

# GLOBAL WELL-POSEDNESS OF MASTER EQUATIONS FOR DETERMINISTIC DISPLACEMENT CONVEX POTENTIAL MEAN FIELD GAMES

WILFRID GANGBO AND ALPÁR R. MÉSZÁROS

ABSTRACT. This manuscript constructs global in time solutions to the *master equations* for potential Mean Field Games. The study concerns a class of Lagrangians and initial values functions, which are *displacement convex* and so, it may be in dichotomy with the class of so-called *monotone* functions, widely considered in the literature. We construct solutions to both the scalar and vectorial master equations in potential Mean Field Games, when the underlying space is the whole space  $\mathbb{R}^d$  and so, it is not compact.

## CONTENTS

Introduction	2
0.1. Summary of our main results	6
1. Preliminaries	8
1.1. Assumptions	8
1.2. Discretization	10
1.3. Direct arguments for $C_{loc}^{1,1}$ -regularity in Hilbert setting	11
2. Comparing regularity properties of functions defined on $\mathcal{P}_2(\mathbb{M})$ , $\mathbb{H}$ and $\mathbb{M}^m$	14
2.1. Semi-convex and semi-concave functions on Hilbert spaces	14
2.2. Notions of convexity on $(\mathcal{P}_2(\mathbb{M}), W_2)$	14
2.3. $C^{1,1}$ functions on $(\mathcal{P}_2(\mathbb{M}), W_2)$ versus $C^{1,1}$ functions on $\mathbb{H}$	16
2.4. Regularity of $\mathcal{U}$ as a by-product of regularity estimates on $U^{(m)}$	19
3. Global well-posedness of master equations	33
3.1. Flows on $\mathbb{H}$ , on $\mathcal{P}_2(\mathbb{M})$ and their properties	33
3.2. The vectorial master equation	35
3.3. The scalar master equation	37
3.4. Examples of initial data	39
4. Further implications of the scalar master equation	55
4.1. Improvements on the notion of weak solution to the vectorial master equation	55
4.2. Convergence of equilibria of games with finitely many players and propagation of chaos	56
Appendix A. Hilbert regularity is too stringent for rearrangement invariant functions	57
Appendix B. Convexity vs displacement convexity	61
B.1. Displacement convexity versus classical convexity	61
B.2. Convexity vs displacement convexity of the action	62
B.3. Convexity of $f(\cdot, \mu)$ is a consequence of the displacement convexity of $\mathcal{F}$	63
B.4. Failure of smoothness of solutions to Hamilton-Jacobi equation for monotone initial data	64
Appendix C. Hamiltonian Flows on the Hilbert space	65
Appendix D. Regularity estimates on solutions to HJEs and Hamiltonian systems for systems of $m$ particles	67
D.1. One particle Hamiltonian flow	67
D.2. $m$ -particles Hamiltonian flow	68
Appendix E. Proofs of the results from Subsection 4.2	76
References	78

## INTRODUCTION

In this manuscript, we study a Hamilton–Jacobi equation on  $\mathcal{P}_2(\mathbb{R}^d)$ , the set of Borel probability measures on  $\mathbb{R}^d$  of finite second moments. This allows to make inferences on the *master equation* in Mean Field Games, introduced by P.-L. Lions in [31]. Our study relies on an special notion of convexity, the so-called displacement convexity, which is a natural for functions  $\mathcal{V} : \mathcal{P}_2(\mathbb{R}^d) \rightarrow \mathbb{R}$ . It differs from the classical notion of convexity on the set of measures, which corresponds to the monotonicity condition, central in most prior work aiming to study global in time solutions to the master equation. A comparison between the classical notion of convexity and displacement convexity can already be made by considering ways of interpolating Dirac masses. Given two Dirac masses  $\delta_{q_0}$  and  $\delta_{q_1}$  the paths

$$[0, 1] \ni t \mapsto \sigma_t := (1-t)\delta_{q_0} + t\delta_{q_1}, \quad [0, 1] \ni t \mapsto \sigma_t^* := \delta_{(1-t)q_0 + tq_1}$$

provide two distinct interpolation these two elements of  $\mathcal{P}_2(\mathbb{R}^d)$ . The function  $\mathcal{V}$  is called convex in the classical sense if it is convexity along classical interpolation, which in particular implies  $t \mapsto \mathcal{V}(\sigma_t)$  is a convex function on  $[0, 1]$ . The function is called *displacement convex* [32] if its restriction to any  $W_2$ -geodesics is convex, which in particular means  $t \mapsto \mathcal{V}(\sigma_t^*)$  is a convex function on  $[0, 1]$ .

A blatant example which shows convexity and displacement convexity cannot be the same is when

$$2\mathcal{V}(\mu) = \int_{\mathbb{R}^{2d}} |q - q'|^2 \mu(dq)\mu(dq'), \quad \mu \in \mathcal{P}_2(\mathbb{R}^d).$$

In this case, it has been long known that  $\mathcal{V}$  is concave in the classical sense while  $\mathcal{V}$  is obviously displacement convex. However, for the purpose of our study, we need to come up with a richer class of examples consistent with our analysis. For instance, let us consider two functions  $\phi, \phi_1 \in C^2(\mathbb{R}^d)$  with bounded second derivatives and such that  $\phi_1$  is even and define

$$2\mathcal{V}(\mu) := \int_{\mathbb{R}^d} (2\phi(q) + \phi_1 * \mu(q)) \mu(dq), \quad \mu \in \mathcal{P}_2(\mathbb{R}^d).$$

Let us recall that (see Lemma B.2) the function  $\mathcal{V}$  is convex in the classical sense if and only if  $\hat{\phi}_1$  – the Fourier transform of  $\phi_1$  – is nonnegative, independently of whether or not additional requirements are imposed on  $\phi$ . Suppose for instance  $\phi$  is  $2\lambda$ -convex for some  $\lambda > 0$ . If  $\phi_1$  is  $\lambda_1$ -convex for some  $2\lambda_1 \in (-\lambda, \lambda)$  then  $\mathcal{V}$  is displacement convex. As discussed in Subsections 3.4 and B.1, we can choose  $\phi_1$  such that  $\hat{\phi}_1$  changes sign, so that  $\mathcal{V}$  fails to be convex in the classical sense.

The theory of well posedness of the so-called master equation in Mean Field Games is well developed on the set of probability measures [9] (for a probabilistic approach to study such equations we refer to [11]), under the so-called monotonicity condition [8] [28] [29] [30], for games where the individual and/or common noises are essential mechanisms governing the games. In the same setting of monotone data, global solutions were also constructed in [13], where the authors can handle even degenerate diffusions in the equations. In the same context, [35] improve the regularity restrictions on the data, which need to be still monotone, and propose a notion of weak solutions for the master equation. When the monotonicity condition fails and the noises are absent, only short time existence results of the scalar master equation were achieved in [24] for special Lagrangians, and later in [33] for more general ones. For classical mean field games systems the smallness of the time horizon sometimes can be replaced by a smallness condition on the data (see for instance [1, 2]). In terms of random variables, a Hilbert space formulation of the master equation incorporating appropriate noises is achieved only for short times [5] for a special class of Lagrangians. The theory of a master equation on a Hilbert space is a delicate to handle if one would like to connect it to an equation on the set of probability measure. For instance imposing more regularity than second order Fréchet differentiability on functions on a Hilbert space may sometimes be a too severe restrictions (see below).

This manuscript constructs global solutions to the master equation in potential Mean Field Games, where *displacement convexity* is used as substitute for the monotonicity condition widely used in the literature. In potential Mean Field Games, one considers smooth enough real valued functions  $\mathcal{U}_0, \mathcal{F}$  defined on  $\mathcal{P}_2(\mathbb{R}^d)$ . We assume there are smooth real valued functions  $u_0, f$  defined on  $\mathbb{R}^d \times \mathcal{P}_2(\mathbb{R}^d)$  which are related to  $\mathcal{U}_0, \mathcal{F}$  in the following sense: the Wasserstein gradient of  $\mathcal{U}_0$  at  $\mu \in \mathcal{P}_2(\mathbb{R}^d)$  equals the finite dimensional gradient  $D_q u_0(\cdot, \mu)$  and the Wasserstein gradient of  $\mathcal{F}$  at  $\mu \in \mathcal{P}_2(\mathbb{R}^d)$  equals the

finite dimensional gradient  $D_q f(\cdot, \mu)$ . Given a Hamiltonian  $H \in C^3(\mathbb{R}^{2d})$  the master equation consists in finding a real valued function  $u$  defined on  $[0, \infty) \times \mathbb{R}^d \times \mathcal{P}_2(\mathbb{R}^d)$ , solution to the non-local equation

$$\begin{cases} \partial_t u + H(q, D_q u) + \mathcal{N}_\mu [D_q u(t, \cdot, \mu), \nabla_w u(t, q, \mu)(\cdot)] = f(x, \mu), & (0, T) \times \mathbb{R}^d \times \mathcal{P}_2(\mathbb{R}^d), \\ u(0, \cdot, \cdot) = u_0, & \mathbb{R}^d \times \mathcal{P}_2(\mathbb{R}^d), \end{cases}$$

Here,  $\mathcal{N}_\mu : L^2(\mu) \times L^2(\mu) \rightarrow \mathbb{R}$  is the non-local operator defined as

$$(0.1) \quad \mathcal{N}_\mu[\eta, \theta] := \int_{\mathbb{R}^d} D_p H(c, \eta(c)) \cdot \theta(c) \mu(dc).$$

Let  $L(q, \cdot)$  be the Legendre transform on  $H(q, \cdot)$  and assume  $L$  is strictly convex and both functions have bounded second order derivatives. Under the assumption that  $\mathcal{U}_0$  and  $\mathcal{F}$  are displacement convex (convex along the Wasserstein geodesics), we construct classical solutions or weak solution to the master equation, depending on the regularity properties imposed on the data. Following [25], the starting point of our study relies on the point of view that the differential structure on  $\mathcal{P}_2(\mathbb{R}^d)$  is inherited from the differential structure on the flat space  $\mathbb{H} := L^2((0, 1)^d, \mathbb{R}^d)$  and the former space can be viewed as the quotient space of the latter. The functions  $\mathcal{U}_0, \mathcal{F}$  are lifted to obtain functions  $\tilde{\mathcal{U}}_0, \tilde{\mathcal{F}}$  defined on the Hilbert space  $\mathbb{H}$ , with the property that they are rearrangement invariant. What we mean by rearrangement invariant is that  $\tilde{\mathcal{U}}_0(x) = \tilde{\mathcal{U}}_0(y)$  whenever the push forward of Lebesgue measure restricted to  $(0, 1)^d$  by  $x, y \in \mathbb{H}$  coincide. In this case, we sometimes say that  $x$  and  $y$  have the same law. The Hamiltonian  $H$  is used to define on the co-tangent bundle  $\mathbb{H}^2$ , another Hamiltonian denoted

$$\tilde{\mathcal{H}}(x, b) := \int_{(0, 1)^d} H(x(\omega), b(\omega)) d\omega - \tilde{\mathcal{F}}(x),$$

The corresponding Lagrangian  $\tilde{\mathcal{L}}$  is on  $\mathbb{H}^2$ , the tangent bundle, and is

$$\tilde{\mathcal{L}}(x, a) := \int_{(0, 1)^d} L(x(\omega), a(\omega)) d\omega + \tilde{\mathcal{F}}(x).$$

Both the Lagrangian and the Hamiltonian are invariant under the action of the group of bijections of  $(0, 1)^d$  onto  $(0, 1)^d$ , which preserves the Lebesgue measure. We are interested in regularity properties of  $\tilde{\mathcal{U}} : (0, \infty) \times \mathbb{H} \rightarrow \mathbb{R}$  solutions to the Hamilton–Jacobi equation

$$\begin{cases} \partial_t \tilde{\mathcal{U}} + \tilde{\mathcal{H}}(\cdot, \nabla_x \tilde{\mathcal{U}}) = 0, & \text{in } (0, \infty) \times \mathbb{H}, \\ \tilde{\mathcal{U}}(0, \cdot) = \tilde{\mathcal{U}}_0 & \text{on } \mathbb{H}. \end{cases}$$

The characteristics of this infinite dimensional PDE and the smoothness properties of  $\tilde{\mathcal{U}}$  will play an essential role in the application of our study to Mean Field Games. They allow us to obtain an explicit representation formula of the solution to the master equation for arbitrarily large times. Similar observations were made also by P.-L. Lions during a recorded seminar talk [31]. This lecture seems to suggest that it was not clear at all how far the displacement convexity assumptions on the data could be used to advance the study the global in time well-posedness of master equations.

Under appropriate growth and convexity conditions on the data, the classical theory of Hamilton–Jacobi equation on Hilbert spaces, ensures that  $\tilde{\mathcal{U}}(t, \cdot)$  is of class  $C_{\text{loc}}^{1,1}(\mathbb{H})$ . Our Hamiltonian and Lagrangian being rearrangement invariant, by the uniqueness theory of Hamilton–Jacobi equation,  $\tilde{\mathcal{U}}(t, \cdot)$  is rearrangement invariant. This allows to define a function  $\mathcal{U}(t, \cdot)$  on  $\mathcal{P}_2(\mathbb{R}^d)$  such that  $\mathcal{U}(t, \mu) = \tilde{\mathcal{U}}(t, x)$  whenever  $x \in \mathbb{H}$  has  $\mu$  as its law. In the same time,  $\mathcal{U}$  will be the unique classical solution to the corresponding Hamilton–Jacobi equation set on  $\mathcal{P}_2(\mathbb{R}^d)$ .

By Lemma 2.13, a function  $\mathcal{V} : \mathcal{P}_2(\mathbb{R}^d) \rightarrow \mathbb{R}$  is of class  $C_{\text{loc}}^{1,1}$  on the Wasserstein space if and only if its lift  $\tilde{\mathcal{V}} : \mathbb{H} \rightarrow \mathbb{R}$  is of class  $C_{\text{loc}}^{1,1}$  on the Hilbert space. Since the Hilbert theory ensures that  $\tilde{\mathcal{U}}(t, \cdot)$  is of class  $C_{\text{loc}}^{1,1}$  on the Hilbert space, we obtain as a by-product that  $\mathcal{U}(t, \cdot)$  is of class  $C_{\text{loc}}^{1,1}$  on the Wasserstein space. This is how far one could push the Hilbert approach in terms of regularity theory if one would like to make useful inference in Mean Field Games. Indeed, imposing that a rearrangement invariant function  $\tilde{\mathcal{V}} : \mathbb{H} \rightarrow \mathbb{R}$  is of class  $C^2$  (twice Fréchet differentiable) is too stringent for the purpose of Mean Field Games. For instance, if  $\phi \in C_c^\infty(\mathbb{R}^d)$  then  $\mathbb{H} \ni x \mapsto \tilde{\mathcal{V}}(x) := \int_{(0, 1)^d} \phi(x(\omega)) d\omega$

does not belong to  $C^2(\mathbb{H})$  unless  $\phi \equiv 0$  (cf. Proposition A.4). Similar conclusions can be drawn on other functionals with a local representation such as

$$\mathbb{H} \ni x \mapsto \tilde{\mathcal{V}}(x) := \int_{(0,1)^{nd}} \phi(x(\omega_1), \dots, x(\omega_n)) d\omega_1 \cdots d\omega_n,$$

when  $\phi \in C^3(\mathbb{R}^{nd})$  is symmetric and have bounded second and third order derivatives (cf. Proposition A.2). Pursuing a deeper analysis, we assume  $\alpha \in (0, 1]$ ,  $\tilde{\mathcal{V}} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$  is rearrangement invariant so that it is the lift of a function  $\mathcal{V} : \mathcal{P}_2(\mathbb{R}^d) \rightarrow \mathbb{R}$ . We show in Lemma A.1 that if (A.1) holds for all  $h, h_* \in \mathbb{H}$  then  $D_q(\nabla_w \mathcal{V}(\mu))$  is constant function on  $\text{spt}(\mu)$ .

A final argument to support the fact that we need a new concepts of higher order derivatives on the set of probability measures is the following. When  $k \geq 3$ , making assumptions on  $k$ -order differentials of Hamiltonians  $\tilde{\mathcal{H}} : \mathbb{H}^2 \rightarrow \mathbb{R}$  and treating them as continuous multi-linear forms on cartesian products of  $\mathbb{H}^2$  is too restrictive for a theory in Mean Field Games. Indeed, frequently used Hamiltonians in Mean Field Games theory are of the form

$$\tilde{\mathcal{H}}(x, b) = \tilde{\mathcal{H}}_H(x, b) - \tilde{\mathcal{F}}(x), \quad \tilde{\mathcal{H}}_H(x, b) \equiv \int_{(0,1)^d} H(x(\omega), b(\omega)) d\omega$$

where  $H \in C^3(\mathbb{R}^{2d})$  is such that  $D^2H$  is bounded. Let  $\alpha \in (0, 1]$ . Even if  $C_{\text{loc}}^{2,\alpha}(\mathbb{H}^2)$  is an infinite dimensional space, its intersection with the set of functions which have a local representation is contained in a finite dimensional space. For instance,

$$(0.2) \quad \dim\left(C_{\text{loc}}^{2,\alpha}(\mathbb{H}^2) \cap \{\tilde{\mathcal{H}}_H : H \in C_{\text{loc}}^{2,\alpha}(\mathbb{R}^{2d}), D^2H \text{ is bounded}\}\right) < \infty.$$

In this manuscript, to write a meaningful master equation, we are interested in functions  $\mathcal{V} : \mathcal{P}_2(\mathbb{R}^d) \rightarrow \mathbb{R}$  which satisfy higher regularity properties than being of  $C_{\text{loc}}^{1,1}$ . We assume at least that their lift  $\tilde{\mathcal{V}} : \mathbb{H} \rightarrow \mathbb{R}$  are such that  $\nabla \mathcal{V}$  is Gâteaux differentiable with bounded second order differential in a sense to be made precise. Due to the rearrangement invariance property of  $\tilde{\mathcal{V}}$ ,  $\nabla^2 \tilde{\mathcal{V}}$  must have a special form. Given  $x \in \mathbb{H}$ , there exist matrix valued maps

$$A_1^* \in L^\infty((0, 1)^d; \mathbb{R}^{d \times d}), \quad A_2^* \in L^\infty((0, 1)^{2d}; \mathbb{R}^{d \times d})$$

such that  $A_1^*$  is symmetric almost everywhere,  $A_2^*(\omega, o) = A_2^*(o, \omega)^\top$  almost everywhere and the operator  $\mathbb{H} \ni \zeta \mapsto \nabla^2 \tilde{\mathcal{V}}(x)\zeta$  can be written

$$(0.3) \quad (\nabla^2 \tilde{\mathcal{V}}(x)\zeta)(\omega) = A_1^*(\omega)\zeta(\omega) + \int_{(0,1)^d} A_2^*(\omega, o)\zeta(o) do.$$

In fact, there are matrices  $A_1$  and  $A_2$  which allow for the factorization

$$A_1^*(\omega) = A_1(x(\omega)), \quad A_2^*(\omega, o) = A_2(x(\omega), x(o)).$$

We argue in Remark 2.12 that  $A_1$  can be interpreted as  $D_q(\nabla_w \mathcal{V}(\mu)(q))$  and indicate the relation between  $A_2$  and the Wasserstein gradient of  $\nabla_w \mathcal{V}$ .

When  $\mathcal{B} \subseteq \mathcal{P}_2(\mathbb{R}^d)$  is an open set, we introduce vector spaces of functions  $C^{2,\alpha,w}(\mathcal{B})$ , as substitutes for the spaces  $C^{2,\alpha}(\mathcal{B})$ . These new spaces are such that whenever  $\mathcal{V} \in C^{2,\alpha,w}(\mathcal{B})$ , its restrictions

$$\mathbb{R}^{nd} \ni (q_1, \dots, q_n) \mapsto \mathcal{V}\left(\frac{1}{n} \sum_{i=1}^n \delta_{q_i}\right)$$

belong to  $C_{\text{loc}}^{2,\alpha}(\mathbb{R}^{nd})$ . The precise definition of this space can be found in Definition 2.11. At least we require that if  $\mathcal{V} \in C^{(2,\alpha,w)}(\mathcal{B})$ , since the second order Gâteaux differential of its lift  $\tilde{\mathcal{V}}$  exists, it must satisfy the property

$$(0.4) \quad \left| \nabla \tilde{\mathcal{V}}(y)(\omega) - \nabla \tilde{\mathcal{V}}(x)(\omega) - \nabla^2 \tilde{\mathcal{V}}(x)(\omega)((y(\omega) - x(\omega))) \right| \leq C\left(|y(\omega) - x(\omega)|^\alpha + \|x - y\|^\alpha\right)$$

whenever  $x, y \in \mathbb{H}$ ,  $x$  pushes  $\mathcal{L}_{(0,1)^d}^d$  forward to  $\mu$ ,  $y$  pushes  $\mathcal{L}_{(0,1)^d}^d$  forward to  $\nu$  and  $\|x - y\| = W_2(\mu, \nu)$ .

A discretization approach, greatly facilitate the task to show (0.3) when  $\tilde{\mathcal{V}}$  is replaced by  $\tilde{\mathcal{U}}(t, \cdot)$ , the solution to the Hamilton–Jacobi equation we constructed on the Hilbert space. This allows us to make inference beyond an estimate such as

$$\sup_{x, h \in \mathbb{H}} \left\{ |D^2 \tilde{\mathcal{U}}(t, x)(h, h)| : \|h\| \leq 1, \|x\| \leq r \right\} < +\infty \quad \forall r > 0.$$

Unlike studies of the master equation in compact settings such as the periodic setting  $\mathbb{R}^d/\mathbb{Z}^d$ , the fact that the range of  $\tilde{\mathcal{U}}$  is certainly unbounded, is a source of additional complications in our study,

When  $\nabla \mathcal{H}$  is Lipschitz, the characteristics of the Hamilton–Jacobi equation are the Hamiltonian flow  $\Sigma = (\Sigma^1, \Sigma^2) : [0, \infty) \times \mathbb{H}^2 \rightarrow \mathbb{H}^2$ , uniquely defined in (1.3). The vector field  $\nabla^\perp \tilde{\mathcal{H}}$  is the velocity in Eulerian coordinates for the trajectory  $\Sigma$  on the cotangent bundle  $\mathbb{H}^2$ . We denote as

$$(\tilde{\xi}, \tilde{\eta}) : [0, \infty) \times \mathbb{H} \rightarrow \mathbb{H}^2$$

the restriction of  $\Sigma$  to the graph of  $\nabla \tilde{\mathcal{U}}_0$  (cf. (1.5)). When  $\tilde{\mathcal{L}}$  and  $\tilde{\mathcal{U}}_0$  are convex, under appropriate standard conditions on  $\tilde{\mathcal{L}}$  and  $\tilde{\mathcal{H}}$ , differentiability properties of  $\tilde{\mathcal{U}}$  are obtained by standard methods. A strict convexity property of  $\tilde{\mathcal{L}}$  ensures that for any fixed  $t \geq 0$ ,  $\xi(t, \cdot)$  is a bijection of  $\mathbb{H}$  onto  $\mathbb{H}$ . The trajectories

$$[0, t] \ni s \mapsto \tilde{S}_s^t[x] := \xi(s, \xi_t^{-1}(x)) \in \mathbb{H}$$

are useful to write the representation formula

$$\tilde{\mathcal{U}}(t, x) = \tilde{\mathcal{U}}_0(\tilde{S}_0^t[x]) + \int_0^t \tilde{\mathcal{L}}(\tilde{S}_s^t[x], \partial_s \tilde{S}_s^t[x]) ds.$$

The identity

$$(0.5) \quad \nabla \tilde{\mathcal{U}}(t, \cdot) = \tilde{\eta}(t, \tilde{S}_0^t)$$

suggests that the smoothness properties of  $\tilde{\mathcal{U}}$  rest on the smoothness properties of  $\tilde{S}_0^t$  and  $\tilde{\eta}$ . While strict convexity of  $\tilde{\mathcal{L}}$  is sufficient to get that the restriction of  $\xi(t, \cdot)^{-1}$  to appropriate finite dimensional spaces is continuously differentiable, it become much harder to show that  $\xi(t, \cdot)^{-1}$  is continuous on the whole space  $\mathbb{H}$  unless appropriate convexity properties are imposed on the data.

Let us consider the vector field

$$B(t, \cdot) := \nabla_b \tilde{\mathcal{H}}(\cdot, \tilde{\eta}(t, \tilde{S}_0^t))$$

which helps to study the second order derivatives of  $\tilde{\mathcal{U}}$  and which represents the velocity of the flow  $\tilde{\xi}$  in physical space, since  $\dot{\tilde{\xi}} = B(s, \tilde{\xi})$ . When  $\tilde{\mathcal{U}}(t, \cdot)$  is twice differentiable then  $\nabla^2 \tilde{\mathcal{U}}(t, x), \nabla B(t, x) : \mathbb{H}^2 \rightarrow \mathbb{R}$  are bilinear forms which satisfy the relation

$$\nabla B(t, x)(h, a) = \nabla^2 \tilde{\mathcal{U}}(t, x) \left( a, D_{pp}^2 H(x, \nabla \tilde{\mathcal{U}}(t, x)) h \right) + \int_{(0,1)^d} \left( D_{qp}^2 H(x, \nabla \tilde{\mathcal{U}}(t, x)) a \right) \cdot h d\omega$$

for  $h, a \in \mathbb{H}$ .

A discretization approach, greatly facilitate the task to show there are Borel maps

$$A_{12} \in L^\infty(\mathbb{R}^d, \mathbb{R}^{d \times d}), \quad A_{22} \in L^\infty(\mathbb{R}^d \times \mathbb{R}^d, \mathbb{R}^{d \times d})$$

such that for  $\varphi \in C_c^\infty(\mathbb{R}^d)$  and  $h := D\varphi \circ x$ ,

$$D^2 \tilde{\mathcal{V}}(x)(h, h) = \int_{(0,1)^d} A_{12}(x(\omega)) h(\omega) \cdot h(\omega) d\omega + \int_{(0,1)^{2d}} A_{22}(x(\omega_1), x(\omega_2)) h(\omega_1) \cdot h(\omega_2) d\omega_1 d\omega_2.$$



By these arguments we can prove Theorem 3.22, the main theorem of this manuscript, which states that under our standing assumptions  $u$  defined in (0.7) is the unique classical solution to the scalar master equation which is of class  $C_{\text{loc}}^{1,1}([0, T] \times \mathbb{R}^d \times \mathcal{P}_2(\mathbb{R}^d))$ .

Theorem 3.22 has several implications. First, the obtained regularity of  $u$  and the fact that  $D_q u(t, \cdot, \mu) = \nabla_w \mathcal{U}(t, \mu)(\cdot)$  on  $\text{spt}(\mu)$ , allow us to deduce that  $D_q u$  is a solution to the vectorial master equation and (0.6) is satisfied for all  $(t, \mu) \in (0, T) \times \mathcal{P}_2(\mathbb{R}^d)$  and for  $\mathcal{L}^d$ -a.e.  $q \in \mathbb{R}^d$ .

Second, since the scalar master equation, and in particular our definition (0.7) possess the features of  $N$ -player differential games, we easily deduce that  $u(t, \cdot, \cdot)$ , when restricted to  $\bigcup_{q \in \mathbb{R}^{Nd}} \mu_q^{(N)} \times \text{spt}(\mu_q^{(N)})$ , provides approximate solutions to a system of Hamilton–Jacobi equation, characterizing the Nash equilibria of the associated  $N$ -player differential game. In the same time, the regularity of  $u$  allows us to deduce the local convergence of Nash equilibria as  $N \rightarrow +\infty$ . Of course, once we have existence of a classical solution to the scalar master equation, these convergence results are expected, as in [9], [18, 19]. The proofs of the results from this subsection are very much inspired by these references. Such rigorous convergence questions for deterministic Mean Field Games were poorly investigated in great generality previously in the literature (we refer to a recent paper [21] for a particular case).

The structure of the rest of the paper is the following. In Section 1 we provide the first part of our standing assumptions, we present the discretization approach and show a direct argument which provides  $C_{\text{loc}}^{1,1}$  regularity for solutions to a class of Hamilton–Jacobi equations set on Hilbert spaces.

In Section 2 we compare notions of convexity and regularity for functions defined on  $\mathcal{P}_2(\mathbb{R}^d)$ , their lifts defined on  $\mathbb{H}$  and their restrictions to discrete measures. Here we also show how can we deduce regularity estimates for functions on  $\mathcal{P}_2(\mathbb{R}^d)$  from precise quantitative derivative estimates on their restrictions to discrete measures.

Section 3 is the core of the manuscript where we investigate the well-posedness of both vectorial and scalar master equations. Additional assumptions need to be imposed to establish the well-posedness of the scalar master equation. These are listed in this section. Here, we also derive important properties of flows on  $\mathbb{H}$  and on their counterparts defined on  $\mathcal{P}_2(\mathbb{R}^d)$  which are used in our proofs.

In Section 4 we have collected two important implications of the scalar master equation. First, the rigorous connection between the vectorial and scalar master equations which in particular leads to an improvement on the notion of weak solution to the vectorial equations. Second, using the solution to the scalar master equation, we present a short discussion on the convergence problem of  $N$ -player differential games, as  $N \rightarrow +\infty$ .

To facilitate the reading of the main text, our manuscript has several appendices. In Appendix A we demonstrate the limitations of the Hilbert space approach, when studying or assuming  $C^{2,\alpha}$  type regularity on rearrangement invariant functionals having local representations.

In Appendix B we emphasize how our setting by imposing displacement convexity of the data can replace the more standard monotonicity assumptions imposed typically in the Mean Field Games literature. Here we provide examples of functionals which produce non-monotone coupling functions and an example of a Hamilton–Jacobi equation on  $\mathcal{P}_2(\mathbb{R}^d)$ , for which the data provides the standard monotonicity condition, yet its classical solution ceases to exist after finite time.

In Appendix C we have collected some standard results on Hamiltonian flows of Hilbert spaces and we explained how the regularity of these flows can be used to show regularity of solution to a Hamilton–Jacobi equations.

Appendix D contains the important quantitative estimates with respect to  $m$  on the Hamiltonian flows of  $m$ -particle systems and the corresponding derivative estimates of the solutions to Hamilton–Jacobi equations set on  $\mathbb{R}^{md}$ . Lastly, in Appendix E we provided the proofs of the results stated in Subsection 4.2.

**ACKNOWLEDGEMENTS** The research of WG was supported by NSF grant DMS-1700202. Both authors acknowledge the support of Air Force grant FA9550-18-1-0502. The authors would like to express their gratitude to P. Cannarsa for the discussions and for pointing out important references on regularity properties of solutions to Hamilton–Jacobi equations on  $\mathbb{R}^d$ . They wish to thank A. Świech for the discussions on regularity of solutions to Hamilton–Jacobi equations on Hilbert spaces. The feedback of P. Cardaliaguet on the manuscript is also greatly appreciated.

## 1. PRELIMINARIES

We start this section with some well-known definitions in the Hilbert setting as well as in the Wasserstein space. We denote as  $\Omega := (0, 1)^d \subset \mathbb{R}^d$  the unit cube and as  $\mathcal{L}_\Omega^d$  the Lebesgue measure restricted to  $\Omega$ . We sometimes refer to any Borel map of  $\Omega$  to  $\mathbb{M}$  as a random variable. We shall work on the Hilbert space

$$\mathbb{H} := L^2(\Omega; \mathbb{R}^d),$$

the set of square integrable Borel vector fields with respect to  $\Omega$ .

Since it is more convenient to write  $\mathbb{M}^m$  instead of  $(\mathbb{R}^d)^m$ , we shall use write  $\mathbb{M}$  in place of  $\mathbb{R}^d$ . Letters  $x, y$  are typically used for elements of  $\mathbb{H}$ , while elements of  $\mathbb{M}$  are typically denoted by  $q, p, v$ . Sometimes, we also use the notation  $\mathbb{R}_+ := [0, +\infty)$ .

Given two topological spaces  $\mathbb{S}_1$  and  $\mathbb{S}_2$ , a Borel measure  $\mu$  on  $\mathbb{S}_1$  and a Borel map  $X : \mathbb{S}_1 \rightarrow \mathbb{S}_2$ ,  $X_\# \mu$  is the measure on  $\mathbb{S}_2$  defined as  $X_\# \mu(B) = \mu(X^{-1}(B))$  for  $B \subset \mathbb{S}_2$ .

The canonical projections  $\pi^1, \pi^2 : \mathbb{M} \times \mathbb{M} \rightarrow \mathbb{M}$  are defined as

$$\pi^1(q_1, q_2) = q_1, \quad \pi^2(q_1, q_2) = q_2 \quad \forall q_1, q_2 \in \mathbb{M}.$$

Given  $\mu_0, \mu_1 \in \mathcal{P}_2(\mathbb{M})$ , we denote as  $\Gamma(\mu_0, \mu_1)$  the set of Borel probability measures  $\gamma$  on  $\mathbb{M} \times \mathbb{M}$  such that  $\pi_\#^1 \gamma = \mu_0$  and  $\pi_\#^2 \gamma = \mu_1$ . We denote as  $\Gamma_o(\mu_0, \mu_1)$  the set of  $\gamma \in \Gamma(\mu_0, \mu_1)$  such that

$$W_2^2(\mu_0, \mu_1) = \int_{\mathbb{R}^{2d}} |q_1 - q_2|^2 \gamma(dq_1, dq_2).$$

The law of  $x \in \mathbb{H}$  is the Borel probability measure  $\sharp(x) := x_\# \mathcal{L}_\Omega^d$ . The map  $\sharp$  maps  $\mathbb{H}$  onto  $\mathcal{P}_2(\mathbb{M})$ , the set of Borel probability measure on  $\mathbb{M}$  of finite second moments. One basic result in measure theory is that as  $\Omega$  has no atoms, any Borel probability measure on  $\mathbb{R}^d$  is the law of a Borel map  $Z : \Omega \rightarrow \mathbb{R}^d$ .

If  $\mu \in \mathcal{P}_2(\mathbb{M})$ , the set of Borel vector fields  $\xi : \mathbb{M} \rightarrow \mathbb{M}$  which are square integrable is denoted as  $L^2(\mu)$ . The tangent space to  $\mathcal{P}_2(\mathbb{M})$  at  $\mu$  denoted as  $T_\mu \mathcal{P}_2(\mathbb{M})$  is closure of  $\nabla C_c^\infty(\mathbb{M})$  in  $L^2(\mu)$ .

If  $\tilde{U} : \mathbb{H} \rightarrow \mathbb{R}$  is differentiable at  $x \in \mathbb{H}$ , we use the notations  $\nabla \tilde{U}(x)$  or  $\nabla_x \tilde{U}(x)$  to denote its Fréchet derivative at  $x$  (as element of  $\mathbb{H}$ ). If  $\tilde{U}$  is twice differentiable at  $x$ , we use the notations  $\nabla^2 \tilde{U}(x)$  or  $\nabla_{xx}^2 \tilde{U}(x)$  to denote its Hessian (as bi-linear form on  $\mathbb{H} \times \mathbb{H}$ ). If  $u : \mathbb{M} \rightarrow \mathbb{R}$  is differentiable at  $q \in \mathbb{M}$ , we use the notation  $Du(q)$  or  $D_q u(q)$  to denote its gradient at  $q$ . If it is twice differentiable at  $q$ , we use the notations  $D^2 u(q)$  or  $D_{qq}^2 u(q)$  to denote its Hessian matrix at  $q$ .

For  $r > 0$ , we define  $\mathcal{B}_r$  to be the closed ball in  $(\mathcal{P}_2(\mathbb{M}), W_2)$ , centered at  $\delta_0$  and of radius  $r$ .  $\mathbb{B}_r(0)$  stands for the closed ball in  $\mathbb{H}$  centered at 0 and of radius  $r$ .

For any integer  $m > 1$  we fix  $(\Omega_i^m)_{i=1}^m$  be a partition of  $\Omega$  into Borel sets of same volume. Given

$$q := (q_1, \dots, q_m), \quad p := (p_1, \dots, p_m) \in \mathbb{M}^m,$$

we set

$$(1.1) \quad M^q := \sum_{i=1}^m q_i \chi_{\Omega_i^m}, \quad M^{mp} := \sum_{i=1}^m (mp_i) \chi_{\Omega_i^m} \equiv mM^p \quad \text{and} \quad \mu_q^{(m)} := \frac{1}{m} \sum_{i=1}^m \delta_{q_i}.$$

We set

$$\mathbb{B}_r^m := \left\{ q \in \mathbb{M}^m : m^{-1} \sum_{j=1}^m |q_j|^2 \leq r^2 \right\}.$$

and

$$\mathcal{P}_2^{(m)}(\mathbb{M}) := \left\{ \sum_{i=1}^m \frac{1}{m} \delta_{q_i} : q \in \mathbb{M}^m \right\}.$$

**1.1. Assumptions.** Throughout this manuscript  $N \geq 1$  is an integer,  $m_*, \kappa_1, \lambda_0 \in \mathbb{R}$  and  $\kappa_0, \lambda_1, \kappa_3 > 0$ . We shall denote as  $\bar{\kappa}$  a generic constant depending on  $m_*, \kappa_0, \kappa_1, r_2, \kappa_3 > 0$ .

Let  $-\infty < s < t < \infty$ , let  $m > 1$  be an integer and let  $\mathbb{R}_+ := [0, \infty)$ .

When  $\mathbb{S}$  is a metric space, we denote as  $AC_2(s, t; \mathbb{S})$  the set of  $S : [s, t] \rightarrow \mathbb{S}$  which are 2-absolutely continuous. When  $\tau \in [s, t]$ , when convenient, we write  $S_\tau$  in place of  $S(\tau)$ . We are imposing the following standing assumptions throughout the paper.



Suppose

$$(H1) \quad \tilde{\mathcal{F}}, \tilde{\mathcal{U}}_0 \in C^{1,1}(\mathbb{H}), \quad \tilde{\mathcal{F}} \geq 0, \tilde{\mathcal{U}}_0 \geq m_*,$$

and are rearrangement invariant in the sense that if  $x, y \in \mathbb{H}$  have the same law, then  $\tilde{\mathcal{F}}(x) = \tilde{\mathcal{F}}(y)$  and  $\tilde{\mathcal{U}}_0(x) = \tilde{\mathcal{U}}_0(y)$ . We assume

$$(H2) \quad \tilde{\mathcal{F}} \text{ is } \kappa_1\text{-convex and } \tilde{\mathcal{U}}_0 \text{ is convex.}$$

and

$$(H3) \quad \nabla \tilde{\mathcal{F}}, \nabla \tilde{\mathcal{U}}_0 \text{ are } \kappa_0\text{-Lipschitz.}$$

Let

$$(H4) \quad H, L \in C^{N+1}(\mathbb{M} \times \mathbb{R}^d), \quad L \geq 0,$$

such that  $L(q, \cdot)$  and  $H(q, \cdot)$  are Legendre transform of each other for any  $q \in \mathbb{M}$ . We assume

$$(H5) \quad D_{vv}^2 L \geq \kappa_3 I_d, \quad D_{pp}^2 H > 0,$$

and

$$(H6) \quad DH, DL \text{ are } \kappa_0\text{-Lipschitz.}$$

We further assume

$$(H7) \quad \lambda_1 |v|^2 + \lambda_0 \leq L(q, v).$$

We set

$$\tilde{\mathcal{L}}(x, a) = \int_{\Omega} L(x(\omega), a(\omega)) d\omega + \tilde{\mathcal{F}}(x), \quad \tilde{\mathcal{H}}(x, b) = \int_{\Omega} H(x(\omega), b(\omega)) d\omega - \tilde{\mathcal{F}}(x)$$

for  $x, a, b \in \mathbb{H}$  and assume

$$(H8) \quad \tilde{\mathcal{L}} \text{ is jointly strictly convex in both variables.}$$

For any  $S \in AC_2(s, t; \mathbb{H})$  we set

$$\tilde{\mathcal{A}}_s^t(S) := \int_s^t \tilde{\mathcal{L}}(S, \dot{S}) d\tau.$$

When  $x, y \in \mathbb{H}$  we set

$$\tilde{C}_s^t(x, y) := \inf_S \left\{ \tilde{\mathcal{A}}_s^t(S) : S(0) = x, S(t) = y, S \in AC_2(s, t; \mathbb{H}) \right\}$$

and define for  $t > 0$ ,

$$(1.2) \quad \tilde{\mathcal{U}}(t, y) = \inf_{z \in \mathbb{H}} \tilde{C}_0^t(z, y) + \tilde{\mathcal{U}}_0(z).$$

We denote as  $AC_2(0, t; \mathbb{H}_y)$  the set of  $S \in AC_2(0, t; \mathbb{H})$  such that  $A_0^t(S) < \infty$  and  $S(t) = y$ .

The second assumption in (H2) and the assumption in (H8) imply  $\tilde{\mathcal{A}}_s^t$  is strictly convex.

**Remark 1.1.** *The following hold.*

- (i) Using (H6), we obtain that  $|H|$  and  $|L|$  are bounded above by quadratic forms.
- (ii) Note that by (H1) and (H7),

$$\tilde{\mathcal{A}}_0^t(S) \geq \lambda_1 \int_0^t \|\dot{S}\|^2 d\tau + \lambda_0 t + m_*.$$

*This ensures a pre-compactness property to the sub-level sets of  $\tilde{\mathcal{A}}_0^t$  when they are contained in  $AC_2(0, t; \mathbb{H}_y)$  for some  $y \in \mathbb{H}$ .*

- (iii) *The functions  $DL, DH, \nabla \tilde{\mathcal{U}}_0$  and  $\nabla \tilde{\mathcal{F}}$  being Lipschitz, there is a constant  $\bar{\kappa}$  such that*

$$|DL(q, v)| \leq \bar{\kappa}(|v| + |q| + 1), \quad |DH(q, p)| \leq \bar{\kappa}(|p| + |q| + 1), \quad \|\nabla \tilde{\mathcal{U}}_0(x)\| + \|\nabla \tilde{\mathcal{F}}(x)\| \leq \bar{\kappa}(\|x\| + 1).$$

The assumptions imposed on  $H$  and  $\tilde{\mathcal{F}}$  ensure  $\nabla\tilde{\mathcal{H}} : \mathbb{H}^2 \rightarrow \mathbb{R}$  is Lipschitz and so, there exists a unique Hamiltonian flow  $\Sigma : \mathbb{R} \times \mathbb{H}^2 \rightarrow \mathbb{H}^2$  on the phase space, solution to the initial value problem

$$(1.3) \quad \begin{cases} \dot{\Sigma}^1(t, \cdot) = \nabla_b \tilde{\mathcal{H}}(\Sigma(t, \cdot)), & \text{in } (0, \infty) \times \mathbb{H}^2, \\ \dot{\Sigma}^2(t, \cdot) = -\nabla_x \tilde{\mathcal{H}}(\Sigma(t, \cdot)), & \text{in } (0, \infty) \times \mathbb{H}^2 \\ \Sigma(0, \cdot) = \text{id}_{\mathbb{H}^2}. \end{cases}$$

By Remark 1.1 (iii) there exists a constant  $\tilde{\kappa} > \bar{\kappa}$  depending only on  $\bar{\kappa}$  such that

$$(1.4) \quad \|\Sigma(t, x, b)\| + 1 \leq (\|(x, b)\| + 1)e^{\tilde{\kappa}t}$$

for any  $t > 0$  and  $x, b \in \mathbb{H}$ . The restriction of  $\Sigma$  to the graph of  $\nabla\tilde{\mathcal{U}}_0$  is the flow map denoted as

$$(1.5) \quad (\tilde{\xi}, \tilde{\eta}) := \Sigma(\cdot, \cdot, \nabla\tilde{\mathcal{U}}_0)$$

on the spatial space, with values in the cotangent bundle. We combine (H3) and (1.4) to find  $c_5 > 0$  depending only on  $\kappa_0$  and  $\|\nabla\tilde{\mathcal{U}}_0(0)\|$  such that

$$(1.6) \quad \|(\tilde{\xi}, \tilde{\eta})\| + 1 \leq c_5(\|x\| + 1)e^{\tilde{\kappa}t}.$$

We discuss some classical properties of the Hamiltonian flow in the setting of Hilbert spaces in Appendix C.

**1.2. Discretization.** Fix a natural number  $m > 1$ . For  $q, v, p \in \mathbb{M}^m$  we define

$$L^{(m)}(q, v) := \int_{\Omega} L(M^q, M^v) d\omega = \frac{1}{m} \sum_{i=1}^m L(q_i, v_i), \quad F^{(m)}(q) := \tilde{\mathcal{F}}(M^q)$$

and

$$H^{(m)}(q, p) := \int_{\Omega} H(M^q, M^{mp}) d\omega = \frac{1}{m} \sum_{i=1}^m H(q_i, mp_i).$$

Then we set

$$\mathcal{L}^m(q, v) := L^{(m)}(q, v) + F^{(m)}(q), \quad \mathcal{H}^m(q, p) := H^{(m)}(q, p) - F^{(m)}(q), \quad U^{(m)}(t, q) := \tilde{\mathcal{U}}(t, M^q).$$

We record the following useful identities. One checks that for each  $j \in \{1, \dots, m\}$ ,  $\nabla\tilde{\mathcal{U}}(t, M^q)$  is constant on  $\Omega_j^m$  and

$$(1.7) \quad D_{q_j} U^{(m)}(t, q_1, \dots, q_m) = \frac{1}{m} \nabla\tilde{\mathcal{U}}(t, M^q)|_{\Omega_j^m}.$$

Note this means in particular,

$$(1.8) \quad \nabla\tilde{\mathcal{U}}_0 : \{M^q : q \in \mathbb{M}^m\} \rightarrow \{M^q : q \in \mathbb{M}^m\}.$$

We infer

$$(1.9) \quad \nabla\tilde{\mathcal{U}}(t, M^q) = m \sum_{j=1}^m \chi_{\Omega_j^m} D_{q_j} U^{(m)}(t, q).$$

Observe

$$(1.10) \quad D_{q_j} \mathcal{L}^m(q, v) = \frac{1}{m} \nabla_x \tilde{\mathcal{L}}(M^q, M^v)|_{\Omega_j^m}, \quad D_{v_j} \mathcal{L}^m(q, v) = \frac{1}{m} \nabla_a \tilde{\mathcal{L}}(M^q, M^v)|_{\Omega_j^m},$$

and so,

$$(1.11) \quad \nabla_x \tilde{\mathcal{L}}(M^q, M^v) = m \sum_{j=1}^m \chi_{\Omega_j^m} D_{q_j} \mathcal{L}^m(q, v), \quad \nabla_a \tilde{\mathcal{L}}(M^q, M^v) = m \sum_{j=1}^m \chi_{\Omega_j^m} D_{v_j} \mathcal{L}^m(q, v).$$

Similarly,

$$(1.12) \quad D_{q_j} \mathcal{H}^m(q, p) = \frac{1}{m} \nabla_x \tilde{\mathcal{H}}(M^q, M^{mp})|_{\Omega_j^m}, \quad D_{p_j} \mathcal{H}^m(q, p) = \nabla_b \tilde{\mathcal{H}}(M^q, M^{mp})|_{\Omega_j^m}.$$

Note that the fact that the coefficient in front of  $\nabla_b \tilde{\mathcal{H}}(M^q, M^{mp})$  is not divided by  $m$  is not a misprint. However, we have

$$(1.13) \quad D_{q_j} \mathcal{H}^m(q, D_q U^{(m)}(t, q)) = \frac{1}{m} \nabla_x \tilde{\mathcal{H}}(M^q, \nabla \tilde{U}(t, M^q))|_{\Omega_j^m},$$

and so,

$$(1.14) \quad \frac{1}{m} \nabla_x \tilde{\mathcal{H}}(M^q, \nabla \tilde{U}(t, M^q)) = \sum_{j=1}^m D_{q_j} \mathcal{H}^m(q, D_q U^{(m)}(t, q)) \chi_{\Omega_j^m}$$

For any natural number  $m$  denote as  $(\Sigma_1^m, \Sigma_2^m) : \mathbb{R} \times \mathbb{M}^{2m} \rightarrow \mathbb{M}^{2m}$  the Hamiltonian flow for  $\mathcal{H}^m$ . For  $x \in \mathbb{H}$  such that  $\sharp(x) = \mu$  the following are well-defined

$$\xi_s[\mu] \circ x = \tilde{\xi}_s[x], \quad \eta_s[\mu] \circ x = \tilde{\eta}_s[x].$$

We consider the spatially discretized flows

$$(1.15) \quad \xi_s^m(q) = \xi_s[\mu_q^{(m)}](q_i), \quad \eta_s^m(q) = \frac{1}{m} \eta_s[\mu_q^{(m)}](q_i).$$

Using the notation  $(\xi^m, \eta^m) = (\xi_1^m, \dots, \xi_m^m, \eta_1^m, \dots, \eta_m^m)$ , the flows are uniquely defined to satisfy

$$(1.16) \quad \begin{cases} \dot{\xi}_i^m(s, q) &= D_{p_i} \tilde{\mathcal{H}}^m(\xi_i^m(s, q), \eta_i^m(s, q)), & \text{for } (s, q) \in (0, \infty) \times \mathbb{M}^m, \\ \dot{\eta}_i^m(s, q) &= -D_{q_i} \tilde{\mathcal{H}}^m(\xi_i^m(s, q), \eta_i^m(s, q)), & \text{for } (s, q) \in (0, \infty) \times \mathbb{M}^m, \\ (\xi^m(0, q), \eta^m(0, q)) &= (q, D_q U_0^{(m)}(q)), & \text{for } q \in \mathbb{M}^m. \end{cases}$$

**1.3. Direct arguments for  $C_{\text{loc}}^{1,1}$ -regularity in Hilbert setting.** Throughout this subsection, we impose (H1)-(H8). We rely on the theory of existence of solutions to Hamilton-Jacobi on Hilbert spaces developed in [16] and [17]. The function  $\tilde{U}$  defined in (1.2) is the unique viscosity solution to

$$(1.17) \quad \begin{cases} \partial_t \tilde{U} + \tilde{\mathcal{H}}(x, \nabla \tilde{U}) = 0, & \text{in } (0, \infty) \times \mathbb{H}, \\ \tilde{U}(0, \cdot) = \tilde{U}_0 & \text{on } \mathbb{H}. \end{cases}$$

The purpose of this subsection is to show that basic analytical tools can be used to verify that  $\tilde{U}$  is of class  $C_{\text{loc}}^{1,1}$ .

**Proposition 1.2.** *There exists  $e_1 \in C(\mathbb{R}_+, \mathbb{R}_+)$  monotone nondecreasing such that the following hold for  $T > 0$ , and  $r > 0$ .*

- (i)  $\tilde{U}$  is  $e_1(r(T+1))$ -Lipschitz on  $[0, T] \times \mathbb{B}_r(0)$ .
- (ii)  $\tilde{U}(t, \cdot)$  is  $e_1(r(t+1))$ -semiconcave on  $\mathbb{B}_r(0)$  for  $t \in [0, T]$ .

*Proof.* The first essential observation to make is that Remark 1.1 (ii) ensures that if  $t > 0$  and  $y \in \mathbb{H}$  then any minimizing sequence for  $\tilde{U}(t, y)$  is bounded in  $AC_2(0, t; \mathbb{H}_y)$ . Denote such a minimizing sequence as  $(S_n)_n \subset AC_2(0, t; \mathbb{H}_y)$ . By Mazur's lemma, we have a convex combination of  $(\dot{S}_n)_n \subset L^2((0, t) \times \mathbb{H})$  which converges strongly. Thus, the appropriate convex combination of  $(S_n)_n$  converges strongly in  $L^2((0, t) \times \mathbb{H})$ . By the convexity property of the functional  $\tilde{\mathcal{A}}_0^t$  and the convexity property of the set  $AC_2(0, t; \mathbb{H}_y)$ , we obtain a new sequence whose limit is a minimizer for  $\tilde{U}(t, y)$ . The proofs presented in [26] extend to our context so that one can show (i) and (ii).  $\square$

**Proposition 1.3.** *There is an increasing function  $e_1 \in C(\mathbb{R}_+, \mathbb{R}_+)$  such that if  $t > 0$  then*

- (i)  $\tilde{U}(t, \cdot)$  is rearrangement invariant.
- (ii)  $\tilde{U}(t, \cdot)$  is convex and so, it is differentiable and  $\nabla \tilde{U}(t, \cdot)$  is  $e_1(r(t+1))$ -Lipschitz on  $\mathbb{B}_r(0)$ .

*Proof.* (i) The invariance property imposed on  $\tilde{U}_0$  and  $\tilde{\mathcal{F}}$  implies  $\tilde{\mathcal{L}}$  satisfies the invariance property

$$\tilde{\mathcal{L}}(x, a) = \tilde{\mathcal{L}}(x \circ E, a \circ E)$$

for  $x, a \in \mathbb{H}$ ,  $E : \Omega \rightarrow \Omega$  such that  $E$  preserves Lebesgue measure. Since  $\tilde{\mathcal{L}}$  is further continuous, we conclude that  $\tilde{U}(t, \cdot)$  is rearrangement invariant for  $t \geq 0$  (cf. [25]).

(ii) The convexity of  $A_0^t$  on  $AC_2(0, t; \mathbb{H})$  yields the convexity of  $\tilde{U}(t, \cdot)$  on  $\mathbb{H}$ . This, together with Proposition 1.2 (ii) completes the proof.  $\square$

**Remark 1.4.** Let  $q \in \mathbb{M}^m$ . Note  $\sigma \mapsto \int_0^t \mathcal{L}^m(\sigma, \dot{\sigma}) d\tau + U_0^{(m)}(\sigma(0))$  is strictly convex on  $AC_2(0, t; q; \mathbb{R}^{md})$ , the set of paths  $\sigma \in AC_2(0, t; \mathbb{R}^{md})$ , such that  $\sigma(t) = q$ . Since  $\tilde{\mathcal{L}}$  is of class  $C^2$  and satisfies the assumptions in Subsection 1.1, standard results of the calculus of variations ensure that  $\int_0^t \mathcal{L}^m(\sigma, \dot{\sigma}) d\tau + U_0^{(m)}(\sigma(0))$  admits a unique minimizer  $\sigma^m$  on  $AC_2(0, t; q; \mathbb{M}^m)$ . The minimizer is completely characterized by the Euler–Lagrange equations

$$(1.18) \quad \frac{d}{d\tau} \left( D_v \mathcal{L}^m(\sigma^m, \dot{\sigma}^m) \right) = D_q \mathcal{L}^m(\sigma^m, \dot{\sigma}^m), \quad \sigma^m(t) = q, \quad D_q U_0^{(m)}(\sigma^m(0)) = D_q \mathcal{L}^m(\sigma^m(0), \dot{\sigma}^m(0)).$$

Define

$$U^m(t, q) := \int_0^t \mathcal{L}^m(\sigma^m, \dot{\sigma}^m) d\tau + U_0^{(m)}(\sigma^m(0)).$$

Then it is well-known that  $U^m$  is the unique continuous viscosity solution to

$$(1.19) \quad \partial_t U^m + \mathcal{H}^m(q, D_q U^m) = 0, \quad \text{on } (0, \infty) \times \mathbb{M}^m, \quad U^m(0, \cdot) = U_0^{(m)}.$$

Setting  $S := M^{\sigma^m}$ , we have  $\dot{S} = M^{\dot{\sigma}^m}$ . We use (1.9) at  $t = 0$ , then use (1.11) and (1.18) to obtain

$$\frac{d}{d\tau} \left( \nabla_a \tilde{\mathcal{L}}(S, \dot{S}) \right) = \nabla_x \tilde{\mathcal{L}}(S, \dot{S}), \quad \nabla \tilde{U}_0(S(0)) = \nabla_a \tilde{\mathcal{L}}(S(0), \dot{S}(0)).$$

This means  $S$  is a critical point of  $A_0^t$  over  $AC_2(0, t; \mathbb{H}_y)$  if we set  $y := M^q$ . Since  $A_0^t$  is convex over  $AC_2(0, t; \mathbb{H}_y)$ , we conclude that  $S$  is a minimizer of  $A_0^t$  over  $AC_2(0, t; \mathbb{H}_y)$ . Thus,

$$U^m(t, q) = A_0^t(S) = \tilde{U}(t, M^q) = U^{(m)}(t, q).$$

Consequently,  $U^{(m)}$  is the unique viscosity solution to (1.19).

**Theorem 1.5.** There exists  $e_0 : [0, \infty) \rightarrow [0, \infty)$ , monotone non-decreasing such that the following hold.

(i) If  $0 \leq t_1 < t_2 \leq T$  then

$$\tilde{U}(t_2, y) - \tilde{U}(t_1, y) = - \int_{t_1}^{t_2} \tilde{\mathcal{H}}(y, \nabla \tilde{U}(\tau, y)) d\tau \quad \forall y \in \mathbb{H}.$$

(ii)  $\tilde{U}$  is continuously differentiable on  $(0, \infty) \times \mathbb{H}$  and  $\partial_t \tilde{U}, \nabla \tilde{U}$  are Lipschitz on  $[0, T] \times \mathbb{B}_r(0)$ .

(iii) For any  $y \in \mathbb{H}$ , there exists a unique  $S \in AC_2(0, t; \mathbb{H}_y)$  such that  $\tilde{U}(t, y) = \tilde{A}_0^t(S) + \tilde{U}_0(S(0))$ .

(iv) Let  $S$  be as in (iii) and set  $P := \nabla_a \tilde{\mathcal{L}}(S, \dot{S})$ . Then  $S, P \in C^2([0, t]; \mathbb{H})$ ,

$$(1.20) \quad \dot{S} = \nabla_b \tilde{\mathcal{H}}(S, P), \quad \dot{P} = \nabla_x \tilde{\mathcal{L}}(S, \dot{S}) = -\nabla_x \tilde{\mathcal{H}}(S, P), \quad \nabla \tilde{U}(\cdot, S) = \nabla_a \tilde{\mathcal{L}}(S, \dot{S}) \quad \text{on } [0, t].$$

In particular,

$$(1.21) \quad \nabla \tilde{U}_0(S(0)) = \nabla_a \tilde{\mathcal{L}}(S(0), \dot{S}(0)).$$

(v) We have

$$\tilde{C}_0^t(S(0), y), \|\dot{S}(\tau)\| \leq e_0((t+1)\|y\|), \quad \|S(\tau)\| \leq \|y\| + te_0((t+1)\|y\|) \quad \forall \tau \in [0, t].$$

*Proof.* Let  $y \in \mathbb{B}_r(0)$ .

(i) By Remark 1.4,  $U^{(m)}$  is a viscosity solution to (1.19) and so, the standard theory of Hamilton–Jacobi equations in finite dimensional spaces yields the pointwise identity

$$U^{(m)}(t_2, q) - U^{(m)}(t_1, q) = - \int_{t_1}^{t_2} \mathcal{H}^m(q, D_q U^{(m)}(\tau, q)) d\tau$$

for  $q \in \mathbb{M}^m$ . We use (1.9) to infer

$$\tilde{U}(t_2, M^q) - \tilde{U}(t_1, M^q) = - \int_{t_1}^{t_2} \tilde{\mathcal{H}}(M^q, \nabla \tilde{U}(\tau, M^q)) d\tau$$

By Proposition 1.3(ii),  $\nabla \tilde{U}$  is bounded on  $[t_1, t_2] \times \mathbb{B}_r(y)$  for all  $r > 1$ . Since  $\nabla \tilde{U}(\tau, \cdot)$  is continuous for each  $\tau \in [t_1, t_2]$  and  $\tilde{\mathcal{H}}$  is continuous, we use the fact that  $\{M^q : q \in \mathbb{M}^m, m \in \mathbb{N}\}$  is dense in  $\mathbb{H}$  to obtain (i).

(ii) Let  $h \in \mathbb{B}_1(0)$  and set  $y_2 := y + h$ . By (i)

$$(1.22) \quad \tilde{\mathcal{U}}(t_2, y_2) - \tilde{\mathcal{U}}(t_1, y_2) - \tilde{\mathcal{U}}(t_2, y) + \tilde{\mathcal{U}}(t_1, y) = \int_{t_1}^{t_2} \left( \tilde{\mathcal{H}}(y_2, \nabla \tilde{\mathcal{U}}(\tau, y_2)) - \tilde{\mathcal{H}}(y, \nabla \tilde{\mathcal{U}}(\tau, y)) \right) d\tau.$$

Since  $\tilde{\mathcal{H}}$  is locally Lipschitz and by Proposition 1.3(ii)  $\nabla \tilde{\mathcal{U}}(\tau, \cdot)$  is uniformly Lipschitz on  $\mathbb{B}_{r+1}(0)$ , we obtain a finite number  $c(r, T)$  increasing in the variables  $r$  and  $T$  such that

$$\int_{t_1}^{t_2} \left| \tilde{\mathcal{H}}(y, \nabla \tilde{\mathcal{U}}(\tau, y_2)) - \tilde{\mathcal{H}}(y, \nabla \tilde{\mathcal{U}}(\tau, y)) \right| d\tau \leq \|h\| c(r, T) |t_2 - t_1|.$$

and

$$\int_{t_1}^{t_2} \left| \tilde{\mathcal{H}}(y_2, \nabla \tilde{\mathcal{U}}(\tau, y_2)) - \tilde{\mathcal{H}}(y, \nabla \tilde{\mathcal{U}}(\tau, y_2)) \right| d\tau \leq \|h\| c(r, T) |t_2 - t_1|.$$

We use (1.22) to infer

$$\int_0^1 \left( \tilde{\nabla} \mathcal{U}(t_2, y + th) - \tilde{\nabla} \mathcal{U}(t_1, y + lh) \right) dl \cdot h \leq 2 \|h\| c(r, T) |t_2 - t_1|.$$

Let  $\epsilon \in \mathbb{R}$  and write  $h = \epsilon \hat{h}$  with  $\|\hat{h}\| = 1$ . We let  $\epsilon$  tend to 0 to conclude that

$$\left( \tilde{\nabla} \mathcal{U}(t_2, y) - \tilde{\nabla} \mathcal{U}(t_1, y) \right) \cdot \hat{h} \leq 2c(r, T) |t_2 - t_1|.$$

Hence,

$$(1.23) \quad \left| \tilde{\nabla} \mathcal{U}(t_2, y) - \tilde{\nabla} \mathcal{U}(t_1, y) \right| \leq 2c(r, T) |t_2 - t_1|.$$

This together with the space Lipschitz property of  $\nabla \tilde{\mathcal{U}}$  implies  $\nabla \tilde{\mathcal{U}}$  is Lipschitz on  $[0, T] \times \mathbb{B}_r(0)$ .

It remains to show that  $\partial_t \tilde{\mathcal{U}}$  is Lipschitz on  $[0, T] \times \mathbb{B}_r(0)$ . As a composition of locally-Lipschitz functions,  $(\tau, x) \rightarrow \tilde{\mathcal{H}}(x, \nabla \tilde{\mathcal{U}}(\tau, x))$  is Lipschitz on  $[0, T] \times \mathbb{B}_r(0)$ . Hence since by (i)  $\partial_t \tilde{\mathcal{U}} = -\tilde{\mathcal{H}}(\cdot, \nabla \tilde{\mathcal{U}})$ , we conclude  $\partial_t \tilde{\mathcal{U}}$  is Lipschitz on  $[0, T] \times \mathbb{B}_r(0)$ .

(iii) is a folklore when  $\mathbb{H}$  is a finite dimensional space. The methods used under the latter assumption extend to infinite dimensional Hilbert space except that in general Hilbert setting,  $\tilde{\mathcal{U}}(t, \cdot)$  is not a minimum. However, due to the convexity properties of the functionals we are minimizing, Mazur's lemma can be applied to replace minimizing sequences by a finite convex combination of minimizing sequence which converge in some stronger topology (cf. also [26]). Unique of the minimizer follows from the strict convexity property of  $\tilde{\mathcal{L}}$ .

(iv-v) One sees from [26] that the arguments used when  $\mathbb{H}$  is a finite dimensional space can be extended to the infinite dimensional case to obtain (iv) and the first two identities in (v). Since  $S(\tau) = y + \int_t^\tau \dot{S}(t) dl$ , the third identity in (v) follows from the second identity there.  $\square$

**Remark 1.6.** (i) We denote the unique  $S$  which appears in Theorem 1.5 (iii) as

$$\tilde{S}_s^t[y](\omega) := S(s, \omega), \quad 0 \leq s \leq t, \quad \omega \in \Omega.$$

It is uniquely characterized by the equation

$$(1.24) \quad \tilde{\mathcal{U}}(t, y) = \int_0^t \tilde{\mathcal{L}}\left(\tilde{S}_s^t[y], \partial_s \tilde{S}_s^t[y]\right) ds + \tilde{\mathcal{U}}_0(\tilde{S}_0^t[y]), \quad S_t^t[y] = y.$$

Defining

$$\tilde{P}_s^t[y] = \nabla_a \tilde{\mathcal{L}}(\tilde{S}_s^t[y], \partial_s \tilde{S}_s^t[y]),$$

we have

$$(1.25) \quad \begin{cases} \partial_s \tilde{S}_s^t[y] &= \nabla_b \tilde{\mathcal{H}}(\tilde{S}_s^t[y], \tilde{P}_s^t[y]), & \text{for } (s, y) \in (0, t) \times \mathbb{H}, \\ \partial_s \tilde{P}_s^t[y] &= -\nabla_x \tilde{\mathcal{H}}(\tilde{S}_s^t[y], \tilde{P}_s^t[y]), & \text{for } (s, y) \in (0, t) \times \mathbb{H} \\ (\tilde{S}_t^t[y], \tilde{P}_t^t[y]) &= (y, \nabla \tilde{\mathcal{U}}_0(y)), & \text{for } y \in \mathbb{H}. \end{cases}$$

(ii) If  $\sharp(y) = \mu$  we define  $S_s^t[\mu]$  and  $P_s^t[\mu]$  on the support of  $\mu$  as

$$S_s^t[\mu] \circ y = \tilde{S}_s^t[y], \quad P_s^t[\mu] \circ y = \tilde{P}_s^t[y] \quad 0 \leq s \leq t.$$

Under appropriate conditions, the flows  $S_s^t[\mu]$  and  $P_s^t[\mu]$  will be extended (cf. Proposition 3.13 and Remark 3.14) to the whole space  $\mathbb{M}$ .

(iii) For any natural number  $m$  and  $q \in \mathbb{M}^m$ , we have

$$(1.26) \quad \tilde{S}_s^t[M^q] = M^{\sigma_s^{t,m}[q]},$$

where  $(\sigma_s^{t,m}[q])_{s \in (0,t)}$  is the optimizer discussed in Remark 1.4.

(iv) When the conditions in Remark 1.6 are satisfied, we define the vector field

$$(1.27) \quad B(t, \cdot) := \nabla_b \tilde{\mathcal{H}}(\cdot, \tilde{\eta}(t, \tilde{S}_0^t)).$$

which will turn out to be the velocity in Eulerian coordinates for the trajectory  $\tilde{\xi}$ .

## 2. COMPARING REGULARITY PROPERTIES OF FUNCTIONS DEFINED ON $\mathcal{P}_2(\mathbb{M})$ , $\mathbb{H}$ AND $\mathbb{M}^m$

Throughout this section, we lift any given function  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  to  $\mathbb{H}$  to obtain the function  $\tilde{\mathcal{U}} : \mathbb{H} \rightarrow \mathbb{R}$  defined as  $\tilde{\mathcal{U}}(x) := \mathcal{U}(\sharp(x))$ . Recall  $(\Omega_j)_{j=1}^m$  is the Borel partition in Section 1. We set

$$U^{(m)}(q) := \mathcal{U}(\mu_q^{(m)}) = \tilde{\mathcal{U}}(M^q).$$

### 2.1. Semi-convex and semi-concave functions on Hilbert spaces.

**Definition 2.1** (Semi-convexity and semi-concavity on  $\mathbb{H}$ ). *Let  $\mathbb{B} \subseteq \mathbb{H}$  be a convex open set. We say that  $\tilde{\mathcal{U}} : \mathbb{B} \rightarrow \mathbb{R}$  is semi-convex (or  $\lambda$ -convex) on  $\mathbb{B}$ , if there exists  $\lambda \in \mathbb{R}$  and for all  $x \in \mathbb{B}$  there exists a continuous linear form  $\theta_x$  on  $\mathbb{H}$  such that*

$$\tilde{\mathcal{U}}(y) \geq \tilde{\mathcal{U}}(x) + \theta_x(y - x) + \frac{\lambda}{2} \|x - y\|^2, \quad \forall y \in \mathbb{B}.$$

We say that a function  $\tilde{\mathcal{U}} : \mathbb{B} \rightarrow \mathbb{R}$  is  $\lambda$ -concave, if  $-\tilde{\mathcal{U}}$  is  $(-\lambda)$ -semi-convex.

**Remark 2.2.** *The previous definition has an equivalent reformulation. Let  $\mathbb{B} \subseteq \mathbb{H}$  be a convex open set. Then  $\tilde{\mathcal{U}} : \mathbb{B} \rightarrow \mathbb{R}$  is  $\lambda$ -convex if and only if*

$$\tilde{\mathcal{U}}((1-t)x + ty) \leq (1-t)\tilde{\mathcal{U}}(x) + t\tilde{\mathcal{U}}(y) - \frac{\lambda}{2} t(1-t) \|x - y\|^2, \quad \forall t \in [0, 1], \quad \forall x, y \in \mathbb{B}.$$

**Definition 2.3** ( $C^{1,1}$  functions). *We say that  $\tilde{\mathcal{U}} : \mathbb{B} \rightarrow \mathbb{R}$  is  $C^{1,1}$  on an open set  $\mathbb{B} \subseteq \mathbb{H}$ , if it is Fréchet differentiable on  $\mathbb{B}$  and its Fréchet differential is Lipschitz continuous, i.e. there exists  $C > 0$  such that*

$$\|\nabla \tilde{\mathcal{U}}(x) - \nabla \tilde{\mathcal{U}}(y)\| \leq C \|x - y\|, \quad \forall x, y \in \mathbb{B}.$$

Inspired from similar results on finite dimensional smooth manifold (see for instance in [20]), we can state the following characterization of  $C^{1,1}$  functions defined on subsets of  $\mathbb{H}$ .

**Remark 2.4.** *In fact  $\tilde{\mathcal{U}} : \mathbb{B} \rightarrow \mathbb{R}$  is  $C^{1,1}$  on a convex set  $\mathbb{B} \subseteq \mathbb{H}$  if and only if it is Fréchet differentiable on  $\mathbb{B}$  and there exists  $K \geq 0$  such that*

$$(2.1) \quad |\tilde{\mathcal{U}}(y) - \tilde{\mathcal{U}}(x) - \nabla \tilde{\mathcal{U}}(x)(y - x)| \leq K \|x - y\|^2, \quad \forall x, y \in \mathbb{B}.$$

**2.2. Notions of convexity on  $(\mathcal{P}_2(\mathbb{M}), W_2)$ .** There are various notions of convexity for functionals defined on the Wasserstein space. The concept of so-called *displacement convexity* [4, 32] is expressed in terms of  $W_2$ -geodesics. Recall that given  $\mu_0, \mu_1 \in \mathcal{P}_2(\mathbb{M})$ , for any geodesics  $[0, 1] \ni t \mapsto \mu_t \in \mathcal{P}_2(\mathbb{M})$ , of constant speed connecting  $\mu_0$  to  $\mu_1$  in  $\mathcal{P}_2(\mathbb{M})$  is of the form  $\mu_t = \mu_t := ((1-t)\pi^1 + t\pi^1)_{\sharp} \gamma$  for some  $\gamma \in \Gamma_o(\mu_0, \mu_1)$ , then

**Definition 2.5** (Semi-convexity and semi-concavity on  $(\mathcal{P}_2(\mathbb{M}), W_2)$ ). *Let  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$ .*

(1-i) *We say that  $\mathcal{U}$  is semi-convex (or  $\lambda$ -convex) in the classical sense if there is  $\lambda \in \mathbb{R}$  such that*

$$\mathcal{U}((1-t)\mu_0 + t\mu_1) \leq (1-t)\mathcal{U}(\mu_0) + t\mathcal{U}(\mu_1) - \frac{\lambda}{2} t(1-t) W_2^2(\mu_0, \mu_1), \quad \forall \mu_0, \mu_1 \in \mathcal{P}_2(\mathbb{M}), \quad \forall t \in [0, 1].$$

- (1-ii) We say that  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  is semi-concave (or  $\lambda$ -concave) in the classical sense if  $-\mathcal{U}$  is  $(-\lambda)$ -convex. We refer to 0-convex and 0-concave functions simply as convex and concave functions, respectively.
- (2-i) We say  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  is displacement semi-convex (or displacement  $\lambda$ -convex) if there exists  $\lambda \in \mathbb{R}$  such that for any  $[0, 1] \ni t \mapsto \mu_t \in \mathcal{P}_2(\mathbb{M})$  stands for any geodesic of constant speed connecting  $\mu_0$  to  $\mu_1$  we have

$$\mathcal{U}(\mu_t) \leq (1-t)\mathcal{U}(\mu_0) + t\mathcal{U}(\mu_1) - \frac{\lambda}{2}t(1-t)W_2^2(\mu_0, \mu_1), \quad \forall \mu_0, \mu_1 \in \mathcal{P}_2(\mathbb{M}), \quad \forall t \in [0, 1].$$

- (2-ii) We say that  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  is displacement semi-concave (or displacement  $\lambda$ -concave) if  $-\mathcal{U}$  is displacement  $(-\lambda)$ -convex. We refer to displacement 0-convex and displacement 0-concave as simply displacement convex and displacement concave, respectively.

The following results link  $\lambda$ -convexity on the Wasserstein, the Hilbert and the finite dimensional space  $\mathbb{M}^m$ . This is a generalization of Proposition 5.79 from [10].

**Lemma 2.6.** Let  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  be a continuous function and let  $\tilde{\mathcal{U}} : \mathbb{H} \rightarrow \mathbb{R}$  be defined as  $\tilde{\mathcal{U}} := \mathcal{U} \circ \sharp$  so that  $\tilde{\mathcal{U}}$  is continuous. As above consider for a natural number  $m$  consider  $U^{(m)} : \mathbb{M}^m \rightarrow \mathbb{R}$ . Finally, fix  $\lambda \in \mathbb{R}$ . Then the followings are equivalent.

- (1)  $\tilde{\mathcal{U}}$  is  $\lambda$ -convex on  $\mathbb{H}$ ;
- (2)  $\mathcal{U}$  is displacement  $\lambda$ -convex on  $(\mathcal{P}_2(\mathbb{M}), W_2)$
- (3) For any natural number  $m$ , we have that  $U^{(m)}$  is  $\frac{\lambda}{m}$ -convex on  $\mathbb{M}^m$ .

*Proof.* (1) $\Rightarrow$ (2). Let us suppose  $\tilde{\mathcal{U}}$  is  $\lambda$ -convex, let  $\mu, \nu \in \mathcal{P}(\mathbb{M})$  and let  $\gamma \in \Gamma_o(\mu, \nu)$ . Then, there exist  $x, y \in \mathbb{H}$  such that  $(x, y)_{\sharp} \mathcal{L}_{\Omega}^d = \gamma$ . In particular, we have  $\sharp(x) = \mu$ ,  $\sharp(y) = \nu$  and  $W_2(\mu, \nu) = \|x - y\|$ . For  $[0, 1] \ni t \mapsto \mu_t := [(1-t)\pi^1 + t\pi^2]_{\sharp} \gamma$  is a geodesic of constant speed connecting  $\mu$  to  $\nu$ . Actually, any geodesic between  $\mu$  and  $\nu$  has this representation. By the  $\lambda$ -convexity of  $\tilde{\mathcal{U}}$  we have

$$\begin{aligned} \mathcal{U}(\mu_t) &= \mathcal{U}(\sharp[(1-t)x + ty]) = \tilde{\mathcal{U}}((1-t)x + ty) \\ &\leq (1-t)\tilde{\mathcal{U}}(x) + t\tilde{\mathcal{U}}(y) - \frac{\lambda}{2}t(1-t)\|x - y\|^2 \\ &= (1-t)\mathcal{U}(\mu) + t\mathcal{U}(\nu) - \frac{\lambda}{2}t(1-t)W_2^2(\mu, \nu). \end{aligned}$$

Thus,  $\mathcal{U}$  is displacement  $\lambda$ -convex.

(2) $\Rightarrow$ (3). Let us suppose that  $\mathcal{U}$  is displacement  $\lambda$ -convex and we show that  $U^{(m)}$  is  $\frac{\lambda}{m}$ -convex on  $\mathbb{M}^m$ . Let us fix  $(q_1, \dots, q_m) \in \mathbb{M}^m$ . It is enough to show the  $\frac{\lambda}{m}$ -convexity of  $U^{(m)}$  in a small neighborhood of this fixed point. Therefore, let  $(q'_1, \dots, q'_m) \in \mathbb{M}^m$  be such that  $\max\{|q_i - q'_i| : i \in \{1, \dots, m\}\}$  is small so that  $W_2^2(\mu_q^{(m)}, \mu_{q'}^{(m)}) = \frac{1}{m} \sum_{i=1}^m |q_i - q'_i|^2$ . By this assumption, we also have that the constant speed geodesic connecting  $\mu_q^{(m)}$  to  $\mu_{q'}^{(m)}$  in a unit time is given by  $[0, 1] \ni t \mapsto \mu_t^{(m)} = \frac{1}{m} \sum_{i=1}^m \delta_{(1-t)q_i + tq'_i}$ .

By this construction, for  $t \in [0, 1]$  we have

$$\begin{aligned} U^{(m)}((1-t)q + tq') &= \mathcal{U}(\mu_t^{(m)}) \\ &\leq (1-t)\mathcal{U}(\mu_q^{(m)}) + t\mathcal{U}(\mu_{q'}^{(m)}) - \frac{\lambda}{2}t(1-t)W_2^2(\mu_q^{(m)}, \mu_{q'}^{(m)}) \\ &= (1-t)U^{(m)}(q) + tU^{(m)}(q') - \frac{\lambda}{2m}t(1-t) \sum_{i=1}^m |q_i - q'_i|^2. \end{aligned}$$

Therefore, the  $\frac{\lambda}{m}$ -convexity of  $U^{(m)}$  in a small neighborhood of  $q$  follows.

(3) $\Rightarrow$ (1) We suppose  $U^{(m)}$  is  $\frac{\lambda}{m}$ -convex for all natural number  $m$ . We plan to show the  $\lambda$ -convexity of  $\tilde{\mathcal{U}}$  on  $\mathbb{H}$ . Note the  $\frac{\lambda}{m}$ -convexity of  $U^{(m)}$  is equivalent to the  $\lambda$ -convexity of the restriction of  $\tilde{\mathcal{U}}$  to  $\{M^q : q \in \mathbb{R}^{md}\} \subset \mathbb{H}$ . In particular, the Lipschitz constants of these restrictions are bounded from above by a number which is independent of  $m$ . These finite dimensional functions then have a unique

extension  $\tilde{\mathcal{V}}$  on  $\mathbb{H}$ , which is  $\lambda$ -convex and coincides with  $\tilde{\mathcal{U}}$  on a dense subset of  $\mathbb{H}$ . It suffices to know that  $\tilde{\mathcal{U}}$  is continuous to conclude that it is nothing but  $\tilde{\mathcal{V}}$ .  $\square$

**2.3.  $C^{1,1}$  functions on  $(\mathcal{P}_2(\mathbb{M}), W_2)$  versus  $C^{1,1}$  functions on  $\mathbb{H}$ .** Given a differentiable function  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  (cf. [4]), we denote as  $\nabla_w \mathcal{U}$  the Wasserstein gradient field of  $\mathcal{U}$ . This subsection exploits the connection between the differential of  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  and the differential of its lift  $\tilde{\mathcal{U}} : \mathbb{H} \rightarrow \mathbb{R}$  ([25]). More precisely, we have the following result.

**Remark 2.7.** *Let  $x \in \mathbb{H}$  and set  $\mu := \sharp(x)$ . Then  $\mathcal{U}$  is differentiable at  $\mu$  if and only if  $\tilde{\mathcal{U}}$  is differentiable at  $x$  and in this case, we have the factorization  $\nabla \tilde{\mathcal{U}}(x) = \nabla_w \mathcal{U}(\mu) \circ x$ .*

**Definition 2.8.** *Let  $\mathcal{B} \subseteq \mathcal{P}_2(\mathbb{M})$  be open and geodesically convex. We say that  $\mathcal{U} \in C^{1,1}(\mathcal{B})$ , if it is continuously differentiable on  $\mathcal{B}$  and there exists a constant  $C \geq 0$  such that*

(1)  $\text{spt}(\mu) \ni q_1 \mapsto \nabla_w \mathcal{U}(\mu)(q_1)$  is Lipschitz continuous with constant  $C$  for any  $\mu \in \mathcal{B}$ .

(2)  $\left| \mathcal{U}(\nu) - \mathcal{U}(\mu) - \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_2 - q_1) d\gamma(q_1, q_2) \right| \leq CW_2^2(\mu, \nu), \forall \mu, \nu \in \mathcal{B}, \forall \gamma \in \Gamma_o(\mu, \nu).$

**Definition 2.9.** *Similarly to the previous definition, let  $\mathcal{B} \subseteq \mathcal{P}_2(\mathbb{M})$  be open and geodesically convex and let  $K \subseteq \mathbb{M}$  be a convex open set. We say that  $u \in C^{1,1}(K \times \mathcal{B})$ , if it is continuously differentiable on  $K \times \mathcal{B}$  and there exists a constant  $C \geq 0$  such that*

(1)  $\text{spt}(\mu) \ni q_1 \mapsto \nabla_w u(q, \mu)(q_1)$  is Lipschitz continuous with constant  $C$  for any  $(q, \mu) \in K \times \mathcal{B}$ .

(2)

$$\left| u(\bar{q}, \nu) - u(q, \mu) - D_q u(q, \mu) \cdot (\bar{q} - q) - \int_{\mathbb{M}^2} \nabla_w u(q, \mu)(q_1) \cdot (q_2 - q_1) d\gamma(q_1, q_2) \right| \leq C (|\bar{q} - q|^2 + W_2^2(\mu, \nu)),$$

$$\forall \bar{q}, q \in K, \mu, \nu \in \mathcal{B}, \forall \gamma \in \Gamma_o(\mu, \nu).$$

**Remark 2.10.** (i) *Let us notice that Definition 2.8(2) implies that  $\nabla_w \mathcal{U}$  is ‘Lipschitz continuous’ in the following sense. We have*

$$\left| \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_1 - q_2) d\gamma(q_1, q_2) - \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\nu)(q_2) \cdot (q_1 - q_2) d\tilde{\gamma}(q_2, q_1) \right| \leq 2CW_2^2(\mu, \nu),$$

for any  $\mu, \nu \in \mathcal{B}$  and  $\gamma \in \Gamma_o(\mu, \nu), \tilde{\gamma} \in \Gamma_o(\nu, \mu)$ .

(ii) *Let us underline that the inequality in Definition 2.8(2) naturally encodes also the fact that  $\mathcal{U}$  is locally Lipschitz continuous. Indeed, that inequality, implies that*

$$\begin{aligned} |\mathcal{U}(\nu) - \mathcal{U}(\mu)| &\leq CW_2^2(\mu, \nu) + \int_{\mathbb{M}^2} |\nabla_w \mathcal{U}(\mu)(q_1)| \cdot |q_2 - q_1| d\gamma(q_1, q_2) \\ &\leq CW_2^2(\mu, \nu) + \|\nabla_w \mathcal{U}(\mu)\|_{L^2(\mu)} W_2(\mu, \nu) = \left( CW_2(\mu, \nu) + \|\nabla_w \mathcal{U}(\mu)\|_{L^2(\mu)} \right) W_2(\mu, \nu), \end{aligned}$$

so the local Lipschitz property follows.

(iii) *Definition 2.9(2) naturally encodes that  $K \ni q \mapsto u(q, \mu)$  is of class  $C^{1,1}$ , uniformly with respect to  $\mu$ .*

**Definition 2.11.** *Let  $\mathcal{B} \subseteq \mathcal{P}_2(\mathbb{M})$  be open and geodesically convex and let  $\alpha \in (0, 1]$ . We say that  $\mathcal{U} \in C^{2,\alpha,w}(\mathcal{B})$ , if  $\mathcal{U} \in C^{1,1}(\mathcal{B})$ , and if there exist a constant  $C > 0$ , and functions*

$$\Lambda_0 : \mathbb{R}^d \times \mathcal{B} \rightarrow \mathbb{R}^{d \times d}, \quad \Lambda_1 : \mathbb{M}^2 \times \mathcal{B} \rightarrow \mathbb{R}^{d \times d}$$

such that

$$\Lambda_0 \in L^\infty(\mathbb{M}; \mu), \quad \Lambda_1 \in L^\infty(\mathbb{M}^2; \mu \otimes \mu)$$

(1)

$$\left| \nabla_w \mathcal{U}(\nu)(\bar{q}_1) - \nabla_w \mathcal{U}(\mu)(q_1) - \Lambda_0(q_1, \mu)(\bar{q}_1 - q_1) - \int_{\mathbb{M}^2} \Lambda_1(q_1, a, \mu)(b - a) d\gamma(a, b) \right| \leq C (|q_1 - \bar{q}_1|^{1+\alpha} + W_2(\mu, \nu)^{1+\alpha})$$



- (2)  $\Lambda_0$  and  $\Lambda_1$  are  $\alpha$ -Hölder continuous, i.e.

$$|\Lambda_0(q_1, \mu) - \Lambda_0(\bar{q}_1, \nu)|_\infty \leq C(|q_1 - \bar{q}_1|^\alpha + W_2^\alpha(\mu, \nu))$$

and

$$|\Lambda_1(q_1, q_2, \mu) - \Lambda_1(\bar{q}_1, \bar{q}_2, \nu)|_\infty \leq C(|q_1 - \bar{q}_1|^\alpha + |q_2 - \bar{q}_2|^\alpha + W_2^\alpha(\mu, \nu)),$$

for any  $\mu, \nu \in \mathcal{B}$ ,  $(q_1, \bar{q}_1), (q_2, \bar{q}_2) \in \text{spt}(\mu) \times \text{spt}(\nu)$  and  $\gamma \in \Gamma_o(\mu, \nu)$ .

We say that  $\mathcal{U} \in C_{\text{loc}}^{2,\alpha,w}(\mathcal{P}_2(\mathbb{M}))$ , if  $\mathcal{U} \in C^{2,\alpha,w}(\mathcal{B}_r)$  for all  $r > 0$ .

**Remark 2.12.** Let  $\Lambda_0$  and  $\Lambda_1$  be as above.

- (1) By abuse of notation we write

$$D_{q_1}(\nabla_w \mathcal{U}(\mu)(q_1)) := \Lambda_0(q_1, \mu) \quad \text{and} \quad \bar{\nabla}_{ww}^2 \mathcal{U}(\mu)(q_1, q_2) := \Lambda_1(q_1, q_2, \mu),$$

for all  $\mu \in \mathcal{P}_2(\mathbb{M})$  and  $x, y \in \text{spt}(\mu)$ . The bar is to recall that  $\Lambda_1$  is not exactly the second Wasserstein gradient as introduced in [15].

- (2) Note that if we choose any matrix  $\Lambda(a, \mu)$  such that any of its rows  $w$  is such that  $\nabla \cdot (w\mu) = 0$  and  $w \in L^2(\mu)$ , then the matrix defined as  $\bar{\Lambda}_1(q, a, \mu) := \Lambda_1(q, a, \mu) + \Lambda(a, \mu)$  also satisfies Definition 2.11 (1). We could determine  $\Lambda_1(q, \cdot, \mu)$  uniquely by imposing that the  $i$ -th row of  $(\Lambda_0(q, \mu), \Lambda_1(q, \cdot, \mu))$  is the unique element of minimal norm of the subdifferential of  $(q, \mu) \rightarrow \nabla_w \mathcal{U}(\mu)(q)$ . The  $i$ -th row of the element of minimal norm belongs to  $\mathbb{M} \times T_\mu \mathcal{P}_2(\mathbb{M})$  and the new matrix will be denoted as  $\nabla_{ww}^2 \mathcal{U}(\mu)$ . This new matrix is selected at the expense of giving up the property that  $\Lambda_1$  is uniformly bounded. Increasing  $C$  if necessary, we can instead ensure

$$\|\nabla_{ww}^2 \mathcal{U}(\mu)(q_1, \cdot)\|_\mu \leq C(r) \quad \forall \mu \in \mathcal{B}, \forall q_1 \in \text{spt}(\mu).$$

- (3) In the spirit of the terminology used in [15], we refer to  $\bar{\nabla}_{ww}^2 \mathcal{U}$  as an extended ‘‘Wasserstein Hessian’’ of  $\mathcal{U}$ . In contrast with the assumptions in [15], in Definition 2.11 (1), we assume slightly different conditions: the expansion here is required only on  $\text{spt}(\mu) \times \text{spt}(\nu)$ ,  $\Lambda_0$  and  $\Lambda_1$  are supposed to be essentially bounded only on  $\text{spt}(\mu)$ , and in addition we require the Hölder/Lipschitz property in Definition 2.11 (2) to be fulfilled.
- (4) Let us compare our definition of  $C_{\text{loc}}^{2,\alpha,w}(\mathcal{P}_2(\mathbb{M}))$  regularity of  $\mathcal{U}$  to  $C_{\text{loc}}^{2,\alpha}(\mathbb{H})$  regularity of  $\tilde{\mathcal{U}}$  (where  $\tilde{\mathcal{U}}(x) = \mathcal{U}(\sharp(x))$ ). If  $\tilde{\mathcal{U}} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$ , then  $\tilde{\mathcal{U}}$  is twice continuously differentiable in the Fréchet sense and for each  $r > 0$  there exists  $C = C(r)$  such that

$$(2.2) \quad \|\nabla \tilde{\mathcal{U}}(y) - \nabla \tilde{\mathcal{U}}(x) - \nabla^2 \tilde{\mathcal{U}}(x)(y - x, \cdot)\| \leq C\|x - y\|^{1+\alpha}, \quad \forall x, y \in \mathbb{B}_r.$$

To heuristically compare this inequality to the setting of  $\mathcal{P}_2(\mathbb{M})$  we proceed as follows. Let  $\sharp(x) = \mu$  and  $\sharp(y) = \nu$  with  $\|x - y\| = W_2(\mu, \nu)$ . Then we know (see [25]) that  $\nabla \tilde{\mathcal{U}}(x) = \nabla_w \mathcal{U}(\mu) \circ x$ ,  $\nabla \tilde{\mathcal{U}}(y) = \nabla_w \mathcal{U}(\nu) \circ y$  and

$$\nabla^2 \tilde{\mathcal{U}}(x)(h, h_*) = \int_{\Omega} D_q(\nabla_w \mathcal{U}(\mu)) \circ x \cdot h \cdot h_* d\omega + \int_{\Omega^2} \nabla_{ww}^2 \mathcal{U}(\mu)(x(\omega), x(\omega_*)) h(\omega) \cdot h_*(\omega_*) d\omega d\omega_*,$$

if  $\xi, \xi_* \in T_\mu \mathcal{P}_2(\mathbb{M})$  and  $h = \xi \circ x$  and  $h_* = \xi_* \circ x$ . Thus, (2.2) would read as

$$(2.3) \quad \sup_{\|h_*\| \leq 1} \left| \int_{\Omega} [\nabla_w \mathcal{U}(\nu)(y(\omega)) \cdot h_*(\omega) - \nabla_w \mathcal{U}(\mu)(x(\omega)) \cdot h_*(\omega)] d\omega - \int_{\Omega} D_q(\nabla_w \mathcal{U}(\mu)) \circ x(y - x) \cdot h_* d\omega - \int_{\Omega^2} \nabla_{ww}^2 \mathcal{U}(\mu)(x(\omega), x(\omega_*))(y - x)(\omega) \cdot h_*(\omega_*) d\omega d\omega_* \right| \leq CW_2(\mu, \nu)^{1+\alpha}.$$

From here we see, a necessary condition to obtain inequality (1) in Definition 2.11 is to have (2.3) hold when we maximize over the set of  $h$  such that  $\|h_*\|_{L^1} \leq 1$  rather than maximizing over the set of  $h$  such that  $\|h_*\| \leq 1$ . In other words, we have not been able to show that if  $\tilde{\mathcal{U}} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$  then  $\mathcal{U} \in C_{\text{loc}}^{2,\alpha,w}(\mathcal{P}_2(\mathbb{M}))$ . However, in Appendix A we show that imposing  $\mathcal{U} \in C_{\text{loc}}^{2,\alpha,w}(\mathcal{P}_2(\mathbb{M}))$  in general does not imply that  $\tilde{\mathcal{U}} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$ .

**Lemma 2.13.**  $\mathcal{U} \in C^{1,1}(\mathcal{P}_2(\mathbb{M}))$  if and only if  $\tilde{\mathcal{U}} \in C^{1,1}(\mathbb{H})$ .

*Proof. Part 1.* Suppose first that  $\tilde{\mathcal{U}} \in C^{1,1}(\mathbb{H})$  so that by Remark 2.4 there exists a constant  $C \geq 0$  such that

$$(2.4) \quad |\tilde{\mathcal{U}}(y) - \tilde{\mathcal{U}}(x) - \nabla \tilde{\mathcal{U}}(x)(y - x)| \leq \frac{C}{2} \|x - y\|^2, \quad \forall x, y \in \mathbb{H}.$$

This implies in particular that  $\mathcal{U} \in C^1(\mathcal{P}_2(\mathbb{M}))$  and for any  $x \in \mathbb{H}$  such that  $\sharp(x) = \mu \in \mathcal{P}_2(\mathbb{M})$ , we have  $\nabla \tilde{\mathcal{U}}(x) = \nabla_w \mathcal{U}(\mu) \circ x$ .

*Claim.* For any  $\mu \in \mathcal{P}_2(\mathbb{M})$ ,  $q \mapsto \nabla_w \mathcal{U}(\mu)(q)$  is Lipschitz continuous on  $\text{spt}(\mu)$  uniformly in  $\mu$ , with Lipschitz constant at most  $C$ .

*Proof of the claim.* Let  $\mu \in \mathcal{P}_2(\mathbb{M})$  and consider  $x, y \in \mathbb{H}$ , such that  $\sharp(x) = \sharp(y) = \mu$  and  $\|x - y\| > 0$ . Since  $\nabla \tilde{\mathcal{U}}$  is Lipschitz continuous, one has that

$$\|\nabla \tilde{\mathcal{U}}(x) - \nabla \tilde{\mathcal{U}}(y)\| \leq C \|x - y\|.$$

This reads off

$$(2.5) \quad \|\nabla_w \mathcal{U}(\mu)(x) - \nabla_w \mathcal{U}(\mu)(y)\| \leq C \|x - y\|.$$

Suppose that  $\text{spt}(\mu)$  contains more than one element, otherwise the statement is trivial. Although  $x$  is defined up to a set of measure zero, we are going to choose a representative which is Borel. Set

$$\Omega_0 := \{\omega \in \Omega \mid \omega \text{ is a Lebesgue point for } x, \nabla \tilde{\mathcal{U}}(x)\} \cap x^{-1}(\text{spt}(\mu))$$

Note that  $\Omega_0$  is a set of full measure in  $\Omega$  and so,  $x(\Omega_0)$  is a set of full  $\mu$ -measure. In fact, we do not know that  $x(\Omega_0)$  is Borel, but we can find a Borel set  $A \subset x(\Omega_0)$  of full  $\mu$ -measure.

We suppose that  $A$  has more than one element, otherwise the statement is trivial. Let  $q_1, q_2 \in A$  with  $q_1 \neq q_2$  and let  $q_1^0, q_2^0 \in \Omega_0$  such that  $x(q_1^0) = q_1$  and  $x(q_2^0) = q_2$ . Let  $r > 0$  small such that  $B_r(q_1^0) \cap B_r(q_2^0) = \emptyset$ . Set

$$(2.6) \quad S_r(\omega) := \begin{cases} \omega, & \text{if } \omega \in \Omega \setminus (B_r(q_1^0) \cup B_r(q_2^0)), \\ \omega - q_1^0 + q_2^0, & \text{if } \omega \in B_r(q_1^0), \\ \omega - q_2^0 + q_1^0, & \text{if } \omega \in B_r(q_2^0). \end{cases}$$

Since  $S_r$  preserves  $\mathcal{L}^d \llcorner \Omega$ ,  $x$  and  $y := x \circ S_r$  have the same law  $\mu$ . We notice that in particular

$$y = x \chi_{\mathbb{M} \setminus (B_r(q_1^0) \cup B_r(q_2^0))} + x(\cdot + q_2^0 - q_1^0) \chi_{B_r(q_1^0)} + x(\cdot + q_1^0 - q_2^0) \chi_{B_r(q_2^0)}.$$

Since  $q_1$  and  $q_2$  are distinct image points of  $x$ , for  $r > 0$  sufficiently small

$$\|x - y\|^2 = \int_{B_r(q_1^0)} |x(z) - x(z + q_2^0 - q_1^0)|^2 dz + \int_{B_r(q_2^0)} |x(z) - x(z + q_1^0 - q_2^0)|^2 dz > 0.$$

Similarly, (2.5) yields

$$\begin{aligned} \|\nabla_w \mathcal{U}(\mu)(x) - \nabla_w \mathcal{U}(\mu)(y)\|^2 &= \int_{B_r(q_1^0)} |\nabla_w \mathcal{U}(\mu)(x(z)) - \nabla_w \mathcal{U}(\mu)(x(z + q_2^0 - q_1^0))|^2 dz \\ &\quad + \int_{B_r(q_2^0)} |\nabla_w \mathcal{U}(\mu)(x(z)) - \nabla_w \mathcal{U}(\mu)(x(z + q_1^0 - q_2^0))|^2 dz \\ &\leq C^2 \left( \int_{B_r(q_1^0)} |x(z) - x(z + q_2^0 - q_1^0)|^2 dz + \int_{B_r(q_2^0)} |x(z) - x(z + q_1^0 - q_2^0)|^2 dz \right) \end{aligned}$$

Now, dividing the inequality by  $\mathcal{L}^d(B_r(q_1^0))$ , and sending  $r \downarrow 0$ , since  $q_1^0$  and  $q_2^0$  are Lebesgue point of  $x$  with  $x(q_1^0) = q_1$  and  $x(q_2^0) = q_2$ , one obtains that

$$|\nabla_w \mathcal{U}(\mu)(q_1) - \nabla_w \mathcal{U}(\mu)(q_2)| \leq C |q_1 - q_2|,$$

as desired. The claim follows.

Now, let  $\mu, \nu \in \mathcal{P}(\mathbb{M})$  and  $x, y \in \mathbb{H}$  such that  $\sharp(x) = \mu$ ,  $\sharp(y) = \nu$  and  $W_2(\mu, \nu) = \|x - y\|$ . Let us note that  $\gamma := \sharp(x, y) \in \Gamma_o(\mu, \nu)$ . We have

$$\nabla \tilde{\mathcal{U}}(x)(y - x) = \int_{\Omega} \nabla_w \mathcal{U}(\mu)(x(\omega)) \cdot (y(\omega) - x(\omega)) d\omega = \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_2 - q_1) d\gamma(q_1, q_2).$$

Thus, by (2.4)

$$\left| \mathcal{U}(\nu) - \mathcal{U}(\mu) - \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_2 - q_1) d\gamma(q_1, q_2) \right| \leq \frac{C}{2} W_2^2(\mu, \nu),$$

which by the arbitrariness of  $\mu, \nu$  implies the statement.

**Part 2.** We now need to prove the reversed implication and start by assuming that  $\mathcal{U}$  is  $C^{1,1}(\mathcal{P}_2(\mathbb{M}))$ . In particular  $\nabla_w \mathcal{U}(\mu)(\cdot)$  is  $C$ -Lipschitz continuous on  $\text{spt}(\mu)$  (uniformly in  $\mu$ ) and increasing the value of  $C$  if necessary, we assume the inequality in Definition 2.8(2) to hold with the same constant  $C$ . Take  $x, y \in \mathbb{H}$  and set  $\mu := \sharp(x)$  and  $\nu := \sharp(y)$ . Recall  $\tilde{\mathcal{U}} \in C^1(\mathbb{H})$  and  $\nabla_{T^2} \tilde{\mathcal{U}}(x) = \nabla_w \mathcal{U}(\mu) \circ x$ . Let  $\gamma := \sharp(x, y)$  and let  $\gamma_0 \in \Gamma_o(\mu, \nu)$ . We have

$$\begin{aligned} & \left| \tilde{\mathcal{U}}(y) - \tilde{\mathcal{U}}(x) - \nabla \tilde{\mathcal{U}}(x)(y - x) \right| \\ &= \left| \mathcal{U}(\nu) - \mathcal{U}(\mu) - \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_2 - q_1) d\gamma(q_1, q_2) \right| \\ &\leq \left| \mathcal{U}(\nu) - \mathcal{U}(\mu) - \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_2 - q_1) d\gamma_0(q_1, q_2) \right| \\ &+ \left| \int_{\mathbb{M}^2} \nabla_w \mathcal{U}(\mu)(q_1) \cdot (q_2 - q_1) d(\gamma_0 - \gamma)(q_1, q_2) \right| \\ &\leq C W_2^2(\mu, \nu) + \frac{1}{2} \|D_q \nabla_w \mathcal{U}(\mu)\|_{L^\infty} \left( \int_{\mathbb{M}^2} |q_1 - q_2|^2 d\gamma(q_1, q_2) + \int_{\mathbb{M}^2} |q_1 - q_2|^2 d\gamma_0(q_1, q_2) \right) \\ &\leq C W_2^2(\mu, \nu) + \frac{1}{2} C (\|x - y\|^2 + W_2^2(\mu, \nu)) \leq 2C \|x - y\|^2, \end{aligned}$$

where in the penultimate line we used an inequality from Lemma 3.3 [25]. Indeed, according to Lemma 3.3 [25] if  $\gamma_1, \gamma_2 \in \Gamma(\mu, \nu)$  and  $\xi \in C^2(\mathbb{M})$ , then

$$\left| \int_{\mathbb{M}^2} D\xi(q_1) \cdot (q_2 - q_1) d(\gamma_1 - \gamma_2)(q_1, q_2) \right| \leq \frac{1}{2} \|D^2 \xi\|_{L^\infty} \left( \int_{\mathbb{M}^2} |q_1 - q_2|^2 d(\gamma_1 + \gamma_2)(q_1, q_2) \right).$$

It is easy to see that this inequality is still valid for  $\xi \in C^{1,1}(\mathbb{M})$ . In our setting  $\xi = \nabla_w \mathcal{U}(\mu)$  is Lipschitz continuous on  $\text{spt}(\mu)$ , uniformly in  $\mu$ , for which we use its Lipschitz extension to  $\mathbb{M}$ .

This completes the verification of the proof of the lemma.  $\square$

**Remark 2.14.** (i) *It seems an interesting open problem whether the equivalence in Lemma 2.13 hold for  $C^{1,\alpha}$  functions for  $\alpha \in (0, 1)$ .*

(ii) *The previous result can be seen as a refinement of Proposition 5.36 from [10].*

**2.4. Regularity of  $\mathcal{U}$  as a by-product of regularity estimates on  $U^{(m)}$ .** This subsection infer regularity properties on functions  $\mathcal{U}$  defined on  $\mathcal{P}_2(\mathbb{M})$ , from estimates on their restrictions  $U^{(m)}$ . Recall that for  $r > 0$   $\mathbb{B}_r^m$  is a ball in  $\mathbb{M}^m$  while  $\mathcal{B}_r$  is a ball in  $\mathcal{P}_2(\mathbb{M})$ . We assume that we have at hand a constant  $C = C(r) > 0$ .

**Property 2.15.** *For a permutation invariant function  $G^{(m)} : \mathbb{M}^m \rightarrow \mathbb{R}$  we define the following properties by assuming for each  $r > 0$ , there is  $C \equiv C(r)$  increasing in  $r$  such that the following hold.*

(1) (a)  $G^{(m)} \in C_{\text{loc}}^{0,1}(\mathbb{M}^m)$  and for every  $m \in \mathbb{N}$  and  $q \in \mathbb{B}_r^m(0)$  we have

$$(2.7) \quad |D_{q_i} G^{(m)}(q)| \leq C m^{-1}, \quad \forall i \in \{1, \dots, m\}.$$

(b)  $G^{(m)} \in C_{\text{loc}}^{0,1}(\mathbb{M}^m)$  and for every  $m \in \mathbb{N}$  and  $q \in \mathbb{B}_r^m(0)$  we have

$$(2.8) \quad \sum_{i=1}^m m |D_{q_i} G^{(m)}(q)|^2 \leq C.$$

(2)  $G^{(m)} \in C_{\text{loc}}^{1,1}(\mathbb{M}^m)$  and for every  $m \in \mathbb{N}$  and  $q \in \mathbb{B}_r^m(0)$  we have

$$(2.9) \quad |D_{q_i q_j}^2 G^{(m)}(q)|_\infty \leq \begin{cases} C m^{-1}, & i = j; i \in \{1, \dots, m\} \\ C m^{-2}, & i \neq j; i, j \in \{1, \dots, m\}. \end{cases}$$

Here for  $A = (A_{ij})_{i,j=1}^m$ , we use the notation  $|A|_\infty := \max_{(i,j)} |A_{ij}|$ .

(3)  $G^{(m)} \in C_{\text{loc}}^{2,1}(\mathbb{M}^m)$  and for every  $m \in \mathbb{N}$  and  $q \in \mathbb{B}_r^m(0)$  we have

$$(2.10) \quad |D_{q_i q_j q_k}^3 G^{(m)}(q)|_\infty \leq \begin{cases} Cm^{-1}, & i = j = k; i \in \{1, \dots, m\} \\ Cm^{-2}, & (i = j \neq k) \text{ or } (i \neq j = k) \text{ or } (i = k \neq j); i, j, k \in \{1, \dots, m\} \\ Cm^{-2}, & i \neq j \neq k, i, j, k \in \{1, \dots, m\}. \end{cases}$$

Here for  $A = (A_{ijk})_{i,j,k=1}^m$ , we use the notation  $|A|_\infty := \max_{(i,j,k)} |A_{ijk}|$ .

**Lemma 2.16.** *Suppose for each  $m \in \mathbb{N}$  fixed,  $U^{(m)} : \mathbb{M}^m \rightarrow \mathbb{R}$  is permutation invariant with respect to its  $m$ -variables and  $|U^{(m)}|$  is bounded on  $\mathbb{B}_r^m$  by a constant which depends on  $r > 0$  but is independent of  $m$ . Then there exists  $C = C(r) > 0$  such that the followings hold true.*

(i) *If  $U^{(m)}$  satisfies Property 2.15 (1)-(b) then for any  $q, b \in \mathbb{B}_r^m$ , we have*

$$|U^{(m)}(q) - U^{(m)}(b)| \leq CW_2(\mu_q^{(m)}, \mu_b^{(m)}).$$

(ii) *If  $U^{(m)}$  satisfies Property 2.15 (2). Then for any  $q, b \in \mathbb{B}_r^m$ , we have*

$$\left| U^{(m)}(b) - U^{(m)}(q) - \sum_{i=1}^m D_{q_i} U^{(m)}(q) \cdot (b_i - q_i) \right| \leq CW_2^2(\mu_q^{(m)}, \mu_b^{(m)}).$$

(iii) *The assumption in (ii) implies for any  $q, b \in \mathbb{B}_r^m$ ,*

(a)

$$m|D_{q_i} U^{(m)}(q) - D_{q_i} U^{(m)}(b)| \leq C \left( |q_i - b_i| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) \right).$$

(b) *We have*

$$m|D_{q_i} U^{(m)}(q) - D_{q_j} U^{(m)}(b)| \leq C \left( |q_i - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{1}{\sqrt{m}} \right), \quad i \neq j.$$

(iv) *Suppose that  $U^{(m)}$  satisfies Property 2.15 (3). If  $i \in \{1, \dots, m\}$  and  $q, b \in \mathbb{B}_r^m$  then*

$$m \left| D_{q_i} U^{(m)}(b) - D_{q_i} U^{(m)}(q) - \sum_{j=1}^m D_{q_i q_j}^2 U^{(m)}(q) (b_j - q_j) \right| \leq C \left( |q_i - b_i|^2 + W_2^2(\mu_q^{(m)}, \mu_b^{(m)}) \right).$$

(v) *The assumption in (iv) implies,  $q, b \in \mathbb{B}_r^m$ ,*

(a) *If  $i \neq j$  then*

$$m^2 |D_{q_i q_j}^2 U^{(m)}(q) - D_{q_i q_j}^2 U^{(m)}(b)| \leq C \left( |q_i - b_i| + |q_j - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) \right).$$

(b) *If  $(i, j) \neq (k, l), i \neq j, k \neq l$  then*

$$m^2 |D_{q_i q_j}^2 U^{(m)}(q) - D_{q_k q_l}^2 U^{(m)}(b)| \leq C \left( |q_i - b_k| + |q_j - b_l| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{1}{\sqrt{m}} \right).$$

(c) *We have*

$$m|D_{q_i q_i}^2 U^{(m)}(q) - D_{q_i q_i}^2 U^{(m)}(b)| \leq C \left( |q_i - b_i| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) \right).$$

(d) *We have*

$$m|D_{q_i q_i}^2 U^{(m)}(q) - D_{q_j q_j}^2 U^{(m)}(b)| \leq C \left( |q_i - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{1}{\sqrt{m}} \right).$$

*Proof.* Since  $U^{(m)}$  is permutation invariant reordering  $q$  and  $b$  if necessary, we may assume

$$\gamma^{(m)} := \frac{1}{m} \sum_{i=1}^m \delta_{(q_i, b_i)} \in \Gamma_o(\mu_q^{(m)}, \mu_b^{(m)}).$$

Below, using Taylor expansion, we may find  $\xi \in \mathbb{B}_r^m$  on the line segment connecting  $q$  to  $b$  such that (using the shorthand notation  $\|\cdot\|_\infty$  to denote  $\|\cdot\|_{L^\infty(\mathbb{B}_r^m)}$ )

(i) we have

$$|U^{(m)}(b) - U^{(m)}(q)| \leq \left| \sum_{i=1}^m D_{q_i} U^{(m)}(\xi) \cdot (b_i - q_i) \right| \leq \left( \sum_{i=1}^m m |D_{q_i} U^{(m)}|^2 \right)^{\frac{1}{2}} \left( \sum_{i=1}^m \frac{1}{m} |q_i - b_i|^2 \right)^{\frac{1}{2}}.$$

Using the fact that

$$\sum_{i=1}^m m |D_{q_i} U^{(m)}(q)|^2 \leq C^2 \quad \text{and} \quad \sum_{i=1}^m \frac{1}{m} |q_i - b_i|^2 = W_2^2(\mu_q^{(m)}, \mu_b^{(m)}),$$

we verify the statement in (i).

(ii) A second order Taylor expansion yields

$$\begin{aligned} U^{(m)}(b) - U^{(m)}(q) - \sum_{i=1}^m D_{q_i} U^{(m)}(q) \cdot (b_i - q_i) &= \frac{1}{2} \sum_{i,j=1}^m \langle (b_i - q_i), D_{q_i q_j}^2 U^{(m)}(\xi) (b_j - q_j) \rangle \\ &= \frac{1}{2} \sum_{i=1}^m \langle (b_i - q_i), D_{q_i q_i}^2 U^{(m)}(\xi) (b_i - q_i) \rangle + \frac{1}{2} \sum_{i \neq j} \langle (b_i - q_i), D_{q_i q_j}^2 U^{(m)}(\xi) (b_j - q_j) \rangle \end{aligned}$$

Thus, under the assumption in (ii), we have

$$\begin{aligned} \left| U^{(m)}(b) - U^{(m)}(q) - \sum_{i=1}^m D_{q_i} U^{(m)}(q) \cdot (b_i - q_i) \right| &\leq \frac{C}{2m} \sum_{i=1}^m |q_i - b_i|^2 + \frac{1}{4} \sum_{i \neq j} \|D_{q_i q_j}^2 U^{(m)}\|_{\infty} |q_i - b_i|^2 \\ &\quad + \frac{1}{4} \sum_{i \neq j} \|D_{q_i q_j}^2 U^{(m)}\|_{\infty} |q_j - b_j|^2 \\ &\leq \left( \frac{C}{2} + \frac{C}{4} + \frac{C}{4} \right) \int_{\mathbb{M}^2} |z - w|^2 d\gamma^{(m)}(z, w) = CW_2^2(\mu_q^{(m)}, \mu_b^{(m)}). \end{aligned}$$

(iii)-(a) Performing again a first order Taylor expansion, we find

$$\begin{aligned} D_{q_i} U^{(m)}(q) - D_{q_i} U^{(m)}(b) &= \sum_{k=1}^m D_{q_k q_i}^2 U^{(m)}(q) (q_k - b_k) \\ &= D_{q_i q_i}^2 U^{(m)}(\xi) (q_i - b_i) + \sum_{k \neq i} D_{q_k q_i}^2 U^{(m)}(\xi) (q_k - b_k). \end{aligned}$$

Thus using the assumptions, we find

$$\begin{aligned} \left| D_{q_i} U^{(m)}(q) - D_{q_i} U^{(m)}(b) \right| &\leq \frac{C}{m} |q_i - b_i| + \left( \sum_{k \neq i} m^3 \|D_{q_k q_i}^2 U^{(m)}\|_{\infty}^2 \right)^{\frac{1}{2}} \left( \sum_{k \neq i} \frac{1}{m^3} |q_k - b_k|^2 \right)^{\frac{1}{2}} \\ &\leq \frac{C}{m} \left( |q_i - b_i| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) \right). \end{aligned}$$

(iii)-(b) Without loss of generality, let us suppose that  $i < j$ . By the permutation invariance of  $U^{(m)}$ , we observe that  $D_{q_i} U^{(m)}(q) = D_{q_1} U^{(m)}(q^{ij})$  and a similar identity holds for  $D_{q_j} U^{(m)}(b)$  if we set

$$(2.11) \quad q^{ij} := (q_i, q_j, q_1, \dots, q_{i-1}, q_{i+1}, \dots, q_{j-1}, q_{j+1}, \dots, q_m).$$

Using a similar identity for  $D_{q_j}U^{(m)}(b)$  we obtain

$$\begin{aligned}
|D_{q_i}U^{(m)}(q) - D_{q_j}U^{(m)}(b)| &= |D_{q_1}U^{(m)}(q^{ij}) - D_{q_1}U^{(m)}(b^{ij})| \\
&\leq \|D_{q_1q_1}^2U^{(m)}\|_\infty|q_i - b_j| + \|D_{q_2q_1}^2U^{(m)}\|_\infty|q_j - b_i| \\
&\quad + \sum_{k=1}^{i-1} \|D_{q_{k+2}q_1}^2U^{(m)}\|_\infty|q_k - b_k| + \sum_{k=i+1}^{j-1} \|D_{q_{k+1}q_1}^2U^{(m)}\|_\infty|q_k - b_k| \\
&\quad + \sum_{k=j+1}^m \|D_{q_kq_1}^2U^{(m)}\|_\infty|q_k - b_k|.
\end{aligned}$$

Thus,

$$\begin{aligned}
|D_{q_i}U^{(m)}(q) - D_{q_j}U^{(m)}(b)| &\leq \frac{C}{m}|q_i - b_j| + \frac{C}{m^2}(|q_j| + |b_i|) + \frac{C}{m^2} \sum_{k=1}^m |q_k - b_k| \\
&\leq \frac{C}{m} \left( |q_i - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{2r\sqrt{m}}{m} \right) \\
&\leq \frac{C}{m} \left( |q_i - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{1}{\sqrt{m}} \right),
\end{aligned}$$

where we have used the assumptions on  $D_{q_iq_j}^2U^{(m)}$  and in the last two rows we used the facts that since  $q, b \in \mathbb{B}_r^m$ , we have that  $|q_i|, |b_j| \leq r\sqrt{m}$ , for all  $i, j \in \{1, \dots, m\}$ .

(iv) Similarly to the previous points, we perform a Taylor expansion (of order two) to obtain

$$D_{q_i}U^{(m)}(b) - D_{q_i}U^{(m)}(q) - \sum_{j=1}^m D_{q_iq_j}^2U^{(m)}(q)(b_j - q_j) = \frac{1}{2} \sum_{j,k=1}^m \langle (b_k - q_k), D_{q_iq_jq_k}^3U^{(m)}(q)(b_j - q_j) \rangle,$$

and thus

$$\begin{aligned}
&\left| D_{q_i}U^{(m)}(b) - D_{q_i}U^{(m)}(q) - \sum_{j=1}^m D_{q_iq_j}^2U^{(m)}(q)(b_j - q_j) \right| \\
&\leq \frac{1}{2} \|D_{q_iq_iq_i}^3U^{(m)}\|_\infty |q_i - b_i|^2 + \frac{1}{2} \sum_{j \neq i} \|D_{q_iq_jq_j}^3U^{(m)}\|_\infty |q_j - b_j|^2 \\
&\quad + \frac{1}{2} \sum_{j \neq k \neq i} \|D_{q_iq_jq_k}^3U^{(m)}\|_\infty |q_j - b_j| \cdot |q_k - b_k|.
\end{aligned}$$

We conclude

$$\begin{aligned}
&\left| D_{q_i}U^{(m)}(b) - D_{q_i}U^{(m)}(q) - \sum_{j=1}^m D_{q_iq_j}^2U^{(m)}(q)(b_j - q_j) \right| \\
&\leq \frac{C}{2m} |q_i - b_i|^2 + \frac{C}{2m} \sum_{j=1}^m \frac{1}{m} |q_j - b_j|^2 + \frac{C}{2m} \left( \sum_{j=1}^m \frac{1}{m} |q_j - b_j| \right) \left( \sum_{k=1}^m \frac{1}{m} |q_k - b_k| \right) \\
&\leq \frac{C}{2m} \left( |q_i - b_i|^2 + W_2^2(\mu_q^{(m)}, \mu_q^{(m)}) \right),
\end{aligned}$$

(v) We write again

$$\begin{aligned}
D_{q_iq_j}^2U^{(m)}(q) - D_{q_iq_j}^2U^{(m)}(b) &= \sum_{k=1}^m D_{q_iq_jq_k}^3U^{(m)}(q)(q_k - b_k) \\
&= D_{q_iq_jq_i}^3U^{(m)}(q)(q_i - q_i) + D_{q_iq_jq_j}^3U^{(m)}(q)(q_j - b_j) \\
&\quad + \sum_{k=1, k \neq i, k \neq j}^m D_{q_iq_jq_k}^3U^{(m)}(q)(q_k - q_k)
\end{aligned}$$

Thus in the case of (a) using the assumptions, we find

$$\begin{aligned} \left| D_{q_i q_j}^2 U^{(m)}(q) - D_{q_i q_j}^2 U^{(m)}(b) \right| &\leq \frac{C}{m^2} (|q_i - b_i| + |q_j - b_j|) + C \sum_{k=1}^m \frac{1}{m^3} |q_k - b_k| \\ &\leq \frac{C}{m^2} \left( |q_i - b_i| + |q_j - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) \right) \end{aligned}$$

In the case of (c), since  $i = j$  in the above expansion, we find

$$\begin{aligned} |D_{q_i q_i}^2 U^{(m)}(q) - D_{q_i q_i}^2 U^{(m)}(b)| &\leq \|D_{q_i q_i q_i}^3 U^{(m)}\|_\infty |q_i - b_i| + \sum_{k \neq i} \|D_{q_i q_i q_k}^3 U^{(m)}\|_\infty |q_k - b_k| \\ &\leq \frac{C}{m} \left( |q_i - b_i| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) \right) \end{aligned}$$

To show (b), let us suppose without loss of generality that  $i < j < k < l$ . By the permutation invariance of  $U^{(m)}$  we have the identities

$$D_{q_i q_j}^2 U^{(m)}(q) = D_{q_1 q_2}^2 U^{(m)}(q_i, q_j, q_k, q_l, \bar{q}) \quad \text{and} \quad D_{q_k q_l}^2 U^{(m)}(b) = D_{q_1 q_2}^2 U^{(m)}(b_k, b_l, b_i, b_j, \bar{b}),$$

where  $\bar{q}, \bar{b} \in \mathbb{R}^{d \times (m-4)}$  obtained from  $q$  and  $b$ , respectively, by deleting the vectors indexed by  $i, j, k, l$ . Therefore, using the local bounds on the third order derivatives of  $U^{(m)}$ , we have

$$|D_{q_i q_j}^2 U^{(m)}(q) - D_{q_k q_l}^2 U^{(m)}(b)| = |D_{q_1 q_2}^2 U^{(m)}(q_i, q_j, q_k, q_l, \bar{q}) - D_{q_1 q_2}^2 U^{(m)}(q_k, q_l, q_i, q_j, \bar{b})|$$

and so,

$$\begin{aligned} |D_{q_i q_j}^2 U^{(m)}(q) - D_{q_k q_l}^2 U^{(m)}(b)| &\leq \|D_{q_1 q_2 q_1}^3 U^{(m)}\|_\infty |q_i - b_k| + \|D_{q_1 q_2 q_2}^3 U^{(m)}\|_\infty |q_j - b_l| \\ &\quad + \|D_{q_1 q_2 q_3}^3 U^{(m)}\|_\infty |q_k - b_i| + \|D_{q_1 q_2 q_4}^3 U^{(m)}\|_\infty |q_l - b_j| \\ &\quad + \sum_{\alpha=1}^{i-1} \|D_{q_1 q_2 q_{\alpha+4}}^3 U^{(m)}\|_\infty |q_\alpha - b_\alpha| + \sum_{\alpha=i+1}^{j-1} \|D_{q_1 q_2 q_{\alpha+3}}^3 U^{(m)}\|_\infty |q_\alpha - b_\alpha| \\ &\quad + \sum_{\alpha=j+1}^{k-1} \|D_{q_1 q_2 q_{\alpha+2}}^3 U^{(m)}\|_\infty |q_\alpha - b_\alpha| + \sum_{\alpha=k+1}^{l-1} \|D_{q_1 q_2 q_{\alpha+1}}^3 U^{(m)}\|_\infty |q_\alpha - b_\alpha| \\ &\quad + \sum_{\alpha=l+1}^m \|D_{q_1 q_2 q_\alpha}^3 U^{(m)}\|_\infty |q_\alpha - b_\alpha|. \end{aligned}$$

Thus,

$$\begin{aligned} &|D_{q_i q_j}^2 U^{(m)}(q) - D_{q_k q_l}^2 U^{(m)}(b)| \\ &\leq \frac{C}{m^2} (|q_i - b_k| + |q_j - b_l|) + \frac{C}{m^3} (|q_k| + |b_i| + |q_l| + |b_j|) + \frac{C}{m^3} \sum_{\alpha=1}^m |q_\alpha - b_\alpha| \\ &\leq \frac{C}{m^2} \left( |q_i - b_k| + |q_j - b_l| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{1}{\sqrt{m}} \right), \end{aligned}$$

where we have used again that since  $q, b \in \mathbb{B}_r^m$ , we have  $|q_\alpha|, |b_\alpha| \leq C\sqrt{m}$  for all  $\alpha \in \{1, \dots, m\}$ .

In the case of (d), we proceed similarly as for (b). Let us suppose without loss of generality that  $i < j$ . Then, by the permutation invariance of  $U^{(m)}$ , we use the expression in (2.11) to obtain

$$D_{q_i q_i}^2 U^{(m)}(q) = D_{q_1 q_1}^2 U^{(m)}(q^{ij}),$$

Using the analogous identity with  $D_{q_j q_j}^2 U^{(m)}(b)$  we conclude

$$\begin{aligned} |D_{q_i q_i}^2 U^{(m)}(q) - D_{q_j q_j}^2 U^{(m)}(b)| &= |D_{q_1 q_1}^2 U^{(m)}(q^{ij}) - D_{q_1 q_1}^2 U^{(m)}(b^{ij})| \\ &\leq \|D_{q_1 q_1 q_1}^3 U^{(m)}\|_\infty |q_i - b_j| + \|D_{q_1 q_1 q_2}^3 U^{(m)}\|_\infty |q_j - b_i| \\ &\quad + \sum_{k=1}^{i-1} \|D_{q_1 q_1 q_{k+2}}^3\|_\infty |q_k - b_k| + \sum_{k=i+1}^{j-1} \|D_{q_1 q_1 q_{k+1}}^3\|_\infty |q_k - b_k| \\ &\quad + \sum_{k=j+1}^m \|D_{q_1 q_1 q_k}^3\|_\infty |q_k - b_k|. \end{aligned}$$

Thus,

$$\begin{aligned} |D_{q_i q_i}^2 U^{(m)}(q) - D_{q_j q_j}^2 U^{(m)}(b)| &\leq \frac{C}{m} |q_i - b_j| + \frac{C}{m^2} (|q_j| + |b_i|) + \frac{C}{m^2} \sum_{k=1}^m |q_k - b_k| \\ &\leq \frac{C}{m} \left( |q_i - b_j| + W_2(\mu_q^{(m)}, \mu_b^{(m)}) + \frac{1}{\sqrt{m}} \right), \end{aligned}$$

where we have used again that since  $q, b \in \mathbb{B}_r^m$ , we have  $|q_\alpha|, |b_\alpha| \leq C\sqrt{m}$  for all  $\alpha \in \{1, \dots, m\}$ .  $\square$

The following two theorems show how the quantified regularity estimates on the restrictions of functions  $u : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  and  $\mathcal{U} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  to  $\mathbb{M} \times \mathbb{M}^m$  and  $\mathbb{M}^m$ , respectively, will imply the corresponding regularity of the original functions.

**Theorem 2.17.** *Let  $u : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  be a continuous function. For  $m \in \mathbb{N}$ , we define  $u^{(m)} : \mathbb{M} \times (\mathbb{M})^m \rightarrow \mathbb{R}$  as*

$$u^{(m)}(q_0, q) := u(q_0, \mu_q^{(m+1)}),$$

where  $(q_0, q) = (q_0, q_1, \dots, q_m) \in (\mathbb{M})^{m+1}$  and  $\mu_q^{(m+1)} = \frac{1}{m+1} \sum_{i=0}^m \delta_{q_i}$ . Suppose that  $u^{(m)} \in C_{\text{loc}}^{1,1}(\mathbb{M} \times (\mathbb{M})^m)$  and that for  $K \subset \mathbb{M}$  compact and  $r > 0$ ,  $u^{(m)}(q_0, \cdot)$  satisfies the estimates of Property 2.15(1)-(a) and (2) for all  $q_0 \in K$ , with a constant  $C = C(K, r) > 0$ . Let us moreover assume that for any  $K \subset \mathbb{M}$  compact and  $r > 0$ , there exists  $C = C(K, r) > 0$  such that

$$(2.12) \quad |D_{q_0} u^{(m)}(q_0, q)| \leq C, \quad |D_{q_0 q_0}^2 u^{(m)}(q_0, q)|_\infty \leq C, \quad \sum_{i=1}^m m |D_{q_i q_0}^2 u^{(m)}(q_0, q)|_\infty^2 \leq C$$

and

$$|D_{q_i q_j}^2 u^{(m)}(q_0, q)|_\infty \leq \begin{cases} \frac{C}{m}, & i = j, \text{ and } i > 0, \\ \frac{C}{m^2}, & i \neq j, \text{ } i, j > 0, \end{cases}$$

for any  $q_0 \in K$  and  $q = (q_1, \dots, q_m) \in \mathbb{B}_r^m$ .

Then, there exists  $\Phi_1 : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \times \mathbb{M} \rightarrow \mathbb{R}^d$  locally Lipschitz continuous function such that for any  $r > 0$  and  $K \subset \mathbb{M}$  compact, there exists  $C = C(K, r) > 0$  such that for any  $q_0, y_0 \in K$ , any  $\mu, \nu \in \mathcal{P}_2(\mathbb{M})$  and  $\gamma \in \Gamma_o(\mu, \nu)$ ,  $u$  satisfies

$$\begin{aligned} &\left| u(y_0, \nu) - u(q_0, \mu) - D_{q_0} u(q_0, \mu) \cdot (y_0 - q_0) - \int_{\mathbb{M}^2} \Phi_1(q_0, \mu, q) \cdot (y - q) d\gamma(q, y) \right| \\ &\leq C (|q_0 - y_0|^2 + W_2^2(\mu, \nu)). \end{aligned}$$

This implies in particular that  $u \in C_{\text{loc}}^{1,1}(\mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ ,  $\nabla_w u(q_0, \mu)(\cdot)$  can be obtained as the projection of  $\Phi_1(q_0, \mu, \cdot)$  onto  $T_\mu \mathcal{P}_2(\mathbb{M})$  and

$$\begin{aligned} &\left| u(y_0, \nu) - u(q_0, \mu) - D_{q_0} u(q_0, \mu) \cdot (y_0 - q_0) - \int_{\mathbb{M}^2} \nabla_w u(q_0, \mu)(q) \cdot (y - q) d\gamma(q, y) \right| \\ &\leq C (|q_0 - y_0|^2 + W_2^2(\mu, \nu)). \end{aligned}$$



*Proof.* Our construction is inspired by [24, Lemma 8.10].

For  $m \in \mathbb{N}$  we define  $\Phi_0^{(m)} : \mathbb{M} \times \mathcal{P}_2^{(m)}(\mathbb{M}) \rightarrow \mathbb{R}^d$  and  $\Phi_1^{(m)} : \mathbb{M} \times \bigcup_{\mu \in \mathcal{P}_2^{(m)}(\mathbb{M})} \text{spt}(\mu) \times \{\mu\} \rightarrow \mathbb{R}^d$  as

$$\Phi_0^{(m)}(q_0, \mu_q^{(m)}) := D_{q_0} u^{(m)}(q_0, q)$$

and

$$\Phi_1^{(m)}(q_0, q_i, \mu_q^{(m)}) := m D_{q_i} u^{(m)}(q_0, q), \quad \forall i \in \{1, \dots, m\}.$$

Here

$$q = (q_1, \dots, q_m) \quad \text{and} \quad \mu_q^{(m)} := \frac{1}{m} \sum_{i=1}^m \delta_{q_i} \in \mathcal{P}_2^{(m)}(\mathbb{M}).$$

From the assumptions of this theorem, as a consequence of Lemma 2.16(i), when restricted to  $K \times \mathcal{P}_2^{(m)}(\mathbb{M}) \cap \mathcal{B}_r$  where  $K \subseteq \mathbb{M}$  is compact and  $r > 0$ ,  $\Phi_0^{(m)}$  is uniformly bounded and uniformly Lipschitz continuous, with respect to  $m$  (and the Lipschitz constant depends solely on  $K$  and  $r$ ).

Let  $\mathcal{K}$  be the collection of compact sets in  $\mathbb{M}$ . We assume there exists a positive function  $C$  defined  $\mathcal{K} \times (0, \infty)$  such that  $C(K, r) \leq C(K', r')$   $K \subset K'$  and  $r \leq r'$ .

We assume to be given a family of functions

$$f^{(m)} : \mathbb{M} \times \mathcal{P}_2^{(m)}(\mathbb{M}) \rightarrow \mathbb{R}$$

such that for each  $r > 0$  and each  $K \in \mathcal{K}$ , the restriction of  $f^{(m)}$  to  $K \times (\mathcal{P}_2^{(m)}(\mathbb{M}) \cap \mathcal{B}_r)$  is  $C(K, r)$ -Lipschitz. We assume there exists a compact subset in the real line which contains all the  $f^{(m)}(0, \delta_0)$ .

In what follows, we will perform Lipschitz extensions of various functions using Kirszbraun extension formula. For  $r > 0$ ,  $q_0 \in \mathbb{M}$  and  $K \in \mathcal{K}$ , we define the Kirszbraun–Valentine extension  $f_{K,r}^{(m)}(q_0, \cdot) : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  as

$$(2.13) \quad f_{K,r}^{(m)}(q_0, \mu) = \inf_{\nu} \left\{ f^{(m)}(q_0, \nu) + C(K, r) W_2(\mu, \nu) : \nu \in \mathcal{P}_2^{(m)}(\mathbb{M}) \cap \mathcal{B}_r \right\}.$$

We have that  $f_{K,r}^{(m)}(q_0, \cdot)$  is  $C(K, r)$ -Lipschitz for all  $q_0 \in \mathbb{M}$  and  $f_{K,r}^{(m)}$  coincides with  $f^{(m)}$  on  $K \times (\mathcal{P}_2^{(m)}(\mathbb{M}) \cap \mathcal{B}_r)$ . Furthermore, for any  $K' \in \mathcal{K}$ ,  $f_{K',r}^{(m)}(\cdot, \mu)$  is  $C(K', r)$ -Lipschitz on  $K' \times \mathcal{P}_2(\mathbb{M})$ .

Let  $\bar{B}_R(0)$  denote the closed ball of radius  $R > 0$ , centered at the origin in  $\mathbb{M}$  and let  $\mathcal{P}_c(\mathbb{M})$  be the union of all the  $\mathcal{P}_2(\bar{B}_R(0))$ . Since  $\mathcal{P}_2(\bar{B}_R(0))$  is a compact subset of  $\mathcal{P}_2(\mathbb{M})$ , we apply the Ascoli–Arzelà theorem and use a diagonalization argument to obtain a function

$$f_{K,r}^{\infty} : \mathbb{M} \times \mathcal{P}_c(\mathbb{M}) \rightarrow \mathbb{R}$$

such that a subsequence of  $(f_{K,r}^{(m)})_m$  converges locally uniformly to  $f_{K,r}^{\infty}$  on compact sets. We have that  $f_{K,r}^{\infty}(q_0, \cdot)$  is  $C(K, r)$ -Lipschitz on  $\mathcal{P}_c(\mathbb{M})$  for all  $q_0 \in \mathbb{M}$  and  $f_{K',r}^{\infty}(\cdot, \mu)$  is  $C(K', r)$ -Lipschitz on  $K'$  for  $\mu \in \mathcal{P}_c(\mathbb{M})$ . In fact

$$(2.14) \quad |f_{K,r}^{\infty}(q_0, \mu) - f_{K,r}^{\infty}(a_0, \nu)| \leq C(K', r) (|q_0 - a_0| + W_2(\mu, \nu))$$

for all  $q_0, a_0 \in K'$  and  $\mu, \nu \in \mathcal{B}_r$ .

The function  $f_{K,r}^{\infty}$  admits a unique  $C(K, r)$ -Lipschitz extension to  $K \times \mathcal{B}_r$  which we continue to denote as  $f_{K,r}^{\infty}$ . Using the construction (2.13) for each coordinate function of  $\Phi_0^{(m)}$ , we construct

$$\Phi_{0,K,r}^{\infty} : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}^d.$$

Similarly, assume we are given a family of functions  $\Phi_1^{(m)}$  defined on

$$\mathbb{M} \times \left\{ \left( q_i, \frac{1}{m} \sum_{j=1}^m \delta_{q_j} \right) : q \in (\mathbb{M})^m \right\}.$$

As a consequence of the assumptions and Lemma 2.16(iii)-(b) we assume for each  $r > 0$  and  $K \in \mathcal{K}$ ,

$$\left| \Phi_1^{(m)}(q_0, q_1, \mu_q^{(m)}) - \Phi_1^{(m)}(\bar{q}_0, \bar{q}_1, \mu_{\bar{q}}^{(m)}) \right| \leq C(K, r) \left( |q_0 - \bar{q}_0| + |q_1 - \bar{q}_1| + W_2(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}) + \frac{1}{\sqrt{m}} \right)$$

for all  $q_0, \bar{q}_0 \in K$  and all  $q, \bar{q} \in \mathbb{B}_r^m$ .

For each  $k \in \{1, \dots, d\}$ ,  $\Phi_1^{(m),k}$  and  $q_0, q_* \in \mathbb{M}$ , define

$$\Phi_{1,K,r}^{(m),k}(q_0, q_*, \mu) := \inf_{\bar{q}} \left\{ \Phi_1^{(m),k}(q_0, \bar{q}_i, \mu_{\bar{q}}^{(m)}) + C(K, r) \left( |q_* - \bar{q}_i| + W_2(\mu, \mu_{\bar{q}}^{(m)}) \right) : \bar{q} \in \mathbb{B}_r^m \right\}$$

Note

$$(2.15) \quad \left| \Phi_{1,K,r}^{(m),k}(q_0, q_i, \mu_q^{(m)}) - \Phi_1^{(m),k}(q_0, q_i, \mu_q^{(m)}) \right| \leq \frac{C}{\sqrt{m}}, \quad \forall (q_0, q) \in K \times \mathbb{B}_r^m.$$

As done earlier, there is a function

$$\Phi_{1,K,r}^{\infty,k} : \mathbb{M} \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$$

and a subsequence (which we may assume subsequence to be the same as the ones above) such that  $(\Phi_{1,K,r}^{(m),k})_m$  converges locally uniformly to  $\Phi_{1,K,r}^{\infty,k}$  on compact sets. Increasing the value of  $C(K', r)$  if necessary, we have

$$(2.16) \quad \left| \Phi_{1,K,r}^{\infty,k}(q_0, q_1, \mu) - \Phi_{1,K,r}^{\infty,k}(\bar{q}_0, \bar{q}_1, \nu) \right| \leq C(K', r) \left( |q_0 - \bar{q}_0| + |q_1 - \bar{q}_1| + W_2(\mu, \nu) \right)$$

if  $q_0, q_1, \bar{q}_0, \bar{q}_1 \in K'$  and  $\mu, \nu \in \mathcal{B}_r$ .

Let  $q_0, \bar{q}_0 \in \mathbb{M}$  and let  $K \subset \mathbb{M}$  be the closure of a bounded open set containing the line segment  $[q_0, \bar{q}_0]$ . Let furthermore  $q, \bar{q} \in \mathbb{B}_r^m$ . By the regularity assumptions on  $u^{(m)}$  one can write the following Taylor expansion

$$\begin{aligned} u^{(m)}(\bar{q}_0, \bar{q}) - u^{(m)}(q_0, q) - D_{q_0} u^{(m)}(q_0, q) \cdot (\bar{q}_0 - q_0) &- \sum_{i=1}^m D_{q_i} u^{(m)}(q_0, q) \cdot (\bar{q}_i - q_i) \\ &= \frac{1}{2} (\bar{q}_0 - q_0) \cdot D_{q_0 q_0}^2 u^{(m)}(z_0, z) (\bar{q}_0 - q_0) + \sum_{i=1}^m (\bar{q}_i - q_i) \cdot D_{q_i q_0}^2 u^{(m)}(z_0, z) (\bar{q}_0 - q_0) \\ &+ \frac{1}{2} \sum_{i=1}^m (\bar{q}_i - q_i) D_{q_i q_i}^2 u^{(m)}(z_0, z) (\bar{q}_i - q_i) + \frac{1}{2} \sum_{i \neq j=1}^m (\bar{q}_j - q_j) D_{q_i q_j}^2 u^{(m)}(z_0, z) (\bar{q}_i - q_i), \end{aligned}$$

where  $(z_0, z) \in \mathbb{M} \times (\mathbb{M})^m$  is a point on the line segment connecting  $(q_0, q)$  to  $(\bar{q}_0, \bar{q})$ . If  $q, \bar{q} \in \mathbb{B}_r^m$ , by convexity, we also have that  $z \in \mathbb{B}_r^m$ . Now, using the uniform bounds on  $D_{q_i q_j}^2 u^{(m)}$  from the assumptions of this theorem, increasing the value of  $C = C(K, r) > 0$  if necessary, we have

$$(2.17) \quad \begin{aligned} &\left| u^{(m)}(\bar{q}_0, \bar{y}) - u^{(m)}(q_0, q) - D_{q_0} u^{(m)}(q_0, q) \cdot (\bar{q}_0 - q_0) - \sum_{i=1}^m D_{q_i} u^{(m)}(q_0, q) \cdot (\bar{q}_i - q_i) \right| \\ &\leq C |\bar{q}_0 - q_0|^2 + C |\bar{q}_0 - q_0| \sum_{i=1}^m \frac{1}{\sqrt{m}} |\bar{q}_i - q_i| \sqrt{m} |D_{q_i q_0}^2 u^{(m)}| \\ &+ \frac{C}{2m} \sum_{i=1}^m |\bar{q}_i - q_i|^2 + \frac{C}{2} \left( \sum_{j=1}^m \frac{1}{m} |\bar{q}_j - q_j|^2 \right)^{\frac{1}{2}} \left( \sum_{i=1}^m \frac{1}{m} |\bar{q}_i - q_i|^2 \right)^{\frac{1}{2}} \\ &\leq C \left( |q_0 - \bar{q}_0|^2 + W_2^2(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}) \right), \end{aligned}$$

where in the last inequality we have used a Cauchy-Schwarz and a Young inequality, i.e.

$$\begin{aligned} |\bar{q}_0 - q_0| \sum_{i=1}^m \frac{1}{\sqrt{m}} |\bar{q}_i - q_i| \sqrt{m} |D_{q_i q_0}^2 u^{(m)}| &\leq |\bar{q}_0 - q_0| \left( \sum_{i=1}^m \frac{1}{m} |\bar{q}_i - q_i|^2 \right)^{\frac{1}{2}} \left( m |D_{q_i q_0}^2 u^{(m)}|^2 \right)^{\frac{1}{2}} \\ &\leq \frac{1}{2} |\bar{q}_0 - q_0|^2 + \frac{C}{2} \sum_{i=1}^m \frac{1}{m} |\bar{q}_i - q_i|^2 \end{aligned}$$

Now, using the previous constructions, the first line in the chain of inequalities (2.17) can be rewritten as

$$\begin{aligned}
& u^{(m)}(\bar{q}_0, \bar{q}) - u^{(m)}(q_0, q) - D_{q_0} u^{(m)}(q_0, q) \cdot (\bar{q}_0 - q_0) - \sum_{i=1}^m D_{q_i} u^{(m)}(q_0, q) \cdot (\bar{q}_i - q_i) \\
&= u(\bar{q}_0, \mu_{\bar{q}}^{(m+1)}) - u(q_0, \mu_q^{(m+1)}) - \Phi_0^{(m)}(q_0, \mu_q^{(m)}) \cdot (\bar{q}_0 - q_0) \\
(2.18) \quad & - \int_{\mathbb{M}^2} \Phi_1^{(m)}(q_0, q, \mu_q^{(m)}) \cdot (\bar{q} - q) \gamma^{(m)}(dq, d\bar{q}),
\end{aligned}$$

where  $(q_i)_{i=1}^m$  and  $(\bar{q}_i)_{i=1}^m$  are ordered in a way that

$$W_2^2(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}) = \frac{1}{m} \sum_{i=1}^m |q_i - \bar{q}_i|^2 \quad \text{and} \quad \gamma^{(m)} := \frac{1}{m} \sum_{i=1}^m \delta_{(q_i, \bar{q}_i)} \in \Gamma_o(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}).$$

In what follows, we pass to the limit all the terms in the previous line, keeping in mind that only the integral term needs some additional effort. We have

$$\begin{aligned}
& \int_{\mathbb{M}^2} \Phi_1^{(m)}(q_0, e, \mu_q^{(m)}) \cdot (\bar{e} - e) \gamma^{(m)}(de, d\bar{e}) \\
&= \int_{\mathbb{M}^2} \Phi_{1,K,r}^{(m)}(q_0, e, \mu_q^{(m)}) \cdot (\bar{e} - e) \gamma^{(m)}(de, d\bar{e}) \\
(2.19) \quad & + \int_{\mathbb{M}^2} \left( \Phi_1^{(m)}(q_0, e, \mu_q^{(m)}) - \Phi_{1,K,r}^{(m)}(q_0, e, \mu_q^{(m)}) \right) \cdot (\bar{e} - e) \gamma^{(m)}(de, d\bar{e})
\end{aligned}$$

Let us observe that

$$\begin{aligned}
& \left| \int_{\mathbb{M}^2} \left( \Phi_1^{(m)}(q_0, e, \mu_q^{(m)}) - \Phi_{1,K,r}^{(m)}(q_0, e, \mu_q^{(m)}) \right) \cdot (\bar{e} - e) \gamma^{(m)}(de, d\bar{e}) \right| \\
(2.20) \quad & \leq \frac{C}{\sqrt{m}} \int_{\mathbb{M}^2} |e - \bar{e}| \gamma^{(m)}(de, d\bar{e}) \leq \frac{2rC}{\sqrt{m}}.
\end{aligned}$$

The next step in our argument to pass to the limit in the remaining integral in the previous line work as follows. Fix a compact set  $K \subset \mathbb{M}$ ,  $R > 0$   $q_0 \in K$  and let  $\mu, \nu \in \mathcal{P}(\bar{B}_R(0))$  and  $\gamma \in \Gamma_o(\mu, \nu)$ . Let moreover  $x, y \in \mathbb{H}$  be such that  $\sharp(x, y) = \gamma$ , which implies  $\sharp(x) = \mu$ ,  $\sharp(y) = \nu$ . For  $m \in \mathbb{N}$ , recall  $(\Omega_j^m)_{j=1}^m$  is the partition of introduced in Section 1. Let us notice that for a.e.  $\omega \in \Omega$ ,  $(x(\omega), y(\omega)) \in \text{spt}(\gamma)$ . Let  $(\omega)_{i=1}^m$  be Lebesgue points of  $(x, y)$  such that  $\omega_i \in \Omega_i$  for all  $i \in \{1, \dots, m\}$ . Let us define

$$q_i := x(\omega_i), \quad \bar{q}_i := y(\omega_i), \quad q := (q_1, \dots, q_m), \quad \bar{q} := (\bar{q}_1, \dots, \bar{q}_m) \in \mathbb{B}_r^m, \quad i \in \{1, \dots, m\}.$$

We will assume we have chosen the Lebesgue points such that  $M_m^q \rightarrow X$ ,  $M_m^{\bar{q}} \rightarrow Y$  as  $m \rightarrow +\infty$ , strongly in  $\mathbb{H}$ . We have that  $\{(q_i, \bar{q}_i)\}_{i=1}^m$  is contained in  $\text{spt}(\gamma)$  and so, it is cyclical monotone. This implies that if we define  $\gamma^{(m)} := 1/m \sum_{i=1}^m \delta_{(q_i, \bar{q}_i)}$  then monotonicity of the set of these points, one has that

$$\gamma^{(m)} \in \Gamma_o(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}).$$

Furthermore, as the supports of the measure involved are contained in the compact set  $\bar{B}_R(0)$ , we have the following narrow convergence

$$\gamma^{(m)} \rightharpoonup \gamma, \quad m \rightarrow +\infty, \quad \lim_{m \rightarrow \infty} W_2(\mu_q^{(m)}, \mu) = \lim_{m \rightarrow \infty} W_2(\mu_{\bar{q}}^{(m)}, \nu) = 0.$$

As,

$$\sharp(M_m^q) = \mu_q^{(m)}, \quad \sharp(M_m^{\bar{q}}) = \mu_{\bar{q}}^{(m)} \quad \text{and} \quad \sharp(M_m^q, M_m^{\bar{q}}) = \gamma^{(m)},$$

we have in particular

$$W_2^2(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}) = \sum_{i=1}^m \frac{1}{m} |q_i - \bar{q}_i|^2 = \|M_m^q - M_m^{\bar{q}}\|^2.$$

By the uniform Lipschitz property of  $\Phi_{1,K,r}^{(m)}$ , we have

$$\lim_{m \rightarrow \infty} \Phi_{1,K,r}^{(m)}(q_0, M_m^q(\omega), \mu_q^{(m)}) = \Phi_{1,K,r}^\infty(q_0, x(\omega), \mu)$$

and

$$\lim_{m \rightarrow \infty} \Phi_{1,K,r}^{(m)}(q_0, M_m^{\bar{q}}(\omega), \mu_{\bar{q}}^{(m)}) = \Phi_{1,K,r}^\infty(q_0, y(\omega), \nu),$$

for a.e.  $\omega$  in  $\Omega$ . Also, since for a.e.  $\omega \in \Omega$ , (2.15) implies

$$\Phi_{1,K,r}^{(m)}(q_0, M_m^q(\omega), \mu_q^{(m)}) = mD_{q_i}u^{(m)}(q_0, q) + O(1/\sqrt{m}),$$

for some  $i \in \{1, \dots, m\}$ , by the assumption Property 2.15(1)(a), we have that  $(\Phi_{1,K,r}^{(m)}(q_0, M_m^q(\cdot), \mu_q^{(m)}))_m$  is a uniformly bounded sequence. Therefore, using all these facts, Lebesgue's dominated convergence theorem yields that up to passing to a suitable subsequence, that we do not relabel, we obtain

$$\lim_{m \rightarrow \infty} \|\Phi_{1,K,r}^{(m)}(q_0, M_m^q, \mu_q^{(m)}) - \Phi_{1,K,r}^\infty(q_0, x, \mu)\| = \lim_{m \rightarrow \infty} \|\Phi_{1,K,r}^{(m)}(q_0, M_m^{\bar{q}}, \mu_{\bar{q}}^{(m)}) - \Phi_{1,K,r}^\infty(q_0, y, \nu)\| = 0.$$

Now, using a suitable subsequence that we do not relabel, we conclude

$$\begin{aligned} & \lim_{m \rightarrow \infty} \int_{\mathbb{M}^2} \Phi_{1,K,r}^{(m)}(q_0, q, \mu_q^{(m)}) \cdot (\bar{e} - e)\gamma^{(m)}(de, d\bar{e}) \\ &= \lim_{m \rightarrow \infty} \int_{\Omega} \Phi_{1,K,r}^{(m)}(q_0, M_m^q(\omega), \mu_q^{(m)}) \cdot (M_m^{\bar{q}}(\omega) - M_m^q(\omega))d\omega \\ &= \int_{\Omega} \Phi_{1,K,r}^\infty(q_0, x(\omega), \mu) \cdot (y(\omega) - x(\omega))d\omega \\ &= \int_{\mathbb{M}^2} \Phi_{1,K,r}^\infty(q_0, e, \mu) \cdot (\bar{e} - e)\gamma(de, d\bar{e}). \end{aligned}$$

We combine (2.17) and (2.18) to obtain

$$\begin{aligned} & \left| u(\bar{q}_0, \nu) - u(q_0, \mu) - \Phi_{0,K,r}^\infty(q_0, \mu) \cdot (\bar{q}_0 - q_0) - \int_{\mathbb{M}^2} \Phi_{1,K,r}^\infty(q_0, e, \mu) \cdot (\bar{e} - e)\gamma(de, d\bar{e}) \right| \\ & \leq C(K, r) (|q_0 - \bar{q}_0|^2 + W_2^2(\mu, \nu)). \end{aligned}$$

We underline that the previous inequality has only been established under the condition that  $\mu, \nu \in \mathcal{B}_r$  have compact support. Since  $u$  is continuous, we combine (2.14) and (2.16) to conclude

$$\begin{aligned} & \left| u(\bar{q}_0, \nu) - u(q_0, \mu) - \Phi_{0,K,r}^\infty(q_0, \mu) \cdot (\bar{q}_0 - q_0) - \int_{\mathbb{M}^2} \Phi_{1,K,r}^\infty(q_0, e, \mu) \cdot (\bar{e} - e)\gamma(de, d\bar{e}) \right| \\ (2.21) \quad & \leq C(K, r) (|q_0 - \bar{q}_0|^2 + W_2^2(\mu, \nu)) \end{aligned}$$

for any  $q_0, \bar{q}_0 \in K$  and  $\mu, \nu \in \mathcal{B}_r$ .

Note that in (2.21),  $\Phi_{0,K,r}^\infty$  and  $\Phi_{1,K,r}^\infty$  depend a priori on  $K$  and  $r$ . However since  $K$  and  $r$  are arbitrary,  $u$  is differentiable at every  $(q_0, \mu) \in \mathbb{M} \times \mathcal{P}_2(\mathbb{M})$ . We have that  $\Phi_{0,K,r}^\infty(q_0, \mu)$  must coincide with  $D_{q_0}u(q_0, \mu)$  which is uniquely determined and so, it is independent of  $K$  and  $r$ . Furthermore, the Wasserstein sub- and super-differentials of  $u(q_0, \cdot)$  at  $\mu$  coincide and contain a unique element of minimal norm  $\nabla_w u(q_0, \mu)$ . We do not know that  $\Phi_{1,K,r}^\infty(q_0, \cdot, \mu)$  equals to  $\nabla_w u(q_0, \mu)(\cdot)$ , however, for  $\gamma \in \Gamma_o(\mu, \nu)$ , (2.21) implies

$$\begin{aligned} & \left| u(\bar{q}_0, \nu) - u(q_0, \mu) - D_{q_0}u(q_0, \mu) \cdot (\bar{q}_0 - q_0) - \int_{\mathbb{M}^2} \nabla_w u(q_0, \mu)(e) \cdot (\bar{e} - e)\gamma(de, d\bar{e}) \right| \\ (2.22) \quad & \leq C(K, r) (|q_0 - \bar{q}_0|^2 + W_2^2(\mu, \nu)) \end{aligned}$$

for any  $q_0, \bar{q}_0 \in K$  and  $\mu, \nu \in \mathcal{B}_r$ . In fact  $\nabla_w u(q_0, \mu)$  is the projection of  $\Phi_{1,K,r}^\infty(q_0, \cdot, \mu)$  onto  $T_\mu \mathcal{P}_2(\mathbb{R}^d)$ .  $\square$

Using the exact same steps as in the proof of Theorem 2.17, we can show an analogous result for functions depending on time as well. We formulate this in the following

**Corollary 2.18.** *Let  $u : (0, +\infty) \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  be a continuous function. For  $m \in \mathbb{N}$ , we define  $u^{(m)} : (0, +\infty) \times \mathbb{M} \times (\mathbb{M})^m \rightarrow \mathbb{R}$  as*

$$u^{(m)}(t_0, q_0, q) := u(t_0, q_0, \mu_q^{(m+1)}),$$

where  $(q_0, q) = (q_0, q_1, \dots, q_m) \in (\mathbb{M})^{m+1}$  and  $\mu_q^{(m+1)} = \frac{1}{m+1} \sum_{i=0}^m \delta_{q_i}$ . Suppose that  $u^{(m)} \in C_{\text{loc}}^{1,1}((0, +\infty) \times \mathbb{M} \times (\mathbb{M})^m)$  and that for  $I \subset (0, +\infty)$  and  $K \subset \mathbb{M}$  compacts and  $r > 0$ ,  $u^{(m)}(t_0, q_0, \cdot)$  satisfies the estimates of Property 2.15(1)-(a) and (2) for all  $(t_0, q_0) \in I \times K$ , with a constant  $C = C(I, K, r) > 0$ . We assume moreover that for any  $I \subset (0, +\infty)$  and  $K \subset \mathbb{M}$  compacts and  $r > 0$ , there exists  $C = C(I, K, r) > 0$  such that

$$(2.23) \quad |D_{q_0} u^{(m)}(t_0, q_0, q)| \leq C, \quad |D_{q_0}^2 u^{(m)}(t_0, q_0, q)|_\infty \leq C, \quad \sum_{i=1}^m m |D_{q_i}^2 u^{(m)}(t_0, q_0, q)|_\infty^2 \leq C$$

$$|D_{q_i q_j}^2 u^{(m)}(t_0, q_0, q)|_\infty \leq \begin{cases} \frac{C}{m}, & i = j, \text{ and } i > 0, \\ \frac{C}{m^2}, & i \neq j, \text{ } i, j > 0, \end{cases}$$

and

$$(2.24) \quad |\partial_{t_0} u^{(m)}(t_0, q_0, q)| \leq C, \quad |\partial_{t_0}^2 u^{(m)}(t_0, q_0, q)| \leq C, \quad |\partial_{t_0} D_{q_0} u^{(m)}(t_0, q_0, q)| \leq C,$$

$$\sum_{i=1}^m m |D_{q_i} \partial_{t_0} u^{(m)}(t_0, q_0, q)|^2 \leq C$$

for any  $(t_0, q_0) \in I \times K$  and  $q = (q_1, \dots, q_m) \in \mathbb{B}_r^m$ .

Then, there exists  $\Phi_1 : (0, +\infty) \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \times \mathbb{M} \rightarrow \mathbb{R}^d$  locally Lipschitz continuous function such that for any  $r > 0$  and  $I \subset (0, +\infty)$  and  $K \subset \mathbb{M}$  compacts, there exists  $C = C(I, K, r) > 0$  such that for any  $s_0, t_0 \in I$ ,  $q_0, y_0 \in K$ , any  $\mu, \nu \in \mathcal{P}_2(\mathbb{M})$  and  $\gamma \in \Gamma_o(\mu, \nu)$ ,  $u$  satisfies

$$\left| u(s_0, y_0, \nu) - u(t_0, q_0, \mu) - D_{q_0} u(t_0, q_0, \mu) \cdot (y_0 - q_0) - \partial_{t_0} u(t_0, q_0, \mu)(s_0 - t_0) \right. \\ \left. - \int_{\mathbb{M}^2} \Phi_1(t_0, q_0, \mu, q) \cdot (y - q) d\gamma(q, y) \right| \\ \leq C (|s_0 - t_0|^2 + |q_0 - y_0|^2 + W_2^2(\mu, \nu)).$$

This implies in particular that  $u \in C_{\text{loc}}^{1,1}((0, +\infty) \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$  and  $\nabla_w u(t_0, q_0, \mu)(\cdot)$  is the projection of  $\Phi_1(t_0, q_0, \mu, \cdot)$  onto  $T_\mu \mathcal{P}_2(\mathbb{M})$  and

$$\left| u(s_0, y_0, \nu) - u(t_0, q_0, \mu) - D_{q_0} u(t_0, q_0, \mu) \cdot (y_0 - q_0) \right. \\ \left. - \partial_{t_0} u(t_0, q_0, \mu)(s_0 - t_0) - \int_{\mathbb{M}^2} \nabla_w u(t_0, q_0, \mu)(q) \cdot (y - q) d\gamma(q, y) \right| \\ \leq C (|s_0 - t_0|^2 + |q_0 - y_0|^2 + W_2^2(\mu, \nu)).$$

**Theorem 2.19.** *Let  $\mathcal{U} \in C_{\text{loc}}^{1,1}(\mathcal{P}_2(\mathbb{M}))$ . Let  $U^{(m)} : (\mathbb{M})^m \rightarrow \mathbb{R}$  be defined as  $U^{(m)}(q) := \mathcal{U}(\mu_q^{(m)})$  for  $q \in \mathbb{M}^m$ , such that Property 2.15(2-3) are satisfied. Then  $\mathcal{U} \in C_{\text{loc}}^{2,1,w}(\mathcal{P}_2(\mathbb{M}))$  in the sense of Definition 2.11, such that the following hold. There exist  $C : (0, \infty) \rightarrow (0, \infty)$  monotone nondecreasing and*

(i) *there are continuous maps*

$$\Lambda_0 : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}^{d \times d} \quad \text{and} \quad \Lambda_1 : \mathbb{M} \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}^{d \times d}$$

such that for  $\mu \in \mathcal{P}_2(\mathbb{M})$  we have

$$\sup_{\mu \in \mathcal{B}_r} \|\Lambda_0(\cdot, \mu)\|_{L^\infty(\mu)}, \quad \sup_{\mu \in \mathcal{B}_r} \|\Lambda_1(\cdot, \cdot, \mu)\|_{L^\infty(\mu \otimes \mu)} \leq C(r).$$

(ii) Let  $\mu, \nu \in \mathcal{B}_r$  and  $\gamma \in \Gamma_o(\mu, \nu)$ . We have

$$(2.25) \quad \left| \nabla_w \mathcal{U}(\nu)(\bar{q}) - \nabla_w \mathcal{U}(\mu)(q) - \Lambda_0(q, \mu)(\bar{q} - q) - \int_{\mathbb{M}^2} \Lambda_1(q, a, \mu)(b - a) d\gamma(a, b) \right| \leq C (|q - \bar{q}|^2 + W_2^2(\mu, \nu))$$

and

$$(2.26) \quad \left| \nabla_w \mathcal{U}(\mu)(q) - \nabla_w \mathcal{U}(\nu)(\bar{q}) \right| \leq C (|q - \bar{q}| + W_2(\mu, \nu)), \quad \forall \mu, \nu \in \mathcal{B}_r, .$$

for all  $(q, \bar{q}) \in \text{spt}(\mu) \times \text{spt}(\nu)$ .

*Proof.* We follow ideas similar to those presented in the proof of Theorem 2.17. Recall that for,  $q \in \mathbb{B}_r^m$  we use the notation  $\mu_q^{(m)} := 1/m \sum_{i=1}^m \delta_{q_i}$  and use a similar notation for  $\bar{q} \in \mathbb{B}_r^m$ . Let us define the matrix valued functions

$$\Lambda_0^{(m)} : \bigcup_{q \in \mathbb{B}_r^m} \text{spt}(\mu_q^{(m)}) \times \{\mu_q^{(m)}\} \rightarrow \mathbb{R}^{d \times d}$$

and

$$\Lambda_1^{(m)} : \bigcup_{q \in \mathbb{B}_r^m} \left( (\text{spt}(\mu_q^{(m)}) \times \text{spt}(\mu_q^{(m)})) \setminus \{(q_i, q_i) : i = 1, \dots, m\} \right) \times \{\mu_q^{(m)}\} \rightarrow \mathbb{R}^{d \times d}$$

as

$$\Lambda_0^{(m)}(q_i, \mu_q^{(m)}) := m D_{q_i q_i}^2 U^{(m)}(q), \quad \text{and} \quad \Lambda_1^{(m)}(q_i, q_j, \mu_q^{(m)}) := m^2 D_{q_i q_j}^2 U^{(m)}(q), \quad \text{if } i \neq j.$$

Let us underline that we have not defined  $\Lambda_1^{(m)}(q_i, q_i, \mu_q^{(m)})$  for  $i = j$ . Because of this, later we will need special care when one passes to the limit the corresponding objects as  $m \rightarrow +\infty$ .

We observe that as a consequence of the assumptions and Lemma 2.16(v)-(b,d), we have that for any  $r > 0$ , there exists a constant  $C = C(r) > 0$  such that

$$|\Lambda_0^{(m)}(q_i, \mu_q^{(m)}) - \Lambda_0^{(m)}(\bar{q}_j, \mu_{\bar{q}}^{(m)})| \leq C \left( |q_i - \bar{q}_j| + W_2(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}) + \frac{1}{\sqrt{m}} \right)$$

and

$$|\Lambda_1^{(m)}(q_i, q_k, \mu_q^{(m)}) - \Lambda_1^{(m)}(\bar{q}_j, \bar{q}_l, \mu_{\bar{q}}^{(m)})| \leq C \left( |q_i - \bar{q}_j| + |q_k - \bar{q}_l| + W_2(\mu_q^{(m)}, \mu_{\bar{q}}^{(m)}) + \frac{1}{\sqrt{m}} \right)$$

for any  $q, \bar{q} \in \mathbb{B}_r^m$ , and for any  $i, j, k, l \in \{1, \dots, m\}$ ,  $i \neq k$ ,  $j \neq l$ . For every coordinate function  $(\Lambda_0^{(m)})_{\alpha\beta}, (\Lambda_1^{(m)})_{\alpha\beta}$  ( $\alpha, \beta \in \{1, \dots, d\}$ ), we define the extensions

$$\left( \Lambda_{0,r}^{(m)} \right)_{\alpha\beta} : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R} \quad \text{and} \quad \left( \Lambda_{1,r}^{(m)} \right)_{\alpha\beta} : \mathbb{M} \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$$

as follows. For  $z, z_1, z_2 \in \mathbb{M}$ ,  $\mu \in \mathcal{P}_2(\mathbb{M})$  we set

$$\left( \Lambda_{0,r}^{(m)} \right)_{\alpha\beta}(z, \mu) := \inf \left\{ (\Lambda_0^{(m)})_{\alpha\beta}(q_i, \mu_q^{(m)}) + C \left( |q_i - z| + W_2(\mu_q^{(m)}, \mu) \right) \right\}$$

and

$$\left( \Lambda_{1,r}^{(m)} \right)_{\alpha\beta}(z_1, z_2, \mu) := \inf \left\{ (\Lambda_1^{(m)})_{\alpha\beta}(q_i, q_k, \mu_q^{(m)}) + C \left( |q_i - z_1| + |q_k - z_2| + W_2(\mu_q^{(m)}, \mu) \right) \right\},$$

where both infima is taken over  $q \in \mathbb{B}_r^m$ ,  $i, k \in \{1, \dots, m\}$ ,  $i \neq k$ .

Recall  $\Lambda_{0,r}^{(m)}$  and  $\Lambda_{1,r}^{(m)}$  are  $C(r)$ -Lipschitz and we have

$$(2.27) \quad \left| \Lambda_{0,r}^{(m)}(q_i, \mu_q^{(m)}) - \Lambda_0^{(m)}(q_i, \mu_q^{(m)}) \right|_{\infty} \leq \frac{C}{\sqrt{m}}, \quad \forall q \in \mathbb{B}_r^m, i \in \{1, \dots, m\}$$

and

$$(2.28) \quad \left| \Lambda_{1,r}^{(m)}(q_i, q_k, \mu_q^{(m)}) - \Lambda_1^{(m)}(q_i, q_k, \mu_q^{(m)}) \right|_{\infty} \leq \frac{C}{\sqrt{m}}, \quad \forall q \in \mathbb{B}_r^m, i, k \in \{1, \dots, m\}, i \neq k.$$

If  $R > 0$ ,  $z_1, z_2 \in B_R(0)$  and  $\mu$  is supported by  $B_R(0)$  then for all  $\alpha, \beta \in \{1, \dots, d\}$

$$-C \leq \left( \Lambda_{1,r}^{(m)} \right)_{\alpha\beta}(z_1, z_2, \mu) \leq C + C \left( |z_1| + |z_2| + W_2(0, \mu) \right) \leq C(3R).$$

We obtain a similar uniform bound on  $\left(\Lambda_{0,r}^{(m)}\right)_m$ . As in the proof of Theorem 2.17, there are  $C$ -Lipschitz functions

$$\Lambda_{0,r} : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}^{d \times d}, \quad \Lambda_{1,r} : \mathbb{M} \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}^{d \times d}$$

locally bounded respectively on  $\mathbb{M} \times \mathcal{P}_2(\mathbb{M})$  and  $\mathbb{M}^2 \times \mathcal{P}_2(\mathbb{M})$  by a constant depending only on  $r$  and  $R$ . Up to a subsequence, as  $m \rightarrow +\infty$ ,  $\left(\Lambda_{0,r}^{(m)}\right)_m$  and  $\left(\Lambda_{1,r}^{(m)}\right)_m$  converge to  $\Lambda_{0,r}$  and  $\Lambda_{1,r}$ , uniformly on  $\overline{B}_R(0) \times \mathcal{P}(\overline{B}_R(0))$  and  $\overline{B}_R(0) \times \overline{B}_R(0) \times \mathcal{P}(\overline{B}_R(0))$ , respectively.

Our next task is to show that

$$\Lambda_{0,r}(\cdot, \mu) \in L^\infty(\mathbb{M}; \mu), \quad \Lambda_{1,r}(\cdot, \cdot, \mu) \in L^\infty(\mathbb{M} \times \mathbb{M}; \mu \otimes \mu), \quad \forall \mu \in \mathcal{B}_r \cap \mathcal{P}(\overline{B}_R(0)).$$

*Claim 1.*  $\Lambda_1(\cdot, \mu) \in L^\infty(\mathbb{M}^2; \mu \otimes \mu)$ .

*Proof of Claim 1.* Let  $r > 0$ ,  $R > 0$  and first let  $\mu \in \mathcal{B}_r \cap \mathcal{P}(\overline{B}_R(0))$ . Let  $z_1, z_2 \in B_R(0)$ . As we plan to let  $m$  tend to  $\infty$  it is not a loss of generality to assume  $R \leq r\sqrt{m}$ . Since  $q = (z_1, z_2, 0, \dots, 0) \in \mathbb{B}_r^m$  we have

$$-C \leq \left(\Lambda_{1,r}^{(m)}\right)_{\alpha\beta}(z_1, z_2, \mu) \leq \left(\Lambda_{1,r}^{(m)}\right)_{\alpha\beta}(z_1, z_2, \mu_q^{(m)}) + C(r) \left(|z_1 - z_1| + |z_2 - z_2| + W_2(\mu_q^{(m)}, \mu)\right) \leq C(r) + 2rC(r)$$

Letting  $m$  tend to  $\infty$  we conclude  $\left|\left(\Lambda_{1,r}^{(m)}\right)_{\alpha\beta}(z_1, z_2, \mu)\right| \leq C(r) + 2rC(r)$  first on  $\mathbb{M}^2 \times \mathcal{P}_c(\mathbb{M})$  and by continuity, this holds on  $\mathbb{M}^2 \times \mathcal{P}_2(\mathbb{M})$ .

*Claim 2.*  $\Lambda_0(\cdot, \mu) \in L^\infty(\mathbb{M}; \mu)$ .

*Proof of Claim 2.* The proof is similar but simpler than that of Claim 1.

For  $q, \bar{q} \in \mathbb{B}_r^m$  we have the expansion

$$(2.29) \quad mD_{q_1}U^{(m)}(\bar{q}) - mD_{q_1}U^{(m)}(q) - mD_{q_1q_1}^2U^{(m)}(q)(\bar{q}_1 - q_1) - m \sum_{k=2}^m D_{q_1q_k}^2U^{(m)}(q)(\bar{q}_k - q_k) \\ = \frac{m}{2} \sum_{k,l=1}^m (\bar{q}_l - q_l) D_{q_1q_kq_l}^3U^{(m)}(z)(\bar{q}_k - q_k)$$

where  $z$  is a point on the line segment connecting  $q$  to  $\bar{q}$ .

Let  $\mu, \nu \in \mathcal{B}_r$ ,  $\gamma \in \Gamma_o(\mu, \nu)$  and let  $(q_1, \bar{q}_1) \in \text{spt}(\mu) \times \text{spt}(\nu)$  (which is not necessarily in  $\text{spt}(\gamma)$ ). Suppose that both  $\text{spt}(\mu)$  and  $\text{spt}(\nu)$  contain more than one element. We choose  $x, y \in \mathbb{H}$  such that  $\sharp(x, y) = \gamma$  and so,  $\sharp(x) = \mu$ ,  $\sharp(y) = \nu$ . Let  $(\Omega_i^{m-1})_{i=1}^{m-1}$  be the partition of  $\Omega$  introduced in Section 1. We are going to choose special values of  $m := 2^l + 1$  and choose Lebesgue points  $\omega_{i+1} \in \Omega_i^{2^l}$  such that all the points in  $\Omega_i^{2^l}$  are kept in  $\Omega_i^{2^{l+1}}$ . We set  $q_i := x(\omega_i)$ ,  $\bar{q}_i := y(\omega_i)$  for  $i = 2, \dots, m$  Set

$$\gamma^{(m-1)} := \frac{1}{m-1} \sum_{i=2}^m \delta_{(q_i, \bar{q}_i)}, \quad \mu_q^{(m-1)} := \frac{1}{m-1} \sum_{i=2}^m \delta_{q_i}, \quad \mu_{\bar{q}}^{(m-1)} := \frac{1}{m-1} \sum_{i=2}^m \delta_{\bar{q}_i}.$$

Since,  $(q_i, \bar{q}_i)_{i=2}^\infty$  is cyclically monotone

$$\gamma^{(m-1)} \in \Gamma_o(\mu_q^{(m-1)}, \mu_{\bar{q}}^{(m-1)}).$$

By construction  $(\gamma^{(m-1)})_m$  converges narrowly to  $\gamma$ . Let  $M_{(m-1)}^q, M_{(m-1)}^{\bar{q}} \in \mathbb{H}$  the random variables corresponding to the previously chosen points  $(q_2, \dots, q_m)$  and  $(\bar{q}_2, \dots, \bar{q}_m)$ , respectively. We have (2.30)

$$\lim_{m \rightarrow +\infty} W_2(\mu_q^{(m)}, \mu) = \lim_{m \rightarrow +\infty} W_2(\mu_q^{(m-1)}, \mu) = \lim_{m \rightarrow +\infty} W_2(\mu_{\bar{q}}^{(m)}, \nu) = \lim_{m \rightarrow +\infty} W_2(\mu_{\bar{q}}^{(m-1)}, \nu) = 0.$$

Furthermore,

$$\sharp\left(M_{(m-1)}^q, M_{(m-1)}^{\bar{q}}\right) = \gamma^{(m-1)},$$

and

$$\lim_{m \rightarrow +\infty} \|M_{(m-1)}^q - x\| = \lim_{m \rightarrow +\infty} \|M_{(m-1)}^{\bar{q}} - y\| = 0.$$

Using the assumptions on  $D_{q_j q_k q_l}^3 U^{(m)}$ , since  $z \in \mathbb{B}_r^m$ , increasing the value of  $C$  if necessary, we have

$$\begin{aligned}
& \left| m \sum_{k,l=1}^m (y_l - x_l) D_{q_1 q_k q_l}^3 U^{(m)}(z) (\bar{q}_k - q_k) \right| \\
& \leq m |D_{q_1 q_1 q_1}^3 U^{(m)}(z)|_\infty |\bar{q}_1 - q_1|^2 + m \sum_{k=2}^m |D_{q_1 q_k q_1}^3 U^{(m)}(z)|_\infty |\bar{q}_k - q_k| |\bar{q}_1 - q_1| \\
& + m \sum_{l=2}^m |D_{q_1 q_1 q_l}^3 U^{(m)}(z)|_\infty |\bar{q}_1 - q_1| |\bar{q}_l - q_l| \\
& + m \sum_{k=2}^m |D_{q_1 q_k q_k}^3 U^{(m)}(z)|_\infty |\bar{q}_k - q_k|^2 + m \sum_{k \neq l=2}^m |\bar{q}_l - q_l| |D_{q_1 q_k q_l}^3 U^{(m)}(z)|_\infty |\bar{q}_k - q_k| \\
& \leq C \left( |\bar{q}_1 - q_1|^2 + |\bar{q}_1 - q_1| \sum_{k=2}^m \frac{1}{m} |\bar{q}_k - q_k| + \sum_{k=2}^m \frac{1}{m} |\bar{q}_k - q_k|^2 + \frac{1}{m^2} \sum_{k \neq l=2}^m |\bar{q}_l - q_l| |\bar{q}_k - q_k| \right) \\
& \leq C \left( |\bar{q}_1 - q_1|^2 + W_2^2(\mu_q^{(m-1)}, \mu_{\bar{q}}^{(m-1)}) \right)
\end{aligned}$$

Thus, this together with (2.29) implies

$$\begin{aligned}
& m \left| D_{q_1} U^{(m)}(\bar{q}) - D_{q_1} U^{(m)}(q) - D_{q_1 q_1}^2 U^{(m)}(q) (\bar{q}_1 - q_1) - \sum_{k=2}^m D_{q_1 q_k}^2 U^{(m)}(q) (\bar{q}_k - q_k) \right| \\
& \leq C \left( |\bar{q}_1 - q_1|^2 + W_2^2(\mu_q^{(m-1)}, \mu_{\bar{q}}^{(m-1)}) \right).
\end{aligned}$$

Using the definition of  $\Lambda_0^{(m)}$  and  $\Lambda_1^{(m)}$  we read off

$$\begin{aligned}
(2.31) \quad & \left| \nabla_w \mathcal{U}(\mu_{\bar{q}}^{(m)})(\bar{q}_1) - \nabla_w \mathcal{U}(\mu_q^{(m)})(q_1) - \Lambda_0^{(m)}(q_1, \mu_q^{(m)})(\bar{q}_1 - q_1) \right. \\
& \quad \left. - \frac{m-1}{m} \int_{\mathbb{M}^2} \Lambda_1^{(m)}(q_1, a, \mu_q^{(m)})(b-a) \gamma^{(m-1)}(da, db) \right| \\
& \leq C \left( |\bar{q}_j - q_i|^2 + W_2^2(\mu_q^{(m-1)}, \mu_{\bar{q}}^{(m-1)}) \right),
\end{aligned}$$

Now, first by the continuity of  $\nabla_w \mathcal{U}$ , (2.30) implies

$$\lim_{m \rightarrow \infty} \nabla_w \mathcal{U}(\mu_q^{(m)})(q_1) = \nabla_w \mathcal{U}(\mu)(q_1), \quad \text{and} \quad \lim_{m \rightarrow \infty} \nabla_w \mathcal{U}(\mu_{\bar{q}}^{(m)})(\bar{q}_1) = \nabla_w \mathcal{U}(\nu)(\bar{q}_1).$$

Before passing to the limit in the other terms, let us *further* suppose that  $\mu, \nu \in \mathcal{P}(\bar{B}_R(0))$  for some  $R > 0$ . In light of (2.27),  $\Lambda_0^{(m)}(q_1, \mu_q^{(m)})$  and  $\Lambda_{0,r}^{(m)}(q_1, \mu_q^{(m)})$  have the same limit. By the local uniform convergence property of  $\Lambda_{0,r}^{(m)}$ , we have that  $\lim_{m \rightarrow \infty} \Lambda_0^{(m)}(q_1, \mu_q^{(m)}) = \Lambda_{0,r}(q_1, \mu)$ .

To handle the limit in the last term on the left hand side of the inequality (2.31), we observe that

$$\begin{aligned}
& \int_{\mathbb{M}^2} \Lambda_1^{(m)}(q_1, a, \mu_q^{(m)})(b-a) \gamma^{(m-1)}(da, db) = \int_{\mathbb{M}^2} \Lambda_{1,r}^{(m)}(q_1, a, \mu_q^{(m)})(b-a) \gamma^{(m-1)}(da, db) \\
& \quad + \int_{\mathbb{M}^2} \left( \Lambda_1^{(m)}(q_1, a, \mu_q^{(m)}) - \Lambda_{1,r}^{(m)}(q_1, a, \mu_q^{(m)}) \right) (b-a) \gamma^{(m-1)}(da, db)
\end{aligned}$$

and by (2.28), increasing  $C$  if necessary, we have that

$$\begin{aligned}
& \left| \int_{\mathbb{M}^2} \left( \Lambda_1^{(m)}(q_1, a, \mu_q^{(m)}) - \Lambda_{1,r}^{(m)}(q_1, a, \mu_q^{(m)}) \right) (b-a) \gamma^{(m-1)}(da, db) \right| \leq \frac{C}{\sqrt{m}} \iint_{\mathbb{M}^2} |b-a| \gamma^{(m-1)}(da, db) \\
& \leq \frac{Cr}{\sqrt{m}}.
\end{aligned}$$

Therefore, it is enough to study the limit of

$$\int_{\mathbb{M}^2} \Lambda_{1,r}^{(m)}(q_1, a, \mu_q^{(m)})(b-a) \gamma^{(m-1)}(da, db).$$



Since

$$\left| \Lambda_{1,r}^{(m)}(q_1, M_{(m-1)}^q(\omega), \mu_q^{(m)}) - \Lambda_1^{(m)}(q_1, M_{(m-1)}^q(\omega), \mu_q^{(m)}) \right| \leq \frac{C}{\sqrt{m}}$$

and since  $\Lambda_1^{(m)}(q_1, M_{(m-1)}^q(\omega), \mu_q^{(m)}) = \Lambda_1^{(m)}(q_1, q_i, \mu_q^{(m)})$  for some  $i \in \{2, \dots, m\}$  for a.e.  $\omega \in \Omega$ , we have that  $\omega \mapsto \Lambda_{1,r}^{(m)}(q_1, M_{(m-1)}^q(\omega), \mu_q^{(m)})$  is uniformly bounded with respect to  $m \in \{2, 3, \dots\}$ . Thus by the previous convergences and by Lebesgue's dominated convergence theorem, up to passing to a subsequence that we do not relabel, we have that

$$\lim_{m \rightarrow \infty} \left\| \Lambda_{1,r}^{(m)}(q_1, M_{(m-1)}^q, \mu_q^{(m)}) - \Lambda_1(q_1, x, \mu) \right\| = 0.$$

Thus, up to a subsequence,

$$\begin{aligned} & \lim_{m \rightarrow \infty} \int_{\mathbb{M}^2} \Lambda_{1,r}^{(m)}(q_1, a, \mu_q^{(m)})(b-a)\gamma^{(m-1)}(da, db) \\ &= \lim_{m \rightarrow \infty} \int_{\Omega} \Lambda_{1,r}^{(m)}(q_1, M_{(m-1)}^q(\omega), \mu_q^{(m)}) \left( M_{(m-1)}^{\bar{q}}(\omega) - M_{(m-1)}^q(\omega) \right) d\omega \\ &= \int_{\Omega} \Lambda_{1,r}(q_1, x(\omega), \mu)(y(\omega) - x(\omega)) d\omega = \int_{\mathbb{M}^2} \Lambda_{1,r}(q_1, a, \mu)(b-a)\gamma(da, db) \end{aligned}$$

We have all the ingredients to conclude that up to subsequence (2.31) implies to obtain

$$\begin{aligned} & \left| \nabla_w \mathcal{U}(\nu)(\bar{q}_1) - \nabla_w \mathcal{U}(\mu)(q_1) - \Lambda_0(q_1, \mu)(\bar{q}_1 - q_1) - \int_{\mathbb{M}^2} \Lambda_{1,r}(q_1, a, \mu)(b-a)\gamma(da, db) \right| \\ & \leq C(|q_1 - \bar{q}_1|^2 + W_2^2(\mu, \nu)). \end{aligned}$$

As  $C$  is independent of  $R$ , we extend the previous inequality to all  $\mu, \nu \in \mathcal{B}_r$  without imposing they lie in  $\mathcal{P}(B_R(0))$ . We also notice that by the assumptions, i.e. Property 2.15(3), the map  $q \mapsto \nabla_w \mathcal{U}(\mu)(q)$  is Lipschitz continuous uniformly with respect to  $\mu \in \mathcal{B}_r$ . More precisely, Lemma 2.16 (iii)-(b) yields that there exists  $C = C(r) > 0$  such that for all  $\mu, \nu \in \mathcal{B}_r$  and  $(q_1, \bar{q}_1) \in \text{spt}(\mu) \times \text{spt}(\nu)$  we have

$$|\nabla_w \mathcal{U}(t, \mu)(q_1) - \nabla_w \mathcal{U}(t, \nu)(\bar{q}_1)| \leq C(|q_1 - \bar{q}_1| + W_2(\mu, \nu)),$$

so (2.26) follows.  $\square$

**Remark 2.20.** Note that  $\Lambda_0$  is a symmetric matrix, as limit of symmetric matrices.

### 3. GLOBAL WELL-POSEDNESS OF MASTER EQUATIONS

Throughout this section, we fix  $T > 0$  and impose (H1)-(H8). We further assume

$$(H9) \quad \mathcal{U}_0, \mathcal{F} \in C_{\text{loc}}^{2,1,w}(\mathcal{P}_2(\mathbb{M})) \quad \text{and} \quad U_0^{(m)}, F^{(m)} \text{ satisfy Property 2.15(3).}$$

Let  $\tilde{\mathcal{U}}$  be the solution obtained in Theorem 1.5 and define  $\mathcal{U} : [0, T] \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  as  $\mathcal{U}(t, \mu) := \tilde{\mathcal{U}}(t, x)$  where  $\mu = \sharp(x)$ . By Lemma 2.13, the regularity property obtained on  $\tilde{\mathcal{U}}$  in Theorem 1.5 ensures that  $\mathcal{U}(t, \cdot)$  is  $C_{\text{loc}}^{1,1}(\mathcal{P}_2(\mathbb{M}))$ . We use Remark 2.7 to obtain that  $\mathcal{U} \in C_{\text{loc}}^{1,1}([0, T] \times \mathcal{P}_2(\mathbb{M}))$  (in the sense of Definition 2.8) and it is a classical solution to the Hamilton-Jacobi equation

$$(3.1) \quad \begin{cases} \partial_t \mathcal{U} + \mathcal{H}(\mu, \nabla_w \mathcal{U}) = \mathcal{F}(\mu), & \text{in } (0, T) \times \mathcal{P}_2(\mathbb{M}), \\ \mathcal{U}(0, \mu) = \mathcal{U}_0(\mu), & \text{in } \mathcal{P}_2(\mathbb{M}). \end{cases}$$

#### 3.1. Flows on $\mathbb{H}$ , on $\mathcal{P}_2(\mathbb{M})$ and their properties.

**Lemma 3.1.** Let  $x, y \in \mathbb{H}$  be such that  $\sharp(x) = \sharp(y)$ . Then for  $0 \leq s \leq t$ , we have  $\sharp(\tilde{S}_s^t[x]) = \sharp(\tilde{S}_s^t[y])$ . As a consequence, given  $\mu \in \mathcal{P}_2(\mathbb{M})$  the following measures are well-defined

$$(3.2) \quad \sigma_s^t[\mu] := \sharp(\tilde{S}_s^t[x])$$

where  $\sharp(x) = \mu$ , depends only on  $\mu$  and is independent of the choice of  $x$ .

*Proof.* Since  $\sharp(x) = \sharp(y)$ , there exist Borel bijective maps  $S_n : \Omega \rightarrow \Omega$  such that (cf. e.g. [8] [25])

$$\sharp(S_n) = \sharp(S_n^{-1}) = \mathcal{L}_\Omega^d, \quad \lim_{n \rightarrow \infty} \|y - x \circ S_n\| = 0.$$

Thus,

$$\lim_{n \rightarrow \infty} \left\| \tilde{S}_s^t[y] - \tilde{S}_s^t[x] \circ S_n \right\| = \lim_{n \rightarrow \infty} \left\| \tilde{S}_s^t[y] - \tilde{S}_s^t[x \circ S_n] \right\| = 0.$$

This proves

$$W_2\left(\sharp\left(\tilde{S}_s^t[y]\right), \sharp\left(\tilde{S}_s^t[x]\right)\right) = \lim_{n \rightarrow \infty} W_2\left(\sharp\left(\tilde{S}_s^t[x] \circ S_n\right), \sharp\left(\tilde{S}_s^t[x]\right)\right) = 0.$$

**Remark 3.2.** *The following hold.*

(i) *By Theorem 1.5, there exists  $e_T : [0, \infty) \rightarrow [0, \infty)$ , monotone non-decreasing such that*

$$\|\tilde{S}_s^t[x]\|, \|\partial_s \tilde{S}_s^t[x]\| \leq e_T(\|x\|) \quad \forall s \in [0, t], \forall t \in [0, T].$$

(ii) *By (i)*

$$\{\sigma_s^t[\mu] : \mu \in \mathcal{B}_r, 0 \leq s \leq t \leq T\} \subset \mathcal{B}_{e_T(r)}$$

(iii) *By Theorem 1.5 again, there exists  $C_T : (0, \infty) \rightarrow (0, \infty)$  monotone non-decreasing such that*

$$\|\nabla \tilde{\mathcal{U}}(t, x)\| \leq C_T(r)(1 + \|x\|), \quad \forall x \in \mathbb{B}_r(0), \forall t \in [0, T].$$

(iv) *By Lemma 2.13, the regularity property obtained on  $\tilde{\mathcal{U}}$  in Theorem 1.5, we have that  $\mathcal{U}$  is differentiable. We use Proposition C.2 (iv) to conclude that  $(s, q) \mapsto D_p H\left(q, \nabla_w \mathcal{U}(s, \sigma_s^t[\mu])(q)\right)$  is a velocity for  $s \mapsto \sigma_s^t[\mu]$ . In other words*

$$(3.3) \quad \partial_s \sigma_s^t[\mu] + \nabla \cdot \left( D_p H(\cdot, \nabla_w \mathcal{U}(s, \sigma_s^t[\mu])) \sigma_s^t[\mu] \right) = 0, \quad \text{in } \mathcal{D}'((0, t) \times \mathbb{M}), \quad \sigma_t^t[\mu] = \mu.$$

**Lemma 3.3.** *Suppose  $0 < t \leq \bar{t} \leq T$  and  $r > 0$ . Then there exists a constant  $C(r, T)$  monotone increasing in  $r$  such that the following hold.*

(i) *If  $x, y \in \mathbb{B}_r(0)$  then*

$$\|\tilde{S}_s^{\bar{t}}[x] - \tilde{S}_s^{\bar{t}}[y]\| \leq e^{C(r, T)(t-s)} \left( |\bar{t} - t| e_T(\|x\|) + \|x - y\| \right) \quad \forall s \in [0, t].$$

and

$$\|\tilde{S}_s^{\bar{t}}[x] - \tilde{S}_t^{\bar{t}}[x]\| \leq (s - t) e_T(r) \quad \forall s \in [t, \bar{t}].$$

(ii) *If  $\mu, \nu \in \mathcal{B}_r$  then*

$$(3.4) \quad W_2\left(\sigma_s^{\bar{t}}[\mu], \sigma_s^{\bar{t}}[\nu]\right) \leq e^{C(r, T)(t-s)} \left( |\bar{t} - t| e_T(r) + W_2(\mu, \nu) \right) \quad \forall s \in [0, t].$$

and

$$W_2\left(\sigma_s^{\bar{t}}[\mu], \sigma_t^{\bar{t}}[\mu]\right) \leq (s - t) e_T(r) \quad \forall s \in [t, \bar{t}].$$

*Proof.* (i) Let  $x, y \in \mathbb{B}_r(0)$ .

We have

$$\|x - \tilde{S}_t^{\bar{t}}[x]\| = \left\| \int_t^{\bar{t}} \partial_s \tilde{S}_s^{\bar{t}}[x] ds \right\| \leq \int_t^{\bar{t}} \|\partial_s \tilde{S}_s^{\bar{t}}[x]\| ds$$

We use Remark 3.2 (i) to infer

$$(3.5) \quad \|x - \tilde{S}_t^{\bar{t}}[x]\| \leq |\bar{t} - t| e_T(\|x\|).$$

Set

$$h(s) := \frac{1}{2} \|\tilde{S}_s^{\bar{t}}[x] - \tilde{S}_s^t[x]\| \quad \forall s \in [0, t].$$

We have

$$h'(s) = \int_\Omega \left( \tilde{S}_s^{\bar{t}}[x] - \tilde{S}_s^t[x] \right) \cdot \left( D_p H(\tilde{S}_s^{\bar{t}}[x], \nabla \tilde{\mathcal{U}}(s, \tilde{S}_s^{\bar{t}}[x])) - D_p H(\tilde{S}_s^t[x], \nabla \tilde{\mathcal{U}}(s, \tilde{S}_s^t[x])) \right) d\omega.$$



**Definition 3.6.** We say that  $\mathcal{V} : [0, T] \times \bigcup_{\mu \in \mathcal{P}_2(\mathbb{M})} \{\mu\} \times \text{spt}(\mu) \rightarrow \mathbb{R}^d$  is a weak solution to (3.8) if it is locally Lipschitz on its domain of definition,  $\mathcal{V}(\cdot, \mu, q)$  is differentiable on  $(0, T)$  for all  $\mu \in \mathcal{P}_2(\mathbb{M})$  and  $q \in \text{spt}(\mu)$ ,  $\mathcal{V}(t, \cdot, \cdot) \in C_{\text{loc}}^{1,1}(\bigcup_{\mu \in \mathcal{P}_2(\mathbb{M})} \{\mu\} \times \text{spt}(\mu))$ ,  $\mathcal{V}(t, \mu, \cdot)$  is differentiable on  $\text{spt}(\mu)$  for all  $t \in [0, T]$  and  $\mu \in \mathcal{P}_2(\mathbb{M})$  and the equation (3.8) is satisfied pointwise on  $[0, T] \times \bigcup_{\mu \in \mathcal{P}_2(\mathbb{M})} \{\mu\} \times \text{spt}(\mu)$ .

**Theorem 3.7.** Suppose  $\mathcal{U}(t, \cdot) \in C_{\text{loc}}^{2,1,w}(\mathcal{P}_2(\mathbb{M}))$  (in the sense of Definition 2.11). Using the notation in Remark 2.12, we have assumed

$$D_q(\nabla_w \mathcal{U}(t, \mu)(\cdot)) \in L^\infty(\mathbb{M}; \mu), \quad \bar{\nabla}_{ww}^2 \mathcal{U}(t, \mu)(\cdot, \cdot) \in L^\infty(\mathbb{M} \times \mathbb{M}; \mu \otimes \mu) \quad \forall \mu \in \mathcal{P}_2(\mathbb{M}), \quad \text{and a.e. } t \in (0, T).$$

Then the vector field  $\mathcal{V}(t, \mu, q) := \nabla_w \mathcal{U}(t, \mu)(q)$  defined on  $[0, T] \times \bigcup_{\mu \in \mathcal{P}_2(\mathbb{M})} \{\mu\} \times \text{spt}(\mu)$ , solves the vectorial master equation (3.8) with initial data  $\mathcal{V}_0 = \nabla_w \mathcal{U}_0$  in the sense of Definition 3.6.

*Proof of Theorem 3.7.* Let  $\mu \in \mathcal{P}_2(\mathbb{M})$ , let  $\varphi \in C_c^\infty(\mathbb{M})$  be arbitrary and set  $\xi := D\varphi$ . Choose  $\varepsilon > 0$  be small enough such that for all  $s \in [0, \varepsilon]$ ,  $X_s := \text{id} + s\xi$  is a diffeomorphism of  $\mathbb{M}$  into  $\mathbb{M}$  and  $|\text{id}|^2/2 + s\varphi$  is convex. For any  $q \in \text{spt}(\mu)$  we have

$$\begin{aligned} \nabla_w \mathcal{U}(t, \sigma_s)(X_s(q)) &= \nabla_w \mathcal{U}(t, \mu)(q) + s D_q \nabla_w \mathcal{U}(t, \mu)(q) \xi(q) + s \int_{\mathbb{M}} \nabla_{ww}^2 \mathcal{U}(t, \mu)(q, a) \xi(a) \mu(da) \\ (3.9) \quad &+ o(s). \end{aligned}$$

Since

$$\int_{\mathbb{M}} H(z, \nabla_w \mathcal{U}(t, \sigma_s)(z)) \sigma_s(dz) = \int_{\mathbb{M}} H(X_s(q), \nabla_w \mathcal{U}(t, \sigma_s)(X_s(q))) \mu(dq),$$

(3.9) implies

$$\begin{aligned} \mathcal{H}(\sigma_s, \nabla_w \mathcal{U}(t, \sigma_s)) &= \mathcal{H}(\mu, \nabla_w \mathcal{U}(t, \mu)) + s \int_{\mathbb{M}} D_q H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \cdot \xi(q) \mu(dq) \\ &+ s \int_{\mathbb{M}} D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \cdot \left( D_q \nabla_w \mathcal{U}(t, \mu)(q) \xi(q) \right) \mu(dq) \\ &+ s \int_{\mathbb{M}^2} D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \cdot \left( \nabla_{ww}^2 \mathcal{U}(t, \mu)(q, a) \xi(a) \mu(da) \right) \mu(dq) \\ (3.10) \quad &- \mathcal{F}(\mu) - s \int_{\mathbb{M}} \nabla_w \mathcal{F}(\mu)(q) \cdot \xi(q) \mu(dq) + o(s). \end{aligned}$$

Similarly,

$$(3.11) \quad \partial_t \mathcal{U}(t, \sigma_s) = \partial_t \mathcal{U}(t, \mu) + s \int_{\mathbb{M}} \partial_t \nabla_w \mathcal{U}(t, \mu)(q) \cdot \xi(q) \mu(dq) + o(s).$$

Let us remark that since  $\mathcal{U}$  is a  $C_{\text{loc}}^{1,1}([0, T] \times \mathcal{P}_2(\mathbb{M}))$  solution to (3.1),  $\nabla_w \mathcal{U}(\cdot, \mu)(q)$  is Lipschitz continuous on  $[0, T]$ . Moreover, from the equation (3.1) and since  $\mathcal{U}(t, \cdot) \in C_{\text{loc}}^{2,1,w}(\mathcal{P}_2(\mathbb{M}))$ , we get that  $\partial_t \mathcal{U}(t, \cdot)$  is differentiable for all  $t \in (0, T)$ . Therefore,  $\partial_t \nabla_w \mathcal{U}(t, \mu)(q) = \nabla_w \partial_t \mathcal{U}(t, \mu)(q)$  for all  $(t, \mu) \in (0, T) \times \mathcal{P}_2(\mathbb{M})$  and  $q \in \text{spt}(\mu)$ .

Since

$$\partial_t \mathcal{U}(t, \sigma_s) + \mathcal{H}(\sigma_s, \nabla_w \mathcal{U}(t, \sigma_s)) = 0,$$

(3.10) and (3.11) imply

$$\begin{aligned} &\int_{\mathbb{M}} \left( \partial_t \nabla_w \mathcal{U}(t, \mu)(q) + D_q H(q, \nabla_w \mathcal{U}(t, \mu)(q)) - \nabla_w \mathcal{F}(\mu)(q) \right) \cdot \xi(q) \mu(dq) \\ &+ \int_{\mathbb{M}} D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \cdot \left( D_q \nabla_w \mathcal{U}(t, \mu)(q) \xi(q) \right) \mu(dq) \\ (3.12) \quad &+ \int_{\mathbb{M}^2} D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \cdot \left( \nabla_{ww}^2 \mathcal{U}(t, \mu)(q, a) \xi(a) \mu(da) \right) \mu(dq) = 0. \end{aligned}$$

Since we asserted in Remark 2.20 that  $D_q \nabla_w \mathcal{U}(t, \mu)(\cdot)$  is symmetric, (3.12) can be rewritten as

$$\begin{aligned} & \int_{\mathbb{M}} \left[ \partial_t \nabla_w \mathcal{U}(t, \mu)(q) + D_q H(q, \nabla_w \mathcal{U}(t, \mu)(q)) - \nabla_w \mathcal{F}(\mu)(q) \right] \cdot \xi(q) \mu(dq) \\ & + \int_{\mathbb{M}} D_q \nabla_w \mathcal{U}(t, \mu)(q) D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \cdot \xi(q) \mu(dq) \\ & + \int_{\mathbb{M}^2} \left( \nabla_{ww}^2 \mathcal{U}(t, \mu)(q, a)^\top D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \right) \mu(dq) \cdot \xi(a) \mu(da) = 0. \end{aligned}$$

Note

$$D_q H(\cdot, \nabla_w \mathcal{U}(t, \mu)) + D_q \nabla_w \mathcal{U}(t, \mu) D_p H(\cdot, \nabla_w \mathcal{U}(t, \mu)) = D_q \left( H(\cdot, \nabla_w \mathcal{U}(t, \mu)) \right) \in T_\mu \mathcal{P}_2(\mathbb{M})$$

Since the rows of  $\nabla_{ww}^2 \mathcal{U}(t, \mu)(q, a)$  belong to  $T_\mu \mathcal{P}_2(\mathbb{M})$ , so does  $\nabla_{ww}^2 \mathcal{U}(t, \mu)(q, a)^\top D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q))$  (as linear combinations of these rows). By the arbitrariness of  $\xi$  and the previous claims, we conclude

$$\partial_t \nabla_w \mathcal{U}(t, \mu) + D_q H(\cdot, \nabla_w \mathcal{U}(t, \mu)) + D_q \nabla_w \mathcal{U}(t, \mu) D_p H(\cdot, \nabla_w \mathcal{U}(t, \mu)) + \overline{\mathcal{N}}_\mu[\mathcal{V}, \nabla_w^\top \mathcal{V}](t, \mu, \cdot) = \nabla_w \mathcal{F}(\mu),$$

$\mu$ -almost everywhere on  $q \in \mathbb{M}$ .  $\square$

**Remark 3.8.** *At this point we do not know whether all the terms appearing in (3.8) could be extended to (at least  $\mathcal{L}^d$ -a.e.)  $q \in \mathbb{M}$ . We have good pointwise continuity properties of  $\overline{\nabla}_{ww}^\top \mathcal{U}(t, \cdot)(\cdot, \cdot)$ , but we do not know much about the continuity properties of  $\nabla_{ww}^\top \mathcal{U}(t, \cdot)(\cdot, \cdot)$ . If we knew*

$$\overline{\mathcal{N}}_\mu[\mathcal{V}, \nabla_{ww}^\top \mathcal{U}](t, \mu, q) = \overline{\mathcal{N}}_\mu[\mathcal{V}, \overline{\nabla}_{ww}^\top \mathcal{U}](t, \mu, q)$$

*we could deduce that  $q \mapsto \overline{\mathcal{N}}_\mu[\mathcal{V}, \nabla_{ww}^\top \mathcal{U}](t, \mu, q)$  is continuous. In the same time, we do not know whether  $\partial_t \mathcal{V}$  admits a continuous extension.*

*As a last remark, despite the fact that  $\mathcal{V}(t, \mu, \cdot)$  itself is defined only on  $\text{spt}(\mu)$ , we know that it is Lipschitz continuous there, uniformly with respect to  $t$  and  $\mu$ . But it is not clear at all whether any Lipschitz continuous extension of this in the same time would produce a valid extension for  $\partial_t \mathcal{V}$  and  $\nabla_w^\top \mathcal{V}$ . As highlighted before, we revisit this question in Subsection 4.1, and in particular there we produce a solution to the vectorial master equation which is defined for (Lebesgue) a.e.  $q \in \mathbb{M}$ .*

**3.3. The scalar master equation.** In this subsection we assume there exists a function  $C$  which assume to each compact set  $K \subset \mathbb{M}$  and each real number  $r > 0$ , a positive value  $C(K, r)$ . We assume to be given

$$(H10) \quad u_0, f \in C_{\text{loc}}^{1,1}(\mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$$

such that

$$(H11) \quad \nabla_w \mathcal{U}_0(\mu)(q) = D_q u_0(q, \mu), \nabla_w \mathcal{F}(\mu)(q) = D_q f(q, \mu), \quad \forall (q, \mu) \in \mathbb{M} \times \mathcal{P}_2(\mathbb{M}).$$

Since we can modify  $L$  or  $\tilde{\mathcal{F}}$  as follows,

$$\tilde{\mathcal{L}}(x, a) = \int_{\Omega} L(x(\omega), a(\omega) - r|x(\omega)|^2) d\omega + \tilde{\mathcal{F}}(x) + r\|x\|^2,$$

we learn from Proposition B.6 that it is not a loss of generality to assume in the sequel that

$$(3.13) \quad \mathbb{M} \ni q \mapsto u_0(q, \mu) \quad \text{and} \quad \mathbb{M} \times \mathbb{R}^d \ni (q, v) \mapsto L(q, v) + f(q, \mu) \quad \text{are strictly convex} \quad \forall \mu \in \mathcal{P}_2(\mathbb{M}).$$

Let us remark that by the fact that  $u_0, f \in C_{\text{loc}}^{1,1}(\mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ , we have that  $u_0$  and  $f$  are locally bounded, i.e.  $\forall K \subset \mathbb{M}$  compact and  $r > 0$ ,  $\exists C = C(K, r) : |u_0(q_0, \mu)|, |f(q_0, \mu)| \leq C, \forall (q_0, \mu) \in K \times \mathcal{B}_r$ .

We are to find a function  $u : [0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  that satisfies the *scalar master equation*

$$(3.14) \quad \begin{cases} \partial_t u(t, q, \mu) + H(q, D_q u(t, q, \mu)) + \mathcal{N}_\mu[D_q u(t, \cdot, \mu), \nabla_w u(t, q, \mu)(\cdot)] = f(q, \mu), & (0, T) \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}), \\ u(0, \cdot, \cdot) = u_0, & \mathbb{M} \times \mathcal{P}_2(\mathbb{M}), \end{cases}$$

where the non-local operator  $\mathcal{N}_\mu$  is defined as in (0.1). We define the notion of classical solution to (3.14) as follows.

**Definition 3.9.** *We say that  $u$  is a classical solution to (3.14), if the following holds. It is continuously differentiable on  $(0, T) \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M})$ , continuous up to the initial time 0 and the PDE is satisfied pointwise. The vector field  $\mathbb{M} \ni q \mapsto D_q u(t, q, \nu)$  is Lipschitz, uniformly with respect to  $(t, \nu) \in [0, T] \times \mathcal{B}_r$  ( $r > 0$ ).*

*Furthermore, for all  $\nu \in \mathcal{P}_2(\mathbb{M})$  and for  $\mathcal{L}^1 \otimes \mathcal{L}^d$ -a.e.  $(s, q) \in (0, T) \times \mathbb{M}$ ,  $D_q \nabla_w u(s, q, \nu)(\cdot)$  and  $\nabla_w D_q u(s, q, \nu)(\cdot)$  exist, belong to  $L^2(\nu)$  and they satisfy additionally*

$$(3.15) \quad \int_{\mathbb{M}} \left( (D_q \nabla_w - \nabla_w D_q) u(s, q, \nu)(y) \right) D_p H(y, D_q u(s, y, \nu)) \nu(dy) = 0.$$

**Remark 3.10.** *The condition (3.15) in the previous definitions needs some comments. In Theorem 3.22 we will actually show existence of  $C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$  solution to (3.14). Let us notice that for functions  $w \in C_{\text{loc}}^{1,1}(\mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ ,  $D_q \nabla_w w(q, \nu)(\cdot)$  is meaningful for all  $\nu \in \mathcal{P}_2(\mathbb{M})$  and for a.e.  $q \in \mathbb{M}$  (see Subsection 4.1). But, since  $D_q w$  is only Lipschitz continuous with respect to the measure variable,  $\nabla_w D_q w(q, \nu)(\cdot)$  might not be meaningful in general (since Rademacher-type theorems in  $(\mathcal{P}_2(\mathbb{M}), W_2)$  are more subtle). So the  $C^{1,1}$  regularity in general is not enough to ensure (3.15).*

*Nevertheless, as the discussion in Subsection 4.1 shows, the solution that we construct for the master equation (3.14) naturally satisfies (3.15). This condition in particular will imply uniqueness of the solution as well.*

For  $m \in \mathbb{N}$ , we define

$$u_0^{(m)}, f^{(m)} : \mathbb{M} \times (\mathbb{M})^m \rightarrow \mathbb{R}, \quad U_0^{(m)}, F^{(m)} : (\mathbb{M})^m \rightarrow \mathbb{R}$$

as

$$u_0^{(m)}(y, q) := u_0(y, \mu_q^{(m)}), \quad f^{(m)}(y, q) := f(y, \mu_q^{(m)}), \quad U_0^{(m)}(q) := \mathcal{U}_0(\mu_q^{(m)}), \quad F^{(m)}(q) := \mathcal{F}(\mu_q^{(m)}),$$

where for  $q = (q_1, \dots, q_m) \in (\mathbb{M})^m$ ,  $\mu_q^{(m)}$  is defined as in (1.1).

We impose the following hypotheses on  $u_0^{(m)}$  and  $f^{(m)}$ .

(H13)

$$u_0^{(m)}(y, \cdot), f^{(m)}(y, \cdot) \text{ satisfy Properties 2.15(1)(a) and 2.15(2), locally uniformly w.r.t. } y \in \mathbb{M}.$$

(H14)  $D_y u_0^{(m)}(y, \cdot), D_y f^{(m)}(y, \cdot)$  satisfy Property 2.15(1)(a), locally uniformly w.r.t.  $y \in \mathbb{M}$ .

Let us notice that based on the previous assumptions, we have that  $D_y u_0^{(m)}$  and  $D_y f^{(m)}$  are locally uniformly bounded, i.e.  $\forall r > 0, K \subset \mathbb{M}$  compact,  $\exists C = C(K, r) : |D_y u_0^{(m)}(y, q)|, |D_y f^{(m)}(y, q)| \leq C$ , if  $(y, q) \in K \times \mathbb{B}_r^m$ . In the same time, by the assumption (H6),  $D_q L$  and  $\partial_y^a \partial_v^b L$  (for all  $a, b$  multi-indices with  $|a| + |b| = 2$ ) are locally uniformly bounded.

We assume that there exists a constant  $C > 0$  such that

$$(H15) \quad \|\partial_q^a \partial_p^b H\|_{L^\infty(\mathbb{M} \times \mathbb{R}^d)} \leq C, \quad \text{for } a, b \text{ multi-indices with } |a| + |b| = 3.$$

We assume there exists a locally bounded continuous function  $\theta : \mathcal{P}_2(\mathbb{M}) \rightarrow [0, \infty)$  such that

$$(H16) \quad L(q, v) + f(q, \mu) \geq \lambda_1 |v|^2 - \theta(\mu)(|q| + 1), \quad \forall (q, v) \in \mathbb{M} \times \mathbb{R}^d, \forall \mu \in \mathcal{P}_2(\mathbb{M}).$$

Note that it suffices to impose that  $f(\cdot, \mu)$  is convex to have that (H7) implies (H16).

Recall that Remark 1.1 (iii) ensures there exists a constant  $C$  such that

We assume that there exists  $C > 0$  such that

$$(3.16) \quad |D_q H(q, p)| \leq C(1 + |q| + |p|), \quad |D_q L(q, v)| \leq C(1 + |q| + |v|) \quad \forall (q, p, v) \in \mathbb{M} \times \mathbb{R}^{2d}.$$

**3.4. Examples of initial data.** We pause for a moment to give an example of initial data, which satisfied our assumptions. Similar examples can be constructed for  $\mathcal{F}$  and  $f$  as well. Let  $\phi_0, \phi_1 : \mathbb{M} \rightarrow \mathbb{R}$  be smooth bounded functions with uniformly bounded derivatives up to order 3. For simplicity, we assume also that they are positive and  $\phi_1$  is even. Fix  $\lambda > 0$  and let  $\phi : \mathbb{M} \rightarrow \mathbb{R}$  be defined as  $\phi(q) := \frac{\lambda}{2}|q|^2 + \phi_0(q)$  and assume  $\lambda$  is large enough such that  $D^2\phi + D^2\phi_1 > 0$  on  $\mathbb{M}$ . Then, let us define  $\mathcal{U}_0 : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  as

$$\mathcal{U}_0(\mu) := \int_{\mathbb{M}} \phi(q)\mu(dq) + \frac{1}{2} \int_{\mathbb{M}} \phi_1 * \mu(q)\mu(dq), \quad \tilde{\mathcal{U}}_0(x) = \mathcal{U}_0(x_{\#}\mathcal{L}_{\Omega}^d), \quad \forall \mu \in \mathcal{P}_2(\mathbb{M}), x \in \mathbb{H}.$$

Then  $\tilde{\mathcal{U}}_0$  fulfills the assumptions (H1)-(H3).

Set

$$u_0(q_0, \mu) = \phi(q_0) + (\phi_1 * \mu)(q_0).$$

For  $q := (q_1, \dots, q_m) \in \mathbb{M}^m$  and  $q_0 \in \mathbb{M}$ , we have

$$u_0^{(m)}(q_0, q) = \phi(q_0) + \sum_{i=1}^m \frac{1}{m} \phi_1(q_0 - q_i), \quad \text{and} \quad U_0^{(m)}(q) = \frac{1}{m} \sum_{i=1}^m \phi(q_i) + \frac{1}{2m^2} \sum_{i,j=1}^m \phi_1(q_i - q_j),$$

and so for  $1 \leq i \leq m$ ,

$$D_{q_i} u_0^{(m)}(q_0, q) = \frac{1}{m} D\phi_1(q_0 - q_i) \quad \text{and} \quad D_{q_0}^2 u_0^{(m)}(q_0, q) = \frac{1}{m} D^2\phi_1(y - x_i).$$

We have

$$D_{q_0} u_0^{(m)}(q_0, q) = D\phi(y) + \sum_{i=1}^m \frac{1}{m} D\phi_1(q_0 - q_i).$$

From these computations, one can easily verify the hypotheses (H10) through (H14).

Under appropriate conditions on functions  $L_0, l$  and  $g$  Lagrangians of the form

$$L(q, v) = L_0(v) + l(q, v) + g(q)$$

satisfy (H4)-(H8).

We are ready now to define the candidate for the solution to the scalar master equation. Given  $t \in [0, T]$ ,  $q \in \mathbb{M}$  and  $\mu \in \mathcal{P}_2(\mathbb{M})$  we define

$$(3.17) \quad u(t, q, \mu) := \inf_{\gamma} \left\{ u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_s, \dot{\gamma}_s) + f(\gamma_s, \sigma_s^t[\mu]) \right) ds : \gamma \in W^{1,2}([0, t], \mathbb{M}), \gamma_t = q \right\}.$$

Here the curve  $(\sigma_s^t[\mu])_{s \in [0, t]}$  is defined in (3.2).

Define

$$M_*(r) := \sup_{B_r(0) \times \mathcal{B}_{e_T}(r)} |\theta| + |u_0| + T(|f| + |L(0, \cdot)|), \quad c_*(r) := \sup_{\bar{B}_1(0) \times \bar{\mathcal{B}}_r} |u_0|$$

**Remark 3.11.** Let  $r > 0$ .

(i) As  $u_0(\cdot, \nu)$  is convex, if  $D_q u(0, \nu) \neq 0$  then

$$u_0 \left( \frac{D_q u(0, \nu)}{|D_q u(0, \nu)|}, \nu \right) \geq u_0(0, \nu) + \frac{D_q u(0, \nu)}{|D_q u(0, \nu)|} \cdot D_q u(0, \nu) = u_0(0, \nu) + \frac{|D_q u(0, \nu)|^2}{|D_q u(0, \nu)|}.$$

Thus, if  $\nu \in \mathcal{B}_r$ , we conclude that

$$|D_q u(0, \nu)| \leq 2c_*(r).$$

Clearly, the previous inequality still holds when  $D_q u(0, \nu) = 0$ . Consequently,

$$u_0(q, \nu) \geq u_0(0, \nu) + D_q u(0, \nu) \cdot q \geq -c_*(r)(1 + |q|).$$

(ii) Suppose  $(t, q, \mu) \in [0, T] \times B_r(0) \times \mathcal{B}_r$ . Then

$$u(t, q, \mu) \leq M_*(r),$$

and so, if  $\gamma$  is the unique minimizer in (3.17), we use (H16) and Remark 3.2 (ii) to obtain

$$M_*(r) \geq u(t, q, \mu) \geq -c_*(e_T(r))(1 + |\gamma(0)|) - M_*(r)T - M_*(r) \int_0^t |\dot{\gamma}| ds + \lambda_1 \int_0^t |\dot{\gamma}|^2 ds.$$

We conclude there exists a constant  $\overline{M}(r)$  independent of  $t$  such that

$$\int_0^t |\dot{\gamma}|^2 ds \leq \overline{M}(r).$$

Hence,

$$(3.18) \quad |\gamma_{\tau_1} - \gamma_{\tau_2}|^2 \leq \overline{M}(r) |\tau_2 - \tau_1| \quad \text{if } 0 \leq \tau_1 \leq \tau_2 \leq t.$$

(iii) By (ii), there is constant  $M^*(r)$  such that

$$|u(t, q, \mu)| \leq M^*(r) \quad (t, q, \mu) \in [0, T] \times B_r(0) \times \mathcal{B}_r$$

Since

$$(q, v) \mapsto L_{s,t}(q, v) := L(q, v) + f(q, \sigma_s^t[\mu]), \quad q \mapsto u_0(q, \sigma_0^t[\mu])$$

are convex, we obtain that  $u(t, \cdot, \mu)$  is a convex function and so as argued above,

$$|D_q u(t, q, \mu)| \leq u\left(t, q + \frac{D_q u(t, q, \mu)}{|D_q u(t, q, \mu)|}\right) - u(t, q, \mu) \leq M^*(r) + M^*(r+1)$$

**Lemma 3.12.** *Let  $(t, q, \mu) \in [0, T] \times B_r(0) \times \mathcal{B}_r$  and let  $\gamma : [0, t] \rightarrow \mathbb{M}$  be the unique optimizer in (3.17). Suppose that the assumptions (H5), (H6), (H7), (H11) and (3.16) take place. Then  $\gamma \in C^{1,1}([0, t])$ .*

*Proof.* The proof is inspired by the proof of [7, Theorem 6.2.5]. First, (H7), the convexity of  $L$  in the  $v$  variable and the Euler-Lagrange equation satisfied by  $\gamma$  implies that there exists a constant  $C = C(r, t) > 0$  such that

$$\begin{aligned} \lambda_1 |\dot{\gamma}_s|^2 + \lambda_0 &\leq L(\gamma_s, \dot{\gamma}_s) \leq L(\gamma_s, 0) + D_v L(\gamma_s, \dot{\gamma}_s) \cdot \dot{\gamma}_s \\ &\leq |L(\gamma_s, 0)| + |D_q u_0(\gamma_0, \sigma_0^t[\mu])| + |\dot{\gamma}_s| \int_0^s |D_q L(\gamma_\tau, \dot{\gamma}_\tau)| + |D_q f(\gamma_\tau, \sigma_\tau^t[\mu])| d\tau \\ &\leq C + C |\dot{\gamma}_s|, \end{aligned}$$

Where in the last inequality, we have used the regularity assumptions on  $L, u_0$  and  $f$ , (3.16) and the fact that  $\gamma_\tau \in B_R(0)$  and  $\sigma_\tau^t[\mu] \in \mathcal{B}_R$  for all  $\tau \in [0, t]$ , for some  $R = R(t, r) > 0$ . This chain of inequalities implies that  $|\dot{\gamma}|$  must be bounded on  $[0, t]$ , and so  $\gamma$  is Lipschitz continuous.

To conclude, let us write the Euler-Lagrange equation in the form

$$D_{vv}^2 L(\gamma_s, \dot{\gamma}_s) \ddot{\gamma}_s = D_q L(\gamma_s, \dot{\gamma}_s) + D_q f(\gamma_s, \sigma_s^t[\mu]) - D_{qv}^2 L(\gamma_s, \dot{\gamma}_s) \dot{\gamma}_s.$$

Since the right hand side of this equation is uniformly bounded on  $[0, t]$ , by a constant depending on  $r$  and  $t$  and since  $D_{vv}^2 L$  satisfies (H5), we conclude that  $|\ddot{\gamma}|$  is uniformly bounded on  $[0, t]$  and hence the thesis follows.  $\square$

**Proposition 3.13.** *Let  $\mu \in \mathcal{P}_2(\mathbb{M})$  and  $t \in [0, T]$ . Recall  $[0, t] \ni s \mapsto \sigma_s^t[\mu]$  is defined in (3.2) in Lemma 3.1.*

- (i) *We have  $u(t, \cdot, \mu) \in C_{\text{loc}}^{1,1}(\mathbb{M})$ . Furthermore, there exists a unique  $\gamma$  minimizer in (3.17) which we denote as  $s \mapsto S_s^t[\mu](q)$ .*
- (ii) *If  $\omega \in \Omega$ ,  $x \in \mathbb{H}$ ,  $\mu = \sharp(x)$  and  $q = x(\omega)$  (meaning in particular that  $q \in \text{spt}(\mu)$ ), then  $\tilde{S}_s^t[x](\omega) = S_s^t[\mu](q)$ .*
- (iii) *Under the assumptions in (ii) we have  $D_q u(t, q, \mu) = \nabla_w \mathcal{U}(t, \mu)(q)$ .*
- (iv)  *$[0, t] \ni s \mapsto D_q u(s, S_s^t[\mu](q), \sigma_s^t[\mu])$  is Lipschitz continuous, for all  $(q, \mu) \in \mathbb{M} \times \mathcal{P}_2(\mathbb{M})$ .*
- (v) *We have that  $u(\cdot, \cdot, \mu) \in C_{\text{loc}}^{0,1}([0, T] \times \mathbb{M})$ , with Lipschitz constants depending on  $r > 0$ , where  $\mu \in \mathcal{B}_r$ .*

*Proof.* (i) By Remark 3.11 (iii),  $u(t, \cdot, \mu)$  is a convex function. One checks that  $u(t, \cdot, \mu)$  is locally semi-concave and so, it is  $C_{\text{loc}}^{1,1}(\mathbb{M})$ .

Since, the action

$$\gamma \mapsto A_t[\gamma] := u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^t L_{s,t}(\gamma_s, \dot{\gamma}_s) ds$$

is strictly convex,  $S_s^t[\mu](q)$  is uniquely defined.



(ii) By the convexity of  $A_t$ , any critical point of  $A_t$  on the set  $\{\gamma \in C^1([0, t], \mathbb{M}) : \gamma_t = q\}$  is a minimizer. Set

$$p_s := P_s^t[\mu](q).$$

The Hamiltonian associated to  $L_{s,t}$  is  $H_{s,t}(q, p) := H(q, p) - f(q, \sigma_s^t[\mu])$ . Since  $D_p H_{s,t}(q, p) \equiv D_p H(q, p)$ , in light of Proposition C.2 (iv) we have

$$(3.19) \quad D_p H_{s,t}(\gamma_s, p_s) = D_p H\left(\tilde{S}_s^t[x](\omega), \tilde{P}_s^t[x](\omega)\right) = \partial_s \tilde{S}_s^t[x](\omega) = \dot{\gamma}_s$$

By (H11)

$$D_q H_{s,t}(q, p) = D_q H(q, p) - D_q f(q, \sigma_s^t[\mu]) = D_q H(q, p) - \nabla_w \mathcal{F}(\sigma_s^t[\mu])(q).$$

Thus, by Remark 2.7

$$(3.20) \quad D_q H_{s,t}(\gamma_s, p_s) = D_q H\left(\tilde{S}_s^t[x](\omega), \tilde{P}_s^t[x](\omega)\right) - \nabla \tilde{\mathcal{F}}(\tilde{S}_s^t[\mu])(\omega) = -\partial_s \tilde{P}_s^t[x](\omega) = -\dot{p}_s.$$

We use first use (H11), second Remark 2.7 and third the last identity in (1.25), to obtain

$$D_q u_0(\gamma_0, \sigma_0^t[\mu]) = \nabla_w \mathcal{U}_0(\sigma_0^t[\mu])(\gamma_0) = \nabla \tilde{\mathcal{U}}_0(\tilde{S}_0^t[\mu])(\omega) = \tilde{P}_0^t[x](\omega) = p_0.$$

This, together with (3.19) and (3.20) implies  $\gamma$  is a critical point of  $A_t$  on the set  $\{\gamma \in C^1([0, t], \mathbb{M}) : \gamma_t = q\}$ . Hence,  $\gamma$  is the unique minimizer, which verifies (ii).

(iii) By the optimality property of  $\gamma$ , the standard Hamilton–Jacobi theory ensures that

$$(3.21) \quad \dot{\gamma}_s = D_p H(\gamma_s, D_q u(s, \gamma_s, \sigma_s^t[\mu])) \quad \forall s \in (0, t).$$

First, by the strict convexity of  $H$  in the second variable, we have that

$$D_q u(s, \gamma_s, \sigma_s^t[\mu]) = D_v L(\gamma_s, \dot{\gamma}_s) \quad \forall s \in (0, t),$$

from where, by Lemma 3.12 and the by the regularity of  $D_v L$  one obtains that  $[0, t] \ni s \mapsto D_q u(s, \gamma_s, \sigma_s^t[\mu])$  is Lipschitz continuous. This shows (iv).

Then, by Proposition C.2 (iv),

$$\dot{\gamma}_s = D_p H\left(\gamma_s, \nabla_w \mathcal{U}(s, \sigma_s^t[\mu])(\gamma_s)\right),$$

which, together with (3.21) implies

$$D_p H\left(\gamma_s, \nabla_w \mathcal{U}(s, \sigma_s^t[\mu])(\gamma_s)\right) = D_p H(\gamma_s, D_q u(s, \gamma_s, \sigma_s^t[\mu])) \quad \forall s \in (0, t).$$

Thus, by (H5), one has

$$\nabla_w \mathcal{U}(s, \sigma_s^t[\mu])(\gamma_s) = D_q u(s, \gamma_s, \sigma_s^t[\mu]) \quad \forall s \in (0, t).$$

Letting  $s$  increase to  $t$  we verify (iii).

(v) It remains to show the Lipschitz regularity of  $u$  with respect to the variable  $t$ . Let us notice that (i) and Lemma 3.16 below imply that  $u(t, \cdot, \cdot) \in C_{\text{loc}}^{1,1}(\mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$  (uniformly with respect to  $t \in [0, T]$ ). Now let  $q \in K \subset \mathbb{M}$  ( $K$  compact),  $\mu \in \mathcal{B}_r$ ,  $0 \leq s < t \leq T$  and let  $(\gamma_s)_{s \in (0, t)}$  be the optimal curve in the definition of  $u(t, q, \mu)$ . By the dynamic programming principle, we have

$$u(t, q, \mu) = u(s, \gamma_s, \sigma_s^t[\mu]) + \int_s^t L(\gamma_\tau, \dot{\gamma}_\tau) + f(\gamma_\tau, \sigma_\tau^t[\mu]) d\tau.$$

First, let us notice that  $(0, t) \ni \tau \mapsto L(\gamma_\tau, \dot{\gamma}_\tau) + f(\gamma_\tau, \sigma_\tau^t[\mu])$  is uniformly bounded by a constant  $C$  depending only on  $T, K$  and  $r$ . Second, we can write

$$\begin{aligned} |u(t, q, \mu) - u(s, q, \mu)| &\leq |u(s, \gamma_s, \sigma_s^t[\mu]) - u(s, q, \mu)| + \int_s^t \left| L(\gamma_\tau, \dot{\gamma}_\tau) + f(\gamma_\tau, \sigma_\tau^t[\mu]) \right| d\tau \\ &\leq C (|\gamma_s - q| + W_2(\sigma_s^t[\mu], \mu)) + C|t - s| \leq C|t - s|, \end{aligned}$$

where in the last inequality we have used the fact that  $(\gamma_s)_{s \in [0, t]}$  and  $(\sigma_s^t[\mu])_{s \in [0, t]}$  (see Lemma 3.3(ii) and Lemma 3.12) are Lipschitz continuous and the constant  $C$  appearing there is depending only on  $t, K$  and  $r$ . The result follows.  $\square$

**Remark 3.14.** (i) Let  $\mu \in \mathcal{P}_2(\mathbb{M})$ ,  $t \in [0, T]$ . Note that in Proposition 3.13  $S_s^t[\mu]$  is defined on the whole set  $\mathbb{M}$  and not just on the support of  $\mu$ . When  $x \in \mathbb{H}$  is such that  $\mu = \#(x)$ , Proposition 3.13 (ii) reads off

$$\tilde{S}_s^t[x] = S_s^t[\mu] \circ x.$$

Also,

$$(3.22) \quad \begin{cases} \partial_s S_s^t[\mu] = D_p H(S_s^t[\mu], \nabla_w \mathcal{U}(s, \sigma_s^t[\mu])(S_s^t[\mu])), & s \in (0, t), \\ S_t^t[\mu] = \text{id}. \end{cases}$$

(ii) It is very important to underline also the fact that by Proposition 3.13(iii) we have that for all  $(t, \mu) \in (0, T) \times \mathcal{P}_2(\mathbb{M})$ ,  $D_q u(t, \cdot, \mu) = \nabla_w \mathcal{U}(t, \mu)(\cdot)$  on  $\text{spt}(\mu)$ . Since  $D_q u(t, \cdot, \mu)$  is defined on the whole  $\mathbb{M}$  (and we will see below that it is locally Lipschitz continuous), this produces a very natural extension for  $\nabla_w \mathcal{U}(t, \mu)(\cdot)$  to the whole  $\mathbb{M}$ . This observation will also help us to improve the previous notion of weak solution to the vectorial master equation, as we will see in Subsection 4.1.

**Proposition 3.15.** For all  $t \in [0, T]$  and  $q \in \mathbb{M}$ , the function  $u(t, q, \cdot)$  is continuous on  $\mathcal{P}_2(\mathbb{M})$ .

*Proof.* We show that for any  $\mu \in \mathcal{P}_2(\mathbb{M})$ ,  $u(t, q, \cdot)$  is continuous at  $\mu$ . To achieve this goal, let  $(\mu_n)_n \subset \mathcal{P}_2(\mathbb{M})$  be a sequence converging to  $\mu$ . Assume without loss of generality that there exists  $r > 0$  such that  $(\mu_n)_n \subset \mathcal{B}_r$ . Let  $\gamma \in W^{1,2}(0, t, \mathbb{M})$  be such that  $\gamma_t = q$  and

$$u(t, q, \mu) = u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_s, \dot{\gamma}_s) + f(\gamma_s, \sigma_s^t[\mu]) \right) ds.$$

We have

$$u(t, q, \mu_n) \leq u_0(\gamma_0, \sigma_0^t[\mu_n]) + \int_0^t \left( L(\gamma_s, \dot{\gamma}_s) + f(\gamma_s, \sigma_s^t[\mu_n]) \right) ds$$

We use Lemma 3.3 (ii) and the uniform bound on provided by Remark 3.2 (ii) to conclude that

$$(3.23) \quad \limsup_{n \rightarrow \infty} u(t, q, \mu_n) \leq u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_s, \dot{\gamma}_s) + f(\gamma_s, \sigma_s^t[\mu]) \right) ds = u(t, q, \mu).$$

For each  $n$ , let  $\gamma^n \in W^{1,2}(0, t, \mathbb{M})$  be such that  $\gamma_t^n = q$  and

$$u(t, q, \mu_n) = u_0(\gamma_0^n, \sigma_0^t[\mu_n]) + \int_0^t \left( L(\gamma_s^n, \dot{\gamma}_s^n) + f(\gamma_s^n, \sigma_s^t[\mu_n]) \right) ds.$$

We use the last inequality in Remark 3.11 (ii) and apply the Ascoli–Arzelà lemma to conclude that there is a subsequence of  $(\gamma^n)_n$  which we don't relabel that converges weakly to some  $\gamma^\infty \in W^{1,2}(0, t, \mathbb{M})$  and converges uniformly on  $[0, t]$ . We use the constant  $\bar{M}(r)$  in the same remark to obtain  $|\gamma_s^n - \gamma_s^\infty| \leq \bar{M}(r)(t - s)$  and so,  $\gamma_t^\infty = q$ . Since  $u_0, f \in C_{\text{loc}}^{1,1}(\mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ , we use the uniform bound on provided by Remark 3.2 (ii) and the fact that  $(\gamma^n)_n$  is bounded for the uniform norm to conclude

$$\liminf_{n \rightarrow \infty} u(t, q, \mu_n) = \liminf_{n \rightarrow \infty} \left\{ u_0(\gamma_0^n, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_s^n, \dot{\gamma}_s^n) + f(\gamma_s^n, \sigma_s^t[\mu]) \right) ds \right\}.$$

We invoke the convexity property of the functions in (3.13) to conclude that

$$\liminf_{n \rightarrow \infty} u(t, q, \mu_n) \geq u_0(\gamma_0^\infty, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_s^\infty, \dot{\gamma}_s^\infty) + f(\gamma_s^\infty, \sigma_s^t[\mu]) \right) ds \geq u(t, q, \mu).$$

This, together with (3.23) verifies the claim.  $\square$

**Lemma 3.16.** Under the assumption of Theorem 3.22,  $u$  defined in (3.17) is of class  $C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ .

*Proof.* We proceed by a discretization approach. Let  $\mu \in \mathcal{P}_2(\mathbb{M})$ ,  $t > 0$ ,  $m \in \mathbb{N}$  and  $q_0 \in \text{spt}(\mu)$  be fixed. Moreover given  $\{q_1, \dots, q_m\} \subset \text{spt}(\mu)$  we shall use the notation of  $q = (q_1, \dots, q_m) \in (\mathbb{M})^m$ . We define

$$\mu_q^{(m+1)} = \frac{1}{m+1} \sum_{i=0}^m \delta_{q_i}, \quad \sigma_s^{(m+1)} := \sigma_s^t[\mu_q^{(m+1)}]$$

so that  $\sigma^{(m+1)}$  is the solution to the continuity equation (3.3) with  $\mu_q^{(m+1)}$  as terminal condition. Note

$$\sigma_s^{(m+1)} = \frac{1}{m+1} \sum_{i=0}^m \delta_{S_s^t[\mu_q^{(m+1)}](q_i)}, \quad \forall s \in (0, t).$$

We define

$$u_0^{(m+1)}, f^{(m+1)} : \mathbb{M} \times (\mathbb{M})^{(m+1)} \rightarrow \mathbb{R}, \quad U^{(m+1)}, u^{(m)} : (0, T) \times (\mathbb{M})^{(m+1)} \rightarrow \mathbb{R}$$

as

$$u_0^{(m+1)}(y_0, q_0, q) := u_0(y_0, \mu_q^{(m+1)}), \quad f^{(m+1)}(y_0, q_0, q) := f(y_0, \mu_q^{(m+1)}),$$

and

$$(3.24) \quad U^{(m+1)}(s, q_0, q) := \mathcal{U}(s, \mu_q^{(m+1)}), \quad u^{(m)}(t, q_0, q) := u(t, q_0, \mu_q^{(m+1)}).$$

Observe

(3.25)

$$\begin{aligned} u^{(m)}(t, q_0, q) &= u_0(Q_0(0, q_0, q), \sigma_0^{(m+1)}) \\ &+ \int_0^t L(Q_0(s, q_0, q), D_p H(Q_0(s, q_0, q), \nabla_w \mathcal{U}(s, \sigma_s^{(m+1)})(Q_0(s, q_0, q)))) ds \\ &+ \int_0^t f(Q_0(s, q_0, q), \sigma_s^{(m+1)}) ds \\ &= u_0^{(m+1)}(Q_0(0, q_0, q), Q_0(0, q_0, q), Q(0, q_0, q)) \\ &+ \int_0^t L(Q_0(s, q_0, q), D_p H(Q_0(s, q_0, q), (m+1)D_{q_0} U^{(m+1)}(s, Q_0(s, q_0, q), Q(s, q_0, q)))) ds \\ &+ \int_0^t f^{(m+1)}(Q_0(s, q_0, q), Q_0(s, q_0, q), Q(s, q_0, q)) ds \end{aligned}$$

where we have set

$$(3.26) \quad Q_i(s, q_0, q) := S_s^t[\mu_q^{(m+1)}](q_i) \quad \text{and} \quad Q(s, q_0, q) := (Q_1(s, q_0, q), \dots, Q_1(s, q_0, q))$$

Now our first goal is to obtain derivative estimates on  $u^{(m)}$  with respect to the ‘distinguished’ variable  $q_0$  and second, with respect to all the other variables  $q$ . Finally, we also derive the necessary estimates involving the time variable  $t$  as well. It is convenient to introduce the notation

$$\tilde{u}_0^{(m+1)}, \tilde{f}^{(m+1)}, V^{(m+1)} : \mathbb{M} \times (\mathbb{M})^m \rightarrow \mathbb{R}$$

defined as

(3.27)

$$\begin{aligned} \tilde{u}_0^{(m+1)}(q_0, q) &:= u_0^{(m+1)}(Q_0(0, q_0, q), Q_0(0, q_0, q), Q(0, q_0, q)), \\ \tilde{f}^{(m+1)}(q_0, q) &:= \int_0^t f(Q_0(s, q_0, q), Q_0(s, q_0, q), Q(s, q_0, q)) ds \\ V^{(m+1)}(q_0, q) &:= \int_0^t L(Q_0(s, q_0, q), D_p H(Q_0(s, q_0, q), (m+1)\nabla_{q_0} U^{(m+1)}(s, Q_0(s, q_0, q), Q(s, q_0, q)))) ds \end{aligned}$$

In Lemma 3.18 and Lemma 3.21 below we establish the necessary derivative estimates on these new quantities. These imply in particular that there exists a constant  $C = C(T, r, K) > 0$  such that for any  $(q_0, q) \in \mathbb{B}_r^{(m+1)}$ ;  $q_0 \in K$  (where  $K \subset \mathbb{M}$  is compact) and for all  $t \in [0, T]$  and  $i, j \in \{0, \dots, m\}$ , we have

$$(3.28) \quad |D_{q_i} u^{(m)}(t, q_0, q)| \leq \begin{cases} C, & i = 0, \\ \frac{C}{m+1}, & i > 0, \end{cases}$$

$$(3.29) \quad |D_{q_i q_j}^2 u^{(m)}(t, q_0, q)|_\infty \leq \begin{cases} C, & i = j = 0, \\ \frac{C}{m+1}, & (i = j, \text{ and } i > 0), \text{ or } (i \cdot j = 0 \text{ and } \max\{i, j\} > 0), \\ \frac{C}{(m+1)^2}, & i \neq j, i, j > 0. \end{cases}$$

and

$$(3.30) \quad |D_{q_0} \partial_t u^{(m)}(t, q_0, q)| \leq C, \quad \sum_{k=1}^m (m+1) |D_{q_k} \partial_t u^{(m)}|^2 \leq C,$$

and

$$(3.31) \quad |\partial_t u^{(m)}(t, q_0, q)| \leq C, \quad |\partial_{tt}^2 u^{(m)}(t, q_0, q)| \leq C.$$

Let us notice that by definition and the assumption (H11),  $u$  is bounded on  $[0, T] \times K \times \mathcal{B}_r$  for any  $K \subseteq \mathbb{M}$  compact and  $r > 0$ . Therefore,  $u^{(m)}$  is uniformly bounded (with respect to  $m$ ) on  $[0, T] \times K \times \mathbb{B}_r^m$ .

Now, all these properties allow us to verify the assumptions of Corollary 2.18 and conclude by this that there exists  $\tilde{u} : [0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  such that after passing to a suitable subsequence  $(u^{(m)})_{m \in \mathbb{N}}$  converges to  $\tilde{u}$  in the sense as described in Corollary 2.18. Let us notice furthermore that  $\tilde{u}(t, q_0, \mu)$  has to be also the limit of  $u(t, q_0, \mu_q^{(m+1)})$  (since by Proposition 3.15  $u(t, q_0, \cdot)$  is continuous) and therefore  $\tilde{u}$  and  $u$  must coincide. Thus, as a consequence of Corollary 2.18  $u \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ .  $\square$

**Corollary 3.17.** *Under the assumptions of Lemma 3.16, we have that the vector field  $\mathbb{M} \ni q \mapsto D_q u(t, q, \mu)$  is globally Lipschitz, uniformly with respect to  $(t, \mu) \in [0, T] \times \mathcal{B}_r$  for any  $r > 0$ .*

*Proof.* Let  $r > 0$ ,  $t \in [0, T]$  and  $\mu \in \mathcal{B}_r$ . Let  $q_1, q_2 \in \mathbb{M}$ . Let  $(\mu_n)_{n \in \mathbb{N}}$  be a sequence in  $\mathcal{B}_r$  such that  $W_2(\mu_n, \mu) \rightarrow 0$  as  $n \rightarrow +\infty$  and  $\text{spt}(\mu_n) = \mathbb{M}$  for all  $n \in \mathbb{N}$ . By Proposition 3.13(iii) we have  $D_q u(t, q_i, \mu_n) = \nabla_w \mathcal{U}(t, \mu_n)(q_i)$ ,  $i = 1, 2$ . In the light of Proposition 1.3 and Lemma 2.13 there exists  $C = C(r, T) > 0$  independent of  $n$  such that

$$|D_q u(t, q_1, \mu_n) - D_q u(t, q_2, \mu_n)| = |\nabla_w \mathcal{U}(t, \mu_n)(q_1) - \nabla_w \mathcal{U}(t, \mu_n)(q_2)| \leq C |q_1 - q_2|.$$

By the continuity of  $D_q u(t, q_i, \cdot)$  provided in Lemma 3.16, one can pass to the limit with  $n \rightarrow +\infty$  to obtain

$$|D_q u(t, q_1, \mu_n) - D_q u(t, q_2, \mu_n)| \leq C |q_1 - q_2|.$$

The result follows.  $\square$

**Lemma 3.18.** *Let  $\tilde{u}_0^{(m+1)}$ ,  $\tilde{f}^{(m+1)}$  and  $V^{(m+1)}$  be defined in (3.27) and suppose the assumptions of Lemma 3.16 are fulfilled. Then, for  $T, r > 0$  and  $K \subset \mathbb{M}$  compact, there exists a constant  $C = C(T, r, K) > 0$  such that for any  $(q_0, q) \in \mathbb{B}_r^{(m+1)}$  with  $q_0 \in K$  and  $i, j \in \{0, \dots, m\}$ , we have*

(1)

$$|D_{q_i} \tilde{u}_0^{(m+1)}(q_0, q)| \leq \begin{cases} C, & i = 0, \\ \frac{C}{m+1}, & i > 0, \end{cases} \quad \text{and} \quad |D_{q_i} \tilde{f}^{(m+1)}(q_0, q)| \leq \begin{cases} C, & i = 0, \\ \frac{C}{m+1}, & i > 0. \end{cases}$$

(2)

$$|D_{q_i q_j}^2 \tilde{u}_0^{(m+1)}(q_0, q)|_\infty \leq \begin{cases} C, & i = j = 0, \\ \frac{C}{m+1}, & (i = j, \text{ and } i > 0), \text{ or } (i \cdot j = 0 \text{ and } \max\{i, j\} > 0), \\ \frac{C}{(m+1)^2}, & i \neq j, i, j > 0, \end{cases}$$

and

(2)

$$|D_{q_i q_j}^2 \tilde{f}^{(m+1)}(q_0, q)|_\infty \leq \begin{cases} C, & i = j = 0, \\ \frac{C}{m+1}, & (i = j, \text{ and } i > 0), \text{ or } (i \cdot j = 0 \text{ and } \max\{i, j\} > 0), \\ \frac{C}{(m+1)^2}, & i \neq j, i, j > 0. \end{cases}$$

(3)

$$|D_{q_i} V^{(m+1)}(q_0, q)| \leq \begin{cases} C, & \text{if } i = 0, \\ \frac{C}{m+1}, & \text{if } i > 0. \end{cases}$$

(4)

$$|D_{q_i q_j}^2 V^{(m+1)}(q_0, q)|_\infty \leq \begin{cases} C, & i = j = 0, \\ \frac{C}{m+1}, & (i = j \text{ and } i > 0) \text{ or } (i \cdot j = 0 \text{ and } \max\{i, j\} > 0), \\ \frac{C}{(m+1)^2}, & i \neq j. \end{cases}$$

As a consequence,  $u^{(m)}$  defined in (3.25) satisfied the estimates (3.28) and (3.29) from Lemma 3.16.

*Proof.* As the computations to obtain the corresponding estimates in the case of  $\tilde{u}_0^{(m+1)}$  and  $\tilde{f}^{(m+1)}$  are completely parallel, we perform these only in the case of  $\tilde{u}_0^{(m+1)}$ .

(1) In the computations below, to facilitate the reading, we will display neither the time nor the space variables in  $Q_i$ . For  $i \geq 0$ , we have

$$(3.32) \quad \begin{aligned} D_{q_i} \tilde{u}_0^{(m+1)}(q_0, q) &= D_y u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i} Q_0 + D_{q_i} u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i} Q_i \\ &\quad + \sum_{k=0, k \neq i}^m D_{q_k} u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i} Q_k. \end{aligned}$$

Now, let us observe recall that by assumption (H11) we have

$$D_y u_0(y, \mu) = \nabla_w \mathcal{U}_0(\mu)(y), \quad u_0^{(m+1)}(y, q_0, q_1, \dots, q_m) = u_0(y, \mu_q^{(m+1)}),$$

for all  $\mu \in \mathcal{P}_2(\mathbb{M})$ , all  $y \in \text{spt}(\mu)$  and all  $q_0, q_1, \dots, q_m \in \mathbb{M}$ . This implies

$$D_y u_0^{(m+1)}(y, q_0, q) = D_y u_0(y, \mu_q^{(m+1)}) = \nabla_w \mathcal{U}_0(\mu_q^{(m+1)})(y),$$

ans so

$$(3.33) \quad D_y u_0^{(m+1)}(q_i, q_0, q) = D_y u_0(q_i, \mu_q^{(m+1)}) = \nabla_w \mathcal{U}_0(\mu_q^{(m+1)})(q_i) = (m+1) D_{q_i} U_0^{(m+1)}(q_0, q)$$

for all  $i \in \{0, \dots, m\}$ .

Let us notice that by (H13)-(H14), Lemma 3.19 and Lemma 3.20, we can find  $C = C(T, r, K)$  such that

$$(m+1) |D_{q_k} u_0^{(m+1)}(Q_0, Q_0, Q_1, \dots, Q_m)| \leq C, \quad |D_y u_0^{(m+1)}(Q_0, Q_0, Q_1, \dots, Q_m)| \leq C.$$

so (1) follows by combining the previous arguments with Lemma 3.19.

(2) Differentiating (3.32) with respect to  $q_j$  one obtains

$$\begin{aligned} D_{q_i q_j}^2 \tilde{u}_0^{(m+1)}(q_0, q) &= D_{q_j} Q_0 D_{yy}^2 u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i} Q_0 + \sum_{k=0}^m D_{q_j} Q_k D_{y q_k}^2 u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i} Q_0 \\ &\quad + D_y u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i q_j}^2 Q_0 + \sum_{k, l=0}^m D_{q_j} Q_l D_{q_k q_l}^2 u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i} Q_k \\ &\quad + \sum_{k=0}^m D_{q_k} u_0^{(m+1)}(Q_0, Q_0, Q) D_{q_i q_j}^2 Q_k \end{aligned}$$

From (3.33) we observe again for any  $i \in \{0, \dots, m\}$ ,

$$D_{yy}^2 u_0^{(m+1)}(q_i, q_0, q) = D_{yy}^2 u_0(q_i, \mu_q^{(m+1)}) = D_y \nabla_w \mathcal{U}_0(\mu_q^{(m+1)})(q_i) = (m+1) D_{q_i q_i}^2 U_0^{(m+1)}(q_0, q).$$

Thus, if  $i, j > 0$  and  $i \neq j$

$$\begin{aligned} |D_{q_i q_j}^2 \tilde{u}_0^{(m+1)}(q_0, q)|_\infty &\leq \frac{C}{m+1} (m+1) |D_{q_0 q_0}^2 U_0^{(m+1)}(Q_0, Q)|_\infty \frac{C}{m+1} \\ &+ \sum_{k=0}^m |D_{q_j} Q_k|_\infty |D_{y q_k}^2 u_0^{(m+1)}(Q_0, Q_0, Q)|_\infty |D_{q_i} Q_0|_\infty \\ &+ (m+1) |D_{q_0} U_0^{(m+1)}(Q_0, Q)| \frac{C}{(m+1)^2} \\ &+ \sum_{k=0}^m |D_{q_j} Q_k|_\infty |D_{q_k q_k}^2 u_0^{(m+1)}(Q_0, Q_0, Q)|_\infty |D_{q_i} Q_k|_\infty \\ &+ \sum_{k \neq l}^m |D_{q_j} Q_l|_\infty |D_{q_k q_l}^2 u_0^{(m+1)}(Q_0, Q_0, Q)|_\infty |D_{q_i} Q_k|_\infty \\ &+ \sum_{k=0}^m |D_{q_k} u_0^{(m+1)}(Q_0, Q_0, Q)| |D_{q_i q_j}^2 Q_k|_\infty \end{aligned}$$

Let us recall that by our assumptions, there exists  $C = C(T, r, K)$  such that

$$\begin{aligned} |D_{q_0 q_0}^2 U_0^{(m+1)}(Q_0, Q)|_\infty &\leq \frac{C}{m+1}, \quad |D_{y q_k}^2 u_0^{(m+1)}(Q_0, Q_0, Q)|_\infty \leq \frac{C}{m+1}, \\ |D_{q_k q_l}^2 u_0^{(m+1)}(Q_0, Q_0, Q)|_\infty &\leq \begin{cases} \frac{C}{m+1}, & k = l, \\ \frac{C}{(m+1)^2}, & k \neq l, \end{cases} \\ |D_{q_k} u_0^{(m+1)}(Q_0, Q_0, Q)| &\leq \frac{C}{m+1} \end{aligned}$$

and by Lemma 3.20 and by the assumptions on  $U_0^{(m+1)}$ ,

$$|D_{q_0} U_0^{(m+1)}(Q_0, Q)| \leq \frac{C}{m+1}.$$

Therefore, combining the previous arguments and computations, we conclude that

$$|D_{q_i q_j}^2 \tilde{u}_0^{(m+1)}(q_0, q)|_\infty \leq \frac{C}{(m+1)^2}.$$

Similar arguments yield that if  $i = j$ , we have

$$|D_{q_i q_i}^2 \tilde{u}_0^{(m+1)}(q_0, q)|_\infty \leq \frac{C}{m+1}.$$

Computations and arguments to the one's above yield that

$$|D_{q_0 q_0}^2 \tilde{u}_0^{(m+1)}(q_0, q)|_\infty \leq C \quad \text{and} \quad |D_{q_0 q_k}^2 \tilde{u}_0^{(m+1)}(q_0, q)|_\infty \leq \frac{C}{m+1}, \quad \text{if } k > 0,$$

and so the thesis of the claim follows.

(3) Let us set  $v_0 := D_p H(Q_0, (m+1) \nabla_{x_0} U^{(m+1)}(s, Q_0, Q))$ . First, we have

$$\begin{aligned} (3.34) \quad D_{q_i} v_0 &= D_{pq}^2 H(Q_0, (m+1) \nabla_{x_0} U^{(m+1)}(s, Q_0, Q)) D_{q_i} Q_0 \\ &+ D_{pp}^2 H(Q_0, (m+1) \nabla_{q_0} U^{(m+1)}(s, Q_0, Q)) (m+1) \sum_{k=0}^m D_{q_0 q_k}^2 U^{(m+1)}(s, Q_0, Q) D_{q_i} Q_k, \end{aligned}$$

from where using the assumptions (H4) and (H6) on  $H$ , Lemma 3.19 and the properties of  $D_{x_0 x_k}^2 U^{(m+1)}$ , we obtain

$$\begin{aligned} |D_{q_i} v_0|_\infty &\leq \frac{C}{m+1} + \frac{C}{m+1} + (m+1) \sum_{k=1}^m |D_{q_0 q_k}^2 U^{(m+1)}(s, Q_0, \dots, Q_m)|_\infty |D_{q_i} Q_k|_\infty \\ &\leq \frac{C}{m+1}, \quad \text{if } i > 0. \end{aligned}$$

The very same computation and arguments yield that  $|D_{q_0} v_0|_\infty \leq C$ .

Now, we compute

$$(3.35) \quad D_{q_i} V^{(m+1)}(q_0, q) = \int_0^t (D_y L(Q_0, v_0) D_{q_i} Q_0 + D_v L(Q_0, v_0) D_{q_i} v_0) ds$$

Using the smoothness property and the assumptions (H4) and (H6) on  $L$ , together with Lemma 3.20, we have that there exists  $C = C(T, r, K)$  such that  $|Q_0(s, \cdot)| \leq C$  and  $|\dot{Q}_0(s, \cdot)| \leq C$  for all  $s \in (0, t)$ , and so  $|D_y L(Q_0, v_0)| \leq C$  and  $|D_v L(Q_0, v_0)| \leq C$ . Therefore, by combining all the previous arguments, the thesis of the claim follows.

(4) From (3.35) one obtains

$$(3.36) \quad \begin{aligned} D_{q_i q_j}^2 V^{(m+1)}(q_0, q) &= \int_0^t (D_{q_j} Q_0 D_{yy}^2 L(Q_0, v_0) D_{q_i} Q_0 + D_{q_j} v_0 D_{yv}^2 L(Q_0, v_0) D_{q_i} Q_0 + D_y L(Q_0, v_0) D_{q_i q_j}^2 Q_0) ds \\ &+ \int_0^t (D_{q_j} Q_0 D_{vy}^2 L(Q_0, v_0) D_{x_i} v_0 + D_{q_j} v_0 D_{vv}^2 L(Q_0, v_0) D_{q_i} v_0 + D_v L(Q_0, v_0) D_{q_i q_j}^2 v_0) ds \end{aligned}$$

We first notice that by the arguments from (3), we have that there exists a constant  $C = C(T, r, K)$  such that  $|Q_0(s, \cdot)| \leq C$  and  $|v_0(s, \cdot)| \leq C$  for all  $s \in (0, t)$ , and so  $|D_{yy}^2 L(Q_0, v_0)| \leq C$ ,  $|D_{yv}^2 L(Q_0, v_0)| \leq C$  and  $|D_{vv}^2 L(Q_0, v_0)| \leq C$ .

To conclude, from (3.34) we compute

$$\begin{aligned} D_{q_i q_j}^2 v_0 &= D_{q_j} Q_0 D_{ppq}^3 H(Q_0, (m+1) D_{q_0} U^{(m+1)}(s, Q_0, Q)) D_{q_i} Q_0 \\ &+ (m+1) \sum_{k=0}^m D_{q_0 q_k}^2 U^{(m+1)}(s, Q_0, Q) D_{q_j} Q_k D_{ppq}^3 H(Q_0, (m+1) D_{q_0} U^{(m+1)}(s, Q_0, Q)) D_{q_i} Q_0 \\ &+ D_{pp}^2 H(Q_0, (m+1) D_{q_0} U^{(m+1)}(s, Q_0, Q)) D_{q_i q_j}^2 Q_0 \\ &+ D_{q_j} Q_0 D_{ppq}^3 H(Q_0, (m+1) D_{q_0} U^{(m+1)}(s, Q_0, Q)) (m+1) \sum_{k=0}^m D_{q_0 q_k}^2 U^{(m+1)}(s, Q_0, Q) D_{q_i} Q_k \\ &+ D_{pp}^2 H(Q_0, (m+1) D_{q_0} U^{(m+1)}(s, Q_0, Q)) (m+1) \sum_{k,l=0}^m D_{q_j} Q_l D_{q_0 q_k q_l}^3 U^{(m+1)}(s, Q_0, Q) D_{q_i} Q_k \\ &+ D_{pp}^2 H(Q_0, (m+1) D_{q_0} U^{(m+1)}(s, Q_0, Q)) (m+1) \sum_{k=0}^m D_{q_0 q_k}^2 U^{(m+1)}(s, Q_0, \dots, Q_m) D_{q_i q_j}^2 Q_k, \end{aligned}$$

From here, using the assumptions (H6) and (H15) on  $H$ , the estimates on  $D_{q_0 q_k}^2 U^{(m+1)}$ , on  $D_{q_0 q_k q_l}^3 U^{(m+1)}$  and Lemma 3.19, we obtain that there exists  $C = C(T, r, K) > 0$  such that

$$|D_{q_i q_j}^2 v_0(q_0, q)|_\infty \leq \begin{cases} C, & i = j = 0, \\ \frac{C}{m+1}, & (i = j \text{ and } i > 0) \text{ or } (i \cdot j = 0 \text{ and } \max\{i, j\} > 0), \\ \frac{C}{(m+1)^2}, & i \neq j. \end{cases}$$

Combining this with the previous arguments and with (3.36) the thesis of the claim follows.  $\square$

**Lemma 3.19.** For  $m \in \mathbb{N}$  and  $q = (q_0, \dots, q_m) \in (\mathbb{M})^{m+1}$ , let

$$\mu_q^{(m+1)} := \frac{1}{(m+1)} \sum_{i=0}^m \delta_{q_i}, \quad Q_i(s, q) := S_s^t[\mu_q^{(m+1)}](q_i), \quad P_i(s, q) := \frac{1}{(m+1)} P_s^t[\mu_q^{(m+1)}](q_i) \quad 0 \leq i \leq m.$$

We set  $U_0^{(m+1)}(q) := \mathcal{U}_0(\mu_q^{(m+1)})$  and  $F^{(m+1)}(q) := \mathcal{F}(\mu_q^{(m+1)})$ . Further assume  $U_0^{(m+1)}$  and  $F^{(m+1)}$  satisfy Property 2.15(3). Then (as in Theorem D.2) for  $r > 0$  and  $t > 0$ , there exists  $C = C(t, r)$  such that for all  $q \in \mathbb{B}_r^{(m+1)}$ ,  $s \in (0, t)$  and  $i, j \in \{0, \dots, m\}$  we have

$$(3.37) \quad |D_{q_j} Q_i(s, q)|_\infty \leq \begin{cases} C, & i = j, \\ \frac{C}{(m+1)}, & i \neq j. \end{cases}$$

and

$$(3.38) \quad |D_{q_k q_j}^2 Q_i(s, q)|_\infty \leq \begin{cases} C, & i = j = k, \\ \frac{C}{(m+1)}, & i = j \neq k, \quad i \neq j = k, \quad i = k \neq j, \\ \frac{C}{(m+1)^2}, & i \neq j \neq k. \end{cases}$$

*Proof.* Let  $\xi(\cdot, z) = (\xi_0(\cdot, z), \dots, \xi_m(\cdot, z))$  be defined as in (1.15) (see also the systems in (1.16) and (D.7)).

By Proposition C.2 we first observe that that  $\xi(t, \cdot)^{-1} = S_0^{t, m}$ . To facilitate the writing, as it is done in Appendix D, we denote  $\zeta(t, \cdot) := \xi^{-1}(t, \cdot)$  and so, we have

$$Q_i(s, q) = \xi_i(s, \zeta(t, q)).$$

Thus, by differentiating and using the estimates on  $(\xi_0, \dots, \xi_m)$  and  $(\zeta_0, \dots, \zeta_m)$  from Theorem D.2, by denoting  $|\cdot|_\infty := \|\cdot\|_{L^\infty(\mathbb{B}_r^{(m+1)})}$ , we have that there exists  $C = C(t, r)$  such that

$$\begin{aligned} |D_{q_j} Q_i(s, \cdot)|_\infty &\leq \sum_{k=0}^m |D_{z_k} \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot))|_\infty |D_{q_j} \zeta_k(t, \cdot)|_\infty \\ &= |D_{z_i} \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot))|_\infty |D_{q_j} \zeta_i(t, \cdot)|_\infty \\ &\quad + \sum_{k \neq i} |D_{z_k} \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot))|_\infty |D_{q_j} \zeta_k(t, \cdot)|_\infty \\ &\leq \begin{cases} C, & i = j, \\ \frac{C}{m+1}, & i \neq j. \end{cases} \end{aligned}$$

Therefore, (3.37) follows. Furthermore, since

$$\begin{aligned} D_{q_k q_j}^2 Q_i(s, \cdot) &= \sum_{l_1, l_2=0}^m D_{q_{l_2} q_{l_1}}^2 \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot)) D_{q_k} \zeta_{l_2}(t, \cdot) D_{q_j} \zeta_{l_1}(t, \cdot) \\ &\quad + \sum_{l_1=0}^m D_{z_{l_1}} \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot)) D_{q_k q_j}^2 \zeta_{l_1}(t, \cdot) \\ &= \sum_{l_1 \neq l_2}^m D_{q_{l_2} q_{l_1}}^2 \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot)) D_{q_k} \zeta_{l_2}(t, \cdot) D_{q_j} \zeta_{l_1}(t, \cdot) \\ &\quad + \sum_{l=0}^m D_{q_l q_l}^2 \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot)) D_{q_k} \zeta_l(t, \cdot) D_{q_j} \zeta_l(t, \cdot) \\ &\quad + \sum_{l_1=0}^m D_{z_{l_1}} \xi_i(s, \zeta_0(t, \cdot), \dots, \zeta_m(t, \cdot)) D_{q_k q_j}^2 \zeta_{l_1}(t, \cdot), \end{aligned}$$

we have that (3.38) follows.  $\square$



**Lemma 3.20.** *Let us suppose that we are in the setting of Lemma 3.16 and in particular all of its assumptions are in place. Let  $(Q_i)_{i=0}^{m+1}$  be defined in (3.26). Let  $(q_0, q) \in \mathbb{M}^{(m+1)}$ . Then  $(0, t) \ni s \mapsto Q_0(s, q_0, q)$  is Lipschitz continuous with a Lipschitz constant independent of  $m$  and for all  $r > 0$  and  $K \subset \mathbb{M}$  compact there exists  $C = C(t, K, r) > 0$  such that  $|Q_0(s, q_0, q)| \leq C$  for all  $s \in (0, t)$ , whenever  $(q_0, q) \in \mathbb{B}_r^{(m+1)}$  and  $q_0 \in K$ .*

*Proof.* Let us notice that  $(Q_0(s, q_0, q))_{s \in (0, t)}$  solves (3.22), with data  $\sigma_s^t[\mu_q^{(m+1)}]$  and final condition  $q_0$ . Furthermore, since  $(\sigma_s^t[\mu_q^{(m+1)}])_{s \in (0, t)}$  belongs to  $\mathcal{B}_{\beta(t, r)}$ , for some  $\beta(t, r) > 0$ , the velocity field  $(0, t) \times \mathbb{M} \ni (s, y) \mapsto D_p H(y, \nabla_w \mathcal{U}(s, \sigma_s^t[\mu_q^{(m+1)}](y)))$  is globally Lipschitz continuous (after a suitable extension of  $\nabla_w \mathcal{U}(s, \sigma_s^t[\mu_q^{(m+1)}](\cdot))$ ). Therefore, classical results in the theory of ODEs imply the thesis of the lemma and the bound on  $Q_0(s, \cdot, \cdot)$  depends only on  $t, K$  and on the Lipschitz constant of the previously mentioned velocity field (hence on  $r$ ).  $\square$

**Lemma 3.21.** *Under the assumptions of Theorem 3.22,  $u^{(m)}$  defined in (3.17) satisfies the estimates (3.30) and (3.31) from Lemma 3.16.*

*Proof.* In Lemma 3.18 we showed that  $u^{(m)}(t, \cdot, \cdot) \in C_{\text{loc}}^{1,1}(\mathbb{M}^{m+1})$  with the corresponding derivative estimates (3.28) and (3.29), uniformly in with respect to  $t \in [0, T]$ . Furthermore, since by Proposition 3.13(v),  $u(\cdot, q, \mu)$  is Lipschitz continuous for all  $q, \mu \in \mathbb{M} \times \mathcal{P}_2(\mathbb{M})$ , this property is inherited by  $u^{(m)}$ , and therefore  $u^{(m)}(\cdot, q_0, q)$  is Lipschitz continuous on  $[0, T]$  for all  $(q_0, q) \in \mathbb{M}^{m+1}$ .

Let us recall now the representation formula (3.25) of  $u^{(m)}(t, q_0, q)$ . We fix  $K$  to be the closure of a bounded open set in  $\mathbb{M}$  and  $r > 0$  such that  $\mu_q^{(m+1)} \in \mathbb{B}_r^{m+1}$ . The regularity properties of  $u^{(m)}$  and (3.25) for almost every  $t \in (0, T)$  and all  $(q_0, q) \in \mathbb{M}^{m+1}$  yield

$$(3.39) \quad \begin{aligned} & \partial_t u^{(m)}(t, q_0, q) + D_{q_0} u^{(m)}(t, q_0, q) \cdot D_p H(q_0, (m+1)D_{q_0} U^{(m+1)}(t, q_0, q)) \\ & + \sum_{j=1}^m D_{q_j} u^{(m)}(t, q_0, q) \cdot D_p H(q_j, (m+1)D_{q_j} U^{(m+1)}(t, q_0, q)) \\ & = L(q_0, D_p H(q_0, (m+1)D_{q_0} U^{(m+1)}(t, q_0, q))) + f^{(m+1)}(q_0, q_0, q). \end{aligned}$$

Proposition 3.13(iii) and (3.24) yield

$$(m+1)D_{q_0} U^{(m+1)}(t, q_0, q) = \nabla_w \mathcal{U}(t, \mu_q^{(m+1)})(q_0) = D_{q_0} u(t, q_0, \mu_q^{(m+1)}).$$

Now, let us notice that by the definition of  $u^{(m)}$ , one has the identity

$$D_{q_0} u^{(m)}(t, q_0, q) = D_{q_0} u(t, q_0, \mu_q^{(m+1)}) + \frac{1}{m+1} \nabla_w u(t, q_0, \mu_q^{(m+1)})(q_0).$$

For an arbitrary  $a \in \mathbb{M}$ , if we set in  $\hat{u}^{(m+1)}(t, a, q_0, q) := u(t, a, \mu_q^{(m+1)})$ , we have that

$$\frac{1}{m+1} \nabla_w u(t, q_0, \mu_q^{(m+1)})(q_0) = D_{q_0} \hat{u}^{(m+1)}(t, a, q_0, q)|_{a=q_0}$$

and so

$$(3.40) \quad (m+1)D_{q_0} U^{(m+1)}(t, q_0, q) = D_{q_0} u(t, q_0, \mu_q^{(m+1)}) = D_{q_0} u^{(m)}(t, q_0, q) - D_{q_0} \hat{u}^{(m+1)}(t, q_0, q_0, q).$$

We notice furthermore that  $\hat{u}^{(m+1)}$  (with respect to the regularity and derivative estimates) essentially behaves as  $u^{(m+1)}(t, q_0, q_0, q)$  and in particular by (3.28) and (3.29) there exists a constant  $C = C(K, r) > 0$  such that the followings hold.

$$|D_{q_0} \hat{u}^{(m+1)}(t, q_0, q_0, q)| \leq \frac{C}{m+2},$$

All these arguments allow us conclude that

$$|(m+1)D_{q_0} U^{(m+1)}(t, q_0, q)| \leq C.$$

Now, we differentiate (3.39) with respect to the spacial variables.

Differentiating with respect to  $q_0$ , denoting the variables of  $f^{(m+1)}$  as  $(y_0, q_0, q)$ , we find that there exists  $C = C(T, K, r)$  such that if  $(t, q_0, q) \in [0, T] \times \mathbb{B}_r^{(m+1)}$  with  $q_0 \in K$ , then

$$\begin{aligned}
|D_{q_0} \partial_t u^{(m)}| &\leq |D_{q_0 q_0}^2 u^{(m)}| |D_p H(q_0, (m+1) D_{q_0} U^{(m+1)})| + |D_{q_0} u^{(m)}| |D_{qp}^2 H(q_0, (m+1) D_{q_0} U^{(m+1)})| \\
&\quad + (m+1) |D_{q_0} u^{(m)}| |D_{pp}^2 H(q_0, (m+1) D_{q_0} U^{(m+1)})| |D_{q_0 q_0}^2 U^{(m+1)}| \\
&\quad + \sum_{j=1}^m |D_{q_0 q_j}^2 u^{(m)}| |D_p H(q_j, (m+1) D_{q_j} U^{(m+1)})| \\
&\quad + \sum_{j=1}^m |D_{q_j} u^{(m)}| |D_{pp}^2 H(q_j, (m+1) D_{q_j} U^{(m+1)})| (m+1) |D_{q_0 q_j}^2 U^{(m+1)}| \\
&\quad + |D_{q_0} L(q_0, D_p H(q_0, (m+1) D_{q_0} U^{(m+1)}))| + |D_v L(q_0, D_p H(q_0, (m+1) D_{q_0} U^{(m+1)}))| |D_{qp}^2 H| \\
&\quad + |D_v L(q_0, D_p H(q_0, (m+1) D_{q_0} U^{(m+1)}))| |D_{pp}^2 H| (m+1) |D_{q_0 q_0}^2 U^{(m+1)}| \\
&\quad + |D_{y_0} f^{(m+1)}(q_0, q_0, q)| + |D_{q_0} f^{(m+1)}(q_0, q_0, q)| \\
&\leq C + C \left( \sum_{j=1}^m m |D_{q_0 q_j}^2 u^{(m)}|^2 \right)^{\frac{1}{2}} \left( \sum_{j=1}^m \frac{1}{m} |D_p H(q_j, (m+1) D_{q_j} U^{(m+1)})|^2 \right)^{\frac{1}{2}} \\
&\quad + C + \sum_{i=0}^m \frac{1}{\sqrt{m+1}} \sqrt{m+1} |D_{q_i} f^{(m+1)}| \\
&\leq C + \left( \sum_{i=0}^m \frac{1}{m+1} \right)^{\frac{1}{2}} \left( \sum_{i=1}^m (m+1) |D_{q_i} f^{(m+1)}|^2 \right)^{\frac{1}{2}} \leq C,
\end{aligned}$$

where we have used all the previous estimates (3.28), (3.29) and the ones on  $U^{(m+1)}$  from Theorem D.2, as well as the hypotheses on the data  $H$  and  $f^{(m+1)}$ . This yields the first part of (3.30), since also  $D_p H(\cdot, \nabla \mathcal{U}(t, \mu_q^{(m+1)})(\cdot)) \in L^2(\mu_q^{(m+1)})$ , with and  $L^2(\mu_q^{(m+1)})$  uniformly bounded with respect to  $m$ .

If  $k \in \{1, \dots, m\}$ , completely parallel computation gives

$$\begin{aligned}
|D_{q_k} \partial_t u^{(m)}| &\leq |D_{q_k q_0}^2 u^{(m)}| |D_p H(q_0, (m+1) D_{q_0} U^{(m+1)})| \\
&\quad + (m+1) |D_{q_0} u^{(m)}| |D_{pp}^2 H(q_0, (m+1) D_{q_0} U^{(m+1)})| |D_{q_k q_0}^2 U^{(m+1)}| \\
&\quad + \sum_{j=1}^m |D_{q_k q_j}^2 u^{(m)}| |D_p H(q_j, (m+1) D_{q_j} U^{(m+1)})| \\
&\quad + |D_{q_k} u^{(m)}| |D_{qp}^2 H(q_k, (m+1) D_{q_k} U^{(m+1)})| \\
&\quad + \sum_{j=1}^m |D_{q_j} u^{(m)}| (m+1) |D_{pp}^2 H(q_j, (m+1) D_{q_j} U^{(m+1)})| |D_{q_k q_j}^2 U^{(m+1)}| \\
&\quad + |D_v L(q_0, D_p H(q_0, (m+1) D_{q_0} U^{(m+1)}))| |D_{pp}^2 H| (m+1) |D_{q_k q_0}^2 U^{(m+1)}| + |D_{q_k} f^{(m+1)}| \\
&\leq C |D_{q_k q_0}^2 u^{(m)}| + \frac{C}{(m+1)} |D_p H(q_k, (m+1) D_{q_k} U^{(m+1)})| + \frac{C}{(m+1)} \\
&\quad + |D_{q_k} f^{(m+1)}|,
\end{aligned}$$

from where, using the same arguments as for the conclusion of the first part of (3.30), we find  $\sum_{k=1}^m (m+1) |D_{q_k} \partial_t u^{(m)}|^2 \leq C$ , as desired.

To show (3.31), we argue similarly. First, from (3.39) we simply have

$$\begin{aligned}
|\partial_t u^{(m)}| &\leq |D_{q_0} u^{(m)}| |D_p H(q_0, (m+1)D_{q_0} U^{(m+1)})| + \sum_{j=1}^m |D_{q_j} u^{(m)}| |D_p H(q_j, (m+1)D_{q_j} U^{(m+1)})| \\
&\quad + |L(q_0, D_p H(q_0, (m+1)D_{q_0} U^{(m+1)}))| + |f^{(m+1)}| \\
&\leq C + \left( \sum_{j=1}^m m |D_{q_j} u^{(m)}|^2 \right)^{\frac{1}{2}} \left( \sum_{j=1}^m \frac{1}{m} |D_p H(q_j, (m+1)D_{q_j} U^{(m+1)})|^2 \right)^{\frac{1}{2}} \\
&\leq C,
\end{aligned}$$

where we used the previous estimates and the fact that  $H(q_0, D_{q_0} u^{(m)})$  and  $f^{(m+1)}$  are locally bounded. Second, differentiating (3.39) with respect to  $t$ , we find

$$\begin{aligned}
|\partial_{tt}^2 u^{(m)}| &\leq |\partial_t D_{q_0} u^{(m)}| |D_p H(q_0, (m+1)D_{q_0} U^{(m+1)})| + |D_{q_0} u^{(m)}| |D_{pp}^2 H|(m+1) |\partial_t D_{q_0} U^{(m+1)}| \\
&\quad + \sum_{j=1}^m |\partial_t D_{q_j} u^{(m)}| |D_p H(q_j, (m+1)D_{q_j} U^{(m+1)})| \\
&\quad + \sum_{j=1}^m |D_{q_j} u^{(m)}| |D_{pp}^2 H(q_j, (m+1)D_{q_j} U^{(m+1)})| (m+1) |\partial_t D_{q_j} U^{(m+1)}| \\
&\quad + |(m+1)D_{q_0} U^{(m+1)}| |D_{pp}^2 H|(m+1) |\partial_t D_{q_0} U^{(m+1)}| \\
&\leq C + \left( \sum_{j=1}^m (m+1) |\partial_t D_{q_j} u^{(m)}|^2 \right)^{\frac{1}{2}} \left( \sum_{j=1}^m \frac{1}{(m+1)} |D_p H(q_j, (m+1)D_{q_j} U^{(m+1)})|^2 \right)^{\frac{1}{2}} \\
&\quad + C(m+1) |\partial_t D_{q_0} U^{(m+1)}| \\
&\quad + C \left( \sum_{j=1}^m (m+1) |\partial_t D_{q_j} U^{(m+1)}|^2 \right)^{\frac{1}{2}}
\end{aligned}$$

Let us notice that by (3.40) we have that

$$(m+1) |\partial_t D_{q_0} U^{(m+1)}| \leq |\partial_t D_{q_0} u^{(m)}| + |\partial_t D_{q_0} \hat{u}^{(m+1)}| \leq C + \frac{C}{\sqrt{m+2}},$$

where we have used that  $\sum_{j=0}^m (m+2) |\partial_t D_{q_0} \hat{u}^{(m+1)}|^2 \leq C$ . Relying on the previously obtained estimates and on the fact that by Theorem D.2(3),

$$\sum_{j=1}^m (m+1) |\partial_t D_{q_j} U^{(m+1)}|^2 \leq C,$$

the claim in (3.31) follows.  $\square$

Recall that throughout this section, we have imposed that (H1)-(H8) and (H9) hold. We are ready to state and prove the main theorem of this section.

**Theorem 3.22.** *Suppose the assumptions (H10) through (3.16) are satisfied. Then, the scalar master equation (3.14) has a unique global in time classical solution of class  $C_{\text{loc}}^{1,1}([0, +\infty) \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$  in sense of Definition 3.9.*

*Proof.* Let  $T > 0$  be fixed time horizon. Notice that Theorem 3.4 yields that  $u$  defined in (3.17) is of class  $C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ .

Let  $\mu \in \mathcal{P}_2(\mathbb{M})$ ,  $q \in \mathbb{M}$  and  $t \in (0, T)$ . Using the representation formula (3.17), by the dynamic programming principle we have that for  $s \in (0, t)$

$$\begin{aligned} u(t, q, \mu) &= u(s, S_s^t[\mu](q), \sigma_s^t[\mu]) \\ &\quad + \int_s^t L\left(S_\tau^t[\mu](q), D_p H\left(S_\tau^t[\mu](q), D_q u(\tau, S_\tau^t[\mu](q), \sigma_\tau^t[\mu])\right)\right) + f\left(S_\tau^t[\mu](q), \sigma_\tau^t[\mu]\right) d\tau. \end{aligned}$$

Hence,

$$\begin{aligned} &\lim_{s \rightarrow t} \frac{u(t, q, \mu) - u(s, S_s^t[\mu](q), \sigma_s^t[\mu])}{t - s} \\ &= \lim_{s \rightarrow t} \int_s^t L\left(S_\tau^t[\mu](q), D_p H\left(S_\tau^t[\mu](q), D_q u(\tau, S_\tau^t[\mu](q), \sigma_\tau^t[\mu])\right)\right) + f\left(S_\tau^t[\mu](q), \sigma_\tau^t[\mu]\right) d\tau, \end{aligned}$$

where both limits exist and are finite, due to the continuity of the integrand on the right hand side. Using the chain rule with respect to the measure variable (provided in Lemma 3.23), this is equivalent to

$$\begin{aligned} &\partial_t u(t, q, \mu) + D_q u(t, q, \mu) \cdot D_p H(q, D_q u(t, q, \mu)) + \int_{\mathbb{M}} \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, \nabla_w \mathcal{U}(s, \mu)(y)) \mu(dy) \\ &= L(q, D_p H(q, D_q u(t, q, \mu))) + f(q, \mu) \end{aligned}$$

Here above we used that the optimal curve  $\tau \mapsto S_\tau^t[\mu](q)$  satisfies (3.21), while the curve  $\tau \mapsto \sigma_\tau^t[\mu]$  solves the continuity equation (3.3).

Using that by Proposition 3.13(ii)

$$D_q u(t, \cdot, \mu) = \nabla_w \mathcal{U}(t, \mu)(\cdot) \quad \mu - \text{a.e.},$$

one obtains

$$\begin{aligned} f(q, \mu) &= \partial_t u(t, q, \mu) + D_q u(t, q, \mu) \cdot D_p H(q, D_q u(t, q, \mu)) \\ &\quad + \int_{\mathbb{M}} \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, D_q u(t, y, \mu)) d\mu(y) - L(q, D_p H(q, D_q u(t, q, \mu))) \\ &= \partial_t u(t, q, \mu) + H(q, D_q u(t, q, \mu)) + \int_{\mathbb{M}} \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, D_q u(t, y, \mu)) \mu(dy), \end{aligned}$$

where we have used the Legendre duality in the last equation. The arguments in Subsection 4.1 imply in particular that  $u$  also satisfies the condition (3.15). This completes the existence part of the theorem.

*Uniqueness.* Let  $u \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$  be a solution to (3.14). Let  $t \in (0, T)$ ,  $\mu \in \mathcal{P}_2(\mathbb{M})$  and  $z \in \mathbb{H}$  be fixed such that  $\sharp(z) = \mu$ . Using the vector field  $D_p H(\cdot, D_q u(\cdot, \cdot, \cdot))$ , let  $(\sigma_s)_{s \in (0, t)}$  be the unique solution to the continuity equation

$$(3.41) \quad \begin{cases} \partial_s \sigma_s + \nabla \cdot (\sigma_s D_p H(\cdot, D_q u(s, \cdot, \sigma_s))) = 0, & \text{in } \mathcal{D}'((0, t) \times \mathbb{M}), \\ \sigma_t = \mu. \end{cases}$$

Since  $D_q u$  is locally Lipschitz on  $[0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M})$  and the vector field  $\mathbb{M} \ni q \mapsto D_q u(t, q, \nu)$  is Lipschitz, uniformly with respect to  $(t, \nu) \in [0, T] \times \mathcal{B}_r$ , the existence and uniqueness of  $\sigma$  above follows from standard arguments and from the adaptation of Theorem 3.3 from [23].

Then, in  $\mathbb{H}$  we consider the ODE

$$(3.42) \quad \begin{cases} x'_s = D_p H(x_s, D_q u(s, x_s, \sigma_s)), & s \in (0, t), \\ x_t = z. \end{cases}$$

This has a unique continuously differentiable solution  $x : (0, t) \rightarrow \mathbb{H}$ .

*Claim 1.* We have that  $\sharp(x_s) = \sigma_s$ .

*Proof of Claim 1.* Indeed, let us denote  $\bar{\sigma}_s := \sharp(x_s)$  we have

$$\partial_s \bar{\sigma}_s + \nabla \cdot (\bar{\sigma}_s D_p H(\cdot, D_q u(s, \cdot, \sigma_s))) = 0,$$

in the sense of distributions. But the vector field  $(s, q) \mapsto D_p H(q, D_q u(s, q, \sigma_s))$  induces a unique solution to the the continuity equation, therefore  $\sigma$  and  $\bar{\sigma}$  must coincide and the claim follows.

*Claim 2.* The unique solution  $x$  to (3.42), satisfies the Euler-Lagrange equations

$$D_q L(x_s, x'_s) + \nabla \tilde{\mathcal{F}}(x_s) = \frac{d}{ds} D_v L(x_s, x'_s) \quad \text{and} \quad D_v L(x(0), x'(0)) = \nabla \tilde{\mathcal{U}}_0(x(0)) \quad \text{a.e. in } \Omega.$$

*Proof of Claim 2.* Let us notice first that by our assumptions  $D_v L(q, \cdot)$  and  $D_p H(q, \cdot)$  are inverses of each others for all  $q \in \mathbb{M}$ . Furthermore, we have

$$D_q L(q, D_p H(q, p)) = -D_q H(q, p), \quad \forall (q, p) \in \mathbb{M} \times \mathbb{R}^d.$$

Indeed, this last equation is a consequence of the Legendre-Fenchel identity

$$H(q, p) = p \cdot D_p H(q, p) - L(q, D_p H(q, p)).$$

Now, from (3.42) by continuity, by (H11) and by the fact  $\nabla_w \mathcal{U}_0(\sigma_s)(x_s) = \nabla \tilde{\mathcal{U}}_0(x_s)$ , one can deduce that

$$x'(0) = D_p H(x(0), D_q u_0(x(0), \sigma_0)) = D_p H(x(0), \nabla_w \mathcal{U}_0(\sigma_0)(x(0))) = D_p H(x(0), \nabla \tilde{\mathcal{U}}_0(x(0))),$$

which by inversion of  $D_p H(x(0), \cdot)$  is equivalent to  $D_v L(x(0), x'(0)) = \nabla \tilde{\mathcal{U}}_0(x(0))$ .

Then, from (3.42), again by inversion of  $D_p H(x_s, \cdot)$  we have

$$D_v L(x_s, x'_s) = D_q u(s, x_s, \sigma_s).$$

Since  $u \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ , for a.e.  $s \in (0, t)$  we have

$$(3.43) \quad \begin{aligned} \frac{d}{ds} D_v L(x_s, x'_s) &= \partial_s D_q u(s, x_s, \sigma_s) + D_{qq}^2 u(s, x_s, \sigma_s) D_p H(x_s, D_q u(s, x_s, \sigma_s)) \\ &\quad + \int_{\mathbb{M}} \nabla_w D_q u(s, x_s, \sigma_s)(a) \cdot D_p H(a, D_q u(s, a, \sigma_s)) \sigma_s(da) \\ &= \partial_s D_q u(s, x_s, \sigma_s) + D_{qq}^2 u(s, x_s, \sigma_s) D_p H(x_s, D_q u(s, x_s, \sigma_s)) \\ &\quad + \int_{\mathbb{M}} D_q \nabla_w u(s, x_s, \sigma_s)(a) \cdot D_p H(a, D_q u(s, a, \sigma_s)) \sigma_s(da), \end{aligned}$$

a.e. in  $\Omega$ , where we have used (3.15) in the last equation. Let us note that the previous computation is meaningful. Indeed, by the regularity on  $u$  (see also the arguments in Subsection 4.1), we can differentiate the master equation (3.14) with respect to  $q$ , and so for  $\mathcal{L}^1 \otimes \mathcal{L}^d$ -a.e.  $(s, q) \in (0, t) \times \mathbb{M}$  and for all  $\nu \in \mathcal{P}_2(\mathbb{M})$  we have

$$(3.44) \quad \begin{aligned} \partial_s D_q u(s, q, \nu) + D_{qq}^2 u(s, q, \nu) D_p H(q, D_q u(s, q, \nu)) \\ + \int_{\mathbb{M}} D_q \nabla_w u(s, q, \nu)(a) D_p H(a, D_q u(s, a, \nu)) \nu(da) = D_q f(q, \nu) - D_q H(q, D_q u(s, q, \nu)) \end{aligned}$$

We notice that (H11) implies that  $D_q f(q, \nu) = \nabla_w \mathcal{F}(\nu)(q)$  and so, by combining (3.43) and (3.44) one deduces

$$\begin{aligned} \frac{d}{ds} D_v L(x_s, x'_s) &= D_q f(x_s, \sigma_s) - D_q H(x_s, D_q u(s, x_s, \sigma_s)) = \nabla_w \mathcal{F}(\sigma_s)(x_s) + D_q L(x_s, D_q u(s, x_s, \sigma_s)) \\ &= \nabla \tilde{\mathcal{F}}(x_s) + D_q L(x_s, D_q u(s, x_s, \sigma_s)), \end{aligned}$$

and so the claim follows.

*Claim 3.* For each  $t \in [0, T]$  and  $\mu \in \mathcal{P}_2(\mathbb{M})$ ,  $u(t, \cdot, \mu)$  is unique on  $\text{spt}(\mu)$ .

*Proof of Claim 3.* By the strict convexity of the action, the previous claims show that  $(x_s)_{s \in (0, t)}$  is the unique solution in the action minimization problem (1.2) for  $\tilde{\mathcal{U}}(t, z)$ . But, since  $\tilde{\mathcal{U}} \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{H})$  (as we showed in Theorem 1.5(ii)), we have in the same time that the optimal velocity for this curve is  $D_p H(x_s, \nabla \tilde{\mathcal{U}}(s, x_s))$  and so, by the convexity of  $H$  in the second variable, one deduces that

$$D_q u(s, x_s(\omega), \sigma_s) = \nabla \tilde{\mathcal{U}}(s, x_s)(\omega),$$

for a.e.  $\omega \in \Omega$ . This further yields that the vector field  $q \mapsto D_q u(s, q, \sigma_s)$  is unique (i.e. does not depend on the solution  $u$ ) on  $\text{spt}(\sigma_s)$  for all  $s \in [0, t]$ . From here we also deduce that for each  $\mu \in \mathcal{P}_2(\mathbb{M})$ , the solution to the continuity equation (3.41) is unique (independent of the solution  $u$ ) and this corresponds to the unique minimizer in the action minimization problem, i.e. to the solution to (3.3).

Now let  $q_1 \in \text{spt}(\mu)$  and let  $(q_s)_{s \in (0,t)}$  be the unique solution to

$$(3.45) \quad \begin{cases} q'_s = D_p H(q_s, D_q u(s, q_s, \sigma_s)), & s \in (0, t), \\ q_t = q_1. \end{cases}$$

It is clear that  $q_s \in \text{spt}(\sigma_s)$  for all  $s \in [0, t]$ . Moreover, for each fixed  $q_1$ , the curve solving (3.45) is unique (independent of the solution  $u$ ).

Using the Legendre duality, the master equation for  $u$  can be rewritten as

$$\begin{aligned} \partial_s u(s, q, \nu) + D_q u(s, q, \nu) \cdot D_p H(q, D_q u(s, q, \nu)) + \int_{\mathbb{M}} \nabla_w u(s, q, \nu)(a) \cdot D_p H(a, D_q u(s, a, \nu)) \nu(da) \\ = f(q, \nu) + L(q, D_p H(q, D_q u(s, q, \nu))) \end{aligned}$$

and replacing in  $(q, \nu) = (q_s, \sigma_s)$  the chain rule gives us

$$(3.46) \quad \frac{d}{ds} (u(s, q_s, \sigma_s)) = f(q_s, \sigma_s) + L(q_s, D_p H(q_s, D_q u(s, q_s, \sigma_s))).$$

Now, let  $\bar{u} \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$  be another solution to (3.14) in the sense of Definition 3.9. By the previous arguments one has  $D_q \bar{u}(s, q, \sigma_s) = D_q u(s, q, \sigma_s)$  for all  $s \in [0, t]$  and  $q \in \text{spt}(\sigma_s)$ . Then, similarly to (3.46), one has that

$$(3.47) \quad \frac{d}{ds} (\bar{u}(s, q_s, \sigma_s)) = f(q_s, \sigma_s) + L(q_s, D_p H(q_s, D_q u(s, q_s, \sigma_s))).$$

By defining now  $w : [0, t] \rightarrow \mathbb{R}$  as  $w(s) := u(s, q_s, \sigma_s) - \bar{u}(s, q_s, \sigma_s)$  we have that  $w'(s) = 0$  (by subtracting (3.47) from (3.46)) and  $w(0) = 0$ . Therefore one must have  $w \equiv 0$  and so  $u(s, q_s, \sigma_s) = \bar{u}(s, q_s, \sigma_s)$ . By continuity one has also that

$$u(t, q_1, \mu) = \bar{u}(t, q_1, \mu), \quad \forall q_1 \in \text{spt}(\mu).$$

*Claim 4.*  $u$  is a unique solution to (3.14).

*Proof of Claim 4.* It remains to show that if  $u$  and  $\bar{u}$  are two solutions to (3.14), one has  $u(t, q, \mu) = \bar{u}(t, q, \mu)$  for all  $q \in \mathbb{M} \setminus \text{spt}(\mu)$ . Suppose that  $\mu$  does not have full support, otherwise there is nothing to prove. Let  $q_0 \in \mathbb{M} \setminus \text{spt}(\mu)$ . For  $\varepsilon > 0$  let  $\rho_\varepsilon$  stand for the heat kernel centered at 0 with variance  $\varepsilon > 0$  and define  $\mu_\varepsilon := \mu * \rho_\varepsilon$ . Then one obtained a fully supported smooth probability measure  $\mu_\varepsilon$  such that  $W_2(\mu, \mu_\varepsilon) \rightarrow 0$  as  $\varepsilon \downarrow 0$ . Therefore, we have

$$u(t, q_0, \mu_\varepsilon) = \bar{u}(t, q_0, \mu_\varepsilon).$$

By the continuity of both  $u$  and  $\mu_\varepsilon$  with respect to the measure variable, one can pass to the limit as  $\varepsilon \downarrow 0$  to obtain that

$$u(t, q_0, \mu) = \bar{u}(t, q_0, \mu),$$

as desired. □

Despite the fact that the velocity field  $v(t, \cdot) := D_p H(\cdot, \nabla_w \mathcal{U}(t, \mu))$  appearing in the continuity equation (3.3) typically does not belong to  $T_\mu \mathcal{P}_2(\mathbb{M})$ , we have the following chain rule (cf. e.g. [33] in the compact setting).

**Lemma 3.23.** *We assume that the hypotheses of Theorem 3.22 take place. Let  $T > 0$ ,  $t_0, t \in (0, T)$ ,  $s \in (0, t)$ ,  $q \in \mathbb{M}$  and  $\mu \in \mathcal{P}_2(\mathbb{M})$  and let  $(0, t) \ni s \mapsto \sigma_s^t[\mu]$  be the solution to the continuity equation (3.3). Then*

$$\lim_{s \rightarrow t} \frac{u(t_0, q, \mu) - u(t_0, q, \sigma_s^t[\mu])}{t - s} = \int_{\mathbb{M}} \nabla_w u(t_0, q, \mu)(y) \cdot D_p H(y, \nabla_w \mathcal{U}(t, \mu)(y)) \mu(dy).$$

## 4. FURTHER IMPLICATIONS OF THE SCALAR MASTER EQUATION

**4.1. Improvements on the notion of weak solution to the vectorial master equation.** Let us recall that the first part of Theorem 3.22 asserts the existence of  $u \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}))$ , which satisfies the scalar master equation

$$(4.1) \quad \partial_t u(t, q, \mu) + H(q, D_q u(t, q, \mu)) + \int_{\mathbb{M}} \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, D_q u(t, y, \mu)) \mu(dy) = f(q, \mu).$$

Let us observe that all the terms in the previous equation are locally Lipschitz continuous with respect to the  $q$  variable. Indeed, except the nonlocal term, the Lipschitz continuity of the others is a consequence of the regularity of  $u$  and the data. Setting  $v(t, y) := D_p H(y, \nabla_w \mathcal{U}(t, \mu)(y))$  and denoting  $\bar{v}(t, \cdot)$  the projection of  $v(t, \cdot)$  onto  $T_\mu \mathcal{P}_2(\mathbb{M})$ , we have that

$$\int_{\mathbb{M}} \nabla_w u(t, q, \mu)(y) \cdot v(t, y) \mu(dy) = \int_{\mathbb{M}} \Phi_1(t, q, \mu, y) \cdot \bar{v}(t, y) \mu(dy),$$

where  $\Phi_1$  is defined in Corollary 2.18. This relationship holds because  $\nabla_w u(t, q, \mu)(\cdot)$  is the projection of  $\Phi_1(t, q, \mu, \cdot)$  onto  $T_\mu \mathcal{P}_2(\mathbb{M})$ . Since  $\Phi_1 \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \times \mathbb{M})$ , the function  $q \mapsto \int_{\mathbb{M}} \Phi_1(t, q, \mu, y) \cdot \bar{v}(t, y) \mu(dy)$  is locally Lipschitz continuous and for (Lebesgue) a.e.  $q \in \mathbb{M}$  we have

$$\int_{\mathbb{M}} D_q \nabla_w u(t, q, \mu)(y) \cdot v(t, y) \mu(dy) = \int_{\mathbb{M}} D_q \Phi_1(t, q, \mu, y) \cdot \bar{v}(t, y) \mu(dy),$$

Therefore, we are allowed to differentiate (4.1) for (Lebesgue) a.e.  $q \in \mathbb{M}$  to obtain

$$\begin{aligned} \partial_t D_q u(t, q, \mu) + D_q H(q, D_q u(t, q, \mu)) + D_{qq}^2 u(t, q, \mu) D_p H(q, D_q u(t, q, \mu)) \\ + \int_{\mathbb{M}} D_q \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, D_q u(t, y, \mu)) \mu(dy) = D_q f(q, \mu). \end{aligned}$$

By Proposition 3.13(iii) we know that for all  $(t, \mu) \in (0, T) \times \mathcal{P}_2(\mathbb{M})$ ,  $D_q u(t, \cdot, \mu) = \nabla_w \mathcal{U}(t, \mu)(\cdot)$  on  $\text{spt}(\mu)$ , where  $\mathcal{U}$  is the unique solution to (3.1). Since  $D_q u$  is locally Lipschitz continuous with respect to all of its variables, it serves a very natural extension for  $\nabla_w \mathcal{U}(t, \mu)(\cdot)$  to the whole space, and so we have

$$(4.2) \quad \begin{aligned} \partial_t \nabla_w \mathcal{U}(t, \mu)(q) + D_q H(q, \nabla_w \mathcal{U}(t, \mu)(q)) + D_q \nabla_w \mathcal{U}(t, \mu)(q) D_p H(q, \nabla_w \mathcal{U}(t, \mu)(q)) \\ + \int_{\mathbb{M}} D_q \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, \nabla_w \mathcal{U}(t, \mu)(y)) \mu(dy) = D_q f(q, \mu) = \nabla_w \mathcal{F}(\mu)(q), \end{aligned}$$

for all  $(t, \mu) \in (0, T) \times \mathcal{P}_2(\mathbb{M})$  and for (Lebesgue) a.e.  $q \in \mathbb{M}$ .

In Theorem 3.7 we have seen that  $\mathcal{V} := \nabla_w \mathcal{U}$  solves the vectorial master equation (3.8), when the variable  $q$  needs to be taken in  $\text{spt}(\mu)$ . Since we have a correspondence between all terms in (3.8) and (4.2), except the nonlocal ones, we can deduce that we must have

$$\bar{\mathcal{N}}_\mu[\mathcal{V}, \nabla_w^\top \mathcal{V}](t, \mu, q) = \bar{\mathcal{N}}_\mu[\nabla_w \mathcal{U}, \nabla_{ww}^2 \mathcal{U}^\top](t, \mu, q) = \int_{\mathbb{M}} D_q \nabla_w u(t, q, \mu)(y) \cdot D_p H(y, \nabla_w \mathcal{U}(t, \mu)(y)) \mu(dy)$$

for  $\mathcal{L}^d$ -a.e.  $q \in \mathbb{M}$ .

This fact implies furthermore that

$$(4.3) \quad \begin{aligned} \int_{\mathbb{M}} D_q \nabla_w u(t, q, \mu)(y) D_p H(y, D_q u(t, y, \mu)) \mu(dy) &= \int_{\mathbb{M}} \nabla_w D_q u(t, q, \mu)(y) D_p H(y, D_q u(t, y, \mu)) \mu(dy) \\ &= \int_{\mathbb{M}} \nabla_{ww}^2 \mathcal{U}(t, \mu)(q, y) D_p H(y, D_q u(t, y, \mu)) \mu(dy) \end{aligned}$$

for all  $\mu \in \mathcal{P}_2(\mathbb{M})$  and for  $\mathcal{L}^1 \otimes \mathcal{L}^d$ -a.e.  $(t, q) \in (0, T) \times \mathbb{M}$ , which shows in particular that the function  $u$  constructed in the first part of the proof of Theorem 3.22 satisfies also (3.15).

All the previous arguments allow to formulate the following

**Proposition 4.1.** *The weak solution  $\mathcal{V}$  to the vectorial master equation (3.8) provided in Theorem 3.7 can be extended in a Lipschitz continuous way to  $[0, T] \times \mathcal{P}_2(\mathbb{M}) \times \mathbb{M}$  such that this extension still solves (3.8) at every  $(t, \mu) \in (0, T) \times \mathcal{P}_2(\mathbb{M})$  and at  $\mathcal{L}^d$ -a.e.  $q \in \mathbb{M}$ .*

**Remark 4.2.** *Relying on the very same procedure as in Theorem D.2 and in Theorem 2.17, if we assume higher regularity properties on the data (as  $H, L \in C^4$  with uniformly bounded fourth order derivatives,  $\mathcal{F}, \mathcal{U} \in C_{\text{loc}}^{3,1,w}$  and  $f, u_0 \in C_{\text{loc}}^{2,1}$ ), one can improve further the regularity of both  $u$  and  $\mathcal{U}$  (as  $u \in C_{\text{loc}}^{2,1}$  and  $\mathcal{U} \in C_{\text{loc}}^{3,1,w}$ ). Such improvements would imply furthermore that one could have the vectorial master equation satisfied for all  $q \in \mathbb{M}$  (rather than  $\mathcal{L}^d$ -a.e.). Since these estimates would not impose additional technical difficulties, to avoid the addition of further pages to the manuscript, we will not pursue them here.*

**4.2. Convergence of equilibria of games with finitely many players and propagation of chaos.** Relying on the solution to the master equation (3.14) one can study the convergence of Nash equilibria of  $N$ -player differential games. The Nash system of Hamilton-Jacobi equations for the value functions  $v^{i,N} : [0, T] \times \mathbb{M}^N \rightarrow \mathbb{R}$  associated to these games reads as

$$(4.4) \quad \begin{cases} \partial_t v^{i,N}(t, q) & + H(q_i, D_{q_i} v^{i,N}) + \sum_{j \neq i} D_{q_j} v^{i,N}(t, q) \cdot D_p H(q_j, D_{q_j} v^{j,N}(t, q)) \\ & = f^{i,N}(q) + r^{i,N}(t, q), & (t, q) \in (0, T) \times \mathbb{M}^N \\ v^{i,N}(0, q) & = v_0^{i,N}(q), & q \in \mathbb{M}^N. \end{cases}$$

For games with individual and/or common noise in the dynamics of the agents, relying on the master equation, such convergence results (together with large deviation principle and central limit theorems) were obtained recently in [9], [18] and [19]. The inspiration for the proofs of the results below came from these references. However, in contrast with these references,  $D_q u$  and  $\nabla_w u$  were assumed to be bounded (and so global convergence results were obtained). In our case these gradients are only locally bounded and so, we can obtain only local convergence results after taking some extra precautions which we specify in Appendix E.

The function  $u$  in (3.17), solution to the scalar master equation (3.14), allows to approximate solutions to  $N$ -player deterministic differential games.

To show this, let  $m \in \mathbb{N}$  and set  $N := m + 1$ . Set

$$q = (q_0, \dots, q_m) \in \mathbb{M}^{(m+1)}, \quad \mu_q^{(N)} = \mu_q^{(m+1)} := \frac{1}{m+1} \sum_{i=0}^m \delta_{q_i}.$$

We define the coupling functions and initial data  $f^{i,N}, u_0^{i,N} : \mathbb{M}^N \rightarrow \mathbb{R}$  as

$$f^{i,N}(q) := f(q_i, \mu_q^{(m+1)}) \quad \text{and} \quad u_0^{i,N}(q) := u_0(q_i, \mu_q^{(m+1)}), \quad i \in \{0, \dots, m\}.$$

Once can notice that by construction both  $f^{i,N}$  and  $u_0^{i,N}$  depend actually on the position  $q_i$  of the player  $i$  and on the empirical distribution of all the players  $\mu_q^{(N)}$ .

In the same time, we define  $u^{i,N} : [0, T] \times \mathbb{M}^N \rightarrow \mathbb{R}$  as

$$u^{i,N}(t, q) := u(t, q_i, \mu_q^{(m+1)}), \quad i \in \{0, \dots, m\}.$$

In Subsection 3.3, in particular in Lemma 3.16 we have shown that  $u^{i,N} \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M}^N)$ . Furthermore, we can formulate the following result.

**Proposition 4.3.** *Let  $u^{i,N}$ ,  $i \in \{0, \dots, m\}$  be defined as before. Then they solve the approximate Nash system*

$$\begin{cases} \partial_t u^{i,N}(t, q) + H(q_i, D_{q_i} u^{i,N}) + \sum_{j \neq i} D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, D_{q_j} u^{j,N}(t, q)) \\ & = f^{i,N}(q) + r^{i,N}(t, q), & (t, q) \in (0, T) \times \mathbb{M}^N \\ u^{i,N}(0, q) = u_0^{i,N}(q), & & q \in \mathbb{M}^N. \end{cases}$$



Furthermore, for all  $T > 0$ ,  $R > 0$  and  $r > 0$ , there exists  $C = C(T, R, r) > 0$  such that

$$(4.5) \quad |r^{i,N}|(t, q) \leq C/N, \quad \forall (t, q) \in [0, T] \times B_R(0)^N, \quad \mu_q^{(N)} \in \mathbb{B}_r^N.$$

Let  $q = (q_0, \dots, q_m) : [0, t] \rightarrow \mathbb{M}^N$  stand for the Nash equilibria of the game associated to (4.4). In particular, for  $t \in (0, T)$  and  $\hat{q} \in \mathbb{M}^N$  they are solutions to the ODE system

$$\begin{cases} \dot{q}_i(s) = D_p H(q_i(s), D_{q_i} v^{i,N}(s, q(s))), & s \in (0, t), \\ q_i(t) = \hat{q}_i. \end{cases}$$

In the same time, let  $Q = (Q_0, \dots, Q_m) : [0, t] \rightarrow \mathbb{M}^N$  stand for the curve that we get by taking the solution in the definition of  $u(t, \hat{q}_i, \mu_{\hat{q}}^{(m+1)})$ . They solve

$$\begin{cases} \dot{Q}_i(s) = D_p H(Q_i(s), D_{q_0} u(s, Q_i(s), \mu_{Q(s)}^{(m+1)})), & s \in (0, t), \\ Q_i(t) = \hat{q}_i. \end{cases}$$

**Proposition 4.4.** *Suppose that  $v^{i,N} : [0, T] \times \mathbb{M}^N \rightarrow \mathbb{R}$ ,  $i \in \{0, \dots, N-1\}$  is a classical solution to (4.4) such that  $D_{q_i} v^{i,N}$  is of class  $C^{0,1}([0, T] \times \mathbb{M}^N)$  uniformly with respect to  $N$ . Then, for all  $R > 0$ , there exists  $C = C(R, T) > 0$  such that if  $\hat{q} \in B_R(0)^N$ , then*

$$W_2 \left( \mu_{Q(s)}^{(N)}, \mu_{q(s)}^{(N)} \right) \leq \frac{C}{N}.$$

**Corollary 4.5.** *Let us suppose that the assumptions of Proposition 4.4 are in place. Let  $t \in (0, T)$ ,  $N \in \mathbb{N}$ ,  $\hat{q} \in B_R(0)^N$ ,  $\mu \in \mathcal{P}_2(\mathbb{M})$  with  $\mu \in \mathcal{B}_r$  for some  $r > 0$  and let  $(\sigma_s)_{s \in (0, t)}$  be the solution to the continuity equation (3.3) with  $\sigma_t = \mu$ . Then, there exists  $C = C(R, T, \cdot)$  we have*

$$W_2 \left( \mu_{\hat{q}}^{(N)}(s), \sigma_s \right) \leq \frac{C}{N} + e^{C(t-s)} W_2 \left( \mu_{\hat{q}}^{(N)}, \mu \right), \quad \forall s \in (0, t).$$

#### APPENDIX A. HILBERT REGULARITY IS TOO STRINGENT FOR REARRANGEMENT INVARIANT FUNCTIONS

Let  $\Phi \in C^2(\mathcal{P}_2(\mathbb{M}))$  and let  $\tilde{\Phi} \in C^2(\mathbb{H})$  be such that  $\Phi(\mu) = \tilde{\Phi}(x)$  if  $\mu$  is the law of  $x$ . Recall that

$$(A.1) \quad \nabla^2 \tilde{\Phi}(x)(h, h_*) = \int_{\Omega} D_q(\nabla_w \Phi(\mu)) \circ x \cdot h \cdot h_* d\omega + \int_{\Omega^2} \nabla_{ww}^2 \Phi(\mu)(x(\omega), x(\omega_*)) h(\omega) \cdot h_*(\omega_*) d\omega d\omega_*$$

if  $\xi, \xi_* \in T_{\mu} \mathcal{P}_2(\mathbb{M})$  and  $h = \xi \circ x$  and  $h_* = \xi_* \circ x$ .

For  $k \in \mathbb{N}$  and  $g \in C^2(\mathbb{M}^k)$ , we define

$$\tilde{\Phi}_g^{(k)}(x) := \int_{\Omega^k} g(x(\omega_1), \dots, x(\omega_k)) d\omega_1 \cdots d\omega_k \quad \forall x \in \mathbb{H},$$

and

$$\Phi_g^{(k)}(\mu) := \int_{\mathbb{M}^k} g(q_1, \dots, q_k) \mu(dq_1) \cdots \mu(dq_k) \quad \forall \mu \in \mathcal{P}_2(\mathbb{M}).$$

Let  $P_k$  be the set of permutations of  $k$  letters. Replacing  $g$  by its symmetrization

$$\tilde{g}(x_1, \dots, x_k) = \frac{1}{k!} \sum_{\tau \in P_k} g(x_{\tau(1)}, \dots, x_{\tau(k)})$$

we have  $\tilde{\Phi}_g^{(k)} = \tilde{\Phi}_{\tilde{g}}^{(k)}$ . Therefore, it is never a loss of generality to assume  $g$  is symmetric.

We do not know how to write (A.1) for general  $h, h_* \in \mathbb{H} \setminus \{\xi \circ x : \xi \in T_{\mu} \mathcal{P}_2(\mathbb{M})\}$ . In some particular cases such as when  $\tilde{\Phi} = \tilde{\Phi}_g^{(k)}$  for some smooth  $g$ , then (A.1) extends to  $h, h_* \in \mathbb{H} \setminus \{\xi \circ x : \xi \in T_{\mu} \mathcal{P}_2(\mathbb{M})\}$ . This can be checked by hand by writing the Taylor expansion of second order of

$$g(x(\omega_1) + h(\omega_1), \dots, x(\omega_k) + h(\omega_k)).$$

Another example is when

$$(A.2) \quad \Phi(\mu) = \theta \left( \frac{1}{2} \int_{\mathbb{M}} |q|^2 \mu(dq) \right) \quad \forall \mu \in \mathcal{P}_2(\mathbb{M}) \quad \text{and so} \quad \tilde{\Phi}(x) = \theta \left( \frac{1}{2} \|x\|^2 \right) \quad \forall x \in \mathbb{H}.$$

Writing the second order Taylor expansion, we have

$$\nabla \tilde{\Phi}(x)(h) = \theta' \left( \frac{1}{2} \|x\|^2 \right) (x, h)$$

and

$$(A.3) \quad \nabla^2 \tilde{\Phi}(x)(h, h) = \theta' \left( \frac{1}{2} \|x\|^2 \right) \|h\|^2 + \theta'' \left( \frac{1}{2} \|x\|^2 \right) (x, h)^2 \quad \forall x, h \in \mathbb{H}.$$

We conclude

$$(A.4) \quad D_q(\nabla_w \Phi(\mu)) = \theta' \left( \frac{1}{2} \int_{\mathbb{M}} |q|^2 \mu(dq) \right) I_d \quad \forall \mu \in \mathcal{P}_2(\mathbb{M})$$

and

$$\nabla_{ww}^2 \Phi(\mu)(q, b) = \theta'' \left( \frac{1}{2} \int_{\mathbb{M}} |q|^2 \mu(dq) \right) q \otimes b \quad \forall \mu \in \mathcal{P}_2(\mathbb{M}) \quad \forall q, b \in \text{spt}(\mu).$$

Thus, when  $\Phi$  is of the form (A.2), (A.1) continues to hold for all  $h, h_* \in \mathbb{H}$ . Note that the expression in (A.4) is constant on  $\mathbb{M}$ . In fact, we shall see this is not a coincidence which is the aim of these notes.

Our goal is to show that if  $\tilde{\Phi} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$ , then  $D_q(\nabla_w \Phi(\mu))$  must be constant function on  $\text{spt}(\mu)$ . This will allow us to make inference about the dimension of  $C_{\text{loc}}^{2,\alpha}(\mathbb{H}) \cap \{\tilde{\Phi}_g^{(k)}\}$  for any natural number  $k$ . In conclusion, the set of  $\tilde{\Phi} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$  maybe too small in some sense and a theory of Mean Field Games for functions  $\tilde{\Phi} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$  may be too restrictive. Hence,  $C_{\text{loc}}^{2,\alpha,w}(\mathcal{P}_2(\mathbb{M}))$  (cf. Definition 2.11) is a better space for a general theory.

**Lemma A.1.** *Let  $\alpha \in (0, 1]$  and assume  $\tilde{\Phi} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$  is rearrangement invariant so that it is the lift of a function  $\Phi$ . If (A.1) holds for all  $h, h_* \in \mathbb{H}$  then  $D_q(\nabla_w \Phi(\mu))$  is constant function on  $\text{spt}(\mu)$ .*

*Proof.* Let  $x \in \mathbb{H}$  and let  $\mu$  be the law of  $x$ . Fix an open ball  $\mathbb{B} \subset \mathbb{H}$  that contains  $x$  and choose  $\kappa_{\mathbb{B}} > 0$  such that

$$(A.5) \quad \left( \nabla^2 \tilde{\Phi}(x) - \nabla^2 \tilde{\Phi}(y) \right) (h, h_*) \leq \kappa_{\mathbb{B}} \|x - y\|^\alpha$$

for all  $y \in \mathbb{B}$  and all  $h, h_* \in \mathbb{H}$  such that  $\|h\|, \|h_*\| \leq 1$ .

Let  $\varrho \in C_c^\infty(\mathbb{M})$  be a probability density function whose support is the unit ball in  $\mathbb{R}^d$ . For  $z, z_* \in \mathbb{R}^d$  unit vectors and for  $\omega, o \in \Omega$ , we set

$$h^\epsilon = z \sqrt{\varrho_\epsilon^o}, \quad h_*^\epsilon = z_* \sqrt{\varrho_\epsilon^o}, \quad \varrho_\epsilon^o(\omega) := \epsilon^{-d} \varrho \left( \frac{\omega - o}{\epsilon} \right).$$

Let  $y \in \mathbb{H}$  have the same law with  $x$ . We have

$$(A.6) \quad \begin{aligned} & \left( \nabla^2 \tilde{\Phi}(y) - \nabla^2 \tilde{\Phi}(x) \right) (h^\epsilon, h_*^\epsilon) \\ &= \int_{\Omega} \left( D_q(\nabla_w \Phi(\mu))(y(\omega)) - D_q(\nabla_w \Phi(\mu))(x(\omega)) \right) h(\omega) \cdot h_*(\omega) \\ &+ \int_{\Omega^2} \left( \nabla_{ww}^2 \Phi(\mu)(y(\omega), y(\omega_*)) - \nabla_{ww}^2 \Phi(\mu)(x(\omega), x(\omega_*)) \right) h(\omega) \cdot h_*(\omega_*) d\omega d\omega_* \\ &= \int_{\Omega} \left( D_q(\nabla_w \Phi(\mu))(y(o + \epsilon a)) - D_q(\nabla_w \Phi(\mu))(x(o + \epsilon a)) \right) z \cdot z_* \varrho(a) da \\ &+ \epsilon^d \int_{\Omega^2} \nabla_{ww}^2 \Phi(\mu)(y(o + \epsilon a), y(o + \epsilon b)) z \cdot z_* \sqrt{\varrho(a)\varrho(b)} dadb \\ &- \epsilon^d \int_{\Omega^2} \nabla_{ww}^2 \Phi(\mu)(x(o + \epsilon a), x(o + \epsilon b)) z \cdot z_* \sqrt{\varrho(a)\varrho(b)} dadb. \end{aligned}$$

Since  $\tilde{\Phi} \in C^{1,1}(\mathbb{B})$ ,  $\nabla_{ww}^2 \Phi(\mu)$  is bounded, we use (A.6) to obtain that if  $o$  is a Lebesgue point for  $(D_q \nabla_w \Phi(\mu)) \circ y$  and  $(D_q \nabla_w \Phi(\mu)) \circ x$  then

$$\lim_{\epsilon \rightarrow 0} \left( \nabla^2 \tilde{\Phi}(y) - \nabla^2 \tilde{\Phi}(x) \right) (h^\epsilon, h_*^\epsilon) = \left( D_q(\nabla_w \Phi(\mu))(y(o)) - D_q(\nabla_w \Phi(\mu))(x(o)) \right) z \cdot z_*$$

This, together with (A.5) implies that if  $y \in \mathbb{B}$  then

$$(A.7) \quad |D_q(\nabla_w \Phi(\mu)) \circ y(o) - D_q(\nabla_w \Phi(\mu)) \circ x(o)| \leq \kappa_{\mathbb{B}} \|x - y\|^\alpha$$

In the spirit of the proof of Lemma 2.13, set

$$\Omega_0 := \{\omega \in \Omega \mid \omega \text{ is a Lebesgue point for } x, D_q \nabla_w \Phi(\mu) \circ x\} \cap x^{-1}(\text{spt}(\mu))$$

Note that  $\Omega_0$  is a set of full measure in  $\Omega$  and so,  $x(\Omega_0)$  is a set of full  $\mu$ -measure. In fact, we do not know that  $x(\Omega_0)$  is Borel, but we can find a Borel set  $A \subset x(\Omega_0)$  of full  $\mu$ -measure.

Assume in the sequel that  $o \in A$  and set  $q_1 := x(o)$ . Assume we can find  $\bar{o} \in A$  such that  $q_2 = x(\bar{o}) \neq q_1$ . Let  $r > 0$  small such that  $B_r(o) \cap B_r(\bar{o}) = \emptyset$ . Set

$$S_r(\omega) := \begin{cases} \omega, & \text{if } \omega \in \Omega \setminus (B_r(o) \cup B_r(\bar{o})), \\ \omega - o + \bar{o}, & \text{if } \omega \in B_r(o), \\ \omega - \bar{o} + o, & \text{if } \omega \in B_r(\bar{o}). \end{cases}$$

Since  $S_r$  preserves Lebesgue measure,  $x$  and  $y := x \circ S_r$  have the same law  $\mu$ . We notice

$$\|x - y\|^2 = 2 \int_{B_r(o)} |x(\omega) - x(\omega + \bar{o} - o)|^2 dz$$

and so, for  $r$  small enough,  $y \in \mathbb{B}$ . By (A.7) implies

$$\begin{aligned} \left| D_q(\nabla_w \Phi(\mu))(q_2) - D_q(\nabla_w \Phi(\mu))(q_1) \right| &= \left| D_q(\nabla_w \Phi(\mu)) \circ y(o) - D_q(\nabla_w \Phi(\mu)) \circ x(o) \right| \\ &\leq \kappa_{\mathbb{B}} \left( 2 \int_{B_r(o)} |x(z) - x(z + \bar{o} - o)|^2 dz \right)^{\frac{\alpha}{2}}. \end{aligned}$$

We let  $r$  tend to 0 to conclude the proof.  $\square$

**Proposition A.2.** *For any  $\alpha \in (0, 1]$  and  $k \in \mathbb{N}$ , we have*

$$\dim \left( C_{\text{loc}}^{2,\alpha}(\mathbb{H}) \cap \{\tilde{\Phi}_g : g \in C_{\text{loc}}^{2,\alpha}(\mathbb{M}^k), \|D^2 g\|_{L^\infty} < \infty\} \right) < \infty.$$

*Proof.* We aim to use Lemma A.1, since this asserts that  $D_q \nabla_w \Phi_g(\mu)(q)$  is a constant matrix  $C(\mu)$  which depends only on  $\mu$ .

In particular, in the case of  $k = 1$ , we have  $D_q \nabla_w \Phi_g(\mu)(q) = D^2 g(q)$  and this being constant implies that  $g$  is a polynomial of degree 2, as the claim follows.

For  $k \in \mathbb{N}$  general we have

$$\begin{aligned} D_q \nabla_w \Phi_g(\mu)(q) &= \int_{\mathbb{M}^{k-1}} D_{q_1 q_1}^2 g(q, q_2, \dots, q_k) \mu(dq_2) \dots \mu(dq_k) \\ &\quad + \dots \\ &\quad + \int_{\mathbb{M}^{k-1}} D_{q_k q_k}^2 g(q_1, q_2, \dots, q_{k-1}, q) \mu(dq_1) \dots \mu(dq_{k-1}) \end{aligned}$$

In fact by [15]

$$(A.8) \quad C(\mu) = D_q \nabla_w \Phi_g(\mu)(q) = k \int_{\mathbb{M}^{k-1}} D_{q_1 q_1}^2 g(q, q_2, \dots, q_k) \mu(dq_2) \dots \mu(dq_k) \\ = \dots$$

$$(A.9) \quad = k \int_{\mathbb{M}^{k-1}} D_{q_k q_k}^2 g(q_1, q_2, \dots, q_{k-1}, q) \mu(dq_1) \dots \mu(dq_{k-1}) \quad \mu - \text{a.e.}$$

For simplicity, let us set  $k = 2$  (the proof of the result for general  $k \in \mathbb{N}$  follows the same lines). Let  $a \in \mathbb{M}$  and  $\varrho \in C_b(\mathbb{M})$  has  $\mathbb{M}$  as its support is a probability density and  $\varrho_\epsilon$  is its standard rescaled function. The measures  $\varrho_\epsilon(q - a)$  have the whole  $\mathbb{M}$  as their support and so,

$$\int_{\mathbb{M}} D_{q_1 q_1}^2 g(q, q_2) \varrho_\epsilon(q_2 - a) dq_2 = \int_{\mathbb{M}} D_{q_1 q_1}^2 g(\bar{q}, q_2) \varrho_\epsilon(q_2 - a) dq_2 \quad \forall q, \bar{q} \in \mathbb{M}.$$

Letting  $\epsilon$  tend to 0 we conclude

$$D_{q_1 q_1}^2 g(q, a) = D_{q_1 q_1}^2 g(\bar{q}, a).$$

In fact,

$$D_{q_1 q_1}^2 g(q, a) = D_{q_1 q_1}^2 g(\bar{q}, a) = D_{q_2 q_2}^2 g(a, q) = D_{q_2 q_2}^2 g(a, \bar{q}) = C(a).$$

From these arguments, one can conclude that both  $q_1 \mapsto D_{q_1 q_1}^2 g(q_1, a)$  and  $q_2 \mapsto D_{q_2 q_2}^2 g(a, q_2)$  are constants for all  $a \in \mathbb{M}$ , therefore the  $q_1 \mapsto g(q_1, a)$  and  $q_2 \mapsto g(a, q_2)$  are polynomials of degree at most two for all  $a \in \mathbb{M}$ . By an adaptation of the result of [12] we conclude that  $g$  needs to be a polynomial of degree at most two. The result follows.  $\square$

**Corollary A.3.** *Similarly, for the example in (A.2), if  $\tilde{\Phi} \in C_{\text{loc}}^{2,\alpha}(\mathbb{H})$ , then by Lemma A.1 and (A.4) we have that  $\theta(t) = c_0 t$  for some  $c_0 \in \mathbb{R}$ .*

The result from Proposition A.2 in case of  $k = 1$  is the consequence of the proposition below, where we show that assuming even only  $C^2$  regularity (instead of  $C^{2,\alpha}$ ) for functionals on  $\mathbb{H}$  having local representations might result in trivialities.

**Proposition A.4.**

$$C^2(\mathbb{H}) \cap \{\tilde{\Phi}_g : g \in C^3(\mathbb{M}), \|D^2 g\|_{L^\infty} < \infty, \|D^3 g\|_{L^\infty} < \infty, D^3 g \neq 0\} = \emptyset.$$

and so,

$$C^2(\mathbb{H}) \cap \{\tilde{\Phi}_g : g \in C^3(\mathbb{M}), \|D^2 g\|_{L^\infty} < \infty, \|D^3 g\|_{L^\infty} < \infty\}$$

is a finite dimensional space.

*Proof.* For simplicity, let us suppose that  $d = 1$  and so  $\Omega = [0, 1]$ . The result in higher dimensions follows from similar arguments.

For  $x, y \in \mathbb{H}$  we can write the following expansion for  $\tilde{\Phi}_g$

$$\begin{aligned} \text{(A.10)} \quad & \int_{\Omega} g(y(\omega)) d\omega - \int_{\Omega} g(x(\omega)) d\omega - \int_{\Omega} g'(x(\omega))(y(\omega) - x(\omega)) d\omega - \frac{1}{2} \int_{\Omega} g''(x(\omega))(y(\omega) - x(\omega))^2 d\omega \\ & = \int_{\Omega} \int_0^1 \int_0^1 \int_0^1 t^2 s g'''(x(\omega) + ts\tau(y(\omega) - x(\omega)))(y(\omega) - x(\omega))^3 d\tau ds dt d\omega. \end{aligned}$$

By the assumptions on  $g'''$ , there exist constants  $c_0, c_1$ , having the same sign, such that on a bounded open interval  $c_0 \leq g''' \leq c_1$ . Without loss of generality, let us suppose that this open interval is  $(-1, 1)$  and  $0 < c_0 < c_1$ .

*Claim.* The right hand side of (A.10) is not of order  $o(\|x - y\|^2)$  when  $x \equiv 0$ .

*Proof of the Claim.* Let  $x(\omega) = 0$  and  $y_n(\omega) = \omega^n$  for  $\omega \in \Omega$  and  $n \in \mathbb{N}$ . Then clearly  $\|y_n\|^2 = \frac{1}{2n+1} \rightarrow 0$ , as  $n \rightarrow +\infty$ . We write the previous expansion for  $y_n$  and  $x$ . In particular, the remainder satisfies

$$\text{(A.11)} \quad \frac{c_0}{6} \int_{\Omega} y_n^3(\omega) d\omega \leq \int_{\Omega} \int_0^1 \int_0^1 \int_0^1 t^2 s g'''(ts\tau y_n(\omega)) y_n^3(\omega) d\tau ds dt d\omega \leq \frac{c_1}{6} \int_{\Omega} y_n^3(\omega) d\omega$$

We easily find  $\int_0^1 y_n^3(\omega) d\omega = \frac{1}{3n+1}$ . Therefore dividing (A.11) by  $\|y_n\|^2$  and taking  $n \rightarrow +\infty$  we find

$$\frac{2c_0}{18} \leq \lim_{n \rightarrow +\infty} \frac{1}{\|y_n\|^2} \int_{\Omega} \int_0^1 \int_0^1 \int_0^1 t^2 s g'''(ts\tau y_n(\omega)) y_n^3(\omega) d\tau ds dt d\omega \leq \frac{2c_1}{18}.$$

The claim follows and so does the thesis of the proposition.  $\square$

## APPENDIX B. CONVEXITY VS DISPLACEMENT CONVEXITY

**B.1. Displacement convexity versus classical convexity.** Using the terminology of [9], in the remaining of this section will consider weakly Fréchet continuously differentiable functions  $\mathcal{V} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  and denote their weak Fréchet differentials as  $\frac{\delta\mathcal{V}}{\delta\mu} : \mathbb{R}^d \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$ . Let  $\phi_1, \phi \in C^2(\mathbb{M})$  be functions of bounded second derivatives such that  $\phi_1$  is even. Set

$$\mathcal{V}_1(\mu) := \frac{1}{2} \int_{\mathbb{R}^d} \phi_1 * \mu(q) \mu(dq), \quad \mu \in \mathcal{P}_2(\mathbb{M}).$$

and

$$\mathcal{V}(\mu) := \mathcal{V}_1(\mu) + \int_{\mathbb{R}^d} \phi(q) \mu(dq), \quad \mu \in \mathcal{P}_2(\mathbb{M}).$$

**Remark B.1.** Recall from [9] that  $\frac{\delta\mathcal{V}}{\delta\mu}$  is monotone if and only if  $\mathcal{V}$  is convex in the classical sense. Furthermore, the function  $\mathcal{V}_1$  is twice weakly Fréchet continuously differentiable function, and

$$\frac{\delta\mathcal{V}_1}{\delta\mu}(q, \mu) = (\phi_1 * \mu)(q), \quad \frac{\delta\mathcal{V}}{\delta\mu}(q, \mu) = (\phi_1 * \mu)(q) + \phi(q),$$

and

$$\frac{\delta^2\mathcal{V}_1}{\delta\mu^2}(q, y, \mu) = \frac{\delta^2\mathcal{V}}{\delta\mu^2}(q, y, \mu) = \phi_1(q - y).$$

**Lemma B.2.** If we further assume  $\phi_1 \in L^1(\mathbb{M})$  then  $\frac{\delta\mathcal{V}}{\delta\mu}$  is monotone if and only if the Fourier transform  $\hat{\phi}_1$  is nonnegative.

*Proof.* Denote the Fourier transform of  $\phi_1$  as  $\hat{\phi}_1$ . Note that for any  $f \in L^2(\mathbb{M})$  by Young's inequality we have  $\phi_1 * f \in L^2(\mathbb{M})$  and so  $f(\phi_1 * f) \in L^1(\mathbb{M})$ . By the Riemann-Lebesgue lemma  $\hat{\phi}_1 \in C_0(\mathbb{M})$ . Furthermore,  $\hat{\phi}_1$  is even and has its range contained in the set of real numbers. By Remark B.1  $\frac{\delta\mathcal{V}}{\delta\mu}$  is monotone if and only if  $\mathcal{V}_1$  is convex. Thus, using the expression of  $\frac{\delta^2\mathcal{V}_1}{\delta\mu^2}$  in Remark B.1 we conclude that  $\frac{\delta\mathcal{V}}{\delta\mu}$  is monotone if and only if for any  $f \in C(\mathbb{M}) \cap L^2(\mathbb{M})$  such that  $\int_{\mathbb{M}} f(q) dq = 0$  we have  $0 \leq \int_{\mathbb{R}^d} (\phi_1 * f)(q) f(q) dq$ . Thanks to Plancherel theorem,  $\frac{\delta\mathcal{V}}{\delta\mu}$  is monotone if and only if

$$0 \leq \int_{\mathbb{R}^d} \widehat{\phi_1 * f}(\xi) \hat{f}^*(\xi) d\xi = \int_{\mathbb{R}^d} \hat{\phi}_1(\xi) \hat{f}(\xi) \hat{f}^*(\xi) d\xi = \int_{\mathbb{R}^d} \hat{\phi}_1(\xi) |\hat{f}(\xi)|^2 d\xi.$$

This concludes the proof of the lemma.  $\square$

**Lemma B.3.** Assume  $\lambda > 0$ ,  $\lambda_1 \in (-\lambda/2, \lambda/2)$ ,  $\phi$  is  $\lambda$ -convex and  $\phi_1$  is  $\lambda_1$ -convex. Then

- (i)  $\mathcal{V}$  is  $\kappa$ -displacement convex, hence displacement convex, where  $\kappa := \lambda - 2|\lambda_1| > 0$ .
- (ii) If we further assume  $\phi_1$  is nonnegative,  $\phi_1 \equiv 1$  on the unit ball, and  $\phi_1 \equiv 0$  outside the ball of radius 2, centered at the origin, then  $\mathcal{V}$  fails to be convex in the classical sense.

*Proof.* (i) As above, denote the Fourier transform of  $\phi_1$  as  $\hat{\phi}_1$ . Let  $\sigma \in AC_2(0, 1; \mathcal{P}_2(\mathbb{M}))$  be a geodesic such that its velocity  $v$  is not identically null. Since  $\|v_t\|_{\sigma_t}$  is independent of  $t$ , it is then positive. We have

$$\begin{aligned} \frac{d^2}{dt^2} \mathcal{V}(\sigma_t) &= \int_{\mathbb{M}} D^2\phi(q) v_t(q) \cdot v_t(q) \sigma_t(dq) + \int_{\mathbb{M}^2} D^2\phi_1(q-w) v_t(q) \cdot v_t(q) \sigma_t(dq) \sigma_t(dw) \\ &\quad + \int_{\mathbb{M}^2} D^2\phi_1(q-w) v_t(q) \cdot v_t(w) \sigma_t(dq) \sigma_t(dw) \\ &\geq \lambda \|v_t\|_{\sigma_t}^2 + \lambda_1 \|v_t\|_{\sigma_t}^2 - |\lambda_1| \|v_t\|_{\sigma_t}^2 \geq \kappa \|v_t\|_{\sigma_t}^2. \end{aligned}$$

This completes the verification of (i).

(ii) Since  $\phi_1$  is even the range of its Fourier transform is contained in the set of real numbers (including negative ones). Assume on the contrary that the range of  $\hat{\phi}_1$  is contained in  $[0, \infty)$ . By Fourier inversion theorem we have for  $x \in \mathbb{M}$ ,

$$|\phi_1(x)| = \left| \int_{\mathbb{M}} \hat{\phi}_1(\xi) e^{2\pi i x \cdot \xi} d\xi \right| \leq \int_{\mathbb{M}} |\hat{\phi}_1(\xi)| d\xi = \int_{\mathbb{M}} \hat{\phi}_1(\xi) d\xi = \phi_1(0).$$

Since  $\phi_1(x) \equiv 1 = \phi_1(0)$  on  $B_1(0)$ , the ball of center 0 and radius 1 we must have

$$(B.1) \quad \hat{\phi}_1(\xi) \cos(2\pi x \cdot \xi) \equiv |\hat{\phi}_1(\xi)| \equiv \hat{\phi}_1(\xi) \quad \forall (x, \xi) \in B_1(0) \times \mathbb{M}.$$

Since  $\phi_1$  is not the null function,  $\hat{\phi}_1$  cannot be the null function. Choose  $\xi_0$  such that  $\hat{\phi}_1(\xi_0) > 0$  and since  $\hat{\phi}_1$  is continuous, assume without loss of generality that  $\xi_0 \neq 0$ . By (B.1),  $\cos(2\pi x \cdot \xi_0) = 1$  for all  $x \in B_1(0)$  which yields a contradiction. One concludes the proof of (ii) by Lemma B.2.  $\square$

**B.2. Convexity vs displacement convexity of the action.** Here we would like to emphasize the fact that imposing the joint convexity assumption on the Lagrangian action, as in (H8) comes as a natural assumption for displacement convex potential Mean Field Games, which are considered in this manuscript. We compare this to the more standard monotonicity assumption in potential MFG.

Assume  $L, H \in C^1(\mathbb{M} \times \mathbb{R}^d)$  are such that  $H(q, \cdot)$  and  $L(q, \cdot)$  are Legendre transform of each other. We consider the actions

$$\mathcal{A}_0^T(\sigma, v) := \int_0^T \left( \int_{\mathbb{M}} L(q, v_t(q)) \sigma_t(dq) + \mathcal{F}(\sigma_t) \right) dt$$

over the set of pairs  $(\sigma, v)$  such that

$$(B.2) \quad \partial_t \sigma + \nabla \cdot (\sigma v) = 0 \quad \mathcal{D}'((0, T) \times \mathbb{M})$$

Recall that if we set  $\nabla_q f(q, \mu) := \nabla_w F(\mu)(q)$  then  $f$  monotone means  $\mathcal{F}$  is convex.

We can rewrite  $\mathcal{A}_0^T(\sigma, v)$  in terms of the momentum by setting

$$\bar{\mathcal{A}}_0^T(\sigma, \eta) := \int_0^T \left( \int_{\mathbb{M}} L\left(q, \frac{d\eta_t}{d\sigma_t}(q)\right) \sigma_t(dq) + \mathcal{F}(\sigma_t) \right) dt$$

over the set of pairs  $(\sigma, \eta)$  such that  $|\eta_t| \ll \sigma_t$  and

$$(B.3) \quad \partial_t \sigma + \nabla \cdot \eta = 0 \quad \mathcal{D}'((0, T) \times \mathbb{M}).$$

In fact, for each  $q \in \mathbb{M}$  we introduce the function  $\bar{L}_q : \mathbb{R} \times \mathbb{R}^d \rightarrow \mathbb{R} \cup \{\infty\}$  defined as

$$(B.4) \quad \bar{L}_q(\rho, e) := \begin{cases} \rho L(q, \frac{e}{\rho}) & \text{if } \rho > 0 \\ 0 & \text{if } \rho = 0, e = \vec{0} \\ +\infty & \text{otherwise .} \end{cases}$$

Here,  $\vec{0} := (0, \dots, 0)$ . Since  $L_q$  is homogeneous of degree 1, whenever  $\mu$  is a probability measure and  $\xi_1, \dots, \xi_d$  are signed Borel measures, the following function is well defined

$$(\mu, \xi) \mapsto A(\mu, \xi) := \begin{cases} \int_{\mathbb{M}} L_q(\mu(dq), d\xi) & \text{if } |\xi| \ll \mu \\ +\infty & \text{if } |\xi| \not\ll \mu \end{cases}$$

We can now extend the definition of  $\bar{\mathcal{A}}_0^T$  over  $\mathcal{C}$  to obtain

$$\bar{\mathcal{A}}_0^T(\sigma, \eta) := \int_0^T \left( A(\sigma_t, \eta_t) + \mathcal{F}(\sigma_t) \right) dt.$$

**Lemma B.4.** *If  $\mathcal{F}$  is convex on  $\mathcal{P}_2(\mathbb{M})$  then  $(\mu, \xi) \mapsto A(\mu, \xi) + \mathcal{F}(\mu)$  is convex (we do not assume  $L$  is jointly convex).*

*Proof.* It suffices to show that  $(\mu, \xi) \mapsto A(\mu, \xi)$  is convex. This is a well-known fact among specialist, and the proof of it can be found for instance in [36], Proposition 5.18.  $\square$

Denote as  $\mathcal{C}$  the set of pairs  $(\sigma, \eta)$  such that  $\sigma \in AC_2(0, T; \mathcal{P}_2(\mathbb{M}))$  and  $t \mapsto \eta_t \in \mathcal{M}(\mathbb{M}) \times \dots \times \mathcal{M}(\mathbb{M})$  is a Borel path of vector fields such that each one of its  $d$  components is a signed Borel measure on  $\mathbb{M}$  and

$$(B.5) \quad \partial_t \sigma + \nabla \cdot \eta = 0 \quad \mathcal{D}'((0, T) \times \mathbb{M}).$$

**Remark B.5.** (i) Note that the classical theory of potential Mean Field Games which consists in assuming that  $f$  is monotone and  $L, H \in C^1(\mathbb{M} \times \mathbb{R}^d)$  are such that  $H(q, \cdot)$  and  $L(q, \cdot)$  are Legendre transform of each other ensures that  $(\mu, \xi) \mapsto A(\mu, \xi) + \mathcal{F}(\mu)$  is a convex function. Therefore, if we extend the definition of  $\bar{\mathcal{A}}_0^T$  to obtain

$$\bar{\mathcal{A}}_0^T(\sigma, \eta) := \int_0^T \left( A(\sigma_t, \eta_t) + \mathcal{F}(\sigma_t) \right) dt$$

over  $\mathcal{C}$ , the action  $\bar{\mathcal{A}}_0^T$  is a convex function in the variables  $(\sigma, \eta)$ .

(ii) When replacing the assumption of convexity on the action by an assumption of displacement convexity, as it is done in this manuscript, it seems natural to impose that  $\mathcal{A}_0^T(\sigma, v)$  is displacement convex on the set of pairs  $(\sigma, v)$  satisfying (B.2). This means that

$$\mathbb{H} \times \mathbb{H} \ni (X, V) \mapsto \int_{\Omega} L(X, V) d\omega + \tilde{\mathcal{F}}(X) \quad \text{is convex,}$$

and thus the Lagrangian  $L$  is assumed to be jointly convex on  $\mathbb{M} \times \mathbb{R}^d$ .

**B.3. Convexity of  $f(\cdot, \mu)$  is a consequence of the displacement convexity of  $\mathcal{F}$ .** To study the scalar master equation, among others we have imposed the assumptions (3.13) and (H11) on the functions  $f$  and  $\mathcal{F}$ . As we have detailed in the previous couple of lines, in our setting it is natural for the Lagrangian  $L$  to impose joint  $\lambda$ -convexity, and we impose that  $\mathcal{F}$  is displacement  $\lambda$ -convex. We show below that in this sense, imposing (3.13), i.e. that  $f(\cdot, \mu)$  is  $\lambda$ -convex, is also natural, and it is a consequence of the displacement  $\lambda$ -convexity of  $\mathcal{F}$ .

**Proposition B.6.** Let  $\mathcal{F} : \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  and  $f : \mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \rightarrow \mathbb{R}$  be of class  $C^2$  such that they are related via (H11). We assume that  $\mathcal{F}$  is displacement  $\lambda$ -convex;  $\mathbb{M} \times \mathcal{P}_2(\mathbb{M}) \ni (q, \mu) \mapsto D_q \nabla_w \mathcal{F}(\mu)(q) = D_{qq}^2 f(q, \mu)$  is continuous and that for any  $\mathcal{K} \subset \mathcal{P}_2(\mathbb{M})$  compact, there exists  $C = C(\mathcal{K}) > 0$  such that  $|D_{ww}^2 \mathcal{F}(\mu)(q_1, q_2)| \leq C$  for any  $\mu \in \mathcal{K}$  and for any  $q_1, q_2 \in \text{spt}(\mu)$ .

Then, for any  $\mu \in \mathcal{P}_2(\mathbb{M})$ , the function  $\text{spt}(\mu) \ni q \mapsto f(q, \mu)$  is  $\lambda$ -convex, i.e.

$$D_{qq}^2 f(x, \mu) \geq \lambda I_d, \quad \forall q \in \text{spt}(\mu).$$

*Proof of Proposition B.6.* Let  $m \in \mathbb{N}$  and we define  $F^{(m)} : (\mathbb{M})^m \rightarrow \mathbb{R}$  as  $F^{(m)}(q_1, \dots, q_m) := \mathcal{F}(\mu_q^{(m)})$ . By the assumptions on  $\mathcal{F}$ , we have that  $F^{(m)}$  is twice differentiable on  $(\mathbb{M})^m$  and by Lemma 2.6, it is  $\frac{\lambda}{m}$ -convex on  $(\mathbb{M})^m$ . This means in particular that

$$D^2 F^{(m)}(q_1, \dots, q_m) \geq \frac{\lambda}{m} I_{md}, \quad \forall (q_1, \dots, q_m) \in (\mathbb{M})^m$$

or equivalently

$$a^\top D^2 F^{(m)}(q_1, \dots, q_m) a \geq \frac{\lambda}{m} |a|_{md}^2, \quad \forall a \in \mathbb{M}^m, (q_1, \dots, q_m) \in (\mathbb{M})^m,$$

where  $|\cdot|_{md}$  stands for the standard Euclidean norm on  $\mathbb{M}^m$ . For  $i \in \{1, \dots, m\}$ , let us choose the vector  $a \in \mathbb{M}^m$  such that its coordinates between the indices  $d(i-1)+1$  and  $di$  are not all zero, while all the others are zero. Then, the previous inequality implies that

$$(B.6) \quad D_{q_i q_i}^2 F^{(m)}(q_1, \dots, q_m) \geq \frac{\lambda}{m} I_d, \quad \forall (q_1, \dots, q_m) \in (\mathbb{M})^m.$$

We also have (see for instance in [15] Remark 3.5(iv)) that

$$m D_{q_i q_i}^2 F^{(m)}(q_1, \dots, q_m) = D_q \nabla_w \mathcal{F}(\mu_q^{(m)})(q_i) + \frac{1}{m} \nabla_{ww}^2 \mathcal{F}(\mu_q^{(m)})(q_i, q_i),$$

$\forall m \in \mathbb{N}, \{q_1, \dots, q_m\} \subseteq \text{spt}(\mu_q^{(m)})$ .

Let  $b \in \mathbb{M}$ . By (B.6), one has that

$$b^\top D_q \nabla_w \mathcal{F}(\mu_q^{(m)})(q_i) b + \frac{1}{m} b^\top \nabla_{ww}^2 \mathcal{F}(\mu_q^{(m)})(q_i, q_i) b \geq \lambda |b|_d^2, \quad \forall m \in \mathbb{N}, \{q_1, \dots, q_m\} \subseteq \text{spt}(\mu_q^{(m)}).$$

Now let us fix  $\mu \in \mathcal{P}_2(\mathbb{M})$  and  $q_1 \in \text{spt}(\mu)$ . For  $m \geq 2$  natural number, let  $q_i \in \text{spt}(\mu)$ ,  $i \in \{2, \dots, m\}$ , and let us build  $\mu_q^{(m)} := \sum_{i=1}^m \delta_{q_i}$ , as an approximation of  $\mu$ .

We have that

$$b^\top D_q \nabla_w \mathcal{F}(\mu_q^{(m)})(q_1) b + \frac{1}{m} b^\top \nabla_{ww}^2 \mathcal{F}(\mu_1^{(m)})(q_1, q_1) b \geq \lambda |b|_d^2.$$

Since  $\mathcal{K} := \left\{ \mu_q^{(m)} : m \in \mathbb{N} \right\} \cup \{ \mu \}$  is a compact set, by the assumptions,  $\nabla_{ww}^2 \mathcal{F}(\mu_q^{(m)})(q_1, q_1)$  is uniformly bounded by a constant  $C = C(\mathcal{K}) > 0$  independent of  $m$ . By the continuity of  $D_q \nabla_w \mathcal{F}$ , one can pass to the limit in the previous inequality to obtain

$$b^\top D_q \nabla_w \mathcal{F}(\mu)(q_1) b \geq \lambda |b|_d^2,$$

and equivalently

$$b^\top D_{qq}^2 f(q_1, \mu) b \geq \lambda |b|_d^2.$$

By the arbitrariness of  $b \in \mathbb{R}^d$  and  $q_1 \in \text{spt}(\mu)$ , the thesis of the proposition follows.  $\square$

**B.4. Failure of smoothness of solutions to Hamilton-Jacobi equation for monotone initial data.** It is well-known in the theory of Hamilton-Jacobi equations on finite dimensional spaces that typically one cannot expect global existence of smooth solutions. This led to the development of the notion of viscosity solution by Crandall-Lions and Evans. We emphasize below that this phenomenon of existence of non-smooth solutions to Hamilton-Jacobi equations is also present on  $\mathcal{P}_2(\mathbb{M})$ .

Let us consider  $d = 1$ . Let  $L : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$  and  $\phi : \mathbb{R} \rightarrow \mathbb{R}$  be defined as

$$L(q, v) := \frac{|v|^2}{2}, \quad \phi(q) := -\sqrt{1 + q^2}.$$

Set

$$\mathcal{U}_*(\mu) := \int_{\mathbb{R}} \phi(q) \mu(dq), \quad u_*(q, \mu) = \phi(q), \quad \mathcal{L}(\mu, \xi) := \int_{\mathbb{R}} L(q, \xi(q)) \mu(dq).$$

Note that  $\mathcal{U}_*$  is convex and so,  $u_*$  is monotone.

Let  $\mathcal{U} : [0, \infty) \times \mathcal{P}_2(\mathbb{R})$  be the unique viscosity solution to the Hamilton-Jacobi equation

$$(B.7) \quad \partial_t \mathcal{U} + \frac{1}{2} \int_{\mathbb{R}} |\nabla_w \mathcal{U}|^2 \mu(dq) = 0, \quad \mathcal{U}(0, \cdot) = \mathcal{U}_*.$$

Assume on the contrary that  $\mathcal{U}$  is of class  $C^1$ . Then  $\mathcal{U}$  must satisfy (B.7) pointwise and so, its restriction defined as

$$u(t, q) = \mathcal{U}(t, \delta_q)$$

must be a  $C^1$  function satisfying

$$(B.8) \quad \partial_t u + \frac{1}{2} |\partial_q u|^2 = 0, \quad u(0, \cdot) = \phi.$$

Thus,

$$(B.9) \quad u(t, q) = \min_y \left\{ \frac{|y - q|^2}{2t} + \phi(y) : y \in \mathbb{R} \right\}.$$

Given  $q$  the minimum in (B.9) is attained by  $y$  such that

$$(B.10) \quad \frac{y - q}{t} - \frac{y}{\sqrt{1 + y^2}} = 0.$$

When  $q = 0$ , (B.10) has three solutions which are

$$y_0 = 0, \quad y_1 = \sqrt{t^2 - 1}, \quad y_2 = -\sqrt{t^2 - 1}.$$

They produce in (B.9) the values

$$-1 \quad \text{and} \quad -\frac{t}{2} - \frac{1}{2t}.$$

Therefore for  $t > 1$ , we have

$$u(t, 0) = -\frac{t}{2} - \frac{1}{2t}.$$

Since

$$u(t, q) - u(t, 0) \leq \frac{|y_i - q|^2}{2t} + \phi(y_i) - \left( \frac{|y_i|^2}{2t} + \phi(y_i) \right) = \frac{-y_i \cdot q}{t} + \frac{|q|^2}{2t},$$

$\pm y_i/t$  belong to the super-differential of  $u(t, \cdot)$  at  $q = 0$ . Thus,  $u(t, \cdot)$  is not differentiable at 0.



## APPENDIX C. HAMILTONIAN FLOWS ON THE HILBERT SPACE

Throughout this subsection, we impose (H1)–(H7). Showing that the value function of our Hamilton–Jacobi equation is of class  $C^{1,1}$  on the Hilbert space is the starting point before improving regularity property via a discretization method. We underline that in Subsection 1.3, using ‘direct techniques’ relying on the convexity of the Lagrangian action, we have shown already that the value function  $\tilde{U}$  is of class  $C_{\text{loc}}^{1,1}$ . In this section, we discuss the regularity properties of the infinite dimensional Hamiltonian flow (1.3), which could also be transferred to the value function. In this section, we further impose the stronger condition that there exists  $\kappa_2 > 0$  such that

$$(C.1) \quad D^2L(\bar{q}, \bar{v}) \begin{pmatrix} q \\ v \end{pmatrix} \cdot \begin{pmatrix} q \\ v \end{pmatrix} \geq \kappa_2 |v|^2 \quad \forall q, \bar{q}, v, \bar{v} \in \mathbb{R}^d.$$

Combining (H2) and (C.1) we have

$$(C.2) \quad \frac{d^2}{dt^2} \tilde{\mathcal{L}}(\bar{x} + tx, \bar{a} + ta) \Big|_{t=0} \geq \kappa_1 \|x\|^2 + \kappa_2 \|a\|^2 \quad \forall x, a, \bar{x}, \bar{a} \in \mathbb{H}.$$

Let us observe that this is a sufficient condition for strict convexity.

Let  $\tilde{\xi}, \tilde{\eta} : [0, \infty) \times \mathbb{H} \rightarrow \mathbb{H}$  be given by (1.5). Using (1.4) and the last inequality in Remark 1.1 (iii), we have

$$(C.3) \quad \|(\tilde{\xi}(t, x), \tilde{\eta}(t, x))\| + 1 \leq \left( \sqrt{\|x\|^2 + \bar{\kappa}^2(\|x\|^2 + 1)} + 1 \right) e^{\bar{\kappa}t}$$

for any  $t > 0$  and  $x \in \mathbb{H}$ . We can formulate the following result.

**Proposition C.1.** *Let  $t \in (0, T)$ ,  $\mu \in \mathcal{P}_2(\mathbb{M})$  and  $q \in \mathbb{M}$ . Suppose  $(t_n)_n \subset [0, T]$  converges to  $t$ ,  $(\mu_n)_n \subset \mathcal{P}_2(\mathbb{M})$  converges to  $\mu$  and  $(q_n)_n \subset \mathbb{M}$  converges to  $q$ . Then for every compact set  $K \subset [0, t]$  we have*

$$\lim_{n \rightarrow \infty} \left\| S_s^{t_n}[\mu_n](q_n) - S_s^t[\mu](q) \right\|_{C(K)} = 0.$$

*Proof.* To alleviate the notation, we set  $\gamma^n(s) := S_s^{t_n}[\mu_n](q_n)$ . It is characterized by the property that

$$(C.4) \quad u(t_n, q_n, \mu_n) = u_0(\gamma_0^n, \sigma_0^{t_n}[\mu_n]) + \int_0^{t_n} \left( L(\gamma_\tau^n, \dot{\gamma}_\tau^n) + f(\gamma_\tau^n, \sigma_\tau^{t_n}[\mu_n]) \right) d\tau, \quad \gamma_{t_n}^n = q_n.$$

We assume without loss of generality that there exists  $r > 0$  such that  $(\mu_n)_n \subset \mathcal{B}_r$  and  $(q_n) \subset B_r(0)$ . By Remark 3.2 (ii)

$$\{\sigma_s^{t_n}[\mu_n] : n \in \mathbb{N}, s \in [0, t_n]\} \subset \mathcal{B}_{e_T(r)}.$$

In light of Remark 3.11 (ii), we may apply the Ascoli–Arzelà lemma to obtain a subsequence which we continue to denote as  $(\gamma^n)_n$  which converges uniformly in  $C([0, t - \delta]; \mathbb{M})$  for every  $\delta \in (0, t)$ . We have  $\gamma \in W^{1,2}(0, t; \mathbb{M})$  and may also assume  $(\gamma^n)_n$  converges weakly to  $\gamma$  in  $W^{1,2}(0, t; \mathbb{M})$ . We use (3.18) to obtain that  $\gamma_t = q$ . We would like to replace  $t_n$  by  $t - \delta$ . Since the integrand there is not known to be non negative, we use (H16) to write

$$\begin{aligned} u(t_n, q_n, \mu_n) &= u_0(\gamma_0^n, \sigma_0^{t_n}[\mu_n]) + \int_0^{t_n} \theta(\sigma_\tau^{t_n}[\mu_n]) (|\gamma_\tau^n| + 1) d\tau \\ &\quad + \int_0^{t_n} \left( L(\gamma_\tau^n, \dot{\gamma}_\tau^n) + f(\gamma_\tau^n, \sigma_\tau^{t_n}[\mu_n]) - \theta(\sigma_\tau^{t_n}[\mu_n]) (|\gamma_\tau^n| + 1) \right) d\tau \end{aligned}$$

Thus, since all the integrands are non negative, we have

$$\begin{aligned} \liminf_{n \rightarrow \infty} u(t_n, q_n, \mu_n) &\geq \liminf_{n \rightarrow \infty} u_0(\gamma_0^n, \sigma_0^{t_n}[\mu_n]) + \liminf_{n \rightarrow \infty} \int_0^{t-\delta} \theta(\sigma_\tau^{t_n}[\mu_n]) (|\gamma_\tau^n| + 1) d\tau \\ &\quad + \liminf_{n \rightarrow \infty} \int_0^{t-\delta} \left( L(\gamma_\tau^n, \dot{\gamma}_\tau^n) + f(\gamma_\tau^n, \sigma_\tau^{t_n}[\mu_n]) - \theta(\sigma_\tau^{t_n}[\mu_n]) (|\gamma_\tau^n| + 1) \right) d\tau. \end{aligned}$$

We invoke the uniform convergence of  $(\gamma^n)_n$ , the pointwise convergence of  $(\sigma_\tau^{t_n}[\mu_n])_n$  provided in (3.3) and the convexity of the functions in (3.13) to conclude that

$$\begin{aligned} \liminf_{n \rightarrow \infty} u(t_n, q_n, \mu_n) &\geq u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^{t-\delta} \left( L(\gamma_\tau, \dot{\gamma}_\tau) + f(\gamma_\tau, \sigma_\tau^t[\mu]) - \theta(\sigma_\tau^t[\mu])(|\gamma_\tau| + 1) \right) d\tau \\ &\quad + \int_0^{t-\delta} \theta(\sigma_\tau^t[\mu])(|\gamma_\tau| + 1) d\tau. \end{aligned}$$

We let  $\delta$  tend to 0 to conclude that

$$\liminf_{n \rightarrow \infty} u(t_n, q_n, \mu_n) \geq u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_\tau, \dot{\gamma}_\tau) + f(\gamma_\tau, \sigma_\tau^t[\mu]) \right) d\tau \geq u(t, q, \mu).$$

Since Proposition 3.15 asserts that  $u$  is continuous, we infer

$$u(t, q, \mu) = u_0(\gamma_0, \sigma_0^t[\mu]) + \int_0^t \left( L(\gamma_\tau, \dot{\gamma}_\tau) + f(\gamma_\tau, \sigma_\tau^t[\mu]) \right) d\tau.$$

and so,  $\gamma_s \equiv S_s^t[\mu](q)$ .

In conclusion, we have proven that every subsequence of  $(S_s^t[\mu_n](q_n))_n$  admits itself a subsequence which converges uniformly on every compact subset of  $[0, t]$ . This is enough to conclude the proof.  $\square$

**Proposition C.2.** *Let  $t > 0$ . Then the following hold.*

- (i)  $\Sigma(t, \cdot)$  given in (1.3) is of class  $C_{\text{loc}}^{0,1}$ .
- (ii)  $\tilde{\xi}_t : \mathbb{H} \rightarrow \mathbb{H}$  is a bijection and its inverse is  $\tilde{S}_0^t$ . For each natural number  $m$ ,  $\tilde{\xi}_t$  is a homeomorphism  $\{M^q : q \in \mathbb{M}^m\}$  onto  $\{M^q : q \in \mathbb{M}^m\}$ . This means  $S_s^{t,m} : \mathbb{M}^m \rightarrow \mathbb{M}^m$  is a homeomorphism.
- (iii)  $\tilde{S}_s^t \circ \tilde{\xi}_t = \tilde{\xi}_s$  and  $\tilde{P}_s^t \circ \tilde{\xi}_t = \tilde{\eta}_s$  for  $s \in [0, t]$ .
- (iv) We have  $\nabla \tilde{U}(t, \tilde{\xi}(t, \cdot)) = \tilde{\eta}(t, \cdot)$ . Furthermore, the vector field  $B$  in (1.27) is a velocity for the flow  $\tilde{\xi}$  in the sense that  $\dot{\tilde{\xi}} = \nabla_b \tilde{\mathcal{H}}(\tilde{\xi}, \tilde{\nabla}U(\cdot, \tilde{\xi}))$

**Remark C.3.** *Although  $\tilde{\xi}_t$  is a homeomorphism, let us underline that in Proposition C.2(ii) we state that the image of  $\{M^q : q \in \mathbb{M}^m\}$  through  $\tilde{\xi}_t$  is not an arbitrarily closed space but is exactly  $\{M^q : q \in \mathbb{M}^m\}$ . Such special vector spaces are mapped onto themselves. Otherwise, we would not be able to conclude that the finite dimensional ODEs are restrictions of the infinite dimensional ones.*

*Proof of Proposition C.2.* (i) Since  $\tilde{\mathcal{H}}$  is of class  $C^{1,1}$ ,  $\Sigma$  is Lipschitz continuous. Let  $\kappa^*$  be the Lipschitz constant of  $\nabla \tilde{\mathcal{H}}$ . We have

$$\text{Lip}(\Sigma(t, \cdot)) \leq \text{Lip}(\Sigma(0, \cdot)) e^{t\kappa^*}$$

for all  $t > 0$ . Here,  $\text{Lip}(\Sigma(t, \cdot))$  stands for the Lipschitz constant of  $\Sigma(t, \cdot)$ .

Since  $\Sigma$  satisfies (1.3), we conclude that  $\Sigma$  is of class  $C_{\text{loc}}^{0,1}$ .

(ii) *Surjectivity.* Given any  $x \in \mathbb{H}$ . Set  $z := \tilde{S}_0^t[x]$  and define

$$\gamma(s) = \tilde{S}_s^t[x], \quad b(s) = \nabla_a \tilde{\mathcal{L}}(\gamma(s), \dot{\gamma}(s)).$$

We have that  $(\gamma, b)$  satisfies the same system of differential equations as  $(\tilde{\xi}, \tilde{\eta})$  on  $(0, t)$ . Furthermore,  $\gamma(0) = z$  and

$$b(0) = \nabla_b \mathcal{L}(\tilde{S}_s^t[x], \partial_s \tilde{S}_s^t[x]|_{s=0}) = \nabla \tilde{U}_0(z).$$

Thus,  $(\gamma, b)$  have the same initial conditions as  $(\tilde{\xi}, \tilde{\eta})$ . Hence, conclude that  $\gamma \equiv \tilde{\xi}(\cdot, z)$  on  $[0, t]$ . In particular,  $x = \tilde{S}_t^t[x] = \tilde{\xi}(t, z) = \tilde{\xi}(t, \tilde{S}_0^t[x])$ . This shows the surjectivity property.

*Injectivity.* The above show that  $\tilde{S}_0^t$  is injective and  $\tilde{\xi}(t, \cdot)$  is its inverse. To show that  $\tilde{\xi}(t, \cdot)$  is injective, it suffices to show that  $\mathbb{H}$  is the range of  $\tilde{S}_0^t$ . Let  $z_0 \in \mathbb{H}$ . Set  $x_0 := \tilde{\xi}(t, z_0)$  set

$$\gamma(s) = \tilde{\xi}(s, z_0), \quad g(s) = \tilde{\eta}(s, z_0).$$

Then  $(\gamma, g)$  satisfies the same system of differential equations as  $[0, t] \ni s \mapsto (\tilde{S}_s^t[x_0], \tilde{P}_s^t[x_0])$  on  $(0, t)$ . We have  $\gamma(t) = x_0$  and

$$g(0) = \tilde{\eta}(0, z_0) = \nabla \tilde{U}_0(z_0) = \nabla \tilde{U}_0(\gamma(0)).$$

Thus,  $(\gamma, g)(s) \equiv (\tilde{S}_s^t[x_0], \tilde{P}_s^t[x_0])$  on  $[0, t]$ . In particular,  $z_0 = \gamma(0) = \tilde{S}_0^t[x_0]$ . Thus,  $\tilde{S}_0^t$  is surjective.

*Continuity.* Since  $\tilde{\xi}_t$  is a bijection of  $\mathbb{H}$  onto  $\mathbb{H}$ , (1.26) and the Invariance of Domain theorem imply that  $\tilde{\xi}_t$  is a homeomorphism of  $\{M^q : q \in \mathbb{M}^m\}$  onto  $\{M^q : q \in \mathbb{M}^m\}$ .

(iii) By (ii)

$$\tilde{S}_0^t \circ \tilde{\xi}_t = \text{id}_{\mathbb{H}} = \tilde{\xi}_0 \quad \text{and} \quad \tilde{P}_0^t \circ \tilde{\xi}_t = \nabla \tilde{U}_0(\tilde{S}_0^t \circ \tilde{\xi}_t) = \nabla \tilde{U}_0 = \tilde{\eta}_0.$$

Since  $s \mapsto (\tilde{S}_s^t \circ \tilde{\xi}_t, \tilde{P}_s^t \circ \tilde{\xi}_t)$  and  $s \mapsto (\tilde{\xi}_s, \tilde{\eta}_s)$  satisfy the same system of differential equations on  $(0, t)$ , we obtain the assertions in (iii).

(iv) We use first Theorem 1.5 (iv) and then (i) of the current Proposition to obtain that  $\nabla \tilde{U}(t, \tilde{\xi}(t, \cdot)) = \tilde{\eta}(t, \cdot)$ . We use the identity  $\dot{\tilde{\xi}} = \nabla_b \tilde{\mathcal{H}}(\tilde{\xi}, \tilde{\eta})$  to conclude the proof.  $\square$

**Remark C.4.** (i) We notice that Proposition C.1, which imposes (3.13), allows to improve the continuity property of  $\tilde{\xi}_t$  and its inverse to the infinite dimensional space, i.e. this implies that  $\tilde{\xi}_t$  is a homeomorphism of  $\mathbb{H}$  onto itself.

(ii) We observe that by Proposition C.2(iv) we have that  $\nabla \tilde{U}(t, \cdot) = \tilde{\eta}(t, \tilde{S}_0^t[\cdot])$ , and since both  $\tilde{\eta}$  and  $\tilde{S}_0^t$  are locally Lipschitz continuous (by (i) of the previous proposition and Lemma 3.3, respectively) we have that  $\nabla \tilde{U}(t, \cdot)$  is locally Lipschitz continuous, just as in Subsection 1.3, by a different perspective one obtains that  $\tilde{U}(t, \cdot) \in C_{\text{loc}}^{1,1}(\mathbb{H})$ .

#### APPENDIX D. REGULARITY ESTIMATES ON SOLUTIONS TO HJES AND HAMILTONIAN SYSTEMS FOR SYSTEMS OF $m$ PARTICLES

In this section we assume  $L$  and  $H$  are such that (H4) - (H7) hold. Let  $u_0 \in C^N(\mathbb{M})$  be convex functions with bounded second derivatives. Let  $F \in C^N(\mathbb{M})$  and  $L$  such that the corresponding Lagrangian action, as in (H8), is strictly convex. We fix  $T > 0$ .

**D.1. One particle Hamiltonian flow.** We study the regularity of viscosity solutions  $u : [0, T] \times \mathbb{M} \rightarrow \mathbb{R}$  of Cauchy problems of the form

$$(D.1) \quad \begin{cases} \partial_t u + H(q, \nabla u) - F(q) = 0, & (0, T) \times \mathbb{M}, \\ u(0, \cdot) = u_0, & \mathbb{M}. \end{cases}$$

Given  $t \in (0, T]$ , we consider the Hamiltonian system

$$(D.2) \quad \begin{cases} \dot{S}(s, q) = D_p H(S(s, q), P(s, q)), & s \in (0, t), q \in \mathbb{M}, \\ \dot{P}(s, q) = -D_q H(S(s, q), P(s, q)) + D_q F(Q(s, q)), & s \in (0, t), q \in \mathbb{M}, \\ S(t, q) = q, P(0, q) = Du_0(S(0, q)), & q \in \mathbb{M}, \end{cases}$$

Such a flow has been considered in a greater generality in Remark 1.6 and has been denoted  $(S, P) = (S^{t,1}, P^{t,1})$ . Recall  $S$  is the unique optimizer in

$$(D.3) \quad u(t, x) := \inf \left\{ u_0(\gamma(0)) + \int_0^t L(\gamma(s), \dot{\gamma}(s)) + F(\gamma(s)) ds : \gamma(t) = x \right\}.$$

Similarly, we shall use the flow

$$(D.4) \quad \begin{cases} \dot{\xi}(s, z) = D_p H(\xi(s, z), \eta(s, z)), & s \in (0, t), z \in \mathbb{M} \\ \dot{\eta}(s, z) = -D_q H(\xi(s, z), \eta(s, z)) + \nabla_q F(\xi(s, z)), & s \in (0, t), z \in \mathbb{M} \\ \xi(0, z) = z, \eta(0, z) = Du_0(z), & z \in \mathbb{M} \end{cases}$$

denoted as  $(\tilde{\xi}, \tilde{\eta})$  in (1.3) when our Hilbert space reduces to  $\mathbb{M}$ .

**Lemma D.1.** Let  $t \in [0, T]$ .

- (1) The map  $\xi_t : \mathbb{M} \rightarrow \mathbb{M}$  is a homeomorphism  $S_s := \xi_s \circ \xi_t^{-1}$  and  $P_s := \eta_s \circ \xi_t^{-1}$ . We have  $\xi_t, \eta_t \in C^{N-1}(\mathbb{M})$ .
- (2) If we further assume  $N \geq 2$ , then  $u \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M})$  is classical solution to (D.1) and  $z \mapsto \xi(t, z)$  is a  $C^{N-1}$  diffeomorphism from  $\mathbb{M}$  onto itself.

*Proof.* (1) The existence and smooth dependence on the data of the solution of (D.2) is classical, Proposition C.2 ensures  $\xi_t : \mathbb{M} \rightarrow \mathbb{M}$  is a homeomorphism and  $S(s, \cdot) := \xi_s \circ \xi_t^{-1}$ ,  $P(s, \cdot) := \eta_s \circ \xi_t^{-1}$ .

(2) By Theorem 1.5,  $u \in C_{\text{loc}}^{1,1}([0, T] \times \mathbb{M})$  and is classical solution to (D.1). Let us show that  $z \mapsto \xi(t, z)$  is a global  $C^{N-1}$  diffeomorphism. Recall that by Proposition C.2,  $\xi$  is a solution to

$$\begin{cases} \dot{\xi}(s, z) = D_p H(\xi(s, z), Du(s, \xi(s, z))), & s \in (0, t), \\ \xi(0, z) = z, \end{cases}$$

from where one has

$$\begin{cases} \partial_s D_z \xi(s, z) = A(s, z) D_z \xi(s, z), & s \in (0, t), \\ D_z \xi(0, z) = I_d, \end{cases}$$

where we used the notation

$$A(s, z) := D_{xp}^2 H(\xi(s, z), Du(s, \xi(s, z))) + D_{pp}^2 H(\xi(s, z), Du(s, \xi(s, z))) D^2 u(s, \xi(s, z)).$$

Since  $A(s, z)$  is locally uniformly bounded, we have that for  $s > 0$  small enough  $D_z \xi(s, z)$  is invertible. Therefore, Jacobi's formula yields

$$\det(D_z \xi(s, z)) = \exp\left(\int_0^s \text{tr}(A(\tau, z)) d\tau\right).$$

Since  $A(\tau, \cdot) \in L_{\text{loc}}^\infty(\mathbb{M})$ , uniformly with respect to  $\tau \in [0, t]$ , we have that  $\det(D_z \xi(s, z)) > 0$  for all  $z \in \mathbb{M}$ , uniformly with respect to  $s$ . Therefore,  $D_z \xi(s, z)$  is invertible for any  $z \in \mathbb{M}$  and for any  $s \in [0, t]$ . Thus, by the fact that  $\xi(t, \cdot) \in C^{N-1}(\mathbb{M})$  and the fact that  $\xi(t, \cdot)$  is bijective, we conclude that  $z \mapsto \xi(t, z)$  is a global  $C^{N-1}$  diffeomorphism of  $\mathbb{M}$  onto itself.  $\square$

**D.2.  $m$ -particles Hamiltonian flow.** Throughout this section, we assume to be given a positive monotone nondecreasing function  $C_0 : (0, \infty) \rightarrow (0, \infty)$ . Furthermore, we impose that in the assumption (H4)  $N \geq 2$  and  $F^{(m)}, U_0^{(m)} \in C^3(\mathbb{M}^m)$ .

As in Subsection 1.2 we define

$$U_0^{(m)}(q) := U_0\left(\frac{1}{m} \sum_{i=1}^m \delta_{q_i}\right), \quad F^{(m)}(q) := \mathcal{F}\left(\frac{1}{m} \sum_{i=1}^m \delta_{q_i}\right) \quad \forall q \in \mathbb{M}^m.$$

We assume to be given  $U_0^{(m)}, F^{(m)} : \mathbb{M}^m \rightarrow \mathbb{R}$  satisfying Property 2.15(2) with  $C = C_0(r)$ . We also consider viscosity solutions  $U^{(m)} : [0, T] \times \mathbb{M}^m \rightarrow \mathbb{R}$  of the Hamilton-Jacobi equation

$$(D.5) \quad \begin{cases} \partial_t U^{(m)}(t, q) + H^{(m)}(q, D_q U^{(m)}(t, q)) - F^{(m)}(q) = 0, & \text{on } (0, T) \times \mathbb{M}^m, \\ U^{(m)}(0, \cdot) = U_0^{(m)}, & \text{on } \mathbb{M}^m. \end{cases}$$

By Remark 1.4

$$U^{(m)}(t, q) \equiv \tilde{U}(t, M^q) \quad \forall (t, q) \in [0, \infty) \times \mathbb{M}^m.$$

Given  $t \in (0, T)$  we consider the  $m$  particles flows  $S^{t,m}, P^{t,m} : \mathbb{M}^m \rightarrow \mathbb{M}^m$  in Remark 1.6. In other words,

$$(D.6) \quad \begin{cases} \dot{S}_i^{t,m}(s, q) = D_p H(S_i^{t,m}(s, q), m P_i^{t,m}(s, q)), & (s, q) \in (0, t) \times \mathbb{M}^m, \\ \dot{P}_i^{t,m}(s, q) = -\frac{1}{m} D_q H(S_i^{t,m}(s, q), m P_i^{t,m}(s, q)) + D_{q_i} F^{(m)}(S^{t,m}(s, q)), & (s, q) \in (0, t) \times \mathbb{M}^m, \\ S_i^{t,m}(t, q) = q_i, \quad P_i^{t,m}(0, q) = D_{q_i} U_0^{(m)}(S^{t,m}(0, q)) & q \in \mathbb{M}^m. \end{cases}$$

This is analogous to the flow  $(S^{t,m}, P^{t,m})$  in Remark 1.6 where we have not displayed the  $m$  and  $t$  dependence to alleviate the notation. We also consider the  $m$  particles flows  $\xi^m, \eta^m : [0, \infty) \times \mathbb{M}^m \rightarrow \mathbb{M}^m$  in (D.4) and do not display the  $m$  dependence. They are defined as

$$(D.7) \quad \begin{cases} \dot{\xi}_i(s, z) = D_p H(\xi_i(s, z), m \eta_i(s, z)), & s \in (0, t), \\ \dot{\eta}_i(s, z) = -\frac{1}{m} D_q H(\xi_i(s, z), m \eta_i(s, z)) + D_{q_i} F^{(m)}(\xi(s, z)), & s \in (0, t), \\ \xi_i(0, z) = z_i, \quad \eta_i(0, z) = D_{q_i} U_0^{(m)}(z), \end{cases}$$

for  $i \in \{1, \dots, m\}$ , where  $z = (z_1, \dots, z_m) \in \mathbb{M}^m$ . We have the following results.

**Theorem D.2.** *Let  $U^{(m)} : (0, T) \times \mathbb{M}^m \rightarrow \mathbb{R}$  be the unique viscosity solution of (D.5) and let  $r > 0$ . Then for all  $t \in (0, T)$  there exists  $C(t, r) > 0$  such that the following hold for all  $m \in \mathbb{N}$ .*

- (1)  $U^{(m)}(t, \cdot)$  satisfies the estimates in Property 2.15(2) in  $\mathbb{B}_r^m(0)$  with constant  $C(t, r)$ .
- (2) Further assume that  $U_0^{(m)}$  and  $F^{(m)}$  satisfy Property 2.15(3) and (H15) takes place. Then  $U^{(m)}(t, \cdot)$  satisfies the estimates in Property 2.15(3) in  $\mathbb{B}_r^m(0)$  with constant  $C(t, r)$ .
- (3) We assume that the assumptions from (1) and (3.16) take place. Then  $\partial_t U^{(m)}(t, \cdot)$  satisfies the estimates in Property 2.15(1)-(b) in  $\mathbb{B}_r^m(0)$  with constant  $C(t, r)$ .

*Proof.* Since we will study asymptotic properties of terms with respect to  $m$ , for an expression  $A(m)$  depending on  $m$ , sometimes we use the notation  $A(m) \sim m$  to mean  $A = O(m)$ .

First, let us notice that by Theorem 1.5  $U^{(m)}$  is a  $C_{\text{loc}}^{1,1}((0, T) \times \mathbb{M}^m)$  classical solution of (D.5), therefore in particular any point  $(t, q) \in (0, T) \times \mathbb{M}^m$  is regular and not conjugate (by the proof of Lemma D.1) in the sense of Definition 6.3.4 of [7].

Furthermore, let us notice that Lemma D.1 asserts that  $\xi^m(s, \cdot)$  is a  $C^N$  diffeomorphism and Theorem 6.4.11 from [7] yields that  $U^{(m)} \in C^3((0, T) \times \mathbb{M}^m)$ . In what follows we aim to obtain quantitative derivative estimates on  $U^{(m)}$  with respect to the discretization parameter  $m$ .

**Step 0.** Basic bounds on  $\xi^m(t, z)$  when  $q := \xi_t^m(z) \in \mathbb{B}_r^m(0)$ . By Proposition C.2  $\xi^m(s, z) = S_s^{t, m}[q]$  since  $q = \xi^m(t, z)$ . By the same Proposition, for  $i \in \{1, \dots, m\}$  and  $z \in \mathbb{M}^m$ , we have

$$(D.8) \quad \begin{cases} \dot{\xi}_i^m(t, z) = D_p H(\xi_i^m(t, z), m D_{q_i} U^{(m)}(t, \xi^m(t, z))), & t \in (0, T), \\ \xi^m(0, z) = z, \end{cases}$$

and

$$(D.9) \quad \eta_i^m(t, z) = D_{q_i} U^{(m)}(t, \xi^m(t, z)) = D_{q_i} U^{(m)}(t, x), \quad \text{and} \quad \eta_i^m(0, z) = D_{q_i} U_0^{(m)}(z).$$

By Theorem 1.5 there exists  $\beta(t, r) > 0$  (independent of  $m$ ) for any  $q \in \mathbb{B}_r^m(0)$  we have

$$(D.10) \quad S_s^{t, m}[q] \equiv \xi^m(s, z) \in \mathbb{B}_{\beta(t, r)}^m, \quad \text{for all } s \in [0, t].$$

Proposition 1.2 ensures  $\tilde{U}$  is locally Lipschitz on  $[0, \infty) \times \mathbb{H}$  and so, there exists  $C_1(t, r) > 0$  (depending on  $\beta(t, r)$ ) such that  $\|\nabla \tilde{U}(t, \xi(t, M^z))\| \leq C_1(t, r)$ . Using the relation between  $\nabla \tilde{U}$  and  $\eta$  provided by Proposition C.2 (iv) we conclude

$$(D.11) \quad \sum_{i=1}^m m |\eta_i^m(t, z)|^2 \leq C_1(t, r).$$

We are now well equipped to start the proof of the assertion (1) of the theorem.

**Step 1.** *Estimates on  $(D_{z_j} \xi_i(t, \cdot), D_{z_j} \eta_i(t, \cdot))_{i, j=1}^m$ .*

*Claim 1.* There exists a constant  $C_2(t, r) > 0$  (independent of  $m$ ) such that if  $\xi(t, z) = q \in \mathbb{B}_r^m(0)$ , then for all  $i, j \in \{1, \dots, m\}$  we have

$$|D_{z_j} \xi_i^m(t, \cdot)|_\infty \leq \begin{cases} C_2(t, r), & i = j, \\ \frac{C_2(t, r)}{m}, & i \neq j, \end{cases}$$

and

$$(D.12) \quad |D_{z_j} \eta_i^m(t, \cdot)|_\infty \leq \begin{cases} \frac{C_2(t, r)}{m}, & i = j, \\ \frac{C_2(t, r)}{m^2}, & i \neq j, \end{cases}$$

*Proof of Claim 1.* By differentiating the Hamiltonian system (D.7) with respect to the  $z_j$ , we get

$$(D.13) \quad \begin{cases} \partial_t D_{z_j} \xi_i^m = D_{qp}^2 H(\xi_i^m, m \eta_i) D_{z_j} \xi_i^m + m D_{pp}^2 H(\xi_i^m, m \eta_i^m) D_{z_j} \eta_i^m, \\ \partial_t D_{z_j} \eta_i^m = -\frac{1}{m} (D_{qq}^2 H(\xi_i^m, m \eta_i) D_{z_j} \xi_i^m + m D_{pq}^2 H(\xi_i^m, m \eta_i) D_{z_j} \eta_i^m) + \sum_{l=1}^m D_{q_l q_i}^2 F^{(m)}(\xi^m) D_{z_j} \xi_l^m, \\ D_{z_j} \xi_i^m(0, \cdot) = \begin{cases} I_{d \times d}, & i = j, \\ 0_{d \times d}, & i \neq j, \end{cases}, \quad D_{z_j} \eta_i^m(0, z) = D_{q_j q_i}^2 U_0^{(m)}(z). \end{cases}$$

Let us set

$$\bar{C}_2 := \max\{|\partial_q^a \partial_p^b H(q, p)| : (q, p) \in \mathbb{R}^d \times \mathbb{R}^d, |a| + |b| = 2\}.$$

If  $\xi^m(t, z) = q \in \mathbb{B}_r^m(0)$ , then in the same way, there exists  $\tilde{C}_2(t, r) > 0$  (depending on  $\beta(t, r)$ ) such that  $D_{q_i}^2 F^{(m)}(\xi_1, \dots, \xi_m)$  and  $D_{q_j}^2 U_0^{(m)}(z)$  satisfy the estimate (2.9) with  $\tilde{C}_2(t, r)$ . Set

$$\hat{C}_2(t, r) := \max\{\bar{C}_2, \tilde{C}_2(t, r)\}.$$

Let us consider the curves  $X(s) := (X_{ij}(s))_{i,j=1}^m$  and  $Y(s) := (Y_{ij}(s))_{i,j=1}^m$  in  $\mathbb{R}^{m \times m}$ , the solution to the ODE system (D.21) in Lemma D.4. Because of the previous bounds on the data in the system (D.13), we can derive the estimates on  $(D_{z_j} \xi_i(t, \cdot), D_{z_j} \eta_i(t, \cdot))_{i,j=1}^m$  from the estimates on  $(X_{ij}, Y_{ij})_{i,j=1}^m$  in Lemma D.4. Therefore, there exists there exists  $\hat{C} > 0$  such that *Claim 1* follows by setting

$$C_2(t, r) := e^{t\hat{C}(t,r)}.$$

Now, let us denote by  $\zeta^m = (\zeta_1^m(t, \cdot), \dots, \zeta_m^m(t, \cdot)) := S_0^{t,m}[q]$  the inverse of  $\xi^m(t, \cdot)$ , in particular, we have that if  $\xi_i^m(t, z) = q_i$ , then  $\zeta_i^m(t, q) = z_i$ . Next, we derive estimates for  $D_{q_j} \zeta_i^m(t, \cdot)$ .

**Step 2.** *Estimates on  $(D_{q_j} \zeta_i^m)_{i,j=1}^m$ .*

*Claim 2.* There exists a constant  $C_3(t, r) > 0$  (independent of  $m$ ) such that for all  $i, j \in \{1, \dots, m\}$  we have

$$|D_{q_j} \zeta_i^m(t, \cdot)|_\infty \leq \begin{cases} C_3(t, r), & i = j, \\ \frac{C_3(t, r)}{m}, & i \neq j, \end{cases} \quad \text{in } \mathbb{B}_r^m(0).$$

Since  $\xi^m(t, \cdot) : \mathbb{M} \rightarrow \mathbb{M}$  is a diffeomorphism, we have

$$(D.14) \quad D_q \zeta^m(t, q) = (D_z \xi^m(t, \cdot))^{-1} \circ \zeta^m(t, q)$$

Since we have a uniform lower bound on  $\det(D_z \xi(t, \cdot))$  in  $\mathbb{M}^m$ , we can simply study the asymptotic behavior of  $D_q \zeta^m(t, q)$  with respect to  $m$  via the asymptotic behavior of  $(D_z \xi^m(t, \cdot))^{-1}$ . By the previous uniform local estimates on  $D_z \xi^m(t, \cdot)$ , we have that there exists a constant  $C(t, r) > 0$  depending on  $C_2(t, r)$  such that

$$(D.15) \quad D_z \xi^m(t, \cdot) \sim C(t, r) \begin{bmatrix} I_d & \frac{1}{m} I_d & \frac{1}{m} I_d & \dots & \frac{1}{m} I_d \\ \frac{1}{m} I_d & I_d & \frac{1}{m} I_d & \dots & \frac{1}{m} I_d \\ \dots & \dots & \dots & \ddots & \dots \\ \frac{1}{m} I_d & \frac{1}{m} I_d & \frac{1}{m} I_d & \dots & I_d \end{bmatrix},$$

and therefore,

$$(D_z \xi(t, \cdot))^{-1} \sim \frac{1}{C(t, r)} \begin{bmatrix} \frac{m-\frac{1}{2}}{m-\frac{1}{2}} I_d & \frac{-m}{(2m-1)(m-1)} I_d & \frac{-m}{(2m-1)(m-1)} I_d & \dots & \frac{-m}{(2m-1)(m-1)} I_d \\ \frac{-m}{(2m-1)(m-1)} I_d & \frac{m-\frac{1}{2}}{m-\frac{1}{2}} I_d & \frac{-m}{(2m-1)(m-1)} I_d & \dots & \frac{-m}{(2m-1)(m-1)} I_d \\ \dots & \dots & \dots & \ddots & \dots \\ \frac{-m}{(2m-1)(m-1)} I_d & \frac{-m}{(2m-1)(m-1)} I_d & \frac{-m}{(2m-1)(m-1)} I_d & \dots & \frac{m-\frac{1}{2}}{m-\frac{1}{2}} I_d \end{bmatrix},$$

and so *Claim 2* follows by setting  $C_3(t, r) := \frac{1}{C(t, r)}$ .

Now we are ready to conclude about the proof of the assertion (1) in this theorem. Let us recall that from (D.9) we have

$$\eta_i^m(t, \zeta^m(t, q)) = D_{q_i} U^{(m)}(t, q).$$

Differentiating this expression with respect to  $q_j$  yields

$$\begin{aligned} D_{q_j q_i} U^{(m)}(t, q) &= \sum_{l=1}^m D_{q_l} \left( \eta_i(t, \zeta^m(t, q)) \right) D_{q_j} \zeta_l^m(t, q) \\ &= D_{q_j} \eta_i^m(t, \zeta^m(t, q)) D_{q_j} \zeta_j^m(t, q) + D_{q_i} \eta_i^m(t, \zeta^m(t, q)) D_{q_j} \zeta_i^m(t, q) \\ &\quad + \sum_{l \neq i, l \neq j} D_{q_l} \eta_i^m(t, \zeta(t, q)) D_{q_j} \zeta_l^m(t, q), \end{aligned}$$

and using the previous estimates, the result follows.

Next, let us show the assertion (2) from the statement of the theorem.

**Step 3.** *Estimates on  $(D_{z_k z_j} \xi_i^m(t, \cdot), D_{z_k z_j} \eta_i^m(t, \cdot))_{i,j,k=1}^m$ .*

*Claim 3.* There exists a constant  $C_4(t, r) > 0$  depending on all the previous ones, but independent of  $m$  such that if  $\xi(t, z) = q \in \mathbb{B}_r^m(0)$ , then for all  $i, j, k \in \{1, \dots, m\}$  we have

$$|D_{z_k z_j}^2 \xi_i^m(t, \cdot)|_\infty \leq \begin{cases} C_4(t, r), & i = j = k, \\ \frac{C_4(t, r)}{m}, & i = j \neq k, i \neq j = k, i = k \neq j, \\ \frac{C_4(t, r)}{m^2}, & i \neq j \neq k, \end{cases}$$

and

$$|D_{z_k z_j}^2 \eta_i^m(t, \cdot)|_\infty \leq \begin{cases} \frac{C_4(t, r)}{m}, & i = j = k, \\ \frac{C_4(t, r)}{m^2}, & i = j \neq k, i \neq j = k, i = k \neq j, \\ \frac{C_4(t, r)}{m^3}, & i \neq j \neq k. \end{cases}$$

*Proof of Claim 3.* Differentiating the system (D.13) with respect to  $z_k$ , we obtain for the first equation

$$\begin{aligned} \partial_t D_{z_k z_j}^2 \xi_i^m &= D_{z_k} \xi_i^m D_{qqp}^3 H(\xi_i^m, m\eta_i) D_{z_j} \xi_i^m + m D_{z_k} \eta_i^m D_{ppp}^3 H(\xi_i^m, m\eta_i) D_{z_j} \xi_i^m \\ &\quad + D_{qp}^2 H(\xi_i^m, m\eta_i^m) D_{z_k z_j}^2 \xi_i^m + m D_{z_k} \xi_i D_{ppp}^3 H(\xi_i^m, m\eta_i) D_{z_j} \eta_i^m \\ &\quad + m^2 D_{z_k} \eta_i^m D_{ppp}^2 H(\xi_i^m, m\eta_i) D_{z_j} \eta_i^m + m D_{pp}^2 H(\xi_i^m, m\eta_i) D_{z_k z_j}^2 \eta_i^m \end{aligned} \quad (\text{D.16})$$

together with the initial condition  $D_{z_k z_j}^2 \xi_i^m(0, \cdot) = 0_{d \times d \times d}$ . From the differentiation of the second equation with respect to  $z_k$ , we obtain

$$\begin{aligned} \partial_t D_{z_k z_j}^2 \eta_i^m &= -\frac{1}{m} (D_{z_k} \xi_i D_{qqq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \xi_i^m + m D_{z_k} \eta_i D_{ppq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \xi_i^m) \\ &\quad - \frac{1}{m} (D_{qq}^2 H(\xi_i^m, m\eta_i^m) D_{z_k z_j}^2 \xi_i^m D_{z_k} \xi_i^m + D_{ppq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \eta_i^m) \\ &\quad - \frac{1}{m} (m^2 D_{z_k} \eta_i D_{ppx}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \eta_i^m + m D_{pp}^2 H(\xi_i, m\eta_i^m) D_{z_k z_j}^2 \eta_i^m) \\ &\quad + \sum_{l_1, l_2=1}^m D_{z_k} \xi_{l_1}^m D_{q_1 l_1 q_2 q_i}^3 F^{(m)}(\xi^m) D_{z_j} \xi_{l_2}^m + \sum_{l=1}^m D_{q_l q_i}^2 F^{(m)}(\xi^m) D_{z_k z_j}^2 \xi_l^m \end{aligned} \quad (\text{D.17})$$

with the initial condition

$$D_{z_k z_j}^2 \eta_i^m(0, z) = D_{q_k q_j q_i}^3 U_0^{(m)}(z) \quad (\text{D.18})$$

Let us notice that for  $k, j$  fixed, the asymptotic behavior of  $(D_{z_k z_j} \xi_i^m(t, \cdot), D_{z_k z_j} \eta_i^m(t, \cdot))$  can be studied via the solutions of the ODE system (D.19), by formally setting  $X_i := D_{q_k q_j}^2 \xi_i^m$  and  $Y_i := D_{q_k q_j}^2 \eta_i^m$ . One just needs to find the asymptotic properties of  $A_1, A_2$  and  $Y_0$  appearing in this system.

Let us set

$$\bar{C}_4 := \max\{|\partial_q^\alpha \partial_p^\beta H(q, p)| : (q, p) \in \mathbb{R}^d \times \mathbb{R}^d, 2 \leq |\alpha| + |\beta| \leq 3\},$$

then we notice that by the assumptions on  $H$ , we have that if  $\xi^m(t, z) = q \in \mathbb{B}_r^m(0)$ , then

$$|\partial_q^\alpha \partial_p^\beta H(\xi_i^m(t, z), m\eta_i^m(t, z))| \leq \bar{C}_4.$$

In the same way, there exists  $\tilde{C}_4(t, r) > 0$  (depending on  $\beta(t, r)$ ) such that  $D_{q_k q_j q_i}^2 F^{(m)}(\xi^m)$  and  $D_{q_k q_j q_i}^2 U_0^{(m)}(q)$  satisfy the estimate (2.10) with  $\tilde{C}_4(t, r)$ . Set

$$\hat{C}_4(t, r) := \max\{\bar{C}_4, \tilde{C}_4(t, r)\} \max\{C_2(t, r), 1\}^2.$$

For  $k, j$  fixed we look for the asymptotic properties of the data

$$\begin{aligned} (A_1)_i &:= D_{z_k} \xi_i D_{qqp}^3 H(\xi_i^m, m\eta_i) D_{z_j} \xi_i^m + m D_{z_k} \eta_i^m D_{ppq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \xi_i^m \\ &\quad + m D_{z_k} \xi_i^m D_{ppp}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \eta_i^m + m^2 D_{z_k} \eta_i^m D_{ppp}^2 H(\xi_i^m, m\eta_i^m) D_{z_j} \eta_i^m, \\ (A_2)_i &:= -\frac{1}{m} (D_{z_k} \xi_i D_{qqq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \xi_i^m + m D_{z_k} \eta_i^m D_{ppq}^3 H(\xi_i^m, m\eta_i) D_{z_j} \xi_i^m) \\ &\quad - \frac{1}{m} (D_{z_k} \xi_i^m m D_{ppq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \eta_i^m + m^2 D_{z_k} \eta_i^m D_{ppq}^3 H(\xi_i^m, m\eta_i^m) D_{z_j} \eta_i^m) \\ &\quad + \sum_{l_1, l_2=1}^m D_{z_k} \xi_{l_1}^m D_{q_{l_1} q_{l_2} q_i}^3 F^{(m)}(\xi^m) D_{z_j} \xi_{l_2}^m \end{aligned}$$

and

$$(Y_0)_i := D_{q_k q_j q_i}^3 U_0^{(m)}$$

Using the obtained asymptotic properties on  $(D_{z_j} \xi_i, D_{z_j} \eta_i)$  in **Step 1** and the properties of  $U_0^{(m)}$ , one checks the following asymptotic properties with respect to  $m$  in  $\mathbb{B}_r^m$

*Sub-claim 3.*

- (1) If  $k = j = i$ , then  $(A_1)_i \sim \hat{C}_4(t, r)$ ,  $(A_2)_i \sim \frac{\hat{C}_4(t, r)}{m}$  and  $(Y_0)_i \sim \frac{\hat{C}_4(t, r)}{m}$ .
- (2) If  $k = j \neq i$  then  $(A_1)_i \sim \frac{\hat{C}_4(t, r)}{m^2}$ ,  $(A_2)_i \sim \frac{\hat{C}_4(t, r)}{m^2}$  and  $(Y_0)_i \sim \frac{\hat{C}_4(t, r)}{m^2}$ .
- (3) If  $k = i \neq j$  or  $i = j \neq k$ ,  $(A_1)_i \sim \frac{\hat{C}_4(t, r)}{m}$ ,  $(A_2)_i \sim \frac{\hat{C}_4(t, r)}{m^2}$  and  $(Y_0)_i \sim \frac{\hat{C}_4(t, r)}{m^2}$ .
- (4) If  $k \neq j \neq i$ , then  $(A_1)_i \sim \frac{\hat{C}_4(t, r)}{m^2}$ ,  $(A_2)_i \sim \frac{\hat{C}_4(t, r)}{m^3}$  and  $(Y_0)_i \sim \frac{\hat{C}_4(t, r)}{m^3}$ .

Now, one can differentiate two cases, when studying the desired properties. Let us notice again that one fixes  $k, j$ .

*Case 1.* If  $k = j$ , (1)-(2) of *Sub-claim 3* can be combined with Lemma D.3(1) to conclude the proof of the Claim.

*Case 2.* If  $k \neq j$ , (3)-(4) of *Sub-claim 3* can be combined with Lemma D.3(2) to conclude the proof of the Claim.

Therefore there exists a constant  $C > 0$  such that *Claim 3* holds for  $C_4(t, r) := e^{tC} \hat{C}_4(t, r)$ .

**Step 4.** *Estimates on  $(D_{q_k q_j} \zeta_i(t, \cdot))_{i,j,k=1}^m$ .*

*Claim 4.* There exists a constant  $C_5(t, r) > 0$  depending on all the previous ones, but independent of  $m$  such that for all  $i, j, k \in \{1, \dots, m\}$ , we have

$$|D_{x_k x_j}^2 \zeta_i(t, \cdot)|_\infty \leq \begin{cases} C_5(t, r), & i = j = k, \\ \frac{C_5(t, r)}{m}, & i = j \neq k, i \neq j = k, i = k \neq j, \\ \frac{C_5(t, r)}{m^2}, & i \neq j \neq k, \end{cases} \quad \text{in } \mathbb{B}_r^m.$$

*Proof of Claim 4.* It is enough to differentiate the expression (D.14) and use all the previous estimates on  $(D_{z_k z_j}^2 \xi_i)_{i,j,k=1}^m$  and on  $(D_{q_j} \zeta_i)_{i,j=1}^m$  from **Step 3** and **Step 2**, respectively.

We have

$$D_{qq}^2 \zeta(t, q) = - \left\{ \left[ (D_z \xi(t, \cdot))^{-1} D_{zz}^2 \xi(t, \cdot) D_q \zeta(t, q) (D_z \xi(t, \cdot))^{-1} \right] \circ \zeta(t, q) \right\}.$$

The previous writing is used for the following short hand notation: for  $k \in \{1, \dots, m\}$ , we have

$$D_{q_k} D_q \zeta(t, q) = - \left\{ \left[ (D_z \xi(t, \cdot))^{-1} \left( \sum_{l=1}^m D_{z_l} D_z \xi(t, \cdot) D_{q_k} \zeta_l(t, q) \right) (D_z \xi(t, \cdot))^{-1} \right] \circ \zeta(t, q) \right\},$$

and in particular for  $i, j \in \{1, \dots, m\}$ , we have

$$\left( \sum_{l=1}^m D_{z_l} D_z \xi(t, \cdot) D_{q_k} \zeta_l(t, q) \right)_{ij} = \sum_{l=1}^m D_{z_l z_j}^2 \xi_i(t, \cdot) D_{q_k} \zeta_l(t, q) =: A_{ij}.$$



For  $k \in \{1, \dots, m\}$  fixed, this last matrix has the following asymptotic behavior: by setting  $\tilde{C}_5(t, r) := C_4(t, r)C_3(t, r)$ , we have

$$|A_{ij}|_\infty \leq \begin{cases} \tilde{C}_5(t, r), & i = j = k, \\ \frac{\tilde{C}_5(t, r)}{m}, & i = j \neq k, i \neq j = k, i = k \neq j, \\ \frac{\tilde{C}_5(t, r)}{m^2}, & i \neq j \neq k. \end{cases}$$

Now, using the asymptotic behavior of  $(D_{\mathbf{z}}\xi(t, \cdot))^{-1}$  from (D.15), by setting  $C_5(t, r) := \tilde{C}_5(t, r)C(t, r)^2$ , we conclude the statement in *Claim 4*.

### Final Step.

Let us recall that from (D.9) we have

$$\eta_i(t, \zeta(t, q)) = D_{q_i}U^{(m)}(t, q).$$

Differentiating this expression with respect to  $x_j$  and  $x_k$  we obtain

$$D_{q_k q_j q_i}^3 U^{(m)}(t, \cdot) = \sum_{l_1, l_2=1}^m D_{q_k} \zeta_{l_2}(t, \cdot) D_{z_{l_2} z_{l_1}}^2 \eta_i(t, \zeta(t, \cdot)) D_{q_j} \zeta_{l_1}(t, \cdot) + \sum_{l=1}^m D_{z_l} \eta_i(t, \zeta(t, \cdot)) D_{q_k q_j}^2 \zeta_l(t, \cdot)$$

from where

$$\begin{aligned} \left| D_{q_k q_j q_i}^3 U^{(m)}(t, \cdot) \right|_\infty &\leq \frac{1}{m} \left( |D_{q_k} \zeta_i|_\infty |D_{q_j} \zeta_i|_\infty + |D_{q_k q_j}^2 \zeta_i|_\infty \right) \\ &+ \frac{1}{m^2} \left( \sum_{l=1, l \neq i}^m |D_{q_k} \zeta_l|_\infty |D_{q_j} \zeta_i|_\infty + \sum_{l=1, l \neq i}^m |D_{q_k} \zeta_i|_\infty |D_{q_j} \zeta_l|_\infty + \sum_{l=1, l \neq i}^m |D_{q_k q_j}^2 \zeta_l|_\infty \right) \\ &+ \frac{1}{m^3} \sum_{\substack{l_1, l_2=1 \\ l_1 \neq l_2 \neq i}}^m |D_{q_k} \zeta_{l_1}|_\infty |D_{q_j} \zeta_{l_2}|_\infty \end{aligned}$$

Using the estimations from the previous steps, we conclude the thesis of points (1) and (2) of the theorem.

The statement in (3) can be easily obtained by differentiating the Hamilton-Jacobi equation satisfied by  $U^{(m)}$  with respect the variable  $q_j$ . Indeed, we have

$$\begin{aligned} |D_{q_j} \partial_t U^{(m)}| &\leq \frac{1}{m} |D_q H(q_j, m D_{q_j} U^{(m)})| + \frac{1}{m} |D_p H(q_j, m D_{q_j} U^{(m)})| m |D_{q_j q_j}^2 U^{(m)}| \\ &+ \sum_{i \neq j} \frac{1}{m} |D_p H(q_i, m D_{q_i} U^{(m)})| m |D_{q_j q_i}^2 U^{(m)}| + |D_{q_j} F^{(m)}| \\ &\leq \frac{1}{m} |D_q H(q_j, m D_{q_j} U^{(m)})| + \frac{1}{m} |D_p H(q_j, m D_{q_j} U^{(m)})| \\ &+ \frac{C}{m} + |D_{q_j} F^{(m)}|, \end{aligned}$$

from where, we obtain

$$\begin{aligned} \sum_{j=1}^m m |D_{q_j} \partial_t U^{(m)}|^2 &\leq \sum_{j=1}^m \frac{1}{m} |D_q H(q_j, m D_{q_j} U^{(m)})|^2 + \sum_{j=1}^m \frac{1}{m} |D_p H(q_j, m D_{q_j} U^{(m)})|^2 \\ &+ C + \sum_{j=1}^m m |D_{q_j} F^{(m)}|^2 \leq C, \end{aligned}$$

where we used the assumption on  $F^{(m)}$ , (3.16) and the fact that since  $\mathcal{U} \in C_{\text{loc}}^{1,1}([0, T] \times \mathcal{P}_2(\mathbb{M}))$  and  $D_p H$  is Lipschitz, we have  $\sum_{j=1}^m \frac{1}{m} |D_p H(q_j, m D_{q_j} U^{(m)})|^2 \leq C$ . The claim follows, which concludes the proof of the theorem.  $\square$

**Lemma D.3.** Let  $[X \ Y]^\top = [X_1 \ \dots \ X_m \ Y_1 \ \dots \ Y_m]^\top \in \mathbb{R}^{2m}$  be the solution of the ODE system

$$(D.19) \quad \partial_t \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} + \begin{bmatrix} B_1 & B_2 \\ B_3 & B_4 \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}, \quad \begin{bmatrix} X(0) \\ Y(0) \end{bmatrix} = \begin{bmatrix} 0_m \\ Y_0 \end{bmatrix},$$

where  $A_1, A_2, Y_0 \in \mathbb{R}^m$ ,  $0_m \in \mathbb{R}^m$  is the zero vector and the  $(m \times m)$ -dimensional blocks  $B_i$  are such that

$$(D.20) \quad B_1 = B_4 = I_{m \times m}; \quad B_2 = mI_{m \times m} \quad \text{and} \quad B_3 = \begin{bmatrix} \frac{1}{m} & \frac{1}{m^2} & \dots & \frac{1}{m^2} \\ \frac{1}{m^2} & \frac{1}{m} & \dots & \frac{1}{m^2} \\ \dots & \dots & \ddots & \dots \\ \frac{1}{m^2} & \dots & \frac{1}{m^2} & \frac{1}{m} \end{bmatrix}.$$

Then there exists a constant  $C > 0$  (independent of  $m$ ), such that

(1) If for  $i_0 \in \{1, \dots, m\}$  fixed

$$(A_1)_{i_0} = 1, \quad (A_1)_i = \frac{1}{m}, \quad \forall i \neq i_0$$

and

$$(A_2)_{i_0} = (Y_0)_{i_0} = \frac{1}{m}, \quad (A_2)_i = (Y_0)_i = \frac{1}{m^2}, \quad \forall i \neq i_0,$$

then

$$|X_i(t)| \leq \begin{cases} e^{tC}, & i = i_0, \\ \frac{e^{tC}}{m}, & i \in \{1, \dots, m\}, i \neq i_0, \end{cases} \quad \text{and} \quad |Y_i(t)| \leq \begin{cases} \frac{e^{tC}}{m}, & i = i_0, \\ \frac{e^{tC}}{m^2}, & i \in \{1, \dots, m\}, i \neq i_0. \end{cases}$$

(2) If for some  $k, j \in \{1, \dots, m\}$  fixed,  $k \neq j$ , we have

$$(A_1)_j = (A_1)_k = \frac{1}{m}, \quad (A_1)_i = \frac{1}{m^2}, \quad \forall i \neq j, i \neq k$$

and

$$(A_2)_j = (A_2)_k = (Y_0)_j = (Y_0)_k = \frac{1}{m^2}, \quad (A_2)_i = (Y_0)_i = \frac{1}{m^3}, \quad \forall i \neq j, i \neq k$$

then

$$|X_i(t)| \leq \begin{cases} \frac{e^{tC}}{m}, & i = j, i = k, \\ \frac{e^{tC}}{m^2}, & i \in \{1, \dots, m\}, i \neq j, i \neq k \end{cases} \quad \text{and} \quad |Y_i(t)| \leq \begin{cases} \frac{e^{tC}}{m^2}, & i = j, i = k, \\ \frac{e^{tC}}{m^3}, & i \in \{1, \dots, m\}, i \neq j, i \neq k. \end{cases}$$

*Proof.* We analyse the representation formula for (D.19) in the different cases. Since we are only interested in the asymptotic properties of the solution with respect to  $m$ , first let us study the asymptotic behavior of the exponential and the inverse of the coefficient matrix.

Let  $B := \begin{bmatrix} B_1 & B_2 \\ B_3 & B_4 \end{bmatrix}$  and for  $n \in \mathbb{N}$ , let us denote the powers of  $B$  as  $B^n := \begin{bmatrix} B_{1,n} & B_{2,n} \\ B_{3,n} & B_{4,n} \end{bmatrix}$ .

*Claim.* We have the following properties for the blocks  $B_{i,n}$  for all  $n \in \mathbb{N}$  and for  $i, j \in \{1, \dots, m\}$

- (1)  $(B_{1,n})_{ii} \sim \text{const.}$ ,  $(B_{1,n})_{ij} \sim \frac{1}{m}$ , if  $i \neq j$ .
- (2)  $(B_{2,n})_{ii} \sim m$ ,  $(B_{2,n})_{ij} \sim \text{const.}$ , if  $i \neq j$ .
- (3)  $(B_{3,n})_{ii} \sim \frac{1}{m}$ ,  $(B_{3,n})_{ij} \sim \frac{1}{m^2}$ , if  $i \neq j$ .
- (4)  $(B_{4,n})_{ii} \sim \text{const.}$ ,  $(B_{4,n})_{ij} \sim \frac{1}{m}$ , if  $i \neq j$ .

*Proof of the Claim.* This follows from a mathematical induction argument in  $n$ .

Since we have a characterization of the asymptotic properties in terms of  $m$  of the elements of the powers  $n \in \mathbb{N}$  of the block matrix (which are uniform in  $n$ ), the property from the *Claim* will also hold true for the blocks of the matrix exponential of  $B$ . Setting  $A := [A_1^\top \ A_2^\top]^\top$ , the representation formula for the solutions of (D.19) reads as

$$\begin{bmatrix} X(t) \\ Y(t) \end{bmatrix} = \exp(tB) ([0_m^\top \ Y_0^\top]^\top + B^{-1}A) - B^{-1}A.$$

It remains to compute  $B^{-1}$  (which exists, since  $B$  is nonsingular), for which we have the formula (using the blocks from (D.20))

$$B^{-1} = \begin{bmatrix} (I_m - mB_3)^{-1} & -m(I_m - mB_3)^{-1} \\ -B_3(I_m - mB_3)^{-1} & I_m + mB_3(I_m - mB_3)^{-1} \end{bmatrix} = \begin{bmatrix} M & -mM \\ -B_3M & I_m + mB_3M \end{bmatrix},$$

where, we have used the notation

$$M := (I_m - mB_3)^{-1} = m \begin{bmatrix} 0 & -1 & \cdots & -1 \\ -1 & 0 & \cdots & -1 \\ \cdots & \cdots & \ddots & \cdots \\ -1 & \cdots & -1 & 0 \end{bmatrix}^{-1} = \begin{bmatrix} m \frac{m-2}{m-1} & \frac{-m}{m-1} & \cdots & \frac{-m}{m-1} \\ \frac{-m}{m-1} & m \frac{m-2}{m-1} & \cdots & \frac{-m}{m-1} \\ \cdots & \cdots & \ddots & \cdots \\ \frac{-m}{m-1} & \cdots & \frac{-m}{m-1} & m \frac{m-2}{m-1} \end{bmatrix}$$

Now, in the case of (1), we have that  $(B^{-1}A)_i = 0$ , if  $i \in \{1, \dots, m\}$ , and  $(B^{-1}A)_{m+i_0} = \frac{1}{m}$  and  $(B^{-1}A)_i = \frac{1}{m^2}$ , if  $i \in \{m+1, \dots, 2m\}$ ,  $i \neq m+i_0$ .

Furthermore, there exists a constant  $C > 0$  (independent of  $m$ ) such that

$$(\exp(tB)[0_m^\top Y_0^\top]^\top)_i \sim \begin{cases} e^{tC}, & i = i_0, \\ \frac{e^{tC}}{m}, & i \in \{1, \dots, m\}, i \neq i_0, \\ \frac{e^{tC}}{m}, & i = m + i_0, \\ \frac{e^{tC}}{m^2}, & i \in \{m+1, \dots, 2m\}, i \neq m + i_0. \end{cases}$$

(1) from the thesis of the lemma follows.

In the case on (2), we compute similarly  $(B^{-1}A)_i = 0$ , if  $i \in \{1, \dots, m\}$ ,  $(B^{-1}A)_i = \frac{1}{m^2}$  if  $i = m+j$  or  $j = m+k$  and  $(B^{-1}A)_i = \frac{1}{m^3}$  otherwise.

Furthermore, there exists a constant  $C > 0$  (independent of  $m$ ) such that

$$(\exp(tB)[0_m^\top Y_0^\top]^\top)_i \sim \begin{cases} \frac{e^{tC}}{m}, & i = j, i = k, \\ \frac{e^{tC}}{m^2}, & i \in \{1, \dots, m\}, i \neq j, i \neq k \\ \frac{e^{tC}}{m^2}, & i = m+j, i = m+k, \\ \frac{e^{tC}}{m^3}, & i \in \{m+1, \dots, 2m\}, i \neq m+j, i \neq m+k. \end{cases}$$

And finally, (2) from the thesis of the lemma follows.  $\square$

**Lemma D.4.** Let  $X = (X_{ij})_{i,j=1}^m$  and  $Y = (Y_{ij})_{i,j=1}^m$  be such that  $[X Y]^\top \in \mathbb{R}^{2m \times m}$  is the solution of the ODE system

$$(D.21) \quad \partial_t \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} B_1 & B_2 \\ B_3 & B_4 \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}, \quad \begin{bmatrix} X(0) \\ Y(0) \end{bmatrix} = \begin{bmatrix} I_m \\ Y_0 \end{bmatrix},$$

where  $Y_0 \in \mathbb{R}^{m \times m}$ , is set to  $Y_0 := B_3$  and the  $(m \times m)$ -dimensional blocks  $B_i$  are defined in (D.20). Then, there exists  $C > 0$  (independent of  $m$ ) such that

$$|X_{ij}(t)| \leq \begin{cases} e^{tC}, & i = j, \\ \frac{e^{tC}}{m}, & i \neq j, \end{cases} \quad \text{and} \quad |Y_{ij}(t)| \leq \begin{cases} \frac{e^{tC}}{m}, & i = j, \\ \frac{e^{tC}}{m^2}, & i \neq j. \end{cases}$$

*Proof.* This result is a consequence of the asymptotic behavior of the matrix exponential  $\exp(tB)$ , where  $B := \begin{bmatrix} B_1 & B_2 \\ B_3 & B_4 \end{bmatrix}$ . Using the asymptotic result from the *Claim* in Lemma D.3 and from the representation formula

$$(D.22) \quad \begin{bmatrix} X(t) \\ Y(t) \end{bmatrix} = \exp(tB)[I_m Y_0]^\top,$$

the result follows.  $\square$

## APPENDIX E. PROOFS OF THE RESULTS FROM SUBSECTION 4.2

*Proof of Proposition 4.3.* By construction we have  $u^{i,N}(0, q) = u_0^{i,N}(q)$ . Using the same arguments as in the proof of Lemma 3.21, we have that  $u^{i,N}$ ,  $i \in \{1, \dots, N\}$ , solve a system similar to (3.39), that is

(E.1)

$$\begin{aligned} \partial_t u^{i,N}(t, q) + D_{q_i} u^{i,N}(t, q) \cdot D_p H(q_i, (m+1)D_{q_i} U^{(m+1)}(t, q)) \\ + \sum_{j \neq i}^m D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, (m+1)D_{q_j} U^{(m+1)}(t, q)) \\ = L(q_i, D_p H(q_i, (m+1)D_{q_i} U^{(m+1)}(t, q))) + f^{i,N}(q), \end{aligned}$$

where as in the proof of Lemma 3.21  $U^{(m+1)}(t, q) = \mathcal{U}(t, \mu_q^{(m+1)})$  and  $\mathcal{U}$  is the unique classical solution to the Hamilton-Jacobi equation (3.1). Furthermore, as we see in that proof, also have

$$(m+1)D_{q_i} U^{(m+1)}(t, q) = \nabla_w \mathcal{U}(t, \mu_q^{(m+1)})(q_i) = D_{q_i} u(t, q_i, \mu_q^{(m+1)}).$$

By the definition of  $u^{i,N}$ , one has the identities

$$D_{q_i} u^{i,N}(t, q) = D_{q_i} u(t, q_i, \mu_q^{(m+1)}) + \frac{1}{m+1} \nabla_w u(t, q_i, \mu_q^{(m+1)})(q_i)$$

and

$$(E.2) \quad D_{q_j} u^{i,N}(t, q) = \frac{1}{m+1} \nabla_w u(t, q_i, \mu_q^{(m+1)})(q_j).$$

We further write

$$D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, (m+1)D_{q_j} U^{(m+1)}(t, q)) = D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, D_{q_j} u^{j,N}(t, q)) + r_j^{i,N}(t, q),$$

where

$$r_j^{i,N}(t, q) := D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, (m+1)D_{q_j} U^{(m+1)}(t, q)) - D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, D_{q_j} u^{j,N}(t, q))$$

By the Lipschitz continuity of  $D_p H$  we have that there exists a constant  $C > 0$  such that

$$|r_j^{i,N}(t, q)| \leq \frac{C}{m+1} |D_{q_j} u^{i,N}(t, q)| |\nabla_w u(t, q_j, \mu_q^{(m+1)})(q_j)|.$$

Similarly,

$$D_p H(q_i, (m+1)D_{q_i} U^{(m+1)}(t, q)) = D_p H(q_i, D_{q_i} u^{i,N}(t, q)) + \tilde{r}^{i,N}(t, q)$$

with

$$\tilde{r}^{i,N}(t, q) := D_p H(q_i, (m+1)D_{q_i} U^{(m+1)}(t, q)) - D_p H(q_i, D_{q_i} u^{i,N}(t, q))$$

and

$$|\tilde{r}^{i,N}(t, q)| \leq \frac{C}{m+1} |\nabla_w u(t, q_i, \mu_q^{(m+1)})(q_i)|.$$

So, we also have

$$\begin{aligned} L(q_i, D_p H(q_i, (m+1)D_{q_i} U^{(m+1)}(t, q))) &= L(q_i, D_p H(q_i, D_{q_i} u^{i,N}(t, q))) \\ &+ D_v L(q_i, D_p H(q_i, D_{q_i} u^{i,N}(t, q))) \cdot \tilde{r}^{i,N}(t, q) + \frac{1}{2} \tilde{r}^{i,N}(t, q) D_{vv}^2 L(q_i, \theta^{i,N}(t, q)) \tilde{r}^{i,N}(t, q) \\ &= L(q_i, D_p H(q_i, D_{q_i} u^{i,N}(t, q))) + D_{q_i} u^{i,N}(t, q) \cdot \tilde{r}^{i,N}(t, q) \\ &+ \frac{1}{2} \tilde{r}^{i,N}(t, q) D_{vv}^2 L(q_i, \theta^{i,N}(t, q)) \tilde{r}^{i,N}(t, q) \\ &= L(q_i, D_p H(q_i, D_{q_i} u^{i,N}(t, q))) + r_i^{i,N}(t, q) + \frac{1}{2} \tilde{r}^{i,N}(t, q) D_{vv}^2 L(q_i, \theta^{i,N}(t, q)) \tilde{r}^{i,N}(t, q), \end{aligned}$$

where  $\theta^{i,N}(t, q)$  is a point in the line segment connecting  $D_p H(q_i, (m+1)D_{q_i} U^{(m+1)}(t, q))$  and  $D_p H(q_i, D_{q_i} u^{i,N}(t, q))$ . Using the fact that  $D_{vv}^2 L$  is uniformly bounded, by setting

$$\hat{r}^{i,N}(t, q) := \frac{1}{2} \tilde{r}^{i,N}(t, q) D_{vv}^2 L(q_i, \theta^{i,N}(t, q)) \tilde{r}^{i,N}(t, q),$$

we have that there exists a constant  $C > 0$  such that

$$|\hat{r}^{i,N}(t, q)| \leq C |\tilde{r}^{i,N}(t, q)|^2 \leq \frac{C}{(m+1)^2} |\nabla_w u(t, q_i, \mu_q^{(m+1)})(q_i)|^2.$$

Having all the previous arguments, one can rewrite (E.1) as

$$\begin{aligned} \text{(E.3)} \quad & \partial_t u^{i,N}(t, q) + D_{q_i} u^{i,N}(t, q) \cdot D_p H(q_i, D_{q_i} u^{i,N}(t, q)) - L(q_i, D_p H(q_i, D_{q_i} u^{i,N}(t, q))) \\ & + \sum_{j \neq i}^m D_{q_j} u^{i,N}(t, q) \cdot D_p H(q_j, D_{q_j} u^{j,N}(t, q)) \\ & = f^{i,N}(q) + r^{i,N}(t, q), \end{aligned}$$

where we set  $r^{i,N} := \hat{r}^{i,N}(t, q) - \sum_{j \neq i} r_j^{i,N}(t, q)$ . Now, by (E.2) we observe that

$$\begin{aligned} |r^{i,N}(t, q)| & \leq \frac{C}{(m+1)^2} |\nabla_w u(t, q_i, \mu_q^{(m+1)})(q_i)|^2 + \frac{C}{(m+1)} \sum_{j \neq i} |D_{q_j} u^{i,N}(t, q)| |\nabla_w u(t, q_j, \mu_q^{(m+1)})(q_j)| \\ & = \frac{C}{(m+1)^2} |\nabla_w u(t, q_i, \mu_q^{(m+1)})(q_i)|^2 + \frac{C}{(m+1)^2} \sum_{j \neq i} |\nabla_w u(t, q_i, \mu_q^{(m+1)})(q_j)| |\nabla_w u(t, q_j, \mu_q^{(m+1)})(q_j)| \\ & \leq \frac{C}{(m+1)^2} \sum_{j=0}^m |\nabla_w u(t, q_j, \mu_q^{(m+1)})(q_j)|^2 + \frac{C}{(m+1)^2} \sum_{j=0}^m |\nabla_w u(t, q_i, \mu_q^{(m+1)})(q_j)|^2 \\ & = \frac{C}{m+1} \left( \int_{\mathbb{M}} |\nabla_w u(t, a, \mu_q^{(m+1)})(a)|^2 \mu_q^{(m+1)}(da) + \int_{\mathbb{M}} |\nabla_w u(t, q_i, \mu_q^{(m+1)})(a)|^2 \mu_q^{(m+1)}(da) \right) \end{aligned}$$

Since the map  $b \mapsto \int_{\mathbb{M}} |\nabla_w u(t, b, \mu)(a)|^2 \mu(da)$  is locally uniformly bounded for  $\mu \in \mathcal{B}_R$ , for any  $R > 0$  we have that

$$\int_{\mathbb{M}} |\nabla_w u(t, a, \mu)(a)|^2 \mu(da) \leq \int_{\mathbb{M}} \sup_{b \in B_R(0)} |\nabla_w u(t, b, \mu)(a)|^2 \mu(da).$$

Thus, we have (4.5) and so the thesis follows.  $\square$

*Proof of Proposition 4.4.* First, let us notice that by the assumption that  $D_{q_i} v^{i,N} \in C^{0,1}([0, T] \times \mathbb{M}^N)$  uniformly with respect to  $N$ , we have that there exists  $\beta = \beta(R, T) > 0$  such that  $q(t) \in B_\beta(0)^N$ , for all  $t \in [0, T]$ ,  $N \in \mathbb{N}$  and  $\hat{q} \in B_R(0)^N$ . Similarly, by the by the assumptions on  $D_p H$  and by the regularity of  $D_{q_0} u$ ,  $Q(t) \in B_\beta(0)^N$ , for all  $t \in [0, T]$ ,  $N \in \mathbb{N}$  and  $\hat{q} \in B_R(0)^N$ .

We closely follow the steps of the proof of Theorem 4.2. from [18].

Using the Lipschitz continuity of  $D_p H$  and the Lipschitz continuity of  $D_{q_0} u$  on  $[0, T] \times B_\beta(0) \times \mathcal{B}_\beta$ , we obtain

$$\begin{aligned} |q_i(s) - Q_i(s)|^2 & \leq \int_s^t |q_i(\tau) - Q_i(\tau)|^2 d\tau \\ & + \int_s^t |D_p H(q_i(\tau), D_{q_i} v^{i,N}(\tau, q(\tau))) - D_p H(Q_i(\tau), D_{q_0} u(\tau, Q_i(\tau), \mu_{Q(\tau)}^{(m+1)}))|^2 d\tau \\ & \leq C \int_s^t |q_i(\tau) - Q_i(\tau)|^2 d\tau + C \int_s^t |D_{q_i} v^{i,N}(\tau, q(\tau)) - D_{q_0} u(\tau, q_i(\tau), \mu_{q(\tau)}^{(m+1)})|^2 d\tau \\ & + C \int_s^t W_2^2(\mu_{q(\tau)}^{(m+1)}, \mu_{Q(\tau)}^{(m+1)}) d\tau \end{aligned}$$

Grönwall's inequality yields

$$|q_i(s) - Q_i(s)|^2 \leq C \int_s^t |D_{q_i} v^{i,N}(\tau, q(\tau)) - D_{q_0} u(\tau, q_i(\tau), \mu_{q(\tau)}^{(m+1)})|^2 d\tau + C \int_s^t W_2^2(\mu_{q(\tau)}^{(m+1)}, \mu_{Q(\tau)}^{(m+1)}) d\tau.$$

Since

$$W_2^2(\mu_{q(\tau)}^{(m+1)}, \mu_{Q(\tau)}^{(m+1)}) \leq \sum_{j=0}^m \frac{1}{(m+1)} |q_j(\tau) - Q_j(\tau)|^2,$$

applying again Grönwall's inequality one has

$$(E.4) \quad W_2^2(\mu_{q(s)}^{(m+1)}, \mu_{Q(s)}^{(m+1)}) \leq \frac{C}{m+1} \sum_{j=0}^m \int_s^t |D_{q_j} v^{j,N}(\tau, q(\tau)) - D_{q_0} u(\tau, q_j(\tau), \mu_{q(\tau)}^{(m+1)})|^2 d\tau.$$

Using Proposition 4.3, the fact that both  $D_{q_0} u(\cdot, \cdot, \mu_{q(\cdot)}^{(N)})$  and  $\nabla_w u(\cdot, \cdot, \mu_{q(\cdot)}^{(N)})(\cdot)$  are uniformly bounded on  $[0, T] \times B_\beta(0)$  and on  $[0, T] \times B_\beta(0) \times B_\beta(0)$ , following the exact same lines of arguments as the one of Theorem 4.2 from [18] we obtain

$$\sum_{j=0}^{N-1} \int_0^T |D_{q_j} v^{j,N}(\tau, q(\tau)) - D_{q_0} u(\tau, q_j(\tau), \mu_{q(\tau)}^{(N)})|^2 d\tau \leq \frac{C}{N}.$$

This, together with (E.4) yields the desired inequality.  $\square$

*Proof of Corollary 4.5.* Since we are in the setting of Proposition 4.4, we have that there exists a constant  $C = C(R, T) > 0$  such that

$$W_2(\mu_{Q(s)}^{(N)}, \mu_{q(s)}^{(N)}) \leq \frac{C}{N}.$$

Then, Lemma 3.3(ii) implies that there exists a constant  $C = C(T, R, r) > 0$  such that

$$W_2(\mu_{q(s)}^{(N)}, \sigma_s) \leq e^{C(t-s)} W_2(\mu_{\hat{q}}^{(N)}, \mu).$$

By the triangle inequality

$$W_2(\mu_{q(s)}^{(N)}, \sigma_s) \leq W_2(\mu_{q(s)}^{(N)}, \mu_{Q(s)}^{(N)}) + W_2(\mu_{Q(s)}^{(N)}, \sigma_s)$$

and so the result follows.  $\square$

## REFERENCES

- [1] D. AMBROSE, *Existence theory for non-separable mean field games in Sobolev spaces*, ArXiv:1807.02223
- [2] D. AMBROSE, *Existence theory for a time-dependent mean field games model of household wealth*, Appl. Math. Optim., to appear.
- [3] L. AMBROSIO, W. GANGBO, *Hamiltonian ODEs in the Wasserstein space of probability measures*, Comm. Pure Appl. Math. 61 (2008), no. 1, 18–53.
- [4] L. AMBROSIO, N. GIGLI, G. SAVARÉ, *Gradient flows in metric spaces and the Wasserstein spaces of probability measures*, *Lectures in Mathematics*, ETH Zürich, Birkhäuser, 2008.
- [5] A. BENSOUSSAN, P. J. GRABER, S.C.P. YAM, *Stochastic Control on Space of Random Variables*, arXiv:1903.12602.
- [6] A. BENSOUSSAN, S.C.P. YAM, *Control problem on space of random variables and master equation*, ESAIM Control Optim. Calc. Var. 25 (2019), Art. 10, 36 pp.
- [7] P. CANNARSA, C. SINISTRARI, *Semiconcave Functions, Hamilton–Jacobi Equations and Optimal Control*, Progress in Nonlinear Differential Equations and their Applications, 58. Birkhäuser Boston, Boston, MA, 2004. xiv+304 pp.
- [8] P. CARDALIAGUET, *Notes on Mean-Field Games*, lectures by P.L. Lions, Collège de France, 2010.
- [9] P. CARDALIAGUET, F. DELARUE, J.-M. LASRY, P.-L. LIONS, *The master equation and the convergence problem in mean field games*, Annals of Mathematics Studies, 201. Princeton University Press, Princeton, NJ, 2019. x+212 pp.
- [10] R. CARMONA, F. DELARUE, *Probabilistic theory of mean field games with applications. I. Mean field FBSDEs, control, and games.*, Probability Theory and Stochastic Modelling, 83. Springer, Cham, 2018. xxv+713 pp.
- [11] R. CARMONA, F. DELARUE, *Probabilistic theory of mean field games with applications. II. Mean field games with common noise and master equations.*, Probability Theory and Stochastic Modelling, 84. Springer, Cham, 2018. xxiv+697 pp.
- [12] F. W. CARROLL, *A polynomial in each variable separately is a polynomial*, Amer. Math. Monthly 68 (1961), 42.
- [13] J.-F. CHASSAGNEUX, D. CRISAN, F. DELARUE, *A probabilistic approach to classical solutions of the master equation for large population equilibria*, Mem. Amer. Math. Soc., to appear.

- [14] J.-F. CHASSAGNEUX, L. SZPRUCH, A. TSE, *Weak quantitative propagation of chaos via differential calculus on the space of measures*, arXiv:1901.02556
- [15] Y.T. CHOW, W. GANGBO, *A partial Laplacian as an infinitesimal generator on the Wasserstein space*, J. Differential Equations 267 (2019), no. 10, 6065–6117.
- [16] M.G. CRANDALL, P.-L. LIONS, *Hamilton-Jacobi Equations in Infinite Dimensions I. Uniqueness of Viscosity Solutions*, J. Funct. Anal. 62 (1985), 379–396.
- [17] M.G. CRANDALL, P.-L. LIONS, *Hamilton-Jacobi equations in infinite dimensions II. Existence of viscosity solutions*, J. Funct. Anal. 65 (1986), 368–405.
- [18] F. DELARUE, D. LACKER, K. RAMANAN, *From the master equation to mean field game limit theory: a central limit theorem*, Electron. J. Probab. 24 (2019), Paper No. 51, 54 pp.
- [19] F. DELARUE, D. LACKER, K. RAMANAN, *From the master equation to mean field game limit theory: large deviations and concentration of measure*, Annals of Probability, to appear.
- [20] A. FATHI, *Weak KAM Theorem in Lagrangian Dynamics*, (preprint), to appear in Cambridge Studies in Advanced Mathematics.
- [21] M. FISCHER, F. SILVA, *On the asymptotic nature of first order mean field games*, arXiv:1903.03602.
- [22] W. GANGBO, T. NGUYEN, A. TUDORASCU, *Hamilton-Jacobi equations in the Wasserstein space*, Meth. Appl. Anal. 15, no. 2 (2008), pp. 155–184.
- [23] W. GANGBO, A. SWIECH, *Optimal transport and large number of particles*, Discrete and Continuous Dynamical System (2014) Vol 34, Issue 4, 1397–1441.
- [24] W. GANGBO, A. SWIECH, *Existence of a solution to an equation arising from the theory of Mean Field Games*, Journal of Differential Equations (2015) Vol 259, Issue 11, 6573–6643.
- [25] W. GANGBO, A. TUDORASCU, *On differentiability in the Wasserstein space and well-posedness for Hamilton-Jacobi equations*, Journal de Mathématiques Pures et Appliquées, Vol 125, 119–174, 2018.
- [26] D. GOMES, L. NURBEKYAN, *On the minimizers of calculus of variations problems in Hilbert spaces*, Calculus of Variations and Partial Differential Equations, Vol 52, Issue 1–2, 65–93
- [27] J. M. LASRY AND P.-L. LIONS, *Jeux à champ moyen. II. Le cas stationnaire*, C. R. Math. Acad. Sci. Paris 343 (2006), no. 9, 619–625.
- [28] J. M. LASRY AND P.-L. LIONS, *Jeux à champ moyen. II. Horizon fini et contrôle optimal*, C. R. Math. Acad. Sci. Paris 343 (2006), no. 10, 679–684.
- [29] J.-M. LASRY AND P.-L. LIONS, *Mean field games*, Jpn. J. Math. 2 (2007), 229–260.
- [30] J. M. LASRY AND P.-L. LIONS, *Large investor trading impacts on volatility*, Ann. Inst. H. Poincaré Anal. Non Linéaire 24 (2007), no. 2, 311–323.
- [31] P.-L. LIONS, *Lectures at Collège de France*, 2007–2013.
- [32] R. McCANN, *A Convexity Principle for Interacting Gases*, Advances in Mathematics, Vol 128, no 2 (1997), 153–179.
- [33] S. MAYORGA, *Short time solution to the master equation of a first order mean field game system*, arXiv:1811.08964.
- [34] S. MISCHLER, C. MOUHOT, *Kac’s program in kinetic theory*, Invent. Math., 193 (2013), no. 1, 1–147.
- [35] C. MOU, J. ZHANG, *Weak Solutions of Mean Field Game Master Equations*, arXiv:1903.09907.
- [36] F. SANTAMBROGIO, *Optimal transport for applied mathematicians., Calculus of variations, PDEs, and modeling. Progress in Nonlinear Differential Equations and their Applications*, 87. Birkhäuser/Springer, Cham, 2015, xxvii+353 pp.

DEPARTMENT OF MATHEMATICS, UCLA, CALIFORNIA, USA  
 Email address: [wgangbo@math.ucla.edu](mailto:wgangbo@math.ucla.edu)

DEPARTMENT OF MATHEMATICAL SCIENCES, UNIVERSITY OF DURHAM, DURHAM DH1 3LE, ENGLAND  
 Email address: [alpar.r.meszáros@durham.ac.uk](mailto:alpar.r.meszáros@durham.ac.uk)