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Weakly non-collapsed RCD spaces are strongly non-collapsed

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Abstract

We prove that any weakly non-collapsed RCD space is actually non-collapsed, up to a renormalization of the measure. This confirms a conjecture raised by De Philippis and the second named author in full generality.

One of the auxiliary results of independent interest that we obtain is about the link between the properties

- $\text{tr}(\text{Hess}f) = \Delta f$ on $U \subseteq X$ for every f sufficiently regular,

- $\mathfrak{m} = c\mathcal{H}^n$ on $U \subseteq X$ for some $c > 0$,

where $U \subseteq X$ is open and X is a - possibly collapsed - RCD space of essential dimension n .

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1 Introduction

1.1 Main result and some comments

The modern theory of metric measure spaces with Ricci curvature bounded from below began with the seminal papers [52], [59, 60], where lower bounds on the Ricci curvature were imposed via suitable convexity properties of entropy functionals in the geometry of optimal transportation. It turned out that the resulting class $\text{CD}(K, N)$ of spaces contains smooth Finslerian structures,

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a property that - at least for some geometric applications - is undesirable. This was one of the motivations that led the second named author develop a research program about heat flow on CD spaces (see [28], [33], [3], [4]) that ultimately led in [31] to the definition of RCD spaces as those CD spaces for which the Sobolev space $W^{1,2}$ is Hilbert. We refer to [61], [1] for an account of the theory and more detailed bibliography.

The study of (R)CD spaces has been strongly influenced by the research program carried out in the late nineties by Cheeger-Colding (see [19, 20, 21, 22]) about the structure of Ricci-limit spaces, i.e. those spaces arising as Gromov-Hausdorff limits of smooth Riemannian manifolds with constant dimension and a uniform lower bound on the Ricci curvature. One of the things that emerged by their analysis (strictly related to Colding's volume convergence theorem [23]) is that the dimension of the limit space is always bounded from above by the dimension of the manifolds, and that if equality holds, then the limit structure - that in this case is called *non-collapsed Ricci limit space* - has better regularity properties.

It is therefore natural to look for a synthetic counterpart of this concept, whose definition should not rely on properties of approximating sequences, but rather be based on intrinsic properties of the space in consideration. Inspecting the properties of non-collapsed Ricci limit spaces, in [24] it has been proposed the following definition:

Definition 1.1. Let $K \in \mathbb{R}$ and $N \in [1, \infty)$. A space (X, d, m) is called *non-collapsed RCD*(K, N) space, $\text{ncRCD}(K, N)$ in short, if it is an $\text{RCD}(K, N)$ space and moreover $m = \mathcal{H}^N$.

Notice that from the structural properties of RCD spaces ([53], [49], [35]) it is clear that if (X, d, m) is $\text{ncRCD}(K, N)$, then N must be an integer. Also, subsequent analysis showed that, as expected, ncRCD spaces have better regularity properties than arbitrary RCD spaces (see for instance [13]).

The analysis carried out by Cheeger-Colding and the analogy with the study of the Bakry-Émery N -Ricci curvature tensor (see (1.3) and the subsequent discussion) suggest that in fact $\text{ncRCD}(K, N)$ spaces should be identifiable among $\text{RCD}(K, N)$ ones by properties seemingly weaker than the one $m = \mathcal{H}^N$. To be more precise we need to introduce the N -dimensional (Bishop-Gromov) density $\theta_N[X, d, m] : X \rightarrow [0, \infty]$ as

$$\theta_N[X, d, m](x) := \lim_{r \rightarrow 0^+} \frac{m(B_r(x))}{\omega_N r^N} \quad \forall x \in X,$$

where $\omega_N := \frac{\pi^{N/2}}{\int_0^\infty t^{N/2} e^{-t} dt}$ is, for $N \in \mathbb{N}$, the volume of the unit ball of \mathbb{R}^N (notice that the existence of the limit is a consequence of the Bishop-Gromov inequality). It is worth pointing out that standard results about differentiation of measures ensure that if \mathcal{H}^N is a Radon measure on X , then

$$\limsup_{r \rightarrow 0^+} \frac{\mathcal{H}^N(B_r(x))}{\omega_N r^N} \leq 1 \quad \text{for } \mathcal{H}^N\text{-a.e. } x \in X.$$

In particular, if X is a $\text{ncRCD}(K, N)$ space we have

$$\theta_N[X, d, m](x) \leq 1 \quad \forall x \in X. \quad (1.1)$$

Then the following conjecture is raised in [24]:

Conjecture 1.2 (De Philippis-Gigli). *If*

$$m(\{x \in X : \theta_N[X, d, m](x) < \infty\}) > 0, \quad (1.2)$$

then $m = c\mathcal{H}^N$ for some $c \in (0, \infty)$. In particular $(X, d, c^{-1}m)$ is a $\text{ncRCD}(K, N)$ space.

Let us make few comments about the statement of the conjecture and its validity.

First of all, we remark that condition (1.2) cannot be replaced by the weaker one

$$\{x \in X : \theta_N[X, d, m](x) < \infty\} \neq \emptyset$$

because for instance the metric measure space $([0, \pi], d_{\mathbb{R}}, \sin^{N-1} t dt)$ is an $\text{RCD}(N-1, N)$ space, the density θ_N is finite on $\{0, \pi\}$ which is null with respect to the reference measure $\sin^{N-1} t dt$, and for any $N > 1$, $\sin^{N-1} t dt$ does not coincide with $c\mathcal{H}^N$ for any $c \in (0, \infty)$.

Moreover let us point out that the Hausdorff dimension of any $\text{CD}(K, N)$ space \mathbf{X} is at most N [60]. In this sense, the assumption in Conjecture 1.2 amounts at asking for the existence of a ‘big’ portion of the space with maximal dimension (notice for instance that if $\mathbf{m} \ll \mathcal{H}^\alpha$ for some $\alpha < N$, then $\theta_N = +\infty$ \mathbf{m} -a.e.). Such ‘maximality’ of N in the conjecture plays an important role. To see why, consider an n -dimensional weighted Riemannian manifold $(M, g, e^{-V} d\text{Vol}_g)$, where $V \in C^\infty(M)$ and Vol_g denotes the Riemannian volume measure and recall that for $N \geq 1$ the Bakry-Émery N -Ricci curvature tensor is defined as

$$\text{Ric}_N := \begin{cases} \text{Ric}_g + \text{Hess}_g(V) - \frac{dV \otimes dV}{N-n} & \text{if } N > n, \\ \text{Ric}_g & \text{if } N = n \text{ and } V \text{ is constant,} \\ -\infty & \text{otherwise,} \end{cases} \quad (1.3)$$

where Ric_g is the standard Ricci curvature induced by the metric tensor g and defined as trace of the Riemann curvature tensor. It is then known (see [14], [5], [27]) that

$$(M, d_g, e^{-V} \text{Vol}_g) \text{ is an } \text{RCD}(K, N) \text{ space if and only if } \text{Ric}_N \geq Kg. \quad (1.4)$$

On the other hand, it is clear that $(e^{-V} \text{Vol}_g)(B_r(x)) \sim r^n$ for every $x \in M$ as $r \rightarrow 0^+$, thus assumption (1.2) holds if and only if $n = N$, and this information together with $\text{Ric}_N \geq Kg$ forces V to be constant by the very definition of Ric_N .

It is now time to point out that thanks to the main result of [17] - and the aforementioned structural properties - we now know that any $\text{RCD}(K, N)$ space $(\mathbf{X}, d, \mathbf{m})$ admits an *essential dimension* $n \in \mathbb{N} \cap [1, N]$, meaning in particular that $\mathbf{m} \ll \mathcal{H}^n \ll \mathbf{m}$ on the Borel set \mathcal{R}_n^* (see (2.17) below), where $\mathbf{m}(\mathbf{X} \setminus \mathcal{R}_n^*) = 0$. We thus see from general results about differentiation of measures that

$$\text{if (1.2) holds, then we have } \theta_N[\mathbf{X}, d, \mathbf{m}] < \infty \quad \mathbf{m}\text{-a.e.} \quad (1.5)$$

$\text{RCD}(K, N)$ spaces for which $\theta_N[\mathbf{X}, d, \mathbf{m}]$ is finite \mathbf{m} -a.e. have been called *weakly non-collapsed* RCD spaces in [24], while spaces such that $\theta_N[\mathbf{X}, d, \mathbf{m}]$ is finite for *every* point have been called ‘non-collapsed’ in [50]. It is then clear from (1.1) that

$$\text{non-collapsed} \implies \text{non-collapsed in the sense of [50]} \implies \text{weakly non-collapsed}$$

and from (1.5) that proving Conjecture 1.2 is equivalent to proving that these three ‘non-collapsing conditions’ are equivalent (up to multiplying the reference measure by a scalar).

It is known that the conjecture holds true in the following three cases:

1. (\mathbf{X}, d) has an upper bound on sectional curvature in a synthetic sense, namely, it is a $\text{CAT}(\kappa)$ space for some $\kappa > 0$: [47]
2. (\mathbf{X}, d) is isometric to a smooth Riemannian manifold, possibly with boundary: [39].
3. (\mathbf{X}, d) is compact: [42].

Our main result is the resolution of Conjecture 1.2 in full generality:

Theorem 1.3. *Conjecture 1.2 holds true.*

Notice that as a consequence of our main result, we obtain that if the Hausdorff dimension of an $\text{RCD}(K, N)$ space is N , then also its topological dimension is N (we refer to [54] for the relevant definitions). Indeed, under this assumption Theorem 2.20 and our main result imply that the space is, up to a scalar multiple of the reference measure, a $\text{ncRCD}(K, N)$ space. Then from the Reifenberg flatness around a regular point (see [20] and then [24], [48]) we see that any regular point has a neighbourhood which is homeomorphic to \mathbb{R}^N . This proves that the topological dimension is at least N and since in general this is at most the Hausdorff one (see e.g. [40, Theorem 8.14]), our claim is proved.

1.2 Strategy of the proof

The basic strategy we adopt in proving this theorem is the one introduced by the third named author in [42] to handle the compact case. Still, moving from compact to non-compact creates additional technical complications that must be handled: one of the things we do here is to replace the approximation of the heat kernel via eigenfunctions - used in [42] - with suitable decay estimates based on Gaussian bounds. Also, in the course of the proof we obtain (by making explicit some ideas that were implicitly used in [42]) interesting intermediate results that are new even in the smooth context, see in particular formula (1.13). Finally, on general RCD spaces X of essential dimension n and $U \subseteq \mathsf{X}$ open we establish relevant links between the properties

- $\mathrm{tr}(\mathrm{Hess}f) = \Delta f$ on $U \subseteq \mathsf{X}$ for every f sufficiently regular,
- $\mathfrak{m} = c\mathcal{H}^n$ on $U \subseteq \mathsf{X}$ for some $c > 0$,

see Theorem 1.5 below for the precise statement.

With this said, let us describe the main idea by having once again a look at the case of a weighted n -dimensional Riemannian manifold $(M, g, e^{-V} \mathrm{dVol}_g)$. Let us consider the reference measure $\mathfrak{m} := e^{-V} \mathrm{Vol}_g$ and the Hausdorff measure $\mathcal{H}^n = \mathrm{Vol}_g$. Assume that $\mathrm{Ric}_N \geq Kg$ for some $K \in \mathbb{R}$ and some $N \in [n, \infty)$ (namely $(M, \mathbf{d}_g, \mathfrak{m})$ is an $\mathrm{RCD}(K, N)$ space, recall (1.3) and (1.4)). Now notice that the following integration by parts formulas hold: for every $f, \varphi \in C_c^\infty(M)$ we have

$$-\int_M \langle \mathrm{d}f, \mathrm{d}\varphi \rangle \mathrm{d}\mathfrak{m} = \int_M \varphi \Delta f \mathrm{d}\mathfrak{m}, \quad (1.6a)$$

$$-\int_M \langle \mathrm{d}f, \mathrm{d}\varphi \rangle \mathrm{d}\mathcal{H}^n = \int_M \varphi \mathrm{tr}(\mathrm{Hess}f) \mathrm{d}\mathcal{H}^n. \quad (1.6b)$$

From these identities it is easy to conclude that

$$\mathfrak{m} = c\mathcal{H}^n \quad \Leftrightarrow \quad \mathrm{tr}(\mathrm{Hess}f) = \Delta f \quad \forall f \in C_c^\infty(M). \quad (1.7)$$

Thus recalling (1.5) we see that the desired result will follow if we can show that

$$\theta_N[M, \mathbf{d}_g, \mathfrak{m}] < \infty \text{ a.e. implies that } \mathrm{tr}(\mathrm{Hess}f) = \Delta f \text{ for any smooth function } f.$$

To see this recall that, as already noticed, having $\theta_N[M, \mathbf{d}_g, \mathfrak{m}](x) < \infty$ for some point $x \in M$ implies that M is N -dimensional (and thus in particular that N is an integer), then recall (1.4) and the definition (1.3) of the N -Ricci curvature tensor.

This establishes the claim in the smooth setting. In the general case we follow the same general ideas, but we have to deal with severe technical complications. Start observing that the analogue of (1.6a) holds in general RCD spaces by the very definition of Δ (see [31]) and that the line below (1.7) is known. Thus to conclude along the lines above it is sufficient to prove that (1.6b) holds on $\mathrm{RCD}(K, N)$ spaces of essential dimension n . We do not have exactly such result, but have instead the following result which is anyway sufficient to conclude:

Theorem 1.4. *Let $(\mathsf{X}, \mathbf{d}, \mathfrak{m})$ be an $\mathrm{RCD}(K, N)$ space of essential dimension n . Let $U \subseteq \mathsf{X}$ be bounded open and assume that*

$$\inf_{r \in (0,1), x \in U} \frac{\mathfrak{m}(B_r(x))}{r^n} > 0. \quad (1.8)$$

Then for every $\varphi \in \mathrm{Lip}(\mathsf{X}, \mathbf{d})$, $f \in D(\Delta)$ with $\mathrm{supp}(\varphi), \mathrm{supp}(f) \subseteq U$ formula (1.6b) holds.

See Theorem 4.1 for a slightly sharper statement. Notice also that by the Bishop-Gromov inequality, assumption (1.8) holds trivially with $n = N$ for any bounded subset U of a weakly non-collapsed RCD space. Also, the statement above is interesting regardless of the application we just described, and valid also in possibly ‘collapsed’ RCD spaces.

Thus everything boils down to the proof of such result, and indeed from both the technical and conceptual perspective this is the most important part of our paper. The basic idea for the proof is

to perform a smoothing of the metric tensor via heat flow. Let us describe the procedure, introduced in [15], in the smooth setting. Consider a compact smooth Riemannian manifold (M, g, dVol_g) and, for every $t > 0$, let $\Phi_t : M \rightarrow L^2(M, \text{Vol}_g)$ be defined as

$$\Phi_t(x) := (y \mapsto p(x, y, t)),$$

where p is the heat kernel. We can use this map to pull-back the flat metric g_{L^2} of $L^2(M, \text{Vol}_g)$ and obtain the metric tensor $g_t := \Phi_t^* g_{L^2}$ that is explicitly given by

$$g_t = \int_M \text{d}p(\cdot, y, t) \otimes \text{d}p(\cdot, y, t) \text{dVol}_g(y) \in C^\infty((T^*)^{\otimes 2} M). \quad (1.9)$$

The interesting fact is that, after appropriate rescaling, the tensors g_t converge to the original one g . More precisely, we have

$$\|4(8\pi)^{n/2} t^{(n+2)/2} g_t - g\|_{L^\infty} \rightarrow 0 \quad \text{as } t \rightarrow 0^+, \quad (1.10)$$

where n denotes the dimension of M . In fact in [15] more is proved, as it is provided the first order Taylor expansion of $t^{(n+2)/2} g_t$, but this is not relevant for our application. A way to read this convergence is via the stability of the heat flow under measured-Gromov-Hausdorff convergence of spaces with Ricci curvature uniformly bounded from below; this observation is more recent than [15], as it has been made by the second author in [28], still, this is the argument used in the RCD setting so let us present this viewpoint. It is clear that for $M = \mathbb{R}^n$ the tensor g_t is just a rescaling of the Euclidean tensor. On the other hand, denoting by M^λ the manifold M equipped with the rescaled metric tensor λg , and by p^λ the associated heat kernel, it is also clear that $p(x, y, t) = p^\lambda(x, y, \lambda^{-1}t)$. Thus the asymptotics of $p(x, y, t)$ as $t \rightarrow 0^+$ corresponds to that of $p^\lambda(x, y, 1)$ as $\lambda \rightarrow \infty$ and, as said, these kernels converge to the Euclidean ones where the evolution of the metric tensors g_t is trivial.

Coming back to the RCD setting, we recall that the heat kernel is well-defined in this context [4], and a differential calculus is available in this framework [30]. Thus the same definition as in (1.9) can be given and one can wonder whether the same convergence result as in (1.10) holds. Interestingly, in this case one has

$$\|t \mathbf{m}(B_{\sqrt{t}}(\cdot)) g_t - c_n g\|_{L^p_{loc}} \rightarrow 0 \quad \text{as } t \rightarrow 0^+, \quad \forall p \in [1, \infty) \quad (1.11)$$

for some constant c_n depending only on the essential dimension of \mathbf{X} (this has been proved in [8] for compact $\text{RCD}(K, N)$ spaces, and is generalized here to the non-compact setting). Notice that the loss from convergence in L^∞ to convergence in L^p_{loc} is unavoidable, but unarmful for our purposes. It is important to remark that the factor in front of g_t is now not constant anymore: this has to do with Gaussian gradient estimates for the heat kernel. Now let $U \subseteq \mathbf{X}$ be open bounded and assume that \mathcal{H}^n is a Radon measure on U (this is always the case if (1.8) holds). In this case by standard results about differentiations of measures we have

$$\lim_{t \rightarrow 0^+} \frac{t \mathbf{m}(B_{\sqrt{t}}(\cdot))}{t^{\frac{n+2}{2}}} = c'_n \frac{\text{d}\mathbf{m}}{\text{d}\mathcal{H}^n} \quad \text{m-a.e. on } U.$$

Thus if (1.8) holds, from (1.11) we deduce that

$$\|t^{\frac{n+2}{2}} g_t - c''_n \frac{\text{d}\mathcal{H}^n}{\text{d}\mathbf{m}} g\|_{L^p(U)} \rightarrow 0 \quad \text{as } t \rightarrow 0^+. \quad (1.12)$$

We couple this information with the following explicit computation of the adjoint ∇^* of the covariant derivative of g_t :

$$\nabla^* g_t(x) = -\frac{1}{4} \text{d}_x \Delta_x p(x, x, 2t). \quad (1.13)$$

This formula was obtained in [42] in the compact setting by expanding the heat kernel via eigenfunctions of the Laplacian. This approach does not work in our current framework and we will rather proceed via a somehow more direct approach based on ‘local’ Bochner integration (see Section 3.1).

We are almost done: by explicit computations based on Gaussian estimates one can see that

$$t^{\frac{n+2}{2}} d_x \Delta_x p(x, x, 2t) \rightarrow 0 \quad \text{as } t \rightarrow 0^+$$

in a suitable sense, thus coupling this information with (1.13), (1.12) and the closure of ∇^* we conclude that

$$\nabla^* \left(\frac{d\mathcal{H}^n}{d\mathbf{m}} g \right) = 0 \quad \text{in } U.$$

This latter equation is a restatement of (1.6b) for f, φ with support in U , i.e. this argument gives Theorem 1.4, as desired.

We conclude emphasizing that our proof also yields the following result, which is of independent interest and will play a prominent role in the proof of Theorem 1.3.

Theorem 1.5. *Let (X, d, \mathbf{m}) be an $\text{RCD}(K, N)$ space of essential dimension n , and let U be a connected open subset of X with*

$$\inf_{r \in (0,1), x \in A} \frac{\mathbf{m}(B_r(x))}{r^n} > 0 \quad (1.14)$$

for any compact subset $A \subseteq U$. Then the following two conditions are equivalent:

1. for every $f \in D(\Delta)$,

$$\Delta f = \text{tr}(\text{Hess} f) \quad \mathbf{m}\text{-a.e. on } U;$$

2. for some $c \in (0, \infty)$,

$$\mathbf{m} \llcorner U = c\mathcal{H}^n \llcorner U.$$

Notice that this has nothing to do with non-collapsing properties and, in particular, it can very well be that the assumption (1.14) holds for $U = X$. Moreover items 1 and 2 may hold only on some $U \subsetneq X$: just consider the case of a weighted Riemannian manifold as before with V constant on U but non-constant outside U .

1.3 Applications

The following applications seem to be already known to experts if Theorem 1.3 is established (for instance [48] and [43]). However for readers' convenience let us give them precisely. Roughly speaking, they are based on a fact that the space of weakly non-collapsed spaces is open in the space of $\text{RCD}(K, N)$ spaces because of the lower semicontinuity of the essential dimensions with respect to pointed measured Gromov-Hausdorff convergence proved in [51] (Theorem 2.16).

It is known that pointed Gromov-Hausdorff (pGH) and pointed measured Gromov-Hausdorff (pmGH) convergences are metrizable (see for instance in [34]). Thus 'ε-pGH close' and 'ε-pmGH close' make sense as appeared in the following theorem. Note that as the sequential compactness of $\text{RCD}(K, N)$ spaces is known (Theorem 2.8), any such metric determines the same compact topology.

The first application is stated as follows.

Theorem 1.6. *For any $K \in \mathbb{R}$, any $N \in \mathbb{N}$, any $\delta \in (0, \infty)$ and any $v \in (0, \infty)$, there exists $\epsilon := \epsilon(K, N, \delta, v) \in (0, 1)$ such that if a pointed $\text{RCD}(K, N)$ space (X, d, \mathbf{m}, x) is so that (X, d, x) is ε-pGH close to (Y, d_Y, y) for some non-collapsed $\text{RCD}(K, N)$ space (Y, d_Y, \mathcal{H}^N) with*

$$\mathcal{H}^N(B_1(y)) \geq v, \quad (1.15)$$

then we have $\mathbf{m} = c\mathcal{H}^N$ for some $c \in (0, \infty)$, and moreover $|\mathcal{H}^N(B_1(x)) - \mathcal{H}^N(B_1(y))| < \delta$.

Next application shows that the non-collapsed condition can be recognized from the point of an infinitesimal view.

Theorem 1.7. *Let (X, d, \mathbf{m}) be an $\text{RCD}(K, N)$ space. If the essential dimension of some tangent cone $(Y, d_Y, \mathbf{m}_Y, y)$ at some point $x \in X$ is equal to N , then $\mathbf{m} = c\mathcal{H}^N$ for some $c \in (0, \infty)$.*

Note that the converse implication also holds in Theorem 1.7, namely if (X, d, \mathcal{H}^N) is a non-collapsed $\text{RCD}(K, N)$ space, then any tangent cone at any point is also a pointed non-collapsed $\text{RCD}(0, N)$ space (see Theorem 2.18).

The following final application shows that the non-collapsed condition can be also recognized from the asymptotical point of view. Note that the LHS of (1.17) exists by the Bishop-Gromov inequality, and does not depend on the choice of $x \in X$.

Theorem 1.8. *Let (X, d, m) be an $\text{RCD}(0, N)$ space and assume that*

$$\sup_{x \in X} m(B_1(x)) < \infty \quad (1.16)$$

and that for some (hence all) $x \in X$

$$\lim_{r \rightarrow \infty} \frac{m(B_r(x))}{r^N} > 0. \quad (1.17)$$

Then $m = c\mathcal{H}^N$ for some $c \in (0, \infty)$.

Notice that the assumption (1.16) is essential, as this simple example shows: just consider the $\text{RCD}(0, N)$ space $([0, \infty), d_{\mathbb{R}}, x^{N-1}\mathcal{H}^1)$, which satisfies (1.17) but is clearly not non-collapsed. Conversely, any non-collapsed $\text{RCD}(K, N)$ space (X, d, \mathcal{H}^N) satisfies (1.16), as a consequence of the Bishop-Gromov inequality and (1.1).

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2 Preliminaries

Throughout the paper:

- by *metric measure space* (X, d, m) we always intend a complete and separable metric space equipped with a non-negative Borel measure finite on bounded sets such that $\text{supp}(m) = X$;
- C denotes a positive constant, that may vary from step to step. Occasionally we may emphasize the parameters on which the constant depends, so that, say, $C(K, N)$ denotes a positive constant depending only on K and N ;
- $\text{Lip}(X, d)$ (resp. $\text{Lip}_b(X, d)$, resp. $\text{Lip}_{bs}(X, d)$) denotes the set of all Lipschitz (resp. bounded Lipschitz, resp. Lipschitz with bounded support) functions on a metric space (X, d) ;
- We denote by $\text{lip } f : X \rightarrow [0, \infty]$ the *local Lipschitz constant* of the function $f : X \rightarrow \mathbb{R}$ defined by

$$\text{lip } f(x) := \limsup_{y \rightarrow x} \frac{|f(y) - f(x)|}{d(y, x)}$$

if x is not isolated and has to be understood as 0 if x is isolated;

- L_{loc}^p means that the restriction (for functions, tensors and so on) to any compact subset of the domain is L^p .

2.1 Definition and heat flow

Fix a metric measure space (X, d, m) . The Cheeger energy $\text{Ch} : L^2(X, m) \rightarrow [0, \infty]$ is defined by

$$\text{Ch}(f) := \inf_{\|f_i - f\|_{L^2} \rightarrow 0} \left\{ \liminf_{i \rightarrow \infty} \int_X (\text{lip } f_i)^2 dm : f_i \in \text{Lip}_b(X, d) \cap L^2(X, m) \right\}. \quad (2.1)$$

Then, the Sobolev space $H^{1,2}(X, d, m)$ is defined as the finiteness domain of Ch . By looking at the optimal sequence in (2.1) one can identify a canonical object $|Df|$, called the minimal relaxed

slope, which is local on Borel sets (i.e. $|Df_1| = |Df_2|$ \mathbf{m} -a.e. on $\{f_1 = f_2\}$) and provides integral representation to Ch , namely

$$\text{Ch}(f) = \int_{\mathbf{X}} |Df|^2 d\mathbf{m} \quad \forall f \in H^{1,2}(\mathbf{X}, d, \mathbf{m}).$$

We are now in a position to introduce the definition of $\text{RCD}(K, N)$ spaces (the equivalence of the following definition with the one proposed in [31] is in [5], [27], see also [11]):

Definition 2.1 ($\text{RCD}(K, N)$ space). For any $K \in \mathbb{R}$ and any $N \in [1, \infty]$, a metric measure space $(\mathbf{X}, d, \mathbf{m})$ is said to be an $\text{RCD}(K, N)$ space if the following four conditions are satisfied.

1. There exist $x \in X$ and $C > 1$ such that $\mathbf{m}(B_r(x)) \leq Ce^{Cr^2}$ holds for any $r > 0$.
2. Ch is a quadratic form. In this case for $f_i \in H^{1,2}(\mathbf{X}, d, \mathbf{m}) (i = 1, 2)$ we put

$$\langle \nabla f_1, \nabla f_2 \rangle := \lim_{\epsilon \rightarrow 0} \frac{|D(f_1 + \epsilon f_2)|^2 - |Df_1|^2}{2\epsilon} \in L^1(\mathbf{X}, \mathbf{m}).$$

3. Any $f \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$ with $|Df| \leq 1$ for \mathbf{m} -a.e. has a 1-Lipschitz representative.
4. For any $f \in D(\Delta)$ with $\Delta f \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$ we have

$$\frac{1}{2} \int_{\mathbf{X}} |Df|^2 \Delta \varphi d\mathbf{m} \geq \int_{\mathbf{X}} \varphi \left(\frac{(\Delta f)^2}{N} + \langle \nabla \Delta f, \nabla f \rangle + K |Df|^2 \right) d\mathbf{m} \quad (2.2)$$

for any $\varphi \in D(\Delta) \cap L^\infty(\mathbf{X}, \mathbf{m})$ with $\varphi \geq 0$, $\Delta \varphi \in L^\infty(\mathbf{X}, \mathbf{m})$, where

$$D(\Delta) := \left\{ f \in H^{1,2}(\mathbf{X}, d, \mathbf{m}) : \exists h \in L^2(\mathbf{X}, \mathbf{m}) \text{ s.t. } \int_{\mathbf{X}} \langle \nabla f, \nabla \varphi \rangle d\mathbf{m} = - \int_{\mathbf{X}} h \varphi d\mathbf{m}, \forall \varphi \in H^{1,2}(\mathbf{X}, d, \mathbf{m}) \right\}$$

and $\Delta f := h$ for any $f \in D(\Delta)$.

We point out that, unless otherwise specified, when we write $\text{RCD}(K, N)$ we implicitly assume $N < \infty$. Notice that, by the very definition, if $(\mathbf{X}, d, \mathbf{m})$ is an $\text{RCD}(K, N)$ space, then $(\mathbf{X}, ad, b\mathbf{m})$ is an $\text{RCD}(a^{-2}K, N)$ space for any $a, b \in (0, \infty)$, for $N \in [1, \infty]$.

In the rest of this subsection, let us fix an $\text{RCD}(K, \infty)$ space $(\mathbf{X}, d, \mathbf{m})$ and let us introduce the fundamental properties, except for the *second order differential calculus* developed in [30] which will be treated in Subsection 2.2.

First let us recall the *heat flow* associated with Ch

$$h_t : L^2(\mathbf{X}, \mathbf{m}) \rightarrow L^2(\mathbf{X}, \mathbf{m}).$$

This family of maps is characterized by the properties: $h_t f \rightarrow f$ in $L^2(\mathbf{X}, \mathbf{m})$ as $t \rightarrow 0^+$, $h_t f \in D(\Delta)$ for any $f \in L^2$, $t > 0$ and for any $t > 0$ it holds

$$\frac{d}{dt} h_t f = \Delta h_t f \quad \text{in } L^2(\mathbf{X}, \mathbf{m}). \quad (2.3)$$

It will be useful to keep in mind the following a-priori estimates ([37, Remark 5.2.11]):

$$\|Dh_t f\|_{L^2} \leq \frac{\|f\|_{L^2}}{\sqrt{t}} \quad \|\Delta h_t f\|_{L^2} \leq \frac{\|f\|_{L^2}}{t} \quad \forall f \in L^2(\mathbf{X}, \mathbf{m}), \forall t > 0 \quad (2.4)$$

as well as the fact that

$$t \mapsto \|h_t f\|_{L^2} \quad \text{is non-increasing for every } f \in L^2(\mathbf{X}, \mathbf{m}). \quad (2.5)$$

Then the 1-*Bakry-Émery* estimate proved in [56, Corollary 4.3] is stated as for any $f \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$,

$$|Dh_t f|(x) \leq e^{-Kt} |Df|(x) \quad \text{for } \mathbf{m}\text{-a.e. } x \in \mathbf{X}, \quad (2.6)$$

which in particular implies

$$h_t f \rightarrow f \quad \text{in } H^{1,2}(\mathsf{X}, \mathsf{d}, \mathsf{m}).$$

It is also worth pointing out that the heat flow h_t also acts on $L^p(\mathsf{X}, \mathsf{m})$ for any $p \in [1, \infty]$ with

$$\|h_t f\|_{L^p} \leq \|f\|_{L^p} \quad \forall f \in L^p(\mathsf{X}, \mathsf{m}).$$

Finally let us recall that the following $(1, 1)$ -Poincaré inequality is satisfied:

$$\int_{B_r(x)} \left| f - \frac{1}{\mathsf{m}(B_r(x))} \int_{B_r(x)} f \, \mathsf{d}\mathsf{m} \right| \mathsf{d}\mathsf{m} \leq 4e^{|K|r^2} r \int_{B_{3r}(x)} |\mathsf{D}f| \, \mathsf{d}\mathsf{m} \quad \forall f \in H^{1,2}(\mathsf{X}, \mathsf{d}, \mathsf{m}), \forall r > 0 \quad (2.7)$$

which is also valid for larger class, $\text{CD}(K, \infty)$ spaces. See [55] for the detail.

2.2 Calculus on $\text{RCD}(K, \infty)$ spaces

Let $(\mathsf{X}, \mathsf{d}, \mathsf{m})$ be a metric measure space. We assume that the readers are familiar with the notion of normed module, introduced in [30], inspired by the theory developed in [62]. Here we just recall few basic definitions, mostly to fix the notation. Unless otherwise stated, the material comes from [30], [32].

A L^0 -normed module is a topological vector space \mathcal{M} that is also a module over the commutative ring with unity $L^0(\mathsf{X}, \mathsf{m})$, possessing a *pointwise norm*, i.e. a map $|\cdot| : \mathcal{M} \rightarrow L^0(\mathsf{X}, \mathsf{m})$ such that

$$|fv + gw| \leq |f||v| + |g||w| \quad \mathsf{m}\text{-a.e.}, \forall v, w \in \mathcal{M}, \forall f, g \in L^0(\mathsf{X}, \mathsf{m}),$$

and such that the distance

$$\mathsf{d}_{\mathcal{M}}(v, w) := \int_{\mathsf{X}} 1 \wedge |v - w| \, \mathsf{d}\mathsf{m}' \quad (2.8)$$

is complete and induces the topology of \mathcal{M} , where here m' is a Borel probability measure such that $\mathsf{m} \ll \mathsf{m}' \ll \mathsf{m}$ (the actual choice of m' affects the distance but not the topology nor completeness).

\mathcal{M} is said to be a Hilbert module provided

$$|v + w|^2 + |v - w|^2 = 2(|v|^2 + |w|^2) \quad \mathsf{m}\text{-a.e.}, \forall v, w \in \mathcal{M}$$

and in this case by polarization we can define a pointwise scalar product as

$$\langle v, w \rangle := \frac{1}{2}(|v + w|^2 - |v|^2 - |w|^2) \quad \mathsf{m}\text{-a.e.}, \forall v, w \in \mathcal{M}$$

that turns out to be L^0 -bilinear and continuous. The tensor product of two Hilbert modules $\mathcal{M}_1, \mathcal{M}_2$ is defined as the completion of the algebraic tensor product as L^0 -modules w.r.t. the distance induced by the pointwise norm that in turn is induced by the pointwise scalar product characterized by

$$\langle v_1 \otimes w_1, v_2 \otimes w_2 \rangle_{\text{HS}} := \langle v_1, v_2 \rangle_1 \langle w_1, w_2 \rangle_2.$$

The pointwise norm and scalar product on a tensor product will often be denoted with the subscript HS , standing for *Hilbert-Schmidt*. The dual \mathcal{M}^* of \mathcal{M} is defined as the collection of L^0 -linear and continuous maps $L : \mathcal{M} \rightarrow L^0(\mathsf{X}, \mathsf{m})$, is equipped with the natural multiplication by L^0 functions ($f \cdot L(v) := L(fv)$) and the pointwise norm

$$|L|_* := \operatorname{ess\,sup}_{v: |v| \leq 1 \text{ m-a.e.}} L(v).$$

It is then easy to check that \mathcal{M}^* equipped with the topology induced by the distance defined as in (2.8) is a L^0 -normed module. If \mathcal{M} is Hilbert, then so is \mathcal{M}^* and the map sending $v \in \mathcal{M}$ to $(w \mapsto \langle v, w \rangle) \in \mathcal{M}^*$ is an isomorphism of L^0 -modules, called Riesz isomorphism.

The kind of differential calculus on metric measure spaces we are going to use in this manuscript is based around the following result, that defines both the *cotangent module* and the *differential* of Sobolev functions:

Theorem 2.2. *Let (X, d, m) be a metric measure space. Then there is a unique, up to unique isomorphism, couple $(L^0(T^*(X, d, m)), d)$ such that $L^0(T^*(X, d, m))$ is a L^0 -normed module, $d : H^{1,2}(X, d, m) \rightarrow L^0(T^*(X, d, m))$ is linear and such that:*

- 1) $|df| = |Df|$ m -a.e. for every $f \in H^{1,2}(X, d, m)$,
- 2) L^0 -linear combinations of elements of the form df for $f \in H^{1,2}(X, d, m)$ are dense in $L^0(T^*(X, d, m))$.

The dual of $L^0(T^*(X, d, m))$ is denoted $L^0(T(X, d, m))$ and called *tangent module*. Elements of $L^0(T^*(X, d, m))$ are called 1-forms and elements of $L^0(T(X, d, m))$ are called vector fields on X .

In this case we shall denote by $\nabla f \in L^0(T(X, d, m))$ the image of df under the Riesz isomorphism.

The tensor product of $L^0(T(X, d, m))$ with itself will be denoted $L^0(T^{\otimes 2}(X, d, m))$, similarly for $L^0(T^*(X, d, m))$. Notice that, rather trivially, $L^0(T^{\otimes 2}(X, d, m))$ and $L^0((T^*)^{\otimes 2}(X, d, m))$ are one the dual of each other, in a natural way.

For $p \in [1, \infty]$, the collection of 1-forms ω with $|\omega| \in L^p(X, m)$ (resp. $L^p_{loc}(X, m)$) will be denoted $L^p(T^*(X, d, m))$ (resp. $L^p_{loc}(T^*(X, d, m))$). Similarly for vector fields and other tensors. Convergence in the spaces $L^p(T^*(X, d, m))$ (resp. $L^p_{loc}(T^*(X, d, m))$) is defined in the obvious way.

All this for general metric measure spaces. In the $RCD(K, \infty)$ case we now recall the definition of the set of *test functions* (introduced in [56]):

$$\text{Test}F(X, d, m) := \{f \in \text{Lip}(X, d) \cap D(\Delta) \cap L^\infty(X, m) : \Delta f \in H^{1,2}(X, d, m)\}$$

which is an algebra. It is known ([56]) that $|\nabla f|^2 \in H^{1,2}(X, d, m)$ for any $f \in \text{Test}F(X, d, m)$, that $\text{Test}F(X, d, m)$ is dense in $(D(\Delta), \|\cdot\|_D)$, where $\|f\|_D^2 := \|f\|_{H^{1,2}}^2 + \|\Delta f\|_{L^2}^2$, and that if $f \in L^2 \cap L^\infty(X, m)$, then $h_t f \in \text{Test}F(X, d, m)$ for any $t > 0$. The following result is proved in [30].

Theorem 2.3. *Let (X, d, m) be an $RCD(K, \infty)$ space. For any $f \in \text{Test}F(X, d, m)$ there exists a unique $T \in L^2((T^*)^{\otimes 2}(X, d, m))$ such that for all $f_i \in \text{Test}F(X, d, m)$,*

$$T(\nabla f_1, \nabla f_2) = \frac{1}{2} (\langle \nabla f_1, \nabla \langle \nabla f_2, \nabla f \rangle \rangle + \langle \nabla f_2, \nabla \langle \nabla f_1, \nabla f \rangle \rangle - \langle f, \nabla \langle \nabla f_1, \nabla f_2 \rangle \rangle) \quad (2.9)$$

holds for m -a.e. $x \in X$. Since T is unique, we denote it by $\text{Hess}f$ and call it the *Hessian* of f . Moreover for any $f \in \text{Test}F(X, d, m)$ and any $\varphi \in D(\Delta) \cap L^\infty(X, m)$ with $\Delta \varphi \in L^\infty(X, m)$ and $\varphi \geq 0$, we have

$$\int_X \varphi |\text{Hess}f|_{\text{HS}}^2 dm \leq \int_X \frac{1}{2} \Delta \varphi \cdot |\nabla f|^2 - \varphi \langle \nabla \Delta f, \nabla f \rangle - K \varphi |\nabla f|^2 dm \quad (2.10)$$

and

$$\int_X |\text{Hess}f|_{\text{HS}}^2 dm \leq \int_X (\Delta f)^2 - K |\nabla f|^2 dm. \quad (2.11)$$

Thanks to (2.10) with the density of $\text{Test}F(X, d, m)$ in $D(\Delta)$, for any $f \in D(\Delta)$ we can also define $\text{Hess}f \in L^2((T^*)^{\otimes 2}(X, d, m))$ with the equality (2.9), where $\langle \nabla f, \nabla f_i \rangle \in H^{1,1}(X, d, m)$.

Definition 2.4 (Divergence div). Let (X, d, m) be an $RCD(K, \infty)$ space. Denote by $D(\text{div})$ (resp. $D_{loc}(\text{div})$) the set of all $V \in L^2(T(X, d, m))$ (resp. $V \in L^2_{loc}(T(X, d, m))$) for which there exists $f \in L^2(X, m)$ (resp. $f \in L^2_{loc}(X, m)$) such that

$$\int_X \langle V, \nabla h \rangle dm = - \int_X f h dm \quad \forall h \in \text{Lip}_{bs}(X, d).$$

Since f is unique (because $\text{Lip}_{bs}(X, d)$ is dense in $L^2(X, m)$), we define $\text{div}V := f$.

Note that for any $f \in H^{1,2}(X, d, m)$, $f \in D(\Delta)$ if and only if $\nabla f \in D(\text{div})$. Moreover if $f \in D(\Delta)$, then for any $\varphi \in \text{Lip}_b(X, d)$ we have $\varphi \nabla f \in D(\text{div})$ with

$$\text{div}(\varphi \nabla f) = \langle \nabla \varphi, \nabla f \rangle + \varphi \Delta f.$$

Recalling that the covariant derivative of $f \nabla h$ is given by $\nabla f \otimes \nabla h + f \text{Hess}h$, the following definition is justified:

Definition 2.5 (Adjoint operator ∇^*). Let (X, d, m) be an $\text{RCD}(K, \infty)$ space. Denote by $D(\nabla^*)$ (resp. $D_{loc}(\nabla^*)$) the set of all $T \in L^2((T^*)^{\otimes 2}(X, d, m))$ (resp. $T \in L^2_{loc}((T^*)^{\otimes 2}(X, d, m))$) for which there exists $\eta \in L^2(T^*(X, d, m))$ (resp. $\eta \in L^2_{loc}(T^*(X, d, m))$) such that

$$\int_X \langle T, df \otimes dh + f \text{Hess} h \rangle_{\text{HS}} dm = \int_X \langle \eta, f dh \rangle dm \quad \forall f \in \text{Lip}_{bs}(X, d), \forall h \in D(\Delta).$$

Since η is unique (because objects of the form $f dh$ generate $L^2(T^*(X, d, m))$), we denote it by $\nabla^* T$.

It follows from a direct calculation that the following holds. See [41, Proposition 2.18] for the proof.

Proposition 2.6. *Let (X, d, m) be an $\text{RCD}(K, \infty)$ space and let $f \in \text{Test}F(X, d, m)$. Then we have $df \otimes df \in D(\nabla^*)$ with*

$$\nabla^*(df \otimes df) = -\Delta f df - \frac{1}{2} d|df|^2.$$

2.3 Structure of $\text{RCD}(K, N)$ spaces and convergence

Let (X, d, m) be an $\text{RCD}(K, N)$ space for some $K \in \mathbb{R}$ and some $N \in [1, \infty)$. The main purpose of this subsection is to provide a more detailed metric measure structure theory of (X, d, m) we will need later. For our purpose it is enough to discuss the case when $K < 0$.

First let us recall the Bishop-Gromov inequality (which is also valid for larger class, so-called $\text{CD}(K, N)$ spaces, see [52, Theorem 5.31], [60, Theorem 2.3]).

$$\frac{m(B_R(x))}{m(B_r(x))} \leq \frac{\int_0^R \sinh\left(t\sqrt{\frac{-K}{N-1}}\right)^{N-1} dt}{\int_0^r \sinh\left(t\sqrt{\frac{-K}{N-1}}\right)^{N-1} dt} \quad \forall x \in X, \forall r < R, \quad (2.12)$$

where, in the case $N = 1$, $\sinh\left(t\sqrt{\frac{-K}{N-1}}\right)^{N-1}$ has to be interpreted as 1. It then follows from (2.12) that

$$\frac{m(B_R(x))}{m(B_r(x))} \leq C(K, N) \exp\left(C(K, N) \frac{R}{r}\right) \quad \forall x \in X, \forall r < R \quad (2.13)$$

and

$$\frac{m(B_r(x))}{m(B_r(y))} \leq C(K, N) \exp\left(C(K, N) \frac{d(x, y)}{r}\right) \quad \forall x, y \in X, \forall r > 0 \quad (2.14)$$

are satisfied. It is well-known that from the Bishop-Gromov inequality it follows that the metric structure (X, d) is proper, hence geodesic, being (X, d) a length space. The length space property of RCD spaces follows quite easily from the so called *Sobolev to Lipschitz* property, namely item 3) of Definition 2.1 (e.g. [5, Theorem 3.10] and references therein).

The following elementary lemma will play a role later.

Lemma 2.7. *Let (X, d, m) be an $\text{RCD}(K, N)$ space. Then for any $t \in (0, 1]$, any $\alpha \in \mathbb{R}$, any $\beta \in (0, \infty)$ and any $x \in X$ we have*

$$\int_X m(B_{\sqrt{t}}(y))^\alpha \exp\left(-\frac{\beta d^2(x, y)}{t}\right) dm(y) \leq C(K, N, \alpha, \beta) m(B_{\sqrt{t}}(x))^{\alpha+1}. \quad (2.15)$$

Proof. Considering a rescaling $\sqrt{\beta/t} \cdot d$ with (2.12), it is enough to prove (2.15) assuming $\beta = t = 1$.

Then by (2.13) and (2.14)

$$\begin{aligned}
& \int_{\mathbf{X}} \mathbf{m}(B_1(y))^\alpha \exp(-\mathbf{d}^2(x, y)) \, \mathrm{d}\mathbf{m}(y) \\
&= \sum_{j=-\infty}^{\infty} \int_{B_{2^{j+1}}(x) \setminus B_{2^j}(x)} \mathbf{m}(B_1(y))^\alpha \exp(-\mathbf{d}^2(x, y)) \, \mathrm{d}\mathbf{m}(y) \\
&\leq C(K, N) \mathbf{m}(B_1(x))^\alpha \sum_{j=-\infty}^{\infty} \int_{B_{2^{j+1}}(x) \setminus B_{2^j}(x)} \exp(C(\alpha, K, N)2^{j+1} - 2^{2j}) \, \mathrm{d}\mathbf{m}(y) \\
&= C(K, N) \mathbf{m}(B_1(x))^\alpha \sum_{j=-\infty}^{\infty} \mathbf{m}(B_{2^{j+1}}(x) \setminus B_{2^j}(x)) \exp(C(\alpha, K, N)2^{j+1} - 2^{2j}) \\
&\leq C(K, N) \mathbf{m}(B_1(x))^\alpha \sum_{j=-\infty}^{\infty} \mathbf{m}(B_1(x)) \cdot \exp(C(K, N)2^j) \cdot \exp(C(\alpha, K, N)2^{j+1} - 2^{2j}) \\
&\leq C(\alpha, K, N) \mathbf{m}(B_1(x))^{\alpha+1}. \quad \square
\end{aligned}$$

For the definition of *pointed measured Gromov-Hausdorff convergence* and the following compactness result we refer, for instance, to [34, Section 3].

Theorem 2.8. *If a sequence of pointed $\mathrm{RCD}(K, N)$ spaces $(\mathbf{X}_i, \mathbf{d}_i, \mathbf{m}_i, x_i)$ satisfies*

$$0 < \liminf_{i \rightarrow \infty} \mathbf{m}_i(B_1(x_i)) \leq \limsup_{i \rightarrow \infty} \mathbf{m}_i(B_1(x_i)) < \infty,$$

then the sequence has a subsequence $(\mathbf{X}_{i_j}, \mathbf{d}_{i_j}, \mathbf{m}_{i_j}, x_{i_j})$ pmGH converging to a pointed $\mathrm{RCD}(K, N)$ space $(\mathbf{X}, \mathbf{d}, \mathbf{m}, x)$.

Next we introduce the notion of *tangent cones*

Definition 2.9 (Tangent cones). Let $(\mathbf{X}, \mathbf{d}, \mathbf{m})$ be an $\mathrm{RCD}(K, N)$ space. For $x \in \mathbf{X}$, we denote by $\mathrm{Tan}(\mathbf{X}, \mathbf{d}, \mathbf{m}, x)$ the set of tangent cones to $(\mathbf{X}, \mathbf{d}, \mathbf{m})$ at x : the collection of all isomorphism classes of pointed metric measure spaces $(\mathbf{Y}, \mathbf{d}_{\mathbf{Y}}, \mathbf{m}_{\mathbf{Y}}, y)$ such that, as $i \rightarrow \infty$, one has

$$\left(\mathbf{X}, \frac{1}{r_i} \mathbf{d}, \frac{1}{\mathbf{m}(B_{r_i}(x))} \mathbf{m}, x \right) \xrightarrow{\mathrm{pmGH}} (\mathbf{Y}, \mathbf{d}_{\mathbf{Y}}, \mathbf{m}_{\mathbf{Y}}, y) \quad (2.16)$$

for some $r_i \rightarrow 0^+$.

Note that Theorem 2.8 proves $\mathrm{Tan}(\mathbf{X}, \mathbf{d}, \mathbf{m}, x) \neq \emptyset$ for any $x \in \mathbf{X}$. We are now in a position to introduce the key notions of *regular sets* and the *essential dimension* as follows.

Definition 2.10 (Regular set \mathcal{R}_k). Let $(\mathbf{X}, \mathbf{d}, \mathbf{m})$ be an $\mathrm{RCD}(K, N)$ space. For any $k \geq 1$, we denote by \mathcal{R}_k the k -dimensional regular set of $(\mathbf{X}, \mathbf{d}, \mathbf{m})$, namely the set of points $x \in \mathbf{X}$ such that

$$\mathrm{Tan}(\mathbf{X}, \mathbf{d}, \mathbf{m}, x) = \left\{ (\mathbb{R}^k, \mathbf{d}_{\mathbb{R}^k}, (\omega_k)^{-1} \mathcal{H}^k, 0_k) \right\},$$

where ω_k is the k -dimensional volume of the unit ball in \mathbb{R}^k with respect to the k -dimensional Hausdorff measure \mathcal{H}^k .

The following result is proved in [17, Theorem 0.1].

Theorem 2.11 (Essential dimension). *Let $(\mathbf{X}, \mathbf{d}, \mathbf{m})$ be an $\mathrm{RCD}(K, N)$ space. Then there exists a unique integer $n \in [1, N]$, called the essential dimension of $(\mathbf{X}, \mathbf{d}, \mathbf{m})$, denoted by $\mathrm{essdim}(\mathbf{X})$, such that*

$$\mathbf{m}(X \setminus \mathcal{R}_n) = 0.$$

Remark 2.12. The essential dimension is a purely metric concept, actually it is equal to the maximal number $n \in \mathbb{N}$ satisfying

$$\left(\mathbf{X}, \frac{1}{r_i} \mathbf{d}, x \right) \xrightarrow{\mathrm{pGH}} (\mathbb{R}^n, \mathbf{d}_{\mathbb{R}^n}, 0_n)$$

for some $x \in \mathbf{X}$ and some $r_i \rightarrow 0^+$ because of the splitting theorem [29, Theorem 1.4] and the phenomenon of *propagation of regularity*. See [51, Remark 4.3], [43, Proposition 2.4] and [16]. ■

Next let us introduce a relationship between \mathbf{m} and the Hausdorff measure of the essential dimension. See [9, 25, 35, 49] for the detail.

Theorem 2.13. *Let (X, d, \mathbf{m}) be an $\text{RCD}(K, N)$ space and let n be its essential dimension. Then $\mathbf{m} \ll \mathcal{H}^n \llcorner \mathcal{R}_n$. Also, letting $\mathbf{m} = \theta \mathcal{H}^n \llcorner \mathcal{R}_n$ and*

$$\mathcal{R}_n^* := \left\{ x \in \mathcal{R}_n : \exists \lim_{r \rightarrow 0^+} \frac{\mathbf{m}(B_r(x))}{\omega_n r^n} \in (0, \infty) \right\} \quad (2.17)$$

we have that $\mathbf{m}(\mathcal{R}_n \setminus \mathcal{R}_n^) = 0$, $\mathbf{m} \llcorner \mathcal{R}_n^*$ and $\mathcal{H}^n \llcorner \mathcal{R}_n^*$ are mutually absolutely continuous and*

$$\lim_{r \rightarrow 0^+} \frac{\mathbf{m}(B_r(x))}{\omega_n r^n} = \theta(x) \quad \text{for } \mathbf{m}\text{-a.e. } x \in \mathcal{R}_n^*.$$

Moreover $\mathcal{H}^n(\mathcal{R}_n \setminus \mathcal{R}_n^) = 0$ if $n = N$.*

A more general and classical result concerning densities, that we shall use later on, is the following (see e.g. [12, Theorem 2.4.3] for a proof):

Lemma 2.14. *Let (X, d, \mathbf{m}) be a metric measure space, $\alpha \geq 0$ and $A \subseteq X$ a Borel subset such that*

$$\limsup_{r \rightarrow 0^+} \frac{\mathbf{m}(B_r(x))}{r^\alpha} > 0 \quad \forall x \in A.$$

Then $\mathcal{H}^\alpha \llcorner A$ is a Radon measure absolutely continuous w.r.t. \mathbf{m} .

The fact that $L^0(T(X, d, \mathbf{m}))$ is a Hilbert module is an indication of the existence of some (weak) Riemannian metric on X . This statement can easily be made more explicit by building upon the fact that such module has local dimension equal to the essential dimension of X (see [36]):

Proposition 2.15. *Let (X, d, \mathbf{m}) be an $\text{RCD}(K, N)$ space of essential dimension n . Then there is a unique $g \in L^0((T^*)^{\otimes 2}(X, d, \mathbf{m}))$ such that*

$$g(V_1 \otimes V_2) = \langle V_1, V_2 \rangle \quad \mathbf{m}\text{-a.e.}, \quad \forall V_1, V_2 \in L^0(T(X, d, \mathbf{m})).$$

Moreover, g satisfies

$$|g|_{\text{HS}} = \sqrt{n}, \quad \mathbf{m}\text{-a.e.} \quad (2.18)$$

We can use this ‘metric tensor’ to define the *trace* of any $T \in L^0((T^*)^{\otimes 2}(X, d, \mathbf{m}))$ by

$$\text{tr}(T) := \langle T, g \rangle_{\text{HS}} \in L^0(X, \mathbf{m}).$$

Notice that by (2.18) and the Cauchy-Schwarz inequality it follows that if $T \in L^p_{loc}((T^*)^{\otimes 2}(X, d, \mathbf{m}))$, then $\text{tr}(T) \in L^p_{loc}(X, d, \mathbf{m})$.

Finally let us end this subsection by recalling the lower semicontinuity of the essential dimensions with respect to pmGH convergence proved in [51, Theorem 1.5], where this is also understood as a consequence of L^2_{loc} -weak convergence of Riemannian metrics (see [8, Remark 5.20]), and an alternative proof of the theorem below can be based on Remark 2.12.

Theorem 2.16. *Let*

$$(X_i, d_i, \mathbf{m}_i, x_i) \xrightarrow{\text{pmGH}} (X, d, \mathbf{m}, x)$$

be a pmGH convergent sequence of pointed $\text{RCD}(K, N)$ spaces. Then

$$\liminf_{i \rightarrow \infty} \text{essdim}(X_i) \geq \text{essdim}(X).$$

2.4 Non-collapsed $\text{RCD}(K, N)$ spaces

Let us start recalling the following:

Definition 2.17 (Non-collapsed $\text{RCD}(K, N)$ space). An $\text{RCD}(K, N)$ space (X, d, \mathbf{m}) is said to be *non-collapsed* if $\mathbf{m} = \mathcal{H}^N$.

This definition was introduced in [24, Definition 1.1] as a synthetic counterpart of non-collapsed Ricci limit spaces. As explained in the introduction, non-collapsed $\text{RCD}(K, N)$ spaces have finer properties rather than general $\text{RCD}(K, N)$ spaces already introduced in subsection 2.2. Let us give one of the properties as follows (see [24, Theorem 1.2]).

Theorem 2.18 (From pGH to pmGH). *Let $K \in \mathbb{R}$, $N \in \mathbb{N}$ and $(X_i, d_i, \mathcal{H}^N, x_i)$ be a sequence of pointed non-collapsed $\text{RCD}(K, N)$ spaces. Then after passing to a subsequence, there exists a pointed proper geodesic space (X, d, x) such that*

$$(X_i, d_i, x_i) \xrightarrow{\text{pGH}} (X, d, x).$$

Moreover, if $\inf_i \mathcal{H}^N(B_1(x_i)) > 0$, then (X, d, \mathcal{H}^N, x) is also a pointed non-collapsed $\text{RCD}(K, N)$ space and the convergence of the $(X_i, d_i, \mathcal{H}^N, x_i)$'s to such space is in the pmGH topology.

We remark that the above theorem is tightly related to the following continuity result, which is the generalization to the RCD class of the classical statement by Colding about volume convergence under lower Ricci bounds [23] (see [24, Theorem 1.3]):

Theorem 2.19 (Continuity of \mathcal{H}^N). *For $K \in \mathbb{R}$, $N \in [1, \infty)$ let $\mathbb{B}(K, N)$ be the collection of (isometry classes of) open unit balls on $\text{RCD}(K, N)$ spaces. Equip $\mathbb{B}(K, N)$ with the Gromov-Hausdorff distance.*

Then the map $\mathbb{B}(K, N) \ni B \mapsto \mathcal{H}^N(B) \in \mathbb{R}$ is continuous.

For our main purpose, we need a notion weaker than the non-collapsed one. In order to give the precise definition, let us recall the following result which is just a combination from previous known ones:

Theorem 2.20. *Let (X, d, m) be an $\text{RCD}(K, N)$ space. Then the following five conditions are equivalent.*

1. *The essential dimension of X is N .*
2. *m is absolutely continuous with respect to \mathcal{H}^N .*
3. *(1.2) holds.*
4. *$N \in \mathbb{N}$ and the Hausdorff dimension of (X, d) is greater than $N - 1$.*
5. *The Hausdorff dimension of (X, d) is N .*

Proof. The equivalence between item 1 and item 2 is proved in [24, Theorem 1.12]. Since the implication from item 2 to item 3 is a direct consequence of Theorem 2.13, let us check the implication from item 3 to 1 as follows. The positivity (1.2) with Theorems 2.11 and 2.13 yields

$$\mathcal{H}^N(\mathcal{R}_n^*) > 0,$$

where n denote the essential dimension. In particular $N \leq n$. Since the converse inequality is always satisfied by Theorem 2.13, we have item 1.

Notice that item 2 implies item 4, we show now that item 4 implies item 1. To see this, notice that the proof of [24, Theorem 1.4] shows that if item 4 holds, then there is an iterated tangent space isomorphic to \mathbb{R}^N . Since the essential dimension of the N -dimensional Euclidean space is N , the conclusion follows from Theorem 2.16.

If we assume item 5, then, since the Hausdorff dimension of (X, d) is at most the integer part of N (by [24, Corollary 1.5]), we see that N is an integer so that item 4 holds. Finally, if item 2 holds, then the Hausdorff dimension of (X, d) is at least N , so that we conclude by [24, Corollary 1.5] again. \square

We are now in a position to introduce the notion of weakly non-collapsed $\text{RCD}(K, N)$ spaces (our definition is trivially equivalent to the one in [24]):

Definition 2.21 (Weakly non-collapsed $\text{RCD}(K, N)$ space). *An $\text{RCD}(K, N)$ space is said to be weakly non-collapsed if one (and thus any) of the items in Theorem 2.20 is satisfied.*

Note that any non-collapsed $\text{RCD}(K, N)$ space is a weakly non-collapsed $\text{RCD}(K, N)$ space.

We conclude the section recalling - see e.g. the introduction - that one expects the notion of non-collapsed space to be related to the fact that the trace of the Hessian is the Laplacian. A first instance of this behaviour is contained in the following result, that is basically extracted from [38, Proposition 3.2] (notice that Definition 2.1 tells that if the stated inequality (2.19) holds without restrictions on the support of φ , then the space is an $\text{RCD}(K, n)$ space and thus, since n is assumed to be the essential dimension, the space is weakly non-collapsed).

Theorem 2.22. *Let (X, d, m) be an $\text{RCD}(K, N)$ space of essential dimension n and let $U \subseteq X$ be open. Then the following two conditions are equivalent:*

1. *For any $f \in \text{TestF}(X, d, m)$ and any $\varphi \in D(\Delta)$ non-negative with $\text{supp}(\varphi) \subseteq U$ and $\Delta\varphi \in L^\infty(X, m)$ we have*

$$\frac{1}{2} \int_U \Delta\varphi |\nabla f|^2 dm \geq \int_U \varphi \left(\frac{(\Delta f)^2}{n} + \langle \nabla \Delta f, \nabla f \rangle + K |\nabla f|^2 \right) dm. \quad (2.19)$$

2. *For any $f \in D(\Delta)$ we have*

$$\Delta f = \text{tr}(\text{Hess}f) \quad m\text{-a.e. in } U. \quad (2.20)$$

Proof. It is easy to see the implication from item 2 to item 1 is trivial because we know

$$|\text{tr}(\text{Hess}f)| = |\langle \text{Hess}f, g \rangle_{\text{HS}}| \leq |\text{Hess}f|_{\text{HS}} |g|_{\text{HS}} = |\text{Hess}f|_{\text{HS}} \cdot \sqrt{n}.$$

Thus item 2 gives $|\text{Hess}f|_{\text{HS}}^2 \geq (\Delta f)^2/n$, and therefore item 1 follows directly from (2.10).

For the reverse implication we closely follow the proof of [38, Proposition 3.2] keeping in mind (2.19) and the existence, for any $A \subseteq U$ with A compact and U open, of a test function identically 1 on A and with support in U (see e.g. [10] or [37, Lemma 6.2.15]). In this way we easily obtain that (2.20) holds for any $f \in \text{TestF}(X, d, m)$. Then by the density of $\text{TestF}(X, d, m)$ in $D(\Delta)$ (see for example [42, Lemma 2.2]) (2.20) holds for $f \in D(\Delta)$. \square

3 Smoothing of the Riemannian metric by the heat kernel

3.1 Local Hille's theorem

In this section we collect some basic results about local (differentiation) operators: the main result we have in mind is the version of Hille's theorem stated in Lemma 3.3 below. We shall apply the notions presented here to the operators d, Δ, ∇^* , but in order to highlight the similarities among the various approaches we shall give a rather abstract presentation.

Thus let us fix a metric measure space (X, d, m) and two L^0 -normed modules \mathcal{M}, \mathcal{N} . For $p \in [1, \infty]$ we shall denote by $L^p(\mathcal{M})$ (resp. $L_{loc}^p(\mathcal{M})$) the collection of those $v \in \mathcal{M}$ with $|v| \in L^p(X, m)$ (resp. $|v| \in L_{loc}^p(X, m)$). Similarly for \mathcal{N} .

Definition 3.1 (Weakly local operators). Let $p \in [1, \infty]$ and $L : D(L) \subseteq L^p(\mathcal{M}) \rightarrow L^p(\mathcal{N})$ be a linear operator. We say that L is *weakly local* provided

$$L(v) = L(w) \quad m\text{-a.e. on the essential interior of } \{v = w\} \text{ for any } v, w \in D(L).$$

In other words, L is weakly local provided for any $v, w \in D(L)$ and $U \subseteq X$ open such that $v = w$ m -a.e. on U , we have $L(v) = L(w)$ m -a.e. on U .

Weakly local operators can naturally be extended as follows (variants of this definition are possible, but for us the following is sufficient):

Definition 3.2 (Extension of weakly local operators). Let $p \in [1, \infty]$ and $L : D(L) \subseteq L^p(\mathcal{M}) \rightarrow L^p(\mathcal{N})$ be a weakly local operator. We then define $D_{loc}(L) \subseteq L_{loc}^p(\mathcal{M})$ as the collection of those v 's such that for every $U \subseteq X$ bounded and open there is $v_U \in D(L) \subseteq L^p(\mathcal{M})$ with $v_U = v$ m -a.e. on U .

For $v \in D_{loc}(L)$ we define $L(v) \in L_{loc}^p(\mathcal{N})$ via

$$L(v) = L(v_U) \quad \mathbf{m}\text{-a.e. on } U, \forall U \subseteq \mathbf{X} \text{ open and bounded,}$$

where v_U is as above.

It is clear from the definition that $L : D_{loc}(L) \subseteq L_{loc}^p(\mathcal{M}) \rightarrow L_{loc}^p(\mathcal{N})$ is well-posed and that the resulting operator is linear. We are interested in a version of Hille's theorem for this kind of operators and to this aim we need first to introduce the notion of integrable function with values in $L^p(\mathcal{M})$.

For the standard notion of Bochner integration of Banach valued maps we refer to [26]. Given a metric measure space (Y, d_Y, μ) (the topology here is not really relevant, but in our applications we shall mostly have $Y = X$) we shall denote by $L^1(Y, \mu; L_{loc}^p(\mathcal{M}))$ the collection of (equivalence classes up to μ -a.e. equality of) maps $y \mapsto v_y \in L_{loc}^p(\mathcal{M})$ such that for any $A \subseteq X$ Borel and bounded the map $y \mapsto \chi_A v_y$ is in $L^1(Y, \mu; L^p(\mathcal{M}))$ (here we are endowing $L^p(\mathcal{M})$ with its natural Banach structure).

With these definitions, the following result is rather trivial (but nevertheless useful):

Lemma 3.3 (Local Hille's theorem - abstract version). *Let (X, d, m) , (Y, d_Y, μ) be metric measure spaces, \mathcal{M}, \mathcal{N} two L^0 -normed modules, $p \in [1, \infty]$ and $L : D(L) \subseteq L^p(\mathcal{M}) \rightarrow L^p(\mathcal{N})$ a weakly local and closed linear operator. Also, let $y \mapsto v_y \in L_{loc}^p(\mathcal{M})$ be in $L^1(Y, \mu; L_{loc}^p(\mathcal{M}))$. Assume that*

i) $v_y \in D_{loc}(L)$ for μ -a.e. y ,

ii) there exists a 'cut-off' operator T : for every $V \subseteq U \subseteq X$ bounded and open with $d(V, X \setminus U) > 0$ there is a linear map $T : L_{loc}^p(\mathcal{M}) \rightarrow L^p(\mathcal{M})$ such that:

$$\begin{aligned} T(v) &= v & \mathbf{m}\text{-a.e. on } V, \\ T(v) &= T(\chi_U v) & \mathbf{m}\text{-a.e.} \end{aligned} \quad (3.1)$$

$$\|T(v)\|_{L^p(\mathcal{M})} \leq C \|\chi_U v\|_{L^p(\mathcal{M})}$$

for every $v \in L_{loc}^p(\mathcal{M})$ and some $C > 0$ independent on v ,

iii) L has the following 'stability under cut-off by T ' property: for any V, U as above and T given by item (ii) we have $T(v_y) \in D(L)$ for μ -a.e. y and the map $y \mapsto L(T(v_y))$ is in $L^1(Y, \mu; L^p(\mathcal{N}))$.

Then $\int_Y v_y dm(y) \in D_{loc}(L)$, the map $y \mapsto L(v_y)$ is in $L^1(Y, \mu; L_{loc}^p(\mathcal{N}))$ and

$$L\left(\int_Y v_y dm(y)\right) = \int_Y L(v_y) dm(y).$$

Proof. Fix $V \subseteq X$ open bounded and then let $U \supseteq V$ open bounded be with $d(V, X \setminus U) > 0$. Let $T : L_{loc}^p(\mathcal{M}) \rightarrow L^p(\mathcal{M})$ be given by item (ii). By the assumption (i) we know that $y \mapsto \chi_U v_y \in L^p(\mathcal{M})$ is in $L^1(X, m; L^p(\mathcal{M}))$ and the third in (3.1) gives that T is continuous as map from $L^p(\mathcal{M})$ to itself. It follows that $y \mapsto T(\chi_U v_y) = T(v_y)$ is in $L^1(Y, \mu; L^p(\mathcal{M}))$. Then assumption (iii) and the classical theorem by Hille ensure that

$$\int_Y T(v_y) d\mu(y) \in D(L) \quad \text{and} \quad L\left(\int_Y T(v_y) d\mu(y)\right) = \int_Y L(T(v_y)) d\mu(y). \quad (3.2)$$

Now notice that the first in (3.1) give that $T(v_y) = v_y$ on V for every y , thus the weak locality of L also gives that $L(T(v_y)) = L(v_y)$ on V for every y . It follows that $y \mapsto \chi_V L(v_y)$ is in $L^1(Y, \mu; L^p(\mathcal{N}))$ and that

$$\int_Y \chi_V v_y d\mu(y) = \int_Y \chi_V T(v_y) d\mu(y) \quad \text{and} \quad \int_Y \chi_V L(v_y) d\mu(y) = \int_Y \chi_V L(T(v_y)) d\mu(y).$$

Thus using again the weak locality of L it follows that

$$\begin{aligned} \chi_V L\left(\int_Y v_y d\mu(y)\right) &= \chi_V L\left(\int_Y T(v_y) d\mu(y)\right) \\ (\text{by (3.2)}) &= \chi_V \int_Y L(T(v_y)) d\mu(y) = \int_Y \chi_V L(T(v_y)) d\mu(y) = \int_Y \chi_V L(v_y) d\mu(y). \end{aligned}$$

Since V was arbitrary, this is the conclusion. \square

We now see how to apply this general statement to the concrete cases of $L = d, \Delta, \nabla^*$. The idea is to use, as map T , the multiplication with a Lipschitz cut-off function φ with support in U and identically 1 on V . For the case of the Laplacian this does not really work, as one would need to multiply by a Lipschitz function with bounded Laplacian in order to remain in the domain of the operator. The problem is that on general $\text{RCD}(K, \infty)$ spaces it is not clear whether this sort of cut-off functions exist (but see [10] or [37, Lemma 6.2.15] for the case of proper RCD spaces). This issue is, however, easily dealt with by recalling that the Laplacian is the divergence of the gradient and applying the above theorem twice (this amounts at localizing Δf by looking at $\text{div}(\varphi \nabla(\varphi f))$).

Let us start recalling that the differential $d : H^{1,2}(\mathbf{X}, d, \mathbf{m}) \subseteq L^2(\mathbf{X}, \mathbf{m}) \rightarrow L^2(T^*(\mathbf{X}, d, \mathbf{m}))$ is weakly local (in fact even more, as there is locality on Borel sets and not just on open ones) by [30, Theorem 2.2.3]. The same holds for the divergence operator $\text{div} : D(\text{div}) \subseteq L^2(T(\mathbf{X}, d, \mathbf{m})) \rightarrow L^2(\mathbf{X}, \mathbf{m})$. Indeed, for $v, w \in D(\text{div})$ equal on some open set U , we have

$$\int_{\mathbf{X}} \varphi \text{div } v \, d\mathbf{m} = - \int_{\mathbf{X}} d\varphi(v) \, d\mathbf{m} \stackrel{(*)}{=} - \int_{\mathbf{X}} d\varphi(w) \, d\mathbf{m} = \int_{\mathbf{X}} \varphi \text{div } w \, d\mathbf{m}$$

for any $\varphi \in \text{Lip}(\mathbf{X}, d)$ with $\text{supp}(\varphi) \subseteq U$, having used the locality of the differential and the assumption $v = w$ on U in the starred equality $(*)$. This is sufficient to prove the claim. Similarly, starting from the locality of the covariant derivative (see [30, Proposition 3.4.9]) it follows the weak locality of ∇^* . Finally, the weak locality of the Laplacian follows from that of the differential and of the divergence.

Below for the domain $D_{\text{loc}}(d) \subseteq L^2_{\text{loc}}(\mathbf{X}, \mathbf{m})$ we shall use the more standard notation $H^{1,2}_{\text{loc}}(\mathbf{X}, d, \mathbf{m})$. We then have the following.

Proposition 3.4 (Local Hille's theorem - concrete version). *Let $(\mathbf{X}, d, \mathbf{m})$ be an $\text{RCD}(K, \infty)$ space and (Y, d_Y, μ) a metric measure space. Let $(f_y) \in L^1(Y, \mu; L^2_{\text{loc}}(\mathbf{X}, \mathbf{m}))$ (resp. $(f_y) \in L^1(Y, \mu; L^2_{\text{loc}}(\mathbf{X}, \mathbf{m}))$, resp. $(A_y) \in L^1(Y, \mu; L^2_{\text{loc}}(T^{\otimes 2}(\mathbf{X}, d, \mathbf{m})))$) be with $f_y \in H^{1,2}_{\text{loc}}(\mathbf{X}, d, \mathbf{m})$ (resp. $f_y \in D_{\text{loc}}(\Delta)$, resp. $A_y \in D_{\text{loc}}(\nabla^*)$) for μ -a.e. $y \in Y$.*

Then for every $U \subseteq \mathbf{X}$ open bounded we have that $y \mapsto \chi_U df_y$ (resp. $y \mapsto \chi_U \Delta f_y$, resp. $y \mapsto \chi_U \nabla^ A_y$) is - the equivalence class up to μ -a.e. equality of - a strongly Borel function (i.e. Borel and essentially separably valued).*

Now assume also that for every $U \subseteq \mathbf{X}$ open bounded we have $\int_Y \|\chi_U df_y\|_{L^2} d\mu(y) < \infty$ (resp. $\int_Y \|\chi_U \Delta f_y\|_{L^2} d\mu(y) < \infty$, resp. $\int_Y \|\chi_U \nabla^ A_y\|_{L^2} d\mu(y) < \infty$).*

Then $\int_Y f_y d\mu(y) \in H^{1,2}_{\text{loc}}(\mathbf{X}, d, \mathbf{m})$ (resp. $\int_Y f_y d\mu(y) \in D_{\text{loc}}(\Delta)$, resp. $\int_Y A_y d\mu(y) \in D_{\text{loc}}(\nabla^)$) with*

$$d \int_Y f_y d\mu(y) = \int_Y df_y d\mu(y)$$

(resp. $\Delta \int_Y f_y d\mu(y) = \int_Y \Delta f_y d\mu(y)$, resp. $\nabla^ \int_Y A_y d\mu(y) = \int_Y \nabla^* A_y d\mu(y)$).*

Proof. We start with the case of differential. We have already noticed that d is weakly local and we know from [30, Theorem 2.2.9] that it is a closed operator. Let us check that the other assumptions in Lemma 3.3 are satisfied. (i) holds by our assumption, thus we pass to (ii). Let U, V as in the statement and let $\varphi \in \text{Lip}(\mathbf{X}, d)$ be identically 1 on V and with support in U (the hypothesis $d(V, \mathbf{X} \setminus U) > 0$ grants that such φ exists). We define $T(f) := \varphi f$ and notice that the properties in (3.1) are trivial. We pass to (iii), and notice that by the very definition of extension of d from $H^{1,2}(\mathbf{X}, d, \mathbf{m})$ to $H^{1,2}_{\text{loc}}(\mathbf{X}, d, \mathbf{m})$ it follows that the Leibniz rule holds even in $H^{1,2}_{\text{loc}}(\mathbf{X}, d, \mathbf{m})$. It is then clear that we have $\varphi f \in H^{1,2}_{\text{loc}}(\mathbf{X}, d, \mathbf{m})$ with $d(\varphi f) = \varphi df + f d\varphi$. Thus

$$|d(\varphi f)| \leq \chi_U |df| \sup |\varphi| + \chi_U C |f| \in L^2(\mathbf{X}, \mathbf{m}), \quad (3.3)$$

where C denotes the Lipschitz constant of φ . Therefore φf is actually in $H^{1,2}(\mathbf{X}, d, \mathbf{m})$.

With this said, let us verify the first claim. Fix $U \subseteq \mathbf{X}$ open bounded, let $\varphi \in \text{Lip}_{bs}(\mathbf{X}, d)$ be identically 1 on U and notice that replacing f_y with φf_y it is sufficient to prove that if $y \mapsto f_y \in L^2(\mathbf{X}, \mathbf{m})$ is Borel and $f_y \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$ for every $y \in Y$, then $y \mapsto df_y \in L^2(T^*(\mathbf{X}, d, \mathbf{m}))$ is strongly Borel. Since $L^2(T^*(\mathbf{X}, d, \mathbf{m}))$ is separable (see [2] and [30, Proposition 2.2.5]), it is enough to check Borel regularity. Also, since $d : H^{1,2}(\mathbf{X}, d, \mathbf{m}) \rightarrow L^2(T^*(\mathbf{X}, d, \mathbf{m}))$ is continuous, it suffices to prove that $y \mapsto f_y \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$ is Borel. To see this it is sufficient to show that the unit ball

in $H^{1,2}(\mathbf{X}, \mathbf{d}, \mathbf{m})$ belongs to the σ -algebra \mathcal{A} generated by L^2 -open sets in $H^{1,2}(\mathbf{X}, \mathbf{d}, \mathbf{m})$. But this is obvious, because the lower semicontinuity of the $H^{1,2}$ -norm w.r.t. L^2 -convergence ensures that closed $H^{1,2}$ -balls are also L^2 -closed, and thus are in \mathcal{A} . Since open balls are countable unions of closed balls, the first claim follows.

For the second we now observe that what just proved, our assumption $\int_Y \|\chi_U df_y\|_{L^2} d\mu(y) < \infty$ and (3.3) ensure that $y \mapsto d(\varphi f_y)$ is in $L^1(Y, \mu; L^2(T^*(\mathbf{X}, \mathbf{d}, \mathbf{m})))$, i.e. (iii) of Lemma 3.3 holds and the conclusion follows from such lemma.

The same line of thought gives the conclusion for ∇^* . For the Laplacian we start noticing that for V, U and φ as above we have

$$\begin{aligned} \int_{\mathbf{X}} |\varphi|^2 |df|^2 d\mathbf{m} &= - \int_{\mathbf{X}} 2f\varphi \langle df, d\varphi \rangle + \varphi^2 f \Delta f d\mathbf{m} \\ &\leq \int_{\mathbf{X}} \frac{1}{2} |\varphi|^2 |df|^2 + 2|d\varphi|^2 |f|^2 + \frac{1}{2} |\varphi|^2 (|f|^2 + |\Delta f|^2) d\mathbf{m}, \end{aligned}$$

i.e. $\frac{1}{2} \int_{\mathbf{X}} |\varphi|^2 |df|^2 d\mathbf{m} \leq C \int_U |f|^2 + |\Delta f|^2 d\mathbf{m}$. This proves that if $f \in D_{loc}(\Delta) \subseteq L^2_{loc}(\mathbf{X}, \mathbf{m})$ then $f \in H^{1,2}_{loc}(\mathbf{X}, \mathbf{d}, \mathbf{m})$ as well. Hence what previously proved tells that for $y \mapsto f_y \in L^2_{loc}$ Borel with $f_y \in D_{loc}(\Delta)$ for μ -a.e. y , we have that $y \mapsto \chi_U df_y \in L^2(T^*(\mathbf{X}, \mathbf{d}, \mathbf{m}))$ is strongly Borel for any $U \subseteq \mathbf{X}$ open bounded. Now we want to prove that the same assumptions ensure that $y \mapsto \chi_U \Delta f_y \in L^2(\mathbf{X}, \mathbf{m})$ is Borel as well. Since the σ -algebra generated by the strong topology coincides with that generated by the weak topology (because the closed unit ball can be realized as countable intersection of weakly-closed halfspaces, so that closed balls are weakly Borel and thus the same holds for open balls since they are countable union of closed balls), by approximation to get the desired Borel regularity it is sufficient to prove that $y \mapsto \int_{\mathbf{X}} \psi \xi \Delta f_y d\mathbf{m}$ is Borel for any $\psi \in \text{Lip}_{bs}(\mathbf{X}, \mathbf{d})$ and ξ varying in a countable dense subset of $L^2(\mathbf{X}, \mathbf{m})$. We pick $\xi \in H^{1,2}(\mathbf{X}, \mathbf{d}, \mathbf{m})$ and notice that

$$\int_{\mathbf{X}} \psi \xi \Delta f_y d\mathbf{m} = - \int_{\mathbf{X}} \langle \nabla(\psi \xi), \nabla f_y \rangle d\mathbf{m} = - \int_U \langle \nabla(\psi \xi), \nabla f_y \rangle d\mathbf{m}$$

for any $U \subseteq \mathbf{X}$ open bounded and containing the support of ψ . By what we already proved we see that the RHS is a Borel function of y , hence the desired Borel regularity follows.

With this said, the conclusion for the Laplacian follows by first applying the result to the differential and then to the divergence (the study of the divergence operator closely follows that of ∇^* that in turn, as said, is largely based on that of d). \square

Remark 3.5. The above version of Hille's theorem is compatible with the more general one recently discussed in [18, Section 3.3]. However, as the presentation here is substantially simpler we preferred giving a direct proof, rather than linking the terminology to that in [18]. \blacksquare

3.2 Gaussian estimates and their consequences

Thanks to (2.7) and (2.12), it follows from [58, Proposition 3.1] that there exists a unique (locally Hölder) continuous function $p : \mathbf{X} \times \mathbf{X} \times (0, \infty) \rightarrow (0, \infty)$, called the *heat kernel* of $(\mathbf{X}, \mathbf{d}, \mathbf{m})$, such that the following holds;

$$h_t f(x) = \int_{\mathbf{X}} p(x, y, t) f(y) d\mathbf{m}(y) \quad \forall f \in L^2(\mathbf{X}, \mathbf{m}), \forall x \in \mathbf{X}. \quad (3.4)$$

Let us denote by $p_{y,t}(x) = p(x, y, t)$ when we consider p as a function on \mathbf{X} for fixed $y \in \mathbf{X}$ and $t > 0$.

Let us recall the Gaussian estimates for the heat kernel p proved in [46], where we are going to use them only specialized to the case $\epsilon = 1$: for any $\epsilon \in (0, 1]$ there exists a positive constant $C := C(K, N, \epsilon)$ depending only on K, N and ϵ such that for any $x, y \in \mathbf{X}$ and any $0 < t < 1$,

$$\frac{C}{\mathbf{m}(B_{\sqrt{t}}(x))} \exp\left(-\frac{d(x, y)^2}{(4 - \epsilon)t} - Ct\right) \leq p(x, y, t) \leq \frac{C}{\mathbf{m}(B_{\sqrt{t}}(x))} \exp\left(-\frac{d(x, y)^2}{(4 + \epsilon)t} + Ct\right), \quad (3.5)$$

and for every $y \in \mathbf{X}$ and $t > 0$ we have

$$|dp_{y,t}|(x) \leq \frac{C}{\sqrt{t}\mathfrak{m}(B_{\sqrt{t}}(x))} \exp\left(-\frac{d(x,y)^2}{(4+\epsilon)t} + Ct\right) \quad \mathfrak{m}\text{-a.e. } x \in \mathbf{X}. \quad (3.6)$$

Notice that (3.5) and Lemma 2.7 ensure that $p(\cdot, y, t) \in L^2(\mathbf{X}, \mathfrak{m})$ for every $y \in \mathbf{X}$, $t > 0$, therefore from (3.4) we deduce the Chapman-Kolmogorov equation:

$$p(x, y, t+s) = h_t p(\cdot, y, s)(x) = \int_{\mathbf{X}} p(x, z, t) p(z, y, s) d\mathfrak{m}(z) \quad \forall t, s > 0, \forall x, y \in \mathbf{X}. \quad (3.7)$$

Also, from (2.3), [57, Corollary 2.7] and (3.5) we deduce the estimate

$$|\Delta p(\cdot, y, t)|(x) \leq \frac{C}{t\mathfrak{m}(B_{\sqrt{t}}(x))} \exp\left(-\frac{d(x,y)^2}{(4+\epsilon)t} + Ct\right) \quad \mathfrak{m}\text{-a.e. } x \in \mathbf{X}, \quad (3.8)$$

for every $y \in \mathbf{X}$, $t > 0$. Notice that the above discussion and estimates easily imply that

$$p_{y,t} \in \text{TestF}(\mathbf{X}, d, \mathfrak{m})$$

for every $y \in \mathbf{X}$, and $t > 0$. We shall frequently use this fact. For future reference we also notice that (3.7) and the estimate (3.5) together with (2.4), (2.12) and Lemma 2.7 give

$$\|p_{y,t}\|_{H^{1,2}} + \|\Delta p_{y,t}\|_{H^{1,2}} \leq C(K, N, t) \mathfrak{m}(B_{\sqrt{t}}(y))^{-\frac{1}{2}}. \quad (3.9)$$

We also notice that the identity $\partial_t p(x, y, t) = \partial_t p_{y,t}(x) = \Delta p_{y,t}(x) = \Delta_x p(x, y, t)$ valid for any $t > 0$, $y \in \mathbf{X}$ and a.e. x together with the symmetry in x, y of the heat kernel - and thus of the LHS - gives

$$\Delta_x p(x, y, t) = \Delta_y p(x, y, t) \quad (\mathfrak{m} \times \mathfrak{m})\text{-a.e. } (x, y), \quad \forall t > 0. \quad (3.10)$$

We conclude pointing out that the continuity of the heat kernel and the estimates (3.5) ensure that for any $t > 0$ the map $y \mapsto p_{y,t} \in L^2(\mathbf{X}, \mathfrak{m})$ is continuous. Thus by the first claim in Proposition 3.4 we deduce that $y \mapsto dp_{y,t} \in L^2(T^*(\mathbf{X}, d, \mathfrak{m}))$ is strongly Borel. Similarly for $y \mapsto \Delta p_{y,t}$ and $y \mapsto d\Delta p_{y,t}$.

3.3 Smoothing metrics g_t and computation of $\nabla^* g_t$

In order to introduce the main tool in this paper, i.e. the *smoothing metrics* g_t , let us start this subsection by observing the smooth case as follows.

For an n -dimensional weighted complete Riemannian manifold $(M, g, e^{-V} d\text{Vol}_g)$ satisfying $\text{Ric}_N \geq Kg$ for some $K \in \mathbb{R}$ and some $N \in [n, \infty)$ (namely $(M, d_g, e^{-V} d\text{Vol}_g)$ is an $\text{RCD}(K, N)$ space, recall (1.3) and (1.4)), for any $t > 0$, define the map $\Phi_t : M \rightarrow L^2(M, e^{-V} d\text{Vol}_g)$ by

$$\Phi_t(x) := (y \mapsto p(x, y, t)) \in L^2(M, e^{-V} d\text{Vol}_g).$$

Then the pull-back $g_t := (\Phi_t)^* g_{L^2}$ is well-defined as a smooth tensor of type $(0, 2)$ and it satisfies

$$g_t(x) = \int_M d_x p_{y,t}(x) \otimes d_x p_{y,t}(x) e^{-V(y)} d\text{Vol}_g(y) \quad \forall x \in M$$

where it is emphasized that the RHS of the above makes sense as Bochner integral for *any* $x \in M$ because of (3.6). In particular, thanks to Fubini's theorem for all smooth vector fields V_i ($i = 1, 2$) on M with bounded supports we have

$$\int_M g_t(V_1, V_2) e^{-V} d\text{Vol}_g = \int_M \int_M d_x p_{y,t}(V_1)(x) d_x p_{y,t}(V_2)(x) e^{-V(x)-V(y)} d\text{Vol}_g(x) d\text{Vol}_g(y)$$

and it is easy to see that this equation also characterizes g_t .

Let us generalize this observation to an $\text{RCD}(K, N)$ space $(\mathbf{X}, d, \mathfrak{m})$ as follows. Start noticing that the identity $|dp_{y,t} \otimes dp_{y,t}|_{\mathfrak{H}} = |dp_{y,t}|^2$, (3.15) below and Lemma 2.7 ensure that for every

$t > 0$ the map $y \mapsto dp_{y,t} \otimes dp_{y,t}$ is in $L^1(X, \mathbf{m}; L^2_{loc}((T^*)^{\otimes 2}(X, \mathbf{d}, \mathbf{m})))$, namely for a bounded $A \subseteq X$ and a fixed $\bar{x} \in A$,

$$\int_X \sqrt{\int_A |dp_{y,t}|^2 d\mathbf{m}(x) d\mathbf{m}(y)} \leq C \sqrt{\mathbf{m}(A)} \int_X e^{-\frac{d^2(\bar{x}, y)}{5t}} d\mathbf{m}(y) < \infty.$$

Hence the following definition is well-posed:

Definition 3.6 (Smoothing metrics g_t). Let $(X, \mathbf{d}, \mathbf{m})$ be an $\text{RCD}(K, N)$ space. We define the $(0, 2)$ tensor $g_t \in L^0((T^*)^{\otimes 2}(X, \mathbf{d}, \mathbf{m}))$ on X as

$$g_t := \int_X d_x p_{y,t} \otimes d_x p_{y,t} d\mathbf{m}(y).$$

Notice that the basic properties of Bochner integration (Hille's Theorem) ensure that for $V_1, V_2 \in L^2(T(X, \mathbf{d}, \mathbf{m}))$ with bounded support we have

$$\int_X g_t(V_1, V_2) d\mathbf{m} = \int_X \int_X dp_{y,t}(V_1) dp_{y,t}(V_2) d\mathbf{m} d\mathbf{m}(y).$$

After a normalization of g_t as follows, the smoothing metrics are uniformly bounded in L^∞ :

Proposition 3.7. *Let $(X, \mathbf{d}, \mathbf{m})$ be an $\text{RCD}(K, N)$ space. Then we have*

$$tm(B_{\sqrt{t}}(\cdot))g_t \leq C(K, N)g \quad \mathbf{m}\text{-a.e.}, \quad \forall t \in (0, 1] \quad (3.11)$$

in the sense of symmetric tensors. In particular we have $g_t \in L^\infty_{loc}((T^)^{\otimes 2}(X, \mathbf{d}, \mathbf{m}))$ and moreover $tm(B_{\sqrt{t}}(\cdot))g_t \in L^\infty((T^*)^{\otimes 2}(X, \mathbf{d}, \mathbf{m}))$.*

Proof. Fix $V \in L^0(T(X, \mathbf{d}, \mathbf{m}))$ and notice that for \mathbf{m} -a.e. x we have

$$\begin{aligned} tm(B_{\sqrt{t}}(x))g_t(V, V)(x) &\leq tm(B_{\sqrt{t}}(x))|V|^2(x) \int_X |dp_{y,t}|^2(x) d\mathbf{m}(y) \\ \text{(by (3.6))} \quad &\leq \frac{C|V|^2(x)}{\mathbf{m}(B_{\sqrt{t}}(x))} \int_X \exp\left(-\frac{d(x, y)^2}{5t} + Ct\right) d\mathbf{m}(y). \end{aligned}$$

The conclusion follows from Lemma 2.7 (with $\alpha = 0$). \square

We now turn to the computation of $\nabla^* g_t$. To this aim, it is convenient to introduce the following function:

$$p_t(x) := p(x, x, t) \stackrel{(3.7)}{=} \int_X p_{y,t/2}^2(x) d\mathbf{m}(y).$$

Notice that thanks to the bounds (3.5) it is easy to see that for every $t > 0$ the map $y \mapsto p_{y,t/2}^2$ is in $L^1(X, \mathbf{m}; L^2(X, \mathbf{m}))$. It is then clear that the identity $p_t = \int_X p_{y,t/2}^2 d\mathbf{m}(y)$ holds also in the sense of Bochner integrals.

Let us start collecting some estimates for this function:

Lemma 3.8. *Let $(X, \mathbf{d}, \mathbf{m})$ be an $\text{RCD}(K, N)$ space.*

Then for any $t > 0$ we have $p_{2t}(x) \in D_{loc}(\Delta)$ with

$$dp_t = 2 \int_X p_{y,t/2} dp_{y,t/2} d\mathbf{m}(y) \quad \text{and} \quad |dp_t| \leq \frac{C(K, N)}{\sqrt{t} \mathbf{m}(B_{\sqrt{t}}(\cdot))} \quad \mathbf{m}\text{-a.e.} \quad (3.12)$$

and

$$\Delta p_t = 2 \int_X p_{y,t/2} \Delta p_{y,t/2} + |dp_{y,t}|^2 d\mathbf{m}(y) \quad \text{and} \quad |\Delta p_t| \leq \frac{C(K, N)}{t \mathbf{m}(B_{\sqrt{t}}(\cdot))} \quad \mathbf{m}\text{-a.e.} \quad (3.13)$$

Finally, we also have $\Delta p_t \in H_{loc}^{1,2}(X, \mathbf{d}, \mathbf{m})$ with

$$d\Delta p_t = 2 \int_X dp_{y,t/2} \Delta p_{y,t/2} + p_{y,t/2} d\Delta p_{y,t/2} + d|dp_{y,t}|^2 d\mathbf{m}(y). \quad (3.14)$$

It is part of the claim the fact that the integrands in (3.12) and (3.14) belong to the space $L^1(X, \mathbf{m}; L^2_{loc}(T^(X, \mathbf{d}, \mathbf{m})))$ and the one in (3.13) belongs to the space $L^1(X, \mathbf{m}; L^2_{loc}(X, \mathbf{m}))$.*

Proof. Using (3.5) and (3.6) we get

$$\int_{\mathbf{X}} |d(p_{y,t/2}^2)| \, d\mathbf{m}(y) \leq 2 \int_{\mathbf{X}} p_{y,t/2} |dp_{y,t/2}| \, d\mathbf{m}(y) \leq \frac{C}{\sqrt{t} \mathbf{m}(B_{\sqrt{t}}(\cdot))^2} \int_{\mathbf{X}} \exp\left(-\frac{2d^2(\cdot, y)}{5t} + Ct\right) \, d\mathbf{m}(y).$$

Thus from Lemma 2.7 and Proposition 3.4 we deduce that $p_t \in H_{loc}^{1,2}(\mathbf{X}, d, \mathbf{m})$ and that (3.12) holds. Similarly, starting from

$$\int_{\mathbf{X}} |\Delta(p_{y,t/2}^2)| \, d\mathbf{m}(y) \leq 2 \int_{\mathbf{X}} p_{y,t/2} |\Delta p_{y,t/2}| + |dp_{y,t/2}|^2 \, d\mathbf{m}(y)$$

and using the estimates (3.5), (3.6) and (3.8) and then again Lemma 2.7 and Proposition 3.4, we conclude that $p_t(x) \in D_{loc}(\Delta)$ and that (3.13) holds.

For the last claim we recall that $p_{y,t} \in \text{TestF}(\mathbf{X}, d, \mathbf{m})$, thus the Leibniz rule for the Laplacian and the basic properties of test functions give $p_{y,t/2} \Delta p_{y,t/2} + |dp_{y,t}|^2 \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$ with

$$d(p_{y,t/2} \Delta p_{y,t/2} + |dp_{y,t}|^2) = dp_{y,t/2} \Delta p_{y,t/2} + p_{y,t/2} d\Delta p_{y,t/2} + 2\text{Hess } p_{y,t}(\nabla p_{y,t}, \cdot).$$

The fact that the first two addends in the RHS are in $L^1(\mathbf{X}, \mathbf{m}; L_{loc}^2(T^*(\mathbf{X}, d, \mathbf{m})))$ can be proved as before. For the last one we let $A \subseteq \mathbf{X}$ be Borel and bounded and $\bar{x} \in \mathbf{X}$. Then we have $d(x, y) \geq d(y, \bar{x}) - R$ for any $x \in A$, $y \in \mathbf{X}$ and some $R > 0$ independent on x, y . Hence (3.6) implies that $\|dp_{y,t}\|_{L^\infty(A)} \leq Ce^{-\frac{d^2(y, \bar{x})}{5t}}$ for some $C = C(t, K, N, A, \bar{x})$, thus

$$\begin{aligned} \int_{\mathbf{X}} \sqrt{\int_A |\text{Hess } p_{y,t}(\nabla p_{y,t}, \cdot)|^2 \, d\mathbf{m}(x)} \, d\mathbf{m}(y) &\leq \int_{\mathbf{X}} \|\text{Hess } p_{y,t}\|_{\text{HS}} \|dp_{y,t}\|_{L^\infty(A)} \, d\mathbf{m}(y) \\ &\stackrel{\text{(by (2.11))}}{\leq} C \int_{\mathbf{X}} (\|\Delta p_{y,t}\|_{L^2} + \|dp_{y,t}\|_{L^2}) e^{-\frac{d^2(y, \bar{x})}{5t}} \, d\mathbf{m}(y) \\ &\stackrel{\text{(by (3.9))}}{\leq} C \int_{\mathbf{X}} \mathbf{m}(B_{\sqrt{t}}(y))^{-\frac{1}{2}} e^{-\frac{d^2(y, \bar{x})}{5t}} \, d\mathbf{m}(y) < \infty, \end{aligned}$$

where the last inequality comes from Lemma 2.7. The conclusion follows. \square

To further analyze the link between g_t and p_t the following result will be crucial:

Lemma 3.9. *Let $(\mathbf{X}, d, \mathbf{m})$ be an $\text{RCD}(K, N)$ space. Then for every $t > 0$ we have that $y \mapsto \Delta p_{y,t} dp_{y,t}$ and $y \mapsto p_{y,t} d\Delta p_{y,t}$ are both in $L^1(\mathbf{X}, \mathbf{m}; L_{loc}^2(T^*(\mathbf{X}, d, \mathbf{m})))$ and*

$$\int_{\mathbf{X}} \Delta p_{y,t} dp_{y,t} \, d\mathbf{m}(y) = \int_{\mathbf{X}} p_{y,t} d\Delta p_{y,t} \, d\mathbf{m}(y).$$

Proof. For the first part of the claim we argue as in the proof of Lemma 3.8 above: let $A \subseteq \mathbf{X}$ be Borel and bounded and $\bar{x} \in \mathbf{X}$. Then, (3.6) implies that for some $C = C(t, K, N, A, \bar{x})$

$$\|dp_{y,t}\|_{L^\infty(A)} \leq \left\| Ce^{-\frac{d^2(y, \cdot)}{(4+1/2)t}} \right\|_{L^\infty(A)} \leq Ce^{-\frac{d^2(y, \bar{x})}{5t}}, \quad (3.15)$$

so that,

$$\int_{\mathbf{X}} \sqrt{\int_A |\Delta p_{y,t} dp_{y,t}|^2 \, d\mathbf{m}(x)} \, d\mathbf{m}(y) \leq C \int_{\mathbf{X}} \|\Delta p_{y,t}\|_{L^2} e^{-\frac{d^2(y, \bar{x})}{5t}} \, d\mathbf{m}(y) < \infty,$$

having used the bound (3.9) and Lemma 2.7 in the last step. This proves that $y \mapsto \Delta p_{y,t} dp_{y,t}$ is in $L^1(\mathbf{X}, \mathbf{m}; L_{loc}^2(T^*(\mathbf{X}, d, \mathbf{m})))$ and an analogous argument gives the same for $y \mapsto p_{y,t} d\Delta p_{y,t}$.

Now write the Chapman-Kolmogorov equation (3.7) as

$$\int_{\mathbf{X}} p(y, z, s) p_{z,t} \, d\mathbf{m}(z) = p_{y,t+s}$$

and observe that the estimates (3.5), (3.6) and the same arguments just used ensure that for any $y \in \mathbf{X}$ the maps $z \mapsto p(y, z, s)p_{z,t}$ and $z \mapsto p(y, z, s)dp_{z,t}$ are in $L^1(\mathbf{X}, \mathbf{m}; L^2_{loc}(\mathbf{X}, \mathbf{m}))$ and $L^1(\mathbf{X}, \mathbf{m}; L^2_{loc}(T^*(\mathbf{X}, \mathbf{d}, \mathbf{m})))$ respectively. Thus Proposition 3.4 gives

$$\int_{\mathbf{X}} p(y, z, s) dp_{z,t} \, d\mathbf{m}(z) = dp_{y,t+s}.$$

Multiplying both sides by $p_{y,t}$, integrating in y and using Fubini's theorem we obtain

$$\int_{\mathbf{X}} p_{z,t+s} dp_{z,t} \, d\mathbf{m}(z) \stackrel{(3.7)}{=} \int_{\mathbf{X}} \int_{\mathbf{X}} p_{y,t} p(y, z, s) dp_{z,t} \, d\mathbf{m}(z) \, d\mathbf{m}(y) = \int_{\mathbf{X}} p_{y,t} dp_{y,t+s} \, d\mathbf{m}(y).$$

Thus to conclude it is sufficient to prove that as $s \rightarrow 0^+$ we have

$$\begin{aligned} \int_{\mathbf{X}} \frac{p_{y,t+s} - p_{y,t}}{s} dp_{y,t} \, d\mathbf{m}(y) &\rightarrow \int_{\mathbf{X}} \Delta p_{y,t} dp_{y,t} \, d\mathbf{m}(y), \\ \int_{\mathbf{X}} p_{y,t} d\left(\frac{p_{y,t+s} - p_{y,t}}{s}\right) d\mathbf{m}(y) &\rightarrow \int_{\mathbf{X}} p_{y,t} d\Delta p_{y,t} \, d\mathbf{m}(y) \end{aligned} \quad (3.16)$$

in $L^2_{loc}(T^*(\mathbf{X}, \mathbf{d}, \mathbf{m}))$. We start noticing that from (3.7) we have

$$\begin{aligned} F_{y,t} &:= \frac{p_{y,t+s} - p_{y,t}}{s} - \Delta p_{y,t} = \int_0^1 \Delta(p_{y,t+rs} - p_{y,t}) \, dr \\ &= s \int_0^1 r \Delta\left(\int_0^1 \Delta p_{y,t+rs} \, dh\right) \, dr \\ &= s \int_0^1 r \Delta h_{t/3} \left(\int_0^1 \Delta h_{t/3} p_{y,t/3+rs} \, dh\right) \, dr \end{aligned}$$

and therefore using twice (2.4) we obtain

$$\|F_{y,t}\|_{L^2} \leq sC(t) \int_0^1 \int_0^1 \|p_{y,t/3+rs}\|_{L^2} \, dh \, dr \stackrel{(2.5)}{\leq} sC(t) \|p_{y,t/3}\|_{L^2} \stackrel{(3.9)}{\leq} sC(K, N, t) \mathbf{m}(B_{\sqrt{\frac{t}{3}}}(y))^{-\frac{1}{2}}. \quad (3.17)$$

Thus for $A \subseteq \mathbf{X}$ Borel and bounded we have

$$\int_{\mathbf{X}} \sqrt{\int_A |F_{y,t} dp_{y,t}|^2 \, d\mathbf{m} \, d\mathbf{m}(y)} \stackrel{(3.15)}{\leq} C \int_{\mathbf{X}} \|F_{y,t}\|_{L^2} e^{-\frac{d^2(y, \bar{x})}{8t}} \, d\mathbf{m}(y) \stackrel{(3.17)}{\leq} sC \int_{\mathbf{X}} \frac{e^{-\frac{d^2(y, \bar{x})}{8t}}}{\mathbf{m}(B_{\sqrt{\frac{t}{3}}}(y))^{\frac{1}{2}}} \, d\mathbf{m}(y)$$

for some $C = C(K, N, t, A, \bar{x})$. Since the last integral is finite by Lemma 2.7, the LHS goes to 0 as $s \rightarrow 0^+$. This proves the first in (3.16). The second follows along very similar lines, we omit the details. \square

We are now in a position to prove the main result of this subsection:

Theorem 3.10. *Let $(\mathbf{X}, \mathbf{d}, \mathbf{m})$ be an $\text{RCD}(K, N)$ space. Then for every $t > 0$ we have $g_t \in D_{loc}(\nabla^*)$ with*

$$\nabla^* g_t = -\frac{1}{4} \mathbf{d} \Delta p_{2t}. \quad (3.18)$$

Proof. For any $y \in \mathbf{X}$ Proposition 2.6 tells $\nabla^*(dp_{y,t} \otimes dp_{y,t}) = -\Delta p_{y,t} dp_{y,t} - \frac{1}{2} \mathbf{d} |\nabla p_{y,t}|^2$. Also, arguing as in Lemma 3.8 it is easy to see that $y \mapsto -\Delta p_{y,t} dp_{y,t} - \frac{1}{2} \mathbf{d} |\nabla p_{y,t}|^2$ belongs to the space $L^1(\mathbf{X}, \mathbf{m}; L^2_{loc}(T^*(\mathbf{X}, \mathbf{d}, \mathbf{m})))$. Thus taking into account Lemma 3.9 we obtain

$$\int_{\mathbf{X}} \nabla^*(dp_{y,t} \otimes dp_{y,t}) \, d\mathbf{m}(y) = -\frac{1}{2} \int_{\mathbf{X}} \Delta p_{y,t} dp_{y,t} + p_{y,t} d\Delta p_{y,t} + \mathbf{d} |dp_{y,t}|^2 \, d\mathbf{m}(y) \stackrel{(3.14)}{=} -\frac{1}{4} \mathbf{d} \Delta p_{2t}.$$

The conclusion comes from the very definition of g_t and Proposition 3.4. \square

3.4 Asymptotic behaviour as $t \rightarrow 0^+$

The goal of this subsection is to study the behaviour of g_t and $\nabla^* g_t$ as $t \rightarrow 0^+$.

We start with the following result, which generalizes to the non-compact setting the analogous statement [8, Theorem 5.10]:

Theorem 3.11. *Let (X, d, m) be an $RCD(K, N)$ space of essential dimension n .*

Then $tm(B_{\sqrt{t}}(\cdot))g_t \rightarrow c_n g$ strongly in L^p_{loc} for any $p \in [1, \infty)$, where c_n is a positive constant depending only on n .

Proof. Since the proof is essentially same to that in [8, Theorem 5.10] after replacing L^p by L^p_{loc} (recall that [8, Theorem 5.10] discussed only on the case when (X, d) is compact), we shall only give a sketch of the proof.

Fix $V \in L^\infty(T(X, d, m))$ with bounded support. First let us discuss the asymptotic behaviour of the following as $t \rightarrow 0^+$ for fixed $y \in X$ and $L > 0$:

$$\begin{aligned} & \int_X tm(B_{\sqrt{t}}(x)) |dp_{y,t}(V)|^2(x) dm(x) \\ &= \int_{B_{L\sqrt{t}}(y)} tm(B_{\sqrt{t}}(\cdot)) |dp_{y,t}(V)|^2 dm + \int_{X \setminus B_{L\sqrt{t}}(y)} tm(B_{\sqrt{t}}(\cdot)) |dp_{y,t}(V)|^2 dm. \end{aligned} \quad (3.19)$$

The key idea to control the each terms in the RHS of (3.19) is to apply *blow-up arguments* (i.e. we discuss the behaviour of the rescaled spaces $(X, \sqrt{t}^{-1}d, m(B_{\sqrt{t}}(y))^{-1}m, y)$ with respect to the pointed measured Gromov-Hausdorff convergence as $t \rightarrow 0^+$) in conjunction with the stability of the heat flow first observed in [28]. More precisely, we use the stability results proved in [7, Corollary 5.5, Theorem 5.7, Lemma 5.8], [6, Theorem 4.4], [9, Theorem 3.3] (with [8, Theorem 2.19]), [34, Theorem 6.8] with Theorem 2.13 and (3.6). Combining these, letting $t \rightarrow 0^+$ and then letting $L \rightarrow \infty$ in the RHS of (3.19), the following hold for m -a.e. $y \in X$:

1. The first term of the RHS of (3.19) converges to $c_n |V|^2(y)$.
2. The second term of the RHS of (3.19) converges to 0.

Thus as $t \rightarrow 0^+$ we obtain

$$\int_X tm(B_{\sqrt{t}}(x)) |dp_{y,t}(V)|^2(x) dm(x) \rightarrow c_n |V|^2(y) \quad m\text{-a.e. } y \in X.$$

Thus combining this with (3.11) and the dominated convergence theorem we get

$$\int_X tm(B_{\sqrt{t}}(\cdot))g_t(V, V) dm \rightarrow c_n \int_X |V|^2 dm$$

which proves that $tm(B_{\sqrt{t}}(\cdot))g_t$ L^p -weakly converge to $c_n g$ on any bounded subset A of X because g_t is symmetric and V is arbitrary.

In order to get the L^p_{loc} -strong convergence it suffices to check

$$\lim_{t \rightarrow 0^+} \int_X \varphi |tm(B_{\sqrt{t}}(\cdot))g_t|_{HS}^2 dm = c_n^2 \int_X \varphi |g|_{HS}^2 dm = c_n^2 n \int_X \varphi dm \quad (3.20)$$

for every $\varphi \in \text{Lip}_{bs}(X, d)$, because this implies the L^2_{loc} -strong convergence and the improvement to the L^p_{loc} -strong one comes from (3.11). Let us check (3.20) as follows.

For any $z \in \mathcal{R}_n$, applying blow-up arguments as explained above again allows us to deduce

$$F(z, t) := \frac{1}{m(B_{\sqrt{t}}(z))} \int_{B_{\sqrt{t}}(z)} |tm(B_{\sqrt{t}}(\cdot))g_t|_{HS}^2 dm \rightarrow c_n^2 n$$

and thus (recalling (3.11) to use the dominated convergence theorem) for $\varphi \in \text{Lip}_{bs}(X, d)$ we have

$$\lim_{t \rightarrow 0^+} \int_X \varphi(z) F(z, t) dm(z) = c_n^2 n \int_X \varphi dm. \quad (3.21)$$

On the other hand, we have

$$\int_X \varphi(z) F(z, t) \, \mathrm{d}\mathbf{m}(z) = \int_X |\mathbf{t}\mathbf{m}(B_{\sqrt{t}}(\cdot)) g_t|_{\mathrm{HS}}^2(x) \underbrace{\int_{B_{\sqrt{t}}(x)} \frac{\varphi(z)}{\mathbf{m}(B_{\sqrt{t}}(z))} \, \mathrm{d}\mathbf{m}(z)}_{=: G(x, t)} \, \mathrm{d}\mathbf{m}(x). \quad (3.22)$$

Now notice that $\sup_{t, x} G(x, t) < \infty$ (because of (2.14)) and $\lim_{t \rightarrow 0^+} G(x, t) = \varphi(x)$ for \mathbf{m} -a.e. x (because of the convergence of the blow-ups to the Euclidean space). It follows (again using (3.11) to use the dominate convergence theorem) that

$$\lim_{t \rightarrow 0^+} \int_X |\mathbf{t}\mathbf{m}(B_{\sqrt{t}}(\cdot)) g_t|_{\mathrm{HS}}^2(x) \left| \int_{B_{\sqrt{t}}(x)} \frac{\varphi(z)}{\mathbf{m}(B_{\sqrt{t}}(z))} \, \mathrm{d}\mathbf{m}(z) - \varphi(x) \right| \, \mathrm{d}\mathbf{m}(x) = 0$$

which together with (3.21) and (3.22) gives (3.20) and the conclusion. \square

Remark 3.12. In Theorem 3.11, the conclusion can not be improved to the case when $p = \infty$ in general. For example, the $\mathrm{RCD}(0, 1)$ space $([0, \pi], \mathbf{d}_{\mathbb{R}}, \mathcal{H}^1)$ satisfies

$$\liminf_{t \rightarrow 0^+} \|t \mathcal{H}^1(B_{\sqrt{t}}(\cdot)) g_t - c_1 g_{\mathbb{R}}\|_{L^\infty} > 0.$$

See [8, Remark 5.11] for details. It is worth pointing out that the verification of

$$\|\mathbf{t}\mathbf{m}(B_{\sqrt{t}}(\cdot)) g_t - c_n g\|_{L_{loc}^\infty} \rightarrow 0 \quad (3.23)$$

is closely related to the nonexistence of singular points (actually the singular points are $\{0, \pi\}$ in this example). See also [44, Theorem 1.1].

In connection with this pointing out, if $(M, g, e^{-V} \mathrm{dVol}_g)$ is any weighted complete n -dimensional Riemannian manifold with $\mathrm{Ric}_N \geq Kg$ for some $K \in \mathbb{R}$ and some $N \in [n, \infty)$, applying a construction of the heat kernel by *parametrix*, we can actually prove that (3.23) holds. More precisely we have as $t \rightarrow 0^+$.

$$\begin{aligned} & 4(8\pi)^{n/2} t^{(n+2)/2} g_t \\ &= e^V g - e^V \left(\frac{2}{3} \left(\mathrm{Ric}_g - \frac{1}{2} \mathrm{Scal}_g g \right) - \mathrm{d}V \otimes \mathrm{d}V - \Delta^g V g + \frac{|\nabla^g V|^2}{2} g \right) t + O(t^2), \end{aligned}$$

which is uniform on any bounded set. See [15, Theorem 5] and [45, Theorem 3.5] for details. \blacksquare

Corollary 3.13. *Let $(X, \mathbf{d}, \mathbf{m})$ be an $\mathrm{RCD}(K, N)$ space of essential dimension n . Let A be a bounded Borel subset of X with*

$$\inf_{r \in (0, 1), x \in A} \frac{\mathbf{m}(B_r(x))}{r^n} > 0. \quad (3.24)$$

Then $\mathcal{H}^n \llcorner A$ is a Radon measure absolutely continuous w.r.t. \mathbf{m} and

$$\chi_A \omega_n t^{(n+2)/2} g_t \rightarrow \chi_A c_n \frac{\mathrm{d}\mathcal{H}^n \llcorner A}{\mathrm{d}\mathbf{m}} g \quad \text{in } L^p((T^*)^{\otimes 2}(X, \mathbf{d}, \mathbf{m})), \forall p \in [1, \infty).$$

Proof. The first part of the claim follows from Lemma 2.14 and (3.24). Then Theorem 2.13 ensures that as $r \rightarrow 0^+$

$$\frac{\omega r^n}{\mathbf{m}(B_r(x))} \rightarrow \frac{\mathrm{d}\mathcal{H}^n \llcorner A}{\mathrm{d}\mathbf{m}} \quad \mathbf{m}\text{-a.e. } x \in A.$$

Thus (3.24), the dominated convergence theorem and Theorem 3.11 give the conclusion. \square

We now turn to the asymptotic of Δp_{2t} :

Proposition 3.14. *Let $(X, \mathbf{d}, \mathbf{m})$ be an $\mathrm{RCD}(K, N)$ space, $K \in \mathbb{R}$, $N \in [1, \infty)$. Then as $t \rightarrow 0^+$ we have*

$$\mathbf{t}\mathbf{m}(B_{\sqrt{t}}(\cdot)) \Delta p_{2t}(\cdot) \rightarrow 0 \quad \text{in } L_{loc}^p(X, \mathbf{m}), \forall p \in [1, \infty).$$

Proof. The proof is based on blow-up arguments which is similar to that of Theorem 3.11. Therefore we give only a sketch of the proof (see also [8]).

Let us first prove that for any $z \in \mathcal{R}_n$, as $t \rightarrow 0^+$,

$$\frac{1}{\mathbf{m}(B_{\sqrt{t}}(z))} \int_{B_{\sqrt{t}}(z)} t \mathbf{m}(B_{\sqrt{t}}(x)) |\Delta p_{2t}(x)| d\mathbf{m}(x) \rightarrow 0. \quad (3.25)$$

In order to prove this, consider the pointed measured Gromov-Hausdorff convergent sequence of the rescaled space:

$$(\mathbf{X}^{t,z}, \mathbf{d}^{t,z}, \mathbf{m}^{t,z}, z) := \left(\mathbf{X}, \frac{1}{\sqrt{t}} \mathbf{d}, \frac{1}{\mathbf{m}(B_{\sqrt{t}}(z))} \mathbf{m}, z \right) \xrightarrow{\text{pmGH}} \left(\mathbb{R}^n, \mathbf{d}_{\mathbb{R}^n}, \frac{1}{\omega_n} \mathcal{H}^n, 0_n \right) \quad (3.26)$$

and denote by $p^{t,z}$, $\Delta^{t,z}$, the heat kernel, the Laplacian of $(\mathbf{X}^{t,z}, \mathbf{d}^{t,z}, \mathbf{m}^{t,z})$, respectively, namely $p^{t,z}(x, y, s) = \mathbf{m}(B_{\sqrt{t}}(z)) p(x, y, ts)$, $\Delta^{t,z} f = t \Delta f$. Thus the LHS of (3.25) is equal to

$$\int_{B_1^{\mathbf{d}^{t,z}}(z)} \mathbf{m}^{t,z}(B_1^{\mathbf{d}^{t,z}}(x)) |\Delta^{t,z} p_2^{t,z}(x)| d\mathbf{m}^{t,z}(x). \quad (3.27)$$

Applying the stability results already used in the proof of Theorem 3.11 shows that $\Delta^{t,z} p_2^{t,z} L_{loc}^2$ -strongly converge to $\Delta^{g_{\mathbb{R}^n}}(\omega_n \tilde{p}_2)$ with respect to (3.26), where $\tilde{p}(x)$ denotes the heat kernel of the n -dimensional Euclidean space evaluated at (x, x) . Since $\Delta^{g_{\mathbb{R}^n}}(\omega_n \tilde{p}_2) = 0$ because \tilde{p}_2 is constant, (3.27) converges to

$$\int_{B_1(0_n)} |\Delta^{g_{\mathbb{R}^n}}(\omega_n \tilde{p}_2)| d\left(\frac{1}{\omega_n} \mathcal{H}^n\right) = 0$$

as $t \rightarrow 0^+$, which proves (3.25).

Fix a $\varphi \in \text{Lip}_{bs}(\mathbf{X}, \mathbf{d})$. Applying (3.25) with (3.13), the dominated convergence theorem yields

$$\int_{\mathbf{X}} \frac{\varphi(z)}{\mathbf{m}(B_{\sqrt{t}}(z))} \int_{B_{\sqrt{t}}(z)} t \mathbf{m}(B_{\sqrt{t}}(x)) |\Delta p_{2t}(x)| d\mathbf{m}(x) d\mathbf{m}(z) \rightarrow 0.$$

On the other hand (3.13) and dominated convergence (recall (2.14)) imply

$$\begin{aligned} & \left| \int_{\mathbf{X}} \frac{\varphi(z)}{\mathbf{m}(B_{\sqrt{t}}(z))} \int_{B_{\sqrt{t}}(z)} t \mathbf{m}(B_{\sqrt{t}}(x)) |\Delta p_{2t}(x)| d\mathbf{m}(x) d\mathbf{m}(z) - \int_{\mathbf{X}} \varphi(z) t \mathbf{m}(B_{\sqrt{t}}(z)) |\Delta p_{2t}(z)| d\mathbf{m}(z) \right| \\ & \leq C(K, N) \int_{\mathbf{X}} \left| \varphi(z) - \int_{B_{\sqrt{t}}(z)} \frac{\varphi(x)}{\mathbf{m}(B_{\sqrt{t}}(x))} d\mathbf{m}(x) \right| d\mathbf{m}(z) \rightarrow 0. \end{aligned}$$

Thus

$$\int_{\mathbf{X}} \varphi(x) t \mathbf{m}(B_{\sqrt{t}}(x)) |\Delta p_{2t}(x)| d\mathbf{m}(x) \rightarrow 0. \quad (3.28)$$

The desired L_{loc}^p -strong convergence comes from (3.28) and (3.13). \square

Corollary 3.15. *Let $(\mathbf{X}, \mathbf{d}, \mathbf{m})$ be an $\text{RCD}(K, N)$ space. Also, let A be a bounded Borel subset of X and $n \in \mathbb{N}$ be such that*

$$\inf_{r \in (0,1), x \in A} \frac{\mathbf{m}(B_r(x))}{r^n} > 0.$$

Then as $t \rightarrow 0^+$

$$t^{(n+2)/2} \Delta p_{2t} \rightarrow 0 \quad \text{in } L^2(A, \mathbf{m}).$$

Proof. Direct consequence of Proposition 3.14. \square

Remark 3.16. Although the above convergence results are stated for the strong convergence in order to get our best knowledges, their weak convergences are enough to justify our main results as easily seen in the next section. \blacksquare

4 Proof of the main results

From both the technical and conceptual points of view, the following is the crucial result in this paper. Its proof is basically a combination of the convergence results established in Corollaries 3.13, 3.15 together with formula (3.18):

Theorem 4.1 (Integration-by-parts formula). *Let (X, d, m) be an $RCD(K, N)$ space of essential dimension n . Let also $U \subseteq X$ be open and assume that*

$$\inf_{r \in (0,1), x \in A} \frac{m(B_r(x))}{r^n} > 0$$

for every compact subset A of U . Then for any $\varphi \in \text{Lip}_{bs}(X, d)$ with $\text{supp}(\varphi) \subseteq U$ and $f \in D(\Delta)$, it holds that

$$\int_X \langle d\varphi, df \rangle d\mathcal{H}^n = - \int_X \varphi \text{tr}(\text{Hess} f) d\mathcal{H}^n.$$

Proof. The assumptions on φ, f ensure that φdf is in the domain of the covariant derivative with $\nabla(\varphi df) = df \otimes d\varphi + \varphi \text{Hess} f$ (see [30, Theorem 3.4.2, Proposition 3.4.5]), with identifications under the Riesz isomorphisms. Thus (3.18) gives

$$\begin{aligned} \int_X \langle t^{(n+2)/2} g_t, \nabla(\varphi df) \rangle_{\text{HS}} d\mathbf{m} &= -\frac{1}{4} \int_X \langle \nabla \Delta(t^{(n+2)/2} p_{2t}), \varphi \nabla f \rangle d\mathbf{m} \\ &= \frac{1}{4} \int_X \Delta(t^{(n+2)/2} p_{2t}) \text{div}(\varphi \nabla f) d\mathbf{m}. \end{aligned} \quad (4.1)$$

Let us take the limit $t \rightarrow 0^+$ in (4.1). The RHS converge to 0 because of Corollary 3.15 applied with $A := \text{supp}(\varphi)$. On the other hand by Corollary 3.13 applied with $A := \text{supp}(\varphi)$, the LHS of (4.1) converges to, up to multiplying by a constant,

$$\int_X \langle g, \nabla(\varphi df) \rangle_{\text{HS}} d\mathcal{H}^n = \int_X \langle df, df \rangle d\mathcal{H}^n + \int_X \varphi \text{tr}(\text{Hess} f) d\mathcal{H}^n.$$

This completes the proof. \square

To deduce from the above the equivalence of the ‘weak’ and ‘strong’ non-collapsed conditions we shall use the following simple result:

Lemma 4.2. *Let (X, d, m) be an $RCD(K, N)$ space. Also, let $U \subseteq X$ be an open connected set and let $\xi \in L_{loc}^\infty(U, m)$. Assume that for every $\psi \in \text{Lip}_{bs}(X, d)$ with support in U and $f \in D(\Delta)$ it holds*

$$\int_X \xi \langle \nabla \psi, \nabla f \rangle d\mathbf{m} = - \int_X \xi \psi \Delta f d\mathbf{m}. \quad (4.2)$$

Then ξ is constant on U .

Proof. It suffices to check that ξ is locally constant on U because U is connected. Let $z \in X$ and $r \in (0, \frac{1}{6})$ with $B_{3r}(z) \subseteq U$ and let $\psi \in \text{Lip}(X, d)$ be identically 1 on $B_{2r}(z)$ and with support in $B_{3r}(z)$. Also, set $\xi_t := h_t(\chi_{B_{2r}(z)} \xi) \in D(\Delta)$, namely $\xi_t(y) = \int_{B_{2r}(z)} p(x, y, t) \xi(x) d\mathbf{m}(x)$ for m -a.e. $y \in X$ and notice that Hille’s theorem (see also Proposition 3.4) gives

$$\Delta \xi_t(y) = \int_{B_{2r}(z)} \Delta_y p(x, y, t) \xi(x) d\mathbf{m}(x) \stackrel{(3.10)}{=} \int_{B_{2r}(z)} \xi \Delta p_{y,t} d\mathbf{m}.$$

This identity and the assumption (4.2) (with $f = p_{y,t}$) give

$$\Delta \xi_t(y) = \int_X (\chi_{B_{2r}(z)} - \psi) \xi \Delta p_{y,t} d\mathbf{m} - \int_X \xi \langle \nabla \psi, \nabla p_{y,t} \rangle d\mathbf{m}$$

for \mathbf{m} -a.e. $y \in \mathbf{X}$. Therefore the assumption $\xi \in L_{loc}^\infty(U, \mathbf{m})$ tells that for $y \in B_r(z)$ we have

$$\begin{aligned} |\Delta \xi_t|(y) &\leq C \int_{B_{3r}(z) \setminus B_{2r}(z)} |\Delta p_{y,t}| d\mathbf{m} + C \int_{B_{3r}(z) \setminus B_{2r}(z)} |\nabla p_{y,t}| d\mathbf{m} \\ (\text{by (3.6), (3.8)}) \quad &\leq C \left(t^{-1} + t^{-1/2} \right) \exp \left(-\frac{r^2}{5t} \right) \int_{B_{3r}(z)} \frac{1}{\mathbf{m}(B_{\sqrt{t}}(x))} d\mathbf{m}(x), \end{aligned}$$

where C is a positive constant which is independent with t and y . Now notice that (2.12) and the assumption $r \in (0, \frac{1}{6})$ ensure that $\frac{1}{\mathbf{m}(B_{\sqrt{t}}(x))} \leq \frac{C(K,N)}{\mathbf{m}(B_1(z))} t^{-\frac{N}{2}}$ for every $t \in (0, 1)$ and $x \in B_{3r}(z)$. It then follows that $\Delta \xi_t$ uniformly converge to 0 on $B_r(z)$.

Let now $\varphi \in \text{Lip}(\mathbf{X}, d)$ be with support in $B_r(z)$ and notice that

$$\int_{\mathbf{X}} |d(\varphi \xi_t)|^2 d\mathbf{m} = \int_{\mathbf{X}} |\xi_t|^2 |d\varphi|^2 + 2\xi_t \varphi \langle d\xi_t, d\varphi \rangle + |\varphi|^2 |d\xi_t|^2 d\mathbf{m} = \int_{\mathbf{X}} |\xi_t|^2 |d\varphi|^2 - |\varphi|^2 \xi_t \Delta \xi_t d\mathbf{m}.$$

By what we proved we see that the RHS is bounded as $t \rightarrow 0^+$, hence the lower semicontinuity of the Cheeger energy ensures that $\varphi \xi \in H^{1,2}(\mathbf{X}, d, \mathbf{m})$. Now choose $\varphi \in \text{Lip}(\mathbf{X}, d)$ identically 1 on $B_{r/2}(z)$ and with support in $B_r(z)$ and let $\eta \in \text{Lip}(\mathbf{X}, d)$ be arbitrary with support in $B_{r/2}(z)$. Since $\text{supp}(\eta) \subseteq \{\varphi = 1\}$, from (4.2) it follows that

$$\int_{\mathbf{X}} \varphi \xi \langle \nabla \eta, \nabla f \rangle d\mathbf{m} = - \int_{\mathbf{X}} \eta \xi \varphi \Delta f d\mathbf{m} \quad (4.3)$$

for any $f \in D(\Delta)$. Moreover, by what we just proved the following computations are justified:

$$- \int_{\mathbf{X}} \varphi \xi \eta \Delta f d\mathbf{m} = \int_{\mathbf{X}} \langle \nabla(\varphi \xi \eta), \nabla f \rangle d\mathbf{m} = \int_{\mathbf{X}} \varphi \xi \langle \nabla \eta, \nabla f \rangle + \eta \langle \nabla(\varphi \xi), \nabla f \rangle d\mathbf{m}.$$

This and (4.3) imply that $\int_{\mathbf{X}} \eta \langle \nabla \xi, \nabla f \rangle d\mathbf{m} = \int_{\mathbf{X}} \eta \langle \nabla(\varphi \xi), \nabla f \rangle d\mathbf{m} = 0$. The arbitrariness of η then gives $\langle \nabla(\varphi \xi), \nabla f \rangle = 0$ \mathbf{m} -a.e. on $B_{r/2}(z)$. Then the density of $D(\Delta)$ in $H^{1,2}(\mathbf{X}, d, \mathbf{m})$ gives $\nabla(\varphi \xi) = 0$ \mathbf{m} -a.e. on $B_{r/2}(z)$. In turn this implies (e.g. from the Sobolev to Lipschitz property) that $\varphi \xi$, and thus ξ , has a representative which is constant in $B_{r/2}(z)$, which is sufficient to conclude. \square

We have now all the ingredients to prove the main equivalence result of this manuscript.

Proof of Theorem 1.5. Under (1.14), we can apply Theorem 4.1 and deduce the integration-by-parts formula:

$$\int_{\mathbf{X}} \langle d\varphi, df \rangle \frac{d\mathcal{H}^n}{d\mathbf{m}} d\mathbf{m} = - \int_{\mathbf{X}} \varphi \text{tr}(\text{Hess} f) \frac{d\mathcal{H}^n}{d\mathbf{m}} d\mathbf{m},$$

valid for any $\varphi \in \text{Lip}(\mathbf{X}, d)$ with support in U and any $f \in D(\Delta)$. Now notice that (1.14) together with Theorem 2.13 imply that $\frac{d\mathcal{H}^n}{d\mathbf{m}} \in L_{loc}^\infty(U, \mathbf{m})$. Hence if item 1 holds, we can apply Lemma 4.2 with $\xi = \chi_U \frac{d\mathcal{H}^n}{d\mathbf{m}}$ to deduce that item 2 holds as well.

Conversely, if item 2 holds, for all φ and f as above, we have

$$- \int_{\mathbf{X}} \varphi \Delta f d\mathbf{m} = \int_{\mathbf{X}} \langle d\varphi, df \rangle d\mathbf{m} = - \int_{\mathbf{X}} \varphi \text{tr}(\text{Hess} f) d\mathbf{m},$$

having used item 2 and the integration-by-parts formula in the last step. By the arbitrariness of φ , this proves item 1. \square

Proof of Theorem 1.3. From the Bishop-Gromov inequality (2.12) it easily follows that for any bounded set A of \mathbf{X} we have

$$\inf_{r \in (0, 1), x \in A} \frac{\mathbf{m}(B_r(x))}{r^N} > 0. \quad (4.4)$$

On the other hand, Theorem 2.20 gives that the essential dimension of \mathbf{X} is N , thus Theorem 2.22 with (2.2) shows

$$\Delta f = \text{tr}(\text{Hess} f) \quad \forall f \in D(\Delta). \quad (4.5)$$

Then the conclusion follows from (4.4), (4.5) and Theorem 1.5. \square

Proof of Theorem 1.6. From the continuity of \mathcal{H}^N in the compact (as a consequence of Theorem 2.8) space of unit balls in $\text{RCD}(K, N)$ spaces stated in Theorem 2.19, we see that picking ϵ sufficiently small, the conclusion $|\mathcal{H}^N(B_1(x)) - \mathcal{H}^N(B_1(y))| < \delta$ holds true. Thus we concentrate on the first part of the claim.

The proof is done by contradiction. If not, there exist a sequence $\epsilon_i \rightarrow 0^+$, a sequence of pointed $\text{RCD}(K, N)$ spaces (X_i, d_i, m_i, x_i) and a sequence of non-collapsed $\text{RCD}(K, N)$ spaces $(Y_i, d_{Y_i}, \mathcal{H}^N, y_i)$ with $\mathcal{H}^N(B_1(y_i)) \geq v$ such that (X_i, d_i, x_i) ϵ_i -pGH close to (Y_i, d_{Y_i}, y_i) and so that m_i is not proportional to \mathcal{H}^N .

Thanks to Theorem 2.8, after passing to a non-relabelled subsequence, there exists a pointed $\text{RCD}(K, N)$ space (Z, d_Z, m_Z, z) such that

$$\left(X_i, d_i, \frac{1}{m_i(B_1(x_i))} m_i, x_i\right) \xrightarrow{\text{pmGH}} (Z, d_Z, m_Z, z)$$

and

$$(Y_i, d_{Y_i}, y_i) \xrightarrow{\text{pGH}} (Z, d_Z, z).$$

Thanks to Theorem 2.18 with (1.15), we have

$$(Y_i, d_{Y_i}, \mathcal{H}^N, y_i) \xrightarrow{\text{pmGH}} (Z, d_Z, \mathcal{H}^N, z),$$

with $\mathcal{H}^N(B_1(z)) \geq v$. Recalling Theorem 2.20, we see that (Z, d_Z, m_Z) is weakly non-collapsed, in particular, has essential dimension N . Then the lower semicontinuity statement given by Theorem 2.16 gives

$$N \geq \liminf_{i \rightarrow \infty} \text{essdim}(X_i) \geq \text{essdim}(Z) = N.$$

It follows that $\text{essdim}(X_i) = N$ for any sufficiently large i . Thus from the characterization of weakly non-collapsed spaces in Theorem 2.20 and our main result Theorem 1.3 it follows that $m_i = c_i \mathcal{H}^N$ for every i sufficiently large. This provides the desired contradiction. \square

Proof of Theorem 1.7. Let us take $r_i \rightarrow 0^+$ with (2.16), according to the assumption $(Y, d_Y, m_Y, y) \in \text{Tan}(X, d, m, x)$. As the essential dimension does not change under rescaling as in the LHS of (2.16), we see, by Theorem 2.16 and the assumption $\text{essdim}(Y) = N$, that $\text{essdim}(X) = N$. Thus we conclude by our main result Theorem 1.3, taking into account also Theorem 2.20. \square

Proof of Theorem 1.8. Let us take $r_i \rightarrow \infty$ and a sequence of rescaled spaces as in the LHS of (2.16); by Theorem 2.8 (here we use the fact that the space is an $\text{RCD}(K, N)$ space with $K = 0$) we can extract a non relabelled subsequence of $\{r_i\}_i$ such that such rescaled spaces converge to the $\text{RCD}(0, N)$ space (Y, d_Y, m_Y, y) in the pmGH topology. Therefore, if $z \in Y$, we take a sequence $\{y_i\}_i \subseteq X$ that converges to z under this pmGH convergence,

$$\frac{m_Y(B_r(z))}{r^N} = \lim_i \frac{m(B_{rr_i}(y_i))}{r^N m(B_{r_i}(x))} = \lim_i \frac{m(B_{rr_i}(y_i))}{(rr_i)^N} \frac{r_i^N}{m(B_{r_i}(x))} \leq \limsup_i m(B_1(y_i)) \frac{r_i^N}{m(B_{r_i}(x))} \leq C$$

where C is independent of r . Here we have used the Bishop-Gromov inequality (2.12) for the first inequality and our assumptions for the last inequality. Therefore, using Theorem 2.20 we see that $\text{essdim}(Y) = N$, so that we can conclude as in the proof of Theorem 1.7. \square

References

- [1] L. AMBROSIO, *Calculus, heat flow and curvature-dimension bounds in metric measure spaces*, in Proceedings of the International Congress of Mathematicians—Rio de Janeiro 2018. Vol. I. Plenary lectures, World Sci. Publ., Hackensack, NJ, 2018, pp. 301–340.
- [2] L. AMBROSIO, M. COLOMBO, AND S. DI MARINO, *Sobolev spaces in metric measure spaces: reflexivity and lower semicontinuity of slope*, in Variational methods for evolving objects, vol. 67 of Adv. Stud. Pure Math., Math. Soc. Japan, [Tokyo], 2015, pp. 1–58.

- [3] L. AMBROSIO, N. GIGLI, AND G. SAVARÉ, *Calculus and heat flow in metric measure spaces and applications to spaces with Ricci bounds from below*, Invent. Math., 195 (2014), pp. 289–391.
- [4] ———, *Metric measure spaces with Riemannian Ricci curvature bounded from below*, Duke Mathematical Journal, 163 (2014), pp. 1405–1490.
- [5] ———, *Bakry-Émery curvature-dimension condition and Riemannian Ricci curvature bounds*, The Annals of Probability, 43 (2015), pp. 339–404.
- [6] L. AMBROSIO AND S. HONDA, *New stability results for sequences of metric measure spaces with uniform Ricci bounds from below*, Measure Theory in Non-Smooth Spaces, (2017), pp. 1–51.
- [7] ———, *Local spectral convergence in $RCD^*(K, N)$ spaces*, Nonlinear Anal., 177 (2018), pp. 1–23.
- [8] L. AMBROSIO, S. HONDA, J. W. PORTEGIES, AND D. TEWODROSE, *Embedding of $RCD^*(K, N)$ spaces in L^2 via eigenfunctions*, J. Funct. Anal., 280 (2021), pp. Paper No. 108968, 72.
- [9] L. AMBROSIO, S. HONDA, AND D. TEWODROSE, *Short-time behavior of the heat kernel and Weyl’s law on $RCD^*(K, N)$ spaces*, Ann. Global Anal. Geom., 53 (2018), pp. 97–119.
- [10] L. AMBROSIO, A. MONDINO, AND G. SAVARÉ, *On the Bakry-Émery condition, the gradient estimates and the Local-to-Global property of $RCD^*(K, N)$ metric measure spaces*, The Journal of Geometric Analysis, 26 (2014), pp. 1–33.
- [11] L. AMBROSIO, A. MONDINO, AND G. SAVARÉ, *Nonlinear diffusion equations and curvature conditions in metric measure spaces*, Mem. Amer. Math. Soc., 262 (2019), pp. v+121.
- [12] L. AMBROSIO AND P. TILLI, *Topics on analysis in metric spaces*, vol. 25 of Oxford Lecture Series in Mathematics and its Applications, Oxford University Press, Oxford, 2004.
- [13] G. ANTONELLI, E. BRUÉ, AND D. SEMOLA, *Volume bounds for the quantitative singular strata of non collapsed RCD metric measure spaces*, Anal. Geom. Metr. Spaces, 7 (2019), pp. 158–178.
- [14] D. BAKRY AND M. ÉMERY, *Diffusions hypercontractives*, in Séminaire de probabilités, XIX, 1983/84, vol. 1123 of Lecture Notes in Math., Springer, Berlin, 1985, pp. 177–206.
- [15] P. BÉRARD, G. BESSON, AND S. GALLOT, *Embedding Riemannian manifolds by their heat kernel*, Geom. Funct. Anal., 4 (1994), pp. 373–398.
- [16] E. BRUÈ, E. PASQUALETTO, AND D. SEMOLA, *Rectifiability of $RCD(K, N)$ spaces via δ -splitting maps*, Ann. Fenn. Math., 46 (2021), pp. 465–482.
- [17] E. BRUÉ AND D. SEMOLA, *Constancy of the dimension for $RCD(K, N)$ spaces via regularity of Lagrangian flows*, Comm. Pure Appl. Math., 73 (2020), pp. 1141–1204.
- [18] E. CAPUTO, N. GIGLI, AND E. PASQUALETTO, *Parallel transport on non-collapsed $RCD(K, N)$ spaces*. Preprint, arXiv:2108.07531.
- [19] J. CHEEGER AND T. H. COLDING, *Lower bounds on Ricci curvature and the almost rigidity of warped products*, Ann. of Math. (2), 144 (1996), pp. 189–237.
- [20] ———, *On the structure of spaces with Ricci curvature bounded below. I*, J. Differential Geom., 46 (1997), pp. 406–480.
- [21] ———, *On the structure of spaces with Ricci curvature bounded below. II*, J. Differential Geom., 54 (2000), pp. 13–35.
- [22] ———, *On the structure of spaces with Ricci curvature bounded below. III*, J. Differential Geom., 54 (2000), pp. 37–74.
- [23] T. H. COLDING, *Ricci curvature and volume convergence*, Ann. of Math. (2), 145 (1997), pp. 477–501.

- [24] G. DE PHILIPPIS AND N. GIGLI, *Non-collapsed spaces with Ricci curvature bounded from below*, J. Éc. polytech. Math., 5 (2018), pp. 613–650.
- [25] G. DE PHILIPPIS, A. MARCHESE, AND F. RINDLER, *On a conjecture of Cheeger*, in Measure theory in non-smooth spaces, Partial Differ. Equ. Meas. Theory, De Gruyter Open, Warsaw, 2017, pp. 145–155.
- [26] J. DIESTEL AND J. J. UHL, JR., *Vector measures*, American Mathematical Society, Providence, R.I., 1977. With a foreword by B. J. Pettis, Mathematical Surveys, No. 15.
- [27] M. ERBAR, K. KUWADA, AND K.-T. STURM, *On the equivalence of the entropic curvature-dimension condition and Bochner’s inequality on metric measure spaces*, Invent. Math., 201 (2014), pp. 1–79.
- [28] N. GIGLI, *On the heat flow on metric measure spaces: existence, uniqueness and stability*, Calc. Var. PDE, 39 (2010), pp. 101–120.
- [29] ———, *The splitting theorem in non-smooth context*. Preprint, arXiv:1302.5555, 2013.
- [30] ———, *Nonsmooth differential geometry - an approach tailored for spaces with Ricci curvature bounded from below*, Mem. Amer. Math. Soc., 251 (2014), pp. v+161.
- [31] ———, *On the differential structure of metric measure spaces and applications*, Mem. Amer. Math. Soc., 236 (2015), pp. vi+91.
- [32] ———, *Lecture notes on differential calculus on RCD spaces*, Publ. Res. Inst. Math. Sci., 54 (2018), pp. 855–918.
- [33] N. GIGLI, K. KUWADA, AND S.-I. OHTA, *Heat flow on Alexandrov spaces*, Communications on Pure and Applied Mathematics, 66 (2013), pp. 307–331.
- [34] N. GIGLI, A. MONDINO, AND G. SAVARÉ, *Convergence of pointed non-compact metric measure spaces and stability of Ricci curvature bounds and heat flows*, Proc. Lond. Math. Soc. (3), 111 (2015), pp. 1071–1129.
- [35] N. GIGLI AND E. PASQUALETTO, *Behaviour of the reference measure on RCD spaces under charts*. Accepted at Comm. Anal. Geom., arXiv: 1607.05188, 2016.
- [36] ———, *Equivalence of two different notions of tangent bundle on rectifiable metric measure spaces*. To appear in Comm. Anal. Geom., arXiv: 1611.09645, 2016.
- [37] ———, *Lectures on Nonsmooth Differential Geometry*, Springer International Publishing, 2020.
- [38] B.-X. HAN, *Ricci tensor on $\mathrm{RCD}^*(K, N)$ spaces*, J. Geom. Anal., 28 (2018), pp. 1295–1314.
- [39] ———, *Measure rigidity of synthetic lower Ricci curvature bound on Riemannian manifolds*, Adv. Math., 373 (2020), pp. 107327, 31.
- [40] J. HEINONEN, *Lectures on Analysis on Metric Spaces*, Universitext, Springer-Verlag, New York, 2001.
- [41] S. HONDA, *Isometric immersions of RCD spaces*. To appear in Comment. Math. Helv., arXiv: 2005.01222.
- [42] S. HONDA, *New differential operator and noncollapsed RCD spaces*, Geom. Topol., 24 (2020), pp. 2127–2148.
- [43] S. HONDA AND I. MONDELLO, *Sphere theorems for RCD and stratified spaces*, Ann. Sc. Norm. Super. Pisa Cl. Sci. (5), 22 (2021), pp. 903–923.
- [44] S. HONDA AND Y. SIRE, *Sobolev mappings between RCD spaces and applications to harmonic maps: a heat kernel approach*. Preprint, arXiv: 2105.08578, 2021.

- [45] S. HONDA AND X. ZHU, *A characterization of non-collapsed $RCD(K, N)$ spaces via Einstein tensors*. Preprint, arXiv:2010.02530, 2020.
- [46] R. JIANG, H. LI, AND H. ZHANG, *Heat Kernel Bounds on Metric Measure Spaces and Some Applications*, Potential Analysis, 44 (2014).
- [47] V. KAPOVITCH AND C. KETTERER, *Weakly noncollapsed RCD spaces with upper curvature bounds*, Anal. Geom. Metr. Spaces, 7 (2019), pp. 197–211.
- [48] V. KAPOVITCH AND A. MONDINO, *On the topology and the boundary of N -dimensional $RCD(K, N)$ spaces*, Geom. Topol., 25 (2021), pp. 445–495.
- [49] M. KELL AND A. MONDINO, *On the volume measure of non-smooth spaces with Ricci curvature bounded below*, Annali della Scuola normale superiore di Pisa, Classe di scienze, XVII (2018), pp. 593–610.
- [50] Y. KITABEPPU, *A Bishop-type inequality on metric measure spaces with Ricci curvature bounded below*, Proc. Amer. Math. Soc., 145 (2017), pp. 3137–3151.
- [51] ———, *A sufficient condition to a regular set being of positive measure on RCD spaces*, Potential Anal., 51 (2019), pp. 179–196.
- [52] J. LOTT AND C. VILLANI, *Ricci curvature for metric-measure spaces via optimal transport*, Ann. of Math. (2), 169 (2009), pp. 903–991.
- [53] A. MONDINO AND A. NABER, *Structure theory of metric measure spaces with lower Ricci curvature bounds*, Journal of the European Mathematical Society, 21 (2019), pp. 1809–1854.
- [54] J.-I. NAGATA, *Modern dimension theory*, vol. 2 of Sigma Series in Pure Mathematics, Heldermann Verlag, Berlin, revised ed., 1983.
- [55] T. RAJALA, *Local Poincaré inequalities from stable curvature conditions on metric spaces*, Calc. Var. Partial Differential Equations, 44 (2012), pp. 477–494.
- [56] G. SAVARÉ, *Self-improvement of the Bakry-Émery condition and Wasserstein contraction of the heat flow in $RCD(K, \infty)$ metric measure spaces*, Discrete Contin. Dyn. Syst., 34 (2014), pp. 1641–1661.
- [57] K.-T. STURM, *Analysis on local Dirichlet spaces. II. Upper Gaussian estimates for the fundamental solutions of parabolic equations*, Osaka J. Math., 32 (1995), pp. 275–312.
- [58] ———, *Analysis on local Dirichlet spaces. III. The parabolic Harnack inequality*, J. Math. Pures Appl. (9), 75 (1996), pp. 273–297.
- [59] ———, *On the geometry of metric measure spaces. I*, Acta Math., 196 (2006), pp. 65–131.
- [60] ———, *On the geometry of metric measure spaces. II*, Acta Math., 196 (2006), pp. 133–177.
- [61] C. VILLANI, *Inégalités isopérimétriques dans les espaces métriques mesurés [d’après F. Cavalletti & A. Mondino]*. Séminaire Bourbaki, available at: <http://www.bourbaki.ens.fr/TEXTES/1127.pdf>.
- [62] N. WEAVER, *Lipschitz algebras and derivations. II. Exterior differentiation*, J. Funct. Anal., 178 (2000), pp. 64–112.