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# A NOTE ON GROMOV-HAUSDORFF-PROKHOROV DISTANCE BETWEEN (LOCALLY) COMPACT MEASURE SPACES

ROMAIN ABRAHAM, JEAN-FRANÇOIS DELMAS, AND PATRICK HOSCHEIT

**ABSTRACT.** We present an extension of the Gromov-Hausdorff metric on the set of compact metric spaces: the Gromov-Hausdorff-Prokhorov metric on the set of compact metric spaces endowed with a finite measure. We then extend it to the non-compact case by describing a metric on the set of rooted complete locally compact length spaces endowed with a locally finite measure. We prove that this space with the extended Gromov-Hausdorff-Prokhorov metric is a Polish space. This generalization is needed to define Lévy trees, which are (possibly unbounded) random real trees endowed with a locally finite measure.

## 1. INTRODUCTION

In the present work, we aim to give a topological framework to certain classes of measured metric spaces. The methods go back to ideas from Gromov [10], who first considered the so-called Gromov-Hausdorff metric in order to compare metric spaces who might not be subspaces of a common metric space. The classical theory of the Gromov-Hausdorff metric on the space of compact metric spaces, as well as its extension to locally compact spaces, is exposed in particular in Burago, Burago and Ivanov [4].

Recently, the concept of Gromov-Hausdorff convergence has found striking applications in the field of probability theory, in the context of random graphs. Evans [7] and Evans, Pitman and Winter [8] considered the space of real trees, which is Polish when endowed with the Gromov-Hausdorff metric. This has given a framework to the theory of continuum random trees, which originated with Aldous [3]. There are also applications in the context of random maps, where there have been significant developments in these last years. In the monograph by Evans [7], the author describes a topology on the space of compact real trees, equipped with a probability measure, using the Prokhorov metric to compare the measures, thus defining the so-called weighted Gromov-Hausdorff metric. Recently Greven, Pfaffelhuber and Winter [9] take another approach by considering the space of complete, separable metric spaces, endowed with probability measures (metric measure spaces). In order to compare two such probability spaces, they consider embeddings of both these spaces into some common Polish metric space, and use the Prokhorov metric to compare the ensuing measures. This puts the emphasis on the probability measure carried by the space rather than its geometrical features. In his monograph, Villani [12] gives an account of the theory of measured metric spaces and the different approaches to their topology. Miermont, in [11], describes a combined approach, using both the Hausdorff metric and the Prokhorov metric to compare compact metric spaces equipped with probability measures. The metric he uses (called the Gromov-Hausdorff-Prokhorov metric) is not the same as Evans's, but they are shown to give rise to the same topology.

In the present paper, we describe several properties of the Gromov-Hausdorff-Prokhorov metric,  $d_{\text{GHP}}^c$ , on the set  $\mathbb{K}$  of (isometry classes of) compact metric spaces, with a distinguished element called

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the root and endowed with a finite measure. Theorem 2.3 ensures that  $(\mathbb{K}, d_{\text{GHP}}^c)$  is a Polish metric space. We extend those results by considering the Gromov-Hausdorff-Prokhorov metric,  $d_{\text{GHP}}$ , on the set  $\mathbb{L}$  of (isometry classes of) rooted locally compact, complete length spaces, endowed with a locally finite measure. Theorem 2.7 ensures that  $(\mathbb{L}, d_{\text{GHP}})$  is also a Polish metric space. The proof of the completeness of  $\mathbb{L}$  relies on a pre-compactness criterion given in Theorem 2.9. The methods used are similar to the methods used in [4] to derive properties about the Gromov-Hausdorff topology of the set of locally compact complete length spaces. This work extends some of the results from [9], which doesn't take into account the geometrical structure of the spaces, as well as the results from [11], which consider only the compact case and probability measures. This comes at the price of having to restrict ourselves to the context of length spaces. In [12] the Gromov-Hausdorff-Prokhorov topology is considered for general Polish spaces (instead of length spaces) but endowed with locally finite measures satisfying the doubling condition. We also mention the different approach of [2], using the ideas of correspondences between metric spaces and couplings of measures.

This work was developed for applications in the setting of weighted real trees (which are elements of  $\mathbb{L}$ ), see Abraham, Delmas and Hoscheit [1]. We give an hint of those applications by stating that the construction of a weighted tree coded in a continuous function with compact support is measurable with respect to the topology induced by  $d_{\text{GHP}}^c$  on  $\mathbb{K}$  or by  $d_{\text{GHP}}$  on  $\mathbb{L}$ . This construction allows us to define random variables on  $\mathbb{K}$  using continuous random processes on  $\mathbb{R}$ , in particular the Lévy trees of [6] that describe the genealogy of the so-called critical or sub-critical continuous state branching processes that become a.s. extinct. The measure  $\mathbf{m}$  is then a “uniform” measure on the leaves of the tree which has finite mass. The construction can be generalized to super-critical continuous state branching processes which can live forever; in that case the corresponding genealogical tree is infinite and the measure  $\mathbf{m}$  on the leaves is also infinite. This paper gives an appropriate framework to handle such tree-valued random variables and also tree-valued Markov processes as in [1].

The structure of the paper is as follow. Section 2 collects the main results of the paper. The application to real trees is given in Section 3. The proofs of the results in the compact case are given in Section 4. The proofs of the results in the locally compact case are given in Section 5.

## 2. MAIN RESULTS

**2.1. Rooted weighted metric spaces.** Let  $(X, d^X)$  be a Polish metric space. The diameter of  $A \in \mathcal{B}(X)$  is given by:

$$\text{diam}(A) = \sup\{d^X(x, y); x, y \in A\}.$$

For  $A, B \in \mathcal{B}(X)$ , we set:

$$d_{\text{H}}^X(A, B) = \inf\{\varepsilon > 0; A \subset B^\varepsilon \text{ and } B \subset A^\varepsilon\},$$

the Hausdorff metric between  $A$  and  $B$ , where

$$(1) \quad A^\varepsilon = \{x \in X; \inf_{y \in A} d^X(x, y) < \varepsilon\}$$

is the  $\varepsilon$ -halo set of  $A$ . If  $X$  is compact, then the space of compact subsets of  $X$ , endowed with the Hausdorff metric, is compact, see theorem 7.3.8 in [4]. To give pre-compactness criterion, we shall need the notion of  $\varepsilon$ -nets.

**Definition 2.1.** Let  $(X, d^X)$  be a metric space, and let  $\varepsilon > 0$ . A subset  $A \subset X$  is an  $\varepsilon$ -net of  $B \subset X$  if:

$$A \subset B \subset A^\varepsilon.$$

Notice that, for any  $\varepsilon > 0$ , compact metric spaces admit finite  $\varepsilon$ -nets and locally compact spaces admit locally finite  $\varepsilon$ -nets.

Let  $\mathcal{M}_f(X)$  denote the set of all finite Borel measures on  $X$ . If  $\mu, \nu \in \mathcal{M}_f(X)$ , we set:

$$d_P^X(\mu, \nu) = \inf\{\varepsilon > 0; \mu(A) \leq \nu(A^\varepsilon) + \varepsilon \text{ and } \nu(A) \leq \mu(A^\varepsilon) + \varepsilon \text{ for any closed set } A\},$$

the Prokhorov metric between  $\mu$  and  $\nu$ . It is well known, see [5] Appendix A.2.5, that  $(\mathcal{M}_f(X), d_P^X)$  is a Polish metric space, and that the topology generated by  $d_P^X$  is exactly the topology of weak convergence (convergence against continuous bounded functionals).

The Prokhorov metric can be extended in the following way. Recall that a Borel measure is locally finite if the measure of any bounded Borel set is finite. Let  $\mathcal{M}(X)$  denote the set of all locally finite Borel measures on  $X$ . Let  $\emptyset$  be a distinguished element of  $X$ , which we shall call the root. We will consider the closed ball of radius  $r$  centered at  $\emptyset$ :

$$(2) \quad X^{(r)} = \{x \in X; d^X(\emptyset, x) \leq r\},$$

and for  $\mu \in \mathcal{M}(X)$  its restriction  $\mu^{(r)}$  to  $X^{(r)}$ :

$$(3) \quad \mu^{(r)}(dx) = \mathbf{1}_{X^{(r)}}(x) \mu(dx).$$

If  $\mu, \nu \in \mathcal{M}(X)$ , we define a generalized Prokhorov metric between  $\mu$  and  $\nu$ :

$$(4) \quad d_{\text{gP}}^X(\mu, \nu) = \int_0^\infty e^{-r} \left( 1 \wedge d_P^X \left( \mu^{(r)}, \nu^{(r)} \right) \right) dr.$$

It is not difficult to check that  $d_{\text{gP}}^X$  is well defined (see Lemma 2.6 in a more general framework) and is a metric. Furthermore  $(\mathcal{M}(X), d_{\text{gP}}^X)$  is a Polish metric space, and the topology generated by  $d_{\text{gP}}^X$  is exactly the topology of vague convergence (convergence against continuous bounded functionals with bounded support), see [5] Appendix A.2.6.

When there is no ambiguity on the metric space  $(X, d^X)$ , we may write  $d$ ,  $d_H$ , and  $d_P$  instead of  $d^X$ ,  $d_H^X$  and  $d_P^X$ . In the case where we consider different metrics on the same space, in order to stress that the metric is  $d^X$ , we shall write  $d_H^{d^X}$  and  $d_P^{d^X}$  for the corresponding Hausdorff and Prokhorov metrics.

If  $\Phi : X \rightarrow X'$  is a Borel map between two Polish metric spaces and if  $\mu$  is a Borel measure on  $X$ , we will note  $\Phi_*\mu$  the image measure on  $X'$  defined by  $\Phi_*\mu(A) = \mu(\Phi^{-1}(A))$ , for any Borel set  $A \subset X'$ .

### Definition 2.2.

- A rooted weighted metric space  $\mathcal{X} = (X, d, \emptyset, \mu)$  is a metric space  $(X, d)$  with a distinguished element  $\emptyset \in X$ , called the root, and a locally finite Borel measure  $\mu$ .
- Two rooted weighted metric spaces  $\mathcal{X} = (X, d, \emptyset, \mu)$  and  $\mathcal{X}' = (X', d', \emptyset', \mu')$  are said to be GHP-isometric if there exists an isometric one-to-one map  $\Phi : X \rightarrow X'$  such that  $\Phi(\emptyset) = \emptyset'$  and  $\Phi_*\mu = \mu'$ . In that case,  $\Phi$  is called a GHP-isometry.

Notice that if  $(X, d)$  is compact, then a locally finite measure on  $X$  is finite and belongs to  $\mathcal{M}_f(X)$ . We will now use a procedure due to Gromov [10] to compare any two compact rooted weighted metric spaces, even if they are not subspaces of the same Polish metric space.

**2.2. Gromov-Hausdorff-Prokhorov metric for compact spaces.** For convenience, we recall the Gromov-Hausdorff metric, see for example Definition 7.3.10 in [4]. Let  $(X, d)$  and  $(X', d')$  be two compact metric spaces. The Gromov-Hausdorff metric between  $(X, d)$  and  $(X', d')$  is given by:

$$(5) \quad d_{\text{GH}}^c((X, d), (X', d')) = \inf_{\varphi, \varphi', Z} d_H^Z(\varphi(X), \varphi'(X')),$$

where the infimum is taken over all isometric embeddings  $\varphi : X \hookrightarrow Z$  and  $\varphi' : X' \hookrightarrow Z$  into some common Polish metric space  $(Z, d^Z)$ . Note that Equation (5) does actually define a metric on the set

of isometry classes of compact metric spaces.

Now, we introduce the Gromov-Hausdorff-Prokhorov metric for compact spaces. Let  $\mathcal{X} = (X, d, \emptyset, \mu)$  and  $\mathcal{X}' = (X', d', \emptyset', \mu')$  be two compact rooted weighted metric spaces, and define:

$$(6) \quad d_{\text{GHP}}^c(\mathcal{X}, \mathcal{X}') = \inf_{\Phi, \Phi', Z} (d^Z(\Phi(\emptyset), \Phi'(\emptyset')) + d_H^Z(\Phi(X), \Phi'(X')) + d_P^Z(\Phi_*\mu, \Phi'_*\mu')),$$

where the infimum is taken over all isometric embeddings  $\Phi : X \hookrightarrow Z$  and  $\Phi' : X' \hookrightarrow Z$  into some common Polish metric space  $(Z, d^Z)$ .

Note that equation (6) does not actually define a metric, as  $d_{\text{GHP}}^c(\mathcal{X}, \mathcal{X}') = 0$  if  $\mathcal{X}$  and  $\mathcal{X}'$  are GHP-isometric. Therefore, we shall consider  $\mathbb{K}$ , the set of GHP-isometry classes of compact rooted weighted metric space and identify a compact rooted weighted metric space with its class in  $\mathbb{K}$ . Then the function  $d_{\text{GHP}}^c$  is finite on  $\mathbb{K}^2$ .

**Theorem 2.3.**

- (i) *The function  $d_{\text{GHP}}^c$  defines a metric on  $\mathbb{K}$ .*
- (ii) *The space  $(\mathbb{K}, d_{\text{GHP}}^c)$  is a Polish metric space.*

We shall call  $d_{\text{GHP}}^c$  the Gromov-Hausdorff-Prokhorov metric. This extends the Gromov-Hausdorff metric on compact metric spaces, see [4] section 7, as well as the Gromov-Hausdorff-Prokhorov metric on compact metric spaces endowed with a probability measure, see [11]. See also [9] for another approach on metric spaces endowed with a probability measure.

We end this Section by a pre-compactness criterion on  $\mathbb{K}$ .

**Theorem 2.4.** *Let  $\mathcal{A}$  be a subset of  $\mathbb{K}$ , such that:*

- (i) *We have  $\sup_{(X, d, \emptyset, \mu) \in \mathcal{A}} \text{diam}(X) < +\infty$ .*
- (ii) *For every  $\varepsilon > 0$ , there exists a finite integer  $N(\varepsilon) \geq 1$ , such that for any  $(X, d, \emptyset, \mu) \in \mathcal{A}$ , there is an  $\varepsilon$ -net of  $X$  with cardinal less than  $N(\varepsilon)$ .*
- (iii) *We have  $\sup_{(X, d, \emptyset, \mu) \in \mathcal{A}} \mu(X) < +\infty$ .*

*Then,  $\mathcal{A}$  is relatively compact: every sequence in  $\mathcal{A}$  admits a sub-sequence that converges in the  $d_{\text{GHP}}^c$  topology.*

Notice that we could have defined a Gromov-Hausdorff-Prokhorov metric without reference to any root. However, the introduction of the root is necessary to define the Gromov-Hausdorff-Prokhorov metric for locally compact spaces, see next Section.

**2.3. Gromov-Hausdorff-Prokhorov metric for locally compact spaces.** To consider an extension to non compact weighted rooted metric spaces, we shall consider complete and locally compact length spaces.

We recall that a metric space  $(X, d)$  is a length space if for every  $x, y \in X$ , we have:

$$d(x, y) = \inf L(\gamma),$$

where the infimum is taken over all rectifiable curves  $\gamma : [0, 1] \rightarrow X$  such that  $\gamma(0) = x$  and  $\gamma(1) = y$ , and where  $L(\gamma)$  is the length of the rectifiable curve  $\gamma$ . We recall that  $(X, d)$  is a length space if it satisfies the mid-point condition (see Theorem 2.4.16 in [4]): for all  $\varepsilon > 0$ ,  $x, y \in X$ , there exists  $z \in X$  such that:

$$|2d(x, z) - d(x, y)| + |2d(y, z) - d(x, y)| \leq \varepsilon.$$

**Definition 2.5.** *Let  $\mathbb{L}$  be the set of GHP-isometry classes of rooted, weighted, complete and locally compact length spaces and identify a rooted, weighted, complete and locally compact length spaces with its class in  $\mathbb{L}$ .*

If  $\mathcal{X} = (X, d, \emptyset, \mu) \in \mathbb{L}$ , then for  $r \geq 0$  we will consider its restriction to the closed ball of radius  $r$  centered at  $\emptyset$ ,  $\mathcal{X}^{(r)} = (X^{(r)}, d^{(r)}, \emptyset, \mu^{(r)})$ , where  $X^{(r)}$  is defined by (2), the metric  $d^{(r)}$  is the restriction of  $d$  to  $X^{(r)}$ , and the measure  $\mu^{(r)}$  is defined by (3). Recall that the Hopf-Rinow theorem implies that if  $(X, d)$  is a complete and locally compact length space, then every closed bounded subset of  $X$  is compact. In particular if  $\mathcal{X}$  belongs to  $\mathbb{L}$ , then  $\mathcal{X}^{(r)}$  belongs to  $\mathbb{K}$  for all  $r \geq 0$ .

We state a regularity Lemma of  $d_{\text{GHP}}^c$  with respect to the restriction operation.

**Lemma 2.6.** *Let  $\mathcal{X}$  and  $\mathcal{Y}$  be in  $\mathbb{L}$ . Then the function defined on  $\mathbb{R}_+$  by  $r \mapsto d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{Y}^{(r)})$  is càdlàg.*

This implies that the following function (inspired by (4)) is well defined on  $\mathbb{L}^2$ :

$$d_{\text{GHP}}(\mathcal{X}, \mathcal{Y}) = \int_0^\infty e^{-r} \left( 1 \wedge d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{Y}^{(r)}) \right) dr.$$

**Theorem 2.7.**

- (i) *The function  $d_{\text{GHP}}$  defines a metric on  $\mathbb{L}$ .*
- (ii) *The space  $(\mathbb{L}, d_{\text{GHP}})$  is a Polish metric space.*

The next result implies that  $d_{\text{GHP}}^c$  and  $d_{\text{GHP}}$  define the same topology on  $\mathbb{K} \cap \mathbb{L}$ .

**Proposition 2.8.** *Let  $(\mathcal{X}_n, n \in \mathbb{N})$  and  $\mathcal{X}$  be elements of  $\mathbb{K} \cap \mathbb{L}$ . Then the sequence  $(\mathcal{X}_n, n \in \mathbb{N})$  converges to  $\mathcal{X}$  in  $(\mathbb{K}, d_{\text{GHP}}^c)$  if and only if it converges to  $\mathcal{X}$  in  $(\mathbb{L}, d_{\text{GHP}})$ .*

Finally, we give a pre-compactness criterion on  $\mathbb{L}$  which is a generalization of the well-known compactness theorem for compact metric spaces, see for instance Theorem 7.4.15 in [4].

**Theorem 2.9.** *Let  $\mathcal{C}$  be a subset of  $\mathbb{L}$ , such that for every  $r \geq 0$ :*

- (i) *For every  $\varepsilon > 0$ , there exists a finite integer  $N(r, \varepsilon) \geq 1$ , such that for any  $(X, d, \emptyset, \mu) \in \mathcal{C}$ , there is an  $\varepsilon$ -net of  $X^{(r)}$  with cardinal less than  $N(r, \varepsilon)$ .*
- (ii) *We have  $\sup_{(X, d, \emptyset, \mu) \in \mathcal{C}} \mu(X^{(r)}) < +\infty$ .*

*Then,  $\mathcal{C}$  is relatively compact: every sequence in  $\mathcal{C}$  admits a sub-sequence that converges in the  $d_{\text{GHP}}$  topology.*

### 3. APPLICATION TO REAL TREES CODED BY FUNCTIONS

A metric space  $(T, d)$  is called real tree (or  $\mathbb{R}$ -tree) if the following properties are satisfied:

- (i) For every  $s, t \in T$ , there is a unique isometric map  $f_{s,t}$  from  $[0, d(s, t)]$  to  $T$  such that  $f_{s,t}(0) = s$  and  $f_{s,t}(d(s, t)) = t$ .
- (ii) For every  $s, t \in T$ , if  $q$  is a continuous injective map from  $[0, 1]$  to  $T$  such that  $q(0) = s$  and  $q(1) = t$ , then  $q([0, 1]) = f_{s,t}([0, d(s, t)])$ .

Note that real trees are always length spaces and that complete real trees are the only complete connected spaces that satisfy the so-called four-point condition:

$$(7) \quad \forall x_1, x_2, x_3, x_4 \in X, \quad d(x_1, x_2) + d(x_3, x_4) \leq (d(x_1, x_3) + d(x_2, x_4)) \vee (d(x_1, x_4) + d(x_2, x_3)).$$

We say that a real tree is rooted if there is a distinguished vertex  $\emptyset$ , which will be called the root of  $T$ .

**Definition 3.1.** *We denote by  $\mathbb{T}$  the set of (GHP-isometry classes of) rooted, weighted, complete and locally compact real trees, in short w-trees.*

We deduce the following Corollary from Theorem 2.7 and the four-point condition characterization of real trees.

**Corollary 3.2.** *The set  $\mathbb{T}$  is a closed subset of  $\mathbb{L}$  and  $(\mathbb{T}, d_{\text{GHP}})$  is a Polish metric space.*

Let  $f$  be a continuous non-negative function defined on  $[0, +\infty)$ , such that  $f(0) = 0$ , with compact support. We set:

$$\sigma^f = \sup\{t; f(t) > 0\},$$

with the convention  $\sup \emptyset = 0$ . Let  $d^f$  be the non-negative function defined by:

$$d^f(s, t) = f(s) + f(t) - 2 \inf_{u \in [s \wedge t, s \vee t]} f(u).$$

It can be easily checked that  $d^f$  is a semi-metric on  $[0, \sigma^f]$ . One can define the equivalence relation associated with  $d^f$  by  $s \sim t$  if and only if  $d^f(s, t) = 0$ . Moreover, when we consider the quotient space

$$T^f = [0, \sigma^f]_{/\sim}$$

and, noting again  $d^f$  the induced metric on  $T^f$  and rooting  $T^f$  at  $\emptyset^f$ , the equivalence class of 0, it can be checked that the space  $(T^f, d^f, \emptyset^f)$  is a rooted compact real tree. We denote by  $p^f$  the canonical projection from  $[0, \sigma^f]$  onto  $T^f$ , which is extended by  $p^f(t) = \emptyset^f$  for  $t \geq \sigma^f$ . Notice that  $p^f$  is continuous. We define  $\mathbf{m}^f$ , the Borel measure on  $T^f$  as the image measure on  $T^f$  of the Lebesgue measure on  $[0, \sigma^f]$  by  $p^f$ . We consider the (compact) w-tree  $\mathcal{T}^f = (T^f, d^f, \emptyset^f, \mathbf{m}^f)$ .

We have the following elementary result (see Lemma 2.3 of [6] when dealing with the Gromov-Hausdorff metric instead of the Gromov-Hausdorff-Prokhorov metric). For a proof, see [1].

**Proposition 3.3.** *Let  $f, g$  be two compactly supported, non-negative continuous functions with  $f(0) = g(0) = 0$ . Then, we have:*

$$(8) \quad d_{GHP}^c(\mathcal{T}^f, \mathcal{T}^g) \leq 6\|f - g\|_\infty + |\sigma^f - \sigma^g|.$$

This result and Proposition 2.8 ensure that the map  $f \mapsto \mathcal{T}^f$  (defined on the space of continuous functions with compact support which vanish at 0, with the uniform topology) taking values in  $(\mathbb{T} \cap \mathbb{K}, d_{GHP}^c)$  or  $(\mathbb{T}, d_{GHP})$  is measurable.

#### 4. GROMOV-HAUSDORFF-PROKHOROV METRIC FOR COMPACT METRIC SPACES

**4.1. Proof of (i) of Theorem 2.3.** In this Section, we shall prove that  $d_{GHP}^c$  defines a metric on  $\mathbb{K}$ .

First, we will prove the following technical lemma, which is a generalization of Remark 7.3.12 in [4]. Let  $\mathcal{X} = (X, d^X, \emptyset^X, \mu^X)$  and  $\mathcal{Y} = (Y, d^Y, \emptyset^Y, \mu^Y)$  be two elements of  $\mathbb{K}$ . We will use the notation  $X \sqcup Y$  for the disjoint union of the sets  $X$  and  $Y$ . We will abuse notations and note  $X, \mu^X, \emptyset^X$  and  $Y, \mu^Y, \emptyset^Y$  the images of  $X, \mu^X, \emptyset^X$  and of  $Y, \mu^Y, \emptyset^Y$  respectively by the canonical embeddings  $X \hookrightarrow X \sqcup Y$  and  $Y \hookrightarrow X \sqcup Y$ .

**Lemma 4.1.** *Let  $\mathcal{X} = (X, d^X, \emptyset^X, \mu^X)$  and  $\mathcal{Y} = (Y, d^Y, \emptyset^Y, \mu^Y)$  be two elements of  $\mathbb{K}$ . Then, we have:*

$$(9) \quad d_{GHP}^c(\mathcal{X}, \mathcal{Y}) = \inf_d \{d(\emptyset^X, \emptyset^Y) + d_H^d(X, Y) + d_P^d(\mu^X, \mu^Y)\},$$

where the infimum is taken over all metrics  $d$  on  $X \sqcup Y$  such that the canonical embeddings  $X \hookrightarrow X \sqcup Y$  and  $Y \hookrightarrow X \sqcup Y$  are isometries.

*Proof.* We only have to show that:

$$(10) \quad \inf_d \{d(\emptyset^X, \emptyset^Y) + d_H^d(X, Y) + d_P^d(\mu^X, \mu^Y)\} \leq d_{GHP}^c(\mathcal{X}, \mathcal{Y}),$$

since the other inequality is obvious. Let  $(Z, d^Z)$  be a Polish space and  $\Phi^X$  and  $\Phi^Y$  be isometric embeddings of  $X$  and  $Y$  in  $Z$ . Let  $\delta > 0$ . We define the following function on  $(X \sqcup Y)^2$ :

$$(11) \quad d(x, y) = \begin{cases} d^Z(\Phi^X(x), \Phi^Y(y)) + \delta & \text{if } x \in X, y \in Y, \\ d^X(x, y) & \text{if } x, y \in X, \\ d^Y(x, y) & \text{if } x, y \in Y. \end{cases}$$

It is obvious that  $d$  is a metric on  $X \sqcup Y$ , and that the canonical embeddings of  $X$  and  $Y$  in  $X \sqcup Y$  are isometric. Furthermore, by definition, we have  $d(\emptyset^X, \emptyset^Y) = d^Z(\Phi^X(\emptyset^X), \Phi^Y(\emptyset^Y)) + \delta$ . Concerning the Hausdorff distance between  $X$  and  $Y$ , we get that:

$$d_H^d(X, Y) \leq d_H^Z(\Phi^X(X), \Phi^Y(Y)) + \delta.$$

Finally, let us compute the Prokhorov distance between  $\mu^X$  and  $\mu^Y$ . Let  $\varepsilon > 0$  be such that  $d_P^Z(\Phi_*^X \mu^X, \Phi_*^Y \mu^Y) < \varepsilon$ . Let  $A$  be a closed subset of  $X \sqcup Y$ . By definition, we have:

$$\begin{aligned} \mu^X(A) &= \mu^X(A \cap X) = \Phi_*^X \mu^X(\Phi^X(A \cap X)) \\ &< \Phi_*^Y \mu^Y(\{z \in Z, d^Z(z, \Phi^X(A \cap X)) < \varepsilon\}) + \varepsilon \\ &= \Phi_*^Y \mu^Y(\{z \in \Phi^Y(Y), d^Z(z, \Phi^X(A \cap X)) < \varepsilon\}) + \varepsilon \\ &\leq \mu^Y(\{y \in Y, d(y, A \cap X) < \varepsilon + \delta\}) + \varepsilon \\ &\leq \mu^Y(\{y \in X \sqcup Y, d(y, A) < \varepsilon + \delta\}) + \varepsilon. \end{aligned}$$

The symmetric result holds for  $(X, Y)$  replaced by  $(Y, X)$  and therefore we get  $d_P^d(\mu^X, \mu^Y) < \varepsilon + \delta$ . This implies:

$$d_P^d(\mu^X, \mu^Y) \leq d_H^Z(\Phi_*^X \mu^X, \Phi_*^Y \mu^Y) + \delta.$$

Eventually, we get:

$$\begin{aligned} d(\emptyset^X, \emptyset^Y) + d_H^d(X, Y) + d_P^d(\mu^X, \mu^Y) \\ \leq d^Z(\Phi^X(\emptyset^X), \Phi^Y(\emptyset^Y)) + d_H^Z(\Phi^X(X), \Phi^Y(Y)) + d_H^Z(\Phi_*^X \mu^X, \Phi_*^Y \mu^Y) + 3\delta. \end{aligned}$$

Thanks to (6) and since  $\delta > 0$  is arbitrary, we get (10).  $\square$

We now prove that  $d_{GHP}^c$  does indeed satisfy all the axioms of a metric (as is done in [4] for the Gromov-Hausdorff metric and in [11] in the case of probability measures on compact metric spaces). The symmetry and positiveness of  $d_{GHP}^c$  being obvious, let us prove the triangular inequality and positive definiteness.

**Lemma 4.2.** *The function  $d_{GHP}^c$  satisfies the triangular identity on  $\mathbb{K}$ .*

*Proof.* Let  $\mathcal{X}_1, \mathcal{X}_2$  and  $\mathcal{X}_3$  be elements of  $\mathbb{K}$ . For  $i \in \{1, 3\}$ , let us assume that  $d_{GHP}^c(\mathcal{X}_i, \mathcal{X}_2) < r_i$ . With obvious notations, for  $i \in \{1, 3\}$ , we consider, as in Lemma 4.1, metrics  $d_i$  on  $X_i \sqcup X_2$ . Let us then consider  $Z = X_1 \sqcup X_2 \sqcup X_3$ , on which we define:

$$(12) \quad d(x, y) = \begin{cases} d_i(x, y) & \text{if } x, y \in (X_i \sqcup X_2)^2 \text{ for } i \in \{1, 3\}, \\ \inf_{z \in X_2} \{d_1(x, z) + d_3(z, y)\} & \text{if } x \in X_1, y \in X_3. \end{cases}$$

The function  $d$  is in fact a metric on  $Z$ , and the canonical embeddings are isometries, since they are for  $d_1$  and  $d_3$ . By definition, we have:

$$d_H^d(X_1, X_3) = \left( \sup_{x_1 \in X_1} \inf_{x_3 \in X_3} d(x_1, x_3) \right) \vee \left( \sup_{x_3 \in X_3} \inf_{x_1 \in X_1} d(x_1, x_3) \right).$$

We notice that:

$$\begin{aligned} \sup_{x_1 \in X_1} \inf_{x_3 \in X_3} d(x_1, x_3) &= \sup_{x_1 \in X_1} \inf_{x_2 \in X_2, x_3 \in X_3} d_1(x_1, x_2) + d_3(x_2, x_3) \\ &\leq d_H^{d_1}(X_1, X_2) + \inf_{x_2 \in X_2, x_3 \in X_3} d_3(x_2, x_3) \\ &\leq d_H^{d_1}(X_1, X_2) + d_H^{d_3}(X_2, X_3). \end{aligned}$$

Thus, we deduce that  $d_H^d(X_1, X_3) \leq d_H^{d_1}(X_1, X_2) + d_H^{d_3}(X_2, X_3)$ .



As far as the Prokhorov distance is concerned, for  $i \in \{1, 3\}$ , let  $\varepsilon_i$  be such that  $d_P^{d_i}(\mu_i, \mu_2) < \varepsilon_i$ . Then, if  $A \subset Z$  is closed, we have:

$$\begin{aligned} \mu_1(A) &= \mu_1(A \cap X_1) < \mu_2(\{x \in X_1 \sqcup X_2, d_1(x, A \cap X_1) < \varepsilon_1\}) + \varepsilon_1 \\ &\leq \mu_2(A^{\varepsilon_1} \cap X_2) + \varepsilon_1 \\ &< \mu_3(\{x \in X_3 \sqcup X_2, d_3(x, A^{\varepsilon_1} \cap X_2) < \varepsilon_3\}) + \varepsilon_1 + \varepsilon_3 \\ &\leq \mu_3(A^{\varepsilon_1 + \varepsilon_3}) + \varepsilon_1 + \varepsilon_3, \end{aligned}$$

where  $A^\varepsilon = \{z \in Z, d(z, A) < \varepsilon\}$ , for  $\varepsilon = \varepsilon_1$  and  $\varepsilon = \varepsilon_1 + \varepsilon_3$ . A similar result holds with  $(\mu_1, \mu_3)$  replaced by  $(\mu_3, \mu_1)$ . We deduce that  $d_P^d(\mu_1, \mu_3) < \varepsilon_1 + \varepsilon_3$ , which implies that  $d_P^d(\mu_1, \mu_3) \leq d_P^{d_1}(\mu_1, \mu_2) + d_P^{d_3}(\mu_2, \mu_3)$ .

By summing up all the results, we get:

$$d(\emptyset_1, \emptyset_3) + d_H^d(X_1, X_3) + d_P^d(\mu_1, \mu_3) \leq \sum_{i \in \{1, 3\}} d^{d_i}(\emptyset_i, \emptyset_2) + d_H^{d_i}(X_i, X_2) + d_P^{d_i}(\mu_i, \mu_2).$$

Then use the definition (6) and Lemma 4.1 to get the triangular inequality:

$$d_{\text{GHP}}^c(\mathcal{X}_1, \mathcal{X}_3) \leq d_{\text{GHP}}^c(\mathcal{X}_1, \mathcal{X}_2) + d_{\text{GHP}}^c(\mathcal{X}_2, \mathcal{X}_3).$$

□

This proves that  $d_{\text{GHP}}^c$  is a semi-metric on  $\mathbb{K}$ . We then prove the positive definiteness.

**Lemma 4.3.** *Let  $\mathcal{X}, \mathcal{Y}$  be two elements of  $\mathbb{K}$  such that  $d_{\text{GHP}}^c(\mathcal{X}, \mathcal{Y}) = 0$ . Then  $\mathcal{X} = \mathcal{Y}$  (as GHP-isometry classes of rooted weighted compact metric spaces).*

*Proof.* Let  $\mathcal{X} = (X, d^X, \emptyset^X, \mu^X)$  and  $\mathcal{Y} = (Y, d^Y, \emptyset^Y, \mu^Y)$  in  $\mathbb{K}$  such that  $d_{\text{GHP}}^c(\mathcal{X}, \mathcal{Y}) = 0$ . According to Lemma 4.1, we can find a sequence of metrics  $(d^n, n \geq 1)$  on  $X \sqcup Y$ , such that

$$(13) \quad d^n(\emptyset^X, \emptyset^Y) + d_H^n(X, Y) + d_P^n(\mu^X, \mu^Y) < \varepsilon_n,$$

for some positive sequence  $(\varepsilon_n, n \geq 1)$  decreasing to 0, where  $d_H^n$  and  $d_P^n$  stand for  $d_H^{d^n}$  and  $d_P^{d^n}$ . For any  $k \geq 1$ , let  $S_k$  be a finite  $(1/k)$ -net of  $X$ , containing the root. Since  $X$  is compact, we get by Definition 2.1 that  $S_k$  is in fact an  $(\frac{1}{k} - \delta)$ -net of  $X$  for some  $\delta > 0$ . Let  $N_k + 1$  be the cardinal of  $S_k$ . We will write:

$$S_k = \{x_{0,k} = \emptyset^X, x_{1,k}, \dots, x_{N_k,k}\}.$$

Let  $(V_{i,k}, 0 \leq i \leq N_k)$  be Borel subsets of  $X$  with diameter less than  $1/k$ , that is:

$$\sup_{x, x' \in V_{i,k}} d^X(x, x') < 1/k,$$

such that  $\bigcup_{0 \leq i \leq N_k} V_{i,k} = X$  and for all  $0 \leq i, i' \leq N_k$ , we have  $V_{i,k} \cap V_{i',k} = \emptyset$  and  $x_{i,k} \in V_{i,k}$  if  $V_{i,k} \neq \emptyset$ . We set:

$$\mu_k^X(dx) = \sum_{i=0}^{N_k} \mu^X(V_{i,k}) \delta_{x_{i,k}}(dx),$$

where  $\delta_{x'}(dx)$  is the Dirac measure at  $x'$ . Notice that:

$$d_H^X(X, S_k) \leq \frac{1}{k} \quad \text{and} \quad d_P^X(\mu_k^X, \mu^X) \leq \frac{1}{k}.$$

We set  $y_{0,k} = y_{0,k}^n = \emptyset^Y$ . By (13), we get that for any  $k \geq 1, 0 \leq i \leq N_k$ , there exists  $y_{i,k}^n \in Y$  such that  $d^n(x_{i,k}, y_{i,k}^n) < \varepsilon_n$ . Since  $Y$  is compact, the sequence  $(y_{i,k}^n, n \geq 1)$  is relatively compact, hence admits a converging sub-sequence. Using a diagonal argument, and without loss of generality (by considering the sequence instead of the sub-sequence), we may assume that for  $k \geq 1, 0 \leq i \leq N_k$ , the sequence  $(y_{i,k}^n, n \geq 1)$  converges to some  $y_{i,k} \in Y$ .

For any  $y \in Y$ , we can choose  $x \in X$  such that  $d^n(x, y) < \varepsilon_n$  and  $i, k$  such that  $d^X(x, x_{i,k}) < \frac{1}{k} - \delta$ . Then, we get:

$$d^Y(y, y_{i,k}^n) = d^n(y, y_{i,k}^n) \leq d^n(y, x) + d^X(x, x_{i,k}) + d^n(x_{i,k}, y_{i,k}^n) \leq \frac{1}{k} - \delta + 2\varepsilon_n.$$

Thus, the set  $\{y_{i,k}^n, 0 \leq i \leq N_k\}$  is a  $(2\varepsilon_n + 1/k - \delta)$ -net of  $Y$ , and the set  $S_k^Y = \{y_{i,k}, 0 \leq i \leq N_k\}$  is an  $1/k$ -net of  $Y$ .

If  $k, k' \geq 1$  and  $0 \leq i \leq N_k, 0 \leq i' \leq N_{k'}$ , then we have:

$$\begin{aligned} d^Y(y_{i,k}, y_{i',k'}) &\leq d^Y(y_{i,k}^n, y_{i,k}^n) + d^Y(y_{i,k}^n, y_{i',k'}^n) + d^Y(y_{i',k'}^n, y_{i',k'}) \\ &\leq d^Y(y_{i,k}^n, y_{i,k}^n) + d^Y(y_{i',k'}^n, y_{i',k'}^n) + 2\varepsilon_n + d^X(x_{i,k}, x_{i',k'}), \end{aligned}$$

and, since the terms  $d(y_{i,k}^n, y_{i,k}^n)$  and  $d(y_{i',k'}^n, y_{i',k'}^n)$  can be made arbitrarily small, we deduce:

$$d(y_{i,k}, y_{i',k'}) \leq d(x_{i,k}, x_{i',k'}).$$

The reverse inequality is proven using similar arguments, so that the above inequality is in fact an equality. Therefore the map defined by  $\Phi(x_{i,k}) = (y_{i,k})$  from  $\cup_{k \geq 1} S_k$  onto  $\cup_{k \geq 1} S_k^Y$  is a root-preserving isometry. By density, this map can be extended uniquely to an isometric one-to-one root preserving embedding from  $X$  to  $Y$  which we still denote by  $\Phi$ . Hence the metric spaces  $X$  and  $Y$  are root-preserving isometric.

As far as the measures are concerned, we set:

$$\mu_k^{Y,n} = \sum_{i=0}^{N_k} \mu^X(V_{i,k}) \delta_{y_{i,k}^n} \quad \text{and} \quad \mu_k^Y = \sum_{i=0}^{N_k} \mu^X(V_{i,k}) \delta_{y_{i,k}}.$$

By construction, we have  $d_P^n(\mu_k^{Y,n}, \mu_k^X) \leq \varepsilon_n$ . We get:

$$\begin{aligned} d_P^Y(\mu_k^Y, \mu^Y) &= d_P^n(\mu_k^Y, \mu^Y) \leq d_P^Y(\mu_k^Y, \mu_k^{Y,n}) + d_P^n(\mu_k^{Y,n}, \mu_k^X) + d_P^X(\mu_k^X, \mu^X) + d_P^n(\mu^X, \mu^Y) \\ &< d_P^Y(\mu_k^Y, \mu_k^{Y,n}) + \varepsilon_n + \frac{1}{k} + \varepsilon_n. \end{aligned}$$

Furthermore, as  $n$  goes to infinity, we have that  $d_P^Y(\mu_k^Y, \mu_k^{Y,n})$  converges to 0, since the  $y_{i,k}^n$  converge towards the  $y_{i,k}$ . Thus, we actually have:

$$d_P^Y(\mu_k^Y, \mu^Y) \leq 1/k.$$

This implies that  $(\mu_k^Y, k \geq 1)$  converges weakly to  $\mu^Y$ . Since by definition  $\mu_k^Y = \Phi_* \mu_k^X$  and since  $\Phi$  is continuous, by passing to the limit, we get  $\mu^Y = \Phi_* \mu^X$ . This gives that  $\mathcal{X}$  and  $\mathcal{Y}$  are GHP-isometric.  $\square$

This proves that the function  $d_{\text{GHP}}^c$  defines a metric on  $\mathbb{K}$ .

**4.2. Proof of Theorem 2.4 and of (ii) of Theorem 2.3.** The proof of Theorem 2.4 is very close to the proof of Theorem 7.4.15 in [4], where only the Gromov-Hausdorff metric is involved. It is in fact a simplified version of the proof of Theorem 2.9, and is thus left to the reader.

We are left with the proof of (ii) of Theorem 2.3. It is in fact enough to check that if  $(\mathcal{X}_n, n \in \mathbb{N})$  is a Cauchy sequence, then it is relatively compact.

First notice that if  $(Z, d^Z)$  is a Polish metric space, then for any closed subsets  $A, B$ , we have  $d_P^Z(A, B) \geq |\text{diam}(A) - \text{diam}(B)|$ , and for any  $\mu, \nu \in \mathcal{M}_f(Z)$ , we have  $d_H^Z(\mu, \nu) \geq |\mu(Z) - \nu(Z)|$ . This implies that for any  $\mathcal{X} = (X, d^X, \emptyset^X, \mu)$ ,  $\mathcal{Y} = (Y, d^Y, \emptyset^Y, \nu) \in \mathbb{K}$ :

$$(14) \quad d_{\text{GHP}}^c(\mathcal{X}, \mathcal{Y}) \geq |\text{diam}(X) - \text{diam}(Y)| + |\mu(X) - \nu(Y)|.$$

Furthermore, using the definition of the Gromov-Hausdorff metric (5), we clearly have:

$$(15) \quad d_{\text{GHP}}^c(\mathcal{X}, \mathcal{Y}) \geq d_{\text{GH}}^c((X, d^X), (Y, d^Y)).$$

We deduce that if  $\mathcal{A} = (\mathcal{X}_n, n \in \mathbb{N})$  is a Cauchy sequence, then (14) implies that conditions (i) and (iii) of Theorem 2.4 are fulfilled. Furthermore, thanks to (15), the sequence  $((X_n, d^{X_n}), n \in \mathbb{N})$  is a Cauchy sequence for the Gromov-Hausdorff metric. Then point (2) of Proposition 7.4.11 in [4] readily implies condition (ii) of Theorem 2.4.

## 5. EXTENSION TO LOCALLY COMPACT LENGTH SPACES

**5.1. First results.** First, let us state two elementary Lemmas. Let  $(X, d, \emptyset)$  be a rooted metric space. Recall notation (2). We set:

$$\partial_r X = \{x \in X; d(\emptyset^x, x) = r\}.$$

**Lemma 5.1.** *Let  $(X, d, \emptyset)$  be a complete rooted length space and  $r, \varepsilon > 0$ . Then we have, for all  $\delta > 0$ :*

$$X^{(r+\varepsilon)} \subset (X^{(r)})^{\varepsilon+\delta}.$$

*Proof.* Let  $x \in X^{(r+\varepsilon)} \setminus X^{(r)}$  and  $\delta > 0$ . There exists a rectifiable curve  $\gamma$  defined on  $[0, 1]$  with values in  $X$  such that  $\gamma(0) = \emptyset$  and  $\gamma(1) = x$ , such that  $L(\gamma) < d(\emptyset, x) + \delta \leq r + \varepsilon + \delta$ . There exists  $t \in (0, 1)$  such that  $\gamma(t) \in \partial_r X$ . We can bound  $d(\gamma(t), x)$  by the length of the fragment of  $\gamma$  joining  $\gamma(t)$  and  $x$ , that is the length of  $\gamma$  minus the length of the fragment of  $\gamma$  joining  $\emptyset$  to  $\gamma(t)$ . The latter being equal to or larger than  $d(\emptyset^X, \gamma(t)) = r$ , we get:

$$d(\gamma(t), x) \leq L(\gamma) - r < \varepsilon + \delta.$$

Since  $\gamma(t) \in X^{(r)}$ , we get  $x \in (X^{(r)})^{\varepsilon+\delta}$ . This ends the proof.  $\square$

**Lemma 5.2.** *Let  $\mathcal{X} = (X, d, \emptyset, \mu) \in \mathbb{L}$ . For all  $\varepsilon > 0$  and  $r > 0$ , we have:*

$$d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{X}^{(r+\varepsilon)}) \leq \varepsilon + \mu(X^{(r+\varepsilon)} \setminus X^{(r)}).$$

*Proof.* The identity map is an obvious embedding  $X^{(r)} \hookrightarrow X^{(r+\varepsilon)}$  which is root-preserving. Then, we have:

$$d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{X}^{(r+\varepsilon)}) \leq d_{\text{H}}(X^{(r)}, X^{(r+\varepsilon)}) + d_{\text{P}}(\mu^{(r)}, \mu^{(r+\varepsilon)}).$$

Thanks to Lemma 5.1, we have  $d_{\text{H}}(X^{(r)}, X^{(r+\varepsilon)}) \leq \varepsilon$ .

Let  $A \subset X$  be closed. We have obviously  $\mu^{(r)}(A) \leq \mu^{(r+\varepsilon)}(A)$ . On the other hand, we have:

$$\mu^{(r+\varepsilon)}(A) \leq \mu^{(r)}(A) + \mu(A \cap (X^{(r+\varepsilon)} \setminus X^{(r)})) \leq \mu^{(r)}(A) + \mu(X^{(r+\varepsilon)} \setminus X^{(r)}).$$

This proves that  $d_{\text{P}}(\mu^{(r)}, \mu^{(r+\varepsilon)}) \leq \mu(X^{(r+\varepsilon)} \setminus X^{(r)})$ , which ends the proof.  $\square$

It is then straightforward to prove Lemma 2.6.

*Proof of Lemma 2.6.* Let  $\mathcal{X} = (X, d^X, \emptyset^X, \mu^X)$  and  $\mathcal{Y} = (Y, d^Y, \emptyset^Y, \mu^Y)$  be two elements of  $\mathbb{L}$ . Using the triangular inequality twice and Lemma 5.2, we get for  $r > 0$  and  $\varepsilon > 0$ :

$$\begin{aligned} |d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{Y}^{(r)}) - d_{\text{GHP}}^c(\mathcal{X}^{(r+\varepsilon)}, \mathcal{Y}^{(r+\varepsilon)})| &\leq d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{X}^{(r+\varepsilon)}) + d_{\text{GHP}}^c(\mathcal{Y}^{(r)}, \mathcal{Y}^{(r+\varepsilon)}) \\ &\leq 2\varepsilon + \mu^X(X^{(r+\varepsilon)} \setminus X^{(r)}) + \mu^Y(Y^{(r+\varepsilon)} \setminus Y^{(r)}). \end{aligned}$$

As  $\varepsilon$  goes down to 0, the expression above converges to 0, so that we get right-continuity of the function  $r \mapsto d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{Y}^{(r)})$ .

We write  $\mathcal{X}^{(r-)}$  for the compact metric space  $X^{(r)}$  rooted at  $\emptyset^X$  along with the induced metric and the restriction of  $\mu$  to the *open* ball  $\{x \in X; d^X(\emptyset^X, x) < r\}$ . We define  $\mathcal{Y}^{(r-)}$  similarly. Similar arguments as above yield for  $r > \varepsilon > 0$ :

$$\begin{aligned} & |d_{\text{GHP}}^c(\mathcal{X}^{(r-)}, \mathcal{Y}^{(r-)}) - d_{\text{GHP}}^c(\mathcal{X}^{(r-\varepsilon)}, \mathcal{Y}^{(r-\varepsilon)})| \\ & \leq d_{\text{GHP}}^c(\mathcal{X}^{(r-)}, \mathcal{X}^{(r-\varepsilon)}) + d_{\text{GHP}}^c(\mathcal{Y}^{(r)}, \mathcal{Y}^{(r-\varepsilon)}) \\ & \leq 2\varepsilon + \mu^X(\{x \in X, r - \varepsilon < d^X(\emptyset^X, x) < r\}) + \mu^Y(\{y \in Y, r - \varepsilon < d^Y(\emptyset^Y, y) < r\}). \end{aligned}$$

As  $\varepsilon$  goes down to 0, the expression above also converges to 0, which shows the existence of left limits for the function  $r \mapsto d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{Y}^{(r)})$ .  $\square$

The next result corresponds to (i) in Theorem 2.7.

**Proposition 5.3.** *The function  $d_{\text{GHP}}$  is a metric on  $\mathbb{L}$ .*

*Proof.* The symmetry and positivity of  $d_{\text{GHP}}$  are obvious. The triangle inequality is not difficult either, since  $d_{\text{GHP}}^c$  satisfies the triangle inequality and the map  $x \mapsto 1 \wedge x$  is non-decreasing and sub-additive.

We need to check that  $d_{\text{GHP}}$  is definite positive. To that effect, let  $\mathcal{X} = (X, d^X, \emptyset^X, \mu)$  and  $\mathcal{Y} = (Y, d^Y, \emptyset^Y, \nu)$  be two elements of  $\mathbb{L}$  such that  $d_{\text{GHP}}(\mathcal{X}, \mathcal{Y}) = 0$ . We want to prove that  $\mathcal{X}$  and  $\mathcal{Y}$  are GHP-isometric. We follow the spirit of the proof of Lemma 4.3.

By definition, we get that for almost every  $r > 0$ ,  $d_{\text{GHP}}^c(\mathcal{X}^{(r)}, \mathcal{Y}^{(r)}) = 0$ . Let  $(r_n, n \geq 1)$  be a sequence such that  $r_n \uparrow \infty$  and such that for  $n \geq 1$ ,  $d_{\text{GHP}}^c(\mathcal{X}^{(r_n)}, \mathcal{Y}^{(r_n)}) = 0$ . Since  $d_{\text{GHP}}^c$  is a metric on  $\mathbb{K}$ , there exists a GHP-isometry  $\Phi^n : X^{(r_n)} \rightarrow Y^{(r_n)}$  for every  $n \geq 1$ . Since all the  $X^{(r)}$  are compact, we may consider, for  $n \geq 1$  and for  $k \geq 1$ , a finite  $1/k$ -net of  $X^{(r_n)}$  containing the root:

$$S_k^n = \{x_{0,k}^n = \emptyset^X, x_{1,k}^n, \dots, x_{N_k^n, k}^n\}.$$

Then, if  $k \geq 1$ ,  $n \geq 1$ ,  $0 \leq i \leq N_k^n$ , the sequence  $(\Phi^j(x_{i,k}^n), j \geq n)$  is bounded since the  $\Phi^j$  are isometries. Using a diagonal procedure, we may assume without loss of generality, that for every  $k \geq 1$ ,  $n \geq 1$ ,  $0 \leq i \leq N_k^n$ , the sequence  $(\Phi^j(x_{i,k}^n), j \geq n)$  converges to some limit  $y_{i,k}^n \in Y$ . We define the map  $\Phi$  on  $S := \bigcup_{n \geq 1, k \geq 1} S_k^n$  taking values in  $Y$  by:

$$\Phi(x_{i,k}^n) = y_{i,k}^n.$$

Notice that  $\Phi$  is an isometry and root preserving as  $\Phi(\emptyset^X) = \emptyset^Y$  (see the proof of Lemma 4.3). The set  $\Phi(S_k^n)$  is obviously a  $2/k$ -net of  $Y^{(r_n)}$ , and thus  $\Phi(S)$  is a dense subset of  $Y$ . Therefore the map  $\Phi$  can be uniquely extended into a one-to-one root preserving isometry from  $X$  to  $Y$ , which we shall still denote by  $\Phi$ . It remains to prove that  $\Phi$  is a GHP-isometry, that is, such that  $\nu = \Phi_*\mu$ .

For  $n \geq 1$ ,  $k \geq 1$ , let  $(V_{i,k}^n, 0 \leq i \leq N_k^n)$  be Borel subsets of  $X^{(r_n)}$  with diameter less than  $1/k$ , such that  $\bigcup_{0 \leq i \leq N_k^n} V_{i,k}^n = X^{(r_n)}$  and for all  $0 \leq i, i' \leq N_k^n$ , we have  $V_{i,k}^n \cap V_{i',k}^n = \emptyset$  and  $x_{i,k}^n \in V_{i,k}^n$  if  $V_{i,k}^n \neq \emptyset$ . We then define the following measures:

$$\mu_k^n = \sum_{i=0}^{N_k^n} \mu(V_{i,k}^n) \delta_{x_{i,k}^n} \quad \text{and} \quad \nu_k^n = \sum_{i=0}^{N_k^n} \mu(V_{i,k}^n) \delta_{y_{i,k}^n}.$$

Let  $A \subset X$  be closed. We obviously have  $\mu_k^n(A) \leq \mu^{(r_n)}(A^{1/k})$  and  $\mu^{(r_n)}(A) \leq \mu_k^n(A^{1/k})$  that is:

$$(16) \quad d_{\text{P}}^X(\mu_k^n, \mu^{(r_n)}) \leq \frac{1}{k}.$$

For any  $n \geq 1$ ,  $k \geq 1$ , we have by construction  $\nu_k^n = \Phi_* \mu_k^n$  and  $\nu^{(r_n)} = \Phi_*^j \mu^{(r_n)}$  for any  $j \geq n \geq 1$ . We can then write, for  $j \geq n$ :

$$\begin{aligned} d_P^Y(\nu_k^n, \nu^{(r_n)}) &= d_P^Y(\Phi_* \mu_k^n, \Phi_*^j \mu^{(r_n)}) \\ &\leq d_P^Y(\Phi_* \mu_k^n, \Phi_*^j \mu_k^n) + d_P^Y(\Phi_*^j \mu_k^n, \Phi_*^j \mu^{(r_n)}) \\ &\leq d_P^Y(\Phi_* \mu_k^n, \Phi_*^j \mu_k^n) + \frac{1}{k}, \end{aligned}$$

where for the last inequality we used  $d_P^Y(\Phi_*^j \mu_k^n, \Phi_*^j \mu^{(r_n)}) = d_P^X(\mu_k^n, \mu^{(r_n)})$  and (16). Since the two measures  $\Phi_* \mu_k^n$  and  $\Phi_*^j \mu_k^n$  have the same masses distributed on a finite number of atoms, and the atoms  $\Phi^j(x_{i,k}^n)$  of  $\Phi_*^j \mu_k^n$  converge towards the atoms  $y_{i,k}^n$  of  $\Phi_* \mu_k^n$ , we deduce that:

$$\lim_{j \rightarrow +\infty} d_P^Y(\Phi_* \mu_k^n, \Phi_*^j \mu_k^n) = 0.$$

Hence,  $(\nu_k^n, k \geq 1)$  converges weakly towards  $\nu^{(r_n)}$ . According to (16), the sequence  $(\mu_k^n, k \geq 1)$  converges weakly to  $\mu^{(r_n)}$ . Since we have  $\nu_k^n = \Phi_* \mu_k^n$  and  $\Phi$  is continuous, we get  $\nu^{(r_n)} = \Phi_* \mu^{(r_n)}$  for any  $n \geq 1$ , and thus  $\nu = \Phi_* \mu$ . This ends the proof.  $\square$

We are now ready to prove Proposition 2.8. Notice that we shall not use (ii) of Theorem 2.7 in this Section as it is not yet proved.

*Proof of Proposition 2.8.* By construction, the convergence in  $\mathbb{K} \cap \mathbb{L}$  for the  $d_{\text{GHP}}$  metric implies the convergence for the  $d_{\text{GHP}}^c$  metric. We only have to prove that the converse is also true.

Let  $\mathcal{X} = (X, d^X, \emptyset, \mu)$  and  $\mathcal{X}_n = (X_n, d^{X_n}, \emptyset_n, \mu_n)$  be elements of  $\mathbb{K} \cap \mathbb{L}$  and  $(\varepsilon_n, n \in \mathbb{N})$  be a positive sequence converging towards 0 such that, for all  $n \in \mathbb{N}$ :

$$d_{\text{GHP}}^c(\mathcal{X}_n, \mathcal{X}) < \varepsilon_n.$$

Using Lemma 4.1, we consider a metric  $d^n$  on the disjoint union  $X_n \sqcup X$ , such that we have for  $n \in \mathbb{N}$ , and writing  $d_{\text{H}}^n$  and  $d_P^n$  respectively for  $d_{\text{H}}^{d^n}$  and  $d_P^{d^n}$ :

$$d^n(\emptyset_n, \emptyset) + d_{\text{H}}^n(X_n, X) + d_P^n(\mu_n, \mu) < \varepsilon_n.$$

If  $x_n \in X_n^{(r)}$ , by definition of the Hausdorff metric, there exists  $x \in X$  such that  $d^n(x_n, x) \leq d_{\text{H}}^n(X_n, X)$ . Then, we have:

$$d^n(\emptyset, x) \leq d^n(\emptyset, \emptyset_n) + d^n(\emptyset_n, x_n) + d^n(x_n, x) \leq d^n(\emptyset_n, \emptyset) + r + d_{\text{H}}^n(X_n, X) < r + \varepsilon_n.$$

We get that  $x$  belongs to  $X^{(r+\varepsilon'_n)}$  for some  $\varepsilon'_n < \varepsilon_n$  and thus, according to Lemma 5.1, it belongs to  $(X^{(r)})^{\varepsilon_n}$ , since  $X$  is a complete length space. Therefore we have  $X_n^{(r)} \subset (X^{(r)})^{\varepsilon_n}$ . Similar arguments yield  $X^{(r)} \subset (X_n^{(r)})^{\varepsilon_n}$ . We deduce that:

$$(17) \quad d_{\text{H}}^n(X_n^{(r)}, X^{(r)}) \leq \varepsilon_n.$$

If  $A \subset X_n \sqcup X$  is closed, we may compute:

$$\begin{aligned} \mu_n^{(r)}(A) &= \mu_n(A \cap X_n^{(r)}) \leq \mu(A^{\varepsilon_n} \cap (X_n^{(r)})^{\varepsilon_n}) + \varepsilon_n \\ &\leq \mu^{(r)}(A^{\varepsilon_n}) + \mu((X_n^{(r)})^{\varepsilon_n} \setminus X^{(r)}) + \varepsilon_n \\ &\leq \mu^{(r)}(A^{\varepsilon_n}) + \mu(X^{(r+2\varepsilon_n)} \setminus X^{(r)}) + \varepsilon_n, \end{aligned}$$

since  $(X_n^{(r)})^{\varepsilon_n} \subset (X^{(r)})^{2\varepsilon_n} \subset X^{(r+2\varepsilon_n)}$ . Similarly, we also have:

$$\begin{aligned} \mu^{(r)}(A) &\leq \mu(A \cap X^{(r-2\varepsilon_n)}) + \mu(X^{(r)} \setminus X^{(r-2\varepsilon_n)}) \\ &\leq \mu_n(A^{\varepsilon_n} \cap (X^{(r-2\varepsilon_n)})^{\varepsilon_n}) + \mu(X^{(r)} \setminus X^{(r-2\varepsilon_n)}) + \varepsilon_n \\ &\leq \mu_n^{(r)}(A^{\varepsilon_n}) + \mu(X^{(r)} \setminus X^{(r-2\varepsilon_n)}) + \varepsilon_n, \end{aligned}$$

since  $(X_n^{(r-2\varepsilon_n)})^{\varepsilon_n} \subset X^{(r)}$ . Hence, we finally deduce:

$$d_{\text{P}}^n(\mu_n^{(r)}, \mu^{(r)}) \leq \varepsilon_n + \mu(X^{(r+2\varepsilon_n)} \setminus X^{(r-2\varepsilon_n)}).$$

This and (17) yield:

$$d_{\text{GHP}}^c(\mathcal{X}_n^{(r)}, \mathcal{X}^{(r)}) \leq 3d_{\text{GHP}}^c(\mathcal{X}_n, \mathcal{X}) + \mu(X^{(r+2\varepsilon_n)} \setminus X^{(r-2\varepsilon_n)}).$$

Therefore, if  $\mu(\partial_r X) = 0$ , we have  $\lim_{n \rightarrow +\infty} d_{\text{GHP}}^c(\mathcal{X}_n^{(r)}, \mathcal{X}^{(r)}) = 0$ . Since  $\mu$  is by definition a finite measure, the set  $\{r > 0, \mu(\partial_r X) \neq 0\}$  is at most countable. By dominated convergence, we get  $\lim_{n \rightarrow +\infty} d_{\text{GHP}}(\mathcal{X}_n, \mathcal{X}) = 0$ .  $\square$

In order to prove Theorem 2.9 on the pre-compactness criterion, we shall approximate the elements of a sequence in  $\mathcal{C}$  by nets of small radius. The following Lemma guarantees that we can construct such nets in a consistent way. We use the convention that  $X^{(r)} = \emptyset$  if  $r < 0$ . In the sequel, if  $r > 0$  and  $k \geq 0$ , we will often use the notation  $A_{r,k}(X)$  for the annulus  $X^{(r)} \setminus X^{(r-2^{-k})}$ .

**Lemma 5.4.** *If  $\mathcal{X} = (X, \emptyset, d, \mu) \in \mathbb{L}$  satisfies condition (i) of Theorem 2.9, then for any  $k, \ell \in \mathbb{N}$ , there exists a  $2^{-k}$ -net of the annulus  $A_{\ell 2^{-k}, k}(X) = X^{(\ell 2^{-k})} \setminus X^{((\ell-1)2^{-k})}$  with at most  $N(\ell 2^{-k}, 2^{-k-1})$  elements.*

*Proof.* Let  $S'$  be a finite  $2^{-k-1}$ -net of  $X^{(\ell 2^{-k})}$  of cardinal at most  $N(\ell 2^{-k}, 2^{-k-1})$ . Let  $S''$  be the set of elements  $x$  in  $S' \cap A_{(\ell-1)2^{-k}, k+1}(X)$  such that there exists at least one element, say  $y_x$ , in  $A_{\ell 2^{-k}, k}(X)$  at distance at most  $2^{-k-1}$  of  $x$ . The set  $(S' \cap A_{\ell 2^{-k}, k}) \cup \{y_x, x \in S''\}$  is obviously a  $2^{-k}$ -net of  $A_{\ell 2^{-k}, k}(X)$ , and its cardinal is bounded by  $N(\ell 2^{-k}, 2^{-k-1})$ .  $\square$

**5.2. Proof of Theorem 2.9.** Notice that we shall not use (ii) of Theorem 2.7 in this Section as it is not yet proved.

The proof will be divided in several parts. The idea, as in [4], is to construct an abstract limit space, along with a measure, and to check that we can get a convergence (up to extraction). Let  $(\mathcal{X}_n, n \in \mathbb{N})$  be a sequence in  $\mathcal{C}$ , with  $\mathcal{X}_n = (X_n, d^{X_n}, \emptyset_n, \mu_n)$ . For  $\ell, k \in \mathbb{N}$ , we will write  $\ell_k$  for  $\ell 2^{-k}$ .

**5.2.1. Construction of the limit space.** Let  $\ell, k \in \mathbb{N}$ . Recall that, by Lemma 5.4, we can consider  $\mathfrak{S}_{\ell_k, k}^n$  a  $2^{-k-1}$ -net of the annulus  $A_{\ell_k, k}(X_n)$  with at most  $N(\ell_k, 2^{-k-2})$  elements. In order to have a finer sequence of nets, we shall consider:

$$S_{\ell_k, k}^n = \bigcup_{0 \leq k' \leq k} \left( A_{\ell_k, k}(X_n) \cap \mathfrak{S}_{\lceil \ell_k 2^{k'} \rceil 2^{-k'}, k'}^n \right).$$

By construction  $S_{\ell_k, k}^n$  is a  $2^{-k-1}$ -net of  $A_{\ell_k, k}(X_n)$  with cardinal at most:

$$\bar{N}(\ell_k, 2^{-k-2}) = \sum_{k'=0}^k N(\lceil \ell_k 2^{k'} \rceil 2^{-k'}, 2^{-k'-2}).$$

Let  $U_{\ell_k, k} = \{(k, \ell, i); 0 \leq i \leq \bar{N}(\ell_k, 2^{-k-2})\}$  and  $U = \bigcup_{k \in \mathbb{N}, \ell \in \mathbb{N}} U_{\ell_k, k}$ . We number the elements of  $S_{\ell_k, k}^n$  in such a way that:

$$(18) \quad S_{\ell_k, k}^n \cup \{\emptyset_n\} = \{x_u^n, u = (k, \ell, i), u \in U_{\ell_k, k}\},$$

where  $(x_u^n, u \in U)$  is some sequence in  $X_n$  and  $x_{(k,\ell,0)}^n = \emptyset_n$ . Notice that  $S_{\ell_k,k}^n$  is empty for  $\ell_k$  large if  $X_n$  is bounded. For  $u, u' \in U$ , we set:

$$d_{u,u'}^n = d^{X_n}(x_u^n, x_{u'}^n).$$

Notice that the sequence  $(d_{u,u'}^n, n \in \mathbb{N})$  is bounded. Thus, without loss of generality (by considering the sequence instead of the sub-sequence), we may assume that for all  $u, u' \in U$ , the sequence  $(d_{u,u'}^n, n \geq 1)$  converges in  $\mathbb{R}$  to some limit  $d_{u,u'}$ . We then consider an abstract space,  $X' = \{x_u, u \in U\}$ . On this space, the function  $d$  defined by  $(x_u, x_{u'}) \mapsto d_{u,u'}$  is a semi-metric. We then consider the quotient space  $X'/\sim$ , where  $x_u \sim x_{u'}$  if  $d_{u,u'} = 0$ . We shall denote by  $x_u$  the equivalent class containing  $x_u$ . Notice that  $d_{u,u'} = 0$  for any  $u = (k, \ell, 0)$  and  $u' = (k', \ell', 0)$  elements of  $U$  and let  $\emptyset$  denote their equivalence class. Finally, we let  $X$  be the completion of  $X'/\sim$  with respect to the metric  $d$ , so that  $(X, d, \emptyset)$  is a rooted complete metric space.

5.2.2. *Approximation by nets.* We set:

$$U_{\ell_k,k}^+ = \bigcup_{0 \leq j \leq \ell} U_{j2^{-k},k}, \quad S_{\ell_k,k}^{n,+} = \bigcup_{0 \leq j \leq \ell} S_{j2^{-k},k}^n = \{x_u^n, u \in U_{\ell_k,k}^+\} \quad \text{and} \quad S_{\ell_k,k}^+ = \{x_u, u \in U_{\ell_k,k}^+\}.$$

By construction  $S_{\ell_k,k}^{n,+}$  is a  $2^{-k-1}$ -net of  $X_n^{(\ell_k)}$  and  $S_{\ell_k,k}^{n,+} \subset S_{\ell'_k,k'}^{n,+}$  as well as  $S_{\ell_k,k}^+ \subset S_{\ell'_k,k'}^+$  for any  $k \leq k'$  and  $\ell_k \leq \ell'_k$ .

*Remark 5.5.* We also have that for  $v \in U \setminus U_{\ell_k,k}^+$ , either  $x_v^n = \emptyset_n$  or  $d^{X_n}(\emptyset_n, x_v^n) > \ell_k$  and either  $x_v = \emptyset$  or  $d(\emptyset, x_v) \geq \ell_k$ . Notice that the former inequality is strict but the latter is large.

A correspondence  $R$  between two sets  $A$  and  $B$  is a subset of  $A \times B$  such that the projection of  $R$  on  $A$  (resp.  $B$ ) is  $A$  (resp.  $B$ ). It is clear that the set defined by:

$$(19) \quad \mathcal{R}_{\ell_k,k}^{n,+} = \{(x_u^n, x_u), u \in U_{\ell_k,k}^+\}$$

is a correspondence between  $S_{\ell_k,k}^{n,+}$  and  $S_{\ell_k,k}^+$ . The distorsion  $\delta_n(\ell_k, k)$  of this correspondence is defined by:

$$(20) \quad \delta_n(\ell_k, k) = \sup\{|d^{X_n}(x_u^n, x_{u'}^n) - d(x_u, x_{u'})|; u, u' \in U_{\ell_k,k}^+\}.$$

Notice that for  $k \leq k'$  and  $\ell_k \leq \ell'_k$ , we have:

$$(21) \quad \delta_n(\ell_k, k) \leq \delta_n(\ell'_k, k').$$

Since  $U_{\ell_k,k}^+$  is finite, for all  $\ell, k \in \mathbb{N}$ , we have by construction  $\lim_{n \rightarrow +\infty} \delta_n(\ell_k, k) = 0$ .

**Lemma 5.6.** *The set  $S_{\ell_k,k}^+$  is a  $2^{-k}$ -net of  $X^{(\ell_k)}$ .*

*Proof.* Let  $x \in X^{(\ell_k)}$ . There exists  $v = (k', \ell', j) \in U$  such that  $d(x, x_v) < 2^{-k-3}$ . Notice that  $d(\emptyset, x_v) < \ell_k + 2^{-k-3}$ . We may choose  $n$  large enough, so that  $\delta_n(\ell_k \vee \ell'_k, k \vee k') < 2^{-k-3}$ . As  $x_v^n \in S_{\ell_k \vee \ell'_k, k \vee k'}^{n,+}$ , we have  $|d^{X_n}(\emptyset_n, x_v^n) - d(\emptyset, x_v)| < 2^{-k-3}$  and thus  $d^{X_n}(\emptyset_n, x_v^n) < \ell_k + 2^{-k-2}$ .

Thanks to Lemma 5.1 and since  $X_n$  is a length space, we get that  $x_v^n$  belongs to  $(X_n^{(\ell_k)})^{2^{-k-2}}$ . As  $S_{\ell_k,k}^{n,+}$  is a  $2^{-k-1}$ -net of  $X_n^{(\ell_k)}$ , there exists  $u \in U_{\ell_k,k}^+$  such that  $d^{X_n}(x_u^n, x_v^n) < 2^{-k-1} + 2^{-k-2}$ . Furthermore, we have that  $x_u^n$  and  $x_v^n$  belongs to  $S_{\ell_k \vee \ell'_k, k \vee k'}^{n,+}$ . We deduce that:

$$d(x, x_u) \leq d(x, x_v) + d(x_v, x_u) \leq 2^{-k-3} + \delta_n(\ell_k \vee \ell'_k, k \vee k') + d^{X_n}(x_u^n, x_v^n) < 2^{-k}.$$

This gives the result.  $\square$

We give an immediate consequence of this approximation by nets.

**Lemma 5.7.** *The metric space  $(X, d)$  is a length space.*

*Proof.* The proof of this Lemma is inspired by the proof of Theorem 7.3.25 in [4]. We shall check that  $(X, d)$  satisfies the mid-point condition.

Let  $k \in \mathbb{N}$  and  $x, x' \in X$ . According to Lemma 5.6, there exists  $\ell \in \mathbb{N}$  large enough and  $u, u' \in U_{\ell, k}^+$  such that  $d(x, x_u) < 2^{-k}$  and  $d(x', x_{u'}) < 2^{-k}$ . For  $n$  large enough, we get that  $\delta_n(\ell, k) < 2^{-k}$ . Since  $(X_n, d^{X_n})$  is a length space, there exists  $z \in X_n$  such that:

$$|2d^{X_n}(z, x_u^n) - d^{X_n}(x_u^n, x_{u'}^n)| + |2d^{X_n}(z, x_{u'}^n) - d^{X_n}(x_u^n, x_{u'}^n)| \leq 2^{-k}.$$

There exists  $u'' \in U_{\ell, k}^+$  such that  $d^{X_n}(x_{u''}^n, z) \leq 2^{-k}$ . Then, we deduce that:

$$\begin{aligned} & |2d(x_{u''}, x) - d(x, x')| + |2d(x_{u''}, x') - d(x, x')| \\ & \leq 4d(x, x_u) + 4d(x', x_{u'}) + |2d(x_{u''}, x_u) - d(x_u, x_{u'})| + |2d(x_{u''}, x_{u'}) - d(x_u, x_{u'})| \\ & \leq 8 \cdot 2^{-k} + 6\delta_n(\ell, k) + |2d^{X_n}(x_{u''}^n, x_u^n) - d^{X_n}(x_u^n, x_{u'}^n)| + |2d^{X_n}(x_{u''}^n, x_{u'}^n) - d^{X_n}(x_u^n, x_{u'}^n)| \\ & \leq 19 \cdot 2^{-k}. \end{aligned}$$

Since  $k$  is arbitrary, we get that  $(X, d)$  satisfies the mid-point condition and thus is a length space.  $\square$

**5.2.3. Approximation of the measures.** Let  $(V_u^n, u \in U_{\ell, k})$  be Borel subsets of  $A_{\ell, k}(X_n)$  with diameter less than  $2^{-k}$  such that  $\bigcup_{u \in U_{\ell, k}} V_u^n = A_{\ell, k}(X_n)$  and for all  $u, u' \in U_{\ell, k}$ , we have  $V_u^n \cap V_{u'}^n = \emptyset$  and  $x_u^n \in V_u^n$  as soon as  $V_u^n \neq \emptyset$ . We set  $U_{\infty, k} = \bigcup_{\ell \in \mathbb{N}} U_{\ell, k}$  and we consider the following approximation of the measure  $\mu_n$ :

$$\mu_{n, k} = \sum_{u \in U_{\infty, k}} \mu_n(V_u^n) \delta_{x_u^n}.$$

Notice that  $\mu_{n, k}^{(\ell_k)} = \sum_{u \in U_{\ell_k, k}} \mu_n(V_u^n) \delta_{x_u^n}$ . The measures  $\mu_{n, k}$  are locally finite Borel measures on  $X_n$ . It is clear that the sequence  $(\mu_{n, k}, k \in \mathbb{N})$  converges vaguely towards  $\mu_n$  as  $k$  goes to infinity, since we have for any  $r \in \mathbb{N}$ ,  $d_P^{d^{X_n}}(\mu_{n, k}^{(r)}, \mu_n^{(r)}) \leq 2^{-k}$ . On the limit space  $X$ , we define:

$$\nu_{n, k} = \sum_{u \in U_{\infty, k}} \mu_n(V_u^n) \delta_{x_u} \quad \text{and} \quad \nu_{n, k}^{\{\ell_k\}} = \sum_{u \in U_{\ell_k, k}} \mu_n(V_u^n) \delta_{x_u}.$$

Notice that  $\nu_{n, k}^{\{\ell_k\}} \leq \nu_{n, k}^{(\ell_k)}$  but they may be distinct as  $\nu_{n, k}^{(\ell_k)}$  may have some atoms on  $\partial_{\ell_k} X$  which are in  $S_{(\ell+1)_k, k}^+$  but not in  $S_{\ell_k, k}^+$ , as indicated in Remark 5.5.

Let us show that the sequence  $(\nu_{n, k}, k \in \mathbb{N})$  converges, up to an extraction, towards a locally finite measure  $\nu$  on  $X$ . For  $m \in 2^{-k}\mathbb{N}$ , we have:

$$\begin{aligned} \nu_{n, k}(X^{(m)}) &= \sum_{u \in U_{\infty, k}} \mu_n(V_u^n) \mathbf{1}_{\{d(x_u, \emptyset) \leq m\}} \leq \sum_{u \in U_{\infty, k}} \mu_n(V_u^n) \mathbf{1}_{\{d^{X_n}(x_u^n, \emptyset_n) \leq m + \delta_n(m, k)\}} \\ (22) \quad &\leq \mu_n(X_n^{(m + \delta_n(m, k) + 2^{-k})}), \end{aligned}$$

where for the first inequality we used (20). Recall that for all  $\ell, k \in \mathbb{N}$ , we have  $\lim_{n \rightarrow +\infty} \delta_n(\ell, k) = 0$ . We define  $\eta_k = \delta_{n_k}(k, k)$ . Using a diagonal argument, there exists a sub-sequence  $(n_k, k \in \mathbb{N})$  such that:

$$(23) \quad \eta_k \leq 2^{-k}.$$

By (21), we have  $\delta_{n_k}(m, k) \leq \eta_k$  for  $k \geq m$ . Thanks to property (ii) of Theorem 2.9, we get that  $\mu_{n_k}(X_{n_k})^{(m + \delta_{n_k}(m, k) + 2^{-k})}$  is uniformly bounded in  $k \in \mathbb{N}$  for  $m$  fixed. From the classical pre-compactness criterion for vague convergence of locally finite measures on a Polish metric space (see Appendix 2.6 of [5]), we deduce that there exists an extraction of the sub-sequence  $(n_k, k \in \mathbb{N})$ , which we still note  $(n_k, k \in \mathbb{N})$ , such that  $(\nu_{n_k, k}, k \in \mathbb{N})$  converges vaguely towards some locally finite



measure  $\nu$  on  $X$ . This implies the weak convergence of the finite measures  $(\nu_{n_k, k}^{(r)}, k \in \mathbb{N})$  towards  $\nu^{(r)}$  as soon as  $\nu(\partial_r X) = 0$ . Since  $\nu$  is locally finite, the set

$$(24) \quad A_\nu = \{r \geq 0; \nu(\partial_r X) > 0\}$$

is at most countable. Thus, we have  $\lim_{n \rightarrow +\infty} d_P(\nu_{n_k, k}^{(r)}, \nu^{(r)}) = 0$  for almost every  $r > 0$ .

5.2.4. *Convergence in the  $d_{GHP}$  metric.* We set  $\mathcal{X} = (X, d, \emptyset, \nu)$ . Notice that  $\mathcal{X} \in \mathbb{L}$  thanks to Lemma 5.7. We shall prove that  $d_{GHP}(\mathcal{X}_{n_k}, \mathcal{X})$  converges to 0.

Let  $r > 0$ . For any  $k \in \mathbb{N}$ , set  $\ell = \lceil 2^k r \rceil$  and recall  $\ell_k = 2^{-k} \lceil 2^k r \rceil$ . We set:

$$\mathcal{Y}_k^n = (S_{\ell_k, k}^{n, +}, d^{X_n}, \emptyset_n, \mu_{n, k}^{(\ell_k)}), \quad \mathcal{Z}_k^n = (S_{\ell_k, k}^+, d, \emptyset, \nu_{n, k}^{\{\ell_k\}}) \quad \text{and} \quad \mathcal{W}_k^n = (X^{(\ell_k)}, d, \emptyset, \nu_{n, k}^{\{\ell_k\}}).$$

The triangular inequalities give:

$$(25) \quad d_{GHP}^c(\mathcal{X}_n^{(r)}, \mathcal{X}^{(r)}) \leq B_n^1 + B_n^2 + B_n^3 + B_n^4 + B_n^5 + B_n^6,$$

with:

$$\begin{aligned} B_n^1 &= d_{GHP}^c(\mathcal{X}_n^{(r)}, \mathcal{X}_n^{(\ell_k)}), \quad B_n^2 = d_{GHP}^c(\mathcal{X}_n^{(\ell_k)}, \mathcal{Y}_k^n), \quad B_n^3 = d_{GHP}^c(\mathcal{Y}_k^n, \mathcal{Z}_k^n), \\ B_n^4 &= d_{GHP}^c(\mathcal{Z}_k^n, \mathcal{W}_k^n), \quad B_n^5 = d_{GHP}^c(\mathcal{W}_k^n, \mathcal{X}^{(\ell_k)}), \quad B_n^6 = d_{GHP}^c(\mathcal{X}^{(\ell_k)}, \mathcal{X}^{(r)}). \end{aligned}$$

Lemma 5.2 implies that:

$$(26) \quad B_n^1 = d_{GHP}^c(\mathcal{X}_n^{(r)}, \mathcal{X}_n^{(\ell_k)}) \leq 2^{-k} + \mu_n(X_n^{(\ell_k)} \setminus X_n^{(r)}).$$

As  $S_{\ell_k, k}^{n, +}$  is a  $2^{-k-1}$ -net of  $X_n^{\ell_k}$  and by definition of  $\mu_{n, k}$ , we clearly have:

$$d_H^{d^{X_n}}(X_n^{(\ell_k)}, S_{\ell_k, k}^{n, +}) \leq 2^{-k-1} \quad \text{and} \quad d_P^{d^{X_n}}(\mu_{n, k}^{(\ell_k)}, \mu_{n, k} \mathbf{1}_{S_{\ell_k, k}^{n, +}}) \leq 2^{-k}.$$

By considering the identity map from  $S_{\ell_k, k}^{n, +}$  to  $X^{(\ell_k)}$ , we deduce that:

$$(27) \quad B_n^2 = d_{GHP}^c(\mathcal{X}_n^{(\ell_k)}, \mathcal{Y}_k^n) \leq 2^{-k+1}.$$

Recall the correspondence (19). It is easy to check that the function defined on  $(S_{\ell_k, k}^{n, +} \sqcup S_{\ell_k, k}^+)^2$  by:

$$(28) \quad d_n(y, z) = \begin{cases} d^{X_n}(y, z) & \text{if } y, z \in S_{\ell_k, k}^{n, +}, \\ d(y, z) & \text{if } y, z \in S_{\ell_k, k}^+, \\ \inf\{d^{X_n}(y, y') + d(z, z') + \frac{1}{2}\delta_n(\ell_k, k); (y', z') \in \mathcal{R}_{\ell_k, k}^{n, +}\} & \text{if } y \in S_{\ell_k, k}^{n, +}, z \in S_{\ell_k, k}^+ \end{cases}$$

is a metric. For this particular metric, we easily have  $d_n(\emptyset_n, \emptyset) \leq \frac{1}{2} \delta_n(\ell_k, k)$  as well as:

$$d_H^{d_n}(S_{\ell_k, k}^{n, +}, S_{\ell_k, k}^+) \leq \frac{1}{2} \delta_n(\ell_k, k) \quad \text{and} \quad d_P^{d_n}(\mu_{n, k}^{(\ell_k)}, \nu_{n, k}^{\{\ell_k\}}) \leq \frac{1}{2} \delta_n(\ell_k, k).$$

We deduce that:

$$(29) \quad B_n^3 = d_{GHP}^c(\mathcal{Y}_k^n, \mathcal{Z}_k^n) \leq \frac{3}{2} \delta_n(\ell_k, k).$$

As  $S_{\ell_k, k}^+$  is a  $2^{-k}$ -net of  $X^{\ell_k}$ , thanks to Lemma 5.6, we get:

$$(30) \quad B_n^4 = d_{GHP}^c(\mathcal{Z}_k^n, \mathcal{W}_k^n) \leq 2^{-k}.$$

Concerning  $B_n^5$ , we only need to bound the Prokhorov distance between  $\nu_{n,k}^{\{\ell_k\}}$  and  $\nu_{n,k}^{(\ell_k)}$ . Recall that  $\nu_{n,k}^{\{\ell_k\}} \leq \nu_{n,k}^{(\ell_k)}$  and that  $\nu_{n,k}^{(\ell_k)}$  may differ only on  $\partial_{\ell_k} X$ . For  $A$  closed, we have:

$$\nu_{n,k}^{\{\ell_k\}}(A) \leq \nu_{n,k}^{(\ell_k)}(A) \quad \text{and} \quad \nu_{n,k}^{(\ell_k)}(A) \leq \nu_{n,k}^{\{\ell_k\}}(A) + \nu_{n,k}(\partial_{\ell_k} X).$$

Recall (24). Let  $\rho(r) \geq r + 3$  such that  $\rho(r) \notin A_\nu$  and:

$$(31) \quad \varepsilon_{n,k} = 2d_P(\nu_{n,k}^{(\rho(r))}, \nu^{(\rho(r))}).$$

As  $\ell_k \leq r + 2^{-k}$ , we have:

$$\nu_{n,k}(\partial_{\ell_k} X) \leq \nu((\partial_{\ell_k} X)^{\varepsilon_{n,k}}) + \varepsilon_{n,k} \leq \nu(X^{(r+2^{-k}+\varepsilon_{n,k})} \setminus X^{(r-2\varepsilon_{n,k})}) + \varepsilon_{n,k}.$$

We deduce that:

$$(32) \quad B_n^5 = d_{\text{GHP}}^c(\mathcal{W}_k^n, \mathcal{X}^{(\ell_k)}) \leq \nu(X^{(r+2^{-k}+\varepsilon_{n,k})} \setminus X^{(r-2\varepsilon_{n,k})}) + \varepsilon_{n,k}.$$

Lemma 5.2 and the fact that  $X$  is a length space gives:

$$(33) \quad B_n^6 = d_{\text{GHP}}^c(\mathcal{X}^{(\ell_k)}, \mathcal{X}^{(r)}) \leq 2^{-k} + \nu(X^{(\ell_k)} \setminus X^{(r)}).$$

Putting (26), (27), (29), (30), (32), (33) in (25), we get:

$$(34) \quad d_{\text{GHP}}^c(\mathcal{X}_n^{(r)}, \mathcal{X}^{(r)}) \leq 5 \cdot 2^{-k} + \mu_n(X_n^{(\ell_k)} \setminus X_n^{(r)}) \\ + \frac{3}{2}\delta_n(\ell_k, k) + \nu(X^{(r+2^{-k}+\varepsilon_{n,k})} \setminus X^{(r-2\varepsilon_{n,k})}) + \varepsilon_{n,k} + \nu(X^{(\ell_k)} \setminus X^{(r)}).$$

We give a more precise upper bound for  $\mu_n(X_n^{(\ell_k)} \setminus X_n^{(r)})$ . Using arguments similar to those used to get (22), we have:

$$\begin{aligned} \mu_n(X_n^{(\ell_k)} \setminus X_n^{(r)}) &\leq \mu_n(X_n^{(\ell_k)}) - \mu_n(X_n^{(\ell_k-2^{-k})}) \\ &\leq \nu_{n,k}(X^{(\ell_k+\delta_n(\ell_k,k)+2^{-k})}) - \nu_{n,k}(X^{(\ell_k-\delta_n(\ell_k,k)-4 \cdot 2^{-k})}). \end{aligned}$$

For  $k \geq r + 1$ , we have  $\delta_n(\ell_k, k) \leq \delta_n(k, k)$  thanks to (21). Then using the sub-sequence  $(n_k, k \in \mathbb{N})$  defined at the end of Section 5.2.3 with (23), we get that:

$$\begin{aligned} \mu_{n_k}(X_{n_k}^{(\ell_k)} \setminus X_{n_k}^{(r)}) &\leq \nu_{n_k,k}(X^{(\ell_k+2 \cdot 2^{-k})}) - \nu_{n_k,k}(X^{(\ell_k-5 \cdot 2^{-k})}) \\ &\leq \nu(X^{(\ell_k+2 \cdot 2^{-k}+\varepsilon_{n_k,k})}) - \nu(X^{(\ell_k-5 \cdot 2^{-k}-\varepsilon_{n_k,k})}) + 2\varepsilon_{n_k,k}. \end{aligned}$$

Notice that the sub-sequence  $(n_k, k \in \mathbb{N})$  does not depend on  $r$ : it is the same for all  $r \geq 0$ . Using (34), we get for  $k \geq r + 1$ :

$$d_{\text{GHP}}^c(\mathcal{X}_{n_k}^{(r)}, \mathcal{X}^{(r)}) \leq 5 \cdot 2^{-k} + \frac{3}{2}\eta_k + 2\nu(X^{(\ell_k+2^{-k}+\varepsilon_{n_k,k})} \setminus X^{(\ell_k-5 \cdot 2^{-k}-2\varepsilon_{n_k,k})}) + 3\varepsilon_{n_k,k}.$$

As  $\lim_{k \rightarrow +\infty} \ell_k = r$  and  $\lim_{k \rightarrow +\infty} \varepsilon_{n_k,k} = 0$ , we get using (23), that for  $r \notin A_\nu$ :

$$\lim_{k \rightarrow +\infty} d_{\text{GHP}}^c(\mathcal{X}_{n_k}^{(r)}, \mathcal{X}^{(r)}) = 0.$$

By dominated convergence, we get that  $\lim_{k \rightarrow +\infty} d_{\text{GHP}}(\mathcal{X}_{n_k}, \mathcal{X}) = 0$ . Thus we have a converging sub-sequence in  $\mathcal{C}$ .

**5.3. Proof of (ii) of Theorem 2.7.** We need to prove that the metric space  $(\mathbb{L}, d_{\text{GHP}})$  is separable and complete.

**Lemma 5.8.** *The metric space  $(\mathbb{L}, d_{\text{GHP}})$  is separable.*

*Proof.* We can notice that the set  $\mathbb{K} \cap \mathbb{L}$  is dense in  $(\mathbb{L}, d_{\text{GHP}})$ , since for  $\mathcal{X} \in \mathbb{L}$ , for all  $r > 0$  we have  $\mathcal{X}^{(r)} \in \mathbb{K}$  and  $d_{\text{GHP}}(\mathcal{X}^{(r)}, \mathcal{X}) \leq e^{-r}$ . Every element of  $\mathbb{K}$  can be approximated in the  $d_{\text{GHP}}^c$  topology by a sequence of metric spaces with finite cardinal, rational edge-lengths and rational weights. Hence,  $(\mathbb{K} \cap \mathbb{L}, d_{\text{GHP}}^c)$  is separable, being a subspace of a separable metric space. According to Proposition 2.8,  $(\mathbb{K} \cap \mathbb{L}, d_{\text{GHP}})$  is also separable. As  $\mathbb{K} \cap \mathbb{L}$  is dense in  $(\mathbb{L}, d_{\text{GHP}})$ , we deduce that  $(\mathbb{L}, d_{\text{GHP}})$  is separable.  $\square$

**Lemma 5.9.** *The metric space  $(\mathbb{L}, d_{\text{GHP}})$  is complete.*

*Proof.* Let  $(\mathcal{X}_n, n \in \mathbb{N})$ , with  $\mathcal{X}_n = (X_n, d^{X_n}, \emptyset_n, \mu_n)$ , be a Cauchy sequence in  $(\mathbb{L}, d_{\text{GHP}})$ . It is enough to prove that it is relatively compact. Thus, we need to prove it satisfies condition (i) and (ii) of Theorem 2.9.

Assume there exists  $r_0 \in \mathbb{R}_+$  such that  $\sup_{n \in \mathbb{N}} \mu_n(X_n^{(r_0)}) = +\infty$ . By considering a sub-sequence, we may assume that  $\lim_{n \rightarrow +\infty} \mu_n(X_n^{(r_0)}) = +\infty$ . This implies that for any  $r \geq r_0$ ,  $\lim_{n \rightarrow +\infty} \mu_n(X_n^{(r)}) = +\infty$ . Thus, we have for any  $m \in \mathbb{N}$ :

$$\lim_{n \rightarrow +\infty} \int_0^{+\infty} e^{-r} \left( 1 \wedge \left| \mu_n(X_n^{(r)}) - \mu_m(X_m^{(r)}) \right| \right) dr \geq e^{-r_0}.$$

Then use (14) to get that  $(\mathcal{X}_n, n \in \mathbb{N})$  is not a Cauchy sequence. Thus, if  $(\mathcal{X}_n, n \in \mathbb{N})$  is a Cauchy sequence, then (ii) of Theorem 2.9 is satisfied.

Let  $g_{n,m}(r) = d_{\text{GH}}^c((X_n^{(r)}, d^{X_n^{(r)}}), (X_m^{(r)}, d^{X_m^{(r)}}))$ . On the one hand, use (15) to get:

$$(35) \quad \lim_{\min(n,m) \rightarrow +\infty} \int_0^{+\infty} e^{-r} (1 \wedge g_{n,m}(r)) dr = 0.$$

On the other hand, using (15) and Lemma 5.2, and arguing as in the proof of Lemma 2.6, we get that for any  $r, \varepsilon \geq 0$ :

$$|g_{n,m}(r) - g_{n,m}(r + \varepsilon)| \leq 2\varepsilon.$$

This implies the functions  $g_{n,m}$  are 2-Lipschitz. Thus, we deduce from (35), that for all  $r \geq 0$ ,  $\lim_{\min(n,m) \rightarrow +\infty} g_{n,m}(r) = 0$ . Thus the sequence  $((X_n^{(r)}, d^{X_n^{(r)}}), n \in \mathbb{N})$  is a Cauchy sequence for the Gromov-Hausdorff metric. Then point (2) of Proposition 7.4.11 in [4] readily implies condition (i) of Theorem 2.9.  $\square$

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