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# Twisted Patterson-Sullivan measures and applications to amenability and coverings

Rémi Coulon, Rhiannon Dougall, Barbara Schapira, Samuel Tapie

January 27, 2019

## Abstract

Let  $\Gamma' < \Gamma$  be two discrete groups acting properly by isometries on a Gromov-hyperbolic space  $X$ . We prove that their critical exponents coincide if and only if  $\Gamma'$  is co-amenable in  $\Gamma$ , under the assumption that the action of  $\Gamma$  on  $X$  is strongly positively recurrent, i.e. has a growth gap at infinity. This generalizes all previously known results on this question, which required either  $X$  to be the real hyperbolic space and  $\Gamma$  geometrically finite, or  $X$  Gromov hyperbolic and  $\Gamma$  cocompact. This result is optimal: we provide several counterexamples when the action is not strongly positively recurrent.

**Keywords.** Twisted Patterson-Sullivan measure, critical exponents, unitary representations, amenability, strongly positively recurrent actions, growth gap at infinity, Gromov hyperbolic spaces

**Primary MSC Classification.** 20F67, 20F65, 57S30, 37A35, 37A25, 37A15, 37D40.

**Secondary MSC Classification.** 06B99, 20C99, 37D35.

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# 1 Introduction

## 1.1 Main result

Let  $(X, d)$  be a proper metric space,  $o \in X$  be some fixed origin, and  $\Gamma$  be a discrete group acting properly by isometries on  $X$ . The *critical exponent* of  $\Gamma$  (for its action on  $X$ ) is

$$h_\Gamma = h_\Gamma(X) = \limsup_{r \rightarrow +\infty} \frac{1}{r} \ln |\{\gamma \in \Gamma \mid d(o, \gamma o) \leq r\}|.$$

Of course, any subgroup  $\Gamma' < \Gamma$  satisfies  $h_{\Gamma'} \leq h_\Gamma$ . This paper is devoted to the study of the equality case.

*When do we have  $h_{\Gamma'} = h_\Gamma$ ?*

We are particularly interested in the case where  $X$  is Gromov hyperbolic. The answer to this question is intimately related to the *co-amenability* of  $\Gamma'$  in  $\Gamma$ , as was first independently shown by Grigorchuk [Gri80], Cohen [Coh82] and Brooks [Bro81]. Saying that  $\Gamma'$  is co-amenable in  $\Gamma$  is a natural way to generalise the fact that the quotient  $\Gamma/\Gamma'$  is amenable when  $\Gamma'$  is not a normal subgroup of  $\Gamma$ , see Definition 6.2. Our main theorem widely extends all previously known results on this question. It holds under the assumption that the action of  $\Gamma$  has a *growth gap at infinity*, i.e. some critical exponent at infinity, representing the growth of  $\Gamma$  far from the orbit of any compact set, is strictly smaller than  $h_\Gamma$ . We also call such actions *strongly positively recurrent*. See below for the rigorous definition. This assumption is much weaker than more usual assumptions such as convex-cocompactness or geometrical finiteness, as shown in [ST18].

**Theorem 1.1.** *Let  $X$  be a proper hyperbolic geodesic space. Let  $\Gamma$  be a group acting properly by isometries on  $X$ , and  $\Gamma'$  a subgroup of  $\Gamma$ . Assume that the action of  $\Gamma$  is strongly positively recurrent. The following are equivalent.*

1.  $h_{\Gamma'} = h_\Gamma$
2. The subgroup  $\Gamma'$  is co-amenable in  $\Gamma$ .

Let us emphasize that this result is new even when  $X$  is a rank one symmetric manifold. As will be shown in Section 6.3, this result is optimal. None of the assumptions can be weakened without hitting numerous counterexamples. Our main theorem closes the above question for group actions on Gromov hyperbolic spaces.

Beyond this, we believe that our main tool, the *twisted Patterson-Sullivan measure*, is at least as important as the result, and should have various other applications in the future. Indeed, the method is completely original and new, and builds a fruitful bridge between invariant measures and ergodic theory of the geodesic flow on the one hand, and representations of the fundamental group on the other hand.

Theorem 1.1 has also a quantified version (Theorem 5.2) which leads to the following wide generalisation of Corlette's growth rigidity result [Cor90], see also [Dou17, CDS17].

**Theorem 1.2.** *Let  $X$  be a proper hyperbolic geodesic space. Let  $\Gamma$  be a group with Kazhdan's property (T) acting properly by isometries on  $X$ . Assume that the action of  $\Gamma$  is strongly positively recurrent. There exists  $\varepsilon \in \mathbb{R}_+^*$  such that for every subgroup  $\Gamma'$  of  $\Gamma$ , either  $h_{\Gamma'} \leq h_\Gamma - \varepsilon$  or  $\Gamma'$  is a finite index subgroup of  $\Gamma$ .*

We now give a brief historical background on this question, introduce the notion of strongly positively recurrent action, and sketch the proof of Theorem 1.2.

## 1.2 Historical background

The first relations between critical exponents and amenability appeared independently in the eighties, in the work of Brooks [Bro81, Bro85], in the context of hyperbolic manifolds, and Grigorchuk [Gri80], Cohen [Coh82] in a combinatorial setting.

Let  $\Gamma$  be a finitely generated free group acting on its Cayley graph  $X$ , with respect to a free basis. Given any normal subgroup  $\Gamma'$  of  $\Gamma$ , Grigorchuk and Cohen relate by a delicate explicit computation the critical exponent of  $\Gamma'$  (also called *co-growth* of  $\Gamma/\Gamma'$ ) to the spectral radius of the random walk on  $\Gamma/\Gamma'$ . Combined with Kesten's amenability criterion, they obtain the following statement.

**Theorem 1.3** (Grigorchuk [Gri80], Cohen [Coh82]). *Let  $\Gamma$  be a finitely generated free group and  $X$  its Cayley graph with respect to a free basis. For every normal subgroup  $\Gamma'$  of  $\Gamma$ , the quotient  $\Gamma/\Gamma'$  is amenable if and only if  $h_{\Gamma'} = h_{\Gamma}$ .*

At the same period, Brooks showed the following statement using the spectral properties of the Laplace-Beltrami operator.

**Theorem 1.4** (Brooks, [Bro85]). *Let  $n \in \mathbb{N}$  and  $M = \mathbb{H}^{n+1}/\Gamma$  be a convex-cocompact hyperbolic manifold with  $h_{\Gamma} > n/2$ . Then for every normal subgroup  $\Gamma'$  of  $\Gamma$ , the quotient  $\Gamma/\Gamma'$  is amenable if and only if  $h_{\Gamma'} = h_{\Gamma}$ .*

Let us discuss briefly the strategy behind this last result. Recall that a negatively curved manifold is convex-cocompact if all closed geodesics are included in a given compact set (or equivalently, if the geodesic flow has a compact nonwandering set). Brooks' approach actually starts in a much larger context. Given a Riemannian manifold  $M$  whose Laplacian satisfies a *spectral gap* condition, he showed that for every normal covering  $M'$  of  $M$  the quotient  $\pi_1(M)/\pi_1(M')$  is amenable if and only if the bottom spectra of their respective Laplace-Beltrami operators satisfy  $\lambda_0(M) = \lambda_0(M')$ . If  $M = \mathbb{H}^{n+1}/\Gamma$  is a hyperbolic manifold with  $h_{\Gamma} > n/2$ , then Sullivan's formula relates  $\lambda_0(M)$  to  $h_{\Gamma}$  [Sul87]. Moreover, Brooks' spectral condition is satisfied for convex-cocompact hyperbolic manifolds with  $h_{\Gamma} > n/2$ , which gives [Theorem 1.4](#).

We will not define this spectral gap condition for the Riemannian Laplacian here – see [Bro85, Section 1] – but it is exactly the spectral analog to the *growth gap at infinity* (or *strongly positive recurrence*) which we will introduce below for group actions, under which our main theorems are valid.

The assumption  $h_{\Gamma} > n/2$  is specific to this approach and cannot be removed as long as one uses Laplace spectrum.

Sullivan's formula relating the bottom of the spectrum of the Laplacian with critical exponents has been extended by Corlette-Iozzi [CI99] to all other locally symmetric hyperbolic manifolds. Therefore Brooks method extends verbatim to these exotic hyperbolic manifolds. Note also that Brooks's result can be extended when  $\Gamma'$  is not normal in  $\Gamma$ . This can be seen following the alternative proof of Brooks' Theorem given in [RT13].

Using Patterson-Sullivan theory, Roblin in [Rob05] is the first to prove the so-called “easy direction” in a much wider context. Namely, if  $\Gamma$  is a discrete group of isometries acting on a  $\text{CAT}(-1)$  space  $X$  and  $\Gamma'$  is a normal subgroup of  $\Gamma$  such that  $\Gamma/\Gamma'$  is amenable, then  $h_{\Gamma} = h_{\Gamma'}$ . His proof extends easily to actions on Gromov hyperbolic spaces, but requires in a crucial way that  $\Gamma'$  be normal in  $\Gamma$ .

The reciprocal statement was generalised by Stadlbauer in [Sta13], using a dynamical argument inspired by Kesten's work on random walks, see also Jaerisch [Jae14]. If  $\Gamma$  is an *essentially free* discrete group of isometries of  $\mathbb{H}^{n+1}$ ,

then for all normal subgroups  $\Gamma'$  of  $\Gamma$ , the quotient  $\Gamma/\Gamma'$  is amenable if and only if  $h_{\Gamma'} = h_{\Gamma}$ . His method allows to remove the artificial assumption  $h_{\Gamma} > n/2$ , and to our knowledge it is the only published work to deal with certain specific non convex-cocompact manifolds (geometrically finite).

Stadlbauer's arguments have been used later on by Dougall-Sharp in [DS16] with a symbolic coding in order to extend the result to convex-cocompact manifolds with pinched negative curvature, when  $\Gamma'$  is a normal subgroup of  $\Gamma$ . A generalization by Coulon, Dal'bo and Sambusetti in [CDS17] allows to deal with proper cocompact actions of  $\Gamma$  on some Gromov-hyperbolic spaces  $X$ , more precisely CAT(-1) spaces or the Cayley graph of  $\Gamma$ . Moreover the subgroup  $\Gamma'$  need not be normal in  $\Gamma$ .

### 1.3 Strongly positively recurrent actions

The notion of strongly positively recurrent action is crucial in our work. Let us present the definition and its origin. A detailed presentation can be found in Section 3. Let  $(X, d)$  be a proper geodesic space and  $\Gamma$  a group acting properly by isometries on  $X$ . Given a compact subset  $K$  of  $X$ , we define  $\Gamma_K$  as the set of elements  $\gamma \in \Gamma$  for which there exists two points  $x, y \in K$  and a geodesic  $c: [a, b] \rightarrow X$  joining  $x$  to  $\gamma y$  such that  $c \cap \Gamma \cdot K$  is contained in  $K \cup \gamma K$ . The critical exponent  $h_{\Gamma_K}$  of  $\Gamma_K$  is called the *entropy outside  $K$* . The *entropy at infinity* of  $\Gamma$  is the quantity

$$h_{\Gamma}^{\infty} = \inf_K h_{\Gamma_K}$$

The action of  $\Gamma$  on  $X$  has a *growth gap at infinity* if  $h_{\Gamma}^{\infty} < h_{\Gamma}$ . We will say then that the action is *strongly positively recurrent*. This notion which has both a dynamical and a geometric origin has been introduced independently in different contexts.

**A dynamical origin.** Heuristically, a dynamical system is strongly positively recurrent (with respect to a constant potential) if its entropy at infinity is strictly smaller than its topological entropy, see for instance [Sar01]. The terminology *stably positively recurrent* has been first introduced in the context of Markov shifts over a countable alphabet by Gurevič-Savchenko [GS98], and became *strongly positively recurrent* later in Sarig [Sar01]. This terminology, with the notion of entropy at infinity, has been used later on by several authors considering dynamical systems on a non-compact space, such as Ruelle [Rue03], Boyle, Buzzi and Gomez [BBGo14], or more recently Riquelme and Velozo [RV18, Vel17]. We do not define here the entropy at infinity of a dynamical system, however for the geodesic flow of a non-compact negatively curved manifold it coincides with the quantity  $h_{\Gamma}^{\infty}$  defined above [RV18, Vel17, ST18].

**A geometric point of view.** Dal'bo, Otal and Peigné in [DOP00] introduced the terminology of *parabolic gap* concerning geometrically finite groups  $\Gamma$  of isometries of a negatively curved space  $X$  whose parabolic subgroups  $P$  all satisfy  $h_P < h_{\Gamma}$ . Extending the work of Dal'bo *et al* [DPPS11], this was later generalized by Arzhantseva, Cashen and Tao [ACT15, Definition 1.6] to the so-called *growth gap* property, which is exactly the *growth gap at infinity* defined above. They showed that if the action of  $\Gamma$  on  $X$  has a growth gap at infinity and admits a contracting element, then  $\Gamma$  is *growth tight* (see [ACT15] for a

definition). This notion has also been studied by Yang [Yan16, Definition 1.4] under the name *statistically convex-cocompact action*. His terminology comes from the following intuition. Given  $r \in \mathbb{R}_+$ , the  $\Gamma$ -orbit of a point  $o \in X$  is in general not  $r$ -quasi-convex. If  $K$  stands for the closed ball  $B(o, r)$ , then  $\Gamma_K$  is exactly the set of elements  $\gamma \in \Gamma$  violating the definition of quasi-convexity. The assumption  $h_\Gamma^\infty < h_\Gamma$  states that most elements of  $\Gamma$  behave as in a convex-cocompact setting.

**Combining dynamical and geometric approaches.** The paper [ST18] by Schapira and Tapie introduced strongly positively recurrent actions in order to study the geodesic flow of negatively curved manifolds (independently but identically to Arzhantseva et al. and Yang), and provided several new examples. It was both inspired by the aforementioned dynamical works of Sarig and Buzzi and the geometric approach of Dal’bo, Otal and Peigné.

In the present work, we combine intuitions from dynamical systems – especially many tools used for the ergodic study of the geodesic flow on non-compact negatively curved manifolds – and geometric group theory to get our main result.

## 1.4 Outline of the proofs

Let us give a brief account on the proofs, and the main novelties of this paper. [Theorem 1.1](#) is the combination of two results:

1. the so-called “*easy direction*”, i.e. showing that if  $\Gamma'$  is a co-amenable subgroup of  $\Gamma$ , then  $h_{\Gamma'} = h_\Gamma$ ;
2. conversely, showing that for any subgroup  $\Gamma'$  of  $\Gamma$ , if  $h_{\Gamma'} = h_\Gamma$  then  $\Gamma'$  is co-amenable in  $\Gamma$ .

The “easy direction”, detailed in [Corollary 6.10](#), is based on an explicit estimation of the spectral radius of some random walks on  $\Gamma/\Gamma'$ , as in [CDS17].

The core of this paper is the other direction. In the context of general Gromov hyperbolic spaces instead of negatively curved manifolds or  $\text{CAT}(-1)$ -spaces, and maybe even more problematic when the action of  $\Gamma$  is not cocompact, all the approaches described above fail. Indeed, the approach via the spectrum of a Laplace-Beltrami operator seems specific to *locally symmetric Riemannian manifolds with negative curvature* and might not be adapted in this more general setting. Moreover, we are not aware of any coding of the geodesic flow which would allow to transpose Stadlbauer’s work. We develop therefore a new strategy combining Patterson-Sullivan theory and representation theory.

Assume for simplicity here that  $X$  is a proper  $\text{CAT}(-1)$  space, for example a rank one symmetric manifold. Recall that our results are new and optimal even in the latter case. Let  $\Gamma$  be a discrete group acting properly by isometries on  $X$ ,  $\Gamma'$  a subgroup of  $\Gamma$  and  $\mathcal{H} = \ell^2(\Gamma/\Gamma')$ . Then  $\Gamma'$  is co-amenable in  $\Gamma$  if and only if the corresponding unitary representation  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  almost admits invariant vectors. Given  $s > 0$ , we associate to this representation the following formal twisted Poincaré series

$$A(s) = \sum_{\gamma \in \Gamma} e^{-sd(o, \gamma o)} \rho(\gamma),$$

and show that there exists a *critical exponent*  $h_\rho$  such that for every  $s > h_\rho$ ,  $A(s)$  is a bounded operator of  $\mathcal{H}$ . Moreover this exponent satisfies

$$h_{\Gamma'} \leq h_\rho \leq h_\Gamma, \quad (1)$$

see [Lemma 6.1](#). By analogy with the standard Patterson-Sullivan measure, we associate to any  $x \in X$ , an operator-valued measure

$$a_{x,s}^\rho = \frac{1}{\|A(s)\|} \sum_{\gamma \in \Gamma} e^{-sd(x,\gamma o)} \text{Dirac}(\gamma o) \rho(\gamma).$$

When  $s$  approaches  $h_\rho$  from above, we are able, using an ultra-filter  $\omega$  (see [Section 5.2](#)) to let these measures “converge” to a measure  $a_x^\rho$  supported on the boundary  $\partial X$  of  $X$  and taking its values in the space of bounded operators  $\mathcal{B}(\mathcal{H}_\omega)$  on a larger Hilbert space  $\mathcal{H}_\omega$ . We call it the *twisted Patterson-Sullivan measure*.

In [Section 5](#) we properly define and study this measure. In particular, we show that it satisfies all the properties of the classical Patterson-Sullivan measures:  $h_\rho$ -conformality ([Lemma 5.14](#)),  $\Gamma$ -invariance twisted by the limit representation  $\rho_\omega: \Gamma \rightarrow \mathcal{U}(\mathcal{H}_\omega)$  induced by  $\rho$  ([Lemma 5.13](#)), Shadow Lemma ([Lemma 5.16](#)), etc.

The existence of a growth gap at infinity is used at a single but crucial place to prove that the measure  $a_x^\rho$  gives full mass to the *radial limit set* ([Corollary 5.18](#)). This apparently technical result allows to approximate the measure of any Borel set by measures of shadows. Then, the proof of [Theorem 1.1](#) becomes particularly simple. Assume indeed that  $h_{\Gamma'} = h_\Gamma$ . By (1) the classical and twisted Patterson-Sullivan measures have the same conformal dimension, namely  $h_\Gamma = h_\rho$ . Using the Shadow Lemma we deduce that  $a_x^\rho$  is absolutely continuous with respect to the standard Patterson-Sullivan measure ([Proposition 5.21](#)). Thanks to the ergodicity of Bowen-Margulis current we prove that the corresponding “Radon-Nikodym derivative” – which takes its values in  $\mathcal{B}(\mathcal{H}_\omega)$  – is essentially constant, equal to say  $D \in \mathcal{B}(\mathcal{H}_\omega) \setminus \{0\}$ . The twisted equivariance of  $a_x^\rho$  directly implies that the image of  $D$  (which is non trivial) is contained in the subspace of  $\rho_\omega$ -invariant vectors. It follows then from the construction of  $\rho_\omega$  that the original representation  $\rho$  almost has invariant vectors, i.e.  $\Gamma'$  is co-amenable in  $\Gamma$  ([Section 5.6](#)).

When  $X$  is a proper Gromov hyperbolic space, the above ideas work exactly in the same way. One just has to be careful that all measures are only quasi-conformal. However, this proof requires an important ergodicity argument. We use the fact that the Bowen-Margulis current is ergodic for the diagonal action of  $\Gamma$  on the double boundary  $\partial^2 X$ . This is well-known when  $X$  is a negatively curved Hadamard manifold, or even a  $\text{CAT}(-1)$  space and the action of  $\Gamma$  is strongly positively recurrent [[Rob03](#), [ST18](#)]. Bader and Furman proved that the statement also holds when  $\Gamma$  acts cocompactly on a Gromov hyperbolic space [[BF17](#)]. Although the result is quite expected, it had not been written yet for a non-cocompact action on a Gromov hyperbolic space, such as strongly positively recurrent actions. As it should be useful to other people, we decided to expose this argument in the fullest possible generality.

More precisely, if  $\Gamma$  is a discrete group acting properly by isometries on a Gromov-hyperbolic space  $X$ , using the abstract geodesic flow already studied in



[BF17], we prove a Hopf-Tsuji-Sullivan dichotomy (Theorem 4.2): the Bowen-Margulis current on the double boundary  $\partial^2 X$  is ergodic with respect to the action of  $\Gamma$  if and only if the geodesic flow is ergodic and conservative (for the Bowen-Margulis measure), if and only if the usual Patterson-Sullivan measure gives full measure to the radial limit set. The desired ergodicity for a strongly positively recurrent action then directly follows from Corollary 3.16.

For the sake of completeness, we also included a finiteness criterion for the Bowen-Margulis measure (Theorem 4.16) inspired from [PS18], which allows to deduce that the Bowen-Margulis measure is finite in the presence of a growth gap at infinity (Corollary 4.17).

Once again, let us insist on the fact that the key novelty of our argument is the construction of a Patterson-Sullivan measure twisted by a unitary representation.

**Outline of the paper.** We recall basics on Gromov hyperbolic spaces and the definition of the classical Patterson-Sullivan measure in Section 2. In Section 3 we define and study strongly positively recurrent actions. In Section 4, we develop the ergodic study of Patterson-Sullivan and Bowen-Margulis measures in the context of Gromov-hyperbolic spaces. Section 5 is devoted to the twisted Patterson-Sullivan measures. In Section 6 we introduce the notion of co-amenable subgroup and prove Theorem 1.1 and other applications of our method. We conclude in Section 7 with some questions.

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## 2 Patterson-Sullivan measures in hyperbolic spaces

### 2.1 Gromov hyperbolic spaces

We review a few important facts about hyperbolic spaces and their compactifications. For more details we refer the reader to Gromov's original paper [Gro87] or [CDP90, GdlH90].

Let  $(X, d)$  be a proper geodesic metric space. We denote by  $B(x, r)$  the closed ball of radius  $r$  centred at  $x$ .

**The four point inequality.** Given three points  $x, y, z \in X$ , the *Gromov product* is defined by

$$\langle x, y \rangle_z = \frac{1}{2} [d(x, z) + d(y, z) - d(x, y)].$$

Let  $\delta \in \mathbb{R}_+$ . The space  $X$  is  $\delta$ -hyperbolic if for all  $x, y, z, t \in X$ , we have

$$\langle x, z \rangle_t \geq \min \{ \langle x, y \rangle_t, \langle y, z \rangle_t \} - \delta. \quad (2)$$

It is said to be *Gromov hyperbolic* if it is  $\delta$ -hyperbolic for some  $\delta \in \mathbb{R}_+$ . Nevertheless, for simplicity we will always assume that  $\delta > 0$ .

**The boundary at infinity.** Let  $o$  be a base point of  $X$ . A sequence  $(x_n)$  of points of  $X$  *converges to infinity* if  $\langle x_n, x_m \rangle_o$  tends to infinity as  $n$  and  $m$  approach to infinity. The set  $\mathcal{S}$  of such sequences is endowed with a binary relation defined as follows. Two sequences  $(x_n)$  and  $(y_n)$  are related if

$$\lim_{n \rightarrow +\infty} \langle x_n, y_n \rangle_o = +\infty.$$

By (2), this relation is an equivalence relation. The *boundary at infinity* of  $X$ , denoted by  $\partial X$ , is the quotient of  $\mathcal{S}$  by this relation. A sequence  $(x_n)$  in the class of  $\xi \in \partial X$  is said *converging* to  $\xi$ . We write

$$\lim_{n \rightarrow +\infty} x_n = \xi.$$

The definition of  $\partial X$  does not depend on the base point  $o$ . As  $X$  is proper and geodesic, the Gromov boundary coincides with the visual boundary of  $X$  [CDP90, Chapitre 2].

The Gromov product of three points can be extended to the boundary. Let  $x \in X$  and  $y, z \in X \cup \partial X$ . Define  $\langle y, z \rangle_x$  as the infimum

$$\liminf_{n \rightarrow +\infty} \langle y_n, z_n \rangle_x$$

where  $(y_n)$  and  $(z_n)$  run over all sequences which converge to  $y$  and  $z$  respectively. This definition coincides with the original one when  $y, z \in X$ . By (2), for any two sequences  $(y_n)$  and  $(z_n)$  converging respectively to  $\eta, \xi \in \partial X$  one has

$$\langle \eta, \xi \rangle_x \leq \liminf_{n \rightarrow \infty} \langle y_n, z_n \rangle_x \leq \limsup_{n \rightarrow \infty} \langle y_n, z_n \rangle_x \leq \langle \eta, \xi \rangle_x + 2\delta.$$

Two points  $\xi$  and  $\eta$  of  $\partial X$  are equal if and only if  $\langle \xi, \eta \rangle_x = +\infty$ . Moreover, for every  $t \in X$ , for every  $x, y, z \in X \cup \partial X$ , the four point inequality (2) leads to

$$\langle x, z \rangle_t \geq \min \{ \langle x, y \rangle_t, \langle y, z \rangle_t \} - \delta. \quad (3)$$

The Gromov boundary is a metrizable compact space. More precisely there exists a metric on  $\partial X$  that we denote  $d_{\partial X}$  and two numbers  $a_0 \in (0, 1)$  and  $\varepsilon_0 \in \mathbb{R}_+$  such that for every  $\eta, \xi \in \partial X$ ,

$$|\ln d_{\partial X}(\eta, \xi) + a_0 \langle \eta, \xi \rangle_o| \leq \varepsilon_0. \quad (4)$$

See for instance [CDP90, Chapitre 11, Lemme 1.7].

**Limit sets.** Assume that  $\Gamma$  is a group acting by isometries on  $X$ . This action extends to an action by homeomorphisms on  $\partial X$ . Given any subset  $S$  of  $\Gamma$ , the *limit set of  $S$* , denoted by  $\Lambda(S)$ , is the intersection  $\overline{Sx} \setminus Sx$  of the closure of the orbit  $Sx$  with  $\partial X$ , for some (hence any) point  $x \in X$ .

Let  $K$  be a compact subset of  $X$ . The  *$K$ -radial limit set* of  $\Gamma$ , denoted by  $\Lambda_{\text{rad}}^K(\Gamma)$ , is the set of points  $\xi \in \partial X$  for which there exists a geodesic ray  $c: \mathbb{R}_+ \rightarrow X$  ending at  $\xi$  whose image intersects infinitely many translates of  $K$  by elements of  $\Gamma$ . It is a  $\Gamma$ -invariant subset of  $\Lambda(\Gamma)$ . The *radial limit set* is the increasing union

$$\Lambda_{\text{rad}}(\Gamma) = \bigcup_{K \subset X} \Lambda_{\text{rad}}^K(\Gamma).$$

If there is no ambiguity we will drop  $\Gamma$  from all the notations.

**Horocompactification.** We denote by  $\mathbf{1}$  the constant function equal to 1. Let  $C(X)$  be the set of continuous functions from  $X$  to  $\mathbb{R}$  endowed with the topology of uniform convergence on every compact subset. We denote by  $C_*(X)$  its quotient by the one-dimensional  $\mathbb{R}\mathbf{1}$  endowed with the quotient topology. As  $X$  is proper,  $C_*(X)$  is compact. Alternatively  $C_*(X)$  can be seen as the space of continuous cocycles on  $X$ , i.e. maps  $b: X \times X \rightarrow \mathbb{R}$  such that  $b(x, z) = b(x, y) + b(y, z)$ , for every  $x, y, z \in X$ . These two realisations of  $C_*(X)$  are canonically identified via the isomorphism sending a map  $f: X \rightarrow \mathbb{R}$  to the cocycle  $b: X \times X \rightarrow \mathbb{R}$  defined by  $b(x, y) = f(x) - f(y)$ .

Given  $x \in X$ , we write  $d_x: X \rightarrow \mathbb{R}$  for the map sending  $y$  to  $d(x, y)$ . The map  $x \rightarrow d_x$  induces a homeomorphism from  $X$  onto its image. The *horocompactification* of  $X$ , denoted by  $\bar{X}_h$  is the closure of  $X$  in  $C_*(X)$ . The *horoboundary*  $\partial_h X$  is defined as  $\partial_h X = \bar{X}_h \setminus X$ .

We extend the Gromov product to  $\bar{X}_h$  as follows. Given  $x \in X$  and  $b, b' \in \partial_h X$ , we set

$$\langle b, b' \rangle_x = \frac{1}{2} \sup_{z \in X} [b(x, z) + b'(x, z)]. \quad (5)$$

Let  $\Gamma$  be a group acting by isometries on  $X$ . This action induces an action of  $\Gamma$  on  $C_*(X)$  as follows. For every cocycle  $b \in C_*(X)$ , for every  $\gamma \in \Gamma$ , and all  $(x, y) \in X^2$ ,

$$[\gamma \cdot b](x, y) = b(\gamma^{-1}x, \gamma^{-1}y).$$

The horoboundary  $\partial_h X$  is invariant under this action. Moreover, the action preserves the Gromov product defined in (5).

**Comparison with the Gromov boundary.** Given a geodesic ray  $\alpha: \mathbb{R}_+ \rightarrow X$  the *Busemann cocycle along  $\alpha$*  is the map  $b: X \times X \rightarrow \mathbb{R}$  defined by

$$b(x, y) = \lim_{t \rightarrow \infty} [d(x, \alpha(t)) - d(y, \alpha(t))].$$

It is an example of point in the horoboundary  $\partial_h X$ . Note that there are in general several geodesic rays ending at a given point of the Gromov boundary  $\partial X$ , which may induce distinct Busemann cocycles.

**Proposition 2.1** (Coornaert-Papadopoulos [CP01, Proposition 3.3 and Corollary 3.8]). *There exists a map  $\pi: \partial_h X \rightarrow \partial X$ , which is continuous,  $\Gamma$ -invariant and onto.*

*Moreover, for every geodesic ray  $\alpha: \mathbb{R}_+ \rightarrow X$  starting at  $x$ , the Busemann cocycle along  $\alpha$  is a preimage of  $\alpha(\infty)$  in  $\partial_h X$ . In addition, two cocycles  $b_1, b_2 \in \partial_h X$  have the same image in  $\partial X$  if and only if  $\|b_1 - b_2\|_\infty \leq 64\delta$ .*

The following lemma ensures that the extension to the horoboundary of the Gromov product is close to its value in the Gromov boundary.

**Lemma 2.2.** *Let  $b, b' \in \partial_h X$  be two cocycles, and  $x \in X$ . Let  $\xi$  and  $\xi'$  be their respective images in  $\partial X$ . Then*

$$\langle \xi, \xi' \rangle_x \leq \langle b, b' \rangle_x \leq \langle \xi, \xi' \rangle_x + 2\delta. \quad (6)$$

*Proof.* First, if  $\xi = \xi'$ , then both  $\langle \xi, \xi' \rangle_x$  and  $\langle b, b' \rangle_x$  are infinite. Indeed the infiniteness of  $\langle \xi, \xi \rangle_x$  follows from the definition of the Gromov product on  $\bar{X}$ . On the other hand,  $b$  and  $b'$  differ by at most  $64\delta$  (Proposition 2.1). Hence

$$\langle b, b' \rangle_x \geq \langle b, b \rangle_x - 32\delta \geq \infty.$$

Therefore we can assume that  $\xi \neq \xi'$ . By definition of the horoboundary, there exist two sequences  $(y_n)$  and  $(y'_n)$  of points of  $X$  which respectively converge to  $b$  and  $b'$  in  $\bar{X}_h$ . Up to passing to a subsequence we may assume that  $(y_n)$  and  $(y'_n)$  respectively converge to  $\xi$  and  $\xi'$  in  $\bar{X}$ . Let  $z \in X$ . Triangle inequality gives for all  $n \in \mathbb{N}$

$$\frac{1}{2} \{ [d(y_n, x) - d(y_n, z)] + [d(y'_n, x) - d(y'_n, z)] \} \leq \langle y_n, y'_n \rangle_x$$

Passing to the limit we get

$$\frac{1}{2} \{ b(x, z) + b'(x, z) \} \leq \liminf_{n \rightarrow \infty} \langle y_n, y'_n \rangle_x \leq \langle \xi, \xi' \rangle_x + 2\delta.$$

This inequality holds for every  $x \in X$ , hence  $\langle b, b' \rangle_x \leq \langle \xi, \xi' \rangle_x$ , which completes the proof of the right inequality.

For every  $n \in \mathbb{N}$ , we denote by  $p_n$  a projection of  $x$  on a geodesic  $[y_n, y'_n]$ . It follows that

$$d(x, p_n) \leq \langle y_n, y'_n \rangle_x + 4\delta,$$

see for instance [CDP90, Chapitre 3, Lemme 2.7]. As  $(y_n)$  and  $(y'_n)$  converges to distinct points in  $\partial X$ , the sequence  $\langle y_n, y'_n \rangle_x$  is uniformly bounded. Recall that  $X$  is proper. Thus, up to passing to a subsequence we can assume that  $(p_n)$  converges to a point  $p \in X$ . Since  $p_n$  lies on  $[y_n, y'_n]$ , for every  $n \in \mathbb{N}$ , we have

$$\langle y_n, y'_n \rangle_x = \frac{1}{2} \{ [d(y_n, x) - d(y_n, p_n)] + [d(y'_n, x) - d(y'_n, p_n)] \}$$

Passing to the limit we get

$$\langle \xi, \xi' \rangle_x \leq \liminf_{n \rightarrow \infty} \langle y_n, y'_n \rangle_x \leq \frac{1}{2} \{ b(x, p) + b'(x, p) \} \leq \langle b, b' \rangle_x,$$

which corresponds to the left inequality.  $\square$

## 2.2 Patterson-Sullivan measures

The Patterson-Sullivan measure is a well-known very useful object in the study of negatively curved manifolds. It was extended by Coornaert in the context of hyperbolic spaces  $X$  [Coo93]. His work used the Gromov compactification  $\bar{X} = X \cup \partial X$ . Nevertheless the measure that he obtains is not exactly conformal but only quasi-conformal. Following [BM96], we run the construction in the horocompactification  $\bar{X}_h = X \cup \partial_h X$  rather than  $\bar{X}$ . We obtain thus easily an *exactly* conformal family of measures, and a  $\Gamma$ -invariant measure on the double Gromov boundary  $\partial^2 X$ , contrarily to the  $\Gamma$ -quasi-invariant construction of [Coo93, Corollaire 9.4].

**Poincaré series and critical exponent.** Let  $\Gamma$  be a group acting properly by isometries on  $X$ . We fix a base point  $o \in X$ . To any subset  $S$  of  $\Gamma$  we associate a *Poincaré series* defined by

$$\mathcal{P}_S(s) = \sum_{\gamma \in S} e^{-sd(\gamma o, o)},$$

Its critical exponent  $h_S$  is also the *exponential growth rate* of  $S$ , i.e.

$$h_S = \limsup_{r \rightarrow \infty} \frac{1}{r} \ln |\{\gamma \in S \mid d(\gamma o, o) \leq r\}|.$$

This quantity does not depend on the choice of  $o$ . The group  $\Gamma$  is called *convergent* (respectively *divergent*) if the Poincaré series  $\mathcal{P}_\Gamma(s)$  converges (respectively diverges) at  $s = h_\Gamma$ . According to Patterson study of Dirichlet series [Pat76], there exists a map  $\theta_0: \mathbb{R}_+ \rightarrow \mathbb{R}_+$  with the following properties.

1. For every  $\varepsilon > 0$ , there exists  $t_0 \geq 0$ , such that for every  $t \geq t_0$  and  $u \geq 0$ , we have  $\theta_0(t+u) \leq e^{\varepsilon u} \theta_0(t)$ .
2. The weighted series

$$\mathcal{P}'_\Gamma(s) = \sum_{\gamma \in \Gamma} \theta_0(d(o, \gamma o)) e^{-sd(\gamma o, o)} \quad (7)$$

is divergent whenever  $s \leq h_\Gamma$ , and convergent otherwise.

**Measure on the horoboundary.** Let us now define the Patterson-Sullivan measure. It is well known that there is a one-to-one correspondence between Radon measures and positive linear forms on the space of continuous functions. We adopt the latter point of view here. It may look overcomplicated, however it emphasizes the analogy with the *twisted Patterson-Sullivan measure* that we are going to define in Section 5.3.

Denote by  $C(\bar{X}_h)$  the set of continuous functions from  $\bar{X}_h$  to  $\mathbb{R}$ . Let  $x \in X$ . For every  $s > h_\Gamma$ , we define a positive continuous linear form  $L: C(\bar{X}_h) \rightarrow \mathbb{R}$  by

$$L_{x,s}(f) = \frac{1}{\mathcal{P}'_\Gamma(s)} \sum_{\gamma \in \Gamma} \theta_0(d(x, \gamma o)) e^{-sd(x, \gamma o)} f(\gamma o).$$

Since  $\bar{X}_h$  is compact, the dual of  $C(\bar{X}_h)$  endowed with the weak-\* topology is compact as well. Thus, there exists a sequence  $(s_n)$  converging to  $h_\Gamma$  such that

$(L_{o,s_n})$  converges to a positive continuous linear form  $L_o: C(\bar{X}_h) \rightarrow \mathbb{R}$ . By Riesz representation Theorem, there exists a unique Radon measure  $\tilde{\nu}_o$  on  $\bar{X}_h$  such that for every  $f \in C(\bar{X}_h)$

$$L_o(f) = \int f d\tilde{\nu}_o.$$

By construction of  $\theta_0$ , the series  $\mathcal{P}'_\Gamma(s_n)$  diverges when  $s_n$  approaches to  $h_\Gamma$ . As a consequence the support of the measure  $\tilde{\nu}_o$  is contained in  $\partial_h X$ . A standard argument shows that for every  $x \in X$ ,  $(L_{x,s_n})$  also converges to a continuous linear form on  $C(\bar{X}_h)$  that can be represented by a measure  $\tilde{\nu}_x$  on  $\bar{X}_h$  which belongs to the same class as  $\tilde{\nu}_o$ . The resulting family  $(\tilde{\nu}_x)_{x \in X}$  is  $h_\Gamma$ -conformal, i.e. for  $\tilde{\nu}_o$ -almost every  $b \in \partial_h X$ ,

$$\frac{d\tilde{\nu}_x}{d\tilde{\nu}_y}(b) = e^{-h_\Gamma b(x,y)}.$$

This family is also  $\Gamma$ -equivariant in the sense that for all  $\gamma \in \Gamma$  and  $x \in X$ , we have  $\gamma_* \tilde{\nu}_x = \tilde{\nu}_{\gamma x}$ .

**Measure on the Gromov boundary.** Recall that  $\pi: \partial_h X \rightarrow \partial X$  denotes the continuous  $\Gamma$ -invariant map from the horoboundary to the Gromov boundary (Proposition 2.1). For  $x \in X$ , denote by  $\nu_x = \pi_* \tilde{\nu}_x$  the push-forward measure. As  $\pi$  is  $\Gamma$ -equivariant, so is the family  $(\nu_x)$ . Recall that any two cocycles  $b, b' \in \partial_h X$  lying in the same fibre of  $\pi$  differ by at most  $64\delta$ . It follows that  $(\nu_x)$  is  $h_\Gamma$ -quasi-conformal, i.e. there exists  $C \in \mathbb{R}_+^*$ , such that for every  $x, y \in X$ , for  $\nu_o$ -almost every  $\xi \in \partial X$ , for every  $b \in \pi^{-1}(\xi)$ ,

$$\frac{1}{C} e^{-h_\Gamma b(x,y)} \leq \frac{d\nu_x}{d\nu_y}(\xi) \leq C e^{-h_\Gamma b(x,y)}. \quad (8)$$

A key tool is the well known Sullivan Shadow Lemma, due to Coornaert in our context [Coo93]. Recall that  $o$  is a fixed base point in  $X$ . Let  $x \in X$  and  $r \in \mathbb{R}_+$ . The shadow of  $B(x, r)$  seen from  $o$ , denoted by  $\mathcal{O}_o(x, r)$ , is the set of points  $y \in \bar{X}$  for which there exists a geodesic from  $o$  to  $y$  intersecting the ball  $B(x, r)$ .

**Lemma 2.3** (Shadow Lemma [Coo93, Proposition 6.1]). *Let  $(\alpha_x)_{x \in X}$  be a  $\Gamma$ -invariant  $a$ -quasi-conformal family of measures on the Gromov boundary  $\partial X$ . There exist  $r_0, C \in \mathbb{R}_+^*$  such that for all  $r \geq r_0$ , for all  $\gamma \in \Gamma$ ,*

$$\frac{1}{C} e^{-ad(o,\gamma o)} \leq \alpha_o(\mathcal{O}_o(\gamma o, r)) \leq C e^{2ar} e^{-ad(o,\gamma o)}.$$

In terms of shadows, the radial limit set (defined in the previous section) is also the set of points  $\xi \in \partial X$  which belong to infinitely many distinct shadows  $\mathcal{O}_x(\gamma_n o, r)$  for some  $x \in X$  and  $r \in \mathbb{R}_+^*$ .

**Corollary 2.4.** *Assume that  $\nu_o$  gives full measure to the radial limit set. Then it is unique, non-atomic, and is ergodic with respect to the action of  $\Gamma$  on  $\partial X$ . Moreover the Poincaré series of  $\Gamma$  diverges at  $h_\Gamma$*

*Proof.* The proof is well known and elementary. We recall the arguments, as they will appear later in a more sophisticated manner (see [Proposition 5.21](#)). First, it is non-atomic. Indeed, [Lemma 2.3](#) implies that any radial limit point has a sequence of decreasing neighbourhoods whose measure decreases to zero.

Let us show that  $\nu_o$  is ergodic. Let  $A \subset \partial X$  be a  $\Gamma$ -invariant set with  $\nu_o(A) > 0$ . Without loss of generality, we can assume that  $A \subset \Lambda_{\text{rad}}^k(\Gamma)$ , for some compact subset  $k \subset X$ . Consider the new family of measures

$$\nu'_x = \frac{1}{\nu_o(A)} \mathbf{1}_A \nu_x,$$

which is also  $\Gamma$ -invariant and  $h_\Gamma$ -quasi-conformal. Therefore, it also satisfies the Shadow Lemma. In particular, for all  $r \in \mathbb{R}_+$ , for all  $\gamma \in \Gamma$ ,

$$\nu_o(\mathcal{O}_o(\gamma o, r)) \leq C(r) \nu'_o(\mathcal{O}_o(\gamma o, r)),$$

where  $C(r) \in \mathbb{R}_+^*$  is a parameter which only depends on  $r$ . By a Vitali type argument, one easily proves that for any compact subset  $K$  containing  $k$ , in restriction to  $\Lambda_{\text{rad}}^K$ , the measure  $\nu_o$  is absolutely continuous with respect to  $\nu'_o$ . We deduce that  $\nu_o(\Lambda_{\text{rad}}^K \setminus A) = 0$  for all  $K \supset k$ , so that  $\nu_o(\partial X \setminus A) = 0$ . Uniqueness directly follows from the ergodicity.

As  $\nu_o$  gives full measure to  $\Lambda_{\text{rad}}$ , there exists some compact subset  $k \subset X$  large enough so that  $\Lambda_{\text{rad}}^k$  has positive measure. In addition, there exists  $r > 0$ , such that for every finite subset  $S$  of  $\Gamma$  the collection

$$(\mathcal{O}_o(\gamma o, r))_{\gamma \in \Gamma \setminus S}$$

covers  $\Lambda_{\text{rad}}^k$ . By [Lemma 2.3](#), there exists  $\varepsilon \in \mathbb{R}_+^*$ , independent of  $S$ , such that

$$\sum_{\gamma \in \Gamma \setminus S} e^{-h_\Gamma d(o, \gamma o)} \geq \varepsilon \sum_{\gamma \in \Gamma \setminus S} \nu_o(\mathcal{O}_o(\gamma o, r)) \geq \varepsilon \nu_o(\Lambda_{\text{rad}}^k) > 0.$$

Hence the Poincaré series of  $\Gamma$  diverges at  $h_\Gamma$ . □

### 2.3 The Bowen-Margulis current.

Given any two cocycles  $b, b' \in \partial_h X$ , we define

$$D(b, b') = e^{-\langle b, b' \rangle_o}.$$

It can be thought of as the analogue of the Bourdon distance (cf [\[Bou95\]](#)), except that it does not satisfy the triangle inequality. By definition of  $\langle b, b' \rangle_o$  we get:

$$D(\gamma^{-1}b, \gamma^{-1}b') = e^{-\frac{1}{2}[b(\gamma o, o) + b'(\gamma o, o)]} D(b, b'). \quad (9)$$

We follow the standard notations for the double boundary of  $X$  and let

$$\partial^2 X = \{(\eta, \xi) \in \partial X \times \partial X \mid \eta \neq \xi\}, \quad (10)$$

$$\partial_h^2 X = \{(b, b') \in \partial_h X \times \partial_h X \mid \pi(b) \neq \pi(b')\}. \quad (11)$$

We still denote by  $\pi$  the continuous  $\Gamma$ -invariant map  $\partial_h X \times \partial_h X \rightarrow \partial X \times \partial X$  induced by  $\pi: \partial_h X \rightarrow \partial X$ .

**Definition 2.5.** The *Bowen-Margulis current* on  $\partial_h^2 X$  is the measure  $\tilde{\mu}$  defined by

$$\tilde{\mu} = \frac{1}{D^{2h_\Gamma}} \tilde{\nu}_o \otimes \tilde{\nu}_o.$$

The *Bowen-Margulis current* on  $\partial^2 X$  is the push-forward measure  $\mu = \pi_* \tilde{\mu}$ .

By [Lemma 2.2](#), there exists  $C_0 \in \mathbb{R}_+^*$  such that for  $\mu$ -almost every  $(\eta, \xi) \in \partial^2 X$ ,

$$\frac{1}{C_0} e^{2h_\Gamma \langle \eta, \xi \rangle_o} \leq \frac{d\mu}{d(\nu_o \otimes \nu_o)}(\eta, \xi) \leq C_0 e^{2h_\Gamma \langle \eta, \xi \rangle_o}. \quad (12)$$

The above definitions combined with [\(9\)](#) give the following lemma.

**Lemma 2.6.** *The Bowen-Margulis currents  $\tilde{\mu}$  on  $\partial_h^2 X$  and  $\mu$  on  $\partial^2 X$  are both  $\Gamma$ -invariant. If the Patterson-Sullivan measure  $\nu_o$  on  $\partial X$  gives full measure to the radial limit set, then  $\mu$  gives full measure to  $(\Lambda_{\text{rad}} \times \Lambda_{\text{rad}}) \cap \partial^2 X$ .*

### 3 Strongly positively recurrent actions

The presentation is strongly inspired from Schapira-Tapie [\[ST18\]](#) but has been slightly modified and simplified to adapt in an easier way to less smooth actions on general hyperbolic spaces.

#### 3.1 Entropy outside a compact set

Let  $(X, d)$  be a proper geodesic metric space, and  $\Gamma$  a group acting properly by isometries on  $X$ . Given a compact subset  $K$  of  $X$ , let  $\Gamma_K$  be the set of elements  $\gamma \in \Gamma$  for which there exists two points  $x, y \in K$  and a geodesic  $c: [a, b] \rightarrow X$  joining  $x$  to  $\gamma y$  such that  $c \cap \Gamma \cdot K$  is contained in  $K \cup \gamma K$ . We call the critical exponent  $h_{\Gamma_K}$  of the Poincaré series  $\mathcal{P}_{\Gamma_K}$  the *entropy outside  $K$* . Given any two compact subsets  $k \subset K$  of  $X$ , observe that  $\Gamma_K \subset \Gamma_k$ , whence  $h_{\Gamma_K} \leq h_{\Gamma_k}$ .

**Definition 3.1.** The *entropy at infinity*  $h_\Gamma^\infty$  is the quantity

$$h_\Gamma^\infty = \inf_K h_{\Gamma_K}$$

where the infimum runs over all compact subsets of  $X$ .

**Definition 3.2.** The action of  $\Gamma$  on  $X$  is *strongly positively recurrent* if  $h_\Gamma^\infty < h_\Gamma$ . We also say that the action has a *growth gap at infinity*.

#### 3.2 Examples

We present some examples of strongly positively recurrent actions. [Example 3.3](#) is a trivial one. The simplest non trivial example is a geometrically finite group acting on a negatively curved manifold with a *parabolic gap*, as studied by Dal'bo et al. in [\[DOP00\]](#), see [Proposition 3.5](#). We refer to [\[ST18\]](#) for more examples in a Riemannian setting such as geometrically finite manifolds, Schottky products, infinite genus Ancona surfaces, etc. If one does not assume that the space  $X$  on which  $\Gamma$  acts is hyperbolic, Arzhantseva et al. [\[ACT15\]](#) and Yang [\[Yan16\]](#) produce other examples, e.g. some rank one actions on CAT(0) spaces and some actions of subgroups of mapping class groups.



**Example 3.3** (Non elementary hyperbolic groups). Let  $\Gamma$  be a group acting properly cocompactly on a geodesic  $\delta$ -hyperbolic space  $X$  (in particular  $\Gamma$  is a hyperbolic group). If  $\Gamma$  is non elementary, this action is always strongly positively recurrent. Indeed, as the action is cocompact, there exists a compact subset  $K$  of  $X$  such that  $\Gamma K$  covers  $X$ . Thus,  $\Gamma_K$  is contained in

$$\{\gamma \in \Gamma \mid K \cap \gamma K \neq \emptyset\}.$$

Since the action is proper, the latter set is finite, hence  $h_{\Gamma_K} = 0$ . As  $\Gamma$  is non-elementary  $h_\Gamma > 0$ . Thus the action is strongly positively recurrent.

**Example 3.4** (Relative hyperbolic groups). There exist many equivalent definitions of relative hyperbolic groups. Let us recall the one that fits to our context, see for instance Bowditch [Bow12] or Hruska [Hru10, Definition 3.3].

Let  $\Gamma$  be a group and  $\mathcal{P}$  a finite collection of finitely generated subgroups of  $G$ . Assume that  $\Gamma$  acts properly by isometries on a geodesic hyperbolic space  $X$ . We say that the action of  $(\Gamma, \mathcal{P})$  on  $X$  is *cuspidal-uniform* if there exists a  $\Gamma$ -invariant family  $\mathcal{Z}$  of pairwise disjoint horoballs in  $X$  with the following properties.

1. The action of  $\Gamma$  on  $X \setminus U$  is cocompact, where  $U$  stands for the union of all horoballs  $Z \in \mathcal{Z}$ .
2. For every  $Z \in \mathcal{Z}$ , the stabilizer of  $Z$  is conjugated to some  $P \in \mathcal{P}$ .

The group  $\Gamma$  is *hyperbolic relative to  $\mathcal{P}$*  if  $(\Gamma, \mathcal{P})$  admits a cuspidal-uniform action on a hyperbolic space.

The definition of cuspidal-uniform action mimics the decomposition of finite volume hyperbolic manifolds as the union of a compact part and finitely many cusps. Hence the proof of the next statement works as in Schapira-Tapie [ST18, Proposition 7.16]. The details are left to the reader.

**Proposition 3.5.** *Let  $\Gamma$  be a group and  $\mathcal{P}$  a finite collection of finitely generated subgroups of  $\Gamma$ . Let  $X$  be a hyperbolic space, endowed with a cuspidal-uniform action of  $(\Gamma, \mathcal{P})$ . The critical exponent at infinity for this action is*

$$h_\Gamma^\infty = \max_{P \in \mathcal{P}} h_P.$$

*In particular the action of  $\Gamma$  on  $X$  is strongly positively recurrent if  $h_P < h_\Gamma$ , for every  $P \in \mathcal{P}$ .*

**Remark.** We recover here the parabolic gap condition, introduced by Dal'bo, Otal and Peigné [DOP00]. It also follows from this statement that if any group  $\Gamma$  (not necessarily a relatively hyperbolic one) admits a strongly positively recurrent action, then it is non-elementary (for this action).

We now focus on a specific cuspidal-uniform action, following with minor variations the Groves-Manning construction [GM08]. Given a geodesic metric space  $Y$ , the *horoball* over  $Y$  is the space  $Z(Y) = Y \times \mathbb{R}_+$  whose metric is modelled on the standard hyperbolic plane  $\mathbb{H}^2$  as follows: if  $x = (y, r)$  and  $x' = (y', r')$  are two points of  $Z(Y)$ , then

$$\cosh d(x, x') = \cosh(r - r') + \frac{1}{2} e^{-(r+r')} d(y, y')^2.$$

It is a geodesic hyperbolic space. It comes with a natural 1-Lipschitz embedding  $\iota: Y \rightarrow Z(Y)$  sending  $y$  to  $(y, 0)$ .

Let  $\Gamma$  be a group and  $\mathcal{P}$  a finite collection of finitely generated subgroups of  $G$ . Let  $S$  be a finite generating subset of  $G$  such that for every  $P \in \mathcal{P}$ , the set  $S \cap P$  generates  $P$ . Let  $X$  (respectively  $Y_P$ ) be the Cayley graph of  $\Gamma$  (respectively  $P$ ) with respect to  $S$  (respectively  $S \cap P$ ). It follows from our assumption that  $Y_P$  isometrically embeds in  $X$ . The *cone-off* space  $\dot{X}$  is the space obtained by attaching for every  $P \in \mathcal{P}$  and  $\gamma \in \Gamma$ , the horocone  $Z(\gamma Y_P)$  onto  $X$  along  $\gamma Y_P$  according to the canonical embedding  $\gamma Y_P \rightarrow Z(\gamma Y_P)$ . We endow this space with the largest pseudo-metric such that the maps  $X \rightarrow \dot{X}$  and  $Z(\gamma Y_P) \rightarrow \dot{X}$  are 1-Lipschitz. It turns out that this pseudo-metric is actually a distance. Moreover the space  $\dot{X}$  is proper and geodesic. In addition, the action of  $\Gamma$  on  $X$  extends to a proper action on  $\dot{X}$ . As  $\Gamma$  is hyperbolic relative to  $\mathcal{P}$ , the space  $\dot{X}$  is hyperbolic, moreover the action of  $(\Gamma, \mathcal{P})$  on  $\dot{X}$  is cusp-uniform.

**Proposition 3.6.** *Assume that every  $P \in \mathcal{P}$  is virtually nilpotent. If the action of  $\Gamma$  on  $\dot{X}$  is non elementary then it is strongly positively recurrent.*

**Remark 3.7.** Being a strongly positively recurrent is a property of the *action* of  $\Gamma$  and not of the group  $\Gamma$  itself. The proposition states that the action of  $\Gamma$  on the *cone-off space*  $\dot{X}$  is strongly positively recurrent. However this is not the case of any cusp-uniform action of  $(\Gamma, \mathcal{P})$  on a  $\delta$ -hyperbolic space. Indeed Dal'bo, Otal and Peigné produced an example of a geometrically finite manifold  $M$  with pinched negative curvature whose fundamental group  $\Gamma = \pi_1(M)$  contains a parabolic subgroup  $P$  (isomorphic to  $\mathbb{Z}$ ) whose critical exponent is the same as the one of  $\Gamma$  [DOP00, Théorème C]. In particular, this action is not strongly positively recurrent. Their construction strongly relies on the fact that the curvature of  $M$  is not constant. Indeed, an explicit computation shows that in locally symmetric spaces with negative curvature, all parabolic groups have a divergent Poincaré series (cf [DOP00] for the case of real hyperbolic surfaces). By Remark 3.9 below, this implies that all groups acting on a locally symmetric space with a geometrically finite action have a growth gap at infinity.

In the above construction, the metric on each horocone  $Z(Y)$  is modelled on the one of the standard hyperbolic plane  $\mathbb{H}^2$ . Hence, although there is no appropriate notion of sectional curvature in this context, it is natural to think of  $\dot{X}$  as a space with constant curvature equal to  $-1$ .

A variation of Proposition 3.6 already appears in the course of the proof of [ACT15, Theorem 8.1]. However the argument is rather terse. For the convenience of the reader, we expose an alternative approach, which is of independent interest. We start with the following statement.

**Lemma 3.8.** *Let  $P \in \mathcal{P}$ . If  $P$  is virtually nilpotent, then the action of  $P$  on  $\dot{X}$  is divergent.*

*Proof.* For simplicity we let  $Y = Y_P$ . Since  $\dot{X}$  is hyperbolic, there exists  $r \geq 0$  such that the subspace  $Z_r(Y) = Y \times [r, \infty)$  of  $Z(Y)$  isometrically embeds in  $\dot{X}$  [CHK15, Proposition 3.12]. Hence it suffices to prove that  $P$  is divergent for its action on  $Z(Y)$ . We denote by  $o$  the image in  $Z(Y)$  of the vertex of  $Y$  corresponding to the trivial element in  $P$ . For every  $\gamma \in P$  we have

$$\cosh d(\gamma o, o) = 1 + \frac{1}{2} |\gamma|^2,$$

where  $|\gamma|$  stands for the length of  $\gamma$  with respect to the word metric on  $P$  induced by  $S \cap P$ . A direct computation shows that

$$e^{-d(\gamma o, o)} = \frac{1}{4} \left( \sqrt{|\gamma|^2 + 4} - |\gamma| \right)^2$$

Hence the Poincaré series of  $P$  for its action on  $Z(Y)$  computed at  $s$  is

$$\mathcal{P}_P(s) = \sum_{k \in \mathbb{N}} |S(k)| a_k \quad \text{where} \quad a_k = \left( \frac{\sqrt{k^2 + 4} - k}{2} \right)^{2s},$$

and  $S(k)$  stands for the sphere of radius  $k$  of  $P$  with respect to the word metric induced by  $S \cap P$ . Using Abel's transformation we compute the partial series associated to  $\mathcal{P}_P(s)$ . More precisely, for every  $n \in \mathbb{N}$ , we have

$$\sum_{k=0}^n |S(k)| a_k = \sum_{k=0}^{n-1} |B(k)| (a_k - a_{k+1}) + |B(n)| a_n,$$

where  $B(k)$  stands for the *ball* of radius  $k$  of  $P$  with respect to the word metric induced by  $S \cap P$ . A simple asymptotic expansion yields

$$a_k \underset{k \rightarrow \infty}{\sim} \frac{1}{k^{2s}} \quad \text{and} \quad (a_k - a_{k+1}) \underset{k \rightarrow \infty}{\sim} \frac{2s}{k^{2s+1}}.$$

Recall that  $P$  is virtually nilpotent. According to Bass [Bas72] and Guivarc'h [Gui71], there exist  $A, B \in \mathbb{R}_+$  and  $d \in \mathbb{N}$  such that for every  $k \in \mathbb{N}$ ,

$$Ak^d \leq |B(k)| \leq Bk^d.$$

Combining this estimate with the previous asymptotic expansion, we deduce that  $\mathcal{P}_P(s)$  converges if and only if  $s > d/2$ . In particular the group  $P$  is divergent.  $\square$

*Proof of Proposition 3.6.* By Proposition 3.5, there exists  $P \in \mathcal{P}$  such that  $h_\Gamma^\infty = h_P$ . Moreover, since the action of  $\Gamma$  on  $X$  is non-elementary, the limit set  $\Lambda(\Gamma)$  is infinite, whereas  $\Lambda(P)$  is a single point. Recall also that  $P$  is divergent (Lemma 3.8). By [DOP00, Proposition 2], we get  $h_\Gamma > h_P = h_\Gamma^\infty$  (this reference is written in the context of negatively curved manifolds, but the proof applies verbatim to our setting).  $\square$

**Remark 3.9.** The previous proof can be adapted, using a variation of the construction of Abbott-Hume-Osin [AHO17] to get the following combination result.

Let  $\mathcal{P}$  be a collection of finitely generated subgroups of  $\Gamma$ . Assume that  $\Gamma$  is hyperbolic relative to  $\mathcal{P}$  and non-elementary. If each parabolic group  $P \in \mathcal{P}$  admits a divergent action on a hyperbolic space  $X_P$ , then there exists a hyperbolic space  $X$  on which  $\Gamma$  admits a strongly positively recurrent action. The proof is left to the interested reader.

We have seen that the action of a relatively hyperbolic group on its coned-off Cayley graph is strongly positively recurrent. Let us now mention another source of examples of cusp-uniform actions due to Crampon and Marquis [CM14b]. Let

$\Omega$  be a properly convex subset of the projective space  $\mathbb{P}^n$ , i.e. there exists an affine chart in which  $\Omega$  is a relatively compact convex subset. Assume that  $\Omega$  is strictly convex with  $C^1$  boundary. Using cross-ratio, one defines the Hilbert metric  $d_\Omega$  on  $\Omega$ , so that the group  $\text{Aut}(\Omega)$  of projective transformations preserving  $\Omega$  acts by isometries on  $(\Omega, d_\Omega)$ . Let  $\Gamma$  be a discrete subgroup of  $\text{Aut}(\Omega)$  whose action on  $\Omega$  is geometrically finite. In this situation the convex hull  $C(\Lambda_\Gamma)$  of the limit set  $\Lambda_\Gamma \subset \partial\Omega$  endowed with the induced metric is Gromov-hyperbolic [CM14a, Théorème 9.1]. Moreover  $\Gamma$  is hyperbolic relative to the collection of maximal parabolic subgroups of  $\Gamma$  [CM14a, Proposition 9.8] and the action of  $\Gamma$  on  $(C(\Lambda_\Gamma), d_\Omega)$  is cusp-uniform. It follows from [CM14b, Lemme 9.8] that every parabolic subgroup of  $\Gamma$  is divergent. Reasoning as in Proposition 3.6, it yields that the action of  $\Gamma$  on  $C(\Lambda_\Gamma)$  is strongly positively recurrent.

To complete this section, we recall other examples of strongly positively recurrent actions described by Schapira-Tapie [ST18]. Note that those examples are *geometrically infinite*.

**Example 3.10** (Schottky product). Let  $X$  be a simply connected Riemannian manifold with pinched negative sectional curvature. Let  $A$  and  $B$  be two groups of isometries of  $X$  in a Schottky position, i.e. there exist two disjoint compact subsets  $U_A$  and  $U_B$  of  $\bar{X} = X \cup \partial X$  such that for every  $a \in A \setminus \{1\}$  and  $b \in B \setminus \{1\}$  we have

$$a(\bar{X} \setminus U_A) \subset U_A \quad \text{and} \quad b(\bar{X} \setminus U_B) \subset U_B$$

Then  $A$  and  $B$  generate a group  $\Gamma$  isometric to  $A * B$ . Moreover

$$h_\Gamma^\infty = \max\{h_A^\infty, h_B^\infty\},$$

see [ST18, Theorem 7.18]. In particular, as we also have

$$\max\{h_A^\infty, h_B^\infty\} \leq \max\{h_A, h_B\} \leq h_\Gamma,$$

if the actions of  $A$  and  $B$  on  $X$  are strongly positively recurrent, then so is the one of  $\Gamma$ .

**Example 3.11** (Ancona type surfaces). Let  $N = \mathbb{H}^2/\Gamma$  be a complete hyperbolic surface with  $1/2 < h_\Gamma < 1$ . Denote by  $g_0$  its Riemannian metric. For example,  $N$  can be built as a non-amenable regular cover of a compact hyperbolic surface  $N_0$ . In any pair of pants decomposition of  $N$ , choose finitely many pairs of pants  $P_1, \dots, P_K$ . Change the metric of  $N$  to a metric  $g_\epsilon$ , which is equal to  $g_0$  far from the pants  $P_i$ , and modified in the neighborhood of the  $P_i$  by shrinking the lengths of the boundary geodesics of the pants  $P_i$  to a length  $\epsilon$ . Let  $\Gamma_\epsilon$  be a discrete group such that the new hyperbolic surface  $(N, g_\epsilon)$  is isometric to  $\mathbb{H}^2/\Gamma_\epsilon$ . If  $\epsilon$  is sufficiently small, then the action of  $\Gamma_\epsilon$  on  $\mathbb{H}^2$  is strongly positively recurrent [ST18, Theorem 7.24].

### 3.3 Radial limit set.

Let  $\Gamma$  be a group with a strongly positively recurrent action on a hyperbolic space  $X$ . This assumption has a key consequence: the Patterson-Sullivan measure gives full measure to  $\Lambda_{\text{rad}}^r$  for some  $r \in \mathbb{R}_+$ , see Corollary 3.16. As mentioned in the introduction, being strongly positively recurrent is useful but

not necessary here, see [Corollary 2.4](#). It will be crucial in [Corollary 5.18](#). Several results in this section have been proven in [\[ST18\]](#) in a Riemannian setting. In our Gromov-hyperbolic setting, some arguments need to be slightly adapted.

Let  $K$  be a compact subset of  $X$ . Denote by  $\mathcal{L}_K$  the set of points  $\xi \in \partial X$  for which there exists a geodesic ray  $c: \mathbb{R}_+ \rightarrow X$  starting in  $K$ , ending at  $\xi$  and such that  $c \cap \Gamma K$  is contained in  $K$ . For every  $T \in \mathbb{R}_+$ , define  $U_K^T$  by

$$U_K^T = \{x \in \bar{X} \mid \exists \xi \in \mathcal{L}_K, \langle x, \xi \rangle_o \geq T\}.$$

**Lemma 3.12** (Compare with [\[ST18, Proposition 7.29\]](#)). *For every compact set  $K \subset X$ , we have*

$$\partial X \setminus \Lambda_{\text{rad}}^K \subset \Gamma \mathcal{L}_K.$$

**Remark.** In comparison with [\[ST18\]](#) observe that  $\Lambda_{\text{rad}}^K \cap \Gamma \mathcal{L}_K$  could be non-empty. This follows from the fact that two points in  $X \cup \partial X$  may be joined by several geodesics, one intersecting infinitely many translates of  $K$  and an the other not.

*Proof.* Let  $\xi \in \partial X \setminus \Lambda_{\text{rad}}^K$ . Let  $c: \mathbb{R}_+ \rightarrow X$  be any geodesic ray starting in  $K$  and ending at  $\xi$ . Since  $\xi$  does not belong to  $\Lambda_{\text{rad}}^K$ , there exists  $t \in \mathbb{R}_+$  and  $\gamma \in \Gamma$  such that  $c(t)$  belongs to  $\gamma K$  and  $c$  restricted to  $(t, \infty)$  does not intersects  $\Gamma K$ . It follows that  $\gamma^{-1}\xi$  belongs to  $\mathcal{L}_K$ , hence the result.  $\square$

**Lemma 3.13.** *Let  $k \subset X$  be a compact set containing the base point  $o$  and  $K$  its  $6\delta$ -neighbourhood. There exist a finite subset  $S \subset \Gamma$  and  $r_0 \in \mathbb{R}_+^*$  with the following property. Let  $x \in K$ ,  $y \in X \cup \partial X$  and  $c: I \rightarrow X$  a geodesic joining  $x$  to  $y$  such that  $c \cap \Gamma K \subset K$ . For every  $\gamma \in \Gamma$ , there exists  $\beta \in S\Gamma_k$  such that*

1.  $\langle x, \gamma o \rangle_{\beta o} \leq r_0$  and  $\langle y, \gamma o \rangle_{\beta o} \leq r_0$ ,
2.  $d(x, \beta o) \geq \langle y, \gamma o \rangle_x - r_0$ .

**Remark.** Working with the Gromov product is very convenient when geodesics are not unique, but sometimes confusing at the first sight. The above statement has the following geometrical meaning. If one approximates the triangle  $[x, y, \gamma o]$  by a tripod, then  $\beta o$  lies close to the branch joining  $\gamma o$  to the centre of the tripod (see [Figure 1](#)).

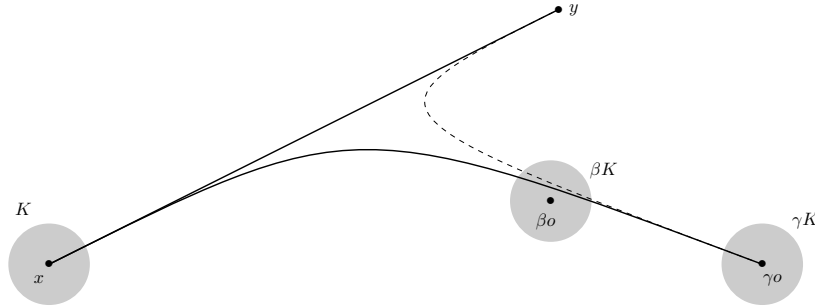


Figure 1 – A geodesic tripod

*Proof.* Let  $D$  be the diameter of  $K$  and  $r_0 = D + 2\delta$ . Since the action of  $\Gamma$  on  $X$  is proper, the set

$$S = \{\gamma \in \Gamma \mid d(o, \gamma o) \leq 3D + 6\delta\}$$

is finite. Let  $x \in K$ ,  $y \in X \cup \partial X$  and  $c: I \rightarrow X$  be a geodesic joining  $x$  to  $y$  such that  $c \cap \Gamma K \subset K$ . Let  $\gamma \in \Gamma$ . We fix a geodesic  $c_\gamma: [0, a] \rightarrow X$  joining  $x$  to  $\gamma o$ . Let  $s$  be the largest time in  $[0, a]$  such that  $s \leq D + 6\delta$  and  $c_\gamma(s)$  belongs to  $\alpha k$ , for some  $\alpha \in \Gamma$ .

Similarly, let  $t > D + 6\delta$  be the smallest time in  $[s, a]$  such that  $c_\gamma(t)$  belongs to  $\beta k \setminus \alpha k$ , for some  $\beta \in \Gamma$ . As  $x$  and  $o$  both belong to  $K$ ,  $d(o, \alpha o) \leq 3D + 6\delta$ , so that  $\alpha$  belongs to  $S$ . It follows from the construction that  $\alpha^{-1}\beta$  belongs to  $\Gamma_k$ , hence  $\beta \in S\Gamma_k$ . Let us now prove that  $\beta$  satisfies the announced inequalities. For simplicity, set  $z = c_\gamma(t)$ . Observe first that

$$\langle x, \gamma o \rangle_{\beta o} \leq \langle x, \gamma o \rangle_z + d(z, \beta o) \leq D \leq r_0.$$

Applying twice the four point inequality (2) we get

$$\min \{\langle x, y \rangle_z, \langle y, \gamma o \rangle_z\} \leq \langle x, \gamma o \rangle_z + 2\delta \leq 2\delta. \quad (13)$$

Assume now that the minimum is achieved by  $\langle x, y \rangle_z$ . In particular  $z$  is  $6\delta$ -close to point  $z'$  on  $c$  [CDP90, Chapitre 3, Lemme 3.7]. Note also that  $z'$  belongs to  $\beta K$ . As  $c \cap \Gamma K$  is contained in  $K$ , the point  $z'$  actually belongs to  $K$ . It forces  $d(x, z) \leq D + 6\delta$ , which contradicts the definition of  $t$ . Consequently the minimum in (13) is achieved by  $\langle y, \gamma o \rangle_z$  which yields  $\langle y, \gamma o \rangle_z \leq 2\delta$ . Hence  $\langle y, \gamma o \rangle_{\beta o} \leq D + 2\delta$ , which completes the proof of the first point. It follows from the triangle inequality that

$$\langle y, \gamma o \rangle_x \leq d(x, z) + \langle y, \gamma o \rangle_z \leq d(x, \beta o) + D + 2\delta,$$

which corresponds to the second point.  $\square$

**Lemma 3.14** (Compare with [ST18, Equation (27)]). *Let  $k \subset X$  be a compact subset containing  $o$  and  $K$  its  $6\delta$ -neighbourhood. There exists a finite subset  $S$  of  $\Gamma$  and  $r \in \mathbb{R}_+$  with the following properties. For every  $T \in \mathbb{R}_+$ ,*

$$U_K^T \cap \Gamma o \subset \bigcup_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T - r}} \mathcal{O}_o(\beta o, r).$$

*Proof.* Let  $S \subset \Gamma$  and  $r_0 \in \mathbb{R}_+$  be given by Lemma 3.13. Set  $r = r_0 + 2D + 4\delta$ , where  $D$  is the diameter of  $K$ . Let  $T \in \mathbb{R}_+$ . Let  $\gamma \in \Gamma$  such that  $\gamma o$  belongs to  $U_K^T$ . In particular there exists  $\xi \in \mathcal{L}_K$  such that  $\langle \xi, \gamma o \rangle_o \geq T$ . By definition of  $\mathcal{L}_K$ , there exists a geodesic ray  $c: \mathbb{R}_+ \rightarrow X$  starting in  $K$ , ending at  $\xi$  such that  $c \cap \Gamma K$  is contained in  $K$ . For simplicity, set  $x = c(0)$ . By Lemma 3.13, there exists  $\beta \in S\Gamma_k$  such that

$$d(x, \beta o) \geq \langle \xi, \gamma o \rangle_x - r_0 \quad \text{and} \quad \langle x, \gamma o \rangle_{\beta o} \leq r_0.$$

Observe that  $d(o, x) \leq D$ , as  $o$  and  $x$  both belongs to  $K$ . It follows from the triangle inequality that

$$d(o, \beta o) \geq \langle \xi, \gamma o \rangle_o - r_0 - 2D \geq T - r \quad \text{and} \quad \langle o, \gamma o \rangle_{\beta o} \leq r_0 + D < r - 4\delta$$

The latter point implies that  $\gamma o$  belongs to  $\mathcal{O}_o(\beta o, r)$  [CDP90, Chapitre 3, Lemme 3.7], whence the result.  $\square$

**Proposition 3.15** (Compare with [ST18, Proposition 7.31]). *Assume that the action of  $\Gamma$  on  $X$  is strongly positively recurrent. There exists a compact subset  $K$  of  $X$  and numbers  $a, C, T_0 \in \mathbb{R}_+^*$  such that for every  $T \geq T_0$ , for every non-negative function  $f \in C^+(\bar{X})$  whose support is contained in  $U_K^T$ ,*

$$\int f d\nu_o \leq C \|f\|_\infty e^{-aT}.$$

*Proof.* Since the action of  $\Gamma$  is strongly positively recurrent, there exists a compact subset  $k$  of  $X$  such that  $h_{\Gamma_k} < h_\Gamma$ . Up to enlarging  $k$ , we may assume that  $o$  belongs to  $k$ . Let  $K$  be the  $6\delta$ -neighbourhood of  $k$ . By Lemma 3.14, there exists a finite subset  $S$  of  $\Gamma$  and a number  $r \in \mathbb{R}_+$  such that for every  $T \in \mathbb{R}_+$ ,

$$U_K^T \cap \Gamma o \subset \bigcup_{\substack{\beta \in S\Gamma_k \\ d(o, \beta o) \geq T-r}} \mathcal{O}_o(\beta o, r). \quad (14)$$

Let  $\varepsilon > 0$  be such that  $h_\Gamma - 2\varepsilon > h_{\Gamma_k}$ . Since  $S$  is finite,  $S\Gamma_k$  and  $\Gamma_k$  have the same critical exponent. In particular the Poincaré series associated to  $S\Gamma_k$  converges at  $h_\Gamma - \varepsilon$ . More precisely there exists  $B \in \mathbb{R}_+$  such that for every  $T \geq 0$ , we have

$$\sum_{\substack{\beta \in S\Gamma_k \\ d(o, \beta o) \geq T-r}} e^{-(h_\Gamma - \varepsilon)d(o, \beta o)} \leq B e^{-(h_\Gamma - h_{\Gamma_k} - 2\varepsilon)T}. \quad (15)$$

Recall that  $\theta_0: \mathbb{R}_+ \rightarrow \mathbb{R}_+$  is the slowly increasing function used in (7) to define the Patterson-Sullivan measure  $\nu_o$ . There exists  $t_0 \geq 0$  such that for every  $t \geq t_0$  and  $u \geq 0$ , we have  $\theta_0(t+u) \leq e^{\varepsilon u} \theta_0(t)$ . Define

$$F = \{\gamma \in \Gamma \mid d(o, \gamma o) < t_0\}.$$

Now, let  $T \geq t_0 + r$  and  $f \in C^+(\bar{X})$  be a map supported in  $U_K^T$ . We may assume that  $\|f\|_\infty = 1$ . Let  $s > h_\Gamma$ . It follows from (14) that

$$L_{o,s}(f) \leq \frac{1}{\mathcal{P}_\Gamma^s(s)} \sum_{\substack{\beta \in S\Gamma_k \\ d(o, \beta o) \geq T-r}} \sum_{\substack{\gamma \in \Gamma \\ \gamma o \in \mathcal{O}_o(\beta o, r)}} \theta_0(d(o, \gamma o)) e^{-sd(o, \gamma o)}. \quad (16)$$

Let  $\beta \in S\Gamma_k$  such that  $d(o, \beta o) \geq T - r$ . We are going to estimate the second sum appearing above. For every  $y \in \mathcal{O}_o(\beta o, r)$  we have

$$d(o, \beta o) + d(\beta o, y) - 2r \leq d(o, y) \leq d(o, \beta o) + d(\beta o, y).$$

Moreover if  $d(\beta o, y) \geq t_0$ , then

$$\theta_0(d(o, y)) \leq e^{\varepsilon d(o, \beta o)} \theta_0(d(\beta o, y)),$$

otherwise, since  $d(o, \beta o) \geq t_0$ , we get

$$\theta_0(d(o, y)) \leq e^{\varepsilon[d(o, \beta o) + d(\beta o, y) - t_0]} \theta_0(t_0) \leq e^{\varepsilon d(o, \beta o)} \theta_0(t_0).$$

Consequently

$$\sum_{\substack{\gamma \in \Gamma \\ \gamma o \in \mathcal{O}_o(\beta o, r)}} \theta_0(d(o, \gamma o)) e^{-sd(o, \gamma o)} \leq e^{2sr} e^{-(s-\varepsilon)d(o, \beta o)} (\Sigma_1 + \Sigma_2),$$

where

$$\begin{aligned}\Sigma_1 &= \sum_{\substack{\gamma \in \Gamma \\ \gamma o \in \mathcal{O}_o(\beta o, r), d(\beta o, \gamma o) < t_0}} \theta_0(t_0) e^{-sd(\beta o, \gamma o)}, \\ \Sigma_2 &= \sum_{\substack{\gamma \in \Gamma \\ \gamma o \in \mathcal{O}_o(\beta o, r), d(\beta o, \gamma o) \geq t_0}} \theta_0(d(\beta o, \gamma o)) e^{-sd(\beta o, \gamma o)}.\end{aligned}$$

The number of terms in  $\Sigma_1$  is at most  $|F|$ , so that  $\Sigma_1 \leq |F| \theta(t_0)$ . On the other hand  $\Sigma_2$  is bounded from above by  $\mathcal{P}'_\Gamma(s) L_{\beta o, s}(\mathbf{1}) = \mathcal{P}'_\Gamma(s)$ . Combining these inequalities, we get

$$L_{o, s}(f) \leq C(s) \sum_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T-r}} e^{-(s-\varepsilon)d(o, \beta o)},$$

with

$$C(s) = e^{2sr} \left( 1 + \frac{|F| \theta_0(t_0)}{\mathcal{P}'_\Gamma(s)} \right).$$

After passing to the limit, it becomes

$$\int f d\nu_o \leq e^{2h_\Gamma r} \sum_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T-r}} e^{-(h_\Gamma - \varepsilon)d(o, \beta o)}.$$

Recall that  $h_\Gamma - \varepsilon > h_{\Gamma_k}$ . Thus, we also get from (15)

$$\int f d\nu_o \leq B e^{2h_\Gamma r} e^{-(h_\Gamma - h_{\Gamma_k} - 2\varepsilon)T}.$$

Recall that  $B$ ,  $k$ ,  $r$  and  $\varepsilon$  do not depend on  $T$  or  $f$ . The result follows.  $\square$

**Corollary 3.16** (Compare with [ST18, Corollary 7.32]). *Assume that the action of  $\Gamma$  on  $X$  is strongly positively recurrent. There exists a compact subset  $K$  of  $X$  such that  $\nu_o(\Lambda_{\text{rad}}^K) = 1$ .*

Recall that this conclusion is also true under the weaker assumption that  $\nu_o$  gives full measure to  $\Lambda_{\text{rad}}$ , as shown in Corollary 2.4.

*Proof.* Let  $K$  be the compact subset of  $X$  given by Proposition 3.15. By definition  $(U_K^T)$  is a family of neighbourhoods of  $\mathcal{L}_K$ . Since  $\nu_o$  is inner regular, it follows from Proposition 3.15, that  $\nu_o(\mathcal{L}_K) = 0$ . Therefore  $\nu_o(\Gamma \cdot \mathcal{L}_K) = 0$ , whence  $\nu_o(\Lambda_{\text{rad}}^K) = 1$ .  $\square$

## 4 Ergodicity of the Bowen-Margulis current

The aim of this section is to prove the following theorem, which will be of crucial importance in the proof of Theorem 1.1.

**Theorem 4.1.** *Let  $\Gamma$  be a discrete group with a proper strongly positively recurrent action on a Gromov-hyperbolic space  $X$ . Then the diagonal action of  $\Gamma$  on  $\partial^2 X$  is ergodic with respect to the Bowen-Margulis current  $\mu$ .*



The statement is well-known if  $X$  is a  $\text{CAT}(-1)$  space. Indeed the Hopf-Tsuji-Sullivan Theorem states that the action of  $\Gamma$  on  $(\partial^2 X, \mu)$  is ergodic if and only if the Patterson-Sullivan measure  $\nu_o$  gives full measure to the radial limit set  $\Lambda_{\text{rad}}$  [Rob03, Chapter 1]. The proof goes through the ergodicity of the geodesic flow on the quotient space  $X/\Gamma$  with respect to the Bowen-Margulis measure. A key ingredient is the exponential contraction/expansion of the geodesic flow along stable/unstable manifolds.

The reader may know that when  $X$  is Gromov hyperbolic, the definition of a good geodesic flow may be a problem. A option to bypass this difficulty would be to use the construction of either Gromov [Gro87, Cha94] or Mineyev [Min05]. They both define a metric geodesic flow, with the needed exponential contraction/expansion properties. However, the statements available in the literature require some additional assumptions. Although it is likely that the proof would adapt to strongly positively recurrent actions on Gromov hyperbolic spaces, it is probably a long technical work.

Instead, we follow with little variations the strategy developed by Bader and Furman for hyperbolic groups [BF17]. We first define a measurable action of  $\Gamma$  on the abstract space  $\partial^2 X \times \mathbb{R}$  and then prove a version of the Hopf-Tsuji-Sullivan theorem, involving the “geodesic flow” on the quotient  $(\partial^2 X \times \mathbb{R})/\Gamma$  (Theorem 4.2). In this approach the contraction property of the geodesic flow is replaced by a contraction property for the action of  $\Gamma$  on the boundary  $\partial X$ .

#### 4.1 The measurable geodesic flow of Bader-Furman

**The space of the geodesic flow.** Recall that  $o \in X$  is a fixed base point. The space  $X$  does not come with a well behaved geodesic flow. Instead we consider the abstract topological space

$$SX = \partial^2 X \times \mathbb{R},$$

and denote by  $\mathcal{B}$  its Borel  $\sigma$ -algebra. As suggested by the notation, it should be thought as the analogue of the unit tangent bundle of  $X$ . For this reason we slightly abuse terminology by calling the elements of  $SX$  *vectors*.

**Measure, flow and action.** Recall that  $(\nu_x)$  is the  $\Gamma$ -invariant  $h_\Gamma$ -quasi-conformal Patterson-Sullivan density on  $\partial X$  and  $\mu$  is the associated  $\Gamma$ -invariant Bowen-Margulis current, which belongs to the same measure class as  $\nu_o \otimes \nu_o$ . The Bowen-Margulis measure on  $SX$  is defined as the product measure

$$m = \mu \otimes dt,$$

where  $dt$  is the Lebesgue measure on  $\mathbb{R}$ . The translation on the  $\mathbb{R}$  component defines a flow  $(\phi_t)_{t \in \mathbb{R}}$  on  $SX$  which preserves the Bowen-Margulis measure  $m$ . If  $v = (\eta, \xi, t)$  is vector of  $SX$ , the points  $\eta$  and  $\xi$  are its respective (asymptotic) *past* and *future*. We now endow  $SX$  with a measurable  $\Gamma$ -action. To that end, we define a map  $\beta: \Gamma \times \partial X \rightarrow \mathbb{R}$  by

$$\beta(\gamma, \xi) = h_\Gamma^{-1} \ln \left( \frac{d\gamma_*^{-1} \nu_o}{d\nu_o}(\xi) \right).$$

It satisfies the following cocycle relation  $\nu_o$ -a.s.

$$\beta(\gamma_2 \gamma_1, \xi) = \beta(\gamma_2, \gamma_1 \xi) + \beta(\gamma_1, \xi), \quad \forall \gamma_1, \gamma_2 \in \Gamma. \quad (17)$$

As  $(\nu_x)$  is the push-forward by  $\pi: \partial_h X \rightarrow \partial X$  of the  $h_\Gamma$ -conformal Patterson-Sullivan density  $(\tilde{\nu}_x)$  on  $\partial_h X$ , for any cocycle  $b \in \pi^{-1}(\xi)$  and  $\gamma \in \Gamma$ ,

$$|\beta(\gamma, \xi) - b(\gamma^{-1}o, o)| \leq 100\delta. \quad (18)$$

For every point  $v = (\eta, \xi, t)$  in  $SX$  and any element  $\gamma \in \Gamma$ , define

$$\gamma v = (\gamma\eta, \gamma\xi, t + \kappa_\gamma(\eta, \xi)), \quad \text{where} \quad \kappa_\gamma(\eta, \xi) = \frac{\beta(\gamma, \xi) - \beta(\gamma, \eta)}{2}. \quad (19)$$

It defines a measurable action of  $\Gamma$  on  $SX$  which preserves the Bowen-Margulis measure  $m$ . Indeed, by (17), as  $\Gamma$  is countable, the set

$$S_0X = \{v \in SX \mid \forall \gamma_1, \gamma_2 \in \Gamma, \gamma_1(\gamma_2 v) = (\gamma_1 \gamma_2)v\} \quad (20)$$

is a  $\Gamma$ -invariant Borel subset of  $SX$ , with full  $m$ -measure. The action of  $\Gamma$  commutes with the flow  $(\phi_t)$ . In particular the set  $S_0X$  defined above is invariant under the flow  $(\phi_t)$ .

**Quotient space.** By analogy with the Riemannian setting, we wish to study the geodesic flow on the quotient space  $SX/\Gamma$ , viewed as an analogue of the unit tangent bundle on  $M = X/\Gamma$ . The action of  $\Gamma$  on  $SX$  is only a measurable action, but we could work in the quotient space  $S_0X/\Gamma$  where  $S_0X$  is the subset defined in (20). We prefer to use a slightly different approach and keep working in  $SX$ . Let  $\mathcal{B}_\Gamma$  be the sub- $\sigma$ -algebra of all Borel subsets which are  $\Gamma$ -invariant (up to measure zero). Let  $D$  be a Borel fundamental domain for the action of  $\Gamma$  on  $SX$ . We endow  $(SX, \mathcal{B}_\Gamma)$  with the restriction  $\bar{m}$  of the measure  $m$  to  $D$ . More precisely, for every  $B \in \mathcal{B}_\Gamma$ , we let

$$\bar{m}(B) = m(B \cap D).$$

This definition of  $\bar{m}$  does not depend on the choice of  $D$ . As  $\Gamma$  is countable we observe that  $\bar{m}(B) = 0$  if and only if  $m(B) = 0$ . Since the flow  $(\phi_t)$  commutes with the action of  $\Gamma$ , it induces a measure preserving flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$ . We think of this new dynamical system as the geodesic flow on  $SX/\Gamma$ .

**The Hopf-Tsuji-Sullivan theorem.** [Theorem 4.1](#) is a direct consequence of [Corollary 3.16](#) and the following statement.

**Theorem 4.2** (Hopf-Tsuji-Sullivan theorem on  $\delta$ -hyperbolic spaces). *Let  $\Gamma$  be a discrete group acting properly by isometries on a Gromov hyperbolic space  $X$ . The following assertions are equivalent.*

1. *The Patterson-Sullivan measure  $\nu_o$  only charges the radial limit set.*
2. *The geodesic flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is conservative.*
3. *The geodesic flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is ergodic.*
4. *The diagonal action of  $\Gamma$  on  $(\partial^2 X, \mu)$  is ergodic.*

*Moreover, if any of these assertions is satisfied, then  $\Gamma$  is divergent.*

**Remark.** If  $X$  is  $\text{CAT}(-1)$ , Roblin shows that the above items are *equivalent* to the divergence of the group  $\Gamma$  [Rob03, Chapter 1]. His proof would adapt to our setting, but is long and useless for our purpose, so we omit it here.

Note that the equivalence (3)  $\Leftrightarrow$  (4) follows immediately from the definition. We will see in Section 4.3 that (1)  $\Leftrightarrow$  (2) is also rather easy. As  $\Gamma$  is non-elementary, the Bowen-Margulis measure is not supported on a single orbit, so that (3)  $\Rightarrow$  (2), see [Aar97, Proposition 1.2.1]. The core of the proof is (2)  $\Rightarrow$  (4), which is shown in Section 4.4.

**Projection from  $SX$  to  $X$ .** In order to prove the Hopf-Tsuji-Sullivan Theorem, we need to relate the dynamical properties of the abstract space  $SX$  to the geometry of the original space  $X$ . To that end, we build a “projection” map  $\text{proj}: SX \rightarrow X$  as follows. For every  $(\eta, \xi) \in \partial^2 X$  we choose first a bi-infinite geodesic  $\sigma_{(\eta, \xi)}: \mathbb{R} \rightarrow X$  joining  $\eta$  to  $\xi$ . Without loss of generality we can assume that  $\sigma_{(\xi, \eta)}$  is obtained from  $\sigma_{(\eta, \xi)}$  by reversing the orientation. The image  $\text{proj}(v)$  of a vector  $v = (\eta, \xi, t)$  in  $SX$  is now defined as the unique point  $x$  on  $\sigma_{(\eta, \xi)}$  such that

$$\frac{1}{2} \left[ b_{\xi}^+(o, x) - b_{\eta}^-(o, x) \right] = t,$$

where  $b_{\xi}^+$  and  $b_{\eta}^-$  stand for the Busemann cocycle along  $\sigma_{(\eta, \xi)}$  and  $\sigma_{(\xi, \eta)}$  respectively. This definition of  $\text{proj}(v)$  involves many choices. However, any another choice would lead to a point  $x'$  such that  $d(x, x') \leq 100\delta$ . It is a standard exercise of hyperbolic geometry to prove that for every vector  $v = (\eta, \xi, t)$  in  $SX$ ,

$$|\langle \eta, \xi \rangle_o + |t| - d(o, \text{proj}(v))| \leq 20\delta. \quad (21)$$

It follows from the construction that for every  $v = (\eta, \xi, t)$  in  $SX$  the map

$$\begin{aligned} \mathbb{R} &\rightarrow X \\ s &\mapsto \text{proj} \circ \phi_s(v) \end{aligned}$$

is a (up to changing the origin) the bi-infinite geodesic  $\sigma_{(\eta, \xi)}$ . The projection  $\text{proj}: SX \rightarrow X$  is not  $\Gamma$ -invariant in general. However, for every  $v \in SX$ , for every  $\gamma \in \Gamma$ ,

$$d(\gamma \text{proj}(v), \text{proj}(\gamma v)) \leq 200\delta. \quad (22)$$

Combined with (21) we get the following useful estimate. For every  $v = (\eta, \xi, t)$  in  $SX$ , for every  $\gamma \in \Gamma$ ,

$$|\langle \gamma\eta, \gamma\xi \rangle_o + |t + \kappa_{\gamma}(\eta, \xi)| - d(o, \gamma \text{proj}(v))| \leq 220\delta, \quad (23)$$

where  $\kappa_{\gamma}(\eta, \xi)$  has been defined in (19).

## 4.2 Changing spaces

We use the strategy of Bader-Furman to go back and forth between the spaces  $(\partial^2 X, \mu)$ ,  $(SX, \mathcal{B}, m)$  and  $(SX, \mathcal{B}_{\Gamma}, \bar{m})$ . We now work at the level of function spaces. We consider first the following operation

$$\begin{aligned} L^1(\partial^2 X, \mu) \times L^1(\mathbb{R}, dt) &\rightarrow L^1(SX, m) \\ (f, \vartheta) &\mapsto f_{\vartheta} \end{aligned} \quad (24)$$

where  $f_\vartheta = f \otimes \vartheta$ , i.e. for every  $(\eta, \xi, t) \in SX$ ,  $f_\vartheta(\eta, \xi, t) = f(\eta, \xi)\vartheta(t)$ .

Let  $f \in L^1_+(SX, m)$  be a non-negative summable function. We define a  $\Gamma$ -invariant function  $\hat{f}: SX \rightarrow \mathbb{R}_+ \cup \{\infty\}$  by

$$\hat{f}(v) = \sum_{\gamma \in \Gamma} f(\gamma v). \quad (25)$$

Recall that  $D$  stands for a Borel fundamental domain for the action of  $\Gamma$  on  $SX$ . As  $m$  is  $\Gamma$ -invariant, we have

$$\int_{SX} \hat{f} d\bar{m} = \sum_{\gamma \in \Gamma} \int_D (f \circ \gamma) dm = \sum_{\gamma \in \Gamma} \int_{\gamma D} f dm = \int_{SX} f dm. \quad (26)$$

In particular,  $\hat{f} \in L^1_+(SX, \bar{m})$ . It follows that the map  $f \mapsto \hat{f}$  is a well defined isometric embedding of  $L^1(SX, \mathcal{B}, m)$  into  $L^1(SX, \mathcal{B}_\Gamma, \bar{m})$ .

### 4.3 Conservativity of the flow

This section is devoted to the proof of (1)  $\Leftrightarrow$  (2) in [Theorem 4.2](#). For a precise definition of *conservativity* we refer the reader to [[Hop37](#), [Aar97](#)]. In this article we will only use the following properties. Assume that  $T$  is an invertible measure preserving map acting on a Borel space  $(Y, \mathcal{B}, m)$ . If for  $m$ -almost every  $y \in Y$  there exists  $B \in \mathcal{B}$  with  $0 < m(B) < \infty$  such that

$$\sum_{n=1}^{\infty} \mathbf{1}_B \circ T^n(y) = \infty,$$

then  $T$  is conservative [[Aar97](#), Proposition 1.1.6]. Reciprocally, by Halmos' recurrence theorem [[Aar97](#), Theorem 1.1.1], if  $T$  is conservative, then for every  $B \in \mathcal{B}$ , with  $m(B) > 0$ , for  $m$ -almost every  $y \in Y$ ,

$$\sum_{n=1}^{\infty} \mathbf{1}_B \circ T^n(y) = \infty.$$

A measure preserving flow  $(\phi_t)$  on  $(Y, \mathcal{B}, m)$  is *conservative* if its time-one map  $T = \phi_1$  is conservative.

For every  $r \in \mathbb{R}_+$ , we define two subsets of  $\partial^2 X$  and  $SX$  respectively by

$$Z(r) = \{(\eta, \xi) \in \partial^2 X \mid \langle \eta, \xi \rangle_o \leq r\}, \quad \text{and} \quad B(r) = Z(r) \times [0, 1]. \quad (27)$$

Note that  $B(r)$  need not be a compact subset of  $SX$  (the Gromov product is not necessarily continuous). Still it has positive finite  $m$ -measure.

**Lemma 4.3.** *For  $\bar{m}$ -almost every vector  $v = (\eta, \xi, t)$  in  $SX$ , the future  $\xi$  of  $v$  belongs to the radial limit set  $\Lambda_{\text{rad}}$  if and only if there exists  $r \in \mathbb{R}_+^*$  such that*

$$\int_0^\infty \mathbf{1}_{\Gamma B(r)} \circ \phi_s(v) ds = \infty. \quad (28)$$

*Proof.* Recall that  $S_0X$  is the  $\Gamma$ - and flow-invariant subset of  $SX$  of full measure given in (20). Let  $v = (\eta, \xi, t)$  be a vector in  $S_0X$ . As we noticed earlier, the path  $\sigma: \mathbb{R} \rightarrow X$  sending  $s$  to  $\text{proj} \circ \phi_s(v)$  is a bi-infinite geodesic joining  $\eta$  to  $\xi$ . Assume first that  $\xi$  belongs to  $\Lambda_{\text{rad}}$ . There exists  $r \in \mathbb{R}_+^*$ , and an infinite sequence  $(\gamma_n)$  of elements of  $\Gamma$  such that  $(\gamma_n o)$  converges to  $\xi$  and for every  $n \in \mathbb{N}$ , we have  $\langle \eta, \xi \rangle_{\gamma_n o} \leq r$ . Set

$$s_n = -t - \kappa_{\gamma_n^{-1}}(\eta, \xi).$$

so that for all  $u \in [0, 1]$ , the vector  $\gamma_n^{-1} \phi_{s_n+u}(v)$  belongs to  $B(r)$ . Since  $v \in S_0X$ , the vector  $\phi_{s_n+u}(v)$  belongs to  $\gamma_n B(r)$ , hence to  $\Gamma B(r)$ . By (23), the point  $\text{proj} \circ \phi_{s_n}(v)$  is approximatively a projection of  $\gamma_n o$  onto  $\sigma$ . As  $(\gamma_n o)$  converges to  $\xi$ , the sequence  $(s_n)$  diverges to infinity. Consequently the positive orbit of  $v$  spends an infinite amount of time in  $\Gamma B(r)$ , whence

$$\int_0^\infty \mathbf{1}_{\Gamma B(r)} \circ \phi_s(v) ds = \infty.$$

Conversely assume that there exists  $r \in \mathbb{R}_+^*$  such that the above equality holds. As  $v$  belongs to  $S_0X$ , it means that there exists a sequence  $(s_n)$  diverging to infinity as well as a sequence  $(\gamma_n)$  of elements of  $\Gamma$  such that  $\gamma_n^{-1} \phi_{s_n}(v)$  belongs to  $B(r)$  for every  $n \in \mathbb{N}$ . Hence  $\langle \eta, \xi \rangle_{\gamma_n o} \leq r$ . By (23) we also get that  $d(\gamma_n o, \text{proj} \circ \phi_{s_n}(v))$  is uniformly bounded. Consequently  $(\gamma_n o)$  converges to  $\xi$ , hence  $\xi$  belongs to  $\Lambda_{\text{rad}}$ .  $\square$

**Proposition 4.4.** *The Patterson-Sullivan measure  $\nu_o$  gives full support to the radial limit set if and only if the flow  $(\phi_t)$  on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is conservative.*

*Proof.* The measure  $\nu_0$  gives full measure to the radial limit set if and only if the measures  $m$  and thus  $\bar{m}$  give full measure to

$$\{(\eta, \xi, t) \in SX \mid (\eta, \xi) \in \Lambda_{\text{rad}} \times \Lambda_{\text{rad}}\}.$$

In view of the properties of conservative systems recalled above, Lemma 4.3 tells us that the  $\nu_0$  gives full measure to the radial limit set if and only if the flow  $(\phi_t)$  is conservative.  $\square$

## 4.4 The Hopf argument

This section is devoted to the implication (2)  $\Rightarrow$  (4) of Theorem 4.2, proven in Corollary 4.15.

**Preliminaries.** We fix once for all a number  $a > 2h_\Gamma$  and a map

$$\begin{aligned} \vartheta: \mathbb{R} &\rightarrow \mathbb{R} \\ t &\mapsto \frac{1}{2} a e^{-a|t|}. \end{aligned}$$

For every  $T_1, T_2 \in \mathbb{R}_+$ , with  $T_1 \leq T_2$ , we write  $\Theta_{T_1}^{T_2}: \mathbb{R} \rightarrow [0, 1]$  for the map defined by

$$\Theta_{T_1}^{T_2}(u) = \int_{T_1}^{T_2} \vartheta(u+t) dt = \int_{T_1+u}^{T_2+u} \vartheta(t) dt.$$

This function is ‘‘almost constant’’ on  $[-T_2, -T_1]$  and decays exponentially outside this interval. More precisely we have the following useful estimates.

1. For every  $u \in \mathbb{R}$ ,

$$\Theta_{T_1}^{T_2}(u) \leq \frac{1}{2} \min \left\{ e^{a(T_2+u)}, e^{-a(T_1+u)} \right\}. \quad (29)$$

2. For every  $u \in [-T_2, -T_1]$ ,

$$\Theta_{T_1}^{T_2}(u) = 1 - \frac{1}{2} \left[ e^{a(T_1+u)} + e^{-a(T_2+u)} \right].$$

Consequently, for every  $u, u' \in [-T_2, -T_1]$ ,

$$\left| \Theta_{T_1}^{T_2}(u) - \Theta_{T_1}^{T_2}(u') \right| \leq \left[ e^{a\left(T_1 + \frac{u+u'}{2}\right)} + e^{-a\left(T_2 + \frac{u+u'}{2}\right)} \right] \sinh \left( \frac{a}{2} |u - u'| \right). \quad (30)$$

See [Figure 2](#) for a sketch of the graph of  $\Theta_{T_1}^{T_2}$ .

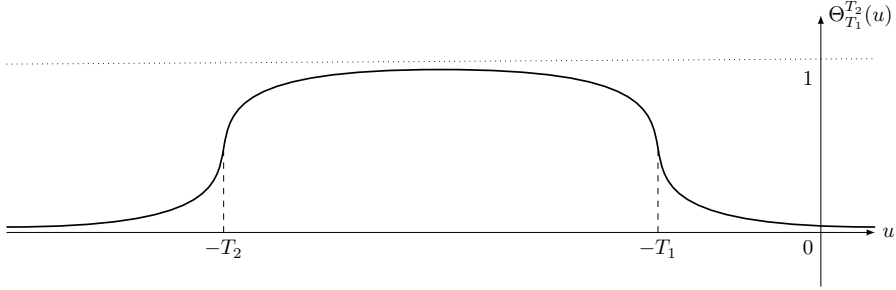


Figure 2 – Graph of the map  $\Theta_{T_1}^{T_2}$ .

We say that a function  $f: \partial^2 X \rightarrow \mathbb{R}$  has *exponential decay* if there exists  $C \in \mathbb{R}_+$  such that for every  $\mu$ -almost every  $(\eta, \xi) \in \partial^2 X$  we have

$$|f(\eta, \xi)| \leq C e^{-a\langle \eta, \xi \rangle_o}. \quad (31)$$

Any such function belongs to  $L^1(\mu)$ . Indeed, as  $a > 2h_\Gamma$ , Inequality (12) yields

$$\int |f| d\mu \leq CC_0 \int e^{(2h_\Gamma - a)\langle \eta, \xi \rangle_o} d\nu_o(\eta) d\nu_o(\xi) \leq CC_0.$$

Recall that the boundary  $\partial X$  is endowed with a visual metric  $d_{\partial X}$  for which there exists  $a_0, \varepsilon_0 \in (0, 1)$  such that for every  $\eta, \xi \in \partial X$ , we have

$$|d_{\partial X}(\eta, \xi) + a_0 \langle \eta, \xi \rangle_o| \leq \varepsilon_0. \quad (32)$$

The product metric induces a distance on  $\partial^2 X$ . We write  $\mathcal{D}^+(\partial^2 X) \subset L^1_+(\mu)$  for the set of all Lipschitz functions  $f: \partial^2 X \rightarrow \mathbb{R}_+$  with exponential decay.

We complete this preliminary discussion with the following easy but useful statements.

**Lemma 4.5.** *There exists  $C \in \mathbb{R}_+$  such that for every  $x \in X$ , for every  $r \in \mathbb{R}_+$ ,*

$$|\{\gamma \in \Gamma \mid d(o, \gamma x) \leq r\}| \leq C e^{2h_\Gamma r}.$$

*Proof.* If  $d(x, \Gamma o) > r$ , then  $\{\gamma \in \Gamma \mid d(o, \gamma x) \leq r\}$  is empty. If  $d(x, \Gamma o) \leq r$ , there exists  $\alpha \in \Gamma$  such that  $d(x, \alpha o) = d(x, \Gamma o)$ . Triangle inequality implies that  $\{\gamma \in \Gamma \mid d(o, \gamma x) \leq r\}$  is contained in  $B_\Gamma(o, 2r)\alpha^{-1}$ , where

$$B_\Gamma(o, 2r) = \{\gamma \in \Gamma \mid d(o, \gamma o) \leq 2r\}.$$

It is well-known that  $|B_\Gamma(o, 2r)| \leq Ce^{2h_\Gamma r}$ , for some universal constant  $C$ , see for instance [Coo93, Corollaire 6.8], which completes the proof.  $\square$

**Lemma 4.6.** *There exists  $C \in \mathbb{R}_+$  such that for every  $x \in X$ , for every  $r \in \mathbb{R}_+$ ,*

$$\sum_{\substack{\gamma \in \Gamma, \\ d(o, \gamma x) \geq r}} e^{-ad(o, \gamma x)} \leq Ce^{-(a-2h_\Gamma)r}.$$

*Proof.* Let  $x \in X$  and  $r \in \mathbb{R}_+$ . We split the sum as follows:

$$\sum_{\substack{\gamma \in \Gamma, \\ d(o, \gamma x) \geq r}} e^{-ad(o, \gamma x)} \leq \sum_{\substack{\ell \in \mathbb{N}, \\ \ell \geq r}} |\{\gamma \in \Gamma \mid \ell \leq d(o, \gamma x) \leq \ell + 1\}| e^{-a\ell}.$$

By Lemma 4.5, there exists  $C \in \mathbb{R}_+$  (independent of  $x$  and  $r$ ) such that

$$\sum_{\substack{\gamma \in \Gamma, \\ d(o, \gamma x) \geq r}} e^{-ad(o, \gamma x)} \leq C \sum_{\substack{\ell \in \mathbb{N}, \\ \ell \geq r}} e^{-(a-2h_\Gamma)\ell}.$$

As  $a > 2h_\Gamma$ , we get (up to changing the constant  $C$ )

$$\sum_{\substack{\gamma \in \Gamma, \\ d(o, \gamma x) \geq r}} e^{-ad(o, \gamma x)} \leq Ce^{-(a-2h_\Gamma)r}. \quad \square$$

**Lemma 4.7.** *If  $f \in \mathcal{D}^+(\partial^2 X)$ , then  $\hat{f}_\vartheta$  is bounded, where  $\hat{f}_\vartheta$  was defined in (24) and (25).*

*Proof.* As  $f$  has exponential decays, there exists  $C \in \mathbb{R}_+$  such that for every  $v \in SX$ ,

$$\hat{f}_\vartheta(v) \leq C \sum_{\gamma \in \Gamma} e^{-a\langle \gamma\xi, \gamma\eta \rangle_o} e^{-a|t + \kappa_\gamma(\xi, \eta)|}.$$

Set  $x = \text{proj}(v)$ . Recall that by  $\langle \gamma\xi, \gamma\eta \rangle_o + |t + \kappa_\gamma(\xi, \eta)|$  is approximately the distance between  $o$  and  $\gamma x$ , see (23). Up to increasing  $C$ , we get

$$\hat{f}_\vartheta(v) \leq C \sum_{\gamma \in \Gamma} e^{-ad(o, \gamma x)},$$

Recall that  $a > 2h_\Gamma$ . It follows from Lemma 4.6 that this last sum is bounded independently of  $v$ .  $\square$

**Contraction property.** In a  $\text{CAT}(-1)$  space  $X$ , a key fact when running the Hopf argument is that two geodesic rays  $\sigma, \sigma': \mathbb{R} \rightarrow X$  with the same point at infinity satisfy a contraction property, namely there exists  $u \in \mathbb{R}$ , such that  $t \rightarrow d(\sigma(t), \sigma'(t+u))$  converges exponentially fast to zero. As a consequence, if  $f: X \rightarrow \mathbb{R}$  is a Hölder continuous map, the difference

$$\int_0^T [f(\sigma(t)) - f(\sigma'(t))] dt$$

converges when  $T \rightarrow +\infty$ . Exponential decay of the distance along asymptotic geodesics is no longer true when  $X$  is Gromov hyperbolic. Indeed two geodesic rays may have the same endpoint at infinity, but only stay at bounded distance one from the other. In this setting, the contraction of geodesics is replaced by the following fact.

**Proposition 4.8** (Contraction lemma). *Let  $f \in \mathcal{D}^+(\partial^2 X)$ . Let  $v = (\eta, \xi, 0)$  and  $v' = (\eta', \xi, 0)$  be two vectors of  $SX$  with the same future. The map*

$$\begin{aligned} \mathbb{R}_+ &\rightarrow \mathbb{R}_+ \\ T &\rightarrow \int_0^T \left( \hat{f}_\vartheta \circ \phi_s(v) - \hat{f}_\vartheta \circ \phi_s(v') \right) ds \end{aligned}$$

is bounded.

*Proof.* Note that since  $f$  is continuous, the function  $\hat{f}_\vartheta$  is defined everywhere (and not just  $\bar{m}$ -almost everywhere). Recall that the map  $\sigma: \mathbb{R} \rightarrow X$  sending  $s$  to  $\text{proj} \circ \phi_s(v)$  is a bi-infinite geodesic joining  $\eta$  to  $\xi$ . Similarly, using the vector  $v'$ , we define a geodesic  $\sigma': \mathbb{R} \rightarrow X$  from  $\eta'$  to  $\xi$ . We start by defining a time shift, to make sure that  $\sigma$  and  $\sigma'$  fellow travel.

By hyperbolicity of  $X$ , there exists  $u, T_0 \in \mathbb{R}$ , such that for every  $s \geq T_0$ , we have  $d(\sigma(s), \sigma'(s+u)) \leq 16\delta$  [GdlH90, Chaptitre 7, Proposition 2]. To have enough flexibility, we let  $T_1 = T_0 + 10^{10}\delta$ . As we already observed from (21) the point  $\sigma(0) = \text{proj}(v)$  is approximately a projection of  $o$  on  $\sigma$ . Similarly, by (23) for every  $\gamma \in \Gamma$ ,  $\sigma(-\kappa_\gamma(\eta, \xi))$  is approximately a projection of  $\gamma^{-1}o$  on  $\sigma$ . The same interpretation holds for  $\sigma'$ . It follows that for every  $\gamma \in \Gamma$  such that  $\kappa_\gamma(\eta, \xi) \leq -T_1 + 5000\delta$  or  $u + \kappa_\gamma(\eta', \xi') \leq -T_1 + 5000\delta$ , the following holds

1.  $|\langle \eta', \xi \rangle_{\gamma^{-1}o} - \langle \eta, \xi \rangle_{\gamma^{-1}o}| \leq 500\delta$ ,
2.  $|\kappa_\gamma(\eta', \xi) + u - \kappa_\gamma(\eta, \xi)| \leq 2000\delta$ ,
3.  $\langle \eta, \eta' \rangle_{\gamma^{-1}o} \geq -\kappa_\gamma(\eta, \xi) - T_1$ .

This general configuration is sketched on Figure 3.

Since the map  $\hat{f}_\vartheta$  is bounded (Lemma 4.7) there exists  $C_0 \in \mathbb{R}_+$ , such that for every  $T \geq T_0$ ,

$$\left| \int_0^T \left( \hat{f}_\vartheta \circ \phi_s(v) - \hat{f}_\vartheta \circ \phi_s(v') \right) ds - \int_{T_1}^T \left( \hat{f}_\vartheta \circ \phi_s(v) - \hat{f}_\vartheta \circ \phi_{s+u}(v') \right) ds \right| \leq C_0.$$

Set  $v'_u = \phi_u(v')$  and define  $F_T$  by

$$\begin{aligned} F_T: SX &\rightarrow \mathbb{R} \\ w &\mapsto \int_{T_1}^T \hat{f}_\vartheta \circ \phi_s(v) ds, \end{aligned}$$



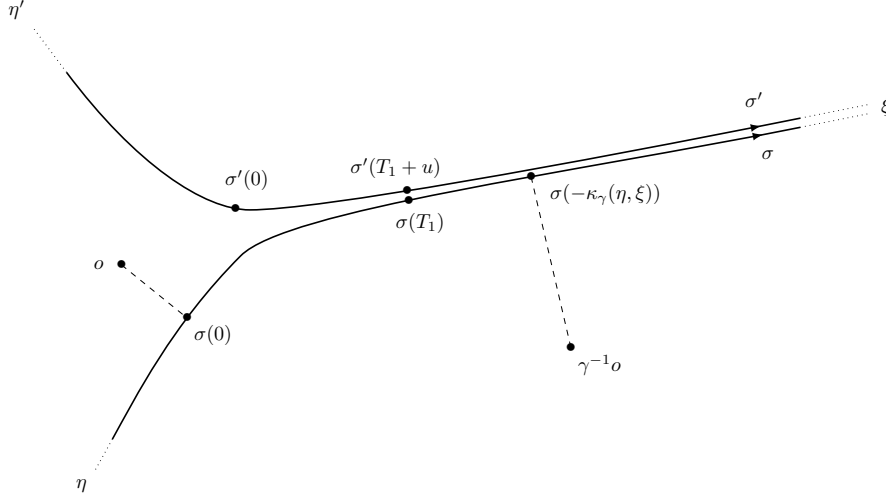


Figure 3 – General configuration of  $\sigma$  and  $\sigma'$ .

To get [Proposition 4.8](#), it suffices to show that the map  $T \rightarrow F_T(v) - F_T(v'_u)$  is bounded. A Fubini argument gives

$$F_T(w) = \sum_{\gamma \in \Gamma} f \otimes \Theta_{T_1}^T(\gamma w) = f \widehat{\otimes} \Theta_{T_1}^T(w). \quad (33)$$

[Figure 4](#) represents the value of  $F_T$ .

We are now going to decompose the sum in [\(33\)](#) according to the value of  $\kappa_\gamma(\eta, \xi)$ . For every  $t \in \mathbb{R}_+$ , we define a subset  $S(t)$  of  $\Gamma$  as follows.

$$S(t) = \{\gamma \in \Gamma \mid -\delta < t + \kappa_\gamma(\eta, \xi) \leq 0\}.$$

Roughly speaking  $S(t)$  corresponds to the set of all elements  $\gamma \in \Gamma$  such that the projection of  $\gamma^{-1}o$  on  $\sigma$  is approximately  $\sigma(t) = \text{proj} \circ \phi_t(v)$ . The sets  $(S(n\delta))_{n \in \mathbb{Z}}$  form a partition of  $\Gamma$ . In particular

$$F_T(w) = \sum_{n \in \mathbb{Z}} \sum_{\gamma \in S(n\delta)} f \otimes \Theta_{T_1}^T(\gamma w). \quad (34)$$

The first lemma handles the tails of this sum.

**Lemma 4.9.** *There exists  $C_1 \in \mathbb{R}_+$  such that for every  $T \geq T_1$ , for every  $w \in \{v, v'_u\}$ , we have*

$$\max \left\{ \sum_{n\delta \leq T_1 + 2000\delta} \sum_{\gamma \in S(n\delta)} f \otimes \Theta_{T_1}^T(\gamma w), \sum_{n\delta \geq T - 2001\delta} \sum_{\gamma \in S(n\delta)} f \otimes \Theta_{T_1}^T(\gamma w) \right\} \leq C_1.$$

*Proof.* Let  $T \geq T_1$ . Observe that

$$\bigcup_{n\delta \geq T - 2001\delta} S(n\delta) = \{\gamma \in \Gamma \mid \kappa_\gamma(\eta, \xi) \leq -T + 2001\delta\}.$$

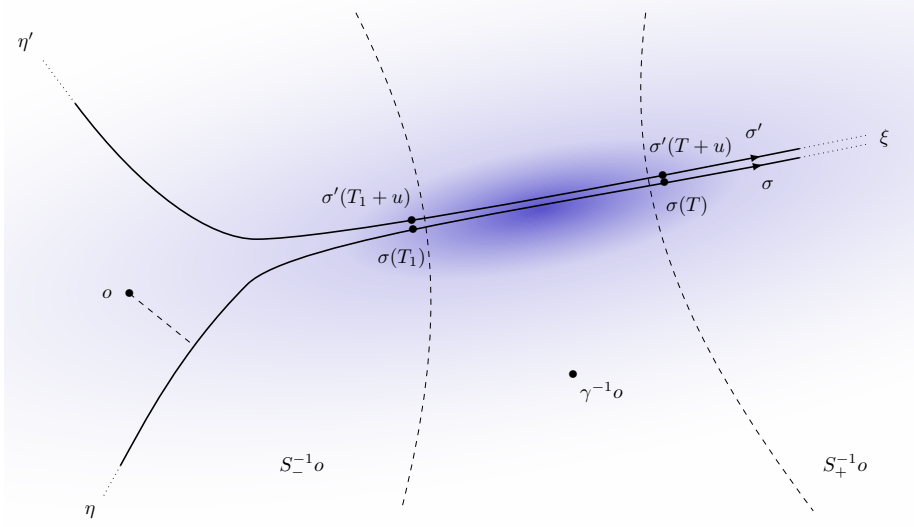


Figure 4 – The function  $F_T$ . The shade represents the magnitude of  $F_T$ . Dark areas (respectively light) corresponds to vectors  $w \in SX$  for which  $|F_T(w)|$  is large (respectively small). The dashed lines split the orbit  $\{\gamma^{-1}o \mid \gamma \in \Gamma\}$  in three parts according to whether  $\gamma$  belongs to  $S_-$ ,  $S_+$  or  $\Gamma \setminus (S_- \cup S_+)$ .

For simplicity we denote this set by  $S_+$  (see Figure 4). Similarly, set

$$S_- = \bigcup_{n\delta \leq T_1 + 2000\delta} S(n\delta) = \{\gamma \in \Gamma \mid \kappa_\gamma(\eta, \xi) \geq -T_1 - 2001\delta\}.$$

We focus now on the right tail of  $F_T(v)$ . Recall that  $f$  has exponential decay, whereas the tails of  $\Theta_{T_1}^T$  decay exponentially – see (29). It follows that

$$\begin{aligned} \sum_{n\delta \geq T - 2001\delta} \sum_{\gamma \in S(n\delta)} f \otimes \Theta_{T_1}^T(\gamma v) &\leq \sum_{\gamma \in S_+} f(\gamma\eta, \gamma\xi) \Theta_{T_1}^T(\kappa_\gamma(\eta, \xi)) \\ &\leq \frac{1}{2} \sum_{\gamma \in S_+} e^{-a\langle \gamma\eta, \gamma\xi \rangle_o} e^{a[T + \kappa_\gamma(\eta, \xi)]}. \end{aligned}$$

However  $(T - 2001\delta) + \kappa_\gamma(\eta, \xi) \leq 0$ , for every  $\gamma \in \Gamma$ . Consequently

$$\langle \gamma\eta, \gamma\xi \rangle_o - [(T - 2001\delta) + \kappa_\gamma(\eta, \xi)] = \langle \gamma\eta, \gamma\xi \rangle_o + |(T - 2001\delta) + \kappa_\gamma(\eta, \xi)|,$$

which, according to (23), differs from  $d(o, \gamma\sigma(T - 2001\delta))$  by at most  $\delta$ . Hence there exists a constant  $C$  (which does not depends on  $T$ ) such that

$$\sum_{n\delta \geq T - \delta} \sum_{\gamma \in S(n\delta)} f \otimes \Theta_{T_1}^T(\gamma v) \leq C \sum_{\gamma \in S_+} e^{-ad(o, \gamma\sigma(T - 2001\delta))}$$

It follows from Lemma 4.6 that the latter sum is bounded from above independently of  $T$ . The upper bound for the left tail of  $F_T(v)$  follows the exact same strategy. For the tails of  $F_T(v'_u)$  we have to be slightly more careful. Indeed the sets  $S(t)$  were defined according to  $v$  (the definition involves its past  $\eta$ )

and not  $v'_u$ . Nevertheless, as we observed at the beginning of the proof if either  $\kappa_\gamma(\eta, \xi) \leq -T_1 + 5000\delta$  or  $u + \kappa_\gamma(\eta', \xi') \leq -T_1 + 5000\delta$ , then these two quantities differ by as most  $2000\delta$ . Consequently

$$\begin{aligned} S_- &\subset \{\gamma \in \Gamma \mid u + \kappa_\gamma(\eta', \xi') \geq -T_1 - 4001\delta\}, \\ S_+ &\subset \{\gamma \in \Gamma \mid u + \kappa_\gamma(\eta', \xi') \leq -T + 4001\delta\}. \end{aligned}$$

The estimation of the tails of  $F_T(v'_u)$  now works as for the one of  $F_T(v)$ .  $\square$

The next step is to estimate in (34) each sum over  $S(n\delta)$  whenever  $n\delta$  belongs to  $[T_1 + 2000\delta, T - 2001\delta]$ .

**Lemma 4.10.** *There exists  $C_2 \in \mathbb{R}_+$  such that for every  $T \geq T_1$ , for every  $n \in \mathbb{Z}$  such that  $T_1 + 2000\delta \leq n\delta \leq T - 2001\delta$ , we have*

$$\begin{aligned} \Delta(n) &:= \sum_{\gamma \in S(n\delta)} |f \otimes \Theta_{T_1}^T(\gamma v) - f \otimes \Theta_{T_1}^T(\gamma v'_u)| \\ &\leq C_2 \left[ \left( e^{a(T_1 - n\delta)} + e^{-a(T - n\delta)} \right) + \frac{1}{n^2} + n^q e^{-a_0 n\delta} \right], \end{aligned}$$

where

$$q = \frac{4h_\Gamma}{a - 2h_\Gamma}.$$

*Proof.* Let  $n \in \mathbb{Z}$ , such that  $T_1 + 2000\delta \leq n\delta \leq T - 2001\delta$ . Observe that  $\Delta(n) \leq \Delta_f(n) + \Delta_\Theta(n)$  where

$$\begin{aligned} \Delta_f(n) &= \sum_{\gamma \in S(n\delta)} |f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)| \Theta_{T_1}^T(u + \kappa_\gamma(\eta', \xi')), \\ \Delta_\Theta(n) &= \sum_{\gamma \in S(n\delta)} f(\gamma\eta, \gamma\xi) |\Theta_{T_1}^T(\kappa_\gamma(\eta, \xi)) - \Theta_{T_1}^T(u + \kappa_\gamma(\eta', \xi))|. \end{aligned}$$

We start with the term  $\Delta_\Theta(n)$ . Let  $\gamma \in S(n\delta)$ . As observed at the beginning of the proof, since  $\kappa_\gamma(\eta, \xi) \leq -T_1$ , this quantity differs from  $u + \kappa_\gamma(\eta', \xi)$  by at most  $2000\delta$ . In particular  $u + \kappa_\gamma(\eta', \xi')$  belongs to  $[-n\delta - 2001\delta, -n\delta + 2000\delta]$ , hence to  $[-T, -T_1]$ . On this interval the function  $\Theta_{T_1}^T$  is almost constant. More precisely, using (30) we get

$$|\Theta_{T_1}^T(\kappa_\gamma(\eta, \xi)) - \Theta_{T_1}^T(u + \kappa_\gamma(\eta', \xi'))| \leq C \left( e^{a(T_1 - n\delta)} + e^{-a(T - n\delta)} \right),$$

for some parameter  $C$ , which does not depends on  $n$  or  $T$ . Consequently

$$\Delta_\Theta(n) \leq C \left( e^{a(T_1 - n\delta)} + e^{-a(T - n\delta)} \right) \sum_{\gamma \in S(n\delta)} f(\gamma\eta, \gamma\xi).$$

Recall that  $-\delta \leq n\delta + \kappa_\gamma(\eta, \xi) \leq 0$ , for every  $\gamma \in S(n\delta)$ . Consequently the latter sum can be bounded above as follows

$$\sum_{\gamma \in S(n\delta)} f(\gamma\eta, \gamma\xi) \leq e^{a\delta} \sum_{\gamma \in S(n\delta)} f(\gamma\eta, \gamma\xi) e^{-a|n\delta + \kappa_\gamma(\eta, \xi)|}.$$

Since  $f$  decays exponentially, we prove as in [Lemma 4.9](#) that this sum is bounded from above independently of  $n$  and  $T$ . To summarize, we have proved that there exists  $C_\Theta \in \mathbb{R}_+$  (which does not depend on  $n$  or  $T$ ) such that

$$\Delta_\Theta(n) \leq C_\Theta \left( e^{a(T_1 - n\delta)} + e^{-a(T - n\delta)} \right). \quad (35)$$

Let us now focus on  $\Delta_f(n)$ . First, as  $\Theta_{T_1}^T \leq 1$ , we have

$$\Delta_f(n) \leq \sum_{\gamma \in S(n\delta)} |f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)|.$$

We split again this sum in two parts according to the value of  $\langle \eta, \xi \rangle_{\gamma^{-1}o}$ . More precisely, we set

$$p = \frac{2}{a - 2h_\Gamma},$$

and

$$\begin{aligned} S_0(n\delta) &= \left\{ \gamma \in S(n\delta) \mid \langle \eta, \xi \rangle_{\gamma^{-1}o} \leq p \ln(n\delta) \right\}, \\ S_\infty(n\delta) &= \left\{ \gamma \in S(n\delta) \mid \langle \eta, \xi \rangle_{\gamma^{-1}o} > p \ln(n\delta) \right\}. \end{aligned}$$

Roughly speaking,  $S_0(n\delta)$  is the set of all  $\gamma \in S(n\delta)$  such that  $\gamma^{-1}o$  stay close to  $\sigma$ . We will bound the corresponding sum using the regularity of  $f$ . On the other hand  $S_\infty(n\delta)$  is the set of all elements  $\gamma \in S(n\delta)$  such that  $\gamma^{-1}o$  is far from  $\sigma$ . The corresponding sum will be controlled using the exponential decay of  $f$ . We split the details in three claims.

**Claim 4.11.** *There exists  $C \in \mathbb{R}_+$  (which does not depend on  $n$  or  $T$ ) such that  $|S_0(n\delta)| \leq Cn^q$ .*

Let  $\gamma \in S_0(n\delta)$ . Using [\(23\)](#) we observe that, up to  $220\delta$  the distance between  $o$  and  $\gamma\sigma(n\delta)$  is at most

$$\langle \gamma\eta, \gamma\xi \rangle_o + |n\delta + \kappa_\gamma(\eta, \xi)| \leq p \ln(n\delta) + \delta.$$

Consequently  $S_0(n\delta)$  is contained in

$$U = \{ \gamma \in \Gamma \mid d(o, \gamma\sigma(n\delta)) \leq r \}, \quad \text{where } r = p \ln(n\delta) + 221\delta.$$

By [Lemma 4.5](#), there exists  $C \in \mathbb{R}_+$  (independent of  $n$  or  $T$ ) such that

$$|U| \leq Ce^{2h_\Gamma r} \leq Ce^{221h_\Gamma\delta} (n\delta)^{2ph_\Gamma},$$

which completes the proof of the first claim.

Recall that  $a_0$  denotes the parameter which allows to approximate the visual metric on  $\partial X$  by Gromov products [\(32\)](#).

**Claim 4.12.** *There exists  $C \in \mathbb{R}_+$  (which does not depend on  $n$  or  $T$ ) such that*

$$\sum_{\gamma \in S_0(n\delta)} |f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)| \leq Cn^q e^{-a_0 n\delta}.$$

According to our assumption  $f$  is Lipschitz with respect to the product metric on  $\partial^2 X$ . Moreover,  $v$  and  $v'$  have the same future, namely  $\xi$ . These observations together with (32) imply that there exists  $M \in \mathbb{R}_+$  such that for every  $\gamma \in S_0(n\delta)$ .

$$|f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)| \leq M e^{-a_0 \langle \eta, \eta' \rangle_{\gamma^{-1}o}}.$$

However, as  $\kappa_\gamma(\eta, \xi) \leq -T_1 - \delta$ , we observed at the beginning of the proof that

$$\langle \eta, \eta' \rangle_{\gamma^{-1}o} \geq -\kappa_\gamma(\eta, \xi) - T_1 \geq n\delta - T_1.$$

Consequently

$$\sum_{\gamma \in S_0(n\delta)} |f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)| \leq M |S_0(n\delta)| e^{-a_0 n\delta}.$$

**Claim 4.12** now follows from the estimate of  $|S_0(n\delta)|$  given by **Claim 4.11**.

**Claim 4.13.** *There exists  $C \in \mathbb{R}_+$  (independent of  $n$  or  $T$ ) such that*

$$\sum_{\gamma \in S_\infty(n\delta)} |f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)| \leq \frac{C}{n^2}.$$

We split this sum in two parts as follows.

$$\sum_{\gamma \in S_\infty(n\delta)} |f(\gamma\eta, \gamma\xi) - f(\gamma\eta', \gamma\xi)| \leq \sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta, \gamma\xi) + \sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta', \gamma\xi).$$

Proceeding as for  $\Delta_\Theta$ , we observe that

$$\sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta, \gamma\xi) \leq e^{a\delta} \sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta, \gamma\xi) e^{-a|n\delta + \kappa_\gamma(\eta, \xi)|}$$

We now argue as in **Lemma 4.9** and prove that there exists a constant  $C \in \mathbb{R}_+$  (which does not depends on  $n$  or  $T$ ) such that

$$\sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta, \gamma\xi) \leq C \sum_{\gamma \in S_\infty(n\delta)} e^{-ad(o, \gamma\sigma(n\delta))}.$$

As usual the distance  $d(o, \gamma\sigma(n\delta))$  can be approximated by

$$\langle \eta, \xi \rangle_{\gamma^{-1}o} + |n\delta + \kappa_\gamma(\eta, \xi)|$$

It follows from the very definition of  $S_\infty(n\delta)$  that  $d(o, \gamma\sigma(n\delta)) > p \ln(n\delta) - 220\delta$ , for every  $\gamma \in S_\infty(n\delta)$ . Hence

$$\sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta, \gamma\xi) \leq C \sum_{\substack{\gamma \in \Gamma, \\ d(o, \gamma\sigma(n\delta)) > p \ln(n\delta) - 220\delta}} e^{-ad(o, \gamma\sigma(n\delta))}.$$

An upper bound of the last sum is given by **Lemma 4.6**. More precisely, up to replacing  $C$  by a larger constant (which still does not depend on  $n$  or  $T$ ) we get

$$\sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta, \gamma\xi) \leq C e^{-(a-2h_\Gamma)p \ln(n\delta)} \leq \frac{C}{(n\delta)^2}.$$

The last inequality is just the definition of  $p$ . Recall that whenever  $\kappa_\gamma(\eta, \xi) \leq -T_1$ , then  $\kappa_\gamma(\eta, \xi)$  and  $u + \kappa_\gamma(\eta', \xi)$  differ by at most  $2000\delta$ . Following the exact same argument we get a similar upper bound for

$$\sum_{\gamma \in S_\infty(n\delta)} f(\gamma\eta', \gamma\xi'),$$

which completes the proof of [Claim 4.13](#). To summarize, the last two claims tell us that there exists  $C_f$  (which does not depend on  $n$  or  $T$ ) such that

$$\Delta_f(n) \leq C_f \left( \frac{1}{n^2} + n^q e^{-a_0 n \delta} \right) \quad (36)$$

[Lemma 4.10](#) is the combination of (35) and (36).  $\square$

Recall that we need to estimate  $F_T(v) - F_T(v'_u)$ . According to [Lemma 4.9](#) there exists  $C_1 \in \mathbb{R}_+$  such that for every  $T \geq 0$ ,

$$|F_T(v) - F_T(v'_u)| \leq C_1 + \sum_{T_1 + \delta \leq n\delta \leq T - \delta} \sum_{\gamma \in S(n\delta)} |f \otimes \Theta_{T_1}^T(\gamma v) - f \otimes \Theta_{T_1}^T(\gamma v'_u)|$$

Combined with [Lemma 4.10](#), we see that there exists  $C_2 \in \mathbb{R}_+$  such that

$$\begin{aligned} & |F_T(v) - F_T(v'_u)| \\ & \leq C_1 + C_2 \sum_{T_1 + \delta \leq n\delta \leq T - \delta} \left[ \left( e^{a(T_1 - n\delta)} + e^{-a(T - n\delta)} \right) + \frac{1}{n^2} + n^q e^{-a_0 n \delta} \right]. \end{aligned}$$

Observe that for every integer  $n$  indexing the sum  $T_1 - n\delta$  is negative, whereas  $T - n\delta$  is positive. Consequently, the latter sum is bounded from above independently of  $T$ , which completes the proof of the proposition.  $\square$

**Running the Hopf argument.** We fix until the end of this section a *bounded positive* function  $g \in \mathcal{D}^+(\partial^2 X)$ , i.e.  $g$  is Lipschitz with exponential decay. For instance one can choose  $g(\eta, \xi) = d_{\partial X}(\eta, \xi)^p$  for a sufficiently large  $p \in \mathbb{R}_+$ . Recall that  $g$  belongs to  $L^1(\mu)$ . Up to rescaling  $g$  we can assume that

$$\int \hat{g}_\vartheta d\bar{m} = \int g_\vartheta dm = \int g d\mu = 1.$$

In addition we define an auxiliary map

$$\begin{aligned} g' : \quad \partial^2 X & \rightarrow \mathbb{R}_+^* \\ (\eta, \xi) & \rightarrow \int_{\mathbb{R}} \hat{g}_\vartheta(\eta, \xi, t) \theta(t) dt. \end{aligned}$$

Note that as  $\hat{g}_\vartheta$  is bounded ([Lemma 4.7](#)),  $g'$  is a bounded positive map.

**Proposition 4.14.** *Assume that the geodesic flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is conservative. If  $f \in L^1(\mu)$ , then for  $\bar{m}$ -almost every  $v \in SX$ ,*

$$\lim_{T \rightarrow \pm\infty} \frac{\int_0^T \hat{f}_\vartheta \circ \phi_t(v) dt}{\int_0^T \hat{g}_\vartheta \circ \phi_t(v) dt} = \int_{\partial^2 X} f g' d\mu.$$

*The same conclusion holds with  $v = (\eta, \xi, 0)$ , for  $\mu$ -almost all  $(\eta, \xi) \in \partial^2 X$ .*

*Proof.* Recall that the map  $\hat{f}_\vartheta: SX \rightarrow \mathbb{R}$  defined as in (26) is  $\Gamma$ -invariant and  $\bar{m}$ -integrable. Since the geodesic flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is conservative, the Hopf ergodic theorem [Hop37] tells us that for  $\bar{m}$ -almost every  $v \in SX$ ,

$$\lim_{T \rightarrow \pm\infty} \frac{\int_0^T \hat{f}_\vartheta \circ \phi_t(v) dt}{\int_0^T \hat{g}_\vartheta \circ \phi_t(v) dt} = f_\infty(v), \quad \text{where} \quad f_\infty(v) = \mathbb{E}_{\hat{g}_\vartheta \bar{m}} \left( \hat{f}_\vartheta \mid \mathcal{I} \right) (v) \quad (37)$$

is the conditional expectation of  $\hat{f}_\vartheta$  with respect to the sub- $\sigma$ -algebra  $\mathcal{I}$  of  $\mathcal{B}_\Gamma$  of all  $(\phi_t)$ -invariant Borel subsets.

Assume that  $f$  belongs to  $\mathcal{D}^+(\partial^2 X)$ . As the geodesic flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is conservative, both the numerator and the denominator in (37) diverge to infinity. Since  $\hat{f}_\vartheta$  and  $\hat{g}_\vartheta$  are bounded (Lemma 4.7), the map  $f_\infty(v)$  does not depend on the time coordinate of  $v = (\eta, \xi, t)$ , hence we write  $f_\infty(v) = f_\infty(\eta, \xi)$ . The crucial ingredient is Proposition 4.8, which implies that the map  $f_\infty$  only depends on the future,  $\bar{m}$ - or  $m$ - or  $\mu$ -almost surely. As the flow is flip invariant, the map  $f_\infty$  depends also only on the past,  $\mu$ -almost surely. Since  $\mu$  is equivalent to a product measure, the standard Hopf argument (based on Fubini Theorem) shows that  $f_\infty$  is constant  $\bar{m}$ - or  $m$ - or  $\mu$ -almost surely.

By construction  $\hat{g}_\vartheta$  is bounded (see Lemma 4.7) so that  $f_\vartheta \hat{g}_\vartheta \in L^1(m)$ . As  $\hat{g}_\vartheta$  is  $\Gamma$ -invariant, (26) yields

$$\int f g' d\mu = \int f_\vartheta \hat{g}_\vartheta dm = \int \widehat{f_\vartheta \hat{g}_\vartheta} d\bar{m} = \int \hat{f}_\vartheta \hat{g}_\vartheta d\bar{m}.$$

By definition of conditional expectation, we deduce that the almost sure value of  $f_\infty$ , say  $M \in \mathbb{R}$ , satisfies

$$M = \int f_\infty \hat{g}_\vartheta d\bar{m} = \int \hat{f}_\vartheta \hat{g}_\vartheta d\bar{m} = \int f g' d\mu.$$

As  $g'$  is bounded, both maps

$$f \mapsto \mathbb{E}_{\hat{g}_\vartheta \bar{m}} \left( \hat{f}_\vartheta \mid \mathcal{I} \right) \quad \text{and} \quad f \mapsto \int_{\partial^2 X} f g' d\mu$$

are bounded linear functionals, which coincide on  $\mathcal{D}^+(\partial^2 X) \subset L^1_+(\mu)$ . As it is a dense subset of  $L^1_+(\mu)$ , they coincide everywhere. It completes the proof of the main statement. The proof of the last statement is a direct corollary of the previous argument. We omit it.  $\square$

We have not quite proved yet that the measure  $\bar{m}$  is ergodic for the flow  $(\phi_t)$ . Indeed Proposition 4.14 does not a priori apply for any function in  $L^1(\bar{m})$ . Nevertheless it is sufficient to deduce that  $\mu$  is ergodic for the diagonal action of  $\Gamma$  on  $\partial^2 X$ . The next statement completes the proof of Theorem 4.2.

**Corollary 4.15.** *Assume that the geodesic flow on  $(SX, \mathcal{B}_\Gamma, \bar{m})$  is conservative. The action of  $\Gamma$  on  $(\partial^2 X, \mu)$  is ergodic.*

*Proof.* Let  $B$  be a  $\Gamma$ -invariant subset of  $\partial^2 X$  such that  $\mu(B) > 0$ . We want to prove that  $\mu(\partial^2 X \setminus B) = 0$ . Let  $K \subset B$  be a compact set with  $\mu(K) > 0$ .

By [Proposition 4.14](#) applied to  $f = \mathbf{1}_K$ , for  $\mu$ -almost every  $(\eta, \xi)$ , for every sufficiently large  $T \in \mathbb{R}_+$ ,

$$\int_0^T \hat{f}_\vartheta \circ \phi_t(v) dt > 0, \quad \text{where } v = (\eta, \xi, 0).$$

It implies that for  $\mu$ -almost every  $(\eta, \xi)$ , some  $(\gamma\xi, \gamma\eta)$  lies in  $K$ , and therefore  $B$ . As  $B$  is  $\Gamma$ -invariant, it means that  $\mu$ -almost every  $(\eta, \xi)$  belongs to  $B$ , i.e.  $B$  has full measure.  $\square$

## 4.5 Finiteness of the Bowen-Margulis measure

As a by-product of our technique, we will show that, when the action of  $\Gamma$  has a growth gap at infinity, the Bowen-Margulis measure  $\bar{m}$  on  $(SX, \mathcal{B}_\Gamma)$  is finite. This statement is not needed for the proof of [Theorem 1.1](#). We include it because it is an important dynamical result, which follows easily from the previous material. In fact, we prove the following more general statement, inspired from the work of Pit and Schapira [[PS18](#), Section 5].

**Theorem 4.16.** *Let  $\Gamma$  be a discrete group acting properly by isometries on a Gromov-hyperbolic space  $X$ . Assume that the Patterson-Sullivan measure  $\nu_0$  gives full measure to the radial limit set  $\Lambda_{\text{rad}}(\Gamma)$ . Then the Bowen-Margulis measure  $\bar{m}$  on  $(SX, \mathcal{B}_\Gamma)$  is finite if and only if there exists a compact subset  $K$  of  $X$  such that the series*

$$\sum_{\gamma \in \Gamma_K} d(o, \gamma o) e^{-h_\Gamma d(o, \gamma o)}$$

*converges.*

Recall that if the action of  $\Gamma$  on  $X$  is strongly positively recurrent, then  $\nu_0$  gives full measure to the radial limit set ([Corollary 3.16](#)). Moreover there exists a compact subset  $K$  of  $\bar{X}$  such that  $h_{\Gamma_K} < h_\Gamma$ . Therefore [Theorem 4.16](#) has the following immediate corollary.

**Corollary 4.17.** *Let  $\Gamma$  be a discrete group acting properly by isometries on a Gromov-hyperbolic space  $X$ . If the action of  $\Gamma$  on  $X$  is strongly positively recurrent, then the Bowen-Margulis measure  $\bar{m}$  on  $(SX, \mathcal{B}_\Gamma)$  is finite.*

From now on, we only assume that  $\nu_0$  gives full measure to the radial limit set. By definition,  $\Lambda_{\text{rad}}$  is the increasing union of all  $\Lambda_{\text{rad}}^K$  where  $K$  runs over all compact subsets of  $X$ . As already noticed before, there exists a compact subset  $k \subset X$ , such that  $\nu_o(\Lambda_{\text{rad}}^k) = 1$  ([Corollary 2.4](#)). Up to enlarging  $k$  we may assume that  $o$  belongs to  $k$ . We now fix a parameter  $r \geq \text{diam}(k) + 1000\delta$ . For the moment  $r$  is fixed, it will vary only at the very end of the proof. For simplicity let

$$Z = Z(r) = \{(\eta, \xi) \in \partial^2 X \mid \langle \eta, \xi \rangle_o \leq r\},$$

and define

$$\Sigma = \{(\eta, \xi, 0) \in SX \mid (\eta, \xi) \in Z\},$$

which we think of as a ‘‘compact’’ subset of a section of the flow. As in the preceding section, we work in  $SX$  modulo  $\Gamma$ . This motivates the next definition.



Given a vector  $v = (\eta, \xi, 0)$  in  $\Sigma$ , the *first return time* of  $v$  in  $\Sigma$  (modulo  $\Gamma$ ), denoted by  $\tau(v)$ , is defined by

$$\tau(v) = \inf \{t > 2r + 500\delta \mid \exists \gamma \in \Gamma, \gamma^{-1}\phi_t(v) \in \Sigma\}.$$

**Remark.** As  $X$  is Gromov hyperbolic, we only control its large scale geometry, which causes some edge effects. For this reason, it is convenient to require the first return time to be larger than  $2r + 500\delta$  (see for instance the proof of [Lemma 4.26](#)).

Define now

$$\Sigma' = \{v \in \Sigma, \tau(v) < +\infty\}.$$

Finally, the *first return core* is defined by

$$W = \{\phi_t(v) \mid v \in \Sigma', 0 \leq t \leq \tau(v)\}.$$

We are going to prove that  $\Gamma W$  has full  $\bar{m}$ -measure ([Proposition 4.19](#)) and that its measure  $\bar{m}(\Gamma W)$  is finite if and only if a certain series converges ([Propositions 4.23](#) and [4.27](#)). We start with the following lemma which provides a useful criterion *in the space  $X$*  to determine when a vector  $v \in SX$  belongs to a translate of  $\Sigma$ .

**Lemma 4.18.** *Let  $v \in SX$  and  $\gamma \in \Gamma$ . If  $d(\gamma o, \text{proj}(v)) \leq r - 220\delta$ , then there exists  $s \in \mathbb{R}$ , with  $|s| \leq r$  such that  $\gamma^{-1}\phi_s(v) \in \Sigma$ .*

*Proof.* We write  $v = (\eta, \xi, t)$ . Combining our assumption with [\(23\)](#) we get

$$\langle \gamma^{-1}\eta, \gamma^{-1}\xi \rangle_o + |t + \kappa_{\gamma^{-1}}(\eta, \xi)| \leq d(\gamma o, \text{proj}(v)) + 220\delta \leq r.$$

It follows first that  $\langle \gamma^{-1}\eta, \gamma^{-1}\xi \rangle_o \leq r$ , i.e. the pair  $(\gamma^{-1}\eta, \gamma^{-1}\xi)$  belongs to  $Z$ . Moreover  $s = -\kappa_{\gamma^{-1}}(\eta, \xi) - t$  satisfies  $|s| \leq r$ . One easily checks that  $\gamma^{-1}\phi_s(v) = (\gamma^{-1}\eta, \gamma^{-1}\xi, 0)$ , which, according to our previous observation, belongs to  $\Sigma$ .  $\square$

**Proposition 4.19.** *The set  $\Gamma W$  is a  $\Gamma$ -invariant set of full  $\bar{m}$ -measure. In particular,  $\bar{m}(SX) \leq m(W)$ .*

*Proof.* By assumption,  $\nu_0(\Lambda_{\text{rad}}^k) = 1$ . Since  $\mu$  belongs to the same measure class as  $\nu_o \otimes \nu_o$ , it gives full measure to the set  $(\Lambda_{\text{rad}}^k \times \Lambda_{\text{rad}}^k) \cap \partial^2 X$ . It follows from [Lemma 4.3](#), that  $m$ -almost every  $v \in SX$ , for every  $T \geq 0$ , there exists  $t \geq T$  and  $\gamma \in \Gamma$  such that  $\gamma^{-1}\phi_t(v) \in \Sigma$ . The same holds for negative times. Hence  $W$  contains a Borel fundamental domain for the action of  $\Gamma$  on  $SX$ . Consequently  $\Gamma W$  has full  $m$ -measure and thus full  $\bar{m}$ -measure. The inequality  $\bar{m}(SX) \leq m(W)$  directly follows from the definition of  $\bar{m}$ .  $\square$

In order to estimate the measure of  $W$  it will be convenient to decompose it according to which translates of  $\Sigma$  the first return map falls in. This motivates the next definitions. For all  $\gamma \in \Gamma$ , we define

$$\begin{aligned} \Sigma'_\gamma &= \{v \in \Sigma' \mid \exists s, \tau(v) \leq s \leq \tau(v) + 2r + 500\delta \text{ and } \gamma^{-1}\phi_s(v) \in \Sigma\} \\ Z'_\gamma &= \{(\eta, \xi) \in \partial^2 X \mid (\eta, \xi, 0) \in \Sigma'_\gamma\} \\ W_\gamma &= \{\phi_t(v) \mid v \in \Sigma'_\gamma, 0 \leq t \leq \tau(v)\}. \end{aligned}$$

Finally we denote by  $\Gamma(\Sigma')$  the set of all elements  $\gamma \in \Gamma$  for which  $\Sigma'_\gamma$  is non-empty. It follows from these definitions that

$$W \subset \bigcup_{\gamma \in \Gamma(\Sigma')} W_\gamma. \quad (38)$$

Let us study the properties of these sets. We start with a series of lemmas that will provide an *upper* bound of  $\bar{m}(SX)$ .

**Lemma 4.20.** *For every  $\gamma \in \Gamma(\Sigma')$ , for every  $v \in \Sigma'_\gamma$ , the vectors  $v$  and  $v' = \phi_{\tau(v)}(v)$  satisfy*

$$d(o, \text{proj}(v)) \leq r + 20\delta \quad \text{and} \quad d(\gamma o, \text{proj}(v')) \leq 3r + 720\delta$$

Moreover  $|d(o, \gamma o) - \tau(v)| \leq 4r + 740\delta$ .

*Proof.* Note that the proof would be rather obvious if the projection  $SX \rightarrow X$  were  $\Gamma$ -equivariant. Let  $v = (\eta, \xi, 0)$  in  $\Sigma'_\gamma$ . As observed in (21), the quantity  $\langle \eta, \xi \rangle_o$  roughly measures the distance between  $o$  and  $\text{proj}(v)$ . Since  $v \in \Sigma$ , we get

$$d(o, \text{proj}(v)) \leq \langle \eta, \xi \rangle_o + 20\delta \leq r + 20\delta.$$

By definition of  $\Sigma'_\gamma$ , there exists  $t \in [\tau(v), \tau(v) + 2r + 500\delta]$  such that  $\gamma^{-1}\phi_t(v)$  belongs to  $\Sigma$ . As before, we get from (23)

$$d(\gamma o, \text{proj}(\phi_t(v))) \leq \langle \gamma^{-1}\eta, \gamma^{-1}\xi \rangle_o + 220\delta \leq r + 220\delta.$$

The map  $\text{proj} \circ \phi_s : \mathbb{R} \rightarrow X$  is a bi-infinite geodesic, so that

$$d(\text{proj}(v'), \text{proj}(\phi_t(v))) \leq 2r + 500\delta \quad \text{and} \quad d(\text{proj}(v), \text{proj}(v')) = \tau(v).$$

It yields  $d(\gamma o, \text{proj}(v')) \leq 3r + 720\delta$ , which completes the first part of the lemma. The second part follows from the triangle inequality.  $\square$

**Lemma 4.21.** *For every  $\gamma \in \Gamma(\Sigma')$ , the set  $Z'_\gamma$  is contained in the product  $\mathcal{O}_{\gamma o}(o, r + 30\delta) \times \mathcal{O}_o(\gamma o, r + 30\delta)$ .*

*Proof.* Let  $(\eta, \xi) \in \partial^2 X$  and  $v = (\eta, \xi, 0)$ . As usual we write  $\sigma : \mathbb{R} \rightarrow X$  for the bi-infinite geodesic sending  $s$  to  $\phi_s(v)$ . Assume first that  $(\eta, \xi) \in Z'_\gamma$ , i.e. the vector  $v$  belongs to  $\Sigma'_\gamma$ . It follows that  $\langle \eta, \xi \rangle_o \leq r$  and  $\langle \eta, \xi \rangle_{\gamma o} \leq r$ . In particular  $o$  and  $\gamma o$  are  $(r + 6\delta)$ -close to  $\sigma$ . As the ideal geodesic triangles in  $X$  are  $24\delta$ -thin,  $\gamma o$  (respectively  $o$ ) is  $(r + 30\delta)$ -close to any geodesic joining  $o$  to  $\xi$  (respectively  $\gamma o$  to  $\eta$ ). Whence the result.  $\square$

**Lemma 4.22.** *Assume that  $K$  is a compact subset contained in  $B(r - 300\delta)$ . There exist two finite subsets  $S_1$  and  $S_2$  of  $\Gamma$  such that  $\Gamma(\Sigma') \setminus S_1$  is contained in  $S_2\Gamma_K S_2$ .*

*Proof.* Set

$$S_1 = \{\gamma \in \Gamma \mid d(o, \gamma o) \leq 8r + 2000\delta\},$$

$$S_2 = \{\gamma \in \Gamma \mid d(o, \gamma o) \leq 5r + 1000\delta\}.$$

Let  $\gamma \in \Gamma(\Sigma') \setminus S_1$  and choose an arbitrary  $v \in \Sigma'_\gamma$ . For simplicity, set  $\tau = \tau(v)$  for the first return time of  $v$  in  $\Sigma$ . Recall that the map  $\sigma: \mathbb{R} \rightarrow X$  sending  $t$  to  $\text{proj} \circ \phi_t(v)$  is a bi-infinite geodesic of  $X$  joining  $\eta$  to  $\xi$ . According to [Lemma 4.20](#)

$$d(o, \sigma(0)) \leq r + 20\delta \quad \text{and} \quad d(\gamma o, \sigma(\tau)) \leq 3r + 720\delta$$

Fix a geodesic  $c: [0, \ell] \rightarrow X$  joining  $o$  to  $\gamma o$ . Let  $s_1, s_2 \in [0, 4r + 1000\delta]$  be the largest times such that  $c(s_1)$  (respectively  $c(\ell - s_2)$ ) belongs  $\alpha_1 K$  for some  $\alpha_1 \in \Gamma$  (respectively  $\gamma \alpha_2 K$  for some  $\alpha_2 \in \Gamma$ ). It follows from the previous claim combined with the triangle inequality that  $d(o, \alpha_i o) \leq 5r + 1000\delta$ . In other words  $\gamma$  can be written  $\gamma = \alpha_1(\alpha_1^{-1}\gamma\alpha_2)\alpha_2^{-1}$  where  $\alpha_1$  and  $\alpha_2^{-1}$  belong to  $S_2$ . Thus we are left to prove that  $\alpha_1^{-1}\gamma\alpha_2$  belongs to  $\Gamma_K$ . As  $\gamma$  does not belong to  $S_1$ , the point  $x, c(s_1), c(\ell - s_2)$  and  $\gamma y$  are aligned in this order along  $c$ . Hence it suffices to prove that  $c$  restricted to  $(s_1, \ell - s_2)$  does not intersect  $\Gamma K$ . Assume on the contrary that there exists  $s \in (s_1, \ell - s_2)$  such that  $y = c(s)$  belongs to  $\beta K$  for some  $\beta \in \Gamma$ . By construction  $d(o, c(s)) > d(o, \sigma(0)) + 3r + 510\delta$  and  $d(\gamma o, c(s)) > d(\gamma o, \sigma(\tau)) + r + 10\delta$ . It is a standard exercise in hyperbolic geometry to observe that  $y$  is  $6\delta$ -close to a point  $x = \sigma(t)$  with  $t \in (3r + 500\delta, \tau - r)$ . In particular,  $d(\beta o, x) \leq r - 220\delta$ . It follows then from [Lemma 4.18](#) that there exists  $t' \in (2r + 500\delta, \tau(v))$  such that  $\beta^{-1}\phi_{t'}(v)$  belongs to  $\Sigma$ . This contradicts the definition of the first return time and completes the proof of the claim.  $\square$

**Proposition 4.23.** *Assume that  $K$  is a compact subset contained in  $B(r - 300\delta)$ . There exists  $C \in \mathbb{R}_+$  such that*

$$\bar{m}(SX) \leq C \sum_{\gamma \in \Gamma_K} d(o, \gamma o) e^{-h_\Gamma d(o, \gamma o)}$$

*Proof.* As we observed earlier  $\bar{m}(SX) \leq m(W)$  ([Proposition 4.19](#)). For every  $(\eta, \xi) \in Z$  define  $\tau(\eta, \xi) = \tau(v)$  where  $v = (\eta, \xi)$ . Recall that  $m = \mu \otimes dt$ . Thus the decomposition of the first return core  $W$  given in (38) yields

$$\bar{m}(SX) \leq \sum_{\gamma \in \Gamma(\Sigma')} m(W_\gamma) \leq \sum_{\gamma \in \Gamma(\Sigma')} \int \mathbf{1}_{Z'_\gamma}(\eta, \xi) \tau(\eta, \xi) d\mu(\eta, \xi),$$

By [Lemma 4.20](#), the first return time  $\tau$  is approximatively  $d(o, \gamma o)$  when restricted to  $Z'_\gamma$ . Moreover by (12)  $\mu$  restricted to  $Z'$  is comparable to  $\nu_o \otimes \nu_o$ . Hence there exists  $C \in \mathbb{R}_+$  such that

$$\bar{m}(SX) \leq C \sum_{\gamma \in \Gamma(\Sigma')} d(o, \gamma o) (\nu_o \otimes \nu_o)(Z'_\gamma).$$

According to [Lemma 4.21](#),  $Z'_\gamma$  is contained in  $\partial X \times \mathcal{O}_o(\gamma o, r + 30\delta)$ . Hence (up to increasing  $C$ ) the Shadow Lemma ([Lemma 2.3](#)) gives

$$\bar{m}(SX) \leq C \sum_{\gamma \in \Gamma(\Sigma')} d(o, \gamma o) e^{-h_\Gamma d(o, \gamma o)}.$$

The conclusion now follows from [Lemma 4.22](#).  $\square$

Let us now provide a *lower* bound of  $\bar{m}(SX)$ . To that end we define

$$W^0 = \{\phi_s(v) \mid v \in \Sigma', 0 \leq s < \tau(v)\}$$

The first step is to estimate the multiplicity of certain families.

**Lemma 4.24.** *There exists  $N \in \mathbb{N}$  such that for  $\bar{m}$ -almost every  $v \in SX$  the set  $\{\gamma \in \Gamma \mid v \in \gamma W^0\}$  contains at most  $N$  elements.*

*Proof.* Recall that  $S_0X$  is the full measure,  $\Gamma$  and flow invariant subset defined in (20). Let  $v \in S_0X$ . Let  $\alpha, \beta \in \Gamma$  such that  $v$  belongs to  $\alpha W^0 \cap \beta W^0$ . We can write  $\alpha \phi_s(u) = v = \beta \phi_t(w)$ , where  $u, w \in \Sigma'$ ,

$$0 \leq s < \tau(u), \quad \text{and} \quad 0 \leq t < \tau(w).$$

In particular  $\alpha^{-1}\beta\phi_{t-s}(w) = u$  and  $\beta^{-1}\alpha\phi_{s-t}(u) = w$  both belong to  $\Sigma$ . By construction either  $0 \leq t - s < \tau(w)$  or  $0 \leq s - t < \tau(u)$ . It follows from our definition of first return time that  $|t - s| \leq 2r + 500\delta$ . Since  $\text{proj}: SX \rightarrow X$  is almost  $\Gamma$ -equivariant (22) and maps orbits of the flow to geodesics we get

$$d(\alpha \text{proj}(u), \beta \text{proj}(w)) \leq 2r + 700\delta.$$

On the other hand, since  $w$  belongs to  $\Sigma$ , we have  $d(o, \text{proj}(w)) \leq r + 20\delta$  (Lemma 4.20). Consequently

$$\{\gamma \in \Gamma \mid v \in \gamma W^0\} \subset \{\gamma \in \Gamma \mid d(x, \gamma o) \leq 3r + 800\delta\}$$

where  $x = \alpha \text{proj}(u)$ . The conclusion follows from Lemma 4.5.  $\square$

**Lemma 4.25.** *There exists  $N \in \mathbb{N}$  such that for every  $v \in SX$  the set  $\{\gamma \in \Gamma \mid v \in W_\gamma\}$  contains at most  $N$  elements.*

*Proof.* Set  $v' = \phi_{\tau(v)}(v)$ . It follows from Lemma 4.20 that

$$\{\gamma \in \Gamma \mid v \in W_\gamma\} \subset \{\gamma \in \Gamma \mid d(\text{proj}(v'), \gamma o) \leq 3r + 720\delta\}.$$

Hence the result follows from Lemma 4.5.  $\square$

**Lemma 4.26.** *There exists a compact subset  $K \subset X$  and a finite subset  $S \subset \Gamma$  such that for every  $\gamma \in \Gamma_K \setminus S$ , the product  $\mathcal{O}_{\gamma o}(o, r - \delta) \times \mathcal{O}_o(\gamma o, r - \delta)$  is contained in  $Z'_\gamma$ . In particular  $\Gamma_K \setminus S \subset \Gamma(\Sigma')$*

*Proof.* Let  $K$  be the closed ball  $K = \bar{B}(o, r + 250\delta)$  and set

$$S = \{\gamma \in \Gamma \mid d(o, \gamma o) \leq 6r + 1000\delta\}.$$

Let  $\gamma \in \Gamma_K \setminus S$  and  $(\eta, \xi) \in \mathcal{O}_{\gamma o}(o, r - \delta) \times \mathcal{O}_o(\gamma o, r - \delta)$ . Since  $\eta$  belongs to  $\mathcal{O}_{\gamma o}(o, r - \delta)$ , it follows from the four point inequality (3) that

$$\min\{\langle \eta, \xi \rangle_o, \langle \gamma o, \xi \rangle_o\} \leq \langle \gamma o, \eta \rangle_o + \delta \leq r.$$

As  $\xi$  belongs to  $\mathcal{O}_{\gamma o}(o, r - \delta)$  and  $\gamma \notin S$ , we have

$$\langle \gamma o, \xi \rangle_o \geq d(o, \gamma o) - r - \delta > r,$$

thus the minimum cannot be achieved by  $\langle \gamma o, \xi \rangle_o$ . Hence  $\langle \eta, \xi \rangle_o \leq r$ , which means that  $v = (\eta, \xi, 0)$  lies in  $\Sigma$ . Similarly we prove that  $\langle \eta, \xi \rangle_{\gamma o} \leq r$ , thus there exists  $t \in \mathbb{R}$  such that  $\gamma^{-1}\phi_t(v)$  belongs to  $\Sigma$ . Since  $d(o, \gamma o) > 6r + 1000\delta$ , we can assume that  $t > 0$ . In particular  $\tau(v) \leq t$ . We now need to prove that  $t \leq \tau(v) + r + \delta$ . Assume on the contrary that it is not the case. In particular there exists  $s \in [\tau(v), t - r - \delta)$  such that  $\alpha^{-1}\phi_s(v) \in \Sigma$ , for some  $\alpha \in \Gamma$ . For simplicity we let  $z_0 = \text{proj}(v)$ ,  $z_s = \text{proj} \circ \phi_s(v)$  and  $z_t = \text{proj} \circ \phi_t(v)$ . By (23) we have

$$\max \{d(o, z_0), d(\alpha o, z_s), d(\gamma o, z_t)\} \leq r + 220\delta.$$

Since  $\gamma$  belongs to  $\Gamma_K$ , there exists  $x, y \in K$  and a geodesic  $c: [0, \ell] \rightarrow X$  joining  $x$  to  $\gamma y$  such that  $c \cap \Gamma K \subset K \cup \gamma K$ . It follows then from the triangle inequality that  $d(x, z_0) \leq 2r + 470\delta$  and  $d(\gamma y, z_t) \leq 2r + 470\delta$ . On the other hand since  $\text{proj}: SX \rightarrow X$  maps orbits of the flow to geodesics, hence  $|s - t| \leq r + \delta$ , we have

$$d(z_0, z_s) \geq \tau(v) > 2r + 500\delta \quad \text{and} \quad d(z_t, z_s) \geq t - s > 2r + 500\delta. \quad (39)$$

A standard exercise of hyperbolic geometry show that  $z_s$  is  $6\delta$ -close to a point  $c(s)$  on  $c$ . In particular  $d(\alpha o, c(s)) \leq r + 250\delta$ , i.e.  $c(s) \in \alpha K$ . It follows from the definition of  $c$  that  $c(s)$  belongs to  $K \cup \gamma K$ . Consequently either  $d(z_0, z_s) \leq 2r + 500\delta$  or  $d(z_t, z_s) \leq 2r + 500\delta$ , which violates (39).  $\square$

**Proposition 4.27.** *There exist  $C \in \mathbb{R}_+^*$  and a compact subset  $K \subset X$  such that*

$$C \sum_{\gamma \in \Gamma_K} \leq \bar{m}(SX).$$

*Proof.* We write  $K$  for the compact subset of  $X$  given by Lemma 4.26. Obviously  $\bar{m}(\Gamma W^0) \leq \bar{m}(SX)$ . Note that the collection  $(\gamma W^0)$  may not be pairwise disjoint, nevertheless thanks to Lemma 4.24 we control its multiplicity. Thus there exists  $C \in \mathbb{R}_+^*$  such that

$$Cm(W^0) \leq \bar{m}(\Gamma W^0) \leq \bar{m}(SX).$$

Similarly (up to decreasing  $C$ ) we get by Lemma 4.24

$$C \sum_{\gamma \in \Gamma(\Sigma')} m(W^0 \cap W_\gamma) \leq \bar{m}(SX).$$

Reasoning as in Proposition 4.23, we get

$$C \sum_{\gamma \in \Gamma(\Sigma')} d(o, \gamma o) (\nu_o \otimes \nu_o)(Z'_\gamma) \leq \bar{m}(SX).$$

By Lemma 4.26,  $\mathcal{O}_{\gamma o}(o, r - \delta) \times \mathcal{O}_o(\gamma o, r - \delta)$  is contained in  $Z'_\gamma$ , for all but finitely many  $\gamma \in \Gamma_K$ . Combined with the Shadow Lemma (Lemma 2.3) it yields

$$C \sum_{\gamma \in \Gamma_K} d(o, \gamma o) e^{-h_\Gamma d(o, \gamma o)} \leq \bar{m}(SX). \quad \square$$

We complete this section with the proof of Theorem 4.16.

*Proof of Theorem 4.16.* Assume first that the Bowen-Margulis measure  $\bar{m}$  is finite. It follows from Proposition 4.27 that there exists a compact subset  $K \subset X$  such that the series

$$\sum_{\gamma \in \Gamma_K} d(o, \gamma o) e^{-h_\Gamma d(o, \gamma o)}$$

converges. Assume on the contrary that there exists a compact subset  $K$  for which the above series converges. Up to enlarging the value of  $r$ , we can always assume that  $K$  is contained in  $B(o, r - 300\delta)$ . It follows from Proposition 4.23 that  $\bar{m}$  is finite.  $\square$

## 5 A twisted Patterson-Sullivan measure

### 5.1 Main theorem

**Setting** Let  $(X, d)$  be a proper geodesic  $\delta$ -hyperbolic space. We fix once and for all a base point  $o \in X$ . Let  $\Gamma$  be a group acting properly by isometries on  $X$ . Recall that  $h_\Gamma$  stands for the critical exponent of the Poincaré series of  $\Gamma$ .

Let  $(\mathcal{H}, \prec)$  be a *Hilbert lattice*, i.e. a Hilbert space endowed with a partial order  $\prec$ , compatible with the vector space structure as well as the norm, which induces a lattice structure on  $\mathcal{H}$ . We refer the reader to Appendix B for a precise definition. All properties of Hilbert lattices that we will use are also recalled in this appendix. Denote by  $\mathcal{H}^+$  its positive cone, i.e. the set of elements  $\phi \in \mathcal{H}$  such that  $0 \prec \phi$ . Let  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  be a *positive* unitary representation, i.e.  $\rho(\gamma)\phi \in \mathcal{H}^+$ , for every  $\gamma \in \Gamma$  and every  $\phi \in \mathcal{H}^+$ .

**Twisted Poincaré series.** For every  $s \in \mathbb{R}_+$  we consider the formal series  $A(s)$  defined as follows

$$A(s) = \sum_{\gamma \in \Gamma} e^{-sd(\gamma o, o)} \rho(\gamma).$$

We say that this series is *bounded* if there exists  $M \in \mathbb{R}_+$  such that for every finite subset  $S$  of  $\Gamma$ ,

$$\left\| \sum_{\gamma \in S} e^{-sd(\gamma o, o)} \rho(\gamma) \right\| \leq M.$$

The *critical exponent* of the representation  $\rho$  is defined as

$$h_\rho = \inf \{s \in \mathbb{R}_+ \mid A(s) \text{ is bounded}\}.$$

According to Proposition B.3, for every  $s > h_\rho$ , the series pointwise converges to a bounded operator of  $\mathcal{H}$ . The following lemma is straightforward.

**Lemma 5.1.** *For every  $s > h_\Gamma$ , the series  $A(s)$  is bounded and  $\|A(s)\| \leq \mathcal{P}_\Gamma(s)$ . In particular,  $h_\rho \leq h_\Gamma$ .*

**Almost invariant vectors.** Let  $S$  be a finite subset of  $\Gamma$  and  $\varepsilon \in \mathbb{R}_+^*$ . A vector  $\phi \in \mathcal{H}$  is  $(S, \varepsilon)$ -invariant (with respect to  $\rho$ ) if

$$\sup_{\gamma \in S} \|\rho(\gamma)\phi - \phi\| < \varepsilon \|\phi\|.$$

The representation  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  almost has invariant vectors if for every finite subset  $S$  of  $\Gamma$ , for every  $\varepsilon \in \mathbb{R}_+^*$ , there exists an  $(S, \varepsilon)$ -invariant vector. The goal of this section is to prove the following statement.

**Theorem 5.2.** *Let  $\Gamma$  be a discrete group acting properly by isometries on a hyperbolic space  $(X, d)$ . Assume that the action of  $\Gamma$  on  $X$  is strongly positively recurrent. For every finite subset  $S$  of  $\Gamma$ , for every  $\varepsilon \in \mathbb{R}_+^*$ , there exists  $\eta \in \mathbb{R}_+^*$  with the following property. Let  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  be a unitary positive representation of  $\Gamma$  into a Hilbert lattice. If  $h_\rho \geq (1 - \eta)h_\Gamma$ , then  $\rho$  has an  $(S, \varepsilon)$ -invariant vector.*

The proof of this result is given in Sections 5.3 - 5.6. For the moment let us mention a first consequence of this statement.

**Corollary 5.3.** *Let  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  be a unitary positive representation of  $\Gamma$  into a Hilbert lattice. The representation  $\rho$  almost has invariant vectors if and only if  $h_\rho = h_\Gamma$ . In this case,  $\|A(s)\| = \mathcal{P}_\Gamma(s)$ , for every  $s > h_\Gamma$ .*

*Proof.* Assume first that the representation almost has invariant vectors. Let  $s > h_\rho$ , and  $S$  be a finite subset of  $\Gamma$  and  $\varepsilon \in \mathbb{R}_+^*$ . There exists a vector  $\phi \in \mathcal{H} \setminus \{0\}$  such that for every  $\gamma \in S$ , we have  $\|\rho(\gamma)\phi - \phi\| < \varepsilon\|\phi\|$ . It yields

$$\left\| \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \rho(\gamma)\phi - \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \phi \right\| \leq \varepsilon \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \|\phi\|,$$

whence

$$(1 - \varepsilon) \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \|\phi\| \leq \left\| \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \rho(\gamma)\phi \right\| \leq \left\| \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \rho(\gamma) \right\| \|\phi\|.$$

Since  $\phi$  is a non-zero vector we get

$$(1 - \varepsilon) \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \leq \left\| \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \rho(\gamma) \right\|.$$

This inequality holds for all  $\varepsilon > 0$ . Hence, for any finite subset  $S$  of  $\Gamma$ , we have

$$\sum_{\gamma \in S} e^{-sd(o, \gamma o)} \leq \left\| \sum_{\gamma \in S} e^{-sd(o, \gamma o)} \rho(\gamma) \right\|.$$

We deduce that for all  $s > h_\rho$ ,  $\mathcal{P}_\Gamma(s) \leq \|A(s)\|$ . It follows that  $h_\Gamma \leq h_\rho$ . By Lemma 5.1, we get  $h_\Gamma = h_\rho$  and  $\|A(s)\| = \mathcal{P}_\Gamma(s)$ . The converse implication follows from of Theorem 5.2.  $\square$

## 5.2 Ultra-limit of Hilbert spaces

Inspired by the standard Patterson-Sullivan construction we are going to build in the next section a linear functional on  $C(\bar{X}_h)$  which we think of as an operator valued measure on  $\bar{X}_h$ . Since  $\bar{X}_h$  is compact, the set of positive *real valued* measures on  $\bar{X}_h$  is compact for the weak-\* topology. This is no more

the case for general vector valued measure. To bypass this difficulty we let our measures converge in a bigger space obtained as the ultra-limit of a sequence of Banach spaces. This section reviews the main properties of ultra-limit of Banach spaces. For more details see Druţu-Kapovich [DK18, Chapter 19].

A *non-principal ultra-filter* is a finitely additive map  $\omega : \mathcal{P}(\mathbb{N}) \rightarrow \{0, 1\}$  such that  $\omega(\mathbb{N}) = 1$  and which vanishes on every finite subset of  $\mathbb{N}$ . A property  $P_n$  is true  $\omega$ -almost surely ( $\omega$ -as) if

$$\omega(\{n \in \mathbb{N} \mid P_n \text{ is true}\}) = 1.$$

A real sequence  $(u_n)$  is  $\omega$ -essentially bounded ( $\omega$ -eb) if there exists  $M$  such that  $|u_n| \leq M$ ,  $\omega$ -as. Given  $\ell \in \mathbb{R}$ , we say that the  $\omega$ -limit of  $(u_n)$  is  $\ell$  and write  $\lim_{\omega} u_n = \ell$  if for all  $\varepsilon > 0$ , we have  $|u_n - \ell| \leq \varepsilon$ ,  $\omega$ -as. Any sequence which is  $\omega$ -eb admits a  $\omega$ -limit [Bou71].

Let  $(E_n)$  a sequence of Banach spaces. We define a restricted product by

$$\prod_{\omega} E_n = \left\{ (\phi_n) \in \prod_{n \in \mathbb{N}} E_n \mid \|\phi_n\| \text{ is } \omega\text{-eb} \right\}$$

Pointwise addition and scalar multiplication define a vector space structure on this set. We define a pseudonorm by

$$\|(\phi_n)\| = \lim_{\omega} \|\phi_n\|.$$

**Definition 5.4.** The  $\omega$ -limit of  $(E_n)$ , denoted by  $\lim_{\omega} E_n$  or simply  $E_{\omega}$ , is the quotient of  $\prod_{\omega} E_n$  by the equivalence relation which identifies two sequences  $(\phi_n)$  and  $(\phi'_n)$  whenever  $\|(\phi_n) - (\phi'_n)\| = 0$ .

The vector space structure on  $\prod_{\omega} E_n$  passes to the quotient and turns  $E_{\omega}$  into a vector space. Similarly the pseudonorm on  $\prod_{\omega} E_n$  defines a norm on  $\lim_{\omega} E_n$  for which  $E_{\omega}$  is complete [Pap96, Preliminaries]. Hence  $E_{\omega}$  is a Banach space. In addition, if for every  $n \in \mathbb{N}$ , the space  $E_n$  is a Hilbert space, then so is  $E_{\omega}$ . Indeed, the parallelogram law only involves four points, thus it passes to the limit [DK18, Corollary 19.3].

**Notation.** If  $(\phi_n)$  is a sequence in  $\prod_{\omega} E_n$  we denote its image in  $\lim_{\omega} E_n$  by  $\lim_{\omega} \phi_n$ .

Let  $(E_n)$  and  $(F_n)$  be two sequences of Banach spaces. Let

$$E_{\omega} = \lim_{\omega} E_n \quad \text{and} \quad F_{\omega} = \lim_{\omega} F_n.$$

For every  $n \in \mathbb{N}$ , the space  $\mathcal{B}(E_n, F_n)$  of bounded linear operator from  $E_n$  to  $F_n$  is a Banach space. In particular, we can consider the limit space  $\lim_{\omega} \mathcal{B}(E_n, F_n)$ . Given an element  $A = \lim_{\omega} A_n$  in  $\lim_{\omega} \mathcal{B}(E_n, F_n)$ , one defines an operator  $\iota(A)$  in  $\mathcal{B}(E_{\omega}, F_{\omega})$  as follows. For every  $\phi = \lim_{\omega} \phi_n$  in  $E_{\omega}$ , we let

$$\iota(A)\phi = \lim_{\omega} [A_n \phi_n].$$

One checks easily that  $\iota(A)$  is well-defined. In particular it does not depend on the choice of the sequences  $(A_n)$  or  $(\phi_n)$ . The resulting map

$$\iota : \lim_{\omega} \mathcal{B}(E_n, F_n) \rightarrow \mathcal{B}(E_{\omega}, F_{\omega})$$



is both a linear map and an isometric embedding. As  $\lim_{\omega} \mathcal{B}(E_n, F_n)$  is complete, its image is closed. In this article, we will omit the map  $\iota$  and see  $\lim_{\omega} \mathcal{B}(E_n, F_n)$  as a closed linear subspace of  $\mathcal{B}(E_{\omega}, F_{\omega})$ . Similarly  $\lim_{\omega} \mathcal{B}(E_n)$  embeds as a closed *subalgebra* of  $\mathcal{B}(E_{\omega})$ . This leads to the following statement.

**Proposition 5.5.** *Let  $\Gamma$  be a group. Let  $(\rho_n)$  be a sequence of unitary representations of  $\Gamma$  into a Hilbert space  $\mathcal{H}_n$ . There exists a unique unitary representation  $\rho_{\omega}: \Gamma \rightarrow \mathcal{U}(\mathcal{H}_{\omega})$  such that for every  $\gamma \in \Gamma$ , for every element  $\phi = \lim_{\omega} \phi_n$  of  $\mathcal{H}_{\omega}$  we have*

$$\rho_{\omega}(\gamma)\phi = \lim_{\omega} [\rho_n(\gamma)\phi_n].$$

*It is denoted by  $\rho_{\omega} = \lim_{\omega} \rho_n$ , and called the (ultra-)limit representation.*

**Lattice structure.** Assume now that each space  $E_n$  comes with a partial order  $\prec$  that turns  $E_n$  into a Banach lattice. We define  $E_{\omega}^+$  as the set

$$E_{\omega}^+ = \left\{ \lim_{\omega} \phi_n \in E_{\omega} \mid \phi_n \in E_n^+, \omega\text{-as} \right\}.$$

It is a positive convex cone. Hence one can define a partial order on  $E_{\omega}$  by declaring that  $\phi \prec \phi'$  if  $\phi' - \phi \in E_{\omega}^+$ .

**Lemma 5.6** (Druţu-Kapovich [DK18, Proposition 19.12]). *The ordered vector space  $(E_{\omega}, \|\cdot\|, \prec)$  is a Banach lattice.*

**Lemma 5.7.** *Let  $\Gamma$  be a group. Let  $(\rho_n)$  be a sequence of unitary representations of  $\rho_n: \Gamma \rightarrow \mathcal{U}(\mathcal{H}_n)$  into a Hilbert lattice  $\mathcal{H}_n$ . If  $\rho_n$  is positive  $\omega$ -as, then so is the limit representation  $\rho_{\omega} = \lim_{\omega} \rho_n$ .*

*Proof.* It directly follows from the definition of  $\rho_{\omega}$ . □

### 5.3 Conformal family of operator valued measures

The next sections are dedicated to the proof of [Theorem 5.2](#).

**Setting.** Let  $(X, d)$  be a proper geodesic hyperbolic space. We fix once and for all a base point  $o \in X$ . Recall that  $\bar{X}$  stands for the Gromov compactification of  $X$  whereas  $\bar{X}_h$  is its horocompactification. Let  $\Gamma$  be a group acting properly by isometries on  $X$ . We assume that this action is strongly positively recurrent. Let  $\omega$  be a non-principal ultra-filter. For every  $n \in \mathbb{N}$ , we fix a Hilbert lattice  $\mathcal{H}_n$ , as well as a unitary positive representation  $\rho_n: \Gamma \rightarrow \mathcal{U}(\mathcal{H}_n)$ . We denote by  $A_n(s)$  the formal series

$$A_n(s) = \sum_{\gamma \in \Gamma} e^{-sd(\gamma o, o)} \rho_n(\gamma)$$

We set

$$h_{\omega} = \lim_{\omega} h_{\rho_n}.$$

We are going to prove that if  $h_{\omega} = h_{\Gamma}$ , then  $\rho_{\omega}$  has a non-zero invariant vector ([Proposition 5.26](#)). This will imply [Theorem 5.2](#).

**Remark.** To prove [Theorem 1.1](#), we can assume  $\rho_n$  is constantly equal to the Koopmann representation associated to the right action of  $\Gamma$  on  $\Gamma \backslash \Gamma$ . In this case  $h_\omega = h_\rho$ . Nevertheless, the quantified version of our main theorem as stated in [Theorem 5.2](#) requires this level of full generality. Note that even if  $(\rho_n)$  is a constant sequence, we cannot avoid using ultra-filters. Indeed, as our Hilbert spaces are not locally compact, ultra-limit of Hilbert spaces provides a convenient tool to make bounded sequences converge.

**Weighted Poincaré series.** Since the action of  $\Gamma$  is strongly positively recurrent, the standard Poincaré series  $\mathcal{P}_\Gamma(s)$  is divergent at the critical exponent  $s = h_\Gamma$ , see [Corollary 3.16](#). However there is no reason that the sequence  $\|A_n(s)\|$  should diverge, at  $s = h_{\rho_n}$ . We bypass this difficulty by adapting the usual Patterson argument [[Pat76](#), Lemma 3.1].

**Lemma 5.8.** *Let  $(s_n)$  be a sequence converging to  $h_\omega$ . There exists a non decreasing map  $\theta: \mathbb{R}_+ \rightarrow \mathbb{R}_+$  with the following properties.*

1. *For every  $\varepsilon \in \mathbb{R}_+^*$ , there exists  $t_0 \in \mathbb{R}_+$  such that for every  $u \in \mathbb{R}_+$  and  $t \geq t_0$ , one has  $\theta(t+u) \leq e^{\varepsilon u} \theta(t)$ .*
2. *The operator series*

$$A'_n(s) = \sum_{\gamma \in \Gamma} \theta(d(\gamma o, o)) e^{-sd(\gamma o, o)} \rho_n(\gamma)$$

*is bounded whenever  $s > h_{\rho_n}$  and unbounded whenever  $s < h_{\rho_n}$ .*

3. *The sequence  $\|A'_n(s_n)\|$  diverges as  $n$  approaches infinity.*

*Proof.* Recall that both  $(h_{\rho_n})$  and  $(s_n)$  converge to  $h_\omega$ . Hence we can find be a decreasing sequence  $(\varepsilon_n)$  of positive numbers converging to zero, such that  $s_n - \varepsilon_n < h_{\rho_n}$  for every  $n \in \mathbb{N}$ . We are going to build by induction an increasing sequence  $(t_n)$  diverging to infinity and a map  $\theta: \mathbb{R}_+ \rightarrow \mathbb{R}_+$  whose restriction to  $[t_n, t_{n+1}]$  is logarithmically affine with slope  $\varepsilon_n$ . We start by letting  $t_0 = 0$  and  $\theta(t_0) = 1$ . Let  $n \in \mathbb{N}$ . Assume now that  $t_n$  and  $\theta$  restricted to  $[t_0, t_n]$  have already be defined. By assumption, the series  $A_n(s)$  is divergent at  $s = s_n - \varepsilon_n$ . Consequently there exists  $t_{n+1} > t_n + 1$  such that

$$\left\| \sum_{\gamma \in S_n} e^{-(s_n - \varepsilon_n)d(\gamma o, o)} \rho_n(\gamma) \right\| \geq n, \quad (40)$$

where

$$S_n = \{\gamma \in \Gamma \mid t_n < d(\gamma o, o) \leq t_{n+1}\}.$$

We define  $\theta$  on  $[t_n, t_{n+1}]$  by  $\theta(t) = e^{\varepsilon_n(t-t_n)} \theta(t_n)$ . This complete the induction step. Points (1) and (2) are proved exactly as for regular Patterson-Sullivan measures. By construction,

$$\left\| \sum_{\gamma \in S_n} \theta(d(\gamma o, o)) e^{-s_n d(\gamma o, o)} \rho_n(\gamma) \right\| = \left\| \sum_{\gamma \in S_n} \theta(t_n) e^{-(s_n - \varepsilon_n)d(\gamma o, o)} \rho_n(\gamma) \right\|.$$

Consequently, (40) yields

$$\|A'_n(s_n)\| \geq \left\| \sum_{\gamma \in S_n} \theta(d(\gamma o, o)) e^{-s_n d(\gamma o, o)} \rho_n(\gamma) \right\| \geq n.$$

Hence the sequence  $\|A'_n(s_n)\|$  diverges as  $n$  approaches infinity, whence (3).  $\square$

**A limit of bounded operators.** We fix once for all a sequence  $(s_n)$  converging to  $h_\omega$  as well as a slowly increasing function  $h: \mathbb{R}_+ \rightarrow \mathbb{R}_+$  as in Lemma 5.8. Following the exposition of Section 5.2, let  $\mathcal{H}_\omega = \lim_\omega \mathcal{H}_n$  be the limit Hilbert space (Definition 5.4) and  $\rho_\omega = \lim_\omega \rho_n$  the limit representation (Proposition 5.5).

Let  $x \in X$ . For every  $n \in \mathbb{N}$ , we define a linear map

$$a_{x,n}^\rho: C(\bar{X}_h) \rightarrow \mathcal{B}(\mathcal{H}_n)$$

as follows. For every  $f \in C(\bar{X}_h)$ , define

$$a_{x,n}^\rho(f) = \frac{1}{\|A'_n(s_n)\|} \sum_{\gamma \in \Gamma} \theta(d(x, \gamma o)) e^{-s_n d(x, \gamma o)} f(\gamma o) \rho(\gamma). \quad (41)$$

By Lemma 5.8, there exists a parameter  $C(x)$  (which does not depend on  $n$ ) such that for every  $\gamma \in \Gamma$ ,

$$\theta(d(x, \gamma o)) \leq C(x) \theta(d(o, \gamma o)).$$

Let  $f \in C(\bar{X}_h)$ . Using the previous inequality, we observe that the series defining  $a_{x,n}^\rho(f)$  is bounded for every  $n \in \mathbb{N}$ . Moreover its norm is bounded above by

$$\|a_{x,n}^\rho(f)\| \leq C(x) e^{s_n d(x,o)} \|f\|_\infty. \quad (42)$$

We define a bounded operator of  $\mathcal{H}_\omega$  by

$$a_x^\rho(f) = \lim_\omega a_{x,n}^\rho(f).$$

This provides a positive continuous linear functional

$$a_x^\rho: C(\bar{X}_h) \rightarrow \mathcal{B}(\mathcal{H}_\omega). \quad (43)$$

**Remark.** This functional can be interpreted as an *operator-valued* measure on  $\bar{X}_h$ . Indeed by construction for every continuous function  $f \in C(\bar{X}_h)$  with  $f \geq 0$ , the associated operator  $a_x^\rho(f)$  is positive. It follows that  $a_x^\rho$  takes its values in the set  $\mathcal{L}_r(\mathcal{H}_\omega)$  of regular operators on  $\mathcal{H}_\omega$ , which is an order-complete vector lattice (Proposition B.2). By Wright [Wri71, Theorem 1], there exists a unique quasi-regular  $\mathcal{L}_r(\mathcal{H}_\omega)$ -valued Borel measure on  $\bar{X}_h$  such that for every  $f \in C(\bar{X}_h)$ , the operator  $a_x^\rho(f)$  equals the integral of  $f$  against this measure. We refer the reader to [Wri71] and the references therein for the theory of lattice-valued measures. We can hence see  $a_x^\rho$  as an operator-valued measure. However, it is simpler to express all the properties of this measure in terms of the functional  $a_x^\rho$ . Still, it justifies the following terminology.

**Definition 5.9.** We call the family  $(a_x^\rho)_{x \in X}$  the *twisted Patterson-Sullivan measure* associated to  $\Gamma$  and  $\rho = (\rho_n)_{n \in \mathbb{N}}$ .

The core of the proof of Theorem 5.2 consists in understanding the properties of this twisted Patterson-Sullivan measure. This new powerful definition and the study below are the main novelty of our paper. It has been inspired from

the weighted Patterson-Sullivan measures of the thermodynamical formalism on the one hand, see [BL98, Bab96, PPS15] but also several papers of Sambarino as [Sam14] or all his later works, and from weighted Ruelle operators on the other hand, as for example [Bow08] and particularly the twisted Ruelle operators used in [CDS17].

**First properties.** The following statement translates the well-known properties of usual Patterson-Sullivan measures in this context.

**Theorem 5.10.** *Let  $\Gamma$  be a discrete group acting properly by isometries on a Gromov-hyperbolic space  $X$ . With the previous notations, the family  $(a_x^\rho)_{x \in X}$  is  $\rho_\omega$ -equivariant,  $h_\omega$ -conformal, gives full support to  $\partial_h X$  and is normalized at  $o$ .*

The proof of this theorem, as well as its precise meaning, is detailed in Lemmas 5.11 to 5.14.

**Lemma 5.11** (Normalization). *The operator  $a_o^\rho(\mathbf{1})$  has norm 1.*

*Proof.* By construction, for every  $n \in \mathbb{N}$ , if  $f = \mathbf{1} \in C(\bar{X}_h)$ , the operator

$$a_{o,n}^\rho(\mathbf{1}) = \frac{1}{\|A'_n(s_n)\|} A'_n(s_n)$$

has norm 1. We get the result by passing to the limit.  $\square$

**Lemma 5.12** (Support). *Let  $x \in X$ . Let  $f \in C(\bar{X}_h)$ . If its support is contained in  $X$ , then  $a_x^\rho(f) = 0$ .*

*Proof.* As the support of  $f$  is a compact subset of  $X$ , there exists a finite subset  $S$  of  $\Gamma$  such that  $\text{Supp}(f) \cap \Gamma o \subset S o$ . Consequently, for every  $n \in \mathbb{N}$ , we have

$$a_{x,n}^\rho(f) = \frac{1}{\|A'_n(s_n)\|} \sum_{\gamma \in S} \theta(d(x, \gamma o)) e^{-s_n d(x, \gamma o)} f(\gamma o) \rho(\gamma).$$

This finite sum is uniformly bounded whereas  $\|A'_n(s_n)\|$  diverges to infinity (Lemma 5.8). Passing to the limit, we get  $a_x^\rho(f) = 0$ .  $\square$

**Lemma 5.13** ( $\rho_\omega$ -equivariance). *Let  $x \in X$  and  $\gamma \in \Gamma$ . For every  $f \in C(\bar{X}_h)$  we have*

$$a_{\gamma x}^\rho(f) = \rho_\omega(\gamma) a_x^\rho(f \circ \gamma).$$

*Proof.* Let  $f \in C(\bar{X}_h)$ . A direct computation shows that for every  $n \in \mathbb{N}$ , we have

$$a_{\gamma x,n}^\rho(f) = \rho_n(\gamma) a_{x,n}^\rho(f \circ \gamma).$$

The result follows by taking the  $\omega$ -limit.  $\square$

Let  $x, y \in X$ . Recall that a point in the horoboundary  $\partial_h X$  of  $X$  can be seen as a cocycle  $b$ . With this in mind, we define for  $s \in \mathbb{R}_+$ , a map  $\chi_{x,y}^s \in C(\bar{X}_h)$ . If  $z \in X$ , then

$$\chi_{x,y}^s(z) = \frac{\theta(d(x, z))}{\theta(d(y, z))} e^{-s[d(x, z) - d(y, z)]}$$

If  $b \in \partial_h X$ , then

$$\chi_{x,y}^s(b) = e^{-sb(x,y)}.$$

The sequence  $(\chi_{x,y}^{s_n})$  uniformly converges to  $\chi_{x,y}^{h_\omega}$ .

**Lemma 5.14** ( $h_\omega$ -conformality). *Let  $x, y \in X$ . For every  $f \in C(\bar{X}_h)$ , we have*

$$a_x^\rho(f) = a_y^\rho(\chi_{x,y}^{h_\omega} f).$$

*Proof.* A standard computation shows that for every  $n \in \mathbb{N}$ ,

$$a_{x,n}^\rho(f) = a_{y,n}^\rho(\chi_{x,y}^{s_n} f).$$

Consequently

$$a_x^\rho f = \lim_\omega a_{y,n}^\rho(\chi_{x,y}^{s_n} f).$$

On the other hand, by the very definition of  $a_y^\rho$  we have

$$a_y^\rho(\chi_{x,y}^{h_\omega} f) = \lim_\omega a_{y,n}^\rho(\chi_{x,y}^{h_\omega} f).$$

Hence it suffices to prove that

$$\lim_\omega a_{y,n}^\rho([\chi_{x,y}^{h_\omega} - \chi_{x,y}^{s_n}] f) = 0.$$

The norm of  $a_{y,n}^\rho$ , as a linear map from  $C(\bar{X}_h)$  to  $\mathcal{B}(\mathcal{H}_n)$ , is uniformly bounded – see (42). In particular, there exists  $M \in \mathbb{R}_+$  such that for every  $n \in \mathbb{N}$ ,

$$\|a_{y,n}^\rho([\chi_{x,y}^{h_\omega} - \chi_{x,y}^{s_n}] f)\| \leq M \|[\chi_{x,y}^{h_\omega} - \chi_{x,y}^{s_n}] f\|_\infty.$$

The result follows from the fact that  $(\chi_{x,y}^{s_n})$  uniformly converges to  $\chi_{x,y}^{h_\omega}$ .  $\square$

As a corollary of the above lemmas, we get the following useful formula, for every  $\gamma \in \Gamma$  and  $f \in C(\bar{X}_h)$ :

$$a_{\gamma o}^\rho(f) = \rho_\omega(\gamma) a_o^\rho(f \circ \gamma) = a_o^\rho(\chi_{\gamma o, o}^{h_\omega} f). \quad (44)$$

## 5.4 Twisted measure on the Gromov boundary

We study now how the family  $(a_x^\rho)$  – thought as a family of measures on  $\partial_h X$  – behaves compared to usual Patterson-Sullivan measures  $\nu_x$ . From a dynamical point of view, it is more appropriate to work in the Gromov boundary  $\partial X$  rather than in the horoboundary  $\partial_h X$ . Therefore, we push forward the family  $(a_x^\rho)$  by the natural  $\Gamma$ -equivariant continuous map  $\pi: \bar{X}_h \rightarrow \bar{X}$ . For every  $x \in X$ , we set

$$\begin{aligned} \pi_* a_x^\rho: C(\bar{X}) &\rightarrow \mathcal{B}(\mathcal{H}_\omega) \\ f &\mapsto a_x^\rho(f \circ \pi). \end{aligned}$$

It follows from the previous study that  $\pi_* a_o^\rho(\mathbf{1})$  has norm 1 (Lemma 5.11) and the support of  $\pi_* a_x^\rho$  is contained in  $\partial X$  for every  $x \in X$  (Lemma 5.12). Since  $\pi: \bar{X}_h \rightarrow \bar{X}$  is  $\Gamma$ -equivariant, the family  $(\pi_* a_x^\rho)$  is  $\rho_\omega$ -equivariant (Lemma 5.13). Let us now focus on the conformality of  $\pi_* a_x^\rho$  which is slightly more technical.

**Lemma 5.15** ( $h_\omega$ -quasi-conformality). *There exists  $C \in \mathbb{R}_+^*$  with the following property. Let  $x, y \in X$  and  $\xi \in \partial X$ . There is a neighbourhood  $V_\xi \subset \bar{X}$  of  $\xi$  such that for every cocycle  $b \in \pi^{-1}(\xi)$ , for every  $f \in C(\bar{X})$  whose support is contained in  $V$  we have*

$$\frac{1}{C} \pi_* a_x^\rho(f) \prec e^{-h_\omega b(x,y)} a_y^\rho(f) \prec C a_x^\rho(f).$$

*Proof.* Let  $x, y \in X$ . Let  $\xi \in \partial X$ . Using the hyperbolicity of  $X$ , we observe that there exists a neighbourhood  $V_\xi \subset \bar{X}$  such that for every  $b \in \pi^{-1}(\xi)$  the following holds: if  $z$  is a point in  $V_\xi \cap X$  then

$$|[d(z, x) - d(z, y)] - b(x, y)| \leq 100\delta;$$

moreover if  $b'$  is a cocycle in  $\pi^{-1}(V_\xi) \cap \partial_h X$ , then  $|b'(x, y) - b(x, y)| \leq 100\delta$ . We now fix  $b \in \pi^{-1}(\xi)$  and  $f \in C(\bar{X})$  whose support is contained in  $V_\xi$ . Let  $\varepsilon > 0$ . Since  $\theta$  is a slowly increasing function, there exists  $t_0 \in \mathbb{R}_+$  such that for every  $t \geq t_0$  and  $u \geq 0$ , we have  $\theta(t+u) \leq e^{\varepsilon u} \theta(t)$ . We fix a map  $g: \bar{X} \rightarrow [0, 1]$  whose support is contained in  $X$  and whose restriction to  $B(x, t_0)$  and  $B(y, t_0)$  is constant equal to 1. It follows from [Lemma 5.12](#) that both  $\pi_* a_x^\rho(gf)$  and  $\pi_* a_y^\rho(gf)$  vanish. Consequently it suffices to compare  $\pi_* a_x^\rho(f')$  and  $\pi_* a_y^\rho(f')$  where  $f' = (1-g)f$ . Using the conformality of  $(a_x^\rho)$  we get

$$\pi_* a_x^\rho(f') = a_x^\rho(f' \circ \pi) = a_y^\rho(\chi_{x,y}^{h_\omega} f' \circ \pi). \quad (45)$$

It follows from our choice of  $t_0$  and  $V_\xi$  that for every  $z \in \bar{X}_h$  lying in the support of  $f'$  we have

$$\frac{1}{C(\varepsilon)} e^{-h_\omega b(x,y)} \leq \chi_{x,y}^{h_\omega}(z) \leq C(\varepsilon) e^{-h_\omega b(x,y)},$$

where  $C(\varepsilon) = e^{100h_\omega \delta} e^{\varepsilon d(x,y)}$ . Since  $a_y^\rho$  is a positive linear functional, [\(45\)](#) becomes

$$\frac{1}{C(\varepsilon)} e^{-h_\omega b(x,y)} \pi_* a_x^\rho(f') \prec e^{-h_\omega b(x,y)} a_y^\rho(f' \circ \pi) \prec C(\varepsilon) \pi_* a_x^\rho(f'),$$

hence

$$\frac{1}{C(\varepsilon)} e^{-h_\omega b(x,y)} \pi_* a_x^\rho(f) \prec e^{-h_\omega b(x,y)} \pi_* a_y^\rho(f \circ \pi) \prec C(\varepsilon) \pi_* a_x^\rho(f).$$

This inequality holds for every  $\varepsilon \in \mathbb{R}_+^*$ , consequently

$$\frac{1}{C} \pi_* a_x^\rho(f) \prec e^{-h_\omega b(x,y)} \pi_* a_y^\rho(f \circ \pi) \prec C \pi_* a_x^\rho(f),$$

where  $C = e^{100\delta h_\omega}$  is a universal parameter.  $\square$

**Remark.** Note that if  $h_\omega < h_\Gamma$ , then the operator valued measures  $(\pi_* a_x^\rho)$  cannot have bounded variation – see [[DUJ77](#), Chapter 1] for a definition. Indeed otherwise their variations would be a  $\Gamma$ -invariant,  $h_\omega$ -quasi-conformal family of measures on  $\partial X$ . Such measures do not exist unless  $h_\omega \geq h_\Gamma$  [[Coo93](#), Corollaire 6.6]. Later we will use a Radon-Nikodym derivative theorem for  $\pi_* a_o^\rho$ . This observation somehow tells us that all the theory exposed in [[DUJ77](#)] does not apply here unless  $h_\omega = h_\Gamma$ .

### Shadow lemma.

**Lemma 5.16** (Half shadow lemma). *For every  $r \in \mathbb{R}_+$ , there exists  $C \in \mathbb{R}_+$ , with the following property. Let  $\gamma \in \Gamma$  and  $f \in C^+(\bar{X})$ . If the support of  $f$  is contained in  $\mathcal{O}_o(\gamma o, r)$ , then*

$$\|\pi_* a_o^\rho(f)\| \leq C e^{-h_\omega d(o, \gamma o)} \|f\|_\infty.$$

*Proof.* Combining Lemmas 5.13 and 5.14 we observe that

$$\rho_\omega(\gamma^{-1})\pi_*a_o^\rho(f) = a_{\gamma^{-1}o}^\rho(f \circ \pi \circ \gamma) = a_o^\rho\left(\chi_{\gamma^{-1}o,o}^{h_\omega}f \circ \pi \circ \gamma\right).$$

For simplicity we set

$$f_\gamma = \chi_{\gamma^{-1}o,o}^{h_\omega}f \circ \pi \circ \gamma.$$

Let  $\varepsilon > 0$ . By Lemma 5.8, there exists  $t_0 \in \mathbb{R}_+$  such that for  $t \geq t_0$  and  $u \geq 0$ ,

$$\theta(t+u) \leq e^{\varepsilon u}\theta(t).$$

We fix a continuous map  $g: X \rightarrow [0, 1]$ , with compact support whose restriction to  $B(o, t_0)$  is constant equal to 1. It allows to decompose  $f_\gamma$  as  $f_\gamma = gf_\gamma + (1-g)f_\gamma$ . Since the support of  $gf_\gamma$  is contained in  $X$  we have  $a_o^\rho(gf_\gamma) = 0$  (Lemma 5.12). Consequently

$$\rho_\omega(\gamma^{-1})a_o^\rho(f) = a_o^\rho((1-g)f_\gamma).$$

Let us now consider a point  $z \in \bar{X}_h$  in the support of  $(1-g)f_\gamma$ . By construction  $z$  belongs to  $\pi^{-1}(\mathcal{O}_{\gamma^{-1}o}(o, r)) \setminus B(o, t_0)$ . If  $z = b \in \partial_h X$  is a cocycle, then

$$b(\gamma^{-1}o, o) \geq d(o, \gamma o) - 2r.$$

On the other hand, if  $z \in X$ , then

$$d(\gamma^{-1}o, z) - d(o, z) \geq d(o, \gamma o) - 2r.$$

In addition  $d(o, \gamma o) \geq t_0$ , thus according to our choice of  $t_0$ ,

$$\theta(d(\gamma^{-1}o, z)) \leq \theta(d(o, \gamma o) + d(o, z)) \leq e^{\varepsilon d(o, \gamma o)}\theta(d(o, z)).$$

In both cases, we get

$$\chi_{\gamma^{-1}o,o}^{h_\omega}(z) \leq e^{2h_\omega r}e^{-(h_\omega - \varepsilon)d(o, \gamma o)}.$$

Hence

$$0 \leq (1-g)f_\gamma \leq e^{2h_\omega r}e^{-(h_\omega - \varepsilon)d(o, \gamma o)} \|f\|_\infty \mathbf{1}.$$

Since  $a_o^\rho$  is a positive functional, we get

$$\rho_\omega(\gamma^{-1})\pi_*a_o^\rho(f) \prec e^{2h_\omega r}e^{-(h_\omega - \varepsilon)d(o, \gamma o)} \|f\|_\infty a_o^\rho(\mathbf{1}).$$

Recall that  $\rho_\omega$  is a unitary representation. Taking the norm, we get

$$\|\pi_*a_o^\rho(f)\| \leq Ce^{-(h_\omega - \varepsilon)d(o, \gamma o)},$$

where  $C = e^{2h_\omega r}\|a_o^\rho(\mathbf{1})\|$ . As it holds for all  $\varepsilon > 0$ , the result follows.  $\square$

## 5.5 Absolute continuity

**Radial limit set.** Let  $K$  be a compact subset of  $X$ . Recall that the  $K$ -radial limit set  $\Lambda_{\text{rad}}^K$  is the set of all points  $\xi \in \partial X$  for which there exists a geodesic ray  $c: \mathbb{R}_+ \rightarrow X$  ending at  $\xi$  whose image  $c(\mathbb{R}_+)$  intersects infinitely many copies  $\gamma K$  of  $K$ . As explained before, we think of  $\pi_*a_o^\rho$  as an operator valued measure on  $\bar{X}$ . The next step consists in proving that this “measure” gives full mass to

$\Lambda_{\text{rad}}^K$  for some compact  $K$  (Corollary 5.18). This is probably the *most crucial* point in the proof. Indeed, Shadow Lemmas Lemma 2.3 and Lemma 5.16 tell us that when  $h_\omega = h_\Gamma$ , the measures  $\pi_* a_o^\rho$  and  $\nu_o$  can be compared on shadows. As both measures give full measure to  $\Lambda_{\text{rad}}^K$  for closed ball  $K = \bar{B}(o, r)$  with fixed  $r > 0$ , a Vitali type argument, approximating any Borel set by a union of shadows, allows to deduce that  $\pi_* a_o^\rho$  is absolutely continuous with respect to  $\nu_o$  (Proposition 5.21). Corollary 5.18 is the only place where we use in an essential way the fact that the action of  $\Gamma$  on  $X$  is strongly positively recurrent. All other arguments in the article work under a weaker assumption (e.g. if the geodesic flow is conservative).

The proof of the next statements follows exactly the same steps as the one of Corollary 3.16. It relies on the same auxiliary sets  $\mathcal{L}_K$  and  $U_K^T$  defined in Section 3.3. However since it is the only place where we use (in a crucial way!) the existence of a growth gap at infinity to get our main theorem, we decided to detail it here.

**Proposition 5.17.** *Assume that  $h_\Gamma^\infty < h_\omega$ . There exists a compact subset  $K$  of  $X$  and numbers  $\alpha, C, T_0 \in \mathbb{R}_+^*$  such that for every  $T \geq T_0$ , for every  $f \in C^+(\bar{X})$  whose support is contained in  $U_K^T$ , we have*

$$\|\pi_* a_o^\rho(f)\| \leq C e^{-\alpha T} \|f\|_\infty.$$

*Proof.* By assumption, there exists a compact subset  $k$  of  $X$  containing  $o$  such that  $h_{\Gamma_k} < h_\omega$ . Let  $K$  be the  $7\delta$ -neighbourhood of  $k$ . By Lemma 3.14, there exists a finite subset  $S$  of  $\Gamma$  and a number  $r \in \mathbb{R}_+$  such that for every  $T \in \mathbb{R}_+$ ,

$$U_K^T \cap \Gamma o \subset \bigcup_{\substack{\beta \in S\Gamma_k \\ d(o, \beta o) \geq T-r}} \mathcal{O}_o(\beta o, r). \quad (46)$$

We fix  $\varepsilon > 0$  such that  $h_\omega - 2\varepsilon > h_{\Gamma_k}$ . Define  $F$  as

$$F = \{\gamma \in \Gamma \mid d(o, \gamma o) \leq t_0\}.$$

Let  $T \geq t_0 + r$ , and  $f \in C^+(\bar{X}_h)$  be a non-negative function whose support is contained  $U_K^T$ . Up to rescaling  $f$ , we assume  $\|f\|_\infty = 1$ . Let  $n \in \mathbb{N}$ . By (46),

$$a_{o,n}^\rho(f) \prec \frac{1}{\|A_n'(s_n)\|} \sum_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T-r}} \sum_{\gamma \in \Gamma} \theta(d(o, \gamma o)) e^{-s_n d(o, \gamma o)} \rho_n(\gamma) \quad (47)$$

Let  $\beta \in S\Gamma_k$  such that  $d(o, \beta o) \geq T - r$ . As in the proof of Proposition 3.15, when  $y \in \mathcal{O}_o(\beta o, r)$ ,

- if  $d(\beta o, y) \geq t_0$ , then  $\theta_0(d(o, y)) \leq e^{\varepsilon d(o, \beta o)} \theta_0(d(\beta o, y))$ , whereas
- if  $d(o, \beta o) \geq t_0$ , then  $\theta_0(d(o, y)) \leq e^{\varepsilon d(o, \beta o)} \theta(t_0)$ .

Consequently,

$$a_{o,n}^\rho(f) \prec \frac{1}{\|A_n'(s_n)\|} \sum_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T-r}} e^{2sr} e^{-(s_n - \varepsilon)d(o, \beta o)} (\Sigma_1 + \Sigma_2),$$



where

$$\begin{aligned}\Sigma_1 &= \sum_{\substack{\gamma \in \Gamma \\ \gamma o \in \mathcal{O}_o(\beta o, r), d(\beta o, \gamma o) < t_0}} \theta(t_0) e^{-s_n d(\beta o, \gamma o)} \rho_n(\gamma), \\ \Sigma_2 &= \sum_{\substack{\gamma \in \Gamma \\ \gamma o \in \mathcal{O}_o(\beta o, r), d(\beta o, \gamma o) \geq t_0}} \theta(d(\beta o, \gamma o)) e^{-s_n d(\beta o, \gamma o)} \rho_n(\gamma).\end{aligned}$$

The number of terms in  $\Sigma_1$  is at most  $|F|$ , so that  $\|\Sigma_1\| \leq |F| \theta(t_0)$ , whereas  $\|\Sigma_2\|$  is bounded above by  $\|A'_n(s_n)\|$ . Combining all these inequalities we get

$$\|a_{o,n}^\rho(f)\| \leq e^{2s_n r} \left(1 + \frac{|F| \theta(t_0)}{\|A'_n(s_n)\|}\right) \sum_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T-r}} e^{-(s_n - \varepsilon) d(o, \beta o)}.$$

After passing to the limit, it becomes

$$\|\pi_* a_o^\rho(f)\| \leq e^{2h_\Gamma r} \sum_{\substack{\beta \in S\Gamma_k, \\ d(o, \beta o) \geq T-r}} e^{-(h_\omega - \varepsilon) d(o, \beta o)}.$$

Since  $h_\omega - 2\varepsilon > h_{\Gamma_k}$ , we obtain as in (15)

$$\|\pi_* a_o^\rho(f)\| \leq B e^{2h_\omega r} e^{-(h_\omega - h_{\Gamma_k} - 2\varepsilon)T}.$$

Recall that  $B, k, r$  and  $\varepsilon$  do not depend on  $T$  or  $f$ , whence the result.  $\square$

**Corollary 5.18.** *Assume that  $h_\Gamma^\infty < h_\omega$ . There exists a compact subset  $K$  of  $X$  such that for every  $\varepsilon > 0$ , there is a open subset  $V \subset \bar{X}$  containing  $\partial X \setminus \Lambda_{\text{rad}}^K$  with the following property. For every  $f \in C^+(\bar{X})$  whose support is contained in  $V$  we have*

$$\|\pi_* a_o^\rho(f)\| \leq \varepsilon \|f\|_\infty.$$

*Proof.* According to Proposition 5.17 there exists a compact subset  $K$  of  $X$  as well as numbers  $C, \alpha, T_0 \in \mathbb{R}_+^*$  such that for every  $T \geq T_0$ , for every  $f \in C^+(\bar{X})$  whose support of  $\bar{X}$  contained in  $U_K^T$ ,

$$\|\pi_* a_o^\rho(f)\| \leq C e^{-\alpha T} \|f\|_\infty.$$

We fix a summable function  $w: \Gamma \rightarrow \mathbb{R}_+^*$  whose sum is 1. Let  $\varepsilon > 0$ . For every  $\gamma \in \Gamma$ , we fix  $T_\gamma \geq T_0$  such that

$$C e^{-\alpha T_\gamma} \leq \varepsilon w(\gamma)$$

and an open subset  $V_\gamma$  of  $\bar{X}$  such that

$$\mathcal{L}_K \subset V_\gamma \subset U_k^{T_\gamma}.$$

According to Lemma 3.12, the set  $\partial X \setminus \Lambda_{\text{rad}}^K$  is contained in  $\Gamma \mathcal{L}_K$ . Hence the set

$$V = \bigcup_{\gamma \in \Gamma} V_\gamma$$

is an open neighbourhood of  $\partial X \setminus \Lambda_{\text{rad}}^K$ . Let  $f \in C^+(\bar{X})$  whose support is contained in  $V$ . Without loss of generality we can assume that  $\|f\|_\infty = 1$ . As this support is compact, it is actually contained in

$$\bigcup_{\gamma \in S} V_\gamma,$$

where  $S$  is a finite subset of  $\Gamma$ . We fix a partition of unity, i.e. a family  $(g_\gamma)_{\gamma \in S}$  of elements of  $C^+(\bar{X})$  such that the support of  $g_\gamma$  is contained in  $V_\gamma$ , for every  $\gamma \in S$  and

$$\sum_{\gamma \in S} g_\gamma$$

is constant equal to 1, when restricted to the support of  $f$ . Combining [Proposition 5.17](#) with our choice of  $T_\gamma$ , we get

$$\|\pi_* a_o^p(f)\| \leq \sum_{\gamma \in S} \|\pi_* a_o^p(f g_\gamma)\| \leq \sum_{\gamma \in S} C e^{-\alpha T_\gamma} \leq \varepsilon \sum_{\gamma \in \Gamma} w(\gamma) \leq \varepsilon. \quad \square$$

**A Vitali type argument.** We now exploit the previous result to prove that whenever  $h_\omega = h_\Gamma$  the “measure”  $\pi_* a_o^p$  is absolutely continuous with respect to the usual Patterson-Sullivan measure  $\nu_o$ . The first lemma is an easy exercise of hyperbolic geometry. Its proof is left to the reader.

**Lemma 5.19.** *There exists  $r_1 \in \mathbb{R}_+^*$  with the following property. Let  $r \geq r_1$ . Let  $x, y \in X$  such that  $d(o, x) \leq d(o, y)$ . If  $\mathcal{O}_o(x, r)$  and  $\mathcal{O}_o(y, r)$  have a non-empty intersection, then  $\mathcal{O}_o(y, r)$  is contained in  $\mathcal{O}_o(x, 4r)$ .*

The second lemma is a Vitali like Lemma.

**Lemma 5.20 (Vitali’s Lemma).** *Let  $K$  be a compact subset of  $X$ . There exists  $r_1 \in \mathbb{R}_+^*$  such that for every  $r \geq r_1$ , for every  $R \in \mathbb{R}_+$ , there exists a subset  $S$  of  $\Gamma$  with the following properties.*

1. For all  $\alpha \in S$ ,  $d(o, \alpha o) \geq R$ .
2. The union  $\bigcup_{\alpha \in S} \mathcal{O}_o(\alpha o, 4r)$  covers  $\Lambda_{\text{rad}}^K$ .
3. The shadows  $(\mathcal{O}_o(\alpha o, r))_{\alpha \in S}$  are pairwise disjoint.

*Proof.* Let  $r_1$  be the parameter given by [Lemma 5.19](#). Without loss of generality, we can assume that  $r_1 \geq \text{diam}(K \cup \{o\})$ . Let  $r \geq r_1$  and  $R \in \mathbb{R}_+$ . For simplicity we set

$$U_R = \{\gamma \in \Gamma \mid d(o, \gamma o) \geq R\}.$$

We build the set  $S$  by induction, adding one element at each step. We start with  $S_0 = \emptyset$ . For every  $n \in \mathbb{N}$ , we define the set  $S_{n+1}$  by adding to  $S_n$  the element  $\gamma \in U_R \setminus S_n$  such that  $\mathcal{O}_o(\gamma o, r)$  is disjoint from all the previous shadows  $(\mathcal{O}_o(\alpha o, r))_{\alpha \in S_n}$  and which minimizes  $d(o, \gamma o)$ . Standard elementary arguments using [Lemma 5.19](#) show that the increasing union of all  $S_n$  satisfies the above statement.  $\square$

**Proposition 5.21.** *Assume that  $h_\omega = h_\Gamma$ . There exists  $C \in \mathbb{R}_+^*$  such that for every  $f \in C(\bar{X})$ ,*

$$\|\pi_* a_o^p(f)\| \leq C \int_{\partial X} |f| d\nu_o.$$

As already mentioned, this proposition is a direct consequence of Shadow lemmas. Indeed, the key [Corollary 5.18](#) allows to approximate every Borel set by unions of shadows of fixed radius, through a Vitali type argument.

*Proof.* Let  $K$  be the compact subset of  $\bar{X}$  given by [Corollary 5.18](#). Fix  $r \geq \max\{r_0, r_1\}$  where  $r_0$  and  $r_1$  are respectively given by [Lemmas 2.3](#) and [5.19](#). By [Shadow Lemmas 2.3](#) and [5.16](#), there exists  $C_0 \in \mathbb{R}_+^*$  such that for every  $\gamma \in \Gamma$ ,

- $\nu_o(\mathcal{O}_o(\gamma o, r)) \geq \frac{1}{C_0} e^{-h_\Gamma d(o, \gamma o)}$
- for every  $f \in C^+(\bar{X})$  whose support is contained in  $\mathcal{O}_o(\gamma o, 4r)$  we have

$$\|\pi_* a_o^\rho(f)\| \leq C_0 e^{-h_\omega d(o, \gamma o)} \|f\|_\infty.$$

Let  $f \in C(\bar{X})$ . We first assume that  $f$  is non-negative. Let  $\varepsilon > 0$ . We fix some auxiliary subsets of  $X$  to decompose the map  $f$  into a sum of functions supported on appropriate small shadows. Since the action of  $\Gamma$  is strongly positively recurrent,  $h_\Gamma^\infty < h_\Gamma = h_\omega$ . According to [Corollary 5.18](#) there exists an open set  $V$  containing  $\partial X \setminus \Lambda_{\text{rad}}^K$  such that for every  $g \in C(\bar{X})$  whose support is contained in  $V$ , we have

$$\|\pi_* a_o^\rho(g)\| \leq \varepsilon \|g\|_\infty.$$

Since  $f$  is continuous, for all  $\varepsilon > 0$ , there exists  $R > 0$  such that on any shadow  $\mathcal{O}_o(y, 4r)$ , with  $d(o, y) \geq R$ , the variations of  $f$  are bounded by  $\varepsilon$ . Let  $S$  be the collection of elements of  $\Gamma$  given by Vitali's [Lemma 5.20](#). Since  $f$  is continuous, there exists a finite subset  $S_0$  of  $S$  such that the support of  $f$  is contained in

$$\left( \bigcup_{\gamma \in S_0} \mathcal{O}_o(\gamma o, 2r) \right) \cup V.$$

We now fix a partition of unity, i.e. a collection  $\{g\} \cup \{g_\gamma\}_{\gamma \in S_0}$  of continuous functions from  $\bar{X}$  to  $[0, 1]$  such that the support of  $g_\gamma$  (respectively  $g$ ) is contained in  $\mathcal{O}_o(\gamma o, 4r)$  (respectively  $V$ ) and

$$g + \sum_{\gamma \in S_0} g_\gamma$$

is constant equal to 1 when restricted to the support of  $f$ . We now first estimate  $\|\pi_* a_o^\rho(f)\|$  from above. The triangle inequality yields

$$\|\pi_* a_o^\rho(f)\| \leq \|\pi_* a_o^\rho(gf)\| + \sum_{\gamma \in S_0} \|\pi_* a_o^\rho(g_\gamma f)\|.$$

By [Corollary 5.18](#),  $\|\pi_* a_o^\rho(gf)\| \leq \varepsilon \|f\|_\infty$ . For every  $\gamma \in S_0$  we let

$$f_\gamma = \sup_{x \in \mathcal{O}_o(\gamma o, 2r)} f(x).$$

so that  $\|g_\gamma f\|_\infty \leq f_\gamma$ . It follows from the Half-Shadow [Lemma 5.16](#) that

$$\sum_{\gamma \in S_0} \|\pi_* a_o^\rho(g_\gamma f)\| \leq C_0 \sum_{\gamma \in S_0} e^{-h_\omega d(o, \gamma o)} f_\gamma.$$

Consequently

$$\|\pi_* a_o^\rho(f)\| \leq \varepsilon \|f\|_\infty + C_0 \sum_{\gamma \in S_0} e^{-h_\omega d(o, \gamma o)} f_\gamma. \quad (48)$$

Let us now estimate  $\nu_o(f)$  from below. Let  $\gamma \in S_0$ . Since  $d(\gamma o, o) \geq R$ , the map  $f$  restricted to  $\mathcal{O}_o(\gamma o, 4r)$  varies by at most  $\varepsilon$ . On the other hand the shadows  $(\mathcal{O}_o(\gamma o, r))_{\gamma \in S}$  are pairwise disjoint. We get from the standard Shadow Lemma

$$\begin{aligned} \int f d\nu_o &\geq \sum_{\gamma \in S_0} \int_{\mathcal{O}_o(\gamma o, r)} f d\nu_o \geq \sum_{\gamma \in S_0} (f_\gamma - \varepsilon) \nu_o(\mathcal{O}_o(\gamma o, r)) \\ &\geq \frac{1}{C_0} \sum_{\gamma \in S_0} f_\gamma e^{-h_\Gamma d(o, \gamma o)} - \varepsilon. \end{aligned} \quad (49)$$

Recall that  $h_\omega = h_\Gamma$ . Hence combining (48) and (49) yields

$$\|\pi_* a_o^\rho(f)\| \leq \varepsilon \|f\|_\infty + C_0^2 \left( \int f d\nu_o + \varepsilon \right).$$

This inequality holds for every  $\varepsilon > 0$ , hence

$$\|\pi_* a_o^\rho(f)\| \leq C_0^2 \int f d\nu_o.$$

If  $f$  is not nonnegative anymore, decomposing  $f$  into its positive and negative part leads immediately to the result.  $\square$

**Corollary 5.22.** *Assume that  $h_\omega = h_\Gamma$ . There exists a unique continuous linear map  $D: \mathcal{H}_\omega \rightarrow L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$  such that for every  $\phi \in \mathcal{H}_\omega$ , for every  $f \in C(\bar{X})$ , we have*

$$\pi_* a_o^\rho(f)\phi = \int f D(\phi) d\nu_o.$$

**Remark.** The integral in the statement is an integral in the sense of Bochner (Section A.1). The map  $D$  can be thought as a kind of Radon-Nikodym derivative of  $\pi_* a_o^\rho$  with respect to  $\nu_o$ .

*Proof.* Let  $C$  be the constant given by Proposition 5.21. Let  $\phi \in \Phi$ . It follows from Proposition 5.21 that for every  $f \in C(\bar{X})$  we have

$$\|\pi_* a_o^\rho(f)\phi\| \leq C \int |f| d\nu_o \|\phi\|.$$

Thus the map sending  $f \in C(\bar{X})$  to  $\pi_* a_o^\rho(f)\phi$  extends to a continuous map  $L^1(\partial X, \nu_o) \rightarrow \mathcal{H}_\omega$ , whose norm is at most  $C\|\phi\|$ . As a Hilbert space,  $\mathcal{H}_\omega$  is reflexive, hence satisfies the Radon-Nikodym property (Theorem A.4). Consequently there exists a vector  $D(\phi) \in L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$ , whose norm is at most  $C\|\phi\|$  such that for every  $f \in C(\bar{X})$  we have

$$\pi_* a_o^\rho(f)\phi = \int f D(\phi) d\nu_o.$$

This construction defines a map  $D: \mathcal{H}_\omega \rightarrow L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$ . Uniqueness and linearity of  $D$  follow from Proposition A.1. By construction,  $\|D(\phi)\|_\infty \leq C\|\phi\|$ , for every  $\phi \in \mathcal{H}_\omega$ . Hence  $D$  is continuous.  $\square$

## 5.6 Invariant vectors

From now on we assume that  $h_\omega = h_\Gamma$ . The goal is now to study the map  $D: \mathcal{H}_\omega \rightarrow L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$  given by [Corollary 5.22](#).

Heuristically the idea is the following. Using the ergodicity of the action of  $\Gamma$  on  $(\partial^2 X, \mu)$  we are going to prove that  $D(\phi)$  is almost surely constant, so that viewed as a measure with values in  $\mathcal{B}(\mathcal{H}_\omega)$ , the twisted Patterson-Sullivan measure  $\pi_* a_o^\rho$  satisfies

$$\pi_* a_o^\rho(f)\phi = D(\phi) \int f d\nu_o, \quad \forall f \in C(\bar{X}).$$

Comparing the invariance of  $\nu_o$  and  $\pi_* a_o^\rho$ , we will observe that  $D(\phi)$  is a  $\rho_\omega$ -invariant vector, that is a limit of  $\rho_n$  almost-invariant vectors. Below is a rigorous exposition of this strategy.

Fix  $\phi \in \mathcal{H}_\omega^+$ . For simplicity, set  $\Psi = D(\phi)$ . Recall that  $\Psi$  is a bounded map from  $\bar{X}$  to  $\mathcal{H}_\omega$ . Actually it directly follow from [Lemma 5.12](#) that the support of  $\Psi$  is contained in  $\partial X$ . Since  $\phi$  is positive,  $\Psi$  takes its values in  $\mathcal{H}_\omega^+$  ([Lemma B.8](#)).

**Lemma 5.23.** *There exists  $C \in \mathbb{R}_+^*$ , which does not depend on  $\phi$ , such that for every  $\gamma \in \Gamma$ , we have*

$$\frac{1}{C}\Psi \prec \rho_\omega(\gamma)\Psi \circ \gamma^{-1} \prec C\Psi.$$

**Remark.** Comparing pointwise two functions defines an order which endows  $L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$  with a lattice structure ([Lemma B.6](#)). The inequalities in the lemma are meant in  $L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$ .

*Proof.* We first fix a measurable section of  $\pi$

$$\begin{aligned} \sigma: \quad \partial X &\rightarrow \partial_h X \\ \xi &\mapsto b_\xi. \end{aligned}$$

Since  $(\nu_x)$  is  $h_\Gamma$ -quasi-conformal, there exists  $C_0 \in \mathbb{R}_+^*$  such that for every  $\gamma \in \Gamma$ , for  $\nu_o$ -almost every  $\xi \in \partial X$ , we have

$$\frac{1}{C_0} e^{-h_\Gamma b_\xi(\gamma o, o)} \leq \frac{d\gamma_* \nu_o}{d\nu_o}(\xi) \leq C_0 e^{-h_\Gamma b_\xi(\gamma o, o)} \quad (50)$$

We denote by  $C_1 \in \mathbb{R}_+^*$  the universal constant given by the  $h_\omega$ -quasi-conformality of  $(\pi_* a_x^\rho)$  ([Lemma 5.15](#)). Let  $\gamma \in \Gamma$ . We are going to work with the points  $x = \gamma o$  and  $y = o$ . For every  $\xi \in \partial X$ , we write  $V_\xi$  for the neighbourhood of  $\xi$  given by [Lemma 5.15](#). Up to decreasing  $V_\xi$  we can always assume that for any  $b, b' \in \pi^{-1}(V_\xi) \cap \partial_h X$ ,

$$|b(x, y) - b'(x, y)| \leq 100\delta.$$

Let  $f \in C(\bar{X})$ . Since the support of  $f$  is compact, there exists a finite subset  $S$  of  $\partial X$  such that this support is contained in

$$\left( \bigcup_{\xi \in S} V_\xi \right) \cup X.$$

We now fix a partition of unity, i.e. a collection of maps  $g: \bar{X} \rightarrow [0, 1]$  and  $g_\xi: \bar{X} \rightarrow [0, 1]$  (one for each  $\xi \in S$ ) such that the support of  $g$  (respectively  $g_\xi$ ) is contained in  $X$  (respectively  $V_\xi$ ) and the sum

$$g + \sum_{\eta \in S} g_\eta$$

equals 1 when restricted to the support of  $f$ . Since the support of  $gf$  is contained in  $X$ , we have  $\pi_* a_{\gamma o}^\rho(gf) = 0$ . Hence the  $\rho_\omega$ -equivariance (Lemma 5.13) of  $(\pi_* a_x^\rho)$  yields

$$\rho_\omega(\gamma) \int (f \circ \gamma) \Psi d\nu_o = \rho_\omega(\gamma) \pi_* a_o^\rho(f \circ \gamma) \phi = \pi_* a_{\gamma o}^\rho(f) \phi = \sum_{\eta \in S} \pi_* a_{\gamma o}^\rho(g_\eta f) \phi$$

Combined with the  $h_\omega$ -quasi-conformality (Lemma 5.15) of  $(\pi_* a_x^\rho)$ , we get

$$\rho_\omega(\gamma) \int (f \circ \gamma) \Psi d\nu_o \prec C_1 \sum_{\eta \in S} e^{-h_\omega b_\eta(\gamma o, o)} a_o^\rho(g_\eta f) \phi.$$

This inequality can be written using the definition  $\Psi$  as

$$\rho_\omega(\gamma) \int (f \circ \gamma) \Psi d\nu_o \prec C_1 \left( \sum_{\eta \in S} e^{-h_\omega b_\eta(o, \gamma o)} \int g_\eta f \Psi d\nu_o \right)$$

Recall now first that the support of  $\nu_o$  is contained in  $\partial X$ , second that for every  $\xi$  in the support of  $g_\eta$  the quantities  $b_\xi(\gamma o, o)$  and  $b_\eta(\gamma o, o)$  differ by at most  $100\delta$ . Consequently Lemma B.8 gives

$$\begin{aligned} \rho_\omega(\gamma) \int (f \circ \gamma) \Psi d\nu_o &\prec C_1 e^{100h_\omega \delta} \left( \sum_{\eta \in S} \int g_\eta(\xi) f(\xi) \Psi(\xi) e^{-h_\omega b_\xi(\gamma o, o)} d\nu_o(\xi) \right) \\ &\prec C_1 e^{100h_\omega \delta} \int f(\xi) \Psi(\xi) e^{-h_\omega b_\xi(\gamma o, o)} d\nu_o(\xi) \end{aligned}$$

Recall that  $h_\omega = h_\Gamma$ . Hence the invariance and quasi-conformality of  $(\nu_x)$  yields

$$\rho_\omega(\gamma) \int (f \circ \gamma) \Psi d\nu_o \prec C_0 C_1 e^{100h_\omega \delta} \int (f \circ \gamma) (\Psi \circ \gamma) d\nu_o$$

Note that this inequality holds for every  $f \in C(\bar{X})$ , hence  $\rho(\gamma) \Psi \prec C(\Psi \circ \gamma)$  where  $C = C_0 C_1 e^{100h_\omega \delta}$  is a universal constant (Proposition B.9). The other inequality follows by symmetry.  $\square$

If  $\partial X$  and  $\partial_h X$  coincide, all the Patterson-Sullivan measures are  $\Gamma$ -equivariant and conformal (not just quasi-conformal). Hence our argument proves that for every  $\gamma \in \Gamma$ , we have

$$\rho_\omega(\gamma) \Psi \circ \gamma^{-1} = \Psi.$$

When the two boundaries differ we do not have quite equality. To deal with this problem, we proceed as follows. By Lemma 5.23 there exists  $\varepsilon \in (0, 1)$ , which does not depend on  $\phi$ , such that the set

$$\{\rho_\omega(\gamma) \Psi \circ \gamma^{-1} \mid \gamma \in \Gamma\}.$$

is non-empty and bounded below by  $\varepsilon\Psi$ . We define  $\Psi' \in L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$  as its greatest lower bound, i.e.

$$\Psi' = \inf_{\gamma \in \Gamma} \rho_\omega(\gamma)\Psi \circ \gamma^{-1}.$$

Such an element is well-defined as  $L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$  is countably order complete (Lemma B.7). By construction

$$\varepsilon\Psi \prec \Psi' \prec \Psi. \quad (51)$$

In particular,  $\Psi'$  takes its values in  $\mathcal{H}_\omega^+$ . Moreover, for every  $\gamma \in \Gamma$  we have

$$\rho_\omega(\gamma)\Psi' \circ \gamma^{-1} = \Psi'. \quad (52)$$

**Lemma 5.24.** *The function  $\Psi' \in L^\infty((\partial X, \nu_o), \mathcal{H}_\omega)$  is constant  $\nu_o$ -almost everywhere.*

*Proof.* According to (52) for every  $\gamma \in \Gamma$ , for  $\nu_o$ -almost every  $\eta, \xi \in \partial X$ , we have

$$(\Psi'(\gamma\eta), \Psi'(\gamma\xi)) = (\rho_\omega(\gamma)\Psi'(\eta), \rho_\omega(\gamma)\Psi'(\xi)) = (\Psi'(\eta), \Psi'(\xi)).$$

It exactly means that the map

$$Q: \begin{array}{ccc} (\partial X \times \partial X, \nu_o \otimes \nu_o) & \rightarrow & \mathbb{R}_+ \\ (\eta, \xi) & \rightarrow & (\Psi'(\eta), \Psi'(\xi)) \end{array}$$

is  $\Gamma$ -invariant. Recall now that by Theorem 4.1, the action of  $\Gamma$  on the space  $(\partial X \times \partial X, \nu_o \otimes \nu_o)$  is ergodic. The map  $Q$  is hence constant  $\nu_o \otimes \nu_o$ -almost everywhere. We write  $m \in \mathbb{R}$  for this value. Observe now that for every  $f_1, f_2 \in L^1(\nu_o)$  we have

$$\left( \int f_1 \Psi' d\nu_o, \int f_2 \Psi' d\nu_o \right) = m \left( \int f_1 d\nu_o \right) \left( \int f_2 d\nu_o \right). \quad (53)$$

A standard argument using the equality case of the Cauchy-Schwarz inequality shows that there exists  $\psi'_0 \in \mathcal{H}_\omega$  such that for every  $f \in L^1_+(\nu_o)$  we have

$$\int_{\bar{X}} f \Psi' d\nu_o = \sqrt{m} \left[ \int_{\bar{X}} f d\nu_o \right] \psi'_0.$$

Consequently  $\Psi'$  is  $\nu_o$ -almost surely constant, equal to  $\sqrt{m}\psi'_0$  (Proposition A.1).  $\square$

**Lemma 5.25.** *The unique essential value of  $\Psi'$  is a  $\rho_\omega$ -invariant vector of  $\mathcal{H}_\omega$ .*

*Proof.* As we proved in Lemma 5.24,  $\Psi'$  is constant  $\nu_o$ -almost surely. To avoid ambiguity we write  $\psi' \in \mathcal{H}_\omega$  for its value. Recall that for every  $\gamma \in \Gamma$  we have  $\rho_\omega(\gamma)\Psi' \circ \gamma^{-1} = \Psi'$ , see (52). Replacing  $\Psi'$  by its value exactly says that  $\psi'$  is  $\rho_\omega$ -invariant.  $\square$

**Remark.** If the horoboundary  $\partial_h X$  coincides with the Gromov boundary  $\partial X$ , our arguments prove that there exists a  $\rho_\omega$ -invariant vector  $\psi \in \mathcal{H}_\omega^+$  such that for every  $f \in C(\bar{X})$ , we have

$$a_o^\rho(f)\phi = \left( \int f d\nu_o \right) \psi.$$

Next proposition summarizes the results of this section.

**Proposition 5.26.** *If  $h_\omega = h_\Gamma$ , then the representation  $\rho_\omega$  has non-zero invariant vectors.*

*Proof.* The operator  $\pi_* a_o^\rho(\mathbf{1})$  has norm 1 (Lemma 5.11). Hence there exists a vector  $\phi \in \mathcal{H}_\omega^+$  such that  $\pi_* a_o^\rho(\mathbf{1})\phi$  is not zero. To such a vector we associate a bounded function  $\Psi: \partial X \rightarrow \mathcal{H}_\omega^+$  such that for every  $f \in C(\bar{X})$

$$\pi_* a_o^\rho(f)\phi = \int f \Psi d\nu_o.$$

In particular  $\Psi$  is a non-zero function. We proved that the map  $\Psi': \partial X \rightarrow \mathcal{H}_\omega^+$  defined by

$$\Psi' = \inf_{\gamma \in \Gamma} \rho(\gamma)\Psi \circ \gamma^{-1}.$$

is constant and its value  $\psi'$  is  $\rho_\omega$ -invariant (Lemma 5.24). Moreover there exists  $\varepsilon \in (0, 1)$ , which does not depend on  $\phi$ , such that  $\varepsilon\Psi \prec \Psi' \prec \Psi$  (Lemma 5.23). It follows from this inequality that  $\psi'$  is non-zero. Indeed otherwise  $\Psi'$  and thus  $\Psi$  would be zero as well.  $\square$

We complete this section with the proof of Theorem 5.2.

*Proof of Theorem 5.2.* The proof proceeds by contradiction. Let  $S$  be a finite subset of  $\Gamma$  and  $\varepsilon \in \mathbb{R}_+^*$ . Assume that the theorem is false. For each  $n \in \mathbb{N}$ , we can find a Hilbert lattice  $\mathcal{H}_n$  and a positive representation  $\rho_n: \Gamma \rightarrow \mathcal{U}(\mathcal{H}_n)$  with the following properties.

1.  $(h_{\rho_n})$  converges to  $h_\Gamma$ .
2. For every  $n \in \mathbb{N}$ , the representation does not have any  $(S, \varepsilon)$ -invariant vector.

Let  $\omega$  be a non-principal ultra-filter. We let  $\mathcal{H}_\omega = \lim_\omega \mathcal{H}_n$  and denote by  $\rho_\omega: \Gamma \rightarrow \mathcal{U}(\mathcal{H}_\omega)$  the limit representation induced by  $(\rho_n)$ . Observe that we are exactly in the setting of Section 5.3. Moreover

$$h_\omega = \lim_\omega h_{\rho_n} = h_\Gamma.$$

It follows from Proposition 5.26 that  $\rho_\omega$  admits an invariant unit vector  $\psi$  that we can write  $\psi = \lim_\omega \psi_n$ , where  $\psi_n$  is a unit vector in  $\mathcal{H}_n$ . By definition of the representation  $\rho_\omega$ , for all  $\gamma \in \Gamma$ , we have

$$\lim_\omega \|\rho_n(\gamma)\psi_n - \psi_n\| = 0.$$

Since  $S$  is finite, it forces

$$\sup_{\gamma \in S} \|\rho_n(\gamma)\psi_n - \psi_n\| < \varepsilon, \omega\text{-as.}$$

Hence  $\psi_n$  is an  $(S, \varepsilon)$ -invariant vector of  $\rho_n$   $\omega$ -as, which contradicts the definition of  $\rho_n$ .  $\square$



## 6 Applications to group theory

Let  $X$  be a hyperbolic proper geodesic space. Let  $\Gamma$  be a group acting by isometries on  $X$ . Let  $\mathcal{H}$  be a Hilbert space and  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  be a unitary representation. Let  $S$  be a finite subset of  $\Gamma$  and  $\varepsilon > 0$ . Recall that an  $(S, \varepsilon)$ -invariant vector is a vector  $\phi \in \mathcal{H}$  such that

$$\sup_{\gamma \in S} \|\rho(\gamma)\phi - \phi\| < \varepsilon \|\phi\|.$$

Moreover, the representation  $\rho$  almost admits invariant vectors if for every finite subset  $S$  of  $\Gamma$  for every  $\varepsilon > 0$ , it has an  $(S, \varepsilon)$ -invariant vector. We now investigate the consequences of [Theorem 5.2](#) by varying the representations of  $\Gamma$ .

Our main source of applications deals with the growth of subgroups of  $\Gamma$ . Let  $\Gamma'$  be a subgroup of  $\Gamma$ . We denote by  $Y$  the space of left cosets  $Y = \Gamma' \backslash \Gamma$  on which  $\Gamma$  acts on the right. Let  $\mathcal{H} = \ell^2(Y)$  be the space of square summable map  $Y \rightarrow \mathbb{R}$  endowed with its usual Hilbert structure and order ([Section B.2.1](#)) We denote by  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  the corresponding Koopman representation. Recall that  $h_\rho$  is the critical exponent of the operator series

$$A(s) = \sum_{\gamma \in \Gamma} e^{-sd(\gamma o, o)} \rho(\gamma),$$

whereas  $h_\Gamma$  is the exponential growth rate of  $\Gamma$  (for its action on  $X$ ).

**Lemma 6.1.** *The critical exponents  $h_\rho$  and  $h_{\Gamma'}$  satisfy  $h_{\Gamma'} \leq h_\rho$ .*

*Proof.* Let  $s > h_\rho$ . We write  $y_0$  for the point of  $Y$  corresponding to the coset  $\Gamma'$  and  $\psi \in \ell^2(Y)$  for the Dirac mass at  $y_0$ . Note that  $\rho(\gamma)\psi = \psi$ , for every  $\gamma \in \Gamma'$ . Hence

$$\mathcal{P}_{\Gamma'}(s)\psi = \sum_{\gamma \in \Gamma'} e^{-sd(\gamma o, o)} \rho(\gamma)\psi \prec \sum_{\gamma \in \Gamma} e^{-sd(\gamma o, o)} \rho(\gamma)\psi = A(s)\psi.$$

Consequently  $\mathcal{P}_{\Gamma'}(s)$  converges. This statement holds for every  $s > h_\rho$ , hence the result  $h_\rho \geq h_{\Gamma'}$ .  $\square$

**Remark.** In the next sections we explore various properties of groups defined in terms of unitary representations. These properties make sense for locally compact groups. However we restrict ourselves to discrete groups as they are the only ones that we consider in this article.

### 6.1 Amenability

**Amenability.** There are numerous equivalent definition of amenability. The most suitable for our purpose can be formulated in terms of the regular representation.

**Definition 6.2.** The action of a discrete group  $\Gamma$  on a set  $Y$  is *amenable* if and only if the induced representation  $\rho: \Gamma \rightarrow \mathcal{U}(\ell^2(Y))$  almost admits invariant vectors. A subgroup  $\Gamma'$  of  $\Gamma$  is *co-amenable in  $\Gamma$*  if the action of  $\Gamma$  on  $Y = \Gamma' \backslash \Gamma$  is amenable.

The action of  $\Gamma$  on  $Y$  is amenable if and only if one of the following equivalent facts holds.

- (Invariant mean) There exists a  $\Gamma$ -invariant positive mean on the set  $\ell^\infty(Y)$ .
- (Følner sets) For every finite subset  $S$  of  $\Gamma$ , for every  $\varepsilon > 0$ , there exists a finite subset  $Y_0$  of  $Y$  such that

$$\sup_{\gamma \in S} \frac{|\gamma Y_0 \Delta Y_0|}{|Y_0|} \leq \varepsilon.$$

- (Reiter’s criterion) For every finite subset  $S$  of  $\Gamma$ , for every  $\varepsilon > 0$  there exists a non-zero map  $L_+^1(Y)$  such that

$$\sup_{\gamma \in S} \|f \circ \gamma - f\| \leq \varepsilon \|f\|$$

The proof for amenable actions works verbatim as for amenable groups, see for instance [BdlHV08, Appendix G] or [Jus15]. Another reference for amenable action is [Eym72]. We can now prove our main theorem, which we recall.

**Theorem 6.3.** *Let  $(X, d)$  be a hyperbolic proper geodesic space. Let  $\Gamma$  be a group acting properly by isometries on  $X$  and  $\Gamma'$  a subgroup of  $\Gamma$ . Assume that the action of  $\Gamma$  is strongly positively recurrent. The following are equivalent.*

1.  $h_{\Gamma'} = h_\Gamma$
2. The subgroup  $\Gamma'$  is co-amenable in  $\Gamma$ .

**From critical exponent to amenability.** We start with the proof of the implication (1)  $\Rightarrow$  (2). Assume that  $h_{\Gamma'} = h_\Gamma$ . Since  $h_{\Gamma'} \leq h_\rho \leq h_\Gamma$  (Lemmas 5.1 and 6.1) we have  $h_\rho = h_\Gamma$ . It follows from Corollary 5.3 that  $\rho$  almost has invariant vectors, which exactly means that  $\Gamma'$  is co-amenable in  $\Gamma$ .

**From amenability to critical exponents.** We now focus on the so called “easy direction”, i.e. (2)  $\Rightarrow$  (1). As explained in the introduction, if  $\Gamma'$  is a *normal* subgroup of  $\Gamma$ , then Roblin’s proof for CAT(−1) spaces [Rob05] directly extends to our setting. However if  $\Gamma'$  is no more a normal subgroup, we are not aware of any existing proof in the literature that would work in the general context of Gromov hyperbolic spaces. We expose here a strategy based on the approach of Coulon-Dal’bo-Sambusetti [CDS17] revisited through ideas of Roblin-Tapie [RT13].

Let  $\Gamma'$  be a subgroup of  $\Gamma$ . We denote by  $Y = \Gamma' \backslash \Gamma$  the space of left cosets of  $\Gamma'$ . The strategy is to estimate in terms of  $h_{\Gamma'}$  the spectral radius of a certain random walk on the space  $Y$ . When  $\Gamma'$  is co-amenable in  $\Gamma$ , Kesten’s amenability criterion tells us that any random walk on  $Y$  has spectral radius 1, which leads to the expected relation between  $h_{\Gamma'}$  and  $h_\Gamma$ .

We begin with general considerations on random walks. Let  $\mathcal{F}(Y, \mathbb{C})$  be the set of *all* maps from  $Y$  to  $\mathbb{C}$  and  $\mathcal{H} = \ell^2(Y)$  the subset consisting of all square summable functions with its canonical Hilbert space structure. The group  $\Gamma$  acts on the right on  $Y$  inducing a left action of  $\Gamma$  on  $\mathcal{F}(Y, \mathbb{C})$  as follows. For every  $\phi \in \mathcal{F}(Y, \mathbb{C})$ , for every  $\gamma \in \Gamma$ ,

$$[\gamma \cdot \phi](y) = \phi(y\gamma), \quad \forall y \in Y.$$

Restricted to  $\mathcal{H}$ , this action defines a unitary representation  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$ . Let  $p: \Gamma \rightarrow [0, 1]$  be a *symmetric* probability measure on  $\Gamma$  with *finite* support. The convolution by  $p$  defines an operator  $M$  on  $\mathcal{F}(Y, \mathbb{C})$  given by

$$M\phi = \phi * p = \sum_{\gamma \in \Gamma} p(\gamma) [\gamma^{-1} \cdot \phi]. \quad (54)$$

Its restriction to  $\mathcal{H}$ , still denoted by  $M$ , is the *Markov operator* of the random walk on  $Y$  associated to  $p$ . Seen as operator of  $\mathcal{H}$ , the spectral radius  $\tau(M)$  of  $M$  is at most 1. The “easy direction” of Kesten’s amenability criterion tells us that if  $\Gamma'$  is co-amenable in  $\Gamma$  then  $\tau(M) = 1$ . Our first task is to relate  $\tau(M)$  to the critical exponents of  $\Gamma'$ . To that end we use a discrete version of Barta’s inequality [Bar37] exposed in the next two statements.

**Lemma 6.4.** *Let  $u, \phi: \Gamma \rightarrow \mathbb{R}_+$  be two non negative maps. Then*

$$(M(u\phi), u\phi) \leq (u^2, \phi M\phi).$$

**Remark.** We do not assume that  $u$  or  $\phi$  are square summable. In particular we allow the above scalar products to be infinite.

*Proof.* Assume first that both  $u$  and  $\phi$  have finite support, so that all objects in the following computations are well-defined. Observe that

$$(M(u\phi), u\phi) - (u^2, \phi M\phi) = \sum_{y \in Y} \sum_{\gamma \in \Gamma} [u(y\gamma^{-1}) - u(y)] u(y) \phi(y\gamma^{-1}) \phi(y) p(\gamma).$$

Recall that  $p$  is symmetric. Reindexing the double sum provides another way to write this difference, namely

$$\begin{aligned} & (M(u\phi), u\phi) - (u^2, \phi M\phi) \\ &= \sum_{y \in Y} \sum_{\gamma \in \Gamma} [u(y) - u(y\gamma^{-1})] u(y\gamma^{-1}) \phi(y\gamma^{-1}) \phi(y) p(\gamma). \end{aligned}$$

Averaging these two expressions yields

$$(M(u\phi), u\phi) - (u^2, \phi M\phi) = -\frac{1}{2} \sum_{y \in Y} \sum_{\gamma \in \Gamma} [u(y\gamma^{-1}) - u(y)]^2 \phi(y\gamma^{-1}) \phi(y) p(\gamma).$$

Hence

$$(M(u\phi), u\phi) \leq (u^2, \phi M\phi).$$

If  $u$  and  $\phi$  are any non-negative maps, we approximate them by functions supported on larger and larger finite subsets of  $Y$ . The conclusion then follows from the monotone convergence theorem.  $\square$

**Proposition 6.5** (Barta’s inequality). *Let  $\lambda \in [0, 1]$ . If there exists a positive function  $\phi: Y \rightarrow \mathbb{R}_+$  such that  $M\phi \leq \lambda\phi$ , then  $\tau(M) \leq \lambda$ , where  $\tau(M)$  is the spectral radius of  $M$  seen as an operator on  $\mathcal{H}$ .*

**Remark.** We think of  $\phi$  as a kind of  $\lambda$  super-harmonic function for  $M$ . The strength of this statement is that it provides an estimate of  $\tau(M)$  without assuming that  $\phi$  is square summable.

*Proof.* Recall that  $\mathcal{H}^+$  stands for the functions in  $\mathcal{H}$  taking values in  $\mathbb{R}_+$ . Since  $p$  is symmetric,  $M$  is a self-adjoint positive operator of  $\mathcal{H}$ . Hence its spectral radius can be computed as follows

$$\tau(M) = \sup_{\psi \in \mathcal{H}^+ \setminus \{0\}} \frac{(M\psi, \psi)}{\|\psi\|^2}.$$

Let  $\psi \in \mathcal{H}^+$ . Since  $\phi$  is positive we can always write  $\psi = u\phi$  where  $u: Y \rightarrow \mathbb{R}_+$  is a non-negative function. It follows from [Proposition 6.5](#) that

$$(M\psi, \psi) \leq (M(u\phi), u\phi) \leq (u^2, \phi M\phi) \leq \lambda (u^2, \phi^2) \leq \lambda \|\psi\|^2$$

This inequality holds for every  $\psi \in \mathcal{H}^+$ , hence the result.  $\square$

We now exploit the previous proposition to estimate the spectral radius of  $M$ . To that end we fix a base point  $o \in X$  and a  $\Gamma'$ -invariant,  $h_{\Gamma'}$ -quasi-conformal family of measures  $(\nu'_x)$  on  $\partial X$ . In addition we choose a measurable section  $\partial X \rightarrow \partial_h X$ , sending  $\xi$  to  $b_\xi$ . We define a function  $\phi: \Gamma \rightarrow \mathbb{R}_+^*$  sending  $\gamma$  to the total mass of  $\nu'_{\gamma o}$ , i.e.

$$\phi(\gamma) = \int \mathbf{1} d\nu'_{\gamma o}.$$

Since the family  $(\nu'_x)$  is  $\Gamma'$ -invariant,  $\phi$  induces a map  $Y \rightarrow \mathbb{R}_+^*$  that we still denote  $\phi$ . This function will play the role of the function  $\phi$  in [Proposition 6.5](#). To that end we need to compute  $M\phi$ . Since  $(\nu'_x)$  is  $h_{\Gamma'}$ -quasi-conformal, there exists a constant  $C_1 \in \mathbb{R}_+$  such that for every point  $y = \Gamma'\beta$  of  $Y$ , we have

$$[M\phi](y) \leq C_1 \int B(\beta^{-1}\xi) d\nu'_{\beta o}(\xi) \quad (55)$$

where  $B: \partial X \rightarrow \mathbb{R}_+$  is defined by

$$B(\xi) = \sum_{\gamma \in \Gamma} e^{-h_{\Gamma'} b_\xi(\gamma o, o)} p(\gamma) \quad (56)$$

Consequently, to estimate  $M\phi$  and thus  $\tau(M)$ , it suffices to bound  $B(\xi)$  uniformly from above.

Until now we worked with an arbitrary symmetric probability measure  $p$ . In order to estimate the map  $B: \partial X \rightarrow \mathbb{R}_+$  defined above we now specialize to a specific measure. Basically we are going to consider measures supported by “spheres” of large radius. Before doing so we make a small digression in order to study the growth of spheres. Let  $r, a \in \mathbb{R}_+$  and  $x \in X$ . We denote by

$$S_\Gamma(x, r, a) = \{\gamma \in \Gamma \mid r - a < d(\gamma o, x) \leq r\}$$

the “sphere” of radius  $r$  (and thickness  $a$ ) centred at  $x$ . Similarly we define the “ball” of radius  $r$  centred at  $x$  by

$$B_\Gamma(x, r) = \{\gamma \in \Gamma \mid d(\gamma o, x) \leq r\}.$$

Since the action of  $\Gamma$  on  $X$  is proper, these sets are finite. Since the usual Patterson-Sullivan measure associated to the ambient group  $\Gamma$  gives full measure to the radial limit set (Corollary 3.16), there exists  $C_2 \in \mathbb{R}_+$ , such that for every  $r \in \mathbb{R}_+$

$$|B_\Gamma(o, r)| \leq C_2 e^{r h_\Gamma}, \quad (57)$$

see for instance [Coo93, Corollaire 6.8]. The next statement precise these estimates in the presence of a growth gap at infinity.

**Lemma 6.6** (Yang [Yan16, Theorem 5.3]). *Let  $\Gamma$  be a discrete group acting properly by isometries on a Gromov-hyperbolic space  $X$ . Assume that the action is strongly positively recurrent, i.e. there exists a growth gap at infinity. There exists  $a, C_3 \in \mathbb{R}_+$ , such that for every  $r \in \mathbb{R}_+$ , we have*

$$\frac{1}{C_3} e^{r h_\Gamma} \leq |S_\Gamma(o, r, a)| \leq C_3 e^{r h_\Gamma}.$$

The previous lemma provides an estimate for the cardinality of any ball centred at a point in the  $\Gamma$ -orbit of  $o$ . The goal of the next proposition is to provide a similar estimate for balls centred at any point  $x \in X$ .

**Proposition 6.7.** *Let  $\Gamma$  be a discrete group acting properly by isometries on a Gromov-hyperbolic space. Assume that the action is strongly positively recurrent. For all  $\varepsilon \in \mathbb{R}_+^*$ , there exists  $C_4(\varepsilon) \in \mathbb{R}_+^*$ , such that for all  $x \in X$ , we have*

$$|B_\Gamma(x, r)| \leq C_4(\varepsilon) e^{(2h_\Gamma^\infty + \varepsilon - h_\Gamma)d(x, \Gamma o)} e^{r h_\Gamma}$$

**Remark.** This estimate is reminiscent from [Sch04, Theorem 3.2]. Following the same proof, it is likely that in geometric situations where the growth of  $\Gamma_K$  is purely exponential, this estimate should admit a similar lower bound.

*Proof.* In the course of this proof, many parameters will appear. Those parameters only depend on  $\varepsilon$  (and not on  $x$ ). We denote them all by  $C$ , or  $C(\varepsilon)$  if we want to emphasize the dependence in  $\varepsilon$ . Without loss of generality, we choose  $0 < \varepsilon < h_\Gamma - h_\Gamma^\infty$ . There exists a compact subset  $k \subset X$  such that  $h_{\Gamma_k} < h_\Gamma^\infty + \varepsilon/4$ . Up to enlarging  $k$ , we assume that  $o$  belongs to  $k$ . Let  $K$  be the  $\delta$ -neighbourhood of  $k$  and  $D$  its diameter. Let  $S \subset \Gamma$  and  $r_0 \in \mathbb{R}_+$  be given by Lemma 3.13 applied to  $k$  and  $K$ . By definition of exponential growth rate, there exists  $C(\varepsilon) \in \mathbb{R}_+$  such that for every  $r \in \mathbb{R}_+$ , we have

$$|S\Gamma_k \cap B_\Gamma(o, r)| \leq C(\varepsilon) e^{r(h_{\Gamma_k} + \varepsilon/4)}.$$

Let  $x \in X$ . For simplicity, set  $d = d(x, \Gamma K)$ . We fix  $\alpha \in \Gamma$  and  $q \in \alpha K$  such that  $q$  is a projection of  $x$  on  $\Gamma K$ . Given any geodesic  $[q, x]$  from  $q$  to  $x$ , the intersection  $\alpha^{-1}[q, x] \cap \Gamma K$  is contained in  $K$ . By Lemma 3.13, for every  $\gamma \in \Gamma$ , there exists  $\beta \in S\Gamma_k$  such that  $\langle \alpha^{-1}x, \alpha^{-1}\gamma o \rangle_{\beta o} \leq r_0$ . In particular,

$$d(\beta o, \alpha^{-1}\gamma o) \leq d(x, \gamma o) - d(\alpha^{-1}x, \beta o) + 2r_0.$$

Consequently

$$\alpha^{-1}B_\Gamma(x, r) \subset \bigcup_{\beta \in S\Gamma_k} B_\Gamma(\beta o, r - d(\alpha^{-1}x, \beta o) + 2r_0)$$

Combined with (57) it yields

$$|B_\Gamma(x, r)| \leq C e^{r h_\Gamma} \sum_{\beta \in S\Gamma_k} e^{-h_\Gamma d(\alpha^{-1}x, \beta o)}. \quad (58)$$

Let us now estimate the latter sum. Recall that  $D$  is the diameter of  $K$ , which contains both  $o$  and  $\alpha^{-1}q$ . Hence for every  $\beta \in S\Gamma_k$ , we have  $d(\alpha^{-1}x, \beta o) \geq d - D$  and

$$d(o, \beta o) \leq d(o, \alpha^{-1}x) + d(\alpha^{-1}x, \beta o) \leq d + d(\alpha^{-1}x, \beta o) + D.$$

Consequently (58) becomes

$$\begin{aligned} |B_\Gamma(x, r)| &\leq e^{r h_\Gamma} \sum_{\substack{\ell \in \mathbb{N} \\ \ell \geq d-D}} \sum_{\substack{\beta \in S\Gamma_k \\ \ell \leq d(\alpha^{-1}x, \beta o) \leq \ell+1}} e^{-\ell h_\Gamma} \\ &\leq e^{r h_\Gamma} \sum_{\substack{\ell \in \mathbb{N} \\ \ell \geq d-D}} |S\Gamma_k \cap B_\Gamma(o, \ell + 1 + d)| e^{-\ell h_\Gamma} \\ &\leq C(\varepsilon) e^{r h_\Gamma} \sum_{\substack{\ell \in \mathbb{N} \\ \ell \geq d-D}} e^{(h_{\Gamma_k} + \varepsilon/4)(\ell + d)} e^{-\ell h_\Gamma}. \end{aligned}$$

Recall that  $h_{\Gamma_k} + \varepsilon/4 < h_\Gamma$ . Up to increasing  $C(\varepsilon)$ , we get

$$|B_\Gamma(x, r)| \leq C(\varepsilon) e^{(2h_{\Gamma_k} + \varepsilon/2 - h_\Gamma)d} e^{r h_\Gamma}.$$

As  $o$  belongs to  $K$ , we have  $d \leq d(x, \Gamma o)$ . Moreover  $h_{\Gamma_k} \leq h_\Gamma^\infty + \varepsilon/4$ , whence the result.  $\square$

We now come back to the study of random walks in  $Y$ . Let  $a$  and  $C_3$  be the parameters given by Lemma 6.6. Without loss of generality we can assume that  $a > 1$ . For every  $n \in \mathbb{N}$ , we denote by  $p_n$  the uniform probability measure on  $S_\Gamma(o, n, a)$ ,  $M_n$  the associated Markov operator (54) and  $B_n: \partial X \rightarrow \mathbb{R}_+$  the auxiliary map associated to  $p_n$  in (56). By Lemma 6.6, we have  $p_n(\gamma) \leq C_3 e^{a h_\Gamma} e^{-n h_\Gamma}$  if  $\gamma \in S_\Gamma(o, n, a)$ , and  $p_n(\gamma) = 0$  otherwise.

**Proposition 6.8.** *For every  $\varepsilon > 0$ , there exists  $C_5(\varepsilon) \in \mathbb{R}_+$ , such that for every  $n \in \mathbb{N}$ , for every  $\xi \in \partial X$ , we have*

$$B_n(\xi) \leq C_5(\varepsilon) \max \left\{ e^{-n h_{\Gamma'}}, e^{n(h_\Gamma^\infty + \varepsilon - h_\Gamma)}, e^{n(h_{\Gamma'} - h_\Gamma)} \right\}.$$

*Proof.* As above, the proof involves many parameters which only depend on  $\varepsilon$  (and not on  $n$  or  $\xi$ ). We still denote them all by  $C$ , or  $C(\varepsilon)$ . Choose  $\varepsilon > 0$  such that  $h_\Gamma^\infty + \varepsilon < h_\Gamma$  and define

$$h_{\text{aux}} = \max\{\varepsilon, 2h_\Gamma^\infty + \varepsilon - h_\Gamma\}.$$

Up to decreasing  $\varepsilon$ , we can assume that  $h_{\Gamma'} \neq (h_\Gamma \pm h_{\text{aux}})/2$ . Note that  $0 < h_{\text{aux}} \leq h_\Gamma^\infty + \varepsilon$ . Let  $n \in \mathbb{N}$  and  $\xi \in \partial X$ . We fix a geodesic  $[o, \xi]$  joining  $o$  to  $\xi$ . For every  $\ell \in \mathbb{N}$  we denote by  $x_\ell$  the point on  $[o, \xi]$  at distance  $\ell$  from  $o$ . We

now split the sum defining  $B_n(\xi)$  according to the value of the Gromov product  $\langle \gamma o, \xi \rangle_o$ .

$$B_n(\xi) = \sum_{\ell \in \mathbb{N}} \sum_{\substack{\gamma \in \Gamma \\ \ell \leq \langle \gamma o, \xi \rangle_o \leq \ell+1}} e^{-h_{\Gamma'} b_\xi(\gamma o, o)} p_n(\gamma).$$

Note first that the first sum is actually a finite sum. Indeed for every  $\gamma \in S_\Gamma(o, n, a)$  the Gromov product  $\langle \gamma o, \xi \rangle_o$  is at most  $n$ . Let  $\ell \in \mathbb{N}$  and  $\gamma \in S_\Gamma(o, n, a)$  such that

$$\ell \leq \langle \gamma o, \xi \rangle_o \leq \ell + 1.$$

A standard exercise of hyperbolic geometry shows that  $\gamma$  belongs to  $B_\Gamma(x_\ell, n - \ell + \delta)$  and  $b_\xi(\gamma o, o) \geq n - 2\ell - (a + \delta)$ . On the other hand, as we noticed before

$$p_n(\gamma) \leq C e^{-nh_\Gamma}$$

Consequently

$$B_n(\xi) \leq C e^{-n(h_\Gamma + h_{\Gamma'})} \sum_{\ell \leq n} \sum_{\gamma \in B_\Gamma(x_\ell, n - \ell + \delta)} e^{2\ell h_{\Gamma'}}.$$

Note that if  $B_\Gamma(x_\ell, n - \ell + \delta)$  is non-empty, then

$$d(x_\ell, \Gamma o) \leq \min\{\ell, n - \ell\} + \delta.$$

Using [Proposition 6.7](#) we get

$$B_n(\xi) \leq C(\varepsilon) e^{-nh_{\Gamma'}} \sum_{\ell \leq n} e^{(2h_{\Gamma'} - h_\Gamma)\ell} e^{h_{\text{aux}} \min\{\ell, n - \ell\}}.$$

We now split the sum according to the value of  $\min\{\ell, n - \ell\}$ . We get

$$B_n(\xi) \leq C(\varepsilon) e^{-nh_{\Gamma'}} \left[ \sum_{\ell \leq n/2} e^{(2h_{\Gamma'} - h_\Gamma + h_{\text{aux}})\ell} + e^{nh_{\text{aux}}} \sum_{n/2 < \ell \leq n} e^{(2h_{\Gamma'} - h_\Gamma - h_{\text{aux}})\ell} \right]. \quad (59)$$

We now distinguish several cases depending on the value of  $h_{\Gamma'}$  compared to  $(h_\Gamma \pm h_{\text{aux}})/2$ . Recall that we chose  $\varepsilon$  in such a way that  $h_{\Gamma'} \neq (h_\Gamma \pm h_{\text{aux}})/2$ .

**Case 1.** Assume that  $h_{\Gamma'} < (h_\Gamma - h_{\text{aux}})/2$ . Then both terms within the bracket in (59) are bounded. We get

$$B_n(\xi) \leq C(\varepsilon) e^{-nh_{\Gamma'}}$$

**Case 2.** Assume that  $(h_\Gamma - h_{\text{aux}})/2 < h_{\Gamma'} < (h_\Gamma + h_{\text{aux}})/2$ . In this case the two terms within the brackets in (59) have exactly the same asymptotic behaviour. More precisely, the computation yields

$$B_n(\xi) \leq C(\varepsilon) e^{(h_{\text{aux}} - h_\Gamma)n/2} \leq C(\varepsilon) e^{(h_\Gamma^\infty + \varepsilon - h_\Gamma)n}$$

**Case 3.** Assume that  $h_{\Gamma'} > (h_{\Gamma} + h_{aux})/2$ . Both sums in (59) diverge exponentially, however the second term dominates the first one. Hence

$$B_n(\xi) \leq C(\varepsilon)e^{(h_{\Gamma'} - h_{\Gamma})n}.$$

The result is the combination of these three cases.  $\square$

**Corollary 6.9.** *The asymptotic behaviour of the spectral radius  $\tau(M_n)$  of  $M_n$  is asymptotically controlled as follows*

$$\limsup_{n \rightarrow \infty} \frac{1}{n} \ln \tau(M_n) \leq \max \{-h_{\Gamma'}, h_{\Gamma}^{\infty} - h_{\Gamma}, h_{\Gamma'} - h_{\Gamma}\}.$$

*Proof.* Let  $\varepsilon > 0$ . Recall that  $\phi: Y \rightarrow \mathbb{R}_+^*$  is the map sending  $y = \Gamma'\beta$  to the total mass of the measure  $\nu'_{\beta o}$ . Let  $n \in \mathbb{N}$ . Injecting in (55) the estimate given by Proposition 6.8, we get

$$M_n \phi \leq C(\varepsilon) \lambda_n \phi, \quad \text{where} \quad \lambda_n \max \left\{ e^{-nh_{\Gamma'}}, e^{n(h_{\Gamma}^{\infty} + \varepsilon - h_{\Gamma})}, e^{n(h_{\Gamma'} - h_{\Gamma})} \right\}.$$

By Barta's inequality (Proposition 6.5), we deduce  $\tau(M_n) \leq C(\varepsilon) \lambda_n$ . Observe that  $C(\varepsilon)$  does not depend on  $n$ . Passing to the limit we obtain

$$\limsup_{n \rightarrow \infty} \frac{1}{n} \ln \tau(M_n) \leq \max \{-h_{\Gamma'}, h_{\Gamma}^{\infty} + \varepsilon - h_{\Gamma}, h_{\Gamma'} - h_{\Gamma}\}.$$

This inequality holds for every  $\varepsilon \in \mathbb{R}_+^*$ , whence the result.  $\square$

The next corollary completes the proof of the “easy direction” in Theorem 6.3.

**Corollary 6.10.** *If  $\Gamma'$  is co-amenable in  $\Gamma$ , then  $h_{\Gamma'} = h_{\Gamma}$ .*

*Proof.* It follows from Kesten's amenability criterion that the spectral radius of any random walk on  $Y = \Gamma' \backslash \Gamma$  is 1 [Kes59, Day64], see also [CDS17] for the case where  $\Gamma'$  is not a normal subgroup of  $\Gamma$ . Consequently Corollary 6.9 yields

$$\max \{-h_{\Gamma'}, h_{\Gamma}^{\infty} - h_{\Gamma}, h_{\Gamma'} - h_{\Gamma}\} \geq 0.$$

Since  $h_{\Gamma}^{\infty} < h_{\Gamma}$ , the only options are  $h_{\Gamma'} = 0$  or  $h_{\Gamma'} = h_{\Gamma}$ . It remains to rule out the first case. Assume that  $h_{\Gamma'} = 0$ . We claim that  $\Gamma'$  is amenable. Since  $\Gamma'$  is countable, it can be written as an increasing union of finitely generated subgroups. Hence, it suffices to prove that every finitely generated subgroup of  $\Gamma'$  is amenable. Let  $S$  be a finite subset of  $\Gamma'$  and  $\Gamma'_S$  the subgroup of  $\Gamma$  generated by  $S$ . Obviously  $h_{\Gamma'_S} = 0$ . However the word metric on  $\Gamma'_S$  (with respect to  $S$ ) dominates the metric induced by the action on  $X$ . It follows that  $\Gamma'_S$  has sub-exponential growth with respect to the word metric, hence  $\Gamma'_S$  is amenable, which completes the proof of our claim. By assumption the action of  $\Gamma$  on  $Y$  is amenable. Moreover the stabiliser of any point  $y \in Y$  is conjugated to  $\Gamma'$ , hence amenable. It follows that  $\Gamma$  is amenable [JM13, Lemma 3.2] or [GM07, Lemma 4.5], which contradicts the fact that  $\Gamma$  is non-elementary.  $\square$



## 6.2 Rigidity and growth gap

We now exploit rigidity properties to exhibit the existence of growth gaps for subgroups of  $\Gamma$ . We first recall the definition of the famous Kazhdan property (T). For more details we refer to [BdlHV08].

**Definition 6.11** (Kazhdan property). A discrete group  $\Gamma$  has *Kazhdan property* (T), if any unitary representation of  $\Gamma$  with almost invariant vectors admits a non-zero invariant vector.

For our purpose this property is too strong. Indeed we only consider unitary representations induced by an action on a countable set. In this context the appropriate rigidity property is Property (FM) studied by Monod and Glasner [GM07] or de Cornulier [dC15]. Similar properties have also been considered by Bekka and Olivier [BO14].

**Definition 6.12.** A discrete  $\Gamma$  has *Property* (FM) if every amenable action of  $\Gamma$  on a discrete countable set has a finite orbit.

Let  $Y$  be a countable discrete set endowed with an action of  $\Gamma$ . The induced representation  $\rho: \Gamma \rightarrow \mathcal{U}(\ell^2(Y))$  has a non-zero invariant vector if and only if  $\Gamma$  has a finite orbit. In view of this remark, Property (FM) can be reformulated as follows.

**Proposition 6.13.** *A discrete group  $\Gamma$  has property (FM) if and only if for every action of  $\Gamma$  on a discrete countable set  $Y$ , if the induced representation  $\rho: \Gamma \rightarrow \mathcal{U}(\ell^2(Y))$  almost admits invariant vectors, then it has a non-zero invariant vector.*

Obviously, Property (T) implies Property (FM). However the converse is not true. For instance the free product of two infinite simple groups with Property (T) has property (FM) [GM07, Lemma 3.2] but cannot have property (T) as it acts on the corresponding Bass-Serre tree without global fixed point. The next statement is an analogue of the existence of Kazhdan pairs, which quantifies Property (FM). The proof works verbatim as in [BdlHV08, Proposition 1.2.1] and is left to the reader.

**Lemma 6.14.** *A discrete group  $\Gamma$  has Property (FM) if and only if there exists a finite subset  $S$  of  $\Gamma$  and  $\varepsilon \in \mathbb{R}_+^*$  with the following property: for every action of  $\Gamma$  on a discrete countable set  $Y$ , if the induced representation  $\rho: \Gamma \rightarrow \mathcal{U}(\ell^2(Y))$  has an  $(S, \varepsilon)$ -invariant vector, then it has a non-zero invariant vector.*

**Theorem 6.15.** *Let  $X$  be a hyperbolic proper geodesic space. Let  $\Gamma$  be a group with Property (FM) acting properly by isometries on  $X$ . We assume that the action of  $\Gamma$  is strongly positively recurrent. There exists  $\eta > 0$  such that for every subgroup  $\Gamma'$  of  $\Gamma$ , if  $h_{\Gamma'} \geq (1 - \eta)h_{\Gamma}$ , then  $\Gamma'$  is a finite index subgroup of  $\Gamma$ .*

*Proof.* Since  $\Gamma$  has Property (FM), there exists a finite subset  $S$  of  $\Gamma$  and  $\varepsilon \in \mathbb{R}_+^*$  such that for every action of  $\Gamma$  on a discrete countable set  $Y$ , if the induced representation  $\Gamma \rightarrow \mathcal{U}(\ell^2(Y))$  has an  $(S, \varepsilon)$ -invariant vector, then it admits a non-zero invariant vector (Lemma 6.14). According to Theorem 5.2 there exists  $\eta \in \mathbb{R}_+^*$  with the following property: assume that  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  is a unitary

representation in a Hilbert lattice; if  $h_\rho \geq (1 - \eta)h_\Gamma$  then  $\mathcal{H}$  admits  $(S, \varepsilon)$ -invariant vectors. Let  $\Gamma'$  be a subgroup of  $\Gamma$  such that  $h_{\Gamma'} \geq (1 - \eta)h_\Gamma$ . We write  $Y = \Gamma' \backslash \Gamma$  for the space of left cosets. Let  $\mathcal{H} = \ell^2(Y)$  the Hilbert lattice of square summable functions and  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  the corresponding Koopman representation. It follows from [Lemma 6.1](#) that  $h_\rho \geq (1 - \eta)h_\Gamma$ . According to our choice of  $\eta$ , the representation  $\rho$  admits an  $(S, \varepsilon)$ -invariant vector, hence a non-zero invariant vector. This exactly means that the action of  $\Gamma$  on  $Y$  has a finite orbit. However this action being transitive,  $Y$  is finite. In other words  $\Gamma'$  has finite index in  $\Gamma$ .  $\square$

### 6.3 Counterexamples

**Counterexample without negative curvature.** If the space  $X$  is not hyperbolic, the “easy direction” of our main theorem fails. Indeed there exists finitely generated amenable groups  $\Gamma$  whose action on their Cayley graph  $X$  has exponential growth, for instance Baumslag Solitar groups  $BS(1, n)$ , lamplighter groups, etc. More generally, any solvable group which is not virtually nilpotent is so. For such a group  $\Gamma$  the trivial subgroup  $\Gamma' = \{1\}$  obviously satisfies  $h_{\Gamma'} < h_\Gamma$  although the quotient  $\Gamma/\Gamma'$  is amenable. Note that the action of a group on its Cayley graph is cocompact, hence strongly positively recurrent.

This problem cannot be “fixed” by strengthening the assumption on the quotient  $\Gamma/\Gamma'$ , e.g. by asking that  $\Gamma/\Gamma'$  has polynomial growth. Consider indeed the lamplighter group  $L$  defined by

$$L = V \rtimes \mathbb{Z}, \quad \text{where} \quad V = \bigoplus_{n \in \mathbb{Z}} \mathbb{Z}_2.$$

An element  $v = (v_n)$  of  $V$  is a sequence of elements of the finite groups  $\mathbb{Z}_2$  which are trivial for all but finitely many  $n \in \mathbb{Z}$ . In particular we write  $a = (a_n)$  for the sequence which is trivial everywhere except at  $n = 0$ . The generator  $t$  of  $\mathbb{Z}$  acts on  $V$  by the usual shift. The set  $\{a, t\}$  generates  $L$ . Let  $X$  be the Cayley graph of  $\Gamma$  with respect to this set (on which  $L$  acts properly cocompactly). Parry [\[Par92\]](#) computed the associated growth series of  $L$ . One can extract from his result that

$$h_L(X) = \frac{1 + \sqrt{5}}{2} \approx 1.618,$$

see for instance [\[BT17\]](#). Actually Parry provides an explicit formula for the length of an element in  $L$  with respect to  $\{a, t\}$  [\[Par92, Theorem 1.2\]](#). In particular the length  $|v|$  of an element  $v = (v_n)$  in  $V$  is the sum of two contributions:

1. the *length* of the shortest loop in  $\mathbb{Z}$ , based at the identity, that visits all indices  $n$  for which  $v_n \neq 1$ .
2. the *number* of indices  $n \in \mathbb{Z}$  such that  $v_n \neq 1$ .

This can be used to compute the growth series  $\zeta_V(z)$  of  $V$  for its action on  $X$ . All computations done we get

$$\zeta_V(z) = \sum_{v \in V} z^{|v|} = 1 + z + \frac{z^2(1+z)(1-z)(2+3z+2z^2)}{[1-z^2(z+1)]^2}.$$

Hence  $h_V(X)$  is the root of  $X^3 - X - 1 = 0$  which approximatively equals 1.3247. In particular  $h_V(X) < h_L(X)$  while the quotient  $L/V$  is isomorphic to  $\mathbb{Z}$ .

**Counterexample without a growth gap at infinity.** We now provide a few counterexamples acting on Gromov hyperbolic spaces where the “hard direction” of our main theorem fails when we drop the strongly positively recurrent assumption.

Parabolic discrete groups acting of  $\mathbb{H}^n$  act by isometries on horospheres, which are Euclidean for their induced metric. Therefore, by Bieberbach theorem they are virtually abelian, hence amenable. Still have non-zero critical exponent: our main theorem cannot apply to such groups. One can elementarily show, using convexity of Busemann functions, that such parabolic groups do not have a growth gap at infinity. Let us now construct non-elementary examples.

For fundamental groups of negatively curved surfaces, having a strongly positively recurrent action is an optimal assumption to get [Theorem 6.3](#), as shown in the next proposition.

**Proposition 6.16.** *Let  $S$  be a locally CAT( $-1$ ) surface,  $\Gamma$  its fundamental group and  $X$  its universal cover. If the action of  $\Gamma$  on  $X$  does not have a growth gap at infinity, then it admits normal subgroups  $\Gamma' \triangleleft \Gamma$  with  $h_\Gamma = h_{\Gamma'}$  and such that  $\Gamma/\Gamma'$  contains a free group.*

*Proof.* Choose two disjoint closed non-separating geodesics  $c_1$  and  $c_2$  on  $S$ . Such disjoint closed curve exist up to taking a finite covering of  $S$ . Cut  $S$  along these curves; using the surface with boundary thus obtained, it is elementary to build a surface  $S'$  which is a regular cover of  $S$  with a covering group isomorphic to  $\mathbb{F}_2$ . If  $K$  is a compact set containing  $c_1$  and  $c_2$  in  $S$ , this surface  $S'$  contains many copies of  $S \setminus K$  so that  $\Gamma' = \pi_1(S')$  satisfies  $h_{\Gamma'} \geq h_\Gamma^\infty = h_\Gamma$ . The proposition follows.  $\square$

This proposition is really due to the fact that  $\Gamma$  is a surface group. It follows from [\[DOP00\]](#) that there exists such surfaces with finitely generated fundamental group and pinched negative curvature. Negatively curved finite volume surfaces without growth gap at infinity were constructed in [\[DPPS17\]](#). Note that some of these examples even have a finite Bowen-Margulis measure. Constant curvature surfaces with finitely generated fundamental group always have a growth gap at infinity. A  $\mathbb{Z}$ -cover of a compact hyperbolic surface is typically a constant curvature surface which does not have a critical gap, and hence satisfies the above proposition.

Let us give a three dimensional constant curvature example.

**Proposition 6.17.** *Let  $M = \mathbb{H}^3/\Gamma_1$  where  $\Gamma_1$  be a simply degenerated representation of a surface group in  $\mathbb{H}^3$ . Then there exists a hyperbolic isometry  $h \in \text{Isom}^+(\mathbb{H}^3)$  satisfying the following. Let  $\Gamma = \langle \Gamma_1, h \rangle$ . Then  $\Gamma_1$  is not co-amenable in  $\Gamma$ , and  $h_\Gamma = h_{\Gamma_1} = 2$ .*

*Sketch of proof.* A simply degenerated representation of a surface group  $\Gamma_1$  is the geometric limit of a sequence of *quasi-fuchsian representations*  $\rho_n(\Gamma_0)$  of a fixed surface group  $\Gamma_0$  such that one end of  $\mathbb{H}^3/\Gamma_1$  remains convex-cocompact, whereas the other end becomes geometrically infinite. We refer to [\[Mar07, Chapters 4 and 5\]](#) for a precise definition of this terminology.

It follows from [\[BJ97\]](#) that  $h_{\Gamma_1} = 2$ . Now, since  $\Gamma_1$  is simply degenerated, its *discontinuity set*  $\partial\mathbb{H}^3 \setminus \Lambda(\Gamma_1)$  is non-empty. It is therefore possible to find a hyperbolic isometry  $h \in \text{Isom}^+(\mathbb{H}^3)$  whose axis has end points in a ball contained

in this discontinuity set. The groups  $\Gamma_1$  and  $\langle h \rangle$  are said to be in *Schottky position*: an easy application of Klein’s ping pong lemma shows then that

$$\Gamma = \langle \Gamma_1, h \rangle = \Gamma_1 * \langle h \rangle.$$

In particular  $\Gamma_1$  is not co-amenable in  $\Gamma$ . Moreover,  $2 = h_{\Gamma_1} \leq h_\Gamma \leq 2$  since any kleinian group in dimension 3 has critical exponent at most 2.  $\square$

We complete this section with a last example coming from geometric group theory.

**Proposition 6.18.** *Let  $\Gamma$  be a group and  $\mathcal{P}$  a finite collection of residually finite subgroups of  $\Gamma$  such that  $\Gamma$  is hyperbolic relative to  $\mathcal{P}$ . Let  $X$  be a metric space endowed with proper cusp-uniform action of  $(\Gamma, \mathcal{P})$ . If  $\mathcal{P}$  contains a subgroup  $P$  such that  $h_P = h_\Gamma$ , then there exists a normal subgroup  $\Gamma'$  of  $\Gamma$  such that*

1.  $h_{\Gamma'} = h_\Gamma$ ;
2.  $\Gamma/\Gamma'$  is non-elementary hyperbolic, hence non-amenable.

*Proof.* Using the group theoretic Dehn filling [GM08, Osi07], there exists a finite index subgroup  $P_0$  of  $P$  such that the quotient of  $\Gamma$  by  $\Gamma' = \langle\langle P_0 \rangle\rangle$  is non-elementary hyperbolic. Since  $P_0$  is a finite index subgroup of  $P$ , it has the same growth rate as  $P$ , i.e.  $h_\Gamma$ . As  $\Gamma'$  contains  $P_0$ , its growth rate is  $h_\Gamma$ .  $\square$

## 7 Comments and questions

Let us present some natural opening directions of this work.

### 7.1 Generalizations of Theorem 1.1 and its variations

**Beyond hyperbolicity.** The approach presented in this paper is most likely applicable to various context beyond groups acting on a  $\delta$ -hyperbolic space. Let  $\Gamma$  be a discrete group acting by isometries on a general proper geodesic metric space  $(X, d)$ . As already noticed by Arzhantseva et al. [ACT15] and Yang [Yan16], the existence of a growth gap at infinity provides many interesting results as soon as this action admits *contracting elements* – see for instance [Yan16] for a definition. This settings includes for instance CAT(0) groups with rank one elements or all convex-cocompact subgroups of the mapping class groups acting on Teichmüller space (including the mapping class group itself). We currently work on the extension of our strategy to this more general context.

**Locally compact groups.** Instead of considering a *discrete* group  $\Gamma$  acting on a metric space, we could also work with locally compact groups. Let  $X$  be a Gromov hyperbolic space such that  $G = \text{Isom}(X)$  is locally compact group containing a lattice. Define its critical exponent  $h_G$  to be the infimum of  $s > 0$  such that

$$\mathcal{P}_G(s) = \int_G e^{-sd(o, go)} dg < \infty,$$

where  $dg$  is the Haar measure on  $G$ . Still replacing Poincaré series by Haar integrals, we can then define analogously the entropy at infinity of  $G$ , Patterson-Sullivan theory on the horoboundary of  $X$ , etc. It seems likely that all the theory

would extend in this larger setting. In particular it should lead to the following wide generalization of Corlette’s rigidity result [Cor90]. Assume that  $\text{Isom}(X)$  has Kazhdan’s Property (T) and its action on  $X$  is strongly positively recurrent. Then there exists  $\varepsilon \in \mathbb{R}_+^*$  such that for every discrete group  $\Gamma$  of isometries of  $X$  either  $\Gamma$  is a lattice or  $h_\Gamma \leq \dim_{\text{vis}}(\partial X) - \varepsilon$ , where  $\dim_{\text{vis}}(\partial X)$  stands for the visual dimension of  $\partial X$ .

## 7.2 Twisted Patterson-Sullivan measures

Let  $\Gamma$  be a discrete group acting on a  $\delta$ -hyperbolic space, and let  $\rho$  be a positive unitary representation of  $\Gamma$  on some Hilbert lattice. The twisted Patterson-Sullivan density  $a^\rho = (a_x^\rho)_{x \in X}$  which we introduced in Section 5 is a powerful tool whose exploration should be fruitful. Let us mention some natural problems raised by our study.

1. If  $h_\rho = h_\Gamma$ , understand the relation between the operator  $a_\rho^\rho(\mathbf{1})$  and the orthogonal projection on the subspace of invariant vectors of the limit representation  $\rho_\omega$ .
2. If  $h_\rho < h_\Gamma$ , what can be said about the operator  $a_\rho^\rho(\mathbf{1})$ ?
3. Let  $\Gamma'$  be a subgroup of  $\Gamma$  and  $\mathcal{H} = \ell^2(\Gamma/\Gamma')$ . The Patterson-Sullivan density twisted by the induced representation  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$  can be seen as a  $\Gamma/\Gamma'$ -extension of the classical Patterson-Sullivan density. Many recent works deal with group extensions of Markov shifts over a finite alphabet, in particular when studying covers of negatively curved convex-compact manifolds or Schottky manifolds (see for instance [CG13, Jae16, Sta13, DS16]). It seems plausible that, using twisted Patterson-Sullivan measure, many ergodic results which have been obtained for group extensions of Markov shifts could be carried to the geodesic flow.

## A Integration of vector-valued functions

### A.1 Bochner spaces

We start by recalling the notion of Bochner integral and Bochner spaces. The goal is to give a rigorous definition for the integral of a Hilbert valued map. For our purpose, everything works verbatim as for the usual Lebesgue integral. We refer the reader to the original article of Bochner [Boc33] or [Din67, DUJ77].

Let  $(X, \mathcal{B}, \nu)$  be a finite measure space and  $(E, \|\cdot\|)$  a Banach space.

**Measurable functions.** A map  $\Phi: X \rightarrow E$  is *simple* if it can be written  $\Phi = \mathbf{1}_{B_1}\phi_1 + \dots + \mathbf{1}_{B_n}\phi_n$  where  $B_i \in \mathcal{B}$  and  $\phi_i \in E$ . A function  $\Phi: X \rightarrow E$  is  $\nu$ -*measurable* if there exists a sequence  $(\Phi_n)$  of simple functions from  $X$  to  $E$  which converges  $\nu$ -almost everywhere to  $\Phi$ .

**Bochner spaces.** Let  $p \in [1, \infty)$ . Observe that if  $\Phi: X \rightarrow E$  is a  $\nu$ -measure map, then the function  $X \rightarrow \mathbb{R}_+$  mapping  $x$  to  $\|\Phi(x)\|$  is measurable (in the usual sense). Hence we can define the  $p$ -norm of  $\Phi$  by

$$\|\Phi\|_p = \left( \int \|\Phi(x)\|^p d\nu(x) \right)^{1/p}$$

The *Bochner space*  $L^p(\nu, E)$  is the set of  $\nu$ -measurable maps  $\Phi: X \rightarrow E$  such that  $\|\Phi\|_p < \infty$ , up to the standard equivalence relation which identifies two maps which coincide  $\nu$ -almost everywhere. The norm  $\|\cdot\|_p$  gives to  $L^p(\nu, E)$  a structure of Banach space. Similarly we define a uniform norm by

$$\|\Phi\|_\infty = \operatorname{ess\,sup}_{x \in X} \|\Phi(x)\|$$

The *Bochner space*  $L^\infty(\nu, E)$  consists of all  $\nu$ -measurable maps  $\Phi: X \rightarrow E$  which are essentially bounded. Again this definition is meant up to equality  $\nu$ -almost everywhere. It is a Banach space.

Since  $\nu$  has finite measure a standard argument shows that  $L^q(\nu, E)$  embeds in  $L^p(\nu, E)$  provided  $1 \leq p \leq q \leq \infty$ . For every  $p \in [1, \infty)$  the set of simple functions is dense in  $L^p(\nu, E)$ .

If  $E = \mathbb{R}$ , these spaces coincide with the usual function spaces  $L^p(\nu)$ . If  $\mathcal{H}$  is a Hilbert space, the Bochner space  $L^2(\nu, \mathcal{H})$  has a structure of Hilbert space, where the scalar product is given by

$$(\Phi_1, \Phi_2) = \int (\Phi_1(x), \Phi_2(x)) d\nu(x), \quad \forall \Phi_1, \Phi_2 \in L^2(\nu, \mathcal{H}).$$

**Bochner integral.** The definition of the Bochner integral follows exactly the same steps than the one of the Lebesgue integral. More precisely one starts by defining the integral of a simple function. Given a simple function  $\Phi = \mathbf{1}_{B_1}\phi_1 + \cdots + \mathbf{1}_{B_n}\phi_n$ , its integral is the vector of  $E$  defined by

$$\int \Phi d\nu = \sum_{i \in I} \nu(B_i)\phi_i.$$

A  $\nu$ -measurable function  $\Phi: X \rightarrow E$  is *Bochner integrable* if there exists a sequence  $(\Phi_n)$  of simple functions from  $X$  to  $E$  such that

$$\lim_{n \rightarrow \infty} \int \|\Phi - \Phi_n\| d\nu = 0,$$

in which case we define the integral of  $\Phi$  as

$$\int \Phi d\nu = \lim_{n \rightarrow \infty} \int \Phi_n d\nu.$$

One checks easily that this integral is well defined and does not depend on the choice of  $(\Phi_n)$ . A function  $\Phi$  is Bochner integrable if and only if it belongs to  $L^1(\nu, E)$  [DUJ77, Chapter II, Theorem 2]. The Bochner integral defines a 1-Lipschitz linear map  $L^1(\nu, E) \rightarrow E$  satisfying the following useful properties.

**Proposition A.1** ([DUJ77, Chapter II, Corollary 5]). *Let  $E$  be a Banach space. Let  $\Phi, \Phi' \in L^1(\nu, E)$ . If*

$$\int \mathbf{1}_B \Phi d\nu = \int \mathbf{1}_B \Phi' d\nu, \quad \forall B \in \mathcal{B},$$

*then  $\Phi = \Phi'$   $\nu$ -almost everywhere.*

**Proposition A.2** ([DUJ77, Chapter II, Theorem 6]). *Let  $E$  and  $F$  be two Banach space. Let  $T: E \rightarrow F$  be a continuous linear operator. For every  $\Phi \in L^1(\nu, E)$ , the function  $T(\Phi)$  belongs to  $L^1(\nu, F)$ . Moreover*

$$T\left(\int \Phi d\nu\right) = \int T(\Phi) d\nu.$$

## A.2 The Radon-Nikodym property

Let  $(X, \mathcal{B}, \nu)$  be a measure space. The standard Radon-Nikodym theorem states that  $L^\infty(\nu)$  is the dual of  $L^1(\nu)$ . In general if  $E$  is an arbitrary Banach space and  $E'$  its dual, the space  $L^\infty(\nu, E')$  is not necessarily the dual of  $L^1(\nu, E)$ . The Radon-Nikodym property defined below is precisely designed to prevent this kind of pathology. See [DUJ77, Chapter III, Definition 3 and Theorem 5].

**Definition A.3.** A Banach space  $E$  has the *Radon-Nikodym property* if for every finite measure space  $(X, \mathcal{B}, \nu)$  the following holds: for every continuous linear map  $T: L^1(\nu) \rightarrow E$  there exists a function  $\Phi \in L^\infty(\nu, E)$  such that

$$T(f) = \int f\Phi d\nu, \quad \forall f \in L^1(\nu).$$

In this definition the integral is a Bochner integral as defined previously. Note that the function  $\Phi$  given by the definition is necessarily unique (Proposition A.1). Moreover one checks that  $\|\Phi\|_\infty = \|T\|$  [DUJ77, Chapter III, Lemma 4].

Recall that a Banach space  $(E, \|\cdot\|)$  is *reflexive* if the evaluation map  $E \rightarrow E''$  from  $E$  to its bidual space  $E''$  is an isomorphism. For instance every Hilbert space is reflexive. The following important result is due to Phillips [Phi43].

**Theorem A.4** ([DUJ77, Chapter III, Corollary 13]). *Reflexive Banach spaces have the Radon-Nikodym property.*

## B Banach lattices

In this section we review the basic properties of Banach spaces endowed with a lattice structure. For an in-depth study of Banach lattices we refer to [Sch74] or [AB06].

### B.1 Definitions and main properties

**Vocabulary and notations.** A *vector lattice*  $(E, \prec)$  (also called Riesz space) is a vector space  $E$  equipped with a partial order  $\prec$ , compatible with the vector space structure, which provides  $E$  with a *lattice* structure, i.e. such that for all  $\phi, \psi \in E$ , the set  $\{\phi, \psi\}$  has a *least upper bound* usually denoted by  $\phi \vee \psi \in E$  and a *greater lower bound*, usually denoted by  $\phi \wedge \psi \in E$ . Given  $\phi \in E$ , its *absolute value*, is the vector

$$|\phi| = \phi \vee (-\phi) = \phi_+ + \phi_-$$

where  $\phi_+ = \phi \vee 0$  and  $\phi_- = (-\phi) \vee 0$  are respectively the positive and negative part of  $\phi$ . The *positive cone* of  $E$ , denoted by  $E^+$ , is the set of vectors  $\phi \in E$

such that  $0 \prec \phi$ . An *ideal* of  $E$  is a vector subspace of  $F$  of  $E$  satisfying the following property: for every  $\phi \in E$  and  $\psi \in F$ , if  $|\phi| \prec |\psi|$ , then  $\phi$  belongs to  $F$ . The vector lattice  $(E, \prec)$  is (*countably*) *order complete* if every non-empty (countable) subset of  $E$  which is bounded from above admits a least upper bound. A norm  $\|\cdot\|$  on  $E$  is *monotone* if we have  $\|\phi_1\| \leq \|\phi_2\|$  whenever  $\phi_1, \phi_2 \in E$  satisfy  $|\phi_1| \prec |\phi_2|$ . If  $E$  is (topologically) complete for such a norm, it is called a *Banach lattice*.

**Monotone convergence.** Recall that a *directed set*  $(A, \prec)$  is a set  $A$  endowed with a partial order  $\prec$  such that for every  $a, a' \in A$ , there exists  $b \in A$  with  $a \prec b$  and  $a' \prec b$ . If  $I$  is a countable set, the collection of all finite subsets of  $I$  endowed with the inclusion is an example of directed set. A *net* is a map  $f: A \rightarrow E$  from a directed set  $(A, \prec)$  to  $(E, \prec)$ . Such a net

- is *non-decreasing* if  $f(a) \prec f(a')$  whenever  $a \prec a'$ ;
- is *norm-bounded* if there exists  $M \in \mathbb{R}_+$  such that for every  $a \in A$ , we have  $\|f(a)\| \leq M$ ;
- *converges to*  $b \in E$  if for every  $\varepsilon \in \mathbb{R}_+^*$ , there exists  $a_0 \in A$ , such that for every  $a \in A$ , with  $a_0 \prec a$ , we have  $\|f(a) - b\| \leq \varepsilon$ . In this case we write  $b = \lim f$ .

**Proposition B.1** (Schaefer [Sch74, Chapter II, Theorem 5.11]). *Assume that  $E$  is a reflexive Banach lattice. Then  $E$  is order complete. Moreover, every non-decreasing norm-bounded net  $f: A \rightarrow E$  converges.*

**Operator between lattices.** Let  $E$  and  $F$  be two vector lattices. A linear operator  $U \in \mathcal{L}(E, F)$  is *positive* if it maps  $E^+$  into  $F^+$ . This defines a partial order on  $\mathcal{L}(E, F)$ : given  $U_1, U_2 \in \mathcal{L}(E, F)$  we say that  $U_1 \prec U_2$  if  $U_2 - U_1$  is positive. However  $\mathcal{L}(E, F)$  endowed with the order is in general not a vector lattice. To bypass this difficult, we consider a smaller subspace of  $\mathcal{L}(E, F)$ . A linear operator  $U: E \rightarrow F$  is *regular* if it can be written as  $U = U_+ - U_-$  where  $U_+$  and  $U_-$  are two positive linear operators from  $E$  to  $F$ . The set of all regular operators from  $E$  to  $F$ , that we denote by  $\mathcal{L}_r(E, F)$ , is a vector subspace of  $\mathcal{L}(E, F)$ .

**Proposition B.2** (Schaefer [Sch74, Chapter IV, Propositions 1.3]). *If  $E$  and  $F$  are two vector lattices and  $F$  is order complete, then  $\mathcal{L}_r(E, F)$  is an order complete vector lattice.*

Suppose now that  $E$  and  $F$  are two Banach lattices and  $F$  is order complete. We write  $\mathcal{B}_r(E, F)$  for the set of *bounded regular operators*, i.e. the elements  $U \in \mathcal{L}_r(E, F)$  such that  $|U|$  is a bounded operator. This space is endowed with an *regular norm* defined by  $\|U\|_r = \||U|\|$  which turn  $\mathcal{B}_r(E, F)$  into a Banach lattice [Sch74, Chapter IV, Propositions 1.4]. Note that both norms  $\|\cdot\|_r$  and  $\|\cdot\|$  coincide on positive operators.

Although  $\mathcal{B}_r(E, F)$  is Banach lattice, we cannot expect as in [Proposition B.1](#) that every non-decreasing norm-bounded net of regular operator converges for the norm  $\|\cdot\|_r$ . However for our purpose, pointwise convergence will be enough.

**Proposition B.3.** *Assume that  $E$  and  $F$  are two Banach lattices and  $F$  is reflexive. Let  $f: A \rightarrow \mathcal{B}_r(E, F)$  be a non-decreasing norm-bounded net. For every  $\phi \in E$ , the net  $f_\phi: A \rightarrow E$  mapping  $a$  to  $f(a)\phi$  converges. Moreover the map  $V: E \rightarrow F$  defined by  $V\phi = \lim f_\phi$  is a bounded regular operator.*



**Remarks.** It  $f(a)$  is positive, for every  $a \in A$ , one easily checks that

$$\|V\| = \sup_{a \in A} \|f(a)\|.$$

*Proof.* Let  $\phi \in E$ . We write  $\phi_+$  and  $\phi_-$  for its positive and negative part respectively. Observe that the nets  $f_{\phi_+}$  and  $f_{\phi_-}$  are non-decreasing and norm-bounded, hence they converge (Proposition B.1). Thus  $f_\phi$  converges as well. One checks easily that the map  $V: E \rightarrow F$  sending  $\phi$  to  $\lim f_\phi$  satisfies the announced properties.  $\square$

**Definition B.4.** Let  $\Gamma$  be a group. We say that a unitary representation  $\rho: \Gamma \rightarrow \mathcal{B}(E)$  is *positive* if  $\rho(\gamma)$  is positive for every  $\gamma \in \Gamma$ .

**Dual space.** Suppose that  $E$  is a Banach lattice. Its (topological) dual space  $E'$  endowed with the order inherited from  $\mathcal{L}(E, \mathbb{R})$  is an order complete Banach lattice [Sch74, Chapter II, Proposition 5.5]. Actually it is isomorphic to  $\mathcal{B}_r(E, \mathbb{R})$  [Sch74, Chapter IV, Theorem 1.5]. Recall that a subspace  $F$  of  $E'$  *separates points* if for every distinct  $\phi, \phi' \in E$ , there exists  $\lambda \in F$  such that  $\lambda(\phi) \neq \lambda(\phi')$ .

**Proposition B.5** ([AB06, Corollary 8.35]). *Assume that  $E$  is a Banach lattice. Let  $F$  be an ideal of  $E'$  which separates the points. A vector  $\phi \in E$  belongs to  $E$  if and only if for every  $\lambda \in F$  such that  $0 \prec \lambda$ , we have  $\lambda(\phi) \geq 0$ .*

## B.2 Examples

We review here the main examples of Banach lattices that are used in the article.

### B.2.1 Koopman representations

In this article we are mostly interested with the following situation. Let  $Y$  be a set endowed with the counting measure. The space  $\mathcal{H} = \ell^2(Y)$  of square summable maps  $\phi: Y \rightarrow \mathbb{R}$ , endowed with the scalar product defined as

$$(\phi_1, \phi_2) = \sum_{y \in Y} \phi_1(y)\phi_2(y),$$

is a Hilbert space, hence a reflexive Banach space. We endow this space with a partial order defined as follows. Given  $\phi, \phi' \in \mathcal{H}$  we say that  $\phi \prec \phi'$  if  $\phi(y) \leq \phi'(y)$  for every  $y \in Y$ . It turns  $\mathcal{H}$  into a Banach lattice.

Let  $\Gamma$  be a discrete group acting on  $Y$ . This action induces a positive unitary representation  $\rho: \Gamma \rightarrow \mathcal{U}(\mathcal{H})$ , called the *Koopman representation*.

### B.2.2 Bochner spaces

Let  $(E, \prec, \|\cdot\|)$  be a Banach lattice and  $(X, \mathcal{B}, \nu)$  a finite measure space. Let  $p \in [1, \infty) \cup \{\infty\}$ . We define a binary relation on the Bochner space  $L^p(\nu, E)$  as follows. Given  $\Phi, \Phi' \in L^p(\nu, E)$ , we say that  $\Phi \prec \Phi'$  if  $\Phi(x) \prec \Phi'(x)$   $\nu$ -almost everywhere. It is obvious that this defines indeed a partial order on  $L^p(\nu, E)$ .

**Lemma B.6.** *The Bochner space  $L^p(\nu, E)$  endowed with  $\prec$  is a Banach lattice.*

*Proof.* It is obvious that the order  $\prec$  is compatible with the vector space structure on  $L^p(\nu, E)$ . Let  $\Phi, \Phi' \in L^p(\nu, E)$ . We define a map  $\Psi: X \rightarrow E$  by  $\Psi(x) = \Phi(x) \vee \Phi'(x)$ , for all  $x \in X$ . We are going to prove that  $\Psi$  is the least upper bound of  $\Phi$  and  $\Phi'$ . Let us first prove that  $\Psi$  is  $\nu$ -measurable and belongs to  $L^p(\nu, E)$ . By definition there exists two sequences  $(\Phi_n)$  and  $(\Phi'_n)$  of simple functions converging  $\nu$ -almost everywhere to  $\Phi$  and  $\Phi'$  respectively. One checks easily that the function  $\Psi_n: X \rightarrow E$  sending  $x$  to  $\Phi_n(x) \vee \Phi'_n(x)$  is also a simple function. On the other hand the operation  $\vee$  is uniformly continuous [Sch74, Chapter II, Proposition 5.1]. It follows that  $(\Psi_n)$  converges  $\nu$ -almost everywhere to  $\Psi$ , hence  $\Psi$  is  $\nu$ -measurable. For every  $x \in X$ , we have

$$\|\Phi(x) \vee \Phi'(x)\| \leq \|\Phi(x)\| + \|\Phi'(x)\|.$$

See for instance [Sch74, Chapter II, Proposition 1.4(6)]. Since  $\Phi$  and  $\Phi'$  belongs to  $L^p(\nu, E)$  so does  $\Psi$ . It is now obvious to check that  $\Psi$  is the least upper bound of  $\Phi$  and  $\Phi'$ . We check in the same manner that the greatest lower bound of  $\Phi$  and  $\Phi'$  is the function  $X \rightarrow E$  sending  $x$  to  $\Phi(x) \wedge \Phi'(x)$ . Thus  $L^p(\nu, E)$  is a vector lattice. Let us prove now that the norm is monotone. Let  $\Phi, \Phi' \in L^p(\nu, E)$  such that  $|\Phi| \prec |\Phi'|$ . It follows from the previous discussion that  $|\Phi|: X \rightarrow E$  is exactly the function sending  $x$  to  $|\Phi(x)|$ . The same holds for  $\Phi'$ , hence  $|\Phi(x)| \prec |\Phi'(x)|$   $\nu$ -almost surely. Since the norm of  $E$  is monotone,  $\|\Phi(x)\| \leq \|\Phi'(x)\|$   $\nu$ -almost surely, hence  $\|\Phi\|_p \leq \|\Phi'\|_p$ . Consequently  $L^p(\nu, E)$  is a Banach lattice.  $\square$

**Lemma B.7.** *If  $E$  is countably order complete, then  $L^p(\nu, E)$  is also .*

*Proof.* Let  $A$  be a non-empty countable subset of  $L^p(\nu, E)$  which is bounded from above. Up to translating  $A$ , we can always assume that  $0$  belongs to  $A$ . Let  $\Psi \in L^p(\nu, E)$  be an upper bound of  $A$ . Since  $A$  is countable, there exists a subset  $B$  of  $X$  with  $\nu(B) = 0$  such that  $\Phi(x) \prec \Psi(x)$  for every  $x \in X \setminus B$ , for every  $\Phi \in A$ . In particular, for every  $x \in X \setminus B$  the set  $\{\Phi(x) \mid \Phi \in A\}$  is non-empty subset of  $E$  containing  $0$  and which is bounded from above. As  $E$  is countably order complete we can define a function  $\Phi_M: X \rightarrow E^+$  by letting

$$\Phi_M(x) = \sup_{\Phi \in A} \Phi(x), \quad \forall x \in X \setminus B.$$

By construction  $0 \prec \Phi_M(x) \prec \Psi(x)$   $\nu$ -almost everywhere. Hence  $0 \prec \Phi_M \prec \Psi$  and  $\|\Phi_M\|_p \leq \|\Psi\|_p$ . In particular  $\Phi_M$  belongs to  $L^p(\nu, E)$ . One checks easily that  $\Phi_M$  is the least upper bound of  $A$ .  $\square$

**Positivity of the Bochner integral.** We now focus on the case where  $p = 1$  and study the behaviour of the Bochner integral with respect the partial order on  $L^1(\nu, E)$ .

**Lemma B.8 (Positivity).** *Let  $\Phi, \Phi' \in L^1(\nu, E)$ . If  $\Phi \prec \Phi'$ , then*

$$\int \Phi d\nu \prec \int \Phi' d\nu.$$

*Proof.* Since the Bochner integral is linear it suffices to prove that the

$$0 \prec \int \Phi d\nu.$$

whenever  $0 \prec \Phi$ . Note that the statement is obvious if  $\Phi$  is a simple function. Hence we are left to prove that every positive function  $\Phi$  is the limit of a sequence  $(\Phi_n)$  of *positive* simple functions. Let  $\Phi \in L^1(\nu, E)$  be such a positive function. There exists a sequence  $(\Phi_n)$  of simple function converging to  $\Phi$  in  $L^1(\nu, E)$ . One checks that  $(\Phi_n \vee 0)$  is a sequence of positive simple functions. As  $L^1(\nu, E)$  is a Banach lattice, the operation  $\vee$  on  $L^1(\nu, E)$  is uniformly continuous, hence  $(\Phi_n \vee 0)$  converges to  $\Phi \vee 0$ , i.e  $\Phi$ .  $\square$

**Proposition B.9.** *Let  $E$  be a Banach lattice. Let  $\Phi \in L^1(\nu, E)$ . If for every  $B \in \mathcal{B}$ , we have*

$$0 \prec \int \mathbf{1}_B \Phi d\nu,$$

then  $0 \prec \Phi$ .

*Proof.* Let  $E'$  be the dual of  $E$ . We consider the bilinear map

$$\begin{aligned} L^\infty(\nu, E') \times L^1(\nu, E) &\rightarrow \mathbb{R} \\ (\Lambda, \Phi) &\rightarrow \int \Lambda(x) [\Phi(x)] d\nu(x) \end{aligned}$$

that we denote by  $(\Lambda, \Phi)$ . This duality product induces an isometric embedding from  $L^\infty(\nu, E')$  into the dual  $D$  of  $L^1(\nu, E)$  [DUJ77, Chapter IV, §1]. Moreover, seen as an subspace of  $D$ , the space  $L^\infty(\nu, E')$  is an ideal that separates the points.

Let  $\lambda \in E'$  such that  $0 \prec \lambda$  and  $B$  be a Borel subspace of  $X$ . It follows from our assumption and Proposition A.2 that the quantity

$$(\mathbf{1}_B \lambda, \Phi) = \int \mathbf{1}_B \lambda \circ \Phi d\nu = \lambda \left( \int \mathbf{1}_B \Phi d\nu \right)$$

is non negative. By linearity, for every positive simple function  $\Lambda \in L^\infty(\nu, E')$ , we have  $(\Lambda, \Phi) \geq 0$ . Let  $\Lambda \in L^\infty(\nu, E')$  be an arbitrary positive function. By definition of  $\nu$ -measurability, there exists a sequence  $(\Lambda_n)$  of simple functions of  $L^\infty(\nu, E')$  which converge to  $\Lambda$   $\nu$ -almost everywhere. Up to replacing  $\Lambda_n$  by  $\Lambda_n \vee 0$  we can assume that each  $\Lambda_n$  is positive. According to the dominated convergence theorem (for Lebesgue integrals)  $(\Lambda_n, \Phi)$  converges to  $(\Lambda, \Phi)$  which is thus non-negative. It follows then from Proposition B.5 that  $0 \prec \Phi$ .  $\square$

## References

- [Aar97] Jon Aaronson, *An introduction to infinite ergodic theory*, Mathematical Surveys and Monographs, vol. 50, American Mathematical Society, Providence, RI, Providence, Rhode Island, 1997.
- [AB06] Charalambos D. Aliprantis and Kim C. Border, *Infinite dimensional analysis*, third ed., Springer, Berlin, 2006, A hitchhiker's guide.
- [ACT15] Goulnara Arzhantseva, Christopher H Cashen, and Jing Tao, *Growth tight actions*, Pacific Journal of Mathematics **278** (2015), no. 1, 1–49.
- [AHO17] C Abbott, D Hume, and Denis V Osin, *Extending group actions on metric spaces*, arXiv.org 1703.03010 (2017).

- [Bab96] Martine Babillot, *Géodésiques et horocycles sur le revêtement d'homologie d'une surface hyperbolique*, Séminaire de Théorie Spectrale et Géométrie, No. 14, Année 1995–1996, Sémin. Théor. Spectr. Géom., vol. 14, Univ. Grenoble I, Saint-Martin-d'Hères, 1996, pp. 89–104.
- [Bar37] Joseph Barta, *Sur la vibration fondamentale d'une membrane*, Comptes Rendus Mathématique. Académie des Sciences. Paris **204** (1937), 472–473.
- [Bas72] Hyman Bass, *The degree of polynomial growth of finitely generated nilpotent groups*, Proceedings of the London Mathematical Society. Third Series **25** (1972), no. 4, 603–614.
- [Bou95] Marc Bourdon, *Structure conforme au bord et flot géodésique d'un CAT(−1)-espace*, L'Enseignement Mathématique. 2e Série **41** (1995), 63–102.
- [BBGo14] Mike Boyle, Jérôme Buzzi, and Ricardo Gómez, *Borel isomorphism of SPR Markov shifts*, Colloquium Mathematicum **137** (2014), no. 1, 127–136.
- [BdlHV08] Bachir Bekka, Pierre de la Harpe, and Alain Valette, *Kazhdan's property (T)*, New Mathematical Monographs, vol. 11, Cambridge University Press, Cambridge, 2008.
- [BF17] Uri Bader and Alex Furman, *Some ergodic properties of metrics on hyperbolic groups*, arXiv.org 1707.02020 (2017).
- [BJ97] Christopher J Bishop and Peter W Jones, *Hausdorff dimension and Kleinian groups*, Acta Mathematica **179** (1997), no. 1, 1–39.
- [BL98] Martine Babillot and François Ledrappier, *Lalley's theorem on periodic orbits of hyperbolic flows*, Ergodic Theory Dynam. Systems **18** (1998), no. 1, 17–39.
- [BM96] Marc Burger and S Mozes, *CAT(−1)-spaces, divergence groups and their commensurators*, Journal of the American Mathematical Society **9** (1996), no. 1, 57–93.
- [BO14] Bachir Bekka and Baptiste Olivier, *On groups with property  $(T_{\ell_p})$* , Journal of Functional Analysis **267** (2014), no. 3, 643–659.
- [Boc33] S Bochner, *Integration von Funktionen, deren Werte die Elemente eines Vektorraumes sind*, Fundamenta Mathematicae **20** (1933), no. 1, 262–176.
- [Bou71] N. Bourbaki, *Éléments de mathématique. Topologie générale. Chapitres 1 à 4*, Hermann, Paris, 1971.
- [Bow08] Rufus Bowen, *Equilibrium states and the ergodic theory of Anosov diffeomorphisms*, revised ed., Lecture Notes in Mathematics, vol. 470, Springer-Verlag, Berlin, Berlin, Heidelberg, 2008.
- [Bow12] Brian H Bowditch, *Relatively hyperbolic groups*, International Journal of Algebra and Computation **22** (2012), no. 3, 1250016–1250066.
- [Bro81] Robert Brooks, *The fundamental group and the spectrum of the Laplacian*, Commentarii Mathematici Helvetici **56** (1981), no. 4, 581–598.

- [Bro85] ———, *The bottom of the spectrum of a Riemannian covering*, Journal für die Reine und Angewandte Mathematik. [Crelle's Journal] **357** (1985), no. 357, 101–114.
- [BT17] Michelle Bucher and Alexey Talambutsa, *Minimal exponential growth rates of metabelian Baumslag–Solitar groups and lamplighter groups*, Groups, Geometry, and Dynamics **11** (2017), no. 1, 189–209.
- [CDP90] Michel Coornaert, Thomas Delzant, and Athanase Papadopoulos, *Géométrie et théorie des groupes*, Lecture Notes in Mathematics, vol. 1441, Springer-Verlag, Berlin, 1990.
- [CG13] J.-P. Conze and Y. Guivarc'h, *Ergodicity of group actions and spectral gap, applications to random walks and Markov shifts*, Discrete Contin. Dyn. Syst. **33**(9) (2013), 4239–4269
- [CDS17] Rémi Coulon, Françoise Dal'Bo, and Andrea Sambusetti, *Growth gap in hyperbolic groups and amenability*, Geometric and Functional Analysis, **28**(5) (2018), 1260–1320 .
- [Cha94] Christophe Champetier, *Petite simplification dans les groupes hyperboliques*, Toulouse. Faculté des Sciences. Annales. Mathématiques. Série 6 **3** (1994), no. 2, 161–221.
- [CHK15] Rémi Coulon, Michael Hull, and Curtis Kent, *A Cartan–Hadamard type result for relatively hyperbolic groups*, Geometriae Dedicata **180** (2015), no. 1, 339–371.
- [CI99] Kevin Corlette and Alessandra Iozzi, *Limit sets of discrete groups of isometries of exotic hyperbolic spaces*, Transactions of the American Mathematical Society **351** (1999), no. 4, 1507–1530.
- [Coh82] Joel M. Cohen, *Cogrowth and amenability of discrete groups*, Journal of Functional Analysis **48** (1982), no. 3, 301–309.
- [Coo93] Michel Coornaert, *Mesures de Patterson–Sullivan sur le bord d'un espace hyperbolique au sens de Gromov*, Pacific Journal of Mathematics **159** (1993), no. 2, 241–270.
- [Cor90] Kevin Corlette, *Hausdorff dimensions of limit sets. I*, Inventiones Mathematicae **102** (1990), no. 3, 521–541.
- [CP01] Michel Coornaert and Athanase Papadopoulos, *Horofunctions and symbolic dynamics on Gromov hyperbolic groups*, Glasgow Mathematical Journal **43** (2001), no. 3, 425–456.
- [CM14a] Mickaël Crampon and Ludovic Marquis, *Finitude géométrique en géométrie de Hilbert*, Annales de l'institut Fourier **64** (2014), no. 6, 2299–2377.
- [CM14b] Mickaël Crampon and Ludovic Marquis, *Le flot géodésique des quotients géométriquement finis des géométries de Hilbert*, Pacific Journal of Mathematics **268** (2014), no. 2, 313–369.
- [Day64] Mahlon Marsh Day, *Convolutions, means, and spectra*, Illinois Journal of Mathematics **8** (1964), 100–111.
- [dC15] Yves de Cornulier, *Irreducible lattices, invariant means, and commensurating actions*, Mathematische Zeitschrift **279** (2015), 1–26.

- [Din67] N Dinculeanu, *Vector measures*, International Series of Monographs in Pure and Applied Mathematics, Vol. 95, Pergamon Press, Oxford-New York-Toronto, Ont.; VEB Deutscher Verlag der Wissenschaften, Berlin, 1967.
- [DOP00] Françoise Dal’Bo, Jean-Pierre Otal, and Marc Peigné, *Séries de Poincaré des groupes géométriquement finis*, Israel Journal of Mathematics **118** (2000), no. 1, 109–124.
- [DPPS11] Françoise Dal’Bo, Marc Peigné, Jean-Claude Picaud, and Andrea Sambusetti, *On the growth of quotients of Kleinian groups*, Ergodic Theory and Dynamical Systems, **31**(3), 835–851 (2011).
- [DPPS17] Françoise Dal’Bo, Marc Peigné, Jean-Claude Picaud, Andrea Sambusetti, *Convergence and counting in infinite measure*, Ann. Inst. Fourier (Grenoble) **67** (2017), no. 2, 483–520
- [DK18] Cornelia Druţu and Michael Kapovich, *Geometric group theory*, American Mathematical Society Colloquium Publications, vol. 63, American Mathematical Society, Providence, RI, 2018.
- [Dou17] Rhiannon Dougall, *Critical exponents of normal subgroups, the spectrum of group extended transfer operators, and Kazhdan distance*, arXiv.org 1702.06115 (2017).
- [DS16] Rhiannon Dougall and Richard Sharp, *Amenability, critical exponents of subgroups and growth of closed geodesics*, Mathematische Annalen **365** (2016), no. 3-4, 1359–1377.
- [DUJ77] J Diestel and J J Uhl Jr, *Vector measures*, American Mathematical Society, Providence, R.I., 1977.
- [Eym72] Pierre Eymard, *Moyennes invariantes et représentations unitaires*, Lecture Notes in Mathematics, Vol. 300, Springer-Verlag, Berlin-New York, 1972.
- [GdlH90] Étienne Ghys and Pierre de la Harpe, *Sur les groupes hyperboliques d’après Mikhael Gromov*, Progress in Mathematics, vol. 83, Birkhäuser Boston, Inc., Boston, MA, Boston, MA, 1990.
- [GM07] Y Glasner and Nicolas Monod, *Amenable actions, free products and a fixed point property*, The Bulletin of the London Mathematical Society **39** (2007), no. 1, 138–150.
- [GM08] Daniel Groves and Jason Fox Manning, *Dehn filling in relatively hyperbolic groups*, Israel Journal of Mathematics **168** (2008), no. 1, 317–429.
- [Gri80] Rostislav I Grigorchuk, *Symmetrical random walks on discrete groups*, Multicomponent random systems, Dekker, New York, 1980, pp. 285–325.
- [Gro87] Michael Gromov, *Hyperbolic groups*, Essays in group theory, Springer, New York, New York, 1987, pp. 75–263.
- [GS98] B M Gurevich and S V Savchenko, *Thermodynamic formalism for symbolic Markov chains with a countable number of states*, Akademiya Nauk SSSR i Moskovskoe Matematicheskoe Obshchestvo. Uspekhi Matematicheskikh Nauk **53** (1998), no. 2(320), 3–106.

- [Gui71] Yves Guivarc'h, *Groupes de Lie à croissance polynomiale*, C. R. Acad. Sci. Paris Sér. A-B **272** (1971), A1695–A1696.
- [Hop37] Eberhard Hopf, *Ergodentheorie*, Springer, Berlin, 1937.
- [Hru10] G Christopher Hruska, *Relative hyperbolicity and relative quasiconvexity for countable groups*, Algebraic & Geometric Topology **10** (2010), no. 3, 1807–1856.
- [Jae14] Johannes Jaerisch, *Fractal models for normal subgroups of Schottky groups*, Transactions of the American Mathematical Society **366** (2014), no. 10, 5453–5485.
- [Jae16] Johannes Jaerisch, *Recurrence and pressure for group extensions*, Ergodic Theory and Dynamical Systems **36**(1) (2016), 108–126.
- [JM13] Kate Juschenko and Nicolas Monod, *Cantor systems, piecewise translations and simple amenable groups*, Annals of Mathematics. Second Series **178** (2013), no. 2, 775–787.
- [Jus15] Kate Juschenko *Amenability of discrete groups by examples* (2015). Current version available at <http://www.math.northwestern.edu/~juschenk/book.html>.
- [Kes59] Harry Kesten, *Symmetric random walks on groups*, Transactions of the American Mathematical Society **92** (1959), 336–354.
- [Mar07] A Marden, *Outer circles*, An Introduction to Hyperbolic 3-Manifolds, Cambridge University Press, Cambridge, Cambridge, 2007.
- [Min05] Igor Mineyev, *Flows and joins of metric spaces*, Geometry & Topology **9** (2005), no. 1, 403–482.
- [Osi07] Denis V Osin, *Peripheral fillings of relatively hyperbolic groups*, Inventiones Mathematicae **167** (2007), no. 2, 295–326.
- [Pap96] Panos Papasoglu, *On the asymptotic cone of groups satisfying a quadratic isoperimetric inequality*, Journal of Differential Geometry **44** (1996), no. 4, 789–806.
- [Par92] Walter Parry, *Growth series of some wreath products*, Transactions of the American Mathematical Society **331** (1992), no. 2, 751–759.
- [Pat76] S J Patterson, *The limit set of a Fuchsian group*, Acta Mathematica **136** (1976), no. 3-4, 241–273.
- [Phi43] R. S. Phillips, *On weakly compact subsets of a Banach space*, Amer. J. Math. **65** (1943), 108–136.
- [PPS15] Frédéric Paulin, Mark Pollicott, and Barbara Schapira, *Equilibrium states in negative curvature*, Astérisque **373** (2015), viii–281.
- [PS18] Vincent Pit and Barbara Schapira, *Finiteness of Gibbs measures on noncompact manifolds with pinched negative curvature*, Université de Grenoble. Annales de l’Institut Fourier **68** (2018), no. 2, 457–510.
- [Rob03] Thomas Roblin, *Ergodicité et équidistribution en courbure négative*, Mémoires de la Société Mathématique de France. Nouvelle Série **95** (2003), vi–96.

- [Rob05] ———, *Un théorème de Fatou pour les densités conformes avec applications aux revêtements galoisiens en courbure négative*, Israel Journal of Mathematics **147** (2005), no. 1, 333–357.
- [RT13] Thomas Roblin and Samuel Tapie, *Exposants critiques et moyennabilité*, Géométrie ergodique, Enseignement Math., Geneva, Hoboken, NJ, USA, 2013, pp. 61–92.
- [Rue03] Sylvie Ruelle, *On the Vere-Jones classification and existence of maximal measures for countable topological Markov chains*, Pacific J. Math. **209** (2003), no. 2, 366–380.
- [RV18] Felipe Riquelme and Anibal Velozo, *Escape of mass and entropy for geodesic flows*, To appear in Ergodic Theory and Dynamical Systems (2018).
- [Sam14] A. Sambarino, *Hyperconvex representations and exponential growth*, Ergodic Theory Dynam. Systems **34** (2014), no. 3, 986–1010.
- [Sar01] Omri M Sarig, *Phase transitions for countable Markov shifts*, Communications in Mathematical Physics **217** (2001), no. 3, 555–577.
- [Sch74] Helmut H Schaefer, *Banach lattices and positive operators*, Springer-Verlag, New York-Heidelberg, 1974.
- [Sch04] Barbara Schapira, *Lemme de l'ombre et non divergence des horosphères d'une variété géométriquement finie*, Ann. Inst. Fourier (Grenoble) **54** (2004), no. 4, 939–987.
- [ST18] Barbara Schapira and Samuel Tapie, *Regularity of entropy, geodesic currents and entropy at infinity*, arXiv.org 1802.04991 (2018).
- [Sta13] Manuel Stadlbauer, *An extension of Kesten's criterion for amenability to topological Markov chains*, Advances in Mathematics **235** (2013), 450–468.
- [Sul87] Dennis Sullivan, *Related aspects of positivity in Riemannian geometry*, Journal of Differential Geometry **25** (1987), no. 3, 327–351.
- [Vel17] Anibal Velozo, *Entropy theory of geodesic flows*, arXiv.org 1711.06796 (2017).
- [Wri71] J D Maitland Wright, *Vector lattice measures on locally compact spaces*, Mathematische Zeitschrift **120** (1971), no. 3, 193–203.
- [Yan16] Wenyan Yang, *Statistically convex-cocompact actions of groups with contracting elements*, arXiv.org 1612.03648 (2016).

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