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# CONVERGENCE AND COUNTING IN INFINITE MEASURE

Françoise Dal'bo  
 Marc Peigné & Jean-Claude Picaud  
 Andrea Sambusetti

## 1. Introduction

Let  $\Gamma$  be a *Kleinian group*, i.e. a discrete, torsionless group of isometries of a Hadamard space  $X$  of negative, pinched curvature  $-B^2 \leq K_X \leq -A^2 < 0$ , with quotient  $\bar{X} = \Gamma \backslash X$ . This paper is concerned with two mutually related problems :

1) The description of the distribution of the orbits of  $\Gamma$  on  $X$ , namely of fine asymptotic properties of the *orbital function* :

$$v_\Gamma(\mathbf{x}, \mathbf{y}; R) := \#\{\gamma \in \Gamma / d(\mathbf{x}, \gamma \cdot \mathbf{y}) \leq R\}$$

for  $\mathbf{x}, \mathbf{y} \in X$ . This has been the subject of many investigations since Margulis' [27] (see Roblin's book [33] and Babillot's report on [1] for a clear overview). The motivations to understand the behavior of the orbital function are numerous : for instance, a simple but important invariant is its *exponential growth rate*

$$\delta_\Gamma = \limsup_{R \rightarrow \infty} \frac{1}{R} \log(v_\Gamma(\mathbf{x}, \mathbf{y}; R))$$

which has a major dynamical significance, since it coincides with the topological entropy of the geodesic flow when  $\bar{X}$  is compact, and is related to many interesting rigidity results and characterization of locally symmetric spaces, cp. [23], [9], [6].

2) The pointwise behavior of the *Poincaré series* associated with  $\Gamma$  :

$$P_\Gamma(\mathbf{x}, \mathbf{y}, s) := \sum_{\gamma \in \Gamma} e^{-sd(\mathbf{x}, \gamma \cdot \mathbf{x})}, \quad \mathbf{x}, \mathbf{y} \in X$$

for and  $s = \delta_\Gamma$ , which coincides with its *exponent of convergence*. The group  $\Gamma$  is said to be *convergent* if  $P_\Gamma(\mathbf{x}, \mathbf{y}, \delta_\Gamma) < \infty$ , and *divergent* otherwise. Divergence can also be understood in terms of dynamics as, by Hopf-Tsuju-Sullivan theorem, it is equivalent to ergodicity and total conservativity of the geodesic flow with respect to the Bowen-Margulis measure on the unit tangent bundle  $U\bar{X}$  (see again [33] for a complete account).

The regularity of the asymptotic behavior of  $v_\Gamma$ , in full generality, is well expressed in Roblin's results, which trace back to Margulis' work in the compact case :

**THEOREM 1.1** (Margulis [27] - Roblin [32], [33]).

Let  $X$  be a Hadamard manifold with pinched negative curvature and  $\Gamma$  a non elementary, discrete subgroup of isometries of  $X$  with non-arithmetic length spectrum<sup>1</sup> :

(i) the exponential growth rate  $\delta_\Gamma$  is a true limit ;

(ii) if  $\|m_\Gamma\| < \infty$ , then  $v_\Gamma(\mathbf{x}, \mathbf{y}; R) \sim \frac{\|\mu_\mathbf{x}\| \cdot \|\mu_\mathbf{y}\|}{\delta_\Gamma \|m_\Gamma\|} e^{\delta_\Gamma R}$  ;

(iii) if  $\|m_\Gamma\| = \infty$  then  $v_\Gamma(\mathbf{x}, \mathbf{y}; R) = o(e^{\delta_\Gamma R})$ ,

where  $(\mu_\mathbf{x})_{\mathbf{x} \in X}$  denotes the family of Patterson conformal densities of  $\Gamma$ , and  $m_\Gamma$  the Bowen-Margulis measure on  $U\bar{X}$ .

Here,  $f \sim g$  means that  $f(t)/g(t) \rightarrow 1$  when  $t \rightarrow \infty$ ; for  $c \geq 1$ , we will write  $f \stackrel{c}{\asymp} g$  when  $\frac{1}{c} \leq f(t)/g(t) \leq c$  for  $t \gg 0$  (or simply  $f \asymp g$  when the constant  $c$  is not specified). The best asymptotic regularity to be expected is the existence of an equivalent, as in (ii); an explicit computation of the second term in the asymptotic development of  $v_\Gamma$  is a difficult question for locally symmetric spaces (and almost a hopeless question in the general Riemannian setting).

1. This means that the set  $\mathcal{L}(\bar{X}) = \{\ell(\gamma) ; \gamma \in \Gamma\}$  of lengths of all closed geodesics of  $\bar{X} = \Gamma \backslash X$  is not contained in a discrete subgroup of  $\mathbb{R}$ .

Theorem 1.1 shows that the key assumption for a regular behavior of  $v_\Gamma$  is that the Bowen-Margulis measure  $m_\Gamma$  is finite. This condition is clearly satisfied for *uniform lattices*  $\Gamma$  (i.e. when  $\bar{X} = X/\Gamma$  is compact), and more generally for groups  $\Gamma$  such that  $m_\Gamma$  has compact support (e.g., *convex cocompact groups*), but it may fail for *nonuniform* lattices, that is when  $\bar{X} = X/\Gamma$  has finite volume but is not compact.

The finiteness of  $m_\Gamma$  has a nice geometrical description in the case of *geometrically finite groups*. Recall that any orbit  $\Gamma \cdot \mathbf{x}$  accumulates on a closed subset  $\Lambda_\Gamma$  of the geometric boundary  $\partial X$  of  $X$ , called the *limit set* of  $\Gamma$ ; the group  $\Gamma$  (or the quotient manifold  $\bar{X}$ ) is said to be geometrically finite if  $\Lambda_\Gamma$  decomposes in the set of *radial limit points* (the limit points  $\xi$  which are approached by orbit points in the  $M$ -neighborhood of any given ray issued from  $\xi$ , for some  $M < \infty$ ) and the set of *bounded parabolic points* (those  $\xi$  fixed by some parabolic subgroup  $P$  acting cocompactly on  $\partial X \setminus \{\xi\}$ ); for a complete study of geometrical finiteness in variable negative curvature see [12] and Proposition 1.10 in [33], and for a description of their topology at infinity see [15]. A finite-volume manifold  $\bar{X}$  is a particular case of geometrically finite manifold : it can be decomposed into a compact set and finitely many *cusps*  $\bar{C}_i$ , i.e. topological ends of  $\bar{X}$  of finite volume which are quotients of a horoball  $\mathcal{H}_{\xi_i}$  centered at a bounded parabolic point  $\xi_i \in \partial X$  by a maximal parabolic subgroup  $P_i \subset \Gamma$  fixing  $\xi_i$ .

The principle ruling the regularity of the orbital function  $v_\Gamma$  of nonuniform lattices, as pointed out in [13] and in the following papers of the authors [16], [17], [18], is that the orbital functions  $v_{P_i}$  (defined in a similar way as  $v_\Gamma$ ) capture the relevant information on the wildness of the metric inside the cusps, which in turn may imply  $\|m_\Gamma\| = \infty$  and the irregularity of  $v_\Gamma$ . In this regard, distinctive properties of the group  $\Gamma$  and of its maximal parabolic subgroups  $P_i$  are their *type* (convergent or divergent, as defined above) and the *critical gap property* (CGP), i.e. if  $\delta_{P_i} < \delta_\Gamma$  for all  $i$ . Actually, in [13] it is proved that, for geometrically finite groups  $\Gamma$ , the divergence of  $P_i$  implies  $\delta_{P_i} < \delta_\Gamma$ , and that the critical gap property implies that the group  $\Gamma$  is divergent with  $\|m_\Gamma\| < \infty$ . On the other hand there exist geometrically finite groups  $\Gamma$  which do not satisfy the CGP : we call such groups *exotic*, and we say that a cusp is *dominant* if it is associated to a parabolic subgroup  $P$  with  $\delta_P = \delta_\Gamma$ . Geometrically finite, exotic groups may as well be convergent or divergent : in the first case, they always have  $\|m_\Gamma\| = \infty$  (by Poincaré recurrence and Hopf-Tsuju-Sullivan theorem, as  $\|m_\Gamma\| < \infty$  implies total conservativity); in the second case, in [13] it is proved that the finiteness of  $m_\Gamma$  depends on the convergence of the special series

$$\sum_{p \in P_i} d(x, px) e^{-\delta_\Gamma d(x, px)} < +\infty.$$

The main aim of this paper is to present examples of lattices  $\Gamma$  for which  $v_\Gamma$  has an irregular asymptotic behavior. According to our discussion, we will then focus on *exotic, non-uniform lattices*. The convergence property of exotic lattices is an interesting question on its own : while uniform lattices (as well as convex-cocompact groups) always are divergent, the only known examples of convergent groups, to the best of our knowledge, are given in [13] and have infinite covolume. The first result of the paper is to show that both convergent and divergent exotic lattices do exist. Actually, in Section 3, by a variation of the construction in [13] we obtain :

**THEOREM 1.2.** *For any  $N \geq 2$ , there exist  $N$ -dimensional, finite volume manifolds of pinched negative curvature whose fundamental group  $\Gamma$  is (exotic and) convergent.*

Constructing exotic, divergent lattices is more subtle. We prove in Section 5 :

**THEOREM 1.3.** *There exist non compact finite area surfaces of pinched negative curvature whose group  $\Gamma$  is exotic and divergent.*

We stress the fact that the examples of Theorem 1.2 have infinite Bowen-Margulis measure ; on the other hand, the surfaces of Theorem 1.3 can have finite or infinite Bowen-Margulis measure, according to the chosen behaviour of the metric in the cusps. Moreover, we believe that the assumption on the dimension in Theorem 1.3 is just technical, but at present we are not able to construct similar examples in dimension  $N \geq 3$ .

Finally, in Section 6 we address the initial question about how irregular the orbital function can be, giving estimates for the orbital function of a large family of exotic lattices with infinite Bowen-Margulis measure :

**THEOREM 1.4.** *Let  $\kappa \in ]1/2, 1[$ . There exist non compact finite area surfaces with pinched negative curvature whose fundamental group  $\Gamma$  satisfies the following asymptotic property : for any  $\mathbf{x}, \mathbf{y} \in X$*

$$v_\Gamma(\mathbf{x}, \mathbf{y}; R) \asymp C \frac{e^{\delta_\Gamma R}}{R^{1-\kappa} L(R)} \quad \text{as } R \rightarrow +\infty$$

for some slowly varying function<sup>2</sup>  $L : \mathbb{R}^+ \rightarrow \mathbb{R}^+$  and some constant  $C = C_{\Gamma, \mathbf{x}, \mathbf{y}} > 0$ .

A general, but more technical, result on the orbital function of divergent, exotic lattices is given in Theorem 6.1. As far as we know, except for some sharp asymptotic formulas established by Pollicott and Sharp [31] for the orbital function of normal subgroups  $\Gamma$  of a cocompact Kleinian group (hence, groups which are far from being geometrically finite or with finite Bowen-Margulis measure), these are the only examples of such precise asymptotic behavior for the orbital function of Kleinian groups with infinite Bowen-Margulis measure.

**Remark.** This work should be considered as a companion paper to [16]& [18], where we study the asymptotic properties of the integral version of  $v_\Gamma$ , i.e. the *growth function* of  $X$  :

$$v_X(\mathbf{x}; R) := \text{vol}_X(B(x, R)).$$

In [18], we obtain optimal conditions on the geometry on the cusps in order that there exists a *Margulis function*, that is a  $\Gamma$ -invariant function  $c : X \rightarrow \mathbb{R}^+$  such that

$$v_X(\mathbf{x}; R) \sim c(\mathbf{x})e^{\omega_X R} \quad \text{for } R \rightarrow +\infty$$

where  $\omega_X$  is the exponential growth rate of the function  $v_X$  (the integral analogue of  $\delta_\Gamma$ ). Notice that  $\omega_X$  can be different from  $\delta_\Gamma$ , also for lattices, as we showed in [16].

## 2. Geometry of negatively curved manifolds with finite volume

**2.1. Landscape.** Additionally to those given in the introduction, we present here notations and familiar results about negatively curved manifolds. Amongst good references we suggest [7], [20], [4] and, more specifically related to this work, [24] and [16]. In the sequel,  $\bar{X} = X/\Gamma$  is a  $N$ -dimensional complete connected Riemannian manifold with metric  $g$  whose sectional curvatures satisfy :  $-B^2 \leq K_X \leq -A^2 < 0$  for fixed constants  $A$  and  $B$ ; we will assume  $0 < A \leq 1 \leq B$  since in most examples  $g$  will be obtained by perturbation of a hyperbolic one and the curvature will equal  $-1$  on large subsets of  $\bar{X}$ .

The family of normalized distance functions :

$$d(\mathbf{x}_0, \mathbf{x}) - d(\mathbf{x}, \cdot)$$

converges uniformly on compacts to the *Busemann function*  $\mathcal{B}_\xi(\mathbf{x}_0, \cdot)$  for  $\mathbf{x} \rightarrow \xi \in \partial X$ . The *horoballs*  $\mathcal{H}_\xi$  (resp. the *horospheres*  $\partial\mathcal{H}_\xi$ ) centered at  $\xi$  are the sup-level sets (resp. the level sets) of the function  $\mathcal{B}_\xi(\mathbf{x}_0, \cdot)$ . Given a horosphere  $\partial\mathcal{H}_\xi$  passing through a point  $\mathbf{x}$ , we also set, for all  $t \in \mathbb{R}$ ,

$$\mathcal{H}_\xi(t) := \{\mathbf{y} / \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{y}) \geq \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{x}) + t\}$$

resp.  $\partial\mathcal{H}_\xi(t) := \{\mathbf{y} / \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{y}) = \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{x}) + t\}$ . We will refer to  $t = \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{y}) - \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{x})$  as to the *height* of  $\mathbf{y}$  (or of the horosphere  $\partial\mathcal{H}_\xi(t)$ ) in  $\mathcal{H}_\xi$ . Also, when no confusion is possible, we will drop the index  $\xi \in \partial X$  denoting the center of the horoball. Also, recall that the Busemann function satisfies the fundamental cocycle relation

$$\mathcal{B}_x(\mathbf{x}, \mathbf{z}) = \mathcal{B}_x(\mathbf{x}, \mathbf{y}) + \mathcal{B}_x(\mathbf{y}, \mathbf{z})$$

which will be crucial in the following.

<sup>2</sup> A function  $L(t)$  is said to be "slowly varying" or "of slow growth" if it is positive, measurable and  $L(\lambda t)/L(t) \rightarrow 1$  as  $t \rightarrow +\infty$  for every  $\lambda > 0$ .

An origin  $\mathbf{x}_0 \in X$  being fixed, the Gromov product between  $x, y \in \partial X \cong \mathbb{S}^{n-1}$ ,  $x \neq y$ , is defined as

$$(x|y)_{\mathbf{x}_0} = \frac{\mathcal{B}_x(\mathbf{x}_0, \mathbf{z}) + \mathcal{B}_y(\mathbf{x}_0, \mathbf{z})}{2}$$

where  $\mathbf{z}$  is any point on the geodesic  $(x, y)$  joining  $x$  to  $y$ ; then, for any  $0 < \kappa^2 \leq A^2$  the expression

$$D(x, y) = e^{-\kappa(x|y)_{\mathbf{x}_0}}$$

defines a distance on  $\partial X$ , cp [10]. Recall that for any  $\gamma \in \Gamma$  one gets

$$(1) \quad D(\gamma \cdot x, \gamma \cdot y) = e^{-\frac{\kappa}{2}\mathcal{B}_x(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)} e^{-\frac{\kappa}{2}\mathcal{B}_y(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)} D(x, y).$$

In other words, the isometry  $\gamma$  acts on  $(\partial X, D)$  as a conformal transformation with coefficient of conformality  $|\gamma'(x)| = e^{-\kappa\mathcal{B}_x(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)}$  at  $x$ , since equality (1) may be rewritten

$$(2) \quad D(\gamma \cdot x, \gamma \cdot y) = \sqrt{|\gamma'(x)||\gamma'(y)|} D(x, y).$$

Recall that  $\Gamma$  is a torsion free nonuniform lattice acting on  $X$  by hyperbolic or parabolic isometries. For any  $\xi \in \partial X$ , denote by  $(\psi_{\xi, t})_{t \geq 0}$  the radial semi-flow defined as follows : for any  $\mathbf{x} \in X$ , the point  $\psi_{\xi, t}(\mathbf{x})$  lies on the geodesic ray  $[\mathbf{x}, \xi)$  at distance  $t$  from  $\mathbf{x}$ . By classical comparison theorems on Jacobi fields (see for instance [24]), the differential of  $\psi_{\xi, t} : \partial\mathcal{H}_\xi \rightarrow \partial\mathcal{H}_\xi(t)$  satisfies  $e^{-Bt}\|v\| \leq \|d\psi_{\xi, t}(v)\| \leq e^{-At}\|v\|$  for any  $t \geq 0$  and any vector  $v$  in the tangent space  $T(\partial\mathcal{H}_\xi)$ ; consequently, if  $\mu_t$  is the Riemannian measure induced on  $\partial\mathcal{H}_\xi(t)$  by the metric of  $X$ , we have, for any Borel set  $F \subset \partial\mathcal{H}_\xi$

$$e^{-B(N-1)t}\mu_0(F) \leq \mu_t(\psi_{\xi, t}(F)) = \int_F |\text{Jac}(\psi_{\xi, t})(x)| d\mu_0(x) \leq e^{-A(N-1)t}\mu_0(F).$$

As  $\bar{X} = \Gamma \backslash X$  is non compact and  $\text{vol}(\bar{X}) < \infty$ , the manifold  $\bar{X}$  can be decomposed into a disjoint union of a relatively compact subset  $\bar{\mathcal{K}}$  and finitely many cusps  $\bar{\mathcal{C}}_1, \dots, \bar{\mathcal{C}}_l$ , each of which is a quotient of a horoball  $\mathcal{H}_{\xi_i}$ , centered at some boundary point  $\xi_i$ , by a maximal parabolic subgroup  $P_i$ . As a consequence of Margulis' lemma, we can choose the family  $(\mathcal{H}_{\xi_i})_{1 \leq i \leq l}$  so that any two  $\Gamma$ -translates of the  $\mathcal{H}_{\xi_i}$  are either disjoint or coincide (cp. [33], Proposition 1.10); we call these  $\mathcal{H}_{\xi_i}$  a *fundamental system of horospheres* for  $X$ . Accordingly, the Dirichlet domain  $\mathcal{D}$  of  $\Gamma$  centered at the base point  $\mathbf{x}_0$  can be decomposed into a disjoint union  $\mathcal{D} = \mathcal{K} \cup \mathcal{C}_1 \cup \dots \cup \mathcal{C}_l$ , where  $\mathcal{K}$  is a convex, relatively compact set containing  $\mathbf{x}_0$  in its interior and projecting to  $\bar{\mathcal{K}}$ , and the  $\mathcal{C}_i$  are connected fundamental domains for the action of  $P_i$  on  $\mathcal{H}_{\xi_i}$ , projecting to  $\bar{\mathcal{C}}_i$ . We let  $\mathcal{S}_i = \mathcal{D} \cap \partial\mathcal{H}_{\xi_i}$  be the corresponding, relatively compact fundamental domain for the action of  $P_i$  on  $\partial\mathcal{H}_{\xi_i}$ , so that  $\mathcal{C}_i = \mathcal{D} \cap \mathcal{H}_{\xi_i} \simeq \mathcal{S}_i \times \mathbb{R}_+$ .

Fixing an end  $\bar{\mathcal{C}}$ , and omitting in what follows the index  $i$ , let  $\mu_t$  be the Riemannian measure induced by the Riemannian metric on the horosphere  $\partial\mathcal{H}_\xi(t)$  corresponding to  $\bar{\mathcal{C}}$ . In [16] we defined the *horospherical area function* associated with the cusp  $\bar{\mathcal{C}}$  as :

$$\mathcal{A}(t) = \mu_t(P \backslash \partial\mathcal{H}_\xi(t)) = \mu_t(\psi_{\xi, t}(\mathcal{S})).$$

This function depends on the choice of the initial horosphere  $\partial\mathcal{H}_\xi$  for the end  $\bar{\mathcal{C}}$ , and the following result shows that this dependance is unessential for our counting problem :

PROPOSITION 2.1. [16] *There exists a constant  $c = c(A, B, \text{diam}(\mathcal{S}))$  such that*

$$v_P(R) \stackrel{c}{\asymp} \frac{1}{\mathcal{A}(\frac{R}{2})}.$$

This weak equivalence is the key to relate the irregularity of the metric in the cusp to the irregular asymptotic behaviour of the orbital function of  $P$ . The second crucial step of our work will then be to describe precisely the contribution of  $v_P$  in the asymptotic behavior of  $v_\Gamma$  assuming  $\delta_P = \delta_\Gamma$ .

**2.2. Cuspidal geometry.** The strategy to construct examples with irregular orbital functions as in Theorems 1.2, 1.3 and 1.4 is to perturb in a suitable manner the metric of a finite volume hyperbolic manifold  $\Gamma \backslash \mathbb{H}^N$  in a cuspidal end  $P \backslash \mathcal{H}$ . If  $\mathcal{H} = \{\mathbf{y} / \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{y}) \geq t_0\}$ , the hyperbolic metric writes on  $\mathcal{H} \simeq \partial \mathcal{H} \times \mathbb{R}_+ \equiv \mathbb{R}^N \times \mathbb{R}_+$  as  $g = e^{-(t-t_0)} d\mathbf{x}^2 + dt^2$  in the horospherical coordinates  $\mathbf{y} = (\mathbf{x}, t)$ , where  $d\mathbf{x}^2$  denotes the induced flat Riemannian metric of  $\partial \mathcal{H}$  and  $t = \mathcal{B}_\xi(\mathbf{x}_0, \mathbf{y}) - t_0$ . We will consider a new metric  $g$  in  $P \backslash \mathcal{H}_\xi$  whose lift to  $\mathcal{H}$  writes, in the same coordinates, as

$$g = \tau^2(t) d\mathbf{x}^2 + dt^2.$$

We extend this metric by  $\Gamma$ -invariance to  $\Gamma \mathcal{H}$  and produce a new Hadamard space  $(X, g)$  with quotient  $\bar{X} = \Gamma \backslash X$ . The new manifold  $\bar{X}$  has again finite volume, provided that

$$\int_0^{+\infty} \tau^{n-1}(t) dt < \infty$$

and the end  $\bar{\mathcal{C}} = P \backslash \mathcal{H}$  is a new cusp; we call the function  $\tau$  the *analytic profile* of the cusp  $\bar{\mathcal{C}}$ . The horospherical area function  $\mathcal{A}$  associated with the profile  $\tau$  satisfies  $\mathcal{A} \asymp \tau^{N-1}$ ; by Proposition 2.1, it implies that :

- (a) the parabolic group  $P$  has critical exponent  $\delta_P = \frac{(N-1)\omega_\tau}{2}$ , for  $\omega_\tau := \limsup_{R \rightarrow +\infty} \frac{1}{R} |\ln(\tau(R))|$ ,
- (b)  $P$  is convergent if and only if  $\int_0^{+\infty} \frac{e^{-\omega_\tau(N-1)t}}{\tau^{N-1}(t)} dt < \infty$ .

Also, notice that the sectional curvatures at  $(\mathbf{x}, t)$  are given by  $K_{(\mathbf{x}, t)}(\frac{\partial}{\partial x_i}, \frac{\partial}{\partial x_j}) = -\left(\frac{\tau'}{\tau}\right)^2$  and  $K_{(\mathbf{x}, t)}(\frac{\partial}{\partial x_i}, \frac{\partial}{\partial t}) = -\frac{\tau''}{\tau}$  (see [5]).

In sections 4, 5 and 6 we will apply this strategy to specific analytic profiles  $\tau$  associated with a function  $\tau$ , and depending on additional real parameters  $a, b, \eta$ , defined as follows. For any convex function  $\tau : \mathbb{R} \rightarrow \mathbb{R}^+$  with  $\int_0^{+\infty} \tau^{n-1}(t) dt < \infty$  and satisfying the conditions

$$(3) \quad \forall t \leq t_0 \quad \tau(t) = e^{-(t-t_0)}$$

$$(4) \quad A < \tau''/\tau < B$$

$$(5) \quad \omega_\tau = \limsup_{t \rightarrow +\infty} \frac{|\ln(\tau(t))|}{t} < B$$

we will set,  $a \geq t_0$

$$\tau_a(t) = e^{-a} \tau(t-a) \quad \text{for } t \in \mathbb{R}.$$

This profile defines a manifold  $\bar{X}$  with a cusp  $\bar{\mathcal{C}}$  which is hyperbolic at height less than  $a$  and then has (renormalized) profile equal to  $\tau$ .

Moreover, given parameters  $a \geq t_0$ ,  $b \geq 0$  and  $\eta \in ]0, A[$ , a straightforward calculus proves the existence of a profile  $\tau_{a,b,\eta}$  such that

$$\begin{cases} A - \eta < \tau''_{a,b,\eta}(t)/\tau_{a,b,\eta}(t) < B + \eta & \text{for all } t, \\ \tau_{a,b,\eta}(t) = e^{-t} & \text{for } t \leq a, \\ \tau_{a,b,\eta}(t) = e^{-\omega_\tau t} & \text{for } t \in [\Delta + a, \Delta + a + b], \\ \tau_{a,b,\eta}(t) = e^{-(2\Delta + a + b)} \tau(t - (2\Delta + a + b)) & \text{for } t \geq 2\Delta + a + b. \end{cases}$$

for some constant  $\Delta = \Delta(A, B, \eta) \gg 0$ . The function  $\tau_{a,b,\eta}$  defines a cusp  $\bar{\mathcal{C}}$  which is hyperbolic till height  $a$ , with constant curvature  $-\omega_\tau^2$  in a band of width  $b$  at height  $\Delta + a$ , and which then has asymptotic (suitable renormalized) profile  $\tau$  after height  $2\Delta + a + b$ .

### 3. Proof of Theorem 1.2 : construction of convergent lattices

An example of manifold of negative curvature with infinite volume and whose fundamental group is convergent is due to Dal'Bo-Otal-Peigné [13]. We propose in this section a variation of their argument to produce a convergent nonuniform *lattice*. We will consider a finite volume hyperbolic manifold  $\Gamma \backslash \mathbb{H}^N$  with *one* cuspidal end  $P \backslash \mathcal{H}$  and deform the metric in this end as explained before to obtain a new Hadamard space  $(X, g)$  such that the quotient  $\bar{X} = \Gamma \backslash X$  has finite volume and a dominant cusp  $\bar{\mathcal{C}} = P \backslash \mathcal{H}$  with a *convergent* parabolic group  $P$ , whose exponent  $\delta_P$  :

- is greater than the Poincaré exponent of  $\Gamma$  acting on  $\mathbb{H}^N$ , that is  $N - 1$  ;
- equals the Poincaré exponent  $\delta_\Gamma$  of  $\Gamma$  corresponding to the new metric.

For this, we choose  $\tau$  satisfying the conditions (3), (4), (5) with  $\delta_P = \frac{(N-1)\omega_\tau}{2} > (N - 1)$  and  $\int_0^{+\infty} \frac{e^{-\omega_\tau(N-1)t}}{\tau(t)^{N-1}} dt < \infty$ , and we consider the profile  $\tau_a$  for some  $a > 0$  to be precised.

Remark that the first condition can be satisfied only if  $\omega_\tau > 2$  which requires  $B^2/A^2 > 4$ . We will denote by  $d$  the distance on  $(X, g)$  corresponding to this new metric, and by  $d_0$  the hyperbolic distance. We emphasize that the perturbation of the metric will not change neither the algebraic structure of the groups  $\Gamma$  and  $P$ , nor the horospheres  $\mathcal{H}(t)$  (which are only modified in size and not as subsets of  $\mathbb{H}^n$ ) and their radial flow ; however, the orbital function has different behavior before and after perturbation.

Now, we need to introduce a natural decomposition of geodesic segments according to their excursions in the cusp, which will enable us to encode elements of  $\Gamma$  by sequences of parabolic elements travelling far in the cusp and elements staying in a fixed, compact subset. We use the same notations as in 2.1 for the compact subset  $\mathcal{K}$ , the fundamental horosphere  $\mathcal{H} = \mathcal{H}_{\xi_1}$  of  $X$ , and the Borel fundamental domain  $\mathcal{S}$  be for the action of  $P$  on  $\partial\mathcal{H}$ . Let  $h > 0$  : for every  $\gamma \in \Gamma$ , the geodesic segment  $[\mathbf{x}_0, \gamma \cdot \mathbf{x}_0]$  intersects  $r = r(\gamma)$  disjoint translates  $g \cdot \mathcal{H}(h)$  (with the convention  $r = 0$  if the intersection with  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(h)$  is empty). In case  $r \geq 1$ , denote by  $\mathbf{z}_1^-, \dots, \mathbf{z}_r^-$  (resp.  $\mathbf{z}_1^+, \dots, \mathbf{z}_r^+$ ) the hitting (resp. exit) points of the oriented geodesic segment  $[\mathbf{x}_0, \gamma \cdot \mathbf{x}_0]$  with translates of  $\mathcal{H}(h)$  in this order. Hence we get

$$[\mathbf{x}_0, \gamma \cdot \mathbf{x}_0] \cap \left( \bigcup_{g \in \Gamma} g \cdot \mathcal{H}(h) \right) = [\mathbf{z}_1^-, \mathbf{z}_1^+] \cup \dots \cup [\mathbf{z}_r^-, \mathbf{z}_r^+].$$

Accordingly, when  $r \geq 1$  we can define the points  $\mathbf{y}_1^-, \mathbf{y}_1^+ \dots \mathbf{y}_r^-, \mathbf{y}_r^+$  on  $[\mathbf{x}_0, g \cdot \mathbf{x}_0]$  such that, for any  $1 \leq i \leq r$ , the geodesic segment  $[\mathbf{y}_i^-, \mathbf{y}_i^+]$  is the connected component of  $[\mathbf{x}_0, \gamma \cdot \mathbf{x}_0] \cap \left( \bigcup_{g \in \Gamma} g \cdot \mathcal{H} \right)$  containing  $[\mathbf{z}_i^-, \mathbf{z}_i^+]$ . We also set  $\mathbf{y}_0^+ = \mathbf{x}_0$  and  $\mathbf{y}_{r+1}^- = \gamma \cdot \mathbf{x}_0$ .

With these notations, there exist uniquely determined isometries  $g_1, \dots, g_r \in \Gamma$  and  $p_1, \dots, p_r \in P$  such that  $\mathbf{y}_1^- \in g_1 \cdot \mathcal{S}$ ,  $\mathbf{y}_1^+ \in g_1 p_1 \cdot \mathcal{S}, \dots, \mathbf{y}_r^+ \in g_1 p_1 \dots g_r p_r \cdot \mathcal{S}$ . Finally, we define  $g_{r+1}$  by the relation

$$\gamma = g_1 p_1 \dots g_r p_r g_{r+1}$$

which we call the *horospherical decomposition of  $\gamma$  at height  $h$* . Notice that this decomposition depends only on the initial hyperbolic metric. We also set  $\mathbf{x}_0^+ = \mathbf{x}_0, \mathbf{x}_{r+1}^- = \gamma \cdot \mathbf{x}_0$  and  $\mathbf{x}_i^- = g_1 p_1 \dots g_i \cdot \mathbf{x}_0, \mathbf{x}_i^+ = g_1 p_1 \dots g_i p_i \cdot \mathbf{x}_0$  for  $1 \leq i \leq r$ . We then have :

**LEMMA 3.1.** *Let  $\gamma = g_1 p_1 \dots p_r g_{r+1}$  be the horospherical decomposition of  $\gamma$  at height  $h$  :*

- (i) *for every  $i \in \{1, \dots, r+1\}$  the geodesic segments  $[\mathbf{x}_{i-1}^+, \mathbf{x}_i^-]$  and  $[\mathbf{x}_0, g_i \cdot \mathbf{x}_0]$  lie outside the set  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(c)$ , for  $c = \text{diam}(\mathcal{K})$  ;*
- (ii) *for every  $i \in \{1, \dots, r\}$  the geodesic segments  $[\mathbf{x}_0, p_i \cdot \mathbf{x}_0]$  have length greater than  $2(h-c)$  and lie outside the set  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(h-c)$ .*

**Proof.** Assume  $r \geq 1$  and fix  $1 \leq i \leq r+1$ . By construction, each geodesic segment  $[\mathbf{y}_{i-1}^+, \mathbf{y}_i^-]$  lies outside  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}$ . Then, each segment  $[\mathbf{x}_{i-1}^+, \mathbf{x}_i^-]$  lies outside  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(c)$  since  $d(\mathbf{x}_{i-1}^+, \mathbf{y}_{i-1}^+)$  and  $d(\mathbf{x}_i^-, \mathbf{y}_i^-)$  are both smaller than  $c$ . Since  $[\mathbf{x}_{i-1}^+, \mathbf{x}_i^-] = g_1 p_1 \dots g_{i-1} p_{i-1} \cdot [\mathbf{x}_0, g_i \cdot \mathbf{x}_0]$  and the set  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(c)$  is  $\Gamma$ -invariant, the same holds for the segment  $[\mathbf{x}_0, g_i \cdot \mathbf{x}_0]$ . To prove statement (2), notice that the segment  $[\mathbf{y}_i^-, \mathbf{y}_i^+]$  intersects the set  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(h)$  and has endpoints in  $\partial\mathcal{H}$ , so that  $d(\mathbf{y}_i^-, \mathbf{y}_i^+) \geq 2h$  ; one concludes using the facts that  $d(\mathbf{x}_i^-, \mathbf{y}_i^-)$  and  $d(\mathbf{x}_i^+, \mathbf{y}_i^+)$  are both smaller than  $c$  and that  $[\mathbf{x}_i^-, \mathbf{x}_i^+] = g_1 p_1 \dots p_{i-1} g_i \cdot [\mathbf{x}_0, p_i \cdot \mathbf{x}_0]$ .  $\square$

Moreover, the distance function is almost additive, with respect to this decomposition :

LEMMA 3.2.

There exists a constant  $C \geq 0$  such that for all  $\gamma \in \Gamma$  with horospherical decomposition  $\gamma = g_1 p_1 \cdots g_r p_r g_{r+1}$  at height  $h$  :

$$d(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0) \geq \sum_{i=1}^{r+1} d(\mathbf{x}_0, g_i \cdot \mathbf{x}_0) + \sum_{i=1}^r d(\mathbf{x}_0, p_i \cdot \mathbf{x}_0) - rC.$$

**Proof.** With the above notations one gets, for  $C := 4\text{diam}(\mathcal{K})$

$$\begin{aligned} d(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0) &= \sum_{i=1}^{r+1} d(\mathbf{y}_{i-1}^+, \mathbf{y}_i^-) + \sum_{i=1}^r d(\mathbf{y}_i^-, \mathbf{y}_i^+) \\ &\geq \sum_{i=1}^{r+1} d(\mathbf{x}_{i-1}^+, \mathbf{x}_i^-) + \sum_{i=1}^r d(\mathbf{x}_i^-, \mathbf{x}_i^+) - 4r\text{diam}(\mathcal{K}) \\ &= \sum_{i=1}^{r+1} d(\mathbf{x}_0, g_i \cdot \mathbf{x}_0) + \sum_{i=1}^r d(\mathbf{x}_0, p_i \cdot \mathbf{x}_0) - rC. \quad \square \end{aligned}$$

Now assume  $a > \max(h, \text{diam}(\mathcal{K}))$  and let

$$P_a = \{p \in P / d_0(\mathbf{x}_0, p \cdot \mathbf{x}_0) \geq 2a\}$$

$$\Gamma_a = \{\gamma \in \Gamma / [\mathbf{x}_0, \gamma \cdot \mathbf{x}_0] \cap g \cdot \mathcal{H}(a) = \emptyset \text{ for all } g \in \Gamma\}$$

for  $t \geq 0$ . Let  $\gamma \in \Gamma$  with horospherical decomposition  $\gamma = g_1 p_1 \cdots g_r p_r g_{r+1}$  at height  $h$ . By Lemma 3.1, the geodesic segments  $[\mathbf{x}_0, g_i \cdot \mathbf{x}_0]$ ,  $1 \leq i \leq r+1$ , stay outside the perturbed set  $\bigcup_{g \in \Gamma} g \cdot \mathcal{H}(a)$ , so that  $g_i \in \Gamma_a$  and  $d(\mathbf{x}_0, g_i \cdot \mathbf{x}_0) = d_0(\mathbf{x}_0, g_i \cdot \mathbf{x}_0)$ . Consequently, the Poincaré series of  $\Gamma$  for the perturbed metric is

$$\begin{aligned} P_\Gamma(\mathbf{x}_0, \delta) &\leq 1 + \sum_{\Gamma_a \setminus \{Id\}} e^{-\delta d(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} + \sum_{p \in P_a} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} + \sum_{r \geq 1} \sum_{\substack{g_1, \dots, g_{r+1} \in \Gamma_a \\ p_1, \dots, p_r \in P_a}} e^{-\delta d(\mathbf{x}_0, g_1 p_1 \cdots g_r p_r g_{r+1} \cdot \mathbf{x}_0)} \\ &\leq \sum_{\gamma \in \Gamma} e^{-\delta d_0(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} + \sum_{p \in P_a} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} + \sum_{r \geq 1} \left( e^{C\delta} \sum_{g \in \Gamma_a} e^{-\delta d(\mathbf{x}_0, g \cdot \mathbf{x}_0)} \sum_{p \in P_a} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \right)^r \\ &\leq \sum_{\gamma \in \Gamma} e^{-\delta d_0(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} + \sum_{p \in P_a} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} + \sum_{r \geq 1} \left( e^{C\delta} \sum_{\gamma \in \Gamma} e^{-\delta d_0(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} \sum_{p \in P_a} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \right)^r \end{aligned}$$

For  $\delta = \delta_P$  the term  $\sum_{\gamma \in \Gamma} e^{-\delta d_0(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} < +\infty$  since  $\delta_P > N-1$ . On the other hand, the group

$P$  being convergent with respect to the new metric  $g$ , we deduce that  $\sum_{p \in P_a} e^{-\delta_P d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \rightarrow 0$

as  $a \rightarrow +\infty$ ; we may thus choose  $a$  large enough so that

$$e^{C\delta_P} \sum_{\gamma \in \Gamma} e^{-\delta_P d_0(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} \sum_{p \in P_a} e^{-\delta_P d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} < 1$$

which readily implies  $P_\Gamma(\mathbf{x}_0, \delta_P) < +\infty$ , hence  $\delta_P \geq \delta_\Gamma$ . As  $P$  is a subgroup of  $\Gamma$ , this implies that  $\delta_P = \delta_\Gamma$ , hence  $\Gamma$  is a convergent group.  $\square$

#### 4. Critical gap property versus divergence

In this section we start constructing a hyperbolic lattice  $\Gamma$  of  $\mathbb{H}^2$  which is generated by suitable parabolic isometries, so that the resulting surface  $\Gamma \backslash \mathbb{H}^2$  has finite volume. In the Poincaré model for the hyperbolic plane, we choose  $r \geq 2$  and  $2r$  boundary points  $\xi_0 = \eta_0, \xi_1, \eta_1, \dots, \xi_r, \eta_r = \xi_0$  of  $\mathbb{S}^1 = \partial \mathbb{B}^2$  in cyclic order, and consider (uniquely determined) parabolic isometries  $p_1, \dots, p_r$  such that for  $1 \leq i \leq r$  we have  $p_i \cdot \xi_i = \xi_i$  and  $p_i \cdot \eta_{i-1} = \eta_i$ . We remark that all  $\eta_i$  belong to the  $\Gamma$  orbit of the point  $\eta_0$ , which is a parabolic fixed point of the isometry  $p_0 := p_r p_{r-1} \cdots p_1$ .



PROPERTY 4.1. *The group  $\Gamma = \langle p_1, \dots, p_r \rangle$  is a free non abelian group over  $p_1, \dots, p_r$ . The quotient  $\Gamma \backslash \mathbb{B}^2$  is a finite surface with  $r + 1$  cuspidal ends, with a cusp  $\mathcal{C}_i$  for each parabolic subgroup  $\mathcal{P}_i = \langle p_i \rangle$  for  $i = 1, \dots, r$ , and another cusp  $\mathcal{C}_0$  corresponding to the parabolic subgroup  $\mathcal{P}_0 = \langle p_0 \rangle$  fixing  $\xi_0$ .*

Each element  $\gamma \in \Gamma \setminus \{\text{Id}\}$  can be written in a unique way as a word with letters in the alphabet  $\mathcal{A} := \{p_1^{\pm 1}, \dots, p_r^{\pm 1}\}$ ; namely, one gets

$$(6) \quad \gamma = p_{j_1}^{\epsilon_1} \cdots p_{j_n}^{\epsilon_n}$$

with  $p_{j_1}^{\epsilon_1}, \dots, p_{j_n}^{\epsilon_n} \in \mathcal{A}$ ,  $n \geq 1$  and with adjacent letters which are not inverse to each other. Such expression with respect to the natural (but not canonical) choice of the alphabet  $\mathcal{A}$  is called a *coding* of elements of  $\Gamma$ . We will call  $j_1$  is the *first index* of  $\gamma$ , denoted by  $i_\gamma$ ; similarly  $j_n$  the *last index* and is denoted by  $l_\gamma$ .

**4.1. A new coding for elements of  $\Gamma$ .** We code here the elements of  $\Gamma$  by blocks, with some admissibility rules to be precised. This new coding is designed to obtain a contraction property for an operator that will be introduced and studied in the next sections whose restriction to some suitable space of functions present remarkable spectral properties. We first rewrite the decomposition (6) as follows

$$(7) \quad \gamma = p_{i_1}^{\ell_1} p_{i_2}^{\ell_2} \cdots p_{i_m}^{\ell_m}$$

with  $m \geq 1$ ,  $\ell_1, \dots, \ell_m \in \mathbb{Z}^*$  and  $i_j \neq i_{j+1}$  for  $1 \leq j < m$ . When all the  $\ell_j$ ,  $1 \leq j \leq m$ , belong to  $\{\pm 1\}$ , one says that  $\gamma$  is a *level 1 word*; the set of such words is denoted by  $\mathcal{W}_1$ . Then, we select all the  $\ell_j$ ,  $1 \leq j \leq m$ , with  $|\ell_j| \geq 2$  and write  $\gamma$  as

$$(8) \quad \gamma = p_{j_0}^{l_0} Q_1 p_{j_1}^{l_1} Q_2 \cdots p_{j_{k-1}}^{l_{k-1}} Q_k p_{j_k}^{l_k}$$

where :

- $k \geq 0$
- $|l_1|, \dots, |l_{k-1}| \geq 2$ ,
- $|l_0|, |l_k| \neq 1$ ,
- each  $Q_j$  is either empty or a level 1 word, with  $i_{Q_j} \neq j_{i-1}$  and  $l_{Q_j} \neq j_i$ .

The decomposition by blocks (8) is still unique; it only uses letters from the new alphabet

$$\mathfrak{B} := \widehat{\mathcal{P}}_1 \cup \cdots \cup \widehat{\mathcal{P}}_r \cup \mathcal{W}_1$$

where  $\widehat{\mathcal{P}}_i := \{p_i^n / |n| \geq 2\}$  for  $1 \leq i \leq r$ , possibly with  $p_{i_0}^{l_0} = 1$  or  $p_{i_r}^{l_r} = 1$ .

We will call *blocks* the letters of this new alphabet, and say that a word  $\beta_1 \cdots \beta_m$  in the alphabet  $\mathfrak{B}$  is *admissible* if the last letter of any block  $\beta_i$  is different from the first one of  $\beta_{i+1}$  for  $1 \leq i \leq m - 1$ . So, any  $\gamma \in \Gamma \setminus \{\text{Id}\}$  can be written as a finite, admissible word  $\beta_1 \cdots \beta_m$  on  $\mathfrak{B}$ ; the ordered sequence of the  $\beta_i$ 's is called the  *$\mathfrak{B}$ -decomposition* of  $\gamma$  and the number  $m$  of blocks is denoted by  $|\gamma|_{\mathfrak{B}}$ . Finally, we denote by  $\Sigma_{\mathfrak{B}}$  the set of all finite admissible words with respect to  $\mathfrak{B}$ .

**4.2. A new metric in the cusps.** We consider a fundamental system of horoballs  $\mathcal{H}_0, \mathcal{H}_1, \mathcal{H}_2, \dots, \mathcal{H}_r$  centered respectively at the parabolic points  $\xi_0, \xi_1, \xi_2, \dots, \xi_r$  and such that all the horoballs  $\gamma \cdot \mathcal{H}_i$ , for  $\gamma \in \Gamma$ ,  $0 \leq i \leq r$ , are disjoint or coincide, as in section 2.1. Then, we modify the hyperbolic metric in the cuspidal ends  $\bar{\mathcal{C}}_i = P_i \backslash \mathcal{H}_i$  as follows. We choose positive constants  $a_0, a_1, \dots, a_{r-1}, a_r, b$  and  $\eta$ , functions  $\tau_0, \tau_1, \dots, \tau_{r-1}$  and  $\tau_r$  as in section 2.2 such that

$$\omega_{\tau_r} = \max(\omega_{\tau_0}, \dots, \omega_{\tau_r}) > 1$$

and we prescribe the profile  $\tau_{i, a_i}$  for the  $i$ -th cusp  $\bar{\mathcal{C}}_i$  for  $0 \leq i \leq r - 1$ , and the profile  $\tau_{r, a_r, b}$  on the last, dominant cusp  $\mathcal{C}_r = \mathcal{C}$ . This yields a new surface  $X = (\mathbb{B}^2, g_{a_0, \dots, a_r, b})$ , with quotient  $\bar{X} = \Gamma \backslash X$  of finite area. Since the metric on  $X$  depends, in particular, on the value of the parameter  $b$ , which will play a crucial role in what follows, we shall denote the induced distances on  $X$ ,  $\partial X \cong \mathbb{S}^1$  and the conformal factor respectively by  $d_b$ ,  $D_b$  and  $|\cdot|_b$ ; on the other hand, we shall omit the index  $b$  in the Busemann function and in the Gromov product, to simplify notations. The dependence of  $D_b$  on the parameter  $b$  is described by the following lemma, whose proof can be found in [30] :

LEMMA 4.2. *Let  $b_0 > 0$  be fixed. There exists  $c \geq 1$  and  $\alpha \in ]0, 1[$  such that the family of distances  $(D_b)_{0 \leq b \leq b_0}$ , are Hölder equivalent; namely for all  $b \in [0, b_0]$  we have*

$$\frac{1}{c} D_0^{1/\alpha} \leq D_b \leq c D_0^\alpha.$$

**4.3. Ping-Pong by blocks.** For any  $1 \leq i \leq r$ , we consider the sub-arcs  $I_i := [\eta_{i-1}, \eta_i]$  and  $I'_i := [p_i^{-1} \cdot \eta_{i-1}, p_i \cdot \eta_i]$  of  $\mathbb{S}^1$  containing  $\xi_i$ . There exists a ping-pong dynamic between these intervals : namely, for any block  $\beta \in \mathfrak{B}$ , we have

- if  $\beta \in \mathcal{W}_1$ , then  $\beta \cdot I'_i \subset I_{i_\beta}$  for any  $i \neq l_\beta$
- if  $\beta \in \widehat{\mathcal{P}}_l$  with  $l = i_\beta = l_\beta$ , then  $\beta \cdot I_i \subset I'_l$  for any  $i \neq l$ .

Moreover, for any  $\gamma$  with  $\mathfrak{B}$ -decomposition  $\beta_1 \cdots \beta_m$ , we define a compact subset  $K_\gamma \subset \mathbb{S}^1$  as follows :

- $K_\gamma = \cup_{i \neq l_\gamma} I'_i$ , if  $\beta_m \in \mathcal{W}_1$
- $K_\gamma = \cup_{i \neq l_\gamma} I_i$ , if  $\beta_m \in \widehat{\mathcal{P}}_l$  with  $l = l_\gamma$ .

Then, using the fact that the closure of the sets  $I'_i$  and  $\partial X \setminus I_i$  are disjoint, one gets :

LEMMA 4.3. *There exists a constant  $C = C(A, \eta) > 0$  such that*

$$d_b(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0) - C \leq \mathcal{B}_x(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) \leq d_b(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)$$

for any  $\gamma \in \Gamma$  and any  $x \in K_\gamma$ .

This lemma implies in particular the following contraction property (see Prop.2.2 in [3] for a detailed proof) :

LEMMA 4.4. *There exist a real number  $r \in ]0, 1[$  and a constant  $C > 0$  such that for any  $\gamma \in \Gamma$  with length  $|\gamma|_{\mathfrak{B}} = k$ , one gets*

$$\forall x \in K_\gamma \quad |\gamma'(x)|_0 \leq C r^k.$$

**4.4. Coding for the limit points.** An infinite word on the alphabet  $\mathfrak{B}$ , i.e. an infinite sequence  $\bar{\beta} = (\beta_n)_{n \geq 1}$  of elements of  $\mathfrak{B}$  is called *admissible* if any finite subword  $\beta_1 \cdots \beta_k$  is admissible; the set of such words is denoted by  $\Sigma_{\mathfrak{B}}^+$ . The contraction property 4.4 implies the following fundamental fact :

LEMMA 4.5. *For any  $\bar{\beta} \in \Sigma_{\mathfrak{B}}^+$ , the sequence  $(\beta_1 \cdots \beta_n \cdot \mathbf{x}_0)_{n \geq 0}$  converges to some point  $\pi(\bar{\beta}) \in \partial X$ ; the map  $\pi : \Sigma_{\mathfrak{B}}^+ \rightarrow \partial X$  is one-to-one, and its image  $\pi(\Sigma_{\mathfrak{B}}^+)$  coincides with the subset  $\partial_0 X := \partial X \setminus \bigcup_{i=0}^r \Gamma \cdot \xi_i$ .*

Notice that, if  $\gamma$  has  $\mathfrak{B}$ -decomposition  $b_1 \cdots b_m$ , then the subset  $K_\gamma$  defined in 4.3 is the closure of the subset corresponding, via the coding map  $\pi$ , to the infinite sequences  $\bar{\beta} = (\beta_n)_{n \geq 1}$  such that the *concatenation*  $\gamma * \bar{\beta} = (b_1 \cdots b_m \beta_1 \cdots \beta_i \cdots)$  is admissible. We also set  $J_\gamma := Cl\{\pi(\gamma * \bar{\beta}) \mid \bar{\beta} \in K_\gamma\}$ , that is the closure of points corresponding to admissible sequences obtained by concatenation with the  $\mathfrak{B}$ -decomposition of  $\gamma$ .

As indicated previously, this coding by blocks is of interest since the classical shift operator on  $\Sigma_{\mathfrak{B}}^+$  induces locally, exponentially expanding maps  $T^n$  on  $\partial_0 X$ ; the map  $T$ , described for instance in details in [14], has countably many inverse branches, each of them acting by contraction on some subset of  $\partial X$ . Namely, we consider on  $\Sigma_{\mathfrak{B}}^+$  the natural shift  $\theta$  defined by

$$\theta(\bar{\beta}) := (\beta_{k+1})_{k \geq 1}, \quad \forall \bar{\beta} = (\beta_k)_{k \geq 1} \in \Sigma_{\mathfrak{B}}^+$$

This map induces a transformation  $T : \partial_0 X \rightarrow \partial_0 X$  via the coding  $\pi$ ; moreover,  $T$  can be extended to the whole  $\partial X$  by setting, for any  $\gamma$  with  $\mathfrak{B}$ -decomposition  $\gamma = \gamma_1 \gamma_2 \cdots \gamma_n$

$$T(\gamma \cdot \xi_i) := \gamma_2 \cdots \gamma_n \cdot \xi_i$$

and  $T(\xi_i) := \xi_i$  for  $i = 0, \dots, n$ . Then, for every block  $\beta \in \mathfrak{B}$ , the restriction of  $T$  to  $J_\beta$  is the action by  $\beta^{-1}$ ; by the dynamic described above, the inverse branches of the map  $T$  have the following property

PROPERTY 4.6. *There exist  $0 < r < 1$  and a constant  $C > 0$  such that, for any  $\gamma \in \Gamma$  with  $|\gamma|_{\mathfrak{B}} = k$  and for  $x, y \in K_\gamma$  we have*

$$D_0(\gamma \cdot x, \gamma \cdot y) \leq Cr^k D_0(x, y).$$

Correspondingly, for  $|\gamma|_{\mathfrak{B}} = k$  and  $x, y \in J_\gamma$ , we have the following expanding property :

$$D_0(T^k x, T^k y) \geq \frac{1}{Cr^k} D_0(x, y)$$

This property is crucial for the investigation of the spectral properties of the transfer operator, which will be introduced in the next section.

## 5. Existence of divergent exotic lattices

This section is devoted to prove Theorem 1.3. An example of an exotic divergent discrete group has already been constructed in [30] : it is a Schottky group  $\Gamma$  generated by both parabolic and hyperbolic isometries, with  $L\Gamma \neq S^1$  and, consequently, the quotient manifold  $\bar{X} = \Gamma \backslash X$  has infinite volume. The strategy in [30] to obtain both exoticity and divergence is the following : one starts from a free, *convergent Schottky group* satisfying a ping-pong dynamics, obtained by perturbation of a hyperbolic metric in one cusp ; then, it is proved that the group becomes divergent if the perturbation of the metric is pushed far away in the cusp ; finally, it is shown that the divergent group can be made exotic (without losing the divergence property) by pushing the perturbation of the metric at a suitable height, by a continuity argument which is consequence of a careful description of the spectrum of a transfer operator naturally associated to  $\Gamma$ . Here, we adapt this approach to obtain a discrete group with finite covolume.

We start from the surface  $\bar{X} = \Gamma \backslash X$  with  $r + 1$  cusps described in 4.2, with a dominant cusp  $\bar{C}_r = P_r \backslash \mathcal{H}_r$  and make  $\Gamma$  convergent by choosing  $a_0, \dots, a_r \gg 0$ , as in Theorem 1.2. Besides a different coding by blocks (due to the generators which are all parabolic) which gives a slightly different expression for the transfer operator associated to  $\Gamma$ , the main difficulty here is to show that  $\Gamma$  can be made divergent. This cannot be achieved now by simply pushing the perturbation far away in the cusp, since in our case  $\delta_{P_r}$  is strictly greater than the critical exponent of the subset of elements staying in the compact, non-perturbed part ; to obtain the divergence we rather modify  $\bar{C}_r$  with a profile  $\tau_{r, a_r, b}$  which equals the profile of a cusp with constant curvature metric  $-\omega_{\tau_r}^2$  on a sufficiently large band of width  $b \gg 0$ . The, we use the spectral properties of the transfer operator to show that there exists a suitable value  $b = b^*$  for which the lattice becomes simultaneously exotic and divergent.

**5.1. On the spectrum of transfer operators.** From the analytic point of view, the action of the geodesic flow is encoded by a *transfer operator* associated to the transformation  $T$  described above. Namely, for any Borel bounded functions  $g : \partial X \rightarrow \mathbb{R}$  we define

$$\mathcal{L}_z \varphi(x) = \sum_{Ty=x} e^{-z\tau(y)} \varphi(y), \quad x \in \partial X$$

for a function  $\tau$  to be defined, depending on the metric  $g_{a_0, \dots, a_r, b}$ , in particular on the width  $b$  of the band in the cusp  $\mathcal{C}_r$  where the curvature is  $-\omega_{\tau_r}^2$ . We will need to understand precisely the dependance on  $b$  when  $b \in [0, b_0]$ , so we stress the dependance on  $b$  writing  $\mathcal{L}_{b, z}$  and  $\tau_b$ . The function  $\tau_b$  we consider is given by

$$\tau_b : y \mapsto \mathcal{B}_{\beta^{-1} \cdot y}(\beta^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) = \mathcal{B}_x(\beta^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)$$

where  $\mathcal{B}_x$  is the Busemann function with respect to the metric  $g = g_{a_0, \dots, a_r, b}$ . The idea behind the choice of  $\tau_b$  is to relate the norm  $|\mathcal{L}_{b, s}^m 1|_\infty$  to the Poincaré series of  $\Gamma$  ; on the other hand, the Busemann functions are good approximations of the distance functions  $d_b$  by 4.3, and are more adapted to express the iterates of  $\mathcal{L}_{b, s}$ , by the cocycle property.

To explicitly express the set  $T^{-1}(x)$  we remark that, the alphabet  $\mathfrak{B}$  being countable, the pre-images of  $x \in \partial X$  by  $T$  are the points  $y = \beta \cdot x$ , for those blocks  $\beta \in \mathfrak{B}$  such that  $x$  belongs to  $K_\beta$ , that is :

- if  $x \in I'_i$  then  $\beta \in \cup_{j \neq i} \hat{\mathcal{P}}_j$  or  $\beta \in \mathcal{W}_1$  with  $l_\beta \neq i$ ,

- if  $x \in I_i \setminus I'_i$  then  $\beta \in \cup_{j \neq i} \widehat{\mathcal{P}}_j$ .

This motivates the introduction of *weight functions*  $w_{b,z}(\gamma, \cdot) : \partial X \rightarrow \mathbb{C}$ , which are defined for  $z \in \mathbb{C}$  and  $\gamma \in \Gamma$  as

$$w_{b,z}(\gamma, x) = 1_{K_\gamma}(x) e^{-z \mathfrak{t}_b(\gamma, x)}$$

We can now make explicit the definition of transfer operators : for  $b \in [0, b_0], z \in \mathbb{C}$  and any bounded Borel function  $\varphi : \partial X \rightarrow \mathbb{C}$  we set

$$(9) \quad (\mathcal{L}_{b,z}\varphi)(x) = \sum_{\beta \in \mathfrak{B}} w_{b,z}(\beta, x) \varphi(\beta \cdot x) = \sum_{\beta \in \mathfrak{B}} 1_{K_\beta}(x) e^{-z \mathcal{B}_x(\beta^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)} \varphi(\beta \cdot x), \quad \forall x \in \partial X$$

The operator  $\mathcal{L}_{b,z}$  is well defined when  $\operatorname{Re}(z) \geq \delta$  and acts on the space  $C(\partial X)$  of  $\mathbb{C}$ -valued continuous functions on  $\partial X$  endowed with the norm  $|\cdot|_\infty$  of the uniform convergence; however, to obtain a quasi-compact operator with good spectral properties, we will consider its restriction to a subspace  $\mathbb{L}_\alpha \subset C(\partial X)$  of Hölder continuous functions with respect to  $D_0$ , for  $\alpha$  given by Lemma 4.2. Namely we let

$$\mathbb{L}_\alpha := \{\varphi \in C(\partial X) : \|\varphi\| = |\varphi|_\infty + [\varphi]_\alpha < +\infty\}$$

where  $[\varphi]_\alpha := \sup_{\substack{x, y \in \partial X \\ x \neq y}} \frac{|\varphi(x) - \varphi(y)|}{D_0^\alpha(x, y)}$ ; then,  $\mathcal{L}_{b,z}$  acts on  $\mathbb{L}_\alpha$  because of the following Lemma

(which is deduced by Lemma 4.2 as Lemma III.3 in [3]) :

LEMMA 5.1. *Each weight  $w_{b,z}(\gamma, \cdot)$  belongs to  $\mathbb{L}_\alpha$  and for any  $z \in \mathbb{C}$ , there exists  $C = C(z) > 0$  such that for any  $\gamma \in \Gamma$*

$$\|w_{b,z}(\gamma, \cdot)\| \leq C e^{-\operatorname{Re}(z) d_b(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)}.$$

Observe now that the  $w_z(\gamma, \cdot)$  satisfy the following cocycle relation : if the  $\mathfrak{B}$ -decomposition of  $\gamma = \gamma_1 \gamma_2$  is given by the simple concatenation  $\gamma_1 * \gamma_2$  of the  $\gamma_i$ , i.e.  $|\gamma_1 \gamma_2|_{\mathfrak{B}} = |\gamma_1|_{\mathfrak{B}} + |\gamma_2|_{\mathfrak{B}}$ , then

$$w_{b,z}(\gamma_1 \gamma_2, x) = w_{b,z}(\gamma_1, \gamma_2 \cdot x) \cdot w_{b,z}(\gamma_2, x).$$

This equality leads to the following simple expression of the iterates of the transfer operators : for any  $n \geq 1$  and  $x \in \partial X$

$$(10) \quad (\mathcal{L}_{b,z}^k \varphi)(x) = \sum_{\substack{\gamma \in \Gamma \\ |\gamma|_{\mathfrak{B}} = n}} w_{b,z}(\gamma, x) \varphi(\gamma \cdot x) = \sum_{\substack{\gamma \in \Gamma \\ |\gamma|_{\mathfrak{B}} = k}} 1_{K_\gamma}(x) e^{-z \mathcal{B}_x(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)} \varphi(\gamma \cdot x).$$

Following [30] and using the contraction property in Lemma 4.4, we first describe the spectrum of the operators  $\mathcal{L}_{b,z}$  for real values of the parameter  $z$  greater than or equal to  $\delta := \omega_\tau/2$  :

PROPOSITION 5.2. *For any  $b \geq 0$  and  $s \geq \delta = \omega_\tau/2$ , the operator  $\mathcal{L}_{b,s}$  acts both on  $(C(\partial X), |\cdot|_\infty)$  and  $(\mathbb{L}_\alpha, \|\cdot\|)$ , with respective spectral radius  $\rho_\infty(\mathcal{L}_{b,s})$  and  $\rho_\alpha(\mathcal{L}_{b,s})$ . Furthermore, the operator  $\mathcal{L}_{b,s}$  is quasi-compact<sup>3</sup> on  $\mathbb{L}_\alpha$ , and :*

- (1) •  $\rho_\alpha(\mathcal{L}_{b,s}) = \rho_\infty(\mathcal{L}_{b,s})$ ,
- $\rho_\alpha(\mathcal{L}_{b,s})$  is a simple, isolated eigenvalue of  $\mathcal{L}_{b,s}$ ,
- the eigenfunction  $h_{b,s}$  associated with  $\rho_\alpha(\mathcal{L}_{b,s})$  is non negative on  $\partial X$ ,
- (2) for any  $s \geq \delta$ , the map  $b \mapsto \mathcal{L}_{b,s}$  is continuous from  $\mathbb{R}^+$  to the space of continuous linear operators on  $\mathbb{L}_\alpha$ ,
- (3) the function  $s \mapsto \rho_\infty(\mathcal{L}_{b,s})$  is decreasing on  $[\delta, +\infty[$ .

REMARK. 5.3. Let  $\rho_{b,s} = \rho_\infty(\mathcal{L}_{b,s})$ . Then,  $\mathcal{L}_{b,s} h_{b,s} = \rho_{b,s} h_{b,s}$ , the function  $h_{b,s}$  being unique up to a multiplicative constant. By duality, there also exists a unique probability measure  $\sigma_{b,s}$  on  $\partial X$  such that  $\sigma_{b,s} \mathcal{L}_{b,s} = \rho_{b,s} \sigma_{b,s}$ ; the function  $h_{b,s}$  becomes uniquely determined imposing the condition  $\sigma_{b,s}(h_{b,s}) = 1$ , which we will assume from now on.

3. In other words its essential spectral radius on this space is less than  $\rho_\alpha(\mathcal{L}_{b,s})$

### 5.2. From convergence to divergence : proof of Theorem 1.3.

Combining expression (10) with Lemma 4.3, one gets for any  $s, b > 0$  and  $k \geq 0$

$$(11) \quad |\mathcal{L}_{b,s}^k 1|_\infty \asymp \sum_{\substack{\gamma \in \Gamma \\ |\gamma|_{\mathfrak{B}} = k}} \exp(-sd_b(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)).$$

Consequently, the Poincaré series  $P_\Gamma(s)$  of  $\Gamma$  relatively to  $d_b$  and the series  $\sum_{k \geq 0} |\mathcal{L}_{b,s}^k 1|_\infty$  converge or diverge simultaneously. Following [30], we see that the function  $s \mapsto \rho_\infty(\mathcal{L}_{b,s})$  is strictly decreasing on  $\mathbb{R}^+$ ; the Poincaré exponent of  $\Gamma$  relatively to  $d_b$  is then equal to

$$\delta_\Gamma = \sup \left\{ s \geq 0 : \rho_\infty(\overline{\mathcal{L}_{b,s}}) \geq 1 \right\} = \inf \left\{ s \geq 0 : \rho_\infty(\mathcal{L}_{b,s}) \leq 1 \right\}.$$

This expression of the Poincaré exponent in terms of the spectral radius of the transfer operator will be useful to prove Theorem 1.3. We first get the

**LEMMA 5.4.** *Assume that the profiles  $\tau_0, \dots, \tau_1, \dots, \tau_r = \tau$  are convergent and satisfy the condition  $\omega_\tau = \max(\omega_{\tau_0}, \dots, \omega_{\tau_r}) > 2$ . Then there exist non negative reals  $a_0, \dots, a_r$  and  $b_0 > 0$  such that*

- *the group  $\Gamma$  has exponent  $\frac{\omega_\tau}{2}$  and is convergent with respect to  $g_{a_0, \dots, a_r, 0}$ ;*
- *the group  $\Gamma$  has exponent  $> \frac{\omega_\tau}{2}$  and is divergent with respect to  $g_{a_0, \dots, a_r, b_0}$ .*

**Proof.** By the previous section and the choice of the profiles  $\tau_i, 0 \leq i \leq r$ , we may fix the constants  $a_0, \dots, a_r$  large enough, in order that the group  $\Gamma$  acting on  $(X, g_{a_0, \dots, a_r, 0})$  is a convergent lattice with exponent  $\delta = \frac{\omega_\tau}{2}$ . Considering just the contribution of words containing powers of  $p_r$ , by the triangle inequality we get

$$\begin{aligned} \sum_{\gamma \in \Gamma} e^{-\delta d_b(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)} &\geq \sum_{k \geq 1} \sum_{\substack{Q_1, \dots, Q_k \in \mathcal{W}_1 \\ |l_1, \dots, l_m| \geq 2}} e^{-\delta d_b(\mathbf{x}_0, p_r^{l_1} Q_1 \cdots p_r^{l_k} Q_k \cdot \mathbf{x}_0)} \\ &\geq \sum_{k \geq 1} \left( \sum_{|l| \geq 2} e^{-\delta d_b(\mathbf{x}_0, p_r^l \cdot \mathbf{x}_0)} \sum_{Q \in \mathcal{W}_1} e^{-\delta d_b(\mathbf{x}_0, Q \cdot \mathbf{x}_0)} \right)^k. \end{aligned}$$

When  $|l|$  is large enough, say  $|l| \geq n_{a_r} \geq 1$ , the geodesic segments  $[\mathbf{x}_0, p^l \cdot \mathbf{x}_0]$  intersect the ‘‘horospherical band’’  $\mathcal{H}_{\xi_r}(a_r, a_r + b) := \mathcal{H}_{\xi_r}(a_r) \setminus \mathcal{H}_{\xi_r}(a_r + b)$  in which the curvature is  $-\omega_\tau^2$ ; more precisely, for any  $b > 0$ , there exists  $n_b \geq n_{a_r}$  such that : for any  $n_{a_r} \leq l \leq n_b$ , two points such that there exist integers  $1 \leq n_{a_r} < n_b$

When  $|l|$  is large enough, say  $|l| \geq n_{a_r} \geq 2$ , the geodesic segments  $[\mathbf{x}_0, p^l \cdot \mathbf{x}_0]$  intersect the horoball  $\mathcal{H}_{\xi_r}(a_r)$ ; furthermore, for any  $b > 0$ , there exists  $n_b \geq n_{a_r}$ , with  $n_b \rightarrow +\infty$  as  $b \rightarrow +\infty$ , such that  $[\mathbf{x}_0, p^l \cdot \mathbf{x}_0] \cap \mathcal{H}_{\xi_r}(a_r + b) = \emptyset$  when  $n_{a_r} \leq |l| \leq b$  so that the geodesic segment  $[\mathbf{x}_0, p^l \cdot \mathbf{x}_0] \cap \mathcal{H}_{\xi_r}(a_r)$  remains in a subset of  $X$  where the curvature is  $-\omega_\tau^2$ . Now, for such  $l$ , the length of the segment  $[\mathbf{x}_0, p^l \cdot \mathbf{x}_0]$ , evaluated either with respect to the metric  $g_b$  or to the hyperbolic metric of curvature  $-\omega_\tau^2$ , equals the length of  $[\mathbf{x}_0, p^l \cdot \mathbf{x}_0] \cap \mathcal{H}_{\xi_r}(a_r)$  up to  $2a_r + c$ , for some  $c > 0$  depending only on the bounds of the curvature; this yields, for  $n_{a_r} \leq |l| \leq n_b$

$$d_b(\mathbf{x}_0, p^l \cdot \mathbf{x}_0) \geq \frac{d_0(\mathbf{x}_0, p^l \cdot \mathbf{x}_0)}{\omega_\tau} - 2(2a_r + c) \geq \frac{2}{\omega_\tau} \ln |l| - 2(2a_r + c)$$

so that, for  $\delta = \frac{\omega_\tau}{2}$  :

$$\sum_{|l| \geq 2} e^{-\delta d_b(\mathbf{x}_0, p^l \cdot \mathbf{x}_0)} \geq \sum_{|l| = n_{a_r}}^{n_b} e^{-\delta d_b(\mathbf{x}_0, p^l \cdot \mathbf{x}_0)} \geq \sum_{|l| = n_{a_r}}^{n_b} \left( \frac{1}{|l|^{2/\omega_\tau}} \right)^{\omega_\tau/2} \rightarrow +\infty \quad \text{as } b \rightarrow +\infty.$$

So, there exists  $b_0 \geq 0$  such that  $\left( \sum_{|l| \geq 2} e^{-\delta d_b(\mathbf{x}_0, p^l \cdot \mathbf{x}_0)} \sum_{Q \in \mathcal{W}_1} e^{-\delta d_b(\mathbf{x}_0, Q \cdot \mathbf{x}_0)} \right) > 1$  as soon as  $b \geq b_0$ ; in particular, by monotone convergence type argument, one gets

$$\left( \sum_{|l| \geq 2} e^{-s d_{b_0}(\mathbf{x}_0, p^l \cdot \mathbf{x}_0)} \sum_{Q \in \mathcal{W}_1} e^{-s d_{b_0}(\mathbf{x}_0, Q \cdot \mathbf{x}_0)} \right) > 1$$

for some  $s > \frac{\omega_\tau}{2}$ . This ensures that  $\delta_\Gamma \geq s > \frac{\omega_\tau}{2} = \delta_{\mathcal{P}_r} = \max\{\delta_{\mathcal{P}_i} \mid 0 \leq i \leq r\}$ , and  $\Gamma$  is divergent with respect to the metric  $g_{a_0, \dots, a_r, b}$  by the critical gap property recalled in the introduction.  $\square$

**Proof of Theorem 1.3.** Recall that  $\delta = \omega_\tau/2$ . Since  $\rho_\alpha(\mathcal{L}_{b, \delta})$  is an eigenvalue of  $\mathcal{L}_{b, \delta}$  which is isolated in the spectrum of  $\mathcal{L}_{b, \delta}$ , the function  $b \mapsto \rho_\alpha(\mathcal{L}_{b, \delta})$  has the same regularity as  $b \mapsto \mathcal{L}_{b, \delta}$ . For  $b_0$  given by Lemma 5.4, we have  $\rho_\alpha(\mathcal{L}_{0, \delta}) = \rho_\infty(\mathcal{L}_{0, \delta}) \leq 1$  and  $\rho_\alpha(\mathcal{L}_{b_0, \delta}) = \rho_\infty(\mathcal{L}_{b_0, \delta}) \geq 1$ ; thus, there exists  $b_* \in [0, b_0]$  such that  $\rho_w(\mathcal{L}_{b^*, \delta}) = \rho_\infty(\mathcal{L}_{b^*, \delta}) = 1$ . Since the function  $s \mapsto \rho_\infty(\mathcal{L}_{b^*, s})$  is strictly decreasing on  $[\delta, +\infty[$ , one gets  $\rho_\infty(\mathcal{L}_{b^*, s}) < 1$  as soon as  $s > \delta$ . For such values of  $s$ , the Poincaré series  $P_\Gamma(s)$  of  $\Gamma$  relatively to the metric  $g_{b^*}$  thus converges, this implies that its Poincaré exponent  $\delta_{\Gamma, b^*}$  is  $\leq \delta$ ; we have in fact  $\delta_{\Gamma, b^*} = \delta$  since  $\delta_{\langle p_r \rangle} = \delta$  and  $p_r \in \Gamma$ . Finally, the eigenfunction  $h_{b^*, \delta}$  of  $\mathcal{L}_{b^*, \delta}$  associated with  $\rho_\alpha(\mathcal{L}_{b^*, \delta})$  being non negative on  $\partial X$ , one gets  $h_{b^*, \delta} \asymp 1$  and so

$$\sum_{k \geq 0} |\mathcal{L}_{b^*, \delta}^k 1|_\infty \asymp \sum_{k \geq 0} |\mathcal{L}_{b^*, \delta}^k h_{b^*, \delta}|_\infty = \sum_{k \geq 0} |h_{b^*, \delta}|_\infty = \infty$$

which implies, by (11), that  $\Gamma$  is divergent with respect to the metric  $g_{b^*}$ .  $\square$

## 6. Counting for some divergent exotic lattices

We consider here the group  $\Gamma = \langle p_1, \dots, p_r \rangle$ ,  $r \geq 2$ , where the  $p_i$ ,  $1 \leq i \leq r$ , satisfy the conditions given in Property 4.1; we endow  $X$  with a metric of the form  $g = g_{a_0, \dots, a_r, b^*}$  as defined in subsection 4.2, where profiles  $\tau_0, \tau_1, \dots, \tau_r$  satisfy conditions (3), (4), (5) and constants  $a_0, a_1, a_2, \dots, a_r$  and  $b^*$  are suitably chosen in such a way

- **H<sub>0</sub>** : the group  $\Gamma$  is exotic and divergent with respect to  $g$ , with Poincaré exponent  $\delta = \delta_\Gamma = \frac{\omega}{2}$  with  $\omega = \max(\omega_{\tau_0}, \dots, \omega_{\tau_r}) > 2$ .

- **H<sub>1</sub>** : the exponential growth of the set  $\{\beta \in \mathcal{W}_1 / d(\mathbf{x}_0, \beta \cdot \mathbf{x}_0) \leq R\}$  as  $R \rightarrow +\infty$  is strictly less than  $\delta$ .

- **H<sub>2</sub>** : there exist  $\kappa \in ]1/2, 1[$  and a slowly varying function <sup>(4)</sup>  $L$  such that

$$(12) \quad \sum_{p \in \mathcal{P}_r / d(\mathbf{x}_0, p \cdot \mathbf{x}_0) > t} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{o})} \underset{t \rightarrow +\infty}{\sim} \frac{L(t)}{t^\kappa}.$$

- **H<sub>3</sub>** : the groups  $\mathcal{P}_l$ ,  $0 \leq l \leq r-1$ , satisfy the condition

$$(13) \quad \sum_{p \in \mathcal{P}_l / d(\mathbf{x}_0, p \cdot \mathbf{x}_0) > t} e^{-\delta d(\mathbf{x}_0, \gamma \cdot \mathbf{o})} = o\left(\frac{L(t)}{t^\kappa}\right).$$

Since  $b^*$  is now fixed, we will omit it in the sequel and set  $d = d_{b^*}$ .

Under those hypotheses, the subgroup  $\mathcal{P}_r$  corresponding to the cusp  $\mathcal{C}_r$  has a dominant influence on the behavior of the orbital function of  $\Gamma$ . Hypothesis **H<sub>2</sub>** is inspired by probability theory, it corresponds to a *heavy tail conditions* satisfied by random walks which have been intensively investigated [21]. Theorem 1.4 will be a direct consequence of the following one :

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4. A function  $L(t)$  is said to be "slowly varying" or "of slow growth" if it is positive, measurable and  $L(\lambda t)/L(t) \rightarrow 1$  as  $t \rightarrow +\infty$  for every  $\lambda > 0$ .

**THEOREM 6.1.** *Let  $\Gamma$  be a finite area Fuchsian group satisfying Property 4.1 and let us endow  $\mathbb{X}$  with a metric  $g$  such that hypotheses  $\mathbf{H}_0, \mathbf{H}_1, \mathbf{H}_2$  and  $\mathbf{H}_3$  hold. Then, for any  $1 \leq j \leq r$ , any fixed  $x_j \notin I_j$ , there exists  $C_j > 0$  such that*

$$(14) \quad \#\{\gamma \in \Gamma_j / \mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) \leq R\} \stackrel{R \rightarrow +\infty}{\sim} C_j \frac{e^{\delta_\Gamma R}}{R^{1-\kappa} L(R)}.$$

where  $\Gamma_j$  denotes the set of  $\gamma \in \Gamma$  with last letter  $j$ .

Indeed, since  $x_j \notin I_j$  is fixed, there exists  $c(x_j) > 0$  such that

$$d(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0) - c(x_j) \leq \mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) \leq d(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0)$$

for any  $\gamma \in \Gamma_j$  and (14) thus implies

$$\#\{\gamma \in \Gamma_j / d(\mathbf{x}_0, \gamma \cdot \mathbf{x}_0) \leq R\} \stackrel{R \rightarrow +\infty}{\sim} \frac{e^{\delta_\Gamma R}}{R^{1-\kappa} L(R)}.$$

Theorem 1.4 follows summing over  $j \in \{1, \dots, r\}$ .

Let us make some remarks :

- (1) We have seen in the previous section how one may choose profiles  $\tau_0, \dots, \tau_r$  and parameters  $a_0, \dots, a_r$  and  $b^*$  in such a way hypothesis  $\mathbf{H}_0$  holds.
- (2) Hypothesis  $\mathbf{H}_1$  holds when  $\omega := \max(\omega_{\tau_0}, \dots, \omega_{\tau_r}) > 2$ ,  $a_0 = +\infty$  and the constants  $a_1, \dots, a_n$  are chosen large enough in such a way all the geodesic paths  $[\mathbf{x}_0, \beta \cdot \mathbf{x}_0], \beta \in \mathcal{W}_1$ , remain in a closed subset of  $X$  where the curvature is  $-1$ ; the exponential growth of  $\{\beta \in \mathcal{W}_1 / d(\mathbf{x}_0, \beta \cdot \mathbf{x}_0) \leq R\}$  as  $R \rightarrow +\infty$  is less or equal to 1 and then strictly less than  $\delta = \omega/2$ .
- (3) Hypothesis  $\mathbf{H}_2$  holds in particular when

$$d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0) = \frac{2 \ln n + 2(1 + \kappa)(\ln \ln n + O(n))}{\omega}$$

for some  $\omega > 2$ . This equality involves only the asymptotic geometry on the cusp  $\mathcal{C}_r$  as it is equivalent to prescribe a profile. Hence it is compatible with any choice of the parameter  $b$ . The critical exponent of  $\mathcal{P}_r$  is thus  $\delta = \omega/2$  and one gets, as  $t \rightarrow +\infty$ ,

$$\begin{aligned} \sum_{p \in \mathcal{P}_r / d(\mathbf{x}_0, p \cdot \mathbf{x}_0) > t} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} &= \sum_{n \in \mathbb{N} / d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0) > t} e^{-\delta d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)} \\ &\asymp \sum_{n > \frac{e^{\omega t/2}}{t^{1+\kappa}}} \frac{1}{n(\ln n)^{1+\kappa}} \\ &\asymp \int_{\frac{e^{\omega t/2}}{t^{1+\kappa}}}^{+\infty} \frac{du}{u(\ln u)^{1+\kappa}} \\ &\asymp \frac{1}{t^\kappa}. \end{aligned}$$

- (4) The condition  $\kappa \in ]1/2, 1[$  readily implies

$$\begin{aligned} \sum_{p \in \mathcal{P}_r} d(\mathbf{x}_0, p \cdot \mathbf{x}_0) e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} &\asymp \sum_{N \geq 1} N \left( \sum_{p \in \mathcal{P}_r / N < d(\mathbf{x}_0, p \cdot \mathbf{x}_0) \leq N+1} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \right) \\ &\asymp \sum_{N \geq 1} \left( \sum_{p \in \mathcal{P}_r / d(\mathbf{x}_0, p \cdot \mathbf{x}_0) > N} e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \right) \\ &\asymp \sum_{N \geq 1} \frac{L(N)}{N^\kappa} = +\infty. \end{aligned}$$

By Theorem B in [13], it readily follows that the Bowen-Margulis measure associated with  $\Gamma$  is infinite.

- (5) Observe at last that hypothesis  $\mathbf{H}_3$  is satisfied in particular when the gap property  $\delta_{\mathcal{P}_l} < \delta$  hold for any  $0 \leq l \leq r-1$ .

We present in this section the main steps of the proof of Theorem 6.1; we refer to [19] for details. For any  $R \geq 0$ , let us denote  $W_j(R, \cdot)$  the measure on  $\mathbb{R}$  defined by : for any Borel non negative function  $\psi : \mathbb{R} \rightarrow \mathbb{R}$

$$W_j(R, \psi) := \sum_{\gamma \in \Gamma_j} e^{-\delta \mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)} \psi(\mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) - R).$$

One gets  $0 \leq W_j(R, \psi) < +\infty$  when  $\psi$  has a compact support in  $\mathbb{R}$  since the group  $\Gamma$  is discrete, furthermore  $\sum_{j=1}^r W_j(R, \psi) = e^{-\delta R} v_\Gamma(R)$  when  $\psi(t) = e^{\delta t} 1_{t \leq 0}$ . If one proves that for any non negative and continuous function  $\psi$  with compact support and such that  $\int_{\mathbb{R}^+} \psi(x) dx > 0$

$$(15) \quad W_j(R, \psi) \underset{R \rightarrow +\infty}{\sim} \frac{C_j}{R^{1-\kappa} L(R)} \int_{\mathbb{R}} \psi(x) dx,$$

this convergence will also hold for non negative functions with compact support in  $\mathbb{R}$  and whose discontinuity set has 0 Lebesgue measure; Theorem 6.1 follows since  $v_\Gamma(R) = e^{\delta R} \sum_{j=1}^r \sum_{n \geq 0} W_j(R, e^{\delta t} 1_{]-(n+1), -n]}(t)$ . From now on, we fix a continuous function  $\psi : \mathbb{R} \rightarrow \mathbb{R}^+$  with compact support; one gets, for  $1 \leq j \leq r$  fixed

$$W_j(R, \psi) = \sum_{k \geq 0} \left( \sum_{\gamma \in \Gamma_j / |\gamma|_{\mathfrak{B}} = k} e^{-\delta \mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0)} \psi(\mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) - R) \right).$$

Notice that for  $\gamma \in \Gamma_j$  with  $\mathfrak{B}$ -decomposition  $\gamma = \beta_1 \cdots \beta_k$ , one gets

$$\begin{aligned} \mathcal{B}_{x_j}(\gamma^{-1} \cdot \mathbf{x}_0, \mathbf{x}_0) &= \mathfrak{r}(\beta_1 \cdots \beta_k \cdot x_j) + \mathfrak{r}(\beta_2 \cdots \beta_k \cdot x_j) + \cdots + \mathfrak{r}(\beta_k \cdot x_j) \\ &= \mathfrak{r}(y) + \mathfrak{r}(T \cdot y) + \cdots + \mathfrak{r}(T^{k-1} \cdot y) = S_k \mathfrak{r}(y) \end{aligned}$$

where one denotes  $y := \gamma \cdot x_j$ , so that

$$(16) \quad W_j(R, \psi) = \sum_{k \geq 0} \sum_{y \in \partial X / T^k \cdot y = x_j} e^{-\delta S_k \mathfrak{r}(y)} \psi(S_k \mathfrak{r}(y) - R).$$

By a classical argument in probability theory due to Stone (see for instance [21]), it suffices to check that the convergence (15) holds when  $\psi$  has a  $C^\infty$  Fourier transform with compact support : indeed, the test function  $\psi$  may vary in the set  $\mathcal{H}$  of functions of the form  $\psi(x) = e^{itx} \psi_0(x)$  where  $\psi_0$  is an integrable and strictly positive function on  $\mathbb{R}$  whose Fourier transform is  $C^\infty$  with compact support. When  $\psi \in \mathcal{H}$ , one can use the inversion Fourier formula and write  $\psi(x) = \frac{1}{2\pi} \int_{\mathbb{R}} e^{-itx} \hat{\psi}(t) dt$ , so that, for any  $0 < s < 1$

$$\begin{aligned} W_j(s, R, \psi) &:= \sum_{k \geq 0} s^k \sum_{y \in \partial X / T^k \cdot y = x_j} e^{-\delta S_k \mathfrak{r}(y)} \psi(S_k \mathfrak{r}(y) - R) \\ &= \sum_{k \geq 0} s^k \sum_{y \in \partial X / T^k \cdot y = x_j} \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} e^{-(\delta+it)S_k \mathfrak{r}(y)} \hat{\psi}(t) dt \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \left( \sum_{k \geq 0} s^k \sum_{y \in \partial X / T^k \cdot y = x_j} e^{-(\delta+it)S_k \mathfrak{r}(y)} \right) dt \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \left( \sum_{k \geq 0} s^k \mathcal{L}_{\delta+it}^k 1(x_j) \right) dt \\ (17) \quad &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) (I - s \mathcal{L}_{\delta+it})^{-1} 1(x_j) dt \end{aligned}$$

where, for any  $z \in \mathbb{C}$ , the operator  $\mathcal{L}_z$  is the transfer operator associated to the function  $\mathfrak{r}$  formally defined in the previous section by : for any Borel bounded function  $\varphi : \partial X \rightarrow \mathbb{C}$  and any  $x \in \partial X$

$$\mathcal{L}_z \varphi(x) := \sum_{y \in \partial X / T \cdot y = x} e^{-z \mathfrak{r}(y)} \varphi(y).$$

We know that the operators  $\mathcal{L}_z, \operatorname{Re}(z) \geq \delta$ , are bounded and quasi-compact on the space  $\mathbb{L}_\omega(\partial X)$  of Hölder continuous function on  $(\partial X, D_0)$ . The subsection 6.1 is devoted to the control of the peripheral spectrum of  $\mathcal{L}_{\delta+it}$  on  $\mathbb{L}_\omega$ . In subsection 6.2, we describe the local



expansion of the dominant eigenvalue. Atlast we achieve the proof using arguments coming from renewal theory (subsection 6.3).

**6.1. The spectrum of  $\mathcal{L}_{\delta+it}$  on  $\mathbb{L}_\omega$ .** First we need to control the spectrum of  $\mathcal{L}_z$  when  $z = \delta + it, t \in \mathbb{R}$ . By Lemma 5.1, the operators  $\mathcal{L}_z$  are bounded on  $\mathbb{L}_\omega$  when  $\operatorname{Re}(z) \geq \delta$ ; the spectral radius of  $\mathcal{L}_z$  will be denoted  $\rho_\omega(z)$  throughout this section. In the following Proposition, we describe its spectrum on  $\mathbb{L}_\omega$  when  $\operatorname{Re}(z) = \delta$ .

**PROPOSITION 6.2.** *There exist  $\epsilon_0 > 0$  and  $\rho_0 \in ]0, 1[$  such that, for any  $t \in \mathbb{R}$  with modulus less than  $\epsilon_0$ , the spectral radius  $\rho_\omega(\delta + it)$  of  $\mathcal{L}_{\delta+it}$  is  $> \rho_0$  and the operator  $\mathcal{L}_{\delta+it}$  has a unique eigenvalue  $\lambda_t$  of modulus  $\rho(\delta + it)$ , which is simple and closed to 1, the rest of the spectrum being included in a disc of radius  $\rho_0$ .*

*Furthermore, for any  $A > 0$ , there exists  $\rho_A \in ]0, 1[$  such that  $\rho_\omega(\delta + it) \leq \rho_A$  for any  $t \in \mathbb{R}$  such that  $\epsilon_0 \leq |t| \leq A$ .*

**NOTATION 6.3.** *We denote  $\sigma$  the unique probability measure on  $\partial X$  such that  $\sigma \mathcal{L}_\delta = \sigma$  and  $h$  the element of  $\mathbb{L}_\omega$  such that  $\mathcal{L}_\delta h = h$  and  $\sigma(h) = 1$ .*

**Proof of Proposition 6.2** This is exactly the same proof that the one presented in [2](Proposition 2.2) and [19] : the operators  $\mathcal{L}_{\delta+it}$  are quasi-compact on  $\mathbb{L}_\omega$  and it is sufficient to control their peripheral spectrum. When  $t$  is closed to 0, we use the perturbation theory to conclude that the spectrum of  $\mathcal{L}_{\delta+it}$  is closed to the one of  $\mathcal{L}_\delta$  : it is thus necessary to prove that the map  $t \mapsto \mathcal{L}_{\delta+it}$  is continuous on  $\mathbb{R}$ . The following Lemma is devoted to precise the type of continuity of this function.

**LEMMA 6.4.** *Under the hypotheses  $\mathbf{H}_1, \mathbf{H}_2$  and  $\mathbf{H}_3$ , there exists a constant  $C > 0$  such that*

$$\|\mathcal{L}_{\delta+it'} - \mathcal{L}_{\delta+it}\| \leq C|t' - t|^\kappa L\left(\frac{1}{|t' - t|}\right)$$

**Proof.** We will use the following classical fact ( [22] p.272 and [21] Lemmas 1 & 2 ) :

**LEMMA 6.5.** *Let  $\mu$  be a probability measure on  $\mathbb{R}^+$ , set  $F_\mu(t) := \mu[0, t]$  and  $m(t) := \int_0^t (1 - F_\mu(s))ds$  and assume that there exist  $\kappa \in \mathbb{R}$  and a slowly varying function  $L$  such that  $1 - F_\mu(t) \sim \frac{L(t)}{t^\kappa}$  as  $t \rightarrow +\infty$ . One thus gets*

$$(18) \quad \lim_{t \rightarrow +\infty} \frac{t(1 - F_\mu(t))}{m(t)} = 1 - \kappa$$

and the characteristic function  $\hat{\mu}(t) := \int_0^{+\infty} e^{itx} \mu(dx)$  of  $\mu$  has the following local expansion as  $t \rightarrow 0^+$

$$(19) \quad \hat{\mu}(t) = 1 - e^{-i\pi \frac{\kappa}{2}} \Gamma(1 - \kappa) t^\kappa L\left(\frac{1}{t}\right) (1 + o(t)).$$

Noticing that  $\tilde{m}(t) := \int_0^t x \mu(dx) = m(t) - t(1 - F_\mu(t))$  one also gets  $\tilde{m}(t) \sim \kappa m(t)$  as  $t \rightarrow +\infty$ ; furthermore, decomposing  $\int_0^{+\infty} |e^{itx} - 1| \mu(dx)$  as  $\int_{[0, 1/t]} |e^{itx} - 1| \mu(dx) + \int_{]1/t, +\infty[} |e^{itx} - 1| \mu(dx)$  and applying the previous estimations, one gets, for any  $t \in \mathbb{R}$

$$\int_0^{+\infty} |e^{itx} - 1| \mu(dx) \preceq t^\kappa L(1/t).$$

We now apply (18) with the probability measures  $\mu_l, 1 \leq l \leq r$ , on  $\mathbb{R}^+$  defined by  $\mu_l := c_l \sum_{p \in \mathcal{P}_l} \delta_{d(\mathbf{x}_0, p \cdot \mathbf{x}_0)}$  where  $c_l > 0$  is some normalizing constant. As a direct consequence, under hypotheses  $\mathbf{H}_1, \mathbf{H}_2$  and  $\mathbf{H}_3$ , one gets (up to a modification of  $L$  by multiplicative constant)

$$(20) \quad \sum_{p \in \mathcal{P}_r / d(\mathbf{x}_0, p \cdot \mathbf{x}_0) \leq t} d(\mathbf{x}_0, p \cdot \mathbf{x}_0) e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \stackrel{t \rightarrow +\infty}{\sim} \frac{t^{1-\kappa}}{1-\kappa} L(t).$$

and

$$(21) \quad \sum_{p \in \mathcal{P}_r} |e^{itd(\mathbf{x}_0, p \cdot \mathbf{x}_0)} - 1| \times e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} \preceq t^\kappa L(1/t);$$

similarly, for  $1 \leq l < r$ , one has

$$(22) \quad \sum_{p \in \mathcal{P}_l} |e^{itd(\mathbf{x}_0, p \cdot \mathbf{x}_0)} - 1| \times e^{-\delta d(\mathbf{x}_0, p \cdot \mathbf{x}_0)} = t^\kappa L(1/t)o(t).$$

In the same way, by lemma 4.3, for any  $x \in \partial X \setminus I_r$ , one gets

$$(23) \quad \sum_{p \in \mathcal{P}_r / \tau(p \cdot x) \leq t} e^{-\delta \tau(p \cdot x)} \preceq \frac{L(t)}{t^\kappa}, \quad \sum_{p \in \mathcal{P}_r / \tau(p \cdot x) > t} \tau(p \cdot x) e^{-\delta \tau(p \cdot x)} \preceq t^{1-\kappa} L(t),$$

$$(24) \quad \sum_{p \in \mathcal{P}_r} |e^{it\tau(p \cdot x)} - 1| \times e^{-\delta \tau(p \cdot x)} \preceq t^\kappa L(1/t)$$

and, for  $1 \leq l \leq r-1$  and  $x \in \partial X \setminus I_l$

$$(25) \quad \sum_{p \in \mathcal{P}_l} |e^{it\tau(p \cdot x)} - 1| \times e^{-\delta \tau(p \cdot x)} = t^\kappa L(1/t)o(t).$$

Similarly, since the exponential growth of the set  $\{\beta \in \mathcal{W}_1 / d(\mathbf{x}_0, \beta \cdot \mathbf{x}_0) \leq R\}$  is  $< \delta$ , we also have, for any  $1 \leq l \leq r$  and  $x \in \cup_{l' \neq l} I_{l'}$

$$(26) \quad \sum_{\substack{\beta \in \mathcal{W}_1 \\ l_\beta = l}} |e^{it\tau(\beta \cdot x)} - 1| \times e^{-\delta \tau(\beta \cdot x)} \preceq t^\kappa L(1/t)o(t).$$

Noticing that for any  $\beta \in \mathfrak{B}$  and  $x \in K_\beta$

$$|w_{\delta+it}(\beta, x) - w_{\delta+it'}(\beta, x)| \leq |e^{i(t-t')\tau(\beta \cdot x)} - 1| \times e^{-\delta \tau(\beta \cdot x)}$$

one readily gets, combining the above estimations (23) to (26) all together

$$(27) \quad |\mathcal{L}_{\delta+it} - \mathcal{L}_{\delta+it'}|_\infty \leq \sum_{\beta \in \mathfrak{B}} |w_{\delta+it}(\beta, \cdot) - w_{\delta+it'}(\beta, \cdot)|_\infty \leq |t - t'|^\kappa L \left( \frac{1}{|t - t'|} \right).$$

Now, for any  $\beta \in \mathfrak{B}$  and  $x, y \in K_\beta$ , one gets

$$\begin{aligned} & \left| (w_{\delta+it}(\beta, x) - w_{\delta+it'}(\beta, x)) - (w_{\delta+it}(\beta, y) - w_{\delta+it'}(\beta, y)) \right| \\ & \leq e^{-\delta \tau(\beta \cdot x)} \times \left| \left( e^{i(t-t')\tau(\beta \cdot x)} - 1 \right) - \left( e^{i(t-t')\tau(\beta \cdot y)} - 1 \right) \right| \\ & \quad + \left| e^{-\delta \tau(\beta \cdot x)} - e^{-\delta \tau(\beta \cdot y)} \right| \times \left| e^{i(t-t')\tau(\beta \cdot y)} - 1 \right| \\ & \leq e^{-\delta \tau(\beta \cdot x)} \times \left| e^{i(t-t')(\tau(\beta \cdot x) - \tau(\beta \cdot y))} - 1 \right| \\ & \quad + e^{-\delta \tau(\beta \cdot y)} \left| e^{\delta(\tau(\beta \cdot y) - \tau(\beta \cdot x))} - 1 \right| \times \left| e^{i(t-t')\tau(\beta \cdot y)} - 1 \right| \\ & \preceq \left( e^{-\delta \tau(\beta \cdot x)} [r \circ \beta] \times |t - t'| + e^{-\delta \tau(\beta \cdot y)} [r \circ \beta] \times \left| e^{i(t-t')\tau(\beta \cdot y)} - 1 \right| \right) D_0(x, y) \end{aligned}$$

so that, as above  $\sum_{\beta \in \mathfrak{B}} [w_{\delta+it}(\beta, \cdot) - w_{\delta+it'}(\beta, \cdot)] \preceq |t - t'|^\kappa L \left( \frac{1}{|t - t'|} \right)$ . We achieve the proof of the Lemma combining this last inequality with (27).  $\square$

**6.2. On the local expansion of the dominant eigenvalue  $\lambda_t$ .** We explicit here the local expansion near 0 of the map  $t \mapsto \lambda_t$ :

PROPOSITION 6.6. *Under the hypotheses  $\mathbf{H}_0$ – $\mathbf{H}_4$ , there exists  $C_\Gamma > 0$  such that*

$$(28) \quad \lambda_t = 1 - C_\Gamma e^{-i\pi \frac{\kappa}{2}} t^\kappa L(1/t) (1 + o(t)).$$

**Proof.** Recall first that 1 is a simple eigenvalue of  $\mathcal{L}_\delta$  with  $\mathcal{L}_\delta h = h$  and  $\sigma(h) = 1$ ; since  $t \mapsto \mathcal{L}_{\delta+it}$  is continuous on  $\mathbb{R}$ , for  $t$  closed to 0 there exists a function  $h_t \in \mathbb{L}_\omega$  such that  $\mathcal{L}_{\delta+it} h_t = \lambda_t h_t$ , this function being unique if we impose the normalization condition  $\sigma(h_t) = 1$ . The maps  $t \mapsto \lambda_t$  and  $t \mapsto h_t$  have the same type of continuity than  $t \mapsto \mathcal{L}_{\delta+it}$  and one gets the identity

$$\lambda_t = \sigma(\mathcal{L}_t h_t) = \sigma(\mathcal{L}_t h) + \sigma((\mathcal{L}_{\delta+it} - \mathcal{L}_\delta)(h_t - h)).$$

By the previous subsection, the second term of this last expression is  $\preceq \left(t^\kappa L(1/t)\right)^2$ . It remains to precise the local behavior of the map  $t \mapsto \sigma(\mathcal{L}_t h)$ ; one gets

$$\sigma(\mathcal{L}_t h) = 1 + \sum_{l=0}^r \sigma_l$$

with  $\sigma_0 := \sum_{\beta \in \mathcal{W}_1} \int_{K_\beta} h(\beta \cdot x) e^{-\delta \mathfrak{r}(\beta \cdot x)} (e^{-it \mathfrak{r}(\beta \cdot x)} - 1) \sigma(dx)$  and, for  $1 \leq l \leq r$

$$\sigma_l := \sum_{\beta \in \mathcal{P}_l} \int_{K_\beta} h(\beta \cdot x) e^{-\delta \mathfrak{r}(\beta \cdot x)} (e^{-it \mathfrak{r}(\beta \cdot x)} - 1) \sigma(dx).$$

By (26), the terms  $\sigma_l, l \neq r$ , are of the form  $t^\kappa L(1/t) o(t)$ . To control the term  $\sigma_r$ , one sets  $\Delta(n, x) := \mathfrak{r}(p_r^n \cdot x) - d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)$  for any  $x \in \partial X \setminus I_r$  and  $n \in \mathbb{Z}$ . The following lemma readily implies that the quantity  $\Delta(n, x)$  tends to  $-(x|\xi_r)_{\mathbf{x}_0}$  as  $|n| \rightarrow +\infty$ .

LEMMA 6.7. *For any parabolic group  $\mathcal{P} := \langle p \rangle$  with fixed point  $\xi$ , we have*

$$\mathcal{B}_x(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_0) = d_b(\mathbf{x}_0, p^n \cdot \mathbf{x}_0) - 2(\xi|x)_{\mathbf{x}_0} + \epsilon_x(n)$$

with  $\lim_{n \rightarrow +\infty} \epsilon_x(n) = 0$ , the convergence being uniform on compact sets of  $\partial X \setminus \{\xi\}$ .

**Proof.** Let  $(\mathbf{x}_m)$  be a sequence of elements of  $X$  converging to  $x$ . We have

$$\begin{aligned} \mathcal{B}_x(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_0) &= \lim_m d(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_m) - d(\mathbf{x}_0, \mathbf{x}_m) \\ &= d(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_0) - \lim_m \left( d(\mathbf{x}_0, \mathbf{x}_m) + d(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_0) - d(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_m) \right) \end{aligned}$$

with

$$\lim_n \left( \lim_m d(\mathbf{x}_0, \mathbf{x}_m) + d(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_0) - d(p^{\pm n} \cdot \mathbf{x}_0, \mathbf{x}_m) \right) = 2 \lim_n (p^{\pm n} \cdot \mathbf{x}_0 | x)_{\mathbf{x}_0} = 2(\xi_h^- | x)_{\mathbf{x}_0}$$

and the conclusion follows as the Gromov product  $(p^{\pm n} \cdot \mathbf{x}_0 | x)_{\mathbf{x}_0}$  tends uniformly to  $(\xi | x)_{\mathbf{x}_0}$  on compacts of  $\mathbb{S}^1 \setminus \{\xi\}$ .  $\square$

We write

$$\begin{aligned} \sigma_r &= \sum_{|n| \geq 2} e^{-\delta d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)} \left( e^{-it d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)} - 1 \right) \int_{\partial X \setminus I_r} h(p_r^n \cdot x) e^{-\delta \Delta(n, x)} \sigma(dx) \\ &\quad + \sum_{|n| \geq 2} e^{-\delta d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)} \int_{\partial X \setminus I_r} h(p_r^n \cdot x) e^{-\delta \Delta(n, x)} \left( e^{-it \mathfrak{r}(p_r^n \cdot x)} - e^{-it d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)} \right) \sigma(dx) \\ &= \sigma_{r1} + \sigma_{r2}. \end{aligned}$$

One gets  $\int_{\partial X \setminus I_r} h(p_r^n \cdot x) e^{-\delta \Delta(n, x)} \sigma(dx) > 0$  for any  $|n| \geq 2$ ; by (19), there exists  $c > 0$  such that

$$\sigma_{r1} = -c e^{-i\pi \frac{\kappa}{2}} \Gamma(1 - \kappa) t^\kappa L\left(\frac{1}{t}\right) (1 + o(t)).$$

On the other hand

$$|\sigma_{r2}| \leq |t| \sum_{|n| \geq 2} e^{-\delta d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)} \int_{\partial X \setminus I_r} h(p_r^n \cdot x) e^{-\delta \Delta(n, x)} |\mathfrak{r}(p_r^n \cdot x) - d(\mathbf{x}_0, p_r^n \cdot \mathbf{x}_0)| \sigma(dx) = O(t).$$

Equality (28) follows immediately.  $\square$

**6.3. Renewal theory and proof of Theorem 6.1.** For technical reasons (see for instance [21]) which will appear in the control of the term  $\widetilde{W}_j^{(3)}(R, \psi)$ , we need to symmetrize the quantities  $W_j(R, \psi)$  and  $W_j(s, R, \psi)$  setting

$$\widetilde{W}_j(R, \psi) := \sum_{k \geq 0} \sum_{y \in \partial X / T^k \cdot y = x_j} e^{-\delta S_k \tau(y)} \left( \psi(S_k \tau(y) - R) + \psi(-S_k \tau(y) - R) \right)$$

and

$$\widetilde{W}_j(s, R, \psi) := \sum_{k \geq 0} s^k \sum_{y \in \partial X / T^k \cdot y = x_j} e^{-\delta S_k \tau(y)} \left( \psi(S_k \tau(y) - R) + \psi(-S_k \tau(y) - R) \right).$$

Notice that, when  $\psi$  is a continuous function with compact support in  $\mathbb{R}^+$ , the terms  $\psi(-S_k \tau(y) - R)$  of these sums vanish for  $R$  large enough, so that  $\widetilde{W}_j(R, \psi) = W_j(R, \psi)$  and  $\widetilde{W}_j(s, R, \psi) = W_j(s, R, \psi)$  in this case. By (17), for any  $0 < s < 1$ , one gets,

$$\begin{aligned} \widetilde{W}_j(s, R, \psi) &:= \sum_{k \geq 0} s^k \sum_{y \in \partial X / T^k \cdot y = x_j} e^{-\delta S_k \tau(y)} \left( \psi(S_k \tau(y) - R) + \psi(-S_k \tau(y) - R) \right) \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \left( (I - s\mathcal{L}_{\delta+it})^{-1} - (I - s\mathcal{L}_{\delta-it})^{-1} \right) 1(x_j) dt. \end{aligned}$$

Fix  $\epsilon_0 > 0$  and let  $\rho(t)$  be a symmetric  $C^\infty$ -function on  $\mathbb{R}$  which is equal to 1 on a  $[-\epsilon_0, \epsilon_0]$  and which vanishes outside  $[-2\epsilon_0, 2\epsilon_0]$ ; one thus decomposes  $\widetilde{W}_j(s, R, \psi)$  as

$$\widetilde{W}_j(s, R, \psi) = \widetilde{W}_j^{(1)}(s, R, \psi) + \widetilde{W}_j^{(2)}(s, R, \psi) + \widetilde{W}_j^{(3)}(s, R, \psi)$$

with

$$\begin{aligned} \widetilde{W}_j^{(1)}(s, R, \psi) &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) (1 - \rho(t)) (I - r\mathcal{L}_{\delta+it})^{-1} 1(x_j) dt \\ &\quad + \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) (1 - \rho(t)) (I - r\mathcal{L}_{\delta-it})^{-1} 1(x_j) dt, \\ \widetilde{W}_j^{(2)}(s, R, \psi) &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \rho(t) \left( (I - r\mathcal{L}_{\delta+it})^{-1} 1(x_j) - \frac{\sigma(\partial X \setminus I_j) h(x_j)}{1 - r\lambda_t} \right) dt \\ &\quad + \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \rho(t) \left( (I - r\mathcal{L}_{\delta-it})^{-1} 1(x_j) - \frac{\sigma(\partial X \setminus I_j) h(x_j)}{1 - r\lambda_{-t}} \right) dt \end{aligned}$$

$$\text{and } \widetilde{W}_j^{(3)}(s, R, \psi) = \frac{\sigma(\partial X \setminus I_j) h(x_j)}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \rho(t) \left( \frac{1}{1 - r\lambda_t} - \frac{1}{1 - r\lambda_{-t}} \right) dt.$$

Using Proposition 6.6, letting  $s \rightarrow 1$ , one gets

$$\widetilde{W}_j(R, \psi) = \widetilde{W}_j^{(1)}(R, \psi) + \widetilde{W}_j^{(2)}(R, \psi) + \widetilde{W}_j^{(3)}(R, \psi)$$

with

$$\begin{aligned} \widetilde{W}_j^{(1)}(R, \psi) &= \lim_{s \nearrow 1} \widetilde{W}_j^{(1)}(s, R, \psi) \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) (1 - \rho(t)) \left( (I - \mathcal{L}_{\delta+it})^{-1} 1(x_j) + (I - \mathcal{L}_{\delta-it})^{-1} 1(x_j) \right) dt, \\ \widetilde{W}_j^{(2)}(R, \psi) &= \lim_{s \nearrow 1} \widetilde{W}_j^{(2)}(s, R, \psi) \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \rho(t) \left( (I - \mathcal{L}_{\delta+it})^{-1} 1(x_j) - \frac{\sigma(\partial X \setminus I_j) h(x_j)}{1 - \lambda_t} \right) dt \\ &\quad + \frac{1}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \rho(t) \left( (I - \mathcal{L}_{\delta-it})^{-1} 1(x_j) - \frac{\sigma(\partial X \setminus I_j) h(x_j)}{1 - \lambda_{-t}} \right) dt \end{aligned}$$

$$\begin{aligned} \text{and } \widetilde{W}_j^{(3)}(R, \psi) &= \lim_{s \nearrow 1} \widetilde{W}_j^{(3)}(s, R, \psi) \\ &= \frac{\sigma(\partial X \setminus I_j) h(x_j)}{2\pi} \int_{\mathbb{R}} e^{itR} \hat{\psi}(t) \rho(t) \operatorname{Re} \left( \frac{1}{1 - \lambda_t} \right) dt. \end{aligned}$$

The functions  $t \mapsto \lambda_t$  has the same regularity as  $t \mapsto L_{\delta+it}$ ; by lemma 6.4 one can thus check that  $\psi_1 : t \mapsto \hat{\psi}(t)(1 - \rho(t)) \left( (I - \mathcal{L}_{\delta+it})^{-1} 1(x_j) + (I - \mathcal{L}_{\delta-it})^{-1} 1(x_j) \right)$  and

$$\begin{aligned} \psi_2 : t \mapsto \hat{\psi}(t)\rho(t) & \left( (I - \mathcal{L}_{\delta+it})^{-1} 1(x_j) - \frac{\sigma(\partial X \setminus I_j)h(x_j)}{1 - \lambda_t} \right. \\ & \left. + (I - \mathcal{L}_{\delta-it})^{-1} 1(x_j) - \frac{\sigma(\partial X \setminus I_j)h(x_j)}{1 - \lambda_{-t}} \right) \end{aligned}$$

satisfy the inequality  $|\psi_k(s) - \psi_k(t)| \preceq |s - t|^\kappa L \left( \frac{1}{|s-t|} \right)$ ,  $k = 1, 2$ . This yields some information on the speed of convergence to 0 of their Fourier transform : indeed, for any  $\theta < \kappa$ , there exists  $C_\theta > 0$  such that

$$(29) \quad \left| \widetilde{W}_j^{(1)}(R, \psi) \right| \leq \frac{C_\theta}{R^\theta} \quad \text{and} \quad \left| \widetilde{W}_j^{(2)}(R, \psi) \right| \leq \frac{C_\theta}{R^\theta}$$

(which readily implies  $\lim_{R \rightarrow +\infty} R^{1-\kappa} L(R) \widetilde{W}_j^{(1)}(R, \psi) = \lim_{R \rightarrow +\infty} R^{1-\kappa} L(R) \widetilde{W}_j^{(2)}(R, \psi) = 0$  as soon as  $\theta \in ]1 - \kappa, \kappa[$ , which is possible since  $\kappa > 1/2$ ).

On the other hand, by section 5 in [21], one gets for  $1/2 < \kappa < 1$

$$\lim_{R \rightarrow +\infty} R^{1-\kappa} L(R) \widetilde{W}_j^{(3)}(R, \psi) = C_j \hat{\psi}(0) = C_j \int_{\mathbb{R}} \psi(x) dx$$

with  $C_j = \sigma(\partial X \setminus I_j)h(x_j) \frac{\sin \pi \kappa}{\pi}$ ; notice that the value  $h(x_j)$  is uniquely determined by the normalization  $\sigma(h) = 1$  (see [26] Theorem 4 for a detailed argument). This achieves the proof of Theorem 6.1.  $\square$

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