TORUS PACKINGS AND SELF-JOININGS OF KLEINIAN GROUPS

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Abstract. For any \(d \geq 1\), we obtain counting and equidistribution results for tori with small volume for a class of \(d\)-dimensional torus packings, invariant under a self-joining \(\Gamma_\rho < \prod_{i=1}^d \text{PSL}_2(\mathbb{C})\) of a Kleinian group \(\Gamma\) formed by a \(d\)-tuple of convex cocompact representations \(\rho = (\rho_1, \cdots, \rho_d)\). More precisely, if \(\mathcal{P}\) is a \(\Gamma_\rho\)-admissible \(d\)-dimensional torus packing, then for any bounded subset \(E \subset \mathbb{C}^d = \mathbb{R}^{2d}\) with boundary contained in a proper real algebraic subvariety, we have

\[
\lim_{s \to 0} s^{L^1(\rho)} \cdot \# \{ T \in \mathcal{P} : \text{Vol}(T) > s, T \cap E \neq \emptyset \} = c_{\mathcal{P}} \cdot \omega_{\psi}(E \cap \Lambda_\rho).
\]

Here \(0 < \delta_{L^1}(\rho) \leq 2/\sqrt{d}\) is the critical exponent of \(\Gamma_\rho\) with respect to the \(L^1\)-metric on the product \(\prod_{i=1}^d \mathbb{H}^3\), \(\Lambda_\rho \subset (\mathbb{C} \cup \{\infty\})^d\) is the limit set of \(\Gamma_\rho\), and \(\omega_{\psi}\) is a locally finite Borel measure on \(\mathbb{C}^d \cap \Lambda_\rho\) which can be explicitly described. The class of admissible torus packings we consider arises naturally from the Teichmüller theory of Kleinian groups. Our work extends previous results of Oh-Shah \cite{os} on circle packings (i.e. one-dimensional torus packings) to \(d\)-torus packings.

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1. Introduction

In this paper, we obtain counting and equidistribution results for a certain class of $d$-dimensional torus packings invariant under self-joinings of Kleinian groups for any $d \geq 1$. One-dimensional torus packings are precisely circle packings. To motivate the formulation of our main results, we begin by reviewing counting results for circle packings that are invariant under Kleinian groups ([13], [20], [21], [22], [24], etc).

Circle packings. A circle packing in the complex plane $\mathbb{C}$ is simply a union of circles in $\mathbb{C}$, for which we allow intersections among themselves. In the whole paper, lines are also considered as circles of infinite radii. Let $\Gamma < \text{PSL}_2(\mathbb{C}) = \text{Isom}^+(\mathbb{H}^3)$ be a Zariski dense convex cocompact discrete subgroup. We call a circle packing $P$ $\Gamma$-admissible if

- $P$ consists of finitely many $\Gamma$-orbits of circles;
- $P$ is locally finite, in the sense that no infinite sequence of circles in $P$ converges to a circle.

We denote by $0 < \delta_\Gamma \leq 2$ the critical exponent of $\Gamma$ that is the abscissa of the Poincare series $P(s) := \sum_{g \in \Gamma} e^{-s d_{\mathbb{H}^3}(go,o)}$ where $o \in \mathbb{H}^3$ is any point and $d_{\mathbb{H}^3}$ is the hyperbolic metric so that $(\mathbb{H}^3, d_{\mathbb{H}^3})$ has the constant curvature $-1$. The extended complex plane $\hat{\mathbb{C}} = \mathbb{C} \cup \{\infty\}$ can be regarded as the geometric boundary of $\mathbb{H}^3$. The limit set of $\Gamma$ is the set of all accumulation points of an orbit $\Gamma(z)$, $z \in \hat{\mathbb{C}}$; we denote it by $\Lambda_\Gamma \subset \hat{\mathbb{C}}$.

Theorem 1.1. [21] For any $\Gamma$-admissible circle packing $P$, there exists a constant $c_P > 0$ such that for any bounded subset $E \subset \mathbb{C}$ whose boundary is contained in a proper real algebraic subvariety of $\mathbb{C} = \mathbb{R}^2$

$$\lim_{s \to 0} s^{\delta_\Gamma} \# \{C \in P : \text{radius}(C) \geq s, \ C \cap E \neq \emptyset\} = c_P \cdot \omega_\Gamma(E \cap \Lambda_\Gamma);$$

here $\omega_\Gamma$ is the $\delta$-dimensional Hausdorff measure on $\mathbb{C} \cap \Lambda_\Gamma$ with respect to the Euclidean metric on $\mathbb{C}$.

This theorem holds for a more general class of circle packings invariant by geometrically finite Kleinian groups, which includes the famous Apollonian circle packings for which the relevant counting result was first obtained in [13] (see [21] for more details and examples).

Torus packings. The main goal of this paper is to prove a higher dimensional analogue of Theorem 1.1. Let $d \geq 1$. A torus in $\mathbb{C}^d$ ($d \geq 1$) is a product of a $d$ number of circles $C_1, \cdots, C_d \subset \mathbb{C}$:

$$T = C_1 \times \cdots \times C_d = (C_1, \cdots, C_d).$$

The volume $\text{Vol}(T)$ of $T$ is given by

$$\text{Vol}(T) = \prod_{i=1}^d 2\pi \cdot \text{radius } C_i.$$
A $d$-dimensional torus packing in $\mathbb{C}^d$ is simply a union of $d$-tori in $\mathbb{C}^d$. We are interested in understanding the asymptotic counting and distribution of tori with small volumes in a torus packing that is invariant under a self-joining of a convex cocompact Kleinian group.

Let $\Gamma < \text{PSL}_2(\mathbb{C})$ be a convex cocompact discrete subgroup and $\rho = (\rho_1 = \text{id}, \rho_2, \cdots, \rho_d)$ be a $d$-tuple of faithful convex cocompact representations of $\Gamma$ into $\text{PSL}_2(\mathbb{C})$. Let $G = \prod_{i=1}^d \text{PSL}_2(\mathbb{C})$. The self-joining of $\Gamma$ via $\rho$ is defined as the following discrete subgroup of $G$:

$$\Gamma_\rho = \left\{ \prod_{i=1}^d \rho_i(g) : g \in \Gamma \right\}.$$

Throughout the paper we will always assume that $\Gamma_\rho$ is Zariski dense in $G$. Each $\rho_i$ induces a unique equivariant homeomorphism $f_i : \Lambda_\Gamma \to \Lambda_{\rho_i}(\Gamma)$, which is called the $\rho_i$-boundary map [30]. The limit set of $\Gamma_\rho$ is given as

$$\Lambda_\rho = \left\{ (f_1(\xi), \cdots, f_d(\xi)) \in \hat{\mathbb{C}}^d : \xi \in \Lambda_\Gamma \right\}.$$

We call a torus $T = (C_1, \cdots, C_d) \Gamma_\rho$-admissible if for each $1 \leq i \leq d$,

- $\rho_i(\Gamma)C_i$ is a locally finite circle packing;
- $f_i(C_i \cap \Lambda_\Gamma) = C_i \cap \Lambda_{\rho_i}(\Gamma)$.

The second condition is equivalent to $T \cap \Lambda_\rho = \{(\xi_1, \cdots, \xi_d) \in \Lambda_\rho : \xi_1 \in C_1 \cap \Lambda_\Gamma\}$, that is, the circular slice $C_1 \cap \Lambda_\Gamma$ completely determines the toric slice $T \cap \Lambda_\rho$.

**Definition 1.2.** A torus packing $\mathcal{P}$ is called $\Gamma_\rho$-admissible if

- $\mathcal{P}$ consists of finitely many $\Gamma_\rho$-orbits of $\Gamma_\rho$-admissible tori;
- $\mathcal{P}$ is locally finite in the sense that no infinite sequence of tori in $\mathcal{P}$ converges to a torus.

**Remark 1.3.** We remark that when $\# C_1 \cap \Lambda_\Gamma \geq 3$, the locally finiteness hypotheses in the above definition can be reduced to the local-finiteness of the circle packing $\Gamma C_1$ (see Prop. [3.10]).
We denote by $\delta_{L^1}(\rho)$ the abscissa of convergence of the series
\[ s \mapsto \mathbb{P}_{L^1}(s) := \sum_{\gamma \in \Gamma} e^{-s \sum_{i=1}^d d_{\mathbb{H}^3}(\rho_i(\gamma) \cdot o, o)} \]
for $o \in \mathbb{H}^3$, which is the critical exponent of $\Gamma_\rho$ with respect to the $L^1$-metric on $\prod_{i=1}^d (\mathbb{H}^3, d_{\mathbb{H}^3})$.

We first state the following special case of the main result of this paper:

**Theorem 1.4.** Let $P$ be a $\Gamma_\rho$-admissible torus packing. There exists a constant $c_P > 0$ such that for any bounded subset $E \subset \mathbb{C}^d$ with boundary contained in a proper real algebraic subvariety, we have
\[ \lim_{s \to 0} s^{\delta_{L^1}(\rho)} \cdot \#\{T \in \mathcal{P} : \text{Vol}(T) > s, T \cap E \neq \emptyset\} = c_P \cdot \omega_{\Gamma_\rho}(E \cap \Lambda_\rho), \]
where $\omega_{\Gamma_\rho}$ is a locally finite Borel measure on $\mathbb{C}^d \cap \Lambda_\rho$ which can be explicitly described. In particular, if $\mathcal{P}$ is bounded, then
\[ \lim_{s \to 0} s^{\delta_{L^1}(\rho)} \cdot \#\{T \in \mathcal{P} : \text{Vol}(T) > s\} = c_P. \]

**Remark 1.5.**

(1) Since $\delta_{L^1}(\rho)$ is bounded above by the usual critical exponent $\delta_{\Gamma_\rho}$ of $\Gamma_\rho$ with respect to the Riemannian metric (=the $L^2$-metric) on $\prod_{i=1}^d \mathbb{H}^3$, we have
\[ 0 < \delta_{L^1}(\rho) \leq \delta_{\Gamma_\rho} \leq \frac{1}{\sqrt{d}} \max_i \left( \dim(\Lambda_{\rho_i}(\Gamma)) \right) \leq \frac{2}{\sqrt{d}} \]
by [11] Coro. 3.6; here the notation $\dim(\cdot)$ means the Hausdorff dimension of a subset of $\hat{\mathbb{C}} \cong \mathbb{S}^2$ with respect to the spherical metric.

(2) If all $\rho_i : \Gamma \to \text{PSL}_2(\mathbb{C})$ are quasiconformal deformations of $\Gamma$ and $\infty \notin \bigcup_{i=1}^d \Lambda_{\rho_i}(\Gamma)$, then for any bounded torus packing $\mathcal{P} = \Gamma_\rho T$ with $T = (C_1, \ldots, C_d)$, $\mathcal{P}$ is locally finite if and only if $\rho_i(\Gamma)C_i$ is a locally finite circle packing for all $1 \leq i \leq d$. This is because the boundary map $f_i$ is the restriction to $\Lambda_{\rho_i}(\Gamma)$ of the quasiconformal homeomorphism $F_i : \hat{\mathbb{C}} \to \hat{\mathbb{C}}$ associated to $\rho_i$ and under the hypothesis $\infty \notin \bigcup_{i=1}^d \Lambda_{\rho_i}(\Gamma)$, $F_i$ are bi-hölder maps on any compact subset of $\mathbb{C}$ ([10], [30]).

**More general torus-counting theorems.** In order to present a more general torus-counting theorem, we define the length vector of a torus $T = (C_1, \ldots, C_d) \in \mathcal{T}$ by
\[ \mathbf{v}(T) = -\left( \log \text{radius}(C_1), \ldots, \log \text{radius}(C_d) \right) \in \mathbb{R}^d; \]
where we used the negative sign so that the $i$-th coordinate of $\mathbf{v}(T)$ tends to $+\infty$ when $C_i$ shrinks to a point. The following is the main theorem of this paper:

**Theorem 1.6.** Let $\psi$ be any linear form on $\mathbb{R}^d$ such that $\psi > 0$ on $\mathbb{R}_{\geq 0}^d - \{0\}$. There exist $\delta_\psi > 0$ and a locally finite Borel measure $\omega_\psi$ on $\Lambda_\rho \cap \mathbb{C}^d$ depending only on $\Gamma_\rho$ and $\psi$ for which the following hold: for any $\Gamma_\rho$-admissible torus
packing $P$, there exists a constant $c_{\psi} = c_{P, \psi} > 0$ such that for any bounded subset $E \subset \mathbb{C}^d$ with boundary contained in a proper real algebraic subvariety, we have, as $R \to \infty$,

$$
\lim_{R \to \infty} \frac{1}{e^{\delta_{\psi} R}} \# \{T \in P : \psi(v(T)) < R, T \cap E \neq \emptyset\} = c_{\psi} \cdot \omega_{\psi}(E \cap \Lambda_\rho). \tag{1.7}
$$

The description of the measure $\omega_{\psi}$ depends on the higher rank Patterson-Sullivan theory. In fact, it is equivalent to the unique $(\Gamma_\rho, \psi_0)$-conformal measure on $\Lambda_\rho$, where $\psi_0$ is unique $\Gamma_\rho$-critical linear form proportional to $\psi$ (cf. Def. (6.1)). We refer to Def. 2.7 for the definition of $\delta_{\psi}$.

**Remark 1.8.**
(1) Theorem 1.4 can be deduced from this theorem by considering the linear form $\sigma(t_1, \cdots, t_d) = t_1 + \cdots + t_d$ (see Ex. 8.3).

(2) Our approach can also handle the case where $\psi(v(T))$ is replaced by the Euclidean norm of $v(T)$ in (1.7); indeed, the analysis involved in that case is easier due to the strict convexity of the Euclidean balls in $\mathbb{R}^d$.

(3) The fact that the sublevel sets $\{t \in \mathbb{R}^d : \psi(t) < c\}$ are linear (hence not strictly convex) presents new technical difficulties which were not dealt with in related previous works such as [21] and [4].

We now discuss examples of admissible torus packings arising naturally from the Teichmüller theory of Kleinian groups.

**Example 1.9.**
(1) Let $\Gamma < \text{PSL}_2(\mathbb{C})$ be a convex cocompact Zariski dense subgroup whose domain of discontinuity $\Omega_\Gamma := \hat{\mathbb{C}} - \Lambda_\Gamma$ has a connected component which is a round open disk $B$. Let $C_1 := \partial B$ and $d \geq 2$. By the Teichmüller theory of $\Gamma$, which relates

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**Figure 2.** The left-hand side is the limit set of a convex cocompact Kleinian group $\Gamma$ and the right-hand side is the limit set of a quasi-conformal deformation, say, $\rho_0$, of $\Gamma$. Denoting by $f$ the associated quasiconformal map, $f$ maps the first green circle, say $C$, to the second green circle. Hence the torus $T = (C, f(C))$ is a $(\text{id} \times \rho_0)(\Gamma)$-admissible torus. (image credit: Y. Zhang)

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(1) Let $\Gamma < \text{PSL}_2(\mathbb{C})$ be a convex cocompact Zariski dense subgroup whose domain of discontinuity $\Omega_\Gamma := \hat{\mathbb{C}} - \Lambda_\Gamma$ has a connected component which is a round open disk $B$. Let $C_1 := \partial B$ and $d \geq 2$. By the Teichmüller theory of $\Gamma$, which relates
the Teichmüller space of the Riemann surface $\Gamma \setminus \Omega_\Gamma$ and the quasi-conformal deformation space of $\Gamma$ \cite[Thm. 5.27]{17}, we may choose quasi-conformal deformations $\rho_i : \Gamma \to \text{PSL}_2(\mathbb{C})$, $2 \leq i \leq d$, whose associated quasiconformal maps $f_i : \hat{\mathbb{C}} \to \hat{\mathbb{C}}$ map $C_1$ to a circle, say, $C_i$. Then $T = (C_1, \ldots, C_d)$ is a $\Gamma_\rho$-admissible torus for $\rho = (\text{id}, \rho_2, \ldots, \rho_d)$ and hence $\mathcal{P} = \Gamma_\rho T$ is a $\Gamma_\rho$-admissible torus packing (see Figure 2 for an example for $d = 2$).

(2) Let $\Gamma$ be rigid acylindrical, that is, $\Omega_\Gamma$ is a union of infinitely many round disks with mutually disjoint closures. Let $\rho_0 : G \to \text{PSL}_2(\mathbb{C})$ be a quasiconformal deformation of $\Gamma$ which is not a conjugation, and $f : \hat{\mathbb{C}} \to \hat{\mathbb{C}}$ the associated quasiconformal map. It follows from \cite{18, 19} that the set of all circles $C \subset \hat{\mathbb{C}}$ meeting $\Lambda_\Gamma$ such that $f(C)$ is a circle is a finite union of closed $\Gamma$-orbits. Therefore the following 2-dimensional torus packing

$$\mathcal{P} := \{(C, f(C)) : C, f(C) \text{ circles, } C \cap \Lambda_\Gamma \neq \emptyset\}$$

is $(\text{id} \times \rho_0)(\Gamma)$-admissible.

**On the proof of Theorem 1.6.** First of all, the self-joining group $\Gamma_\rho$ is a so-called *Anosov subgroup* of $G$ introduced in \cite{8} (see Def. (2.2)), which enables us to apply the general ergodic theory developed for Anosov subgroups. While certain types of counting problems for orbits of Anosov subgroups in affine symmetric spaces were studied in our earlier paper \cite{4} using higher rank Patterson-Sullivan theory, there were certain serious technical restrictions imposed in \cite{4} which made it unclear what kind of torus packing counting problems could be approached using techniques there. The main novelty of this paper is to have isolated a natural class of torus packings (which are provided by the Teichmüller theory of Kleinian groups) for which we can apply the counting machinery of \cite{4}.

It is not hard to reduce the proof of Theorem 1.6 to the case where $\mathcal{P}$ is of the form $\Gamma_\rho T_0$, where $T_0$ is the product of the unit circles centered at the origin and $\psi$ is the so-called $\Gamma_\rho$-critical linear form (see Def. 2.9). As in \cite{21}, we first translate the counting problem for torus packings into an orbital counting problem in $H \setminus G$ where $H = \text{Stab}_G(T_0)$; by introducing a suitable bounded subset $B_\psi(E, R) \subset H \setminus G$ in (4.12), we are led to consider the asymptotic behavior of

$$\#([c] \Gamma_\rho \cap B_\psi(E, R)) \quad (1.10)$$

as $R \to \infty$. The key ingredient for obtaining (1.7) as $R \to \infty$ is to describe the asymptotic behavior of

$$\int_{B_\psi(E, R)} \left( \int_{\Gamma_\rho \cap H \setminus H} f([h][g]) \, d[h] \right) \, d[g] \quad (1.11)$$

for $f \in C_c(\Gamma_\rho \setminus G)$, as $R$ tends to infinity, as given in Theorem 7.1. The $\Gamma_\rho$-admissibility assumption on $\mathcal{P} = \Gamma_\rho T_0$ is used to guarantee
• the existence of some compact subset $S \subset \Gamma_{\rho} \cap H \setminus H$, independent of $R$, such that the integral (1.11) can be expressed as
\[
\int_{[g] \in B_\psi(E,R)} \left( \int_{[h] \in S} f([h]g) \, d[h] \right) \, d[g]
\] (1.12)
• the finiteness of the skinning constant of $\Gamma_{\rho} \cap H \setminus H$ (see (5.5)).

With this information, as well as the analysis of the asymptotic shape of the family of the subsets $\{B_\psi(E,R) : R > 0\}$, we are able to apply the mixing result from [5, Thm. 3.4] and [3, Thm. 1.3 & Thm. 1.4] and the equidistribution result from [4] which describes the asymptotic of the integral (1.10) in terms of the Burger-Roblin measures introduced in [4]. We emphasize that due to the higher rank nature of the subsets $B_\psi(E,R)$, combined with the linear nature of $\psi$ whose sublevel sets are not strict concave, the uniformity aspect in these results (see Propositions 5.6 and 5.8 for the nature of the uniformity that is required) is very crucial for our analysis. In fact, working on this article led us to conjecture the precise uniformity formulation of the mixing results in [3], which were verified and appeared in an updated version by the authors. Finally, we remark that the measure $\omega_\psi$ is the leafwise measure of the Burger-Roblin measure on the strict upper triangular subgroup of $G (\simeq \mathbb{C}^d)$ (see Proposition 6.3).

Organization.
• In Section 2, we start by recalling the basic higher rank Patterson-Sullivan theory of self-joining groups.
• In Section 3, we discuss an important property of a $\Gamma_{\rho^*}$-admissible torus packing and its consequence.
• In Section 4, we define the family $\{B_\psi(E,R) \subset H \setminus G : R > 0\}$ and explain how Theorem 1.4 can be translated into an orbital-counting problem for a $\Gamma_{\rho^*}$-orbit in $H \setminus G$ with respect to the family $\{B_\psi(E,R) : R > 0\}$.
• In Section 5, mixing and equidistribution results from [3] and [4] will be recalled with an emphasis on their uniformity aspects.
• In Section 6, the measure $\omega_\psi$ will be given explicitly and analyzed.
• In Section 7, we prove the key technical ingredient (Theorem 7.1) of the paper, which accounts for the asymptotic distribution of the average of translates of the $H$-orbit over the set $B_\psi(E,R)$ as $R \to \infty$.
• In Section 8, we prove the main theorem (Theorem 1.4).
• In Section 9, we prove that every proper subvariety of $\mathbb{C}^d$ has zero Patterson-Sullivan measure and hence zero $\omega_\psi$ measure; we prove this for a general Anosov subgroup of a semisimple real algebraic group.

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2. **Self-joinings and higher rank Patterson-Sullivan theory**

Let \( \mathbb{H}^3 = \{(z, r) : z \in \mathbb{C}, r > 0\} \) denote the upper half space model of the hyperbolic 3-space of constant curvature \(-1\) and \(d = d_{\mathbb{H}^3}\) the hyperbolic metric on \(\mathbb{H}^3\). The geometric boundary of \(\mathbb{H}^3\) is the extended complex plane \(\hat{\mathbb{C}} := \mathbb{C} \cup \{\infty\}\), which is the Riemann sphere. The Möbius transformation action of the group \(\mathrm{PSL}_2(\mathbb{C})\) on \(\hat{\mathbb{C}}\) extends to the action on the compactification \(\mathbb{H}^3 \cup \hat{\mathbb{C}}\) and gives rise to the identification \(\mathrm{PSL}_2(\mathbb{C}) \cong \text{Isom}^+(\mathbb{H}^3)\), the identity component of the isometry group of \(\mathbb{H}^3\). Similarly, the product group

\[
G = \prod_{i=1}^{d} \mathrm{PSL}_2(\mathbb{C})
\]

acts on \(\hat{\mathbb{C}}^d\) component-wise, giving rise to an isomorphism of the group \(G\) with \(\text{Isom}^+(\prod_{i=1}^{d} \mathbb{H}^3)\), the identity component of the isometry group of the Riemmanian product of \(\mathbb{H}^3\)s.

**Self-joinings of convex cocompact subgroups.** Let \(\Gamma < \mathrm{PSL}_2(\mathbb{C})\) be a (torsion-free) convex cocompact subgroup, that is, the convex core of the associated hyperbolic manifold \(\Gamma \backslash \mathbb{H}^3\) is compact.

Let \(\rho = (\rho_1 = \text{id}, \rho_2, \cdots, \rho_d)\) be a \(d\)-tuple of faithful convex cocompact representations of \(\Gamma\) into \(\mathrm{PSL}_2(\mathbb{C})\), that is, each \(\rho_i(\Gamma)\) is a convex cocompact subgroup of \(\mathrm{PSL}_2(\mathbb{C})\).

**Definition 2.1.** The self-joining of \(\Gamma\) by \(\rho\) is defined as the following discrete subgroup of \(G\):

\[
\Gamma_{\rho} = \left(\prod_{i=1}^{d} \rho_i\right)(\Gamma) = \{(\rho_1(g), \cdots, \rho_d(g)) : g \in \Gamma\}.
\]

Recall that throughout the entire paper we assume that

\(\Gamma_{\rho}\) is Zariski dense in \(G\).

**Anosov subgroups.** Let \(|\cdot|\) denote the word length on \(\Gamma\) with respect to a fixed finite set of generators. Since each \(\rho_i\) is convex cocompact, there exists \(C > 0\) such that

\[
d(\rho_i(g)o, o) > C|g| - C^{-1} \text{ for all } g \in \Gamma \text{ and } 1 \leq i \leq d.
\]

In other words, \(\Gamma_{\rho}\) is an Anosov subgroup (with respect to a minimal parabolic subgroup) ([10] and [8]). This is the most important feature of the self-joining \(\Gamma_{\rho}\) which will be used in this paper. We remark that any Anosov subgroup of \(G\) arises in this way.
**Limit set.** The product $F = \hat{C}^d$ is equal to the so-called Furstenberg boundary of $G$; note that for $d > 1$, $F$ is not the geometric boundary of $\prod_{i=1}^{d} \mathbb{H}^3$. Let $P < G$ be the product of the upper triangular subgroups of the $\text{PSL}_2(\mathbb{C})$ components of $G$, i.e., $P = \text{Stab}_G(\infty, \cdots, \infty)$. Then

$$F \simeq G/P.$$  

The limit set of $\Gamma_{\rho}$ is defined by the collection of all accumulation points of the $\Gamma_{\rho}$-orbits in $\prod_{i=1}^{d} \mathbb{H}^3$ on $F = \hat{C}^d$:

$$\Lambda_{\Gamma_{\rho}} := \{\lim_{j \to \infty} (\rho_1(g_j)o, \cdots, \rho_d(g_j)o) \in \hat{C}^d : g_j \in \Gamma, g_j \to \infty\}, \quad (2.3)$$

where $o$ is any point in $\mathbb{H}^3$. For simplicity, we sometimes write $\Lambda_{\rho}$ for $\Lambda_{\Gamma_{\rho}}$. This definition coincides with the definition of the limit set given by Benoist ([15, Lemma 2.13], [1]). Note that for $d = 1$, this is the usual limit set of a Kleinian group. As usual, $\Lambda_{\rho}(\Gamma) \subset \hat{C}$ denotes the limit set of $\rho_i(\Gamma)$.

By the convex cocompact assumption on $\rho_i$, there exists a unique $\rho_i$-equivariant homeomorphism $f_i : \Lambda_{\Gamma} \to \Lambda_{\rho_i(\Gamma)}:

$$f_i(g\xi) = \rho_i(g)f_i(\xi) \quad \text{for all } g \in \Gamma \text{ and } \xi \in \Lambda_{\Gamma}. \quad (2.4)$$

In particular, we have

$$\Lambda_{\rho} = \{(f_1(\xi), \cdots, f_d(\xi)) : \xi \in \Lambda_{\Gamma}\}.$$  

**Cartan projection.** For $t = (t_1, \cdots, t_d) \in \mathbb{R}^d$, set

$$a_t = \left( \begin{array}{cc} e^{t_1/2} & 0 \\ 0 & e^{-t_1/2} \\ \vdots & \vdots \\ e^{t_d/2} & 0 \\ 0 & e^{-t_d/2} \end{array} \right). \quad (2.5)$$

We let

$$A = \{a_t : t \in \mathbb{R}^d\} < G \quad \text{and} \quad A^+ = \{a_t : t_i \geq 0 \text{ for all } 1 \leq i \leq d\},$$

We respectively identify $\mathbb{R}^d$ and $\mathbb{R}_{\geq 0}^d$ with the Lie algebra $a = \log(A)$ and its positive Weyl chamber $a^+ = \log A^+$ via the map $t \mapsto \log a_t$. For $g = (g_1, \cdots, g_d) \in G$, the Cartan projection of $g$ is defined as

$$\mu(g) = (d(g_1o,o), \cdots, d(g_do,o)) \in a^+.$$  

**Limit cone and its dual cone.**

**Definition 2.6.** The limit cone of $\Gamma_{\rho}$ is the asymptotic cone of $\{\mu(\gamma) \in \mathbb{R}_{\geq 0}^d : \gamma \in \Gamma_{\rho}\}$, which we denote by $L_{\rho} = L_{\Gamma_{\rho}}$. Alternatively, it is the smallest closed cone in $a^+$ containing $\{(\ell_1(g), \cdots, \ell_d(g)) : g \in \Gamma\}$, where $\ell_i(g)$ denotes the length of the closed geodesic representing the conjugacy class of $\rho_i(g)$ ([2], [1 Thm. 1.2]).

Since $\sup_{g \in \Gamma}(\ell_i(g)/\ell_j(g)) < \infty$ for all $i, j$, we have

$$L_{\rho} \subset \text{int } a^+,$$

where $\text{int } C$ denotes the interior of a cone $C$. We denote by $a^*$ the space of all linear forms on $a$. The dual cone of $L_{\rho}$ is given by

$$L^*_{\rho} := \{\psi \in a^* : \psi|_{L_{\rho}} \geq 0\}.$$
Note that
\[ \psi|_{L^*_\rho - \{0\}} > 0 \text{ if and only if } \psi \in \text{int } L^*_\rho. \]

**Definition 2.7.** For \( \psi \in \text{int } L^*_\rho \), let \( \delta_\psi \) denote the abscissa of convergence for the series
\[ s \mapsto \sum_{\gamma \in \Gamma_\rho} e^{-s\psi(\mu(\gamma))}. \]

We have \( 0 < \delta_\psi < \infty \) (see Lemma 2.10 below).

**Critical linear forms.** Let \( \|\cdot\| \) denote the Euclidean norm on \( a = \mathbb{R}^d \).

The *growth indicator function* \( \Phi_\rho = \Phi_\Gamma \rho : a^+ \to \mathbb{R} \cup \{-\infty\} \) is defined as follows: for any vector \( u \in a^+ \),
\[ \Phi_\rho(u) := \|u\| \inf_{D \subset \text{open cones } \mathcal{D} \subset a^+} \tau_D, \]
where \( \tau_D \) is the abscissa of convergence of the series
\[ P_D(s) = \sum_{\gamma \in \Gamma_\rho, \mu(\gamma) \in \mathcal{D}} e^{-s\|\mu(\gamma)\|}. \]

**Definition 2.9.** A linear form \( \psi \in a^* \) is said to be \( \Gamma_\rho \)-critical if
- \( \psi \geq \Phi_\rho \) on \( a^+ \);
- \( \psi(u) = \Phi_\rho(u) \) for some \( u \in a^+ - \{0\} \).

The following lemma is due to Quint:

**Lemma 2.10.** [26 Lem. IV. 2.2, III.1.3, III.1.6]
- For each \( \psi \in \text{int } L^*_\rho \), there exists \( s > 0 \) such that \( s\psi \) is a \( \Gamma_\rho \)-critical linear form.
- If \( \psi \) is \( \Gamma_\rho \)-critical, then \( \delta_\psi = 1 \).

**Proof.** Set \( s_0 := \inf\{s \geq 0 : s\psi \geq \Phi_\rho\} \); we have \( s_0 \in (0, \infty) \) by [26 Lem. IV. 2.2]. It follows that \( s_0\psi \geq \Phi_\rho \) and \( s_0\psi(u) = \Phi_\rho(u) \) for some \( u \in a^+ \) with \( \|u\| = 1 \), by the upper semi-continuity of \( \Phi_\rho \) [26 Lem. III. 1.7]. In particular, \( s_0\psi \) is \( \Gamma_\rho \)-critical and the first assertion follows. The second assertion follows from [26 Lem. III.1.3]. \( \square \)

**Patterson-Sullivan measures.** Fix \( o = (0, 1) \in \mathbb{H}^3 \). By abuse of notation, we set
\[ o = (o, \cdots, o) \in \prod_{i=1}^{d} \mathbb{H}^3. \]

For \( \xi = (\xi_1, \cdots, \xi_d) \in \hat{\mathbb{C}}^d \) and \( g = (g_1, \cdots, g_d) \in G \), the *vector-valued Busemann map* is defined as
\[ \beta_{\xi}(go, o) = (\beta_{\xi_1}(g_1o, o), \cdots, \beta_{\xi_d}(g_do, o)) \in a, \]
where \( \{\xi_i(t) : t \geq 0\} \) is a geodesic ray in \( \mathbb{H}^3 \) with \( \lim_{t \to +\infty} \xi_i(t) = \xi_i \) and
\[ \beta_{\xi_i}(g_i o, o) = \lim_{t \to +\infty} d(g_i o, \xi_i(t)) - d(o, \xi_i(t)). \]
Given a linear form $\psi \in \mathfrak{a}^*$, a Borel probability measure $\nu$ supported on $\Lambda_\rho$ is called a $(\Gamma_\rho, \psi)$-Patterson-Sullivan (PS) measure if for all $\gamma \in \Gamma_\rho$ and $\xi \in \mathcal{F}$,

$$\frac{d\gamma_*\nu}{d\nu}(\xi) = e^{-\psi(\beta_\xi(\gamma_0, o))}.$$ 

We will say that $\nu$ is a $\Gamma_\rho$-PS measure if it is a $(\Gamma_\rho, \psi)$-PS measure for some $\psi \in \mathfrak{a}^*$. Extending the Patterson-Sullivan theory in rank one groups ([25], [28]), Quint [27] constructed a $(\Gamma_\rho, \psi)$-PS measure for each $\Gamma_\rho$-critical linear form $\psi \in \mathfrak{a}^*$ (see [2] for earlier works on this). As $\Gamma_\rho$ is a Zariski dense Anosov subgroup of $G$, the following is a special case of [15]:

**Lemma 2.11.** [15] For each $u \in \text{int} \mathcal{L}_\rho$, there exists a unique $\Gamma_\rho$-critical linear form $\psi_u \in \mathfrak{a}^*$ such that $\psi_u(u) = \Phi_\rho(u)$ and a unique $(\Gamma_\rho, \psi_u)$-PS measure $\nu_{\psi_u}$. The maps $u \mapsto \psi_u$ and $u \mapsto \nu_{\psi_u}$ give bijections among

$$\{u \in \text{int} \mathcal{L}_\rho : \|u\| = 1\} \leftrightarrow \{\text{\(\Gamma_\rho\)-critical linear forms}\} \leftrightarrow \{\text{\(\Gamma_\rho\)-PS measures}\}.$$ 

### 3. Properties of admissible torus packings

**Notations.** We will be using the following notations throughout the paper:

For $z = (z_i) \in \mathbb{C}^d$, set

$$n_z = \left( \left( \begin{smallmatrix} 1 & z_1 \\ 0 & 1 \end{smallmatrix} \right), \ldots, \left( \begin{smallmatrix} 1 & z_d \\ 0 & 1 \end{smallmatrix} \right) \right) \in G.$$ 

(3.1)

We also define the following subgroups:

$$N = \{n_z : z \in \mathbb{C}^d\}, \quad \tilde{N} = \{n_z^t : z \in \mathbb{C}^d\},$$

$$K = \prod_{i=1}^d \text{PSU}(2) \quad \text{and} \quad H = \prod_{i=1}^d (\text{PSU}(1, 1) \cup \left( \begin{smallmatrix} 0 & 1 \\ -1 & 0 \end{smallmatrix} \right) \text{PSU}(1, 1)),$$

where

$$\text{PSU}(2) = \{ \left( \begin{smallmatrix} a & b \\ -\bar{b} & \bar{a} \end{smallmatrix} \right) : |a|^2 + |b|^2 = 1 \} \quad \text{and} \quad \text{PSU}(1, 1) = \{ \left( \begin{smallmatrix} a & b \\ \bar{b} & \bar{a} \end{smallmatrix} \right) : |a|^2 - |b|^2 = 1 \}.$$ 

We set

$$M = \{ \left( \begin{smallmatrix} e^{i\theta_1} & 0 \\ 0 & e^{-i\theta_1} \end{smallmatrix} \right), \ldots, \left( \begin{smallmatrix} e^{i\theta_d} & 0 \\ 0 & e^{-i\theta_d} \end{smallmatrix} \right) : \theta_1, \ldots, \theta_d \in \mathbb{R} \};$$

note that $M$ is equal to the centralizer of $A$ in $K$.

Let $\mathcal{C}$ denote the space of all circles in $\hat{\mathbb{C}}$ (here a line is considered as a circle with infinite radius) and $\mathcal{T} = \mathcal{C} \times \cdots \times \mathcal{C}$ the space of all tori in $\prod_{i=1}^d \hat{\mathbb{C}}$.

**H-orbits corresponding to admissible torus packings.** Throughout the paper, we fix the following torus

$$T_0 = (C_0, \ldots, C_0) \in \mathcal{T}$$

where $C_0 = \{|z| = 1\}$ is the unit circle centered at the origin. Note that

$$H = \text{Stab}_G(T_0) \quad \text{and} \quad K = \text{Stab}_G(o).$$

We call a torus $T = (C_1, \ldots, C_d)$ $\Gamma_\rho$-admissible if for each $1 \leq i \leq d$,

- $\rho_i(\Gamma)C_i$ is a locally finite circle packing;
• \( f_i(C_1 \cap \Lambda_{\Gamma}) = C_i \cap \Lambda_{\rho_i(\Gamma)} \).

**Definition 3.2.** A torus packing \( \mathcal{P} \) is called \( \Gamma_\rho \)-admissible if

- \( \mathcal{P} \) consists of finitely many \( \Gamma_\rho \)-orbits of \( \Gamma_\rho \)-admissible tori;
- \( \mathcal{P} \) is locally finite in the sense that no infinite sequence of tori in \( \mathcal{P} \) converges to a torus.

The following lemma is rather standard (see for instance [21, Lem. 3.2].)

**Lemma 3.3.** The followings are equivalent:

1. The torus packing \( \Gamma_\rho(T_0) \) is locally finite;
2. The inclusion map \( f : (\Gamma_\rho \cap H) \setminus H \to \Gamma_\rho \setminus G \) is proper;
3. \( \Gamma_\rho \backslash \Gamma_\rho H \) is closed in \( G_\rho \backslash G \).

**Proposition 3.4.** If \( \mathcal{P} = \Gamma_\rho T_0 \) is \( \Gamma_\rho \)-admissible, then for any bounded subset \( \mathcal{O} \subset \Gamma_\rho \backslash G \), the subset

\[
\{ [h] \in \Gamma_\rho \cap H \setminus H : [h]A^+ \cap \mathcal{O} \neq \emptyset \}
\]

is bounded.

**Proof.** Suppose not. Then there exist sequences \( g_i \in \Gamma, (h_{i,1}, \ldots, h_{i,d}) \in H \), and \((t_{i,1}, \ldots, t_{i,d}) \in \mathfrak{a}^+ \) such that \((h_{i,1}, \ldots, h_{i,d}) \to \infty \) in \( \Gamma_\rho \cap H \setminus H \) as \( i \to \infty \) and for each \( 1 \leq j \leq d \),

\[
s_{i,j} := \rho_j(g_i)h_{i,j} \begin{pmatrix} e^{t_{i,j}/2} & 0 \\ 0 & e^{-t_{i,j}/2} \end{pmatrix}
\]

is a bounded sequence.

Let \( H_0 = \text{Stab}_{\text{PSL}_2(\mathbb{C})}(C_0) \) and \( D \) be a Dirichlet fundamental domain for the action of \( \Gamma \cap H_0 \) on the convex hull \( \mathcal{C}_0 \subset \mathbb{H}^3 \) of \( C_0 \). By the admissibility hypothesis, \( \Gamma_\rho C_0 \) is a locally finite circle packing. Hence the inclusion map \( \Gamma_\rho \cap H_0 \mathcal{C}_0 \to \Gamma_\rho \mathbb{H}^3 \) is a proper map. Since \( \Gamma \) is convex cocompact, it follows that \( \partial D \cap \Lambda_{\Gamma} = \emptyset \) [23 Prop. 5.1].

By replacing \( h_{i,1} \) with an element of \( (\Gamma \cap H_0)h_{i,1} \) and modifying \( g_i \) if necessary, we may assume that \( h_{i,1} \in D \). Since \((h_{i,1}, \ldots, h_{i,d}) \to \infty \) in \( \Gamma_\rho \cap H \setminus H \) as \( i \to \infty \), we must have \( h_{i,\ell} \to \infty \) in \( H_0 \) for some \( 1 \leq \ell \leq d \). By (3.6) and by the assumption that the sequence \( \{s_{i,j} : i = 1, 2, \ldots \} \) is bounded for each \( 1 \leq j \leq d \), we have

\[
\xi_j := \lim_{i \to \infty} h_{i,j} \begin{pmatrix} e^{t_{i,j}/2} & 0 \\ 0 & e^{-t_{i,j}/2} \end{pmatrix} o = \lim_{i \to \infty} \rho_j(g_i^{-1})s_{i,j} o \in \Lambda_{\rho_j(\Gamma)}. \tag{3.7}
\]

It follows from the \( \rho_i \)-equivariance of \( f_i \) that \( \xi_j = f_j(\xi_1) \) for each \( 1 \leq j \leq d \). Since \( h_{i,\ell} \to \infty \), it follows from (3.7) that \( \xi_\ell \in C_0 \cap \Lambda_{\rho_\ell(\Gamma)} \).

Since \( C_0 \cap \Lambda_{\Gamma} = f_\ell^{-1}(C_0 \cap \Lambda_{\rho_\ell(\Gamma)}) \) by the assumption that \( \mathcal{P} \) is \( \Gamma_\rho \)-admissible, we have \( \xi_1 = f_\ell^{-1}(\xi_\ell) \in C_0 \cap \Lambda_{\Gamma} \). On the other hand, since \( h_{i,1} \in D \), we have \( \xi_1 \in \partial D \). Hence \( \xi_1 \in \partial D \cap \Lambda_{\Gamma} \); this yields a contradiction since \( \partial D \cap \Lambda_{\Gamma} = \emptyset \).

**Proposition 3.8.** If \( \mathcal{P} = \Gamma_\rho T_0 \) is \( \Gamma_\rho \)-admissible, then the following hold:
Proof. \(C\) is closed in the projection \(G\). Let \(\delta H_{\gamma}\) and \(D \subset \Lambda\) be as in Lemma 3.9. Choose any closed cone \(D \subset \text{int} \ a^+\) whose interior contains \(\mathcal{L}_\rho - \{0\}\), we can find sequences \(\gamma_i \in \Gamma\) and \(\log a_i \to \infty\) in \(D\) such that
\[\gamma_i g a_i \in \mathcal{Q}\quad \text{for all } i \geq 1.
\]

\textbf{Proof of Proposition 3.8.} Let \(\mathcal{Q} \subset G\) be as in Lemma 3.9. Choose any closed cone \(D \subset \text{int} \ a^+\) whose interior contains \(\mathcal{L}_\rho - \{0\}\). Since the inclusion map \(\Gamma\) is a proper map, Lemma 3.9 implies that
\[\{|h| \in \Gamma \cap H : hP \in \Lambda\} \subset \{|h| \in \Gamma \cap H : |h| \exp D \cap Q = \emptyset\}.
\]

By Proposition 3.4 the subset on the right-hand side is bounded. Therefore (1) follows.

Suppose (2) is false. Then there exists a bounded subset \(S \subset G\) and infinite sequences \(t_i \in \mathcal{E}, t_i \to \infty, \gamma_i \in \Gamma, h_i \in H, \) and \(s_i \in S\) such that
\[\gamma_i = h_i a_i s_i,
\]
and \(H \gamma_i \neq H \gamma_j\) for \(i \neq j\). Since the image of \(\gamma_i^{-1} h_i a_i s_i = s_i \in S^{-1}\) under the projection \(G \to \Gamma\) is bounded, it follows again from Proposition 3.4 that there exists a sequence \(\delta_i \in \Gamma \cap H\) such that the sequence \(h_i := \delta_i h_i\) is bounded. Set \(\tilde{\gamma}_i := \delta_i \gamma_i\). Note that \(H \tilde{\gamma}_i = H \gamma_i\) and \(\tilde{\gamma}_i = h_i a_i s_i \in \Gamma\). Since both \(\tilde{\gamma}_i\) and \(s_i\) are bounded, the sequence \(t_i\) are within bounded distance of the \(\mu(\tilde{\gamma}_i)\). Since \(\mathcal{L}_\rho\) is the asymptotic cone of \(\{\mu(\gamma) : \gamma \in \Gamma\}\) and \(\mathcal{E} \cap \mathcal{L}_\rho = \emptyset\), we have \(t_i \notin \mathcal{E}\) for all sufficiently large \(i\), which is a contradiction.

\textbf{Closedness of }\(\Gamma\). The following proposition says the local finiteness of \(\Gamma\) is a consequence of the local finiteness of \(\Gamma C_0\) when \(T_0\) is an admissible torus with \(#C_0 \cap \Lambda \geq 3\).

\textbf{Proposition 3.10.} Let \(\Gamma C_0\) be closed in \(C\) with \(#C_0 \cap \Lambda \geq 3\). If \(f_i(C_0 \cap \Lambda) = C_0 \cap \Lambda_{\rho_i(\Gamma)}\) for each \(1 \leq i \leq d\), then \(\Gamma_{\rho T_0}\) is closed in \(T\) and \(\rho_{T_0} C_0\) is closed in \(C\) for all \(2 \leq i \leq d\).

\textbf{Proof.} Suppose that a sequence \(T_n = (\rho_1(g_n)C_0, \rho_2(g_n)C_0, \ldots, \rho_d(g_n)C_0)\) converges to some torus \(T = (C_1, C_2, \ldots, C_d)\) for \(g_n \in \Gamma\). We need to show that \(T \in \Gamma_{\rho T_0}\). Since \(\Gamma C_0\) is closed and hence discrete, we may assume that for all \(n \geq 1\), \(g_n C_0 = C_1\) by throwing away finitely many \(g_n\)’s (recall
\(\rho_1 = \text{id}\). Observe that \(\rho_i(g_n)f_i(C_0 \cap \Lambda_\Gamma) = f_i(g_n(C_0 \cap \Lambda_\Gamma)) = f_i(C_1 \cap \Lambda_\Gamma)\) by \([\ref{2.4}]\). On the other hand \(f_i(C_0 \cap \Lambda_\Gamma) = C_0 \cap \Lambda_{\rho_i(\Gamma)}\) and it contains at least 3 distinct points. Since two circles sharing three distinct points must be equal to each other, we get \(\rho_i(g_n)C_0 = C_1\) for all \(1 \leq i \leq d\) and all \(n\). It follows that \(T_n = T = T_0\) for all \(n\), proving the first claim. The second claim can be proved similarly. \(\square\)

Although we won’t be using the following proposition in the rest of our paper, this is of independent interest which extends the analogous fact for convex cocompact groups for \(d = 1\).

**Proposition 3.11.** Suppose \(\Gamma_\rho T_0\) is closed with \(\#T \cap \Lambda_\rho \geq 3\). Then \(H \cap \Gamma_\rho\) is a non-elementary Anosov subgroup and

\[T_0 \cap \Lambda_\rho = \Lambda_{H \cap \Gamma_\rho} \cap \Lambda_\rho.\]

**Proof.** We use the characterization of an Anosov subgroup as a subgroup of \(G\) satisfying Regularity, Conicality, Antipodality, shown in \([\ref{9}]\). Since \(H \cap \Gamma_\rho\) is a subgroup of an Anosov subgroup \(\Gamma_\rho\), \(A \subset H\), and \(H/(H \cap P) \subset G/P\) is the Furstenberg boundary of \(H\), the regularity and antipodality are immediate.

We deduce the conicality as follows. Let \(\xi \in T_0 \cap \Lambda_\rho\). We can choose \(h \in H\) such that \(h(H \cap P) = \xi\). Since \(\Gamma_\rho\) is Anosov, \(\xi\) is a radial limit point of \(\Gamma_\rho\), that is, there exist \(a_n \to \infty\) in \(A^+\) and \(\delta_n \in \Gamma_\rho\) such that \(\delta_n h a_n\) is bounded. Since the map \((H \cap \Gamma_\rho) \backslash H \to \Gamma_\rho \backslash G\) is proper by Lemma \([\ref{3.3}]\) and \(h a_n \in H\), it follows that there exists \(\delta_n \in H \cap \Gamma_\rho\) that

\[\delta_n h a_n\]

is bounded. This implies that \(\xi = h(H \cap P)\) is a radial limit point of \(H \cap \Gamma_\rho\) in \(H/(H \cap P)\). Hence we have shown that \(T_0 \cap \Lambda_\rho\) is equal to the set \(\Lambda_{H \cap \Gamma_\rho}^{\text{rad}}\) of all radial limit points of \(H \cap \Gamma_\rho\). Since \(\Lambda_{H \cap \Gamma_\rho} \subset T_0 \cap \Lambda_\rho\), it follows that

\[\Lambda_{H_0 \cap \Gamma_\rho}^{\text{rad}} = \Lambda_{H \cap \Gamma_\rho}^{\text{rad}}.\]

Hence \(H_0 \cap \Gamma_\rho\) is conical. This proves that \(H_0 \cap \Gamma_\rho\) is Anosov. The hypothesis \(\#T_0 \cap \Lambda_\rho \geq 3\) now implies that \(H_0 \cap \Gamma_\rho\) is non-elementary. \(\square\)

### 4. Torus Counting Function for Admissible Torus Packings

We write \(r(C)\) for the radius of a circle \(C\). Given a torus \(T = (C_1, \ldots, C_d) \in \mathcal{T}\), we define its length vector by

\[\nu(T) = -(\log r(C_1), \ldots, \log r(C_d)) \in \mathfrak{a}.

We will call a linear form \(\psi \in \mathfrak{a}^+\) positive if

\[\psi > 0\] on \(\mathfrak{a}^+ - \{0\}\).

In the rest of this section, we fix

- a \(\Gamma_\rho\)-admissible torus packing \(\mathcal{P} = \Gamma_\rho T_0\);
- a positive \(\Gamma_\rho\)-critical linear form \(\psi \in \mathfrak{a}^+\).
Definition 4.1 (Counting function). For a bounded subset $E \subset \mathbb{C}^d$ and $R > 0$, we set

$$N_R(\mathcal{P}, \psi, E) = \# \{ T \in \mathcal{P} : \psi(v(T)) < R, T \cap E \neq \emptyset \}. \quad (4.2)$$

The local finiteness assumption on $\mathcal{P}$ together with the positivity hypothesis on $\psi$ guarantees that

Lemma 4.3. For any bounded subset $E \subset \mathbb{C}^d$ and $R > 0$,

$$N_R(\mathcal{P}, \psi, E) < \infty.$$  

Proof. By the positivity hypothesis on $\psi$, we have $c := \inf_{v \in a^+, \|v\|=1} \psi(v) > 0$ and hence $\psi(v) \geq c\|v\|$ for all $v \in a^+$. Hence

$$N_R(\mathcal{P}, \psi, E)$$

$$\leq \# \{ T = (C_1, \cdots, C_d) \in \mathcal{P} : \sum_{i=1}^{d} \left| \log r(C_i) \right|^2 \leq R^2/c^2 \text{ and } T \cap E \neq \emptyset \}$$

$$\leq \# \sum_{i=1}^{d} \{ C \in \rho_i(\Gamma)C_0 : e^{-R^2/c^2} \leq r(C_i) \leq e^{R^2/c^2} \text{ and } C \cap \pi_i(E) \neq \emptyset \}$$

where $\pi_i(E)$ denotes the projection of $E$ to the $i$-th factor $\hat{C}$. By the local-finiteness of $\rho_i(\Gamma)C_0$, there are only finitely many circles of radius bounded from below intersecting a fixed bounded set. This proves the claim. \qed

We will introduce a subset $\tilde{B}_\psi(E, R) \subset H \setminus G$ and explain how $N_R(\mathcal{P}, \psi, E)$ is related with the number of $\Gamma_\rho$-orbits in the set $\tilde{B}_\psi(E, R)$.

Definition of $\tilde{B}_\psi(E, R)$. For $R > 0$, we define

$$A^+_{\psi, R} = \{ a_t \in A^+ : \psi(t) < R \}$$

where $a_t$ is defined as in (2.5). As $\psi$ is positive, $A^+_{\psi, R}$ is bounded.

Definition 4.4. For any bounded $E \subset \mathbb{C}^d$ and $R > 0$, we define the following bounded subset of $H \setminus G$ by

$$\tilde{B}_\psi(E, R) := H \setminus HK A^+_{\psi, R} N_{-E} \subset H \setminus G. \quad (4.5)$$

The following proposition allows us to reformulate the counting problem in terms of the sets $\tilde{B}_\psi(E^\pm, R)$ (cf. [21, Proposition 3.7]): For $\varepsilon > 0$, set

$$q_0(\mathcal{P}, E, \varepsilon) := \# \{ T = (C_1, \cdots, C_d) \in \mathcal{P} : \sum_{i=1}^{d} r(C_i)^2 > \varepsilon^2/4 \text{ and } T \cap E \neq \emptyset \}. \quad (4.6)$$

The finiteness of $q_0(\mathcal{P}, E, \varepsilon)$ can be seen similarly to the proof of Lemma 4.3.
Proposition 4.7. Let $E \subset \mathbb{C}^d$ be a bounded subset. For any small $\varepsilon > 0$ and any $R > 0$, we have
\[
\#([e] \Gamma_\rho \cap \tilde{B}_\psi(E_\varepsilon^-, R)) - q_0 \leq N_R(\mathcal{P}, \psi, E) \leq \#([e] \Gamma_\rho \cap \tilde{B}_\psi(E_\varepsilon^+, R)) + q_0
\]
where $q_0 = q_0(\mathcal{P}, E, \varepsilon)$,
\[
E_\varepsilon^- := \bigcap_{\|w\| < \varepsilon} E + w, \quad \text{and} \quad E_\varepsilon^+ := \bigcup_{\|w\| < \varepsilon} E + w. \tag{4.8}
\]

Proof. Note that
\[
\#([e] \Gamma_\rho \cap H \backslash HK A^+_{\psi, R} N_{-E_\varepsilon^+})
\]
\[
= \#\{ \gamma \in \Gamma_\rho \cap H \backslash \Gamma_\rho : H \gamma \cap KA^+_{\psi, R} N_{-E_\varepsilon^+} \neq \emptyset \}
\]
\[
= \#\{ \gamma \in \Gamma_\rho / \Gamma_\rho \cap H : \gamma HK \cap N_{E_\varepsilon^+}(A^+_{\psi, R})^{-1} K \neq \emptyset \}
\]
\[
= \#\{ \gamma T_0 \in \mathcal{P} : \gamma T_0 \cap N_{E_\varepsilon^+}(A^+_{\psi, R})^{-1} o \neq \emptyset \}. \tag{4.9}
\]

Note that if $\gamma T_0 \in \mathcal{P}$, $\gamma T_0 \cap N_{E_\varepsilon^+}(A^+_{\psi, R})^{-1} o \neq \emptyset$ and $\sum_{i=1}^d r(\rho_i(\gamma) C_0) \leq \varepsilon^2/4$, then $\gamma T_0 \cap E \neq \emptyset$ and $\psi(\psi(\gamma T_0)) < R$. This observation combined with (4.9) gives the lower bound in the statement of the proposition. Similarly, if $\gamma T_0 \in \mathcal{P}$ satisfies $\gamma T_0 \cap E \neq \emptyset$, $\psi(\psi(\gamma T_0)) < R$ and $\sum_{i=1}^d r(\rho_i(\gamma) C_0) \leq \varepsilon^2/4$, then $\gamma T_0 \subset E_\varepsilon^+$ and hence $\psi(\gamma T_0) \subset N_{E_\varepsilon^+}(A^+_{\psi, R})^{-1} o \neq \emptyset$. This combined with (4.9) gives the upper bound, proving the proposition. \qed

Definition of $B_\psi(E, R)$. Let $\mathcal{D} \subset \text{int} \ a^+$ be any closed cone such that
\[
\text{int} \mathcal{D} \supset L_\rho - \{0\}. \tag{4.10}
\]
Throughout the section we fix one such $\mathcal{D}$ and set, for any $R > 0$,
\[
D := \exp \mathcal{D} \quad \text{and} \quad D_{\psi, R} = D \cap A^+_{\psi, R}. \tag{4.11}
\]

Analogously to $\tilde{B}_\psi(E, R)$, we now define
\[
B_\psi(E, R) = B_{D_{\psi, R}}(E, R) := H \backslash H K D_{\psi, R} N_{-E} \subset H \backslash G. \tag{4.12}
\]

$B_\psi(E, R)$ in terms of $G = HA^+ K$ decomposition. We will now express $B_\psi(E, R)$ in terms of the generalized Cartan decomposition $G = HA^+ K$ (cf. [2], p. 18). Given $\varepsilon > 0$ and for a subset $W \subset G$, let $W_\varepsilon$ denote the intersection of $W$ and the $\varepsilon$-ball around $e$ in $G$.

Lemma 4.13. [21] Proposition 4.2] For $d = 1$, we have

1. If $a_t \in HKA_s K$ for some $s \geq 0$, then $|t| \leq s$.
2. For any $\varepsilon > 0$, there exists $R_1(\varepsilon) > 0$ such that
\[
\{ k \in K : a_t k \in HKA^+ \text{ for some } t > R_1(\varepsilon) \} \subset K_\varepsilon M.
\]

We set
\[
X_\varepsilon := \{ a_t \in A^+ : \min_{1 \leq i \leq d} t_i \leq R_1(\varepsilon/\sqrt{d}) \}, \tag{4.14}
\]
that is the closed $R_1(\varepsilon/\sqrt{d})$-neighborhood of $\partial A^+$, where $R_1(\varepsilon/\sqrt{d}) > 0$ is the constant as given in Lemma 4.13(2).
We deduce the following:

**Lemma 4.15.** For any $\varepsilon > 0$ and $R > 0,$
\[
KA^+_{\psi,R} \subset H(A^+_{\psi,R} - \mathcal{X}_\varepsilon)K_\varepsilon \cup H\mathcal{X}_\varepsilon K.
\]

**Proof.** For any $k = (k_1, \cdots, k_d) \in K$ and $a_t \in A^+,$ using the decomposition $G = HA^+K,$ we can find $h = (h_1, \cdots, h_d) \in H,$ $a_s \in A^+$ and $\ell = (\ell_1, \cdots, \ell_d) \in K$ such that
\[
\begin{equation}
\begin{aligned}
k_i \begin{pmatrix} e^{s_i/2} & 0 \\ 0 & e^{-s_i/2} \end{pmatrix} = h_i \begin{pmatrix} e^{s_i/2} & 0 \\ 0 & e^{-s_i/2} \end{pmatrix} \ell_i
\end{aligned}
\end{equation}
\]
for all $i = 1, \cdots, d,$ where $t = (t_i)$ and $s = (s_i).$ From Lemma 4.13(1), we then have $s_i < t_i.$ Since $\psi|_{a^+} \geq 0,$ we have
\[
\psi(s) \leq \psi(t) < R.
\]
Hence if $a_t \in A^+_{\psi,R},$ then $a_s \in A^+_{\psi,R}.$ Furthermore, if $a_s \notin \mathcal{X}_\varepsilon,$ we have $s_i > R_1(\varepsilon/\sqrt{d})$ for each $i$ and hence $\ell \in K_\varepsilon M$ by Lemma 4.13(2). This proves the lemma.

□

**Further refinement.** The following lemma appears in [21] Prop. 4.7 for the case $d = 1,$ and this implies the general $d$-case as the computations can be reduced to each component:

**Lemma 4.17.** [21] Prop. 4.7] There exists $\ell \geq 1$ such that for all small enough $\varepsilon > 0,$ $a \in A^+$ and $m \in M$
\[
aK_\varepsilon m \subset H(aA_{\ell\varepsilon})N_{\ell\varepsilon}.
\]

Using Lemma 4.17, we obtain:

**Lemma 4.18.** For any $\varepsilon > 0$ and a bounded subset $E \subset \mathbb{C}^d,$ there exists a compact subset $Z = Z(E, D, \varepsilon) \subset H\setminus G$ such that
\[
\tilde{B}_\psi(E, R) \subset H\setminus HD\psi,R A_{\ell\varepsilon} N_{-E_{\ell\varepsilon}} \cup H\setminus H(A^+ - D)K_{N-E} \cup Z
\]
where $\ell > 0$ is as in Lemma 4.17.

**Proof.** Since $D$ is a closed cone contained in $a^+, D \cap \mathcal{X}_\varepsilon$ is a compact subset. Therefore $Z := H\setminus H(D \cap \mathcal{X}_\varepsilon)K_{N-E}$ is a bounded subset of $H\setminus G.$

Note that by Lemma 4.15(1) and Lemma 4.17
\[
KA^+_{\psi,R} \subset H(A^+_{\psi,R} - \mathcal{X}_\varepsilon)K_\varepsilon \cup H\mathcal{X}_\varepsilon K
\]
\[
\subset HD\psi,R K_{\varepsilon} \cup H(A^+ - D)K \cup H(D \cap \mathcal{X}_\varepsilon)K \quad (4.19)
\]
\[
\subset HD\psi,R A_{\ell\varepsilon} N_{\ell\varepsilon} \cup H(A^+ - D)K \cup H(D \cap \mathcal{X}_\varepsilon)K \quad (4.20)
\]
The claim now follows from the definition $\tilde{B}_\psi(E, R).$ □

**Corollary 4.21.** For any $\varepsilon > 0,$ there exist $q_1 = q_1(E, D, \varepsilon) > 0$ and $\ell = \ell(\psi)$ such that
\[
\#([\varepsilon]_\Gamma \cap B_\psi(E, R)) \leq \#([\varepsilon]_\Gamma \cap \tilde{B}_\psi(E, R)) \leq \#([\varepsilon]_\Gamma \cap B_\psi(E, R + \ell\varepsilon)) + q_1.
\]
Proof. The first inequality is trivial. The second inequality follows by applying Lemma 4.18 for a slightly smaller closed cone $D_0 \subset \text{int} D$ such that $L_\rho - \{0\} \subset \text{int} D_0$ and applying Proposition 3.8 with $E = a^+ - D_0$. □

5. Mixing and equidistribution with uniform bounds

We fix a positive $\Gamma_\rho$-critical linear form $\psi \in \mathfrak{a}^*$ and the $(\Gamma_\rho, \psi)$-PS measure $\nu_\psi$ given by Lemma 2.11. In this section, we recall the results of [3] and [4] on mixing (Proposition 5.6) and equidistribution (Proposition 5.8), with emphasis placed on their uniformity aspects that are crucial in our application.

Burger-Roblin measures $m^{BR}$ and $m^{BR^*}$. Recall that $P = \text{Stab}_G(\infty, \cdots, \infty)$ denotes the product of upper triangular subgroups. We also denote by $\tilde{P} = \text{Stab}_G(0, \cdots, 0)$ the product of lower triangular subgroups.

For $g \in G$, its visual images are defined by

$$g^+ := gP \in \mathcal{F} \quad \text{and} \quad g^- := g\tilde{P} \in \mathcal{F}.$$

Let $\mathcal{F}^{(2)}$ denote the unique open $G$-orbit in $\mathcal{F} \times \mathcal{F}$ under the diagonal action, that is, $\mathcal{F}^{(2)} = \{(g^+, g^-) : g \in G\}$.

The map

$$gM \mapsto (g^+, g^- , b = \beta_{g^-}(o, go))$$

gives a homeomorphism $G/M \simeq \mathcal{F}^{(2)} \times \mathfrak{a}$, called the Hopf parametrization of $G/M$. We define a locally finite Borel measure $\tilde{m}^{BR}_\psi$ on $G/M$ as follows: for $g = (g^+, g^-, b) \in \mathcal{F}^{(2)} \times \mathfrak{a}$,

$$d\tilde{m}^{BR}_\psi(g) = e^{\psi(\beta_{g^+}(o, go)) + 2\sigma(\beta_{g^-}(o, go))} d\nu_\psi(g^+) dm_o(g^-) db,$$  

(5.1)

where $m_o$ is the unique $K$-invariant probability measure on $\mathcal{F}$, $db$ is the Lebesgue measure on $\mathfrak{a}$, and $\sigma$ is the linear form on $\mathfrak{a}$ defined by

$$\sigma(t_1, \cdots, t_d) = t_1 + \cdots + t_d.$$  

(5.2)

By abusing notation slightly, we will also use $\tilde{m}^{BR}_\psi$ to denote the corresponding $M$-invariant measure on $G$ induced by $\tilde{m}^{BR}_\psi$. The measure $\tilde{m}^{BR}_\psi$ is left $\Gamma_\rho$-invariant and induces an $N$-invariant locally finite measure on $\Gamma_\rho \setminus G$, which we denote by $m^{BR}_\psi$.

Similarly, but with a different parameterization $g = (g^+, g^-, b = \beta_{g^+}(o, go))$, we define the following $N$-invariant locally finite Borel measure:

$$d\tilde{m}^{BR^*}_\psi(g) = e^{2\sigma(\beta_{g^+}(e, g)) + \psi(\beta_{g^-}(e, g))} dm_o(g^+) d\nu_\psi(g^-) db.$$  

(5.3)

We have the following decomposition (see (4.8) of [4]):

Lemma 5.4. For $f \in C_c(P\tilde{N})$ and $n \tilde{m} \in NAM\tilde{N}$,

$$\tilde{m}^{BR}_\psi(f) = \int_{NAM} \left( \int_{\tilde{N}} f(n \tilde{m}\tilde{n}) \, d\tilde{n} \right) e^{-\psi(\log \alpha)} \, dm \, da \, d\nu_\psi(n),$$

where $dm$, $da$, $d\tilde{n}$ denote the Haar measures for $M$, $A$, $\tilde{N}$, respectively.
Patterson-Sullivan measure $\mu_{\Gamma \rho \cap H \backslash H, \psi}^{PS}$ \cite{Definition 8.7}. We define a measure $\mu_{H, \psi}^{PS}$ on $H$ as follows: for $\omega \in C_c(H)$, let

$$
\mu_{H, \psi}^{PS}(\omega) = \int_{h \in H/H \cap P} \int_{p \in H \cap P} \omega(hp)e^{\psi(\beta_{h+}(e, hp))} dp d\nu(h^+),
$$

where $dp$ is a right-Haar measure on $H \cap P$; for $h \in H/H \cap P$, $h^+$ is well-defined independent of the choice of a representative. The measure defined above is $\Gamma \rho \cap H$-invariant: for any $\gamma \in \Gamma \rho \cap H$, $\gamma^* \mu_{H, \psi}^{PS} = \mu_{H, \psi}^{PS}$. Therefore, if $\Gamma \rho \backslash \Gamma \rho H$ is closed in $\Gamma \rho \backslash G$, $d\mu_{H, \psi}^{PS}$ induces a locally finite Borel measure on $\Gamma \rho \backslash \Gamma \rho H \cong \Gamma \rho \backslash P \backslash H$, which we denote by $\mu_{\Gamma \rho \cap H \backslash H, \psi}^{PS}$.

The skinning constant of $\Gamma \rho \cap H \backslash H$ with respect to $\nu_\psi$ is defined as the total mass:

$$
\text{sk}^{\Gamma \rho, \psi}_{H}(H) := |\mu_{\Gamma \rho \cap H \backslash H, \psi}^{PS}| \in [0, \infty].
$$

(5.5)

Uniform mixing. We fix the unique unit vector $u = u_\psi \in \text{int} \mathcal{L}_\rho$ such that $\psi(u) = \Phi^\rho(u)$ provided by Lemma \cite{Lemma 2.11}.

Since the cone $\mathfrak{a}^+$ is contained in the closed half space $\{ \psi \geq 0 \}$, it can be parameterized by the map

$$
\mathbb{R}_{\geq 0} \times \ker \psi \to \mathfrak{a}
$$

$$
(s, w) \mapsto su_\psi + \sqrt{sw}.
$$

The following mixing result is due to \cite{Thm. 3.4} and \cite{Thm. 1.4 & Thm. 1.5}: the uniform bound as stated in the second part is crucial in our application as remarked before.

Proposition 5.6. There exists an inner product $\langle \cdot, \cdot \rangle_\ast$ on $\mathfrak{a}$ and $\kappa > 0$ such that for any $f_1, f_2 \in C_c(\Gamma \rho \backslash G)$ and $w \in \ker \psi$,

$$
\lim_{s \to +\infty} s^{(d-1)/2} e^{(2\sigma - \psi)(su_\psi + \sqrt{sw})} \int_{\Gamma \rho \backslash G} f_1(x \exp(su_\psi + \sqrt{sw})) f_2(x) dx = \kappa e^{-I(w)} m_\psi^{BR}(f_1)m_\psi^{BR}(f_2)
$$

where $I : \ker \psi \to \mathbb{R}_{\geq 0}$ is given by $I(w) = \frac{||w||^2 - \langle w, u_\psi \rangle^2}{||u_\psi||^2}$. Moreover, there exist $s_0, \ell > 0$ and $C' = C'(s_0, \ell) > 0$ such that for all $(s, w) \in (s_0, \infty) \times \ker \psi$ with $su_\psi + \sqrt{sw} \in \mathfrak{a}^+$, we have:

$$
\left| s^{(d-1)/2} e^{(2\sigma - \psi)(su_\psi + \sqrt{sw})} \int_{\Gamma \rho \backslash G} f_1(x \exp(su_\psi + \sqrt{sw})) f_2(x) dx \right| \leq C' e^{-\ell I(w)}.
$$

(5.7)
Uniform equidistribution. Using Proposition 5.6, the following equidistribution result can be obtained as in [4, Proposition 8.11]:

**Proposition 5.8.** Let \( f \in C_c(\Gamma_\rho \backslash G) \) and \( \phi \in C_c(H) \). For any \( w \in \ker \psi \), we have

\[
\lim_{s \to +\infty} s^{(d-1)/2} e^{(2\sigma-\psi)(su + \sqrt{sw})} \int_{\Gamma_\rho \backslash \Gamma_H} f([h] \exp(su + \sqrt{sw})) \phi(h) \, dh = \kappa e^{-I(w)} m_{\psi}^{BR}(f) \mu_{H, \psi}^{PS}(\phi)
\]  

where \( \kappa > 0 \) and \( I : \ker \psi \to \mathbb{R}_{\geq 0} \) are given as in Proposition 5.6. Moreover, there exists \( C'' = C''(f, \phi) > 0 \) such that for all \((s, w) \in (s_0, \infty) \times \ker \psi\) with \( su + \sqrt{sw} \in a_+^+ \),

\[
\left| s^{(d-1)/2} e^{(2\sigma-\psi)(su + \sqrt{sw})} \int_{H} f([h] \exp(su + \sqrt{sw})) \phi(h) \, dh \right| < C'' e^{-\ell I(w)},
\]

where \( s_0, \ell > 0 \) are given as in Proposition 5.6.

6. The measure \( \omega_\psi \)

Fix a positive \( \Gamma_\rho \)-critical linear form \( \psi \in \mathfrak{a}^* \) and the \((\Gamma_\rho, \psi)\)-PS measure \( \nu_\psi \) given by Lemma 2.11.

**Definition 6.1.** We define a locally finite Borel measure \( \omega_\psi = \omega_{\Gamma_\rho, \psi} \) on \( \mathbb{C}^d \) as follows: for all \( f \in C_c(\mathbb{C}^d) \),

\[
\omega_\psi(f) = \int_{\mathbb{C}^d} f(z) e^{\psi(\beta z)} \, d\nu_\psi(z).
\]

For each small \( \varepsilon > 0 \), let \( \phi^\varepsilon \in C_c(N_\varepsilon A_\varepsilon M_\varepsilon N_\varepsilon) \) be a non-negative function such that \( \int_G \phi^\varepsilon \, dg = 1 \) where \( dg \) is a Haar measure on \( G \) and set

\[
\phi^\varepsilon_N(g) := \int_M \phi^\varepsilon(gmn) \, dm.
\]

The main goal of this section is to establish Corollary 6.5 which roughly says

\[
\int_{-E} m_{\psi}^{BR}(\phi^\varepsilon_N) \, dz \approx \omega_\psi(E).
\]

To be precise, let \( E \subset \mathbb{C}^d \) be a bounded Borel set and \( \varepsilon > 0 \) be small enough so that

\( A_\varepsilon M_\varepsilon N_\varepsilon N_{-E} N_1 \subset NAMN \).

We will fix \( E \) for the rest of the section. Define \( \Phi_E^\varepsilon \in C_c(N) \) by

\[
\Phi_E^\varepsilon(n) := \int_{N_{-E} M N} \phi^\varepsilon(n) \, dg = \int_{N_{-E} A_\varepsilon M_\varepsilon N_\varepsilon} \phi^\varepsilon(n) \, dg.
\]

Recalling the definition of \( E_\varepsilon^\pm \) from (4.8), we have:
Lemma 6.2. For all \( n \in \mathbb{N} \),
\[
1_{E_n^{-}}(n) \leq \Phi_E^\varepsilon(n) \leq 1_{E_n^+}(n).
\]

Proof. Trivially, \( 0 \leq \Phi_E^\varepsilon(n) \leq 1 \). If \( n \in E_n^0 \), then \( n^{-1}N_z \subset N_E \), hence
\[
\Phi_E^\varepsilon(n) = \int_{N^{-1}N_z MAN} \phi^\varepsilon(ng) \, dg \geq \int_{n^{-1}N_z MAN} \phi^\varepsilon(ng) \, dg = \int_G \phi^\varepsilon(g) \, dg = 1.
\]

On the other hand, if \( n \notin E_n^+ \), then \( n^{-1}N_z \cap N_E = \emptyset \), hence \( \phi^\varepsilon(ng) = 0 \) for all \( g \in N^{-1}N_z MAN \) by uniqueness of the \( NAMN \) decomposition, giving \( \Phi_E^\varepsilon(n) = 0 \).

We now relate the Burger-Roblin measure of \( \phi^\varepsilon \) and Patterson-Sullivan measure of \( \Phi^\varepsilon \):

Proposition 6.3. There exist \( C, c > 0 \) such that for all sufficiently small \( \varepsilon > 0 \), we have
\[
(1 - C\varepsilon) \omega_{\psi}(\Phi_{E_n^\varepsilon}) \leq \int_{-E} m_{\psi}^{BR}(\phi^\varepsilon) \, dz \leq (1 + C\varepsilon) \omega_{\psi}(\Phi_{E_n^\varepsilon}).
\]

Proof. By Lemma 5.4 we have
\[
\int_{-E} m_{\psi}^{BR}(\phi^\varepsilon) \, dz = \int_{-E} \int_{M} \int_{N} \int_{AMN} \phi^\varepsilon(nam\tilde{n}m) \times e^{-(\log a) \, d\tilde{n} \, da \, d\omega_{\psi}(n) \, dm} \, dz
\]
\[
= \int_{N} \left( \int_{AMN_{-E}} \phi^\varepsilon(nam\tilde{n}m) \, e^{-(\log a) \, d\tilde{n} \, dm} \, da \right) \, d\omega_{\psi}(n),
\]
where all the densities appearing in the expression are those of the corresponding Haar measures, except for \( d\omega_{\psi} \). Note that if \( \phi^\varepsilon(nam\tilde{n}m) \neq 0 \), then \( nam\tilde{n}m \in N_A M N_{-E} \), hence
\[
am\tilde{n}m \in AMN_{-E} \cap n^{-1}N_z n \exp \left( A_{n_z} (\log(A_{n_z} M_z N_z)) \right)
\]
\[
\subset AMN_{-E} \cap n^{-1}N_{c\varepsilon} A_{c\varepsilon} M_{c\varepsilon} N_{c\varepsilon}
\]
\[
= A_{c\varepsilon} M_{c\varepsilon} N_{c\varepsilon}.
\] (6.4)

for some \( c \geq 1 \) depending only on \( E \). Decomposing the Haar measure \( dg \) on \( G \) according to \( AMN_{-E} \) and then restricting to \( A_{c\varepsilon} M_{c\varepsilon} N_{c\varepsilon} N_{-E} \) gives
\[
e^{-\psi(\log a) \, dz \, d\tilde{n} \, dm} = (1 + O(\varepsilon)) \, dg
\]
since \( a \in A_{c\varepsilon} \) and \( dg = dz \, d\tilde{n} \, dm \, da \) for \( g = amn_z \) [12, Ch. 8]. Hence
\[
\int_{-E} m_{\psi}^{BR}(\phi^\varepsilon) \, dz = (1 + O(\varepsilon)) \int_{N} \int_{AMN_{-E}} \phi^\varepsilon(ng) \, dg \, d\omega_{\psi}(n),
\]
with the implied constant depending only on \( E \). Now using the maximum of \( \| Ad_{n_z} \| \) over \( z \in \pm E \) together with the \( NAMN \) decomposition.
of \( \exp(\text{Ad}_{n-1} (\log(A_{c,x} M_{c,x} \tilde{N}_{c,x}))) \) as above gives \( c \geq c' \) such that
\[
N_{-E_{c,x}} A_{c,x} M_{c,x} \tilde{N}_{c,x} \subset A_{c,x} M_{c,x} \tilde{N}_{c,x} N_{-E} \subset N_{-E_{c,x}} A_{c,x} M_{c,x} \tilde{N}_{c,x}.
\]
Combined with \[(6.4), \text{ we have}
\[
\int_{N_{-E_{c,x}} H E} \phi^{\varepsilon}(ng) \, dg \leq \int_{H E} \phi^{\varepsilon}(ng) \, dg \leq \int_{N_{-E_{c,x}} H E} \phi^{\varepsilon}(ng) \, dg,
\]
giving the desired inequality. \( \square \)

Combining Lemma 6.2 and Proposition 6.3 gives

**Corollary 6.5.** There exist \( C, c > 0 \) such that for all \( \varepsilon > 0 \) sufficiently small,
\[
(1 - C\varepsilon) \omega_\psi(E_{-}^{(1+c)\varepsilon}) \leq \int_{E} m_{\psi}^{BR}(\phi^{\varepsilon}_x) \, dz \leq (1 + C\varepsilon) \omega_\psi(E_{+}^{(1+c)\varepsilon}).
\]

7. **Equidistribution in average.**

We fix a positive \( \Gamma_{\rho} \)-critical \( \psi \in a^* \), \( \nu_\psi \) and \( u = u_\psi \), continuing the notations from sections 4 and 5. We also fix a closed cone \( D \subset \text{int } a^* \) such that \( \text{int } D \supset L_{\rho} - \{0\} \) and set \( D := \exp D \) as in \((4.10)\) and \((4.11)\). Recall the notation \( B_{\psi}(E, R) = H \setminus HKD_{\psi,R} \tilde{N}_{-E} \) for a bounded subset \( E \subset \mathbb{C}^d \).

The main goal of this section is to prove the following main technical ingredient of the proof of Theorem 1.6 using Proposition 5.8.

**Theorem 7.1.** For any \( f \in C_c(\Gamma_{\rho} \setminus G) \) and a bounded set \( E \subset \mathbb{C}^d \) such that \( \omega_\psi(\partial E) = 0 \),
\[
\lim_{R \to \infty} \int_{B_{\psi}(E, R)} \int_{\Gamma_{\rho} \cap H \setminus H} f([h]g) \, d[h] \, d[g] = c_{\Gamma_{\rho}, \psi} \int_{E} m_{\psi}^{BR}(f_z) \, dz,
\]
where \( c_{\Gamma_{\rho}, \psi} := \frac{\kappa_{\text{skf}_{\rho}(H)}}{\Phi_\rho(u)} \left( \int_{\ker \psi} e^{-I(w)} \, dw \right) \) and \( f_z \in C_c(\Gamma_{\rho} \setminus G) \) defined by \( f_z(x) := \int_M f(xmn_z) \, dm \).

In the above, \( d[g] \) denotes the \( G \)-invariant measure on \( H \setminus G \) which is compatible to Haar measures \( dg \) and \( dh \) on \( G \) and \( H \) respectively, that is, for any \( f \in C_c(G) \),
\[
\int_G f(g) \, dg = \int_{H \setminus G} \left( \int_H f(hg) \, dh \right) \, d[g].
\]

**Integral computation.** For each \( w \in \ker \psi \), let \( Q_R(w) \subset [0, \infty) \) be defined as
\[
Q_R(w) := \{ s \in \mathbb{R}_{>0} : su + \sqrt{s}w \in A_{\psi,R}^+ \} = (s_w, R).
\]
for some \( s_w \in \mathbb{R}_{>0} \), with the understanding that \( Q_R(w) = \emptyset \) if \( s_w > R \).

The uniform bound in Proposition 5.8 enables us to use the dominated convergence theorem to prove:
Lemma 7.2. For $f \in C_c(\Gamma\rho \backslash G)$, $\phi \in C_c(H)$ and a bounded $E \subset \mathbb{C}^d$, define for each $w \in \ker \psi$,

$$p_R(w) = e^{-R} \int_E \int_{Q_R(w)} \frac{d-1}{s^2} e^{2\sigma(su + \sqrt{s}w)} \int_H f_z([h] \exp(su + \sqrt{s}w)) \phi(h) \, dh \, ds \, dz.$$ 

Then

1. $\lim_{R \to \infty} p_R(w) = \frac{\kappa \mu_{\Gamma\rho \backslash H}^{\mu_{\Gamma\rho \backslash H}}(\phi)}{\Phi_{\rho}(u)} e^{-I(w)} \int_E m_{\psi}^{BR}(f_z) \, dz$ and

2. $p_R(w) \leq C e^{-\ell I(w)}$ for some $C = C(f, E, \phi) > 0$.

Proof. For simplicity, set $c_u = \Phi_{\rho}(u)$ in this proof. For all sufficiently large $R > 0$, we may rewrite $p_R(w)$ as

$$p_R(w) = e^{-R} \int_E \int_{s w}^{R/c_u} e^{c_u s J(s, w, z)} \, ds \, dz$$

$$= \int_E \int_{s w - R/c_u}^{0} e^{c_u s J(s + R/c_u, w, z)} \, ds \, dz$$

where

$$J(s, w, z) = s \frac{d-1}{s^2} e^{2\sigma(su + \sqrt{s}w)} \int_H f_z([h] \exp(su + \sqrt{s}w)) \phi(h) \, dh.$$ 

By Proposition 5.8, $J(s, w, z) \to \kappa e^{-\ell I(w)} m_{\psi}^{BR}(f_z) \mu_{\Gamma\rho \backslash H}^{PS}(\phi)$ as $s \to \infty$ and

$$J(s, w, z) \leq C'' e^{-\ell I(w)}$$

where $C'' = C''(\sup_{z \in E} f_z, \phi)$ is as in Proposition 5.8. Hence (1) follows from the dominated convergence theorem. (2) follows from the bound

$$p_R(w) \leq \Vol(E) \int_{s w - R/c_u}^{0} e^{c_u s J(s + R/c_u, w, z)} \, ds$$

by setting $C = \frac{1}{2} \Vol(E)C''$. □

Proof of Theorem 7.1. Without loss of generality, we may assume that $f \geq 0$. For $\lfloor g \rfloor \in H \backslash G$, set

$$f^H(\lfloor g \rfloor) := \int_{\Gamma\rho \cap H \backslash H} f([h]g) \, dh.$$ 

By Proposition 3.4 (2), we can choose $\phi \in C_c(H)$ depending only on the support of $f$ and $E$ such that

$$f_z^H(\lfloor g \rfloor) = \int_{H} f_z([h]g) \phi(h) \, dh$$

(7.3)

for all $z \in E$. This will allow us to apply Proposition 5.8 directly to $f_z^H$. Furthermore, by Proposition 3.8 (1), the support of $\mu_{\Gamma\rho \cap H \backslash H, \phi}$ is compact,
so we may additionally assume that $\phi = 1$ on the support of $\mu_{\Gamma,\psi}^{PS}$ and hence $\text{sk}_{\Gamma,\psi}(H) = \mu_{\Gamma,\psi}^{PS}(H,\psi)(\phi)$. By Proposition 3.4

$$\int_{H \setminus H(A+D)K \setminus E} f^H([g]) d[g] < \infty.$$ 

Since $d[a_t n_z] = e^{2\sigma(t)} dt dz$ where $\sigma(t) = \sum t_i$, we deduce from Lemma 4.18 and the inclusion $B_\psi(E, R) \subset B_\psi(E, R)$:

$$\limsup_{R \to \infty} e^{-R} \int_{B_\psi(E, R)} f^H([g]) d[g] \leq \limsup_{R \to \infty} e^{-R} \int_{E_\ell \setminus A_\psi, R+\ell \varepsilon} f^H([a_t n_z]) e^{2\sigma(t)} dt dz. \quad (7.4)$$

Since $M \subset H$, we have

$$f^H([a_t n_z]) = f^H([m a_t n_z]) = f^H([a_t m n_z]) = \int_M f^H([a_t m n_z]) dm = f^H([a_t]).$$

We now compute the limit in (7.4).

Using (7.3) together with the fact that $dt = s^{d-1} ds dw$, we first rewrite (7.4) as $\int_{\ker \psi} p_R(w) dw$ where

$$p_R(w) := e^{-R} \int_{E_\ell(\varepsilon)} \int_{Q_{R+\ell \varepsilon}(w)} s^{d-1} e^{2\sigma(su+\sqrt{\varepsilon} w)} f^H([\exp(su + \sqrt{\varepsilon} w)]) ds dz.$$

$$= e^{-R} \int_{E_\ell(\varepsilon)} \int_{Q_{R+\ell \varepsilon}(w)} s^{d-1} e^{2\sigma(su+\sqrt{\varepsilon} w)} \int_H f_z([\exp(su + \sqrt{\varepsilon} w)]) \phi(h) dh dz.$$

Applying Lemma 7.2 by replacing $R$ with $R + \ell \varepsilon$ and $E$ with $-E_\ell^{+\varepsilon}$ by the dominated convergence theorem,

$$\lim_{R \to \infty} \int_{\ker \psi} p_R(w) dw = \int_{\ker \psi} \lim_{R \to \infty} p_R(w) dw$$

$$= \int_{\ker \psi} e^{-I(w)} dw \int_{-E_\ell^{+\varepsilon}} m^{BR}_\psi(f_z) dz.$$

Altogether, we have thus obtained

$$\limsup_{R \to \infty} e^{-R} \int_{B_\psi(E, R)} f^H([g]) d[g] \leq c_\psi e^{\ell \varepsilon} \int_{-E_\ell^{+\varepsilon}} m^{BR}_\psi(f_z) dz.$$ 

Similarly, but using $H \setminus HD_{\psi, R} \setminus \Gamma \setminus E \subset B_\psi(E, R)$ instead of Lemma 4.18 and $D_{\psi, R}$ instead of $A_\psi, R$ in the definition of $Q_R(w)$, we have

$$\liminf_{R \to \infty} e^{-R} \int_{B_\psi(E, R)} f^H([g]) d[g] \geq c_\psi e^{\ell \varepsilon} \int_{-E_\ell^{+\varepsilon}} m^{BR}_\psi(f_z) dz.$$ 

Since $\omega_\psi(\partial E) = 0$, by Corollary 6.5, taking $\varepsilon \to 0^+$ completes the proof.
8. Proof of the main counting theorem

In this section, we prove the following main theorem of this paper:

**Theorem 8.1.** Let \( P \) be a \( \Gamma_\rho \)-admissible torus packing. For any positive linear form \( \psi \in \mathfrak{a}^* \), there exists a constant \( c_\psi = c_{P,\psi} > 0 \) and a locally finite Borel measure \( \omega_\psi = \omega_{\Gamma_\rho,\psi} \) on \( \mathbb{C}^d \) such that for any bounded subset \( E \subset \mathbb{C}^d \) with locally algebraic boundary, we have

\[
\lim_{R \to \infty} e^{-\delta_\psi R} \cdot N_R(P, \psi, E) = c_\psi \cdot \omega_\psi(E).
\]  

(8.2)

**Example 8.3.** Note that \( \text{Vol}(T) = (2\pi)^d e^{-\sigma(v(T))} \) since \( \sigma(t_1, \ldots, t_d) = t_1 + \cdots + t_d \). Hence we have

\[
N_R(P, \sigma, E) = \# \{ T \in P : \text{Vol}(T) \geq (2\pi)^d e^{-R}, T \cap E \neq \emptyset \}.
\]

Since \( \sigma \in \mathfrak{a}^* \) is positive, Theorem 1.4 is a special case of Theorem 8.1, with \( \delta_{L_1,\rho} = \delta_\sigma \), \( c_P = (2\pi)^d c_{P,\sigma} \), and \( \omega_\psi = \omega_{\Gamma_\rho,\sigma} \).

Since every homothety class of a positive linear form can be represented by a positive \( \Gamma_\rho \)-critical linear form (Lemma 2.10) and \( \delta_\psi = 1 \) for critical forms, Theorem 8.1 follows from the following:

**Proposition 8.4.** For any positive \( \Gamma_\rho \)-critical linear form \( \psi \in \mathfrak{a}^* \), we have

\[
\lim_{R \to \infty} e^{-R} \cdot N_R(P, \psi, E) = c_\psi \cdot \omega_\psi(E)
\]

for some constant \( c_\psi > 0 \).

**Special case:** \( P = \Gamma_\rho T_0 \). We will first prove Proposition 8.4 for the special case when \( P = \Gamma_\rho T_0 \). This will allow us to apply the results obtained in previous sections.

Let \( D \) be as defined in (4.10). Fix closed cones \( D^\pm \subset \text{int} \mathfrak{a}^+ \) such that

\[
L_\rho - \{0\} \subset \text{int} D^-, \quad D^- = \{0\} \subset \text{int} D, \quad \text{and} \quad D - \{0\} \subset \text{int} D^+.
\]

Let \( D^\pm = \exp D^\pm \) and \( R_0 > 0 \) be such that

\[
D^- - A_{R_0} \subset \bigcap_{a \in A_1} Da, \quad \bigcup_{a \in A_1} (D - A_{R_0})a \subset D^+.
\]

Recall the definition of \( E_\varepsilon^\pm \) from (4.8). Now defining

\[
B_\psi^0(E, R) := H \backslash HKD_{(R_0, R)} N_{-E} \quad B_\psi^\varepsilon(E, R)^- := H \backslash HKD_{(R_0, R)} N_{-E_{\varepsilon}^-} \quad \text{and} \quad B_\psi^\varepsilon(E, R)^+ := H \backslash HKD_{(R_0, R)} N_{-E_{\varepsilon}^+},
\]

(8.5)

where \( D_{(R_0, R)}^\pm = \exp(D_{(R_0, R)}^- - D_{(R_0, R)}^+) \), we have the following inclusions:

**Lemma 8.6.** [21, Lemma 6.3] For all \( \varepsilon > 0 \) small enough, there exists a neighbourhood \( O_\varepsilon \subset G \) of the identity such that for all \( R > R_0 \),

\[
B_\psi^\varepsilon(E, R - \varepsilon)^- \subset B_\psi^0(E, R)O_\varepsilon \subset B_\psi^\varepsilon(E, R + \varepsilon)^+.
\]
We will now use the sets $B^\varepsilon_\psi(E, R \pm \varepsilon)^\pm$ to obtain the asymptotic of $\#([e]\Gamma_\rho \cap B^0_\psi(E, R))$. Define functions $F_R$, and $F^{\varepsilon, \pm}_R$ on $\Gamma_\rho\setminus G$ by

$$F_R([g]) := \sum_{\gamma \in (\Gamma_\rho \cap H) \setminus \Gamma_\rho} 1_{B^0_\psi(E, R)}([\gamma g]),$$

and

$$F^{\varepsilon, \pm}_R([g]) := \sum_{\gamma \in (\Gamma_\rho \cap H) \setminus \Gamma_\rho} 1_{B^\varepsilon_\psi(E, R \pm \varepsilon)^\pm}([\gamma g]).$$

(8.7)

Note that

$$F_R([e]) = \#([e]\Gamma_\rho \cap B^0_\psi(E, R)),$$

(8.8)

and by Lemma 8.6, we have

$$F^{\varepsilon, -}_R([g]) \leq F_R([e]) \leq F^{\varepsilon, +}_R([g]),$$

for all $[g] \in [e]O_\varepsilon$ and all $\varepsilon$ less than the injectivity radius of $[e] \in \Gamma_\rho \setminus G$. Now fix any non-negative function $\phi^\varepsilon \in C_c(\Gamma_\rho \setminus \Gamma_\rho \setminus G)$ such that $\int \phi^\varepsilon([g])\,dg = 1$. Then

$$\langle F^{\varepsilon, -}_R, \phi^\varepsilon \rangle \leq F_R([e]) \leq \langle F^{\varepsilon, +}_R, \phi^\varepsilon \rangle,$$

(8.9)

where $\langle \psi_1, \psi_2 \rangle = \int_{\Gamma_\rho \setminus G} \psi_1(x)\psi_2(x)\,dx$ whenever the integral converges. We will use Theorem 7.1 to estimate the integrals $\langle F^{\varepsilon, \pm}_R, \phi^\varepsilon \rangle$ (cf. [21, (6.6), p. 30] and [4, Proposition 9.10]):

**Proposition 8.10.** For any $\varepsilon > 0$ small enough,

$$\langle F^{\varepsilon, \pm}_R, \phi^\varepsilon \rangle_{\Gamma_\rho \setminus G} \sim c_\psi e^{R\pm\varepsilon} \int_{-E_\varepsilon^\pm} m_{\psi}^{BR}(\phi^\varepsilon_z)\,dz \quad \text{as } R \to \infty$$

where the constant $c_\psi = c_{\Gamma_\rho, \psi}$ is given in Theorem 7.1.

**Proof.** Using unfolding, we have

$$\langle F^{\varepsilon, \pm}_R, \phi^\varepsilon \rangle = \int_{\Gamma_\rho \setminus G} \left( \sum_{\gamma \in (\Gamma_\rho \cap H) \setminus \Gamma_\rho} 1_{B^\varepsilon_\psi(E, R \pm \varepsilon)^\pm}([\gamma g]) \right) \phi^\varepsilon([g])\,dg$$

$$= \int_{\Gamma_\rho \cap H \setminus G} 1_{B^\varepsilon_\psi(E, R \pm \varepsilon)^\pm}([g])\phi^\varepsilon([g])\,dg$$

$$= \int_{B^\varepsilon_\psi(E, R \pm \varepsilon)^\pm} \int_{\Gamma_\rho \cap H \setminus H} \phi^\varepsilon([hg])\,dh\,dg.$$

Since the set difference between $B^\varepsilon_\psi(E, R \pm \varepsilon)^\pm$ and $B^\varepsilon_{D, \psi}(E^\varepsilon_\pm, R \pm \varepsilon)$ is bounded independent of $R$, Theorem 7.1 then gives the claimed identity. □

**Proof of Proposition 8.4 when $P = \Gamma_\rho T_0$.** Note that the set difference between $B^0_\psi(E, R)$ and $B^0_{D, \psi}(E, R)$ is bounded independent of $R$. Hence, by
Proposition 8.10 and Corollary 4.21
\[\lim_{R \to \infty} e^{-R} \#([e]\Gamma_\rho \cap B_0^0(E_\ell^- , R)) \leq \lim_{R \to \infty} e^{-R} N_R(\mathcal{P}, \psi, E) \]
\[\leq \lim_{R \to \infty} e^{-R} N_R(\mathcal{P}, \psi, E) \leq \lim_{R \to \infty} e^{-R} \#([e]\Gamma_\rho \cap B_0^0(E_\ell^+, R + \ell \varepsilon)).\]

Let \(\varepsilon_0 = (\ell + 2)\varepsilon\). The above computation, combined with (8.8), (8.9) and Proposition 8.10 gives
\[c_\psi e^{-\varepsilon_0} \int_{-E_{\varepsilon_0}^-} m_{\psi}^{BR}(\phi_{\varepsilon_0}^\varepsilon) \, dz \leq \lim_{R \to \infty} e^{-R} N_R(\mathcal{P}, \psi, E) \]
\[\leq \lim_{R \to \infty} e^{-R} N_R(\mathcal{P}, \psi, E) \leq c_\psi e^{\varepsilon_0} \int_{-E_{\varepsilon_0}^+} m_{\psi}^{BR}(\phi_{\varepsilon_0}^\varepsilon) \, dz.\]

Corollary 6.5 now gives
\[c_\psi e^{-\varepsilon_0}(1 - C\varepsilon_0) \omega_\psi(E_{(2 + \varepsilon)\varepsilon}) \leq \lim_{R \to \infty} e^{-R} N_R(\mathcal{P}, \psi, E) \]
\[\leq \lim_{R \to \infty} e^{-R} N_R(\mathcal{P}, \psi, E) \leq c_\psi e^{\varepsilon_0}(1 + C\varepsilon_0) \omega_\psi(E_{(2 + \varepsilon)\varepsilon}).\]

The assumption that \(\omega_\psi(\partial E) = 0\) and regularity of \(\omega_\psi\) gives
\[\lim_{\varepsilon \to 0^+} c_\psi e^{\pm \varepsilon}(1 \pm C\varepsilon) \omega_\psi(E_{(2 + \varepsilon)\varepsilon}) = c_\psi \omega_\psi(E),\]
completing the proof. \(\square\)

**General case.** Without loss of generality, we may assume that \(\mathcal{P}\) consists of a single \(\Gamma_\rho\)-orbit; hence let \(\mathcal{P} = \Gamma_\rho T\) be a \(\Gamma_\rho\)-admissible torus packing. We write
\[T = g_0 T_0,\]
where \(g_0 = n_{2a_{log} r_0}\); here \(z_0\) is the vector consisting of the centers of the circles of \(T\) and \(r_0 = (r_1, \ldots, r_d)\) are the corresponding radii. Set
\[\Gamma_\rho^{g_0} := g_0^{-1}\Gamma_\rho g_0.\]

Note that
\[N_R(\mathcal{P}, \psi, E) = \# \{ T' \in \Gamma_\rho T : T' \cap E \neq \emptyset \text{ and } \psi(v(T')) \leq R \}\]
\[= \# \{ T' \in \Gamma_\rho^{g_0} T_0 : T' \cap E \neq \emptyset \text{ and } \psi(v(T')) \leq R \}\]
\[= \# \{ \gamma \in (\Gamma_\rho^{g_0} \cap H) \backslash \Gamma_\rho^{g_0} : g_0 \gamma^{-1} T_0 \cap E \neq \emptyset \text{ and } \psi(v(g_0 \gamma^{-1} T_0)) \leq R \}.\]
Similarly as in Proposition 4.7 we can obtain the following estimate of \(N_R(\mathcal{P}, \psi, E)\) in terms of \(\tilde{B}_\psi(E_\ell^- , R)\):

**Proposition 8.11.** For any \(\varepsilon > 0\), there exists \(g_0 = g_0(\mathcal{P}, \varepsilon) > 0\) such that for any \(R > 0\) and a bounded subset \(E \subset \mathbb{C}^d\), we have
\[\#([e]\Gamma_\rho^{g_0} \cap \tilde{B}_\psi(E_\ell^- , R)g_0) - q_0 \leq N_R(\mathcal{P}, \psi, E) \leq \#([e]\Gamma_\rho^{g_0} \cap \tilde{B}_\psi(E_\ell^+, R)g_0) + q_0.\]
Note that $\Gamma_0^\rho$ is also a self-joining of convex cocompact representations. Let $\Lambda_0^\rho = \Lambda_{\Gamma_0^\rho}$ and $\mathcal{L}_0^\rho = \mathcal{L}_{\Gamma_0^\rho}$ denote its limit set and limit cone, respectively. It is immediate from the definition that

$$\Lambda_0^\rho = g_0^{-1} \Lambda_\rho$$

and $\mathcal{L}_0^\rho = \mathcal{L}_\rho$.

Now, writing $g_0 = (g_{0,1}, \ldots, g_{0,d})$, the homeomorphisms in (2.3) associated to $\Gamma_0^\rho$ can be written as $g_0^{-1} f_i (g_{0,1})$ ($1 \leq i \leq d$). A direct computation shows that $T$ is $\Gamma_\rho$-admissible if and only if $T_0$ is $\Gamma_0^\rho$-admissible. Hence, we can apply the results obtained in previous sections for a new subgroup $\Gamma_0^\rho$.

**Transition from $\Gamma_\rho$ to $\Gamma_0^\rho$.** Let $\Phi_\rho^\rho = \Phi_{\Gamma_0^\rho}$ denote the growth indicator function associated to $\Gamma_0^\rho$. The following lemma is standard and can be proved directly from the definition of $\Phi_\rho$:

**Lemma 8.12.** We have

$$\Phi_\rho^\rho = \Phi_\rho.$$

Since $\psi$ is $\Gamma_\rho$-critical, it follows from Lemma 8.12 that $\psi$ is $\Gamma_0^\rho$-critical. Let $\nu_\psi^\rho$ denote the $(\Gamma_0^\rho, \psi)$-PS measure supported on $\Lambda_0^\rho$. Define a measure $\overline{\nu}_\psi^\rho$ on $\mathbb{C}^d$ via the formula

$$d\overline{\nu}_\psi^\rho (z) = e^{-\psi (\beta_z (\cdot, g_0, o))} d((g_0)_* \nu_\psi^\rho) (z).$$

**Lemma 8.13.** We have:

$$\frac{\overline{\nu}_\psi^\rho}{|\overline{\nu}_\psi^\rho|} = \nu_\psi.$$

**Proof.** Since the support of $\nu_\psi^\rho$ is $\Lambda_0^\rho = g_0^{-1} \Lambda_\rho$, we have

$$(g_0)_* \nu_\psi^\rho (\Lambda) = \nu_\psi^\rho (g_0^{-1} \Lambda_\rho) = 1.$$

Therefore, $\overline{\nu}_\psi^\rho$ is also supported on $\Lambda_\rho$. Furthermore, for any $\gamma \in \Gamma_\rho$, we have

$$d_{\gamma_*} \overline{\nu}_\psi^\rho (z) = e^{-\psi (\beta_{\gamma^{-1}} (\cdot, g_0, o))} d_{\gamma_*} (g_0)_* \nu_\psi^\rho (z) = e^{-\psi (\beta_{\gamma^{-1}} (\cdot, g_0, o))} d (g_0)_* \nu_\psi^\rho (z) = e^{-\psi (\beta_{\gamma^{-1}} (\cdot, g_0, o))} e^{-\psi (\beta_{g_0^{-1}} (\cdot, g_0, o))} d_{\gamma_*} \nu_\psi^\rho (z) = e^{\psi (\beta_z (\cdot, g_0, o))} e^{\psi (\beta_{g_0^{-1}} (\cdot, g_0, o))} d_{\gamma_*} \nu_\psi^\rho (z) = e^{\psi (\beta_z (\cdot, g_0, o))} \overline{\nu}_\psi^\rho (z),$$

i.e.

$$\frac{d_{\gamma_*} \overline{\nu}_\psi^\rho (z)}{\overline{\nu}_\psi^\rho (z)} = e^{-\psi (\beta_{\gamma^{-1}} (\cdot, g_0, o)).}$$
This shows that $\tilde{\nu}_{\psi}^{g_0}$ is a $(\Gamma_\rho, \psi)$-PS measure. By [15] Thm. 1.3, $\nu_\psi$ is the unique $(\Gamma_\rho, \psi)$-PS measure, and hence the lemma is proved. \[\square\]

Let $\omega_{g_0, \psi}$ denote the measure defined as in (6.1), associated to $\Gamma_\rho$ and $\psi$. Using Lemma [8.13] we can now show that

**Lemma 8.14.** There exists $c_{g_0} > 0$ such that

$$\omega_{g_0, \psi}(g_0^{-1} \cdot E) = c_{g_0} \cdot \omega_\psi(E)$$

for all Borel sets $E \subset \mathbb{C}^d$.

**Proof.** By Lemma [8.13]

$$\omega_{g_0, \psi}(g_0^{-1} \cdot E) = \int_E d(g_0) \omega_{g_0, \psi}(z) = \int_E e^{\psi(\beta_{-1}^{-1}(0, \nu_{g_0}^{-1}(o)))} d(g_0) \nu_{\psi}^{g_0}(z)$$

Now writing $g_0 = n \cdot a \cdot t_0$, we thus have

$$\omega_{g_0, \psi}(g_0^{-1} \cdot E) = \int_E e^{\psi(\beta_{-1}^{-1}(0, n \cdot a \cdot t_0^{-1}))} e^{\psi(\beta_z(0, \nu_{g_0}^{-1}(o)))} d\nu_{\psi}^{g_0}(z)$$

$$= |\tilde{\nu}_{\psi}^{g_0}| \int_E e^{\psi(\beta_z(g_0^{-1} \cdot (0, n \cdot a \cdot t_0^{-1})))} e^{\psi(\beta_z(0, \nu_{g_0}^{-1}(o)))} d\nu_{\psi}^{g_0}(z)$$

$$= |\tilde{\nu}_{\psi}^{g_0}| \int_E e^{\psi(\beta_z(n \cdot a \cdot t_0^{-1} \cdot (0, \nu_{g_0}^{-1}(o))))} d\omega_\psi(z)$$

$$= |\tilde{\nu}_{\psi}^{g_0}| e^{\psi(\beta_z(0, \nu_{g_0}^{-1}(o)))} \omega_\psi(E)$$

$$= |\tilde{\nu}_{\psi}^{g_0}| e^{-\psi(t_0)} \omega_\psi(E),$$

as desired. \[\square\]

Next, let $m_{g_0, \psi}^{BR} = m_{g_0, \psi}^{BR}$ denote the Burger-Roblin measure associated to $\Gamma_\rho$ and the linear form $\psi$.

**Lemma 8.15.** For all small enough $\varepsilon > 0$,

$$\int_{-\varepsilon E^2} m_{g_0, \psi}^{BR}(g_0 \cdot \phi^z) dz = \psi(\log r_0) \int_{-\varepsilon E^2} m_{g_0, \psi}^{BR}(\phi^z) dz.$$

**Proof.** Denote the $\Gamma_\rho$-invariant lift of $m_{g_0, \psi}^{BR}$ to $G$ by $\tilde{m}_{g_0, \psi}^{BR}$. We will use the $G = KA\tilde{N}$ decomposition to write

$$d\tilde{m}_{g_0, \psi}^{BR}(kau) = e^{-\psi(\log r_0)} du da d\tilde{\nu}_{\psi}^{g_0}(k),$$

where the measure $\tilde{\nu}_{\psi}^{g_0}$ on $K$ is defined by

$$\int_K f(k) d\tilde{\nu}_{\psi}^{g_0}(k) = \int_{K/M} f(km) dm d\nu_{\psi}^{g_0}(k)$$
for all \( f \in C(K) \) \([4]\) Lem. 4.9. For any \( f \in C_c(G) \), and \( L \subset \mathbb{C}^d \), using the fact that \( g_0 = n_{z_0} a_{\log r_0} \), we have
\[
\int_{-L} \widetilde{m}^{BR}_{g_0, \psi}((g_0 \cdot f)_z) \, dz = \int_{-L} \int_M \int_G f(gmnzg_0) \, d\widetilde{m}^{BR}_{g_0, \psi}(g) \, dm \, dz = e^{2\sigma(\log r_0)} \int_{-\log r_0}^{\log r_0} \int_M \int_G f(gmnzg_0) \, d\widetilde{m}^{BR}_{g_0, \psi}(g) \, dm \, dz.
\]
From [8.16], we obtain
\[
\int_{G} f(ga_{\log r_0}mnzg_0) \, d\widetilde{m}^{BR}_{g_0, \psi}(g) = \int_{K\tilde{A}} f(kaua_{\log r_0}mnz) e^{-\psi(\log a)} \, du \, d\tau^{\theta(g_0)}(k) = e^{-2\sigma(\log r_0)} \int_{K\tilde{A}} f(kaua_{\log r_0}mnz) e^{-\psi(\log a)} \, du \, d\tau^{\theta(g_0)}(k) = e^{\psi(\log r_0)} \int_{G} f(gmnz) \, d\widetilde{m}^{BR}_{g_0, \psi}(g).
\]
This gives
\[
\int_{-L} \widetilde{m}^{BR}_{g_0, \psi}((g_0 \cdot f)_z) \, dz = e^{\psi(\log r_0)} \int_{-g_0^{-1} \cdot L} \widetilde{m}^{BR}_{g_0, \psi}(f_z) \, dz,
\]
proving the claim. \( \square \)

We are now ready to give:

**Proof of Proposition 8.4 for the general case.** We define a counting function \( F_R \) on \( \Gamma^{g_0}_\rho \setminus G \) by
\[
F_R([g]) = \sum_{\gamma \in (\Gamma^{g_0}_\rho \cap H) \setminus \Gamma^{g_0}_\rho} 1_{B_\psi(E, R)}(\gamma g);
\]
denoting the right \( G \)-action on functions on \( \Gamma^{g_0}_\rho \setminus G \) by \((g \cdot f)([h]) = f([hg])\), we have:
\[
\# \{ [e] \Gamma^{g_0} \cap B_\psi^0(E, R) g_0 \} = (g_0^{-1} \cdot F_R)([e]). \tag{8.17}
\]
Let \( B_\psi^0(E, R) \pm \) be as in \((8.5)\) and \( O_\varepsilon \) be as in Lemma 8.6. Set
\[
F_R^{\varepsilon, \pm}([g]) := \sum_{\gamma \in (\Gamma^{g_0}_\rho \cap H) \setminus \Gamma^{g_0}_\rho} 1_{B_\psi^0(E, R \pm \varepsilon)}(\gamma g). \tag{8.18}
\]
Then
\[
(g_0^{-1} \cdot F_R^{\varepsilon, -})([g]) \leq (g_0^{-1} \cdot F_R)([e]) \leq (g_0^{-1} \cdot F_R^{\varepsilon, +})([g])
\]
for all \( g \in O_\varepsilon \). Thus, choosing a non-negative \( \phi^\varepsilon \in C_c([e] O_\varepsilon) \) such that \( \int_{O_\varepsilon} \phi^\varepsilon([g]) \, dg = 1 \) gives
\[
(F_R^{\varepsilon, -}, g_0 \cdot \phi^\varepsilon)_{\Gamma^{g_0}_\rho \setminus G} \leq F_R([g_0]) \leq (F_R^{\varepsilon, +}, g_0 \cdot \phi^\varepsilon)_{\Gamma^{g_0}_\rho \setminus G}. \tag{8.19}
\]
Similarly as in Proposition 8.10, we have
\[ \langle F_\varepsilon^+, g_0 \cdot \phi^\varepsilon \rangle_{\Gamma_\rho} \sim c \cdot e^{R \varepsilon} \int_{-E_\rho}^{E_\rho} m_{g_0, \psi}((g_0 \cdot \phi^\varepsilon)_{\gamma}) \, dz, \]  
(8.20)
as \( R \to \infty \), where \( c = c_{\Gamma_\rho, \psi} \).

Similarly to the proof for the special case, from Proposition 8.11, (8.17), (8.19) and (8.20), we obtain
\[ c \cdot e^{-\varepsilon} \int_{-E_\rho}^{E_\rho} m_{g_0, \psi}((g_0 \cdot \phi^\varepsilon)_{\gamma}) \, dz \leq \liminf_{R \to \infty} e^{-R N_R(\mathcal{P}, E)} \leq \limsup_{R \to \infty} e^{-R N_R(\mathcal{P}, E)} \leq c \cdot e^{-\varepsilon} \int_{-E_\rho}^{E_\rho} m_{g_0, \psi}((g_0 \cdot \phi^\varepsilon)_{\gamma}) \, dz. \]

Applying Lemma 8.15 and Corollary 6.5 gives
\[ e^{\psi(\log r_0)}(1 - C \varepsilon) \cdot \omega_{g_0, \psi}(g_0^{-1} \cdot E_{(2+c)\varepsilon}) \leq \int_{-E_\rho}^{E_\rho} m_{g_0, \psi}((g_0 \cdot \phi^\varepsilon)_{\gamma}) \, dz \]
\[ \leq e^{\psi(\log r_0)}(1 + C \varepsilon) \cdot \omega_{g_0, \psi}(g_0^{-1} \cdot E_{(2+c)\varepsilon}). \]

We now use Lemma 8.14 to change \( \omega_{g_0, \psi} \) to \( \omega_\psi \) and then taking \( \varepsilon \to 0 \) as in the case \( T = T_0 \) gives
\[ \lim_{R \to \infty} e^{-R N_R(\mathcal{P}, \psi, E)} = c_0 \cdot \omega_\psi(E) \]
for some positive constant \( c_0 > 0 \). Since the left-hand side of the above equation does not depend on the choice of \( g_0 \), we in fact have \( c_0 \) cannot depend on \( g_0 \) either, proving the theorem. □

9. PS-measures are null on algebraic varieties

In this section, we prove that \( \nu_\psi(S) = 0 \) for any proper real algebraic subvariety \( S \) of \( \hat{\mathbb{C}}^d \). Since \( \omega_\psi \) is absolutely continuous with respect to \( \nu_\psi \), it follows that \( \omega(\partial E) = 0 \) whenever \( E \) has locally algebraic boundary. We will in fact prove this in a more general setup, which we now explain.

Let \( G \) be any connected semisimple linear real algebraic group. Let \( P = MAN < G \) be a minimal parabolic subgroup with a fixed Langlands decomposition. Let \( \mathfrak{a} \) denote the Lie algebra of \( A \). Let \( i \) denote the opposition involution on \( \mathfrak{a} \); that is \( i(x) = -\text{Ad}_{w_0}(x) \) for all \( x \in \mathfrak{a} \). We remark that the opposition involution is non-trivial if and only if \( G \) has a simple factor of type \( A_n \) (\( n \geq 2 \)), \( D_{2n+1} \) (\( n \geq 2 \)) and \( E_6 \) [29, 1.5.1]. For instance, when \( G \) is a product of rank one groups, \( i \) is trivial.

A Borel probability measure \( \nu \) on \( \mathcal{F} = G/P \) is called a \((\Gamma, \psi)\)-conformal measure for a linear form \( \psi \in \mathfrak{a}^* \) if for all \( \gamma \in \Gamma \) and \( \xi \in \mathcal{F} \),
\[ \frac{d\gamma_\nu}{d\nu}(\xi) = e^{-\psi(\beta(\gamma, e))}, \]
where \( \beta \) denotes the \( \mathfrak{a} \)-valued Busemann map [4, Def. 2.3]. When supported on the limit set \( \Lambda \), it is called a \((\Gamma, \psi)\)-PS-measure.

We recall the following result: consider the diagonal action of \( \Gamma \) on \( \mathcal{F} \times \mathcal{F} \).
Proposition 9.1. [16] Prop. 6.3  Let $\Gamma < G$ be a Zariski dense Anosov subgroup of $G$ (with respect to $P$). Let $\psi \in \mathfrak{a}^*$ be a linear form. Let $\nu$ and $\nu_i$ be respectively $(\Gamma, \psi)$ and $(\Gamma, \psi \circ i)$-PS measures. Then $(\nu \times \nu_i, F \times F)$ is $\Gamma$-ergodic.

Theorem 9.2. Let $\Gamma < G$ be a Zariski dense Anosov subgroup of $G$. For any $(\Gamma, \psi)$-PS measure $\nu$ for some $\psi \in \mathfrak{a}^*$ with $\psi \circ i = \psi$, we have $\nu(S) = 0$ for any any proper real algebraic subvariety $S$ of $F$.

Proof. Suppose the theorem is false. Let $S$ be a proper subvariety of $F$ with $\nu(S) > 0$ and of minimal dimension. We may assume without loss of generality that $S$ is irreducible.

Since $\psi = \psi \circ i$, we may apply Proposition 9.1 to the product $\nu \times \nu$. Since $(\nu \times \nu)(S \times S) = \nu(S) \times \nu(S) > 0$ the $\Gamma$-ergodicity of $\nu \times \nu$ implies that $\Gamma(S \times S)$ must have full $\nu \times \nu$-measure.

Since for any $\gamma_0 \in \Gamma$, $(\nu \times \nu)(S \times \gamma_0 S) > 0$, there must exist $\gamma \in \Gamma$ such that $(S \cap \gamma_0 S) \cap (\gamma S \times \gamma S)$ has positive $\nu \times \nu$-measure. This implies that $\nu(S \cap \gamma S) > 0$ and $\nu(\gamma_0 S \cap \gamma S) > 0$. Since $S$ is an irreducible variety, for any $\gamma \in \Gamma$, either $S = \gamma S$ or the dimension of $S \cap \gamma S$ is strictly smaller than that of $S$, and hence $\nu(S \cap \gamma S) = 0$. Therefore $S = \gamma S = \gamma_0 S$. Since $\gamma_0$ was arbitrary, it follows that $\Gamma S = S$; a contradiction. \hfill \Box

References


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