AHLFORS REGULARITY OF PATTERSON-SULLIVAN MEASURES OF ANOSOV GROUPS AND APPLICATIONS

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Abstract. For all Zariski dense Anosov subgroups of a semisimple real algebraic group, we prove that their limit sets are Ahlfors regular for intrinsic conformal premetrics. As a consequence, we obtain that a Patterson-Sullivan measure is equal to the Hausdorff measure if and only if the associated linear form is symmetric. We also discuss several applications, including analyticity of \((p, q)\)-Hausdorff dimensions on the Teichmüller spaces, new upper bounds on the growth indicator, and \(L^2\)-spectral properties of associated locally symmetric manifolds.

1. Introduction

Let \(G\) be a connected semisimple real algebraic group. Let \(\Gamma \subset G\) be a discrete subgroup. Patterson-Sullivan measures are certain families of Borel measures on a generalized flag variety, supported on the limit set of \(\Gamma\). They play a crucial role in the study of dynamics on the associated locally symmetric space, especially in the counting and equidistribution of \(\Gamma\)-orbits of various geometric objects. The original construction is due to Patterson and Sullivan for Kleinian groups ([44], [55]), which was generalized by Quint [49] (see [2] and [13] for earlier works).

Sullivan showed that for convex cocompact Kleinian groups of Isom\(^+\)(\(\mathbb{H}^n_\mathbb{R}\)), Patterson-Sullivan measures are Ahlfors regular Hausdorff measures on the limit sets in \(S^{n-1}\) [55, Theorem 8]. Since Patterson-Sullivan measures are constructed from the weighted Dirac measures on an orbit of \(\Gamma\) in the symmetric space \(\mathbb{H}^n_\mathbb{R}\), it is remarkable that they can be given the geometric characterization purely in terms of the internal metric on the limit set of \(\Gamma\) which is a subset of the boundary \(\partial \mathbb{H}^n_\mathbb{R} \simeq S^{n-1}\).

In recent decades, Anosov subgroups have emerged as a higher rank generalization of convex cocompact Kleinian groups. Therefore it is natural to ask when the Patterson-Sullivan measures of Anosov subgroups arise as Ahlfors regular Hausdorff measures on the limit sets with respect to appropriate metrics. The main goal of this paper is to answer this question.

To state our results, fix a Cartan decomposition \(G = KA^+K\) where \(K\) is a maximal compact subgroup and \(A^+\) is a positive Weyl chamber of a maximal real split torus \(A\). We denote by \(X\) the associated Riemannian symmetric space \(G/K\). Let \(\mathfrak{g}\) and \(\mathfrak{a}\) denote the Lie algebras of \(G\) and \(A\)

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respectively, and set $\alpha^+ = \log A^+$. Let $\Pi$ denote the set of all simple roots of $(g, a)$ with respect to the choice of $\alpha^+$.

Fix a non-empty subset $\theta$ of $\Pi$. Let $P_\theta$ be the standard parabolic subgroup of $G$ associated with $\theta$. The quotient space 

$$\mathcal{F}_\theta = G/P_\theta$$

is called the $\theta$-boundary, or a generalized flag variety. We denote by $\Lambda_\theta$ the limit set of $\Gamma$ in $\mathcal{F}_\theta$. For $\theta = \Pi$, we omit the subscript $\theta$ from now on; so $P = P_{\Pi}$ is a minimal parabolic subgroup of $G$.

Set $a_\theta = \bigcap_{\alpha \in \Pi - \theta} \ker \alpha$ and let $a^*_\theta$ denote the set of all linear forms on $a_\theta$. We may think of $a^*_\theta$ as a subspace of $a^*$ via the canonical projection $p_\theta : a \to a_\theta$. For $\psi \in a^*_\theta$, a $(\Gamma, \psi)$-Patterson-Sullivan measure is a Borel probability measure $\nu$ on $\Lambda_\theta$ such that for all $\gamma \in \Gamma$ and $\xi \in \Lambda_\theta$,

$$\frac{d\gamma_*\nu}{d\nu}(\xi) = e^{\psi(\beta_2(e, \gamma))}$$

where $\beta$ denotes the Busemann map (see (2.8)).

A finitely generated subgroup $\Gamma < G$ is called $\theta$-Anosov if there exists a constant $C > 1$ such that for all $\alpha \in \theta$,

$$\alpha(\mu(\gamma)) \geq C^{-1}|\gamma| - C$$

for all $\gamma \in \Gamma$

where $| \cdot |$ is a word metric on $\Gamma$ with respect to a fixed finite generating set and $\mu : G \to a^+$ is the Cartan projection defined by the condition that $g \in K(\exp \mu(g))K$ for all $g \in G$. See ([34], [25], [28], [29], [24], [7], etc.) for other equivalent definitions of Anosov subgroups.

In the rest of the introduction, let $\Gamma$ be a $\theta$-Anosov subgroup of $G$. Throughout the paper, all $\theta$-Anosov subgroups are assumed to be non-elementary, that is, their limit sets $\Lambda_\theta$ have at least three points.

The space of all Patterson-Sullivan measures of $\Gamma$ is parameterized by the set $\mathcal{T}_\Gamma \subset a^*_\theta$ of all linear forms tangent to the $\theta$-growth indicator $\psi^0_\Gamma$ (Definition 3.1):

$$\mathcal{T}_\Gamma = \{ \psi \in a^*_\theta : \psi \geq \psi^0_\Gamma, \psi(u) = \psi^0_\Gamma(u) \text{ for some } u \in a_\theta - \{0\} \}.$$ 

More precisely, for any $\psi \in \mathcal{T}_\Gamma$, there exists a unique $(\Gamma, \psi)$-Patterson-Sullivan measure

$$\nu_{\psi}$$

and every Patterson-Sullivan measure of $\Gamma$ on $\Lambda_\theta$ arises in this way (Theorem 3.4). Denote by $\mathcal{L}_\theta \subset a^*_\theta$ the $\theta$-limit cone of $\Gamma$, which is the asymptotic cone of $p_\theta(\mu(\Gamma))$. Then $\mathcal{T}_\Gamma$ is in bijection with the set $\{ \psi \in a^*_\theta : \psi > 0 \text{ on } \mathcal{L}_\theta - \{0\} \}/\sim$, where $\psi_1 \sim \psi_2$ if and only if $\psi_1 = c \cdot \psi_2$ for some $c > 0$. When the limit cone $\mathcal{L}_\theta$ has non-empty interior (e.g., when $\Gamma$ is Zariski dense in $G$), $\mathcal{T}_\Gamma$ is homeomorphic to $\mathbb{R}^{\#\theta - 1}$. 

Ahlfors regularity and Hausdorff measures. Anosov subgroups of a rank one Lie group $G$ are precisely convex cocompact subgroups. In general rank one groups, the unique Patterson-Sullivan measure of $\Gamma$ is Ahlfors regular and coincides with the Hausdorff measure on $\Lambda$ with respect to a $K$-invariant sub-Riemannian metric on the boundary $\partial_\infty X$ which is defined in terms of the Gromov product [17, Theorem 5.4]. Except for the case of $SO(n,1)$, this sub-Riemannian metric is not a Riemannian metric.

In this paper, we prove an analogous theorem for general Anosov subgroups. Let $\psi \in \mathcal{T}_\Gamma$. The $\theta$-Anosov property of $\Gamma$ implies that any two distinct points of $\Lambda_\theta$ are in general position and hence the following defines a premetric $d_\psi$ on $\Lambda_\theta$: for $\xi, \eta \in \Lambda_\theta$,

$$d_\psi(\xi, \eta) = \begin{cases} e^{-\psi(G(\xi, \eta))} & \text{if } \xi \neq \eta \\ 0 & \text{if } \xi = \eta \end{cases}$$

where $G$ is the $a$-valued Gromov product (see Definition 2.3). This premetric turns out to be a correct replacement of the sub-Riemannian metric of the rank one case.

For $s > 0$, we denote by $\mathcal{H}^s_\psi$ the $s$-dimensional Hausdorff measure on $\Lambda_\theta$ with respect to the premetric $d_\psi$, which is a Borel outer measure (Definition 9.3). For $s = 1$, we simply write $\mathcal{H}_\psi$ for $\mathcal{H}^1_\psi$. It turns out that the metric properties of the Patterson-Sullivan measure $\nu_\psi$ depends on the symmetricity of $\psi \in a_\theta^+$: $\psi$ is called symmetric if $\psi$ is invariant under the opposition involution $\iota$ of $a$ (see (2.2)).

Our main theorem is as follows:

Theorem 1.1. Let $\Gamma$ be a non-elementary $\theta$-Anosov subgroup of $G$. Let $\psi \in \mathcal{T}_\Gamma$ be a symmetric linear form. The Patterson-Sullivan measure $\nu_\psi$ is Ahlfors 1-regular and equal to the one-dimensional Hausdorff measure $\mathcal{H}_\psi$, up to a constant multiple.

The Ahlfors 1-regularity of $\nu_\psi$ means that there exists $C \geq 1$ such that for any $\xi \in \Lambda_\theta$ and $0 \leq r < \text{diameter}(\Lambda_\theta, d_\psi)$,

$$C^{-1}r \leq \nu_\psi(B_\psi(\xi, r)) \leq Cr$$

where $B_\psi(\xi, r) = \{\eta \in \Lambda_\theta : d_\psi(\xi, \eta) < r \}$ and the implied constants are independent of $\xi$ and $r$ (see Definition 8.1). Noting that $\mathcal{H}_{a_\psi} = \mathcal{H}^s_\psi$ for $s > 0$, the reason that the Patterson-Sullivan measure is the one-dimensional Hausdorff measure in the above theorem is due to the normalization of $\psi$ made by the choice that $\psi$ is a tangent form, i.e., $\psi \in \mathcal{T}_\Gamma$ (see Remark 8.3).

Remark 1.2. If $\psi$ is symmetric and has gradient in the interior of $a_\theta^+$, then $\psi$ can be used to define a Finsler metric on $X$ and Dey-Kapovich [18, Theorem A] showed that $\nu_\psi$ is the Hausdorff measure, without addressing the Ahlfors regularity (see Remark 9.4). Our approach in this paper is different;
indeed, we first establish the Ahlfors regularity of \( \nu_\psi \) and deduce the rest as a consequence of this.

The opposition involution \( i \) of \( a \) is known to be trivial if and only if \( G \) does not have a simple factor of type \( A_n \) \((n \geq 2)\), \( D_{2n+1} \) \((n \geq 2)\) or \( E_6 \) [57, 1.5.1]. When \( i \) is non-trivial, the symmetric hypothesis on \( \psi \) cannot be removed.

In fact, we prove the following (Theorem 9.2, see also Remark 9.8):

**Theorem 1.3.** Let \( \Gamma \) be a Zariski dense \( \theta \)-Anosov subgroup of \( G \). For any non-symmetric \( \psi \in \mathcal{T}_\Gamma \), \( \nu_\psi \) is Ahlfors \( s \)-regular for some \( 0 < s < 1 \) but is not comparable\(^2\) to any \( H_s^\psi, s > 0 \).

**Critical exponents and Hausdorff dimensions.** For \( \psi \in a_\theta^* \) which is positive on \( L_\theta - \{0\} \), we set

\[
(1.3) \quad \delta_\psi := \delta_\psi(\Gamma) = \limsup_{T \to \infty} \frac{\log \# \{ \gamma \in \Gamma : \psi(\mu(\gamma)) \leq T \}}{T}.
\]

The Hausdorff dimension of \( (\Lambda_\theta, d_\psi) \) is defined as:

\[
\dim_\psi \Lambda_\theta := \inf \{ s > 0 : \mathcal{H}_s^\psi(\Lambda_\theta) < \infty \}.
\]

A natural question is whether \( \dim_\psi \Lambda_\theta \) is equal to \( \delta_\psi \).

**Theorem 1.4.** For any \( \psi \in a_\theta^* \) which is positive on \( L_\theta - \{0\} \), we have

\[
\dim_\psi \Lambda_\theta = \overline{\delta_\psi},
\]

where \( \overline{\psi} = \frac{\psi + \psi i}{2} \). In particular, if \( \psi \) is symmetric, then \( \dim_\psi \Lambda_\theta = \delta_\psi \).

**Remark 1.5.**
- We remark that for \( \psi \) non-symmetric, \( \dim_\psi \Lambda_\theta \) is not equal to \( \delta_\psi \) in general (Proposition 9.10).
- When \( G \) is of rank-one, Theorem 1.4 is due to Patterson, Sullivan ([44], [55]) and Corlette [17].

Together with a work of Bridgeman-Canary-Labourie-Sambarino [10, Proposition 8.1], Theorem 1.4 implies that for any \( \psi \) non-negative on \( a_\theta^* \), \( \dim_\psi \Lambda_\theta \) changes analytically on \( \theta \)-Anosov representations (Corollary 9.13). We describe one concrete example as follows.

**\((p, q)\)-Hausdorff dimension and Teichmüller space.** Let \( \Sigma \) be a torsion-free uniform lattice of \( \text{PSL}_2(\mathbb{R}) \), and let \( \text{Teich}(\Sigma) \) be the Teichmüller space:

\[
\text{Teich}(\Sigma) = \{ \sigma : \Sigma \to \text{PSL}_2(\mathbb{R}) : \text{discrete, faithful representation} \} / \sim
\]

where the equivalence relation is given by conjugations. It is well-known that \( \text{Teich}(\Sigma) \simeq \mathbb{R}^{6g-6} \) where \( g \) is the genus of the surface \( \Sigma \setminus \mathbb{H}^2_\mathbb{R} \). For \( \sigma \in \text{Teich}(\Sigma) \), denote by \( \Lambda_{\sigma} \subset S^1 \times S^1 \) the limit set of the self-joining subgroup \( (\text{id} \times \sigma)(\Sigma) = \{ (\gamma, \sigma(\gamma)) : \gamma \in \Sigma \} \), which is well-defined up to translations. The Hausdorff dimension of \( \Lambda_{\sigma} \) with respect to a Riemannian metric on \( S^1 \times S^1 \) is equal to 1 for any \( \sigma \in \text{Teich}(\Sigma) \) [30, Theorem 1.1]. For

\(^2\)Two measures \( \nu_1 \) and \( \nu_2 \) are comparable if \( C^{-1} \nu_2 \leq \nu_1 \leq C \nu_2 \) for some \( C \geq 1 \).
any pair \((p, q)\) of positive real numbers, consider the premetric on \(S^1 \times S^1\) given by
\[
d_{p,q}(\xi, \eta) = d_{S^1}(\xi_1, \eta_1)^p d_{S^1}(\xi_2, \eta_2)^q
\]
for any \(\xi = (\xi_1, \xi_2)\) and \(\eta = (\eta_1, \eta_2)\) in \(S^1 \times S^1\), where \(d_{S^1}\) is a Riemannian metric on \(S^1\). For a subset \(S \subset S^1 \times S^1\), denote by \(\dim_{p,q} S\) the Hausdorff dimension of \(S\) with respect to \(d_{p,q}\). Note that on the diagonal of \(S^1 \times S^1\), \(d_{p,q}\) is the \((p+q)\)-th power of \(d_{S^1}\) and hence
\[
\dim_{p,q} \Lambda_{id} = \frac{1}{p+q}.
\]

For each \(\sigma \in \text{Teich}(\Sigma)\), denote by \(\delta_{p,q}(\sigma)\) the critical exponent of the Poincaré series \(s \mapsto \sum_{\gamma \in \Sigma} e^{-s(pd_{S^1}(o, \gamma o) + qd_{S^1}(o, \sigma(\gamma) o))}\).

**Corollary 1.6.** Let \(p, q > 0\).

1. For any \(\sigma \in \text{Teich}(\Sigma)\), we have
\[
\dim_{p,q} \Lambda_{\sigma} = \delta_{p,q}(\sigma);
\]
2. For any \(\sigma \in \text{Teich}(\Sigma)\), we have
\[
\dim_{p,q} \Lambda_{\sigma} \leq \frac{1}{p+q}
\]
and the equality holds if and only if \(\sigma = id\);
3. The map
\[
\sigma \mapsto \dim_{p,q} \Lambda_{\sigma}
\]
is an analytic function on \(\text{Teich}(\Sigma)\).

Part (2) is an immediate consequence of (1) by the rigidity theorem on \(\delta_{p,q}(\sigma)\), due to Bishop and Steger [6, Theorem 2] and to Burger [13, Theorem 1(a)]. See Corollary [9.14] for a more general version on convex cocompact representations. If we denote by \(f = f_{\sigma}\) the \(\sigma\)-equivariant homeomorphism \(S^1 \to S^1\), then \(\Lambda_{\sigma} = \{(x, f(x)) : x \in S^1\}\) and \(\dim_{p,q} \Lambda_{\sigma}\) can also be understood as the Hausdorff dimension of \(\Lambda_{\Sigma} = S^1\) with respect to the premetric \(d_{\sigma, p,q}(x, y) = d_{S^1}(x, y)^p d_{S^1}(f(x), f(y))^q\), \(x, y \in S^1\).

**Hausdorff dimension of \(\Lambda_\theta\) with respect to a Riemannian metric.** We denote by \(\dim \Lambda_\theta\) the Hausdorff dimension of \(\Lambda_\theta\) with respect to a Riemannian metric on \(F_\theta\); since all Riemannian metrics on \(F_\theta\) are Lipschitz equivalent to each other, this is well-defined. With the exception of \(G = \text{SO}^\circ(n, 1)\), \(\dim \Lambda\) is not in general equal to the critical exponent of \(\Gamma\) even in rank one case. See [19] for a discussion on this for the case of \(G = \text{SU}(n, 1)\).

From Theorem [1.4], we derive an estimate on \(\dim \Lambda_\theta\) in terms of critical exponents. Let \(\chi_\alpha\) denote the Tits weight of \(G\) associated to \(\alpha \in \Pi\) as given in [10.2]. When \(G\) is split over \(\mathbb{R}\), \(\chi_\alpha\) is simply the fundamental weight associated to \(\alpha\). We prove:
Theorem 1.7. For any $\theta$-Anosov subgroup $\Gamma$ of $G$, we have
\[ \max_{\alpha \in \theta} \delta_{\chi_\alpha + \chi_i(\alpha)} \leq \dim \Lambda_\theta \leq \max_{\alpha \in \theta} \delta_\alpha. \]
Moreover, both the upper and lower bounds are attained by some Anosov subgroups.

For $G = \text{PSL}_n(\mathbb{R})$, we have the set of simple roots given by
\[ \alpha_k(\text{diag}(a_1, \ldots, a_n)) = a_k - a_{k+1}, \quad 1 \leq k \leq n - 1. \]
When $G = \text{PSL}_n(\mathbb{R})$ and $\theta = \{\alpha_1\}$, the lower bound in Theorem 1.7 was obtained by Dey-Kapovich [18], and the upper bound by Pozzetti-Sambarino-Wienhard [47] (see also [14]). Recently, Li-Pan-Xu proved that for $G = \text{PSL}_3(\mathbb{R})$, $\dim \Lambda_{\alpha_1} = 1$ by ([34], [14]) and $\delta_{\alpha_1} = 1$ for all $\alpha_1 \in \Pi$ by [45] Theorem B. Hence
\[ \dim \Lambda_\theta = 1 = \delta_\alpha \quad \text{for all} \ \alpha \in \theta. \]

The upper bound in Theorem 1.7 is also obtained for Anosov subgroups of the product of $\text{SO}^+(n, 1)$'s [30]. For the lower bound, let $\Gamma$ be the image of a uniform lattice $\Sigma \subset \text{PSL}_2(\mathbb{R})$ under the embedding $\text{PSL}_2(\mathbb{R}) \hookrightarrow \left( \begin{array}{cc} \text{PSL}_2(\mathbb{R}) & 0 \\ 0 & I_{n-2} \end{array} \right) < \text{PSL}_n(\mathbb{R})$ where $I_{n-2}$ is the $(n-2) \times (n-2)$ identity matrix. Then $\Gamma$ is $\{\alpha_1\}$-Anosov. On one hand, the limit set $\Lambda_{\alpha_1}$ of $\Gamma$ in $\mathcal{F}_{\alpha_1} = \mathbb{P}(\mathbb{R}^n)$ is the projective line, and hence $\dim \Lambda_{\alpha_1} = 1$. On the other hand, since $(\chi_{\alpha_1} + \chi_i(\alpha_1))(\text{diag}(a_1, \ldots, a_n)) = a_1 - a_n$, we have
\[ \delta_{\chi_{\alpha_1} + \chi_i(\alpha_1)} = \delta_\Sigma = 1 = \dim \Lambda_{\alpha_1}. \]
Therefore the lower bound in Theorem 1.7 is achieved for this example.

Growth indicator bounds and $L^2$-spectral properties. The growth indicator $\psi_{\Gamma} : \mathfrak{a} \to \mathbb{R} \cup \{-\infty\}$ is a higher rank version of the critical exponent of $\Gamma$ that captures the growth rate of $\mu(\Gamma)$ in each direction of $\mathfrak{a}$ (Definition 3.1). This was introduced by Quint [48]. Denote by $\rho$ the half-sum of all positive roots of $(\mathfrak{g}, \mathfrak{a})$ counted with multiplicity. Then for
any discrete subgroup $\Gamma < G$, $\psi_T \leq 2\rho$, and if $G$ has no rank one factor and \(\text{Vol}(\Gamma \backslash G) = \infty\), then Quint showed a gap theorem that $\psi_T \leq 2\rho - \Theta$ where $\Theta$ denotes the half-sum of all roots in a maximal strongly orthogonal system of $(\mathfrak{g}, a)$ ([51], [43], [36, Theorem 7.1]). We obtain the following bound on $\psi_T$ for Anosov subgroups:

**Corollary 1.8.** For any $\theta$-Anosov subgroup $\Gamma$ of $G$, we have

\[
\psi_T \leq \dim \Lambda_{\theta} \cdot \min_{\alpha \in \theta} (\chi_\alpha + \chi_{i(\alpha)}) \quad \text{on } a.
\]

Recall that $X = G/K$ denotes the associated Riemannian symmetric space. The size of $\psi_T$ is closely related to the spectral properties of the locally symmetric manifold $\Gamma \backslash X$. Let $\lambda_0(\Gamma \backslash X)$ denote the bottom of the $L^2$-spectrum of $\Gamma \backslash X$ (see (11.4)). As first introduced by Harish-Chandra [26], a unitary representation $(\pi, H_{\pi})$ of $G$ is tempered if all of its matrix coefficients belong to $L^2_{+}(\epsilon; G)$ for all $\epsilon > 0$, or, equivalently, if $\pi$ is weakly contained in the regular representation $L^2(G)$. Hence the temperedness of the quasi-regular representation $L^2(\Gamma \backslash G)$ means that $\Gamma \backslash G$ looks like $G$ from the $L^2$-viewpoints. If a discrete subgroup $\Gamma$ of $G$ satisfies that $\psi_T \leq \rho$, then $L^2(\Gamma \backslash G)$ is tempered and $\lambda_0(\Gamma \backslash X) = \|\rho\|^2$ as shown in [21, Theorem 1.6] for II-Anosov groups and in [39] in general. Moreover, $\lambda_0(\Gamma \backslash X)$ is not an $L^2$-eigenvalue ([21], [20]). However it is not easy to decide whether $\psi_T \leq \rho$ holds or not. We give a criterion on this in terms of $\dim \Lambda_\theta$ using Corollary 1.8.

Define

\[
c_G := \inf \{c > 0 : \sum_{\alpha \in \Pi} \chi_\alpha \leq c \cdot \rho\}.
\]

If $G$ is $\mathbb{R}$-split, then $\sum_{\alpha \in \Pi} \chi_\alpha = \rho$ [11, Proposition 29], and hence $c_G = 1$. In general, we have

\[
0 < c_G \leq 1
\]

by Lemma 10.3 due to Smilga. We obtain:

**Corollary 1.9.** Let $\Gamma$ be a $\theta$-Anosov subgroup. Suppose that

- $\dim \Lambda_\theta \leq \#\theta / c_G$ if $\theta \cap i(\theta) = \emptyset$;
- $\dim \Lambda_\theta \leq \#\theta / 2c_G$ otherwise.

Then $L^2(\Gamma \backslash G)$ is tempered and $\lambda_0(\Gamma \backslash X) = \|\rho\|^2$. In particular, the conclusion holds for any II-Anosov subgroup with $\dim \Lambda \leq \frac{\text{rank } G}{2c_G}$.

See Remark 11.5 for a more general statement. Corollary 1.9 recovers Sullivan’s theorem [56] in rank one Lie groups (see Remark 11.6) and immediately applies to many examples of Anosov subgroups with limit sets of low Hausdorff dimensions; for example to all II-Anosov subgroups of higher

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3π is weakly contained in a unitary representation $\sigma$ of $G$ if any diagonal matrix coefficients of $\pi$ can be approximated, uniformly on compact sets, by convex combinations of diagonal matrix coefficients of $\sigma$. 
rank Lie groups with \( \dim \Lambda \leq 1 \) such as Hitchin subgroups \(\text{[14, Proposition 1.5]}\). Although the conclusion of Corollary \(\text{[19]}\) was already known for Hitchin subgroups by \(\text{[31]}\) and \(\text{[21]}\) relying on the work of \(\text{[45]}\), we obtain a completely different proof in this paper.

Since the opposition involution \( i \) of \( \operatorname{PSL}_n(\mathbb{R}) \) sends the simple root \( \alpha_i \) to \( \alpha_{n-i} \) for \( 1 \leq i \leq n-1 \), we deduce:

**Corollary 1.10.** Let \( n \geq 3 \). If \( \Gamma < \operatorname{PSL}_n(\mathbb{R}) \) is \( \{ \alpha_i \} \)-Anosov with \( \dim \Lambda_{\alpha_i} \leq 1 \) for some \( i \neq \frac{n}{2} \), then \( L^2(\Gamma \setminus \operatorname{PSL}_n(\mathbb{R})) \) is tempered and \( \lambda_0(\Gamma \setminus X) = \| \rho \|^2 \).

This corollary applies to any \((1,1,2)\)-hyperconvex subgroup whose Gromov boundary is homeomorphic to a circle, since such a subgroup is \( \{ \alpha_1 \} \)-Anosov with \( \dim \Lambda_{\alpha_1} = 1 \) by Pozzetti-Sambarino-Wienhard \(\text{[46]}\). It also applies to the image of a purely hyperbolic Schottky representation of the free group \( F_k \) on \( k \)-generators in \( \operatorname{PSL}_n(\mathbb{R}) \) in the sense of Burelle-Treib \(\text{[12]}\) by \(\text{[14, Proposition 11.1]}\).

**On the proof of Theorem 1.1** The main point is to show that the Patterson-Sullivan measure \( \nu_\psi \) is Ahlfors one-regular, that is, for all \( \xi \in \Lambda_\theta \) and \( 0 < r < \operatorname{diam}(\Lambda_\theta, d_\psi) \),

\[
(1.6) \quad \nu_\psi(B_\psi(\xi, r)) \geq C r^\theta.
\]

Fix \( o = [K] \in X \). The \( \theta \)-Anosov property of \( \Gamma \) implies that \( \Gamma \) is a hyperbolic group and that the orbit map \( \gamma \mapsto \gamma o \) is a quasi-isometric embedding that continuously extends to a \( \Gamma \)-equivariant homeomorphism between the Gromov boundary \( \partial \Gamma \) and limit set \( \Lambda_\theta \).

One key feature of a Gromov hyperbolic space is that the Gromov product measures the distance between a fixed point and a geodesic, up to an additive error. The main philosophy of our proof of \((1.6)\) is to establish an analogue of this property, by showing that there is a metric-like function \( d_\psi \) on \( \Gamma o \) that is closely related to the \( \psi \)-Gromov product \( \psi \circ \mathcal{G} \) on the limit set \( \Lambda_\theta \). For \( \gamma_1, \gamma_2 \in \Gamma \), set

\[
(1.7) \quad d_\psi(\gamma_1 o, \gamma_2 o) = \psi(\mu(\gamma_1^{-1} \gamma_2)).
\]

We prove that \( d_\psi \) satisfies the coarse triangle inequality \(\text{[14, Theorem 1.1]}\), using a higher rank Morse lemma due to Kapovich-Leeb-Porti \(\text{[29]}\): there exists \( D > 0 \) such that for any \( \gamma_1, \gamma_2, \gamma_3 \in \Gamma \),

\[
(1.8) \quad d_\psi(\gamma_1 o, \gamma_3 o) \leq d_\psi(\gamma_1 o, \gamma_2 o) + d_\psi(\gamma_2 o, \gamma_3 o) + D.
\]

This allows us to treat \( d_\psi \) as a “metric” on \( \Gamma o \). Moreover \( (\Gamma o, d_\psi) \) has a uniform thin-triangle property. That is, there exists \( \delta > 0 \) such that for any \( \xi_1, \xi_2, \xi_3 \in \Gamma \cup \partial \Gamma \), the image of the geodesic triangle \( [\xi_1, \xi_2] \cup [\xi_2, \xi_3] \cup [\xi_3, \xi_1] \) under the orbit map is \( \delta \)-thin in the \( d_\psi \)-metric. On the other hand, since \( (\Gamma o, d_\psi) \) is not a geodesic space in general, the thin-triangle property

\[\text{[4] We write } f(r) \ll g(r) \text{ if for some constant } C > 0, f(r) \leq C g(r) \text{ for all } r > 0. \text{ The notation } f(r) \asymp g(r) \text{ means that } f(r) \ll g(r) \text{ and } g(r) \ll f(r).\]
does not imply that \((\Gamma_0, d_\psi)\) is a Gromov hyperbolic space. Nevertheless, investigating fine geometric properties of thin-triangles in \((\Gamma_0, d_\psi)\) leads us to proving that the \(\psi\)-Gromov product measures the \(d_\psi\)-distance between \(o\) and a geodesic (Proposition 6.7). That is, for \(\xi \neq \eta \in \Lambda_\theta \simeq \partial \Gamma\),
\[
(1.9) \quad \psi(G(\xi, \eta)) = d_\psi(o, [\xi, \eta]o) + O(1)
\]
where \([\xi, \eta]o\) is the image of a bi-infinite geodesic \([\xi, \eta]\) in \(\Gamma\) connecting \(\xi\) and \(\eta\) under the orbit map. We also prove that shadows on the Gromov boundary \(\partial \Gamma\) are comparable to shadows on \(\Lambda_\theta\) (Proposition 7.2) and use it to establish the compatibility of the \(d_\psi\)-balls and shadows in \(\Lambda_\theta\) (Theorem 6.2): for all large \(R > 1\) there exists \(c \geq 1\) such that for any \(\xi \in \Lambda_\theta\) and \(\gamma \in \Gamma\) on a geodesic ray in \(\Gamma\) toward \(\xi \in \Lambda_\theta \simeq \partial \Gamma\) from the identity \(e \in \Gamma\), we have
\[
(1.10) \quad B_\psi(\xi, ce^{-\psi(\mu(\gamma))}) \subset O_R(o, \gamma o) \cap \Lambda_\theta \subset B_\psi(\xi, e^{-\psi(\mu(\gamma))})
\]
where the shadow \(O_R(o, \gamma o)\) is the set of endpoints of all positive Weyl chambers based at \(o\) passing the Riemannian ball in \(X\) of radius \(R > 0\) with center \(\gamma o\) in \(X\). Then the Ahlfors one-regularity of \(\nu_\psi\) is deduced by applying the higher rank version of Sullivan’s shadow lemma (Lemma 8.4).

While positivity of \(H_\psi(\Lambda_\theta)\) is a standard consequence of (1.6), finiteness of \(H_\psi(\Lambda_\theta)\) is not immediate since \(d_\psi\) is not a genuine metric. We rely on the Vitali covering type lemma for the conformal premetric \(d_\psi\) on \(\Lambda_\theta\) (Lemma 5.6).

Organisation.

- In section 2, we review some basic structures of Lie groups and \(\theta\)-boundaries. The notations set up in this section will be used throughout the paper.
- In section 3, we recall the classification of Patterson-Sullivan measures of Anosov subgroups using tangent forms and some basic properties of Anosov subgroups.
- In section 4, we show that for each \(\psi \in a_\theta^*\) positive on \(L_\theta - \{0\}\), the composition \(\psi \circ \mu\) defines a metric-like function \(d_\psi\) on the \(\Gamma\)-orbit \(\Gamma o\). The coarse triangle inequality of \(d_\psi\) (Theorem 4.1) is a crucial ingredient of this paper. Its proof makes a heavy use of the notion of diamonds and the Morse lemma due to Kapovich-Leeb-Porti (Theorem 4.11).
- In section 5, we define a conformal premetric \(d_\psi\) on the limit set \(\Lambda_\theta\) and discuss its basic properties.
- Sections 6 and 7 are devoted to the proof of the compatibility between shadows and \(d_\psi\)-balls in the limit set \(\Lambda_\theta\) as in (1.10).
- In sections 8 and 9, we prove Theorem 1.1. In section 8, we prove that for symmetric \(\psi \in a_\theta^*\), the \((\Gamma, \psi)\)-Patterson-Sullivan measure is Ahlfors one-regular. In section 9, we prove that Patterson-Sullivan measures for symmetric linear forms are Hausdorff measures on the limit set, up to a constant multiple. We also prove Theorem 1.4.
• In section 10, we prove Theorem 1.7 on the estimate of the Hausdorff dimension of \( \Lambda \theta \) with respect to a Riemannian metric.

• In section 11, we obtain an upper bound on the growth indicator and discuss its implications on the temperedness of \( L^2(\Gamma \backslash G) \).

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2. Basic structure theory of Lie groups and \( \theta \)-boundaries

Throughout the paper, let \( G \) be a connected semisimple real algebraic group, more precisely, \( G \) is the identity component \( G(\mathbb{R})^0 \) of the group of real points of a semisimple algebraic group \( G \) defined over \( \mathbb{R} \). In this section, we review some basic facts about the Lie group structure of \( G \).

Let \( G \) be a maximal real split torus of \( G \). Let \( g \) and \( a \) respectively denote the Lie algebras of \( G \) and \( A \). Fix a positive Weyl chamber \( a^+ \subset a \) and set \( A^+ = \exp a^+ \), and a maximal compact subgroup \( K < G \) such that the Cartan decomposition \( G = KA^+K \) holds. Let \( \Phi = \Phi(g, a) \) denote the set of all roots and \( \Pi \) the set of all simple roots given by the choice of \( a^+ \). Denote by \( N_K(A) \) and \( C_K(A) \) the normalizer and centralizer of \( A \) in \( K \) respectively. The Weyl group \( W \) is given by \( N_K(A)/C_K(A) \). Consider the real vector space \( E^* = X(A) \otimes \mathbb{Z} \mathbb{R} \) where \( X(A) \) is the group of all real characters of \( A \) and let \( E \) be its dual. Denote by \( (, ) \) a \( W \)-invariant inner product on \( E \). We denote by \( \{ \omega_\alpha : \alpha \in \Pi \} \) the (restricted) fundamental weights of \( \Phi \) defined by

\[
2 \frac{(\omega_\alpha, \beta)}{(\beta, \beta)} = c_\alpha \delta_{\alpha, \beta}
\]

where \( c_\alpha = 1 \) if \( 2\alpha \notin \Phi \) and \( c_\alpha = 2 \) otherwise.

Fix an element \( w_0 \in N_K(A) \) of order 2 representing the longest Weyl element so that \( \text{Ad}_{w_0} a^+ = -a^+ \). The map

\[
i = -\text{Ad}_{w_0} : a \to a
\]

is called the opposition involution. It induces an involution of \( \Phi \) preserving \( \Pi \), for which we use the same notation \( i \), so that \( i(\alpha) = \alpha \circ i \) for all \( \alpha \in \Phi \).

Henceforth, we fix a non-empty subset \( \theta \) of \( \Pi \). Let

\[
a_\theta = \bigcap_{\alpha \in \Pi - \theta} \ker \alpha, \quad a_\theta^+ = a_\theta \cap a^+,
\]

\[
A_\theta = \exp a_\theta, \quad \text{and} \quad A_\theta^+ = \exp a_\theta^+.
\]

Let

\[
p_\theta : a \to a_\theta
\]

denote the projection invariant under all \( w \in W \) fixing \( a_\theta \) pointwise.

Let \( P_\theta \) denote a standard parabolic subgroup of \( G \) corresponding to \( \theta \); that is, \( P_\theta = L_\theta N_\theta \) where \( L_\theta \) is the centralizer of \( A_\theta \) and \( N_\theta \) is the unipotent
radical of $P_\theta$ such that $\log N_\theta$ is generated by root subgroups associated to all positive roots which are not $\mathbb{Z}$-linear combinations of $\Pi - \theta$.

We set $M_\theta = K \cap P_\theta = C_K(A_\theta)$. The Levi subgroup $L_\theta$ can be written as $L_\theta = A_\theta S_\theta$ where $S_\theta$ is an almost direct product of a connected semisimple real algebraic subgroup and a compact center. Letting $B_\theta = S_\theta \cap A$ and $B_\theta^+ = \{ b \in B_\theta : \alpha(\log b) \geq 0 \text{ for all } \alpha \in \Pi - \theta \}$, we have the Cartan decomposition of $S_\theta$:

$$S_\theta = M_\theta B_\theta^+ M_\theta.$$  

Note that $A = A_\theta B_\theta$ and $A^+ \subset A_\theta^+ B_\theta^+$. The space $a_\theta^* = \text{Hom}(a_\theta, \mathbb{R})$ can be identified with the subspace of $a^*$ consisting of $p_\theta$-invariant linear forms:

$$a_\theta^* = \{ \psi \in a^* : \psi \circ p_\theta = \psi \}.$$  

Hence for $\theta_1 \subset \theta_2$, we have

$$a_{\theta_1}^* \subset a_{\theta_2}^*.$$  

When $\theta = \Pi$, we will omit the subscript. So $P = P_{\Pi}$ is a minimal parabolic subgroup and $P = MAN$.

**Cartan projection.** Recall the Cartan decomposition $G = KA^+K$, which means that for every $g \in G$, there exists a unique element $\mu(g) \in a^+$ such that $g \in K \exp \mu(g)K$. The map $G \to a^+$ given by $g \mapsto \mu(g)$ is called the Cartan projection. We have

$$\mu(g^{-1}) = i(\mu(g)) \quad \text{for all } g \in G.$$  

Let $X = G/K$ be the associated Riemannian symmetric space, and set $o = [K] \in X$. Fix a $K$-invariant norm $\| \cdot \|$ on $g$ and a Riemannian metric $d$ on $X$, induced from the Killing form on $g$; so that

$$d(go, ho) = \| \mu(g^{-1}h) \|$$  

for any $g, h \in G$. For $p \in X$ and $R > 0$, let $B(p, R)$ denote the metric ball $\{ x \in X : d(x, p) < R \}$.

**Lemma 2.1.** [3, Lemma 4.6] For any compact subset $Q \subset G$, there exists a constant $C = C_Q > 0$ such that for all $g \in G$,

$$\sup_{q_1, q_2 \in Q} \| \mu(q_1gq_2) - \mu(g) \| < C.$$  

We then write

$$\mu_\theta := p_\theta \circ \mu : G \to a_\theta^+.$$  

In view of (2.3), we have $\psi \circ \mu_\theta = \psi \circ \mu$ for all $\psi \in a_\theta^*$. 

The $\theta$-boundary $\mathcal{F}_\theta$. We set
\[ \mathcal{F}_\theta = G/P_\theta \quad \text{and} \quad \mathcal{F} = G/P. \]
Let
\[ \pi_\theta : \mathcal{F} \to \mathcal{F}_\theta \]
denote the canonical projection map given by $gP \mapsto gP_\theta$, $g \in G$. We set
\begin{equation}
\xi_\theta = [P_\theta] \in \mathcal{F}_\theta.
\end{equation}
By the Iwasawa decomposition $G = KP = KAN$, the subgroup $K$ acts transitively on $\mathcal{F}_\theta$, and hence $\mathcal{F}_\theta \simeq K/M_\theta$.

Definition 2.2. For a sequence $g_i \in G$ and $\xi \in \mathcal{F}_\theta$, we write $\lim_{i \to \infty} g_i = \lim_{i \to \infty} o = \xi$ if $\xi_{\theta}$ converges to $\xi$ if
\begin{itemize}
    \item $g_i \to \infty$ $\theta$-regularly; and
    \item $\lim_{i \to \infty} \kappa_i \xi_{\theta} = \xi$ in $\mathcal{F}_\theta$ for some $\kappa_i \in K$ such that $g_i \in \kappa_i A^+ K$.
\end{itemize}

Points in general position. Let $P_\theta^+$ be the standard parabolic subgroup of $G$ opposite to $P_\theta$ such that $P_\theta \cap P_\theta^+ = L_\theta$. We have $P_\theta^+ = w_0 P_{i(\theta)} w_{0}^{-1}$ and hence $\mathcal{F}_{i(\theta)} = G/P_\theta^+$.

For $g \in G$, we set
\[ g_\theta^+ := gP_\theta \quad \text{and} \quad g_\theta^- := gw_0 P_{i(\theta)}; \]
as we fix $\theta$ in the entire paper, we write $g^\pm = g_\theta^\pm$ for simplicity when there is no room for confusion. Hence for the identity $e \in G$, $(e^+, e^-) = (P_\theta, P_\theta^+) = (\xi_{\theta}, w_0 \xi_{i(\theta)})$. The $G$-orbit of $(e^+, e^-)$ is the unique open $G$-orbit in $G/P_\theta \times G/P_\theta^+$ under the diagonal $G$-action. We set
\begin{equation}
\mathcal{F}_\theta^{(2)} = \{(g_\theta^+, g_\theta^-) : g \in G\}.
\end{equation}
Two elements $\xi \in \mathcal{F}_\theta$ and $\eta \in \mathcal{F}_{i(\theta)}$ are said to be in general position (or antipodal) if $(\xi, \eta) \in \mathcal{F}_\theta^{(2)}$.

Busemann maps and Gromov products. The $a$-valued Busemann map $\beta : \mathcal{F} \times G \times G \to a$ is defined as follows: for $\xi \in \mathcal{F}$ and $g, h \in G$,
\[ \beta_\xi(g, h) := \sigma(g^{-1}, \xi) - \sigma(h^{-1}, \xi) \]
where $\sigma(g^{-1}, \xi) \in a$ is the unique element such that $g^{-1}k \in K \exp(\sigma(g^{-1}, \xi))N$ for any $k \in K$ with $\xi = kP$. For $(\xi, g, h) \in \mathcal{F}_\theta \times G \times G$, we define
\begin{equation}
\beta_\xi^\theta(g, h) := p_\theta(\beta_{\xi_0}(g, h)) \quad \text{for} \ \xi_0 \in \pi_{\theta}^{-1}(\xi); \end{equation}
this is well-defined independent of the choice of $\xi_0$ [49, Lemma 6.1]. We also have $\|\beta^{\theta}_\xi(g, h)\| \leq d(go, ho)$ for all $g, h \in G$ [49, Lemma 8.9]. The Busemann map has the following properties: for all $\xi \in F_\theta$ and $g_1, g_2, g_3 \in G$,

\begin{align*}
\text{(Invariance)} & \quad \beta^{\theta}_\xi(g_1, g_2) = \beta^{\theta}_{g_3\xi}(g_1 g_3, g_2); \\
\text{(Cocycle property)} & \quad \beta^{\theta}_\xi(g_1, g_2) = \beta^{\theta}_\xi(g_1, g_3) + \beta^{\theta}_\xi(g_3, g_2).
\end{align*}

For $p, q \in X$ and $\xi \in F_\theta$, we set $\beta^{\theta}_\xi(p, q) := \beta^{\theta}_\xi(g, h)$ where $g, h \in G$ satisfies $go = p$ and $ho = q$. It is easy to check that this is well-defined.

**Definition 2.3.** For $(\xi, \eta) \in F_\theta^{(2)}$, we define the $\theta$-Gromov product as

$$G^{\theta}(\xi, \eta) = \frac{1}{2}(\beta^{\theta}_\xi(e, g) + i(\beta^{\theta}_\eta(e, g)))$$

where $g \in G$ satisfies $(g^+, g^-) = (\xi, \eta)$. This does not depend on the choice of $g$ [33, Lemma 9.11].

### 3. Classification of Patterson-Sullivan measures by tangent forms

Let $G$ be a connected semisimple real algebraic group. We fix a non-empty subset $\theta$ of the set $\Pi$ of all simple roots. Throughout this section, let $\Gamma$ be a discrete subgroup of $G$. When $\Gamma$ is $\theta$-Anosov, we have a complete classification of all linear forms $\psi \in a^*_\theta$ admitting a $(\Gamma, \psi)$-Patterson-Sullivan measure ([37] [53], [33]). The goal of this section is to review this classification, in addition to recalling some basic notions such as the limit cone and the growth indicator of $\Gamma$. We refer to [33] for more details on this section.

The $\theta$-limit set of $\Gamma$ is defined as follows:

$$\Lambda_\theta = \Lambda_\theta(\Gamma) := \{\lim \gamma_i \in F_\theta : \gamma_i \in \Gamma\}$$

where $\lim \gamma_i$ is defined as in Definition 2.2. If $\Gamma < G$ is Zariski dense, then the limit set $\Lambda_\theta$ is the unique $\Gamma$-minimal subset of $F_\theta$ ([3, Section 3.6], [49, Theorem 7.2]). Furthermore, if we set $\Lambda = \Lambda_\Pi$, then $\pi_\theta(\Lambda) = \Lambda_\theta$. For $\psi \in a^*_\theta$, a Borel probability measure $\nu$ on $F_\theta$ is called a $(\Gamma, \psi)$-conformal measure if for all $g \in \Gamma$ and $\xi \in F_\theta$,

$$\frac{d\gamma_*\nu}{d\nu}(\xi) = e^{\psi(\beta^{\theta}_\xi(e, g))}$$

where $\gamma_*\nu(B) = \nu(\gamma^{-1}B)$ for any Borel $B \subset F_\theta$. A $(\Gamma, \psi)$-conformal measure is called a $(\Gamma, \psi)$-Patterson-Sullivan measure if it is supported on $\Lambda_\theta$.

In order to discuss which linear forms $\psi$ admits a Patterson-Sullivan measure, we need the definitions of the $\theta$-limit cones and growth indicators.

The $\theta$-limit cone $L_\theta = L_\theta(\Gamma)$ of $\Gamma$ is defined as the asymptotic cone of $\mu_\theta(\Gamma)$ in $a^*_\theta$, that is, $u \in L_\theta$ if and only if $u = \lim t_i \mu_\theta(\gamma_i)$ for some sequences $t_i \to 0$ and $\gamma_i \in \Gamma$. If $\Gamma$ is Zariski dense, $L_\theta$ is a convex cone with non-empty interior by [3, Section 1.2]. Recalling the convention of dropping the subscript $\theta$ when $\theta = \Pi$, we write $L = L_\Pi$. We then have $p_\theta(L) = L_\theta$. 
Growth indicators. We say that $\Gamma$ is $\theta$-discrete if the restriction $\mu_\theta|_\Gamma : \Gamma \to a^\theta_+$ is proper. The $\theta$-discreteness of $\Gamma$ implies that $\mu_\theta(\Gamma)$ is a closed discrete subset of $a^\theta_+$. Indeed, $\Gamma$ is $\theta$-discrete if and only if the counting measure on $\mu_\theta(\Gamma)$ weighted with multiplicity is a Radon measure on $a^\theta_+$.

**Definition 3.1** ($\theta$-growth indicator ([48], [33]). For a $\theta$-discrete subgroup $\Gamma < G$, the $\theta$-growth indicator $\psi^\theta_\Gamma : a^\theta \to [-\infty, \infty]$ is defined as follows: if $u \in a^\theta$ is non-zero,

\[ \psi^\theta_\Gamma(u) = \|u\| \inf_{u \in C} \tau^\theta_C \]

where $C \subset a^\theta$ ranges over all open cones containing $u$, and $\psi^\theta_\Gamma(0) = 0$. Here $-\infty \leq \tau^\theta_C \leq \infty$ denotes the abscissa of convergence of the series $P^\theta_C(s) = \sum_{\gamma \in \Gamma, \mu_\theta(\gamma) \in C} e^{-s\|\mu_\theta(\gamma)\|}$. As mentioned, we simply write $\psi^\theta_\Pi := \psi^\theta_\Pi^\Gamma$.

This definition is independent of the choice of a norm on $a^\theta$. It was proved in ([48, Theorem 1.1.1], [33, Theorem 3.3]) that $\psi^\theta_\Gamma < \infty$, $L^\theta = \{\psi^\theta_\Gamma \geq 0\}$ and $\psi^\theta_\Gamma > 0$ on int $L^\theta$ where int $L^\theta$ denotes the interior of $L^\theta$ in the relative topology. Moreover, $\psi^\theta_\Gamma$ is upper semi-continuous and concave. When $\theta = i(\theta)$, it follows from (2.5) that $\psi^\theta_\Gamma$ is $i$-invariant.

We say a linear form $\psi$ is tangent to $\psi^\theta_\Gamma$ (at $u \in a^\theta - \{0\}$) if $\psi \geq \psi^\theta_\Gamma$ and $\psi(u) = \psi^\theta_\Gamma(u)$. For any $u \in \text{int} L^\theta$, there exists $\psi \in a^\theta_+$ tangent to $\psi^\theta_\Gamma$ at $u$. Moreover, for any $\psi \in a^\theta_+$ tangent to $\psi^\theta_\Gamma$ at an interior direction of $a^\theta_+$, there exists a $(\Gamma, \psi)$-Patterson-Sullivan measure ([49, Theorem 8.4], [33, Proposition 5.9]).

For $\theta$-Anosov subgroups, we have a more precise classification of Patterson-Sullivan measures in terms of tangent forms.

**Definition 3.2.** A finitely generated subgroup $\Gamma < G$ is $\theta$-Anosov if there exists a constant $C > 1$ such that for all $\alpha \in \theta$ and $\gamma \in \Gamma$, we have

\[ \alpha(\mu(\gamma)) \geq C^{-1}|\gamma| - C \]

where $|\cdot|$ denotes a fixed word metric on $\Gamma$.

We recall that all $\theta$-Anosov subgroups are assumed to be non-elementary in this paper. Define

\[ \mathcal{T}_\Gamma = \{ \psi \in a^\theta_+ : \psi \text{ is tangent to } \psi^\theta_\Gamma \} \]

The following theorem can be deduced from ([33, Theorem A], [50, Section 4] and [52, Lemma 4.8]) (see [33, Theorem 12.2]):

**Theorem 3.3.** Let $\Gamma$ be a $\theta$-Anosov subgroup. Then

1. $\psi^\theta_\Gamma$ is analytic, strictly concave and vertically tangent\(^5\).

\(^5\)It means that there is no linear form tangent to $\psi^\theta_\Gamma$ at some $u \in \partial L^\theta$. 
For any $\psi \in T_\Gamma$, there exists a unique unit vector $u = u_\psi \in \text{int} L_\theta$ such that $\psi(u) = \psi_\Gamma(u)$. If $\Gamma$ is Zariski dense, the map $\psi \mapsto u_\psi$ is a bijection between $T_\Gamma$ and $\{ u \in \text{int} L_\theta : \|u\| = 1 \}$.

The following theorem was proved in [37, Theorem 1.3] for $\theta = \Pi$ and $\Gamma$ Zariski dense. The general case follows from [53, Theorem A], [33, Theorem 1.12], and [32, Theorem 1.3, Theorem 9.4].

**Theorem 3.4.** Let $\Gamma$ be a $\theta$-Anosov subgroup. For any $\psi \in T_\Gamma$, there exists a unique $(\Gamma, \psi)$-Patterson-Sullivan measure on $\Lambda_\theta$ which we denote by $\nu_\psi = \nu_{\psi, \theta}$. The map $\psi \mapsto \nu_\psi$ is a surjection from $T_\Gamma$ to the space of all $\Gamma$-Patterson-Sullivan measures. If $\Gamma$ is Zariski dense, then the map $\psi \mapsto \nu_\psi$ is bijective. Moreover, if $\psi_1 \neq \psi_2$ in $T_\Gamma$, then $\nu_{\psi_1}$ and $\nu_{\psi_2}$ are mutually singular to each other.

**Remark 3.5.** One immediate consequence of the last statement of Theorem 3.4 is that at most one Patterson-Sullivan measure can be a Hausdorff measure on $\Lambda_\theta$ with respect to a fixed metric (e.g., Riemannian metric).

When $\psi \in a_\theta^*$ is positive on $L_\theta - \{0\}$, the abscissa of convergence of the $\psi$-Poincaré series

$$s \mapsto \sum_{\gamma \in \Gamma} e^{-s\psi(\mu(\gamma))}$$

is a well-defined positive number we denote it by $\delta_\psi$ [33, Lemma 4.3]. Equivalently, $\delta_\psi$ is also given by (1.3).

**Lemma 3.6.** [33, Lemma 4.5] If $\psi \in a_\theta^*$ is positive on $L_\theta - \{0\}$, then $\delta_\psi \psi \in T_\Gamma$.

In particular, $\psi \in T_\Gamma$ if and only if $\delta_\psi = 1$.

Since $\mu(g^{-1}) = i(\mu(g))$ for all $g \in G$, we have that $\Gamma$ is $\theta$-Anosov if and only if $\Gamma \cap i(\theta)$-Anosov. If $\Gamma$ is $\theta$-Anosov, then the canonical projection map $p : \Lambda_{\theta \cup i(\theta)} \to \Lambda_\theta$ is a $\Gamma$-equivariant homeomorphism. Recalling that $a_\theta^*$ can be considered as a subset of $a_{\theta \cup i(\theta)}^*$ from (2.4), we recall the following which will be of use.

**Lemma 3.7.** [33, Lemma 9.5] Let $\Gamma$ be a $\theta$-Anosov subgroup. For any $\psi \in T_\Gamma$, the measure $\nu_{\psi, \theta}$ coincides with the push-forward of $\nu_{\psi, \theta \cup i(\theta)}$ by $p$.

**Gromov hyperbolic space and quasi-isometry.** We collect a few basic facts about $\theta$-Anosov subgroups which will be used repeatedly.

Recall that a geodesic metric space $(Z, d_Z)$ is called a Gromov hyperbolic space if it satisfies a uniformly thin-triangle property, that is, there exists $T > 0$ such that for any geodesic triangle in $Z$, one side of the triangle is contained in the $T$-neighborhood of the union of two other sides. We
denote by $\partial Z$ the Gromov boundary of $Z$, which is the equivalence classes of geodesic rays. For any $z_1 \neq z_2 \in Z \cup \partial Z$, there may be more than one geodesic connecting $z_1$ and $z_2$. By the notation $[z_1, z_2]$, we mean "a" geodesic in $Z$ connecting $z_1$ to $z_2$. For $w \in Z$, the nearest-point projection of $w$ to a geodesic $[z_1, z_2]$ is any point $w' \in [z_1, z_2]$ satisfying $d_Z(w, w') = \inf \{d_Z(w, z) : z \in [z_1, z_2]\}$. This is coarsely well-defined. One can refer to [11] for basics on Gromov hyperbolic spaces. Recall that $d$ denotes the Riemannian metric on $X = G/K$.

**Theorem 3.8** ([29], Corollary 1.6], [28] Proposition 5.16, Lemma 5.23], see also [24]). Let $\Gamma$ be a $\theta$-Anosov subgroup. Fix a word metric $d_\Gamma$ on $\Gamma$ with respect to a finite symmetric generating set. We have:

1. $(\Gamma, d_\Gamma)$ is a Gromov hyperbolic space.
2. $L_\theta - \{0\} \subset \text{int} a_\theta^+$.
3. The orbit map $(\Gamma, d_\Gamma) \to (\Gamma_0, d)$ given by $\gamma \mapsto \gamma o$ is a quasi-isometry, i.e., there exist $Q = Q_\Gamma \geq 1$ such that for all $\gamma_1, \gamma_2 \in \Gamma$,
   \[Q^{-1} \cdot d_\Gamma(\gamma_1, \gamma_2) - Q \leq d(\gamma_1 o, \gamma_2 o) \leq Q \cdot d_\Gamma(\gamma_1, \gamma_2) + Q.\]
4. The orbit map $\Gamma \to \Gamma_0$ extends to the $\Gamma$-equivariant homeomorphism $f : \Gamma \cup \partial \Gamma \to \Gamma_0 \cup \Lambda_\theta$ where $\Gamma \cup \partial \Gamma$ is given the topology of the Gromov compactification, so that two distinct points in $\partial \Gamma$ are mapped to points in general position.

We will henceforth identity $\partial \Gamma$ and $\Lambda_\theta$ using $f$. For any $\xi \neq \eta \in \Gamma \cup \partial \Gamma$, note that $f([\xi, \eta]) = [\xi, \eta]o$ is the image of $[\xi, \eta]$ under the orbit map.

4. Metric-like functions on $\Gamma$-orbits and diamonds

We fix a non-empty subset $\theta \subset \Pi$. In this section, we assume that $\theta$ is symmetric, i.e., $\theta = i(\theta)$. Recall the notation $X = G/K$ and $o = [K] \in X$.

For a linear form $\psi \in a_\theta^*$, define $d_\psi : X \times X \to \mathbb{R}$ as follows: for $g, h \in G$,
\begin{equation}
(4.1) \quad d_\psi(go, ho) := \psi(g^{-1}h) = \psi(\mu(g^{-1}h)).
\end{equation}

Since the Cartan projection $\mu$ is bi-$K$-invariant, $d_\psi$ is a well-defined left $G$-invariant function.

The main goal of this section is to prove the following theorem saying that when $\Gamma$ is $\theta$-Anosov, $d_\psi$ behaves like a metric, restricted to the $\Gamma$-orbit $\Gamma o$ for a proper class of $\psi$'s:

**Theorem 4.1** (Coarse triangle inequality). Let $\Gamma$ be a $\theta$-Anosov subgroup. Let $\psi \in a_\theta^*$ be such that $\psi > 0$ on $L_\theta - \{0\}$. Then there exists a constant $D = D_\psi > 0$ such that for all $\gamma_1, \gamma_2, \gamma \in \Gamma$,
\[d_\psi(\gamma_1 o, \gamma_2 o) \leq d_\psi(\gamma_1 o, \gamma o) + d_\psi(\gamma o, \gamma_2 o) + D.\]

Indeed, we prove Theorem 4.1 in a greater generality where the orbit $\Gamma o$ is replaced by the image of a uniformly regular quasi-isometric embedding of a geodesic metric space into $X$.\footnote{note that the metric space $(\Gamma, d_\Gamma)$ is clearly a proper geodesic space}
Coarse triangle inequalities for uniformly regular quasi-isometric embeddings. We set $\mathcal{W}_\theta = \{ w \in \mathcal{W} : w(\theta) = \theta \}$. We define a closed cone $C$ in $a^+$ to be $\theta$-admissible if the following three conditions hold:

1. $C$ is $i$-invariant: $i(C) = C$;
2. $\mathcal{W}_\theta \cdot C = \bigcup_{w \in \mathcal{W}_\theta} A_w C$ is convex;
3. $C \cap (\bigcup_{x \in \ker \alpha} \ker \alpha) = \{0\}$.

For a $\theta$-admissible cone $C$, we say that an ordered pair $(x_1, x_2)$ of distinct points in $X$ is $C$-regular if for $g_1, g_2 \in G$ such that $g_1 \circ = x_1$ and $g_2 \circ = x_2$, we have

$$\mu(g_1^{-1} g_2) \in C.$$ 

In this case, $x_2 = g_2 \circ \in g_1 K(\exp C) \circ$ and hence for some $g \in g_1 K$, $x_1 = g_1 \circ = go$ and $x_2 \in g(\exp C) \circ$. Note that if $(x_1, x_2)$ is $C$-regular, then $(x_2, x_1)$ is $i(C)$-regular and hence $C$-regular by the $i$-invariance of $C$.

**Definition 4.2.** Let $(Z, d_Z)$ be a metric space and $f : Z \to X$ be a map. For a cone $C \subset a^+$ and a constant $B \geq 0$, $f$ is called $(C, B)$-regular if the pair $(f(z_1), f(z_2))$ is $C$-regular for all $z_1, z_2 \in Z$ with $d_Z(z_1, z_2) \geq B$. We simply say $f$ is $C$-regular if it is $(C, B)$-regular for some $B \geq 0$.

Theorem 4.1 will be deduced as a special case of the following theorem: we write $C_\theta = p_\theta(C)$.

**Theorem 4.3.** Let $Z$ be a geodesic metric space and $C \subset a^+$ a $\theta$-admissible cone. Let $f : Z \to X$ be a $C$-regular quasi-isometric embedding. If $\psi \in a^*_\theta$ is positive on $C_\theta - \{0\}$, then there exists a constant $D = D_\psi \geq 0$ such that for all $x_1, x_2, x_3 \in f(Z)$,

$$d_\psi(x_1, x_3) \leq d_\psi(x_1, x_2) + d_\psi(x_2, x_3) + D.$$ 

**Proof of Theorem 4.1 assuming Theorem 4.3.** Since $\theta = i(\theta)$ by hypothesis, it follows from (2.5) that $i|_{a_\theta}$ is an involution preserving $L_\theta$. Since $\psi$ is positive on $L_\theta - \{0\}$ and $L_\theta - \{0\} \subset \text{int} a^*_\theta$ (Theorem 3.8(2)), we can choose a slightly larger closed cone $C_0 \subset \text{int} a^*_\theta \cup \{0\}$ satisfying

1. $L_\theta - \{0\} \subset \text{int} C_0$;
2. $i(C_0) = C_0$;
3. $\psi > 0$ on $C_0 - \{0\}$.

Define

$$C := p_\theta^{-1}(C_0) \cap a^+.$$ 

Using the fact that $p_\theta : a \to a_\theta$ is $\mathcal{W}_\theta$-equivariant, we have that $\mathcal{W}_\theta \cdot C = \mathcal{W}_\theta \cdot (p_\theta^{-1}(C_0) \cap a^+) = p_\theta^{-1}(C_0) \cap (\mathcal{W}_\theta \cdot a^+)$. Since both $\mathcal{W}_\theta \cdot a^+$ and $p_\theta^{-1}(C_0)$ are convex cones, it follows that their intersection $\mathcal{W}_\theta \cdot C$ is also convex. After

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8A map $f : (Z, d_Z) \to (Y, d_Y)$ between metric spaces is called a $Q$-quasi-isometric embedding for $Q \geq 1$ if for all $z_1, z_2 \in Z$, $Q^{-1}d_Z(z_1, z_2) - Q \leq d_Y(f(z_1), f(z_2)) \leq Qd_Z(z_1, z_2) + Q$. A map is called a quasi-isometric embedding if it is a $Q$-quasi-isometric embedding for some $Q \geq 1$. 
removing some small enough conical neighborhoods of $\bigcup_{\alpha \in \theta} \ker \alpha$ from $\mathcal{C}$, we can assume that

$$\mathcal{C} \cap \bigcup_{\alpha \in \theta} \ker \alpha = \{0\}$$

while keeping the convexity of $W_{\theta} \cdot \mathcal{C}$. Moreover, we can choose those neighborhoods thin so that $\mathcal{C}$ still contains a neighborhood of $\mathcal{L} - \{0\}$ in $a^+$. The resulting $\mathcal{C}$ is therefore $\theta$-admissible and $\psi > 0$ on $\mathcal{C} - \{0\}$. Since the orbit map $(\Gamma, d_\Gamma) \to (X, d)$, $\gamma \mapsto \gamma_0$, is a quasi-isometric embedding as stated in Theorem 3.8(3), Theorem 4.1 follows from Theorem 4.3 once we prove that the orbit map is a $\mathcal{C}$-regular embedding, as below.

**Lemma 4.4.** Let $\mathcal{C}$ be a closed cone containing a neighborhood of $\mathcal{L} - \{0\}$ in $a^+$. Then the orbit map $(\Gamma, d_\Gamma) \to (X, d)$ is $\mathcal{C}$-regular.

**Proof.** Suppose not. Then there exist two sequences $\{\gamma_i\}, \{\gamma'_i\} \subset \Gamma$ such that $d_\Gamma(\gamma_i, \gamma'_i) = |\gamma_i^{-1}\gamma'_i| > i$ and $\mu(\gamma_i^{-1}\gamma'_i) \notin \mathcal{C}$ for all $i \geq 1$. Setting $g_i = \gamma_i^{-1}\gamma'_i \in \Gamma$, we then have that $\frac{\mu(g_i)}{||\mu(g_i)||} \notin \mathcal{C}$ for all $i \geq 1$. Since a neighborhood of $\mathcal{L} - \{0\}$ in $a^+$ is contained in $\mathcal{C}$, no limit of the sequence $\frac{\mu(g_i)}{||\mu(g_i)||}$ is contained in $\mathcal{C}$. On the other hand, since $|g_i| \to \infty$, we have $||\mu(g_i)|| \to \infty$ and hence any limit of the sequence $\frac{\mu(g_i)}{||\mu(g_i)||}$ must belong to the asymptotic cone of $\mu(\Gamma)$, that is, $\mathcal{L}$. This yields a contradiction. \qed

The rest of this section is devoted to the proof of Theorem 4.3. We begin by recalling the following theorem; in particular, the metric space $Z$ in Theorem 4.3 is always Gromov hyperbolic.

**Theorem 4.5.** [29, Theorem 1.4] Let $Z$ and $f : Z \to X$ be as in Theorem 4.3. Then $Z$ is Gromov hyperbolic. If $Z$ is proper in addition, then $f$ continuously extends to

$$f : \hat{Z} \to X \cup \mathcal{F}_\theta$$

where $\hat{Z} = Z \cup \partial Z$ is the Gromov compactification and $f$ maps two distinct points in $\partial Z$ to points in general position.

**Diamonds.** The notion of diamonds in $X$, due to Kapovich-Leeb-Porti, plays a key role in the proof of Theorem 4.3. We fix

a $\theta$-admissible cone $\mathcal{C} \subset a^+$

in the following. For a $\mathcal{C}$-regular pair $(x_1, x_2)$ of points in $X$, define the $\mathcal{C}$-cone with the tip at $x_1$ containing $x_2$ to be

$$V_\mathcal{C}(x_1, x_2) = gM_\theta(\exp \mathcal{C})o,$$

where $g = g(x_1, x_2) \in G$ is any element such that $x_1 = go$ and $x_2 \in g(\exp \mathcal{C})o$; it is easy to check such $g$ always exists and this definition is independent of the choice of $g$. For any $h \in G$, we have $hV_\mathcal{C}(x_1, x_2) = V_\mathcal{C}(hx_1, hx_2)$. 


Definition 4.6 (Diamonds). For a $C$-regular pair $(x_1, x_2)$ of points in $X$, the $C$-diamond with tips at $x_1$ and $x_2$ is defined as

$$\Diamond_C(x_1, x_2) = V_C(x_1, x_2) \cap V_C(x_2, x_1).$$

The $C$-cones and $C$-diamonds are convex subsets of $X$, see [28, Propositions 2.10 and 2.13]. Note also the equivariance property that for $h \in G$, $h\Diamond_C(x_1, x_2) = \Diamond_C(hx_1, hx_2)$. It follows that for any $C$-regular pair $(x_1, x_2)$, the diamond $\Diamond_C(x_1, x_2)$ is of the form $h\Diamond_C(o, ao)$ for some $a \in \exp C$ and $h \in G$. Therefore the following example describes all diamonds up to translations.

Example 4.7. For $a \in \exp C$, the diamond $\Diamond_C(o, ao)$ can be explicitly described as follows. First note that as we can take $g(o, ao) = e$, we have $V_C(o, ao) = M_\theta(\exp C)o$. Recalling that $i = -\Ad w_0$, we also have $ao = aw_0 o$ and $o = (aw_0)(w_0^{-1}a^{-1}w_0)o \in aw_0(\exp C)o$. So we can take $g(ao, o) = aw_0$. Since $w_0M_\theta w_0^{-1} = M_\theta$ and $w_0(\exp C)w_0^{-1} = \exp(\theta)$, we have $V_C(\exp C)o = aw_0M_\theta(\exp C)o = aM_\theta \exp(\theta)o$. Therefore

$$\Diamond_C(o, ao) = M_\theta(\exp C)o \cap aM_\theta \exp(\theta)o.$$ 

See Figure 1.

**Figure 1.** Diamond drawn in $a$

Lemma 4.8 (Simultaneously nesting property). If $(x_1, x_2)$ is $C$-regular, then for any $x \in \Diamond_C(x_1, x_2)$, there exist $g \in G$ and $a \in \exp C$ such that

$$x_1 = go, \quad x = gao, \quad x_2 \in gM_\theta(\exp C)o \cap ga(M_\theta(\exp C)o.$$

Proof. We may first assume that $x_1 = o$. By the $C$-regularity of the pair $(x_1, x_2)$, we have $x_2 \in K(\exp C)o$. By multiplying an element of $K$ to $x_1$ and $x_2$, we may also assume that $x_1 = o$ and $x_2 \in (\exp C)o$, and hence $x \in M_\theta(\exp C)o$. We again multiply an element of $M_\theta$ to $x_1, x_2$ and $x$ if necessary so that we have $x_1 = o$, $x_2 \in M_\theta(\exp C)o$, and $x = ao$ for some $a \in \exp C$. Then it suffices to show that $x_2 = aka'o$ for some $k \in M_\theta$ and...
$a' \in \exp \mathcal{C}$. We write $x_2 = ma_0 o$ for $m \in M_\theta$ and $a_0 \in \exp \mathcal{C}$. We then have $o \in V_\mathcal{C}(x_2, o) = ma_0 k_0 M_\theta (\exp \mathcal{C}) o$ for some $k_0 \in K$. Hence we have

$$k_0^{-1} w_0^{-1} (w_0 a_0^{-1} w_0^{-1}) \in M_\theta (\exp \mathcal{C}) K.$$ 

This implies $k_0^{-1} \in M_o w_0$ and hence $k_0 \in w_0 M_\theta$. Since $ao \in V_\mathcal{C}(x_2, o)$ as well, we now have $ao \in ma_0 w_0 M_\theta (\exp \mathcal{C}) o$. Then for some $k \in K$, we have

$$ak \in ma_0 w_0 M_\theta \exp C w_0^{-1} = ma_0 M_\theta \exp (-\mathcal{C}).$$

Hence for some $a' \in \exp \mathcal{C}$, we have

$$aka' \in ma_0 M_\theta.$$ 

Looking at $G/P_\theta$, we have $kP_\theta = a^{-1} ma_0 M_\theta a^{-1} P_\theta = P_\theta$. Therefore $k \in M_\theta$. Since $x_2 = ma_0 o = aka' o$, the claim follows. \qed

**Lemma 4.9.** For any $\mathcal{C}$-regular pair $(g_1 o, g_2 o)$ with $g_1, g_2 \in G$ and for any $g o \in \Diamond_\mathcal{C}(g_1 o, g_2 o)$ with $g \in G$,

$$(4.2) \quad \mu_\theta (g_1^{-1} g) + \mu_\theta (g^{-1} g_2) = \mu_\theta (g_1^{-1} g_2).$$

**Proof.** By Lemma 4.8, there exists $h \in G$, $a, \tilde{a}, a' \in \exp \mathcal{C}$ and $\tilde{k}, k \in M_\theta$ such that $g_1 o = ho$, $go = hao$, and $g_2 o = h\tilde{kao} = hak'o$. Without loss of generality, we may assume $h = e$ in proving (4.2).

We write

$$a = a_1 a_2 \in A_\theta^+ B_\theta^+ \quad \text{and} \quad a' = a'_1 a'_2 \in A_\theta^+ B_\theta^+.$$ 

We then have

$$aka' = a_2 k a'_2 (a_1 a'_1).$$

Since $a_2 k a'_2 \in S_\theta$, we can write its Cartan decomposition $a_2 k a'_2 = mbm' \in M_\theta B_\theta^+ M_\theta$, and hence

$$aka' = m (ba_1 a'_1) m'.$$

Let $w \in \mathcal{W}$ be a Weyl element such that $ba_1 a'_1 \in w A^+ w^{-1}$. Since $\tilde{a} = \exp \mu (aka')$, we must have $ba_1 a'_1 = w\tilde{a} w^{-1}$. Hence we have

$$g_2 o = aka' o = mw\tilde{o}.$$ 

On the other hand, we also have $g_2 o = \tilde{k}\tilde{o}$ where $\tilde{k} \in M_\theta$. This implies $mw \in M_\theta$; in particular, $w \in M_\theta$. Therefore $\tilde{a} = w^{-1} ba_1 a'_1 w = (w^{-1} b w)(a_1 a'_1) \in B_\theta A_\theta^+$, which implies

$$(4.3) \quad p_\theta (\log \tilde{a}) = \log a_1 + \log a'_1 = p_\theta (\log a) + p_\theta (\log a').$$

Since

$$\mu_\theta (g_1^{-1} g) = p_\theta (\log a), \quad \mu_\theta (g^{-1} g_2) = p_\theta (\log a'), \quad \text{and} \quad \mu_\theta (g_1^{-1} g_2) = p_\theta (\log \tilde{a}),$$

this finishes the proof. \qed

As an immediate corollary, we get that $d_\psi$ is additive on each diamond for any $\psi \in a_\theta^*$:
Lemma 4.10 (Additivity of $d_\psi$ on diamonds). Let $\psi \in a^+_\theta$. For any $C$-regular pair $(x_1, x_2)$ and for any $x \in \mathcal{O}_C(x_1, x_2)$, we have

$$d_\psi(x_1, x) + d_\psi(x, x_2) = d_\psi(x_1, x_2).$$

KLP Morse lemma. The Morse lemma due to Kapovich-Leeb-Porti, which we will call the KLP Morse lemma, is stated as follows [29, Theorem 5.16, Corollary 5.28]: the image of an interval in $\mathbb{R}$ under a $Q$-quasi-isometry is called a $Q$-quasi-geodesic.

Theorem 4.11 (KLP Morse lemma). Let $C, C' \subset a^+ \theta$ be $\theta$-admissible cones such that $C'$ contains a neighborhood of $C - \{0\}$. Let $Q, B \geq 1$ be constants. There exists a constant $D_0 = D_0(C, C', Q, B) \geq 0$ so that the following holds: let $I \subset \mathbb{R}$ be an interval and $c : I \to X$ a $(C, B)$-regular $Q$-quasi-geodesic.

1. If $I = [a, b]$ with $b - a \geq B$, then the image $c(I)$ is contained in the $D_0$-neighborhood of the diamond $\mathcal{D}_C(c(a), c(b))$.
2. If $I = [a, \infty)$ for some $a \in \mathbb{R}$, then $c(I)$ is contained in the $D_0$-neighborhood of the cone $gM_0(\exp C'o$ where $g \in G$ is such that $g_0 = c(a) \text{ and } g^+ = c(\infty) \in F_\theta$.
3. If $I = \mathbb{R}$, then $c(I)$ is contained in the $D_0$-neighborhood of the parallel set $gM_0Ao$ where $g \in G$ is such that $g^+ = c(\pm \infty) \in F_\theta$.

We note that the above applies for an interval in $\mathbb{Z}$, as any $C$-regular quasi-isometric embedding $c : I \cap \mathbb{Z} \to X$ can be extended to a $C$-regular quasi-geodesic $I \to X$ simply by setting $c(t) := c([t])$ where $[t]$ is the largest integer not bigger than $t$.

![Figure 2. Choice of $C'$ viewed on the unit sphere of $a^+$](image)

As an application of Theorem 4.11, we get the following:

Corollary 4.12. Given $C, C', Q, B \geq 1$ as in Theorem 4.11 and $\psi \in a^+_\theta$, there exists a constant $D_1 = D_1(C, C', Q, B, \psi) \geq 0$ so that the following holds: let $I \subset \mathbb{R}$ be an interval and $c : I \to X$ a $(C, B)$-regular $Q$-quasi-geodesic. Then for all $a \leq t \leq b$ in $I$, we have

$$|d_\psi(c(a), c(b)) - d_\psi(c(a), c(t)) - d_\psi(c(t), c(b))| \leq D_1.$$

Proof. Suppose that $b - a \geq B$. Since $c$ is $(C, B)$-regular, the pair $(c(a), c(b))$ is $C$-regular. Applying Theorem 4.11, we obtain that the image of $c : [a, b] \to$
X lies in the $D_0$-neighborhood of $\Delta(c(a), c(b))$. For each $a < t < b$, choose $x_t \in \Delta(c(a), c(b))$ so that $d(x_t, c(t)) \leq D_0$. Hence by Lemma 4.10

(4.5) \[ d_\psi(c(a), x_t) + d_\psi(x_t, c(b)) = d_\psi(c(a), c(b)). \]

For each $a \leq t \leq b$, write $c(t) = g_{t0}$ and $x_t = h_{t0}$ for $g_t, h_t \in G$. We then have $\|\mu(h_t^{-1}g_t)\| \leq D_0$. By applying Lemma 2.1 to a compact subset $\{g \in G : \|\mu(g)\| \leq D_0\}$, we have for all $a < t < b$,

$$|d_\psi(c(a), x_t) - d_\psi(c(a), c(t))| = |\psi(\mu(g_a^{-1}h_t) - \mu(g_a^{-1}g_t))| \leq C$$

where $C > 0$ is a uniform constant depending only on $\psi$ and $D_0$. Similarly, we have $|d_\psi(x_t, c(b)) - d_\psi(c(t), c(b))| \leq C$. By (4.5), this implies that

$$|d_\psi(c(a), c(b)) - d_\psi(c(a), c(t)) - d_\psi(c(t), c(b))| \leq 2C.$$

Setting $D_1 = 2C + 3\|\psi\|(QB + Q)$ where $\|\psi\|$ is the operator norm of $\psi$, we have shown that (4.4) holds whenever $b - a \geq B$. If $b - a < B$, then the image of $c([a, b])$ has diameter smaller than $Q(b - a) + Q < QB + Q$. Then

$$d_\psi(c(t_1), c(t_2)) < \|\psi\|(QB + Q)$$

for all $t_1, t_2 \in [a, b]$, and hence the left hand side of (4.4) is bounded above by $3\|\psi\|(QB + Q) \leq D_1$. This completes the proof. \qed

We are ready to give:

**Proof of Theorem 4.3.** Let $f : Z \to X$ be as in Theorem 4.3. Let $\psi \in a_0^*$ be such that $\psi > 0$ on $C - \{0\}$. Choose a $\theta$-admissible cone $C' \subset a^+$ which contains a neighborhood of $C - \{0\}$ in $a^+$ and such that $\psi > 0$ on $C' - \{0\}$. Let $x_1, x_2, x_3 \in f(Z)$ be a triple of distinct points. We choose $z_1, z_2, z_3 \in Z$ such that $x_i = f(z_i)$ for $i = 1, 2, 3$. Choose geodesics $c_1$ and $c_2$ in $Z$ connecting $z_1$ to $z_2$ and $z_2$ to $z_3$ respectively. By Theorem 4.5 $(Z, d_Z)$ is Gromov hyperbolic. We denote by $z$ the nearest-point projection of $z_2$ to a geodesic segment connecting $z_1$ and $z_3$. Then by the Gromov hyperbolicity of $(Z, d_Z)$, there exists a uniform constant $\delta > 0$ so that the $\delta$-neighborhood of $z$ intersects both geodesics $c_1$ and $c_2$. We choose two points $y_1 \in c_1$ and $y_2 \in c_2$ which are $\delta$-close to $z$. We concatenate the segment of $c_1$ connecting $z_1$ and $y_1$, a geodesic connecting $y_1$ and $y_2$, and the segment of $c_2$ connecting $y_2$ and $z_3$, and denote the concatenated path by $c$. We can parameterize $c : [0, b] \to Z$ so that $c$ is a $q$-quasi-geodesic for some $b > 0$ and uniform $q \geq 1$ by the Gromov hyperbolicity of $(Z, d_Z)$ and the choice of $y_1$ and $y_2$.

Since $f$ is a $C$-regular quasi-isometric embedding, so is $f \circ c$. Hence we get

(4.6) \[ d_\psi(x_1, x_3) \leq d_\psi(x_1, f(y_1)) + d_\psi(f(y_1), x_3) + D_1 \]

where $D_1$ is the constant given by Corollary 4.12. Applying Corollary 4.12 to the restriction of $f \circ c$ to the interval $[c^{-1}(y_1), b]$ again, we have

(4.7) \[ d_\psi(f(y_1), x_3) \leq d_\psi(f(y_1), f(y_2)) + d_\psi(f(y_2), x_3) + D_1. \]
Since $d_Z(y_1, y_2) \leq 2\delta$, combining (4.6) and (4.7) yields

$$d_\psi(x_1, x_3) \leq d_\psi(x_1, f(y_1)) + d_\psi(f(y_2), x_3) + D'_1.$$  

(4.8)

where $D'_1 := \sup\{d_\psi(f(w_1), f(w_2)) : d_Z(w_1, w_2) \leq 2\delta\} + 2D_1 < \infty$.

Since $f$ is $C$-regular and $\psi > 0$ on $C - \{0\}$, there exists $D_2 > 0$ such that

$$d_\psi(f(w_1), f(w_2)) \geq -D_2$$

for all $w_1, w_2 \in Z$; indeed, if $f$ is $(C, B)$-regular for some $B \geq 0$, then $d_\psi(f(w_1), f(w_2)) \geq 0$ whenever $d_Z(w_1, w_2) \geq B$, and $\sup\{d_\psi(f(w_1), f(w_2)) : d_Z(w_1, w_2) < B\}$ is bounded by a uniform constant depending only on $B$, the quasi-isometry constant of $f$, and $\|\psi\|$.

Hence applying (4.9) and Corollary 4.12 to $f(c_1)$, we have

$$d_\psi(x_1, f(y_1)) \leq d_\psi(x_1, f(y_1)) + d_\psi(f(y_1), x_2) + D_2$$

(4.10)

$$\leq d_\psi(x_1, x_2) + D_1 + D_2.$$

Similarly, we also get

$$d_\psi(f(y_2), x_3) \leq d_\psi(x_2, x_3) + D_1 + D_2.$$  

(4.11)

Combining (4.8), (4.10) and (4.11), we obtain

$$d_\psi(x_1, x_3) \leq d_\psi(x_1, x_2) + d_\psi(x_2, x_3) + D'_1 + 2(D_1 + D_2).$$

This completes the proof of Theorem 4.3. □

We state the following consequence of the KLP Morse lemma applied to Anosov subgroups:

**Theorem 4.13** (Morse lemma for Anosov subgroups). Let $\Gamma$ be a $\theta$-Anosov subgroup and $f : \Gamma \cup \partial \Gamma \to \Gamma \cup \Lambda_\theta$ be the extension of the orbit map $\gamma \mapsto \gamma_0$ given in Theorem 3.8(4). Then there exists a cone $C \subset a^+$ and constants $B, D_0 \geq 1$ such that for any geodesic $[\xi, \eta]$ in $\Gamma$, the following holds:

1. If $\xi, \eta \in \Gamma$ and $d_\Gamma(\xi, \eta) \geq B$, then $f([\xi, \eta])$ is contained in the $D_0$-neighborhood of the diamond $\diamond_C(f(\xi), f(\eta))$.
2. If $\xi \in \Gamma$ and $\eta \in \partial \Gamma$, then $f([\xi, \eta])$ is contained in the $D_0$-neighborhood of $gM_\theta(\exp C)\xi$ where $g \in G$ is such that $g\xi = \xi$ and $gP_\theta = f(\eta)$.
3. If $\xi, \eta \in \partial \Gamma$, then $f([\xi, \eta])$ is contained in the $D_0$-neighborhood of $gM_\theta A \eta$ where $g \in G$ is such that $gP_\theta = f(\xi)$ and $g\omega P_\theta = f(\eta)$.

Moreover, the cone $C$ can be taken arbitrarily close to $\mathcal{L}$ as long as it contains a neighborhood of $\mathcal{L} - \{0\}$ in $a^+$.

**Proof.** Let $C \subset a^+$ be the $\theta$-admissible cone as in the proof of Theorem 4.1 and choose a $\theta$-admissible cone $C' \subset a^+$ which contains a neighborhood of $C - \{0\}$ in $a^+$. Then by Lemma 4.4 and Theorem 3.8(3), the orbit map $f|_\Gamma$ is a $(C, B)$-regular $Q$-quasi-isometry between $(\Gamma, d_\Gamma)$ and $(\Gamma_0, d)$ for some $B, Q \geq 1$. Let $D_0 = D_0(C, C', Q, B)$ be as given by Theorem 4.11.

Now note that any geodesic $[\xi, \eta]$ in $(\Gamma, d_\Gamma)$ can be written as $[\xi, \eta] = \{\gamma_i : i \in I\}$ for an interval $I$ in $\mathbb{Z}$, and $\iota : i \mapsto \gamma_i$ is an isometry between $I$ and $[\xi, \eta]$. Since $c := f \circ \iota$ is a $(C, B)$-regular $Q$-quasi-geodesic, we can apply...
Theorem 4.11 which implies the above claims (1)-(3) where the cone $C$ in the statement is given by $C'$ in this proof. Note from the proof of Theorem 4.1 that the cone $C'$ can be taken arbitrarily close to the limit cone $L$ of $\Gamma$ as long as $C'$ contains a neighborhood of $L - \{0\}$ in $a^+$. \qed

5. Conformal premetrics on limit sets

Let $\Gamma$ be a $\theta$-Anosov subgroup of a connected semisimple real algebraic group $G$. We assume $\theta = i(\theta)$ in this section. Fix a linear form $\psi \in a_\theta^*$ positive on $L_\theta - \{0\}$. The goal of this section is to define a premetric $d_\psi$ on the limit set $\Lambda_\theta$, which is conformal, almost symmetric, and satisfies almost triangle inequality with bounded multiplicative error. We also discuss how this definition can be extended to non-symmetric $\theta$ at the end of the section.

Recall the definition of the Gromov product from Definition 2.3. The $\theta$-Anosov property of $\Gamma$ implies that any two distinct points in $\Lambda_\theta$ are in general position: if $\xi \neq \eta$ in $\Lambda_\theta$, then $(\xi, \eta) \in \mathcal{F}^{(2)}_{\theta}$. Therefore the following premetric on $\Lambda_\theta$ is well-defined:

**Definition 5.1.** For $\xi, \eta \in \Lambda_\theta$, we set

\[
(5.1) \quad d_\psi(\xi, \eta) = \begin{cases} 
    e^{-\psi(G_\theta(\xi, \eta))} & \text{if } \xi \neq \eta \\
    0 & \text{if } \xi = \eta.
\end{cases}
\]

We first observe the following $\Gamma$-conformal property of $d_\psi$:

**Lemma 5.2.** For $\gamma \in \Gamma$ and $\xi, \eta \in \Lambda_\theta$, we have

\[
d_\psi(\gamma^{-1} \xi, \gamma^{-1} \eta) = e^{\frac{1}{2} \psi(\beta^\theta_\gamma(e, \gamma) + i(\beta^\theta_\gamma(e, \gamma)))} d_\psi(\xi, \eta).
\]

**Proof.** Let $\xi \neq \eta$, and $g \in G$ be such that $g^+ = \xi$ and $g^- = \eta$. Then for any $\gamma \in \Gamma$,

\[
2G^\theta(\gamma^{-1} \xi, \gamma^{-1} \eta) = \beta^\theta_{\gamma^{-1}}(e, \gamma^{-1} g) + i(\beta^\theta_{\gamma^{-1}}(e, \gamma^{-1} g))
\]

\[
= 2G^\theta(\xi, \eta) + \beta^\theta_{\gamma}(\gamma, e) + i(\beta^\theta_{\gamma}(\gamma, e))
\]

\[
= 2G^\theta(\xi, \eta) - \beta^\theta_{\gamma}(e, \gamma) - i(\beta^\theta_{\gamma}(e, \gamma)).
\]

Now the claim follows from the definition of $d_\psi$. \qed

Recall that $G^\theta(\xi, \eta) = i(G^\theta(\eta, \xi))$ for all $\xi, \eta \in \Lambda_\theta$. Hence if $\psi$ is $i$-invariant, then $d_\psi$ is symmetric. We have the following in general:

**Proposition 5.3** (Metric-like properties of $d_\psi$).

1. There exists $R = R(\psi) > 1$ such that for all $\xi, \eta \in \Lambda_\theta$,

\[
R^{-1}d_\psi(\eta, \xi) \leq d_\psi(\xi, \eta) \leq R d_\psi(\eta, \xi).
\]

2. There exists $N = N(\psi) > 0$ such that for all $\xi_1, \xi_2, \xi_3 \in \Lambda_\theta$,

\[
d_\psi(\xi_1, \xi_3) \leq N(d_\psi(\xi_1, \xi_2) + d_\psi(\xi_2, \xi_3)).
\]
The second property was obtained in [37, Lemma 6.11] and the same proof can be repeated for a general θ in verbatim. The first property follows from Lemma 5.4 below. For \( x \neq y \) in the Gromov boundary \( \partial \Gamma \) and a bi-infinite geodesic \([x, y]\) in \( \Gamma \), we denote by \( \gamma_{x,y} \in [x, y] \) the nearest-point projection of the identity \( e \) to \([x, y]\) in \((\Gamma, d_{\Gamma})\), that is, \( \gamma_{x,y} \in [x, y] \) is an element such that \( d_{\Gamma}(e, \gamma_{x,y}) = \inf\{ d_{\Gamma}(e, g) : g \in [x, y] \} \), which is coarsely well-defined. Recall the homeomorphism \( f : \Gamma \cup \partial \Gamma \to \Gamma \cup \Lambda_{\theta} \) from Theorem 3.8(4). The following was proved in [37, Lemma 6.6] for \( \theta = \Pi \) and the same proof works for a general \( \theta \):

**Lemma 5.4.** There exists \( C_1 > 0 \) such that for any \( x \neq y \in \partial \Gamma \),

\[
\left\| \mathcal{G}^\theta(f(x), f(y)) - \frac{\mu_\theta(\gamma_{x,y}) + i(\mu_\theta(\gamma_{x,y}))}{2} \right\| < C_1.
\]

In particular, for \( \xi \neq \eta \in \Lambda_{\theta} \), we have

\[
\| \mathcal{G}^\theta(\xi, \eta) - \mathcal{G}^\theta(\eta, \xi) \| < 2C_1.
\]

**Symmetrization.** Consider the following symmetrization of \( \psi \in a_{\theta}^* \):

\[
\tilde{\psi} := \frac{\psi + \psi \circ i}{2} \in a_{\theta, i(\theta)}^*.
\]

Since we are assuming \( \theta = i(\theta) \), we have \( \tilde{\psi} \in a_{\theta}^* \) as well. Since \( \mathcal{L}_{\theta} \) is \( \theta \)-invariant, we have \( \tilde{\psi} > 0 \) on \( \mathcal{L}_{\theta} - \{0\} \). Lemma 5.4 implies that \( d_{\tilde{\psi}} \) and \( d_{\psi} \) are Lipschitz equivalent:

**Proposition 5.5.** There exists \( R \geq 1 \) such that for any \( \xi, \eta \in \Lambda_{\theta} \), we have

\[
R^{-1} d_{\psi}(\xi, \eta) \leq d_{\tilde{\psi}}(\xi, \eta) \leq Rd_{\psi}(\xi, \eta).
\]

**Proof.** Since \( \mathcal{G}^\theta(\eta, \xi) = i(\mathcal{G}^\theta(\xi, \eta)) \) for all \( \eta \neq \xi \in \Lambda_{\theta} \), it follows from Lemma 5.4 with the constant \( C_1 \) therein that

\[
|\psi(\mathcal{G}^\theta(\xi, \eta)) - \tilde{\psi}(\mathcal{G}^\theta(\xi, \eta))| = \frac{1}{2} |\psi(\mathcal{G}^\theta(\xi, \eta) - \mathcal{G}^\theta(\eta, \xi))| < \|\psi\| C_1.
\]

It suffices to set \( R = e^{\|\psi\| C_1} \) to finish the proof.

We also record the following Vitali covering type lemma which is a standard consequence of Proposition 5.3(2) (cf. [37]): here \( B_{\psi}(\xi, r) = \{ \eta \in \Lambda_{\theta} : d_{\psi}(\xi, \eta) < r \} \).

**Lemma 5.6.** [37, Lemma 6.12] There exists \( N_0 = N_0(\psi) \geq 1 \) satisfying the following: for any finite collection \( B_{\psi}(\xi_1, r_1), \ldots, B_{\psi}(\xi_n, r_n) \) with \( \xi_i \in \Lambda_{\theta} \) and \( r_i > 0 \) for \( i = 1, \ldots, n \), there exists a disjoint subcollection \( B_{\psi}(\xi_{i_1}, r_{i_1}), \ldots, B_{\psi}(\xi_{i_k}, r_{i_k}) \) such that

\[
\bigcup_{i=1}^{n} B_{\psi}(\xi_i, r_i) \subset \bigcup_{j=1}^{k} B_{\psi}(\xi_{i_j}, N_0 r_{i_j}).
\]
Remark 5.7. Recall that the canonical projection \( p : \Lambda_{\theta, i(\theta)} \to \Lambda_\theta \) is a \( \Gamma \)-equivariant homeomorphism and that \( a_\theta^* \subset a_{\theta, i(\theta)}^* \). Using this homeomorphism, we can also define a function \( d_\psi \) on \( \Lambda_\theta \) even when \( \theta \) is not symmetric, so that \( p : (\Lambda_{\theta, i(\theta)}, d_\psi) \to (\Lambda_\theta, d_\psi) \) is an isometry:

\[
d_\psi(\xi, \eta) := d_\psi(p^{-1}(\xi), p^{-1}(\eta))
\]
for all \( \xi, \eta \in \Lambda_\theta \). In this regard, the above discussion is still valid without the symmetric hypothesis on \( \theta \).

6. Compatibility of shadows and \( d_\psi \)-balls

As before, let \( \Gamma \) be a \( \theta \)-Anosov subgroup of a connected semisimple real algebraic group \( G \). We fix a word metric \( d_\Gamma \) on \( \Gamma \). Fix a linear form \( \psi \in a_\theta^* \) which is positive on \( L \setminus \{0\} \) and \( \psi = \psi \circ i \). Recall the premetric \( d_\psi \) on \( \Gamma_0 \) defined in (4.1) and the conformal premetric \( d_\psi \) on \( \Lambda_\theta \) defined by (5.1).

Lemma 6.1. Both \((\Gamma_0, d_\psi)\) and \((\Lambda_\theta, d_\psi)\) are symmetric.

Proof. For \( g_1, g_2 \in G \), we have

\[
d_\psi(g_1 o, g_2 o) = \psi(\mu(g_1^{-1} g_2)) = \psi \circ i(\mu(g_2^{-1} g_1)) = d_\psi(g_2 o, g_1 o).
\]

The second claim follows similarly since \( G_{\theta, i(\theta)}(\xi, \eta) = i G_{\theta, i(\theta)}(\eta, \xi) \) for all \( \xi, \eta \in F_{\theta, i(\theta)} \) in general position. \( \Box \)

Shadows play a basic role in studying the metric property of \((\Lambda_\theta, d_\psi)\) in relation with the geometry of the symmetric space \( X \), as in the original work of Sullivan. We recall the definition of shadows in \( F_\theta \). For \( p, q \in X \), the shadow \( O_\theta^R(p, q) \) of the Riemannian ball \( B(q, R) \) viewed from \( p \) is defined as

\[
O_\theta^R(p, q) = \{ gP_\theta \in F_\theta : g \in G, go = p, d(q, gA^o + o) < R \}.
\]

We refer to [32] and [33] for basic properties of these shadows.

The main technical ingredient of this paper is the following theorem which says that shadows in \( \Lambda_\theta \) are comparable with \( d_\psi \)-balls.

Theorem 6.2. Let \( \psi \in a_\theta^* \) be such that \( \psi > 0 \) on \( L \setminus \{0\} \) and \( \psi = \psi \circ i \). Then there exist constants \( c, R_0 > 0 \) such that for any \( R > R_0 \), there exists \( c' = c'_R > 0 \) so that the following holds: for any \( \xi \in \Lambda_\theta \) and any \( g \in \Gamma \) on a geodesic ray \([e, \xi]\) in \( \Gamma \), we have

\[
B_\psi(\xi, ce^{-d_\psi(o, go)}) \subset O_\theta^R(o, go) \cap \Lambda_\theta \subset B_\psi(\xi, c'e^{-d_\psi(o, go)}).
\]

Since the proof of this theorem is quite lengthy, we will prove the first inclusion in this section and the second inclusion in the next section. The rest of this section is devoted to the proof of the first inclusion. In view of Remark 5.7 we assume that

\[
\theta = i(\theta).
\]
Strictly speaking, $d_\psi$ is not a metric on the $\Gamma$-orbit $\Gamma o$. Nevertheless, we will still employ terminologies for the metric space on $(\Gamma o, d_\psi)$ for convenience. For instance, for a subset $B \subset \Gamma o$, $d_\psi(go, B) = \inf_{ho \in B} d_\psi(go, ho)$ and the $R$-neighborhood of $B$ is given by $\{go \in \Gamma o : d_\psi(go, B) < R\}$, etc.

Two main ingredients of the proof of the first inclusion of (6.1) are the following, which allow us to treat $(\Gamma o, d_\psi)$ almost like a Gromov hyperbolic space:

1. $(\Gamma o, d_\psi)$ satisfies a triangle inequality up to an additive error (Theorem 4.1);
2. the $\psi$-Gromov product $\psi(G(\xi, \eta))$ is equal to the premetric $d_\psi(o, [\xi, \eta]o)$ up to an additive error (Proposition 6.7).

In the rank one case, the property (2) is a well-known consequence of a uniform thin-triangle property and the Morse lemma of the rank one symmetric space. Higher rank symmetric spaces have neither of these properties. Our proof of (2) is based on the KLP Morse lemma using diamonds as well as a uniform thin-triangle property of the orbit $(\Gamma o, d_\psi)$.

We begin with the following:

**Proposition 6.3.** The orbit map $(\Gamma, d_\Gamma) \to (\Gamma o, d_\psi)$, $\gamma \mapsto \gamma o$, is a quasi-isometry, i.e., there exists $Q_\psi \geq 1$ such that for any $\gamma_1, \gamma_2 \in \Gamma$,

$$Q_\psi^{-1} \cdot d_\Gamma(\gamma_1, \gamma_2) - Q_\psi \leq d_\psi(\gamma_1 o, \gamma_2 o) \leq Q_\psi \cdot d_\Gamma(\gamma_1, \gamma_2) + Q_\psi.$$  

In particular, the images of geodesic triangles in $\Gamma$ under the orbit map are uniformly thin, that is, there exists $T_\psi > 0$ such that for any $\xi_1, \xi_2, \xi_3 \in \Gamma \cup \partial \Gamma$, the image $[\xi_1, \xi_3]o$ is contained in the $T_\psi$-neighborhood of $([\xi_1, \xi_2] \cup [\xi_2, \xi_3])o$ with respect to $d_\psi$.

**Proof.** The second part follows since $(\Gamma, d_\Gamma)$ is a Gromov hyperbolic space (Theorem 3.8(1)), and hence it has a uniform thin-triangle property which is a quasi-isometry invariance. Since the orbit map $(\Gamma, d_\Gamma) \to (\Gamma o, d)$ is a quasi-isometry (Theorem 3.8(3)), the first part of the above proposition follows from the following claim that the identity map $(\Gamma o, d) \to (\Gamma o, d_\psi)$ is a quasi-isometry: there exists $C_\psi \geq 1$ such that for all $\gamma_1, \gamma_2 \in \Gamma$, we have

$$C_\psi^{-1}d(\gamma_1 o, \gamma_2 o) - C_\psi \leq d_\psi(\gamma_1 o, \gamma_2 o) \leq C_\psi d(\gamma_1 o, \gamma_2 o) + C_\psi.$$  

We can take a cone $C$ containing a neighborhood of $\mathcal{L} - \{0\}$ in $\mathbb{R}^+$ such that $\psi > 0$ on $C - \{0\}$. Hence we can choose $C_1 > 1$ so that

$$C_1^{-1} < \min_{u \in C, \|u\|=1} \psi(u) \leq \max_{u \in C, \|u\|=1} \psi(u) < C_1.$$

On the other hand, $\mu(\gamma) \in C$ for all but finitely many $\gamma \in \Gamma$ (Lemma 4.4), and hence $C_2 := \max\{|\psi(\mu(\gamma))| : \mu(\gamma) \notin C\} < \infty$. If we set $C = C_1 + C_2$, then

$$C_1^{-1} \|\mu(\gamma)\| - C \leq \psi(\mu(\gamma)) \leq C \|\mu(\gamma)\| + C.$$  

Since both $d$ and $d_\psi$ are left $\Gamma$-invariant, this implies the claim.
We use the Morse property to obtain that the image of a geodesic ray under the orbit map has a uniform progression:

**Lemma 6.4** (Uniform progression lemma). For any $r > 0$, there exists $n_r > 0$ such that for any geodesic ray $\{\gamma_0 = e, \gamma_1, \gamma_2, \cdots\}$ in $(\Gamma, d_\Gamma)$,

$$d_\psi(o, \gamma_{i+n}o) \geq d_\psi(o, \gamma_i o) + r$$

for all $i \in \mathbb{N}$ and all $n \geq n_r$.

**Proof.** Fix $r > 0$. By Theorem 4.13, there exist a cone $C \subset a^+$ and $B, D_0 \geq 0$ so that for all $n \geq B$ and $i \geq 0$, the sequence $o, \gamma_1 o, \cdots, \gamma_{i+n} o$ is contained in the $D_0$-neighborhood of the diamond $\Diamond_C(o, \gamma_{i+n}o)$ in $(X, d)$. We may also assume that $\psi > 0$ on $C - \{0\}$ as $C$ can be arbitrarily close to $L$. For each $i \geq 0$, choose a point $x_i \in \Diamond_C(o, \gamma_{i+n}o)$ which is $D_0$-close to $\gamma_i o$. Applying Lemma 4.10, we obtain that

$$d_\psi(o, x_i) + d_\psi(x_i, \gamma_{i+n}o) = d_\psi(o, \gamma_{i+n}o). \tag{6.3}$$

Since the orbit map $(\Gamma, d_\Gamma) \rightarrow (\Gamma o, d)$ is a $Q_\psi$-quasi-isometry by Proposition 6.3, we get that for all $i \geq 0$,

$$d_\psi(\gamma_i o, \gamma_{i+n}o) \geq Q_\psi^{-1} d_\Gamma(\gamma_i, \gamma_{i+n}) - Q_\psi = Q_\psi^{-1} n - Q_\psi. \tag{6.4}$$

By applying Lemma 2.1 to a compact subset $\{g \in G : \|\mu(g)\| \leq D_0\}$, we have

$$|d_\psi(o, x_i) - d_\psi(o, \gamma_i o)| \leq C \quad \text{and} \quad |d_\psi(x_i, \gamma_{i+n}o) - d_\psi(\gamma_i o, \gamma_{i+n}o)| \leq C \tag{6.5}$$

where $C$ depends only on $D_0$ and $\|\psi\|$. Putting (6.3), (6.4), and (6.5) together, we get

$$d_\psi(o, \gamma_{i+n}o) = d_\psi(o, x_i) + d_\psi(x_i, \gamma_{i+n}o)$$

$$\geq d_\psi(o, \gamma_i o) + d_\psi(\gamma_i o, \gamma_{i+n}o) - 2C$$

$$\geq d_\psi(o, \gamma_i o) + (Q_\psi^{-1} n - Q_\psi) - 2C.$$

Hence setting $n_r = B + Q_\psi(r + 2C + Q_\psi)$ finishes the proof. \qed

**Lemma 6.5** (Small inscribed triangle). There exists $C > 0$ satisfying the following property: Let $[\xi, \eta]$ be a bi-infinite geodesic in $(\Gamma, d_\Gamma)$. If $\gamma o$ is the nearest-point projection of $o$ to $[\xi, \eta]o$ in the $d_\psi$-metric, i.e., $\gamma \in [\xi, \eta]$ is such that $d_\psi(o, \gamma o) = d_\psi(o, [\xi, \eta]o)$, then there exist $u \in [e, \xi]$ and $v \in [e, \eta]$ so that $\{u o, v o, \gamma o\}$ has $d_\psi$-diameter less than $C$.

**Proof.** Recall from Proposition 6.3 that there exists $T_\psi > 0$ so that every triangle in $\Gamma o$, obtained as the image of a geodesic triangle in $(\Gamma, d_\Gamma)$ under the orbit map, is $T_\psi$-thin in the $d_\psi$-metric. By the $T_\psi$-thinness of $(\Gamma o, d_\psi)$, we have either $d_\psi(\gamma o, [e, \xi] o) \leq T_\psi$ or $d_\psi(\gamma o, [e, \eta] o) \leq T_\psi$. We will assume the latter case; the other case can be treated similarly. We write $[e, \eta] = \{v_i\}_{i \geq 0}$. We then can choose $j$ so that $j = \min\{i \geq 0 : d_\psi(\gamma o, v_i o) \leq T_\psi + D\}$ where...
Let $n' = n_{3T_\psi} + 3D$ be the constant from Lemma 6.4. If $j < n'$, then we set $u = v = e$ and note that

$$d_\psi(\gamma o, o) \leq d_\psi(\gamma o, v_j o) + d_\psi(v_j o, o) + D$$

$$\leq D_1 := T_\psi + (n' + 1)Q_\psi + 2D$$

where $Q_\psi$ is given by Proposition 6.3. Hence the triangle $\{uo, vo, \gamma o\} = \{o, o, \gamma o\}$ has $d_\psi$-diameter at most $D_1$.

Now suppose that $j > n'$. We claim that $d_\psi(v_{j-n'} o, [\xi, \eta] o) > T_\psi$.

Indeed, otherwise, $d_\psi(v_{j-n'} o, \gamma' o) \leq T_\psi$ for some $\gamma' \in [\xi, \eta]$, and hence we have

$$d_\psi(o, \gamma' o) \leq d_\psi(o, v_{j-n'} o) + d_\psi(v_{j-n'} o, \gamma' o) + D$$

$$\leq (d_\psi(o, v_j o) - 3T_\psi - 3D) + T_\psi + D$$

$$= d_\psi(o, v_j o) - 2T_\psi - 2D$$

$$\leq d_\psi(o, v_j o) - d_\psi(\gamma o, v_j o) - T_\psi - D$$

$$\leq d_\psi(o, \gamma o) - T_\psi,$$

where the first and the last inequalities follow from Theorem 4.1 and the second is from Lemma 6.4. This yields a contradiction to the minimality of $d_\psi(o, \gamma o)$, proving the claim.

Since the triangle consisting of the sides $[\xi, \eta] o$, $[e, \xi] o$, and $[e, \eta] o = \{v_i o\}_{i \geq 0}$ is $T_\psi$-thin, the above claim implies that $v_{j-n'} o$ lies in the $T_\psi$-neighborhood of $[e, \xi] o$. Hence there exists $u \in [e, \xi]$ such that $d_\psi(v_{j-n'} o, u o) \leq T_\psi$ (see Figure 4). Since $d_\psi(v_j, v_{j-n'}) \leq Q_\psi n' + Q_\psi$, we have so far obtained

- $d_\psi(\gamma o, v_j o) \leq T_\psi + D$;
- $d_\psi(v_j o, u o) \leq Q_\psi n' + Q_\psi + T_\psi + D$;
- $d_\psi(\gamma o, u o) \leq Q_\psi n' + Q_\psi + 2T_\psi + 3D$.

Therefore the triangle $\{uo, v_j o, \gamma o\}$ has $d_\psi$-diameter at most $D_2 = Q_\psi n' + Q_\psi + 2T_\psi + 3D$. It remains to set $C = \max(D_1, D_2)$.
The following was shown for $\theta = \Pi$ in \cite[Lemma 5.7]{37} which directly implies the statement for general $\theta$:

**Lemma 6.6.** There exists $\kappa > 0$ such that for any $g, h \in G$ and $R > 0$, we have

$$\sup_{\xi \in O_R^\theta(\gamma o, h o)} \| \beta_\xi^\theta(g o, h o) - \mu_\theta(g^{-1} h) \| \leq \kappa R.$$  

We now prove that the $\psi$-Gromov product $\psi(\mathcal{G}(\xi, \eta))$ behaves like the distance $d_\psi(o, [\xi, \eta] o)$ up to an additive error:

**Proposition 6.7** (Comparison between $\psi$-Gromov product and $d_\psi$-distance). There exists $C_1 > 0$ such that for any $\xi \neq \eta \in \Lambda_\theta = \partial \Gamma$, we have

$$|\psi(\mathcal{G}(\xi, \eta)) - d_\psi(o, [\xi, \eta] o)| \leq C_1.$$  

**Proof.** Let $\gamma \in [\xi, \eta]$ be such that $d_\psi(o, \gamma o) = d_\psi(o, [\xi, \eta] o)$. Consider geodesic rays $[e, \xi]$ and $[e, \eta]$ in $(\Gamma, d_\Gamma)$. Let $k, \ell \in K$ and $h \in G$ be such that $kP_\theta = \xi$, $\ell P_\theta = \eta$, $hP_\theta = \xi$ and $hw_0P_\theta = \eta$. For the constant $D_0$ given by Theorem 4.13, we have

$$\sup_{u \in [e, \xi]} d(uo, k M_\theta A^+ o) \leq D_0;$$
$$\sup_{v \in [e, \eta]} d(vo, \ell M_\theta A^+ o) \leq D_0;$$
$$\sup_{g \in [\xi, \eta]} d(g o, h M_\theta A o) \leq D_0.$$

(6.7)

Since $\gamma \in [\xi, \eta]$ by the choice, the third inequality implies that $d(\gamma o, h M_\theta A o) \leq D_0$. We may assume that $h$ satisfies that $d(ho, \gamma o) \leq D_0$, by replacing $h$ with an element of $h M_\theta A$ if necessary.

We first claim that for some uniform $R > 0$ depending only on $\Gamma$ and $\psi$,

$$\xi, \eta \in O_R^\theta(o, \gamma o).$$
To show the claim, let \( C > 0 \) be the constant given by Lemma 6.5 and choose \( u \in [e, \xi] \) and \( v \in [e, \eta] \) so that the triangle \( \{uo, vo, \gamma o\} \) has \( d_\psi \)-diameter smaller than \( C \) (see Figure 5). Hence, for the constant \( C' := C_\psi (C + C_\psi) \), where \( C_\psi \) is given in (6.2), the Riemannian diameter of the triangle \( \{uo, vo, \gamma o\} \) is less than \( C' \). It then follows from the first two inequalities of (6.7) that

\[
d(\gamma o, kM \theta A^+ o) < D_0 + C' \quad \text{and} \quad d(\gamma o, \ell M \theta A^+ o) < D_0 + C'.
\]

Since \( kP_\theta = \xi \) and \( \ell P_\theta = \eta \), we have

\[
\xi, \eta \in O_{D_0 + C'}(o, \gamma o),
\]

showing the claim with \( R = D_0 + C' \)

Therefore by Lemma 6.6, we get

\[
\| \beta_\xi^\theta(o, \gamma o) - \mu_\theta(\gamma) \| \leq \kappa R \quad \text{and} \quad \| \beta_\eta^\theta(o, \gamma o) - \mu_\theta(\gamma) \| \leq \kappa R.
\]

Since \( \beta_\xi^\theta(o, \gamma o) = \beta_\xi^\theta(o, ho) + \beta_\xi^\theta(ho, \gamma o) \) and \( \| \beta_\xi^\theta(ho, \gamma o) \| \leq d(ho, \gamma o) \leq D_0 \), we have

\[
\| \beta_\xi^\theta(o, ho) - \mu_\theta(\gamma) \| \leq \kappa R + D_0
\]

and similarly

\[
\| \beta_\eta^\theta(o, ho) - \mu_\theta(\gamma) \| \leq \kappa R + D_0.
\]

Recalling the definition \( G^\theta(\xi, \eta) = \frac{1}{2}(\beta_\xi^\theta(o, ho) + i(\beta_\eta^\theta(o, ho))) \), and using \( \psi = \psi \circ i \), we obtain that

\[
|\psi(G^\theta(\xi, \eta)) - d_\psi(o, \gamma o) | \leq \| \psi \| (\kappa R + D_0),
\]

as desired. \( \square \)

We are now ready to prove the first inclusion in Theorem 6.2 which we formulate again as follows:
Proposition 6.8. There exist constants $c, R_0 > 0$ such that for any $\xi \in \Lambda_\theta$ and $g \in [e, \xi]$ in $\Gamma$, we have

\begin{equation}
(6.8) \quad B_\psi(\xi, ce^{-d_\psi(o, go)}) \subset O^\theta_{R_0}(o, go) \cap \Lambda_\theta.
\end{equation}

Proof. Let $C_1, D > 0$ be the constants given by Proposition 6.7 and Theorem 4.1 respectively. Recall the constant $T_\psi$ in Proposition 6.3; the image of any geodesic triangle in $(\Gamma, d_\Gamma)$ under the orbit map, is $T_\psi$-thin in the $d_\psi$-metric. We now claim that (6.8) holds with $c := e^{-2(T_\psi + C_1 + D)}$. Fix $\xi \in \Lambda_\theta$ and an element $g \in [e, \xi]$. Let $\eta \in B_\psi(\xi, ce^{-d_\psi(o, go)})$, that is,

\begin{equation}
(6.9) \quad \psi(G^\theta(\xi, \eta)) > d_\psi(o, go) + 2T_\psi + C_1 + D.
\end{equation}

Let $\gamma \in [\xi, \eta]$ be chosen so that $d_\psi(o, \gamma o) = d_\psi(o, [\xi, \eta] o)$. By Proposition 6.7, we have

\begin{equation}
(6.10) \quad d_\psi(o, \gamma o) \geq \psi(G^\theta(\xi, \eta)) - C_1.
\end{equation}

Hence by (6.9),

\begin{equation}
(6.11) \quad d_\psi(o, \gamma o) > d_\psi(o, go) + 2T_\psi + D.
\end{equation}

Let $g' \in [\xi, \eta]$ be such that $d_\psi(go, g' o) = d_\psi(go, [\xi, \eta] o)$. By Theorem 4.1, we also have

\begin{equation}
(6.12) \quad d_\psi(o, \gamma o) \leq d_\psi(o, g' o) \leq d_\psi(o, go) + d_\psi(go, [\xi, \eta] o) + D.
\end{equation}

Together with (6.10), this implies

\begin{equation}
(6.13) \quad d_\psi(go, [\xi, \eta] o) > 2T_\psi.
\end{equation}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{go is far from $[\xi, \eta] o$ and hence close to $[e, \eta] o$; so $\eta$ lies in the shadow $O^\theta_{T_\psi + D_0}(o, go)$.}
\end{figure}

Since the triangle $[e, \xi] o \cup [\xi, \eta] o \cup [e, \eta] o$ is $T_\psi$-thin in $d_\psi$-metric, $go$ is contained in the $T_\psi$-neighborhood of $[\xi, \eta] o \cup [e, \eta] o$. Since $d_\psi(go, [\xi, \eta] o) >$
2T_\psi by \((6.11)\), we must have \(d_\psi(g_0, [e, \eta]o) \leq T_\psi\) (see Figure 6). For the constant \(T' := C_\psi(T_\psi + C_\psi)\) where \(C_\psi\) is as in \((6.2)\), we have
\[
d(go, [e, \eta]o) \leq T'.
\]
With the constant \(D_0\) given in Theorem \((4.13)\), there exists \(\ell \in K\) so that \(\ell M_\theta = \eta\) and \([e, \eta]o\) is contained in the \(D_0\)-neighborhood of \(\ell M_\theta, o\) in the Riemannian metric \(d\). This implies that
\[
\eta \in O^\theta_{T'} + D_0(o, go) \cap \Lambda_\theta.
\]
This completes the proof with \(R_0 = T' + D_0\).

\[\square\]

7. Shadows inside balls: the second inclusion in Theorem \((6.2)\)

We continue the setup from section \((6)\). Hence \(i(\theta) = \theta\) and \(\psi \in a^*_\theta\) is a linear form such that \(\psi > 0\) on \(L - \{0\}\) and \(\psi = \psi \circ i\). In this section, we prove the second inclusion of Theorem \((6.2)\) which can be stated as follows:

**Proposition 7.1.** For any \(r > 0\), there exists \(c' = c'_r > 0\) such that for any \(\xi \in \Lambda_\theta\) and any \(g \in [e, \xi]\) in \(\Gamma\), we have
\[
O^\theta_{\psi}(o, go) \cap \Lambda_\theta \subset B_\psi(\xi, c'e^{-d_\psi(o, go)}).
\]

In addition to the coarse triangle inequality of \(d_\psi\) (Theorem \((4.1)\)) and the uniform progression lemma (Lemma \((6.4)\)), we will use the property that the shadows in \((\Gamma, d_\Gamma)\) are compatible via the boundary map \(f: \partial \Gamma \to \Lambda_\theta\) (Lemma \((7.1)\)).

In the Gromov hyperbolic space \((\Gamma, d_\Gamma)\), for \(R > 0\) and \(\gamma_1, \gamma_2 \in \Gamma\), the shadow \(O_R^\Gamma(\gamma_1, \gamma_2)\) is defined as the set of all \(\xi \in \partial \Gamma\) such that a geodesic ray \([\gamma_1, \xi]\) intersects the \(R\)-ball centered at \(\gamma_2\):
\[
O_R^\Gamma(\gamma_1, \gamma_2) = \{\xi \in \partial \Gamma: d_\Gamma([\gamma_2, [\gamma_1, \xi]]) < R\}.
\]

Clearly, shadows are \(\Gamma\)-equivariant in the sense that for any \(\gamma \in \Gamma\), we have \(\gamma O_R^\Gamma(\gamma_1, \gamma_2) = O_R^\Gamma(\gamma_1, \gamma_2)\).

The following proposition states that shadows in \(\partial \Gamma\) and shadows in \(\Lambda_\theta\) are compatible via the boundary map \(f: \partial \Gamma \to \Lambda_\theta\): recall that the orbit map \((\Gamma, d_\Gamma) \to (\Gamma, d)\) is a \(Q\)-quasi-isometry for some \(Q \geq 1\) (Theorem \((3.8)\)) and let \(R_0 := Q + D_0 + 1\) where \(D_0\) is given in Theorem \((4.13)\).

**Proposition 7.2.** For any \(R > R_0\), there exists \(R_1, R_2 > 0\) such that for any \(\gamma_1, \gamma_2 \in \Gamma\),
\[
f(O_{R_1}^\Gamma(\gamma_1, \gamma_2)) \subset O^\theta_{\psi}(\gamma_10, \gamma_20) \cap \Lambda_\theta \subset f(O_{R_2}^\Gamma(\gamma_1, \gamma_2)).
\]

In proving this proposition, we will also need to consider shadows whose viewpoints are on the boundary \(F_\theta\). For \(\eta \in F_\theta\), \(p \in X\), and \(R > 0\), the \(\theta\)-shadow \(O_R^\theta(\eta, p)\) is defined as follows:
\[
O_R^\theta(\eta, p) = \{gP_{\theta} \in F_\theta: g \in G, gw_0P_\theta = \eta, d(p, go) < R\}.
\]

We will need the following proposition on continuity of shadows:
Proposition 7.3 (Continuity of shadows on viewpoints, [32, Proposition 3.4]). Let $p \in X$, $\eta \in F_\theta$ and $r > 0$. If a sequence $q_i \in X$ converges to $\eta$ as $i \to \infty$ as in Definition 2.2, then for any $0 < \varepsilon < r$, we have

$$
(7.1) \quad O^\theta_{r-\varepsilon}(\eta, p) \subset O^\theta_r(q_i, p) \subset O^\theta_{r+\varepsilon}(\eta, p) \quad \text{for all large } i \geq 1.
$$

Proof of Proposition 7.2 Let $R > R_0$. By the $\Gamma$-equivariance of $f$ as well as of shadows, we may assume $\gamma_1 = e$ and write $\gamma_2 = \gamma$. By applying Theorem 4.13(2), we get that for any $\xi \in \partial \Gamma$ and $k \in K$ with $kP_0 = f(\xi)$, the image $[e, \xi]o$ is contained in the $D_0$-neighborhood of $kM_0(\exp^\gamma)o \subset kM_0A^+o$ in the symmetric space $(X, d)$. Since $R > R_0 = Q + D_0 + 1$, we can choose $R_1 > 0$ so that $QR_1 + Q + D_0 < R$. Now if $\xi \in O^\Gamma_{R_1}(e, \gamma)$, and hence $[e, \xi]o$ intersects the ball $\{g \in \Gamma : d_\Gamma(\gamma, g) < R_1\}$, then $kM_0A^+o$ intersects the $QR_1 + Q + D_0$-neighborhood of $\gamma o$, and hence the $R$-neighborhood of $\gamma o$. Therefore $f(\xi) \in O^\theta_R(o, \gamma o)$. This shows the first inclusion.

To prove the second inclusion, suppose that the claim does not hold for some $R > R_0$. Then for each $i \geq 1$, there exists $\gamma_i \in \Gamma$ such that

$$
O^\theta_R(o, \gamma_i o) \cap A_\theta \not\subset f(O^\Gamma_{R}(e, \gamma_i));
$$

in other words, there exists $x_i \in \partial \Gamma - O^\Gamma_{R}(e, \gamma_i)$ such that $f(x_i) \notin O^\theta_R(o, \gamma_i o)$. By the $\Gamma$-equivariance of $f$, it follows that

$$
(\gamma_i^{-1}x_i) \notin O^\Gamma_{R}(\gamma_i^{-1}, e) \quad \text{and} \quad f(\gamma_i^{-1}x_i) \in O^\theta_R(\gamma_i^{-1}o, o) \quad \text{for all } i \geq 1.
$$

After passing to a subsequence, we may assume that $\gamma_i^{-1} \to y \in \partial \Gamma$ and $\gamma_i^{-1}x_i \to x$ as $i \to \infty$. By Theorem 3.8(4), we deduce $\gamma_i^{-1}o \to f(y)$ as $i \to \infty$. Applying Proposition 7.3 to $q_i = \gamma_i^{-1}o$, $p = o$ and $\eta = f(y)$, we have for some $\varepsilon > 0$ that

$$
O^\theta_R(\gamma_i^{-1}o, o) \subset O^\theta_{R+\varepsilon/2}(f(y), o) \quad \text{for all } i \geq 1.
$$

Since $f(\gamma_i^{-1}x_i) \in O^\theta_R(\gamma_i^{-1}o, o)$ for all $i \geq 1$ and $f(\gamma_i^{-1}x_i)$ converges to $f(x)$ as $i \to \infty$, we have

$$
f(x) \in O^\theta_{R+\varepsilon}(f(y), o).
$$

This implies that $f(x)$ is in general position with $f(y)$, i.e., $(f(x), f(y)) \in F^{(2)}_\theta$, and in particular $f(x) \neq f(y)$. On the other hand, since $\gamma_i^{-1}x_i \notin O^\Gamma_{R}(\gamma_i^{-1}, e)$ for all $i \geq 1$, the sequence of geodesics $[\gamma_i^{-1}x_i, \gamma_i^{-1}]$ escapes any large ball centered at $e$. This implies that two sequences $\gamma_i^{-1}x_i$ and $\gamma_i^{-1}$ must have the same limit, and hence $x = y$ which is a contradiction. Therefore the claim follows. 

The Gromov product in $(\Gamma, d_\Gamma)$ is defined as follows: for $\alpha, \beta, \gamma \in \Gamma$,

$$
(\alpha, \beta)_\gamma = \frac{1}{2} (d_\Gamma(\alpha, \gamma) + d_\Gamma(\beta, \gamma) - d_\Gamma(\alpha, \beta))
$$

and for $x, y \in \partial \Gamma$,

$$
(x, y)_\gamma = \sup_{i,j \to \infty} \liminf_{i,j} (x_i, y_j)_\gamma
$$
where the supremum is taken over all sequences \( \{ x_i \}, \{ y_j \} \) in \( \Gamma \) such that \( \lim_{i \to \infty} x_i = x \) and \( \lim_{j \to \infty} y_j = y \). The Gromov product for a pair of a point in \( \Gamma \) and a point in \( \partial \Gamma \) is defined similarly. The Gromov product \( (x, y)_\gamma \) is known to measure distance from \( \gamma \) and to a geodesic \([x, y]\) up to a uniform additive error (see [11] for basic properties of Gromov hyperbolic spaces).

The following lemma says that the half-space spanned by the shadow is opposite to the light; more precisely, for any \( x \in \partial \Gamma \) and \( \gamma \in [e, x] \), the half-space spanned by all geodesics connecting \( x \) and \( O_{R}(e, \gamma) \) lies farther than \( \gamma \), viewed from \( e \):

**Lemma 7.4.** Given \( R > 0 \), there exists \( r = r_R > 0 \) such that for any \( x \in \partial \Gamma \), \( \gamma \in [e, x] \), and \( y \in O_{R}(e, \gamma) \), we have

\[
d_{\Gamma}(\gamma_{x,y}, [\gamma, x]) \leq r
\]

where \( \gamma_{x,y} \in [x, y] \) denotes the nearest-point projection of \( e \) to a geodesic \([x, y]\).

**Proof.** Let \( [e, x] = \{ \gamma_i \}_{i \geq 0} \). We fix \( \gamma := \gamma_i \) and \( y \in O_{R}(e, \gamma) \). In terms of the Gromov product, we have \( (e, y)_{\gamma} < R + \delta/2 \) for some uniform \( \delta > 0 \) depending only on \( \Gamma \). On the other hand, the hyperbolicity of \( \Gamma \) also implies that we can take \( \delta \) large enough so that

\[
(e, y)_{\gamma} \geq \min \{(e, \gamma_{x,y})_{\gamma}, (\gamma_{x,y}, y)_{\gamma}\} - \delta/2
\]

and that every geodesic triangle in \( \Gamma \cup \partial \Gamma \) is \( \delta \)-thin. Therefore

\[
\min \{(e, \gamma_{x,y})_{\gamma}, (\gamma_{x,y}, y)_{\gamma}\} < R + \delta.
\]

First consider the case when \( (\gamma_{x,y}, y)_{\gamma} < R + \delta \). Then for some constant \( \delta_1 \) depending on \( R + \delta \), there exists \( \gamma' \in [\gamma_{x,y}, y] \) such that \( d_{\Gamma}(\gamma', \gamma) < \delta_1 \). Consider the geodesic triangle with vertices \( x, \gamma, \gamma' \). Since this triangle is \( \delta \)-thin and \( \gamma_{x,y} \in [x, \gamma'] \), the \( \delta \)-neighborhood of \( \gamma_{x,y} \) intersects \([x, \gamma] \cup [\gamma, \gamma']\). Hence it follows from \( d_{\Gamma}(\gamma, \gamma') < \delta_1 \) that the \( (\delta + \delta_1) \)-neighborhood of \( \gamma_{x,y} \) intersects the geodesic \([x, \gamma]\). Namely,

\[
d_{\Gamma}(\gamma_{x,y}, [\gamma, x]) \leq \delta + \delta_1.
\]
Now consider the case that \((e, \gamma_{x,y})_\gamma < R + \delta\). Since \(\gamma_{x,y}\) is the nearest-point projection of \(e\) to \([x,y]\), there exists a constant \(\delta_2\) depending only on \(\Gamma\) such that the \(\delta_2\)-neighborhood of \(\gamma_{x,y}\) intersects both geodesic rays \([e,x]\) and \([e,y]\). In particular, there exists \(\gamma_k \in [e,x]\) such that \(d_\Gamma(g_{\gamma_{x,y}}, \gamma_k) < \delta_2\).

This implies
\[
(e, \gamma_k)_\gamma \leq (e, \gamma_{x,y})_\gamma + d_\Gamma(g_{\gamma_{x,y}}, \gamma_k) < R + \delta + \delta_2.
\]

Since both \(\gamma = \gamma_i\) and \(\gamma_k\) lie on the geodesic \([e,x]\), this implies that \(k \geq i - (R + \delta + \delta_2)\). Let \(j\) be the unique integer such that \(k + R + \delta + \delta_2 \leq j \leq k + R + \delta + \delta_2 + 1\). Note that since \(k \geq i - (R + \delta + \delta_2)\), we have \(j \geq i\), and hence \(\gamma_j \in [\gamma, x]\).

Then for \(\gamma_j\), we have
\[
d_\Gamma(g_{\gamma_{x,y}}, [\gamma, x]) \leq d_\Gamma(g_{\gamma_{x,y}}, \gamma_j) \leq d_\Gamma(g_{\gamma_{x,y}}, \gamma_k) + d_\Gamma(\gamma_k, \gamma_j) \leq \delta_2 + (j - k) \leq R + \delta + 2\delta_2 + 1.
\]

Therefore it remains to set \(r = R + \delta + \delta_1 + 2\delta_2 + 1\). \(\square\)

**Proof of Proposition 7.1**. Let \(\xi \in \Lambda_\theta = \partial\Gamma\) and \(g \in [e, \xi]\) in \(\Gamma\). Fix \(r > 0\), and let \(\eta \in O^\Gamma_R(o, go) \cap \Lambda_\theta\) distinct from \(\xi\). We will continue to use the convention of identifying \(\Lambda_\theta\) and \(\partial\Gamma\) in this proof. As in Lemma 7.4, we let \(\gamma_{\xi, \eta}\) be the nearest-point projection of \(e\) to a bi-infinite geodesic \([\xi, \eta]\) in \((\Gamma, d_\Gamma)\).

By Proposition 7.2, there exists \(R > 0\), depending only on \(r\), such that \(\eta \in O^\Gamma_R(e, g)\). Write the geodesic ray \([e, \xi]\) as a sequence \(\{g_k\}_{k \geq 0}\) with \(g_0 = e\). Since \(g \in [e, \xi]\) by the hypothesis, we have \(g_i = g\) for some \(i \geq 0\).

Then for \(r_R > 0\) given in Lemma 7.4, there exists \(j \geq i\) such that
\[
d_\Gamma(\gamma_{\xi, \eta}, g_j) \leq r_R.
\]

Let \(n_1 \geq 0\) and \(D \geq 0\) be given by Lemma 6.4 (uniform progression lemma) and Theorem 4.1 (coarse triangle inequality) respectively. We then have
\[
d_\psi(o, g_j o) \geq d_\psi(o, g_{i-n_1} o) + 1 \geq d_\psi(o, go) - d_\psi(g_{i-n_1} o, go) - D + 1.
\]

Since \(g = g_i\), we have \(d_\psi(g_{i-n_1} o, go) \leq Q_\psi(n_1 + 1)\) where \(Q_\psi\) is the constant in Proposition 6.3. Hence we deduce by setting \(D' := Q_\psi(n_1 + 1) + D\) that
\[
d_\psi(o, g_j o) \geq d_\psi(o, go) - D'.
\]

On the other hand, applying the coarse triangle inequality (Theorem 4.1) again, we have
\[
d_\psi(o, g_j o) \leq d_\psi(o, \gamma_{\xi, \eta} o) + d_\psi(\gamma_{\xi, \eta} o, g_j o) + D.
\]

Since \(d_\Gamma(\gamma_{\xi, \eta}, g_j) \leq r_R\), we have \(d_\psi(\gamma_{\xi, \eta} o, g_j o) \leq Q_\psi(r_R + 1)\) by Proposition 6.3 and hence
\[
d_\psi(o, \gamma_{\xi, \eta} o) \geq d_\psi(o, go) - D' - Q_\psi(r_R + 1) - D.
\]
Since we have $|\psi(G^\theta(\xi,\eta)) - d_\psi(o,\gamma o)| < \|\psi\|C_1$ with $C_1$ given by Lemma 5.4,

$$\psi(G^\theta(\xi,\eta)) \geq d_\psi(o, go) - D' - Q_\psi(rR + 1) - D - \|\psi\|C_1.$$ 

Setting $c' := e^{D' + Q_\psi(rR+1)} + D + \|\psi\|C_1$, we have

$$d_\psi(\xi, \eta) \leq c'e^{-d_\psi(o, go)}.$$

Hence $c' \in B_\psi(\xi, c'e^{-d_\psi(o, go)})$ as desired. $\square$

8. Ahlfors regularity of Patterson-Sullivan measures

As before, let $\Gamma$ be a $\theta$-Anosov subgroup of a connected semisimple real algebraic group $G$. Recall from Theorem 3.4 that the space of $\Gamma$-Patterson-Sullivan measures on $\Lambda^\theta$ is parameterized by the set

$$\mathcal{T}_\Gamma = \{\psi \in a_\theta^*: \psi \text{ is tangent to } \psi^\theta\}.$$

We continue to use the notation $\nu_\psi$ for the unique $(\Gamma, \psi)$-Patterson-Sullivan measure on $\Lambda_\theta$. Recall that $d_\psi$ is the premetric on $\Lambda_\theta$ defined by

$$d_\psi(\xi, \eta) = e^{-\psi(G(\xi, \eta))}$$

for all $\xi \neq \eta$ in $\Lambda_\theta$ and $B_\psi(\xi, r) = \{\eta \in \Lambda_\theta: d_\psi(\xi, \eta) < r\}$.

The Ahlfors regularity is an important notion in fractal geometry:

**Definition 8.1.** A premetric space $(Z, d)$ is called Ahlfors $s$-regular if there exist a Borel measure $\nu$ on $Z$ and $C \geq 1$ so that for all $z \in Z$ and $r \in [0, \text{diam} Z)$,

$$C^{-1}r^s \leq \nu(B(z, r)) \leq Cr^s$$

where $B(z, r) = \{w \in Z : d(z, w) < r\}$. Such a measure $\nu$ is also called Ahlfors $s$-regular.

The goal of this section is to deduce the following from Theorem 6.2:

**Theorem 8.2.** For any symmetric $\psi \in \mathcal{T}_\Gamma$, the measure $\nu_\psi$ is Ahlfors one-regular on $(\Lambda_\theta, d_\psi)$.

**Remark 8.3.** When $\Gamma$ is a convex cocompact subgroup of $G = \text{SO}^\theta(n, 1)$, $\mathcal{T}_\Gamma$ is a singleton consisting of the critical exponent $\delta_\Gamma$ (more precisely, the multiplication by $\delta_\Gamma$ on $\mathbb{R}$), and the metric $d_\delta_\Gamma$ is the $\delta_\Gamma$-power of a $K$-invariant Riemannian metric on $S^{n-1}$. Hence Theorem 8.2 is equivalent to Sullivan’s theorem [55, Theorem 7] that the Patterson-Sullivan measure of a Riemannian ball of radius $r$ is comparable to $r^{\delta_\Gamma}$.

We use the higher rank version of Sullivan’s shadow lemma. The following is a special case of [33, Lemma 7.2]:

**Lemma 8.4 (Shadow lemma).** Let $\Gamma < G$ be a non-elementary $\theta$-Anosov subgroup. For all large enough $R > 0$, there exists $c_0 = c_0(\psi, R) \geq 1$ such that for all $\gamma \in \Gamma$,

$$c_0^{-1}e^{-\psi(\mu_0(\gamma))} \leq \nu_\psi(O_R^\theta(o, \gamma o)) \leq c_0 e^{-\psi(\mu_0(\gamma))}.$$
Proof of Theorem 6.2. By Lemma 3.7 and Remark 5.7, it suffices to consider the case of $\theta = i(\theta)$. Let $c$ and $R_0$ be the constants as in Theorem 6.2. Fix $\xi \in \Lambda_\theta$ and $0 < r < \text{diam}(\Lambda_\theta, d_\psi)$. Write the geodesic ray $[c, \xi]$ as \(\{\gamma_k\}_{k \geq 0}\) in \((\Gamma, d_\Gamma)\). Setting
\[
i = i_r := \max\{k : r \leq ce^{-d_\psi(\alpha, \gamma_k o)}\},
\]
Theorem 6.2 implies that for any $R > R_0$,
\[
B_\psi(\xi, r) \subset B_\psi(\xi, ce^{-d_\psi(\alpha, \gamma_i o)}) \subset O_R^\theta(o, \gamma_i o).
\]
By Lemma 8.4, we get
\[
u_\psi(B_\psi(\xi, r)) \leq c_0 e^{-d_\psi(\alpha, \gamma_i o)}.
\]
By the coarse triangle inequality of $d_\psi$ (Theorem 4.1), we have
\[
d_\psi(o, \gamma_{i+1} o) \leq d_\psi(o, \gamma_i o) + d_\psi(\gamma_i o, \gamma_{i+1} o) + D
\]
where $D$ is as in loc. cit. Since $d_\psi(\gamma_i o, \gamma_{i+1} o) \leq 2Q_\psi$ with $Q_\psi$ in Proposition 6.3 we have
\[
d_\psi(o, \gamma_{i+1} o) \leq d_\psi(o, \gamma_i o) + D'
\]
where $D' = D + 2Q_\psi$. This implies
\[
ce^{-D'} e^{-d_\psi(\alpha, \gamma_i o)} \leq ce^{-d_\psi(\alpha, \gamma_{i+1} o)} < r
\]
where the last inequality follows from the definition of $i = i_r$ in (8.1). Hence we deduce from (8.2) that
\[
u_\psi(B_\psi(\xi, r)) \leq (c_0 e^{D'/c}) \cdot r.
\]
Now let $c' = c'_R > 0$ be given by Theorem 6.2 and set
\[
j = j_r := \min\{k : c'e^{-d_\psi(\alpha, \gamma_k o)} \leq r\}.
\]
By Theorem 6.2, we have
\[
O_R^\theta(o, \gamma_{j} o) \cap \Lambda_\theta \subset B_\psi(\xi, c'e^{-d_\psi(\alpha, \gamma_j o)}) \subset B_\psi(\xi, r),
\]
and hence applying Lemma 8.4 yields
\[
c_0^{-1} e^{-d_\psi(\alpha, \gamma_j o)} \leq \nu_\psi(B_\psi(\xi, r)).
\]
By the minimality of $j = j_r$ as defined in (8.3) and the coarse triangle inequality of $d_\psi$ (Theorem 4.1), we have
\[
r \leq c'e^{-d_\psi(\alpha, \gamma_{j-1} o)} \leq c'e^{D'} e^{-d_\psi(\alpha, \gamma_j o) + d_\psi(\gamma_j o, \gamma_{j-1} o, \gamma_j o)}.
\]
Recalling that $d_\psi(\gamma_{j-1} o, \gamma_j o) \leq 2Q_\psi$ and $D' = D + 2Q_\psi$, we have
\[
r \leq c'e^{D'} e^{-d_\psi(\alpha, \gamma_j o)}
\]
and hence
\[
(c_0 c' e^{D'})^{-1} \cdot r \leq \nu_\psi(B_\psi(\xi, r)).
\]
Therefore the theorem is proved with $c_1 = \max(c_0 e^{D'/c}, c_0 c' e^{D'})$. \(\Box\)
9. Hausdorff measures on limit sets

Let $\Gamma < G$ be a $\theta$-Anosov subgroup where $G$ is a connected semisimple real algebraic group. For a linear form $\psi \in \mathfrak{a}_G^*$ which is positive on $\mathcal{L} - \{0\}$, consider the associated conformal premetric $d_\psi$ on $\Lambda_\theta$. For $s > 0$, we denote by $\mathcal{H}_\psi^s$ the associated Hausdorff measure of dimension $s$, that is, for any subset $B \subset \Lambda_\theta$, let

$$ (9.1) \quad \mathcal{H}_\psi^s(B) := \lim_{\varepsilon \to 0} \inf \left\{ \sum_i (\text{diam}_\psi U_i)^s : B \subset \bigcup_i U_i, \sup \text{diam}_\psi U_i \leq \varepsilon \right\} $$

where $\text{diam}_\psi U = \sup_{\xi, \eta \in U} d_\psi(\xi, \eta)$. This is an outer measure which induces a Borel measure on $\Lambda_\theta$ (see [22], [18, Appendix A]). For $s = 1$, we simply write $\mathcal{H}_\psi$ for $\mathcal{H}_\psi^1$. Recall that $\mathcal{T}_\Gamma$ is the space of all linear forms tangent to the growth indicator $\psi^{(\theta)}_\Gamma$. In this section, we first deduce the following two theorems from Theorem 8.2, which imply Theorems 1.1 and 1.3. We also prove Theorems 9.12 and 1.4.

**Theorem 9.1.** For any symmetric $\psi \in \mathcal{T}_\Gamma$, the associated Patterson-Sullivan measure $\nu_\psi$ coincides with the one-dimensional Hausdorff measure $\mathcal{H}_\psi^1$, up to a constant multiple. In other words, $\mathcal{H}_\psi$ is the unique $(\Gamma, \psi)$-conformal measure on $\Lambda_\theta$ (up to a constant multiple).

We also show that the symmetric hypothesis is necessary:

**Theorem 9.2.** If $\psi \in \mathcal{T}_\Gamma$ is not symmetric and $\Gamma$ is Zariski dense, then $\nu_\psi$ is not comparable to $\mathcal{H}_\psi^s$ for any $s > 0$.

**Remark 9.3.** If $\psi \in \mathfrak{a}_G^*$ is positive on $\mathcal{L} - \{0\}$, then $\delta_\psi \psi \in \mathcal{T}_\Gamma$. Since $\mathcal{H}_{\delta_\psi \psi} = \mathcal{H}_\psi^{\delta_\psi}$, Theorem 9.1 says that if $\psi$ is symmetric in addition,

$$ (9.2) \quad \mathcal{H}_\psi^{\delta_\psi} = \nu_{\delta_\psi \psi} \quad \text{up to a constant multiple.} $$

**Remark 9.4.** For a special class of symmetric $\psi$ whose gradient lies in the interior of $\mathfrak{a}_G^+$, Dey-Kapovich [18, Corollary 4.8] showed that $(\Gamma_0, d_\psi)$ is a Gromov hyperbolic space and they proved Theorem 9.1 relying upon the work of Coornaert [16] which gives the positivity and finiteness of $\mathcal{H}_\psi$, for the Gromov hyperbolic space. In our generality, $(\Gamma_0, d_\psi)$ is not even a metric space, and hence their approach cannot be extended.

The main work is to establish the positivity and the finiteness of $\mathcal{H}_\psi$ and the key ingredient is the Ahlfors regular property of $\nu_\psi$ obtained in Theorem 8.2. For example, positivity of $\mathcal{H}_\psi$ is a standard consequence of the Ahlfors regularity of $(\Lambda_\theta, d_\psi)$. However, we cannot conclude finiteness of $\mathcal{H}_\psi$ directly from Ahlfors regularity due to the lack of the triangle inequality:

**Proposition 9.5 (Positivity).** For any symmetric $\psi \in \mathcal{T}_\Gamma$, we have

$$ \mathcal{H}_\psi(\Lambda_\theta) > 0. $$
Proof. Fix \( \varepsilon > 0 \) and a countable cover \( \{U_i\}_{i \in \mathbb{N}} \) such that \( \text{diam}_\psi U_i \leq \varepsilon \) for all \( i \in \mathbb{N} \). For each \( i \in \mathbb{N} \), we choose \( \xi_i \in U_i \). By Theorem \[8.2\] we have
\[
\sum_{i \in \mathbb{N}} \text{diam}_\psi U_i \gg \sum_{i \in \mathbb{N}} \nu_\psi(\psi(\xi_i, \text{diam}_\psi U_i))
\]
where the implied constant depends only on \( \psi \). Since \( \Lambda_\theta \subset \bigcup_{i \in \mathbb{N}} U_i \subset \bigcup_{i \in \mathbb{N}} B_\psi(\xi_i, \text{diam}_\psi U_i) \), it follows that \( \sum_{i \in \mathbb{N}} \text{diam}_\psi U_i \gg \nu_\psi(\Lambda_\theta) = 1 \). Since \( \{U_i\}_{i \in \mathbb{N}} \) is an arbitrary countable cover, it follows that \( \mathcal{H}_{\psi, \varepsilon}(\Lambda_\theta) \gg 1 \) with the implied constant depending only on \( \psi \). Since \( \varepsilon > 0 \) is arbitrary, we have \( \mathcal{H}_\psi(\Lambda_\theta) > 0 \).

Proposition 9.6 (Finiteness). For any symmetric \( \psi \in \mathcal{R}_\Gamma \), we have
\[
\mathcal{H}_\psi(\Lambda_\theta) < \infty.
\]

Proof. Let \( N = N(\psi) \) and \( N_0 = N_0(\psi) \) be the constants given in Proposition \[5.3\] and Lemma \[5.6\] respectively. Fix \( \varepsilon > 0 \). Since \( \Lambda_\theta \) is compact, we have a finite cover \( \Lambda_\theta \) by \( \bigcup_{j=1}^k B_\psi(\xi_j, \varepsilon/2N_0) \) for some finite set \( \xi_1, \ldots, \xi_n \in \Lambda_\theta \). Applying the Vitali covering type lemma (Lemma \[5.6\]), there exists a disjoint subcollection \( B_\psi(\xi_{i_1}, \varepsilon/2N_0), \ldots, B_\psi(\xi_{i_k}, \varepsilon/2N_0) \) such that
\[
\Lambda_\theta \subset \bigcup_{j=1}^k B_\psi(\xi_{i_j}, \varepsilon/2N_0).
\]

Since \( \text{diam}_\psi B_\psi(\xi_{i_j}, \varepsilon/2N) \leq \varepsilon \) for each \( 1 \leq j \leq k \) by Proposition \[5.3\](2), we have
\[
\mathcal{H}_{\psi, \varepsilon}(\Lambda_\theta) \leq \sum_{j=1}^k \text{diam}_\psi B_\psi(\xi_{i_j}, \varepsilon/2N_0) \leq k \cdot \varepsilon.
\]
Applying Theorem \[8.2\] we obtain
\[
k \cdot \varepsilon \ll \sum_{j=1}^k \nu_\psi(\psi(\xi_{i_j}, \varepsilon/2N_0)) = \nu_\psi\left(\bigcup_{j=1}^k B_\psi(\xi_{i_j}, \varepsilon/2N_0)\right) \leq \nu_\psi(\Lambda_\theta) = 1
\]
where the equality follows from the disjointness. This implies \( \mathcal{H}_{\psi, \varepsilon}(\Lambda_\theta) \ll 1 \). Since \( \varepsilon \) is arbitrary, we have \( \mathcal{H}_\psi(\Lambda_\theta) \ll 1 \).

Hence \( \mathcal{H}_\psi \) is a non-trivial measure on \( \Lambda_\theta \). It is also \( (\Gamma, \psi) \)-conformal:

Lemma 9.7 (Conformality). For any symmetric \( \psi \in \mathcal{R}_\Gamma \), we have
\[
\frac{d\gamma_*\mathcal{H}_\psi(\xi)}{d\mathcal{H}_\psi(\xi)} = e^{\psi(\beta^p(\xi, e, \gamma))}
\]
for all \( \gamma \in \Gamma \) and \( \xi \in \Lambda_\theta \).

Proof. Since \( d_\psi \) is invariant under the \( \Gamma \)-equivariant homeomorphism \( p : \Lambda_{\theta, \xi}(\theta) \to \Lambda_\theta \) by the definition of \( d_\psi \) (Remark \[5.7\]), the measure \( (\mathcal{H}_\psi, \Lambda_\theta) \) is the push-forward of the Hausdorff measure \( (\mathcal{H}_\psi, \Lambda_{\theta, \xi}(\theta)) \) via \( p \). Therefore it suffices to prove this lemma assuming that \( \theta = \iota(\theta) \). We simply write \( \beta^{\theta} = \beta \) in this proof to ease the notations.
Fix $\gamma \in \Gamma$ and $\xi \in \Lambda_\theta$. Let $U \subset \Lambda_\theta$ be a small open neighborhood of $\xi$. To estimate $\gamma U$ in terms of $\mathcal{H}_\psi(U)$, we fix $\varepsilon > 0$ and take any cover $\{U_i\}_{i \in \mathbb{N}}$ of $U$ such that $\text{diam}_\psi U_i \leq \varepsilon$ and that $U \cap U_i \neq \emptyset$ for all $i \in \mathbb{N}$.

For simplicity, we write $s_{\xi,R}(\gamma) := \sup_{\eta \in B_\psi(\xi,R)} e^{\psi(\eta e,\gamma)}$. By Lemma 5.2 and Proposition 5.3 with $N = N(\psi) > 0$ therein, we have that for each $i \geq 1$,

$$\text{diam}_\psi \gamma^{-1} U_i \leq \sup_{\eta \in U_i} e^{\psi(\eta e,\gamma)} \text{diam}_\psi U_i \leq s_{\xi,R_\varepsilon}(\gamma) \text{diam}_\psi U_i$$

where $R_\varepsilon = R_\varepsilon(U) = N \cdot (\text{diam}_\psi U + \varepsilon)$. We then have for $\tilde{\varepsilon} := s_{\xi,R_\varepsilon}(\gamma)\varepsilon$,

$$\mathcal{H}_{\psi,\tilde{\varepsilon}}(\gamma^{-1} U) \leq \sum_{i \in \mathbb{N}} \text{diam}_\psi \gamma^{-1} U_i \leq s_{\xi,R_\varepsilon}(\gamma) \sum_{i \in \mathbb{N}} \text{diam}_\psi U_i.$$

Since $\{U_i\}_{i \in \mathbb{N}}$ is an arbitrary countable open cover of $U$, the above inequality implies

$$\mathcal{H}_{\psi,\tilde{\varepsilon}}(\gamma^{-1} U) \leq s_{\xi,R_\varepsilon}(\gamma) \mathcal{H}_\psi(U).$$

Taking $\varepsilon \to 0$, we have $\tilde{\varepsilon} = s_{\xi,R_\varepsilon}(\gamma)\varepsilon \to 0$ and $R_\varepsilon \to R_U := N \cdot \text{diam}_\psi U$. Therefore

$$\mathcal{H}_\psi(\gamma^{-1} U) \leq s_{\xi,R_U}(\gamma) \mathcal{H}_\psi(U).$$

(9.3)

Applying (9.3) after replacing $U$ with $\gamma^{-1} U$, and $\gamma$ by $\gamma^{-1}$, we have

$$\mathcal{H}_\psi(U) = \mathcal{H}_\psi(\gamma(\gamma^{-1} U)) \leq s_{\gamma^{-1} \xi,R_{\gamma^{-1} U}}(\gamma^{-1}) \mathcal{H}_\psi(\gamma^{-1} U).$$

(9.4)

If we set $c = \sup_{\xi \in \Lambda_\theta} e^{\psi(\beta_x(\xi,\gamma),\gamma^{-1})}$, then for any $\eta \in B_\psi(\gamma^{-1} \xi, R_{\gamma^{-1} U})$, it follows from Lemma 5.2 that

$$d_\psi(\xi, \eta) \leq c d_\psi(\gamma^{-1} \xi, \eta) \leq c R_{\gamma^{-1} U}.$$

This implies

$$s_{\gamma^{-1} \xi,R_{\gamma^{-1} U}}(\gamma^{-1}) = \sup_{\eta \in B_\psi(\gamma^{-1} \xi,R_{\gamma^{-1} U})} e^{\psi(\beta_x(\xi,\gamma^{-1}))}$$

$$\leq \sup_{\eta \in B_\psi(\xi,R_{\gamma^{-1} U})} e^{\psi(\beta_x(\xi,\gamma^{-1}))} = \sup_{\eta \in B_\psi(\xi,R_{\gamma^{-1} U})} e^{\psi(\beta_x(\xi,\gamma))}.$$

Hence we obtain from (9.4) that

$$\mathcal{H}_\psi(U) \leq \sup_{\eta \in B_\psi(\xi,R_{\gamma^{-1} U})} e^{-\psi(\beta_x(\xi,\gamma))} \mathcal{H}_\psi(\gamma^{-1} U).$$

Together with (9.3), we deduce

$$\inf_{\eta \in B_\psi(\xi,R_{\gamma^{-1} U})} e^{\psi(\beta_x(\xi,\gamma))} \leq \frac{\gamma s_{\mathcal{H}_\psi(U)}}{\mathcal{H}_\psi(U)} \leq \sup_{\eta \in B_\psi(\xi,R_{\gamma^{-1} U})} e^{\psi(\beta_x(\xi,\gamma))}. $$
Now shrinking $U \to \xi$, we have $R_U, R_{\gamma^{-1}U} \to 0$ and hence the both sides in the above inequality converge to $e^{\psi(\beta_\xi(e,\gamma))}$, by the continuity of the Busemann map $\beta_\eta(e,\gamma)$ on the $\eta$-variable. Therefore
\[ \frac{d\gamma_* H_\psi}{dH_\psi}(\xi) = e^{\psi(\beta_\xi(e,\gamma))} \]
as desired. □

Proof of Theorem 9.1. By Propositions 9.5 and 9.6, we have $H_\psi(\Lambda_\theta) \in (0, \infty)$. Moreover, it follows from Lemma 9.7 that $\frac{1}{H_\psi(\Lambda_\theta)} H_\psi$ is a $(\Gamma, \psi)$-Patterson-Sullivan measure. Since there exists a unique $(\Gamma, \psi)$-Patterson-Sullivan measure on $\Lambda_\theta$ (Theorem 3.4), this completes the proof. □

Proof of Theorem 9.2. By Lemma 3.7, we may assume $\theta = i(\theta)$. Since $\psi \neq \psi \circ i$, two linear forms $\psi$ and $\tilde{\psi}$ are not proportional. Since $d_\psi$ and $d_{\tilde{\psi}}$ are bi-Lipschitz by Proposition 5.5, $H_{\tilde{\psi}}$ is in the same measure class as $H_\psi$ for all $s > 0$. Hence it follows from Theorem 9.1 (see also Remark 9.3) that $H_{\bar{\nu}_{\tilde{\psi}}}(\Lambda_\theta) = 0$ or $\infty$ if $s \neq \delta_{\bar{\nu}_{\tilde{\psi}}}$. Now it suffices to show that $\nu_\psi$ is not comparable to $H_{\bar{\nu}_{\tilde{\psi}}}$. Since $\psi$ and $\tilde{\psi}$ are not proportional, $\psi$ and $\delta_{\bar{\nu}_{\tilde{\psi}}}$ are two different forms tangent to $\psi_\theta$. By Theorem 3.4, it follows that $\nu_\psi$ is mutually singular to $\nu_{\delta_{\bar{\nu}_{\tilde{\psi}}}}$. Since the latter is proportional to $H_{\bar{\nu}_{\tilde{\psi}}}$ by Theorem 9.1, $\nu_\psi$ is singular to $H_{\bar{\nu}_{\tilde{\psi}}}$ and hence singular to $H_{\bar{\nu}_{\tilde{\psi}}}$ as well. This finishes the proof. □

Remark 9.8. In fact, without Zariski dense hypothesis, it was shown in [53, Theorem A] that for $\psi_1, \psi_2 \in \mathcal{F}_T$, $\nu_{\psi_1}$ and $\nu_{\psi_2}$ are mutually singular unless $\psi_1 = \psi_2$ on $L_\theta$. Hence Theorem 9.2 holds provided that $\psi$ and $\psi \circ i$ are not identical on $L_\theta$.

Critical exponents and Hausdorff dimensions. The Hausdorff dimension of $\Lambda_\theta$ with respect to $d_\psi$ is defined as
\[
\dim_\psi \Lambda_\theta := \inf\{s > 0 : H_\psi^s(\Lambda_\theta) = 0\} = \sup\{s > 0 : H_\psi^s(\Lambda_\theta) = \infty\}.
\]
As a corollary of Theorem 9.1, we obtain the following (Theorem 1.4):

Corollary 9.9. For any $\psi \in \mathfrak{a}_\theta^*$ positive on $L - \{0\}$, we have
\[
\delta_{\bar{\psi}} = \dim_\psi \Lambda_\theta
\]
where $\bar{\psi} = \frac{\psi \circ i}{2}$.

Proof. By Proposition 5.5, we have $\dim_\psi \Lambda_\theta = \dim_{\bar{\psi}} \Lambda_\theta$. Applying Theorem 9.1 to $\delta_{\bar{\psi}}$ (see Remark 9.3), we have $H_{\bar{\nu}_{\bar{\psi}}}(\Lambda_\theta) \in (0, \infty)$, which implies $\dim_{\bar{\psi}} \Lambda_\theta = \delta_{\bar{\psi}}$. This shows the claim. □

For $\psi$ non-symmetric, $\dim_\psi \Lambda_\theta$ is not in general equal to $\delta_{\bar{\psi}}$.
Proposition 9.10. For $\psi \in a_\theta^s$ positive on $L - \{0\}$, we have
$$\delta_\psi \leq \delta_\psi.$$ If $\Gamma$ is Zariski dense, then the equality holds if and only if $\psi = \psi \circ i$.

Proof. As before, we may assume $\theta = i(\theta)$. Suppose that $\psi \neq \psi \circ i$. Note that $\delta_\psi = \delta_\psi \circ i$ and hence both $\delta_\psi \psi$ and $\delta_\psi(\psi \circ i)$ are tangent to the $\theta$-growth indicator $\psi^\theta_T$ (31 Theorem 2.5], [33 Lemma 4.5]). We then have $\psi^\theta_T \leq \delta_\psi \psi$ and $\psi^\theta_T \leq \delta_\psi(\psi \circ i)$. Hence $\psi^\theta_T \leq \delta_\psi \psi$. Since $\delta_\psi \psi$ is tangent to $\psi^\theta_T$, it follows that $\delta_\psi \leq \delta_\psi$.

Now suppose that $\Gamma$ is Zariski dense and that $\psi \neq \psi \circ i$. By Theorem 3.3, there exists a unique unit vector $u = u_\psi \in \text{int} \, \mathcal{L}_\theta$ such that $\psi^\theta_T(u) = \delta_\psi \psi(u)$. Since $\psi^\theta_T$ is $i$-invariant, it implies that $\psi^\theta_T(i(u)) = \delta_\psi \psi(i(u))$. On the other hand, $u \neq i(u)$ by Theorem 3.3. Hence the inequality $\psi^\theta_T \leq \delta_\psi \psi$ and $\psi^\theta_T \leq \delta_\psi(\psi \circ i)$ cannot become equalities simultaneously at the same vector. This implies that $\psi^\theta_T < \delta_\psi \psi$ and hence $\delta_\psi < \delta_\psi$.

By Corollary 9.9 and Proposition 9.10, we obtain:

Corollary 9.11. Let $\Gamma$ be Zariski dense in $G$. For any $\psi \in \mathcal{F}$, we have $\dim \, \Lambda_\theta \leq 1$ and the equality holds if and only if $\psi$ is symmetric.

We now prove the Ahlfors regularity of $(\Lambda_\theta, d_\psi)$ for general $\psi \in \mathcal{F}$:

Theorem 9.12. Let $\Gamma$ be a $\theta$-Anosov subgroup. For any $\psi \in \mathcal{F}$, the premetric space $(\Lambda_\theta, d_\psi)$ is Ahlfors s-regular for some $0 < s \leq 1$. Moreover if $\Gamma$ is Zariski dense, we have $s = 1$ if and only if $\psi$ is symmetric.

Proof. Let $\psi \in \mathcal{F}$. By Proposition 5.5, the identity map $(\Lambda_\theta, d_\psi) \to (\Lambda_\theta, d_\psi)$ is bi-Lipschitz. Noting that $\delta_\psi \psi \in \mathcal{F}$ by Lemma 3.6, we denote by $\nu := \nu_\delta_\psi \psi$ the $(\Gamma, \delta_\psi \psi)$-Patterson-Sullivan measure on $\Lambda_\theta$. By Theorem 8.2 for any $\xi \in \Lambda_\theta$ and $r \in [0, \text{diam}_\psi \Lambda_\theta)$, we have

$$\nu(B_{\delta_\psi \psi}(\xi, r)) \asymp r.$$ Since $B_{\delta_\psi \psi}(\xi, r_{\delta_\psi}) = B_{\psi}(\xi, r)$ and the identity map $(\Lambda_\theta, d_\psi) \to (\Lambda_\theta, d_\psi)$ is bi-Lipschitz by Proposition 5.5, (9.5) implies

$$\nu(B_\psi(\xi, r)) \asymp r_{\delta_\psi}.$$ Recall $\delta_\psi = 1$ for $\psi \in \mathcal{F}$ (Lemma 3.6). Hence $\delta_\psi < 1$ for $\psi$ non-symmetric and $\Gamma$ Zariski dense by Proposition 9.10. This finishes the proof.

Analyticity of Hausdorff dimensions. For a hyperbolic group $\Sigma$, a representation $\sigma : \Sigma \to G$ is called $\theta$-Anosov if $\sigma$ has a finite kernel and its image $\sigma(\Sigma)$ is a $\theta$-Anosov subgroup of $G$. For a given $\psi \in a_\theta^s$ which is non-negative on $a_\theta^s$, the $\psi$-critical exponents $\delta_\psi(\sigma(\Sigma))$ vary analytically on analytic families of $\theta$-Anosov representations $\sigma$ in the variety $\text{Hom}(\Sigma, G)$ by Bridgeman-Canary-Labourie-Sambarino [10, Proposition 8.1] (see also [15]...
Section 4.4]). Hence the following is an immediate consequence of Corollary 9.9.

**Corollary 9.13.** Let $\Sigma$ be a non-elementary hyperbolic group and $\psi \in a_\theta^+$ be non-negative on $a_\theta^+$. Let $D \subset \text{Hom}(\Sigma, G)$ be an analytic family of $\theta$-Anosov representations. Then

$$\sigma \mapsto \dim_\psi \Lambda_\theta(\sigma(\Sigma))$$

is analytic on $D$.

**(p, q)-Hausdorff dimensions.** Let $\Sigma$ be a non-elementary convex cocompact subgroup of $\text{SO}^0(n, 1) = \text{Isom}^+(\mathbb{H}^n)$, $n \geq 2$. Let $\text{CC}(\Sigma)$ denote the space

$$\{ \sigma : \Sigma \to \text{SO}^0(n, 1) : \text{convex cocompact, faithful representation}\} / \sim$$

where the equivalence relation is given by conjugations. As in the introduction, for $\sigma \in \text{CC}(\Sigma)$, we denote by $\Lambda_\sigma \subset S^{n-1} \times S^{n-1}$ the limit set of the self-joining subgroup $\Sigma_\sigma := (\text{id} \times \sigma)(\Sigma) \subset \text{SO}^0(n, 1) \times \text{SO}^0(n, 1)$, which is well-defined up to translations. The Hausdorff dimension of $\Lambda_\sigma$ with respect to a Riemannian metric on $S^{n-1} \times S^{n-1}$ is equal to $\max (\dim \Lambda_\Sigma, \dim \Lambda_{\sigma(\Sigma)})$, where $\Lambda_\Sigma \subset S^{n-1}$ and $\Lambda_{\sigma(\Sigma)} \subset S^{n-1}$ are limit sets of $\Sigma$ and $\sigma(\Sigma)$ respectively and Hausdorff dimensions are computed with respect to a Riemannian metric on $S^{n-1}$ [30, Theorem 1.1].

For a pair $(p, q)$ of positive real numbers, let $d_{p,q}$ be the premetric on $S^{n-1} \times S^{n-1}$ defined as

$$d_{p,q}(\xi, \eta) = d_{S^{n-1}}(\xi_1, \eta_1)^p d_{S^{n-1}}(\xi_2, \eta_2)^q$$

where $\xi = (\xi_1, \xi_2), \eta = (\eta_1, \eta_2) \in S^{n-1} \times S^{n-1}$ and $d_{S^{n-1}}$ is a Riemannian metric on $S^{n-1}$. We also denote by $\dim_{p,q}$ the Hausdorff dimension with respect to $d_{p,q}$. Let $\delta_{p,q}(\sigma)$ denote the critical exponent of the series

$$s \mapsto \sum_{\gamma \in \Sigma} e^{-s(pd_{H^0}(o,\gamma)+qd_{H^0}(o,\sigma(\gamma) o))}.$$  

We deduce the following:

**Corollary 9.14.** Let $\Sigma$ be a non-elementary convex cocompact subgroup of $\text{SO}^0(n, 1)$, $n \geq 2$. Let $p, q$ be positive real numbers.

1. For any $\sigma \in \text{CC}(\Sigma)$, we have

$$\dim_{p,q} \Lambda_\sigma = \delta_{p,q}(\sigma).$$

2. For any $\sigma \in \text{CC}(\Sigma)$, we have

$$\dim_{p,q} \Lambda_\sigma \leq \left(\frac{p}{\dim \Lambda_\Sigma} + \frac{q}{\dim \Lambda_{\sigma(\Sigma)}}\right)^{-1}$$

and the equality holds if and only if $\rho = \text{id}$.

---

9 A hyperbolic group is non-elementary if its Gromov boundary has at least three points.
Moreover the map 
\[ \sigma \mapsto \dim_{p,q} \Lambda_\sigma \]
is an analytic function on any analytic subfamily of \( \text{CC}(\Sigma) \). In particular, for \( n = 2, 3 \), it is analytic on \( \text{CC}(\Sigma) \).

**Proof.** Identifying the Cartan subspace \( a \) of \( \text{SO}^\circ(n,1) \times \text{SO}^\circ(n,1) \) with \( \mathbb{R}^2 \) and \( a^+ \) with \( \mathbb{R}^2_{\geq 0} \), consider the linear form \( \Psi \in a^+ \) defined by \( \Psi(u_1, u_2) = pu_1 + qu_2 \). Since \( d_{\mathbb{H}^n}(\xi, \eta) = e^{-\mathcal{G}(\xi, \eta)} \) is a \( \text{SO}(n) \)-invariant metric and hence a Riemannian metric where \( \mathcal{G} \) is the Gromov product on \( \mathbb{S}^{n-1} \simeq \partial \mathbb{H}^n \), we have \( d_\Psi = d_{p,q} \), where \( d_\Psi \) is defined in \((5.1)\). Since the opposition involution \( i \) is trivial for \( \text{SO}^\circ(n,1) \times \text{SO}^\circ(n,1) \), the linear form \( \Psi \) is symmetric and hence the claims (1) and (3) respectively follow from Corollary \( 9.9 \) and Corollary \( 9.13 \) applied to any analytic subfamily of \( \{ (i \times \sigma) : \Sigma \to \text{SO}^\circ(n,1) \times \text{SO}^\circ(n,1) \} \). For \( n = 2, 3 \), \( \text{CC}(\Sigma) \) is known to be analytic (cf. \cite[11 Theorem 10.8]{27}). Hence the last claim of (3) follows. Claim (2) follows from (1) and the following Theorem \( 9.15 \). \( \square \)

The following theorem is due to Bishop-Steger \cite[Theorem 2]{6} for \( n = 2 \) and to Burger \cite[Theorem 1(a)]{13} in general. We denote by \( \delta_\Sigma \) the critical exponent of \( \Sigma \), the abscissa of convergence of the Poincaré series \( s \mapsto \sum_{\gamma \in \Sigma} e^{-s d_{\mathbb{H}^n}(o, \gamma o)} \).

**Theorem 9.15.** For each \( \sigma \in \text{CC}(\Sigma) \), we have 
\[ \delta_{p,q}(\sigma) \leq \left( \frac{p}{\delta_\Sigma} + \frac{q}{\delta_{\sigma(\Sigma)}} \right)^{-1} \]
and the equality holds if and only if \( \sigma = \text{id} \).

**Proof.** We explain how to deduce this from \cite[Theorem 1(a)]{13}. We again identify the Cartan subspace \( a \) of \( \text{SO}^\circ(n,1) \times \text{SO}^\circ(n,1) \) with \( \mathbb{R}^2 \). For each \( i = 1, 2 \), denote by \( \delta_\Sigma \) the \( \alpha_i \)-critical exponent of \( \Sigma_\sigma = (i \times \sigma)(\Sigma) \) where \( \alpha_i : a \to \mathbb{R}, (u_1, u_2) \mapsto u_i \). Then \( \delta_1 = \delta_\Sigma \) and \( \delta_2 = \delta_{\sigma(\Sigma)} \). If we set \( \alpha'_i := \delta_i \alpha_i \), then \( \delta_{\alpha'_i} = 1 \) for each \( i = 1, 2 \) and hence Burger’s theorem \cite[Theorem 1(a)]{13} implies that the critical exponent of any convex combination of \( \alpha'_1 \) and \( \alpha'_2 \) is at most one and is equal to one only when \( \sigma = \text{id} \).

Since 
\[ p\alpha_1 + q\alpha_2 = \left( \frac{p}{\delta_1} + \frac{q}{\delta_2} \right) \frac{p}{\delta_1} \alpha'_1 + \frac{q}{\delta_2} \alpha'_2 = \left( \frac{p}{\delta_1} + \frac{q}{\delta_2} \right) \Psi_0 \]
where \( \Psi_0 := \frac{p\alpha'_1 + q\alpha'_2}{\delta_1 + \delta_2} \) is a convex combination of \( \alpha'_1 \) and \( \alpha'_2 \), we get
\[ \delta_{p,q}(\sigma) = \delta_{p\alpha_1 + q\alpha_2} = \left( \frac{p}{\delta_1} + \frac{q}{\delta_2} \right)^{-1} \delta_{\Psi_0} \leq \left( \frac{p}{\delta_1} + \frac{q}{\delta_2} \right)^{-1} \]
and the equality holds if and only if \( \sigma = \text{id} \). \( \square \)
Remark 9.16. We remark that in Corollary 9.14, the hypothesis \( p, q > 0 \) was imposed to be able to consider all \( \sigma \in \text{CC}(\Sigma) \). If we replace \( \text{CC}(\Sigma) \) by a subset \( D \subset \text{CC}(\Sigma) \), then Corollary 9.14 holds for any \( p, q \in \mathbb{R} \) such that \( pu_1 + qu_2 > 0 \) for all non-zero \((u_1, u_2) \in \mathcal{L}(\Sigma_\sigma)\) and all \( \sigma \in D \).

10. Hausdorff dimensions with respect to Riemannian metrics

Let \( G \) be a connected semisimple real algebraic group. As before, let \( \theta \) be a non-empty subset of the set \( \Pi \) of simple roots of \((g, a)\). We denote by

\[
\dim \Lambda_\theta
\]

the Hausdorff dimension of \( \Lambda_\theta \) with respect to a Riemannian metric \( d_{\text{Riem}} \) on \( \mathcal{F}_\theta \). As any two Riemannian metrics are bi-Lipschitz, \( \dim \Lambda_\theta \) is well-defined independent of the choice of a Riemannian metric. In this section, we present an estimate on \( \dim \Lambda_\theta \).

**Tits representations and the sum of Tits weights.** Let \( G \) be the semisimple algebraic group defined over \( \mathbb{R} \) such that \( G = G(\mathbb{R})^\circ \). There exists an exact sequence \( \tilde{G} \rightarrow_\tilde{p} G \rightarrow_\tilde{p} \tilde{G} \) where \( \tilde{G} \) and \( G \) are respectively simply connected and adjoint semisimple \( \mathbb{R} \)-groups and \( \tilde{p} \) and \( \tilde{p} \) are central \( \mathbb{R} \)-isogenies ([8], [52, Proposition 1.4.11]).

Recall that for \( \alpha \in \Pi \), \( \omega_\alpha \) denotes the (restricted) fundamental weight associated to \( \alpha \) as defined in (2.1). The first part of the following theorem immediately follows as a special case of a theorem of Tits [58], and the second part is remarked in [3] and proved in [54].

**Theorem 10.1** ([58, Theorem 7.2], [54, Lemma 2.13]). For each \( \alpha \in \Pi \), there exists an irreducible \( \mathbb{R} \)-representation \( \tilde{\rho}_\alpha : \tilde{G} \rightarrow \text{GL}(V_\alpha) \) whose highest (restricted) weight \( \chi_\alpha \) is equal to \( k_\alpha \omega_\alpha \) for some positive integer \( k_\alpha \) and whose highest weight space is one-dimensional. Moreover, all weights of \( \tilde{\rho}_\alpha \) are \( \chi_\alpha \), \( \chi_\alpha - \alpha \) and weights of the form \( \chi_\alpha - \alpha - \sum_{\beta \in \Pi} n_\beta \beta \) with \( n_\beta \) non-negative integers.

For each \( \alpha \in \Pi \), we fix once and for all a representation \( \tilde{\rho}_\alpha : \tilde{G} \rightarrow \text{GL}(V_\alpha) \) as in Theorem 10.1 with minimal \( k_\alpha \). Since \( \tilde{p} \) and \( \tilde{p} \) are central isogenies and \( \tilde{p}(G(\mathbb{R})) = G \), the representation \( \tilde{\rho}_\alpha \) induces a projective representation

\[
(10.1) \quad \rho_\alpha : G \rightarrow \text{PGL}(V_\alpha)
\]

where \( V_\alpha = V_\alpha(\mathbb{R}) \). Since the restriction of \( \tilde{\rho}_\alpha \) to \( \tilde{G}(\mathbb{R}) \) and \( \rho_\alpha \) induce the same representation of the Lie algebra \( g \) to \( \mathfrak{gl}(V_\alpha) \), their restricted weights are the same. We call

\[
(10.2) \quad \rho_\alpha \text{ and } \chi_\alpha
\]

the Tits representation and the Tits weight associated to \( \alpha \) respectively.

Let \( \rho \) denote the half-sum of all positive roots for \((g, a)\) counted with multiplicity: \( 2\rho = \sum_{\alpha \in \Phi^+} (\dim \mathfrak{g}^a)\alpha \). In terms of the restricted fundamental
weights $\omega_\alpha$, we then have

$$\rho = \sum_{\alpha \in \Pi} c_\alpha \omega_\alpha$$

(10.3)

where $c_\alpha = \dim g^\alpha$ if $2\alpha$ is not a root, and $c_\alpha = \frac{1}{2}(\dim g^\alpha + 2 \dim g^{2\alpha})$ otherwise (cf. [9]). If $G$ is split over $\mathbb{R}$, we have $\chi_\alpha = \omega_\alpha$ for all $\alpha \in \Pi$ and hence $\sum_{\alpha \in \Pi} \chi_\alpha = \rho$. In general, we do not have this identity, which motivates the following definition:

**Definition 10.2.** Define $c_G$ to be the infimum number $c > 0$ such that

$$\sum_{\alpha \in \Pi} \chi_\alpha \leq c \cdot \rho.$$
(b) \(2\omega_i = \bar{\omega}_j + \bar{\omega}_k\) for some distinct \(j\) and \(k\);
(c) \(2\omega_i = 2\bar{\omega}_j\) for some \(j\).

We can rule out case (c), because then \(\omega_i = \bar{\omega}_j\) would be proximal which contradicts \(\kappa_i = 2\). In case (a), we get that \(c_{j,i} = 2\) and hence \(d_i\) is at least 2. In case (b), applying \(\pi\) on both sides, we necessarily have \(\pi(\bar{\omega}_j) = \pi(\bar{\omega}_k) = \omega_i\), so \(c_{j,i} = c_{k,i} = 1\) and hence \(d_i\) is also at least 2. \(\square\)

The bound on \(c_G\) can be improved in certain cases. For example, for \(g = \mathfrak{so}(n,1), n \geq 2\), we have \(\Pi = \{\alpha\}\), \(\rho = \frac{n-1}{2}\alpha\) and \(\chi_\alpha = \omega_\alpha = \frac{\alpha}{2}\); hence \(c_g = \frac{1}{n-1}\).

**Riemannian metric on** \(F_\theta\). For each \(\alpha \in \Pi\), we denote by \(V_\alpha^+\) the highest weight space of \(\rho_\alpha\) and by \(V_\alpha^-\) its unique complementary \(A\)-invariant subspace in \(V_\alpha\). Then the map \(g \in G \mapsto (\rho_\alpha(g)V_\alpha^+)_\alpha \in \theta\) factors through a proper immersion
\[
F_\theta \to \prod_{\alpha \in \theta} \mathbb{P}(V_\alpha).
\]

Let \(\langle \cdot, \cdot \rangle_\alpha\) be a \(K\)-invariant inner product on \(V_\alpha\) with respect to which \(V_\alpha^+\) is perpendicular to \(V_\alpha^-\). We denote by \(\| \cdot \|_\alpha\) the norm on \(V_\alpha\) induced by \(\langle \cdot, \cdot \rangle_\alpha\). We also use the notation \(\| \cdot \|_\alpha\) for a \(bi\)-\(\rho_\alpha(K)\)-invariant norm on \(GL(V_\alpha)\). The angle \(\angle(E, F)\) between a line \(E\) and a subspace \(F\) is defined as minimum of all angles between all non-zero \(v \in E\) and non-zero \(w \in F\).

We write \(gV_\alpha^+ := \rho_\alpha(g)V_\alpha^+\) and \(gV_\alpha^- := \rho_\alpha(g)V_\alpha^-\) for \(g \in G\) and \(\alpha \in \Pi\). Up to a Lipschitz equivalence, the Riemannian distance \(d_{\text{Riem}}\) on \(F_\theta = G/P_\theta\) satisfies that for all \(g_1, g_2 \in G\),
\[
d_{\text{Riem}}(g_1P_\theta, g_2P_\theta) = \sqrt{\sum_{\alpha \in \theta} \sin^2 \angle(g_1V_\alpha^+, g_2V_\alpha^+)}. \tag{10.4}
\]

The Gromov product \(\mathcal{G}\) on \(F^{(2)}\) can be expressed in terms of angles between appropriate subspaces as follows:

**Lemma 10.4** ([49 Lemma 6.4], [37 Lemma 3.11]). For \((\xi, \eta) \in F^{(2)}\), we have that for any \(\alpha \in \Pi\),
\[
2\chi_\alpha(\mathcal{G}(\xi, \eta)) = -\log \sin \angle(gV_\alpha^+, gV_\alpha^-)
\]
where \(g \in G\) is such that \(\xi = gP\) and \(\eta = gw_0P\).

We then have the following estimates on the Riemannian distance using Gromov products and Tits weights:

**Lemma 10.5.** There exists a constant \(C > 0\) such that for all \(g \in G\),
\[
d_{\text{Riem}}(gP_\theta, gw_0P_\theta) \geq C \left(\sum_{\alpha \in \theta} e^{-4\chi_\alpha(\mathcal{G}(gP,gw_0P))}\right)^{1/2}.
\]
Proof. We first note that for each \( \alpha \in \Pi \), \( w_0 V_\alpha^+ \subset V_<^\alpha \); to see this, recall that \( V_<^\alpha \) is the sum of all weight subspaces of \( V_\alpha \) whose weight is not equal to \( \chi_\alpha \). On the other hand, \( w_0 V_\alpha^+ \) is a weight space with the weight given by \( \chi_\alpha \circ \text{Ad}_{w_0} = -\chi_\alpha \circ i \). Since \( -\chi_\alpha \circ i(a^+) \leq 0 \) while \( \chi_\alpha(a^+) \geq 0 \), we have \( \chi \circ \text{Ad}_{w_0} \neq \chi_\alpha \), which shows \( w_0 V_\alpha^+ \subset V_<^\alpha \).

Therefore for all \( g \in G \),

\[
\sin^2 \angle(gV_\alpha^+, gV_<^\alpha) \leq \sin^2 \angle(gV_\alpha^+, gw_0 V_\alpha^+)
\]

Hence, up to a Lipschitz constant, we have that for all \( g \in G \),

\[
d_{\text{Riem}}(gP_\theta, gw_0 P_\theta) = \sqrt{\sum_{\alpha \in \theta} \sin^2 \angle(gV_\alpha^+, gw_0 V_\alpha^+)}
\]

\[
\geq \sqrt{\sum_{\alpha \in \theta} \sin^2 \angle(gV_\alpha^+, gV_<^\alpha)}
\]

\[
= \left( \sum_{\alpha \in \theta} e^{-4\chi_\alpha(G(gP_\theta, gw_0 P_\theta))} \right)^{1/2}
\]

where the last equality follows from Lemma 10.4.

\[\square\]

Lower bounds. In the rest of this section, we assume that \( \Gamma \) is a \( \theta \)-Anosov subgroup of \( G \).

Since the Tits weights \( \{ \chi_\alpha : \alpha \in \theta \} \) form a basis of \( a_\theta^* \), each linear form \( \psi \in a_\theta^* \) can be uniquely written as \( \psi = \sum_{\alpha \in \theta} \kappa_{\psi,\alpha} \chi_\alpha \) with \( \kappa_{\psi,\alpha} \in \mathbb{R} \). We consider the following height of \( \psi \):

\[
\kappa_\psi := \sum_{\alpha \in \theta} \kappa_{\psi,\alpha} \in \mathbb{R}
\]

Denote by \( E_\theta \) the collection of all linear forms which are non-negative linear combinations of \( \{ \chi_\alpha : \alpha \in \theta \} \). That is,

\[
E_\theta := \{ \psi \in a_\theta^* : \kappa_{\psi,\alpha} \geq 0 \text{ for all } \alpha \in \theta \}.
\]

Since \( \chi_\alpha > 0 \) on \( \text{int} a_\theta^+ \) for all \( \alpha \in \theta \), each non-zero \( \psi \in E_\theta \) is positive on \( \text{int} a_\theta^+ \). Since \( L_\theta - \{ 0 \} \subset \text{int} a_\theta^+ \) by Theorem 3.8(2), each non-zero \( \psi \in E_\theta \) is positive on \( L_\theta - \{ 0 \} \) and hence we have the corresponding conformal premetric \( d_\psi \) on \( \Lambda_\theta \) discussed in section 5.

Lemma 10.6. For any non-zero \( \psi \in E_\theta \), the identity map

\[
(\Lambda_\theta, d_{\text{Riem}}) \to (\Lambda_\theta, d_\psi^{2/\kappa_\psi})
\]

is a Lipschitz map.

Proof. For each \( \xi \neq \eta \in \Lambda_\theta \), there exists \( g \in G \) such that \( \xi = gP_\theta \) and \( \eta = gw_0 P_\theta \) (Theorem 3.8(4)). By Lemma 10.5, we have that for each \( \alpha \in \theta \),
up to a Lipschitz constant, 

\[
(10.6) \quad d_{\text{Riem}}(\xi, \eta) \geq \left( \sum_{\alpha \in \theta} e^{-4 \chi_\alpha(G(gP,gw_0P))} \right)^{1/2} \geq e^{-2 \chi_\alpha(G(gP,gw_0P))}.
\]

Recalling

\[
d_{2\chi_\alpha}(\xi, \eta) = e^{-2 \chi_\alpha(G(gP,gw_0P))}
\]

and writing \( \psi = \sum_{\alpha \in \theta} \kappa_{\psi, \alpha} \chi_\alpha \in E_\theta \), since all \( \kappa_{\psi, \alpha} \) are non-negative, (10.6) implies

\[
d_{\psi}(\xi, \eta) = \prod_{\alpha \in \theta} d_{2\chi_\alpha}(\xi, \eta)^{\kappa_{\psi, \alpha}} \leq \prod_{\alpha \in \theta} d_{\text{Riem}}(\xi, \eta)^{\kappa_{\psi, \alpha}} = d_{\text{Riem}}(\xi, \eta)^{\kappa_{\psi}}
\]

up to a Lipschitz constant. Hence the claim follows.

\[\square\]

Remark 10.7. Since \( d_{\psi} \) and \( d_{\bar{\psi}} \) are bi-Lipschitz (Proposition 5.5), Proposition 6.8 and the above lemma imply that there exist \( c, R > 0 \) such that for any \( \xi \in \Lambda_\theta \) and \( g \in [e, \xi] \) in \( \Gamma \), the shadow \( O^\theta_R(o, go) \cap \Lambda_\theta \) contains the Riemannian ball of center \( \xi \) and of radius \( ce^{-\frac{a}{2}d_{\psi}(o,go)} \).

**Theorem 10.8.** For any non-zero \( \psi \in E_\theta \), we have

\[
\dim \Lambda_\theta \geq \frac{\kappa_{\psi}}{2} \cdot \dim_{\psi} \Lambda_\theta = \frac{\kappa_{\psi}}{2} \cdot \delta_{\bar{\psi}}.
\]

**Proof.** It follows from Lemma 10.6 and a standard property of Hausdorff dimension that we get

\[
\dim \Lambda_\theta \geq \frac{\kappa_{\psi}}{2} \cdot \dim_{\psi} \Lambda_\theta.
\]

Since \( \dim_{\psi} \Lambda_\theta = \delta_{\bar{\psi}} \) by Corollary 9.9, the claim follows. \[\square\]

Applying Theorem 10.8 to each \( \chi_\alpha, \alpha \in \theta \), we obtain the following uniform lower bound on the Hausdorff dimension of all non-elementary \( \theta \)-Anosov subgroups:

**Corollary 10.9.** We have

\[
\dim \Lambda_\theta \geq \max_{\alpha \in \theta} \delta_{\chi_\alpha + \chi_i(\alpha)}.
\]

**Example 10.10.** For \( G = \text{PSL}_n(\mathbb{R}) \), we have \( \Pi = \{\alpha_1, \ldots, \alpha_{n-1}\} \) where

\[
\alpha_i : \text{diag}(a_1, \ldots, a_n) \mapsto a_i - a_{i+1}.
\]

Let \( 1 \leq p \leq n - 1 \). Since \( \chi_{\alpha_p} \) is equal to the fundamental weight \( \omega_p \) which is given by \( \omega_p(\text{diag}(a_1, \ldots, a_n)) = a_1 + \cdots + a_p \), we deduce from Corollary 10.9 that for all non-elementary \( \alpha_p \)-Anosov subgroups of \( \text{PSL}_n(\mathbb{R}) \), we have

\[
\dim \Lambda_{\alpha_p} \geq \delta_{\omega_p + \omega_{n-p}}.
\]

When \( p = 1 \), this lower bound is obtained in [18, Theorem 10.1].

The following upper bound in Proposition 10.11 was obtained in ([47, Theorem B], [14, Theorem 1.2]) for \( G = \text{PSL}_n(\mathbb{R}) \) and \( \theta \) is a singleton.
Proposition 10.11. We have
\[ \dim \Lambda_\theta \leq \max_{\alpha \in \theta} \delta_\alpha. \]

Proof. Via the proper immersion of \( F_\theta \) into \( \prod_{\alpha \in \theta} \mathbb{P}(V_\alpha) \) as discussed in (10.4), we may consider the following metric on \( F_\theta \): for \( g_1, g_2 \in G \),
\[ d_{F_\theta}(g_1 P_\theta, g_2 P_\theta) = \max_{\alpha \in \theta} d_{\mathbb{P}(V_\alpha)}(g_1 V_\alpha^+, g_2 V_\alpha^+) \]
where \( d_{\mathbb{P}(V_\alpha)} \) is the metric on \( \mathbb{P}(V_\alpha) \) given by \( d_{\mathbb{P}(V_\alpha)}(v_1, v_2) = \sin \angle(v_1, v_2) \). Then \( d_{F_\theta} \) is Lipschitz equivalent to the Riemannian metric on \( F_\theta \) and hence we can use \( d_{F_\theta} \) to compute \( \dim \Lambda_\theta \).

Fix \( \alpha \in \theta \) and consider the Tits representation \((\rho_\alpha, V_\alpha)\). We write \( V_\alpha = \mathbb{R}^{n_\alpha} \) and \( \text{PGL}(V_\alpha) = \text{PGL}_{n_\alpha}(\mathbb{R}) \) by fixing a basis. We denote by \( \beta_{1,\alpha} \) the simple root of \( \text{PGL}_{n_\alpha}(\mathbb{R}) \) given by \( \beta_{1,\alpha}(\text{diag}(u_1, \ldots, u_{n_\alpha})) = u_1 - u_2 \). Since the highest weight of \( \rho_\alpha \) is \( \chi_\alpha \) and the second highest weight is \( \chi_\alpha - \alpha \) by Theorem 10.1, we have that for all \( \gamma \in \Gamma \),
\[ \beta_{1,\alpha}(\mu(\rho_\alpha(\gamma))) = \alpha(\mu(\gamma)). \]
Since \( \Gamma \) is an \( \{\alpha\}\)-Anosov subgroup of \( G \), there exists \( C > 1 \) such that for all \( \gamma \in \Gamma \), \( \alpha(\mu(\gamma)) \geq C^{-1}|\gamma| - C \), and hence \( \beta_{1,\alpha}(\mu(\rho_\alpha(\gamma))) \geq C^{-1}|\gamma| - C \). Therefore \( \rho_\alpha(\Gamma) \) is a \( \{\beta_{1,\rho}\}\)-Anosov subgroup of \( \text{PGL}_{n_\alpha}(\mathbb{R}) \).

We denote by \( f_\alpha : \partial \Gamma \to \mathbb{P}(V_\alpha) \) the \( \rho_\alpha(\Gamma) \)-equivariant embedding obtained as the extension of the orbit map of \( \rho_\alpha(\Gamma) \) (Theorem 3.8). It is shown in [17] Proposition 3.5, Proposition 3.8 that there exists a constant \( C_\alpha > 0 \) such that for each \( \gamma \in \Gamma \), there exists a ball \( B_\alpha(\gamma) \) of radius \( C_\alpha e^{-\beta_{1,\alpha}(\mu(\rho_\alpha(\gamma)))} \) in \( \mathbb{P}(V_\alpha) \) so that for any \( x \in \partial \Gamma \) such that \( \gamma \in [e, x] \) in \( \Gamma \), we have \( f_\alpha(x) \in B_\alpha(\gamma) \). In particular, for every \( k \geq 1 \), the collection
\[ \{B_\alpha(\gamma) : \gamma \in \Gamma, |\gamma| = k\} \]
covers the limit set of \( \rho_\alpha(\Gamma) \) in \( \mathbb{P}(V_\alpha) \). Hence \( \Lambda_\theta \) is covered by the collection
\[ \left\{ \prod_{\alpha \in \theta} B_\alpha(\gamma) : \gamma \in \Gamma, |\gamma| = k \right\} \]
via the immersion \( F_\theta \to \prod_{\alpha \in \theta} \mathbb{P}(V_\alpha) \). Since \( \prod_{\alpha \in \theta} B_\alpha(\gamma) \) has \( d_{F_\theta} \)-diameter at most
\[ \max_{\alpha \in \theta} C_\alpha e^{-\beta_{1,\alpha}(\mu(\rho_\alpha(\gamma)))} \leq C e^{-\min_{\alpha \in \theta} \alpha(\mu(\gamma))} \]
where \( C = \max_{\alpha \in \theta} C_\alpha \) by (10.7), we have that for each \( s > 0 \), the \( s \)-dimensional Hausdorff measure \( \mathcal{H}^s(\Lambda_\theta) \) with respect to \( d_{F_\theta} \) satisfies
\[ \mathcal{H}^s(\Lambda_\theta) \leq \limsup_{k \to \infty} C^s \sum_{\gamma \in \Gamma, |\gamma| = k} e^{-s \min_{\alpha \in \theta} \alpha(\mu(\gamma))}. \]
Therefore, denoting by \( \delta_{\min_{\alpha \in \theta} \alpha} \) the abscissa of convergence of the series \( s \mapsto \sum_{\gamma \in \Gamma} e^{-s \min_{\alpha \in \theta} \alpha(\mu(\gamma))} \), if \( s > \delta_{\min_{\alpha \in \theta} \alpha} \), we have \( \mathcal{H}^s(\Lambda_\theta) = 0 \) and hence
\[ \dim \Lambda_\theta \leq \delta_{\min_{\alpha \in \theta} \alpha}. \]
On the other hand, we have
\[ \frac{1}{\#\theta} \sum_{\alpha \in \theta} \sum_{\gamma \in \Gamma} e^{-s \alpha(\mu(\gamma))} \leq \sum_{\gamma \in \Gamma} e^{-s \min_{\alpha \in \theta} \alpha(\mu(\gamma))} \leq \sum_{\alpha \in \theta} \sum_{\gamma \in \Gamma} e^{-s \alpha(\mu(\gamma))}. \]

The first inequality implies \( \max_{\alpha \in \theta} \delta_\alpha \leq \delta_{\min_{\alpha \in \theta} \alpha} \) and the second gives \( \delta_{\min_{\alpha \in \theta} \alpha} \leq \max_{\alpha \in \theta} \delta_\alpha \). Hence \( \delta_{\min_{\alpha \in \theta} \alpha} = \max_{\alpha \in \theta} \delta_\alpha \), which completes the proof. □

Theorem 1.7 is a combination of Corollary 10.9 and Proposition 10.11.

11. GROWTH INDICATOR BOUNDS AND APPLICATIONS TO THE \( L^2 \)-SPECTRUM

As before, let \( \Gamma < G \) be a \( \theta \)-Anosov subgroup where \( G \) is a connected semisimple real algebraic group. In this final section, we deduce bounds on the growth indicator \( \psi^\theta_{\Gamma} : a_\theta \to [0, \infty) \cup \{-\infty\} \) of \( \Gamma \) (see Definition 3.1) from Corollary 10.9. Recall Tits weights \( \chi_\alpha, \alpha \in \Pi, \) of \( G \) from (10.2). We have the following (Corollary 1.8):

**Corollary 11.1.** We have

\[ \psi^\theta_{\Gamma} \leq \dim \Lambda_\theta \cdot \min_{\alpha \in \theta} (\chi_\alpha + \chi_{i(\alpha)}). \]

Moreover,

\[ \psi_{\Gamma} \leq \dim \Lambda_\theta \cdot \min_{\alpha \in \theta} (\chi_\alpha + \chi_{i(\alpha)}). \]

**Proof.** For any linear form \( \psi \in a^*_\theta \cup i(\theta) \) positive on \( \mathcal{L}^\theta_{\theta,i(\theta)} - \{0\} \), the scaled linear form \( \delta_\psi \psi \) is tangent to the growth indicator (Lemma 3.6). Hence it follows from Corollary 10.9 that for each \( \alpha \in \theta \), we have

\[ \psi^\theta_{\Gamma} \leq \delta_{\chi_\alpha + \chi_{i(\alpha)}} \cdot (\chi_\alpha + \chi_{i(\alpha)}) \leq \dim \Lambda_\theta \cdot (\chi_\alpha + \chi_{i(\alpha)}) \text{ on } a_{\theta,i(\theta)}. \]

Therefore taking minimum among \( \alpha \in \theta \) finishes the proof of (11.1).

By [33] Lemma 3.12, we have

\[ \psi_{\Gamma} \leq \psi^\theta_{\Gamma} \circ p_{\theta,i(\theta)} \text{ on } a. \]

Hence by (11.1), we have

\[ \psi_{\Gamma} \leq \dim \Lambda_\theta \cdot \min_{\alpha \in \theta} (\chi_\alpha + \chi_{i(\alpha)}) \circ p_{\theta,i(\theta)}. \]

Since the linear form \( \chi_\alpha + \chi_{i(\alpha)} \in a^*_{\theta,i(\theta)} \) is \( p_{\theta,i(\theta)} \)-invariant for each \( \alpha \in \theta \), (11.2) follows. □

Using the constant \( c_G \) in Definition 10.2, we have

\[ \min_{\alpha \in \theta} (\chi_\alpha + \chi_{i(\alpha)}) \leq \frac{1}{\#\theta} \sum_{\alpha \in \theta} (\chi_\alpha + \chi_{i(\alpha)}) \leq \frac{2}{\#\theta} \sum_{\alpha \in \Pi} \chi_\alpha \leq \frac{2c_G}{\#\theta} \cdot \rho \text{ on } a^+. \]
Moreover, if \( \theta \cap i(\theta) = \emptyset \), we can sharpen the inequality to
\[
\min_{\alpha \in \theta}(\chi_{\alpha} + \chi_{i(\alpha)}) \leq \frac{1}{\#\theta} \sum_{\alpha \in \theta} \chi_{\alpha} + \chi_{i(\alpha)} \leq \frac{1}{\#\theta} \sum_{\alpha \in \Pi} \chi_{\alpha} \leq \frac{c_G}{\#\theta} \cdot \rho \quad \text{on } a^+.
\]
Hence Corollary 11.1 implies the following:

**Corollary 11.2.** For any \( \theta \)-Anosov subgroup of \( G \), we have
\[
(11.3) \quad \psi_T \leq \frac{2c_G \dim \Lambda_\theta}{\#\theta} \cdot \rho.
\]
Moreover, if \( \theta \cap i(\theta) = \emptyset \), we have
\[
\psi_T \leq \frac{c_G \dim \Lambda_\theta}{\#\theta} \rho.
\]

Define the real number \( \lambda_0(\Gamma \setminus X) \in [0, \infty) \) as follows:
\[
(11.4) \quad \lambda_0(\Gamma \setminus X) := \inf \left\{ \frac{\int_{\Gamma \setminus X} \| \text{grad} f \|^2 d\text{Vol}}{\int_{\Gamma \setminus X} |f|^2 d\text{Vol}} : f \in C^\infty_c(\Gamma \setminus X), f \neq 0 \right\}.
\]
This number is equal to the bottom of the \( L^2 \)-spectrum of \( \Gamma \setminus X \) of the Laplace-Beltrami operator \([56, \text{Theorem } 2.2]\). The following was proved in \([21, \text{Theorem } 1.6]\) for \( \Pi \)-Anosov subgroups and in \([39, \text{Corollary } 3]\) in general:

**Theorem 11.3.** If \( \Gamma < G \) is a torsion-free discrete subgroup of \( G \) with \( \psi_T \leq \rho \), then \( L^2(\Gamma \setminus G) \) is tempered and \( \lambda_0(\Gamma \setminus X) = \| \rho \|^2 \).

Applying Theorem 11.3, we obtain from (11.3) the following criterion on the temperedness of \( L^2(\Gamma \setminus G) \) in terms of the size of the limit set (Corollary 1.9):

**Corollary 11.4.** Let \( \Gamma \) be a torsion-free \( \theta \)-Anosov subgroup. Suppose that

- \( \dim \Lambda_\theta \leq \frac{\#\theta}{c_G} \) if \( \theta \cap i(\theta) = \emptyset \);
- \( \dim \Lambda_\theta \leq \frac{\#\theta}{2c_G} \) otherwise.

Then \( L^2(\Gamma \setminus G) \) is tempered and \( \lambda_0(\Gamma \setminus X) = \| \rho \|^2 \).

Moreover \( \lambda_0 \) is not an \( L^2 \)-eigenvalue \(([21, 20], \text{see also } [59, \text{Corollary } 5.2]) \) for the absence of any principal joint \( L^2 \)-eigenvalues as well).

**Remark 11.5.** Indeed, it is shown in \([39, \text{Theorem } 11]\) that if \( \psi_T \leq (2 - \frac{2}{p}) \rho \) for some \( p \geq 1 \), then \( L^2(\Gamma \setminus G) \) is strongly \( L^{p+\varepsilon} \)-integrable for all \( \varepsilon > 0 \), that is, for a dense subset of vectors, the associated matrix coefficients belong to \( L^{p+\varepsilon}(G) \). Hence if \( \dim \Lambda_\theta \leq (2 - \frac{2}{p}) \frac{\#\theta}{c_G} \) when \( \theta \cap i(\theta) = \emptyset \) or \( \dim \Lambda_\theta \leq (1 - \frac{1}{p}) \frac{\#\theta}{c_G} \) in general, we obtain that \( L^2(\Gamma \setminus G) \) is strongly \( L^{p+\varepsilon} \)-integrable for all \( \varepsilon > 0 \).
Remark 11.6. Using that $c_G = \frac{1}{n-1}$ for $G = \text{SO}(n,1)$, Corollary 11.4 says that for a Zariski dense convex cocompact $\Gamma < \text{SO}(n,1)$, if $\dim \Lambda \leq \frac{n-1}{2}$, then $L^2(\Gamma \setminus \text{SO}(n,1))$ is tempered and $\lambda_0(\Gamma \setminus \mathbb{H}^n) = \frac{(n-1)^2}{4}$, as shown by Sullivan [56, Theorem 2.21].

REFERENCES


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