DYNAMICS FOR DISCRETE SUBGROUPS OF $\text{SL}_2(\mathbb{C})$

HEE OH

Dedicated to Gregory Margulis

Abstract. Margulis wrote in the preface of his book *Discrete subgroups of semisimple Lie groups* [29]: “A number of important topics have been omitted. The most significant of these is the theory of Kleinian groups and Thurston’s theory of 3-dimensional manifolds: these two theories can be united under the common title *Theory of discrete subgroups of $\text{SL}_2(\mathbb{C})$*”.

In this article, we will discuss a few recent advances regarding this missing topic from his book, which were influenced by his earlier works.

Contents

1. Introduction 1
2. Kleinian groups 2
3. Mixing and classification of $N$-orbit closures 10
4. Almost all results on orbit closures 13
5. Unipotent blowup and renormalizations 18
6. Interior frames and boundary frames 25
7. Rigid acylindrical groups and circular slices of $\Lambda$ 27
8. Geometrically finite acylindrical hyperbolic 3-manifolds 32
9. Unipotent flows in higher dimensional hyperbolic manifolds 35

References 43

1. Introduction

A discrete subgroup of $\text{PSL}_2(\mathbb{C})$ is called a Kleinian group. In this article, we discuss dynamics of unipotent flows on the homogeneous space $\Gamma \backslash \text{PSL}_2(\mathbb{C})$ for a Kleinian group $\Gamma$ which is not necessarily a lattice of $\text{PSL}_2(\mathbb{C})$. Unlike the lattice case, the geometry and topology of the associated hyperbolic 3-manifold $M = \Gamma \backslash \mathbb{H}^3$ influence both topological and measure theoretic rigidity properties of unipotent flows.

Around 1984-6, Margulis settled the Oppenheim conjecture by proving that every bounded $\text{SO}(2,1)$-orbit in the space $\text{SL}_3(\mathbb{Z}) \backslash \text{SL}_3(\mathbb{R})$ is compact ([27], [26]). His proof was topological, using minimal sets and the polynomial divergence property of unipotent flows. With Dani ([11], [12]), he also gave a classification of orbit closures for a certain family of one-parameter unipotent subgroups of $\text{SL}_3(\mathbb{R})$. Based on Margulis’ topological approach, Shah [47] obtained a classification of orbit closures

Supported in part by NSF Grant #1361673.
for the action of any connected closed subgroup generated by unipotent elements in the space $\Gamma \backslash PSL_2(\mathbb{C})$ when $\Gamma$ is a lattice. This result in a much greater generality, as conjectured by Raghunathan, was proved by Ratner using her measure rigidity theorem ([42], [43]).

The relation between invariant measures and orbit closures for unipotent flows is not as tight in the infinite volume case as it is in the finite volume case. Meanwhile, the topological approach in the orbit closure classification can be extended to the class of rigid acylindrical hyperbolic 3-manifolds, yielding the complete classification of orbit closures for the action of any connected closed subgroup generated by unipotent elements. This was done jointly with McMullen and Mohammadi ([35], [36]). Much of this article is devoted to explaining these results, although we present slightly different viewpoints in certain parts of the proof. Remarkably, this approach can handle the entire quasi-isometry class of rigid acylindrical hyperbolic 3-manifolds, as far as the action of the subgroup $PSL_2(\mathbb{R})$ is concerned [37]. An immediate geometric consequence is that for any convex cocompact acylindrical hyperbolic 3-manifold $M$, any geodesic plane is either closed or dense inside the interior of the convex core of $M$; thereby producing the first continuous family of locally symmetric manifolds for which such a strong rigidity theorem for geodesic planes holds. This result extends to geometrically finite acylindrical hyperbolic 3-manifolds as shown in joint work with Benoist [4]. We also present a continuous family of quasifuchsian 3-manifolds containing geodesic planes with wild closures [37], which indicates the influence of the topology of the associated 3-manifold in the rigidity problem at hand.

We call a higher dimensional analogue of a rigid acylindrical hyperbolic 3-manifold a convex cocompact hyperbolic $d$-manifold with Fuchsian ends, following Kerckhoff and Storm [21]. For these manifolds $\Gamma \backslash \mathbb{H}^d$, in joint work with Lee [22], we have established a complete classification of orbit closures in $\Gamma \backslash SO^\circ(d,1)$ for the action of any connected closed subgroup of $SO^\circ(d,1)$ generated by unipotent elements. The possibility of accumulation on closed orbits of intermediate subgroups presents new challenges, and the avoidance theorem and the induction arguments involving equidistribution statement are major new ingredients in higher dimensional cases (Theorems 9.10 and 9.11). We note that these manifolds do not admit any non-trivial local deformations for $d \geq 4$ [21].

Acknowledgement This survey article is mostly based on the papers [35], [37], [36], [4], and [22]. I am grateful to my co-authors Curt McMullen, Amir Mohammadi, Yves Benoist and Minju Lee. I would like to thank Yair Minsky and Amir Mohammadi for helpful comments on the preliminary version of this article.

2. Kleinian groups

We give a brief introduction to Kleinian groups, including some basic notions and examples. General references for this section include [42], [25], [23], [32], [46], [17] and [8]. In particular, all theorems stated in this section with no references attached can be found in [25] and [32].

We will use the upper half-space model for hyperbolic 3-space:

$$\mathbb{H}^3 = \{(x_1, x_2, y) : y > 0\}, \quad ds = \frac{\sqrt{dx_1^2 + dx_2^2 + dy^2}}{y}.$$
In this model of $\mathbb{H}^3$, a geodesic is either a vertical line or a vertical semi-circle. The geometric boundary of $\mathbb{H}^3$ is given by the Riemann sphere $S^2 = \hat{C}$, when we identify the plane $(x_1, x_2, 0)$ with the complex plane $\mathbb{C}$.

The group $G := SL_2(\mathbb{C})$ acts on $\hat{C}$ by Möbius transformations:

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} z = \frac{az + b}{cz + d} \text{ with } a, b, c, d \in \mathbb{C} \text{ such that } ad - bc = 1.$$  

This action of $G$ extends to an isometric action on $\mathbb{H}^3$ as follows: each $g \in G$ can be expressed as a composition $\text{Inv}_{C_1} \circ \cdots \circ \text{Inv}_{C_k}$, where $\text{Inv}_C$ denotes the inversion with respect to a circle $C \subset \hat{C}$.\footnote{If $C = \{z : |z - z_0| = r\}$, then $\text{Inv}_C(z)$ is the unique point on the ray $\{tz : t \geq 0\}$, satisfying the equation $|z - z_0| \cdot |\text{Inv}_C(z) - z_0| = r^2$ for all $z \neq z_0$, and $\text{Inv}_C(z_0) = \infty$.} If we set $\Phi(g) = \text{Inv}_{C_1} \circ \cdots \circ \text{Inv}_{C_k}$ where $\text{Inv}_{\hat{C}}$ denotes the inversion with respect to the sphere $\hat{C}$ in $\mathbb{R}^3$ which is orthogonal to $C$ and $\hat{C} \cap C = C$, then $\Phi(g)$ preserves $(\mathbb{H}^3, ds)$. Moreover, the Poincaré extension theorem says that $\Phi$ is an isomorphism between the two real Lie groups:

$$PSL_2(\mathbb{C}) = \text{Isom}^+ (\mathbb{H}^3),$$

where $PSL_2(\mathbb{C})$ is regarded as a 6-dimensional real Lie group and $\text{Isom}^+ (\mathbb{H}^3)$ denotes the group of all orientation preserving isometries of $\mathbb{H}^3$.

**Definition 2.1.** A discrete subgroup $\Gamma$ of $G$ is called a Kleinian group.

For a (resp. torsion-free) Kleinian group $\Gamma$, the quotient $\Gamma \backslash \mathbb{H}^3$ is a hyperbolic orbifold (resp. manifold). Conversely, any complete hyperbolic 3-manifold $M$ can be presented as a quotient

$$M = \Gamma \backslash \mathbb{H}^3$$

for a torsion-free Kleinian group $\Gamma$. The study of hyperbolic manifolds is therefore directly related to the study of Kleinian groups.

Throughout the remainder of the article, we assume that a Kleinian group $\Gamma$ is non-elementary i.e., $\Gamma$ does not contain an abelian subgroup of finite index. By Selberg’s lemma, every Kleinian group has a torsion-free subgroup of finite index. We will henceforth treat the torsion-free condition loosely.

### 2.1. Lattices.

The most well-studied Kleinian groups are lattices of $G$: a Kleinian group $\Gamma < G$ is a lattice if $M = \Gamma \backslash \mathbb{H}^3$ has finite volume. When $M$ is compact, $\Gamma$ is called a a uniform or cocompact lattice. If $d > 0$ is a square-free integer, then $PSL_2(\mathbb{Z}[\sqrt{-d}])$ is a non-uniform lattice of $G$. More lattices, including uniform ones, can be constructed by number theoretic methods using the Lie group isomorphism $G \simeq \text{SO}^+(3,1)$.

Let $Q(x_1, x_2, x_3, x_4)$ be a quadratic form with coefficients over a totally real number field $k$ of degree $n$ such that $Q$ has signature $(3,1)$ and for any non-trivial embedding $\sigma : k \to \mathbb{R}$, $Q^\sigma$ has signature $(4,0)$ or $(0,4)$; the orthogonal group $\text{SO}(Q^\sigma)$ is thus compact.

Then for $G = \text{SO}^+(Q)$ and for the ring $\mathfrak{o}$ of integers of $k$, the subgroup

$$\Gamma := G \cap \text{SL}_4(\mathfrak{o})$$

is a lattice in $G$ by a theorem of Borel and Harish-Chandra [6]. Moreover, if $Q$ does not represent 0 over $k$ (which is always the case if the degree of $k$ is bigger than 1), then $\Gamma$ is a uniform lattice in $G$ by the Godement’s criterion. These examples
contain all arithmetic lattices (up to a commensurability) which contain cocompact Fuchsian subgroups, that is, uniform lattices of \( \text{SO}^\circ(2,1) \cong \text{PSL}_2(\mathbb{R}) \) \cite{23}.

Take two arithmetic non-commensurable hyperbolic 3-manifolds \( N_1 \) and \( N_2 \) which share a common properly imbedded closed geodesic surface \( S \), up to an isometry. We cut each \( N_i \) along \( S \), which results in one or two connected components. Let \( M_i \) be the metric completion of a component of \( N_i - S \), which has geodesic boundary isometric to one or two copies of \( S \). We now glue one or two copies of \( M_1 \) and \( M_2 \) together along their geodesic boundary and get a connected finite-volume hyperbolic 3-manifold with no boundary. The resulting 3-manifold is a non-arithmetic hyperbolic 3-manifold, and its fundamental group is an example of the so-called hybrid lattices constructed by Gromov and Piatetski-Schapiro \cite{16}.

Mostow rigidity theorem says that any two isomorphic lattices of \( G \) are conjugate to each other. Since a lattice is finitely presented, it follows that a conjugacy class of a lattice is determined by its presentation. Hence, despite the presence of non-arithmetic lattices in \( G \), there are only countably many lattices of \( G \) up to conjugation, or equivalently, there are only countably many hyperbolic manifolds of finite volume, up to isometry.

2.2. Finitely generated Kleinian groups. We will mostly focus on finitely generated Kleinian groups. When studying a finitely generated Kleinian group \( \Gamma \), the associated limit set and the convex core play fundamental roles.

Using the Möbius transformation action of \( \Gamma \) on \( S^2 \), we define:

**Definition 2.2.** The limit set \( \Lambda \subset S^2 \) of \( \Gamma \) is the set of all accumulation points of \( \Gamma(z) \) for \( z \in \mathbb{H}^3 \cup S^2 \).

This definition is independent of the choice of \( z \in \mathbb{H}^3 \cup S^2 \), and \( \Lambda \) is a minimal \( \Gamma \)-invariant closed subset of \( S^2 \).

**Definition 2.3.** The convex core of \( M \) is the convex submanifold of \( M \) given by

\[
\text{core } M := \Gamma \setminus \text{hull } \Lambda \subset M = \Gamma \setminus \mathbb{H}^3
\]

where \( \text{hull } \Lambda \subset \mathbb{H}^3 \) is the smallest convex subset containing all geodesics connecting two points in \( \Lambda \).

If \( \text{Vol}(M) < \infty \), then \( \Lambda = S^2 \) and hence \( M \) is equal to its convex core.

**Definition 2.4.** (1) A Kleinian group \( \Gamma \) is called geometrically finite if the unit neighborhood of core \( M \) has finite volume. 
(2) A Kleinian group $\Gamma$ is called convex cocompact if $\text{core} \ M$ is compact, or equivalently, if $\Gamma$ is geometrically finite without any parabolic elements.

An element $g \in G$ is either hyperbolic (if it is conjugate to a diagonal element whose entries have modulus not equal to 1), elliptic (if it is conjugate to a diagonal element whose entries have modulus 1) or parabolic (if it is conjugate to a strictly upper triangular matrix). By discreteness, an element of a torsion-free Kleinian group is either hyperbolic or parabolic.

Geometrically finite (resp. convex cocompact) Kleinian groups are natural generalization of (resp. cocompact) lattices of $G$. Moreover, the convex core of a geometrically finite hyperbolic manifold admits a thick-thin decomposition: there exists a constant $\varepsilon > 0$ such that $\text{core} \ M$ is the union of a compact subset of injectivity radius at least $\varepsilon > 0$ and finitely many cusps. In the class of geometrically finite groups, lattices are characterized by the property that their limit sets are the whole of $S^2$, and the limit sets of other geometrically finite groups have Hausdorff dimension strictly smaller than 2 ([51],[52]).

The group $G = \text{PSL}_2(C)$ can be considered as a real algebraic subgroup, more precisely, the group of real points of an algebraic group $G$ defined over $R$. A subset $S \subset G$ is called Zariski dense if $S$ is not contained in any proper real algebraic subgroup of $G$. The Zariski density of a Kleinian group $\Gamma$ in $G$ is equivalent to the property that its limit set $\Lambda$ is not contained in any circle of $S^2$. When $\Lambda$ is contained in a circle, $\Gamma$ is conjugate to a discrete subgroup of $\text{PSL}_2(R)$; such Kleinian groups are referred to as Fuchsian groups. Geometrically finite Kleinian groups are always finitely generated, but the converse is not true in general; see (2.6).

2.3. **Examples of geometrically finite groups.** Below we give examples of three different kinds of geometrically finite groups which are relevant to subsequent discussion. Their limit sets are respectively totally disconnected, Jordan curves, and Sierpinski carpets. We note that a geometrically finite non-lattice Zariski dense Kleinian group $\Gamma$ is determined by its limit set $\Lambda$ up to commensurability, more precisely, $\Gamma$ is a subgroup of finite index in the discrete subgroup $\text{Stab}(\Lambda) = \{g \in G : g(\Lambda) = \Lambda\}$.

2.3.1. **Schottky groups.** The simplest examples of geometrically finite groups are Schottky groups. A subgroup $\Gamma < G$ is called (classical) Schottky if $\Gamma$ is generated by hyperbolic elements $g_1, \ldots, g_k \in G$, $k \geq 2$, satisfying that there exist mutually disjoint closed round disks $B_1, \ldots, B_k$ and $B'_1, \ldots, B'_k$ in $S^2$ such that each $g_i$ maps the exterior of $B_i$ onto the interior of $B'_i$.

If $g_1, \ldots, g_k$ are hyperbolic elements of $G$ whose fixed points in $S^2$ are mutually disjoint, then $g_1^N, \ldots, g_k^N$ generate a Schottky group for all $N$ large enough. A Schottky group $\Gamma$ is discrete and free; the common exterior of the hemi-spheres bounded by $B_i, B'_i$ is a fundamental domain $F$ of $\Gamma$. Since the limit set of $\Gamma$, which is totally disconnected, is contained in the union of interiors of $B_i$ and $B'_i$’s, it is easy to see that the intersection of the hull of $\Lambda$ and the fundamental domain $F$ is a bounded subset of $F$. Hence $\Gamma$ is a convex cocompact subgroup. Its convex core is the handle body of genus $k$; in particular, the boundary of core $M$ is a closed surface of genus $k$.

Any Kleinian group $\Gamma$ contains a Schottky subgroup which has the same Zariski closure. If $\Gamma$ is Zariski dense, take any two hyperbolic elements $\gamma_1$ and $\gamma_2$ of $\Gamma$ with
disjoint sets of fixed points. Suppose that all of four fixed points lie in a circle, say, $C \subset S^2$; note that $C$ is uniquely determined. Since the set of fixed points of hyperbolic elements of $\Gamma$ forms a dense subset of $\Lambda$, there exists a hyperbolic element $\gamma_3 \in \Gamma$ whose fixed points are not contained in $C$. Now, for any $N \geq 1$, the subgroup generated by $\gamma_1^N, \gamma_2^N, \gamma_3^N$ is Zariski dense, as its limit set cannot be contained in a circle. By taking $N$ large enough, we get a Zariski dense Schottky subgroup of $\Gamma$. This in particular implies that any Kleinian group contains a convex cocompact subgroup, which is as large as itself in the algebraic sense.

2.3.2. Fuchsian groups and deformations: quasifuchsian groups. An orientation preserving homeomorphism $f : S^2 \rightarrow S^2$ is called $\kappa$-quasiconformal if for any $x \in S^2$,

$$\limsup_{r \to 0} \frac{\sup \{|f(y) - f(x)| : |y - x| = r\}}{\inf \{|f(y) - f(x)| : |y - x| = r\}} \leq \kappa.$$ 

The 1-quasiconformal maps are precisely conformal maps [25, Sec.2]. The group $G = \text{PSL}_2(\mathbb{C})$ is precisely the group of all conformal automorphisms of $S^2$.

A Kleinian group $\Gamma$ is called quasifuchsian if it is a quasiconformal deformation of a (Fuchsian) lattice of $\text{PSL}_2(\mathbb{R})$, i.e., there exists a quasiconformal map $f$ and a lattice $\Delta \subset \text{PSL}_2(\mathbb{R})$ such that $\Gamma = \{f \circ \delta \circ f^{-1} : \delta \in \Delta\}$. Any quasi-conformal deformation of a geometrically finite group is known to be geometrically finite; so a quasifuchsian group is geometrically finite.

A quasifuchsian group is also characterized as a finitely generated Kleinian group whose limit set $\Lambda$ is a Jordan curve and which preserves each component of $S^2 - \Lambda$. If $\Omega_{\pm}$ are components of $S^2 - \Lambda$, then $S_{\pm} := \Gamma \backslash \Omega_{\pm}$ admits a hyperbolic structure by the uniformization theorem, and the product $\text{Teich}(S_+) \times \text{Teich}(S_-)$ of Teichmüller spaces gives a parameterization of all quasifuchsian groups which are quasiconformal deformations of a fixed lattice of $\text{PSL}_2(\mathbb{R})$.

2.3.3. Rigid acylindrical groups and their deformations. A Kleinian group $\Gamma \subset G$ is called rigid acylindrical if the convex core of the associated hyperbolic manifold $M = \Gamma \backslash \mathbb{H}^3$ is a compact manifold with non-empty interior and with totally geodesic boundary. If core $M$ has empty boundary, then $M$ is compact and hence $\Gamma$ is a
uniform lattice. Rigid acylindrical non-lattice groups are characterized as convex cocompact Kleinian groups whose limit set satisfies that

\[ S^2 - \Lambda = \bigcup B_i \]

where \( B_i \)'s are round disks with mutually disjoint closures.

If \( M \) is a rigid acylindrical hyperbolic 3-manifold of infinite volume then the double of core \( M \) is a closed hyperbolic 3-manifold; hence any rigid acylindrical group is a subgroup of a uniform lattice of \( G \), which contains a co-compact Fuchsian lattice \( \pi_1(S) \) for a component \( S \) of \( \partial \text{core} \) \( M \). Conversely, if \( \Gamma_0 \) is a torsion-free uniform lattice of \( G \) such that \( \Delta := \Gamma_0 \cap \text{PSL}_2(\mathbb{R}) \) is a uniform lattice in \( \text{PSL}_2(\mathbb{R}) \), then \( M_0 = \Gamma_0 \setminus \mathbb{H}^3 \) is a closed hyperbolic 3-manifold which contains a properly immersed totally geodesic surface \( \Delta \setminus \mathbb{H}^2 \). By passing to a finite cover of \( M_0 \), \( M_0 \) contains a properly embedded totally geodesic surface, say \( S \) [23, Theorem 5.3.4].

Now the metric completion of a component of \( M_0 - S \) is a compact hyperbolic 3-manifold with totally geodesic boundary, and its fundamental group, which injects to \( \Gamma_0 = \pi_1(M_0) \), is a rigid acylindrical Kleinian group.

Rigid acylindrical Kleinian groups admit a huge deformation space, comprised of convex cocompact acylindrical groups. We begin with the notion of acylindricality for a compact 3-manifold. Let \( D^2 \) denote a closed 2-disk and let \( C^2 = S^1 \times [0,1] \) be a cylinder. A compact 3-manifold \( N \) is called acylindrical

1. if \( \partial N \) is incompressible, i.e., any continuous map \( f : (D^2, \partial D^2) \to (N, \partial N) \) can be deformed into \( \partial N \) or equivalently if the inclusion \( \pi_1(S) \to \pi_1(N) \) is injective for any component \( S \) of \( \partial N \); and
2. if any essential cylinder of \( N \) is boundary parallel, i.e., any continuous map \( f : (C^2, \partial C^2) \to (N, \partial N) \), injective on \( \pi_1 \), can be deformed into \( \partial N \).

A convex cocompact hyperbolic 3-manifold \( M \) is called acylindrical if its convex core is acylindrical. When \( M \) has infinite volume, it is also described by the property that its limit set is a Sierpinski carpet: \( S^2 - \Lambda = \bigcup B_i \) is a dense union of Jordan disks \( B_i \)'s with mutually disjoint closures and with \( \text{diam}(B_i) \to 0 \). By Whyburn [54], all Sierpinski carpets are known to be homeomorphic to each other. We refer to a recent preprint [56] for a beautiful picture of the limit set of a convex cocompact (non-rigid) acylindrical group.

Any convex cocompact acylindrical Kleinian group \( \Gamma \) is a quasi-conformal deformation of a unique rigid acylindrical Kleinian group \( \Gamma_0 \), and its quasi-conformal class is parametrized by the product \( \prod_i \text{Teich}(S_i) \) where \( S_i \)'s are components of...
In terms of a manifold, any convex cocompact acylindrical hyperbolic 3-manifold is quasi-isometric to a unique rigid acylindrical hyperbolic 3-manifold $M$, and its quasi-isometry class is parametrized by $\prod_i \text{Teich}(S_i)$.

The definition of acylindricality can be extended to geometrically finite groups with cusps using the notion of a compact core. If $M$ is a hyperbolic 3-manifold with finitely generated $\pi_1(M)$, then there exists a a compact connected submanifold $C \subset M$ (with boundary) such that the inclusion $C \subset M$ induces an isomorphism $\pi_1(C) \simeq \pi_1(M)$; such $C$ exists uniquely, up to homeomorphism, and is called the compact core of $M$. Now a geometrically finite hyperbolic 3-manifold $M$ is called acylindrical if its compact core is an acylindrical compact 3-manifold.

2.4. **Thurston’s geometrization theorem.** The complement $\Omega := S^2 - \Lambda$ is called the set of discontinuity. Let $\Gamma$ be a finitely generated Kleinian group. Ahlfors finiteness theorem says that $\Gamma \setminus \Omega$ is a union of finitely many closed Riemann surfaces with at most a finite number of punctures. The Kleinian manifold associated to $\Gamma$ is defined by adding $\Gamma \setminus \Omega$ to $\Gamma \setminus \mathbb{H}^3$ on the conformal boundary at infinity:

$$M(\Gamma) = \Gamma \setminus \mathbb{H}^3 \cup \Omega, \quad \partial M(\Gamma) = \Gamma \setminus \Omega.$$

The convex cocompactness of $\Gamma$ is equivalent to the compactness of $M(\Gamma)$. If $\Gamma$ is geometrically finite with cusps, then $M(\Gamma)$ is compact except possibly for a finite number of rank one and rank two cusps. We denote by $M_0(\Gamma)$ the compact submanifold of $M(\Gamma)$ obtained by removing the interiors of solid pairing tubes corresponding to rank one cusps and solid cusp tori corresponding to rank two cusps (cf. [25]).

The following is a special case of Thurston’s geometrization theorem under the extra non-empty boundary condition (cf. [20]):

**Theorem 2.5.** Let $N$ be a compact irreducible\(^2\) orientable atoroidal\(^3\) 3-manifold with non-empty boundary. Then $N$ is homeomorphic to $M_0(\Gamma)$ for some geometrically finite Kleinian group $\Gamma$.

We remark that if $\partial N$ is incompressible and $N$ does not have any essential cylinders, then $\Gamma$ is a geometrically finite acylindrical group.

By applying Thurston’s theorem to the compact core of $\Gamma \setminus \mathbb{H}^3$, we deduce that every finitely generated Kleinian group $\Gamma$ is isomorphic to a geometrically finite group.

2.5. **Density of geometrically finite groups.** The density conjecture of Bers, Sullivan and Thurston says that most of Kleinian groups are geometrically finite. This is now a theorem whose proof combines the work of many authors with the proof in full generality due to Namazi-Souto and Ohshika (we refer to [25, Sec. 5.9] for more details and background).

**Theorem 2.6 (Density theorem).** The class of geometrically finite Kleinian groups is open and dense in the space of all finitely generated Kleinian groups.

In order to explain the topology used in the above theorem, let $\Gamma$ be a finitely generated Kleinian group. By Thurston’s geometrization theorem, there exists a geometrically finite Kleinian group $\Gamma_0$ and an isomorphism $\rho : \Gamma_0 \to \Gamma$. In fact, a

\(^{2}\)every 2-sphere bounds a ball

\(^{3}\)any $\mathbb{Z}^2$ subgroup comes from boundary tori
more refined version gives that $\rho$ is type-preserving, i.e., $\rho$ maps a parabolic element to a parabolic element. Fix a finite generating set $\gamma_1, \cdots, \gamma_k$ of $\Gamma_0$. The density theorem says there exists a sequence of geometrically finite groups $\Gamma_n < G$, and isomorphisms $\rho_n : \Gamma_0 \to \Gamma_n$ such that $\rho_n$ converges to $\rho$ as $n \to \infty$, in the sense that $\rho(\gamma_i) = \lim_n \rho_n(\gamma_i)$ for each $i = 1, \cdots, k$.

Here is an alternative way to describe the density theorem: Fix a geometrically finite Kleinian group $\Gamma$ with a fixed set of generators $\gamma_1, \cdots, \gamma_k$ and relations $\omega_1, \cdots, \omega_r$. Define

$$R(\Gamma) := \{ \rho : \Gamma \to G \text{ homomorphism} \} / \sim$$

with the equivalence relation given by conjugation by elements of $G$. The set $R(\Gamma)$ can be identified with the algebraic variety $\{(g_1, \cdots, g_k) \in G \times \cdots \times G : \omega_i(g_1, \cdots, g_k) = e \text{ for } 1 \leq i \leq r\} / \sim$ where $\sim$ is given by conjugation by an element of $G$ under the diagonal embedding. This defines a topology on $R(\Gamma)$, called the algebraic convergence topology.

The discrete locus is then defined by the subcollection of discrete and faithful representations:

$$AH(\Gamma) := \{ \rho \in R(\Gamma) : \rho \text{ type preserving isomorphism to a Kleinian group} \}.$$

Then $AH(\Gamma)$ is a closed subset, which parametrizes hyperbolic structures on $\Gamma \setminus \mathbb{H}^3$. The interior of $AH(\Gamma)$ consists of geometrically finite Kleinian groups, and the density theorem says that

$$\operatorname{Int} AH(\Gamma) = AH(\Gamma).$$

When $\Gamma$ is a lattice in $G$, $AH(\Gamma)$ is a single point by Mostow rigidity theorem. For all other geometrically finite Kleinian groups, $AH(\Gamma)$ is huge; the quasiconformal deformation space of $\Gamma$ given by

$$\mathcal{T}(\Gamma) = \{ \rho \in AH(\Gamma) : \rho \text{ is induced by a quasiconformal deformation of } \Gamma \}$$

is a connected component of the interior of $AH(\Gamma)$ and is a complex analytic manifold of dimension same as the dimension of $\operatorname{Teich}(\Gamma \setminus \Omega)$, i.e., $\sum_{i=1}^m (3g_i + n_i - 3)$ where $g_i$ is the genus of the $i$-th component of $\Gamma \setminus \Omega = \partial M(\Gamma)$ and $n_i$ is the number of its punctures [25, Thm. 5.13]. Moreover when $\Gamma$ is rigid acylindrical, the interior of $AH(\Gamma)$, modulo the orientation (in other words, modulo the conjugation by elements of $\operatorname{Isom}(\mathbb{H}^3)$), is connected, and hence is equal to $\mathcal{T}(\Gamma)$; this can be deduced from [9], as explained to us by Y. Minsky. Therefore $\operatorname{Int} AH(\Gamma) / \pm = \mathcal{T}(\Gamma) = \operatorname{Teich}(\Gamma \setminus \Omega)$.

2.6. Examples of geometrically infinite groups. Not every finitely generated Kleinian group is geometrically finite. An important class of finitely generated geometrically infinite Kleinian groups is given by the fundamental groups of $\mathbb{Z}$-covers of closed hyperbolic 3-manifolds. The virtual fibering theorem, proved by Agol, building upon the previous work of Wise, says that every closed hyperbolic 3-manifold is a surface bundle over a circle, after passing to a finite cover [25, Sec 6.4]. This implies that, up to passing to a subgroup of finite index, any uniform lattice $\Gamma$ of $G$ contains a normal subgroup $\Delta$ such that $\Gamma_0 / \Delta \simeq \mathbb{Z}$ and $\Delta$ is a surface subgroup, i.e., isomorphic to the fundamental group of a closed hyperbolic surface. Note that $\Delta$ is finitely generated (being a surface subgroup) but geometrically infinite; as no normal subgroup of a geometrically finite group of infinite index is geometrically finite. In fact, any finitely generated, geometrically infinite, subgroup
10 HEE OH

3. Mixing and classification of $N$-orbit closures

Let $\Gamma \leq G = \text{PSL}_2(\mathbb{C})$ be a Zariski dense geometrically finite Kleinian group, and $M := \Gamma \backslash \mathbb{H}^3$ the associated hyperbolic 3-manifold. We denote by

$$\pi : \mathbb{H}^3 \to M = \Gamma \backslash \mathbb{H}^3$$

the quotient map.

We fix $o \in \mathbb{H}^3$ and a unit tangent vector $v_o \in T_o(\mathbb{H}^3)$ so that $K = \text{SU}(2)$ and $M_0 = \{\text{diag}(e^{i\theta}, e^{-i\theta}) : \theta \in \mathbb{R}\}$ are respectively the stabilizer subgroups of $o$ and $v_o$. The action of $G$ on $\mathbb{H}^3$ induces identifications $G/K \simeq \mathbb{H}^3$, $G/M_0 \simeq T^1(\mathbb{H}^3)$, and $G \simeq F(\mathbb{H}^3)$, where $T^1(\mathbb{H}^3)$ and $F(\mathbb{H}^3)$ denote respectively the unit tangent bundle and the oriented frame bundle over $\mathbb{H}^3$.

Thus we may understand the oriented frame bundle $F M$ as the homogeneous space $\Gamma \backslash G$. Denote by

$$p : \Gamma \backslash G \to M$$

the base-point projection map.

Unless $\Gamma$ is a lattice, the $G$-invariant measure on $\Gamma \backslash G$ is infinite, and dissipative for natural geometric flows such as the geodesic flow and horospherical flow. Two locally finite measures on $\Gamma \backslash G$, called the Bowen-Margulis-Sullivan measure, and the Burger-Roblin measure, play important roles, and they are defined using the Patterson-Sullivan density on the limit set of $\Gamma$.

3.1. Patterson-Sullivan density. We denote by $\delta$ the critical exponent of $\Gamma$, i.e., the infimum over all $s \geq 0$ such that the Poincare series $\sum_{\gamma \in \Gamma} e^{-sd(o, \gamma(o))}$ converges. As $\Gamma$ is geometrically finite, $\delta$ is equal to the Hausdorff dimension of $\Λ$ [51].

Bishop and Jones proved that $\delta$ is strictly bigger than 1, unless $\Lambda$ is totally disconnected or contained in a circle [5]. As $\Gamma$ is assumed to be Zariski dense, we have:

![Figure 4. Frame bundle of $\mathbb{H}^3$](image)
**Theorem 3.1.** If \( \Lambda \) is connected, then \( \delta > 1 \).

Recall that for \( x, y \in \mathbb{H}^3 \) and \( \xi \in \mathbb{S}^2 \), the Busenmann function \( \beta_\xi(x, y) \) is given by \( \lim_{t \to \infty} d(x, \xi_t) - d(y, \xi_t) \) where \( \xi_t \) is a geodesic ray toward \( \xi \).

**Definition 3.2.** A \( \Gamma \)-invariant conformal density of dimension \( s > 0 \) is a family \( \{ \mu_x : x \in \mathbb{H}^3 \} \) of finite measures on \( \mathbb{S}^2 \) satisfying:

1. For any \( \gamma \in \Gamma \) and \( x \in \mathbb{H}^3 \), \( \gamma_* \mu_x = \mu_{\gamma(x)} \);
2. For all \( x, y \in \mathbb{H}^3 \) and \( \xi \in \mathbb{S}^2 \), \( \frac{d\mu_x}{d\nu}(\xi) = e^{s\beta_{\xi}(y,x)} \).

**Theorem 3.3** (Patterson-Sullivan). There exists a \( \Gamma \)-invariant conformal density \( \{ \nu_x : x \in \mathbb{H}^3 \} \) of dimension \( \delta \), unique up to a scalar multiple.

We call this Patterson-Sullivan density. Denoting by \( \Delta \) the hyperbolic Laplacian on \( \mathbb{H}^3 \), the Patterson-Sullivan density is closely related to the bottom of the spectrum of \( \Delta \) for its action on smooth functions on \( \Gamma \backslash \mathbb{H}^3 \). The function \( \phi_0 \) defined by

\[
\phi_0(x) := |\nu_x|
\]

for each \( x \in \mathbb{H}^3 \) is \( \Gamma \)-invariant, and hence we may regard \( \phi_0 \) as a function on the manifold \( \Gamma \backslash \mathbb{H}^3 \). It is the unique function (up to a constant multiple) satisfying \( \Delta \phi_0 = \delta(2 - \delta)\phi_0 \); so we call \( \phi_0 \) the base eigenfunction.

Set \( \nu := \nu_0 \) and call it the Patterson-Sullivan measure (viewed from \( o \)). When \( \Gamma \) is convex-cocompact, the Patterson-Sullivan measure \( \nu_0 \) is simply proportional to the \( \delta \)-dimensional Hausdorff measure on \( \Lambda \) in the spherical metric of \( \mathbb{S}^2 \).

### 3.2. Mixing of the BMS measure.

Consider the following one-parameter subgroup of \( G \):

\[
A := \left\{ a_t \equiv \begin{pmatrix} e^{t/2} & 0 \\ 0 & e^{-t/2} \end{pmatrix} : t \in \mathbb{R} \right\}.
\]

The right translation action of \( A \) on \( F \mathbb{H}^3 = G \) induces the frame flow: if \( g = (e_1, e_2, e_3) \), then \( ga_t \) for \( t > 0 \) is the frame given by translation in direction of \( e_1 \) by hyperbolic distance \( t \). Let \( v_o^+ \in \mathbb{S}^2 \) denote the forward and backward end points of the geodesic given by \( v_o \) respectively. In the upper half space model of \( \mathbb{H}^3 \), choosing \( v_o \) to be the upward normal vector at \( o = (0, 0, 1) \), we have \( v_o^+ = \infty \) and \( v_o^- = 0 \).

For \( g \in G \), we define

\[
g^+ = g(v_o^+) \in \mathbb{S}^2 \quad \text{and} \quad g^- = g(v_o^-) \in \mathbb{S}^2.
\]

The map \( g \mapsto (g^+, g^-, s = \beta_{\gamma} - (o, g)) \) induces a homeomorphism between \( T^1(\mathbb{H}^3) \) and \( (\mathbb{S}^2 \times \mathbb{S}^2 - \text{diagonal}) \times \mathbb{R} \); called the Hopf-parametrization.

We define a locally finite measure \( \tilde{\nu}^{\text{BMS}} \) on \( T^1(\mathbb{H}^3) = G/M_0 \) as follows:

\[
d\tilde{\nu}^{\text{BMS}}(g) = e^{s\beta_{\gamma} - (o, g)} \, \nu(g^+) d\nu(g^-) ds
\]

where \( ds \) is the Lebesgue measure on \( \mathbb{R} \).

Denote by \( m^{\text{BMS}} \) the unique \( M_0 \)-invariant measure on \( \Gamma \backslash G \) which is induced by \( \tilde{\nu}^{\text{BMS}} \); we call this the Bowen-Margulis-Sullivan measure (or the BMS measure for short).

Sullivan showed that \( m^{\text{BMS}} \) is a finite \( A \)-invariant measure. The following is due to Babillot [2] for \( M_0 \)-invariant functions and to Winter [55] for general functions:
Theorem 3.4. The frame flow on \((\Gamma \backslash G, m^{\text{BMS}})\) is mixing, that is, for any \(\psi_1, \psi_2 \in L^2(\Gamma \backslash G, m^{\text{BMS}})\),
\[
\lim_{t \to \infty} \int_{\Gamma \backslash G} \psi_1(ga_t)\psi_2(g) \, dm^{\text{BMS}}(g) = \frac{1}{|m^{\text{BMS}}|} m^{\text{BMS}}(\psi_1) \cdot m^{\text{BMS}}(\psi_2).
\]

We define the renormalized frame bundle of \(M\) as:
\[RF \, M := \{[g] \in \Gamma \backslash G : g^\pm \in \Lambda\}.\]

This is a closed \(A\)-invariant subset of \(\Gamma \backslash G\) which is precisely the support of \(m^{\text{BMS}}\), and an immediate consequence of Theorem 3.4 is the topological mixing of the \(A\)-action on \(RF \, M\): for any two open subsets \(O_1, O_2\) intersecting \(RF \, M\), \(O_1 \cap O_2 \neq \emptyset\) for all sufficiently large \(|t|\).

3.3. Essential unique-ergodicity of the BR measure. We denote by \(N := \{g \in G : a_+ ga_t \to e\} \) the contracting horospherical subgroup for the action of \(A\), which is explicitly given as
\[N = \left\{ u_t = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix} : t \in \mathbb{C} \right\}.\]

The projection \(\pi(gN)\) in \(H^3\) is a Euclidean sphere tangent to \(S^2\) at \(g^+\) and \(gN\) consists of frames \((e_1, e_2, e_3)\) whose last two vectors \(e_2, e_3\) are tangent to \(\pi(gN)\). That \(N\) is a contracting horospherical subgroup means geometrically that \(\pi(gNa_t)\) for \(t > 0\) is a Euclidean sphere based at \(g^+\) but shrunk toward \(g^+\) by the hyperbolic distance \(t\).

We define \(\tilde{m}^{\text{BR}}\) on \(G/M_0 = \text{T}^1(\mathbb{H}^3)\) as follows:
\[d\tilde{m}^{\text{BR}}(g) = e^{\delta \beta_s \circ \nu} \, e^{2\beta_s \circ \nu} \, d\nu(g^+) \, dg^- \, ds\]
where \(dg^-\) is the Lebesgue measure on \(S^2\). We denote by \(m^{\text{BR}}\) the unique \(M_0\)-invariant measure on \(\Gamma \backslash G\) which is induced by \(\tilde{m}^{\text{BR}}\). We call this measure the Burger-Roblin measure (or the BR measure for short). If \(\Gamma\) is a lattice, \(m^{\text{BR}}\) is simply the \(G\)-invariant measure. Otherwise \(m^{\text{BR}}\) is an infinite, but locally finite, Borel \(N\)-invariant measure whose support is given by
\[RF_+ \, M := \{[g] \in \Gamma \backslash G : g^+ \in \Lambda\} = RF \, M \cdot N.\]

The projection of the BR measure to \(M\) is an absolutely continuous measure on \(M\) with Radon-Nikodym derivative given by \(\phi_\circ\): if \(f \in C_c(\Gamma \backslash G)\) is \(K\)-invariant, then
\[m^{\text{BR}}(f) = \int_{\Gamma \backslash G} f(x) \phi_\circ(x) \, dx\]
where \(dx\) is a \(G\)-invariant measure on \(\Gamma \backslash G\). Using Theorem 3.4, Roblin and Winter showed the following measure classification of \(N\)-invariant locally finite measures, extending an earlier work of Burger [7]:

Theorem 3.5. ([45], [55]) Any locally finite \(N\)-ergodic invariant measure on \(\Gamma \backslash G\) is either supported on a closed \(N\)-orbit or proportional to \(m^{\text{BR}}\).
3.4. **Closures of \(N\)-orbits.** If \(x \notin RF_+ M\), then \(xN\) is a proper immersion of \(N\) to \(\Gamma \backslash G\) via the map \(n \mapsto xn\), and hence \(xN\) is closed. In understanding the topological behavior of \(xN\) for \(x = [g] \in RF_+ M\), the relative location of \(g^+\) in the limit set becomes relevant. The hypothesis that \(\Gamma\) is geometrically finite implies that any \(\xi \in \Lambda\) is either radial (any geodesic ray \(\xi_t \in M\) converging to \(\xi\) accumulates on a compact subset) or parabolic (it is fixed by some parabolic element of \(\Gamma\)). Since this property is \(\Gamma\)-invariant, we will say that \(x^+\) is radial (resp. parabolic) if \(g^+\) is for \(x = [g]\). When \(\Gamma\) is convex cocompact, \(\Lambda\) consists only of radial limit points.

The topological mixing of the \(A\)-action on \(RF M\) implies the following dichotomy for the closure of an \(N\)-orbit:

**Theorem 3.6.** ([15], [55]) For \(x \in RF_+ M\), \(xN\) is closed (if \(x^+\) is parabolic) or dense in \(RF_+ M\) (if \(x^+\) is radial).

4. **Almost all results on orbit closures**

Let \(\Gamma < G = \text{PSL}_2(\mathbb{C})\) be a Zariski dense geometrically finite Kleinian group, and \(M := \Gamma \backslash \mathbb{H}^3\) the associated hyperbolic 3-manifold.

We are mainly interested in the action of the following two subgroups on \(\Gamma \backslash G\):

\[
H := \text{PSL}_2(\mathbb{R})
\]

\[
U := \{u_t = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix} : t \in \mathbb{R}\}.
\]

Any one-parameter unipotent subgroup of \(G\) is conjugate to \(U\), and any connected closed subgroup of \(G\) generated by unipotent one-parameter subgroups is conjugate to either \(N\), \(H\) or \(U\). We also note that the subgroups \(N\), \(H\) and \(U\) are normalized by the subgroup \(A\), which is an important point for the following discussion, as the measures \(m^{\text{BMS}}\) and \(m^{\text{BR}}\) are invariant and quasi-invariant under \(A\) respectively.

The first question is whether there exist almost all results for the closures of these orbits for appropriate measures.

We recall:

**Theorem 4.1** (Moore’s ergodicity theorem). Let \(\Gamma < G\) be a lattice. For any unbounded subgroup \(W\) of \(G\), \(xW\) is dense in \(\Gamma \backslash G\) for almost all \(x \in \Gamma \backslash G\).

When \(\Gamma\) is geometrically finite but not a lattice in \(G\), no orbit of a proper connected subgroup \(W\) is dense in \(\Gamma \backslash G\). Moreover, it is easy to verify that if \(\partial(gW) \subset S^2\) does not intersect \(\Lambda\), then the map \(W \to [g]W \subset \Gamma \backslash G\) given by \(w \mapsto [g]w\) is a proper map, and hence \([g]W\) is closed \(^4\).

Hence if \(W\) has the property that \(\partial(gW) = (gW)^+\), for instance, if \(W = H\) or \(U\), then the non-trivial dynamics of the action of \(W\) on \(\Gamma \backslash G\) exists only inside the closure of \(RF_+ M \cdot W\).

We will see that \(RF_+ M \cdot H\) is always closed; it is useful to understand the geometric description of \(RF_+ M \cdot H\) in order to understand its closedness.

4.1. **Geodesic planes and almost all \(H\)-orbits.** A geodesic plane in \(\mathbb{H}^3\) is a totally geodesic imbedding of \(\mathbb{H}^2\), which is simply either a vertical plane or a vertical hemisphere in the upper half space model.

\(^4\)For a subset \(S \subset G\), we use the notation \(\partial S\) to denote \(\pi(S) \cap S^2\) under the projection \(\pi : F \to \mathbb{H}^3 \cup S^2\).
Let $\mathcal{P}$ denote the set of all oriented geodesic planes of $\mathbb{H}^3$, and $\mathcal{C}$ the set of all oriented circles in $S^2$. The map $P \mapsto \partial P$ gives an isomorphism between $\mathcal{P}$ and $\mathcal{C}$.

On the other hand, the map $gH \mapsto P_g := \pi(gH)$ gives an isomorphism between the quotient space $G/H$ and the set $\mathcal{P}$, whose inverse can be described as follows: for $P \in \mathcal{P}$, the set of frames $(e_1, e_2, e_3)$ based in $P$ such that $e_1$ and $e_2$ are tangent to $P$ and $e_3$ is given by the orientation of $P$ is precisely a single $H$-orbit. Consequently, the map $gH \rightarrow C_g := \partial P_g$

gives an isomorphism between $G/H$ and $\mathcal{C}$.

**Definition 4.2.** An oriented geodesic plane $P \subset M$ is a totally geodesic immersion of an oriented hyperbolic plane $\mathbb{H}^2$ in $M$, or equivalently, $P$ is the image of an oriented geodesic plane of $\mathbb{H}^3$ under $\pi$.

In this paper, geodesic planes and circles are always considered to be oriented. Note that any geodesic plane $P \subset M$ is of the form:

$$P = p(gH) \quad \text{for some } g \in G.$$  

Therefore the study of $H$-orbits on $\Gamma \backslash G$ has a direct implication on the behavior of geodesic planes in the manifold $\Gamma \backslash \mathbb{H}^3$.

We set

$$F_\Lambda := RF_+ M \cdot H \quad \text{and} \quad C_\Lambda := \{ C \in \mathcal{C} : C \cap \Lambda \neq \emptyset \}.$$  

It follows from the compactness of $\Lambda$ that $C_\Lambda$ is a closed subset of $\mathcal{C} = G/H$. As $F_\Lambda/H = \Gamma \backslash C_\Lambda$,

we deduce:

**Lemma 4.3.** The set $F_\Lambda$ is a closed $H$-invariant subset of $\Gamma \backslash G$.
Proposition 4.4. For \( m^{\text{BMS}} \)-a.e. \( x \in \text{RF} \, M \),
\[
\overline{xH} = F_\Lambda;
\]
in particular, the geodesic plane \( p(xH) \) is dense in \( M \).

Proof. We have \( \text{RF} \, M \cdot U = \text{RF} \, M + M \) [33] and hence \( \text{RF} \, M \cdot H = F_\Lambda \). Theorem 3.4 implies that \( m^{\text{BMS}} \) is ergodic, and hence by the Birkhoff ergodic theorem, for almost all \( x \), \( xA \) is dense in \( \text{RF} \, M \). Since \( A \subset H \), we deduce
\[
\overline{xH} \supset \text{RF} \, M \cdot H = F_\Lambda.
\]

\( \square \)

4.2. Horocycles and almost all \( U \)-orbits. A horocycle in \( \mathbb{H}^3 \) is a Euclidean circle tangent to \( S^2 \).

Definition 4.5. A horocycle \( \chi \) in \( M \) is an isometrically immersed copy of \( \mathbb{R} \) with zero torsion and geodesic curvature 1, or equivalently, \( \chi \) is the image of a horocycle of \( \mathbb{H}^3 \) under \( \pi \).

The right translation action of \( U \) on \( \Gamma \backslash G \) is the horocyclic action: if \( g = (e_1, e_2, e_3) \), then \( gu_t \) for \( t > 0 \) is the frame given by translation in the direction of \( e_2 \) by Euclidean distance \( t \). In fact, any horocycle \( \chi \subset M \) is of the form
\[
\chi = p(gU) \quad \text{for some} \quad g \in G.
\]

Note that both \( gA \) and \( gU \) have their trajectories inside the plane \( P_g = \pi(gH) \).
In particular, \( \pi(gU) \) is a Euclidean circle lying on \( P_g \) tangent to \( S^2 \) at \( g^+ \).

We now discuss the almost all results for \( U \)-orbits in terms of the Burger-Roblin measure. It turns out that the size of the critical exponent \( \delta \) matters in this question. The following was proved in joint work with Mohammadi for \( \Gamma \) convex cocompact [38] and by Maucourant and Schapira [33] for geometrically finite groups.

Theorem 4.6. If \( \delta > 1 \), \( m^{\text{BR}} \) is \( U \)-ergodic and conservative.

Proposition 4.7. Let \( \delta > 1 \) (e.g., \( \Lambda \) is connected). Then for \( m^{\text{BR}} \)-a.e. \( x \in \text{RF} \, M \),
\[
\overline{xU} = \text{RF} \, M;
\]
In particular, the horocycle \( p(xU) \) is dense in \( M \).
Proof. Since \( m^{BR} \) is an infinite measure, unless \( \Gamma \) is a lattice, the Birkhoff ergodic theorem does not apply. Instead we use the Hopf ratio theorem which applies by Theorem 4.6, and hence the claim follows. \( \square \)

In [33], it was proved that if \( \delta < 1 \), \( m^{BR} \) is totally \( U \)-dissipative and hence almost all \( U \)-orbits are divergent (cf. [14]). Whether \( m^{BR} \) is ergodic or not at \( \delta = 1 \) remains an open question.

### 4.3. Orbit closure theorem for lattices

The almost all results on orbit closures in Propositions 4.4 and 4.7 do not describe the topological behavior of a given individual orbit. In the lattice case, we have the following remarkable classification of all possible orbit closures, due to Ratner [44] and Shah [47] independently:

**Theorem 4.8.** Let \( \Gamma < G \) be a lattice, and \( x \in \Gamma \backslash G \).

1. The closure \( xH \) is either \( xH \) or \( \Gamma \backslash G \).
2. The closure \( xU \) is either \( xU \), \( xv^{-1}Hv \), for some \( v \in N \), or \( \Gamma \backslash G \).

This theorem immediately implies the first part of the following theorem; the rest follows from the results in the same paper loc.cit.

**Theorem 4.9.** If \( M \) has finite volume, the closures of a geodesic plane and a horocycle are properly immersed submanifolds of \( M \). Moreover,

1. any properly immersed geodesic plane has finite area;
2. there are at most countably many properly immersed geodesic planes in \( M \);
3. any infinite sequence of properly immersed geodesic planes \( P_i \) becomes dense in \( M \), i.e, \( \lim_{i \to \infty} P_i = M \) in the Hausdorff topology on closed subsets of \( M \).

The density statement (3) above, which is a topological version of Mozes-Shah theorem [40], implies that every properly immersed geodesic plane \( P \) is topologically isolated, in the sense that there exists an open neighborhood of \( P \) which does not contain any other properly immersed geodesic plane in its entirety.

### 4.4. Topological obstructions to orbit closure theorem

In this section, we describe a family of quasi-fuchsian manifolds some of whose geodesic planes have fractal closures, in particular, they have non-integral dimensions. These geodesic planes pass through the interior of the convex core of \( M \) but their boundaries meet the limit set \( \Lambda \) only at two points.

These examples can be seen easily for Fuchsian manifolds, and by performing a small bending deformation along a simple closed geodesic far away from our fractal closures of a fixed plane, we will obtain quasi-fuchsian manifolds keeping the fractal closure intact.

#### 4.4.1. Fuchsian 3-manifolds

Consider a Fuchsian 3-manifold \( M \) which can be expressed as

\[
M = S \times \mathbb{R}
\]

in cylindrical coordinates where \( S \) is a closed hyperbolic surface of genus at least 2. Or equivalently, take a torsion-free uniform lattice \( \Gamma < \text{PSL}_2(\mathbb{R}) \), and consider \( \Gamma \) as a subgroup of \( G \), so that \( M = \Gamma \backslash \mathbb{H}^3 = (\Gamma \backslash \mathbb{H}^2) \times \mathbb{R} \). We have core \( M = S \).

It is well-known that geodesics on a closed hyperbolic surface \( S \) can behave as wild as we wish for, in particular, for any \( \beta \geq 1 \), there exists a geodesic whose closure has Hausdorff dimension precisely \( \beta \).
(1) The closure of a geodesic plane needs not be a submanifold: if \( \gamma \subset S \) is a geodesic and \( P \) is a geodesic plane orthogonal to \( S \) with \( P \cap S = \gamma \), then \( P \cong \gamma \times \mathbb{R} \).

Therefore if we take a geodesic \( \gamma \subset S \) whose closure \( \overline{\gamma} \) is wild, then \( P \) is very far from being a submanifold.

(2) There are uncountably many properly immersed geodesic planes intersecting \( \text{core } M \); if \( \gamma \subset S \) is a closed geodesic and \( P \) is a geodesic plane with \( P \cap S = \gamma \), then \( P \) is a properly immersed geodesic plane. By varying angles between \( P \) and \( S \), we obtain a continuous family of such \( P \).

We can now use a small bending deformation of \( M \) to obtain quasifuchsian manifolds in which the same phenomenon persists.

4.4.2. \textit{Quasifuchsian hyperbolic 3-manifolds.} Let \( \gamma_0 \in \Gamma \) be a primitive hyperbolic element representing a separating simple closed geodesic \( \beta \) in \( S \). Without loss of generality, we assume \( \gamma_0 \in A \), up to conjugation. If \( S_1 \) and \( S_2 \) are components of \( S - \beta \), then each \( \Gamma_i := \pi_1(S_i) \) is a subgroup of \( \Gamma \) and \( \Gamma \) can be presented as the amalgamated free product

\[ \Gamma = \Gamma_1 *_{\langle \gamma_0 \rangle} \Gamma_2. \]

Setting \( m_\theta = \text{diag}(e^{i\theta}, e^{-i\theta}) \), note that \( m_\theta \) centralizes \( \gamma_0 \). For each non-trivial \( m_\theta \), we have \( \Gamma_1 \cap m_\theta^{-1} \Gamma_2 m_\theta = \langle \gamma_0 \rangle \) and the map which maps \( \gamma \) to \( \gamma \) if \( \gamma \in \Gamma_1 \) and to \( m_\theta^{-1} \gamma m_\theta \) if \( \gamma \in \Gamma_2 \) extends to an isomorphism \( \Gamma \to \Gamma_\theta \) where

\[ \Gamma_\theta := \Gamma_1 *_{\langle \gamma_0 \rangle} m_\theta^{-1} \Gamma_2 m_\theta. \]

If \( \theta \) is sufficiently small, then

- \( \Gamma_\theta \) is a discrete subgroup of \( G \);
- \( M_\theta := \Gamma_\theta \backslash \mathbb{H}^3 \) is a quasifuchsian manifold and
- there is a path isometric embedding \( j_\theta : S \to \partial \text{ core } M_\theta \) such that its image \( S_\theta \) is bent with a dihedral angle of \( \theta \) along the image of \( \beta \) and otherwise totally geodesic.

Fix \( \varepsilon > 0 \) sufficiently small that \( \beta \) has an embedded annular collar neighborhood in \( S \) of width \( 2\varepsilon \). Let \( \gamma \subset S_1 \) be a geodesic whose closure \( \overline{\gamma} \) is disjoint from a \( 2\varepsilon \)-neighborhood \( O(\beta, 2\varepsilon) \) of \( \beta \). Now if we set \( S_1(\varepsilon) := S_1 - O(\beta, 2\varepsilon) \), then there is a unique orientation-preserving isometric immersion

\[ j_\theta : S_1(\varepsilon) \times \mathbb{R} \to M_\theta \]
which extends $j_\theta|_{S_1(\varepsilon)}$ and sends geodesics normal to $S_1(\varepsilon)$ to geodesics normal to $j_\theta(S_1(\varepsilon))$. Now, if $\theta$ is small enough (relative to $\varepsilon$), then $J_\theta$ is a proper isometric embedding.

This can be proved using the following observation. Let $\alpha = [a, b_1] \cup [b_1, b_2] \cup \cdots \cup [b_{n-1}, b_n] \cup [b_n, c]$ be a broken geodesic in $\mathbb{H}^3$, which is a union of geodesic segments and which bends by angle $0 \leq \theta < \pi/2$ at each $b_i$’s. Suppose the first and the last segments have length at least $\varepsilon > 0$ and the rest have length at least $2\varepsilon$. Let $P_i$ denote the geodesic plane orthogonal to $[b_i, b_{i+1}]$ at $b_i$. If $\theta = 0$, then the distance among $P_i$’s are at least $\varepsilon$. Now if $\theta$ is small enough so that $\sin(\theta/2) < \tanh \varepsilon$, then the planes $P_i$ remain a positive distance apart, giving a nested sequence of half-planes in $\mathbb{H}^3$. This implies that $J_\theta$ is a proper imbedding.

It now follows that for the plane $P := \gamma \times \mathbb{R} \subset S_1(\varepsilon) \times \mathbb{R}$, its image $P_\theta := J_\theta(P) \subset M_\theta$ is an immersed geodesic plane whose closure $\overline{P}_\theta$ is isometric to $\overline{P} \simeq \gamma \times \mathbb{R}$. Therefore by choosing $\gamma$ whose closure is wild, we can obtain a geodesic plane $P_\theta$ of $M_\theta$ with wild closure (cf. [35] for more details).

This example demonstrates that the presence of an essential cylinder in $M$ gives an obstruction to the topological rigidity of geodesic planes. For the behavior of an individual geodesic plane $P$, it also indicates that the finite intersection $\partial P \cap \Lambda$ can be an obstruction.

5. Unipotent Blowup and Renormalizations

The distinguished property of a unipotent flow on the homogeneous space $\Gamma \backslash G$ is the polynomial divergence of nearby points. Given a sequence $zg_n \in \Gamma \backslash G$ where $g_n \to e$ in $G$, the transversal divergence between two orbits $zg_nU$ and $zU$ can be understood by studying the double coset $Ug_nU$ in view of the equality:

$$zg_nu_t = zu_s(u_s^{-1}g_nu_t)$$

and the behavior of rational maps $t \mapsto u_{\alpha_n(t)}g_nu_t$ for certain reparametrizations $\alpha_n : \mathbb{R} \to \mathbb{R}$ so that $\limsup_{n \to \infty} \{u_{\alpha_n(t)}g_nu_t : t \in \mathbb{R}\}$ contains a non-trivial element of $G - U$.

We denote by $V$ the transversal subgroup

$$V = \{u_t : t \in \mathbb{R}\}$$

to $U$ inside $N$, so that $N = UV$. Note that the normalizer $N(U)$ of $U$ is equal to $AN$, and the centralizer $C(U)$ of $U$ is equal to $N$.

The following unipotent blowup lemma (though stated in the setting of $\text{SL}_3(\mathbb{R})$) was first observed by Margulis [26, Lemma 5], in his proof of Oppenheim conjecture.

**Lemma 5.1.**

1. If $g_n \to e$ in $G - AN$, then $\limsup_{n \to \infty} Ug_nU$ contains a one-parameter semigroup of $AV$.

2. If $g_n \to e$ in $G - HV$, then $\limsup_{n \to \infty} Ug_nH$ contains a one-parameter semigroup of $V$.

---

5If $Q_n$ is a sequence of subsets of $G$, $q \in \limsup_{n \to \infty} Q_n$ if and only if every neighborhood of $q$ meets infinitely many $Q_n$, and $q \in \liminf_{n \to \infty} Q_n$ if and only if every neighborhood of $q$ meets all but finitely many $Q_n$. If $\limsup_{n} Q_n = Q_\infty = \liminf_{n} Q_n$, then $Q_n$ is said to be convergent and $Q_\infty$ is the limit of $Q_n$ [19].

6A one-parameter semigroup of $V$ is given by $\{\exp t\xi : t \geq 0\}$ for some non-zero $\xi \in \text{Lie}(V)$.
5.1. Use of unipotent blowup in the compact $\Gamma \backslash G$ case. In order to demonstrate the significance of this lemma, we present a proof of the following orbit closure theorem, which uses the notion of $U$-minimal subsets. A closed $U$-invariant subset $Y \subset \Gamma \backslash G$ is called $U$-minimal if every $U$ orbit in $Y$ is dense in $Y$. By Zorn’s lemma, any compact $U$-invariant subset of $\Gamma \backslash G$ contains a $U$-minimal subset.

**Theorem 5.2.** Let $\Gamma \subset G$ be a uniform lattice. For any $x \in \Gamma \backslash G$, $xH$ is either closed or dense.

**Proof.** Set $X := xH$. Suppose that $X \neq xH$. By the minimality of the $N$-action on $\Gamma \backslash G$ (Corollary 3.6), it suffices to show that $X$ contains an orbit of $V$.

**Step 1:** For any $U$-minimal subset $Y \subset X$, $YL = Y$ for a one-parameter subgroup $L < AV$.

It suffices to show that $Yg_n = Y$ for some sequence $g_n \to e$ in $AV$. Fix $y_0 \in Y$. As $Y$ is $U$-minimal, there exists $t_n \to \infty$ such that $y_0u_{-t_n} \to y_0$. Write $y_0u_{t_n} = y_0g_n$ for $g_n \in G$. Then $g_n \to e$ in $G - U$, because if $g_n$ belonged to $U$, the orbit $y_0U$ would be periodic, which is a contradiction to the assumption that $\Gamma$ is a uniform lattice and hence contains no parabolic elements. If $g_n \in AN$, then we may take $q_n = g_n$. If $g_n \notin AN$, then by Lemma 5.1, $\limsup_{n \to \infty} U g_n U$ contains a one-parameter semigroup $L$ of $AV$. Hence for any $q \in L$, there exist $t_n, s_n \in \mathbb{R}$ such that $q = \lim u_{t_n} g_n u_{s_n}$. (5.1)

Since $Y$ is compact, $y_0u_{-t_n}$ converges to some $y_1 \in Y$, by passing to a subsequence. Therefore $y_0g_n u_{s_n} = y_0u_{-t_n}(u_{t_n} g_n u_{s_n})$ converges to $y_1q \in Y$. Since $q \in N(U)$ and $Y$ is $U$-minimal, we have

$$y_1qU = y_1Uq = Yq = Y.$$  

This proves the claim.

**Step 2:** There exists a $U$-minimal subset $Y \subset X$ such that $X - y_0H$ is not closed for some $y_0 \in Y$. 

**Figure 8.** Divergence of $U$-orbits of two nearby points.
If $xH$ is not locally closed, i.e., $X - xH$ is not closed, then let $Y$ be any $U$-minimal subset of $X$. If $Y \subset xH$, then for any $y_0 \in Y$, $X - y_0H = X - xH$ is not closed. If $Y \notin xH$, then choose $y_0 \in Y - xH$. If $xH$ is locally closed, then let $Y$ be an $U$-minimal subset of $X - xH$. Then $X - y_0H$ is not closed for any $y_0 \in Y$.

**Step 3:** For $Y$ from Step (2), we have $Y_v \subset X$ for some non-trivial $v \in V$. By Step (2), we have $y_0g_n \in Y$ for some $y_0 \in Y$ and a sequence $g_n \to e$ in $G - H$. If $g_n \in HV$ for some $n$, then the claim follows. If $g_n \notin HV$ for all $n$, then by Lemma 5.1(2), $\limsup_{n \to \infty} Ug_n U$ contains a non-trivial element $v \in V$. Since $v = \lim u_{t_n} g_n u_{s_n}$ for some $t_n, s_n$, we deduce $Yv \subset X$ as in Step (1).

**Step 4:** $X$ contains a $V$-orbit. It suffices to show that $X$ contains $x_0V_+$ for a one-parameter semigroup $V_+$ of $V$; because if $v_n \to \infty$ in $V_+$ and $x_0v_n \to x_1$, then

$$x_1V = x_1 \cdot \limsup_n (v_n^{-1}V_+) \subset \overline{x_0V_+} \subset X.$$ 

Let $Y \subset X$ be a $U$-minimal subset from Step 2. By Step 1, $YL \subset Y$ where $L$ is either $V$ or $v_0Av_0^{-1}$ for some $v_0 \in V$. If $L = V$, this finishes the proof. If $L = A$, then by Step 3, we get $Yv = Yv(v^{-1}Av) \subset X$. Hence we get $X \supset x_0v^{-1}AvA$ for some $x_0 \in X$ and a non-trivial $v \in V$. Since $v^{-1}AvA$ contains a one-parameter semigroup of $V$, this finishes the proof.

We highlight the importance of $(5.1)$ from the above proof: if $q$ belongs to the set $\limsup_{n \to \infty} Ug_n U$ in Lemma 5.1, i.e., $q = \lim_{n \to \infty} u_{t_n} g_n u_{s_n}$ for some $t_n, s_n \in \mathbb{R}$, then the size of $t_n$ and $s_n$ are essentially determined by the sequence $g_n \to e$, up to multiplicative constants. On the other hand, we need the convergence of the sequence $y_0u_{-t_n}$ in order to derive $Yq \subset Y$. That is, if $y_0u_{-t_n}$ diverges, which will be typical when $\Gamma \setminus G$ is not compact, Lemma 5.1, whose proof depends on the polynomial property of unipotent action, does not lead anywhere in the study of orbit closure problem.

**5.2. Unipotent blowup and renormalizations of the return time.** Loosely speaking, for a given $y_0 \in \Gamma \setminus G$, we now would like to understand the set

$$\limsup_{n \to \infty} Tg_n U$$

where $T$ is the recurrence time of $y_0U$ into a fixed compact subset of $\Gamma \setminus G$. Most of time, $\limsup_{n \to \infty} Tg_n U$ may be empty. In order to make sure that this set is non-trivial enough for our purpose, we need a certain polynomial $\phi(t)$ (cf. proof of Lemma 5.1).
5.5) not to vanish on the renormalized set \( \limsup \lambda_n^{-1} T \) where \( \lambda_n > 0 \) is a sequence whose size is dictated by the speed of convergence of the sequence \( g_n \to e \). Since we do not have a control on \( g_n \) in general, the following condition on \( T \), or more generally on a sequence \( T_n \), is necessary for an arbitrary sequence \( \lambda_n \to \infty \).

**Definition 5.3.** We say that a sequence \( T_n \subset \mathbb{R} \) has accumulating renormalizations if for any sequence \( \lambda_n \to \infty \),

\[
T_\infty := \limsup_{n \to \infty} \lambda_n^{-1} T_n
\]

accumulates both at 0 and \( \infty \).

That is, \( T_\infty \) contains a sequence tending to 0, as well as a sequence tending to \( \infty \). We allow a constant sequence \( T_n \) in this definition.

The following lemma is immediate:

**Lemma 5.4.** If there exists \( \kappa > 1 \) such that each \( T_n \) is \( \kappa \)-thick in the sense that for all \( r > 0 \), \( T_n \cap \pm \left[ r, \kappa r \right] \neq \emptyset \), then the sequence \( T_n \) has accumulating renormalizations.

We now present a refined version of Lemma 5.1, which will be a main tool in the study of \( U \)-orbits in the infinite volume homogeneous space: via the map \( t \mapsto u_t \), we identify \( \mathbb{R} \) whose size is dictated by the speed of convergence of the sequence.

**Lemma 5.5** *(Unipotent blowup).* Let \( T_n \subset U \) be a sequence with accumulating renormalizations.

1. For any \( g_n \to e \) in \( G - AN \), the subset \( AV \cap \left( \limsup_{n \to \infty} T_n g_n U \right) \) accumulates at \( e \) and \( \infty \).
2. For any \( g_n \to e \) in \( G - VH \), the subset \( V \cap \left( \limsup_{n \to \infty} T_n g_n H \right) \) accumulates at \( e \) and \( \infty \).
3. For any \( g_n \to e \) in \( \exp \mathfrak{h}^\perp - V \), the subset \( V \cap \left( \limsup_{n \to \infty} \left\{ u_t g_n u_{-t} : t \in T_n \right\} \right) \) accumulates at \( e \) and \( \infty \).

**Proof.** For (1), we will find a sequence \( \lambda_n \to \infty \) (depending on \( g_n \)) and a rational map \( \psi : \mathbb{R} \to AV \) such that for \( T_\infty := \limsup_{n \to \infty} \lambda_n^{-1} T_n \),

- \( \psi(T_\infty) \subset \limsup_{n \to \infty} T_n g_n U \);
- \( \psi(T_\infty) \) accumulates at \( e \) and \( \infty \).

The construction of \( \psi \) follows the arguments of Margulis and Tomanov [31]. Since \( U \) is a real algebraic subgroup of \( G \), by Chevalley’s theorem, there exists an \( \mathbb{R} \)-regular representation \( G \to \text{GL}(W) \) with a distinguished point \( p \in W \) such that \( U = \text{Stab}_G(p) \). Then \( pG \) is locally closed, and

\[
N(U) = \{ g \in G : pg u = pg \text{ for all } u \in U \}.
\]

Set \( \mathcal{L} := VAMN^+ \) where \( N^+ \) is the transpose of \( N \). Then \( U \mathcal{L} \) is a Zariski dense open subset of \( G \) and \( p \mathcal{L} \) is a Zariski open neighborhood of \( p \) in the Zariski closure of \( pG \). We choose a norm on \( W \) so that \( B(p, 1) \cap pG \subset p \mathcal{L} \), where \( B(p, 1) \subset W \) denotes the closed ball of radius 1 centered at \( p \).

Without loss of generality, we may assume \( g_n \in U \mathcal{L} \) for all \( n \). For each \( n \), define \( \tilde{\phi}_n : \mathbb{R} \to W \) by

\[
\tilde{\phi}_n(t) = pg_n u_t.
\]
which is a polynomial of degree uniformly bounded for all \( n \). Define \( \lambda_n \geq 0 \) by

\[
\lambda_n := \sup \{ \lambda \geq 0 : \phi_n[-\lambda, \lambda] \subseteq B(p, 1) \}.
\]

As \( g_n \not\in N(U) = AN \), \( \phi_n \) is non-constant, and hence \( \lambda_n < \infty \). As \( \phi_n(0) = pg_n \to p \), we have \( \lambda_n \to \infty \). We reparametrize \( \phi_n \) using \( \lambda_n \):

\[
\phi_n(t) := \phi_n(\lambda_n t).
\]

Then for all \( n \),

\[
\phi_n[-1, 1] \subseteq B(p, 1).
\]

Therefore the sequence \( \phi_n \) forms an equicontinuous family of polynomials, and hence, after passing to a subsequence, \( \phi_n \) converges to a polynomial

\[
\phi : \mathbb{R} \to pG \subseteq W
\]

uniformly on every compact subset of \( \mathbb{R} \). Note that \( \phi \) is non-constant, since \( \phi(0) = p \) and \( \max \|\phi(\pm 1)\| = 1 \). As the map \( \rho : \mathcal{L} \to p\mathcal{L} \) defined by \( \ell \mapsto p\ell \) is a regular isomorphism, and \( p\mathcal{L} \) is a Zariski open neighborhood of \( p \) in the Zariski closure of \( pG \), we now get a rational map \( \psi : \mathbb{R} \to \mathcal{L} \) given by

\[
\psi(t) = \rho^{-1}(\phi(t)).
\]

If we define \( \psi_n(t) \) as the unique \( \mathcal{L} \)-component of \( g_n u_t \) in the \( \mathcal{U} \mathcal{L} \) decomposition, that is, \( g_n u_t = u_{s_n} \psi_n(t) \) for some \( s_n \in \mathbb{R} \), then

\[
\psi(t) = \lim_{n \to \infty} \psi_n(\lambda_n t)
\]

where the convergence is uniform on compact subsets of \( \mathbb{R} \). It is easy to check that \( \text{Im} \psi \subseteq N(U) \cap \mathcal{L} = \mathcal{A} \mathcal{V} \) using (5.2).

Set

\[
T_{\infty} := \limsup_{n \to \infty} \lambda_n^{-1} T_n.
\]

By the hypothesis on \( T_n \), \( T_{\infty} \) accumulates at 0 and \( \infty \). Since \( \psi : \mathbb{R} \to \mathcal{A} \mathcal{V} \) is a non-constant rational map with \( \psi(0) = e \), \( \psi(T_{\infty}) \) accumulates at 0 and \( \infty \).

Letting \( t \in T_{\infty} \), choose a sequence \( t_n \in T_n \) such that \( \lim_{n \to \infty} \lambda_n^{-1} t_n = t \). Since \( \psi_n \circ \lambda_n \to \psi \) uniformly on compact subsets,

\[
\psi(t) = \lim_{n \to \infty} (\psi_n \circ \lambda_n)(\lambda_n^{-1} t_n) = \lim_{n \to \infty} \psi_n(t_n) = \lim_{n \to \infty} u_{s_n} g_n u_{t_n}.
\]

for some sequence \( s_n \in \mathbb{R} \). Hence

\[
\psi(T_{\infty}) \subset \limsup_{n \to \infty} U g_n T_n.
\]

By applying this argument to \( g_n^{-1} \), we may switch the position of \( U \) and \( T_n \), and hence finish the proof of (1).

To prove (2), by modifying \( g_n \) using an element of \( H \), we may assume that \( g_n = \exp q_n \in \exp \mathfrak{h}^+ - V \). Hence (2) follows from (3). We define a polynomial \( \psi_n : \mathbb{R} \to \mathfrak{h}^+ \) by

\[
\psi_n(t) = u_t q_n u_{-t} \quad \text{for all } t \in \mathbb{R}.
\]

Since \( g_n \not\in V \) and hence does not commute with \( U \), \( \psi_n \) is a nonconstant polynomial. Define

\[
\lambda_n := \sup \{ \lambda \geq 0 : \psi_n([-\lambda, \lambda]) \subseteq B(0, 1) \}
\]

where \( B(0, 1) \) is the closed unit ball around 0 in \( \mathfrak{h}^+ \). Then \( 0 < \lambda_n < \infty \) and \( \lambda_n \to \infty \).
Now the rescaled polynomials \( \phi_n = \psi_n \circ \lambda_n : \mathbb{R} \to \mathfrak{h}^\perp \) form an equicontinuous family of polynomials of uniformly bounded degree and \( \lim_{n \to \infty} \phi_n(0) = 0 \). Therefore \( \phi_n \) converges to a non-constant polynomial

\[
\phi : \mathbb{R} \to \mathfrak{h}^\perp
\]

uniformly on compact subsets.

We claim that \( \text{Im}(\phi) \subset \text{Lie}(V) \). For any fixed \( s, t \in \mathbb{R} \),

\[
\begin{align*}
    u_s \phi(t) u_{-s} &= \lim_{n \to \infty} u_{\lambda_n t + s} g_n u_{-\lambda_n t - s} \\
    &= \lim_{n \to \infty} u_{\lambda_n (t + \lambda_n^{-1} s)} g_n u_{-\lambda_n (t + \lambda_n^{-1} s)} \\
    &= \lim_{n \to \infty} u_{\lambda_n t} g_n u_{-\lambda_n t} = \phi(t).
\end{align*}
\]

Hence \( \phi(t) \) commutes with \( U \). Since the centralizer of \( U \) in \( \mathfrak{h}^\perp \) is equal to \( \text{Lie}(V) \), the claim follows. Define \( \psi : \mathbb{R} \to V \) by \( \psi(t) = \exp(\phi(t)) \), noting that \( \exp : \text{Lie}(V) \to V \) is an isomorphism. Setting

\[
T_\infty := \limsup_{n \to \infty} \lambda_n^{-1} T_n,
\]

we deduce that \( \psi(T_\infty) \) accumulates at \( e \) and \( \infty \). For any \( t \in T_\infty \), we choose \( t_n \in T_n \) so that \( t = \lim \lambda_n^{-1} t_n \). Then

\[
\psi(t) = \lim_{n \to \infty} u_{t_n} g_n u_{-t_n},
\]

as \( \phi_n(t) \to \phi(t) \) uniformly on compact subsets. Hence,

\[
\psi(T_\infty) \subset V \cap \left( \limsup_{n \to \infty} \{ u_{t} g_n u_{-t} : t \in T_n \} \right).
\]

This completes the proof of (3). \( \square \)

5.3. **Relative minimal sets and additional invariance.** Let \( \Gamma < G \) be a discrete subgroup. Let \( X \subset \Gamma \backslash G \) be a closed \( H \)-invariant subset with no periodic \( U \)-orbits\(^7\). Let \( W \subset \Gamma \backslash G \) be a compact subset such that \( X \cap W \neq \emptyset \). We suppose that for any \( y \in X \cap W \),

\[
(5.3) \quad T(y) := \{ t \in \mathbb{R} : y u_t \in W \}
\]

has accumulating renormalizations.

Under this hypothesis, we can obtain analogous steps to Step (1) and (3) in the proof of Theorem 5.2 for relative \( U \)-minimal subsets of \( X \). Since \( X \) is not compact in general, a \( U \)-minimal subset of \( X \) may not exist. Hence we consider a relative \( U \)-minimal subset of \( X \) instead.

**Definition 5.6.** A closed \( U \)-invariant subset \( Y \subset X \) is called \( U \)-minimal with respect to \( W \), if \( Y \cap W \neq \emptyset \) and \( yU \) is dense in \( Y \) for every \( y \in Y \cap W \).

As \( W \) is compact, it follows from Zorn’s lemma that \( X \) always contains a \( U \)-minimal subset with respect to \( W \).

**Lemma 5.7** (Translates of \( Y \) inside of \( Y \)). Let \( Y \subset X \) be a \( U \)-minimal subset with respect to \( W \). Then

\[
Y L \subset Y
\]

for some one-parameter semigroup \( L < AV \).

\(^7\)The case when \( X \) contains a periodic \( U \)-orbit turns out to be more manageable; see [4, Prop. 4.2]
Proof. It suffices to find a sequence $g_n \to e$ in $AV$ such that $y_0 g_n \subset Y$.

Fix $y_0 \in Y \cap W$. We claim that there exists $g_n \to e$ in $G - U$ such that

$$y_0 g_n \in Y \cap W.$$ 

By the minimality assumption on $Y$, there exists $t_n \to \infty$ in $T(y_0)$ so that $y_0 u_{t_n}$ converges to $y_0 \in Y \cap W$ (cf. [4, Lemma 8.2]). Hence there exists $g_n \to e$ such that

$$y_0 u_{t_n} = y_0 g_n.$$ 

Then $g_n \notin U$, because if $g_n$ belonged to $U$, $y_0 U$ would be periodic, contradicting the assumption that $X$ contains no periodic $U$-orbit.

Case (1): $g_n \in AN$. By modifying $g_n$ with elements of $U$, we may assume that $g_n \in AV$. Since $g_n \in N(U)$ and $y_0 \in Y \cap W$, we get $y_0 U g_n = y_0 g_n U \subset Y$ and hence

$$\overline{y_0 U g_n} = y_0 g_n \subset Y.$$ 

Case (2): $g_n \notin AN$. By Lemma 5.5, for any neighborhood $O$ of $e$, there exist $t_n \in T(y_0)$ and $s_n \in \mathbb{R}$ such that $u_{-s_n} g_n u_{s_n}$ converges to some $q \in (AV - \{e\}) \cap O$. Since $y_0 u_{t_n} \in W$ and $W$ is compact, $y_0 u_{t_n}$ converges to some $y_1 \in Y \cap W$, by passing to a subsequence. Therefore as $n \to \infty$,

$$y_0 u_{t_n} = (y_0 u_{t_n})(u_{-s_n} g_n u_{s_n}) \to y_1 q \in Y.$$ 

As $y_1 \in Y \cap W$ and $q \in N(U)$, it follows $Y q \subset Y$. Since such $q$ can be found in any neighborhood of $e$, this finishes the proof.

Lemma 5.8 (One translate of $Y$ inside of $X$). Let $Y \subset X$ be a $U$-minimal subset with respect to $W$ such that $X - y_0 H$ is not closed for some $y_0 \in Y \cap W$. Then

$$Y v \subset X$$ 

for some non-trivial $v \in V$.

Proof. By the hypothesis, there exists $g_n \to e$ in $G - H$ such that $y_0 g_n \in X$.

If $g_n \in VH$ for some $n$, the claim is immediate as $X$ is $H$-invariant. If $g_n \notin VH$ for all $n$, by Lemma 5.5, there exist $t_n \in T(y_0)$ and $h_n \in H$ so that $u_{-t_n} g_n h_n$ converges to some non-trivial $v \in V$. Since $y_0 u_{t_n}$ belongs to the compact subset $W$, by passing to a subsequence $y_0 u_{t_n}$ converges to some $y_1 \in Y \cap W$. Hence $y_0 g_n h_n = y_0 u_{t_n}(u_{-t_n} g_n h_n)$ converges to $y_1 v$. By the minimality of $Y$ with respect to $W$, we get $Y v \subset Y$, as desired.

For a subset $I \subset \mathbb{R}$, we write $V_I = \{u_{it} : t \in I\}$. When the conditions for Lemmas 5.7 and 5.8 are met, we can deduce that $X$ contains some interval of an $V$-orbit:

Lemma 5.9. Let $X$ be a closed $H$-invariant subset of $\Gamma \backslash G$ containing a compact $A$-invariant subset $W$. Let $Y \subset X$ be a $U$-minimal subset with respect to $W$. Suppose

1. $Y L \subset Y$ for some one-parameter semigroup $L < AV$;
2. $Y v \subset X$ for some non-trivial $v \in V$.

Then $X$ contains $x_0 V_I$ for some $x_0 \in W$ and an interval $0 \in I$.

Proof. Any one-parameter semigroup $L < AV$ is either a one-parameter semigroup $V_+ < V$ or $v_0 A_+ v_0^{-1}$ for some $v_0 \in V$ and a one-parameter semigroup $A_+ < A$.

Case (a). If $L = V_+$, we are done.

Case (b). If $L = v_0 A_+ v_0^{-1}$ for a non-trivial $v_0 \in V$, then

$$X \supset Y(v_0 A_+ v_0^{-1}) A.$$
Since \( v_0 A v_0^{-1} A \) contains \( V_I \) for some interval \( 0 \in I \), the claim follows.

**Case (c).** If \( L = A_+ \), we first note that \( YA \subset Y \); take any sequence \( a_n \to \infty \) in \( A_+ \), and \( y_0 \in Y \cap W \). Then \( y_0 a_n \in Y \cap W \) converges to some \( y_1 \in Y \cap W \). Now \( \limsup_{n \to \infty} a_n^{-1} A_+ = A \). Therefore \( Y \supset y_1 A \). Since \( y_1 U = Y \), we get \( Y \supset Y A \).

Since \( AvA \) contains a semigroup \( V_+ \) of \( V \), we deduce \( X \supset Y v A \supset Y Av A \supset Y V_+ \).

\( \square \)

In the next section, we discuss the significance of the conclusion that \( X \) contains a segment \( x_0 V_I \) depending on the relative location of \( x_0 \) to \( \partial \text{core } M \).

### 6. Interior frames and boundary frames

Let \( \Gamma < G \) be a Zariski dense geometrically finite group, and let \( M = \Gamma \backslash \mathbb{H}^3 \). When \( M \) has infinite volume, its convex core has a non-empty boundary, which makes the dynamical behavior of a frame under geometric flows different depending on its relative position to \( \partial \text{core } M \).

Recall the notation \( F_\Lambda \) from (4.2). We denote by \( F^* \) the interior of \( F_\Lambda \), and \( \partial F \) the boundary of \( F_\Lambda \). We explain that in order to show that a given closed \( H \)-invariant subset \( X \subset F_\Lambda \) with no periodic \( U \)-orbits is equal to \( F_\Lambda \), it suffices to show that \( X \) contains \( x_0 V_I \) for some \( x_0 \in F^* \cap RF_+ M \) and an interval \( 0 \in I \) (Lemma 6.1). It is important to get \( x_0 \in F^* \), as the similar statement is not true if \( x_0 \in \partial F \). For example, in the rigid acylindrical case, if \( x_0 \in \partial F \), then \( x_0 H V_+, H \) is a closed \( H \)-invariant subset of \( \partial F \) for a certain semigroup \( V_+ \subset V \) (cf. Theorem 7.1 below), and hence if \( V_I \) belongs to \( V_+ \), we cannot use \( x_0 V_I \) to obtain useful information on \( X \cap F^* \).

#### 6.1. Interior frames

In this section, we assume that \( \Lambda \) is connected. Under this hypothesis, the closed \( H \)-invariant set \( F_\Lambda = RF_+ M \cdot H \) has non-empty interior which can be described as follows:

\[
F^* = \{ [g] \in \Gamma \backslash G : \pi(P_g) \cap M^* \neq \emptyset \} = \bigcup \{ xH \subset \Gamma \backslash G : p(xH) \cap M^* \neq \emptyset \}
\]

where \( M^* \) denotes the interior of core \( M \).

The condition \( \pi(P_g) \cap M^* \neq \emptyset \) is equivalent to the condition that the circle \( C_g = \partial P_g \) separates the limit set \( \Lambda \), that is, both components of \( S^2 - C_g \) intersects \( \Lambda \) non-trivially. If we set

\[
C^* := \{ C \in \mathcal{C} : C \text{ separates } \Lambda \},
\]

we have

\[
F^*/H = \Gamma \backslash C^*.
\]

We observe that the connectedness of \( \Lambda \) implies the following two equivalent statements:

1. For any \( C \in C^* \), \( \#C \cap \Lambda \geq 2 \);
2. \( F^* \cap RF_+ M \subset RF M \cdot U \)
By the openness of $F^*$ and (2) above, for any $x \in F^* \cap RF_+ M$, there exists a neighborhood $O$ of $e$ in $G$ such that

\begin{equation}
O \cap RF_+ M \subset RF M \cdot U.
\end{equation}

Thanks to this stability, we have the following lemma:

**Lemma 6.1.** Let $X \subset F_\Lambda$ be a closed $H$-invariant subset intersecting $RF M$ and with no periodic $U$-orbits. If $X$ contains $x_0 v_I$ for some $x_0 \in F^* \cap RF_+ M$ and an interval $0 \in I$, then

$$X = F_\Lambda.$$

**Proof.** It suffices to find $z_0 V$ inside $X$ for some $z_0 \in RF M$ by Theorem 3.6. Without loss of generality, we may assume $I = [0, s]$ for some $s > 0$. We write $v_t := u_{i t}$. Since $x_0 \in F^* \cap RF_+ M$, there exists $0 < \varepsilon < s$ such that $x_0 v_{\varepsilon} \in X \cap RF M \cdot U$ by (6.1). Hence there exists $x_1 \in x_0 v_{\varepsilon} U \cap RF M \cap X$; so $x_1 v_{\varepsilon}^{-1} v_I = x_1 V_{[-\varepsilon, s - \varepsilon]} \subset X$. Since $X$ has no periodic $U$-orbit, $x_1 t$ is a radial limit point of $\Lambda$, and hence there exists $t_n \to +\infty$ such that $x_1 a_t$ converges to some $z_0 \in RF M$. Since

$$\limsup_{n \to \infty} a_{-\varepsilon}^{-1} V_{[-\varepsilon, s - \varepsilon]} a_{t_n} = V$$

and $x_1 V_{[-\varepsilon, s - \varepsilon]} a_{t_n} = x_1 a_t (a_{-\varepsilon}^{-1} V_{[-\varepsilon, s - \varepsilon]} a_{t_n}) \subset X$, we obtain $z_0 V \subset X$ as desired. \qed

### 6.2. Boundary frames

The geometric structure of the boundary $\partial F = F_\Lambda - F^*$ plays an important (rather decisive) role in the rigidity study. For instance, unless $x H$ is bounded, $x H$ is expected to accumulate on $\partial F$. In the most dramatic situation, all the accumulation of $x H$ may fall into the boundary $\partial F$ so that $x H \subset x H \cup \partial F$. Unless we have some analysis on what possible closed $H$-invariant subsets of $\partial F$ are, there isn’t too much more we can say on such situation.

A geodesic plane $P \subset \mathbb{H}^3$ is called a supporting plane if it intersects hull($\Lambda$) and one component of $\mathbb{H}^3 - P$ is disjoint from hull($\Lambda$), or equivalently, the circle $C = \partial P$ is a supporting circle in the sense that $\# C \cap \Lambda \geq 2$ and $C$ does not separate $\Lambda$.

For $C \in \mathcal{C}$, we denote by $\Gamma^C$ the stabilizer of $C$ in $\Gamma$. The theory of bending laminations yields:

**Theorem 6.2.** [37, Theorem 5.1] For any supporting circle $C \in \mathcal{C}$,

1. $\Gamma^C$ is a finitely generated Fuchsian group;
2. there exists a finite subset $\Lambda_0 \subset C \cap \Lambda$ such that

$$C \cap \Lambda = \Lambda(\Gamma^C) \cup \Gamma^C \Lambda_0$$

where $\Lambda(\Gamma^C)$ denotes the limit set of $\Gamma^C$.

**Definition 6.3.** We call $x \in \partial F$ a boundary frame, and call $x = [g] \in \partial F$ a thick boundary frame if there exists a supporting circle $C$ with non-elementary stabilizer $\Gamma^C$ such that $C_g = C$ or $C_g$ is tangent to $C$ at $g^+ \in \Lambda(\Gamma^C)$.

**Theorem 6.4.** If $x \in \partial F$ is a thick boundary frame such that $x U$ is not closed, then $x U \supset x v a v^{-1}$ for some $v \in V$. If $x \in RF M$ in addition, then $x U \supset x A$.

**Proof.** Choose $g \in G$ so that $[g] = x$. By the hypothesis on $x$, there exists a supporting circle $C$ with $\Gamma^C$ non-elementary and $g^+ \in \Lambda(\Gamma^C)$. The circle $C_g$ is equal to $C$ or tangent to $C$ at $g^+$. It follows that there exists $v \in V$ such that $C = C_g v$. By Theorem 6.2, the stabilizer $\Gamma^C$ is finitely generated and non-elementary. It now
follows from a theorem Dalbo [10] that \( xvU \) is either periodic (if \( g^+ = (gv)^+ \) is a parabolic fixed point of \( \Gamma^C \)) or \( xvU \) contains \( xvH \cap \text{RF}_+M \supset xvA \). Since \( v \) commutes with \( U \), the first claim follows. If \( x \in \text{RF} M \) in addition, then \( C_g \) must be equal to \( C \), and hence \( v = e \).

**Lemma 6.5.** Let \( X \subset F_\Lambda \) be a closed \( H \)-invariant subset intersecting \( \text{RF} M \) and with no periodic \( U \)-orbits. If \( X \cap F^* \) contains \( zv_0 \) for some thick boundary frame \( z \in \partial F \cap \text{RF} M \) and \( v_0 \in V - \{e\} \), then

\[ X = F_\Lambda. \]

**Proof.** By Lemma 6.1, it suffices to find \( x_0V_I \) inside \( X \) for some \( x_0 \in F^* \) and an interval \( 0 \in I \). By Theorem 6.4, we have \( zU \supset zA \). Therefore

\[ X \supset zv_0U\overline{A} = zv_0V_+ \overline{A} \supset zA \overline{V}_+ \supset zV_+ \]

where \( V_+ \) is the one-parameter semigroup contained in \( V \cap A \overline{V}_0A \). Since \( zv_0 \in zV_+ \cap F^* \neq \emptyset \), and \( F^* \) is open, \( zv_0V_I \subset zV_+ \cap F^* \) for some interval \( 0 \in I \), as desired. \( \square \)

7. Rigid acylindrical groups and circular slices of \( \Lambda \)

Let \( \Gamma < G \) be a rigid acylindrical Kleinian group, and \( M := \Gamma \backslash H^3 \) the associated hyperbolic 3-manifold. We assume \( \text{Vol}(M) = \infty \).

7.1. **Boundary frames for rigid acylindrical groups.** In this case, we have a complete understanding of the orbit closures in the boundary \( \partial F \); which makes it possible to give a complete classification for all orbit closures in \( F \).

When \( \Gamma \) is rigid acylindrical, \( \text{every} \) supporting circle \( C \) is contained in the limit set, so that \( C \cap \Lambda = C \). It follows that \( \Gamma^C \) is a uniform lattice of \( G^C \) and the orbit \( xH = p(\gamma H) \) is compact whenever \( C_g \) is a supporting circle. This implies:

**Theorem 7.1.** [35] Let \( \Gamma \) be rigid acylindrical, and let \( x \in \partial F \) be a boundary frame.

1. If \( x \in \text{RF}_+M \), then
   \[ \overline{xU} = xvHv^{-1} \quad \text{for some} \ v \in V. \]
2. If \( x \in \text{RF} M \), then \( xH \) is compact.
3. If \( x \in \text{RF}_+M - \text{RF} M \), there exist a one-parameter semigroup \( V_+ \) of \( V \) and a boundary frame \( x_0 \in \partial F \) with \( x_0H \) compact such that
   \[ \overline{TH} = x_0HV_+H. \]

7.2. **Circular slices of \( \Lambda \).** Circular slices of the limit set \( \Lambda \) control the recurrence time of \( U \)-orbits into the compact subset \( \text{RF} M \). For \( x \in \text{RF} M \), set

\[ T(x) := \{ t \in \mathbb{R} : xu_t \in \text{RF} M \}. \]

If \( x = [g] \), then \( (gu_t)^+ = g^+ \in C_g \cap \Lambda \) and hence

\[ t \in T(x) \text{ if and only if } (gu_t)^- \in C_g \cap \Lambda. \]

We will use the following geometric fact for a rigid acylindrical manifold \( M \): if we write \( S^2 - \Lambda = \bigcup B_i \) where \( B_i \)'s are round open disks, then

\[ \inf_{i \neq j} d(\text{hull}(B_i), \text{hull}(B_j)) \geq \varepsilon_0 \]
Figure 10. Circular slice of Λ

where \(2\varepsilon_0\) is the systol of the double of the convex core of \(M\). This follows because a geodesic in \(\mathbb{H}^3\) which realizes the distance \(d(\text{hull}(B_i), \text{hull}(B_j))\) is either a closed geodesic in \(M\) or the half of a closed geodesic in the double of core(\(M\)).

**Proposition 7.2.** Let \(\Gamma\) be rigid acylindrical. There exists \(\kappa > 1\) such that for all \(x \in RF M\), \(T(x)\) is \(\kappa\)-thick. In particular, for any sequence \(x_i \in RF M\), \(T(x_i)\) has accumulating renormalizations.

**Proof.** For \(\varepsilon_0 > 0\) given by (7.1), consider the upper-half plane model of \(\mathbb{H}^2 = \{(x_1, 0, y) : x_1 \in \mathbb{R}, y > 0\}\). For \(a < b\), \(\text{hull}_{\mathbb{H}^2}(a, b) \subset \mathbb{H}^2\) denotes the convex hull of the interval connecting \((a, 0, 0)\) and \((b, 0, 0)\). Define \(\kappa > 1\) by the equation

\[d_{\mathbb{H}^2}(\text{hull}(-\kappa, -1), \text{hull}(1, \kappa)) = \varepsilon_0/2;\]

since \(\lim_{s \to \infty} d_{\mathbb{H}^2}(\text{hull}(-s, -1), \text{hull}(1, s)) = 0\), such \(\kappa > 1\) exists.

Since \(z \mapsto tz\) is a hyperbolic isometry in \(\mathbb{H}^2\) for any \(t > 0\), we have

\[d_{\mathbb{H}^2}(\text{hull}(-\kappa t, -t), \text{hull}(t, \kappa t)) = \varepsilon_0/2.\]

We now show that \(T(x)\) is \(\kappa\)-thick for \(x \in RF M\). It suffices to show the claim for \(x = [g]\) where \(g = (e_1, e_2, e_3)\) is based at \((0, 0, 1)\) with \(e_2\) in the direction of the positive real axis and \(g^+ = \infty, g^- = 0\). Note that \(гу_1 \in RF M\) if and only if \(t = (gu_1)^{-} \in \Lambda\) and hence

\[T(x) = \mathbb{R} \cap \Lambda.\]

Suppose that \(T(x)\) is not \(\kappa\)-thick. Then for some \(t > 0\), \(T(x)\) does not intersect \([-\kappa t, -t] \cup [t, \kappa t]\), that is, \([-\kappa t, -t] \cup [t, \kappa t] \subset \bigcup B_i\). Since \(B_i\)'s are convex and \(0 \in \Lambda\), there exist \(i \neq j\) such that \([-\kappa t, -t] \subset B_i\) and \([t, \kappa t] \subset B_j\). Hence

\[d(\text{hull}(-\kappa t, -t), \text{hull}(t, \kappa t)) = \varepsilon_0/2 \geq d(\text{hull}(B_i), \text{hull}(B_j)) \geq \varepsilon_0,\]

yielding contradiction. The second claim follows from Lemma 5.4. \(\square\)

**7.3. Closed or dense dichotomy for \(H\)-orbits.** In Theorem 7.1, we have described all possible orbit closures for \(H\) and \(U\)-action inside \(\partial F\). It remains to consider orbits of \(x \in F^*\).
Theorem 7.3. [35] For any $x \in F^*$, $xH$ is either closed or dense in $F\Lambda$.

Proof. Set $X := \overline{xH}$, and assume that $X \neq xH$. We then need to show $X = F\Lambda$. Since $F^* \cap RF^+ M \subset RF M \cdot U$, and $xH \subset F^* \cap RF^+ M \cdot H$, we may assume without loss of generality that $x = [g] \in RF M$.

Set $W := X \cap F^* \cap RF M$.

Case 1: $W$ is not compact. In this case, there exists $x_n \in W$ converging to some $z \in \partial F \cap RF M$. Write $x_n = zg_n$ with $g_n \to e$ in $G - H$.

Suppose that $g_n = h_n u_n \in HV$ for some $n$. Since $zh_n \in zH \subset \partial F \cap RF M$ and $(zh_n)v_n \in F^* \cap RF M$, the claim follows from Lemma 6.5.

Now suppose that $g_n \notin HV$ for all $n$. By Lemma 5.5, there exist $t_n \in T(x_n)$ and $h_n \in H$ such that $h_n g_n u_n$ converges to some $v \in V - \{e\}$. Since $zH$ is compact, $zh_n^{-1}$ converges to some $z_0 \in \partial F \cap RF M$ by passing to a subsequence. Hence, as $n \to \infty$,

$$x_n u_n = zh_n^{-1}(h_n g_n u_n) \to z_0 v.$$ 

Since $z_0 \in \partial F \cap RF M$ and $z_0 v \in RF M$, we get $z_0 v \in F^*$; hence the claim follows by Lemma 6.5.

Case 2: $W$ is compact. It follows from the definition of $W$ that for any $x \in W$,

$$T(x) = \{t : xu_t \in W\}.$$ 

We claim that $X$ contains a $U$-minimal subset $Y$ with respect to $W$ such that $X - y_0 H$ is not closed for some $y_0 \in W$. We divide our proof into two cases:

Case (a). Suppose that $xH$ is not locally closed, i.e., $X - xH$ is not closed. First, if $Y \cap W \subset xH$, then choose any $y_0 \in Y \cap W$. Observe that $\overline{xH} - y_0 H = \overline{xH} - xH$ is not closed, which implies the claim. If $Y \cap W \notin xH$, choose $y_0 \in (Y \cap W) - xH$. Then $\overline{xH} - y_0 H$ contains $xH$, and hence cannot be closed.

Case (b). Suppose that $xH$ is locally closed, and $X - xH$ intersects $W$ non-trivially. Therefore $X - xH$ contains a $U$-minimal subset $Y$ with respect to $W$. Then any $y_0 \in Y \cap W$ has the desired property; since $y_0 \in X - xH$, there exists $h_n \in H$ such that $x h_n \to y$. If we write $x h_n = y g_n$, then $g_n \to e$ in $G - H$, since $y \notin xH$.

By Lemmas 5.7, 5.8 and 5.9, $X$ contains $x_0 V_I$ for some $x_0 \in W$ and for an interval $I \in I$; since $x_0 \in F^*$, this finishes the proof by Lemma 6.1.

7.4. Topological rigidity of geodesic planes. In ([35], [36]), the following theorem was also obtained:

Theorem 7.4. Let $M$ be a rigid acylindrical hyperbolic 3-manifold. Then

1. any geodesic plane $P$ intersecting core $M$ is either properly immersed or dense;

2. the fundamental group of a properly immersed $P$ intersecting core $M$ is a non-elementary Fuchsian subgroup;

3. there are at most countably many properly immersed geodesic planes in $M$ intersecting core $M$;

4. any infinite sequence of geodesic planes $P_i$ intersecting core $M$ becomes dense in $M$, i.e., $\lim P_i = M$.

Remark 7.5. (1) There exists a closed arithmetic hyperbolic 3-manifold $\Gamma \setminus \mathbb{H}^3$ without any properly immersed geodesic plane, as shown by Maclachlan-Reid [24].
(2) When $M$ has finite volume and has at least one properly immersed geodesic plane, then $M$ is arithmetic if and only if there are infinitely many properly immersed geodesic planes ([30], [3]).

(3) A natural question is whether a rigid acylindrical hyperbolic 3-manifold $M$ necessarily covers an arithmetic hyperbolic 3-manifold if there exists infinitely many properly immersed (unbounded) geodesic planes intersecting its core. The reason for the word “unbounded” in the parenthesis is that in any geometrically finite hyperbolic 3-manifold of infinite volume, there can be only finitely many bounded geodesic planes ([35], [4]). In view of the proofs given in ([30], [3]), the measure-theoretic equidistribution of infinitely many closed $H$-orbits needs to be understood first.

7.5. Classification of $U$-orbit closures. In the rigid acylindrical case, the complete classification of the $U$-orbit closures inside $\partial F$ given in Theorem 7.1 can be extended to the whole space $RF_+ M$:

**Theorem 7.6.** [36] For any $x \in RF_+ M$,

$$xU = xL \cap RF_+ M$$

where $L$ is either $v^{-1}Hv$ for some $v \in N$, or $G$.

There are two main features of a rigid acylindrical group which our proof is based on. The first property is that

there exists a compact $H$-orbit in $RF_+ M$,

namely those $[g]H$ whose corresponding plane $P_g$ is a supporting plane. This is a very important feature of $M$ which is a crucial ingredient of our proof. In particular, the following singular set is non-empty:

$$\mathcal{S}(U) = \bigcup zHV \cap RF_+ M.$$  

where the union is taken over all closed $H$ orbits $zH$.

We set

$$\mathcal{G}(U) := RF_+ M - \mathcal{S}(U)$$

and call it the generic set. Note that

$$\mathcal{G}(U) \subset F^*.$$  

The second property is the following control on the pre-limiting behavior of $RF M$-points, whose proof is based on the totally geodesic nature of $\partial core M$.

**Lemma 7.7.** [36, Lemma 4.2] If $x_n \in F^*$ converges to some $y \in RF M$, then there exists a sequence $x'_n \in x_n U \cap RF M$ converging to $y$, or converging to some boundary frame $y' \in \partial F \cap RF M$.

For $x \in \mathcal{S}(U)$, Theorem 7.6 follows from a theorem of Hedlund [18] and Dalbo [10] on the minimality of horocyclic action on the Fuchsian case.

**Proposition 7.8.** [36] If $x \in \mathcal{G}(U)$, then

$$xU = RF_+ M.$$
Proof. Setting $X := \overline{xU}$, we first claim that

$$X \cap \mathcal{S}(U) \neq \emptyset.$$  

If $X \cap \partial F \neq \emptyset$, the claim follows from Theorem 7.1(1). Hence we assume that $X \subset F^*$. Let $Y$ be a $U$-minimal subset of $X$ with respect to $RF M$. By Lemma 5.7, $YL \subset Y$ where $L < AV$ is a one-parameter semigroup. If $L$ is a semigroup of $V$, say, $V_+$, then take a sequence $v_n \to \infty$ in $V_+$. Since $YV^+ \subset Y \subset F^* \subset RF M \cdot U$, up to passing to a subsequence, there exists $y_n \in Y$ such that $y_nv_n$ converges to an $RF M$-point, say $y_0$. Then

$$y_0V = \lim_{n \to \infty} (y_nv_n) \cdot \limsup_{n} (v_n^{-1}V_+) \subset \overline{Vv_+} \subset Y.$$  

Hence $Y = X = RF_+ M$, proving the claim. If $L = vA_+ v^{-1}$ for some semigroup $A_+$ of $A$, since $\mathcal{S}(U)$ is $V$-invariant, we may assume that $L = A_+$. Take a sequence $a_n \to \infty$ in $A_+$. Then for any $y \in Y$, $ya_n$ converges to an $RF M$-point, say $y_0 \in Y$, by passing to a subsequence. So

$$y_0A = \lim_{n \to \infty} (ya_n) \cdot \limsup_{n} (a_n^{-1}A_+) \subset \overline{YA_+} \subset Y.$$  

On the other hand, either $y_0 \in \mathcal{S}(U)$ or $\overline{y_0H} = F_\Lambda$ (Theorem 7.3). In the latter case, $\overline{y_0H}$ contains a compact $H$-orbit $zH$. Since $\overline{y_0AU} = \overline{y_0H}$, it follows that $\overline{y_0AU} \cap zH \neq \emptyset$, proving the claim (7.2).

Therefore $X$ contains $\overline{yU} = yHv^{-1} \cap RF_+ M$ for some $y \in \mathcal{S}(U)$. Without loss of generality, we may assume $X \supset yH \cap RF_+ M$ by replacing $x$ with $xv$. Set $Y := yH \cap RF_+ M$, which is a $U$-minimal subset. There exists $s_n \in \mathbb{R}$ such that $y = \lim_{n \to \infty} xu_{s_n}$. In view of Lemma 5.7, we may assume that $xu_{s_n} \in RF M$ for all $n$. Write $xu_{s_n} = yg_n$ for some sequence $g_n \to e$ in $G$. Since $y \in \mathcal{S}(U)$ and $x \in \mathcal{S}(U)$, it follows that $g_n \notin HV$ for all $n$. Hence by Lemma 5.5, there exist $t_n \in T(yg_n)$ and $h_n \in H$ such that $h_ng_{u_{s_n}}$ converges to some $v \in V$; moreover $v$ can be taken arbitrarily large. By passing to a subsequence, $yg_{u_{s_n}}$ converges to some $y_0 \in RF M$, and hence $yh_n^{-1}$ converges to $y_1 := y_0v^{-1} \in yH \cap RF_+ M = Y$. Therefore $X \supset y_0 = yv$ and hence $X \supset Yv$. As $yv \in RF M$, $Yv \cap RF M \neq \emptyset$. As $v$ can be taken arbitrarily large, there exists a sequence $v_n \to \infty$ in $V$ such that $X$ contains $Yv_n$. Choose $y_n \in Y$ so that $y_nv_n \in RF M$ converges to some $x_0 \in RF M$, by passing to a subsequence. Since $Y$ is $A$-invariant and $\limsup_{n \to \infty} v_n^{-1}Av_n \supset V$, we deduce

$$X \supset \lim_{n \to \infty} (y_nv_n) \cdot \limsup_{n \to \infty} (v_n^{-1}Av_n) \supset x_0V.$$  

Therefore $X = RF_+ M$. 

As an immediate corollary, we deduce:

**Corollary 7.9.** [36] Let $M$ be a rigid acylindrical hyperbolic 3-manifold. Then the closure of any horocycle is either a properly immersed surface, parallel to a geodesic plane, or equal to $M$.

7.6. Measure rigidity? If there exists a closed orbit $xH$ for $x \in RF_+ M$, then the stabilizer of $x$ in $H$ is a non-elementary convex cocompact fuchsian subgroup and there exists a unique $U$-invariant ergodic measure supported on $xH \cap RF_+ M$, called the Burger-Roblin measure $m_{xH}^{BR}$ on $xH$. 

**Question:** Let $M$ be a rigid acylindrical hyperbolic 3-manifold. Is any locally finite $U$-ergodic measure on $RF_+ M$ either $m_{BR}$ or $m_{xH}$ for some closed $H$ orbit $xH$, up to a translation by the centralizer of $U$?

Theorem 7.6 implies the positive answer to this question at least in terms of the support of the measure: the support of any locally finite $U$-ergodic measure on $RF_+ M$ is either $RF_+ M$ or $RF_+ M \cap xHv$ for some closed orbit $xH$ and $v \in N$.

8. **Geometrically finite acylindrical hyperbolic 3-manifolds**

Let $\Gamma < G$ be a Zariski dense geometrically finite group, and let $M = \Gamma \backslash \mathbb{H}^3$. We assume $\text{Vol}(M) = \infty$. In the rigid acylindrical case, we were able to give a complete classification of all possible closures of a geodesic plane in $M$; this is largely due to the rigid structure of the boundary of core $M$. In particular, the intersection of a geodesic plane and the convex core of $M$ is either closed or dense in core $M$.

In general, the convex core of $M$ is not such a natural ambient space to study the topological behavior of a geodesic plane, because of its non-homogeneity property. Instead, its interior, which we denote by $M^*$, is a better space to work with; first of all, $M^*$ is a hyperbolic 3-manifold with no boundary (although incomplete), which is diffeomorphic to $M$, and a geodesic plane $P$ which does not intersect $M^*$ cannot come arbitrarily close to $M^*$, as $P$ must be contained in the ends $M - M^*$.

**Definition 8.1.** A geodesic plane $P^*$ in $M^*$ is defined to be a non-empty intersection $P \cap M^*$ for a geodesic plane $P$ of $M$.

Let $P = \pi(\tilde{P})$ for a geodesic plane $\tilde{P} \subset \mathbb{H}^3$, and set $S = \text{Stab}_G(\tilde{P}) \setminus \tilde{P}$. Then the natural map $f : S \to P \subset M$ is an immersion (which is generically injective), $S^* := f^{-1}(M^*)$ is a non-empty convex subsurface of $S$ with $\pi_1(S) = \pi_1(S^*)$ and $P^*$ is given as the image of the restriction of $f$ to $S^*$. The group $\pi_1(S^*)$ will be referred to as the fundamental group of $P^*$. We note that a geodesic plane $P^*$ is always connected as $P^*$ is covered by the convex subset $\tilde{P} \cap \text{Interior}(\text{hull} \Lambda)$.

8.1. **Rigidity of geodesic planes in $M^*$**. An analogous topological rigidity of planes to Theorem 7.4 continues to hold inside $M^*$, provided $M$ is a geometrically finite acylindrical hyperbolic 3-manifold.

The following rigidity theorem was proved jointly with McMullen and Mohammadi for convex cocompact cases in [36], and extended to geometrically finite cases jointly with Benoist [4]:

**Theorem 8.2.** Let $M$ be a geometrically finite acylindrical hyperbolic 3-manifold. Then geodesic planes in $M^*$ are topologically rigid in the following sense:

1. any geodesic plane $P^*$ in $M^*$ is either properly immersed or dense;
2. the fundamental group of a properly immersed $P^*$ is a non-elementary geometrically finite Fuchsian subgroup;
3. there are at most countably many properly immersed geodesic planes in $M^*$;
4. any infinite sequence of geodesic planes $P^*_i$ becomes dense in $M^*$, i.e., $\lim P^*_i = M^*$.

This theorem is deduced from following results on $H$-orbits in $F^*$:

**Theorem 8.3.** ([36], [4]) Let $M$ be a geometrically finite acylindrical hyperbolic 3-manifold. Then
(1) any $H$-orbit in $F^*$ is either closed or dense;
(2) if $xH$ is closed in $F^*$, then $\text{Stab}_H(x)$ is Zariski dense in $H$;
(3) there are at most countably many closed $H$-orbits in $F^*$;
(4) any infinite sequence of closed $H$-orbits $x_iH$ becomes dense in $F^*$, i.e., $\lim x_iH = F^*$.

8.2. Closed or dense dichotomy for acylindrical groups. In this section, we discuss the proof of the following closed or dense dichotomy:

**Theorem 8.4.** Let $M$ be a geometrically finite acylindrical hyperbolic 3-manifold. Then any $H$-orbit in $F^*$ is either closed or dense.

Indeed, the proof of Theorem 7.3 for the rigid acylindrical case can be modified to prove the following proposition.

**Proposition 8.5** (Main proposition). Let $\Gamma$ be a Zariski dense convex cocompact subgroup of $G$ with connected limit set. Let $R$ be a closed $A$-invariant subset of $RFM$ satisfying that for any $x \in R$, $T(x) := \{t : xu_t \in R\}$ has accumulating renormalizations. Then for any $x \in R \cap F^*$, $xH$ is either locally closed or dense in $F$. When $xH$ is locally closed, it is closed in $RH \cap F^*$.

**Proof.** Let $X := xH$ for $x \in R \cap F^*$. Set $W := X \cap R \cap F^*$. Suppose that either $xH$ is not locally closed or $(X - xH) \cap W \neq \emptyset$. We claim that $X = F^*_\Lambda$.

**Case 1: $W$ is not compact.** By repeating verbatim the proof of Theorem 7.3, we obtain $xv \in X \cap R$ for some $z \in \partial F \cap R$ and non-trivial $v \in V$. As $z = [g] \in R$, $g^{-1}v$ is non-elementary and hence $z$ is a thick boundary frame. Since $zv \in F^*$, the claim follows from Lemma 6.5.

**Case 2: $W$ is compact.** By repeating verbatim the proof of Theorem 7.3, we show that $X$ contains a $U$-minimal subset $Y$ with respect to $W$ such that $X - y_0H$ is not closed for some $y_0 \in Y \cap W$. Hence by applying Lemmas 5.7, 5.8, 5.9 and 6.1, we get $X = F^*_\Lambda$. \hfill \Box

When $\Gamma$ is rigid acylindrical, note that $R = RFM$ satisfies the hypothesis of Proposition 8.5. In view of this proposition, Theorem 8.4 for a convex cocompact case now follows from the following theorem, and a general geometrically finite case can be proved by an appropriately modified version, taking account of closed horoballs, which is responsible for the non-compactness of $RFM$.

**Theorem 8.6.** Let $M$ be a geometrically finite acylindrical hyperbolic 3-manifold. Then there exists a closed $A$-invariant subset $R \subset RFM$ such that for any $x \in R$, $T(x) := \{t : xu_t \in R\}$ accumulating renormalizations. Moreover $F^* \subset RH$.

We use the notion of a conformal modulus in order to find a closed subset $R$ satisfying the hypothesis of Theorem 8.6. An annulus $A \subset S^2$ is an open region whose complement consists of two components. If neither component is a single point, $A$ is conformally equivalent to a unique round annulus of the form $\{z \in \mathbb{C} : 1 < |z| < R\}$. The modulus $\text{mod}(A)$ is then defined to be $\log R$. If $P$ is a compact set of a circle $C$ such that its complement $C - P = \bigcup I_i$ is a union of at least two intervals with disjoint closures, we define the modulus of $P$ as

$$\text{mod} P := \inf_{i \neq j} \text{mod} (I_i, I_j)$$

where $\text{mod} (I_i, I_j) := \text{mod} (S^2 - \overline{T_i \cup T_j})$. 
For $\varepsilon > 0$, define $\mathcal{R}_\varepsilon \subset RF \ M$ as the following subset:

$$\mathcal{R}_\varepsilon := \{ [g] : C_g \cap \Lambda \text{ contains a compact set of modulus } \geq \varepsilon \text{ containing } g^\pm \}.$$ 

**Lemma 8.7.** For $\varepsilon > 0$, the set $\mathcal{R}_\varepsilon$ is closed.

**Proof.** Suppose that $g_n \in \mathcal{R}_\varepsilon$ converges to some $g \in RF \ M$. We need to show $g \in \mathcal{R}_\varepsilon$. Let $P_n \subset C_{g_n} \cap \Lambda$ be a compact set of modulus $\geq \varepsilon$ containing $g_n^\pm$. Since the set of all closed subsets of $S^2$ is a compact space in the Hausdorff topology on closed subsets, we may assume $P_n$ converges to some $P_\infty$, by passing to a subsequence. This means that $P_\infty = \limsup_n P_n = \liminf_n P_n$ [19].

Write $C_g - P_\infty = \bigcup_{i \in I} I_i$ as the disjoint union of connected components. As $g^\pm \in P_\infty$, $|I| \geq 2$. Let $i \neq j \in I$, and write $I_i = (a_i, b_i)$ and $I_j = (a_j, b_j)$. There exist $a_{i,n}, b_{i,n}, a_{j,n}, b_{j,n} \in P_n$ converging to $a_i, b_i, a_j$ and $b_j$ respectively. Set $I_{i,n}$ and $I_{j,n}$ to be the intervals $(a_{i,n}, b_{i,n})$ and $(a_{j,n}, b_{j,n})$ respectively. Since $I_{i,n} \rightarrow I_i$, and $I_{j,n} \rightarrow I_j$, $I_{i,n} \cup I_{j,n} \subset C_{g_n} - P_n$ for all large $n$. Since $a_{i,n}, b_{i,n} \in P_n$, $I_{i,n}$ is a connected component of $C_{g_n} - P_n$. Similarly, $I_{j,n}$ is a connected component of $C_{g_n} - P_n$. Since $\mod(I_{i,n} \cup I_{j,n}) \geq \varepsilon$ for all $n$, it follows that $I_i$ and $I_j$ have disjoint closures and $\mod(I_i, I_j) \geq \varepsilon$. This shows that $P_\infty$ is a compact subset of $C_g \cap \Lambda$ of modulus at least $\varepsilon$ containing $g^\pm$. Therefore $g \in \mathcal{R}_\varepsilon$. 

There exists $\kappa = \kappa(\varepsilon) > 1$ such that for any $x \in \mathcal{R}_\varepsilon$, $T(x) := \{ t : xu_t \in \mathcal{R}_\varepsilon \}$ is $\kappa$-thick (see [36, Prop. 4.3]); hence $\mathcal{R}_\varepsilon$ satisfies the hypothesis of Theorem 8.6.

In general, $\mathcal{R}_\varepsilon$ may be empty! However for geometrically finite acylindrical manifolds, there exists $\varepsilon > 0$ such that

$$F^* \subset \mathcal{R}_\varepsilon H$$

([36], [4]); hence Theorem 8.4 follows. The inclusion (8.1) is proved using bridge arguments devised in [36], and the monotonicity of conformal moduli, based on the property that for a convex cocompact acylindrical manifold $M$, $\Lambda$ is a Sierpinski carpet of positive modulus, that is,

$$\inf_{i \neq j} \mod(S^2 - (\overline{B}_i \cup \overline{B}_j)) > 0$$

where $B_i$’s are components of $S^2 - \Lambda$ (see [36] for details).

When $M$ has cusps, the closures of some components of $S^2 - \Lambda$ may meet each other, and hence $\Lambda$ is not even a Sierpinski carpet in general. Nevertheless, under the assumption that $M$ is a geometrically finite acylindrical manifold, $\Lambda$ is still a quotient of a Sierpinski carpet of positive modulus, in the sense that we can present $S^2 - \Lambda$ as the disjoint union $\bigcup T_\ell$ where $T_\ell$’s are maximal trees of components of $S^2 - \Lambda$ so that

$$\inf_{i \neq k} \mod(S^2 - (\overline{T}_\ell \cup \overline{T}_k)) > 0.$$ 

**Question:** Let $\Gamma$ be a Zariski dense geometrically finite subgroup of $G$ with a connected limit set. Let $C \subset C^*$. If $C \cap \Lambda$ contains a Cantor set,

is $\Gamma C$ either discrete or dense in $C^*$?

If $C \cap \Lambda$ contains a Cantor set of positive modulus, this question has been answered affirmatively in [4].

One particular case of interest is when $\Lambda$ is the Apollonian gasket. The corresponding geometrically finite hyperbolic 3-manifold is not acylindrical in this case, because its compact core is a handle body of genus 2, and hence it is not boundary
incompressible; this can also be seen from the property that the Apollonian gasket contains a loop of three consecutively tangent disks.

**Question:** Can we classify all possible closures of $U$-orbits in a geometrically finite acylindrical group? In order to answer this question, we first need to classify all possible $H$-orbit closures in $\partial F$, which is unsettled yet.

9. Unipotent flows in higher dimensional hyperbolic manifolds

Let $\mathbb{H}^d$ denote the $d$-dimensional hyperbolic space for $d \geq 2$ with $\partial(\mathbb{H}^d) = S^{d-1}$, and let $G := \text{SO}^+(d, 1)$, which is the isometry group $\text{Isom}^+(\mathbb{H}^d)$. Any complete hyperbolic $d$-manifold is given as the quotient $M = \Gamma \backslash \mathbb{H}^d$ for a torsion-free discrete subgroup $\Gamma < G$ (also called a Kleinian group). The limit set of $\Gamma$ and the convex core of $M$ are defined just like the dimension 3 case. As we have seen in the dimension 3 case, the geometry and topology of hyperbolic manifolds becomes relevant in the study of unipotent flows in hyperbolic manifolds of infinite volume, unlike in the finite volume case. Those hyperbolic 3-manifolds in which we have a complete understanding of the topological behavior of unipotent flows are rigid acylindrical hyperbolic 3-manifolds.

9.1. Convex cocompact hyperbolic manifolds with Fuchsian ends. The higher dimensional analogues of rigid acylindrical hyperbolic 3-manifolds are as follows:

**Definition 9.1.** A convex cocompact hyperbolic $d$-manifold $M$ is said to have Fuchsian ends if the convex core of $M$ has non-empty interior and has totally geodesic boundary.

The term *Fuchsian ends* reflects the fact that each component of the boundary of core $M$ is a $(d-1)$-dimensional closed hyperbolic manifold, and each component of the complement $M - \text{core}(M)$ is diffeomorphic to the product $S \times (0, \infty)$ for some closed hyperbolic $(d-1)$-manifold $S$. For $d = 2$, any convex cocompact hyperbolic surface has Fuchsian ends. For $d = 3$, these are precisely rigid acylindrical hyperbolic 3-manifolds.

Convex cocompact hyperbolic manifolds with non-empty Fuchsian ends are constructed from closed hyperbolic manifolds as follows. Begin with a closed hyperbolic $d$-manifold $N_0 = \Gamma_0 \backslash \mathbb{H}^d$ with a fixed collection of finitely many, mutually disjoint, properly embedded totally geodesic hypersurfaces. Cut $N_0$ along those
hypersurfaces and perform the metric completion to obtain a compact hyperbolic manifold \( W \) with totally geodesic boundary hypersurfaces. Then \( \pi_1(W) \) injects to \( \pi_1(N_0) = \Gamma \), and \( M := \Gamma \backslash \mathbb{H}^d \) is a convex cocompact hyperbolic manifold with Fuchsian ends.

Unlike \( d = 3 \) case, Kerckhoff and Storm showed that if \( d \geq 4 \), a convex cocompact hyperbolic manifold \( M = \Gamma \backslash \mathbb{H}^d \) with Fuchsian ends does not allow any non-trivial local deformation, in the sense that the representation of \( \Gamma \) into \( G \) is infinitesimally rigid [21].

9.2. Orbit closure of unipotent flows are relatively homogeneous. We let \( A = \{a_t\} \) be the one parameter subgroup of semisimple elements of \( G \) which give the frame flow, and let \( N \cong \mathbb{R}^{d-1} \) denote the contracting horospherical subgroup. We have a compact \( A \)-invariant subset \( RF_M = \{x \in \Gamma \backslash G : xA \text{ is bounded}\} \).

The following presents a generalization of Theorems 7.3 and 7.6 to any dimension:

**Theorem 9.2.** [22] Let \( d \geq 2 \) and \( M \) be a convex cocompact hyperbolic \( d \)-manifold with Fuchsian ends. Let \( U \) be any connected closed subgroup of \( G \) generated by unipotent elements. Suppose that \( U \) is normalized by \( A \). Then the closure of any \( U \)-orbit is relatively homogeneous in \( RF_M \), in the sense that for any \( x \in RF_M \),

\[
\overline{xU \cap RF_M} = xL \cap RF_M
\]

for a connected closed reductive subgroup \( U < L < G \) such that \( xL \) is closed.

When \( M \) has finite volume, this is a special case of Ratner’s orbit closure theorem [44]. This particular case was also proved by Shah by topological methods [48].

Theorem 9.2 and its refinements made in [22] yield the analogous topological rigidity of geodesic planes and horocycles. A geodesic \( k \)-plane of \( M \) is the image of a totally geodesic immersion \( f : \mathbb{H}^k \rightarrow M \).

**Theorem 9.3.** [22] Let \( M \) be a convex cocompact hyperbolic \( d \)-manifold with Fuchsian ends. Then for any \( 2 \leq k \leq d - 1 \),

1. the closure of any geodesic \( k \)-plane intersecting core \( M \) is a properly immersed geodesic \( m \)-plane for some \( k \leq m \leq d \);
2. a properly immersed geodesic \( k \)-plane is a convex cocompact (immersed) hyperbolic \( k \)-manifold with Fuchsian ends;
3. there are at most countably many maximal properly immersed geodesic planes intersecting core \( M \);
any infinite sequence of maximal properly geodesic planes intersecting core $M$ becomes dense in $M$.

A $k$-horosphere in $\mathbb{H}^d$ is a Euclidean sphere of dimension $k$ which is tangent to a point in $\mathbb{S}^{d-1}$. A $k$-horosphere in $M$ is simply the image of a $k$-horosphere in $\mathbb{H}^d$ under the covering map $\mathbb{H}^d \to M = \Gamma \backslash \mathbb{H}^d$.

**Theorem 9.4.** [22] Let $\chi$ be a $k$-horosphere of $M$ for $k \geq 1$. Then either
1. $\chi$ is properly immersed; or
2. $\chi$ is a properly immersed $m$-dimensional submanifold, parallel to a convex cocompact geodesic $m$-plane of $M$ with Fuchsian ends for some $m \geq k+1$.

### 9.3. Avoidance of singular set.

An important ingredient of the proof of Theorem 9.2 which appears newly for $d \geq 4$ is the avoidance of the singular set along the recurrence time of unipotent flows to $\text{RF} \ M$.

Let $U = \{u_t\}$ be a one parameter unipotent subgroup of $N$. Extending the definition given by Dani-Margulis [13] to the infinite volume setting, we define the singular set $\mathcal{S}(U)$ as

$$ (9.1) \quad \mathcal{S}(U) := \bigcup xL \cap \text{RF}_+ M $$

where $\text{RF}_+ M = \text{RF} M \cdot N$, and the union is taken over all closed orbits $xL$ of proper connected closed subgroups $L$ of $G$ containing $U$. Its complement in $\text{RF}_+ M$ is denoted by $\mathcal{G}(U)$, and called the set of *generic* elements of $U$.

The structure of $\mathcal{S}(U)$ as the countable union of *singular tubes* is an important property which plays crucial roles in both measure theoretic and topological aspects of the study of unipotent flows. Let $\mathcal{H}$ denote the collection of all proper connected closed subgroups $H$ of $G$ containing a unipotent element such that $\Gamma \backslash \Gamma H$ is closed and $H \cap \Gamma$ is Zariski dense in $H$. For each $H \in \mathcal{H}$, we define the singular tube:

$$ X(H, U) := \{g \in G : gu g^{-1} \subset H\}. $$

We have the following:
1. $\mathcal{H}$ is countable;
2. $X(gH_1, U) \cap gX(H_2, U) = X(H_1 \cap gH_2 g^{-1}, U)$ for any $g \in G$;
3. If $H_1, H_2 \in \mathcal{H}$ with $X(H_1 \cap H_2, U) \neq \emptyset$, there exists a closed subgroup $H_0 \subset H_1 \cap H_2$ such that $H_0 \in \mathcal{H}$. 
In particular \( \mathcal{I}(U) \) can be expressed as the union of countable singular tubes:

\[
\mathcal{I}(U) = \bigcup_{H \in \mathcal{H}} \Gamma \backslash \Gamma X(H, U) \cap RF_+ M.
\]

**Remark 9.5.** If \( \Gamma < G = \text{PSL}_2(\mathbb{C}) \) is a uniform lattice, and \( U \) is the one-parameter subgroup as in (4.1), then \( H \in \mathcal{H} \) if and only if \( H = g^{-1} \text{PSL}_2(\mathbb{R})g \) for \( g \in G \) such that \( \Gamma \) intersects \( g^{-1} \text{PSL}_2(\mathbb{R})g \) as a uniform lattice. It follows that if \( H_1, H_2 \in \mathcal{H} \) and \( X(H_1, U) \cap X(H_2, U) \neq \emptyset \), then \( H_1 = H_2 \).

We note that \( \mathcal{H} \) and hence \( \mathcal{I}(U) \) may be empty in general; see Remark 7.5(1).

When the singular set \( \mathcal{I}(U) \) is non-empty, it is very far from being closed in \( RF_+ M \); in fact, it is dense, which is an a posteriori fact. Hence presenting a compact subset of \( \mathcal{I}(U) \) requires some care, and we will be using the following family of compact subsets \( \mathcal{I}(U) \) in order to discuss the recurrence of \( U \)-flows relative to the singular set \( \mathcal{I}(U) \). We define \( E = E_U \) to be the collection of all subsets of \( \mathcal{I}(U) \) which are of the form

\[
\bigcup \Gamma \backslash \Gamma H_i D_i \cap RF M
\]

where \( H_i \in \mathcal{H} \) is a finite collection, and \( D_i \) is a compact subset of \( X(H_i, U) \).

The following theorem was obtained by Dani and Margulis [13] and independently by Shah [50] using the linearization methods, which translates the study of unipotent flows on \( \Gamma \backslash G \) to the study of vector-valued polynomial maps via linear representations.

**Theorem 9.6 (Avoidance theorem for lattice case).** [13] *Let \( \Gamma < G \) be a uniform lattice, and let \( U < G \) be a one-parameter unipotent subgroup. Then for any \( \varepsilon > 0 \), there exists a sequence of compact subsets \( E_1 \subset E_2 \subset \cdots \) in \( E \) such that \( \mathcal{I}(U) = \bigcup_{n \geq 1} E_n \) which satisfies the following: Let \( x_j \) be a sequence converging to \( x \in \mathcal{I}(U) \). For each \( n \geq 1 \), there exist a neighborhood \( O_n \) of \( E_n \) and \( j_n \geq 1 \) such that for all \( j \geq j_n \),

\[
\ell \{ t \in [0, T] : x_j u_t \in \bigcup_{i \leq n} O_i \} \leq \varepsilon T
\]

where \( \ell \) denotes the Lebesgue measure.

If we set

\[
T_n := \{ t \in \mathbb{R} : x_{j_n} u_t \notin \bigcup_{i \leq n} O_i \},
\]

then for any sequence \( \lambda_n \to \infty \), \( \limsup \lambda_n^{-1} T_n \) accumulates at \( 0 \) and \( \infty \); and hence the sequence \( T_n \) has accumulating renormalizations.

When \( xL \) is a closed orbit of a connected closed subgroup of \( L \) containing \( U \), the relative singular subset \( \mathcal{I}(U, xL) \) of \( xL \cap RF_+ M \) is defined similarly by replacing \( \mathcal{H} \) by its subcollection of proper connected closed subgroups of \( L \), and \( \mathcal{G}(U, xL) \) is defined as its complement inside \( xL \cap RF_+ M \). And Theorem 9.6 applies in the same way to \( \mathcal{G}(U, xL) \) with the ambient space \( \Gamma \backslash G \) replaced by \( xL \).

In order to explain some ideas of the proof of Theorem 9.6, we will discuss the following (somewhat deceptively) simple case when \( G = \text{PSL}_2(\mathbb{C}) \) and \( \Gamma \) is a uniform lattice. Let \( U = \{ u_t \} \) be as in (4.1).
Proposition 9.7. Let $E \in \mathcal{E}_U$. If $x \in \mathcal{G}(U)$, then $xU$ spends most of its time outside a neighborhood of $E$, more precisely, for any $\varepsilon > 0$, we can find a neighborhood $E \subset \mathcal{O}$ such that for all $T > 0$,

\[(9.3) \quad \ell\{t \in [0, T] : xu_t \in \mathcal{O}\} \leq \varepsilon T.\]

Proof. Since $xU$ is dense in $\Gamma \backslash G$ a posteriori, $xu_t$ will go into any neighborhood of $E$ for an infinite sequence of $t$'s, but that the proportion of such $t$ is very small is the content of Proposition 9.7. In view of Remark 9.5, we may assume that $E$ is of the form $\Gamma \backslash \Gamma N(H)D$ where $H = \text{PSL}_2(\mathbb{R})$, and $D \subset V$ is a compact subset; note $X(H, U) = N(H)V$, and $N(H)$ is generated by $H$ and $\text{diag}(i, -i)$.

As remarked before, we prove this proposition using the linear representation and the polynomial-like behavior of unipotent action. As $N(H)$ is the group of real points of a connected reductive algebraic subgroup, there exists an $\mathbb{R}$-regular representation $\rho : G \to \text{GL}(W)$ with a distinguished point $p \in W$ such that $N(H) = \text{Stab}(p)$ and $pG$ is Zariski closed. The set $pX(H, U) = pV$ is a real algebraic subvariety. 

8Note that for $x = [g]$, the following are equivalent:

1. $xu_t \in [c]N(H)\mathcal{O}$;
2. $\rho_\gamma gu_t \in p\mathcal{O}$ for some $\gamma \in \Gamma$.

Therefore, we now try to find a neighborhood $p\mathcal{O}$ of $pD$ so that the set

\[
\{t \in [0, T] : xu_t \in [c]N(H)\mathcal{O}\} \subset \bigcup_{q \in p\Gamma} \{t \in [0, T] : qgu_t \in p\mathcal{O}\}
\]

is an $\varepsilon$-proportion of $T$. Each set $\{t \in [0, T] : qgu_t \in p\mathcal{O}\}$ can be controlled by the following lemma, which is proved using the property that the map $t \mapsto \|qgu_t\|^2$ is a polynomial of degree uniformly bounded for all $q \in p\Gamma$, and polynomial maps of bounded degree have uniformly slow divergence.

Lemma 9.8. [13, Prop. 4.2] Let $\mathcal{A} \subset W$ be an algebraic variety. Then for any compact subset $C \subset \mathcal{A}$ and any $\varepsilon > 0$, there exists a compact subset $C' \subset \mathcal{A}$ such that the following holds: for any neighborhood $\Phi'$ of $C'$ in $W$, there exists a neighborhood $\Phi$ of $C$ of $W$ such that for any $q \in W - \Phi'$ and any $T > 0$,

\[
\ell\{t \in [0, T] : qu_t \in \Phi\} \leq \varepsilon \cdot \ell\{t \in [0, T] : qu_t \in \Phi'\}.
\]

Applying this lemma to $\mathcal{A} = pV$, and $C = pD$, we get a compact subset $C' = pD'$ for $D' \subset V$. Since $x \notin [c]N(H)D'$, we can find a neighborhood $\mathcal{O}'$ so that $x \notin [c]N(H)\mathcal{O}'$. Fix a neighborhood $\Phi'$ of $C'$, so that $\Phi' \cap pG \subset p\mathcal{O}'$. We then get a neighborhood $\Phi$ of $C$ such that if $\mathcal{O}$ is a neighborhood of $D$ such that $p\mathcal{O} \subset \Phi$, then

\[(9.4) \quad \ell(J_q \cap [0, T]) \leq \varepsilon \cdot \ell(I_q \cap [0, T])\]

where $J_q := \{t \in \mathbb{R} : qgu_t \in p\mathcal{O}\}$ and $I_q := \{t \in \mathbb{R} : qgu_t \in p\mathcal{O}'\}$.

We now claim that in the case at hand, we can find a neighborhood $\mathcal{O}'$ of $D'$ so that all $I_q$'s are mutually disjoint:

\[(9.5) \quad \text{if } q_1 \neq q_2 \text{ in } p\Gamma, \text{ then } I_{q_1} \cap I_{q_2} = \emptyset.\]

8We can explicitly take $\rho$ and $p$ as follows. Consider the Adjoint representation of $G$ on its Lie algebra $\mathfrak{g}$. We then let $\rho$ be the induced representation on the wedge product space $\wedge^3 \mathfrak{g}$ and set $p = w_1 \wedge w_2 \wedge w_3$ where $w_1, w_2, w_3$ is a basis of $\mathfrak{h}$. 
Using (9.4), this would finish the proof, since
\[ \ell\{t \in [0, T] : xu_t \in [e] N(H)O\} \leq \sum_{q \in p\Gamma} \ell(J_q \cap [0, T]) \leq \varepsilon \cdot \sum_{q \in p\Gamma} \ell(I_q \cap [0, T]) \leq \varepsilon T. \]

To prove (9.5), we now observe the special feature of this example, namely, no singular tube \( \Gamma \setminus \Gamma X(H, U) \) has self-intersection, meaning that
\[ (9.6) \quad X(H, U) \cap \gamma X(H, U) = \emptyset \quad \text{if} \quad \gamma \in \Gamma - N(H). \]
If non-empty, by Remark 9.5, we must have \( H \cap \gamma H^{-1} = H \), implying that \( \gamma \in N(H) \). Now if \( t \in I_\gamma H \cap I_{p\gamma_2} \), then \( gu_t \in \gamma^{-1}HV \cap \gamma^{-1}HV \) and hence \( \gamma_1 \gamma_2^{-1} \in N(H) \). So \( p\gamma_1 = p\gamma_2 \), proving (9.5).

In the higher dimensional case, we cannot avoid self-intersections of \( \Gamma X(H, U) \); so \( I_q \)'s are not pairwise disjoint, which means a more careful study of the nature of the self-intersection is required. Thanks to the countability of \( \mathcal{H} \), an inductive argument on the dimension of \( H \in \mathcal{H} \) is used to take care of the issue, using the fact that the intersections among \( \gamma X(H, U) \), \( \gamma \in \Gamma \) are essentially of the form \( X(H_0, U) \) for a proper connected closed subgroup \( H_0 \) of \( H \) contained in \( \mathcal{H} \) (see [13] for details).

In order to illustrate the role of Theorem 9.6 in the study of orbit closures, we prove the following sample case: let \( G = SO^{g}(4, 1) \), \( H = SO^{g}(2, 1) \) and \( L = SO^{g}(3, 1) \); the subgroups \( H \) and \( L \) are chosen so that \( A < H < L \) and \( H \cap N \) is a one-parameter unipotent subgroup. The centralizer \( C(H) \) of \( H \) is \( SO(2) \). We set \( H' = H C(H) \).

**Proposition 9.9.** Let \( \Gamma < G \) be a uniform lattice. Let \( X = \overline{\epsilon \mathcal{H}} \) for some \( x \in \Gamma \setminus G \).

If \( X \) contains a closed orbit \( zL \) properly, then \( X = \Gamma \setminus G \).

A geometric consequence of this proposition is as follows: let \( M \) be a closed hyperbolic 4-manifold, and let \( P \subset M \) be a geodesic 2-plane. If \( P \) contains a properly immersed geodesic 3-plane \( P' \), then the closure \( \overline{P} \) is either \( P' \) or \( M \).

**Proof.** Let \( U_1 = H \cap N \) and \( U_2 = H \cap N^+ \) where \( N^+ \) is the expanding horospherical subgroup of \( G \). Then the subgroups \( U_1 \) and \( U_2 \) generate \( H \), and the intersection of the normalizers of \( U_1 \) and \( U_2 \) is equal to \( C(H) \). Since \( zL \) is compact, each \( U_\ell \) acts ergodically on \( zL \) by Moore’s ergodicity theorem. Therefore we may choose \( z \) so that \( zU_\ell \) is dense in \( zL \) for each \( \ell = 1, 2, 3 \).

It suffices to show \( X \) contains either \( N \) or \( N^+ \)-orbit. Since \( zL \) is a proper subset of \( X \), there exists \( g \in G \) such that \( x = zg \in X \). As \( L \) is reductive, the Lie algebra of \( G \) decomposes into \( \text{Ad}(l) \)-invariant subspaces \( l \oplus l^\perp \) with \( l \) the Lie algebra of \( L \). Hence we write \( g = \ell r \) with \( \ell \in L \) and \( r \in \exp l^\perp - C(H) \).

As \( g \notin C(H) \), there exists \( 1 \leq \ell \leq 2 \) such that \( r \notin \exp l^\perp - C(H) \).

By Theorem 9.6 applied to \( zL = \zeta \subset SO^g(3, 1) \), \( T_n \) has accumulating renormalizations.
Now by a similar argument as in the proof of Lemma 5.5(3), we can show that
\[ \limsup \{ u_t r_n u_{-t} : t \in T_n \} \]
accumulates at 0 and \( \infty \) in \( V \) where \( V \) is the one-dimensional unipotent subgroup \((L \cap N)V = N\). In particular, there exists \( v \in V \) or arbitrarily large size such that
\[ v = \lim u_{-t_n} r_n u_{t_n} \text{ for some } t_n \in T_n. \]

Note that \( zL_n u_{t_n} \) is contained in the compact subset \( zL - \bigcup_{i \leq n} O_i \). Since \( \bigcup_i O_i \) is a neighborhood of \( S \), \( zL_n u_{t_n} \) converges to some
\[ z_0 \in \mathcal{G}(U, zL). \]

Therefore
\[ zg_n u_{t_n} = zL_n u_{t_n} (u_{-t_n} r_n u_{t_n}) \to z_0 v. \]

Since \( z_0 \in \mathcal{G}(U, zL) \), we have
\[ X \supset z_0 v U = z_0 U v = zLv. \]

As \( v \) can be taken arbitrarily large, we get a sequence \( v_n \to \infty \) in \( V \) such that
\[ X \supset zL v_n. \] Using the \( A \)-invariance of \( X \), we get \( X \supset zL(Av_n A) \supset z(L \cap N)V_+ \)
for some one-parameter semigroup \( V_+ \) of \( V \). Since \( X \supset zv_n (L \cap N)V_+^{-1}V_+ \), and
\[ \limsup v_n^{-1}V_+ = V, \quad X \text{ contains an } N \text{ orbit, finishing the proof.} \]

Roughly speaking, if \( H \) is a connected closed subgroup of \( G \) generated by unipotent elements, the proof of the theorem that \( \overline{\mathcal{H}} \) is homogeneous uses an inductive argument on the codimension of \( H \cap N \) in \( N \) and involves repeating the following two steps:

1. Find a closed orbit \( zL \) inside \( \overline{\mathcal{H}} \) for some connected reductive subgroup \( L < G \).
2. If \( \overline{\mathcal{H}} \neq zL \), then enlarge \( zL \), i.e., find a closed orbit \( zL' \) inside \( \overline{\mathcal{H}} \) with
   \[ \dim(L' \cap N) > \dim(L \cap N). \]

The proof of Proposition 9.9 is a special sample case of the step (2), demonstrating the importance of getting accumulating renormalizations for the sequence of return time avoiding the exhausting sequence of compact subsets of the singular set.

The following version of the avoidance theorem in [22] is a key ingredient in the proof of Theorem 9.2:

**Theorem 9.10 (Avoidance theorem).** Let \( M = \Gamma \backslash \mathbb{H}^d \) be a convex cocompact hyperbolic manifold with Fuchsian ends. Let \( U < N \) be a one-parameter unipotent subgroup. There exists a sequence of compact subsets \( E_1 \subseteq E_2 \subseteq \cdots \in \mathcal{E} \) such that \( \mathcal{G}(U) \cap \text{RF } M = \bigcup_{n \geq 1} E_n \) which satisfies the following: Let \( x_j \in \text{RF } M \) be a sequence converging to \( x \in \mathcal{G}(U) \). For each \( n \geq 1 \), there exist a neighborhood \( O_n \) of \( E_n \) and \( j_n \geq 1 \) such that for all \( j \geq j_n \),
\[ T^{(j)}(x_j) := \{ t \in \mathbb{R} : x_j u_t \in \text{RF } M - O_n \} \]
has accumulating renormalizations.

Note that in the lattice case, one can use the Lebesgue measure \( \ell \) to understand the return time away from the neighborhoods \( O_n \) to prove Theorem 9.6, as was done in [13] (also see the proof of Proposition 9.7). In the case at hand, the relevant return time is a subset of \( \{ t \in \mathbb{R} : x_n u_t \in \text{RF } M \} \) on which it is not clear if there exists any friendly measure. This makes the proof of Theorem 9.10 very delicate, as we have to examine each return time to \( \text{RF } M \) and handpick the time outside
First of all, we cannot reduce a general case to the case \( E \subset \Gamma \backslash \Gamma X(H, U) \) for a single \( H \in \mathcal{H} \). This means that not only do we need to understand the self-intersections of \( \Gamma X(H, U) \), but we also have to control intersections among different \( \Gamma X(H, U) \)'s in \( \mathcal{S}(U) \), \( H \in \mathcal{H} \).

We cannot also use an inductive argument on the dimension of \( H \). When \( G = \text{SO}(3, 1) \), there are no intersections among closed orbits in \( \mathcal{S}(U) \) and the proof is much simpler in this case. In general, our arguments are based on the \( k \)-th thick recurrence time to \( RF_M \), a much more careful analysis on the graded intersections among \( \Gamma X(H, U) \)'s, \( H \in \mathcal{H} \), and a combinatorial inductive search argument.

We prove that there exists \( \kappa > 1 \), depending only on \( \Gamma \) such that \( T^\circ(x_n) \) is \( \kappa \)-thick in the sense that for any \( r > 0 \),

\[
T^\circ(x_n) \cap \pm[r, \kappa r] \neq \emptyset.
\]

We remark that unlike the lattice case, we are not able to prove that \( \{ t \in \mathbb{R} : x_n u_t \in RF_M - \bigcup_{j \leq n} \mathcal{O}_j \} \) has accumulating renormalizations. This causes an issue in carrying out a similar proof as in Proposition 9.9, as we cannot conclude the limit of \( x_n u_t \) for \( t_n \in T^\circ(x_n) \) belongs to a generic set as in (9.8).

Fortunately, we were able to devise an inductive argument (in the proof of Theorem 9.11 below) which involves an extra step of proving equidistribution of translates of maximal closed orbits and overcome this difficulty.

### 9.4. Induction

For a connected closed subgroup \( U < N \), we denote by \( H(U) \) the smallest closed simple Lie subgroup of \( G \) which contains both \( U \) and \( A \). If \( U \simeq \mathbb{R}^k \), then \( H(U) \simeq \text{SO}^\circ(k+1, 1) \). A connected closed subgroup of \( G \) generated by one-parameter unipotent subgroups is, up to conjugation, of the form \( U < N \) or \( H(U) \) for some \( U < N \).

We set \( F_{H(U)} := RF_+ M \cdot H(U) \), which is a closed subset. We define the following collection of closed connected subgroups of \( G \):

\[
\mathcal{L}_U := \left\{ L = H(\widehat{U}) C : \text{for some } z \in RF_+ M, zL \text{ is closed in } \Gamma \backslash G \text{ and } \text{Stab}_L(z) \text{ is Zariski dense in } L \right\}.
\]

where \( U < \widehat{U} < N \) and \( C \) is a closed subgroup of the centralizer of \( H(\widehat{U}) \). We also define:

\[
Q_U := \{ vL v^{-1} : L \in \mathcal{L}_U \text{ and } v \in N \}.
\]

Theorem 9.2 follows from the following:

**Theorem 9.11.** [22] Let \( M = \Gamma \backslash \mathbb{H}^d \) be a convex cocompact hyperbolic manifold with Fuchsian ends.

1. For any \( x \in RF_M \),

\[
\overline{xH(U)} = xL \cap F_{H(U)}
\]

where \( xL \) is a closed orbit of some \( L \in \mathcal{L}_U \).

2. Let \( x_0 \widehat{L} \) be a closed orbit for some \( \widehat{L} \in \mathcal{L}_U \) and \( x_0 \in RF_M \).
   a. For any \( x \in x_0 \widehat{L} \cap RF_+ M \),

\[
\overline{xU} = xL \cap RF_+ M
\]

where \( xL \) is a closed orbit of some \( L \in Q_U \).
(b) For any \( x \in x_0 \hat{L} \cap RF M \),
\[
xAU = xL \cap RF_M
\]
where \( xL \) is a closed orbit of some \( L \in \mathcal{L}_U \).

(3) Let \( x_0 \hat{L} \) be a closed orbit for some \( \hat{L} \in \mathcal{L}_U \) and \( x_0 \in RF M \). Let \( y_i L_i v_i \subset x_0 \hat{L} \) be a sequence of maximal closed orbits such that \( y_i L_i v_i \cap RF M \neq \emptyset \), where \( y_i \in RF_M, L_i \in \mathcal{L}_U \), and \( v_i \in \hat{L} \cap N \). Suppose either
- \( v_i \to \infty \) modulo \( L_i \) or
- \( v_i \) is bounded modulo \( L_i \) and \( y_i L_i \) are all distinct,
Then
\[
\lim_{i \to \infty} (y_i L_i v_i \cap RF_M) = x_0 \hat{L} \cap RF_M.
\]
where the limit is taken in the Hausdorff topology on the space of all closed subsets in \( \Gamma \setminus G \).

We prove (1) by induction on the co-dimension of \( U \) in \( N \), and (2) and (3) by induction on the co-dimension of \( U \) in \( \hat{L} \cap N \). Let us say (1)\(_m\) holds, if (1) is true for all \( U \) satisfying co-dim\( N(U) \leq m \). We will say (2)\(_m\) holds, if (2) is true for all \( U \) and \( \hat{L} \) satisfying co-dim\( \hat{L} \cap N(U) \leq m \) and similarly for (3)\(_m\).

We then deduce (1)\(_{m+1}\) from (2)\(_m\) and (3)\(_m\), and (2)\(_{m+1}\) from (1)\(_{m+1}\), (2)\(_m\), and (3)\(_m\) and finally (3)\(_{m+1}\) from (1)\(_{m+1}\), (2)\(_{m+1}\) and (3)\(_m\). In proving Theorem 9.2 for lattice case, we don’t need (3)\(_m\) in the induction proof. In the case at hand, (3)\(_m\) is needed since we could not obtain a stronger version of Theorem 9.10 with \( O_n \) replaced by \( \cup_{j \leq n} O_j \).

We remark that in the step of proving (2)\(_{m+1}\) the following geometric feature of convex cocompact hyperbolic manifolds \( M \) of Fuchsian ends is used to insure that \( S(U, x_0 \hat{L}) \neq \emptyset \).

Proposition 9.12. For any \( 2 \leq k \leq d \), any properly immersed geodesic \( k \)-plane of \( M \) is either compact or contains a compact geodesic \((k-1)\)-plane.

This proposition follows from the hereditary property that any properly immersed geodesic \( k \)-plane \( P \) of \( M \) is a convex cocompact hyperbolic \( k \)-manifold of Fuchsian ends; hence either \( P \) is compact (when \( P \) has empty ends) or the boundary of core \( P \) provides a co-dimension one compact geodesic plane.

References


[34] C. McMullen. Iteration on Teichmüller space *Inventiones Mathematicae.* Vol 99 (1990), 425-454


[56] Y. Zhang. Construction of acylindrical hyperbolic 3-manifolds with quasifuchsian boundary *Preprint, 2019*
Mathematics department, Yale University, New Haven, CT 06511 and Korea Institute for Advanced Study, Seoul, Korea

E-mail address: hee.oh@yale.edu