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# EQUIDISTRIBUTION IN THE SPACE OF 3-LATTICES AND DIRICHLET-IMPROVABLE VECTORS ON PLANAR LINES

DMITRY KLEINBOCK, NICOLAS DE SAXCÉ, NIMISH A. SHAH, AND PENGYU YANG

ABSTRACT. Let  $X = \mathrm{SL}_3(\mathbb{R})/\mathrm{SL}_3(\mathbb{Z})$ , and  $g_t = \mathrm{diag}(e^{2t}, e^{-t}, e^{-t})$ . Let  $\nu$  denote the push-forward of the normalized Lebesgue measure on a straight line segment in the expanding horosphere of  $\{g_t\}_{t>0}$  by the map  $h \mapsto h\mathrm{SL}_3(\mathbb{Z}), \mathrm{SL}_3(\mathbb{R}) \rightarrow X$ . We give explicit necessary and sufficient Diophantine conditions on the line for equidistribution of each of the following families in  $X$ :

- (1)  $g_t$ -translates of  $\nu$  as  $t \rightarrow \infty$ .
- (2) averages of  $g_t$ -translates of  $\nu$  over  $t \in [0, T]$  as  $T \rightarrow \infty$ .
- (3)  $g_{t_i}$ -translates of  $\nu$  for some  $t_i \rightarrow \infty$ .

We apply this dynamical result to show that Lebesgue-almost every point on the planar line  $y = ax + b$  is not Dirichlet-improvable if and only if  $(a, b) \notin \mathbb{Q}^2$ .

## 1. INTRODUCTION

**1.1. Equidistribution of expanding translates of curves.** Let  $G = \mathrm{SL}_{n+1}(\mathbb{R})$ ,  $\Gamma = \mathrm{SL}_{n+1}(\mathbb{Z})$  and  $X = G/\Gamma$ . Let  $\mu_X$  denote the unique  $G$ -invariant probability measure on  $X$ . Let  $g_t = \mathrm{diag}(e^{nt}, e^{-t}, \dots, e^{-t})$ , so that the expanding horospherical subgroup of  $G$  associated to  $g_1$  is

$$U^+ = \{g \in G \mid g_{-t}gg_t \rightarrow e, t \rightarrow +\infty\} = \left\{ \begin{pmatrix} 1 & * & \cdots & * \\ & 1 & & \\ & & \ddots & \\ & & & 1 \end{pmatrix} \right\}.$$

Let  $x_0 = e\Gamma \in X$ . Using the Margulis thickening method (see e.g. [KM96]), one can show that the  $g_t$ -translates of the horosphere  $U^+x_0$  get equidistributed in  $X$ . One may ask what happens if we replace the whole horosphere with a bounded piece of a real-analytic submanifold therein. We note that  $X$  can be identified with the space of unimodular lattices in  $\mathbb{R}^{n+1}$ , hence numerous applications of dynamics on this space to Diophantine approximation, see e.g. [Dan85, KM98, KW08].

If the submanifold is *non-degenerate*, i.e. is not contained in a proper affine subspace, then a result of the third named author in [Sha09a] tells us that equidistribution still holds. See also [SY18] for generalization to differentiable submanifolds.

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It is thus a natural question to ask for conditions for equidistribution of degenerate manifolds, such as proper affine subspaces. One expects those conditions to be expressed in terms of Diophantine properties of those subspaces.

The main goal of this article is to give a complete solution to this problem in the case  $n = 2$ , that is, study the case of straight lines in  $\mathbb{R}^2$ . In this case we will show that the dynamics is completely controlled by Diophantine conditions on the parameters of the straight line, and will give criteria for several equidistribution phenomena.

In what follows we will specialize to  $n = 2$ , that is, let  $G = \mathrm{SL}_3(\mathbb{R})$ ,  $\Gamma = \mathrm{SL}_3(\mathbb{Z})$ , and  $g_t = \mathrm{diag}(e^{2t}, e^{-t}, e^{-t})$ , so that the expanding horospherical subgroup of  $G$  associated to  $g_1$  is

$$U^+ = \left\{ \begin{pmatrix} 1 & * & * \\ & 1 & * \\ & & 1 \end{pmatrix} \right\}.$$

As before, we let  $x_0 = e\Gamma \in X = G/\Gamma$ .

Let  $\mathcal{W}_2$  denote the set of vectors  $(a, b) \in \mathbb{R}^2$  for which there exists  $C > 0$  such that the system of inequalities<sup>1</sup>

$$(1.1) \quad \begin{cases} |qb + p_1| \leq C|q|^{-2} \\ |qa + p_2| \leq C|q|^{-2} \end{cases}$$

has infinitely many solutions  $(p_1, p_2; q) \in \mathbb{Z}^2 \times \mathbb{Z}_+$ , where  $\mathbb{Z}_+$  denotes the set of positive integers.

Similarly, let  $\mathcal{W}'_2$  denote the set of vectors for which (1.1) has a non-zero solution  $(p_1, p_2; q) \in \mathbb{Z}^2 \times \mathbb{Z}_+$  for every  $C > 0$ . One has an obvious inclusion  $\mathcal{W}'_2 \subset \mathcal{W}_2$ . It is not difficult to check that this inclusion is strict, even if those two sets both have Hausdorff dimension equal to 1, by [Dod92].

Throughout the paper,  $I = [s_0, s_1]$  denotes an arbitrary compact interval with non-empty interior, i.e.  $s_0 < s_1$ . For  $(a, b) \in \mathbb{R}^2$ , let  $\phi_{a,b} : I \rightarrow U^+$  be the line segment defined by

$$\phi_{a,b}(s) = \begin{pmatrix} 1 & s & as+b \\ & 1 & * \\ & & 1 \end{pmatrix}, \quad \forall s \in I.$$

Let  $\lambda_{a,b}$  denote the push-forward of the normalized Lebesgue measure on  $I$  under the map  $s \mapsto \phi_{a,b}(s)x_0$  from  $I$  to  $X$ , and for any  $t \in \mathbb{R}$ , let  $g_t\lambda_{a,b}$  denote the translate of  $\lambda_{a,b}$  by  $g_t$ ; that is, for any  $f \in C_c(X)$ ,

$$(1.2) \quad \int_X f \, d\lambda_{a,b} = \int_I f(\phi_{a,b}(s)x_0) \, ds := \frac{1}{|I|} \int_I f(\phi_{a,b}(s)x_0) \, ds,$$

$$(1.3) \quad \int_X f \, d(g_t\lambda_{a,b}) = \int_I f(g_t\phi_{a,b}(s)x_0) \, ds,$$

where  $|A|$  is the Lebesgue measure of  $A$  for any measurable subset  $A$  of  $\mathbb{R}$ .

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<sup>1</sup>Here and throughout the paper, the notation with a brace and several inequalities is used to indicate that *all* of the inequalities hold.

We say that a family  $\{\lambda_i\}_{i \in \mathcal{I}}$  of probability measures on  $X$  has **no escape of mass** if for every  $\varepsilon > 0$  there exists a compact subset  $K$  of  $X$  such that  $\lambda_i(K) > 1 - \varepsilon$  for all  $i \in \mathcal{I}$ .

We will prove the following criterion for non-escape of mass.

**Theorem 1.1.** *The translates  $\{g_t \lambda_{a,b}\}_{t>0}$  have no escape of mass if and only if  $(a, b) \notin \mathcal{W}'_2$ .*

Furthermore, for  $\mathcal{I} = \mathbb{N}$  or  $\mathbb{R}_{>0}$ , we say that a family  $\{\lambda_i\}_{i \in \mathcal{I}}$  of probability measures on  $X$  gets **equidistributed** in  $X$  if

$$\int f d\lambda_i \xrightarrow{i \rightarrow \infty} \int f d\mu_X, \quad \forall f \in C_c(X);$$

that is,  $\lambda_i$  converges to  $\mu_X$  with respect to the weak-\* topology as  $i \rightarrow \infty$ .

**Theorem 1.2.** *The translates  $\{g_t \lambda_{a,b}\}_{t>0}$  get equidistributed in  $X$  if and only if  $(a, b) \notin \mathcal{W}_2$ .*

Since the set  $\mathcal{W}_2$  has Lebesgue measure 0 in  $\mathbb{R}^2$ , a typical line gets equidistributed under the flow  $g_t$ .

Chow and Yang [CY19] proved effective equidistribution for translates of a Diophantine line by diagonal elements near  $\text{diag}(e^t, e^{-t}, 1)$ . Unfortunately their method does not seem to apply to the flow  $g_t = \text{diag}(e^{2t}, e^{-t}, e^{-t})$  here. We will instead use Ratner's measure rigidity theorem for unipotent flows [Rat91], and tools from geometric invariant theory.

**1.2. Averaging over the time parameter.** Define

$$\mathcal{W}_2^+ = \left\{ (a, b) \in \mathbb{R}^2 \mid \limsup_{(p_1, p_2; q) \in \mathbb{Z}^2 \times \mathbb{Z}_+} \frac{-\log \max\{|qb + p_1|, |qa + p_2|\}}{\log q} > 2 \right\}.$$

In other words,  $\mathcal{W}_2^+$  consists of vectors  $(a, b) \in \mathbb{R}^2$  for which there exists  $\varepsilon > 0$  such that the system of inequalities

$$\begin{cases} |qb + p_1| \leq q^{-(2+\varepsilon)} \\ |qa + p_2| \leq q^{-(2+\varepsilon)} \end{cases}$$

has infinitely many solutions  $(p_1, p_2; q) \in \mathbb{Z}^2 \times \mathbb{Z}_+$ . Again, we observe that we have the sequence of strict inclusions

$$\mathcal{W}_2^+ \subset \mathcal{W}'_2 \subset \mathcal{W}_2$$

even though all of these sets have Hausdorff dimension equal to 1.

We are also interested in the limit distributions of the **averages** of  $g_t$ -translates of  $\lambda_{a,b}$ , namely the family  $\{\frac{1}{T} \int_0^T g_t \lambda_{a,b} dt\}_{T>0}$  of probability measures on  $X$ . Similar questions have been considered by [SW17] and from the measure rigidity point of view by [ES19].

**Theorem 1.3.** *The following are equivalent:*

- (1) *The averages  $\{\frac{1}{T} \int_0^T g_t \lambda_{a,b} dt\}_{T>0}$  get equidistributed in  $X$ .*

- (2) The averages  $\{\frac{1}{T} \int_0^T g_t \lambda_{a,b} dt\}_{T>0}$  have no escape of mass.  
(3)  $(a, b) \notin \mathcal{W}_2^+$ .

1.2.1. *Remark.* It is shown in [Kle03] that the planar line  $\{y = ax + b\}$  is *extremal* if and only if  $(a, b) \notin \mathcal{W}_2^+$ .

1.3. **Equidistribution along a sequence.** We are also interested in understanding when  $g_t \lambda_{a,b}$  equidistributes along some subsequence  $t_i \rightarrow \infty$ .

**Theorem 1.4.** *Let  $(a, b) \in \mathbb{R}^2$ . Then the following are equivalent:*

- (1)  $(a, b) \notin \mathbb{Q}^2$ .  
(2) For every subinterval  $J \subset I$  of positive measure, there exists a sequence  $t_i \rightarrow \infty$  such that the  $g_{t_i}$ -translates of  $\lambda_{a,b}$  restricted to  $J$  get equidistributed in  $X$ .  
(3) For almost every  $s \in I$ , the trajectory  $\{g_t \phi_{a,b}(s)x_0\}_{t \geq 0}$  is dense in  $X$ .

1.3.1. *Remark.* For  $(a, b) \in \mathbb{Q}^2$  without much effort one can show that the  $g_t$ -translates of  $\lambda_{a,b}$  will diverge, i.e. eventually leave any fixed compact set. Hence Theorem 1.4 gives us a dichotomy which was somewhat unexpected: the  $g_t$ -translates of  $\lambda_{a,b}$  either diverge as  $t \rightarrow \infty$ , or get equidistributed along some sequence  $t_i \rightarrow \infty$ .

1.3.2. *Remark.* We also have dual versions of Theorem 1.1, Theorem 1.2, Theorem 1.3 and Theorem 1.4 above. Let  $\tilde{g}_t = \text{diag}(e^t, e^t, e^{-2t})$ , consider the map  $\tilde{\phi}_{a,b}: s \mapsto \begin{pmatrix} 1 & as+b \\ & 1 & s \\ & & 1 \end{pmatrix}$ , and let  $\tilde{\lambda}_{a,b}$  denote the push-forward of the normalized Lebesgue measure on  $I$  under the map  $s \mapsto \tilde{\phi}_{a,b}(s)x_0$  from  $I$  to  $X$ . Then all the four theorems are still valid for  $\tilde{g}_t$  in place of  $g_t$  and  $\tilde{\lambda}_{a,b}$  in place of  $\lambda_{a,b}$ . Indeed, it suffices to consider the outer automorphism  $g \mapsto w \cdot {}^t g^{-1} \cdot w$  of  $G$ , where  $w = \begin{pmatrix} & & 1 \\ & -1 & \\ & & 1 \end{pmatrix}$ ; under this automorphism  $g_t$  is sent to  $\tilde{g}_t$ ,  $\lambda_{a,b}$  is sent to  $\tilde{\lambda}_{a,b}$ , and  $\mu_X$  is preserved. See [Sha09a, Page 511].

1.4. **Dirichlet-improvable vectors on planar lines.** The motivation for our study came from Diophantine approximation. Denote by  $\|\cdot\|$  the supremum norm on  $\mathbb{R}^n$  (unless specified otherwise, all the norms on  $\mathbb{R}^n$  will be taken to be the supremum norm). Following Davenport and Schmidt [DS70b], for  $0 < \delta < 1$  we say that a vector  $\mathbf{x} \in \mathbb{R}^n$  is  $\delta$ -*improvable* if for every sufficiently large  $T$ , the system of inequalities

$$\begin{cases} \|q\mathbf{x} + \mathbf{p}\| \leq \delta T^{-1} \\ |q| \leq T^n \end{cases}$$

has a solution  $(\mathbf{p}, q)$ , where  $\mathbf{p} \in \mathbb{Z}^n$  and  $q \in \mathbb{Z} \setminus \{0\}$ . One says that  $\mathbf{x}$  is *Dirichlet-improvable* if it is  $\delta$ -improvable for some  $0 < \delta < 1$ , and that it is *singular* if it is  $\delta$ -improvable for all  $0 < \delta < 1$ .

Similarly, a real linear form on  $\mathbf{q} \in \mathbb{Z}^n$  is given by  $\mathbf{q} \mapsto \mathbf{x} \cdot \mathbf{q}$ , parametrized by  $\mathbf{x} \in \mathbb{R}^n$ . We say that this linear form is  $\delta$ -*improvable* if there exists  $0 < \delta < 1$  such

that for every sufficiently large  $T$ , the system of inequalities

$$(1.4) \quad \begin{cases} |\mathbf{x} \cdot \mathbf{q} + p| \leq \delta T^{-n} \\ \|\mathbf{q}\| \leq T \end{cases}$$

has a solution  $(p, \mathbf{q})$ , where  $p \in \mathbb{Z}$  and  $\mathbf{q} \in \mathbb{Z}^n \setminus \{0\}$ .

The notation  $\text{DI}(n, 1)$  and  $\text{DI}(1, n)$  (resp.,  $\text{Sing}(n, 1)$  and  $\text{Sing}(1, n)$ ) is used in the literature to denote the set of Dirichlet-improvable (resp., singular) vectors and linear forms. It is known that  $\text{DI}(n, 1) = \text{DI}(1, n)$  and  $\text{Sing}(n, 1) = \text{Sing}(1, n)$ , see [DS70a] and [Cas57, Chapter V, Theorem XII] respectively.

The readers who would like to know more background information are referred to [KW08, Sha09a] and references therein for Dirichlet-improvable vectors, and [CC16, Dan85] and references therein for singular vectors.

Now let us again specialize to  $n = 2$ , and take  $\mathbf{x}$  of the form  $(s, as + b)$ . In the simplest possible case  $(a, b) \in \mathbb{Q}^2$  it is very easy to see that every point on the planar line

$$L_{a,b} = \{(x, y) \in \mathbb{R}^2 \mid y = ax + b\}$$

is singular: indeed, take  $a = k/m$  and  $b = \ell/m$  and notice that one has

$$(x, y) \cdot (-k, m) = \left(s, \frac{k}{m}s + \frac{\ell}{m}\right) \cdot (-k, m) = \ell;$$

thus one can always find  $(p, \mathbf{q})$  such that the left hand side of the first inequality in (1.4) is zero.

Our next main theorem is the following stronger converse to the above computation:

**Theorem 1.5.** *Let  $(a, b) \in \mathbb{R}^2$ . If  $(a, b) \notin \mathbb{Q}^2$ , then almost every point on the planar line  $L_{a,b}$  is not Dirichlet-improvable.*

The deduction of Theorem 1.5 from Theorem 1.4 uses Dani's correspondence, and has become a standard argument. We give the proof below for completeness.

*Proof of Theorem 1.5 assuming Theorem 1.4.* For  $0 < \delta < 1$ , let  $K_\delta$  denote the set of unimodular lattices in  $\mathbb{R}^3$  whose shortest non-zero vector has norm at least  $\delta$ . Then  $K_\delta$  contains an open neighborhood of  $x_0$ , and is compact by Mahler's compactness criterion. For  $0 < \delta < 1$ , let  $D_\delta$  denote the set of  $s \in \mathbb{R}$  such that  $(s, as + b)$  is a  $\delta$ -improvable linear form. By Dani's correspondence [Dan85] and [KW08, Proposition 2.1],

$$D_\delta = \{s \in \mathbb{R} \mid g_t \phi_{a,b}(s)x_0 \notin K_{\delta^{1/3}} \text{ for all large } t\}.$$

In particular,  $\{g_t \phi_{a,b}(s)x_0\}_{t \geq 0}$  is not dense in  $G/\Gamma$  for all  $s \in D_\delta$ . By Theorem 1.4 we have  $|D_\delta| = 0$  for all  $0 < \delta < 1$ . Finally, we conclude the proof by noting that the set of  $s$  such that  $(s, as + b)$  is a Dirichlet-improvable point on  $L_{a,b}$  equals  $\bigcup_{m \geq 1} D_{\frac{m-1}{m}}$ , and hence has Lebesgue measure 0.  $\square$

**1.5. Strategy of the proof.** Given any sequence  $t_i \rightarrow \infty$ , after passing to a subsequence we obtain that  $g_{t_i} \lambda_{a,b}$  converges to a measure, say  $\mu$ , on  $X$  with respect to the weak- $*$  topology. It is straightforward to see that  $\mu$  must be invariant under a non-trivial unipotent subgroup of  $G$  (Proposition 6.1). There are two possibilities: if  $\mu$  is not a probability measure then we apply the Dani-Margulis non-divergence criterion (Proposition 5.1), and if  $\mu$  is positive and not  $G$ -invariant then we apply Ratner's description of ergodic invariant measures for unipotent flows, combined with the linearization technique (Theorem 4.1). In both cases we obtain the following *linear dynamical obstruction to equidistribution*: There exist a finite-dimensional representation  $V$  of  $G$  over  $\mathbb{Q}$ , a non-zero vector  $v_0 \in V(\mathbb{Q})$ , a constant  $R > 0$ , and a sequence  $\{\gamma_i\} \subset \Gamma = \mathrm{SL}_3(\mathbb{Z})$  such that for each  $i$ ,

$$(1.5) \quad \sup_{s \in I} \|g_{t_i} \phi_{a,b}(s) \gamma_i v_0\| \leq R.$$

The major effort involved in this proof is to analyze this linear dynamical obstruction and show that  $(a, b)$  must satisfy certain Diophantine approximation condition.

Using Kempf's numerical criterion in geometric invariant theory, when the  $Gv_0$  is not Zariski closed, we reduce the obstruction to the case of  $v_0$  being a highest weight vector (Theorem 2.1). Then we further reduce to the case of  $v_0$  being a highest weight vector of a fundamental representation of  $G$ , namely the standard representation  $\mathbb{R}^3$ , or its exterior power  $\bigwedge^2 \mathbb{R}^3$  (Lemma 2.2). It is straightforward to show that the obstruction (1.5) does not arise for the exterior representation (Lemma 2.3), so we are left only with the case of  $V$  being the standard representation. In the case of the standard representation the dynamical obstruction leads to the Diophantine condition that  $(a, b) \in \mathcal{W}_2$  (Lemma 3.1).

We are left with the case of  $Gv_0$  being Zariski closed. Using explicit descriptions of finite-dimensional irreducible representations of  $\mathrm{SL}_2$  and  $\mathrm{SL}_3$ , we show that in this case after passing to a further subsequence  $\{\gamma_i v_0\}$  is constant and  $(a, b) \in \mathbb{Q}^2$  (Theorem 4.1).

We remark that for  $G = \mathrm{SL}_n$  for  $n > 3$ , analyzing the Zariski closed orbit case involves much greater complexities, and the above strong conclusion about  $(a, b)$  is not possible.

**1.6. Comparison with previous work.** We remark that Theorem 1.3 and Theorem 1.5 sharpen the main results of Shi and Weiss [SW17]. More precisely, it was shown in [SW17] that the averages of  $g_t$ -translates of  $\lambda_{a,b}$  get equidistributed in  $X$  if the line  $\{y = ax + b\}$  contains a badly approximable vector. Lemma 3.2 below shows that this condition implies in particular that  $(a, b) \notin \mathcal{W}'_2$ , and so is strictly stronger than  $(a, b) \notin \mathcal{W}_2^+$ . Our results give sharp conditions of non-escape of mass and equidistribution for not only averages, but also pure translates (which was not considered in [SW17]). This is why we are able to prove the much stronger Theorem 1.5.

**1.7. Future directions.** Instead of  $g_t$ , one may consider more general flows. It seems that our method is also applicable to the study of translates by elements in a Weyl chamber, at least for certain cones. Then the non-effective version of Theorem

1.1 of [CY19] will be recovered. One would also be able to say something about improbability of weighted Dirichlet Theorem, and the readers are referred to [Sha10] for a detailed introduction to this subject.

One may also ask what happens to other Lie groups, e.g.  $G = \mathrm{SL}_n(\mathbb{R})$  for  $n > 3$ . When  $n = 4$ , things already become more complicated. Roughly speaking,  $\mathrm{SL}_3(\mathbb{R})$  is small and one does not have many choices of possible intermediate subgroups. However, in  $\mathrm{SL}_n(\mathbb{R})$  where  $n > 3$ , there are more possibilities of intermediate subgroups, and a more careful study is needed.

We will study the above-mentioned generalizations in subsequent work.

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## 2. INSTABILITY AND INVARIANT THEORY

To analyze limiting distributions of sequences of translates of measures on homogeneous spaces a technique has been developed, where one applies the Dani-Margulis and Kleinbock-Margulis non-divergence criteria, Ratner’s theorem and the linearization method, and reduces the problem to dynamics of subgroup actions on finite-dimensional representations of semisimple groups, see [Sha09a, SY20]. In [Yan20], this kind of linear dynamics was analysed in a very general situation using invariant theory results due to Kempf [Kem78]. We follow the same approach, and this section is devoted to the basic tools from geometric invariant theory that we shall need in our argument.

Let  $G$  be a reductive algebraic  $\mathbb{Q}$ -group, and  $\rho : G \rightarrow \mathrm{GL}(V)$  a linear representation of  $G$  defined over  $\mathbb{Q}$ . We say that a nonzero vector  $v$  is *unstable* if the Zariski closure of the orbit  $Gv$  contains the origin. Mumford’s instability criterion states that a vector  $v$  is unstable if and only if there exists a cocharacter  $\lambda : \mathbb{G}_m \rightarrow G$  such that  $\lambda(t)v \rightarrow_{t \rightarrow \infty} 0$ . Kempf [Kem78] refined this criterion by studying the set of cocharacters  $\lambda$  that bring  $v$  to 0 at maximal speed. Let us briefly recall his results.

Write  $X_*(G)$  for the set of  $\mathbb{Q}$ -cocharacters of  $G$ . For any  $v \in V(\mathbb{Q})$  and any nontrivial cocharacter  $\lambda$  in  $X_*(G)$ , one can write  $v = \sum_{i \in \mathbb{Z}} v_i$ , where  $\lambda(t)v_i = t^i v_i$  for all  $i$ . Let  $m(v, \lambda) = \min_{i \in \mathbb{Z}} \{v_i \neq 0\}$ . Then

$$v = v_{m(v, \lambda)} + \sum_{i > m(v, \lambda)} v_i.$$

If  $S$  is a maximal  $\mathbb{Q}$ -split torus in  $G$ , we may fix a positive definite integral bilinear form on  $X_*(S)$  which is invariant under the Weyl group; it induces a norm on  $X_*(S)$  defined by  $\|\lambda\| = \sqrt{(\lambda, \lambda)}$ . This norm extends uniquely to a  $G$ -invariant norm on



the set  $X_*(G)$  of  $\mathbb{Q}$ -cocharacters of  $G$ . Kempf proved that if  $v \in V(\mathbb{Q})$  is an unstable vector, then  $\max_{\lambda \in X_*(G)} \frac{m(v, \lambda)}{\|\lambda\|} > 0$ . Moreover, the parabolic subgroup

$$P(\lambda) = \{p \in G \mid \lim_{t \rightarrow 0} \lambda(t)p\lambda(t)^{-1} \text{ exists}\}$$

is independent of the choice of the cocharacter  $\lambda$  such that  $\frac{m(v, \lambda)}{\|\lambda\|}$  is maximal; we denote it by  $P_v$ . Finally, any maximal  $\mathbb{Q}$ -split torus in  $P_v$  contains a unique element  $\lambda$  maximizing  $\frac{m(v, \lambda)}{\|\lambda\|}$ , and if  $u \in G$  is such that  $\lambda(t)u\lambda(t)^{-1} \rightarrow e$  as  $t \rightarrow 0$ , then

$$(2.1) \quad uv = v_{m(v, \lambda)} + \sum_{i > m(v, \lambda)} (uv)_i.$$

We shall apply these results for the group  $G = \mathrm{SL}_3(\mathbb{R})$ . In that case, the maximal torus  $S$  is the subgroup of  $G = \mathrm{SL}_3(\mathbb{R})$  consisting of diagonal matrices. Let  $K = \mathrm{SO}(3)$ . Choose simple roots  $\alpha_1: (t_1, t_2, t_3) \mapsto t_1 t_2^{-1}$ ,  $\alpha_2: (t_1, t_2, t_3) \mapsto t_2 t_3^{-1}$ . The corresponding fundamental weights are  $\omega_1: (t_1, t_2, t_3) \mapsto t_1$  and  $\omega_2: (t_1, t_2, t_3) \mapsto t_1 t_2$ . The standard parabolic subgroups of  $G$  are

$$P_0 = \left\{ \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \right\}, \quad P_1 = \left\{ \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \right\}, \quad P_2 = \left\{ \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \right\}.$$

We shall also use the following algebraic subgroups of  $G$ :

$$\begin{aligned} Q_0 &= \left\{ \begin{pmatrix} 1 & * & * \\ & 1 & * \\ & & 1 \end{pmatrix} \right\}, & Q_1 &= \left\{ \begin{pmatrix} 1 & * & * \\ & * & * \\ & & * \end{pmatrix} \right\}, & Q_2 &= \left\{ \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & 1 \end{pmatrix} \right\}. \\ S_0 &= \left\{ \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \right\}, & S_1 &= \left\{ \begin{pmatrix} t^2 & & \\ & t^{-1} & \\ & & t^{-1} \end{pmatrix} \right\}, & S_2 &= \left\{ \begin{pmatrix} t & & \\ & t & \\ & & t^{-2} \end{pmatrix} \right\}. \\ H_0 &= \{1\}, & H_1 &= \left\{ \begin{pmatrix} 1 & * & * \\ & * & * \\ & & * \end{pmatrix} \right\}, & H_2 &= \left\{ \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & 1 \end{pmatrix} \right\}. \\ U_0 &= \left\{ \begin{pmatrix} 1 & * & * \\ & 1 & * \\ & & 1 \end{pmatrix} \right\}, & U_1 &= \left\{ \begin{pmatrix} 1 & * & * \\ & 1 & * \\ & & 1 \end{pmatrix} \right\}, & U_2 &= \left\{ \begin{pmatrix} 1 & * & * \\ & 1 & * \\ & & 1 \end{pmatrix} \right\}. \end{aligned}$$

One has  $P_i = S_i Q_i = S_i H_i U_i$ , for  $i = 0, 1, 2$ .

**2.1. Reduction to a highest weight vector.** The next result (Theorem 2.1) provides a very powerful new technique that allows one to reduce the study of linear dynamics of an arbitrary vector in an arbitrary representation to that of a highest weight vector. From this we will further reduce the study to fundamental representations (Lemma 2.2), opening the doors to directly relate the linear dynamics to Diophantine properties of vectors (Lemma 3.1).

The proof of the following result was motivated by [Yan20, Proposition 2.4].

**Theorem 2.1.** *Let  $V$  be a representation of  $G$  defined over  $\mathbb{Q}$ . Let  $v$  be an unstable vector in  $V(\mathbb{Q})$ . Then there exists an irreducible representation  $W$  of  $G$  defined over  $\mathbb{Q}$ , a highest weight vector  $w' \in W(\mathbb{Q})$ , an element  $g_0 \in G(\mathbb{Q})$ , and constants  $C > 0$ ,  $\beta > 0$  such that for any  $g \in G$  one has*

$$\|gg_0 w'\| \leq C \|gv\|^\beta.$$

*Proof.* Without loss of generality, we may assume that the norms are  $K$ -invariant.

Given  $v$  unstable in  $V(\mathbb{Q})$ , by the above-mentioned result of Kempf [Kem78, Theorem 4.2] one associates to  $v$  a parabolic subgroup  $P_v$  defined over  $\mathbb{Q}$ . By [Bor91, Proposition 21.12], there exists  $g_0 \in G(\mathbb{Q})$  and  $0 \leq j \leq 2$  such that  $P_v = g_0 P_j g_0^{-1}$ . Let  $v' = g_0^{-1}v$ , so that  $P_{v'} = g_0^{-1}P_v g_0 = P_j$ . Let  $\Lambda_{v'}$  be the set of elements  $\lambda \in X_*(G)$  such that  $\frac{m(v', \lambda)}{\|\lambda\|}$  is maximal. Kempf's theorem shows that  $\frac{m(v', \lambda)}{\|\lambda\|} > 0$  for any  $\lambda \in \Lambda_{v'}$ , and that  $\Lambda_{v'}$  contains a unique indivisible element  $\delta$  of  $X_*(S)$ . Then  $\delta$  is a dominant cocharacter,  $\text{Im } \delta \subset S_j$ , and

$$P(\delta) = P_{v'} = P_j.$$

Now let  $\delta^\vee \in X^*(S)$  be the dual of  $\delta$  with respect to  $(\cdot, \cdot)$  in the following sense: for any  $\lambda$  in  $X_*(S)$ , one has

$$\langle \delta^\vee, \lambda \rangle = (\delta, \lambda) \in \mathbb{Z}.$$

Let  $S_\delta$  denote the  $\mathbb{Q}$ -subtorus of  $S_j$  which is the identity component of the kernel of  $\delta^\vee$  in  $S_j$ . We have that  $\text{Im } \delta \cap S_\delta$  is finite and  $(\text{Im } \delta)S_\delta = S_j$ .

Take any  $d \in \mathbb{Q}_{>0}$  such that there exists an irreducible representation  $W$  of  $G$  with highest weight  $\omega = d\delta^\vee$ . Let  $w' \in W(\mathbb{Q})$  be a highest weight vector. Let

$$\beta = \frac{(\delta, \delta)d}{m(v', \delta)} > 0.$$

Now it suffices to show that there exists  $C > 0$  such that for any  $g \in G$  we have

$$\|gw'\| \leq C\|gv'\|^\beta.$$

We argue by contradiction. Suppose that there exists a sequence  $g_i$  in  $G$  such that  $\|g_i v'\|^\beta / \|g_i w'\| \rightarrow 0$  as  $i \rightarrow \infty$ .

We note that  $P(\delta) = P_j$  acts on  $w'$  via the character  $d\delta^\vee$ . So  $Q_j = H_j U_j$  fixes  $w'$ . Since  $G = KP_j = KS_j Q_j = KS_j H_j U_j$ , we can write  $g_i = k_i s_i h_i u_i$  where  $k_i \in K$ ,  $s_i \in S_j$ ,  $h_i \in H_j$  and  $u_i \in U_j$ . Since the norms are  $K$ -invariant, we may assume that  $k_i = e$  for all  $i$ . Now  $s_i h_i u_i w' = \delta^\vee(s_i)^d w'$ . Hence  $\|g_i w'\| = |\delta^\vee(s_i)|^d \|w'\|$ . Since  $S_j = (\text{Im } \delta)S_\delta$ , we can write  $s_i = \delta(\tau_i)\sigma_i$ , where  $\tau_i \in \mathbb{R}^\times$  and  $\sigma_i \in S_\delta$ . Then

$$(2.2) \quad \|g_i w'\| = |\delta^\vee(\delta(\tau_i))|^d \|w'\| = |\tau_i|^{(\delta, \delta)d} \|w'\|.$$

Let  $\pi$  denote the  $S_j H_j$ -equivariant projection from  $V$  to

$$\tilde{V} := \{x \in V \mid \delta(t)x = t^{m(v', \delta)}x\}.$$

Then there exists  $C_1 > 0$  such that  $\|\pi(x)\| \leq C_1 \|x\|$  for all  $x \in V$ . It follows that

$$(2.3) \quad \frac{\|\pi(g_i v')\|^\beta}{\|g_i w'\|} \leq C_1^\beta \frac{\|g_i v'\|^\beta}{\|g_i w'\|} \rightarrow_{i \rightarrow \infty} 0.$$

For any  $u \in U_j$ ,  $\delta(t)u\delta(t)^{-1} \rightarrow e$  as  $t \rightarrow 0$ , so by Equation (2.1),  $\pi(uv') = \pi(v')$ . Hence

$$(2.4) \quad \|\pi(g_i v')\| = |\tau_i|^{m(v', \delta)} \|\pi(\sigma_i h_i u_i v')\| = |\tau_i|^{m(v', \delta)} \|\sigma_i h_i \pi(v')\|.$$

Combining (2.2), (2.3) and (2.4), one gets  $\|\sigma_i h_i \pi(v')\| \rightarrow 0$ , and this implies that  $\pi(v')$  is  $S_\delta H_j$ -unstable in  $\tilde{V}$ . We apply once more [Kem78, Theorem 4.2] to the group  $S_\delta H_j$  to deduce that there exists  $l \in (S_\delta H_j)(\mathbb{Q})$  such that  $\Lambda_{l\pi(v')}^{S_\delta H_j} \cap X_*(S_\delta H_j \cap S)$  is non-empty; we let  $\delta_l$  denote its unique element. Note that  $S_\delta H_j \cap S$  is a maximal  $\mathbb{Q}$ -split torus of  $S_\delta H_j$ . Since  $S_\delta H_j \cap S = \ker \delta^\vee$ , we have

$$(2.5) \quad (\delta, \delta_l) = \langle \delta^\vee, \delta_l \rangle = \delta^\vee \circ \delta_l = 0 \in \text{Hom}(\mathbb{G}_m, \mathbb{G}_m).$$

Since  $l \in P(\delta) = P_{v'}$ , we have  $\Lambda_{lv'} = \Lambda_{v'}$  and thus  $\delta \in \Lambda_{lv'}$ .

For a positive integer  $N$ , let  $\delta_N = N\delta + \delta_l$ . For  $N$  large enough, we claim that

$$(2.6) \quad \frac{m(lv', \delta_N)}{\|\delta_N\|} > \frac{m(lv', \delta)}{\|\delta\|} = B_{lv'},$$

which will contradict the maximality of  $B_{lv'}$ .

To prove the claim, consider the weight space decomposition  $V = \bigoplus V_\chi$ , where  $S$  acts on  $V_\chi$  by multiplication via the character  $\chi$  of  $S$ . Let

$$\begin{aligned} \Xi &= \{\chi \in X^*(S) \mid (lv')_\chi \neq 0 \text{ and } \langle \chi, \delta \rangle = m(lv', \delta)\} \\ &= \{\chi \in X^*(S) \mid (\pi(lv'))_\chi \neq 0\}. \end{aligned}$$

It suffices to prove that for any  $\chi \in \Xi$ , one has

$$(2.7) \quad \frac{\langle \chi, \delta_N \rangle}{\|\delta_N\|} > \frac{\langle \chi, \delta \rangle}{\|\delta\|}.$$

To prove (2.7), we define an auxiliary function:

$$f(s) = \frac{\langle \chi, \delta + s \cdot \delta_l \rangle^2}{\|\delta + s \cdot \delta_l\|^2} = \frac{\langle \chi, \delta \rangle^2 + 2s\langle \chi, \delta \rangle \langle \chi, \delta_l \rangle + s^2 \langle \chi, \delta_l \rangle^2}{(\delta, \delta) + 2s(\delta, \delta_l) + s^2(\delta_l, \delta_l)}.$$

Compute its derivative at 0:

$$f'(0) = \frac{2\langle \chi, \delta \rangle \langle \chi, \delta_l \rangle (\delta, \delta) - 2(\delta, \delta_l) \langle \chi, \delta \rangle^2}{(\delta, \delta)^2}.$$

Since  $\delta_l \in \Lambda_{l\pi(v')}^{S_\delta H_j} = \Lambda_{\pi(lv')}^{S_\delta H_j}$  and  $(\pi(lv'))_\chi \neq 0$ , we know that  $\langle \chi, \delta_l \rangle > 0$ . Since  $\delta \in \Lambda_{lv'}$ , we know that  $\langle \chi, \delta \rangle > 0$ . And  $(\delta, \delta_l) = 0$  by Equation (2.5). Combining the above one gets  $f'(0) > 0$ . Hence for  $N$  large we have

$$(2.8) \quad f(1/N) > f(0),$$

and (2.7) follows because each side of (2.8) is the square of each side of (2.7) respectively. Therefore (2.6) holds, contradicting the maximality of  $B_{lv'}$ .  $\square$

**2.2. Reduction to fundamental representations.** Let  $W_1 = \mathbb{R}^3$  and  $W_2 = \bigwedge^2 \mathbb{R}^3$ . Let  $w_1 = e_1 \in W_1$  and  $w_2 = e_1 \wedge e_2 \in W_2$ . Let  $\omega_1$  and  $\omega_2$  be the highest weights of  $W_1$  and  $W_2$ . Then  $\omega_1$  and  $\omega_2$  are the fundamental weights of  $G$ , and any dominant integral weight is a non-negative integral linear combination of  $\omega_1$  and  $\omega_2$ .

**Lemma 2.2.** *Let  $W$  be an irreducible representation of  $G$  with highest weight  $\omega = n_1\omega_1 + n_2\omega_2$ , and  $w \in W$  a highest weight vector. Then for any real-analytic map  $\psi: I \rightarrow G$ , where  $I \subset \mathbb{R}$  is any non-empty interval, there exists a constant  $c > 0$  such that for any  $h_1, h_2 \in G$ ,*

$$\sup_{s \in I} \|h_1\psi(s)h_2w\| \geq c \cdot \left( \min_{1 \leq i \leq 2} \sup_{s \in I} \|h_1\psi(s)h_2w_i\| \right)^{n_1+n_2}.$$

*Proof.* Let the notation be as in the beginning of this section. We have  $G = KS_0U_0$ . Hence for  $g \in G$ , we can write  $g = ktu$  for  $k \in K, t \in S_0 = S$  and  $u \in U_0$ . We note that  $w_1$  and  $w_2$  are both fixed by  $U_0$ . Taking any  $K$ -invariant norms on  $W_1$  and  $W_2$ , we have  $\|gw_1\| = |\omega_1(t)|\|w_1\|$  and  $\|gw_2\| = |\omega_2(t)|\|w_2\|$ . We take a  $K$ -invariant norm on  $W$  such that  $\|w\| = \|w_1\|^{n_1}\|w_2\|^{n_2}$ . Then for any  $g \in G$ ,  $\|gw\| = \|gw_1\|^{n_1}\|gw_2\|^{n_2}$ . Now let

$$F(g) = \|h_1gh_2w\|^2 \quad \text{and} \quad F_i(g) = \|h_1gh_2w_i\|^2, \quad i = 1, 2.$$

Then  $F, F_1, F_2$  are regular functions on  $G$ , and

$$F(g) = F_1(g)^{n_1}F_2(g)^{n_2}.$$

Let  $Z$  be the Zariski closure of  $\psi(I)$  in  $G$ . Since  $\psi$  is analytic,  $Z$  is an irreducible algebraic set. We use the norm

$$\|F\| = \sup_{s \in I} |F(\psi(s))|$$

on the space of regular functions on  $Z$ . We claim that for any positive integers  $d_1$  and  $d_2$ , there exists a constant  $c = c(d_1, d_2) > 0$  such that for any polynomials  $E_1$  and  $E_2$  of degrees  $d_1$  and  $d_2$  respectively on  $Z$ , we have  $\|E_1E_2\| \geq c\|E_1\|\|E_2\|$ . Indeed, by homogeneity we only need to check this for  $\|E_1\| = \|E_2\| = 1$ , and then the possible values of  $\|E_1E_2\|$  form a compact subset of  $\mathbb{R}_{>0}$ . Therefore,

$$\|F\| \geq c\|F_1\|^{n_1}\|F_2\|^{n_2} \geq c \cdot \left( \min_{1 \leq i \leq 2} \|F_i\| \right)^{n_1+n_2}.$$

□

### 2.3. From fundamental representations to the standard representation.

Let the notation be as before: We fix  $(a, b) \in \mathbb{R}^2$ ,  $I = [s_0, s_1] \subset \mathbb{R}$  for some  $s_0 < s_1$ , and for any  $s \in I$  and  $t \in \mathbb{R}$ , we have

$$\phi_{a,b}(s) = \begin{pmatrix} 1 & s & as+b \\ & 1 & \\ & & 1 \end{pmatrix} \quad \text{and} \quad g_t = \begin{pmatrix} e^{2t} & & \\ & e^{-t} & \\ & & e^{-t} \end{pmatrix}.$$

The following observation allows us to reduce our possibilities from all fundamental representations to only the standard representation.

**Lemma 2.3.** *There exists a constant  $C_I$  depending only on  $I$  such that for any non-zero  $v \in W_2(\mathbb{Z}) = \bigwedge^2 \mathbb{Z}^3$  and  $t \geq 0$ ,*

$$(2.9) \quad \sup_{s \in I} \|g_t\phi_{a,b}(s)v\| \geq C_I e^t.$$

*Proof.* Let  $e_1, e_2, e_3$  denote the standard basis of  $\mathbb{R}^3$  (and  $\mathbb{Z}^3$ ). We write  $e_{ij} = e_i \wedge e_j$  for the standard basis of  $\wedge^2 \mathbb{R}^3$ . For any  $s \in I$  and  $t \geq 0$ , one can readily compute the matrix of  $g_t \phi_{a,b}(s)$  in the standard basis  $(e_{23}, e_{13}, e_{12})$ :

$$\wedge^2 g_t \phi_{a,b}(s) = \begin{pmatrix} e^{-2t} & 0 & 0 \\ se^t & e^t & 0 \\ -e^t(as+b) & 0 & e^t \end{pmatrix}.$$

So, for any  $v = \begin{pmatrix} p \\ q \\ r \end{pmatrix}$  in  $\wedge^2 \mathbb{R}^3$ ,  $s \in I$  and  $t \geq 0$ ,

$$g_t \phi_{a,b}(s)v = \begin{pmatrix} e^{-2t}p \\ e^t(sp+q) \\ e^t[-(as+b)p+r] \end{pmatrix}.$$

Now observe that

$$\max\{|s_0p + q|, |s_1p + q|\} \geq \min\left\{\frac{|p|(s_1 - s_0)}{2}, \frac{|q|(s_1 - s_0)}{|s_0| + |s_1|}\right\},$$

so that if  $(p, q, r) \in \mathbb{Z}^3 \setminus \{0\}$ , then

$$\max_{s \in \{s_0, s_1\}} \{|sp + q|, |-(as + b)p + r|\} \geq C_I,$$

where

$$C_I = \min\left\{\frac{s_1 - s_0}{2}, \frac{s_1 - s_0}{|s_0| + |s_1|}, 1\right\} > 0,$$

because if  $(p, q) = (0, 0)$  then  $|-(as + b)p + r| = |r| \geq 1$ . So (2.9) follows.  $\square$

By combining the above results we obtain the following:

**Proposition 2.4.** *Let  $V$  be a finite-dimensional representation of  $G$  defined over  $\mathbb{Q}$  and let  $v_0 \in V(\mathbb{Q}) \setminus \{0\}$ . Suppose that  $Gv_0$  is not Zariski closed. Then given  $C > 0$  there exists  $R > 0$  such that the following holds: There exists  $t_0 > 0$  such that for any  $t > t_0$  and any  $\gamma \in \Gamma$ , if*

$$(2.10) \quad \sup_{s \in I} \|g_t \phi_{a,b}(s) \gamma v_0\| \leq C,$$

then there exists  $v \in \mathbb{Z}^3 \setminus \{0\}$  such that

$$(2.11) \quad \sup_{s \in I} \|g_t \phi_{a,b}(s)v\| \leq R.$$

*Proof.* Let  $S$  denote the boundary of  $Gv_0$ . By [Kem78, Lemma 1.1], there exists a representation  $V'$  of  $G$  and a  $G$ -equivariant polynomial map  $f: V \rightarrow V'$ , both defined over  $\mathbb{Q}$ , such that  $S = f^{-1}(0)$ . It follows that  $f(v_0) \in V'(\mathbb{Q})$  is unstable in  $V'$ , and there exists a constant  $C' > 0$  and a norm on  $V'$  such that (2.10) holds for  $(f(v_0), V', C')$  in place of  $(v_0, V, C)$ . Hence by replacing  $v_0$  with  $f(v_0)$  we may assume that  $v_0$  is unstable in  $V$ .

Now we can apply Theorem 2.1, and conclude that there exists an irreducible representation  $W$  of  $G$  defined over  $\mathbb{Q}$ , a highest weight vector  $w \in W(\mathbb{Q})$ , an element  $g_0 \in G(\mathbb{Q})$ , and a constant  $D > 0$  such that for any  $t \geq 0$  and  $\gamma \in \Gamma$  if (2.10) holds then

$$\sup_{s \in I} \|g_t \phi_{a,b}(s) \gamma g_0 w\| \leq D.$$

Combined with Lemma 2.2, this implies that there exists  $D' > 0$ , depending only on  $w$  and  $D$ , such that

$$(2.12) \quad \min_{1 \leq j \leq 2} \sup_{s \in I} \|g_t \phi_{a,b}(s) \gamma g_0 w_j\| \leq D'.$$

Since  $g_0 \in G(\mathbb{Q})$ , there exists  $N \in \mathbb{Z}_+$  such that  $N \cdot \Gamma g_0 w_1 \subset W_1(\mathbb{Z}) = \mathbb{Z}^3$  and  $N \cdot \Gamma g_0 w_2 \subset W_2(\mathbb{Z}) = \bigwedge^2 \mathbb{Z}^3$ .

Let  $R = ND'$ . Lemma 2.3 shows that for  $t \geq 0$  large enough, no integer vector in  $\bigwedge^2 \mathbb{Z}^3$  can satisfy (2.12): in particular, if  $t > t_0 := \log RC_I^{-1}$ , then

$$\sup_{s \in I} \|g_t \phi_{a,b}(s) (\gamma g_0 w_2)\| > R/N = D'.$$

Therefore, the vector  $v = N\gamma g_0 w_1$  must satisfy (2.11), as desired.  $\square$

### 3. DYNAMICS IN THE STANDARD REPRESENTATION AND DIOPHANTINE CONDITIONS

In this section we relate asymptotic dynamics of the  $g_t$ -action on the curve  $\{\phi_{a,b}(s) : s \in I\}$  in the standard representation with some Diophantine approximation properties of the vector  $(a, b)$ . Our first lemma characterizes the condition  $(a, b) \in \mathcal{W}_2$  in terms of vectors of bounded size in the lattices  $g_t \phi_{a,b}(s) \mathbb{Z}^3$ ,  $s \in I$ .

**Lemma 3.1.** *The following are equivalent:*

- (1)  $(a, b) \in \mathcal{W}_2$ .
- (2) There exists  $R > 0$ ,  $t_i \rightarrow \infty$  and  $\{v_i\} \subset \mathbb{Z}^3 \setminus \{0\}$  such that for all  $i$ ,

$$(3.1) \quad \sup_{s \in I} \|g_{t_i} \phi_{a,b}(s) v_i\| \leq R.$$

*Proof.* We write  $v_i = \begin{pmatrix} p_{1,i} \\ p_{2,i} \\ q_i \end{pmatrix} \in \mathbb{Z}^3 \setminus \{0\}$ . It follows that

$$(3.2) \quad g_{t_i} \phi_{a,b}(s) v_i = \begin{pmatrix} e^{2t_i} ((bq_i + p_{1,i}) + (aq_i + p_{2,i})s) \\ e^{-t_i} p_{2,i} \\ e^{-t_i} q_i \end{pmatrix}.$$

Suppose (3.1) holds. Let  $R_1 = \left\| \begin{pmatrix} 1 & s_0 \\ 1 & s_1 \end{pmatrix}^{-1} \right\| \cdot R$ , where  $\|\cdot\|$  denotes the operator norm with respect to the sup-norm. Then for all  $i$ ,

$$(3.3) \quad \begin{cases} |q_i b + p_{1,i}| \leq R_1 e^{-2t_i}, \\ |q_i a + p_{2,i}| \leq R_1 e^{-2t_i}, \\ |q_i| \leq R e^{t_i}. \end{cases}$$

*Case 1.* Suppose a subsequence of  $\{q_i\}$  is bounded.

After passing to a subsequence, we may assume that  $q_i = q$  is constant, and then (3.3) forces  $qb + p_{1,i} = 0$  and  $qa + p_{2,i} = 0$  for  $t_i$  large enough, because  $p_{1,i}$  and  $p_{2,i}$  are integers. Since  $(p_{1,i}, p_{2,i}, q_i) \neq 0$ , we get  $q \neq 0$  and  $(a, b) \in \mathbb{Q}^2$ .

*Case 2.* Suppose  $|q_i| \rightarrow \infty$  as  $i \rightarrow \infty$ .

Put  $R_2 = R_1 R^2$ . Then (3.3) shows that for all  $i$ ,

$$(3.4) \quad \begin{cases} |q_i b + p_{1,i}| \leq R_2 |q_i|^{-2} \\ |q_i a + p_{2,i}| \leq R_2 |q_i|^{-2}. \end{cases}$$

Therefore  $(a, b) \in \mathcal{W}_2 \setminus \mathbb{Q}^2$ . Combining both cases we proved that (2)  $\Rightarrow$  (1).

Conversely, suppose  $(a, b) \in \mathcal{W}_2$ . By (1.1) we pick a sequence  $(p_{1,i}, p_{2,i}, q_i) \in \mathbb{Z}^3$  such that  $0 \neq q_i \rightarrow \infty$  and (3.4) holds for some  $R_2 \geq 0$ . Then for  $t_i = \log|q_i|$ , we get (3.3) for  $R_1 = R_2$  and  $R = 1$  and  $|p_{2,i}| \leq R_1 e^{-2t_i} + |a|e^{t_i}$ . So in view of (3.2), we get that (3.1) holds for  $R = (|s_0| + |s_1| + 1)R_1 + |a| + 1$ .  $\square$

The second lemma shows that  $(a, b) \in \mathcal{W}'_2$  if and only if the curve  $\phi_{a,b}$  is entirely sent to the cusp under the action of  $g_t$  in the space of lattices, along a subsequence of times  $t_i$  going to infinity.

**Lemma 3.2.** *We have  $(a, b) \in \mathcal{W}'_2$  if and only if there exist  $t_i \rightarrow \infty$  and  $\{v_i\} \subset \mathbb{Z}^3 \setminus \{0\}$  such that*

$$\sup_{s \in I} \|g_{t_i} \phi_{a,b}(s) v_i\| \rightarrow 0.$$

*Proof.* The proof is identical to that of Lemma 3.1, and we leave it to the reader.  $\square$

The stronger condition that the measures  $g_t \lambda_{a,b}$  go to the cusp for *all* large values of  $t$  can only be satisfied if  $(a, b) \in \mathbb{Q}^2$ ; this is the content of the following lemma.

**Lemma 3.3.** *The following statements are equivalent:*

- (1)  $(a, b) \in \mathbb{Q}^2$ .
- (2) *There exists  $v \in \mathbb{Z}^3 \setminus \{0\}$  such that  $\sup_{s \in I} \|g_t \phi_{a,b}(s) v\| \rightarrow 0$  as  $t \rightarrow \infty$ .*
- (3) *There exists  $R > 0$  such that for each large  $t > 0$ , there exists  $v \in \mathbb{Z}^3 \setminus \{0\}$  such that*

$$(3.5) \quad \sup_{s \in I} \|g_t \phi_{a,b}(s) v\| \leq R.$$

*Proof.* It is easily seen that (1)  $\Rightarrow$  (2) and that (2)  $\Rightarrow$  (3). For the last implication (3)  $\Rightarrow$  (1), we observe using (3.3) that (3) implies that for any  $c > 0$ , and any large enough  $t > 0$  there exists  $(p_1, p_2, q) \in \mathbb{Z}^3 \setminus \{0\}$  such that, setting  $T = R_1 e^t$ , all the following inequalities hold:

$$\begin{cases} |q| \leq R_1 e^t = T, \\ |qb + p_1| \leq R_1 e^{-2t} \leq cT^{-1}, \\ |qa + p_2| \leq R_1 e^{-2t} \leq cT^{-1}. \end{cases}$$

This implies that  $a$  and  $b$  are both singular real numbers. But singular real numbers are rational, see [Khi26] or [Cas57, Remark before Theorem XIV].  $\square$

Finally, we have a version of Lemma 3.1 for the behavior on average of the measures  $g_t \lambda_{a,b}$ ; this will relate to the diophantine set  $\mathcal{W}_2^+$ . For  $R > 0$ , define

$$(3.6) \quad \mathcal{I}_R = \left\{ t \in [0, +\infty) : \exists v \in \mathbb{Z}^3 \setminus \{0\} \text{ such that } \sup_{s \in I} \|g_t \phi_{a,b}(s) v\| < R \right\}.$$

**Lemma 3.4.** *The following are equivalent:*

(1) For any  $R > 0$ ,

$$(3.7) \quad \limsup_{T \rightarrow \infty} \frac{|\mathcal{I}_R \cap [0, T]|}{T} > 0.$$

(2) There exists  $R > 0$  such that (3.7) holds.

(3)  $(a, b) \in \mathcal{W}_2^+$ .

We defer the proof of this result to Section 8.

#### 4. REDUCTION OF LINEAR DYNAMICS TO THE STANDARD REPRESENTATION

The following is one of the main technical results in this article. It shows that Proposition 2.4 still holds even if the orbit  $G \cdot v_0$  is closed, as long as it is not reduced to  $\{v_0\}$ .

**Theorem 4.1.** *Let  $V$  be a finite-dimensional representation of  $G$  over  $\mathbb{Q}$  and  $v_0 \in V(\mathbb{Q}) \setminus \{0\}$  such that  $v_0$  is not  $G$ -fixed. Then given  $C > 0$  there exists  $R > 0$  and  $t_0 > 0$  such that the following holds: For any  $t > t_0$ , if there exists  $\gamma \in \Gamma$  such that*

$$\sup_{s \in I} \|g_t \phi_{a,b}(s) \gamma v_0\| \leq C,$$

then there exists  $v \in \mathbb{Z}^3 \setminus \{0\}$  such that

$$\sup_{s \in I} \|g_t \phi_{a,b}(s) v\| \leq R.$$

For the proof of the above theorem we introduce some notation and make some observations.

**4.1. Linear dynamics of  $g_t$  and  $\phi_{a,b}(s)$  actions.** Let  $V$  be an irreducible real representation of  $G = \mathrm{SL}_3(\mathbb{R})$  over  $\mathbb{Q}$ . Since  $G$  is  $\mathbb{Q}$ -split,  $V \otimes \mathbb{C}$  is  $G$ -irreducible over  $\mathbb{C}$ .

We express

$$g_t = c_t b_t, \text{ where } b_t = \mathrm{diag}(e^{t/2}, e^{t/2}, e^{-t}) \text{ and } c_t = \mathrm{diag}(e^{3t/2}, e^{-3t/2}, 1).$$

Let

$$(4.1) \quad u_{23}(s) = \begin{pmatrix} 1 & & \\ & 1 & s \\ & & 1 \end{pmatrix}, \quad u_{12}(s) = \begin{pmatrix} 1 & s & \\ & 1 & \\ & & 1 \end{pmatrix}, \quad u_{a,b} = \begin{pmatrix} 1 & b \\ & 1 & a \\ & & 1 \end{pmatrix}.$$

Then we have  $\phi_{a,b}(s) = u_{23}(-a)u_{12}(s)u_{a,b}$ . Since  $g_t$  commutes with  $u_{23}(-a)$  and  $b_t$  commutes with  $u_{12}(s)$ ,

$$(4.2) \quad g_t \phi_{a,b}(s) = u_{23}(-a)g_t u_{12}(s)u_{a,b} \text{ and } g_t u_{12}(s)u_{a,b} = c_t u_{12}(s)b_t u_{a,b}.$$

Let  $H = H_2 = \left( \begin{smallmatrix} \mathrm{SL}_2(\mathbb{R}) & \\ & 1 \end{smallmatrix} \right) < G$ , and consider  $V$  as the restricted representation of  $H$ . We have a decomposition  $V = V_1 \oplus V_2$ , where  $V_1 = \{v \in V \mid \forall h \in H, hv = v\}$  is the subspace fixed by  $H$ , and  $V_2$  is the complement of  $V_1$  stable under the action of  $H$ . Let  $\pi_1$  and  $\pi_2$  be the  $H$ -equivariant projections from  $V$  to  $V_1$  and  $V_2$  respectively. Since  $b_t$  centralizes  $H$ ,  $\pi_1$  and  $\pi_2$  are also  $b_t$ -equivariant.

The following observation is based on [Sha09b, Lemma 2.3].



**Lemma 4.2** (Linear dynamics of an  $\mathrm{SL}_2$  action). *For any  $m \geq 0$ , let  $W$  denote the  $(m + 1)$ -dimensional irreducible representation of  $\mathrm{SL}_2(\mathbb{R})$ . Let*

$$a_t = \begin{pmatrix} e^t & \\ & e^{-t} \end{pmatrix} \text{ and } u(s) = \begin{pmatrix} 1 & s \\ & 1 \end{pmatrix}.$$

*Then there exists  $C_I > 0$  such that for any  $w \in W$  and  $t \in \mathbb{R}$ ,*

$$\sup_{s \in I} \|a_t u(s) w\| \geq e^{mt} (C_I m)^{-m} \|w\|.$$

*Proof.* Let  $e_0, \dots, e_m$  denote a basis of  $W$  such that  $a_t e_k = e^{(m-2k)t} e_k$  for all  $k$ . For any  $w \in W$ , we express  $w = \sum_{k=0}^m w_k e_k$ , where  $w_k \in \mathbb{R}$ . Then

$$(u(s)w)_0 = \sum_{k=0}^m w_k s^k.$$

Let  $\|w\| = \max_{0 \leq k \leq m} |w_k|$ . Recall  $I = [s_0, s_1]$  and let  $\tau_j = s_0 + (j/m)(s_1 - s_0)$  for  $0 \leq j \leq m$ . Then

$$(4.3) \quad \sup_{s \in I} |(u(s)w)_0| \geq \max_{0 \leq j \leq m} \left| \sum_{k=0}^m w_k \tau_j^k \right| \geq (C_I m)^{-m} \|w\|,$$

where  $C_I = (1 + \max\{|s_0|, |s_1|\}) / (s_1 - s_0)$ , from an estimate for the norm of the inverse of the  $(m + 1) \times (m + 1)$ -Vandermonde matrix  $(\tau_j^k)$  [Gau62, Theorem 1].  $\square$

**Corollary 4.3.** *There exist constants  $C_2 > 0$  and  $\beta \geq 3/2$  such that for all  $v \in V_2$  and all  $t \geq 0$ ,*

$$(4.4) \quad \sup_{s \in I} \|c_t u_{12}(s) v\| \geq C_2 e^{\beta t} \|v\|.$$

*Proof.* Consider the action of  $H \cong \mathrm{SL}_2(\mathbb{R})$  on any irreducible component  $W$  of  $V_2$ . By definition of  $V_2$ , the representation  $W$  is non-trivial, i.e.  $\dim W = m + 1$ , with  $m \geq 1$ . Noting that “ $c_t = a_{3t/2}$ ” and “ $u_{12}(s) = u(s)$ ”, Lemma 4.2 shows that

$$\sup_{s \in I} \|c_t u_{12}(s) w\| \geq C_2 e^{\frac{3m}{2}t} \|w\|.$$

Since this holds for every  $H$ -irreducible component  $W \subset V_2$ , we indeed obtain the desired inequality for all  $v$  in  $V_2$ , with

$$\beta = \min \left\{ \frac{3m}{2} ; m = \dim W - 1, W \subset V_2 \text{ irreducible} \right\}.$$

$\square$

Let  $U_{12} = \{u_{12}(s)\}_{s \in \mathbb{R}}$ , and  $V^{U_{12}}$  be the subspace of  $U_{12}$ -fixed vectors in  $V$ . Let  $\pi_{U_{12}} : V \rightarrow V^{U_{12}}$  denote the  $\{c_t\}_{t \in \mathbb{R}}$ -equivariant projection. We apply (4.3) of Lemma 4.2 to each  $H$ -irreducible component of  $V$  to obtain the following:

**Corollary 4.4.** *There exists  $C_4 = C_4(I, V) > 0$  such that for any  $v \in V$ ,*

$$\sup_{s \in I} \|\pi_{U_{12}}(u_{12}(s)v)\| \geq C_4 \|v\|.$$

4.2. **Consequences of the description of irreducible representations of  $SL(3, \mathbb{R})$ .** Let  $\omega = n_1\omega_1 + n_2\omega_2$  be the highest weight of  $V$ , where  $n_1, n_2$  are non-negative integers.

**Lemma 4.5.**  $\dim(V_1) = 1$  and its weight is  $-(n_1 - n_2)\omega_2$ . In particular,  $b_t$  acts on  $V_1$  as the scalar multiplication by  $e^{-(n_1 - n_2)t}$ .

*Proof.* We consider the weight diagram and multiplicities of the weights of an irreducible  $SL_3$ -representation as in Figure 4.1; see [FH91, §13.2].

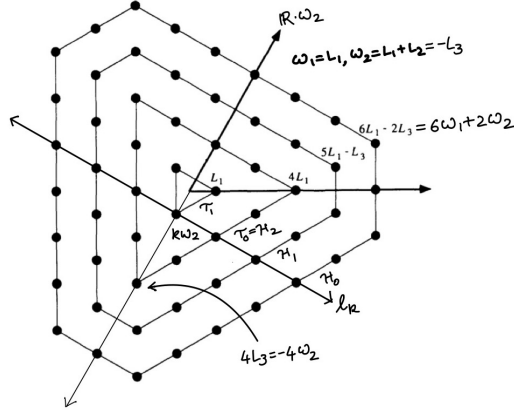


FIGURE 4.1.  $SL_3$ -representation with the highest weight  $6\omega_1 + 2\omega_2$ . (Based on [FH91, Figure (13.6)].)

The weights of  $V$  lie on hexagons  $\mathcal{H}_0, \dots, \mathcal{H}_{m-1}$ , where  $m = \min(n_1, n_2)$ , and triangles  $\mathcal{T}_0, \dots, \mathcal{T}_{\lfloor |n_1 - n_2|/3 \rfloor}$ . We set  $\mathcal{H}_m = \mathcal{T}_0$  and also call it a hexagon, which is degenerate. The multiplicity of a weight on any  $\mathcal{H}_i$  is  $i + 1$  and on any triangle is  $m + 1$ .

Consider any weight of  $V_1$ . Then it is fixed by the Weyl reflection corresponding to  $H$ , so it must be  $k\omega_2$  for some  $k \in \mathbb{Z}$ . Let  $\ell_k$  be the line perpendicular to  $\omega_2$  and passing through  $k\omega_2$ . Then  $\ell_k \cap \mathcal{H}_i \neq \emptyset$  if and only if  $0 \leq i \leq j_k - 1$ , where  $j_k$  is the multiplicity of  $k\omega_2$  in  $V$ , and for each such  $i$ ,  $\ell_k \cap \mathcal{H}_i$  contains the highest and the lowest weights of an irreducible representation of  $H$  containing  $k\omega_2$ .

In the above description, there is exactly one case when we have a trivial  $H$ -representation; that is, when  $k\omega_2$  is a vertex of the triangle  $\mathcal{T}_0 = \mathcal{H}_m$  and  $\ell_k \cap \mathcal{H}_m = \{k\omega_2\}$ . In particular,  $\dim V_1 = 1$ . The dominant vertex of  $\mathcal{T}_0$  is  $(n_1 - n_2)\omega_1$  or  $(n_2 - n_1)\omega_2$ . A Weyl reflection sends  $\omega_1$  to  $-\omega_2$ . So in both cases,  $-(n_1 - n_2)\omega_2$  is a vertex of  $\mathcal{T}_0$  and  $k = -(n_1 - n_2)$ . This proves the claim.  $\square$

**Lemma 4.6.** Suppose  $n_1 \leq n_2$ . Then all the weights occurring in  $V^{U^{12}}$  are non-negative for the Lie algebra element  $\text{diag}(2, -1, -1)$  corresponding to  $g_t$ .

In particular, by Corollary 4.4, for any  $v \in V$  and  $t \geq 0$ ,

$$(4.5) \quad \sup_{s \in I} \|g_t u_{12}(s)v\| \geq C_4 \|v\|.$$

*Proof.* We consider the weight diagram of an irreducible  $SL_3$ -representation as in Figure 4.2; see [FH91, Proposition 12.18].

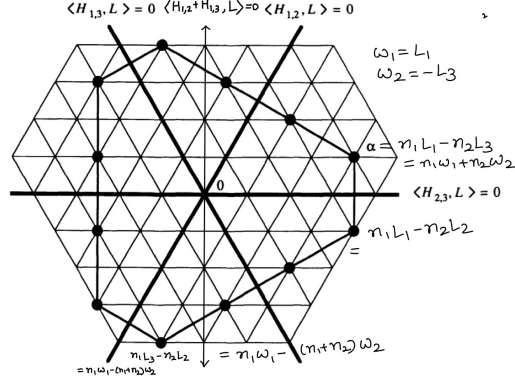


FIGURE 4.2. Arrangement of weights of an  $SL_3$ -representation. (Based on [FH91, Figure (12.14)].)

We note that the weights on the vertical line passing through the origin in the weight diagram vanish on  $\text{diag}(2, -1, -1)$  and those on the right half take positive values.

The weights occurring in  $V^{U_{12}}$  are the highest weights of irreducible representations of  $H$  in  $V$ , and they lie on the two sides of the hexagons  $\mathcal{H}_i$ , where  $0 \leq i \leq \min(n_1, n_2) = n_1$ ; if one draws the set of weights as in Figure 4.2 above, then for each  $i$ , one of the sides is a vertical segment from the dominant weight  $(n_1 - i)L_1 - (n_2 - i)L_3$  to the weight  $(n_1 - i)L_1 - (n_2 - i)L_2$ , and the other side is the segment joining the last weight to  $(n_1 - i)L_3 - (n_2 - i)L_2$ . For  $\text{diag}(2, -1, -1)$ , all the weights on the vertical segment have constant non-negative value  $2(n_1 - i) + (n_2 - i) \geq n_2 - n_1$ , and the weight  $(n_1 - i)L_3 - (n_2 - i)L_2$  has the value  $(n_1 - i)(-1) - (n_2 - i)(-1) = n_2 - n_1 \geq 0$ . So all the weights on both segments have a non-negative value for  $\text{diag}(2, -1, -1)$ . (Note that this is not the case in the above picture, where  $n_1 = 3 > 1 = n_2$ .)  $\square$

**4.3. Proof of Theorem 4.1.** If  $Gv_0$  is not Zariski closed, then the result follows from Proposition 2.4. So we assume that  $Gv_0$  is Zariski closed.

If the theorem fails to hold, then there exist sequences  $t_i \rightarrow \infty$  and  $\gamma_i \in \Gamma$  such that

$$(4.6) \quad \sup_{s \in I} \|g_{t_i} \phi_{a,b}(s) \gamma_i v_0\| \leq C,$$

and for any sequence  $v_i \in \mathbb{Z}^3 \setminus \{0\}$ ,

$$(4.7) \quad \sup_{s \in I} \|g_{t_i} \phi_{a,b}(s) v_i\| \rightarrow \infty.$$

There are two possible cases, and we will show that both will lead to a contradiction.

*Case 1:  $\{\gamma_i v_0\}_{i \in \mathbb{N}}$  is unbounded in  $V$ .*

Write  $\|\cdot\|_V$  to denote the operator norm on the linear space  $V$ . By (4.6) and (4.2), for  $C_1 = \frac{C}{\|u_{23}(-a)\|_V} > 0$ , for all  $i$ ,

$$(4.8) \quad C_1 \geq \sup_{s \in I} \|g_{t_i} u_{12}(s)(u_{a,b} \gamma_i v_0)\| = \sup_{s \in I} \|c_{t_i} u_{12}(s)(b_{t_i} u_{a,b} \gamma_i v_0)\|.$$

By (4.4), this implies that there exist  $C_3 > 0$  and  $\beta \geq 3/2$  such that

$$(4.9) \quad \forall i, \quad \|\pi_1(b_{t_i} u_{a,b} \gamma_i v_0)\| \leq C_3 \quad \text{and} \quad \|\pi_2(b_{t_i} u_{a,b} \gamma_i v_0)\| \leq C_3 e^{-\beta t_i}.$$

The highest weight of the irreducible  $G$ -representation  $V$  is  $n_1 \omega_1 + n_2 \omega_2$  for some non-negative integers  $n_1$  and  $n_2$ .

First suppose that  $n_1 > n_2$ . The highest eigenvalue of  $b_t$  on  $V$  is  $e^{(n_1/2 + n_2)t}$ . We pick  $\varepsilon > 0$  such that  $\varepsilon(n_1/2 + n_2) < \beta$ . By Lemma 4.5,  $b_t$  acts on  $V_1$  by the scalar  $e^{-(n_1 - n_2)t}$ . Therefore, by (4.9), for all  $i$ ,

$$\|\pi_1(b_{\varepsilon t_i} u_{a,b} \gamma_i v_0)\| \leq C_3 e^{-\varepsilon(n_1 - n_2)t_i}, \quad \|\pi_2(b_{\varepsilon t_i} u_{a,b} \gamma_i v_0)\| \leq C_3 e^{(-\beta + \varepsilon(n_1/2 + n_2))t_i}.$$

So  $b_{\varepsilon t_i} u_{a,b} \gamma_i v_0 \rightarrow 0$  as  $i \rightarrow \infty$ . This contradicts the fact that  $Gv_0$  is Zariski closed.

Hence we must have  $n_1 \leq n_2$ . Then by (4.5) and (4.8) we get  $\{u_{a,b} \gamma_i v_0\}_{i \in \mathbb{N}}$  is bounded, and it follows that  $\{\gamma_i v_0\}_{i \in \mathbb{N}}$  is bounded. This contradicts the assumption of Case 1.

*Case 2:  $\{\gamma_i v_0\}_{i \in \mathbb{N}}$  is bounded in  $V$ .*

In this case using (4.6) we will deduce  $(a, b) \in \mathbb{Q}^2$ , and so (4.7) will fail.

Since  $\Gamma v_0$  is discrete, by passing to a subsequence and replacing  $v_0$  with  $\gamma_1 v_0$  for some  $\gamma_1$  in  $\Gamma$ , we may assume that  $\gamma_i v_0 = v_0$  for all  $i$ . Let

$$F = \text{Stab}_G v_0.$$

Since  $Gv_0$  is closed, Matsushima's criterion [Bor69, §7.10] shows that  $F$  is a proper reductive subgroup of  $G$ , and it is defined over  $\mathbb{Q}$ . Now (4.9) implies that  $\{b_{t_i} u_{a,b} v_0\}_{i \in \mathbb{N}}$  is bounded. Therefore after passing to a subsequence we may assume that

$$b_{t_i} u_{a,b} v_0 \rightarrow v_\infty \quad \text{for some } v_\infty \in V.$$

Since  $Gv_0$  is Zariski closed, we may write  $v_\infty = gv_0$  for some  $g \in G$ . Let

$$L = \text{Stab}_G v_\infty$$

so that  $L = gFg^{-1}$ . It is clear from (4.9) that  $v_\infty$  is fixed by  $H$ , and we also know that  $v_\infty$  is fixed by  $\{b_t\}_{t \in \mathbb{R}}$  by definition of  $v_\infty$ . Hence  $L$  is a reductive subgroup of  $G$  which contains the group generated by  $H$  and  $\{b_t\}_{t \in \mathbb{R}}$ , i.e. the normalizer  $N_G(H)$  of  $H$ . But  $N_G(H)$  is a maximal reductive subgroup of  $G$ . Hence

$$L = N_G(H).$$

*Claim.* We can pick  $h_0 \in G(\mathbb{Q})$  such that  $v_\infty = h_0 v_0$ .

To prove the claim, consider the center

$$Z(F) = g^{-1}Z(L)g = g^{-1}S_2g, \quad \text{where } S_2 = \left\{ \begin{pmatrix} t & 0 & 0 \\ 0 & t & 0 \\ 0 & 0 & t^{-2} \end{pmatrix} \right\}.$$

This is a one-dimensional torus in  $G$  defined over  $\mathbb{Q}$ . Moreover, any element  $\gamma$  in  $Z(F)(\mathbb{Q})$  has a repeated eigenvalue, and is therefore diagonalizable over  $\mathbb{Q}$ . This shows that  $Z(F)$  is a  $\mathbb{Q}$ -split torus. So there exists  $h_1 \in G(\mathbb{Q})$  such that

$$h_1 Z(F) h_1^{-1} \subset S,$$

where  $S$  denotes the full diagonal subgroup of  $G$ . Since any element in  $Z(F)$  has a repeated eigenvalue, we may in fact write

$$h_1 Z(F) h_1^{-1} = h_2 S_2 h_2^{-1} \quad \text{for some permutation matrix } h_2.$$

Letting  $h_0 = h_2^{-1} h_1 \in G(\mathbb{Q})$ , one finds  $Z(F) = h_0^{-1} S_2 h_0$ , and taking centralizers on both sides we have  $g^{-1} L g = F = h_0^{-1} L h_0$ . Since  $N_G(L) = L$ , it follows that  $h_0 g^{-1} \in L$ , whence  $h_0 v_0 = h_0 g^{-1} v_\infty = v_\infty$ . This proves the claim.

Thus  $b_{t_i} u_{a,b} h_0^{-1} v_\infty \rightarrow v_\infty$ . Since  $\text{Stab}_G v_\infty = N_G(H)$ , and the orbit  $Gv_\infty$  is locally compact, one deduces that

$$b_{t_i} u_{a,b} h_0^{-1} [N_G(H)] \rightarrow [N_G(H)]$$

in  $G/N_G(H)$  as  $i \rightarrow \infty$ . Consider the standard projective action of  $G$  on  $\mathbb{P}(\mathbb{R}^3)$ . Then  $N_G(H)$  fixes  $\langle e_3 \rangle$ . So

$$b_{t_i} u_{a,b} h_0^{-1} \langle e_3 \rangle \rightarrow \langle e_3 \rangle$$

as  $i \rightarrow \infty$ . Since  $b_t = \text{diag}(e^{t/2}, e^{t/2}, e^{-t})$ , we conclude that  $u_{a,b} h_0^{-1} \langle e_3 \rangle = \langle e_3 \rangle$ . So  $h_0^{-1} e_3 = \lambda u_{a,b}^{-1} e_3$  for some  $\lambda \neq 0$ . Since  $h_0^{-1} \in G(\mathbb{Q})$ , by (4.1) we get  $\lambda(-b, -a, 1) \in \mathbb{Q}^3$ . Hence  $(a, b) \in \mathbb{Q}^2$ .

Write  $b = p_2/q$  and  $a = p_1/q$  for some  $p_1, p_2, q \in \mathbb{Z}$  with  $q \neq 0$ , and set

$$v_i = \begin{pmatrix} -p_1 \\ -p_2 \\ qe_3 \end{pmatrix} \quad \text{for all } i.$$

It follows that  $g_{t_i} \phi_{a,b}(s) v_i = e^{-t_i} \begin{pmatrix} 0 \\ -p_2 \\ q \end{pmatrix}$  for all  $s \in I$ . This contradicts (4.7).  $\square$

## 5. THE DANI-MARGULIS CRITERION FOR NON-ESCAPE OF MASS

Let  $\lambda_{a,b}$  be as in the introduction. The goal of this section is to give a necessary and sufficient condition for non-escape of mass for  $\{g_{t_i} \lambda_{a,b}\}$  as  $t_i \rightarrow \infty$ .

Define the unipotent one-parameter subgroup

$$W = \{w(r) := \begin{pmatrix} 1 & r & ar \\ & 1 & \\ & & 1 \end{pmatrix} : r \in \mathbb{R}\} \subset G.$$

For any  $t \in \mathbb{R}$  and  $s \in I = [s_0, s_1]$ , we have

$$(5.1) \quad g_t \phi_{a,b}(s) = w(r) h_t, \quad \text{where } r = e^{3t}(s - s_0), \quad h_t = g_t \phi_{a,b}(s_0).$$

Hence the trajectory  $\{g_t\phi_{a,b}(s)x_0 : s \in I\}$  equals  $\{w(r)h_t x_0 : r \in [0, e^{3t}|I|]\}$ , which is a segment of a unipotent orbit.

By a criterion due to Dani and Margulis for analyzing non-escape of mass for unipotent trajectories on the space of unimodular lattices, we obtain the following:

**Proposition 5.1.** *For any  $\varepsilon > 0$  and  $R > 0$ , there exist a compact set  $K \subset X$  and  $t_I \geq 0$  such that for any  $t \geq t_I$ , one of the following two possibilities holds:*

- (1)  $|\{s \in I : g_t\phi_{a,b}(s)x_0 \in K\}| \geq (1 - \varepsilon)|I|$ .
- (2) *There exists  $w \in \mathbb{Z}^3 \setminus \{0\}$  such that*

$$\sup_{s \in I} \|g_t\phi_{a,b}(s)w\| < R.$$

*Proof.* By the result of Dani and Margulis [DM89, 1.1. Theorem], given any  $\varepsilon > 0$  and  $R > 0$ , we can pick a compact set  $K \subset X$  such that given any finite interval  $I \subset \mathbb{R}$  and any  $t \geq 0$  one of the following three statements holds: the above condition (1), or the above condition (2) or the following additional condition (3): there exists  $w \in \bigwedge^2 \mathbb{Z}^3 \setminus \{0\}$  such that

$$\sup_{s \in I} \|g_t\phi_{a,b}(s)w\| \leq R.$$

Now if (3) holds for some  $t$ , then  $C_I e^t \leq R$  by Lemma 2.3. So the additional condition (3) will not occur for  $t \geq t_I := \log(C_I^{-1}R)$ .  $\square$

**Proposition 5.2.** *Let  $\{t_i\}_{i \in \mathbb{N}}$  be a sequence of real numbers such that  $t_i \rightarrow \infty$ . The following are equivalent:*

- (1) *For every compact set  $K \subset X$ ,  $g_{t_i}\phi_{a,b}(I) \cap K = \emptyset$  for all large  $i$ .*
- (2) *There exists  $\varepsilon > 0$  such that for every compact set  $K \subset X$ ,*

$$(5.2) \quad g_{t_i}\lambda_{a,b}(K) \leq 1 - \varepsilon, \text{ for all large } i.$$

- (3) *There exist vectors  $\{v_i\} \subset \mathbb{Z}^3 \setminus \{0\}$  such that*

$$(5.3) \quad \sup_{s \in I} \|g_{t_i}\phi_{a,b}(s)v_i\| \rightarrow 0 \text{ as } i \rightarrow \infty.$$

*Proof.* (1)  $\Rightarrow$  (2) is obvious.

(2)  $\Rightarrow$  (3): Fix  $\varepsilon > 0$  so that (5.2) holds for every compact  $K \subset X$ . For each  $j \in \mathbb{N}$  and  $R = 1/j$ , obtain a compact set  $K_j \subset X$  as in Proposition 5.1. Then for all  $i$ ,

$$g_{t_i}\lambda_{a,b}(K_j) = \frac{1}{|I|} |\{s \in I : g_{t_i}\phi_{a,b}(s)x_0 \in K_j\}|.$$

So, by (5.2) there exists  $i_j \in \mathbb{N}$  such that the possibility (1) of Proposition 5.1 does not hold for all  $i \geq i_j$ ; and hence its second assertion (2) must hold. So for all  $i \geq i_j$ , there exists  $w_{j,i} \in \mathbb{Z}^3 \setminus \{0\}$  such that

$$(5.4) \quad \sup_{s \in I} \|g_{t_i}\phi_{a,b}(s)w_{j,i}\| \leq 1/j.$$

For each  $i \geq i_1$ , let  $j$  be maximal such that  $i \geq i_j$ , and put  $v_i = w_{j,i}$ . Then (5.3) follows from (5.4).

(3)  $\Rightarrow$  (1) is a straightforward consequence of Mahler's compactness criterion.  $\square$

*Proof of Theorem 1.1.* To say that the sequence of  $g_t$ -translates of  $\lambda_{a,b}$  has no escape of mass means that there exists a sequence  $t_i \rightarrow \infty$  such that condition (2), and hence equivalently condition (3), of Proposition 5.2 fails to hold. It remains to apply Lemma 3.2.  $\square$

## 6. RATNER'S THEOREM AND A LINEAR DYNAMICAL CRITERION FOR AVOIDANCE OF SINGULAR SETS

The collection of probability measures on the one-point compactification, say  $\bar{X} = G/\Gamma \cup \{\infty\}$ , of  $X = G/\Gamma$  is compact with respect to the weak-\* topology on  $\bar{X}$ . So given any sequence  $t_i \rightarrow \infty$ , after passing to a subsequence, we obtain that  $g_{t_i}\lambda_{a,b}$  converges to a probability measure  $\bar{\mu}$  on  $\bar{X}$ . Let  $\mu$  denote the restriction of  $\bar{\mu}$  to  $X$ . Then  $g_{t_i}\lambda_{a,b}$  converges to  $\mu$  with respect to the weak-\* topology; that is, for any  $f \in C_c(X)$ , we have

$$\lim_{i \rightarrow \infty} \int_X f \, d(g_{t_i}\lambda_{a,b}) = \int_X f \, d\mu.$$

For the proposition below, recall that

$$W = \left\{ w(r) = \begin{pmatrix} 1 & r & ar \\ & 1 & \\ & & 1 \end{pmatrix}; r \in \mathbb{R} \right\}.$$

**Proposition 6.1.** *Suppose that  $\mu$  is a weak-\* limit of  $g_{t_i}\lambda_{a,b}$  for a sequence  $t_i \rightarrow \infty$ . Then  $\mu$  is invariant under the action of  $W$ .*

*Proof.* By (5.1), for any  $t > 0$  and any  $f \in C_c(X)$ ,

$$(6.1) \quad \int_X f \, d(g_t\lambda_{a,b}) = \int_I f(g_t\phi_{a,b}(s)x_0) \, ds = \frac{1}{e^{3t}} \int_0^{e^{3t}} f(w(r)h_t x_0) \, dr,$$

where  $h_t = g_t\phi_{a,b}(s_0)$ . So for any  $r_0 \in \mathbb{R}$ ,

$$(6.2) \quad \begin{aligned} \int_X f(w(r_0)x) \, d(g_t\lambda_{a,b})(x) &= \frac{1}{e^{3t}} \int_0^{e^{3t}} f(w(r_0)w(r)h_t x_0) \, dr \\ &= \frac{1}{e^{3t}} \int_{r_0}^{r_0+e^{3t}} f(w(r)h_t x_0) \, dr = \frac{1}{e^{3t}} \int_0^{e^{3t}} f(w(r)h_t x_0) \, dr + \varepsilon_t \\ &= \int_X f \, d(g_t\lambda_{a,b}) + \varepsilon_t, \end{aligned}$$

where  $|\varepsilon_t| \leq 2r_0 e^{-3t} \|f\|_\infty$ ; and the left-most term converges to  $\int_X f(w(r_0)x) \, d\mu(x)$  and the right-most term converges to  $\int_X f \, d\mu$  as  $t = t_i \rightarrow \infty$ .  $\square$

**Proposition 6.2.** *Suppose that  $\mu$  is a weak-\* limit of  $(1/T_i) \int_0^{T_i} g_t\lambda_{a,b} \, dt$  for a sequence  $T_i \rightarrow \infty$ . Then  $\mu$  is invariant under the action of  $W$ .*

*Proof.* We perform the average over  $t \in [0, T_i]$  in (6.1) and (6.2) and take the limit as  $i \rightarrow \infty$  to conclude that  $\mu$  is  $w(r_0)$ -invariant.  $\square$

With Proposition 6.1, we will be able to apply Ratner's description of ergodic invariant measures for actions of unipotent one-parameter subgroups on  $X$  to analyze the limiting distributions of  $\{g_t\lambda_{a,b}\}$  as  $t \rightarrow \infty$ . For this purpose we will apply what is now called 'the linearization technique' [DM93].

Let  $\pi: G \rightarrow X$  denote the natural quotient map. Let  $\mathcal{H}$  denote the collection of closed connected subgroups  $H$  of  $G$  such that  $H \cap \Gamma$  is a lattice in  $H$ , and such that

a unipotent one-parameter subgroup contained in  $H$  acts ergodically with respect to the  $H$ -invariant probability measure on  $H/H \cap \Gamma$ . Then any  $H \in \mathcal{H}$  is a real algebraic group defined over  $\mathbb{Q}$  [Sha91, (3.2) Proposition]. In particular,  $\mathcal{H}$  is a countable collection [Rat91].

Let  $W$  be a one-parameter unipotent subgroup of  $G$ . For a closed connected subgroup  $H$  of  $G$ , define

$$N(H, W) = \{g \in G: g^{-1}Wg \subset H\}.$$

Now, suppose that  $H \in \mathcal{H}$ . We define the associated singular set

$$S(H, W) = \bigcup_{F \in \mathcal{H}, F \subsetneq H} N(F, W).$$

Note that  $N(H, W)N_G(H) = N(H, W)$ . By [MS95, Proposition 2.1, Lemma 2.4],

$$N(H, W) \cap N(H, W)\gamma \subset S(H, W), \quad \forall \gamma \in \Gamma \setminus N_G(H).$$

By Ratner's theorem [Rat91, Theorem 1], as explained in [MS95, Theorem 2.2], we have the following.

**Theorem 6.3** (Ratner). *Given a  $W$ -invariant probability measure  $\lambda$  on  $X$ , there exists  $H \in \mathcal{H}$  such that*

$$\lambda(\pi(N(H, W))) > 0 \quad \text{and} \quad \lambda(\pi(S(H, W))) = 0.$$

*Moreover, almost every  $W$ -ergodic component of  $\lambda$  on  $\pi(N(H, W))$  is a measure of the form  $g\mu_H$ , where  $g \in N(H, W) \setminus S(H, W)$  and  $\mu_H$  is a finite  $H$ -invariant measure on  $\pi(H) \cong H/H \cap \Gamma$ .*

*Further, if  $H$  as above is a normal subgroup of  $G$ , then  $g\mu_H$  is  $H$ -invariant for each  $g \in G$ , and hence the restriction of  $\lambda$  to  $\pi(N(H, W))$  is  $H$ -invariant.*

Now let  $H \in \mathcal{H}$  and put  $d = \dim H$ . Let  $\mathfrak{g}$  denote the Lie algebra of  $G$  and take  $V = \bigwedge^d \mathfrak{g}$ . Then  $V$  admits a  $\mathbb{Q}$ -structure corresponding to the standard  $\mathbb{Q}$ -structure on  $\mathfrak{g}$ . Also  $G$  acts on  $V$  via the adjoint action of  $G$  on  $\mathfrak{g}$ . Since  $H$  is defined over  $\mathbb{Q}$ , its Lie algebra  $\mathfrak{h}$  is a  $\mathbb{Q}$ -subspace of  $\mathfrak{g}$ . Fix  $p_H \in \bigwedge^d \mathfrak{h}(\mathbb{Q}) \setminus \{0\}$ . Then the orbit  $\Gamma p_H$  is a discrete subset of  $V$ . We note that for any  $g \in N_G(H)$ ,  $gp_H = \det(\text{Ad } g|_{\mathfrak{h}})p_H$ . Hence the stabilizer of  $p_H$  in  $G$  equals

$$N_G^1(H) := \{g \in N_G(H): \det(\text{Ad } g|_{\mathfrak{h}}) = 1\}.$$

Fix  $w_0 \in \mathfrak{g}$  such that  $\text{Lie}(W) = \mathbb{R}w_0$ , and for  $V$  as above define

$$\mathcal{A} = \{v \in V: v \wedge w_0 = 0\}.$$

Then  $\mathcal{A}$  is a linear subspace of  $V$  and we observe that

$$N(H, W) = \{g \in G: g \cdot p_H \in \mathcal{A}\}.$$

By the linearization technique [DM93, Proposition 4.2] we obtain the following:

**Proposition 6.4.** *Let  $\mathcal{C}$  be a compact subset of  $N(H, W) \setminus S(H, W)$ . Given  $\varepsilon > 0$ , there exists a compact set  $\mathcal{D} \subset \mathcal{A}$  such that, given a neighborhood  $\Phi$  of  $\mathcal{D}$  in  $V$ , there exists a neighborhood  $\mathcal{O}$  of  $\pi(\mathcal{C})$  in  $X$  such that for any  $t \in \mathbb{R}$  and any subinterval  $J \subset I$ , one of the following statements holds:*



- (1)  $|\{s \in J: g_t \phi_{a,b}(s)x_0 \in \mathcal{O}\}| \leq \varepsilon |J|$ .
- (2) *There exists  $\gamma \in \Gamma$  such that  $g_t \phi_{a,b}(s)\gamma p_H \in \Phi$  for all  $s \in J$ .*

Let  $\lambda_{a,b}$  be as in (1.2).

**Proposition 6.5.** *Let  $\mu$  be a weak-\* limit of  $g_{t_i} \lambda_{a,b}$  for a sequence  $t_i \rightarrow \infty$ . Suppose  $\mu$  is not the  $G$ -invariant probability measure  $\mu_X$ . Then there exists  $R > 0$  and a sequence  $\{v_i\} \subset \mathbb{Z}^3 \setminus \{0\}$  such that*

$$(6.3) \quad \sup_{s \in I} \|g_{t_i} \phi_{a,b}(s)v_i\| \leq R.$$

*In particular  $(a, b) \in \mathcal{W}_2$ .*

*Proof.* If  $\mu$  is not a probability measure on  $X$ , then condition (2), and hence condition (3), of Proposition 5.2 hold. So (6.3) follows.

Therefore, we now assume that  $\mu$  is a probability measure on  $X$ . By Proposition 6.1  $\mu$  is  $W$ -invariant. By Theorem 6.3, there exists  $H \in \mathcal{H}$  such that  $\mu(\pi(N(H, W))) > 0$  and  $\mu(\pi(S(H, W))) = 0$ ; and since  $\mu$  is not  $G$ -invariant,  $H \neq G$ . So  $\dim(H) < \dim(G)$ .

We thus conclude that there exists  $\varepsilon > 0$  and a compact set  $\mathcal{C} \subset N(H, W) \setminus S(H, W)$  such that  $\mu(\pi(\mathcal{C})) > \varepsilon$ . By Proposition 6.4 applied to  $\varepsilon/2$  in place of  $\varepsilon$ , we obtain a compact set  $\mathcal{D} \subset \mathcal{A}$ . Then we pick  $R_1 > 0$  such that  $\mathcal{D}$  is contained in the open norm-ball of radius  $R_1$  in  $V$ , denoted  $\Phi$ , and obtain a neighborhood  $\mathcal{O}$  of  $\pi(\mathcal{C})$  in  $G/\Gamma$  so that the conclusion of Proposition 6.4 holds.

There exists  $i_0 \in \mathbb{N}$  such that for all  $i \geq i_0$ ,  $g_{t_i} \lambda_{a,b}(\mathcal{O}) > \varepsilon$ . So for  $i \geq i_0$ ,  $t = t_i$  and  $J = I$  condition (1) of the conclusion of Proposition 6.4 fails to hold, and hence condition (2) of the conclusion holds for some  $\gamma_i \in \Gamma$ ; that is,

$$\sup_{s \in I} \|g_{t_i} \phi_{a,b}(s)(\gamma_i p_H)\| \leq R_1.$$

Therefore (6.3) follows from Theorem 4.1 for a choice of  $R > 0$  depending on  $p_H \in V(\mathbb{Q}) \setminus \{0\}$  and  $R_1 > 0$ .  $\square$

**Proposition 6.6.** *Let  $\mu$  be a weak-\* limit of  $\mu_i := (1/T_i) \int_0^{T_i} g_t \lambda_{a,b} dt$  for a sequence  $T_i \rightarrow \infty$ . Suppose  $\mu \neq \mu_X$ . Then there exists  $R > 0$  such that*

$$(6.4) \quad \liminf_{I \rightarrow \infty} \frac{|\mathcal{I}_R \cap [0, T_i]|}{T_i} > 0,$$

*where  $\mathcal{I}_R$  is defined in (3.6).*

*Proof.* There are two possibilities:  $\mu$  is not a probability measure, or  $\mu$  is not  $G$ -invariant. By Proposition 6.2,  $\mu$  is  $W$ -invariant. So there exists  $\varepsilon > 0$  such that one of the following two possibilities occur:

- (1)  $\mu(X) < 1 - \varepsilon$ ;
- (2) or, by Theorem 6.3, there exists  $H \in \mathcal{H}$ , with  $H \neq G$  and a compact set  $\mathcal{C} \subset N(H, W) \setminus S(H, W)$  such that  $\mu(\pi(\mathcal{C})) > \varepsilon$ .

First suppose possibility (1) occurs. Take any  $R > 0$  and pick a compact  $K \subset X$  given by Proposition 5.1 for  $\varepsilon/2$  in place of  $\varepsilon$ . Then, for each non-negative  $t \notin \mathcal{I}_R$ , we have  $g_t \lambda_{a,b}(K) > 1 - \varepsilon/2$ . Write  $\kappa_i = |\mathcal{I}_R \cap [0, T_i]|/T_i$ . So for all large  $i$ ,

$$(1 - \kappa_i)(1 - \varepsilon/2) \leq \frac{1}{T_i} \int_0^{T_i} g_t \lambda_{a,b}(K) dt < 1 - \varepsilon;$$

and hence  $\kappa_i \geq \varepsilon/2$ . So (6.4) holds.

Now suppose possibility (2) occurs. Then for any open neighborhood  $\mathcal{O}$  of  $\pi(\mathcal{C})$ ,  $\mu(\mathcal{O}) > \varepsilon$ , and so for all large  $i$ ,

$$\frac{1}{T_i} \int_0^{T_i} g_t \lambda_{a,b}(\mathcal{O}) dt > \varepsilon.$$

Let

$$\mathcal{I}_{\mathcal{O}} = \{t \in [0, \infty) : g_t \lambda_{a,b}(\mathcal{O}) > \varepsilon/2\} \text{ and } \kappa_i = \frac{|\mathcal{I}_{\mathcal{O}} \cap [0, T_i]|}{T_i}.$$

Then for all large  $i$ ,

$$(1 - \kappa_i)\varepsilon/2 + \kappa_i \geq \frac{1}{T_i} \int_0^{T_i} g_t \lambda_{a,b}(\mathcal{O}) dt > \varepsilon,$$

and hence  $\kappa_i > \varepsilon/2$ .

By Proposition 6.4 applied to the set  $\mathcal{C} \subset N(H, W) \setminus S(H, W)$  and  $\varepsilon/2$  in place of  $\varepsilon$ , we obtain a compact set  $\mathcal{D} \subset V$ . Pick  $R_1 > 0$  such that  $\mathcal{D}$  is contained in the open norm-ball of radius  $R_1$  in  $V$ , denoted  $\Phi$ , and obtain a neighborhood  $\mathcal{O}$  of  $\pi(\mathcal{C})$  in  $G/\Gamma$  so that the conclusion of Proposition 6.4 holds.

Now suppose  $t \in \mathcal{I}_{\mathcal{O}}$ . Then for  $J = I$ , the condition (1) of Proposition 6.4 fails to hold, so condition (2) of Proposition 6.4 holds: there exists  $\gamma \in \Gamma$  such that

$$(6.5) \quad \sup_{s \in I} \|g_t \phi_{a,b}(s) \gamma p_H\| < R_1.$$

Let  $R > 0$  be the quantity given by Theorem 4.1 applied to  $v_0 = p_H \in V(\mathbb{Q}) \setminus \{0\}$  and  $C = R_1$ . Under (6.5), Theorem 4.1 shows that there exists  $v \in \mathbb{Z}^3 \setminus \{0\}$  such that  $\sup_{s \in I} \|g_t \phi_{a,b}(s) v\| \leq R$ ; that is,  $t \in I_R$ . Thus  $\mathcal{I}_{\mathcal{O}} \subset I_R$ . Therefore

$$|I_R \cap [0, T_i]|/T_i \geq \kappa_i > \varepsilon/2$$

for all large  $i$  and (6.4) follows.  $\square$

## 7. PROOF OF THEOREM 1.2 AND THEOREM 1.4

In this section we prove Theorem 1.2 and Theorem 1.4.

**Proof of Theorem 1.2.** First suppose that the  $g_t$ -translates of  $\lambda_{a,b}$  do *not* get equidistributed in  $X$  as  $t \rightarrow \infty$ . Then there exists  $t_i \rightarrow \infty$  such that  $g_{t_i} \lambda_{a,b}$  weak-\* converge to a measure which is not  $\mu_X$ . So by Proposition 6.5 we have  $(a, b) \in \mathcal{W}_2$ .

Conversely, suppose  $(a, b) \in \mathcal{W}_2$ . We want to show that the  $g_t$ -translates of  $\lambda_{a,b}$  do *not* get equidistributed in  $X$ .

By Lemma 3.1, there exists  $R \geq 1$ ,  $t_i \rightarrow \infty$  and  $\{\gamma_i\} \subset \Gamma$  such that for all  $i \in \mathbb{N}$ ,

$$(7.1) \quad \sup_{s \in I} \|g_{t_i} \phi_{a,b}(s) \gamma_i e_1\| \leq R.$$

*Case 1:* Suppose there exists  $c > 0$  such that for all  $i \geq 1$  and all  $s \in I$ ,

$$\|g_{t_i} \phi_{a,b}(s) \gamma_i e_1\| \geq c.$$

So by Proposition 5.2, after passing to a subsequence, we may assume that  $g_{t_i} \lambda_{a,b}$  weak-\* converge to a probability measure  $\mu$ . It suffices to show that the support of  $\mu$  is not full.

Let  $E$  denote the closed set of unimodular lattices in  $\mathbb{R}^3$  containing a primitive vector whose (sup)norm is in the interval  $[c, R]$ . Then the support of each  $g_{t_i} \lambda_{a,b}$ , and hence that of  $\mu$ , is contained in  $E$ . But  $E$  is not full, as it does not contain the unimodular lattice  $\mathbb{Z}M^{-2}e_1 + \mathbb{Z}Me_2 + \mathbb{Z}Me_3$ , for any  $M > R$  such that  $M^{-2} < c$ .

*Case 2:* Suppose Case 1 does not occur. Then after passing to a subsequence, there exists a sequence  $\{s_i\} \subset I$  such that

$$(7.2) \quad \|g_{t_i} \phi_{a,b}(s_i) \gamma_i e_1\| = c_i \rightarrow 0 \text{ as } i \rightarrow \infty.$$

We write  $\gamma_i e_1 = \begin{pmatrix} p_{1,i} \\ p_{2,i} \\ q_i \end{pmatrix} \in \mathbb{Z}^3$ . Then for all  $s \in I$  and  $t \in \mathbb{R}$

$$(7.3) \quad g_t \phi_{a,b}(s) \gamma_i e_1 = \begin{pmatrix} e^{2t} x_1(s) \\ e^{-t} p_{2,i} \\ e^{-t} q_i e_3 \end{pmatrix},$$

where  $x_1(s) = (aq_i + p_{2,i})s + (bq_i + p_{1,i})$ . So by (7.2),  $e^{-t_i} |p_{2,i}| \leq c_i$  and  $e^{-t_i} |q_i| \leq c_i$ , and by (7.1),  $|e^{2t_i} x_1(s)| \leq R$ . We note that if  $p_{2,i} = 0$  and  $q_i = 0$ , then  $|x_1(s)| = |p_{1,i}| \geq 1$ , and hence  $e^{2t_i} \leq R$  for all large  $i$ , which is absurd. Hence

$$c_i e^{t_i} \geq \max\{|p_{2,i}|, |q_i|\} \geq 1;$$

that is,  $t_i + \log c_i \geq 0$  for all  $i$ . Let  $t'_i := t_i + (1/3) \log c_i \geq -(2/3) \log c_i$ , so  $t'_i \rightarrow \infty$ . By (7.3), for all  $s \in I$ ,

$$\begin{aligned} \left\| g_{t'_i} \phi_{a,b}(s) \gamma_i e_1 \right\| &\leq \max \left\{ \left| c_i^{2/3} e^{2t'_i} x_1(s) \right|, \left| c_i^{-1/3} e^{-t'_i} p_{2,i} \right|, \left| c_i^{-1/3} e^{-t'_i} q_i \right| \right\} \\ &\leq \max \left\{ R c_i^{2/3}, c_i^{-1/3} c_i \right\} \leq R c_i^{2/3}. \end{aligned}$$

Since  $c_i \rightarrow 0$ , by Proposition 5.2, for any compact  $K \subset X$ ,  $g_{t'_i} \lambda_{a,b}(K) = 0$  for all large  $i$ .  $\square$

*Proof of Theorem 1.4.* (1)  $\Rightarrow$  (2): Assume  $(a, b) \notin \mathbb{Q}^2$  and let  $J \subset I$  be any subinterval of positive measure. Then (3) of Lemma 3.3 fails to hold, so there exists a sequence  $t_i \rightarrow \infty$  such that

$$(7.4) \quad \min_{0 \neq v \in \mathbb{Z}^3} \sup_{s \in J} \|g_{t_i} \phi_{a,b}(s) v\| \rightarrow \infty.$$

By Proposition 6.5, this implies  $g_{t_i} \lambda_{a,b} \xrightarrow{\text{weak}^*} \mu_X$ .

(2)  $\Rightarrow$  (3): Assume (2) and argue by contradiction, supposing that the set

$$E = \{s \in I \mid \{g_t \phi_{a,b}(s) x_0\}_{t \geq 0} \text{ is not dense in } X\}$$

has positive Lebesgue measure. We take a countable topological basis  $\{B_i\}_{i \in \mathbb{N}}$  of  $X$ , and let

$$E_i = \{s \in \mathbb{R} \mid \{g_t \phi_{a,b}(s) x_0\}_{t \geq 0} \cap B_i = \emptyset\}.$$

One has  $E = \bigcup_{i \in \mathbb{N}} E_i$ . Since  $|E| > 0$ , there exists  $i_0 \in \mathbb{N}$  such that  $|E_{i_0}| > 0$ . Without loss of generality we may assume that  $|E_1| > 0$ . By the Lebesgue density theorem, there exists an interval  $J \subset I$  such that

$$(7.5) \quad \frac{|J \cap E_1|}{|J|} \geq 1 - \frac{\mu_X(B_1)}{2}.$$

Because we assumed (2), there exists  $t_i \rightarrow \infty$  such that the  $g_{t_i}$ -translates of  $\lambda_{a,b}(J)$  get equidistributed in  $X$ . In particular, for all large  $i$ ,

$$\frac{1}{|J|} |\{s \in J \mid g_{t_i} \phi_{a,b}(s) x_0 \in B_1\}| > \frac{\mu_X(B_1)}{2},$$

which, by definition of  $E_1$ , implies that

$$\frac{|J \setminus E_1|}{|J|} > \frac{\mu_X(B_1)}{2}.$$

This contradicts (7.5). Hence we must have  $|E| = 0$ .

(3)  $\Rightarrow$  (1): We argue by contrapositive, assuming  $(a, b) = (\frac{p_2}{q}, \frac{p_1}{q})$  for some  $p_1, p_2, q \in \mathbb{Z}^3$  and  $q \neq 0$ . For  $v = \begin{pmatrix} -p_1 \\ -p_2 \\ q \end{pmatrix} \in \mathbb{Z}^3 \setminus \{0\}$ ,  $\phi_{a,b}(s)v = \begin{pmatrix} 0 \\ -p_2 \\ q \end{pmatrix}$  for all  $s \in \mathbb{R}$ . Therefore,  $\sup_{s \in I} \|g_t \phi_{a,b}(s)v\| \rightarrow 0$  as  $t \rightarrow \infty$ . So by Proposition 5.2, for any  $s \in I$  and any compact set  $K \subset X$ , we have  $g_t \phi(s)x_0 \notin K$  for all large  $t \geq 1$ . This certainly shows that (3) cannot hold, and even more: every trajectory  $\{g_t \phi_{a,b}(s)x_0\}_{t \geq 0}$  escapes to the cusp.  $\square$

## 8. BEHAVIOR ON AVERAGE — PROOFS OF LEMMA 3.4 AND THEOREM 1.3

In this section, we discuss the averages of the  $g_t$ -translates, and prove Theorem 1.3. As Lemma 3.4 will be used in the proof of Theorem 1.3, we first provide its proof.

*Proof of Lemma 3.4.* (1) $\Rightarrow$ (2) is obvious.

To prove that (2) $\Rightarrow$ (3), we pick  $R \geq 1$  such that (3.7) holds. Then by (3.3) for any  $v = \begin{pmatrix} p_1 \\ p_2 \\ q \end{pmatrix} \in \mathbb{Z}^3$ , and  $t \geq 0$  we get

$$(8.1) \quad \sup_{s \in I} \|g_t \phi_{a,b}(s)v\| < R \Rightarrow \begin{cases} |qb + p_1| < R_1 e^{-2t} \\ |qa + p_2| < R_1 e^{-2t} \\ |q| < R e^t \end{cases} \Rightarrow \begin{cases} \langle q \begin{pmatrix} b \\ a \end{pmatrix} \rangle < R_1 e^{-2t} \\ |q| < R e^t, \end{cases}$$

where  $R_1 = \left\| \begin{pmatrix} 1 & s_0 \\ 1 & s_1 \end{pmatrix}^{-1} \right\| R \geq R$ , and  $\langle \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \rangle$  denotes the sup-norm distance between  $\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$  and its nearest integral vector.

For each  $t \geq 0$  and  $q \in \mathbb{Z}_+$ , define

$$(8.2) \quad \begin{aligned} E_q &= \{t \in [0, +\infty) : e^{-t}q < R \text{ and } e^{2t} \langle q \begin{pmatrix} b \\ a \end{pmatrix} \rangle < R_1\} \\ &= \{t : R^{-1}q < e^t < R_1^{1/2} \langle q \begin{pmatrix} b \\ a \end{pmatrix} \rangle^{-1/2}\} \\ &= \left( \log q - \log R, -\frac{1}{2} \log \langle q \begin{pmatrix} b \\ a \end{pmatrix} \rangle + \frac{1}{2} \log R_1 \right). \end{aligned}$$

Now  $t \in E_q$  if and only if the right-most term of (8.1) holds, so

$$(8.3) \quad E_q \neq \emptyset \iff \langle q \binom{b}{a} \rangle < R_1 R^2 q^{-2}.$$

Let  $\mathcal{P}(\mathbb{Z}^3)$  denote the set of primitive integral vectors in  $\mathbb{Z}^3$ . Recall from (3.6) that

$$(8.4) \quad \mathcal{I}_R = \left\{ t \in [0, +\infty) : \sup_{s \in I} \|g_t \phi_{a,b}(s)v\| < R, \text{ for some } v \in \mathcal{P}(\mathbb{Z}^3) \setminus \{0\} \right\}.$$

Let  $\mathcal{Q}$  be the collection of those  $q \in \mathbb{Z}_+$  such that  $E_q \neq \emptyset$ . Then by (8.4), (8.1) and (8.2) we get

$$(8.5) \quad \mathcal{I}_R \subset \bigcup_{q \in \mathcal{Q}} E_q.$$

We may assume that  $(a, b) \notin \mathbb{Q}^2$ , because otherwise  $(a, b) \in \mathcal{W}_2^+$  and we are done. Then for any  $q \in \mathcal{Q}$ ,  $E_q$  is a finite interval. Therefore by (3.7),  $\mathcal{Q}$  is infinite. We write  $\mathcal{Q} = \{q_1, q_2, \dots\}$ , where  $q_i < q_{i+1}$  for all  $i$ .

*Claim 1.* If  $E_q$  and  $E_{q'}$  are both non-empty for some  $q, q' \in \mathcal{Q}$  and  $q' > q$ , then  $q^2 < Cq'$ , where  $C = 2R_1 R^2 > 1$ . In particular, for any  $n \in \mathbb{N}$ ,

$$(8.6) \quad \log q_i < \log C + 2^{-(n-i)} \log q_n, \forall i < n.$$

Indeed, by (8.3) there exist integral vectors  $\mathbf{p}, \mathbf{p}' \in \mathbb{Z}^2$  such that

$$\left\| \binom{b}{a} - \frac{\mathbf{p}}{q} \right\| < R_1 R^2 q^{-3}, \quad \left\| \binom{b}{a} - \frac{\mathbf{p}'}{q'} \right\| < R_1 R^2 q'^{-3}.$$

Since  $q, q' \in \mathcal{Q}$  and  $q \neq q'$ , we have  $\frac{\mathbf{p}}{q} \neq \frac{\mathbf{p}'}{q'}$ . Hence  $\left\| \frac{\mathbf{p}}{q} - \frac{\mathbf{p}'}{q'} \right\| \geq \frac{1}{qq'}$ . It follows that

$$(2R_1 R^2)q^{-3} > q^{-3} + q'^{-3} \gg \left\| \frac{\mathbf{p}}{q} - \frac{\mathbf{p}'}{q'} \right\| \geq \frac{1}{qq'}.$$

Hence  $q^2 < (2R_1 R^2)^{-1} q'$ . This proves the first part of the claim. For the second assertion, apply iteratively the above to  $q = q_j$  and  $q' = q_{j+1}$ ,  $j = i, \dots, n-1$  to get

$$\begin{aligned} \log q_i &< \frac{\log C}{2} + \frac{\log q_{i+1}}{2} \\ &< \frac{\log C}{2} + \frac{\log C}{4} + \frac{\log q_{i+2}}{4} \\ &< \dots \\ &< \log C + 2^{-(n-i)} \log q_n. \end{aligned}$$

To achieve the quantity  $\limsup_{T \rightarrow \infty} \frac{|[0, T] \cap \bigcup_{q \in \mathcal{Q}} E_q|}{T}$ , one can let  $T$  describe the sequence  $\{T_n\}$  of right endpoints of intervals  $E_{q_n}$ , which, by (8.2), can be rewritten  $T_n = \log q_n - \log R + |E_{q_n}|$ . Then,

$$\frac{|[0, T_n] \cap \bigcup_{q \in \mathcal{Q}} E_q|}{T_n} \leq \frac{\sum_{i=1}^n |E_{q_i}|}{\log q_n - \log R + |E_{q_n}|}.$$

We infer from (3.7) and (8.5) that

$$\limsup_{n \rightarrow \infty} \frac{\sum_{i=1}^n |E_{q_i}|}{\log q_n - \log R + |E_{q_n}|} > 0.$$

It follows that there exists  $\varepsilon > 0$  such that

$$(8.7) \quad \limsup_{n \rightarrow \infty} \frac{\sum_{i=1}^n |E_{q_i}|}{\log q_n} = 4\varepsilon > 0.$$

*Claim 2. We claim that*

$$(8.8) \quad \limsup_{n \rightarrow \infty} \frac{|E_{q_n}|}{\log q_n} > \varepsilon.$$

Indeed, suppose  $\limsup_{n \rightarrow \infty} \frac{|E_{q_n}|}{\log q_n} \leq \varepsilon$ . Then there exists  $N > 0$  such that  $q_N > C$  and for all  $n \geq N$ ,  $|E_{q_n}| < 2\varepsilon \log q_n$ . Therefore

$$\begin{aligned} \limsup_{n \rightarrow \infty} \frac{\sum_{i=1}^n |E_{q_i}|}{\log q_n} &= \limsup_{n \rightarrow \infty} \frac{\sum_{i=N}^n |E_{q_i}|}{\log q_n} < \limsup_{n \rightarrow \infty} \frac{\sum_{i=N}^n 2\varepsilon \log q_i}{\log q_n} \\ &\leq \limsup_{n \rightarrow \infty} \frac{2\varepsilon(n - N + 1) \log C + 2\varepsilon \sum_{i=N}^n 2^{-(n-i)} \log q_n}{\log q_n} \leq 4\varepsilon, \end{aligned}$$

because by (8.6), for any  $i < n$ ,

$$\log q_i < \log C + 2^{-(n-i)} \log q_n \text{ and } \log q_n > 2^{(n-N)}(\log q_N - \log C).$$

This contradicts (8.7) and proves Claim 2.

Now in view of (8.8), for any  $Q > 0$  there exists a  $q > Q$  such that  $|E_q| > \varepsilon \log q$ . By (8.2), this means

$$(1/2) \log R_1 + \log R - \log q - \frac{1}{2} \log \langle q \left( \begin{smallmatrix} b \\ a \end{smallmatrix} \right) \rangle > \varepsilon \log q,$$

or equivalently,

$$\langle q \left( \begin{smallmatrix} b \\ a \end{smallmatrix} \right) \rangle < R_1 R^2 q^{-(2+2\varepsilon)}.$$

Hence  $\langle q \left( \begin{smallmatrix} b \\ a \end{smallmatrix} \right) \rangle \leq q^{-(2+\varepsilon)}$  has infinitely many solutions  $q \in \mathbb{Z}_+$ , which means  $(a, b) \in \mathcal{W}_2^+$ . This proves (2) $\Rightarrow$ (3).

Now to prove (3) $\Rightarrow$ (1), suppose that  $(a, b) \in \mathcal{W}_2^+$ . Then there exists  $\varepsilon > 0$  and an increasing sequence  $\{q_n\}_{n \in \mathbb{N}}$  of positive integers such that

$$(8.9) \quad \begin{cases} |q_n b + p_{1,n}| \leq q_n^{-(2+\varepsilon)} \\ |q_n a + p_{2,n}| \leq q_n^{-(2+\varepsilon)} \end{cases}, \text{ for some } p_{1,n}, p_{2,n} \in \mathbb{Z}.$$

Let  $n \in \mathbb{N}$  and  $v_n = \begin{pmatrix} p_{1,n} \\ p_{2,n} \\ q_n \end{pmatrix} \in \mathbb{Z}^3$ . Then for any  $t \in \mathbb{R}$ ,

$$(8.10) \quad g_t \phi_{a,b}(s) v_n = \begin{pmatrix} e^{2t} \left( (bq_n + p_{1,n}) + (aq_n + p_{2,n})s \right) \\ e^{-t} p_{2,n} \\ e^{-t} q_n \end{pmatrix}.$$

Pick any constants  $0 < c_1 < c_2 < 1/2$ , independent of  $n$ . Let

$$t \in [(1 + c_1 \varepsilon) \log q_n, (1 + c_2 \varepsilon) \log q_n].$$

Then

$$q_n^{-(2+\varepsilon)} \leq e^{-\left(\frac{(1-2c_2)\varepsilon}{1+c_2\varepsilon}\right)t} e^{-2t} \text{ and } q_n \leq e^{-\left(\frac{c_1\varepsilon}{1+c_1\varepsilon}\right)t} e^t.$$

By (8.9),

$$|p_{2,n}| \leq q_n^{-(2+\varepsilon)} + |a|q_n < 1 + |a|q_n$$

and so, by (8.10),

$$(8.11) \quad \|g_t \phi_{a,b}(s) v_n\| \leq C e^{-\varepsilon_1 t}, \forall s \in I = [s_0, s_1],$$

where  $\varepsilon_1 := \min\left\{\frac{c_1\varepsilon}{1+c_1\varepsilon}, \frac{(1-2c_2)\varepsilon}{1+c_2\varepsilon}\right\} > 0$  and  $C := (1 + |s_0| + |s_1| + |a|)$ .

Given any  $R > 0$ , let  $N > 0$  such that for every  $n > N$ ,

$$C q_n^{-(1+c_1\varepsilon)\varepsilon_1} < R.$$

For  $n > N$ , by (8.11), one has  $[(1 + c_1\varepsilon) \log q_n, (1 + c_2\varepsilon) \log q_n] \subset \mathcal{I}_R$ . So, setting  $T_n = (1 + c_2\varepsilon) \log q_n$ , we get

$$\frac{|\mathcal{I}_R \cap [0, T_n]|}{T_n} \geq \frac{|[(1 + c_1\varepsilon) \log q_n, (1 + c_2\varepsilon) \log q_n]|}{T_n} = \frac{(c_2 - c_1)\varepsilon}{1 + c_2\varepsilon}.$$

Therefore

$$\limsup_{T \rightarrow \infty} \frac{|\mathcal{I}_R \cap [0, T]|}{T} \geq \frac{(c_2 - c_1)\varepsilon}{1 + c_2\varepsilon} > 0.$$

This proves that (3)  $\Rightarrow$  (1). □

Now we are ready to prove Theorem 1.3.

**Proof of Theorem 1.3.** (1)  $\Rightarrow$  (2) is obvious.

To prove (2)  $\Rightarrow$  (3) by contrapositive, suppose that  $(a, b) \in \mathcal{W}_2^+$ . Let  $K$  be a compact subset of  $X$ , which is identified with the space of unimodular lattices in  $\mathbb{R}^3$ . By Mahler's criterion, there exists  $R > 0$  such that every nonzero vector in any lattice in  $K$  has norm at least  $R$ . So, by (3.6), for any  $t \in \mathcal{I}_R$ , we have  $g_t \phi_{a,b}(s) \mathbb{Z}^n \notin K$  for all  $s \in I$ ; in particular,

$$(8.12) \quad g_t \lambda_{a,b}(K) = 0.$$

Since  $(a, b) \in \mathcal{W}_2^+$ , Lemma 3.4 shows that there exists a sequence  $T_n \rightarrow \infty$  and an  $\varepsilon > 0$  such that for all  $n$ ,

$$\frac{|\mathcal{I}_R \cap [0, T_n]|}{T_n} \geq \varepsilon,$$

and hence, by (8.12),

$$\frac{1}{T_n} \int_0^{T_n} g_t \lambda_{a,b}(K) dt \leq 1 - \varepsilon.$$

Thus, the family of averages  $\left\{\frac{1}{T} \int_0^T g_t \lambda_{a,b} dt\right\}_{T>0}$  has escape of mass. This proves that (2)  $\Rightarrow$  (3).

To prove (3)  $\Rightarrow$  (1) by contrapositive, suppose that (1) fails to hold. Then there exists a sequence  $T_i \rightarrow \infty$  such that  $\mu_i := (1/T_i) \int_0^{T_i} g_t \lambda_{a,b} dt$  does not converge to  $\mu_X$ . Since the  $\mu_i$  are probability measures, by passing to a subsequence, without loss

of generality we may assume that  $\mu_i$  converges to a Borel measure  $\mu$  on  $X$  which is not  $\mu_X$ . Then by Proposition 6.6 there exists  $R > 0$  such that

$$\liminf_{i \rightarrow \infty} \frac{|\mathcal{Z}_R \cap [0, T_i]|}{T_i} > 0.$$

Then by Lemma 3.4, we get  $(a, b) \in \mathcal{W}_2^+$ , which contradicts (3).  $\square$

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BRANDEIS UNIVERSITY, GOLDSMITH 207, WALTHAM, MA 02454-9110

*Email address:* `kleinboc@brandeis.edu`

CNRS, UNIVERSITÉ PARIS-NORD 13, PARIS, FRANCE

*Email address:* `desaxce@math.univ-paris13.fr`

THE OHIO STATE UNIVERSITY, COLUMBUS, OH 43210

*Email address:* `shah@math.osu.edu`

DEPARTMENT OF MATHEMATICS, ETH ZÜRICH, ZÜRICH, SWITZERLAND

*Email address:* `pengyu.yang@math.ethz.ch`