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## Word length statistics for Teichmüller geodesics and singularity of harmonic measure

Vaibhav Gadre, Joseph Maher and Giulio Tiozzo

**Abstract.** Given a measure on the Thurston boundary of Teichmüller space, one can pick a geodesic ray joining some basepoint to a randomly chosen point on the boundary. Different choices of measures may yield typical geodesics with different geometric properties. In particular, we consider two families of measures: the ones which belong to the Lebesgue or visual measure class, and harmonic measures for random walks on the mapping class group generated by a distribution with finite first moment in the word metric.

We consider the word length of approximating mapping class group elements along a geodesic ray, and prove that this quantity grows superlinearly in time along almost all geodesics with respect to Lebesgue measure, while along almost all geodesics with respect to harmonic measure the growth is linear. As a corollary, the harmonic and Lebesgue measures are mutually singular. We also prove a similar result for the ratio between the word metric and the relative metric (i.e. the induced metric on the curve complex).

**Mathematics Subject Classification (2010).** 30F60, 32G15, 60G50, 60J50.

**Keywords.** Random walks, mapping class group, Teichmüller flow, harmonic measure, cusp excursion.

### 1. Introduction

Let  $G = \text{Mod}(S)$  be the mapping class group of an orientable surface  $S$  of finite type, which acts on the Teichmüller space  $\mathcal{T}(S)$  of marked hyperbolic metrics on  $S$ . Following Thurston, a boundary of Teichmüller space is given by the space  $\mathcal{PMF}$  of projective measured foliations, which carries several measures:

- on the one hand, there is a natural *Lebesgue measure class*  $\text{Leb}$  on  $\mathcal{PMF}$  given by pulling back Lebesgue measure from the charts defined using train track coordinates;
- on the other hand, Kaimanovich and Masur [18] showed that if  $\mu$  is a probability distribution on  $G$ , whose support generates a non-elementary subgroup, then the image of a random walk on  $G$  under the orbit map  $g \mapsto gX_0$  converges to a point in  $\mathcal{PMF}$  almost surely. We let  $\nu$  be the corresponding *hitting measure* (also known as *harmonic measure*).

In this paper, we analyze geometric properties of typical geodesics with respect to these measures. To define what we mean by typical geodesics, let us fix a basepoint  $X_0 \in \mathcal{T}(S)$ . Then there is a map from  $\mathcal{PMF}$  to the set of Teichmüller geodesic rays based at  $X_0$ . In fact, we can associate to each measured foliation  $F$  the unique unit area quadratic differential at  $X_0$  which has vertical foliation proportional to  $F$ , and this quadratic differential determines a geodesic ray based at  $X_0$ . Thus, we can think of the above measures as measures on the set of geodesic rays from  $X_0$ , and we can talk about the behavior of geodesics which are typical with respect to either measure.

**1.1. The word length ratio.** Let us denote as  $\|g\|_G$  the *word length* of a group element  $g$  with respect to some fixed generating set. As different choices of generators lead to quasi-isometric metrics, our results will be independent of the particular choice. Let  $\mathcal{T}_\epsilon$  denote the  $\epsilon$ -thin part of Teichmüller space, i.e. the set of surfaces with an essential curve of hyperbolic length less than  $\epsilon$ , and fix some  $\epsilon$  which is smaller than the Margulis constant.

Let  $\gamma$  be a Teichmüller geodesic ray based at  $X_0$ . For each time  $t$ , we denote as  $\gamma_t$  the point at distance  $t$  from the basepoint along  $\gamma$ . If  $\gamma_t$  does not lie in the thin part, we let  $g_t$  be a group element such that  $g_t X_0$  is a closest element of the  $G$ -orbit of  $X_0$  to  $\gamma_t$ . This is illustrated schematically in Figure 1 below. We then define the *word length ratio* as the quantity

$$\rho(\gamma) := \lim_{\substack{t \rightarrow \infty \\ \gamma_t \notin \mathcal{T}_\epsilon}} \frac{\|g_t\|_G}{t},$$

whenever the limit exists. Note that there may be several choices for  $g_t$ , but since we restrict the definition of  $g_t$  to points  $\gamma_t$  which do not lie in the thin part, the distance between different choices is bounded. Moreover, with respect to the measures we consider, generic geodesics are recurrent to the thick part, so the above limit makes sense almost surely.

Our first result establishes that the word metric grows superlinearly along geodesics which are typical with respect to Lebesgue measure:

**Theorem 1.1.** *Let  $X_0$  be a point in Teichmüller space. Then for Lebesgue-almost every geodesic ray  $\gamma$  based at  $X_0$ , the word length ratio is infinite:*

$$\rho(\gamma) = \infty.$$

We now state a corresponding result for random walks. Recall that a measure  $\mu$  on the mapping class group  $G$  has *finite first moment* in the word metric if  $\int_G \|g\|_G d\mu(g) < \infty$ . Moreover, we say that  $\mu$  is *non-elementary* if the support of  $\mu$  generates a non-elementary subgroup of  $G$  as a semigroup. The word length ratio is almost surely finite along typical geodesics with respect to harmonic measure:

**Theorem 1.2.** *Let  $\mu$  be a non-elementary probability measure on  $\text{Mod}(S)$  with finite first moment in the word metric, let  $X_0 \in \mathcal{T}(S)$  be a basepoint, and let  $\nu$  be the*

harmonic measure determined by the corresponding random walk. Then there is a constant  $c > 0$  such that

$$\rho(\gamma) = c$$

for  $\nu$ -almost every geodesic ray  $\gamma$  based at  $X_0$ .

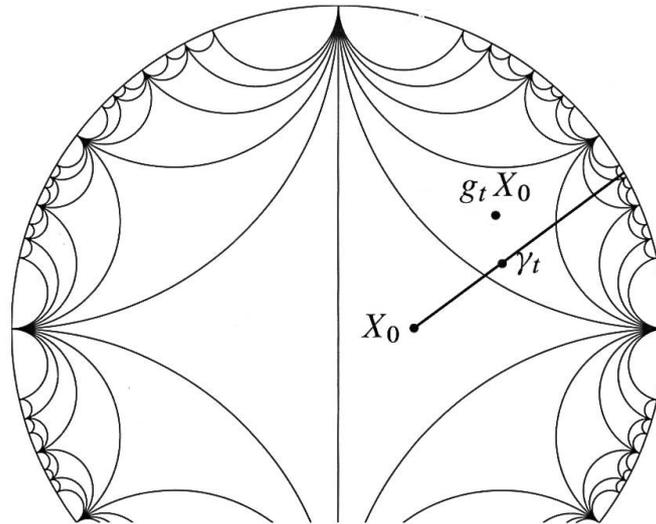


Figure 1. Our definition of  $g_t$ . The point  $\gamma_t$  lies on the geodesic  $\gamma$ , and  $g_t X_0$  is a closest orbit point to  $\gamma_t$ . In the case of genus 1, this corresponds to taking  $g_t$  to be the element in the orbit of  $X_0$  which lies in the same tile as  $\gamma_t$  of the Farey tessellation.

**1.2. The relative metric.** A way to interpret this result is in term of different metrics on the mapping class group. If  $G$  acts isometrically on a metric space  $(X, d)$ , one can pick a basepoint  $x_0 \in X$  and consider the distance on  $G$  given by  $d(g, h) := d(gx_0, hx_0)$ . In particular, the mapping class group acts on the following three different metric spaces, and this can be used to define three metrics on  $G$ :

- (1) the *word metric*  $\|\cdot\|_G$  (or  $d_G$ ) previously mentioned arises from the action of  $G$  on its Cayley graph;
- (2) the mapping class group acts on the Teichmüller space equipped with the *Teichmüller metric*: we will denote this metric as  $\|\cdot\|_{\mathcal{T}}$  or  $d_{\mathcal{T}}$ ;
- (3) the mapping class group acts on the curve complex  $\mathcal{C}(S)$ : the resulting metric is called the *relative metric*  $\|\cdot\|_{\text{rel}}$  (or  $d_{\text{rel}}$ ). The curve complex is a locally infinite, hyperbolic, simplicial complex. The relative metric on  $G$  can also be seen as the word metric with respect to an infinite generating set, constructed by adding to a finite generating set the stabilizers of simple closed curves  $\alpha_i$ , where the  $\alpha_i$  are a set of representatives for orbits of simple closed curves under  $G$  [27].

It is well known (see [28, 29]) that  $\|\cdot\|_{\text{rel}} \lesssim \|\cdot\|_{\mathcal{T}} \lesssim \|\cdot\|_G$ , and the three metrics are not quasi-isometric to each other. Moreover, except in some cases of low complexity, neither the word metric nor the Teichmüller metric are hyperbolic

in the sense of Gromov; the curve complex, on the other hand, is known to be hyperbolic [27], but this comes at the price of not being locally compact.

However, if one restricts to geodesics that lie completely in some thick part, then the three metrics are indeed quasi-isometric. Thus, one can interpret the results of Theorem 1.1 and Theorem 1.2 by saying that typical geodesics with respect to Lebesgue measure have larger excursions in the thin part than typical geodesics with respect to harmonic measure.

We can also modify the word length ratio and define the *relative word length ratio*  $\rho_{\text{rel}}(\gamma)$  as

$$\rho_{\text{rel}}(\gamma) := \lim_{\substack{t \rightarrow \infty \\ \gamma_t \notin \mathcal{T}_\epsilon}} \frac{\|g_t\|_G}{\|g_t\|_{\text{rel}}}.$$

For the relative word length ratio we have a similar result.

**Theorem 1.3.** *Let  $X_0$  be a point in Teichmüller space. Then for Lebesgue-almost every geodesic ray  $\gamma$  based at  $X_0$ , we have*

$$\rho_{\text{rel}}(\gamma) = \infty.$$

*Moreover, let  $\mu$  be a non-elementary probability measure on  $\text{Mod}(S)$  with finite first moment in the word metric, and let  $\nu$  be the harmonic measure determined by the corresponding random walk. Then there exists a constant  $c > 0$  such that*

$$\rho_{\text{rel}}(\gamma) = c$$

*for  $\nu$ -almost every geodesic ray  $\gamma$  based at  $X_0$ .*

Let us remark that in the special case of  $G = SL_2(\mathbb{Z})$  (mapping class group of the torus), Theorem 1.3 is equivalent to the following classical statement in terms of continued fractions. For each  $r \in \mathbb{R}$ , let us denote as  $a_n(r)$  the  $n^{\text{th}}$  coefficient in the continued fraction expansion of  $r$ . Then for Lebesgue-almost every  $r$ , we have

$$\lim_{n \rightarrow \infty} \frac{a_1(r) + \cdots + a_n(r)}{n} = +\infty,$$

while for almost every  $r$  with respect to harmonic measure, we have

$$\lim_{n \rightarrow \infty} \frac{a_1(r) + \cdots + a_n(r)}{n} = c < \infty.$$

Note that the statement of Theorem 1.3 for the Lebesgue measure follows immediately from Theorem 1.1, as the Teichmüller metric is a coarse upper bound for the relative metric. For the same reason, the statement of Theorem 1.3 implies that for the harmonic measure the word length ratio  $\rho(\gamma)$  is almost surely bounded above and below between two positive constants: this is almost the statement of Theorem 1.2, except for the existence of the limit.

**1.3. Singularity of harmonic measure.** The theorem has the following corollary for the harmonic measure:

**Theorem 1.4.** *Let  $\mu$  be a measure on the mapping class group with finite first moment in the word metric, and such that the semigroup generated by its support is a non-elementary subgroup of  $\text{Mod}(S)$ . Then the corresponding harmonic measure  $\nu$  on  $\mathcal{PMF}$  is singular with respect to Lebesgue measure.*

The singularity of harmonic measure for random walks on the mapping class group was conjectured by Kaimanovich and Masur [18]. The origin of this conjecture lies in the following analogy with Riemannian manifolds. If  $\widetilde{M}$  is the universal cover of a compact surface  $M$  of negative curvature, the harmonic measure on the ideal boundary of  $\widetilde{M}$  given by the Brownian motion is singular with respect to the visual measure unless the surface has constant curvature (see Katok [16] and Ledrappier [20]). In this light, the singularity of Theorem 1.4 is to be expected as Teichmüller space is inhomogeneous (e.g. its isometry group is discrete). Note that the Teichmüller metric is not Riemannian, so it is not clear how to define a Brownian motion, but one can use the random walk as a discrete analog.

Note that the finite first moment assumption is essential; indeed, it is conjectured that there exists a measure  $\mu$  on  $\text{Mod}(S)$  such that the hitting measure of the corresponding random walk is absolutely continuous on  $\mathcal{PMF}$ : as a consequence of our result, such a measure must have infinite first moment.

In [10], Gadre proved singularity of the harmonic measure for random walks on  $\text{Mod}(S)$  generated by measures with finite support, while here we consider arbitrary measures of finite first moment. His proof uses train track splittings on  $\mathcal{PMF}$ , and relies on the exponential decay of measures of shadow sets, which are not known for measures of finite first moment.

In this paper, we get the Lebesgue measure statistics by using the ergodicity of the Teichmüller geodesic flow, combined with estimates on the volume of the thin part of the space of quadratic differentials. In particular, we define the following function  $L : \mathcal{QM} \rightarrow \mathbb{R}$  on the moduli space of quadratic differentials:

$$L(q) := \sum_{\alpha \in C_q(\delta, \epsilon)} \frac{1}{\ell_q^2(\alpha)},$$

where  $\ell_q(\alpha)$  is the length of the curve  $\alpha$  in the flat metric  $q$ , and  $C_q(\delta, \epsilon)$  the set of cylinders which have core length  $\leq \sqrt{\epsilon}$  and area  $\geq \delta$ . We then prove, using results of Eskin–Masur [7], that the ergodic average of  $L$  is infinite along orbits of the Teichmüller flow; Theorem 1.1 follows since the time integral of  $L$  is a lower bound for the word metric  $\|\cdot\|_G$ .

The statistics for harmonic measure follows from linear progress in the relative metric, combined with sublinear tracking between geodesics and sample paths. In particular, in [32] it is proven that random walks on the mapping class group track Teichmüller geodesics sublinearly (in the Teichmüller metric). In order to transfer

the information about the ratio between the word and the relative metric along sample paths, we will prove a tracking result in the word metric.

**1.4. Background and remarks.** For random walks on general groups, the question of singularity of harmonic measure has a long history (see also the introduction of Kaimanovich and Le Prince [17]). In the context of lattices in Lie groups, Furstenberg [8, 9] first constructed random walks on discrete groups whose hitting measure is absolutely continuous on the boundary. For non-uniform lattices of rank 1, these random walks have finite first moment in the Riemannian metric on the Lie group, but do not have finite first moment in the word metric on the discrete subgroup.

For non-uniform lattices  $\Gamma$  in  $SL(2, \mathbb{R})$ , Guivarc'h and Le Jan [13, 14] proved the singularity of harmonic measures by studying the asymptotic winding around the cusp of the geodesic flow on  $\Gamma \backslash \mathbb{H}^2$ . Other approaches are given by Deroin, Kleptsyn and Navas [4] and by Blachère, Haïssinsky and Mathieu [2]. Our approach via the word length ratio can be also applied to non-uniform lattices in  $SL(2, \mathbb{R})$  [12]. On the other hand, for finitely supported measures on uniform lattices in  $SL(2, \mathbb{R})$ , harmonic measure is expected to be singular; however, the question appears to be still open.

Several authors have considered cusp excursions of Lebesgue-typical geodesics; in particular, Sullivan [31] showed that on a non-compact hyperbolic manifold a generic geodesic ray ventures into the cusps infinitely often with maximum depth in the cusps of about  $\log t$ , where  $t$  is the time along the geodesic ray. The same approach has been then adapted to the Teichmüller geodesic flow by Masur [26].

Our method uses essentially only the geometry of the cusp, so it is natural to expect it to apply to other group actions for which the orbit space is a non-compact manifold of finite volume and the geodesic flow is ergodic, e.g. for fundamental groups of higher-dimensional hyperbolic manifolds with cusps.

**1.5. Outline of the paper.** In Section 2 we present background material on Teichmüller theory; in particular, we review the curve complex and marking complex, define the concept of excursion and use results of Rafi in order to prove the coarse monotonicity in the word metric of the approximating group elements along Teichmüller geodesics. In particular, in the case of curves corresponding to flat annuli, we obtain an estimate for the excursion in terms of the twist parameter and the area of the flat annulus. In Section 3, we prove the asymptotic result for the Lebesgue measure, i.e. Theorem 1.1. This is done by considering the ergodic average with respect to the Teichmüller flow of an appropriate function defined on the moduli space of quadratic differentials (Theorem 3.3) and then relate the average to the growth rate of the word metric along typical geodesics. We use results of Masur [26] and Eskin–Masur [7], which give the growth rate of the number of flat annuli, and enable us to apply the excursion estimates obtained in the previous section. Finally, in Section 4, we prove Theorem 1.2, namely the asymptotics for harmonic measure.

**1.6. Notation.** We shall find it convenient to occasionally use *big O* notation. We say that  $f(x) = O(g(x))$  if there are constants  $A$  and  $B$  such that  $|f(x)| \leq A|g(x)|$  for all  $x \geq B$ . In particular,  $f(x) = O(1)$  means that the function  $f(x)$  is bounded. We will also write  $f(x) \lesssim g(x)$  to mean that the inequality holds up to additive and multiplicative constants, i.e. there are constants  $K$  and  $c$  such that

$$f(x) \leq Kg(x) + c,$$

and similarly  $f(x) \asymp g(x)$  will mean that there exist constants  $K, c$  such that

$$\frac{1}{K}g(x) - c \leq f(x) \leq Kg(x) + c.$$

Unless otherwise specified, the constants  $K, c$  depend only on the topology of  $S$ , the constant  $\epsilon$  defining the thin part, and the generating set for  $\text{Mod}(S)$ .

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## 2. Preliminaries from Teichmüller theory

In Sections 2.1–2.4 we review some background material on quadratic differentials, subsurface projections and short markings. In Section 2.5 we review in detail some results of Rafi [29, 30] which relate subsurface projection distance first to the twist parameter along a Teichmüller geodesic, and then to the excursion distance along the geodesic. In Section 2.6, we use these results to show that word length grows coarsely monotonically along Teichmüller geodesics, and finally in Section 2.7, we show that a similar result holds for the nearest lattice points to the geodesic, if they lie in the thick part of Teichmüller space.

**2.1. Quadratic differentials and Teichmüller discs.** Let  $S$  be a hyperbolic surface of finite type, i.e. a surface of finite area which may have boundary components or punctures. We say such a surface  $S$  is *sporadic* if it is a sphere with at most four punctures or boundary components, or a torus with at most one puncture or boundary component. We shall primarily be interested in non-sporadic surfaces, as in the sporadic cases the Teichmüller spaces are either trivial, or isometric to  $\mathbb{H}^2$ , and covered by the case of  $SL(2, \mathbb{Z})$  (see [12]).

Let  $S$  be a non-sporadic surface with no boundary components, but which may have punctures. We will write  $\mathcal{T}(S)$  for the Teichmüller space of a surface  $S$ , or

just  $\mathcal{T}$  if we do not need to explicitly refer to the surface. We shall consider  $\mathcal{T}$  together with the Teichmüller metric

$$d_{\mathcal{T}}(x, y) = \frac{1}{2} \inf_f \log K(f),$$

where the infimum is taken over all quasiconformal maps  $f: x \rightarrow y$  in the correct homotopy class, and  $K(f)$  is the quasiconformal constant of  $f$ . The mapping class group  $G = \text{Mod}(S)$  of the surface acts by isometries on  $\mathcal{T}$ , and we shall write  $\mathcal{T}_\epsilon$  for the *thin part* of Teichmüller space, i.e. all surfaces which contain an essential curve of hyperbolic length at most  $\epsilon$ . We shall write  $\mathcal{M}$  for the quotient  $G \backslash \mathcal{T}$ , which is known as moduli space. The thin part of Teichmüller space is mapping class group invariant, and we shall write  $\mathcal{M}_\epsilon$  for the subset of moduli space given by  $G \backslash \mathcal{T}_\epsilon$ .

Let  $\mathcal{Q}$  be the space of unit area quadratic differentials, which may be identified with the unit cotangent bundle to Teichmüller space [15]. We shall write  $\pi$  for the projection  $\pi: \mathcal{Q} \rightarrow \mathcal{T}$  which sends a quadratic differential to its underlying Riemann surface, and we shall write  $\mu_{\text{hol}}$  for the Masur-Veech measure, also known as the holonomy measure, as it may be defined in terms of holonomy coordinates. The measure  $\mu_{\text{hol}}$  is mapping class group invariant, and so gives a measure on the moduli space of unit area quadratic differentials  $\mathcal{MQ} = G \backslash \mathcal{Q}$ , which has finite volume [25, 33].

A quadratic differential  $q$  determines a flat structure on the surface, which may be thought of as a union of polygons glued together along parallel sides, where the vertices of the polygons may correspond to points of cone angle  $n\pi$ , for  $n \geq 1$ . If  $n \geq 2$ , then the vertex corresponds to a zero of order  $n - 2$  for the quadratic differential  $q$ , and for  $n = 1$  the vertices correspond to cone points of angle  $\pi$  which are simple poles for the quadratic differential, and correspond to the punctures of the surface. There is an affine action of  $SL(2, \mathbb{R})$  on the flat surface, which gives rise to a new quadratic differential. The orbits of quadratic differentials under the action of  $SL(2, \mathbb{R})$  give a foliation of  $\mathcal{Q}$  by copies of  $SL(2, \mathbb{R})$ , and we shall write  $\tilde{D}_q$  for the orbit of the quadratic differential  $q$ . We shall write  $D_q$  for the image of  $\tilde{D}_q$  in  $\mathcal{T}$ , and this is called a Teichmüller disc, which is geodesically embedded in  $\mathcal{T}$ . With the metric induced from the Teichmüller metric,  $D_q$  is isometric to the hyperbolic plane of constant curvature  $-4$ , and it will be convenient for us to use coordinates coming from the disc model of hyperbolic plane, with the initial quadratic differential  $q$  corresponding to the vector  $(1, 0)$  at the origin.

The group of rotations of  $\mathbb{R}^2$  acts on flat surfaces, and hence on  $\mathcal{Q}$ . In terms of quadratic differentials, rotation by angle  $\theta$  in  $\mathbb{R}^2$  sends  $q \mapsto e^{-2i\theta} q$ , and this action is trivial on Teichmüller space  $\mathcal{T}$ . It follows from the definition that holonomy measure is invariant under rotation, i.e.  $\mu_{\text{hol}}(U) = \mu_{\text{hol}}(e^{i\theta} U)$ , for all  $\theta$ , for any subset  $U \subset \mathcal{Q}$ . In particular, this means that if we consider the conditional measure of  $\mu_{\text{hol}}$  on the image of a quadratic differential  $q \in \mathcal{Q}$  under rotation, i.e.  $\{e^{i\theta} q : \theta \in [0, 2\pi]\}$ , then this is precisely the invariant Haar or Lebesgue measure on the circle.

Finally, given  $X \in \mathcal{T}$ , the space  $\mathcal{Q}(X)$  of unit area quadratic differentials on  $X$  is the unit cotangent space at  $X$ , and we can denote by  $s_X$  the conditional measure induced by the holonomy measure on  $\mathcal{Q}(X)$ . The map  $\mathcal{Q}(X) \rightarrow \mathcal{PMF}$  which associates to each quadratic differential on  $X$  the projective class of its vertical foliation pushes forward the measure  $s_X$  to a measure in the Lebesgue measure class (see Athreya, Bufetov, Eskin and Mirzakhani [1, Section 2]), so we can indifferently use  $s_X$  and Lebesgue measure on  $\mathcal{PMF}$  when discussing sets of full measure. For a discussion of the different measures on  $\mathcal{T}(S)$ ,  $\mathcal{PMF}$  and related spaces, see also Dowdall, Duchin and Masur [6, Section 3].

**2.2. Curve complex and subsurface projections.** In this section we review the properties we will use of two combinatorial objects associated with a surface, namely the *curve complex* and the *marking complex*.

We say a simple closed curve on a surface  $S$  is *essential* if it does not bound a disc, and is not parallel to a puncture or boundary component. The *curve complex*  $\mathcal{C}(S)$  is a finite dimensional but locally infinite simplicial complex whose vertices are isotopy classes of essential simple closed curves on  $S$ , and whose simplices consist of collections of curves which can be realised disjointly on the surface. For the non-sporadic surfaces, the curve complex is a non-empty, connected, simplicial complex. In the case of a torus with one puncture or boundary component, or a sphere with four punctures or boundary components, the definition above gives a complex with no edges, so we alter the definition to connect two vertices if their corresponding curves can be realised by curves which intersect at most once (in the case of the once punctured torus) or at most twice (in the case of the four punctured sphere). In the case of the annulus, the curve complex is defined to be the infinite graph with vertices consisting of arcs connecting the two boundary components of the annulus, modulo isotopy fixing the endpoints, and with edges between two arcs if they can be realised disjointly. The curve complex of the annulus is quasi-isometric to  $\mathbb{Z}$  with a quasi-isometry given by the algebraic intersection number with a fixed transversal. We define the curve complex to be empty for the remaining sporadic surfaces.

We say a subsurface  $Y \subseteq S$  is *essential* if each boundary component is an essential simple closed curve in  $S$ . Given an essential subsurface  $Y \subseteq S$ , which is not a disc or a three-punctured sphere, one can also consider  $\mathcal{C}(Y)$ , the complex of curves of  $Y$ . There is a coarsely well-defined *subsurface projection*  $\pi_Y: \mathcal{C}(S) \rightarrow \mathcal{C}(Y)$  which we now describe. Choose an element in the isotopy class of the curve  $\gamma$  which has the minimal possible number of intersections with  $Y$ , and then take a regular neighbourhood of the union of the boundary of  $Y$  with the intersection of the curve  $\gamma$  with  $Y$ , i.e.  $N(\partial Y \cup (\gamma \cap Y))$ . Choose an essential component of the boundary of this regular neighbourhood to be  $\pi_Y(\gamma)$ . This is coarsely well defined.

To define the annular projection  $\pi(\gamma)$  of a curve  $\gamma$  with essential intersection with an annulus  $A$  one passes to the annular cover  $\tilde{S}$  of  $S$  given by the core curve  $\alpha$  of  $A$  and chooses  $\pi_A(\gamma)$  to be a component of the lift of  $\gamma$  that is an arc running from one

boundary component of  $\widetilde{S}$  to the other. The set of components of the lift of  $\gamma$  that satisfy this property form a finite diameter set in the curve complex of the annulus  $\widetilde{S}$  and so the projection is coarsely well-defined. Finally the map  $\pi_A$  has the property that if  $D_\alpha$  denotes the Dehn twist about  $\alpha$ , then for any  $n \in \mathbb{Z}$

$$d_{\mathcal{C}(A)}(\pi_A(D_\alpha^n(\gamma)), \pi_A(\gamma)) \asymp |n|. \quad (1)$$

Thus, defining the projection this way achieves the desired property of recording the twisting around  $\alpha$ . There is a natural  $\mathbb{Z}$ -action on  $\mathcal{C}(A)$  by Dehn twisting around the core curve of the annular cover  $\widehat{S}$ . The group  $\mathbb{Z}$  also has an inclusion into the mapping class group of  $S$  as Dehn twists around  $\alpha$ , and so it acts on  $\mathcal{C}(A)$  through this inclusion. The projection map  $\pi_A$  is coarsely equivariant with respect to the two  $\mathbb{Z}$  actions. We will often abuse notation and write  $\pi_\alpha$  to mean the subsurface projection to an annulus whose core curve is  $\alpha$ .

**2.3. Markings.** A *marking* consists of a collection of simple closed curves  $\alpha_i$  forming a maximal simplex in the curve complex, or equivalently, a pants decomposition of the surface, together with a *transverse curve*  $\tau_i$  for each pants curve  $\alpha_i$ , which is an element of the annular curve complex corresponding to  $\alpha_i$ . The curves  $\alpha_i$  are known as the *base curves* of the marking. We remark that the definition we give here corresponds to the definition of a *complete* marking from [28]. They consider more general markings, in which the set of base curves does not need to form a maximal simplex in  $\mathcal{C}(S)$ , and all base curves are not required to have a transversal. However, complete markings suffice for our purposes.

If  $\alpha$  is a simple closed curve in  $S$ , then a *clean transverse curve* for  $\alpha$  is a simple closed curve  $\beta$ , such that a regular neighbourhood of  $\alpha \cup \beta$ , isotoped to have minimal intersection, is either a sphere with four boundary components, or a torus with a single boundary component. A *clean marking* is a marking  $(\alpha_i, \tau_i)$ , such that each transverse curve  $\tau_i$  is of the form  $\pi_{\alpha_i}(\beta_i)$ , for some clean transverse curve  $\beta_i$ , which is disjoint from the union  $\bigcup_{j \neq i} \alpha_j$  of the other base curves. A clean marking  $m' = (\alpha_i, \beta_i)$  is *compatible* with a marking  $m = (\alpha_i, \tau_i)$  if the base curves of  $m$  are the same as the base curves of  $m'$ , and for each base curve  $\alpha_i$ , the distance  $d_{\mathcal{O}_i}(\tau_i, \pi_{\alpha_i}(\beta_i))$  is minimal. There are only finitely many clean markings  $m'$  compatible with a given marking  $m$ , and the distance between any two of them is bounded independently of  $m$ .

The *marking complex*  $M(S)$  is a graph whose vertices are clean markings, and whose edges are given by *elementary moves* as defined by Masur and Minsky [28]. These moves are called twists and flips. In a *twist*, a transverse curve  $\beta_i$  is replaced by the image of the transverse curve under a Dehn twist along its corresponding pants curve  $D_{\alpha_i}(\beta_i)$ . In a *flip*, a transverse curve  $\beta_i$  and its corresponding base curve  $\alpha_i$  are interchanged, i.e. a new clean marking is chosen which is compatible with the marking formed by replacing  $(\alpha_i, \pi_{\alpha_i}(\beta_i))$  with  $(\beta_i, \pi_{\beta_i}(\alpha))$ . The mapping class

group acts on the marking complex and the space of orbits is finite. We will write  $d_M$  for the induced metric on the marking complex obtained by setting the length of each edge equal to one.

The mapping class group is finitely generated, so a choice of generating set gives rise to a word metric, in which the length of a group element is the shortest length of any product of generators representing the group element. Different generating sets give rise to quasi-isometric metrics. We shall assume we have fixed a generating set, and we shall write  $\|\cdot\|_G$ , or  $d_G$ , for the word metric distance in the mapping class group. Masur and Minsky showed that the distance  $d_M$  in the marking complex is quasi-isometric to the word metric in the mapping class group.

**Theorem 2.1** ([28, Theorems 6.10 and 7.1]). *Fix a complete clean marking  $m_0$  and a system of generators for  $\text{Mod}(S)$ . Then there exist constants  $C_1, C_2$  such that for each  $g \in \text{Mod}(S)$*

$$C_1^{-1} \|g\|_G - C_2 \leq d_M(m_0, gm_0) \leq C_1 \|g\|_G + C_2.$$

For any essential subsurface  $Y \subseteq S$ , there is a coarsely well-defined projection map  $p_Y : M(S) \rightarrow \mathcal{P}(\mathcal{C}(Y))$  to the set of subsets of  $\mathcal{C}(Y)$ , which is defined for each marking  $\mu$  as follows. If  $Y$  is an annulus whose core curve  $\alpha$  is a base curve of  $\mu$ , then the image of  $\mu$  is the transverse curve to  $\alpha$ . Otherwise, the projection of  $\mu$  is the set of subsurface projections to  $Y$  of the base curves of  $\mu$ .

Given markings  $m$  and  $n$ , denote by  $d_Y(m, n)$  the diameter in  $\mathcal{C}(Y)$  of the union of the projections of  $m$  and  $n$ . If  $\alpha$  is a simple closed curve, then  $d_\alpha$  will denote the distance in the curve complex of the annulus with core curve  $\alpha$ .

Masur and Minsky [28, Theorem 6.12] proved a distance formula expressing the distance in the marking complex  $M(S)$ , and hence by Proposition 2.1, the distance in  $\text{Mod}(S)$  in the word metric, in terms of subsurface projections. We now describe their formula, using the cutoff function  $\lfloor x \rfloor_A$ , defined by

$$\lfloor x \rfloor_A = \begin{cases} x & \text{if } x \geq A \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

**Theorem 2.2** (Quasi-distance formula [28]). *There exists a constant  $A_0 > 0$ , which depends only on the topology of the surface  $S$ , such that for any  $A \geq A_0$ , there are constants  $C_1$  and  $C_2$ , which depend only on  $A$  and the topology of  $S$ , such that for any pair of complete clean markings  $m$  and  $m'$  in  $M(S)$ ,*

$$C_1^{-1} d_M(m, m') - C_2 \leq \sum_{Y \subseteq S} \lfloor d_Y(m, m') \rfloor_A \leq C_1 d_M(m, m') + C_2$$

where the sum runs over all subsurfaces  $Y$  of  $S$ , including  $S$ .

**2.4. Short curves and short markings.** Let us recall the definition of extremal length of a curve  $\alpha$  on a surface:

$$\text{Ext}_\sigma(\alpha) := \sup_\rho \frac{(\ell_\rho(\alpha))^2}{A(\rho)}$$

where the sup is taken over all metrics  $\rho$  in the same conformal class as  $\sigma$ . For any quadratic differential  $q$  with area 1 and any curve  $\alpha$ ,

$$(\ell_q(\alpha))^2 \leq \text{Ext}_\sigma(\alpha) \leq \frac{L_\sigma(\alpha)}{2} e^{L_\sigma(\alpha)/2}$$

where the left-hand side is by definition, while the right-hand side is due to Maskit [23], and  $L_\sigma(\alpha)$  is the length of  $\alpha$  in the hyperbolic metric corresponding to the conformal structure  $\sigma$ .

Let now  $q \in \mathcal{Q}(S)$  be a quadratic differential, and define the *short marking*  $m(q)$  in the following way. First, choose a pants decomposition by picking the simple closed curves of shortest extremal length, using the greedy algorithm. To be precise, start by choosing one of the shortest curves on the surface, then choose one of the shortest curves on the complementary surface, and continue until you have a pants decomposition of the original surface.

Then, for each curve  $\alpha_i$  of the pants decomposition choose a transverse curve  $\tau_i$  which is perpendicular to  $\alpha_i$  in the flat metric associated to  $q$ . This produces a complete marking  $m'$  on  $S$ . Finally, let us pick  $m(q)$  to be a clean marking which is compatible with  $m'$ .

Note that the short marking need not be unique (for instance if there are multiple shortest curves), but there are only a finite number of choices, with a bound depending on the topology of the surface.

This gives a map  $m : \mathcal{Q}(S) \rightarrow M(S)$ , which is coarsely well-defined and mapping class group equivariant. This map is not Lipschitz over all of  $\mathcal{Q}(S)$ , but it is over the pre-image of the thick part of Teichmüller space. Once we fix a base point  $q_0$ , we shall write  $q_t$  for the quadratic differential given by flowing  $q_0$  for time  $t$ , and  $m_t = m(q_t)$  for the short marking associated to  $q_t$ .

We remark that our definition of marking follows [30], but there are other definitions of short markings in the literature [28, 29], as one can choose to take the short pants decomposition with respect to either the hyperbolic or extremal length, and to define the transversals using either the hyperbolic or flat length. In fact, the choice of extremal or hyperbolic length to define the pants decomposition only changes the marking up to bounded distance, while changing the definition of transversal may yield two markings whose distance is not bounded.

**2.5. Excursions and twist parameter.** The material in this section is due to Rafi [29, 30], and gives estimates for the twist parameters of flat annuli which depend on their

area. This suffices for our purposes, as the results of Masur [26] and Eskin–Masur [7] guarantee the existence of sufficiently many flat annuli with area bounded below. However, we need versions of his results in terms of the excursion parameter, and we use some of the contents of the proofs, not just the main stated results, so we write out all of the details for the convenience of the reader.

A horoball  $H$  in the hyperbolic plane is a subset of the plane which in the Poincaré disc model corresponds to a Euclidean disc whose boundary circle is tangent to the boundary at infinity. Given a horoball  $H$  and a geodesic  $\gamma$  which spends a finite amount of time in  $H$ , let us define the *excursion*  $E(\gamma, H)$  of  $\gamma$  in  $H$  as the “relative visual size” of the set of rays which go deeper than  $\gamma$  inside  $H$ . Namely, consider a basepoint  $X_0$  on the Teichmüller disc in  $\mathcal{T}$ , and let  $\gamma_H$  be the geodesic through  $X_0$  which tends to the cusp of  $H$ , and  $\gamma_T$  a geodesic through  $X_0$  which is tangent to  $H$ . Let  $\phi_0$  be the angle between  $\gamma$  and  $\gamma_H$ , and  $\phi_{\max}$  be the angle between  $\gamma_H$  and  $\gamma_T$  (see Figure 2). Then

**Definition 2.3.** The *excursion* of the geodesic  $\gamma$  in the horoball  $H$  is defined as

$$E(\gamma, H) := \frac{\phi_{\max}}{\phi_0}. \quad (3)$$

It turns out that  $E(\gamma, H)$  equals, up to an additive error, the hyperbolic length of the closest point projection of  $\gamma \cap H$  to the complement of  $H$ .

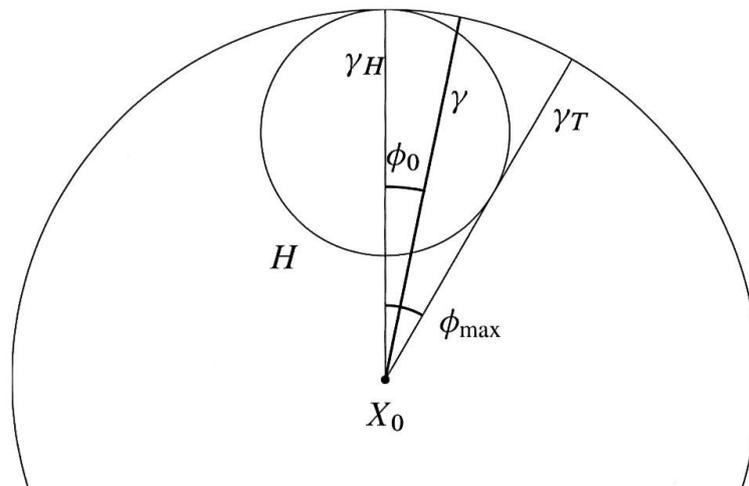


Figure 2. Excursion in the horoball  $H$ .

Let  $(X, q)$  be a quadratic differential on  $X$ , and  $\alpha$  a simple closed curve on  $X$ . The choice of  $q$  determines a Teichmüller geodesic  $\gamma$  and a pair  $(F^+, F^-)$  of contracting and expanding foliations. Each  $t$  determines a new quadratic differential  $q_t$  and hence a flat metric on  $X$ , which we will call the  $q_t$ -metric.

For a given  $t$ ,  $\alpha$  is realised by either a family of parallel flat closed geodesics or by a union of saddle connections, and we will denote as  $\tau_t$  a perpendicular to  $\alpha$  in the

$q_t$ -metric (there are several such choices, but we can pick any one of them as they are disjoint). The *twist parameter*  $tw_t^+(\alpha)$  is the highest intersection number between a leaf of  $F^+$  and the transversal  $\tau_t$ , and similarly we define  $tw_t^-(\alpha)$ .

Given a simple closed curve  $\alpha$  corresponding to a metric cylinder, there is a unique rotation  $e^{i\theta_\alpha}$  which takes the metric cylinder to a vertical metric cylinder. The endpoint of the geodesic ray corresponding to the quadratic differential  $e^{i\theta_\alpha}q$  determines a point  $\xi_\alpha$  on the boundary at infinity of the Teichmüller disc  $\mathbb{D}$ . We shall write  $H_\epsilon(\alpha)$  as the set of points in the disc for which  $\alpha$  is short in the flat metric:

$$H_\epsilon(\alpha) := \{q \in \mathbb{D} : \ell_q^2(\alpha) \leq \epsilon\}.$$

As seen in the disc, this set is a horoball tangent to the boundary at infinity at  $\xi_\alpha$ . The fundamental estimate is the following:

**Proposition 2.4.** *Let  $H = H_\epsilon(\alpha)$  as above, and let  $t_1$  and  $t_2$  respectively be the entry time and exit time from  $H$  (i.e.  $t_1 \leq t_2$ ) along the Teichmüller geodesic  $\gamma$ . Let moreover  $A$  be the area of the maximal flat cylinder in  $(X, q_0)$  with core curve  $\alpha$ . Then we have, up to universal multiplicative and additive constants,*

$$tw_{t_2}^-(\alpha) - tw_{t_1}^-(\alpha) \asymp \frac{A}{\epsilon} E(\gamma, H).$$

*Proof.* Consider the universal cover of the flat cylinder corresponding to  $\alpha$  at time  $t$ , in the flat metric  $q_t$ . We shall assume that the contracting foliation is vertical, and the expanding foliation is horizontal. Let  $\ell_t$  be the length of  $\alpha$  at time  $t$ , and let  $\theta_t$  be the angle  $\alpha_t$  makes with the vertical contracting foliation, as illustrated below in Figure 3.

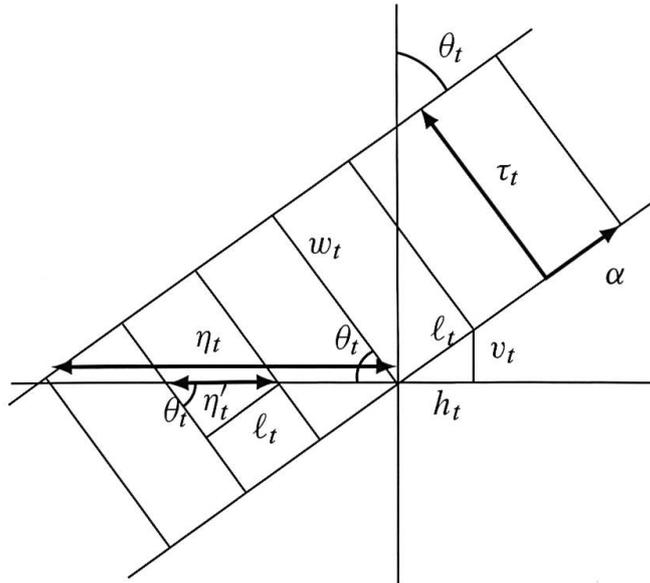


Figure 3. Estimating intersections in the flat annulus.

Let  $h_t$  and  $v_t$  be the horizontal and vertical lengths of  $\ell_t$  in the  $q_t$  metric, i.e.

$$\begin{aligned} h_t &= h_0 e^t = \ell_0 \sin \theta_0 e^t \\ v_t &= v_0 e^{-t} = \ell_0 \cos \theta_0 e^{-t}. \end{aligned}$$

Let  $w_t$  be the length of  $\tau_t$ , which is the width of the flat annulus. Let  $\eta_t$  be the length of the intersection of a leaf of the horizontal foliation with the universal cover of the flat annulus, and let  $\eta'_t$  be the length of the intersection of the horizontal leaf with two adjacent translates of  $\tau_t$ .

Recall that by definition  $t w_t^-(\alpha)$  is the maximum number of intersections between the horizontal leaf of the foliation and  $\tau_t$ . Hence, by looking at the universal cover of the annulus as in Figure 3, one gets that  $t w_t^-(\alpha)$  is given, up to a bounded additive error, by  $\eta_t/\eta'_t$ . Therefore

$$t w_t^-(\alpha) = \frac{\eta_t}{\eta'_t} + O(1) = \frac{w_t \sin \theta_t}{\ell_t \cos \theta_t} + O(1).$$

The area of the annulus is  $A = w_t \ell_t$ , and  $\tan \theta_t = \tan \theta_0 e^{2t}$ , so this implies that

$$t w_t^-(\alpha) = \frac{A}{\ell_t^2} \tan \theta_0 e^{2t} + O(1). \quad (4)$$

The total length of  $\alpha$  is given by

$$\ell_t^2 = h_t^2 + v_t^2 = \ell_0^2 (\sin^2 \theta_0 e^{2t} + \cos^2 \theta_0 e^{-2t}), \quad (5)$$

and recall that we choose  $t_i$  such that  $\ell_{t_i}^2 = \epsilon$ , which by (4) implies

$$t w_{t_2}^-(\alpha) - t w_{t_1}^-(\alpha) = \frac{A}{\epsilon} \tan \theta_0 (e^{2t_2} - e^{2t_1}) + O(1). \quad (6)$$

Note that by definition the  $t_i$  are solutions to the equation

$$\ell_{t_i}^2 = \ell_0^2 (\sin^2 \theta_0 e^{2t_i} + \cos^2 \theta_0 e^{-2t_i}) = \epsilon \quad i = 1, 2$$

If we set  $X_i := e^{2t_i}$ , then  $X_i$  are the solutions to

$$X^2 - \frac{\epsilon^2}{\ell_0^2 \sin^2 \theta_0} X + \frac{1}{\tan^2 \theta_0} = 0 \quad (7)$$

hence

$$e^{2t_2} - e^{2t_1} = X_2 - X_1 = \sqrt{\frac{\epsilon^2}{\ell_0^4 \sin^4 \theta_0} - \frac{4}{\tan^2 \theta_0}} \quad (8)$$

and putting (6) and (8) together

$$\begin{aligned} t w_{t_2}^-(\alpha) - t w_{t_1}^-(\alpha) &= \frac{A \tan \theta_0}{\epsilon} (e^{2t_2} - e^{2t_1}) + O(1) \\ &= \frac{A}{\epsilon} \sqrt{\frac{\epsilon^2}{\ell_0^4 \sin^2 \theta_0 \cos^2 \theta_0} - 4} + O(1). \end{aligned} \quad (9)$$

Let us now relate this quantity to the excursion in the horoball  $H$ .

**Lemma 2.5.** *Let  $\phi_{\max}$  be the angle between a geodesic  $\gamma_T$  tangent to  $H$  and the geodesic  $\gamma_H$  which goes straight into the cusp of  $H$ . Then*

$$\sin \phi_{\max} = \frac{\epsilon}{\ell_0^2},$$

where  $\ell_0$  is the length of  $\alpha$  at time  $t = 0$ .

*Proof.* When  $\theta_0 = \theta_{\max}$  then the geodesic is tangent to the horoball  $H$ , hence  $t_1 = t_2$  in equation (8), so

$$\frac{\epsilon^2}{\ell_0^4 \sin^4 \theta_{\max}} = \frac{4}{\tan^2 \theta_{\max}}.$$

The claim follows by recalling that a rotation of angle  $\theta$  in the flat metric picture corresponds to multiplying the quadratic differential by  $e^{2i\theta}$ , hence  $\phi_{\max} = 2\theta_{\max}$ .  $\square$

The proposition now follows easily from the lemma, equation (9) and the fact that  $\phi_0 = 2\theta_0$ :

$$t w_{t_2}^-(\alpha) - t w_{t_1}^-(\alpha) = \frac{2A \sin \phi_{\max}}{\epsilon \sin \phi_0} \sqrt{1 - \frac{\sin^2 \phi_0}{\sin^2 \phi_{\max}}} + O(1) \asymp \frac{A}{\epsilon} E(\gamma, H)$$

where in the last equality we used equation (3) and the fact that  $\sin \phi \asymp \phi$  (note that we can assume  $\sin \phi_0 \leq \frac{1}{2} \sin \phi_{\max}$ , otherwise the claim is trivially verified).  $\square$

**Remark.** As a corollary of the previous computation we have for each  $t$  the formula

$$t w_t^-(\alpha) = \frac{A \tan \theta_0}{\ell_0^2 (\sin^2 \theta_0 + \cos^2 \theta_0 e^{-4t})}$$

so the function  $t w_t^-(\alpha)$  is monotonically increasing, with

$$t w_t^-(\alpha) \rightarrow 0 \quad \text{as } t \rightarrow -\infty$$

and

$$t w_t^-(\alpha) \rightarrow \frac{2A \sin \phi_{\max}}{\epsilon \sin \phi_0} \asymp \frac{A}{\epsilon} E(\gamma, H) \quad \text{as } t \rightarrow +\infty.$$

The distance between the projections from the marking complex to the complex of the annulus can be compared to the excursion in the horoball:

**Proposition 2.6.** *Let  $\epsilon > 0$  sufficiently small, and  $(X_0, q)$  a unit area quadratic differential, which determines the geodesic ray  $\gamma_t$ . Let  $A$  be the  $q$ -area of the maximal flat cylinder with core curve  $\alpha$ , and suppose that  $\alpha$  is not short in the  $q$ -metric (i.e.  $\ell_q^2(\alpha) \geq \epsilon$ ). If the geodesic  $\gamma$  crosses the horoball  $H = H_\epsilon(\alpha)$  and  $t$  is larger than the exit time of  $\gamma$  from  $H$ , then*

$$d_\alpha(m_0, m_t) \asymp \frac{A}{\epsilon} E(\gamma, H)$$

where  $m_t$  is the short marking on  $\gamma_t$ , and the quasi-isometry constants depend only on  $X_0$ ,  $\epsilon$  and the topology of  $S$ .

*Proof.* Note that by the above remark the twist function  $tw_t(\alpha)^-$  is monotone in  $t$ ; hence, if  $t_1$  and  $t_2$  are the two times such that  $\ell_{t_1}^2 = \epsilon$  and  $0 < t_1 < t_2 < t$ , then

$$tw_{t_2}^-(\alpha) - tw_{t_1}^-(\alpha) \leq tw_{q_t}^-(\alpha) - tw_{q_0}^-(\alpha) \leq \lim_{s \rightarrow +\infty} tw_{q_s}^-(\alpha) - \lim_{s \rightarrow -\infty} tw_{q_s}^-(\alpha)$$

and by Proposition 2.4 and the remark both sides are comparable to  $\frac{A}{\epsilon}E(\gamma, H)$ , hence

$$d_\alpha(m_0, m_t) = |tw_{q_0}^-(\alpha) - tw_{q_t}^-(\alpha)| \asymp \frac{A}{\epsilon}E(\gamma, H)$$

as claimed.  $\square$

**2.6. Coarse monotonicity for the word metric.** In [30], Rafi shows the following non-backtracking or reverse triangle inequality for subsurface projections along a Teichmüller geodesic. Recall that given a Teichmüller geodesic  $\gamma_t$  we write  $m_t$  for the short marking at  $\gamma_t$ , and we write  $d_Y(m_s, m_t)$  to mean the distance in the curve complex  $\mathcal{C}(Y)$  between the images of  $m_s$  and  $m_t$  under subsurface projection to  $Y$ .

**Theorem 2.7** ([30, Theorem 6.1]). *There exists a constant  $C$ , only depending on the topology of  $S$ , such that for every Teichmüller geodesic  $\gamma$ , and every subsurface  $Y$ ,*

$$d_Y(m_r, m_s) + d_Y(m_s, m_t) \leq d_Y(m_r, m_t) + C, \quad (10)$$

for all constants  $r \leq s \leq t$ .

The above theorem along with the Masur–Minsky quasi-distance formula (2.2) implies that the distance in the marking complex is coarsely monotone along a Teichmüller ray.

**Proposition 2.8.** *There exist constants  $C_1 > 0$  and  $C_2$ , that depend only on  $S$ , such that along a Teichmüller geodesic  $\gamma_t$ , for  $r < s < t$  the distance in the marking complex satisfies*

$$d_M(m_r, m_s) \leq C_1 d_M(m_r, m_t) + C_2.$$

*Proof.* Let  $C$  be the constant in Rafi’s reverse triangle inequality, Theorem 2.7. Assume  $r < s < t$ , then (10) implies

$$d_Y(m_r, m_t) \geq d_Y(m_r, m_s) - C \quad (11)$$

for all subsurfaces  $Y \subseteq S$ . The Masur–Minsky quasi-distance formula (Theorem 2.2) holds for all floor constants sufficiently large, though the quasi-isometry constants depend on  $A$ . Choose a floor constant  $A > 2C$ , and let  $K_1$  and  $K_2$  be the associated

quasi-isometry constants. By the definition of the floor function, if  $\lfloor x \rfloor_A$  is non zero, then  $x \geq A$ . This implies that  $x - A/2 \geq x/2$ , and as the floor function is monotone,

$$\lfloor x - A/2 \rfloor_A \geq \lfloor x/2 \rfloor_A. \quad (12)$$

As we have chosen  $A > 2C$ , combining (11) and (12) implies

$$\lfloor d_Y(m_r, m_t) \rfloor_A \geq \lfloor \frac{1}{2} d_Y(m_r, m_s) \rfloor_A, \quad (13)$$

again for all subsurfaces  $Y \subseteq S$ . Now summing (13) over all subsurfaces  $Y \subseteq S$ , the quasi-distance formula implies

$$d_M(m_r, m_t) \geq \frac{1}{K_1} \left( \sum \lfloor \frac{1}{2} d_Y(m_r, m_s) \rfloor_A - K_2 \right).$$

By definition of the floor function,  $\lfloor \frac{1}{2} x \rfloor_A = \frac{1}{2} \lfloor x \rfloor_{2A}$ , so

$$d_M(m_r, m_t) \geq \frac{1}{2K_1} \left( \sum \lfloor d_Y(m_r, m_s) \rfloor_{2A} - 2K_2 \right).$$

The quasi-distance formula holds for all  $A$  sufficiently large, so in particular holds for  $2A$ , though with different quasi-isometry constants, which we shall denote  $K_3$  and  $K_4$ . This implies that

$$d_M(m_r, m_t) \geq \frac{1}{2K_1 K_3} (d_M(m_r, m_s) - K_3 K_4 - K_2)$$

whence the result. □

**2.7. Projection to closest Teichmüller lattice point.** Let  $q$  be a quadratic differential, let  $q_t$  be the image of  $q$  under the Teichmüller geodesic flow after time  $t$ , and let  $X_t$  be the image of  $q_t$  in  $\mathcal{T}$ . The orbit of  $X_0$  under the mapping class group is called a *Teichmüller lattice*, and let  $g_t X_0$  be a choice of closest lattice point in  $\mathcal{T}$  to  $X_t$ , i.e. such that

$$d_{\mathcal{T}}(g_t X_0, X_t) \leq d_{\mathcal{T}}(g X_0, X_t) \text{ for all } g \in \text{Mod}(S).$$

For any given point  $X_t$ , there are at most finitely many closest lattice points, however it is possible that the number of closest lattice points increases as you choose points deeper in the thin part. Let  $m_t$  be a short marking on  $X_t$ , and  $\| \cdot \|_G$  the word metric on the mapping class group with respect to some choice of generators.

**Lemma 2.9.** *If  $X_0$  and  $X_t$  both lie in the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$ , then*

$$\|g_t\|_G \asymp d_M(m_0, m_t)$$

where the quasi-isometry constants only depend on  $X_0$ , the choice of  $\epsilon$  and the generating set for the mapping class group.

*Proof.* Let  $K_1$  be the diameter of the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$  in moduli space; then, by definition there exists a group element  $g$  such that in Teichmüller space  $d_{\mathcal{T}}(gX_0, X_t) \leq K_1$ , so by definition of  $g_t$

$$d_{\mathcal{T}}(g_t X_0, X_t) \leq K_1.$$

Hence by group invariance

$$d_{\mathcal{T}}(X_0, g_t^{-1} X_t) \leq K_1.$$

In the Teichmüller ball of radius  $K_1$  only finitely many markings appear as short markings, hence there exists  $K_2$ , depending only on  $K_1$  and the surface  $S$ , such that the distance in the marking complex is bounded:

$$d_M(m_0, g_t^{-1} m_t) \leq K_2.$$

As a consequence,

$$|d_M(m_0, m_t) - d_M(m_0, g_t m_0)| \leq d_M(g_t m_0, m_t) = d_M(m_0, g_t^{-1} m_t) \leq K_2.$$

Finally, the distance in the word metric  $\|g_t\|_G$  is quasi-isometric to the distance  $d_M(m_0, g_t m_0)$  in the marking complex by Proposition 2.1.  $\square$

By combining the previous lemma with the coarse monotonicity statement of Proposition 2.8, we get that the word length of the closest point projection to the Teichmüller lattice is coarsely monotone along the thick part of a Teichmüller ray:

**Proposition 2.10.** *There exists constants  $C_1 > 0$  and  $C_2$ , that depend only on  $X_0$  and  $\epsilon$  and the choice of generators, such that along a Teichmüller geodesic  $\gamma_t$ , for  $0 < s < t$  the word metric satisfies*

$$\|g_s\|_G \leq C_1 \|g_t\|_G + C_2$$

whenever  $\gamma_0$ ,  $\gamma_s$  and  $\gamma_t$  all lie in the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$ .

### 3. Lebesgue measure sampling

The goal of this section is to study the asymptotic behaviour of typical Teichmüller geodesics with respect to Lebesgue measure, proving Theorem 1.1. More precisely, we want to keep track of short curves in the flat metric as the metric changes under the action of Teichmüller flow, and prove an asymptotic result, Theorem 3.3. In Section 3.1 we recall results of Masur [26] and Eskin and Masur [7] which show that the growth rate of the number of metric cylinders with area bounded below is quadratic. In Section 3.2 we consider the function given by the sum of the squares of the reciprocals of the short curves, and show that the average value of this function

tends to infinity along almost every Teichmüller geodesic with respect to Lebesgue measure. Then in Section 3.3 we show that this function gives a lower bound for the average of the sums of the excursions along the geodesic. Finally in Section 3.4 we show that the sum of the excursions is a lower bound for the word metric along the Teichmüller geodesic, and so the word metric along the geodesic has faster than linear growth, which completes the proof of the Theorem 1.1.

**3.1. Metric cylinders with bounded area.** Let  $q$  be a quadratic differential of unit area. A *metric cylinder* for  $q$  is a cylinder in the flat metric associated to  $q$  which is the union of freely homotopic closed trajectories of  $q$ . We shall label each metric cylinder by the homotopy class  $\alpha$  of the corresponding closed trajectory.

Let us now fix some  $0 < \delta < 1$ , and let  $C_q(\delta)$  be the set of metric cylinders for the  $q$ -metric with area bounded below by  $\delta$ . Moreover, let us denote by  $C_q(\delta, \epsilon)$  the set of cylinders whose area is bounded below by  $\delta$  and whose core curve has length shorter than the square root of  $\epsilon$ :

$$C_q(\delta, \epsilon) := \{\alpha \in C_q(\delta) : \ell_q^2(\alpha) \leq \epsilon\}.$$

**Lemma 3.1.** *Suppose  $\epsilon < \delta$ . Then any two distinct elements of  $C_q(\delta, \epsilon)$  are disjoint on  $q$ . As a corollary, the cardinality of  $C_q(\delta, \epsilon)$  is bounded above by a constant which depends only on the topology of  $S$ .*

*Proof.* We follow the argument in [26, Lemma 2.2]. Denote by  $\alpha$  the core curve of some cylinder which belongs to  $C_q(\delta, \epsilon)$ . Since the metric cylinder of  $\alpha$  has area  $A(\alpha) \geq \delta$ , any curve  $\tau$  which crosses  $\alpha$  is such that  $\delta \leq \ell_q(\alpha)\ell_q(\tau) \leq \ell_q(\tau)\sqrt{\epsilon}$ , hence  $\ell_q(\tau) > \sqrt{\epsilon}$ , so  $\tau$  cannot belong to  $C_q(\delta, \epsilon)$ .  $\square$

Given the quadratic differential  $q$ , let us denote as  $N_q(\delta, T)$  the number of cylinders in the  $q$ -metric which have area bounded below by  $\delta$  and length smaller than  $T$ . As Eskin and Masur showed,  $N_q(\delta, T)$  grows quadratically as a function of  $T$ :

**Theorem 3.2.** *There exists  $0 < \delta < 1$  and a constant  $c_\delta > 0$  such that, for almost every quadratic differential  $q$  of unit area, we have*

$$\lim_{T \rightarrow \infty} \frac{N_q(\delta, T)}{T^2} = c_\delta.$$

*Proof.* Let  $0 < \delta < 1$ . By the general counting argument of Eskin–Masur [7, Theorem 2.1] applied to the set of metric cylinders with area bounded below by  $\delta$ , we get the existence of the limit  $c_\delta$  almost everywhere. On the other hand, by [26, Proposition 2.5], for every quadratic differential there exists some  $\delta > 0$  such that  $\liminf_{T \rightarrow \infty} \frac{N_q(\delta, T)}{T^2} > 0$ , so the constant  $c_\delta$  must be positive for some  $\delta$ .  $\square$

A finer statement, at least in the case of translation surfaces, is due to Vorobets [34].

**3.2. Asymptotic length of short curves.** Let us now quantify the idea of keeping track of short curves in the flat metric. For the rest of the paper, we will fix some  $\delta > 0$  for which Theorem 3.2 holds, and some  $\epsilon < \delta$ . Let us define the function  $L : \mathcal{QM} \rightarrow \mathbb{R}$  as

$$L(q) := \sum_{\alpha \in C_q(\delta, \epsilon)} \frac{1}{\ell_q^2(\alpha)}.$$

Note that by Lemma 3.1 the number of terms in the sum is always finite, so the function is well-defined. Let us fix denote by  $q_t$  the image of the quadratic differential  $q$  under the Teichmüller geodesic flow after time  $t$ . Our goal is to prove that the ergodic average of  $L$  is infinite:

**Theorem 3.3.** *For  $\mu_{\text{hol}}$ -a.e. quadratic differential  $q$  of unit area, we have*

$$\lim_{T \rightarrow \infty} \frac{\int_0^T L(q_t) dt}{T} = \infty.$$

In the proof of Theorem 3.3, we will make use of the following relations between metric cylinders and the geometry of Teichmüller discs. Let us fix a base point  $q_0$  in the space of quadratic differentials, and call  $D_{q_0}$  the Teichmüller disc given by the  $SL_2(\mathbb{R})$ -orbit of  $q_0$ . For every metric cylinder  $\alpha$  on  $q_0$ , there is an angle  $\theta_\alpha$  such that  $\alpha$  is vertical in the quadratic differential  $e^{i\theta_\alpha} q_0$ . The angle  $\theta_\alpha$  determines a point in the circle at infinity of  $D_{q_0}$ . For each metric cylinder on  $q_0$  with core curve  $\alpha$ , let us define the set

$$H_\epsilon(\alpha) := \{q \in D_{q_0} : \ell_q^2(\alpha) \leq \epsilon\},$$

of points in the Teichmüller disc for which the length of  $\alpha$  is less than the square root of  $\epsilon$ . Recall the metric induced on  $D_{q_0}$  by the Teichmüller metric is the hyperbolic metric of constant curvature  $-4$ , and  $H_\epsilon(\alpha)$  is a horoball for that metric.

**Lemma 3.4.** *The Euclidean diameter  $s$  of the horoball  $H_\epsilon(\alpha)$  is*

$$s = \frac{2\epsilon}{\epsilon + \ell_{q_0}^2(\alpha)}$$

where  $\ell_{q_0}(\alpha)$  is the length of  $\alpha$  in the flat metric associated to the quadratic differential  $q_0$ .

*Proof.* By integrating the hyperbolic metric of curvature  $-4$  we have

$$d(q_0, H_\epsilon(\alpha)) = \int_0^{1-s} \frac{dx}{1-x^2} = \frac{1}{2} \log \frac{2-s}{s}$$

and, since the Teichmüller map exponentially shrinks the curve  $\alpha$ ,

$$e^{-2d(q_0, H_\epsilon(\alpha))} \ell_{q_0}^2(\alpha) = \epsilon$$

hence the claim. □

We will need the following estimate from elementary Euclidean geometry:

**Lemma 3.5.** *In the unit disc, let  $\theta(r, R)$  be the angle at the center of the disc corresponding to the intersection of the circle of radius  $R \geq \frac{1}{2}$  centered at the origin, with a circle of radius  $r \leq \frac{1}{2}$  tangent to the boundary, with  $R + 2r - 1 \geq 0$ . Then there is a constant  $K$  such that*

$$\frac{1}{K} \sqrt{(1-R)(R+2r-1)} \leq \theta(r, R) \leq K \sqrt{(1-R)(R+2r-1)}.$$

*Proof.* By the law of cosines,  $r^2 = (1-r)^2 + R^2 - 2R(1-r) \cos(\theta/2)$ . The claim follows by standard algebraic manipulation and approximation.  $\square$

In the following lemma, we let  $q_{t,\theta}$  be the quadratic differential given by flowing the quadratic differential  $e^{i\theta} q_0$  for time  $t$ .

**Lemma 3.6.** *For almost every quadratic differential  $q_0$  there exists a constant  $c > 0$ , such that for each  $\epsilon > 0$  there exists a time  $t_\epsilon$  such that*

$$\sum_{\alpha \in C_{q_0}(\delta)} \text{Leb}(\{\theta \in [0, 2\pi] : q_{t,\theta} \in H_\epsilon(\alpha)\}) \geq c\epsilon \quad \forall t \geq t_\epsilon,$$

where  $\text{Leb}$  denotes Lebesgue measure on the circle.

*Proof.* Let  $\frac{1}{2} < R < 1$ , and consider the set of horoballs of the collection  $H_\epsilon(\alpha)$  with  $\alpha \in C_{q_0}(\delta)$  and Euclidean diameter  $s \geq \frac{3}{2}(1-R)$ . By Lemma 3.4, these horoballs correspond precisely to metric cylinders with core curve  $\alpha$  such that

$$\ell_{q_0}^2(\alpha) \leq \frac{3R+1}{3(1-R)}\epsilon.$$

By Theorem 3.2, the number of such cylinders is, for  $R$  large, at least  $\frac{c\delta}{2} \frac{3R+1}{3(1-R)}\epsilon$ . By Lemma 3.5, every corresponding horoball intersects the circle of Euclidean radius  $R$  centered at the origin in an arc of visual angle

$$\theta \geq \frac{1}{K\sqrt{2}}(1-R)$$

and by Lemma 3.1 every quadratic differential belongs to at most a universally bounded number  $M$  of horoballs, hence the total visual angle is at least  $\frac{c\delta}{6KM\sqrt{2}}\epsilon$ .  $\square$

In order to prove Theorem 3.3, let us first define a discrete version of  $L$ . Namely, for each  $n$  and  $\alpha$  we denote as  $H_n(\alpha)$  the horoball

$$H_n(\alpha) := \{q \in D_{q_0} : \ell_q^2(\alpha) \leq 2^{-n}\epsilon\}.$$

Now, the function  $\Psi : \mathcal{QM} \rightarrow \mathbb{R}$  is defined as

$$\Psi(q) := \sum_{\alpha \in C_q(\delta)} \sum_{n=1}^{\infty} 2^n \chi_{H_n(\alpha)}.$$

It is easy to see that  $\Psi$  is bounded above by a multiple of  $L$ :

**Lemma 3.7.** *For each quadratic differential  $q$ , we have*

$$\Psi(q) \leq 4\epsilon L(q)$$

*Proof.* Let  $\alpha \in C_q(\delta)$  be a short curve on  $q$ : then there exists a positive integer  $M$  such that

$$2^{-M}\epsilon \leq \ell_q^2(\alpha) \leq 2^{-M+1}\epsilon.$$

Now, since  $q$  lies in  $H_1(\alpha) \cup \dots \cup H_M(\alpha)$ ,

$$\sum_{n=1}^{\infty} 2^n \chi_{H_n(\alpha)} \leq 1 + 2 + \dots + 2^M \leq 2 \cdot 2^M \leq \frac{4\epsilon}{\ell_q^2(\alpha)}$$

and summing over  $\alpha$  yields the claim. □

*Proof of Theorem 3.3.* By Lemma 3.7, it is enough to prove the statement for  $\Psi$ . Let us now truncate the function  $\Psi$  by defining, for each  $N$ ,

$$\Psi_N(q) := \sum_{\alpha \in C_q(\delta)} \sum_{n=1}^N 2^n \chi_{H_n(\alpha)}.$$

Let us now fix  $N$ . By Lemma 3.1,  $\Psi_N$  is bounded on the moduli space  $\mathcal{MQ}$  of unit area quadratic differentials, hence  $\mu_{\text{hol}}$ -integrable; by ergodicity of the geodesic flow, for a generic Teichmüller disc for almost all radial directions  $\theta$  the ergodic average of  $\Psi_N$  along the flow tends to its integral:

$$\lim_{T \rightarrow \infty} \int_0^T \frac{\Psi_N(q_t, \theta) dt}{T} = \int_{\mathcal{MQ}} \Psi_N(q) d\mu_{\text{hol}} \quad \text{for a.e. } \theta.$$

Then, if we integrate both sides w.r.t. to the angular measure  $d\theta$  and apply the dominated convergence theorem,

$$\lim_{T \rightarrow \infty} \int_{S^1} d\theta \int_0^T \frac{\Psi_N(q_t, \theta) dt}{T} = \int_{\mathcal{MQ}} \Psi_N(q) d\mu_{\text{hol}}$$

and by Fubini

$$\lim_{T \rightarrow \infty} \frac{\int_0^T dt \int_{S^1} \Psi_N(q_t, \theta) d\theta}{T} = \int_{\mathcal{MQ}} \Psi_N(q) d\mu_{\text{hol}}.$$

Now, by Lemma 3.6, for each  $t > T_{2^{-N}}$

$$\int_{S^1} \Psi_N(q_{t,\theta}) d\theta \geq \sum_{n=1}^N 2^n \cdot c2^{-n} = cN$$

hence

$$\int_{\mathcal{MQ}} \Psi_N(q) d\mu_{\text{hol}} = \lim_{T \rightarrow \infty} \frac{\int_0^T dt \int_{S^1} \Psi_N(q_{t,\theta}) d\theta}{T} \geq cN.$$

Since the previous estimate works for all  $N$ , then also

$$\int_{\mathcal{MQ}} L(q) d\mu_{\text{hol}} = \infty$$

hence the ergodic average tends to infinity almost everywhere:

$$\lim_{T \rightarrow \infty} \int_0^T \frac{L(q_t) dt}{T} = \int_{\mathcal{MQ}} L(q) d\mu_{\text{hol}} = \infty \quad \text{for a.e. } q \in \mathcal{MQ}. \quad \square$$

**3.3. Average excursion.** Let us now turn the asymptotic estimate of the previous section into an asymptotic about excursions. If  $q$  is a quadratic differential, let us denote as  $\gamma_q$  the corresponding Teichmüller geodesic ray. We now define the concept of *total excursion* traveled by the geodesic  $\gamma_q$  inside the horoballs up to time  $T$ :

**Definition 3.8.** Given a quadratic differential  $q$ , the *total excursion*  $E(q, T)$  is the sum of all excursions in all horoballs crossed by the geodesic ray  $\gamma_q$  up to time  $T$ :

$$E(q, T) := \sum_{\gamma_q([0, T]) \cap H_\epsilon(\alpha) \neq \emptyset} E(\gamma_q, H_\epsilon(\alpha)).$$

Our goal is to prove that also the average total excursion is infinite.

**Theorem 3.9.** For  $\mu_{\text{hol}}$ -almost every quadratic differential  $q$  of unit area, we have

$$\lim_{T \rightarrow \infty} \frac{E(q, T)}{T} = \infty.$$

Theorem 3.9 follows from Theorem 3.3 and the following

**Proposition 3.10.** Let  $q$  be a quadratic differential with geodesic ray  $\gamma_q$ , and let  $T > 0$  be such that both  $q$  and  $\gamma_q(T)$  lie outside all horoballs of the type  $H_\epsilon(\alpha)$ . Then

$$\int_0^T L(q_t) dt \leq \frac{C}{\epsilon} E(q, T)$$

for some universal constant  $C$ .

*Proof.* Let  $\alpha \in C_q(\delta)$  be a curve which has become short before time  $T$ , i.e. such that  $\gamma_q([0, T]) \cap H_\epsilon(\alpha)$  is non-empty. Let  $T_1$  be the time the geodesic enters  $H_\epsilon(\alpha)$ , and  $T_2$  the time the geodesic exits. Moreover, let  $N$  be the maximum integer  $k$  such that the geodesic enters  $H_k(\alpha)$ . Note that there is a universal constant  $C_1$  such that for each  $n \geq 1$  and each  $\alpha$

$$\text{Leb}(\{t \in [0, T] : q_t \in H_{n+1}(\alpha) \setminus H_n(\alpha)\}) \leq C_1.$$

Then

$$\int_{T_1}^{T_2} \frac{1}{\ell_{q_t}^2(\alpha)} dt \leq \sum_{n=1}^N \frac{2^n}{\epsilon} \text{Leb}(\{t \in [0, T] : q_t \in H_{n+1}(\alpha) \setminus H_n(\alpha)\}) \leq \frac{C_1 \cdot 2^{N+1}}{\epsilon}.$$

In order to compare the right hand side with the excursion, let us denote by  $\tilde{\epsilon}$  the smallest value of  $\ell_{q_t}^2(\alpha)$  along the geodesic ray  $\gamma_q$ . By the definition of  $N$ , we have  $\tilde{\epsilon} \asymp 2^{-N} \epsilon$ . Now, by the definition of excursion and Lemma 2.5,

$$E(\gamma_q, H_\epsilon(\alpha)) = \frac{\phi_{\max}}{\phi_0} \asymp \frac{\sin \phi_{\max}}{\sin \phi_0} = \frac{\epsilon}{\tilde{\epsilon}} \asymp 2^N$$

(where all the approximate equalities hold up to multiplicative constants), hence the claim follows. □

**Remark.** A precise analysis of how  $E(q, T)$  grows along Leb-typical geodesics is carried out in [11]. It culminates in a strong law analogous to the one established by Diamond and Vaaler for continued fractions [5].

**3.4. The word metric.** Let us complete the proof of Theorem 1.1 and Theorem 1.3 for the Lebesgue measure by proving that the word metric is bounded below by the total excursion. Let us pick  $\epsilon_0$  smaller than the Margulis constant to define the thick part, and let us choose  $\delta$  so that Theorem 3.2 holds. Finally, we choose  $\epsilon$  so that if  $X$  belongs to the thick part  $\mathcal{T} \setminus \mathcal{T}_{\epsilon_0}$  and  $\alpha$  is the core curve of a metric cylinder of  $q$ -area larger than  $\delta$  on  $X$ , then  $\ell_q^2(\alpha) \geq \epsilon$ .

Let  $X_0$  lie in the thick part  $\mathcal{T} \setminus \mathcal{T}_{\epsilon_0}$ , and let  $\gamma$  be a Teichmüller geodesic with  $\gamma(0) = X_0$ . Recall that for each time  $t$ ,  $g_t$  is a closest point projection of  $\gamma(t)$  to the Teichmüller lattice.

**Proposition 3.11.** *If  $\gamma(T)$  lies in the thick part  $\mathcal{T} \setminus \mathcal{T}_{\epsilon_0}$ , then*

$$\|g_T\|_G \geq C_1 E(\gamma, T) - C_2$$

where the constants depend only on  $X_0$ , the choice of  $\epsilon_0$  and the choice of generating set for  $\text{Mod}(S)$ .

*Proof.* Since  $\gamma(0)$  and  $\gamma(T)$  lie in the thick part, by Lemma 2.9

$$\|g_T\|_G \asymp d_M(m_0, m_T).$$

By the Masur–Minsky quasi-distance formula (Theorem 2.2), for any  $B$  large enough

$$d_M(m_0, m_T) \asymp \sum_{Y \subseteq S} \lfloor d_Y(m_0, m_T) \rfloor_B \geq \sum_{\gamma([0, T]) \cap H_\epsilon(\alpha) \neq \emptyset} \lfloor d_\alpha(m_0, m_T) \rfloor_B$$

where on the right-hand side we only consider projections to annuli which are realised as flat cylinders of area bounded below by  $\delta$ , and whose core curve becomes short before time  $T$ . Now by Proposition 2.6, for some constants  $K_1$  and  $K_2$ ,

$$d_\alpha(m_0, m_T) \geq K_1 E(\gamma, H_\epsilon(\alpha)) - K_2$$

so if  $B \geq K_2$

$$\lfloor d_\alpha(m_0, m_T) \rfloor_B \geq \lfloor K_1 E(\gamma, H_\epsilon(\alpha)) - K_2 \rfloor_B \geq \frac{K_1}{2} \lfloor E(\gamma, H_\epsilon(\alpha)) \rfloor_{\frac{2B}{K_1}}$$

and we can choose  $\tilde{\epsilon}$  a bit smaller than  $\epsilon$  so that  $\lfloor E(\gamma, H_\epsilon(\alpha)) \rfloor_{\frac{2B}{K_1}} \geq E(\gamma, H_{\tilde{\epsilon}}(\alpha))$ , hence

$$\sum_{\gamma([0, T]) \cap H_\epsilon(\alpha) \neq \emptyset} \lfloor d_\alpha(m_0, m_T) \rfloor_B \geq \sum_{\gamma([0, T]) \cap H_{\tilde{\epsilon}}(\alpha) \neq \emptyset} E(\gamma, H_{\tilde{\epsilon}}(\alpha)) = E(q, T).$$

□

*Proofs of Theorem 1.1 and Theorem 1.3 (Lebesgue measure).* Theorem 1.1 follows directly from Theorem 3.9 and Proposition 3.11. The first part of Theorem 1.3 follows from Theorem 1.1 and the fact that the relative metric is coarsely bounded above by the Teichmüller metric. □

#### 4. Hitting measure sampling

In Section 4.1 we review some background material from the theory of random walks, and recall some previous results which show that the ratio between the word metric and the relative metric along the locations  $w_n X_0$  of a sample path of the random walk remains bounded for almost all sample paths. This means that if a location  $w_n X_0$  of the sample path is close to the geodesic, then this ratio is also bounded for points on the geodesic close to  $w_n X_0$ . However, the results of the previous section apply to all points along the geodesic which lie in the thick part of Teichmüller space, so we need to extend the bounds to these other points. In Section 4.2 we use some results of [32] to show that the distance between the locations of the sample path and the corresponding geodesic grows sublinearly, and then in Section 4.3 we use the coarse monotonicity of word length along the geodesic to show that this also bounds the ratio between word length and relative length for all points along the geodesic which lie in the thick part.

**4.1. Random walks.** Let  $\mu$  be a measure on the mapping class group  $G = \text{Mod}(S)$ . We say that  $\mu$  has *finite first moment* with respect to the word metric on  $G$  if

$$\int_G \|g\|_G d\mu(g) < \infty$$

where  $\|\cdot\|_G$  is a word metric on  $G$  with respect to a choice of finite set of generators (note that the finiteness does not depend on this choice). The *step space* is the infinite product  $G^{\mathbb{N}}$  with the product measure  $\mathbb{P} := \mu^{\mathbb{N}}$ . Let  $w_n = g_1 g_2 \dots g_n$  be the location of the random walk after  $n$  steps. The *path space* is  $G^{\mathbb{N}}$ , with the pushforward of the product measure under the map

$$(g_1, g_2, g_3, \dots) \mapsto (w_1, w_2, w_3, \dots).$$

It will also be convenient to consider *bi-infinite* sample paths. In this case the step space is the set  $G^{\mathbb{Z}}$  of bi-infinite sequences of group elements with the product measure. The location of the random walk is given by  $w_n = g_1 g_2 \dots g_n$  if  $n$  is positive, and  $w_n = g_0^{-1} g_{-1}^{-1} \dots g_{n-1}^{-1}$  if  $n$  is negative (we also set  $w_0 = 1$ ). The path space is  $G^{\mathbb{Z}}$ , as a set, but with measure coming from the pushforward of  $\mathbb{P}$  under the map

$$(\dots, g_{-1}, g_0, g_1, g_2, \dots) \mapsto (\dots, w_{-1}, w_0, w_1, w_2, \dots).$$

Let us fix a base point  $X_0 \in \mathcal{T}$ , and consider the image of the sample paths  $w_n X_0$  in  $\mathcal{T}$ . Kaimanovich and Masur showed that almost every sample path converges to a uniquely ergodic foliation in the space  $\mathcal{PMF}$  of projective measured foliations, Thurston's boundary for Teichmüller space. Recall that the *harmonic measure*  $\nu$  on  $\mathcal{PMF}$  is defined as the hitting measure of the random walk, i.e. for any measurable subset  $A \subseteq \mathcal{PMF}$ ,

$$\nu(A) := \mathbb{P}(w_n : \lim_{n \rightarrow \infty} w_n X_0 \in A).$$

**Theorem 4.1** (Kaimanovich and Masur [18]). *Let  $\mu$  be a probability distribution on the mapping class group whose support generates a non-elementary subgroup. Then almost every sample path  $(w_n)_{n \in \mathbb{N}}$  converges to a uniquely ergodic foliation in  $\mathcal{PMF}$ , and the resulting hitting measure  $\nu$  is the unique non-atomic  $\mu$ -stationary measure on  $\mathcal{PMF}$ .*

Since the mapping class group is non-amenable, the random walk makes linear progress in the word metric  $\|\cdot\|_G$ , or indeed in any metric quasi-isometric to the word metric.

**Theorem 4.2** (Kesten [19], Day [3]). *Let  $\mu$  be a probability distribution on a group, whose support generates a non-amenable subgroup. Then there exists a constant  $c_1 > 0$  such that for almost all sample paths*

$$\lim_{n \rightarrow \infty} \frac{\|w_n\|_G}{n} = c_1. \tag{14}$$

Even though the relative metric is smaller than the word metric, more recent results prove that the growth rate is still linear in the number of steps.

**Theorem 4.3** (Maher [21], Maher–Tiozzo [22]). *Let  $\mu$  be a probability distribution on the mapping class group which has finite first moment in the word metric, and such that the semigroup generated by its support is a non-elementary subgroup. Then there is a constant  $c_2 > 0$  such that for almost all sample paths*

$$\lim_{n \rightarrow \infty} \frac{\|w_n\|_{\text{rel}}}{n} = c_2.$$

Note that in [21], the result is proven under the additional condition that the support of  $\mu$  is bounded in the relative metric, while such condition is not needed in [22].

From these results it follows that the quotient between the word metric and the relative metric converges to  $c_1/c_2$  for almost every sample path, i.e.

$$\lim_{n \rightarrow \infty} \frac{\|w_n\|_G}{\|w_n\|_{\text{rel}}} = \frac{c_1}{c_2}$$

for almost all sample paths. The limit above is a limit taken along the locations  $(w_n)_{n \in \mathbb{N}}$  of the random walk. In order to compare this to the previous statistic we need to relate locations of the random walk to points on a Teichmüller geodesic.

By the work of Kaimanovich and Masur [18], for almost every bi-infinite sample path  $w \in G^{\mathbb{Z}}$ , there are well-defined maps

$$F^{\pm} : G^{\mathbb{Z}} \rightarrow \mathcal{PMF}$$

given by

$$F^+(w) := \lim_{n \rightarrow \infty} w_n X_0$$

and

$$F^-(w) := \lim_{n \rightarrow \infty} w_{-n} X_0.$$

Furthermore, the two foliations  $F^+(w)$  and  $F^-(w)$  are almost surely uniquely ergodic and distinct, so there is a unique oriented Teichmüller geodesic  $\gamma_w$  whose forward limit point in  $\mathcal{PMF}$  is  $F^+(w)$  and whose backward limit point is  $F^-(w)$ . There is also a unique geodesic ray  $\rho_w$  starting at the basepoint  $X_0$  whose forward limit point is  $F^+$ . We shall always parameterize  $\rho_w$  as unit speed geodesic with  $\rho_w(0) = X_0$ . As  $F^+$  is uniquely ergodic, the distance between  $\gamma_w$  and  $\rho_w$  tends to zero, by Masur [24], and we shall parameterize  $\gamma_w$  such that  $d_{\mathcal{T}}(\rho_w(t), \gamma_w(t)) \rightarrow 0$ .

For each bi-infinite sample path we can define the function

$$D : G^{\mathbb{Z}} \rightarrow \mathbb{R}$$

given by

$$D(w) := d_{\mathcal{T}}(X_0, \gamma_w)$$

which represents the Teichmüller distance between the base point  $X_0$  and the geodesic  $\gamma_w$ . This is well-defined and measurable, by Lemma 1.4.4 of [18]. In particular, this implies that for any  $\epsilon > 0$  there is a constant  $M$  such that the probability that  $D(w) \leq M$  is at least  $1 - \epsilon$ .

The shift map  $\sigma$  maps the step space to itself by incrementing the index of each step by one, i.e.

$$\sigma: (g_n)_{n \in \mathbb{Z}} \mapsto (g_{n+1})_{n \in \mathbb{Z}}.$$

This is a measure preserving ergodic transformation on the step space, and the induced action of  $\sigma$  on the path space is given by

$$\sigma: (w_n)_{n \in \mathbb{Z}} \mapsto (w_1^{-1} w_{n+1})_{n \in \mathbb{Z}}.$$

**4.2. Distance between geodesic and sample path.** The geodesic  $\gamma_w$  is determined by its endpoints  $F^+(w)$  and  $F^-(w)$ , and the distribution of these pairs is given by harmonic measure  $\nu$  and reflected harmonic measure  $\check{\nu}$  respectively.

The distance from a location  $w_n$  to the corresponding geodesic  $\gamma_w$  is given by

$$d_{\mathcal{T}}(w_n X_0, \gamma_w) = d_{\mathcal{T}}(X_0, w_n^{-1} \gamma_w)$$

since the mapping class group acts on  $\mathcal{T}$  by isometries, and by the definition of the shift map,

$$d_{\mathcal{T}}(w_n X_0, \gamma_w) = d_{\mathcal{T}}(X_0, \gamma_{\sigma^n w}).$$

As already noted in [18], if  $\epsilon$  is sufficiently small, almost every geodesic with respect to harmonic measure returns to the  $\epsilon$ -thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$  infinitely often.

Our goal is to show that every step of the random walk lies within sublinear distance in the word metric from some point in the thick part of the limit geodesic.

In [32], sublinear tracking is proven in the Teichmüller metric: we will adapt the argument to the word metric. The fundamental argument for sublinear tracking in [32] is the following lemma.

**Lemma 4.4** (Tiozzo [32]). *Let  $T : \Omega \rightarrow \Omega$  a measure-preserving, ergodic transformation of the probability measure space  $(\Omega, \lambda)$ , and let  $f : \Omega \rightarrow \mathbb{R}^{\geq 0}$  any measurable, non-negative function. If the function*

$$g(\omega) := f(T\omega) - f(\omega)$$

*belongs to  $L^1(\Omega, \lambda)$ , then for  $\lambda$ -almost every  $\omega \in \Omega$  one has*

$$\lim_{n \rightarrow \infty} \frac{f(T^n \omega)}{n} = 0.$$

We now explain how to apply the lemma above in the current setting. Given a point  $X \in \mathcal{T}$ , let us denote as  $\text{proj}(X)$  the set of lattice points at minimal distance from  $X$ :

$$\text{proj}(X) := \{h \in G : d_{\mathcal{T}}(hX_0, X) \text{ is minimal}\}.$$

Such a projection may possibly vary wildly if  $X$  lies in the thin part, but it is controlled in the thick part: namely, given  $\epsilon > 0$  there is a constant  $K(\epsilon)$  such that

$$d_{\mathcal{T}}(X, hX_0) \leq K(\epsilon), \quad \forall X \notin \mathcal{T}_\epsilon \quad \forall h \in \text{proj}(X).$$

We now associate to almost every sample path  $w$  a subset  $P(w)$  of the mapping class group, which we now describe. Almost every bi-infinite sample path  $w \in G^{\mathbb{Z}}$  determines two uniquely ergodic foliations,  $F^\pm(w)$ . Let  $\gamma_w$  be the bi-infinite Teichmüller geodesic joining them. Now, let us define  $P(w)$  as the set of mapping class group elements  $h \in G$  such that  $hX_0$  is the closest projection from some point  $X$  in  $\gamma_w \setminus \mathcal{T}_\epsilon$ , i.e.

$$P(w) := \bigcup_{X \in \gamma_w \setminus \mathcal{T}_\epsilon} \text{proj}(X).$$

This is illustrated in Figure 4.

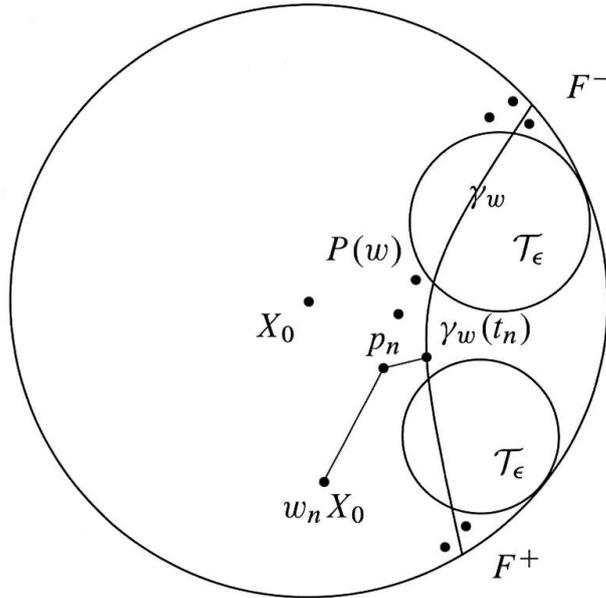


Figure 4. Sample path locations and basepoint orbits close to the geodesic.

The key result is the following:

**Proposition 4.5.** *Fix  $\epsilon > 0$ , sufficiently small. Then for almost every sample path  $(w_n)_{n \in \mathbb{N}}$ , with corresponding Teichmüller ray  $\rho_w$ , there exists a sequence of times  $t_n \rightarrow \infty$  with  $\rho_w(t_n) \in \rho_w \setminus \mathcal{T}_\epsilon$ , such that*

$$\lim_{n \rightarrow \infty} \frac{d_G(w_n, h_n)}{n} = 0$$

for any  $h_n \in \text{proj}(\rho_w(t_n))$ .

*Proof.* Let us fix  $\epsilon > 0$  sufficiently small. Recall that  $P(w)$  is the collection of group elements corresponding to closest lattice points to points on the geodesic  $\gamma_w$  which lie in the thick part of Teichmüller space. Note that, since the mapping class group acts by isometries with respect to both the Teichmüller and word metrics, then  $P$  is equivariant, in the sense that

$$P(\sigma^n w) = w_n^{-1} P(w).$$

Let us now define the function  $\varphi : G^{\mathbb{Z}} \rightarrow \mathbb{R}$  on the space of bi-infinite sample paths as

$$\varphi(w) := d_G(1, P(w))$$

i.e. the minimal word-metric distance between the base point  $X_0$  and the set of closest projections from the thick part of the geodesic  $\gamma_w$ . The shift map  $\sigma : G^{\mathbb{Z}} \rightarrow G^{\mathbb{Z}}$  acts on the space of sequences, ergodically with respect to the product measure  $\mu^{\mathbb{Z}}$ . By the equivariance of  $P$ , we have for each  $n$  the equality

$$\varphi(\sigma^n w) = d_G(w_n, P(w)). \tag{15}$$

We shall now apply Lemma 4.4, setting  $(\Omega, \lambda) = (G^{\mathbb{Z}}, \mu^{\mathbb{Z}})$ ,  $T = \sigma$ , and  $f = \varphi$ . The only condition to be checked is the  $L^1$ -condition on the function  $g(w) = f(Tw) - f(w)$ , which in this case becomes

$$g(w) = \varphi(\sigma w) - \varphi(w) = d_G(1, P(\sigma w)) - d_G(1, P(w)).$$

Now, using (15) we have

$$|d_G(1, P(\sigma w)) - d_G(1, P(w))| = |d_G(w_1, P(w)) - d_G(1, P(w))| \leq d_G(1, w_1)$$

which has finite integral precisely by the finite first moment assumption. Thus, it follows from Lemma 4.4 that for almost all bi-infinite paths  $w$  one gets

$$\lim_{n \rightarrow \infty} \frac{d_G(w_n, P(w))}{n} = 0.$$

By definition of  $P(w)$ , there exists a sequence of times  $t_n$ , such that  $\gamma_w(t_n)$  lies in  $\gamma_w \setminus \mathcal{T}_\epsilon$ , the  $\epsilon$ -thick part of the geodesic  $\gamma_w$ , and group elements  $p_n \in G$  such that  $p_n \in \text{proj}(\gamma_w(t_n))$ , and furthermore

$$\lim_{n \rightarrow \infty} \frac{d_G(w_n, p_n)}{n} = 0. \tag{16}$$

Now let  $F^+$  be the terminal foliation of the geodesic  $\gamma_w$ , and denote as  $\rho_w$  the geodesic ray through  $X_0$  with terminal foliation  $F^+$ . We have obtained a sequence of points lying in the intersection of the geodesic  $\gamma_w$  with the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$ , and we now show how to obtain a sequence of points lying in the intersection of the geodesic  $\rho_w$  with the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$ .

*Proof.* Let us fix  $\epsilon > 0$  sufficiently small. Recall that  $P(w)$  is the collection of group elements corresponding to closest lattice points to points on the geodesic  $\gamma_w$  which lie in the thick part of Teichmüller space. Note that, since the mapping class group acts by isometries with respect to both the Teichmüller and word metrics, then  $P$  is equivariant, in the sense that

$$P(\sigma^n w) = w_n^{-1} P(w).$$

Let us now define the function  $\varphi : G^{\mathbb{Z}} \rightarrow \mathbb{R}$  on the space of bi-infinite sample paths as

$$\varphi(w) := d_G(1, P(w))$$

i.e. the minimal word-metric distance between the base point  $X_0$  and the set of closest projections from the thick part of the geodesic  $\gamma_w$ . The shift map  $\sigma : G^{\mathbb{Z}} \rightarrow G^{\mathbb{Z}}$  acts on the space of sequences, ergodically with respect to the product measure  $\mu^{\mathbb{Z}}$ . By the equivariance of  $P$ , we have for each  $n$  the equality

$$\varphi(\sigma^n w) = d_G(w_n, P(w)). \quad (15)$$

We shall now apply Lemma 4.4, setting  $(\Omega, \lambda) = (G^{\mathbb{Z}}, \mu^{\mathbb{Z}})$ ,  $T = \sigma$ , and  $f = \varphi$ . The only condition to be checked is the  $L^1$ -condition on the function  $g(w) = f(Tw) - f(w)$ , which in this case becomes

$$g(w) = \varphi(\sigma w) - \varphi(w) = d_G(1, P(\sigma w)) - d_G(1, P(w)).$$

Now, using (15) we have

$$|d_G(1, P(\sigma w)) - d_G(1, P(w))| = |d_G(w_1, P(w)) - d_G(1, P(w))| \leq d_G(1, w_1)$$

which has finite integral precisely by the finite first moment assumption. Thus, it follows from Lemma 4.4 that for almost all bi-infinite paths  $w$  one gets

$$\lim_{n \rightarrow \infty} \frac{d_G(w_n, P(w))}{n} = 0.$$

By definition of  $P(w)$ , there exists a sequence of times  $t_n$ , such that  $\gamma_w(t_n)$  lies in  $\gamma_w \setminus \mathcal{T}_\epsilon$ , the  $\epsilon$ -thick part of the geodesic  $\gamma_w$ , and group elements  $p_n \in G$  such that  $p_n \in \text{proj}(\gamma_w(t_n))$ , and furthermore

$$\lim_{n \rightarrow \infty} \frac{d_G(w_n, p_n)}{n} = 0. \quad (16)$$

Now let  $F^+$  be the terminal foliation of the geodesic  $\gamma_w$ , and denote as  $\rho_w$  the geodesic ray through  $X_0$  with terminal foliation  $F^+$ . We have obtained a sequence of points lying in the intersection of the geodesic  $\gamma_w$  with the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$ , and we now show how to obtain a sequence of points lying in the intersection of the geodesic  $\rho_w$  with the thick part  $\mathcal{T} \setminus \mathcal{T}_\epsilon$ .

*Proof of Theorem 1.2 and Theorem 1.3 (harmonic measure).* Given a sample path  $w$ , let  $\rho_w$  be the geodesic ray joining the base point  $X_0$  to the limit foliation  $F^+(w)$ , and let  $t_n$  be the sequence of times given by Proposition 4.5. Let now  $T > 0$  be a time for which the geodesic  $\rho_w(T)$  lies in the thick part, and let  $g_T X_0$  be a projection of  $\rho_w(T)$  to the Teichmüller lattice. Since  $t_n \rightarrow \infty$ , there exists an index  $n = n(T)$  such that  $t_n \leq T \leq t_{n+1}$ . By Proposition 2.10, there exist constants  $C_1 > 0, C_2$  such that

$$d_G(h_n, g_T) \leq C_1 d_G(h_n, h_{n+1}) + C_2.$$

Moreover, by Proposition 4.5 and triangle inequality,

$$\lim_{n \rightarrow \infty} \frac{d_G(h_n, h_{n+1})}{n} \leq \lim_{n \rightarrow \infty} \frac{d_G(h_n, w_n) + d_G(w_n, w_{n+1}) + d_G(w_{n+1}, h_{n+1})}{n} = 0$$

(where we used the finite first moment condition to ensure  $d_G(w_n, w_{n+1})/n \rightarrow 0$ ). Thus, we also have

$$\lim_{n \rightarrow \infty} \frac{d_G(h_n, g_T)}{n} = 0$$

and again by Proposition 4.5

$$\lim_{n \rightarrow \infty} \frac{d_G(w_n, g_T)}{n} \leq \lim_{n \rightarrow \infty} \frac{d_G(w_n, h_n) + d_G(h_n, g_T)}{n} = 0.$$

Similarly, since the relative metric is bounded above by the word metric,

$$\lim_{n \rightarrow \infty} \frac{d_{\text{rel}}(w_n, g_T)}{n} = 0.$$

Finally, by computing the ratio between the word and relative metric,

$$\lim_{\substack{T \rightarrow \infty \\ \rho_w(T) \notin \mathcal{T}_\epsilon}} \frac{\|g_T\|_G}{\|g_T\|_{\text{rel}}} = \lim_{T \rightarrow \infty} \frac{\frac{d_G(1, g_T)}{n(T)}}{\frac{d_{\text{rel}}(1, g_T)}{n(T)}} = \lim_{n \rightarrow \infty} \frac{\frac{d_G(1, w_n)}{n}}{\frac{d_{\text{rel}}(1, w_n)}{n}} = \frac{c_1}{c_2} > 0.$$

This completes the proof of Theorem 1.3. The proof of Theorem 1.2 is exactly the same, replacing  $d_{\text{rel}}$  with  $d_{\mathcal{T}}$  and noting that, since the Teichmüller metric is a coarse upper bound for the relative metric, Theorem 4.3 implies also positive drift in the Teichmüller metric.  $\square$

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