

DETERMINING HYPERBOLIC 3-MANIFOLDS BY THEIR SURFACES

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ABSTRACT. In this article, we prove that the commensurability class of a closed, orientable, hyperbolic 3–manifold is determined by the surface subgroups of its fundamental group. Moreover, we prove that there can be only finitely many closed, orientable, hyperbolic 3–manifolds that have the same set of surfaces.

1. INTRODUCTION

The geodesic length spectrum of a Riemannian manifold M is a basic invariant that has been well-studied due to its connection with the geometric and analytic structure of M . When M has negative sectional curvatures, there is a strong relationship between this spectrum and the eigenvalue spectrum of the Laplace–Beltrami operator (see [10], [11]), and the latter is well known to determine basic geometric/topological invariants like the dimension, volume, and total scalar curvature of M .

In this article, we focus on variations of the surface analog of the geodesic length spectrum for closed, orientable, hyperbolic 3–manifolds introduced by the authors in [24] (see also [17], [25]). We take this theme further and study *the full surface spectrum (or set)* of such manifolds (see §2 for definitions) which loosely takes into account all of the π_1 –injective surface subgroups of the fundamental group of M . Our main result can be informally stated as follows (see Theorem 3.1 for the precise statement). Recall that two Riemannian manifolds M_1, M_2 are *commensurable* if there exist a Riemannian manifold M and finite Riemannian covers $M \rightarrow M_1, M_2$.

Theorem 1.1. *For any closed, orientable, hyperbolic 3–manifold M , there are at most finitely many non-isometric closed, orientable, hyperbolic 3–manifolds with the same surface set as M . Furthermore, all such manifolds are commensurable.*

By way of comparison, for the eigenvalue or geodesic length spectra, many commensurability and finiteness results have been established. The second author [28] proved that isospectral (i.e., the same eigenvalue spectra) or length isospectral

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(i.e., the same geodesic length spectra) arithmetic hyperbolic 2–manifolds are commensurable (see [19] for a thorough treatment of arithmetic hyperbolic 2– and 3–manifolds). Chinburg–Hamilton–Long–Reid [9, Thm 1.1] proved an identical result for arithmetic hyperbolic 3–manifolds. Prasad–Rapinchuk [27, Thm 8.12] determined when these commensurability rigidity results hold for general, arithmetic, locally symmetric orbifolds, proving that in many settings the commensurability class of the manifold is determined by the eigenvalue or geodesic length spectra. It was already known that the commensurability class is not always determined by these spectra as Lubotzky–Samuels–Vishne [18, Thm 1] produced higher rank, arithmetic, locally symmetric incommensurable isospectral examples prior to [27]. In [24, Thm 1.1], the authors proved a result similar to Theorem 1.1. Namely, if M_1, M_2 are arithmetic hyperbolic 3–manifolds that contain a totally geodesic surface, and have the same set of totally geodesic surfaces, then they are commensurable. Meyer [25, Thm C] established a higher dimensional analog for certain classes of arithmetic hyperbolic n –manifolds. It is worth emphasizing that our present work differs from all the above works in one important and fundamental way. Namely, we do not impose an arithmetic assumption.

In an effort to see whether or not [28] holds in the non-arithmetic setting, Millichap [26] constructed $(2n)!$ incommensurable, non-arithmetic hyperbolic 3–manifolds with the same first $2n + 1$ (complex) geodesic lengths. The manifolds have the same volume and the volume of these manifolds is linear in n . Since the completion of this paper, Futer–Millichap [12] and Linowitz–McReynolds–Pollack–Thompson [16] have produced additional examples of non-arithmetic and arithmetic hyperbolic 2– and 3–manifolds that share the same geodesic lengths for the first n lengths or any finite subset of lengths, respectively. Both constructions give control on the volumes of the examples as well.

In [24, Thm 1.2], examples of non-isometric, closed, hyperbolic 3–manifolds with the same spectra of totally geodesic surfaces were constructed (see also [22, §5] and [23]). Those methods can be employed to also produce arbitrarily large finite sets of non-isometric closed hyperbolic 3–manifolds $\{M_j\}$ that pairwise have the same totally geodesic surface spectra (the spectra can be ensured to be infinite as well). However, it is unknown if an infinite set of such manifolds can exist. In particular, the totally geodesic surface analog of our finiteness result is unknown. Finally, for the full surface spectrum, there are no known examples of non-isometric hyperbolic 3–manifolds M_1, M_2 with the same full surface spectrum.

Question. Do there exist non-isometric hyperbolic 3–manifolds with the same full surface spectrum?

2. NOTATION AND PRELIMINARIES

Throughout, $M = \mathbf{H}^3/\Gamma$ will be a closed, orientable, hyperbolic 3–manifold and Σ_g will denote the closed orientable surface of genus g . It was proved by Thurston [32, Cor 8.8.6] that the number of Γ –conjugacy classes of subgroups of Γ isomorphic to $\pi_1(\Sigma_g)$ is finite. A breakthrough was provided by Kahn–Markovic [14, Thm 1.1] who proved that this number is non-zero for certain values of g . Building on previous work of Masters [21, Thm 1.2], Kahn–Markovic [15, Thm 1.1] also provide estimates for these numbers.

For each discrete, faithful representation $\rho: \pi_1(\Sigma_g) \rightarrow \mathrm{PSL}(2, \mathbf{C})$, we refer to the image Δ_ρ as a *Kleinian surface group*. For each Δ_ρ , let $\ell_\rho(M)$ denote the number

of Γ -conjugacy classes of subgroups $\Delta < \Gamma$ that are $\mathrm{PSL}(2, \mathbf{C})$ -conjugate to Δ_ρ . Typically the value of $\ell_\rho(M)$ will be zero (e.g., for those Δ_ρ that contain an element with transcendental trace). We define the *full surface spectrum* of M to be the set

$$\mathcal{S}(M) = \{(\Delta_\rho, \ell_\rho(M)) : \ell_\rho(M) \neq 0\}.$$

We define the *surface set* of M to be the set $\mathrm{S}(M) = \{\Delta_\rho : \ell_\rho(M) \neq 0\}$. The case when Δ_ρ is Fuchsian was studied in [24], and we denote the associated spectrum here by $\mathrm{S}_{\mathrm{Fuc}}(M)$ and call this the *genus spectrum*. In this note, particular emphasis will be placed upon those Kleinian surface groups Δ_ρ corresponding to virtual fiber subgroups of Γ . These subgroups arise as fibers of mapping tori of finite covers of M . That is, if $\pi_1(S) = \Delta_\rho$, then there is a finite cover $M' \rightarrow M$ and a diffeomorphism $\psi: S \rightarrow S$ such that M' is the mapping torus of S with respect to ψ where Δ_ρ is the kernel of the associated homomorphism $\pi_1(M') \rightarrow \mathbf{Z}$. It is a well-known consequence of the solution to the Tameness Conjecture (by Agol [1] and Calegari–Gabai [6]) and Canary’s Covering Theorem [8] that these virtual fiber subgroups of Γ are precisely those $\Delta_\rho < \Gamma$ that are finitely generated and geometrically infinite (see also the earlier work of Bonahon [4] and Thurston [32]). Since being geometrically infinite depends only on ρ , these surface subgroups provide an important subclass of surface subgroups that can be used to control the topology of 3–manifolds. For future reference, we denote the associated spectrum for this class of surface subgroups by

$$\mathrm{S}_{vf}(M) = \{\Delta_\rho \in \mathrm{S}(M) : \Delta_\rho \text{ is a virtual fiber subgroup}\}.$$

Essential in our work is the groundbreaking work of Agol [2] and the aforementioned work of Kahn–Markovic [14]. We summarize from their collective work what is needed for us in the following theorem.

Theorem 2.1. *Let $M = \mathbf{H}^3/\Gamma$ be a closed, orientable, hyperbolic 3–manifold. Then*

- (a) $\mathrm{S}(M) \neq \emptyset$.
- (b) $\mathrm{S}_{vf}(M) \neq \emptyset$.
- (c) $\mathrm{S}_{vf}(M)$ contains infinitely many elements F_ρ that are not commensurable and in particular have arbitrarily large genus.

Proof. Given the preamble to the statement of the theorem, only (c) requires comment. By [2] there is a finite sheeted cover $M_0 \rightarrow M$ such that $b_1(M_0) \geq 2$ and M_0 is fibered. In particular, by [33], M_0 is fibered in infinitely many different ways. Indeed, it follows from [33] that we can find fibered surfaces of arbitrarily large genus occurring as integral lattice points in the (open) cone over a top dimensional face of the Thurston norm ball. Moreover, by [7, Corollary 3.7] we can assume that infinitely many of these provide incommensurable virtual fibers. \square

3. PROOF OF THEOREM 1.1

We now state the precise version of Theorem 1.1 that we will prove in this section.

Theorem 3.1. *If M is a closed, orientable, hyperbolic 3–manifold, then the set*

$$\mathcal{S}_M = \{N : \mathcal{S}(M) = \mathcal{S}(N)\}$$

is finite. Moreover, if $N \in \mathcal{S}_M$, then M, N are commensurable.

As noted above, since being a virtual fiber depends only on Δ_ρ and not on the ambient manifolds, if $\mathcal{S}(M) = \mathcal{S}(N)$, then $\mathcal{S}_{vf}(M) = \mathcal{S}_{vf}(N)$. In particular, to prove Theorem 3.1, it suffices to prove the following result.

Theorem 3.2. *If M is a closed, orientable, hyperbolic 3–manifold, then the set*

$$\mathcal{S}_{M,vf} = \{N : \mathcal{S}_{vf}(M) = \mathcal{S}_{vf}(N)\}$$

is finite. Moreover, if $N \in \mathcal{S}_{M,vf}$, then M, N are commensurable.

Proof of Theorem 3.2: We first prove that if $\mathcal{S}_{vf}(M) = \mathcal{S}_{vf}(N)$, then M, N are commensurable. To that end, let $\Delta = \Delta_\rho$ denote a common virtual fiber subgroup and set g to be the genus of Δ . Since Δ is a virtual fiber, we can find pseudo-Anosov maps $\phi, \psi : \Sigma_g \rightarrow \Sigma_g$ so that $M_\phi \rightarrow M$, $M_\psi \rightarrow N$ are finite sheeted covers and $\pi_1(M_\phi), \pi_1(M_\psi)$ have a common fiber group Δ . Associated to the fiber group Δ is a unique pair of ending laminations ν^\pm in the projective measured lamination space of Σ_g which are left invariant by ϕ, ψ (see [4]). As a result, there exist integers r, s such that the mapping classes ϕ, ψ satisfy $\phi^r = \psi^s$. Consequently, the bundles M_{ϕ^r} and M_{ψ^s} are isometric. In particular, we have

$$\begin{array}{ccc} & M_{\phi^r} \cong M_{\psi^s} & \\ & \swarrow \text{finite} \quad \searrow \text{finite} & \\ M_\phi & & M_\psi \\ \downarrow \text{finite} & & \downarrow \text{finite} \\ M & & N \end{array}$$

and thus conclude that M, N are commensurable. \square

It remains to establish the finiteness of $\mathcal{S}_{M,vf}$. We will argue by contradiction, and to that end, we assume that there are infinitely many non-isometric $M_i = \mathbf{H}^3/\Gamma_i$, $i = 1, 2, \dots$ with $\mathcal{S}_{vf}(M) = \mathcal{S}_{vf}(M_i)$ for all i . We will prove that there is $i \geq i_0$ such that the groups Γ_i have uniformly bounded rank. We will then show that for an even larger i_1 , the groups Γ_i for $i \geq i_1$ must have rank larger than this uniform bound. Towards that goal, we first assert that the volumes of the manifolds M_i must be unbounded. Specifically, we have the following general lemma.

Lemma 3.3. *The set of volumes for any infinite set $\{M_i\}$ of commensurable, finite volume, hyperbolic 3–manifolds is unbounded.*

Proof. We split into two cases depending on whether the manifolds are arithmetic or not. Note that since arithmeticity is a commensurability invariant, either all of the M_i are arithmetic or all of the M_i are non-arithmetic. If the M_i are arithmetic, the assertion follows from work of Borel [5] since there are only finitely many arithmetic hyperbolic 3–manifolds of bounded volume. If the M_i are non-arithmetic, by work of Margulis [20], there is a unique maximal lattice in the common commensurability class that contains all of the Γ_i as finite index subgroups. In particular, all the M_i

cover the fixed closed hyperbolic 3-orbifold Q associated to this unique maximal lattice. Since Q has only finitely many degree d covers for any d , the covering degrees must go to infinity. Consequently, the volumes cannot be bounded in this case either. \square

Recall that the *injectivity radius at a point* $p \in M$ is the largest radius for which the exponential map at p is a diffeomorphism. The *injectivity radius of* M (which we denote by $\text{InjRad}(M)$) is the infimum of the injectivity radius of M at p over all $p \in M$.

We note that in our setting, as the manifolds M_i are all commensurable, there is also a uniform lower bound of the injectivity radii of the M_i . This again can be established using the arithmetic/non-arithmetic dichotomy. Briefly, in the non-arithmetic case, the injectivity radius is bounded below by the injectivity radius of the orbifold associated to the maximal lattice in the commensurability class containing the M_i . In the arithmetic setting, since the injectivity radius is one half of the systole (which is the length of the shortest, closed, and non-trivial geodesic), the systole of any orbifold in the commensurability class is uniformly bounded below by a constant that depends only on the invariant trace field (see [19, Ch 12, pp. 378–380]). For future reference, we denote the lower bound for $\text{InjRad}(M)$ by s .

Thus we can now assume that we have a sequence of manifolds M_i with injectivity radius at least s and whose volumes get arbitrarily large. We now show how to use this to bound the ranks of the groups Γ_i for i sufficiently large. Towards that goal, set Δ_0 to be a common, minimal genus, virtual fiber group in Γ_i , and set g to be this common, minimal genus. In order to control the ranks of the groups Γ_i , we will utilize a quantitative virtual fibering result of Soma [29, Thm 0.5]. To state his result, let $\text{Vol}(M)$ denote the volume of M , and set $d_1(g, s) = \frac{4s(g-1)}{\sinh^2(s/2)}$.

Theorem 3.4 (Soma). *If M is a closed, orientable, hyperbolic 3-manifold with*

$$\text{InjRad}(M) \geq s \text{ and } \text{Vol}(M) \geq 2\pi d_1(g, s) \sinh^2(d_1(g, s) + 1),$$

then any immersed virtual fiber in M of genus g is embedded.

Theorem 3.4 with the above conditions on $\text{InjRad}(M_i)$, $\text{Vol}(M)$ implies that there is $i_{g,s} \in \mathbf{N}$ such that if $i \geq i_{g,s}$, the virtual fiber group Δ_0 corresponds to an embedded incompressible surface of genus g in M_i . This incompressible surface limits the possibilities for the M_i . Specifically, M_i is either a fiber bundle over the circle with fiber group Δ_0 , or M_i is the union of two twisted I -bundles. Moreover, in the latter case, we have a double cover $N_i \rightarrow M_i$ such that N_i is a fiber bundle with fiber group Δ_0 (see [13, Ch 11]).

We now leverage the above fiber bundle structure to obtain bounds for the rank of Γ_i for i sufficiently large. The rank of Γ_i will be denoted by $\text{Rank}(\Gamma_i)$.

Lemma 3.5. *There exists $i_0 \geq i_{g,s}$ such that if $i \geq i_0$, then $g + 1 \leq \text{Rank}(\Gamma_i) \leq 2g + 2$.*

Proof. We assume throughout that $i \geq i_{g,s}$. Let \mathcal{I}_1 be the set of $i \geq i_{g,s}$ such that M_i is a fiber bundle with fiber group Δ_0 and let \mathcal{I}_2 be the set of $i \geq i_{g,s}$ such that M_i is double covered by N_i where N_i is a fiber bundle with fiber group Δ_0 . We first consider $\{M_i\}_{i \in \mathcal{I}_1}$. We know from the proof of the commensurability invariance of S_{vf} that each M_i must have the form $M_{\phi^{r_i}}$ for some pseudo-Anosov element ϕ .

Applying Souto [30, Thm 1], there exist $i' \in \mathbf{N}$ such that $\text{Rank}(\Gamma_i) = 2g + 1$ for all $i \geq i'$. Next, we consider $\{M_i\}_{i \in \mathcal{I}_2}$ and apply the above argument to N_i . We obtain $i'' \in \mathbf{N}$ such that $\text{Rank}(\pi_1(N_i)) = 2g + 1$ for all $i \geq i''$. As N_i is a double cover of M_i , we can adjoin one element to $\pi_1(N_i)$ to generate $\pi_1(M_i)$. Therefore, $\text{Rank}(\Gamma_i) \leq 2g + 2$ for all $i \geq i''$.

Now, set $i_0 = \max\{i', i''\}$ and note that $\text{Rank}(\Gamma_i) \leq 2g + 2$ for all $i \geq i_0$. For the lower bound, by the Nielsen–Schreier formula, we have $\text{Rank}(\pi_1(N_i)) \leq 2\text{Rank}(\Gamma_i) - 1$ for all $i \geq i_0$ and $i \in \mathcal{I}_2$. In particular, $g + 1 \leq \text{Rank}(\Gamma_i)$ for all $i \geq i_0$. \square

We now use Lemma 3.5 to complete the proof of Theorem 3.2. By Theorem 2.1 (c), we can find incommensurable virtual fiber subgroups of arbitrarily large genus. Choosing a virtual fiber subgroup Δ_1 of genus g_1 with $2g + 2 < g_1 + 1$ and repeating the above argument, we obtain an integer $i_1 \geq i_{g_1, s}$ such that $g_1 + 1 \leq \text{Rank}(\Gamma_i)$ for all $i \geq i_1$. For all $i \geq \max\{i_0, i_1\}$, we must have $g_1 + 1 \leq \text{Rank}(\Gamma_i) \leq 2g + 2 < g_1 + 1$, a contradiction. Hence $\mathcal{S}_{M, vf}$ is finite as required. \square

Remarks. (1) In the proof of Lemma 3.5 we could also have used [3] for both the bundle case and the union of two twisted I –bundles. However, the setting of [30] is more appropriate in this case (i.e., commensurable manifolds), and only a mild extension is needed for us to handle the union of two twisted I –bundles. Hence this is the reason for not using [3] in this case. In §4, we will need to use [3].

(2) As noted in the introduction, we do not know if there exists a pair of non-isometric, closed, orientable, hyperbolic 3–manifolds M_1, M_2 with $\mathcal{S}(M_1) = \mathcal{S}(M_2)$. Since being either a virtual fiber or Fuchsian depends only on Δ_ρ and not the ambient manifold, such a pair would also satisfy both $\mathcal{S}_{vf}(M_1) = \mathcal{S}_{vf}(M_2)$, $\mathcal{S}_{Fuc}(M_1) = \mathcal{S}_{Fuc}(M_2)$. Examples where the latter equality holds were constructed in [24] using a variation of the method of Sunada [31] for constructing isospectral and length isospectral manifolds. That method does not seem well-suited for also arranging equality between virtual fibers. As with the full spectrum, we do not presently know if there exists a pair of non-isometric, closed, hyperbolic 3–manifolds M_1, M_2 with $\mathcal{S}_{vf}(M_1) = \mathcal{S}_{vf}(M_2)$.

(3) All our results and methods of proof use the fact the hyperbolic 3–manifolds we consider are closed. It would seem like an interesting problem to generalize the results of this paper to the case of finite volume non-compact hyperbolic 3–manifolds.

4. A CONJECTURAL STRENGTHENING FOR ARITHMETIC HYPERBOLIC 3–MANIFOLDS

In this section we deal with closed, arithmetic, hyperbolic 3–manifolds, and prove a stronger result (conjecturally) that involves only topological data. We refer the reader to [19] for background on arithmetic hyperbolic 3–manifolds. Let us define the *topological virtual fiber set* of M to be the set

$$\mathcal{S}_{tvf}(M) = \{\Delta : \Delta \text{ is isomorphic to a virtual fiber subgroup}\}.$$

Our strengthening relies on the following conjecture often referred to as the *short geodesic conjecture*.

Conjecture 1 (Short Geodesic Conjecture). *Let M be a closed, orientable, arithmetic, hyperbolic 3-manifold. Then there is a constant $C > 0$ (independent of M) so that the length of the shortest closed geodesic in M is at least C .*

Assuming this conjecture, we establish the following result.

Theorem 4.1. *Assuming Conjecture 1 there are at most finitely many closed orientable arithmetic hyperbolic 3-manifolds $M_1, M_2 \dots M_n$ so that $S_{tvf}(M_i) = S_{tvf}(M_j)$ for each i, j .*

Proof. The proof of Theorem 4.1 is similar to the proof of Theorem 3.2 and is done by contradiction. If there is an infinite sequence of such manifolds M_i , by Borel [5] their volumes are unbounded and Conjecture 1 with the relationship between injectivity radius and systole implies that the injectivity radii are bounded from below. Choosing a minimal genus (topological) virtual fiber in each M_i and applying Theorem 3.4, it follows that for sufficiently large i , M_i is either a genus g fiber bundle or a union of two twisted I -bundles which is double covered by a genus g fiber bundle. We now apply Biringer's extension of [30], namely [3, Thms 1.1, 5.2]. That allows us to get control of the rank as in the proof of Lemma 3.5, and in particular, following the argument in the proof of Lemma 3.5 leads to a similar contradiction on ranks as used in the proof of Theorem 3.2. \square

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REFERENCES

- [1] I. Agol, *Tameness of hyperbolic 3-manifolds*, arXiv:math/0405568.
- [2] Ian Agol, *The virtual Haken conjecture*, Doc. Math. **18** (2013), 1045–1087. With an appendix by Agol, Daniel Groves, and Jason Manning. MR3104553
- [3] Ian Biringer, *Geometry and rank of fibered hyperbolic 3-manifolds*, Algebr. Geom. Topol. **9** (2009), no. 1, 277–292, DOI 10.2140/agt.2009.9.277. MR2482077
- [4] Francis Bonahon, *Bouts des variétés hyperboliques de dimension 3* (French), Ann. of Math. (2) **124** (1986), no. 1, 71–158, DOI 10.2307/1971388. MR847953
- [5] A. Borel, *Commensurability classes and volumes of hyperbolic 3-manifolds*, Ann. Scuola Norm. Sup. Pisa Cl. Sci. (4) **8** (1981), no. 1, 1–33. MR616899
- [6] Danny Calegari and David Gabai, *Shrinkwrapping and the taming of hyperbolic 3-manifolds*, J. Amer. Math. Soc. **19** (2006), no. 2, 385–446, DOI 10.1090/S0894-0347-05-00513-8. MR2188131
- [7] Danny Calegari, Hongbin Sun, and Shicheng Wang, *On fibered commensurability*, Pacific J. Math. **250** (2011), no. 2, 287–317, DOI 10.2140/pjm.2011.250.287. MR2794601
- [8] Richard D. Canary, *A covering theorem for hyperbolic 3-manifolds and its applications*, Topology **35** (1996), no. 3, 751–778, DOI 10.1016/0040-9383(94)00055-7. MR1396777
- [9] T. Chinburg, E. Hamilton, D. D. Long, and A. W. Reid, *Geodesics and commensurability classes of arithmetic hyperbolic 3-manifolds*, Duke Math. J. **145** (2008), no. 1, 25–44, DOI 10.1215/00127094-2008-045. MR2451288
- [10] J. J. Duistermaat and V. W. Guillemin, *The spectrum of positive elliptic operators and periodic bicaracteristics*, Invent. Math. **29** (1975), no. 1, 39–79, DOI 10.1007/BF01405172. MR0405514
- [11] Ramesh Gangolli, *The length spectra of some compact manifolds of negative curvature*, J. Differential Geom. **12** (1977), no. 3, 403–424. MR0650997
- [12] David Futer and Christian Millichap, *Spectrally similar incommensurable 3-manifolds*, Proc. Lond. Math. Soc. (3) **115** (2017), no. 2, 411–447, DOI 10.1112/plms.12045. MR3684110

- [13] John Hempel, *3-Manifolds*, Princeton University Press, Princeton, N. J.; University of Tokyo Press, Tokyo, 1976. Ann. of Math. Studies, No. 86. MR0415619
- [14] Jeremy Kahn and Vladimir Markovic, *Immersing almost geodesic surfaces in a closed hyperbolic three manifold*, Ann. of Math. (2) **175** (2012), no. 3, 1127–1190, DOI 10.4007/annals.2012.175.3.4. MR2912704
- [15] Jeremy Kahn and Vladimir Marković, *Counting essential surfaces in a closed hyperbolic three-manifold*, Geom. Topol. **16** (2012), no. 1, 601–624, DOI 10.2140/gt.2012.16.601. MR2916295
- [16] Benjamin Linowitz, D. B. McReynolds, Paul Pollack, and Lola Thompson, *Bounded gaps between primes and the length spectra of arithmetic hyperbolic 3-orbifolds* (English, with English and French summaries), C. R. Math. Acad. Sci. Paris **355** (2017), no. 11, 1121–1126, DOI 10.1016/j.crma.2017.07.002. MR3724874
- [17] Benjamin Linowitz and Jeffrey S. Meyer, *Systolic surfaces of arithmetic hyperbolic 3-manifolds*, In the tradition of Ahlfors-Bers. VII, Contemp. Math., vol. 696, Amer. Math. Soc., Providence, RI, 2017, pp. 215–223, DOI 10.1090/comm/696/14025. MR3715449
- [18] Alexander Lubotzky, Beth Samuels, and Uzi Vishne, *Division algebras and noncommensurable isospectral manifolds*, Duke Math. J. **135** (2006), no. 2, 361–379, DOI 10.1215/S0012-7094-06-13525-1. MR2267287
- [19] Colin Maclachlan and Alan W. Reid, *The arithmetic of hyperbolic 3-manifolds*, Graduate Texts in Mathematics, vol. 219, Springer-Verlag, New York, 2003. MR1937957
- [20] G. A. Margulis, *Discrete subgroups of semisimple Lie groups*, *Ergebnisse der Mathematik und ihrer Grenzgebiete (3) [Results in Mathematics and Related Areas (3)]*, vol. 17, Springer-Verlag, Berlin, 1991. MR1090825
- [21] Joseph D. Masters, *Counting immersed surfaces in hyperbolic 3-manifolds*, Algebr. Geom. Topol. **5** (2005), 835–864, DOI 10.2140/agt.2005.5.835. MR2153105
- [22] D. B. McReynolds, *Geometric spectra and commensurability*, Canad. J. Math. **67** (2015), no. 1, 184–197, DOI 10.4153/CJM-2014-003-9. MR3292699
- [23] David McReynolds, Jeffrey S. Meyer, and Matthew Stover, *Constructing geometrically equivalent hyperbolic orbifolds*, Algebr. Geom. Topol. **17** (2017), no. 2, 831–846, DOI 10.2140/agt.2017.17.831. MR3623673
- [24] D. B. McReynolds and A. W. Reid, *The genus spectrum of a hyperbolic 3-manifold*, Math. Res. Lett. **21** (2014), no. 1, 169–185, DOI 10.4310/MRL.2014.v21.n1.a14. MR3247048
- [25] Jeffrey S. Meyer, *Totally geodesic spectra of arithmetic hyperbolic spaces*, Trans. Amer. Math. Soc. **369** (2017), no. 11, 7549–7588, DOI 10.1090/tran/6970. MR3695838
- [26] Christian Millichap, *Mutations and short geodesics in hyperbolic 3-manifolds*, Comm. Anal. Geom. **25** (2017), no. 3, 625–683, DOI 10.4310/CAG.2017.v25.n3.a5. MR3702548
- [27] Gopal Prasad and Andrei S. Rapinchuk, *Weakly commensurable arithmetic groups and isospectral locally symmetric spaces*, Publ. Math. Inst. Hautes Études Sci. **109** (2009), 113–184, DOI 10.1007/s10240-009-0019-6. MR2511587
- [28] Alan W. Reid, *Isospectrality and commensurability of arithmetic hyperbolic 2- and 3-manifolds*, Duke Math. J. **65** (1992), no. 2, 215–228, DOI 10.1215/S0012-7094-92-06508-2. MR1150584
- [29] Teruhiko Soma, *Virtual fibers in hyperbolic 3-manifolds*, Topology Appl. **41** (1991), no. 3, 179–192, DOI 10.1016/0166-8641(91)90002-4. MR1135096
- [30] Juan Souto, *The rank of the fundamental group of certain hyperbolic 3-manifolds fibering over the circle*, The Zieschang Gedenkschrift, Geom. Topol. Monogr., vol. 14, Geom. Topol. Publ., Coventry, 2008, pp. 505–518, DOI 10.2140/gtm.2008.14.505. MR2484715
- [31] Toshikazu Sunada, *Riemannian coverings and isospectral manifolds*, Ann. of Math. (2) **121** (1985), no. 1, 169–186, DOI 10.2307/1971195. MR782558
- [32] W. P. Thurston, *The Geometry and Topology of 3-manifolds*, Princeton University mimeographed notes (1979).
- [33] William P. Thurston, *A norm for the homology of 3-manifolds*, Mem. Amer. Math. Soc. **59** (1986), no. 339, i–vi and 99–130. MR823443

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