THREE-MANIFOLD SUBGROUP GROWTH, HOMOLOGY OF COVERINGS AND SIMPLICIAL VOLUME

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1. Introduction

This paper deals with the conjecture, communicated to the first author by A. Lubotzky and A. Shalev:

Conjecture 1.1. *Let M be a hyperbolic three-manifold. Let $f(d)$ denote the number of subgroups of index d in $\pi_1(M)$. There exists an absolute positive constant C_1 such that, for all d sufficiently large, $f(d) > \exp(C_1 d)$.*

This conjecture follows easily from the following one:

Conjecture 1.2. *Let M be as above. For any prime p there exists infinitely many finite d-sheated coverings N of M such that*

$$rank_p\,(H_1(N)) > C_2 d, \tag{1}$$

where C_2 is an absolute positive constant.

Observe that for any finitely generated group G, and a subgroup H of index d, $\text{rank}_p\,(H_1(H)) \leq \text{const} \cdot d$, so that (1) is sharp up to a constant.

A much weaker growth rate than conjectured in (1), namely, $\text{rank}_p\,(H_1(N)) > (\log d)^{2-\epsilon}$ has been proved by Shalev [Sh]. It follows from the Class Tower Theorem of [R1] that $\text{rank}_p\,(H_1(N)) > (\log d)^2$.

These conjectures about the subgroup growth should be compared with the results of [Tu] and [SW] concerning the word growth of $\pi_1(M)$.

Here we prove the following result for a priori a much wider class of manifolds than hyperbolic manifolds (given the present status of the hyperbolization conjecture). Recall the definition of rich fundamental groups given in [R1]:

(R) A closed irreducible three-manifold satisfies condition (R) if either
(a) the Casson invariant $\lambda(M) > \sharp($ representations of $\pi_1(M)$ in $SL_2(\mathbb{F}_5))$ or
(b) M is hyperbolic.

Main Theorem 1.1. *Suppose the three-manifold M is a rational homology sphere (that is $H_1(M,\mathbb{Q}) = 0$) satisfying (R). Then for all, but at most two, primes ℓ with $\ell \equiv 3 \pmod 4$, there exists a positive α such that there exist infinitely many finite d-sheated coverings N of M such that either the inequality $rank_\ell\, H_1(N) > c\, d^\alpha$, or $rank_{\mathbb{Z}}\, H_1(N) > c\, d^{1/3}$, holds.*

As a corollary we have:

Theorem 1.2 (subgroup growth). *Let M be as in the Main Theorem. Then $f(d) > \exp(C\, d^{\alpha})$.*

Strategy of the proof. Step 1. By Theorem 9.1 of [R1], $\pi_1(M)$ admits a Zariski dense representation to $SL_2(\mathbb{C})$. We use the strong approximation of [W] to find surjective maps from $\pi_1(M)$ onto $SL_2(\mathbb{F}_q)$, where $\mathbb{F}_q$ are residue fields of an algebraic number field K.

Step 2. If ℓ is a prime, q, s are prime powers such that ℓ divides both $|SL_2(\mathbb{F}_q)|$ and $|SL_2(\mathbb{F}_s)|$, and $1 \to \pi_1(N) \to \pi_1(M) \to SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s) \to 1$ is a Galois covering, then $H_1(N)_{(\ell)}$, the ℓ-torsion part of $H_1(N)$, is nontrivial. This is proved in Proposition 2.1. Moreover, the action of $SL_2(\mathbb{F}_q)$ in $H_1(N)_{(\ell)}$ is nontrivial (Proposition 2.2).

Step 3. Using Theorem 3.2 it follows that for appropriate ℓ, q the ℓ-rank of $H_1(N)_{(\ell)}$ must be $\sim p$, where q is a power of p.

It may in principle happen, that just one surjective map $\pi_1(M) \xrightarrow{\alpha} SL_2(\mathbb{F}_q)$ is not enough to produce nontrivial ℓ-homology in N, where $\pi_1(N) = \operatorname{Ker}\alpha$ (see Step 2 above). We will prove that if this phenomenon happens for infinitely many p, then M is hyperbolic in a weak sense (the Gromov simplicial volume is positive).

Theorem 1.3 (weak hyperbolization). *Let M be atoroidal. Let $\mathcal{O} = \mathcal{O}(K)$ and let $\rho : \pi_1(M) \to SL_2(\mathcal{O}_S)$ be a Zariski dense representation. Suppose that for infinitely many primes ℓ, there exists a rational prime $p \equiv \pm 1 \pmod{\ell}$ and a prime ideal $\mathfrak{p} \subset \mathcal{O}$ over p with residue field $\mathbb{F}_q$, such that the covering N defined by $1 \to \pi_1(N) \to \pi_1(M) \to SL_2(\mathbb{F}_q) \to 1$ has trivial ℓ-homology. Then M has positive Gromov invariant.*

Remark. It is enough to demand that $\ell \nmid |H_3(SL_2(\mathcal{O}_s)|_{\text{tors}}$, so given the field K, the conditions can be effectively checked.

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2. Homology of $SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s)$-coverings

In this section, we will study $SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s)$-coverings of M where q and s are prime powers and ℓ divides the orders of $SL_2(\mathbb{F}_q)$ and $SL_2(\mathbb{F}_s)$, but not qs.

Proposition 2.1. *Let $1 \to \pi_1(N) \to \pi_1(M) \to SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s) \to 1$ be a Galois covering. Then either $b_1(N) > 0$, or $(H_1(N))_{(\ell)} \neq 0$.*

Proof. If N is a ℓ-homology sphere, then the direct product $SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s)$ has periodic ℓ-cohomology, see [CE], so any abelian ℓ-group in $SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s)$ should be cyclic, which is obviously wrong. Q.E.D.

Consider the tower of coverings $Q \to N \to M$, where $1 \to \pi_1(N) \to \pi_1(M) \to SL_2(\mathbb{F}_q) \to 1$ and $1 \to \pi_1(Q) \to \pi_1(N) \to SL_2(\mathbb{F}_s) \to 1$ are exact. Suppose $(H_1(M))_{(\ell)} = 0$. Then either $(H_1(N))_{(\ell)} \neq 0$, or $(H_1(N))_{(\ell)} = 0$ and $(H_1(Q))_{(\ell)} \neq 0$. Replacing M by N in the latter case, we can assume that the first case holds.

Proposition 2.2. *Suppose* $1 \to \pi_1(N) \to \pi_1(M) \to SL_2(\mathbb{F}_q) \to 1$ *is a Galois covering of rational homology spheres. Suppose* $H_1(M)_{(\ell)} = 0$ *and* $H_1(N)_{(\ell)} \neq 0$. *Then the natural action of* $SL_2(\mathbb{F}_q)$ *in* $H^1(N, \mathbb{F}_\ell)$ *is nontrivial.*

Proof. By Quillen [Qu], the cohomology ring $H^*(SL_2(\mathbb{F}_q), \mathbb{Z})_\ell$ is freely generated by one element of degree 4. Let $W = H^1(N, \mathbb{F}_\ell)$, then as an $SL_2(\mathbb{F}_q)$-module, $H^2(N, \mathbb{F}_\ell) \approx W^*$. The spectral sequence of the covering will look like

$$\begin{array}{l}
\mathbb{F}_\ell \quad 0 \quad 0 \quad \mathbb{F}_\ell \quad \mathbb{F}_\ell \quad \dots \\
H^i(SL_2(\mathbb{F}_q), W^*) \qquad\qquad\qquad\qquad \Rightarrow H^{i+j}(M, \mathbb{F}_\ell) \\
H^i(SL_2(\mathbb{F}_q), W) \\
\mathbb{F}_\ell \quad 0 \quad 0 \quad \mathbb{F}_\ell \quad \mathbb{F}_\ell \quad 0 \quad 0 \quad \mathbb{F}_\ell \quad \dots
\end{array}$$

If the action of $SL_2(\mathbb{F}_q)$ in W were trivial, then this would reduce to

$$\begin{array}{cccccccccc}
\mathbb{F}_\ell & 0 & 0 & \mathbb{F}_\ell & \mathbb{F}_\ell & 0 & 0 & \dots & & \\
W^* & 0 & 0 & W^* & W^* & 0 & 0 & & & \Rightarrow H^{i+j}(M, \mathbb{F}_\ell) \\
W & 0 & 0 & W & W & 0 & 0 & & & \\
\mathbb{F}_\ell & 0 & 0 & \mathbb{F}_\ell & \mathbb{F}_\ell & 0 & 0 & & &
\end{array}$$

Then we see that W^* which is indexed by $(4k+3, 2)$ in the E^2-term is not hit by any differential and survives in E^∞. This contradicts the finite-dimensionality of $H^*(M)$. Q.E.D.

3. A variant of Artin's primitive root conjecture

In 1927 Artin conjectured that if $a \neq -1$ or a square, then a is a primitive root mod p for infinitely many primes p or, in other words, $< a >= \mathbb{F}_p^*$ for infinitely many primes p. Under the assumption that the Riemann Hypothesis holds for certain number fields, a quantitative version of the conjecture was proved by Hooley [Ho]. The best known unconditional result to date is due to Heath-Brown [HB]. His main result has the following theorem as a corollary:

Theorem 3.1. *Let* q, r *and* s *be three distinct primes. Then at least one of them is a primitive root for infinitely many primes.*

In the proof of the Main Theorem we will use the following variant of Heath-Brown's result:

Theorem 3.2. *Let* q, r, s *be three distinct primes each congruent to* $3 \pmod 4$. *Then for at least one of them, say* q, *there are infinitely many primes* p *such that* q *is a primitive root mod* p, $p \equiv \pm 1 \pmod q$, *and moreover,* $|\{p \leq x : < q >= \mathbb{F}_p^*,\ p \equiv -1 \pmod q\}| \gg x(\log x)^{-2}$.

(Notice that if $\ell \equiv 1 \pmod 4$ with ℓ a prime, then, by quadratic reciprocity, there are no primes p such that $p \equiv \pm 1 \pmod \ell$ and $< \ell >= \mathbb{F}_p^*$.) The proof of Theorem 3.2 can be obtained by making minor modifications to Heath-Brown's proof of [Theorem 1, HB]. We start with a lemma:

Lemma 3.1. *Let q, r and s be three non-zero integers which are multiplicatively independent. Suppose that none of q, r, s, $-3qr$, $-3qs$, $-3rs$ and qrs is a square. Then there exists a prime p_0 such that*

$$(\frac{-3}{p_0}) = (\frac{q}{p_0}) = (\frac{r}{p_0}) = (\frac{s}{p_0}) = -1$$

and $(p_0 - 1, 16qrs)|8$.

Proof. Let $\pi(x)$ denote the number of primes not exceeding x. Asymptotically the sum

$$\sum_{p \le x}(1 - (\frac{-3}{p}))(1 - (\frac{q}{p}))(1 - (\frac{r}{p}))(1 - (\frac{s}{p}))$$

is not less than $\pi(x)$ (see [HB, p. 35]). Thus there are infinitely many primes p satisfying

$$(\frac{-3}{p}) = (\frac{q}{p}) = (\frac{r}{p}) = (\frac{s}{p}) = -1. \tag{2}$$

Using quadratic reciprocity and the supplementary law of quadratic reciprocity, we see that there exists an integer d with $16 \nmid d$ such that, for all p large enough, p satisfies (2) iff p is in a set of progressions modulo d, each with begin term coprime to d. Since there are infinitely many primes p satisfying (2), this set must be non-empty. Since $16 \nmid d$, it follows using the prime number theorem for arithmetic progressions, that the number of primes $p \le x$ satisfying (2) and $p \not\equiv 1 \pmod{16}$ is $\gg x/\log x$. Let $\omega(n)$ denote the number of distinct prime factors of n. Notice that there are at most $\ll \log^{\omega(qrs)} x$ primes $p \le x$ such that $p \not\equiv 1 \pmod{16}$ and $(p-1, 16qrs) \nmid 8$. By taking x large enough, it then follows there exists a prime p_0 satisfying the conditions such that $(p_0 - 1, 16qrs)|8$. Q.E.D.

From the proof of [Theorem 1, HB] it is clear (see especially pp. 35-36) that it is actually a proof of the following slightly stronger statement:

Theorem 3.3. *Let q, r, s be nonzero integers which are multiplicatively independent. Suppose none of q, r, s, $-3qr$, $-3qs$, qrs is a square. Then the number $N'_{q,r,s}(x)$ of primes $p \le x$, $p \equiv p_0 \pmod{16qrs}$, with p_0 as in Lemma 3.1, for which at least one of q, r, s is a primitive root, satisfies $N'_{q,r,s}(x) \gg x(\log x)^{-2}$.*

Now we are in the position to prove Theorem 3.2.

Proof of Theorem 3.2. We show that we can find p_0 satisfying the conditions of Lemma 3.1 and, in addition, $p_0 \equiv -1 \pmod{qrs}$. The result then follows from Theorem 3.3. Let p be a prime satisfying

$$p \equiv 5 \pmod 6,\ p \equiv 5 \pmod 8 \text{ and } p \equiv -1 \pmod{qrs}. \tag{3}$$

(There exist infinitely many such primes by the chinese remainder theorem and the prime number theorem for arithmetic progressions.) Since $p \equiv 2 \pmod 3$, $(-3/p) = -1$. Since $p \equiv 1 \pmod 4$, $(q/p) = (p/q)$. So, since $p \equiv -1 \pmod q$ and, by assumption, $q \equiv 3 \pmod 4$, $(q/p) = (-1/q) = -1$. Similarly, $(r/p) = (s/p) =$

-1. By an argument as in the proof of Lemma 3.1 it can be shown that there exists a prime p_0 satisfying (3) such that in addition $(p_0-1, 16qrs)|8$. Thus p_0 satisfies the conditions of Lemma 3.1 and in addition $p_0 \equiv -1 \pmod{qrs}$. Theorem 3.2 now follows from Theorem 3.3. Q.E.D.

The conjecture alluded to in the heading of this section, is the conjecture that if $\ell \not\equiv 1 \pmod 4$, then there are infinitely many primes p such that $p \equiv \pm 1 \pmod \ell$ and $<\ell>= \mathbb{F}_p^*$. On the generalized Riemann hypothesis this can be shown to be true, and moreover a quantitative version can be established [Mo].

4. Proof of the Main Theorem

By Theorem 9.1 of [R1], there is a Zariski dense representation of $\pi_1(M)$ in $SL_2(\bar{\mathbb{Q}})$. Let K be the splitting field of this representation, and let $n = [K:\mathbb{Q}]$. By [We], there exists a finite covering N of M, such that for almost all rational primes p the reduction modulo any prime over p in K will define a surjective map $\pi_1(N) \to SL_2(\mathbb{F}_q), q = p^m, m \le n$, and moreover, for two such primes p, f the map $\pi_1(N) \to SL_2(\mathbb{F}_q) \times SL_2(\mathbb{F}_s)$, $q = p^m, s = f^r$, is surjective. From now on we only look at primes congruent to -1 modulo ℓ. Relabel N by M again. Suppose that the ℓ-part of the homology of one such $SL_2(\mathbb{F}_s)$-covering N is zero. If this happens for ℓ big enough, this alone has far reaching consequences for the nature of M (the Gromov invariant is positive), as we will see in the proof of Theorem 1.3. Now we just notice that, by Proposition 2.1, we can relabel N by M and assume that for the rest of the primes p, either the ℓ-part of the homology of the $SL_2(\mathbb{F}_q)$-covering is nontrivial, or these coverings have positive b_1. In the first case, by Proposition 2.2, the action of $SL_2(\mathbb{F}_q)$ in $H^1(N, \mathbb{F}_\ell)$ is nontrivial. Since $PSL_2(\mathbb{F}_q)$ is simple, any element of order p in $SL_2(\mathbb{F}_q)$ also acts nontrivially. If $m = \dim H^1(N, \mathbb{F}_\ell)$, then we see that p divides $|GL_m(\mathbb{F}_\ell)|$, so that $p|(\ell-1)(\ell^2-1)\cdots(\ell^{m-1}-1)$. By Theorem 3.2 for appropriate ℓ, there are infinitely many primes p such that the order of ℓ in $\mathbb{F}_p^*$ equals $p-1$. It follows that $m \ge p$. On the other hand, $|SL_2(\mathbb{F}_q)| \sim q^3$ and $n = \log_p q$ is bounded above by the degree of the number field, over which the representation of $\pi_1(M)$ is defined. Finally, $m > \text{const} \cdot |SL_2(\mathbb{F}_q)|^\alpha$, where $1/3\alpha$ is the degree of the splitting field. The proof is complete in this case. In the other case, we get infinitely many $SL_2(\mathbb{F}_q)$-coverings with $b_1(N) > 0$. Since $b_1(M) = 0$, the representation of $SL_2(\mathbb{F}_q)$ in $H_1(N, \mathbb{C})$ does not have a trivial constituent. However, the smallest nontrivial irreducible representation of $SL_2(\mathbb{F}_q)$ has dimension $\sim q$, so $b_1(N) > d^{1/3}$. Q.E.D.

Proof of Theorem 1.2. Let N be as above and $m = \text{rank}_\ell(H_1(N)) > Cd^\alpha$. There are at least ℓ^{m-1} subgroups of index ℓ in $H_1(N)_{(\ell)}$. So there are at least $\ell^{Cd^\alpha - 1}$ subgroups of index ℓd in $\pi_1(M)$. Q.E.D.

Proof of Theorem 1.3. Suppose the Gromov invariant of M is zero. By Proposition 5.4 of [R2], for representation $\sigma : \pi_1(M) \to SL_2(K)$, the homology class $\sigma_*[M] \in H_3(SL_2(K), \mathbb{Z})$ is torsion. This applies to the representation $\rho : \pi_1(M) \to SL_2(\mathcal{O}_S)$. Since the real cohomology of $SL_2(\mathcal{O}_S)$ and $SL_2(K)$ are isomorphic, $\rho_*[M] \in H_3(SL_2(\mathcal{O}_S))$ is also torsion. Now, the $H_i(SL_2(\mathcal{O}_S))$ are finitely generated [BS], so for some $0 \neq N \in \mathbb{Z}$, we have $N \cdot \rho_*[M] = 0$. From now on we assume that ℓ does not divide N. Then $\rho_*[M]_{(\ell)} \in (H_3(SL_2(\mathcal{O}_S))_{\text{tors}})_{(\ell)} = 0$. For any surjective homomorphism $SL_2(\mathcal{O}_S) \xrightarrow{\beta} SL_2(\mathbb{F}_q)$, we will have $0 = (\beta\rho)_*[M]_{(\ell)} \in$

$H_3(SL_2(\mathbb{F}_q))_{(\ell)}$. On the other hand by Quillen [Qu], $H_3(SL_2(\mathbb{F}_q))_{(\ell)} \neq 0$ if $\ell | p^2-1$. Consider the homology spectral sequence of the covering $1 \to \pi_1(N) \to \pi_1(M) \to SL_2(\mathbb{F}_q) \to 1$:

$$\begin{array}{ll} H_i(SL_2(\mathbb{F}_q),\mathbb{Z}) & \\ H_i(SL_2(\mathbb{F}_q),H_2(N)) & \\ H_i(SL_2(\mathbb{F}_q),H_1(N)) & \Rightarrow H_{i+j}(M,\mathbb{Z}) \\ H_i(SL_2(\mathbb{F}_q),\mathbb{Z}) & \end{array}$$

Since the map $H_3(M,\mathbb{Z}) \to H_3(SL_2(\mathbb{F}_q),\mathbb{Z})$ is zero, one of the two differentials $d_2 : H_3(SL_2(\mathbb{F}_q),\mathbb{Z})_{(\ell)} \to H_1(SL_2(\mathbb{F}_q),H_1(N))_{(\ell)}, d_3 : \operatorname{Ker} d_2 \to H_0(SL_2(\mathbb{F}_q),H_2(N))_{(\ell)}$ is nonzero. But if $H_2(N) \neq 0$ then N is hyperbolic [Th] and the Gromov invariant of M is positive. If $H_2(N)=0$, then $d_2 \neq 0$, so $H_1(N)_{(\ell)} \neq 0$. Q.E.D.

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