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SPECTRAL DISTRIBUTION AND L^2 -ISOPERIMETRIC PROFILE OF LAPLACE OPERATORS ON GROUPS

ALEXANDER BENDIKOV, CHRISTOPHE PITTET, AND ROMAN SAUER

To the memory of Andrzej Hulanicki

ABSTRACT. We give a formula relating the L^2 -isoperimetric profile to the spectral distribution of the Laplace operator associated to a finitely generated group Γ or a Riemannian manifold with a cocompact, isometric Γ -action. As a consequence, we can apply techniques from geometric group theory to estimate the spectral distribution of the Laplace operator in terms of the growth and the Følner's function of the group, generalizing previous estimates by Gromov and Shubin. This leads, in particular, to sharp estimates of the spectral distributions for several classes of solvable groups. Furthermore, we prove the asymptotic invariance of the spectral distribution under changes of measures with finite second moment.

1. INTRODUCTION

What is the relation between the asymptotic behavior of the *return probability* $p(t)$ of the random walk of a probability measure μ on a finitely generated group Γ , the L^2 -*isoperimetric profile* $\Lambda(v)$ of the Laplace operator Δ associated to μ , and the *spectral distribution* $N(\lambda)$ of Δ ?

Recall that one has the equality

$$(1.1) \quad p(2t) = \mu^{(2t)}(\{e\}) = \int_0^\infty (1 - \lambda)^{2t} dN(\lambda), \quad t \in \mathbb{N},$$

between $p(2t)$, the measure of the unit element $e \in \Gamma$ with respect to the $2t$ -th convolution power of μ , and $N(\lambda)$ (see also (1.3) below). However, deducing from the above equality a relation between the asymptotic behaviors of $p(2t)$ and $N(\lambda)$ is in general a difficult task involving Tauberian theory (see [4; 20, Appendix]). The relationship between $p(2t)$ and $\Lambda(v)$ has been essentially settled in a series of works by Coulhon and Grigor'yan [7]. They prove

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under a mild regularity assumption that the function $\gamma(t)$ defined by the equation

$$(1.2) \quad t = \int_1^{\gamma(t)} \frac{dv}{\Lambda(v)v}, t \geq 0,$$

satisfies $\frac{1}{\gamma(t)} \simeq p(2t)$ for $t \in \mathbb{N}$ near infinity in the sense of Section 1.1.

The asymptotic relation between p , Λ , and N is fully understood for non-amenable and for virtually nilpotent groups due to work of Kesten, Varopoulos and Gromov-Shubin, respectively. The computation of $p(2t)$ and $\Lambda(v)$ is a field of active research (see [10, 11, 13, 14, 19, 26] – just to name a few).

We combine the asymptotic relations between $N(\lambda)$ and $p(2t)$, obtained from (1.1) via Legendre transform techniques, and between $p(2t)$ and $\Lambda(v)$ in (1.2) to establish a surprisingly simple formula relating $N(\lambda)$ and $\Lambda(v)$ that holds under a mild regularity assumption. This formula (Theorem 1.3), which is our main contribution, leads to explicit estimates of $N(\lambda)$ for many examples (see Table 1.4). Furthermore, we show that the asymptotic behavior of $N(\lambda)$ is stable under changes of the measure μ as long as μ is symmetric, has finite second moment, and its support generates Γ (Theorem 1.10).

1.1. Basic notions. Some definitions are in order to state the precise result. Let Γ be a finitely generated group. A probability measure μ on Γ is called *symmetric* if $\mu(\{\gamma\}) = \mu(\{\gamma^{-1}\})$ for every $\gamma \in \Gamma$. It is said to have *finite second moment* if $\int_{\Gamma} l(\gamma)^2 d\mu(\gamma) < \infty$, where l denotes the length function associated to some word metric on Γ . Further, we say that μ is *admissible* if it is symmetric, has finite second moment, and its support contains a finite generating set. Let $l^2(\Gamma)$ be the Hilbert space of square-integrable, complex-valued functions on Γ . Right convolution with μ defines a self-adjoint operator (*Markov-operator*)

$$R_{\mu} : l^2(\Gamma) \rightarrow l^2(\Gamma), \quad R_{\mu}(f)(x) = \sum_{\gamma \in \Gamma} f(x\gamma^{-1})\mu(\gamma).$$

with operator norm bounded by 1. The *Laplace operator* Δ of μ is the positive operator defined as $\Delta = \text{id} - R_{\mu}$. Both Δ and R_{μ} lie in the *von Neumann algebra* $\mathcal{N}(\Gamma)$ of Γ which is defined as the algebra of bounded operators on $l^2(\Gamma)$ that are equivariant with respect to the obvious isometric left Γ -action on $l^2(\Gamma)$. The *von Neumann trace* $\text{tr}_{\Gamma} : \mathcal{N}(\Gamma) \rightarrow \mathbb{C}$ is defined as $\text{tr}_{\Gamma}(A) = \langle A(\delta_e), \delta_e \rangle_{l^2(\Gamma)}$. For a self-adjoint operator $A \in \mathcal{N}(\Gamma)$ the spectral projection $E_{\lambda}^A = \chi_{(-\infty, \lambda]}(A)$ of A (see e.g. [22, p. 56]) lies in $\mathcal{N}(\Gamma)$. The *spectral distribution* of Δ is the right-continuous function $N : [0, \infty) \rightarrow [0, \infty)$ with

$$N(\lambda) = \text{tr}_{\Gamma}(E_{\lambda}^{\Delta}).$$

The probability to return to $e \in \Gamma$ after t steps of the random walk defined by μ and starting at $e \in \Gamma$ is called the *return probability* $p(t)$ of μ . The return probability can be expressed as

$$(1.3) \quad \begin{aligned} p(2t) &= \mu^{(2t)}(\{e\}) = \langle R_{\mu}^{2t}(\delta_e), \delta_e \rangle_{l^2(\Gamma)} = \text{tr}_{\Gamma}(R_{\mu}^{2t}) = \text{tr}_{\Gamma}\left(\int_0^{\infty} (1-\lambda)^{2t} dE_{\lambda}^{\Delta}\right) \\ &= \int_0^{\infty} (1-\lambda)^{2t} dN(\lambda). \end{aligned}$$

The *L^2 -isoperimetric profile* of Δ is the function $\Lambda : [1, \infty) \rightarrow (0, \infty)$ such that $\Lambda(v)$ is, by definition, the smallest eigenvalue of Δ restricted to a set $\Omega \subset \Gamma$ of cardinality less or equal

to v :

$$\Lambda(v) = \inf_{1 \leq |\Omega| \leq v} \lambda_1(\Omega) \quad \text{where} \quad \lambda_1(\Omega) = \inf_{\emptyset \neq \text{supp}(f) \subset \Omega} \frac{\langle \Delta(f), f \rangle}{\|f\|_2^2}.$$

If the choice of the measure μ in the definition of N , Λ , Δ , or p needs to be specified, we write N_μ , Λ_μ , Δ_μ , and p_μ .

The function Λ is a decreasing right-continuous step function. It is stable under changes of measures; more precisely, if μ and ν are two admissible measures on Γ , then there exists constants $C \geq 1$ and $c > 0$, such that for all $v \geq 1$,

$$(1.4) \quad c\Lambda_\mu(v) \leq \Lambda_\nu(v) \leq C\Lambda_\mu(v).$$

This follows from [15, Proposition 4]. For finitely generated groups, Cheeger's inequality (Theorem 4.1) and Følner's characterization of amenability imply that $\Lambda(v) \rightarrow 0$ for $v \rightarrow \infty$ if and only if the group is amenable.

We say that $f \preceq g$ holds *near zero*, for functions $f, g : [0, \infty) \rightarrow [0, \infty)$, if there are constants $C, D, \epsilon > 0$ such that $f(\lambda) \leq Cg(D\lambda)$ for all $\lambda \in [0, \epsilon)$. We say that $f \preceq g$ holds *near infinity* if there are constants $C, D, x_0 > 0$ such that $f(x) \leq Cg(Dx)$ for all $x \in [x_0, \infty)$. Further we write $f \simeq g$ *near zero* or *near infinity* if $f \preceq g$ and $g \preceq f$ hold near zero or near infinity, respectively. We say that $f \simeq g$ *holds in the dilatational sense* or $f \simeq g$ *are dilatationally equivalent* if the outer constant C can be taken to be $C = 1$ in the above definition. Similarly, one defines \preceq in the dilatational sense. The same definitions apply for functions $f, g : \mathbb{N} \rightarrow [0, \infty]$ by considering their piecewise linear extensions.

Remark 1.1. *The return probability and the L^2 -isoperimetric profile can be defined for measures on arbitrary graphs (not just Cayley graphs) whilst the definition of $N(\lambda)$ uses in an essential way the trace on the von Neumann algebra of the group. Similarly, the heat kernel and the L^2 -isoperimetric profile are defined for complete Riemannian manifolds. Actually, their relationship was first extensively studied in this context by Grigor'yan [16]. The definition of the spectral distribution $N(\lambda)$ on complete Riemannian manifolds requires the existence of a proper, free, cocompact, isometric group action [20].*

1.2. The formula. The computations of the spectral distribution and the L^2 -isoperimetric profile of virtually nilpotent groups are classic results (see the first row of Table 1.4) due to the work of Gromov-Shubin and Varopoulos [6, 20].

Theorem 1.2 (Gromov-Shubin-Varopoulos – reformulated). *Let Γ be an infinite finitely generated group, and let μ be an admissible probability measure on Γ . Assume that there is $\alpha \in (-\infty, 0)$ such that $\Lambda_\mu(v) \leq v^\alpha$ near infinity. Then Γ is virtually nilpotent and, near zero,*

$$N_\mu(\lambda) \simeq \frac{1}{\Lambda_\mu^{-1}(\lambda)}.$$

In fact, we have $\Lambda_\mu(v) \simeq v^{-2/d}$ near infinity and $N_\mu(\lambda) \simeq \lambda^{d/2}$ near zero, where d is the degree of growth of Γ .

Proof. According to the inequality (1.4) above, we may assume that the probability measure μ is uniform with support a finite symmetric generating set S of Γ . Let $B(r) \subset \Gamma$ denote the ball of radius r around the identity element of Γ with respect to the word metric defined by S . Let Φ be the inverse of the growth function, that is for $v \geq 0$,

$$\Phi(v) = \min\{r : |B(r)| > v\}.$$

We have for large enough $v > 1$:

$$\begin{aligned}
 v^\alpha &\geq \Lambda(v) = \inf_{|\Omega| \leq v} \lambda_1(\Omega) \\
 (1.5) \quad &\geq \inf_{|\Omega| \leq v} \inf_{\omega \subset \Omega} \frac{1}{2|S|^2} \left(\frac{|\partial_S \omega|}{|\omega|} \right)^2 = \inf_{|\omega| \leq v} \frac{1}{2|S|^2} \left(\frac{|\partial_S \omega|}{|\omega|} \right)^2 \\
 (1.6) \quad &\geq \inf_{|\omega| \leq v} \frac{1}{2|S|^2} \left(\frac{1}{4|S|\Phi(2|\omega|)} \right)^2 \geq \frac{1}{2|S|^2} \left(\frac{1}{4|S|\Phi(2v)} \right)^2;
 \end{aligned}$$

the inequality (1.5) is Cheeger's inequality (Theorem 4.1); the first inequality in (1.6) is due to Coulhon and Saloff-Coste [8] (see also [24, Theorem 3.2]). The above chain of inequalities implies that the growth rate of the balls in Γ is bounded above, up to a multiplicative constant, by $v^{-2/\alpha}$. Gromov's theorem on polynomial growth [18], implies that Γ is virtually nilpotent. The lower bound $\Lambda_\mu(v) \geq v^{-2/d}$ near infinity, follows from the above chain of inequalities because $\Phi(v) \simeq v^{1/d}$ near infinity [18, Appendix, Proposition 2]. The upper bound $\Lambda_\mu(v) \leq v^{-2/d}$ is proved in [10, 2.12]. Starting from Varopoulos estimate $p(2t) \simeq t^{-d/2}$ near infinity, Gromov and Shubin [20] apply Karamata type methods to deduce that $N_\mu(\lambda) \simeq \lambda^{d/2}$ near zero (see also [22, Lemma 2.46]). \square

The reason we interpret Gromov-Shubin's computation of $N(\lambda)$ via the inverse of the L^2 -isoperimetric profile in the above theorem is that it is, as turns out through the present work, suited for generalization.

The following theorem is our main result (proved in Section 3). Notice that a function like $\Lambda(v) = \log(v)^{-\gamma}$ with $\gamma > 0$ does not satisfy the assumption in Theorem 1.2 but the one of Theorem 1.3 (see Table 1.4 for many more such examples). This opens the way for many computations beyond nilpotent groups.

Theorem 1.3. *Let Γ be an infinite finitely generated amenable group, and let μ be an admissible probability measure on Γ . Assume that the function $\Lambda_\mu \circ \exp$ is doubling near infinity (Definition 3.4). Then we have the following dilatational equivalence near zero between N_μ and the reciprocal of the generalized inverse (Definition 3.4) of Λ_μ :*

$$N_\mu(\lambda) \simeq \frac{1}{\Lambda_\mu^{-1}(\lambda)}.$$

Actually, Theorem 1.3 follows from the following more general statement:

Theorem 1.4. *Retain the setting of Theorem 1.3. Let $L : (0, \infty) \rightarrow (0, \infty)$ be a decreasing function such that $\lim_{x \rightarrow \infty} L(x) = 0$. Assume that $L \circ \exp$ is doubling near infinity.*

- (1) *If $L(v) \preceq \Lambda_\mu(v)$ near infinity, then $N_\mu(\lambda) \preceq \frac{1}{L^{-1}(\lambda)}$ near zero in the dilatational sense.*
- (2) *If $L(v) \succeq \Lambda_\mu(v)$ near infinity, then $N_\mu(\lambda) \succeq \frac{1}{L^{-1}(\lambda)}$ near zero in the dilatational sense.*

So far we do not know an example of amenable Γ and μ such that Λ_μ neither satisfies the hypothesis of Theorem 1.2 nor the one of Theorem 1.3 or 1.4.

There is an analogous version of Theorem 1.3 (similarly, of Theorem 1.4) in the Riemannian setting:

Corollary 1.5. *Let M be a connected complete non-compact Riemannian manifold and Γ be an amenable group. Let Γ act freely, properly discontinuously and with cocompact quotient on M by isometries. Let Λ be the L^2 -isoperimetric profile of M and $N(\lambda)$ be the spectral*

distribution of the Laplace operator of M on functions. Let Λ^{-1} be the generalized inverse of Λ . If $\Lambda \circ \exp$ is doubling near infinity, then, near zero,

$$N(\lambda) \simeq \frac{1}{\Lambda^{-1}(\lambda)}.$$

Indeed, Efremov proved that the spectral distributions of the Riemannian Laplace operator on M and the combinatorial Laplace operator Δ_μ on Γ for the probability measure

$$(1.7) \quad \mu = \frac{1}{|S|} \sum_{s \in S} \delta_s$$

of the simple random walk associated to a finite, symmetric, generating set S are equivalent near zero [22, Section 2.4]. The corresponding statement for the L^2 -isoperimetric profile can be deduced from [9, 11].

1.3. Exponential and sub-exponential growth, Følner's function, and almost flat spectra. If not specified otherwise below, we consider the probability measure (1.7) associated to a finite, symmetric generating set of the group in consideration. According to Theorem 1.10 we may as well take any other admissible probability measure as long as we are only interested in the asymptotic properties of N_μ .

Geometric methods allow to compute $\Lambda(v)$ and verify the doubling assumption in many cases – the computation usually uses information about Følner's function $\text{Føl} : (0, \infty) \rightarrow \mathbb{N}$ defined for finitely generated amenable groups by

$$(1.8) \quad \text{Føl}(r) = \min \left\{ |\Omega|; \Omega \subset \Gamma : \frac{|\partial_S \Omega|}{|\Omega|} < \frac{1}{r} \right\}.$$

Here the boundary $\partial_S \Omega$ of Ω is, by definition, $\partial_S \Omega = \{x \in \Omega; \exists s \in S : xs \in \Gamma \setminus \Omega\}$. The function $\text{Føl}(r)$ is an increasing, right-continuous step function. It satisfies $\text{Føl}(r) \rightarrow \infty$ as $r \rightarrow \infty$, if and only if the group Γ is infinite. If the Følner's function grows sufficiently fast, we can deduce an upper bound on $N(\lambda)$:

Proposition 1.6. *Let Γ be an infinite, finitely generated amenable group. Let $F : (x_0, \infty) \rightarrow (0, \infty)$ be a continuous, strictly increasing function such that*

- (1) $F(r) \rightarrow \infty$ as $r \rightarrow \infty$,
- (2) there is $C > 1$ such that $F(r)^2 \leq F(Cr)$ for large $r > 0$,
- (3) $F(r) \preceq \text{Føl}(r)$ near infinity.

Then, near zero,

$$N(\lambda) \preceq \frac{1}{F(\lambda^{-1/2})}$$

in the dilatational sense.

Remark 1.7. *In all known examples there is the equivalence*

$$\text{Føl}(r) \simeq \Lambda^{-1}\left(\frac{1}{r^2}\right)$$

near infinity, hence condition (2) can be considered dual to the doubling condition on $\Lambda \circ \exp$ in Theorem 1.4, which itself is equivalent to the existence of a constant $c > 0$ such that $\Lambda(v^2) \geq c\Lambda(v)$ for $v \geq 1$ large enough.

The proof of the above proposition is based on Theorem 1.4 and Cheeger's inequality (see Section 4). We refer the reader to [8, 13, 19] for lower bounds on Følner's function. For lower bounds on $N(\lambda)$ we refer to Theorem 1.4 and Proposition 4.3 in Section 4.

Corollary 1.8. *Let Γ be a finitely generated amenable group. Let $0 < \alpha \leq 1$. Assume there exists $\epsilon > 0$ such that the cardinality of a ball of radius r in Γ is bounded below by $\exp(\epsilon r^\alpha)$ for large r . Then, near zero,*

$$N(\lambda) \preceq \exp(-\lambda^{-\alpha/2}).$$

In particular, if Γ has exponential growth, then $N(\lambda) \preceq \exp(-\lambda^{-1/2})$ near zero.

This follows from Proposition 1.6 and an inequality of Coulhon and Saloff-Coste [8], which implies that, under the above hypothesis, $\text{Føl}(r) \succeq \exp(r^\alpha)$ near infinity.

Given any locally bounded function $f : (x_0, \infty) \rightarrow (0, \infty)$, we can find a continuous function $F : (x_0, \infty) \rightarrow (0, \infty)$ with $F(r) \geq f(r^2)$ for every $r \in (x_0, \infty)$. By making F even bigger, we may also assume that $F(r)^2 \leq F(2r)$ and $F(r) \rightarrow \infty$ as $r \rightarrow \infty$. By a result of Erschler [14, Theorem 1] there exists a finitely generated amenable group whose Følner's function exceeds F . Thus we obtain the following corollary:

Corollary 1.9. *For any positive, locally bounded function f defined in a neighborhood of ∞ there exists a finitely generated amenable group Γ such that, near zero,*

$$N(\lambda) \preceq \frac{1}{f(\lambda^{-1})}.$$

This means that $N(\lambda)$ can be as flat as desired for amenable groups; on the other hand, $N(\lambda)$ is identically zero near zero if and only if the group is not amenable due to Kesten's spectral gap characterization.

1.4. Explicit computations. The $N(\lambda)$ -column of Table 1.4 gives some samples of explicit computations obtained from Proposition 1.6, Proposition 4.3, and Theorem 1.3. Previous to the present work, estimates for $N(\lambda)$ were only known for virtually nilpotent groups [20] (first row in Table 1.4) and for rank 1 lamplighter groups with special generating sets [1] (third row in Table 1.4 with $d = 1$). Many examples from Table 1.4 are *wreath products*. We recall the definition. If Γ and Q are groups, let $F(Q, \Gamma)$ be the set of functions from Q to Γ which are almost everywhere equal to the identity $e \in \Gamma$. The semi-direct product $F(Q, \Gamma) \rtimes Q$ with respect to the action $(q \cdot f)(x) = f(q^{-1}x)$ is called the *wreath product* of Γ with Q and is denoted by $\Gamma \wr Q$. It is not difficult to check that the wreath product of two finitely generated groups is finitely generated.

1.5. Stability. The following theorem (proved in Section 5) shows that the asymptotic behavior of N_μ near zero is an invariant of the group (in the sense of [17]).

Theorem 1.10. *Let Γ be a finitely generated group. Let μ_1 and μ_2 be admissible probability measures on Γ . Then we have the dilatational equivalence near zero*

$$N_{\mu_1} \simeq N_{\mu_2}.$$

Building on this, we prove in a forthcoming paper [2] the invariance under quasi-isometry.

Theorem 1.11. *Let Γ and Λ be finitely generated amenable groups. Let μ and ν be admissible probability measures on Γ and Λ , respectively. If Γ and Λ are quasi-isometric, then, near zero,*

$$N_\mu(\lambda) \simeq N_\nu(\lambda).$$

TABLE 1. Computations for several classes of solvable groups

Group	$p(2t)$ as $t \rightarrow \infty$	$N(\lambda)$ as $\lambda \rightarrow 0$	$\Lambda(v)$ as $v \rightarrow \infty$	$F(r)$ as $r \rightarrow \infty$
Virtually nilpotent of polynomial growth d	$t^{-d/2}$ (a)	$\lambda^{d/2}$ (b)	$v^{-2/d}$ (e)	r^d (f)
Virtually torsion-free solvable of exponential growth and finite Prüfer rank ^(c)	$\exp(-t^{1/3})$ (d)	$\exp(-\lambda^{-1/2})$	$\log(v)^{-2}$ (g)	$\exp(r)$ (h)
$F \wr N$, F finite and N of polynomial growth d	$\exp(-t^{\frac{d}{d+2}})$ (i)	$\exp(-\lambda^{-d/2})$	$\log(v)^{-2/d}$ (j)	$\exp(r^d)$ (j)
$\Lambda \wr N$, Λ infinite and of polynomial growth, N of polynomial growth d	$\exp(-t^{\frac{d}{d+2}}(\log(t))^{\frac{2}{d+2}})$ (k)	$\exp(-\lambda^{-\frac{d}{2}} \log(\frac{1}{\lambda}))$ (n)	$(\frac{\log(v)}{\log \log(v)})^{-2/d}$ (l)	$\exp(r^d \log(r))$ (l)
$F \wr (\dots (F \wr (F \wr \mathbb{Z})) \dots)$, F finite, k times iterated wreath product, $k \geq 2$	$\exp\left(-\frac{t}{(\log_{(k-1)}(t))^2}\right)$ (m)	$\exp(-\exp_{(k-1)}(\lambda^{-1/2}))$	$\log_{(k)}(v)^{-2}$ (l)	$\exp_{(k)}(r)$ (l)
$\mathbb{Z} \wr (\dots (\mathbb{Z} \wr (\mathbb{Z} \wr \mathbb{Z})) \dots)$, k times iterated wreath product, $k \geq 2$	$\exp\left(-t\left(\frac{\log_{(k)}(t)}{\log_{(k-1)}(t)}\right)^2\right)$ (m)	$\exp(-\exp_{(k-1)}(\lambda^{-1/2} \log(\frac{1}{\lambda})))$ (n)	$(\frac{\log_{(k)}(v)}{\log_{(k+1)}(v)})^{-2}$ (l)	$\exp_{(k)}(r \log(r))$ (l)

^(a) This is a well known result of Varopoulos [6]. See [10] for a short proof. ^(b) This follows from [6, 20]. See also [22, pp. 94-95].

^(c) Every polycyclic group of exponential growth is in this class. ^(d) See [26]. ^(e) See [10, 11]. ^(f) See [9, 21].

^(g) See [11, 26]. ^(h) See [9, 26]. ⁽ⁱ⁾ See [25]. See also [10] for an easier proof. ^(j) See [24] for the upper bound and [13] for the lower bound.

^(k) See [25] for the lower bound and [13] for the upper bound. ^(l) Proved in [13]. See [19] for an alternative proof. The notation \exp_k stands for the k -times iterated exponential function. Similarly for $\log_{(k)}$. ^(m) See [13]. ⁽ⁿ⁾ This expression is different from but equivalent to the functional inverse of the reciprocal of the one right next to it.

This result is an instance of a more general invariance result for arbitrary groups (i.e. not necessarily amenable) with respect to uniform measure equivalence that also holds in any degree, not only for the Laplace operator on functions. In [2] we also discuss how the stability of the return probability due to Pittet and Saloff-Coste [27] (actually, a slightly stronger version thereof) can be deduced from Theorem 1.11.

1.6. Structure of the paper. All results of the paper are stated in full detail in the introduction. The rest of the paper is devoted to their proofs. Proposition 3.1, needed in the proof of Theorem 1.4, as well as Proposition 4.3, which brings matching lower bounds on $N(\lambda)$ for all examples from Table 1.4, may also be of independent interest.

2. PROPERTIES OF THE LEGENDRE TRANSFORM

We collect some elementary properties of the *Legendre transform* for later reference.

Definition 2.1 (see [29, Section 26]).

- (1) Let $M : (0, \infty) \rightarrow (0, \infty)$ be decreasing such that $\lim_{x \rightarrow 0} M(x) = \infty$. For $t > 0$, we define the Legendre transform $\mathfrak{L}\mathfrak{e}_M(t)$ of M as

$$\mathfrak{L}\mathfrak{e}_M(t) = \inf\{tx + M(x); x > 0\}.$$

- (2) Let $G : [0, \infty) \rightarrow [0, \infty)$ be increasing such that $\lim_{x \rightarrow \infty} G(x)/x = 0$. For $t > 0$, we define the Legendre conjugate transform $\mathfrak{L}\mathfrak{e}_G^*(t)$ of G as

$$\mathfrak{L}\mathfrak{e}_G^*(t) = \sup\{-tx + G(x); x \geq 0\}.$$

Lemma 2.2. Let M and G be as in Definition 2.1. Let $t > 0$.

- (1) If M is right-continuous, then the infimum $\inf\{tx + M(x); x > 0\}$ is a minimum.
(2) If G is right-continuous, then the supremum $\sup\{-tx + G(x); x \geq 0\}$ is a maximum.

Proof. The proofs of both assertions are very similar, and we only prove the first one as a sample. Since $f(x) = tx + M(x) \rightarrow \infty$ for both $x \rightarrow 0$ and $x \rightarrow \infty$, there exist $0 < a \leq b < \infty$ and a sequence $(x_n)_{n \in \mathbb{N}}$ in $[a, b]$ such that $f(x_n) \rightarrow \inf\{f(x); x > 0\}$. By compactness of $[a, b]$, we may assume that $x_n \rightarrow y \in [a, b]$. We have to show that y realizes the minimum. We may assume that either $x_n \geq y$ for every $n \in \mathbb{N}$ or $x_n \leq y$ for every $n \in \mathbb{N}$. In the first case, $f(x_n) \rightarrow f(y)$ follows from right-continuity. In the second case, we have $tx_n + M(y) \leq tx_n + M(x_n)$ since M is decreasing. Taking limits, we obtain that $f(y) \leq \inf\{f(x); x > 0\}$. \square

We will need the following reformulation of [3, Lemma 3.2].

Lemma 2.3. Let F be an increasing positive right-continuous function defined on $[0, \infty)$ which is bounded by 1. Assume moreover that $F(0) = 0$ and that $F(\lambda) > 0$ if $\lambda > 0$. Let M be the decreasing positive function defined on $(0, \infty)$ as $M(x) = -\log(F(x))$. Then, for all $t > 0$, we have

$$(2.1) \quad \exp(-\mathfrak{L}\mathfrak{e}_M(t)) \leq \int_0^\infty \exp(-t\lambda) dF(\lambda) \leq (1 + \mathfrak{L}\mathfrak{e}_M(t)) \exp(-\mathfrak{L}\mathfrak{e}_M(t)).$$

Remark 2.4. The hypothesis of right-continuity should be added in [3, Lemma 3.2] and the convexity assumption on the function $x \mapsto tx + M(x)$ should be removed. (The convexity assumption is used only to ensure that the infimum $\inf_{x>0}\{tx + M(x)\}$ is a minimum and the convexity assumption in the context of [3, Lemma 3.2] implies anyway that M is right-continuous.)

Proof. To prove Lemma 2.3, apply Lemma 2.2; then follow the proof of [3, Lemma 3.2] without using convexity (see the remark above). \square

Proposition 2.5. *Let $M : (0, \infty) \rightarrow (0, \infty)$ be right-continuous and decreasing such that $\lim_{\lambda \rightarrow 0} M(\lambda) = \infty$.*

(1) *Let $t_0 > 0$, and let $G : [t_0, \infty) \rightarrow (0, \infty)$ be a function such that, for every $t \geq t_0$,*

$$\mathfrak{L}\mathfrak{e}_M(t) \leq G(t).$$

If $G/\text{id} : [t_0, \infty) \rightarrow (0, \infty)$, defined as $(G/\text{id})(t) = G(t)/t$, has an inverse $(G/\text{id})^{-1}$, then

$$M(\lambda) \leq G \circ (G/\text{id})^{-1}(\lambda)$$

holds for all $\lambda \in (G/\text{id})([t_0, \infty))$.

(2) *Let $G : [0, \infty) \rightarrow [0, \infty)$ be right-continuous and increasing such that $\lim_{t \rightarrow \infty} G(t) = \infty$ and $\lim_{t \rightarrow \infty} G(t)/t = 0$. Assume that*

$$\mathfrak{L}\mathfrak{e}_M(t) \geq G(t)$$

near infinity. Then, near zero,

$$M(\lambda) \geq \mathfrak{L}\mathfrak{e}_G^*(\lambda).$$

(3) *Let $G : [0, \infty) \rightarrow [0, \infty)$ be continuous such that $\lim_{t \rightarrow \infty} G(t)/t = 0$. Assume that $t \mapsto G(t)/t$ is strictly decreasing near infinity. Let $\epsilon \in (0, 1)$. Then, near zero,*

$$\mathfrak{L}\mathfrak{e}_G^*(\lambda) \geq (1 - \epsilon)G \circ (G/\text{id})^{-1}(\lambda/\epsilon).$$

Proof. (1) By Lemma 2.2, for each $t \geq t_0$, there exists $y = y(t) > 0$ such that $\mathfrak{L}\mathfrak{e}_M(t) = ty + M(y)$. Hence $y \leq G(t)/t$. As M is decreasing, $M(G(t)/t) \leq M(y) \leq \mathfrak{L}\mathfrak{e}_M(t) \leq G(t)$.

(2) Notice first that for every $t_0 > 0$ the function $t \mapsto -t\lambda + G(t)$ attains its maximum in (t_0, ∞) provided $\lambda > 0$ is sufficiently small. Indeed, let $T > t_0$ be such that $G(T) > 1 + G(t_0)$. Then for $\lambda \in (0, 1/T)$ we have $-t\lambda + G(t) < -T\lambda + G(T)$ for every $t \in (0, t_0)$ because G is increasing. Inequality (2) now readily follows from the definition of $\mathfrak{L}\mathfrak{e}_M$ and $\mathfrak{L}\mathfrak{e}_G^*$.

(3) By hypothesis, the inverse $(G/\text{id})^{-1}$ is well defined in a neighborhood of zero. For sufficiently small $\lambda > 0$, there exists $s = s(\lambda)$, such that $\lambda s = \epsilon G(s)$, and thus $(G/\text{id})^{-1}(\lambda/\epsilon) = s$. Hence, $\mathfrak{L}\mathfrak{e}_G^*(\lambda) \geq -\lambda s + G(s) = (1 - \epsilon)G(s) = (1 - \epsilon)G \circ (G/\text{id})^{-1}(\lambda/\epsilon)$. \square

3. PROOF OF THE MAIN THEOREM

Section 3 is devoted to the proof of Theorem 1.4, which implies Theorem 1.3.

3.1. The relation between $N_\mu(\lambda)$ and $p_\mu(t)$ via the Laplace transform. We discuss the following equivalence near infinity between the return probability of the random walk associated to μ and the Laplace transform of N_μ .

Proposition 3.1. *Let Γ be a finitely generated infinite amenable group and let μ be an admissible probability measure on Γ . Then, for $t \in \mathbb{N}$ near infinity,*

$$(3.1) \quad p_\mu(2t) \simeq \int_0^\infty \exp(-\lambda t) dN_\mu(\lambda).$$

This equivalence is well known – at least, if the Markov operator R_μ is positive (but it is often not, like in the case of the simple random walk $\mu = (\delta_1 + \delta_{-1})/2$ on $\Gamma = \mathbb{Z}$). In practice, it is often sufficient to apply the equivalence to the positive operator R_μ^2 , but we do need the general case here. The proof relies on our stability result (Theorem 1.10). Firstly we need the following two lemmas.

Lemma 3.2. *Let \mathcal{H} be a separable Hilbert space and let $A \in B(\mathcal{H})$ be a self-adjoint operator such that $\|A\| \leq 1$. For each $0 \leq \lambda \leq 1$, the spectral projections of $I - A^2$ and of $I - A$ satisfy:*

$$E_\lambda^{I-A^2} = E_{1-\sqrt{1-\lambda}}^{I-A} + I - E_{1+\sqrt{1-\lambda}}^{I-A}.$$

Proof. By definition of the spectral projections, it is enough to check the corresponding equality at the level of functions. But if $-1 \leq x \leq 1$ and if $0 \leq \lambda \leq 1$, then

$$\chi_{(-\infty, \lambda]}(1 - x^2) = \chi_{(-\infty, 1-\sqrt{1-\lambda}]}(1 - x) + 1 - \chi_{(-\infty, 1+\sqrt{1-\lambda}]}(1 - x). \quad \square$$

Lemma 3.3. *Let $F, G : [a, b] \rightarrow \mathbb{R}$ be two functions of bounded variation. Assume that $F(a) = G(a)$ and that $F(x) \leq G(x)$ on $[a, b]$. If $f : [a, b] \rightarrow [0, \infty)$ is a continuous decreasing function, then the Stieltjes integrals of f with respect to F and G satisfy:*

$$\int_{[a, b]} f(x) dF(x) \leq \int_{[a, b]} f(x) dG(x).$$

Proof. Integration by parts reads (see [28, Chapitre II. 54])

$$\int_{[a, b]} f(x) dF(x) = f(x)F(x)|_a^b - \int_{[a, b]} F(x) df(x).$$

The hypotheses $F(a) = G(a)$ and $\forall x \in [a, b], F(x) \leq G(x)$, and the assumption that f is non-negative imply that

$$f(x)F(x)|_a^b \leq f(x)G(x)|_a^b.$$

On the other hand, as f is decreasing and as $\forall x \in [a, b], F(x) \leq G(x)$, we obtain:

$$- \int_{[a, b]} F(x) df(x) \leq - \int_{[a, b]} G(x) df(x). \quad \square$$

Proof of the \succeq -assertion of Proposition 3.1. Let $0 < \lambda_0 < 1$ be sufficiently small such that

$$-\frac{\log(1-\lambda)}{\lambda} = 1 + \frac{\lambda}{2} + \frac{\lambda^2}{3} + \dots < \frac{3}{2} \quad \text{for every } \lambda \in (0, \lambda_0).$$

This implies that

$$\exp(-3t\lambda) < (1-\lambda)^{2t} \quad \text{for every } t \geq 1 \text{ and } 0 \leq \lambda < \lambda_0.$$

It is important that the choice of λ_0 does not depend on t . As Γ is infinite, $N_\mu(0) = 0$. Notice also that as Γ is amenable, if $\lambda > 0$ then $N(\lambda) > 0$. In particular $N(\lambda_0) > 0$. We

obtain for every $t \in \mathbb{N}$ that

$$\begin{aligned}
\int_{[0,\infty)} \exp(-3t\lambda) dN_\mu(\lambda) &= \int_{[0,\lambda_0]} \exp(-3t\lambda) dN_\mu(\lambda) + \int_{(\lambda_0,2]} \exp(-3t\lambda) dN_\mu(\lambda) \\
&\leq \int_{[0,\lambda_0]} \exp(-3t\lambda) dN_\mu(\lambda) + \exp(-3t\lambda_0)(N_\mu(2) - N_\mu(\lambda_0)) \\
&\leq \int_{[0,\lambda_0]} \exp(-3t\lambda) dN_\mu(\lambda) + \frac{N_\mu(2) - N_\mu(\lambda_0)}{N_\mu(\lambda_0)} \int_{[0,\lambda_0]} \exp(-3t\lambda) dN_\mu(\lambda) \\
&= \left(1 + \frac{N_\mu(2) - N_\mu(\lambda_0)}{N_\mu(\lambda_0)}\right) \int_{[0,\lambda_0]} \exp(-3t\lambda) dN_\mu(\lambda) \\
&< \left(1 + \frac{N_\mu(2) - N_\mu(\lambda_0)}{N_\mu(\lambda_0)}\right) \int_{[0,\infty)} (1-\lambda)^{2t} dN_\mu(\lambda) \\
&= \left(1 + \frac{N_\mu(2) - N_\mu(\lambda_0)}{N_\mu(\lambda_0)}\right) p_\mu(2t). \quad \square
\end{aligned}$$

Proof of the \preceq -assertion of Proposition 3.1. The support of $\mu^{(2)}$ (convolution of μ with itself) either generates Γ or a subgroup in Γ of index 2. (To prove it, notice that the support of the admissible measure μ contains a finite symmetric generating set S of Γ . Hence $S^2 \subset \text{supp}(\mu)^2 \subset \text{supp}(\mu^{(2)})$. But the subgroup H generated by S^2 is of index at most 2 in Γ because, for any $s \in S$, $H \cup Hs = \Gamma$.)

In the first case, Theorem 1.10 immediately yields that $N_{\mu^{(2)}} \simeq N_\mu$ in the dilatational sense. In the latter case, Theorem 1.10 and [22, Theorem 2.55 (6) on p. 98] imply that $N_{\mu^{(2)}} \simeq 2N_\mu$ holds dilatationally. Hence there are $1 \geq \lambda_1 > 0$ and $D \geq 1$ such that

$$(3.2) \quad N_{\mu^{(2)}}(\lambda) \leq 2N_\mu(D\lambda) \quad \text{for every } \lambda \in [0, \lambda_1].$$

One verifies that

$$(3.3) \quad (1-\lambda)^{2t} \leq \exp(-2t\lambda) \quad \text{for every } t \geq 1 \text{ and every } \lambda \in [0, 1].$$

Set $\lambda_0 = \min\{1, \lambda_1/2\}$. Also notice that $(1-\lambda)^{2t} \leq (1-\lambda_0)^{2t}$ for $\lambda_0 \leq \lambda \leq 2-\lambda_0$. Thus,

$$\begin{aligned}
p_\mu(2t) &\stackrel{(1.3)}{=} \int_{[0,\lambda_0]} (1-\lambda)^{2t} dN_\mu(\lambda) + \int_{(\lambda_0,2-\lambda_0]} (1-\lambda)^{2t} dN_\mu(\lambda) + \underbrace{\int_{(2-\lambda_0,2]} (1-\lambda)^{2t} dN_\mu(\lambda)}_{=R(\lambda_0)} \\
&\leq \int_{[0,\lambda_0]} (1-\lambda)^{2t} dN_\mu(\lambda) + \int_{(\lambda_0,2-\lambda_0]} (1-\lambda_0)^{2t} dN_\mu(\lambda) + R(\lambda_0) \\
(3.4) \quad &\leq \int_{[0,\lambda_0]} \exp(-2t\lambda) dN_\mu(\lambda) + \exp(-2t\lambda_0) + R(\lambda_0) \\
&\leq (1 + N_\mu(\lambda_0)^{-1}) \int_{[0,\lambda_0]} \exp(-2t\lambda) dN_\mu(\lambda) + R(\lambda_0).
\end{aligned}$$

(Again, since Γ is amenable, there is no spectral gap, hence $N_\mu(\lambda_0) > 0$.) The estimate of $R(\lambda_0)$ relies on two observations:

i) Applying Lemma 3.2 to the Markov-operator $R_\mu = 1 - \Delta_\mu$, we obtain for every $0 \leq \lambda \leq \lambda_1$ that

$$\begin{aligned}
 (3.5) \quad 1 - N_\mu\left(2 - \frac{\lambda}{2}\right) &\leq 1 - N_\mu\left(2 - \frac{\lambda}{2}\right) + N_\mu\left(\frac{\lambda}{2}\right) \\
 &\leq 1 - N_\mu\left(2 - \frac{\lambda}{1 + \sqrt{1 - \lambda}}\right) + N_\mu\left(\frac{\lambda}{1 + \sqrt{1 - \lambda}}\right) \\
 &= 1 - N_\mu(1 + \sqrt{1 - \lambda}) + N_\mu(1 - \sqrt{1 - \lambda}) \\
 &= N_{\mu^{(2)}}(\lambda) \\
 &\stackrel{(3.2)}{\leq} 2N_\mu(D\lambda).
 \end{aligned}$$

ii) We conclude from the change of variable $\lambda \mapsto 2 - \lambda$ and Lemma 3.3 and (3.5) that

$$\begin{aligned}
 R(\lambda_0) &= \int_{[0, \lambda_0)} (1 - \lambda)^{2t} d(1 - N_\mu(2 - \lambda)) \\
 &\leq 2 \int_{[0, 2D\lambda_0)} \left(1 - \frac{\lambda}{2D}\right)^{2t} dN_\mu(\lambda) \\
 &\stackrel{(3.3)}{\leq} 2 \int_{[0, 2D\lambda_0)} \exp\left(-t \frac{\lambda}{D}\right) dN_\mu(\lambda).
 \end{aligned}$$

Combining the latter estimate with (3.4) and using that $D \geq 1$ we obtain that

$$p_\mu(2t) \leq (3 + N_\mu(\lambda_0)^{-1}) \int_{[0, 2D\lambda_0)} \exp\left(-t \frac{\lambda}{D}\right) dN_\mu(\lambda) \quad \text{for every } t \in \mathbb{N}. \quad \square$$

3.2. General properties of doubling functions and generalized inverses.

Definition 3.4. Let $L : (0, \infty) \rightarrow (0, \infty)$ be a decreasing function.

- (1) The generalized inverse of L is the function $L^{-1} : (\inf L, \infty) \rightarrow (0, \infty)$ defined as $L^{-1}(x) = \inf\{v > 0; L(v) \leq x\}$.
- (2) We say that L is doubling (near infinity) if there exists a constant $c > 0$ such that $L(2x) \geq cL(x)$ for all $x > 0$ (sufficiently large $x > 0$).

Lemma 3.5. Let $L : (0, \infty) \rightarrow (0, \infty)$ be a decreasing function. Assume that L is doubling. Then there is a continuous, decreasing function $L_{ct} : (0, \infty) \rightarrow (0, \infty)$ such that $L_{ct} \simeq L$. If, in addition, $L \circ \exp$ is doubling, then $L_{ct} \circ \exp$ is doubling.

Proof. The function

$$L_{ct}(x) = \frac{2}{x} \int_{x/2}^x L(s) ds$$

is continuous and differentiable almost everywhere by the Lebesgue differentiation theorem. It is decreasing because of

$$\begin{aligned}
 \frac{xL'_{ct}(x)}{2} &= L(x) - \frac{L(x/2)}{2} - \frac{1}{x} \int_{x/2}^x L(s) ds \\
 &\leq L(x) - \frac{L(x/2)}{2} - \frac{L(x)}{2} = \frac{L(x) - L(x/2)}{2} \leq 0.
 \end{aligned}$$

It is equivalent to L because of $L_{ct}(x) \geq L(x)$ and $L_{ct}(x) \leq L(x/2) \leq c^{-1}L(x)$. The last assertion also follows from this. \square

Lemma 3.6. *Let $f, g : (0, \infty) \rightarrow (0, \infty)$ be decreasing functions such that $f(x) \rightarrow 0$ and $g(x) \rightarrow 0$ for $x \rightarrow \infty$. So the generalized inverses f^{-1} and g^{-1} are defined on $(0, \infty)$. Then the following holds:*

- (1) *If $f \circ \exp$ is doubling near infinity, then f is doubling near infinity.*
- (2) *Let $l : (0, \infty) \rightarrow (0, \infty)$ be a strictly increasing, continuous function (i.e. l^{-1} in the usual sense exists) such that $l(x) \rightarrow \infty$ as $x \rightarrow \infty$. Then $(f \circ l)^{-1} = l^{-1} \circ f^{-1}$.*
- (3) *If $f \simeq g$ and f, g are doubling near infinity, then there is a constant $D > 0$ such that $D^{-1}g(x) \leq f(x) \leq Dg(x)$ for large $x > 0$.*
- (4) *If $f \preceq g$ near infinity, then $f^{-1} \preceq g^{-1}$ near zero.*
- (5) *If there is $D > 0$ with $f(x) \leq Dg(x)$ near infinity, then $f^{-1}(\lambda) \leq g^{-1}(D^{-1}\lambda)$ near zero.*
- (6) *If $f \simeq g$ and f and g are doubling near infinity, then $f^{-1} \simeq g^{-1}$ holds near zero in the dilatational sense.*

Proof. (1) If $x \geq 2$, then

$$f(2x) = f(\exp(\log(2x))) \geq f(\exp(2 \log(x))) \geq cf(\exp(\log(x))) = cf(x).$$

(2) By continuity, there is $x_0 > 0$ with $l(0, \infty) = (x_0, \infty)$. Hence, if $\lambda > 0$ is small enough, we have

$$\inf\{y > 0; f(y) \leq \lambda\} = \inf\{l(x); f(l(x)) \leq \lambda, x > 0\}.$$

Thus, as l^{-1} is increasing and continuous,

$$(l^{-1} \circ f^{-1})(\lambda) = l^{-1}(\inf\{l(x); f(l(x)) \leq \lambda, x > 0\}) = \inf\{x > 0; f(l(x)) \leq \lambda\} = (f \circ l)^{-1}(\lambda).$$

(3)–(5) are easy; the proof is omitted.

(6) follows from (3) and (5). \square

3.3. Coulhon's and Grigoryan's functional equation. In the proof of Theorem 1.4 we relate the L^2 -isoperimetric profile to the return probability. This relies on work of Coulhon and Grigor'yan [11].

Proposition 3.7. *Let $L : (0, \infty) \rightarrow (0, \infty)$ be decreasing and continuous. Assume that $\lim_{x \rightarrow \infty} L(x) = 0$. Then the functional equation*

$$(3.6) \quad t = \int_0^{v(t)} \frac{ds}{(L \circ \exp)(s)}$$

uniquely defines a strictly increasing C^1 -function $v : [0, \infty) \rightarrow [0, \infty)$. Further, the following properties hold:

- (1) *$v(2t) \leq 2v(t)$ for $t \geq 0$.*
- (2) *If $L \circ \exp$ is doubling near infinity, then there is $c > 0$ with $v'(2t) \geq cv'(t)$ near infinity.*
- (3) *For $t > 0$, the function $t \mapsto v(t)t^{-1}$ is decreasing and strictly decreasing near infinity.*

Proof. (1) Since the derivative $v'(t) = (L \circ \exp)(v(t))$ is decreasing,

$$\begin{aligned} v(2t) &= \int_0^{2t} v'(s)ds + v(0) \leq \int_0^{2t} v'(s/2)ds + v(0) \leq 2 \int_0^t v'(s)ds + 2v(0) \\ &= 2v(t). \end{aligned}$$

(2) We have

$$v'(2t) = (L \circ \exp)(v(2t)) \geq (L \circ \exp)(2v(t)) \geq c(L \circ \exp)(v(t)) = cv'(t).$$

(3) Differentiating yields

$$\begin{aligned} \frac{d}{dt} \frac{v(t)}{t} &= \frac{v(t)}{t^2} \left(\frac{v'(t)t}{v(t)} - 1 \right) = \frac{v(t)}{t^2} \left(\frac{(L \circ \exp)(v(t))t}{v(t)} - 1 \right) \\ &\leq \frac{v(t)}{t^2} \left(\frac{t}{\int_0^{v(t)} \frac{ds}{(L \circ \exp)(s)}} - 1 \right) = \frac{v(t)}{t^2} \left(\frac{t}{t} - 1 \right) = 0. \end{aligned}$$

Let us show that the inequality

$$\int_0^{v(t)} \frac{ds}{(L \circ \exp)(s)} \leq \frac{v(t)}{(L \circ \exp)(v(t))}$$

we just used is strict provided t is large enough. Assume the equality case for some $t > 0$. Then, for every $x \in [0, t]$, we have $(L \circ \exp)(v(x)) = (L \circ \exp)(v(t))$ since $L \circ \exp \circ v$ is decreasing. This is a contradiction for large $t > 0$ because $L(x) \rightarrow 0$ as $x \rightarrow \infty$. \square

Theorem 3.8 (Coulhon-Grigor'yan). *Let Γ be an infinite, finitely generated, amenable group, and let μ be an admissible measure on Γ . Let $L : (0, \infty) \rightarrow (0, \infty)$ be a decreasing, continuous function, and let $v(t)$ be defined by (3.6).*

- (1) *If $L(v) \preceq \Lambda_\mu(v)$ near infinity, then $p_\mu(t) \preceq \exp(-v(t))$ near infinity.*
- (2) *Assume, in addition, that $L \circ \exp$ is doubling. If $L(v) \succeq \Lambda_\mu(v)$ near infinity, then $p_\mu(2t) \succeq \exp(-v(t))$.*

Proof. This is a straightforward application of [11, Section 3] (see also [10, Propositions 2.1 and 4.1]); the technical condition (D) of [11, Section 3], needed for the lower bounded on $p_\mu(t)$, is satisfied because of Proposition 3.7 (1) and (2). \square

Lemma 3.9. *Retain the setting of Proposition 3.7. Assume $L \circ \exp$ is doubling near infinity. Then there is a constant $D > 0$ such that near infinity*

$$(L \circ \exp \circ v)(t) \leq \frac{v(t)}{t} \leq D \cdot (L \circ \exp \circ v)(t).$$

In particular, we have

$$\lim_{t \rightarrow \infty} \frac{v(t)}{t} = 0.$$

Proof. Since L is decreasing, we obtain that

$$\frac{v(t)}{t} = v(t) \left(\int_0^{v(t)} \frac{ds}{(L \circ \exp)(s)} \right)^{-1} \geq (L \circ \exp)(v(t)).$$

If $C > 0$ is the doubling constant, then we obtain for every $v > 0$ that

$$\int_0^v \frac{ds}{(L \circ \exp)(s)} \geq \int_{v/2}^v \frac{ds}{(L \circ \exp)(s)} \geq \frac{v}{2(L \circ \exp)(v/2)} \geq \frac{v}{2C(L \circ \exp)(v)}.$$

Thus,

$$\begin{aligned} \frac{v(t)}{t} &= v(t) \left(\int_0^{v(t)} \frac{ds}{(L \circ \exp)(s)} \right)^{-1} \leq v(t) \left(\frac{v(t)}{2C(L \circ \exp \circ v)(t)} \right)^{-1} \\ &= 2C(L \circ \exp \circ v)(t). \end{aligned}$$

\square

3.4. Conclusion of the proof of Theorem 1.4. By assumption, $L \circ \exp$, thus, by Lemma 3.6 (1), L itself, are doubling near infinity. Let $L_1 = L_{ct}$ be the continuous, decreasing function obtained from Lemma 3.5; $L_1 \circ \exp$ is also doubling near infinity and $L_1 \simeq L$. Let v_1 be the continuous, increasing function defined by the functional equation (3.6) where we replace L with L_1 . The proof now splits into two parts.

Proof of the upper bound on $N_\mu(\lambda)$ in Theorem 1.4. Due to Theorem 3.8, we have $p_\mu(t) \preceq \exp(-v_1(t))$ near infinity since $L_1 \simeq L \preceq \Lambda_\mu$. Combining this with Proposition 3.1, we obtain that

$$-\log\left(\int_0^\infty \exp(-\lambda t) dN_\mu(\lambda)\right) \succeq v_1(t)$$

near infinity. Since Γ is infinite and amenable, $N_\mu(0) = 0$ and $N_\mu(\lambda) > 0$ for every $\lambda > 0$. Hence, Lemma 2.3 applies, and we deduce that near infinity,

$$\mathfrak{L}\mathfrak{e}_M(t) \succeq v_1(t),$$

where, by definition, $M(x) = -\log(N_\mu(x))$. In other words, there exists $\alpha, \beta > 0$, such that near infinity,

$$\mathfrak{L}\mathfrak{e}_M(t) \geq v_2(t),$$

where $v_2(t) = \alpha v_1(\beta t)$. Define the function L_2 by

$$(3.7) \quad L_2 \circ \exp(x) = \alpha\beta(L_1 \circ \exp)(\alpha^{-1}x).$$

One verifies that v_2 and L_2 satisfy the assumptions in Proposition 3.7 and, in particular, the functional equation (3.6). Furthermore, $L_2 \circ \exp$ is doubling near infinity because $L_1 \circ \exp$ is so. By Lemma 3.9, $v_2(t)/t \rightarrow 0$. Hence Proposition 2.5 (2) implies that

$$M(\lambda) \geq \mathfrak{L}\mathfrak{e}_{v_2}^*(\lambda)$$

near zero. By Proposition 3.7 and Lemma 3.9, the function $v_2(t)/t$ is strictly decreasing near infinity and converges to 0. Thus its inverse $(v_2/\text{id})^{-1}$ is well defined near zero. Proposition 2.5 (3) applies, and we deduce that

$$\mathfrak{L}\mathfrak{e}_{v_2}^*(\lambda) \geq \frac{1}{2}v_2 \circ (v_2/\text{id})^{-1}(2\lambda)$$

near zero. By Lemma 3.9, $v_2/\text{id} \geq L_2 \circ \exp \circ v_2$. Applying, in this order, Lemma 3.6 (5) and (2), yields

$$(v_2/\text{id})^{-1} \geq (L_2 \circ \exp \circ v_2)^{-1} = v_2^{-1} \circ (L_2 \circ \exp)^{-1}$$

near zero. Let $L_3 : (0, \infty) \rightarrow (0, \infty)$ be the function defined by $L_3(\exp(x)) = L_2(\exp(2x))$. Putting all together and using Lemma 3.6 (2) for the last two equalities below, we obtain that

$$\begin{aligned} -\log(N_\mu(\lambda/2)) &= M(\lambda/2) \geq \mathfrak{L}\mathfrak{e}_{v_2}^*(\lambda/2) \geq \frac{1}{2}(L_2 \circ \exp)^{-1}(\lambda) \\ &= (L_3 \circ \exp)^{-1}(\lambda) = \log \circ L_3^{-1}(\lambda) \end{aligned}$$

near zero. Thus, near zero,

$$N_\mu(\lambda) \preceq \frac{1}{L_3^{-1}(\lambda)}$$

holds in the dilatational sense. It remains to see that $L_3^{-1} \simeq L^{-1}$ near zero in the dilatational sense. Since near infinity $L_3 \simeq L_2 \simeq L_1 \simeq L$ and all these functions are doubling, this follows from Lemma 3.6 (6). \square

Proof of the lower bound on $N_\mu(\lambda)$ in Theorem 1.4. Since $L_1 \simeq L \succeq \Lambda_\mu$ and $L_1 \circ \exp$ is doubling at infinity, Theorem 3.8 can be applied and yields that $p_\mu(2t) \succeq \exp(-v_1(t))$ near infinity. We proceed similarly as for the upper bound and apply Proposition 3.1 and Lemma 2.3. This implies

$$v_1(t) \succeq -\log\left(\int_0^\infty \exp(-t\lambda) dN_\mu(\lambda)\right) \geq \mathfrak{L}\mathfrak{e}_M(t) - \log(1 + \mathfrak{L}\mathfrak{e}_M(t)) \geq \frac{1}{2}\mathfrak{L}\mathfrak{e}_M(t)$$

for large $t > 0$. Thus there are constants $\alpha, \beta > 0$ such that for $v_2(t) = \alpha v_1(\beta t)$ we have

$$v_2(t) \geq \mathfrak{L}\mathfrak{e}_M(t)$$

for large $t > 0$. Let L_2 be defined as in (3.7). With the same argument as for the upper bound, the function v_2/id has a well defined inverse near zero. Hence Proposition 2.5 (1) can be applied, implying that near zero:

$$M(\lambda) \leq v_2 \circ (v_2/\text{id})^{-1}(\lambda).$$

By Lemmas 3.9 and 3.6 (5) and (2),

$$(v_2/\text{id})^{-1}(\lambda) \leq v_2^{-1} \circ (L_2 \circ \exp)^{-1}(\lambda/D).$$

We conclude that

$$M(D\lambda) \leq \log \circ L_2^{-1}(\lambda).$$

near zero. Now we proceed exactly as for the upper bound, but with reversed inequalities. \square

4. FØLNER'S FUNCTIONS AND CHEEGER'S INEQUALITY

In this section, we combine Theorem 1.4 with some geometric tools and prove Proposition 1.6. This leads to estimates of the spectral distribution in terms of the Følner's function (1.8), the growth function, and Følner couples.

Throughout this section, Γ denotes a finitely generated group and S denotes a finite symmetric generating set of Γ . The Laplace operator Δ , the spectral distribution N , and the L^2 -isoperimetric profile Λ are taken with respect to the probability measure (1.7). For statements up to equivalence, the specific choice of an admissible probability measure does not matter (Theorem 1.10).

We refer to [12, Theorem 2.3] for a proof of the combinatorial version of Cheeger's inequality:

Theorem 4.1 (Cheeger's inequality).

$$\lambda_1(\Omega) \geq \frac{1}{2|S|^2} \left(\inf_{\omega \subset \Omega} \frac{|\partial_S \omega|}{|\omega|} \right)^2.$$

Lemma 4.2. *Let F be a continuous strictly increasing positive function defined on a neighborhood of infinity with $\lim_{r \rightarrow \infty} F(r) = \infty$. Let $\alpha > 0$ and $\beta \geq 0$. For large $v > 0$ we define*

$$L(v) = \frac{\alpha}{(F^{-1}(v) - \beta)^2}.$$

Assume that there exists a constant $C > 1$ such that for large $r > 0$

$$F(Cr) \geq F(r)^2.$$

Then the function $L \circ \exp$ is doubling near infinity.

Proof. In a neighborhood of zero, we have:

$$L^{-1}(\lambda) = F(\alpha^{1/2}\lambda^{-1/2} + \beta).$$

This function is dilatationally equivalent to $F(\lambda^{-1/2})$. Hence we have the dilatational equivalence

$$\log \circ L^{-1}(\lambda) \simeq \log \circ F(\lambda^{-1/2}).$$

But,

$$2 \log(F(\lambda^{-1/2})) = \log(F(\lambda^{-1/2})^2) \leq \log(F(C\lambda^{-1/2})) = \log(F((C^{-2}\lambda)^{-1/2})).$$

Hence there is a constant $\delta > 0$ such that, near zero,

$$2 \log \circ L^{-1}(\lambda) \leq \log \circ L^{-1}(\alpha\lambda).$$

From this we deduce that $L \circ \exp$ is doubling near infinity. \square

Proof of Proposition 1.6. We will apply Theorem 1.4 (1) with

$$L(v) = \frac{1}{F^{-1}(v)^2}.$$

The doubling of $L \circ \exp$ follows from Lemma 4.2. Hence the corollary will be proved if we show that

$$\Lambda(v) \succeq L(v),$$

for large $v > 0$. Let $\alpha \geq 1, \beta \geq 1$ such that $F(r) \leq \alpha \text{F}\phi l(\beta r)$ near infinity. As $\text{F}\phi l$ increases and $\lim_{r \rightarrow \infty} \text{F}\phi l(r) = \infty$, for a given large $v > 0$, there exists $x > 0$ such that

$$\text{F}\phi l(x-1) < v \leq \text{F}\phi l(x).$$

Hence, if $|\Omega| < v$, then

$$\frac{|\partial_S \Omega|}{|\Omega|} \geq \frac{1}{x}.$$

On the other hand, as F^{-1} is strictly increasing, we obtain

$$(x-1)/\beta = F^{-1}(F((x-1)/\beta)) \leq F^{-1}(\alpha \text{F}\phi l(x-1)) < F^{-1}(\alpha v).$$

Cheeger's inequality implies that

$$\Lambda(v-1) \geq \frac{1}{2|S|^2} \min_{|\Omega| \leq v-1} \left(\frac{|\partial_S \Omega|}{|\Omega|} \right)^2.$$

We deduce that

$$\Lambda(v/2) \geq \frac{1}{2|S|^2(\beta F^{-1}(\alpha v) + 1)^2},$$

which yields $\Lambda \succeq L$. \square

Proposition 4.3. *Let Γ be a finitely generated group. Assume there exists a sequence of finite subsets $(\Omega_n)_{n \in \mathbb{N}}$ of Γ with the following properties:*

- (1) *There exists a constant $\alpha \geq 1$, such that $\lambda_1(\Omega_n) \leq \alpha/n^2$.*
- (2) *$|\Omega_n| < |\Omega_{n+1}|$.*
- (3) *There exists $C > 1$ such that the piecewise linear extension $F : [1, \infty) \rightarrow \mathbb{R}$ of the function $n \mapsto |\Omega_n|$ satisfies $F(Cr) \geq F(r)^2$ for large $r > 0$.*

Then, near zero,

$$N(\lambda) \succeq \frac{1}{F(\lambda^{-1/2})}.$$

Proof. Define

$$L(v) = \frac{\alpha}{(F^{-1}(v) - 1)^2}.$$

The inverse function $L^{-1}(\lambda) = F(\alpha^{1/2}\lambda^{-1/2} + 1)$ is dilatationally equivalent to $F(\lambda^{-1/2})$ near zero. By Lemma 4.2 the function $L \circ \exp$ is doubling near infinity. Hence the assertion will follow from Theorem 1.4 (2) once it has been shown that $\Lambda(v) \leq L(v)$ near infinity. Let $v > 1$. Let $n \in \mathbb{N}$ be determined by $F^{-1}(v) - 1 < n \leq F^{-1}(v)$. From the definition of F we get

$$|\Omega_n| = F(n) \leq F(F^{-1}(v)) = v.$$

But, by hypothesis,

$$\lambda_1(\Omega_n) \leq \frac{\alpha}{n^2} \leq \frac{\alpha}{(1 - F^{-1}(v))^2} = L(v). \quad \square$$

The above proposition is inspired from [13, Proposition 2] and [10, Theorem 4.7]. As mentioned in [13, Proposition 2], the required upper bound $\lambda_1(\Omega_n) \leq \frac{\alpha}{n^2}$ holds in the case there exists $\omega_n \subset \Omega_n$ such that $d_S(\omega_n, \Gamma \setminus \Omega_n) > \epsilon n$, and such that $|\Omega_n| \leq C|\omega_n|$, where $\epsilon > 0, C \geq 1$ are constants independent of n . The pairs (Ω_n, ω_n) are called *Følner couples*. In several examples, this approach leads to lower bounds on $N(\lambda)$ that match the upper bounds deduced from Proposition 1.6. In particular, for all the examples listed in Table 1.4 it leads to matching bounds. We refer the reader to [10, 13, 23, 26] for the construction of Følner couples.

5. STABILITY

This section is devoted to the proof of Theorem 1.10. It is possible to deduce this theorem from [20, Proposition 4.1] if both measures are assumed to have finite support. The general case requires a direct proof:

Proof of Theorem 1.10. For a probability measure μ on Γ , consider the following bounded, Γ -equivariant operator

$$C_\mu : \bigoplus_{s \in \text{supp}(\mu)} l^2(\Gamma) \xrightarrow{\oplus_{s \in \text{supp}(\mu)} (\mu(s)/2)^{1/2} R_{s-1}} l^2(\Gamma),$$

where $R_{s-1} : l^2(\Gamma) \rightarrow l^2(\Gamma)$ is right convolution by $\delta_s - \delta_e$ (or in other words, right multiplication by $s - 1$). If μ is symmetric, we compute

$$\begin{aligned} C_\mu C_\mu^* &= \sum_{s \in \text{supp}(\mu)} \frac{\mu(s)}{2} R_{2-s-s^{-1}} = \sum_s \mu(s) \text{id} - \frac{1}{2} \sum_s \mu(s) R_s - \frac{1}{2} \sum_s \mu(s) R_{s^{-1}} \\ (5.1) \quad &= 1 - \sum_s \mu(s) R_s \\ &= \Delta_\mu. \end{aligned}$$

So we have to show that the spectral distributions of $C_{\mu_1} C_{\mu_1}^*$ and $C_{\mu_2} C_{\mu_2}^*$ are equivalent near zero. Without loss of generality, we may and will assume that the density of μ_2 is $\sum_{s \in S} \delta_s / |S| \in l^1(\Gamma)$ for a finite, symmetric generating set S . Throughout, direct sums of Hilbert spaces are understood to be completed direct sums.

Firstly, we show that there is a bounded, Γ -equivariant operator F that makes the following square commutative.

$$\begin{array}{ccc} \bigoplus_{h \in \text{supp}(\mu_1)} l^2(\Gamma) & \xrightarrow{C_{\mu_1}} & l^2(\Gamma) \\ \downarrow F & & \downarrow \text{id} \\ \bigoplus_{s \in S} l^2(\Gamma) & \xrightarrow{C_{\mu_2}} & l^2(\Gamma) \end{array}$$

To this end, choose for every $\gamma \in \Gamma$ a path w^γ in the Cayley graph $\text{Cayl}(\Gamma, S)$ from e to γ of length $n = l(\gamma)$. Further, let $(v_0^\gamma, \dots, v_n^\gamma)$ denote the successive vertices of w^γ , and $(w_1^\gamma, \dots, w_n^\gamma)$ the successive oriented edges of w^γ . Note that $v_0^\gamma = e$ and w_i^γ has endpoints v_{i-1}^γ and v_i^γ . The matrix representation $F = (F_{s,h})_{h \in \text{supp}(\mu_1), s \in S}$ of F is given by

$$F_{s,h} = (|S|\mu_1(h))^{1/2} \sum_{1 \leq i \leq l(h), w_i^h = s} R_{v_{i-1}^h}.$$

The map F is well defined on the dense subset $\bigoplus_{s \in \text{supp}(\mu_1)} \mathbb{C}\Gamma$. It is straightforward to verify that F is bounded with operator norm

$$\|F\|^2 \leq \sum_{h \in \text{supp}(\mu_1)} |S|^2 \mu_1(h) l(h)^2 < \infty.$$

To see that this F makes the above square commutative, by $\mathbb{C}\Gamma$ -linearity, one only has to verify that for the unit element $1_h \in \bigoplus_{\text{supp}(\mu_1)} l^2\Gamma$ in the copy of $l^2\Gamma$ associated to some $h \in \text{supp}(\mu_1)$ we have

$$C_{\mu_2} \left(\sum_{s \in S} F_{s,h}(1_h) \right) = C_{\mu_1}(1_h) = \left(\frac{\mu_1(h)}{2} \right)^{1/2} (h-1).$$

But this follows from:

$$\begin{aligned} C_{\mu_2} \left(\sum_{s \in S} F_{s,h}(1_h) \right) &= \sum_{s \in S} \left(\frac{\mu_2(s)|S|\mu_1(h)}{2} \right)^{1/2} \sum_{1 \leq i \leq l(h), w_i^h = s} v_{i-1}^h (s-1) \\ &= \left(\frac{\mu_1(h)}{2} \right)^{1/2} \sum_{s \in S} \sum_{1 \leq i \leq l(h), w_i^h = s} v_{i-1}^h (s-1) \\ &= \left(\frac{\mu_1(h)}{2} \right)^{1/2} \sum_{1 \leq i \leq l(h)} v_i^h - v_{i-1}^h \\ &= \left(\frac{\mu_1(h)}{2} \right)^{1/2} (h-1). \end{aligned}$$

Let $\alpha : \mathbb{C}\Gamma \rightarrow \mathbb{C}$ be the linear map uniquely defined by $\alpha(\gamma) = 1$ for every $\gamma \in \Gamma$. For a finite generating set $T \subset \Gamma$, consider the map

$$\phi_T : \bigoplus_{t \in T} \mathbb{C}\Gamma \xrightarrow{\oplus R_{t-1}} \mathbb{C}\Gamma.$$

It satisfies $\text{im}(\phi_T) = \ker(\alpha)$. This is either proved directly (see [5, Exercise 1 on p. 12]) or by noting that ϕ_T is the first differential in a free $\mathbb{C}\Gamma$ -resolution of \mathbb{C} (or, topologically, in the cellular chain complex of a model of the universal space $E\Gamma$ that has $\text{Cayl}(\Gamma, T)$ as

its 1-skeleton [5, (4.3) Example on p. 16]). By assumption there is a finite generating set $T \subset \text{supp}(\mu_1)$. So we have

$$\text{im}(C_{\mu_1}|_{\bigoplus_{t \in T} \mathbb{C}\Gamma}) = \text{im}(\phi_T) = \ker(\alpha).$$

Similarly, we have

$$\text{im}(C_{\mu_2}|_{\bigoplus_{s \in S} \mathbb{C}\Gamma}) = \ker(\alpha).$$

For every $s \in S$, pick $x_s \in \bigoplus_{t \in T} \mathbb{C}\Gamma$ with $C_{\mu_1}(x_s) = C_{\mu_2}(1_s) \in \ker(\alpha)$ where $1_s \in \Gamma \subset \mathbb{C}\Gamma$ is the unit element in the s -th component of $\bigoplus_{s \in S} \mathbb{C}\Gamma$. Define $G : \bigoplus_{s \in S} \mathbb{C}\Gamma \rightarrow \bigoplus_{t \in T} \mathbb{C}\Gamma$ to be the unique Γ -equivariant, linear map with $G(1_s) = x_s$ for every $s \in S$. Then G is bounded. We obtain a commutative square:

$$\begin{array}{ccc} \bigoplus_{h \in \text{supp}(\mu_1)} l^2(\Gamma) & \xrightarrow{C_{\mu_1}} & l^2(\Gamma) \\ \uparrow G & & \uparrow \text{id} \\ \bigoplus_{s \in S} l^2(\Gamma) & \xrightarrow{C_{\mu_2}} & l^2(\Gamma). \end{array}$$

Let $\text{pr}_1 : \bigoplus_{h \in \text{supp}(\mu_1)} l^2(\Gamma) \rightarrow \ker(C_{\mu_1})^\perp$ be the projection onto the orthogonal complement $\ker(C_{\mu_1})^\perp$ of $\ker(C_{\mu_1})$, and similarly, let pr_2 be the projection onto $\ker(C_{\mu_2})^\perp$. Then we obtain two commutative squares

$$\begin{array}{ccc} \ker(C_{\mu_1})^\perp & \xrightarrow{C_{\mu_1}} & l^2(\Gamma) \\ \downarrow \text{pr}_2 \circ F & & \downarrow \text{id} \\ \ker(C_{\mu_2})^\perp & \xrightarrow{C_{\mu_2}} & l^2(\Gamma) \end{array} \quad \begin{array}{ccc} \ker(C_{\mu_1})^\perp & \xrightarrow{C_{\mu_1}} & l^2(\Gamma) \\ \uparrow \text{pr}_1 \circ G & & \uparrow \text{id} \\ \ker(C_{\mu_2})^\perp & \xrightarrow{C_{\mu_2}} & l^2(\Gamma). \end{array}$$

The commutativity and the injectivity of C_{μ_1} and C_{μ_2} when restricted to $\ker(C_{\mu_1})^\perp$ and $\ker(C_{\mu_2})^\perp$, respectively, already imply that $\text{pr}_2 \circ F$ is an isomorphism with inverse $\text{pr}_1 \circ G$. One easily verifies that

$$(5.2) \quad (C_{\mu_i}|_{\ker^\perp}) \circ (C_{\mu_i}|_{\ker^\perp})^* = C_{\mu_i} \circ C_{\mu_i}^*.$$

We apply Efremov-Shubin's *min-max principle* [20, (1.3); 22, Definition 2.1 and Lemma 2.3 on pp. 73-74] which says that

$$\text{tr}_\Gamma(E_{\lambda^2}^{A^*A}) = \sup\{\text{tr}_\Gamma(\text{pr}_L); L \subset l^2(\Gamma) \text{ closed } \Gamma\text{-invariant}, \|Ax\| \leq \lambda\|x\| \ \forall x \in L\}.$$

to the operator $A = (C_{\mu_1}|_{\ker(C_{\mu_1})^\perp})^* = (\text{pr}_2 \circ F)^*(C_{\mu_2}|_{\ker(C_{\mu_2})^\perp})^*$. From this, combined with (5.1) and (5.2), we obtain, setting $B = (C_{\mu_2}|_{\ker(C_{\mu_2})^\perp})^*$ and $T = (\text{pr}_2 \circ F)^*$, that

$$\begin{aligned} N_{\mu_1}(\lambda^2) &= \sup\{\text{tr}_\Gamma(\text{pr}_L); L \subset l^2(\Gamma), \|Ax\| = \|TBx\| \leq \lambda\|x\| \ \forall x \in L\} \\ &\leq \sup\{\text{tr}_\Gamma(\text{pr}_L); L \subset l^2(\Gamma), \|Bx\| = \|T^{-1}TBx\| \leq \|T^{-1}\|\lambda\|x\| \ \forall x \in L\} \\ &= N_{\mu_2}(\|T^{-1}\|^2 \lambda^2). \end{aligned}$$

A similar argument yields $N_{\mu_2}(\lambda^2) \leq N_{\mu_1}(\|T\|^2 \lambda^2)$. □

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