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EIGENVALUE PINCHING ON CONVEX DOMAINS IN SPACE FORMS

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Abstract. In this paper, we show that the convex domains of $\mathbb{H}^n$ which are almost extremal for the Faber-Krahn or the Payne-Polya-Weinberger inequalities are close to geodesic balls. Our proof is also valid in other space forms and allows us to recover known results in $\mathbb{R}^n$ and $\mathbb{S}^n$.

1. Introduction

This paper aims to study some optimal inequalities involving the first eigenvalues of the Dirichlet spectrum of convex domains in space forms, and to ask how stable they are. The paper essentially deals with the most intricate case of the hyperbolic space.

The inequalities we are interested in are the Faber-Krahn inequality and the Payne-Polya-Weinberger inequality. The Faber-Krahn inequality asserts that among all bounded domains with the same volume in a given space form, the geodesic ball has the smallest first Dirichlet eigenvalue. Moreover, the geodesic ball is the unique minimizer (up to an isometry) among smooth domains. In this setting, such an inequality is stable if a bounded domain Ω whose $\lambda_1(\Omega)$ is close to $\lambda_1(B)$ (B is a geodesic ball with the same volume as Ω) is close for the Hausdorff distance to B (up to an isometry). This general statement does not hold true, because it is possible to attach very long and thin tentacles to a ball without affecting significantly the volume and the spectrum. In fact, for Euclidean domains, weaker forms of stability have been established. One form is to prove that a domain whose first Dirichlet eigenvalue is close to the first eigenvalue of a suitable ball, resembles a ball up to sets of small volume (see [17] for a precise statement). The other form is to consider only convex bodies; in this case, the Faber-Krahn inequality is stable [16]. The stability of the Faber-Krahn inequality has also been established for convex domains in $\mathbb{H}^2$ and $\mathbb{S}^2$ [3].

The first result of this paper is to prove the stability of the Faber-Krahn inequality for convex domains in a space form of arbitrary dimension and arbitrary curvature. In the sequel, we will denote by $X^1 = (\mathbb{S}^n, can)$, $X^0 = (\mathbb{R}^n, can)$ and $X^{-1} = (\mathbb{H}^n, can)$ the space forms of curvature 1, 0 and -1 respectively. Except when stated otherwise, the results in this paper hold true for $\delta \in \{-1, 0, 1\}$.

Theorem 1.1. *Let $V_0 > 0$. Let $\lambda_1^*(V_0)$ be the first Dirichlet eigenvalue of a geodesic ball B of volume V_0 in X^δ. For any $\epsilon > 0$, there exists $\eta > 0$ such that, if Ω is*

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a convex domain of volume V_0 in X^δ and if $\lambda_1(\Omega) \le \lambda_1^*(V_0) + \eta$, then, up to an isometry,

$$d_H(\Omega, B) \le \epsilon,$$

where d_H denotes the Hausdorff distance. In the case $\delta=0$, we have $\eta=\eta'(\epsilon)V_0^{-2/n}$.

The method developed is the same whatever the space form. Nevertheless, the case $\delta = -1$ is considerably harder since the hyperbolic space comprises unbounded convex domains with finite volume (this is contrary to the case of $\mathbb{R}^n$, where an upper bound of the type $\mathrm{Diam}\Omega \le C(\mathrm{Vol}\,\Omega, \lambda_1(\Omega), n)$ holds). To deal with this difficulty, we need to prove the thus far unsolved Faber-Krahn inequality for unbounded convex domains.

Proposition 1.2 (Faber-Krahn inequality)**.** *Let Ω be a convex set in X^δ of finite volume V_0. The first Dirichlet eigenvalue of Ω satisfies $\lambda_1(\Omega) \ge \lambda_1^*(V_0)$ where $\lambda_1^*(V_0)$ denotes the first Dirichlet eigenvalue of a geodesic ball of volume V_0. Moreover, the equality $\lambda_1(\Omega) = \lambda_1^*(V_0)$ implies that Ω is isometric to a geodesic ball.*

The second result of this paper concerns the stability of the Payne-Polya-Weinberger inequality (PPW inequality for short). This famous conjecture has been proved by M.S. Ashbaugh and R.D. Benguria [1].

Theorem 1.3 ([1])**.** *Let Ω be a smooth bounded domain in a Euclidean space (resp. a smooth domain included in a hemisphere in $\mathbb{S}^n$). Then, the following inequality holds:*

$$\frac{\lambda_2}{\lambda_1}(\Omega) \le \frac{\lambda_2}{\lambda_1}(B),$$

where B is an arbitrary Euclidean ball (resp. a spherical ball such that $\mathrm{Vol}\, B = \mathrm{Vol}\,\Omega$). Moreover the equality is achieved if and only if Ω is isometric to a geodesic ball.

Remark 1.4. Let us notice that the ratio $\frac{\lambda_2(B)}{\lambda_1(B)}$ is scale-invariant in Euclidean space and that M. Ashbaugh and R. Benguria also showed in [2], that the ratio of the first two eigenvalues of a geodesic ball in $\mathbb{S}^n$ is an increasing function of the radius r (if $r \le \pi/2$). Consequently, the PPW inequality follows directly from the following theorem.

Theorem 1.5 ([1, 2, 4])**.** *Let Ω be a smooth bounded domain in X^δ and such that Ω is included in a hemisphere if $\delta = 1$. The second Dirichlet eigenvalue of Ω satisfies $\lambda_2(\Omega) \le \lambda_2(B)$ where B is a geodesic ball such that $\lambda_1(B) = \lambda_1(\Omega)$. Moreover, the equality holds if and only if Ω is isometric to B.*

It is shown in [4] that λ_2/λ_1 is a decreasing function of the radius of hyperbolic balls and that the PPW is false in $\mathbb{H}^n$. This theorem can be seen as a generalized PPW inequality on space forms. We prove the following stability results.

Theorem 1.6. *Let Ω be a convex domain of $\mathbb{R}^n$ or $\mathbb{S}^n$, whose volume is equal to V_0. For any $\epsilon > 0$ there exists $\eta > 0$ such that for all Ω as above, the assumption $\frac{\lambda_2(\Omega)}{\lambda_1(\Omega)} \ge \frac{\lambda_2(B)}{\lambda_1(B)} - \eta$ implies*

$$d_H(\Omega, B) \le \varepsilon,$$

where B is a (well-centered) geodesic ball of volume V_0.

Remark 1.7. The previous result was already known in Euclidean space; it has been proved by A. Melas [16].

Theorem 1.8. *Let Ω be a convex domain of X^δ with $\lambda_1(\Omega) = \lambda$ ($\lambda > \frac{(n-1)^2}{4}$ if $\delta = -1$). For any $\varepsilon > 0$, there exits η such that for all Ω as above, the assumption $\lambda_2(\Omega) \geq \lambda_2^*(\lambda) - \eta$ implies*

$$d_H(\Omega, B) \leq \varepsilon,$$

where $\lambda_2^*(\lambda)$ is the second Dirichlet eigenvalue of a (well-centered) geodesic ball B of X^δ such that $\lambda_1(B) = \lambda$.

Remark 1.9. Note that in Theorem 1.8, we do not assume the convex domains have finite volume.

As for the Faber-Krahn inequality, we will have to generalize the PPW inequality and the characterization of the case of equality to a more general setting than smooth bounded domains, in order to prove Theorems 1.6 and 1.8 (see Theorems 4.8 and 4.9 for precise statements).

The method we apply to solve these stability questions is rather general and based on the following abstract stability lemma. The proof is straightforward, therefore omitted.

Let X be a topological space and $f : X \to \mathbb{R}$ be a function. We say that f is *coercive* if there exists a compact subset K of X such that $\inf_{X\setminus K} f > \inf_X f$ (we set $\inf_\emptyset f = +\infty$).

Lemma 1.10. *Let X be a topological space. If $f : X \to \mathbb{R}$ is coercive and lower semi-continuous, then f is bounded below, reaches its minimal value and the set $M_f = f^{-1}\{\inf f\}$ of its minima satisfies the following stability property: for any neighborhood U of M_f, there exists $\eta > 0$ such that*

$$f^{-1}\big(]-\infty, \inf f + \eta]\big) \subset U.$$

This lemma is very close to the so-called *lower semi-continuity and compacity method.* This is typically used in the calculus of variations to deal with the problem of the existence of minimizers (see [20, Chapter 1]). It can be applied to a wide variety of problems (as large as the lower semi-continuity and compacity method). It does not, however, give an explicit η.

Our proof also shows that the infimum of the functional λ_1 (resp. $\frac{\lambda_1}{\lambda_2}$) on unbounded convex domains of $\mathbb{H}^n$ with a given volume (resp. with a given λ_1) is strictly larger than those on bounded domains. To our knowledge, this is also a new result.

The paper is organized as follows:

In Section 2 we define a metric on the space $\mathcal{C}$ of convex, bounded domains in X^δ. In Section 3 we show that the eigenvalues and volume functions are continuous on $\mathcal{C}$. In Section 4 we extend the classical Faber-Krahn and Payne-Polya-Weinberger (as its generalized version) inequalities to the set of convex unbounded domains. This level of generality is required in our proof even if this set is restricted to bounded convex domains for the proof of the coercivity. Finally, we reduce the proof of the stability theorems to the proof of the coercivity of the functionals λ_1 and λ_1/λ_2 on the set of bounded convex domains of given volume (resp. given λ_1) and prove the coercivity of these functionals in Sections 5 and 6. For that purpose, we prove several new qualitative results on the spectrum and the eigenfunctions of domains in space forms. For instance, we prove that a convex Euclidean domain with a spectral gap is bounded (hence has a discrete spectrum) and that its diameter is bounded from above by $C(n)\big(\frac{1+\lambda_1}{\lambda_2-\lambda_1}\big)^{3/2}$, where $C(n)$ is a universal (explicit) constant.

2. A distance on convex domains

In the following, we set $s_1(t)=\sin t$, $s_0(t)=t$, $s_{-1}(t)=\sinh t$ and $c_\delta=s'_\delta$. Let x_0 denote a fixed point in X^δ.

Definition 2.1. Let $\mathcal{C}$ be the set of convex, bounded and open subsets Ω strictly included in X^δ, which contain the point x_0.

Remark 2.2. The isometry group of X^δ acts transitively on X^δ.

Remark 2.3. Each proper, convex set of the sphere is included in a hemisphere. Hence, up to the sphere itself, all convex domains Ω in $\mathbb{S}^n$ satisfy $\mathrm{Vol}(\Omega)\leq \mathrm{Vol}\,\mathbb{S}^n/2$ and $\lambda_1(\Omega)\geq n$.

So, Theorems 1.1, 1.6 and 1.8 are obvious in the case $\Omega=\mathbb{S}^n$, and we just have to prove them for domains $\Omega\in\mathcal{C}$.

In the remaining part of this section we define a (proper) metric on $\mathcal{C}$. We chose to work with a metric which has a better behaviour than the usual Hausdorff metric with respect to the volume and the Dirichlet spectrum. To define this metric, we need some facts on support functions.

2.1. Support functions.

For any $\Omega\in\mathcal{C}$, the following function will be called *the support of* Ω:

$$\rho_\Omega : v\in S_{x_0}\mapsto \sup\{t\in\mathbb{R}_+|\exp_{x_0}(sv)\in\Omega \text{ for all } s\in[0,t]\}\in\mathbb{R}_+,$$

where S_{x_0} and $\exp_{x_0}$ are the set of unit tangent vectors and the exponential map of X^δ at x_0 respectively. Note that $\rho_\Omega\leq R$ as soon as $\Omega\subset B(x_0,R)$. The properties of ρ_Ω needed subsequently are summarized in the following lemma.

Lemma 2.4. *The function ρ_Ω is a Lipschitz function. Under the assumption $B(x_0,r)\subset\Omega\subset B(x_0,R)$, its Lipschitz constant is bounded above by $s_\delta(R)\sqrt{\left(\frac{s_\delta(R)}{s_\delta(r)}\right)^2-1}$ if $\delta\neq1$, and by* $\operatorname{cotg} r$ *otherwise. Moreover,*

$$\overline{\Omega}=\exp_{x_0}\{t.v|\,v\in S_{x_0},\,0\leq t\leq\rho_\Omega(v)\},\ \ \Omega=\exp_{x_0}\{t.v|\,v\in S_{x_0},\,0\leq t<\rho_\Omega(v)\},$$
$$\partial\Omega=\exp_{x_0}\{\rho_\Omega(v).v|\,v\in S_{x_0}\}.$$

Proof. Fix $y_0=\exp_{x_0}(\rho_\Omega(u_0)u_0)\in\partial\,\Omega$ and consider the geodesic double cone centered at y_0 and tangent to the ball $B(x_0,r)$. For each $v\in S_{x_0}\setminus\{u_0\}$ close enough to u_0, the geodesic $\gamma_v(t)=\exp_{x_0}(tv)$ meets the cone in exactly two points $Z(v),Z'(v)$ and we have $l(d_{S_{x_0}}(v,u_0))\leq\rho_\Omega(v)\leq L(d_{S_{x_0}}(v,u_0))$, where

$$l\big(d_{S_{x_0}}(v,u_0)\big)=\min\{d(x_0,Z(v)),d(x_0,Z'(v))\},$$

and

$$L\big(d_{S_{x_0}}(v,u_0)\big)=\max\{d(x_0,Z(v)),d(x_0,Z'(v))\}.$$

We denote by β the half angle at y_0 of the geodesic double cone tangent to the ball $B(x_0,r)$. By the law of sines we have $\sin\beta=\frac{s_\delta(r)}{s_\delta\left(d(x_0,y_0)\right)}$ and $\frac{s_\delta\left(l(t)\right)}{\sin\beta}=\frac{s_\delta\left(l_1(t)\right)}{\sin t}$, where $l_1\big(d(u_0,v)\big)=d(x_0,Z(v))$. By letting t tend to 0 we get $l_1'(0)=\frac{s_\delta^2\left(d(x_0,y_0)\right)}{s_\delta(r)}$. On the other hand, the cosine law gives us the equation $c_\delta(l)=c_\delta(l_1)c_\delta\big(d(x_0,y_0)\big)+$

$\delta s_\delta(l_1)s_\delta\big(d(x_0,y_0)\big)\cos\beta$ (resp. $l^2=l_1^2+\big(d(x_0,y_0)\big)^2-2l_1d(x_0,y_0)\cos\beta$ if $\delta=0$), whose derivative at $t=0$ gives $l'(0)=-l_1'(0)\cos\beta$. So

$$l'(0)=-s_\delta\big(d(x_0,y_0)\big)\sqrt{\Big(\frac{s_\delta\big(d(x_0,y_0)\big)}{s_\delta(r)}\Big)^2-1}.$$

By replacing β by $\pi-\beta$ in what precedes we get $L'(0)=-l'(0)$. Hence we have

$$\begin{aligned}\liminf_{v\to u_0}\frac{\rho_\Omega(v)-\rho_\Omega(u_0)}{d_{S_{x_0}}(v,u_0)}&\geq\liminf_{v\to u_0}\frac{l\big(d_{S_{x_0}}(v,u_0)\big)-l(0)}{d_{S_{x_0}}(v,u_0)}\\&=l'(0)=-s_\delta\big(d(x_0,y_0)\big)\sqrt{\Big(\frac{s_\delta\big(d(x_0,y_0)\big)}{s_\delta(r)}\Big)^2-1}\end{aligned}$$

and

$$\begin{aligned}\limsup_{v\to u_0}\frac{\rho_\Omega(v)-\rho_\Omega(u_0)}{d_{S_{x_0}}(v,u_0)}&\leq\limsup_{v\to u_0}\frac{L\big(d_{S_{x_0}}(v,u_0)\big)-L(0)}{d_{S_{x_0}}(v,u_0)}\\&=L'(0)=s_\delta\big(d(x_0,y_0)\big)\sqrt{\Big(\frac{s_\delta\big(d(x_0,y_0)\big)}{s_\delta(r)}\Big)^2-1},\end{aligned}$$

which implies that ρ_Ω is Lipschitzian and gives the bound on the constant by monotony properties of s_δ.

The last three equalities of the statement follow easily from the continuity of ρ_Ω and standard properties of the exponential map. □

2.2. **A distance on convex bounded domains.**

Definition 2.5. We set $d(\Omega_1,\Omega_2)=\|\ln\big(\frac{\rho_{\Omega_1}}{\rho_{\Omega_2}}\big)\|_\infty$, a metric on $\mathcal{C}$.

Proposition 2.6. *Every closed, bounded subset of $\big(\mathcal{C},d\big)$ is compact.*

Proof. Let $(\Omega_i)_{i\in\mathbb{N}}$ be a bounded sequence in $\mathcal{C}$. Since there exist r and R such that $B(x_0,r)\subset\Omega_i\subset B(x_0,R)$ for every $i\in\mathbb{N}$, the functions $\rho_{\Omega_i}:S_{x_0}\to[r,R]$ are equicontinuous by Lemma 2.4, and so the sequence $(\rho_{\Omega_i})_{i\in\mathbb{N}}$ converges uniformly on S_{x_0} to a function $r\leq\rho_\infty\leq R$, up to an extraction. We have that $\lim\limits_{i\to\infty}\|\ln\big(\rho_{\Omega_i}/\rho_\infty\big)\|_\infty=0$ and the set $\Omega_\infty=\{\exp_{x_0}\big(t.v\big)/\,v\in S_{x_0},\,t\in[0,\rho_\infty(v)[\}$ is bounded, star-shaped and $\rho_{\Omega_\infty}=\rho_\infty$ since ρ_∞ is continuous and $\exp_{x_0}$ is a diffeomorphism of a neighbourhood of $B(0,R)$ onto a neighbourhood of $B(x_0,R)$. It remains to prove that Ω_∞ is convex.

Let y_1 and y_2 be any pair of points in Ω_∞. There exists only one minimizing geodesic γ from y_1 to y_2 in X^δ (Ω_∞ is an open set of a hemisphere in the case $\delta=1$). Since y_1 and y_2 are in Ω_j for all j large enough, we easily infer that $\gamma\subset\overline{\Omega}_\infty=\{\exp_{x_0}\big(t.v\big)|\,v\in S_{x_0},\,t\in[0,\rho_\infty(v)]\}$. So for any $r>0$ small enough, the union of the minimizing geodesic from y_1 (resp. from y_2) to a point of $B(y_2,r)$ (resp. of $B(y_1,r)$) is contained in $\overline{\Omega}_\infty$. Since y_1 (resp. y_2) is in the injectivity domain of y_2 (resp. y_1), the union of these two sets is an open neighbourhood of γ contained in $\overline{\Omega}_\infty$, which implies the convexity of Ω_∞, the interior set of $\overline{\Omega}_\infty$. □

Corollary 2.7. *For any $R\geq r>0$, the Ω of $\mathcal{C}$ with $B(x_0,r)\subset\Omega\subset B(x_0,R)$ form a compact set.*

3. Continuity of the volume and the eigenvalues

As proved in [9], any weak solution in $H_0^1(\Omega)$ of $\Delta u = \lambda u$ on a convex (in fact Lipschitzian) domain Ω belongs to $C^\infty(\Omega)\cap\mathcal{C}^0(\overline{\Omega})$ and is equal to 0 on $\partial\Omega$. Moreover, the Dirichlet spectrum of any open subset Ω of finite volume in X^δ is discrete [19, Corollary 10.10]. In this case, all the eigenvalues $\big(\lambda_k(\Omega)\big)_{k\in\mathbb{N}^*}$ satisfy the min-max principle below:

$$\lambda_k(\Omega) = \inf\{m(E)|\, E \text{ subspace of } \mathcal{C}_c^\infty(\Omega), \dim E = k\} \quad \text{where } m(E) = \sup_{f\in E}\frac{\int_\Omega |\nabla f|^2}{\int_\Omega f^2}.$$

We will say that an arbitrary open set Ω *has a spectral gap* if $\lambda_1(\Omega) < \lambda_2(\Omega)$ (where $\lambda_1(\Omega)$ and $\lambda_2(\Omega)$ are defined by the min-max principle). This implies that $\lambda_1(\Omega)$ is an eigenvalue of the Dirichlet problem and always occurs when the volume is finite.

Proposition 3.1. *For any $k\geq 1$, the following inequalities hold:*

$$\Big|\ln\Big(\frac{\lambda_k(\Omega_1)}{\lambda_k(\Omega_2)}\Big)\Big| \leq \Lambda_\delta\big[d(\Omega_1,\Omega_2),R\big] \qquad \textit{and} \qquad \Big|\ln\Big(\frac{\operatorname{Vol}\Omega_1}{\operatorname{Vol}\Omega_2}\Big)\Big| \leq \Lambda'_\delta\big[d(\Omega_1,\Omega_2),R\big],$$

where

$$\Omega_1\cup\Omega_2\subset B(x_0,R),\quad \Lambda_\delta(s,t) = \ln\Big[e^{2s}\Big(\frac{e^{2s}s_\delta(te^{-2s})}{s_\delta(t)}\Big)^{\delta(n-1)}\Big],$$

$$\Lambda'_1(s,t) = \Lambda'_0(s,t) = ns \quad \textit{and} \quad \Lambda'_{-1} = \ln\Big[e^{ns}\Big(\frac{e^{-s}\sinh(t)}{\sinh(e^{-s}t)}\Big)^{n-1}\Big].$$

Proof. In the case $\delta = 1$, we denote by y_0 the antipodal point of x_0 in $\mathbb{S}^n$. For $\lambda\in\,]0,1]$, we define the map

$$\begin{aligned} H_\lambda : X^\delta \text{ (resp. } X^1\setminus\{y_0\}) &\ \rightarrow\ X^\delta \\ \exp_{x_0}(tv) &\ \mapsto\ \exp_{x_0}(\lambda t v). \end{aligned} \tag{3.1}$$

Set $d = d(\Omega_1,\Omega_2)$. Since $H_{e^{-d}}(\Omega_1)\subset\Omega_2$ we just have to bound the quotient $\lambda_k\big(H_\lambda(\Omega_1)\big)/\lambda_k(\Omega_1)$ for $\lambda = e^{-d}$. For that purpose, we define a linear injective map $\Phi_\lambda : \mathcal{C}_c^\infty(\Omega)\to\mathcal{C}_c^\infty\big(H_\lambda(\Omega)\big)$ by $\Phi_\lambda(f) = f\circ H_{1/\lambda}$. Easy computations involving Jacobi fields give

$$\lambda\Big(\inf_{t\in]0,R]}\frac{s_\delta(\lambda t)}{s_\delta(t)}\Big)^{n-1}\|f\|_1 \leq \|\Phi_\lambda(f)\|_1 \leq \lambda\Big(\sup_{t\in]0,R]}\frac{s_\delta(\lambda t)}{s_\delta(t)}\Big)^{n-1}\|f\|_1,$$

$$\frac{\big|d\big(\Phi_\lambda(f)\big)\big|^2(x)}{\Phi_\lambda\big(|df|^2\big)(x)} \leq \max\Big(\frac{1}{\lambda^2},\frac{s_\delta^2(d(x_0,x)/\lambda)}{s_\delta^2(d(x_0,x))}\Big).$$

The first inequality applied to $f\equiv 1$ gives the volume estimate. The two inequalities imply

$$\frac{\|d\big(\Phi_\lambda(f)\big)\|_2^2}{\|\Phi_\lambda(f)\|_2^2} \leq e^{\Lambda_\delta(d,R)}\frac{\|df\|_2^2}{\|f\|_2^2}.$$

Using the min-max principle, we obtain

$$\lambda_k(\Omega_2) \leq \lambda_k\big(H_{e^{-d}}(\Omega_1)\big) \leq e^{\Lambda_\delta(d,R)}\lambda_k(\Omega_1).$$

□

4. Extremal convex domains

4.1. **Schwarz symmetrization on noncompact domains.** In this paragraph we recall some basic properties of the Schwarz symmetrization. However, we will have to work with unbounded domains for which additional assumptions on the functions to be symmetrized will be needed. For more details on symmetrization, we refer to [8, 13, 5, 14].

Definition 4.1 (Schwarz symmetrization)**.** Let f be a nonnegative function defined on an open set Ω in the space form X^δ. Let μ_f be the distribution function defined for $s \geq 0$ by $\mu_f(s) = \mathrm{Vol}(\{f > s\})$ and let $V : r \mapsto \mathrm{Vol}(B(r))$ $(r \geq 0)$. The nonincreasing Schwarz symmetrization of f is

$$f^* = \mu_f^\sharp \circ V \circ d_{x_0},$$

where $d_{x_0}(x) = d(x_0, x)$ and $.^\sharp$ refers to the right inverse function of a nonincreasing function (i.e. $u^\#(s) = \inf\{t \geq 0 | u(t) \leq s\}$). If the volume of Ω is finite, the Schwarz nondecreasing symmetrization of f is defined by

$$f_* = \mu_f^\sharp \circ H \circ d_{x_0},$$

where $H : r \mapsto \mathrm{Vol}\,(\Omega) - V(r)$. These symmetrized functions satisfy $\mu_{f^*} = \mu_{f_*} = \mu_f$.

Proposition 4.2. *Let Ω be an open set of finite volume in the space form X^δ. For nonnegative measurable functions f, g on Ω we have that*

$$\int_{\Omega^*} f_* g^* \leq \int_\Omega fg \leq \int_{\Omega^*} f^* g^*. \tag{4.1}$$

If f is in $L^2(\Omega)$ (resp. in $H_0^1(\Omega)$), then u^* is in $L^2(\Omega^*)$ (resp. in $H_0^1(\Omega^*)$) and we have

$$||f||_{L^2(\Omega)} = ||f^*||_{L^2(\Omega^*)}. \tag{4.2}$$

$$(\textit{resp. and} \quad \int_{\Omega^*} |\nabla f^*|^2 \quad \leq \quad \int_\Omega |\nabla f|^2). \tag{4.3}$$

Remark 4.3. In the sequel, we will use the Schwarz symmetrization on convex domains of $\mathbb{H}^n$ whose volume is not assumed to be finite. A priori, the nondecreasing Schwarz symmetrization cannot be defined in this setting; however the inequality

$$\int_{\Omega^*} f_* g^* \leq \int_\Omega fg$$

remains true for a function $f = F \circ d_{x_0}$, where F is a nonnegative and nondecreasing bounded function such that F is constant outside a compact set if we define f_* as $f_*(x) = \begin{cases} (f|_{\Omega \cap B(x_0,r)})_* & \text{if } |x| < r \\ ||f||_\infty & \text{otherwise} \end{cases}$ for r large enough.

Lemma 4.4. *Let Ω be an open set of finite volume in X^δ and f be a smooth nonnegative function in $H_0^1(\Omega) \cap \mathcal{C}^0(\overline{\Omega})$, which is zero on $\partial\Omega$ and whose level sets are compact sets (except maybe $\{f = 0\}$) of measure zero. If $\int_{\Omega^*} |\nabla f|^2 = \int_\Omega |\nabla f|^2$, then the set $\{f > 0\}$ is a ball.*

Proof. By assumption, the set $\mathrm{Reg}(f)$ of regular points of f included in $\{x \in \Omega \,|\, f > 0\}$ is an open set of full measure in $\{x \in \Omega \,|\, f > 0\}$. As a consequence, we deduce that f^* is continuously differentiable on an open set of full measure of $\{f^* > 0\}$

and satisfies the inequality (4.3) thanks to the coarea formula and the isoperimetric inequality (we refer to [6] for more details). We conclude that $\{f > 0\}$ is a ball, using a decreasing sequence of regular values which goes to 0 and the case of equality in the isoperimetric inequality. □

Remark 4.5. The set of functions which satisfy the assumptions of Lemma 4.4 contains the smooth functions with compact support and only nondegenerate critical points; therefore it is dense in $H_0^1(\Omega)$ (see [6] and the references herein).

4.2. **Faber-Krahn inequality.** In this section, we prove Proposition 1.2. The characterization of the case of equality without assuming that Ω is bounded will be crucial in our proof of Theorem 1.1, when $\delta = -1$.

Proof. The proof of the inequality follows from Proposition 4.2 and does not rely on the convexity of Ω. As the volume of Ω is assumed to be finite, the Dirichlet spectrum of Ω is discrete [19, Corollary 10.10] and the eigenfunctions belong to $C^\infty(\Omega)\cap\mathcal{C}^0(\overline{\Omega})$ [9, Corollary 8.11 and Theorem 8.29]. To prove the case of equality, it is sufficient to prove that the first eigenfunction (denoted by f_1) satisfies the assumptions of Lemma 4.4, which is a consequence of the lemma below. Indeed, thanks to this lemma and Sard's Theorem, the set of singular values of f_1 is a closed set of measure zero. Then, thanks to the fact that the function $\Delta f_1 = \lambda_1 f_1$ is positive on Ω, we deduce that each level set of the first eigenfunction is of measure zero. □

Lemma 4.6. *Under the assumptions of Proposition* 1.2*, the first Dirichlet eigenfunction f_1 on Ω can be assumed to be positive and proper: for all $s > 0$, the set $f_1^{-1}([s, +\infty[)$ is a compact set.*

Proof. By the maximum principle, we can suppose f_1 to be positive. To prove the second assertion, set y_0 to be a fixed point of Ω, $R \geq 1$ and $x_0 \in \Omega \setminus B(y_0, 2R)$. Recall (see for instance [7]) that there exists a constant $C(n)$ such that

$$(*) \qquad \forall x_0 \in X^\delta, \quad \forall v \in H_0^1\big(B(x_0,1)\big), \quad \|v\|^2_{\frac{2n}{n-2}} \leq C(n)\|dv\|_2^2.$$

Note that in dimension $n = 2$, this inequality has to be replaced by $\|v\|_4^2 \leq C\|dv\|_2^2$ in what follows. A standard Moser's iteration gives

$$f_1^2(x_0) \leq A(n)\big(1+\lambda_1\big)^{\gamma(n)} \int_{B(x_0,1)} f_1^2 \tag{4.4}$$

(where $A(n)$ and $\gamma(n)$ are constants that depend only on the dimension n; see [10] for a proof), and from which we infer that

$$\sup_{\Omega\setminus B(y_0,2R)} f_1^2 \leq A(n)\big(1+\lambda_1\big)^{\gamma(n)} \int_{\Omega\setminus B(y_0,R)} f_1^2.$$

This gives the compactness of the sets $f_1^{-1}\big([s,+\infty[\big)$ for all $s > 0$ since $\int_{\Omega\setminus B(y_0,R)} f_1^2 \to 0$ when $R \to \infty$ and f_1 is continuous on the convex set $\overline{\Omega}$ and is equal to 0 on $\partial\Omega$. □

Remark 4.7. Let us remark that the assumption on the finiteness of the volume in Proposition 1.2 and Lemma 4.6 is used only to ensure that the bottom of the spectrum is an eigenvalue. This fact will be used in paragraph 4.3.

On the contrary, even when the domain is bounded, some regularity on the boundary is needed to deduce the case of equality. Indeed each ball with closed sets of capacity zero removed satisfies the case of equality.

4.3. **Payne-Polya-Weinberger inequality.** In this paragraph we prove the following extensions of Theorems 1.3 and 1.5.

Theorem 4.8 (Payne-Polya-Weinberger inequality)**.** *Let Ω be a convex set of finite volume V_0 in X^δ ($\delta \in \{0,1\}$). Under these assumptions, the following inequality is satisfied:*

$$\frac{\lambda_2}{\lambda_1}(\Omega) \leq \frac{\lambda_2^*}{\lambda_1^*}(V_0).$$

Moreover, the equality is achieved if and only if Ω is isometric to a geodesic ball.

Theorem 4.9. *Let Ω be a convex set in X^δ such that $\Omega \neq X^\delta$. Then the spectral gap of Ω is smaller or equal to $\lambda_2(B) - \lambda_1(B)$ (where B is a geodesic ball such that $\lambda_1(B) = \lambda_1(\Omega)$). If the spectral gap is equal to $\lambda_2(B) - \lambda_1(B)$, Ω is isometric to a geodesic ball.*

Let us remark that contrary to the cases $\delta \in \{0,1\}$, the assumptions in Theorem 4.9 do not imply an upper bound on the volume of Ω in $\mathbb{H}^n$.

We will prove Theorems 4.8 and 4.9 simultaneously. The scheme of the proof is the same as in [1, 2, 4], so we will mainly focus on the extra arguments needed in our setting. The first step of the proof is the following proposition.

Proposition 4.10. *Let Ω be an open subset of X^δ (included in a hemisphere if $\delta = 1$) with a spectral gap, u_1 an eigenfunction of Ω for the first eigenvalue and g be a positive, piecewise $\mathcal{C}^1$ function on $[0,\infty[$ (and with $\liminf_{+\infty} g > 0$ if Ω is not bounded). Then, there exists a point $x_m \in X^\delta$ such that*

$$\lambda_2(\Omega) - \lambda_1(\Omega) \leq \frac{\int_\Omega b\big(d(x_m,y)\big)u_1^2(y)\,dy}{\int_\Omega g^2\big(d(x_m,y)\big)u_1^2(y)\,dy},$$

where $b = g'^2 + \frac{n-1}{s_\delta^2}g^2$.

Note that in the proof of Theorem 4.9, we can suppose that the spectral gap is nonzero.

Proof. The min-max principle implies that

$$\lambda_2(\Omega) - \lambda_1(\Omega) \leq \frac{\int_\Omega |\nabla P|^2 u_1^2}{\int_\Omega P^2 u_1^2},$$

for every nonzero function P such that Pu_1 is in $H_0^1(\Omega)$ and $\int_\Omega P u_1^2 = 0$.

The next step consists in choosing n suitable test functions. For that purpose, we need the following lemma which extends a result of [1, 2, 4] (the proof is postponed to Section 7).

Lemma 4.11. *For any $u \in L^2(X^\delta)$ (with support in a hemisphere if $\delta = 1$) and any $g : \mathbb{R}^+ \to \mathbb{R}^+$ continuous (bounded and with $\liminf_{+\infty} g > 0$ if u does not have compact support), there is $x \in X^\delta$ such that*

$$\int_{X^\delta} g\big(d(x,y)\big)\frac{\exp_x^{-1}(y)}{d(x,y)}u^2(y)\,dy = 0_{T_xX^\delta}.$$

In order to construct test functions, we apply this lemma to $u = u_1.1_\Omega$ and g a nonnegative, increasing and bounded function (g will be specified later). The functions $P_i = g(r)X_i$, where (r, X_i) are the geodesic coordinates at the point x_m given by Lemma 4.11, satisfy $\int_\Omega P_i u_1^2 = 0$ for every i. To conclude the proof of Proposition 4.10, we just have to sum the n inequalities given by the min-max principle applied to the P_i ,and note that $\sum_i P_i^2 = g^2$ and $\sum_i |\nabla P_i|^2 = b$.

Now, we choose g to be a radial function such that the equality below holds:

$$\lambda_2(B) - \lambda_1(B) = \frac{\int_B bz^2}{\int_B g^2 z^2},$$

where z is a positive first eigenfunction of B. It is shown in [1, 2, 4] that we can choose g positive, nondecreasing and constant outside B and such that b is radial, positive and nonincreasing. We recall that B is such that $\lambda_1(B) = \lambda_1(\Omega)$. It remains to compare the spectral gaps. For that purpose, we first use properties of the Schwarz symmetrization (Proposition 4.2). We get

$$\int_\Omega b\, u_1^2 \leq \int_{\Omega^*} b^* u_1^{*2} \leq \int_{\Omega^*} b\, u_1^{*2} \qquad \text{and} \qquad \int_\Omega g\, u_1^2 \geq \int_{\Omega^*} g_* u_1^{*2} \geq \int_{\Omega^*} g\, u_1^{*2}.$$

The inequality involving the nonincreasing Schwarz symmetrization is valid without any assumption on the volume, thanks to Remark 4.3. We conclude using the Chiti comparison result, which allows us to compare z with u_1^* on B. This comparison result is valid as soon as the first eigenfunction u_1 satisfies the assumptions of Lemma 4.4 (this has been established in the proof of Proposition 1.2 and does not rely on any assumption on the volume); we refer to [1, pages 21-24] for more details. Using the Chiti comparison result, we get [1, page 607]

$$\int_{\Omega^*} g\, u_1^{*2} \geq \int_B g\, z^2 \qquad \text{and} \qquad \int_{\Omega^*} b\, u_1^{*2} \leq \int_B b\, z^2,$$

and this concludes the proof of the inequality. The case of equality follows from the characterization of the equality in the Chiti comparison result. □

5. Coercivity of the functional λ_1

In this section, we show that λ_1 is coercive on appropriate subsets of $\mathcal{C}$. We first need a control of the in-radii of elements of $\mathcal{C}$.

5.1. **In-radius estimate in $\mathcal{C}$.** For any bounded domain Ω in X^δ, let $\operatorname{Inrad}(\Omega)$ be the maximum radius of a geodesic ball included in $\overline{\Omega}$.

Proposition 5.1. *Let Ω be a bounded convex set in X^δ. Then*

$$\operatorname{Inrad}(\Omega) \geq \frac{\pi}{2\sqrt{\lambda_1(\Omega) + (n-1)}}.$$

This proposition has been proved by P. Li and S.T. Yau [15] for smooth domains of nonnegative mean curvature. It can be readily extended to any (nonsmooth) convex domains: indeed, for any $\epsilon > 0$ small enough, there exists a smooth convex domain Ω_ϵ such that $H_{1-\epsilon}(\Omega) \subset \Omega_\epsilon \subset H_{1+\epsilon}(\Omega)$, where H is the map defined by (3.1) (see [11, Lemma 2.3.2] for the Euclidean case and use the Klein projective model of the hyperbolic space and the open hemisphere to infer this property in $\mathbb{H}^n$ and $\mathbb{S}^n$). The continuity of λ_1 on $\mathcal{C}$ completes the proof.

Subsequently, we denote by $\mathcal{C}_{V_0}$ the set of convex bounded domains Ω of X^δ with $\operatorname{Vol}\Omega = V_0$ and $B(x_0, \operatorname{Inrad}(\Omega)) \subset \overline{\Omega}$ (note that $\mathcal{C}_{V_0}$ contains, up to isometry, all convex bounded domains of X^δ with volume V_0). Combining Corollary 2.7 and Proposition 5.1, we get

Corollary 5.2. *For any $M > 0$, the set of elements Ω of $\mathcal{C}$ (resp. $\mathcal{C}_{V_0}$) with $\Omega \subset B(x_0, M)$ and $\lambda_1(\Omega) \le M$ is compact.*

5.2. **Case $\delta = 1$.** Corollary 5.2 shows the compactness of the set $\{\Omega \in \mathcal{C}_{V_0} \,|\, \lambda_1(\Omega) \le M\}$. This implies that λ_1 is coercive. Actually, $\mathcal{C}_{V_0}$ itself is compact (see Section 6).

5.3. **Case $\delta = 0$.** In this case, $\{\Omega \in \mathcal{C}_{V_0} \,|\, \lambda_1(\Omega) \le M\}$ is also a compact set and so λ_1 is coercive. Indeed by Proposition 5.1, a convex domain Ω in this set contains the ball $B(x_0, \frac{\pi}{2\sqrt{M+n-1}})$. Set $y \in \Omega$ such that $d(x_0, y) = \operatorname{diam} \Omega/4$. Since Ω is convex, it contains the convex hull of $B(x_0, \frac{\pi}{2\sqrt{M}}) \cup \{y\}$ whose volume must be bounded from above by V_0. We deduce that $\operatorname{diam} \Omega$ is bounded from above by a function of M and V_0. We conclude by Corollary 5.2.

5.4. **Case $\delta = -1$.** We cannot argue as easily as in the previous cases because in $\mathbb{H}^n$, the volume of the convex hull of $B(x_0, \frac{\pi}{2\sqrt{M+n-1}}) \cup \{y\}$ does not tend to ∞ with $d(x_0, y)$. We will prove simultaneously the coercivity of λ_1 and the property

$$\inf_{\mathcal{C}'} \lambda_1(\Omega) > \lambda_1^*(V_0), \tag{5.1}$$

where $\mathcal{C}' = \{\Omega \text{ unbounded convex sets; } \operatorname{Vol}(\Omega) = V_0\}$. These two facts prove Theorem 1.1. First, we need to establish some lemmata.

Lemma 5.3. *Let Ω be a domain of a complete Riemannian manifold (M^n, g). Then for any $R \ge 1$, $\alpha, \gamma \in]0, 1[$ and $y_0 \in M$, we have*

$$\min\Big[\lambda_1\big(\Omega \cap B(y_0, R)\big), \lambda_1\big(\Omega \setminus B(y_0, \gamma R)\big)\Big] \le \frac{1}{(1 - R^{-\alpha})^2}\Big[\lambda_1(\Omega) + \frac{8}{(1-\gamma)^2 R^{2(1-\alpha)}}\Big],$$

where λ_1 stands for the bottom of the spectrum, Ω can be of infinite volume and we have set $\lambda_1(\emptyset) = \infty$.

Proof. The proof relies on the variational characterization of the first eigenvalue. We set $N = E(R^\alpha) + 1$, $B_r = B(y_0, r)$, $A_{r,r'} = \Omega \cap (B_r \setminus B_{r'})$ and $r_k = \gamma R + (1-\gamma) R \frac{k}{N}$ for any integer $0 \le k \le N$. Then, for any $u \in H_0^1(\Omega)$, we have

$$\int_\Omega u^2 \ge \sum_{k=0}^{N-1} \int_{A_{r_{k+1}, r_k}} u^2 \ge N \int_{A_{r_{k_0+1}, r_{k_0}}} u^2,$$

for at least one integer $0 \le k_0 \le N - 1$. Let ϕ and ψ be the two functions defined on $\mathbb{R}^+$ by:

- ϕ is nondecreasing, $\phi = 0$ on $[0, \frac{r_{k_0} + r_{k_0+1}}{2}]$, $\phi = 1$ on $[r_{k_0+1}, \infty[$ and $\|\nabla \phi\|_\infty \le \frac{2N}{(1-\gamma)R}$,
- ψ is nonincreasing, $\psi = 1$ on $[0, r_{k_0}]$, $\psi = 0$ on $[\frac{r_{k_0} + r_{k_0+1}}{2}, \infty[$ and $\|\nabla \psi\|_\infty \le \frac{2N}{(1-\gamma)R}$.

For $g(x) = \psi\big(d(y_0, x)\big) u(x)$ and $h(x) = \phi\big(d(y_0, x)\big) u(x)$, we have

$$\int_{\Omega \cap B_{\frac{r_{k_0} + r_{k_0+1}}{2}}} g^2 + \int_{\Omega \setminus B_{\frac{r_{k_0} + r_{k_0+1}}{2}}} h^2 = \int_\Omega (g+h)^2 \ge \int_\Omega u^2 - \int_{A_{r_{k_0+1}, r_{k_0}}} u^2 \ge \frac{N-1}{N} \int_\Omega u^2.$$

Since $|dg+dh|^2=|(\psi+\phi)du+ud(\psi+\phi)|^2$, we obtain

$$\int_{\Omega\cap B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}|dg|^2+\int_{\Omega\setminus B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}|dh|^2=\int_\Omega|dg+dh|^2$$
$$\leq(1+R^{-\alpha})\int_\Omega(\phi+\psi)^2|du|^2+(1+R^\alpha)\int_\Omega u^2|d\phi+d\psi|^2$$
$$\leq(1+R^{-\alpha})\int_\Omega|du|^2+(1+R^\alpha)\int_{A_{r_{k_0+1},\,r_{k_0}}}u^2\frac{4N^2}{(1-\gamma)^2R^2}$$
$$\leq(1+R^{-\alpha})\int_\Omega|du|^2+(1+R^\alpha)\int_\Omega u^2\frac{4N}{(1-\gamma)^2R^2}.$$

We infer

$$\min\Big[\lambda_1\big(\Omega\cap B(y_0,R)\big),\lambda_1(\Omega\setminus B(y_0,\gamma R))\Big]$$
$$\leq\min\Big(\frac{\int_{\Omega\cap B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}|dg|^2}{\int_{\Omega\cap B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}g^2},\frac{\int_{\Omega\setminus B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}|dh|^2}{\int_{\Omega\setminus B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}h^2}\Big)$$
$$\leq\frac{\int_{\Omega\cap B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}|dg|^2+\int_{\Omega\setminus B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}|dh|^2}{\int_{\Omega\cap B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}g^2+\int_{\Omega\setminus B_{\frac{r_{k_0}+r_{k_0+1}}{2}}}h^2}$$
$$\leq\frac{1}{(1-R^{-\alpha})^2}\Big[\frac{\int_\Omega|du|^2}{\int_\Omega u^2}+\frac{8}{(1-\gamma)^2R^{2(1-\alpha)}}\Big].$$

□

This lemma implies the following result.

Lemma 5.4. *For any* $V_0>0$ *there exist* $C(V_0,n)>\lambda_1^*(V_0)$ *and* $R(V_0,n)>0$ *such that, for any bounded convex set* Ω *which satisfies* $\mathrm{Vol}(\Omega)\leq V_0$ *and* $\lambda_1(\Omega)\in[\lambda_1^*(V_0),C(V_0,n)]$, *we have*

$$\lambda_1(\Omega)\leq\lambda_1\big(\Omega\cap B(x_0,R)\big)\leq\frac{1}{(1-R^{-\alpha})^2}\Big[\lambda_1(\Omega)+\frac{32}{R^{2(1-\alpha)}}\Big],$$

for any $\alpha\in\,]0,1[$, $R\geq R(V_0,n,\alpha)$ *and* x_0 *such that* $B\big(x_0,\mathrm{Inrad}(\Omega)\big)\subset\overline{\Omega}$.

Proof. We set $r(V_0,n)=\frac{\pi}{\sqrt{2\lambda_1^*(V_0)+n-1}}$ and

$$C(V_0,n)=\min\big[2\lambda_1^*(V_0),\frac{\lambda_1^*(V_0)+\lambda_1^*\big(V_0-\mathrm{Vol}\,B(x_0,r(V_0,n)/2)\big)}{2}\big].$$

Then, by Proposition 5.1, we have $B(x_0,r(V_0,n)/2)\subset\Omega$ and so $\mathrm{Vol}\,\big(\Omega\setminus B(x_0,R/2)\big)\leq V_0-\mathrm{Vol}\,B(x_0,r(V_0,n)/2)$ for any $R\geq r(V_0,n)$. By the Faber-Krahn inequality, this implies that $\lambda_1\big(\Omega\setminus B(x_0,R/2)\big)$ is larger than $\lambda_1^*\big(V_0-\mathrm{Vol}\,B(x_0,r(V_0,n)/2)\big)$. Now, we can choose $R(V_0,n)$ large enough in order to have

$$\frac{1}{(1-R^{-\alpha})^2}\Big[C(V_0,n)+\frac{32}{R^{2(1-\alpha)}}\Big]\leq\lambda_1\big(\Omega\setminus B(x_0,R/2)\big)$$

for any $R\geq R(V_0,n)$. Lemma 5.1 then applies. □

Now, we prove (simultaneously) the coercivity of λ_1 and (5.1). By definition of the bottom of the spectrum, it is sufficient to prove that every sequence of bounded convex domains $(\Omega_i)_{i\in\mathbb{N}}$ such that $\mathrm{Vol}(\Omega_i) \le V_0$ and $\lim_i \lambda_1(\Omega_i) = \lambda_1^*(V_0)$ converges, up to isometries and extraction, to $B(x_0, r_0)$ ($\mathrm{Vol}(B(x_0, r_0)) = V_0$).

Let $(\Omega_i)_{i\in\mathbb{N}}$ be such a sequence. Up to isometries, we can suppose that the fixed point $x_0 \in \mathbb{H}^n$ satisfies the condition $B\big(x_0, \mathrm{Inrad}(\Omega_i)\big) \subset \Omega_i$ for every i. By the lemma above and Corollary 5.2, the sequence $\big(\Omega_i \cap B_R\big)_{i\in\mathbb{N}}$ is precompact in $\mathcal{C}$ for all $R \ge R(V_0, n)$. Up to a diagonal extraction, we can now suppose that for any $n \in \mathbb{N}$ the sequence $\big(\Omega_i \cap B_n\big)_{i\in\mathbb{N}}$ converges to an element U_n of $\mathcal{C}$. Using the continuity of λ_1 and the volume on $\mathcal{C}$, we get

$$\lambda_1^*(V_0) \le \lambda_1(U_n) \le \frac{1}{(1-n^{-1/2})^2}\Big[\lambda_1^*(V_0) + \frac{32}{n}\Big] \qquad \text{and} \qquad \mathrm{Vol}\,(U_n) \le V_0.$$

So $\lambda_1(U_n)$ tends to $\lambda_1^*(V_0)$ and by the Faber-Krahn inequality, we must have $\mathrm{Vol}\, U_n \to V_0$. Moreover, $(U_n)_{n\in\mathbb{N}}$ is a nondecreasing sequence of convex sets for the inclusion. As a consequence, $\Omega = \bigcup_n U_n$ is a convex domain of volume V_0 and the first eigenvalue $\lambda_1(\Omega) = \lambda_1^*(V_0)$. By Proposition 1.2, $\Omega = B(x_0, r_0)$ and we infer that the sequence $(\Omega_i)_{i\in\mathbb{N}}$ converges to $B(x_0, r_0)$ in $\mathcal{C}$.

6. Coercivity of the λ_1/λ_2 functional

6.1. **Case $\delta = 0$.** We show that, on $\mathcal{C}_{V_0}$, λ_1/λ_2 tends to 1 when λ_1 tends to ∞. By section 5.3, $\inf_{\mathcal{C}_{V_0}} \lambda_1/\lambda_2 < 1$ and the fact that λ_1/λ_2 is invariant under homothety on the domains, this implies Theorem 1.6 in $\mathbb{R}^n$.

By a classical result due to Jones, for any $\Omega \in \mathcal{C}_{V_0}$ there exists an ellipsoid $\mathcal{E}$ such that $\mathcal{E} \subset \Omega \subset \sqrt{n}\mathcal{E}$. We easily infer that there is an n-rectangle R with edges of lengths $L_1 \le \cdots \le L_n$, such that $R \subset \Omega \subset nR$. This gives

$$\lambda_1(\Omega) \le \lambda_1(R) \le \frac{n\pi^2}{L_1^2} \quad \text{and} \quad V_0 \le L_n^{n-1} n^n L_1, \tag{6.1}$$

and so $L_n \ge \Big(\frac{V_0\sqrt{\lambda_1}}{\pi n^{n+\frac{1}{2}}}\Big)^{\frac{1}{n-1}}$. Following [12], we can translate and rotate Ω so that R is centred in $(0, \dots, 0)$ and the edge of R of length L_n is parallel to the last coordinate axis. We denote $\Omega^y = \{x \in \mathbb{R}^{n-1} |\, (x, y) \in \Omega\}$ and $\lambda(y) = \lambda_1\big(\Omega^y\big)$. Then, if f is an eigenfunction of Ω associated to the first eigenvalue, we have

$$\int_\Omega f^2 = \int_\Omega \frac{|\nabla f|^2}{\lambda_1(\Omega)} \ge \int_{\mathbb{R}} \int_{\Omega^y} \frac{|\nabla_x f(x,y)|^2}{\lambda_1(\Omega)} dxdy \ge \int_{\mathbb{R}} \frac{\lambda(y)}{\lambda_1(\Omega)} \int_{\Omega^y} |f(x,y)|^2 dxdy.$$

Thus, there is y such that $\lambda_1(\Omega) \ge \lambda(y)$. By convexity of Ω we deduce that $\big(1 - (\frac{L_n}{2})^{-\frac{2}{3}}\big)\Omega^y \times [y - (\frac{L_n}{2})^{\frac{1}{3}}, y + (\frac{L_n}{2})^{\frac{1}{3}}]$ is contained in Ω and consequently,

$$\begin{aligned} \lambda_1(\Omega) \le \lambda_2(\Omega) &\le \lambda_2\Big(\big(1 - (\frac{L_n}{2})^{-\frac{2}{3}}\big)\Omega^y \times [y - (\frac{L_n}{2})^{\frac{1}{3}}, y + (\frac{L_n}{2})^{\frac{1}{3}}]\Big) \\ &\le \frac{\lambda(y)}{\big(1 - (\frac{L_n}{2})^{-\frac{2}{3}}\big)^2} + \frac{2\pi^2}{(\frac{L_n}{2})^{\frac{2}{3}}} \le \frac{\lambda_1(\Omega)}{\big(1 - (\frac{L_n}{2})^{-\frac{2}{3}}\big)^2} + \frac{2\pi^2}{(\frac{L_n}{2})^{\frac{2}{3}}}. \end{aligned} \tag{6.2}$$

Since we have shown above that $L_n \to \infty$ when $\lambda_1 \to \infty$, we obtain that λ_1/λ_2 tends to 1 when λ_1 tends to ∞.

Remark 6.1. The same method could be used to show that for any integers $p \le q$, λ_p/λ_q tends to 1 when λ_1 tends to ∞ on $\mathcal{C}_{V_0}$. We conclude that for any $p \le q$ there exists a convex domain (to be determined) which minimizes the quotient λ_p/λ_q.

Remark 6.2. The inequalities (6.2) imply that for any convex domain Ω of $\mathbb{R}^n$, $x_0\in\Omega$ and $R>0$ such that $B(x_0,R)$ does not contain Ω, we have

$$\lambda_1(\Omega\cap B(x_0,R))\leq\lambda_2(\Omega\cap B(x_0,R))\leq\frac{\lambda_1(\Omega\cap B(x_0,R))}{\big(1-C(n)R^{-\frac{2}{3}}\big)^2}+\frac{C(n)}{R^{\frac{2}{3}}},$$

and so $\lambda_2(\Omega\cap B(x_0,R))$ tends to $\lambda_1(\Omega)$ when R tends to ∞. We conclude that a convex Euclidean domain with a spectral gap is bounded (hence has a discrete spectrum) and that its diameter is bounded from above by $C(n)\big(\frac{1+\lambda_1}{\lambda_2-\lambda_1}\big)^{3/2}$. This implies readily the coercivity of λ_1/λ_2 on the set of convex Euclidean domains of fixed λ_1, from which we infer Theorem 1.8 in $\mathbb{R}^n$.

6.2. **Case $\delta=1$.** The coercivity λ_1/λ_2 on the set of convex domains with $\lambda_1=\lambda$ follows from Lemma 5.2. On $\mathcal{C}_{V_0}$, this follows from the compactness of $\mathcal{C}_{V_0}$ which, by Corollary 5.2, is a consequence of the inequality $\mathrm{Inrad}\,(\Omega)\geq C(n)\mathrm{Vol}\,(\Omega)$. This inequality holds true for any convex domain of $\mathbb{S}^n$ as explained below.

First, using the inequality (6.1), based on the Jones ellipsoid, we get easily that for any convex domain contained in a geodesic ball of radius R in $\mathbb{R}^n$, we have $\mathrm{Vol}\,(\Omega)\leq n^nR^{n-1}\mathrm{Inrad}\,(\Omega)$. Now, since $\mathbb{S}^n$ can be covered by $2(n+1)$ balls of radius $R_n=\arccos(\frac{1}{\sqrt{n+1}})$ we infer that there is a point x_0 in $\mathbb{S}^n$ such that $\mathrm{Vol}\big(\Omega\cap B(x_0,R_n)\big)\geq\frac{1}{2(n+1)}\mathrm{Vol}\,(\Omega)$. Using the canonical embedding of $\mathbb{S}^n$ in $\mathbb{R}^{n+1}$, we can project $B(x_0,R_n)$ onto the tangent space $T_{x_0}\mathbb{S}^n$ (using the origin of Euclidean space). This map P_0 is a quasi-isometry from the ball $B(x_0,R_n)$ in $\mathbb{S}^n$ to the geodesic ball $B(x_0,\sqrt{n})$ in Euclidean space, which preserves the convexity. Then, we have

$$\begin{aligned}\mathrm{Inrad}_{\mathbb{S}^n}(\Omega)\geq\mathrm{Inrad}_{\mathbb{S}^n}\big(\Omega\cap B(x_0,R_n)\big)&\geq C_1(n)\mathrm{Inrad}_{T_{x_0}\mathbb{S}^n}\big(P_0\big(\Omega\cap B(x_0,R_n)\big)\big)\\&\geq C_2(n)\mathrm{Vol}_{T_{x_0}\mathbb{S}^n}\big(P_0\big(\Omega\cap B(x_0,R_n)\big)\big)\geq C(n)\mathrm{Vol}_{\mathbb{S}^n}(\Omega).\end{aligned}$$

6.3. **Case $\delta=-1$.** In this section, we prove simultaneously the coercivity of the functional λ_1/λ_2 on bounded convex domains whose first eigenvalue is fixed and with the property

$$\sup_{\mathcal{C}'}\lambda_2(\Omega)<\lambda_2^*(\lambda),\tag{6.3}$$

where $\mathcal{C}'=\{\Omega \text{ unbounded convex sets}\mid\lambda_1(\Omega)=\lambda\}$. These two properties imply Theorem 1.8.

We need the following result whose proof follows easily from the min-max principle (see [18, theorem XIII.1]).

Lemma 6.3. *Let Ω be a convex domain in $\mathbb{H}^n$ whose bottom of the spectrum is an eigenvalue. Then for any fixed point $x_0\in\mathbb{H}^n$, we have*

$$\lim_{R\to\infty}\lambda_i(\Omega\cap B(x_0,R))=\lambda_i(\Omega),\quad \textit{for } i=1,2.$$

Thanks to this lemma, the coercivity property and the inequality (6.3) reduce to the fact that every sequence $(\Omega_i)_{i\in\mathbb{N}}\in\mathcal{C}$ such that $\lim_i\lambda_1(\Omega_i)=\lambda$ and $\lim_i\lambda_2(\Omega_i)=\lambda_2^*(\lambda)$ converges (up to extraction) to a ball such that $\lambda_1(B)=\lambda$.

First, we show that a lower bound on the spectral gap implies some estimates on the first eigenfunction.

Lemma 6.4. *Let Ω be a bounded domain of $\mathbb{H}^n$. If $u \in H_0^1(\Omega)$ satisfies $\triangle u = \lambda_1(\Omega) u$, then there is a point $x_m \in \mathbb{H}^n$ such that*

$$\Big(\lambda_2(\Omega) - \lambda_1(\Omega) - \frac{n-1}{\sinh^2(R)}\Big) \int_{\Omega \setminus B(x_m,R)} u^2 \leq \frac{n}{R^2} \int_{\Omega \cap B(x_m,R)} u^2,$$

for any $R > 0$. This implies, for any $R \geq 2\sqrt{\frac{n-1}{\lambda_2(\Omega)-\lambda_1(\Omega)}}$,

$$\begin{aligned} \lambda_1(\Omega) &\leq \lambda_1\big(\Omega \cap B(x_m,R)\big) \\ &\leq \frac{(1+\frac{1}{R^2})}{1 - \frac{4n}{(\lambda_2(\Omega)-\lambda_1(\Omega))R^2+4})} \Big(\lambda_1(\Omega) + \frac{4n}{(\lambda_2(\Omega)-\lambda_1(\Omega))R^2+4}\Big). \end{aligned}$$

Proof. Proposition 4.10 applied to $g(s) = s/R$ on $[0,R]$ and $g(s) = 1$ on $[R, \infty[$ gives a point $x_m \in \mathbb{H}^n$ such that

$$\lambda_2(\Omega) - \lambda_1(\Omega) \leq \frac{\frac{n}{R^2}\int_{\Omega \cap B(x_m,R)} u^2(x)dx + \frac{n-1}{\sinh^2 R}\int_{\Omega \setminus B(x_m,R)} u^2(x)dx}{\int_{\Omega \setminus B(x_m,R)} u^2(x)dx},$$

which gives the first estimate.

For the second estimate, we let ψ be the nonincreasing Lipschitzian function defined on $\mathbb{R}^+$ by $\psi = 1$ on $[0, R/2]$, $\psi = 0$ on $[R, \infty[$ and $\|\nabla\psi\|\infty = \frac{2}{R}$. Then, we have

$$\begin{aligned} |d(\psi u)|^2 &= \psi^2|du|^2 + 2u\psi(d\psi, du) + u^2|d\psi|^2 \\ &\leq (1+\frac{1}{R^2})\psi^2|du|^2 + (1+R^2)|d\psi|^2u^2. \end{aligned}$$

So, we infer

$$\begin{aligned} \lambda_1\big(\Omega \cap B(x_m,R)\big) &\leq \frac{\int_{\Omega \cap B(x_m,R)} |d(\psi u)|^2}{\int_{\Omega \cap B(x_m,R)} (\psi u)^2} \\ &\leq (1+\frac{1}{R^2})\frac{\int_\Omega \psi^2|du|^2}{\int_{\Omega \cap B(x_m,R/2)} u^2} + (1+R^2)\frac{\int_\Omega |d\psi|^2u^2}{\int_{\Omega \cap B(x_m,R/2)} u^2} \\ &\leq (1+\frac{1}{R^2})\frac{\int_\Omega |du|^2}{\int_\Omega u^2}\Big(1 + \frac{\int_{\Omega \setminus B(x_m,R/2)} u^2}{\int_{\Omega \cap B(x_m,R/2)} u^2}\Big) + 4(1+\frac{1}{R^2})\frac{\int_{\Omega \setminus B(x_m,R/2)} u^2}{\int_{\Omega \cap B(x_m,R/2)} u^2}. \end{aligned}$$

By the first estimate, we have

$$\frac{\int_{\Omega \setminus B(x_m,R/2)} u^2}{\int_{\Omega \cap B(x_m,R/2)} u^2} \leq \frac{4n}{(\lambda_2(\Omega)-\lambda_1(\Omega))R^2 - 4(n-1)},$$

from which we infer

$$\begin{aligned} &\lambda_1\big(\Omega \cap B(x_m,R)\big) \\ &\leq \frac{(1+\frac{1}{R^2})\big((\lambda_2(\Omega)-\lambda_1(\Omega))R^2+4\big)}{(\lambda_2(\Omega)-\lambda_1(\Omega))R^2 - 4(n-1)}\Big(\lambda_1(\Omega) + \frac{4n}{(\lambda_2(\Omega)-\lambda_1(\Omega))R^2+4}\Big). \end{aligned}$$

□

Let $(\Omega_i)_{i\in\mathbb{N}} \in \mathcal{C}$ such that $\lim_i \lambda_1(\Omega_i) = \lambda$ and $\lim_i \lambda_2(\Omega_i) = \lambda_2^*(\lambda)$. We can assume that $\lambda_2(\Omega_i) - \lambda_1(\Omega_i) > \frac{\lambda_2^*(\lambda)-\lambda}{2} > 0$. Note that by the preceding lemma, we infer that for any $R \geq 4\sqrt{\frac{n-1}{\lambda_2^*(\lambda)-\lambda}}$ we have $\lambda_1\big(\Omega_i \cap B(x_m^i, R)\big) \leq C(\lambda, n)$ (where $C(\lambda, n)$ is a universal funtion and x_m^i is the center of mass of Ω_i). This implies, by Proposition 5.1, that we can suppose (up to isometry) $x_m^i \in B\big(x_0, 4\sqrt{\frac{n-1}{\lambda_2^*(\lambda)-\lambda}}\big)$ and $B\big(x_0, r(\lambda,n)\big) \subset \Omega_i$ for all i. Then, the sequence $\big(\Omega_i \cap B(x_0,R)\big)$ is included in a compact set of $\mathcal{C}$ (see Corollary 5.2). By diagonal extraction, we can suppose that for any $k \in \mathbb{N}$ the sequence $\big(\Omega_i \cap B(x_0,k)\big)_{i\in\mathbb{N}}$ converges to an element U_k of $\mathcal{C}$. By continuity of λ_1 on $\mathcal{C}$, we have

$$\begin{aligned}\lambda \leq \lambda_1(U_k) &= \lim_i \lambda_1\big(\Omega_i \cap B(x_0,k)\big)\\ &\leq \lim_i \lambda_1\Big(\Omega_i \cap B(x_m^i, k - 4\sqrt{\frac{n-1}{\lambda_2^*(\lambda)-\lambda}})\Big) \leq f(k,\lambda,n),\end{aligned}$$

where $f(k,\lambda,n)$ is a universal function given by the preceding lemma and which converges to λ when k tends to ∞. So $\lambda_1(U_k)$ tends to λ. As in subsection 5.4, we set $\Omega = \bigcup_k U_k$. Then Ω is a convex domain with $\lambda_1(\Omega) = \lim_k \lambda_1(U_k) = \lambda$ (since $U_k = \Omega \cap B(x_0,k)$) and

$$\lambda_2(\Omega) = \lim_k \lambda_2(U_k) = \lim_k \lim_i \lambda_2(\Omega_i \cap B(x_0,k)) \geq \lim_i \lambda_2(\Omega_i) = \lambda_2^*(\lambda).$$

Then, we conclude the proof by Theorem 4.9.

7. Proof of lemma 4.11

In this appendix, we prove Lemma 4.11. This lemma is essentially proven in [1, 2, 4] for u with compact support (which includes the case $\delta = 1$), but we will apply it for u an eigenfunction of an unbounded domain Ω and so we have to extend it in the case $\delta = 0, -1$.

In the sequel of the proof, X denotes $\mathbb{R}^n$ or $\mathbb{H}^n$. We fix $x_0 \in X$ and define

$$\begin{aligned} F \;:\; T_{x_0}X &\;\to\; T_{x_0}X \\ v &\;\mapsto\; d(\exp_{x_0}^{-1})\Big(\int_X g\big(d(\bar v, y)\big)\frac{\exp_{\bar v}^{-1}(y)}{d(\bar v,y)}u^2(y)\,dy\Big),\end{aligned}$$

where we have set $\bar v = \exp_{x_0}(v)$. We set $m = \liminf_{+\infty} g$. Let $R_1 > 0$ such that $\int_{X\setminus B(x_0,R_1)} u^2 \leq \min\big(\frac{m}{32\|g\|_\infty}, \frac12\big)$. Then for any $v \in T_{x_0}X$ with $|v| \geq R_1$ we easily have

$$\Big|F(v) - d(\exp_{x_0}^{-1})\Big(\int_{B(x_0,R_1)} g\big(d(\bar v,y)\big)\frac{\exp_{\bar v}^{-1}(y)}{d(\bar v,y)}u^2(y)\,dy\Big)\Big| \leq \frac{m}{32}.$$

Note that $d(\exp_{x_0}^{-1}) \circ \exp_{\bar v}^{-1}(x_0) = -v$ and so we infer that for any $v \in T_{x_0}X$ with $|v| \geq R_1$ we have

$$\Big|F(v) + \lambda(v)\frac{v}{|v|}\Big| \leq \|g\|_\infty \int_{B(x_0,R_1)} \Big|\frac{\exp_{\bar v}^{-1}(x_0)}{d(\bar v,x_0)} - \frac{\exp_{\bar v}^{-1}(y)}{d(\bar v,y)}\Big|\,dy + \frac{m}{32},$$

where we have set $\lambda(v) = \int_{B(x_0,R_1)} g\big(d(\bar v,y)\big)u^2(y)\,dy$ and used the fact that $d(\exp_{x_0}^{-1})$ is a contraction. Then we have $\lambda(v) \geq \frac{m}{4} > 0$ for any v with $|v| \geq R_2 \geq R_1$. Note also that the integrand above measures the difference between the unit tangent vectors at $\bar v$ to the minimizing geodesic from $\bar v$ to x_0 and $y \in B(x_0,R_1)$. By the law of cosines, we can easily show that this quantity uniformly tends to zero on $B(x_0,R_1)$ when $|v|$ tends to $+\infty$. Hence, there exists $R_3 > 0$ such that for any $v \in T_{x_0}X$ which satisfies $|v| \geq R_3$, we have

$$\Big|F(v) + \lambda(v)\frac{v}{|v|}\Big| \leq \frac{m}{16} \quad \text{and} \quad \lambda(v) \geq \frac{m}{4}.$$

We have to show that F is zero somewhere. If not, the following map (with $R > R_3$) is well defined:

$$\begin{array}{rcl} G \ : \ B(0,1) \subset T_{x_0}X & \to & S(0,1) \subset T_{x_0}X \\ v & \mapsto & \dfrac{F(-Rv)}{|F(-Rv)|}. \end{array}$$

Moreover, the map G is continuous and satisfies

$$|G(v) - v| \leq \frac{2\big|F(-Rv) + \lambda(-Rv)\big|}{|F(-Rv)|} \leq 4/3$$

for any $v \in S(0,1)$. So, we could then easily construct a retraction from $B(0,2)$ to $S(0,2)$.

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References

[1] M. Ashbaugh, R. Benguria, A sharp bound for the ratio of the first two eigenvalues of Dirichlet Laplacians and extensions. *Ann. of Math. (2)*, 135(3):601–628, 1992. MR1166646 (93d:35105)

[2] M. Ashbaugh, R. Benguria, A sharp bound for the ratio of the first two Dirichlet eigenvalues of a domain in a hemisphere of S^n. *Trans. Amer. Math. Soc.*, 353(3):1055–1087, 2001. MR1707696 (2001f:35298)

[3] A. Ávila, Stability results for the first eigenvalue of the Laplacian on domains in space forms. *J. Math. Anal. Appl.*, 267(2):760–774, 2002. MR1888036 (2003j:35237)

[4] R. Benguria, H. Linde, *A second eigenvalue bound for the Dirichlet Laplacian in hyperbolic space*, Duke Math. J. 140:245–279, 2007. MR2359820

[5] P. Bérard, *Spectral geometry: Direct and inverse problems*, volume 1207 of *Lecture Notes in Mathematics*. Springer-Verlag, Berlin, 1986. With an appendix by Gérard Besson. MR861271 (88f:58146)

[6] P. Bérard, D. Meyer, *Inégalités isopérimétriques et applications*, Ann. Sci. École Norm. Sup. 15(3):513–541, 1982. MR690651 (84h:58147)

[7] I. Chavel, *Isoperimetric inequalities*, Cambridge Tracts in Mathematics, Vol. **145**, Cambridge University Press, Cambridge, 2001. MR1849187 (2002h:58040)

[8] K. Chong, N. Rice, *Equimeasurable rearrangements of functions*. Queen's University, Kingston, Ont., 1971. Queen's Papers in Pure and Applied Mathematics, n° 28. MR0372140 (51:8357)

[9] D. Gilbarg, N. Trudinger, *Elliptic partial differential equations of second order*, Grundlehren der Mathematischen Wissenschaften [Fundamental Principles of Mathematical Sciences] Vol. **224**, Springer-Verlag, Berlin, 1977. MR0473443 (57:13109)

[10] Q. Han, F. Lin Elliptic partial differential equations. *Courant Lecture Notes in Mathematics*, **1**, New York, 1997. MR1669352 (2001d:35035)

[11] L. Hörmander, *Notions of convexity*, Progress in Mathematics, Vol. **127**, Birkhäuser, Boston, 1994. MR1301332 (95k:00002)

[12] D. Jerison, *The first nodal set of a convex domain*, Essays in Fourier Analysis in honor of E.M. Stein (C.F. Fefferman, ed.), Princeton Univ. Press, Princeton, NJ, 1993. MR1315550 (96h:35141)

[13] B. Kawohl, *Rearrangements and convexity of level sets in PDE*, volume 1150 of *Lecture Notes in Mathematics*. Springer-Verlag, Berlin, 1985. MR810619 (87a:35001)

[14] E. Lieb, M. Loss, Analysis. Second edition. *Graduate Studies in Mathematics*, **14**, American Mathematical Society, Providence, RI, 2001. MR1817225 (2001i:00001)

[15] P. Li and S. Yau, Estimates of eigenvalues of a compact Riemannian manifold. In *Geometry of the Laplace operator (Proc. Sympos. Pure Math., Univ. Hawaii, Honolulu, Hawaii, 1979)*, Proc. Sympos. Pure Math., XXXVI, pages 205–239. Amer. Math. Soc., Providence, R.I., 1980. MR573435 (81i:58050)

[16] A. Melas, *The stability of some eigenvalue estimates*, J. Differential Geom., 36(1):19–33, 1992. MR1168980 (93d:58178)

[17] T. Povel, Confinement of Brownian motion among Poissonian obstacles in $\mathbf{R}^d$, $d \geq 3$. *Probab. Theory Related Fields*, 114(2):177–205, 1999. MR1701519 (2000i:60121)

[18] M. Reed, B. Simon, *Methods of modern mathematical physics IV: Analysis of operators*, Academic Press, London (1978). MR0493421 (58:12429c)

[19] M. Shubin, *Spectral theory of the Schrödinger operators on non-compact manifolds: Qualitative results*, In Spectral Theory and Geometry (Edinburgh, 1998), Vol. **273** of London Math. Soc. Lecture Note Ser., pages 226–283. Cambridge Univ. Press, Cambridge, (1999). MR1736869 (2001d:58037)

[20] M. Struwe, *Variational Methods*, Ergeb. Math. Grenz., Vol. **34**, Springer-Verlag, Berlin (2000). MR1736116 (2000i:49001)

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