

# Spectral Optimization Problems with Internal Constraint

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## Abstract

We consider spectral optimization problems with internal inclusion constraints, of the form

$$\min \{ \lambda_k(\Omega) : D \subset \Omega \subset \mathbb{R}^d, |\Omega| = m \},$$

where the set  $D$  is fixed, possibly unbounded, and  $\lambda_k$  is the  $k^{\text{th}}$  eigenvalue of the Dirichlet Laplacian on  $\Omega$ . We analyze the existence of a solution and its qualitative properties, and rise some open questions.

**Keywords:** shape optimization, capacity, eigenvalues, Sobolev spaces, concentration-compactness

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## 1 Introduction

A spectral optimization problem is a minimization problem of the form

$$\min \{ J(\Omega) : \Omega \in \mathcal{A} \} \tag{1.1}$$

where  $J$  is a cost functional depending on the spectrum of an elliptic operator defined on the (quasi) open set  $\Omega$  and  $\mathcal{A}$  is a class of admissible domains. A wide literature on the subject is available, dealing with existence, regularity, necessary conditions of optimality, relaxation, explicit solutions and numerical computations of the optimal shapes. We quote for instance the books [7, 18, 19], where the reader may find a complete list of references on the field.

The simplest situation for the existence of a solution of problem (1.1) occurs when the class of admissible domains  $\mathcal{A}$  satisfies an *external* inclusion constraint, i.e. consists on quasi-open sets which are supposed *a priori* contained in a given *bounded* open set  $D$  of the Euclidean space  $\mathbb{R}^d$ ,

$$\mathcal{A} = \{ \Omega : \Omega \subset D, \Omega \text{ quasi-open} \}.$$

In this case a general existence result, due to Buttazzo and Dal Maso (see [11]), states that problem (1.1), with the additional constraint  $|\Omega| \leq m$  on the Lebesgue measure of the competing domains, admits a solution provided the cost functional  $J$  satisfies the following conditions:

- (i)  $J$  is lower semicontinuous for the  $\gamma$ -convergence, suitably defined;
- (ii)  $J$  is monotone decreasing for the set inclusion.

When the surrounding box  $D$  is unbounded the existence result above is no longer true, as some simple examples show. In the case  $D = \mathbb{R}^d$  a quite different approach to the

proof of the existence of optimal domains has been considered by Bucur in [5, 6], using a refined argument related to the Lions concentration-compactness principle (see [22]), and by Mazzoleni and Pratelli in [21] using a more direct approach. However, the latter approach only works in the case  $D = \mathbb{R}^d$ , while the concentration-compactness approach seems more flexible for our purposes.

In this paper we consider problem (1.1) where the admissible class  $\mathcal{A}$  is defined through an *internal* constraint:

$$\mathcal{A} = \{ \Omega : D \subset \Omega \subset \mathbb{R}^d, \Omega \text{ quasi-open, } |\Omega| \leq m \} \quad (1.2)$$

where  $D$  is a fixed quasi-open set of finite measure, possibly unbounded. We consider mainly the cases  $J(\Omega) = \lambda_k(\Omega)$ ; the case of general monotone decreasing functionals is at present still open (see Section 6).

In spite of its simplicity, even for cost functionals like  $J(\Omega) = \lambda_1(\Omega)$ , the existence proof is rather involved, and several interesting questions arise. For this functional, together with the existence of a solution, we prove some global properties for the optimal set: it has to lie at a finite distance from  $D$  (in particular the optimal set is bounded, provided  $D$  is bounded), it has finite perimeter outside  $\overline{D}$ , it is an open set as soon as its measure is strictly greater than the measure of (the quasi-connected)  $D$ . Local regularity properties, outside  $\overline{D}$  are not discussed here, being similar to the bounding box situation, and we refer the reader for instance to [4]. We discuss as well the existence question for  $J(\Omega) = \lambda_k(\Omega)$ . We refer the reader to [6] and to [21] for the analysis of these functionals in the absence of any inclusion constraint in  $\mathbb{R}^d$ .

It is convenient for our purposes to consider also the problem

$$\min \{ \lambda_k(\Omega) + \Lambda |\Omega| : D \subset \Omega \subset \mathbb{R}^d, \Omega \text{ quasi-open} \}, \quad (1.3)$$

where the measure constraint  $|\Omega| \leq m$  is replaced by the Lagrange multiplier penalisation  $\Lambda |\Omega|$ . The relations between the constrained problem

$$\min \{ \lambda_k(\Omega) : D \subset \Omega \subset \mathbb{R}^d, \Omega \text{ quasi-open, } |\Omega| \leq m \}. \quad (1.4)$$

and the penalized version (1.3) have been analyzed for  $k = 1$  in [4], while for general  $k$  only a partial result is available (see Lemma 5.10), which is enough for our purposes.

## 2 Notations and preliminaries

We introduce here the main tools we use in the following; further details can be found for instance in [7, 9].

In the sequel, we will work in the Euclidean space  $\mathbb{R}^d$  with  $d \geq 2$ . Given a subset  $E \subset \mathbb{R}^d$  we define the capacity of  $E$  by

$$\text{cap}(E) = \inf \left\{ \int |\nabla u|^2 dx + \int u^2 dx : u \in \mathcal{U}_E \right\},$$

where  $\mathcal{U}_E$  is the set of all functions  $u$  of the Sobolev space  $H^1(\mathbb{R}^d)$  such that  $u \geq 1$  almost everywhere in a neighborhood of  $E$ . If a property  $P(x)$  holds for all  $x \in E$  except for the elements of a set  $Z \subset E$  with  $\text{cap}(Z) = 0$ , we say that  $P(x)$  holds *quasi-everywhere* (shortly *q.e.*) on  $E$ , whereas the expression *almost everywhere* (shortly *a.e.*) refers, as usual, to the Lebesgue measure, that we often denote by  $|\cdot|$ .

A subset  $\Omega$  of  $\mathbb{R}^d$  is said to be *quasi-open* if for every  $\varepsilon > 0$  there exists an open subset  $\Omega_\varepsilon$  of  $\mathbb{R}^d$ , with  $\Omega \subset \Omega_\varepsilon$ , such that  $\text{cap}(\Omega_\varepsilon \setminus \Omega) < \varepsilon$ . Similarly, a function  $f : \mathbb{R}^d \rightarrow \mathbb{R}$  is

said to be *quasi-continuous* (resp. *quasi-lower semicontinuous*) if there exists a decreasing sequence of open sets  $(\omega_n)_{n>0}$  such that  $\lim_{n \rightarrow \infty} \text{cap}(\omega_n) = 0$  and the restriction  $f_n$  of  $f$  to the set  $\omega_n^c$  is continuous (resp. lower semicontinuous). It is well known (see for instance [23]) that every function  $u \in H^1(\mathbb{R}^d)$  has a quasi-continuous representative  $\tilde{u}$ , which is uniquely defined up to a set of capacity zero, and given by

$$\tilde{u}(x) = \lim_{\varepsilon \rightarrow 0} \frac{1}{|B_\varepsilon(x)|} \int_{B_\varepsilon(x)} u(y) dy,$$

where  $B_\varepsilon(x)$  denotes the ball of radius  $\varepsilon$  centered at  $x$ . We often identify the function  $u$  with its quasi-continuous representative  $\tilde{u}$ ; in this way, we have that quasi-open sets can be characterized as the sets of strict positivity of functions in  $H^1(\mathbb{R}^d)$  and that the capacity can be equivalently defined by

$$\text{cap}(E) = \min \left\{ \int |\nabla u|^2 dx + \int u^2 dx : u \in H^1(\mathbb{R}^d), u \geq 1 \text{ q.e. on } E \right\}.$$

The closure  $\overline{D}$  of a quasi-open set  $D$  depends on the representative set of  $D$  which is only defined up to a set of capacity zero. A canonical minimal representative of  $\overline{D}$  can be defined as

$$\overline{D} = \bigcap_{\text{cap}(N)=0} \{C \text{ closed} : C \supseteq D \setminus N\},$$

which contains  $D$  q.e. since it can be reduced to a countable intersection.

For every quasi-open set  $\Omega \subset \mathbb{R}^d$  we denote by  $H_0^1(\Omega)$  the space of all functions  $u \in H^1(\mathbb{R}^d)$  such that  $u = 0$  q.e. on  $\mathbb{R}^d \setminus \Omega$ , with the Hilbert space structure inherited from  $H^1(\mathbb{R}^d)$ ,

$$\langle u, v \rangle_{H_0^1(\Omega)} = \langle u, v \rangle_{H^1(\mathbb{R}^d)} = \int \nabla u \nabla v dx + \int uv dx.$$

The usual properties of Sobolev functions on open sets extend to quasi-open sets.

Let  $\Omega$  be a quasi-open set of finite measure. By  $R_\Omega$  we denote the resolvent operator of the Laplace equation with Dirichlet boundary condition,

$$R_\Omega : L^2(\mathbb{R}^d) \rightarrow L^2(\mathbb{R}^d),$$

where  $R_\Omega(f)$  is the weak solution of the equation

$$\begin{cases} -\Delta u = f \in L^2(\mathbb{R}^d), \\ u \in H_0^1(\Omega). \end{cases}$$

It is well known that  $R_\Omega$  is a compact, self adjoint and positive operator, so its spectrum consists on a discrete decreasing sequence of eigenvalues, which we denote (counting the multiplicities) by  $1/\lambda_k(\Omega)$ . From now on, we call  $\lambda_k(\Omega)$  the eigenvalues of the Dirichlet Laplacian.

### 3 The $\gamma$ -convergence

We endow the admissible class of domains with the following notion of convergence.

**Definition 3.1.** *Let  $(\Omega_n)_n$  be a sequence of quasi-open sets of uniformly bounded measure. We say that  $\Omega_n$   $\gamma$ -converges to  $\Omega$  if the resolvent operators  $R_{\Omega_n}$  converge to the resolvent operator  $R_\Omega$  in the operator norm of  $\mathcal{L}(L^2(\mathbb{R}^d))$ .*

The  $\gamma$ -convergence is metrizable but not compact (see for instance [7, Chapter 4]). This convergence is very strong and the eigenvalues  $\lambda_k(\Omega)$  turn out to be  $\gamma$ -continuous. Its (local) compactification has been characterised in [13] as a space of measures.

We denote by  $\mathcal{M}_0$  the set of capacity measures on  $\mathbb{R}^d$ , that is the set of all Borel measures, possibly taking the value  $+\infty$ , vanishing on all sets of zero capacity. Observe that for each Borel set  $S$  the measure

$$\infty_S(B) = \begin{cases} 0 & \text{if } \text{cap}(B \cap S) = 0 \\ +\infty & \text{otherwise} \end{cases}$$

is a capacity measure.

For each capacity measure  $\mu$ , we define the linear vector space

$$H_\mu^1 = H^1(\mathbb{R}^d) \cap L^2(\mathbb{R}^d, \mu) = \left\{ u \in H^1(\mathbb{R}^d) : \int_{\mathbb{R}^d} |u|^2 d\mu < \infty \right\}.$$

Taking  $\Omega$  a quasi-open set,  $S = \Omega^c$  and  $\mu = \infty_S$  gives  $H_\mu^1 = H_0^1(\Omega)$ . In [10] it was shown that the space  $H_\mu^1$ , endowed with the scalar product

$$\langle u, v \rangle = \int_{\mathbb{R}^d} \nabla u \nabla v dx + \int_{\mathbb{R}^d} uv dx + \int_{\mathbb{R}^d} uv d\mu,$$

is a Hilbert space. Moreover, the space  $H_\mu^1$  is separable when seen as a subset of the separable metric space  $H^1(\mathbb{R}^d)$ . If  $\{u_n\}_{n \geq 0} \subset H_\mu^1$  is a dense countable subset, then we define the regular set of the capacity measure  $\mu \in \mathcal{M}_0$  as

$$\Omega_\mu = \bigcup_{n \geq 0} \{u_n \neq 0\}.$$

Notice that if  $\mu = \infty_S$ , we have  $\Omega_\mu = S^c$ . If the set  $\Omega_\mu$  has finite Lebesgue measure, then

$$\|u\|^2 = \int_{\mathbb{R}^d} |\nabla u|^2 dx + \int_{\mathbb{R}^d} |u|^2 d\mu,$$

is an equivalent norm on  $H_\mu^1$ . We define the resolvent  $R_\mu$  as the map

$$R_\mu : L^2(\mathbb{R}^d) \rightarrow L^2(\mathbb{R}^d),$$

which associates to each function  $f \in L^2(\mathbb{R}^d)$  the solution  $u$  of the relaxed problem formally written as

$$-\Delta u + \mu u = f, \quad u \in H_\mu^1,$$

which has to be rigorously defined in the weak form

$$\begin{cases} \int_{\mathbb{R}^d} \nabla u \nabla \varphi dx + \int_{\mathbb{R}^d} u \varphi d\mu = \int_{\Omega} f \varphi dx & \forall \varphi \in H_\mu^1, \\ u \in H_\mu^1. \end{cases}$$

If  $\mu$  is a capacity measure with regular set of finite Lebesgue measure then  $R_\mu$  is a compact, self adjoint, positive operator and we denote by  $\lambda_k(\mu)$  the eigenvalues of  $R_\mu^{-1}$ . In this case the constant function 1 is in the dual space  $(H_\mu^1)'$  and  $R_\mu$  can be extended to an operator from  $(H_\mu^1)'$  to  $H_\mu^1$ , so we can define  $w_\mu := R_\mu(1)$  and we have  $\Omega_\mu = \{w_\mu > 0\}$  up to zero capacity sets.

We consider the following relation of equivalence on  $\mathcal{M}_0$ :

$$\mu_1 \sim \mu_2 \iff \mu_1(\Omega) = \mu_2(\Omega), \quad \forall \Omega \text{ quasi-open.}$$

From now on, we work with the quotient set  $\mathcal{M}_0 / \sim$  which we still denote by  $\mathcal{M}_0$  and we call its elements capacity measures. We introduce the following convergence on  $\mathcal{M}_0$ :

**Definition 3.2.** We say that  $\mu_n$   $\gamma$ -converges to  $\mu$ , if the sequence of regular sets  $\Omega_{\mu_n}$  is of uniformly bounded Lebesgue measure and

$$R_{\mu_n} \xrightarrow{\mathcal{L}(L^2(\mathbb{R}^d))} R_{\mu}.$$

*Remark 3.3.* With the definition above, we have the equivalence

$$\mu_n \xrightarrow{\gamma} \mu \iff (w_{\mu_n})_{n \geq 0} \text{ converges in } L^2(\mathbb{R}^d) \text{ to } w_{\mu}.$$

Indeed, for the " $\Leftarrow$ " implication, we refer to [5, Proposition 3.3]. For the direct implication, the proof is immediate. On the one hand, we have

$$R_{\mu_n}(1_{\Omega_{\mu_n}}) - R_{\mu}(1_{\Omega_{\mu_n}}) \rightarrow 0 \text{ in } L^2(\mathbb{R}^d),$$

and on the other hand

$$R_{\mu_n}(1_{\Omega_{\mu}}) - R_{\mu}(1_{\Omega_{\mu}}) \rightarrow 0 \text{ in } L^2(\mathbb{R}^d).$$

Making the difference we get that

$$\|R_{\mu_n}(1_{\Omega_{\mu_n}}) - R_{\mu_n}(1_{\Omega_{\mu}}) + R_{\mu}(1_{\Omega_{\mu}}) - R_{\mu}(1_{\Omega_{\mu_n}})\|_{L^2(\mathbb{R}^d)} \rightarrow 0$$

and using the maximum principle we conclude with

$$\|R_{\mu_n}(1) - R_{\mu}(1)\|_{L^2(\mathbb{R}^d)} \rightarrow 0.$$

**Definition 3.4.** We say that the sequence of capacity measures  $\mu_n$   $\gamma_{loc}$ -converges to the capacity measure  $\mu$ , if for each bounded open set  $\omega \subset \mathbb{R}^d$ , we have that the sequence of capacity measures  $\mu_n \vee \infty_{\omega^c}$   $\gamma$ -converges to the capacity measure  $\mu \vee \infty_{\omega^c}$ .

*Remark 3.5.* In [3, Definition 2.7] the  $\gamma_{loc}$ -convergence introduced above was called  $\gamma$ -convergence (see also [13]) and was related to the  $\Gamma$ -convergence in  $L^2(\mathbb{R}^d)$  of the integral functionals

$$F_{\mu}(u, \omega) = \int_{\mathbb{R}^d} |\nabla u|^2 dx + \int_{\mathbb{R}^d} u^2 d\mu + \chi_{H_0^1(\omega)}(u),$$

for each bounded open set  $\omega \subset \mathbb{R}^d$ , where

$$\chi_{H_0^1(\omega)}(u) = \begin{cases} 0 & \text{if } u \in H_0^1(\omega), \\ +\infty & \text{otherwise.} \end{cases}$$

In [13], it was also proven that with this convergence the space  $\mathcal{M}_0$  is metrizable ([13, Theorem 4.9]) and compact ([13, Theorem 4.14]).

For each  $t > 0$ , we will denote with  $\mathcal{M}_0^t$  the following set of capacity measures

$$\mathcal{M}_0^t = \left\{ \mu \in \mathcal{M}_0 : |\Omega_{\mu}| \leq t \right\}.$$

**Proposition 3.6.** The set  $\mathcal{M}_0^t$  endowed with the metric

$$d_{\gamma}(\mu_1, \mu_2) = \|w_{\mu_1} - w_{\mu_2}\|_{L^2(\mathbb{R}^d)},$$

is a complete metric space.

*Proof.* Let  $(\mu_n)_{n \geq 0}$  be a sequence such that  $|\Omega_{\mu_n}| \leq t$  and  $(w_{\mu_n})_{n \geq 0}$  converges strongly in  $L^2(\mathbb{R}^d)$  to some function  $w \in H^1(\mathbb{R}^d)$ . By the compactness of the  $\gamma_{loc}$ -convergence, each subsequence of  $(\mu_n)_{n \geq 0}$  has a  $\gamma_{loc}$ -convergent subsequence, which we still denote by  $\mu_n$  and whose limit is  $\mu$ . By Remark 5.6 in [5], we have that  $w = w_\mu$ ,  $|\Omega_\mu| \leq t$  and  $\mu_n$   $\gamma$ -converges to  $\mu$ . Since  $\mu$  is uniquely determined by the relation  $w = w_\mu$  (see [14, Theorem 5.1]), we have the thesis.  $\square$

The Proposition below deals with the continuity of  $\lambda_k$  with respect to the  $\gamma$ -convergence.

**Proposition 3.7.** *Consider a sequence  $(\Omega_n)_{n \geq 0}$  of quasi-open sets of uniformly bounded measure such that  $\Omega_n$   $\gamma$ -converges to the capacitary measure  $\mu$  with regular set  $\Omega_\mu$ . Then, for every  $k \geq 1$*

$$\lambda_k(\Omega_\mu) \leq \lambda_k(\mu) = \lim_{n \rightarrow \infty} \lambda_k(\Omega_n).$$

*Proof.* By Remark 3.3,  $R_{\Omega_n} \rightarrow R_\mu$  in the operator norm of  $\mathcal{L}(L^2(\mathbb{R}^d))$ , and so we have

$$\lambda_k(\Omega_n) \rightarrow \lambda_k(\mu).$$

The inequality

$$\lambda_k(\Omega_\mu) \leq \lambda_k(\mu),$$

now follows as a consequence of the inequality of the measures  $\infty_{\Omega_\mu^c}(B) \leq \mu(B)$ , for each quasi-open set  $B$ , in the min-max definition of the eigenvalues.  $\square$

## 4 Existence of an optimal set

A fundamental tool allowing to understand the behaviour of a minimizing sequence in  $\mathbb{R}^d$  is the concentration-compactness result (see [5, Theorem 2.2]) for the resolvent operators. We adapt it below in order to manage the internal constraint. The main changes deal with the compactness situation, where translations disappear.

**Theorem 4.1.** *Let  $(\Omega_n)_{n \geq 0}$  be a sequence of quasi-open sets of uniformly bounded measure, all containing a given quasi-open set  $D$ . Then, there exists a subsequence, still denoted by  $(\Omega_n)_{n \geq 0}$ , such that one of the following situations occurs.*

(i) **Compactness.** *The sequence  $(\Omega_n)_{n \geq 0}$   $\gamma$ -converges to a capacitary measure  $\mu$  and  $R_{\Omega_n}$  converges in the uniform operator topology of  $L^2(\mathbb{R}^d)$  to  $R_\mu$ . Moreover, we have that  $D \subset \Omega_\mu$ .*

(ii) **Dichotomy.** *There exists a sequence of subsets  $\tilde{\Omega}_n \subseteq \Omega_n$ , such that:*

- $\|R_{\Omega_n} - R_{\tilde{\Omega}_n}\|_{\mathcal{L}(L^2(\mathbb{R}^d), L^2(\mathbb{R}^d))} \rightarrow 0$ ;
- $\tilde{\Omega}_n$  is a union of two disjoint quasi-open sets  $\tilde{\Omega}_n = \Omega_n^+ \cup \Omega_n^-$ ;
- $d(\Omega_n^+, \Omega_n^-) \rightarrow \infty$ ;
- $\liminf_{n \rightarrow \infty} |\Omega_n^\pm| > 0$ ;
- $\limsup_{n \rightarrow \infty} |\Omega_n^+ \cap D| = 0$  or  $\limsup_{n \rightarrow \infty} |\Omega_n^- \cap D| = 0$ .

*Proof.* Since  $(\Omega_n)_{n \geq 1}$  is a sequence of quasi-open sets of uniformly bounded measure we can apply [5, Theorem 2.2]. If the compactness situation holds in [5, Theorem 2.2], then one can take the sequence  $y_n$  introduced there convergent. In fact, suppose that  $y_n$  is divergent

and notice that the solution  $w_{D+y_n}$  is just  $w_D$  translated to the left by  $y_n$ . By the maximum principle, we have that  $w_{\Omega_n+y_n} \geq w_{D+y_n}$  and so

$$\int w_{D+y_n} w_{\Omega_n+y_n} dx \geq \int w_D^2 dx > 0.$$

Since  $y_n \rightarrow \infty$ , we have that  $w_{D+y_n} \rightarrow 0$  weakly in  $L^2$ . By the strong convergence of  $w_{\Omega_n+y_n}$  we have

$$\int w_{D+y_n} w_{\Omega_n+y_n} dx \rightarrow 0,$$

which is a contradiction and so we have that  $y_n$  is bounded and thus, we can extract a convergent subsequence. It remains to prove that we can take  $y_n = 0$ , for every  $n \in \mathbb{N}$ . Let  $y_n \rightarrow y$  and set  $w = L^2\text{-}\lim_{n \rightarrow \infty} w_{\Omega_n+y_n}$ . We have

$$\begin{aligned} \|w_{\Omega_n} - w(\cdot - y)\|_{L^2(\mathbb{R}^d)} &\leq \|w_{\Omega_n} - w(\cdot - y_n)\|_{L^2(\mathbb{R}^d)} + \|w(\cdot - y_n) - w(\cdot - y)\|_{L^2(\mathbb{R}^d)} \\ &\leq \|w_{\Omega_n+y_n} - w\|_{L^2(\mathbb{R}^d)} + \|w(\cdot - y_n) - w(\cdot - y)\|_{L^2(\mathbb{R}^d)}, \end{aligned}$$

and both last terms converge to zero as  $n \rightarrow \infty$ . Thus, by Proposition 3.6, we have that  $w_{\Omega_n}$   $\gamma$ -converges to a capacitary measure  $\mu$  and  $w(\cdot - y) = w_\mu$ . Moreover, since  $w_{\Omega_n} \geq w_D$  for every  $n \in \mathbb{N}$ , we have that also  $w_\mu \geq w_D$  and so  $D \subset \Omega_\mu$  a.e.

If the dichotomy occurs in [5, Theorem 2.2], we have only to show that we can choose a subsequence such that  $\limsup_{n \rightarrow \infty} |\Omega_n^+ \cap D| = 0$  or  $\limsup_{n \rightarrow \infty} |\Omega_n^- \cap D| = 0$ . In fact, since  $d(\Omega_n^+, \Omega_n^-) \rightarrow \infty$ , we have that one of the sequences of characteristic functions  $1_{\Omega_n^+}$  or  $1_{\Omega_n^-}$  has a subsequence, which converges weakly in  $L^2(\mathbb{R}^d)$  to zero. Taking into account that  $1_D \in L^2(\mathbb{R}^d)$ , we have the thesis.  $\square$

We study the existence of a solution for problem (1.4). We notice that if a solution  $\Omega$  of problem (1.4) exists, then necessarily the measure of  $\Omega$  is precisely equal to  $m$ . Indeed, assume by contradiction that  $\Omega$  is an optimal set with measure strictly less than  $m$ . Since the map  $t \mapsto |t\Omega \cup D|$  is continuous, we can choose some  $t > 1$  such that the set  $\Omega_t = t\Omega \cup D$  is still of measure less than  $m$ . But  $\lambda_k(\Omega_t) \leq \lambda_k(t\Omega) = \frac{1}{t^2} \lambda_k(\Omega)$  and so, the  $k$ -th eigenvalue strictly diminishes, which contradicts the optimality of  $\Omega$ .

In the sequel we study problem (1.4) for any  $k$ ; we will see that the most complete result is for  $k = 1$ , while the case  $k \geq 2$  requires some additional assumptions on the internal constraint  $D$  (see Remark 5.14).

**Theorem 4.2.** *Let  $D$  be a quasi-open set and let  $m \geq |D|$ . Then, the problem*

$$\min\{\lambda_1(\Omega) : \Omega \text{ quasi-open, } D \subset \Omega, |\Omega| \leq m\} \quad (4.1)$$

*has at least one solution.*

*Proof.* We consider a minimizing sequence  $(\Omega_n)_{n \geq 1}$  with the property that  $\liminf_{n \rightarrow \infty} |\Omega_n|$  is minimal. Clearly, this value can not be equal to zero. According to Theorem 4.1, if we are in the compactness situation, for a subsequence (still denoted with the same indices) there exists a measure  $\mu$  such that  $\Omega_n$   $\gamma$ -converges to  $\mu$ . Moreover, the regular set  $\Omega_\mu$  is admissible since  $|\Omega_\mu| \leq m$  and  $D \subset \Omega_\mu$ . By Proposition 3.7 we obtain that  $\Omega_\mu$  is a solution of (4.1).

If we are in the dichotomy situation, we get a contradiction. Since  $\Omega_n^+$  and  $\Omega_n^-$  are at positive distance, we may assume that  $\lambda_1(\Omega_n^+ \cup \Omega_n^-) = \lambda_1(\Omega_n^+)$ . Then, the sequence  $\Omega_n^+ \cup D$  is also minimizing since  $|\lambda_1(\Omega_n^+) - \lambda_1(\Omega_n)| \rightarrow 0$  (see [5, Proposition 3.7]), but either

$$\liminf_{n \rightarrow \infty} |\Omega_n^+ \cup D| < \liminf_{n \rightarrow \infty} |\Omega_n|$$

or  $|\Omega_n^- \setminus D| \rightarrow 0$ . The first assertion is in contradiction with our assumption on the choice of a least measure minimizing sequence. The second assertion is also impossible, since it implies that  $d(\Omega_n^+, \{0\}) \rightarrow +\infty$ , otherwise the measure of  $D$  would be infinite. Consequently, since the measure of  $D$  is finite, we get that  $|\Omega_n^+ \cap D| \rightarrow 0$  and consider the ball  $B$  of measure equal to  $\limsup |\Omega_n^+|$ . Therefore,  $B \cup D$  is a solution for every position of the ball  $B$ . In particular, this leads to a contradiction if the ball intersects, but not cover, a quasi-connected component of  $D$ .  $\square$

*Remark 4.3.* Let us notice that from every minimizing sequence we can extract a  $\gamma$ -convergent subsequence. The basic observation is that any minimizing sequence for which  $\liminf_{n \rightarrow \infty} |\Omega_n|$  is minimal leads to an optimal set, which necessarily has the measure equal to  $m$ . Since the Lebesgue measure is lower semicontinuous for the  $\gamma$ -convergence, this means that any minimizing sequence should satisfy  $\lim_{n \rightarrow \infty} |\Omega_n| = m$  excluding the dichotomy in the proof above.

In the sequel we show a result which gives a rather explicit behavior of a minimizing sequence for problem (1.4). For every  $m > 0$  we introduce the value

$$\lambda_k^*(m) = \inf \{ \lambda_k(\Omega) : \Omega \text{ quasi-open, } |\Omega| \leq m \}.$$

Following [6], there exists a bounded quasi-open set  $\Omega^m$ , with measure equal to  $m$  such that  $\lambda_k(\Omega^m) = \lambda_k^*(m)$ .

**Theorem 4.4.** *Let  $D$  be a quasi-open set and let  $m \geq |D|$ . For  $k \in \mathbb{N}$ ,  $k \geq 2$ , we define*

$$\alpha_k = \inf \{ \lambda_k(\Omega) : \Omega \text{ quasi-open, } D \subset \Omega, |\Omega| \leq m \}.$$

*One of the following assertions holds:*

- (i) *problem (1.4) has a solution;*
- (ii) *there exists  $l \in \{1, \dots, k-1\}$  and an admissible quasi-open set  $\Omega$  such that  $\alpha_k = \lambda_{k-l}(\Omega) = \lambda_l^*(m - |\Omega|)$ ;*
- (iii) *there exists  $l \in \{1, \dots, k-1\}$  such that  $\alpha_k = \lambda_l^*(m - |D|) > \lambda_{k-l}(D)$ .*

*Proof.* Let us consider a minimizing sequence  $(\Omega_n)_{n \geq 1}$  with the property that  $\liminf_{n \rightarrow \infty} |\Omega_n|$  is minimal. If compactness occurs in Theorem 4.1, then the existence of a solution follows as in Theorem 4.2.

If dichotomy occurs, as in Theorem 4.2 we may assume that

$$|\Omega_n^+| \rightarrow \alpha^+, \quad |\Omega_n^-| \rightarrow \alpha^-, \quad |\Omega_n^+ \cap D| \rightarrow 0.$$

Then, up to a subsequence there exists  $l \in \{1, \dots, k-1\}$  such that one of the two possibilities below holds:

- (A)  $|\lambda_k(\Omega_n) - \lambda_{k-l}(\Omega_n^-)| \rightarrow 0$  and  $\lambda_l(\Omega_n^+) \leq \lambda_{k-l}(\Omega_n^-) \leq \lambda_{l+1}(\Omega_n^+)$ ;
- (B)  $|\lambda_k(\Omega_n) - \lambda_l(\Omega_n^+)| \rightarrow 0$  and  $\lambda_{k-l}(\Omega_n^-) \leq \lambda_l(\Omega_n^+) \leq \lambda_{k-l+1}(\Omega_n^-)$ .

We may take the maximal  $l$  with such a property. We use now an induction argument as follows. For  $k = 1$  as proved in Theorem 4.2, dichotomy does not occur, so the compactness gives (i). Assume that for  $1, \dots, k-1$  Theorem 4.4 is true. We prove it for  $k$ . If compactness occurs, then (i) holds. If dichotomy occurs and we are in situation (A) we get that  $(\Omega_n^- \cup D)_n$  is minimizing for the  $k-l$  eigenvalue with the inclusion constraint and the corresponding measure  $m - \alpha^+ \geq \liminf_{n \rightarrow \infty} |\Omega_n^- \cup D|$ . Since  $l$  is maximal with this property, for the sequence  $(\Omega_n^- \cup D)_n$  dichotomy cannot occur again, so finally (ii) holds.

If (B) occurs, then  $|\Omega_n^- \setminus D| \rightarrow 0$  and we are in situation (iii).  $\square$

*Remark 4.5.* Theorem 4.4 gives a complete description of the behaviour of a minimizing sequence for  $\lambda_k$ ,  $k \geq 2$ . Assertion i) implies the existence of a solution. As well if  $D$  has some suitable geometric properties (for instance if  $D$  is bounded), both alternatives (ii) and (iii) lead to the existence of a solution. In fact, if for instance ii) occurs, the set  $\Omega \cup \Omega^{m-|\Omega|}$  is a minimizer provided that  $\Omega \cap \Omega^{m-|\Omega|} = \emptyset$ . Similarly, for iii) the set  $D \cup \Omega^{m-|D|}$  is a minimizer, provided that  $D \cap \Omega^{m-|D|} = \emptyset$ . A complete proof of the existence for the original problem (1.4) and for the penalized problem (1.3), will be achieved later through an induction argument and some additional analysis on the qualitative properties of minimizers (see Remark 5.14).

## 5 Qualitative properties of the optimal sets

A natural question that arises in the shape optimization problems with constraints like (4.1) is to understand the influence of the inclusion domain  $D$  on the optimal sets: does boundedness and/or convexity of  $D$  imply the same properties on the optimal set? As we shall see, the answer is positive for the boundedness constraint, but negative for the convexity constraint.

### 5.1 Regularity of the optimal set for $k = 1$

In this section we deal with the penalized version of problem (4.1)

$$\min \{ \lambda_1(\Omega) + \Lambda |\Omega| : \Omega \subset \mathbb{R}^d, \Omega \text{ quasi-open}, D \subset \Omega \}, \quad (5.1)$$

for some  $\Lambda > 0$ . For the local equivalence of the two problems we refer the reader to [4]. As well, we refer the reader to [4] for a complete analysis of a similar problem, in which the internal constraint  $D \subset \Omega$  is replaced by an external constraint  $\Omega \subset D$ , with a bounded open set  $D$ .

In the case of internal constraint, new behaviours can be noticed with respect to [4]; we prove that the optimal set of (5.1) is open even if  $D$  is only quasi-open, provided that  $D$  is quasi-connected and the optimal set has a measure strictly greater than  $|D|$ .

**Definition 5.1.** *We say that the quasi-open set  $D$  is quasi-connected if for every pair of non-empty quasi-open sets  $A_1$  and  $A_2$  having intersection of positive capacity with  $D$  and such that  $D \subset A_1 \cup A_2$ , we get  $\text{cap}(A_1 \cap A_2) > 0$ .*

The quasi-connectedness has a topological counterpart. Indeed, a quasi-open, quasi-connected set  $A$  has a fine interior (which differs from  $A$  by a set of zero capacity) which is finely connected (the fine topology being the coarsest topology making all superharmonic functions continuous). A nonnegative superharmonic function in  $H_0^1(A)$  with  $A$  finely connected, is either equal to 0 or is strictly positive (see [8, 16, 20]).

*Example 5.2.* The assumption  $D$  quasi-connected is essential to obtain that the optimal set  $\Omega$  is open even when  $D$  is only quasi-open. Indeed, consider  $D = B_0 \cup D_0$ , where  $B_0$  is a large ball and  $D_0$  is a quasi-open and not open set, whose distance from  $B_0$  is large enough and whose measure is less than  $|B_0|$ . It is easy to see that in this case the optimal set is of the form  $B \cup D_0$ , where  $B$  is a ball containing  $B_0$ .

*Remark 5.3.* In spite of the example above, if  $D$  is an *arbitrary* open set, then every optimal set  $\Omega$  for problem (5.1) is open. Indeed, a careful inspection of the proof of Proposition 5.6 below gives that  $\{u > 0\}$  is open; since  $\Omega = \{u > 0\} \cup D$  we have that  $\Omega$  is open.

In the following, without loss of generality we assume that  $\Lambda = 1$ .

*Remark 5.4.* The existence of a solution to (5.1) follows by the same argument we used in the proof of Theorem 4.2 and so we omit the proof.

Let  $D$  be a quasi-open, quasi-connected set of finite measure. Let  $\Omega$  be a solution of problem (5.1), let  $\lambda := \lambda_1(\Omega)$ , and let  $u := u_\Omega$  be the first normalized eigenfunction:

$$\begin{cases} -\Delta u = \lambda u, \\ u \in H_0^1(\Omega), \quad \|u\|_{L^2} = 1. \end{cases}$$

As  $D$  is quasi-connected, if  $\Omega$  is optimal, then  $u$  is a solution of the minimization problem

$$\min \left\{ \frac{\int |\nabla v|^2 dx}{\int v^2 dx} + |\{v > 0\}| : v \in H^1(\mathbb{R}^d), D \subset \{v > 0\} \right\}. \quad (5.2)$$

The following Lemma has a proof similar to [1, Lemma 3.2] and [4, Lemma 3.1], so we omit it.

**Lemma 5.5.** *Let  $u$  be a solution of problem (5.2). Then there is a constant  $C$  depending only on the dimension  $d$  such that for each  $r > 0$ , the following implication holds:*

$$Cr \leq \frac{1}{|\partial B_r|} \int_{\partial B_r} u d\mathcal{H}^{d-1} \implies B_r \subset \{u > 0\}. \quad (5.3)$$

The next proposition follows the approach first introduced in [1]; nevertheless, we give the proof below to stress the fact that the quasi-open internal constraint does not change the argument too much.

**Proposition 5.6.** *Let  $D$  be a quasi-open, quasi-connected set of finite measure. Every solution  $\Omega$  of problem (5.1) is an open set up to a set of capacity 0.*

*Proof.* Since  $D$  is quasi-connected, the optimal domain  $\Omega$  is quasi-connected too. Indeed, otherwise  $\Omega$  would have at least two quasi-connected components, one of which contains  $D$ . Then:

- (i) either  $\lambda_1(\Omega)$  is realized on a component not containing  $D$ , in which case  $D \cup B$ , for a suitable ball  $B$ , is a better competitor;
- (ii) or  $\lambda_1(\Omega)$  is realized on the component  $\Omega_1$  containing  $D$ , in which case replacing  $\Omega$  by a suitable enlargement of  $\Omega_1$  gives again a better competitor.

Let  $u$  be a solution of (5.2). We prove that if  $u(x) > 0$ , then  $u$  is positive in a small ball centered at  $x$ . Without loss of generality, we can suppose that  $x = 0$  and that 0 is a regular point in the sense that

$$u(0) = \lim_{r \rightarrow 0} \frac{1}{|B_r(0)|} \int_{B_r(0)} u(y) dy.$$

Denote by  $\varphi_r$  the solution of

$$\begin{cases} -\Delta \varphi_r = 1, \\ \varphi_r \in H_0^1(B_r), \end{cases} \quad (5.4)$$

where  $B_r$  denotes the ball centered in 0 of radius  $r$ . An explicit computation gives

$$\varphi_r(y) = \frac{r^2 - |y|^2}{2d}.$$

Since  $0 \leq \Delta u + \lambda u$  in the distributional sense on  $\mathbb{R}^d$  (see for instance [13], Proposition 2.6), we have

$$\Delta(u - \|u\|_\infty \lambda \varphi_r) \geq -\lambda u + \lambda \|u\|_\infty \geq 0$$

on each ball  $B_r$ , so the function  $u - \|u\|_\infty \lambda \varphi_r$  is subharmonic on  $B_r$ . By the Poisson's formula, we have

$$u(0) - \|u\|_\infty \lambda \varphi_r(0) \leq C(d) \frac{1}{|\partial B_r|} \int_{\partial B_r} u(y) d\mathcal{H}^{d-1}(y),$$

$$u(0) - \|u\|_\infty \lambda C_1 r^2 \leq C(d) \frac{1}{|\partial B_r|} \int_{\partial B_r} u(y) d\mathcal{H}^{d-1}(y).$$

Suppose that  $u(0) > 0$ . Then, choosing  $r$  small enough, we have

$$u(0) \leq \frac{2C(d)}{|\partial B_r|} \int_{\partial B_r} u(y) d\mathcal{H}^{d-1}(y).$$

Now choose  $C$  as in Lemma 5.5 and  $r$  such that  $2rCC(d) \leq u(0)$ . Then

$$Cr \leq \frac{1}{|\partial B_r|} \int_{\partial B_r} u(y) d\mathcal{H}^{d-1}(y),$$

and so  $u > 0$  on  $B_r$ . □

*Remark 5.7.* Alternatively, one can formulate the proposition above, requiring that the inclusion  $D \subset \Omega$  holds quasi-everywhere, and in this case the optimal sets  $\{u > 0\}$  in (5.2) are open and  $u$  is continuous. In fact, in [1] it is proven a stronger result on the Lipschitz continuity of  $u$ , even if this does not provide a higher regularity of the optimal set  $\Omega$ .

*Remark 5.8.* The regularity of the free parts of the boundary is the same as in [4, Theorem 1.2], being independent on the fact that the inclusion constraint is internal or external.

*Remark 5.9.* If  $D$  is a quasi-open set such that there does not exist an open set containing  $D$  and having the same Lebesgue measure, then Proposition 5.6 asserts that the measure of any optimal set is strictly greater than the measure of  $D$ .

In general, this is not the case if  $D$  is an open set. Indeed, following a simple computation one can consider  $D$  to be a ball  $B$  and take a constant  $\Lambda$  large enough, so that the optimal set is  $B$  itself. More generally, if the partial metric derivative of the first eigenvalue on  $D$  is finite, i.e.

$$\lambda'_1(D) := \limsup_{|E \setminus D| \rightarrow 0, E \supset D} \frac{\lambda_1(D) - \lambda_1(E)}{|E \setminus D|} < +\infty,$$

then for every  $\Lambda > \lambda'_1(D)$  there exists  $\Lambda' > \Lambda$  such that the optimal solution of (5.1) with  $\Lambda'$  is  $D$ . Indeed, by contradiction for every  $\Lambda > \lambda'_1(D)$  there exists  $\varepsilon > 0$  such that for every  $\Omega \supset D$  such that  $|\Omega| \leq |D| + \varepsilon$  we have

$$\lambda_1(D) + \Lambda|D| \leq \lambda_1(\Omega) + \Lambda|\Omega|.$$

Then, replacing  $\Lambda$  with  $\Lambda' > \Lambda$  such that  $\Lambda' \geq \frac{\lambda_1(D)}{\varepsilon}$ , we get that  $D$  is a global minimizer.

## 5.2 Bounded constraint implies bounded minimizers

In this paragraph we consider the penalized version (1.3). In fact the following Lemma gives a relation between the solutions of the constrained problem (1.4) and the subsolutions of the Lagrange multiplier penalized version (1.3). Adapting a notion introduced in [6], we say that  $\Omega^*$  is a shape subsolution for  $\lambda_k$  if there exists  $c > 0$  such that

$$\lambda_k(\Omega^*) + c|\Omega^*| \leq \lambda_k(\Omega) + c|\Omega| \quad \forall D \subset \Omega \subset \Omega^*. \quad (5.5)$$

For simplicity, we consider the internal constraint  $D$  regular enough such that

$$\limsup_{t \rightarrow 1^+} \frac{|D \setminus tD|}{t-1} < \infty. \quad (5.6)$$

This condition is for instance satisfied if  $D$  is bounded and Lipschitz, or if  $D$  is starshaped.

**Lemma 5.10.** *Suppose that the internal constraint  $D$  satisfies (5.6) and assume that  $\Omega_m$  is a solution of*

$$\min \left\{ \lambda_k(\Omega) : D \subset \Omega \subset \mathbb{R}^d, \Omega - \text{quasi-open}, |\Omega| \leq m \right\}. \quad (5.7)$$

Then  $\Omega_m$  is a shape subsolution for  $\lambda_k$ .

*Proof.* We first notice that  $|\Omega_m| = m$ . Suppose by contradiction, that for each  $\varepsilon > 0$ , there is some quasi-open set  $\Omega_\varepsilon$  such that  $D \subset \Omega_\varepsilon \subset \Omega_m$  and

$$\lambda_k(\Omega_\varepsilon) + \varepsilon|\Omega_\varepsilon| < \lambda_k(\Omega_m) + \varepsilon|\Omega_m|. \quad (5.8)$$

By the compactness of the inclusion  $H_0^1(\Omega) \subset L^2(\Omega)$ , we can suppose, up to a subsequence that  $\Omega_\varepsilon$   $\gamma$ -converges to some capacitary measure  $\mu$ , whose regular set  $\Omega_\mu$  is such that

$$|\Omega_\mu| \leq \liminf_{\varepsilon \rightarrow 0} |\Omega_\varepsilon|,$$

$$\lambda_k(\Omega_\mu) \leq \lambda_k(\mu) = \lim_{\varepsilon \rightarrow 0} \lambda_k(\Omega_\varepsilon) \leq \lambda_k(\Omega_m),$$

where the last inequality is due to (5.8) and Lemma 3.7. Thus, we obtain that  $\Omega_\mu$  is a solution of (5.7) and so  $|\Omega_\mu| = m$  and  $\lambda_k(\Omega_\mu) = \lambda_k(\Omega_m)$ .

Let  $\Omega'_\varepsilon = t_\varepsilon \Omega_\varepsilon \cup D$ , where  $t_\varepsilon$  is such that  $|\Omega'_\varepsilon| = m$ . Then, we have that

$$\begin{aligned} \lambda_k(\Omega_\varepsilon) + \varepsilon|\Omega_\varepsilon| &< \lambda_k(\Omega_m) + \varepsilon|\Omega_m| \\ &\leq \lambda_k(\Omega'_\varepsilon) + \varepsilon|\Omega'_\varepsilon| \\ &\leq \lambda_k(t_\varepsilon \Omega_\varepsilon) + \varepsilon|t_\varepsilon \Omega_\varepsilon \cup D| \\ &\leq \frac{1}{t_\varepsilon^2} \lambda_k(\Omega_\varepsilon) + \varepsilon(|t_\varepsilon \Omega_\varepsilon| + |D \setminus t_\varepsilon \Omega_\varepsilon|) \\ &\leq \frac{1}{t_\varepsilon^2} \lambda_k(\Omega_\varepsilon) + \varepsilon(|t_\varepsilon \Omega_\varepsilon| + |D \setminus t_\varepsilon D|), \end{aligned} \quad (5.9)$$

and so

$$\frac{t_\varepsilon^2 - 1}{t_\varepsilon^2} \lambda_k(\Omega_\varepsilon) \leq \varepsilon \left( (t_\varepsilon^d - 1)|\Omega_\varepsilon| + |D \setminus t_\varepsilon D| \right). \quad (5.10)$$

By hypothesis (5.6) passing to the limit as  $t_\varepsilon \rightarrow 1^+$ , there is some constant  $C$  such that

$$\lambda_k(\Omega_\varepsilon) \leq \varepsilon C, \quad (5.11)$$

for  $\varepsilon$  small enough. But, by (5.9),  $\lambda_k(\Omega_\varepsilon) \rightarrow \lambda_k(\Omega_m)$  and so, we have a contradiction.  $\square$

We give the following technical result for which we refer to [1, Lemma 3.4] and to [4, Lemma 3.1] in the case  $k = 1$  and to [6, Lemma 2.3] for the general case.

**Lemma 5.11.** *Let  $\Omega$  be a shape subsolution for  $\lambda_k$  and let  $w$  be the solution of the equation*

$$\begin{cases} -\Delta w = 1 \in \Omega, \\ w \in H_0^1(\Omega). \end{cases}$$

*Then there exists two constants  $C_0$  and  $r_0$  such that for each  $x \in \mathbb{R}^d$  such that  $d(x, D) > r_0$  and for each  $r < r_0$  the following implication holds:*

$$(\|w\|_{L^\infty(B_r)} \leq C_0 r) \Rightarrow \left( w = 0 \text{ on } B_{\frac{r}{2}} \right). \quad (5.12)$$

The proof of this lemma relies on the fact that shape subsolutions for  $\lambda_k$  are local *shape subsolutions* for the energy problem (see [6, Definition 2.1] for more details).

**Proposition 5.12.** *Suppose that  $D$  is a quasi-open set of finite measure and that  $\Omega$  is a shape subsolution for  $\lambda_k$ . Then there exists  $L > 0$  such that  $\Omega \subset \overline{D} + B_L(0)$ . In particular if  $D$  is bounded, then  $\Omega$  is bounded.*

*Proof.* With no loss of generality we set  $c = 1$  in (5.5). Assume by contradiction that such  $L$  does not exist. Then, there is a sequence  $(x_n)_{n \geq 1} \subset \Omega$  such that  $d(x_n, \overline{D}) \rightarrow +\infty$  and  $|x_n - x_m| \geq 2r_0$ , when  $n \neq m$ . Since  $\Omega = \{w > 0\}$ , we have  $w(x_n) > 0$ , for every  $n$  and so, by Lemma 5.11, there are constants  $C_0 > 0$  and  $0 < r_0$  such that we have the bound

$$\|w\|_{L^\infty(B_r(x_n))} \geq C_0 r \quad \forall r < r_0.$$

For each  $n$ , consider  $y_n \in B_r(x_n)$  such that

$$w(y_n) \geq \frac{1}{2} C_0 r.$$

Consider the function  $\varphi_r(\cdot - y_n)$ , as defined in (5.4). Then  $w - \varphi_r(\cdot - y_n)$  is subharmonic, since

$$\Delta(w - \varphi_r(\cdot - y_n)) \geq 0.$$

So, we have the inequalities

$$\begin{aligned} \int_{B_r(y_n)} (w(x) - \varphi_r(x - y_n)) dx &\geq |B_r| (w(y_n) - \varphi_r(x - y_n)) \geq |B_r| \left( \frac{C_0}{2} r - r^2 \varphi_1(0) \right); \\ \int_{B_r(y_n)} w(x) dx &\geq r^{2+d} \|\varphi\|_{L^1} + |B_r| \left( \frac{C_0}{2} r - r^2 \varphi_1(0) \right). \end{aligned}$$

Choose now  $0 < r < r_0$  small enough such that  $\frac{C_0}{2} r - r^2 \varphi_1(0) > 0$ . Then there is a constant  $c > 0$ , such that

$$\int_{B_r(y_n)} w(x) dx \geq c \forall n \in \mathbb{N}.$$

The fact that the balls  $B_r(y_n)$  are all disjoint contradicts the integrability of  $w$ .  $\square$

*Remark 5.13.* The constant  $c$ , depends on  $C_0, r_0$  and  $\lambda_k(D)$ . In fact, the proof of the proposition above gives an estimate on the number of admissible points  $x_n$ . Therefore the value of  $L$  could be estimated more explicitly.

*Remark 5.14.* In view of the Proposition 5.12, Theorem 4.4 gives an existence result of optimal domains for the penalized problem (1.3) by an argument similar to [6]. Precisely, if for a sufficiently large  $R > 0$ , there exists  $x \in \mathbb{R}^d$  such that  $B_R(x) \cap D = \emptyset$ , then existence of a solution occurs. Indeed, for  $k = 1$  Theorem 4.2 leads to an optimal domain, while for  $k > 1$ , the existence relies either on option i) of Theorem 4.4 in a direct way, or on options ii) and iii) by an induction argument. We do not know whether the existence of an optimal domain occurs without this assumption on  $D$ .

*Remark 5.15.* If the internal constraint  $D$  satisfies in addition the assumption (5.6), we may conclude that an optimal solution for problem (1.4) exists. Indeed, thanks to Lemma 5.10 the existence question can be reduced to the previous Remark.

### 5.3 Convex constraint does not imply convex optimal set

In this section we will prove that the solution  $\Omega$  of the optimization problem (4.1) might not be convex even if the constraint  $D$  is convex. Consider the sequence of constraints  $(D_n)_{n \geq 1}$ , where  $D_n = (-\frac{1}{n}, \frac{1}{n}) \times (-1, 1)$  and consider the sequence of bounded open sets  $(\Omega_n)_{n \geq 1}$  such that for each  $n$  big enough,  $\Omega_n$  is a solution of the shape optimization problem:

$$\min \{ \lambda_1(\Omega) : D_n \subset \Omega, \Omega \text{ quasi-open}, |\Omega| = m \}. \quad (5.13)$$

**Proposition 5.16.** *For every  $m < 4/\pi$ , there is  $N > 0$  such that  $\Omega_n$  is not convex for all  $n \geq N$ .*

*Proof.* We begin with some observations on the optimal sets.

1. By a Steiner symmetrization argument, all the sets  $\Omega_n$  are Steiner symmetric with respect to the axes  $x$  and  $y$  (in consequence, they are also star shaped sets).
2. For  $n$  large enough, we consider the set  $\Omega'_n = D_n \cup B^*(m - \frac{4}{n})$ , where for any  $a > 0$ ,  $B^*(a)$  denotes the ball centered in 0 of measure  $a$ . By the optimality of  $\Omega_n$ , we have

$$\lambda_1(\Omega_n) \leq \lambda_1(\Omega'_n) \leq \lambda_1(B^*(m - \frac{4}{n})).$$

By Theorem 4.1, there is a  $\gamma$ -converging subsequence still denoted by  $(\Omega_n)_{n \geq 1}$ . Let  $\Omega$  be the  $\gamma$ -limit of this subsequence. Then

- $\lambda_1(\Omega) \leq \liminf_{n \rightarrow \infty} \lambda_1(\Omega_n) \leq \liminf_{n \rightarrow \infty} \lambda_1(B^*(m - \frac{4}{n})) = \lambda_1(B^*(m));$
- $|\Omega| \leq \liminf_{n \rightarrow \infty} |\Omega_n| = m.$

Using the fact that the ball is the unique minimizer of  $\lambda_1$  under a measure constraint, we obtain  $\Omega = B^*(m)$ . Consider a ball  $B'$  of center  $(0, \sqrt{\frac{m}{\pi}} - \varepsilon)$  and radius  $\varepsilon$  and a ball  $B''$  of center  $(0, -\sqrt{\frac{m}{\pi}} + \varepsilon)$  and radius  $\varepsilon$ . Then

$$\Omega_n \cap B' \xrightarrow[n \rightarrow \infty]{\gamma} \Omega \cap B' = B', \quad \Omega_n \cap B'' \xrightarrow[n \rightarrow \infty]{\gamma} \Omega \cap B'' = B''.$$

Then there is some  $n$  large enough such that both sets  $B' \cap \Omega_n$  and  $B'' \cap \Omega_n$  are non-empty, and  $\Omega_n$  cannot be convex (see Figure 1).

In fact, if by contradiction  $\Omega_n$  was convex, then we should have that the rhombus  $R$  with vertices  $(-1, 0), (0, -\sqrt{\frac{m}{\pi}} + \varepsilon), (1, 0), (0, \sqrt{\frac{m}{\pi}} - \varepsilon)$  is contained in  $\Omega_n$ . But

$$|R| = 2(\sqrt{\frac{m}{\pi}} - \varepsilon) > m$$

for  $\varepsilon$  small enough and  $m \leq 4/\pi$ , and this is a contradiction.  $\square$

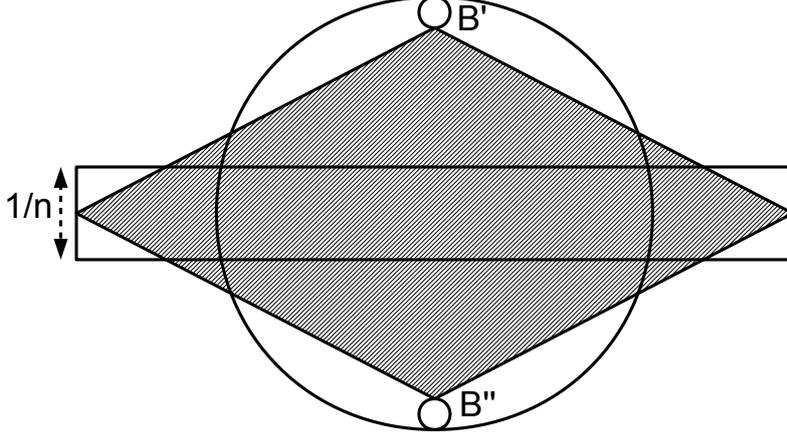


Figure 1: Convex obstacle does not imply convex optimal set.

#### 5.4 Lack of monotonicity

We show here that in problem (4.1) the optimal solutions are not monotone with respect to  $m$ , i.e.  $m_1 < m_2$  does not imply in general that  $\Omega_1 \subset \Omega_2$  where  $\Omega_i$  is optimal with the constraint  $m_i$ . Similarly, in the penalized problem (5.1), the same lack of monotonicity occurs with respect to  $\Lambda$ , i.e.  $\Lambda_1 < \Lambda_2$  does not imply in general that  $\Omega^1 \supset \Omega^2$  where  $\Omega^i$  is optimal with the penalization  $\Lambda_i$ . Here we consider only the case of penalization, since the first one follows as a consequence, taking  $m_1 = |\Omega^2|$  and  $m_2 = |\Omega^1|$ .

Let us consider in  $\mathbb{R}^2$  the internal constraint  $D$  of the form  $D = B_{1/2}(0) \cup R^{\varepsilon,\eta}$  where  $R^{\varepsilon,\eta}$  is the rectangle  $(\eta, 0) + (-\frac{\varepsilon}{2}, \frac{\varepsilon}{2}) \times (-\frac{1}{2\varepsilon}, \frac{1}{2\varepsilon})$ . The parameters  $\varepsilon, \eta$  will be fixed later.

Note that  $\frac{\pi}{4} = |B_{1/2}(0)| < |R^{\varepsilon,\eta}| = 1$  and that  $\lambda_1(B_{1/2}(0)) < \lambda_1(R^{\varepsilon,\eta})$  for  $\varepsilon$  small enough. As well, we notice that the distance between  $B_{1/2}(0)$  and  $R^{\varepsilon,\eta}$  tends to  $+\infty$  as  $\eta \rightarrow +\infty$ . Following Remark 5.13 for every  $\Lambda$  and  $\varepsilon > 0$ , there exists  $\eta$  large enough such that every solution  $\Omega$  of (5.1) satisfies one of the following two possibilities:

- (A)  $\Omega = B \cup R^{\varepsilon,\eta}$ , where  $B$  is a ball containing  $B_{1/2}(0)$  and disjoint from  $R^{\varepsilon,\eta}$ ;
- (B)  $\Omega = B_{1/2}(0) \cup A$ , where  $A$  is a connected open set containing  $R^{\varepsilon,\eta}$  and disjoint from  $B_{1/2}(0)$ .

**Lemma 5.17.** *Let  $\Lambda > 0$  be fixed, let  $\Omega_\varepsilon$  be a solution of the problem*

$$\min \{ \lambda_1(\Omega) + \Lambda|\Omega| : \Omega \supset R^{\varepsilon,0} \},$$

and let  $B$  be a ball solving

$$\min \{ \lambda_1(\Omega) + \Lambda|\Omega| : \Omega \subset \mathbb{R}^2 \}.$$

Then we have

$$\lambda_1(B) = \lim_{\varepsilon \rightarrow 0} \lambda_1(\Omega_\varepsilon), \quad |B| + 1 = \lim_{\varepsilon \rightarrow 0} |\Omega_\varepsilon|.$$

*Proof.* By Steiner symmetrization along both axes, the sets  $\Omega_\varepsilon$  are Steiner symmetric, and so star shaped. Therefore the sets  $\Omega_\varepsilon$  fulfill a uniform exterior segment condition which, together with the compactness result [13, Theorem 4.14], is enough (see [7, Chapter 4]) to give that  $\Omega_\varepsilon$   $\gamma_{loc}$ -converges to some open set  $\Omega$ .

We first notice that

$$\lambda_1(\Omega_\varepsilon) + \Lambda|\Omega_\varepsilon| \leq \lambda_1(B_1(0)) + \Lambda|B_1(0)| + \Lambda := c, \quad (5.14)$$

which gives that both measure of  $\Omega_\varepsilon$  and  $\lambda_1(\Omega_\varepsilon)$  are uniformly bounded. Because of that and of the Steiner symmetrization above, all  $\Omega_\varepsilon$  are contained in the set

$$\{(x, y) : |xy| \leq c\}. \quad (5.15)$$

From the properties of the  $\gamma_{loc}$ -convergence, for every ball  $B_R(0)$  we have that

$$|\Omega \cap B_R(0)| \leq \liminf_{\varepsilon \rightarrow 0} |\Omega_\varepsilon \cap B_R(0)|.$$

Since

$$\liminf_{\varepsilon \rightarrow 0} |\Omega_\varepsilon \cap B_R(0)| \leq \liminf_{\varepsilon \rightarrow 0} |\Omega_\varepsilon| - 1$$

we get

$$|\Omega| + 1 \leq \liminf_{\varepsilon \rightarrow 0} |\Omega_\varepsilon|. \quad (5.16)$$

We prove now that

$$\lambda_1(\Omega) \leq \liminf_{\varepsilon \rightarrow 0} \lambda_1(\Omega_\varepsilon). \quad (5.17)$$

Let  $u_\varepsilon$  be the first normalized eigenfunction on  $\Omega_\varepsilon$ . By the concentration compactness principle, we may have: compactness, vanishing or dichotomy. The vanishing is ruled out by the fact that in this case we would have  $\lambda_1(\Omega_\varepsilon) \rightarrow +\infty$ , which contradicts (5.14). The dichotomy is ruled out too, by the following argument. Let  $u_\varepsilon^i$ ,  $i = 1, 2$  be the two sequences provided by the dichotomy. From the concentration compactness principle, at least one sequence of quasi-open sets  $\{u_\varepsilon^i > 0\}$  has a distance from the origin going to  $+\infty$ . In the same time  $\lambda_1(\{u_\varepsilon^i > 0\})$  are equibounded. This is in contradiction with the inclusion (5.15). Therefore the compactness occurs, i.e.  $u_\varepsilon(\cdot + y_\varepsilon)$  converges strongly in  $L^2(\mathbb{R}^2)$  to some function  $u \in H_0^1(\Omega)$ . Again, by Steiner symmetrization the vectors  $y_\varepsilon$  can be taken equal to 0. Consequently (5.17) is achieved.

Taking test domains of the form  $B \cup R^{\varepsilon,0}$  with  $B \cap R^{\varepsilon,0} = \emptyset$  we have that

$$\lambda_1(B) + \Lambda|B| + \Lambda \geq \lambda_1(\Omega_\varepsilon) + \Lambda|\Omega_\varepsilon|$$

and passing to the limit

$$\lambda_1(B) + \Lambda|B| + \Lambda \geq \lambda_1(\Omega) + \Lambda|\Omega| + \Lambda.$$

Using the optimality of the ball  $B$  we get  $\Omega = B$  and inequalities (5.16)-(5.17) become equalities.  $\square$

Let us fix  $\Lambda_2$  such that a global solution of

$$\min \{ \lambda_1(\Omega) + \Lambda_2|\Omega| : \Omega \subset \mathbb{R}^2 \}$$

is the ball  $B_1(0)$ . Then for  $\varepsilon$  small enough given by Lemma 5.17 and for  $\eta$  large enough given by Remark 5.13 the solution of (5.1) with  $\Lambda_2$  is

$$\Omega_\varepsilon^2 = B_1(0) \cup R^{\varepsilon,\eta}.$$

Indeed, from Lemma 5.17, for  $\varepsilon$  small enough we have

$$\lambda_1(\Omega_\varepsilon) + \Lambda_2|\Omega_\varepsilon| + \Lambda_2|B_{1/2}(0)| > \lambda_1(B_1(0)) + \Lambda_2|B_1(0)| + \Lambda_2|R^{\varepsilon,\eta}|,$$

so situation (A) occurs.

For the  $\varepsilon$  fixed above, take  $\Lambda_1$  small enough such that a ball  $B'$  containing  $R^{\varepsilon,0}$  is a global minimizer for

$$\min \{ \lambda_1(\Omega) + \Lambda_1|\Omega| : \Omega \subset \mathbb{R}^2 \}.$$

Then we are in situation (B) since  $|B_{1/2}(0)| < |R^{\varepsilon,0}|$ . This concludes our argument since no monotonicity may occur.

## 5.5 The optimal set for $\lambda_k$ has finite perimeter

The proof of the fact that the solution of the problem (1.3) has a finite perimeter of the free boundary (i.e. outside the closure of the constraint), is based on a shape subsolutions technique involving the energy functional  $E(\Omega)$ , whose definition we recall here (see [6]).

**Definition 5.18.** For each quasi-open set  $\Omega$  of finite Lebesgue measure, we define the energy functional

$$E(\Omega) = \inf \left\{ \frac{1}{2} \int_{\Omega} |\nabla w|^2 dx - \int_{\Omega} w dx : w \in H_0^1(\Omega) \right\}. \quad (5.18)$$

We denote by  $w_{\Omega}$  the solution of

$$\begin{cases} -\Delta w_{\Omega} = 1, \\ w_{\Omega} \in H_0^1(\Omega), \end{cases} \quad (5.19)$$

which, in particular, is the minimizer in (5.18).

The proof of the following Proposition uses the same argument as in Theorem 2.2. of [6]. We adapt this technique to the case of the internal constraint. Note that, when  $k = 1$ , the Proposition below can be proven directly, working with the first eigenfunction  $u_1$ , instead of  $w_{\Omega}$ .

**Proposition 5.19.** Let  $\Omega$  be an optimal domain for (1.3). Then the perimeter of  $\Omega$  in  $\mathbb{R}^d \setminus \bar{D}$  is finite.

*Proof.* By Lemma 4.1 of [6], we have that there exists some positive constant  $c$  depending on  $\Omega$  such that

$$\lambda_k(\tilde{\Omega}) - \lambda_k(\Omega) \leq c(E(\tilde{\Omega}) - E(\Omega)) \quad \forall D \subset \tilde{\Omega} \subset \Omega \text{ quasi-open}. \quad (5.20)$$

Using the optimality of  $\Omega$ , we have

$$E(\Omega) + \Lambda|\Omega| \leq E(\tilde{\Omega}) + \Lambda|\tilde{\Omega}| \quad \forall D \subset \tilde{\Omega} \subset \Omega \text{ quasi-open}, \quad (5.21)$$

where  $\Lambda = 1/c$ , i.e.  $\Omega$  is an energy sub-solution. Let  $w = w_{\Omega}$  be the solution of (5.19). Consider the set  $\Omega_{\varepsilon} = D \cup \{w > \varepsilon\}$  instead of  $\tilde{\Omega}$  in (5.21). By the fact that  $(w - \varepsilon)^+ \in H_0^1(\Omega_{\varepsilon})$ , we have

$$\begin{aligned} E(\Omega) + \Lambda|\Omega| &\leq E(\Omega_{\varepsilon}) + \Lambda|\Omega_{\varepsilon}| \\ &\leq \frac{1}{2} \int |\nabla(w - \varepsilon)^+|^2 dx - \int (w - \varepsilon)^+ dx + \Lambda|\Omega_{\varepsilon}|, \end{aligned} \quad (5.22)$$

and since  $E(\Omega) = \frac{1}{2} \int |\nabla w|^2 dx - \int w dx$ , we obtain

$$\begin{aligned} \varepsilon|\Omega| &\geq \int w dx - \int (w - \varepsilon)^+ dx \\ &\geq \frac{1}{2} \int_{\{0 < w \leq \varepsilon\}} |\nabla w|^2 dx + \Lambda|\Omega \setminus \Omega_{\varepsilon}| \\ &\geq \frac{1}{2} \int_{\{0 < w \leq \varepsilon\} \setminus \bar{D}} |\nabla w|^2 dx + \Lambda|\{0 < w \leq \varepsilon\} \setminus \bar{D}| \\ &\geq \frac{1}{2|\{0 < w \leq \varepsilon\} \setminus \bar{D}|} \left( \int_{\{0 < w \leq \varepsilon\} \setminus \bar{D}} |\nabla w|^2 dx \right)^2 + \Lambda|\{0 < w \leq \varepsilon\} \setminus \bar{D}|. \end{aligned} \quad (5.23)$$

Thus, we have that

$$\int_{\{0 < w \leq \varepsilon\} \setminus \bar{D}} |\nabla w(x)| dx \leq \varepsilon |\Omega| \sqrt{\Lambda/2}. \quad (5.24)$$

By the co-area formula

$$\frac{1}{\varepsilon} \int_0^\varepsilon P(\{w > t\}; \mathbb{R}^d \setminus \bar{D}) dt \leq |\Omega| \sqrt{\Lambda/2}, \quad (5.25)$$

for each  $\varepsilon > 0$  small enough. Then, there is a sequence  $(\varepsilon_n)_{n \geq 1}$  converging to 0 such that

$$P(\{w > \varepsilon_n\}; \mathbb{R}^d \setminus \bar{D}) \leq |\Omega| \sqrt{\Lambda/2}.$$

Passing to the limit we have

$$P(\{w > 0\}; \mathbb{R}^d \setminus \bar{D}) \leq |\Omega| \sqrt{\Lambda/2}$$

as required.  $\square$

## 6 Open problems and complements

We give a list of some open problems that arose during the work on this article. We denote by  $\Omega(D, m)$  a quasi-open set of Lebesgue measure  $m$ , which solves the shape optimization problem (4.1).

1. Let  $D$  be an open convex set such that for every  $m \geq |D|$  there exists a convex solution to the shape optimization problem (4.1). Is it true that then  $D$  is a ball?
2. Is it true that for every quasi-open set  $D$  with finite measure, problem (1.4) has a solution?
3. If  $D$  is not a ball, is there some  $\varepsilon > 0$ , such that for every  $0 < m < \varepsilon$ , the set  $\Omega(D, |D| + m)$  is unique? Note that this is certainly not true when  $m$  is large, since for a bounded  $D$  any ball of measure  $m$  and containing  $D$  is a solution.
4. If  $m' > m$ , is there an optimal set  $\Omega(D, m')$  containing the optimal set  $\Omega(D, m)$ ? Note that the symmetric statement (if  $m' < m$ , then for each optimal set  $\Omega(D, m)$ , there is an optimal set  $\Omega(D, m') \subset \Omega(D, m)$ ) is false. Indeed, take for instance  $D$  the unit square in  $\mathbb{R}^2$  centered in 0 and  $m' = \frac{\pi}{2} < m$ . Then  $\Omega(D, m')$  is the ball centered at 0 with radius  $\frac{1}{\sqrt{2}}$  and  $\Omega(D, m)$  is any ball of radius  $\sqrt{\frac{m}{\pi}}$ . Clearly, there are balls  $\Omega(D, m)$  which do not contain  $\Omega(D, m')$ .
5. An interesting problem, similar to (4.1), is given by the minimization of the energy integral functional

$$E(\Omega) = - \int w_\Omega(x) dx.$$

We can repeat in this case all the arguments above, obtaining similar existence, boundedness and regularity results. In particular, working with the energy functional simplifies the analysis of Proposition 5.6, obtaining that optimal sets are open, even without the quasi-connectedness assumption on  $D$ .

One can consider more general spectral optimization problems where the cost is

$$J(\Omega) = \Phi(\lambda(\Omega))$$

for a suitable function  $\Phi$ . If  $\Phi$  is:

- (a) monotone increasing, that is  $\Phi(\lambda) \leq \Phi(\lambda')$  whenever  $\lambda_k \leq \lambda'_k$ , for every  $k$ ,
- (b) lower semicontinuous, that is  $\Phi(\lambda) \leq \liminf_{n \rightarrow \infty} \Phi(\lambda^n)$ , whenever  $\lambda_k^n \rightarrow \lambda_k$  for every  $k$ ,

then the optimization problem with an external bounded constraint has a solution thanks to [11]. The general case for the internal constraint problem on the contrary remains open.

Finally, one can consider shape optimization problems with cost functional of integral form. Given a right-hand side  $f$  we consider the PDE

$$-\Delta u = f \text{ in } \Omega, \quad u \in H_0^1(\Omega)$$

which provides, for every admissible domain  $\Omega$ , a unique solution  $u_\Omega$  that we assume extended by zero outside of  $\Omega$ . The cost is in this case of the form

$$J(\Omega) = \int_{\mathbb{R}^d} j(x, u_\Omega(x)) dx.$$

If  $j(x, \cdot)$  is lower semicontinuous, decreasing and such that  $j(x, s) \geq a(x) - c|s|^2$  for suitable  $a \in L^1(\mathbb{R}^d)$  and  $c > 0$ , then the optimization problem with an external bounded constraint has again a solution thanks to [11] but the general case for the internal constraint problem remains open.

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