A curious instability phenomenon for a problem of rounded corner in presence of negative material

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Joint work with X. Claeys[2] and S.A. Nazarov[3]

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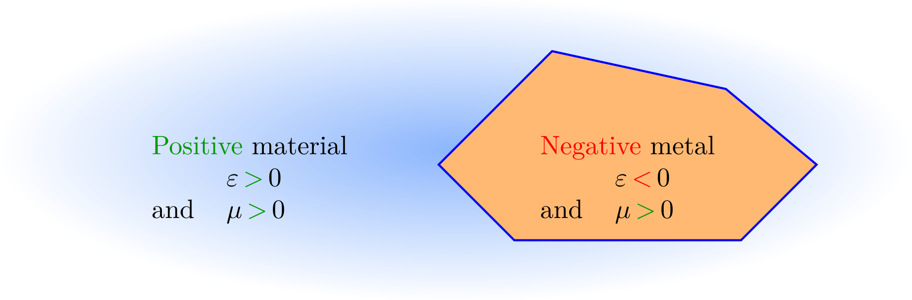
Introduction: general framework

- Scattering by a metal in electromagnetism in time-harmonic regime at optical frequency.
- For metals at optical frequency, $\Re e\, \varepsilon(\omega) < 0$ and $\Im m\, \varepsilon(\omega) << |\Re e\, \varepsilon(\omega)|$.
  $\Rightarrow$ We neglect losses and study the ideal case $\varepsilon(\omega) \in (-\infty; 0)$.



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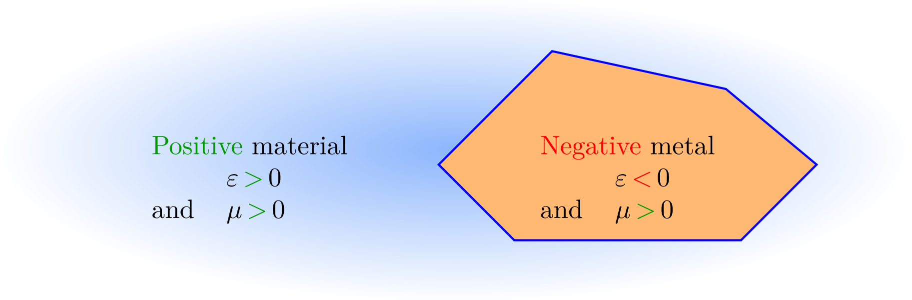
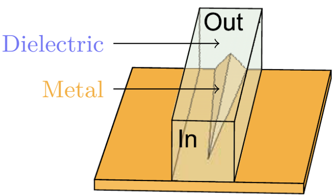
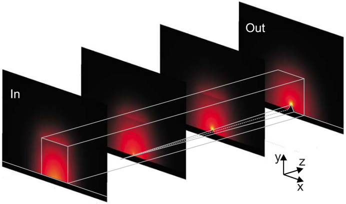


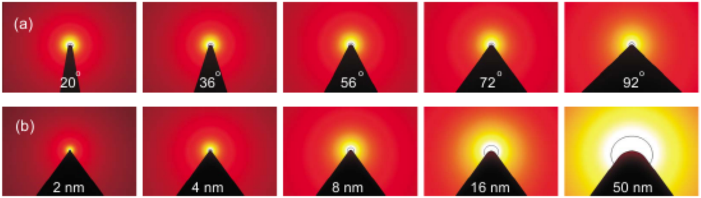
- Waves called Surface Plasmon Polaritons can propagate at the interface between a dielectric and a negative metal.

Introduction: applications

- Surface Plasmons Polaritons can propagate information. Physicists hope to exploit them to reduce the size of computer chips.







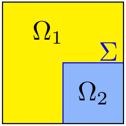
Figures from `O'Connor` *`et al.`*`, Appl. Phys. Lett. 95, 171112 (2009)`

- In this context, physicists use singular geometries to focus energy. It allows to stock information.

Introduction: in this talk

- We study a scalar model problem set in a bounded domain $\Omega \subset \mathbb{R}^2$:

$$(\mathscr{P}) \quad \left| \begin{array}{l} \text{Find } u \in \mathrm{H}^1_0(\Omega) \text{ s.t.:} \\ -\mathrm{div}(\sigma \nabla u) = f \text{ in } \Omega. \end{array} \right.$$



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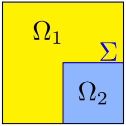

- $\mathrm{H}^1_0(\Omega) = \{v \in \mathrm{L}^2(\Omega) \,|\, \nabla v \in \mathrm{L}^2(\Omega);\ v|_{\partial\Omega} = 0\}$
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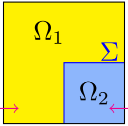

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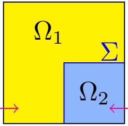

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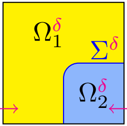

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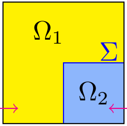

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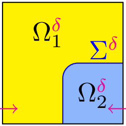

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? What is the behaviour of the sequence $(u^\delta)_\delta$ when δ tends to zero?

Outline of the talk

1. Numerical experiments

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We present the properties of the limit problem in the geometry with the real corner ($\delta = 0$). Since σ changes sign, original phenomena appear.

3. Asymptotic analysis

We prove a curious instability phenomenon: for certain configurations, $(\mathscr{P}^\delta)$ critically depends on δ.

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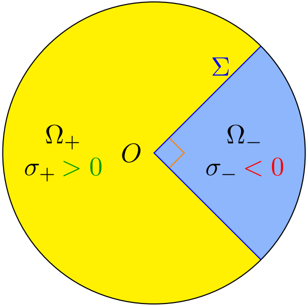
2. Properties of the limit problem
3. Asymptotic analysis

Numerical experiments: setting

- For the numerical experiments, we round the corner in a particular way



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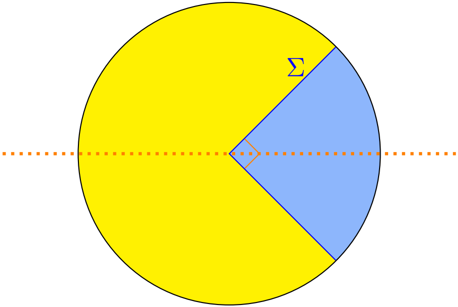

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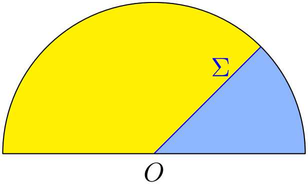

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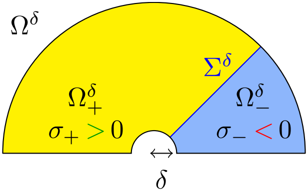

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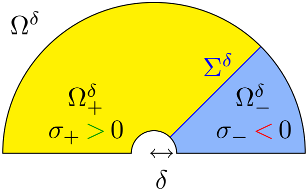

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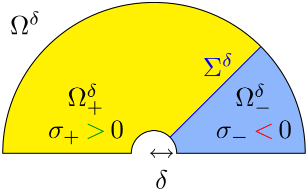

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- Our goal is to study the behaviour of the solution, *if it is well-defined*, of

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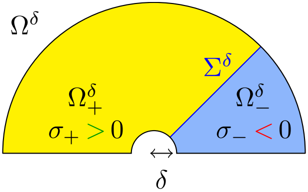

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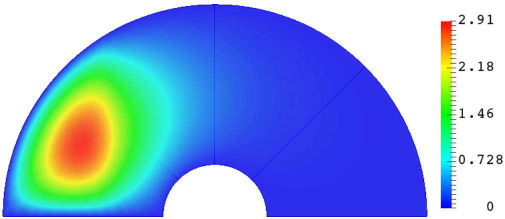
- We approximate u^δ, *assuming it is well-defined*, by a usual P1 Finite Element Method. We compute the solution u_h^δ of the discretized problem with *FreeFem++*.

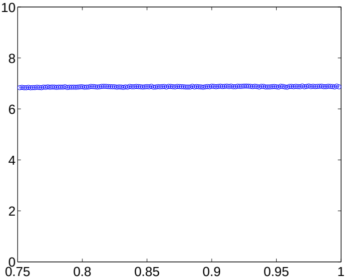
We display the behaviour of u_h^δ as $\delta \to 0$.

Numerical experiments: results 1/2

$\sigma_+ = 1$ and $\sigma_- = 1$ (positive materials)



u_h^δ w.r.t. δ



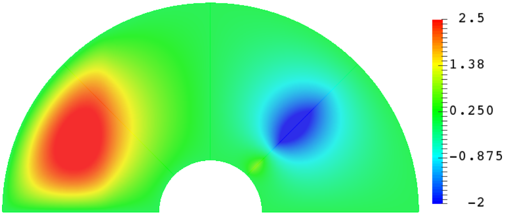
$\|\nabla u_h^\delta\|_{\Omega^\delta}$ w.r.t. $1-\delta$

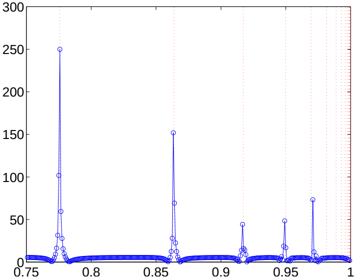
- For positive materials, it is well-known that $(u^\delta)_\delta$ converges to u, the solution in the limit geometry.
- The rate of convergence depends on the regularity of u.
- To avoid to mesh Ω^δ, we can approximate u^δ by u_h.

Numerical experiments: results 2/2

... and what about for a sign-changing σ???

$$\boxed{\sigma_+ = 1 \text{ and } \sigma_- = -0.9999}$$





u_h^δ w.r.t. δ $\qquad$ $\|\nabla u_h^\delta\|_{\Omega^\delta}$ w.r.t. $1-\delta$

- For this configuration, u^δ seems to depend critically on δ.

In this talk, our goal is to explain the presence of these peaks.

Mathematical difficulty

- Classical case $\sigma > 0$ everywhere:

$$a(u,u) = \int_\Omega \sigma \, |\nabla u|^2 \geq \min(\sigma) \, \|u\|^2_{\mathrm{H}^1_0(\Omega)} \qquad \text{coercivity}$$

Lax-Milgram theorem $\Rightarrow$ $(\mathscr{P})$ well-posed.

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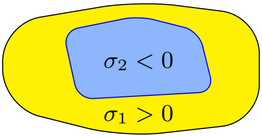
  - When $\sigma_2 = -\sigma_1$, $(\mathscr{P})$ is always ill-posed (`Costabel-Stephan 85`). For a symmetric domain (w.r.t. Σ) we can build a kernel of infinite dimension.

Problems with a sign changing coefficient

$$(\mathscr{P}) \quad \left| \begin{array}{l} \text{Find } u \in \mathrm{H}_0^1(\Omega) \text{ such that:} \\ -\mathrm{div}(\sigma\nabla u) = f \quad \text{in } \Omega. \end{array} \right.$$

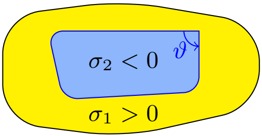
► We have the following properties (see Costabel and Stephan 85, Dauge and Texier 97, Bonnet-Ben Dhia *et al.* 99,10,12,13):

Smooth interface Σ



✔ $(\mathscr{P})$ well-posed in the Fredholm sense iff $\kappa_\sigma = \sigma_2/\sigma_1 \neq -1$.

Interface Σ with a corner



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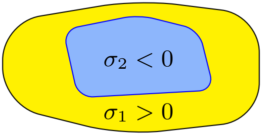

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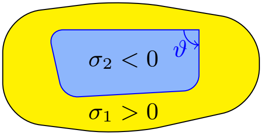

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Well-posedness depends on the smoothness of Σ and on σ.

The problematic of the rounded corner

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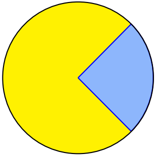

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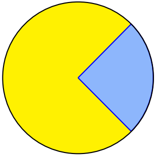

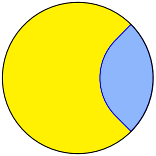

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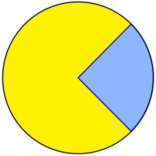

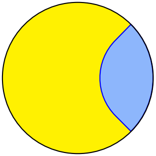

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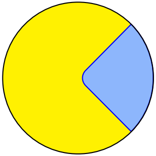
What happens for a slightly rounded corner when $\kappa_\sigma \in I_c \setminus \{-1\}$?



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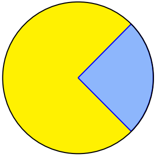

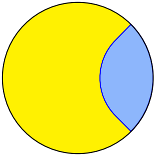

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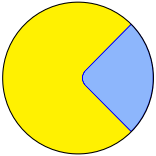

- We need to clarify the properties of $(\mathscr{P})$ when the interface has a corner in the case $\kappa_\sigma \in I_c \setminus \{-1\}$.

Properties of the limit problem inside the critical interval

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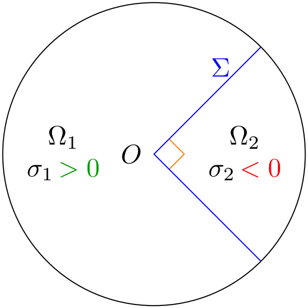
- To simplify the presentation, we work on a particular configuration.



Properties of the limit problem inside the critical interval

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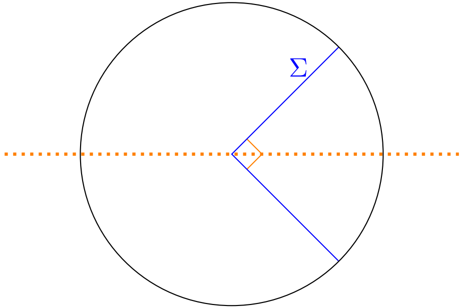

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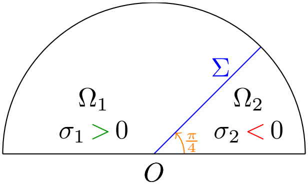

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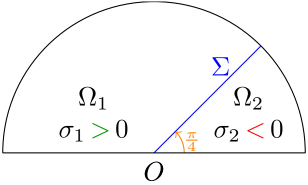

- Using the variational method of the T-coercivity, we prove the

Proposition. The problem $(\mathscr{P})$ is well-posed as soon as the contrast $\kappa_\sigma = \sigma_2/\sigma_1$ satisfies $\kappa_\sigma \notin I_c = [-1; -1/3]$.

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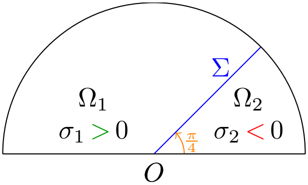

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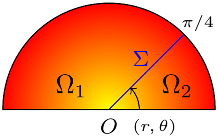
What happens when $\kappa_\sigma \in (-1; -1/3]$?

Analogy with a waveguide problem

- Bounded sector Ω

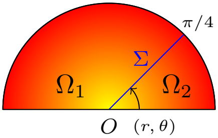


- Equation:

$$\underbrace{-\mathrm{div}(\sigma\nabla u)}_{-r^{-2}(\sigma(r\partial_r)^2+\partial_\theta\sigma\partial_\theta)u} \qquad = f$$

Analogy with a waveguide problem

- Bounded sector Ω



- Equation:

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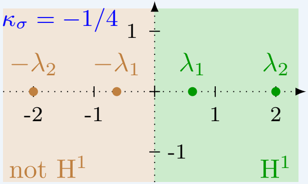
- Singularities in the sector

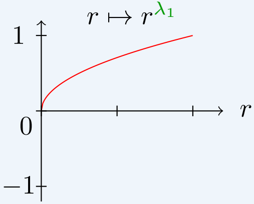
$s(r,\theta) = r^{\lambda}\varphi(\theta)$

Analogy with a waveguide problem

We compute the singularities $s(r,\theta) = r^{\lambda}\varphi(\theta)$ and we observe two cases:

- Outside the critical interval





Analogy with a waveguide problem

We compute the singularities $s(r,\theta) = r^{\lambda}\varphi(\theta)$ and we observe two cases:

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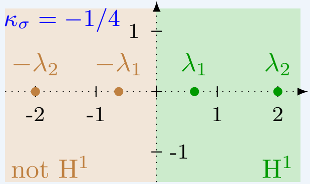

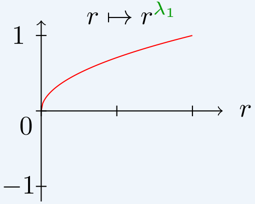

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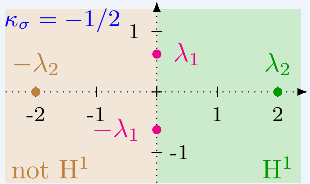

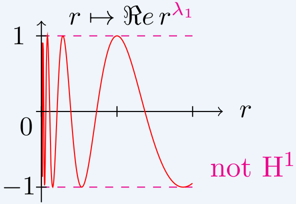

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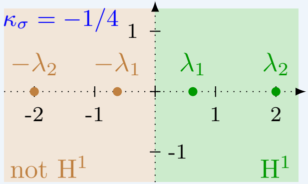

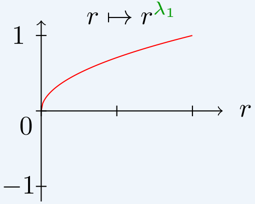

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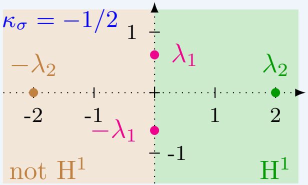
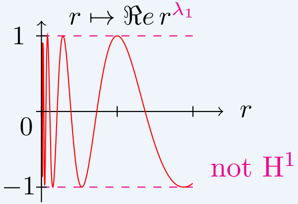
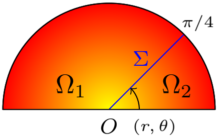




How to deal with the propagative singularities inside the critical interval?

Analogy with a waveguide problem

- Bounded sector Ω



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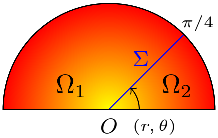
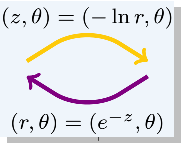
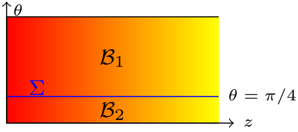
Analogy with a waveguide problem

- Bounded sector Ω





- Half-strip $\mathcal{B}$



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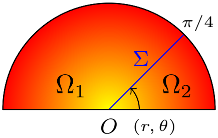
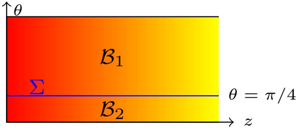


$$(z,\theta) = (-\ln r, \theta)$$

$$(r,\theta) = (e^{-z}, \theta)$$

- Half-strip $\mathcal{B}$



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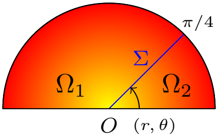
Analogy with a waveguide problem

- Bounded sector Ω



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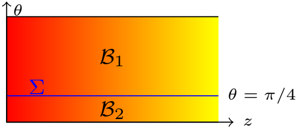

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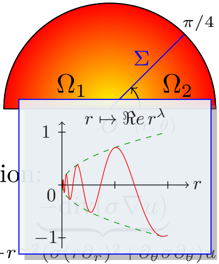
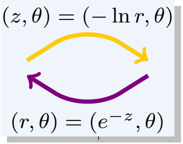
- Modes in the strip

$m(z,\theta) = e^{-\lambda z}\varphi(\theta)$

Analogy with a waveguide problem

- Bounded sector Ω





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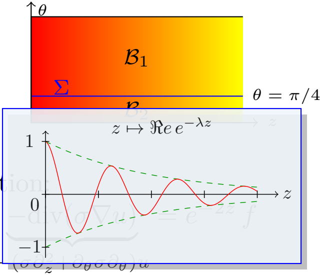

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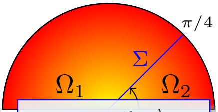
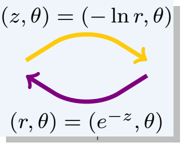
$s \in \mathrm{H}^1(\Omega)$ $\qquad \Re e\,\lambda > 0$ $\qquad m$ is evanescent

Analogy with a waveguide problem

- Bounded sector Ω





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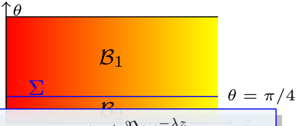

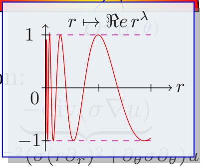

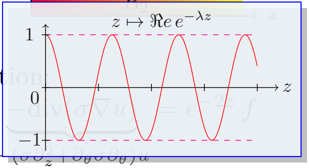

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$$s(r,\theta) = r^\lambda\varphi(\theta) = \cancel{r^a}\,(\cos b\ln r + i\sin b\ln r)\varphi(\theta)$$

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$(\Re e\,\lambda = a,\ \Im m\,\lambda = b)$

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Analogy with a waveguide problem

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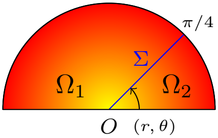

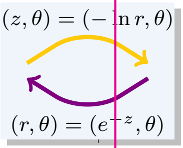

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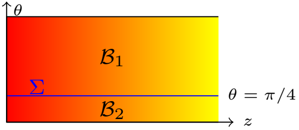

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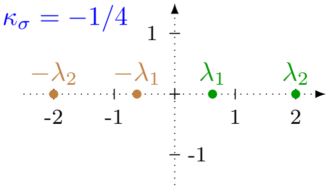
► This encourages us to use modal decomposition in the half-strip.

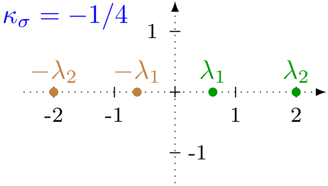
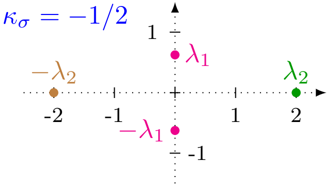
Modal analysis in the waveguide



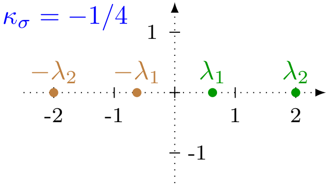
- Outside the critical interval. All the modes are exponentially growing or decaying.

$\rightarrow$ We look for an exponentially decaying solution. $\boxed{\mathrm{H}^1 \text{ framework}}$

Modal analysis in the waveguide

	► Outside the critical interval. All the modes are exponentially growing or decaying. → We look for an exponentially decaying solution. $\boxed{\text{H}^1 \text{ framework}}$
	► Inside the critical interval. There are exactly two propagative modes.

Modal analysis in the waveguide



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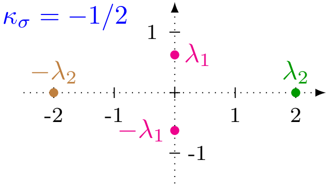

- Inside the critical interval. There are exactly two propagative modes.

$\rightarrow$ The decomposition on the outgoing modes leads to look for a solution of the form

$$u = \underbrace{c_1\, \varphi_1\, e^{\lambda_1 z}}_{\text{propagative part}} + \underbrace{u_e}_{\text{evanescent part}}.$$

$\boxed{\text{non H}^1 \text{ framework}}$

The new functional framework

Consider $0 < \beta < 2$, ζ a cut-off function (equal to 1 in $+\infty$) and define

$\mathrm{W}_{-\beta} = \{v \,|\, e^{\beta z} v \in \mathrm{H}^1_0(\mathcal{B})\}$ space of exponentially decaying functions

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$$\mathrm{W}_{\beta} = \{v \,|\, e^{-\beta z} v \in \mathrm{H}^1_0(\mathcal{B})\} \qquad \text{space of exponentially growing functions}$$

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$$\begin{array}{lll} \mathrm{W}_{-\beta} & = \{v \,|\, e^{\beta z} v \in \mathrm{H}^1_0(\mathcal{B})\} & \text{space of exponentially decaying functions} \\ \mathrm{W}^+ & = \mathrm{span}(\zeta \varphi_1 \, e^{\lambda_1 z}) \oplus \mathrm{W}_{-\beta} & \text{propagative part + evanescent part} \\ \mathrm{W}_{\beta} & = \{v \,|\, e^{-\beta z} v \in \mathrm{H}^1_0(\mathcal{B})\} & \text{space of exponentially growing functions} \end{array}$$

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Theorem. Let $\kappa_\sigma \in (-1; -1/3)$ and $0 < \beta < 2$. The operator $A^+ : \mathrm{div}(\sigma \nabla \cdot)$ from W^+ to ${\mathrm{W}_\beta}^*$ is an isomorphism.

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Theorem. Let $\kappa_\sigma \in (-1; -1/3)$ and $0 < \beta < 2$. The operator $A^+ : \mathrm{div}(\sigma\nabla\cdot)$ from W^+ to ${\mathrm{W}_\beta}^*$ is an isomorphism.

Ideas of the proof:

1. $A_{-\beta} : \mathrm{div}(\sigma\nabla\cdot)$ from $\mathrm{W}_{-\beta}$ to ${\mathrm{W}_\beta}^*$ is injective but not surjective.

The new functional framework

Consider $0 < \beta < 2$, ζ a cut-off function (equal to 1 in $+\infty$) and define

$$\begin{array}{lll} \mathrm{W}_{-\beta} & = \{v \,|\, e^{\beta z} v \in \mathrm{H}^1_0(\mathcal{B})\} & \text{space of exponentially decaying functions} \\ \cap & & \\ \mathrm{W}^+ & = \mathrm{span}(\zeta\varphi_1\, e^{\lambda_1 z}) \oplus \mathrm{W}_{-\beta} & \text{propagative part + evanescent part} \\ \cap & & \\ \mathrm{W}_{\beta} & = \{v \,|\, e^{-\beta z} v \in \mathrm{H}^1_0(\mathcal{B})\} & \text{space of exponentially growing functions} \end{array}$$

Theorem. Let $\kappa_\sigma \in (-1; -1/3)$ and $0 < \beta < 2$. The operator $A^+ : \mathrm{div}(\sigma\nabla\cdot)$ from W^+ to $\mathrm{W}_\beta{}^*$ is an isomorphism.

Ideas of the proof:

1. $A_{-\beta} : \mathrm{div}(\sigma\nabla\cdot)$ from $\mathrm{W}_{-\beta}$ to $\mathrm{W}_\beta{}^*$ is injective but not surjective.
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THEOREM. Let $\kappa_\sigma \in (-1;-1/3)$ and $0 < \beta < 2$. The operator A^{+} : $\mathrm{div}(\sigma\nabla\cdot)$ from W^{+} to ${\mathrm{W}_\beta}^*$ is an isomorphism.

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4. Limiting absorption principle to select the outgoing mode.

Naive approximation

► Let us try a usual Finite Element Method (P1 Lagrange Finite Element). We solve the problem

$$\left|\begin{array}{l}\text{Find } u_h \in \mathrm{V}_h \text{ s.t.:}\\ \displaystyle\int_\Omega \sigma \nabla u_h \cdot \nabla v_h = \int_\Omega f v_h, \quad \forall v \in \mathrm{V}_h,\end{array}\right.$$

where V_h approximates $\mathrm{H}_0^1(\Omega)$ as $h \to 0$ (h is the mesh size).

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- We display u_h as $h \to 0$.

Naive approximation

THE SEQUENCE (u_h) DOES NOT CONVERGE AS $h \to 0$!!!

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$(\ldots)$

Contrast $\kappa_\sigma = -0.999 \in (-1; -1/3)$.

Remark

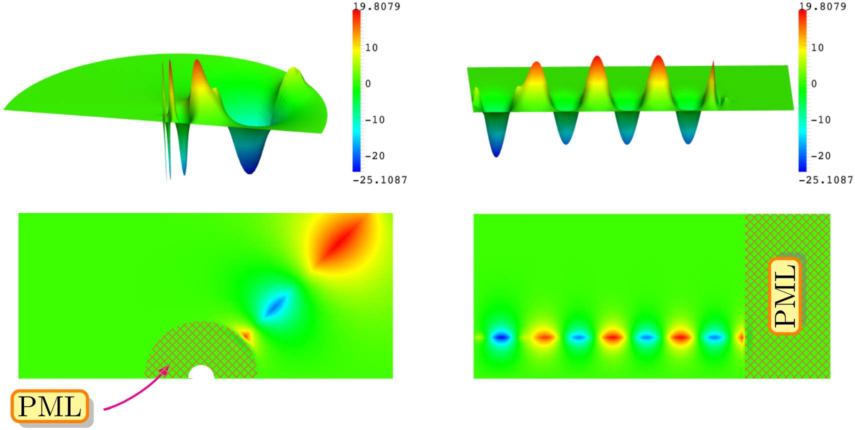
- Outside the critical interval, the sequence (u_h) converges with the naive approximation.

$(\dots)$

Contrast $\kappa_\sigma = -1.001 \notin (-1; -1/3)$.

How to approximate the solution?

- We use a PML (*Perfectly Matched Layer*) to bound the domain $\mathcal{B}$ + finite elements in the truncated strip ($\kappa_\sigma = -0.999 \in (-1; -1/3)$).



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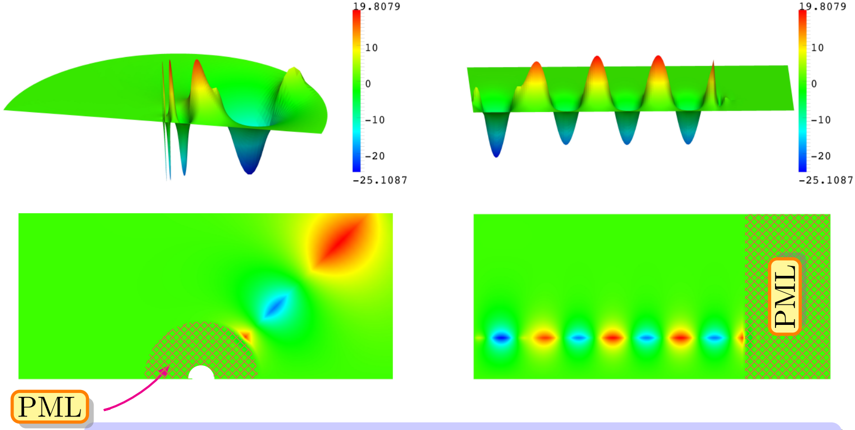
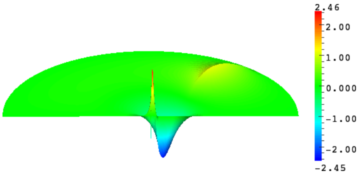


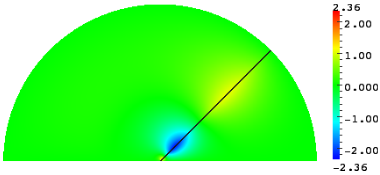
Without the PML, the solution in the truncated strip of length L does not converge when $L \to \infty$. This is what we observed in our numerical experiment for the rounded corner.

A black hole phenomenon

- The same phenomenon occurs for the Helmholtz equation.

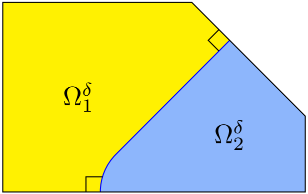
$$(\boldsymbol{x}, t) \mapsto \Re e\left(u(\boldsymbol{x})e^{-i\omega t}\right) \quad \text{for } \kappa_\sigma = -1/1.3$$

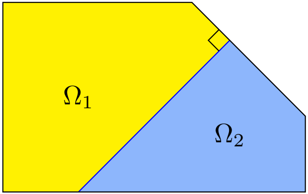




- Analogous phenomena occur in cuspidal domains in the theory of water-waves and in elasticity (`Cardone, Nazarov, Taskinen`).

Source term problem





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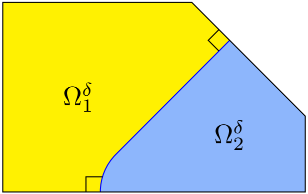

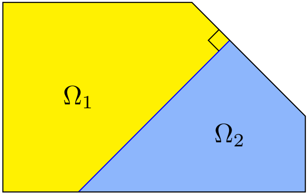

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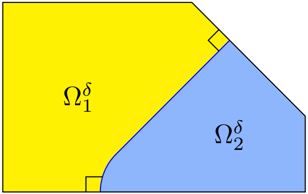

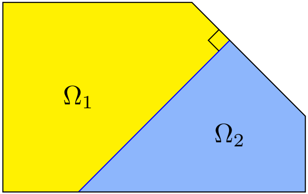

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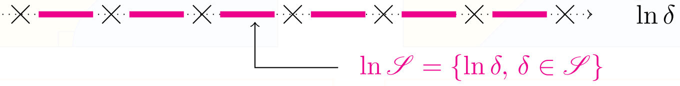
If the limit problem is well-posed only in the exotic framework, then $(\mathscr{P}^\delta)$ critically depends on the value of the rounding parameter δ.

Source term problem

IDEA OF THE APPROACH:

1 We prove the *a priori* estimate $\|u^\delta\|_{\mathrm{H}^1_0(\Omega)} \leq c\,|\ln\delta|^{1/2}\|f\|_\Omega$ for all δ in some set $\mathscr{S}$ which excludes a discrete set accumulating in zero (♠ hard part of the proof, `Nazarov's` technique).



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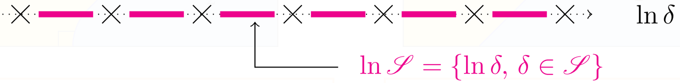

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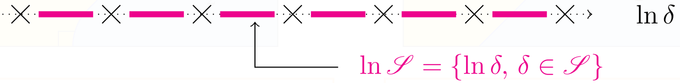

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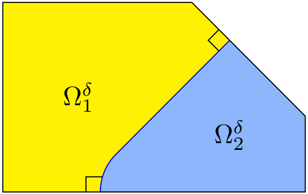
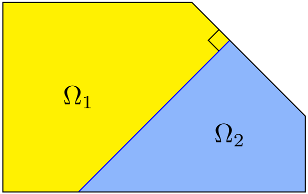
4. Conclusion.

The sequence $(u^\delta)_\delta$ does not converge, even for the L^2-norm!

Source term problem





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- In the geometry with a rounded corner, we consider the spectral problem

$$\boxed{\left|\begin{array}{l}\text{Find } (\lambda^\delta, u^\delta) \in \mathbb{C} \times (\mathrm{H}^1_0(\Omega) \setminus \{0\}) \text{ s.t.:}\\ -\mathrm{div}(\sigma^\delta \nabla u^\delta) = \lambda^\delta u^\delta \quad \text{ in } \Omega.\end{array}\right.}$$

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PROPOSITION. Assume that $\kappa_\sigma \neq -1$. For $\delta > 0$ (in this case the interface is "smooth"), the operator A^δ is selfadjoint and has compact resolvent. Its spectrum $\mathfrak{S}(\mathrm{A}^\delta)$ consists in two sequences of isolated eigenvalues:

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$\Rightarrow$ This depends on the features of the limit operator for $\delta = 0$...

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♣ When $\kappa_\sigma \notin I_c$, A is selfadjoint and has compact resolvent. Its spectrum $\mathfrak{S}(\mathrm{A})$ consists in two sequences of isolated eigenvalues:

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♣ When $\kappa_\sigma \in I_c \setminus \{-1\}$, there holds $D(\mathrm{A}^*) = D(\mathrm{A}) \oplus \mathrm{span}(s_+, s_-)$ where $s_\pm = \zeta r^{\pm i\eta}\varphi(\theta)$ (in particular A is not selfadjoint). Moreover, $\mathfrak{S}(\mathrm{A}) = \mathbb{C}$.

Inside the critical interval:

1. The selfadjoint extensions of A are the operators $\mathrm{A}(\tau) : D(\mathrm{A}(\tau)) \to \mathrm{L}^2(\Omega)$, $\tau \in \mathbb{R}$, such that

$$\left|\begin{array}{l} D(\mathrm{A}(\tau)) = D(\mathrm{A}) \oplus \mathrm{span}(s_+ + e^{i\tau} s_-) \\ \mathrm{A}(\tau)u = \mathrm{div}(\sigma\nabla u). \end{array}\right.$$

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In this case, there holds $\mathfrak{S}(\mathrm{A}^\delta) \underset{\delta\to0}{\rightarrow} \mathfrak{S}(\mathrm{A})$.

♣ When $\kappa_\sigma \in I_c \setminus \{-1\}$, there holds $D(\mathrm{A}^*) = D(\mathrm{A}) \oplus \mathrm{span}(s_+, s_-)$ where $s_\pm = \zeta r^{\pm i\eta}\varphi(\theta)$ (in particular A is not selfadjoint). Moreover, $\mathfrak{S}(\mathrm{A}) = \mathbb{C}$.

INSIDE THE CRITICAL INTERVAL:

❶ The selfadjoint extensions of A are the operators $\mathrm{A}(\tau) : D(\mathrm{A}(\tau)) \to \mathrm{L}^2(\Omega)$, $\tau \in \mathbb{R}$, such that

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❷ Using matched asymptotic expansions techniques, we have proved the

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3. Conclusion.

> The spectrum of A^δ does not converge when $\delta \to 0$. Asymptotically, $\mathfrak{S}(\mathrm{A}^\delta)$ is $2\pi/a$–periodic in $\ln \delta$–scale.

- Let $\mathrm{A} : D(\mathrm{A}) \to \mathrm{L}^2(\Omega)$ denote the limit operator ($\delta = 0$) such that

$$\left| \begin{array}{l} D(\mathrm{A}) = \{u \in \mathrm{H}^1_0(\Omega) \,|\, \mathrm{div}(\sigma\nabla u) \in \mathrm{L}^2(\Omega)\} \\ \mathrm{A}u = \mathrm{div}(\sigma\nabla u). \end{array} \right.$$

- For $\delta = 0$, the interface is no longer "smooth" and the properties of A depend on the values of κ_σ:

♣ When $\kappa_\sigma \notin I_c$, A is selfadjoint and has compact resolvent. Its spectrum $\mathfrak{S}(\mathrm{A})$ consists in two sequences of isolated eigenvalues:

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Selfadjoint extensions of A inside I_c

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? Maybe $\mathfrak{S}(\mathrm{A}^\delta) \to \mathfrak{S}(\mathrm{A}(\tau))$ for some τ as $\delta \to 0$. But for which τ?

Asymptotic expansion

- From now, we assume that $\kappa_\sigma \in (-1; -1/\ell)$.
- Consider $(\lambda^\delta, u^\delta)$ an eigenpair of the original spectral problem.

$$\left|\begin{array}{l} \text{Find } (\lambda^\delta, u^\delta) \in \mathbb{C} \times (\mathrm{H}^1_0(\Omega) \setminus \{0\}) \text{ s.t.:} \\ -\mathrm{div}(\sigma^\delta \nabla u^\delta) = \lambda^\delta u^\delta \quad \text{ in } \Omega. \end{array}\right.$$

- To compute an asymptotic expansion of $(\lambda^\delta, u^\delta)$, we make the ansatz

$$\begin{array}{rclcll} \lambda^\delta & = & \eta^\delta & + & \dots & \\ u^\delta(x) & = & v^\delta(x) & + & \dots & \text{far from } O \\ u^\delta(x) & = & V^\delta(x/\delta) & + & \dots & \text{near } O \end{array}$$

where η^δ, v^δ, V^δ have to be determined ($\dots$ stand for lower order terms).

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where η^δ, v^δ, V^δ have to be determined ($\dots$ stand for lower order terms).

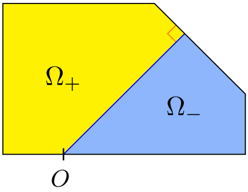
- Note that η^δ, v^δ, V^δ will be defined as solutions of problems set in geometries independent of δ.

Far field

- The far field is defined in the geometry obtained taking $\delta = 0$.

- We find that the pair (η^δ, v^δ) must verify

$$\left| \begin{array}{rcll} -\mathrm{div}(\sigma^0 \nabla v^\delta) & = & \eta^\delta v^\delta & \text{in } \Omega \\ v^\delta & = & 0 & \text{on } \partial\Omega. \end{array} \right.$$



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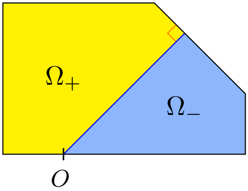


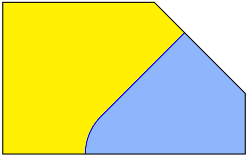
- Since we do not know which behaviour to prescribe at O, we allow decomposition on the two singularities $s_\pm$ and search for v^δ under the form

$$\boxed{\begin{array}{rcccccc} v^\delta & = & c_+^\delta \, s_+ & + & c_-^\delta \, s_- & + & \tilde{v}^\delta \\ & = & c_+^\delta \, r^{i\mu} \phi(\theta) & + & c_-^\delta \, r^{-i\mu} \phi(\theta) & + & \tilde{v}^\delta, \end{array}}$$

where the jauge functions $c_\pm^\delta$ and $\tilde{v}^\delta \in D(\mathrm{A})$ have to be determined.

Near field

- Introduce the rapid coordinate $\xi := x/\delta$ and let $\delta \to 0$.



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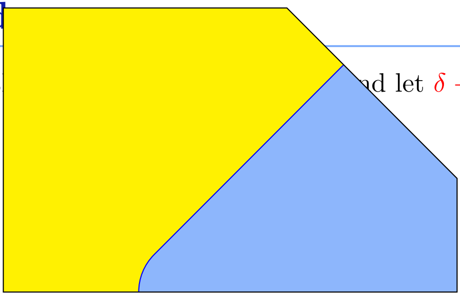
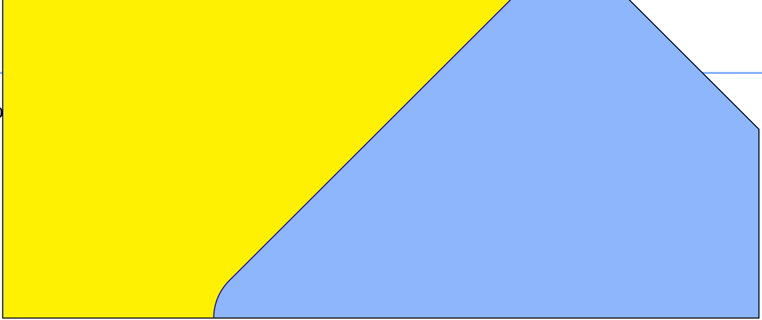
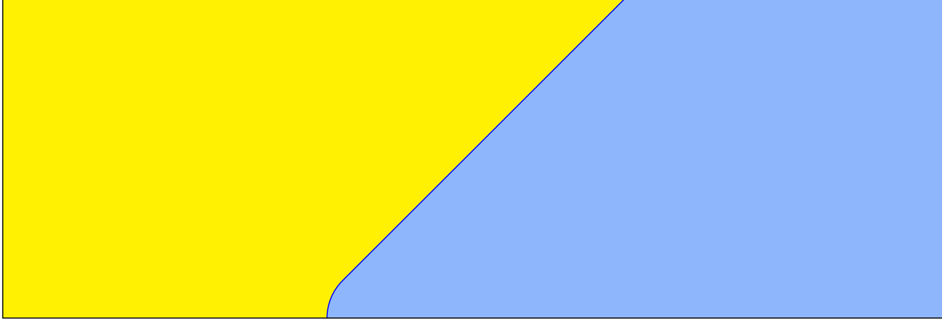
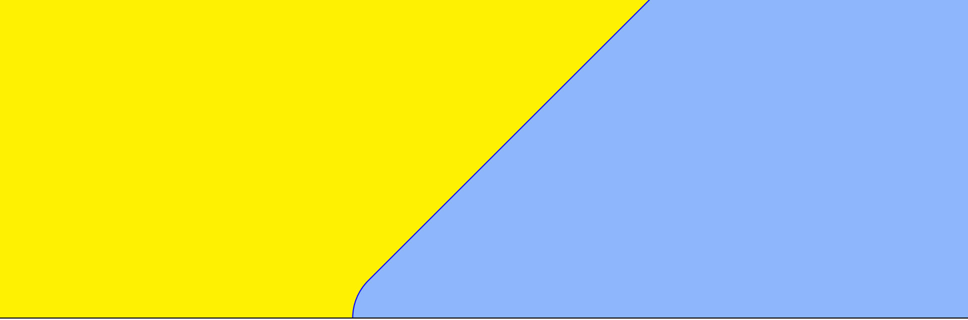


Near

- Intro







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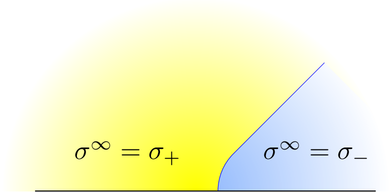

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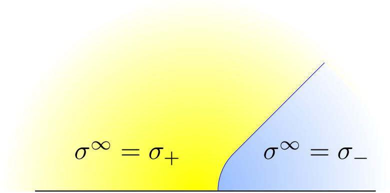

Set $U^\delta(\xi) = u^\delta(\delta\xi)$. We have

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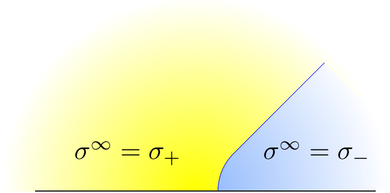

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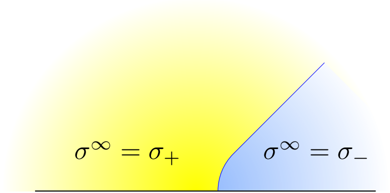

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- There is V^δ solution of this problem admitting the expansion

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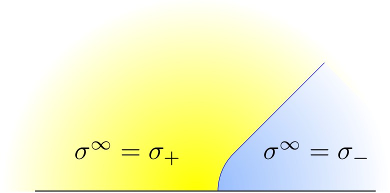

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Important: there holds $|\alpha| = 1$.

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From
$$-\mathrm{div}(\sigma^\infty \nabla V^\delta) = 0 \text{ in } \Xi, \qquad V^\delta = 0 \text{ on } \partial\Xi,$$
multiplying by $\overline{V^\delta}$ and integrating by parts on $\{\xi \in \Xi \,|\, |\xi| < R\}$, we find
$$0 \quad = \quad \Im m \int_{\Xi\cap\{|\xi|=R\}} \sigma^\infty \partial_r V^\delta \overline{V^\delta}\, d\theta$$

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Taking the limit $R \to +\infty$ gives $|\alpha| = 1$.

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Important: there holds $|\alpha| = 1$.

Matching procedure

- We match the far field and near field expansions in some intermediate region where $r \to 0$ and $r/\delta \to +\infty$ (for example where $r \sim \sqrt{\delta}$).

$$\begin{array}{llcccccc} \text{Far field:} & v^\delta(x) & = & c_+^\delta\, r^{i\mu}\phi(\theta) & + & c_-^\delta\, r^{-i\mu}\phi(\theta) & + & \dots \\ \text{Near field:} & V^\delta(x/\delta) & = & (r/\delta)^{i\mu}\phi(\theta) & + & \alpha(r/\delta)^{-i\mu}\phi(\theta) & + & \dots \end{array}$$

- Since $r \mapsto r^{i\mu}$ and $r \mapsto r^{-i\mu}$ are linearly independent, we impose

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This suggests that the eigenpairs of A^δ behave as the eigenpairs of the model operator $\mathscr{M}(\delta)$ such that

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$$c_+^\delta = \delta^{-i\mu} \quad \text{and} \quad c_-^\delta = \alpha\,\delta^{i\mu} \qquad \Rightarrow \qquad c_-^\delta / c_+^\delta = \alpha\,\delta^{2i\mu}.$$

This suggests that the eigenpairs of A^δ behave as the eigenpairs of the model operator $\mathscr{M}(\delta)$ such that

$$\left|\begin{array}{l} D(\mathscr{M}(\delta)) = D(\mathrm{A}) \oplus \mathrm{span}(s_+ + \alpha\,\delta^{2i\mu} s_-) \\ \mathscr{M}(\delta)u = \mathrm{div}(\sigma\nabla u). \end{array}\right.$$

- The model operator at first order depends and δ. Moreover, for $\delta > 0$, we have $|\alpha\,\delta^{2i\mu}| = 1$.

Matching procedure

- We match the far field and near field expansions in some intermediate region where $r \to 0$ and $r/\delta \to +\infty$ (for example where $r \sim \sqrt{\delta}$).

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THEOREM. For $\kappa_\sigma \in (-1; -1/\ell)$, on each compact set of $\mathbb{R}$, we have

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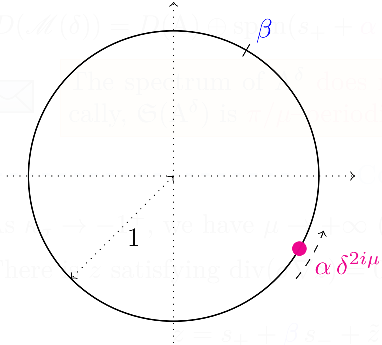

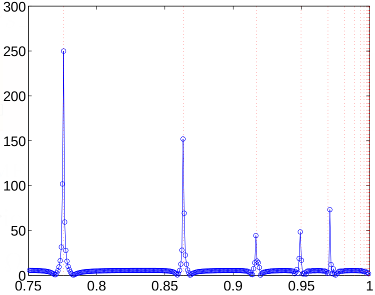

$\|\nabla u_h^\delta\|_{\Omega^\delta}$ w.r.t. $1-\delta$

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Comments concerning the proof

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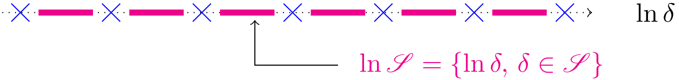

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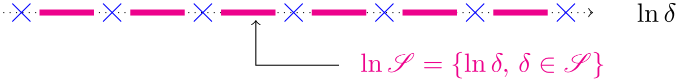

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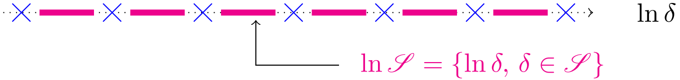

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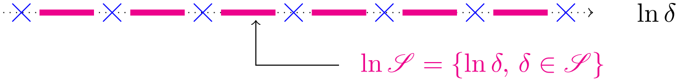

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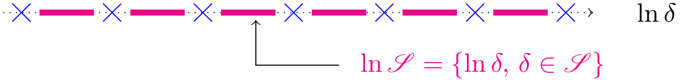

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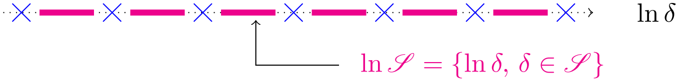

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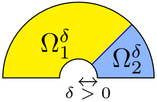
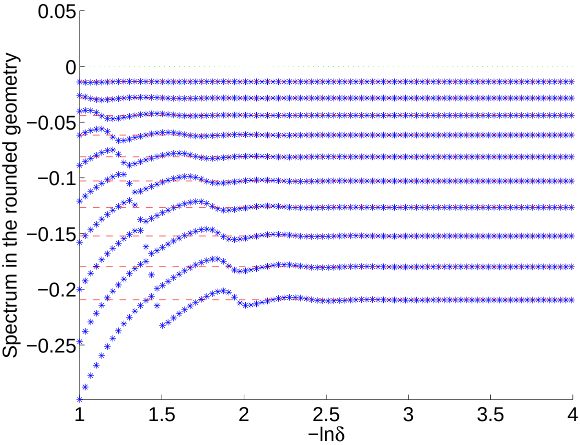
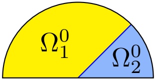
♠ Proving (1), (2) is not straightforward due to the change of sign of σ. This aspect is interesting in itself (`S.A. Nazarov's` technique).

Spectral problem: numerical experiments 3/4

$\kappa_\sigma = -1.0001$ (outside the critical interval)







- $\mathfrak{S}(A^\delta)$ converges to $\mathfrak{S}(A)$ (A is the limit operator) when $\delta \to 0$.

Spectral problem: numerical experiments 4/4

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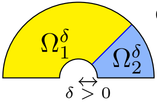

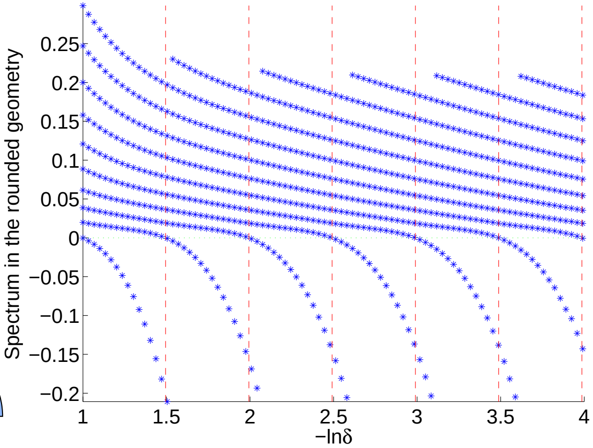

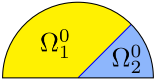

- Asymptotically, $\mathfrak{S}(\mathrm{A}^\delta)$ is periodic in $\ln\delta$–scale as $\delta \to 0$.

Spectral problem: numerical experiments 4/4

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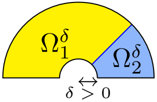

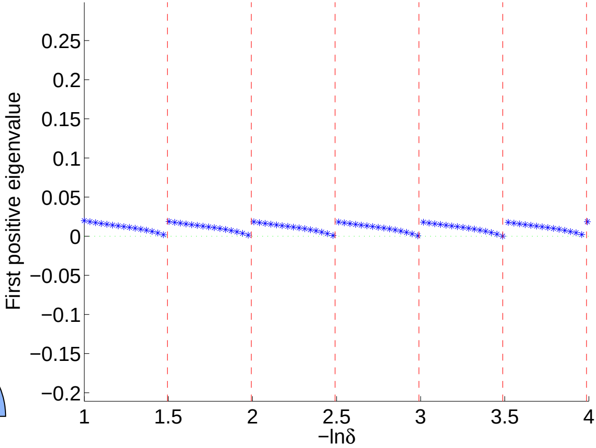

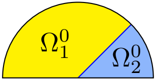

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Spectral problem: numerical experiments 4/4

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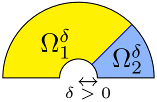

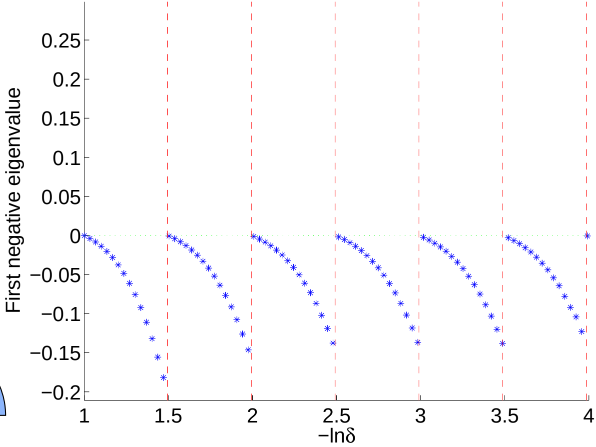

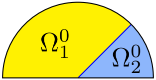

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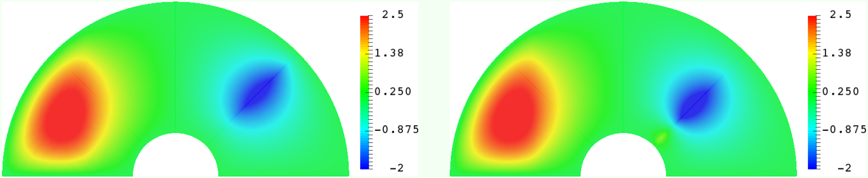
Conclusion 1/2

Let us remind the initial question:

What is the behaviour of $(u^\delta)_\delta$ when δ tends to zero?

This depends on the features of the limit problem.



$\kappa_\sigma = -1.0001 \notin I_c$

$\kappa_\sigma = -0.9999 \in I_c$

When $\kappa_\sigma \in I_c$, $(u^\delta)_\delta$ does not converge, even for the L^2-norm!

In this case, it is impossible to simulate the fields since it is impossible to measure exactly δ. $\Rightarrow$ What happens physically?

Conclusion 2/2

And concerning the spectral problem?

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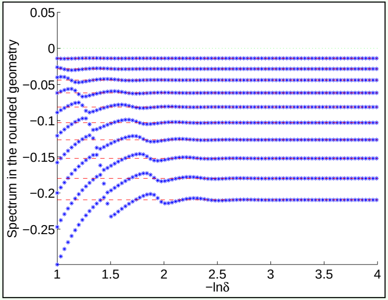

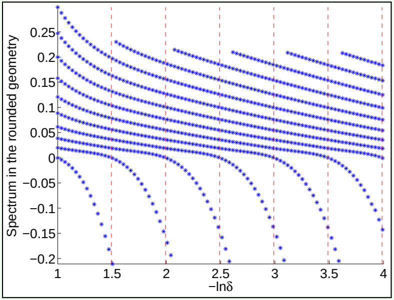

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$\star$ $\mathfrak{S}(\mathrm{A}^\delta)$ tends to $\mathfrak{S}(\mathrm{A})$ where A is the limit operator for $\delta = 0$.

$\kappa_\sigma = -0.9999 \in I_c$

$\star$ $\mathfrak{S}(\mathrm{A}^\delta)$ behaves as $\mathfrak{S}(\mathscr{M}(\delta))$, which is periodic in $\ln\delta$-scale.

Thank you for your attention!

A.-S. Bonnet-Ben Dhia, L. Chesnel, X. Claeys, *Radiation condition for a non-smooth interface between a dielectric and a metamaterial*, M3AS, 23, 2013.

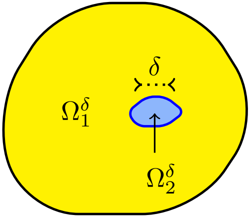
L. Chesnel, X. Claeys, S.A. Nazarov, *A curious instability phenomenon for a rounded corner in presence of a negative material*, Asymp. Anal., vol. 88, 1-2:43-74, 2014.

L. Chesnel, X. Claeys, S.A. Nazarov, *Oscillating behaviour of the spectrum for a plasmonic problem in a domain with a rounded corner*, accepted in Math. Mod. Num. Anal., 2016.

Spectrum for a small inclusion: setting

- Let Ω, Ξ be smooth domains of $\mathbb{R}^3$ such that $O \in \Xi$, $\overline{\Xi} \subset \Omega$.
- For $\delta \in (0;1]$, we consider the spectral problem

$$\left|\begin{array}{l}\text{Find } (\lambda^\delta, u^\delta) \in \mathbb{C} \times (\mathrm{H}^1_0(\Omega) \setminus \{0\}) \text{ s.t.:}\\ -\mathrm{div}(\sigma^\delta \nabla u^\delta) = \lambda^\delta u^\delta \quad \text{ in } \Omega,\end{array}\right.$$



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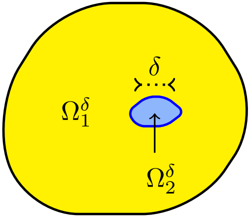

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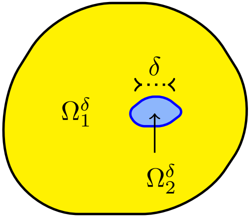

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PROPOSITION. Assume that $\kappa_\sigma \neq -1$. For $\delta > 0$, the operator A^δ is selfadjoint and has compact resolvent. Its spectrum $\mathfrak{S}(\mathrm{A}^\delta)$ consists in two sequences of isolated eigenvalues:

$$-\infty \underset{n\to+\infty}{\leftarrow} \dots \lambda^\delta_{-n} \le \dots \le \lambda^\delta_{-1} < 0 \le \lambda^\delta_1 \le \lambda^\delta_2 \le \dots \le \lambda^\delta_n \dots \underset{n\to+\infty}{\rightarrow} +\infty.$$

Spectrum for a small inclusion: setting

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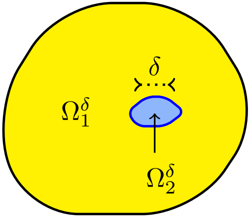

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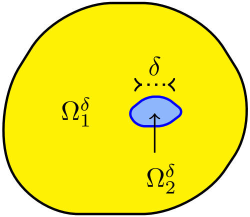

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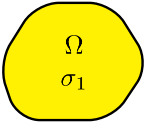
? What happens to the negative spectrum when δ tends to zero?

Limit operators

- As $\delta \to 0$, the small inclusion of negative material disappears. We introduce the far field operator A^0 such that

$$\left|\begin{array}{l} D(\mathrm{A}^0) = \{v \in \mathrm{H}^1_0(\Omega) \,|\, \Delta v \in \mathrm{L}^2(\Omega)\} \\ \mathrm{A}^0 v = -\sigma_1 \Delta v. \end{array}\right.$$



There holds $\mathfrak{S}(\mathrm{A}^0) = \{\mu_n\}_{n\ge 1}$ with $0 < \mu_1 < \mu_2 \le \dots \le \mu_n \dots \underset{n\to+\infty}{\to} +\infty$.

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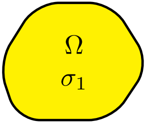

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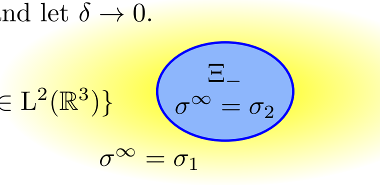
- Introduce the rapid coordinate $\boldsymbol{\xi} := \delta^{-1}\boldsymbol{x}$ and let $\delta \to 0$. Define the near field operator B^∞ such that



$$\left|\begin{array}{lcl} D(\mathrm{B}^\infty) & := & \{w \in \mathrm{H}^1(\mathbb{R}^3)\,|\,\mathrm{div}\,(\sigma^\infty \nabla w) \in \mathrm{L}^2(\mathbb{R}^3)\} \\ \mathrm{B}^\infty w & = & -\mathrm{div}\,(\sigma^\infty \nabla w). \end{array}\right.$$

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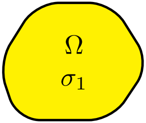

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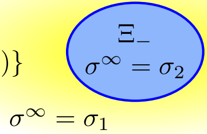

Proposition. Assume that $\kappa_\sigma \neq -1$. The continuous spectrum of B^∞ is equal to $[0;+\infty)$ while its discrete spectrum is a sequence of eigenvalues:

$$\mathfrak{S}(\mathrm{B}^\infty) \setminus \overline{\mathbb{R}_+} = \{\mu_{-n}\}_{n\geq 1} \quad \text{with} \quad 0 > \mu_{-1} \geq \cdots \geq \mu_{-n} \ldots \underset{n\to+\infty}{\to} -\infty.$$

Spectrum for a small inclusion: results

Assume that $\kappa_\sigma \neq -1$ and that B^∞ is injective. For $n \in \mathbb{N}^*$, we denote $\lambda^\delta_{\pm n}$, μ^δ_n, μ^δ_{-n} the eigenvalues of A^δ, A^0, B^∞ as in the previous slides.

THEOREM. (POSITIVE SPECTRUM) For all $n \in \mathbb{N}^*$, $\varepsilon \in (0;1)$, there exist constants $C, \delta_0 > 0$ depending on n, ε but independent of δ, such that

$$|\lambda^\delta_n - \mu_n| \leq C\,\delta^{3/2-\varepsilon}, \qquad \forall \delta \in (0;\delta_0].$$

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Theorem. (Positive spectrum) For all $n \in \mathbb{N}^*$, $\varepsilon \in (0;1)$, there exist constants $C, \delta_0 > 0$ depending on n, ε but independent of δ, such that

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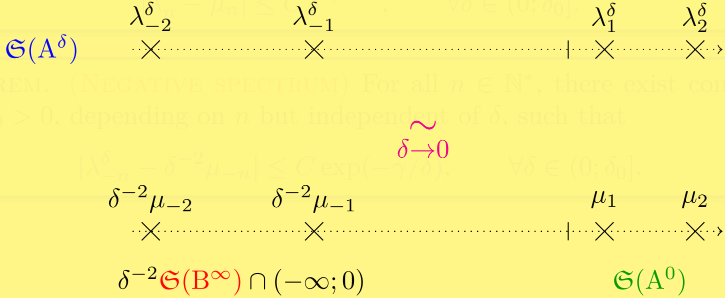
Schematically, we have:



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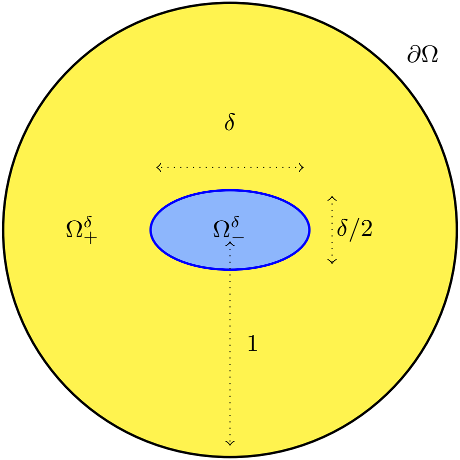
$$|\lambda^\delta_{-n} - \delta^{-2}\mu_{-n}| \le C\exp(-\gamma/\delta), \qquad \forall \delta \in (0;\delta_0].$$

Proposition. (Localization effect) For all $n \in \mathbb{N}^*$, let u^δ_{-n} be an eigenfunction corresponding to the negative eigenvalue λ^δ_{-n}. There exist constants $C, \gamma, \delta_0 > 0$, depending on n but independent of δ, such that

$$\int_\Omega (|u^\delta_{-n}|^2 + |\nabla u^\delta_{-n}|^2) e^{\gamma x/\delta} d\boldsymbol{x} \le C\,\|u^\delta_{-n}\|_\Omega, \qquad \forall \delta \in (0;\delta_0].$$

Numerical experiments for the small inclusion

- We approximate numerically the spectrum of A^δ using a usual P1 Finite Element Method and we make δ goes to zero.
- We consider the following 2D geometry:



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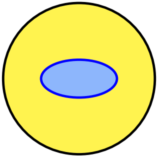
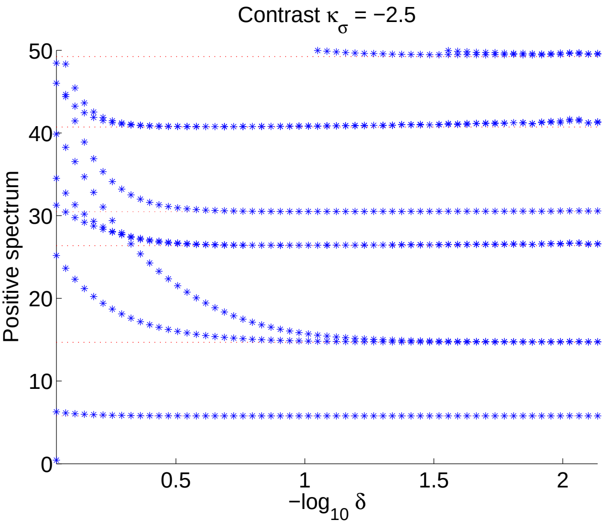
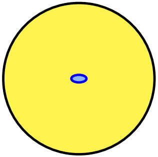
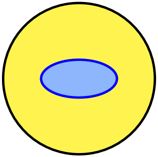


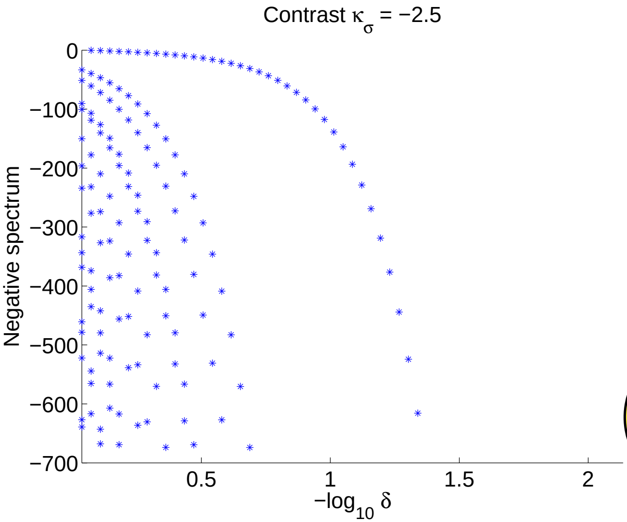


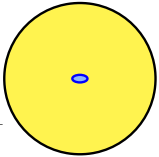


- The positive part of $\mathfrak{S}(\mathrm{A}^\delta)$ converges to $\mathfrak{S}(\mathrm{A}^0)$ when $\delta \to 0$.

Numerical experiments for the small inclusion

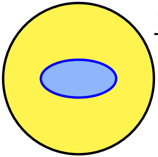


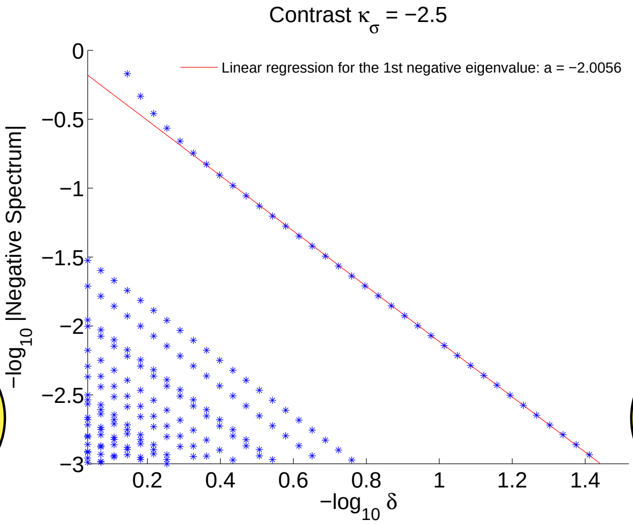


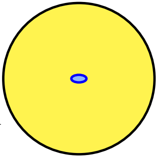


- The negative part of $\mathfrak{S}(\mathrm{A}^{\delta})$ is asymptotically equivalent to the negative part of $\delta^{-2}\mathfrak{S}(\mathrm{B}^{\infty})$ when $\delta \to 0$.

Numerical experiments for the small inclusion







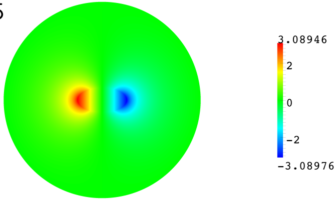
- The negative part of $\mathfrak{S}(\mathrm{A}^{\delta})$ is asymptotically equivalent to the negative part of $\delta^{-2}\mathfrak{S}(\mathrm{B}^{\infty})$ when $\delta \to 0$.

Localization effect

Eigenfunction associated to the first negative eigenvalue

Eigenfunction associated to the first positive eigenvalue

δ=0.5



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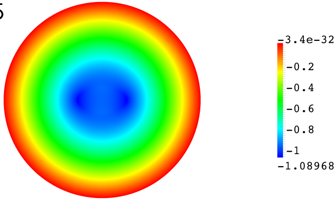

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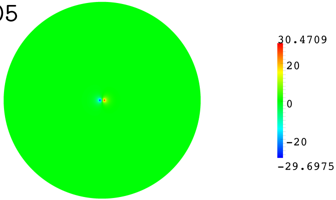

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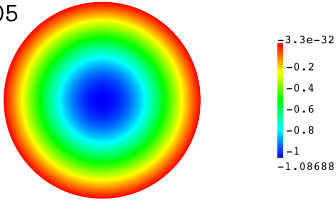

- The eigenfunctions corresponding to the negative eigenvalues are localized around the small inclusion. Here, $\kappa_\sigma = -2.5$.