Laboratoire Kastler Brossel
Physique quantique et applications

Enrico Fermi Fellowships

JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

LSU
Department of Physics & Astronomy

Analogue Gravity in 2026
Tuesday, January 16

Superradiance and Ergoregion Instabilities in Rotating Polariton Fluids

Paula A. Calizaya Cabrera

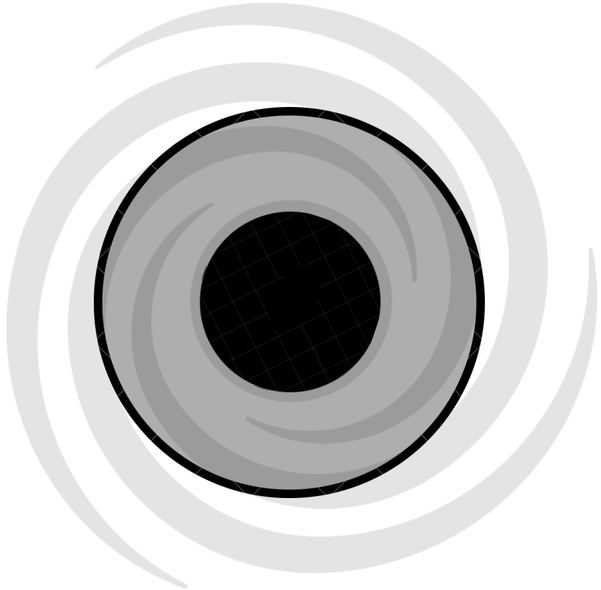
in collaboration with Killian Guerrero, Luca Giacomelli,
Adria Delhom, Maxime Jacquet & Ivan Agullo

The Basics of Rotational Superradiance

Rotating (Kerr) Black Holes

One can **extract energy and angular momentum from Kerr Black Holes**

Penrose, et al. Nature Physical Science (1971)



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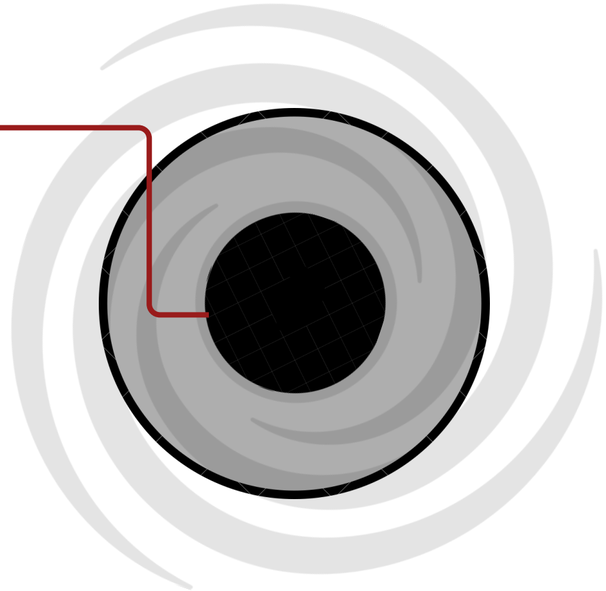
Event Horizon: boundary of the region of spacetime excluding the causal past of future null infinity

Observers many never escape this region



Rotating (Kerr) Black Holes

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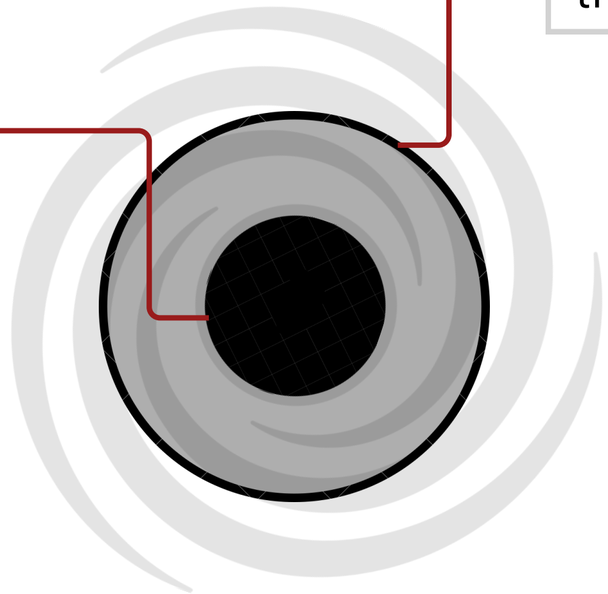
Ergosurface: Where the time translation Killing vector becomes null

Event Horizon: boundary of the region of spacetime excluding the causal past of future null infinity



Observer at the **ergoregion** are dragged and forced to co-rotate with the black hole.

Observers may escape the ergoregion

Observers many never escape this region

Amplification of scattered waves (from an ergoregion)

$$W_-^{\rm in} \longrightarrow T\, W_-^{\rm out} + R\, W_+^{\rm out}$$

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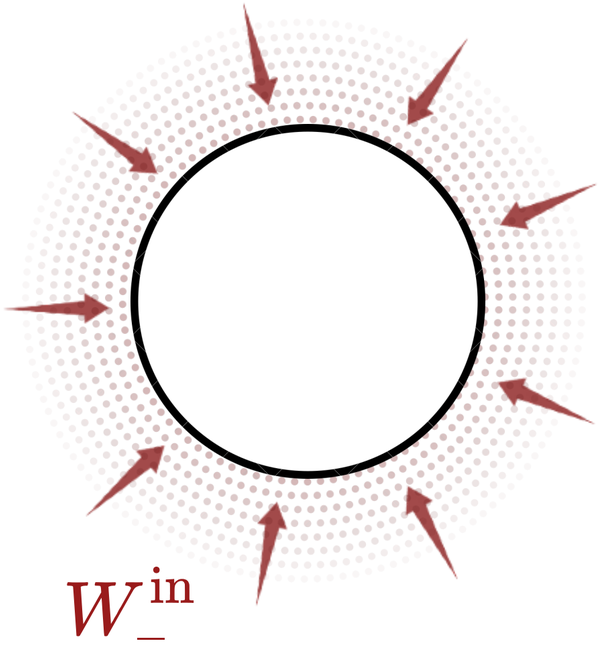
INPUT:

spheroidal waves of **specific frequency** and **angular momentum**

Zel'dovich, Zh.Eksp.Teor.Fiz. (1972)



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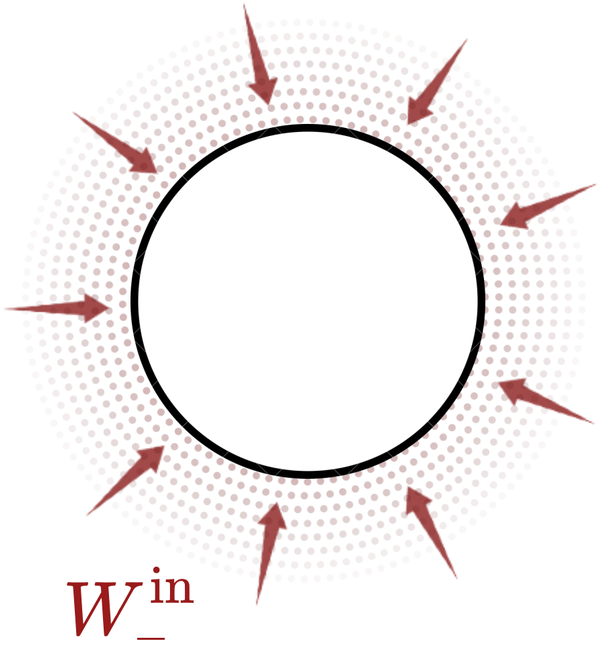
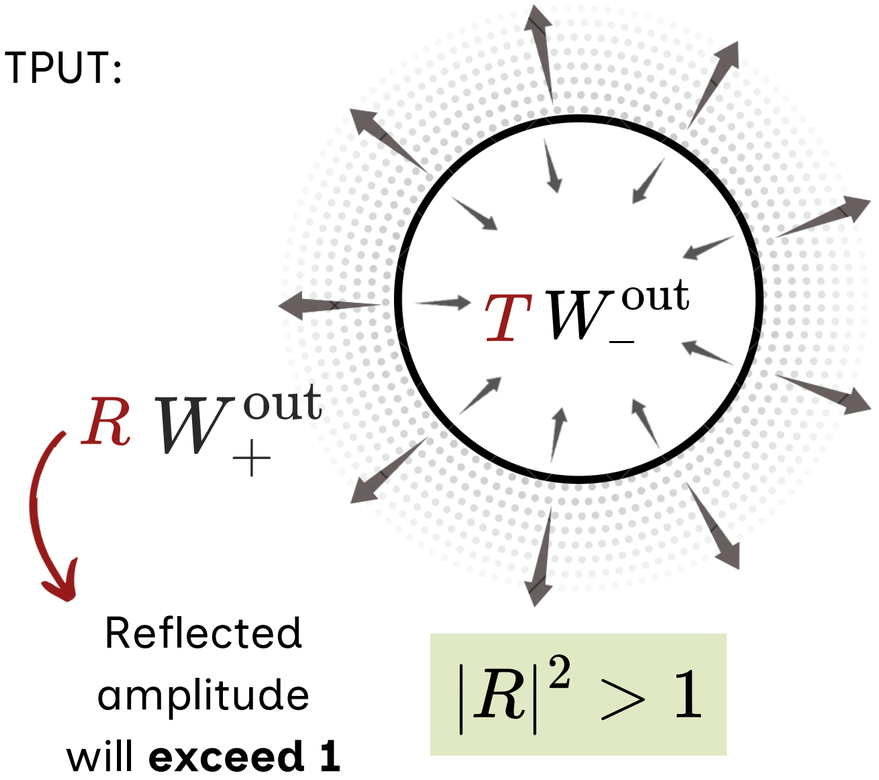


OUTPUT:



Reflected amplitude will **exceed 1**

$$|R|^2 > 1$$

Why does Superradiance Happen?

Bosonic field theory allows for superradiance

Consider the KG equation $\left[\nabla^{\mu}\nabla_{\mu} + M^2\right]\Phi(t,x) = 0$

With conserved quantity $\mathrm{N}(\Phi) = (\Phi,\Phi)_{\mathrm{KG}}$ given by the pseudoscalar product

$$(\Phi_1,\Phi_2)_{\mathrm{KG}} = i\int dx(\Phi_1^*\,\pi_2 - \pi_1^*\,\Phi_2)$$

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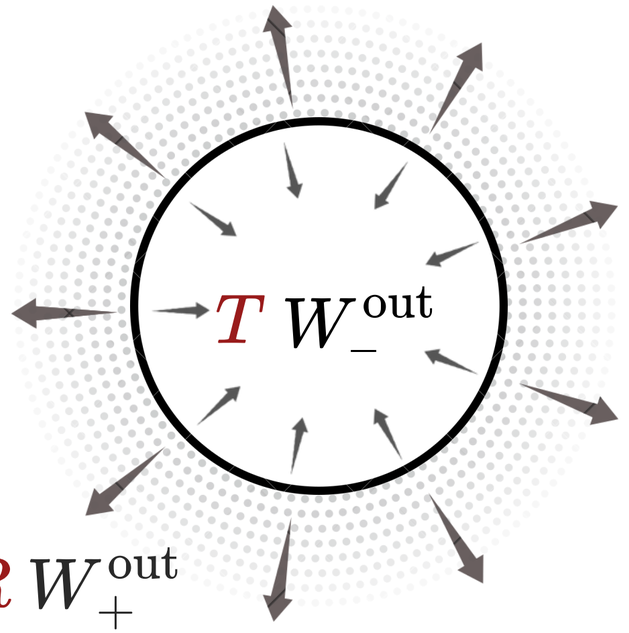

Norm conservation requires

$$1 = \frac{\mathrm{N}(W_+^{\mathrm{out}})}{\mathrm{N}(W_-^{\mathrm{in}})}|R|^2 + \frac{\mathrm{N}(W_-^{\mathrm{out}})}{\mathrm{N}(W_-^{\mathrm{in}})}|T|^2$$

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Superradiance happens when

$$\mathrm{N}(W_-^{\mathrm{out}}) < 0$$

Bosonic field theories allow negative norms ✓

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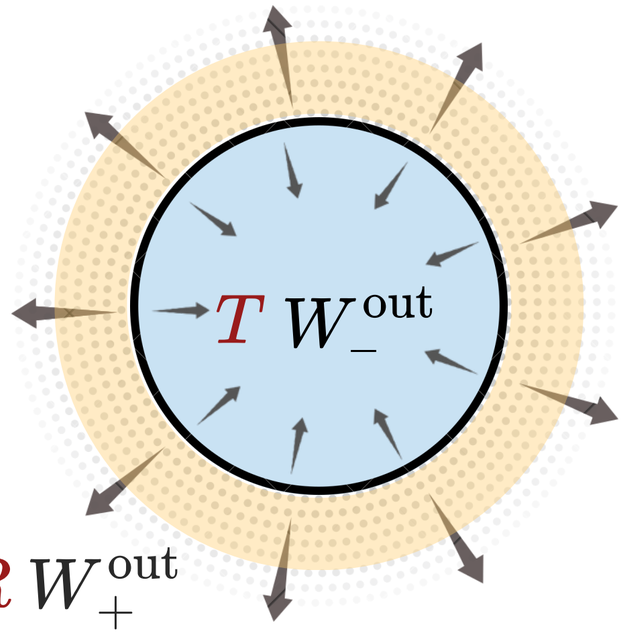

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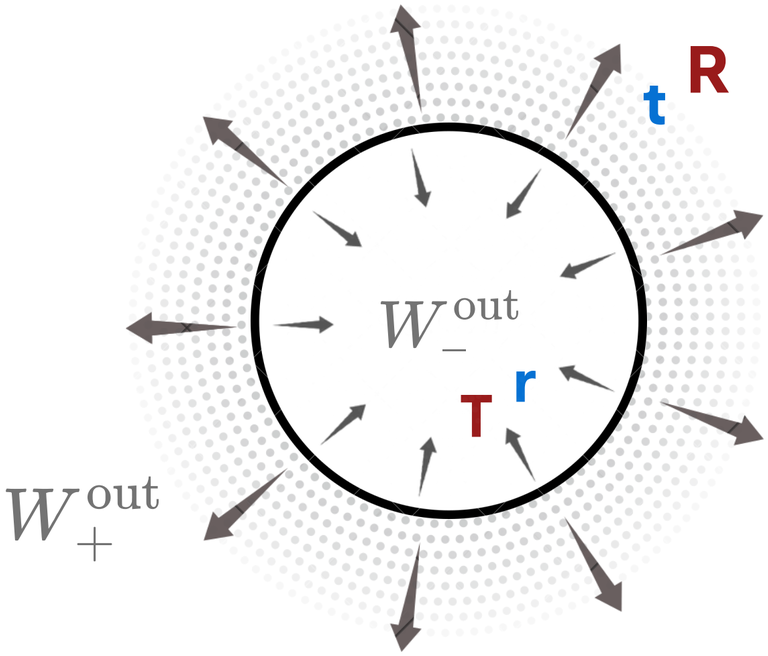
$$1 = |R|^2 - |T|^2$$

Superradiance Generates Entangled Pairs

Delhom, Guerrero, Jacquet, PC et al. Phys. Rev. D 109, 105024 (2024)



Take a complex solution to the KG equation, W_i centered at some specific frequency.

bosonic field operator

$$\mathrm{N}(W_i) = 1 \quad \xrightarrow{\text{defines}} \quad \hat{a}_i = (W_i, \hat{\Phi})_{\mathrm{KG}}$$

$$\mathrm{N}(W_i) = -1 \quad \xrightarrow{\text{defines}} \quad \hat{a}_i^\dagger$$

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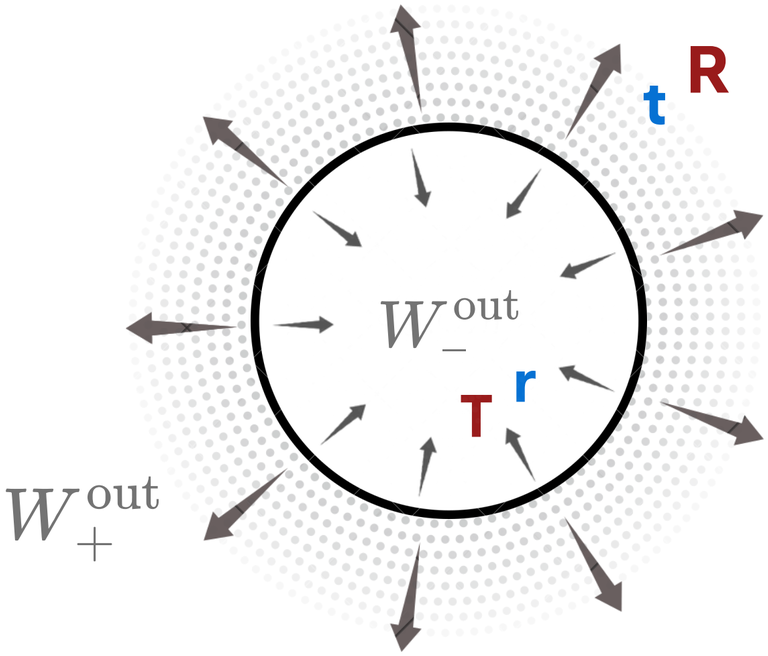

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The scattering problem leads to a **mixing** of creation and annihilation operators, i.e.

$$\hat{a}_-^{\text{out}} = r\,\hat{a}_+^{\text{in}} + T\,\hat{a}_-^{\text{in}\dagger}$$

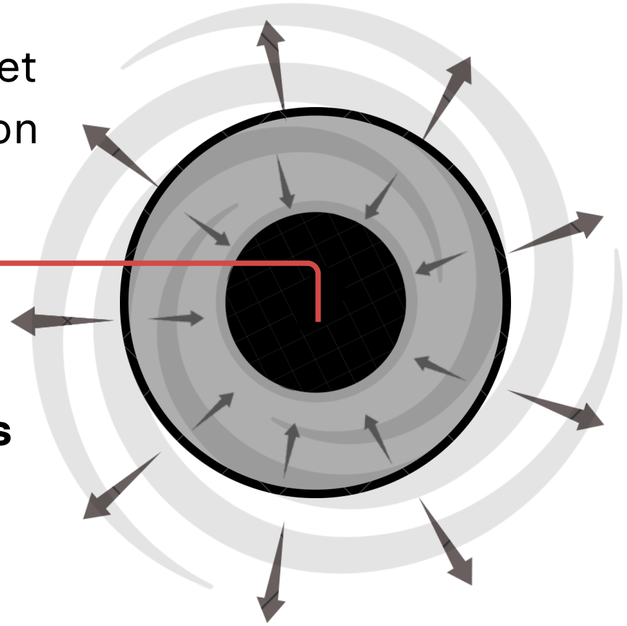
Superradiant scattering is a two-mode squeezer

End of Superradiance Basics

Ergoregions

Superradiant Scattering from a Rotating Black Hole

Transmitted waves get sucked in by the horizon



Superradiant waves are reflected back

Superradiant Scattering from a Rotating Black Hole

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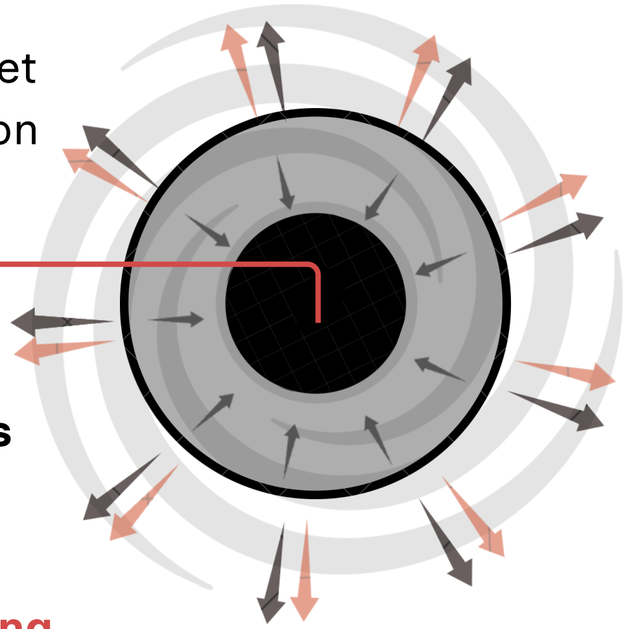

Superradiant waves are reflected back

Along with **Hawking Radiation** from the Horizon

Superradiant Scattering from a Rotating Black Hole

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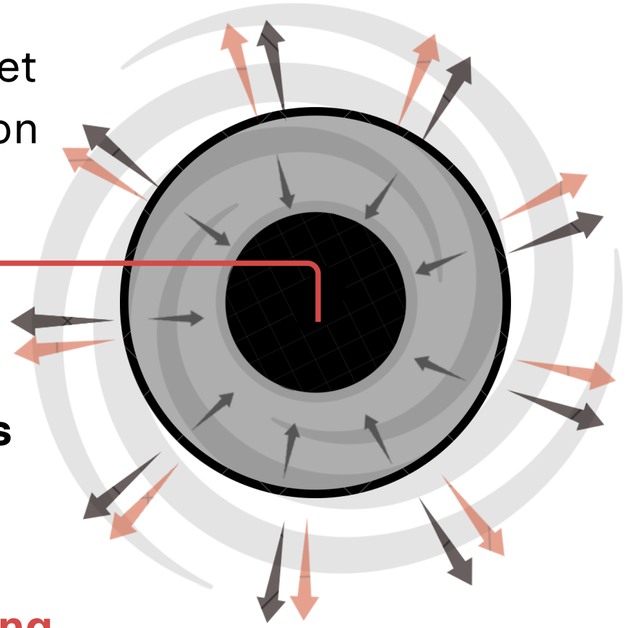

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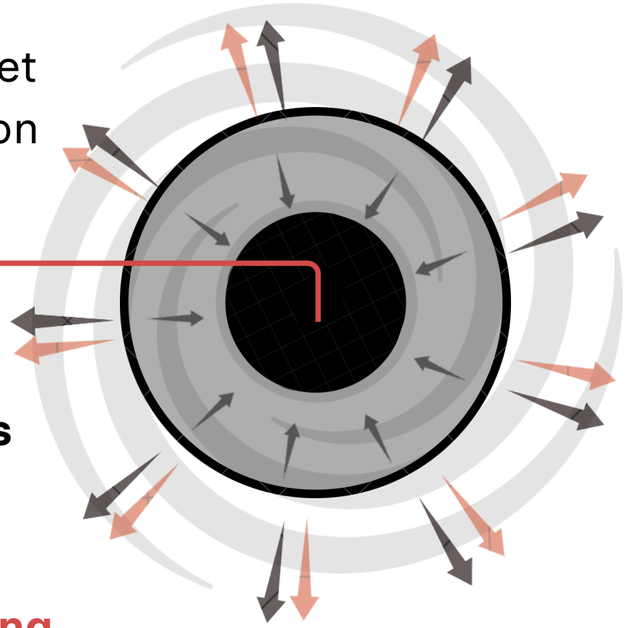

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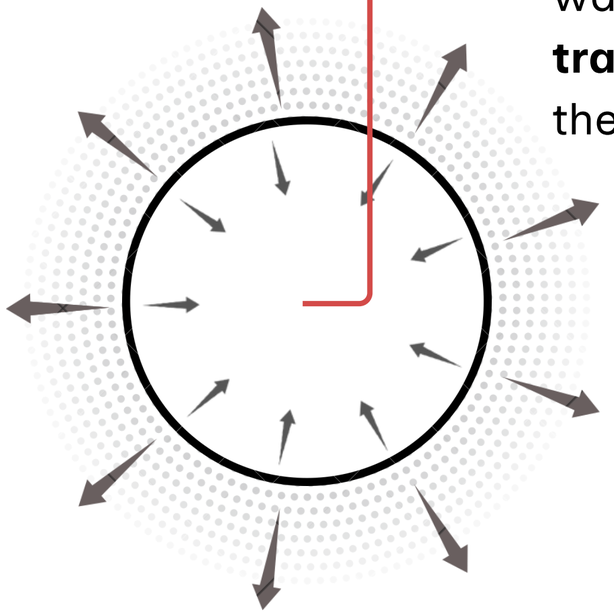
Superradiant Scattering from an Isolated Ergoregion

Transmitted waves get **trapped inside** the ergoregion



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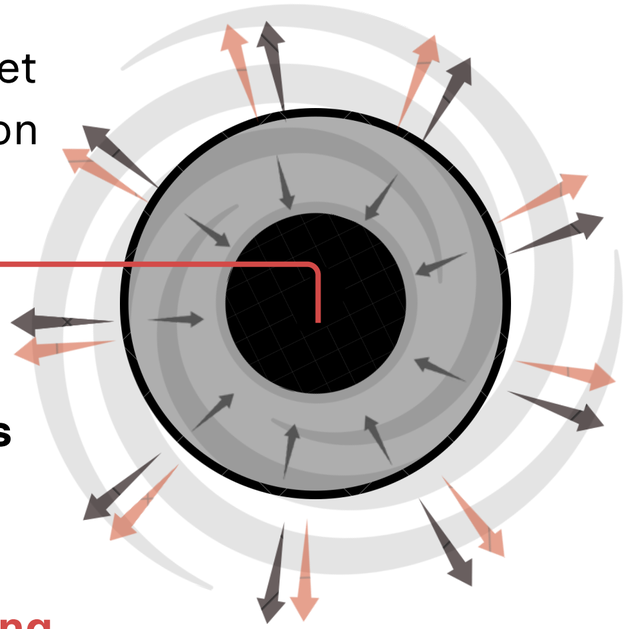

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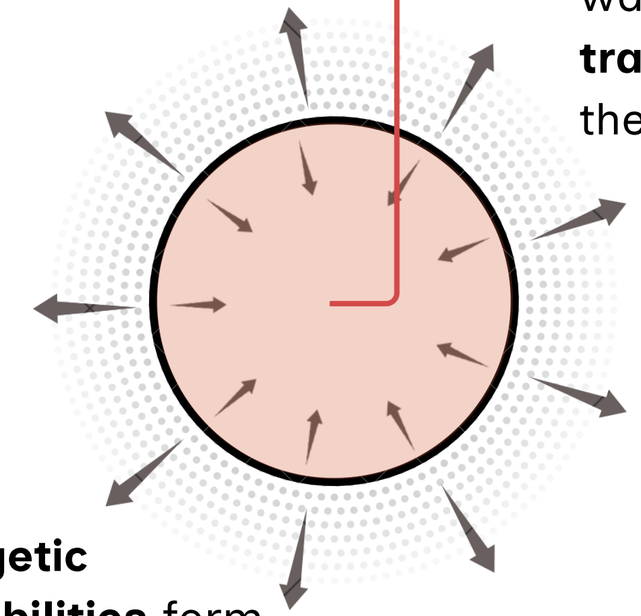

Energetic Instabilities form when superradiance occurs from within

$$\omega = \omega_r + i\Gamma$$

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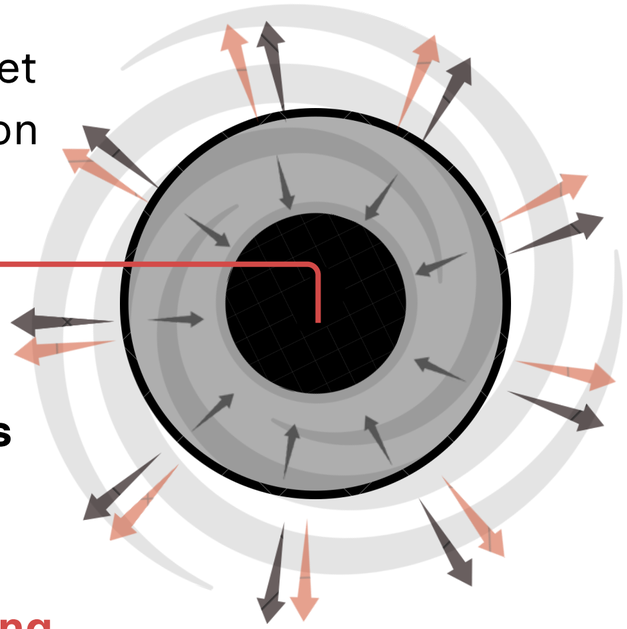

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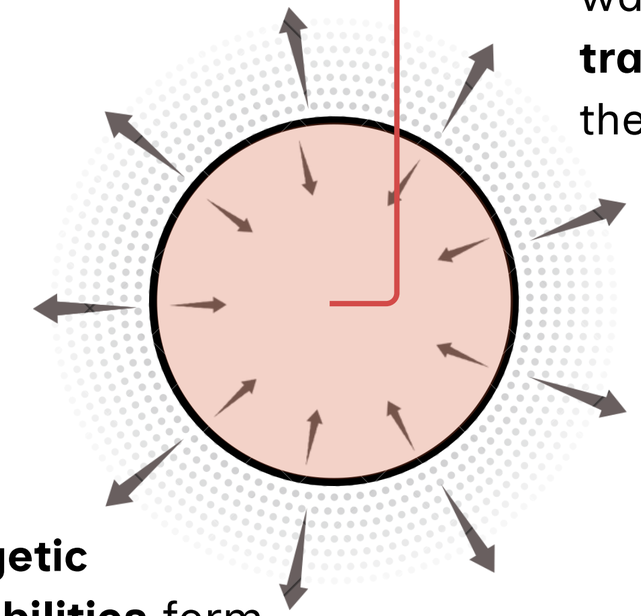


Energetic Instabilities form when superradiance occurs from within

$$\omega = \omega_r + i\Gamma$$

you need dissipation to avoid instabilities

Isolated Ergoregions in the Lab

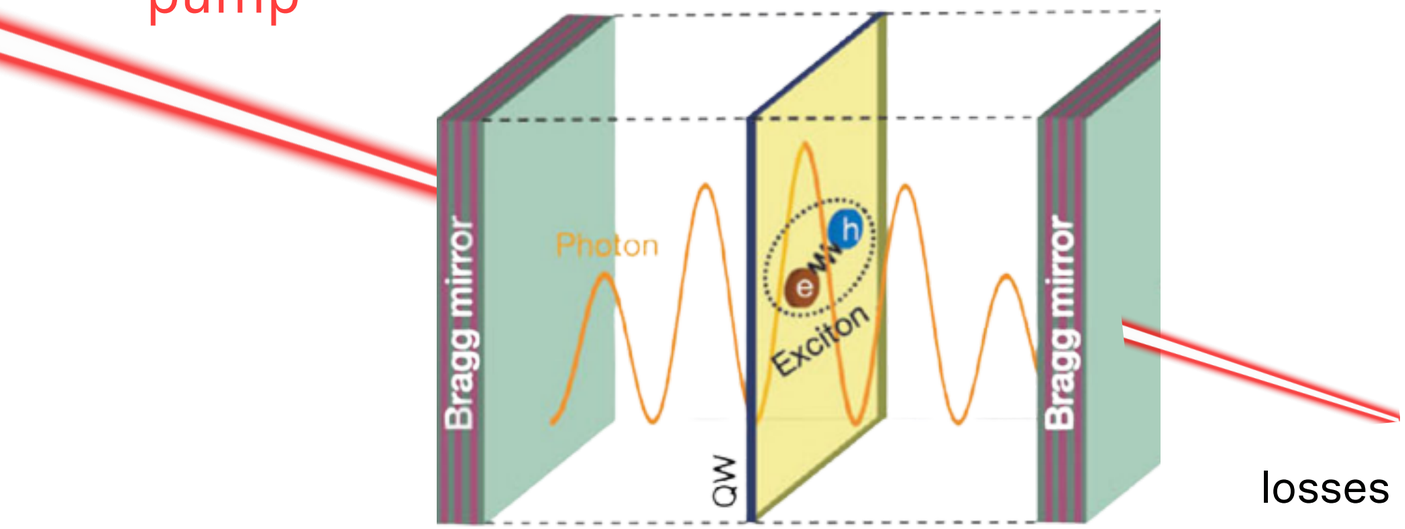
Experiment: Rotating Polariton Fluid

Polaritons: Quasi-particles made of the strong coupling of a photon to an exciton

Polariton lifetime

$$\tau = 10\text{ps}$$

pump



Continuous pumping compensates for the losses and let us create a steady state

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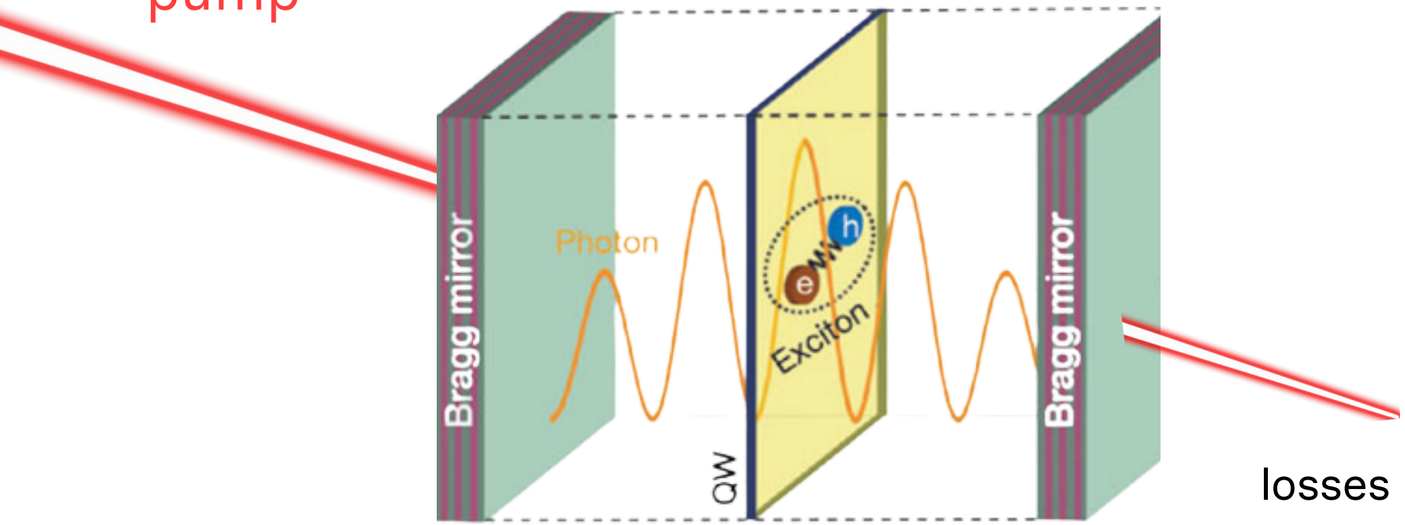

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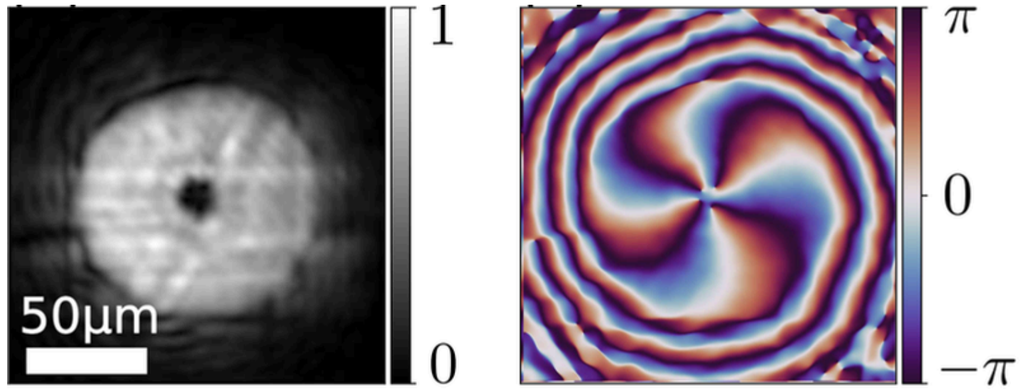
Stationary C=4 Vortex Solution



Density and Phase of the Polariton Field

Guerrero et al. Phys. Rev. Lett. 135, 243801 (2025)

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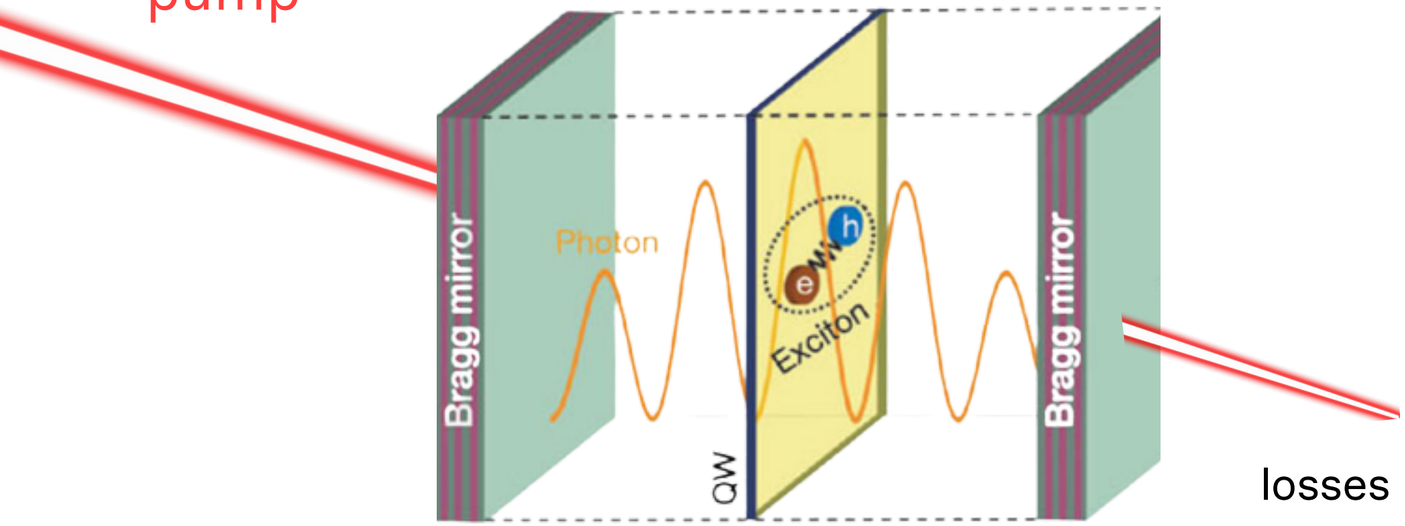

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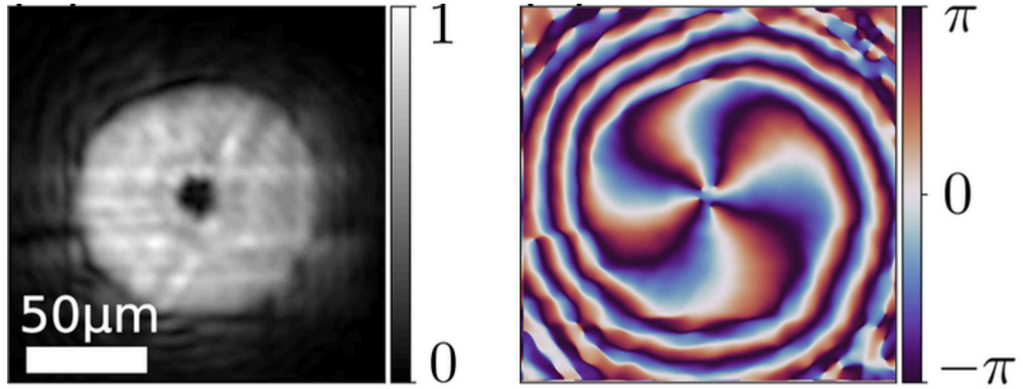
note the rotational symmetry



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We want to study the scattering of small perturbations on a steady polariton background

The Polariton Background

Characterized by a mean-field wavefunction

$$\Psi(t, \mathbf{r}) = \sqrt{n(\mathbf{r})}\, e^{i\phi(\mathbf{r})}$$

solving the driven-dissipative GPE:

$$i\hbar \frac{\partial \Psi}{\partial t} = \left(\hbar\omega_0 - \frac{\hbar^2 \nabla^2}{2M} + \hbar g |\Psi|^2 - i\hbar \frac{\gamma}{2} \right) \Psi + i\hbar \mathcal{F}(\mathbf{r}, t)$$

Fluid velocity

$$\mathbf{v} \propto \nabla \phi$$

Speed of sound

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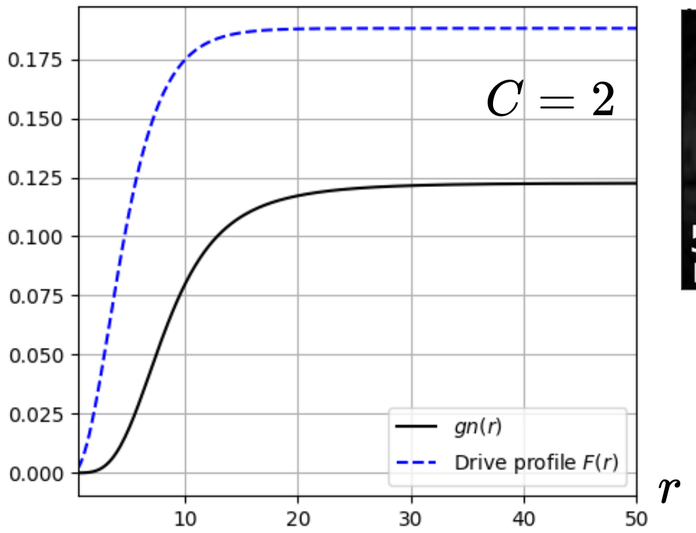

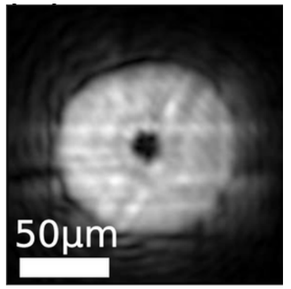

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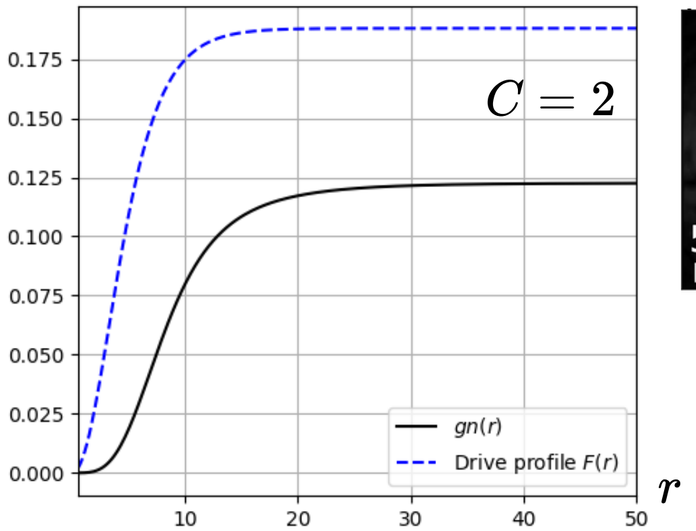

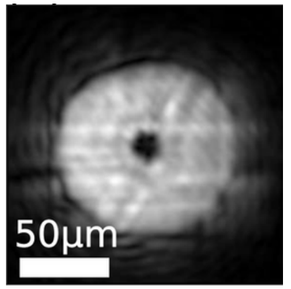

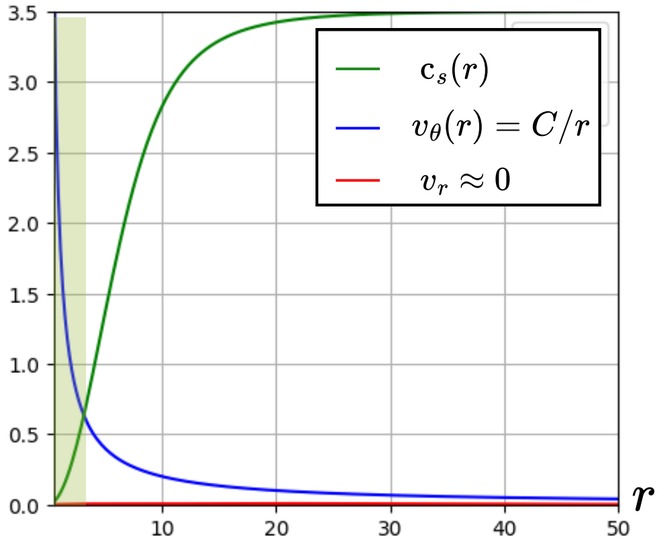

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ergoregion : $c_s < v_\theta$ ✓

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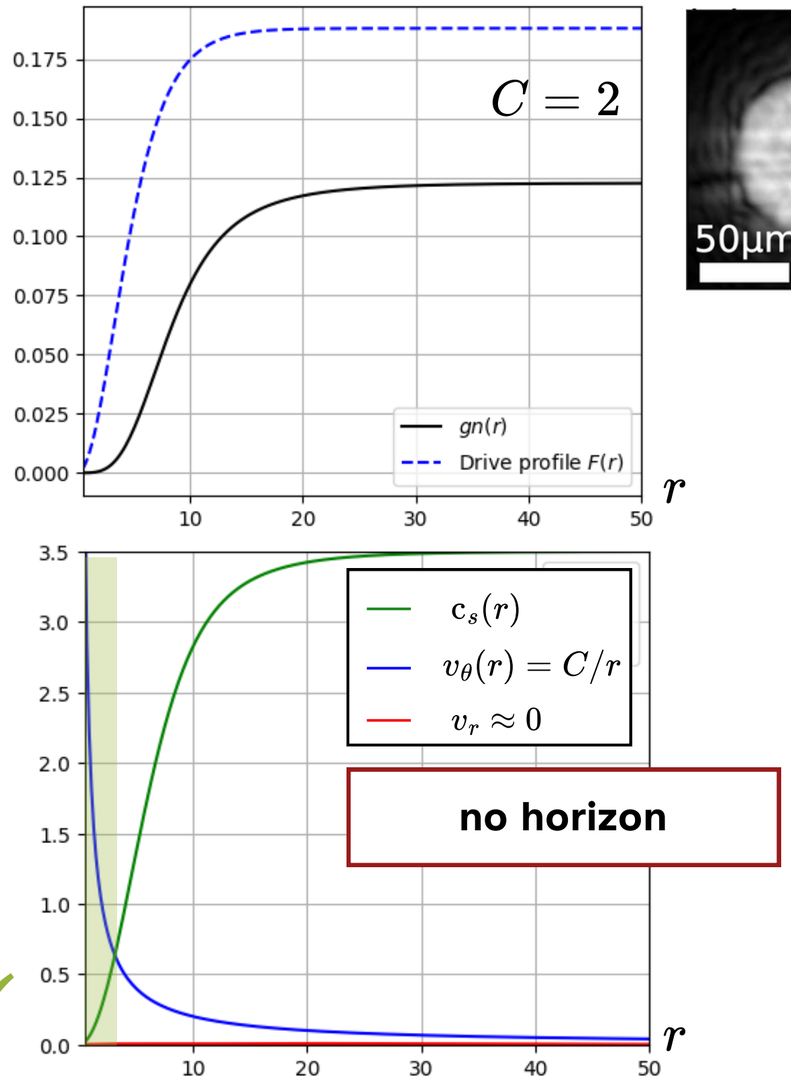
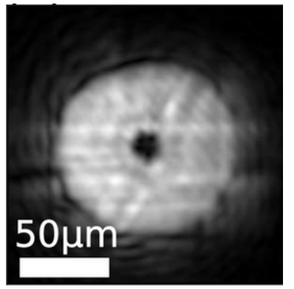
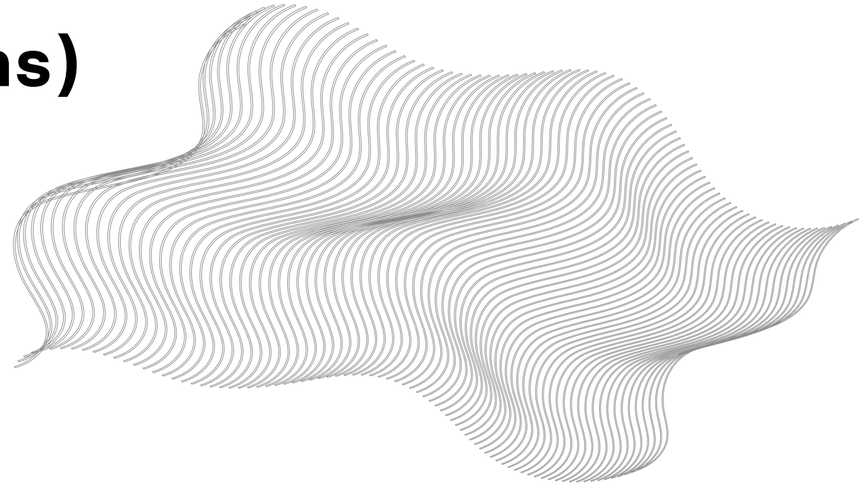




no horizon

Scattering of Linear Perturbations (Phonons)



$$\Psi = \Psi_0 + \psi$$

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(\hbar\omega_0 - \frac{\hbar^2\nabla^2}{2M} + \hbar g|\Psi|^2 - i\hbar\frac{\gamma}{2}\right)\Psi + i\hbar\mathcal{F}(\mathbf{r},t)$$

non-linearity — losses — pump

Linearize and obtain the **Bogoliubov de-Gennes equation**

$$i\hbar\,\frac{d}{dt}\begin{pmatrix}\psi\\ \psi^*\end{pmatrix} = (\mathcal{L}_{\mathrm{BdG}} + i\hbar\frac{\gamma}{2})\begin{pmatrix}\psi\\ \psi^*\end{pmatrix}$$

$$\mathcal{L}_{\mathrm{BdG}} = \begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix}$$

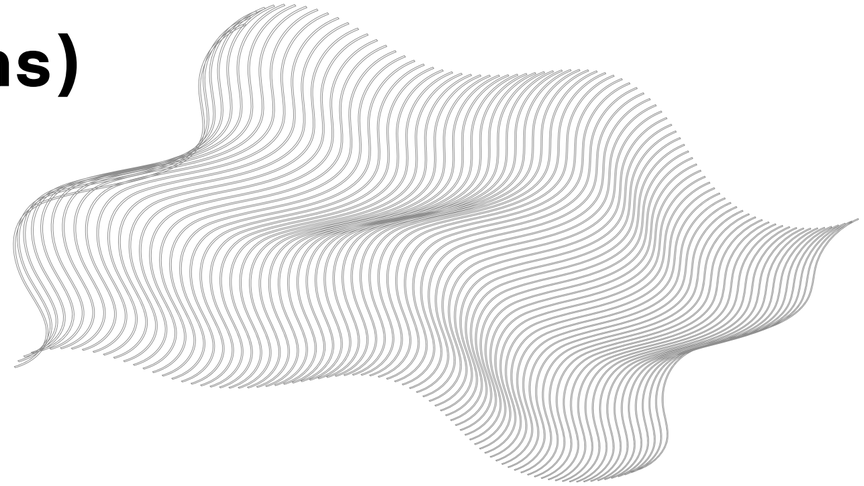
$$A = -\frac{\hbar^2}{2m}\nabla^2 + 2gn_0 - \hbar(\omega_p - \omega_0)$$

background — detuning

$$B = g\Psi_0^2$$

background

Scattering of Linear Perturbations (Phonons)



$$\Psi = \Psi_0 + \psi$$

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(\hbar\omega_0 - \frac{\hbar^2\nabla^2}{2M} + \hbar g|\Psi|^2 - i\hbar\frac{\gamma}{2}\right)\Psi + i\hbar\mathcal{F}(\mathbf{r},t)$$

non-linearity — losses — pump

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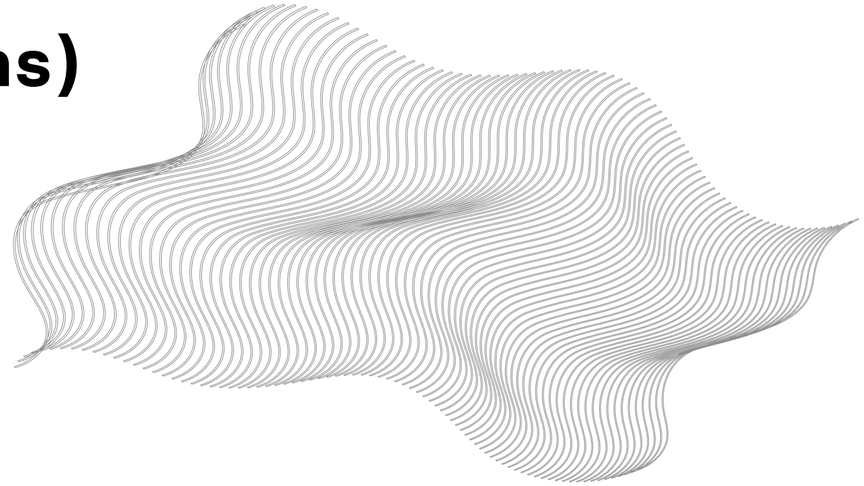

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Eigenstates of the equation:

$$\hbar(\omega - \frac{i\gamma}{2})\begin{pmatrix}u\\ v\end{pmatrix} = \mathcal{L}_{\mathrm{BdG}}\begin{pmatrix}u\\ v\end{pmatrix}$$

in this basis, the norm is computed as

$$N = 2\pi\int(|u|^2 - |v|^2)\,r\,dr$$

Analysis of Solutions

Analytical Solution via WKB

plane wave ansatz: $u(t, \mathbf{r}) = e^{-i(\omega t - m\theta)} A(r) e^{i \int p \, dr}$

set angular momentum $m = 2$

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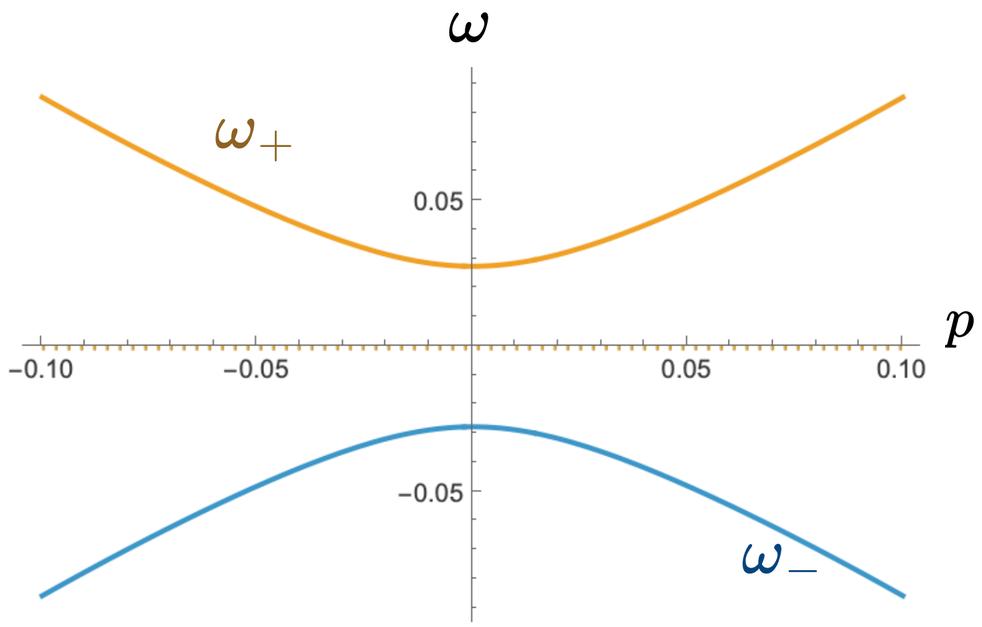

$r = 150\,\mu\text{m}$

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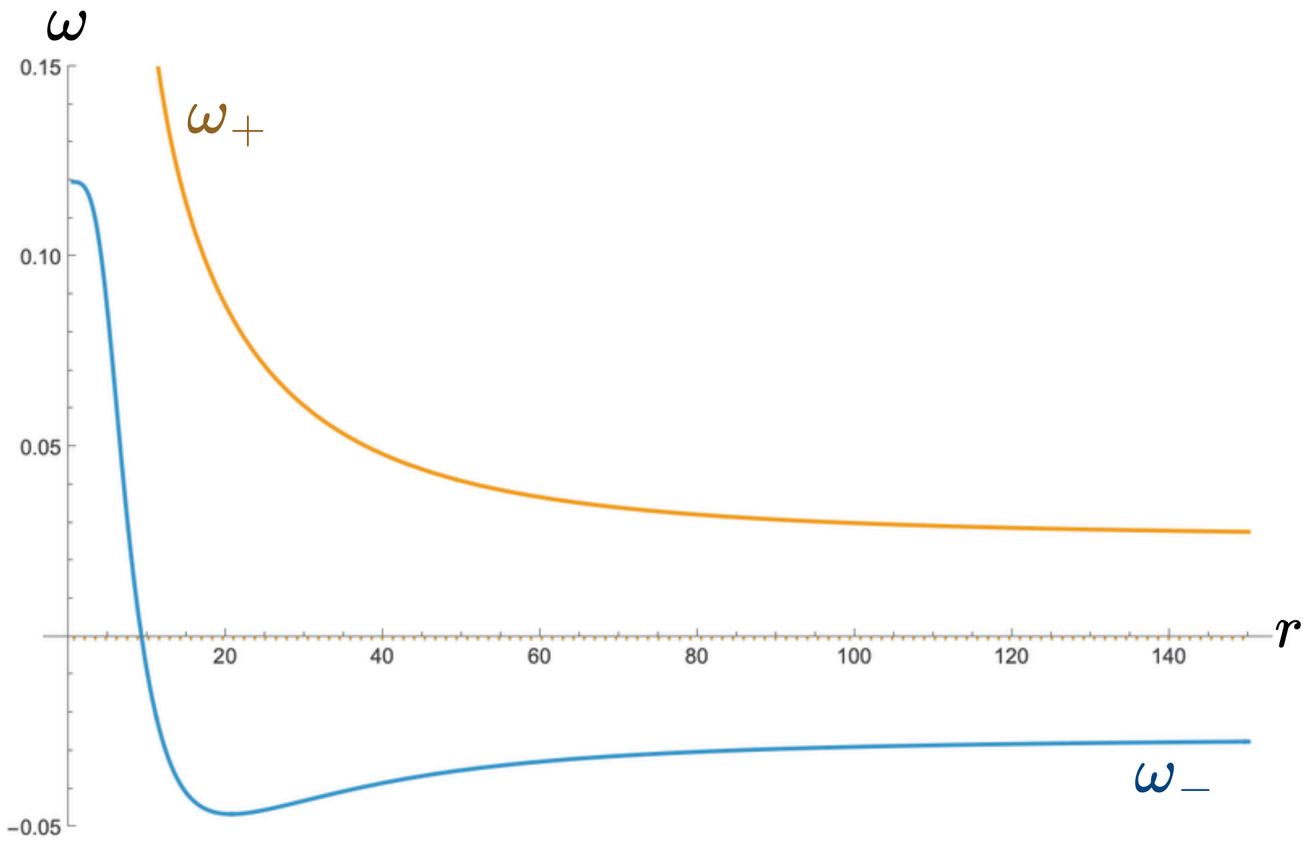
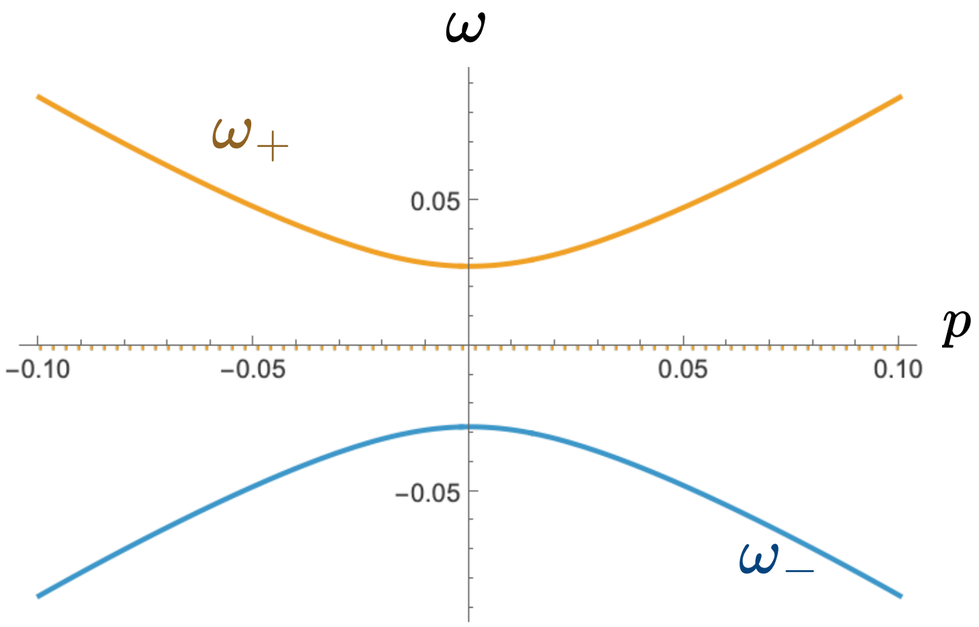


$p = 0$



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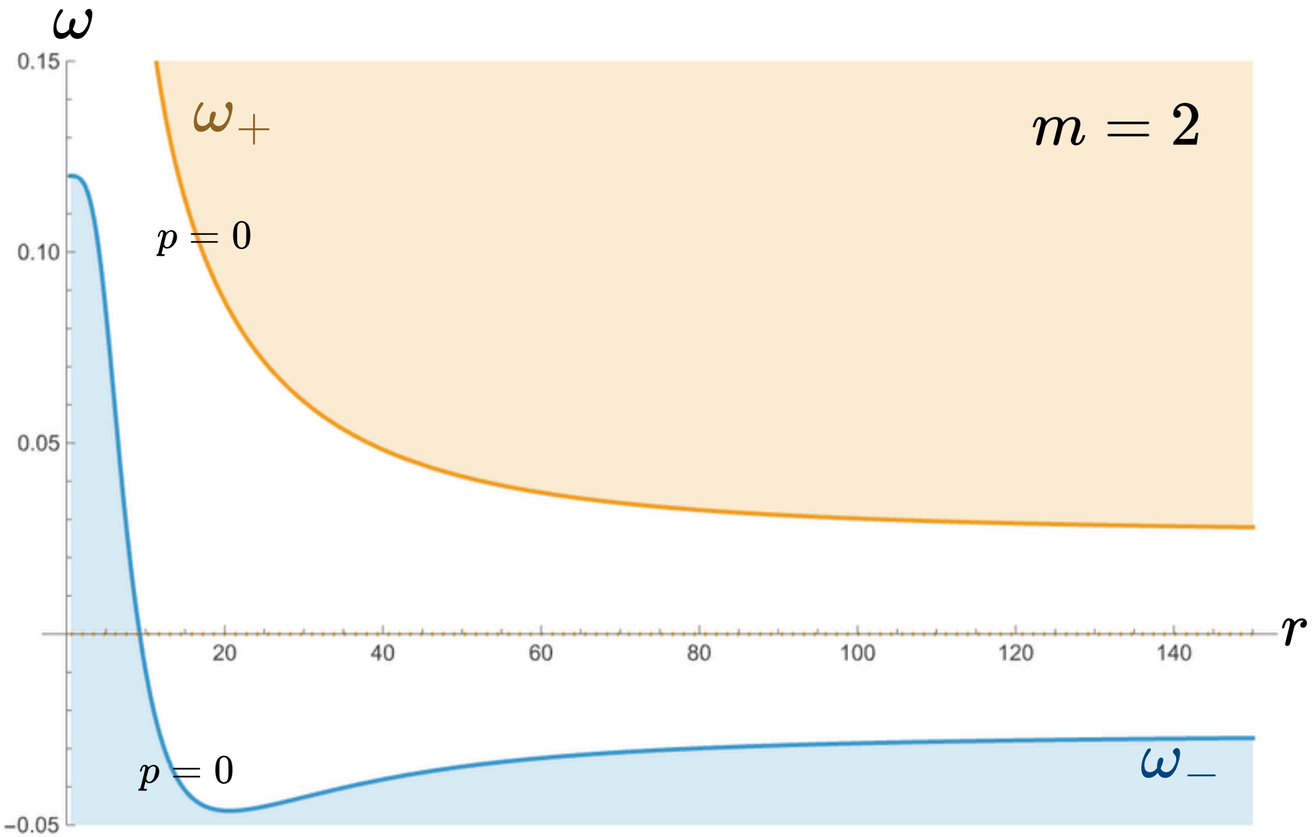

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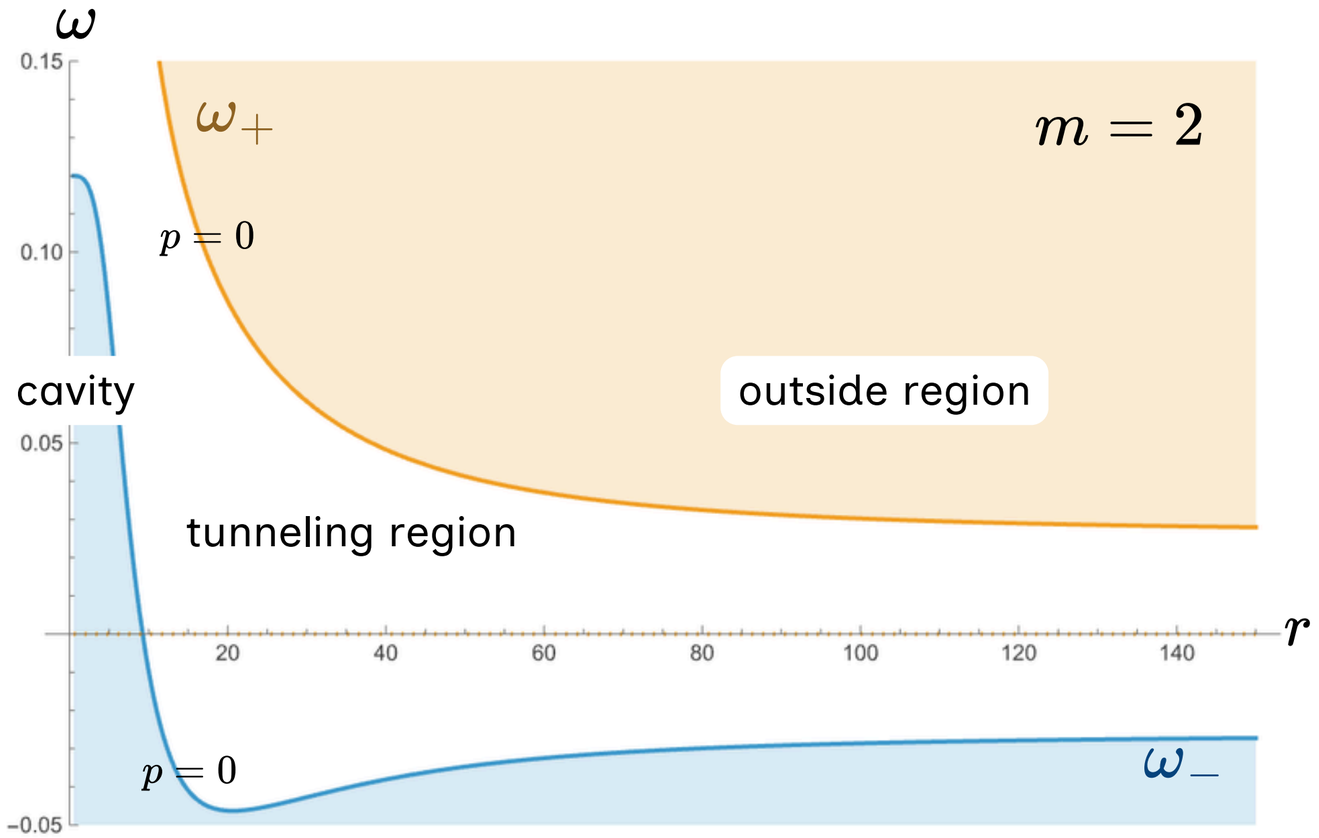

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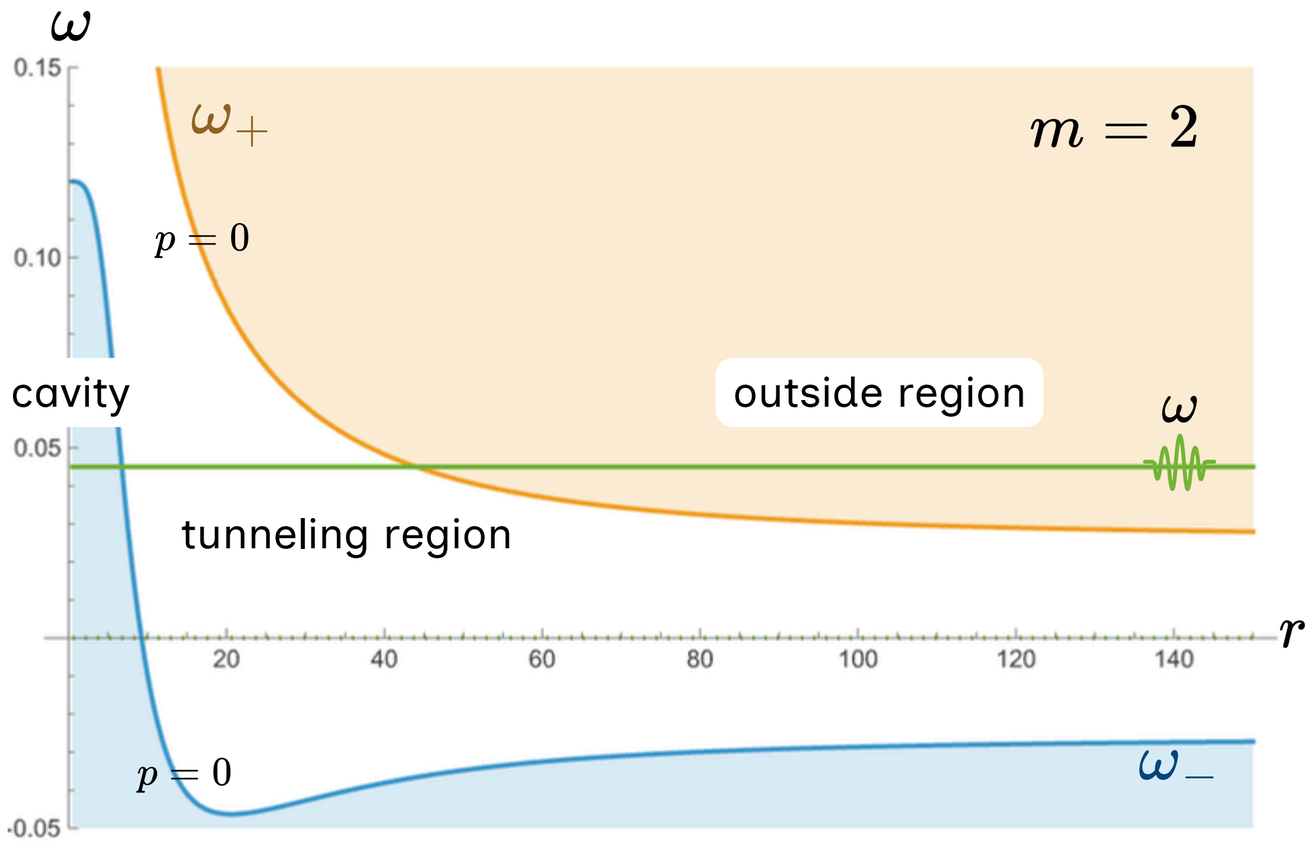

Resonant Frequency (without losses shift)

$$\hbar(\omega - \frac{i\gamma}{2}) \begin{pmatrix} u \\ v \end{pmatrix} = \mathcal{L}_{\mathrm{BdG}} \begin{pmatrix} u \\ v \end{pmatrix}$$

resonant (cavity) frequency $\omega = \omega_r + i\Gamma$

	WKB Analysis
ω_r	$0.0410\ \mathrm{ps}^{-1}$
Γ	$7.18 \times 10^{-6}\ \mathrm{ps}^{-1}$

S. Patrick et al. Phys. Rev. Research 4, 033117 (2022)

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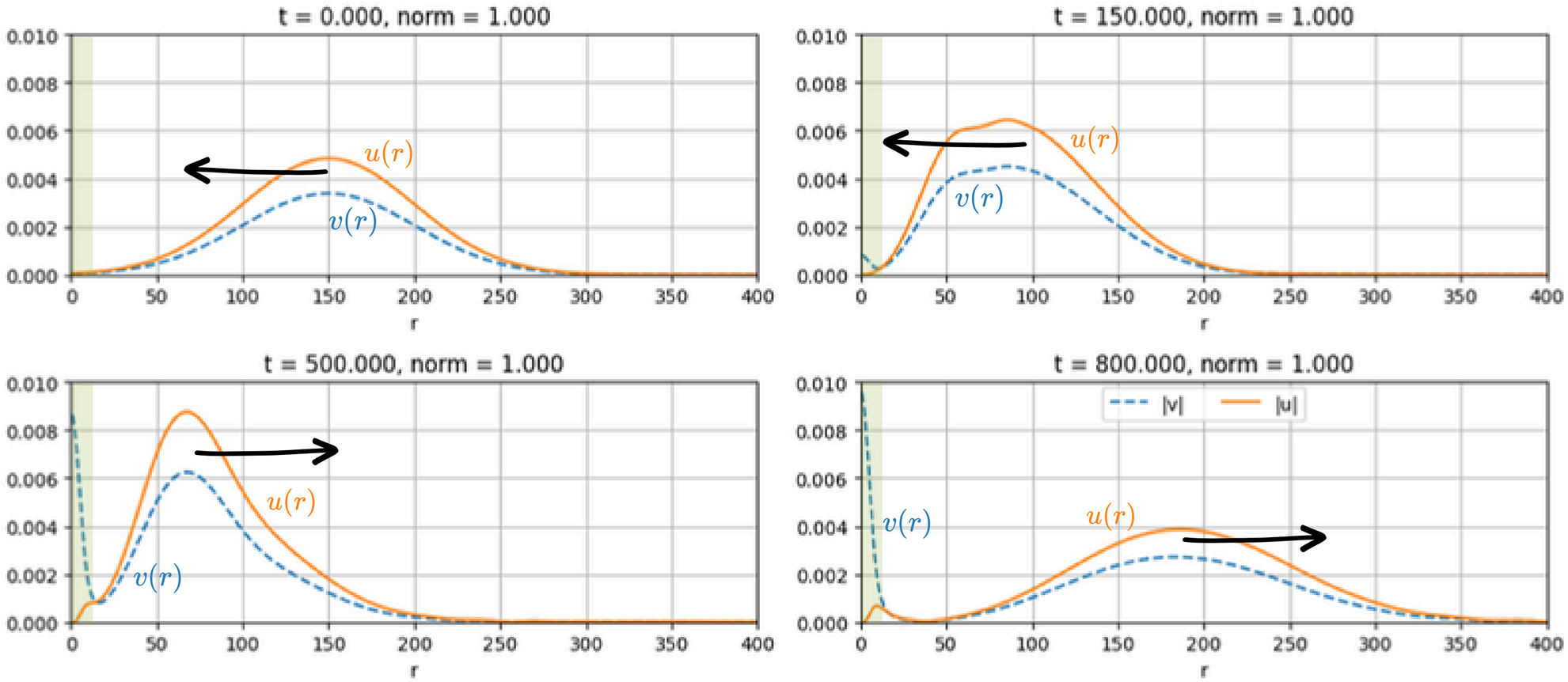
S. Patrick et al. Phys. Rev. Research 4, 033117 (2022)

Time Propagation of Wavepackets
Numerical Solutions

Wavepacket Propagation (no losses)

$$i\hbar \frac{d}{dt}\begin{pmatrix}\psi \\ \psi^*\end{pmatrix} = \mathcal{L}_{\mathrm{BdG}}\begin{pmatrix}\psi \\ \psi^*\end{pmatrix}$$

$$N = 2\pi \int (|u|^2 - |v|^2)\, r\, dr$$



Analysis of v(t) in the Cavity Over Time

plane wave ansatz: $v(t, \mathbf{r}) = e^{-i(\omega t - m\theta)} B(r) e^{i \int p \, dr}$

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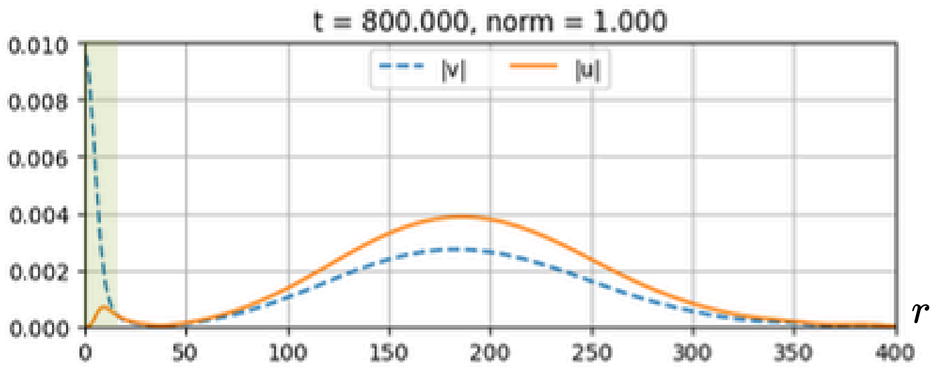

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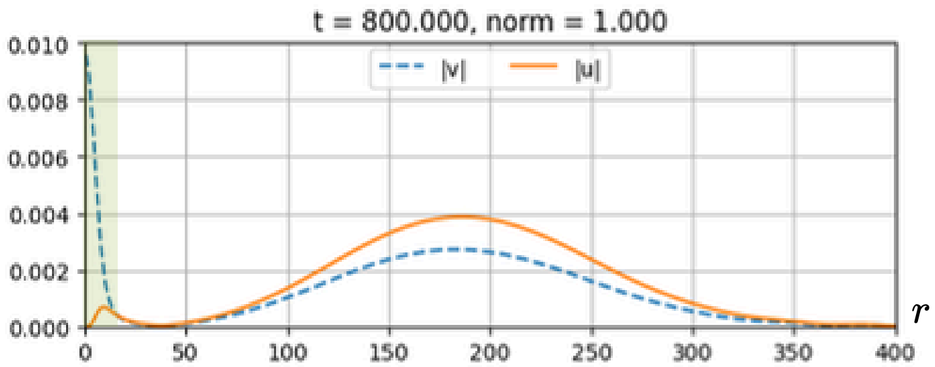

Fitting to cosine form at $r = 0.5\,\mu\text{m}$

$$\text{Re}[v(t, r = 0.5)] = B\, e^{\Gamma t} \cos(\omega_r + \phi)$$

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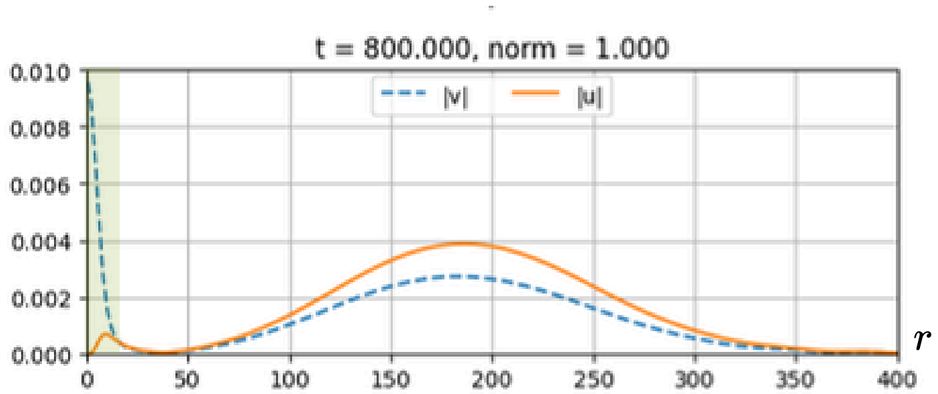

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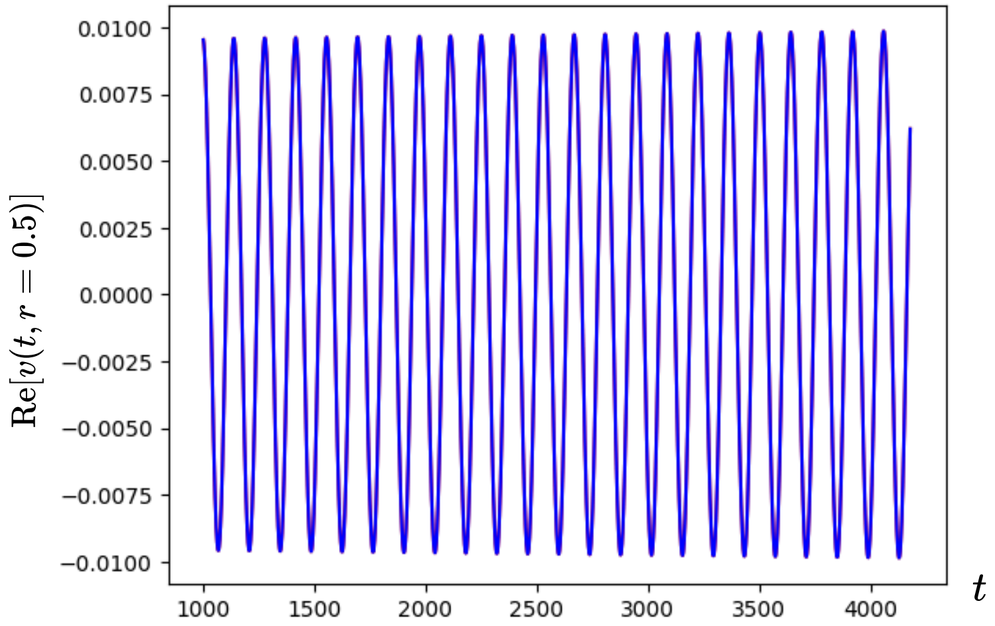
$$B = -9.4916822810^{-3},$$
$$\Gamma = 9.3430354610^{-6},$$
$$\omega = 0.0451479720,$$
$$\phi = -0.168227685$$



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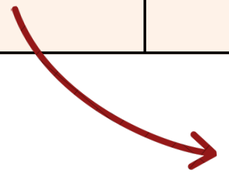
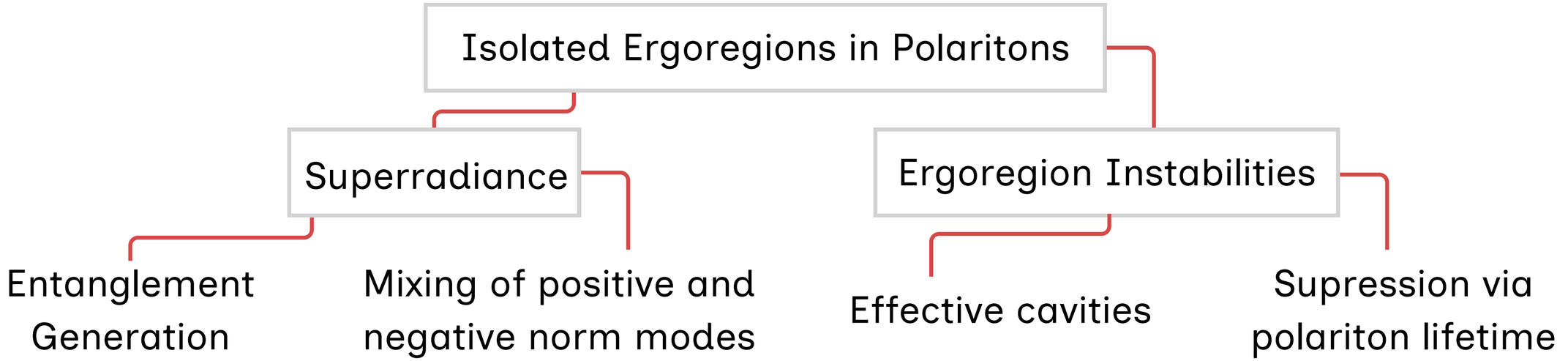
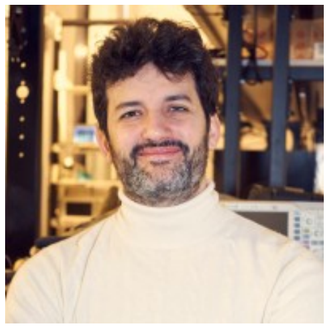
Γ	$7.18 \times 10^{-6}\ \mathrm{ps}^{-1}$	$1.01 \times 10^{-5}\ \mathrm{ps}^{-1}$	$9.34 \times 10^{-6}\ \mathrm{ps}^{-1}$



instability is supressed by the losses $\Gamma \ll \gamma \sim 0.1\ \mathrm{ps}^{-1}$

Main Ideas





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LKB, Paris

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LKB, Paris

Adrià Delhom
UCM, Madrid

Luca Giacomelli
Laboratoire MPQ, Paris

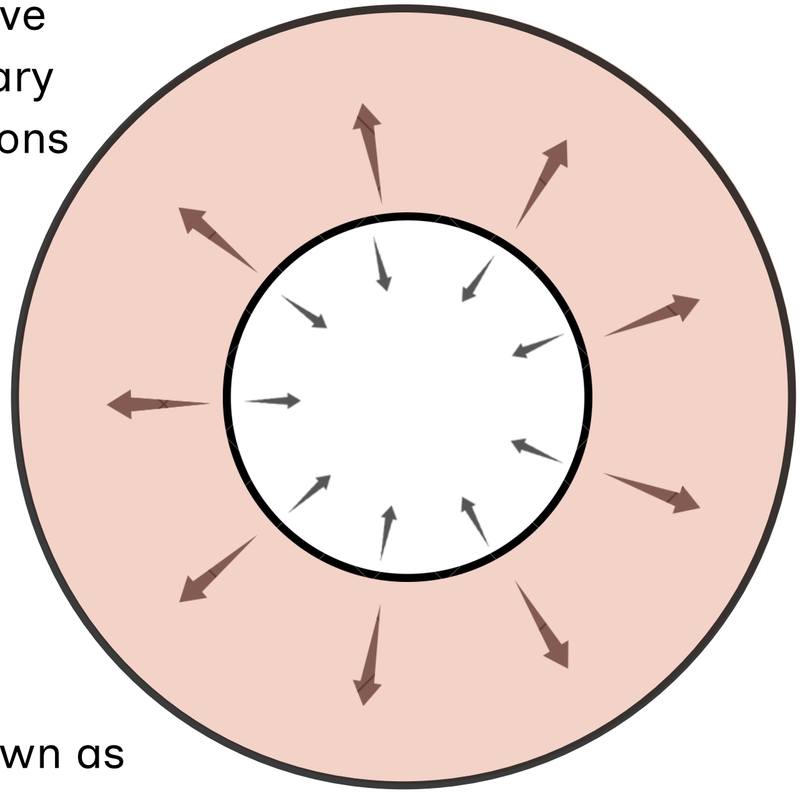
Ivan Agullo
LSU

Thank You!

Extra Material

Superradiant Scattering with Closed Boundary Conditions

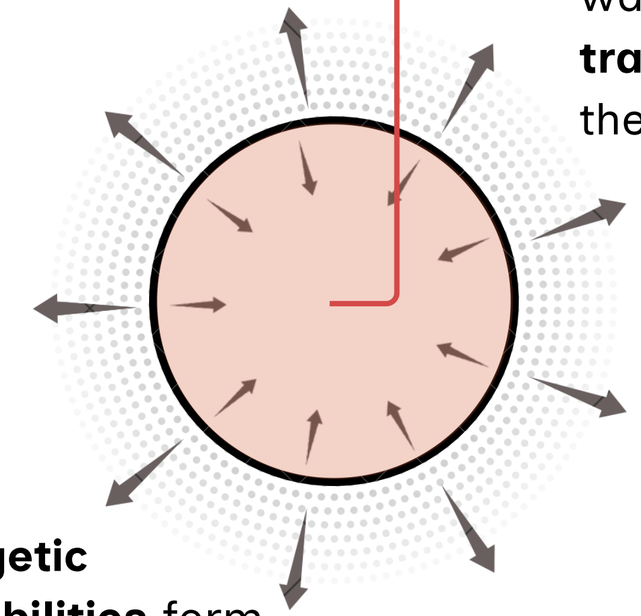
reflective boundary conditions



Also known as
Black Hole bomb

Superradiant Scattering from an Isolated Ergoregion

Transmitted waves get **trapped inside** the ergoregion



Energetic Instabilities form when superradiance occurs from within

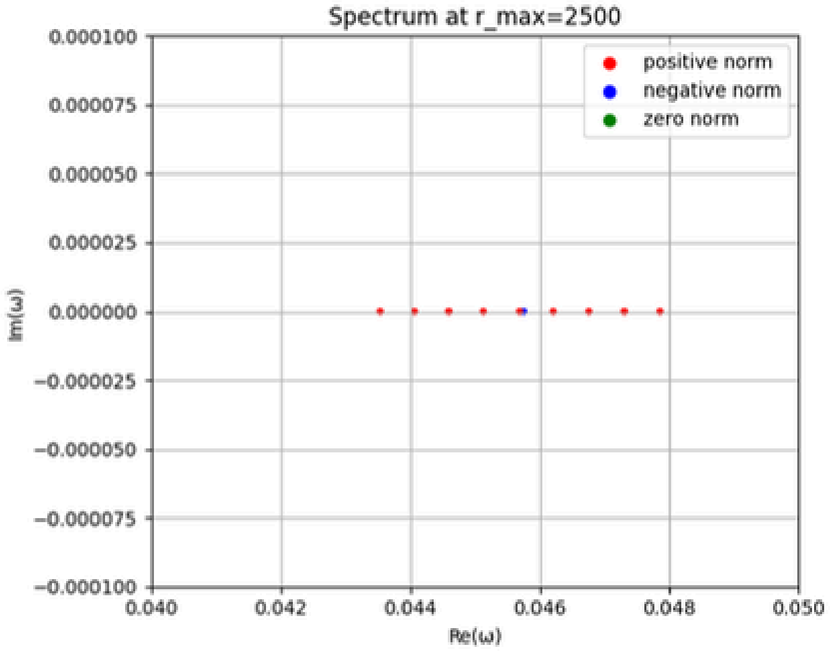
you need dissipation to avoid instabilities

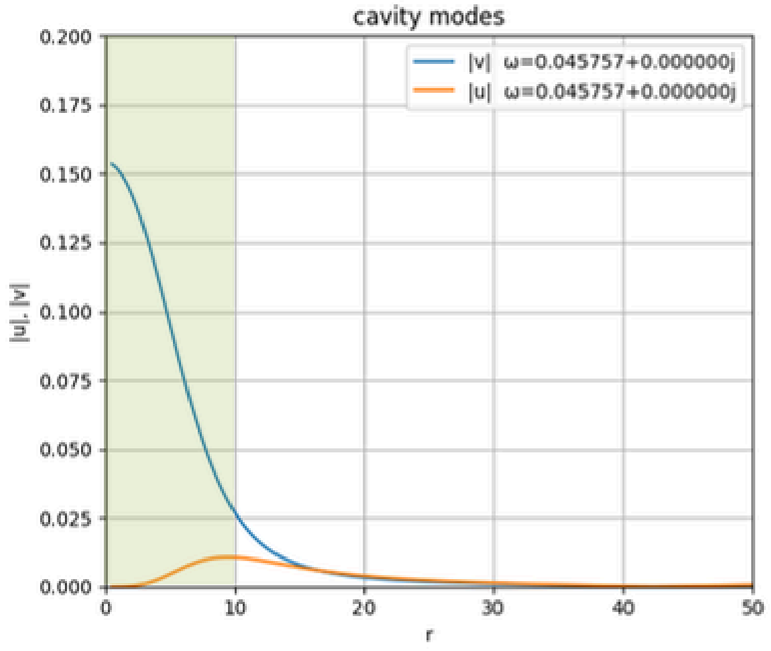
Solutions by (discretized) Diagonalization

$$\hbar\omega \begin{pmatrix} u \\ v \end{pmatrix} = \mathcal{L}_{\mathrm{BdG}} \begin{pmatrix} u \\ v \end{pmatrix}$$

$$N = 2\pi \int (|u|^2 - |v|^2)\, r\, dr$$

To find the eigenfrequencies of the system, diagonalize $\mathcal{L}_{\mathrm{BdG}}$





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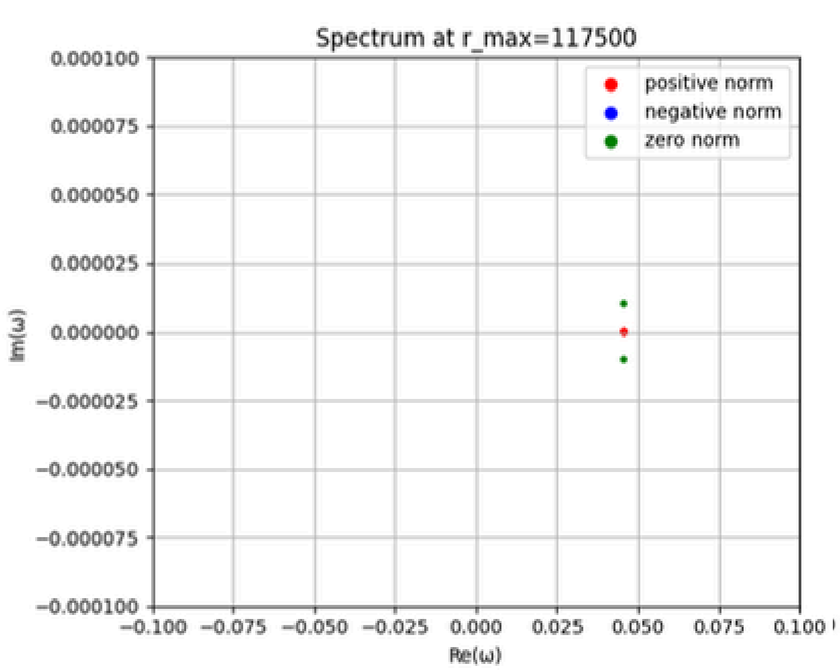

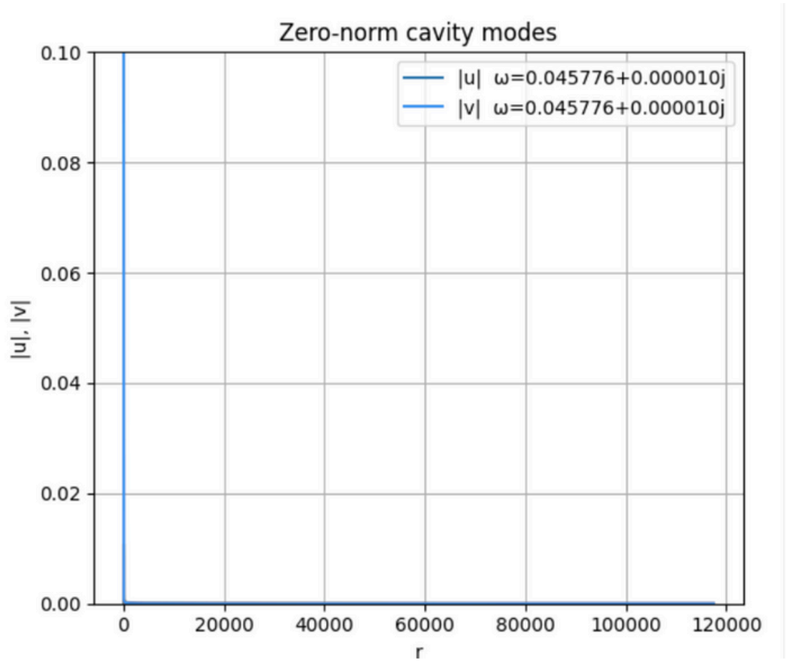
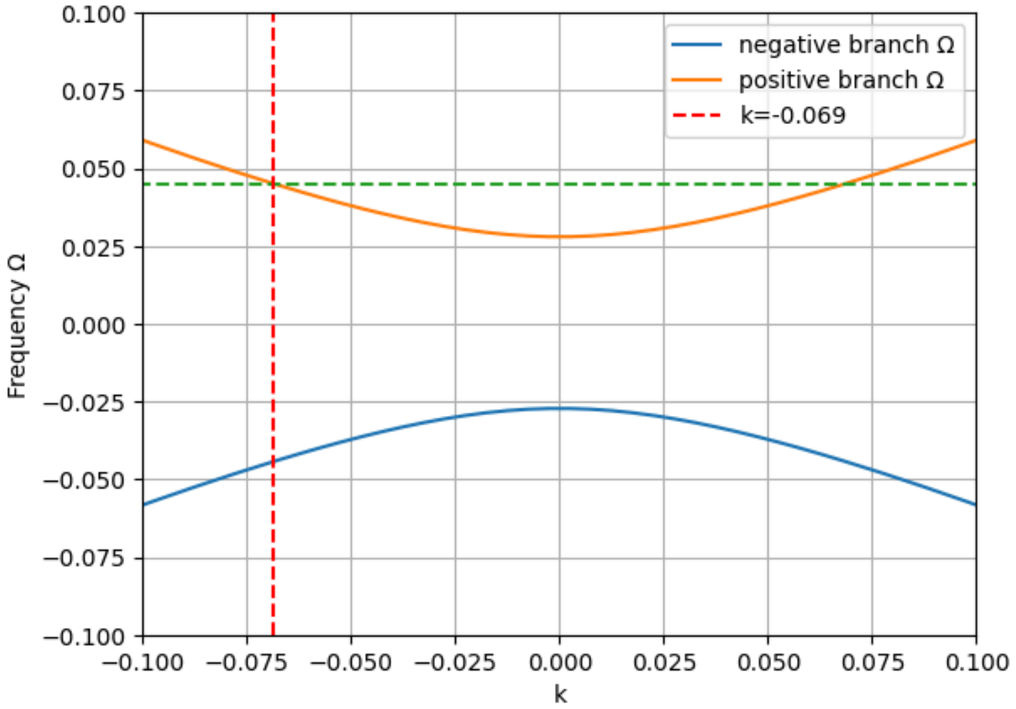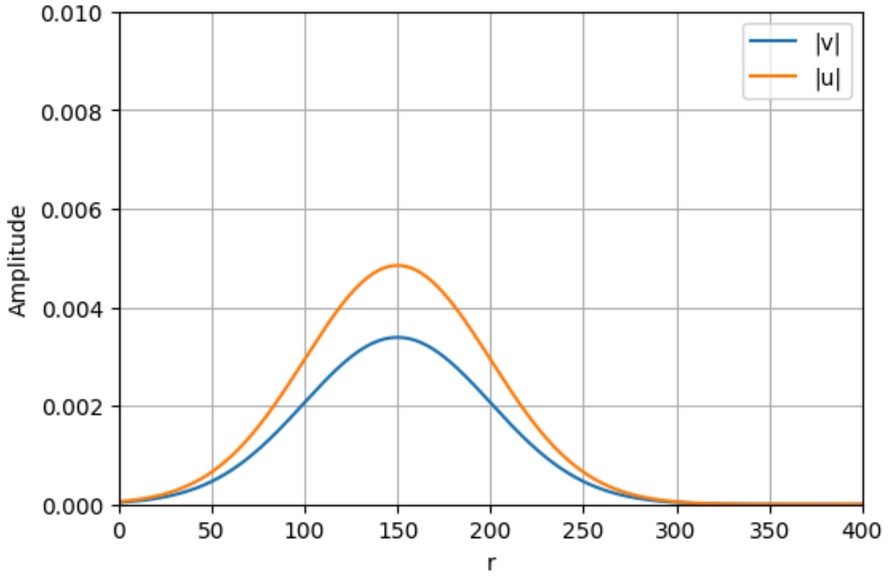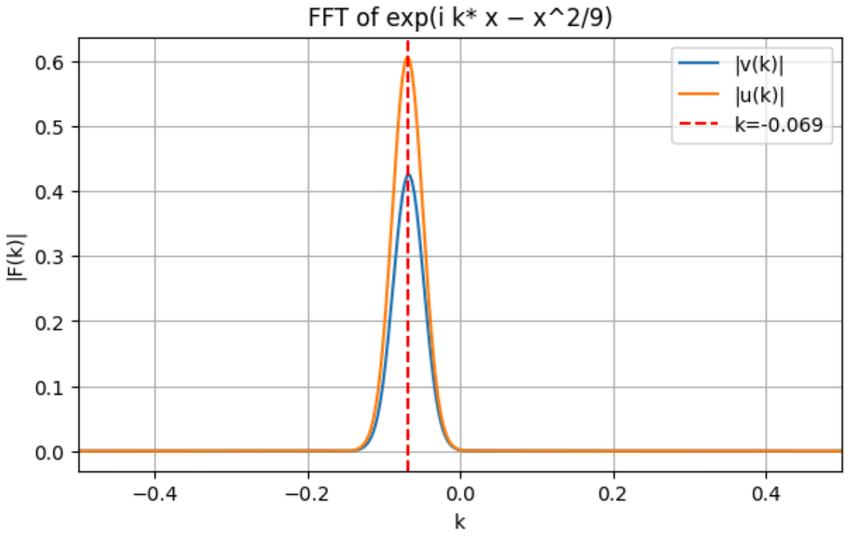
Input Wavepacket: