# Polariton fluid

# for rotational super-radiance

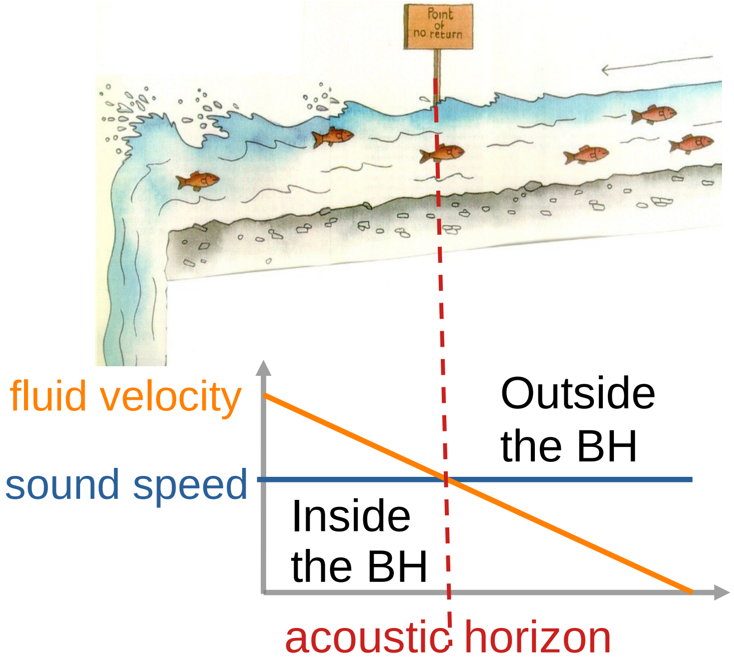
Killian Guerrero, Kévin Falque, Quentin Glorieux,
Elisabeth Giacobino, Alberto Bramati, Maxime Jacquet

Collab: Adrià D I Latorre, Paula A. Calizaya Cabrera, Iván Agulló
(Louisiana State University)

Analogue Gravity in 2023
Benasque 30/05/2023

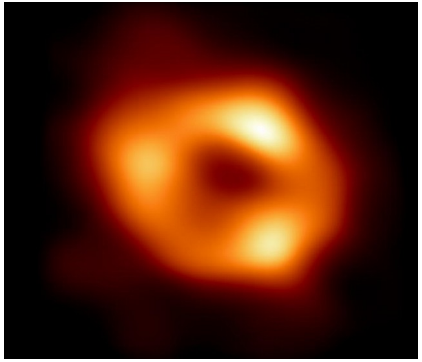
# Fluids for analogue gravity?

Sonic waves in acoustic blackholes




*Experimental Black-Hole Evaporation?*
W. G. Unruh, 1981

Scalar field in blackholes gravitational field



*Sagittarius A*, EHT Collaboration*

# Kerr blackhole simulation: the DBT flow

$$\boldsymbol{v}(r,\theta) = -\frac{D}{r}\boldsymbol{u_r} + \frac{C}{r}\boldsymbol{u_\theta}$$

D: Drain
C: Circulation

$$ds^2_{BTF} = -\big(1 - \frac{r_e^2}{r^2}\big)c_s^2 dt^2 - 2C\frac{r_e^2}{r^2}dtd\theta$$

$$+\big(1 - \frac{r_h^2}{r^2}\big)^{-1}dr^2 + \Big[r^2 + \frac{C^2}{c_s^2}\big(1 - \frac{r_e^2}{r^2}\big)\Big]d\theta$$

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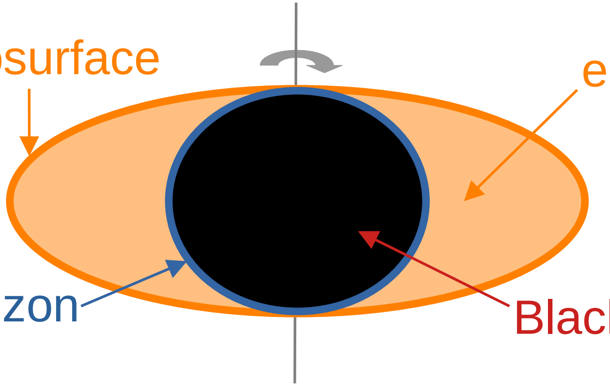


(In equatorial plane)

$$ds^2_{KERR} = -(c^2 - \beta^2)dt^2 - 2\beta a dt d\theta$$
$$+\frac{dr^2}{c - \beta + a^2/r^2} + (r^2 + a^2 + \beta a^2)d\theta^2$$

$$a = \frac{J}{Mc}$$

$$\beta = \frac{2M}{r}$$

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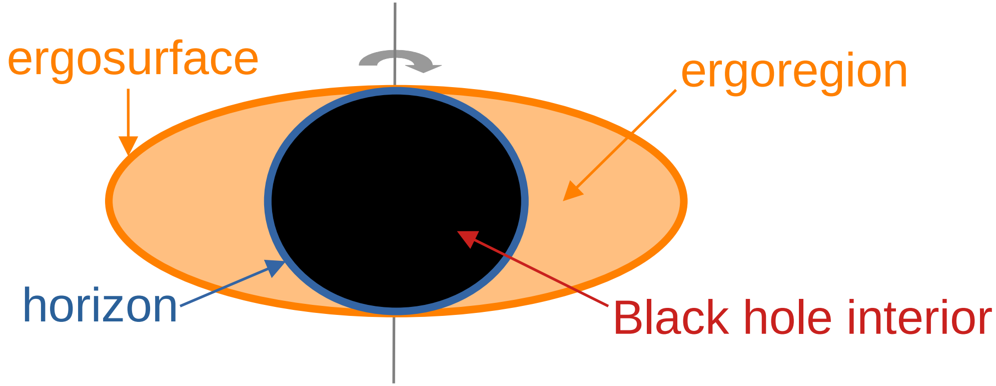


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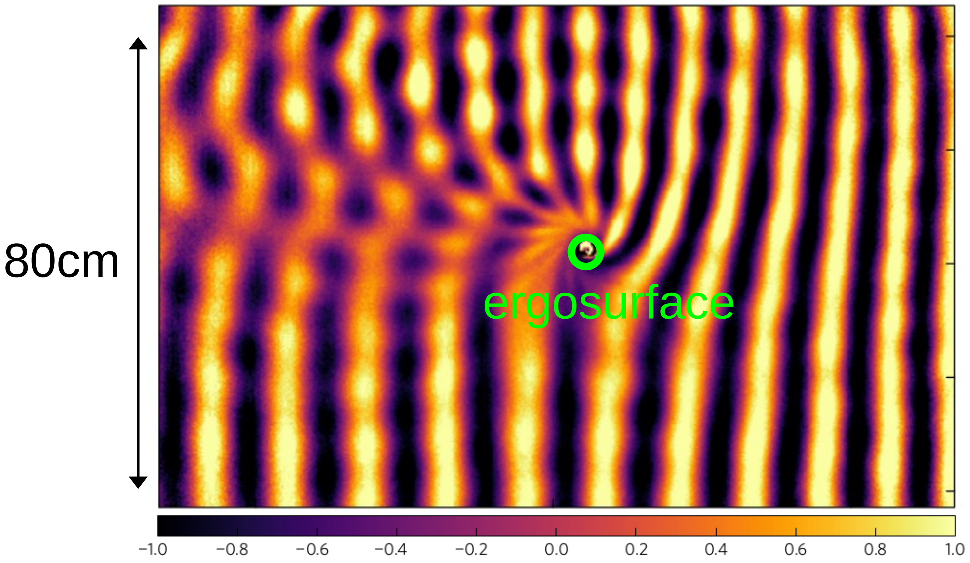
Ergosurface ($v_{tot}=c_s$) at $r_e = \frac{\sqrt{C^2+D^2}}{c_s}$

Horizon ($v_r=c_s$) at $r_h = \frac{D}{c_s}$

# Kerr blackhole simulation: First Experimental demonstration

Torres *et al.* Nat Phys 2017




Planar wavefront of surface waves incoming from the right on the DBT flow.

Partial, total or over-reflection on the ergosurface seen in the interference pattern.
Over-reflection → rotational super-radiance.

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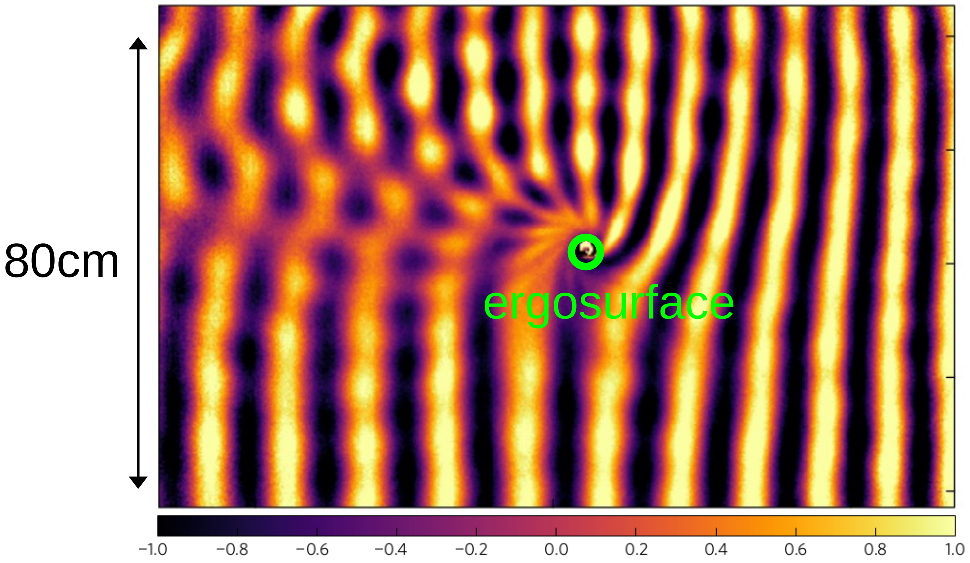


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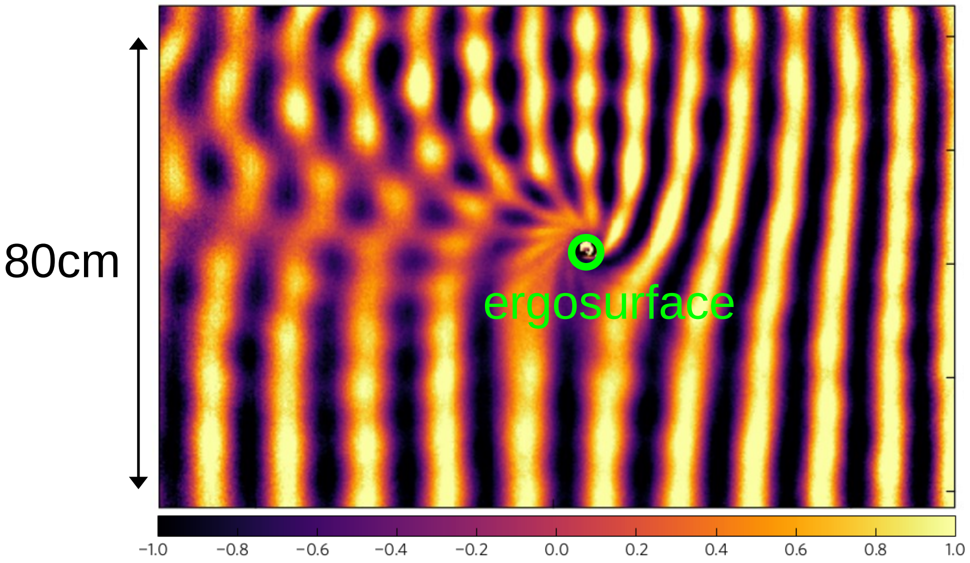


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MC Braidotti *et al,* PRL 2022 *Measurement of Penrose Superradiance in a Photon Superfluid*

# What do we want to do?

Study the quantum properties of rotational super-radiance:
**correlations, entanglement**

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Polariton quantum fluid of light:

A. Prain *et al,* PRD 2019
S. Patrick, Classical and Quantum Gravity 2021

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Study the quantum properties of rotational super-radiance:
**correlations, entanglement**

Polariton quantum fluid of light:

- Fully optically controlled → not limited to DBT flow
  → avoid cross talk between Hawking radiation (horizon) and super-radiance (ergosurface)

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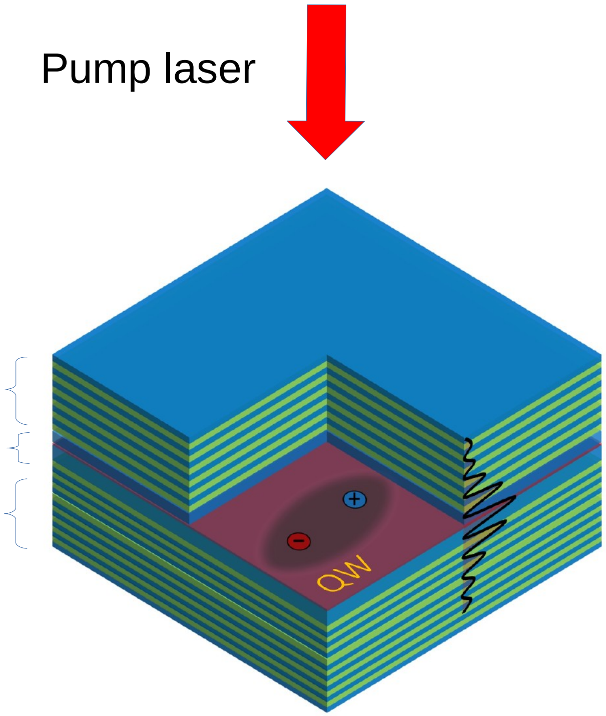
A. Prain *et al,* PRD 2019
S. Patrick, Classical and Quantum Gravity 2021
I. Agullo, A.J Brady, D. Kranas, PRL 2022

# Polariton fluid: brief recap



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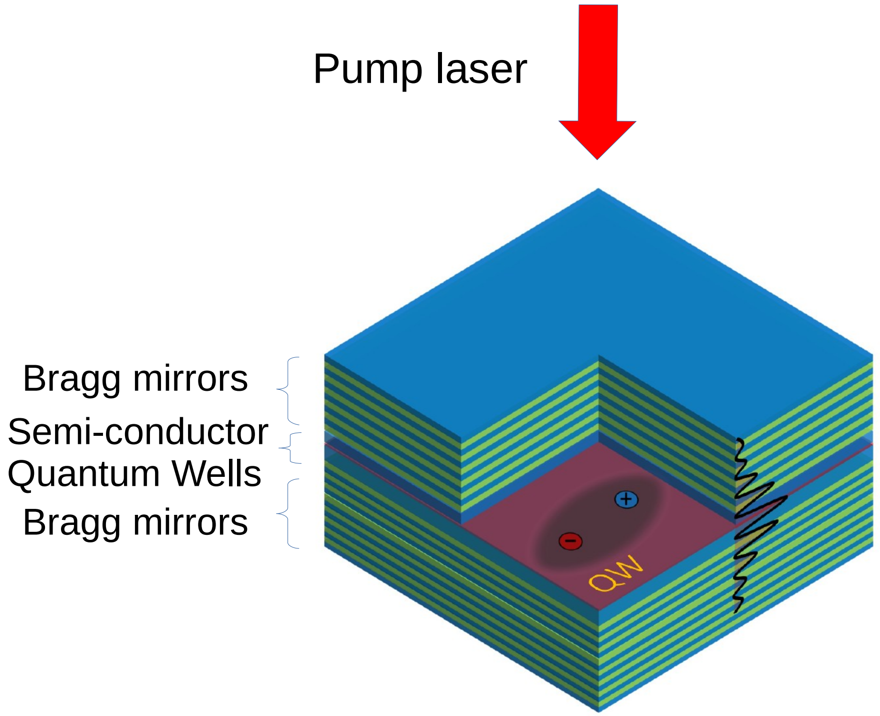


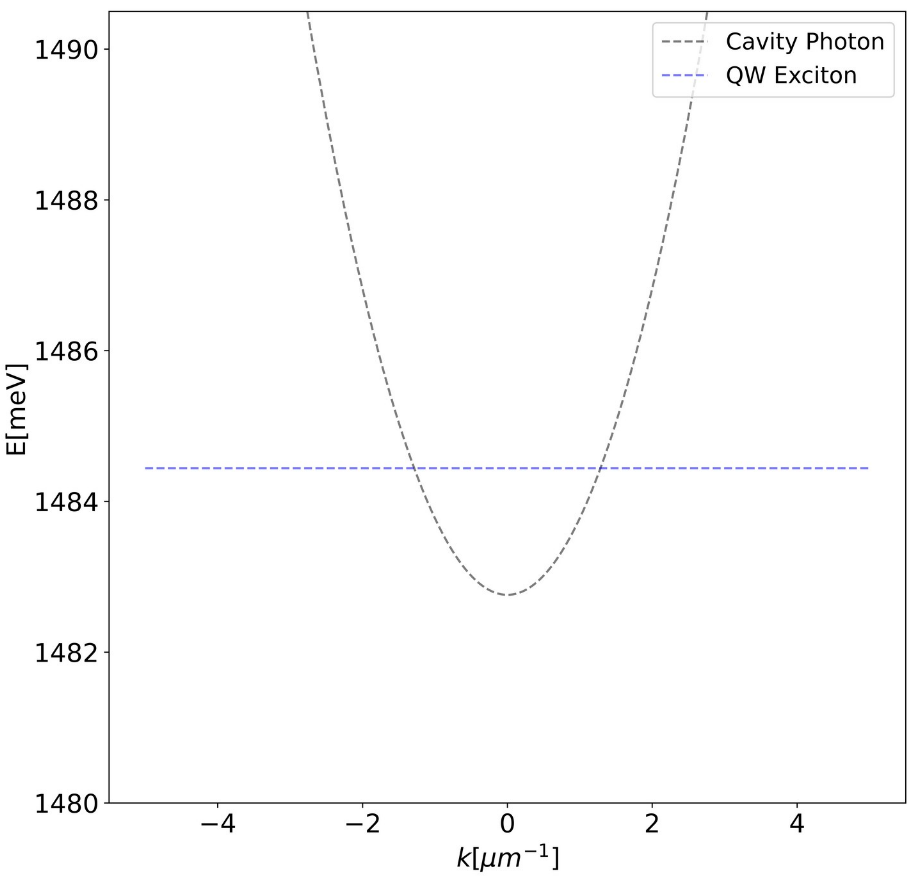

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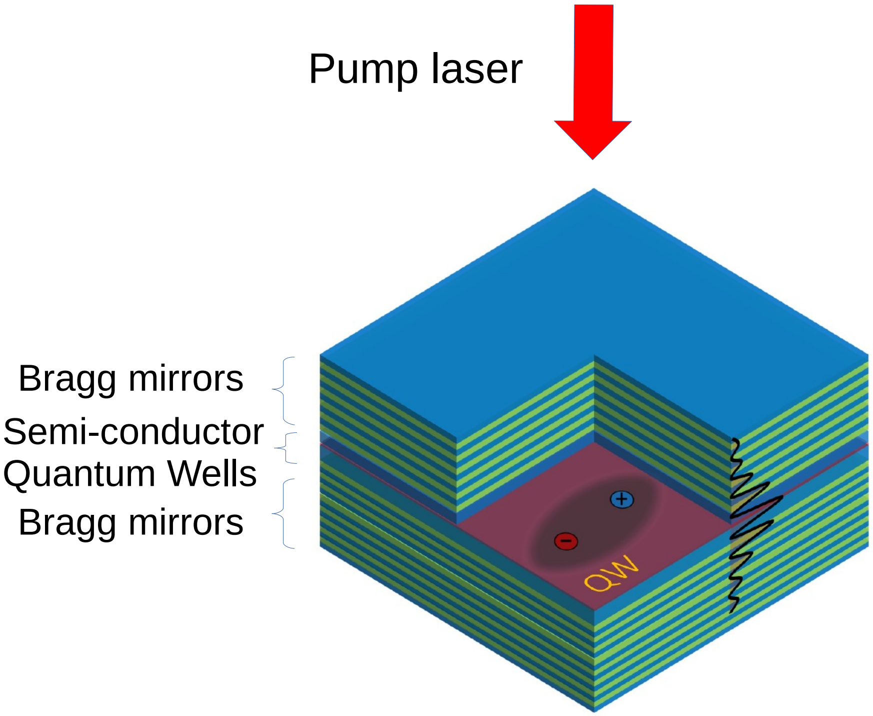
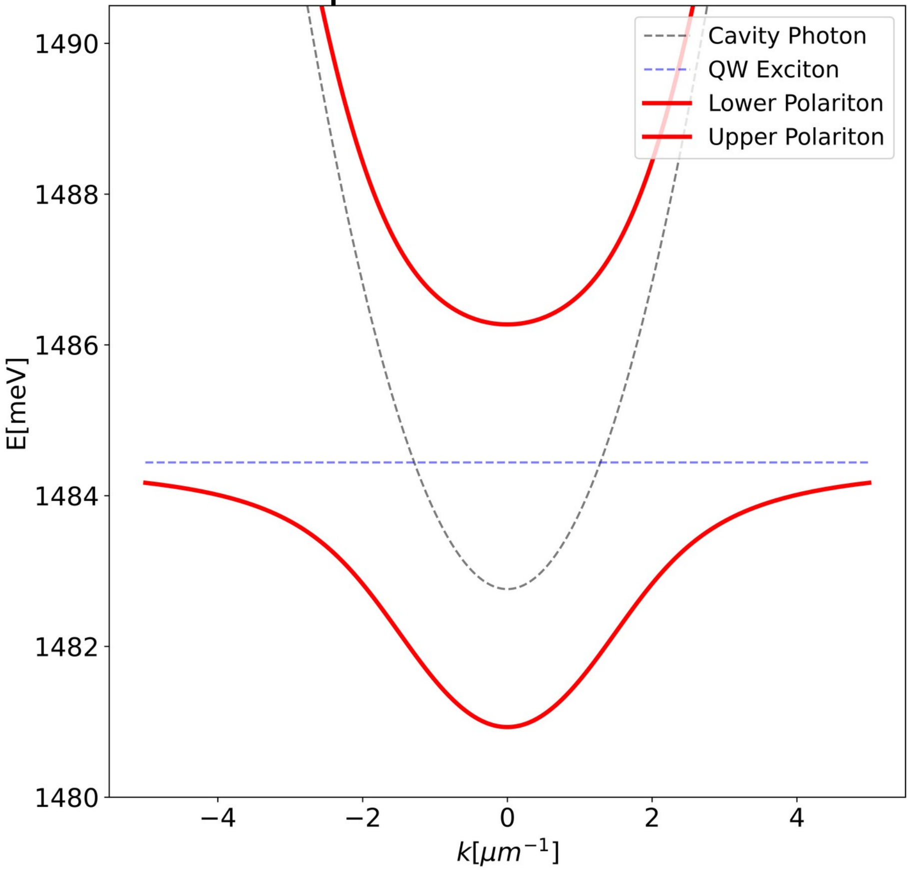



Strong coupling between cavity photons and quantum well excitons



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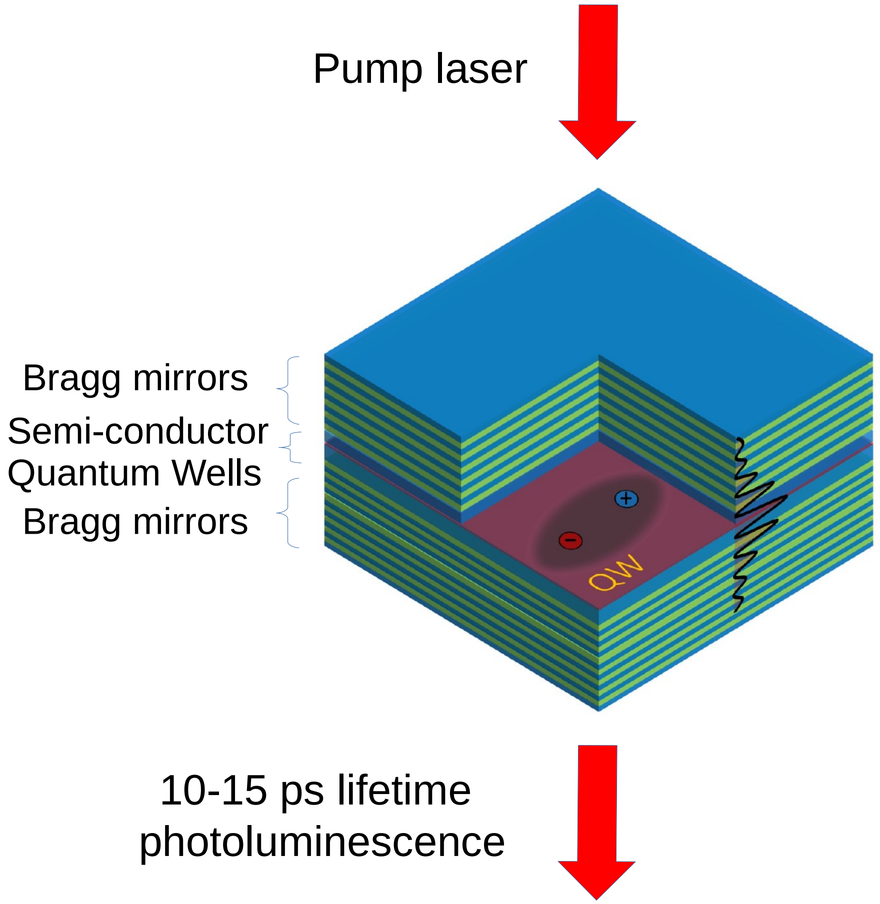


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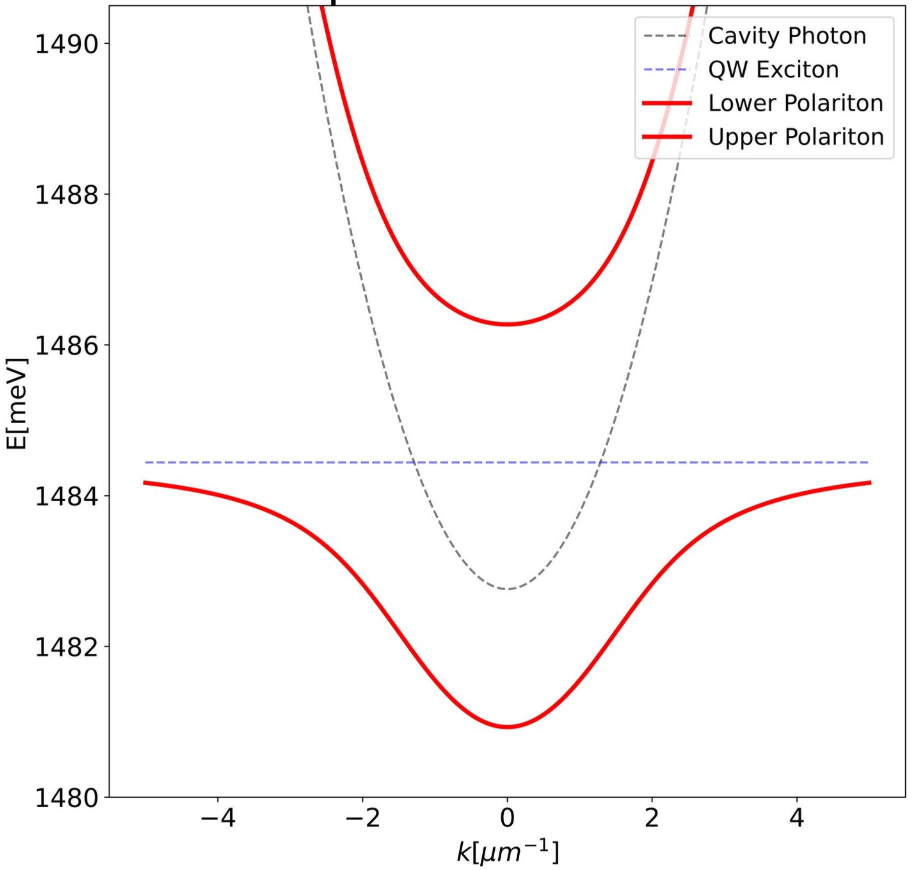

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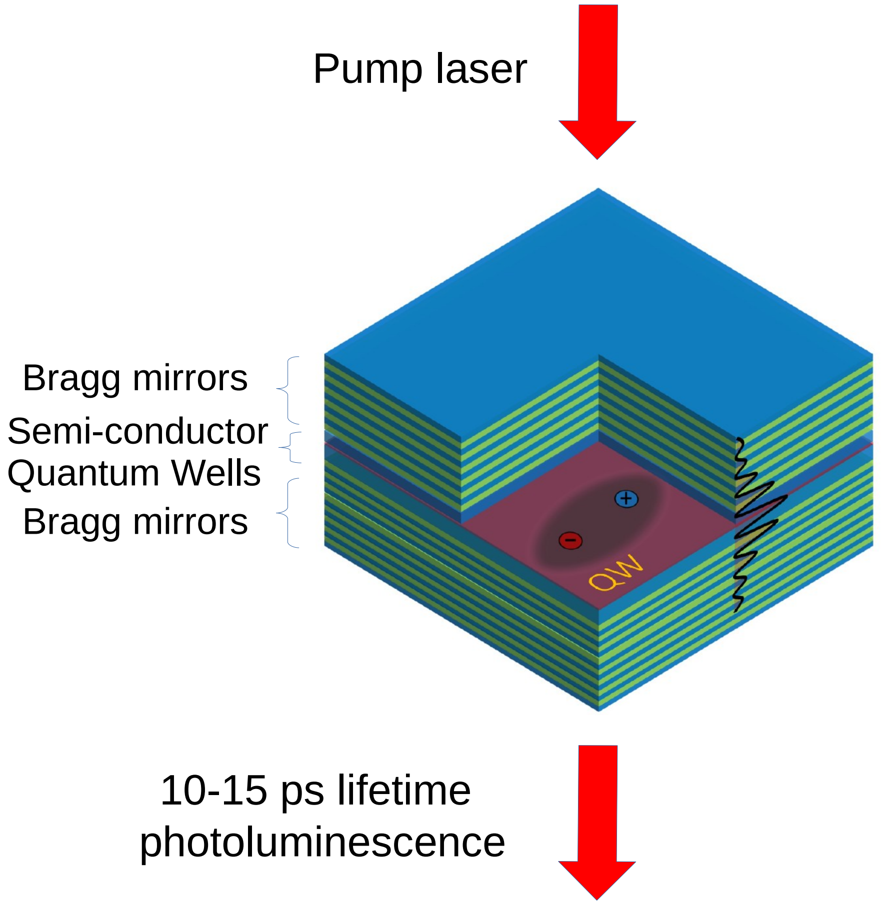


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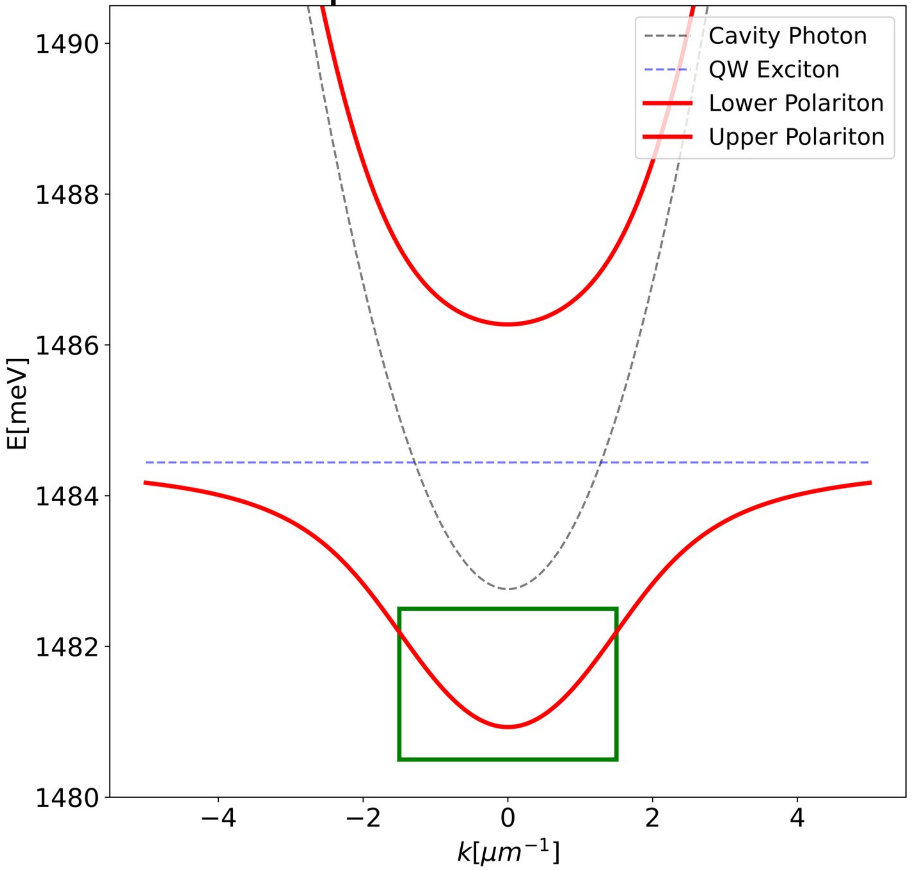

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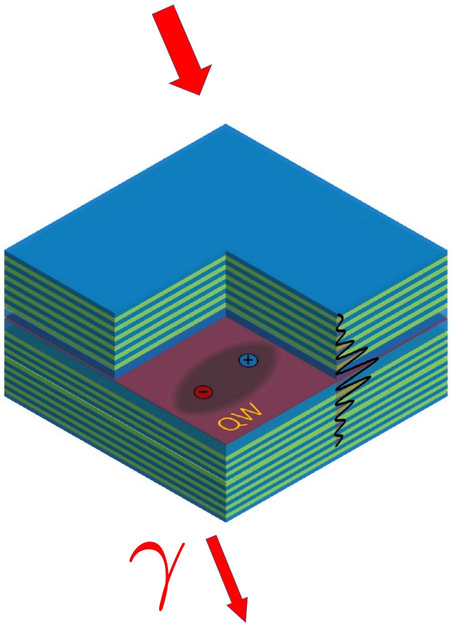
pump laser

$$Fe^{i(k_p.\boldsymbol{r}-\omega_p t)}$$




$\gamma$

photoluminescence

## Generalised Gross Pitaevskii Equation

$$i\hbar\partial_t\psi = \left[-\frac{\hbar^2}{2m}\partial_{\boldsymbol{r}}^2 + V(x) - \hbar\Delta - i\frac{\hbar\gamma}{2} + g|\psi|^2\right]\psi + Fe^{i\boldsymbol{k_p}.\boldsymbol{r}}$$

$g$ : interaction term

$V$ : external potential

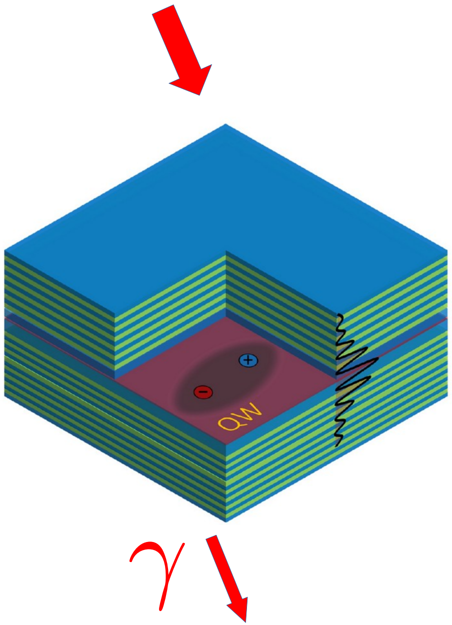
$\Delta = \hbar(\omega_{LP}(k_p) - \omega_p)$

$F$ : pump intensity

$\gamma$ : losses

# Polariton fluid: brief recap

pump laser $Fe^{i(k_p.\boldsymbol{r}-\omega_p t)}$

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## 2D Quantum Fluid of Light

$$\psi = \sqrt{n}e^{i\phi}$$

Speed of sound: $c_s \propto \sqrt{n}$

Fluid velocity: $v \propto \nabla\phi$

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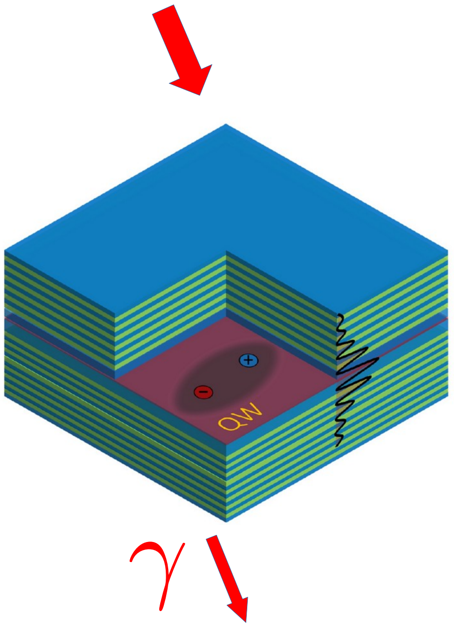


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Fluid velocity: $v \propto \nabla\phi \quad \longleftarrow \nabla\phi_{laser}$

**Resonant pumping → optical control of the flow**

# Generating flows in a polariton fluid

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Spatial Light Modulator

Allows to give an arbitrary phase to an optical beam

# Generating flows in a polariton fluid

$$\boldsymbol{\nabla}\phi_{SLM} = \frac{C}{r}\boldsymbol{u_\theta} - \frac{D}{r}\boldsymbol{u_r}$$

$$\phi_{SLM} = -Dln(r) + C\theta$$

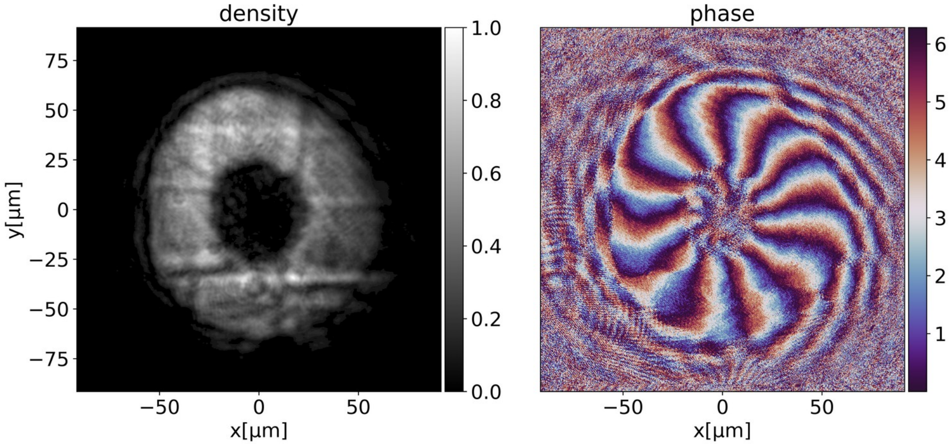
C=6

C=12

D=0 → D=9

# Generating flows in a polariton fluid

$$D = 0, C = 12$$



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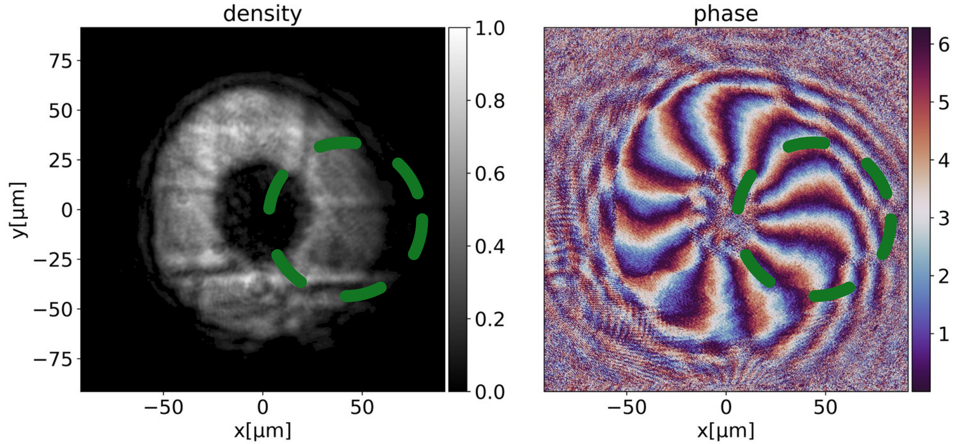
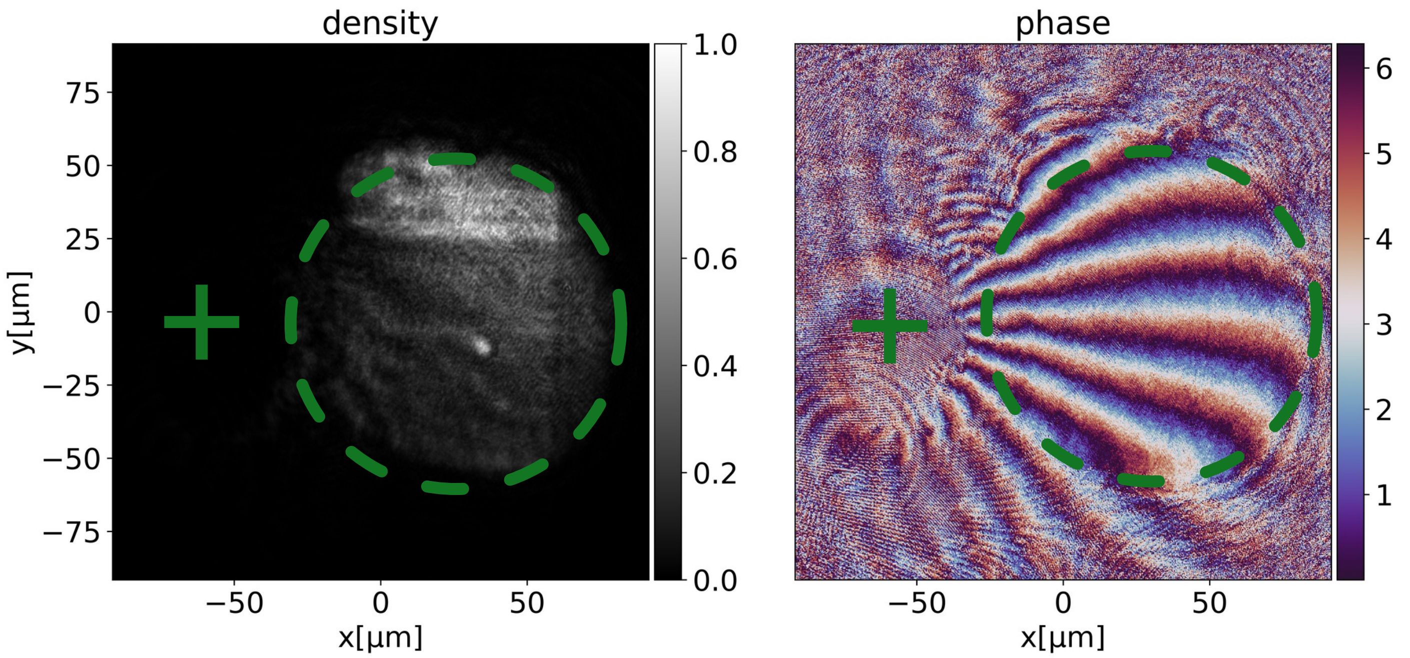


# Vortex edge configuration




About 90µm of high density background flow

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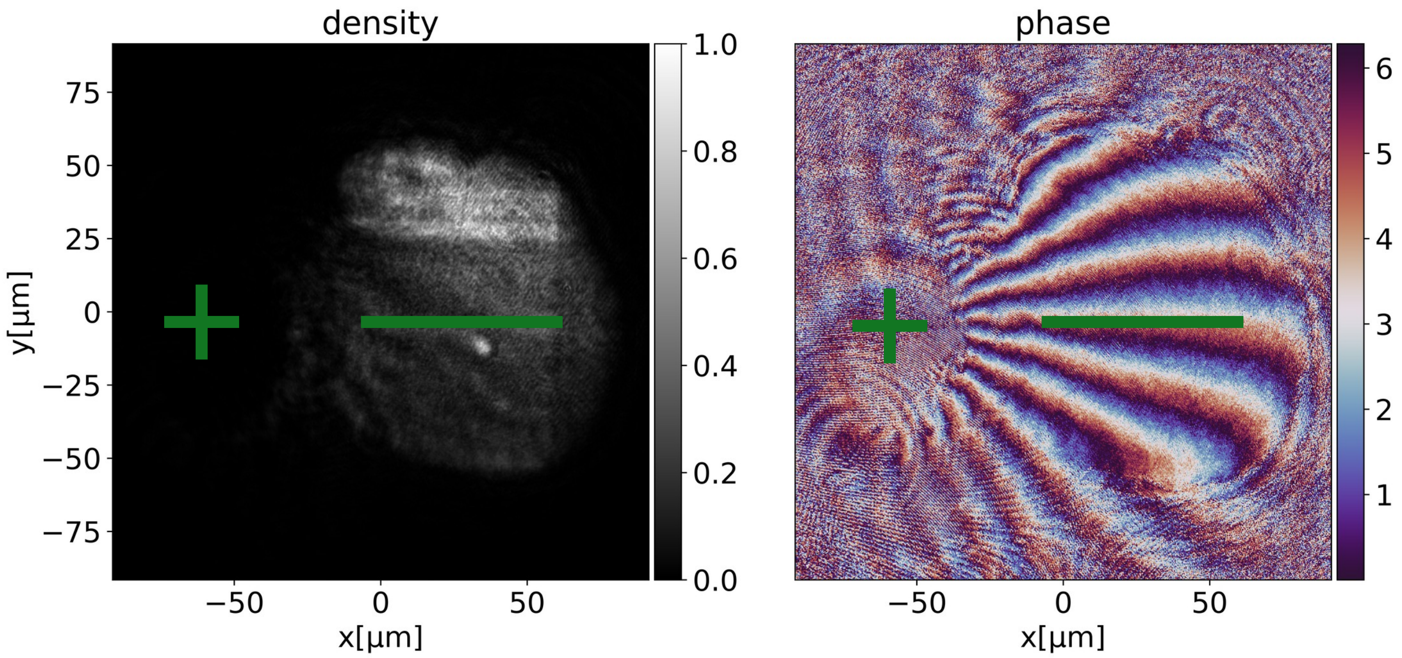
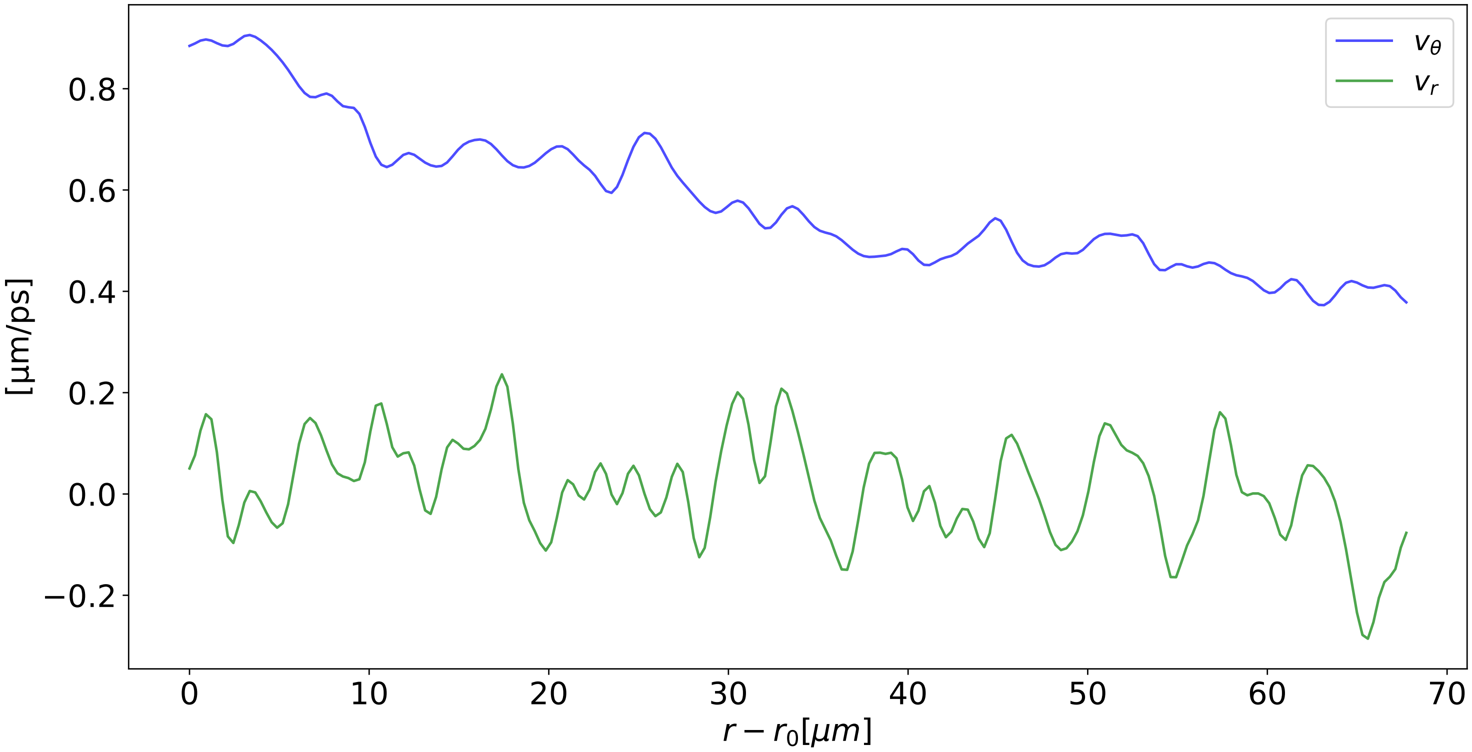


# Velocities analysis on a vortex edge



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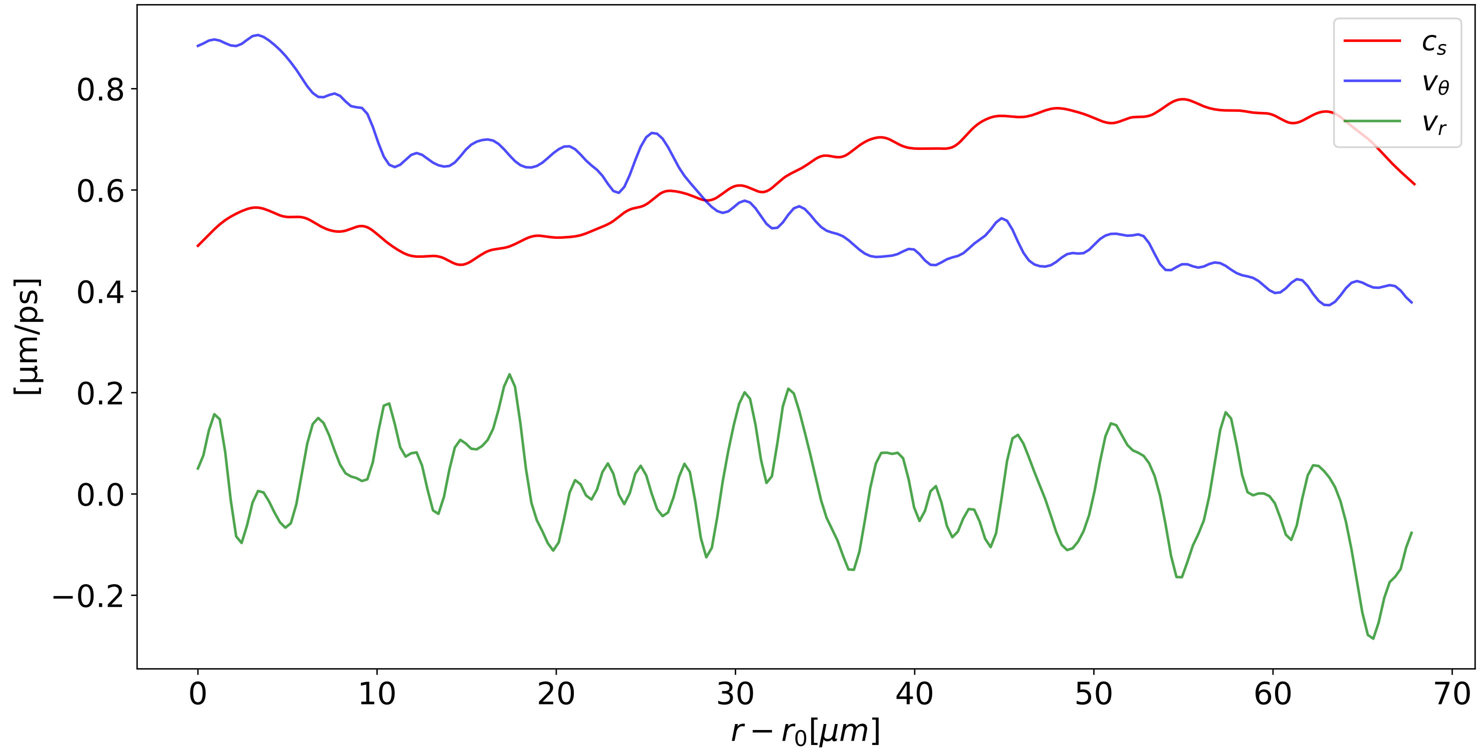

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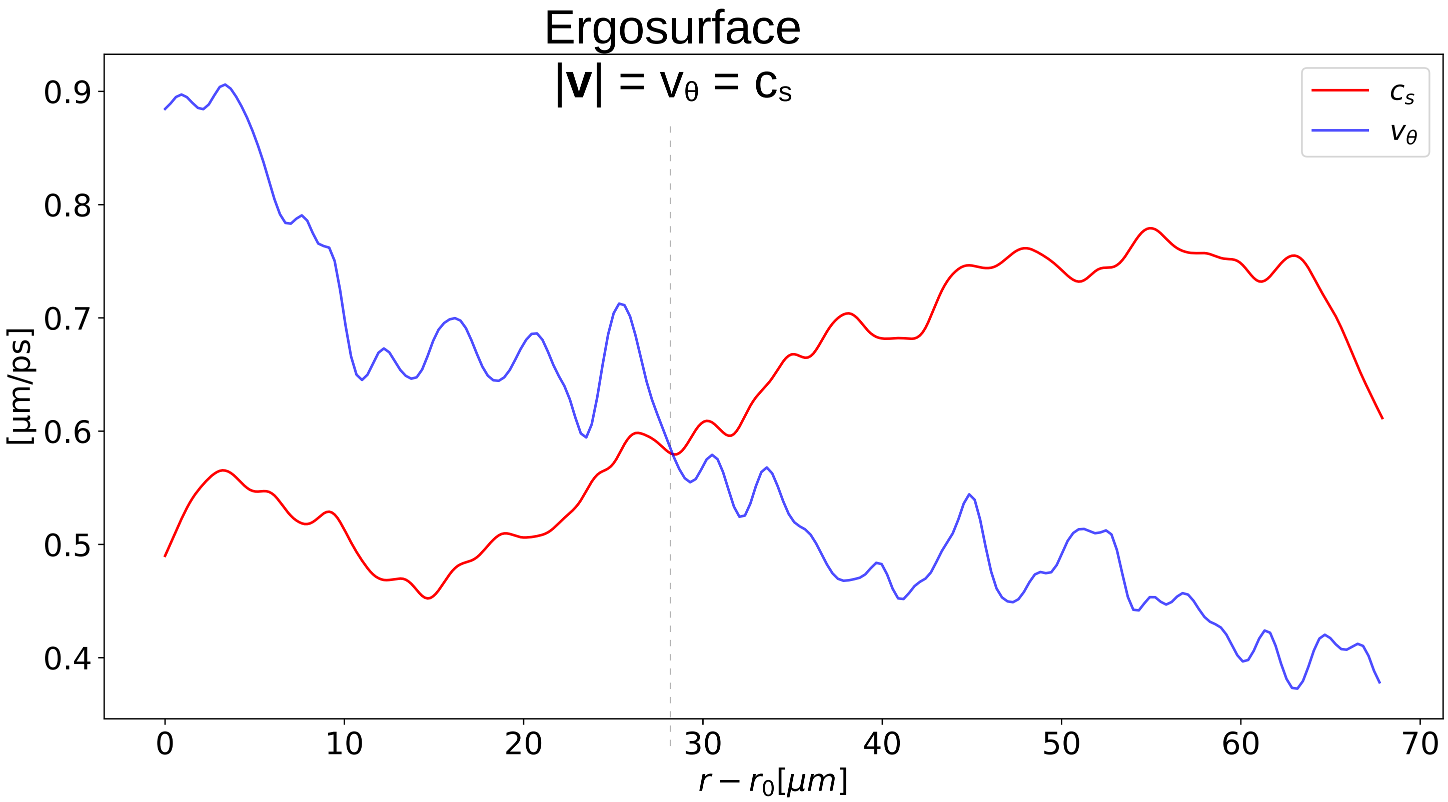
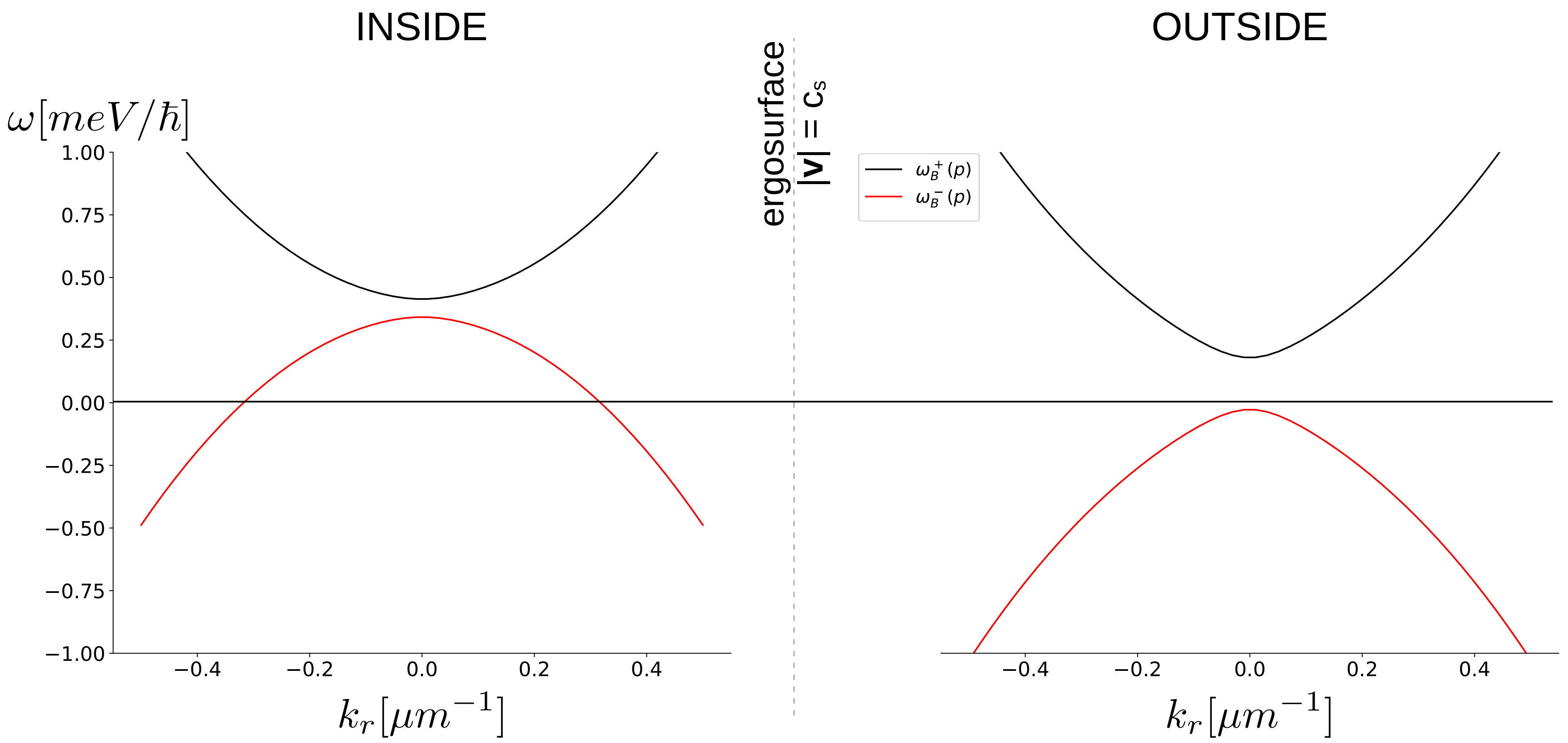
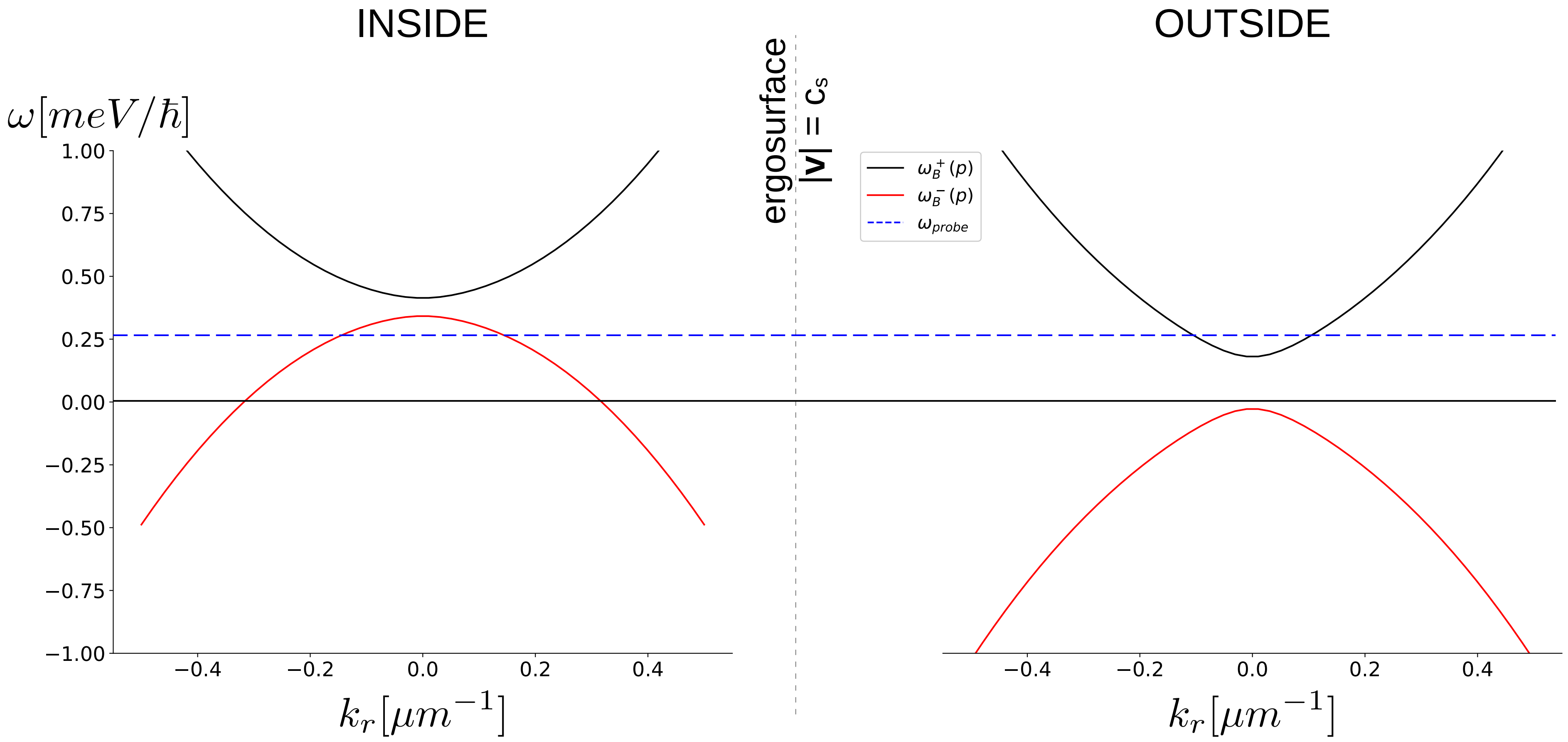


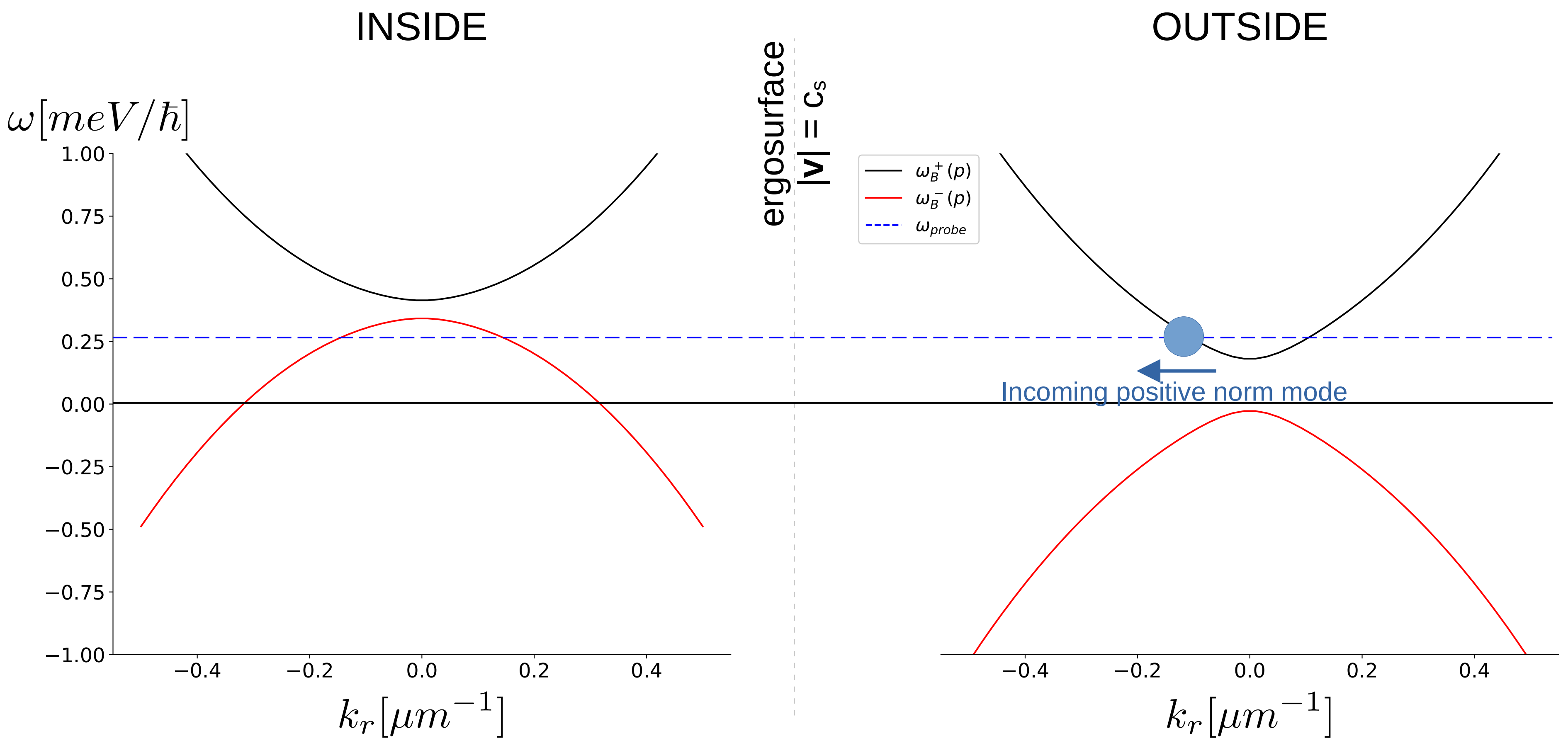
# Collective excitations of the fluid



# Super-radiance conditions



# Stimulated (classical) super-radiance



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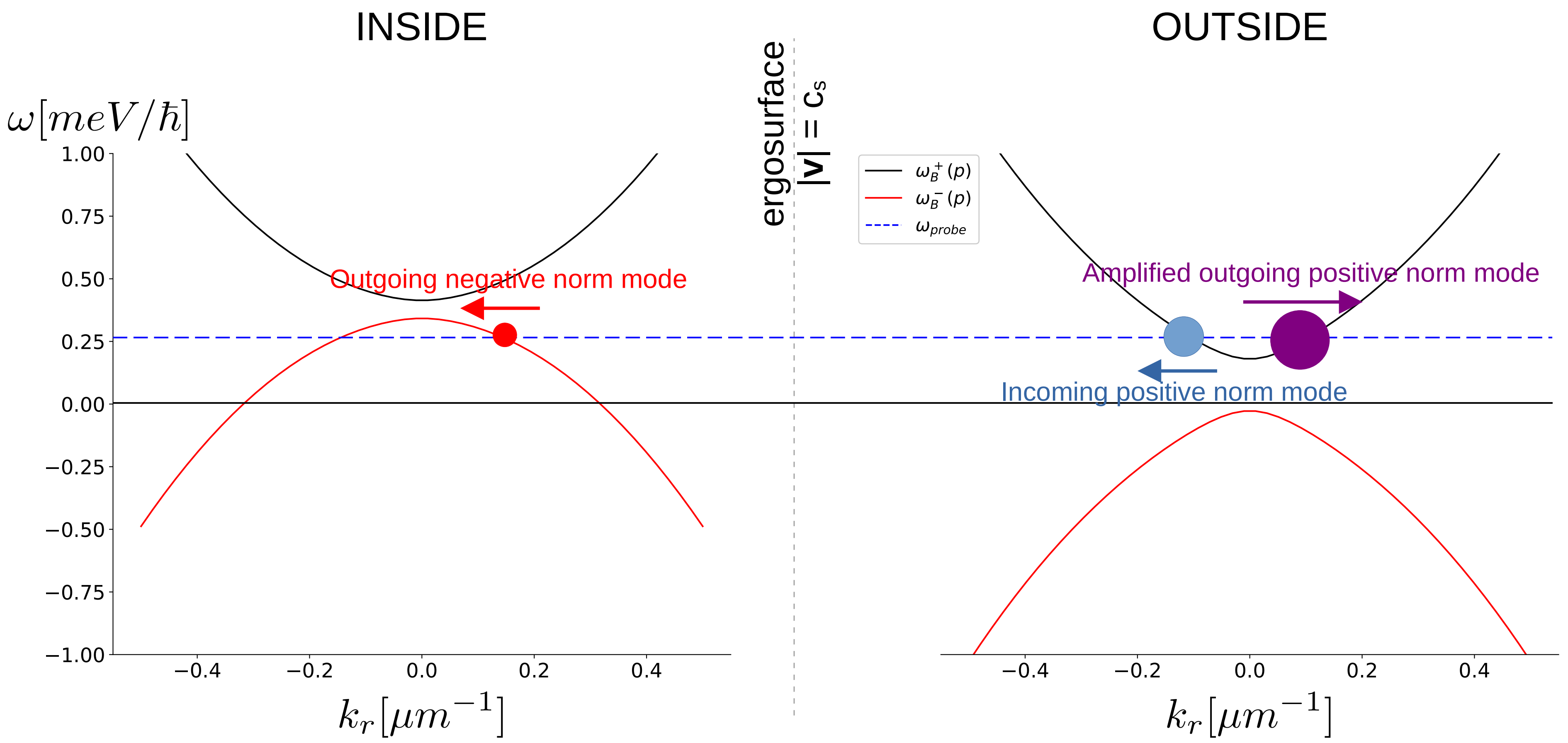

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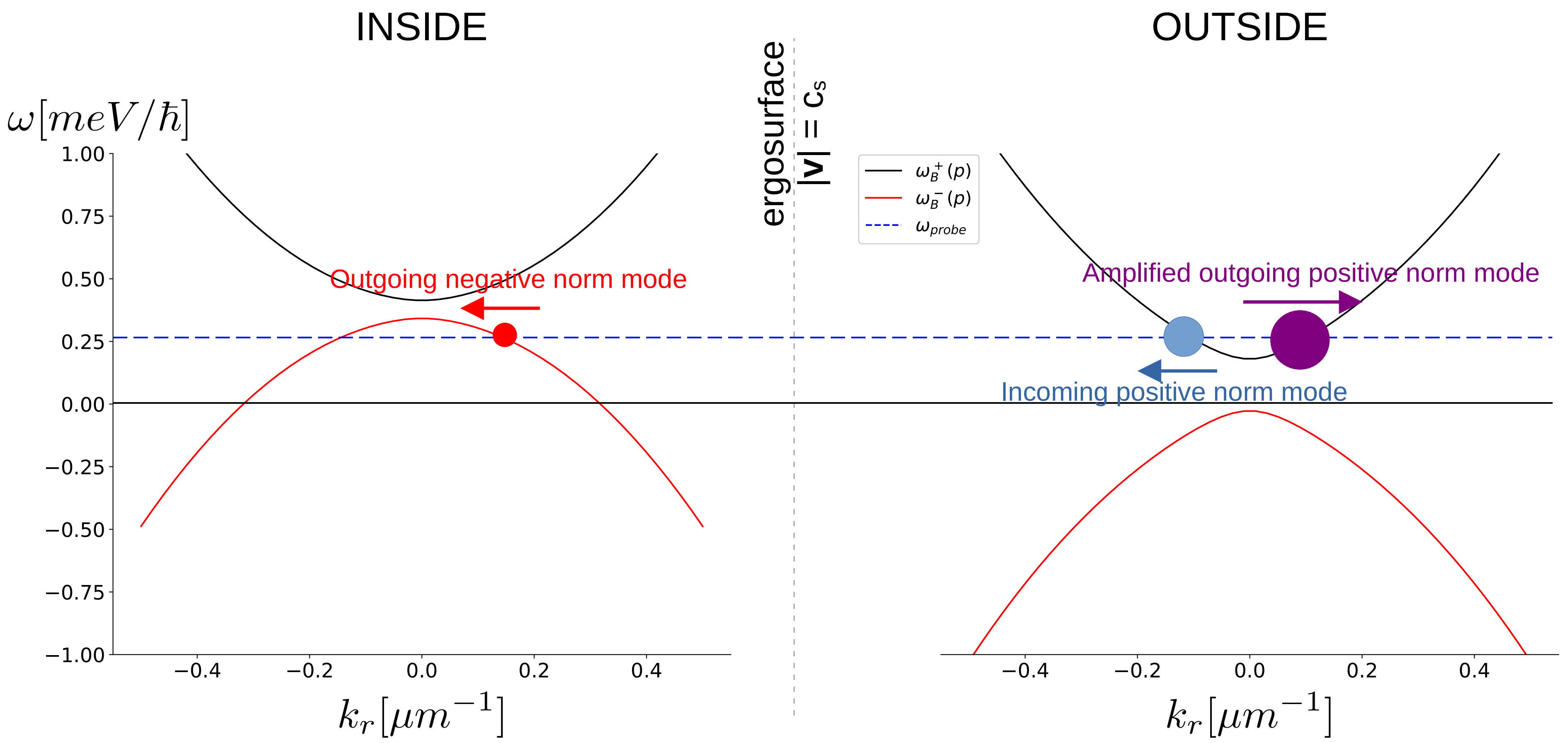


F. Claude *et al*, PRL 2022 High-resolution coherent probe spectroscopy of a polariton quantum fluid

# Conclusion / Outlooks

→ Optical control of the analogue space-time → generation of isolated ergosurface

What next ?

- Stimulated super-radiance with recently developed spectroscopy method

- Entanglement and correlations produced at the ergosurface

# Thanks to the team!

Thank you!