Laboratoire Kastler Brossel
Physique quantique et applications

ENS SORBONNE UNIVERSITÉ COLLÈGE DE FRANCE cnrs

Polariton fluid for black hole rotational superradiance

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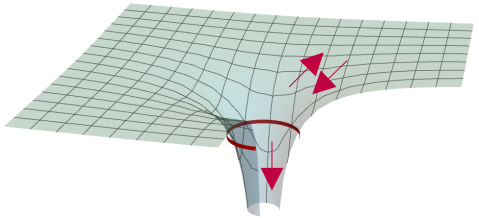
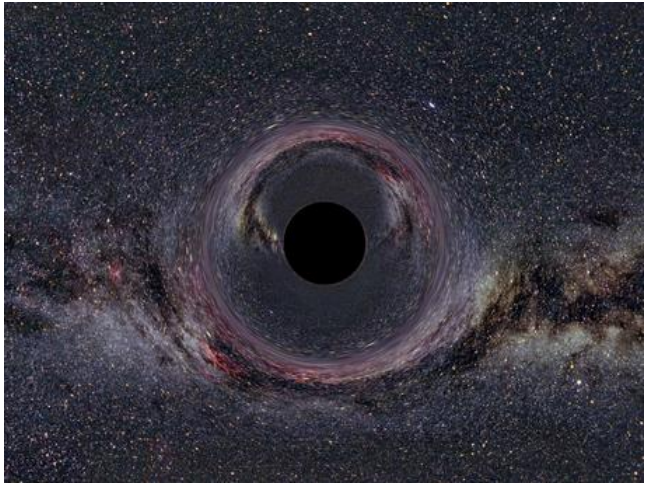
Elisabeth Giacobino, Alberto Bramati, Maxime Jacquet

CG SFP
03/07/2023

Black holes



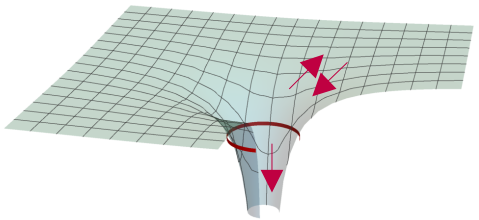
Event horizon : inside, everything falls towards the central singularity



Ute Kraus 2012

Mass curves spacetime → curved trajectories of light
↔ gravitational lensing

A primer in black holes



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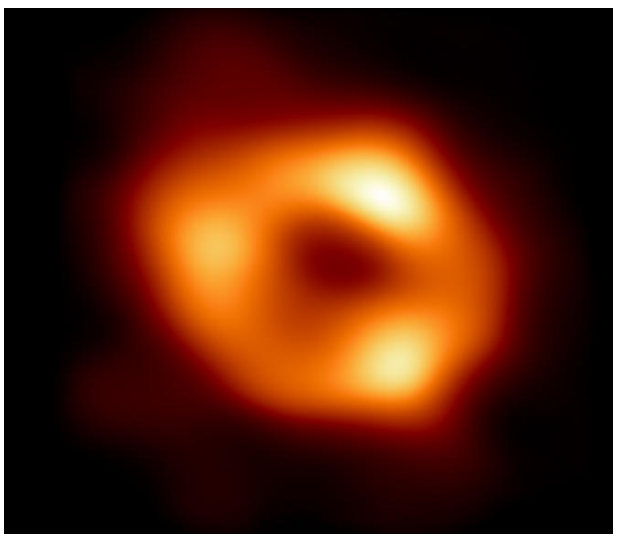
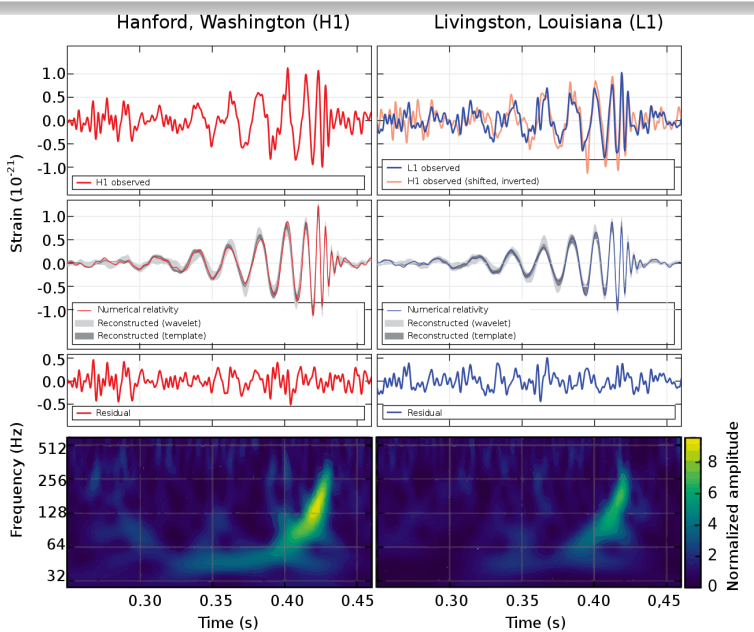


Sagittarius A, EHT Collaboration, 2022*

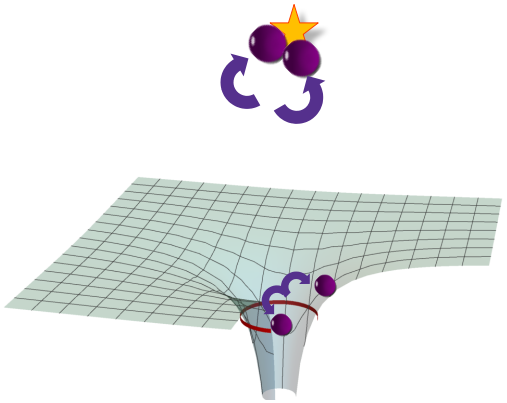


LIGO-VIRGO, 2016 Gravitational waves

Quantum effects of black holes

Hawking radiation

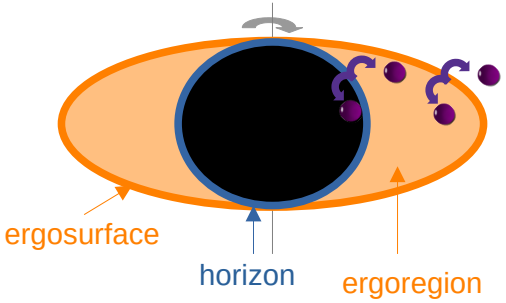
Hawking 1974



Horizon scatters vacuum fluctuations → paired emission

Black hole rotational superradiance

Zeldovich 1971



Rotating black hole: horizon surrounded by ergoregion

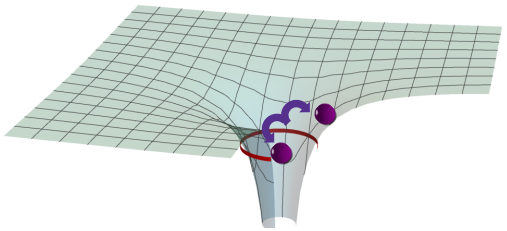
Ergoregion: the fields co-rotate with the black hole

Ergosurface scatters vacuum fluctuations → paired emission

Quantum effects of black holes

Hawking radiation

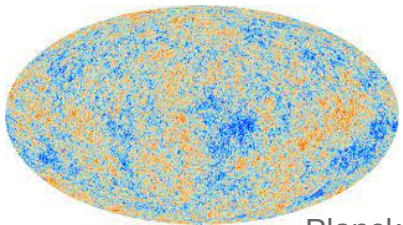
Hawking 1974



Horizon scatters vacuum fluctuations → paired emission

$$k_B T = \frac{\hbar c^3}{8\pi G M}$$

Strength of Hawking radiation inversely proportional to the black hole mass



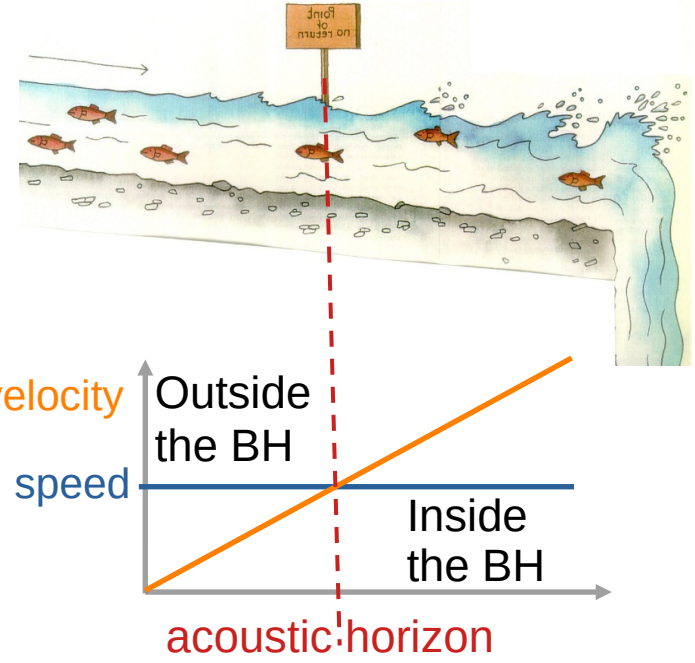
Planck 2016

Pb: T_{max} ~ 50nK vs T_{CMB} = 3K

Signal to noise ratio 10^{-9}: impossible to observe in astrophysics!

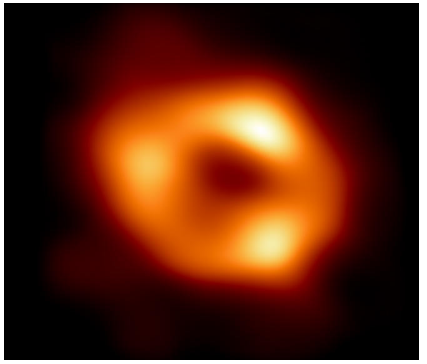
Analogue gravity in fluids

Sonic waves in acoustic black holes



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

Scalar field in black holes gravitational field



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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

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

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

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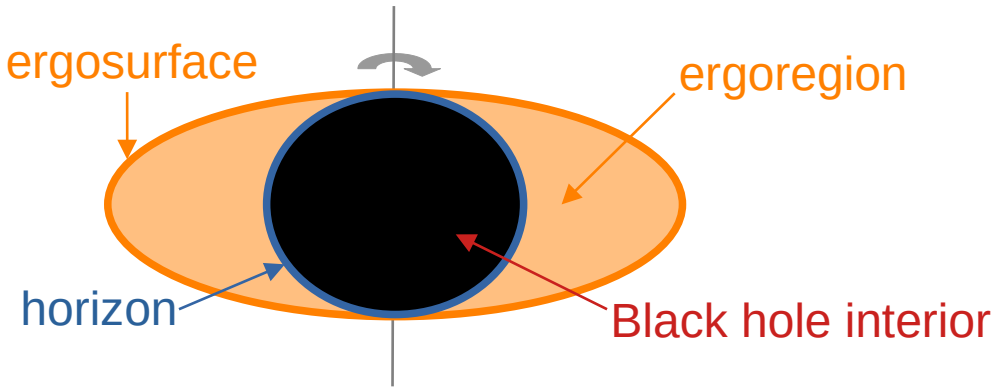

(In equatorial plane)

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

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

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

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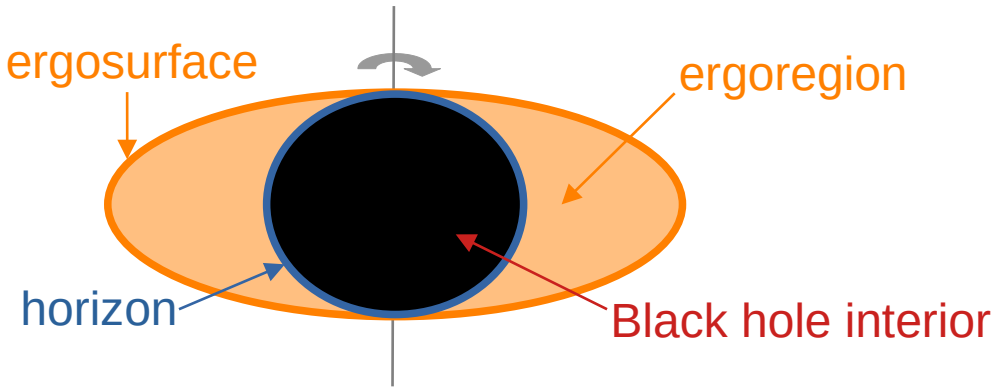

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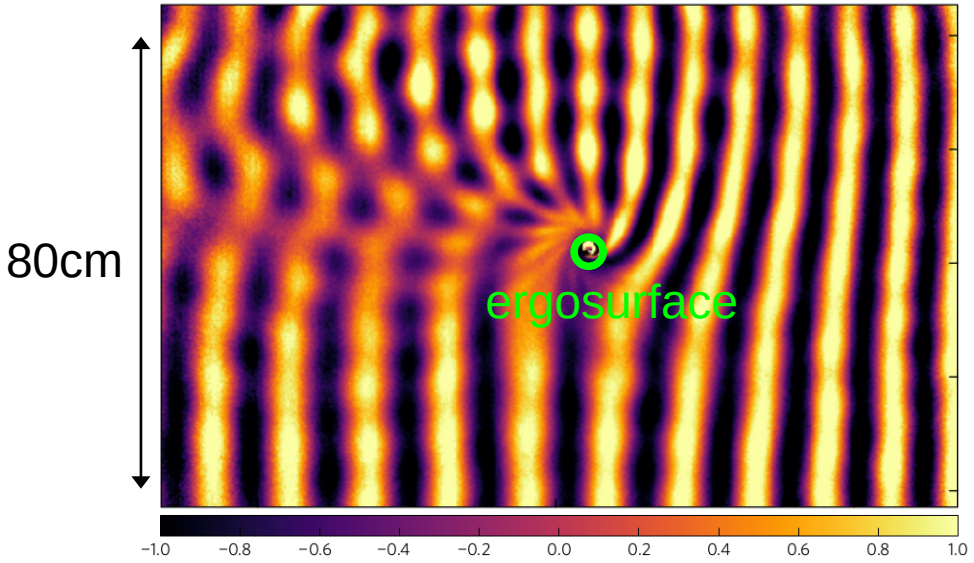
Ergosurface ($v_{tot}=c_s$) at $r_e = \frac{\sqrt{C^2+D^2}}{c_s}$

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 coming from the right on the DBT flow.

Scattering on the ergosurface seen in the interference pattern
Over-reflection → signature of rotational superradiance

Kerr blackhole simulation: First Experimental demonstration

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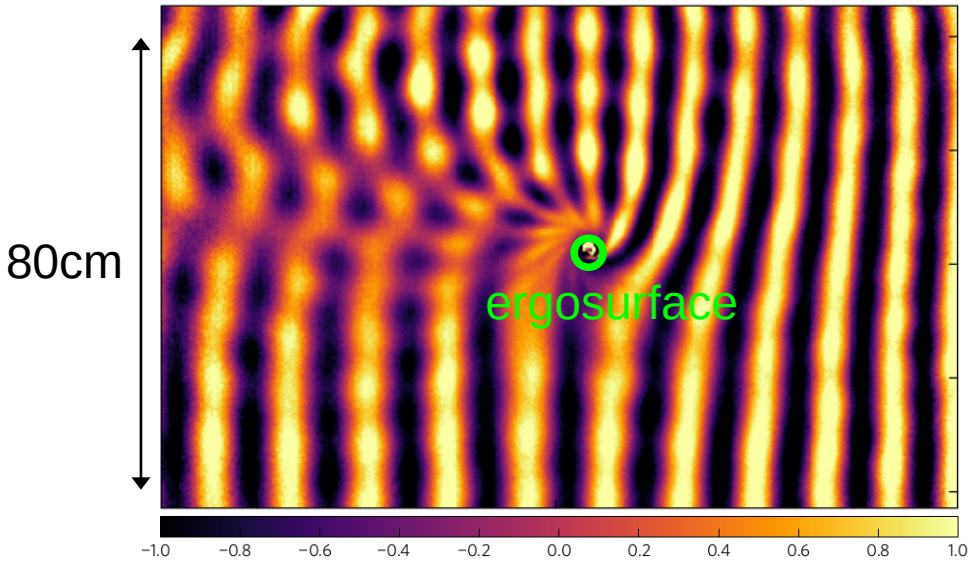

Planar wavefront of surface waves coming from the right on the DBT flow.

Scattering on the ergosurface seen in the interference pattern
Over-reflection → signature of rotational superradiance

Classical fluid → Classical rotational supperadiance

What do we want to do?

Study the quantum properties of rotational super-radiance:
correlations, entanglement between the scattered modes

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Polariton quantum fluid of light:

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

What do we want to do?

Study the quantum properties of rotational super-radiance:
correlations, entanglement between the scattered modes

Polariton quantum fluid of light:

- Fully optically controlled → any arbitrary flow can be generated

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Study the quantum properties of rotational super-radiance:
correlations, entanglement between the scattered modes

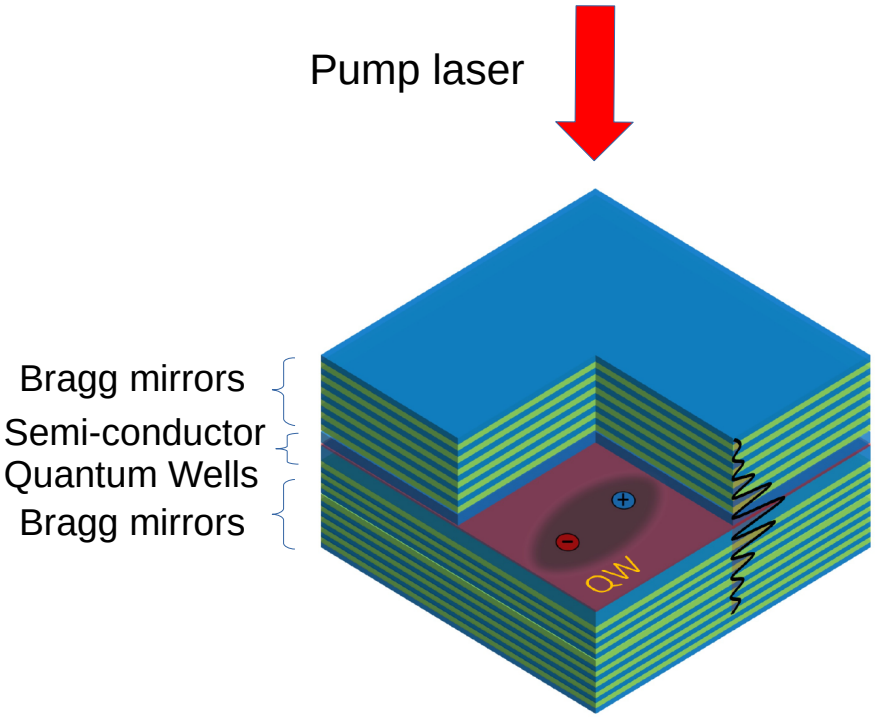
Polariton quantum fluid of light:

- Fully optically controlled → any arbitrary flow can be generated

- High sensitive technique from quantum optics: homodyne detection

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

Polariton fluid: brief recap



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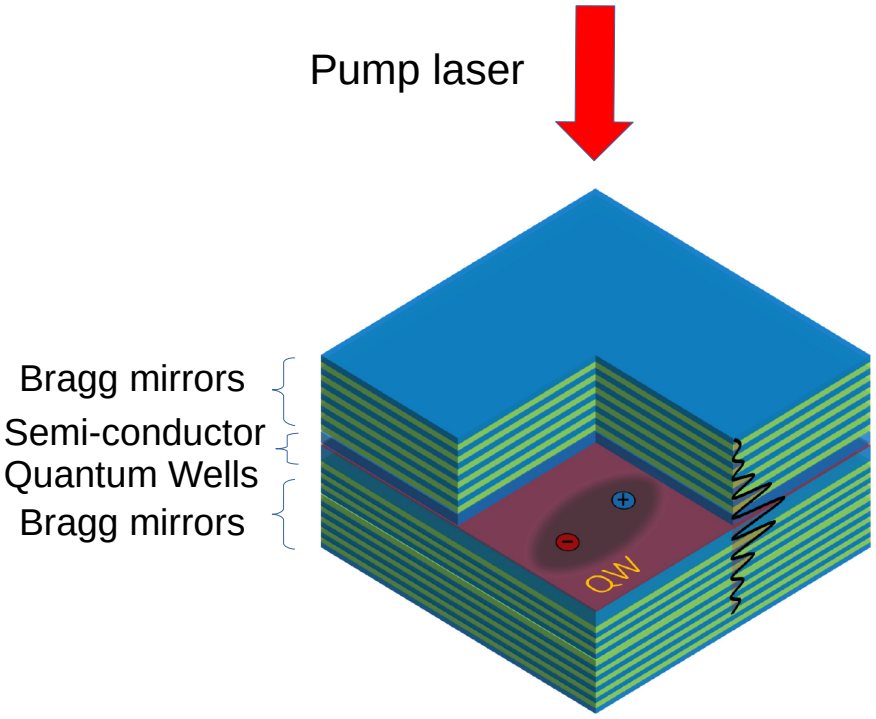
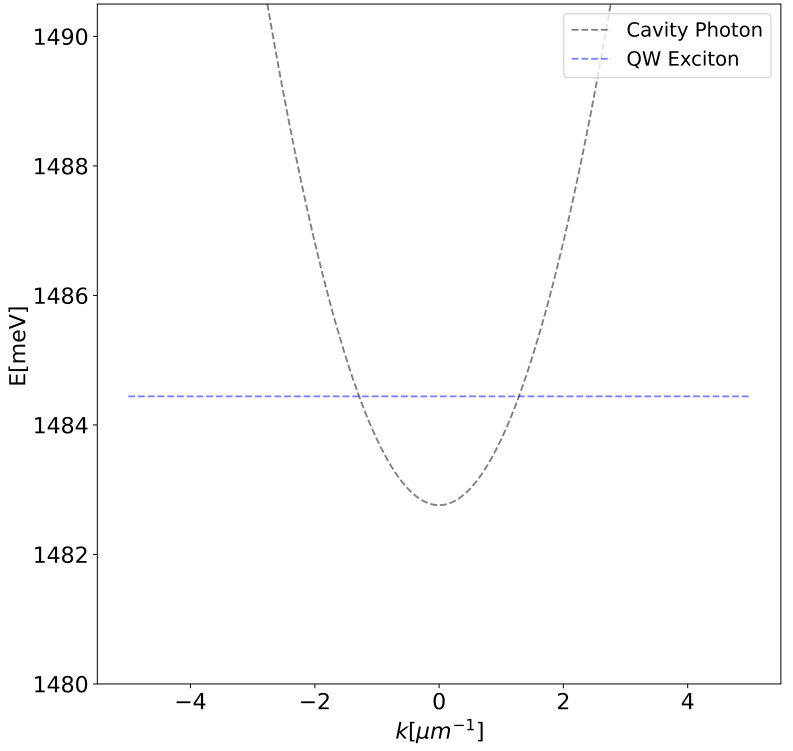


Strong coupling between cavity photons and quantum well excitons



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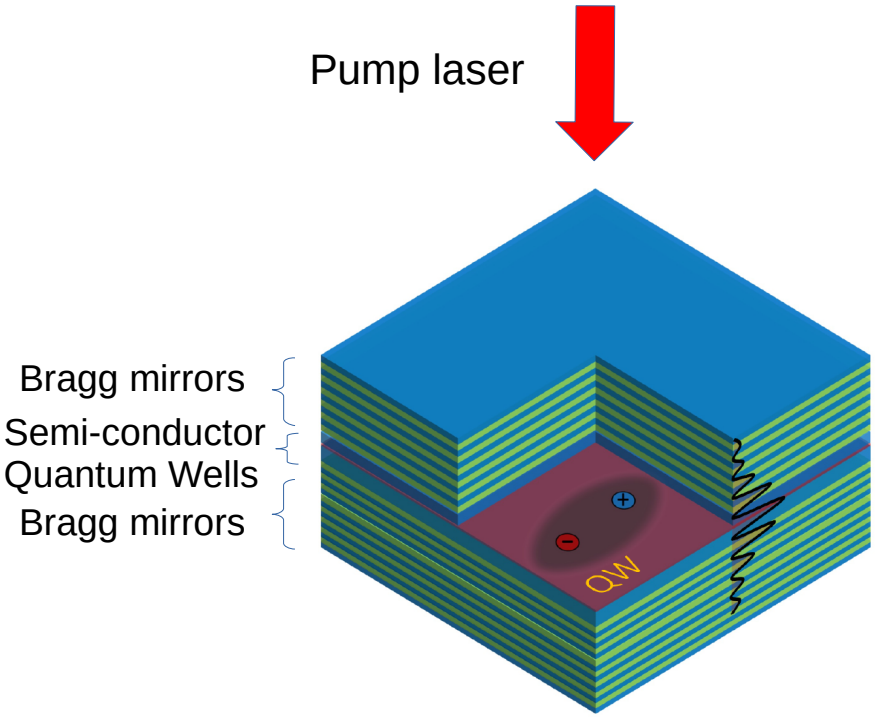

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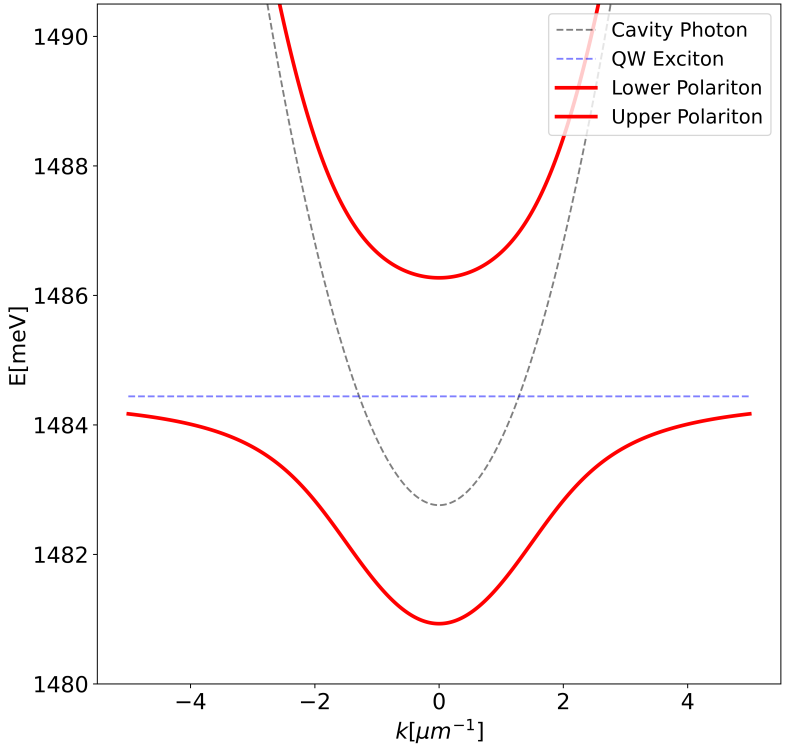
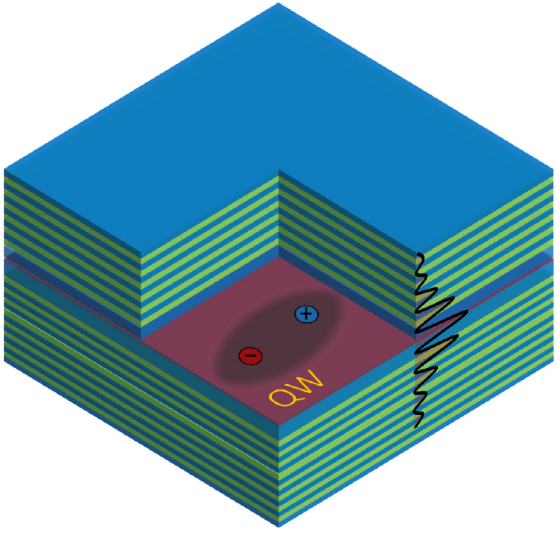


Polariton fluid: brief recap

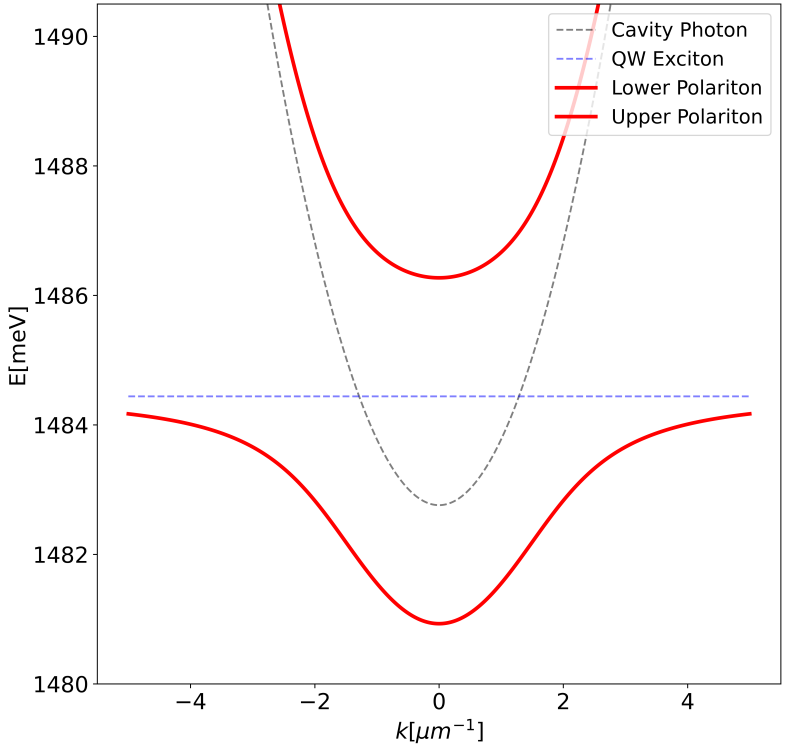
Pump laser



Bragg mirrors
Semi-conductor
Quantum Wells
Bragg mirrors

10-15 ps lifetime
photoluminescence

Strong coupling between cavity photons and quantum well excitons



Polariton fluid: brief recap

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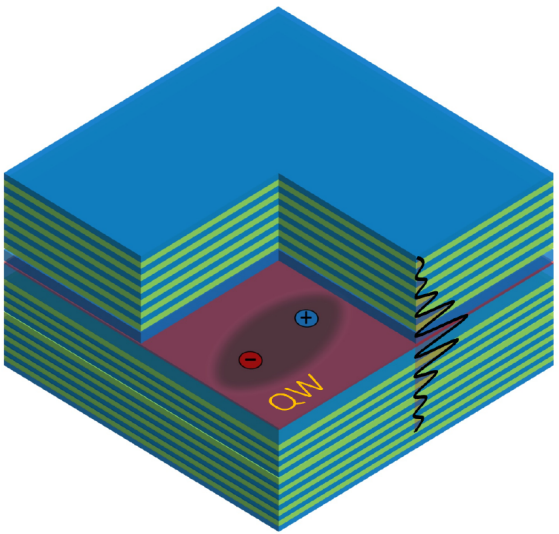

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Strong coupling between cavity photons
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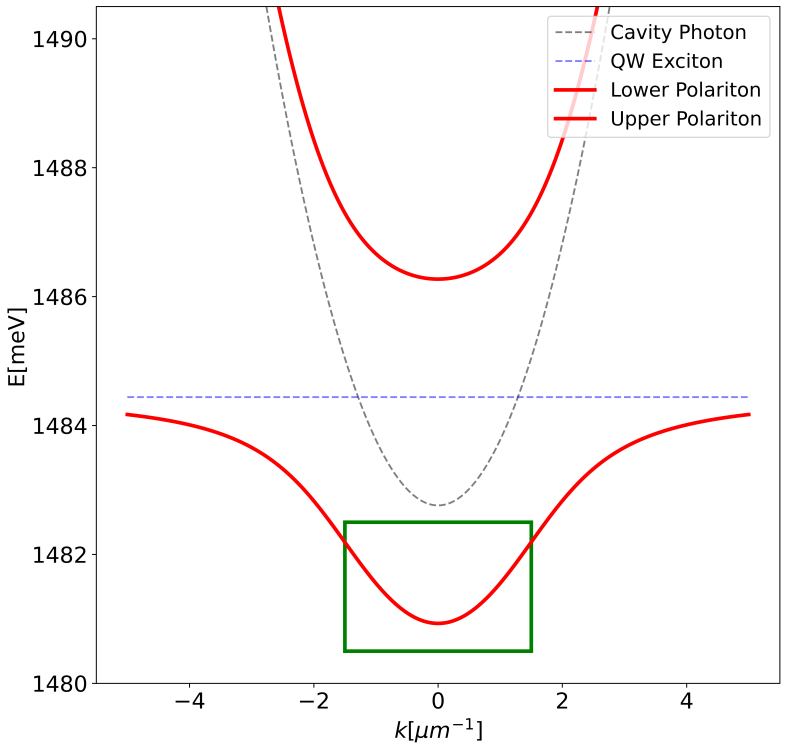
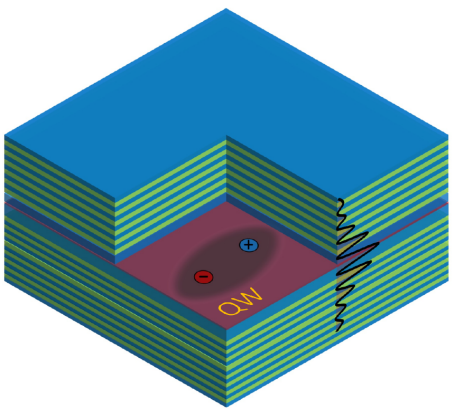


+ polariton-polariton interactions
due to excitonic nature

Polariton fluid: brief recap

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



γ

photoluminescence

Generalised Gross Pitaevskii Equation

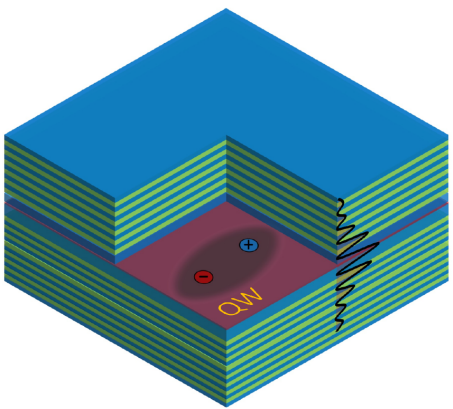
$$i\hbar\partial_t\psi = \Big[-\frac{\hbar^2}{2m}\partial^2_{\boldsymbol{r}} + V(x) - \hbar\Delta - i\frac{\hbar\gamma}{2} + g|\psi|^2 \Big]\psi + F e^{i\boldsymbol{k_p}.\boldsymbol{r}}$$

g : interaction term
V : external potential
$\Delta = \hbar(\omega_{LP}(k_p) - \omega_p)$

F : pump intensity
γ : losses

Polariton fluid: brief recap

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



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2D Quantum Fluid of Light

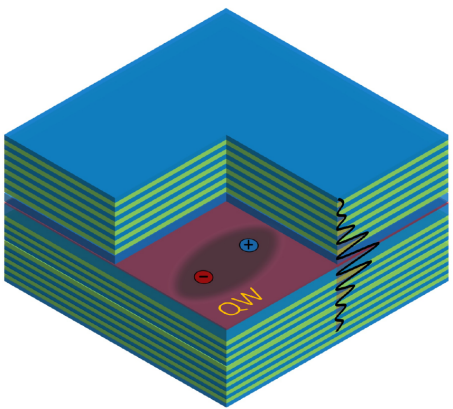
$\psi = \sqrt{n}e^{i\phi}$

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

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

Polariton fluid: brief recap

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



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2D Quantum Fluid of Light

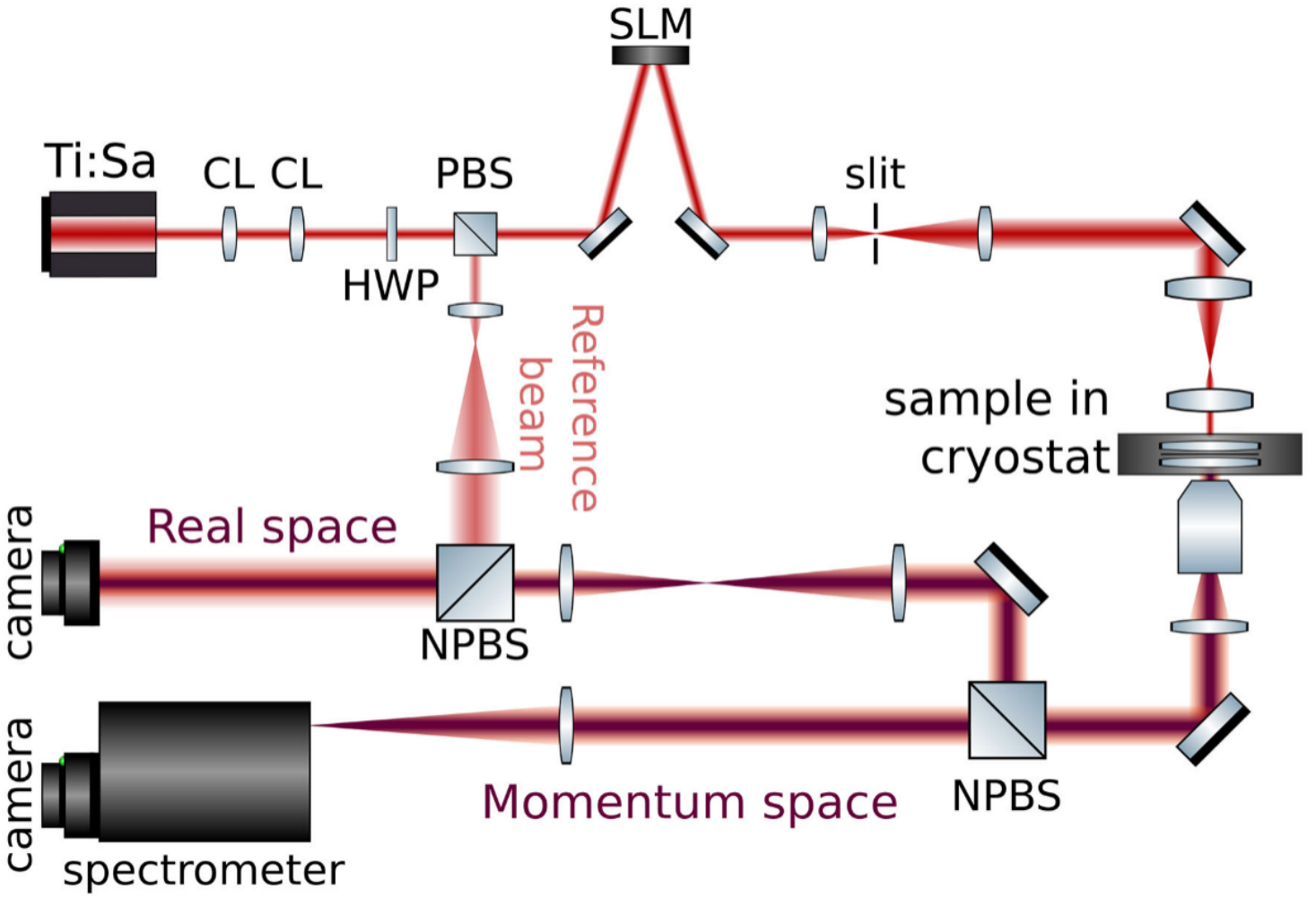
$\psi = \sqrt{n}e^{i\phi}$

Speed of sound: $c_s \propto \sqrt{n}$ ← F^2, Δ

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

Resonant pumping → optical control of the flow

Generating flows in a polariton fluid



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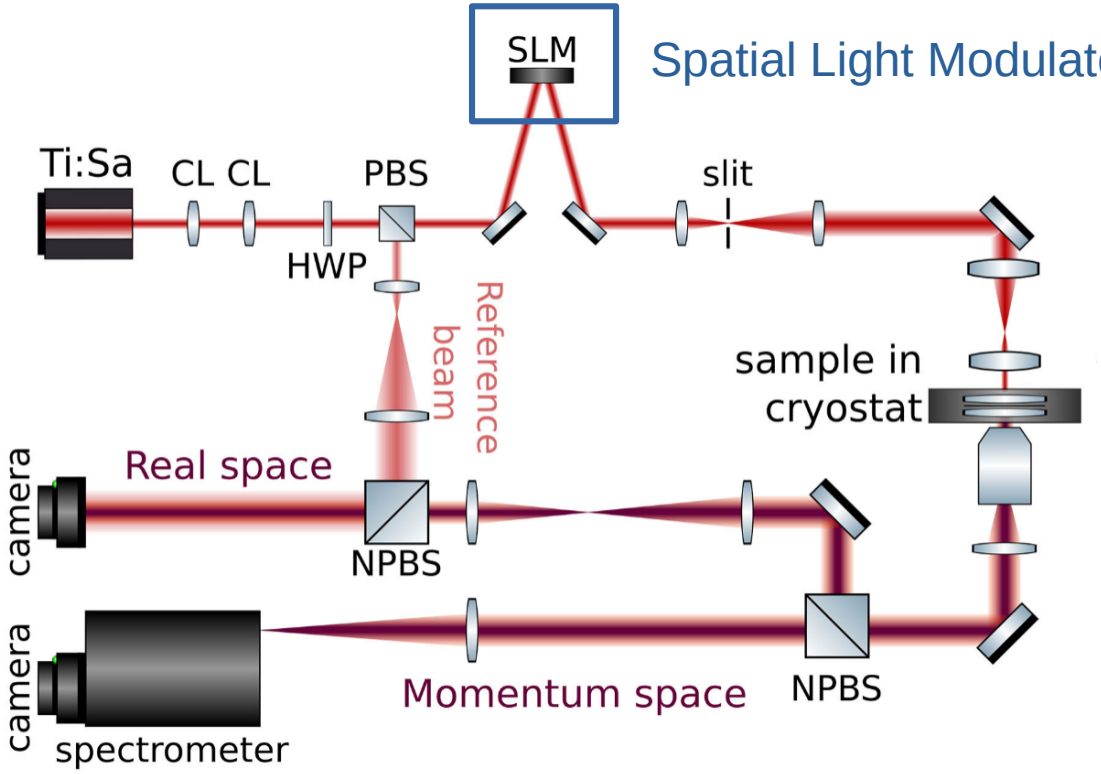
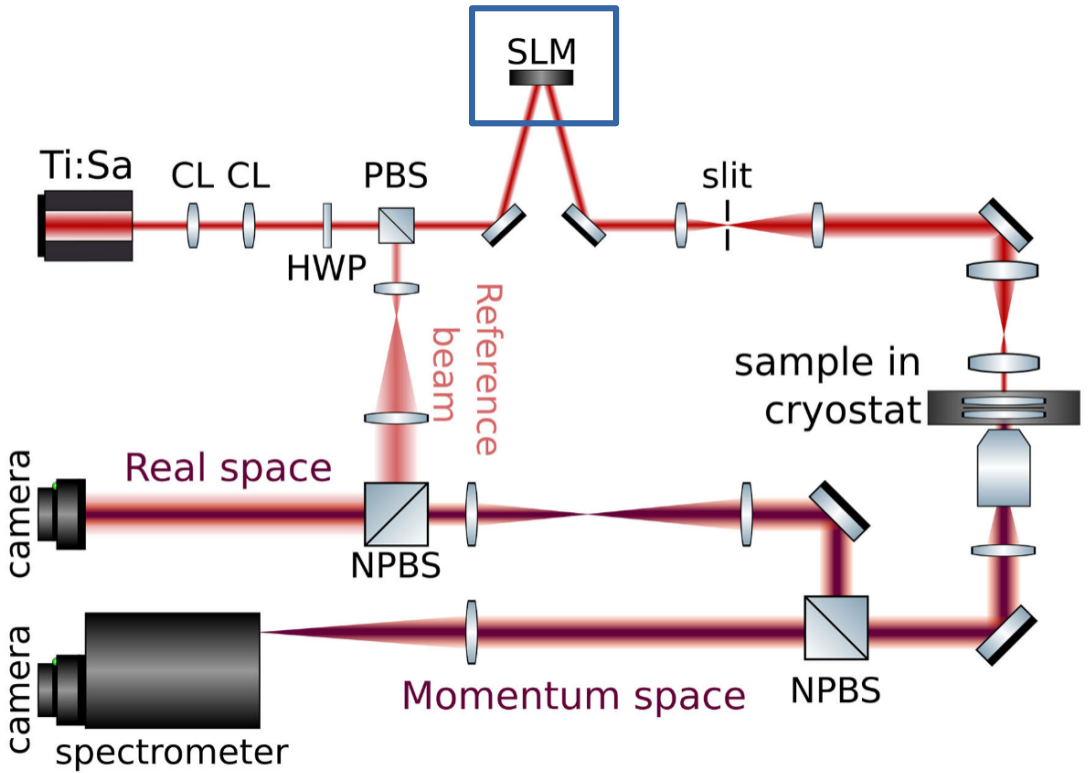


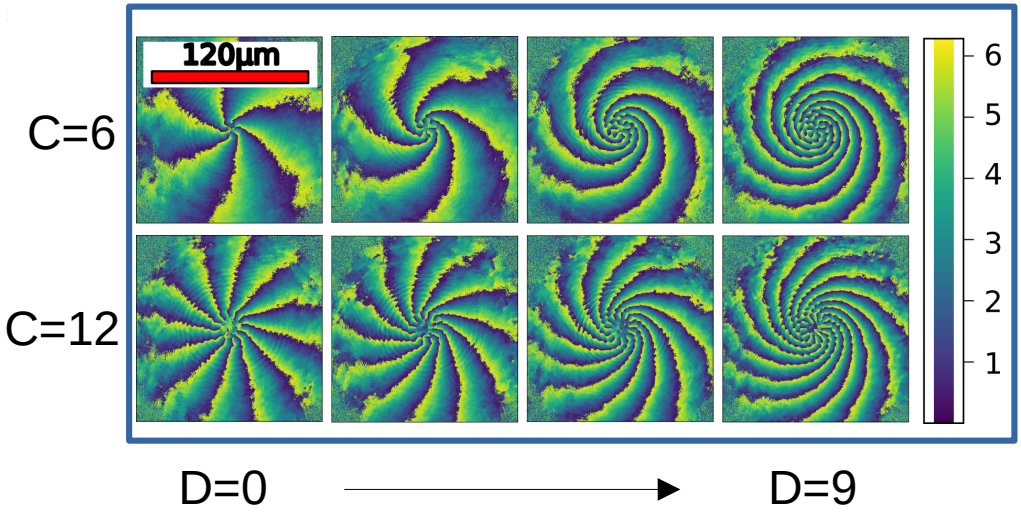
Spatial Light Modulator: allows to give an arbitrary phase to an optical beam

Generating flows in a polariton fluid



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

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



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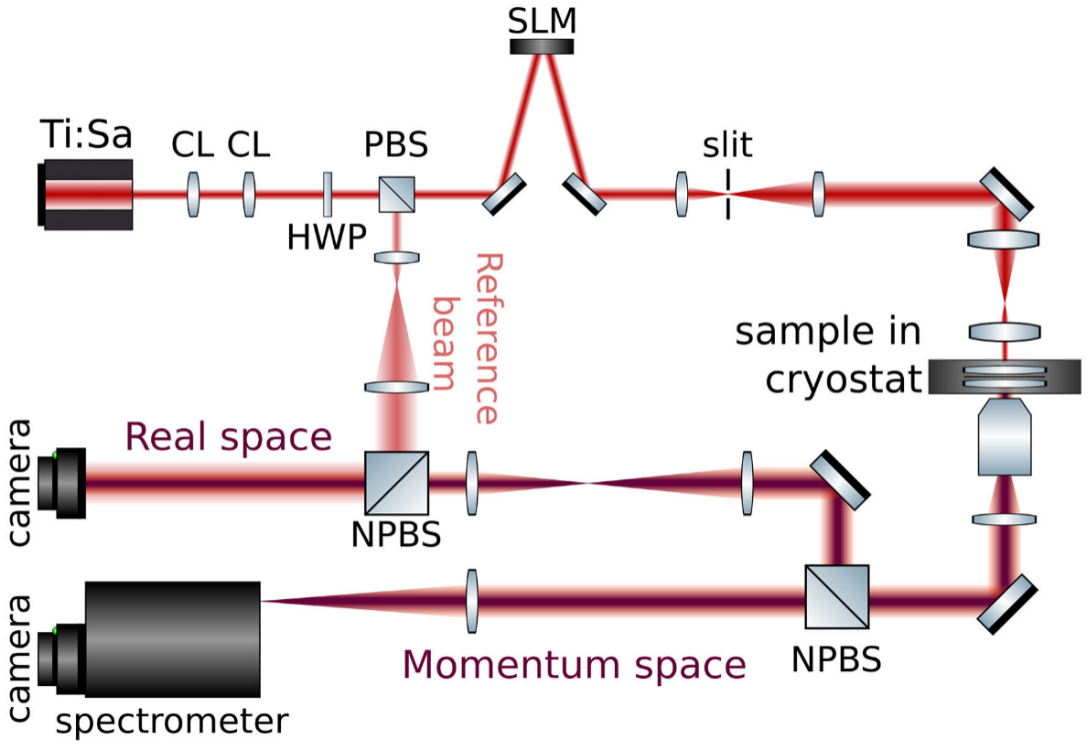
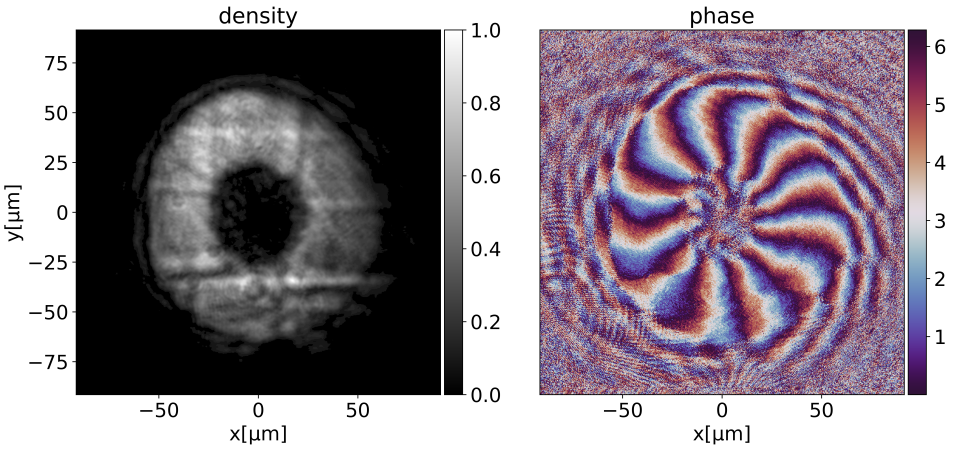
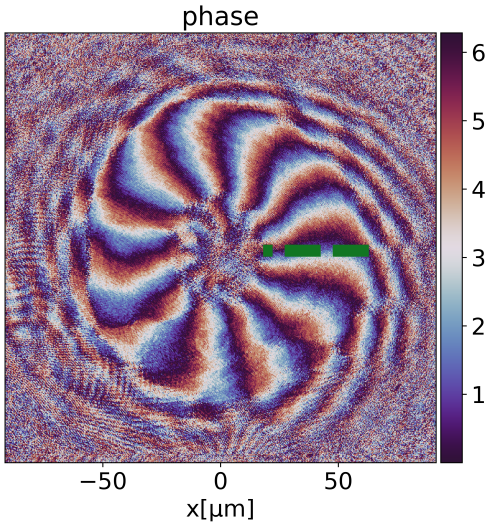


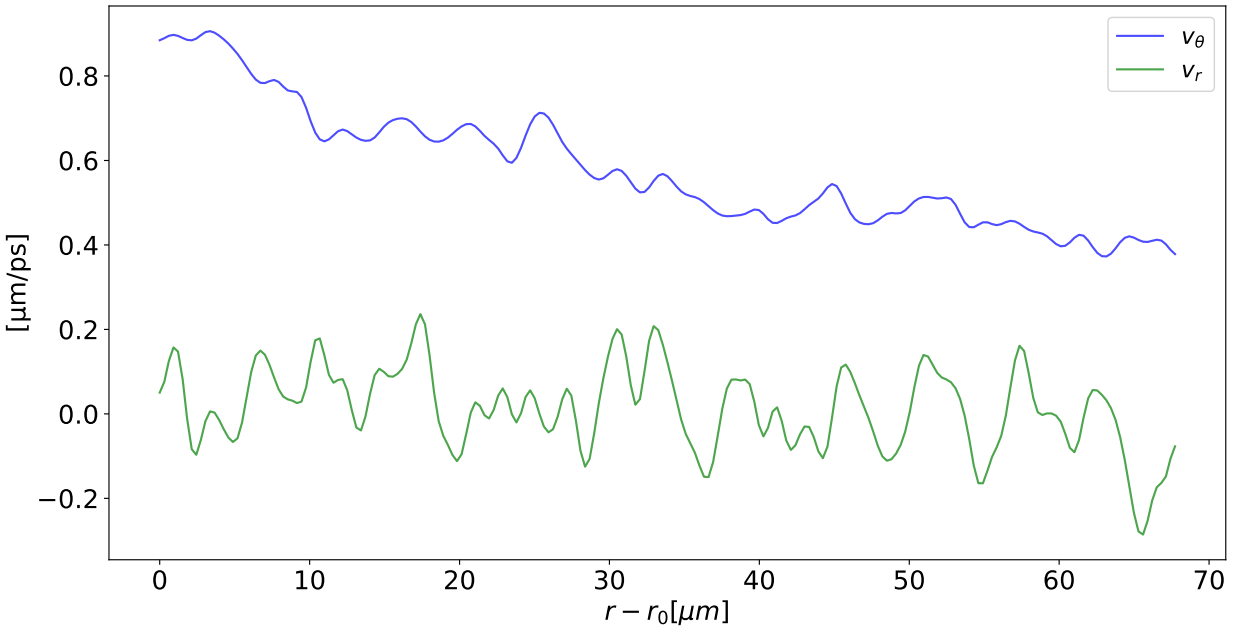
$$D = 0, C = 12$$

$$\boldsymbol{\nabla}\phi_{SLM} = \frac{12}{r}\boldsymbol{u_\theta}$$



Velocities analysis along the radial dimension





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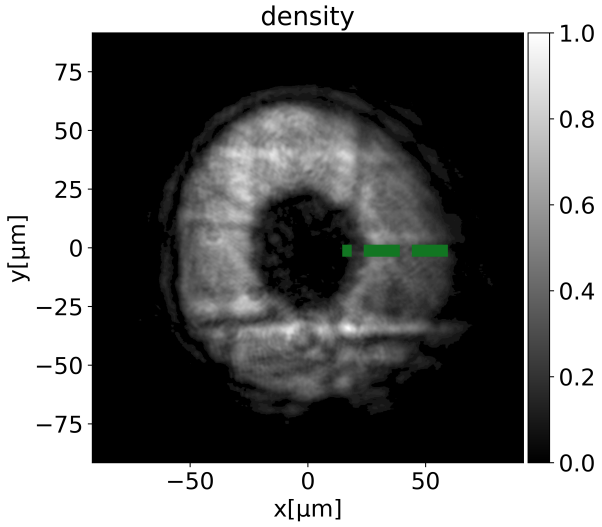

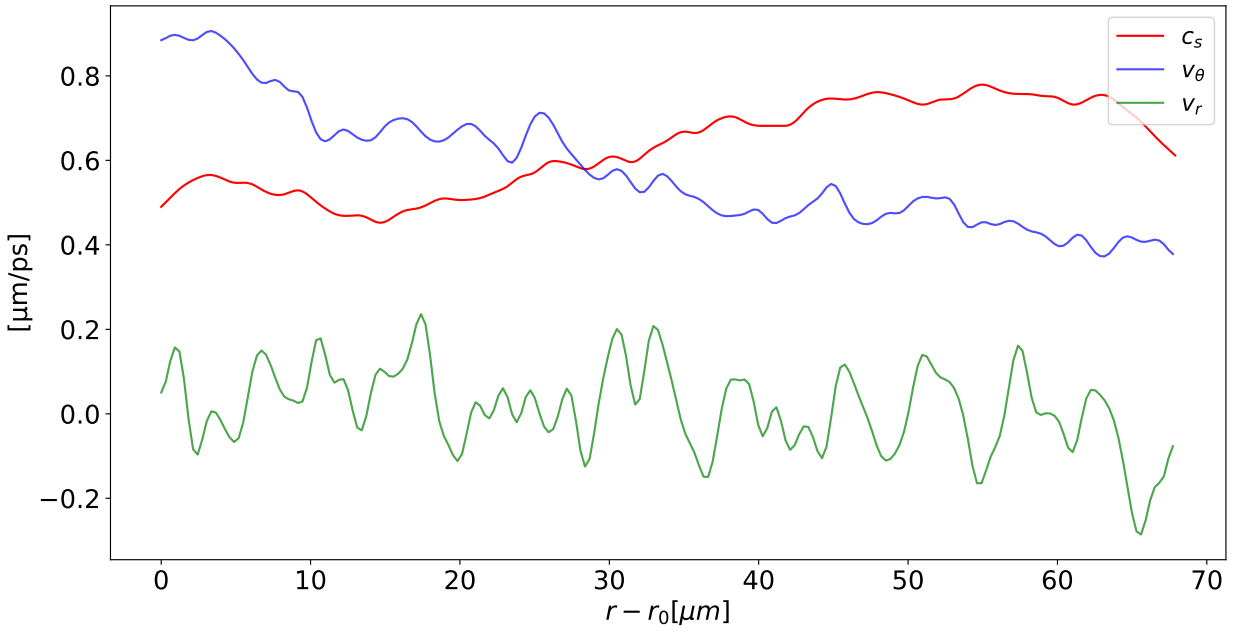

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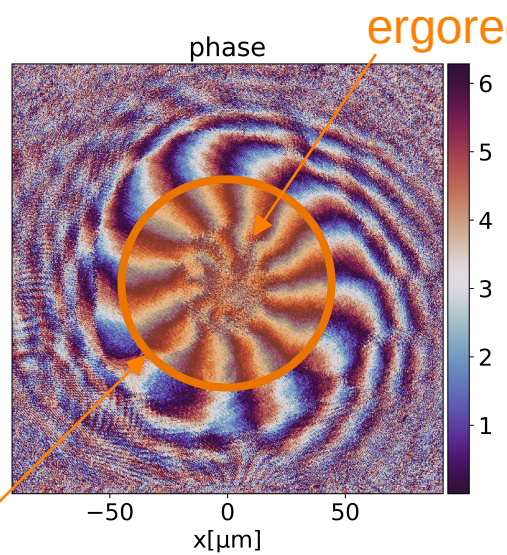
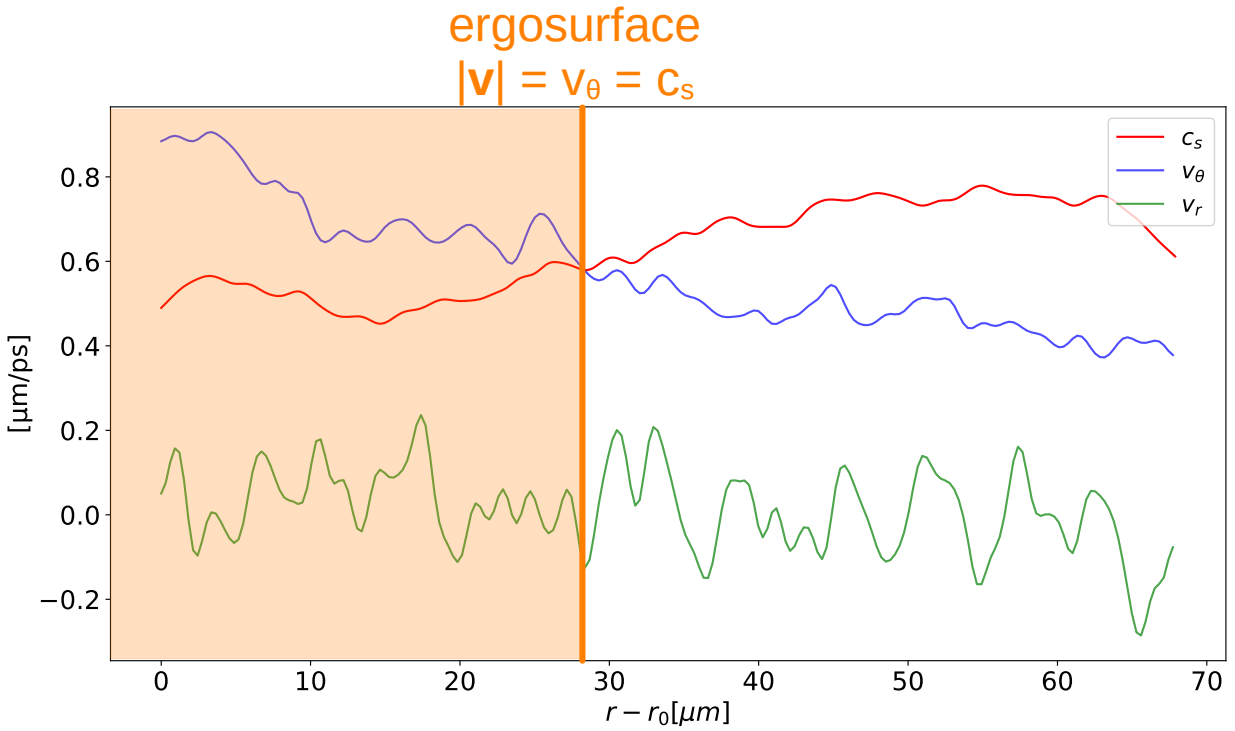
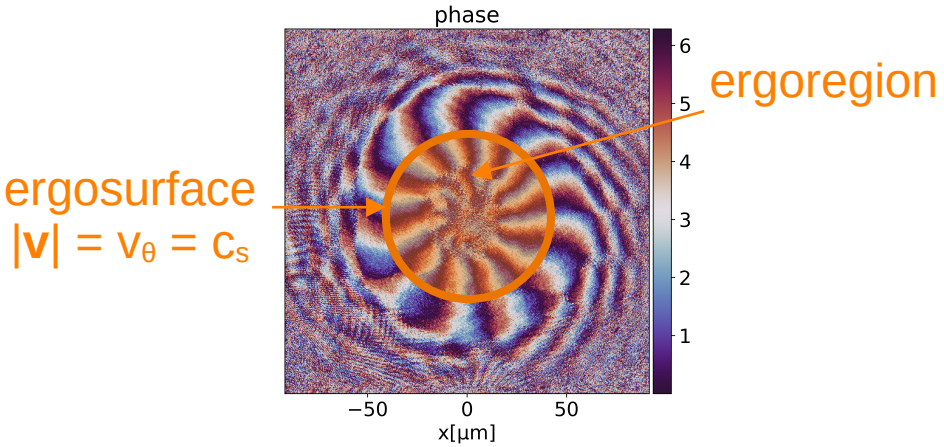
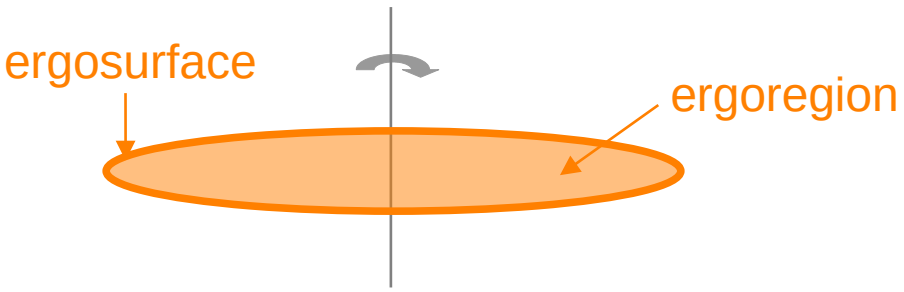


ergosurface
$|\mathbf{v}| = v_\theta = c_s$

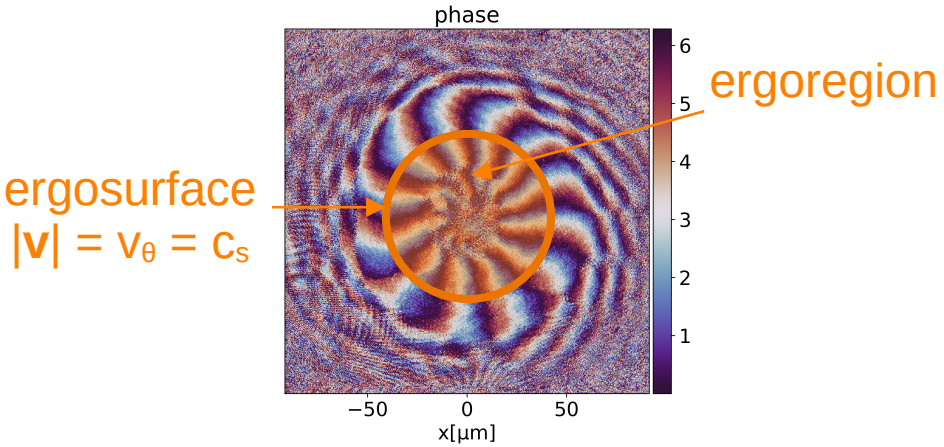


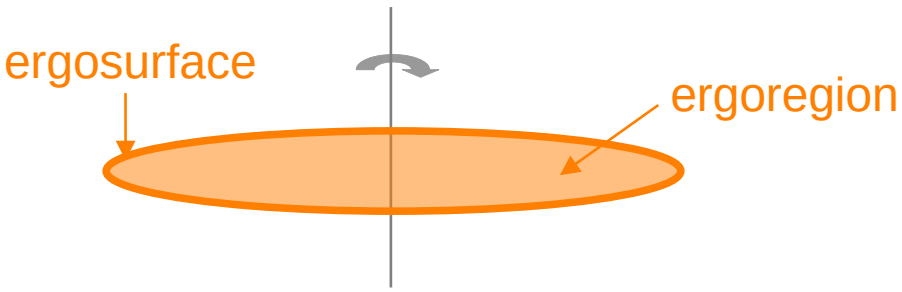
Superradiance in a polariton vortex flow





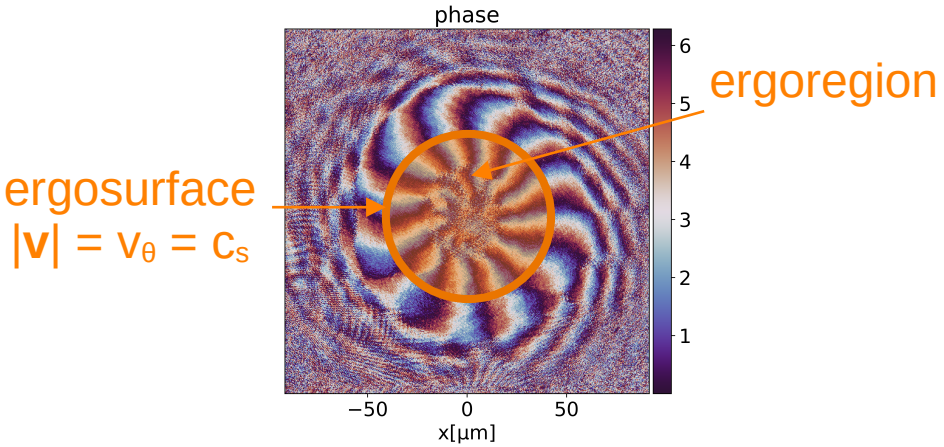
Superradiance in a polariton vortex flow

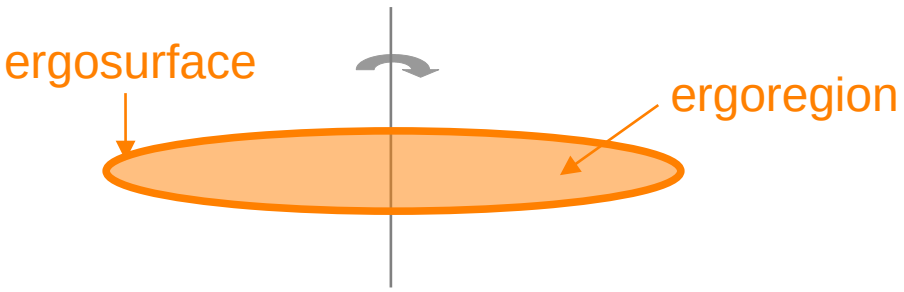




Superradiance: scattering of
scalar field at the ergosurface

Superradiance in a polariton vortex flow





Superradiance in polaritons: scattering of **Bogolioubov excitations** at the ergosurface

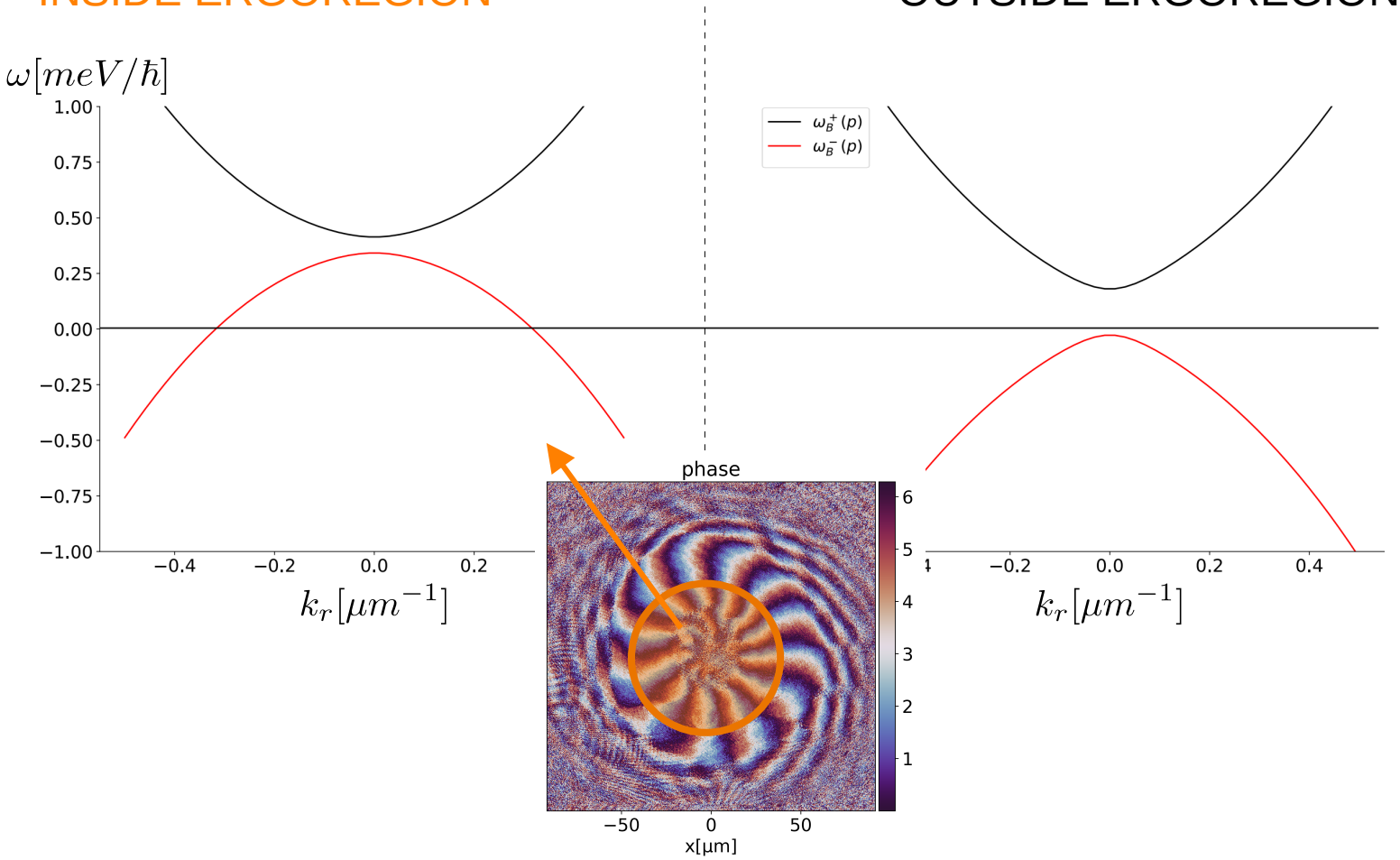
$$\psi = \psi_0 + \delta\psi$$

Superradiance: scattering of **scalar field** at the ergosurface

Bogolioubov excitations on top of the vortex

INSIDE ERGOREGION

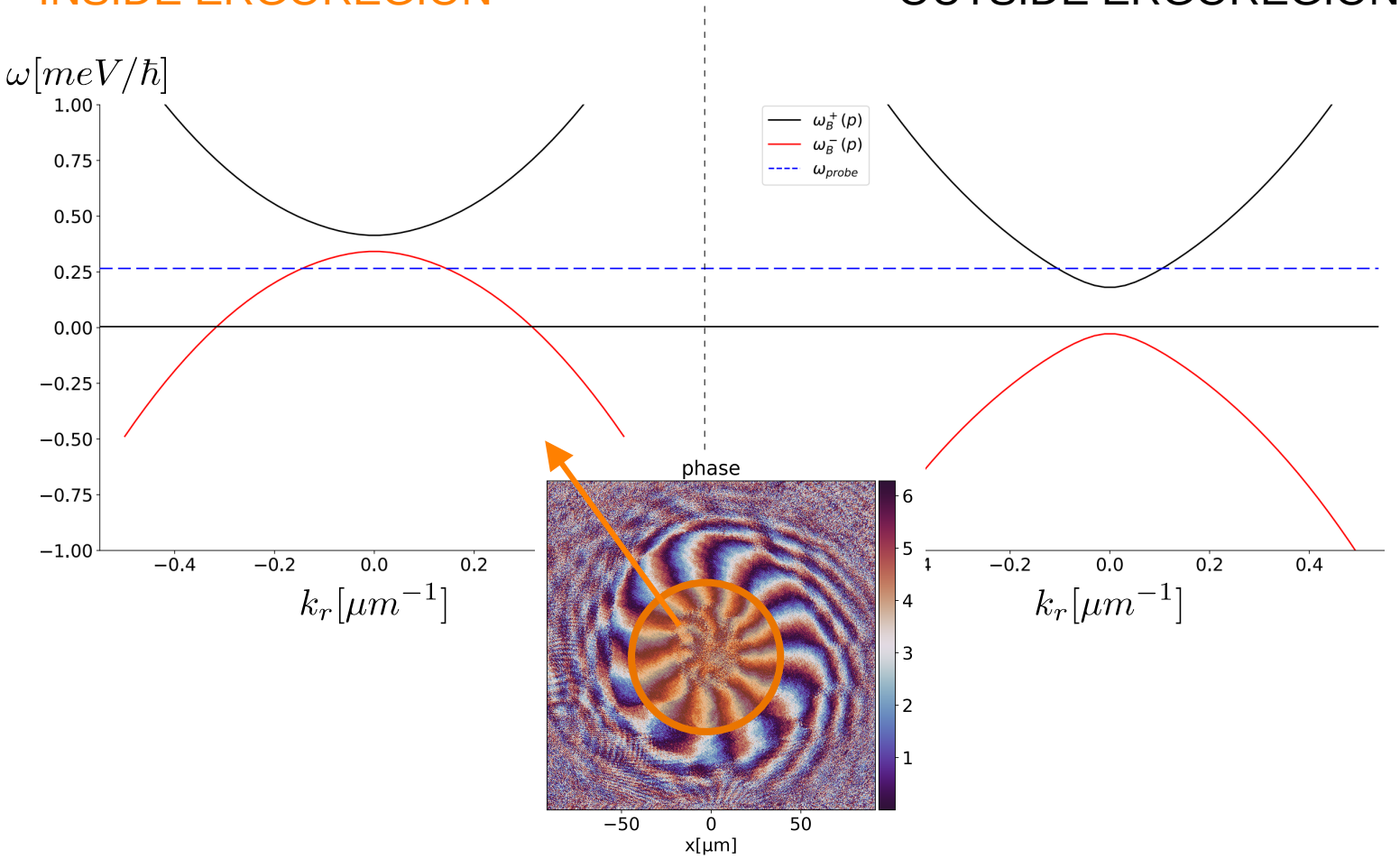
OUTSIDE ERGOREGION



Superradiant conditions

INSIDE ERGOREGION

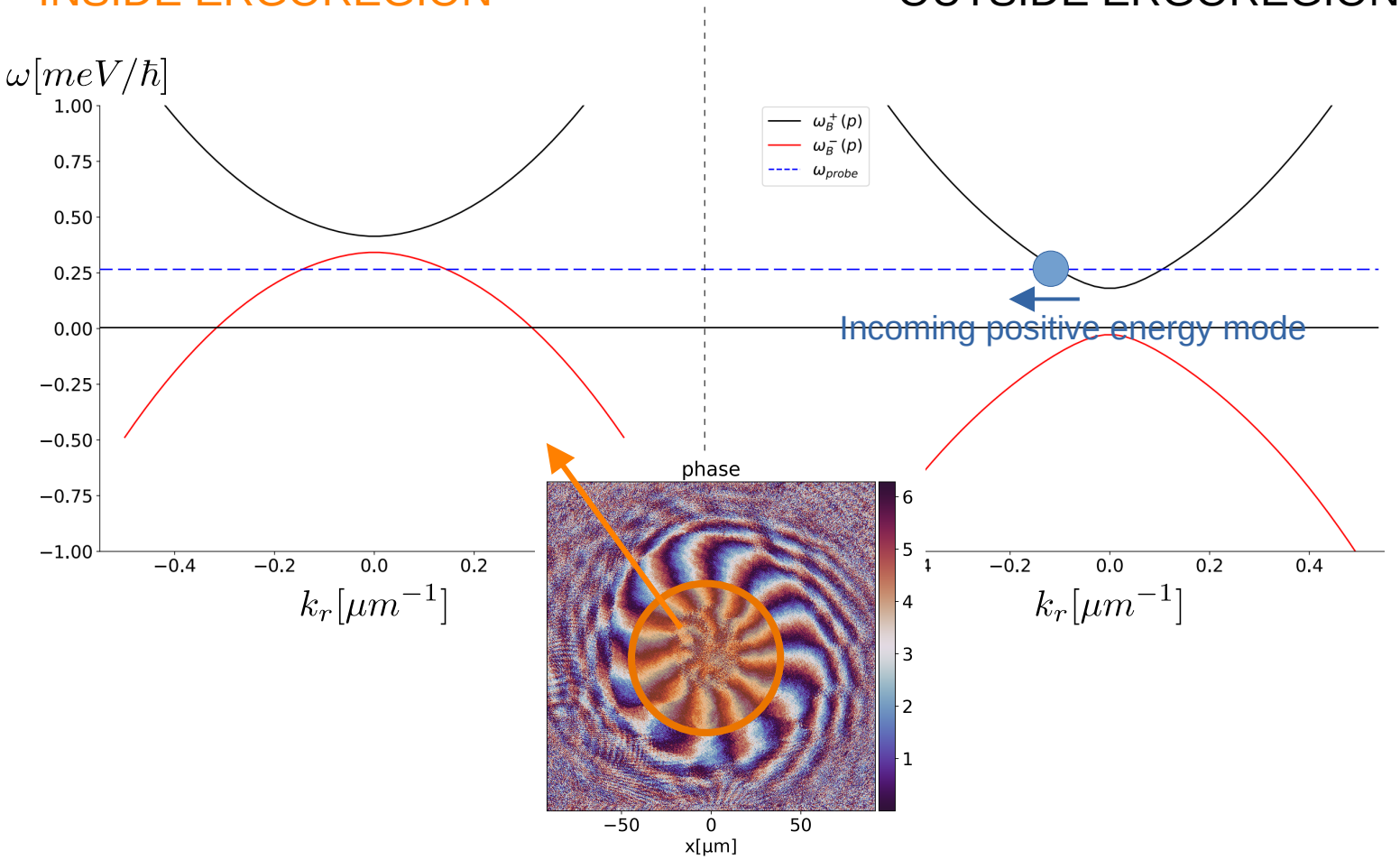
OUTSIDE ERGOREGION



Stimulated (classical) superradiance

INSIDE ERGOREGION

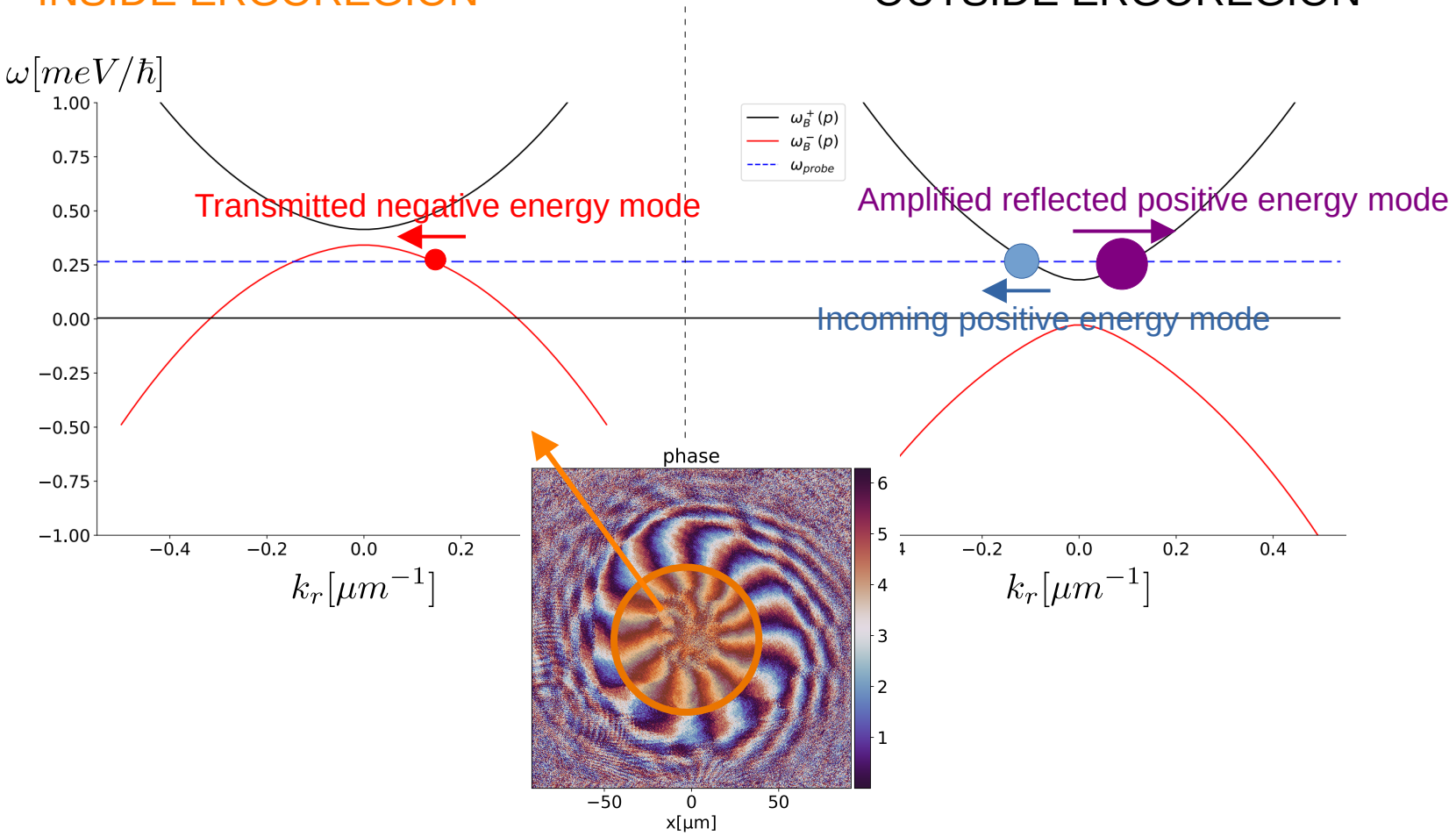
OUTSIDE ERGOREGION



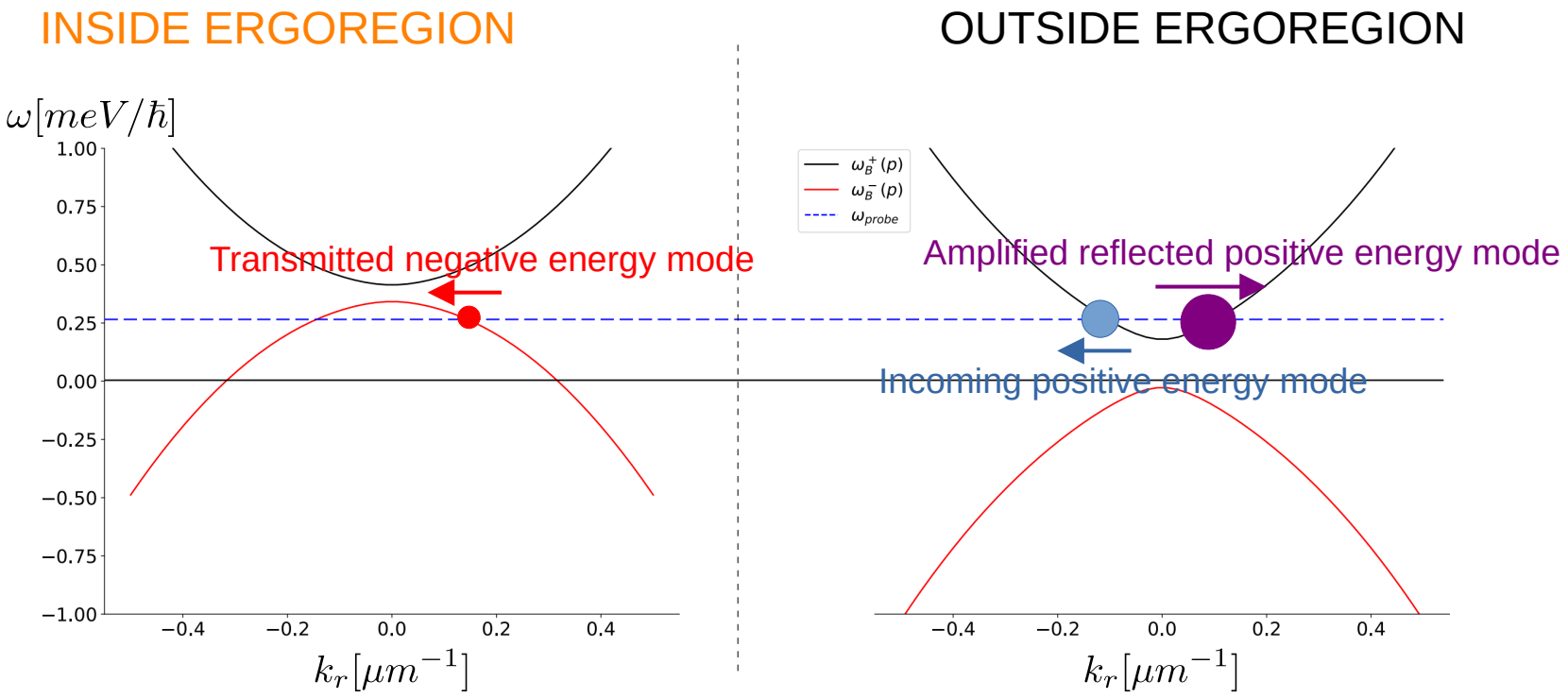
Stimulated (classical) superradiance

INSIDE ERGOREGION

OUTSIDE ERGOREGION



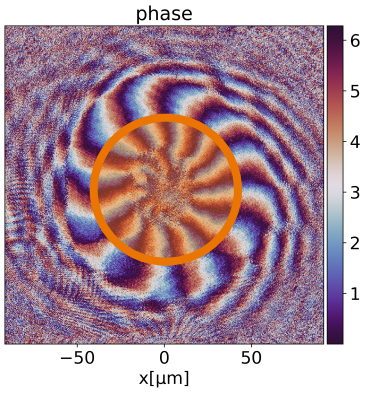
Stimulated (classical) superradiance



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 for the generation of ergosurface



What next ?

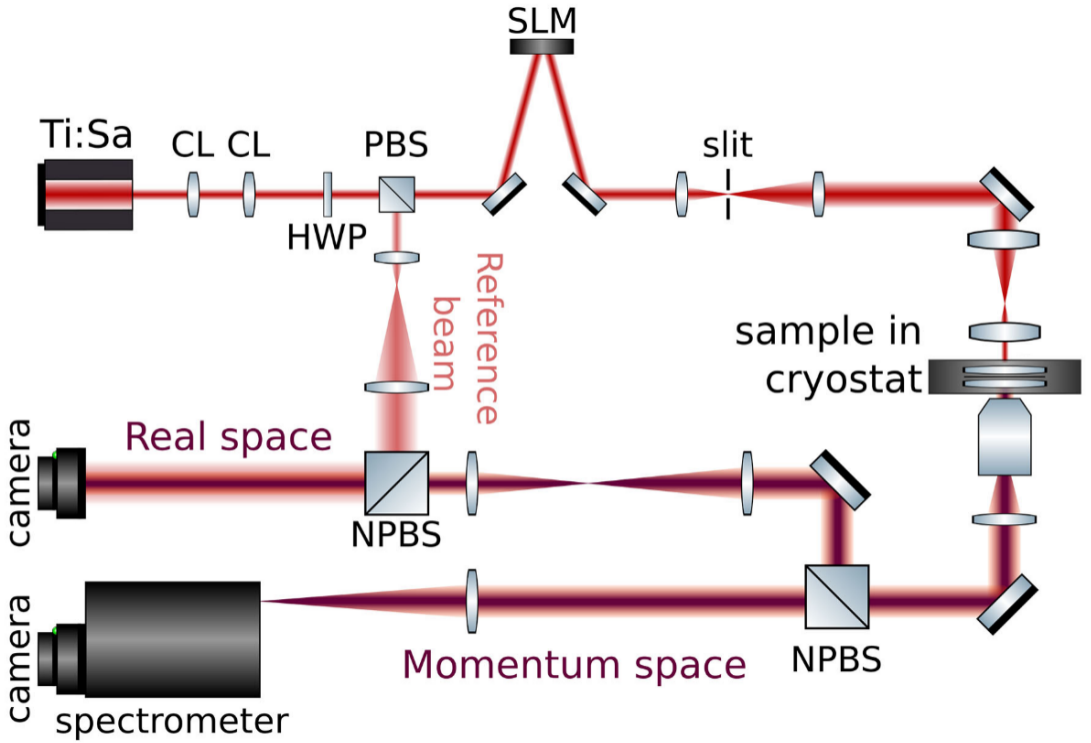
- Stimulated superradiance with recently implemented spectroscopy method
- Long term: study correlations and entanglement of the scattered modes

Jacquet *et al.* Phil. Trans. Roy. Soc. **378** 2020
Jacquet *et al.* PRL **130** 2023, EPJD **76** 2022
F. Claude *et al,* PRL 2022

Thanks to the team!

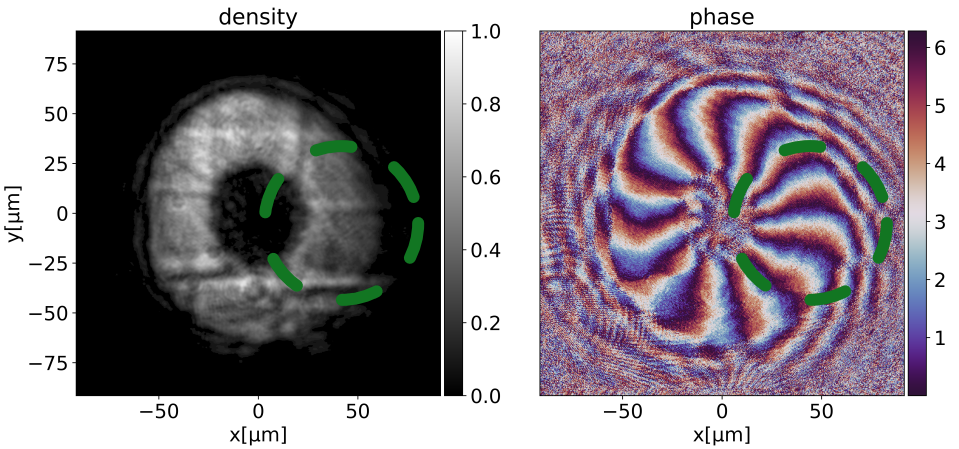
Thank you!

Generating flows in a polariton fluid

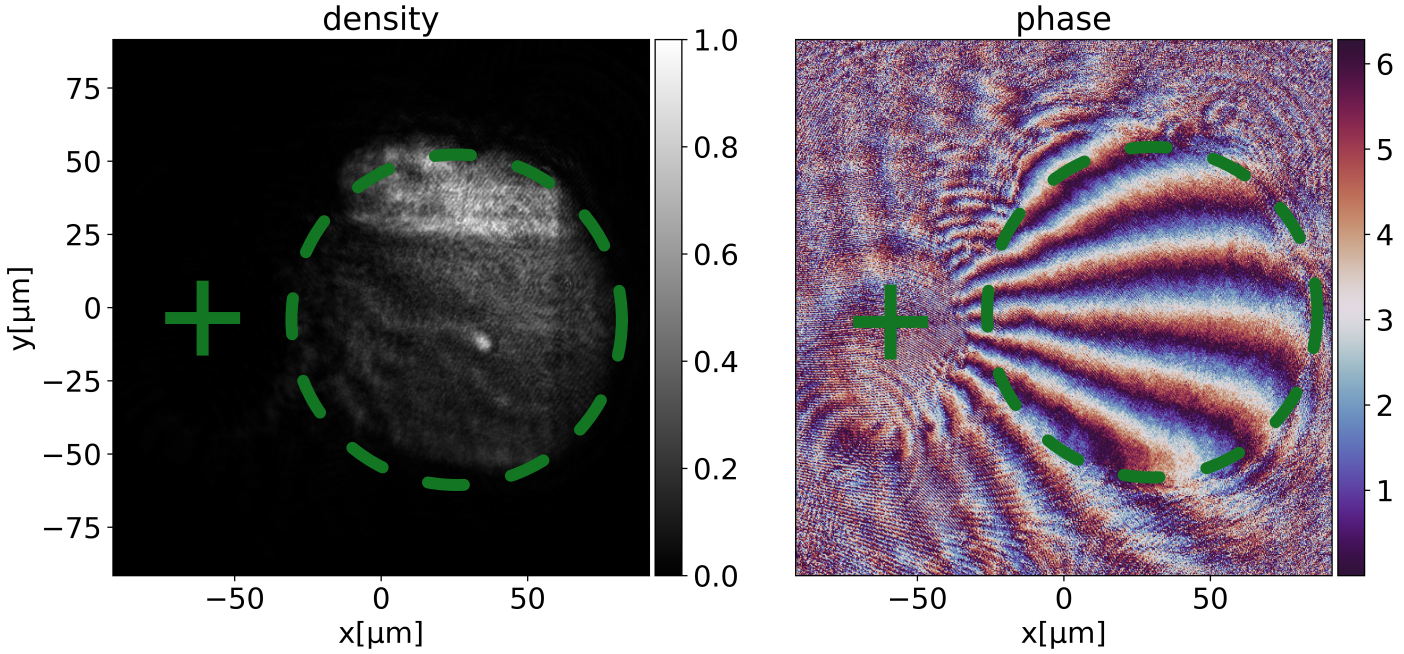


$$D = 0, C = 12$$

$$\boldsymbol{\nabla}\phi_{SLM} = \frac{12}{r}\boldsymbol{u_\theta}$$

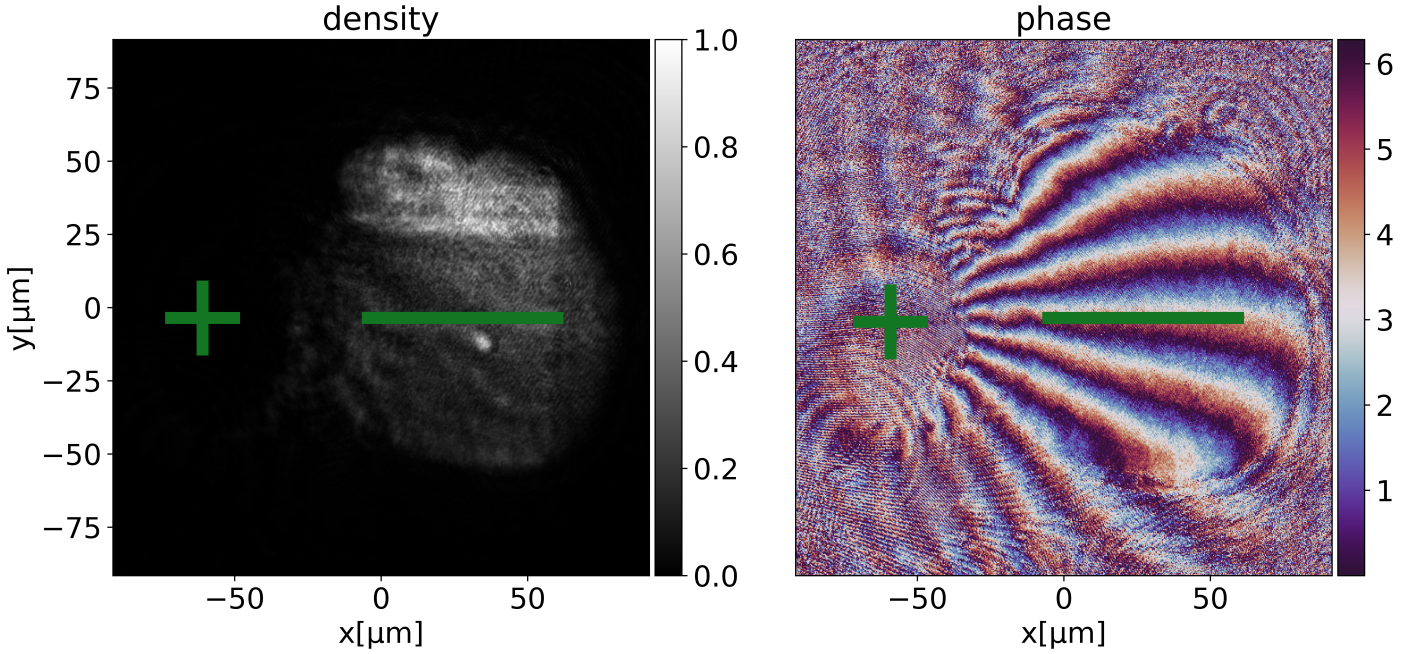


Vortex edge configuration



About 90μm of high density background flow

Vortex edge configuration



$$E = E^0 + \frac{1}{2} \sum_{w,k} \hbar\omega < \delta\psi | \sigma_3 | \delta\psi >$$