
Winter school analogue gravity/cosmology in Benasque 7th - 17th January 2026

# Investigating rotational superradiance in a fluid of light

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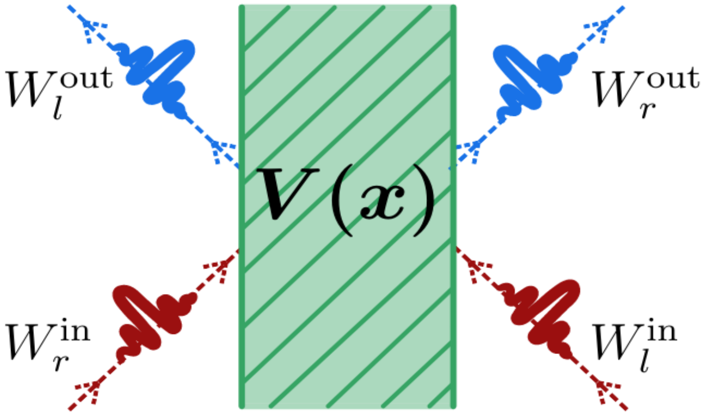
TUG 2025

# Superradiant scattering

Delhom, Guerrero *et al.*, *PRD* **109** 105024 (2024)




Wave packet scattering by a time-independent potential

$$\psi_{t\to-\infty} = W_l^{in} + W_r^{in} \xrightarrow{time} \psi_{t\to\infty} = W_l^{out} + W_r^{out}$$

Bosonic field → Noether charge conserved

$$\mathrm{Q}(\phi)_{KG} = i/\hbar \int dx(\phi^*\pi_\phi - \pi_\phi^*\phi) \;\rightarrow\; 1 = \left||T|^2 - |R|^2\right|$$

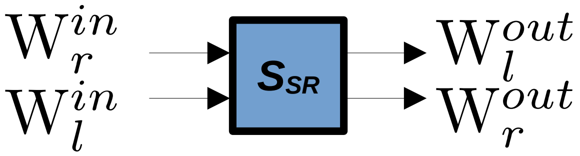
Wave packet scattering

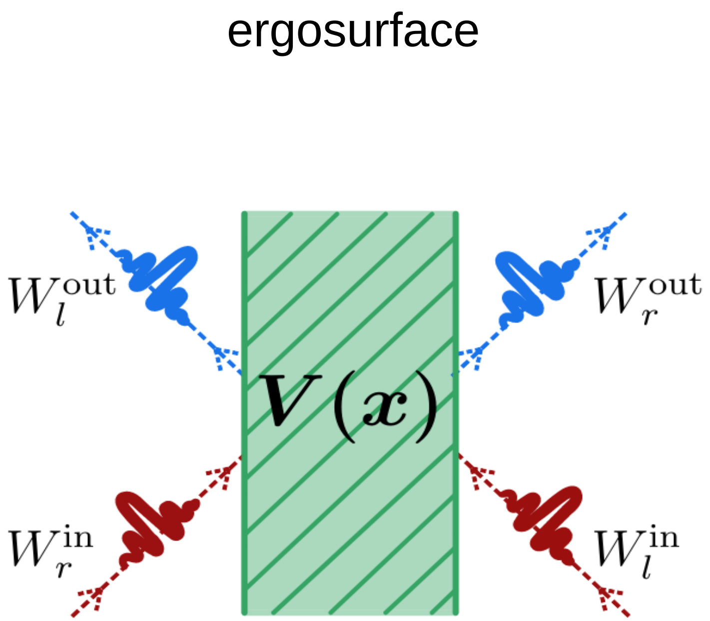
$$\left(W_r^{in}, W_l^{in}\right)_{t\to\infty} = \left(W_r^{out}, W_l^{out}\right)\cdot B \qquad \mathrm{B}=\begin{pmatrix} T & r \\ R & t \end{pmatrix}$$

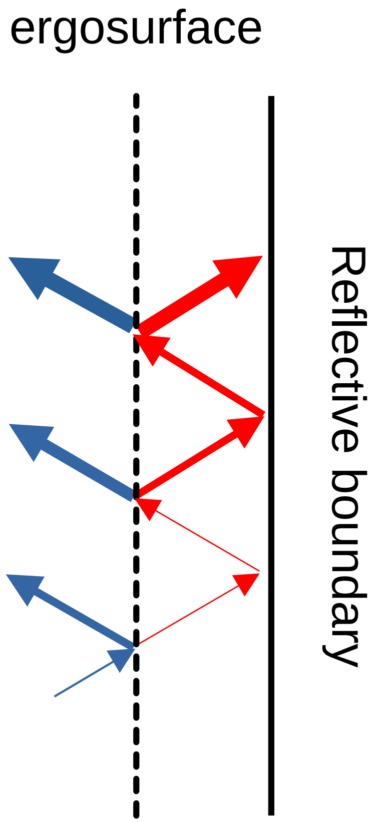
$$\mathrm{T},\ \mathrm{r},\ \mathrm{R},\ \mathrm{t} \in \mathbb{C}$$

*W* of same frequency but different sign(*Q*) + B non-unitary → amplification == superradiant scattering

Amplification <=> squeezing





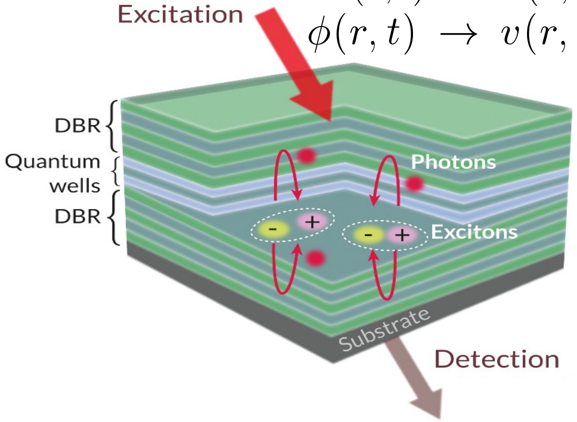

Amplification → energetic instability

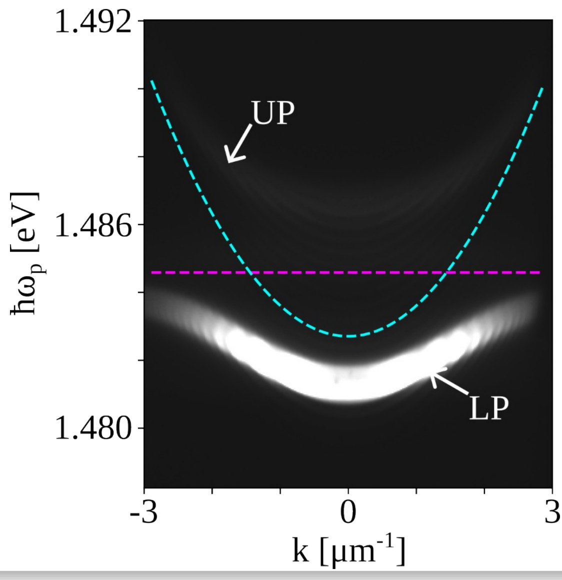
Amplitude growth → dynamical instability

# Microcavity polaritons

Carusotto and Ciutti RMP **85** 299 (2013)

$$\mathrm{I}(r,t) \to n(r,t)$$
$$\phi(r,t) \to v(r,t)$$




cavity photon
→ effective mass

exciton
→ interactions

Polaritons= photons dressed with material excitations that live in the cavity plane

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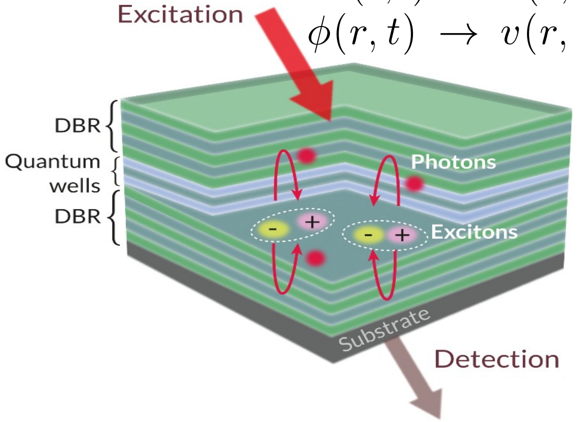


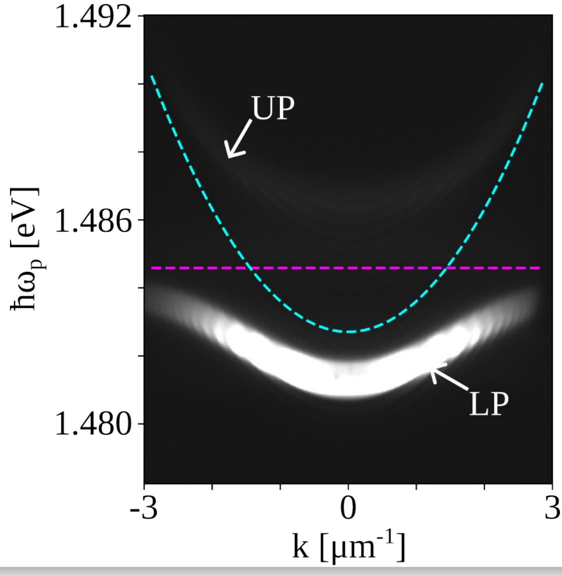


cavity photon
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Polaritons= photons dressed with material excitations that live in the cavity plane

**Dynamics in the cavity plane** described by Gross-Pitaevskii (Nonlinear Schrödinger) equation:

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2\nabla^2}{2m^*_{LP}} + g\underbrace{n}_{|\psi|^2}\right)\psi - \frac{i\hbar\gamma}{2}\psi + P(r,t)$$

**Driven-dissipative dynamics → Out-of-equilibrium system**

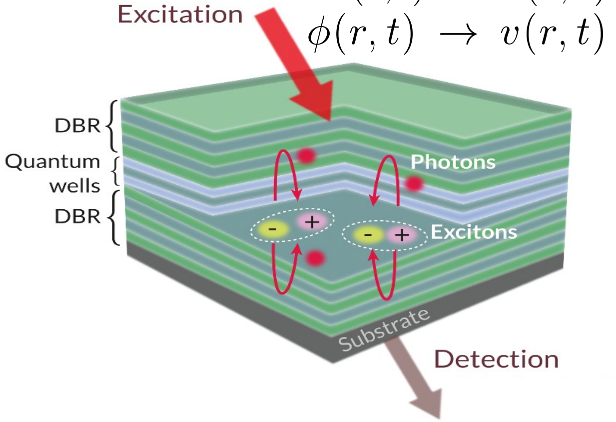
$g$ polariton-polariton interaction constant
$\gamma$ Losses
P pump

# Microcavity polaritons

Carusotto and Ciutti RMP **85** 299 (2013)

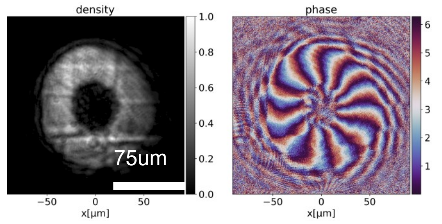
$I(r,t) \rightarrow n(r,t)$
$\phi(r,t) \rightarrow v(r,t)$

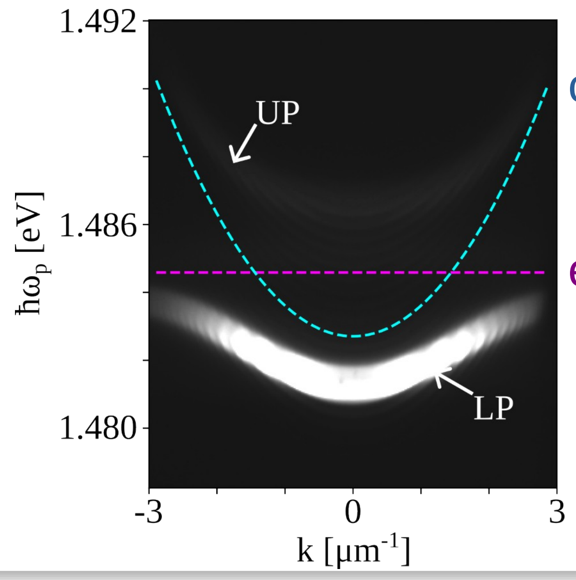
SLM to control phase and mode of pump




Imaging photons leaking out of the cavity

$n(r,t) \rightarrow I(r,t)$   $v(r,t) \rightarrow \phi(r,t)$




cavity photon
→ effective mass

exciton
→ interactions

Polaritons= photons dressed with material excitations that live in the cavity plane

**Dynamics in the cavity plane** described by Gross-Pitaevskii (Nonlinear Schrödinger) equation:

$|\psi|^2$

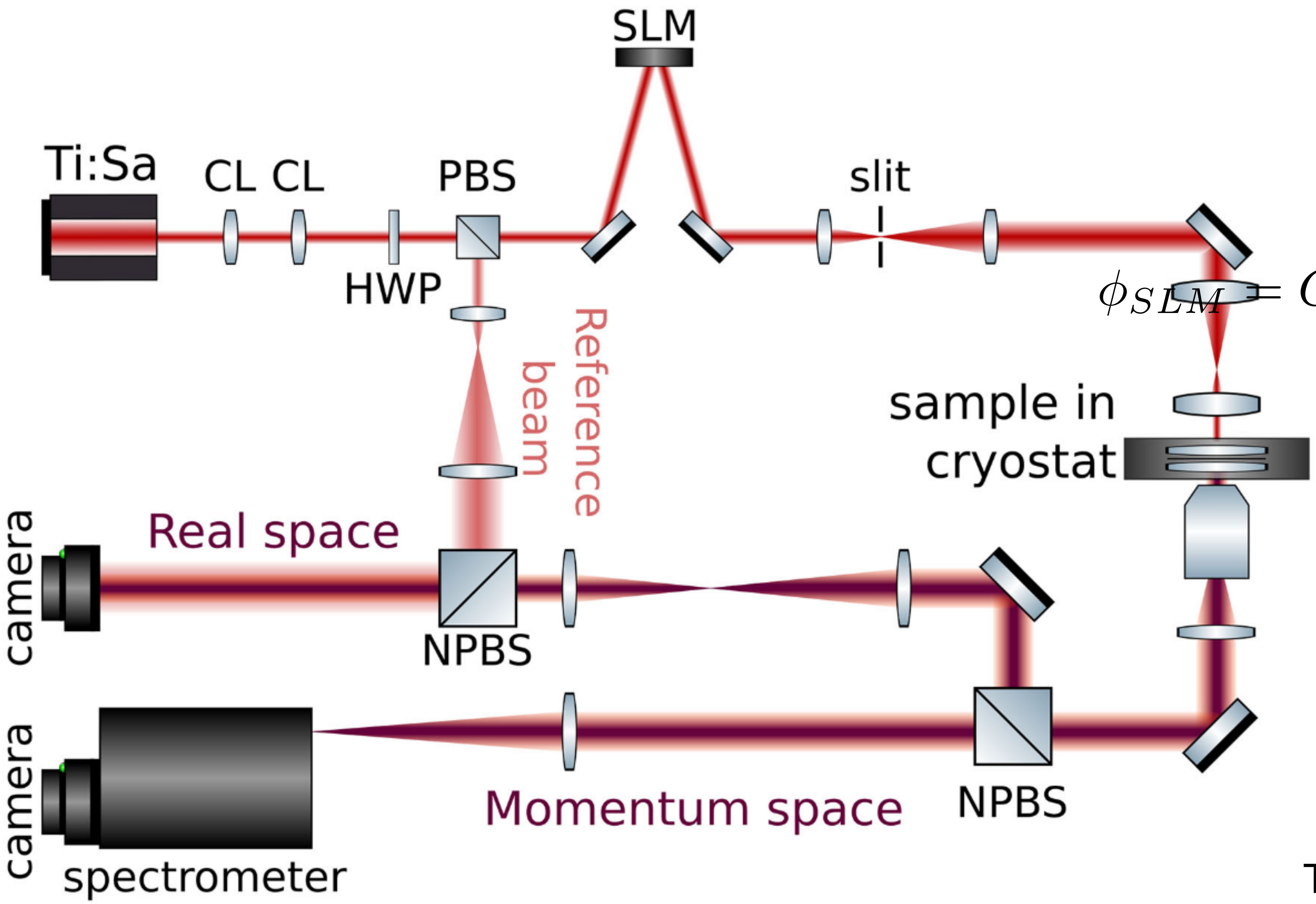
$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2\nabla^2}{2m^*_{LP}} + gn\right)\psi - \frac{i\hbar\gamma}{2}\psi + P(r,t)$$

**Driven-dissipative dynamics → Out-of-equilibrium system**

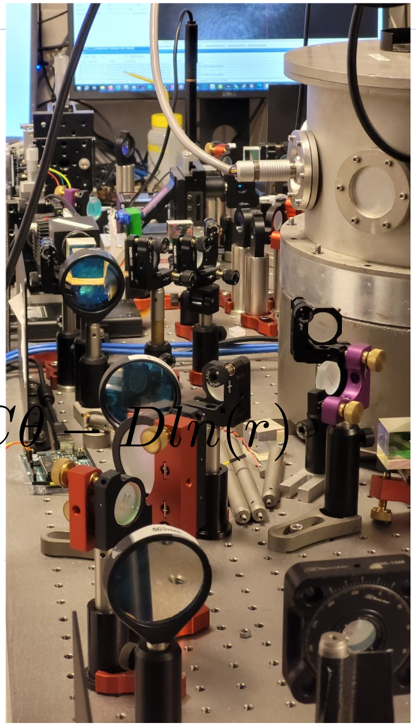
$g$ polariton-polariton interaction constant
$\gamma$ Losses
$P$ pump

Our sample: DBR GaAs, QW InGaAs, $Q$ = 3000, T=4K, $\hbar\gamma/2 = 90\mu eV$

# Experimental scheme




$\phi_{SLM} = C\theta - D\ln(r)$



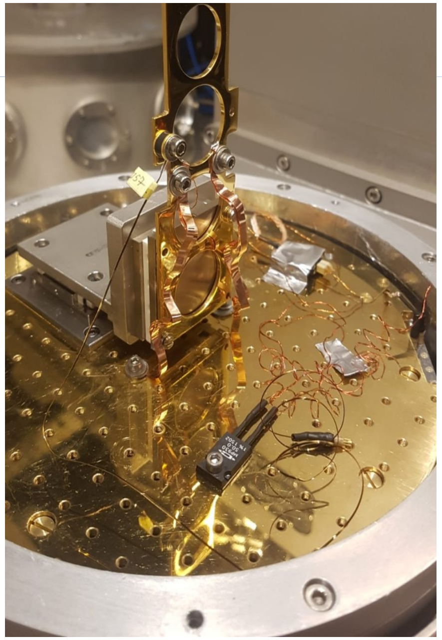


Image SLM plane on cavity plane
→ control of phase $k_p$ of beam

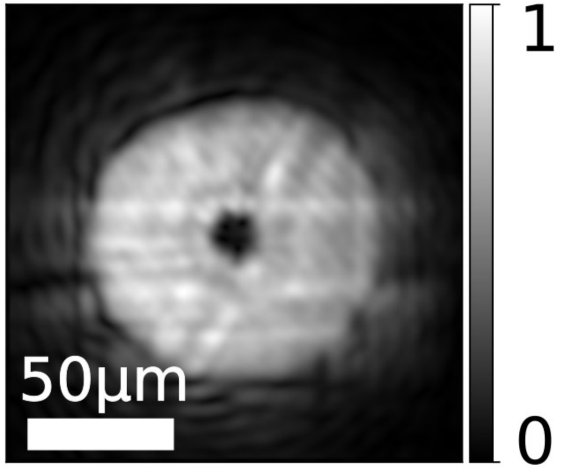
$$F_{laser} e^{i(C.\theta - \omega_{laser} t)}$$

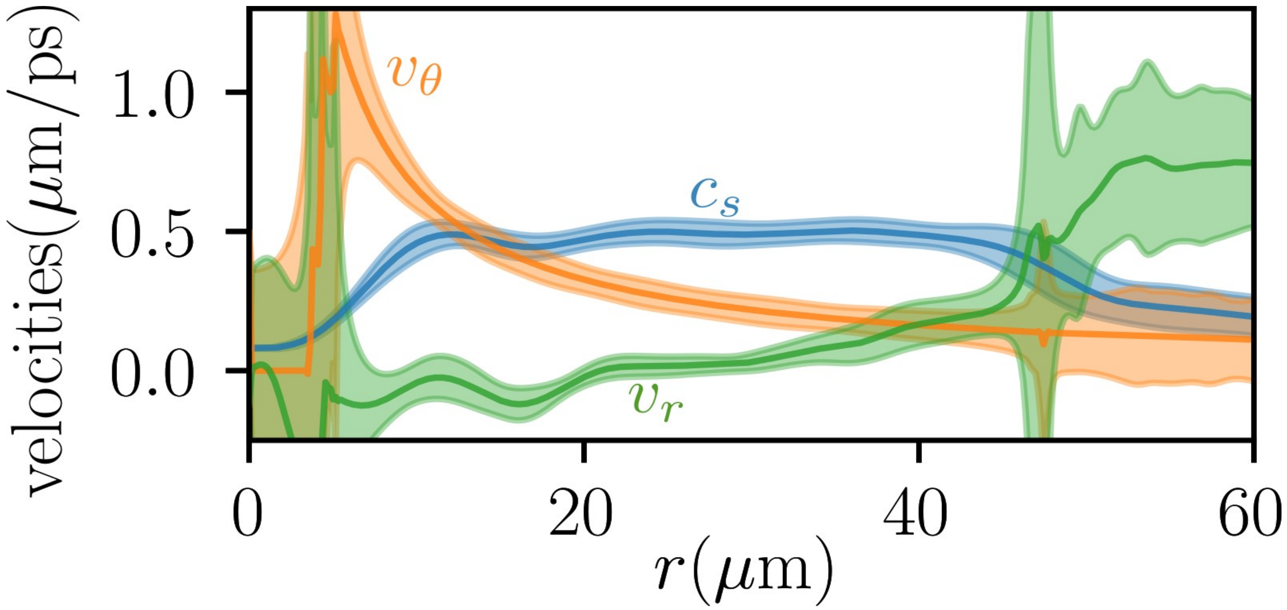
Target velocity profile: purely azimuthal flow

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

# Experimental data : C = 4 vortex

Target velocity profile: purely azimuthal flow $\boldsymbol{v} = \boldsymbol{\nabla}\phi_{SLM} = \frac{C}{r}\boldsymbol{u_\theta}$



# Experimental data : C = 4 vortex

Guerrero K *et al.*, arxiv 2025

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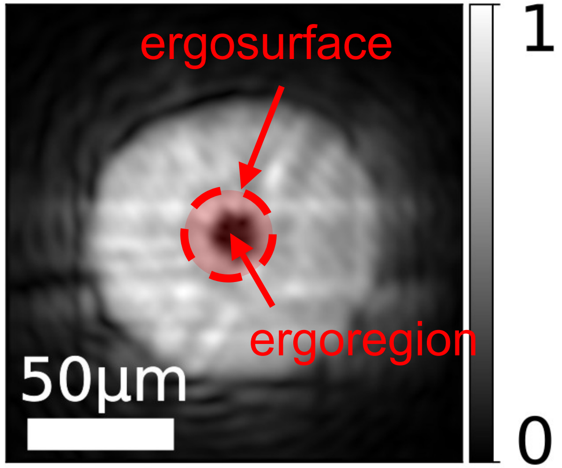


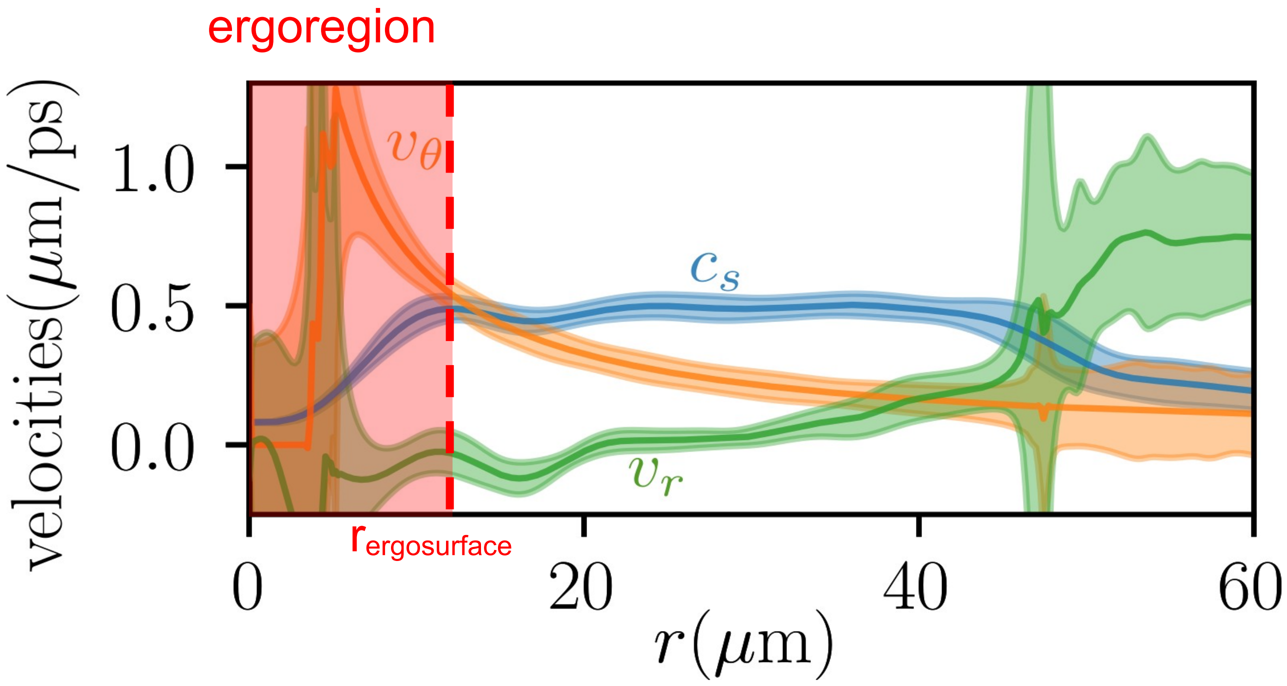

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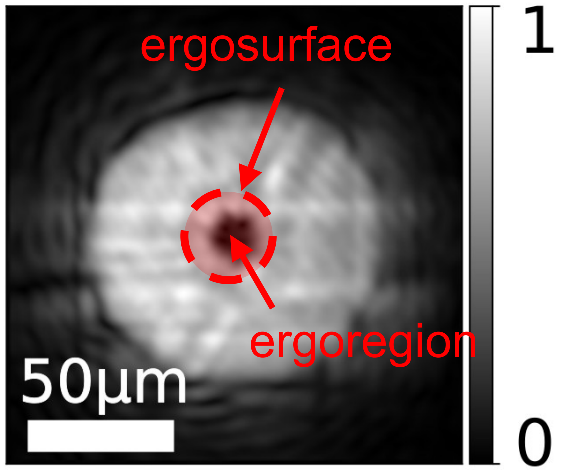
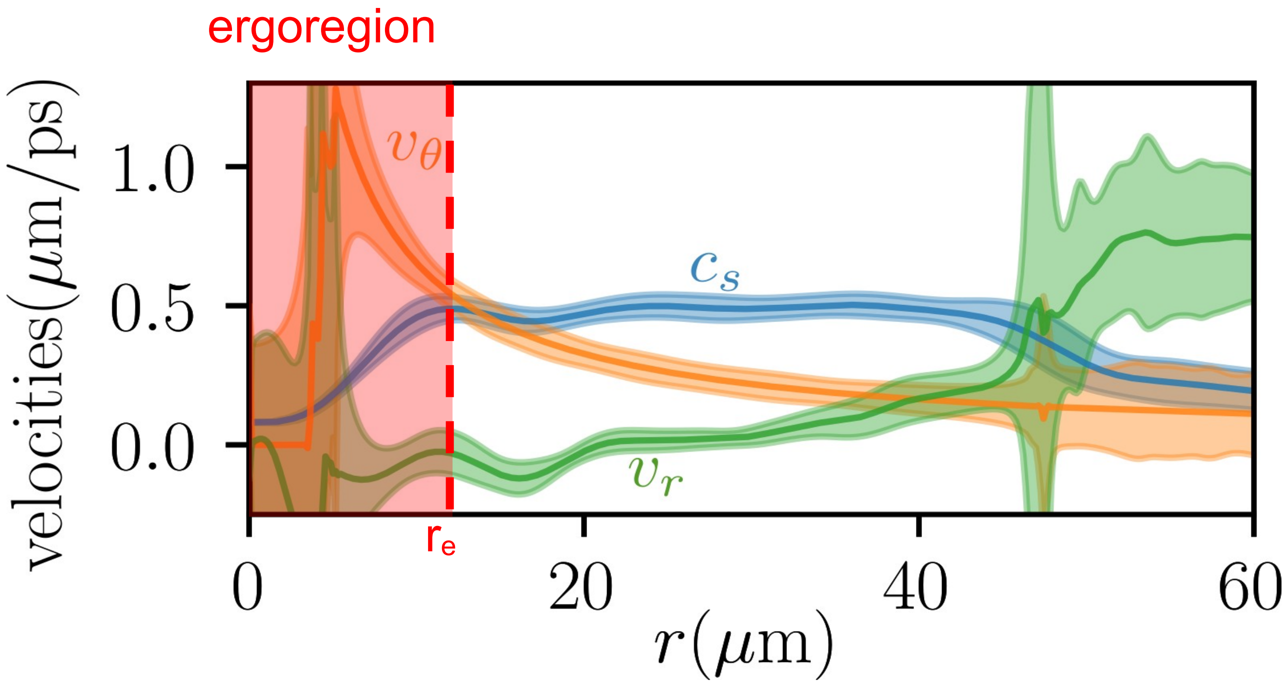


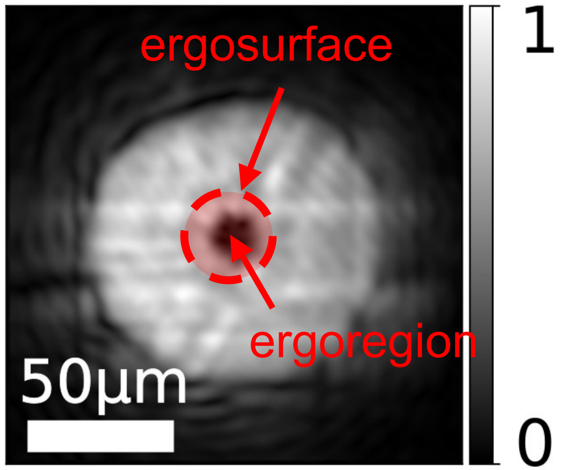



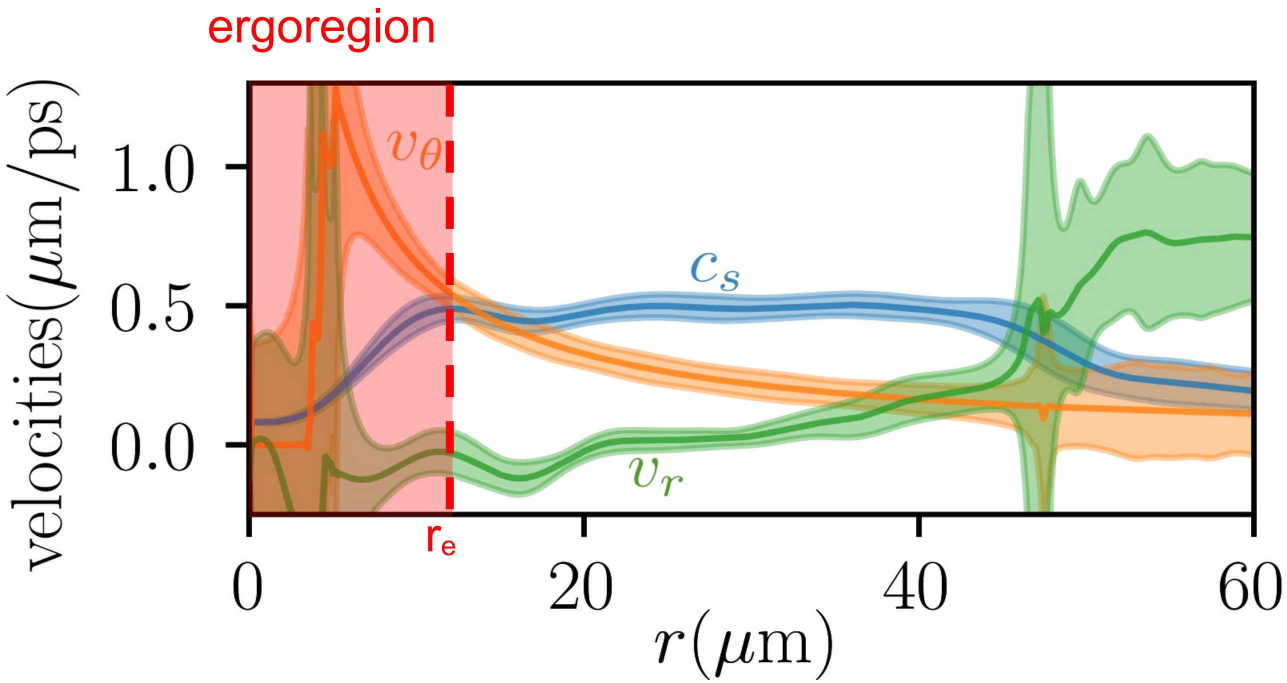

But… there is no horizon inside the ergosurface!
→ reflection at low *r*
→ dynamically unstable system with $\gamma_{sr}$

But… this is a steady-state image???

# Experimental data : C = 4 vortex

Target velocity profile: purely azimuthal flow $\boldsymbol{v} = \boldsymbol{\nabla} \phi_{SLM} = \frac{C}{r} \boldsymbol{u_\theta}$




$$i\hbar \frac{\partial \psi}{\partial t} = \left( -\frac{\hbar^2 \nabla^2}{2m^*_{LP}} + gn \right) \psi - \frac{i\hbar\gamma}{2} \psi + P(r, t)$$

$\boxed{\gamma > \gamma_{sr}}$

# Bogoliubov spectrum out of equilibrium

Falque K *et al.*, PRL **135** 023401 2025

GPE: $$i\hbar\frac{\partial\psi}{\partial t}=\left(-\frac{\hbar^2\nabla^2}{2m^*_{LP}}+gn\right)\psi-\frac{i\hbar\gamma}{2}\psi+P(r,t)$$

Linearise GPE around steady-state solution $\psi=(\sqrt{n_0}+e^{-\imath\gamma/2}\psi_1)e^{-i(\omega_p t+\phi_p r)}$

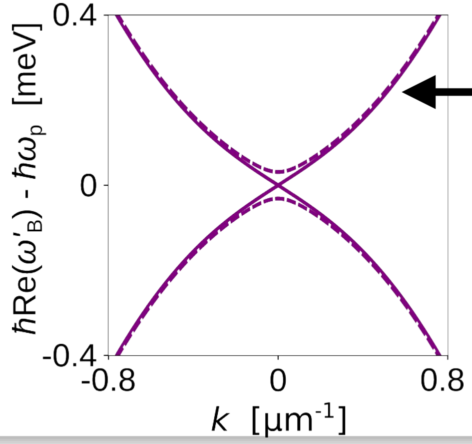
→ Bogoliubov – de Gennes dynamics for $\psi_1$

WKB dispersion relation $$\omega^{\pm}(k)=\pm\sqrt{(\underbrace{\alpha^2k^4}_{\text{nonlinearities}}+(k^2+\underbrace{m_{det}^2)c_s^2}_{\text{pump-dependent mass}}}$$

## Pump-dependent mass

$$\boxed{\mathrm{m}_{det}\propto\delta(0)-gn_0}$$

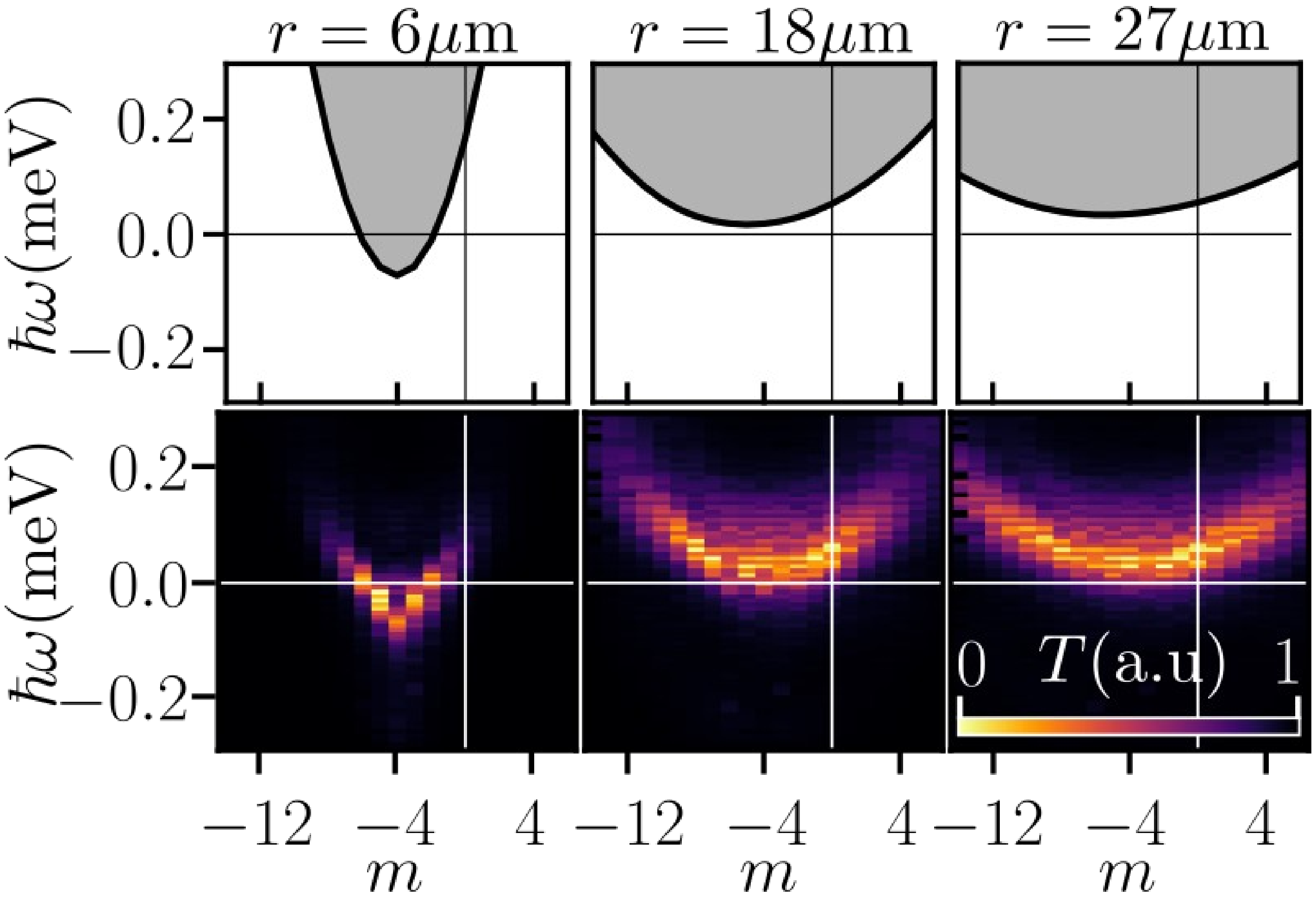
$$\left[\frac{1}{\sqrt{|\eta|}}\partial_\mu\sqrt{|\eta|}\eta^{\mu\nu}\partial_\nu-\frac{(m_{\text{det}})^2}{\hbar^2}\right]\psi_1=0$$




positive-norm modes

Guerrero K *et al.*, arxiv 2025

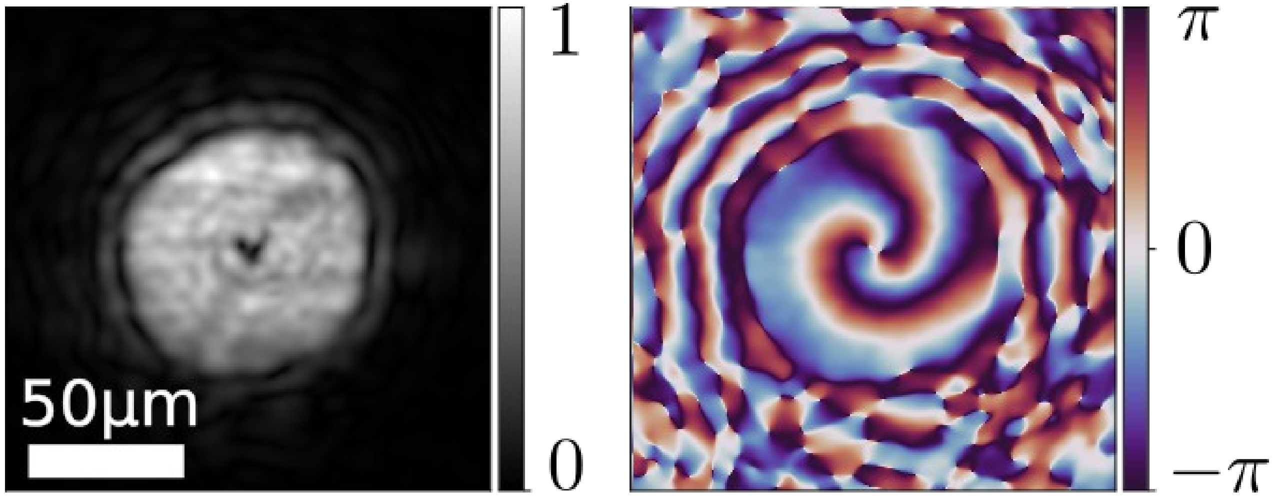
$$\omega^{\pm}(k) = \pm\sqrt{(\alpha^2 k^4 + (k^2 + m_{det}^2)c_s^2}$$

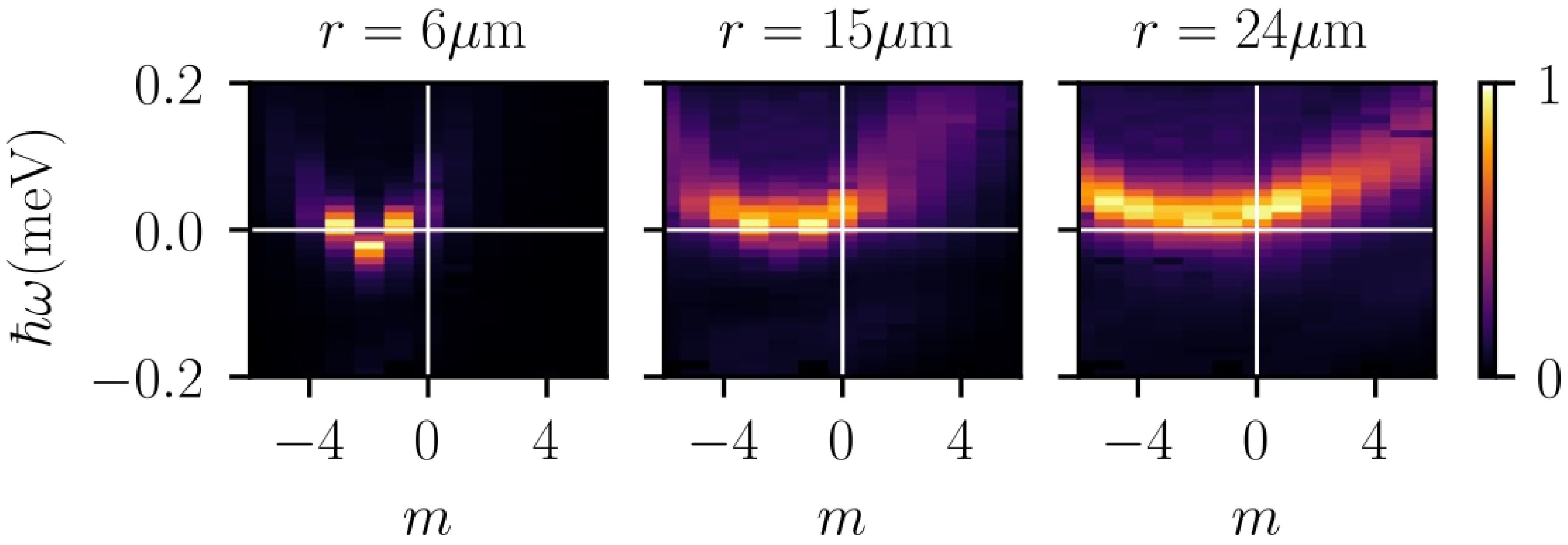


# Superradiant scattering in a C=2 vortex



Mean-field



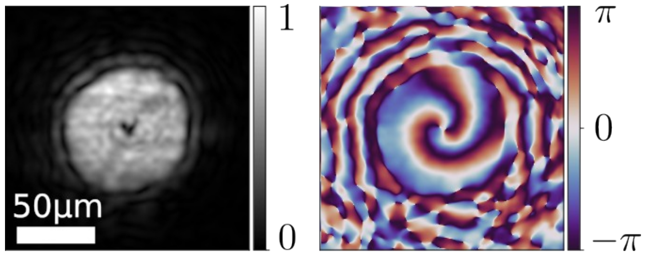



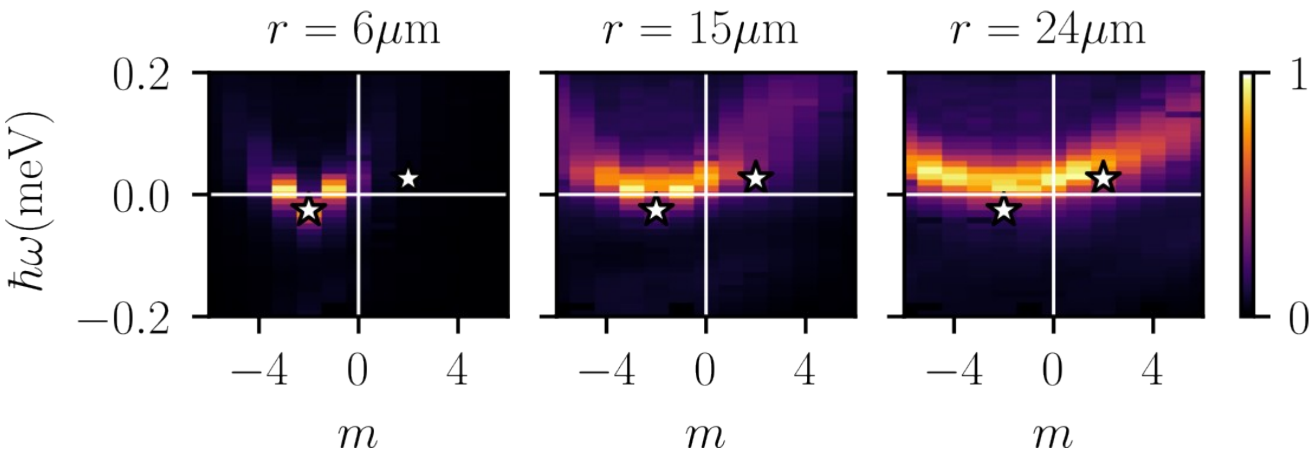
# Superradiant scattering in a C=2 vortex



Mean-field

Amplitude Phase



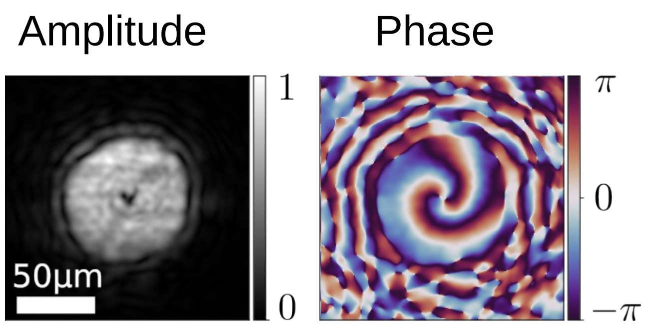

Global mode allowing superradiance $\delta\psi(r,t) = u(r)e^{i(2\theta-\omega_{\mathrm{scat}}t)} + v(r)^* e^{-i(2\theta-\omega_{\mathrm{scat}}t)}$

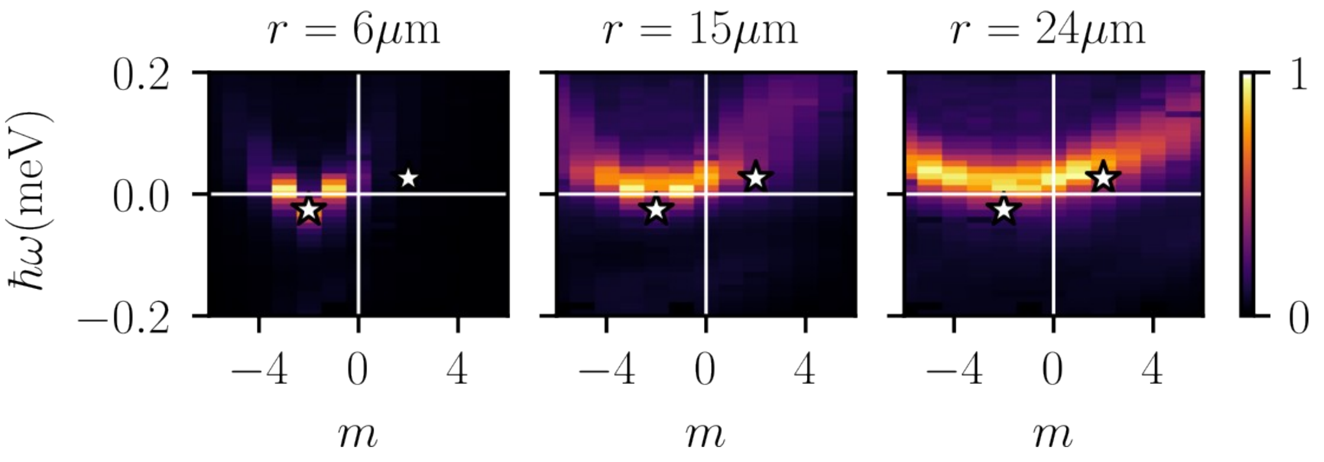
$(m, \omega_{\mathrm{scat}})$ are conserved during propagation

# Superradiant scattering in a C=2 vortex

Preliminary experimental data

Mean-field

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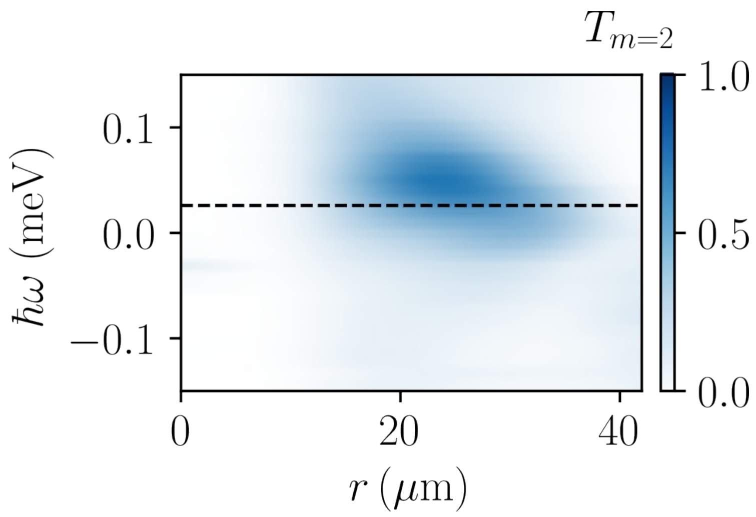
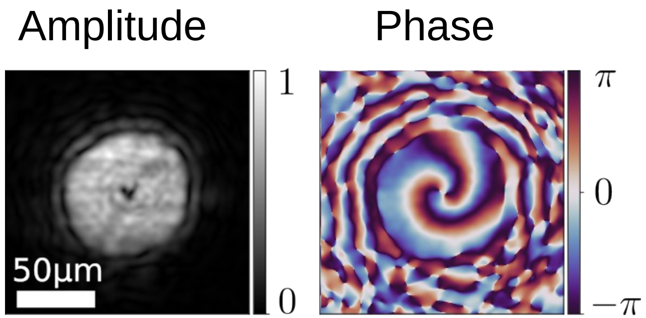
Transmission cut at m = 2

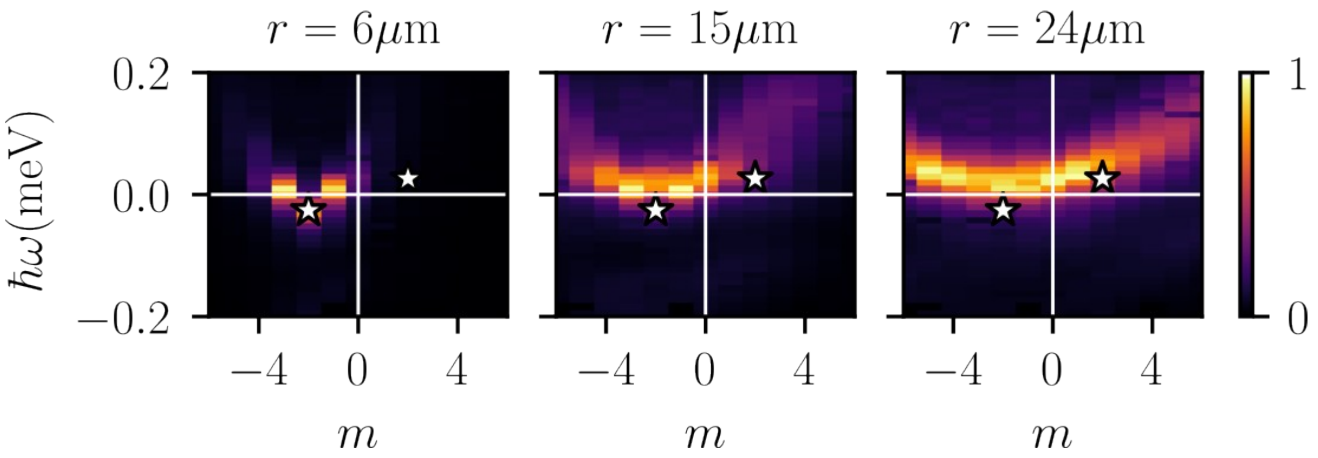


# Superradiant scattering in a C=2 vortex

Preliminary experimental data

Mean-field

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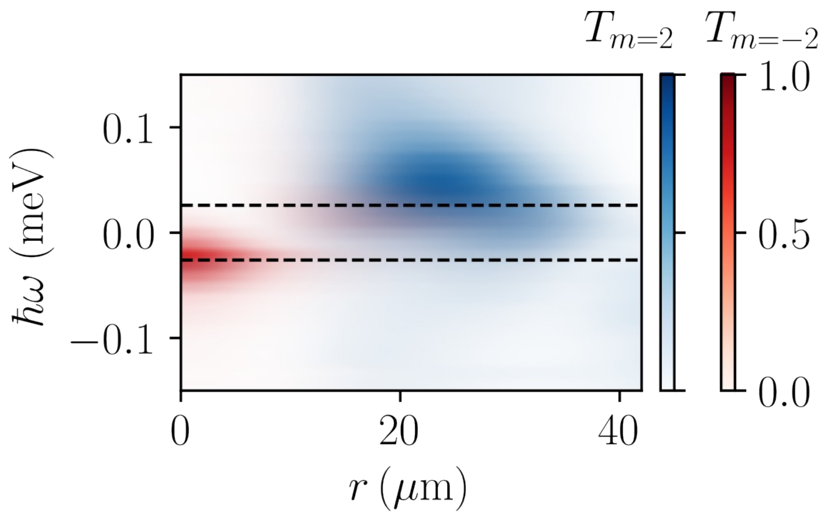
$(m, \omega_{\mathrm{scat}})$ are conserved during propagation

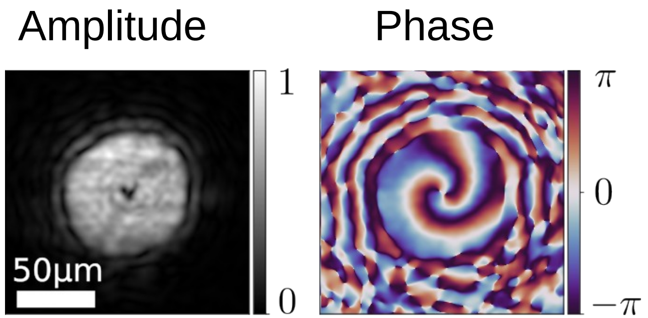
Transmission cut at m = 2 and m = -2



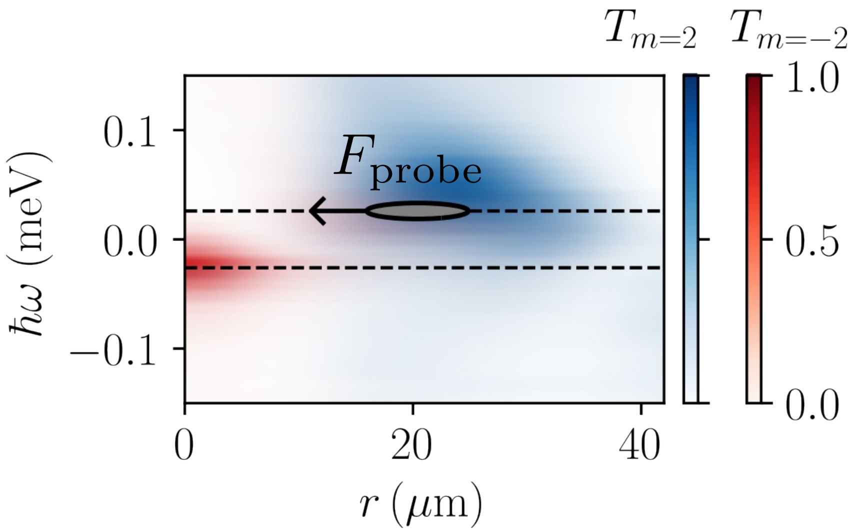
# Superradiant scattering in a C=2 vortex

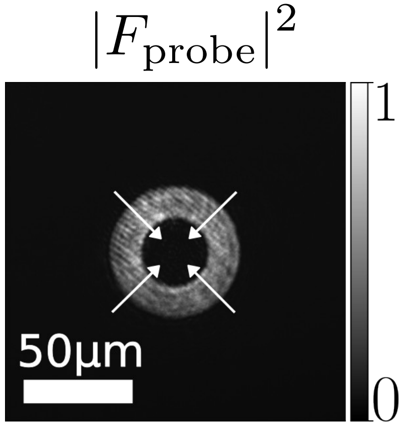


Mean-field




$$\begin{bmatrix} u(r) \\ v(r) \end{bmatrix} = -i \left[ \mathcal{L}_2 - \hbar\omega_{\mathrm{scat}} - i\frac{\hbar\gamma}{2} \right]^{-1} \begin{bmatrix} F_{\mathrm{pr}}(r) \\ F_{\mathrm{pr}}(r)^* \end{bmatrix}$$



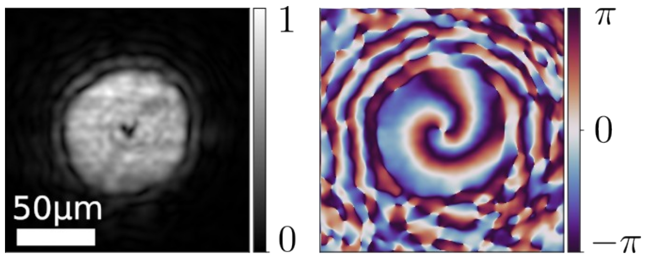



# Superradiant scattering in a C=2 vortex

Preliminary experimental data

Mean-field

Amplitude        Phase

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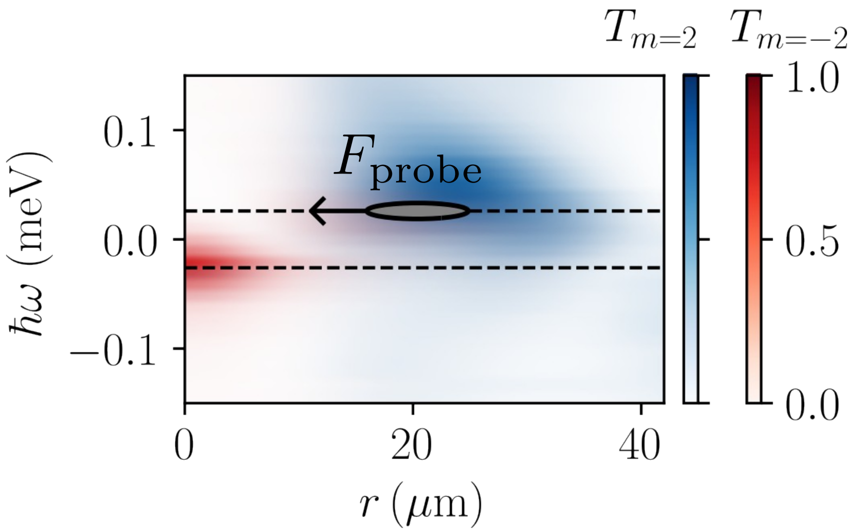
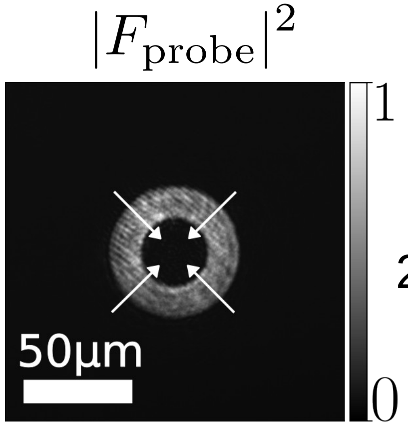
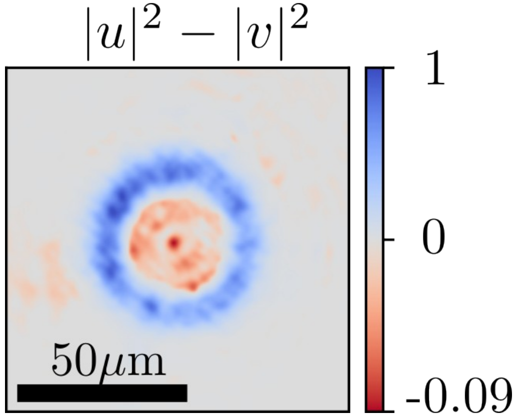



2D in plane dynamics




Transmission of negative energy inside the vortex core

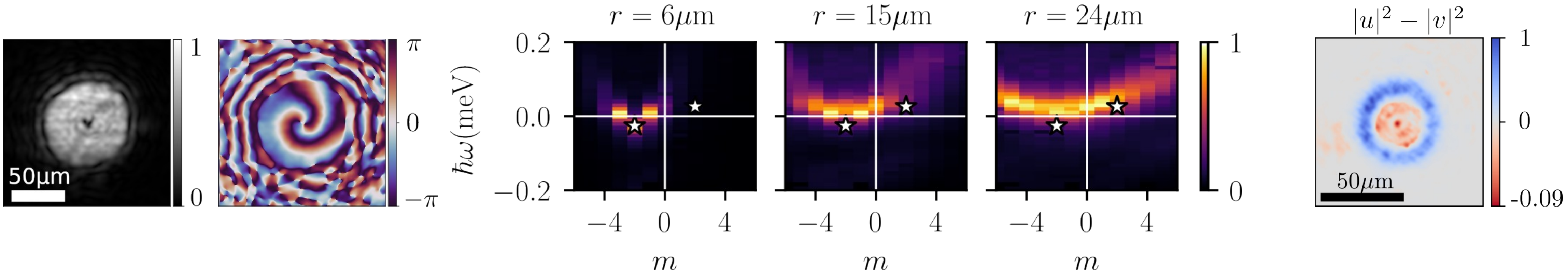
# Today

- Driven-dissipative dynamics → losses quench instability that does not develop
  → Stationary horizonless ergosurface

- Observation of spectrum → trapped negative energy waves inside the ergosurface

- Experimental data: scattering of probe field on ergosurface
  → observation of transmission to trapped negative energy wave
  → smocking gun of rotational superradiance

- What next?
  - quantitative analysis → reflection coefficient, dynamical instability rate?
  - Observation of correlations → entanglement ?




Winter school analogue gravity/cosmology in Benasque 7th - 17th January 2026

# Bogoliubov spectrum out of equilibrium

Falque K *et al.*, PRL **135** 023401 2025

Linearise GPE around steady-state solution $\psi = (\sqrt{n_0} + e^{-\imath\gamma/2}\psi_1)e^{-i(\omega_p t + \phi_p r)}$

→ Bogoliubov – de Gennes dynamics for $\psi_1$

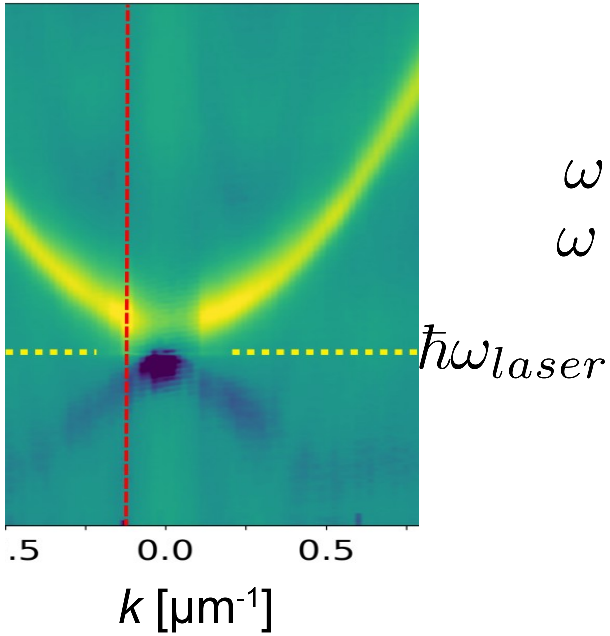
WKB dispersion relation $\omega^{\pm}(\delta k) = \pm\sqrt{(\alpha^2 k^4 + (k^2 + m_{det}^2)c_s^2} - \imath\frac{\gamma}{2}$

higher order derivatives

pump-dependent mass

spectral linewidth

Dispersion relation in fluid rest frame




$\omega > \omega_{laser}$ positive-norm mode

$\omega < \omega_{laser}$ negative-norm mode