Winter school analogue gravity/cosmology in Benasque in January 2026!

Experiments with fluids of light

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Effective spacetime in fluid flows

In a (quantum) fluid

Fluid velocity $\mathrm{v}=(\hbar/m)\boldsymbol{\nabla}\phi$ Speed of sound $c_s \propto \sqrt{\frac{g\rho_0}{m}}$

m – mass
g – interaction constant
ρ_0 – density

Wave eq for collective excitations of (super)fluid $\psi = \psi_0 + \epsilon_1\psi_1$

$$-\partial_t\left(\frac{\rho_0}{c_s^2}\left(\partial_t\rho_1 + \boldsymbol{v_0}\boldsymbol{\nabla}\rho_1\right)\right) + \boldsymbol{\nabla}\left(\rho_0\boldsymbol{\nabla}\rho_1 - \frac{\rho_0\boldsymbol{v_0}}{c_s^2}\ \partial_t\rho_1 + \boldsymbol{v_0}\boldsymbol{\nabla}\rho_1)\right) = 0$$

Relavistic form of wave eq for collective excitations: $\Delta\rho_1 = \frac{1}{\sqrt{-\eta}}\partial_\mu\left(\sqrt{-\eta}\eta^{\mu\nu}\partial_\nu\rho_1\right) = 0$

with $$\eta_{\mu\nu} = \begin{pmatrix} -(c_s^2 - \boldsymbol{v_0}^2) & -v_o^x & -v_o^y \\ -v_o^x & 1 & 0 \\ -v_o^y & 0 & 1 \end{pmatrix}$$

Motion of collective excitations in inhomogeneous fluid flow ↔ scalar field on curved spacetime

Control parameters: $\boldsymbol{v_0}$, $\boldsymbol{c_s}$

Unruh *PRL* **46** 1351 (1981), Visser *Class Quant Grav* **15** 1767 (1998)

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Possible geometries with $$\eta_{\mu\nu} = \begin{pmatrix} -(c_s^2 - \boldsymbol{v_0}^2) & -v_o^x & -v_o^y \\ -v_o^x & 1 & 0 \\ -v_o^y & 0 & 1 \end{pmatrix}$$

(i) accelerating flow along 1 spatial dimension → static 1D spacetime
Horizon where $\mathrm{v}_0 = c_s$

(ii) radially accelerating flow in 2 spatial dimensions → static spherically symmetric 2D spacetime
Horizon where $\mathrm{v}_r = c_s$

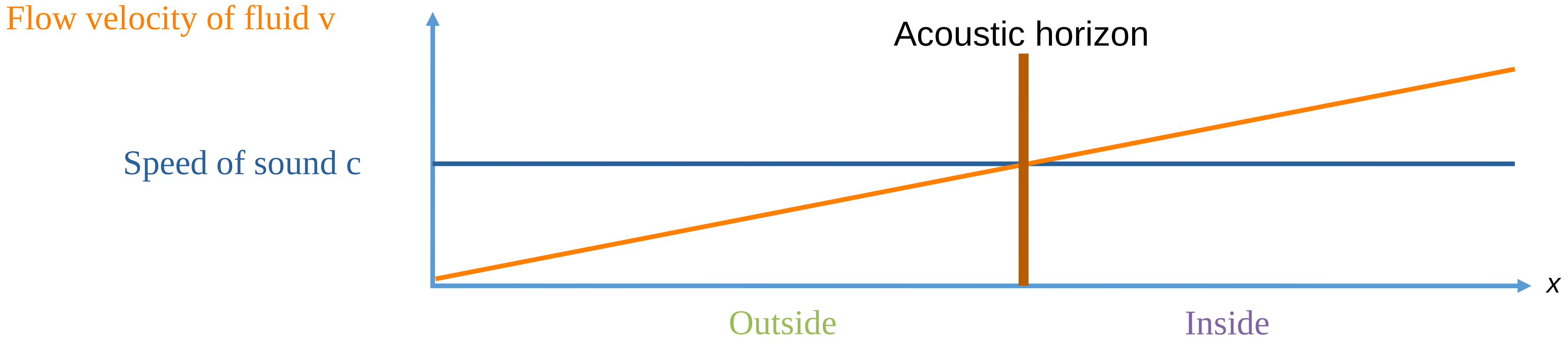
(iii) radially and azimuthally accelerating flow in 2 spatial dimensions → static rotating spacetime
Horizon where $\mathrm{v}_r = c_s$
Ergosurface where $|\boldsymbol{v_0}| = c_s$

Unruh *PRL* **46** 1351 (1981), Visser *Class Quant Grav* **15** 1767 (1998)

Quantised acoustic field in waterfall geometry

Unruh *PRL* **46** 1351 (1981)

Static 1D geometry ↔ waterfall geometry



Quantised acoustic field:

in: $\phi = \int d\omega \left(a_\omega f_\omega + a^\dagger_\omega f^*_\omega \right) \quad a\,|0\rangle = 0$

out: $\phi = \int d\omega \left(\bar{a}_\omega F_\omega + \bar{a}^\dagger_\omega F^*_\omega \right) \quad \bar{a}\,|\bar{0}\rangle = 0$

Express out modes in terms of in modes:

$$F_\omega = \int d\omega' \left(\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} f^*_{\omega'} \right)$$

Different speeds on either side of the horizon ⇒ $|\bar{0}\rangle \neq |0\rangle$ ⇒ $\beta_{\omega\omega'} \neq 0$

Mixing of positive and negative frequency waves ⇒ mixing of creation and annihilation operators

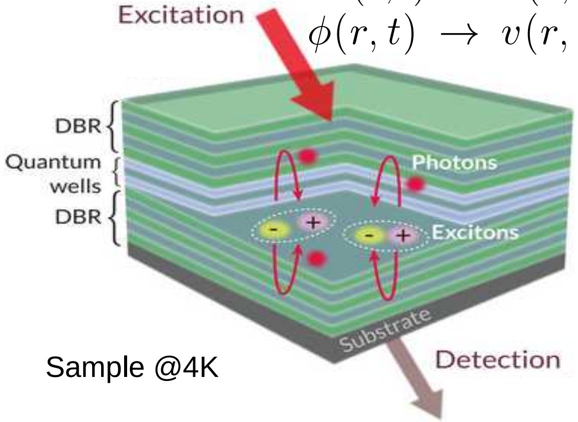
$$\mathrm{a}\;|\bar{0}\rangle = \sum_{\omega'} \beta_{\omega\omega'}\,|\bar{1}\rangle > 0$$

Microcavity polaritons

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

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

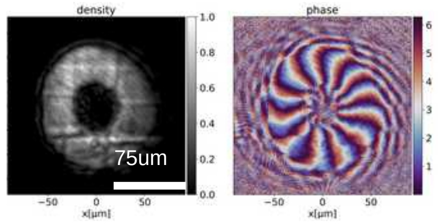
SLM to control phase and mode of pump

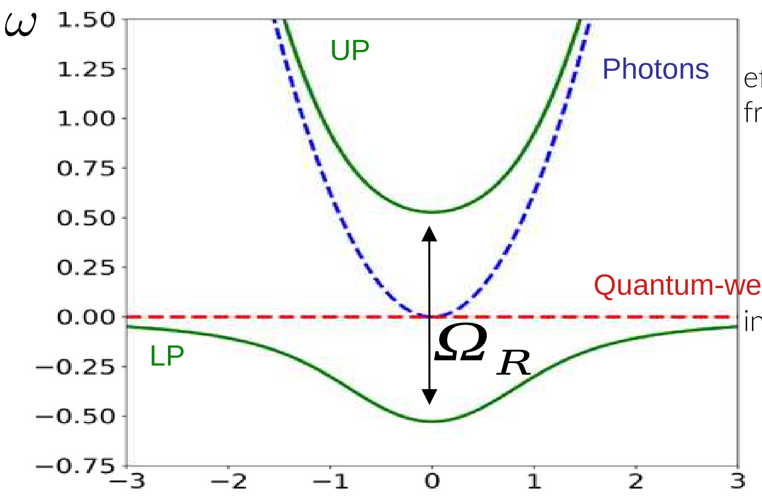


Sample @4K

Imaging photons leaking out of the cavity

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





effective mass from confinement

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 $\rightarrow$ Out-of-equilibrium system

g polariton-polariton interaction constant

γ Losses

P pump

Collective excitations of polariton fluid

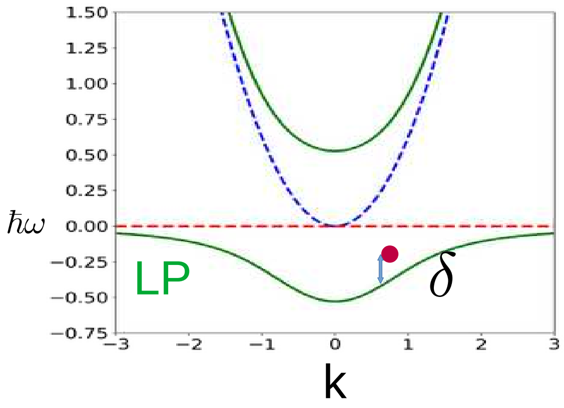
F Claude *et al* PRL **129** 103601 (2022)
F Claude *et al* PRB **107** 174507 (2023)

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

Bogoliubov theory:

1. Linearise GPE around steady-state solution $\psi(r,t) = \psi_0(r,t) + \delta\psi(r,t)$
2. Equation of motion of weak perturbations $$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\delta\psi(r,t)\\ \delta\psi^*(r,t)\end{pmatrix} = L_{\mathrm{Bog}}\begin{pmatrix}\delta\psi(r,t)\\ \delta\psi^*(r,t)\end{pmatrix}$$
3. Eigenvalues of L_{Bog} == dispersion relation

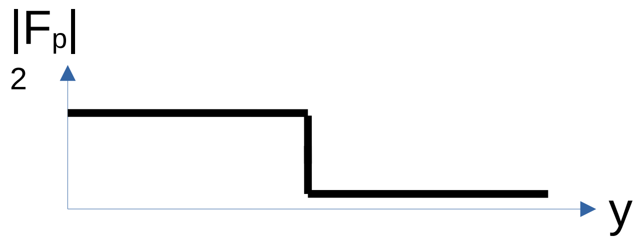
$$\hbar\omega(k) = \pm\sqrt{\left(\frac{\hbar^2k^2}{2m} - \delta + 2gn\right)^2 - (gn)^2} - i\gamma$$



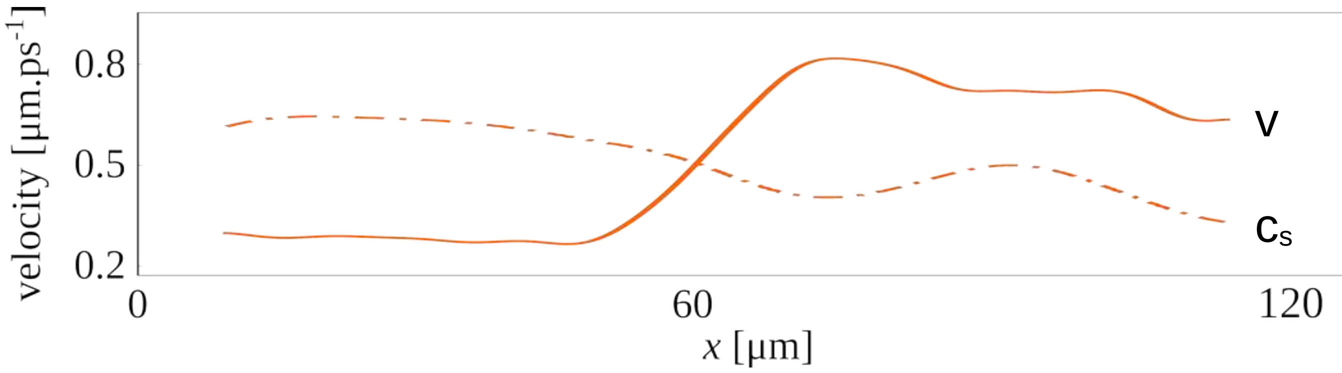
resonant photon injection

1D geometry : static horizon

Data by Kévin Falque arXiv:2311.01392

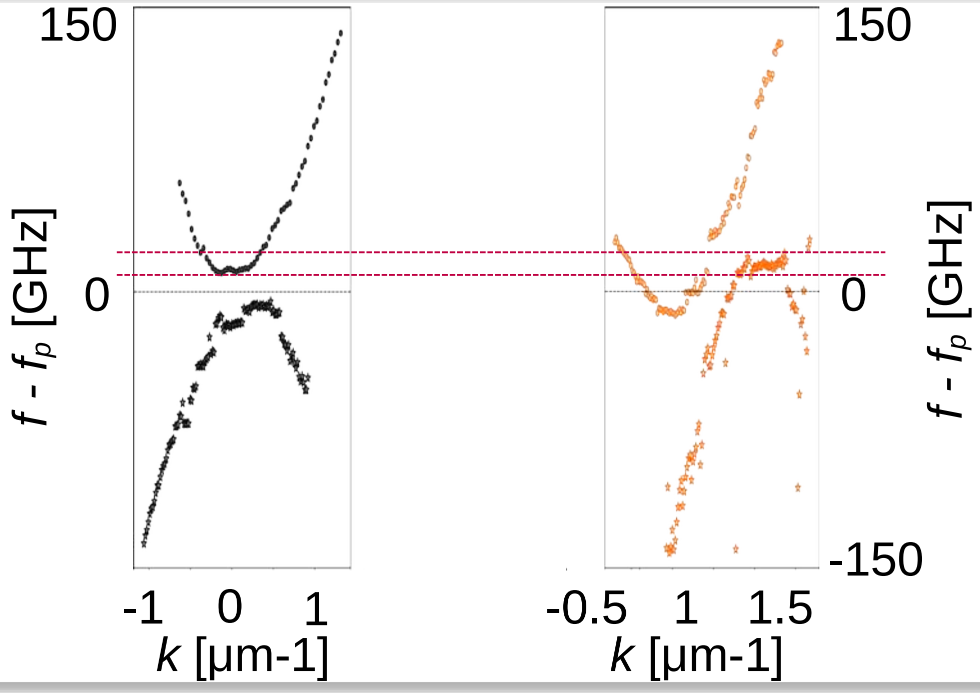


+ phase controlled with SLM $F\, e^{i(k_p.\boldsymbol{r}-\omega_p t)}$



Spectrum of collective excitations

$$\omega^{\pm}(k) - v(x)\cdot k(x) = \frac{i\gamma}{2} \pm \sqrt{\left(\frac{\hbar k(x)^2}{2m} - \delta(k_p) + 2gn(x)\right)^2 - (gn(x))^2}$$



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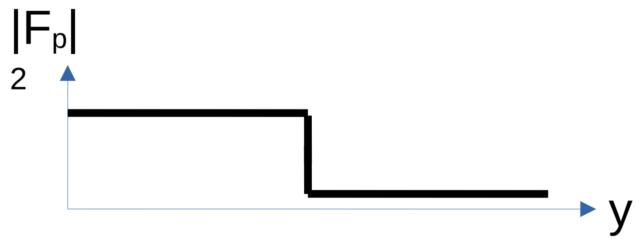

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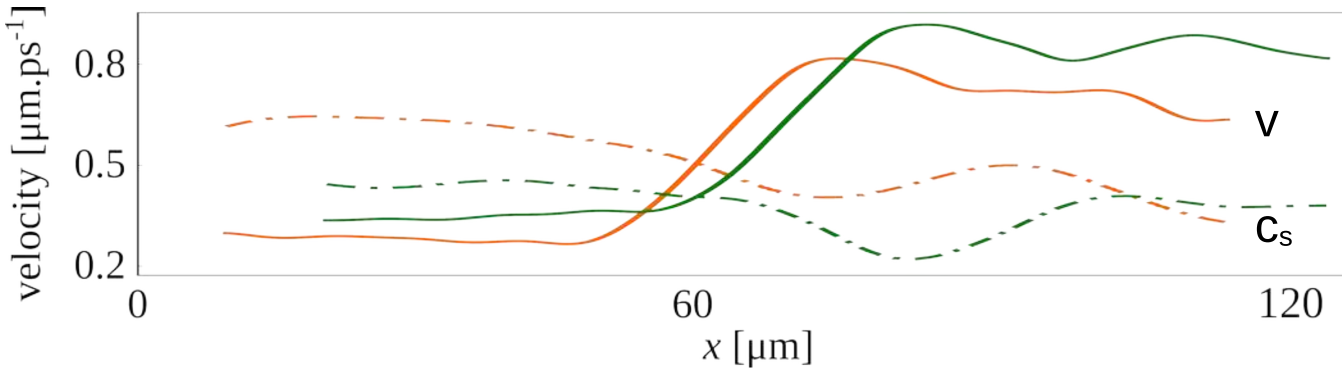

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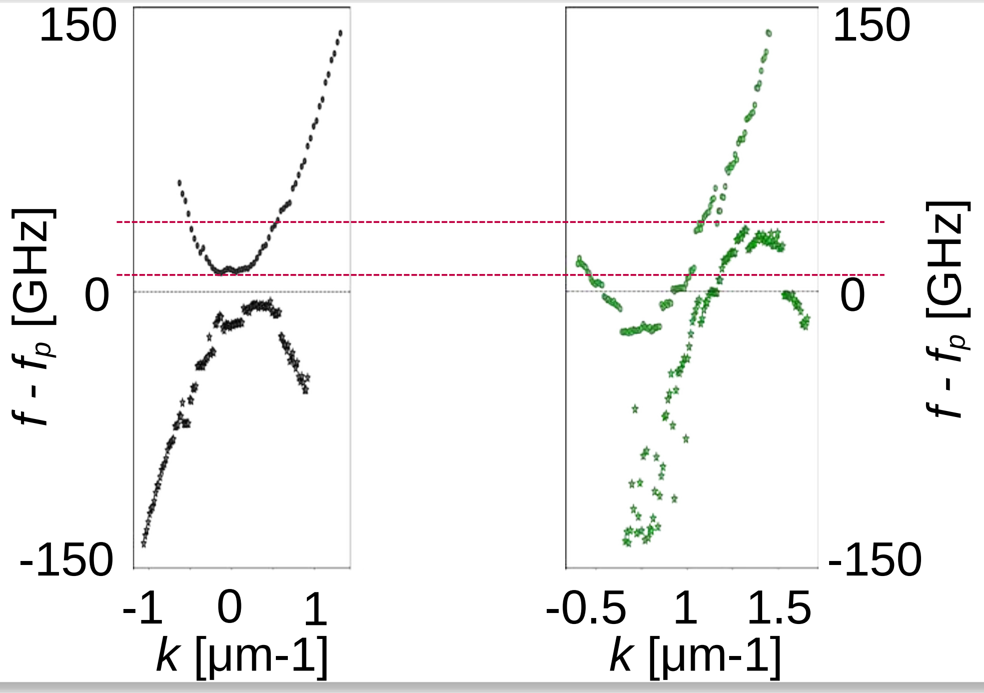
Mach number: $\mathrm{M} = c_s / v$

Horizon steepness: $\partial M / \partial x|_{x_H}$

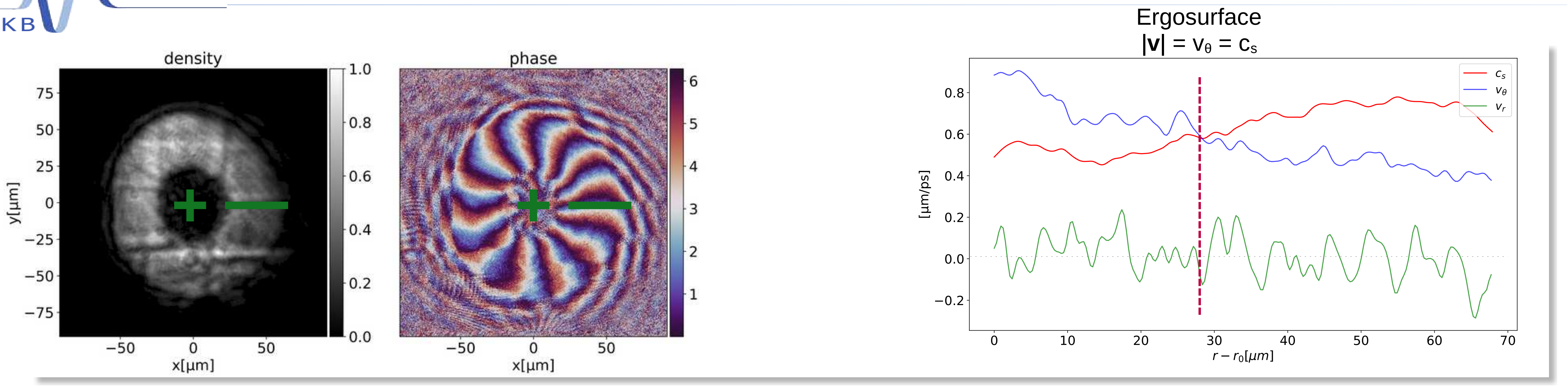
orange $0.08\mu m^{-1}$

green $0.04\mu m^{-1}$



Rotating geometry without a drain

Data by Killian Guerrero arXiv:2310.16031



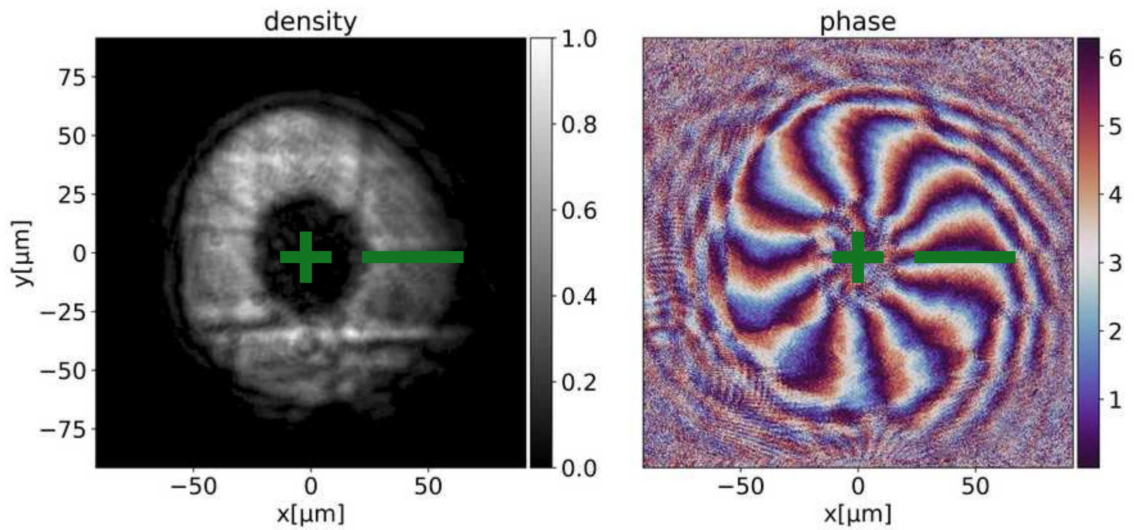
$$\nabla\phi_{SLM} = \frac{C}{r}\boldsymbol{u_\theta} - \frac{D}{r}\boldsymbol{u_r}$$

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

$$C = 12, D = 0$$

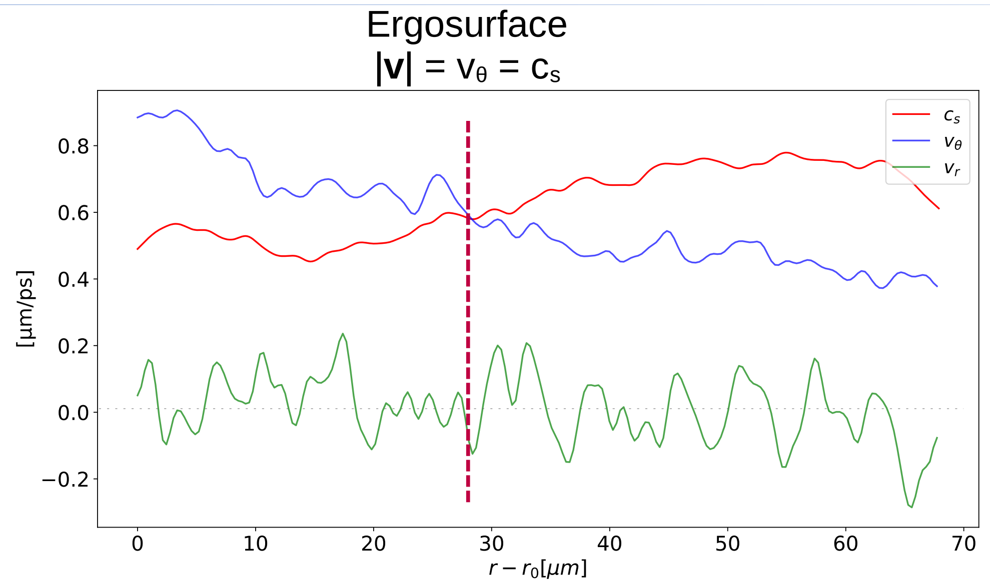
Rotating geometry $D = 0, C = 12$

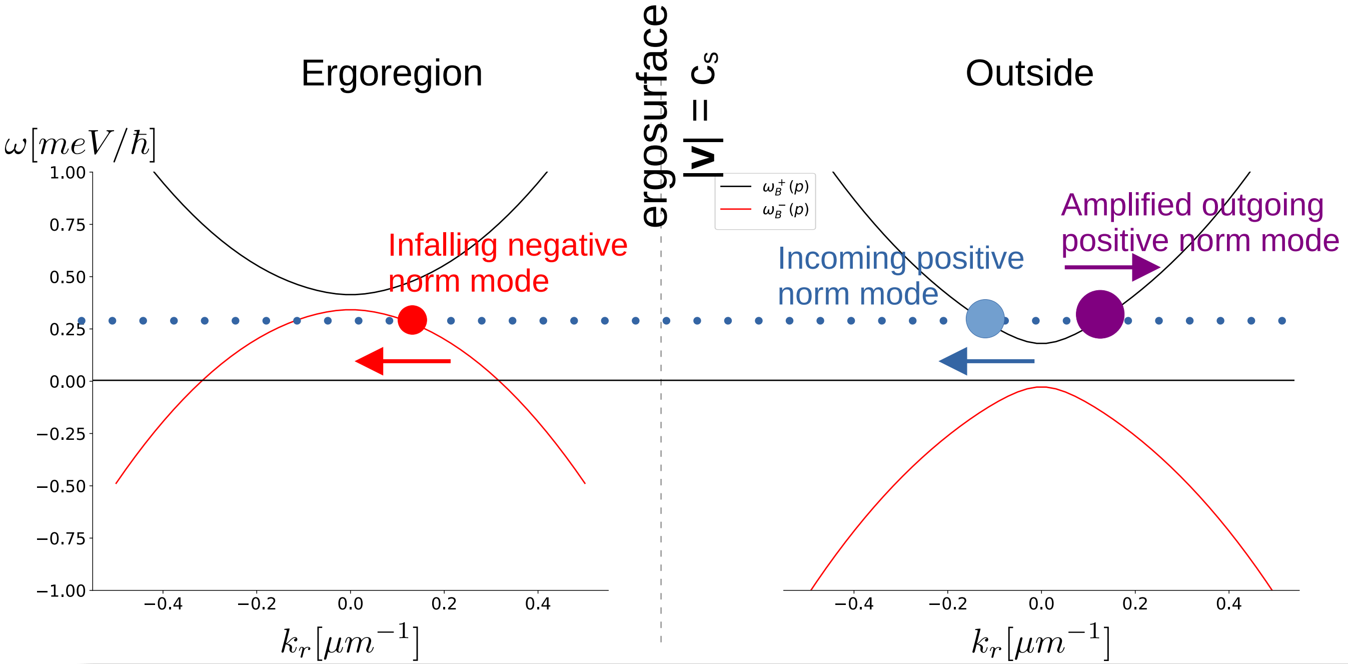
Data by Killian Guerrero arXiv:2310.16031



$$c_s \propto \sqrt{gn}$$

$$v_{fluid} \propto \nabla\phi$$

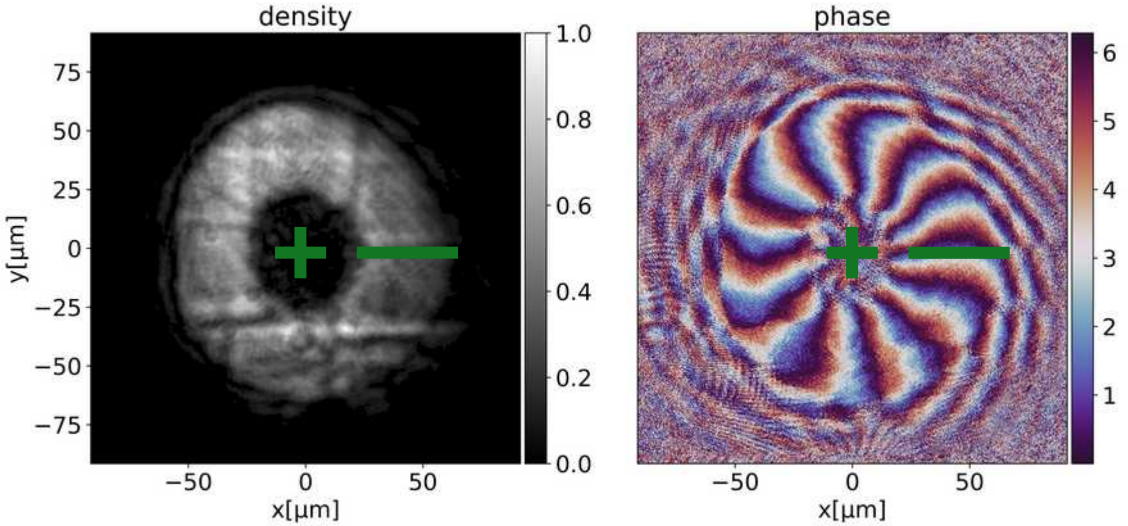




$$Q(\phi) = i\int_0^\infty \int_0^{2\pi} d\theta \frac{r}{c^2}\left(\phi^*\partial_t\phi - \partial_t\phi^*\phi\right)$$

Rotating geometry $D = 0, C = 12$

Data by Killian Guerrero arXiv:2310.16031



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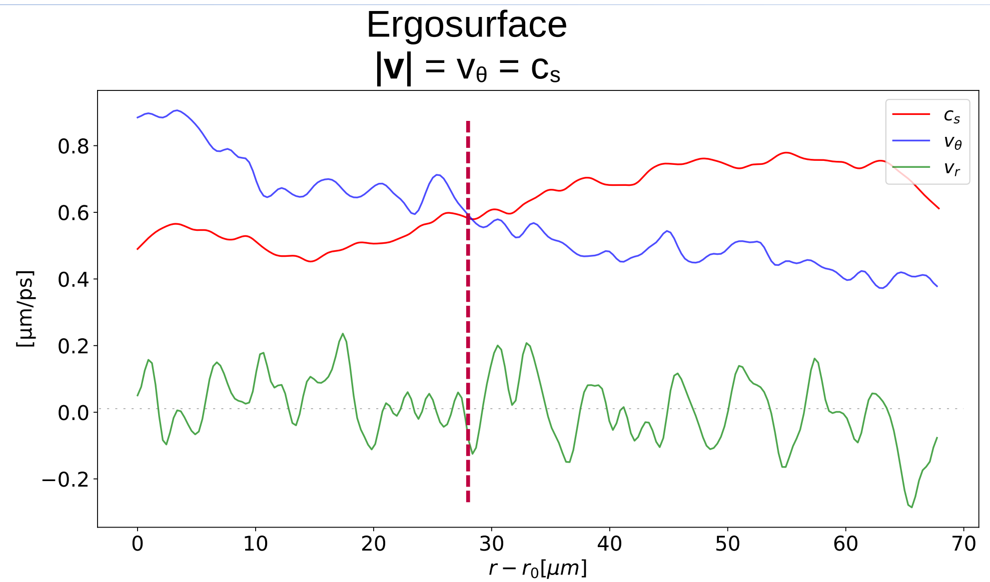
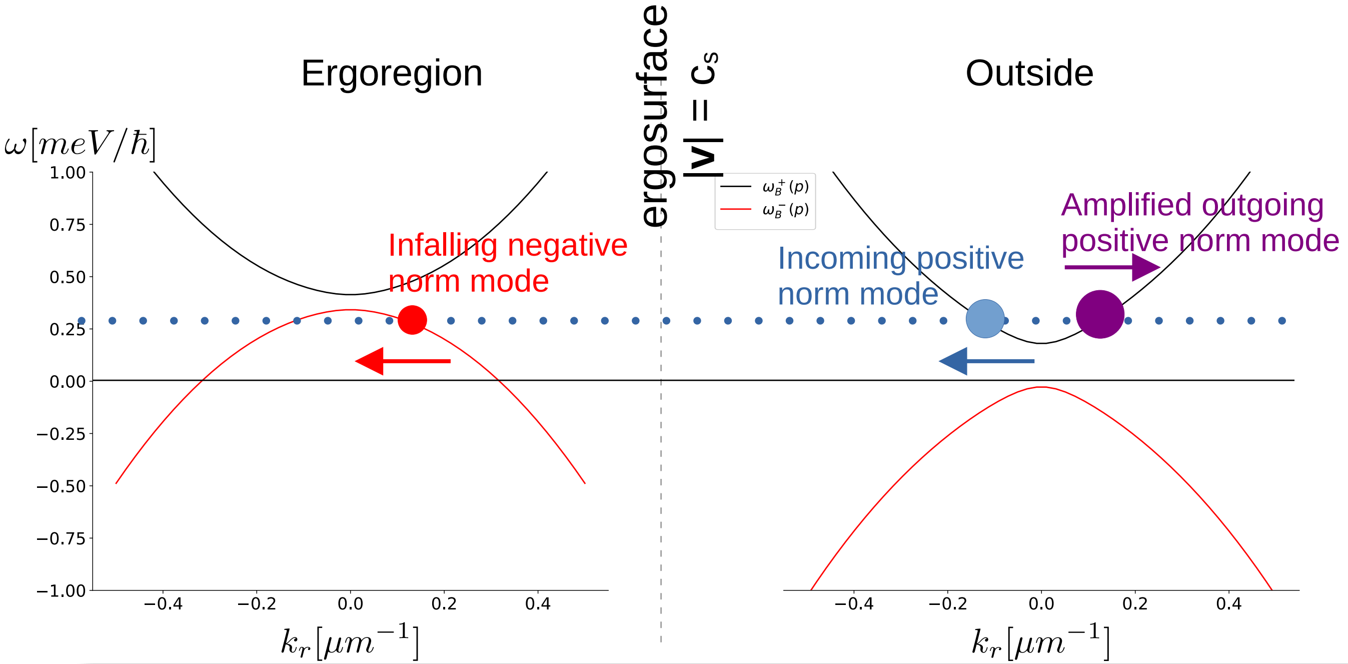


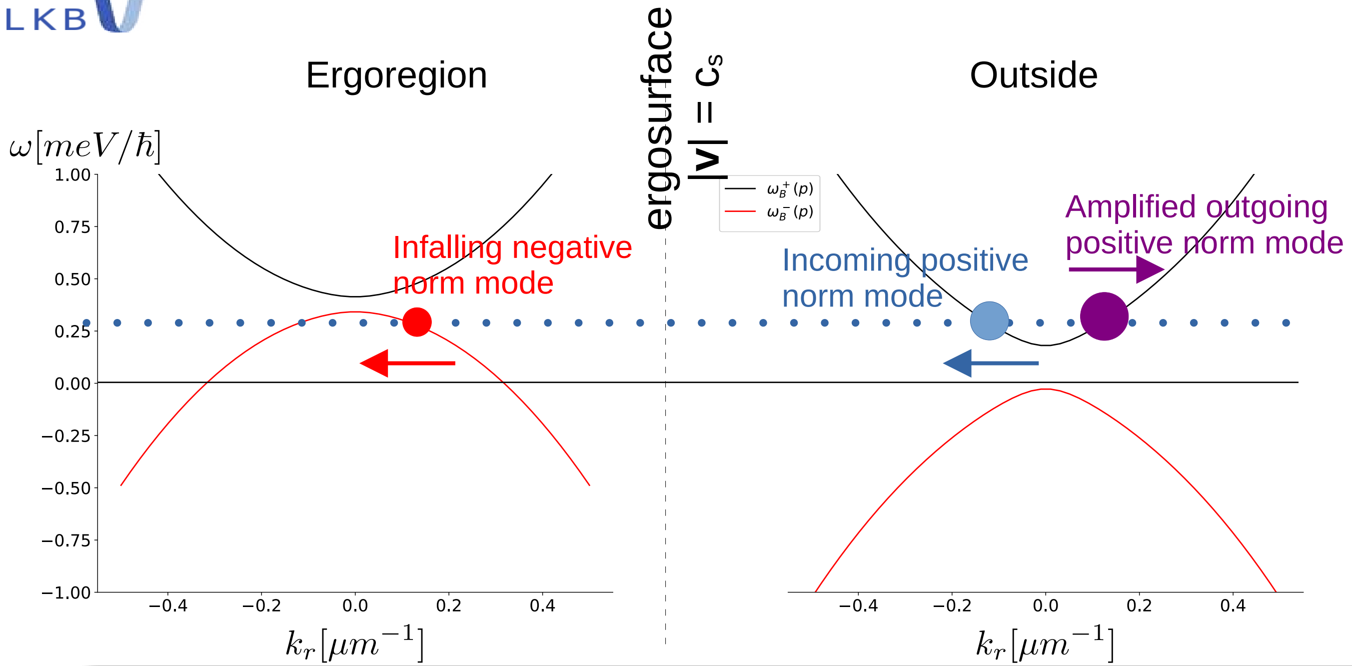


Stable ergosurface without a horizon?

$$v_g = 1\mu m.ps^{-1} \qquad \tau = 15ps$$

Entanglement in rotating geometry

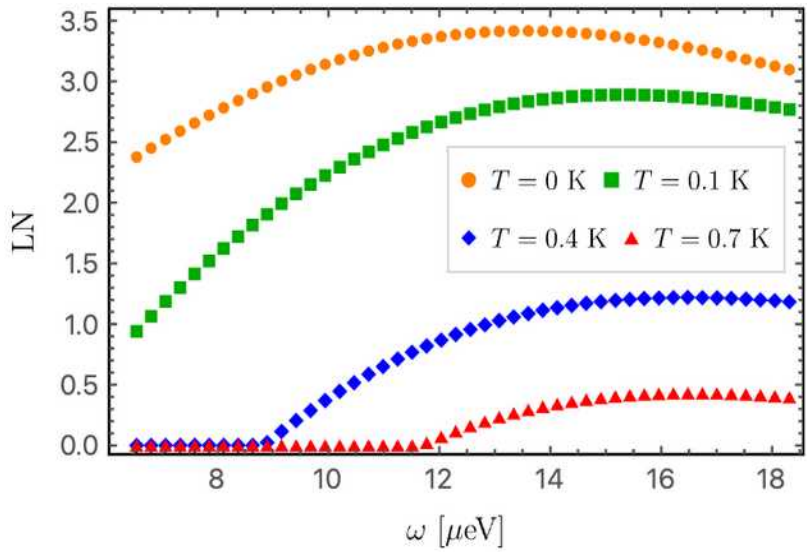
Calculations by Aria Delhom arXiv:2310.16031



$$(W_r^{in}, W_l^{in}) \rightarrow (W_r^{out}, W_r^{out})$$

$$B_{\omega l} = \begin{pmatrix} T_{\omega l} & r_{\omega l} \\ R_{\omega l} & t_{\omega l} \end{pmatrix}$$

Vacuum + thermal $|0\rangle \otimes |Th\rangle$ noise at input



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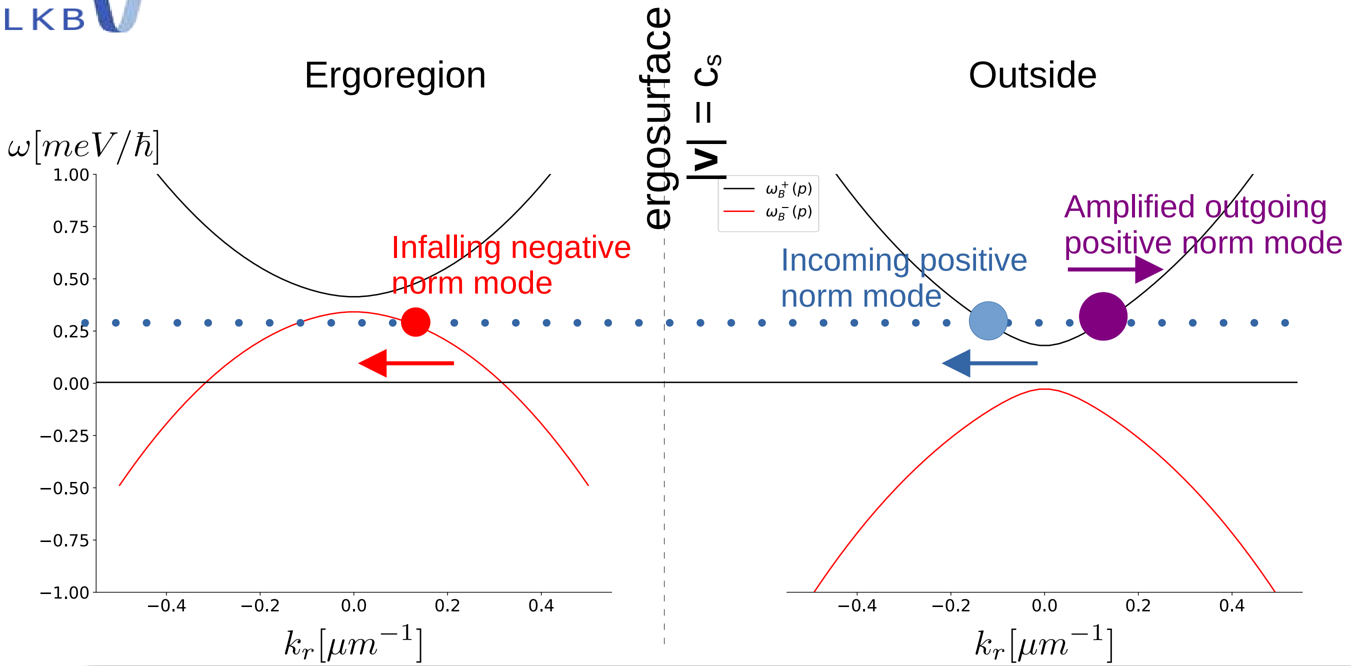

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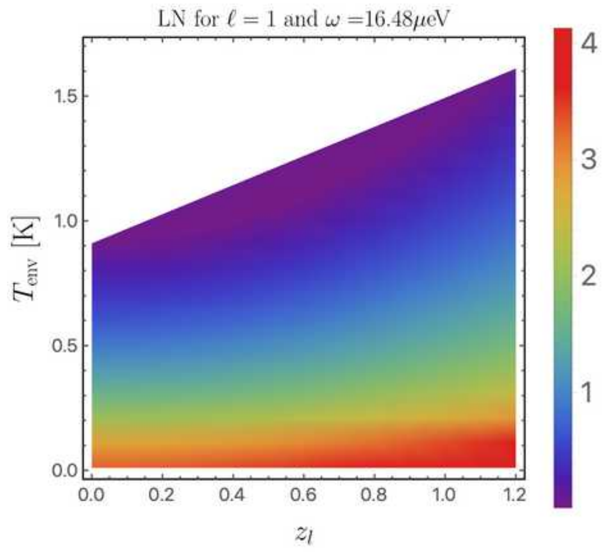
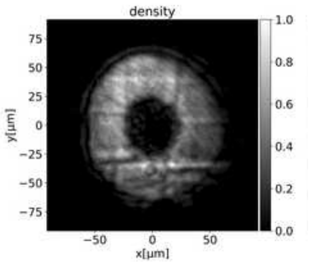
Vacuum + thermal noise + single mode squeezed state at input

$$|0\rangle \otimes |Th\rangle \otimes |SMST\rangle$$



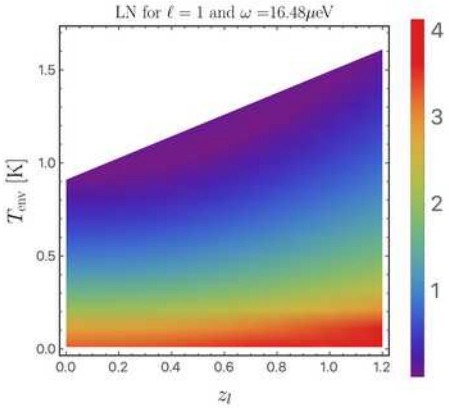
Where do we go from here?



Experiments with polaritons

- Measure Hawking radiation and rotational superradiance independently from one another
- Measure interplay between the two effects → modification of correlations?

Static 1D geometry: arXiv:2311.01392
Rotating geometry: arXiv:2310.16031

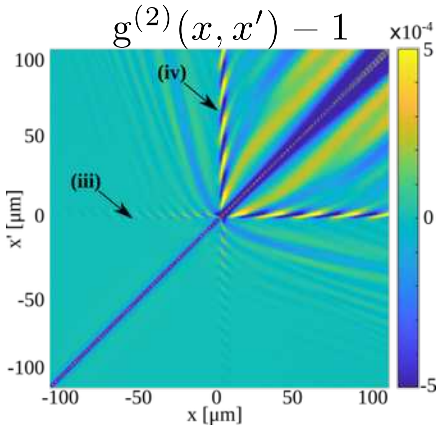


F Claude *et al* PRL **129** 103601 2022,
PRB **107** 174507 2023

All optical experiments

- Measure phase and density → access full field statistics and dynamics
- High resolution spectroscopy in 1 and 2D with and without rotation
- Homodyne detection to enhance signal strength and measure quantum correlations
- Enhance strength of emission and degree of entanglement by probing with squeezed state

I Agullo *et al* PRL **128** 091301 2022



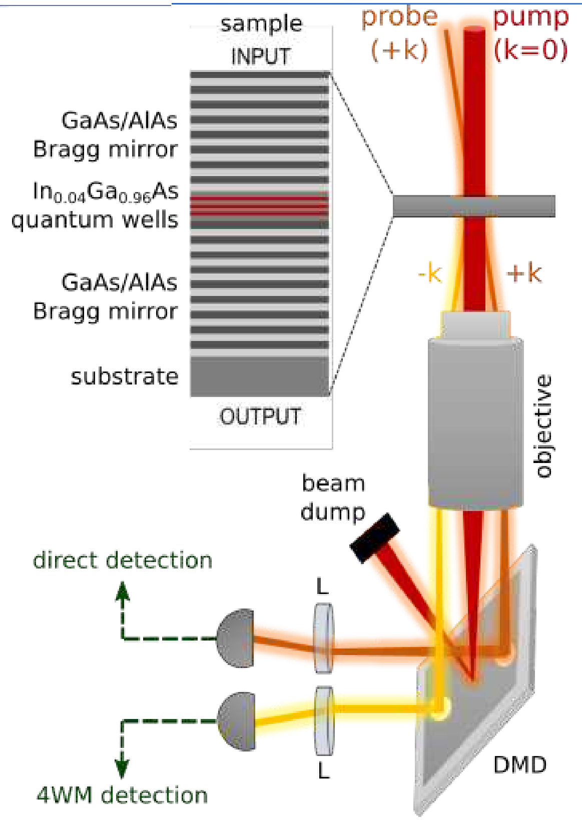
Numerical simulations

- New effect of quantum fields predicted: vacuum excitation of quasi-normal mode of acoustic field
- Good experimental configuration to observe strong correlations

Jacquet *et al.* PRL **130** 2023, EPJD **76** 2022

High-resolution coherent probe spectroscopy (CPS)

F Claude *et al* PRL **129** 103601 (2022)
F Claude *et al* PRB **107** 174507 (2023)



Probe: scan to find probe resonance with fluid @ different k
energy scan: ~100GHz

Detection: probe resonates with fluid → transmission = dip in reflectivity

ω resolution fixed by the probe laser linewidth (<250kHz)
k resolution fixed by the k-space filtering ($0.02\mathrm{um}^{-1}$)

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F Claude *et al* PRL **129** 103601 (2022)
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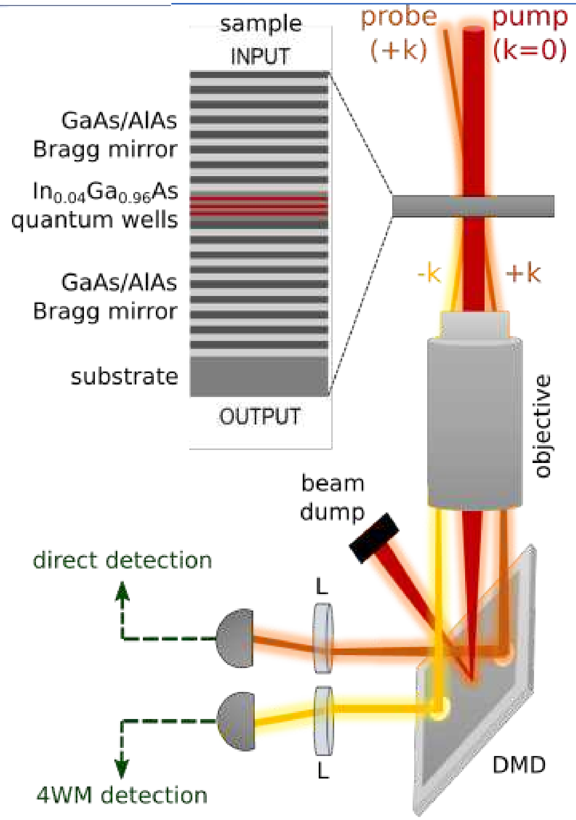

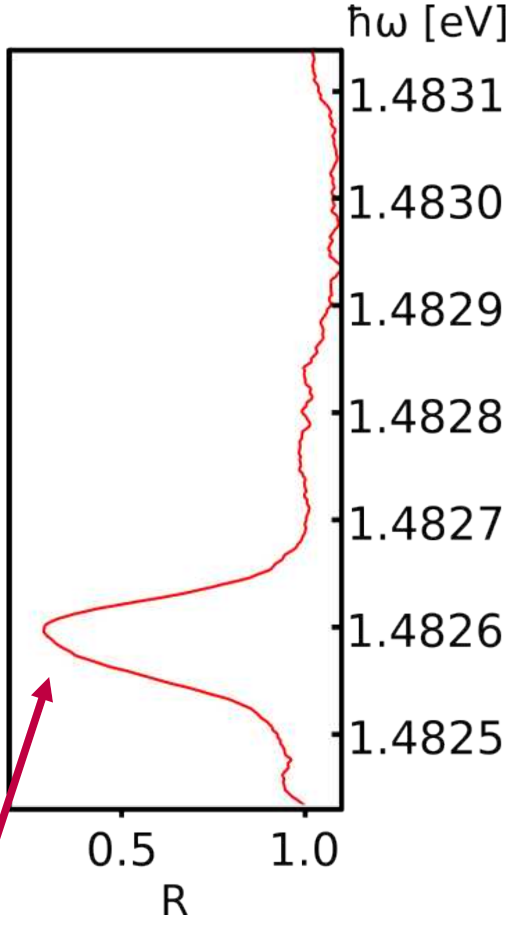

Reflectivity of probe @k

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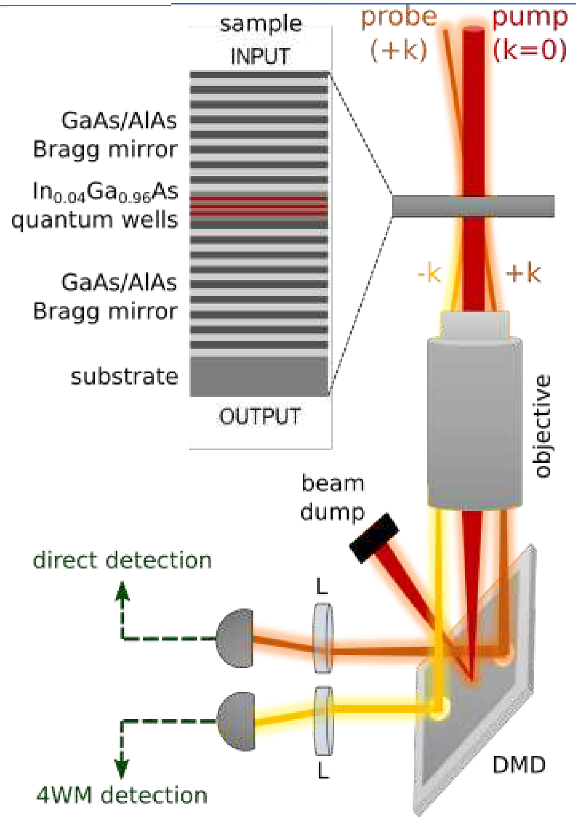

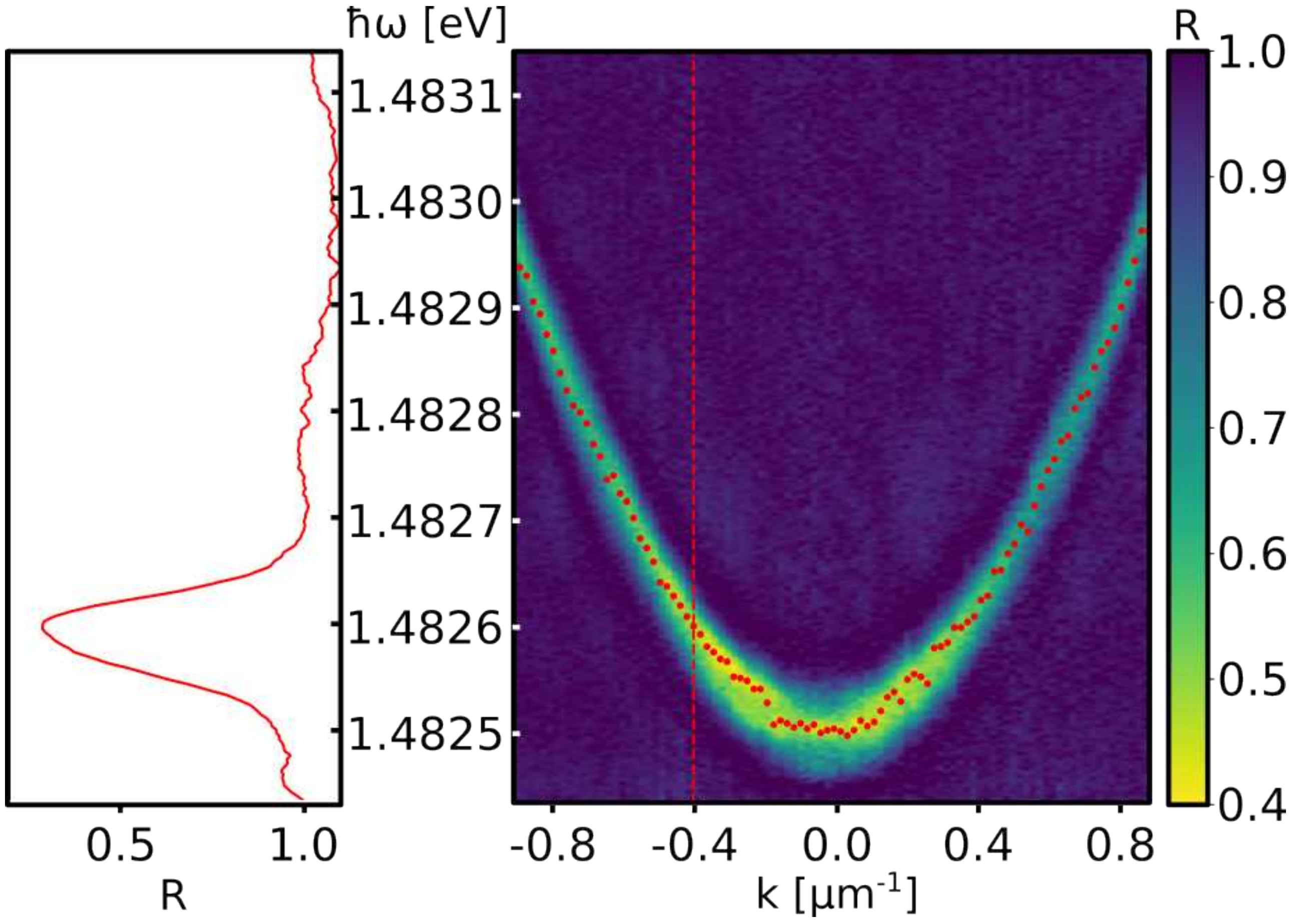

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Coherent probe spectroscopy: Reflectivity map of probe vs (k, ω) ↔ spectrum of collective excitations

ω resolution fixed by the probe laser linewidth (<250kHz)
k resolution fixed by the k-space filtering (0.02um^{-1})