Black hole simulation with a polariton quantum fluid

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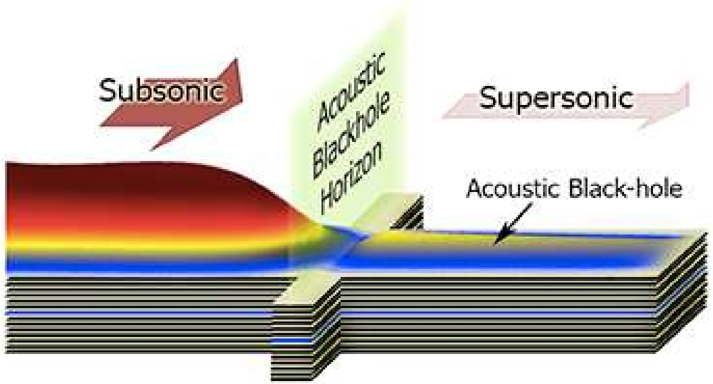
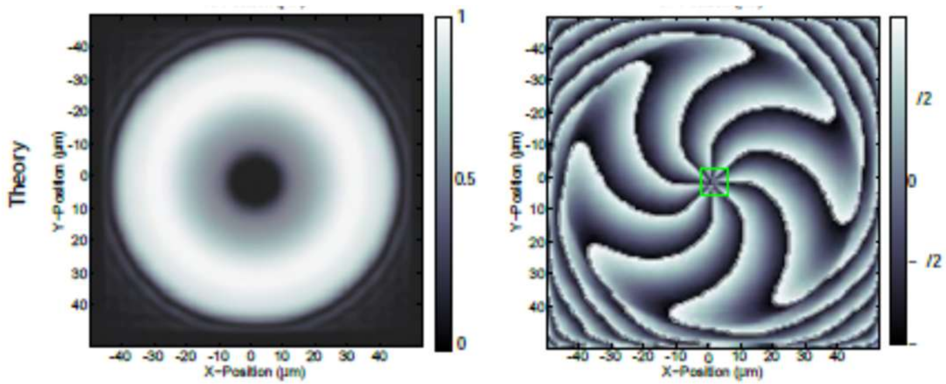
Analog gravity physics with polaritons

- Simulation of analog static black holes
- Simulation of rotating Kerr black holes

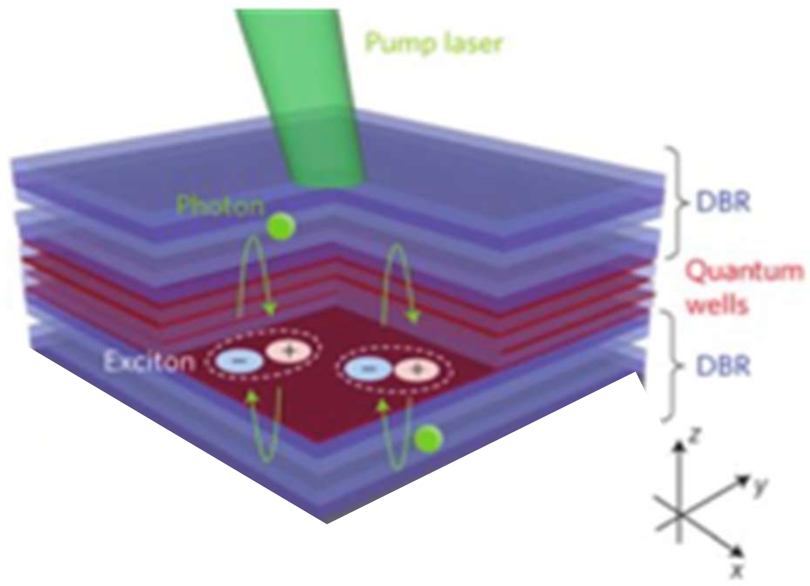
Perspectives

- Hawking radiation in analog black holes
- Penrose process
- Zel'dovich amplification

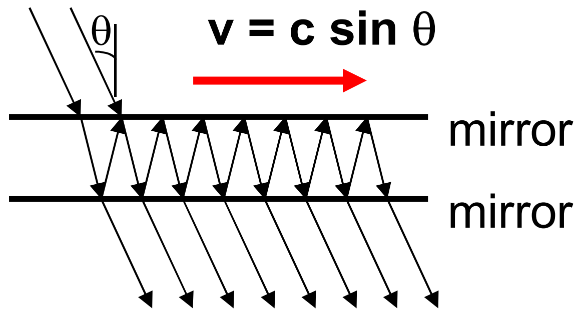




Quantum Fluid of Light



- **Quantum fluids of light in a semiconductor nonlinear cavity :**
  - 2D fluid in the transverse plane
  - Effective mass from confinement
  - Coupling of photons with excitons yielding polaritons
  - Driven-dissipative dynamics

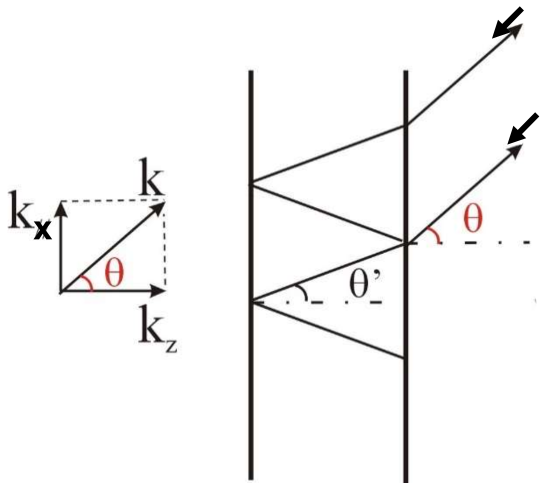


C. Weisbuch, M. Nishioka, A. Ishikawa, Y. Arakawa, Phys. Rev. Lett. 69, 3314 (1992)

The fluid of light propagates in the direction of the red arrow

Dispersion curves

Dispersion of cavity mode: $\lambda_{cav,\theta'} = \lambda_{cav,0} \cos\theta'$



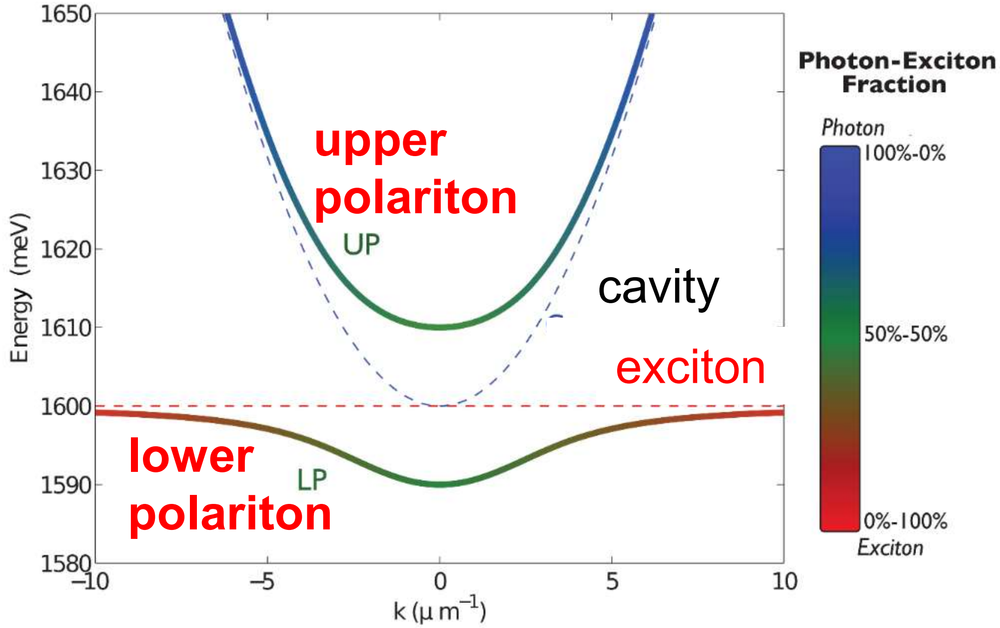
$$\boldsymbol{E} \approx \hbar c k_z \left(1 + \frac{k_x^2}{2k_z^2}\right) = \hbar c k_z + \frac{\hbar^2 k_x^2}{2m^*}$$

Exciton dispersion:

$$E = E_{exc} + \frac{\hbar^2 K_{//}^2}{2M^*_{exc//}}$$

the exciton kinetic energy is negligible, because M^*_{exc} very large

Strong coupling yields polaritons



In addition, the interaction between excitons yields an effective interaction between polaritons

$$H_{PP}^{eff} = \hbar\alpha\, X^4 p_3^+ p_4^+ p_1 p_2$$

Polaritons

Polaritons are weakly interacting composite bosons

$$P_+ = -C\,a + X\,b$$
$$P_- = X\,a + C\,b$$

Very small effective mass m ~ 10^{-5} m_e

Large coherence length λ_T ~ 1-2 µm at 5K

$$\lambda_T = \left(\frac{2\pi\hbar^2}{mk_B T} \right)^{\frac{1}{2}}$$

and
mean distance between polaritons d ~ 0,1-0,2 µm

This enables the building of many-body quantum coherent effects : condensation, superfluidity at temperatures of ~4K

Quantum fluid properties of polaritons

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Probing Microcavity Polariton Superfluidity through Resonant Rayleigh Scattering

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Quantum fluids of light

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(published 21 February 2013)

Gross-Pitaevksii Equation

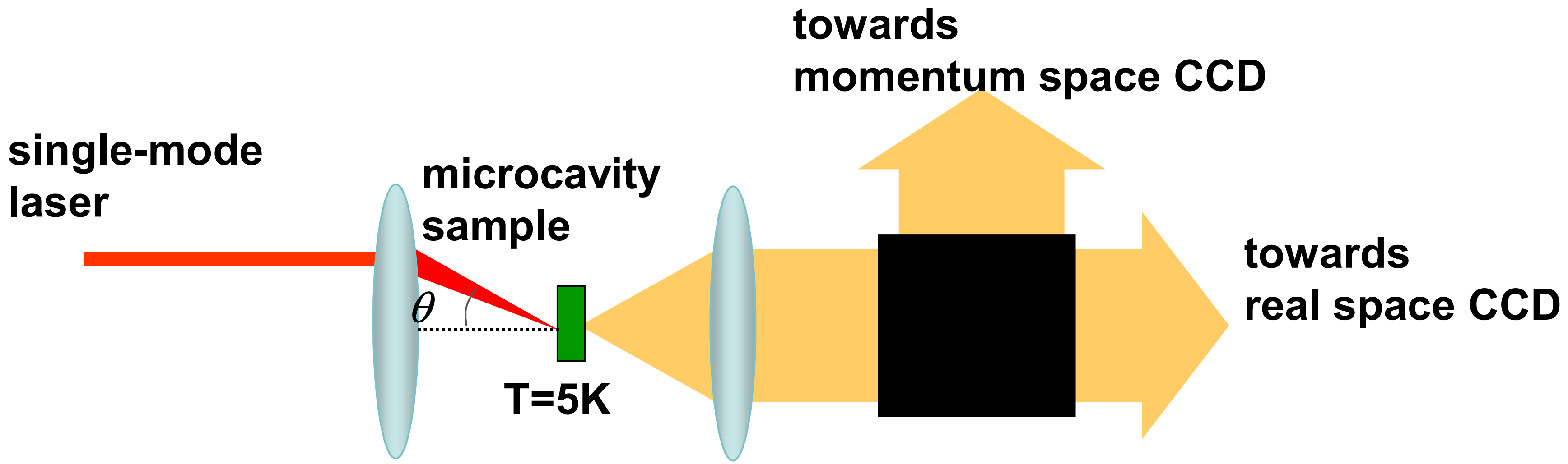
- **Polariton propagation in the cavity**

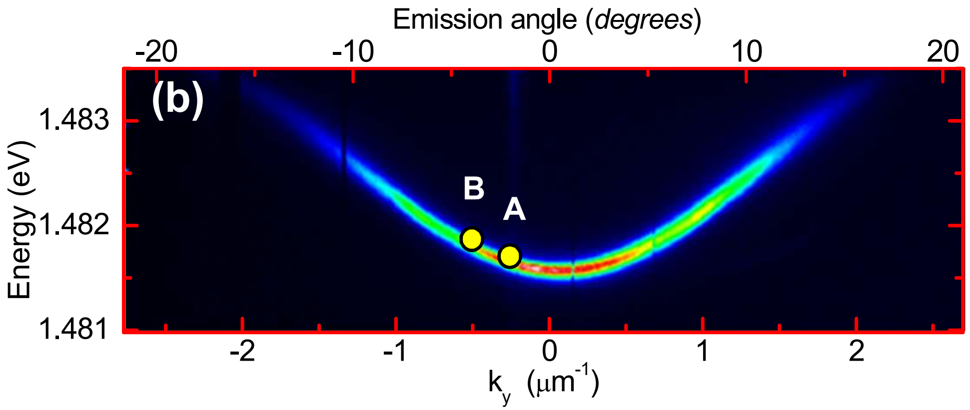
$$i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V_{ext}\psi + g\;|\psi|^2\psi + i\gamma\psi + iF_p$$

kinetic energy — external potential — non-linear interaction — losses and pumping

Nonlinear Schrödinger equation
Gross Pitaevskii equation

Microcavity : experimental scheme





Control parameters

✓**Polariton density**
with pump intensity

✓**Fluid velocity**
with laser excitation angle

✓**Oscillation frequency**
with laser frequency

Evolution of a pumped polariton fluid

Assuming the pump beam to be monochromatic with frequency

$F_p(x,t) = F_p(x)\, e^{-i\omega_p t}$ $\Psi(x,t) = \Psi(x)\, e^{-i\omega_p t}$

In the steady state the Gross-Pitaevskii equation becomes

$$\left(\omega_0 - \omega_p - \frac{\hbar}{2m^*}\partial_x^2 + V(x) + \frac{g}{\hbar}|\Psi(x)|^2 - i\frac{\gamma}{2\hbar}\right)\Psi(x) + \frac{i}{\hbar}F_p(x) = 0$$

where $\hbar\,\omega_0$ is the energy of the polariton ground state

We study the evolution of small excitations in the vicinity of the resonant point

$$\Delta_p = \omega_p - \omega_0 - \frac{\hbar k_p^2}{2m^*} = \frac{g}{\hbar}|\Psi|^2$$

Study of superfluidity
Weak excitations and Bogoliubov dispersion

Weakly excited states : bosonic modes obtained **by linearizing the Gross Pitaevskii equation**

$$\psi(\mathbf{r},t) = \left(\psi_0(\mathbf{r},t) + \delta\psi(\mathbf{r},t)\right)$$

$$i\hbar\frac{\partial}{\partial t}\begin{bmatrix}\delta\psi(\mathbf{r},t)\\ \delta\psi^*(\mathbf{r},t)\end{bmatrix} = \mathcal{L}_{Bog}\begin{bmatrix}\delta\psi(\mathbf{r},t)\\ \delta\psi^*(\mathbf{r},t)\end{bmatrix}$$

Bogoliubov operator when $k_p = 0$

$$\mathrm{L}_{Bog} = \begin{bmatrix}\frac{\hbar^2k^2}{2m} + g|\psi_0|^2 & g|\psi_0|^2\\ -g|\psi_0|^2 & -\frac{\hbar^2k^2}{2m} - g|\psi_0|^2\end{bmatrix}$$

Look for eigenvalues of the Bogoliubov operator

Solution of Bogoliubov equation

$$|\psi_0(\mathbf{r}, t)| = \sqrt{n}$$

$$\hbar\omega_{Bog}(\mathbf{k}) = \pm\sqrt{\frac{\hbar^2k^2}{2m}\left(\frac{\hbar^2k^2}{2m} + 2gn\right)}$$

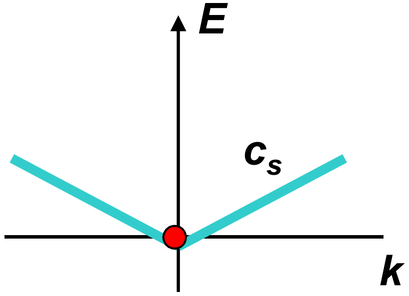
healing length

$$\xi = \sqrt{\hbar^2 / mgn}$$

- **Large k** $k\xi >> 1$ $\hbar\omega_{Bog}(\mathbf{k}) = \frac{\hbar^2k^2}{2m} + 2gn$

usual parabolic dispersion for a massive system

- **Small k** $k\xi << 1$ $\hbar\omega_{Bog}(\mathbf{k}) = c_S k$



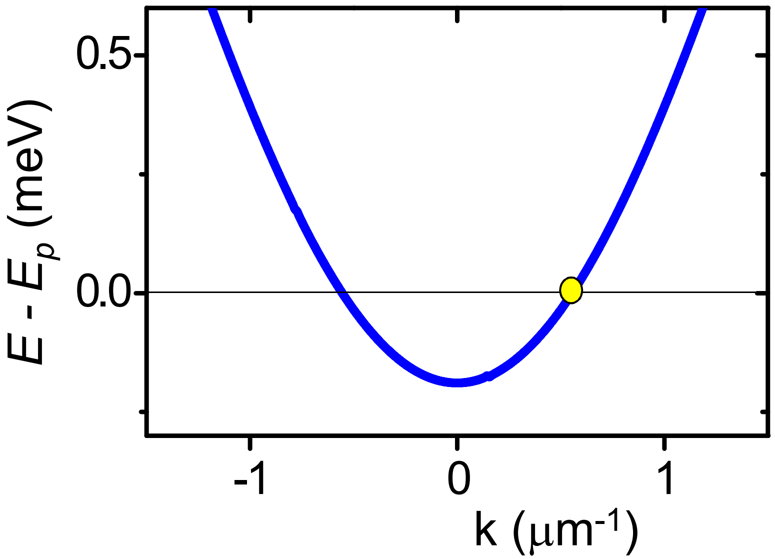
phononic excitation with a sonic dispersion: superfluidity

$$c_s = \sqrt{gn / m}$$

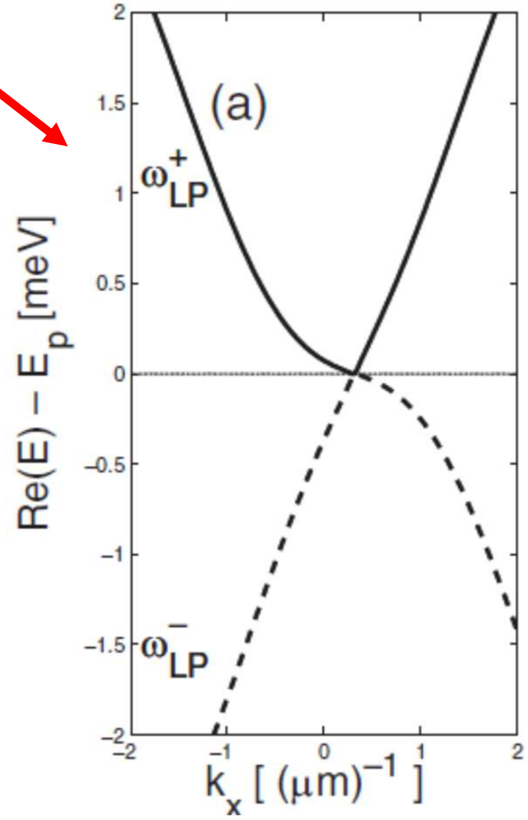
speed of sound

Bogoliubov modes for $k_p \neq 0$

$$\hbar\omega_{\rm Bog}^{(\mathbf{v})}(\mathbf{k}) = \hbar\mathbf{v}\cdot(\mathbf{k}-\mathbf{k_p}) \pm \sqrt{\frac{\hbar^2(\mathbf{k}-\mathbf{k_p})^2}{2m}\left(\frac{\hbar^2(\mathbf{k}-\mathbf{k_p})^2}{2m}+2gn\right)}$$



No pump



Pump with k_0

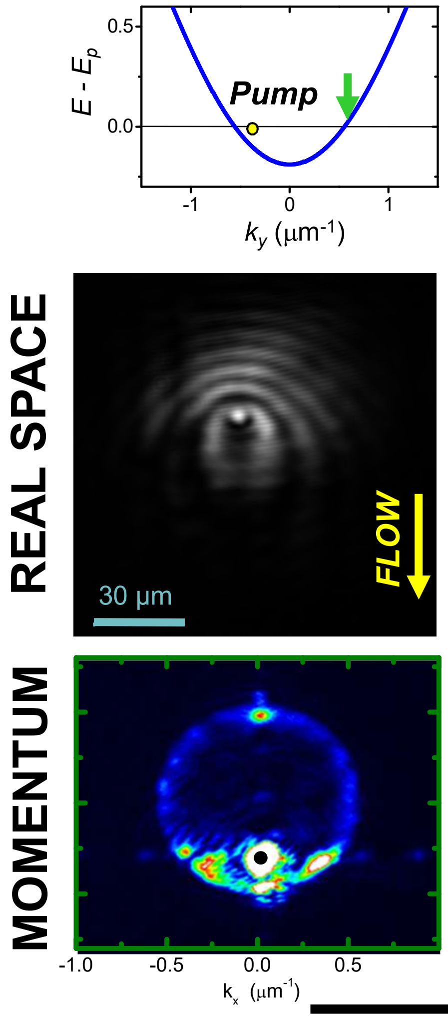
Polariton flow around a defect : low density

Point [A]
low momentum

$v_f < c_s$

$v_f =$
$5.2\ 10^5$ m/s

Elastic scattering



Polariton density

Amo *et al.*, Nature Physics, 5, 805 (2009)

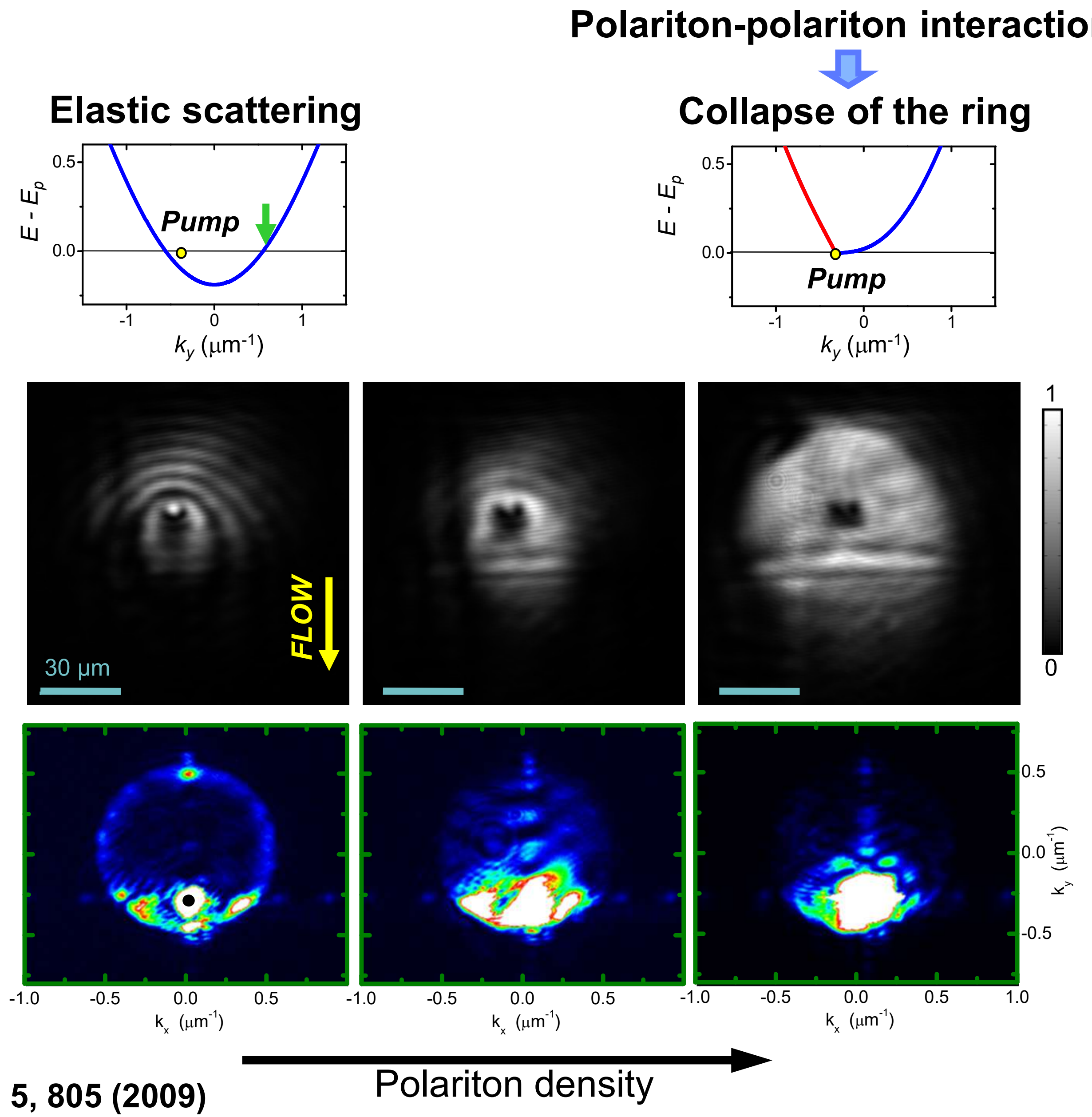
Higher density : superfluid regime

Point [A]
low momentum

$v_f < c_s$

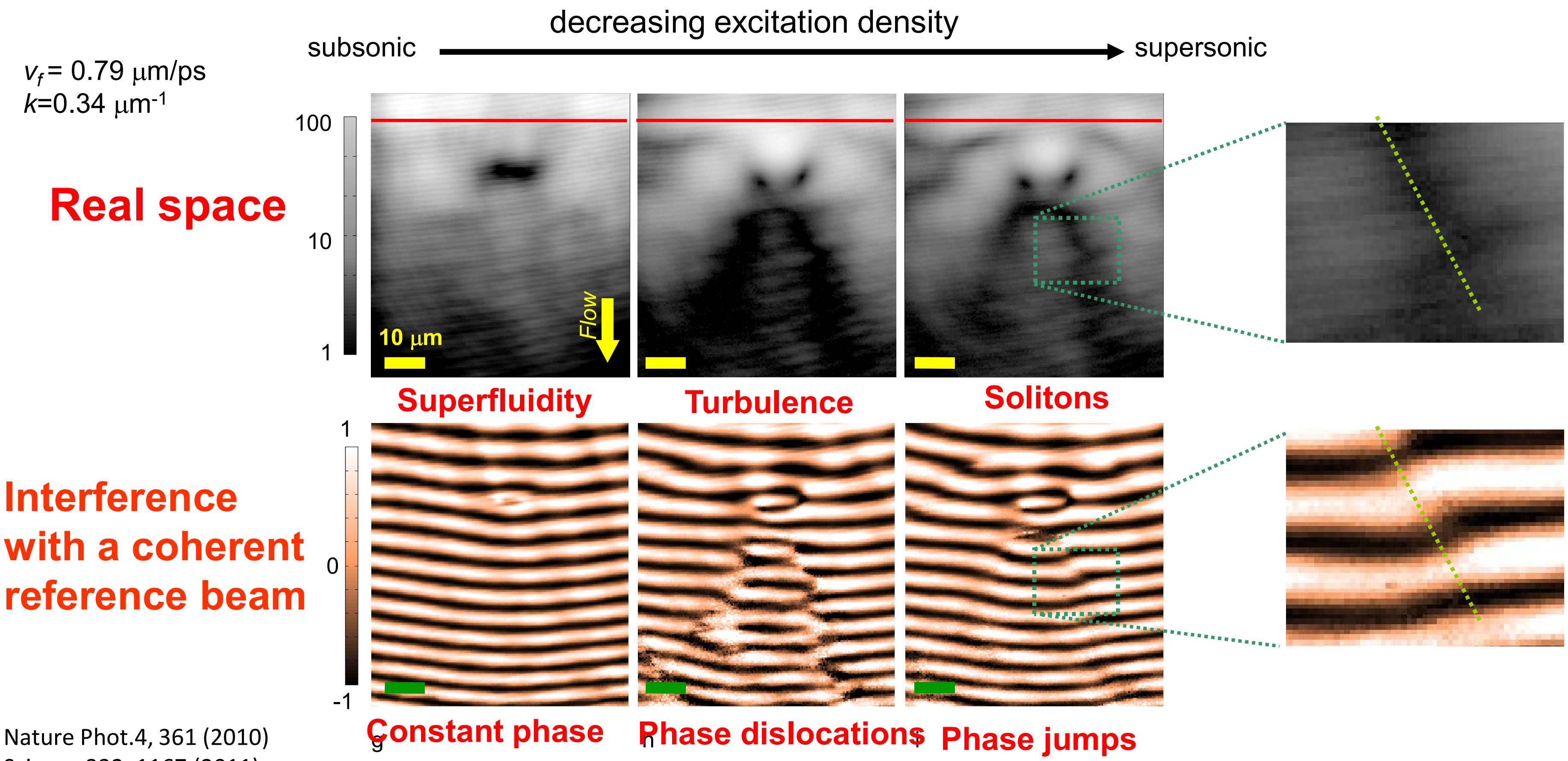
v_f =
5.2 10^5 m/s

Superfluidity appears for a polariton density of ~ 10^9/cm2



Amo *et al.*, Nature Physics, 5, 805 (2009)

Soliton and vortex nucleation in the supersonic regime with a large defect



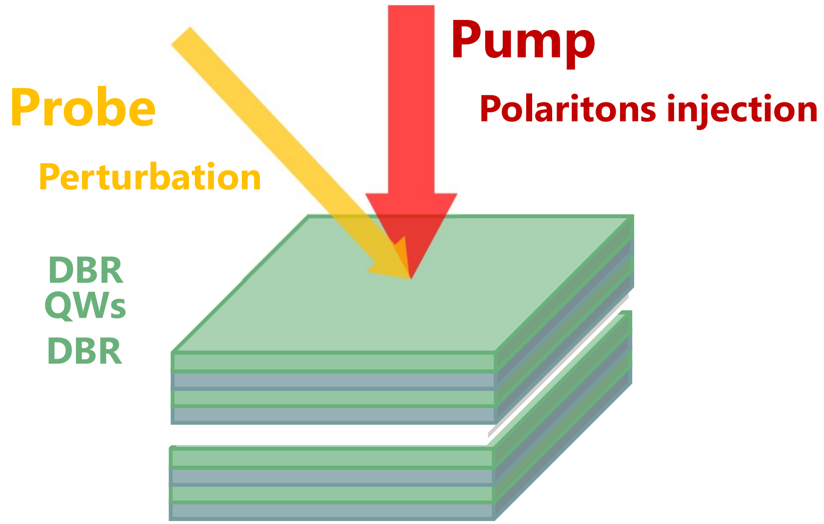
Nature Phot.4, 361 (2010)
Science 332, 1167 (2011)
Nature Physics 8, 724 (2012)
Scientific Reports, 5,9230, (2015)
PRL, 116, 116402 (2016)

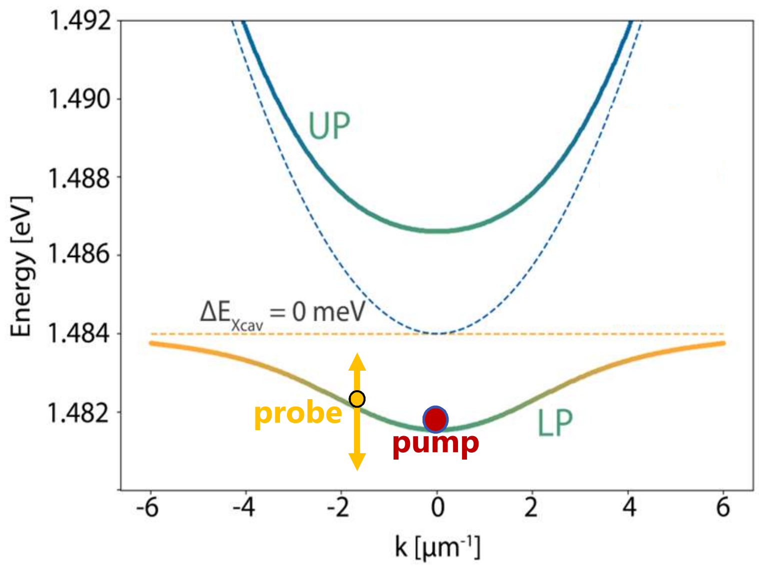
A new method for dispersion curves: coherent probe spectroscopy

Ferdinand Claude

Probe laser : excitation of small perturbations on top of the polariton fluid for different values of k

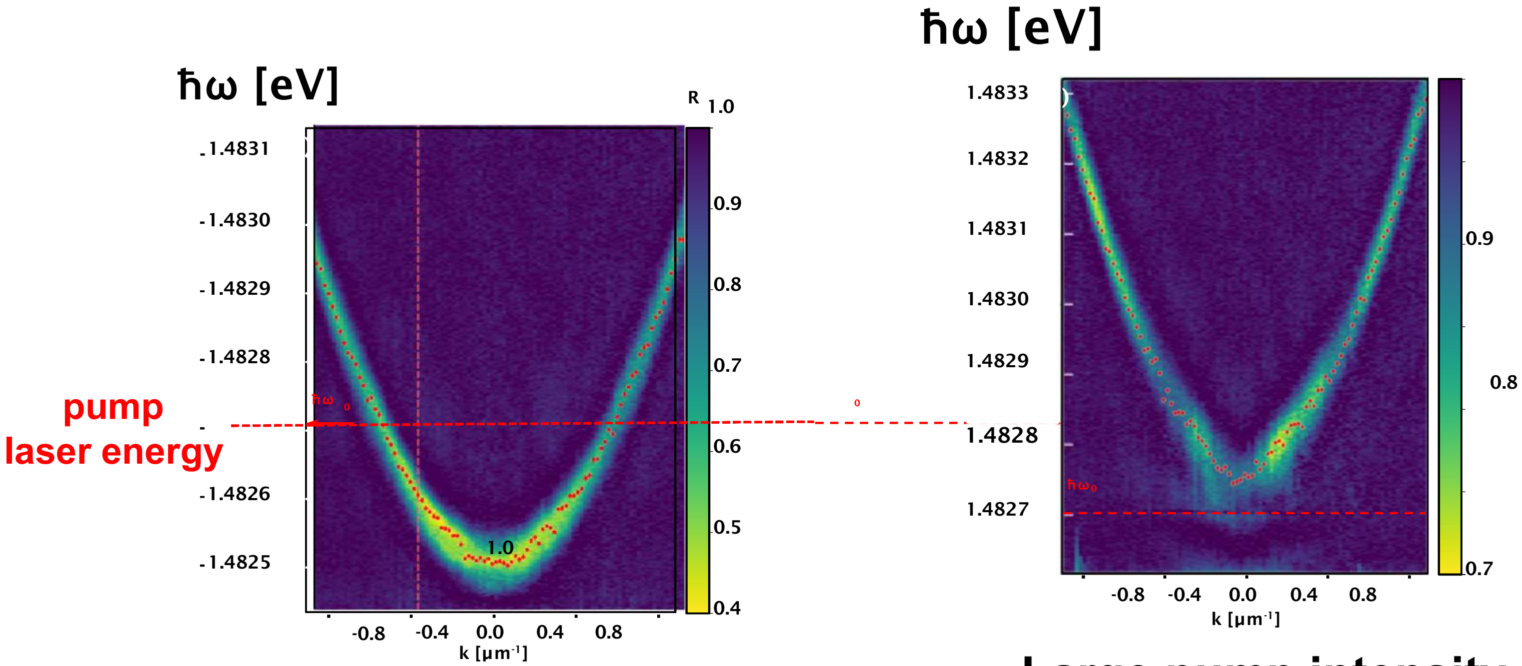
for each k the energy is scanned over ~100 GHz





- Probe absorption (transmission) when $(k_{pr}, \omega_{pr}) = (k_{pol}, \omega_{pol})$

Measured dispersion curves of probe field for various pump laser intensities

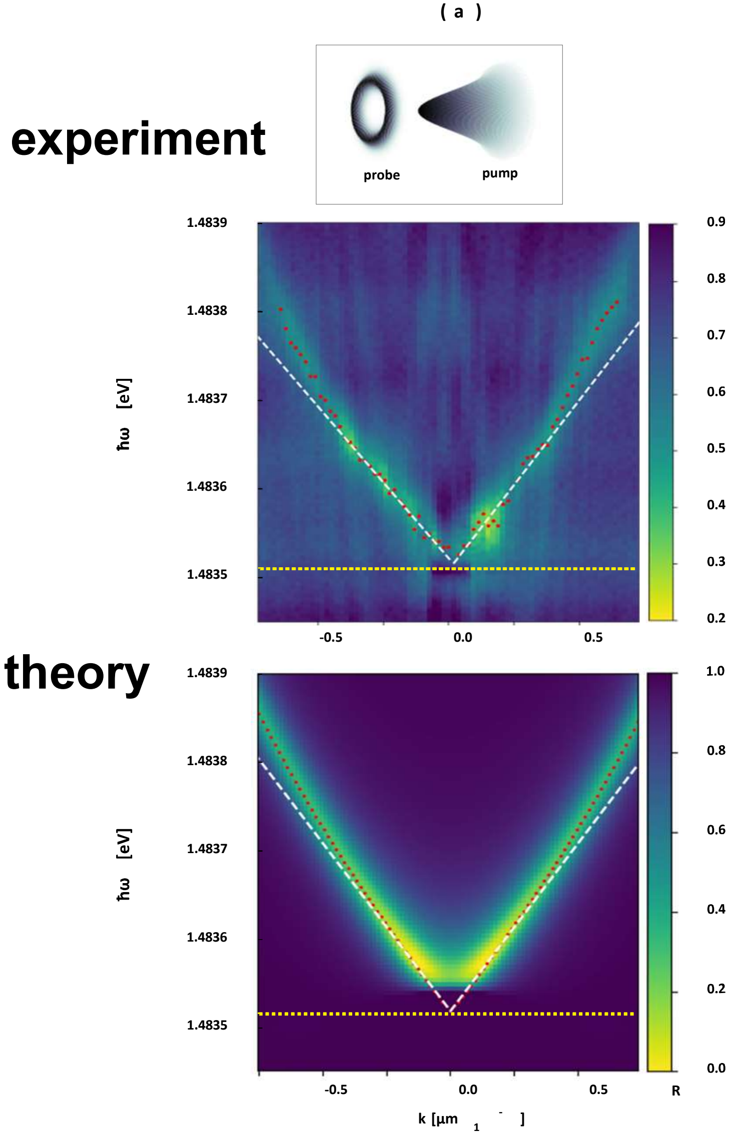


Very weak pump

Large pump intensity : strong blue shift

The linear dispersion cannot be observed directly in these conditions.
The problem comes from the Gaussian shape of the pump, which leads to a mixing of different pump intensities on the probe transmission

Demonstration of the linear dispersion



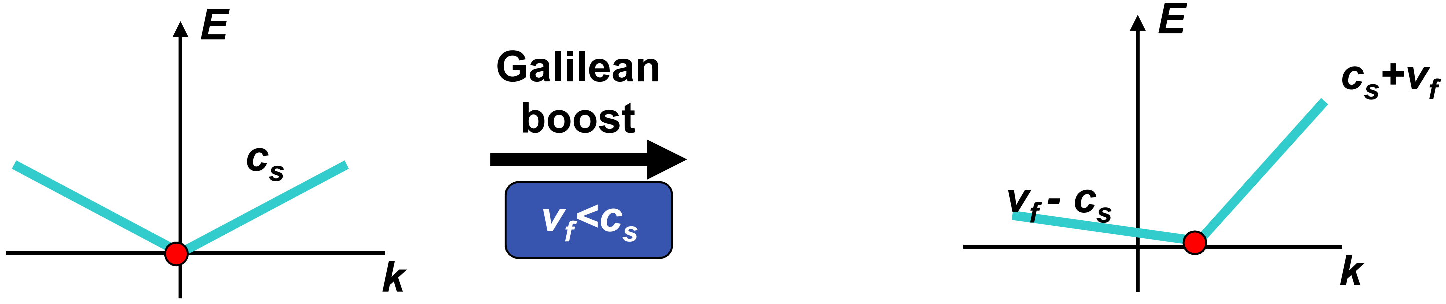
The problem can be solved by using **a probe with an annular shape** **that selects a homogeneous value of the pump intensity.**

adjusting the diameter of the probe ring allows to find the region for linear dispersion

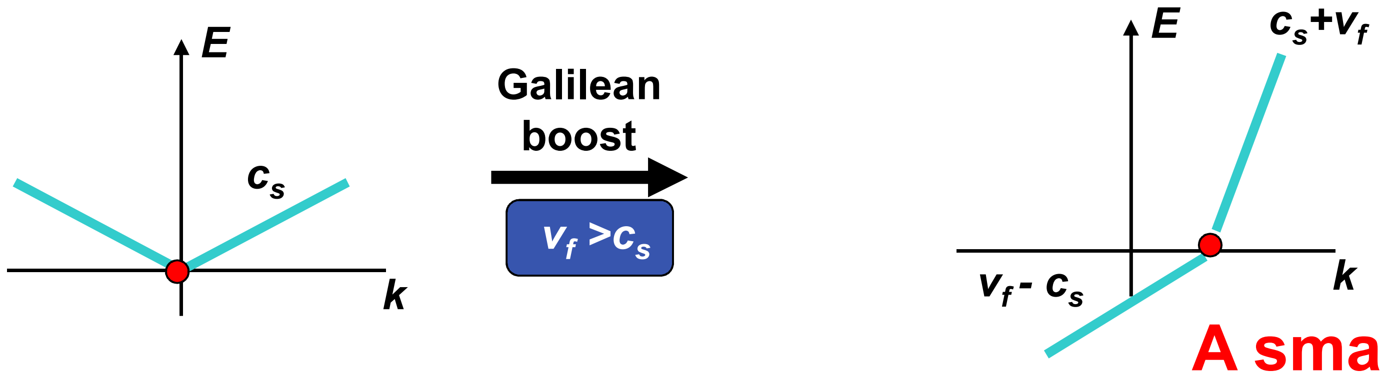
F. Claude et al, Phys. Rev. Lett. 129, 103601 (2022)

Quantum fluid effects in the supersonic case

superfluid



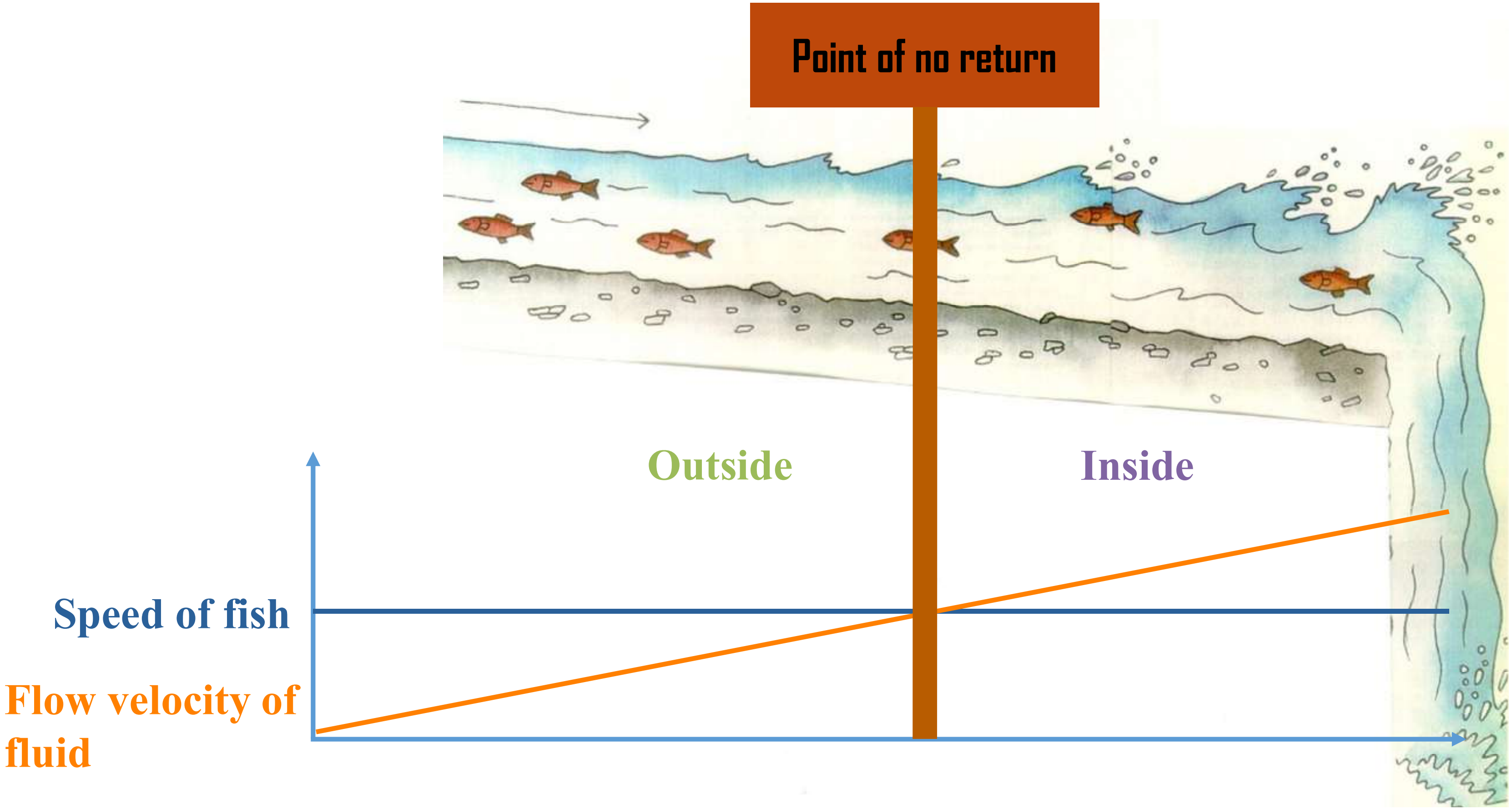
supersonic



A small perturbation cannot go back

Horizon at the limit between superfluid and supersonic regions

In the polaritons experiments, waves are limited as small fishes in a fast flow



Unruh PRL 46 1351 (1981)

Black Hole simulation

A **black hole** : a region of spacetime where gravity is so strong that nothing, not even light and other electromagnetic waves can escape it. The boundary of no escape is the **event horizon** .

Moreover, quantum field theory in curved spacetime predicts that event horizons emit **Hawking radiation**, correlated radiations emitted on each side of the horizon

Hawking radiation is black body radiation which is emitted by black holes, due to quantum effects near the event horizon.
Each Hawking particle is entangled with a partner particle in the black hole.

Similarity of the polariton field with a relativistic field

The polariton evolution equation for small perturbations can be rewritten with the Madelung transformation

Coordinate transformation $\psi = \sqrt{\rho} e^{i\phi}$ $\rho = \rho_0 + \rho_1, \Phi = \psi_0 + \psi_1$

$$-\partial_t \left(\frac{\rho_0}{c_s^2} (\partial_t \psi_1 + \boldsymbol{v_0} \cdot \nabla \psi_1) \right) + \nabla \cdot \left(\rho_0 \nabla \psi_1 - \frac{\rho_0 \boldsymbol{v_0}}{c_s^2} (\partial_t \psi_1 + \boldsymbol{v_0} \cdot \nabla \psi_1) \right) = 0$$

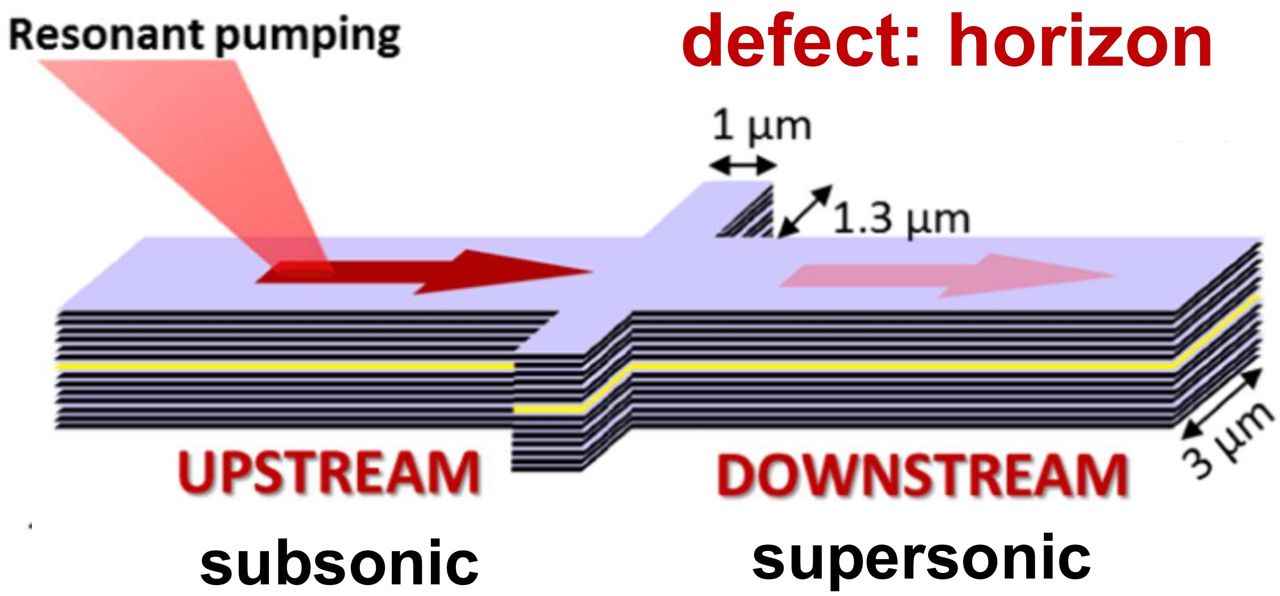
This equation is isomorphic to the wave equation of a massless scalar field propagating on a 2+1D curved spacetime

$$\frac{1}{\sqrt{-\eta}} \partial_\mu \left(\sqrt{-\eta}\, \eta^{\mu\nu} \partial_\nu \psi_1 \right) = 0.$$

$\eta^{\mu\nu}$ is the metric

This allows to **simulate a black hole.**
There is an event horizon when the flow velocity equals the speed of sound

Analog horizon in a polariton fluid



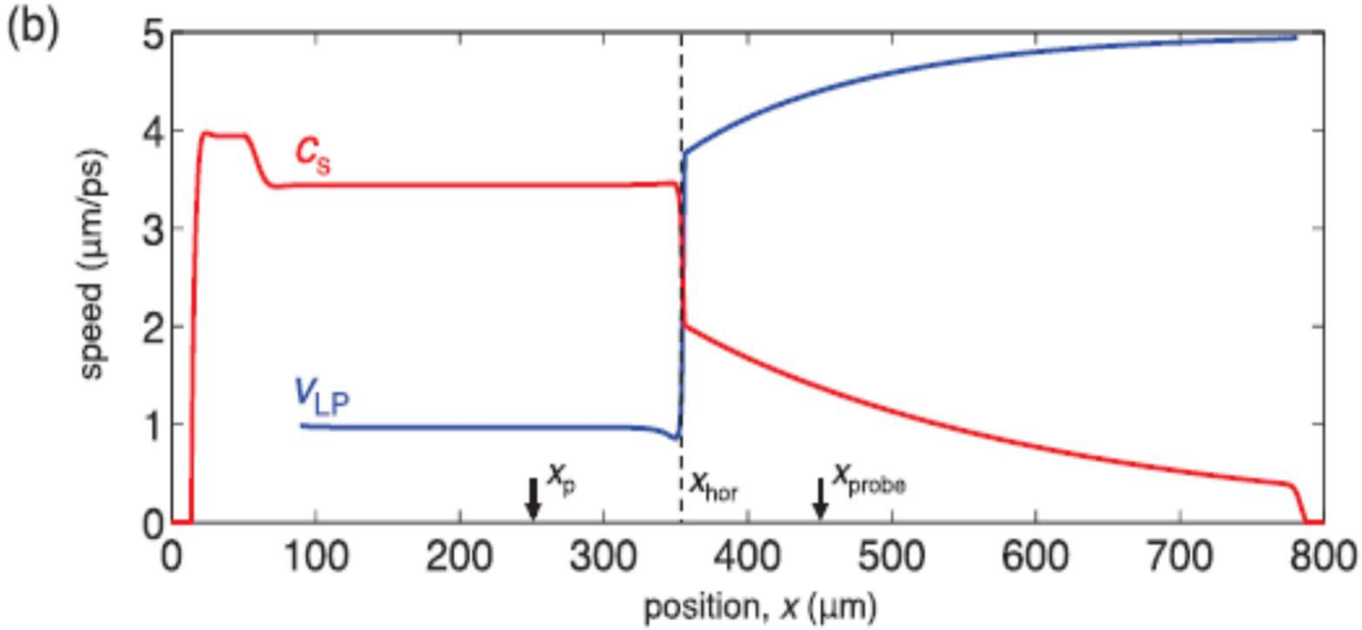
H. S. Nguyen, et al, PRL 114 036401 (2015)

The etched defect causes an acceleration of the flow and a decrease of the density giving a lower sound velocity

An optically engineered landscape can also create an acoustic horizon

Analogue horizon and black hole

V_{LP} : fluid velocity
C_s : sound velocity

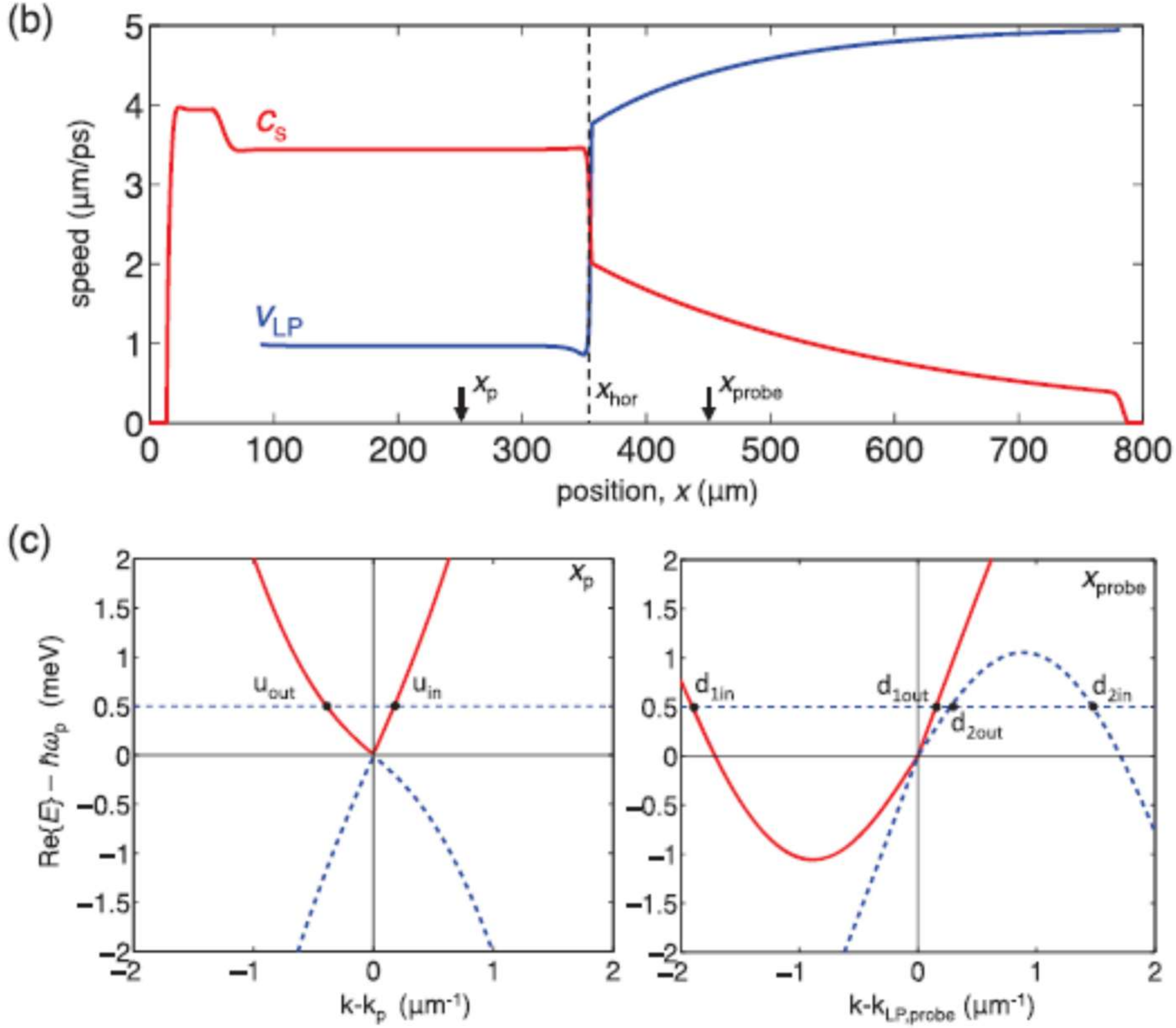


Subsonic: outside the black hole

Event Horizon

Supersonic : inside the black hole

For polaritons in the microcavity
dispersion curves on each side of the horizon

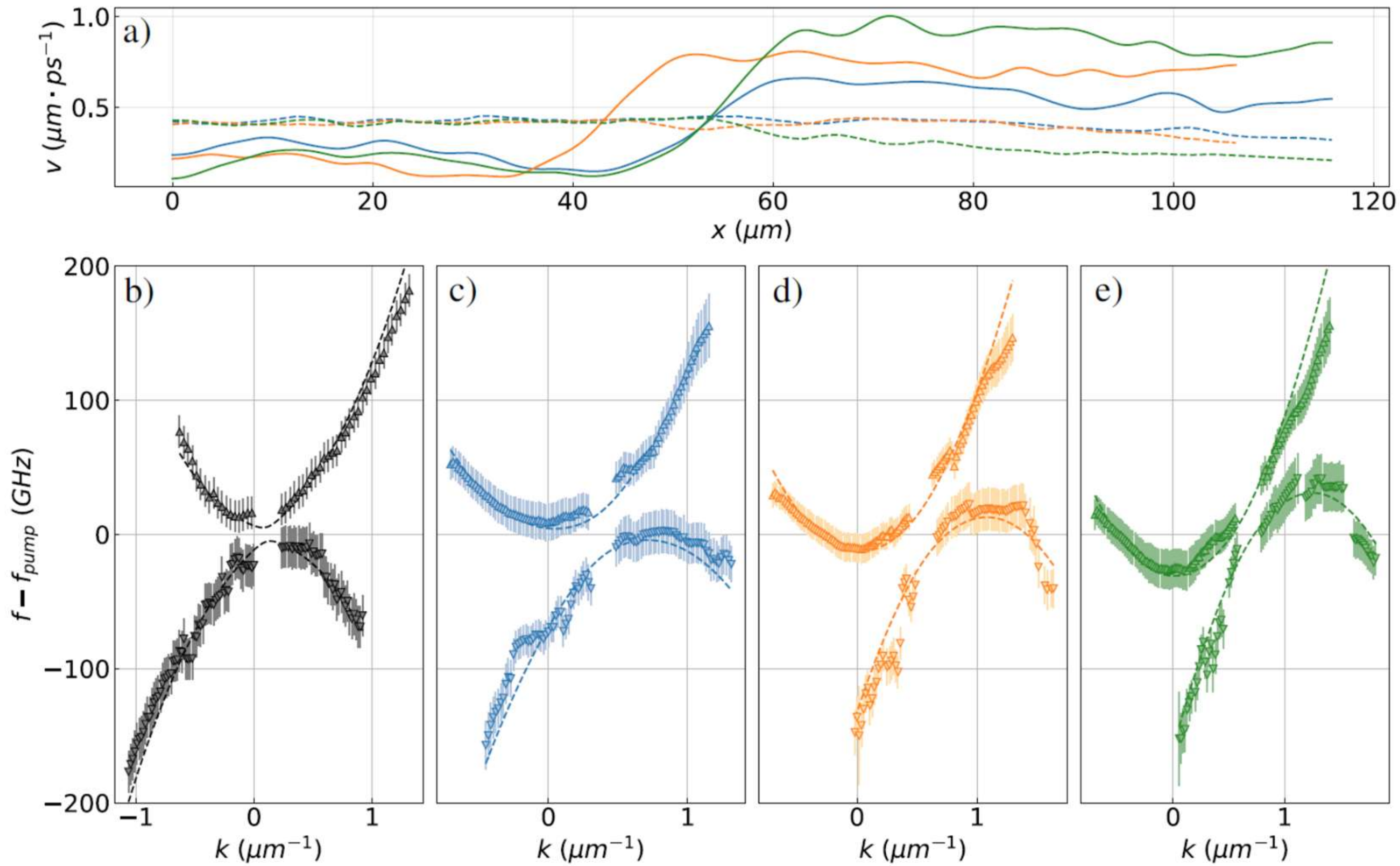


Solid red line : modes with positive norm

Dotted blue lines : modes with negative norm

Measurements : experimental dispersion curves for subsonic and supersonic cases

Velocities
——— fluid
------ sound

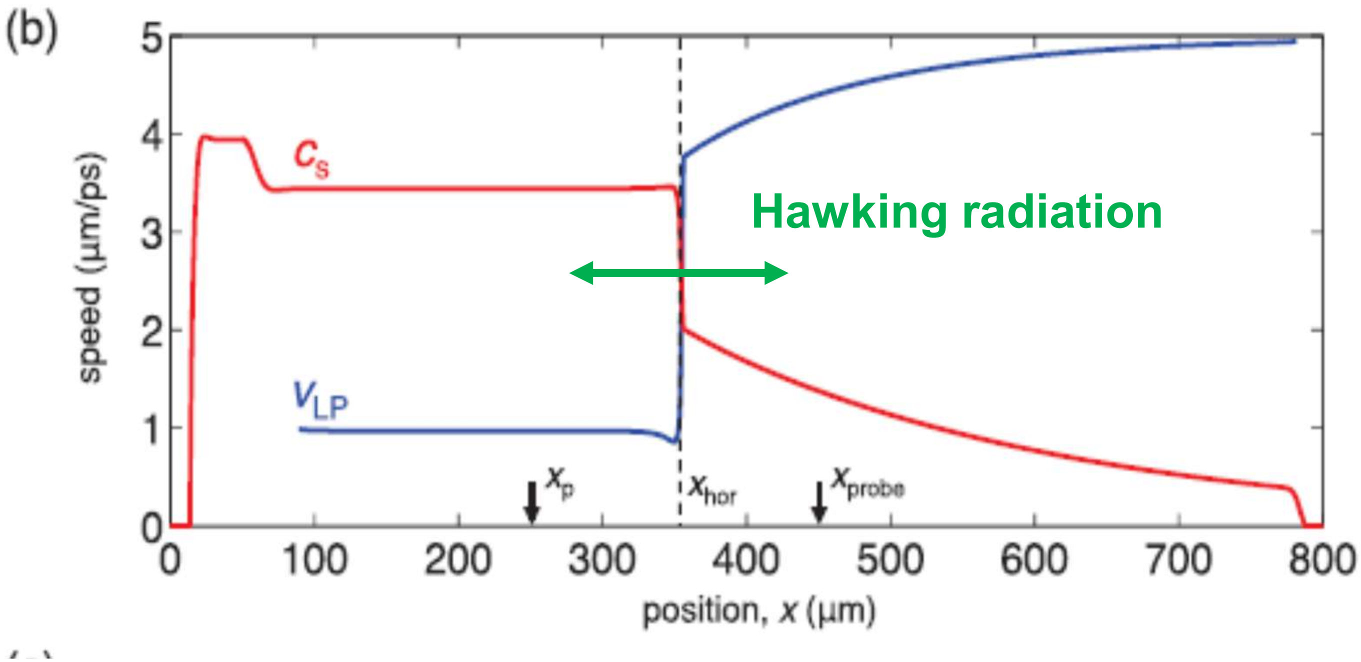


$\mathbf{v_{fluid}}$	0.15µm/ps	0.53µm/ps	0.70µm/ps	0.86µm/ps
$\mathbf{c_s}$	0.4µm/ps	0.4µm/ps	0.4µm/ps	0.24µm/ps

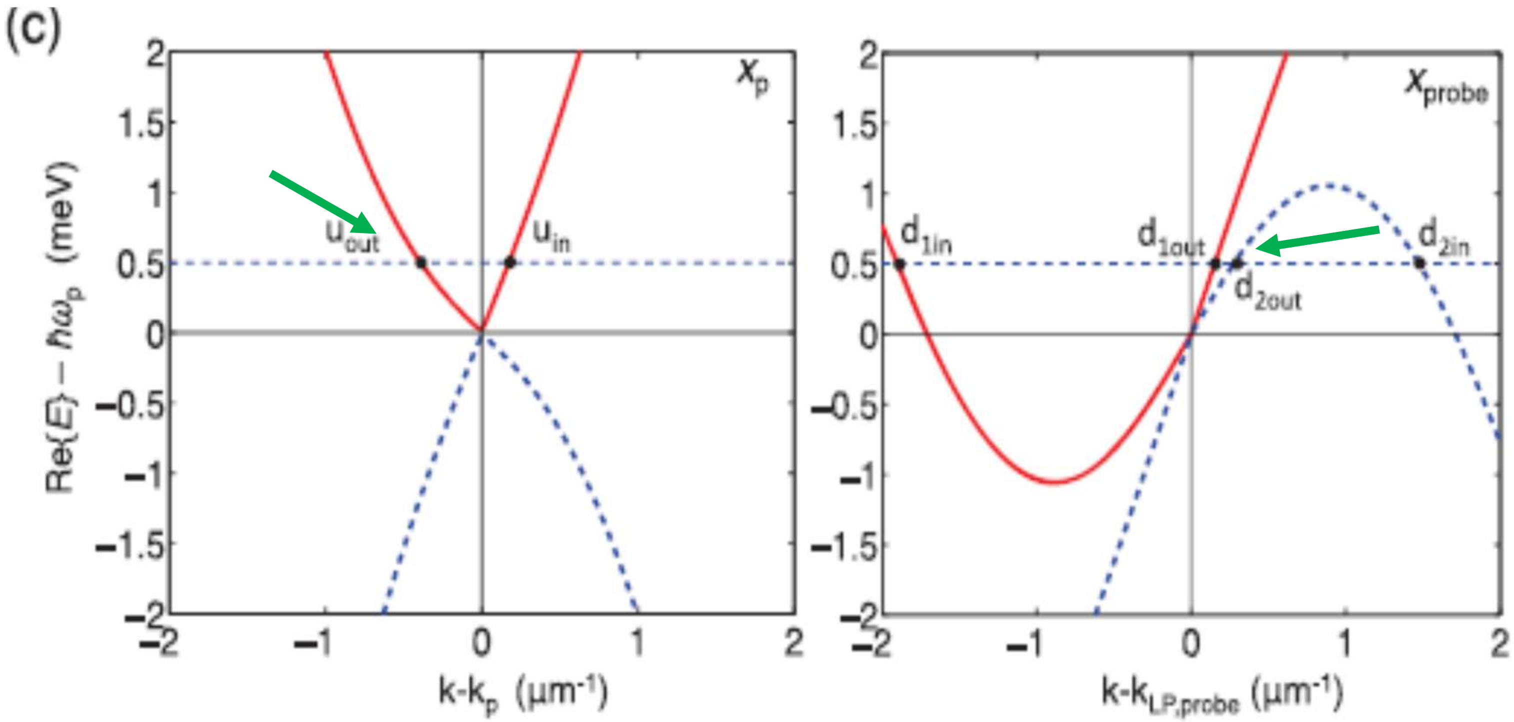
K Falque et al PRL 135 (2), 023401 (2025)

Hawking radiation

Correlated excitations emitted from each side of the horizon



Correlated Bogoliubov modes: Hawking radiation analogue



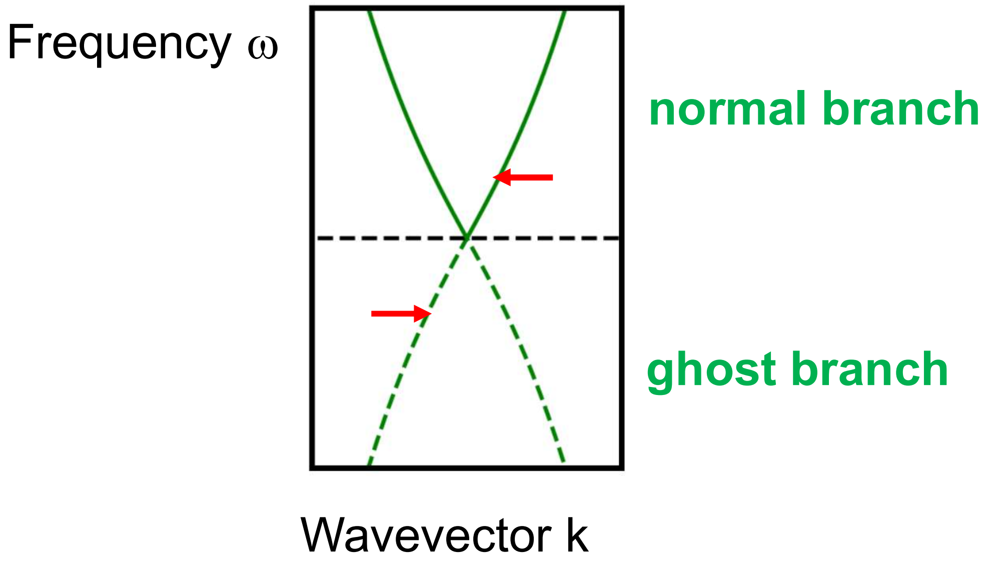
Solid red line : modes with positive norm
Dotted blue lines : modes with negative norm

Green lines : Hawking effect, expected from the density correlation function

Preliminary study of correlations

The idea is to investigate the noise correlations between the normal and the ghost beams

Pump at normal incidence : the fluid has zero velocity
Shape of the dispersion curve

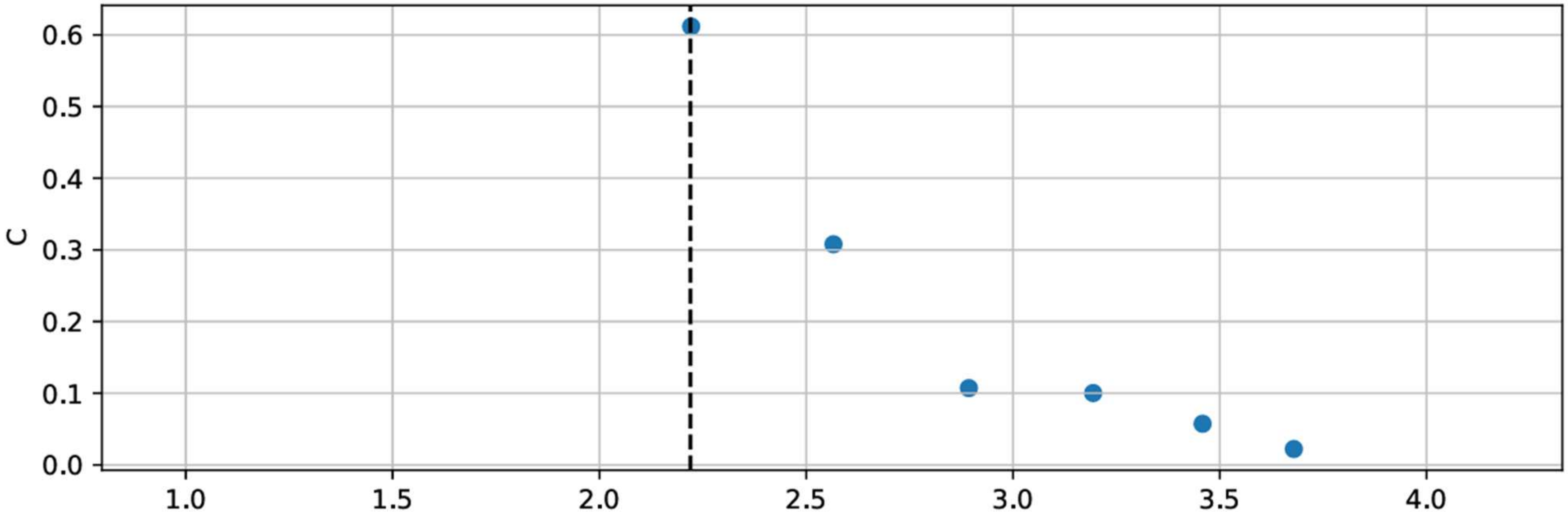


The noise is measured at the points k= +0.2 and -0.2 μ^{-1}

Normalized correlations

$$C_{k,-k} = \frac{[(S_k + S_{-k}) - S_-]}{2\sqrt{S_k S_{-k}}}$$

Correlations

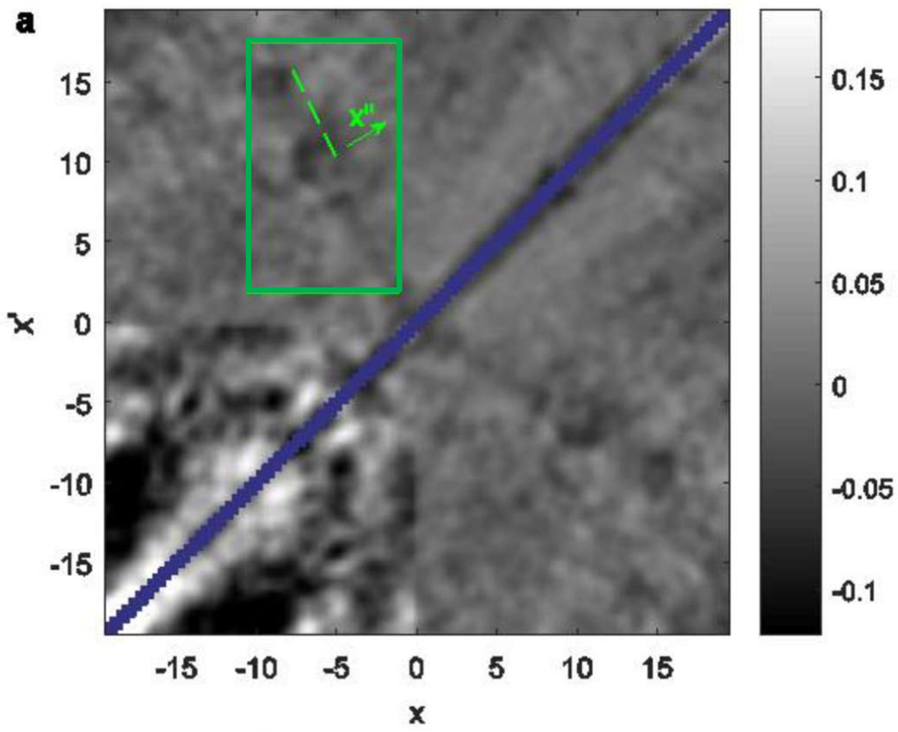


Pump intensity (a.u.)

Acoustic black hole in atomic Bose-Einstein condensate

Measured spatial density correlations: Hawking radiation

Steinhauer et al Nature 569, 688 (2019), Nat Phys 12 959 (2016)



Hawking radiation is also expected with polaritons

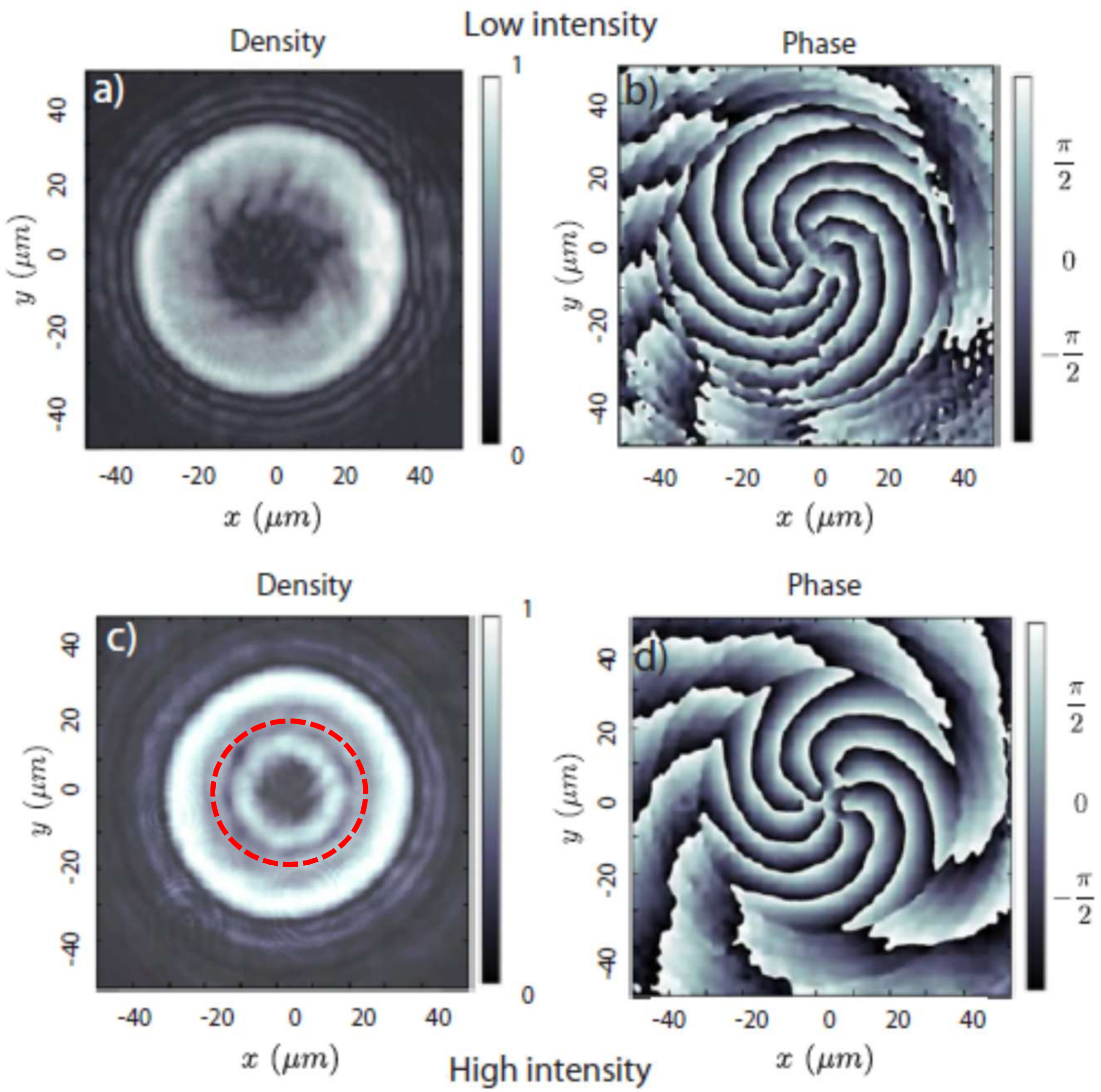
Quantum analogue of a Kerr black hole

Injection of angular momentum
in a polariton condensate

Injection scheme:

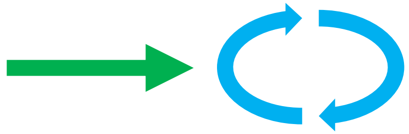
Laguerre-Gauss beam (*l* = 8)

A horizon can be achieved:
red dashed line

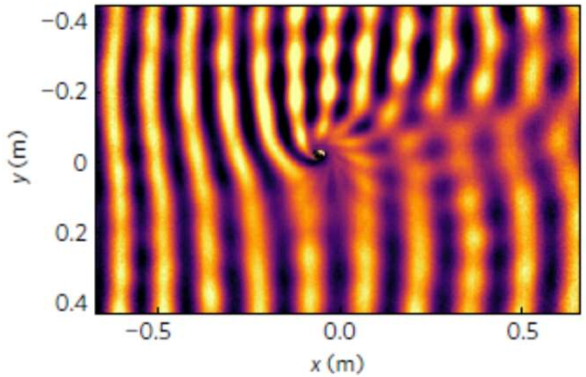


Amplification with Zel'Dovich effect

Scattering of a plane wave on a rotating black hole



Wave amplification on one side of the black hole can extract energy from the scatterer



Initial proposal with a rotating conduction cylinder

Demonstration in water :

Torres, Patrick, Coutant, Richartz, Tedford, Weinfurtner Nature Physics 13, 833 (2017)

Amplification of light in a nonlinear rotation medium *D. Faccio and EM Wright PRL 118 093901 (2017)*

experiment in progress with polaritons : plane wave hitting a Laguerre Gauss mode K Guerrero, K Falque et al arXiv preprint arXiv:2507.14539

Conclusion and perspectives

Polariton Quantum Fluids

- Superfluidity, Čerenkov regime
- Vortices, solitons, turbulence
- Sonic propagation of small pertubations

A new platform for quantum simulation

- Polaritons offer the possiblity of simulating static and rotating black holes
- Hawking radiation in analog black holes
- Penrose superradiance
- Zel'dovich amplification

Quantum fluids in microcavities - LKB

A. Bramati, Q. Glorieux

M. Jacquet,

F. Claude, K. Falque, K. Guerrero

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Thank you for your attention