Laboratoire Kastler Brossel
Physique quantique et applications

ENS SORBONNE UNIVERSITÉ COLLÈGE DE FRANCE CNRS

PhoQuS Photons for Quantum Simulation

QUANTUM FLAGSHIP

Observation of a diffusive Goldstone mode in a driven dissipative Polariton quantum fluid

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MajuLab

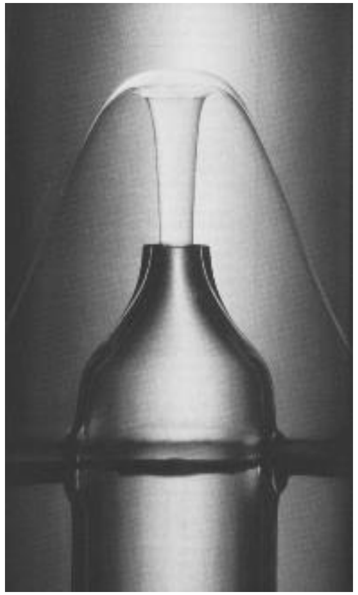
IUF

100 Years of Quantum Physics

2025 QUY NHON

Quantum Fluids

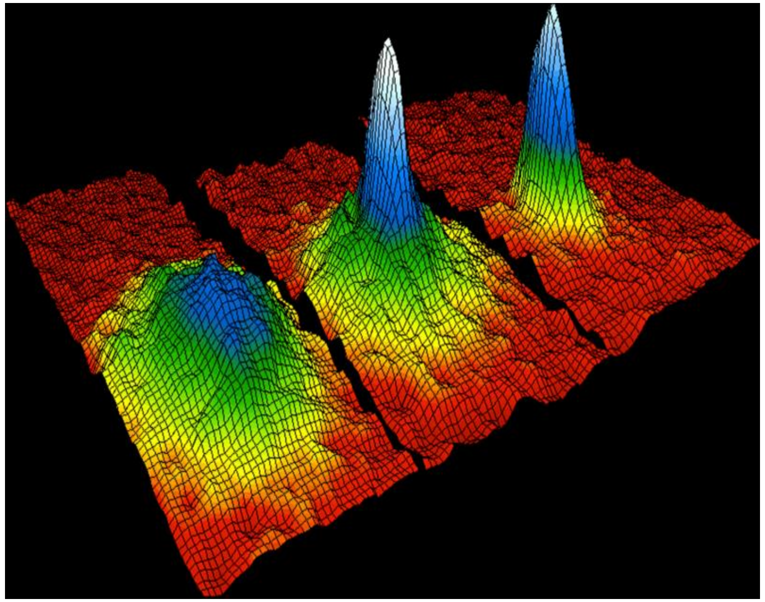
Liquid Helium



Helium-4 (boson)
Helium-3 (fermion)

J.F. Allen (1971)

Ultracold atomic condensates



Rubidium-87 (boson)
Lithium-6 (fermion)

See e.g.,
A. J. Leggett, Quantum Liquids: Bose Condensation and Cooper Pairing in Condensed Matter Systems (2006)
S.Giorgini, L.Pitaevskii, and S.Stringari, Rev. Mod. Phys. (2008)

What about Light

Light field/beam are composed by a large number of photons but in the vacuum photons do not interact

Optics is typically dominated by single particle behaviuor, however..

- Can we attribute a mass to the photons?
- Can photon-photon interactions make light behave as a fluid?

•In photonic structures

•$\chi^{(3)}$ non linearities ⇨ photon-photon interactions
•Spatial confinement ⇨ effective photon mass

Collective behaviour of a photonic quantum fluid

Outline

Collective excitations of a polariton fluid

- Introduction
- Bogoliubov dispersion

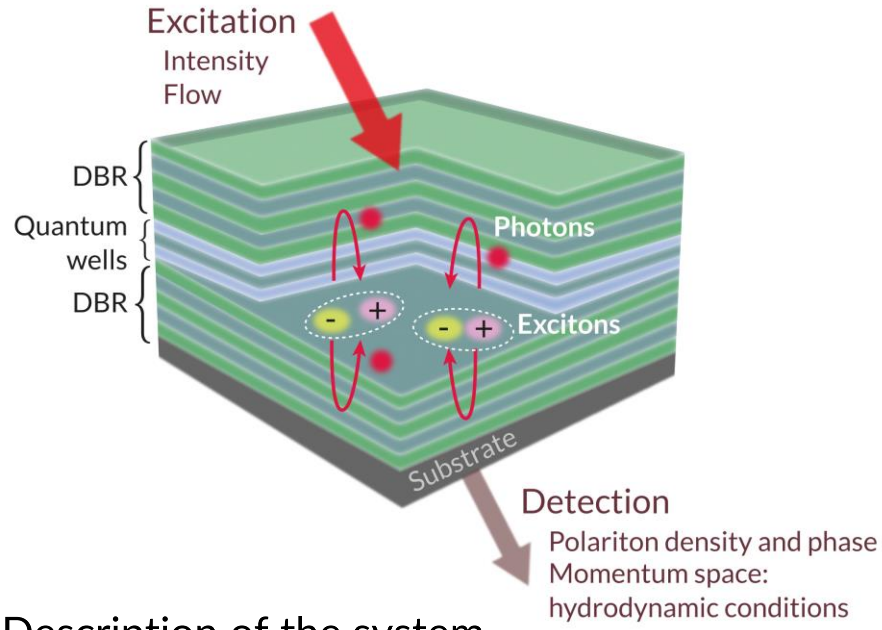
Goldstone mode in a parametrically driven polariton fluid

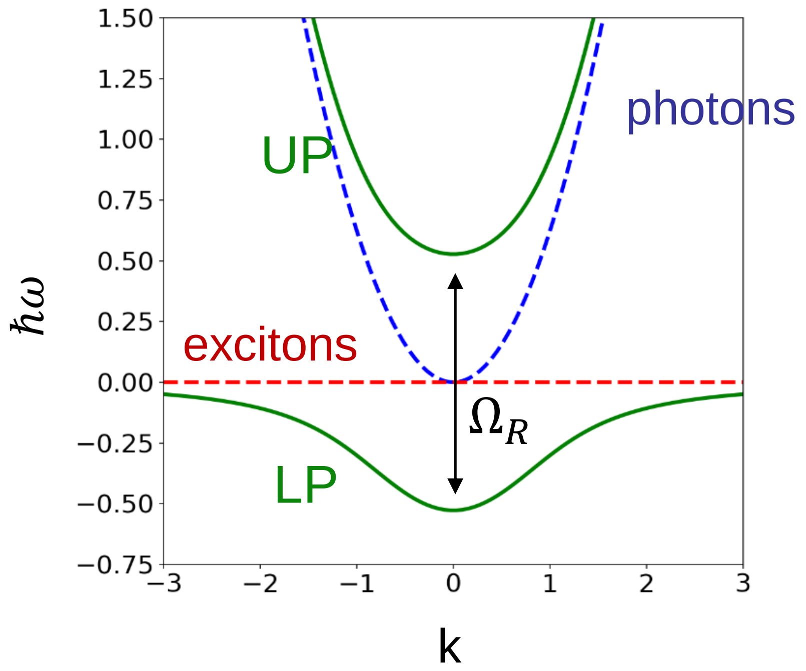
- Spontaneous symmetry breaking
- Phase fixing: Goldstone mode destruction

Semiconductor microcavity

- **Polaritons:** quasi-particles resulting from the *strong coupling* of cavity *photons* with quantum wells *excitons*

C. Weisbuch et al. PRL 69, 3314 (1992)





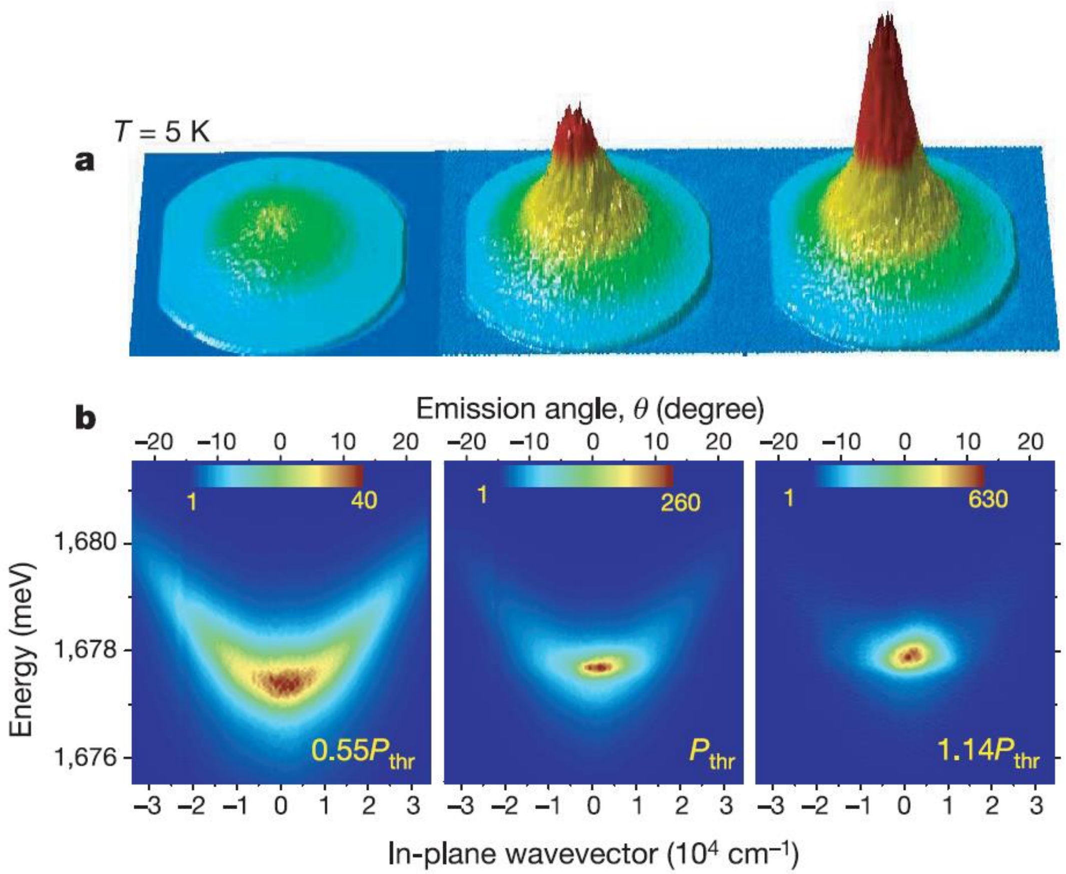
- Description of the system
  - Photons in a microcavity: effective mass from confinement
  - Quantum-well excitons: interactions

- **New eigenstates:** upper & lower polaritons
  - Half-matter, half-light particules

- Strong coupling regime: $\Omega_R \gg \gamma_c, \gamma_X$
  - Photons/Excitons energies anticrossing

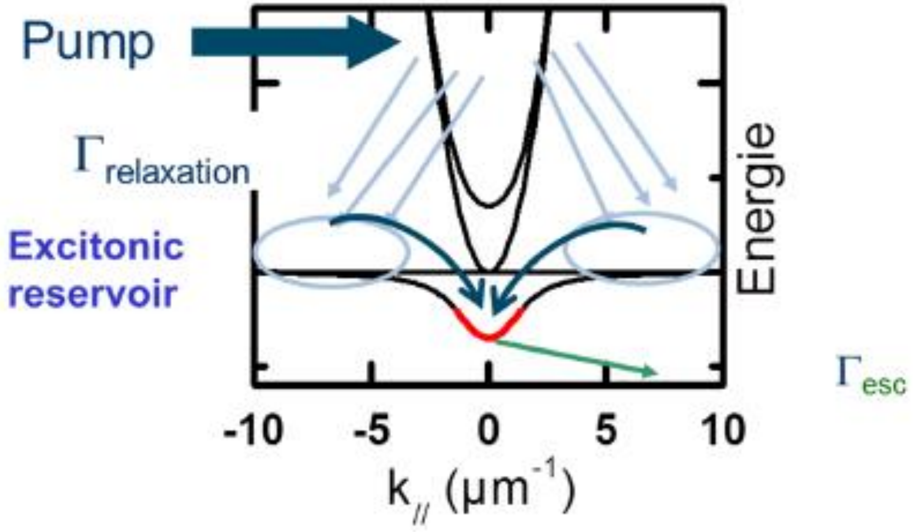
Polaritons are weakly interacting composite bosons

Polariton BEC



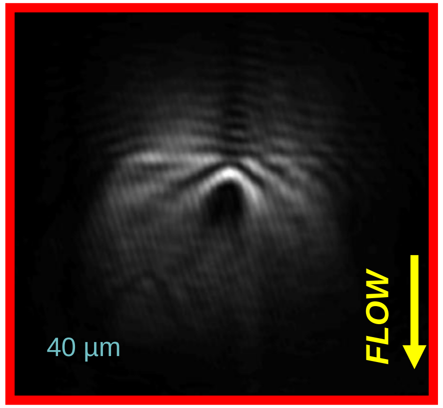
Kasprzak *et al.* Nature, **443**, 409 (2006)

Non resonant excitation

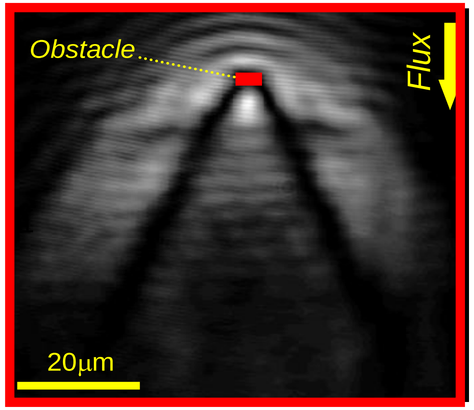


Carusotto&Ciuti, Rev. Mod. Phys.85, 299 (2013)

Hydrodynamics of polariton quantum fluids

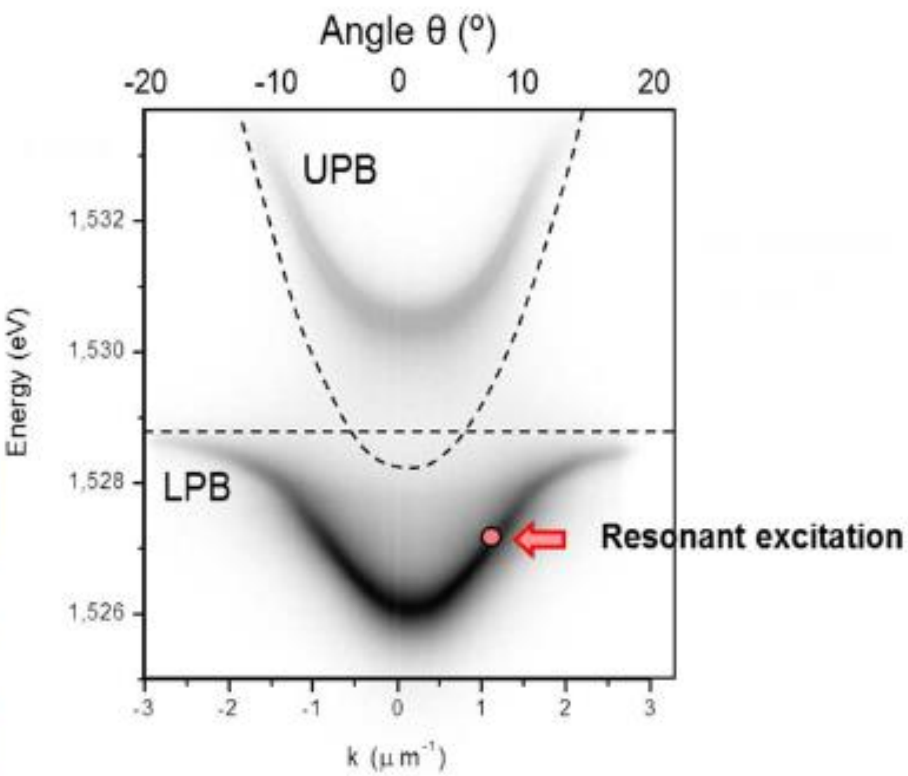


Superfluidity and Cerenkov waves
(*Nature Physics 2009*)



Dark solitons and vortices
(*Science 2011, Nature Photonics 2011*)

Resonant excitation



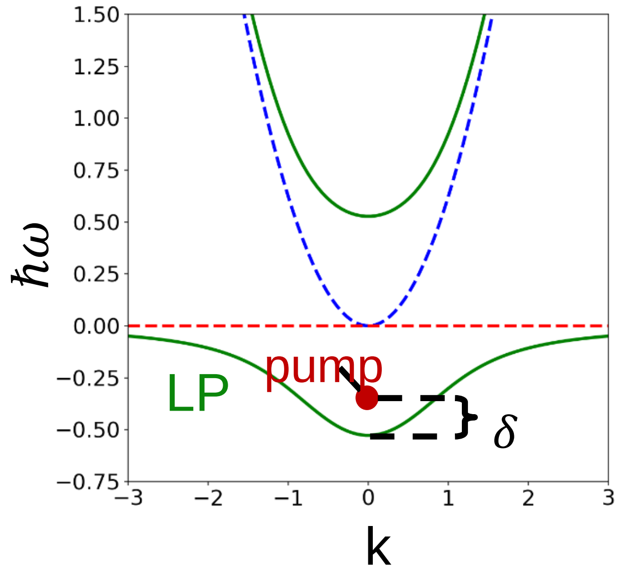
Dynamics of the polariton fluid

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

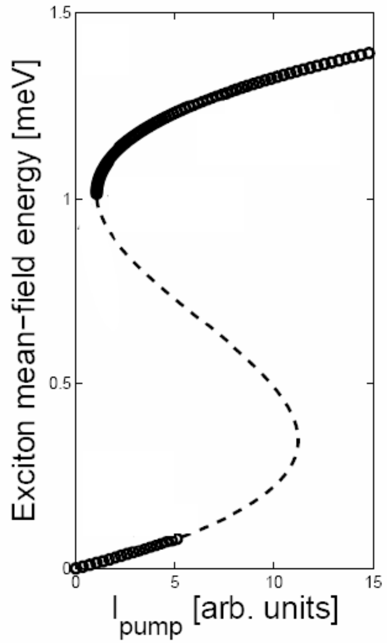
kinetic energy — external potential — non-linear interaction — losses and pumping

Driven-dissipative Gross-Pitaevskii equation: Out-of-equilibrium system

Steady state solutions: Bistability



- Bistability if $\delta > \frac{\sqrt{3}}{2}\gamma$



Bogoliubov modes

- Collective excitations = perturbations on top of polaritons
- **Driven-Dissipative nature**: dependence with the driving field

- Bogoliubov theory

1) GPE linearization around its steady state solution

$$\psi(r,t) = \psi_0(r,t) + \delta\psi(r,t)$$

2) Equation of motion of the weak perturbations
   - $\mathcal{L}_{Bog}$ Bogoliubov operator

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

3) Dispersion relation
   - quasi-resonant excitation
   - positive/negative solutions

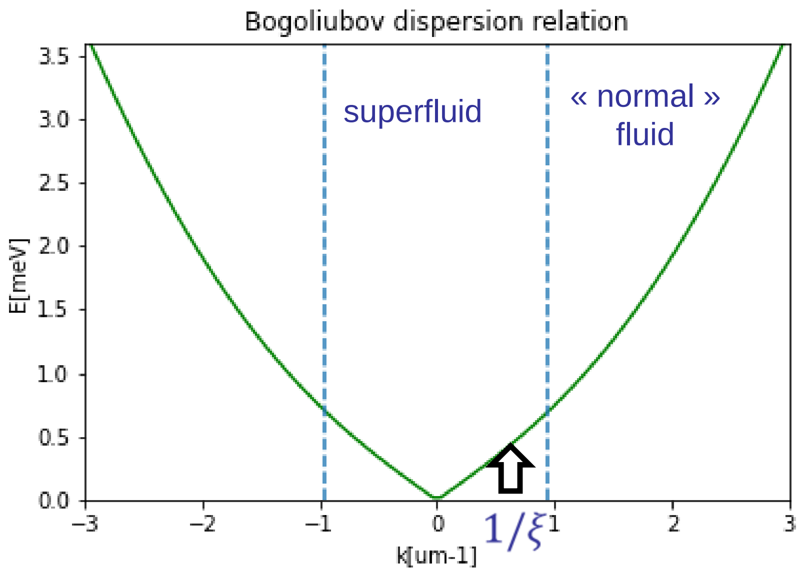
$$\hbar\omega_{Bog}(k) = \pm\sqrt{\left(\frac{\hbar^2 k^2}{2m} - \delta + 2gn\right)^2 - (gn)^2} - i\gamma$$

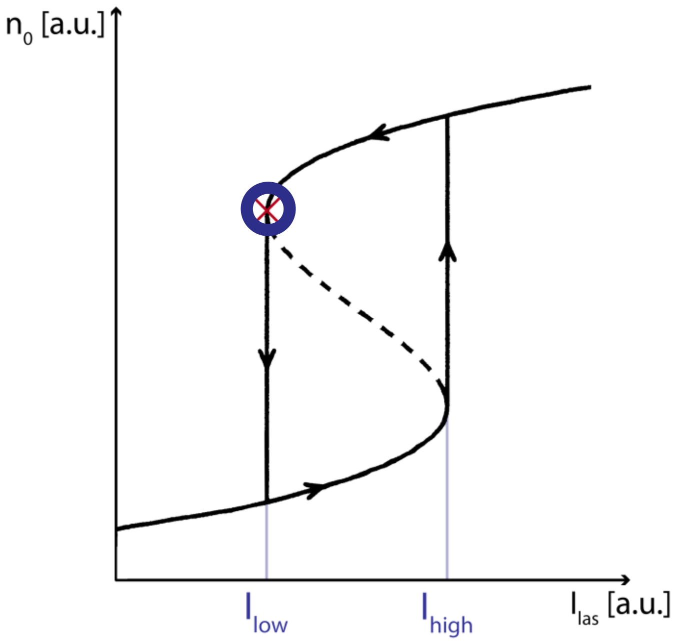
Bogoliubov modes

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

Sonic Point

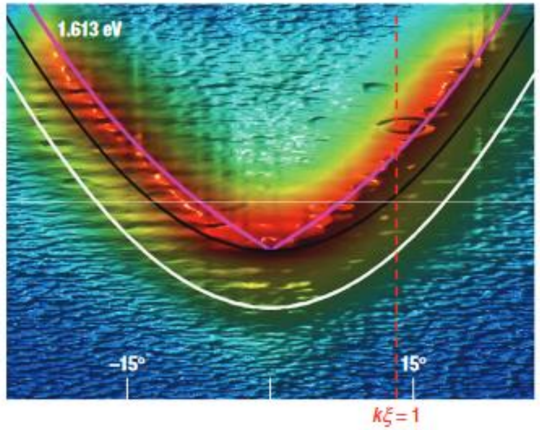
- Turning point $\delta = gn$
- For low k $\hbar\omega_{Bog}(k) = c_s k$
- Speed of sound: $c_s = \sqrt{gn/m}$



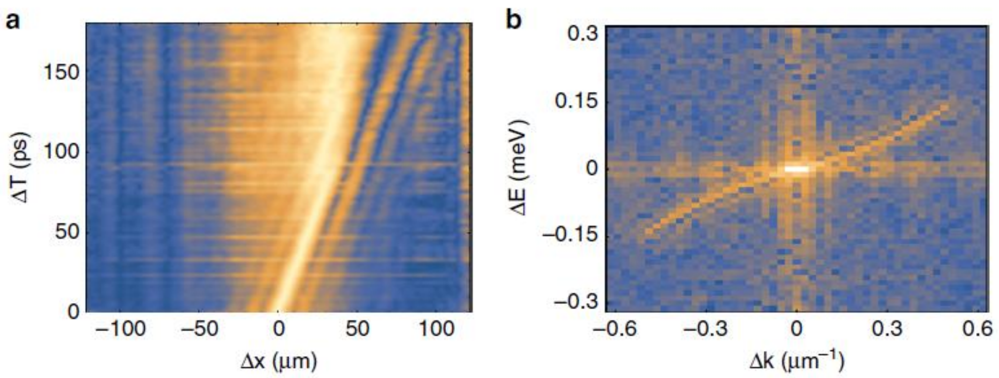


Measurements of the Bogoliubov dispersion

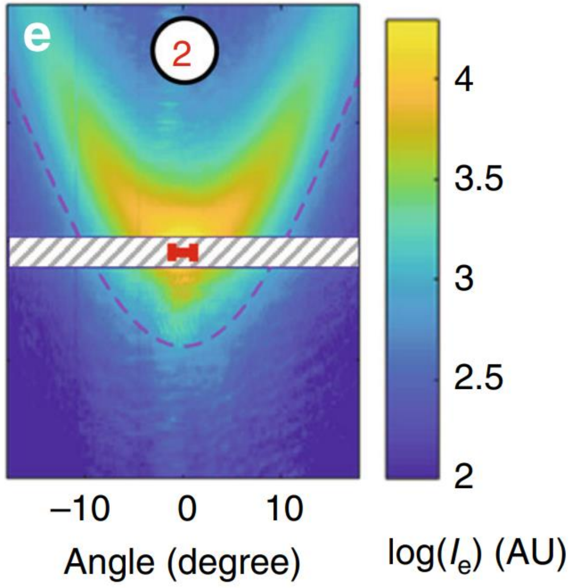
S. Utsunomiya et al. Nat. Phys. **4**, 700 (2008) PL
V. Kohnle et al. PRB **86**, 064508 (2012) FWM
P. Stepanov et al., Nat. Com. **10**, 3869 (2019) PL
M. Pieczarka et al., Nat. Com. **11**, 429 (2019) PL
D. Ballarini et al., Nat. Com. 11, 217 (2020) FT of g^1



S. Utsunomiya et al. Nat. Phys. **4**, 700 (2008)



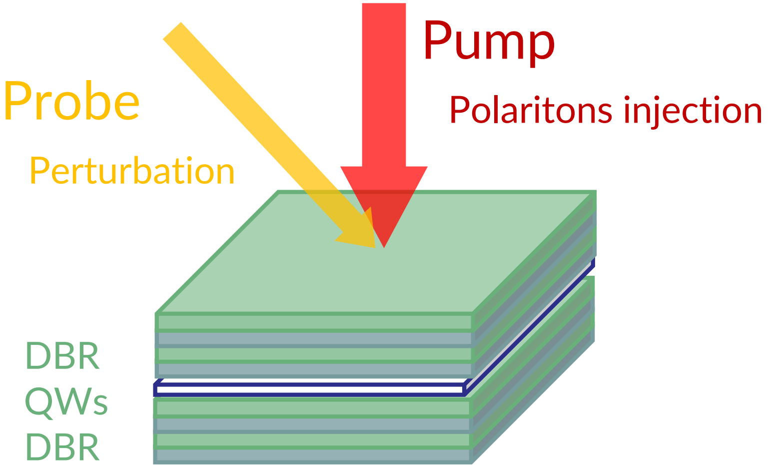
D. Ballarini et al. Nat. Comm. **4**, 700 (2020)

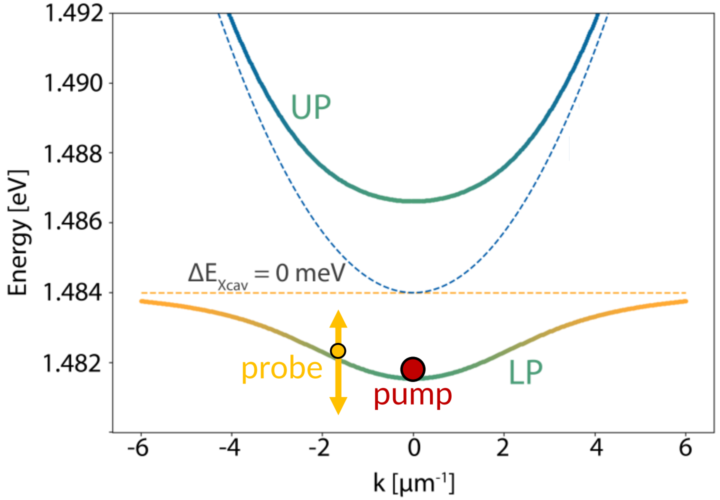


P. Stepanov et al., Nat. Com. **10**, 3869 (2019)

Coherent probe spectroscopy

- **Probe:** excitation of small perturbations on top of the polaritons fluid
  - @ different k_{pr}
  - energy scan: $\Delta\omega_{pr}$ ~100Ghz

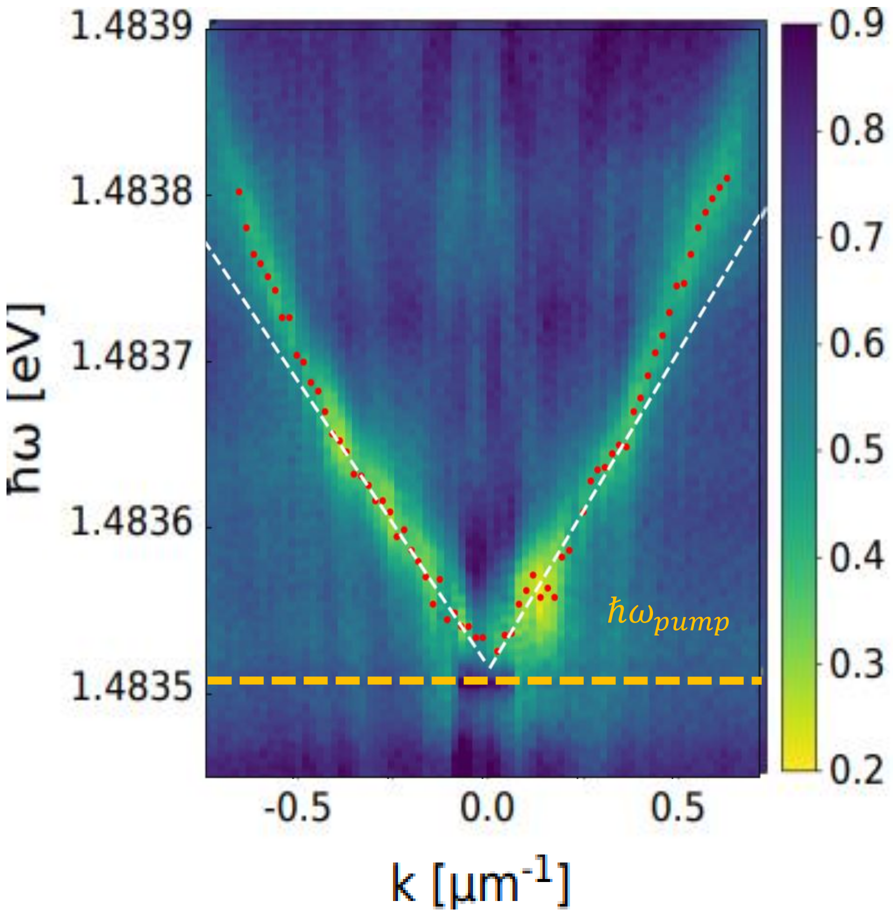




- **Detection:** (k, ω) of the probe transmission peaks
- The probe is modulated at 5MHz
- Detection at 5MHz via a spectrum analyser to filter out the pump
  - δE resolution fixed by the laser linewidth
  - δk resolution fixed by the k-space filtering/transmission (DMD)

Sonic dispersion

- Reflectivity map of the probe vs (k, $\hbar\omega$) = Bogoliubov dispersion relation



- Sonic dispersion
  - $k\xi \gg 1$ parabolic dispersion
  - $k\xi \ll 1$ sonic dispersion: fit of the speed of sound c_s

Superfluidity

F. Claude et al., Phys. Rev. Lett. 129, 103601 (2022)
F. Claude et al., Phys. Rev. B, 107, 174507 (2023); Viewpoint in Physics

Study of a driven dissipative phase transition: Observation of a diffusive Goldstone Mode

Goldstone Theorem

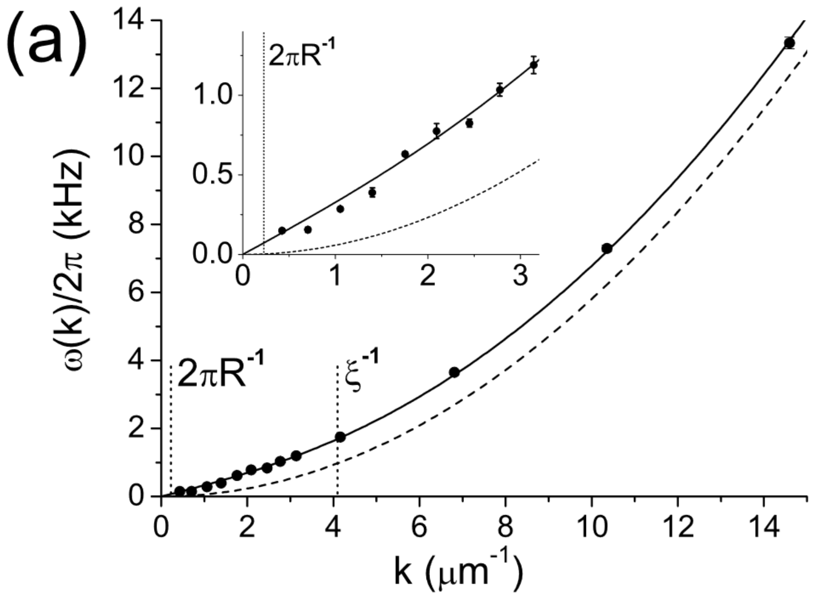
- Spontaneous breaking of a continuous symmetry is accompanied by the appearance of a Goldstone mode

Nambu *et al* Phys Rev **122** 345 (1961)
Goldstone Il Nuovo Cimento **19** 154 (1961)
Goldstone *et al* Phys Rev **127** 965 (1962)

The case of equilibrium Atomic BEC

The spontaneous symmetry breaking of the U(1) phase symmetry at the BEC threshold triggers the appearance of a Goldstone mode which is the Sound Mode

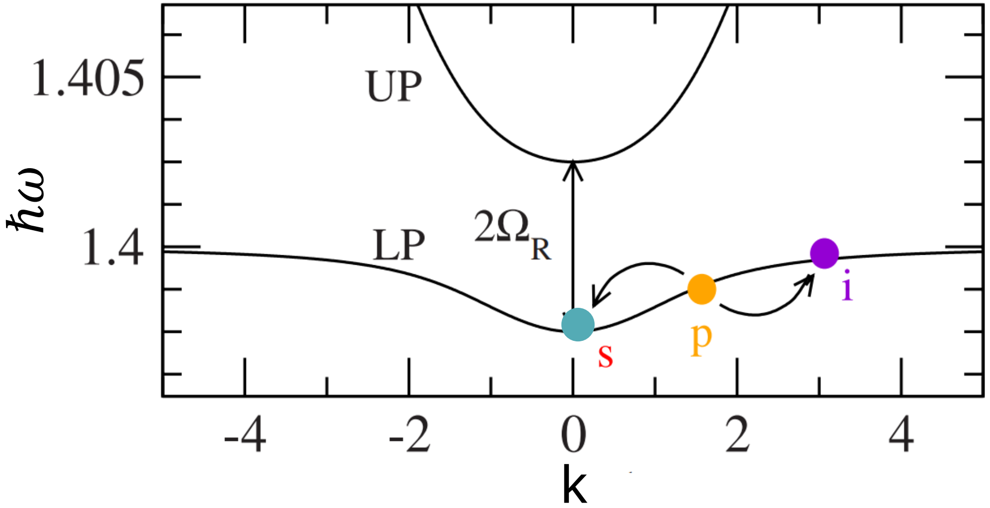
Propagative Goldstone Mode: the collective excitations propagate at the speed of sound in the fluid



Steinhauer *et al* PRL **88** 120407 (2002)

Polariton Optical Parametric Oscillation (OPO) regime

- **OPO:** conversion of pump (P) polaritons into signal (S) and idler (I) polaritons



- Phase matching condition:
  - $k_i = 2k_p - k_s$
  - $\omega_i = 2\omega_p - \omega_s$

- **Hamiltonian invariant under simultaneous and opposite phase rotation of S & I:**

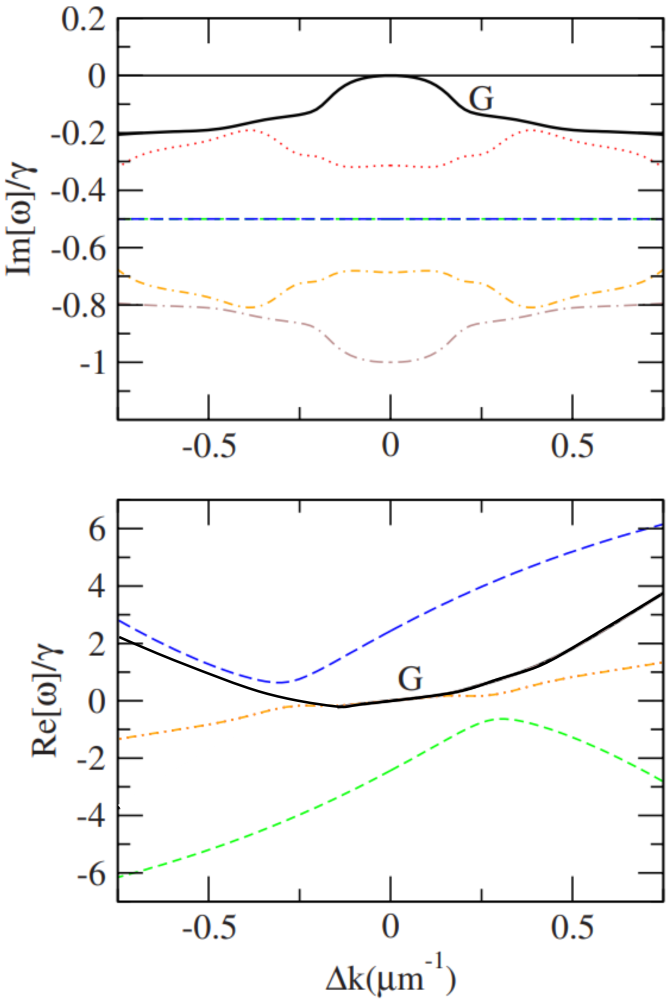
$$S \rightarrow S\, e^{i\phi}, \quad I \rightarrow I\, e^{-i\phi}$$

1- The sum of the S & I phases is fixed, the phase difference is free
2- Above threshold of parametric oscillation: phase difference randomly selected by spontaneous breaking of the phase rotation symmetry
3- Appearence of a Goldstone modes in S & I

M. Wouters et I. Carusotto, PRA, 76, 043807 (2007)

Goldstone Mode

- Bogoliubov dispersion of the Signal condensate



- Spectral signatures at low-k: $\omega_{exc}(k) \simeq -i\frac{c^2}{\Gamma}k^2$

  – $Im(\omega_{exc}(k=0)\,) = 0$ **Narrowing of the linewidth**

  – $Re(\omega_{exc}(k=0)) = 0$ **Plateau for a finite range of k**

- Specific feature of driven-dissipative systems:

Goldstone mode is DIFFUSIVE

M. Wouters et I. Carusotto, PRA, 76, 043807 (2007)

Goldstone mode

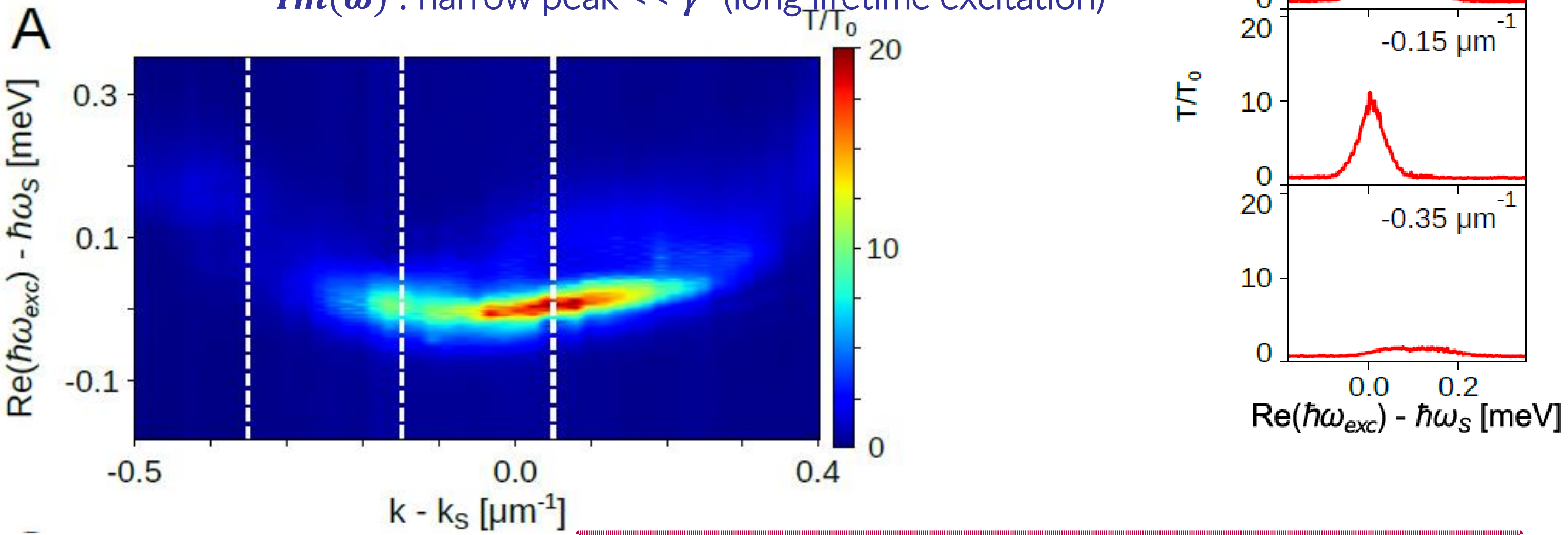
Measurement of the Bogoliubov dispersion of the signal condensate

High-k: $\boldsymbol{Re(\omega)}$: parabolic dispersion

$\boldsymbol{Im(\omega) = \gamma}$

Low-k: $\boldsymbol{Re(\omega)}$: plateau (diffusive mode)

$\boldsymbol{Im(\omega)}$: narrow peak << $\boldsymbol{\gamma}$ (long lifetime excitation)

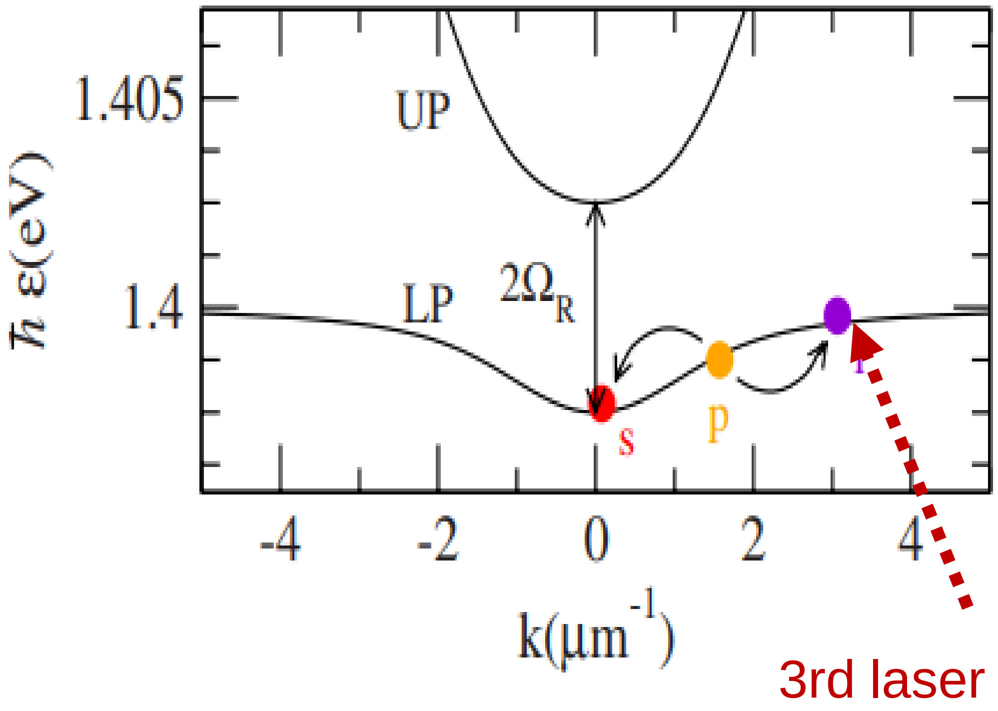


Have we observed spontaneous symmetry breaking?

Destruction of Goldstone mode

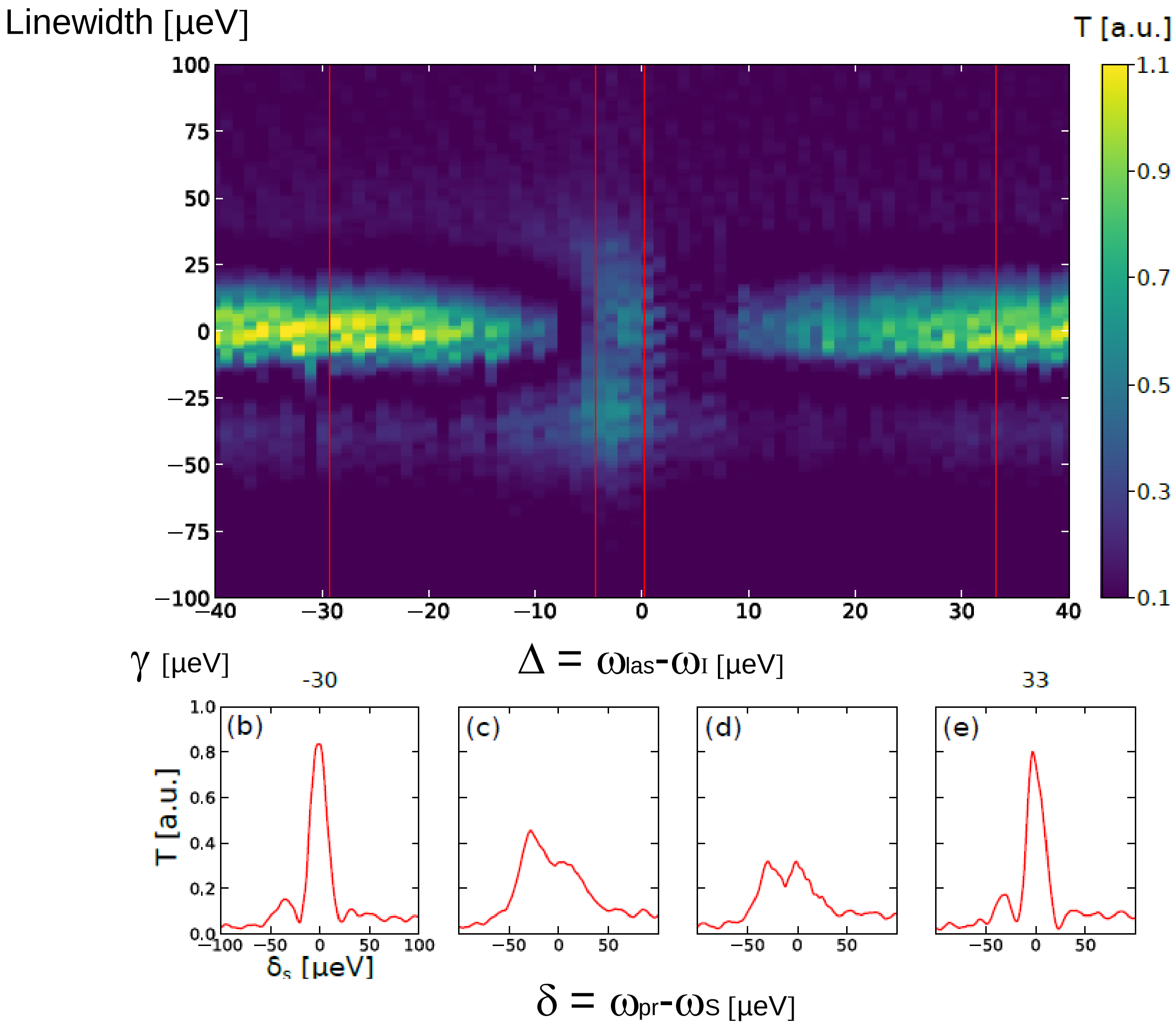
- Addition of a 3rd laser beam
  - At k_i and ω_i
  - Phase fixation of the I mode

- The phase symmetry breaking is forced by the 3rd laser
  - No more spontaneous symmetry breaking
  - Goldstone destruction



Destruction of Goldstone mode

- Addition of a 3rd laser beam on the Idler
  - Scan of the S condensate with the probe @ $k = 0\ \mu m^{-1}$
  - Tuning of the third laser energy



- $\hbar\omega_{las} = \hbar\omega_I$:
  - Broadening of the linewidth & decrease of the transmission peak
  - Destruction of the Goldstone mode

Claude F *et al.*, Nat. Phys. (2025).
https://doi.org/10.1038/s41567-025-02902-z

Bogoliubov dispersion: resonant vs parametric excitation

Resonant case

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

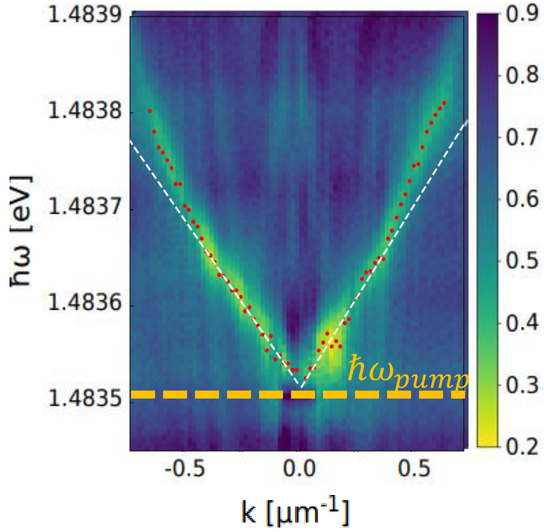
Parametric case

$$\omega_{\pm}(k) = -\frac{i\Gamma}{2} \pm \sqrt{\omega_{Bog}(k)^2 - \frac{\Gamma^2}{4}},$$

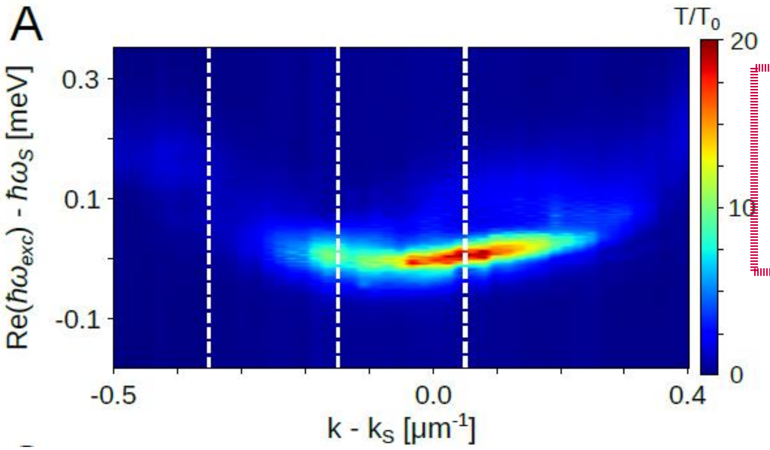
Low k regime

$$\hbar\omega_{Bog}(k) = c_s k$$

$$\omega_{exc}(k) \simeq -i\frac{c^2}{\Gamma}k^2$$



Superfluid like behaviour, propagative Goldstone mode

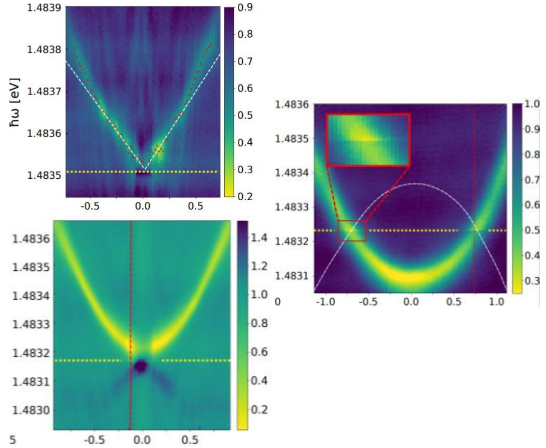


Diffusive Goldstone mode due to dissipation

CONCLUSION & OUTLOOKS

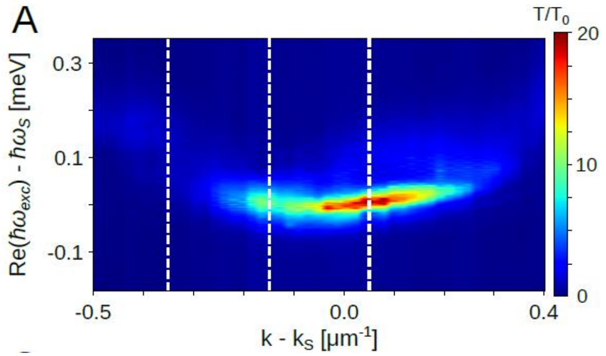
- High resolution spectroscopy experiment in a polariton fluid

  Claude F *et al.*, PRL 129 103601 (2022)
  Claude F *et al.*, PRB 107 174507 (2023) **Viewpoint in Physics**



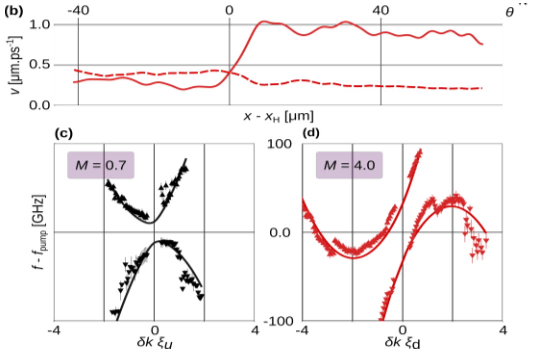
- Observation of a diffusive Goldstone mode: towards the observation of supersolidity

  Claude F *et al.*, Nat. Phys. (2025) https://doi.org/10.1038/s41567-025-02902-z



- QFT simulator in curved space time: towards the observation of Hawking radiation, superradiance in rotating geometry

  K. Falque et al. PRL 135, 023401 (2025)
  A. Delhom et al. PRD 109, 105024 (2024)



Collaborations

Quantum fluids of light

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Thank you for the attention