Quantum fluids of light

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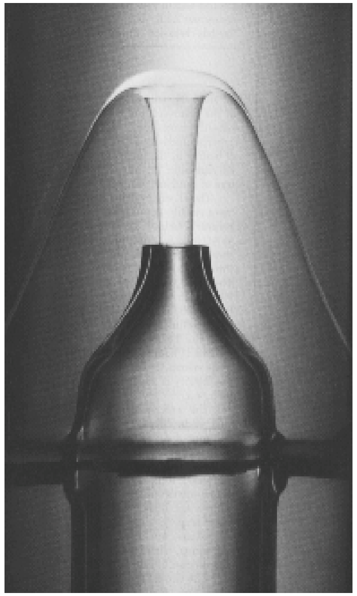
Physique quantique et applications

Quantum Fluids

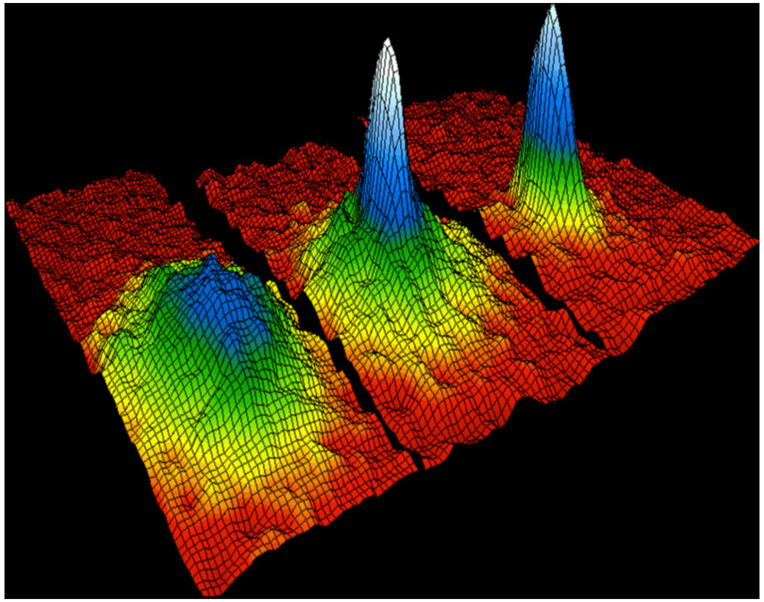
Liquid Helium



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

J.F. Allen (1971)

Ultracold atomic condensates



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

NIST/JILA/CU-Boulder (1995)

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 give photons a mass ?
- Can photon-photon interactions make light behave as a fluid ?

•In photonic structures

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

Collective behaviour of a photonic quantum fluid

C. R. Acad. Sci. Paris, t. 317, Série II, p. 1287-1292, 1993

Optique/*Optics*

Diffraction non linéaire

Yves Pomeau et Sergio Rica

Résumé – Une expérience classique en mécanique des fluides est la formation de structures verticales à l'arrière d'un obstacle, comme par exemple l'écoulement de Bénard-von-Kármán. Est-il possible d'imaginer une expérience similaire en optique ? C'est-à-dire, en illuminant un obstacle pourrait-on engendrer des structures tourbillonnaires caractéristiques d'un régime pré-turbulent ? Cette Note est consacrée au problème de la génération de vorticité dans les ondes électromagnétiques.

Nonlinear diffraction

Abstract – *A classical experiment in fluid mechanics is the formation of vortical structures in wakes as for instance the Bénard-von-Kármán flow. Is it possible to imagine a similar experiment in optics?* i. e. *is it possible to generate vortical structures characteristics of a pre-turbulent regime by sending light to an object? This Note is devoted to the problem of generation of vortices in electromagnetic waves.*

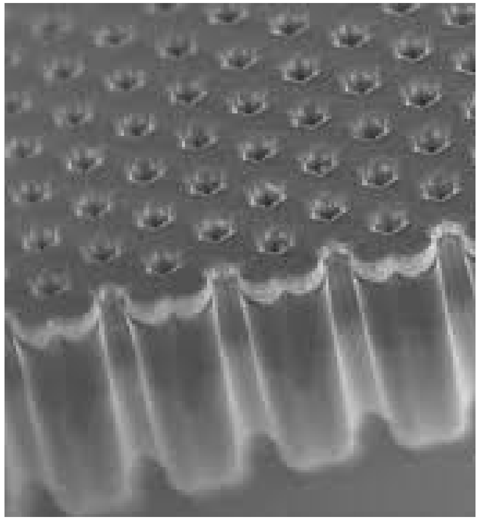
PHYSICAL REVIEW A VOLUME 60, NUMBER 5 NOVEMBER 1999

Bogoliubov dispersion relation and the possibility of superfluidity for weakly interacting photons in a two-dimensional photon fluid

Raymond Y. Chiao* and Jack Boyce†
Department of Physics, University of California, Berkeley, California 94720-7300

(Received 3 May 1999; revised manuscript received 22 July 1999)

Two families of fluids of light

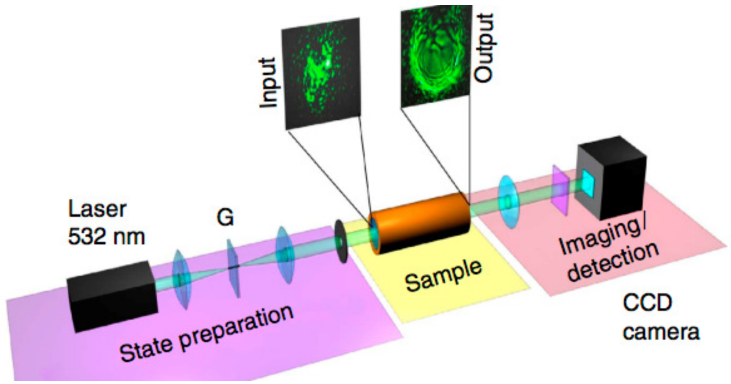


Cavity configuration

Photons fluids in microcavity polaritons

Photon BEC in optical cavity with dye molecules

Cavity-less configuration



Photon fluids in propagating geometry (Rb vapors, photorefractive crystals, thermo-optic liquids)

REVIEWS OF MODERN PHYSICS, VOLUME 85, JANUARY–MARCH 2013

Quantum fluids of light

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(published 21 February 2013)

Outline

Polaritons

- Introduction
- Superfluidity
- Vortices, solitons and more

Hot Rb Vapors

- The System
- Superfluid behaviour

Outlook

- Fluids of light for analogue physics?

Microcavity Polaritons

➡ Excitonic polaritons : Mixed light-matter particles

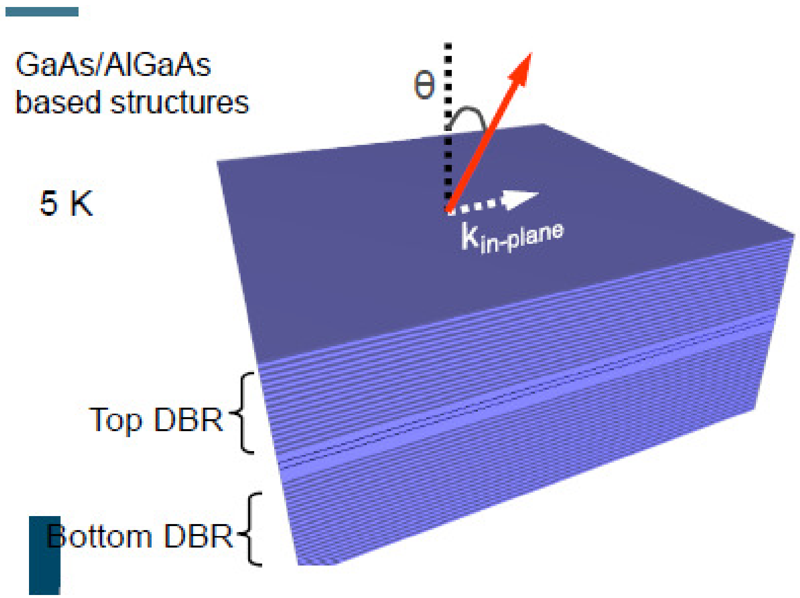
Photons confined in an optical cavity

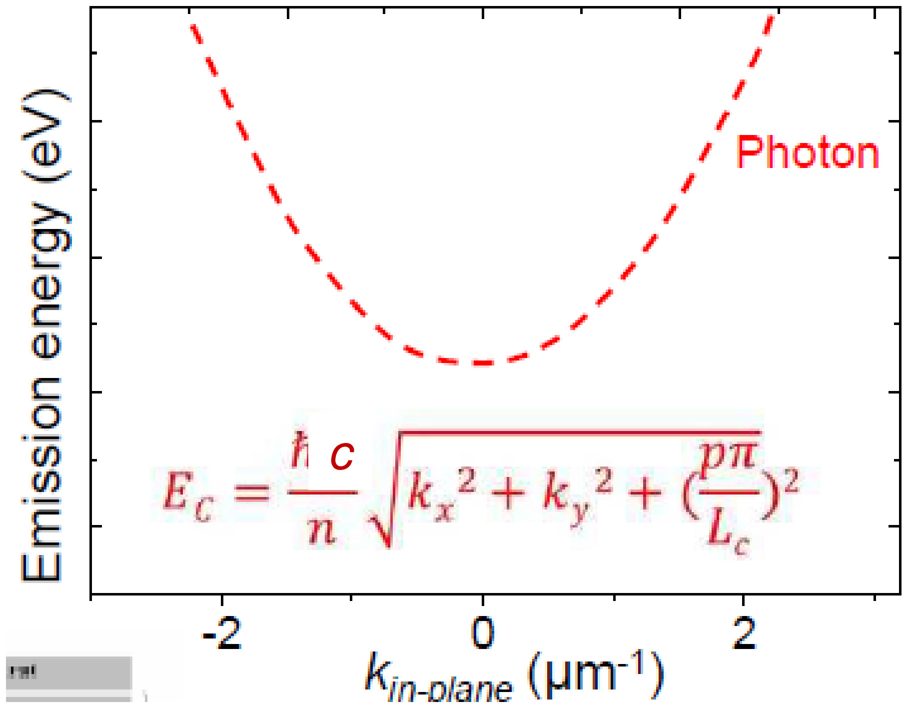
- **Very light (m=0 in vacuum)**
- Very fast
- No interactions

Excitons confined in a quantum well

- Very heavy
- Very slow
- **Interactions**

Microcavity Polaritons





Resonance of cavity mode: $p\,\lambda/2 = L_c$

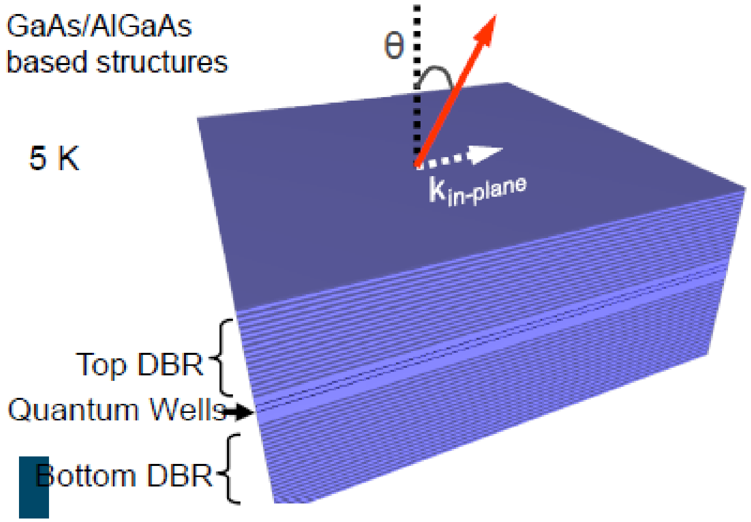
***k_z* is fixed**

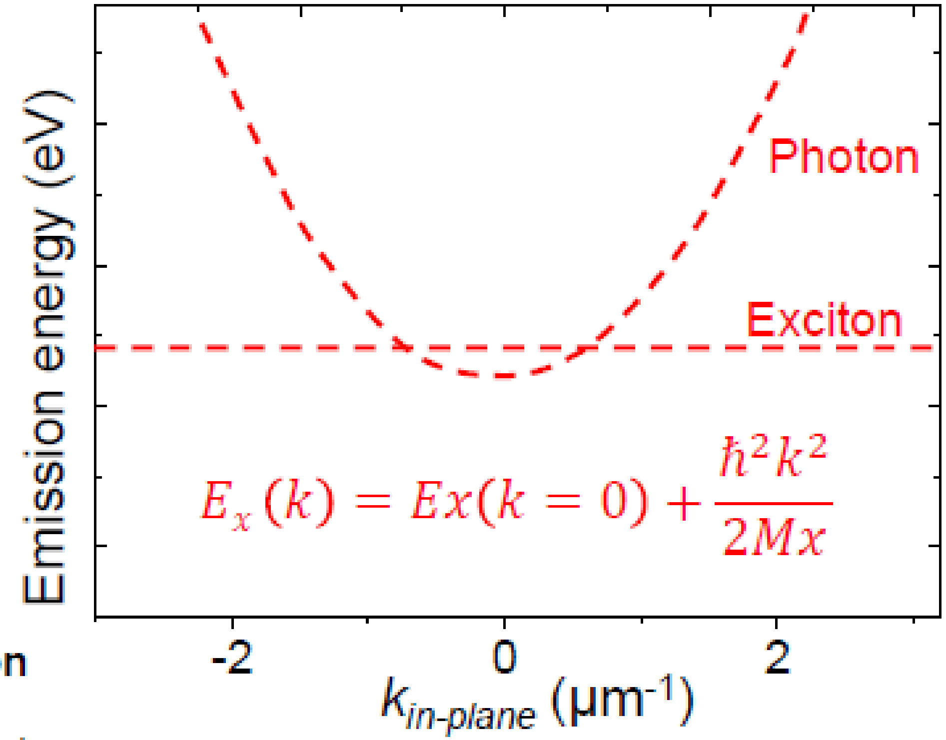
$$E_C(k) = Ec(k=0) + \frac{\hbar^2 k^2}{2Mp_{hot}}$$

For a motion in the plane of the cavity
the photons acquire an effective photon mass

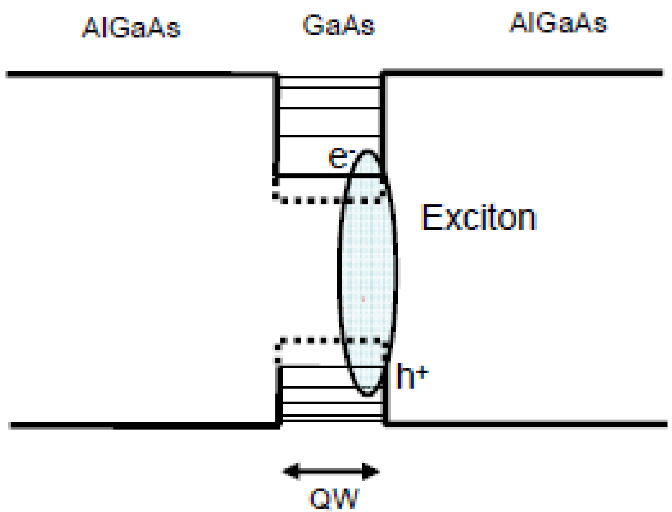
with $M_{phot} = \frac{p^2\pi^2\hbar^2}{L_c^{\,2} n^2}$

Microcavity Polaritons





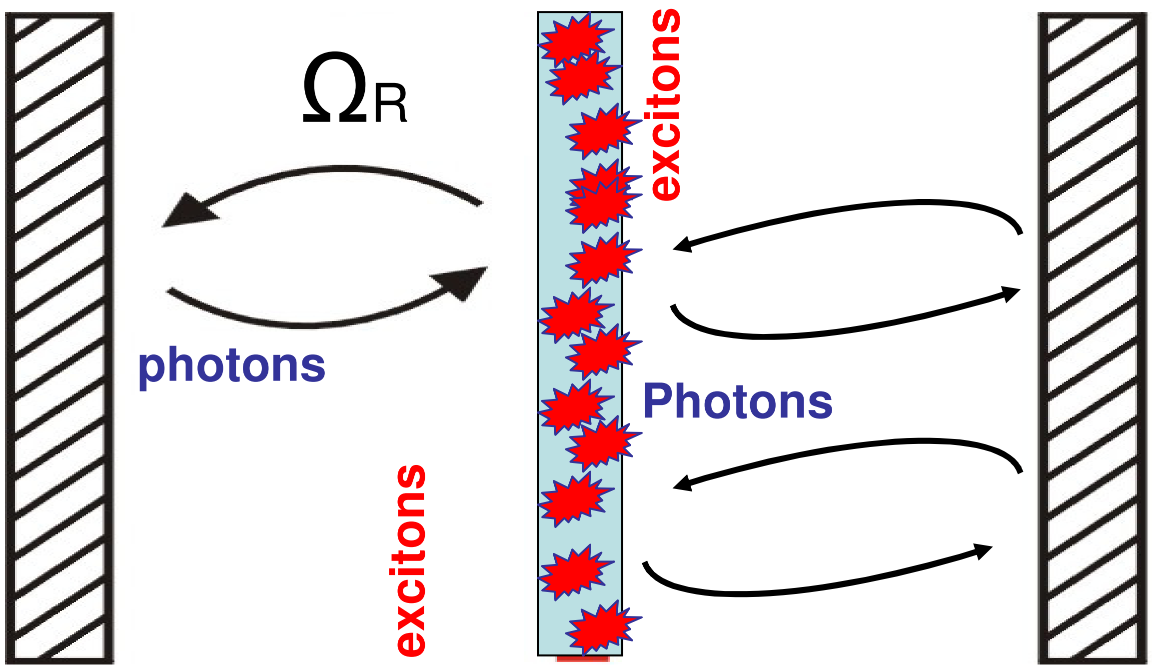
Quantum well exciton



with $M_x = m_e + m_h$

Typically $\frac{M_x}{M_{phot}} = 10^4$

Strong coupling of excitons with photons: polaritons



$$\boxed{\Omega >> \gamma_C, \gamma_{ex}}$$

C. Weisbuch, M. Nishioka, A. Ishikawa, Y. Arakawa, PRL 92

Strong Coupling Regime: Cavity Polaritons

$$H_k = \mathrm{E}_{\mathrm{cav}}(\mathrm{k})\hat{\mathrm{a}}_\mathrm{k}^\dagger \hat{\mathrm{a}}_\mathrm{k} + \mathrm{E}_{\mathrm{exc}}(\mathrm{k})\hat{\mathrm{b}}_\mathrm{k}^\dagger \hat{\mathrm{b}}_\mathrm{k} + \frac{\Omega_R}{2}(\hat{\mathrm{a}}_\mathrm{k}^\dagger \hat{\mathrm{b}}_\mathrm{k} + \hat{\mathrm{b}}_\mathrm{k}^\dagger \hat{\mathrm{a}}_\mathrm{k})$$

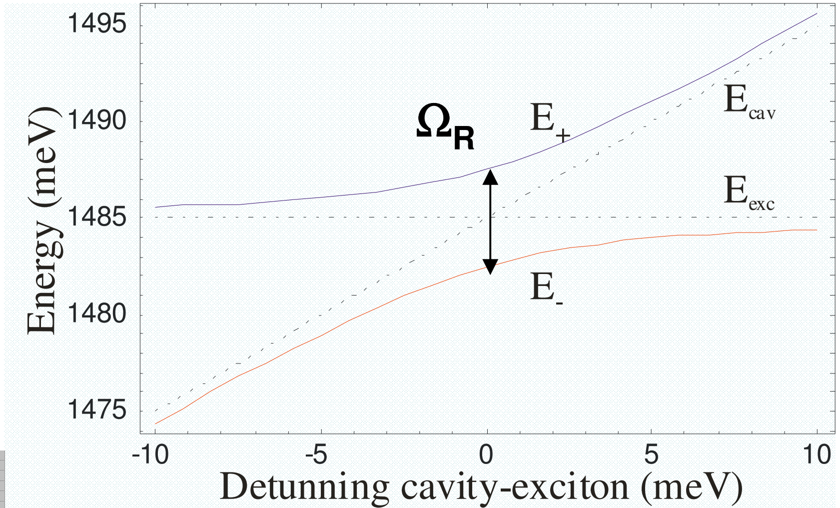
Strong coupling regime $\Omega >> \gamma_C, \gamma_{ex}$

Ω_R = 5.1 meV
$\gamma_a, \gamma_b \approx 0.1$ meV ≈ 25 GHz

Normal modes: Cavity polaritons

$$\hat{p}_k = -C_k \hat{a}_k + X_k \hat{b}_k$$
$$\hat{q}_k = X_k \hat{a}_k + C_k \hat{b}_k$$

Energies anticrossing

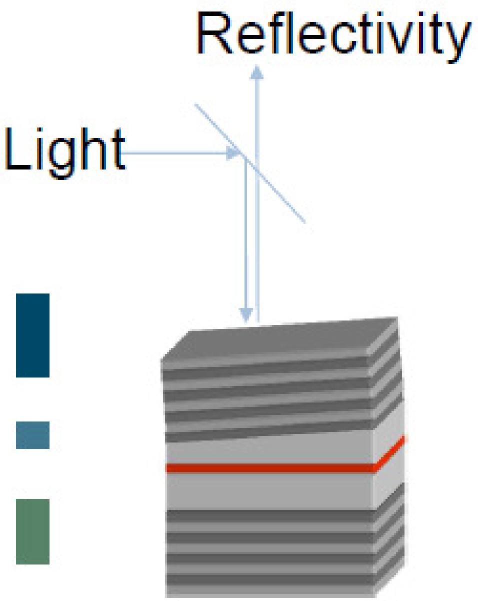


$$H_k = \mathrm{E}_{\mathrm{LP}}(\mathrm{k})\hat{\mathrm{p}}_\mathrm{k}^\dagger \hat{\mathrm{p}}_\mathrm{k} + \mathrm{E}_{\mathrm{UP}}(\mathrm{k})\hat{\mathrm{q}}_\mathrm{k}^\dagger \hat{\mathrm{q}}_\mathrm{k}$$

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

Observation of the Coupled Exciton-Photon Mode Splitting in a Semiconductor Quantum Microcavity

C. Weisbuch,[a] M. Nishioka,[b] A. Ishikawa, and Y. Arakawa
Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Meguro-ku, Tokyo 153, Japan
(Received 12 May 1992)



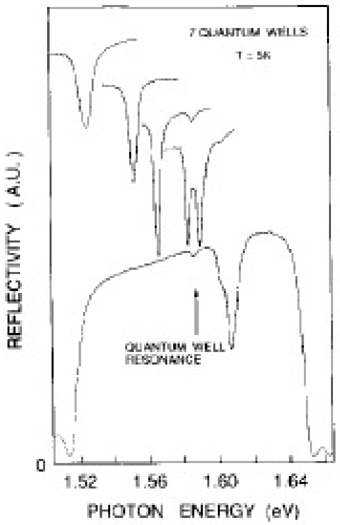


FIG. 2. 5-K reflectivity curves on a seven-QW microcavity structure. Various detuning conditions between cavity and QW exciton frequencies are obtained by choosing various points on the wafer, typically 0.5 mm apart. Note the line narrowing approaching and at resonance, the resonance mode splitting, and the indication of a light-hole exciton mode splitting around 1.605 eV for the lowest trace.

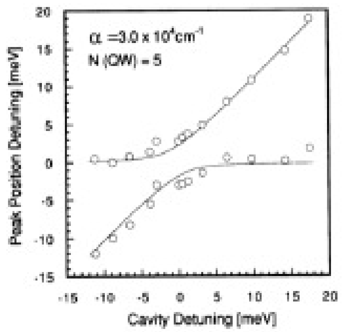
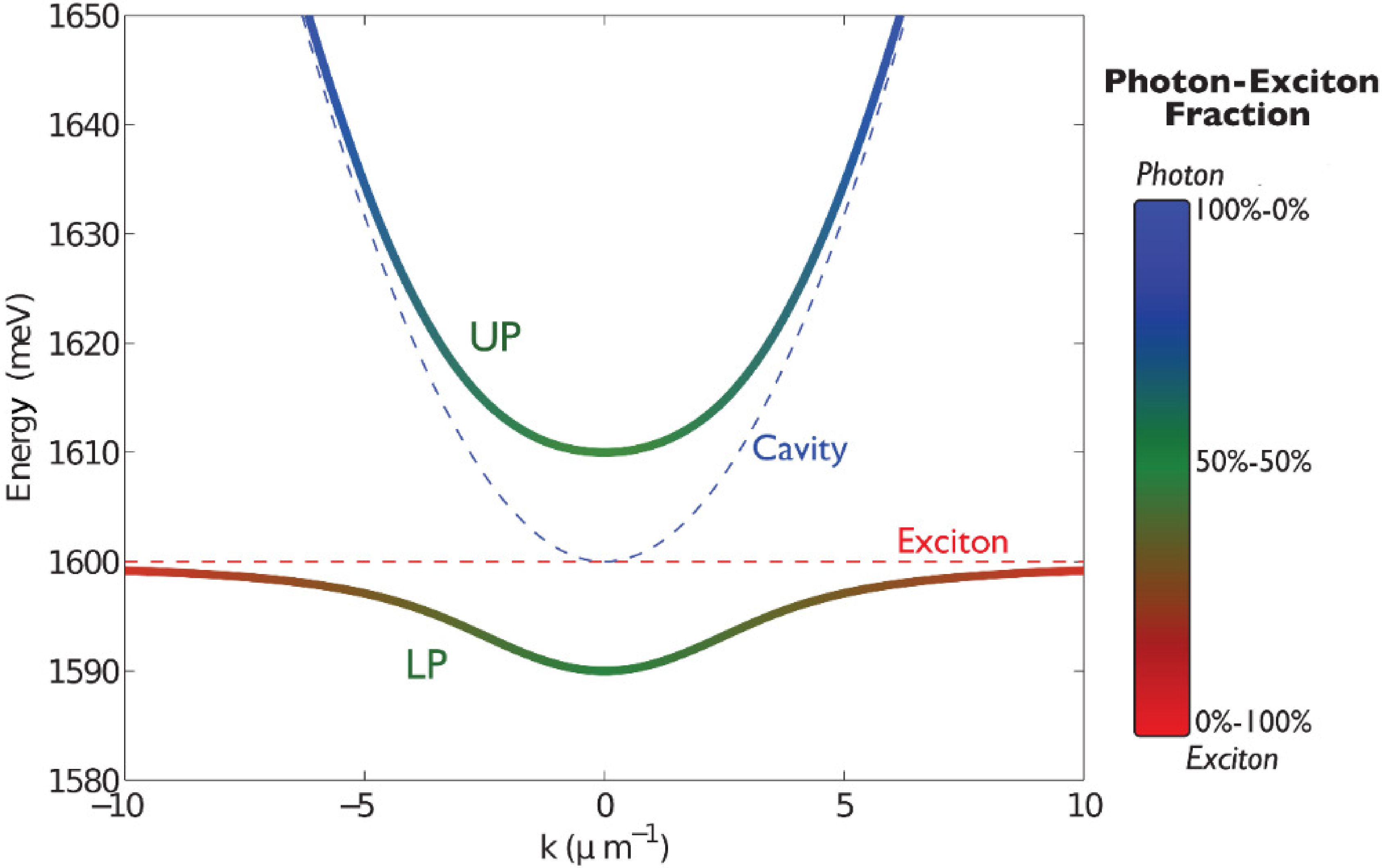


FIG. 3. Reflectivity peak positions as a function of cavity detuning for a five-quantum-well sample at $T = 5$ K. The theoretical fit is obtained through a standard multiple-interference analysis of the DBR–Fabry-Pérot–quantum-well structure.

Claude Weisbuch
PRL **69**, 3314 (1992)



1650
1640
1630
1620
1610
1600
1590
1580
Energy (meV)
−10
−5
0
5
10
k (μ m^{-1})
UP
Cavity
Exciton
LP
Photon-Exciton Fraction
Photon
100%-0%
50%-50%
0%-100%
Exciton

Polaritons Nonlinear Properties

When the exciton density rises (strong excitation), interactions between excitons are large.

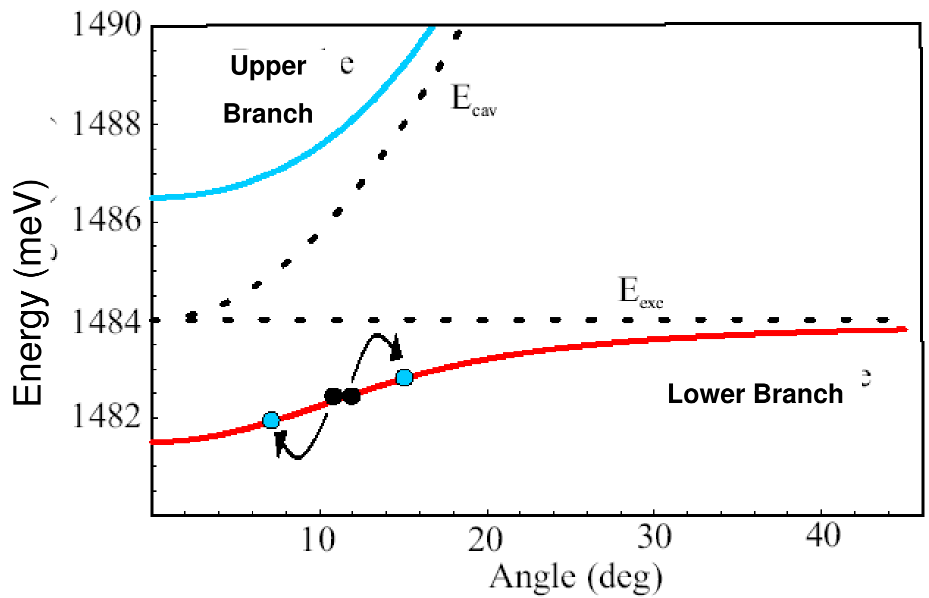
Hamiltonian for the lower polariton branch:

$$\boxed{H = H_{lin} + H_{PP}^{eff}}$$

$$\boxed{H_{PP}^{eff} = \frac{1}{2}\sum_{k,k',q} V_{k,k',q}^{PP} p_{k+q}^{\dagger} p_{k'-q}^{\dagger} p_k p_{k'}}$$

Polaritons four-wave mixing

$\{k_p , k_p\} \rightarrow \{k_p+q , k_p-q\}$



This yields an effective photon-photon interaction at the output of the cavity

C. Ciuti et al PRB 2000, G. Messin at al PRL 2001

Microcavity Polaritons

Polaritons are weakly interacting composite bosons

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

Very small effective mass $m \sim 10^{-5}\ m_e$

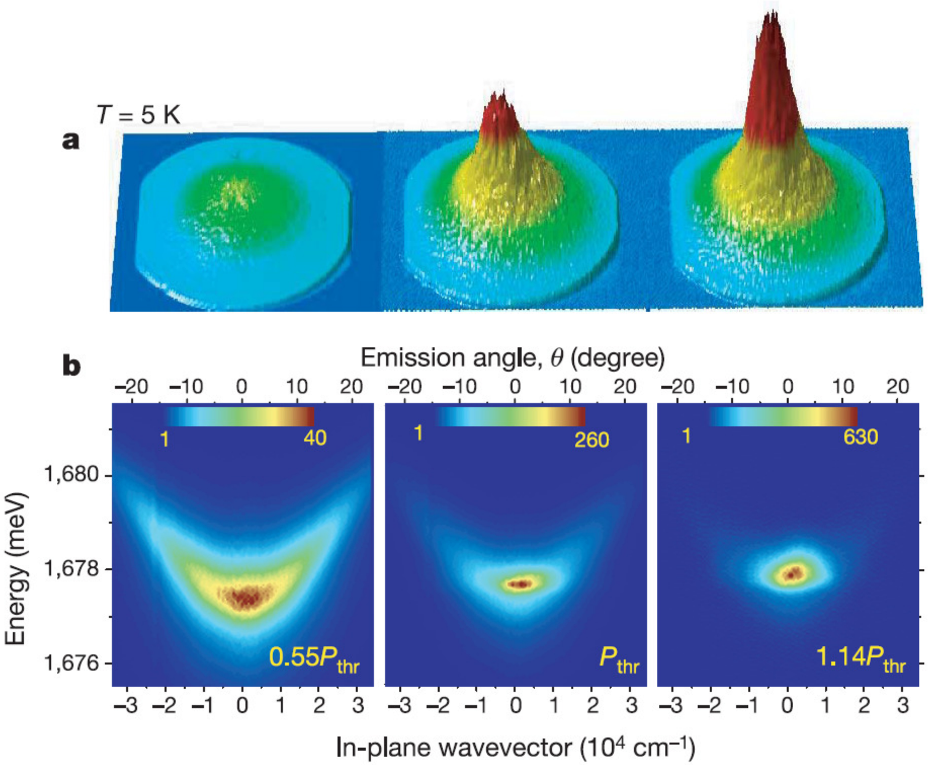
Large coherence length $\lambda_T \sim$ 1-2 µm at 5K

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

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

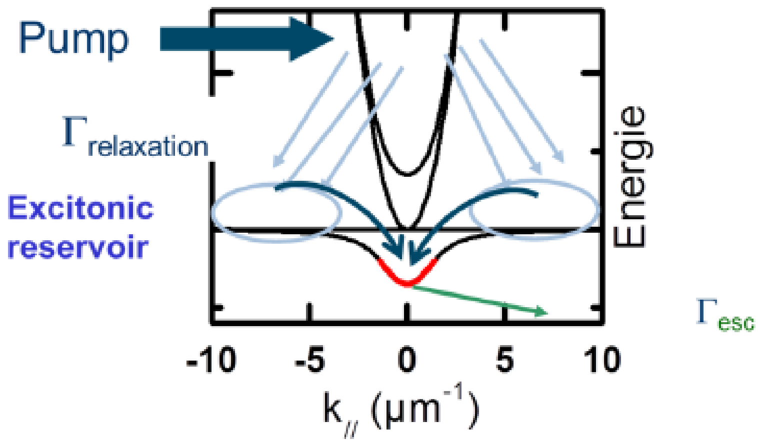
This enables the building of many-body quantum coherent effects : condensation, superfluidity

Polariton BEC



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

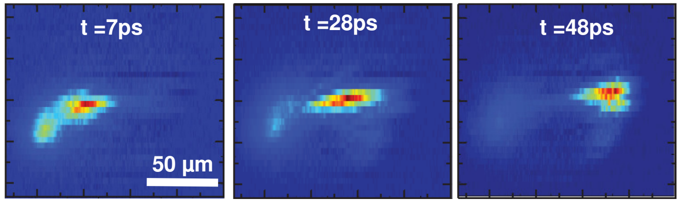
Non resonant excitation



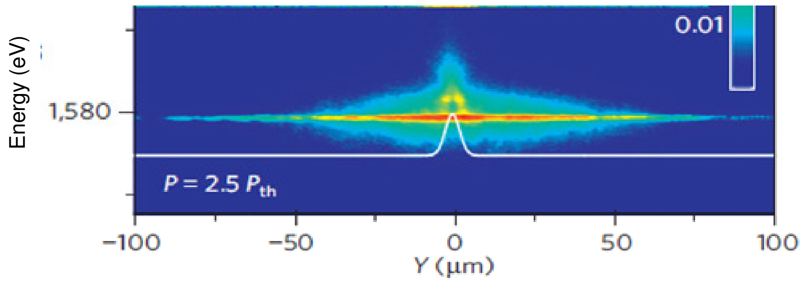
Carusotto&Ciuti, Rev. Mod. Phys.85, 299 (2013)

Boson quantum fluids: polaritons

Coherent propagation

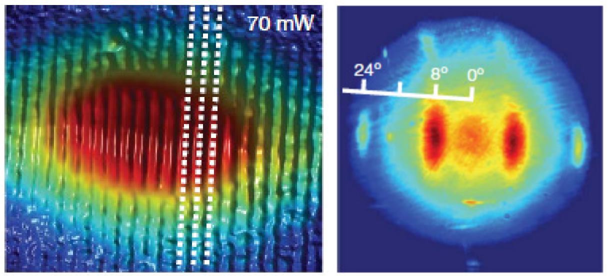


Amo *et al.,* Nature **457**, 295 (2009)



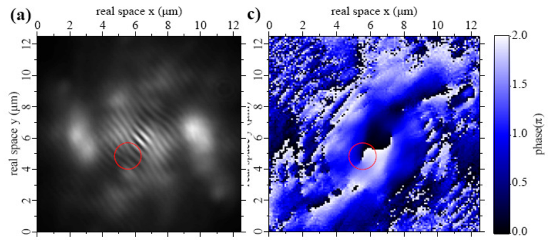
Wertz *et al.,* Nature Phys. **6**, 860 (2010)

Long-range order phases



Lai *et al.,* Nature **450**, 529 (2007)

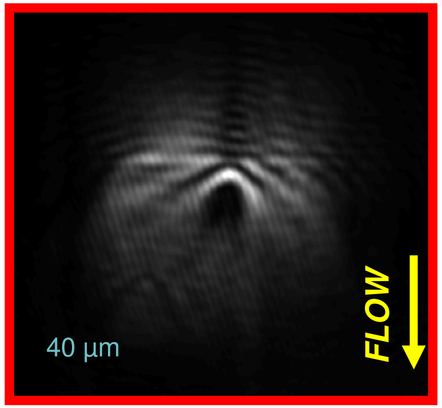
Vortex and half vortex



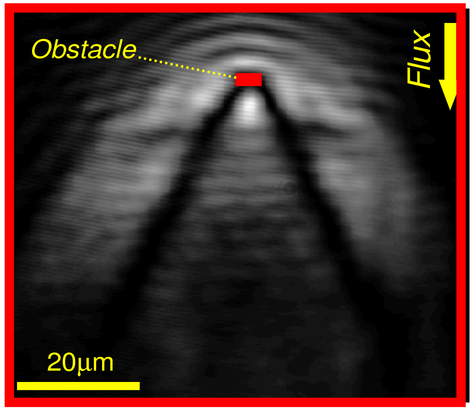
Lagoudakis *et al.*, Nature Phys. **4**, 706 (2008), and Science 326, 974 (2009)

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

Hydrodynamics of polariton quantum fluids

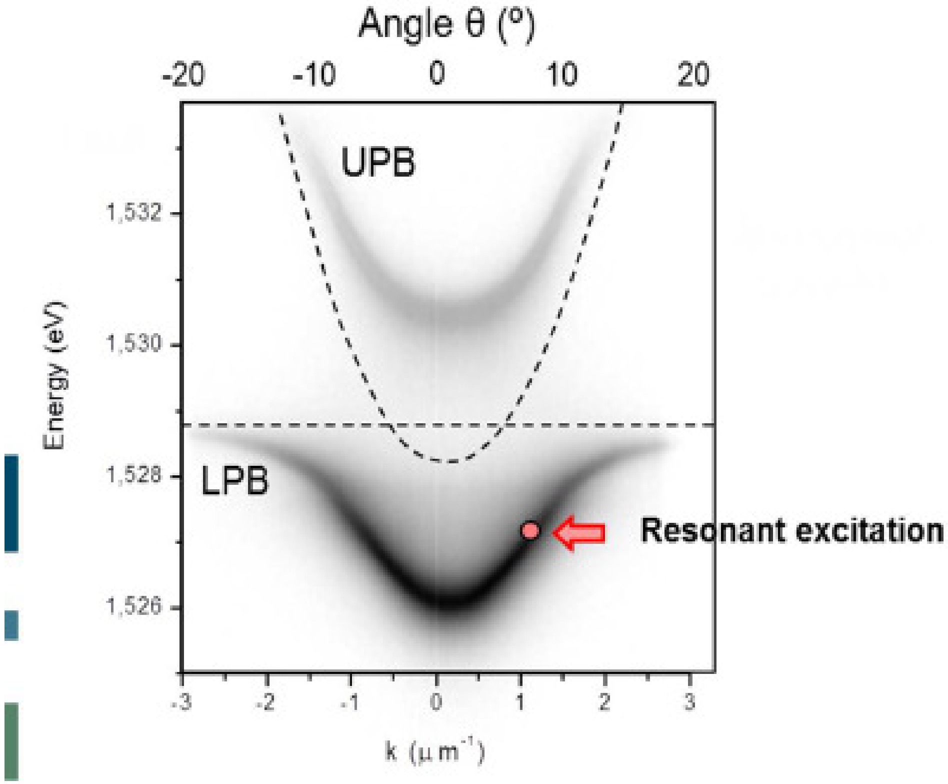


Superfluidity and Cerenkov waves
(*Nature Physics 2009*)



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

Resonant excitation



Excitation & detection

EXCITATION

- Resonant photon injection

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

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

DETECTION

- Imaging of the leaking photons

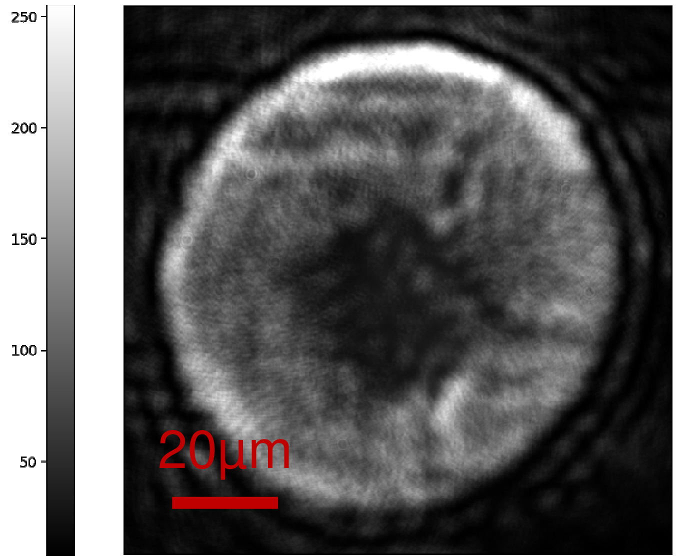
$$I(r,t) \leftarrow n(r,t)$$

$$\phi(r,t) \leftarrow v(r,t)$$

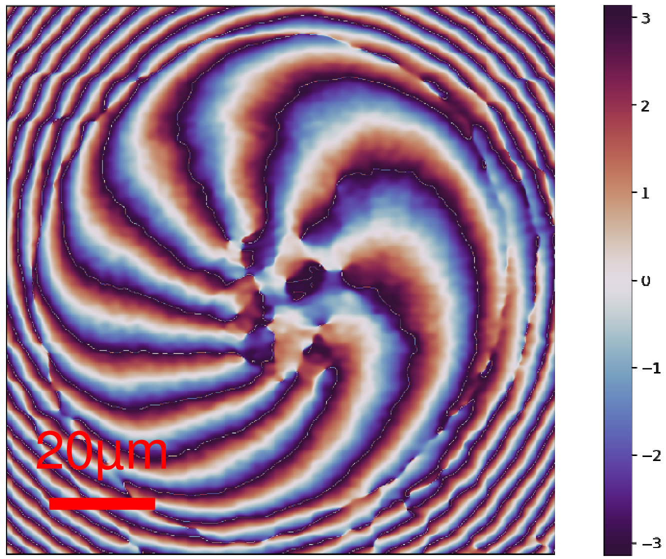
Full optical experiment

Excitation & detection

n [a.u.]

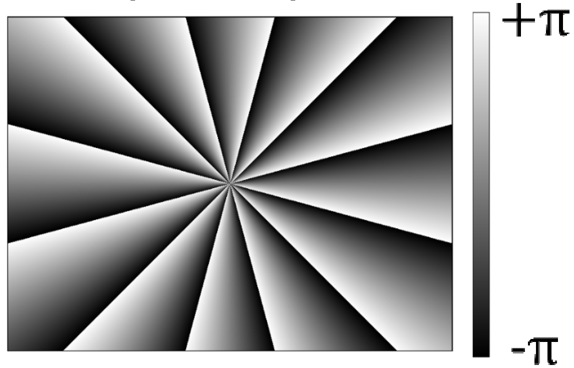


phase [rad]



- Image of the cavity plane:
  - density map: $n(x,y) \propto I(x,y)$
  - velocity map: $\mathbf{v}(x,y) \propto \nabla\phi(x,y)$
- Reshaping of the phase profile of the driving field
  - Use of a Spatial Light Modulator (SLM)
  - Rotating phase ⇒ Rotating fluid

SLM phase pattern



Full optical experiment

Microcavity Polaritons: Mean field approach

Generalized Gross-Pitaevskii equation

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

kinetic energy

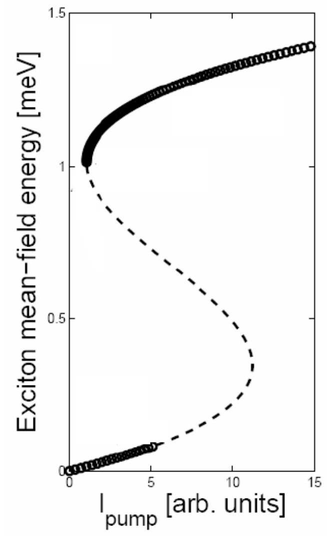
external potential

non-linear interaction

losses and pumping

Driven dissipative system, out of equilibrium quantum fluids

Steady state solutions: Bistability



Study of superfluidity
Weak excitations and Bogoliubov dispersion

Weakly excited states : bosonic modes obtained by linearizing the Gross Pitaevskii equation around the steady state solutions

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

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

Bogoliubov operator

$$\mathcal{L}_{Bog} = \begin{bmatrix}\frac{\hbar^2 k^2}{2m} + g|\psi_0|^2 & g|\psi_0|^2 e^{2ik_0x}\\ -g|\psi_0|^2 e^{-2ik_0x} & -\frac{\hbar^2 k^2}{2m} - g|\psi_0|^2\end{bmatrix}$$

Look for eigenvalues of the Bogoliubov operator

Bogoliubov dispersion

- Solutions of Bogoliubov equation
  - healing length $\xi = \sqrt{\hbar^2/mgn}$

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

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

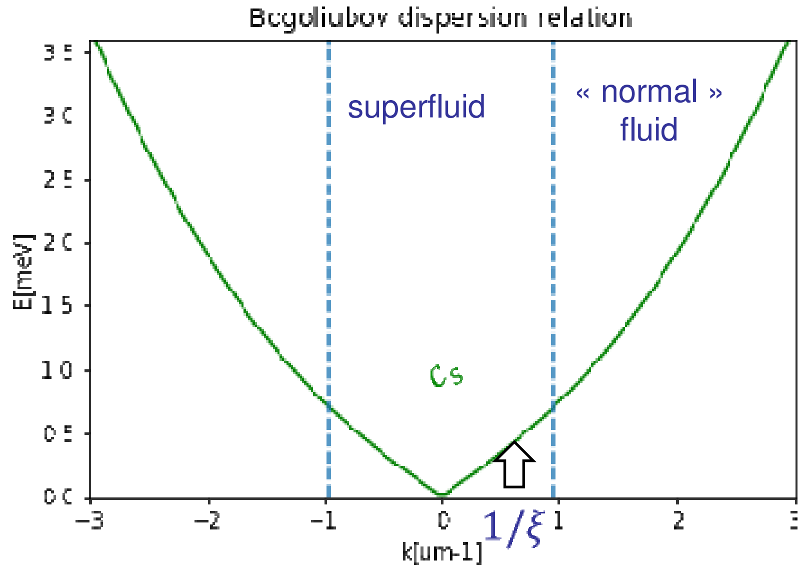
- Large k $(k\xi \gg 1)$:
  - parabolic dispersion
  - "normal" fluid

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

- Small k $(k\xi \ll 1)$:
  - sonic dispersion
  - superfluidity

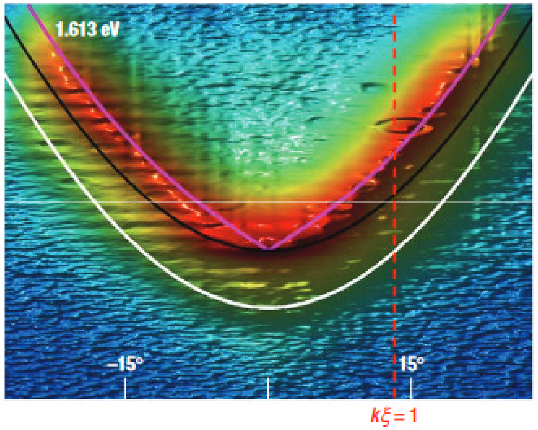
$$\hbar\omega_{Bog}(k) = c_s k$$

Speed of sound: $c_s = \sqrt{gn/m}$

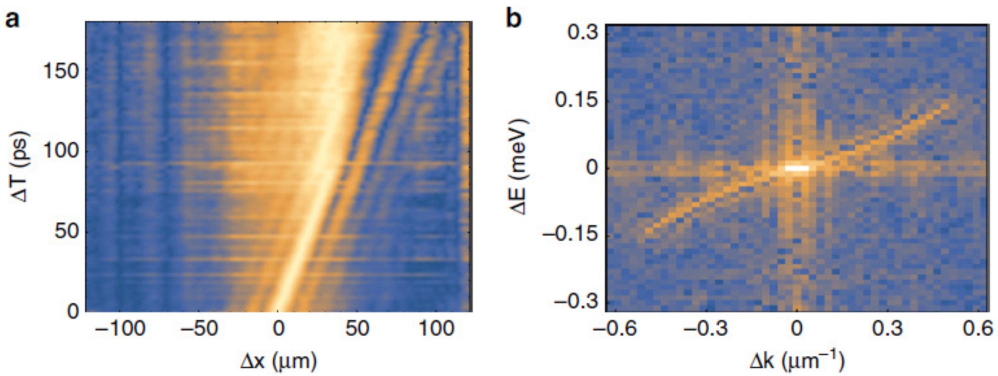


Measurements of the Bogoliubov dispersion

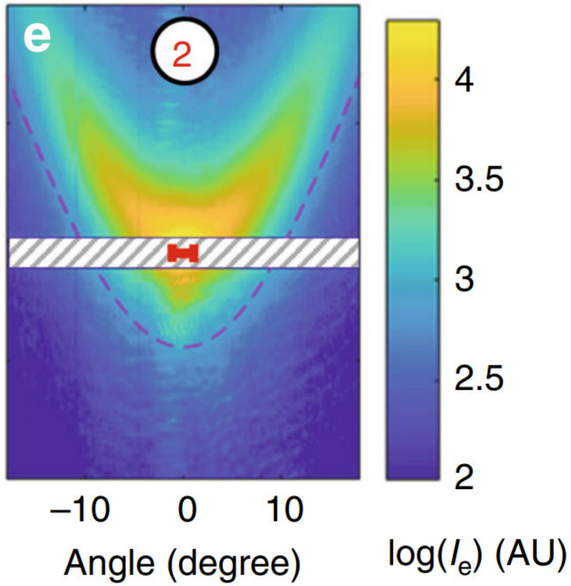
S. Utsunomiya et al. Nat. Phys. 4, 700 (2008) PL
V. Kohnle et al. PRB 86, 064508 (2012) FWM
P. Stepanov et al., Nat. Com. 10, 3869 (2019) PL
M. Pieczarka et al., Nat. Com. 11, 429 (2019) PL
D. Ballarini et al., Nat. Com. 11, 217 (2020) FT of g^1



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



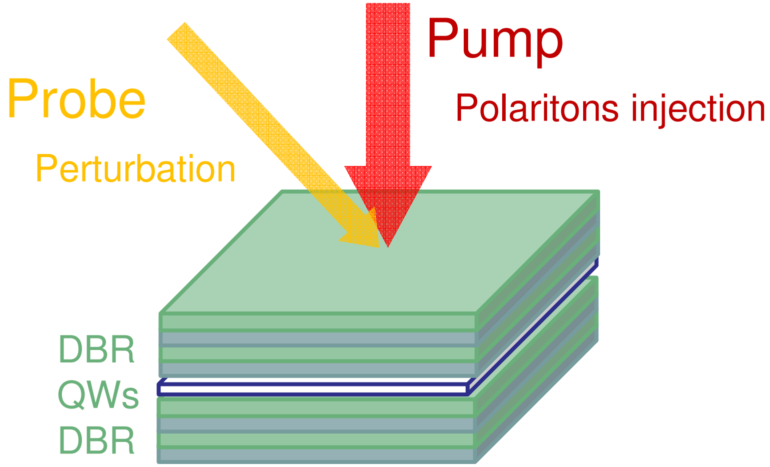
D. Ballarini et al. Nat. Comm. 4, 700 (2020)

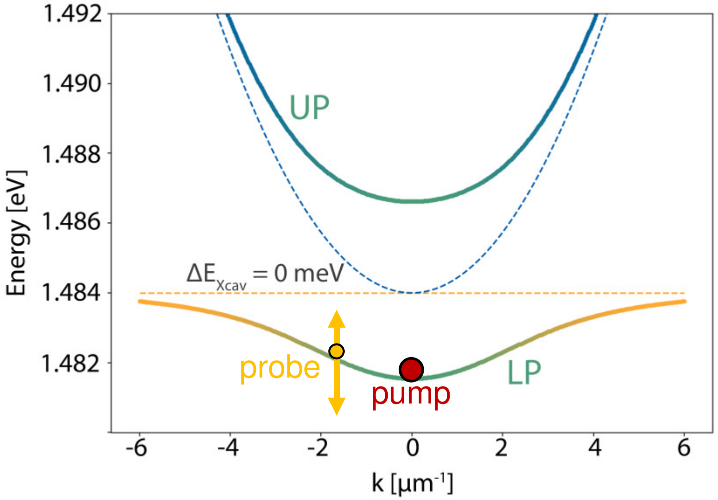


P. Stepanov et al., Nat. Com. 10, 3869 (2019)

Coherent probe spectroscopy

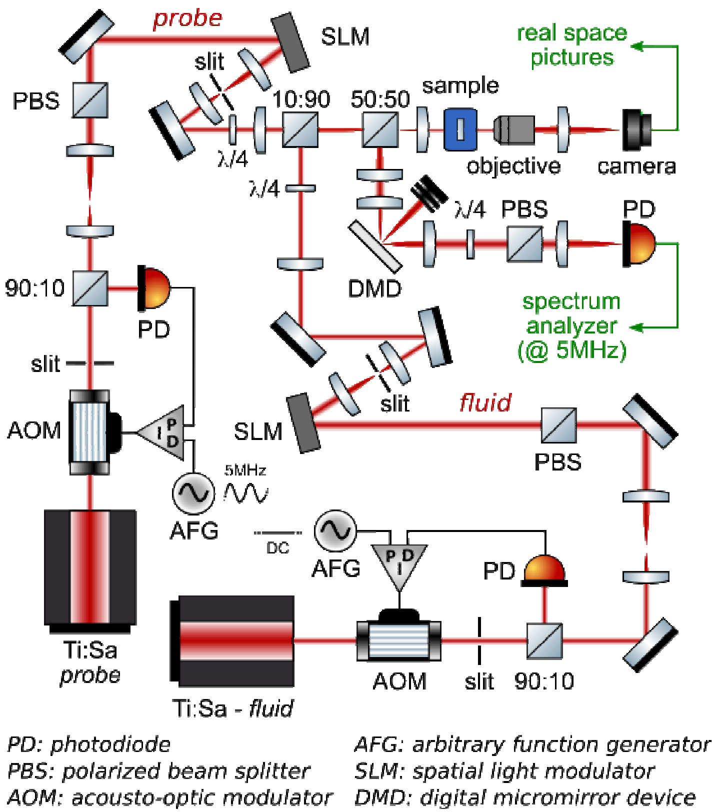
- **Probe:** excitation of small perturbations on top of the polaritons fluid
  - @ different k_{pr}
  - energy scan: $\Delta\omega_{pr}$ ~100Ghz





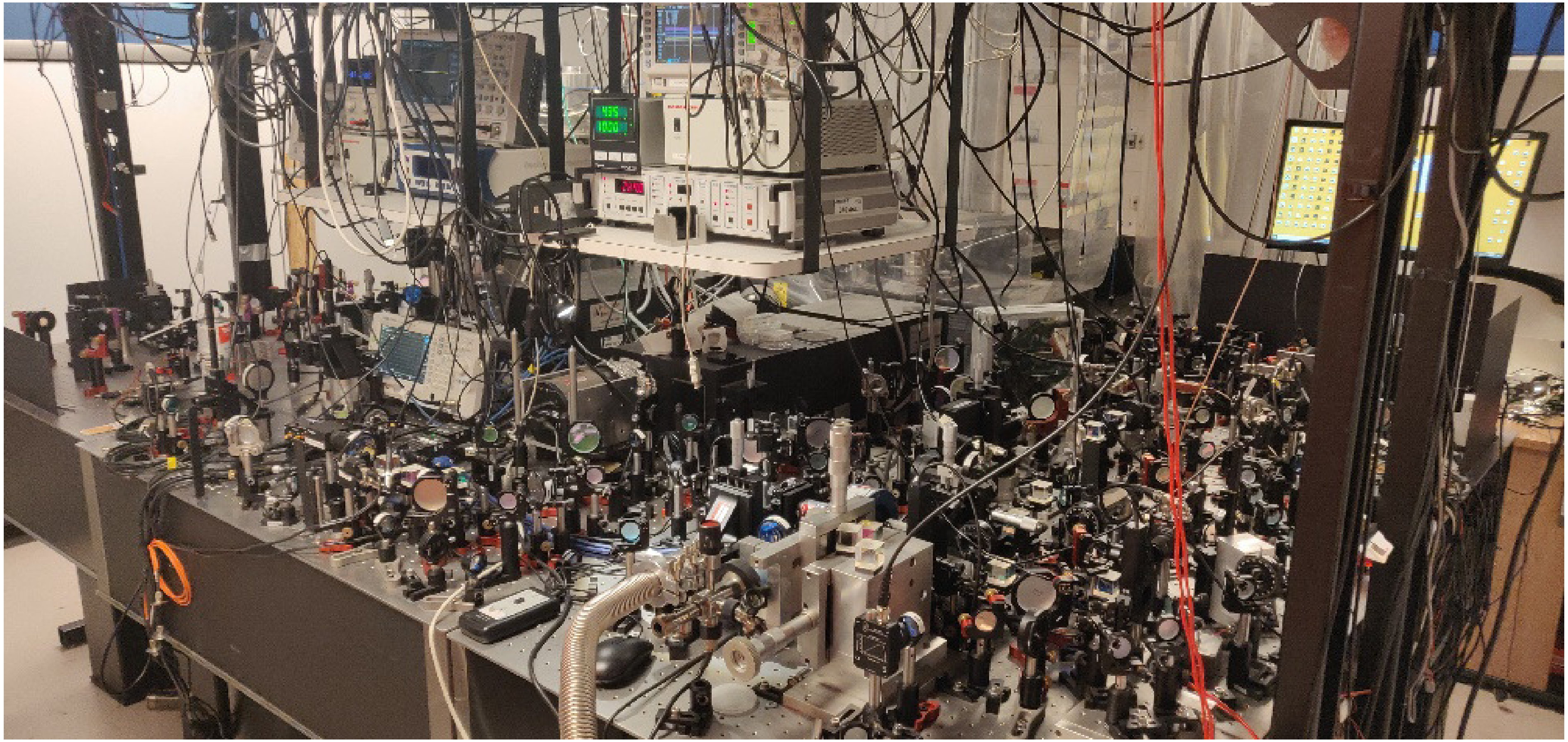
- Probe absorption (transmission) when $(k_{pr}, \omega_{pr}) = (k_{pol}, \omega_{pol})$

Spectroscopy setup

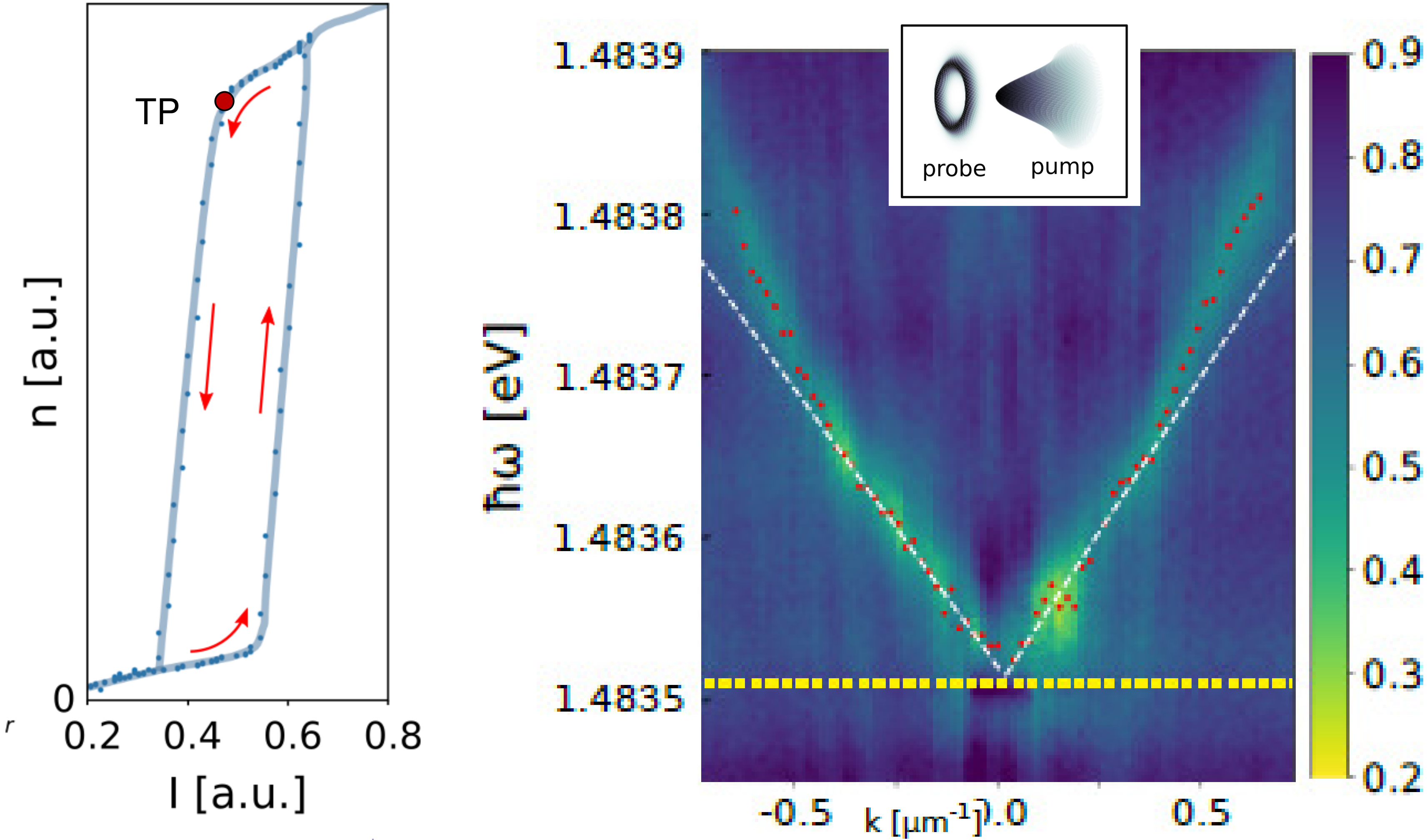


- Sample:
  - In cryostat (<4K)
- Pump: excitation of polaritons
  - Phase and intensity profile reshaped with an SLM
- **Probe:** scan of the polariton fluid resonances
  - @ different k_{pr}
  - energy scan: $\Delta\omega_{pr}$ ~100GHz
- **Detection:** (k, ω) of the probe reflectivity dips
  - δE resolution fixed by the laser linewidth
  - δk resolution fixed by the k-space filtering

Spectroscopy setup



Bogoliubov Dispersion

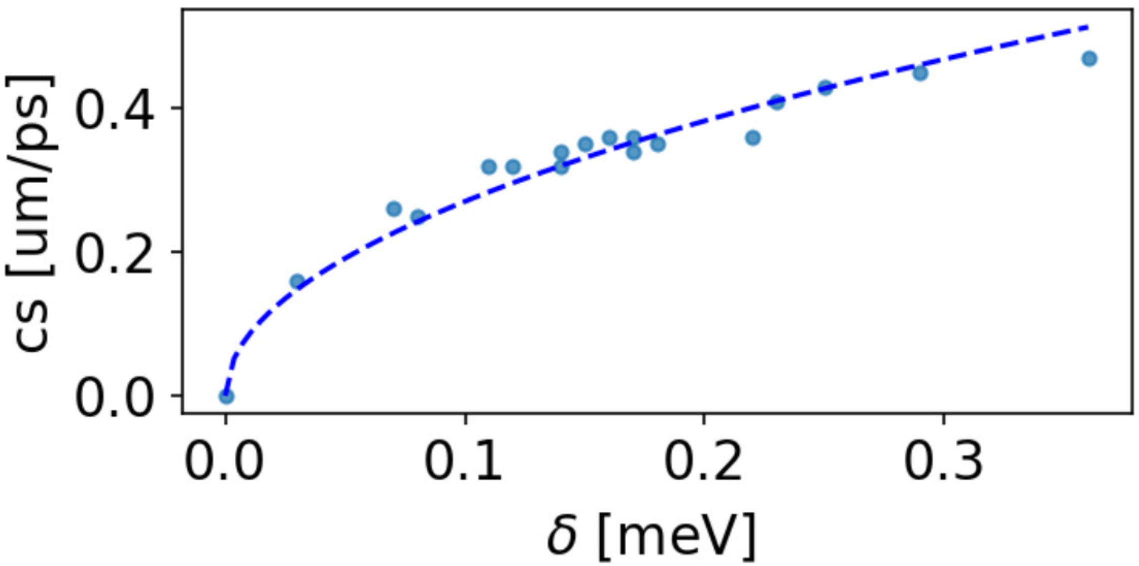


- Bogolioubov dispersion
  - $k\xi \gg 1$ parabolic dispersion (same as the linear regime)
  - $k\xi \ll 1$ sonic dispersion: fit of the speed of sound c_s

Claude et al. , submitted

Speed of sound

• Changing the fluid density (proportional to the detuning δ)



• The speed of sound c_s is proportional to √n

Claude et al. arxiv 2112.09903 (2022), **submitted**

Probing the superfluidity

VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Probing Microcavity Polariton Superfluidity through Resonant Rayleigh Scattering

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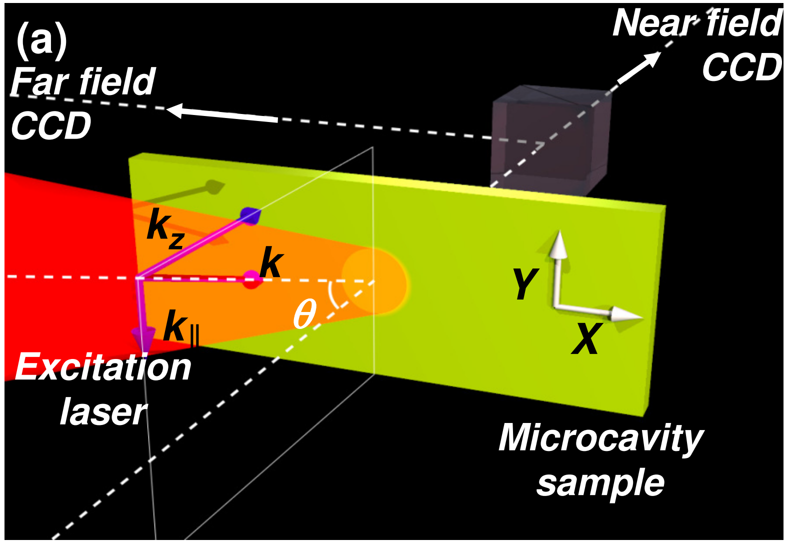
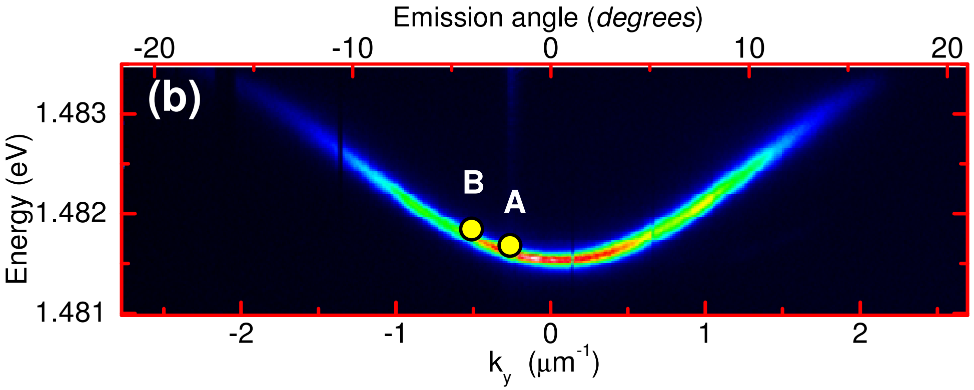
(Received 23 April 2004; published 13 October 2004)

Probing the superfluidity

We probe the behaviour of the fluid through its interaction with defects





Control parameters

✓Polariton density
(pump intensity)

✓Fluid velocity
(excitation angle)

✓Oscillation frequency
(laser frequency)

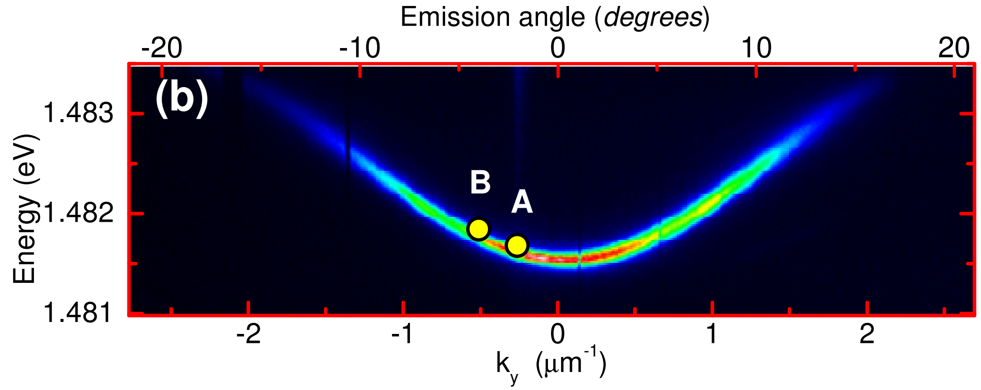
Polariton flow around a defect

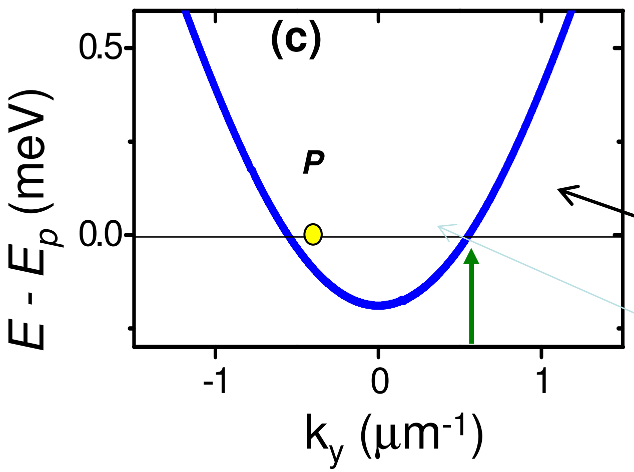
defect :
4 μm diameter

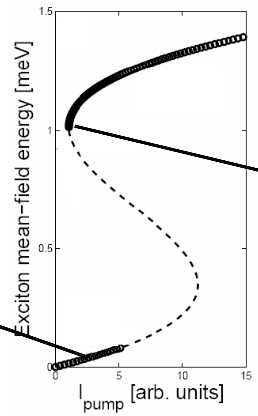
Point [A]
low momentum

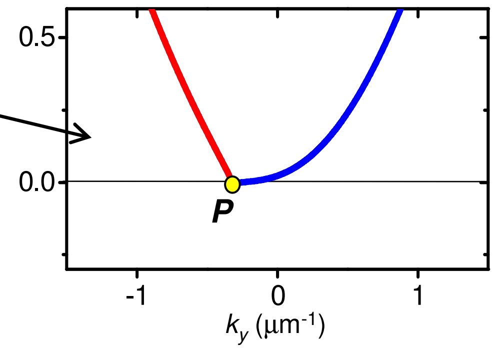
$v_f < c_s$

experiment



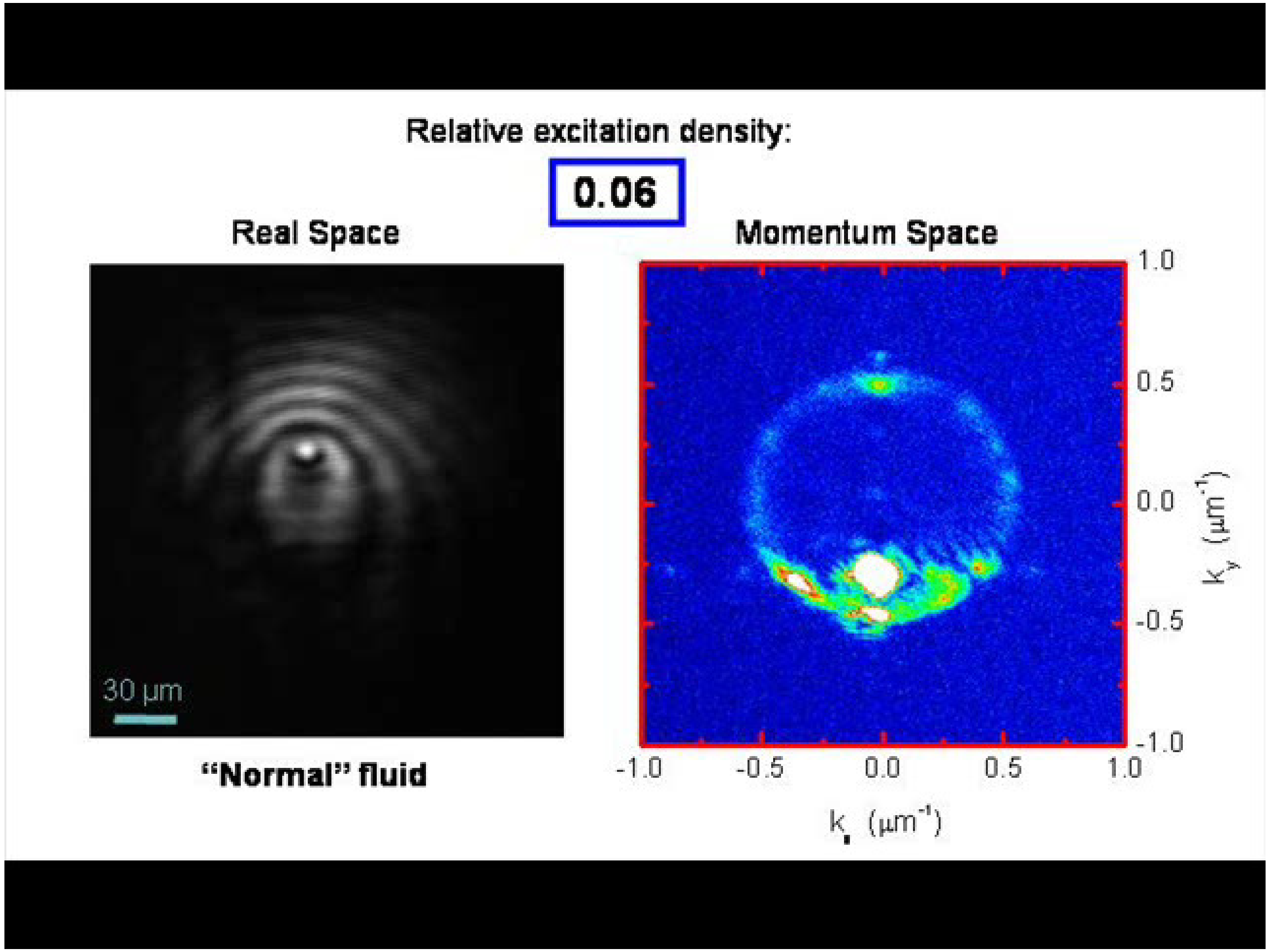






Polariton density

Transition to the superfluid regime

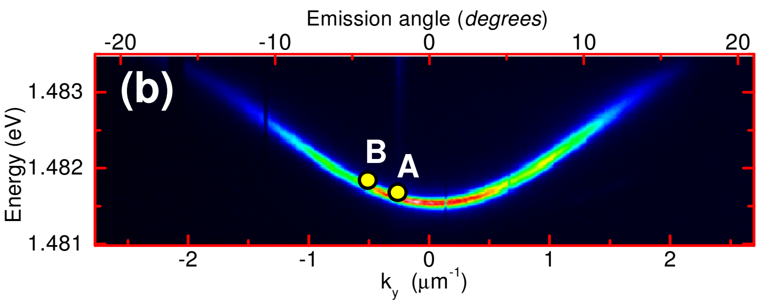


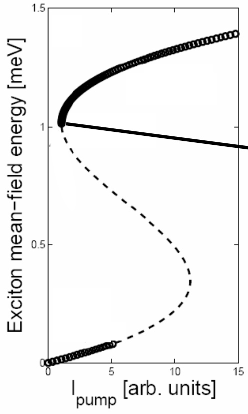
Amo et al., Nat. Phys.,5, 805 (2009)

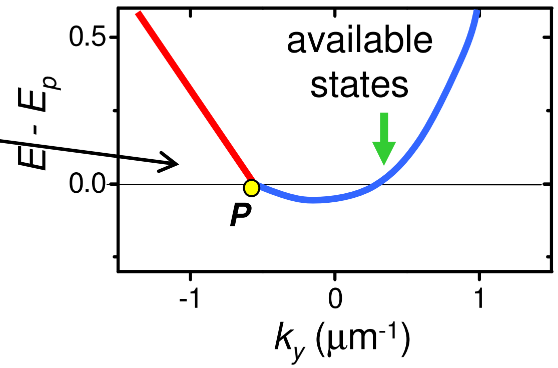
Čerenkov regime

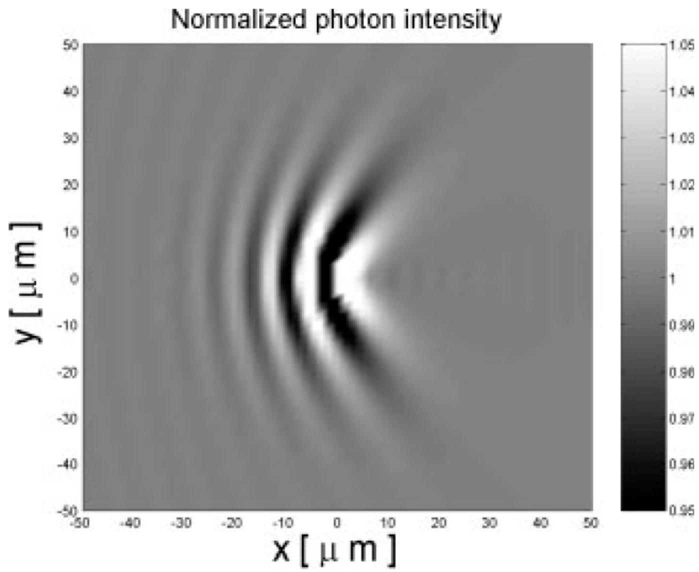
Point [B]
high momentum

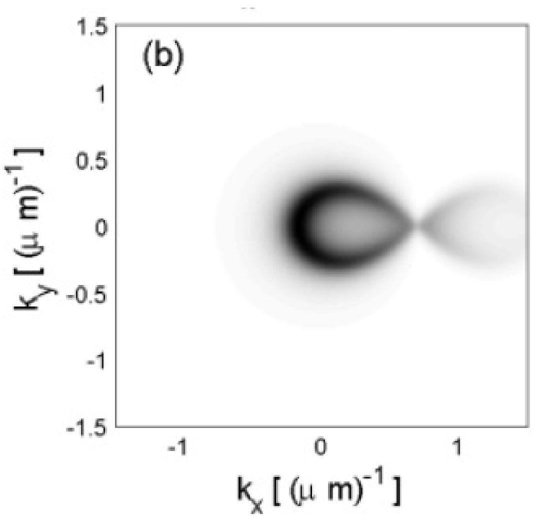
$v_f > c_{sound}$ ***supersonic regime*** ~~**Landau condition**~~







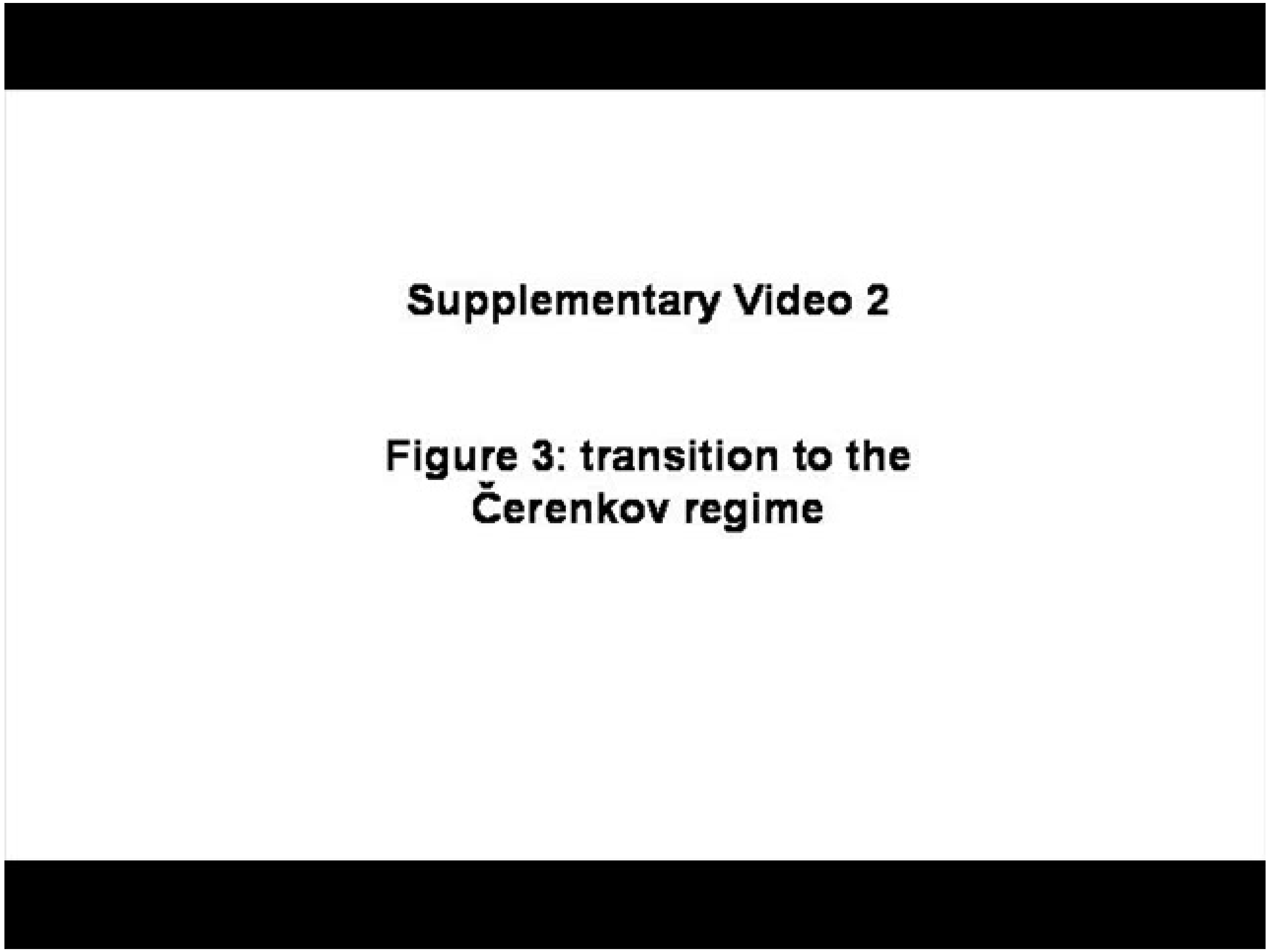




Cerenkov effect

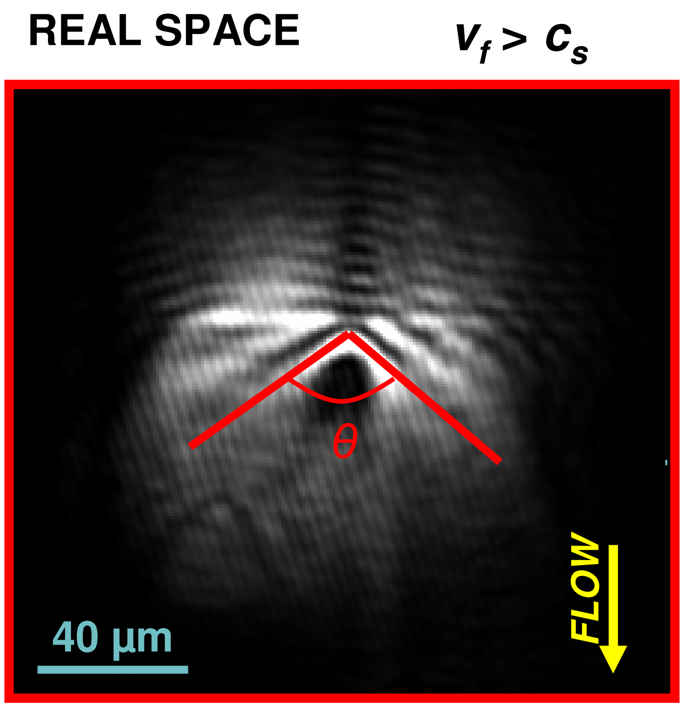
$v > v_{sound}$ *supersonic flight*

Transition to the Čerenkov regime



Amo et al., Nat. Phys.,5, 805 (2009)

Speed of sound



Existence of a well defined speed of sound $c_s = \sqrt{g|\psi|^2/m}$

$$\sin\vartheta = \frac{c_s}{v_f}$$

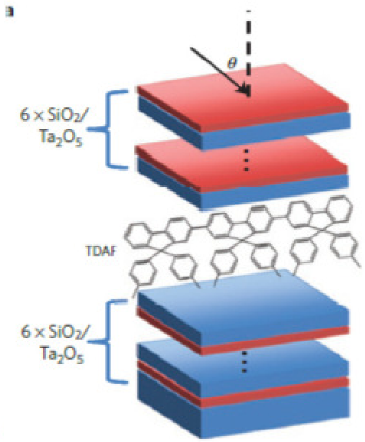
Measure of the sound speed

$$c_s = 8.1x10^5 m/s$$

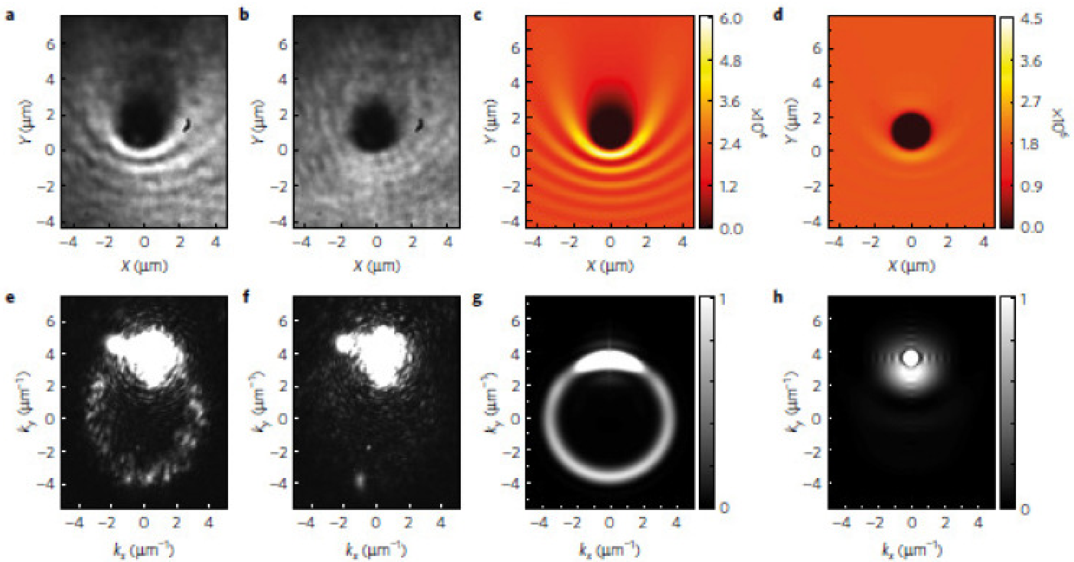
nature physics
LETTERS
PUBLISHED ONLINE: 5 JUNE 2017 | DOI: 10.1038/NPHYS4147

Room-temperature superfluidity in a polariton condensate

Giovanni Lerario[1], Antonio Fieramosca[1,2], Fábio Barachati[3], Dario Ballarini[1]*, Konstantinos S. Daskalakis[4], Lorenzo Dominici[1], Milena De Giorgi[1], Stefan A. Maier[5], Giuseppe Gigli[1,2], Stéphane Kéna-Cohen[3]* and Daniele Sanvitto[1,6]*



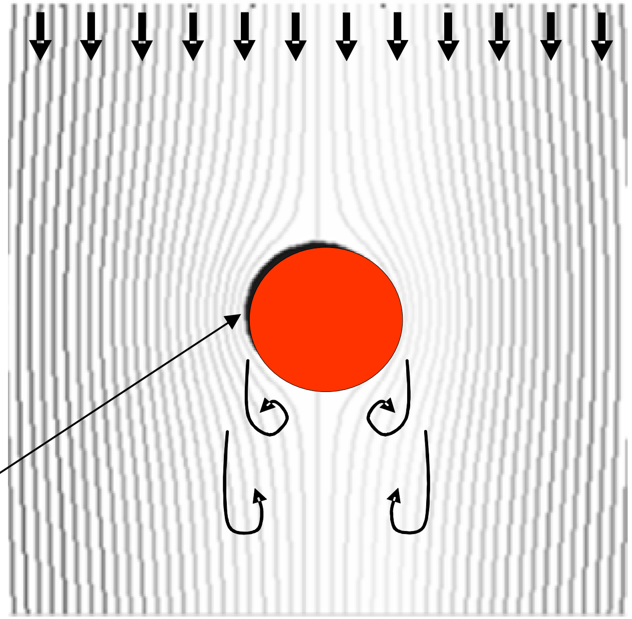
Organic cavity + pulsed excitation



Superfluidity breakdown: vortices and solitons formation?

The case of spatially extended defects; the size of the defect is larger than the healing length

$$v_f = v_\infty < c_s$$



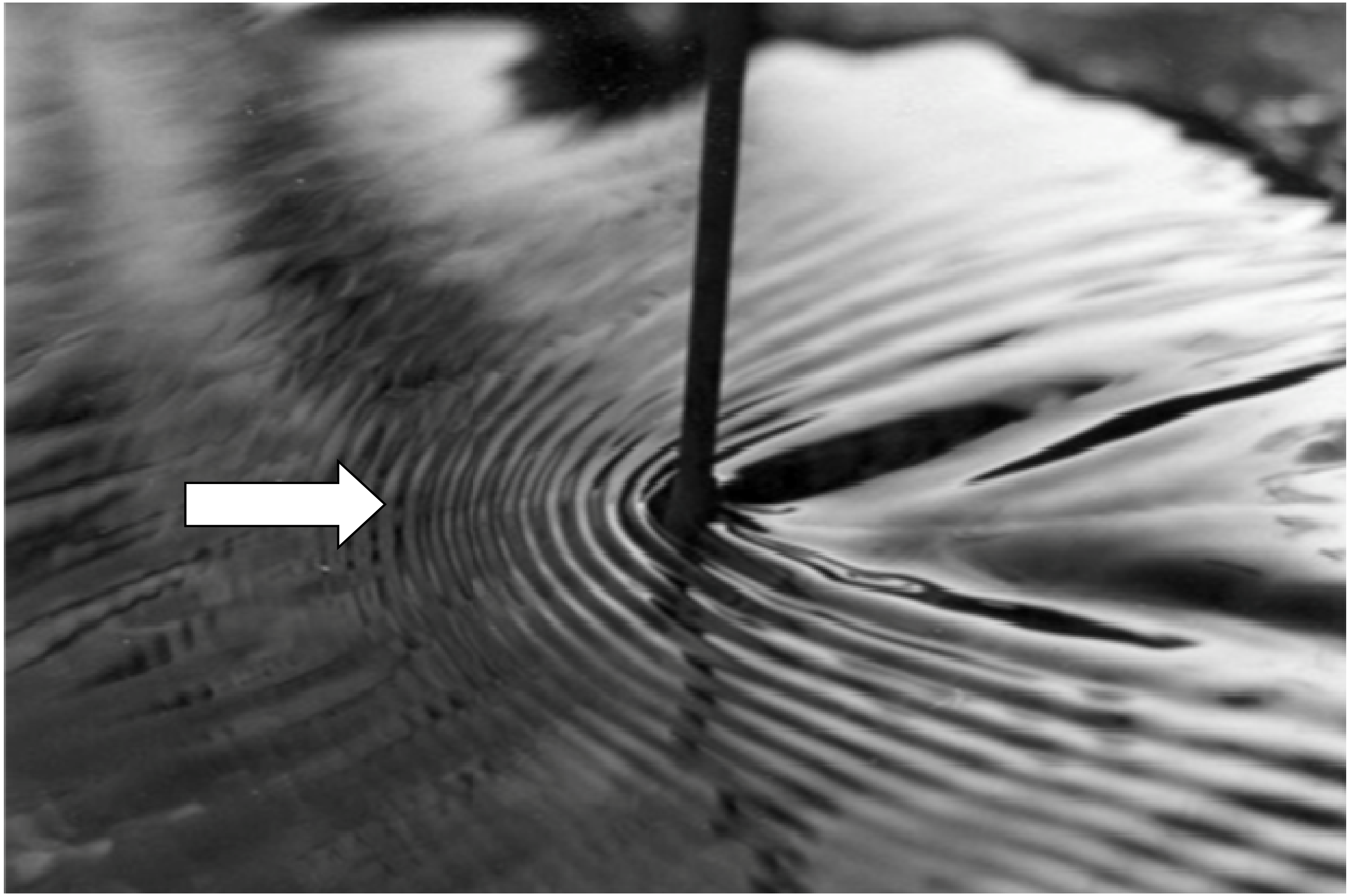
Acceleration of the fluid near the defect: the Landau criterion is locally violated

$$v_f = 2v_\infty$$

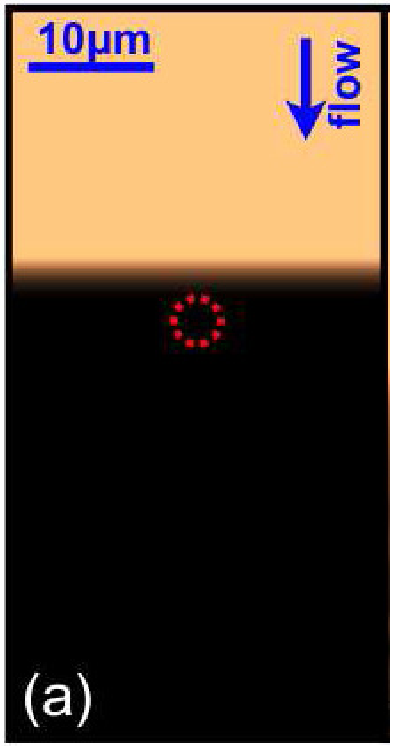
Frisch et al., PRL 69, 1644 (1992)

The currents formed in the fluid passing around a large obstacle can give rise to turbulence in its wake

Quantized vortices
Dark Solitons



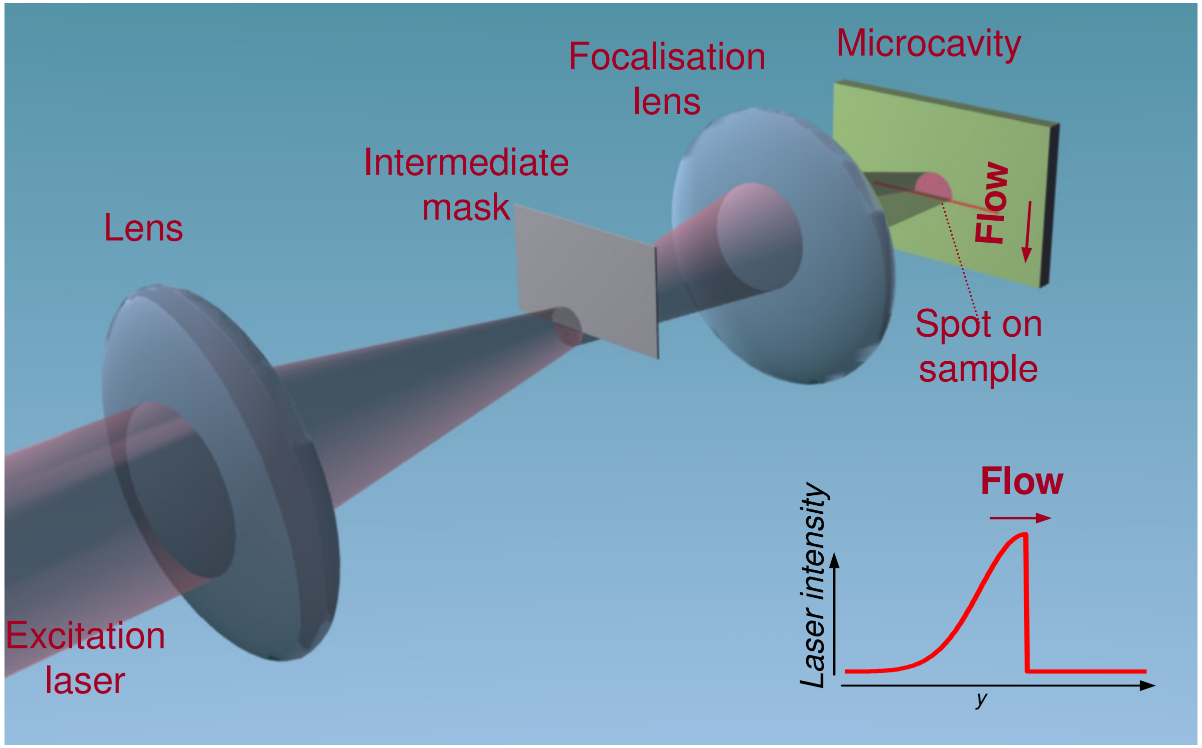
Resonant excitation: shaped pump



Resonant excitation

✓Shaped pump: free evolution for the fluid phase

Experimental set-up



Key points

✓CW laser (precise control of the fluid quantum state)

✓Mask (free evolution for the superfluid phase)

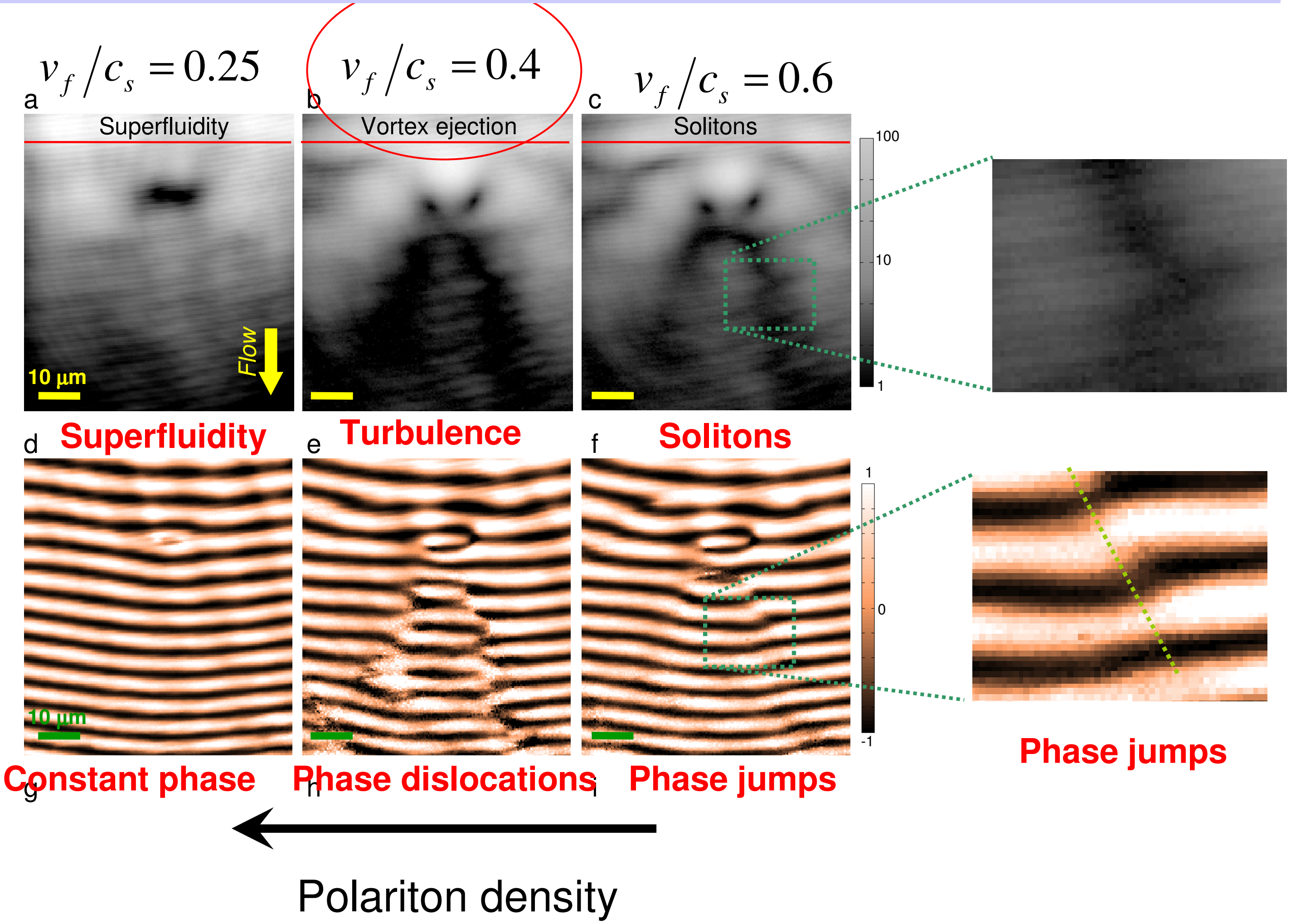
✓ Possibility to generate topological excitations

Vortices and Solitons

Big defect (15μm) >> healing length

Real space

Interferogram



Resonant excitation

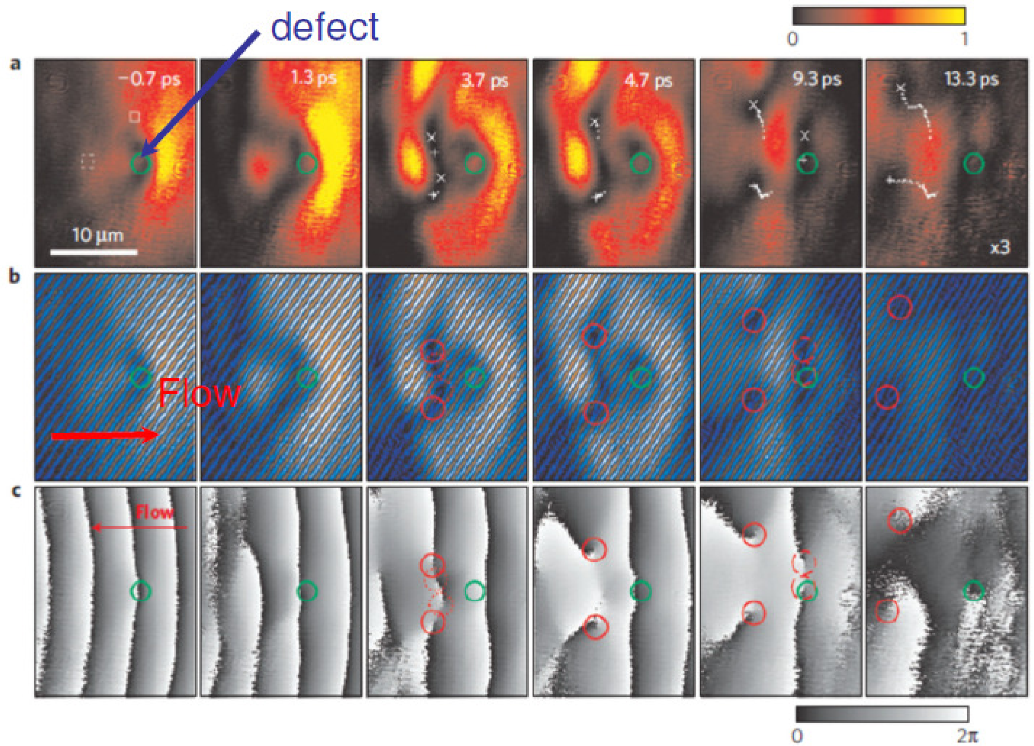
✓Problem: short propagation due to the dissipation

Amo et al., Science, 332, 1167 (2011)

nature physics
ARTICLES
PUBLISHED ONLINE: 3 APRIL 2011 | DOI: 10.1038/NPHYS1959

Hydrodynamic nucleation of quantized vortex pairs in a polariton quantum fluid

Gaël Nardin*, Gabriele Grosso, Yoan Léger, Barbara Piętka†, François Morier-Genoud and Benoît Deveaud-Plédran

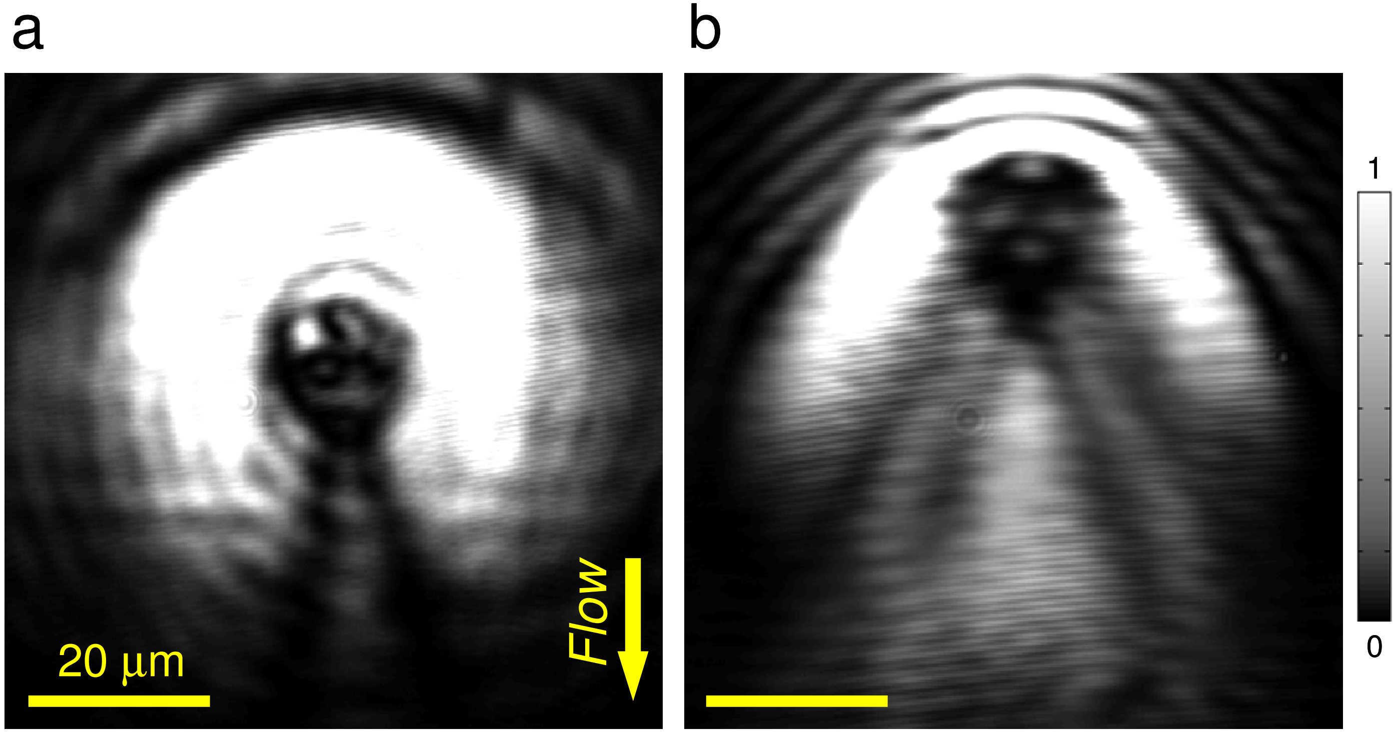


Nardin *et al.*,Nature Phys. **7**, 635 (2011)

See also:
Sanvitto *et al.*, Nature Phot. **5**, 610 (2011

Soliton doublet and quadruplet

Big defect (17µm) >> healing length



Low momentum; k= 0.2 µm^{-1} **High momentum; k= 1.1 µm^{-1}**

Amo et al., Science, 332, 1167 (2011)

Hydrodynamic Dark Solitons: theory

PRL 97, 180405 (2006) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2006

Oblique Dark Solitons in Supersonic Flow of a Bose-Einstein Condensate

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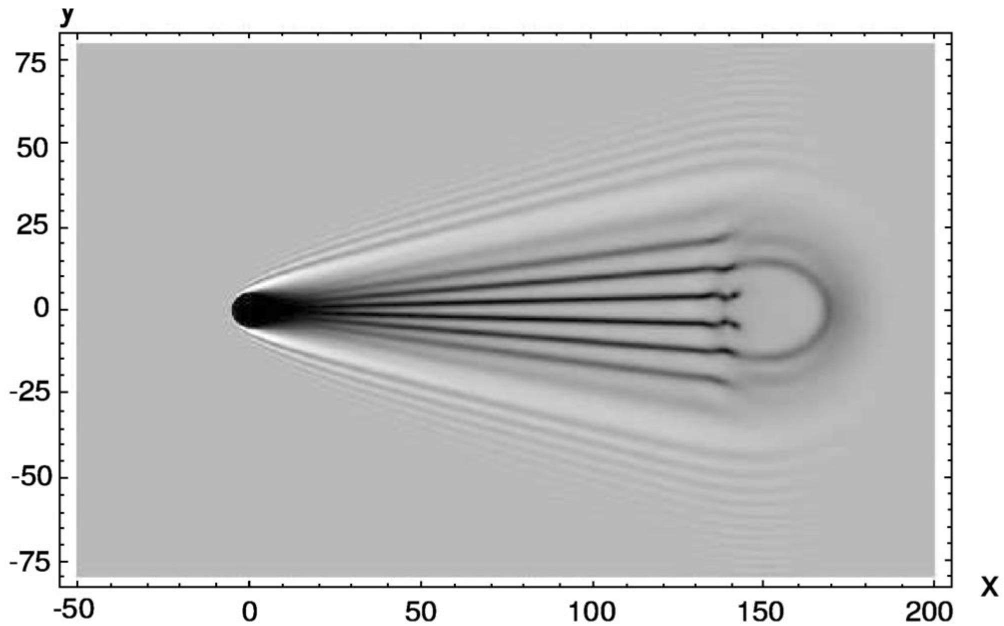
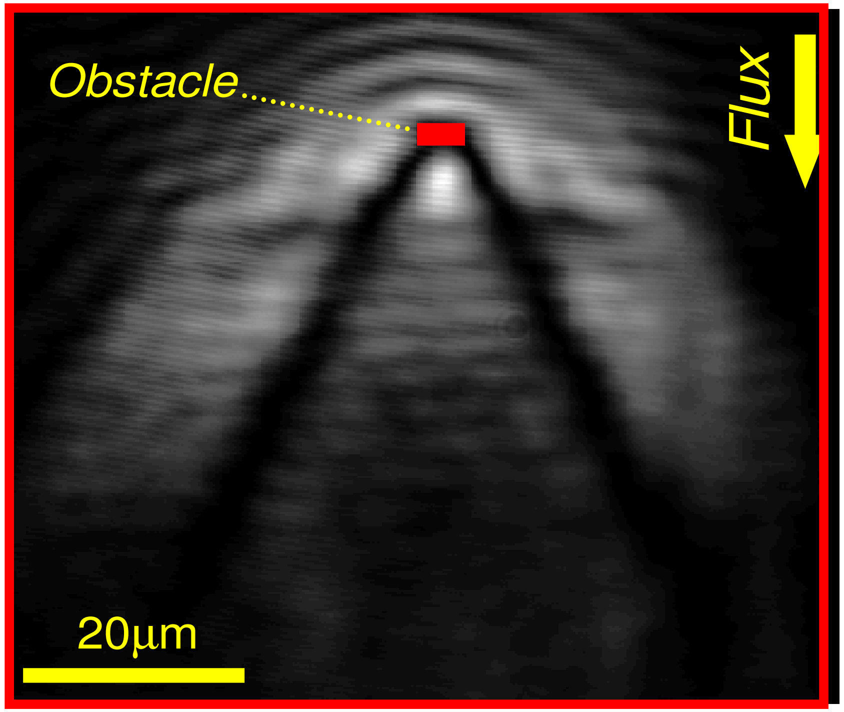
[2]*Instituto de Física, Universidade de São Paulo, 05315-970, C.P. 66318 São Paulo, Brazil*
[3]*Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, 142190, Russia*
(Received 21 April 2006; published 1 November 2006)



Hard to observe in atomic BEC; the dissipation in polariton fluids helps in stabilizing dark solitons

Dissipation: short propagation

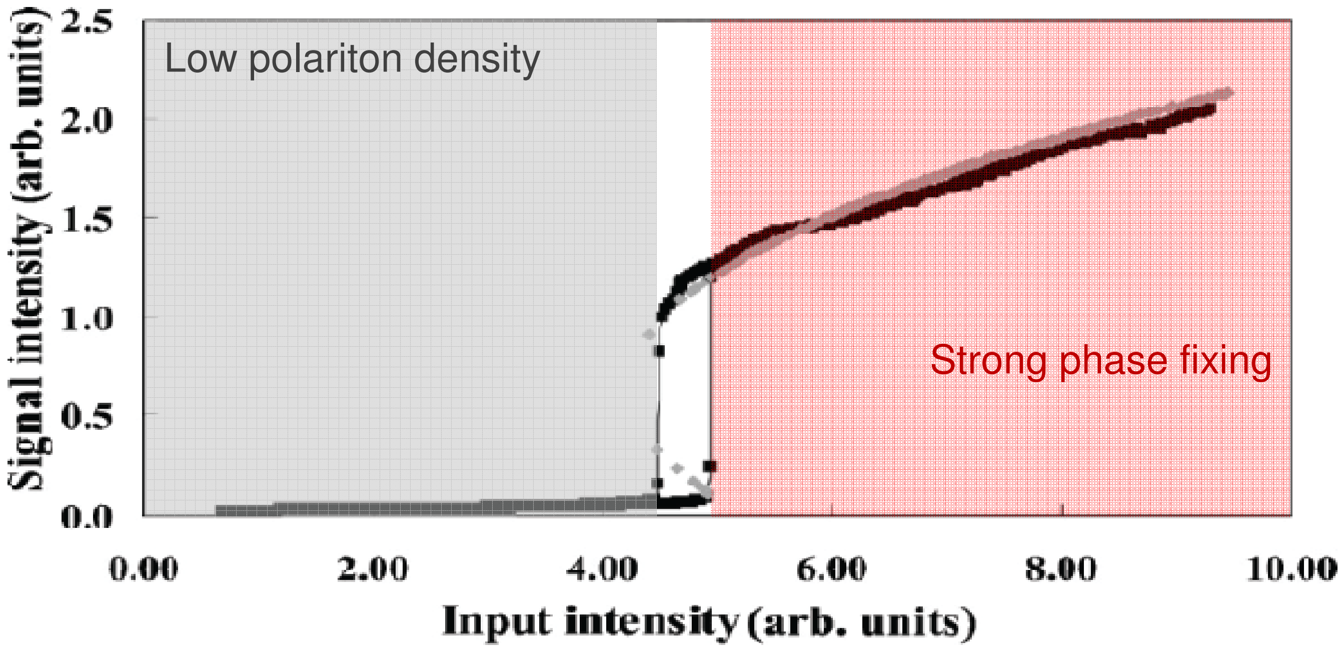


Dissipation

✓Problem: the polariton density decreases rapidly; only short propagation is achieved (about 30- 40 µm)

The idea: to exploit the bistability

Proposal: S. Pigeon et al, NJP, 2018

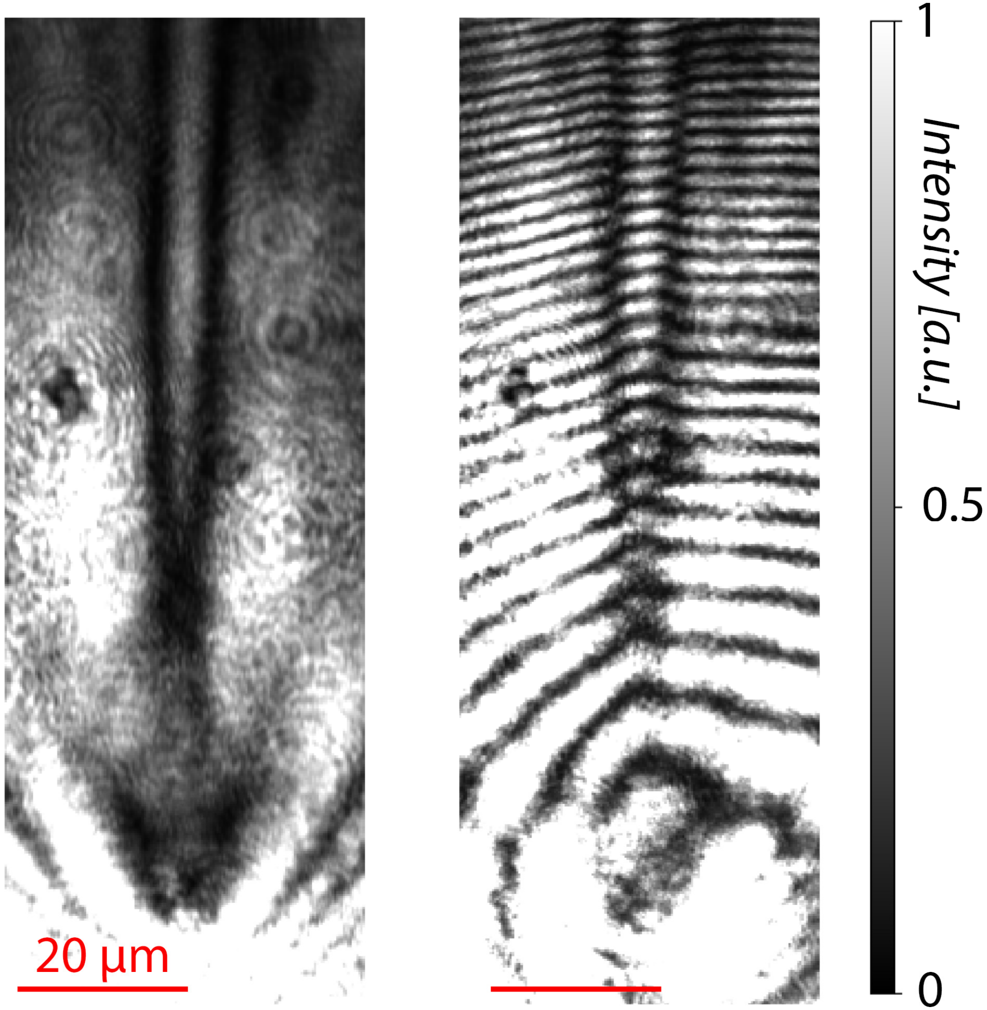


.A. Baas et al., Phys. Rev. A 69, 23809 (2004)

Bistability: high polariton density and no phase fixing

Dark Soliton Enhanced Propagation

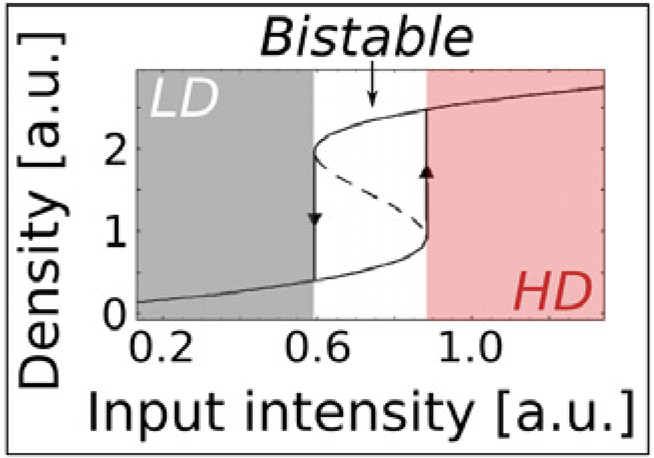
Up to 150µm propagation distance

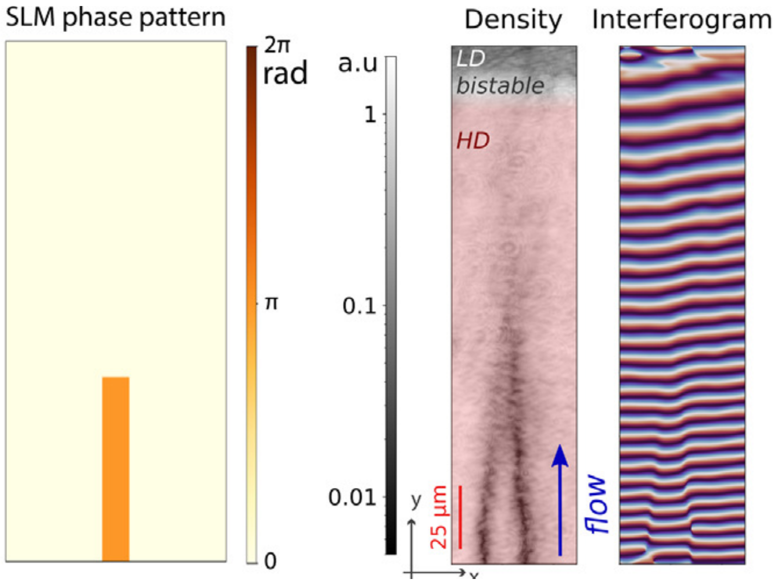


New feature: solitons are parallel each other and to the direction of the flow

G. Lerario et al., Phys. Rev. Research 2, 042041(R) (2020)

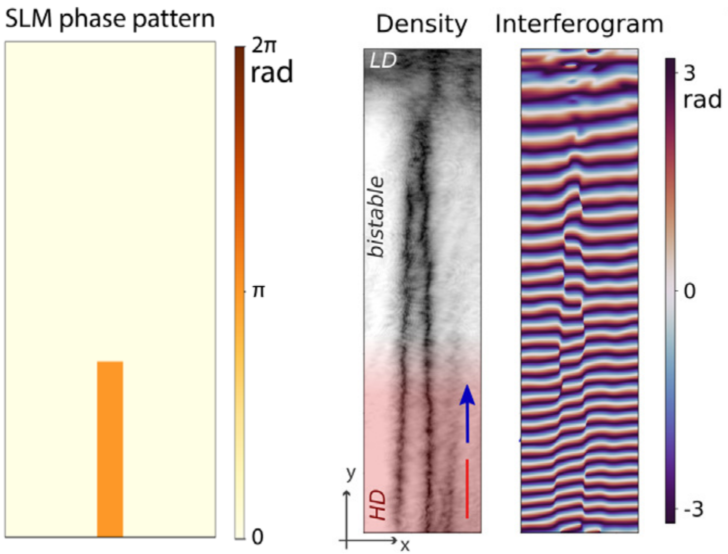
All-optical imprinting of solitons





Pump phase profile

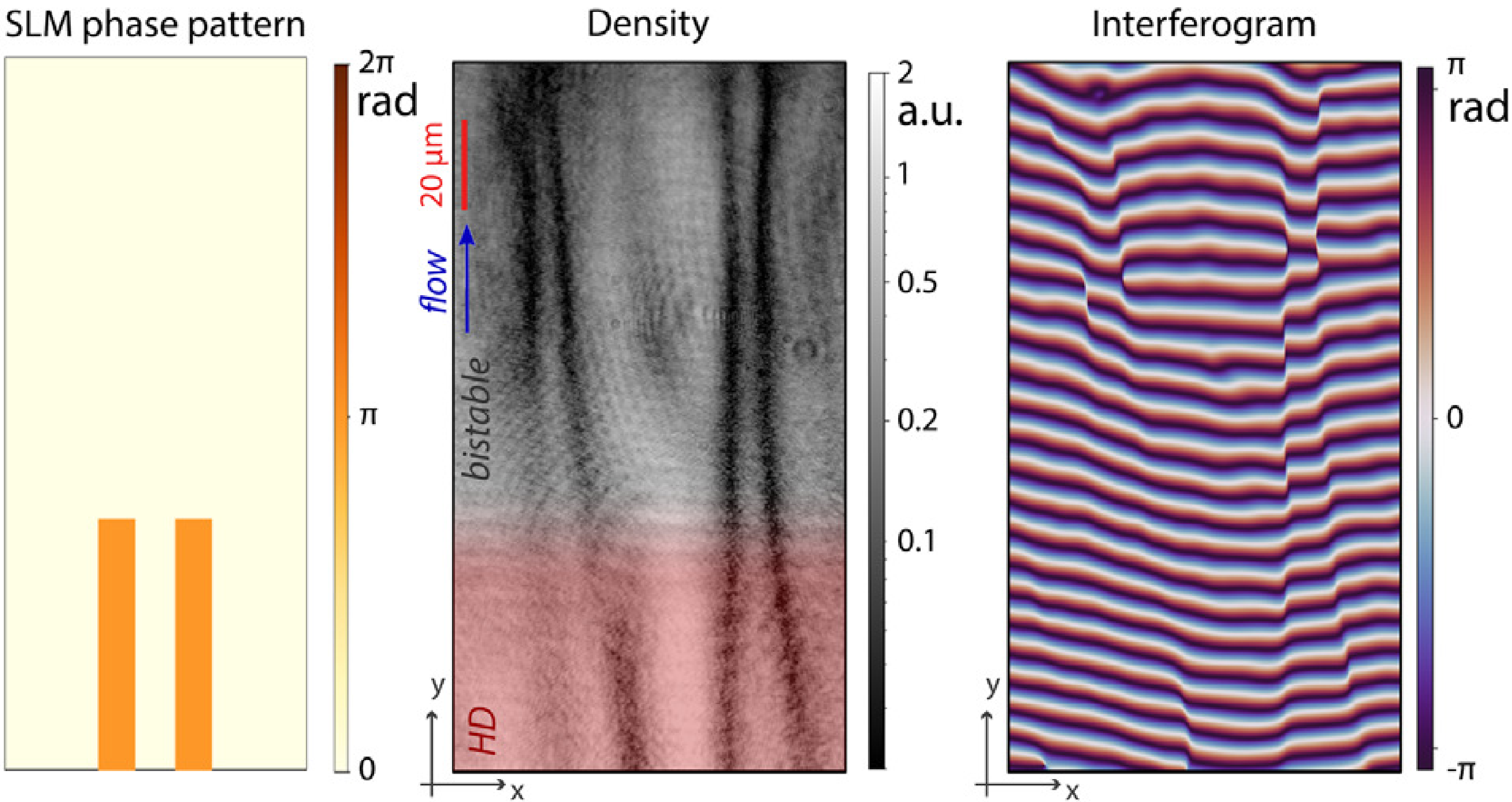
High density regime: the phase of the pump is copied onto the fluid



In the bistable region the phase of the fluid is not fixed by the pump: solitons propagate through the bistable region for very long distances

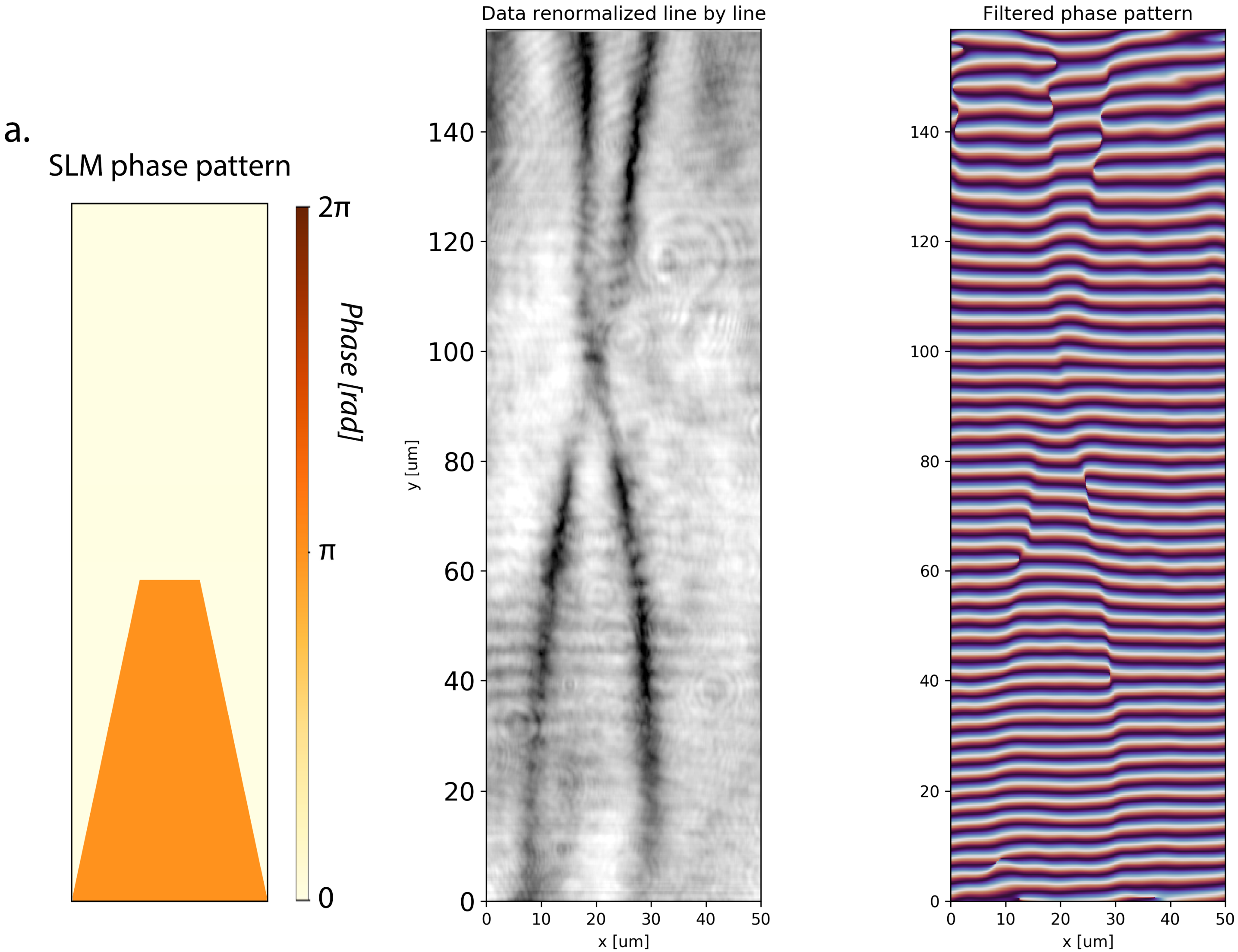
A. Maitre. et al, Phys. Rev. X 10, 4 (2020)

Solitons arrays



Scalable technique to create in a controlled way soliton arrays

Colliding Solitons



Flexible technique to study in a controlled way the soliton interactions

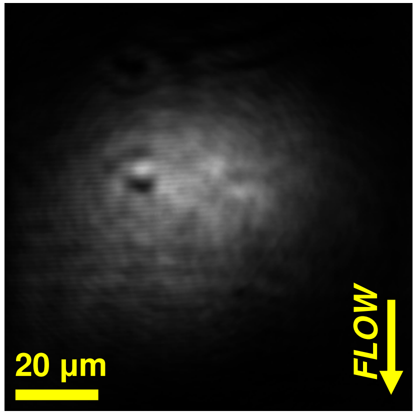
Light engineering of the polariton landscape:

using polariton-polariton interactions

Engineered landscape

Sample from R. Houdré

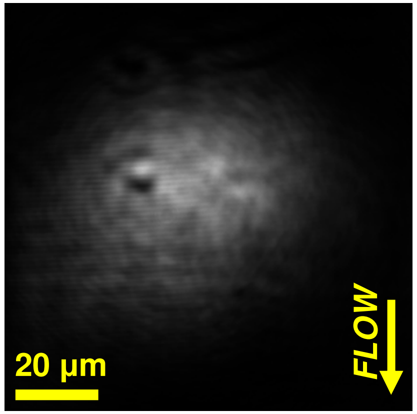
probe σ^+



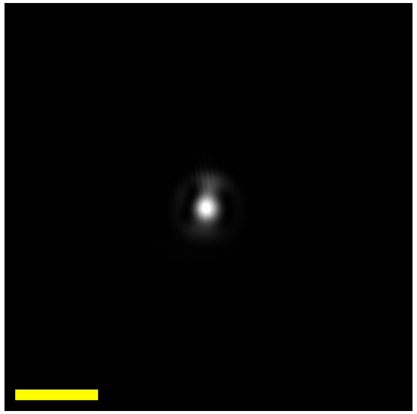
Defect-free area

Engineered landscape

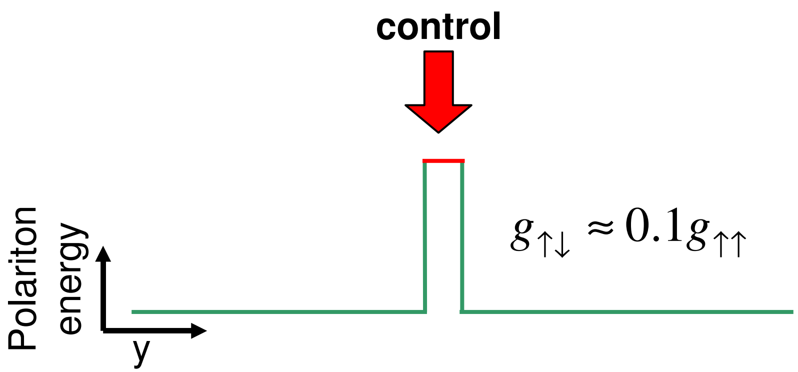
probe σ^+



control σ^-



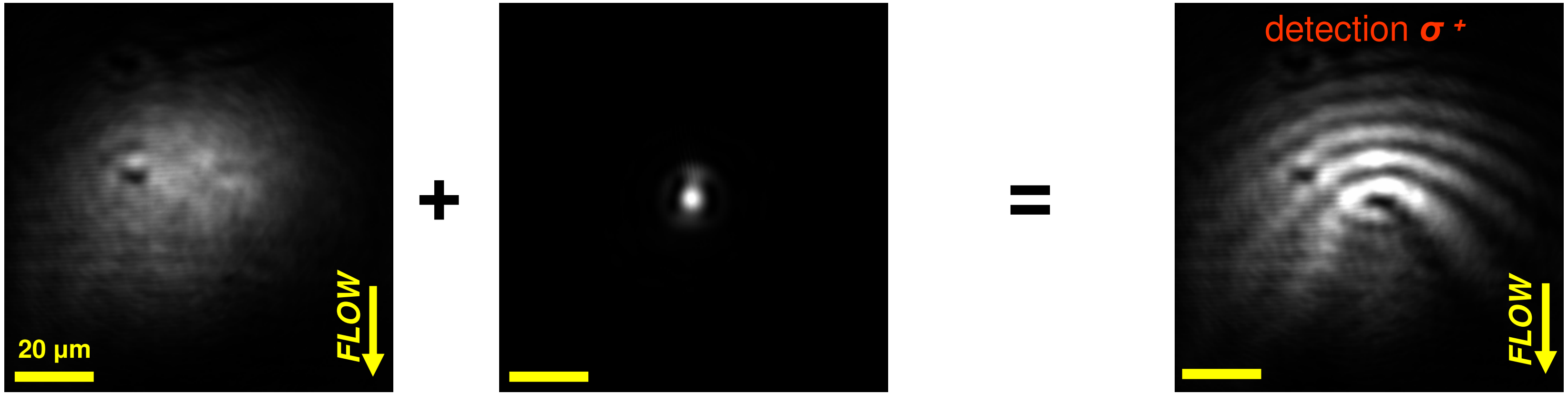
strong field: renormalization of the polariton energy



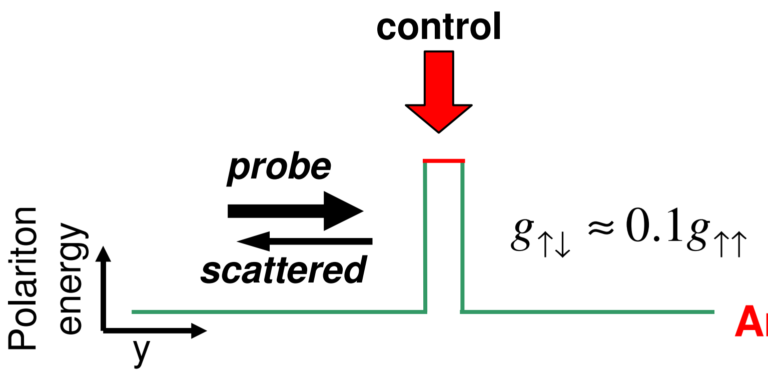
$$g_{\uparrow\downarrow} \approx 0.1 g_{\uparrow\uparrow}$$

Engineered landscape

probe σ^+ control σ^- probe σ^+ + control σ^-



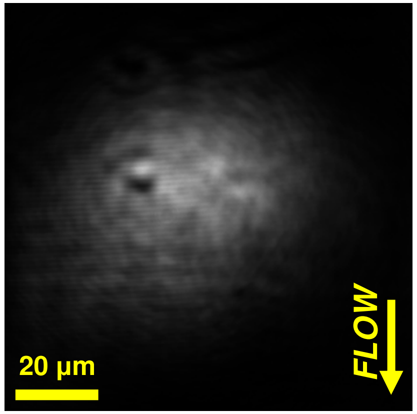
strong field: renormalization of the polariton energy



Amo *et al.*, PRB Rapid Comm. (2010)

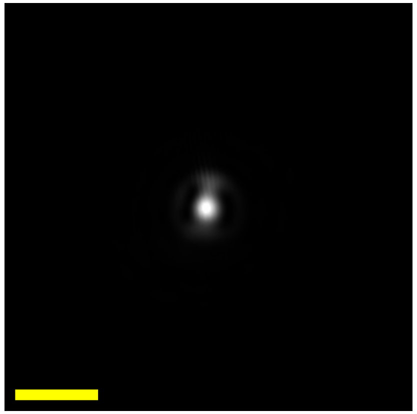
Engineered landscape

probe σ^+



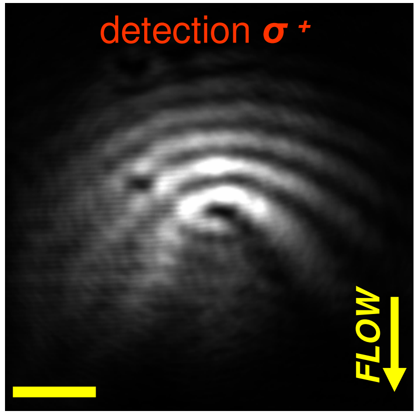
+

control σ^-

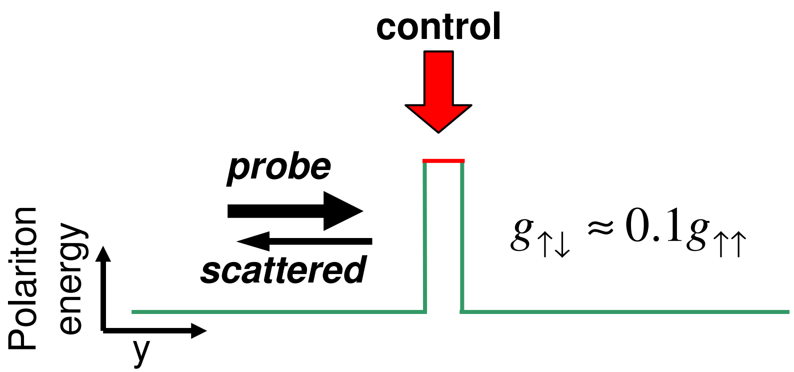


=

probe σ^+ + control σ^-

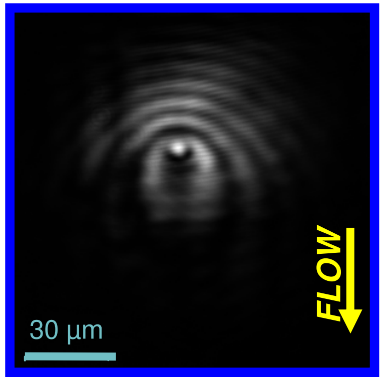


strong field: renormalization of the polariton energy



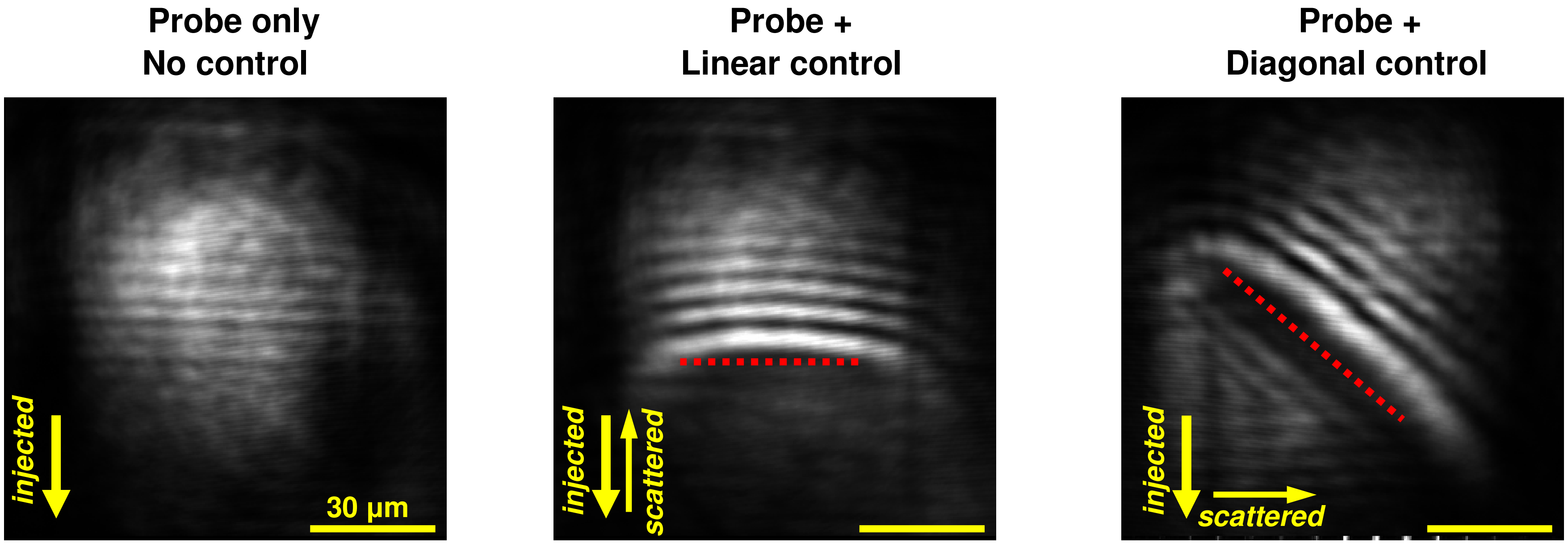
$$g_{\uparrow\downarrow} \approx 0.1 g_{\uparrow\uparrow}$$

Real defect



Amo *et al.*, PRB Rapid Comm. (2010)

Engineered landscape

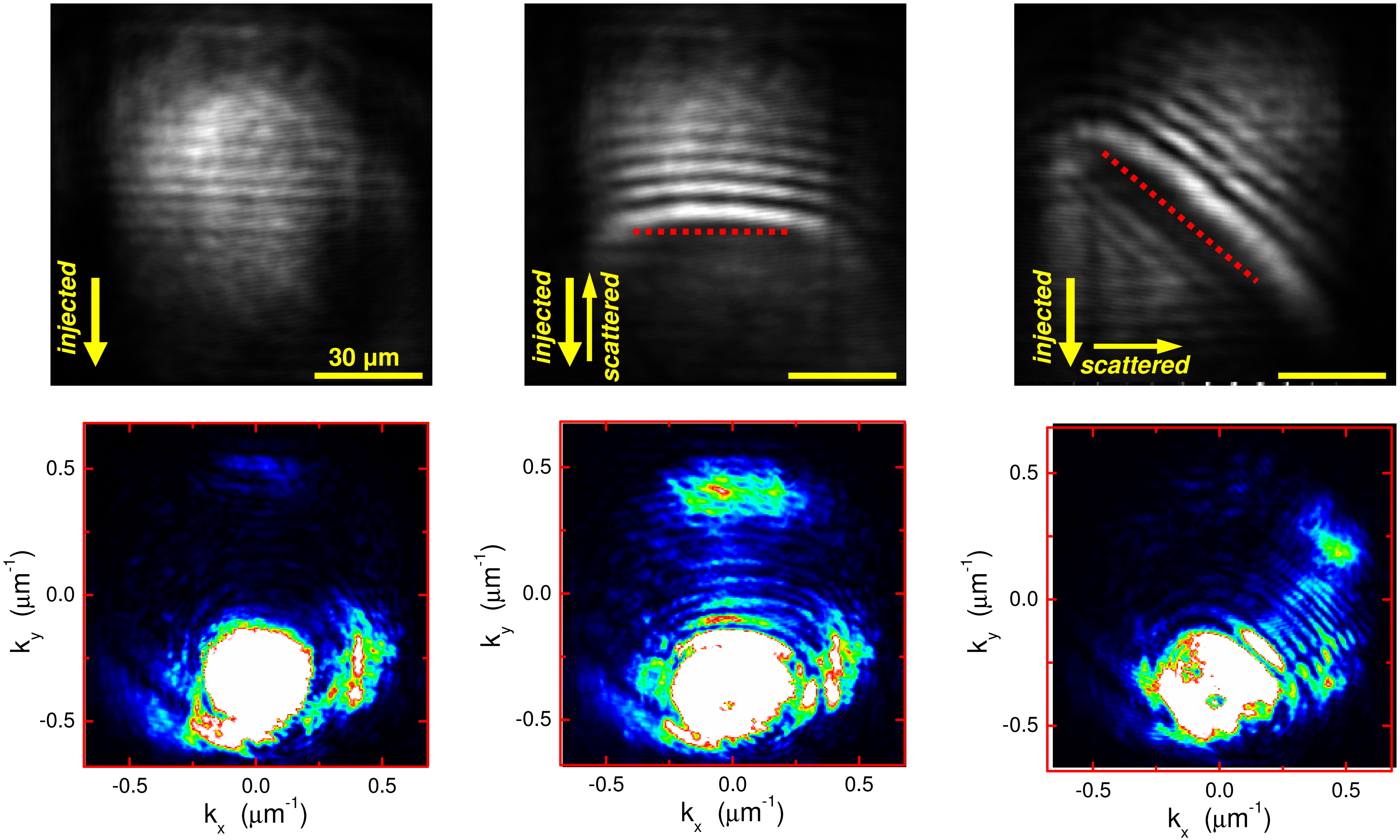


Engineered landscape

Probe only
No control

Probe +
Linear control

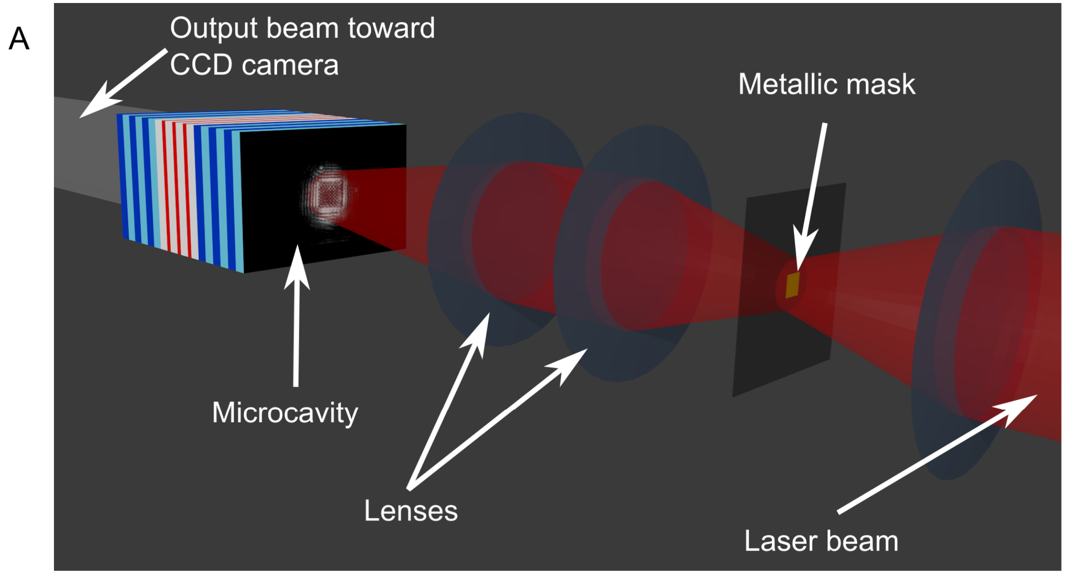
Probe +
Diagonal control



Creation of optically controlled traps for polaritons

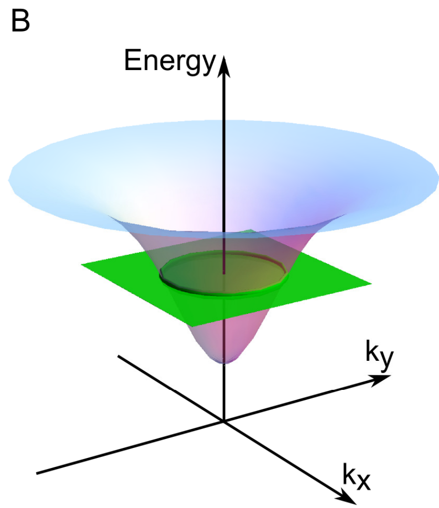
Polariton trap

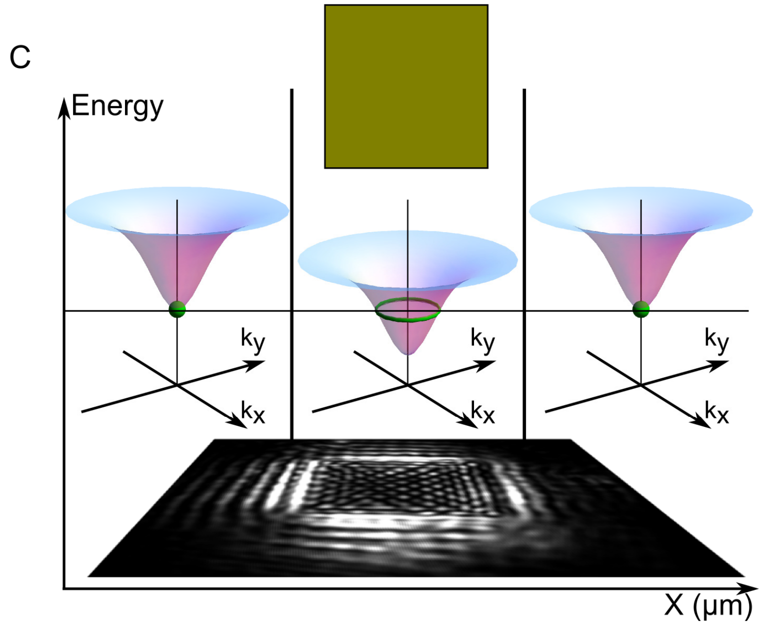
A mask is put in the center of the beam and imaged on the microcavity



Outside the mask: high polariton density

Inside the mask: low polariton density

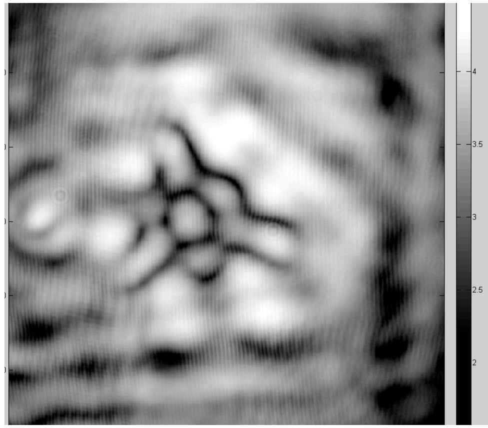


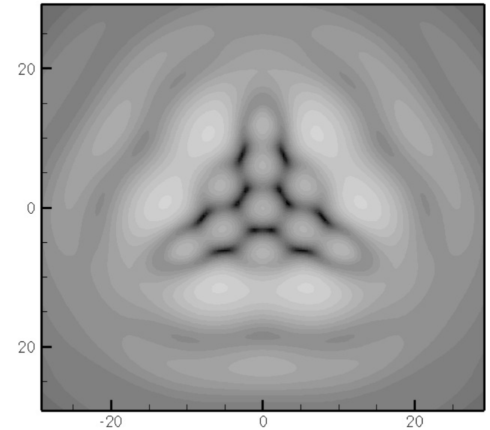


Vortex-antivortex lattices in optical traps

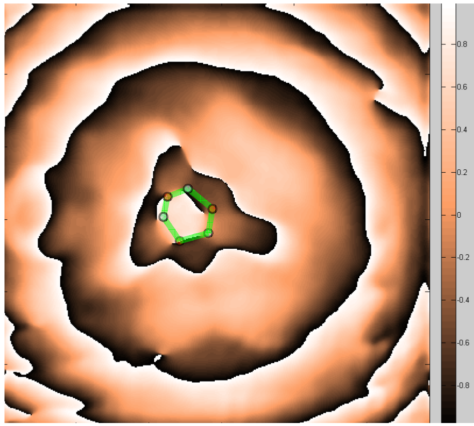
Small triangular trap

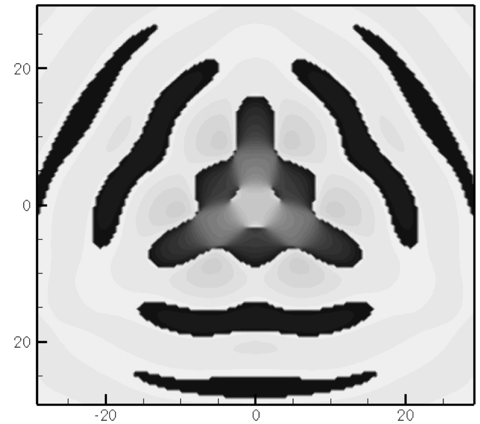
Experiment **Theory**





Polariton density



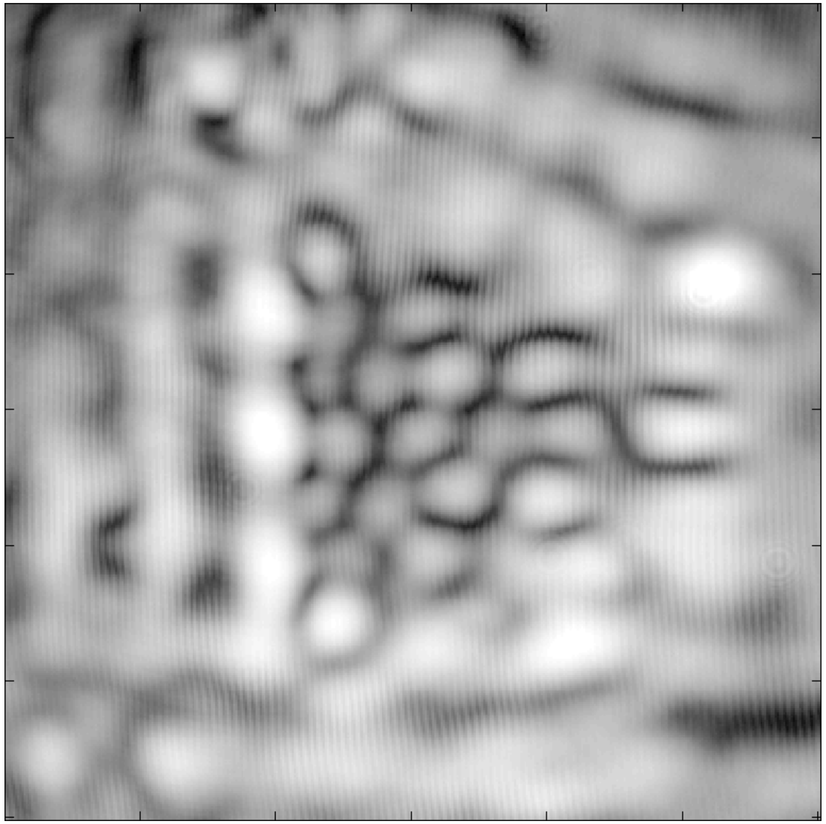


Phase

Lattice shape fixed by the trap geometry

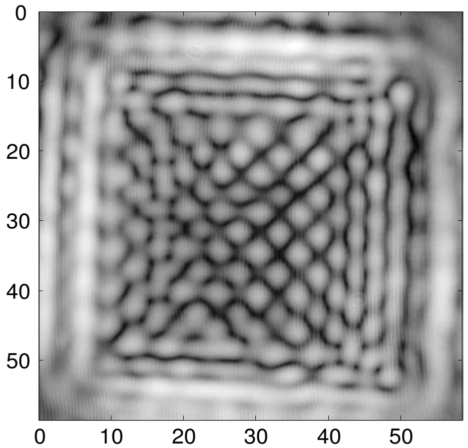
Vortex-antivortex lattices in optical traps

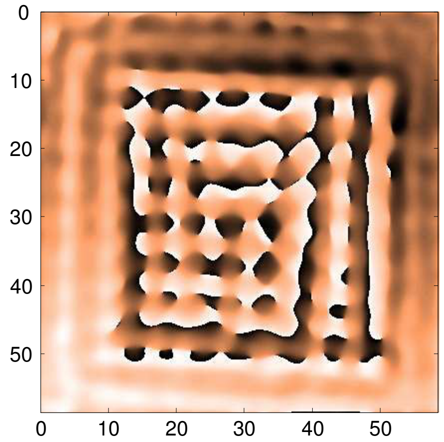
Increasing the size of the trap, a larger number of hexagonal unit cells is formed



Vortex-antivortex lattices in optical traps

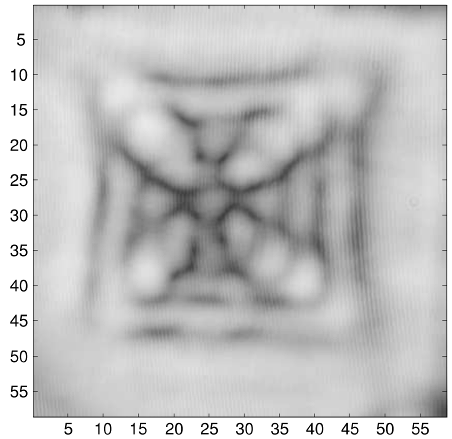
Low density

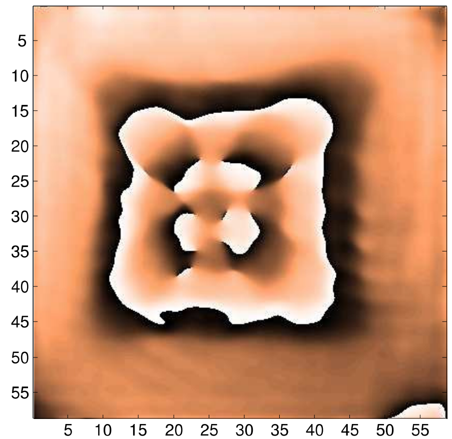




Polariton density **Phase**

High density



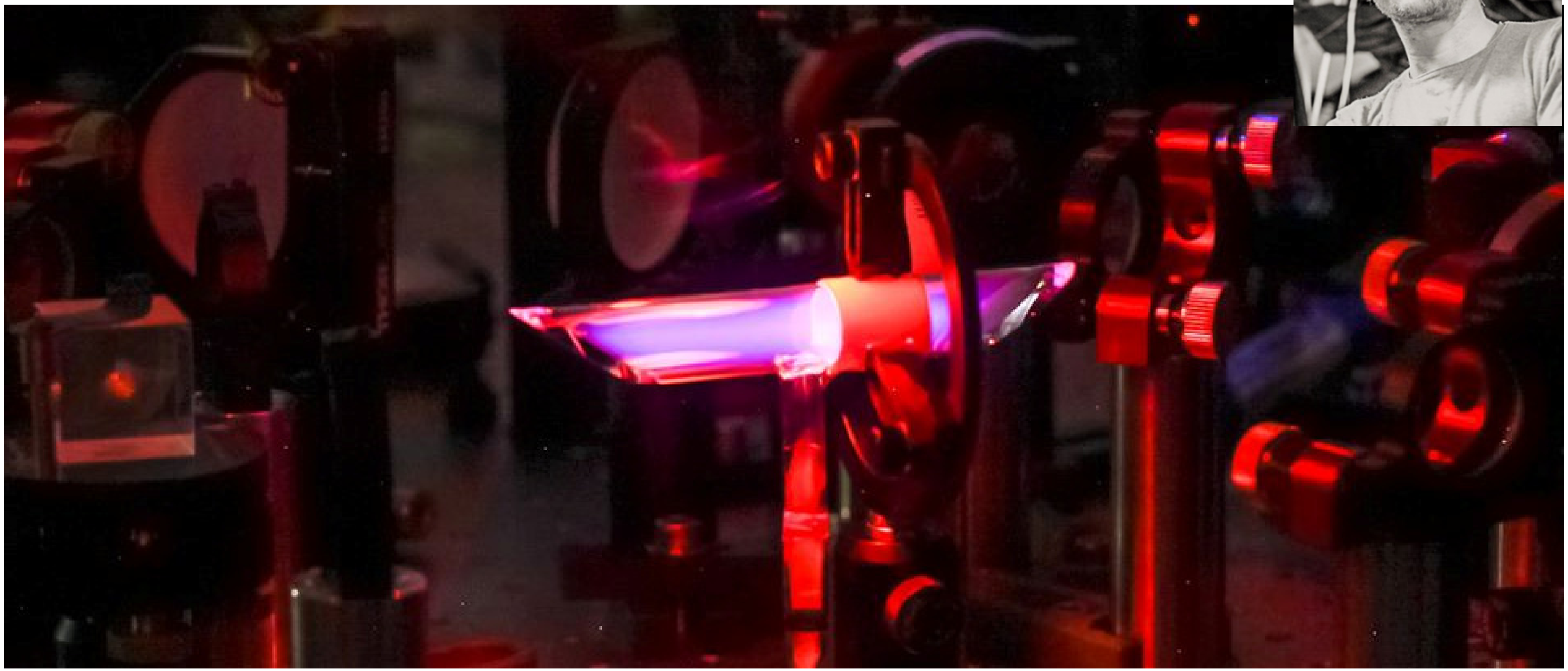


Effects of the interactions **(Hivet et al, PRB 2014)**

Polaritons

- Superfluidity
- Quantized Vortices
- Dark Solitons
- All-optical generation of steady-state topological excitations with macroscopic propagation
- All optical manipulation: polariton landscape, polariton traps

Paraxial fluids of light in hot atomic vapors



Quantum fluids of light in propagating geometry

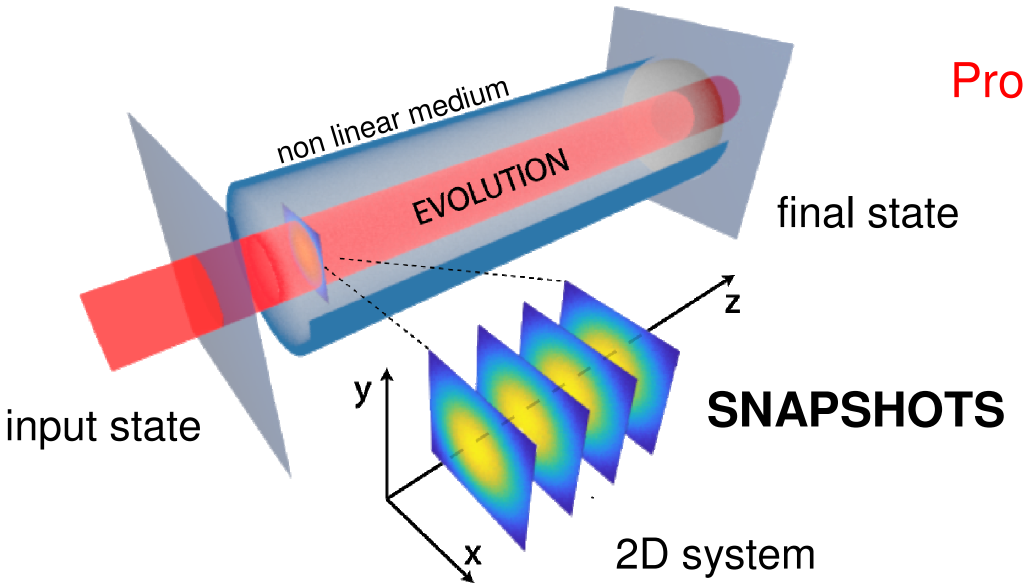
Paraxial approximation of wave propagation in a Kerr medium:

$$i\frac{\partial}{\partial z}E = \boxed{-\frac{1}{2k_0}\nabla_\perp^2 E} - \boxed{\frac{k_0\delta\epsilon}{2\epsilon}E} - \boxed{\frac{k_0\chi^{(3)}}{2\epsilon}|E|^2 E}$$

kinetic energy

external potential

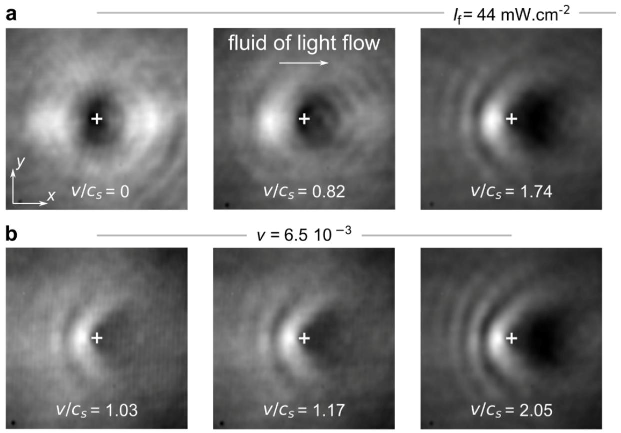
non-linear interaction



Propagation through a nonlinear medium:

- 2D fluid in the transverse plane
- Effective mass in the paraxial approximation
- Interactions from the non-linearity
- Direction of propagation = time
- CONSERVATIVE DYNAMICS.

Experimental Implementations

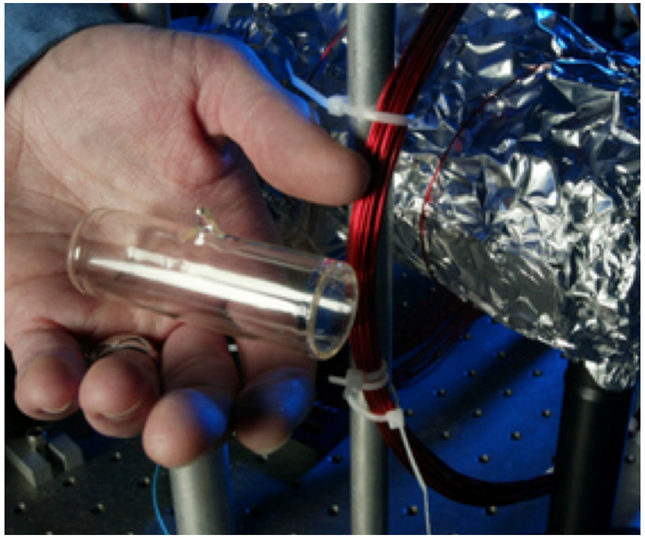


arXiv:1710.03081

Photorefractive crystal

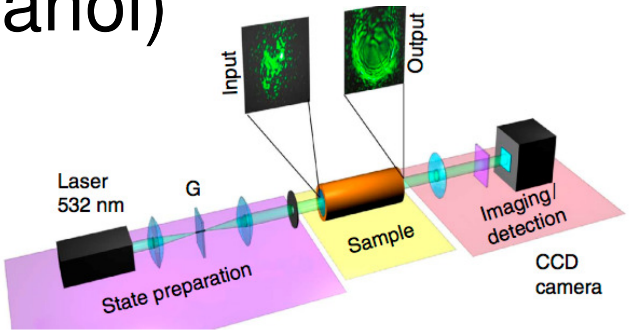
M. Bellec & C. Michel, InPhyNi, Nice
J. W. Fleischer, Princeton

Atomic vapor



R. Kaiser, InPhyNi, Nice
Q. Glorieux, A. Bramati, LKB, Paris

Thermo-Optic liquid (methanol)



D.Faccio - Glasgow

Rb atomic vapor

We work with Rb D2 atomic line (780 nm)

Detuning >> Doppler broadening

We can neglect the fine structure and model the Rb atoms as a two-level system:

$$\chi^{(3)} = -\frac{4}{3} N (\rho_{bb} - \rho_{aa})^{(\mathrm{eq})} |\mu_{ba}|^4 \frac{1}{\hbar^3 \Delta^3} \frac{T_1}{T_2}.$$

Atomic density

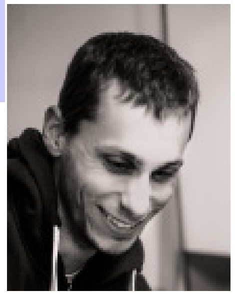
detuning

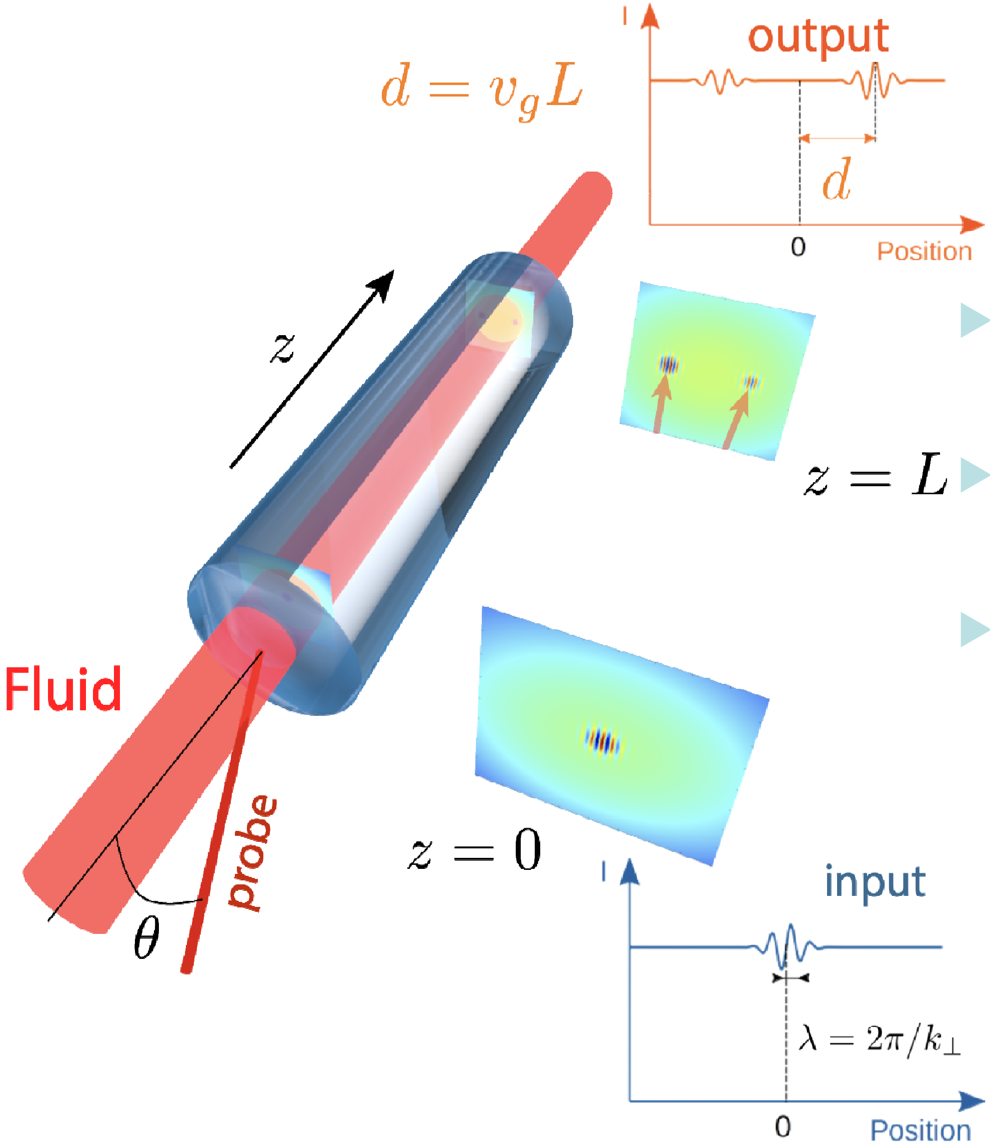
By properly choosing the detuning and the atomic density (via the cell temperature) we can have at the same time

High enough repulsive non linearities

Low absorption (less than 30%)

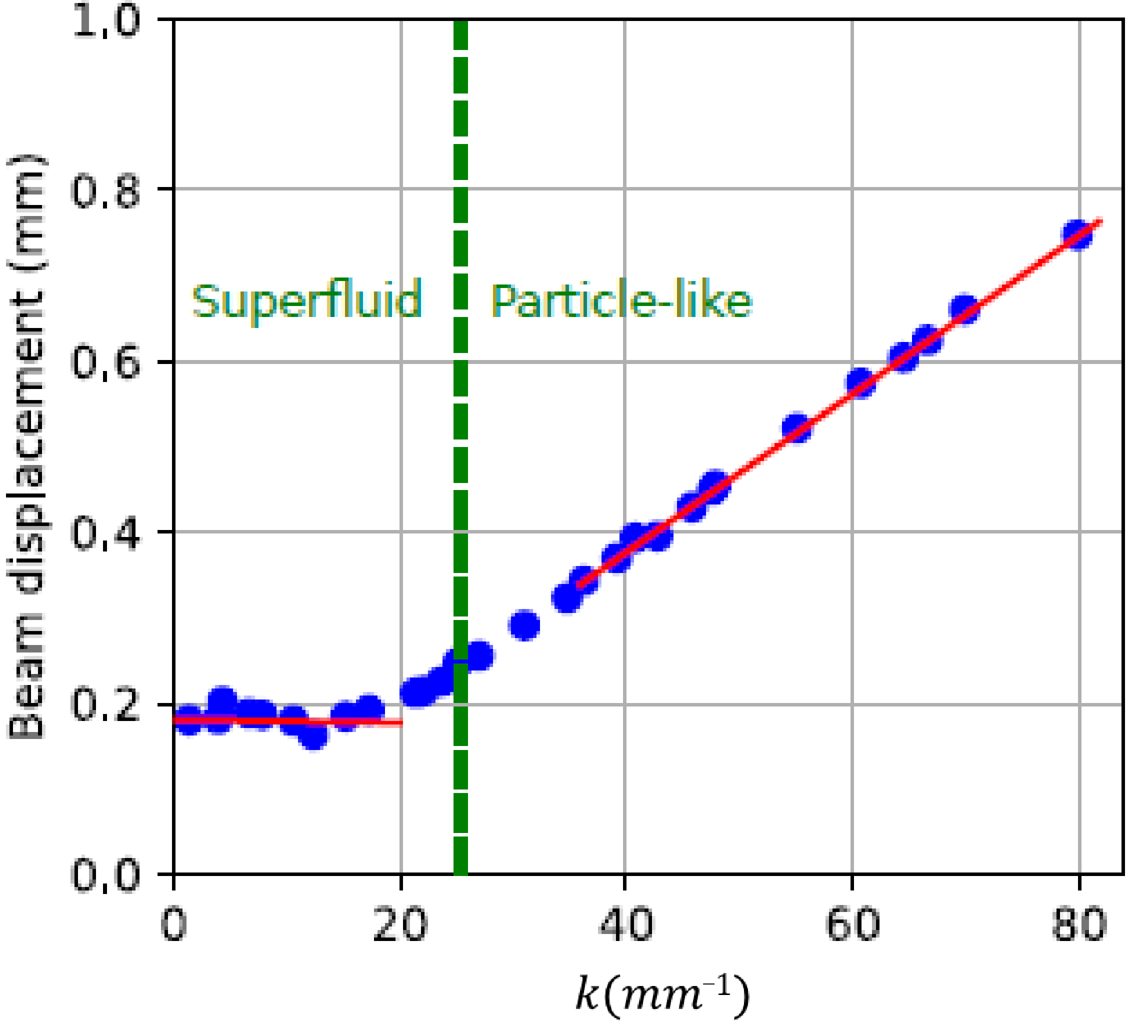
Probing the superfluid behaviour

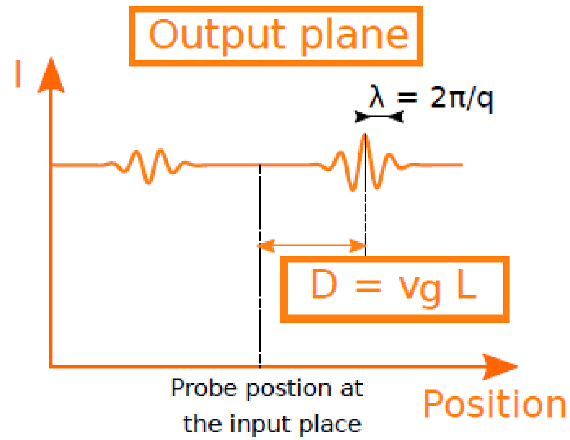




- An intense Pump beam creates the photon fluid
- A weak localized probe beam creates the perturbation
- We measure the displacement of the perturbation as a function of the probe wave-vector

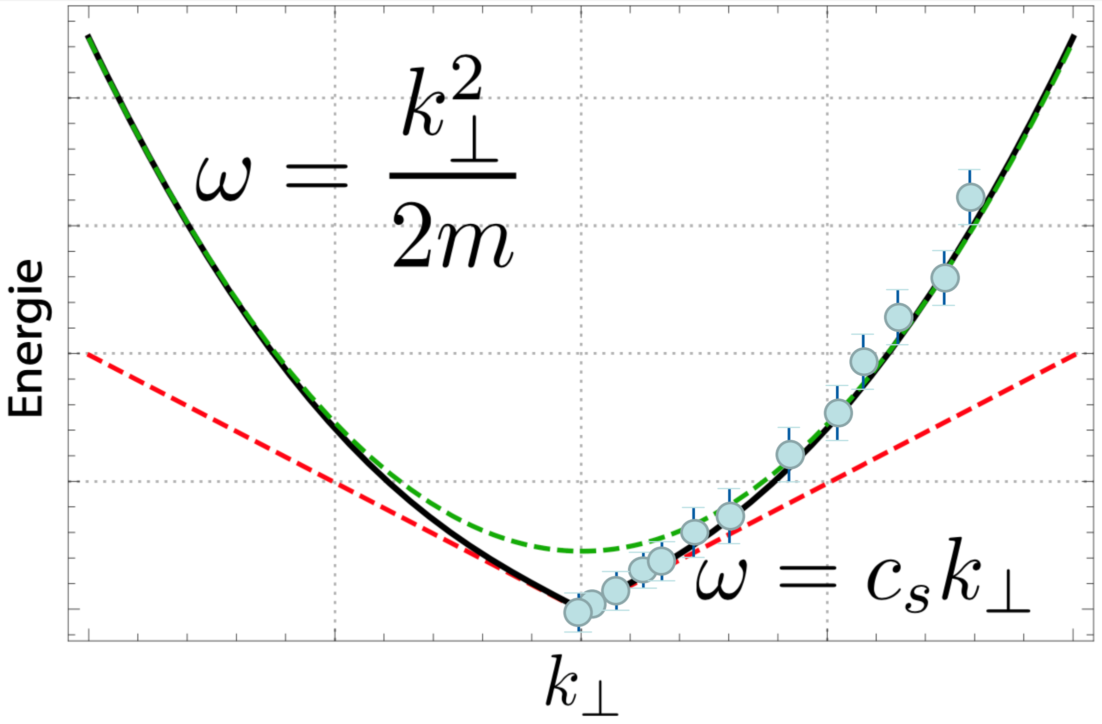
Probing the superfluid behaviour





Q. Fontaine et al, Phys. Rev. Lett. 121, 183604 (2018)

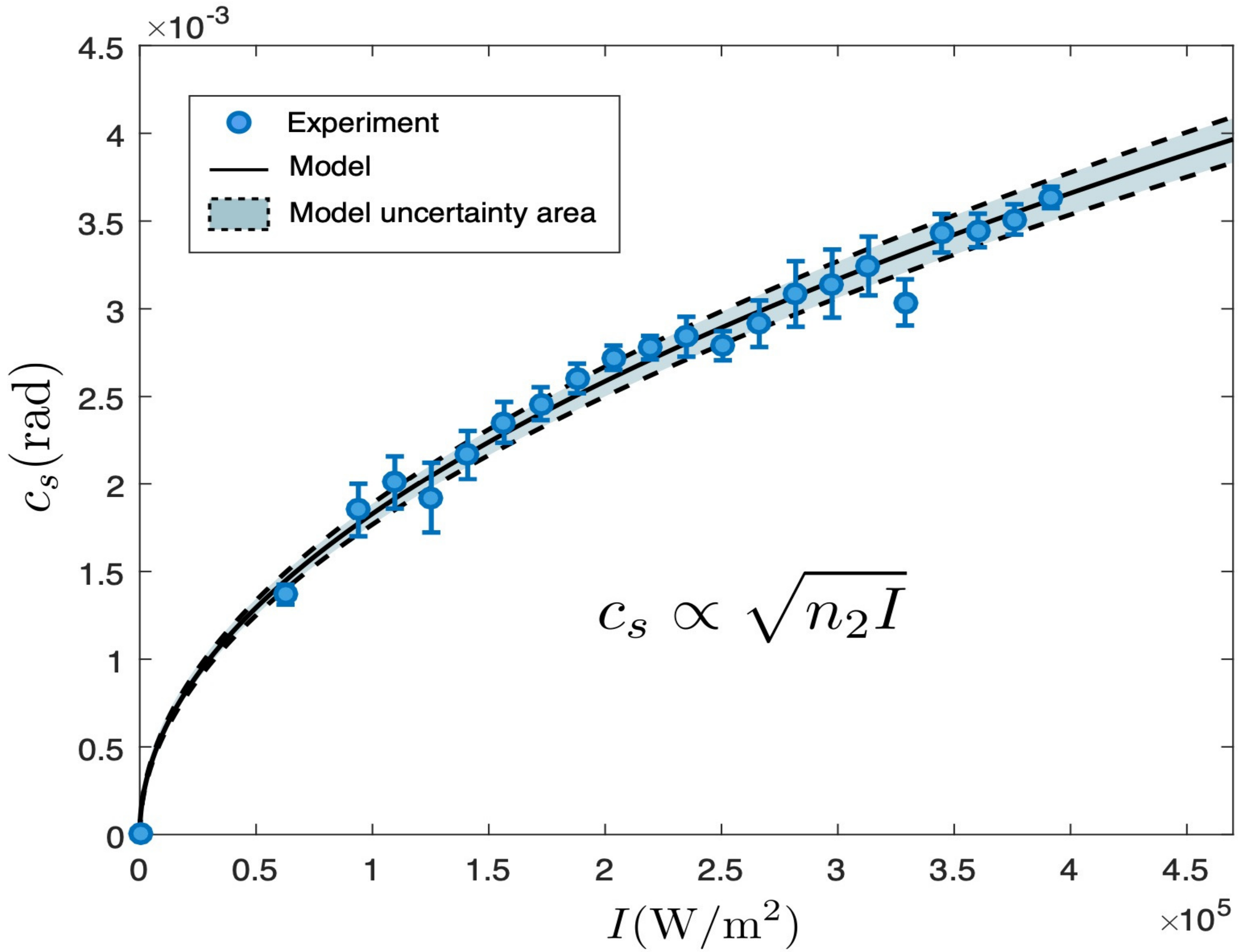
Probing the superfluid behaviour



Group velocity: $v_g = \frac{\partial \omega}{\partial k_\perp}$

Q. Fontaine, et al. PRL, **121**, 183604 (2018)
C. Piekarski, et al. PRL, **127**, 023401 (2021)

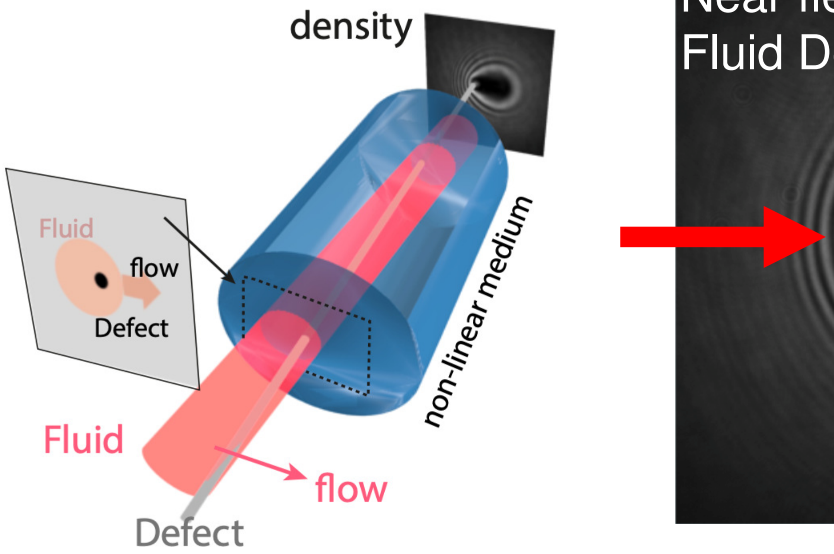
Speed of sound

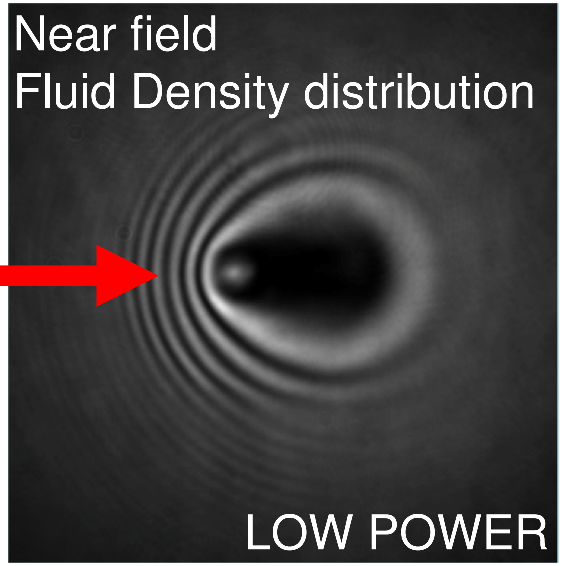


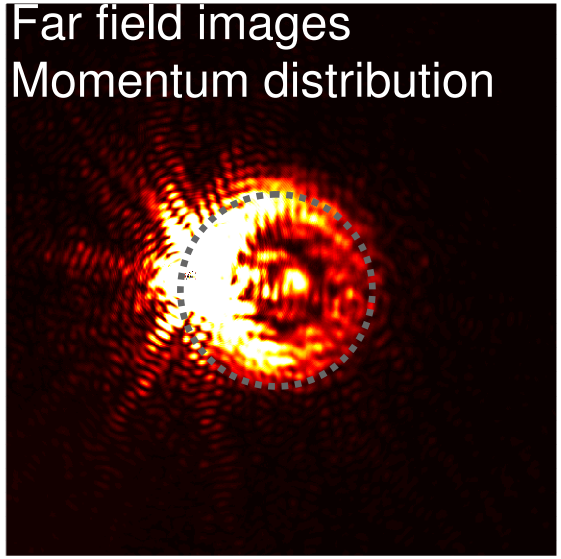
$$n = n_0 + n_2 I$$

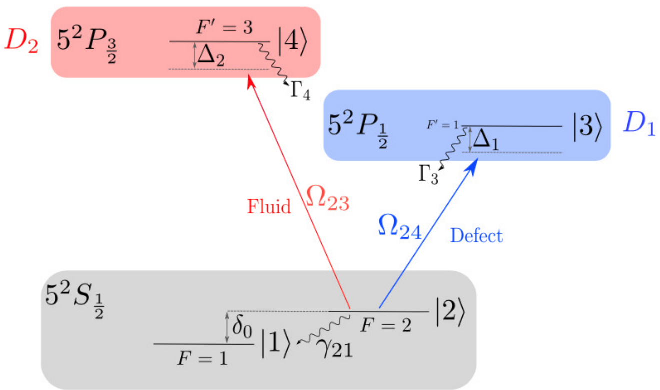
$$\boxed{n_2^I = \frac{3}{4}\frac{\chi^{(3)}}{\epsilon_0 n_0^2 c}}$$

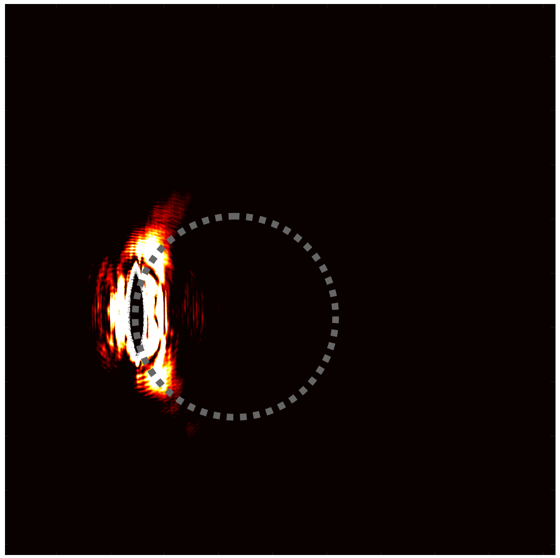
Scattering on an optical defect





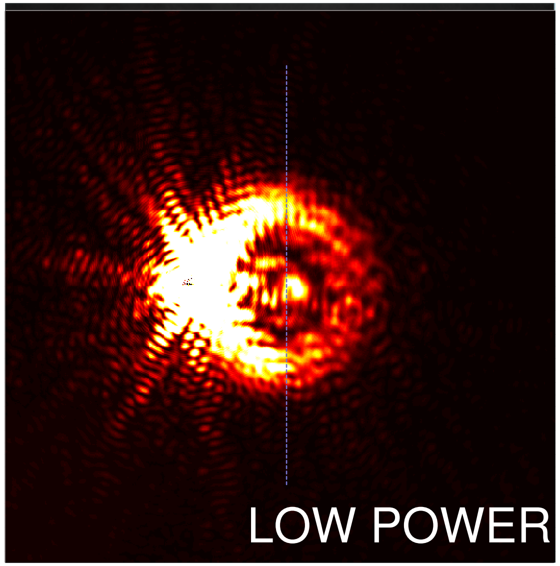


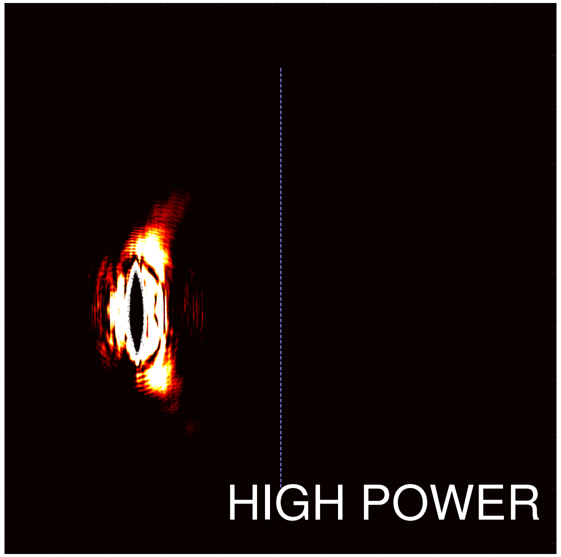


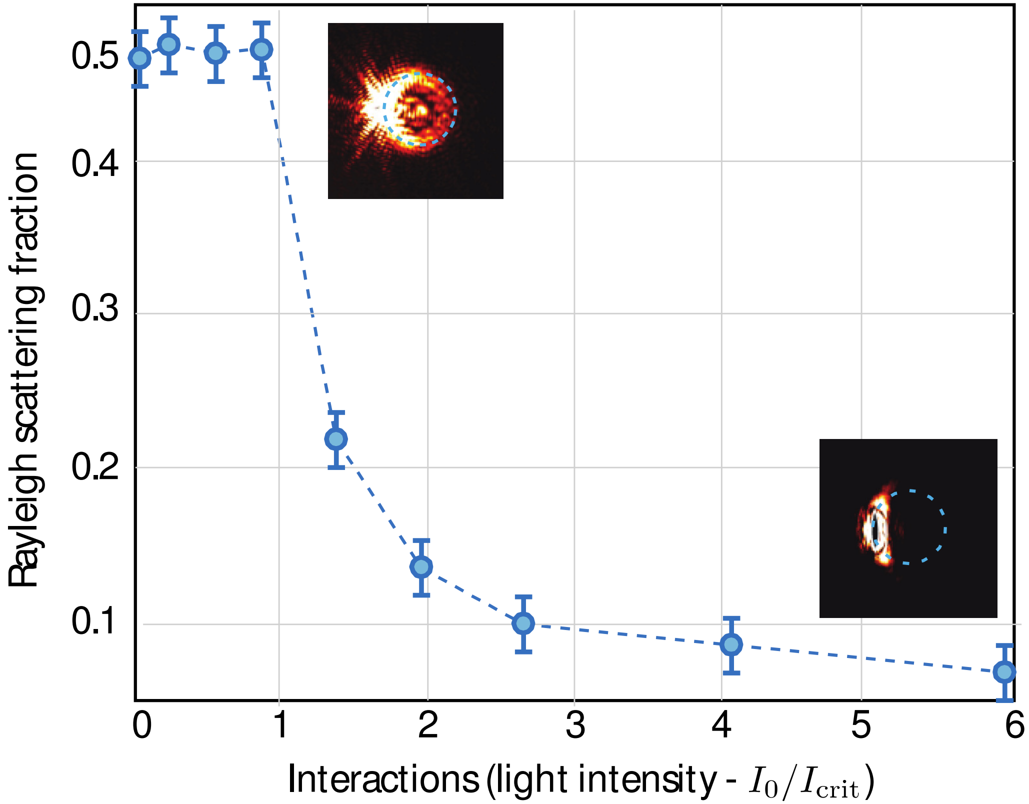


Q. Fontaine, H. Hu, S. Pigeon, T. Bienaime, E Wu, Giacobino E., A. Bramati, Q. Glorieux – Opt. Express (2019)

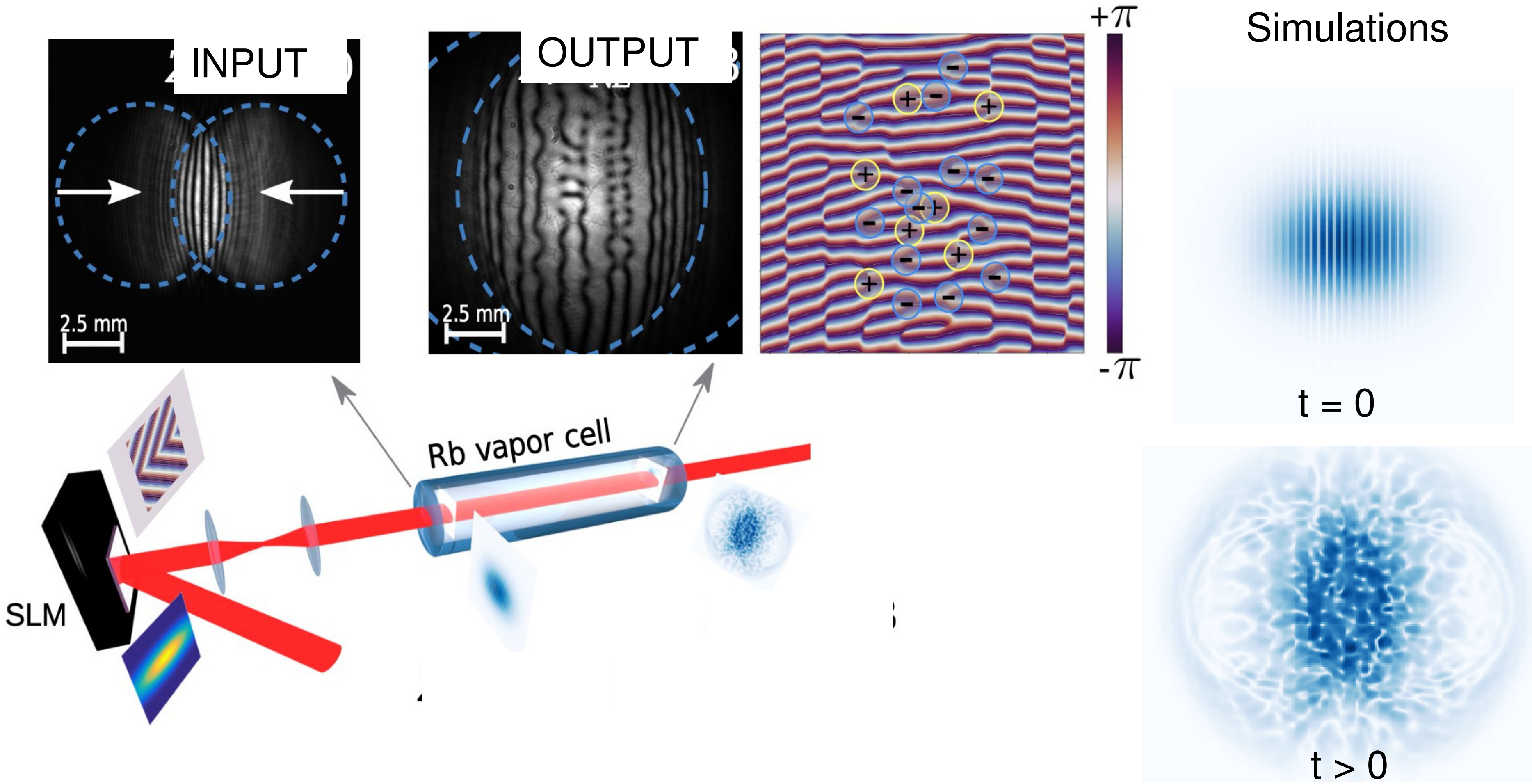
Scattering on an optical defect







Turbulence with two counter streaming flows



Energy cascade, inverse energy cascade, Kelvin-Helmotz instabilities

Conclusions

- ✓ Quantum fluid of light in a hot Rb vapor
- ✓ Observation of the Bogoliubov dispersion; strong indication of supefluid like behavior in these systems
- ✓ Scattering suppression and turbulence measurements

Outlook: quantum fluids of light for analogue gravity experiments

See the Kevin Falque's poster

Analogue quantum simulation of field theories on curved spacetimes

Laboratory experiments

Parametric amplification effects:
Hawking radiation
Zeldovich superradiance
Penrose effect
Preheating and reheating of early universe

Black holes
Cosmology

The team

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Thank you for your attention