Hydrodynamics of out of equilibrium polariton fluids

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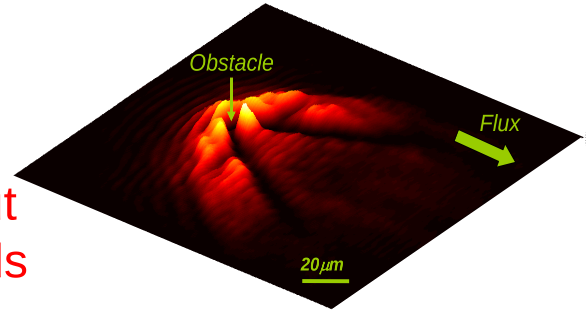
Physique quantique et applications

Quantum Optics Team: topics

Quantum fluid phenomena in polariton gases

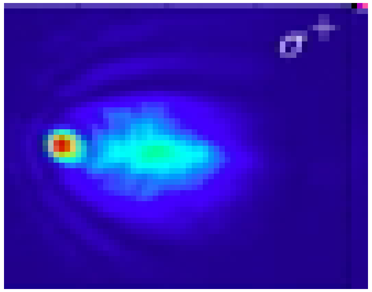
⇒ An ideal system to study out of equilibrium quantum fluids



Superfluidity, hydrodynamic dark solitons and vortices (*Nature Physics 2009, Science 2011, Nature Photonics 2011, Nature Physics 2012*)

Spin dependent non linearities in microcavities

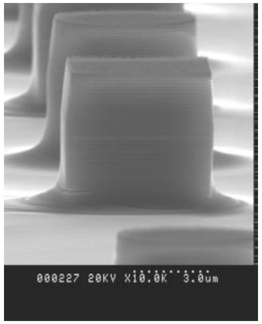
⇒ Towards integrated optoelectronic devices



Logic gates, All Optical Spin Switches *(Nature Physics 2007, PRL 2007, Nature Photonics 2010, PRL 2011)*

Quantum Effects in semiconductor nano and microcavities in strong coupling regime

⇒ Towards a compact, integrable nano- source of entangled beams



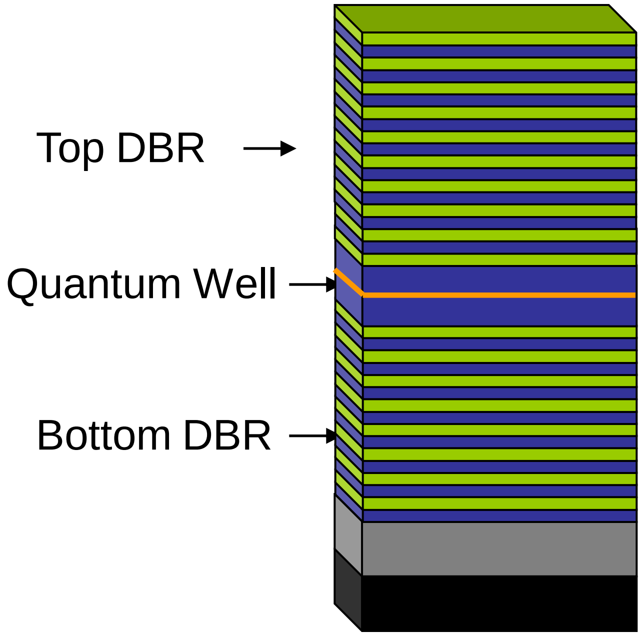
Microcavities, quantum wires, micropillars *(PRL 2007, APL 2010,PRB 2011)*

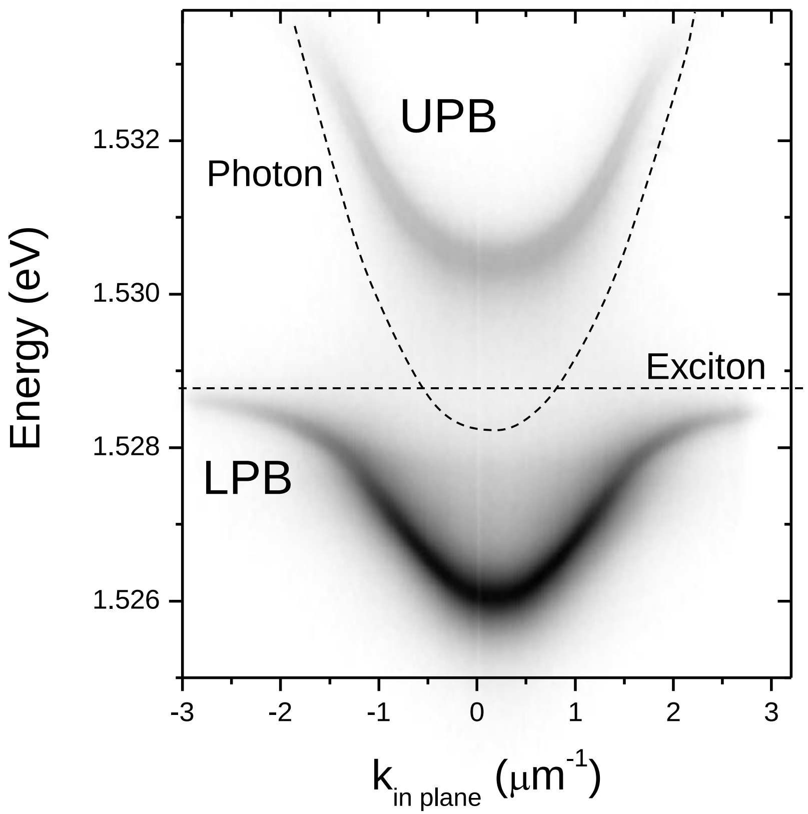
Outline

Quantum fluid phenomena

- Introduction
- Superfluidity and Čerenkov regime
- Hydrodynamic Vortices and Dark Solitons
- Towards Vortex Lattices
- Perspectives and conclusion

Microcavity Polaritons





Linear combination of excitons and photons

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

Microcavity Polaritons

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

Polaritons are weakly interacting composite bosons

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

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

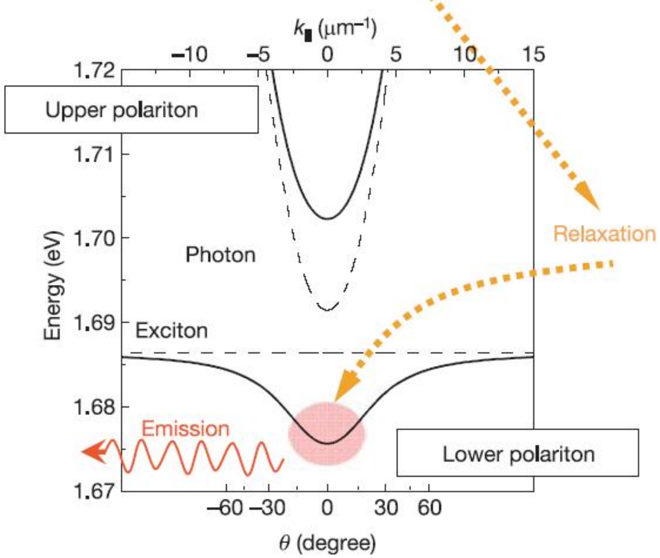
$$\lambda_T = \left(\frac{2\pi\hbar^2}{m k_B T} \right)^{\frac{1}{2}}$$

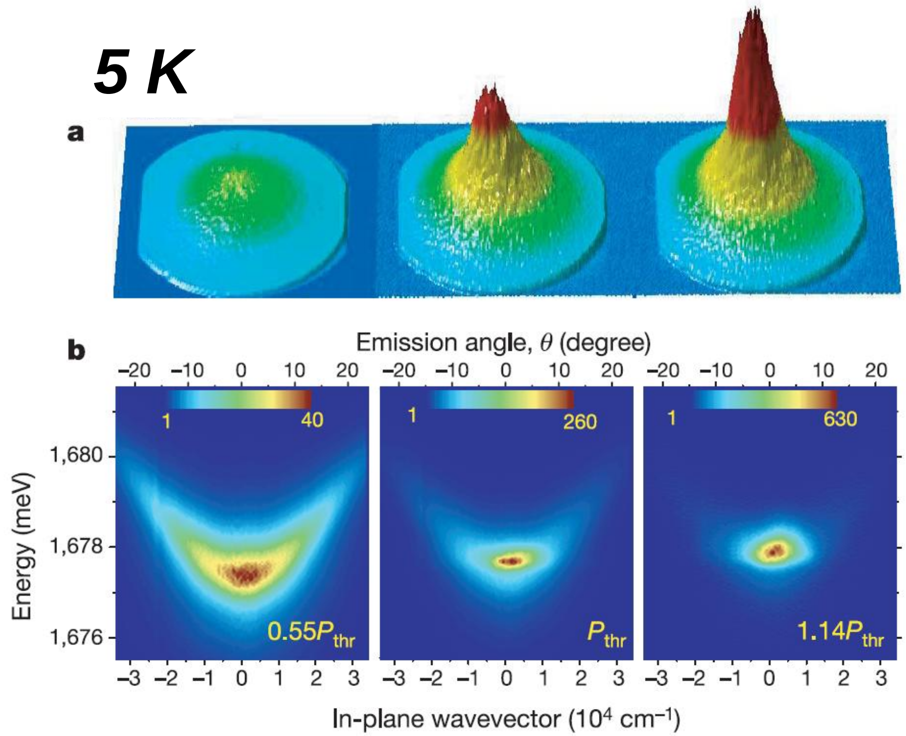
and
mean distance between polaritons d ~ 0,1-0,2 µm

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

Bose Einstein condensation of polaritons

Excitation CW laser 1.755 eV



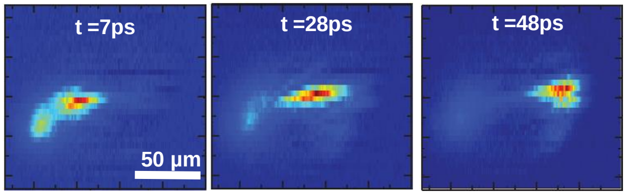


- **2D system**
- Out of equilibrium system **:**
  - Creation and recombination (polariton life time ~5 ps)

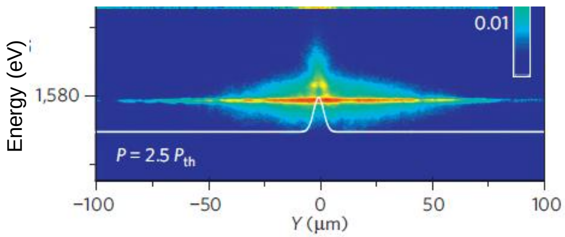
Kasprzak *et al.* Nature, **443**, 409 (2006)

Boson quantum fluids: polaritons

Coherent propagation

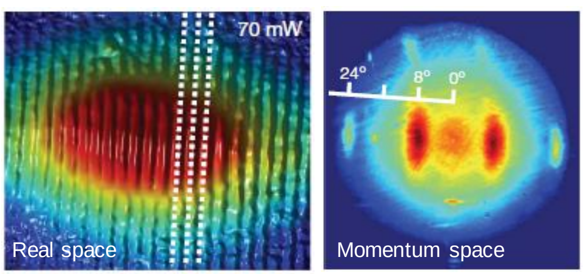


Amo *et al.,* Nature **457**, 295 (2009)



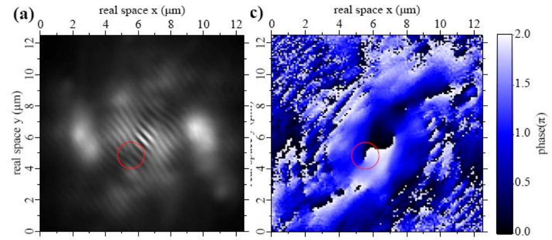
Wertz *et al.,* Nature Phys. **6**, 860 (2010)

Long-range order phases



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

Vortex and half vortex



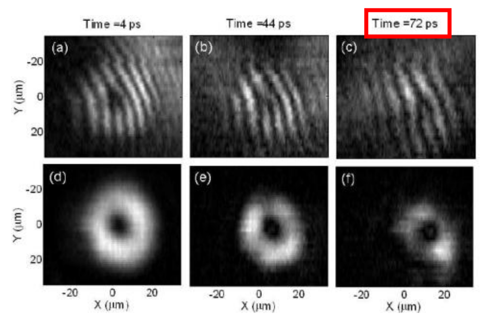
Lagoudakis *et al.*, Nature Phys. **4**, 706 (2008), and Science 326, 974 (2009)

Nardin *et al.*, arXiv:1001.0846v3

Krizhanovskii *et al.*, PRL **104**, 126402 (2010)

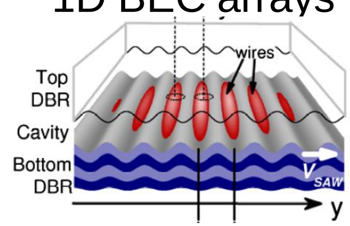
Roumpos et al., Nature Phys. **7**, 129 (2010)

Persistent currents



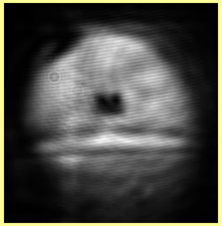
Sanvitto *et al*., Nature Phys. **6**, 527 (2010)

1D BEC arrays



Cerda-Méndez *et al.,* PRL **105**, 116402 (2010)

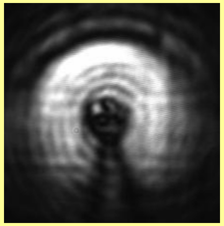
Superfluidity



This talk

Hydrodynamics: vortex

Hydrodynamics: solitons



This talk

I. Carusotto and C. Ciuti, to appear on Rev. Mod. Phys..(2012)

Wave equation for polaritons

Evolution of exciton and cavity fields, in the presence of exciton-exciton interaction

Gross-Pitaevskii equation in the presence of defects

$$
i\frac{d}{dt}\begin{pmatrix}\psi_C(\mathbf{x},t)\\ \psi_X(\mathbf{x},t)\end{pmatrix} = \begin{pmatrix}F_p e^{i(\mathbf{k}_p\mathbf{x}-\omega_p t)}\\ 0\end{pmatrix} e^{-\frac{(\mathbf{x}-\mathbf{x}_0)^2}{2\delta_\mathbf{x}^2}} +
$$

$$
\left[\mathrm{h}^0 + \begin{pmatrix} V_C(\mathbf{x}) - i\frac{\gamma_C}{2} & 0 \\ 0 & V_X(\mathbf{x}) - i\frac{\gamma_X}{2} + g|\psi_X(\mathbf{x},t)|^2 \end{pmatrix}\right]\begin{pmatrix}\psi_C(\mathbf{x},t)\\ \psi_X(\mathbf{x},t)\end{pmatrix}
$$

CW Pump

normal mode coupling

defects

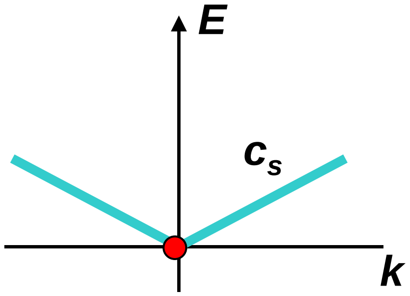
decay

pol-pol interaction

with $\mathrm{h}^0 = \begin{pmatrix}\omega_C(-i\nabla) & \Omega_R \\ \Omega_R & \omega_X(-i\nabla)\end{pmatrix}$

Quantum fluid effects: superfluidity

The Landau Criterion for superfluidity



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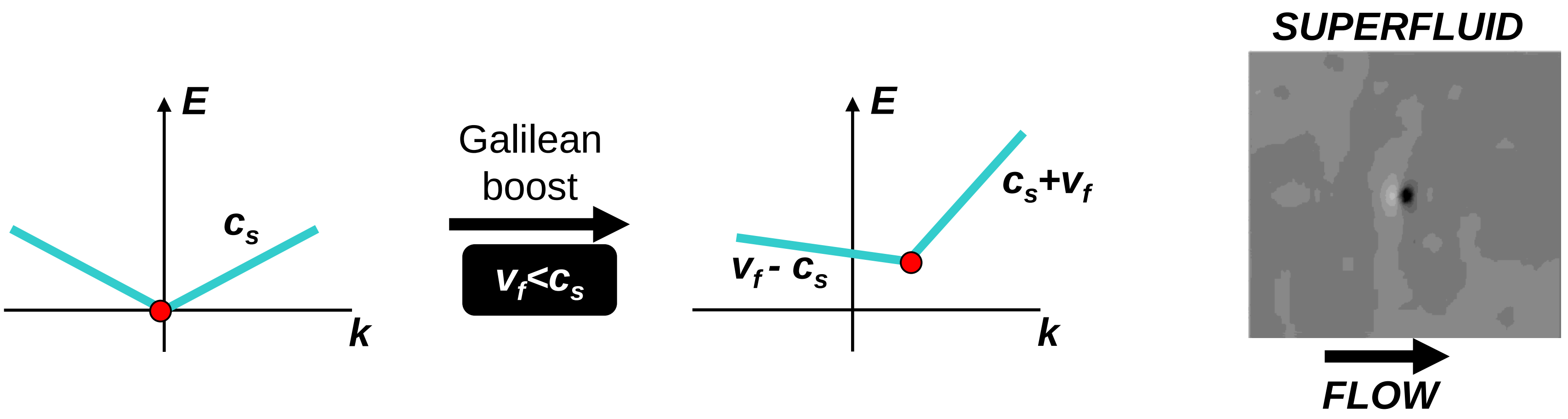
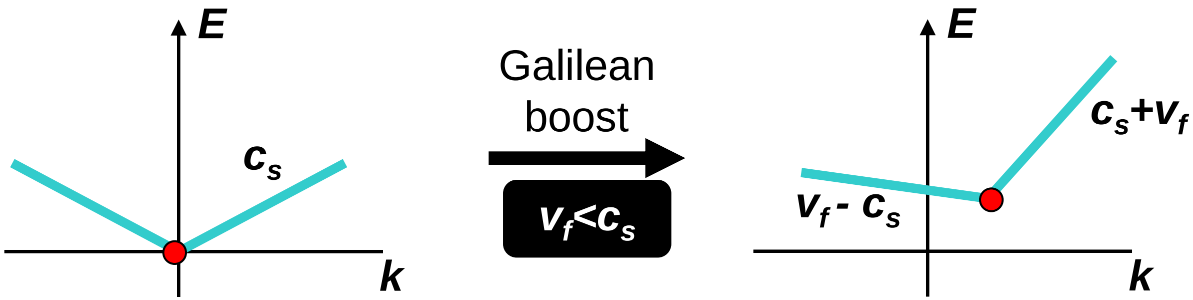
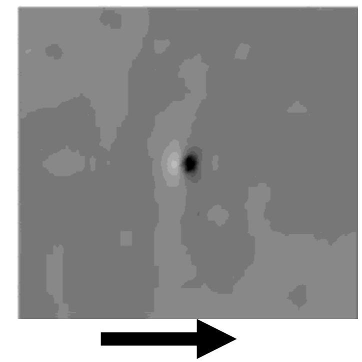


Quantum fluid effects: superfluidity

The Landau Criterion for superfluidity

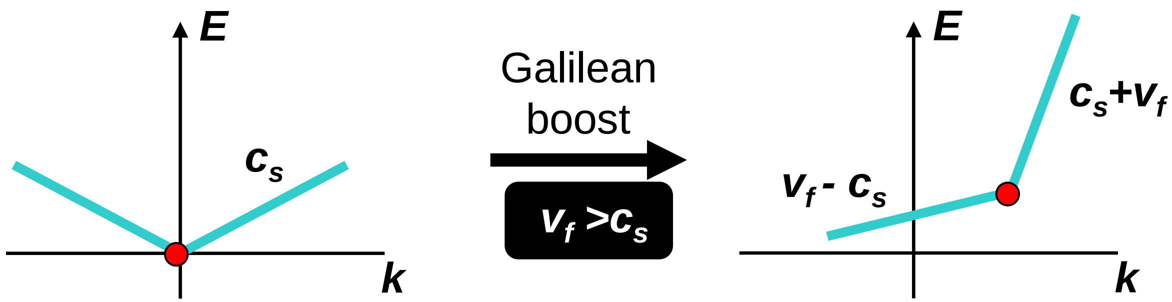


SUPERFLUID

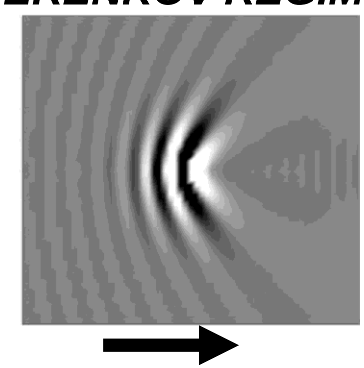


FLOW

critical flow velocity for the onset of excitations: c_s



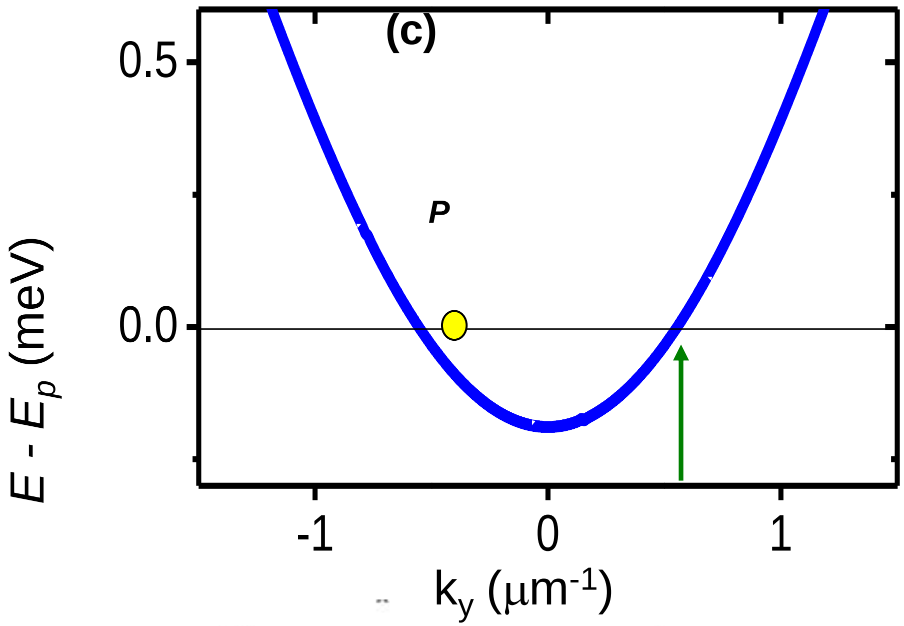
CERENKOV REGIME



FLOW

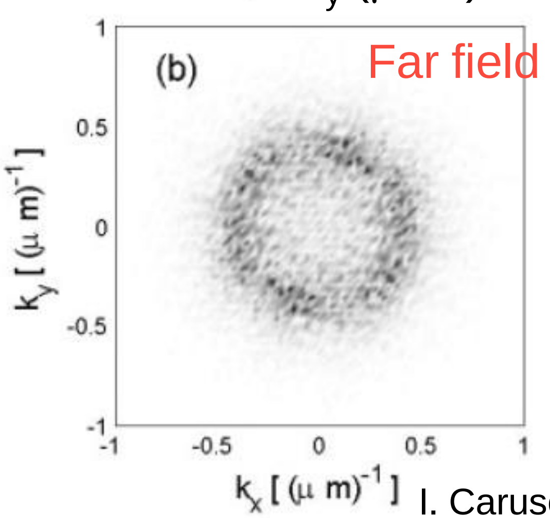
Propagation of a polariton fluid

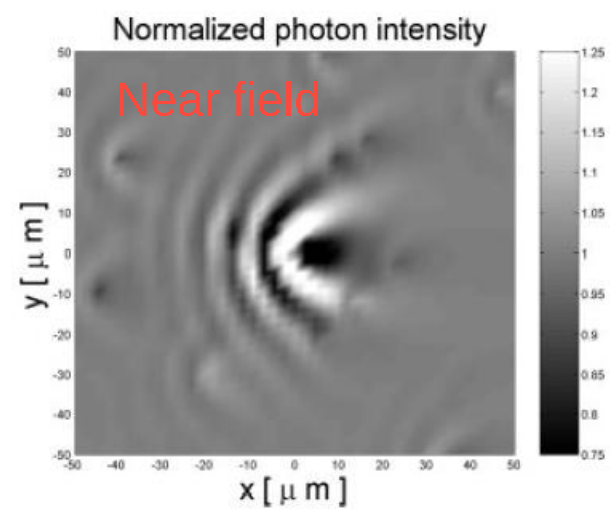
We probe the behaviour of the fluid through its interaction with defects



Linear regime, interactions between polaritons are negligible

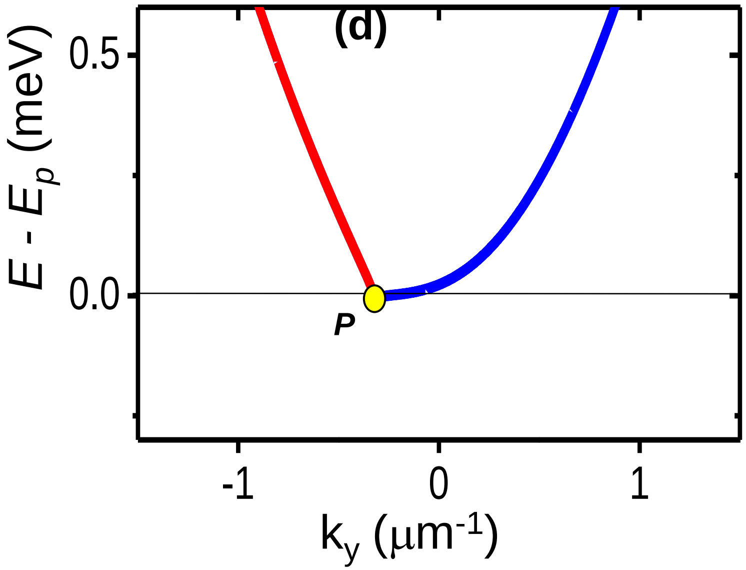
elastic scattering is possible





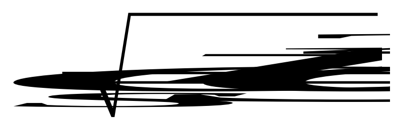
I. Carusotto and C. Ciuti, PRL (2004); *Phys. Stat. Sol. (b).* **242**, 2224 (2005)

Superfluid regime



Nonlinear regime
strong interactions between polaritons,
dispersion curve modified

a sound velocity appears



If $v_f < c_s$ *and density large enough*

Landau criterion for superfluidity is fulfilled:
no states available any more for scattering

Observation of a linear spectrum of excitation for polaritons:

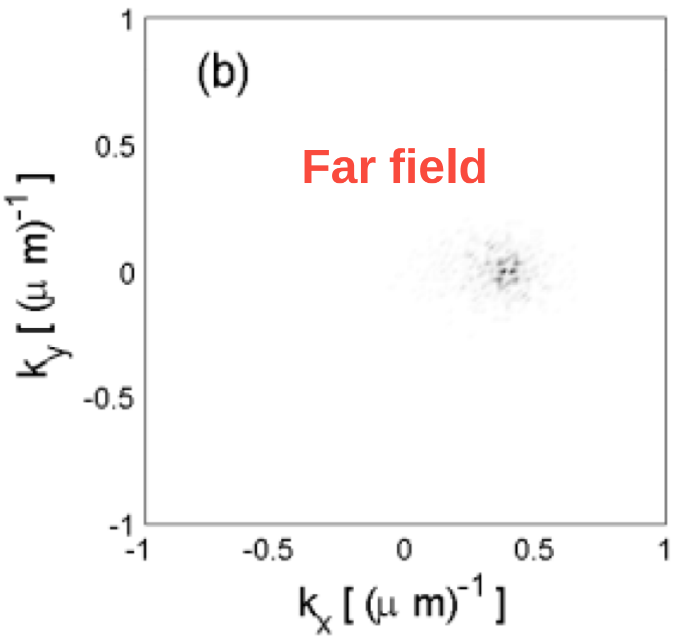
- Utsunomiya *et al.,* Nature Phys. **4**, 700 (2008)
- Kohnle *et al.,* PRL, 106, 255302 (2011)

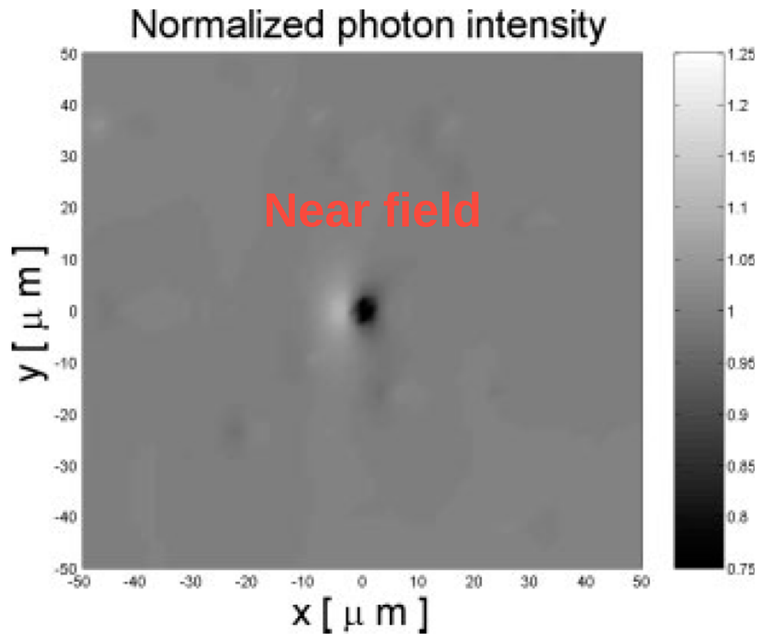
I. Carusotto and C. Ciuti, PRL (2004);
Phys. stat. sol. (b). **242**, 2224 (2005)

Superfluid regime

Landau criterium: $E_{LP}^{ren} > E_{signal} \qquad k \neq k_{signal}$

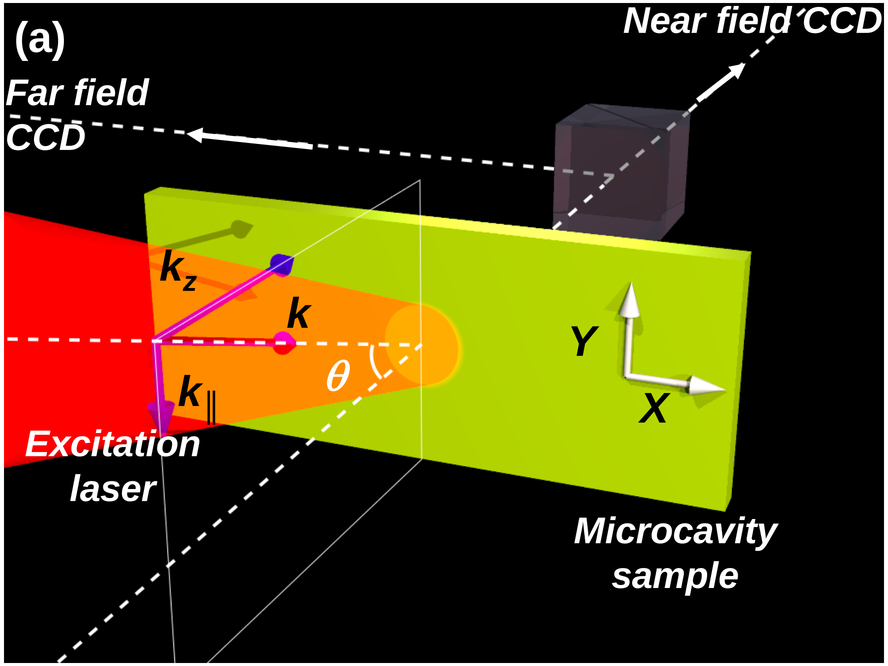
No elastic scattering

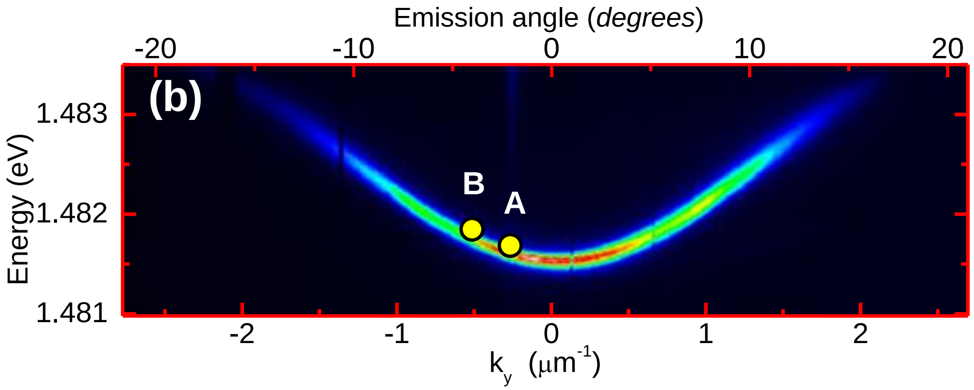




I. Carusotto and C. Ciuti, PRL (2004);*phys. stat. sol. (b).* **242**, 2224 (2005)

Experimental scheme





Control parameters

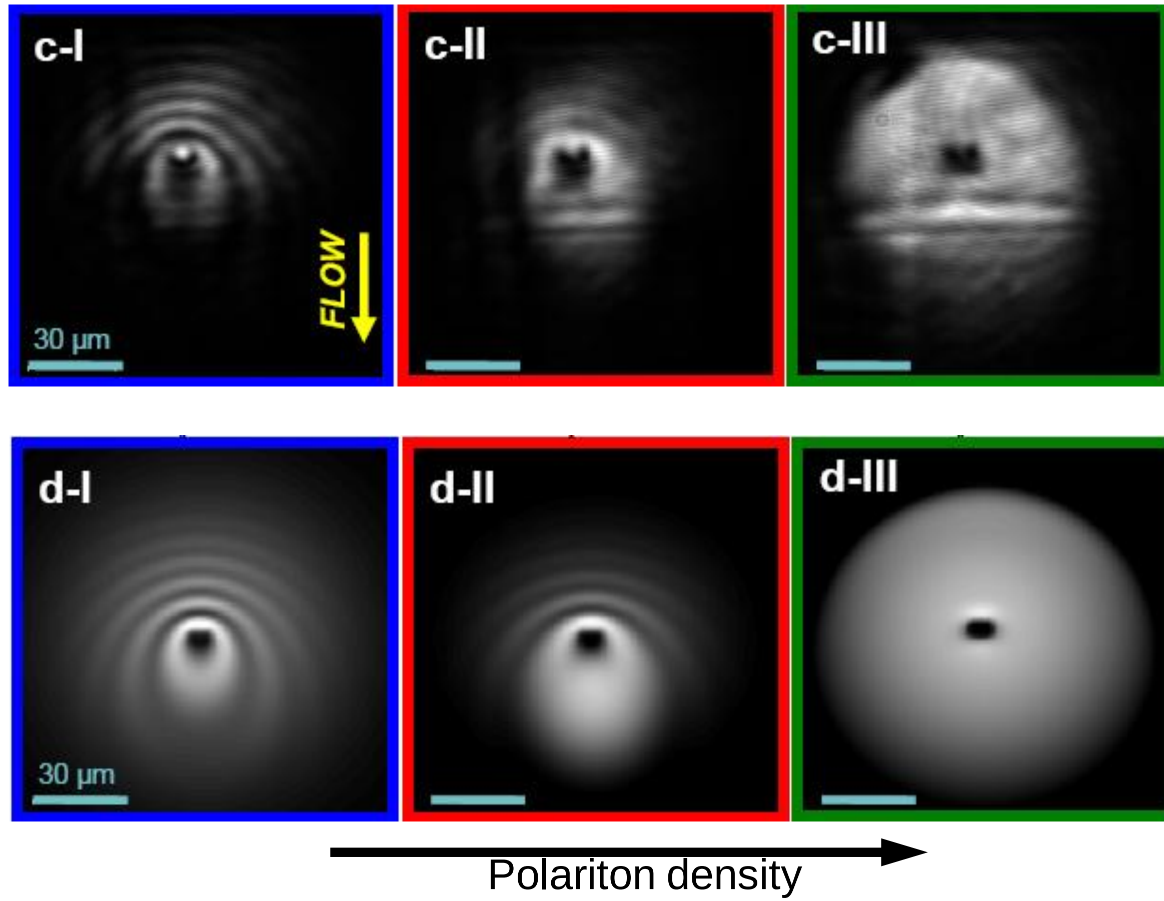
✓Polariton density (pump intensity)

✓Fluid velocity (excitation angle)

✓Oscillation frequency (laser frequency)

Polariton flow around a defect : near field image = real space

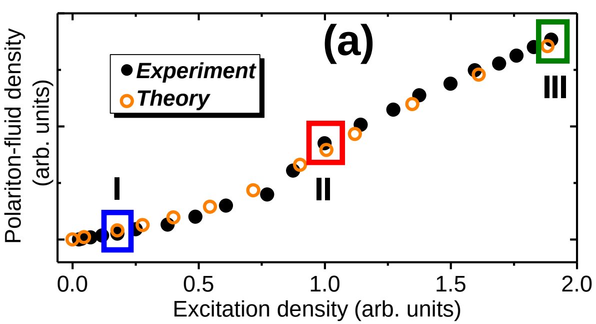
defect :
4 µm diameter



experiment

Point [A]
low momentum
$v_f < c_s$

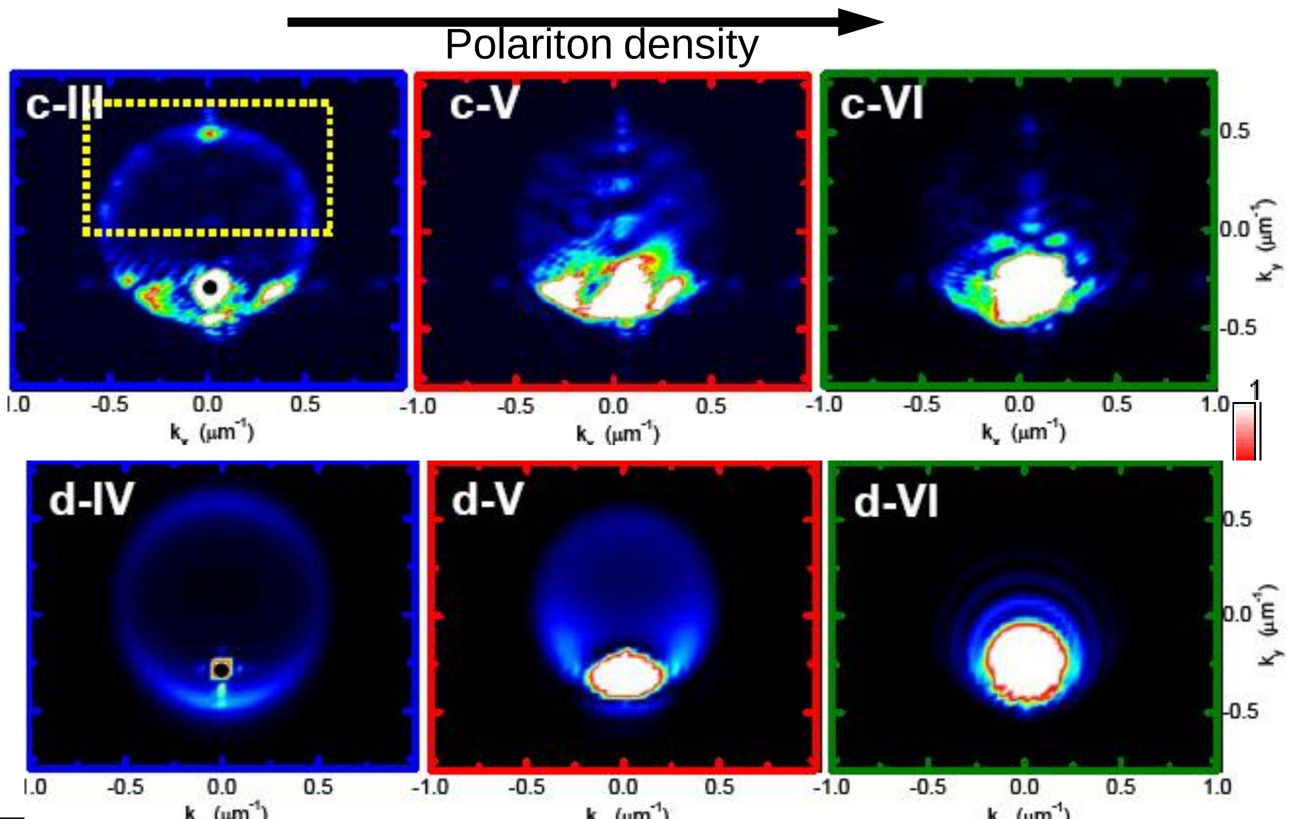
theory



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

Superfluidity appears for a polariton density of ~ $10^9/cm^2$

Polariton flow around a defect : far field image = momentum space

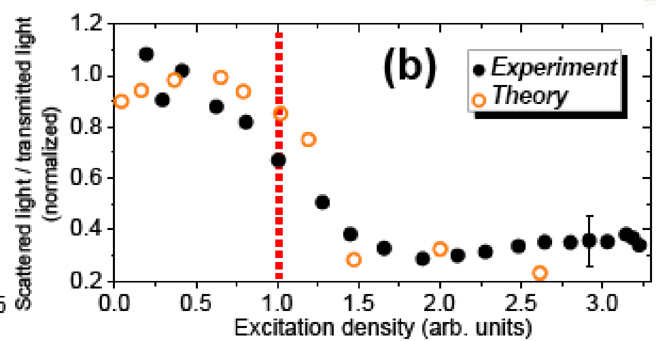


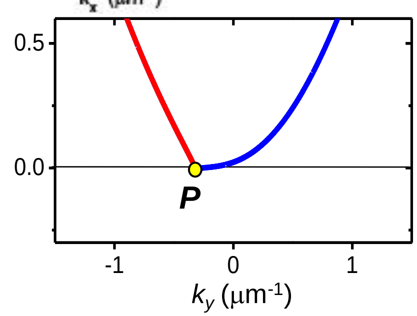
experiment

Point [A]
low momentum
$v_f < c_s$

Landau criterion ✓

theory

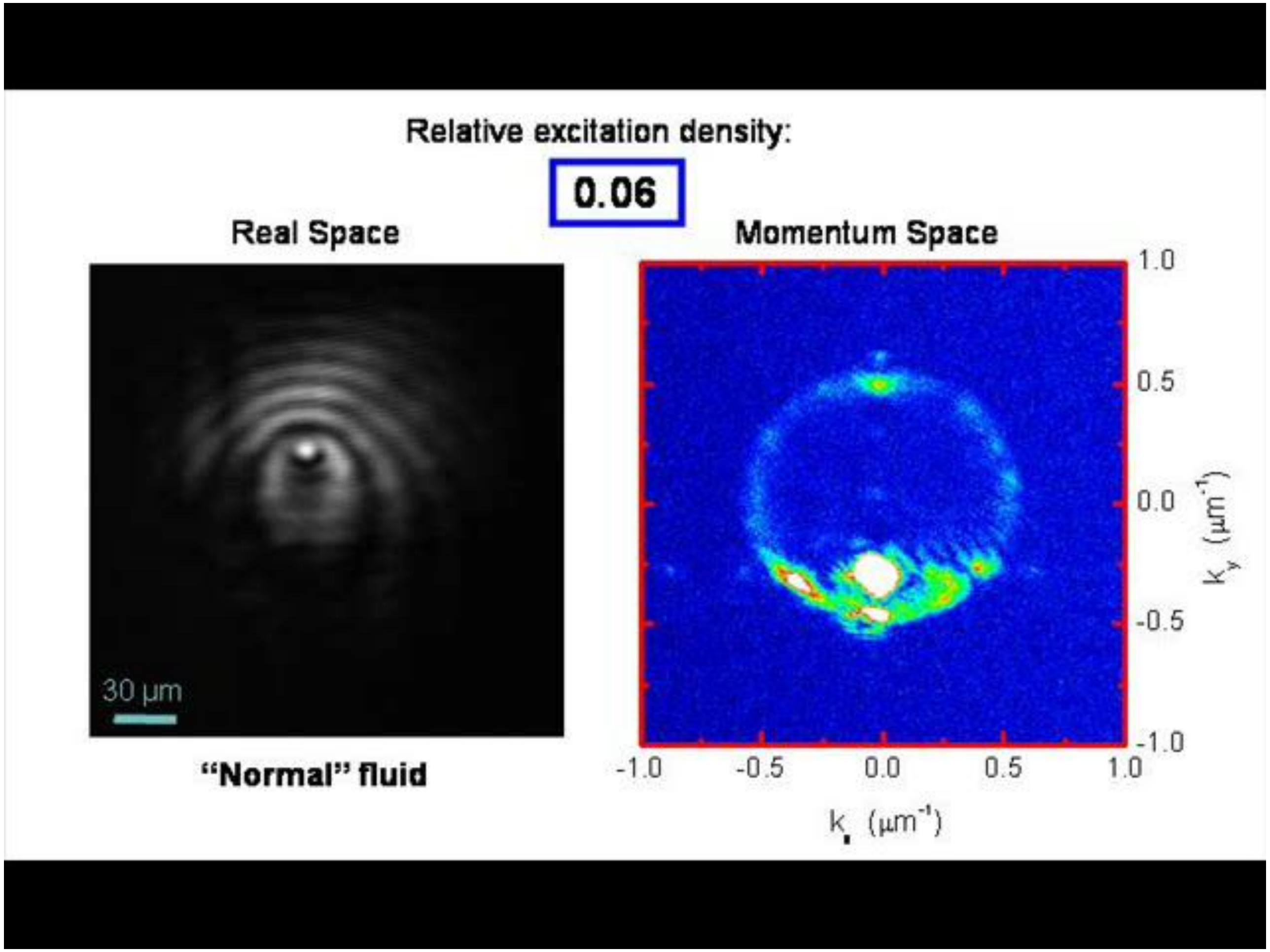




Collapse of the ring

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

Transition to the superfluid regime

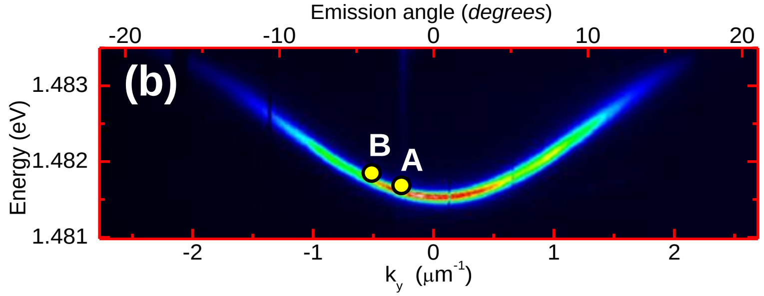


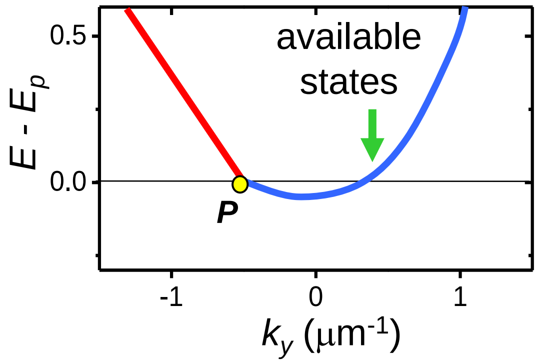
Amo et al., Nat. Phys.,5, 805 (2009)

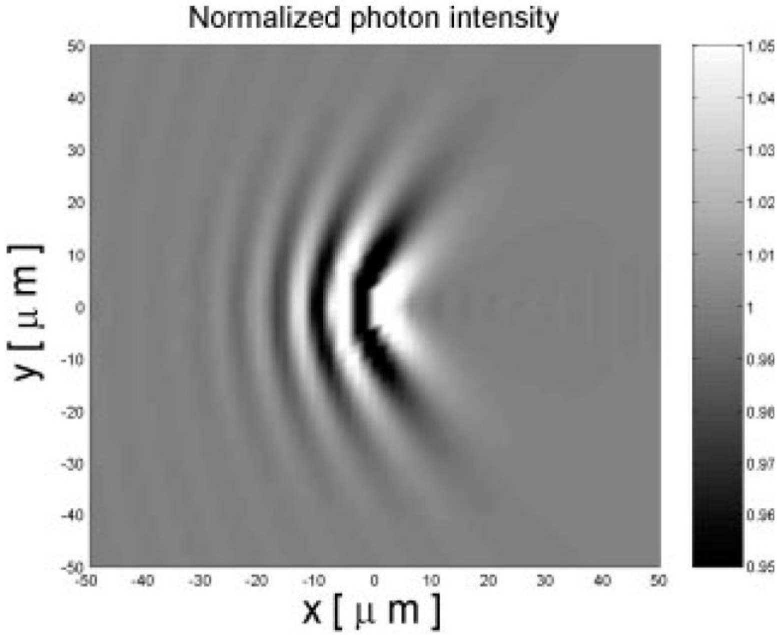
Čerenkov regime

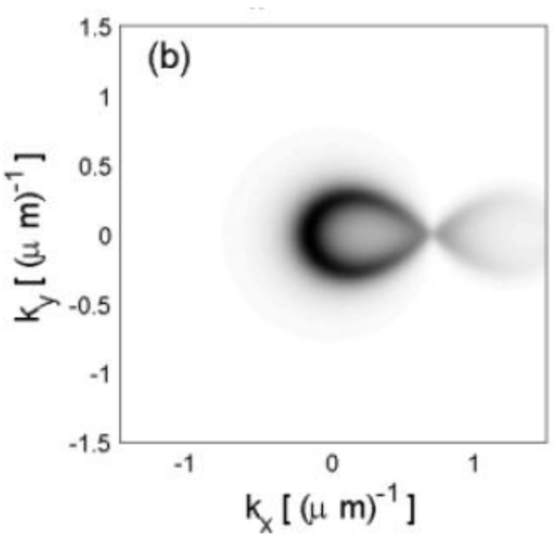
Point [B]
high momentum

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





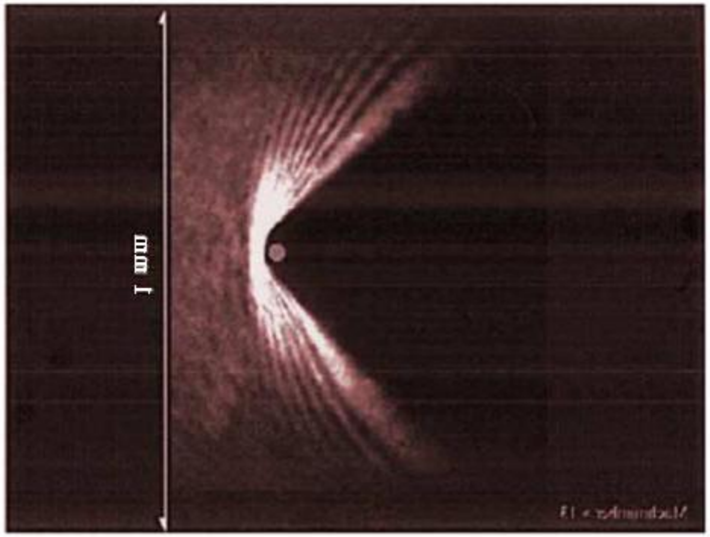


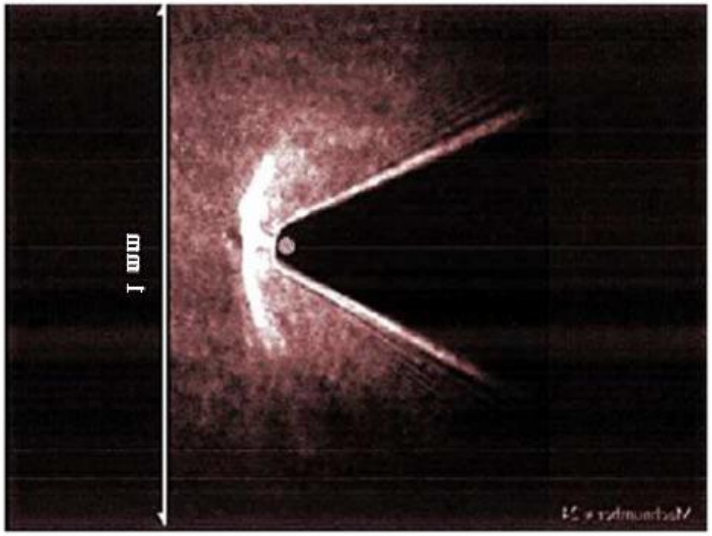


Čerenkov effect in an atomic BEC

Čerenkov shock waves of a BEC against an obstacle at supersonic velocities

v_f =13c_s ***FLOW*** → ***v_f =24c_s***





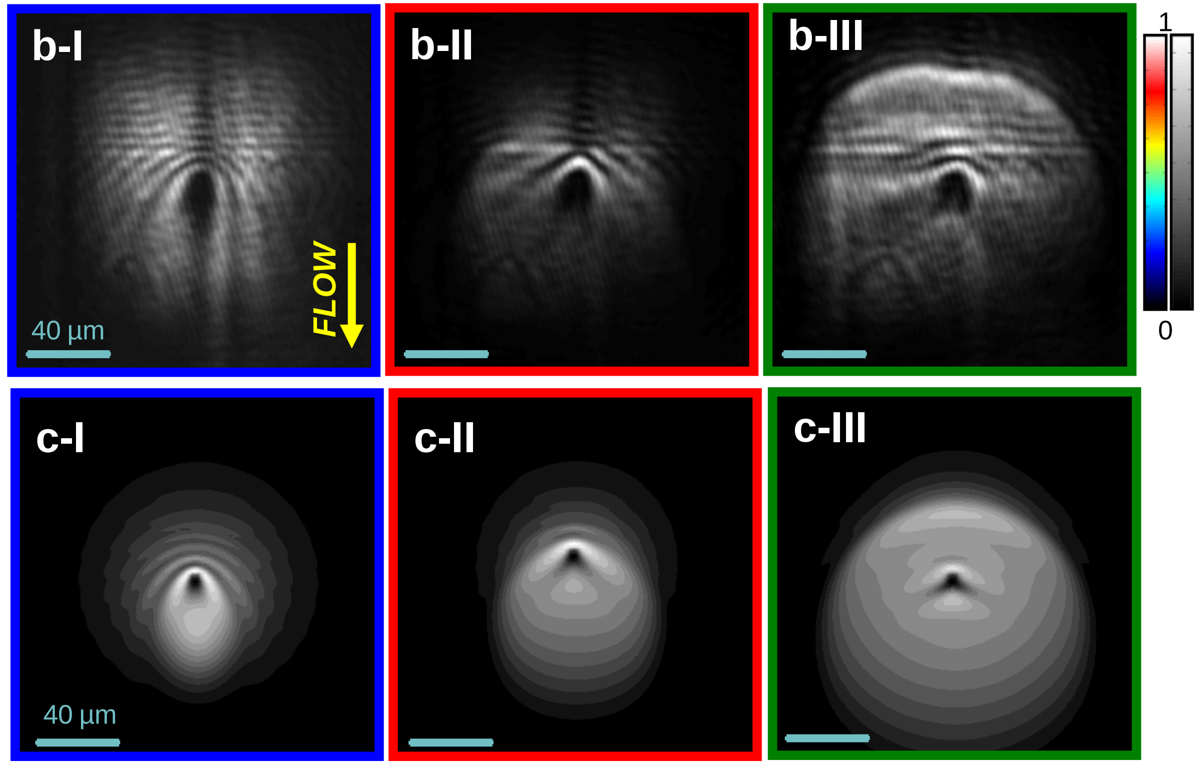
E. Cornell's talk at the KITP Conference on QuantumGases
http://online.itp.ucsb.edu/online/gases_c04/cornell/.

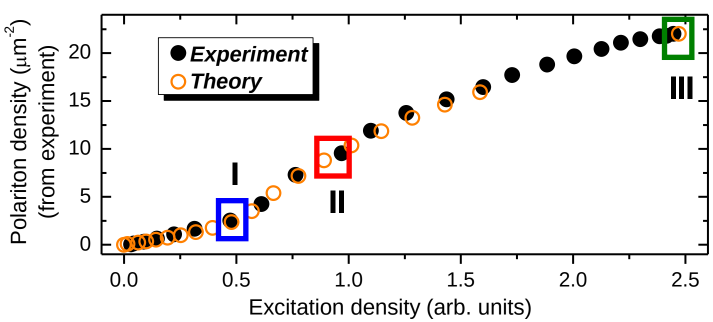
Observation of Čerenkov waves indicates the existence of a well defined sound velocity in the system

Čerenkov waves : near field image

experiment

theory

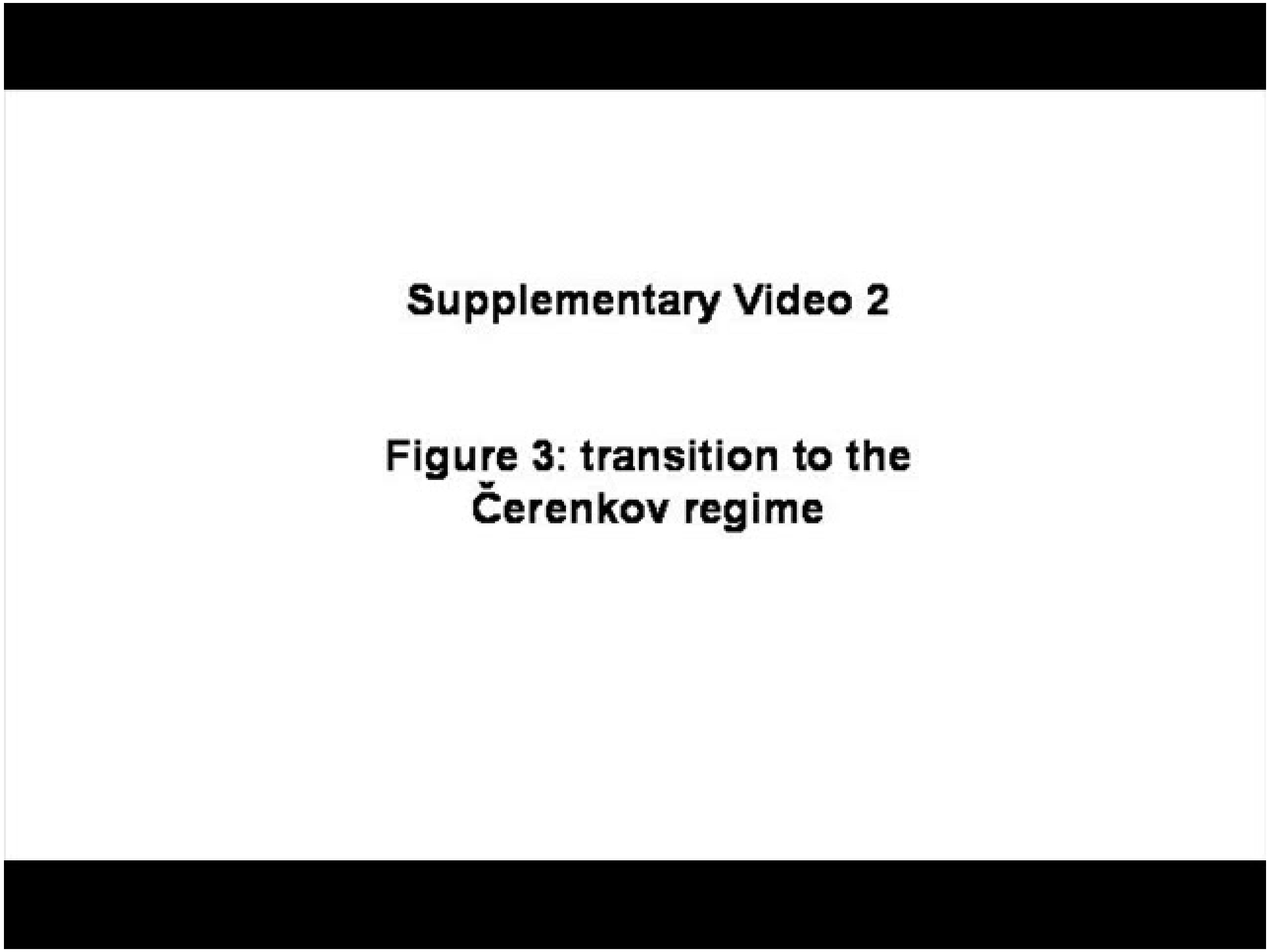




Polariton density

Characteristic linear density wavefronts of the Čerenkov waves

Transition to the Čerenkov regime

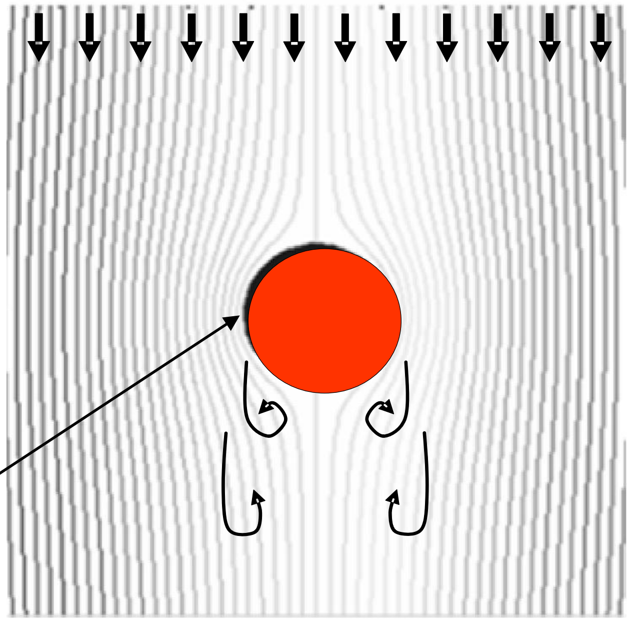


Amo et al., Nat. Phys.,5, 805 (2009)

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

$$v_f = 2v_\infty$$

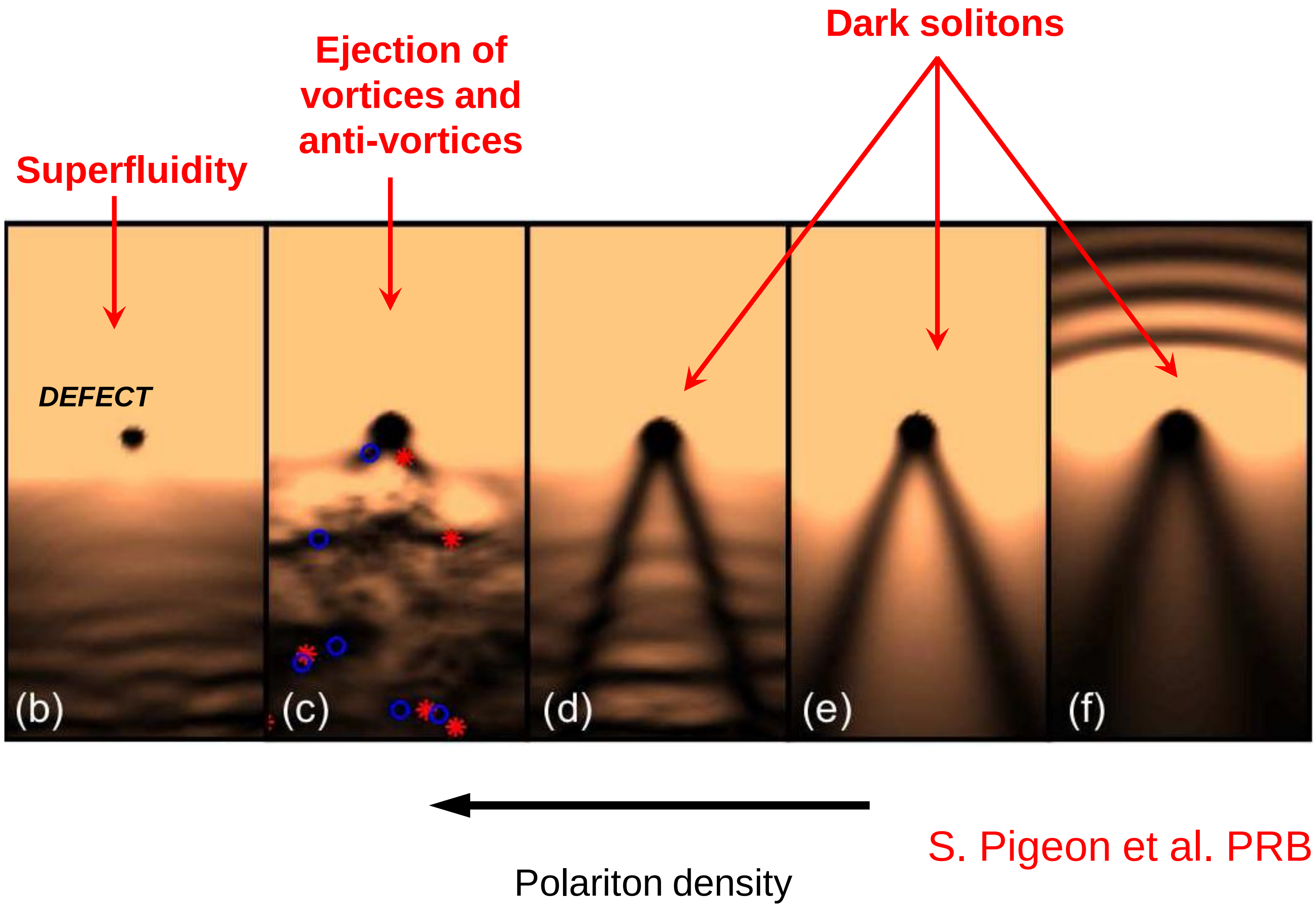
The currents formed in the fluid passing around a large obstacle can give rise to turbulence in its wake

Quantized vortices

Dark Solitons

Superfluidity breakdown: vortices and solitons formation?

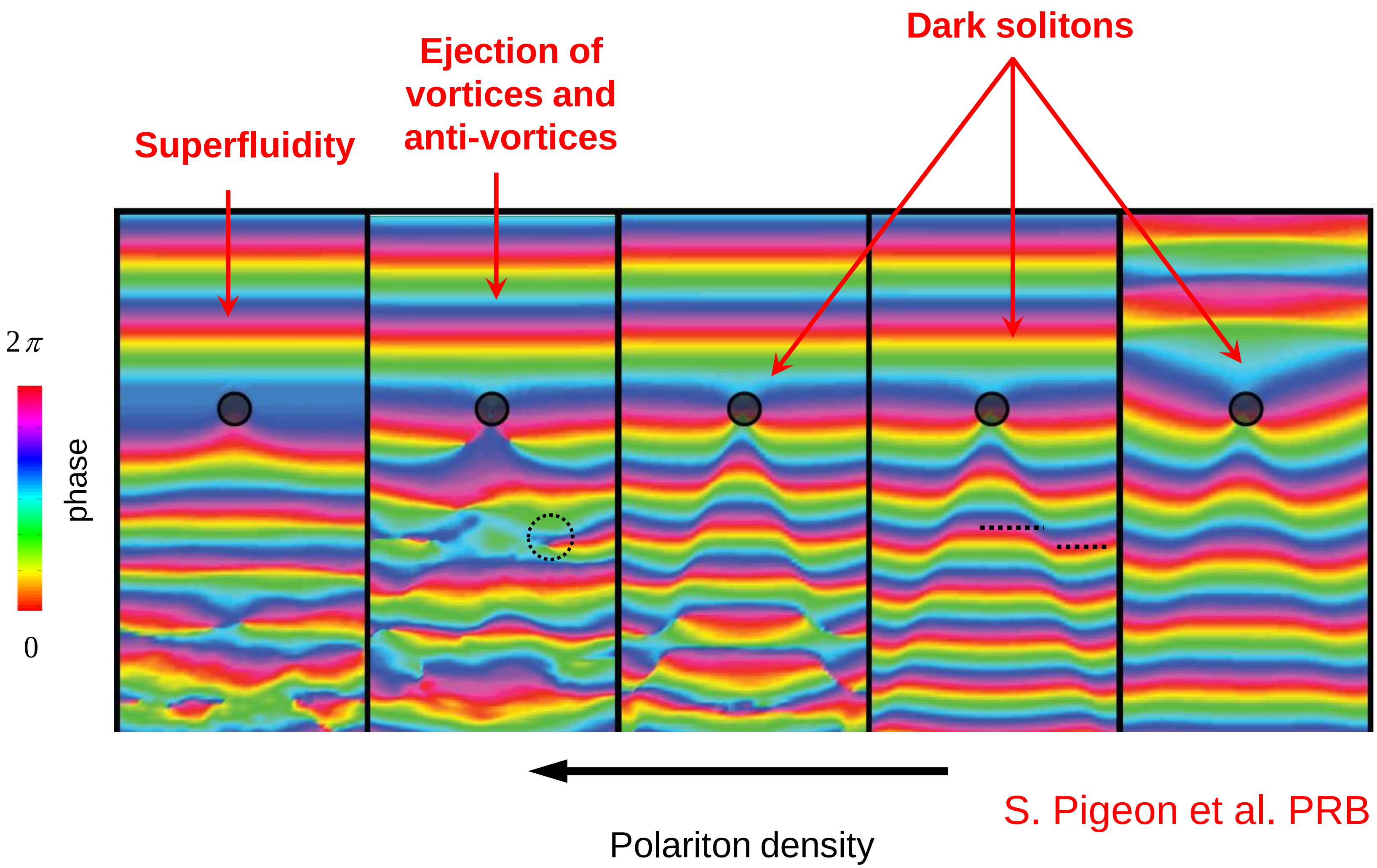
The case of spatially extended defects; the size of the defect is larger than the healing length



S. Pigeon et al. PRB (2010)

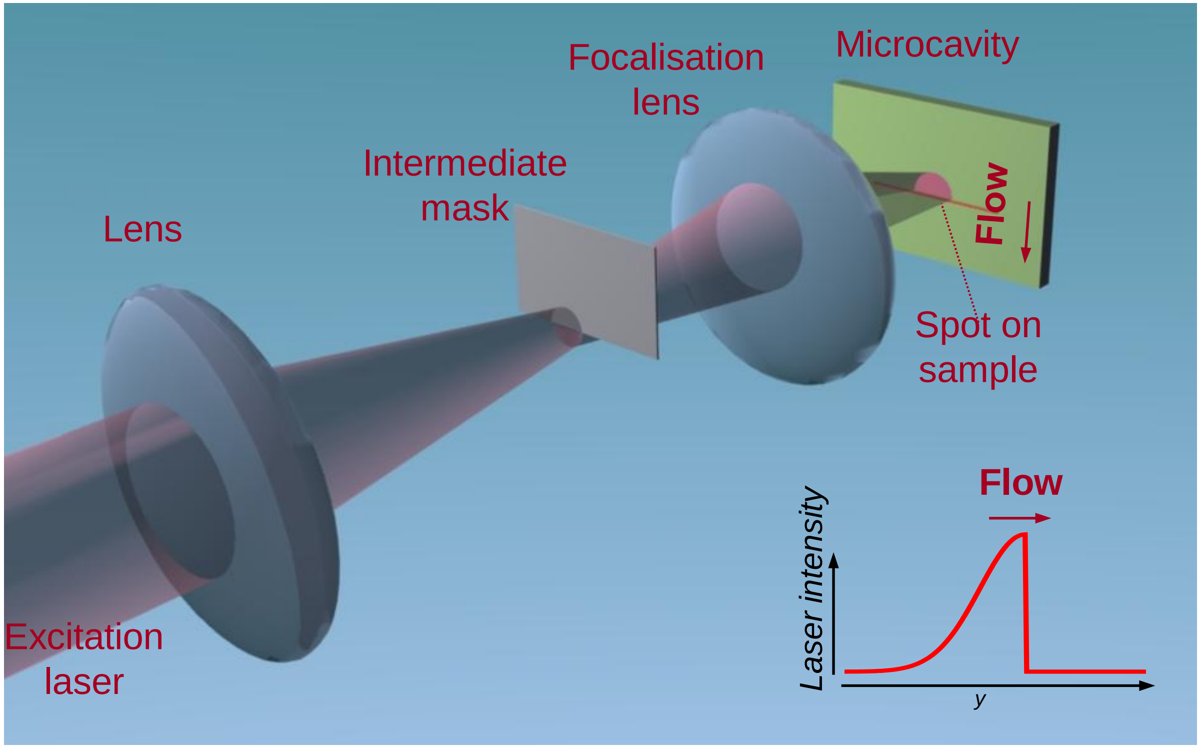
Superfluidity breakdown: vortices and solitons formation?

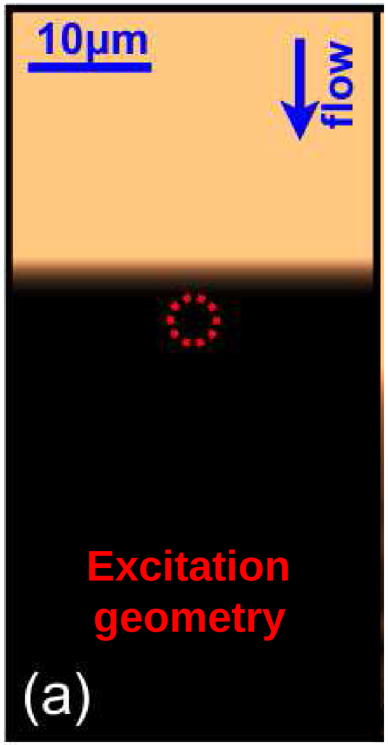
The case of spatially extended defects; the size of the defect is larger than the healing length



S. Pigeon et al. PRB (2010)

Experimental set-up





Key points

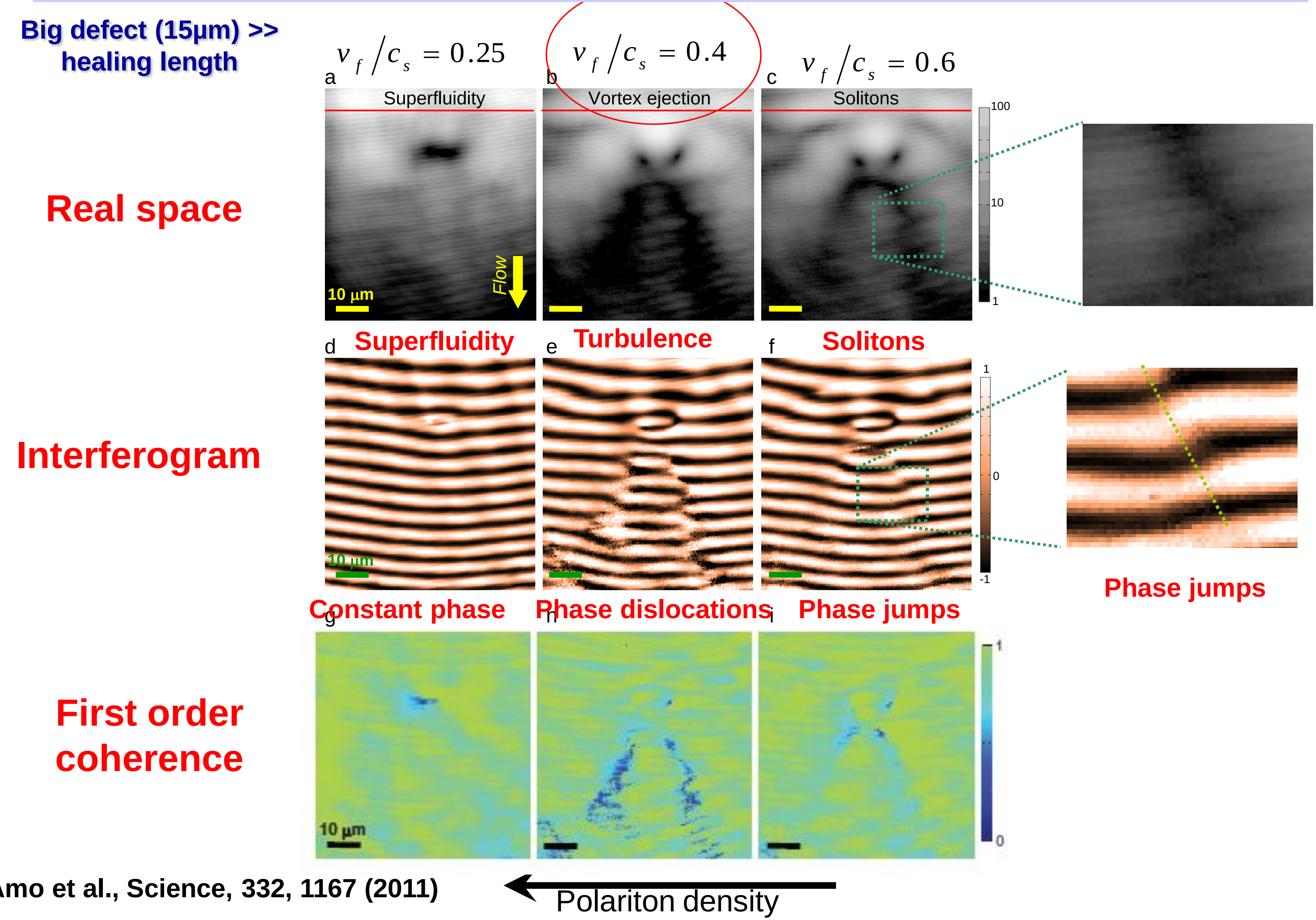
✓CW laser (precise control of the fluid quantum state)

✓Mask (free evolution for the superfluid phase)

✓ Possibility to generate topological excitations

Vortices and Solitons

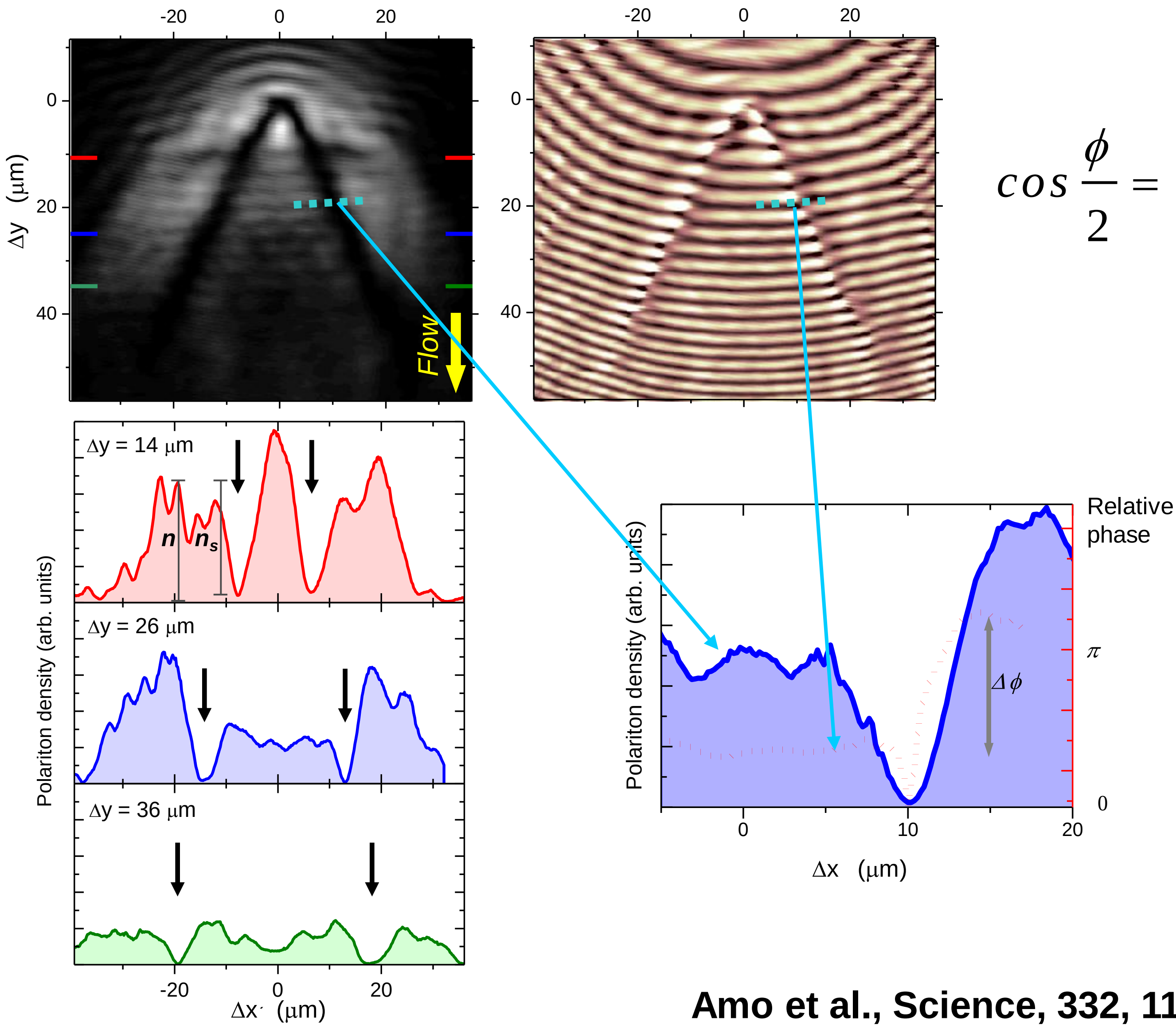
Big defect (15μm) >> healing length



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

Hydrodynamic Dark Solitons

v_f = 1.7 μm/ps
k = 0.73 μm^{-1}



$$\cos\frac{\phi}{2} = \left(1 - \frac{n_s}{n}\right)^{\frac{1}{2}}$$

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*
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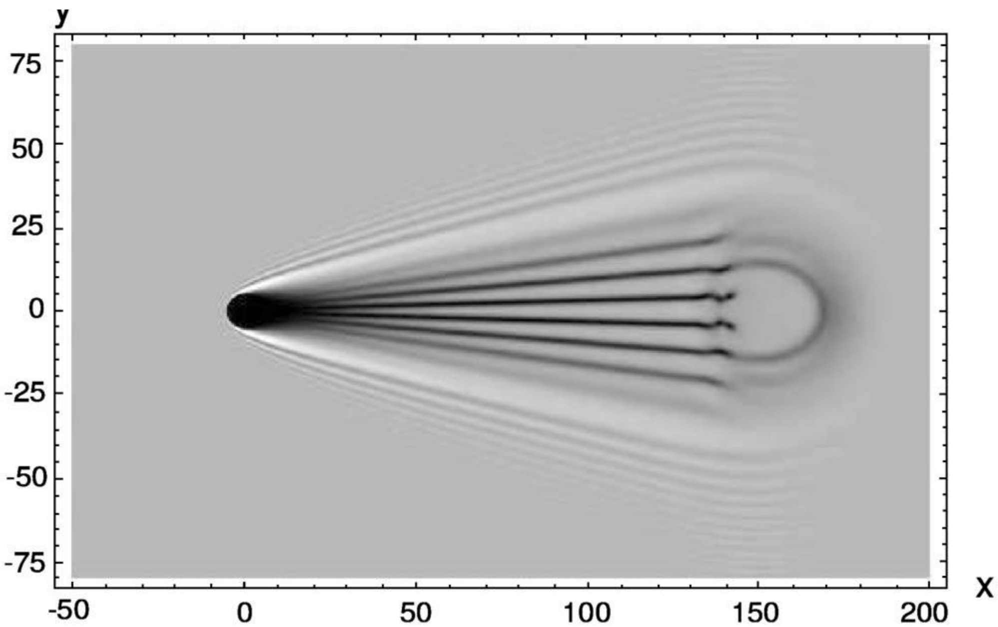
(Received 21 April 2006; published 1 November 2006)



Not yet observed in atomic BEC; the dissipation in polariton fluids helps in stabilizing dark solitons (Kamchatnov et al. arXiv:1111.4170)

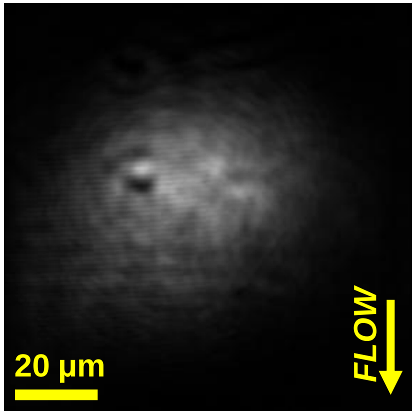
Light engineering of the polariton landscape:

using polariton-polariton interactions

Engineered landscape

Sample from R. Houdré

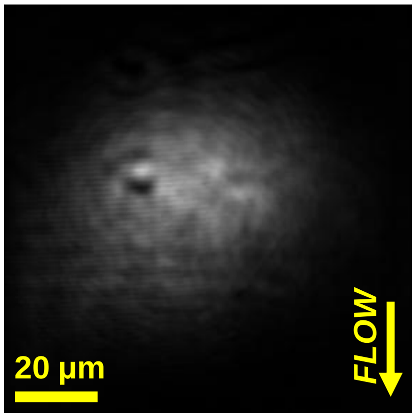
probe σ^+



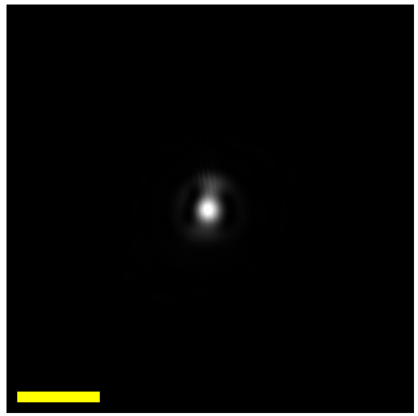
Defect-free area

Engineered landscape

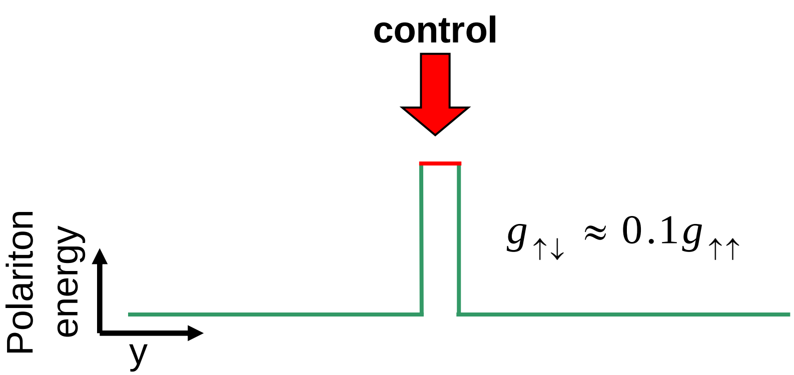
probe σ^+



control σ^-



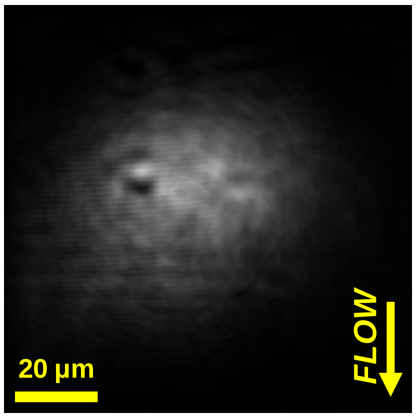
strong field: renormalization of the polariton energy



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

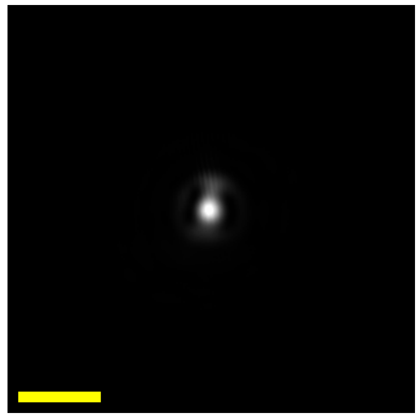
Engineered landscape

probe σ^+



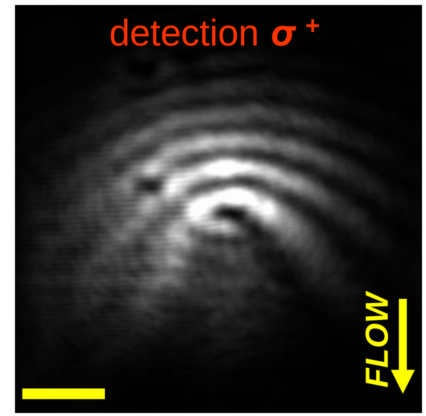
+

control σ^-

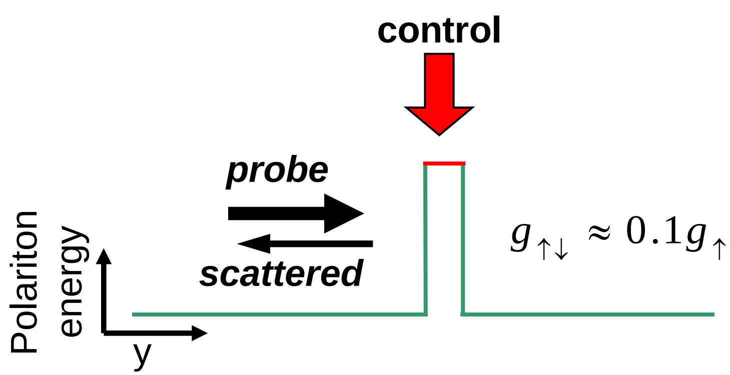


=

probe σ^+ + control σ^-



strong field: renormalization of the polariton energy

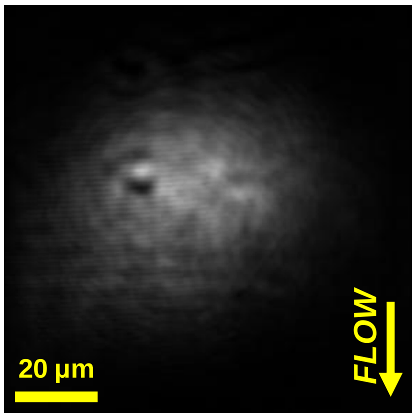


$g_{\uparrow\downarrow} \approx 0.1 g_{\uparrow\uparrow}$

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

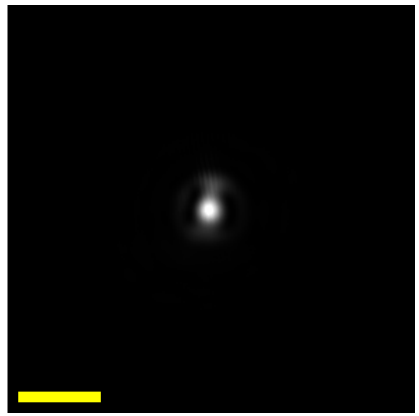
Engineered landscape

probe σ^+



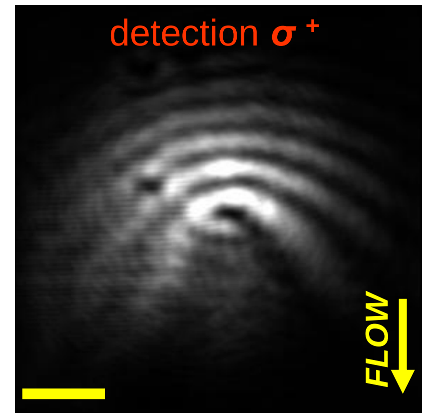
\+

control σ^-



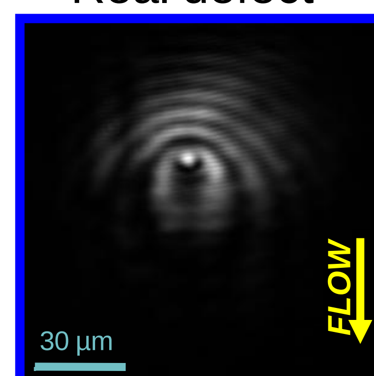
=

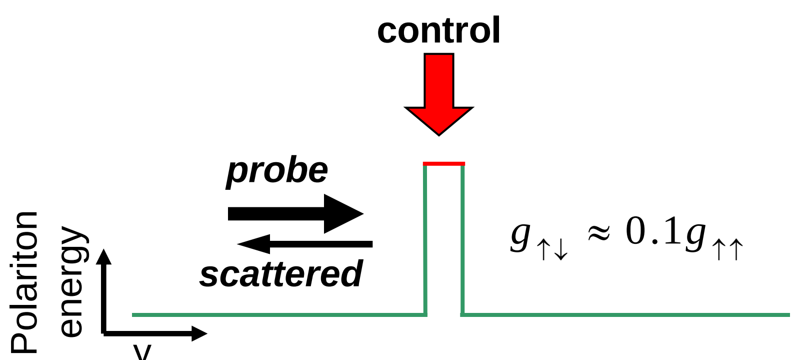
probe σ^+ + control σ^-



strong field: renormalization of the polariton energy

Real defect



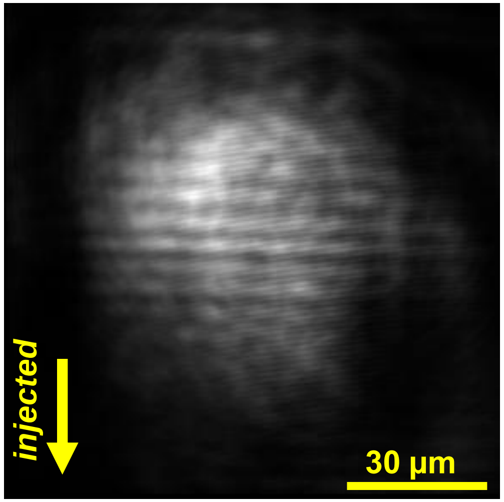


$$g_{\uparrow\downarrow} \approx 0.1 g_{\uparrow\uparrow}$$

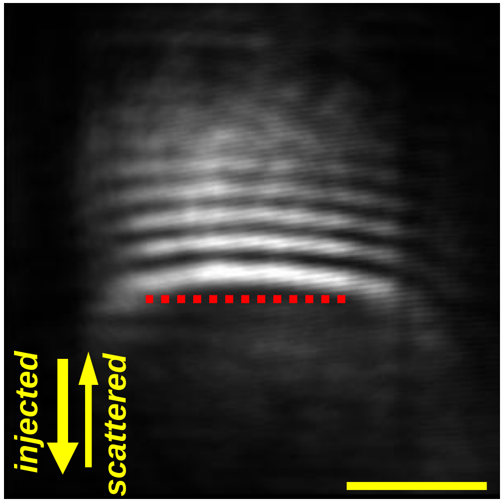
Amo *et al.*, PRB Rapid Comm. (2010)

Engineered landscape

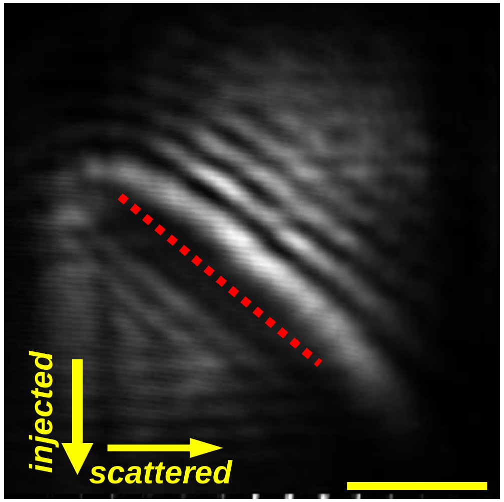
Probe only
No control



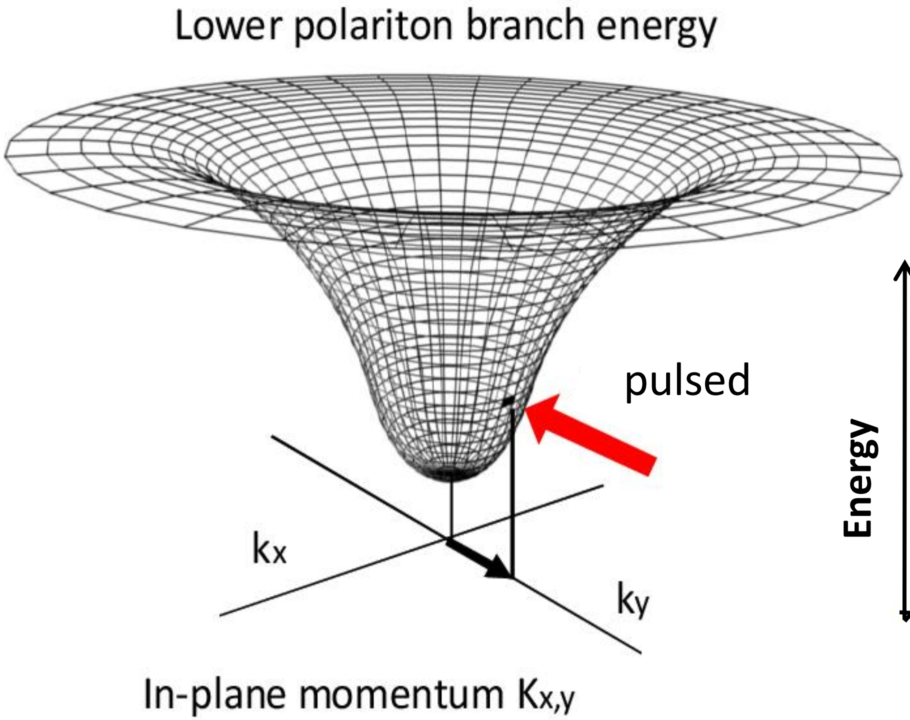
Probe +
Linear control

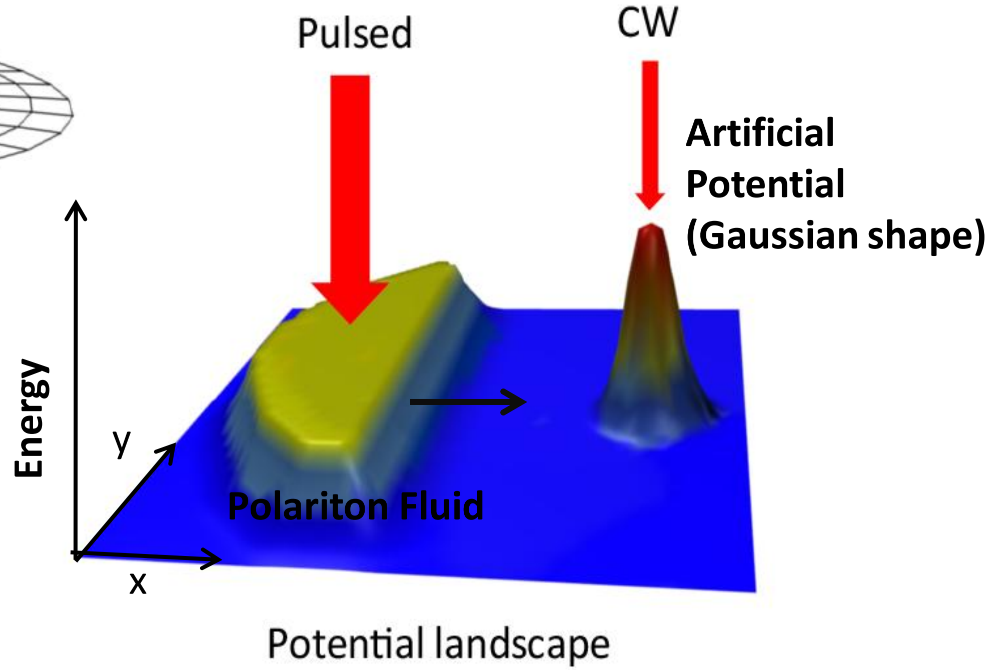


Probe +
Diagonal control



Optical control of vortex formation





All-optical control of the quantum flow of a polariton condensate

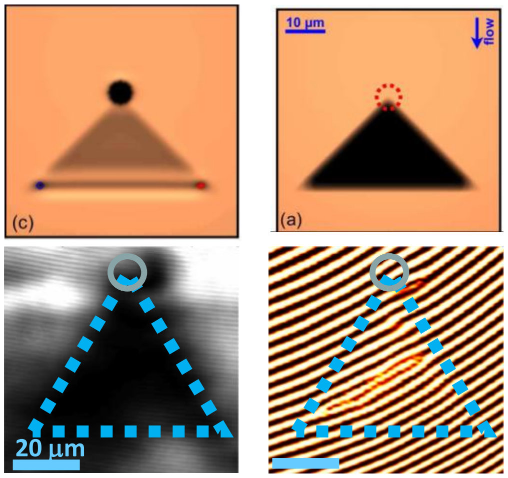
D. Sanvitto, *et al.*, Nature Photonics 5, 610 (2011)

Tailoring the potential landscape to trap vortices

S. Pigeon, *et al.*, Phys. Rev. B 83, 144513 (2011)

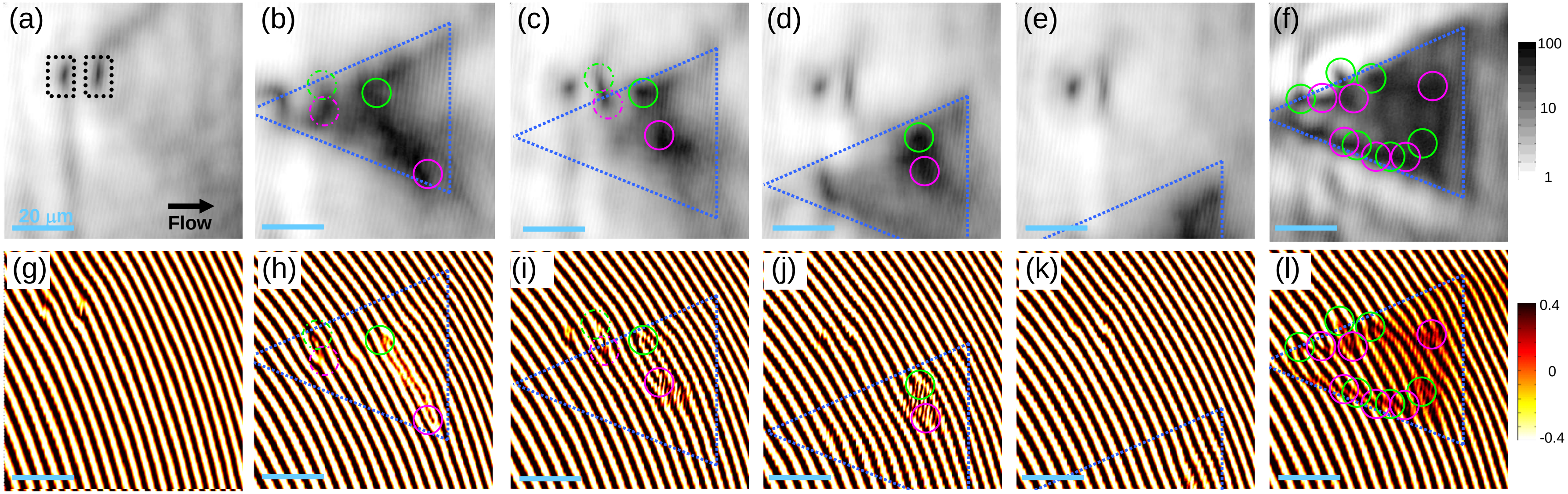
D. Sanvitto, *et al.*,Nature Photonics 5, 610 (2011)

Triangular Trapping Mask behind the defect:
the vortices created in the wake of the defect are trapped inside the trap



No mask frame readjusted

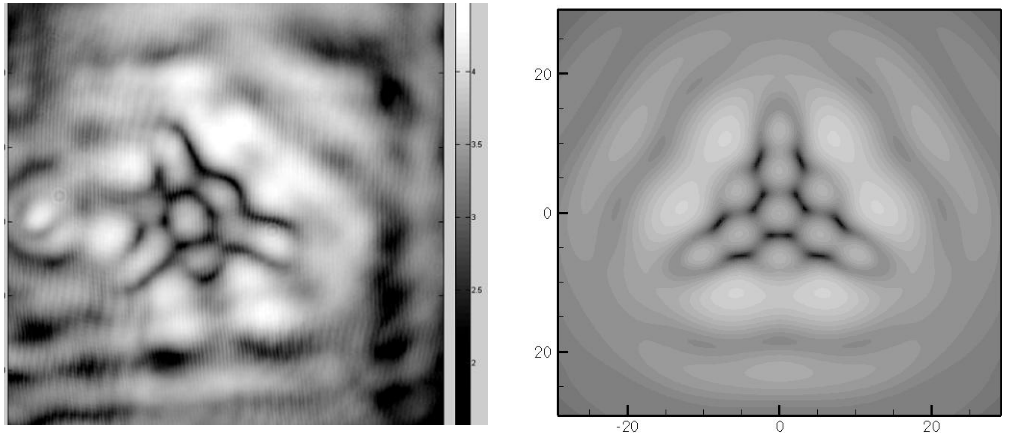
Low power



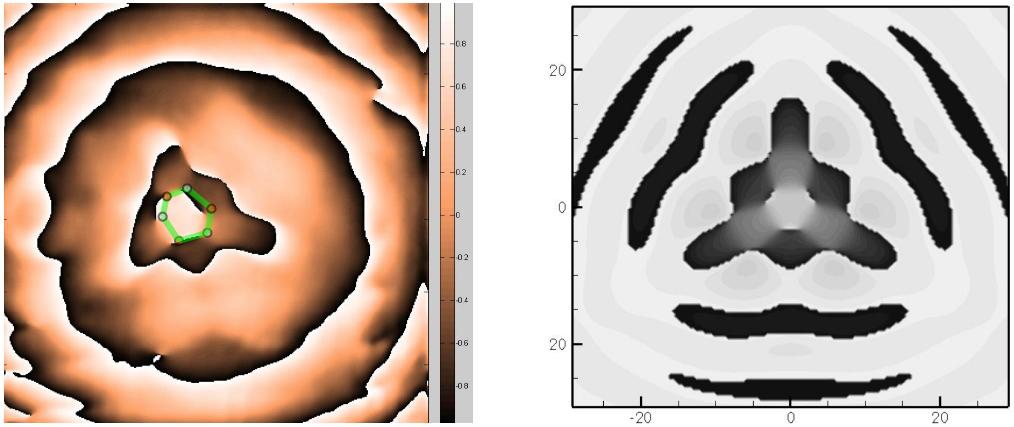
Towards spontaneous formation of vortex lattices

Small triangular trap

Experiment **Theory**



Polariton density

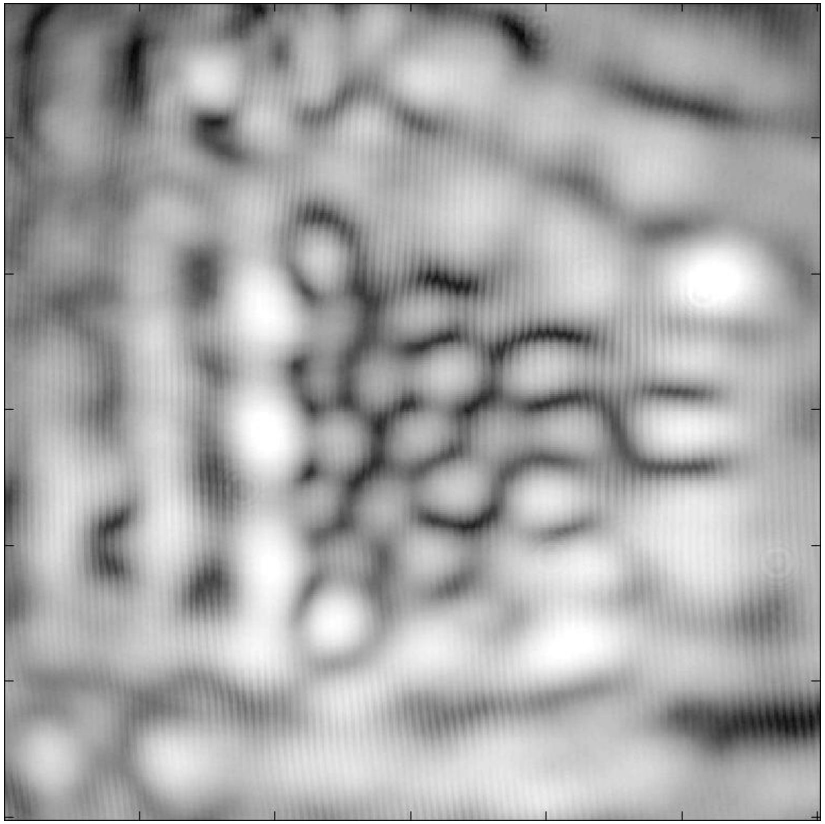


Phase

Self-organization of vortices and anti-vortices in hexagonal lattices

Towards spontaneous formation of vortex lattices

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



Conclusion and perspectives

- **Polariton Quantum Fluids**
  - Superfluidity
  - Čerenkov regime
  - Hydrodynamic vortices and dark solitons
- **Perspectives**
  - Engineering of polariton landscape: Dynamical Potentials, Optical traps for polaritons
  - Study and control of Quantum turbulence?
  - Lattices of vortices?
  - Spinor polariton condensates

    (Hivet et al. Nature Physics, in press; arXiv:1204.3564)

Collaborations

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