Polaritons in semiconductor microcavities: from quantum optics to quantum fluids

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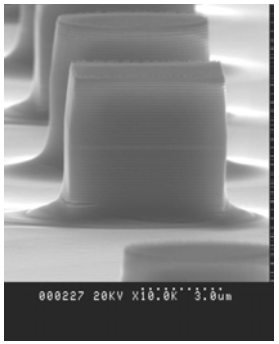
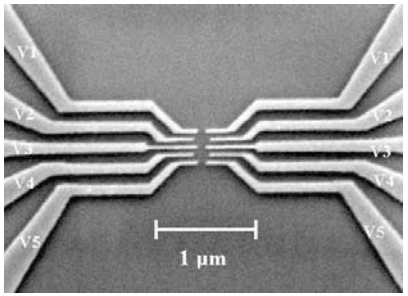
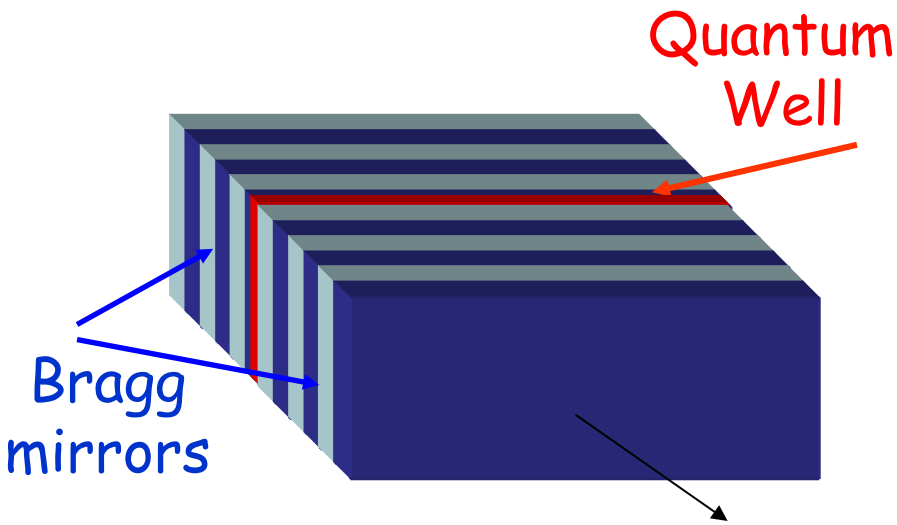
Semiconductor devices

Future Quantum Information on chips





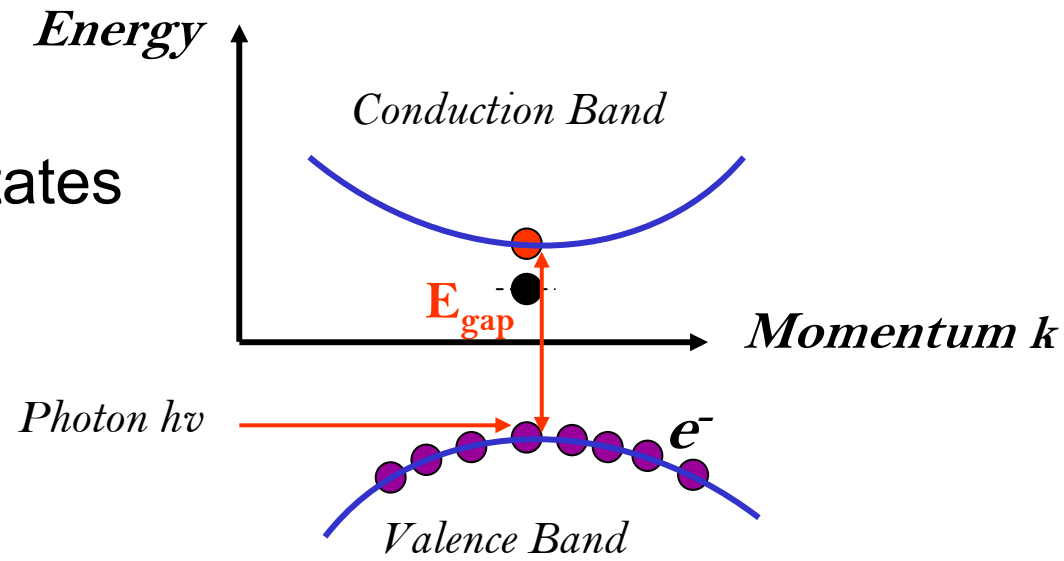
- **Microcavity :**



- 2 Bragg mirrors forming a high finesse Fabry-Perot cavity f~4000
- 1 quantum well (InGaAS/GaAs) where electrons are confined

Bulk semiconductor

Continuum of states in 3D



Absorption of a photon can create an electron-hole pair :

- electron in the conduction band
- hole in the valence band

$hv > E_{gap}$ → *Free electron-hole pair*

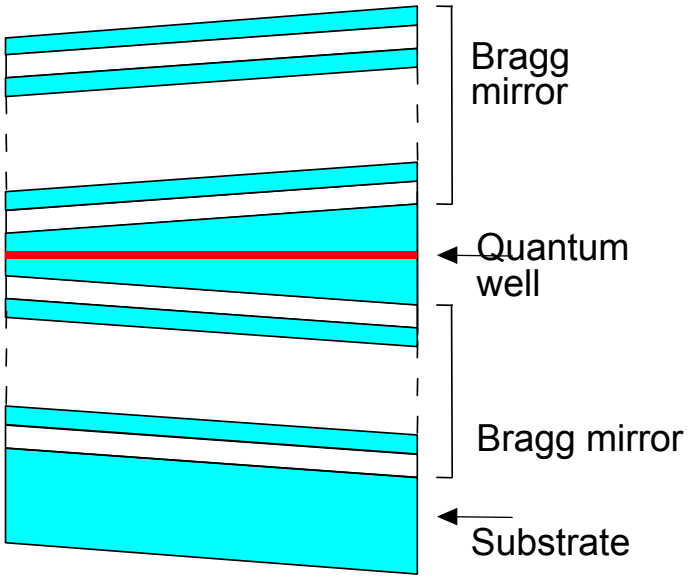
$hv < E_{gap}$ → *Bound electron-hole pair*

Radiative recombination:

electron-hole pair → *photon*

Quantum well microcavity

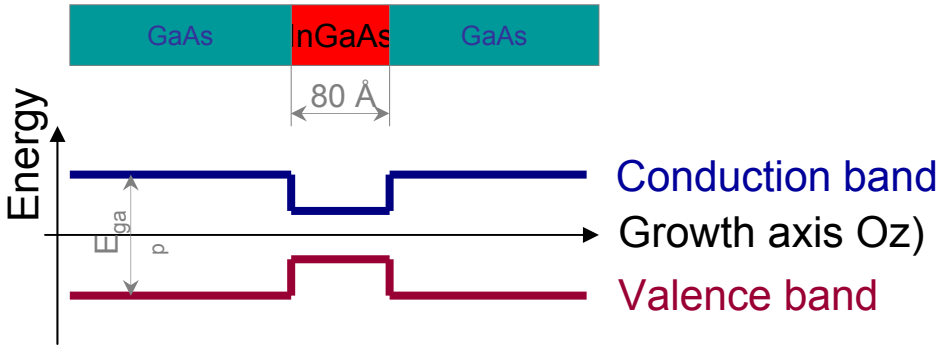
- **Microcavity :**



- 2 Bragg mirrors forming a high finesse Fabry-Perot cavity f~5000
- 1 quantum well (InGaAS/GaAs) in which electron hole pairs are created by laser excitation
- there is a slight angle between the two mirrors: cavity length can be scanned

Polaritons in a semiconductor microcavity

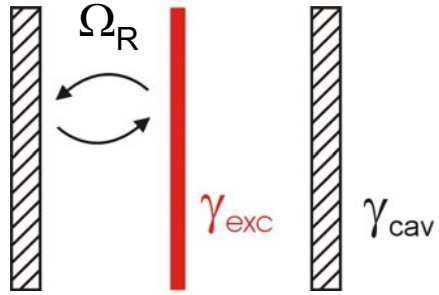
- **Quantum well**



$$E = E_{exc} + \hbar^2 K_{//}^2 / 2M_{//}$$

Excitons (electron hole bound states) are confined along z direction and free in the xy plane

- **Cavity : strong coupling regime**



$$\Omega_R >> \gamma_{exc}, \gamma_{cav}$$

$$\Omega_R = 2g\sqrt{N}$$ Vacuum Rabi splitting

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

Polariton : mixed exciton photon states

Hamiltonian:

$$H = \hbar\omega_{cav}\hat{a}^{\dagger}\hat{a} + \hbar\omega_{exc}\hat{b}^{\dagger}\hat{b} + \hbar\Omega_R/2\left(\hat{a}^{\dagger}\hat{b} + \hat{a}\hat{b}^{\dagger}\right)$$

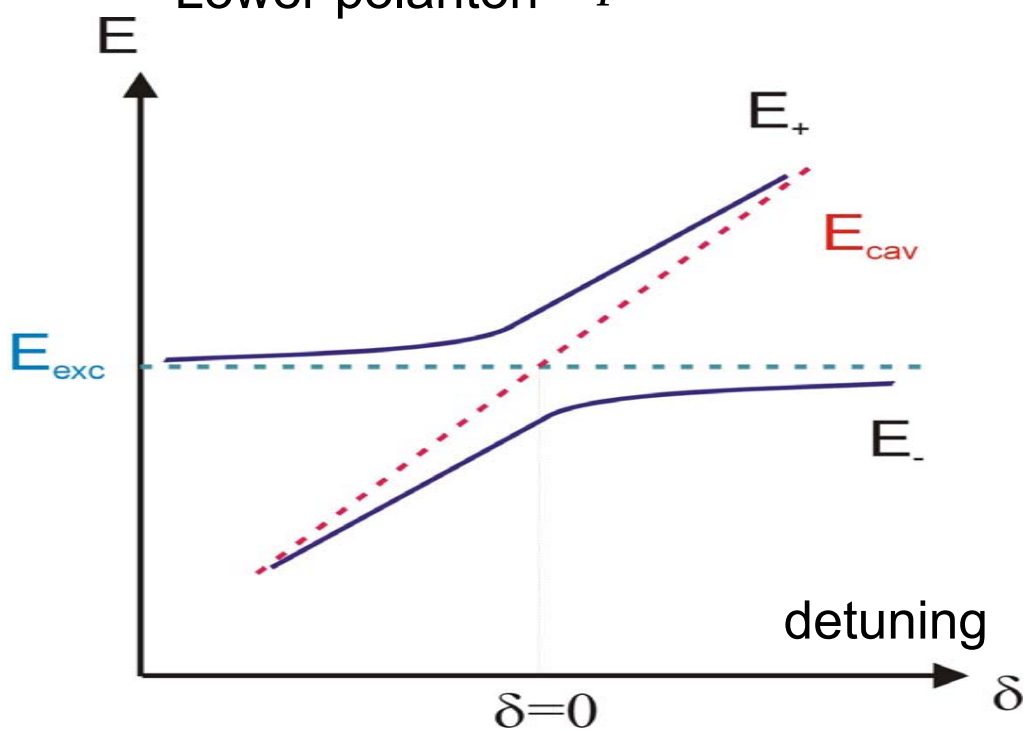
In a coupled basis:

$$H = E_{(-)}\hat{p}_-^{\dagger}\hat{p}_- + E_{(+)}\hat{p}_+^{\dagger}\hat{p}_+$$

Upper polariton $p_+ = -C\,a + X\,b$

Lower polariton $p_- = X\,a + C\,b$

with $C^2 + X^2 = 1$



$$E_{\pm} = \frac{\hbar\omega_{cav}}{2} \pm \hbar\sqrt{\delta^2 + \Omega_R^2}$$

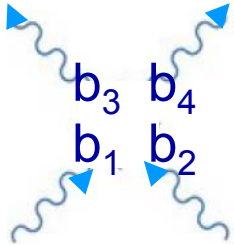
$$\delta = \omega_{cav} - \omega_{exc}$$

Anticrossing when the detuning between cavity and exciton is changed (by changing the cavity length).

Polariton-polariton interaction

Interaction between excitons:

$$H_{exc-exc} = \hbar\alpha \; b_3^+ b_4^+ b_1 b_2$$



Resonant excitation of the lower polariton

$\Rightarrow$ Hamiltonian in the polariton basis, upper branch neglected

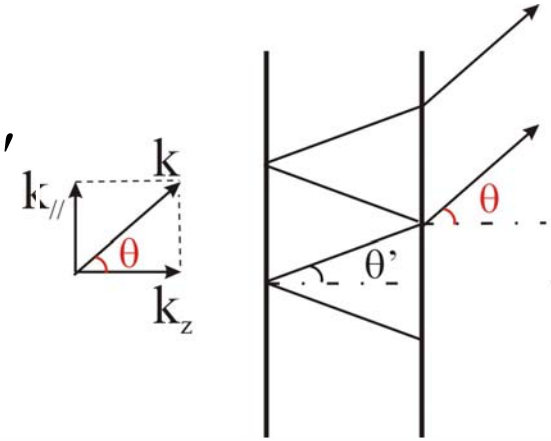
$$H_{LP}^{eff} = \hbar\alpha \; X^4 p_3^+ p_4^+ p_1 \, p_2$$

Polariton polariton interaction ~ 4 wave mixing

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

Polariton dispersion

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



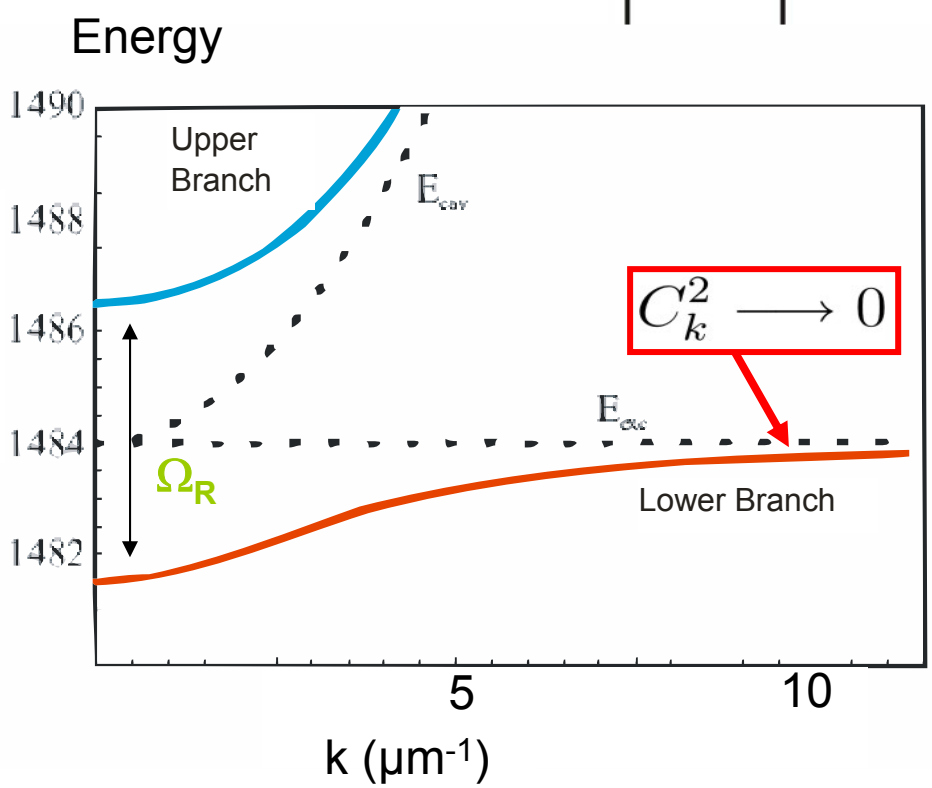
Exciton dispersion:

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

Relation between angle of incidence and in-plane wavevector:

$$k_{//} = k \sin \theta$$

A laser beam with a given K//
excites a polariton with the same K//
A polariton with K// emits a photon with the same K//



Evolution equation for the polaritons

Hamiltonian for the lower branch polariton

$$H_{PP}^{eff} = \hbar\omega_{LP} p^{+} p + \hbar\alpha\, X^{4} p^{+} p^{+} pp$$

Evolution equation for the lower branch polariton

$$\frac{d\hat{p}_0}{dt} = -(\gamma + i\delta_0)\hat{p}_0 - i\alpha(\hat{p}_0\hat{p}_0)\hat{p}_0^{+} + \sqrt{2\frac{\gamma}{\tau}}\hat{p}_0^{in}$$

origin of squeezing

▷ γ polariton relaxation rate, τ cavity round trip time

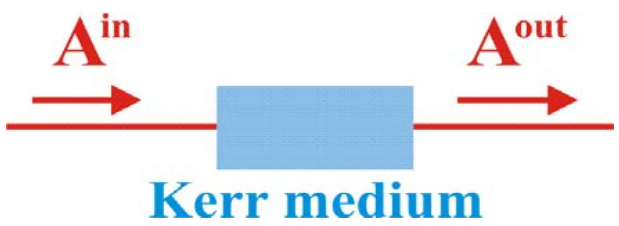
▷ $\sqrt{2\gamma/\tau}\,\hat{p}_0^{in}$ input fluctuations associated to relaxation

Langevin forces for the polariton

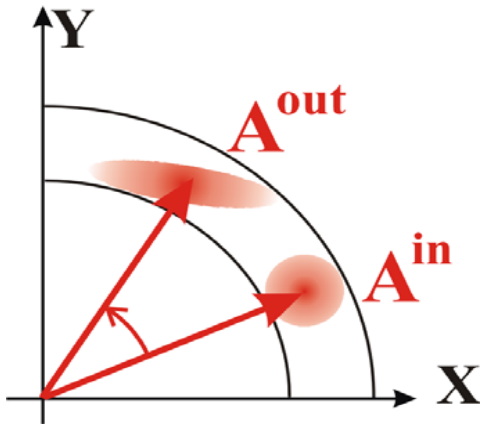
$$\sqrt{2\gamma}\,\hat{p}_0^{in} = \sqrt{2\gamma_{cav}}\,C\hat{a}^{in} + \sqrt{2\gamma}_{exc}\,X\hat{b}^{in}$$

Nonlinear optical effects can squeeze quantum fluctuations

Squeezing via Kerr effect



$$n = n_0 - n_2 I$$

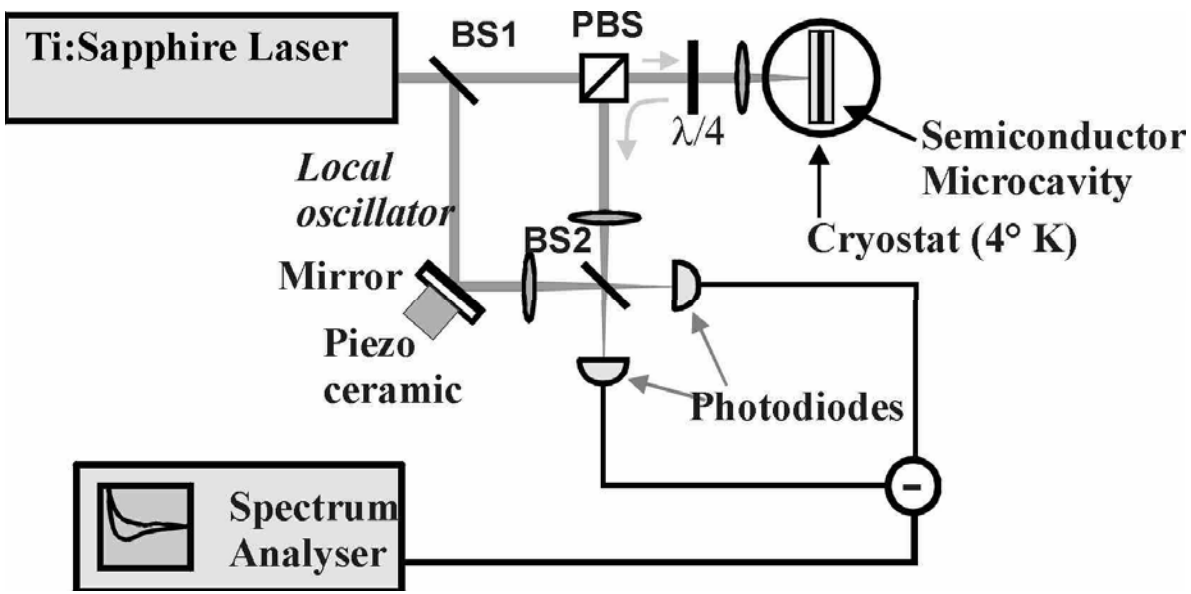


⇒ ***Semiconductors***

⇒***Atomic medium***

Non linear effect enhanced in an optical cavity

Nonlinear and quantum effects at normal incidence

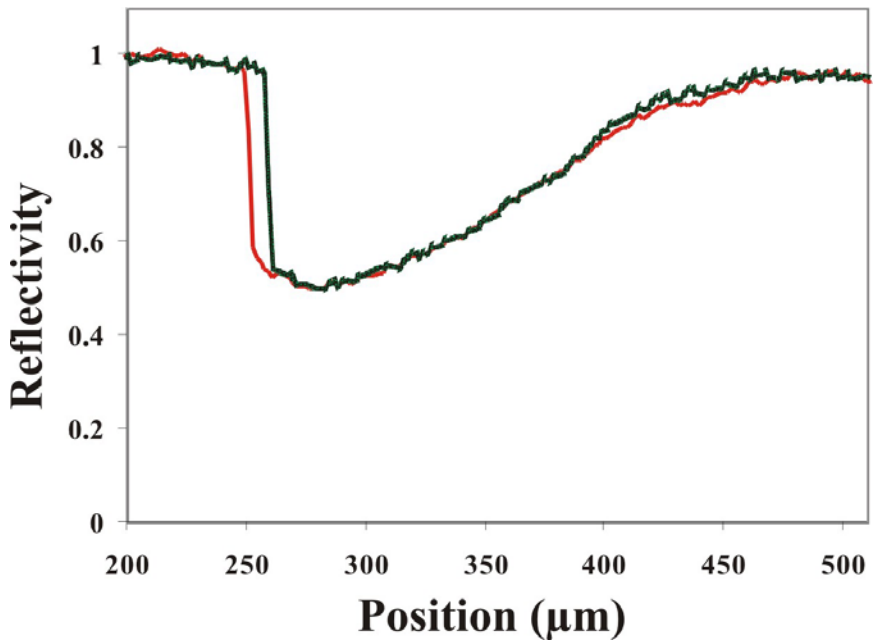


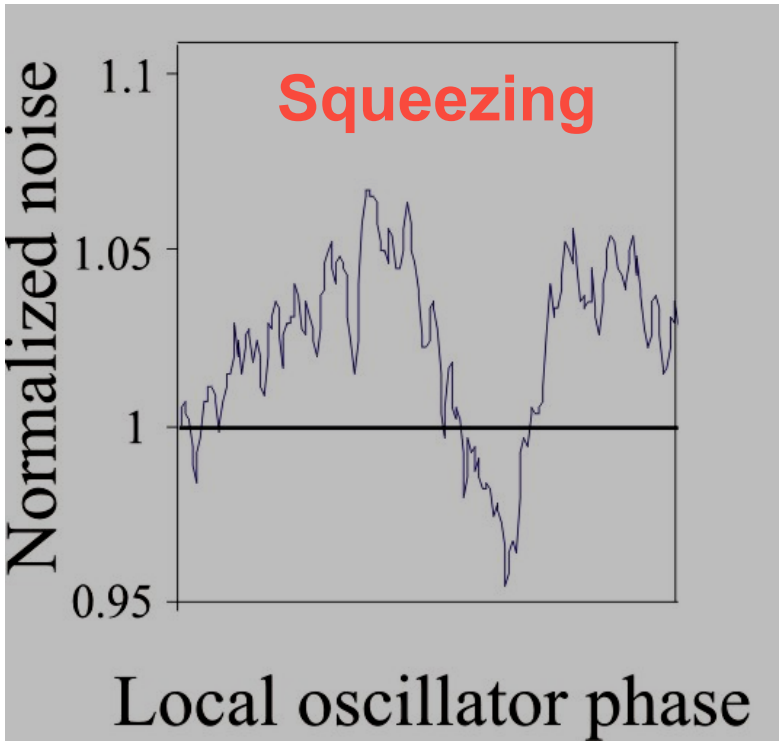
Homodyne detection set-up

- cavity exciton detuning can be changed by moving the laser spot on the sample
- very low laser intensity (here: 2.2 mW over a 50 µm spot)

Bistability and Squeezing

Bistability





positive detuning (here: $\delta = +0.3$ meV)

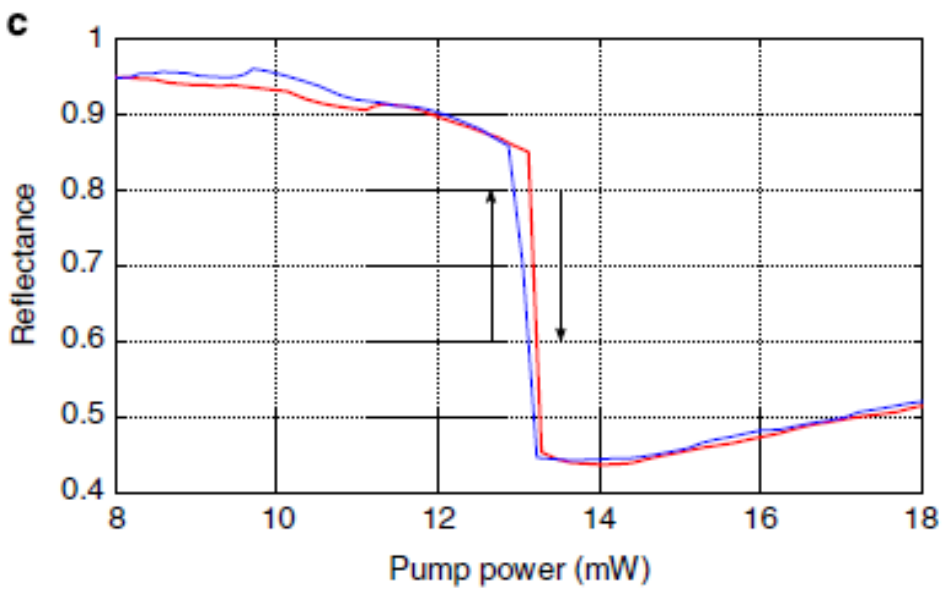
vicinity of the bistability turning point

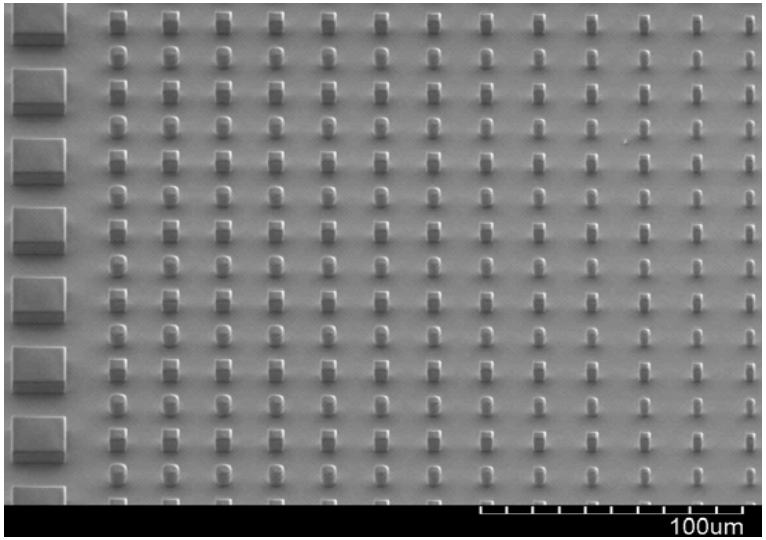
A. Baas et al, Phys. Rev. A **69**, 023809 (2004)

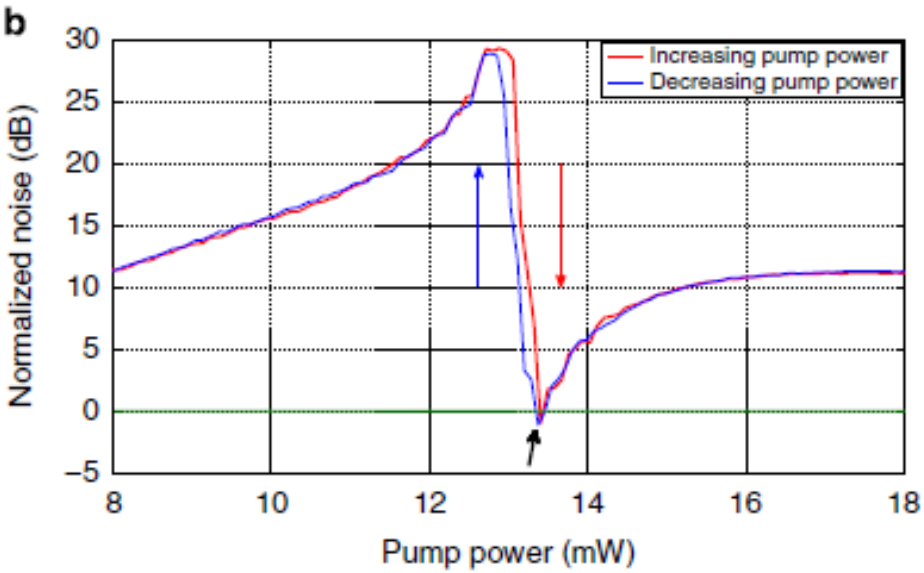
G. Messin et al,, *PRL.* **87**, 127403 (2001)

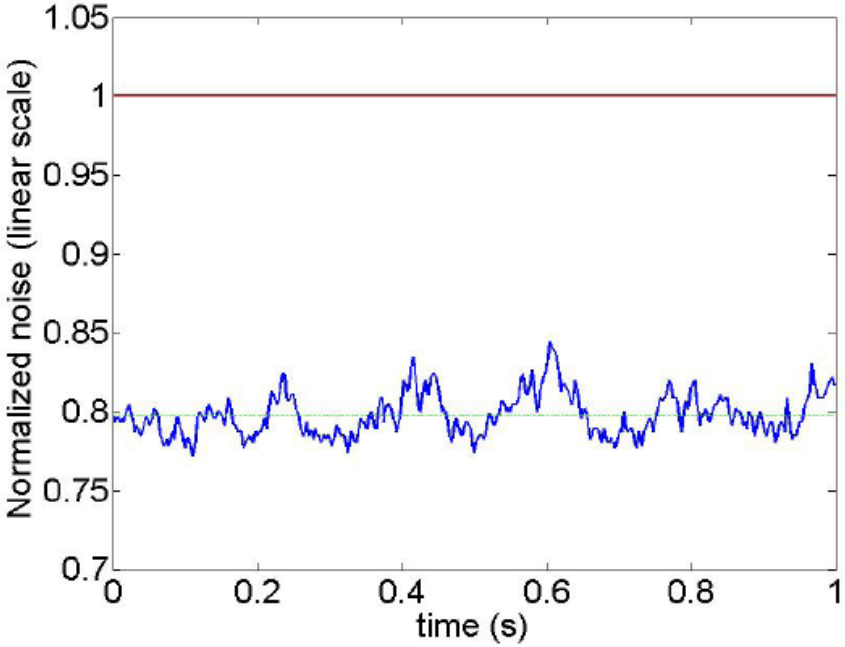
J.P. Karr et al, Phys. Rev. A69 031802(R) (2004)

Recent results : Squeezing with micropillars









T. Boulier et al. Nat. Com. 5, 3260 (2014)

Symetrical polaritons generation with two pumps

Parametric 4-wave mixing of polaritons

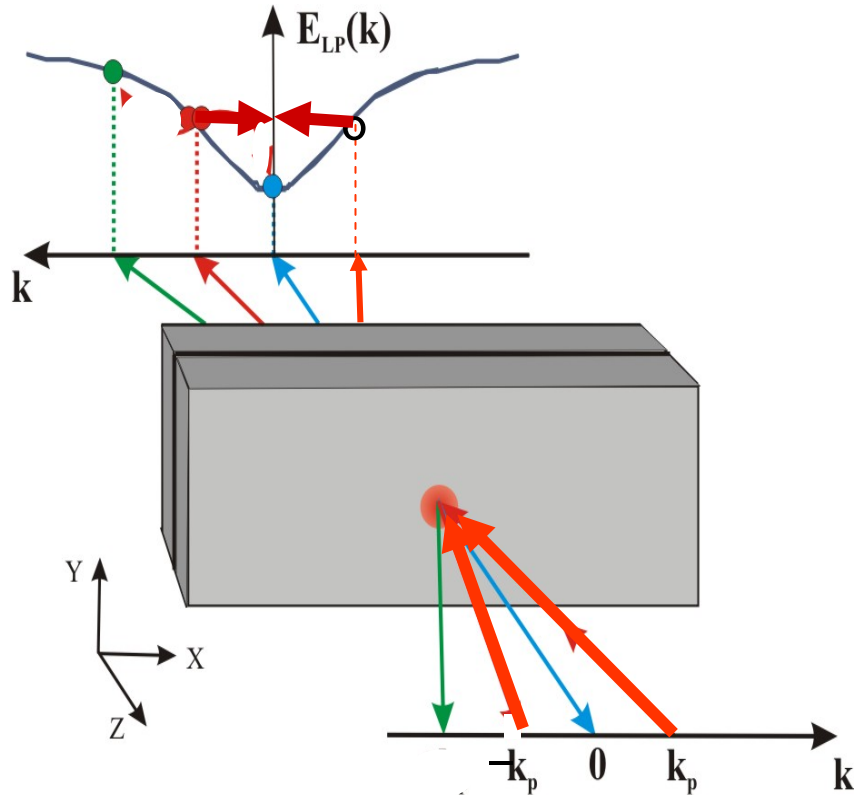
$$H_{PP}^{eff} = \hbar\alpha X^4 p_{k_p} p_{-k_p} p_k^{+} p_{-k}^{+}$$

$$\boxed{\{k_p, -k_p\} \rightarrow \{k, -k\}}$$

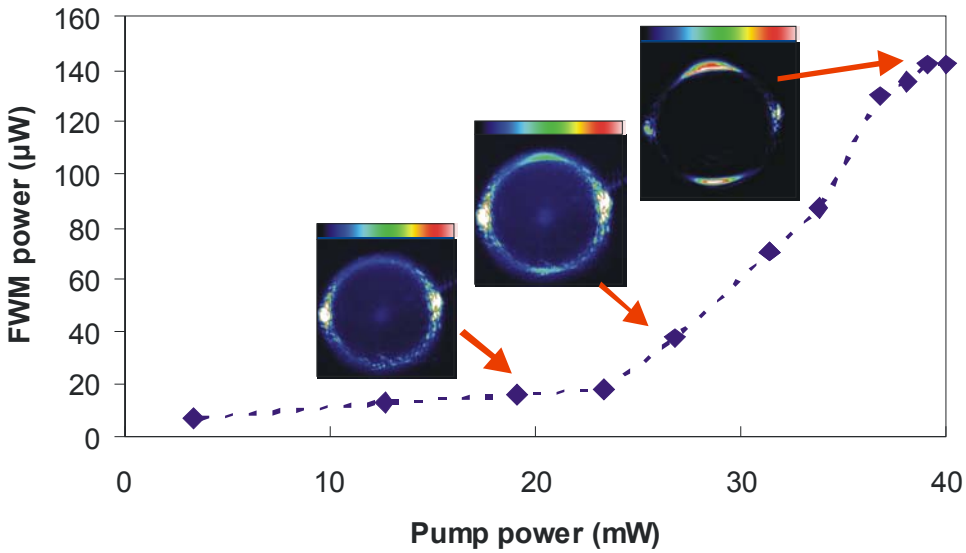
$$with \quad |k| = |k_p|$$

With energy conservation

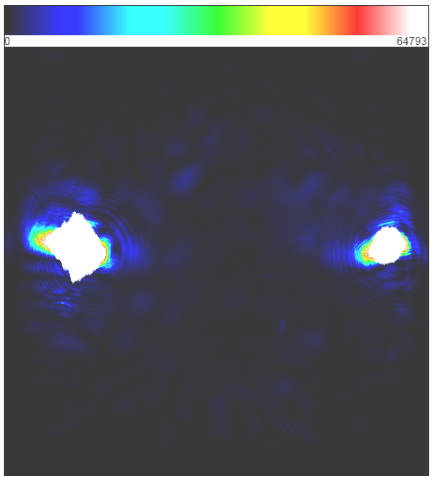
$$\boxed{2E(k_p) = 2E(k)}$$



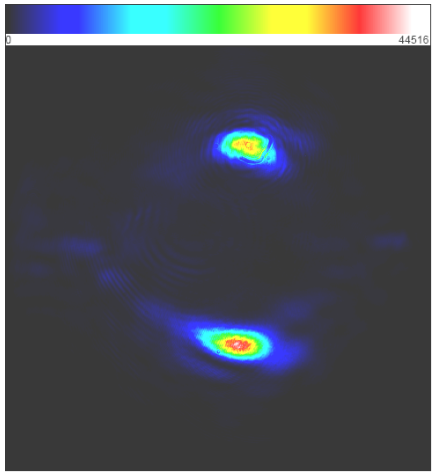
Correlated polaritons generation



Parametric oscillation of signal and idler modes above threshold



Polarization //



Polarization ⊥

Strong classical noise correlations

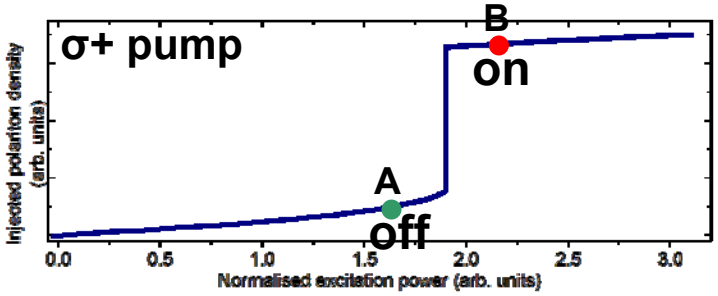
$$\frac{\Delta(I_1 - I_2)}{\Delta(I_1 + I_2)} = 0.99$$

but the noise in the difference is slightly above shot noise

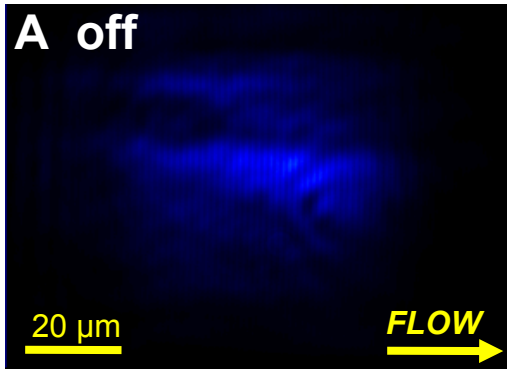
Romanelli, Leyder et al, PRL, 98, 106401 (2007)

Non-local switch

- **Sub-threshold Pump**
- **Weak probe**
- **Angle of incidence: 3.8°**



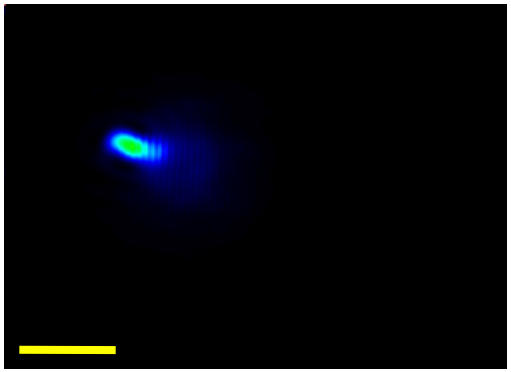
Pump (**σ+**)



Transmitted power
9 mW

+

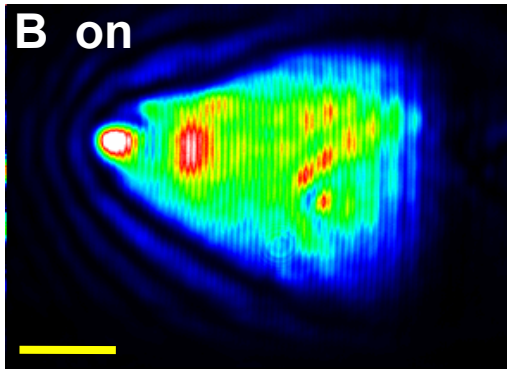
Probe (**σ+**)



Transmitted power
3 mW

=

Pump+Probe



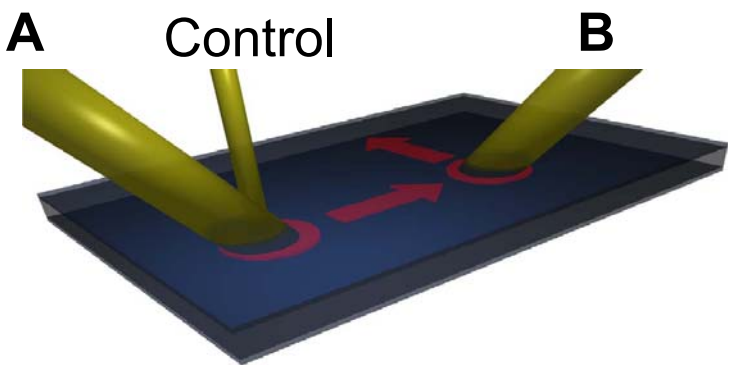
Transmitted power
54 mW

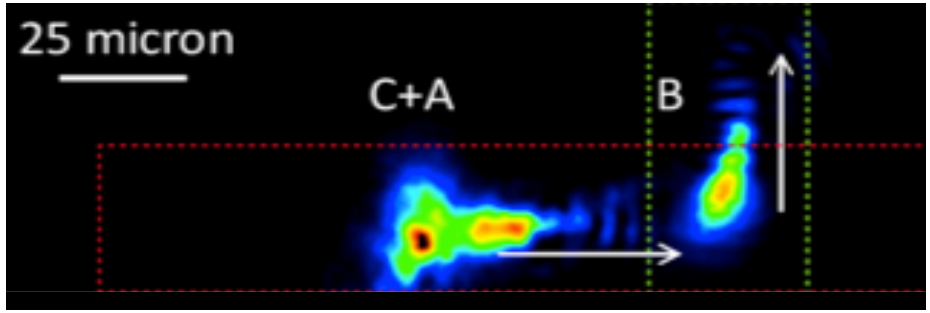
The whole pump spot switches ON

M. Degiorgi et al, “Control and ultrafast dynamics of a two-fluids polariton switch” Phys. Rev. Lett. 109, 266407 (2012)

E. Cancellieri et al, “Ultra-fast Stark-induced polaritonic switches” Phys. Rev. Lett. 112, 053601 (2014)

Polariton transistor





Idea : to exploit the polariton flow from beam A to control the ON/OFF states of beam B, spatially separated from A.

Polariton-based optoelectronic devices

D. Ballarini et al, “All Optical Polariton Transistor”
(Nature Communications 2013)

Quantum fluid properties of polaritons

Polaritons as particles

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

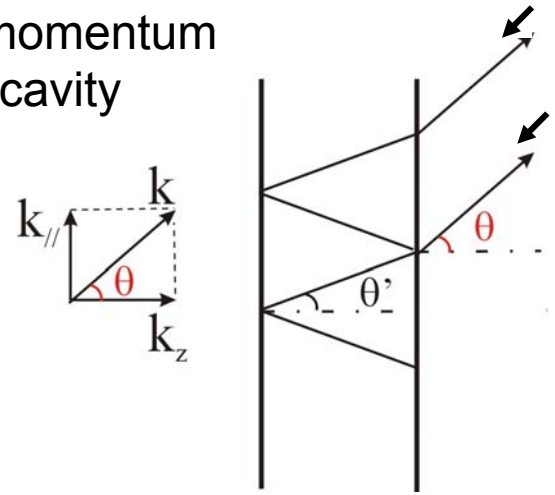
$$\lambda_T = \left(\frac{2\pi\hbar^2}{mk_BT}\right)^{\frac{1}{2}}$$

and
mean distance between polaritons d ~ 0,1-0,3 µm

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

Photon effective mass

k photon momentum inside the cavity



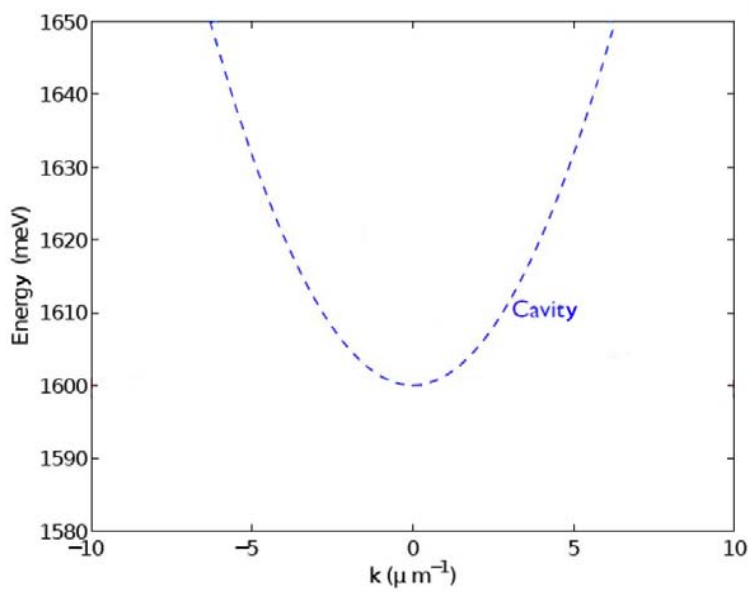
Resonance of cavity mode:

$$p\,\lambda/2 = \ell \cos\theta' \qquad k_z = \frac{2\pi p}{2l} = k_z^0$$

$$\omega = \frac{c}{n}\sqrt{k_z^2 + k_x^2} \approx \frac{ck_z}{n}\left(1 + \frac{k_x^2}{2k_z^2}\right) \approx \frac{ck_z}{n} + \frac{\hbar k_x^2}{2m}$$

With an effective photon mass

$$\boxed{m = \frac{n\hbar k_z}{c}}$$



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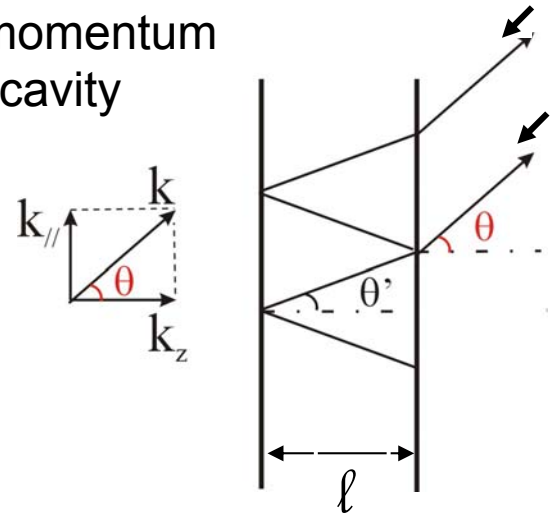

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With an effective photon mass

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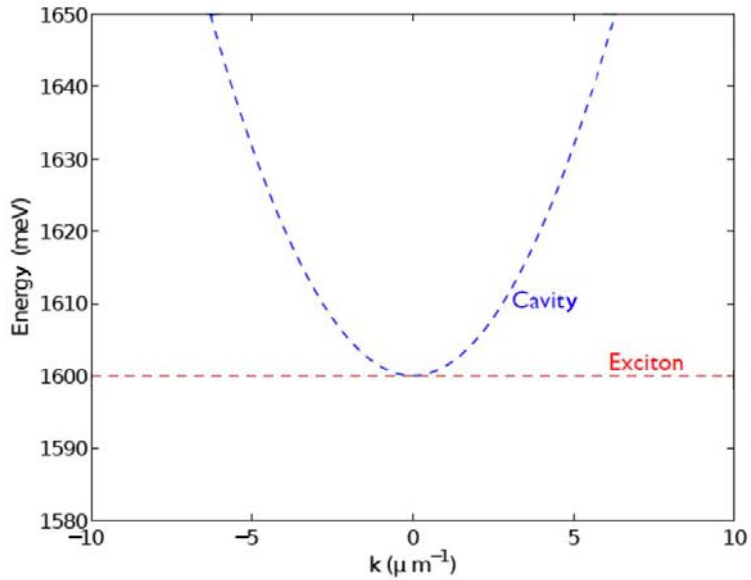
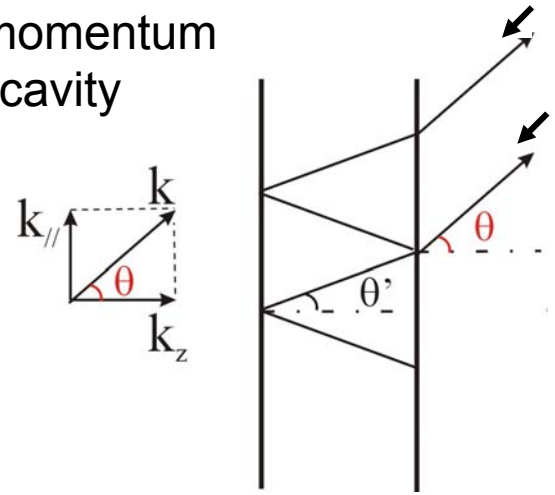


Photon and polariton effective mass

k photon momentum inside the cavity



Resonance of cavity mode:

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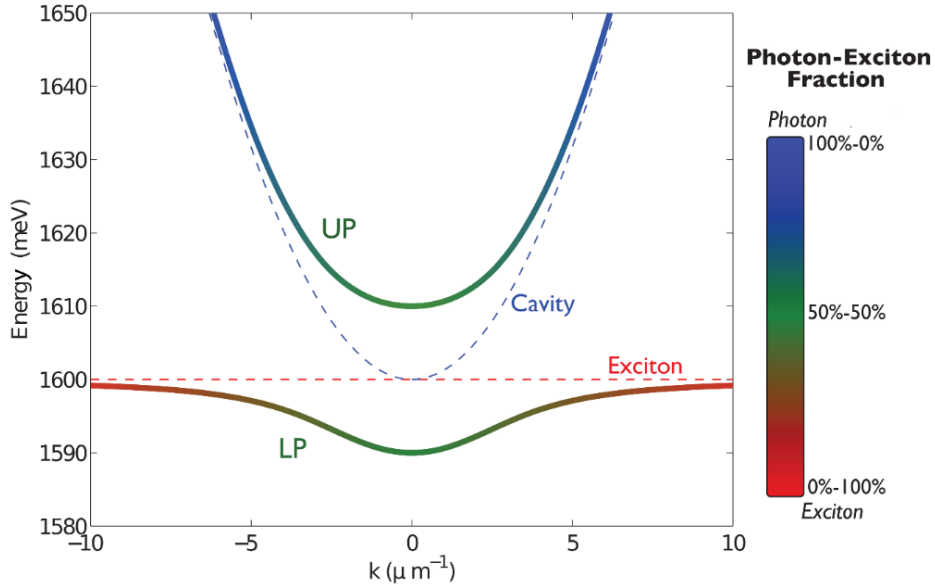
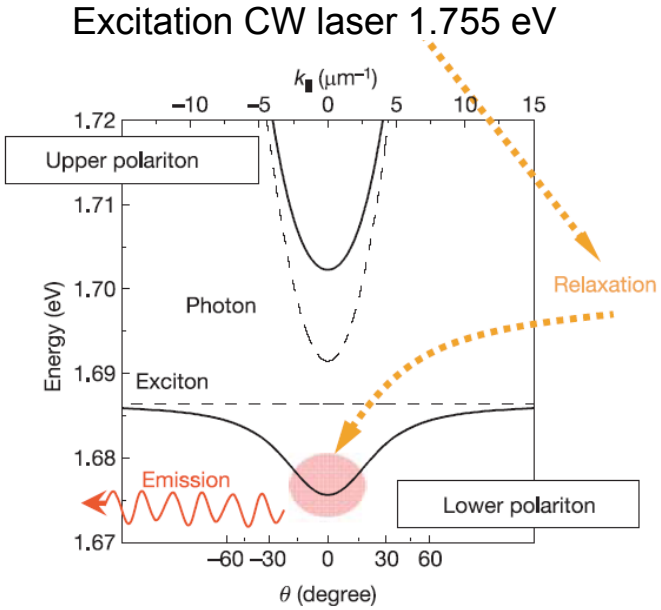
With an effective photon mass

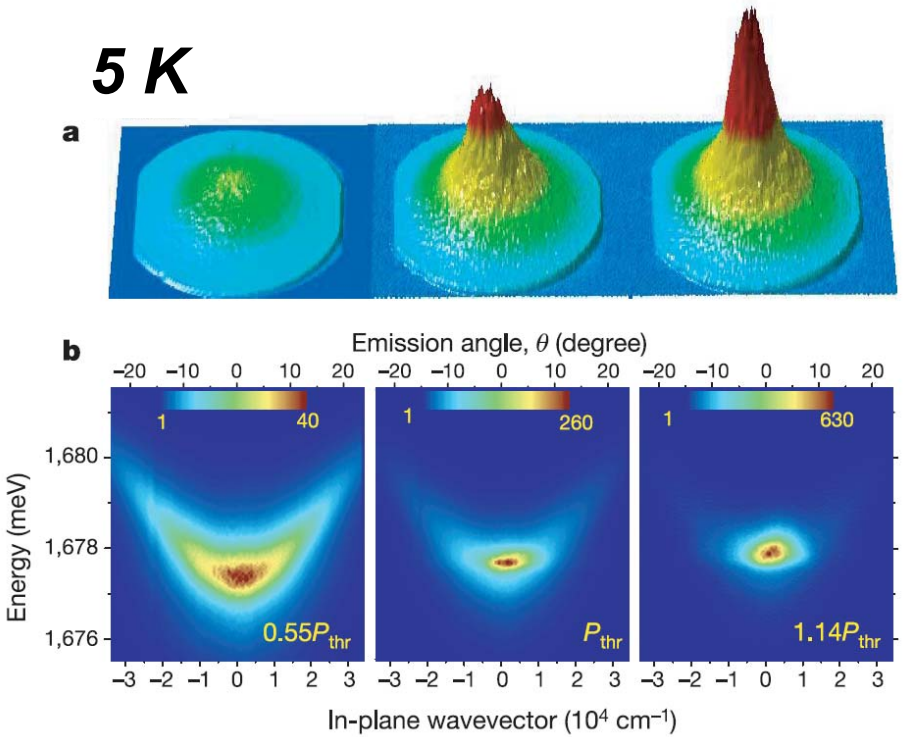
$$\boxed{m = \frac{n\hbar k_z}{c}}$$

Due to strong coupling, the lower polariton also has an effective mass, equal to the photon mass



Bose Einstein condensation of polaritons





- **2D system** Berezinski-Kosterlitz-Thousless transition
- non-resonant optical pump : quasi-thermal polariton distribution **:**

polariton creation et recombination (polariton life time ~4 ps)

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

Quantum fluid properties of polaritons

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

Probing Microcavity Polariton Superfluidity through Resonant Rayleigh Scattering

Iacopo Carusotto[1,2,*] and Cristiano Ciuti[3]
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[2]*CRS BEC-INFM and Dipartimento di Fisica, Università di Trento, I-38050 Povo, Italy*
[3]*Laboratoire Pierre Aigrain, École Normale Supérieure, 24 rue Lhomond, 75005 Paris, France*
(Received 23 April 2004; published 13 October 2004)

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)

Wave equation for polaritons

Evolution of the lower polariton in the presence of laser excitation, exciton-exciton interaction and of a defect

Gross-Pitaevskii equation

$$i\partial_t \Psi_{\mathrm{LP}}(\mathbf{r},t) = \left[\omega^o_{\mathrm{LP}} - \frac{\hbar}{2m_{\mathrm{LP}}}\nabla^2 + V_{\mathrm{LP}}(\mathbf{r})\right]\Psi_{\mathrm{LP}}(\mathbf{r},t)$$

$$+ g_{\mathrm{LP}}|\Psi_{\mathrm{LP}}(\mathbf{r},t)|^2\Psi_{\mathrm{LP}}(\mathbf{r},t) - \frac{i\gamma_{\mathrm{LP}}}{2}\Psi_{\mathrm{LP}}(\mathbf{r},t)$$

$$+ i\eta_{\mathrm{LP}}E^{\mathrm{inc}}(\mathbf{r},t).$$

lower polariton energy

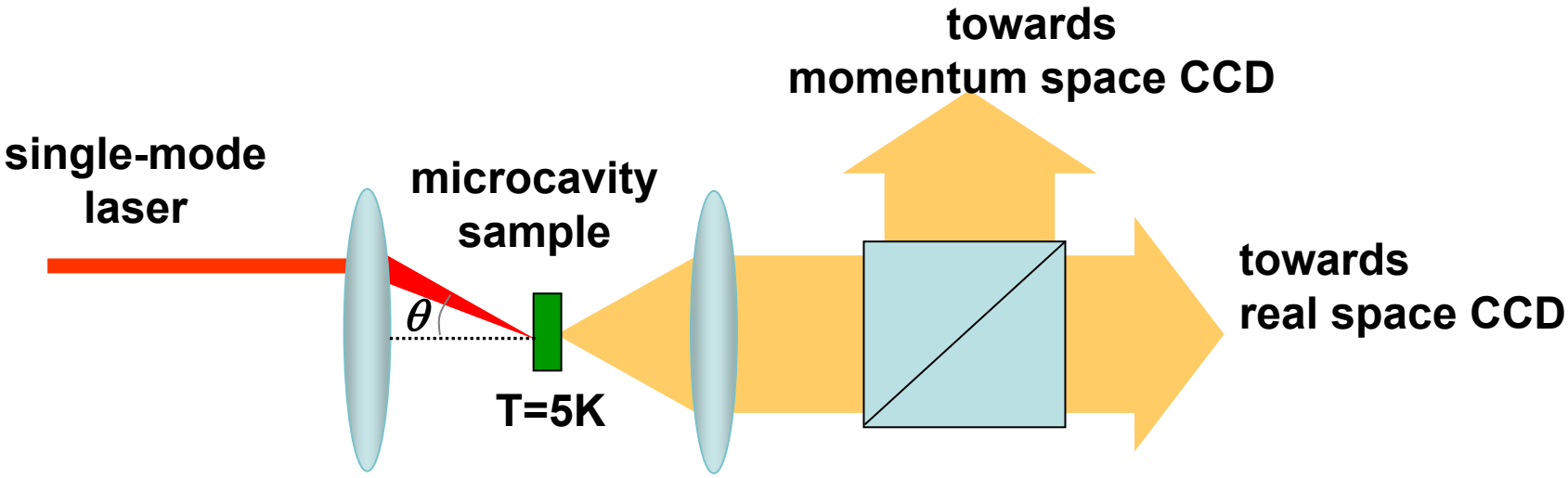
pol-pol interaction

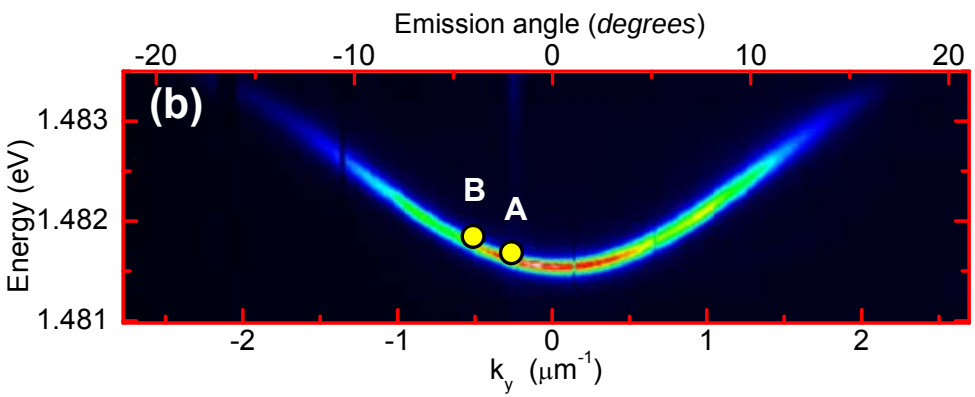
CW pump laser

Same equation as for superfluid helium

Look for solutions of the form $\Psi_{\mathrm{LP}}(\mathbf{r},t) = \Psi^0_{\mathrm{LP}} e^{i\mathbf{k}_{\mathrm{inc}}\cdot\mathbf{r}} e^{-i\omega_{\mathrm{inc}}t}$

Experimental scheme





Control parameters

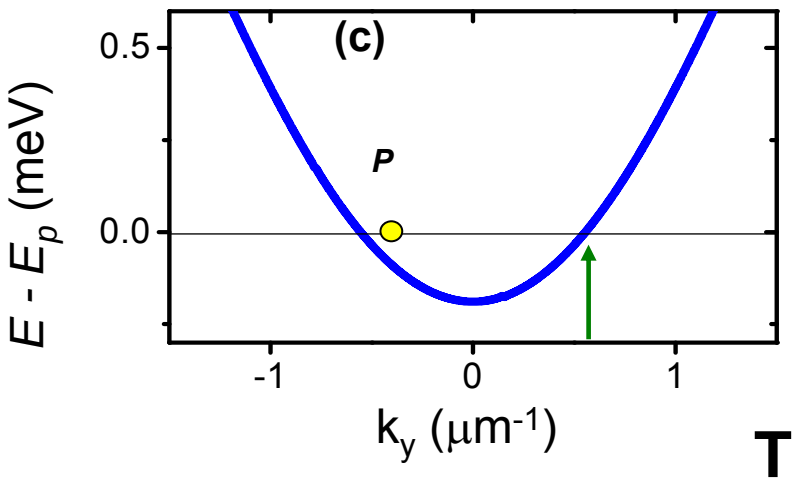
✓Polariton density
with pump intensity

✓Fluid velocity
with laser excitation angle

✓Oscillation frequency
with laser frequency

Propagation of a polariton fluid

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

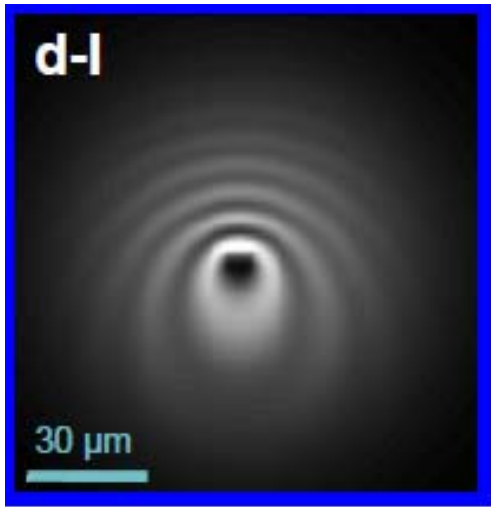


Linear regime, interactions between polaritons are negligible

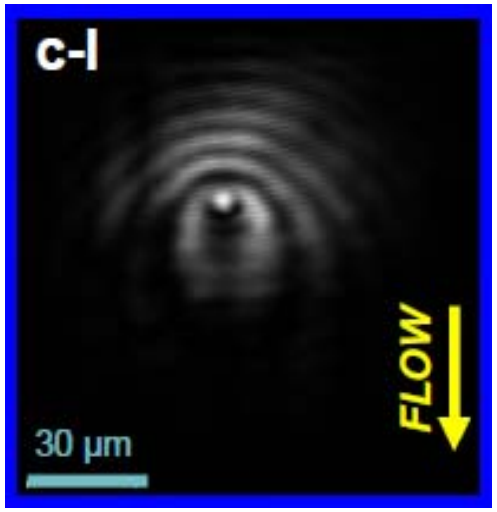
Elastic scattering on a defect is possible

I. Carusotto and C. Ciuti, PRL 93, 166401 (2004)

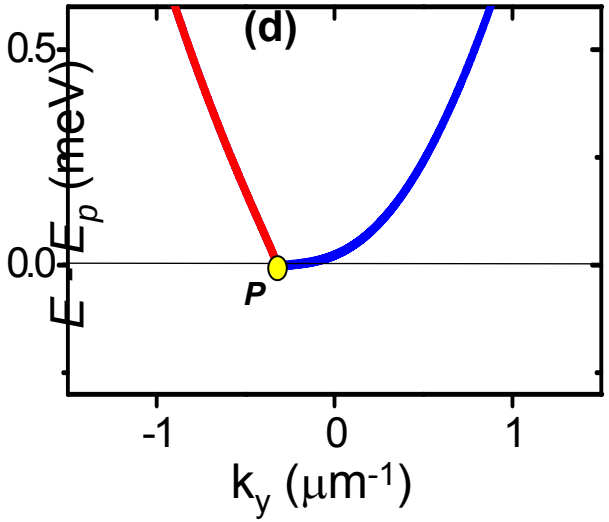
Theory



Experiment



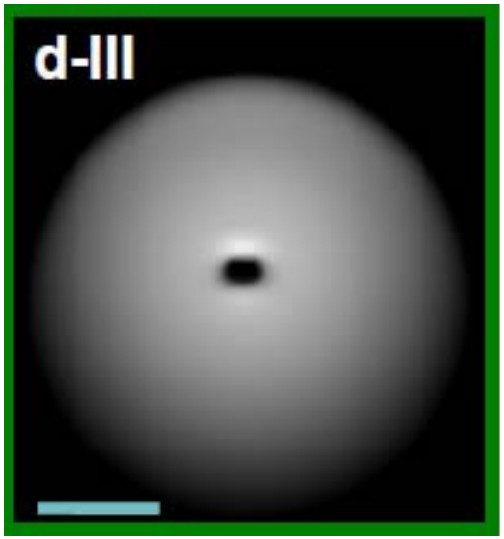
Superfluid regime



Nonlinear regime : interactions between polaritons, dispersion curve modified

a sound velocity appears $c_s = \sqrt{\hbar g |\psi|^2 / m}$

Theory **Experiment**



***If vg < cs* the Landau criterion for superfluidity is fulfilled: no more scattering on a defect**

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

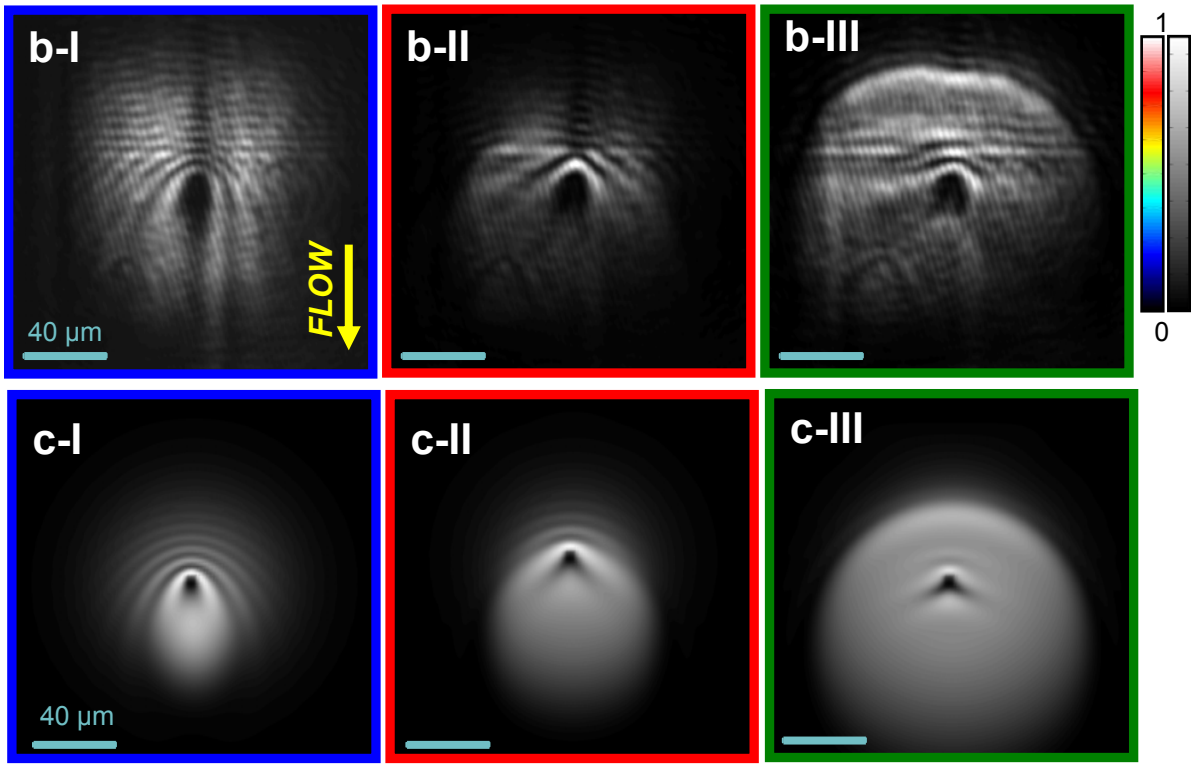
vp = 5.2 105 m/s, density $10^9/cm^2$

Supersonic regime : Cerenkov waves

$v_g > v_{sound}$

experiment

theory



Characteristic linear density wavefronts of the Cerenkov waves

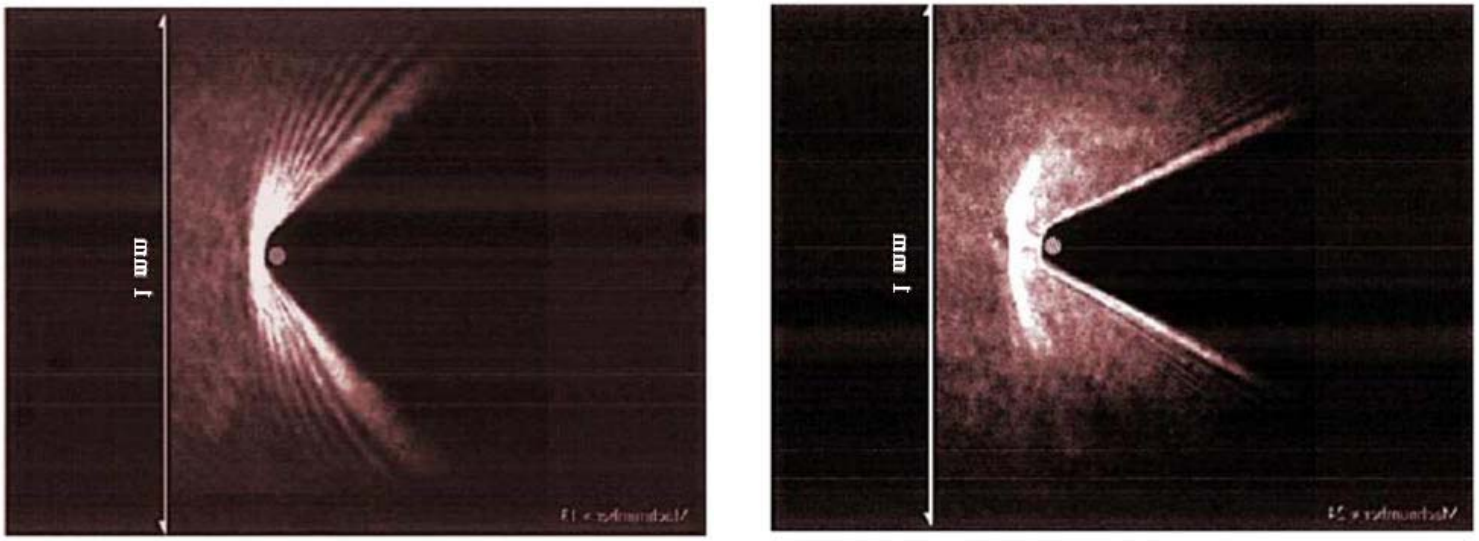
Existence of a well defined speed of sound

$$\sin(\phi) = c_s / v_p$$

Čerenkov effect in an atomic BEC

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

$v_f = 13c_s$ **FLOW** $v_f = 24c_s$



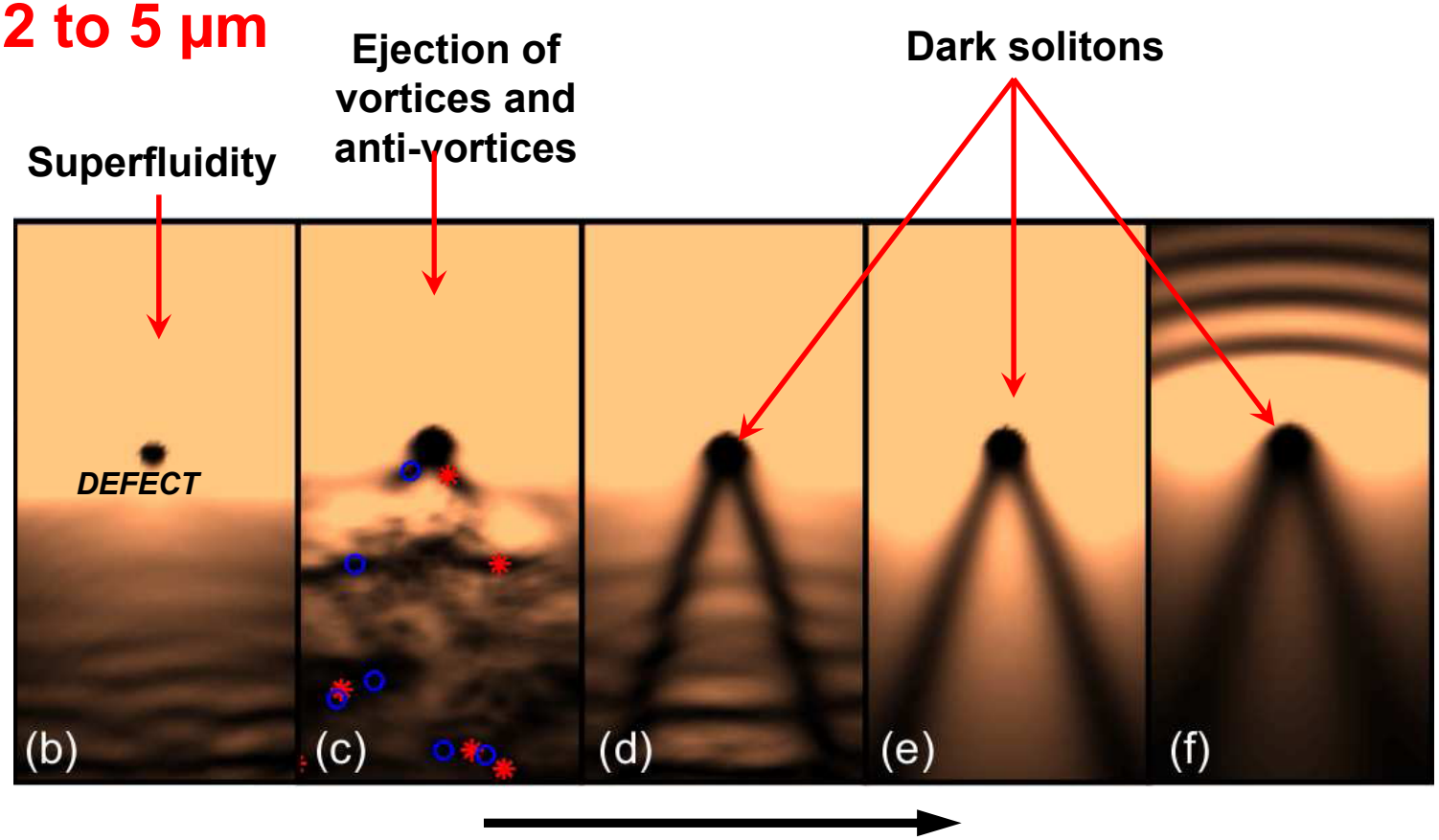
E. Cornell's talk at the KITP Conference on QuantumGases
http://online.itp.ucsb.edu/online/gases_c04/cornell/.

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

Superfluidity breakdown: vortices and solitons formation

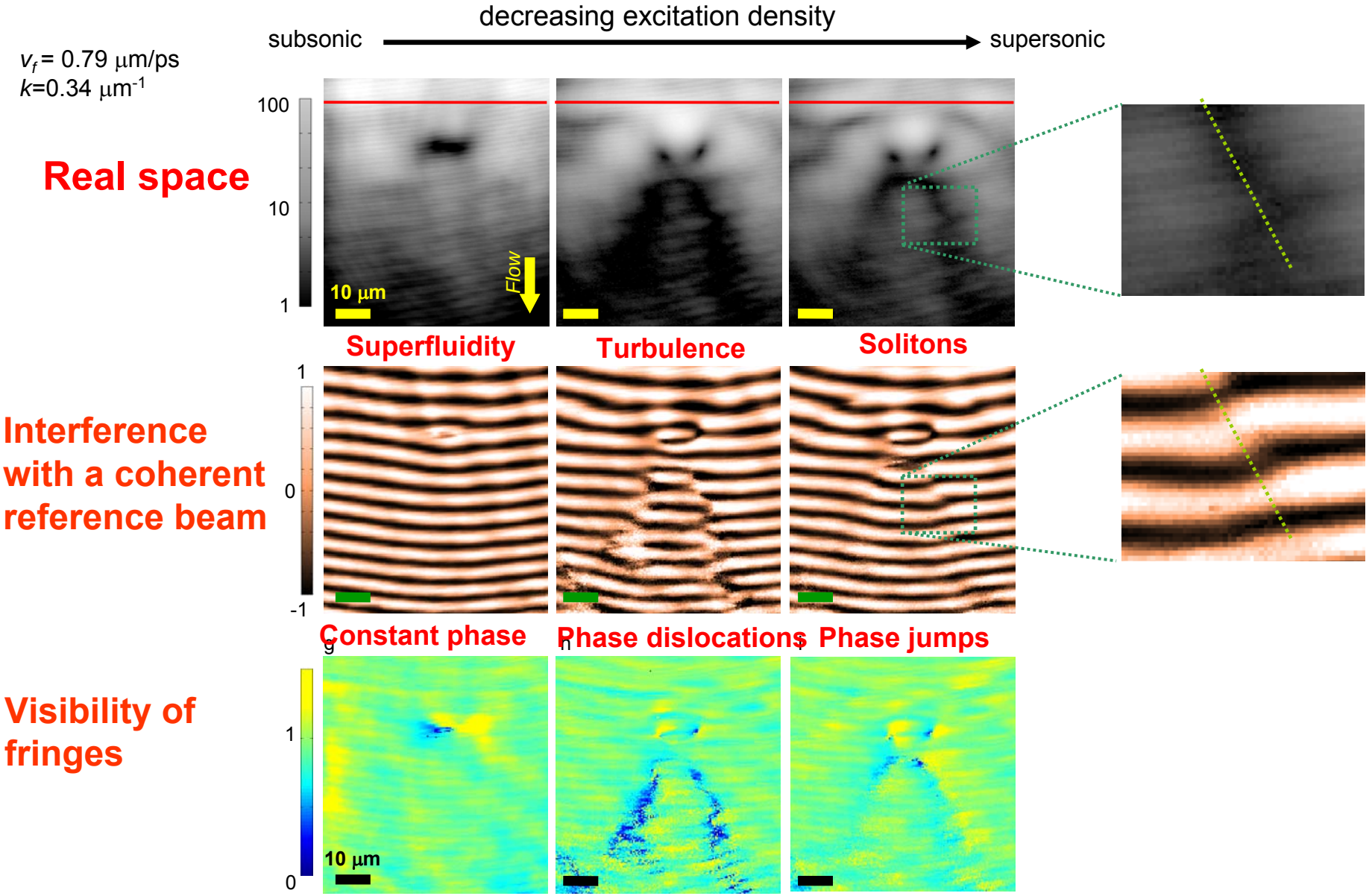
Theoretical prediction : case of spatially extended defects : the size of the defect is larger than the healing length $\xi = h / m_{pol}\, c_s$

ξ ~ 2 to 5 µm



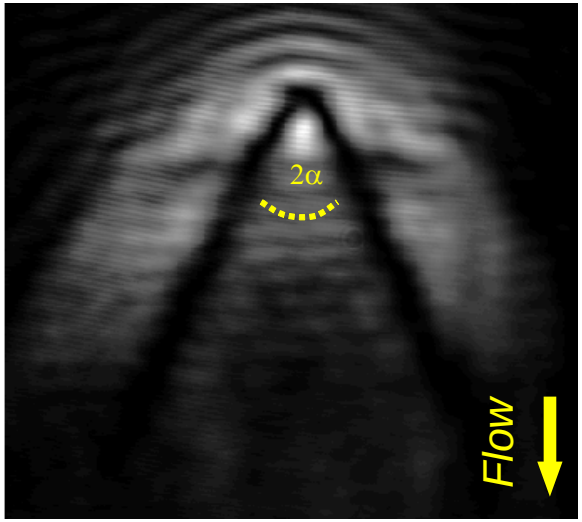
decreasing polariton density : decreasing speed of sound

Soliton nucleation with a large defect

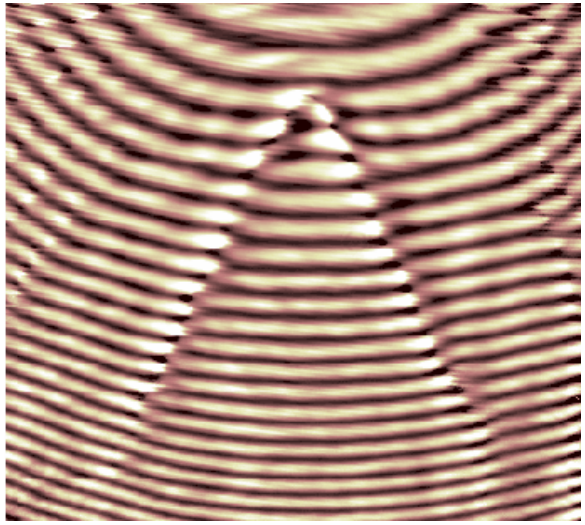


Hydrodynamic Dark Solitons

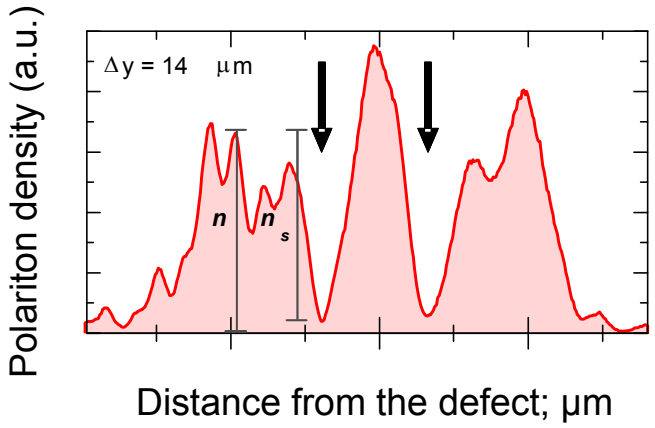
REAL SPACE

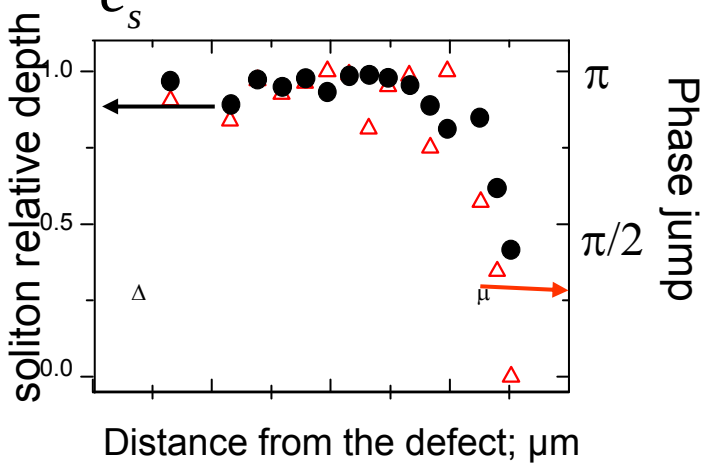


INTERFEROGRAM



$$\cos\left(\frac{\delta}{2}\right) = \left(1 - \frac{n_s}{n}\right)^{1/2} = \frac{v_s}{c_s}$$





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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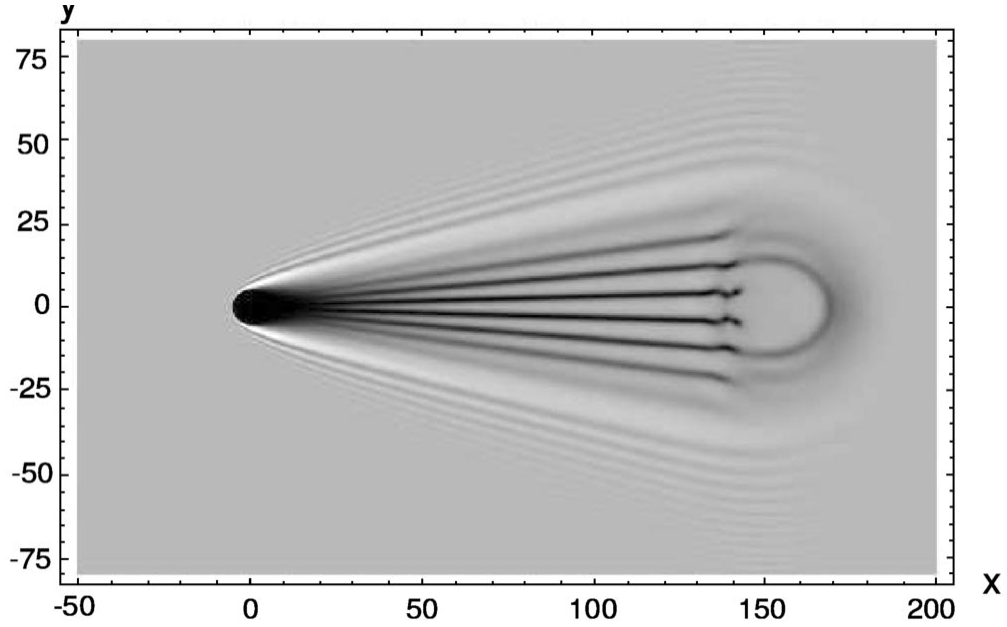
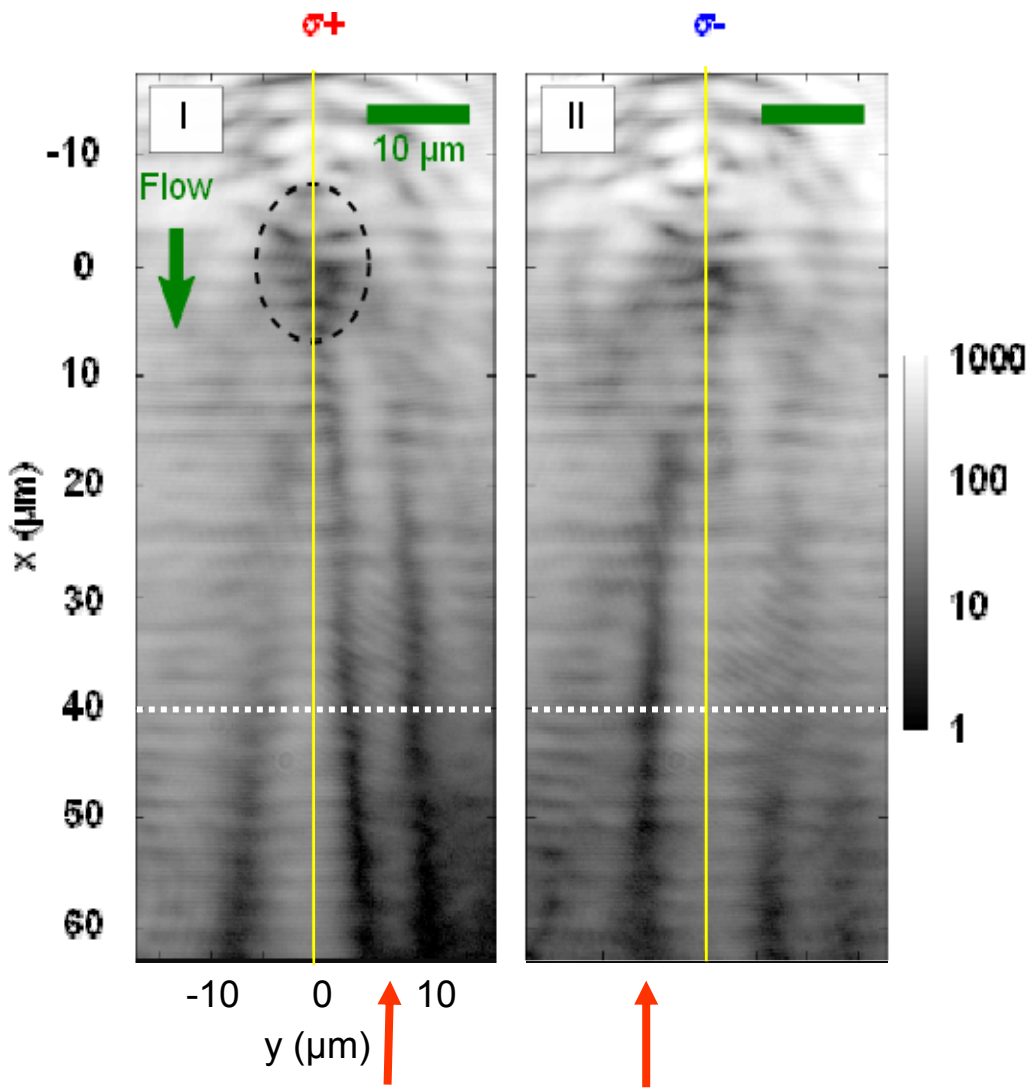
[2]*Instituto de Física, Universidade de São Paulo, 05315-970, C.P. 66318 São Paulo, Brazil*
[3]*Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, 142190, Russia*

(Received 21 April 2006; published 1 November 2006)



Not yet observed in atomic BEC; the dissipation in polariton fluids helps in stabilizing dark solitons

Solitons with linear polarization excitation



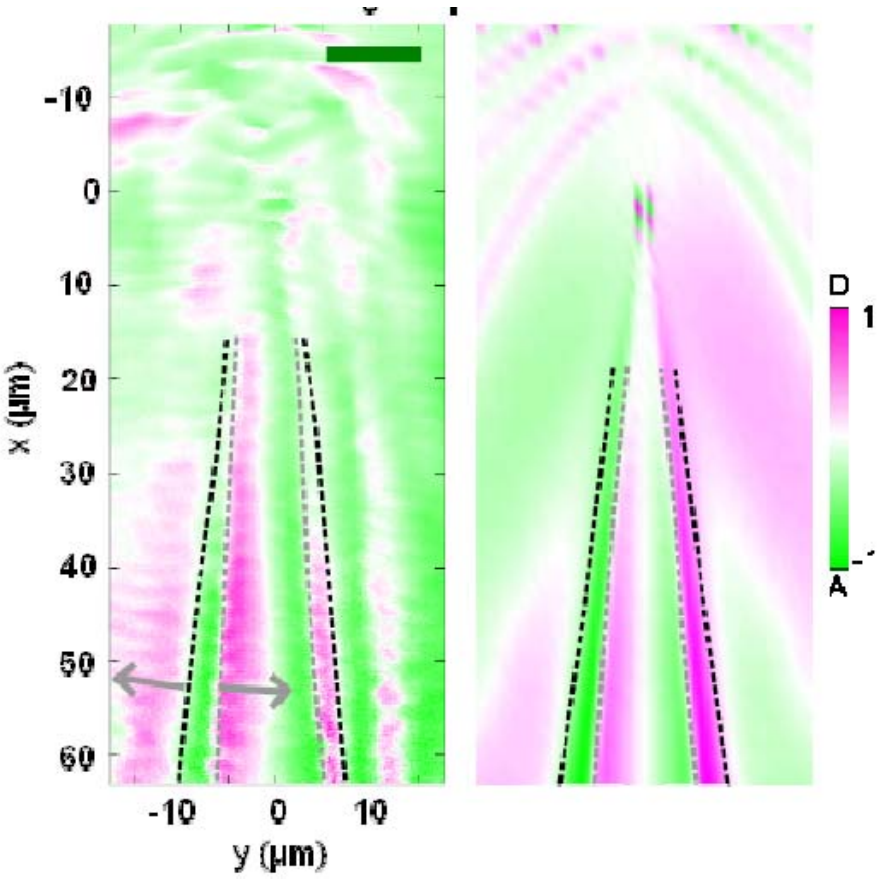
Excitation : linear polarization parallel to the flow (TM)

Observation : Circular Polarization Basis

Because of the effective magnetic field (due to TE-TM splitting), the polarization rotates differently according to the propagation direction

Half-Solitons: diagonal polarization basis

Diagonal Polarization



Experiment **Theory**

Close to the defect: balanced superposition of half-solitons with opposite charge

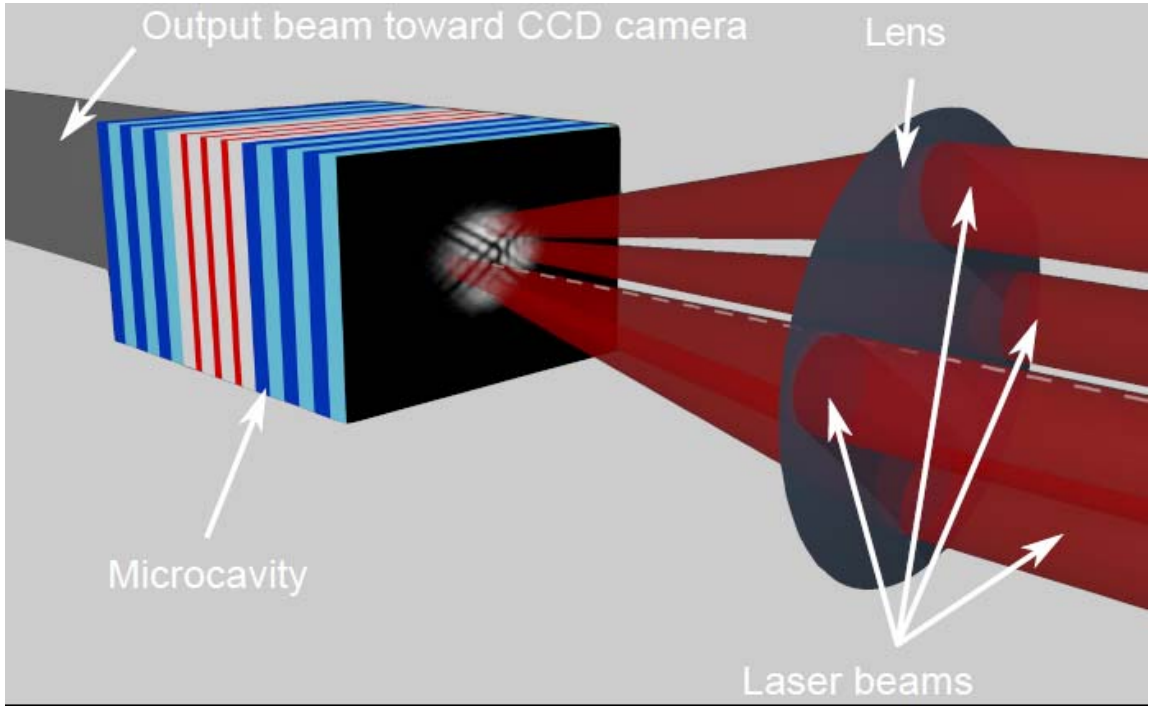
Soliton trajectories: domain walls between diagonal and antidiagonal polarizations

The inner half-solitons are decelerated and become darker (stable)

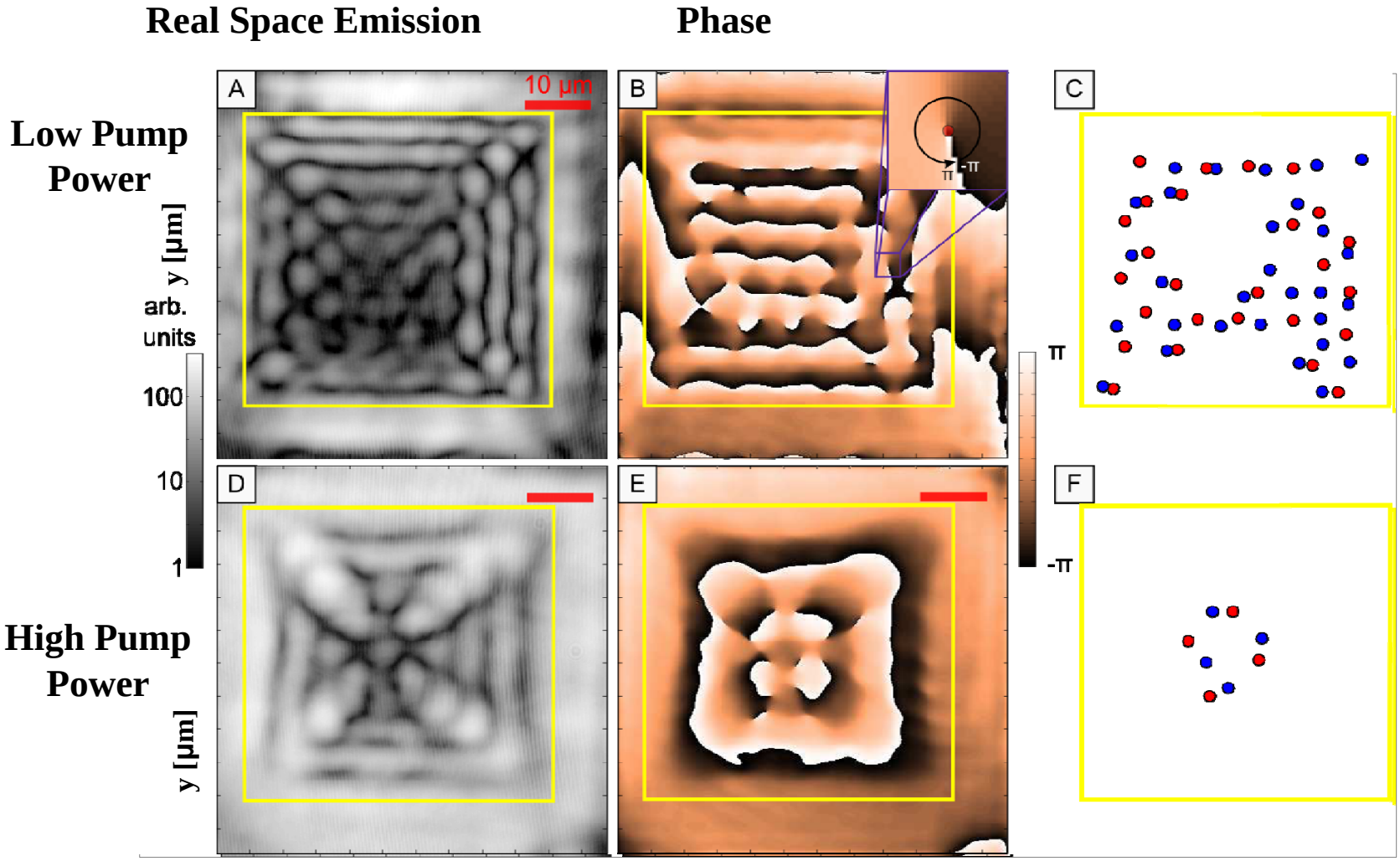
The outer half-solitons are accelerated and become shallower (unstable)

R. Hivet, et al, Nat. Phys. 8, 724 (2012)

Experimental set-up to observe vortex lattices



Vortex lattices with 4 pumps



In the strongly interacting (superfluid) regime, vortices tend to recombine

R. Hivet et al Phys. Rev. B 89, 134501 (2014)

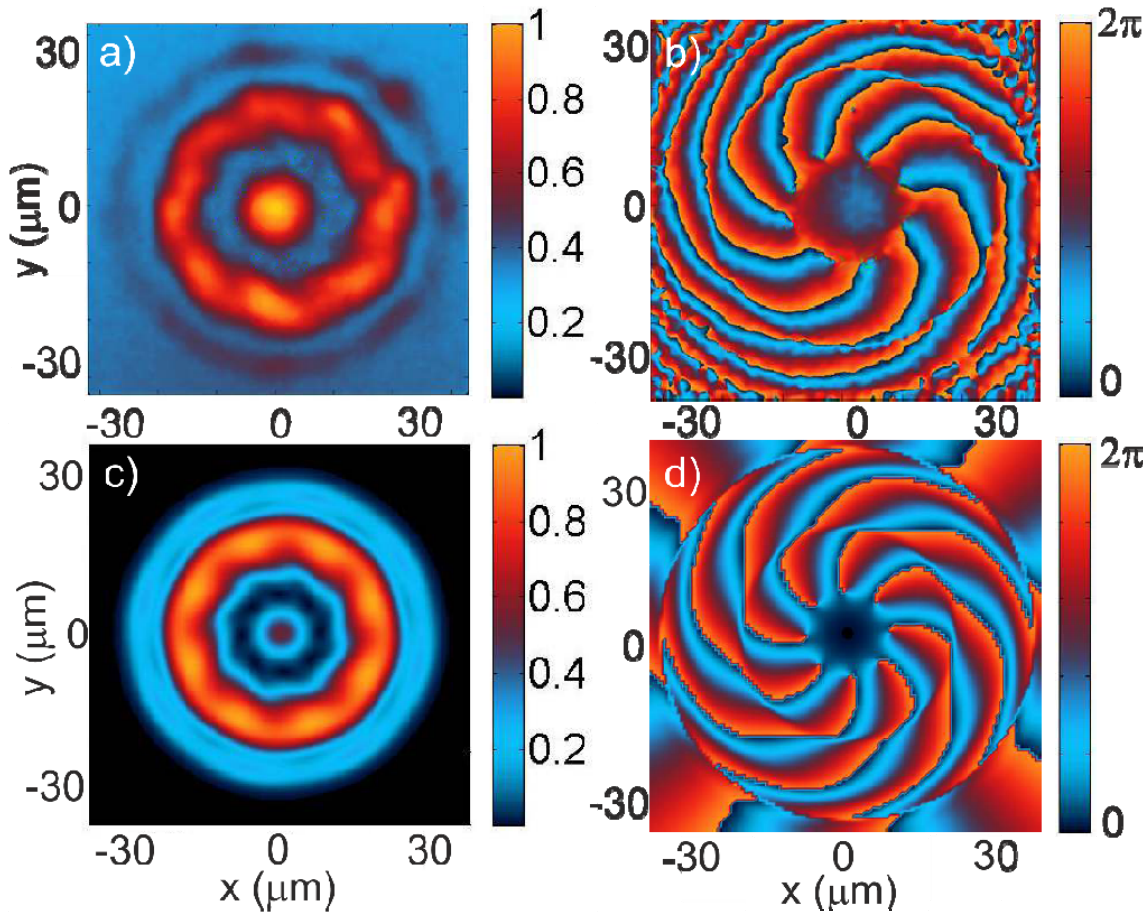
Annular vortex chain : linear regime

Injection of angular momentum in a polariton ensemble by a l = 8 Laguerre-Gauss beam

low intensity I_0

experiment

theory



Annular vortex chain : linear regime

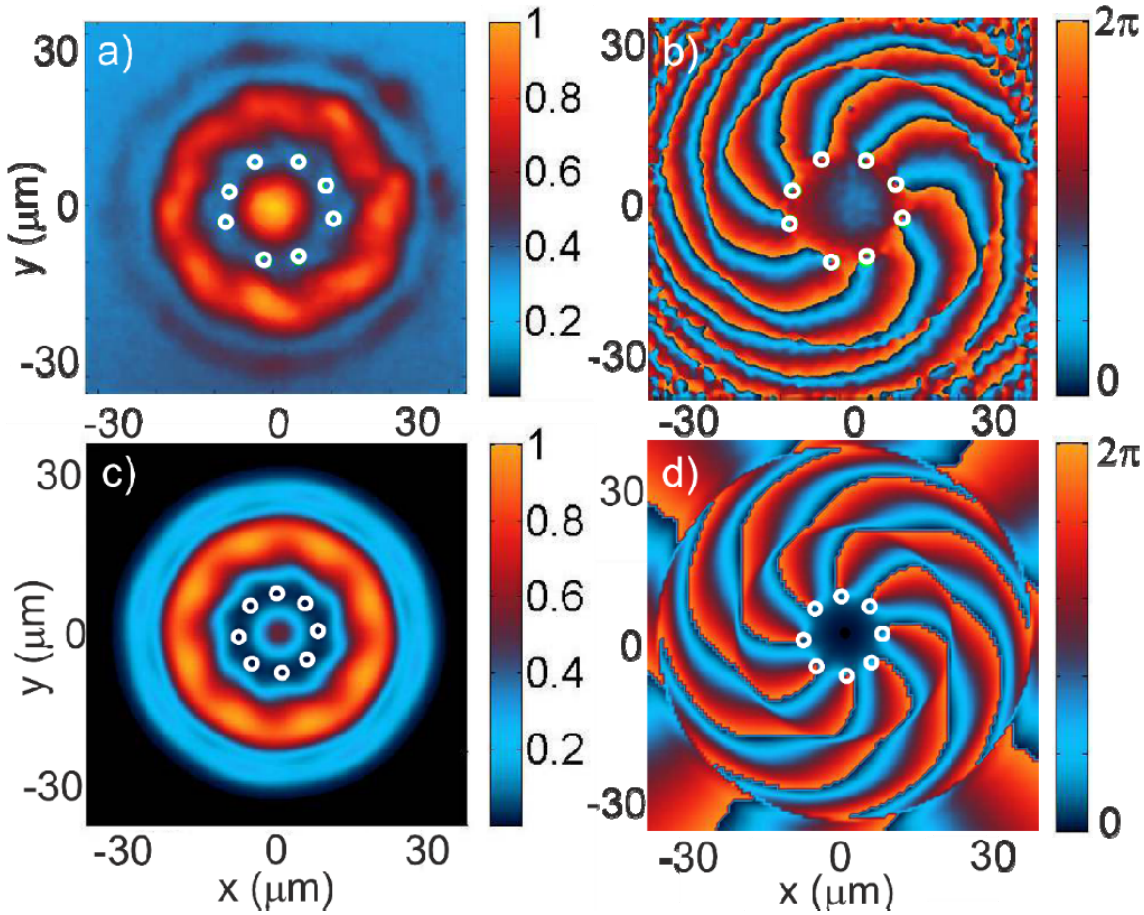
Injection of angular momentum in a polariton ensemble by a l = 8 Laguerre-Gauss beam

low intensity I_0

experiment

Phase singularities

theory

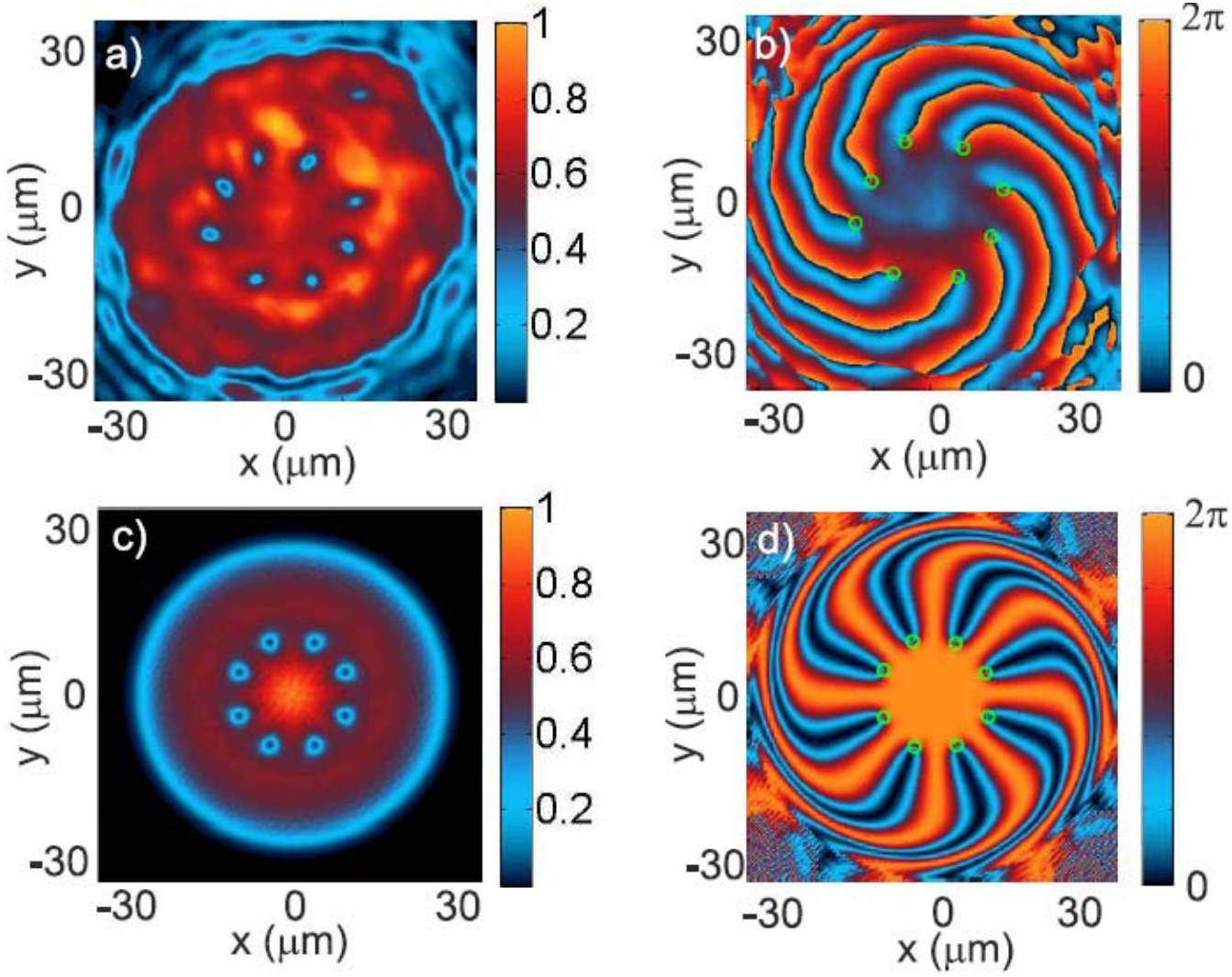


Annular vortex chain superfluid regime

intensity
4 I_0

experiment

theory



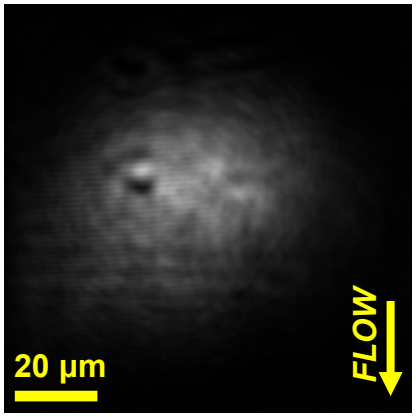
T. Boulier et al, submitted

Light engineering of the polariton landscape

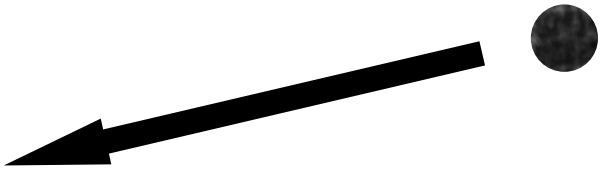
using polariton-polariton interactions

Field of view: $\phi \sim 100$ μm

probe σ^+



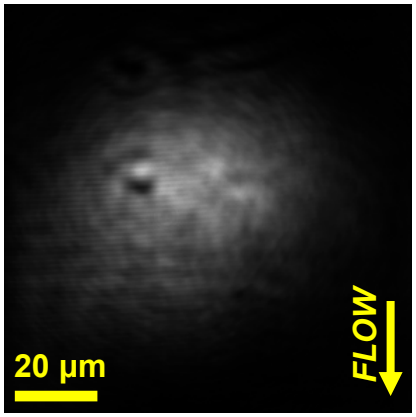
Defect-free area



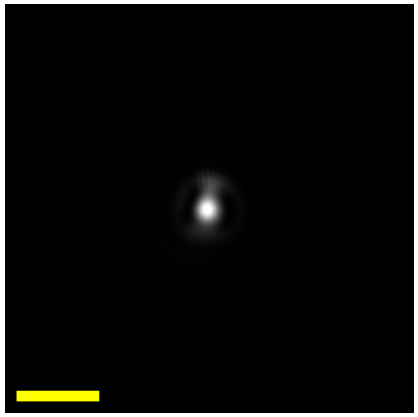
Light engineering of the polariton landscape

Field of view: $\phi \sim 100$ μm

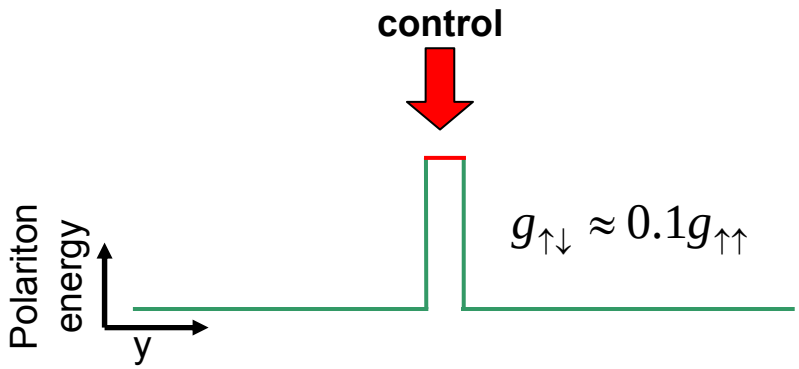
probe σ^+



control σ^-



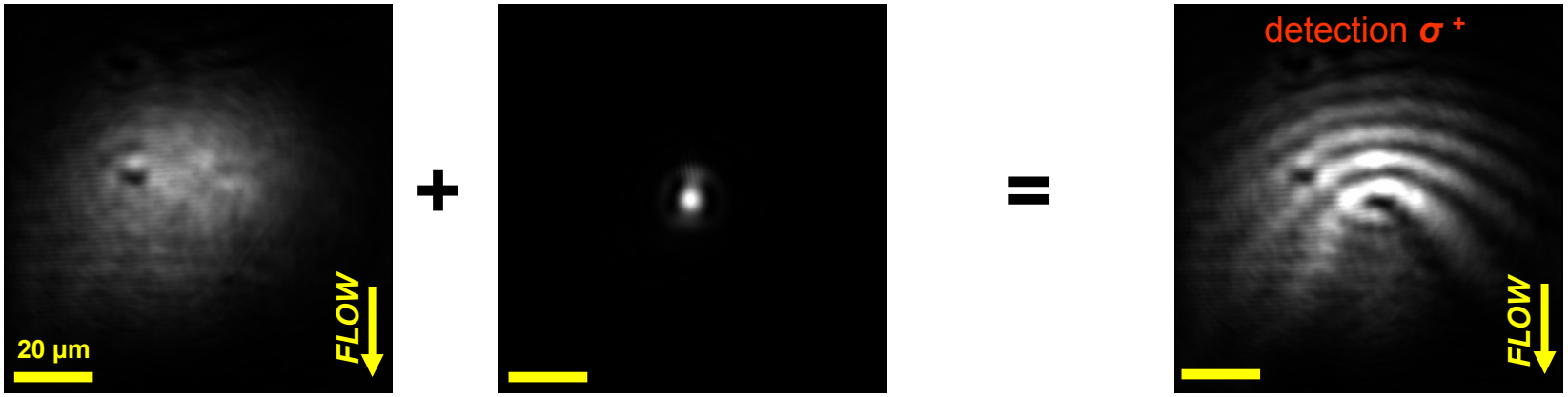
strong field: renormalization of the polariton energy



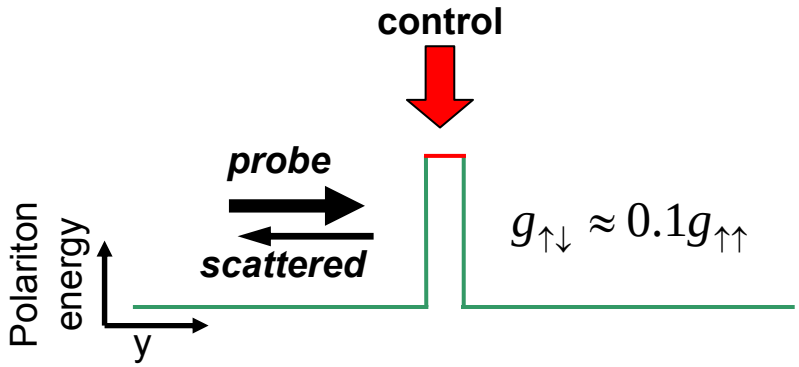
Light engineering of the polariton landscape

Field of view: $\phi \sim 100$ μm

probe σ^+ + control σ^- = probe σ^+ + control σ^- detection σ^+



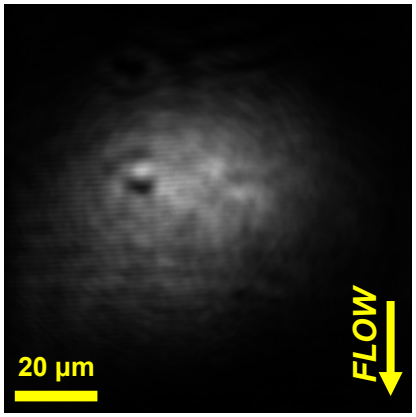
strong field: renormalization of the polariton energy



Light engineering of the polariton landscape

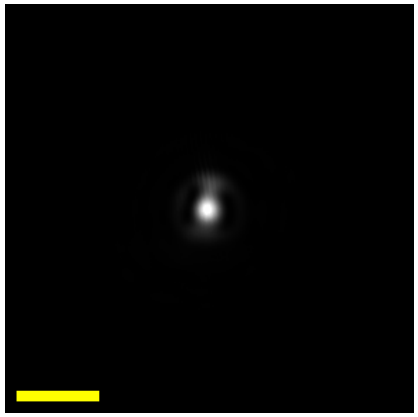
Field of view: $\phi \sim 100$ μm

probe σ^+



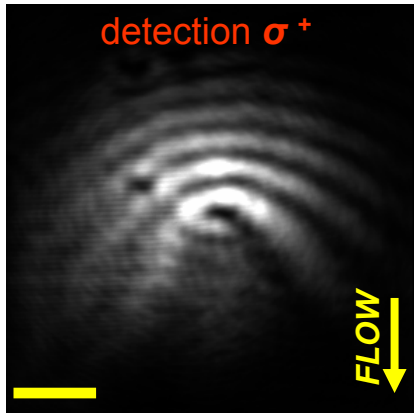
+

control σ^-

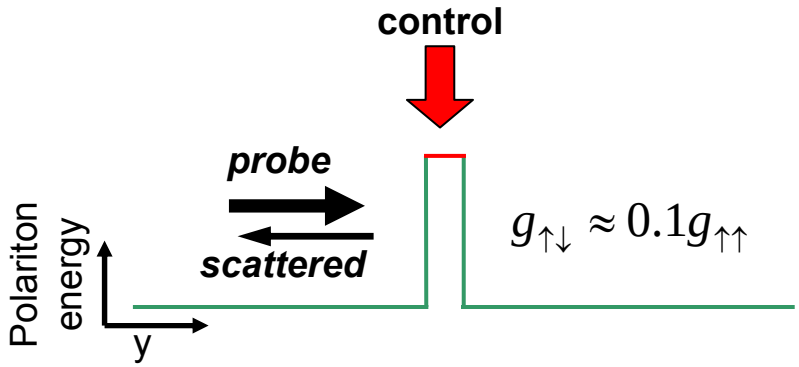


=

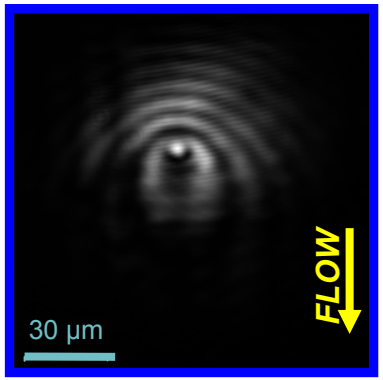
probe σ^+ + control σ^-



strong field: renormalization of the polariton energy

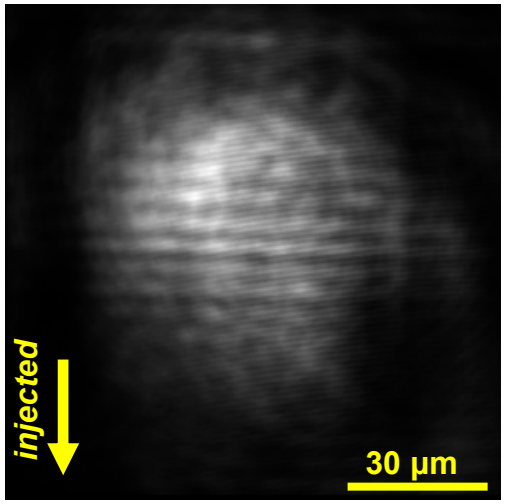


Real defect

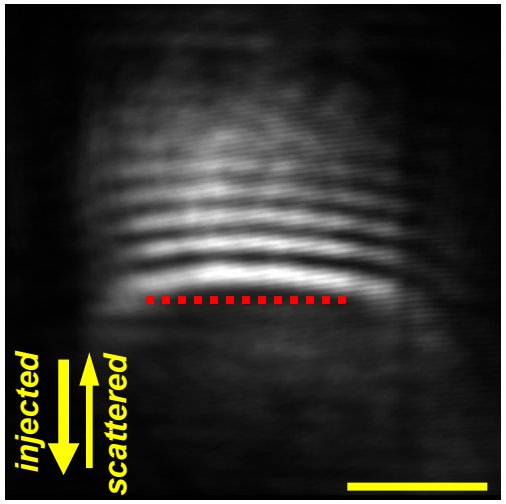


Light engineering of the polariton landscape

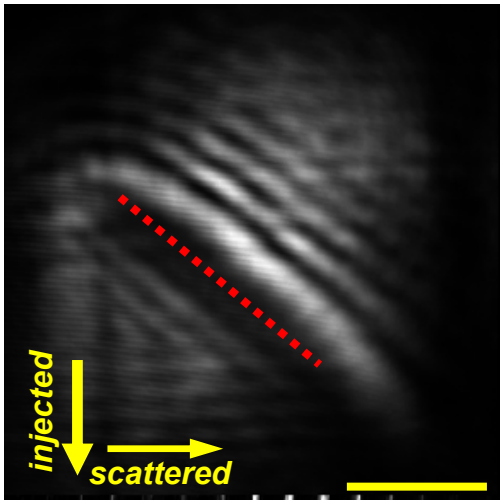
Probe only
No control



Probe +
Linear control

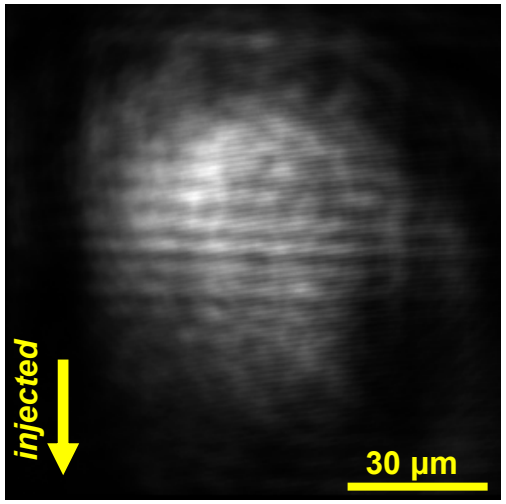


Probe +
Diagonal control

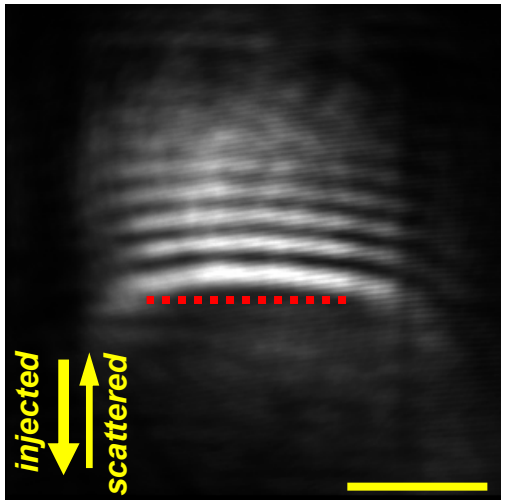


Light engineering of the polariton landscape

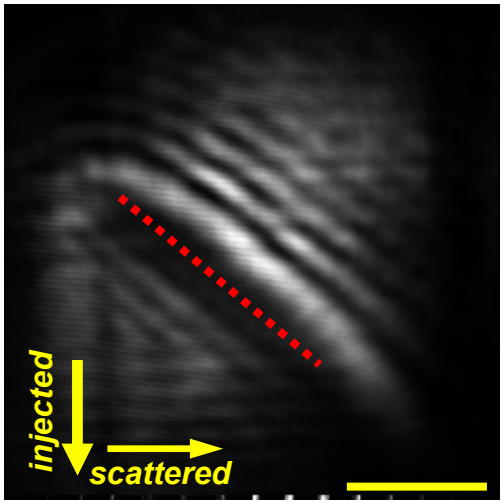
Probe only
No control



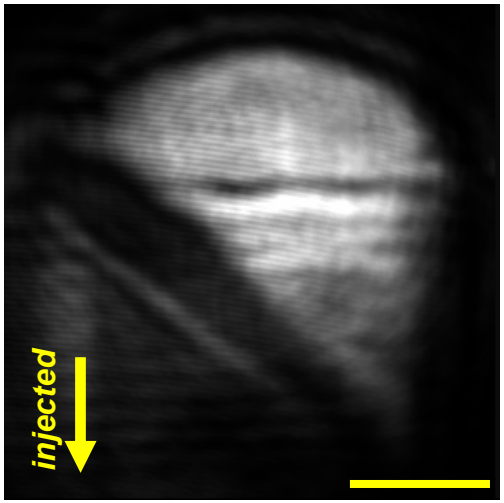
Probe +
Linear control



Probe +
Diagonal control



SUPERFLUID REGIME



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

Conclusion and perspectives

- Coupling light with matter produces quantum optical effects
  - Squeezed light and correlations generated
  - Ultrafast switch and gate
  - Perspective: Quantum operation
- Polariton Quantum Fluids
  - Superfluidity
  - Čerenkov regime
  - Solitons and vortices
  - Optical lattices

Quantum fluids in microcavities - LKB

A. Bramati, Q. Glorieux

R. Hivet, T. Boulier, E. Cancellieri

A. Amo, M. Romanelli, C. Leyder, A. Baas, J.-Ph. Karr, H. Eleuch, J. Lefrère, C. Adrados, V. Sala

Collaborations

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A. Lemaître & J. Bloch, A. Amo *LPN*, CNRS

T. Liew & A. Kavokin, University of Southampton

C. Ciuti, S. Pigeon MPQ, University Paris 7

I. Carusotto, University of Trento, Italy

D. Sanvitto, D. Ballarini, LLN, Lecce, Italy