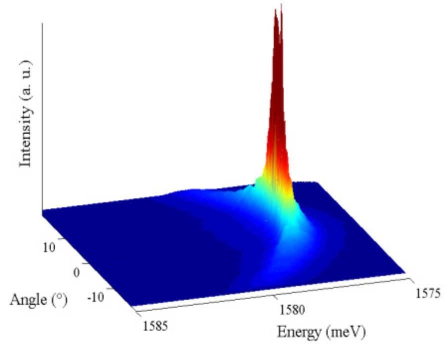
QUANTUM FLUIDS IN SEMICONDUCTOR MICROCAVITIES



Jacqueline Bloch

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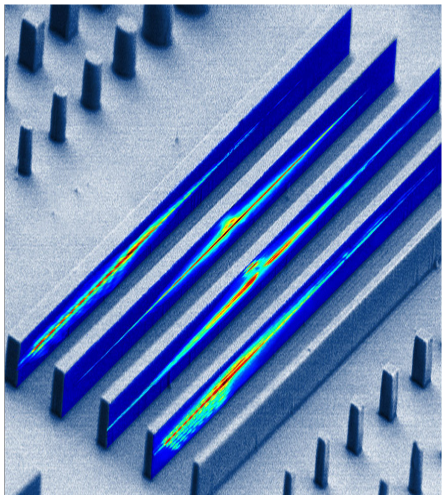
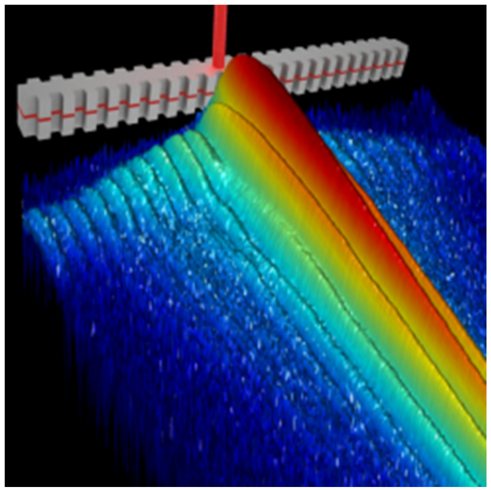
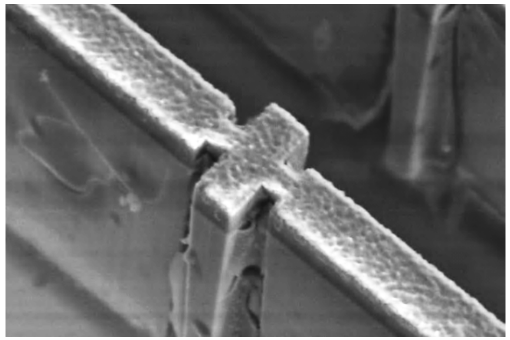
Jacqueline.bloch@lpn.cnrs.fr
http://www.lpn.cnrs.fr/fr/GOSS/CFMC.php



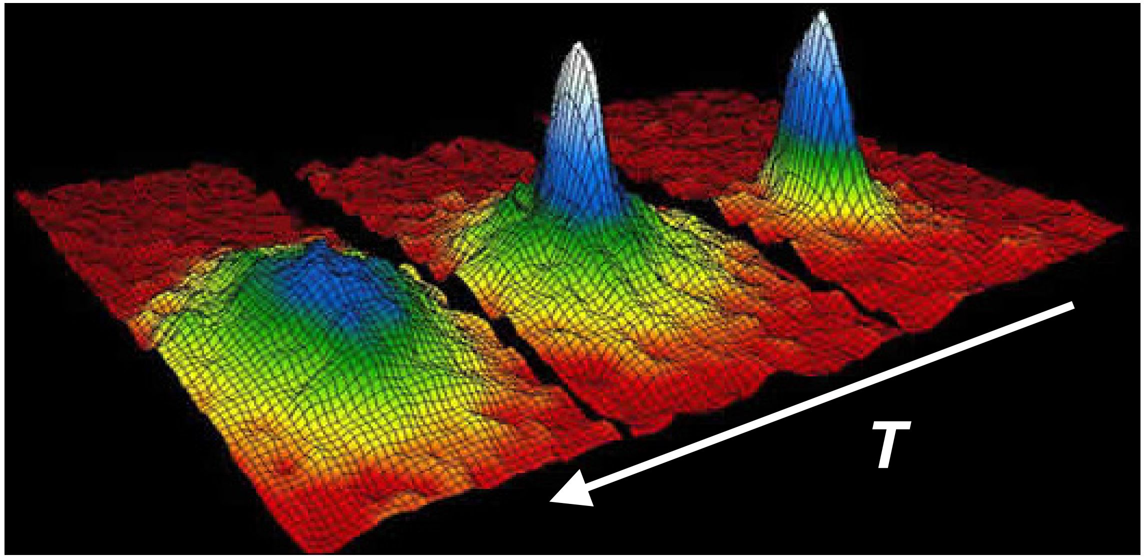




Bose-Einstein condensation

Macroscopic wavefunction

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



http://jilawww.colorado.edu/bec/

Cornell's and Wieman's groups:
condensation of Rb atoms (1995)

BEC with atoms

- Large mass: $m = 10^4\ m_e$

⇓

- Low critical temperatures: < 1 μK
- Large experimental set-ups

BEC in the solid state

- Quasiparticles with $m << m_e$

⇓

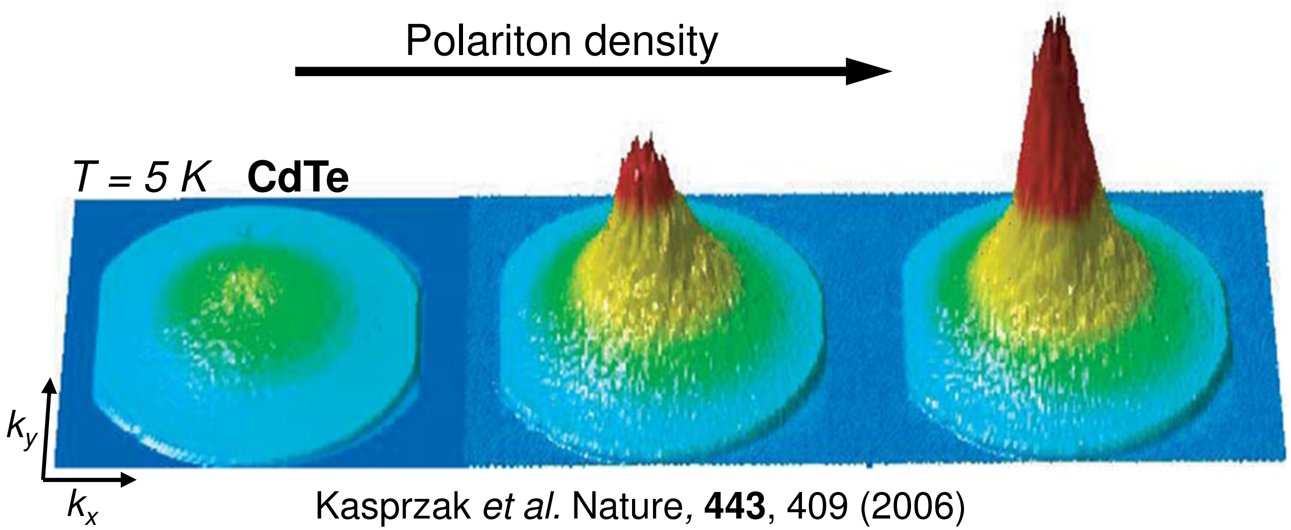
- High critical temperatures: ~10-300 K
- Mixed light-matter particles
  easy creation, control and detection

Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]

T = 10 K

Nature 443, 409 (2006)

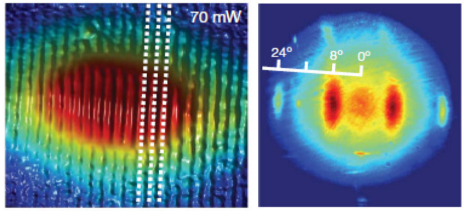


Kasprzak *et al.* Nature, **443**, 409 (2006)

See also LPN, Stanford, Pittsburgh, Cambridge, Southampton …

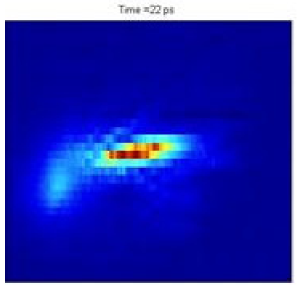
Boson quantum fluids: fundamental properties

Long-range order phases



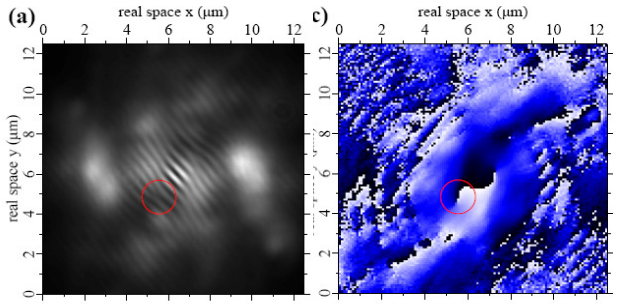
Lai *et al.,* Nature **450**, 529 (2007)
Kim et al. Nature Phys. (2011)

Coherent and frictionless propagation



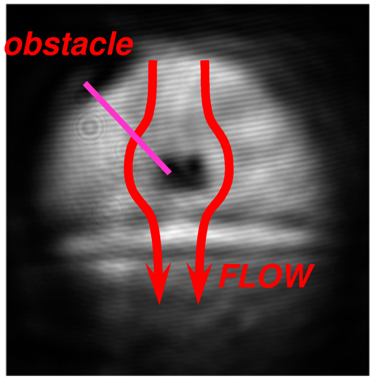
A.Amo, *et al.,* Nature **457**, 295 (2009)

Quantised vortices



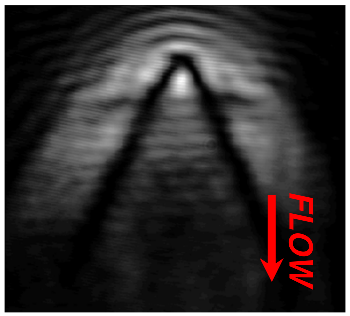
Lagoudakis *et al*., Nature Phys. **4**, 706 (2008),
Lagoudakis *et al*., Science **326**, 974 (2009)
Sanvitto *et al*., Nature Phys. **6**, 527 (2010)
Krizhanovskii *et al*., PRL **104**, 126402 (2010)
Roumpos *et al*., Nature Phys. **7**, 129 (2010)
Nardin *et al*., Nature Phys. **7,** 635 (2011)
Sanvitto *et al.,* Nature Phot. **5**, 610 (2011)

Superfluidity



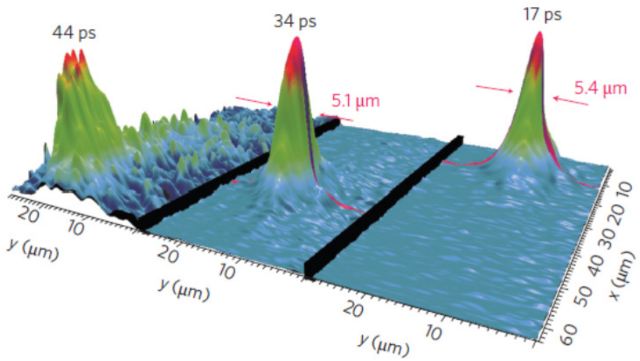
A. Amo *et al.,* Nature Phys. **5**, 805 (2009)

Dark solitons



A. Amo *et al*., Science **332**, 1167 (2011)
R. Hivet et al., Nat. Phys. 8, 724 (2012)

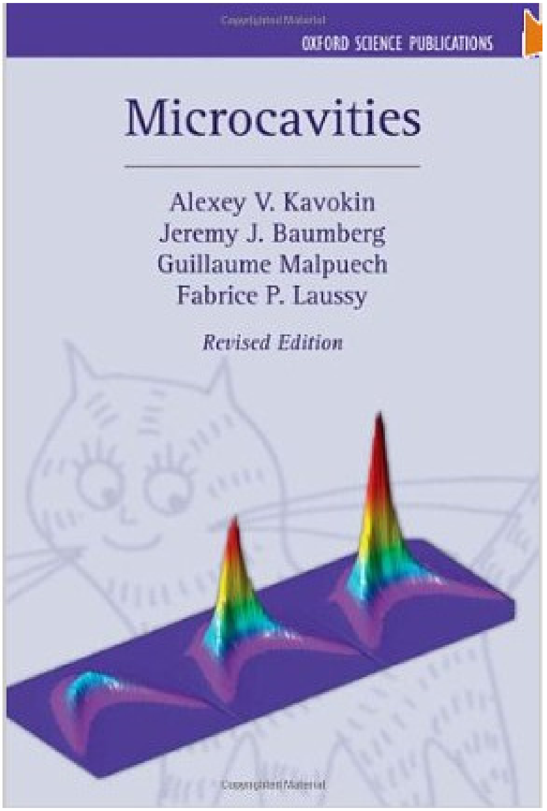
Bright solitons



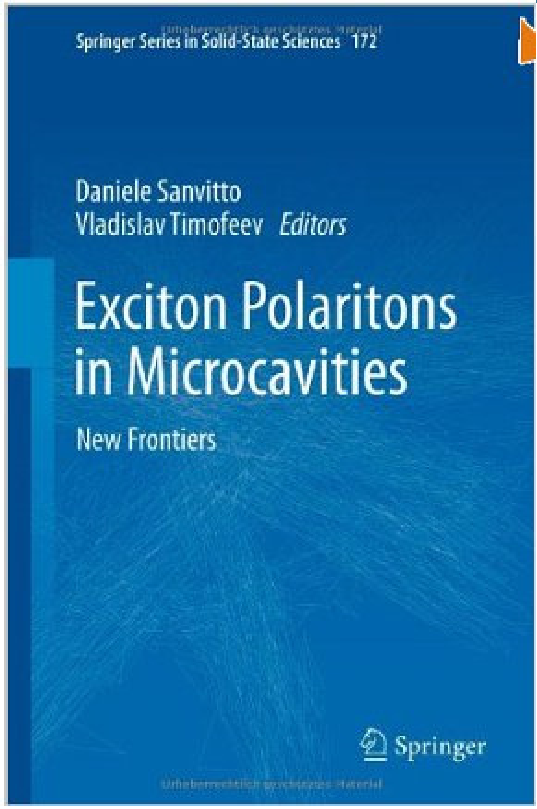
Sich *et al.,* Nature Phot. **6**, 50 (2012)

Recent reviews

2011



2013



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

Quantum fluids of light

Iacopo Carusotto*

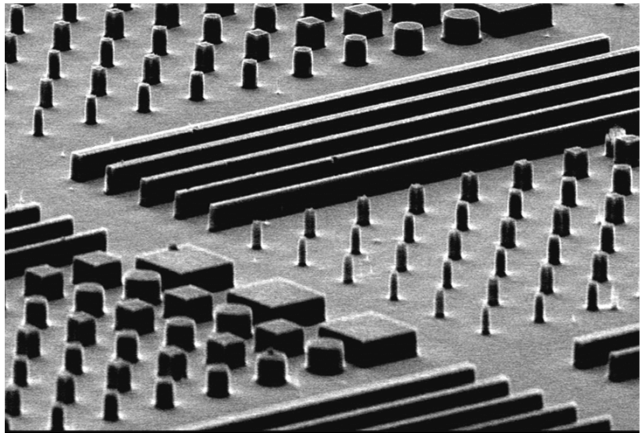
INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy

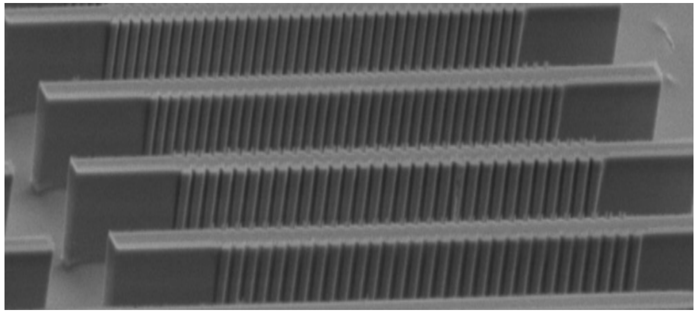
Cristiano Ciuti†

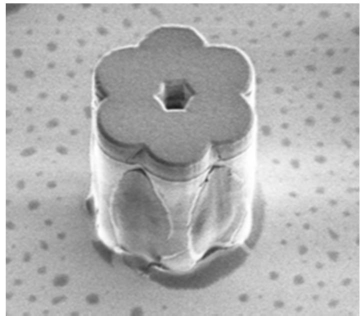
Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot-Paris 7 et CNRS, Bâtiment Condorcet, 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France

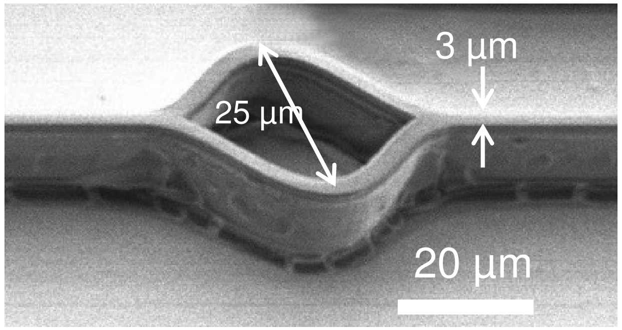
Cavity polariton condensates in microstructures

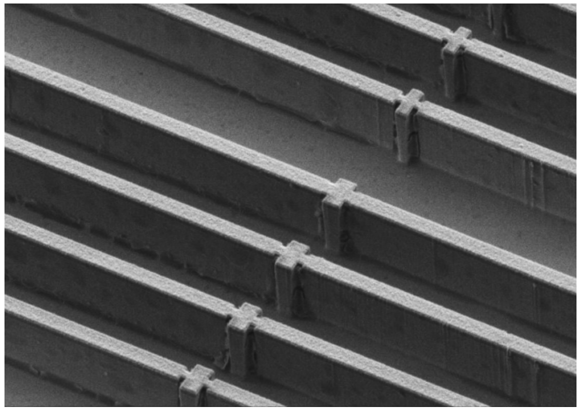
Use of nanotechnology to engineer the potential landscape: Toward Polaritonic circuits





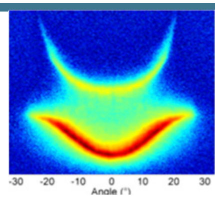




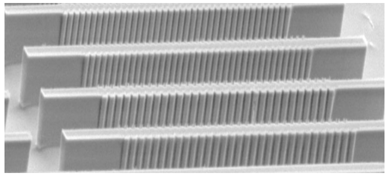


Outline

1. Introduction to cavity polaritons



2. Polariton condensation in 1D microstructures

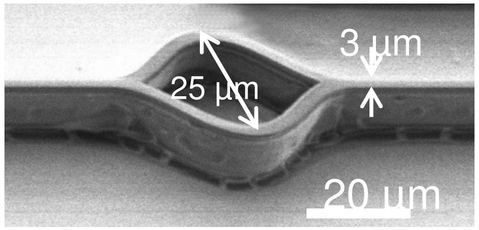


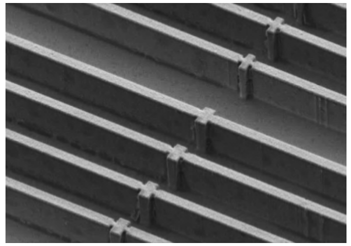
Extended spatial coherence,

Optical manipulation, strong non-linearities

3. Toward polariton devices

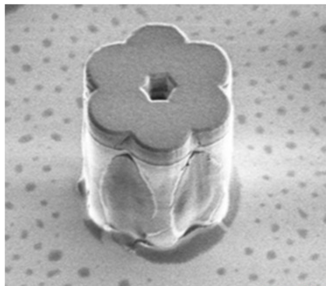
- *Polariton interferometer*
- *Resonant tunneling diode*

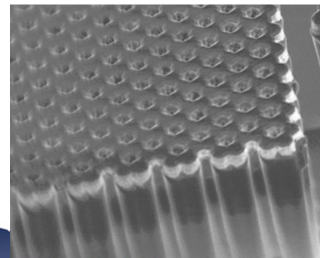




4. Coupled 0D polaritons

Benzene molecule, Honeycomb lattice





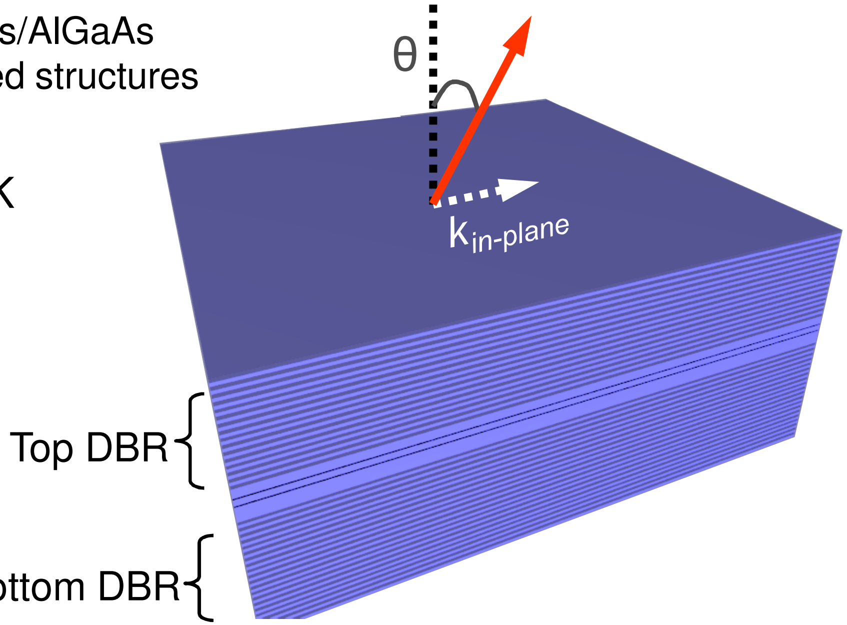
Conclusion and Perspectives

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

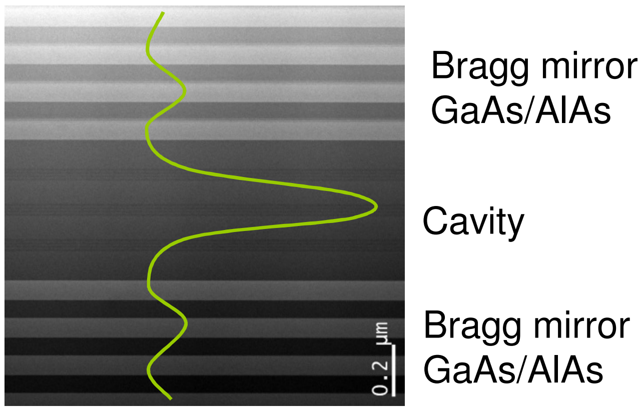
Microcavity polaritons

GaAs/AlGaAs based structures

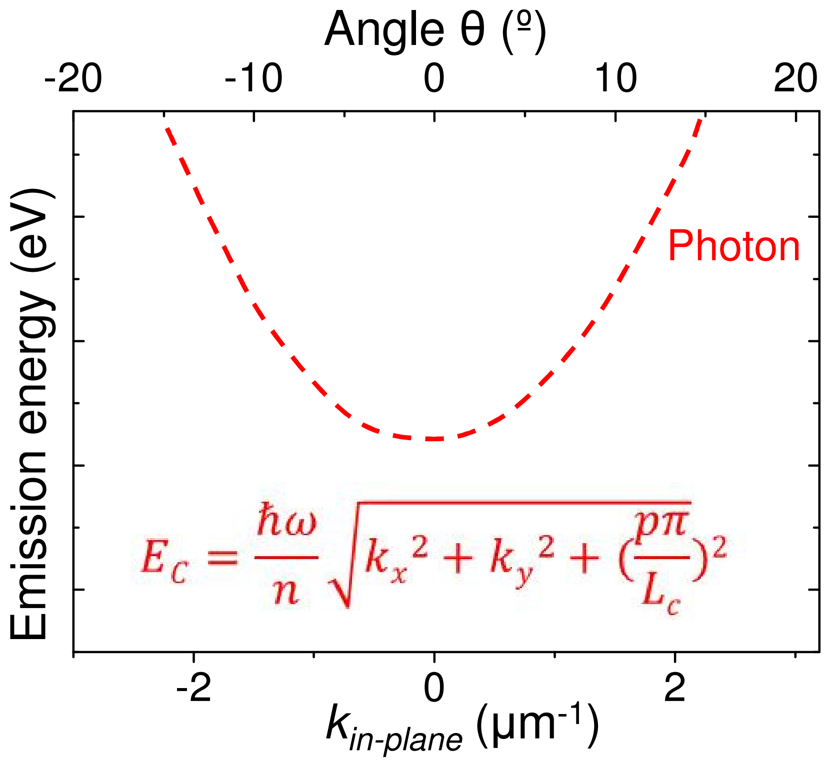
5 K



Optical cavity



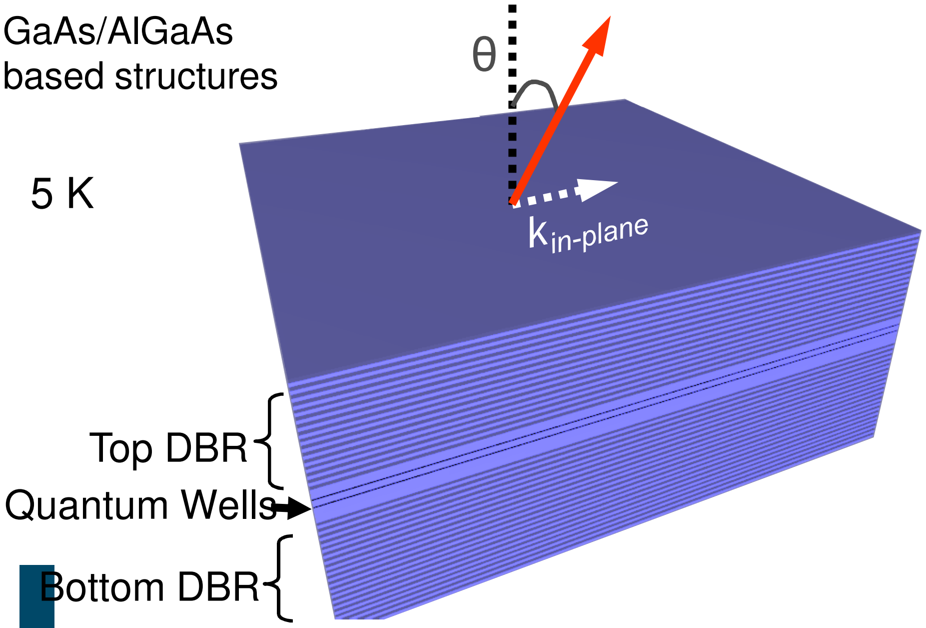
TEM, G. Patriarche, LPN

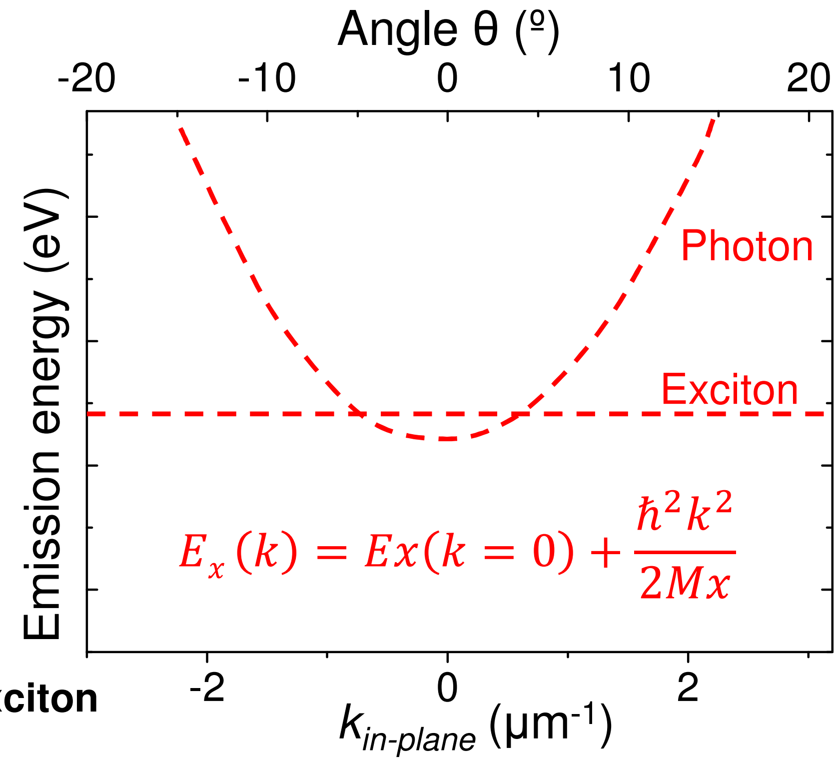


Microcavity polaritons

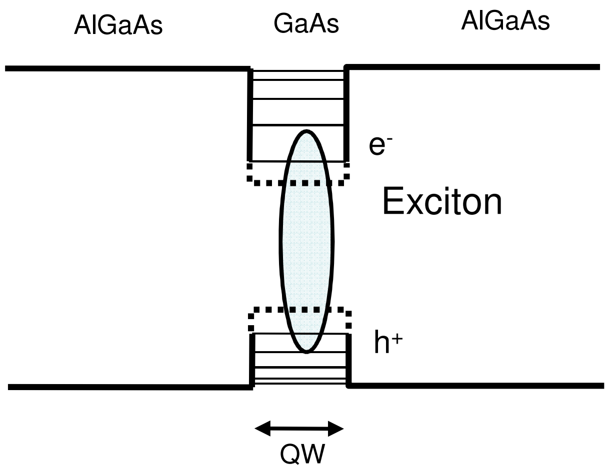
GaAs/AlGaAs based structures

5 K





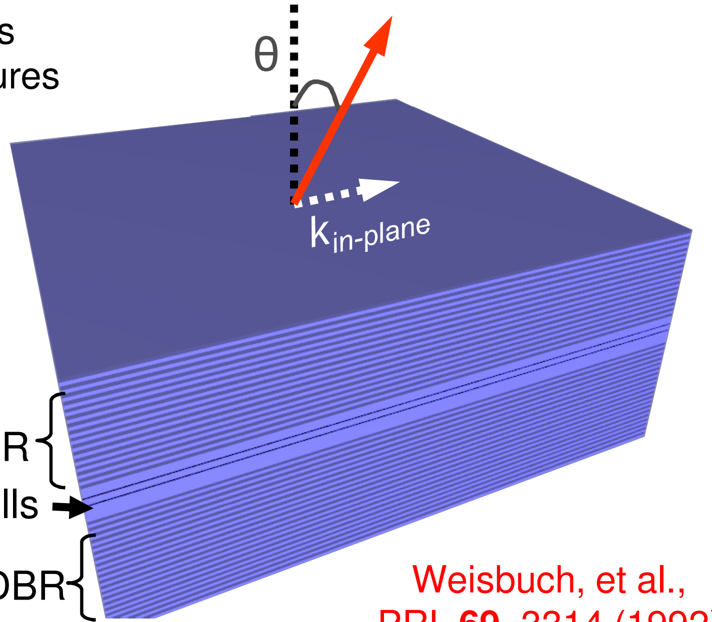
Quantum well exciton



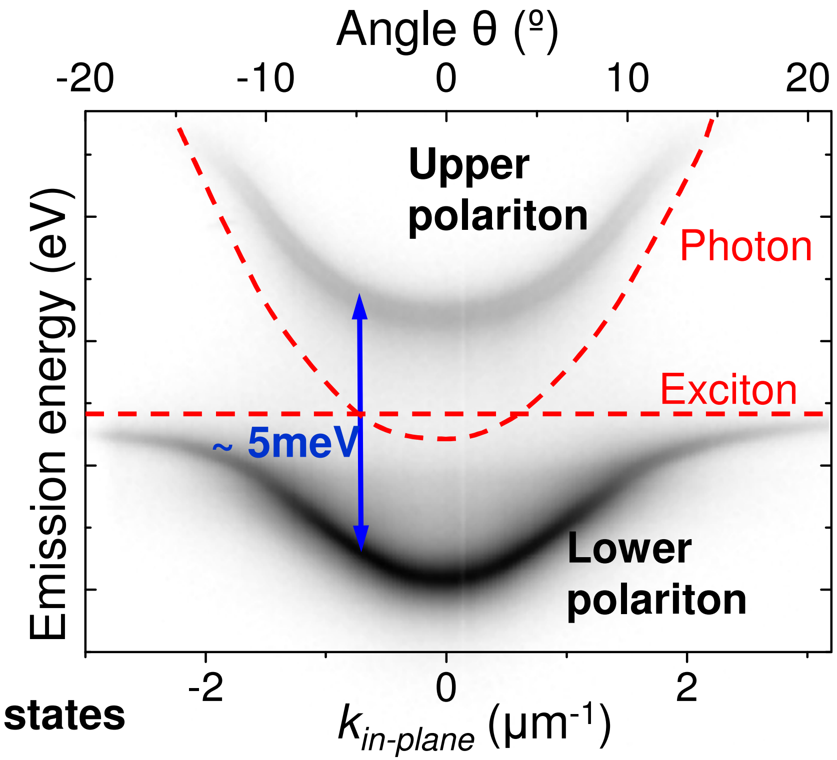
Microcavity polaritons

GaAs/AlGaAs based structures

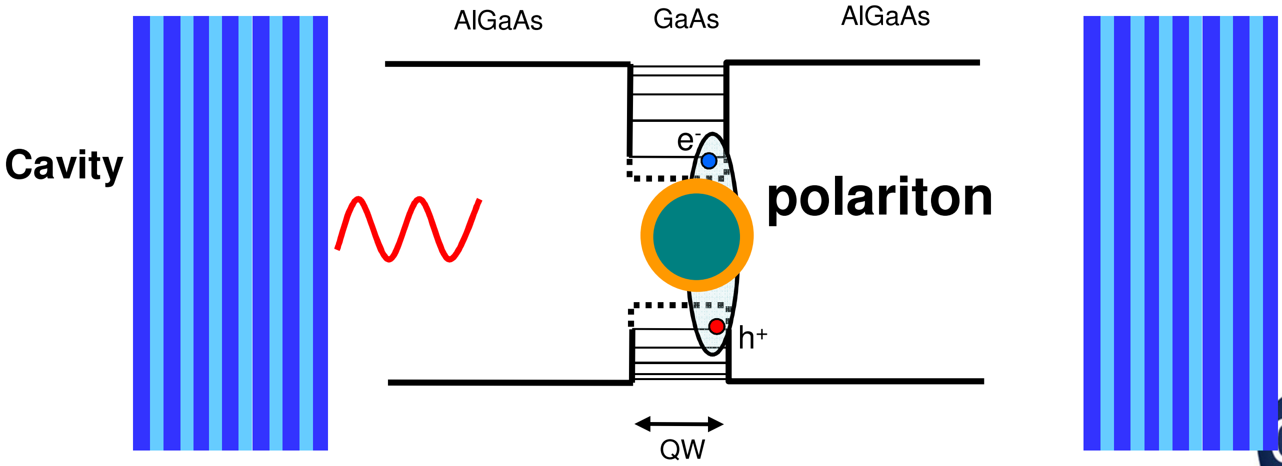
5 K



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



Microcavity polaritons : mixed exciton-photon states

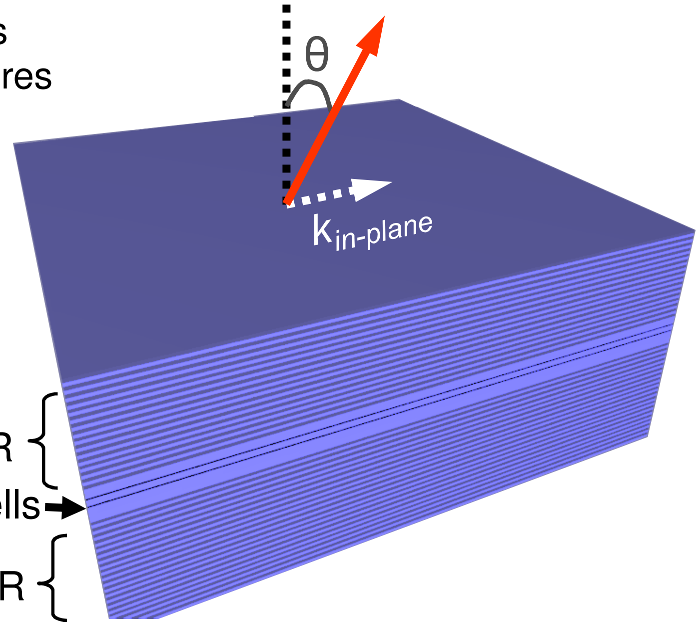


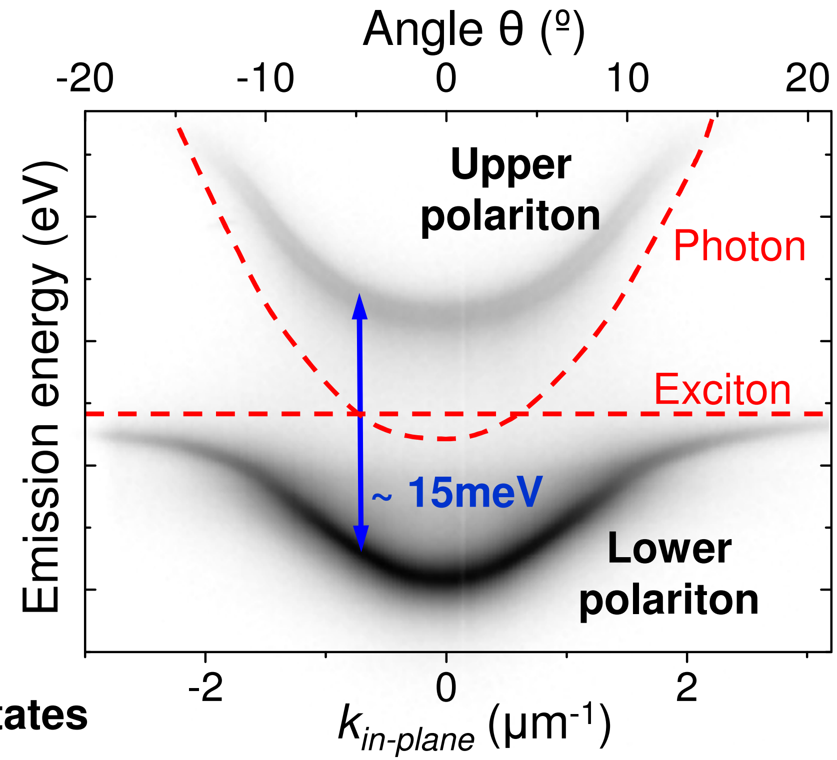
Courtesy D.Sanvitto

Microcavity polaritons

GaAs/AlGaAs based structures

5 K





Microcavity polaritons : mixed exciton-photon states

Properties

$$|pol\rangle = X_k |exc\rangle + C_k |phot\rangle$$

- Bosons
- Photonic component ➡ **low mass (10^{-5} m_e)**
  condensation at high temperature
- Short lifetime (~1-50 ps) ➡ **escape out of the cavity**
  optical access
- **Excitonic component ➡ repulsive interactions**

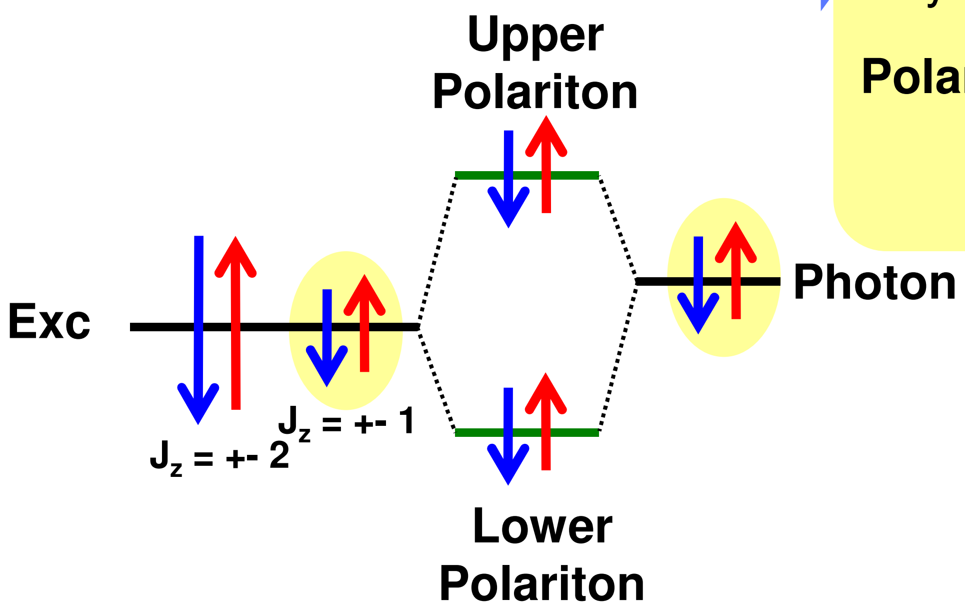
Polariton spin

- Spin : electron : +- ½
  heavy hole : +- 3/2

Exciton : J_z = +- 1 e↑⬇h e↓⬆h

J_z =+- 2 e↑⬆h e↓⬇h

- Photon have an angular momentum : +- 1



- Only J=1 excitons are coupled to light

Polaritons have two spin projections:

$$\left.\begin{array}{ll} \mathbf{j_z = +1} & \sigma+ \\ \mathbf{j_z = -1} & \sigma- \end{array}\right\} \tfrac{1}{2} \text{ pseudospin}$$

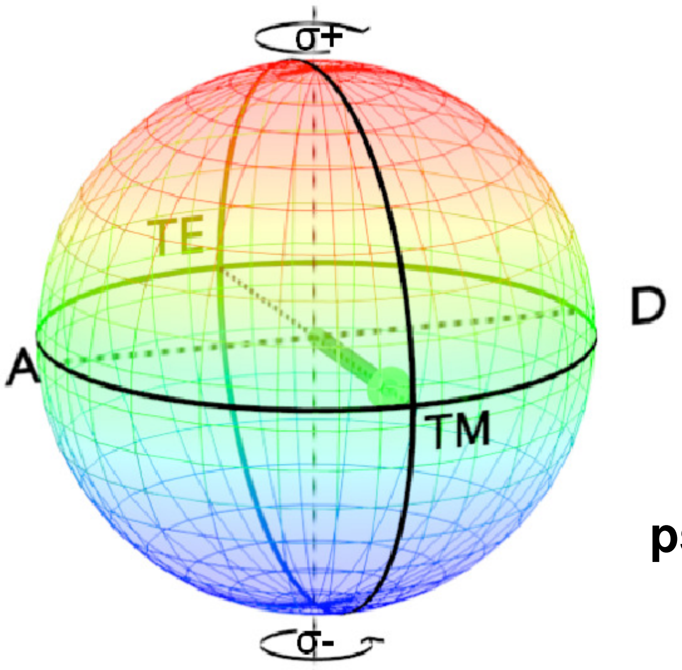
Polariton spin

- Spin : electron : +- ½
  heavy hole : +- 3/2

Exciton : J_z = +- 1 $e \uparrow \Downarrow h$ $e \downarrow \Uparrow h$

J_z =+- 2 $e \uparrow \Uparrow h$ $e \downarrow \Downarrow h$

- Photon have an angular momentum : +- 1



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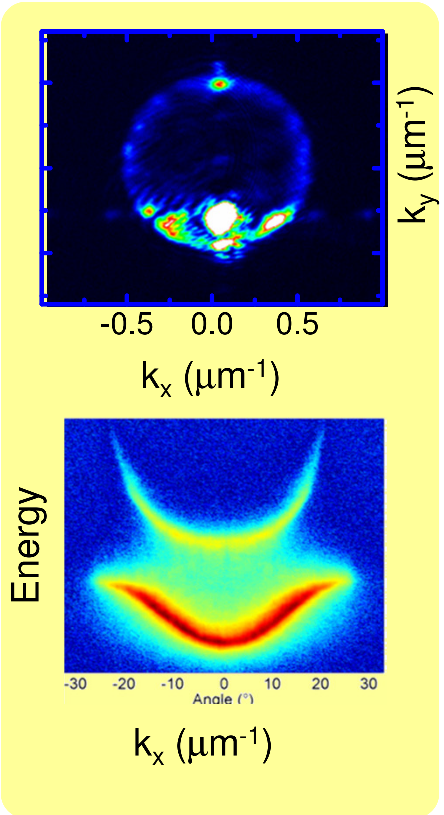
$$\left.\begin{array}{ll} \mathbf{j_z = +1} & \sigma+ \\ \mathbf{j_z = -1} & \sigma- \end{array}\right\} \tfrac{1}{2} \text{ pseudospin}$$

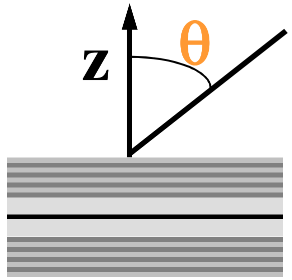
One-to-one relationship between pseudospin state and polarisation degree

Probing polariton states

Far field imaging: k space

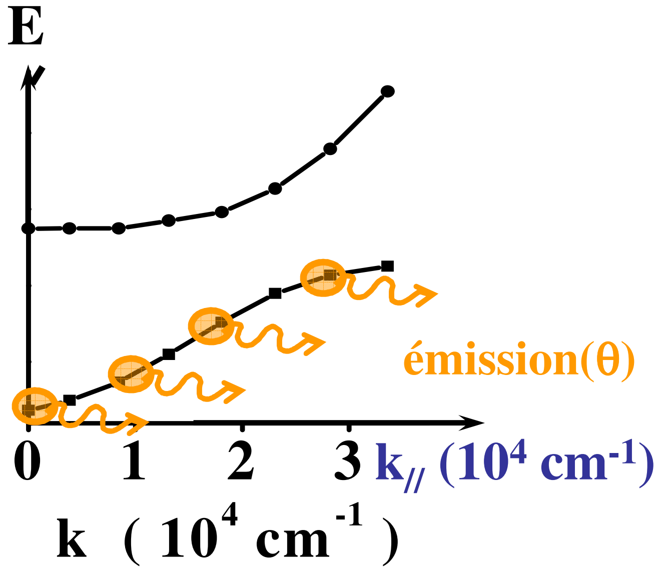


R. Houdré et al., Phys. Rev. Lett. **73**, 2043 (1994)



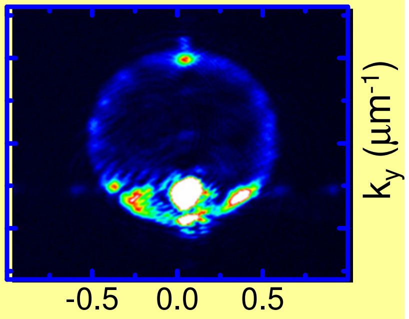
$\theta \Longleftrightarrow k_{//}$

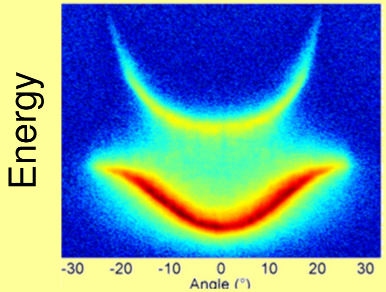
$$k_{//} = \omega/c \sin(\theta)$$



Probing polariton states

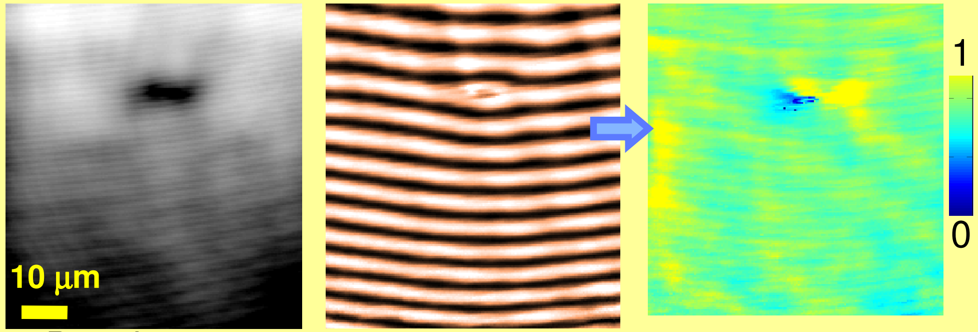
Far field imaging: k space





R. Houdré et al., Phys. Rev. Lett. **73**, 2043 (1994)

Real space imaging

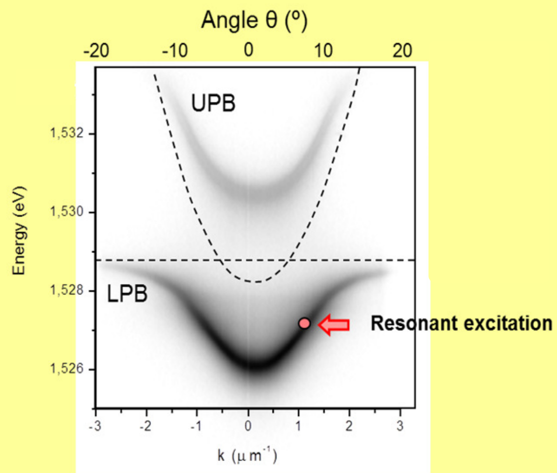


Density

Interference with a reference beam

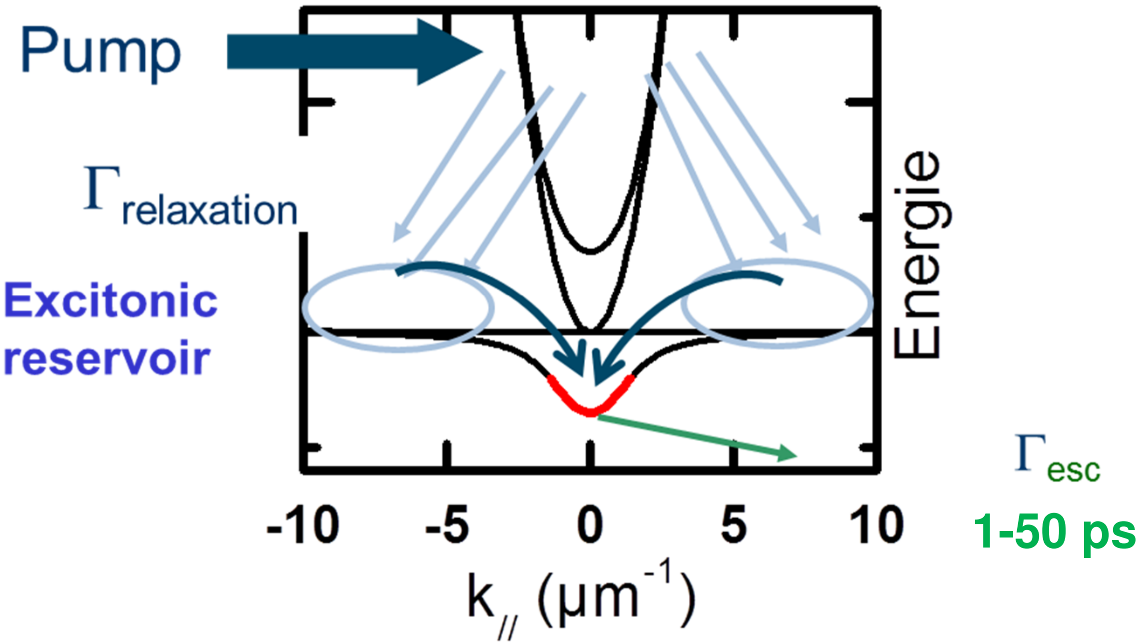
Coherence map $g^{(1)}$

Phase dislocations
- vortices
- solitons

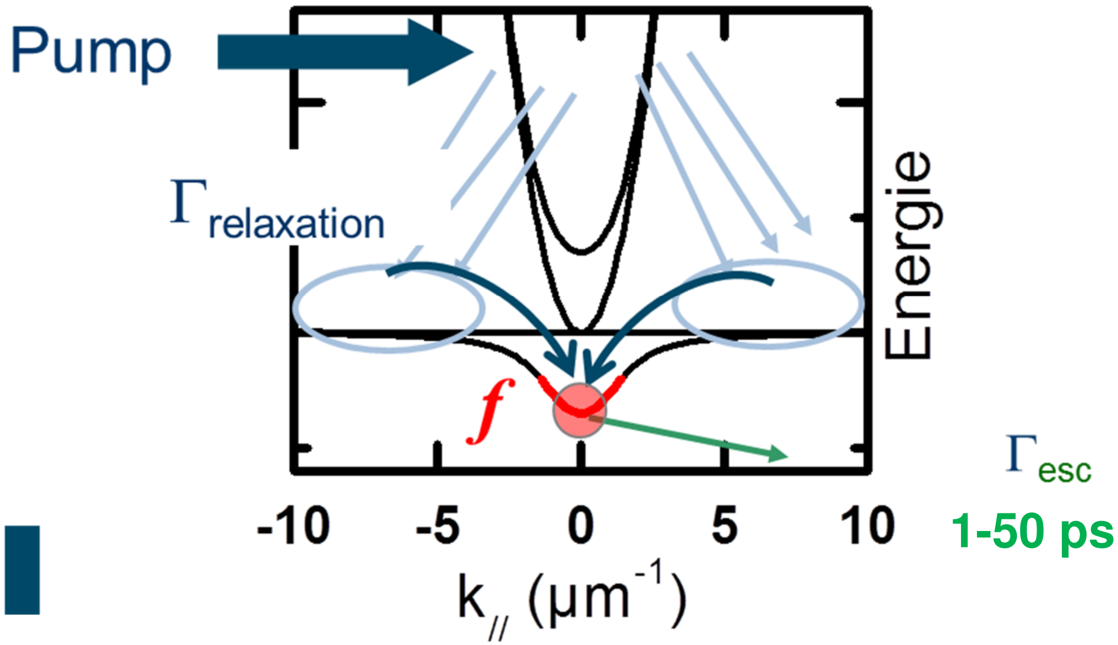


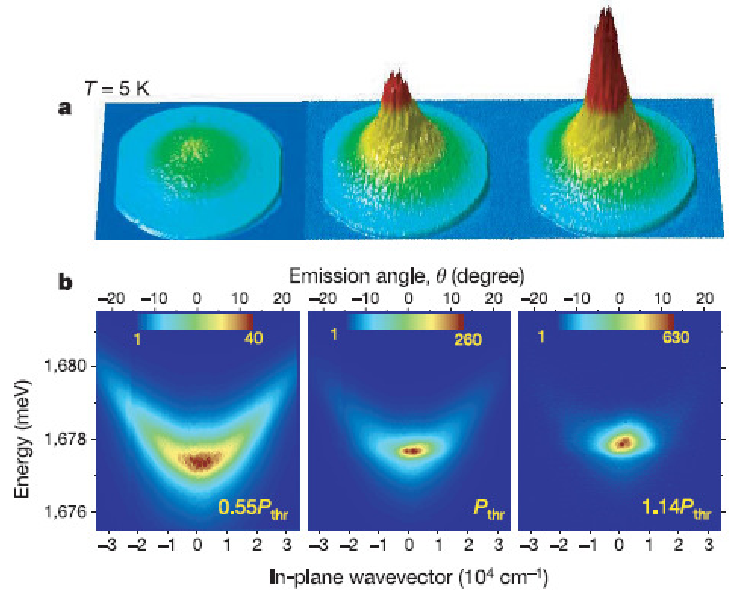
Resonant injection of polaritons

Polariton condensation under non resonant excitation



Polariton condensation under non resonant excitation





Nature 443, 409 (2006)

When f exceeds unity : $\Gamma_{relaxation} \propto (f+1)$ Bosonic stimulation

Massive occupation of the lowest energy states

- Out of equilibrium system
- Coexistence of the polariton condensate with the reservoir of uncondensed exciton

Ginzburg Landau equation for the polariton wavefunction

Polariton wavefunction:

Kinetic energy

Confinement potential

Interactions with the excitonic reservoir

$$i\hbar\frac{\partial\psi(x,t)}{\partial t}=\left\{-\frac{\hbar^2\nabla^2}{2m^*}+V_{ext}(x)-i\frac{\hbar}{2}\left[\gamma_C-Rn_R(x,t)\right]+g_C\left|\psi(x,t)\right|^2+g_R n_R(x,t)\right\}\psi(x,t)$$

Decay

Populating term

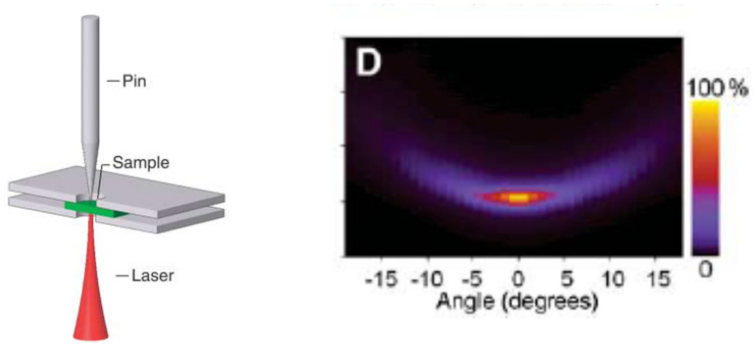
Interactions within the condensate

Excitonic reservoir

$$\frac{dn_R(x,t)}{dt}=P_{pump}(x,t)-\frac{n_R(x,t)}{\tau_{rad}}-Rn_R(x,t)$$

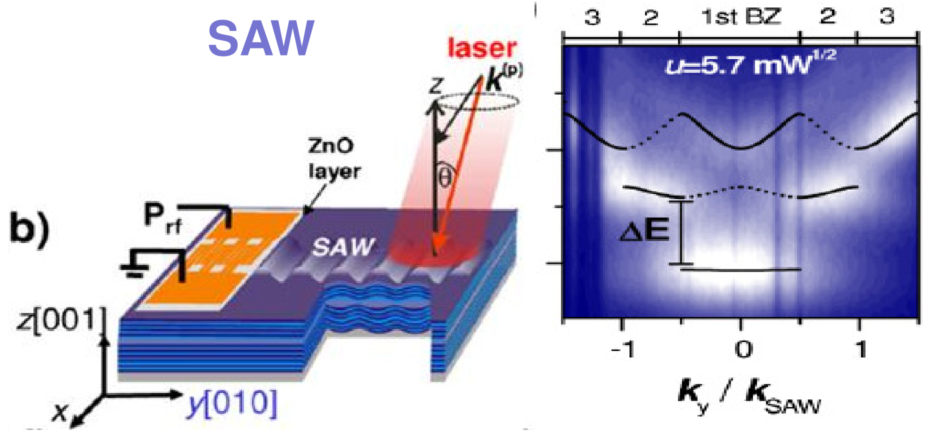
Confining polaritons in lower dimension

Strain with a tip



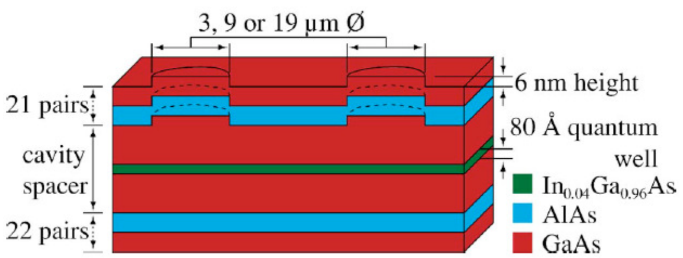
R. Balili *Science 2007*

SAW



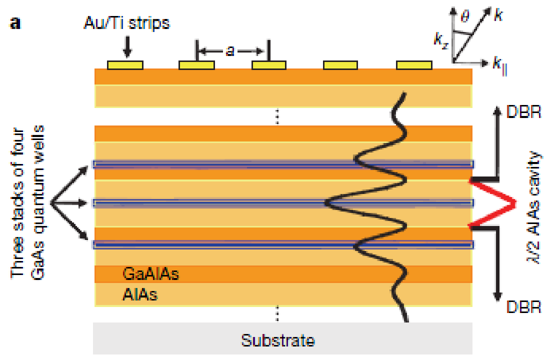
E. A. Cerda-Méndez, PRL (2010).

Engeering of the cavity



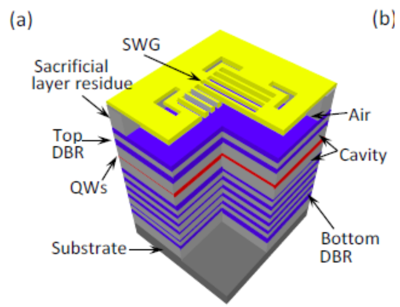
O. El Daïf *APL 2006*

Engeering of the top mirror



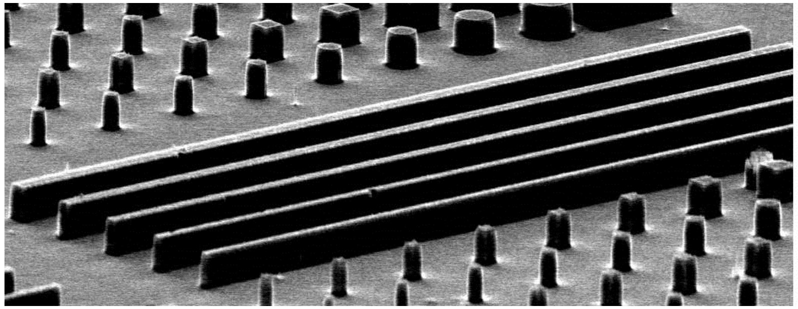
Lai et al., Nature **450**, 529 (2007)

Kim et al., Nature Phys. 7, 681 (2011)

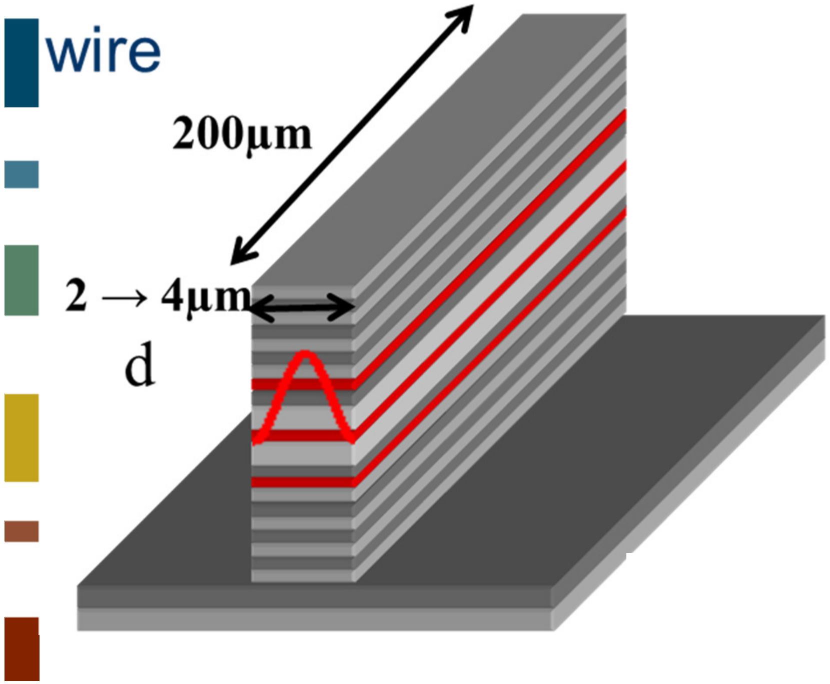


Bo Zhang et al., et al. arXiv:1304.2061

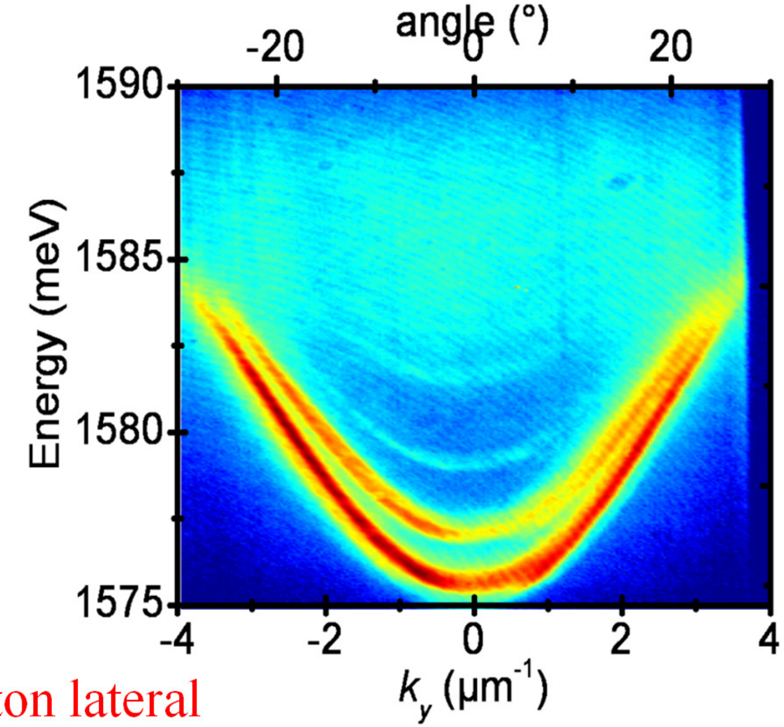
Polariton in 1D cavities



Fabrication : *E-beam lithography*
Reactive Etching(RIE or ICP)



1D polariton sub-bands



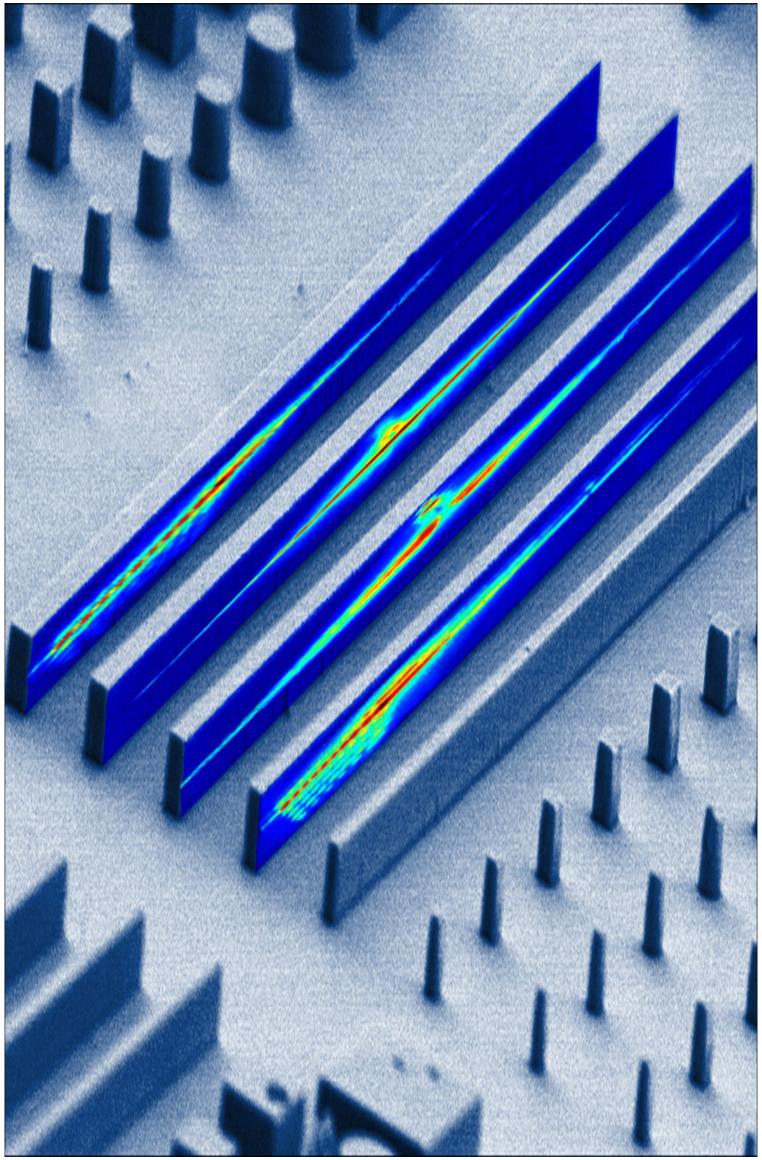
Polariton lateral confinement

Discretisation of k_x:

$$k_x = n\pi/d$$
$$n = 1,2,3,\ldots$$

J. Bloch et al.. *Superlatt. and Microst.* **22**, 371 (1998).
T. Gutbrod et al. *Phys. Rev. B* **57**, 950 (1998).
A. Kuther et al., *Phys. Rev. B* **58**, 15744 (1998)

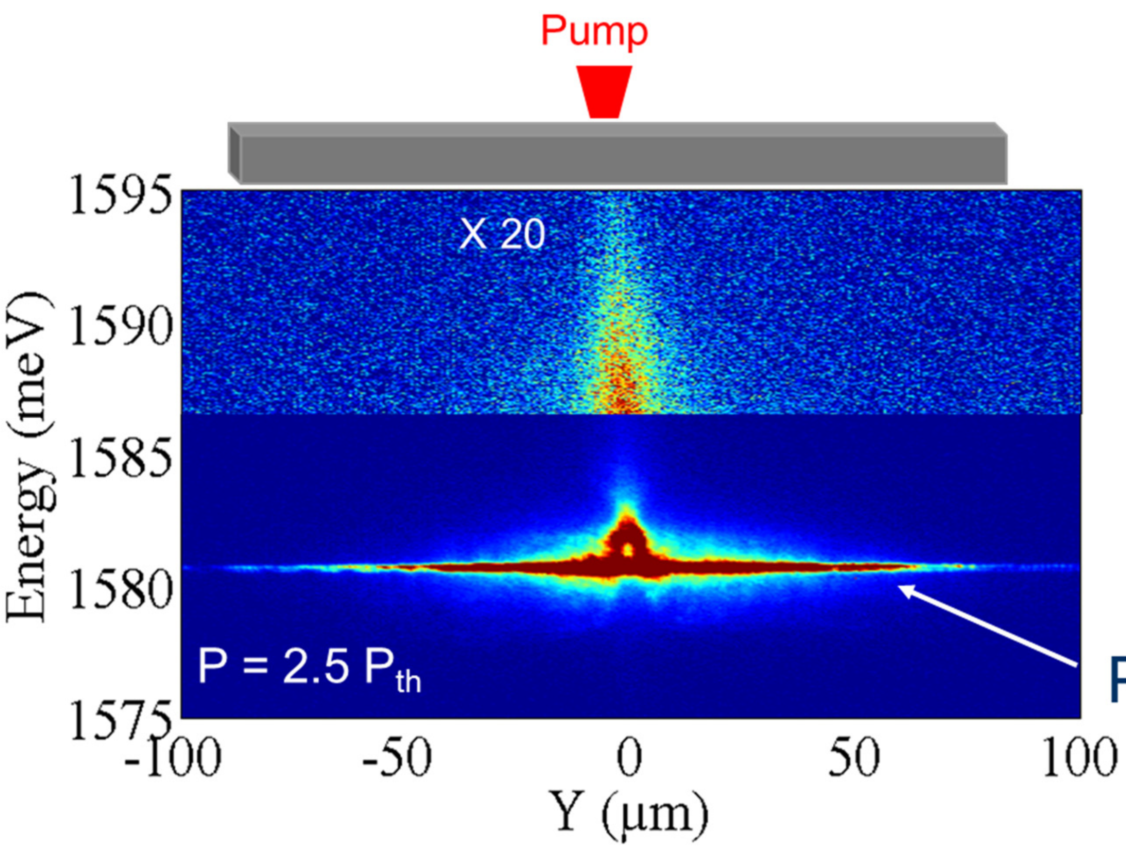
Condensation in 1D microcavities

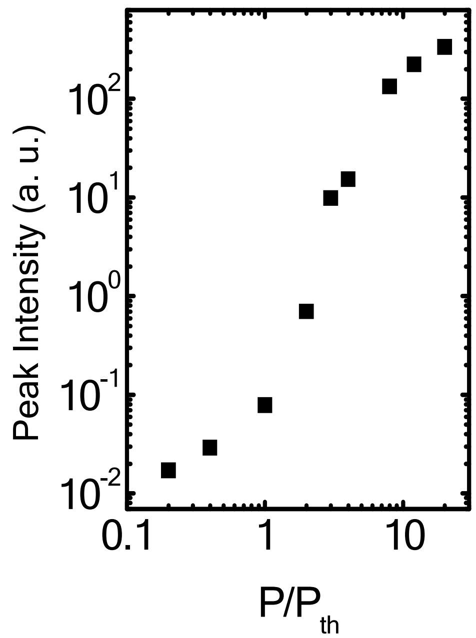


E. Wertz et al., **Nat. Phys. 6**, 860 (2010)
L. Ferrier et al., **Phys. Rev. Lett**. 106, 126401 (2011)
D. Tanese et al., **Phys. Rev. Lett.** 108, 36405 (2012)
E. Wertz et al., **Phys. Rev. Lett.** 109, 216404 (2012)
D. Tanese et al., **Nat. Commun**. 4, 1749 (2013)

Macroscopic speading of polariton condensates

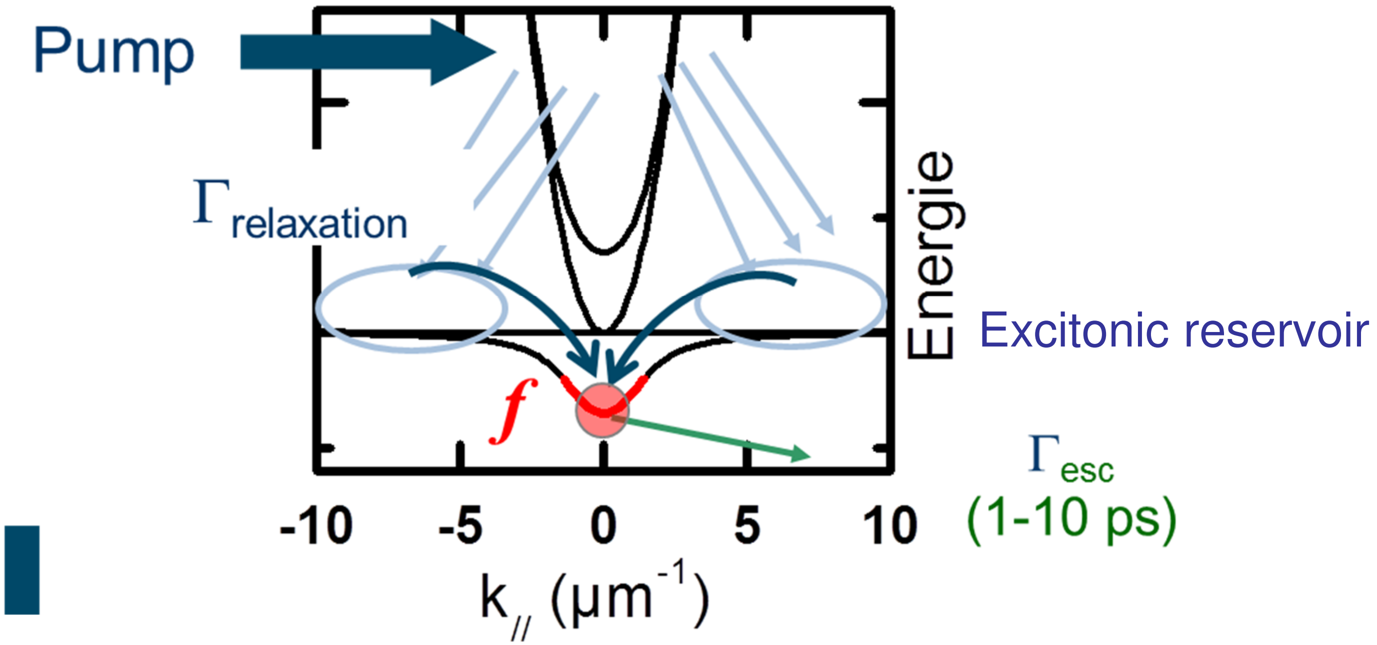
T = 10 K



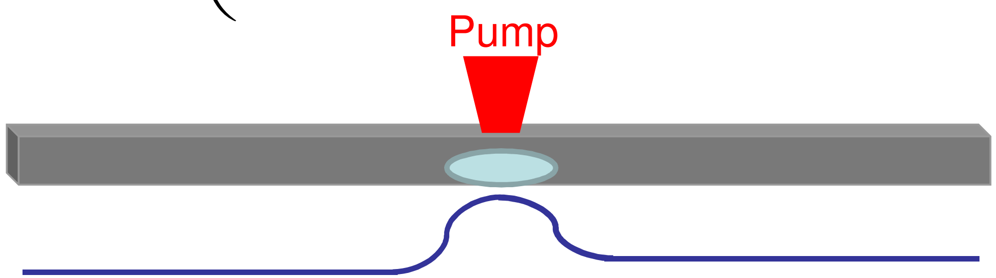


E. Wertz et al., Nature Physics **6**, 860 (2010)

Macroscopic speading of polariton condensates

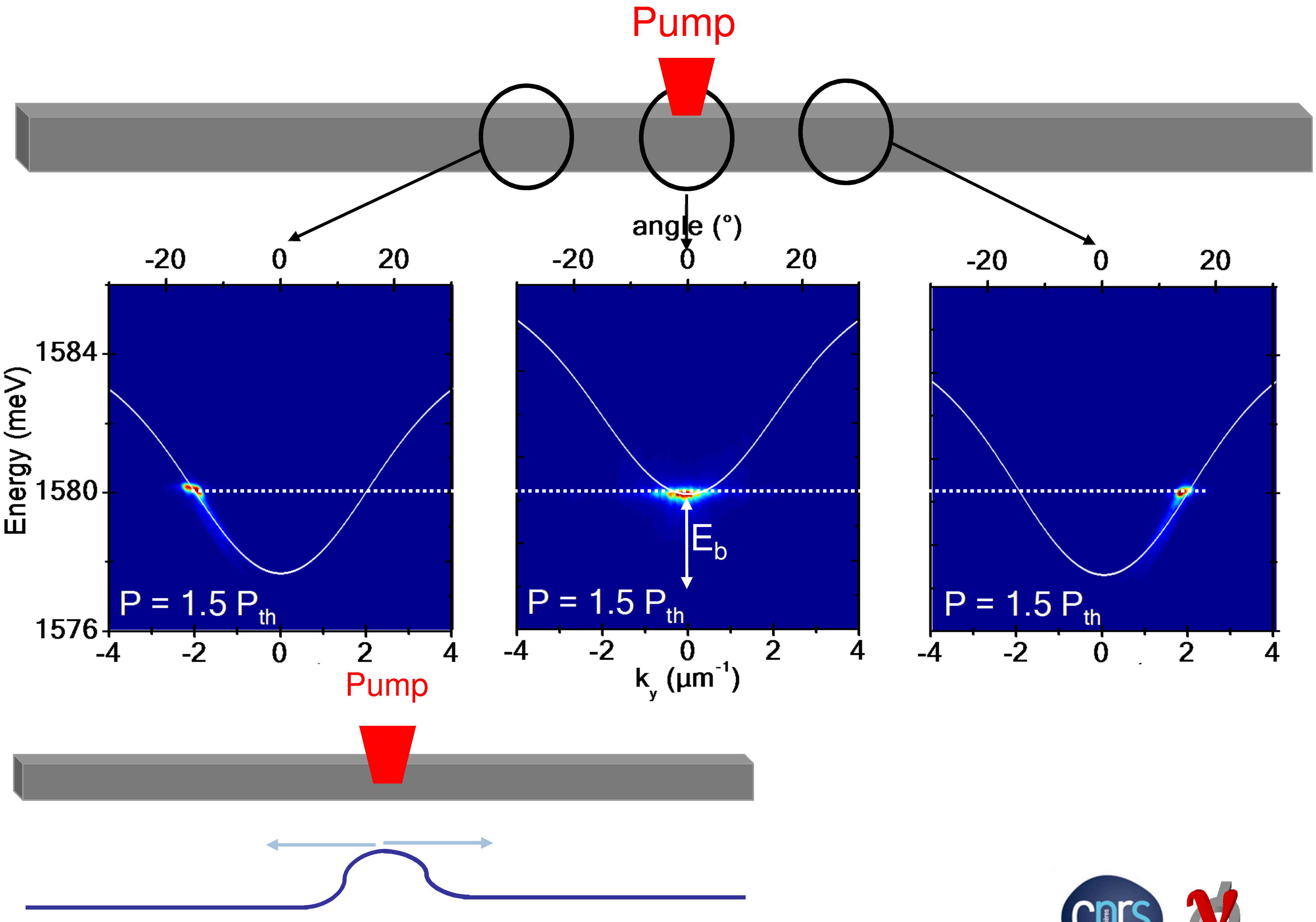


$$\left(-\frac{\hbar^2\nabla^2}{2m}+V_{ext}(r)+g_{res}n_{Res}(r)\right)\psi(r)=\mu\psi(r)$$



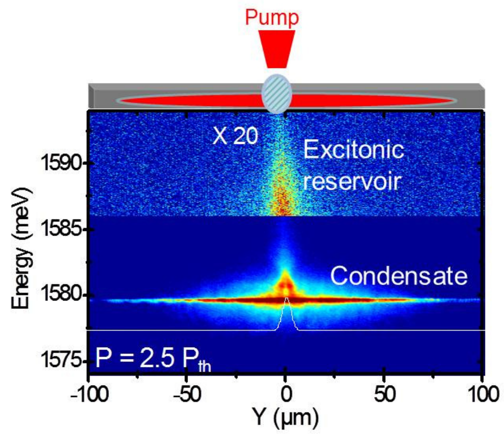
Local blueshift

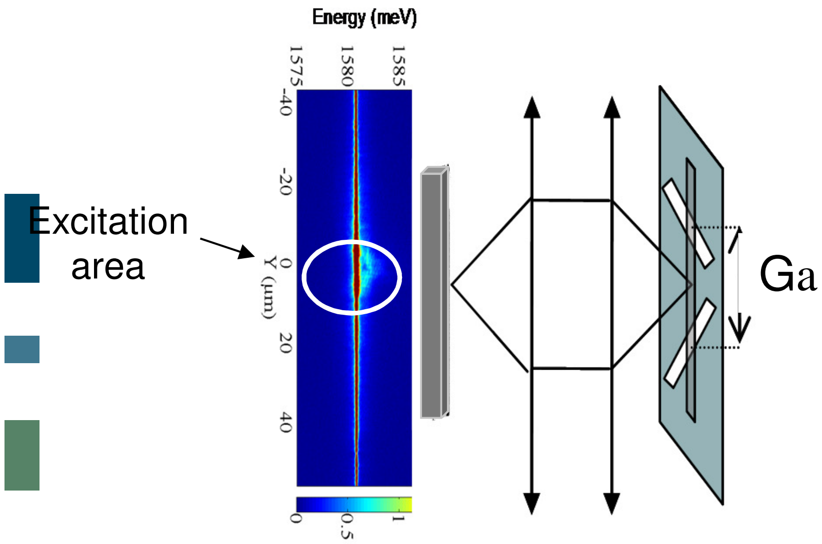
Polariton condensation in 1D cavities

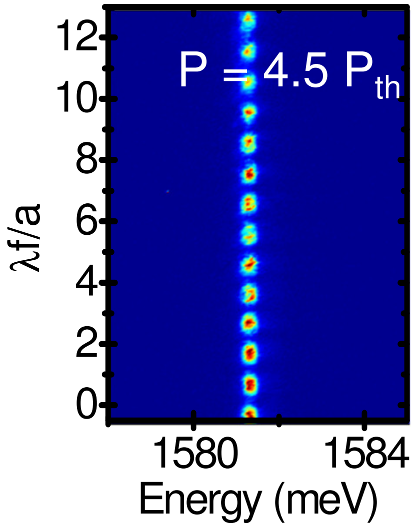


Probing the condensate spatial coherence

Young slit interferometry
(see F. Dubin et al., Nature Physics 2, 32 (2005)
H. Deng, Phys. Rev. Lett. 99, 126403, (2007))



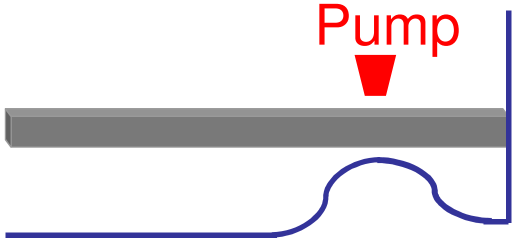


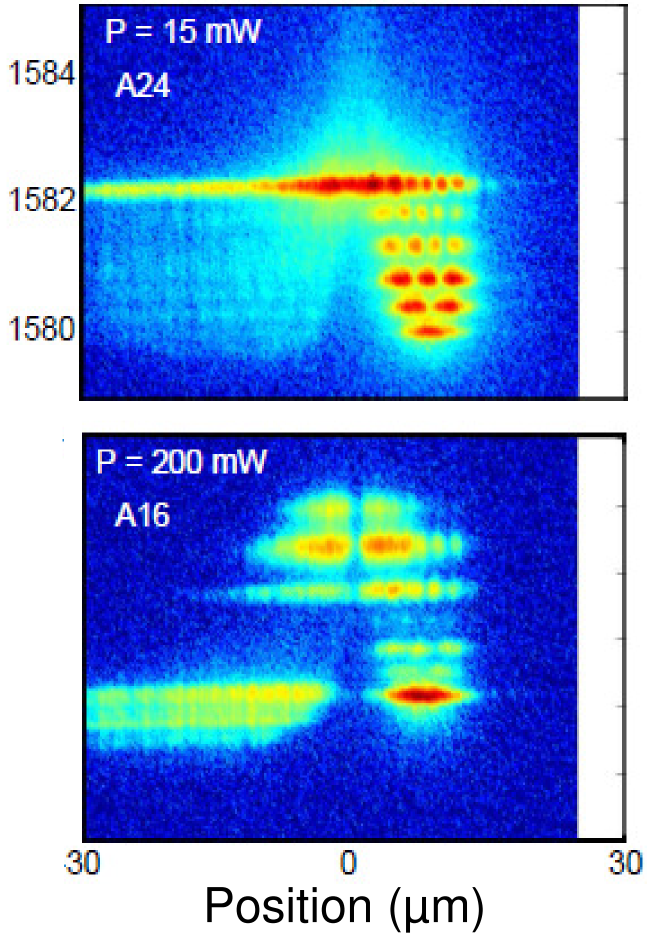


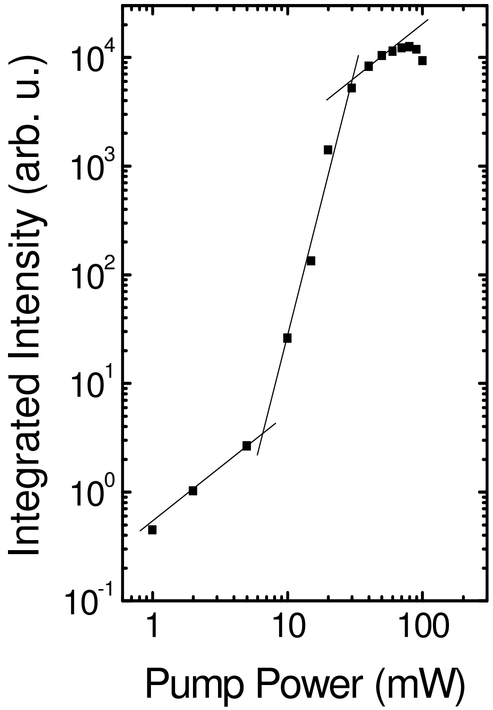
Spatial coherence over more than 200 µm (entire wire sample)

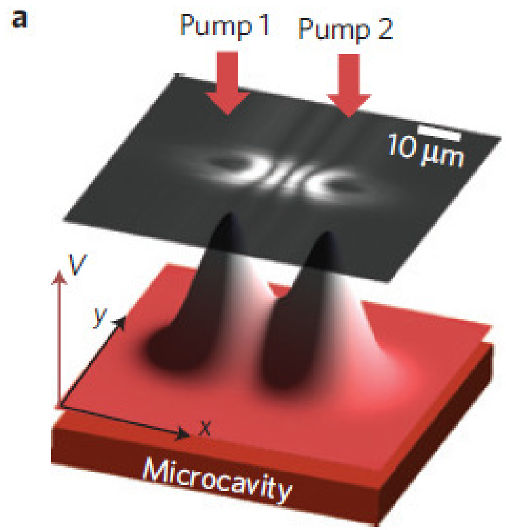
E. Wertz et al., Nature Physics **6**, 860 (2010)

Trapping polaritons optically







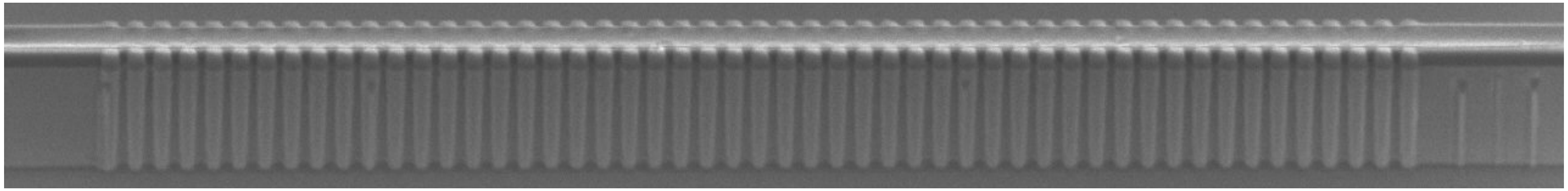


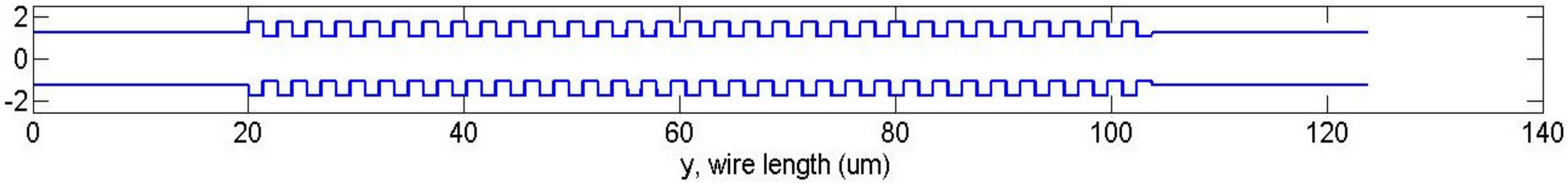
G. Tosi et al., Nature Phys. **8**, 190 (2012)
A. Amo, *Phys. Rev. B* **82**, 081301 (2010).

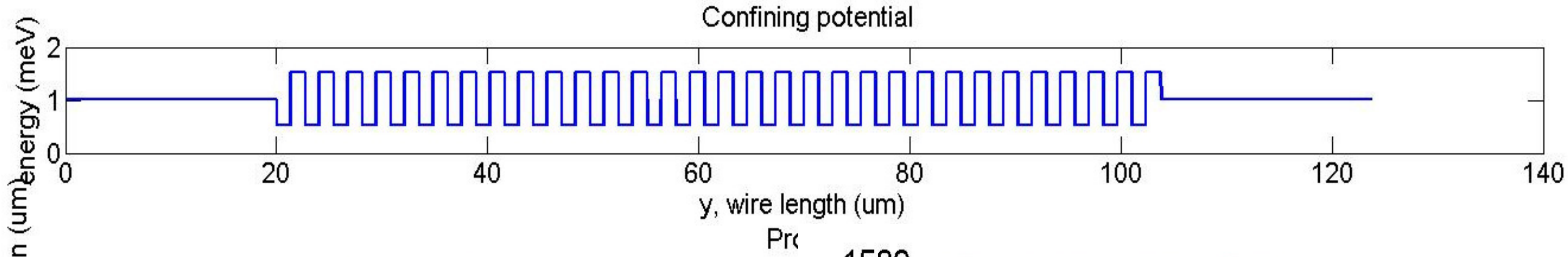
$N_{\text{polaritons}} \approx$ few 1000

L. Ferrier et al., Phys. Rev. Lett. 106, 126401 (2011)

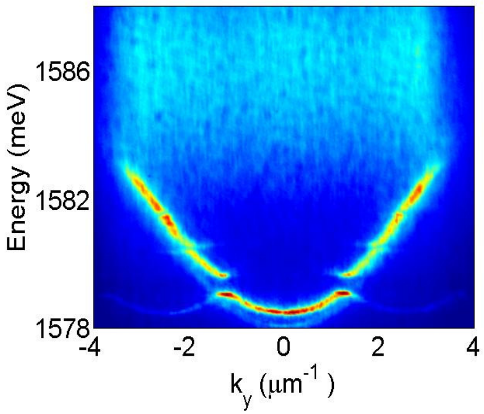
Condensation in a periodic potential

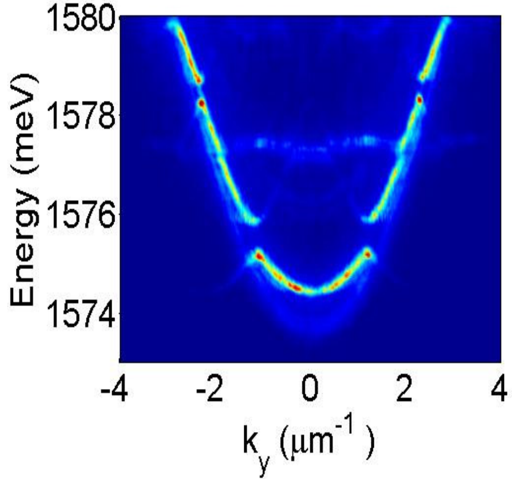






Period = 2.1 µm

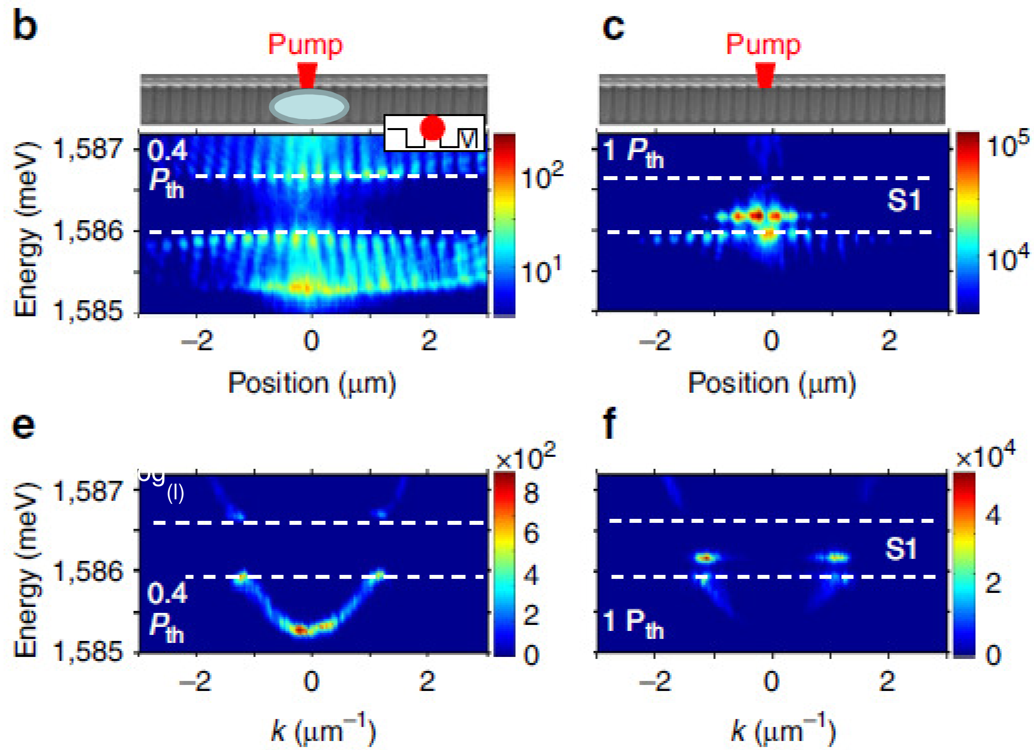




Period = 2.7 µm

Condensation in a periodic potential

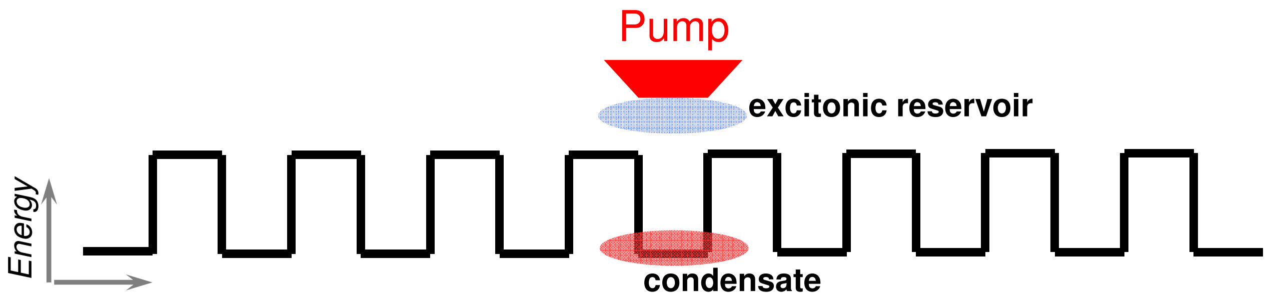
cw non resonant excitation



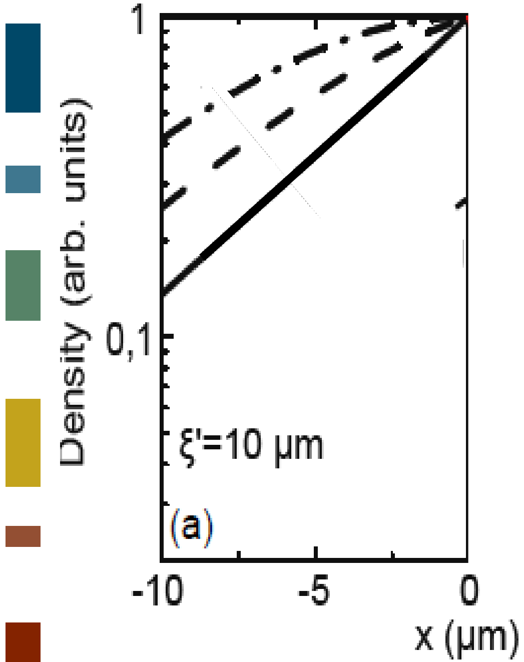
Condensation in a highly localized gap state

D. Tanese et al., Nat. Commun. 4, 1749 (2013)

Condensation in a periodic potential



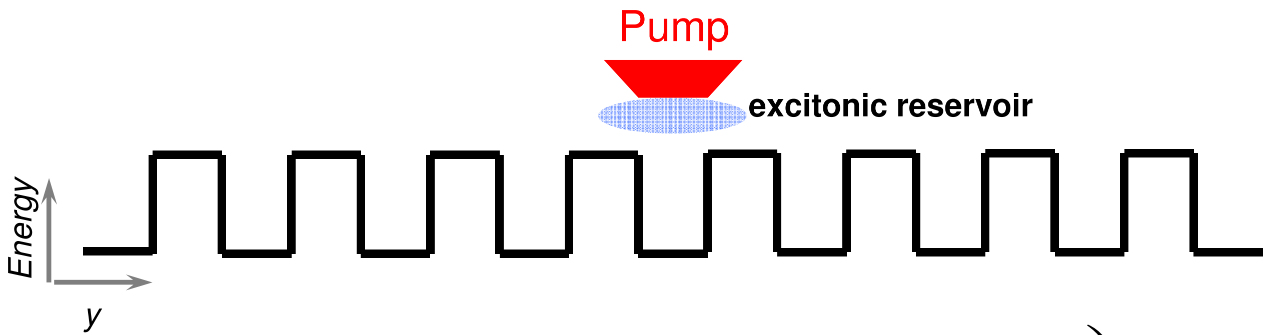
$$\left(-\frac{\hbar^2\nabla^2}{2m}+V_{per}(r)+g_C\left|\psi(r)\right|^2+g_{res}n_{\mathrm{Res}}(r)\right)\psi(r)=\mu\psi(r)$$



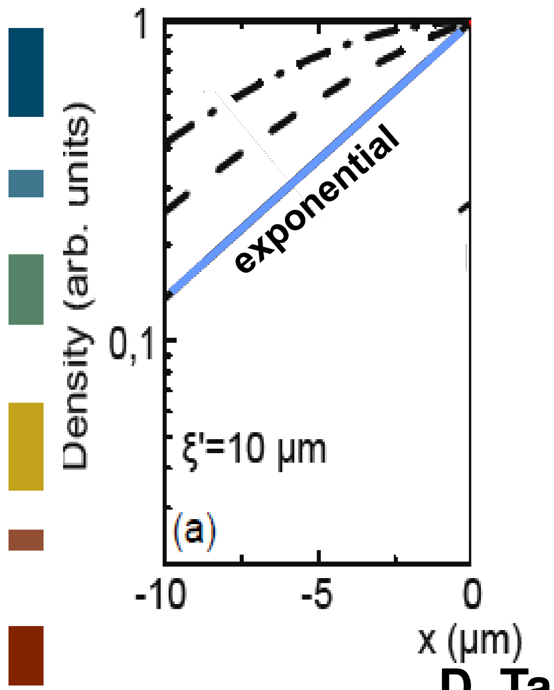
D. Tanese et al., Nat. Commun. 4, 1749 (2013)

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Condensation in a periodic potential



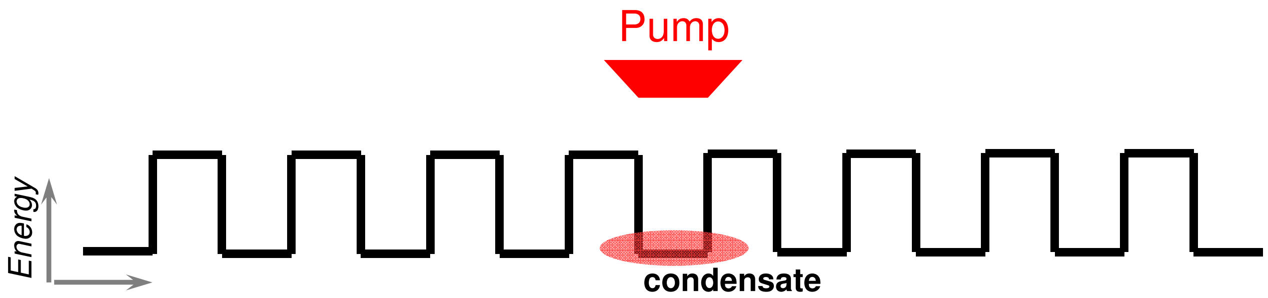
$$\left(-\frac{\hbar^2\nabla^2}{2m}+V_{per}(r)+ \qquad +g_{res}n_{Res}(r)\right)\psi(r)=\mu\psi(r)$$



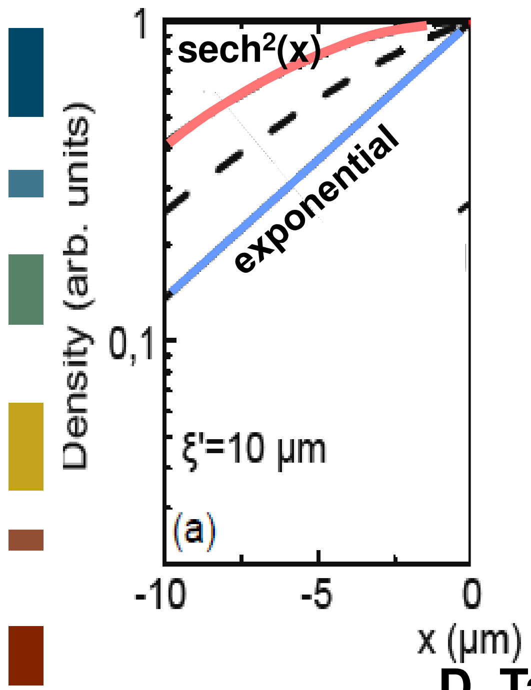
Excitonic potential → cavity → localised state

D. Tanese et al., Nat. Commun. 4, 1749 (2013)

Condensation in a periodic potential



$$\left(-\frac{\hbar^2\nabla^2}{2m}+V_{per}(r)+g_C\left|\psi(r)\right|^2+\qquad\qquad\right)\psi(r)=\mu\psi(r)$$



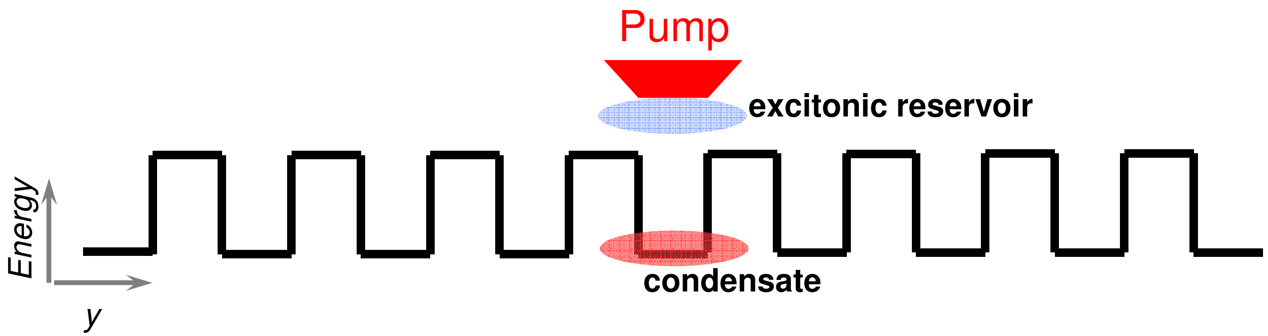
Excitonic potential ➡ **cavity** ➡ **localised state**

Condensate interactions ➡ **GAP SOLITON**

D. Tanese et al., Nat. Commun. 4, 1749 (2013)

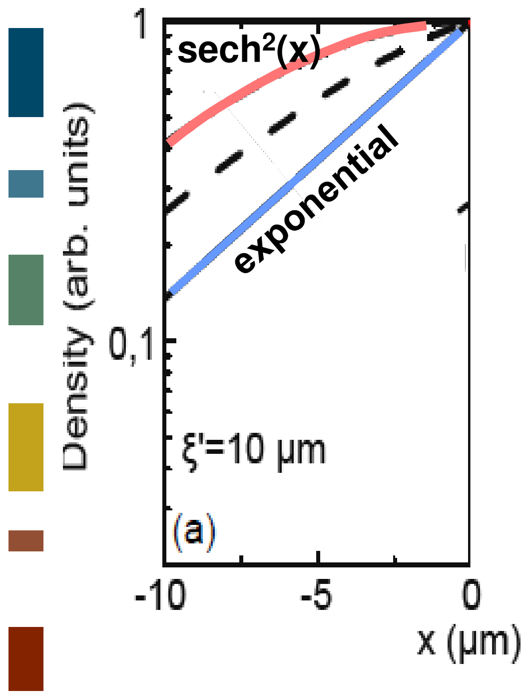
LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

Condensation in a periodic potential

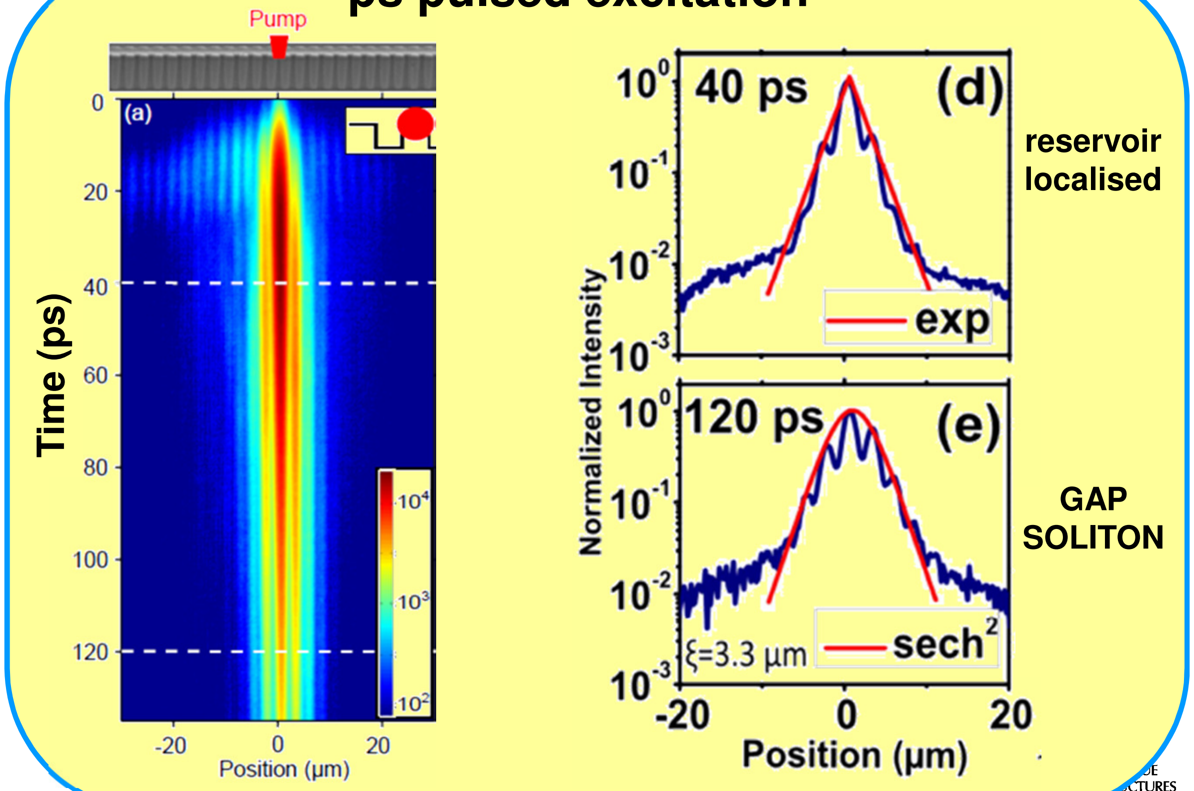


$$\left(-\frac{\hbar^2\nabla^2}{2m}+V_{per}(r)+g_C\left|\psi(r)\right|^2+g_{res}n_{\mathrm{Res}}(r)\right)\psi(r)=\mu\psi(r)$$

D. Tanese et al., Nat. Commun. 4, 1749 (2013)



ps pulsed excitation



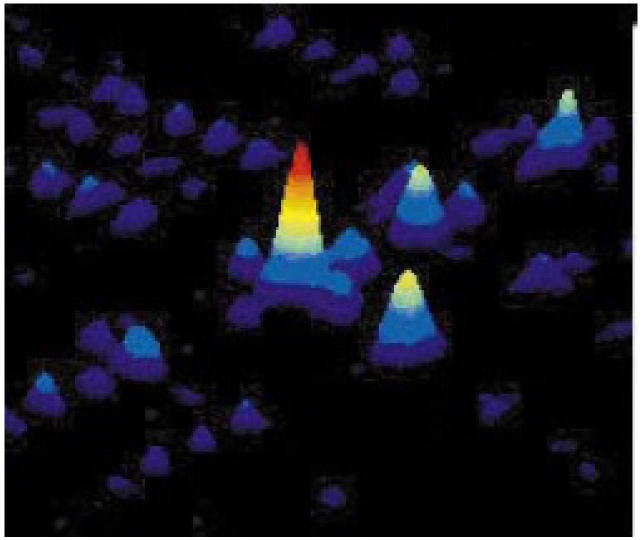
Gap solitons in non-linear periodic media

Nature 422, 147 (2003)

Observation of two-dimensional discrete solitons in optically induced nonlinear photonic lattices

Jason W. Fleischer*†, Mordechai Segev*†, Nikolaos K. Efremidis‡ & Demetrios N. Christodoulides‡

** Physics Department, Technion—Israel Institute of Technology, Haifa 32000, Israel*
† Electrical Engineering Department, Princeton University, New Jersey 08544, USA
‡ School of Optics/CREOL, University of Central Florida, Florida 32816-2700, USA

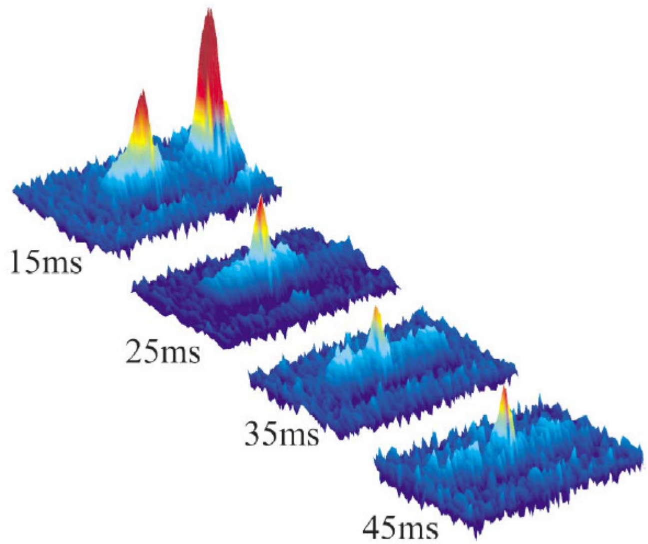


VOLUME 92, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 11 JUNE 2004

Bright Bose-Einstein Gap Solitons of Atoms with Repulsive Interaction

B. Eiermann,[1] Th. Anker,[1] M. Albiez,[1] M. Taglieber,[2] P. Treutlein,[2] K.-P. Marzlin,[3] and M. K. Oberthaler[1]
[1]*Kirchhoff Institut für Physik, Universität Heidelberg, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany*
[2]*Max-Planck-Institut für Quantenoptik und Sektion Physik der Ludwig-Maximilians-Universität, Schellingstrasse 4, 80799 München, Germany*
[3]*Department of Physics and Astronomy, Quantum Information Science Group, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4*
(Received 16 December 2003; published 8 June 2004)

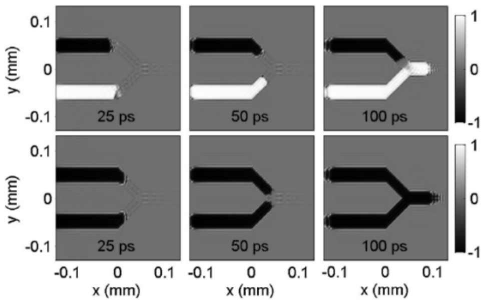
We report on the first experimental observation of bright matter wave solitons for ^{87}Rb atoms with repulsive atom-atom interaction. This counterintuitive situation arises inside a weak periodic potential, where anomalous dispersion can be realized at the Brillouin zone boundary. If the coherent atomic wave packet is prepared at the corresponding band edge, a bright soliton is formed inside the gap. The strength of our system is the precise control of preparation and real time manipulation, allowing the systematic investigation of gap solitons.



First steps toward polaritonics circuits

PROPOSALS

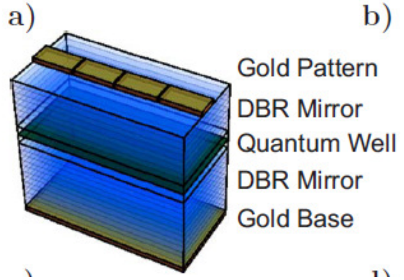
Polaritonic neurons



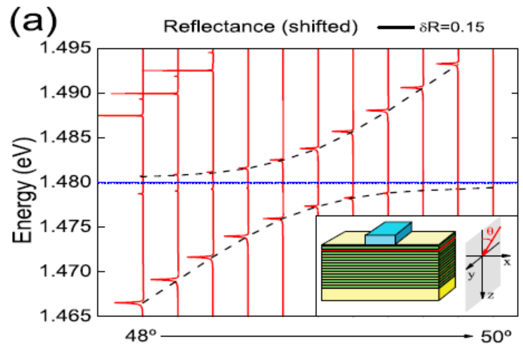
T. C. H. Liew, et al.,
Phys. Rev. Lett. 101, 016402 (2008)

Espinosa-Ortega. & Liew,,
Phys. Rev. *B* **87**, 195305 (2013)

Integrated circuits



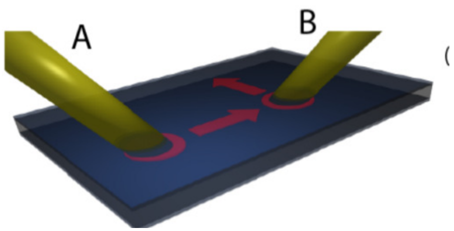
T. Liew et al.,
Phys. Rev. B 82, 033302 (2010)



M. Liscidini APL 98, 121118 (2011)

EXPERIMENTS

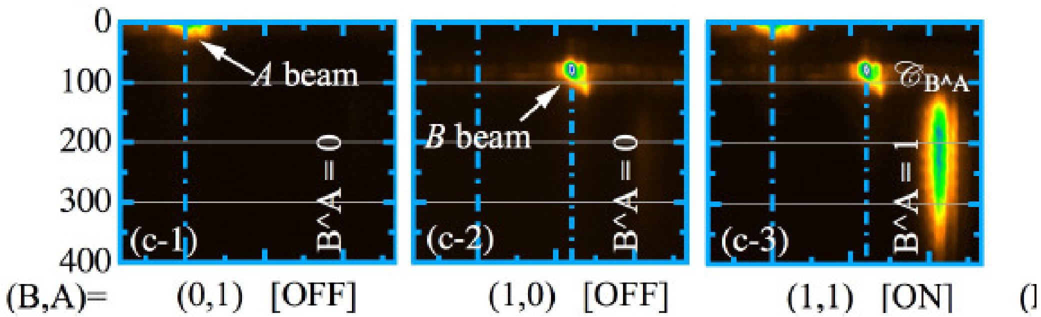
All optical polariton transistor



Ballarini *et al.*, Nature Comm. **4** 1778 (2012)

C. Anton, APL **101**, 261116 (2012)

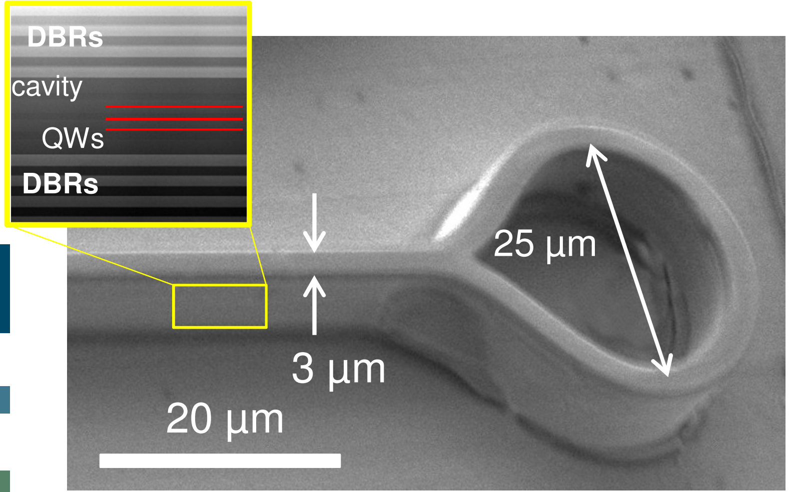
AND Optical polariton Gate



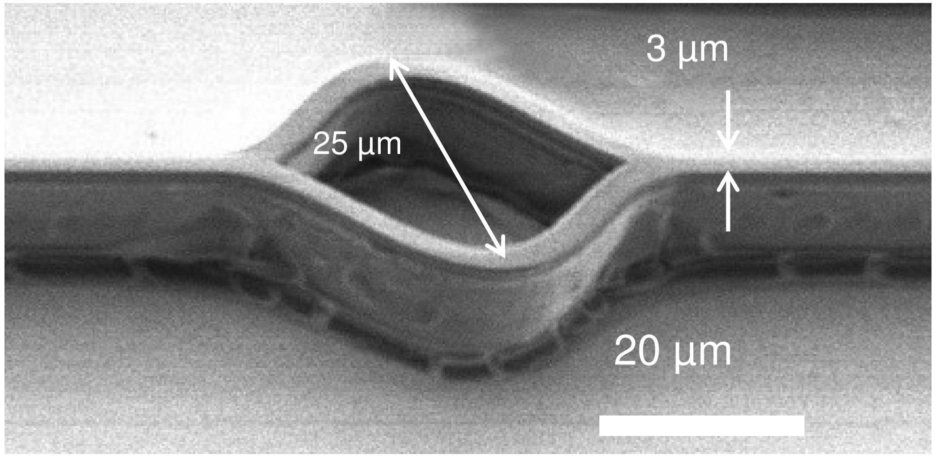
C. Anton, arXiv:1305.5678

Polariton interferometers

Sagnac interferometer

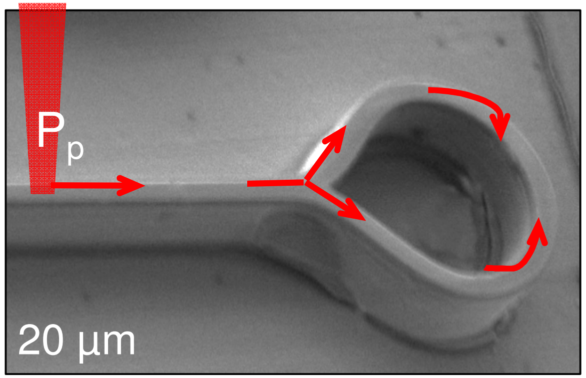


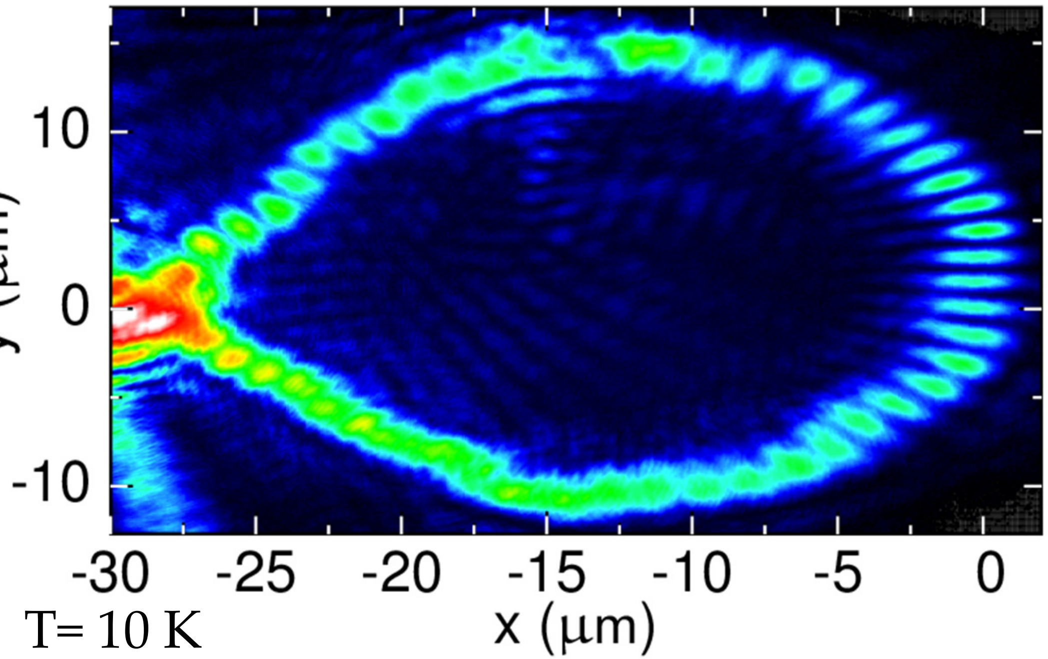
Mach-Zehnder interferometer



C. Sturm et al., arXiv:1303.1649

Sagnac interferometer

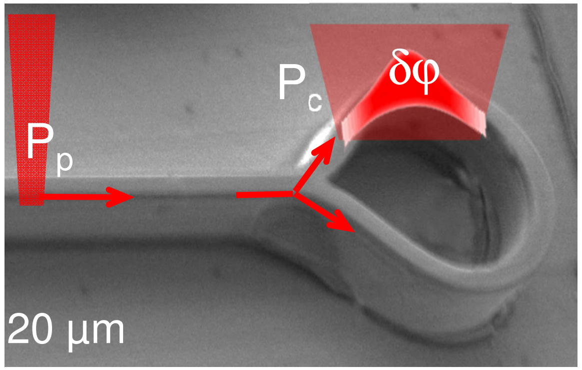


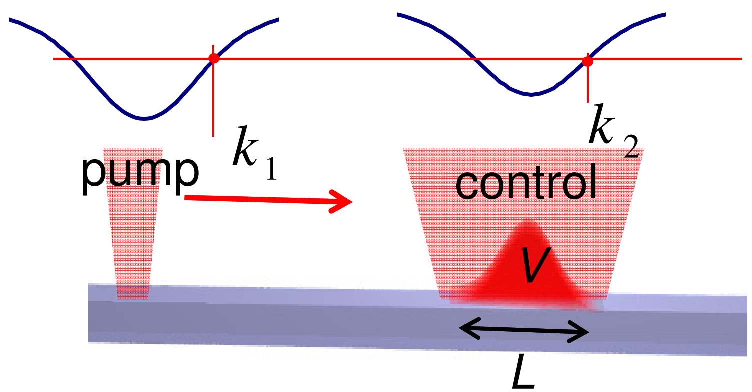


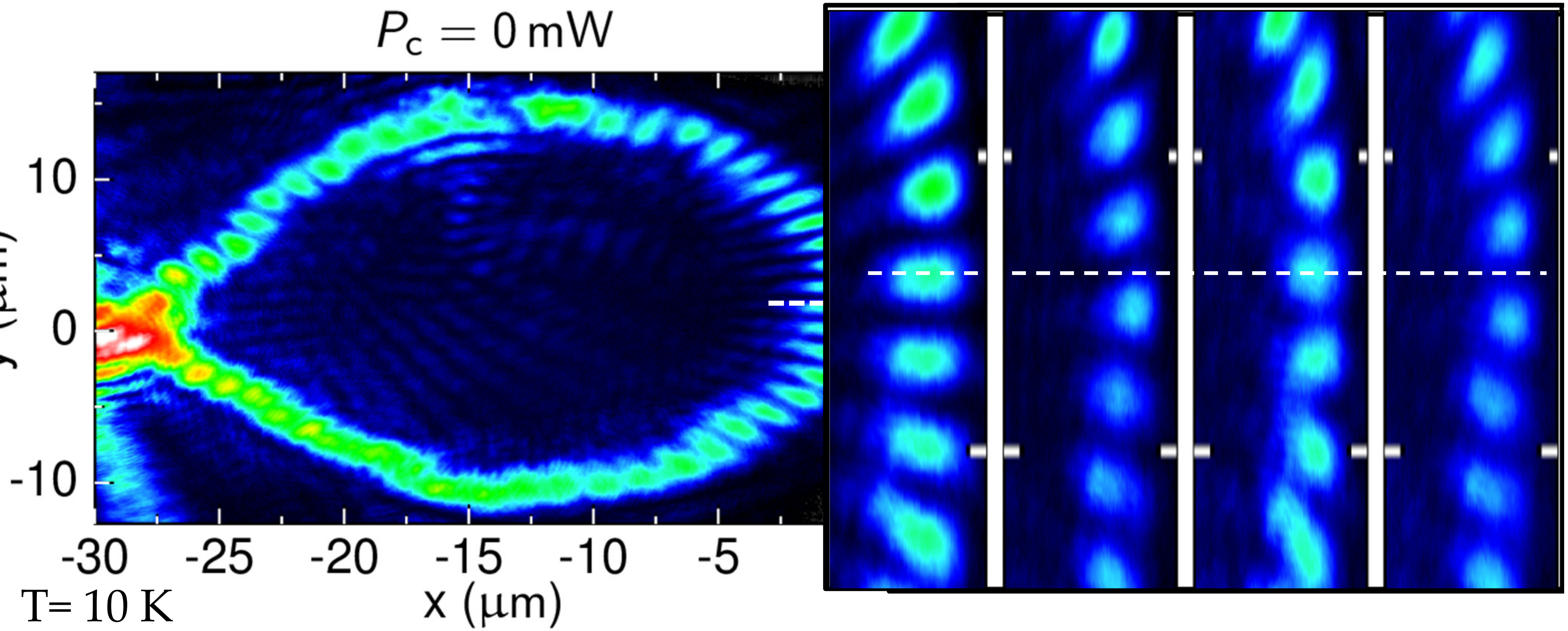
T= 10 K

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

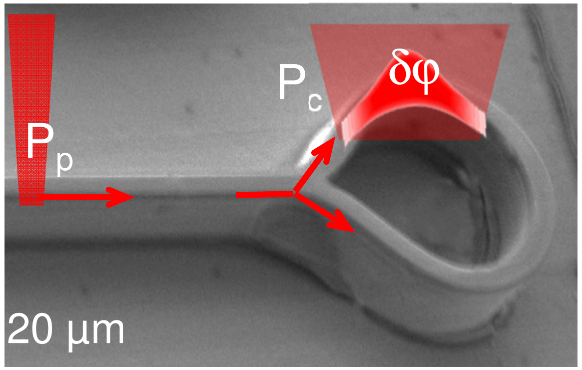
MZI Interferometer

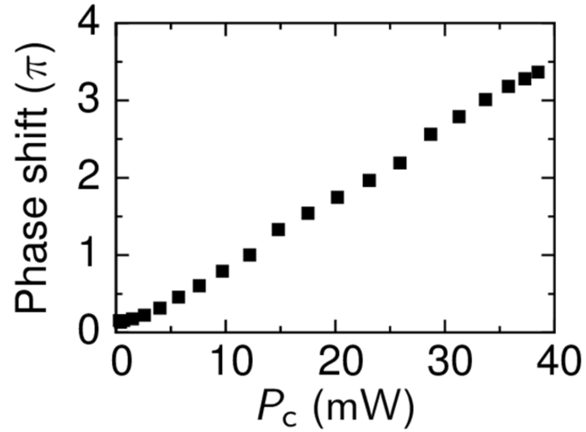


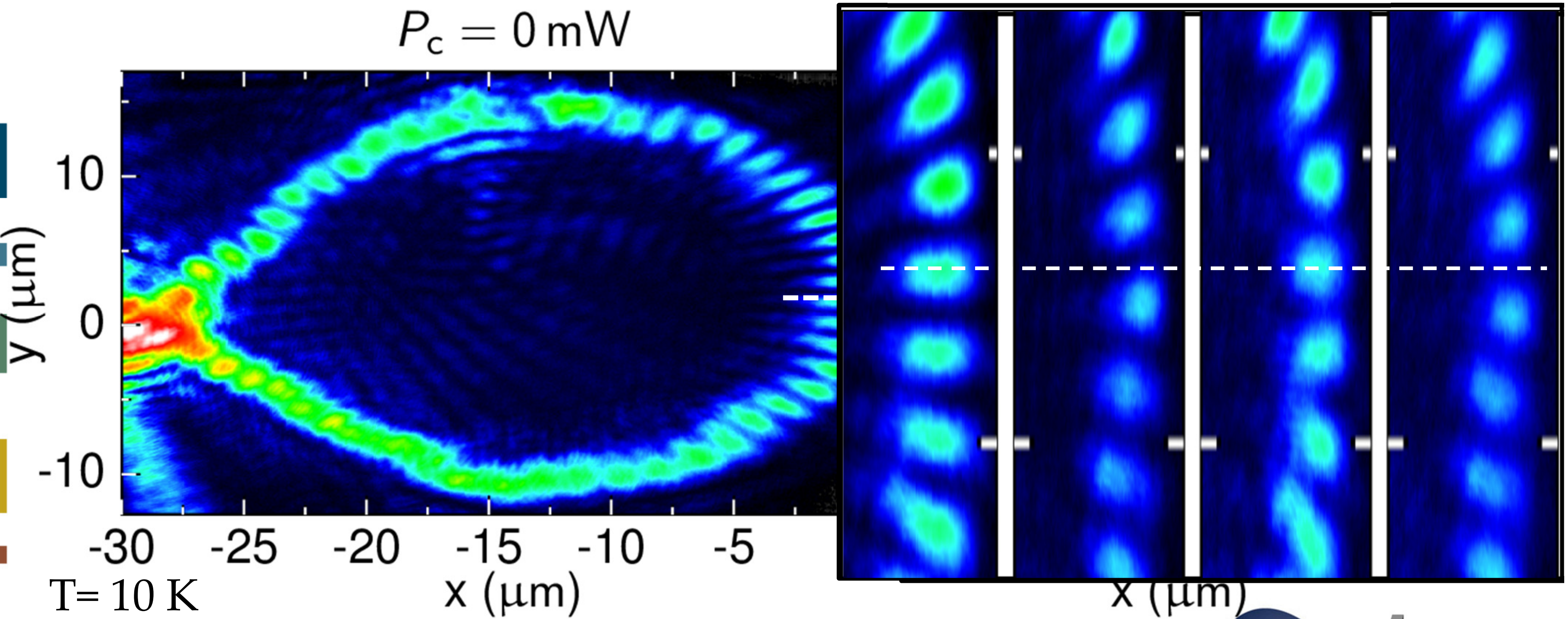




MZI Interferometer



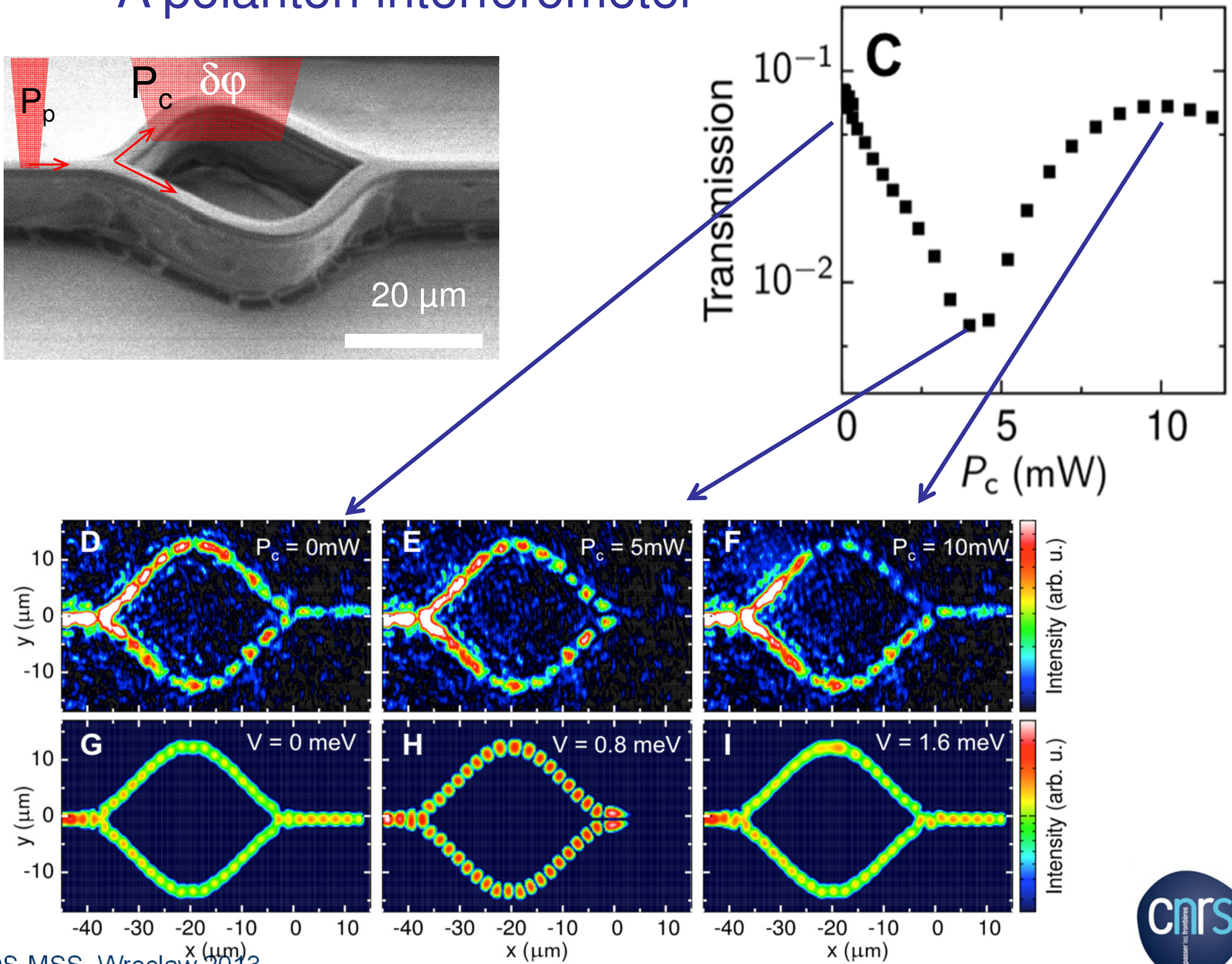




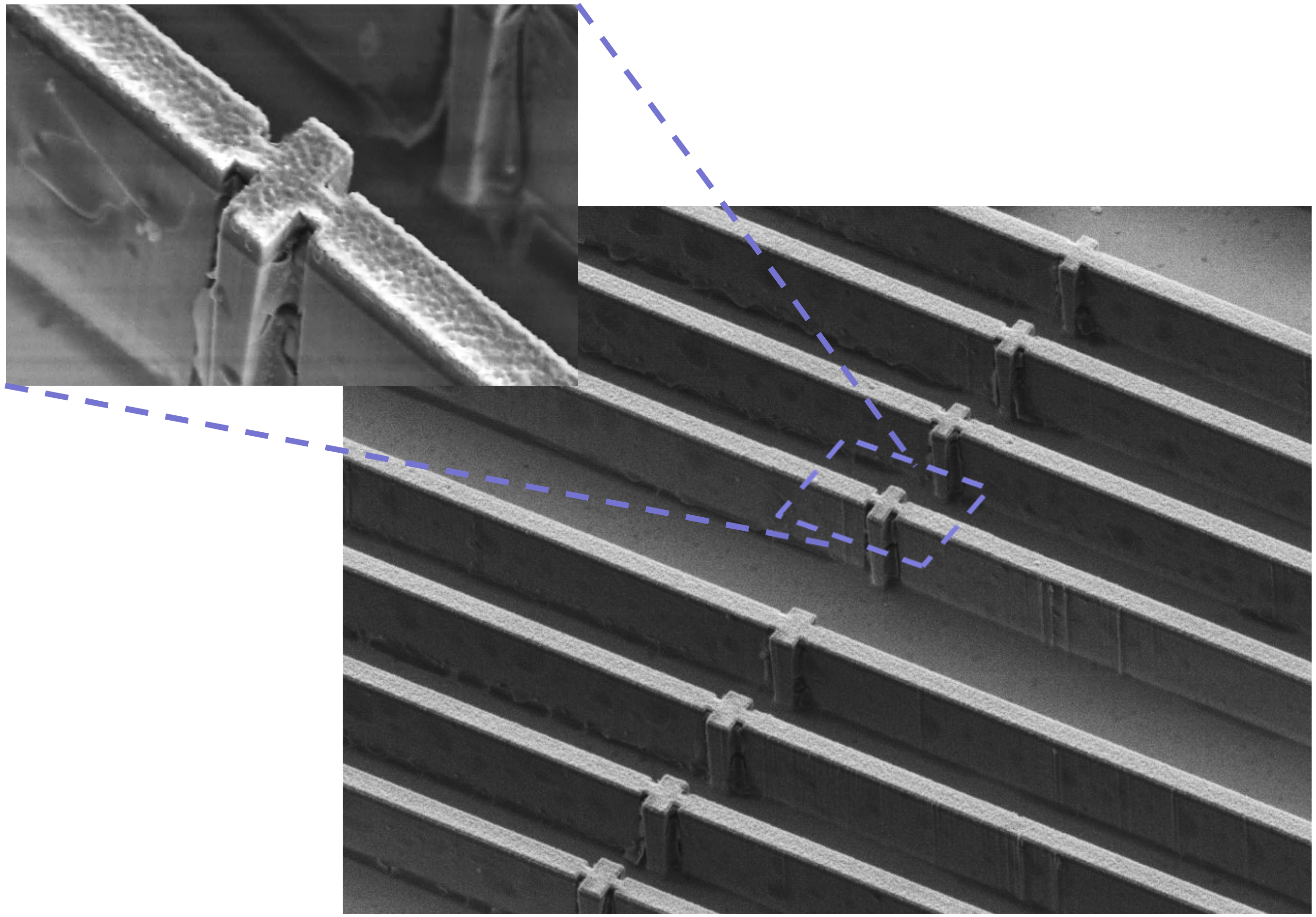
T= 10 K

MZI Interferometer

A polariton interferometer

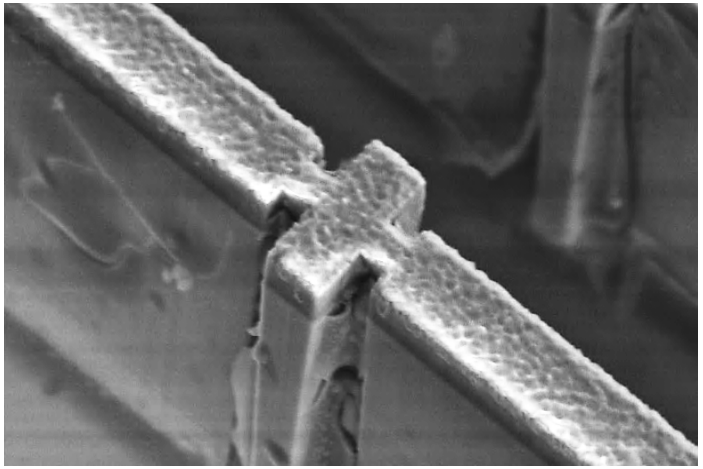


A polariton resonant diode

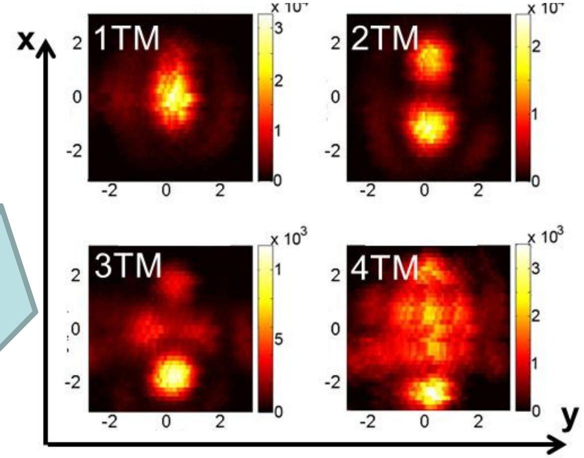


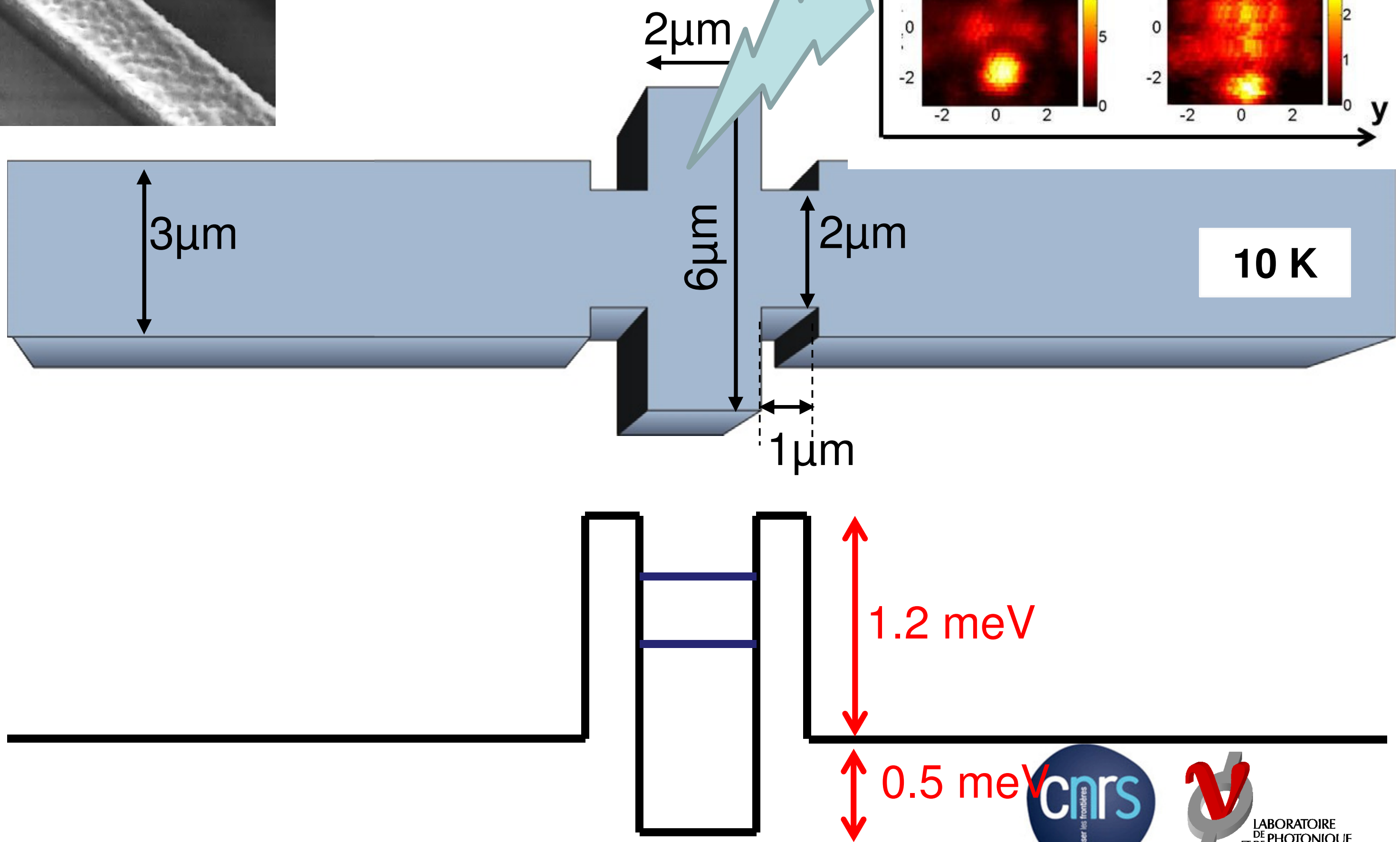
H.S. Nguyen et al., Phys. Rev. Lett. **110**, 236601 (2013)
Viewpoint: L. Pilozzi, Physics 6, 64 (2013)

1D cavity with double potential barrier

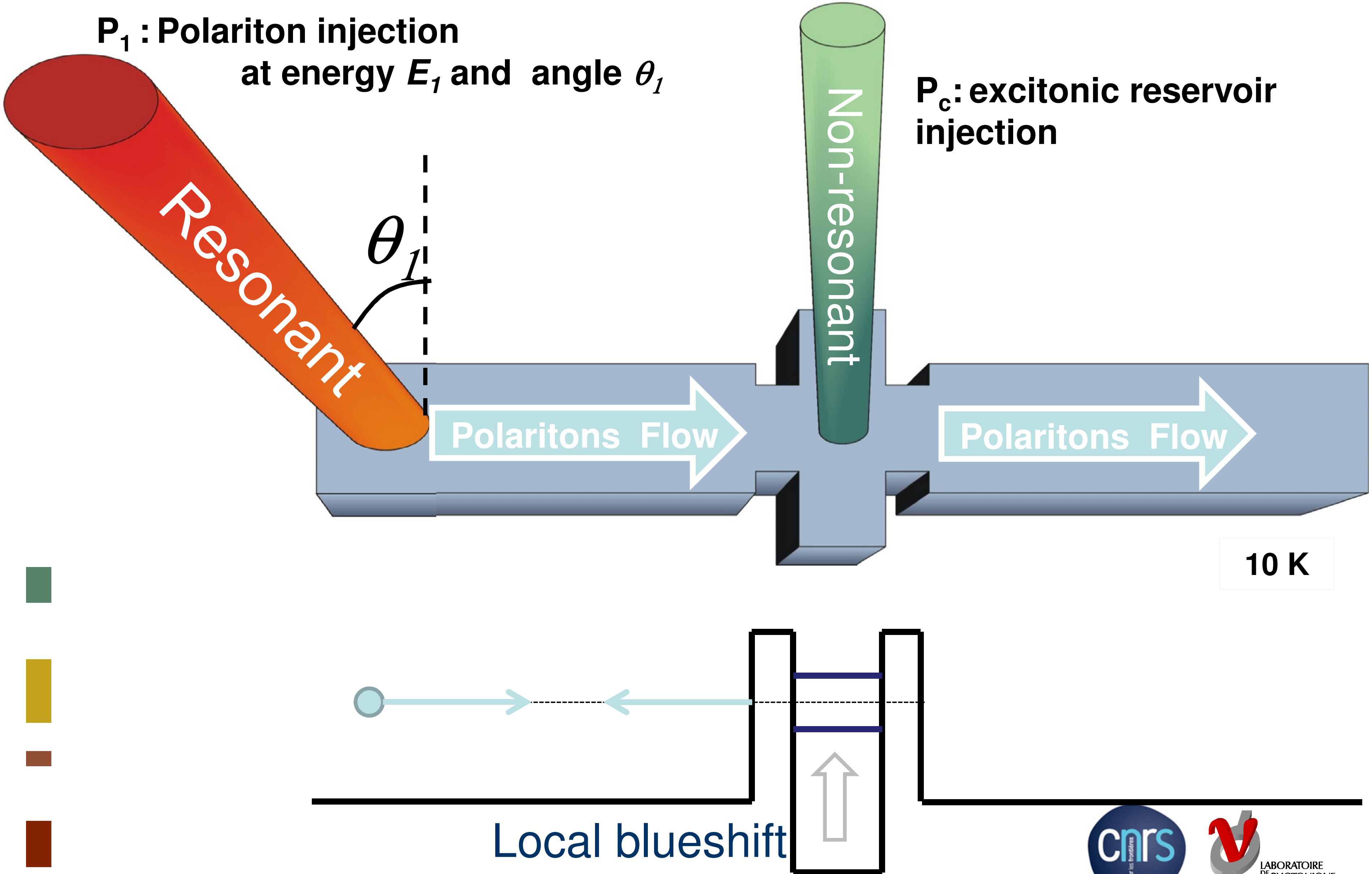


Luminescence of the island

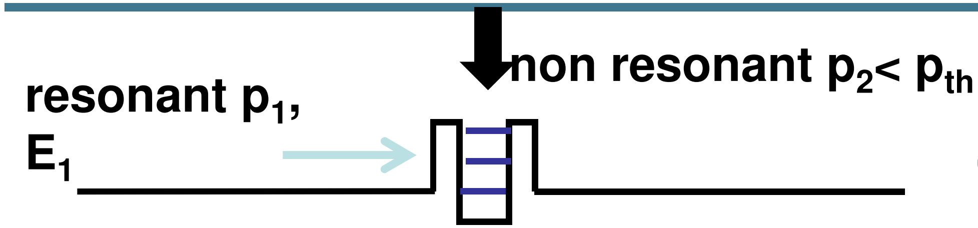




RTD operation

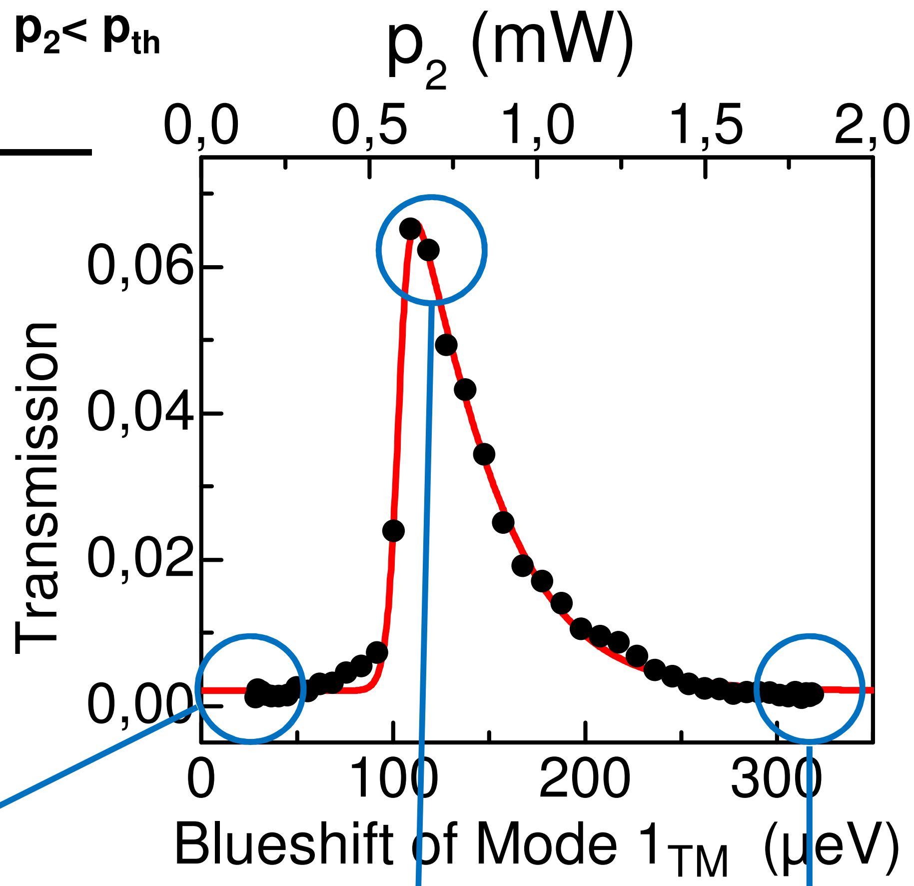


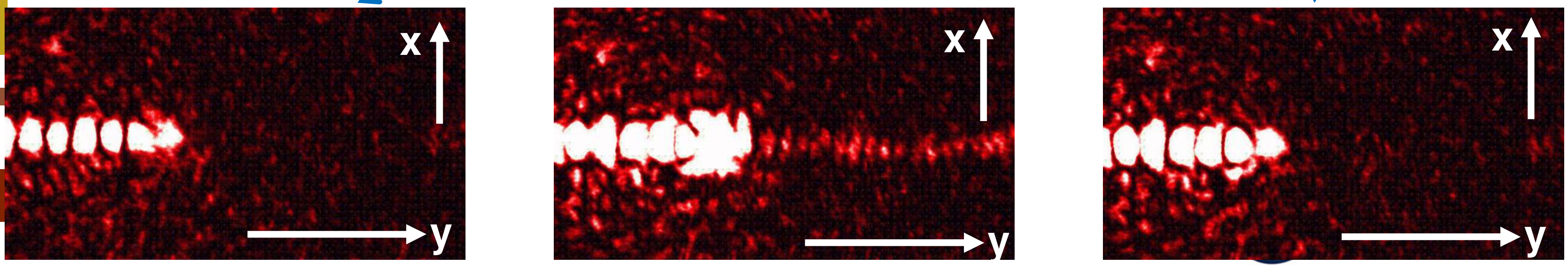
RTD demonstration



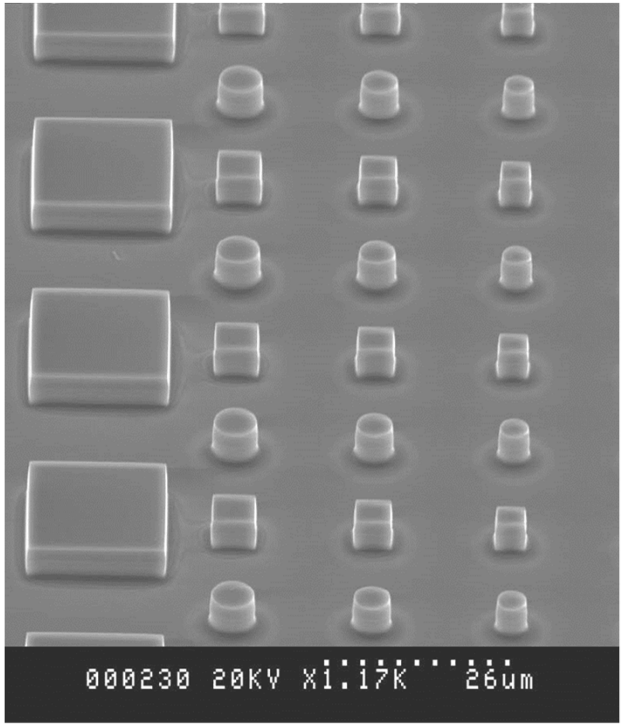
Theory for cold atoms :
T. Paul et al., Phys. Rev. Lett. 94, 020404 (2005)

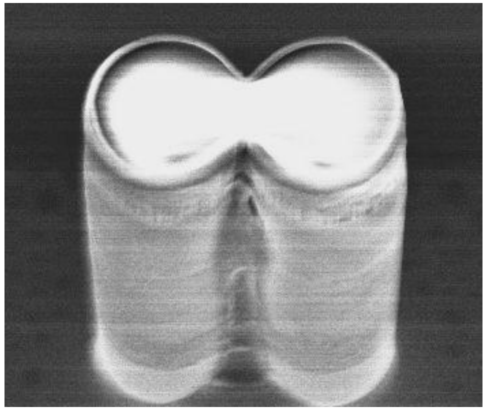
Photonic crystal single cavity :
K. Nozaki et al., Nat. Phot. 6, 248 (2012)

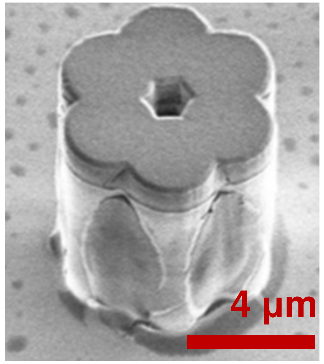




Coupling 0D polaritons

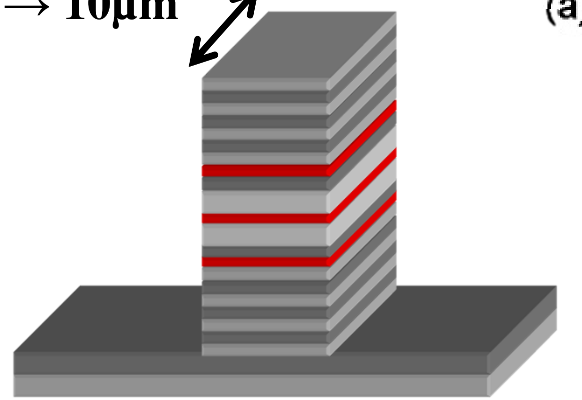




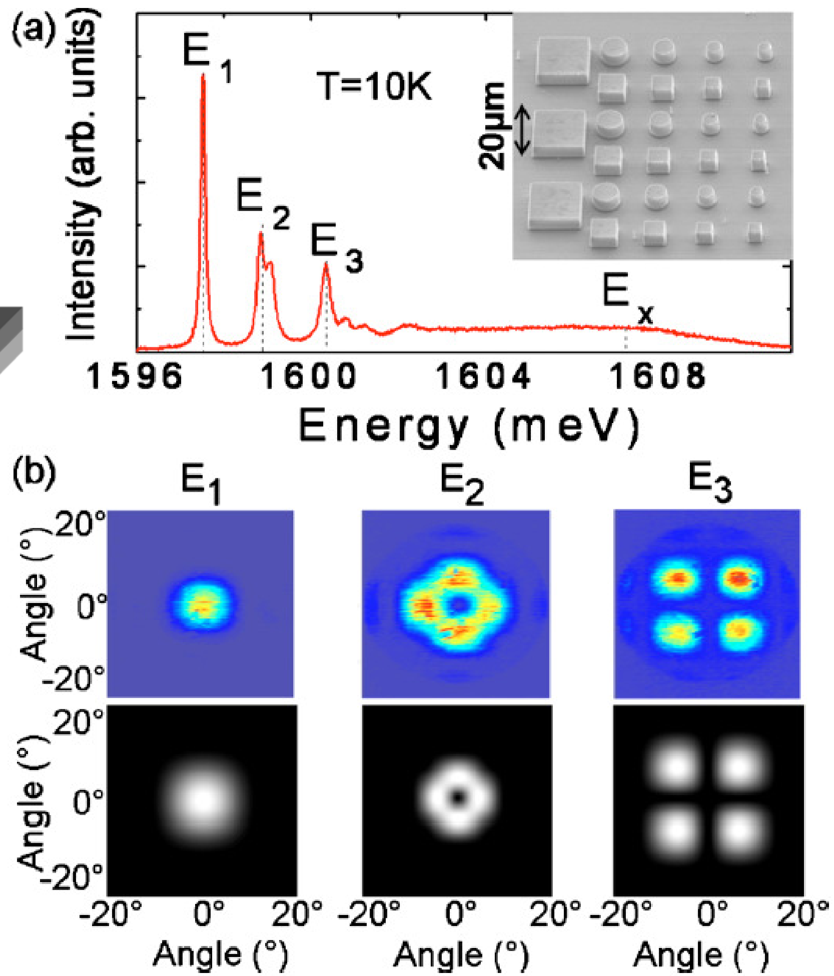


Polaritons in micropillars

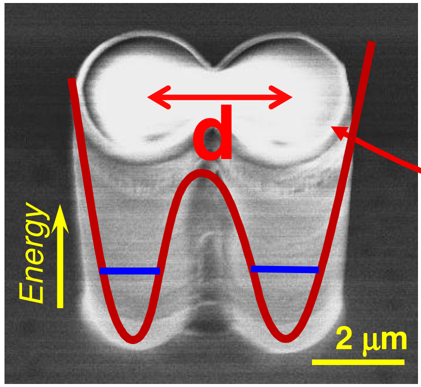
Micropillars: photonic atoms



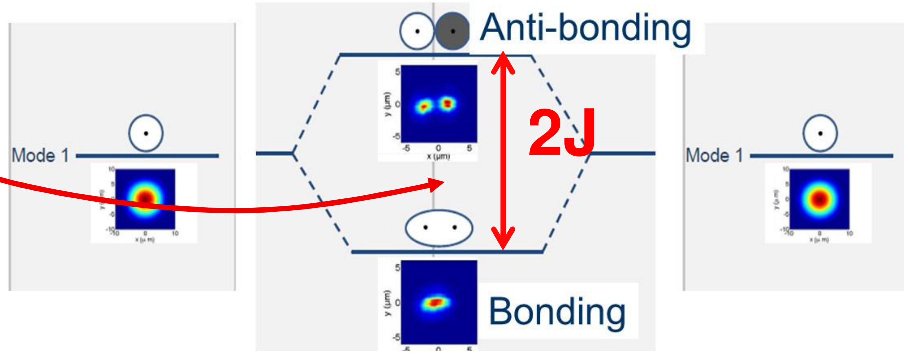
$$k_x = p_x \pi / L_x$$
$$k_y = p_y \pi / L_y$$



Two coupled micropillars



Michaelis de Vasconcellos et al., APL **99**, 101103 (2011)



Galbiati et al., PRL **108**, 126403 (2012)

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LETTERS
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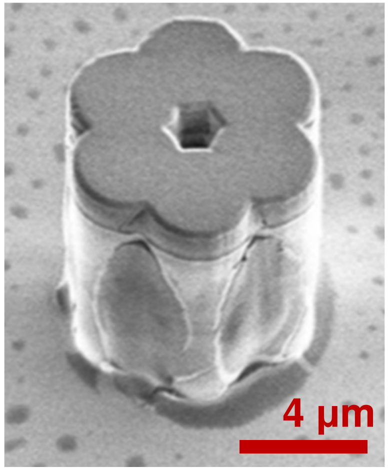
Macroscopic quantum self-trapping and Josephson oscillations of exciton polaritons

M. Abbarchi[1,2], A. Amo[1]*, V. G. Sala[1,3], D. D. Solnyshkov[4], H. Flayac[4], L. Ferrier[1], I. Sagnes[1], E. Galopin[1], A. Lemaître[1], G. Malpuech[4] and J. Bloch[1]

LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

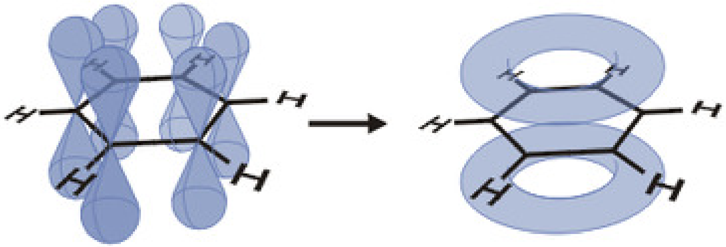
Periodic structures: benzene



Periodic boundary conditions

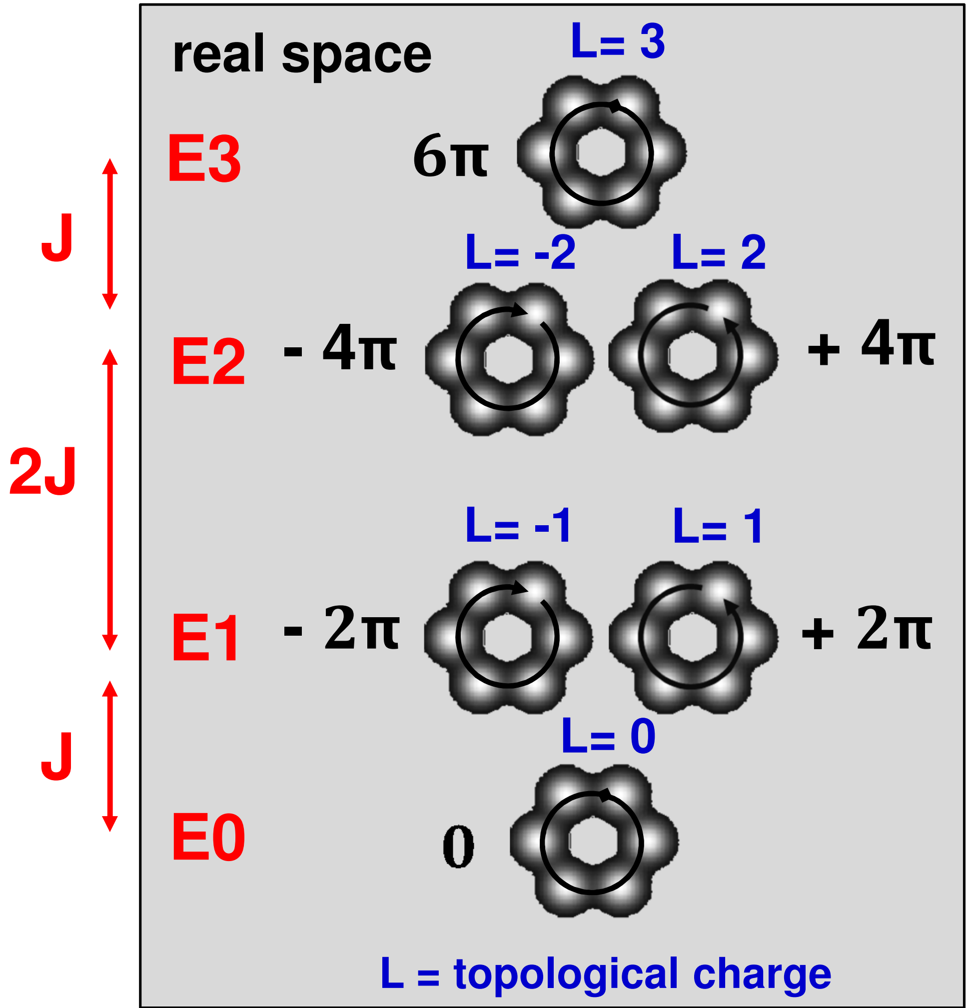
vortical eigenstates

Benzene molecule

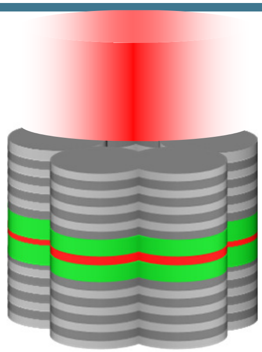


Tight binding model

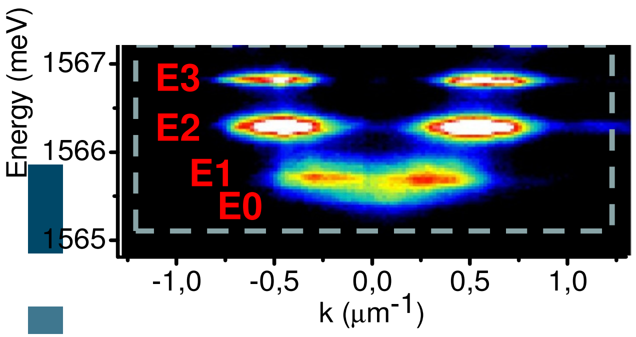
$$|\psi_L\rangle = \frac{1}{\sqrt{6}} \sum_{v=1}^{6} e^{i\frac{L\pi v}{3}} |\phi_\upsilon\rangle$$

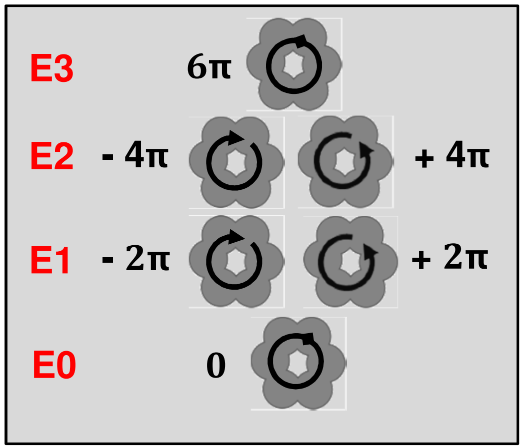


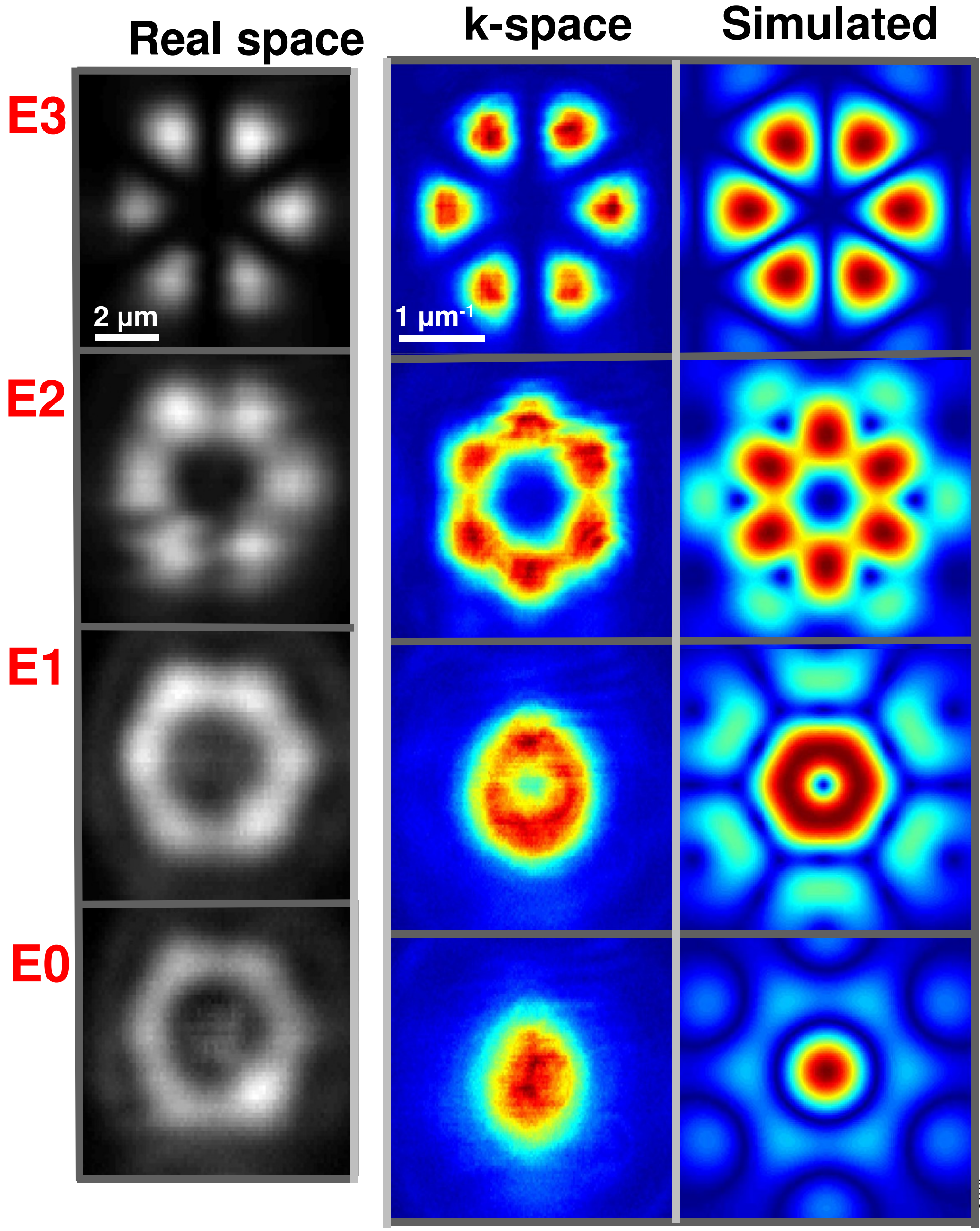
Polariton eigenstates



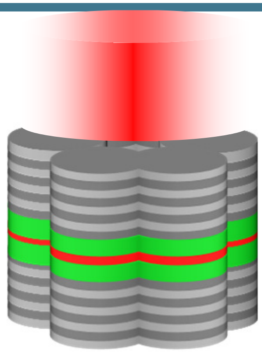
CW, out of resonance



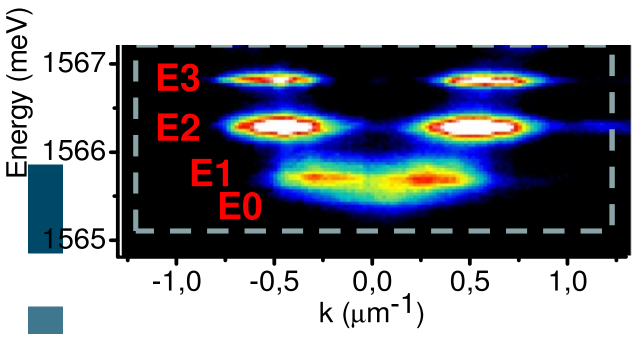


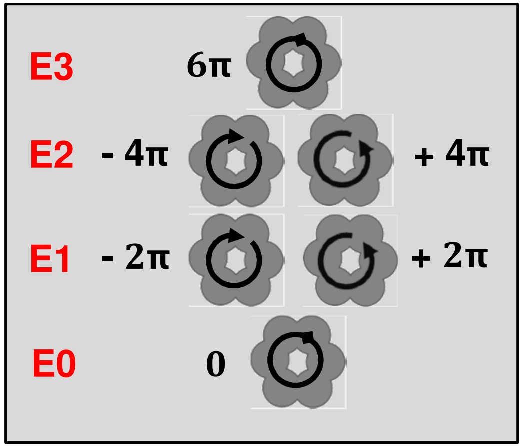


Polariton eigenstates

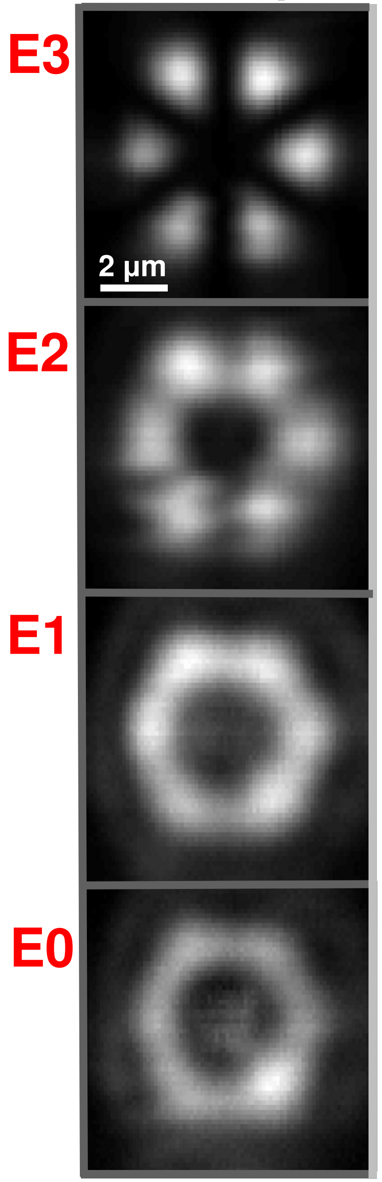


CW, out of resonance

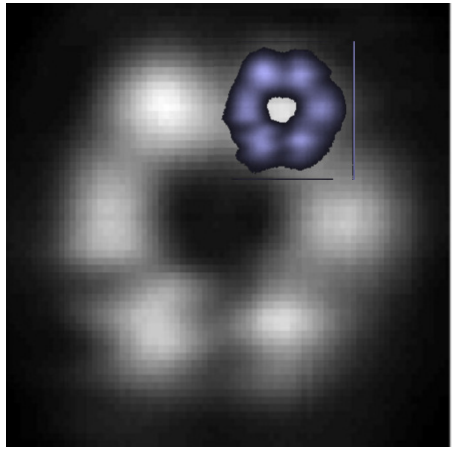




Real space

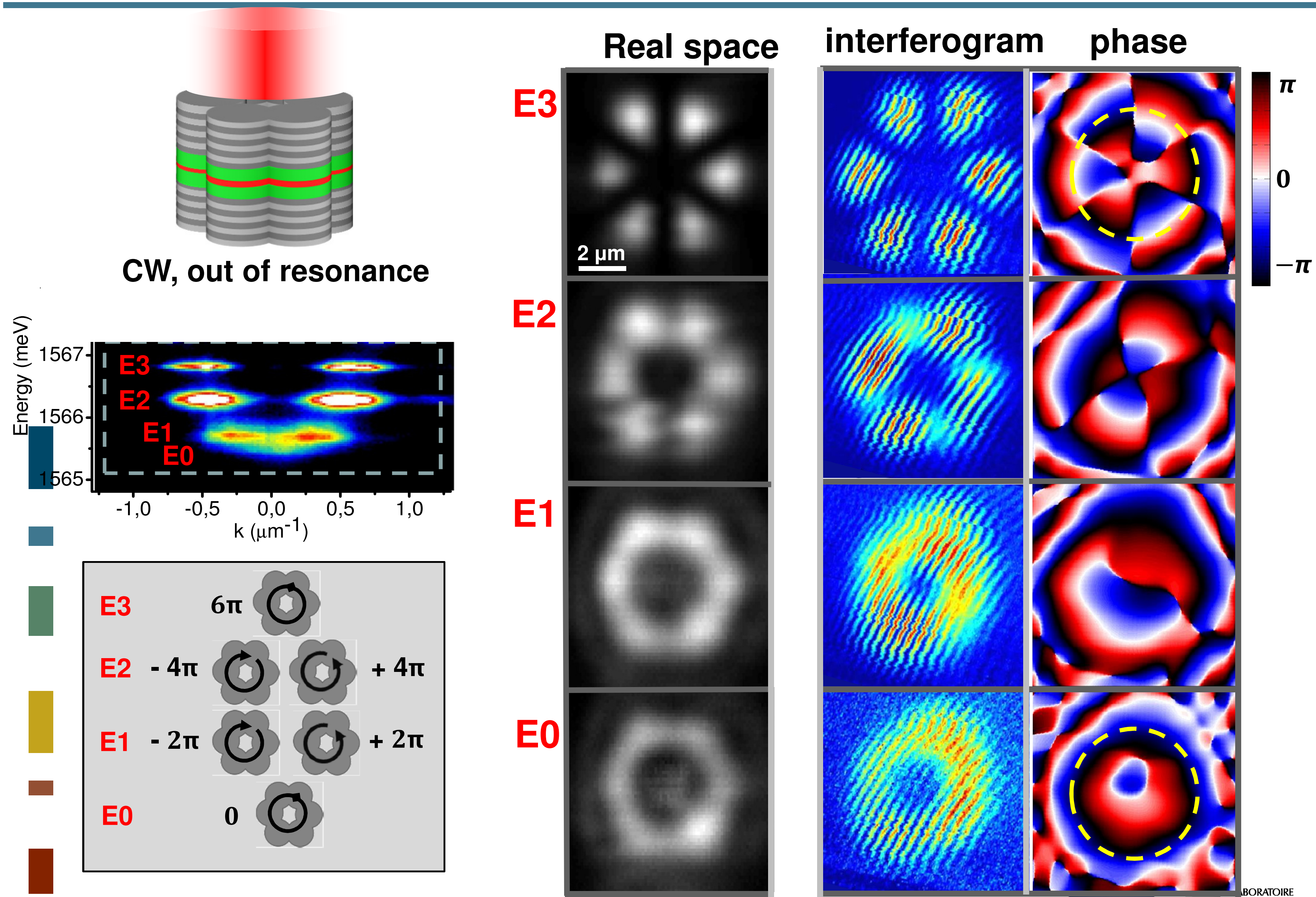


interference between
two images

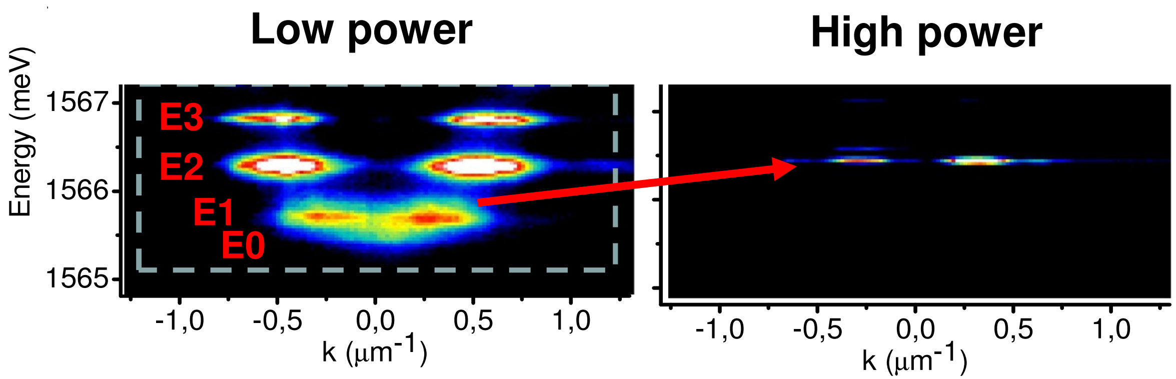


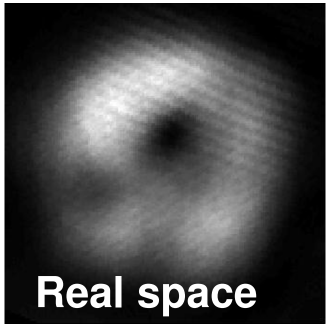
PHASE

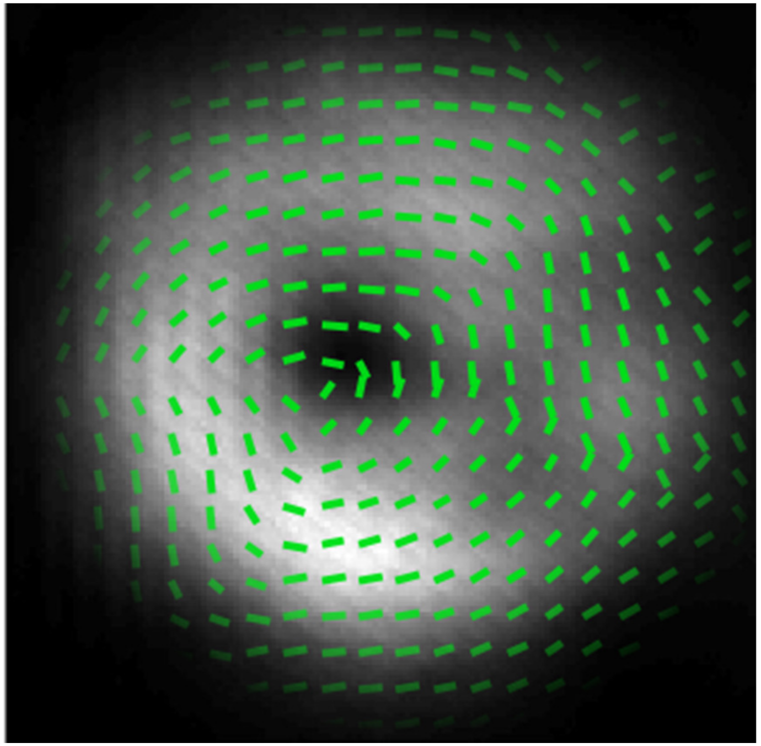
Polariton eigenstates



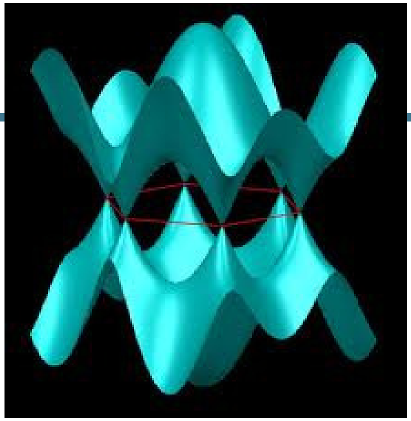
Condensation in polaritonic benzene



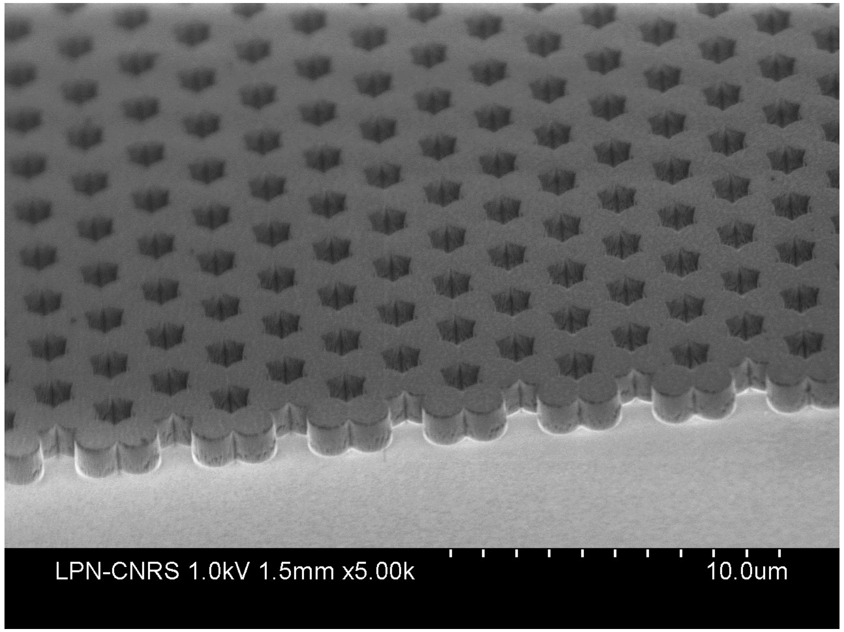




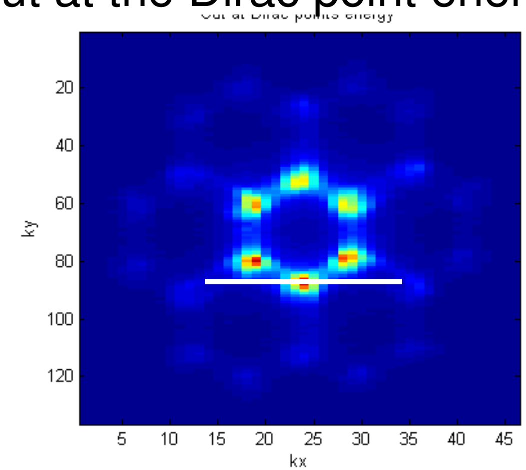
Photonic Graphene with polaritons

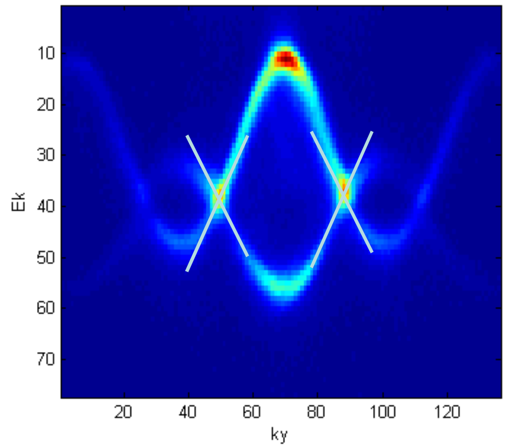


Honeycomb lattice



Cut at the Dirac point energy





See also M. C. Rechtsman et al., Nature Photonics 7, 153 (2013)

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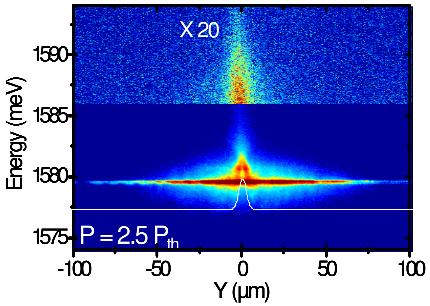
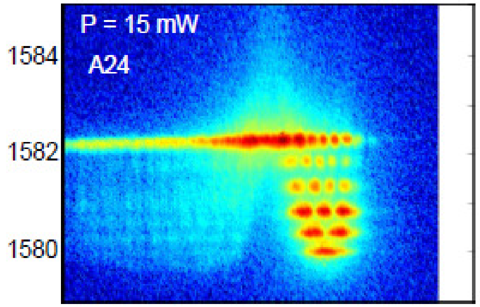
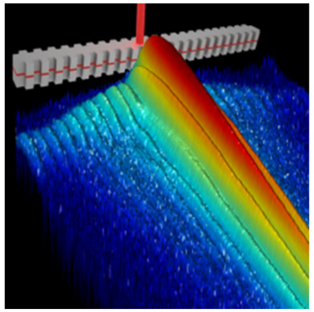
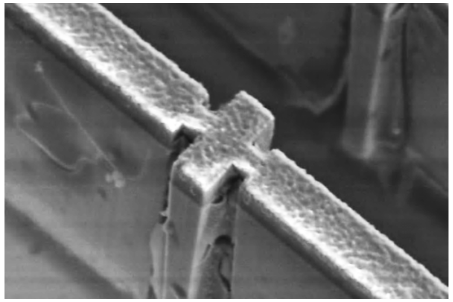
Photonic system with enhanced non-linearities

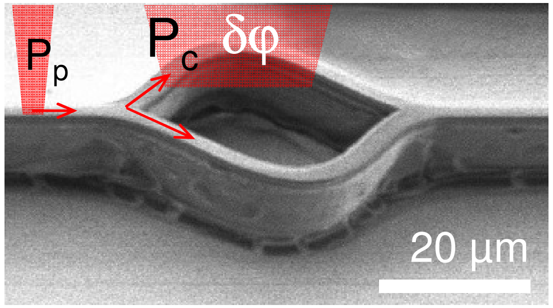




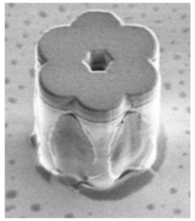


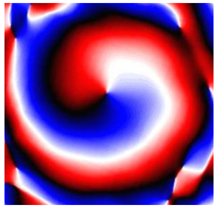
Polariton devices



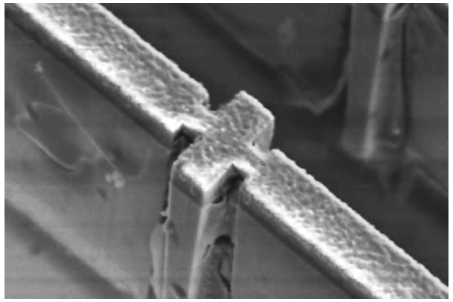


Effective magnetic field, Spin dependant interactions



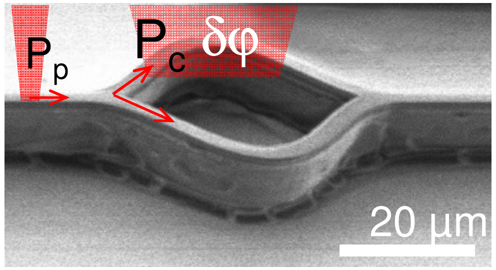


Perspectives



- **Optical memory, optical gates**
- **Quantum regime : single polariton non-linearity**

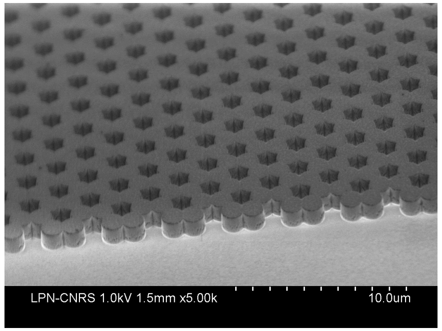
A. Verger et al., Phys. Rev. B 73, 193306 (2006)
I. Carusotto et al., Phys. Rev. Lett. 103, 033601 (2009)



- **Polaritons in a magnetic field : Berry Phase**

$$\theta_B = \pm\pi\left(1 - \frac{\Delta_Z}{\sqrt{\Delta_Z^2 + \Delta_{LT}^2}}\right),$$

I.A.. Shelykh, et al., Phys. Rev. Lett. 102, 046407 (2009)



- **Polariton fluids in lattices**

Toward topological insulator?

A Quantum simulator

This is the work of :

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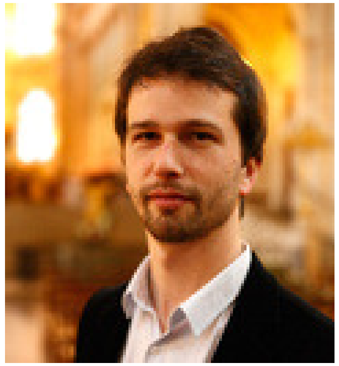
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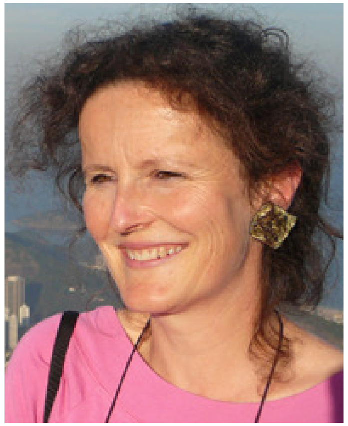
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