LECTURE 7.1

towards polariton-based devices: quantum confinement and nanostructure engineering

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Polariton confinement

engineering local variation of polariton energy

- Modification of wave function by the external parameter (lateral confinement)
- Control of the discrete states by an external laser

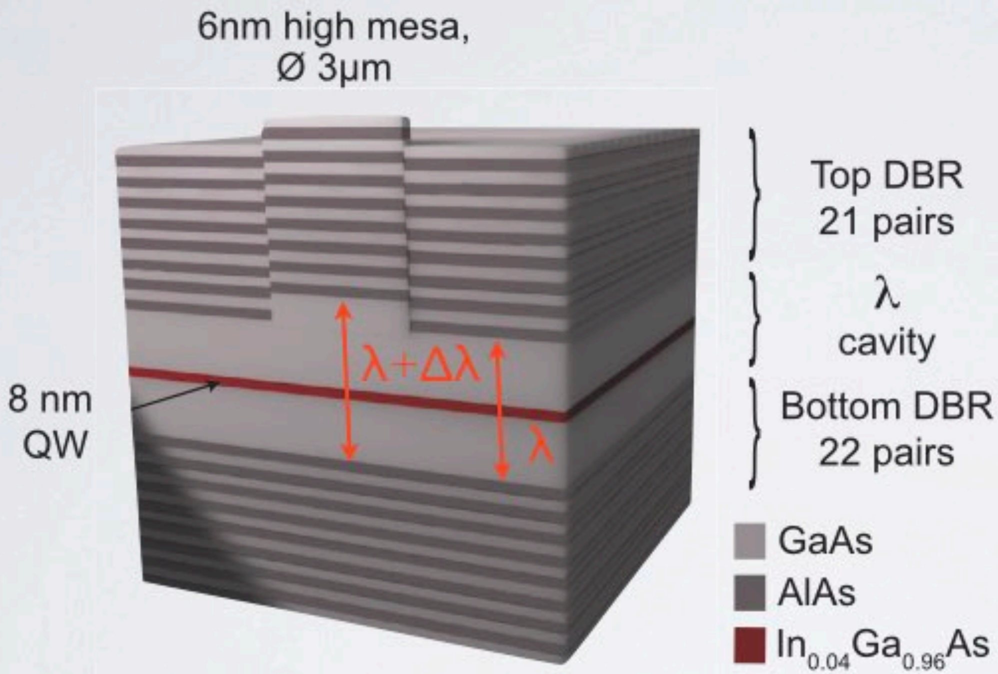
Polaritronics

B. Deveaud, Nature (2008)

- optoelectronics based on exciton-polaritons

Polariton confinement

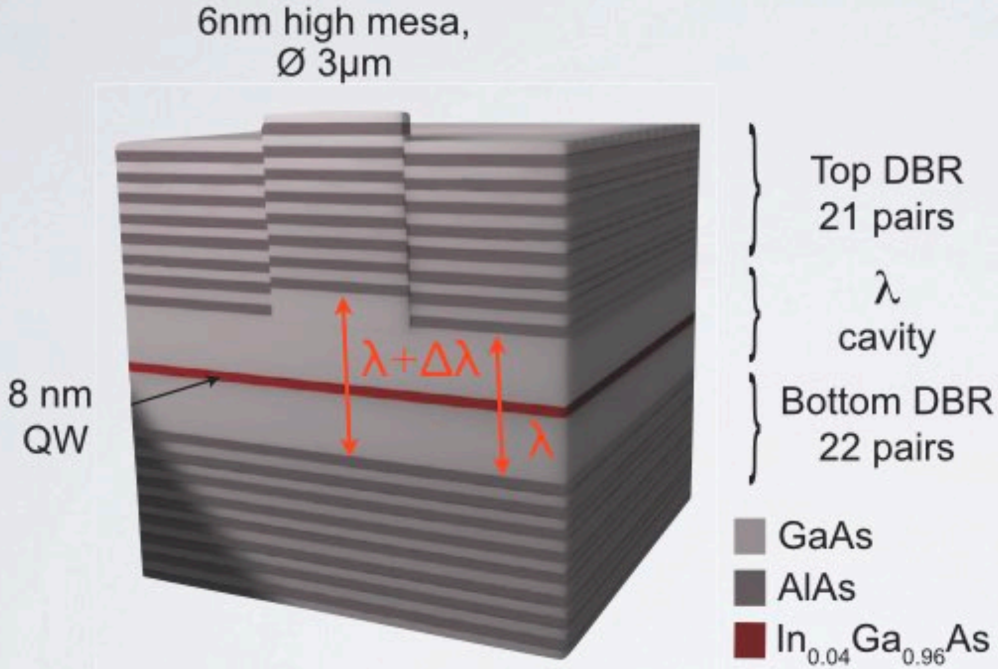
polaritonic quantum dot (with bosonic statistics)

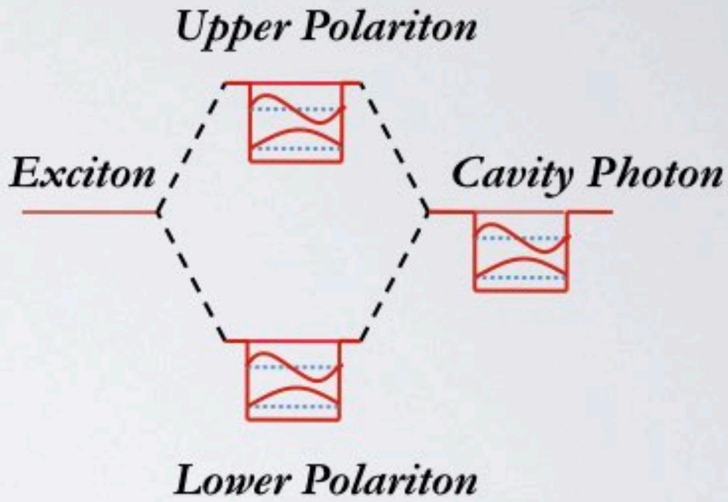


- Local circular variations of the cavity length provide traps for the photonic component of polaritons.
- Diameter of the traps :
  up to 30 µm

Polariton confinement

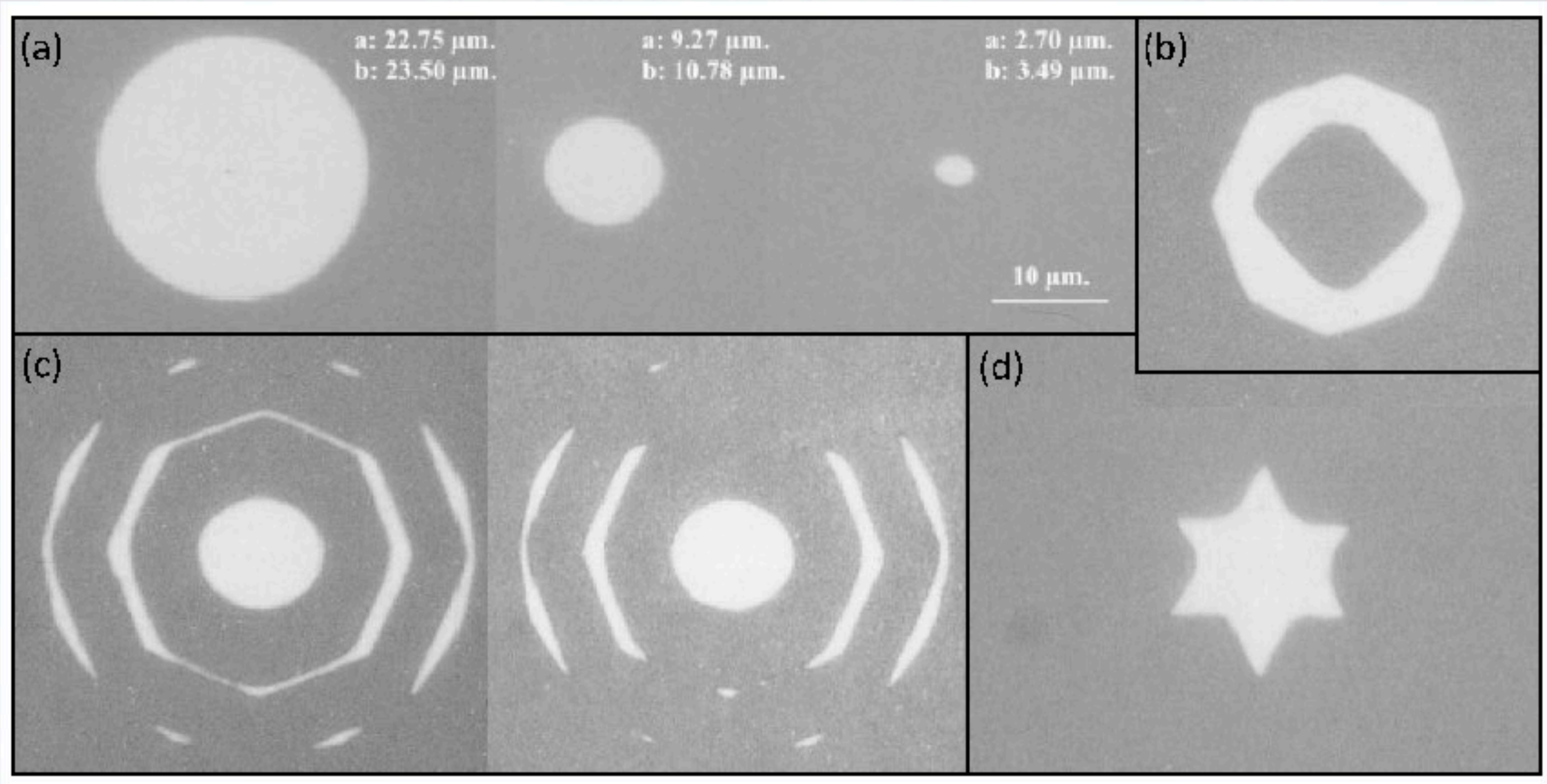
polaritonic quantum dot (with bosonic statistics)





Polariton confinement
structures determined by litography

round and more complicated MEZA STRUCTURES

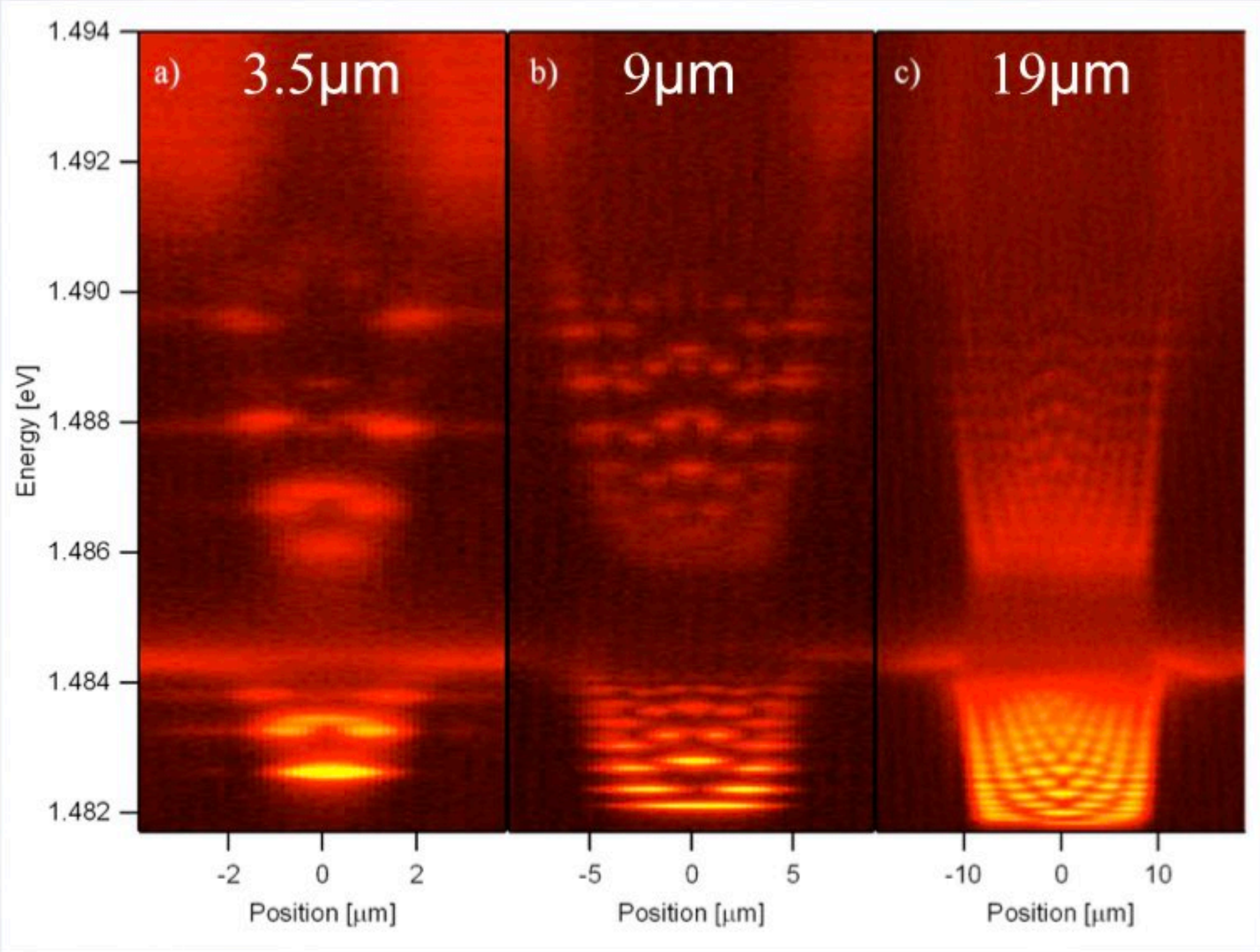


O. El Daif, et al. Applied Physics Letters, **92**, 0819101 (2008)

G. Nardin, et al. Applied Physics Letters, 94, 181103 (2009)

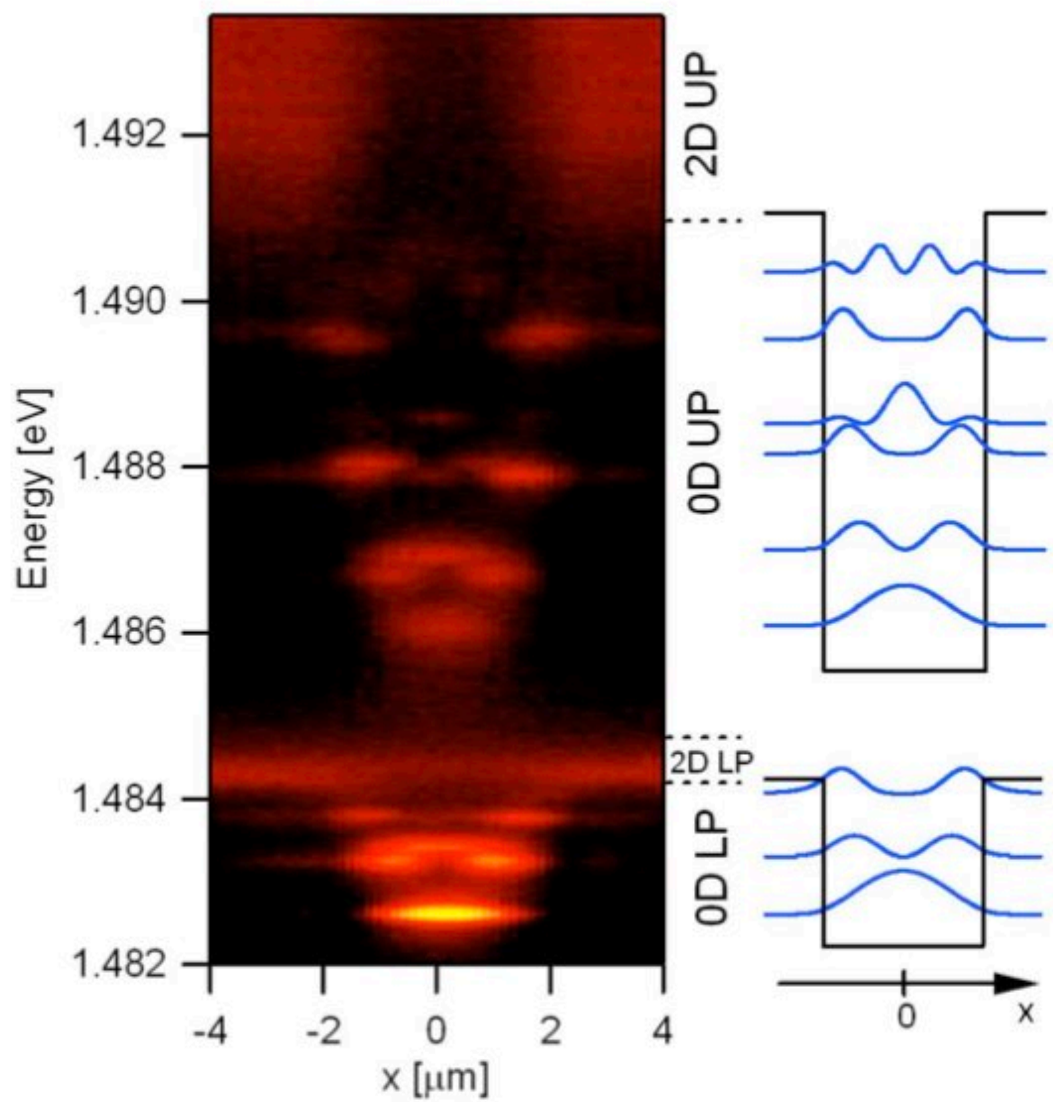
Polariton confinement

polaritonic quantum dot (with bosonic statistics)



G. Nardin, et al. Applied Physics Letters, 94, 181103 (2009)

Particle in a box



G. Nardin, et al. Applied Physics Letters, 94, 181103 (2009)

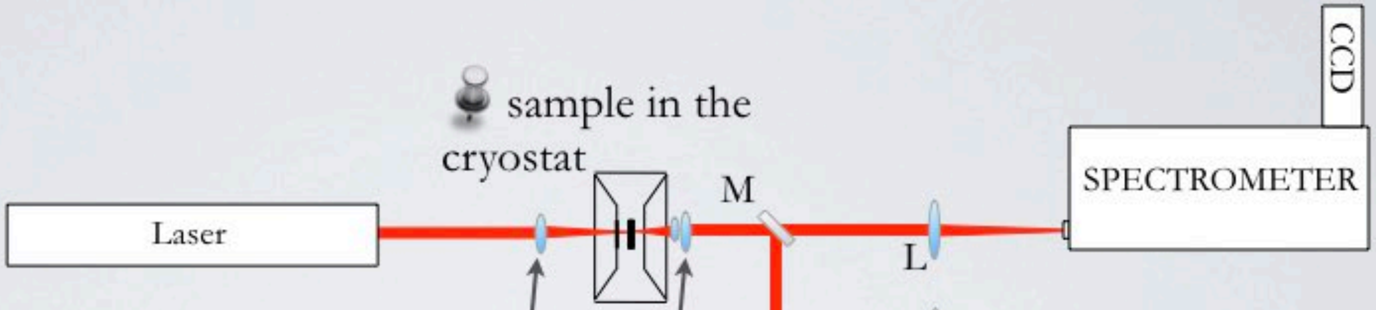
$m_{eff} \sim 0.7\ meV \cdot ps^2 \cdot \mu m^{-2}$

$m_{eff} \sim 10^{-4}\ m_0$

Full wave-function imaging

full wave function amplitude tomography

- sample in the cryostat



EXCITATION

- Non-resonant excitation
- Resonant excitation

CAMERA OBJECTIVE

- Spot size 40µm

MICROSCOPE OBJECTIVE

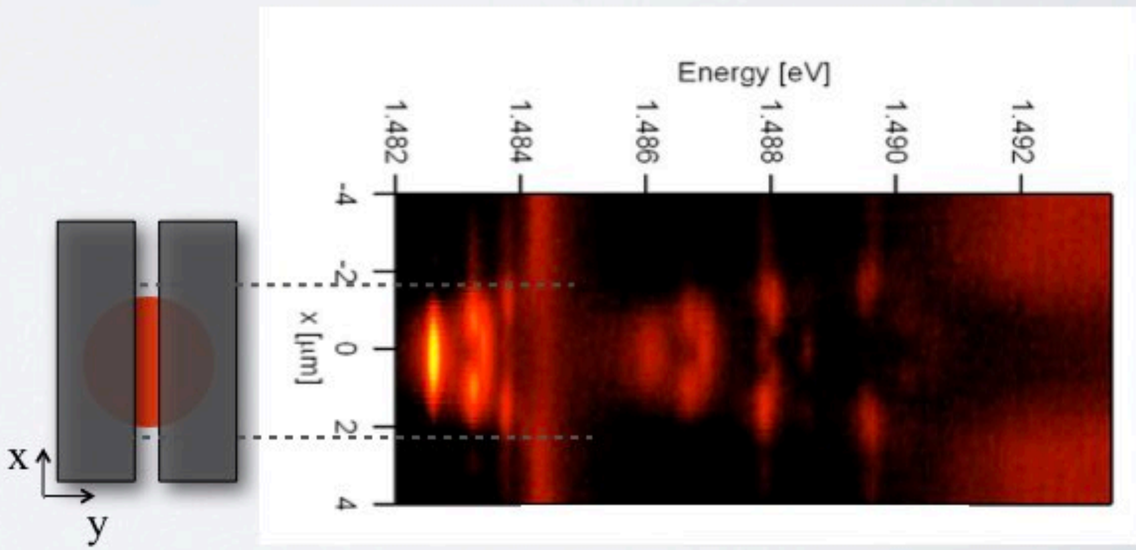
- high numerical aperture
- Diffraction limited resolution

Imaging PL of the mesa on the slits of the monochromator.

- 1D spatially resolved spectrum.

Scanning the mesa along the y direction.

- A stack of 3D data I(x,y,E) from wich we can extract the PL at any energy.

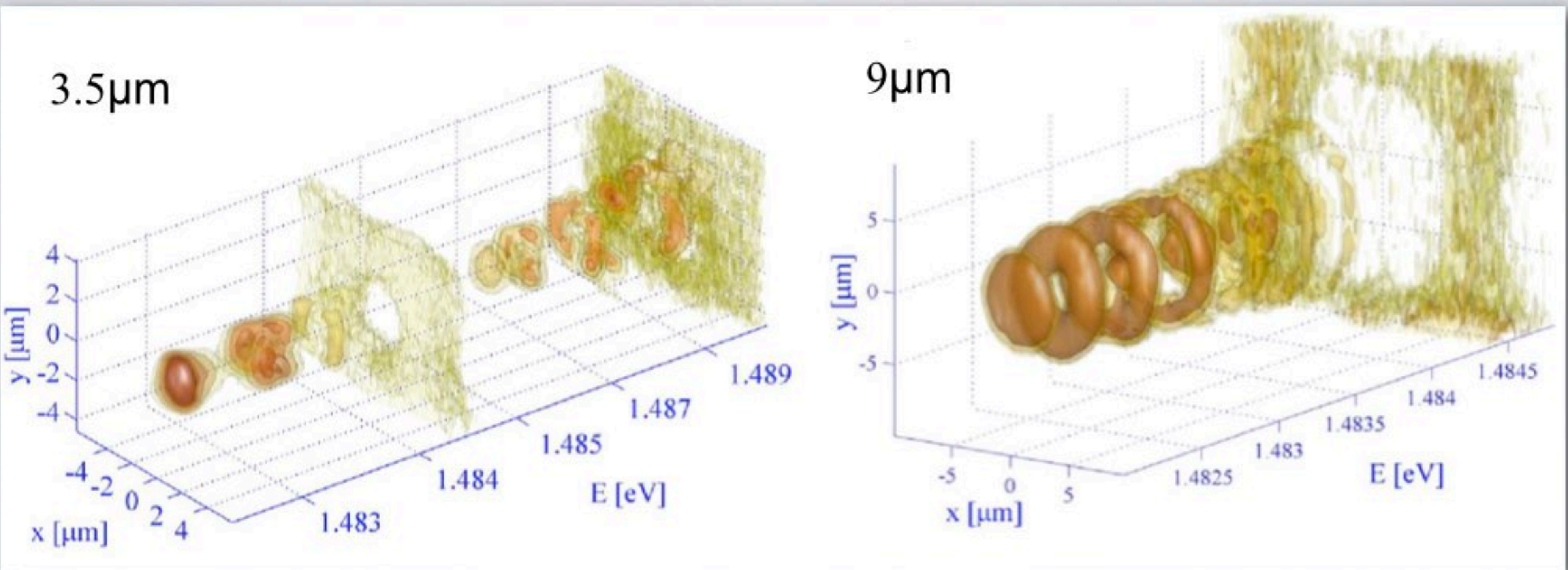


G. Nardin, et al. Applied Physics Letters, 94, 181103 (2009)

Full wave-function imaging

amplitude and phase detection

photoluminescence spectra in 3D



- All confined and delocalized states visible in a single view !
- Absence of PL from the trap at the energy of the 2D lower polariton !

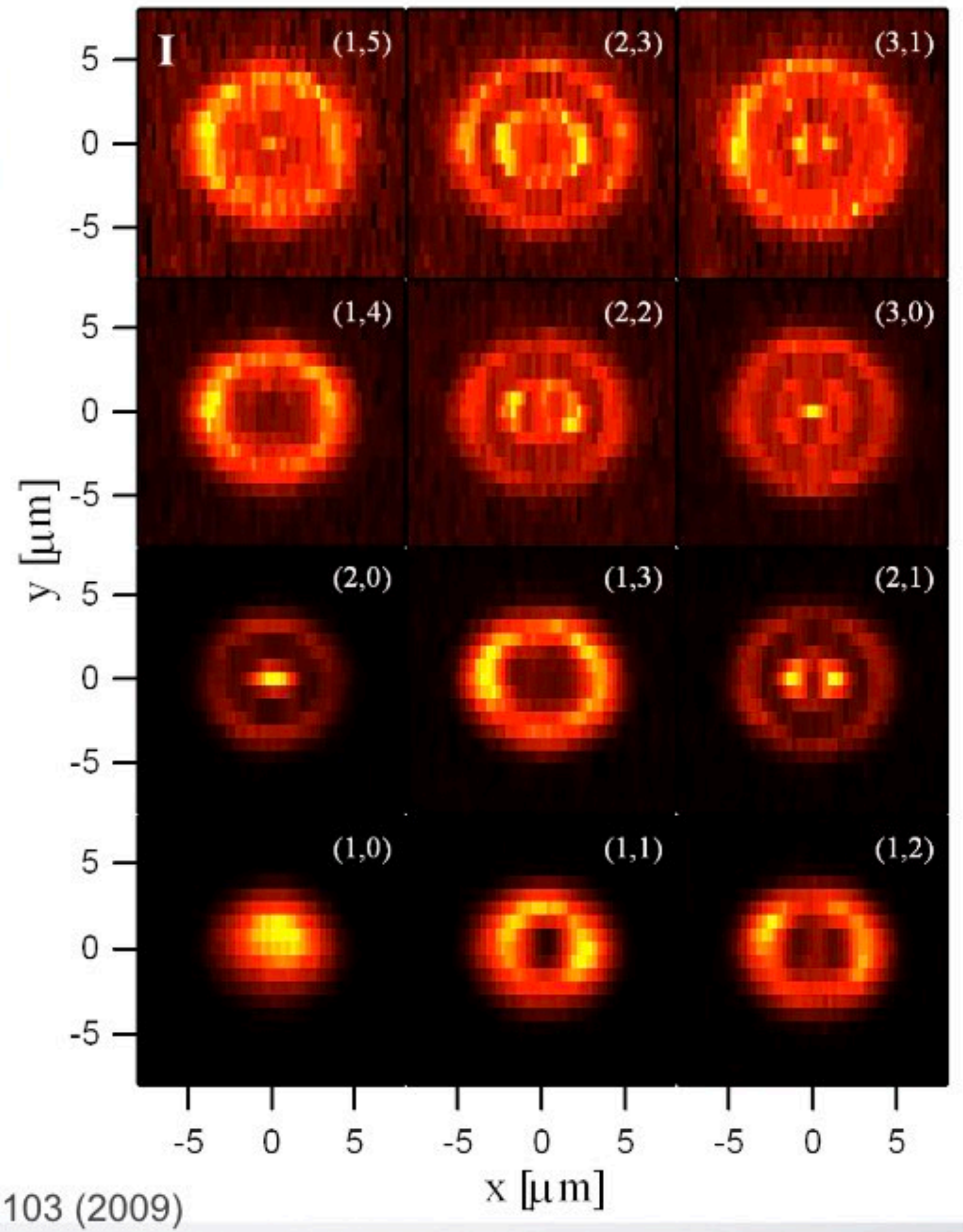
G. Nardin, et al. Applied Physics Letters, 94, 181103 (2009)

Full wave-function imaging

amplitude and phase detection

9μm box

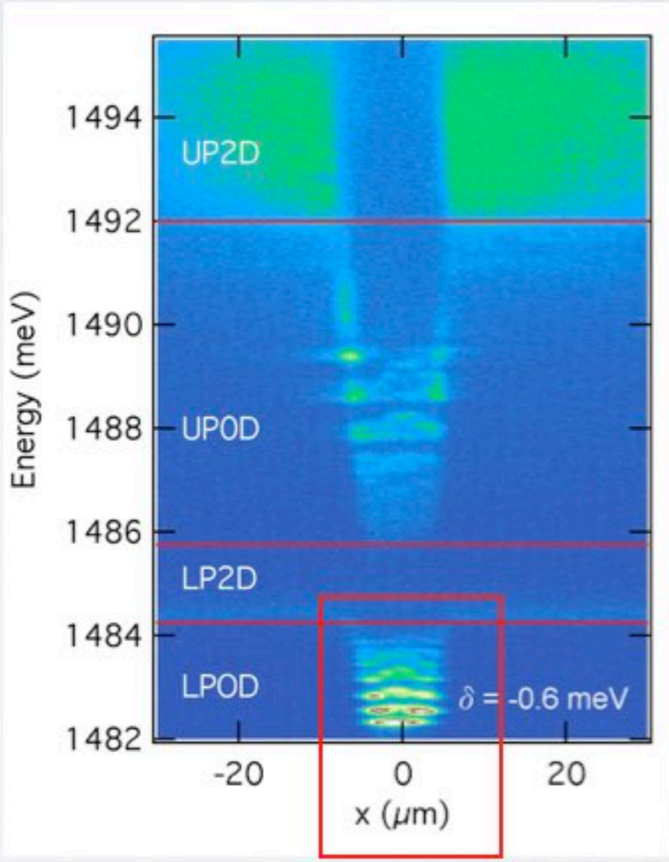
« Tomographic » technique : No Symmetry breaking



- Nearly cylindrical symmetry
- Symmetry can be broken by laser (with resonant excitation)

G. Nardin, et al. Applied Physics Letters, 94, 181103 (2009)

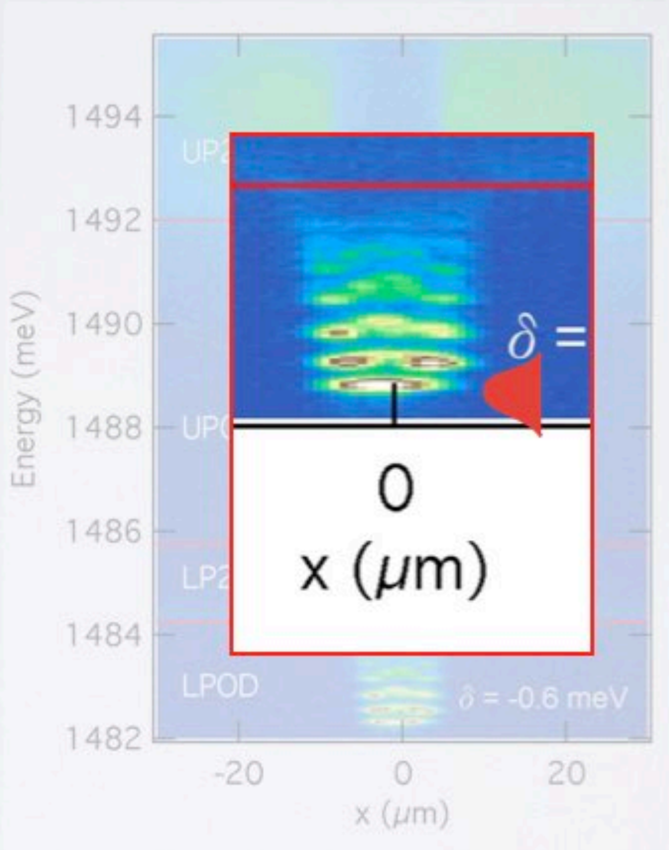
Selective excitation of particular state
laser induced symmetry breaking

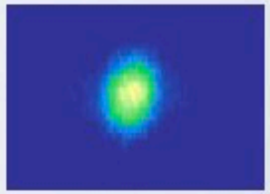


T. Paraiso, PhD, EPFL, Lasuanne, Switzerland

Selective excitation of particular state

laser induced symmetry breaking





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Selective excitation of particular state

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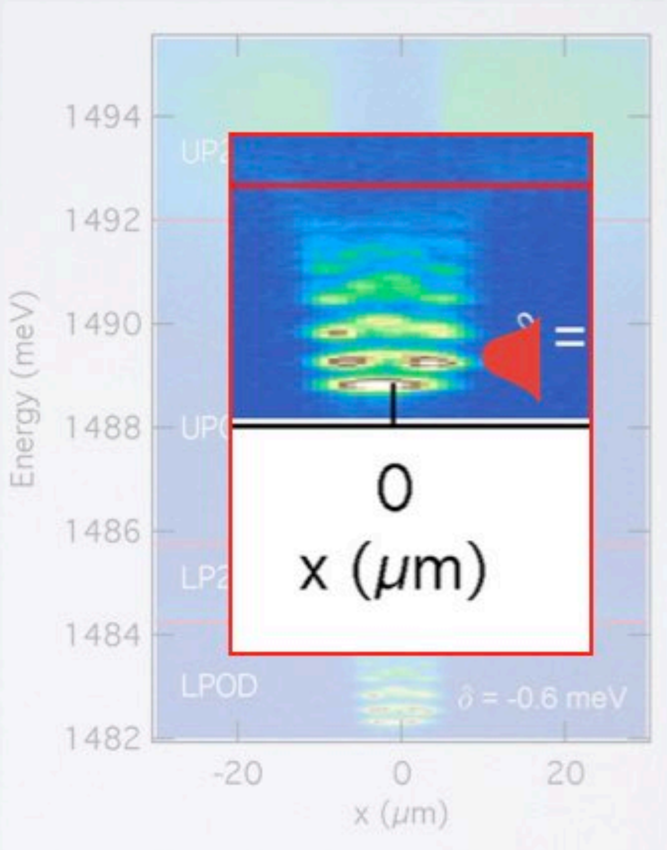

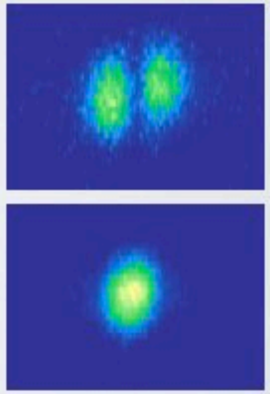

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Selective excitation of particular state

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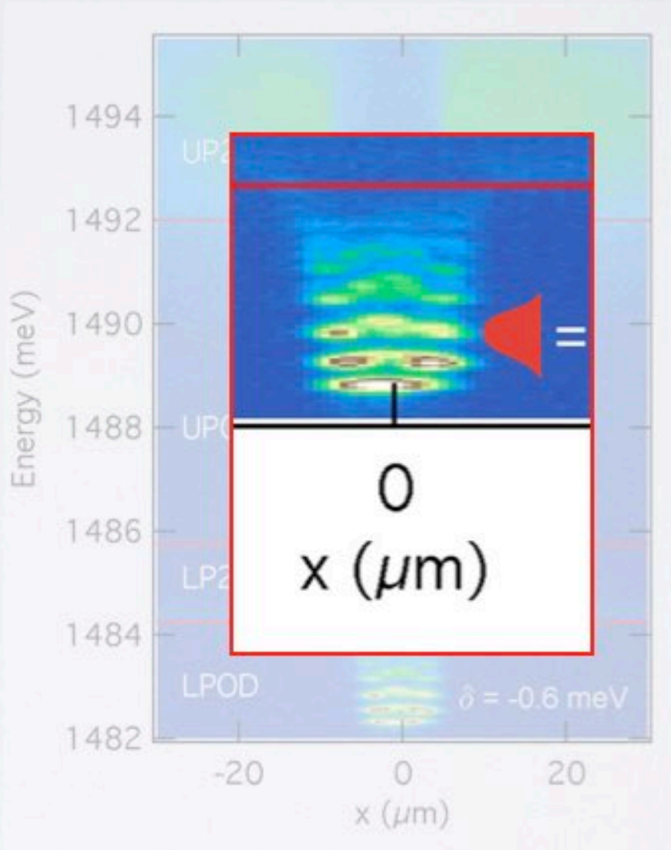

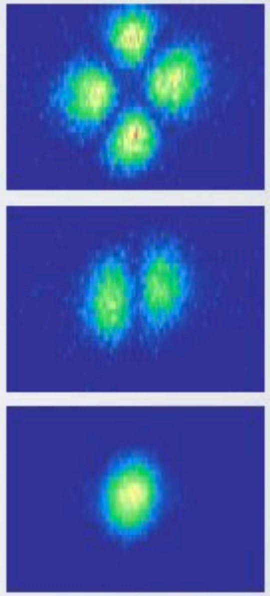

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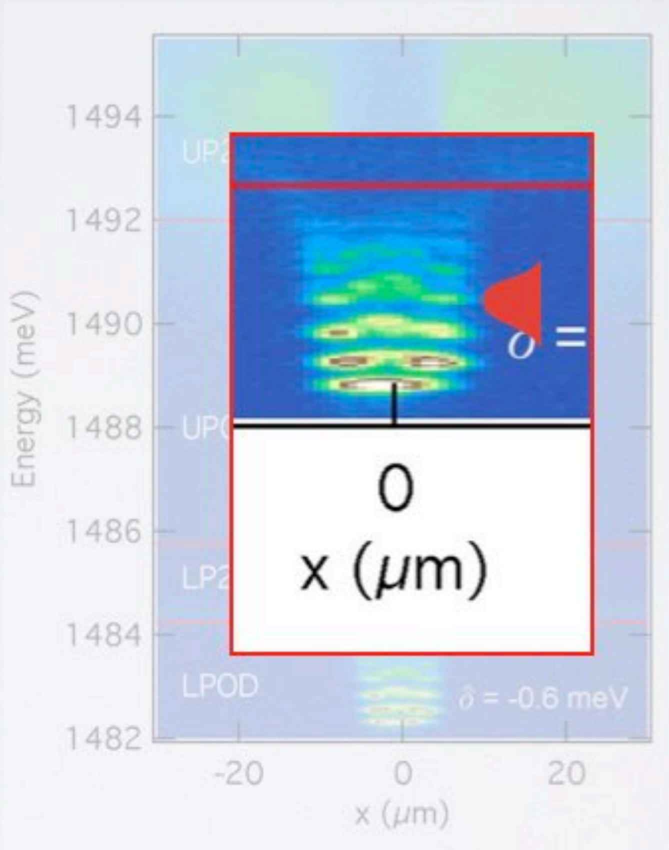
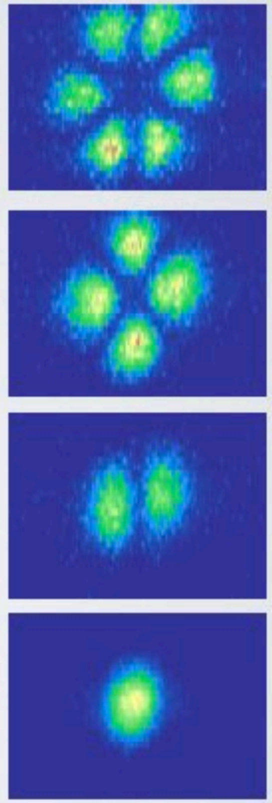
Selective excitation of particular state

laser induced symmetry breaking





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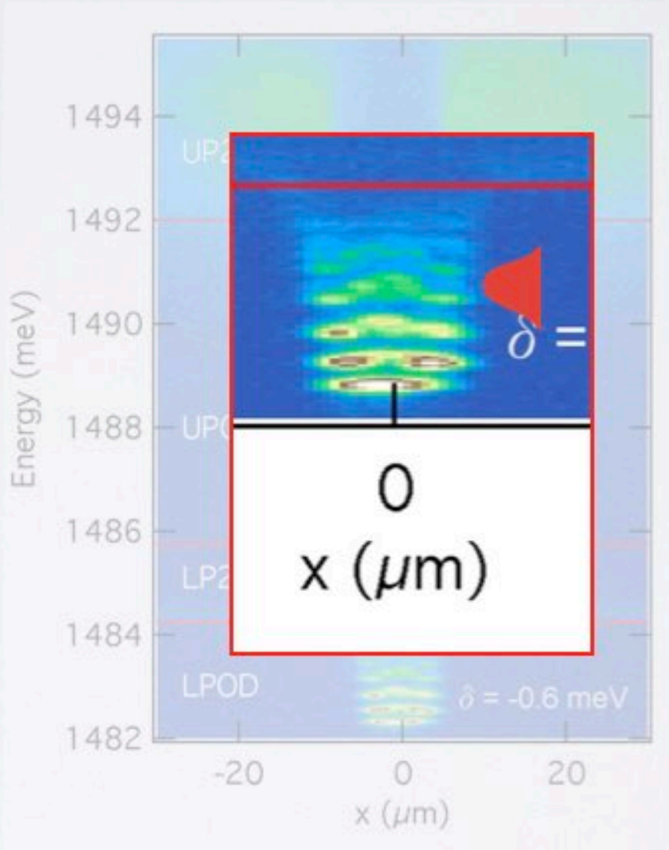
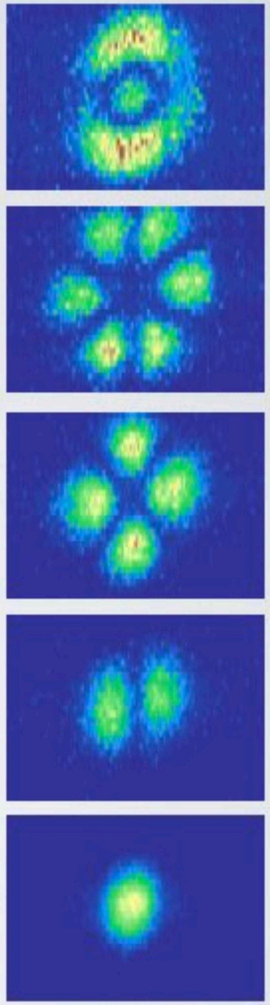
Selective excitation of particular state

laser induced symmetry breaking





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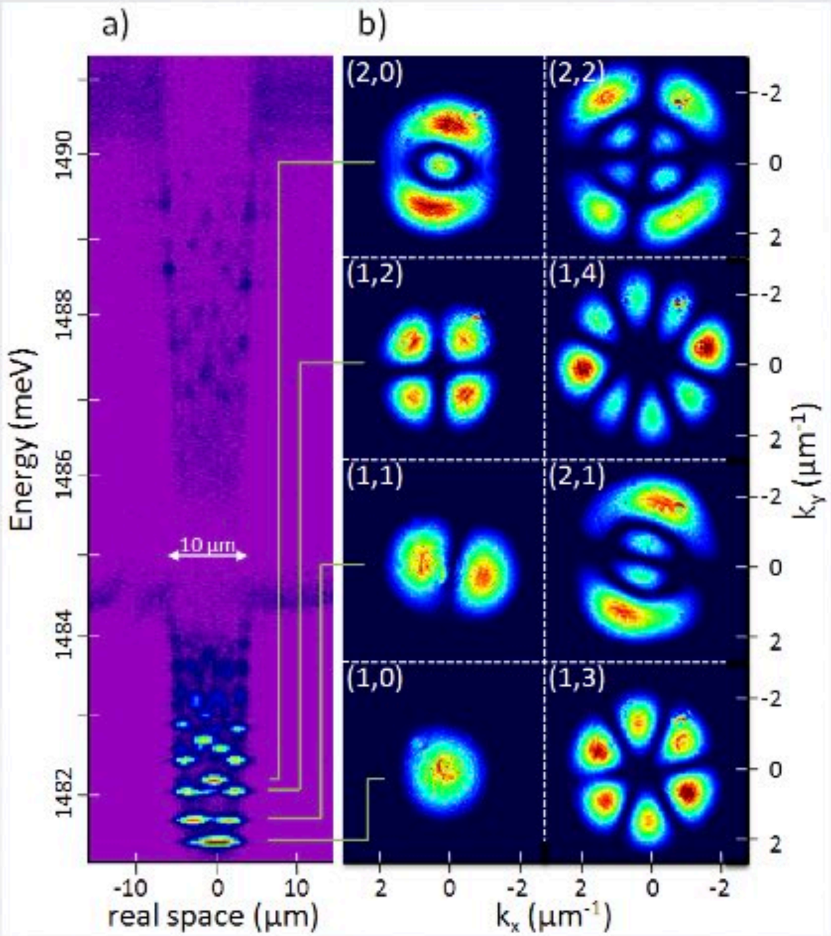
Selective excitation of particular state

laser induced symmetry breaking

Coherent optical control of the wave function of zero dimensional exciton polaritons



R. Cerna, et al. Physical Review B: Rapid Communications, vol. 80, num. 121309, 2009

Selective excitation of particular state

laser induced symmetry breaking

Coherent optical control of the wave function of zero dimensional exciton polaritons

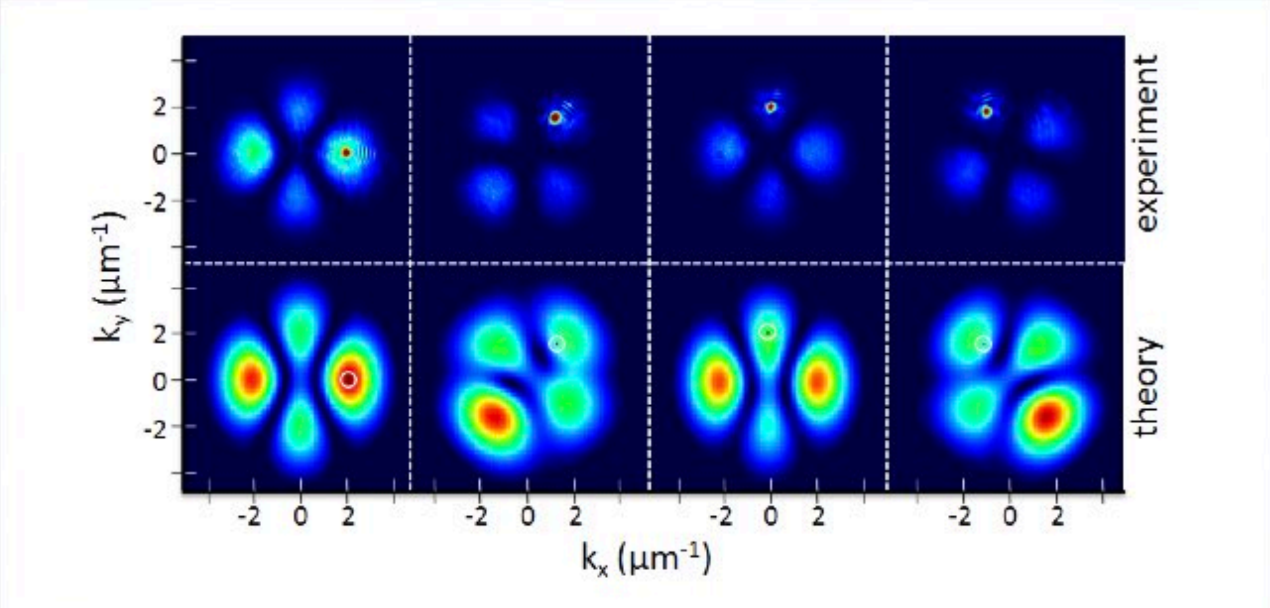
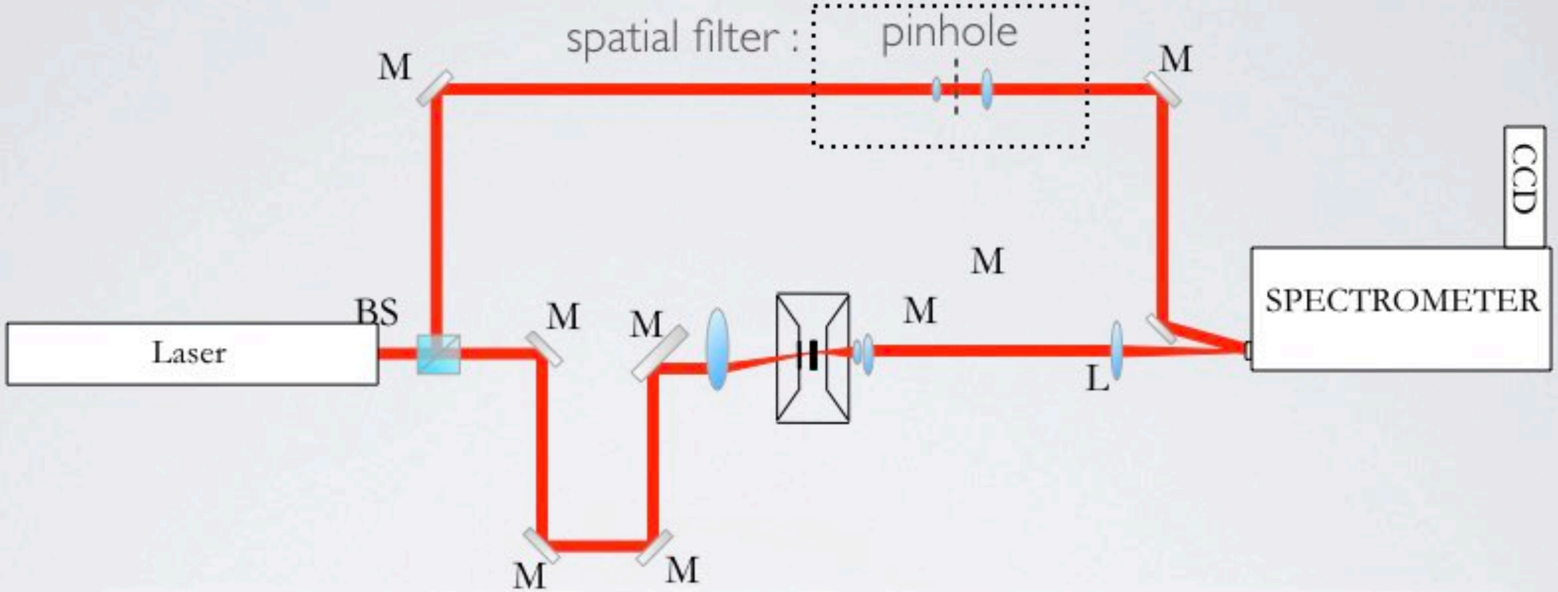


FIG. 2: (Color) Lobes of the degenerate second doublet state in a 3 μm mesa following the rotation of the laser in k-space. The mesa was at zero detuning. The upper part shows the experimental results and the theoretical results from the simulation are shown in the lower part of the figure. The red spot which is visible in each experimental image of this figure is an emission maximum arising from the laser light transmitted directly through the cavity beside the mesa. This makes it easy to observe the excitation angle. In the simulation images the laser position is marked by a circle.

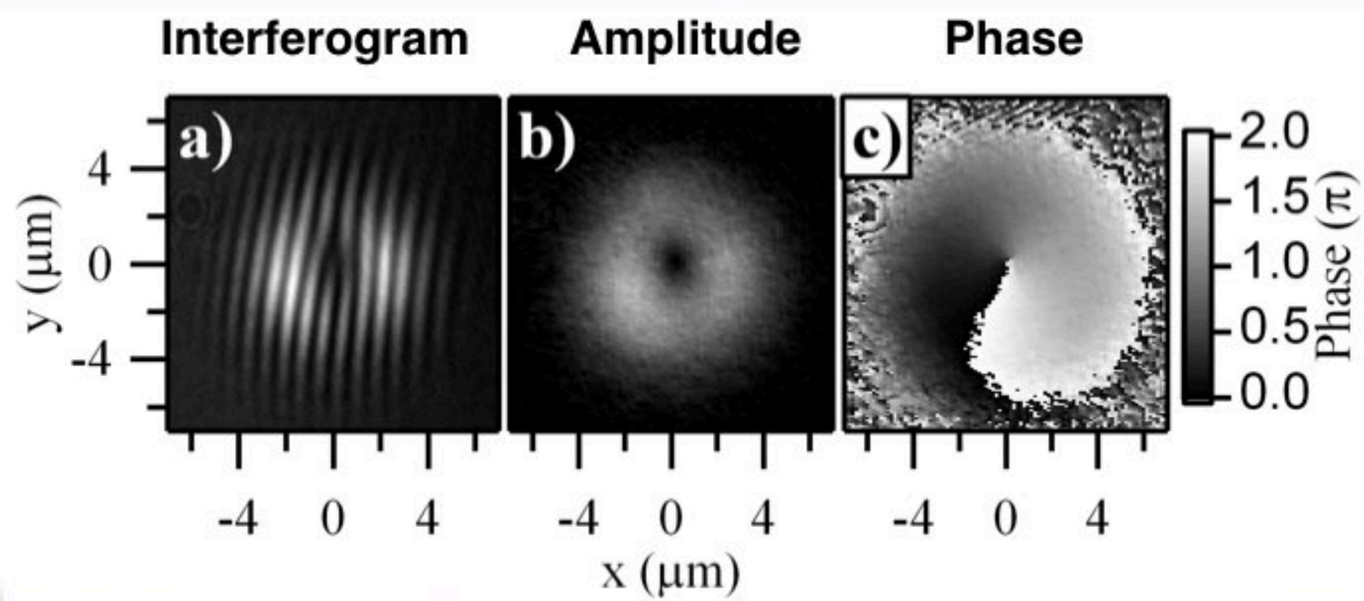
R. Cerna, et al. Physical Review B: Rapid Communications, vol. 80, num. 121309, 2009

Full wave-function imaging

!!! AMPLITUDE & PHASE !!!



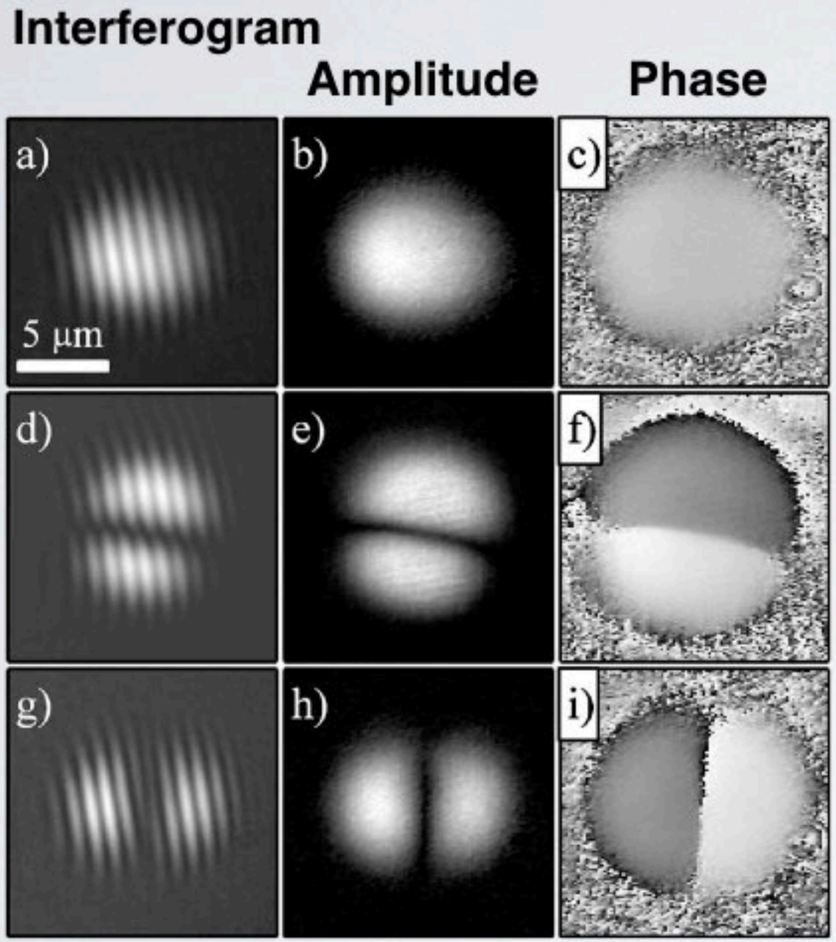
G. Nardin, et al., Physical Review B 82, 045304 (2010)

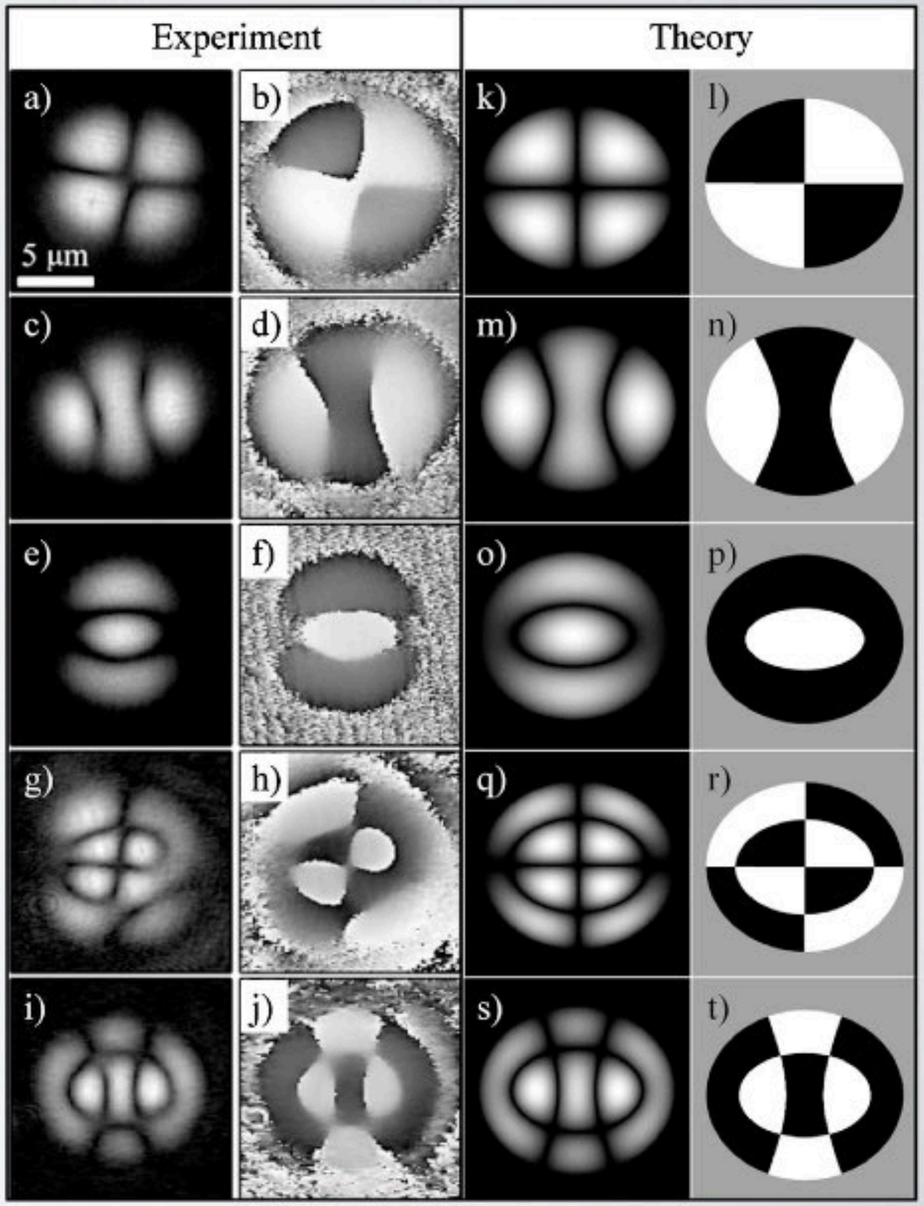


AMPLITUDE & PHASE OF CONFINED STATES

@ resonant excitation

Experiment:



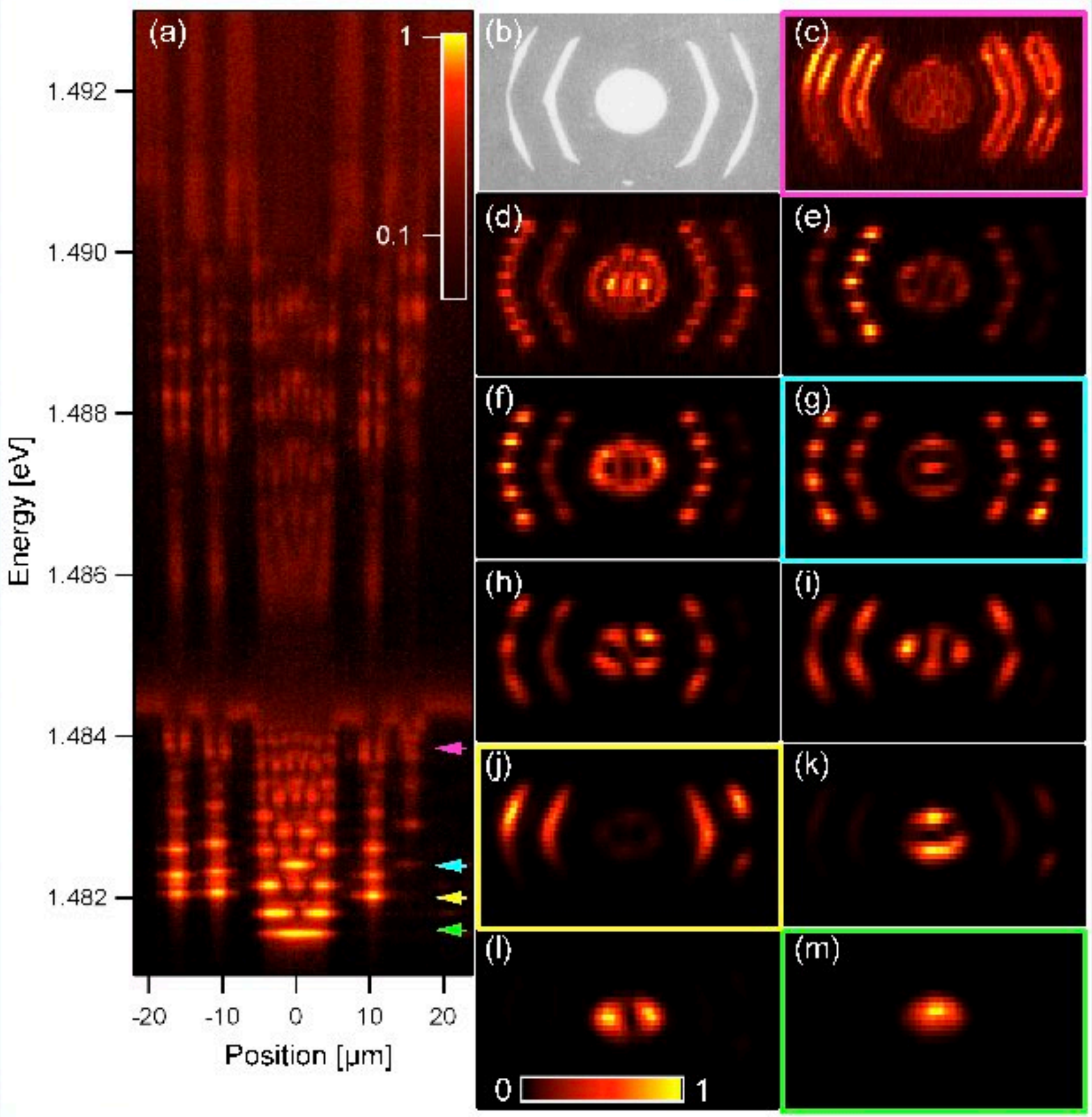


G. Nardin, et al., Physical Review B 82, 045304 (2010)

Polariton confinement

more complicated structures

DOUBLE BRACKET MEZA



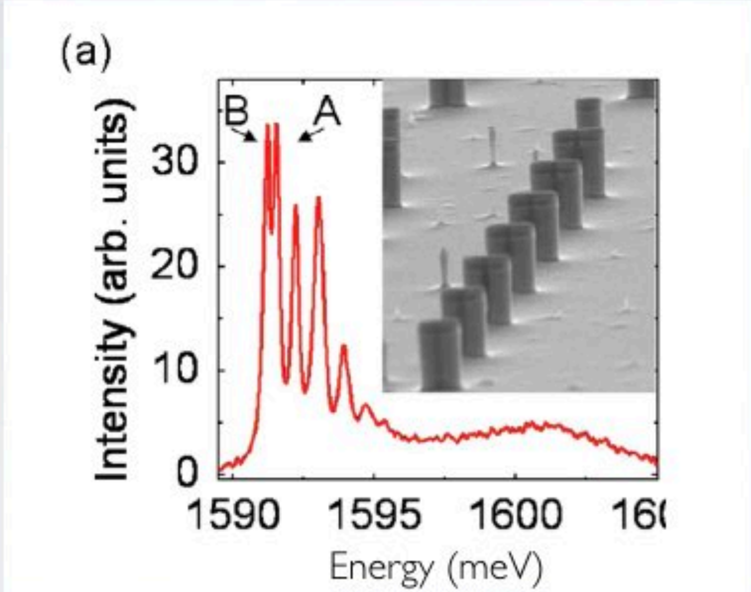
G. Nardin, PhD Thesis, EPFL Lausanne, Switzerland

Polariton molecule
double 0D potential

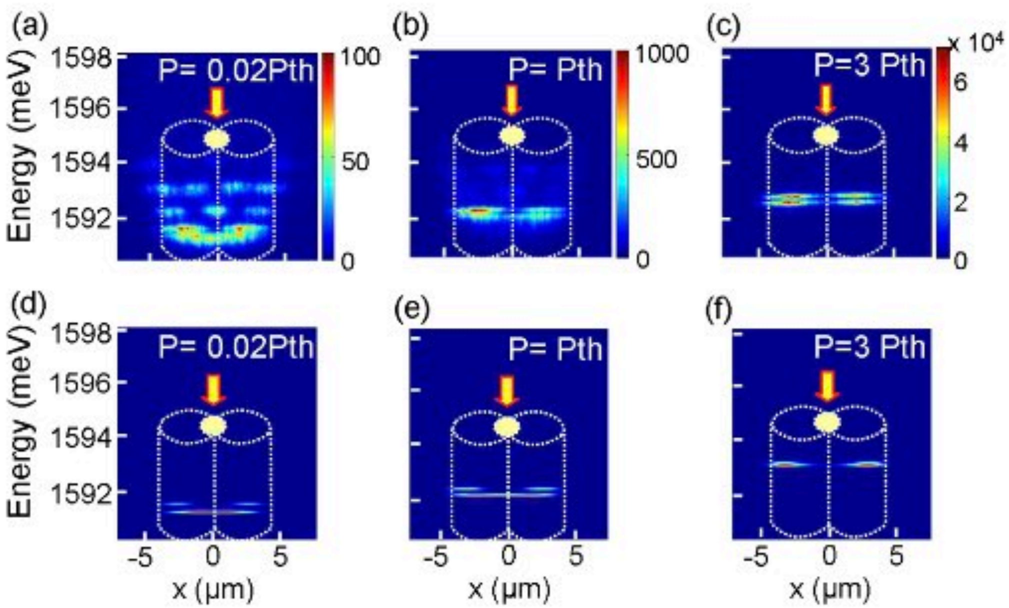
PRL **108,** 126403 (2012) PHYSICAL REVIEW LETTERS week ending 23 MARCH 2012

Polariton Condensation in Photonic Molecules

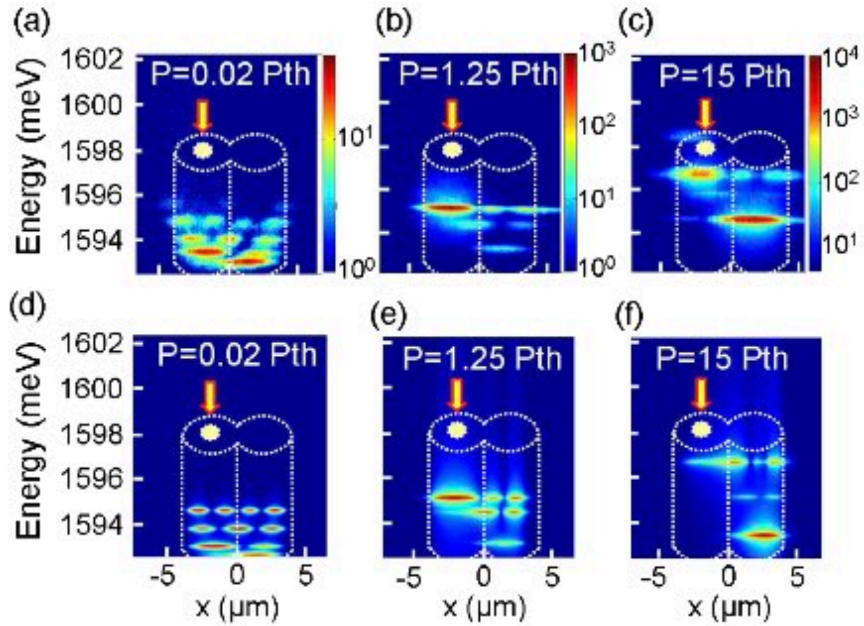
Marta Galbiati,[1] Lydie Ferrier,[1] Dmitry D. Solnyshkov,[2] Dimitrii Tanese,[1] Esther Wertz,[1] Alberto Amo,[1] Marco Abbarchi,[1] Pascale Senellart,[1] Isabelle Sagnes,[1] Aristide Lemaître,[1] Elisabeth Galopin,[1] Guillaume Malpuech,[2] and Jacqueline Bloch[1,*]



symmetric excitation - condensation in GS



asymmetric excitation - condensation in metastable state

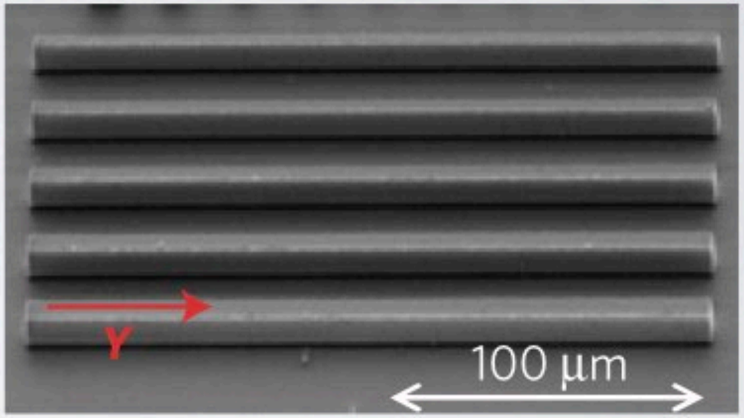


Propagating condensate
1D potential

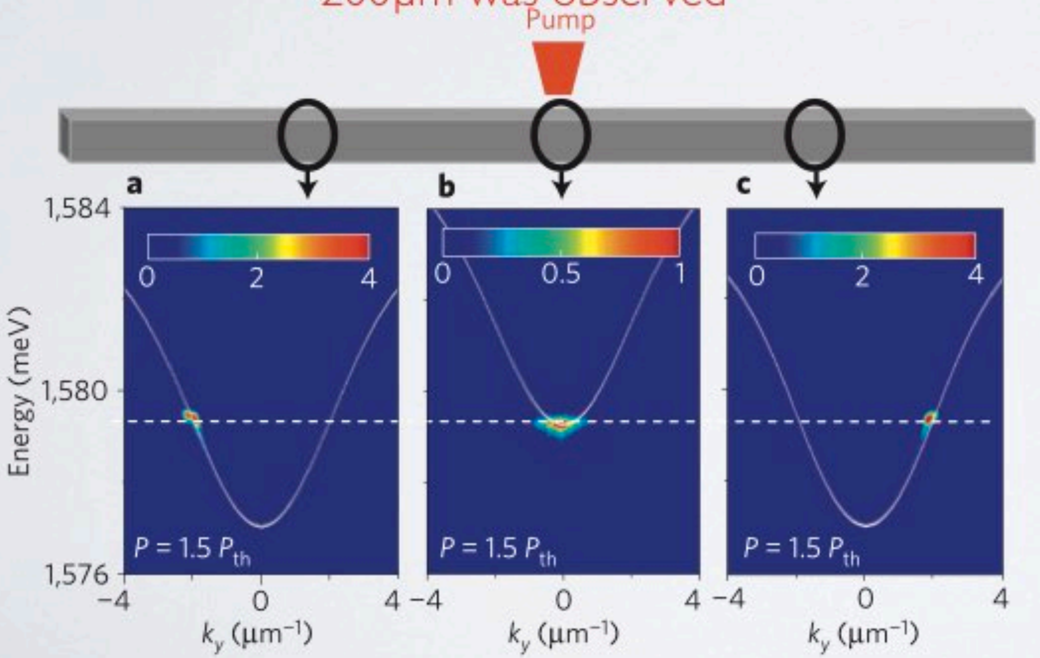
LETTERS
PUBLISHED ONLINE: 29 AUGUST 2010 | DOI:10.1038/NPHYS1750
nature physics

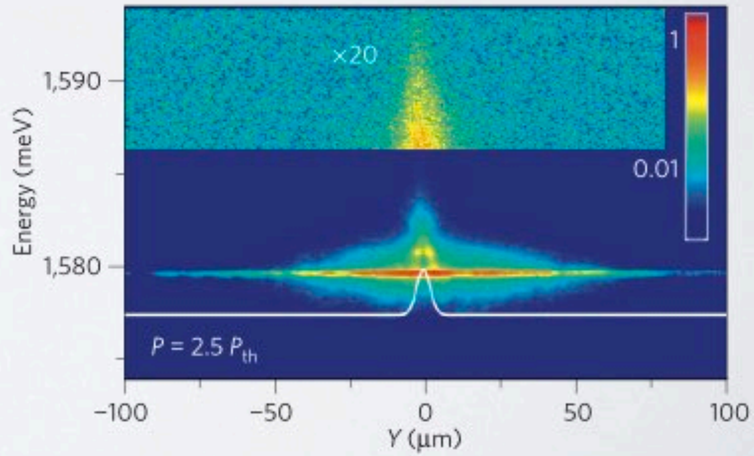
Spontaneous formation and optical manipulation of extended polariton condensates

E. Wertz[1], L. Ferrier[1], D. D. Solnyshkov[2], R. Johne[2], D. Sanvitto[3], A. Lemaître[1], I. Sagnes[1], R. Grousson[4], A. V. Kavokin[5], P. Senellart[1], G. Malpuech[2] and J. Bloch[1]*



the polariton propagation up to 200µm was observed





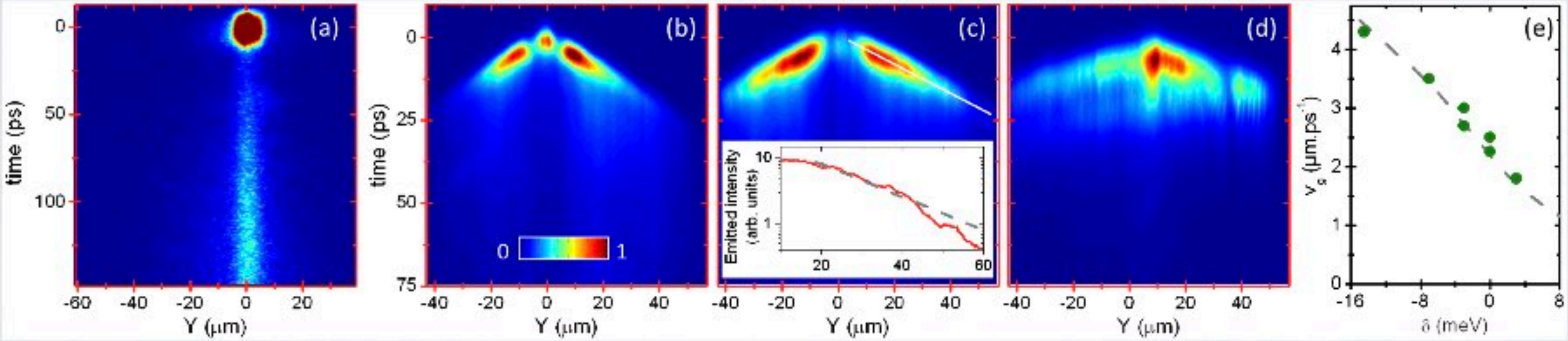
Propagating condensate

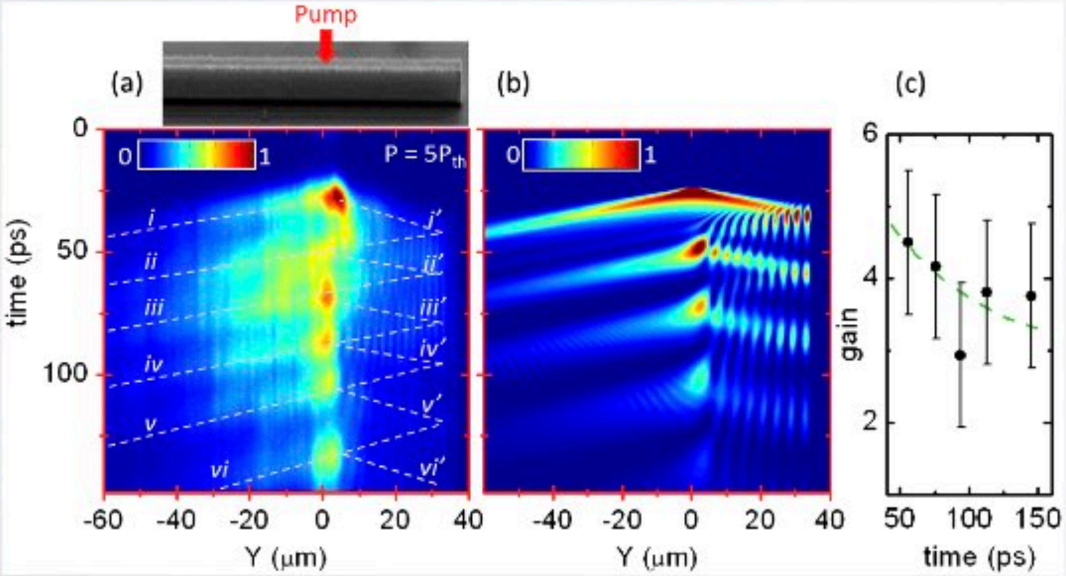
1D potential

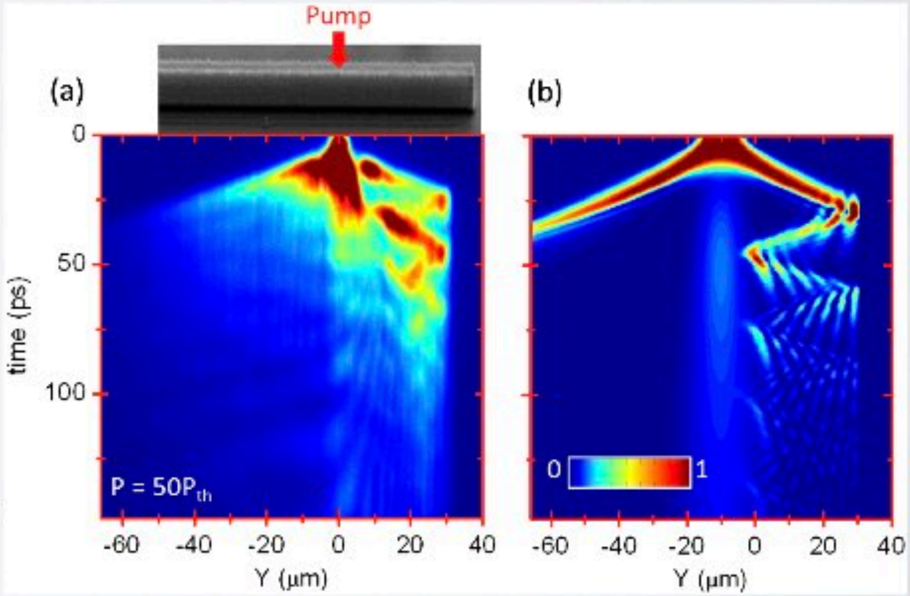
PRL 109, 216404 (2012) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2012

Propagation and Amplification Dynamics of 1D Polariton Condensates

E. Wertz,[1] A. Amo,[1] D. D. Solnyshkov,[2] L. Ferrier,[1] T. C. H. Liew,[3] D. Sanvitto,[4,5] P. Senellart,[1] I. Sagnes,[1] A. Lemaître,[1] A. V. Kavokin,[6,7] G. Malpuech,[2] and J. Bloch[1,*]







Polariton band structure
1D periodic potential

D.Tanese et al. Nature Commun. (2013)

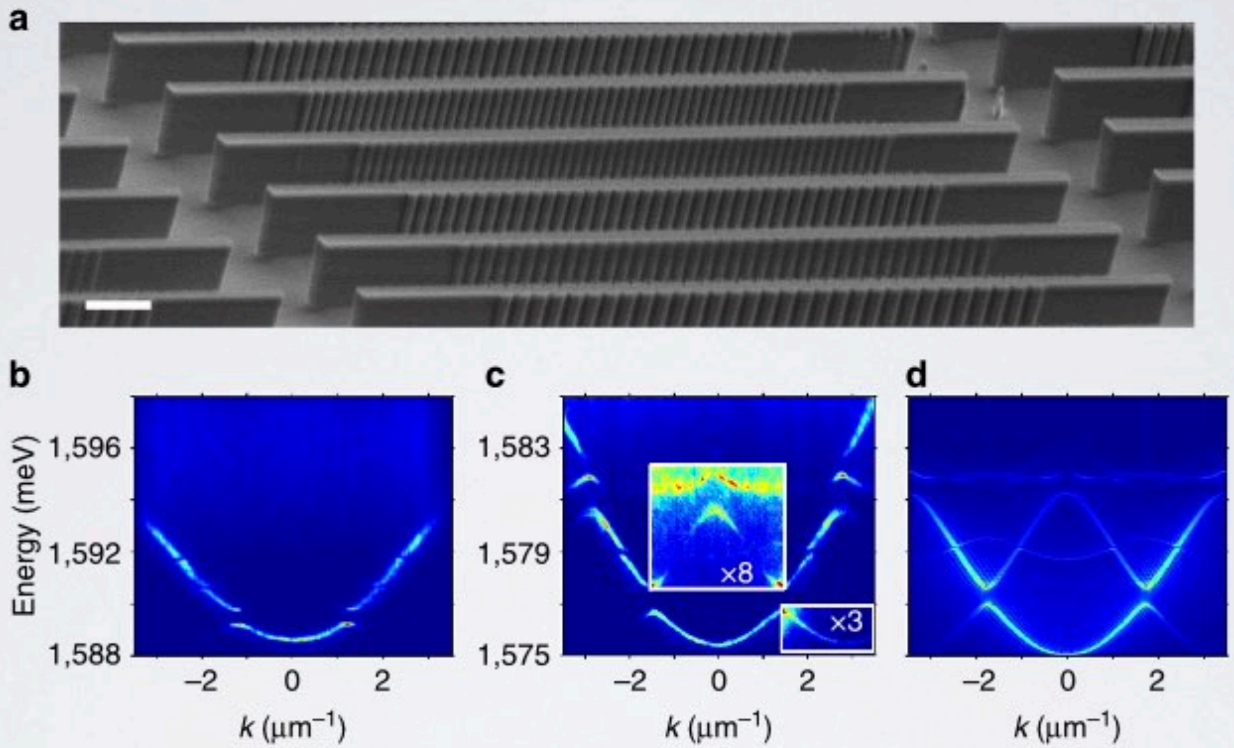


Figure 1 | Polariton dispersion in modulated microwires. (**a**) Scanning electron microscopy image of an array of laterally modulated wires; the white scale bar corresponds to a length of 10 μm. (**b**) Angle-resolved emission measured on a single modulated wire in the low density regime; the modulation period is $P = 2.7$ μm and the wire width is modulated between $W_{min} = 1.9$ μm and $W_{max} = 2.8$ μm, inducing a periodic potential of amplitude $V_{opt} = 1.6$ meV on the cavity mode, the detuning is $\delta = -1$ meV ($E_c = 1{,}595.5$ meV, $E_x = 1{,}596.5$ meV). (**c**) Same as (**b**) with $P = 2.1$ μm, $W_{min} = 1.8$ μm and $W_{max} = 3.5$ μm inducing a periodic potential $V_{opt} = 2.4$ meV, $\delta = -9.5$ meV ($E_c = 1{,}579.5$ meV, $E_x = 1{,}589$ meV). The signal inside the rectangles has been amplified to better show the band folding. (**d**) Simulated polariton dispersion of the wire shown in (**c**).

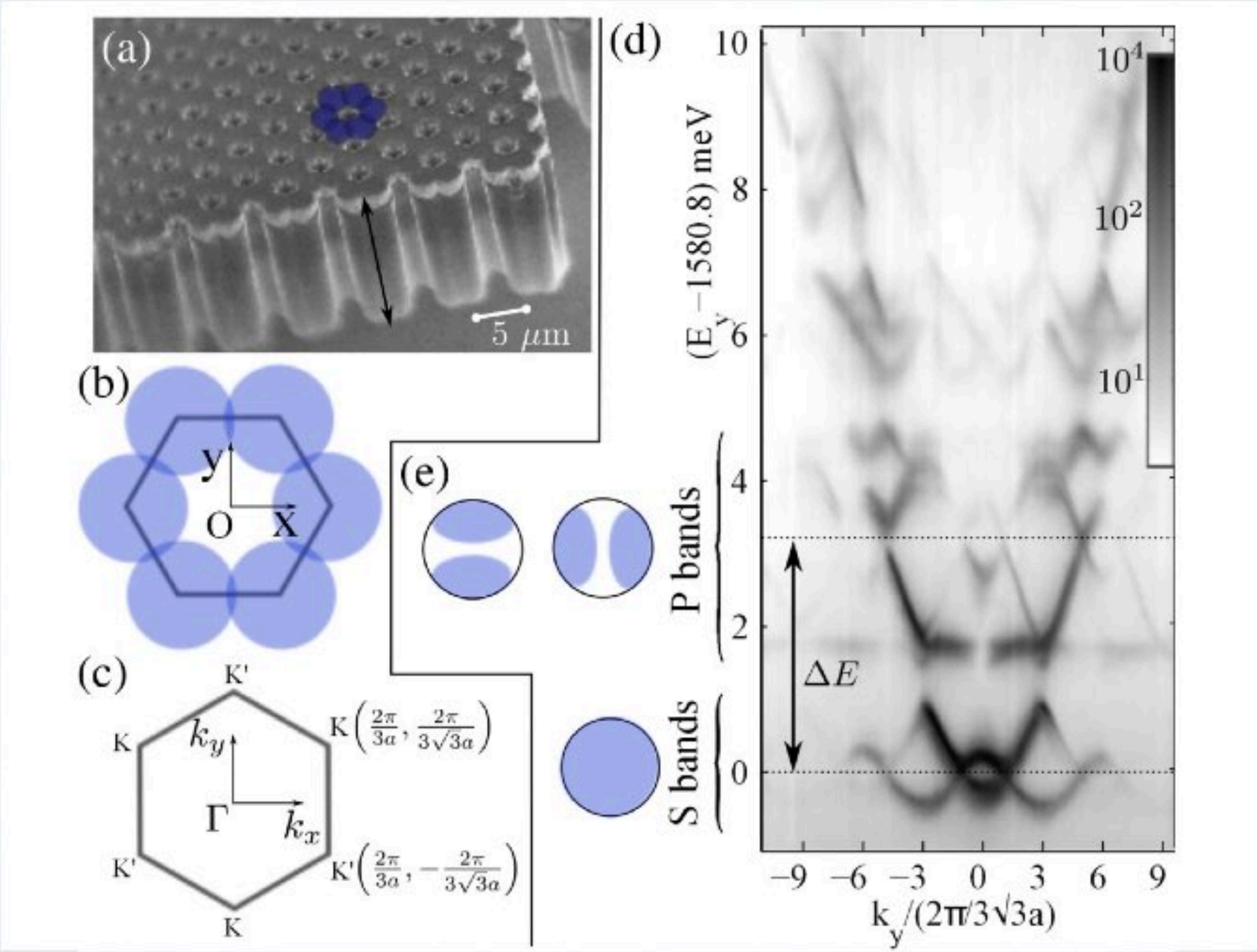
Exciton - polariton graphene

0D potential in a lattice

PRL **112,** 116402 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

Direct Observation of Dirac Cones and a Flatband in a Honeycomb Lattice for Polaritons

T. Jacqmin,[1] I. Carusotto,[2] I. Sagnes,[1] M. Abbarchi,[1,*] D. D. Solnyshkov,[3] G. Malpuech,[3] E. Galopin,[1] A. Lemaître,[1] J. Bloch,[1] and A. Amo[1]



Exciton - polariton graphene

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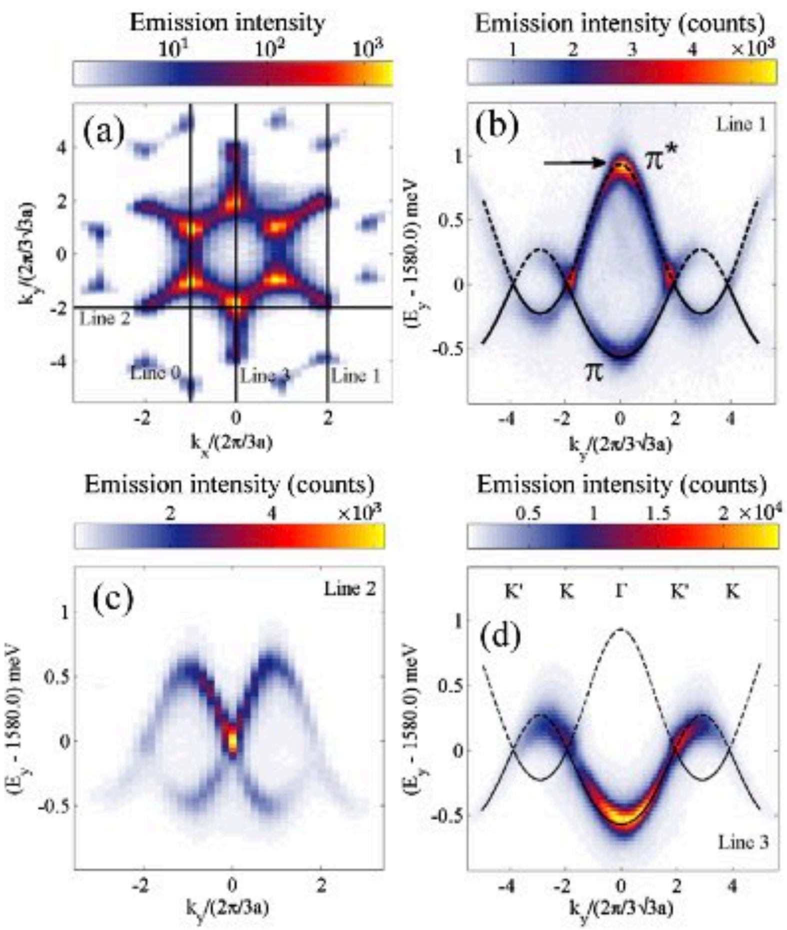
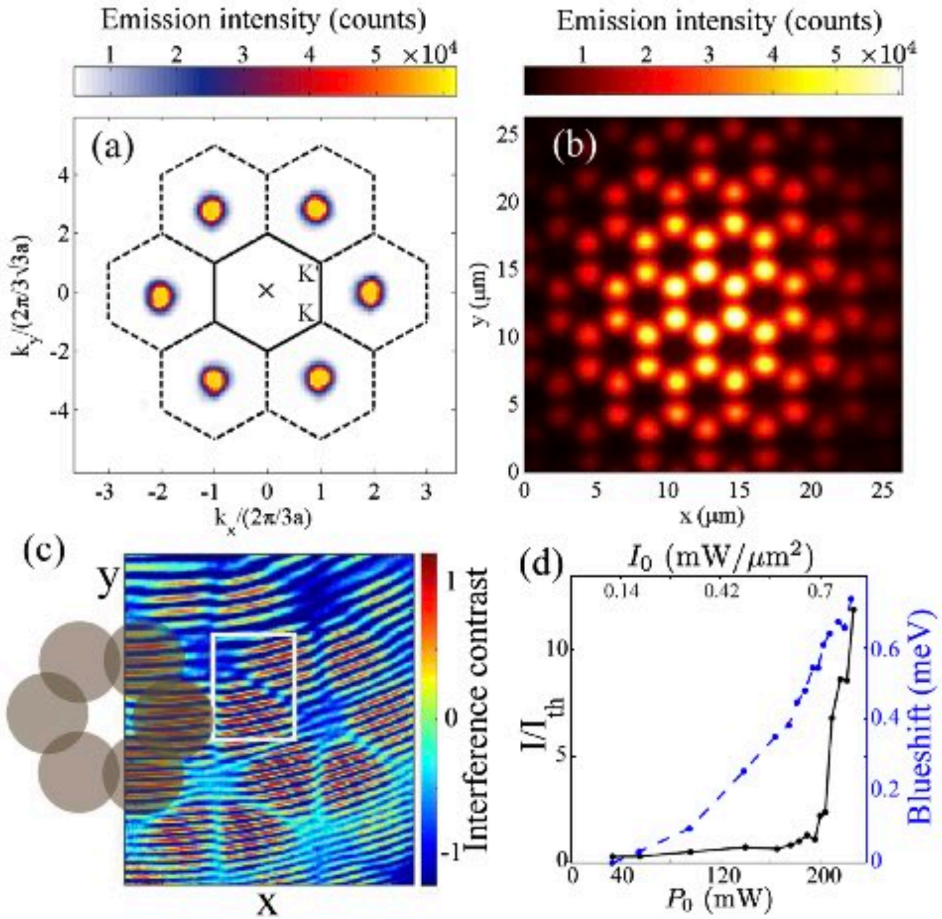




Exciton - polariton Sagnac interferometer

shaped 1D potential

C. Strum, et al. Nature Commun (2014)

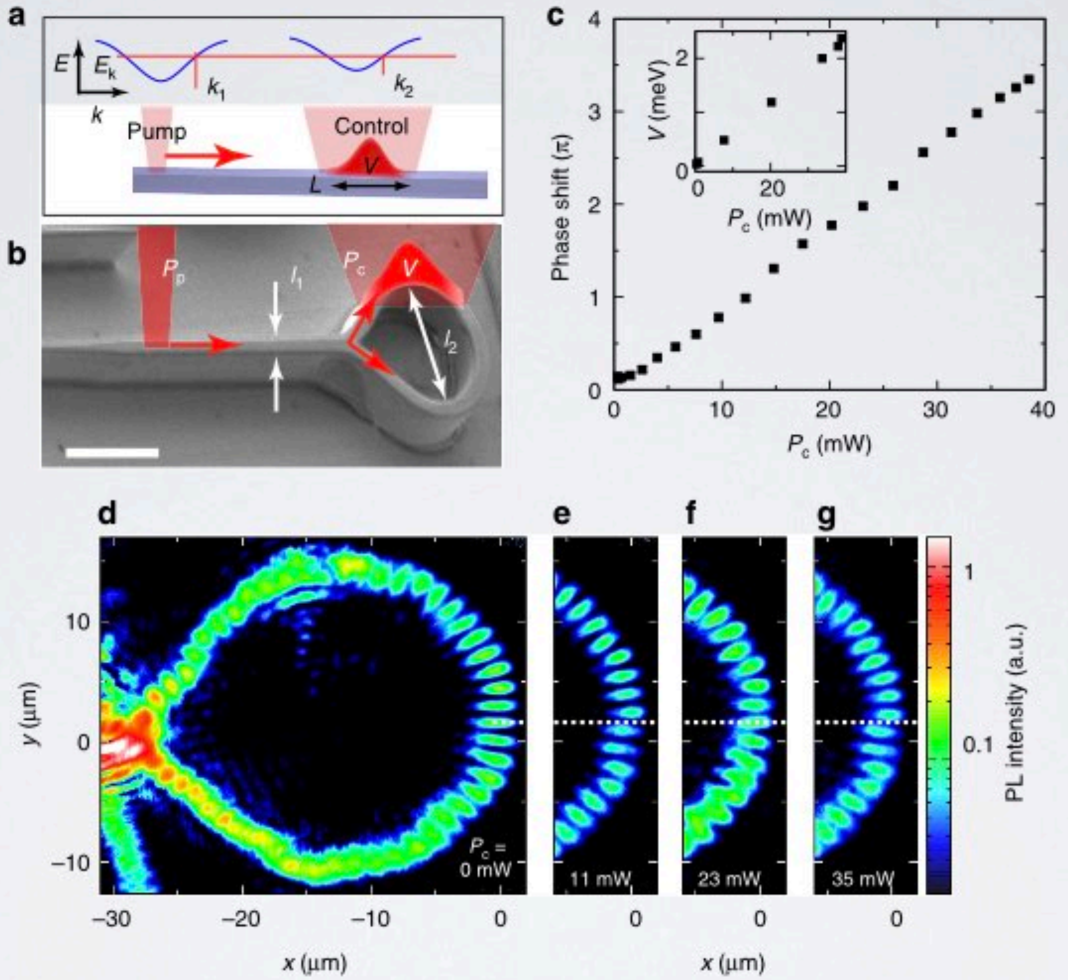


Figure 1 | Sagnac interferometer. (**a**) Schematic of the mechanism used to slow down the polariton flow. (**b**) SEM image of the SI; the white scale bar corresponds to a length of 20 μm and l_1 and l_2 corresponds to 3 and 25 μm, respectively. (**c**) Measured phase shift as a function of P_c. The uncertainty is about $\pm 5 \times 10^{-2}\,\pi$; inset: measured potential height V as a function of P_c. (**d**–**g**) Real-space imaging of polariton emission in the SI device for $P_c = 0$ mW, 11 mW, 23 mW and 35 mW.

output and polarization can be optically controlled

Exciton - polariton Mach-Zender interferometer

shaped 1D potential

C. Strum, et al. Nature Commun (2014)

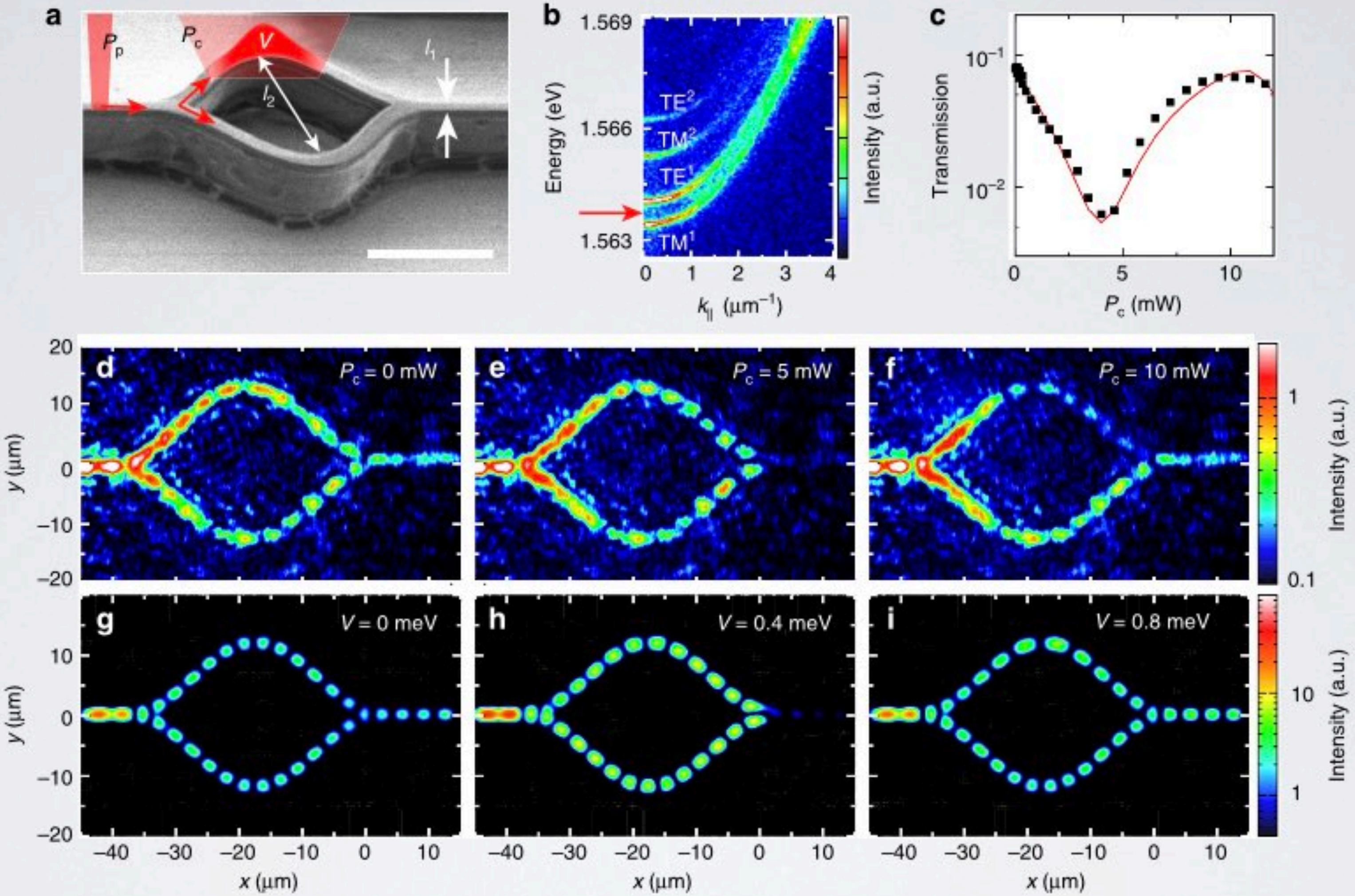


Figure 2 | Modulation of the MZI transmission. (**a**) SEM image of the polariton MZI; the white scale bar corresponds to a length of 20 μm and l_1 and l_2 corresponds to 3 and 25 μm, respectively. (**b**) Measured polariton dispersion. The red arrow indicates energy of injected polariton flow. (**c**) (black squares) Measured transmission as a function of P_c (red line) calculated transmission using equation (1) assuming a rectangular potential profile and a polariton lifetime of 20 ps. (**d–f**) Spatially resolved polariton emission measured for different values of P_c; (Note that the modulation of the signal at the output is probably caused by disorder) (**g–i**) Calculated emission pattern for different heights of a Gaussian ($\sigma = 4\,\mu m$) induced potential (parameters: $E_k = 0.8$ meV, $m = 4 \times 10^{-5}\, m_0$). (The fringes in the output are caused by polaritons backscattered from the end of the device.)

output and polarization can be optically controlled

Exciton - polariton resonant tunelling diode

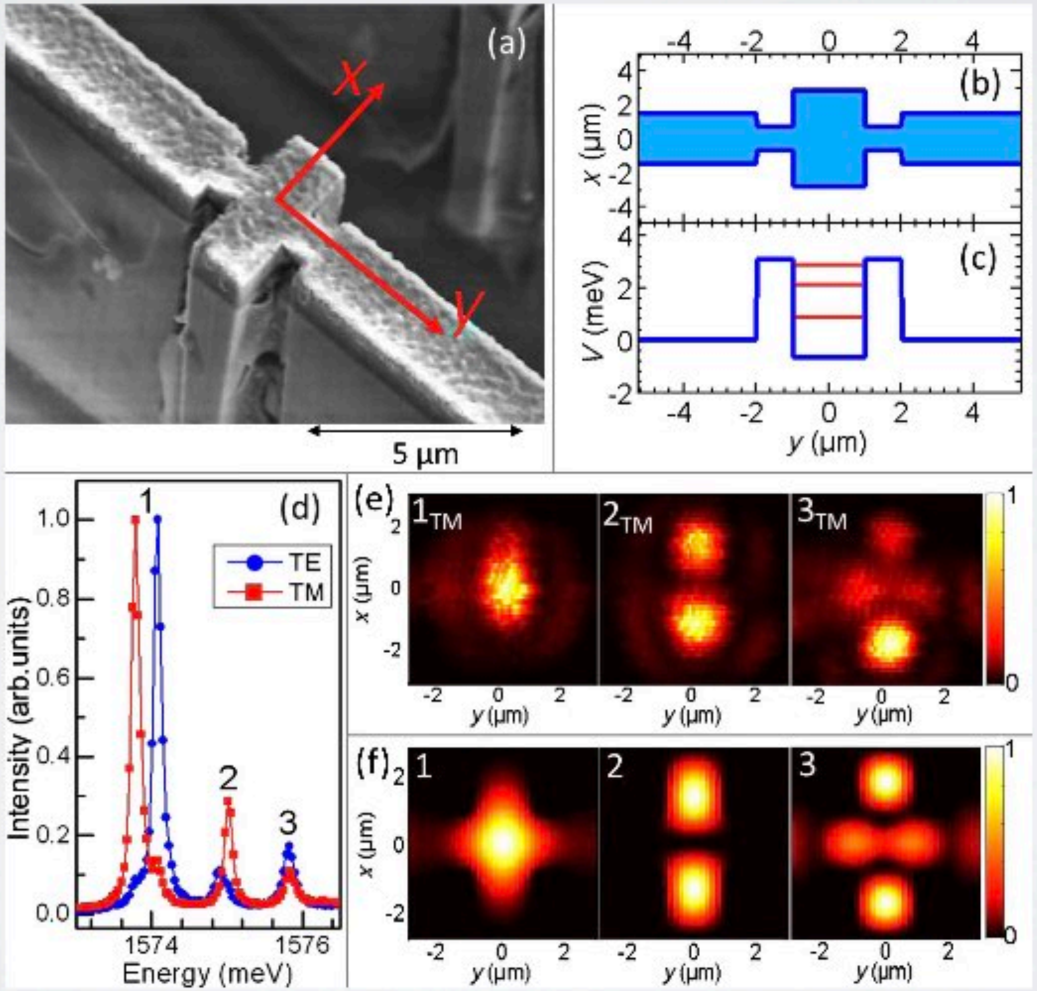
shaped 1D potential

Selected for a Viewpoint in *Physics*

PRL **110,** 236601 (2013) PHYSICAL REVIEW LETTERS week ending 7 JUNE 2013

Realization of a Double-Barrier Resonant Tunneling Diode for Cavity Polaritons

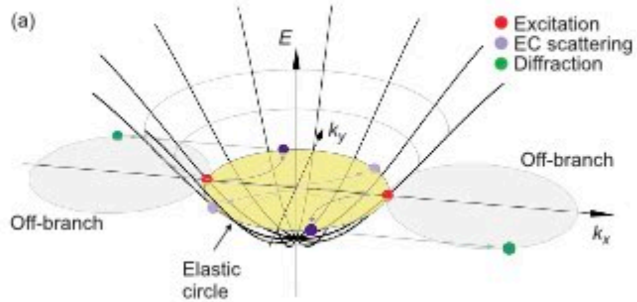
H. S. Nguyen,[1] D. Vishnevsky,[2] C. Sturm,[1] D. Tanese,[1] D. Solnyshkov,[2] E. Galopin,[1] A. Lemaître,[1] I. Sagnes,[1] A. Amo,[1] G. Malpuech,[2] and J. Bloch[1,*]



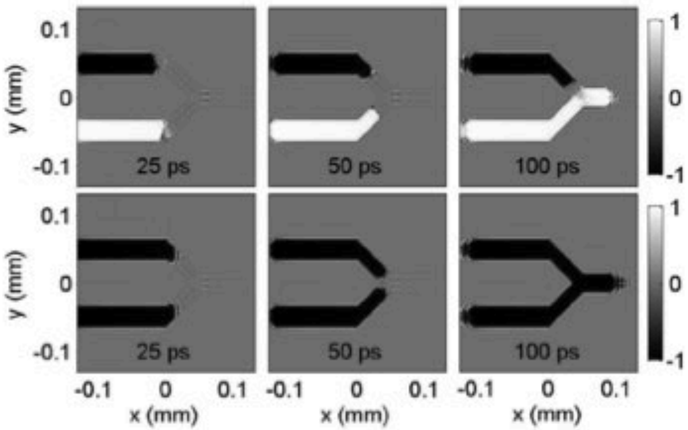
THEORETICAL PROPOSALS – NEAR FUTURE REALITY ?

Polariton logic gates polarization controlled

T. Ostatnicky et al., PRB 81, 125319 2010

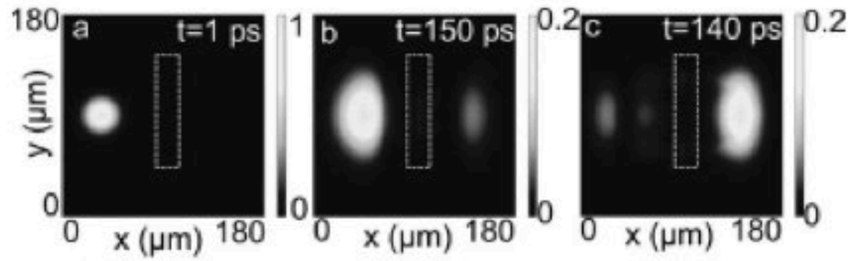


POLARITON « NEURONS » – OPTICAL CIRCUITS



T.C.H Liew *et al*,PRL **101**, 016402 (2008)

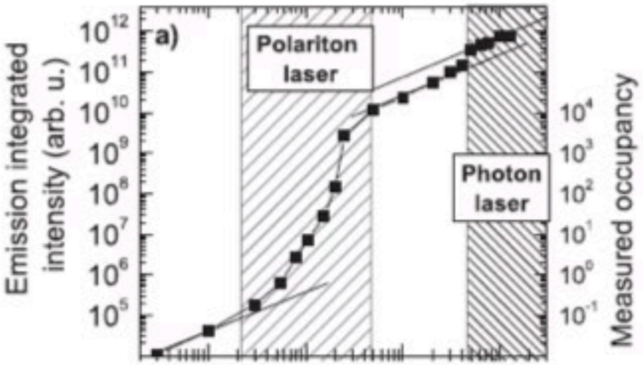
Spin Transistors



R. Johne *et al*, Phys. Rev. B **81**, 125327 (2010)

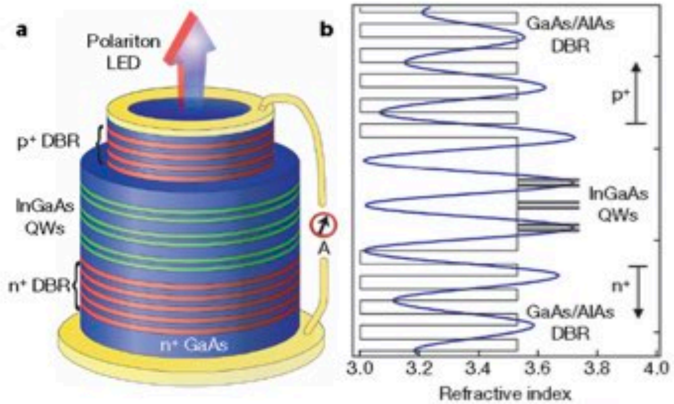
« POLARITRONIC » DEVICES

Polariton Lasers



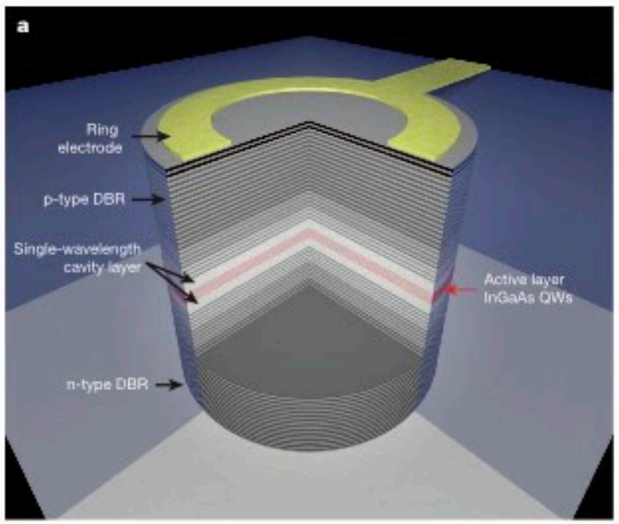
D. Bajoni *et al*, PRL **100**, 047401 (2008)

Polariton LED near room temperature



Tsintzos, S. I., et al. *Nature* **453**, 372–375 (2008).

An electrically pumped polariton laser, C. Schneider, et al., *Nature* **497**, 348–352 (2013)



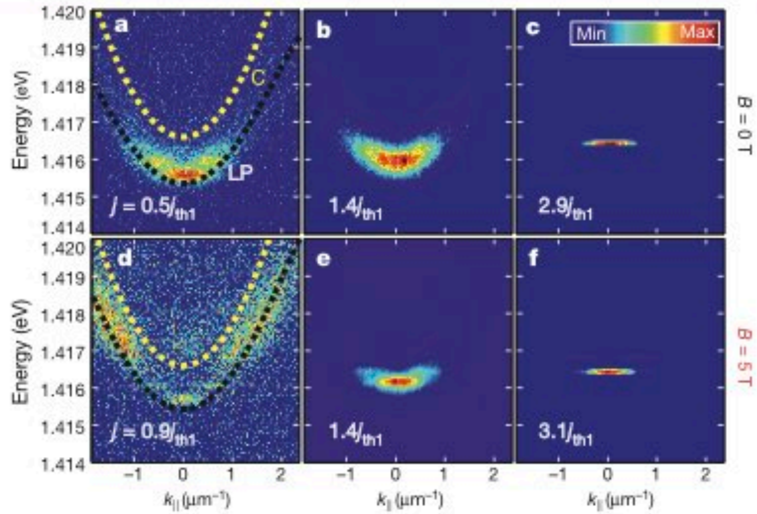


Figure 2 | Spectral emission features in various excitation regimes. **a–c**, Energy–momentum dispersions ($k_{||}$, in-plane wavevector) with false-colour intensity profiles (normalized to maximum intensity) corresponding to current densities, *j*, of ~44, ~113 and ~241 A cm^{-2} at 0 T. Below threshold, the polaritonic system is characterized by a thermal distribution of particles (**a**). High ground-state population is observed at higher injection currents (**b**). At even higher pump rates, photonic lasing occurs (**c**). **d–f**, Corresponding dispersions at 5 T exhibiting similar, yet more-pronounced, characteristic transition features.