Quantum fluids of light in semiconductor microcavities

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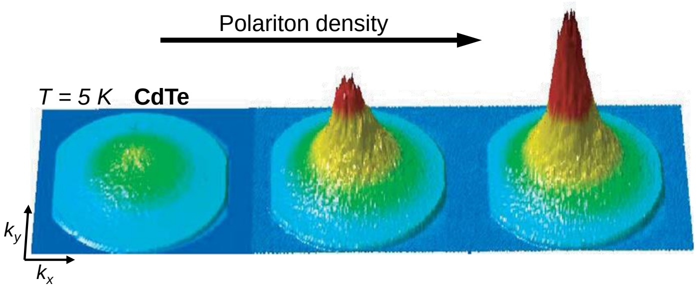
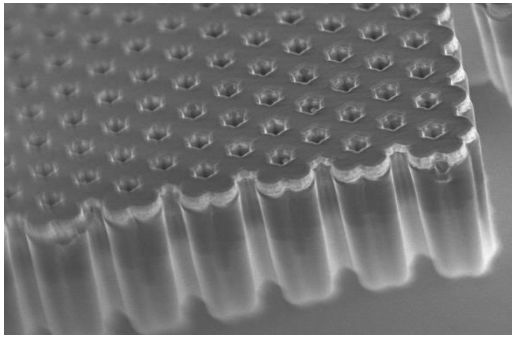
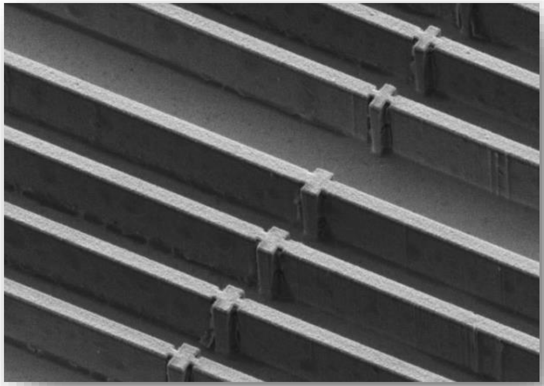
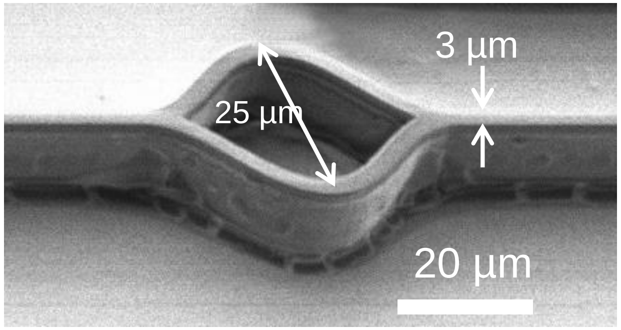
France

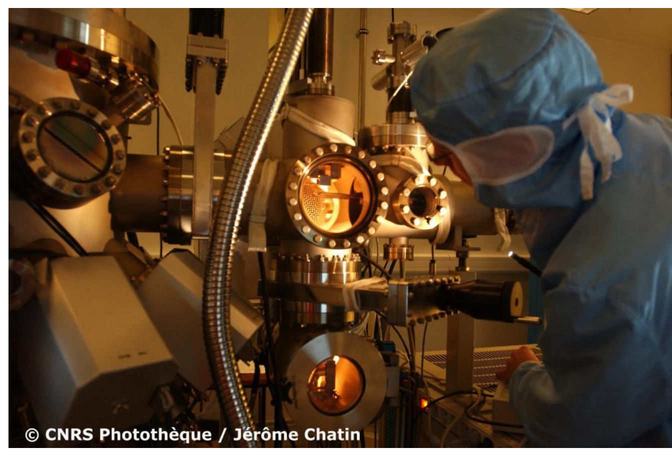


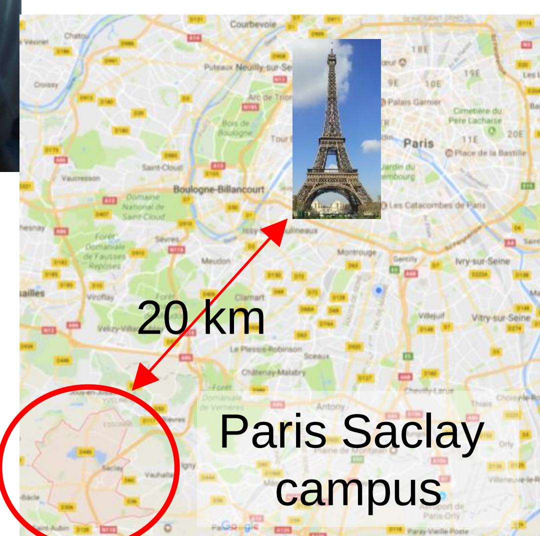






A new laboratory: C2N





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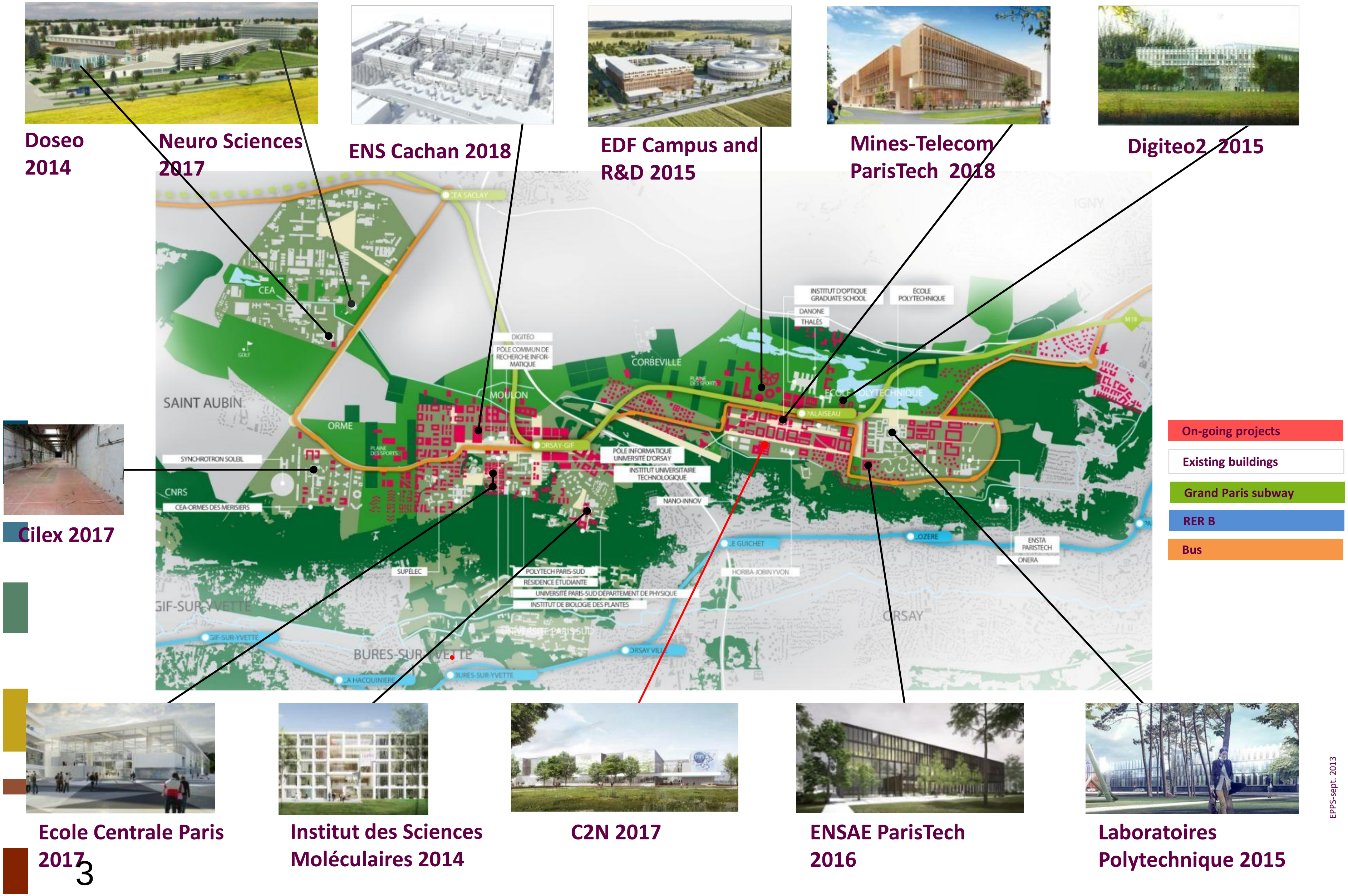
cnrs dépasser les frontières

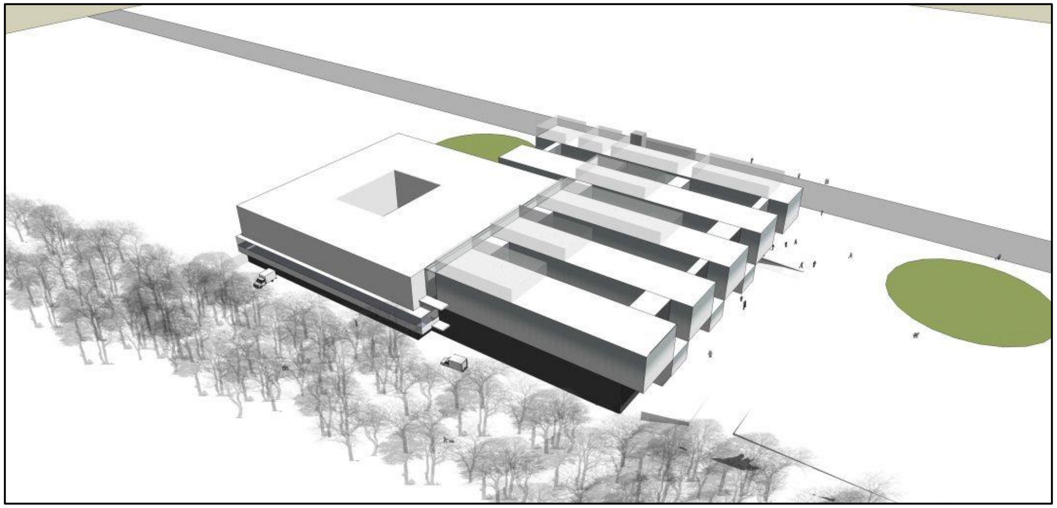
UNIVERSITÉ PARIS SUD

New Academic Buildings at Campus Paris – Saclay



EPPS-sept. 2013

C2N by numbers



~ 450 researchers, post-doc, PhD students, engineers, technicians, administrative staff

4 Departments:

Photonics, Nanoelectronics, Microsystems & NanoBioFluidics, Materials

2,800 m² high-class clean-room facility

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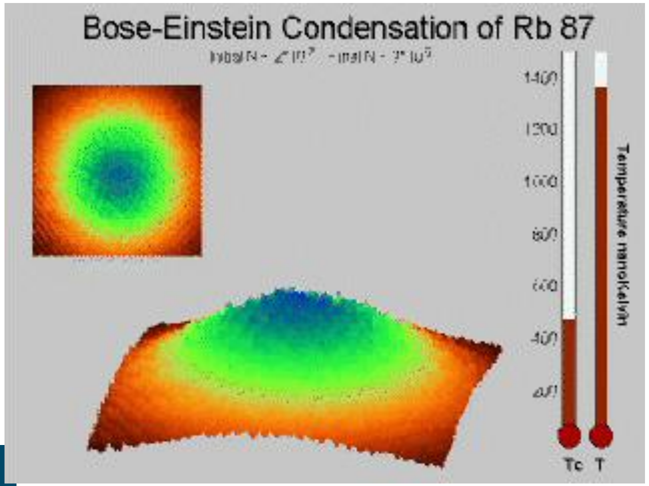
Centre de Nanosciences et de Nanotechnologies

Bose Einstein Condensation in atoms

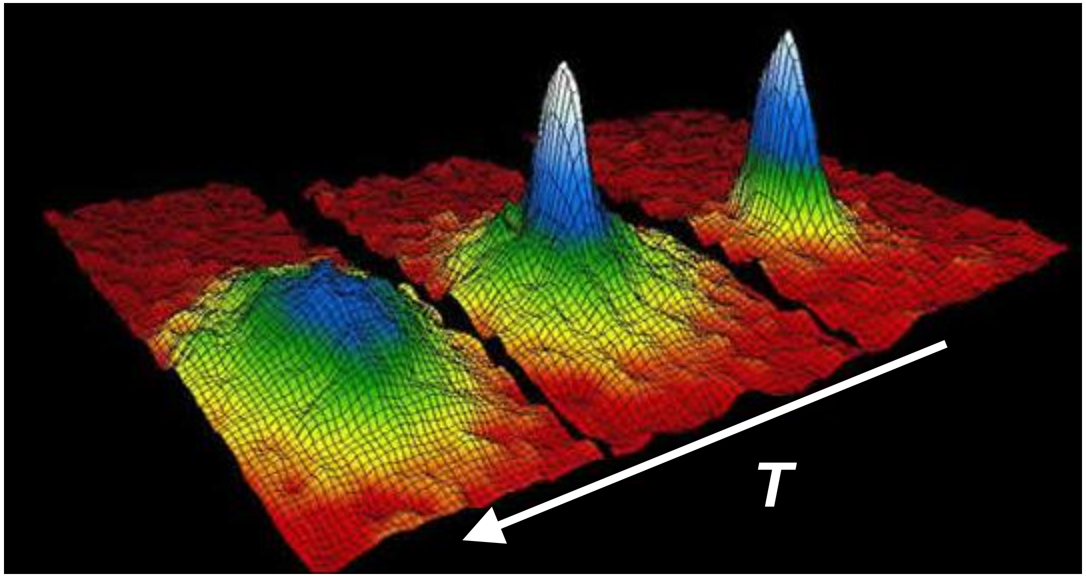


Macroscopic wavefunction

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

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

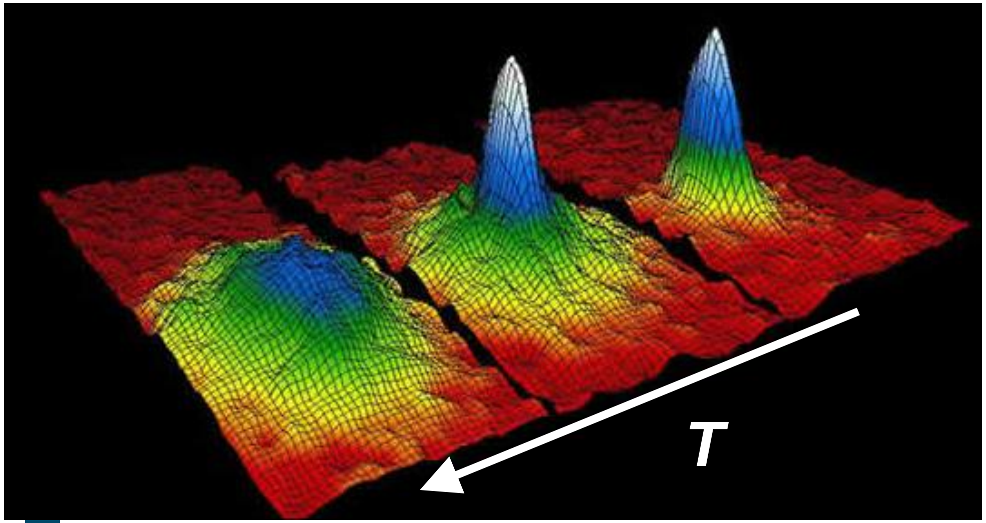
- $m = 10^4\, m_e$
- $T_c = 200$ nK



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

New physical systems appearing in the 1990's

Atomic condensates



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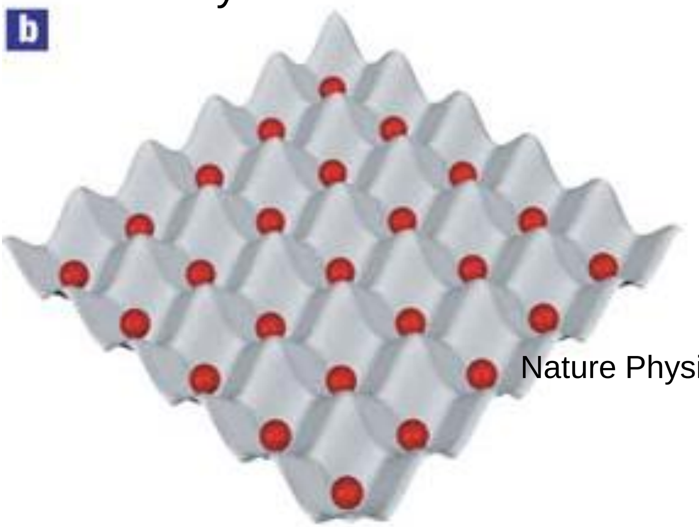
Cornell and Wieman's groups : condensation of Rb atoms (1995)

- $m = 10^4\, m_e$
- $T_c = 200$ nK

- **Atom laser**
- **Superfluidity**
- **Vortex lattices**
- **Insulator-superfluid transition**
- **Anderson localisation**
- **Artificial gauge fields**

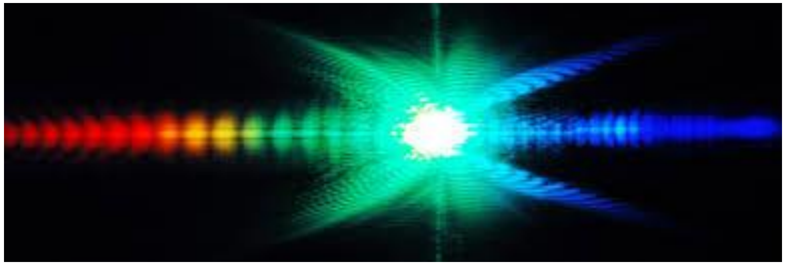
- **<u>Quantum simulators</u>**

Fabricate the Hamiltonian of system difficult to access

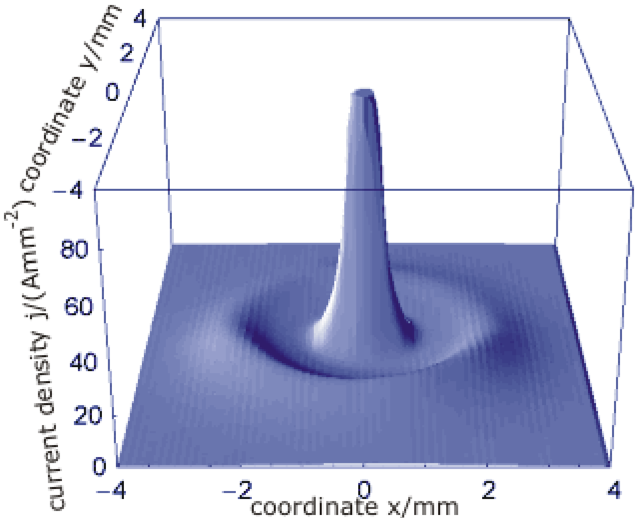


I. Bloch et al. Nature Physics **1**, 23 (2005

New physical systems appearing in the 1990's



Non-linear optics



from wikipedia

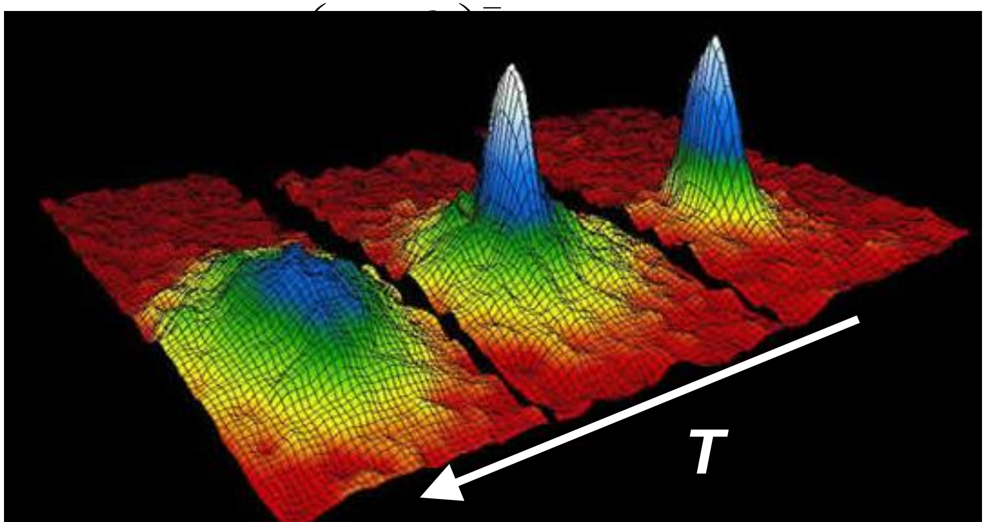
- Spatial and temporal solitons
- Fiber solitons
- Non-linear waveguide arrays
- Bi-stability
- Optical paremetric oscillation
- Parametric down-conversion
- Photon quantum state manipulation
- …

Development of non-linear optical media $\chi^{(2)}, \chi^{(3)}$

New physical systems appearing in the 1990’s

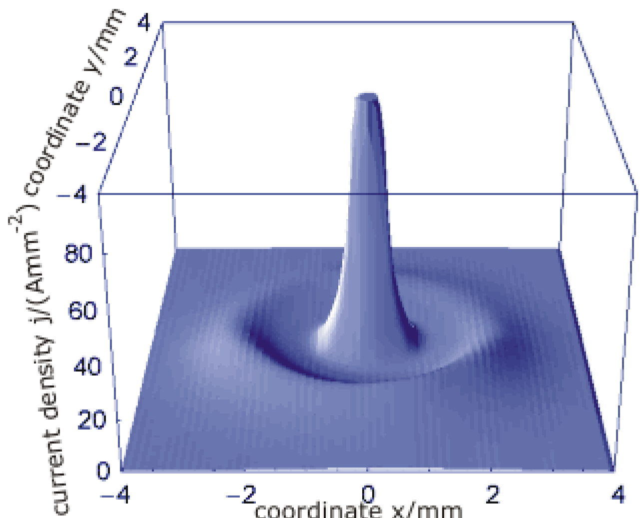
Macroscopic wavefunction

Atomic condensates



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

Non-linear optics



from wikipedia

atoms

photons

$\chi^{(3)}$

Show common phenomena

$$i\partial_t \psi(x,t) = \left[\nabla + V(x) + g\left|\psi(x,t)\right|^2\right]\psi(x,t)$$

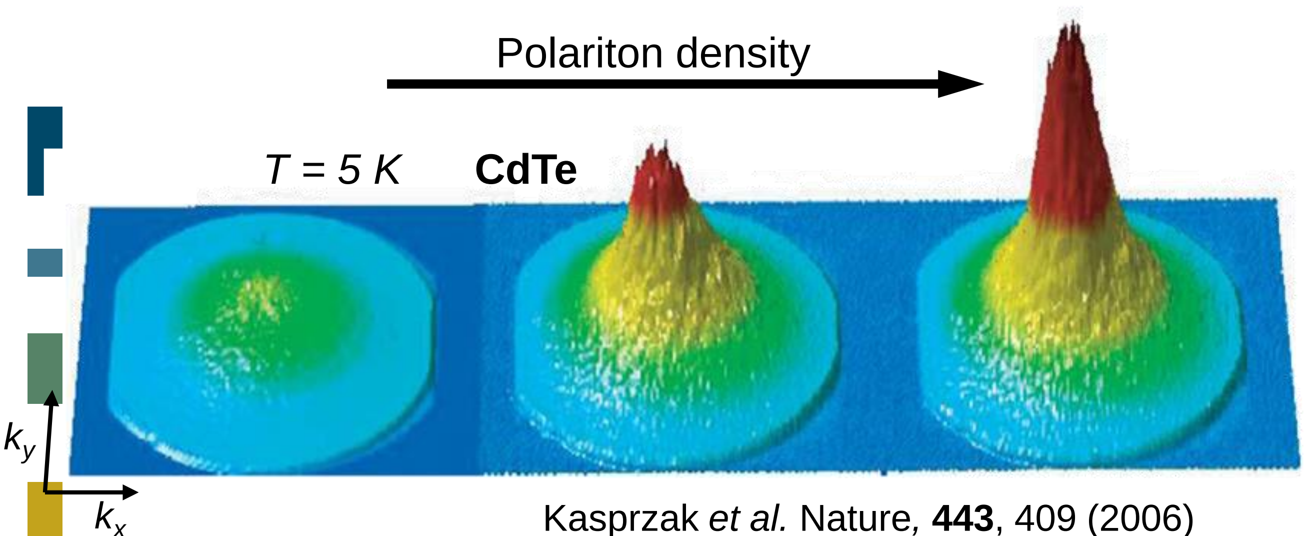
Cavity polaritons mix both worlds in a semiconductor structure

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]

Nature 443, 409 (2006)

T = 10 K



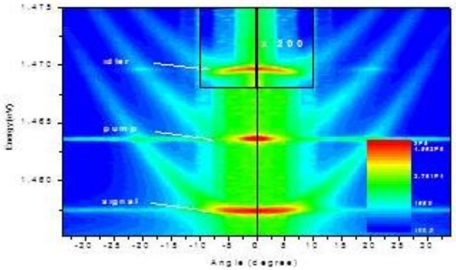
Kasprzak *et al.* Nature, **443**, 409 (2006)

Benoid Deveaud

Le Si Dang

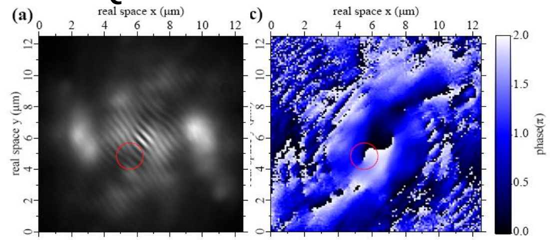
Polaritons: non-linear properties

Optical Parametric Oscillation



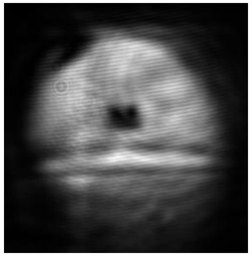
Diederichs *et al., Nature* **440**, 904 (2006)

Quantised vortices



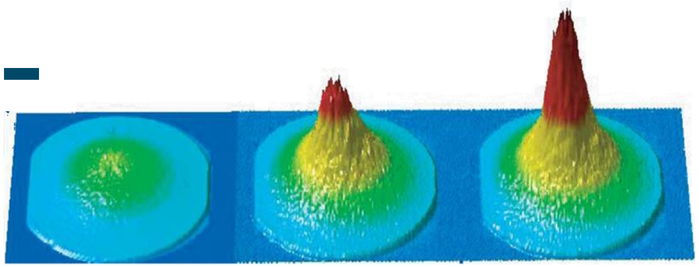
Lagoudakis *et al*., Nature Phys. **4**, 706 (2008), and Science **326**, 974 (2009)

Superfluidity



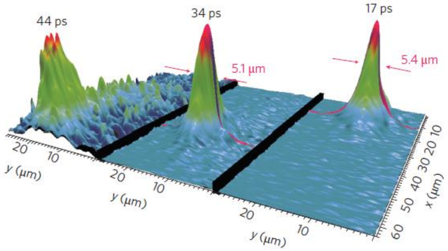
AA, Lefrère *et al.,* Nature Phys. **5**, 805 (2009)

Bosonic condensation



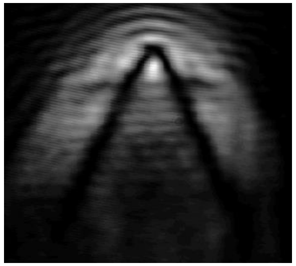
Kasprzak *et al.* Nature, **443**, 409 (2006)

Bright solitons



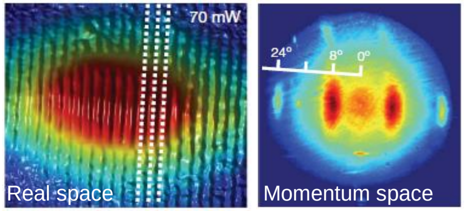
Sich *et al*., Nature Phot. **6**, 50 (2012)

Dark solitons



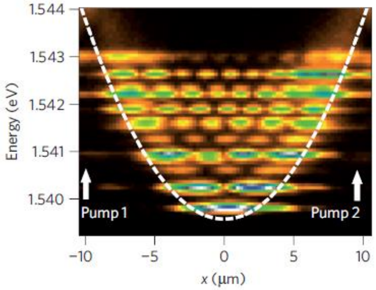
A.A., Pigeon *et al*., Science **332**, 1167 (2012)

Long-range order phases



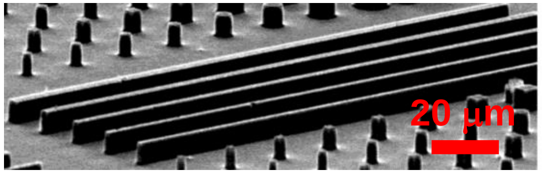
Lai *et al.,* Nature **450**, 529 (2007)
Kim et al. Nature Phys. (2011)

Non-linear oscillators



Tosi *et al*., Nature Phys. **8**, 190 (2012)

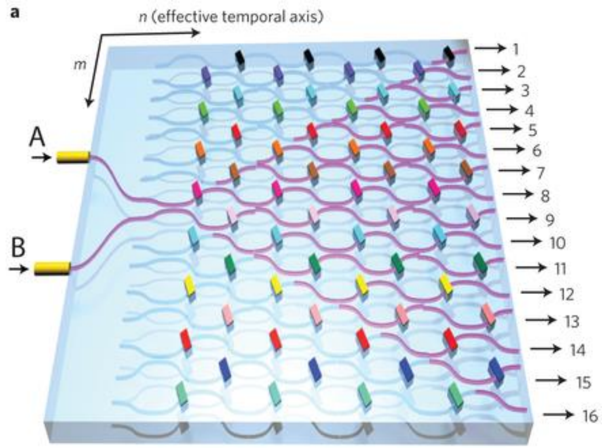
Condensates in low dimensions



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

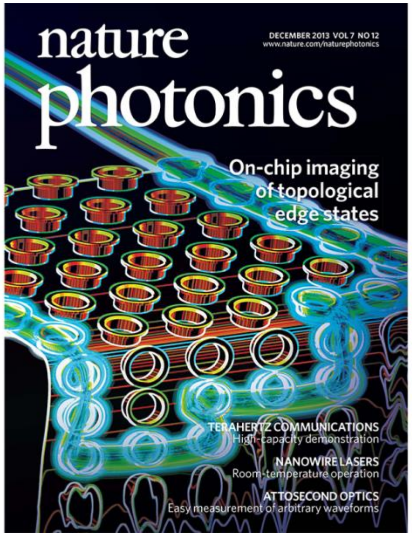
Emulation with photons

Random quantum walk



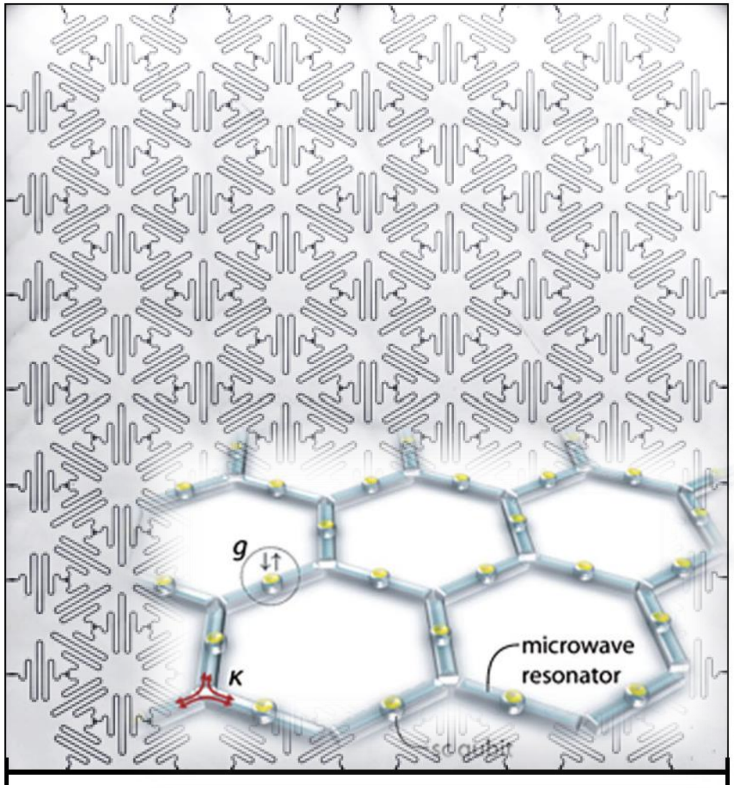
A. Crespi, Nature Photonics 7, 322 (2013)

Topological photonics



M. Hafezi et al., Nature Photonics, 7, 1001 (2013)

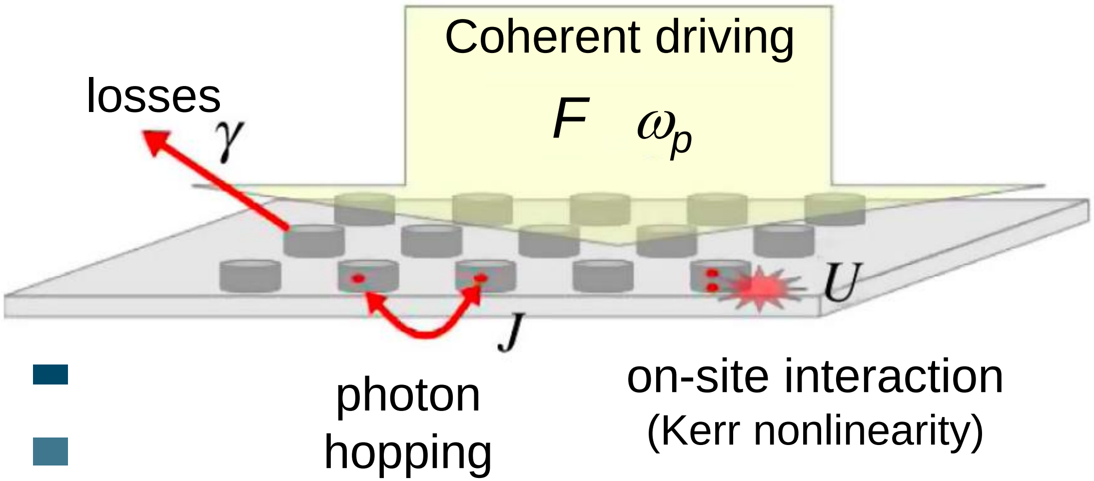
Strongly interacting microwave photons

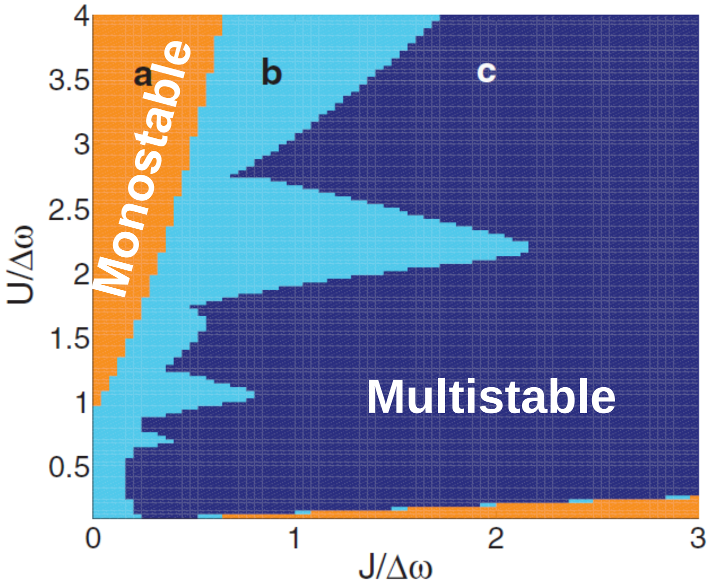


A. Houck et al., Nature Physics 8, 292 (2012)

Driven-dissipative photonic Bose-Hubbard model

Interplay of photon **hopping, interaction, coherent driving, and decay**, leads to strongly correlated steady-state phases and instabilities.





Le Boite *et al.*, PRL 110, 233601 (2013); PRA **90**, 063821 (2014).

Review on Quantum Fluids of Light: Ciuti & Carusotto, Rev. Mod. Phys. **85**, 299 (2013)

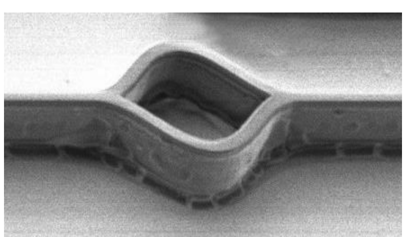
Quantum simulation with photons:

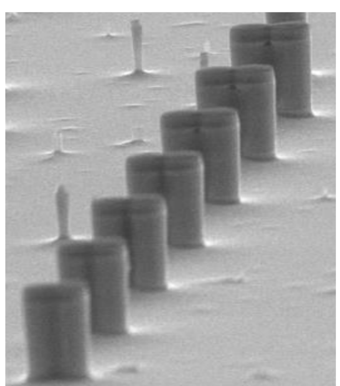
M. J Hartmann, et al., Nature Phys. 2, 849{855 (2006).
A. D Greentree, et al., Nature Phys. 2, 856{861 (2006).
D. G. Angelakis, et al., Phys. Rev. A 76, 031805 (2007).

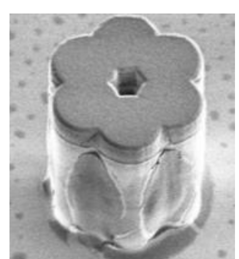
Our research at C2N

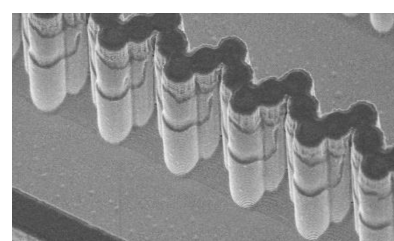
Use of nanotechnology to pattern microcavities

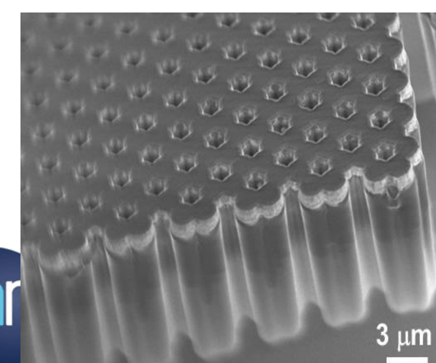
* Manipulation of quantum fluids of light
* A photonic emulator



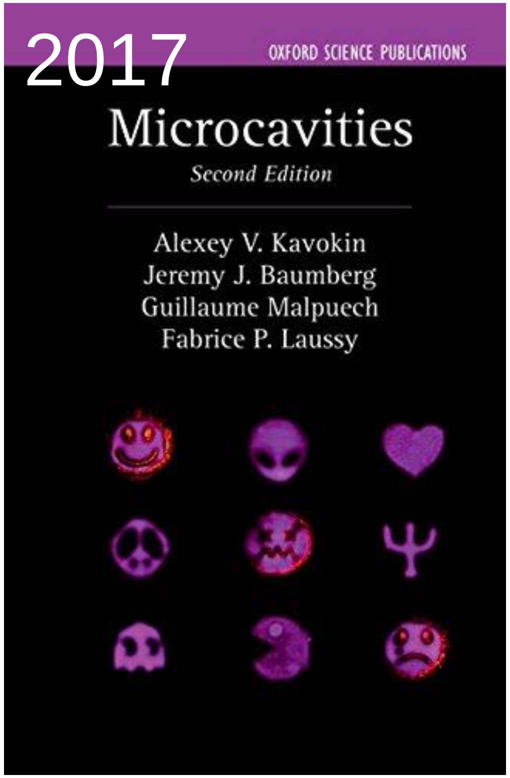


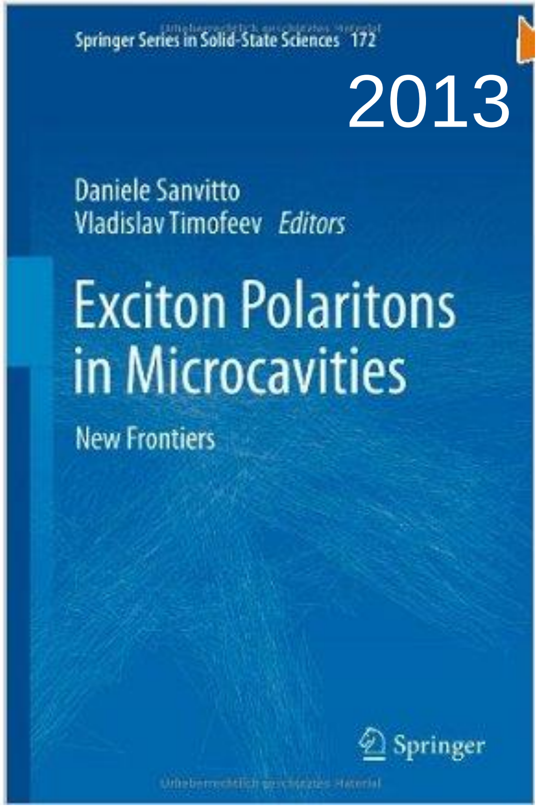


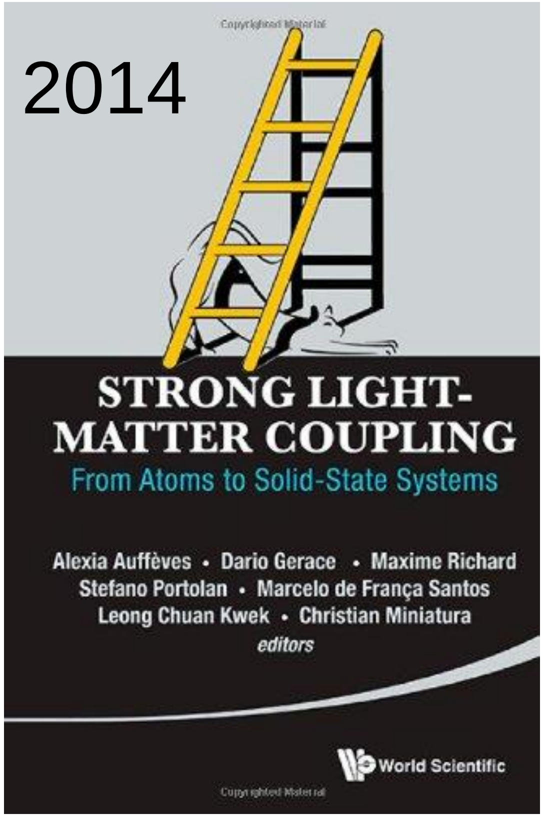




Recent reviews







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

Quantum fluids of light

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

Cristiano Ciuti†
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Outline

Lecture 1 : **Introduction to cavity polaritons**

- Hybrid light-matter quasi-particle: basic properties
- Confinement in microstructures
- Interactions

II Lecture 2: **Polariton condensation; Quantum fluids of light**

Coherence; Instability; Superfluidity; Dark solitons

III Lecture 3: **Polariton in lattices : quantum simulation**

- 1D Fibonacci quasi-crystals: fractal spectrum, edge states
- 1D SSH : topological laser
- 2D Honeycomb lattice: Dirac cones, edge states

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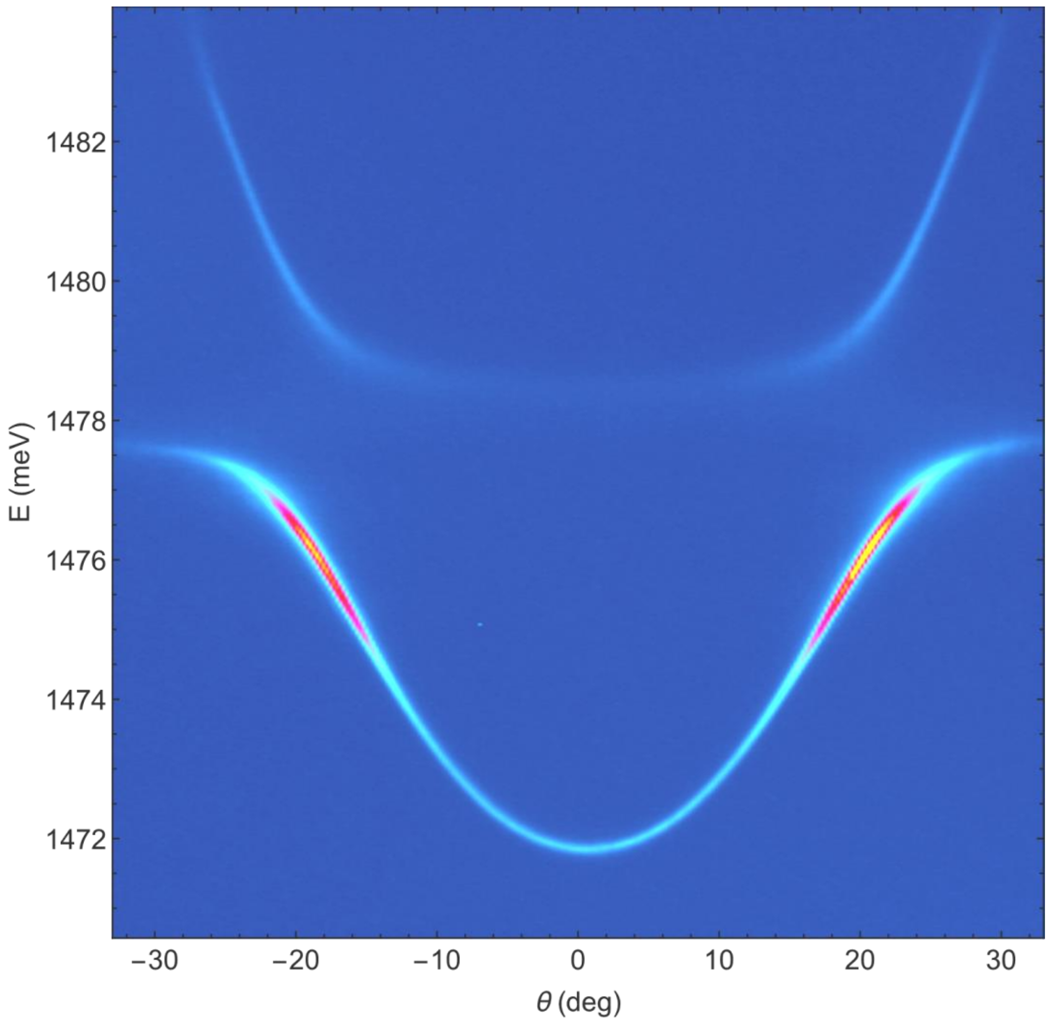
Introduction to cavity polaritons



Microcavity polaritons

→ Mixed light-matter particles

Photons confined in an optical cavity

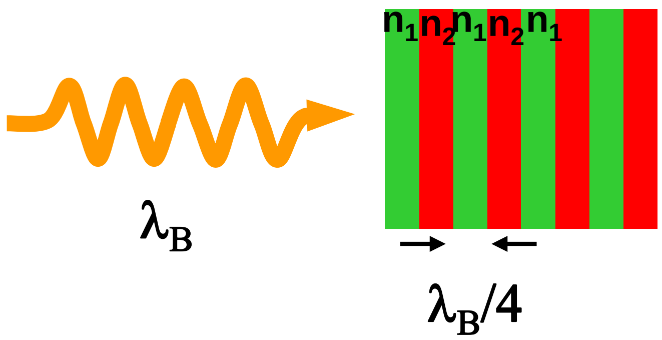
- **Very light (m=0 in vacuum)**
- Very fast
- No interactions

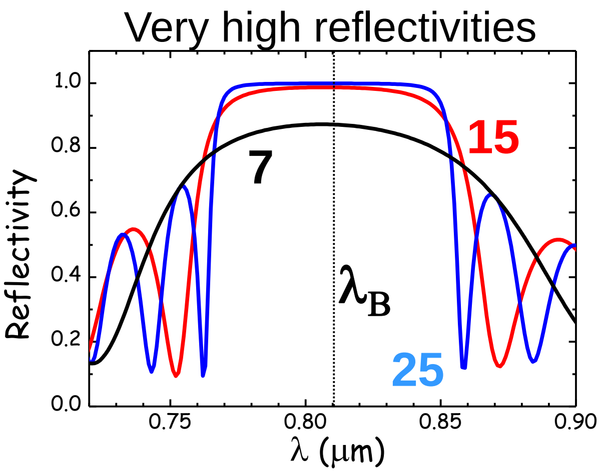
Excitons confined in a quantum well

- Very heavy
- Very slow
- **Strong interactions**

Photon confinement

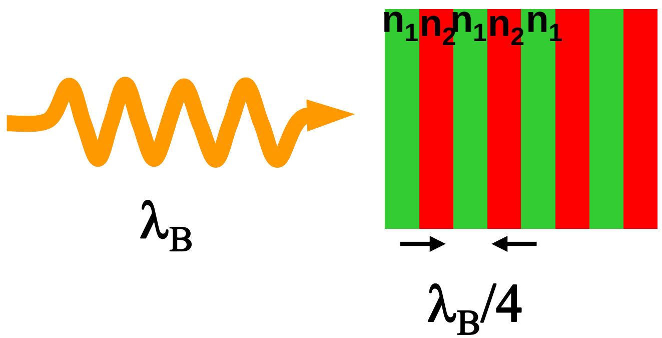
Distributed Bragg reflector

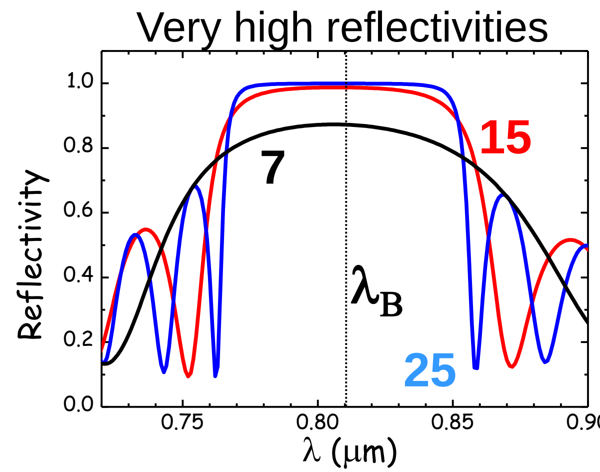




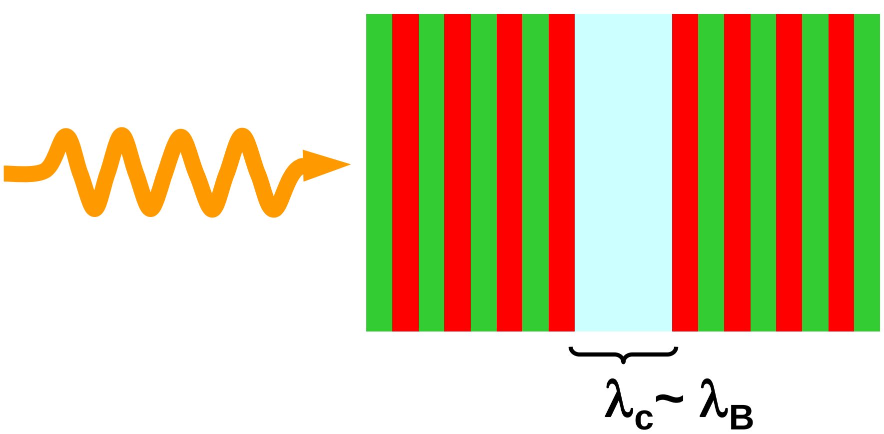
Photon confinement

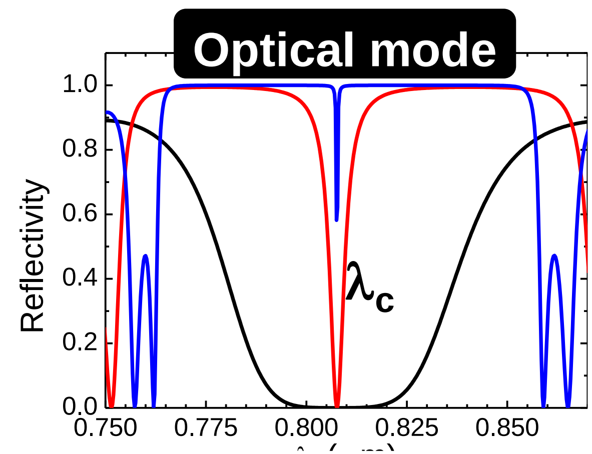
- Distributed Bragg reflector





- Fabry-Perot resonator (microcavity)



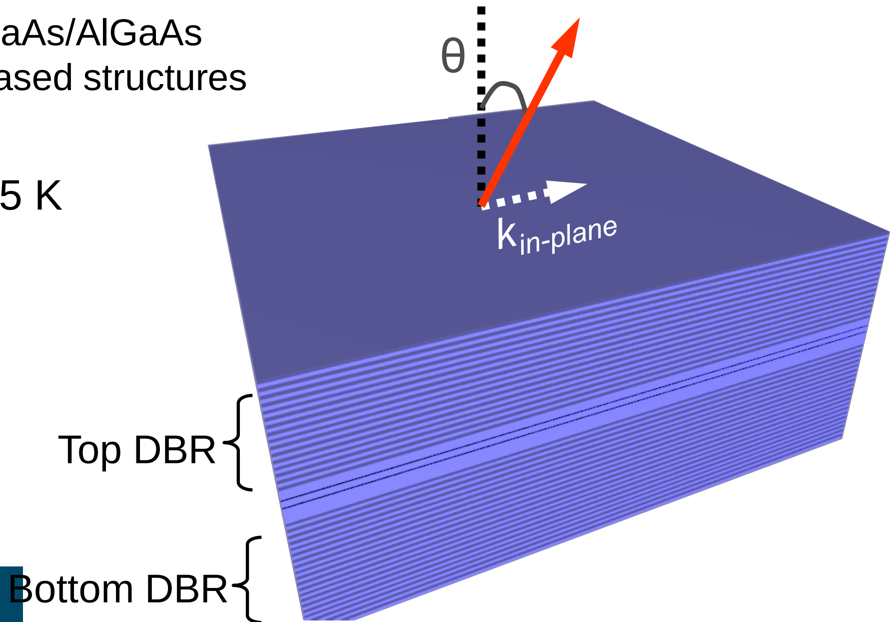


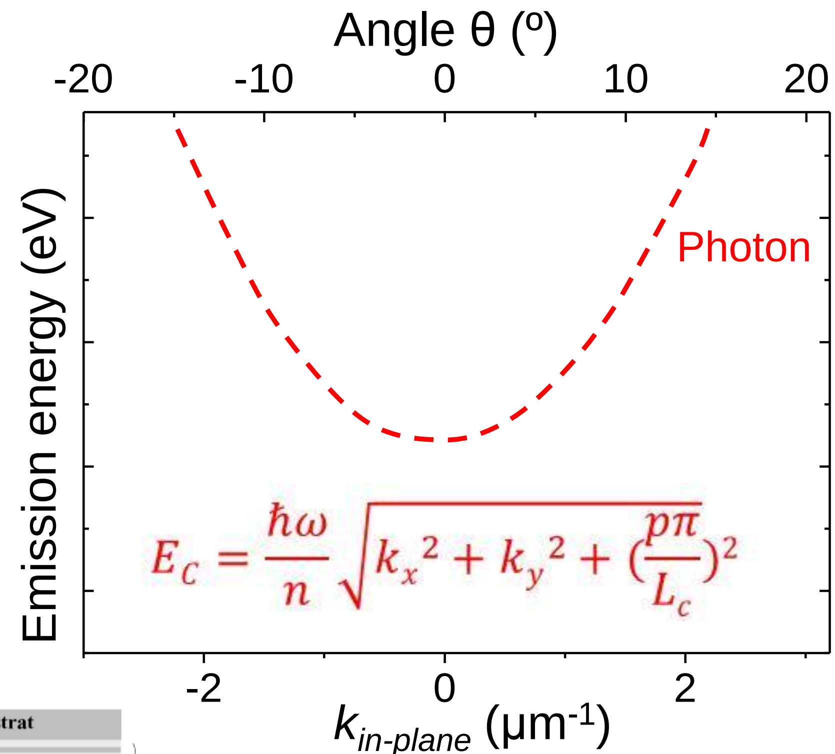
normal incidence

Microcavity polaritons

GaAs/AlGaAs
based structures

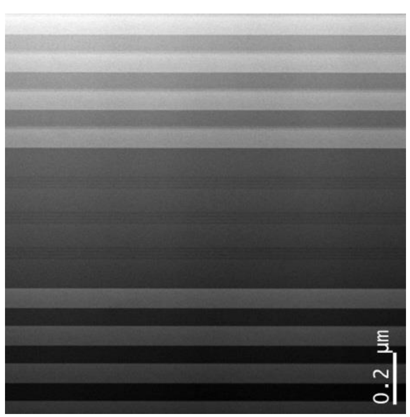
5 K





$$E_C = \frac{\hbar\omega}{n}\sqrt{k_x{}^2 + k_y{}^2 + (\frac{p\pi}{L_c})^2}$$

Optical cavity

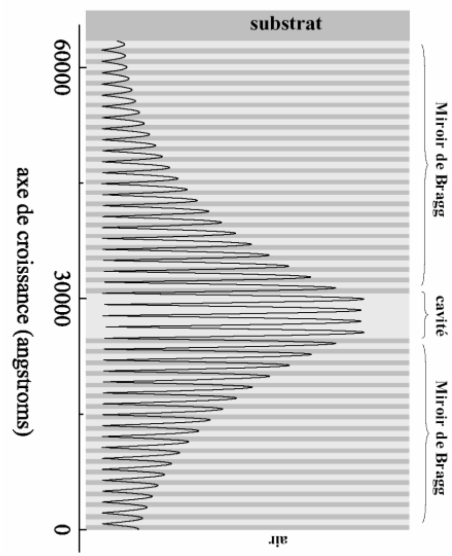


Bragg mirror
GaAs/AlAs

Cavity

Bragg mirror
GaAs/AlAs

TEM, G. Patriarche, LPN



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

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

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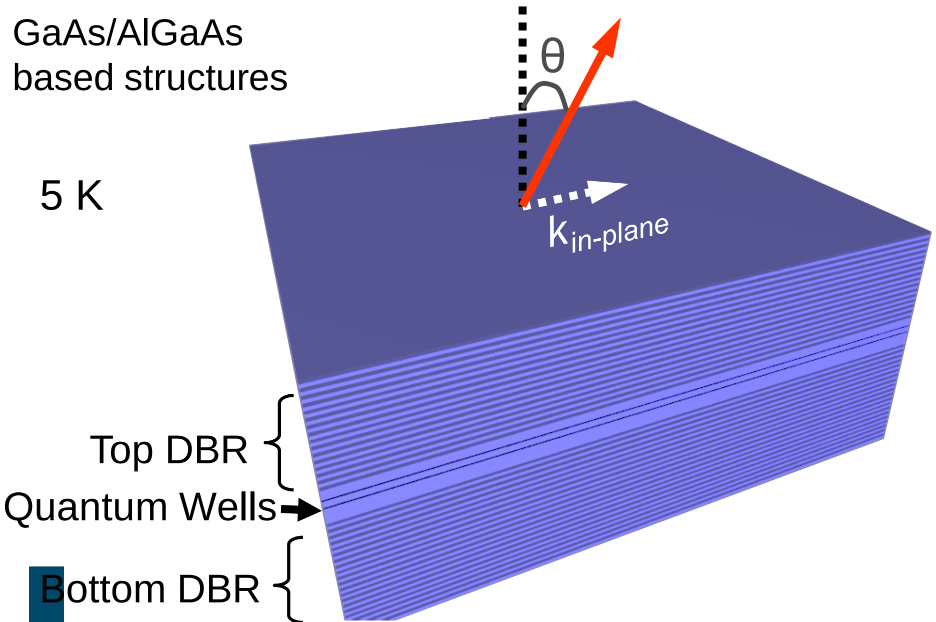
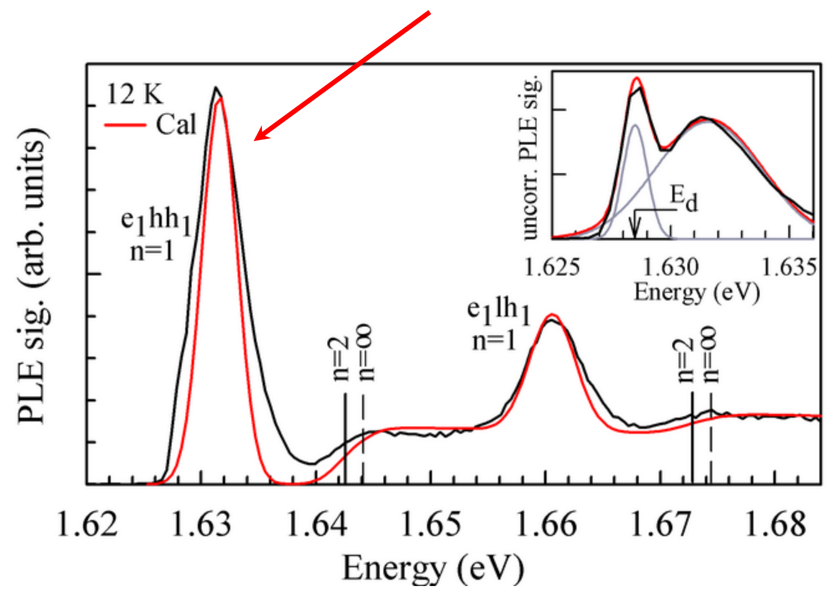
Microcavity polaritons

GaAs/AlGaAs based structures

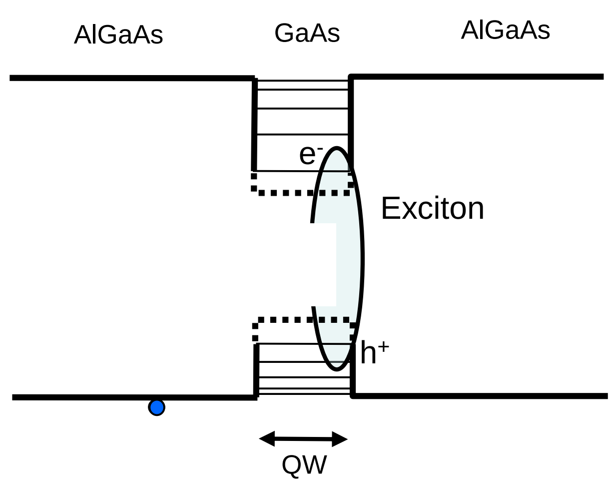
5 K



Excitonic resonance



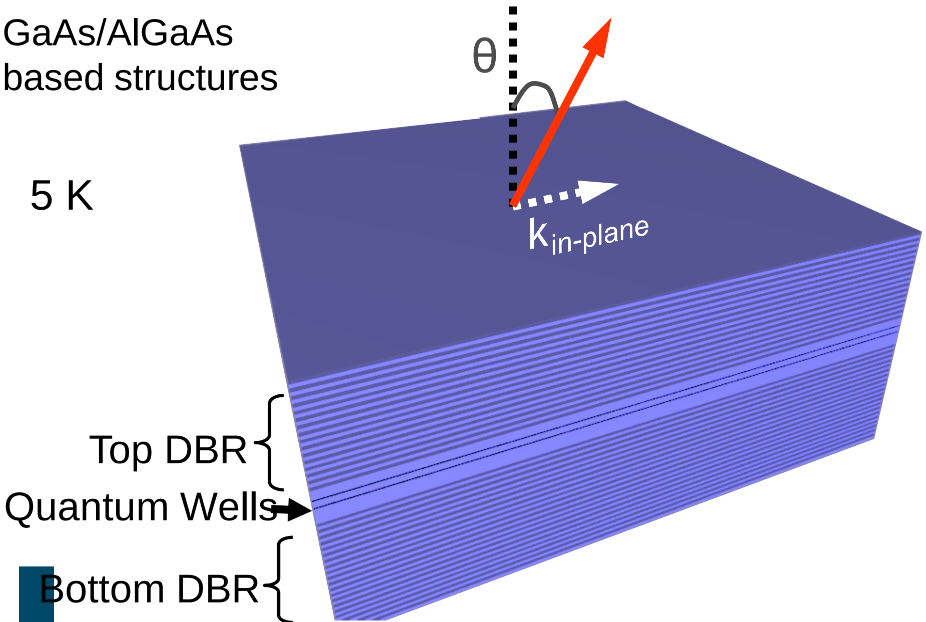
Quantum well exciton

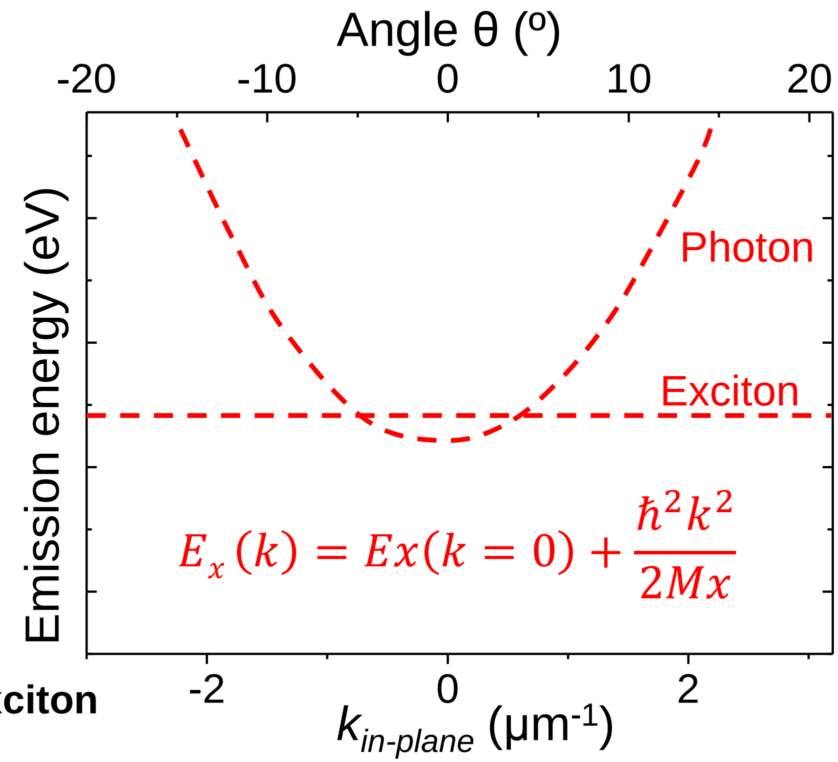


Microcavity polaritons

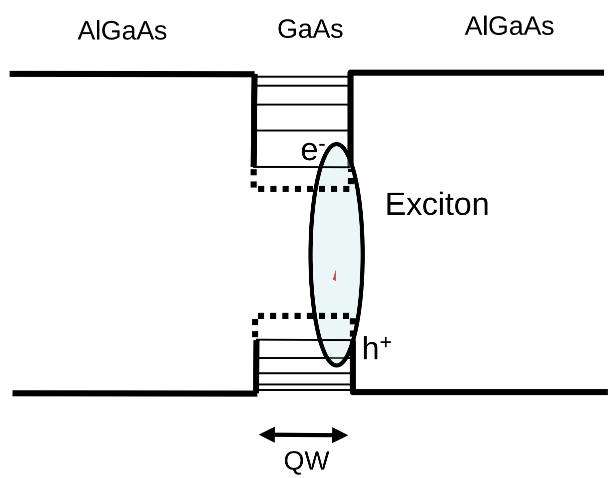
GaAs/AlGaAs based structures

5 K





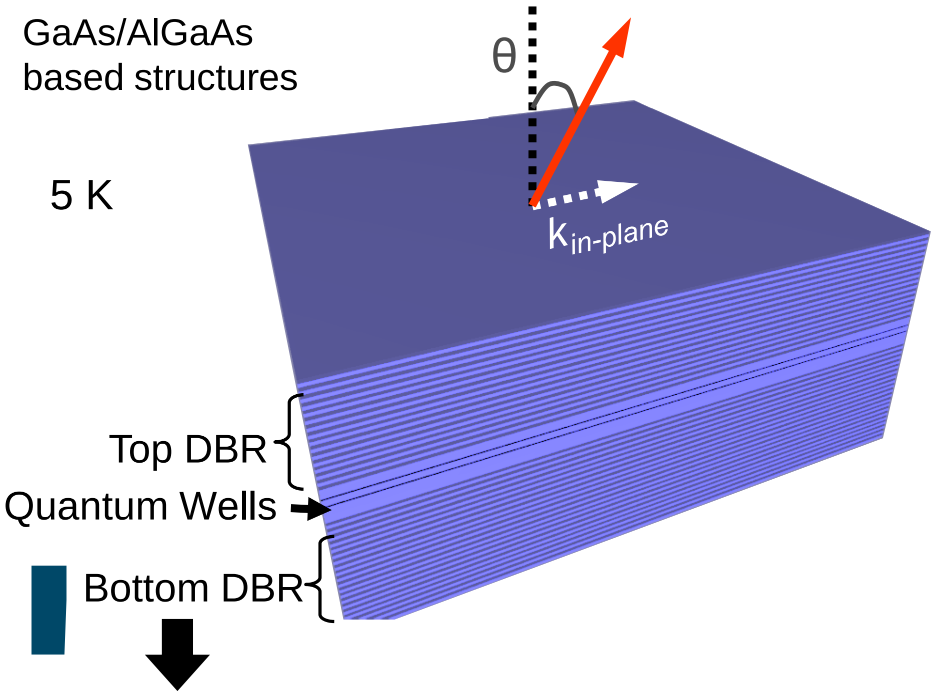
Quantum well exciton

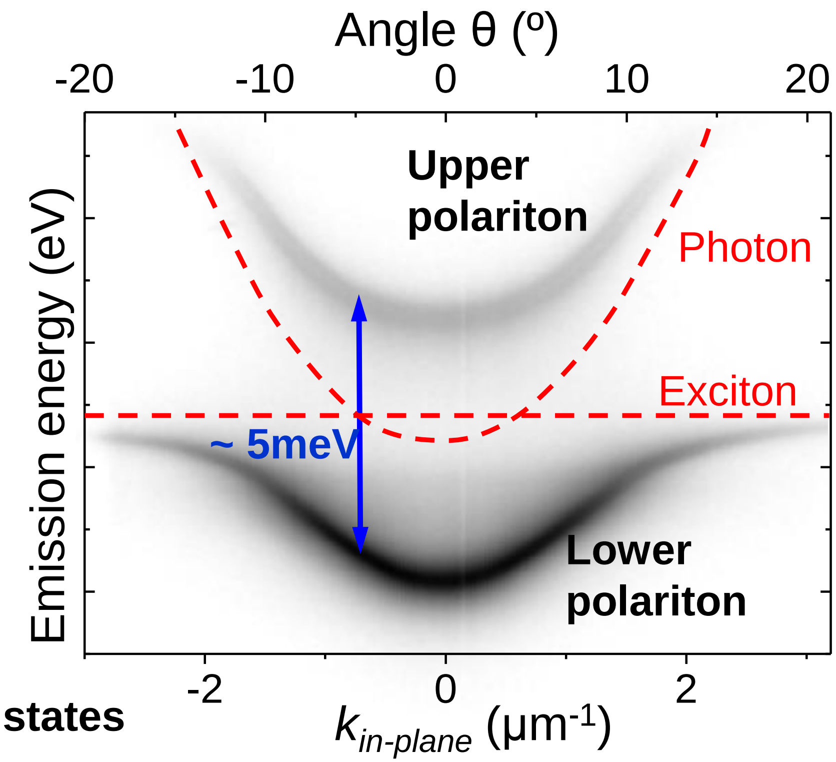


with $M_x = m_e + m_h$

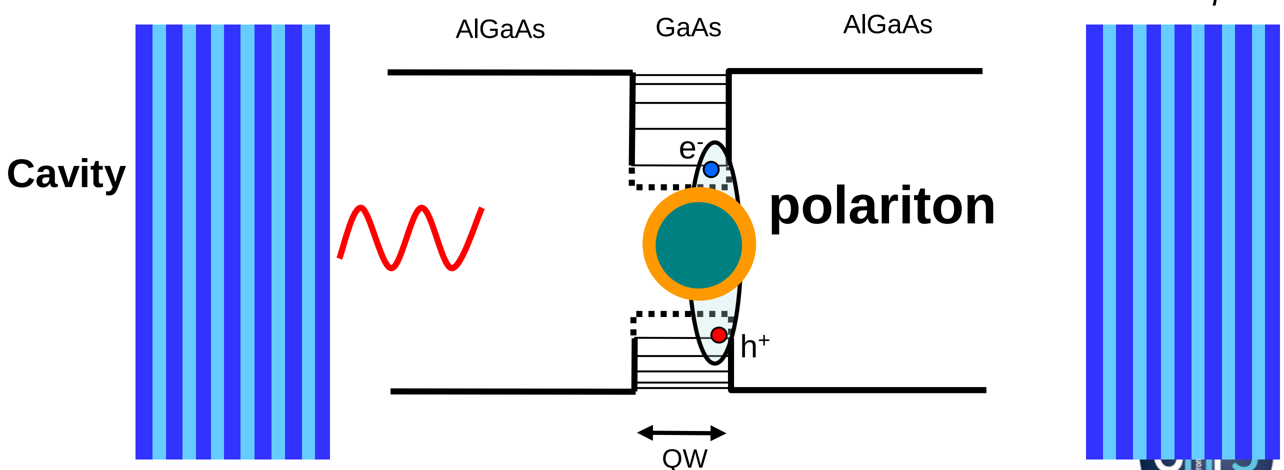
Typically $\frac{M_x}{M_{phot}} = 10^4$

Microcavity polaritons





Microcavity polaritons : mixed exciton-photon states



VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

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

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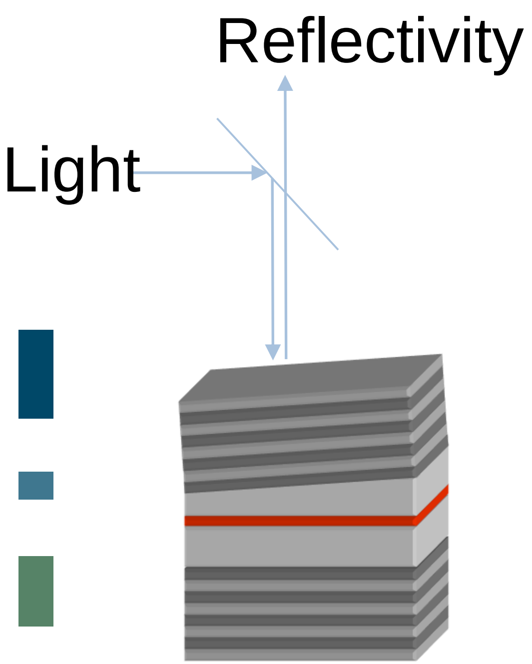
Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Meguro-ku, Tokyo 153, Japan

(Received 12 May 1992)



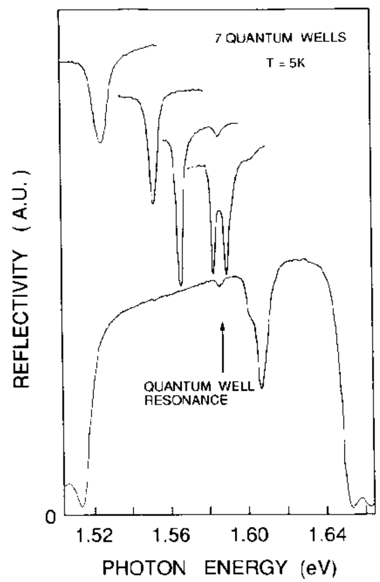


FIG. 2. 5-K reflectivity curves on a seven-QW microcavity structure. Various detuning conditions between cavity and QW exciton frequencies are obtained by choosing various points on the wafer, typically 0.5 mm apart. Note the line narrowing approaching and at resonance, the resonance mode splitting,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

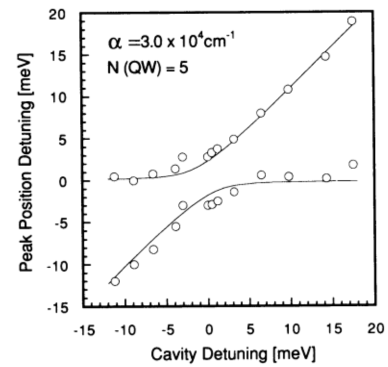
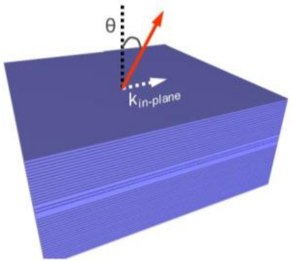
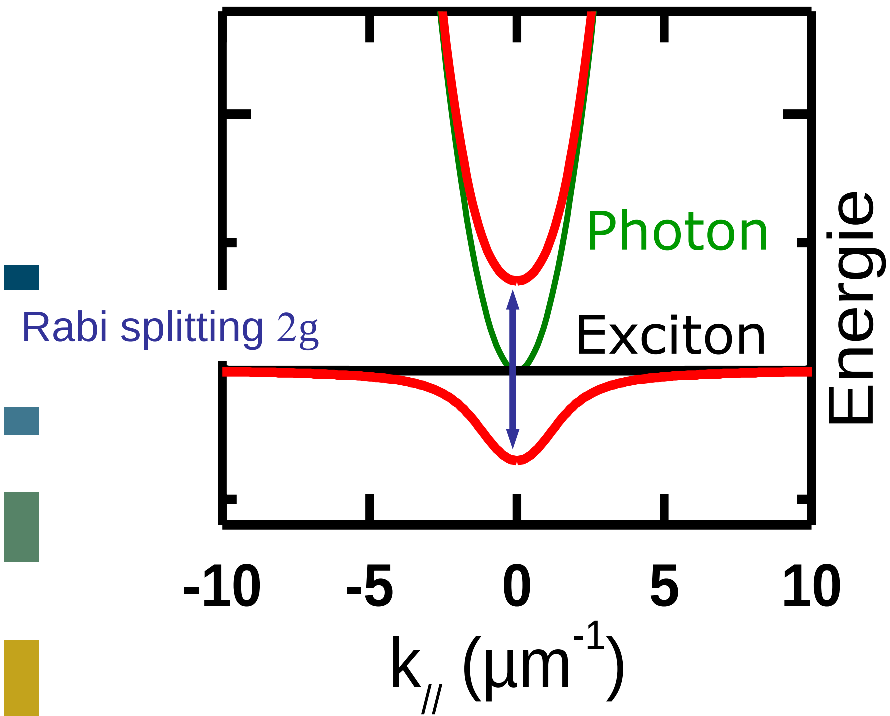


FIG. 3. Reflectivity peak positions as a function of cavity detuning for a five-quantum-well sample at $T = 5$ K. The theoretical fit is obtained through a standard multiple-interference analysis of the DBR-Fabry-Pérot-quantum-well structure.

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

Microcavity polaritons





$$H_{k_{//}} = \begin{pmatrix} E_X(k_{//}) & g \\ g & E_C(k_{//}) \end{pmatrix}$$

$$E_1 = \frac{E_X(k_\parallel) + E_C(k_\parallel)}{2} - \frac{\Delta(k_\parallel)}{2}$$

$$E_2 = \frac{E_X(k_\parallel) + E_C(k_\parallel)}{2} + \frac{\Delta(k_\parallel)}{2}$$

with

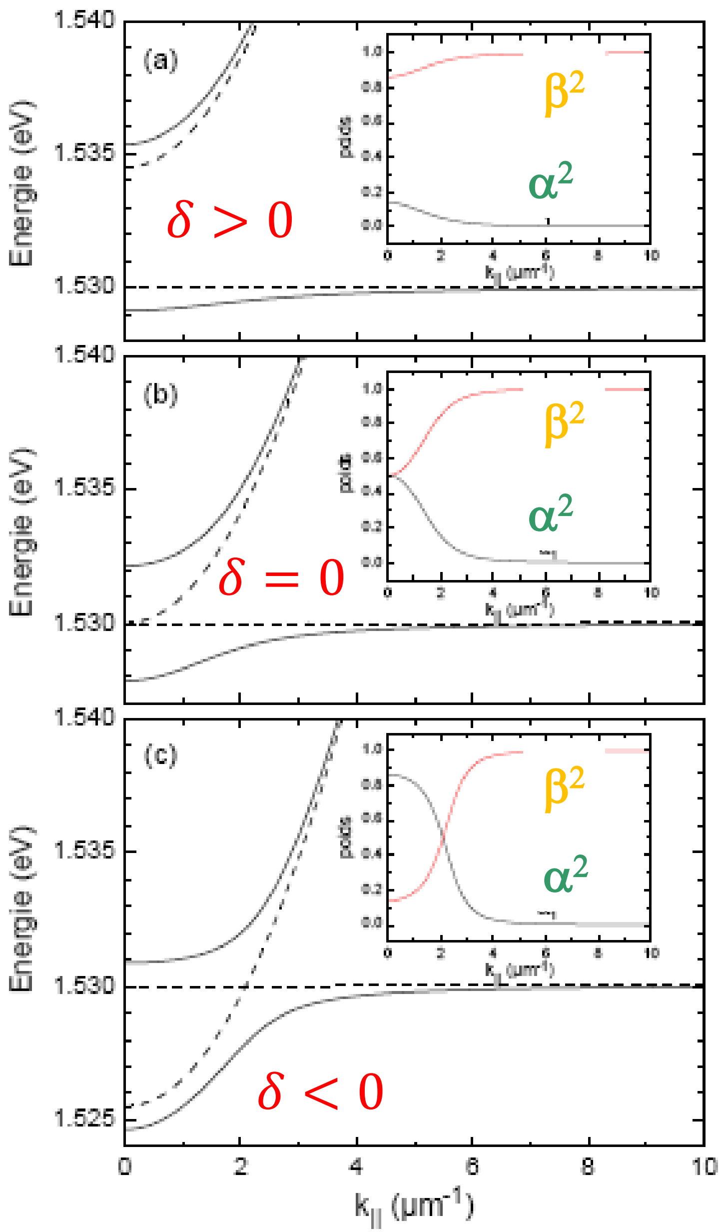
$$\Delta(k_{//}) = \sqrt{\left(E_C(k_{//}) - E_X(k_{//})\right)^2 + 4g^2}$$

Microcavity polaritons

| polariton > **=** α **|photon>**
+ β **|exciton>**

Exciton photon detuning:
$\delta = Ec(k=0) - Ex\ (k=0)$

s-shaped dispersion : inflexion point



Microcavity polaritons

| polariton > = α |photon>
+ β |exciton>

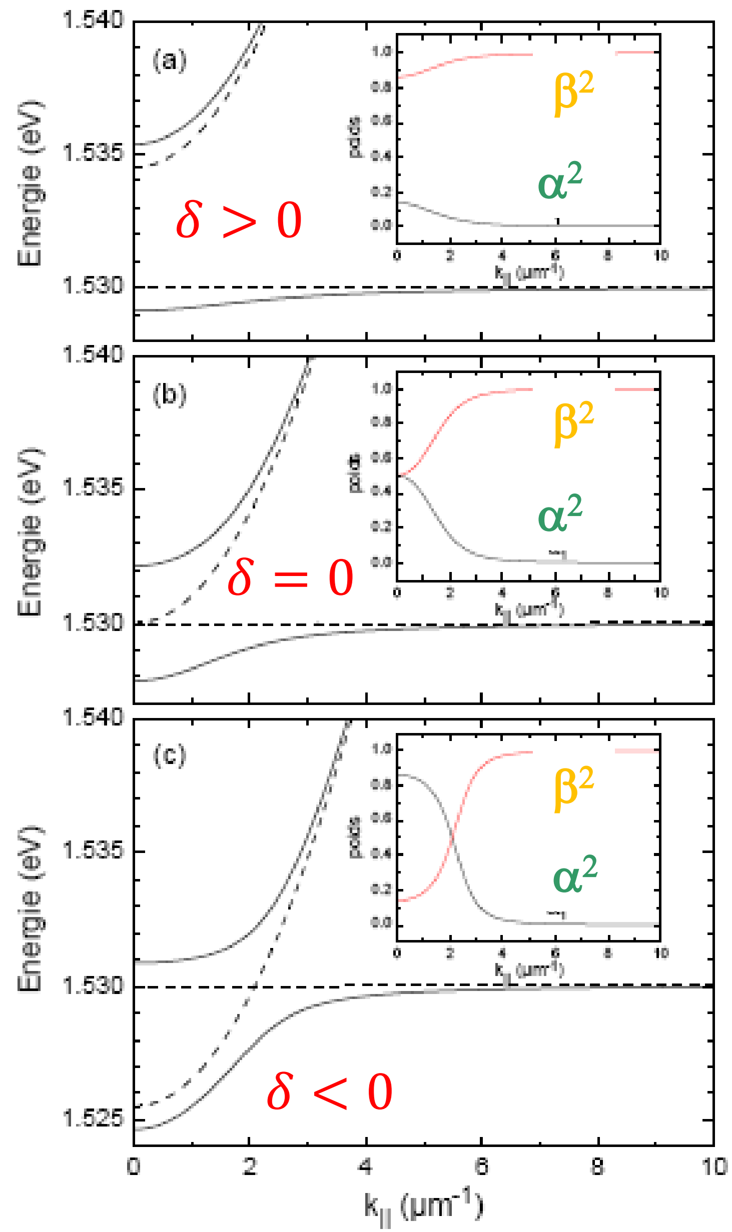
Exciton photon detuning:
$\delta = Ec(k=0) - Ex\ (k=0)$

s-shaped dispersion : inflexion point

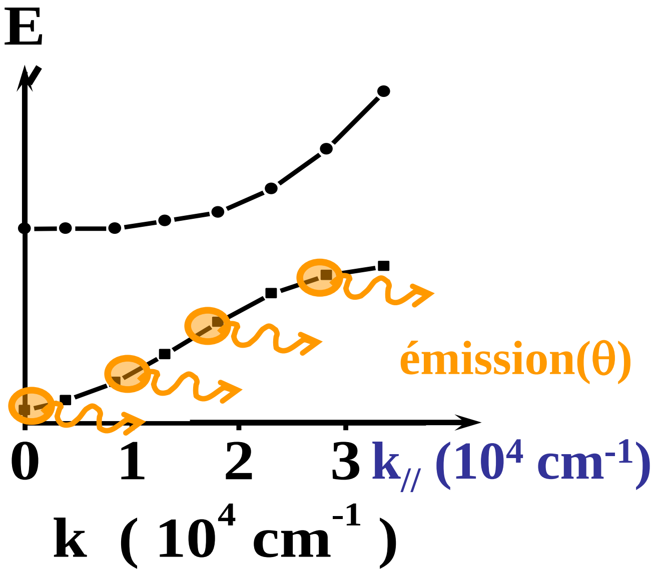
Effective mass: $\frac{1}{M_{pol}} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k^2}$

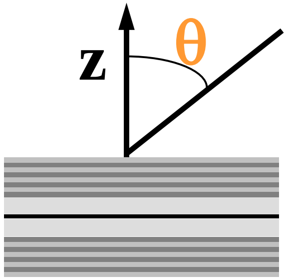
At k = 0: $\frac{1}{M_{pol}} = \frac{\alpha^2}{M_{phot}} + \frac{\beta^2}{M_{exc}}$

Beyond inflexion point: negative effective mass



Probing polariton states: Angle resolved experiments



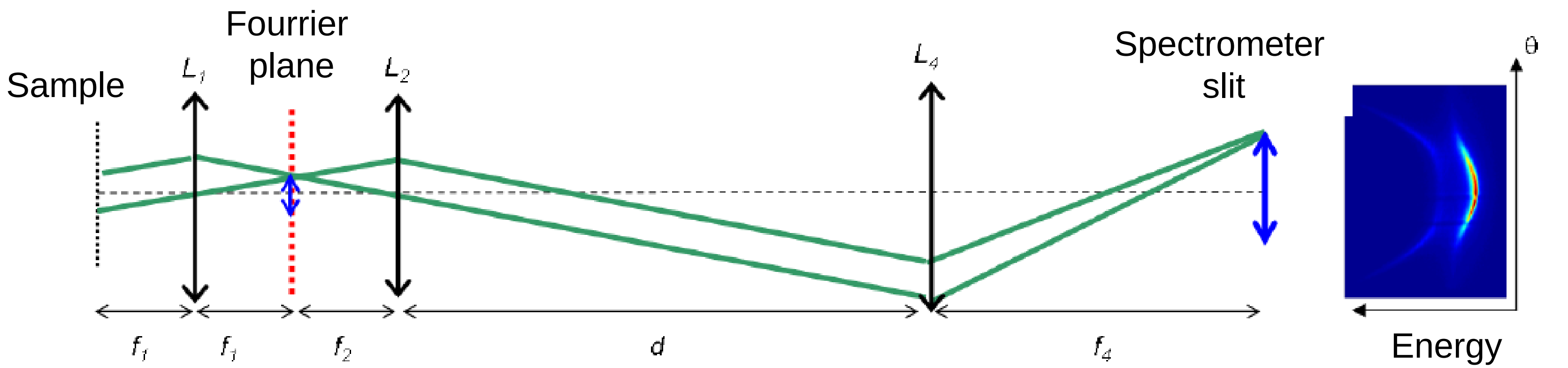


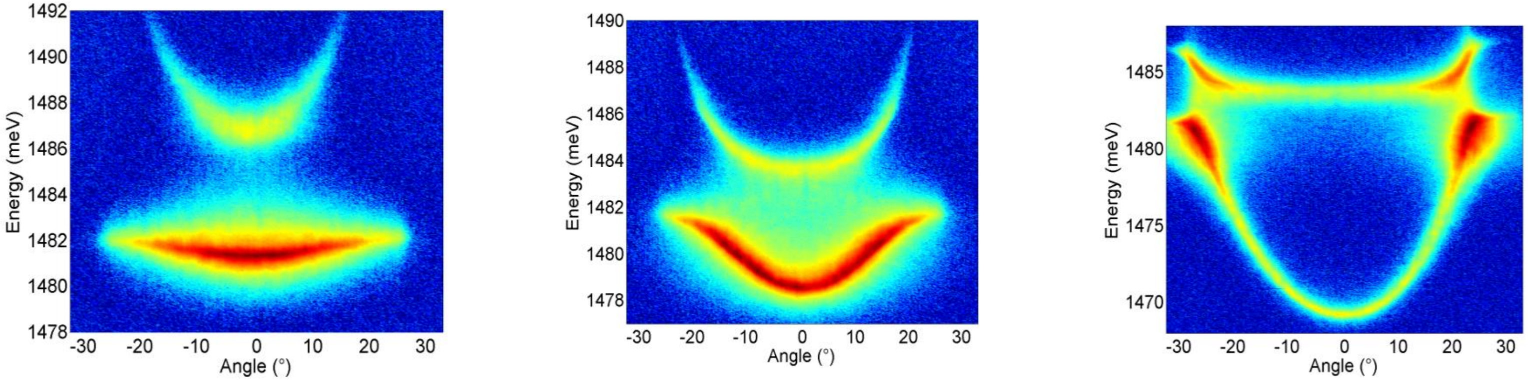
$\theta \Leftrightarrow k_{//}$

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

Selective excitation and probe of polariton states

Probing polariton states: Angle resolved experiments





Measurement of Cavity-Polariton Dispersion Curve from Angle-Resolved Photoluminescence Experiments

R. Houdré,[1] C. Weisbuch,[1,2] R. P. Stanley,[1] U. Oesterle,[1] P. Pellandini,[1] and M. Ilegems[1]
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(Received 11 March 1994)

Phys. Rev. Lett. **73**, 2043 (1994)

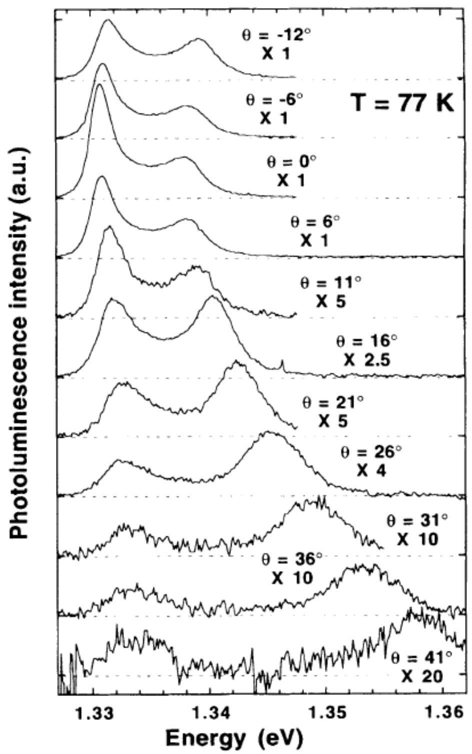


FIG. 2. Series of photoluminescence spectra at $T = 77$ K, for an emission angle from $-12°$ to $41°$. The Fabry-Pérot at normal incidence is resonant with the quantum well exciton.

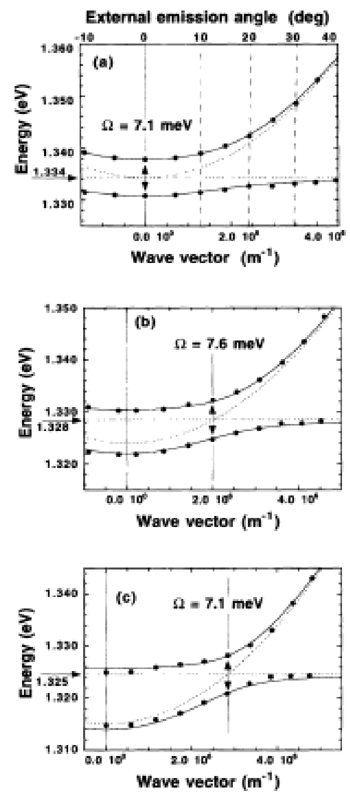
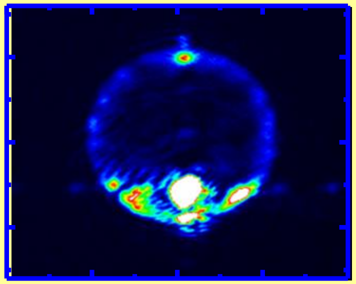


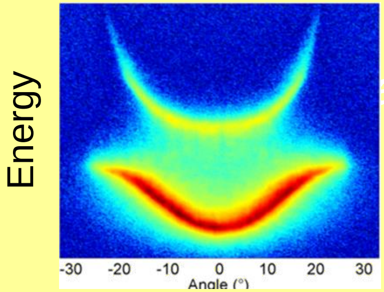
FIG. 3. Cavity-polariton dispersion curves, deduced from angle-resolved photoluminescence measurements, for different resonance conditions. (a) Resonance at $\theta = 0°$ (case of Fig. 2), (b) resonance at $\theta = 29°$, and (c) $\theta = 35°$. The continuous lines are theoretical calculations and the dashed lines are the uncoupled exciton and cavity dispersion curves. The interaction energy Ω and exact resonance position are determined from the minimum splitting between both photoluminescence lines. An external emission angle grid is drawn on (a).

Romuald Houdré

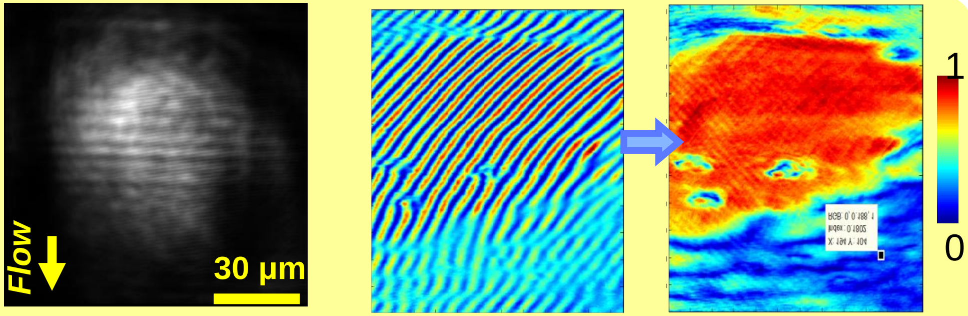
Typical experimental scheme

Far field imaging: k space





Real space imaging

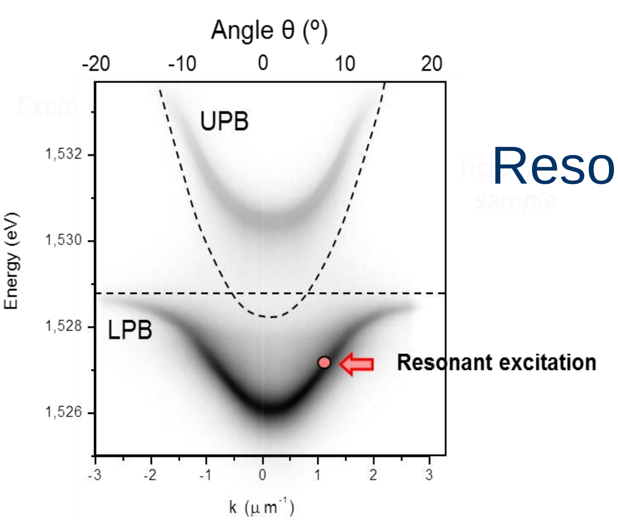


Density

Interference with a reference beam

Coherence map $g^{(1)}$

Phase dislocations
- vortices
- solitons



Resonant injection of polaritons

Cavity polaritons : an exciton-photon mixed state

| polariton > = α |photon> + β |exciton>

α^2 photon part

Coupling to free space optical modes

Low effective mass

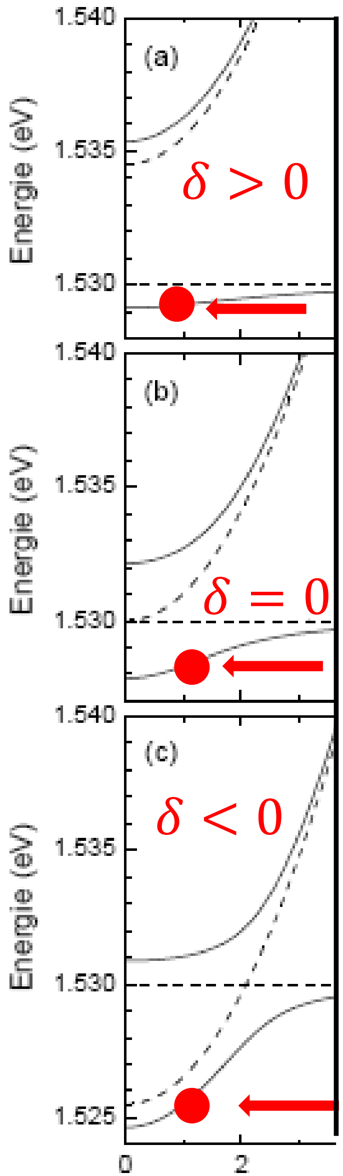
β^2 exciton part

Polariton-phonon Interactions
Polariton-polariton Interactions

Properties

- Photonic component ➡ **low mass (10^{-5} m_e)**
-
-
-

Probing polariton states: Real space propagation



Resonant pulsed excitation

PHYSICAL REVIEW B VOLUME 61, NUMBER 11 15 MARCH 2000-

In-plane propagation of excitonic cavity polaritons

T. Freixanet
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(Received 16 November 1999)

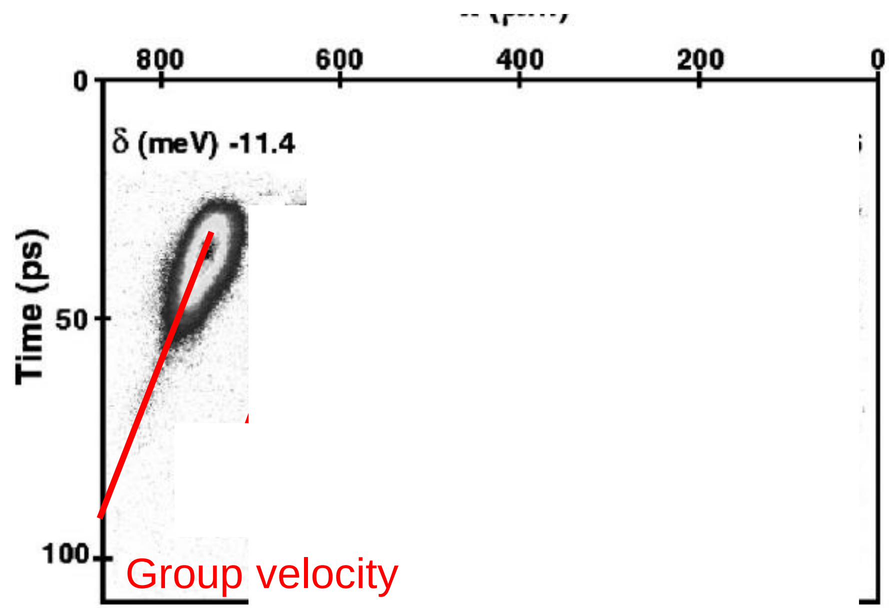
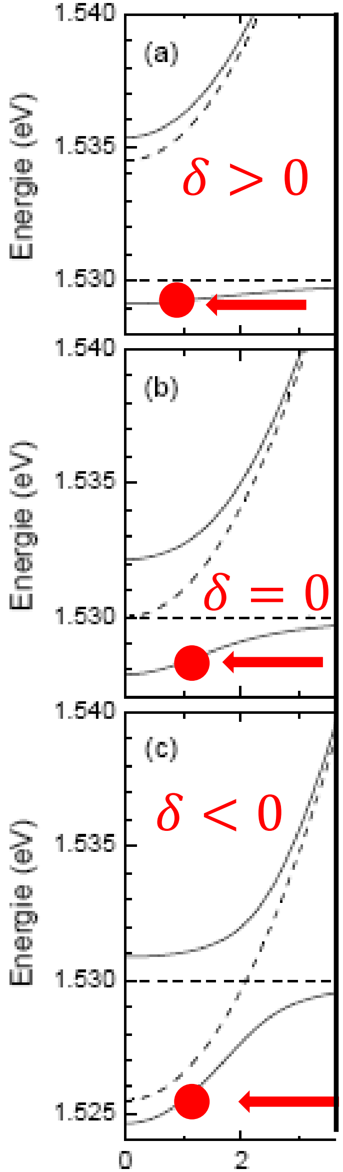


FIG. 2. Propagation in real space of the secondary emission source as observed on the streak camera for several detunings. The diaphragm is close to the reflection and $\theta_i = 7.8°$.

Probing polariton states: Real space propagation



Resonant pulsed excitation

PHYSICAL REVIEW B VOLUME 61, NUMBER 11 15 MARCH 2000-

In-plane propagation of excitonic cavity polaritons

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(Received 16 November 1999)

$$v_g = \frac{1}{\hbar}\frac{\partial E}{\partial k} \qquad v_{g(k)} = \alpha^2 v_{phot}(k) + \beta^2 v_{x}(k)$$

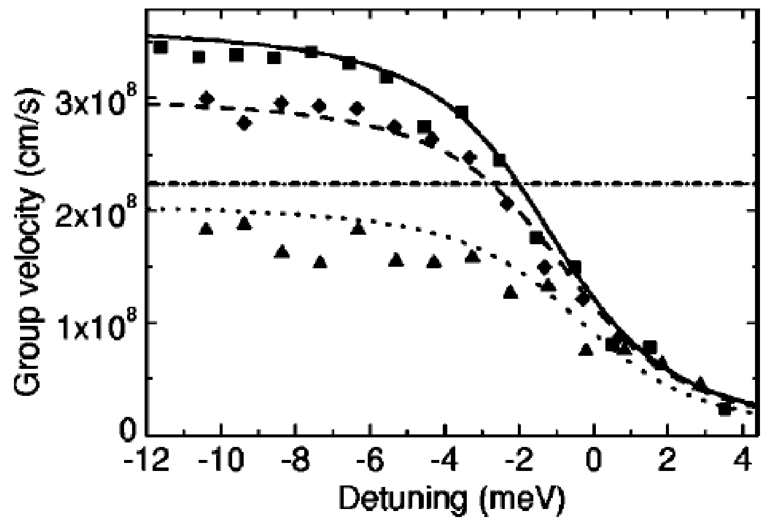

FIG. 3. Group velocity of the resonantly excited lower branch polaritons as a function of the detuning for different incident angles θ_I. The points are the measured values for $\theta_I = 7.8°$ (■), $\theta_I = 6.2°$ (◆), and $\theta_I = 4.3°$ (▲). The solid, dashed, and dotted lines

Cavity polaritons : an exciton-photon mixed state

| polariton > = α |photon> + β |exciton>

α^2 photon part

Coupling to free space optical modes

Low effective mass

β^2 exciton part

Polariton-phonon Interactions
Polariton-polariton Interactions

Properties

- Photonic component ➡ **low mass (10^{-5} m_e)**
- Short lifetime (~ps) ➡ **escape out of the cavity**
-
-

Polariton lifetime

PHYSICAL REVIEW B VOLUME 53, NUMBER 24 15 JUNE 1996-II

Time-resolved spontaneous emission of excitons in a microcavity: Behavior of the individual exciton-photon mixed states

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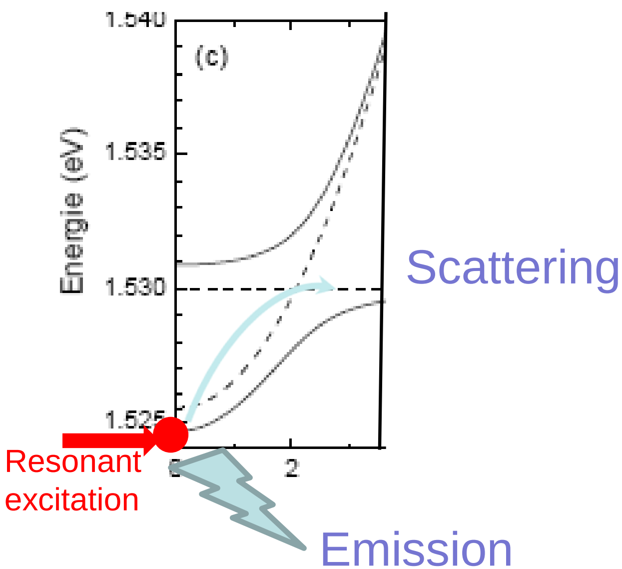
(Received 1 May 1995; revised manuscript received 12 January 1996)



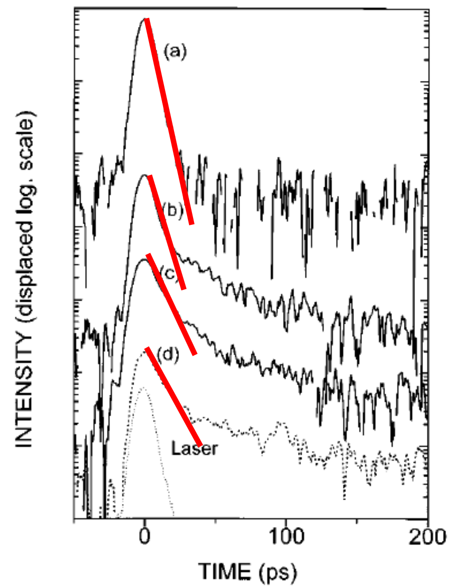
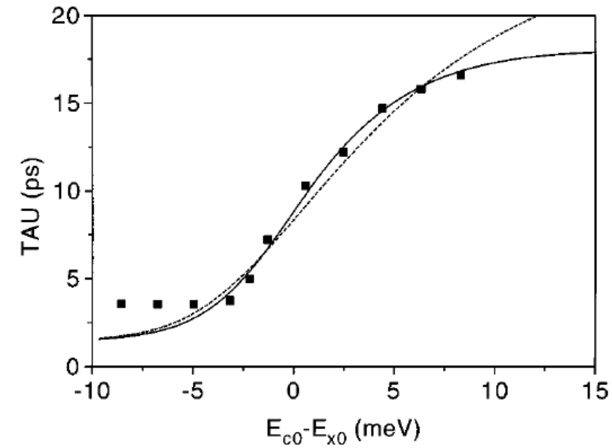


FIG. 1. Luminescence decay curves obtained with a laser excitation resonant with the lower state for different values of the detuning: (a) $\delta_0 = E_{c0} - E_{x0} = -8.5$ meV, (b) $\delta_0 = -1.5$, and (c) $\delta_0 = 3.5$ meV. The dashed curve (d) is the luminescence decay of the reference sample excited resonantly. The dotted curve (labeled "Laser") is the instrument response function.



$$\frac{1}{\tau_{pol}} = \frac{\alpha^2}{\tau_{phot}} + \frac{\beta^2}{\tau_{exc}}$$

Polariton have a short lifetime : 1-100 ps

Cavity polaritons : an exciton-photon mixed state

| polariton > = α |photon> + β |exciton>

α^2 photon part

Coupling to free space optical modes

Low effective mass

β^2 exciton part

Polariton-phonon Interactions
Polariton-polariton Interactions

Properties

- Photonic component ➡ **low mass (10^{-5} m_e)**
- Short lifetime (~ps) ➡ **escape out of the cavity**
- Pseudo spin

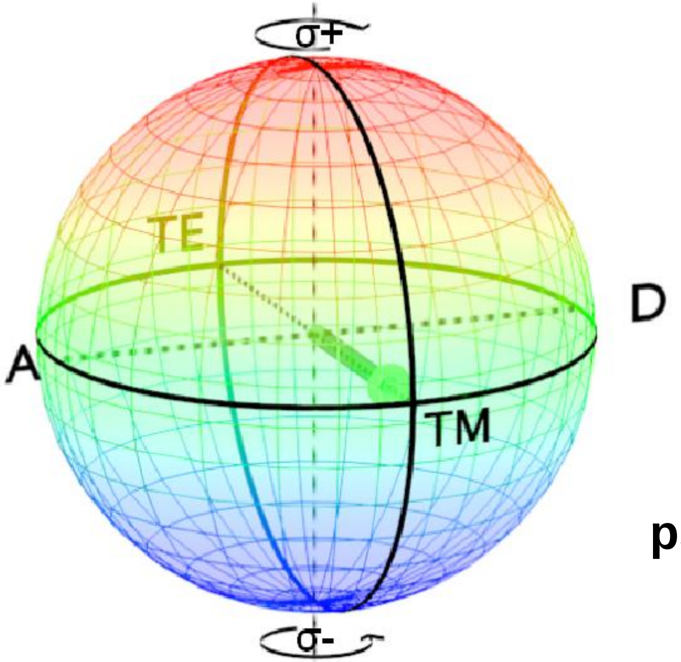
Polariton spin

- 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

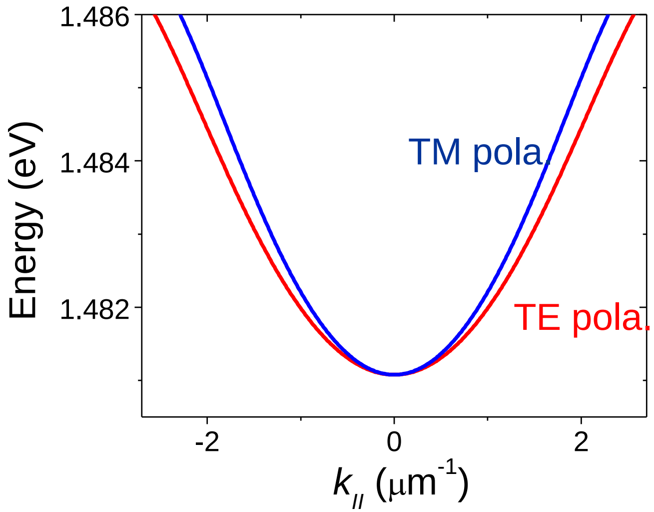
Polaritons have two spin projections:

j_z = +1 $\sigma+$
j_z = -1 $\sigma-$
½ pseudospin

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

Polariton spin: Intrinsic magnetic field

Cavity modes linearly polarized: TE-TM splitting

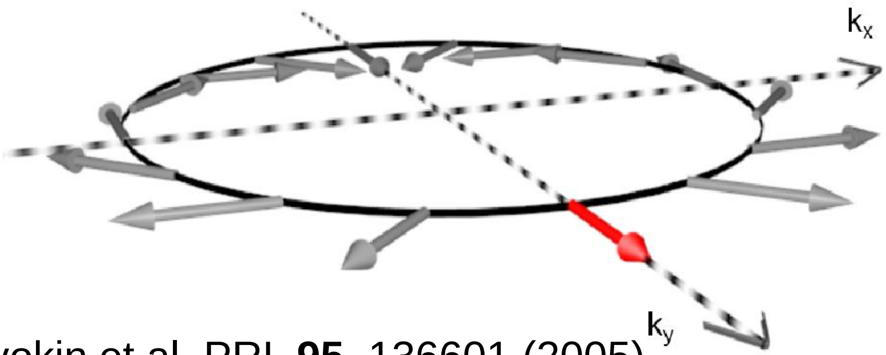


boundary conditions for the electromagnetic field at the interface of the different dielectric layers

Effective magnetic field $\mathbf{H}_{\text{eff}} = \frac{\hbar}{\mu_B g}\mathbf{\Omega_k}$

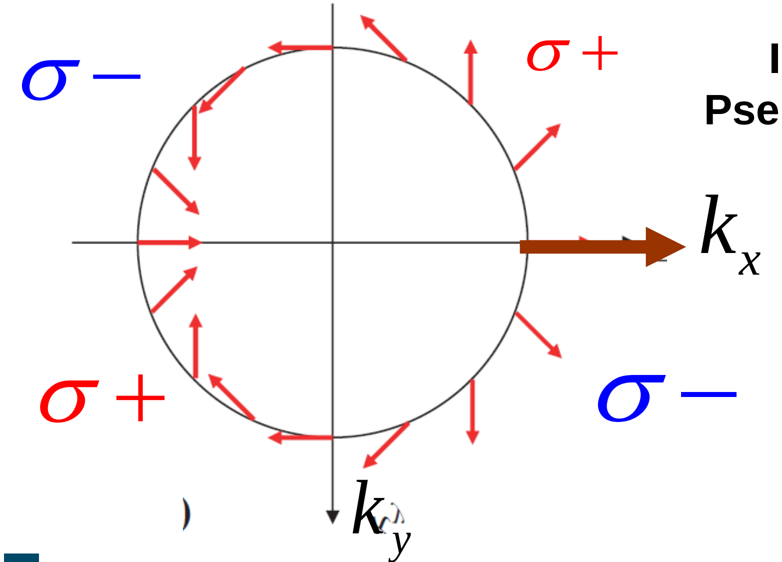
$$\Omega_x = \frac{\Omega}{k^2}(k_x^2 - k_y^2), \qquad \Omega_y = 2\frac{\Omega}{k^2}k_x k_y,$$

$$\Omega = \frac{\Delta_{\text{LT}}}{\hbar}$$



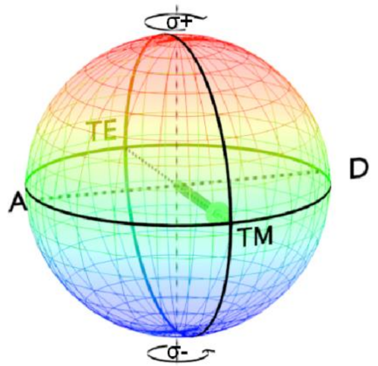
Kavokin et al. PRL **95**, 136601 (2005)

Optical spin Hall effect



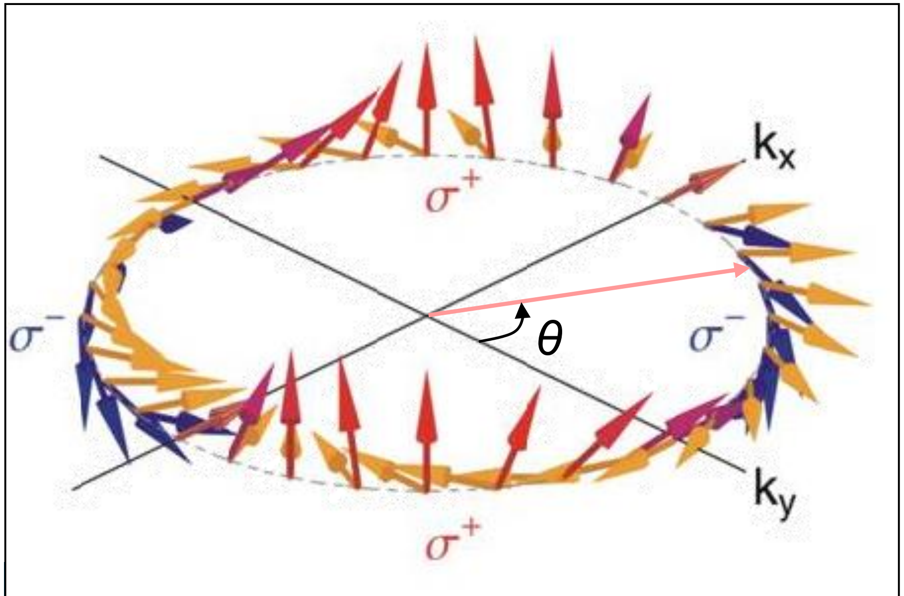
Initial Pseudospin

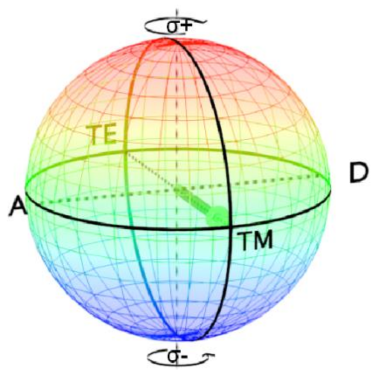
Linear polarisation along



$$\frac{\partial \vec{S}}{\partial t} = \vec{S} \wedge \vec{\Omega}(\theta) + \frac{\vec{S}_0}{\tau_1} - \frac{\vec{S}}{\tau}$$

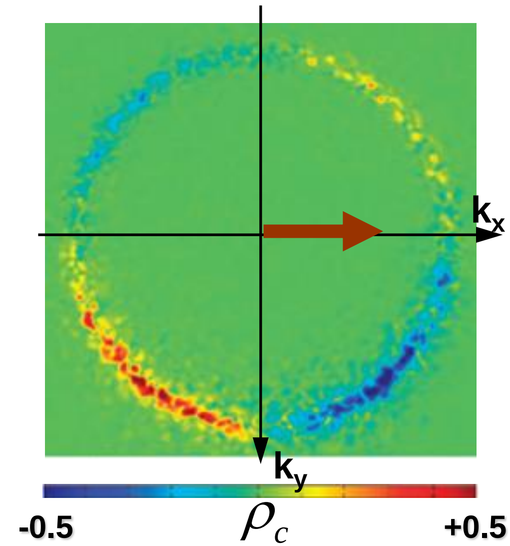
Optical spin Hall effect



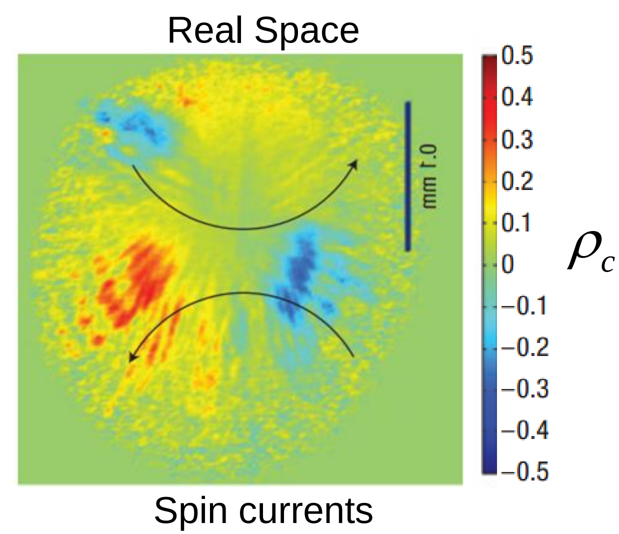


$$\frac{\partial \vec{S}}{\partial t} = \vec{S} \wedge \vec{\Omega}(\theta) + \frac{\vec{S}_0}{\tau_1} - \frac{\vec{S}}{\tau}$$

τ_{pol}= 10ps

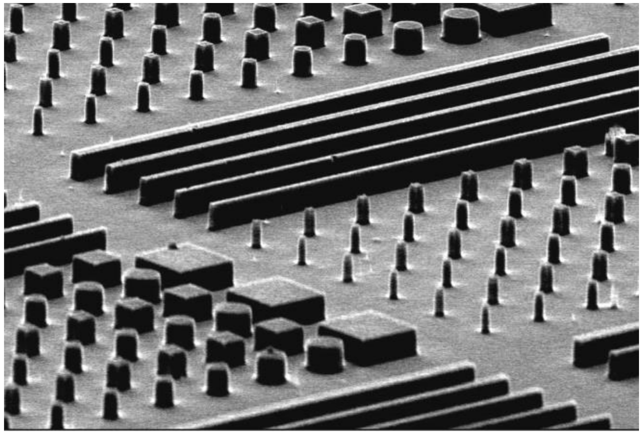


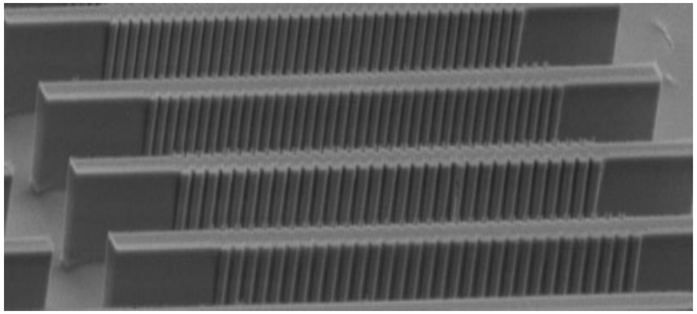
Kavokin et al. PRL **95**, 136601 (2005)
Leyder et al. Nature Phys. **3**, 628 (2007).

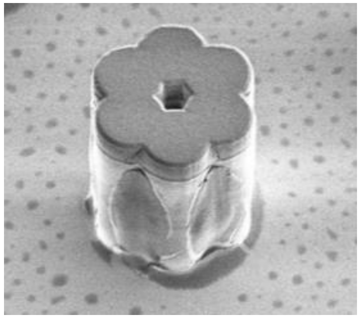


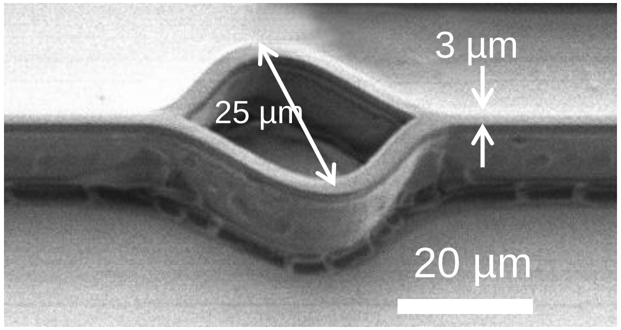
Cavity polariton in microstructures

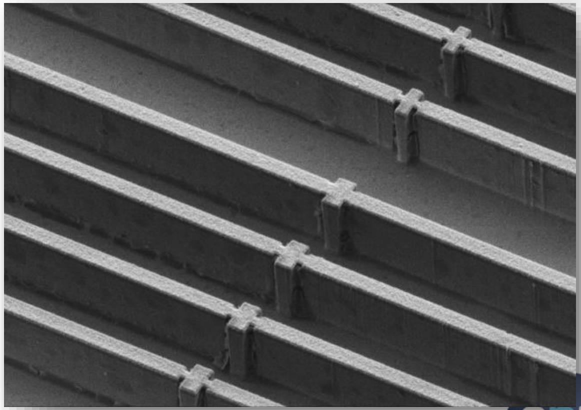
Use of nanotechnology to engineer the potential landscape
Polaritonic circuits and quantum simulation











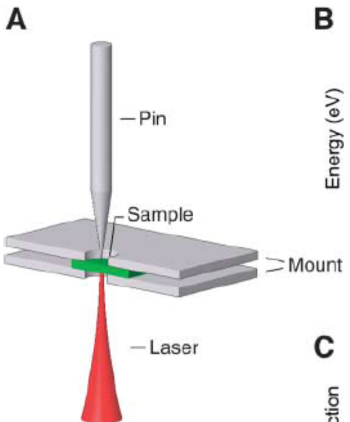
Polariton confinement

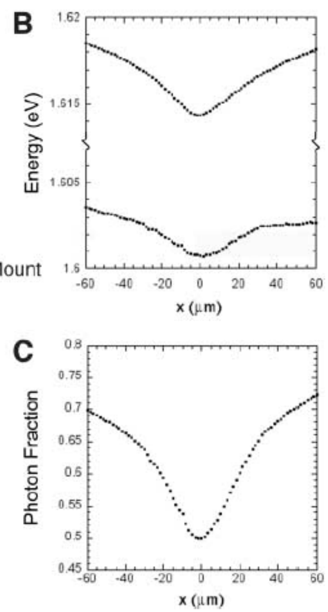
$$|pol\rangle = C_k\,|phot\rangle + X_k\,|exc\rangle$$ excitonic component

Pressure induced traps

Snoke's group

Fig. 1. (**A**) Stress geometry for the microcavity structure. (**B**) Upper and lower polariton energies (top and bottom traces, respectively), deduced from photoluminescence and reflectivity spectra at very low excitation density and low lattice temperature (T = 4 K), when a force of 0.975 N on the pin stressor is applied to the sample. (**C**) Photon fraction of the lower polariton branch as a function of position in the trap, calculated from the polariton energies shown in (B) and the standard Hopfield coefficients.





Balili *et al.*, Science 316, 1007 (2007)

Polariton confinement

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

Pressure induced traps
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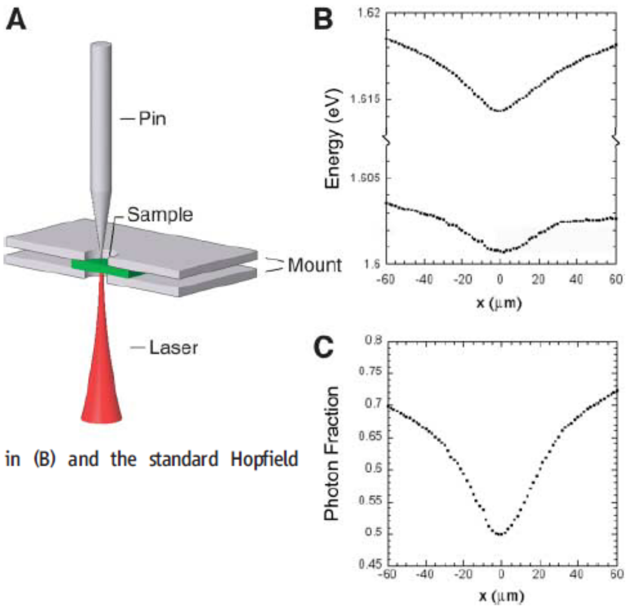
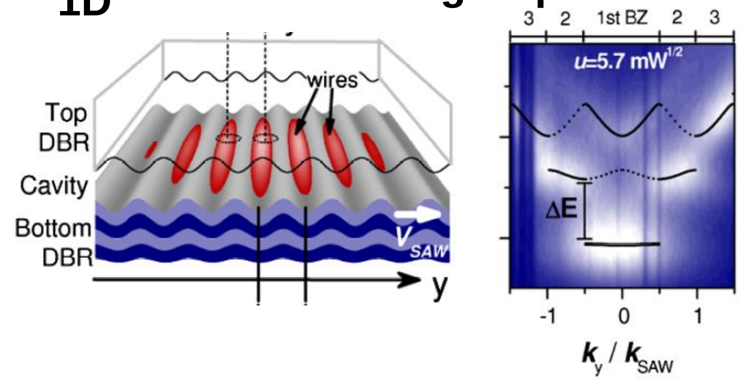


Balili *et al.*, Science 316, 1007 (2007)

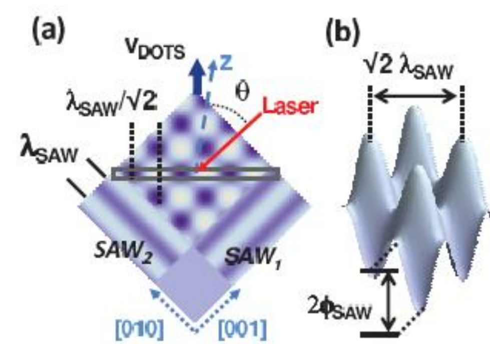
Surface acoustic waves
Santos's group

1D



Cerda-Méndez *et al.*, PRL **105**, 116402 (2010)
de Lima *et al.*, PRL **97**, 045501 (2006)

2D



Cerda-Méndez *et al.* PRB **86**, 100301(R) (2012)

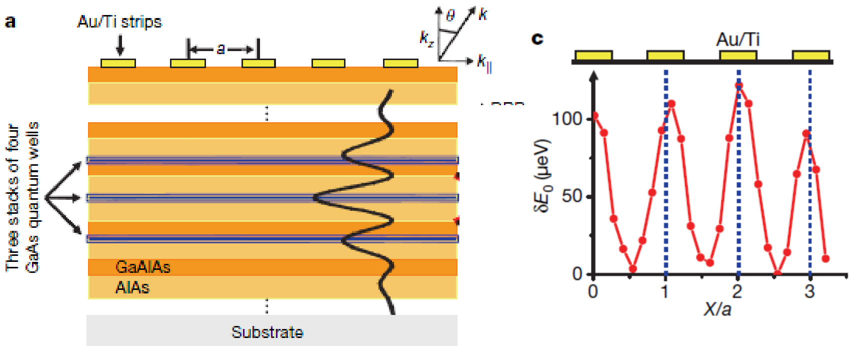
Polariton confinement

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

photonic component

Metal deposition

Metalic deposition

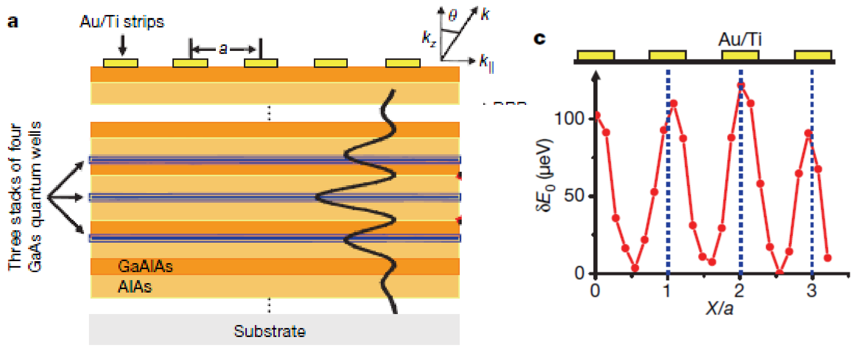


Yamamoto’s group

- Optical potential: up to 200 μeV

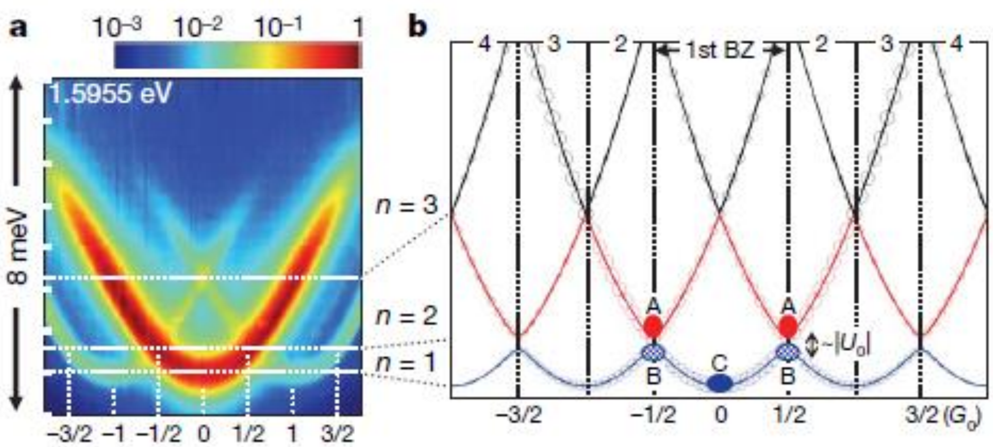
Metal deposition

Metalic deposition



1D array

π-wave condensation

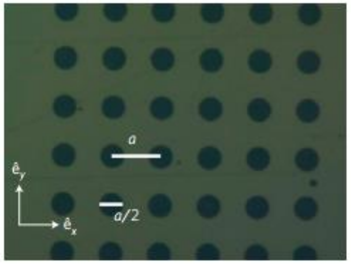


Lai et al., Nature **450**, 529 (2007)

Yamamoto's group

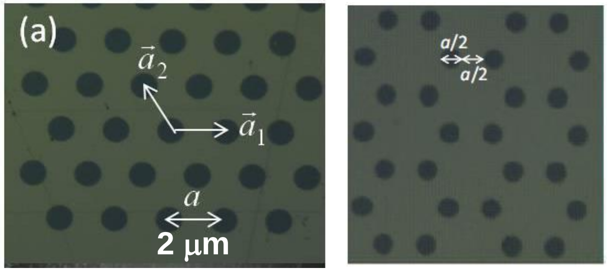
Optical potential: up to 200 μeV

2D square lattice



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

Other 2D lattices

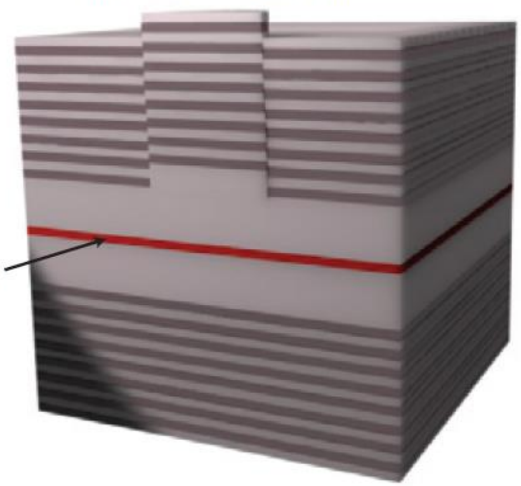


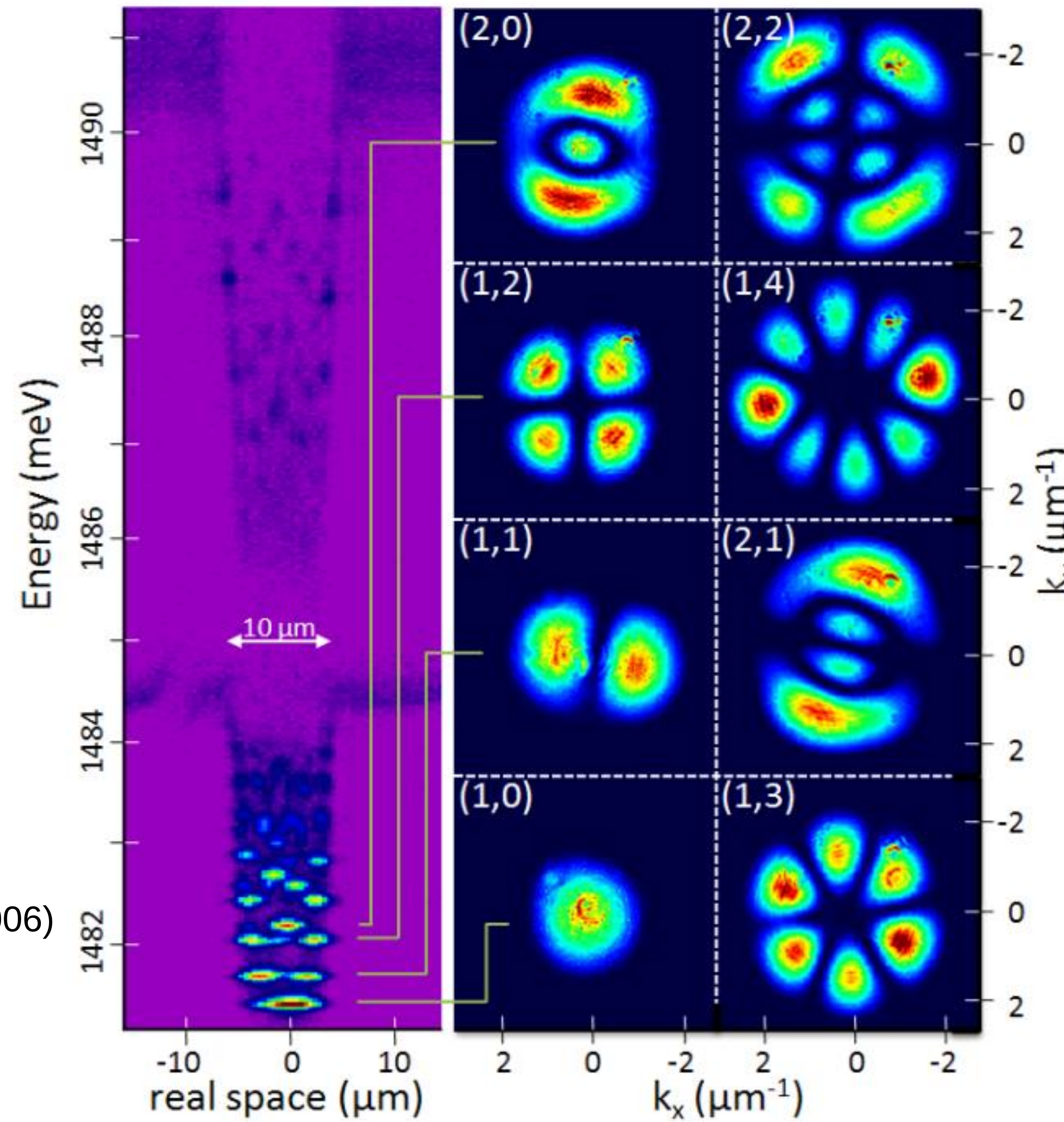
Kim et al., arXiv:1210.2153

Kusudo et al., arXiv:1211.3833

During-growth photonic trap

Deveaud's group at EPFL



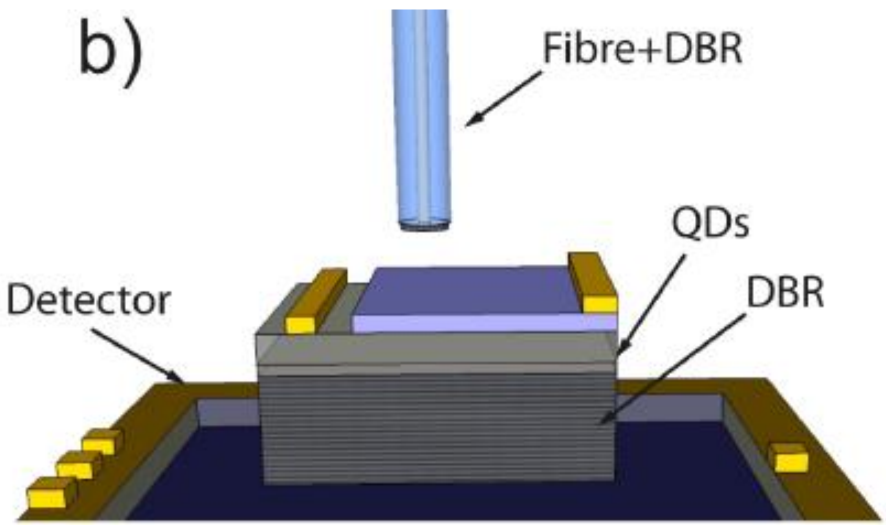


El Daïf et al., APL **88**, 061105 (2006)

Idrissi Kaitouni et al., PRB **74**, 155311 (2006)

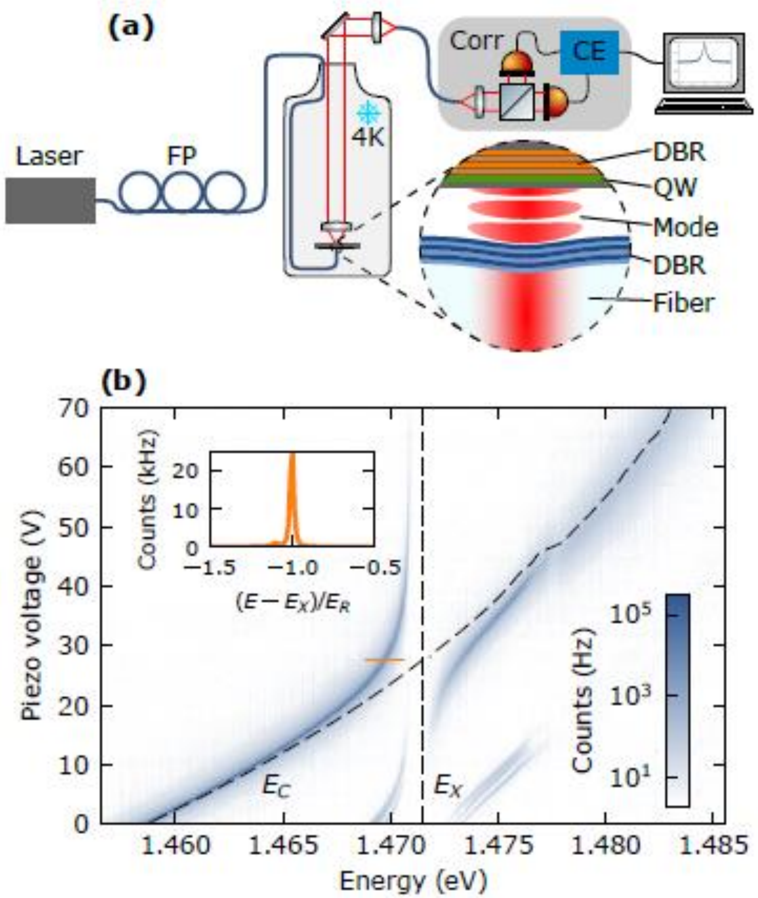
Cerna et al., PRB **80**, 121309 (2009)

Hybrid cavities



Fiber-closed cavity

Imamoglu, Reichel,

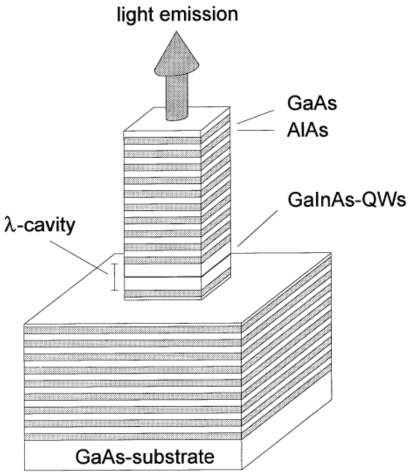


Besga et al., Light: S&A 3, e135 (2014)
S. Dufferwiel et al. Appl. Phys. Lett. 104, 192107 (2014)

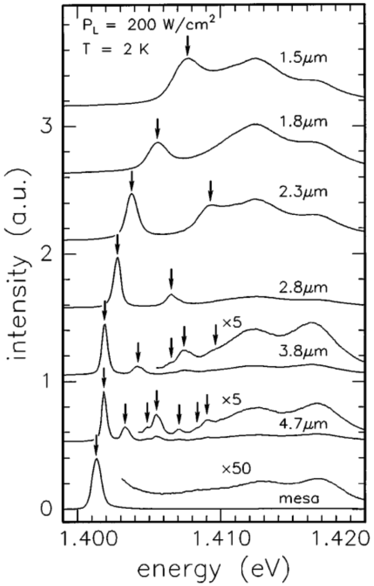
Also T. Fink et al., arXiv:1707.01837

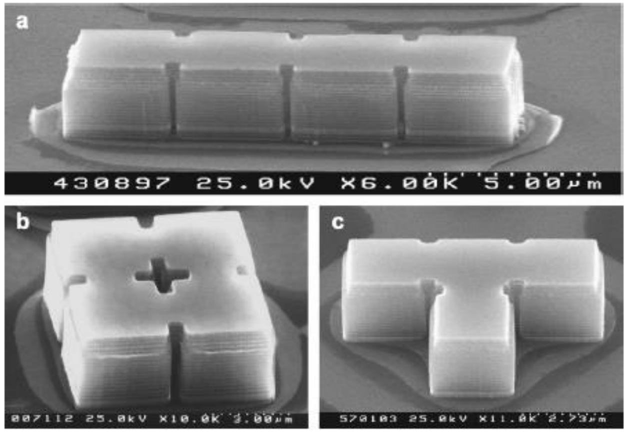
Post-growth etching

Bayer-Forchel



Reithmaier et al., PRL **78**, 378 (1997)

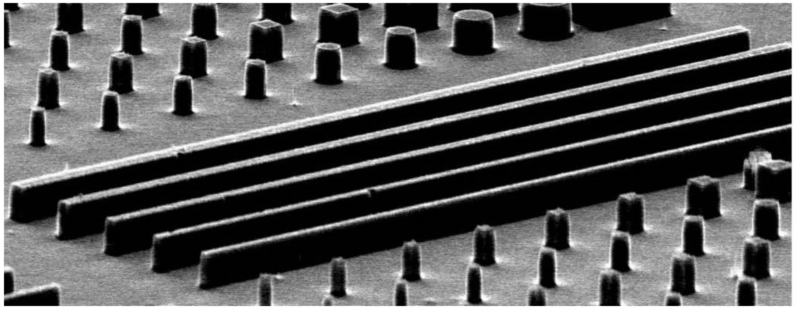




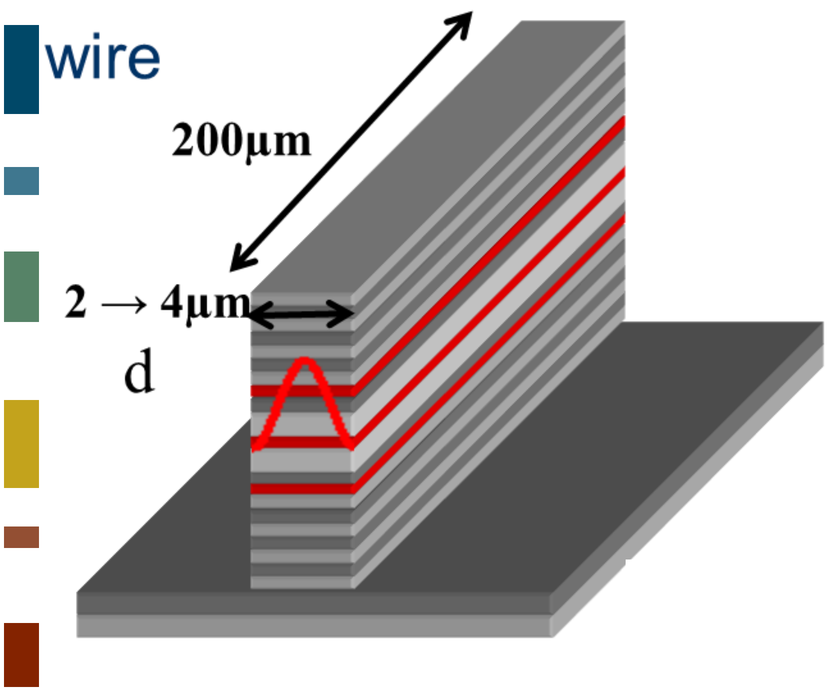
Guttroff et al., PRE **63**, 036611 (2001)

- Quasi infinite barrier
- Sub micrometer resolution

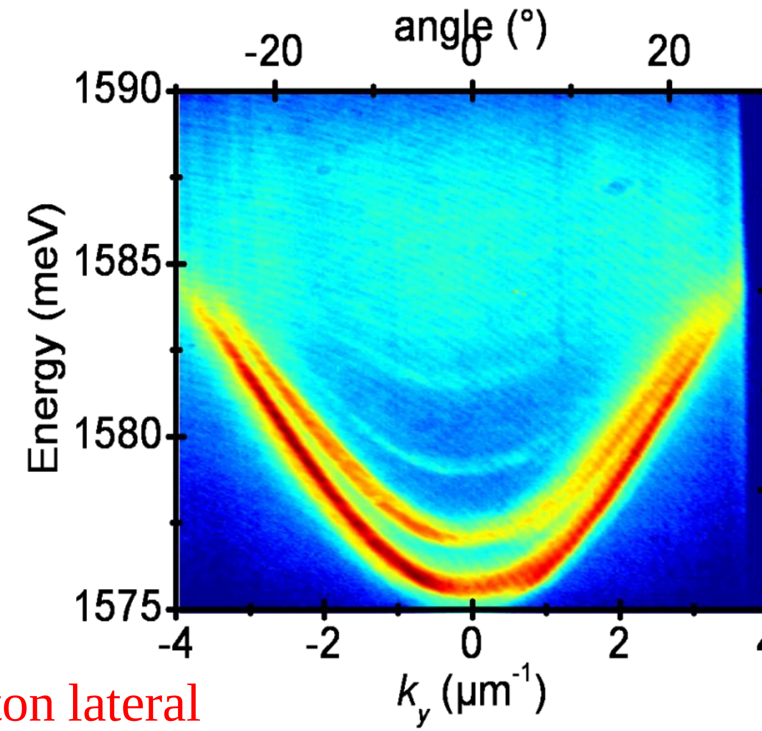
Polariton in 1D cavities



Fabrication : *E-beam lithography*
Dry Etching



1D polariton sub-bands

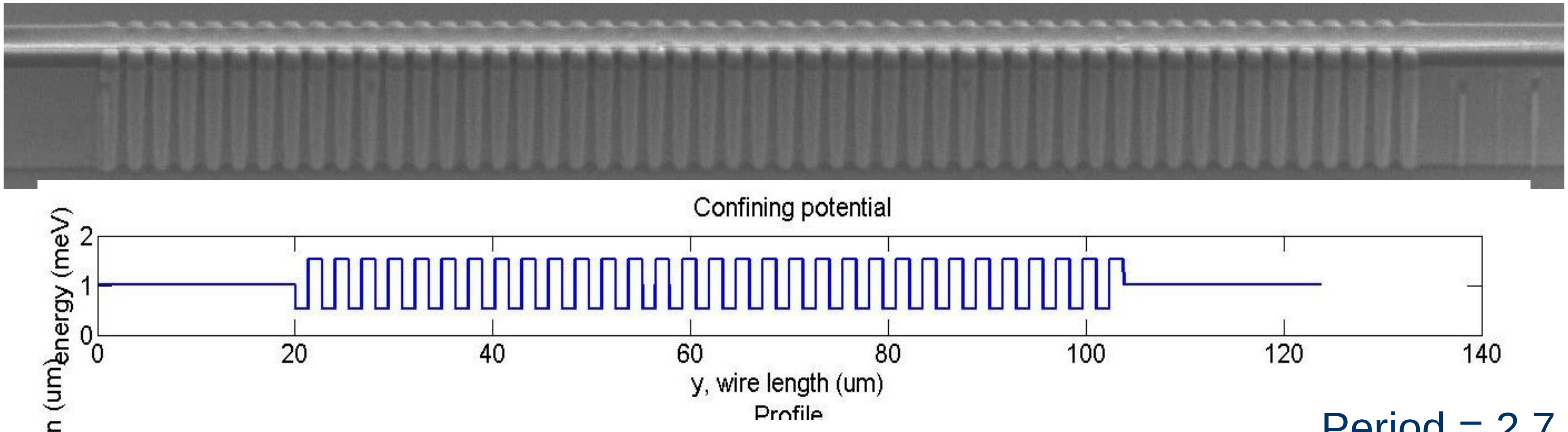


Polariton lateral confinement

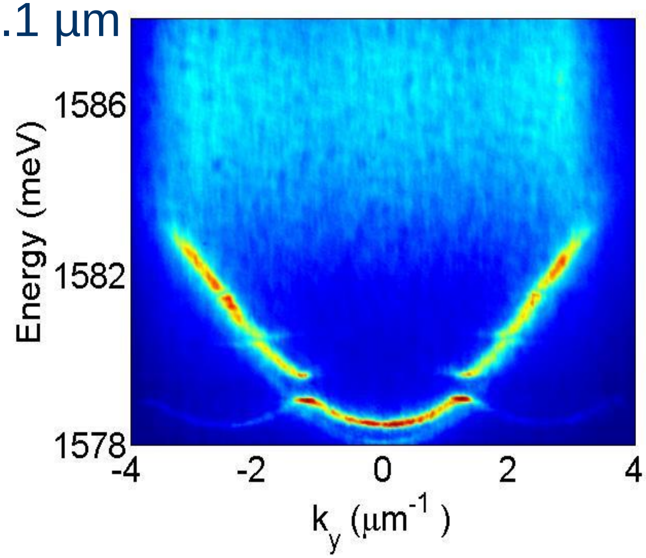
Discretisation of k_x: $k_x = n\pi/d$
$n = 1,2,3,\dots$

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)

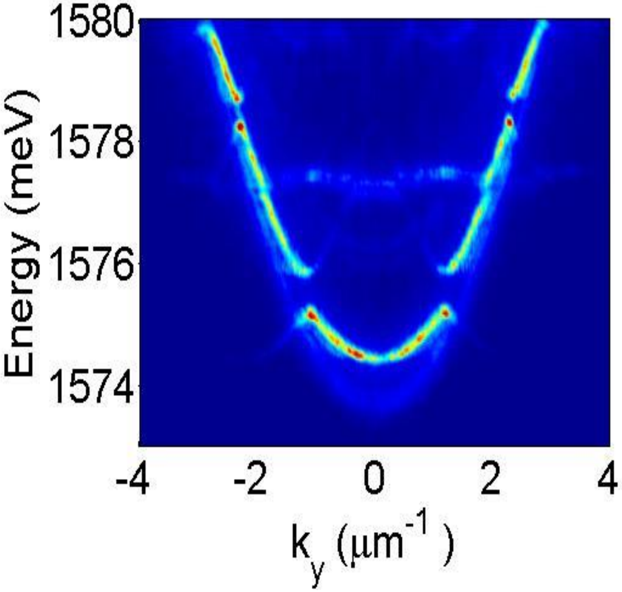
1D Periodic potential



Period = 2.1 µm



Period = 2.7 µm



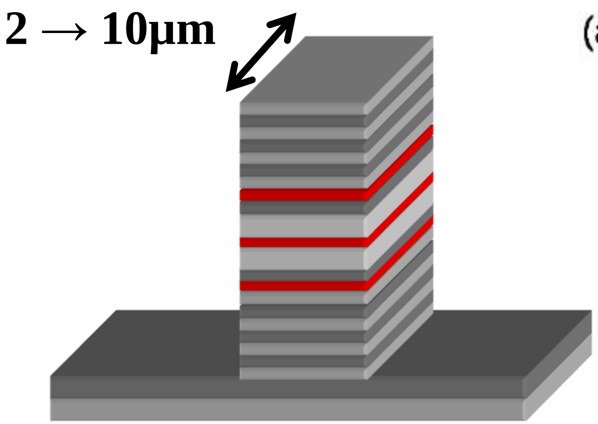
Other methods:

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

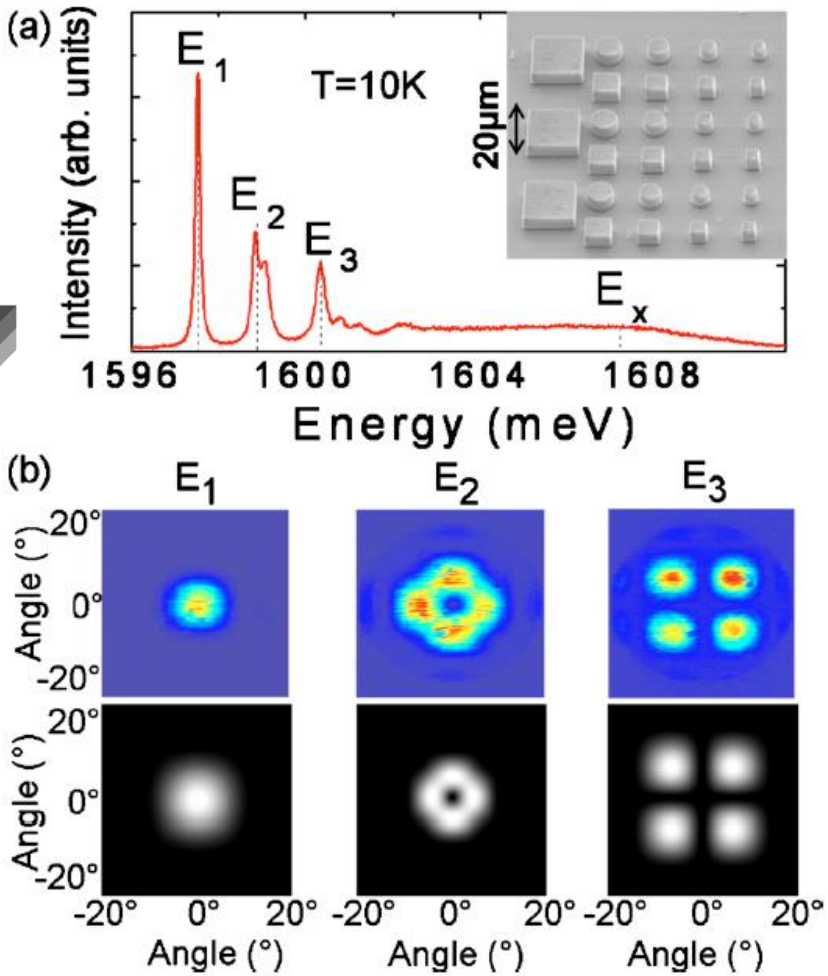
SAW :E. A. Cerda-Méndez, PRL (2010).

Polaritons in micropillars

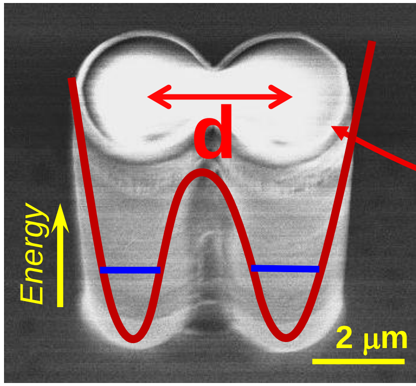
Micropillars: photonic atoms



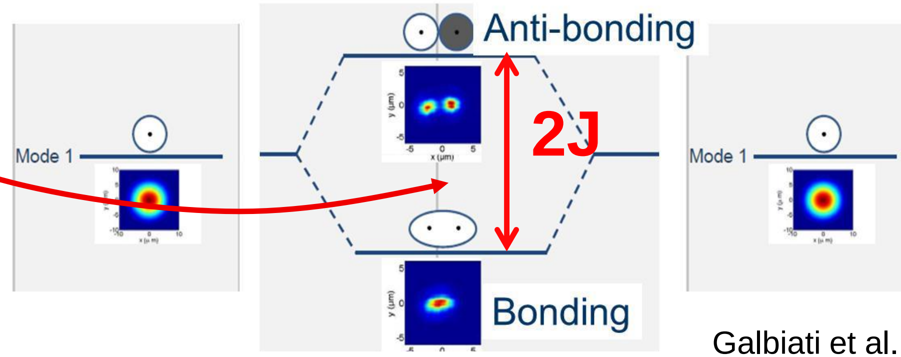
$$k_x = p_x\pi/L_x$$
$$k_y = p_y\pi/L_y$$



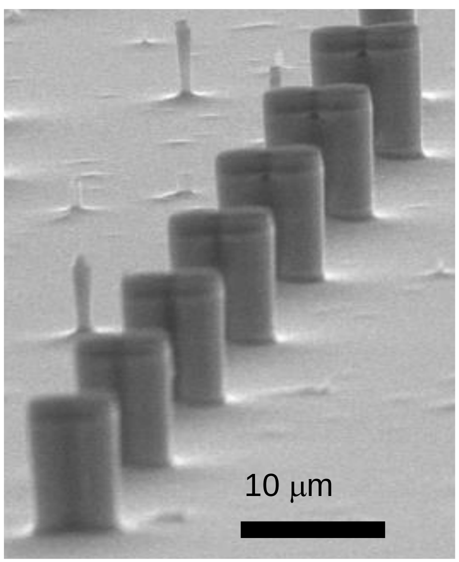
Two coupled micropillars

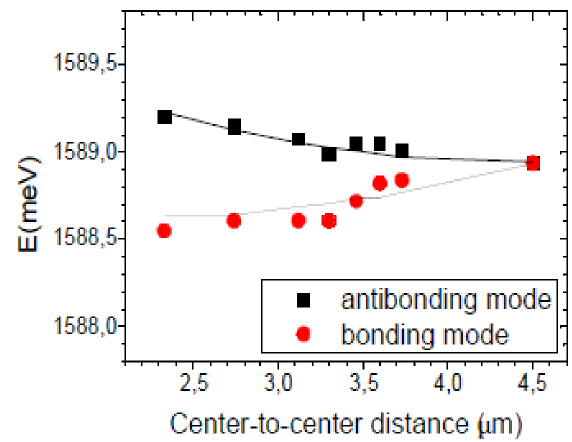


Michaelis de Vasconcellos et al., APL **99**, 101103 (2011)



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





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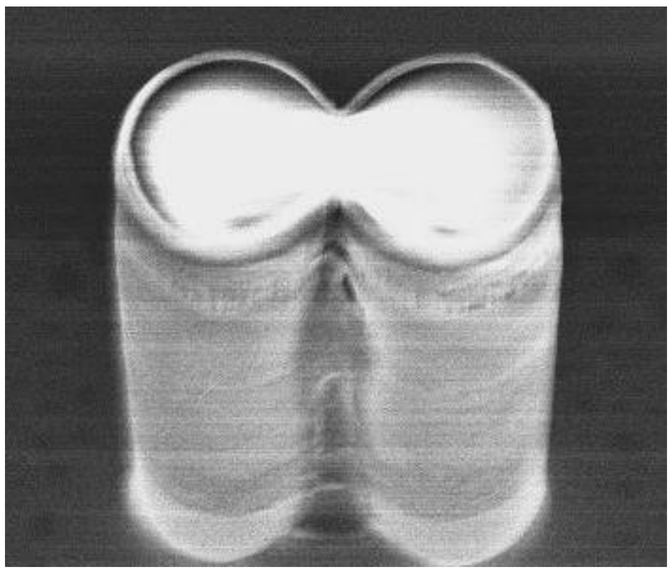
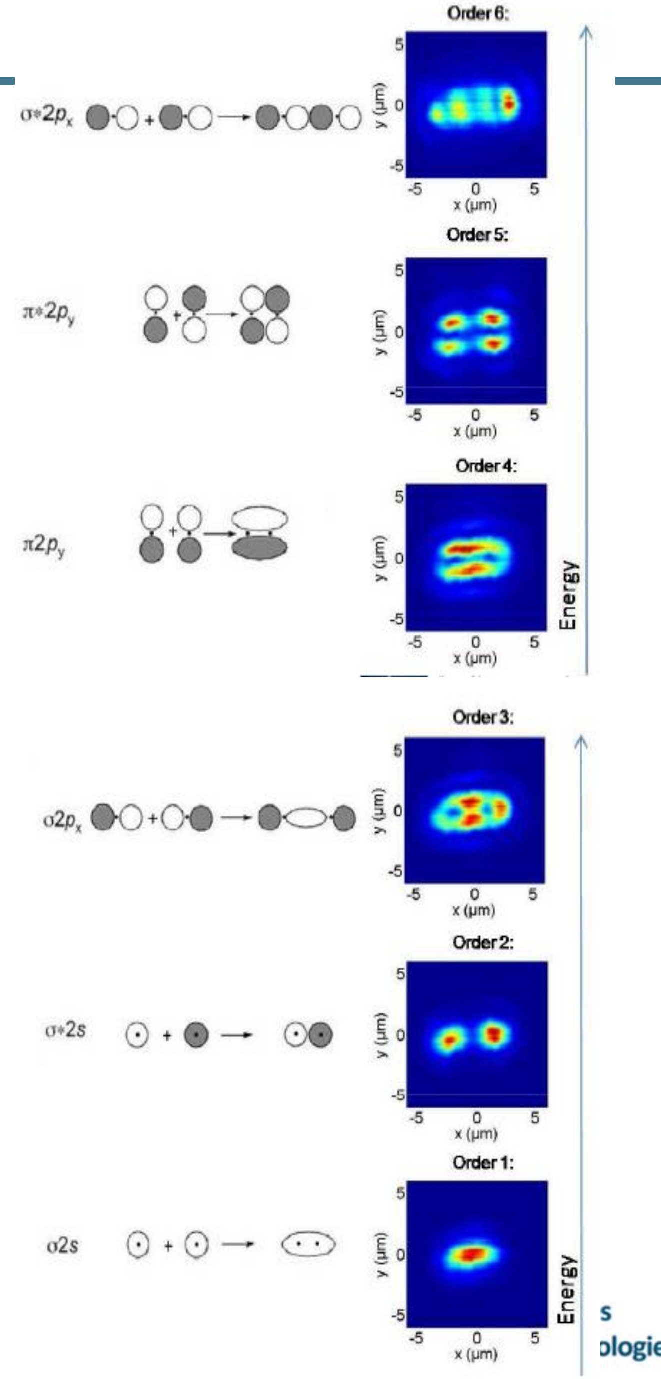
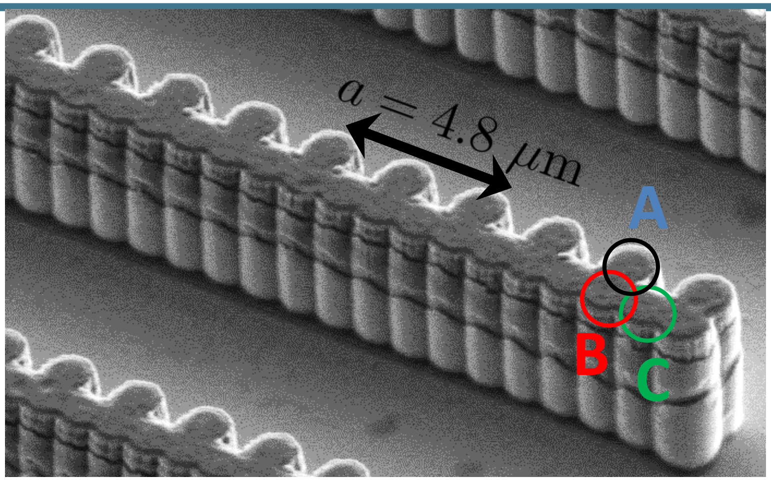
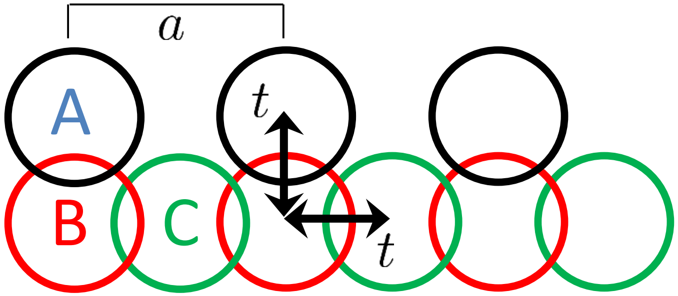
Hybridization of the p-states in a photonic molecule





Engineering of a 1D flat band : 1D Lieb lattice

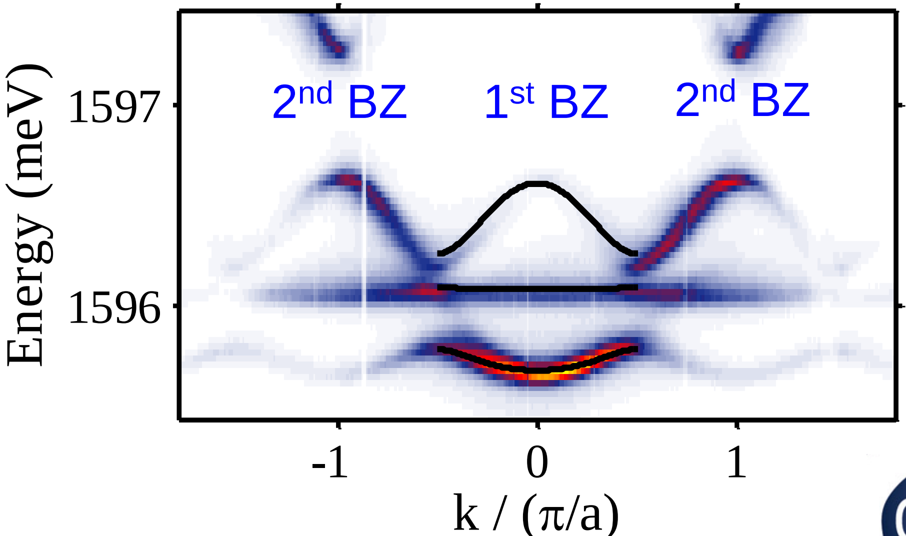




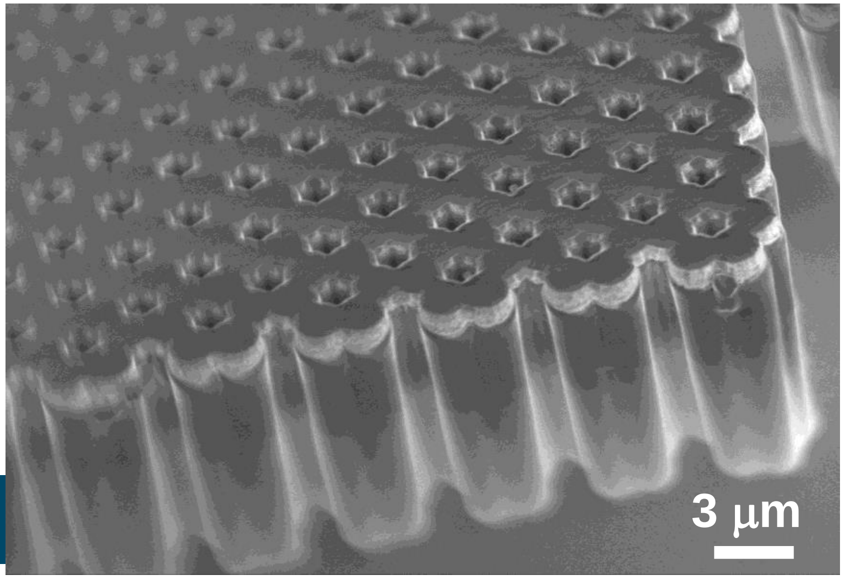
See e.g. Hyrkäs et al., PRA **87**, 023614 (2013)

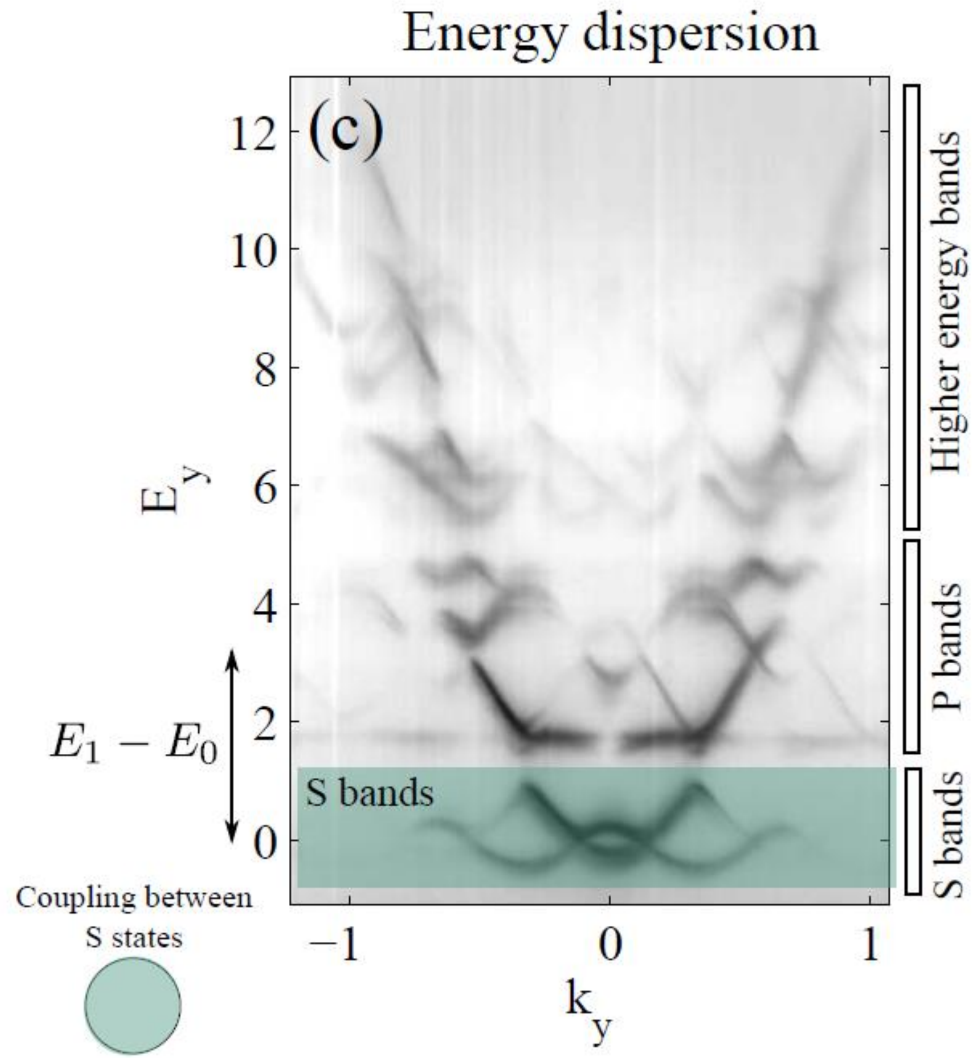
Pillar diameter = 3 µm
Interpillar distance= 2,4 µm

Far field emission



Polariton in honeycomb lattices: Dirac cones





T. Jacqmin et al., PRL **112**, 116402 (2014)

Cavity polaritons : an exciton-photon mixed state

| polariton > = α |photon> + β |exciton>

α^2 photon part	β^2 exciton part
Coupling to free space optical modes *Low effective mass*	*Polariton-phonon Interactions* *Polariton-polariton Interactions*

Properties

- Photonic component ➡ **low mass (10^{-5} m_e)**
- Short lifetime (~ps) ➡ **escape out of the cavity**
- Pseudo spin
- Excitonic component ➡ **strong non-linearity**
- Bosons

Polariton-polariton interaction

Exciton-exciton interaction

Exciton wavefunction:

$$\Psi_Q(\mathbf{r}_e,\mathbf{r}_h)=\frac{1}{\sqrt{A}}\exp[iQ\cdot(\beta_e\mathbf{r}_e+\beta_h\mathbf{r}_h)]$$

$$\times\sqrt{\frac{2}{\pi}}\frac{1}{\lambda_{2D}}\exp\left(-\frac{|\mathbf{r}_e-\mathbf{r}_h|}{\lambda_{2D}}\right),$$

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

Exciton : J = +- 1 e ↑↓ h e ↓↑ h

J =+- 2 e ↑↑ h e ↓↓ h

Polariton-polariton interaction

Exciton-exciton interaction

PHYSICAL REVIEW B VOLUME 58, NUMBER 12 15 SEPTEMBER 1998-II

Role of the exchange of carriers in elastic exciton-exciton scattering in quantum wells

C. Ciuti, V. Savona, C. Piermarocchi, and A. Quattropani
Institut de Physique Théorique, Ecole Polytechnique Fédérale, CH-1015 Lausanne, Switzerland

P. Schwendimann
Defense Procurement, System Analysis Division, CH-3003 Bern, Switzerland

(Received 15 December 1997)

Two Excitons:

$$H=-\frac{\hbar^2}{2m_e}\nabla_e^2-\frac{\hbar^2}{2m_h}\nabla_h^2-\frac{\hbar^2}{2m_e}\nabla_{e'}^2-\frac{\hbar^2}{2m_h}\nabla_{h'}^2-V(|\mathbf{r}_e-\mathbf{r}_h|)-V(|\mathbf{r}_{e'}-\mathbf{r}_{h'}|)+V(|\mathbf{r}_e-\mathbf{r}_{e'}|)+V(|\mathbf{r}_h-\mathbf{r}_{h'}|)-V(|\mathbf{r}_e-\mathbf{r}_{h'}|)-V(|\mathbf{r}_h-\mathbf{r}_{e'}|), \quad (5)$$

$$H = H_0(\text{exc1}) + H_0(\text{exc2}) + W$$

Polariton-polariton interaction

Exciton-exciton interaction

PHYSICAL REVIEW B VOLUME 58, NUMBER 12 15 SEPTEMBER 1998-II

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Exc 1 Exc 1

$$(1s,\mathbf{Q},S)+(1s,\mathbf{Q}',S')\rightarrow(1s,\mathbf{Q}+\mathbf{q},S_f)+(1s,\mathbf{Q}'-\mathbf{q},S'_f).$$

$$H_{SS'}^{S_fS'_f}(\mathbf{Q},\mathbf{Q}',\mathbf{q})=\langle S|S_f\rangle\langle S'|S'_f\rangle H_{\mathrm{dir}}(\mathbf{Q},\mathbf{Q}',\mathbf{q})$$

Direct term

$$+\langle S|S'_f\rangle\langle S'|S_f\rangle H^{X}_{\mathrm{exch}}(\mathbf{Q},\mathbf{Q}',\mathbf{q})$$

Exchange of both electrons and holes

$$+S^{e}_{\mathrm{exch}}(S,S',S_f,S'_f)H^{e}_{\mathrm{exch}}(\mathbf{Q},\mathbf{Q}',\mathbf{q})$$

$$+S^{h}_{\mathrm{exch}}(S,S',S_f,S'_f)H^{h}_{\mathrm{exch}}(\mathbf{Q},\mathbf{Q}',\mathbf{q}).$$

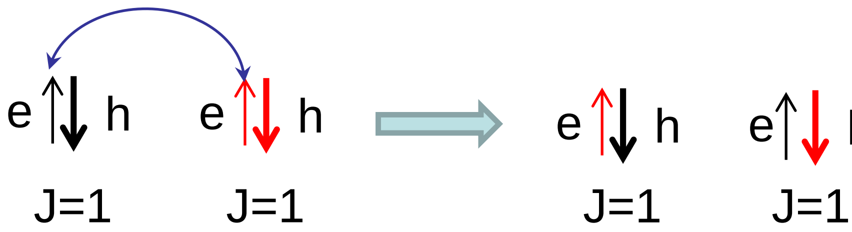
Exchange of electrons

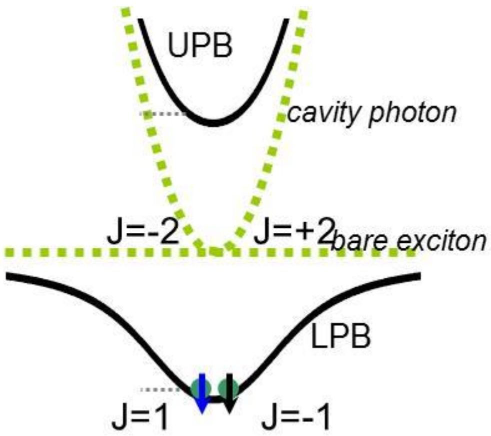
Exchange of holes

Dominant terms

Spin dependant polariton-polariton interaction

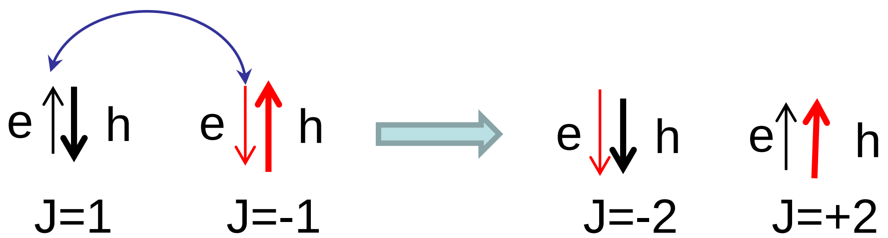
Interactions between 2 polaritons with **parallel** spins :

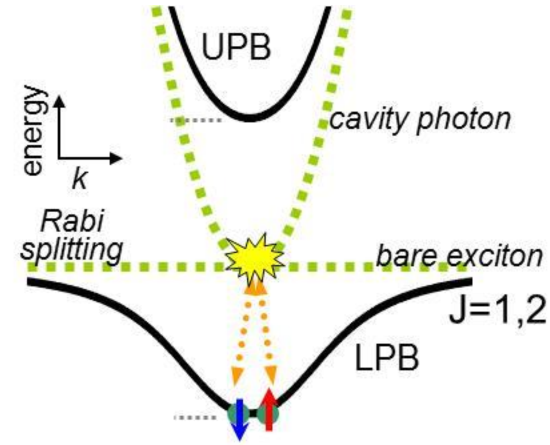




Resonant term

Interactions between 2 polaritons with **opposite** spins :





Non Resonant term => much weaker

Wouters, PRB **76**, 045319 (2007)
Schumacher *et al.*, PRB **76**, 245324 (2007)

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Spin dependent polariton-polariton interaction

Parallel spin : resonant process: Strong and Repulsive interaction

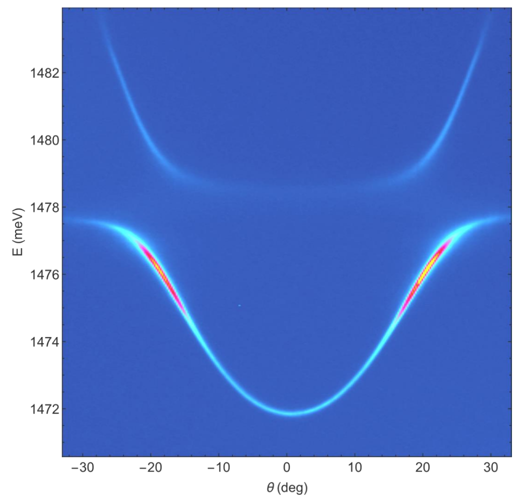
Anti-parallel : via dark exciton intermediate states: Weaker and attractive interaction

$$|\alpha_{\uparrow\uparrow}| >> |\alpha_{\uparrow\downarrow}|$$

Interactions : a tool to manipulate polaritons
highly non-linear system
spin dependant

Summary

- ➢ Hybrid exciton-photon quasi-particles
- ➢ Tunable properties : lifetime, effective mass
- ➢ Lateral confinement : engineering of band structure
- ➢ Optical access to all physical properties



Why so interesting ?   Because of interactions, strong non-linearity

- Spin dependent polariton polariton interactions
- Repulsive polariton-exciton interactions

Outline

Lecture 1 : **Introduction to cavity polaritons**

- Hybrid light-matter quasi-particle: basic properties
- Confinement in microstructures
- Interactions

II Lecture 2: **Polariton condensation; Quantum fluids of light**

Coherence; Instability; Superfluidity; solitons

III Lecture 3: **Polariton in lattices : quantum simulation**

- 1D Fibonacci quasi-crystals: fractal spectrum, edge states
- 1D SSH : topological laser
- 2D Honeycomb lattice: Dirac cones, edge states

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