# Quantum fluids of light

**Jacqueline Bloch**

Centre de Nanosciences et de Nanotechnologies
C2N, CNRS/Universités Paris Sud/ Paris Saclay
Palaiseau, France

Jacqueline.bloch@c2n.upsaclay.fr
http://www.polaritonquantumfluid.fr

# Quantum fluids of light?

**Jacqueline Bloch**

Centre de Nanosciences et de Nanotechnologies
C2N, CNRS/Universités Paris Sud/ Paris Saclay
Marcoussis, France

General motivations

Why cavity polaritons?

How do we perform experiments?

Band structure?

Why non-linearities?

Where do we go??

Jacqueline.bloch@c2n.upsaclay.fr
http://www.polaritonquantumfluid.fr

université PARIS-SACLAY

RENATECH French national nanofabrication network

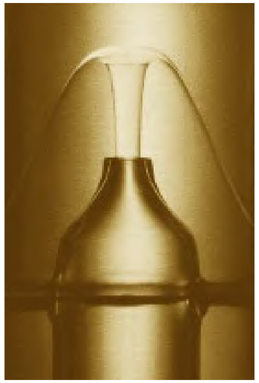
UNIVERSITÉ PARIS SUD

cnrs

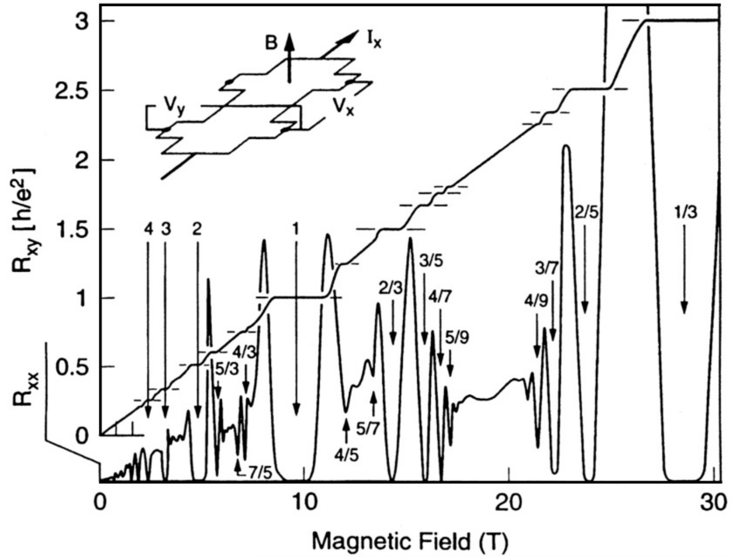
C2N Centre de Nanosciences et de Nanotechno

# Many body physics: facinating macroscopic physics

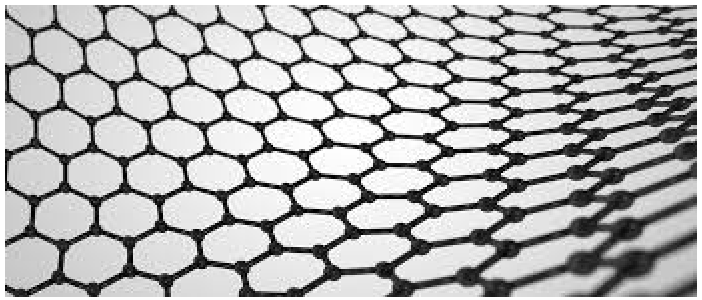
Superfluidity



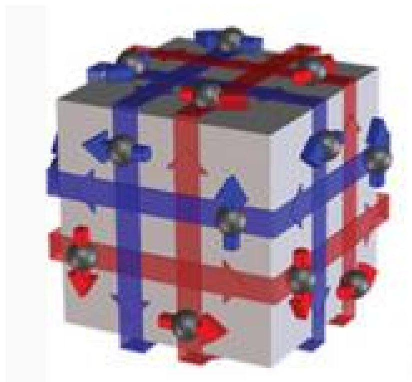
Fractional Quantum Hall effect




Graphene



Topological insulators



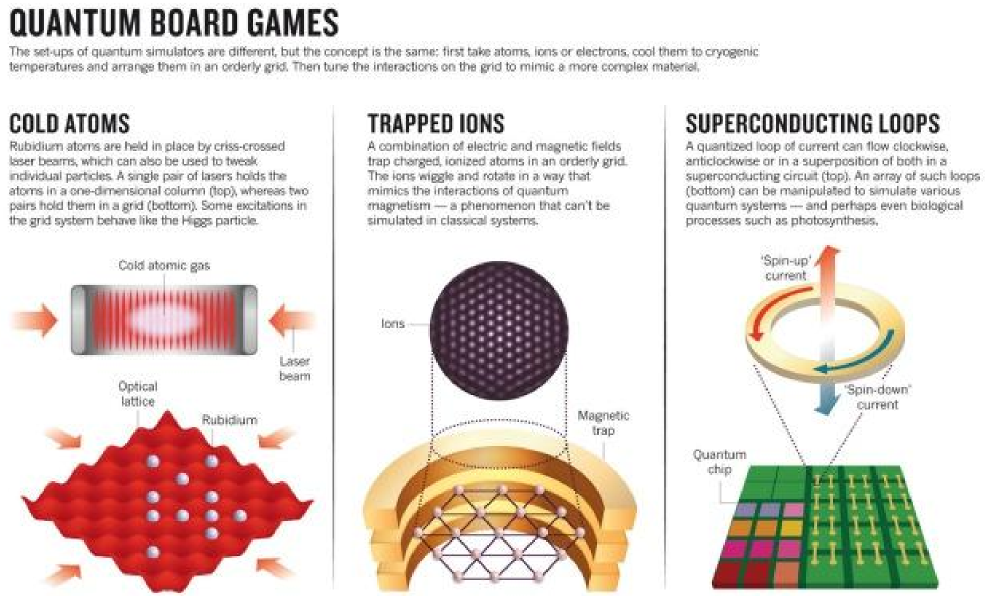
# Quantum fluids of light as an analogous system

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi$$

Same Hamiltonian => Same physical properties

## Why use synthetic quantum material?

- System « easier » to probe, manipulate
- Create new geometries, new properties => Applications
- Realize experiments impossible to predict because of complexity of numerical simulations (many body physics): **quantum simulations**




Nature 14 November 2012

Original idea: [R. Feynman., Int. J. Theor. Phys. **21**, 467 (1982)]

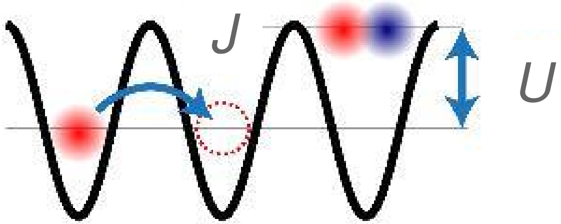
# Quantum fluids of light as an analogous system

- Photons have no mass !
- Photons have no charge !
- Photons do not interact (or so weakly) !
- Photons are bosons (not fermions like electrons !)

# Quantum fluids of light as an analogous system

- Photons have no mass ! **Effective mass in a cavity**
- Photons have no charge ! ! **Artificial gauge field**
- Photons do not interact (or so weakly) ! **Yes when coupled to electronic excitations**
- Photons are bosons (not fermions like electrons !) **Nobody is perfect!**

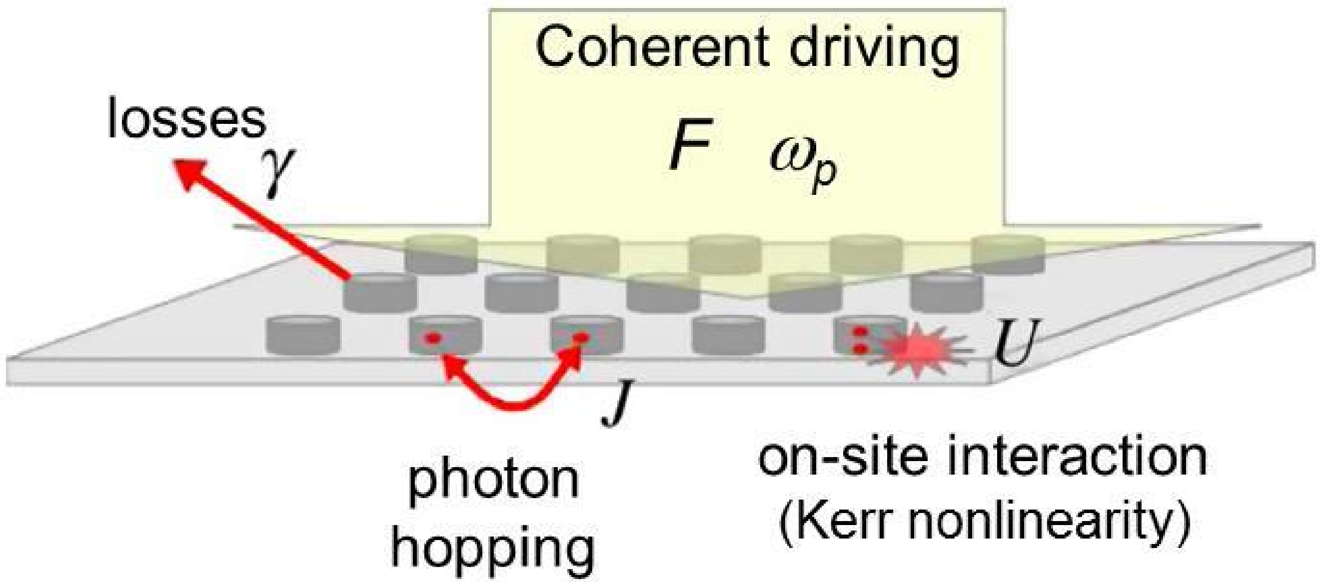
Bose-Hubbard $$\hat{H} = -J \sum_{\langle m,n \rangle} \hat{a}_m^\dagger \hat{a}_n + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$




Centre de Nanosciences et de Nanotechnologies

# Driven-dissipative photonic Bose-Hubbard model

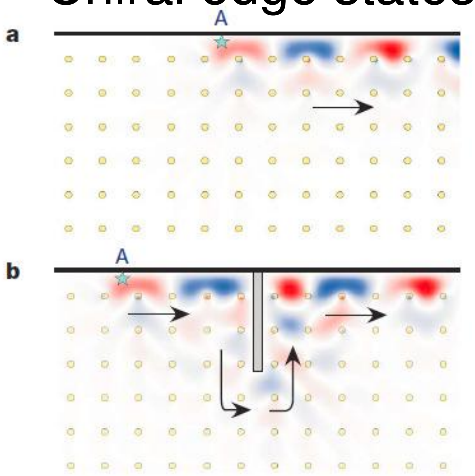
## Out of equilibrium quantum physics




Ciuti & Carusotto, Rev. Mod. Phys. **85**, 299 (2013)
M.J. Hartman, Journal of Optics (2016)
C.Noh and DG Angelakis, Report on progress in Physics (2016)
A. Biella et al., Phys. Rev. A 96, 023839 (2017)
F. Vincentini et al., Phys. Rev. A 97, 013853 (2018)

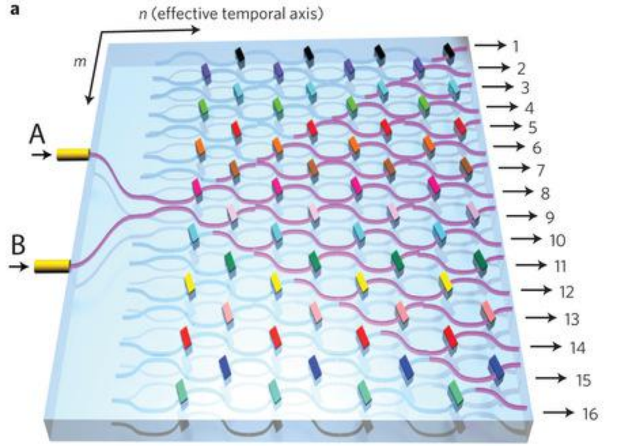
# Emulation with light

## Chiral edge states



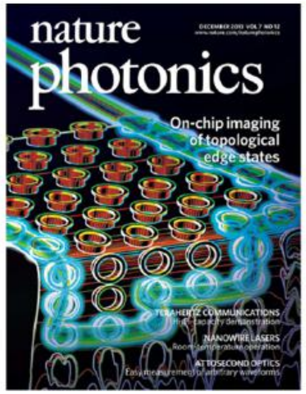

Zheng Wang et al.,
Nature **461** 772 (2009)

## Randon quantum walk



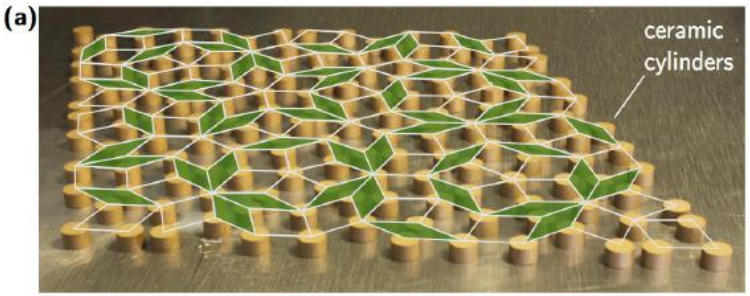

A. Crespi, Nature Photonics 7, 322 (2013)

## Topological edge states Si



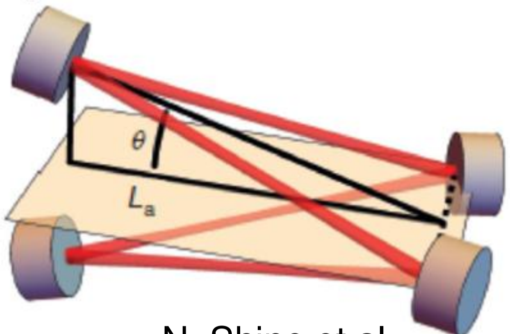

M. Hafezi,
Nat. Phot. **7** 1001 (2013)

## Quasicrystal



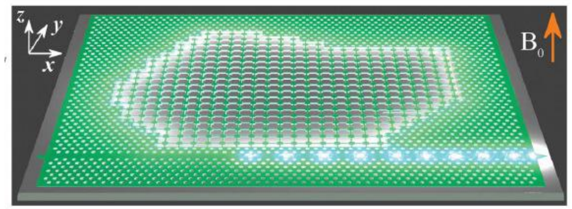

P. Vignolo et al., New J. Phys. 16 (2014) 043013

## Synthetic Landau levels




N. Shine et al.
Nature 354, 671 (2016)

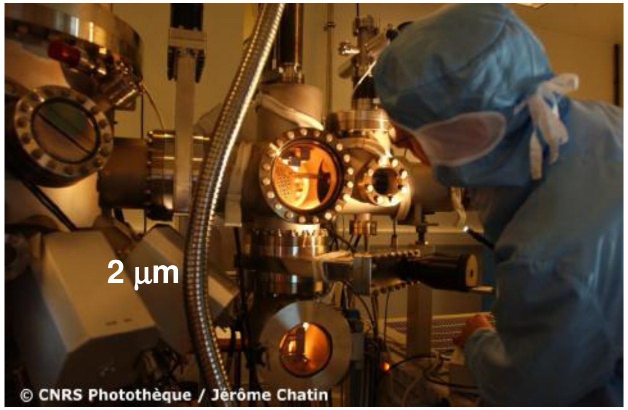
## Non reciprocal lasing



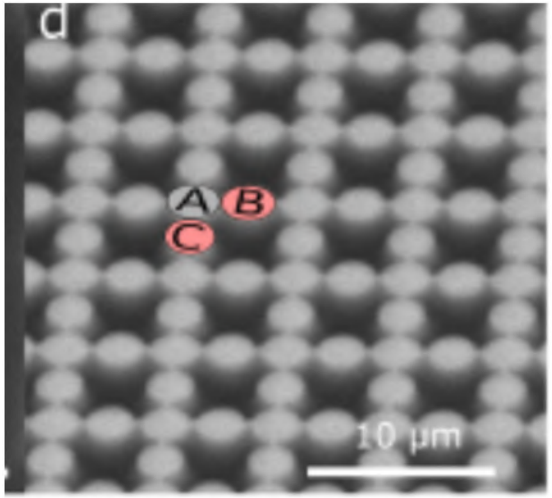

B.Bahari et al., Science
10.1126/science.aao4551(2017)

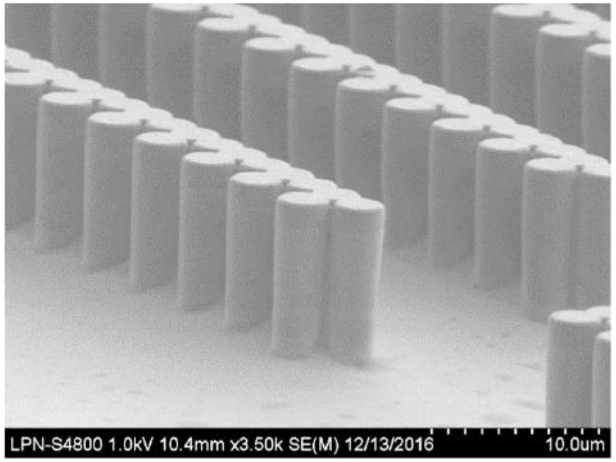
M. A. Bandres et al. Science
10.1126/science.aar4005 (2018)

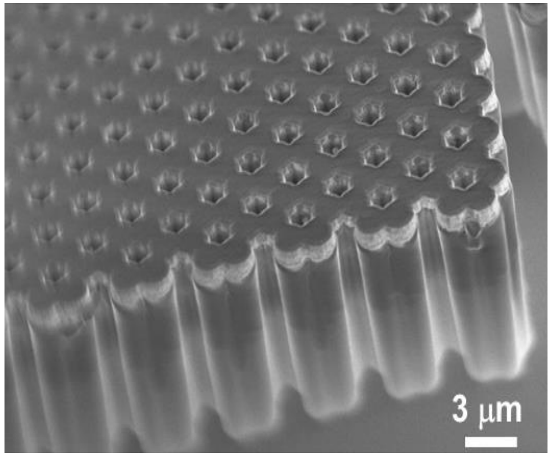
# Semiconductor microcavities : cavity polaritons







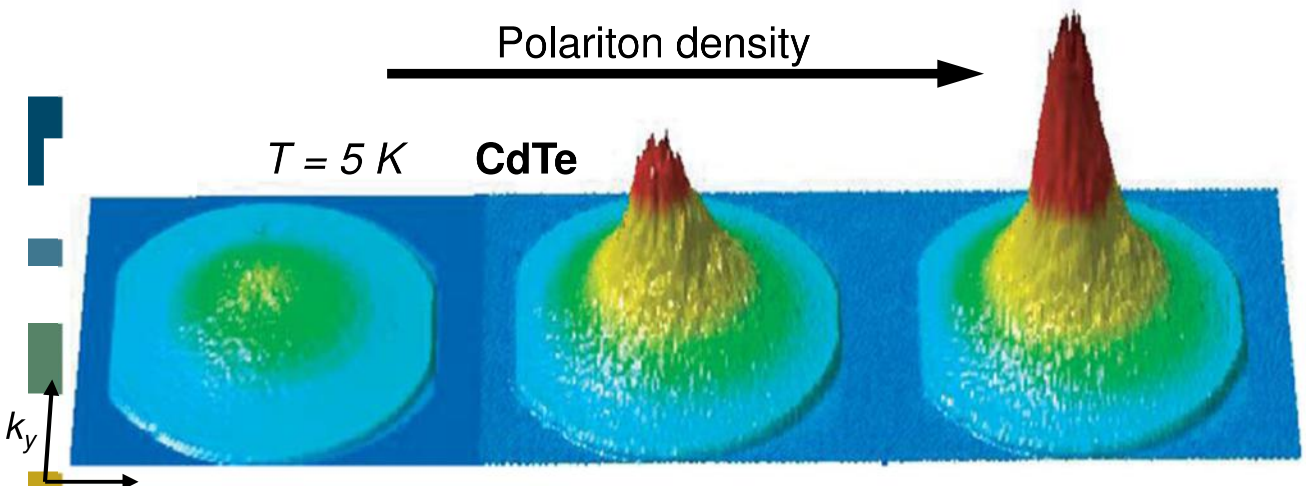



# Bose-Einstein condensation of exciton polaritons

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

# Polariton superfluidity

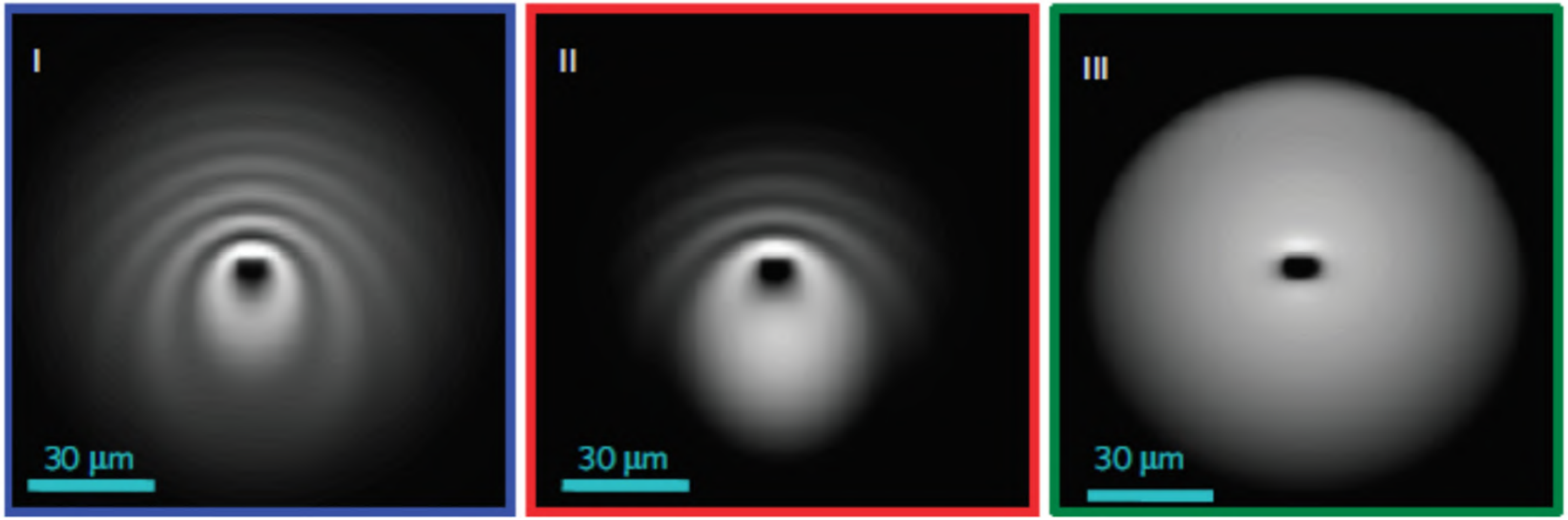
Iacopo Carusotto

Cristiano Ciuti

Alberto Amo

Alberto Bramati

Elisabeth Giacobino

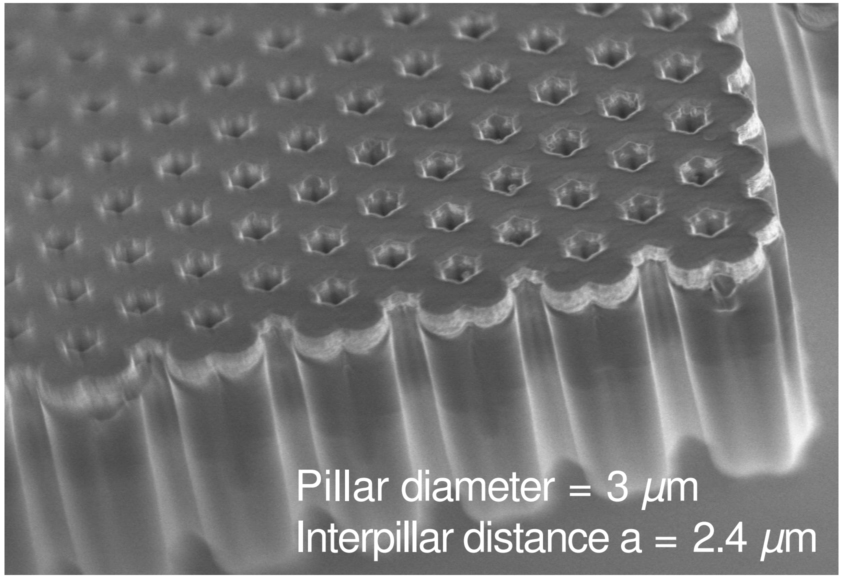


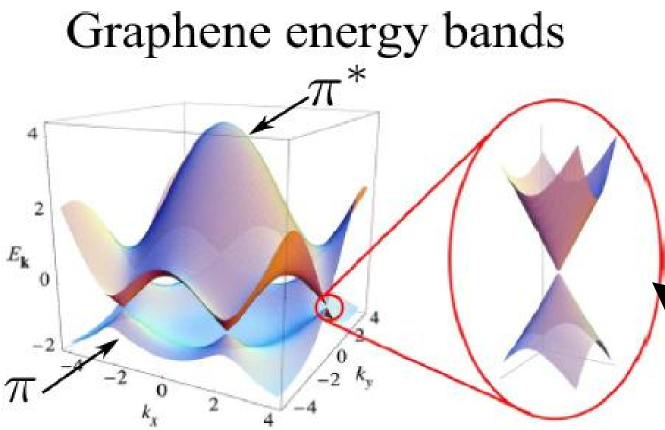

C. Ciuti and I. Carusotto PRL 242, 2224 (2005)

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

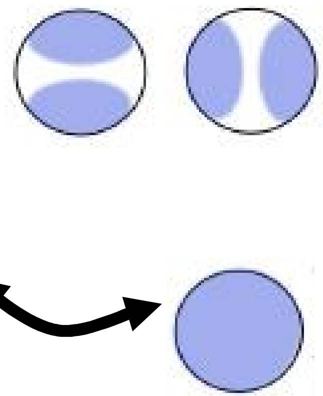
C. Ciuti & I. Carusotto, Rev. Mod. Phys. **85**, 299 (2013)

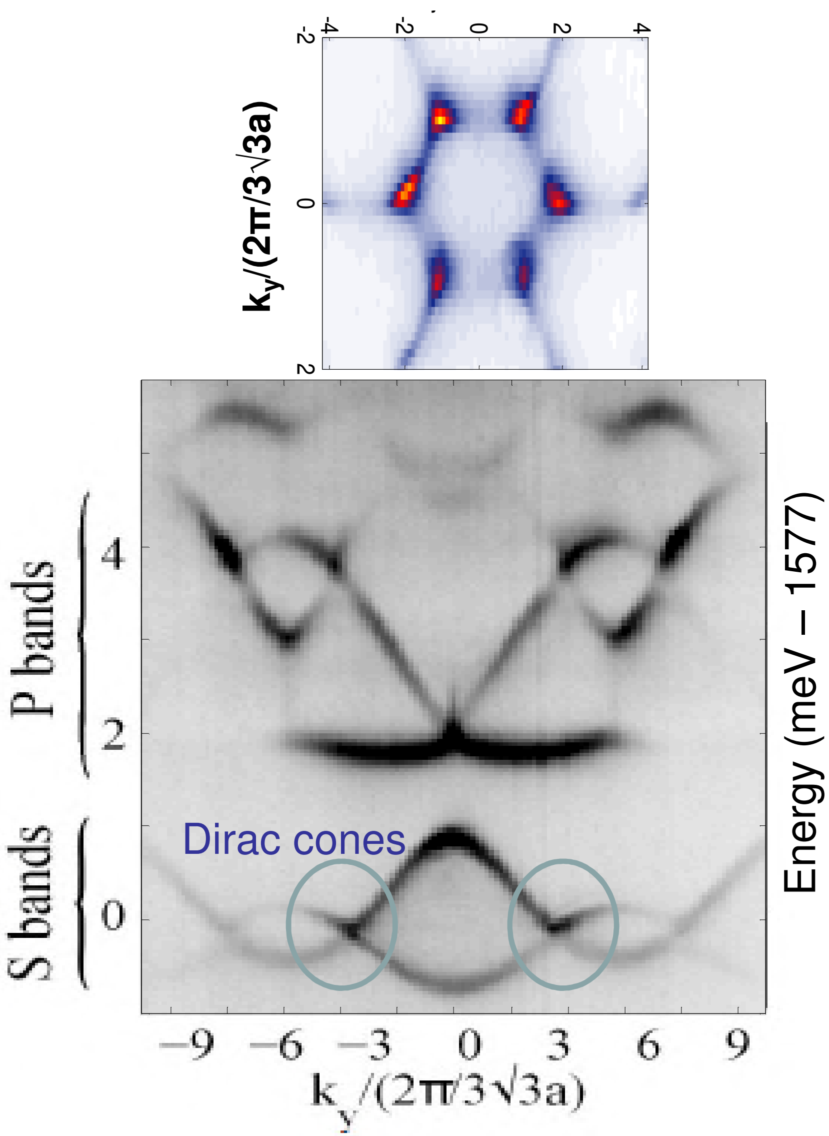
# Emulating Dirac Physics




Castro Neto et al., Rev. Mod. Phys. 81 (2009)

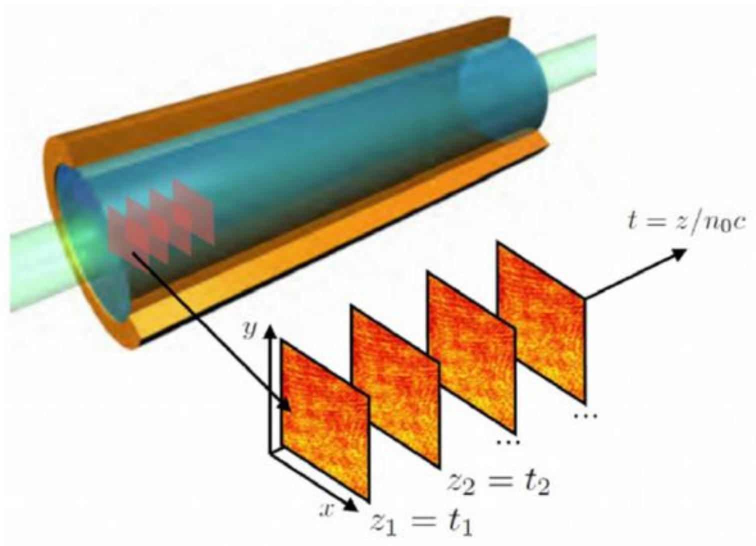





- Jacqmin *et al.*, PRL **112,** 116402 (2014)
  See also Yamamot (Stanford), Krizhanovskii (Sheffield)

de Nanosciences et de Nanotechnologies

# Propagation of light in a non-linear medium



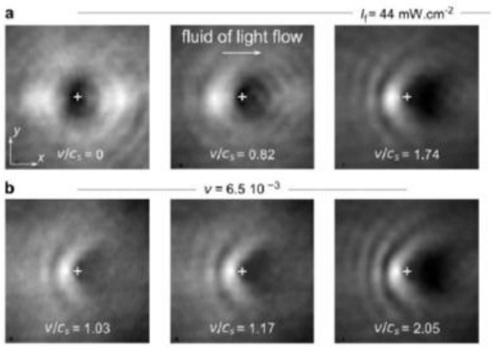

$$i\frac{\partial \mathcal{E}}{\partial z} = \boxed{-\frac{1}{2k_0}\nabla_\perp^2 \mathcal{E}} + \boxed{U\mathcal{E}} + \boxed{\gamma|\mathcal{E}|^2\mathcal{E}}$$

kinetic energy — external potential — non-linear interaction

# Propagation of light in a non-linear medium

Quentin Glorieux

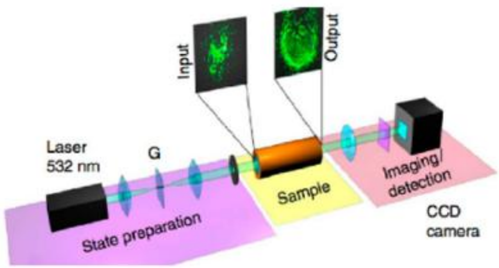
## Photorefractive crystal




M. Bellec, C. Michel (INPHYNI)

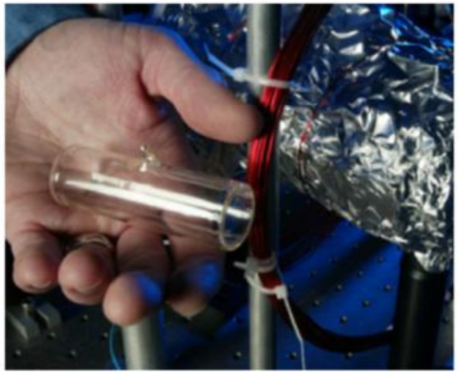
C. Michel et al. Nature Com 2018

## Thermo-optic liquid (methanol)




D. Faccio Edimburgh

## Atomic vapor



Q. Glorieux, A. Bramati (LKB)
PRL 120, 055301 (2018)

# Outline

Lecture 1 : Introduction to cavity polaritons

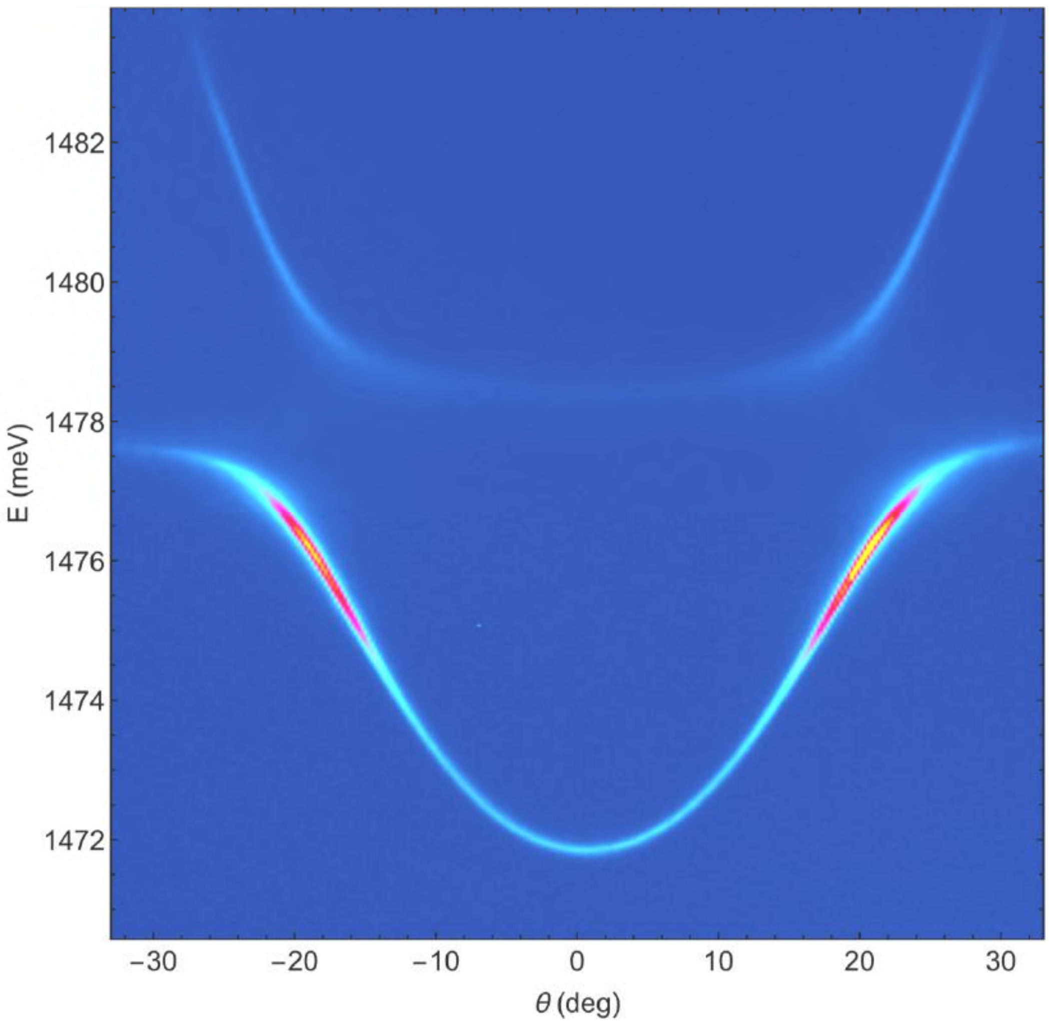
Lecture 2: Polariton non-linearities : Superfluidity, BEC **December 10th**

Lecture 3: Polariton lattices **December 12th**

Lecture 4: Quantum fluids of light in propagating geometry **December 17th**

Quentin Glorieux, LKB

# Lecture 1: Introduction to cavity polaritons



# Microcavity polaritons

➡ Excitonic polaritons : Mixed light-matter particles

Photons confined in an optical cavity

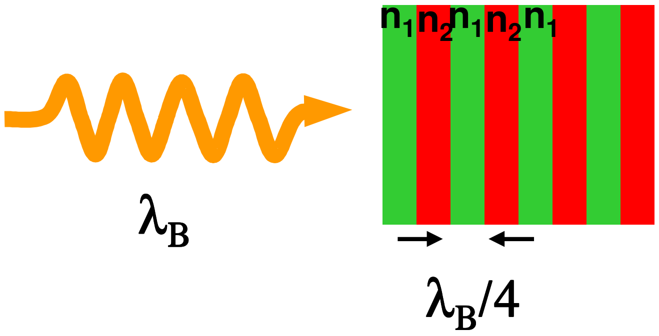
- **Very light (m=0 in vacuum)**
- Very fast
- No interactions

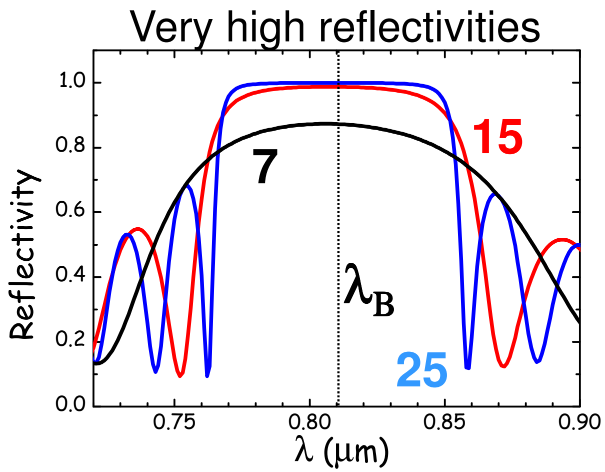
Excitons confined in a quantum well

- Very heavy
- Very slow
- **Interactions**

# Photon confinement

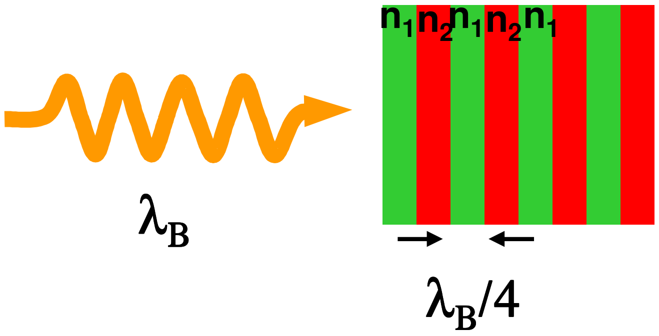
➡ Distributed Bragg reflector



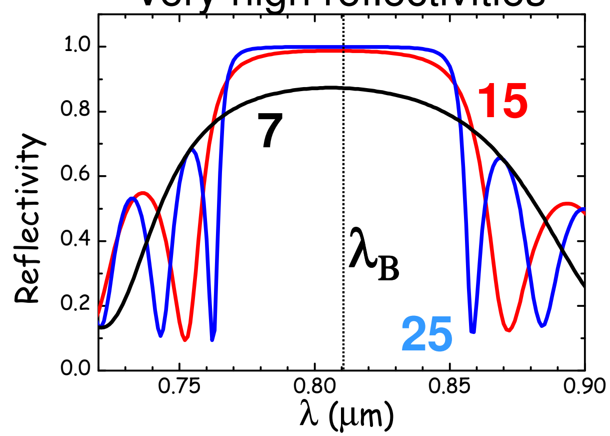



# Photon confinement

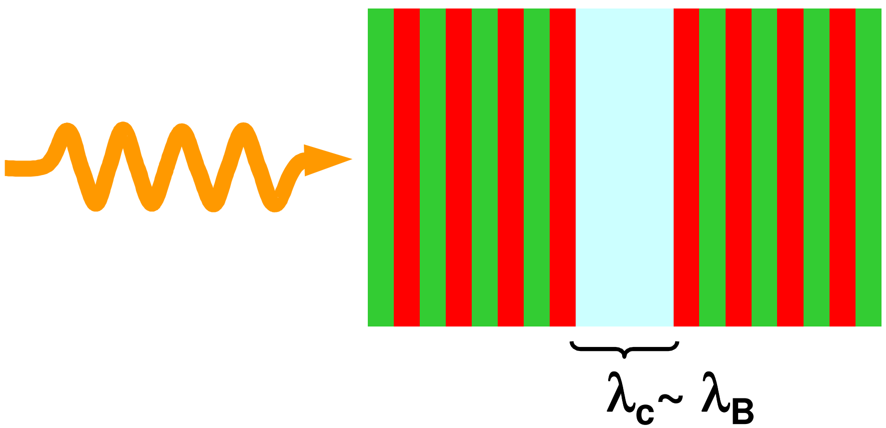
- Distributed Bragg reflector



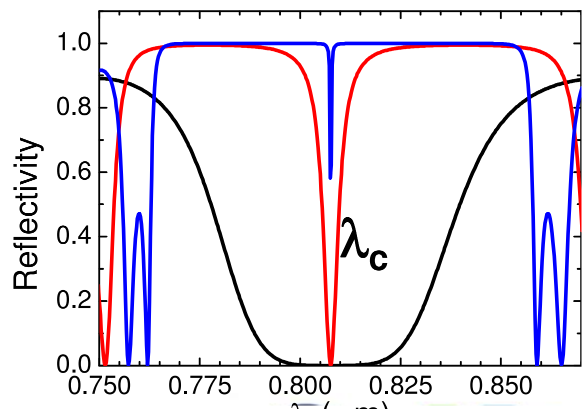

Very high reflectivities




- Fabry-Perot resonator (microcavity)




**Optical mode**

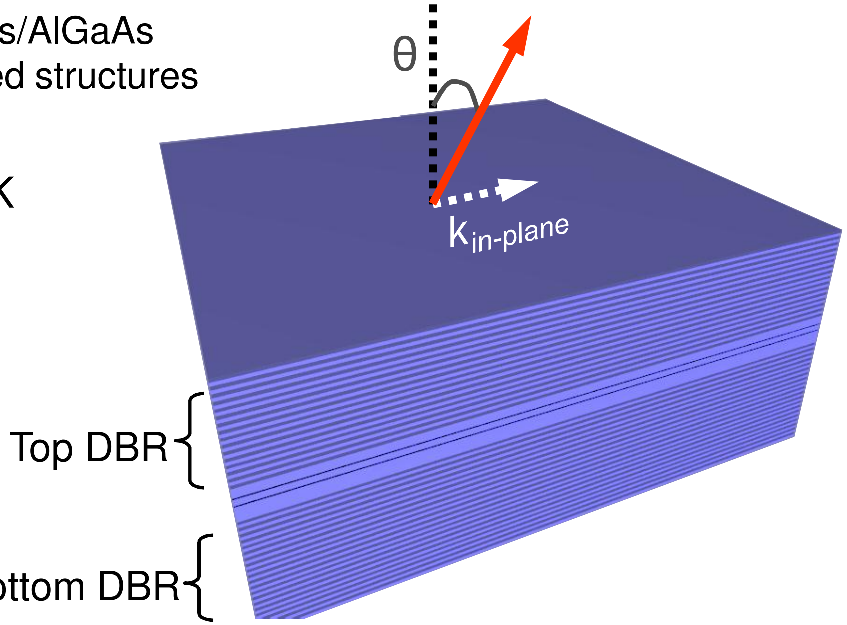


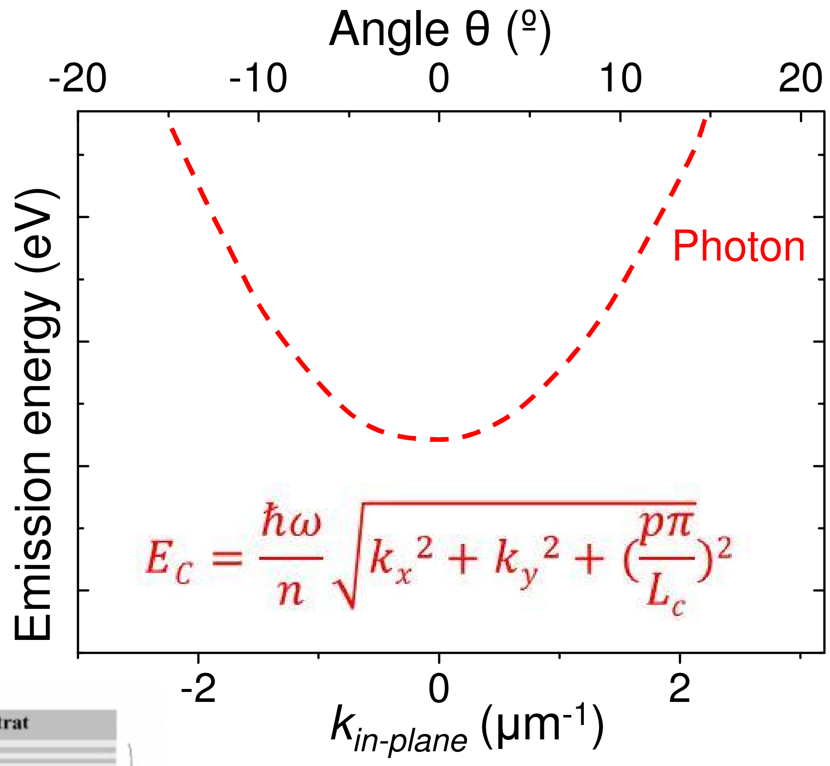

normal incidence

# Microcavity polaritons

GaAs/AlGaAs
based structures

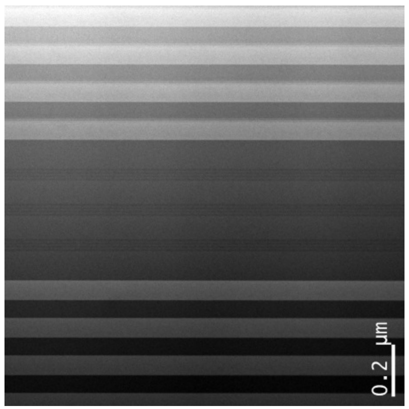
5 K




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

**Optical cavity**

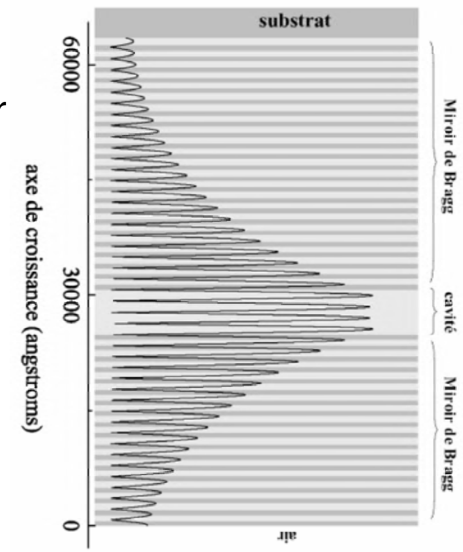



Bragg mirror
GaAs/AlAs

Cavity

Bragg mirror
GaAs/AlAs

TEM, G. Patriarche, LPN

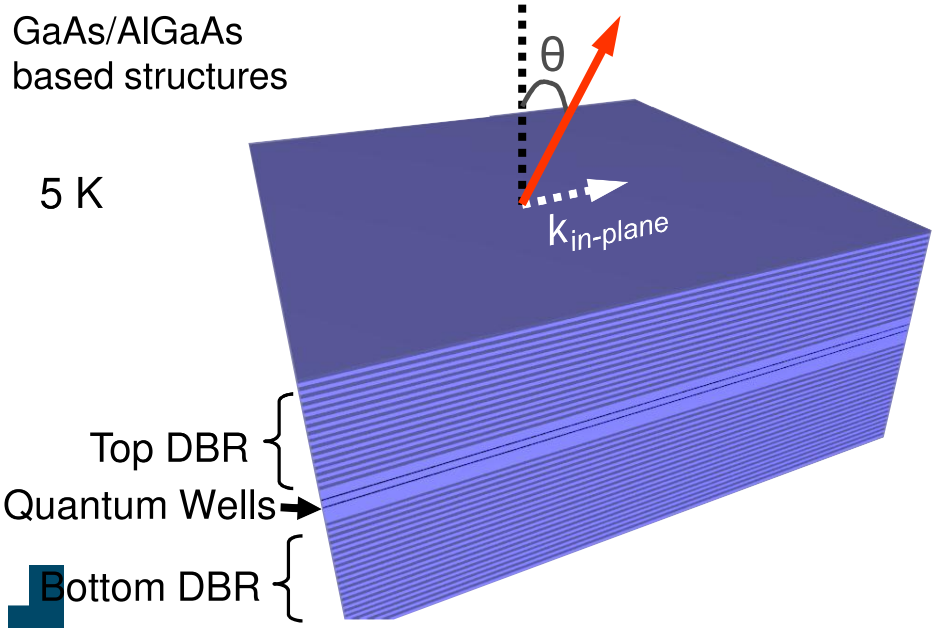



$$E_C(k) = Ec(k=0) + \frac{\hbar^2 k^2}{2M_{phot}}$$

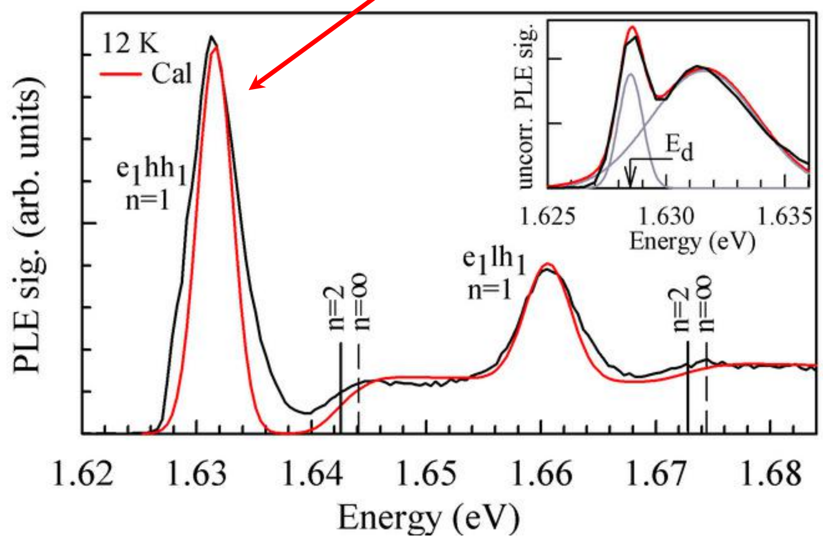
with $M_{phot} = \frac{p^2\pi^2\hbar^2}{{L_c}^2 n^2}$

Centre de Nanosciences et de Nanotechnologies

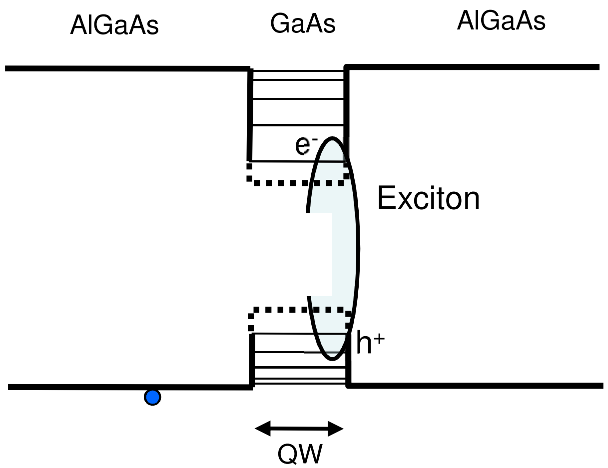
# Microcavity polaritons




Excitonic resonance



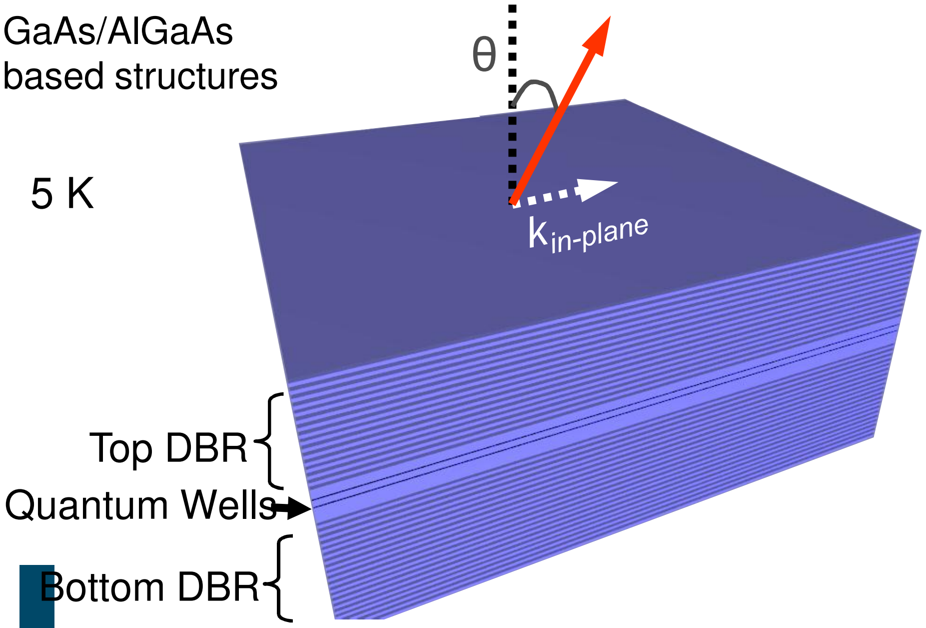

**Quantum well exciton**

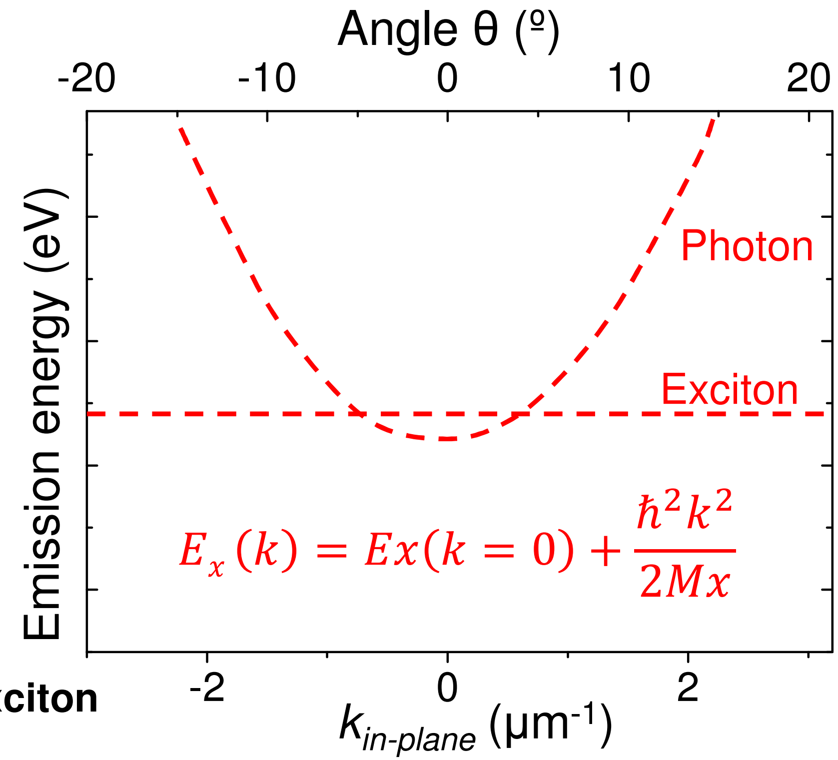


# Microcavity polaritons

GaAs/AlGaAs based structures

5 K

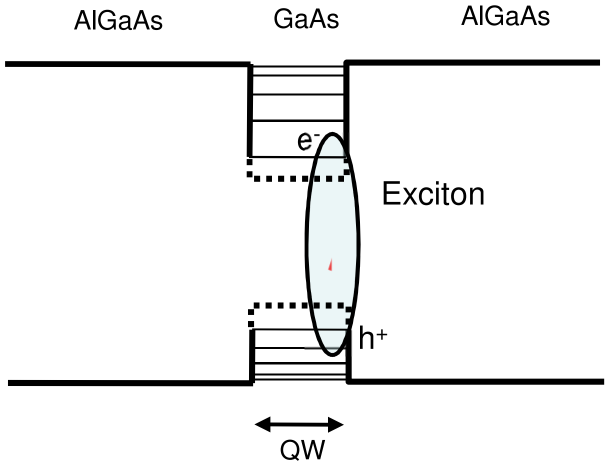



with $M_x = m_e + m_h$

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

**Quantum well exciton**

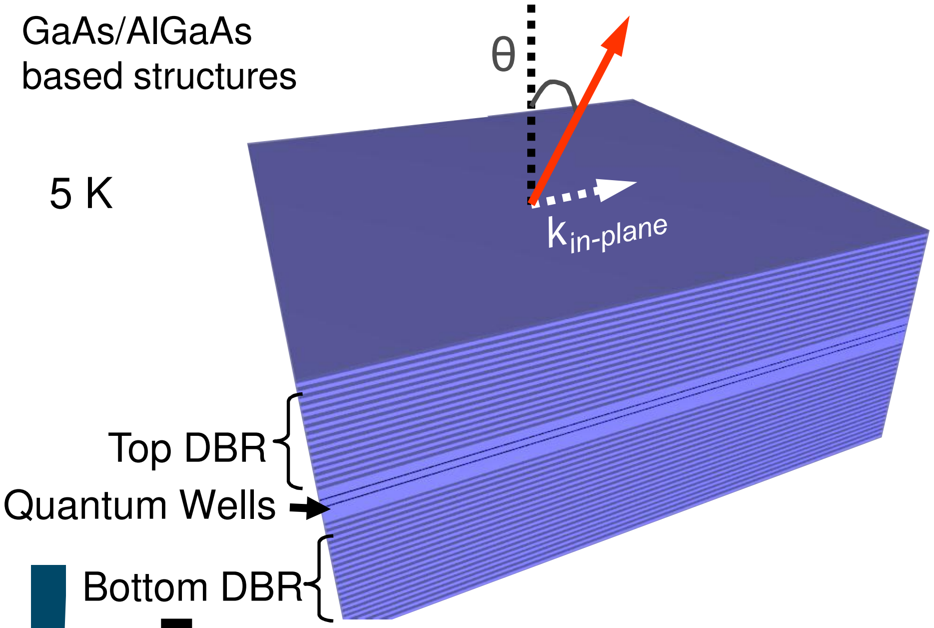


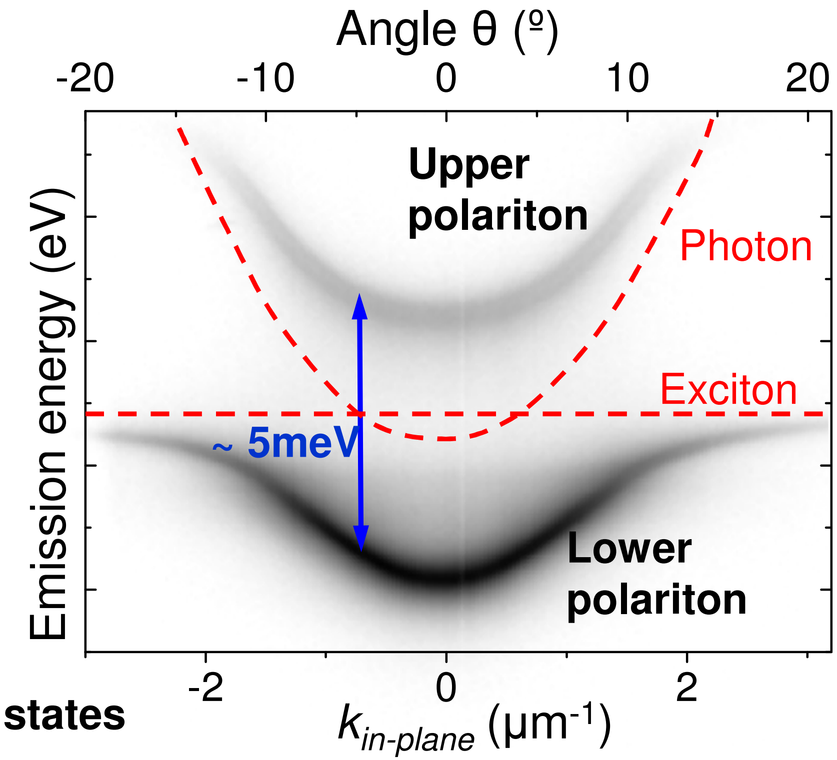

Centre de Nanosciences et de Nanotechnologies

# Microcavity polaritons

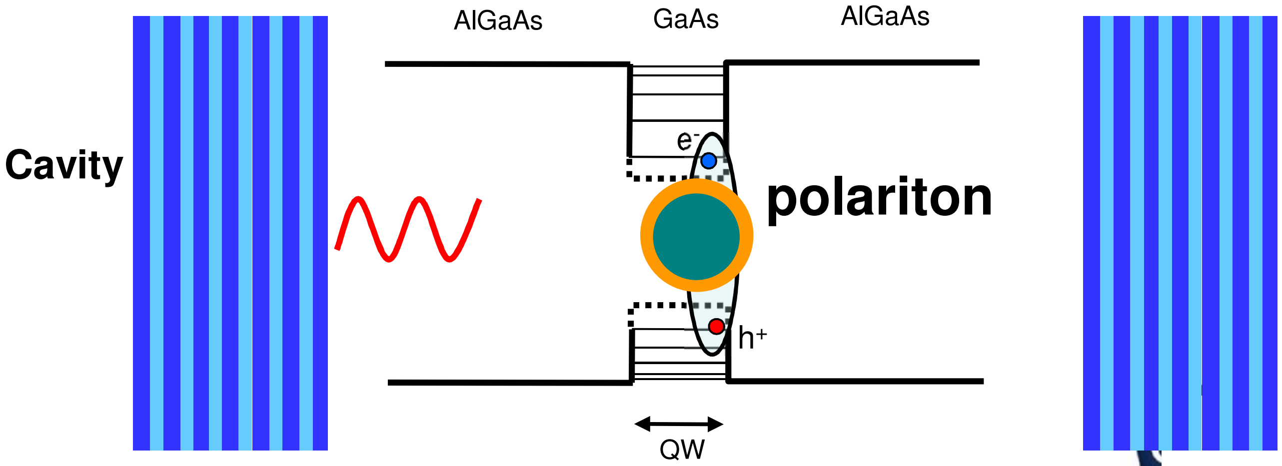
GaAs/AlGaAs based structures

5 K



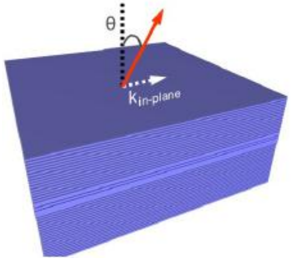




**Microcavity polaritons : mixed exciton-photon states**



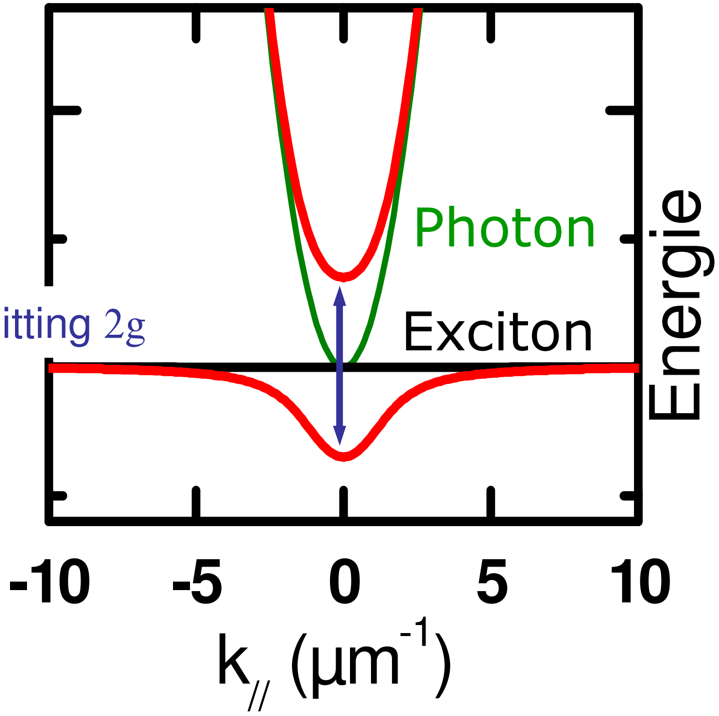

Claude Weisbuch
PRL **69**, 3314 (1992)

# Microcavity polaritons




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

Rabi splitting 2g




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

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

with

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

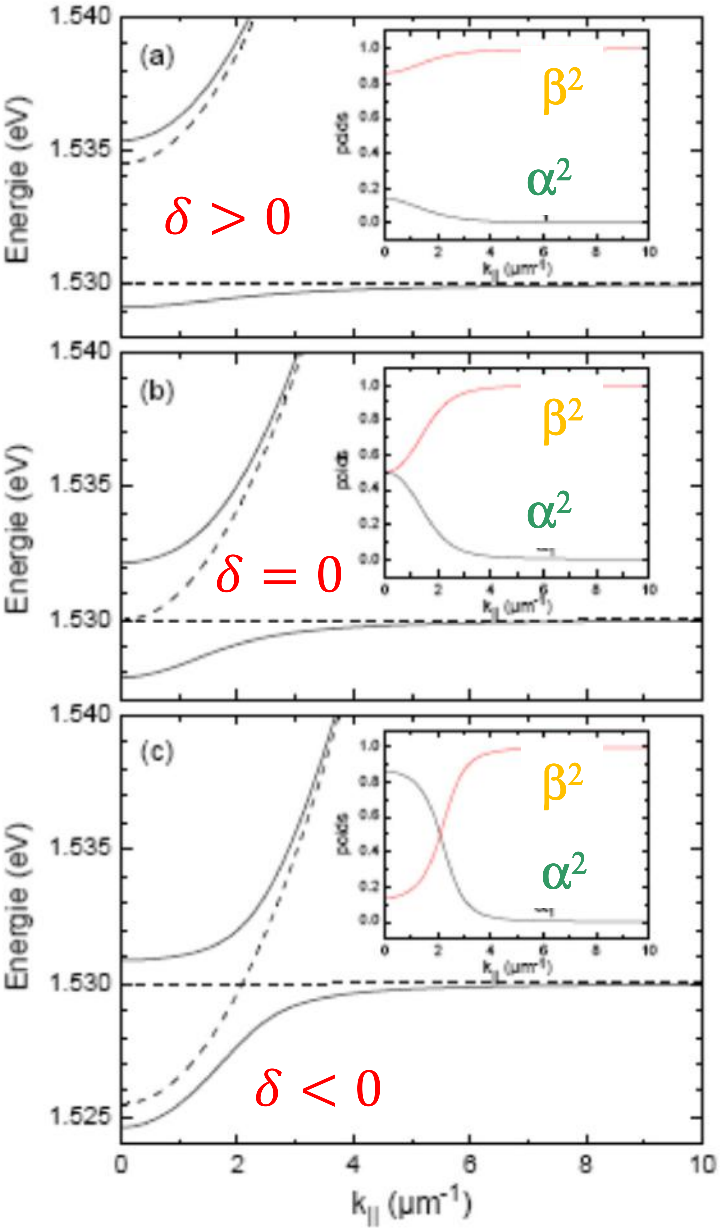
Centre de Nanosciences et de Nanotechnologies

# Microcavity polaritons

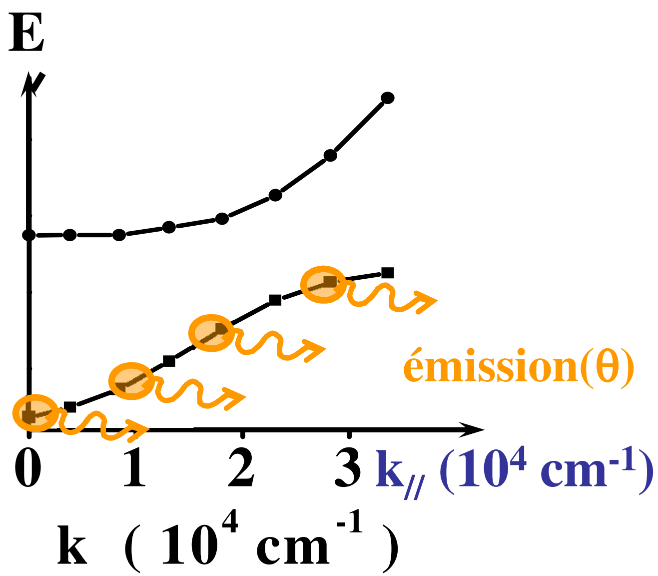
**| polariton >** = $\alpha$ **|photon>**
+ $\beta$ **|exciton>**

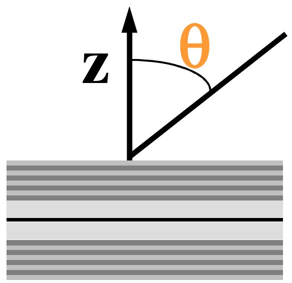
*Exciton photon detuning:*
$\delta = Ec(k=0) - Ex\ (k=0)$

s-shaped dispersion : inflexion point



# Probing polariton states: Angle resolved experiments



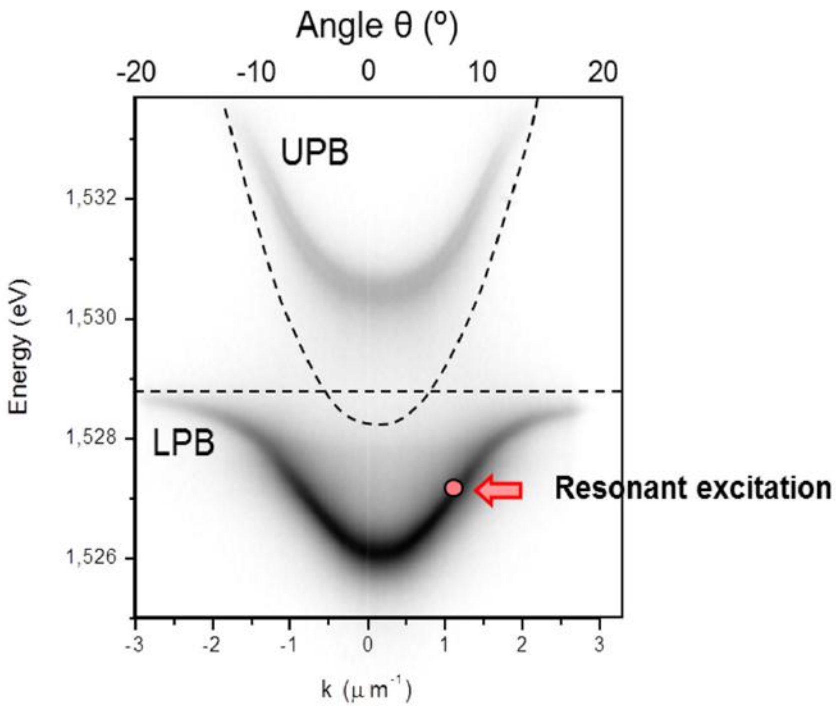

$\theta \Leftrightarrow k_{//}$

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

**Selective excitation and probe of polariton states**

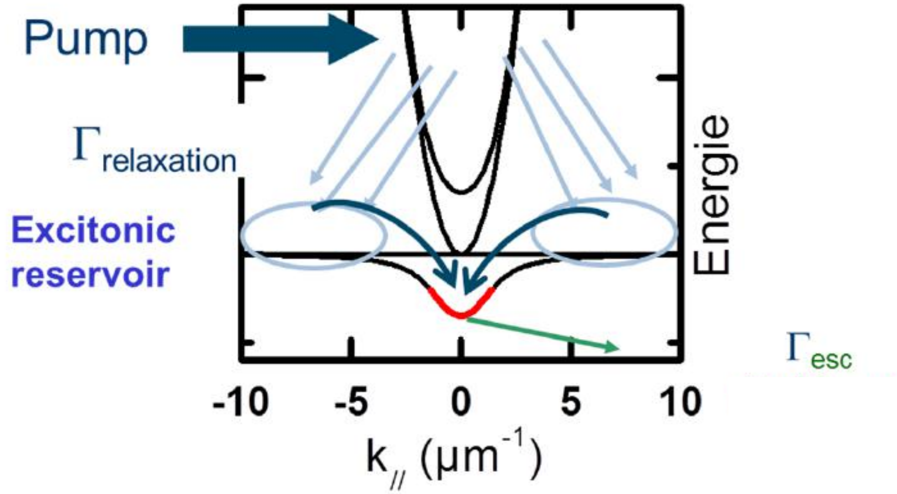
# How to generate microcavity polaritons?

## Resonant excitation




Control of :
- Energy
- $k_{//}$
- Phase

## Non resonant excitation




- Population of many low energy modes
- Creation of an excitonic reservoir
- Possibility to enter a stimulated regime: lasing, Bose E

VOLUME 73, NUMBER 15 PHYSICAL REVIEW LETTERS 10 OCTOBER 1994

# 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]

[1]*Institut de Micro- et Optoélectronique, Ecole Polytechnique Fédérale de Lausanne, CH 1015, Lausanne, Switzerland*

[2]*Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, F 91128 Palaiseau, France*

(Received 11 March 1994)

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

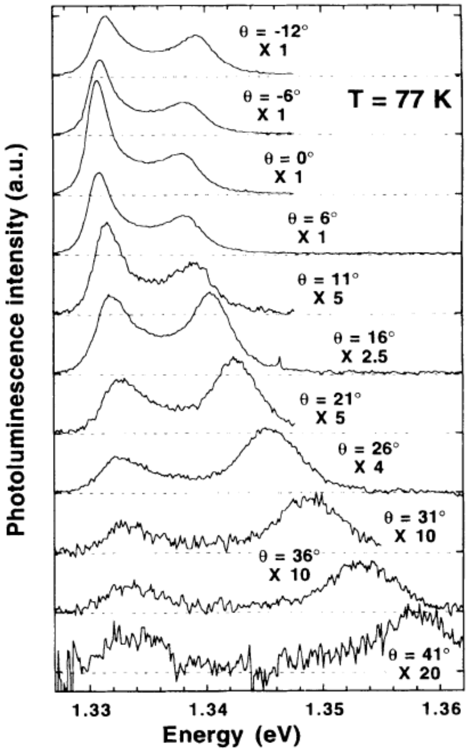



FIG. 2. Series of photoluminescence spectra at $T = 77$ K, for an emission angle from $-12°$ to $41°$. The Fabry-Pérot at normal incidence is resonant with the quantum well exciton.

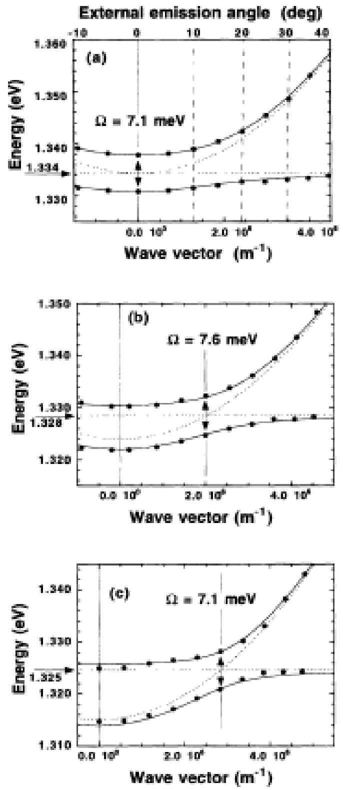
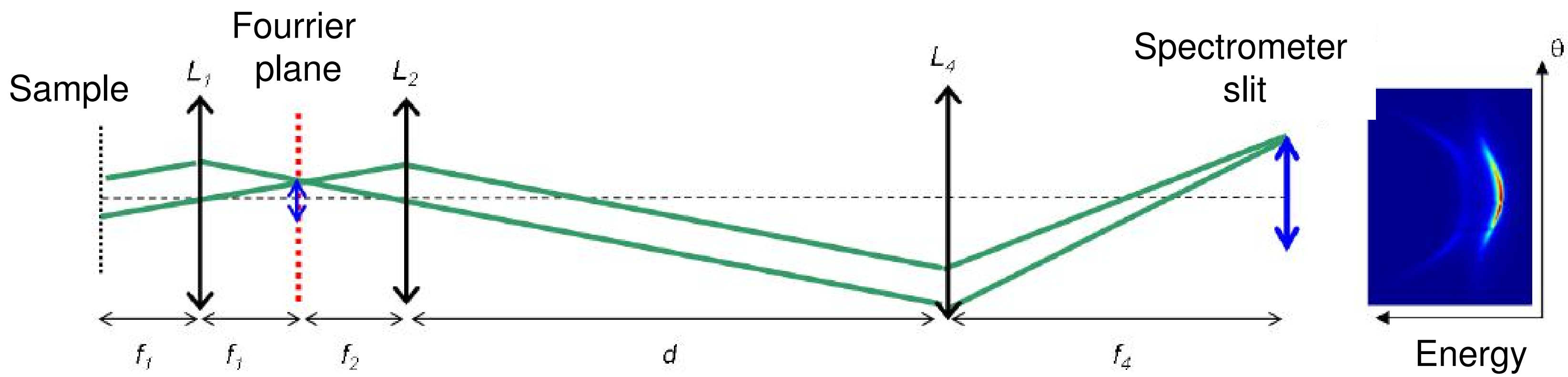


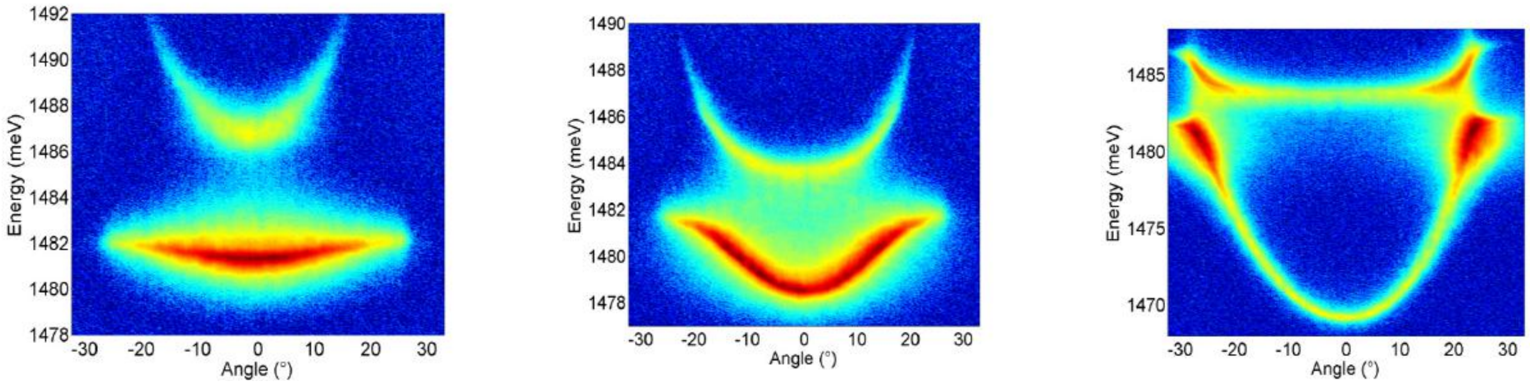

FIG. 3. Cavity-polariton dispersion curves, deduced from angle-resolved photoluminescence measurements, for different resonance conditions. (a) Resonance at $\theta = 0°$ (case of Fig. 2), (b) resonance at $\theta = 29°$, and (c) $\theta = 35°$. The continuous lines are theoretical calculations and the dashed lines are the uncoupled exciton and cavity dispersion curves. The interaction energy $\Omega$ 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

EPFL

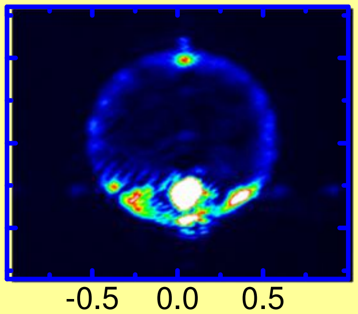
# Probing polariton states: Angle resolved experiments

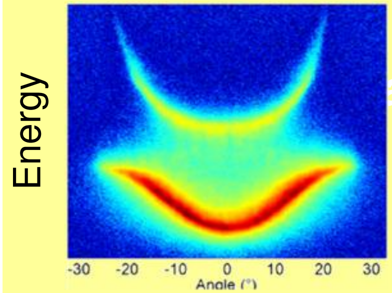


# Typical experimental scheme

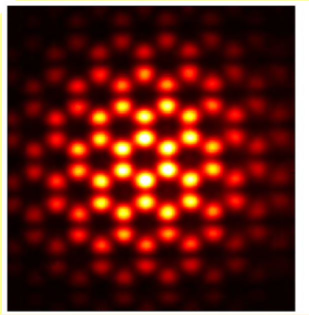
## Far field imaging: k space



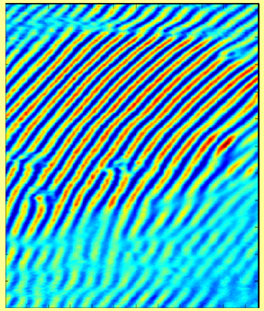




$k_x$ ($\mu m^{-1}$)

## Real space imaging



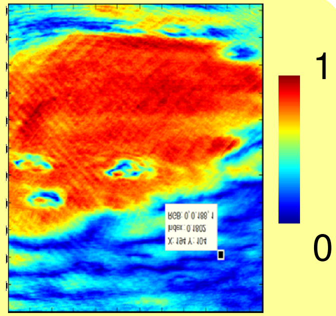
Density



Interference with a reference beam

⇩

Phase dislocations
- vortices
- solitons




Coherence map $g^{(1)}$

Emission statistics $g^{(2)}$

# Cavity polaritons : an exciton-photon mixed state

$$|\,\text{polariton}\,\rangle = \alpha\ |\text{photon}\rangle + \beta\ |\text{exciton}\rangle$$

$\alpha^2$ **photon part**

$\beta^2$ **exciton part**

**Properties**

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

# Microcavity polaritons

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

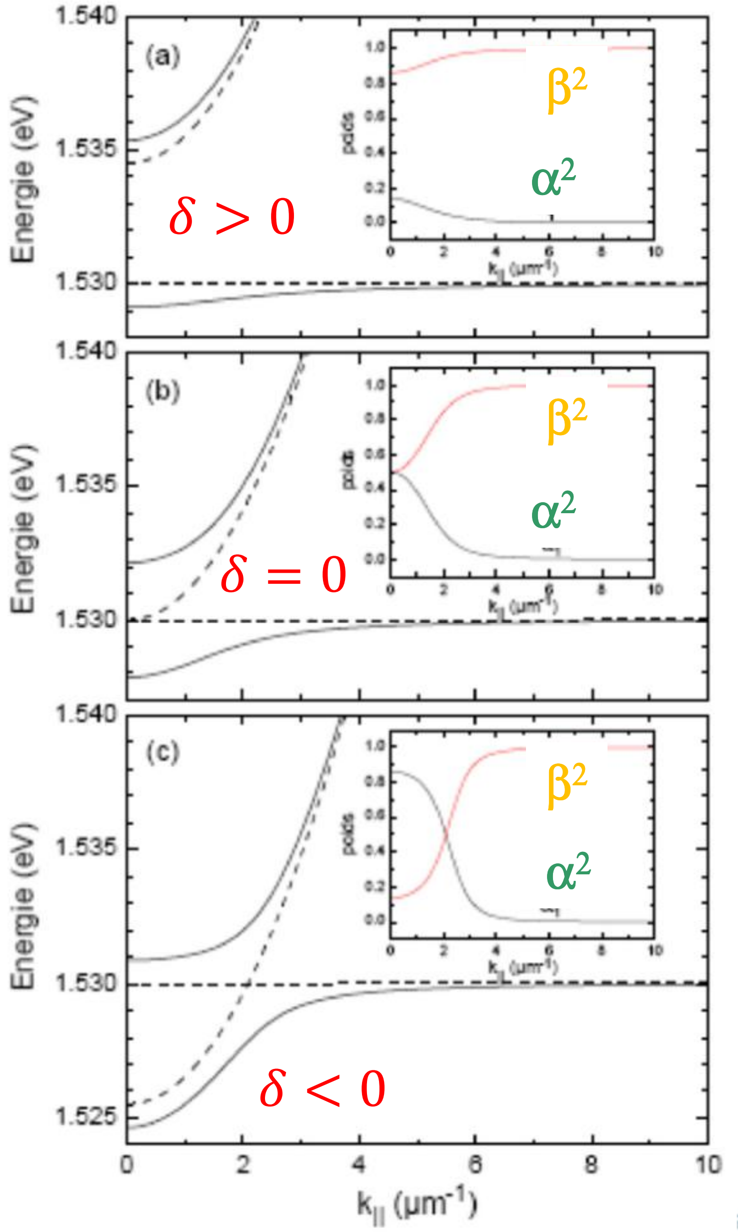
*Exciton photon detuning:*
$\delta = Ec(k=0) - Ex\,(k=0)$

s-shaped dispersion : inflexion point

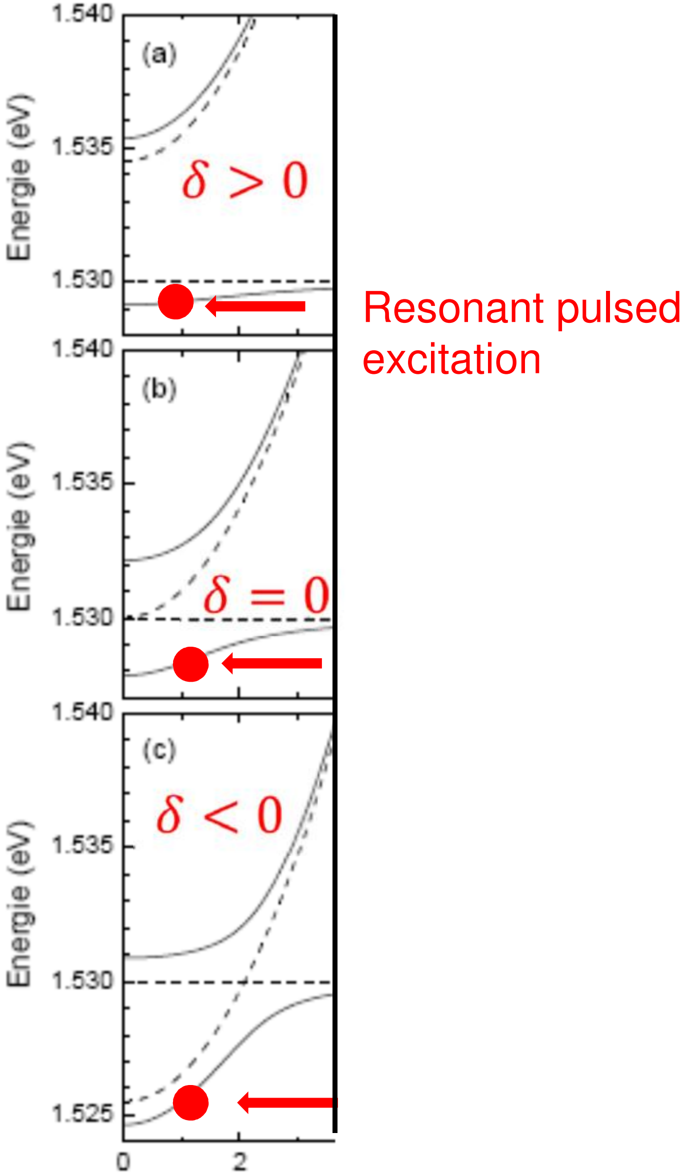
Effective mass: $\dfrac{1}{M_{pol}} = \dfrac{1}{\hbar^2}\dfrac{\partial^2 E}{\partial k^2}$

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

Beyond inflexion point: negative effective mass



# Probing polariton states: Real space propagation




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

**In-plane propagation of excitonic cavity polaritons**

T. Freixanet
*Laboratoire de Microstructures et de Microélectronique, Boîte Postale 107, 92225 Bagneux, France*

B. Sermage and A. Tiberj
*Centre National d'Etudes des Télécommunications, Boîte Postale 107, 92225 Bagneux, France*

R. Planel
*Laboratoire de Microstructures et de Microélectronique, Boîte Postale 107, 92225 Bagneux, France*

(Received 16 November 1999)

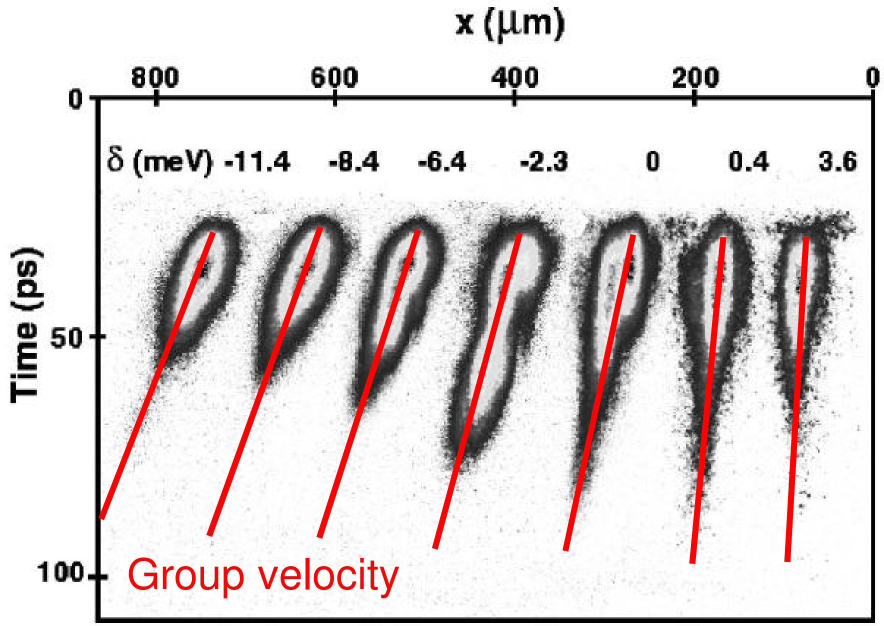
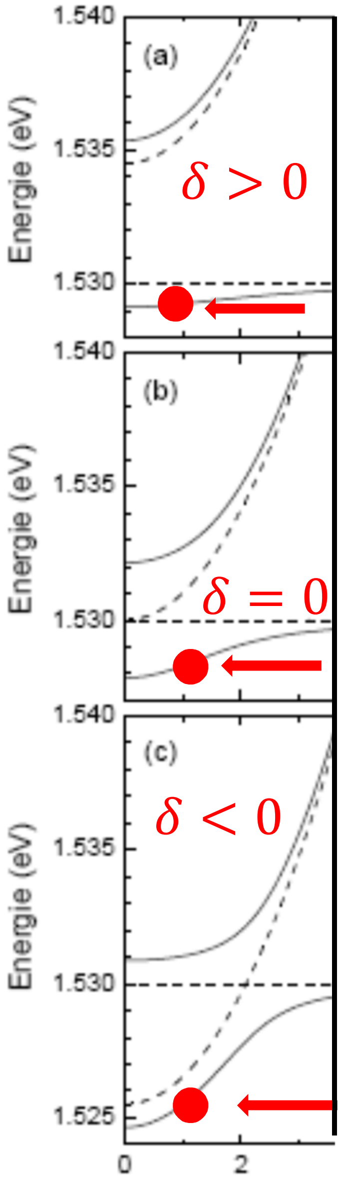



FIG. 2. Propagation in real space of the secondary emission source as observed on the streak camera for several detunings. The diaphragm is close to the reflection and $\theta_i = 7.8°$.

# Probing polariton states: Real space propagation




Resonant excitation

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

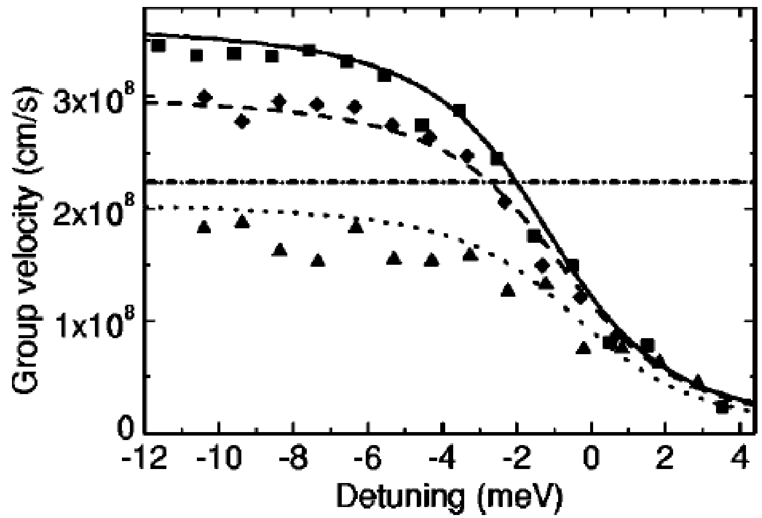



FIG. 3. Group velocity of the resonantly excited lower branch polaritons as a function of the detuning for different incident angles $\theta_i$. The points are the measured values for $\theta_i = 7.8°$ (■), $\theta_i = 6.2°$ (◆), and $\theta_i = 4.3°$ (▲). The solid, dashed, and dotted lines

# Cavity polaritons : an exciton-photon mixed state

**| polariton >** = $\alpha$ **|photon>** + $\beta$ **|exciton>**

**$\alpha^2$ photon part**

**$\beta^2$ exciton part**

**Properties**

- Photonic component ➔ **low mass ($10^{-5}$ $m_e$)**
- Short lifetime (1-100 ps) ➔ **dissipative system**
-
-

# Polariton lifetime

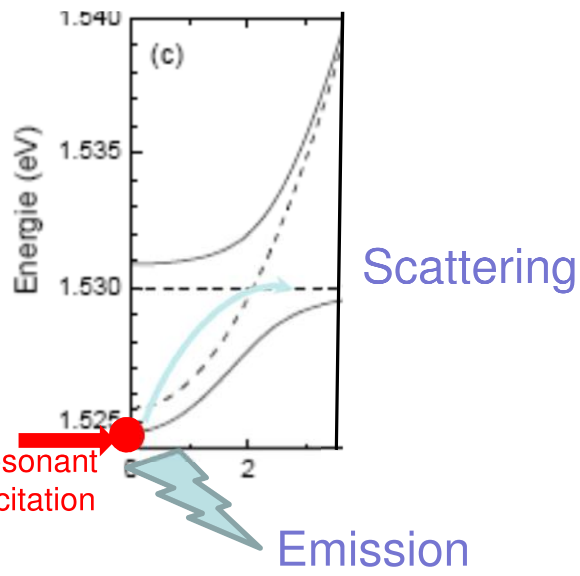
PHYSICAL REVIEW B VOLUME 53, NUMBER 24 15 JUNE 1996-II

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

B. Sermage, S. Long, I. Abram, and J. Y. Marzin
*FRANCE TELECOM, Centre National d'Etudes des Télécommunications, Paris B, Laboratoire de Bagneux, Boite Postale 107, 92225 Bagneux Cedex, France*

J. Bloch, R. Planel, and V. Thierry-Mieg
*Laboratoire de Microstructures et de Microélectronique, Centre National de la Recherche Scientifique, Boite Postale 107, 92225 Bagneux Cedex, France*

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



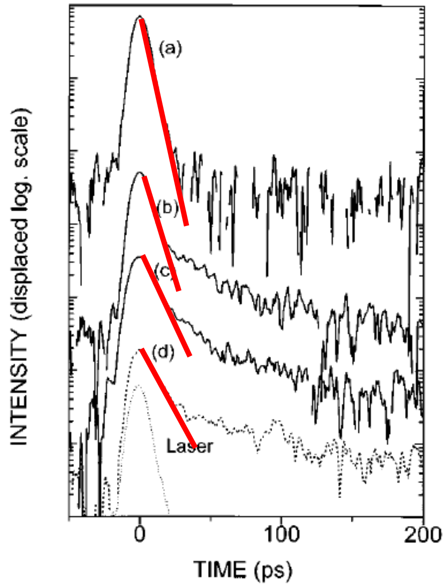
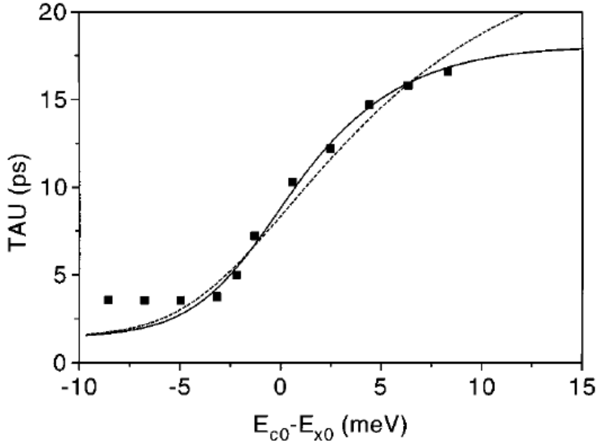




FIG. 1. Luminescence decay curves obtained with a laser excitation resonant with the lower state for different values of the detuning: (*a*) $\delta_0 = E_{c0} - E_{x0} = -8.5$ meV, (*b*) $\delta_0 = -1.5$, and (*c*) $\delta_0 = 3.5$ meV. The dashed curve (*d*) is the luminescence decay of the reference 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 finite (short) lifetime : 1-100 ps

# Cavity polaritons : an exciton-photon mixed state

**| polariton >** **=** $\alpha$ **|photon>** **+** $\beta$ **|exciton>**

**$\alpha^2$ photon part**

**$\beta^2$ exciton part**

**Properties**

- Photonic component ➡ **low mass ($10^{-5}$ $m_e$)**
- Short lifetime (1-100 ps) ➡ **dissipative system**
- Pseudo spin
-

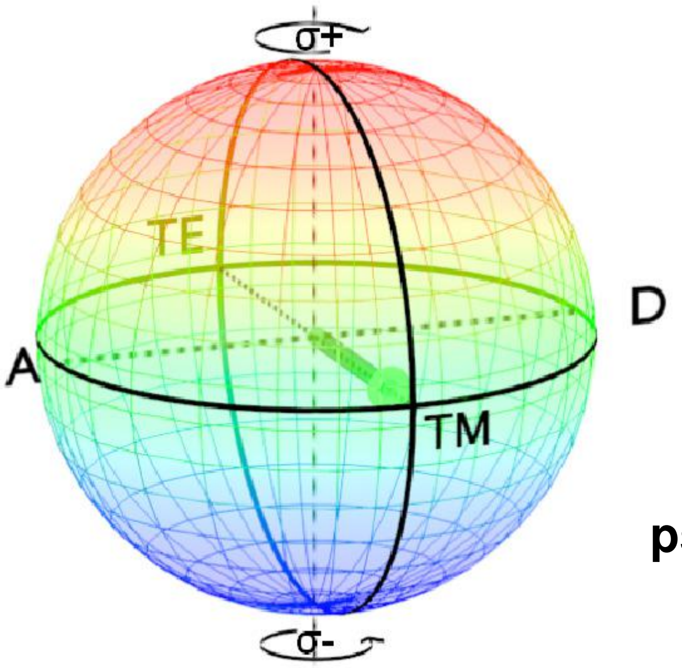
# Polariton spin

- 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



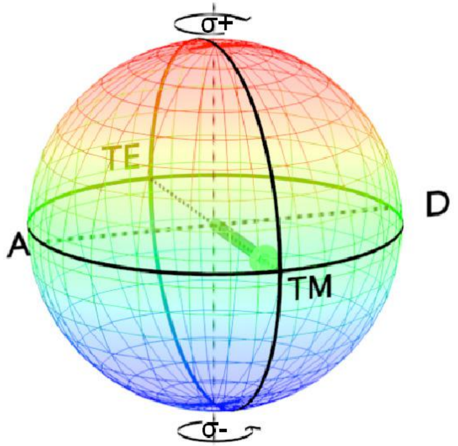

- Only J=1 excitons are coupled to light

**Polaritons have two spin projections:**

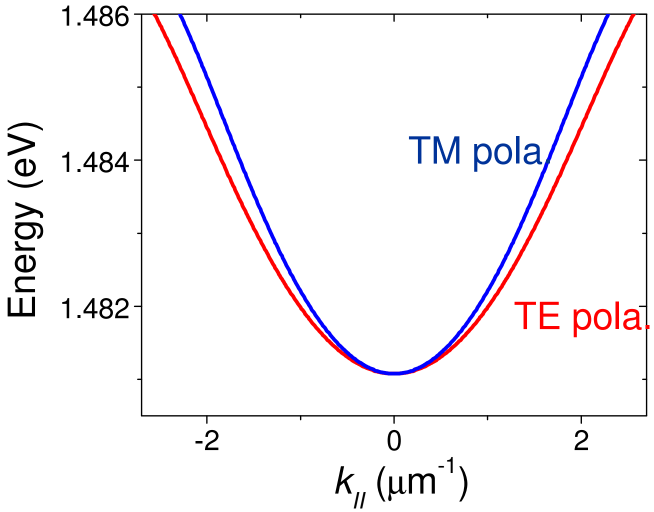
**$j_z$ = +1**  $\sigma +$
**$j_z$ = -1**  $\sigma -$
} ½ pseudospin

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

# Polariton spin: Intrinsic magnetic field




Cavity modes linearly polarized: TE-TM splitting

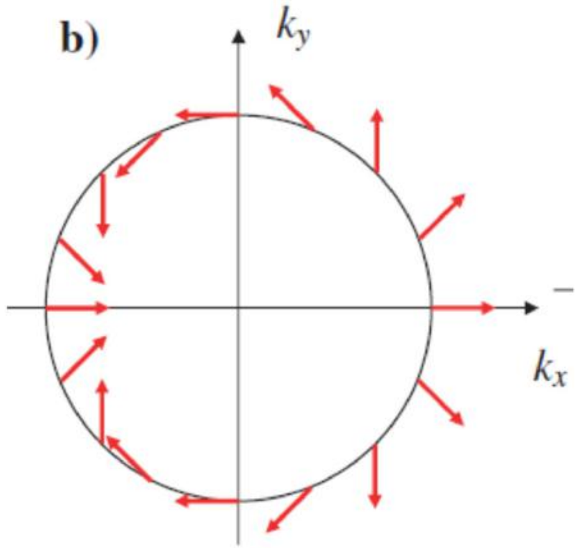



boundary conditions for the electromagnetic field at the interface of the different dielectric layers

Effective magnetic field $\mathbf{H}_{\mathrm{eff}} = \frac{\hbar}{\mu_B g} \mathbf{\Omega}_{\mathbf{k}}$

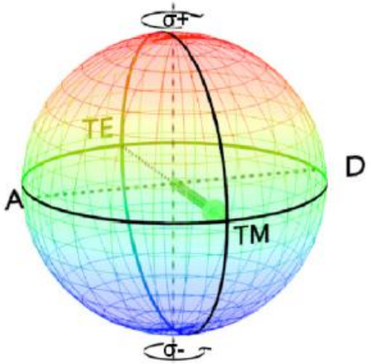
$$\Omega_x = \frac{\Omega}{k^2}(k_x^2 - k_y^2), \qquad \Omega_y = 2\frac{\Omega}{k^2}k_x k_y,$$

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




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

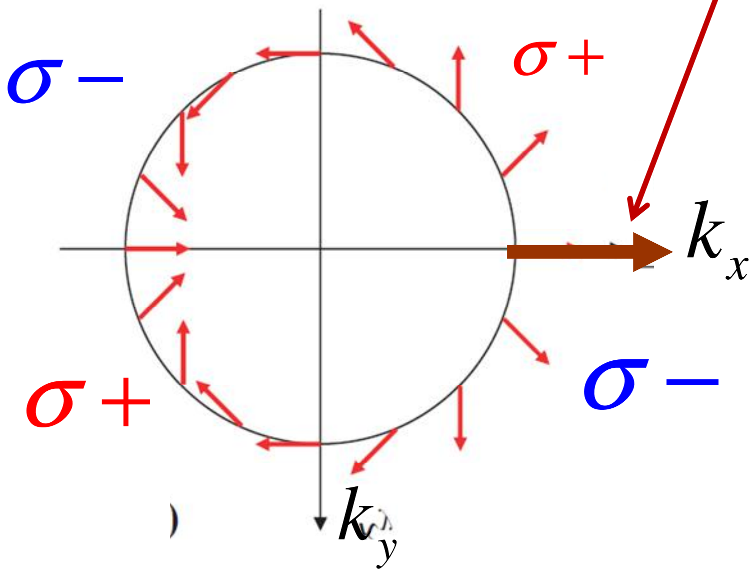
# Optical spin Hall effect

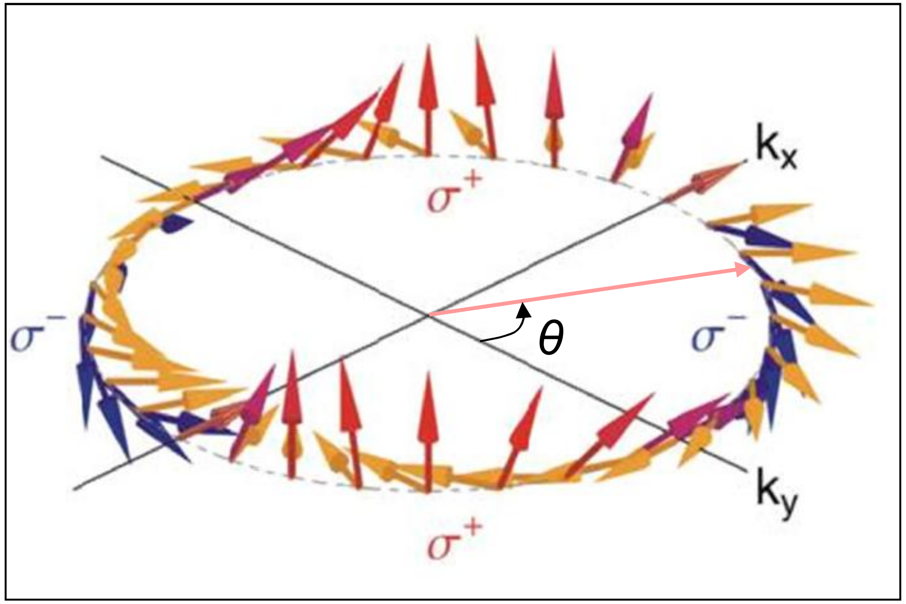



**Initial Pseudospin**

Linear polarisation along x

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



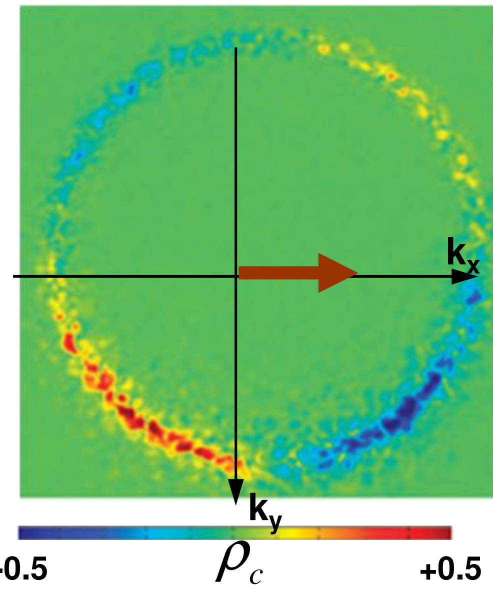




Kavokin et al. PRL **95**, 136601 (2005)
Leyder et al. Nature Phys. **3**, 628 (2007).

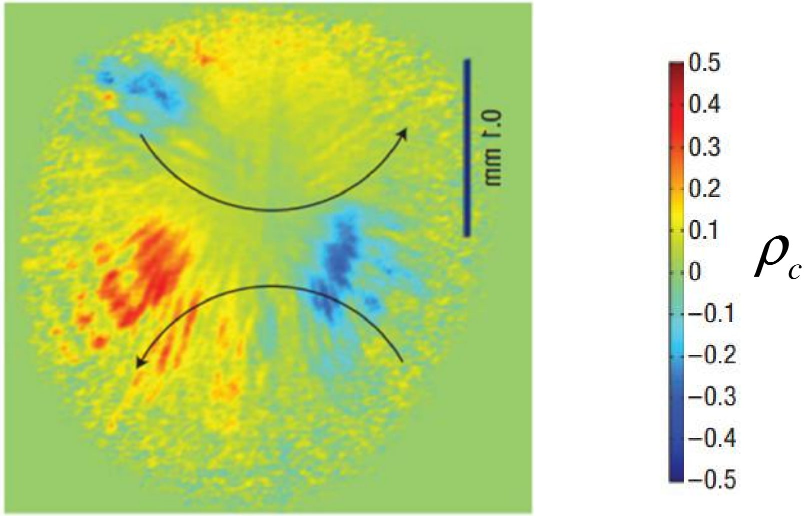
# Optical spin Hall effect

$\tau_{pol}$= 10ps

**Reciprocal Space**




**Real Space**




Spin currents

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

# Cavity polaritons : an exciton-photon mixed state

**| polariton >** = $\alpha$ **|photon>** + $\beta$ **|exciton>**

**$\alpha^2$ photon part**

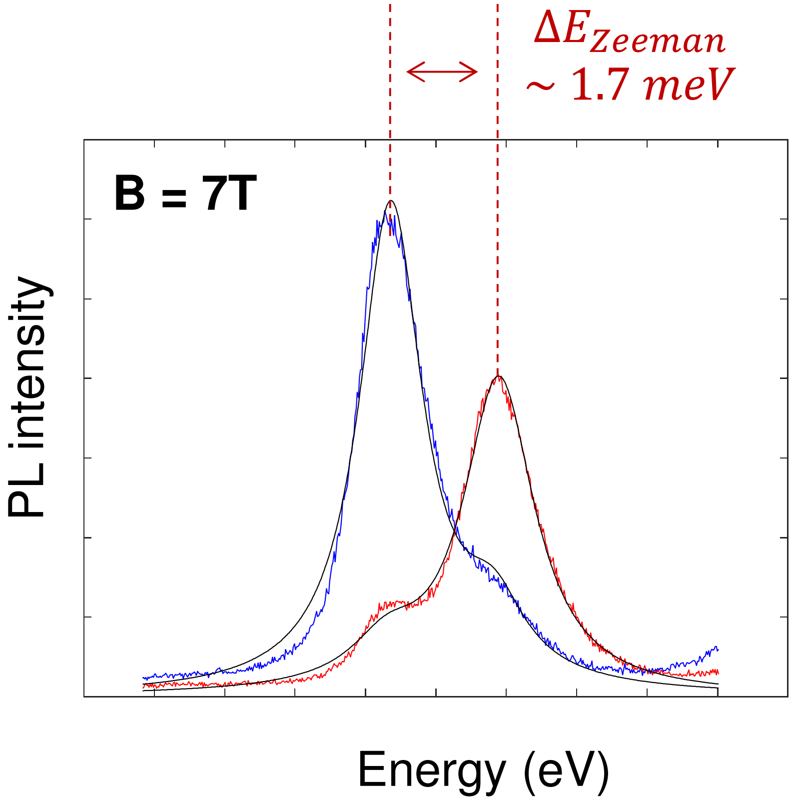
**$\beta^2$ exciton part**

**Properties**

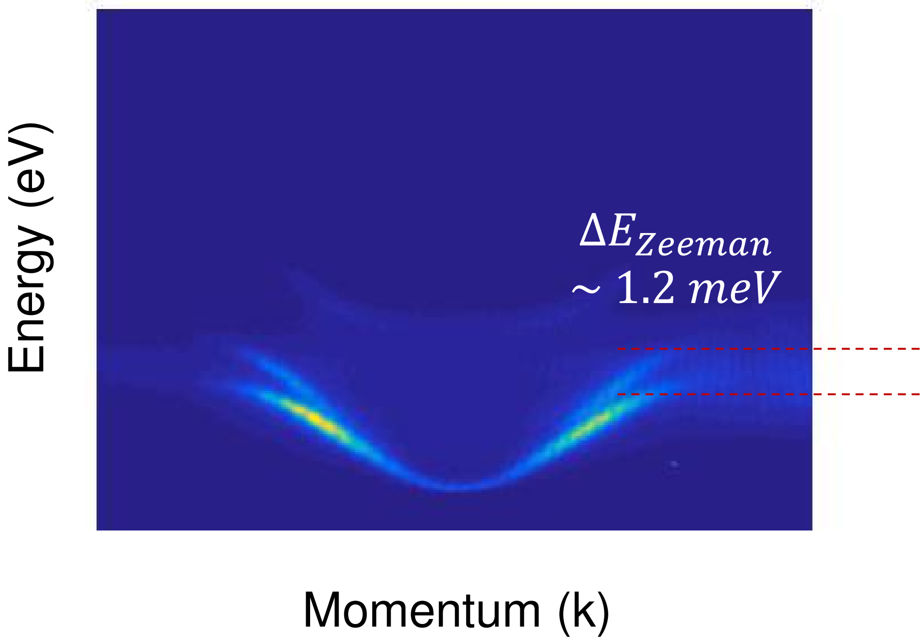
- Photonic component ➡ **low mass ($10^{-5}$ $m_e$)**
- Short lifetime (1-100 ps) ➡ **dissipative system**
- Pseudo spin
- Sensitivity to magnetic field

# Magneto-luminescence

## Quantum well




## Cavity




Centre de Nanosciences et de Nanotechnologies

# Cavity polaritons : an exciton-photon mixed state

$$| \text{polariton} \rangle = \alpha \, |\text{photon}\rangle + \beta \, |\text{exciton}\rangle$$

$\alpha^2$ **photon part**

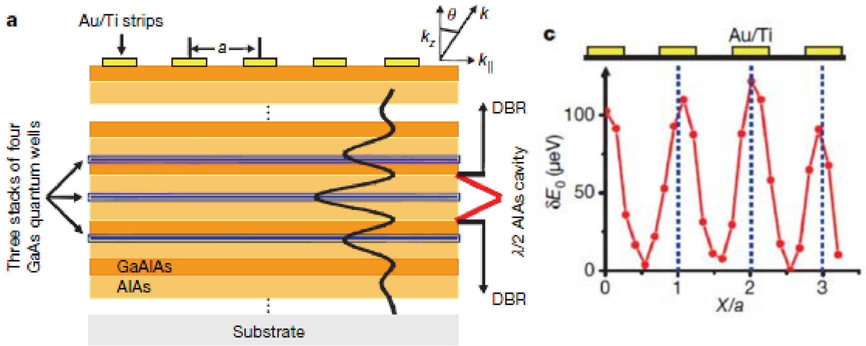
$\beta^2$ **exciton part**

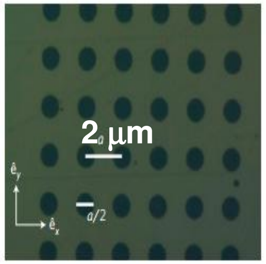
**Properties**

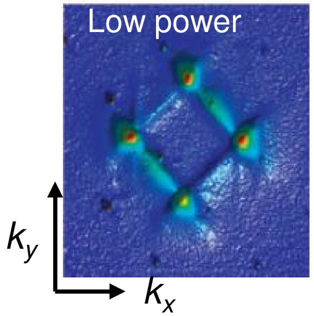
- Photonic component ➡ **low mass ($10^{-5}$ $m_e$)**
- Short lifetime (1-100 ps) ➡ **dissipative system**
- Pseudo spin
- Sensitivity to magnetic field
- Polariton Interaction ➡ Highly non linear system (Kerr like)
- Polariton lattices

# Polariton lattices

## Gold deposition on top mirror



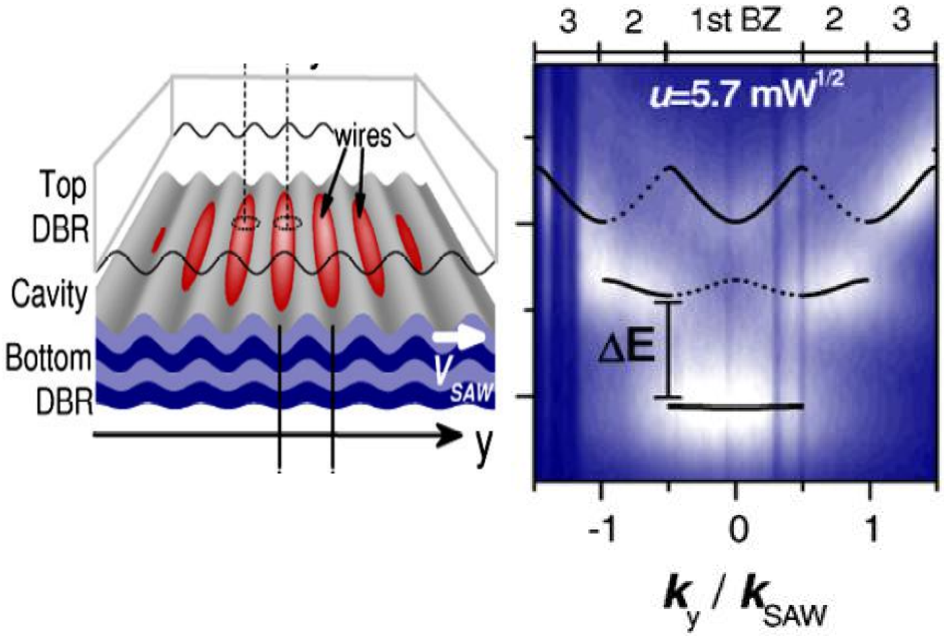




d-wave condensation

Lai et al., Nature **450**, 529 (2007)
Kim et al., Nature Phys **7**, 681 (2011)

**Stanford**

## Surface acoustic waves



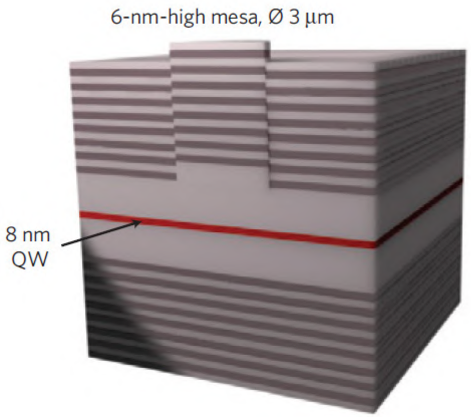

Cerda-Méndez *et al.*, PRL **105**, 116402 (2010)
de Lima *et al.*, PRL **97**, 045501 (2006)

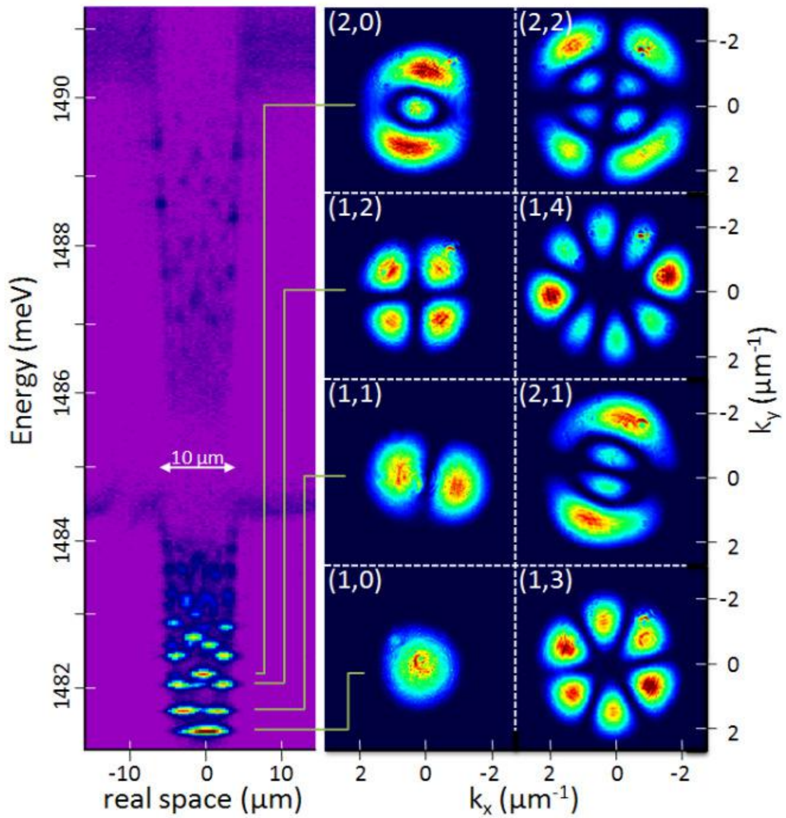
Cerda-Méndez *et al.* PRB **86**, 100301(R) (2012)

**Berlin**

# During-growth photonic trap

## Deveaud’s group at EPFL



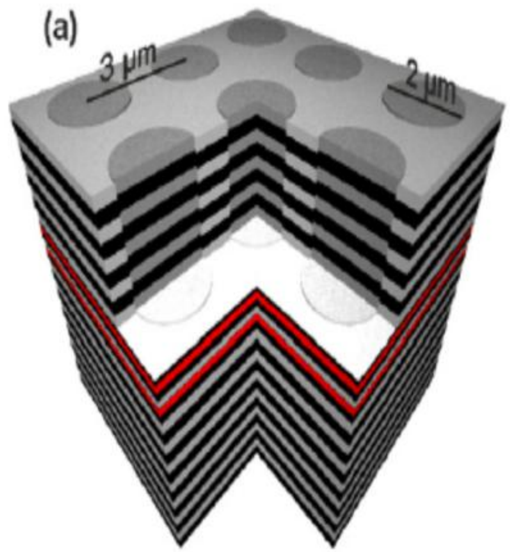

El Daïf et al., APL **88**, 061105 (2006)

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

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

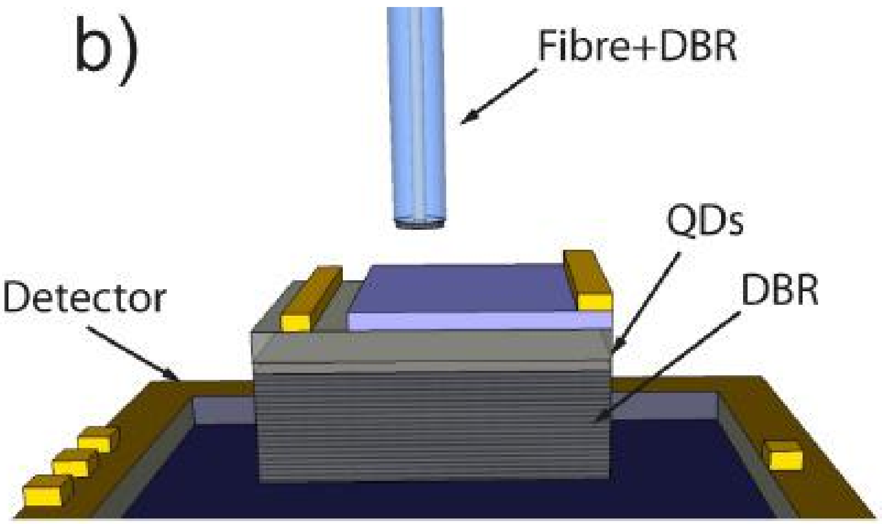
## Würzburg

### Coupled mesas




Winkler et al., New J. Phys. **17**, 23001 (2015)

# Hybrid cavities

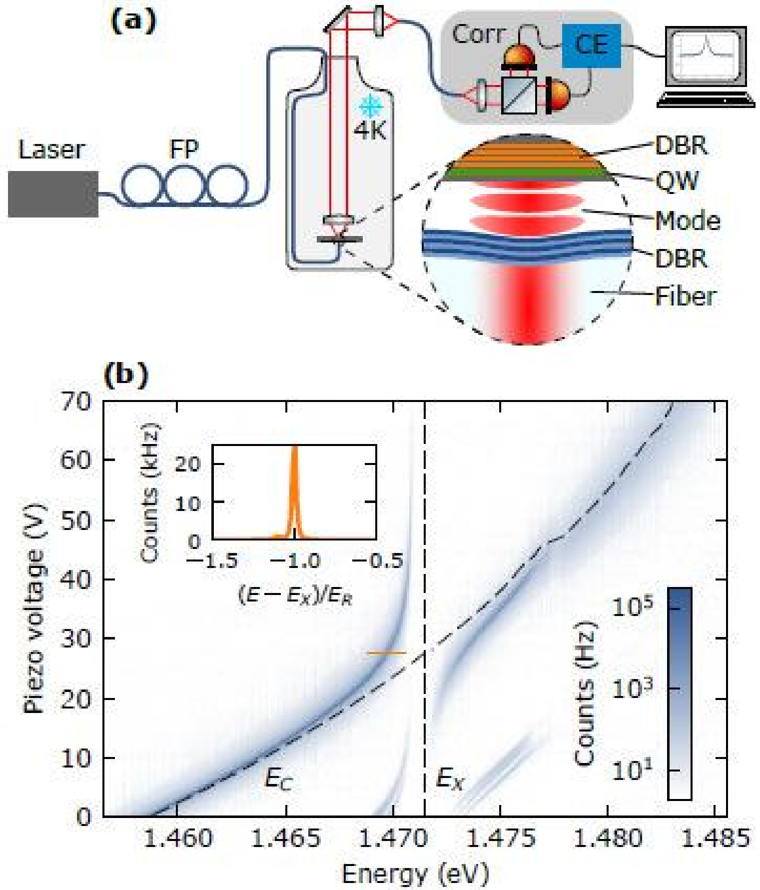



Besga et al., Light: S&A 3, e135 (2014)
S. Dufferwiel et al. Appl. Phys. Lett. 104, 192107 (2014)

See also T. Fink et al., Nature Physics 14, 365 (2018)
G. Muñoz-Matutano et al, Nature Materials 18, 213 (2019)
A. Delteil et al., Nature Materials 18, 219 (2019)

**Fiber-closed cavity**

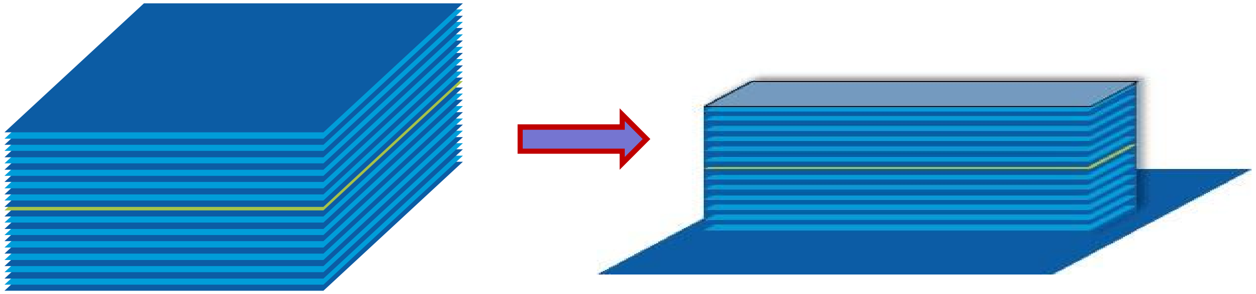
Imamoglu, Reichel,

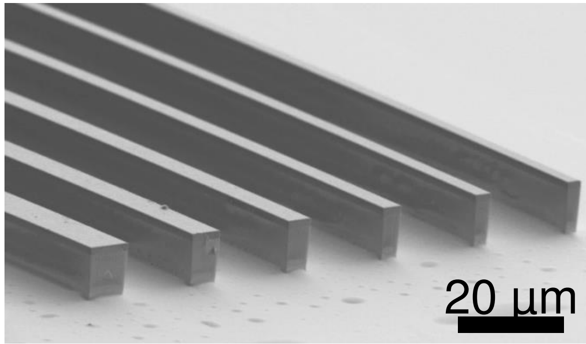


# Polariton in 1D cavities

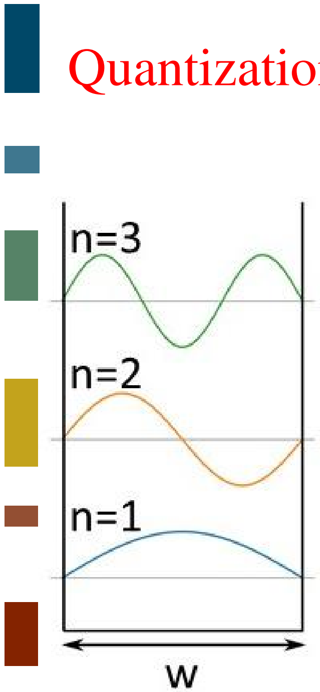
Electron beam lithography
+ ion dry etching

Polariton lateral confinement



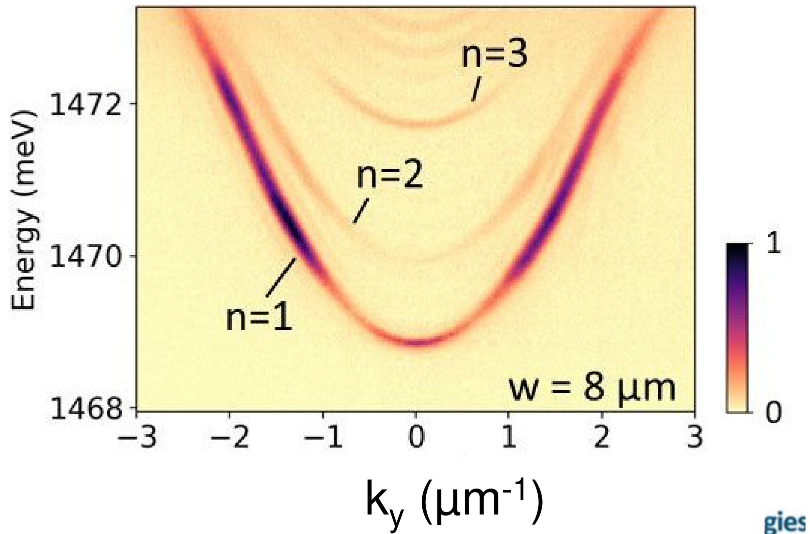



Quantization of $k_x$: $k_x = n\pi/w$
n=1,2,3,…

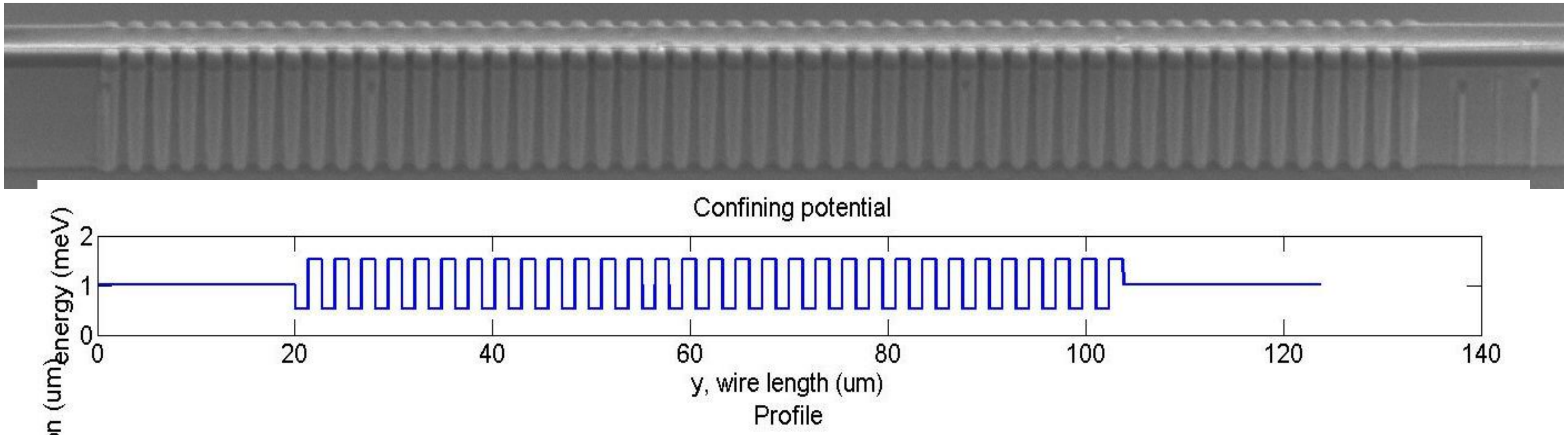



$$E_n(k_y) = E_0 + \frac{\hbar^2}{2m}\left(\frac{n^2\pi^2}{w^2} + k_y^2\right)$$

## 1D polariton sub-bands

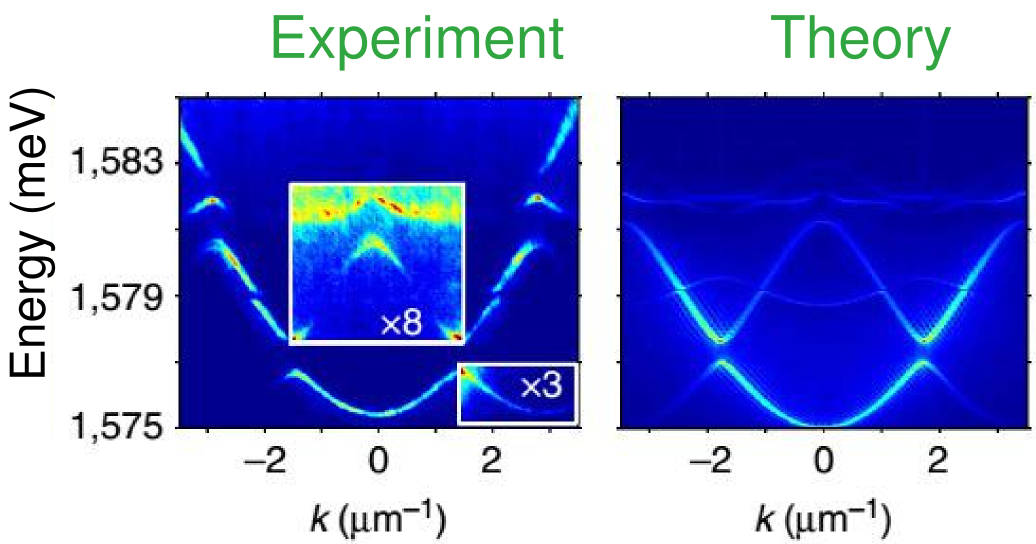


# 1D periodic potential: free particle approach




$$E\psi(x) = -\frac{\hbar^2}{2m}\frac{\partial\psi(x)}{\partial x} + \quad V(x)\psi(x)$$

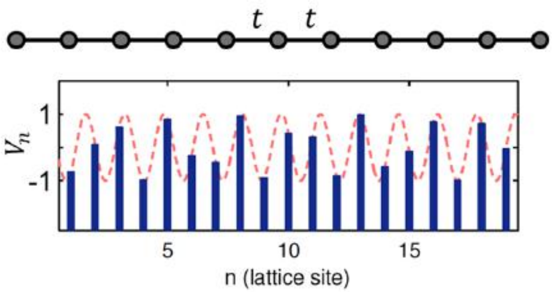
$$V(x) = \frac{\hbar^2}{2m}\frac{n^2\pi^2}{w(x)^2}$$

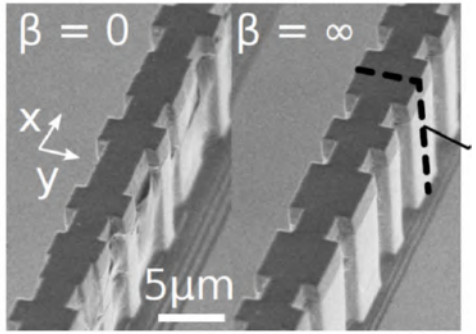



D. Tanese et al., Nature Com. **4**, 1749 (2013)

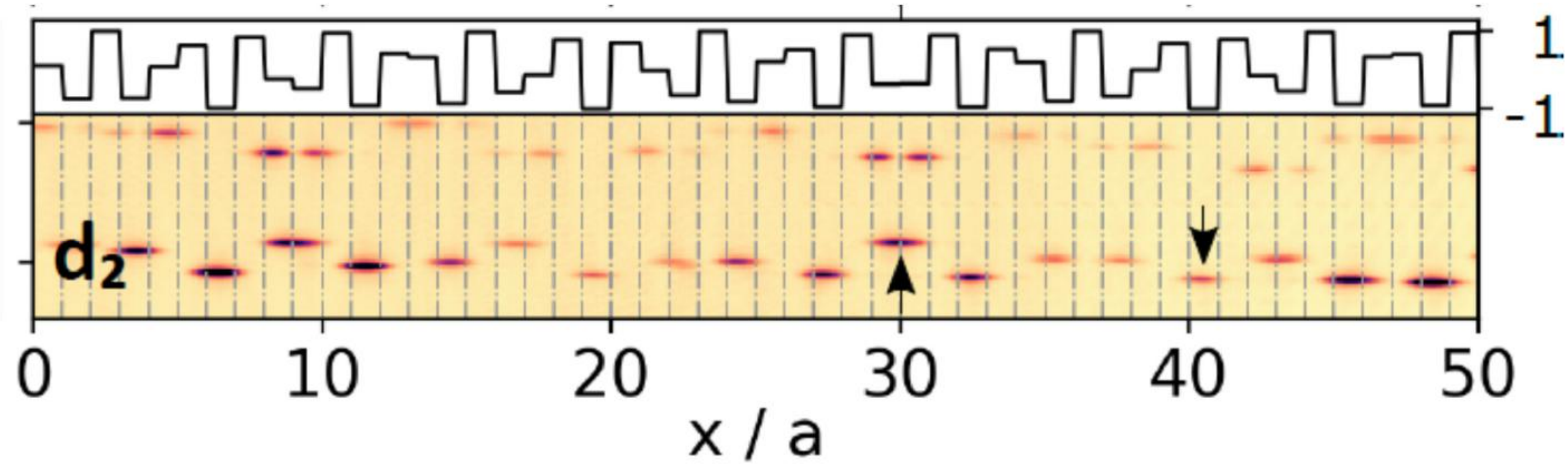
# Aubry André (Harper) quasi-periodic potential

On-site potential incommensurate with the lattice period




a = 2 µm

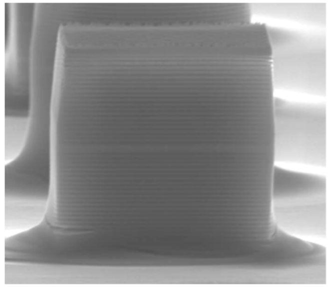


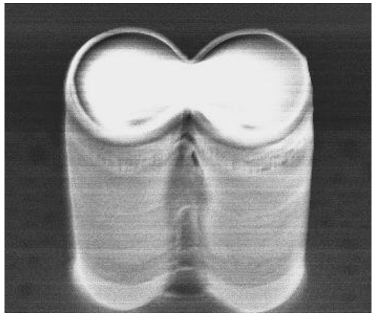

V. Goblot et al., Arxiv1911.07809

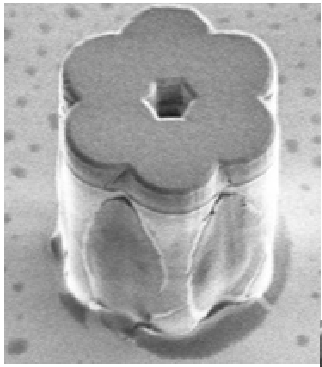
Roati *et al.*, Nature **453**, 895 (2008)
Lahini *et al.*, Phys. Rev. Lett. **103**, 013901 (2009)

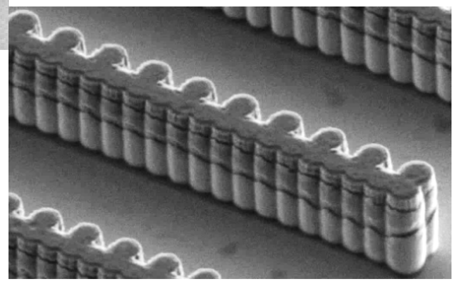
Centre de Nanosciences et de Nanotechnologies

# Polariton lattices:Tight binding approach

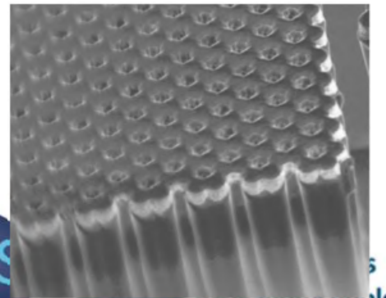




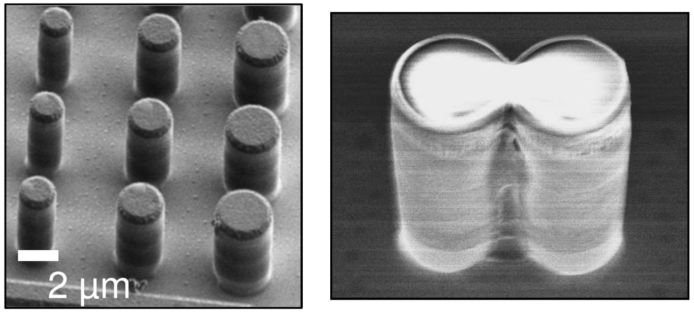


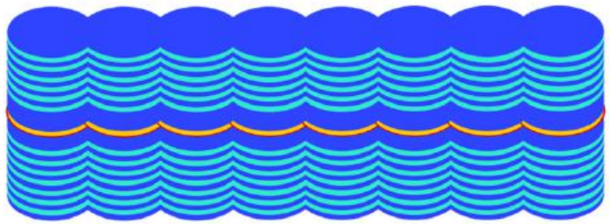


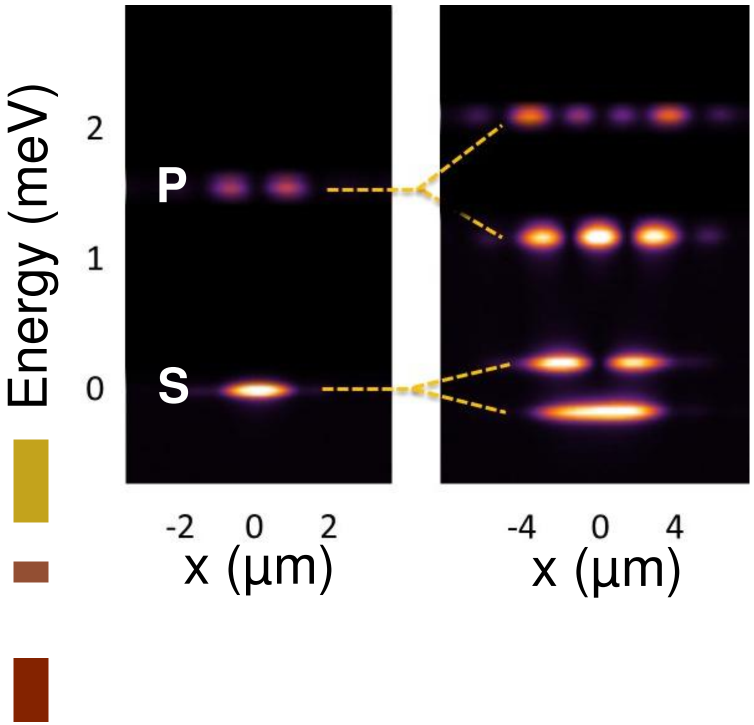
Review: C. Schneider et al., Rep. Prog. Phys. 80, 16503 (2017)

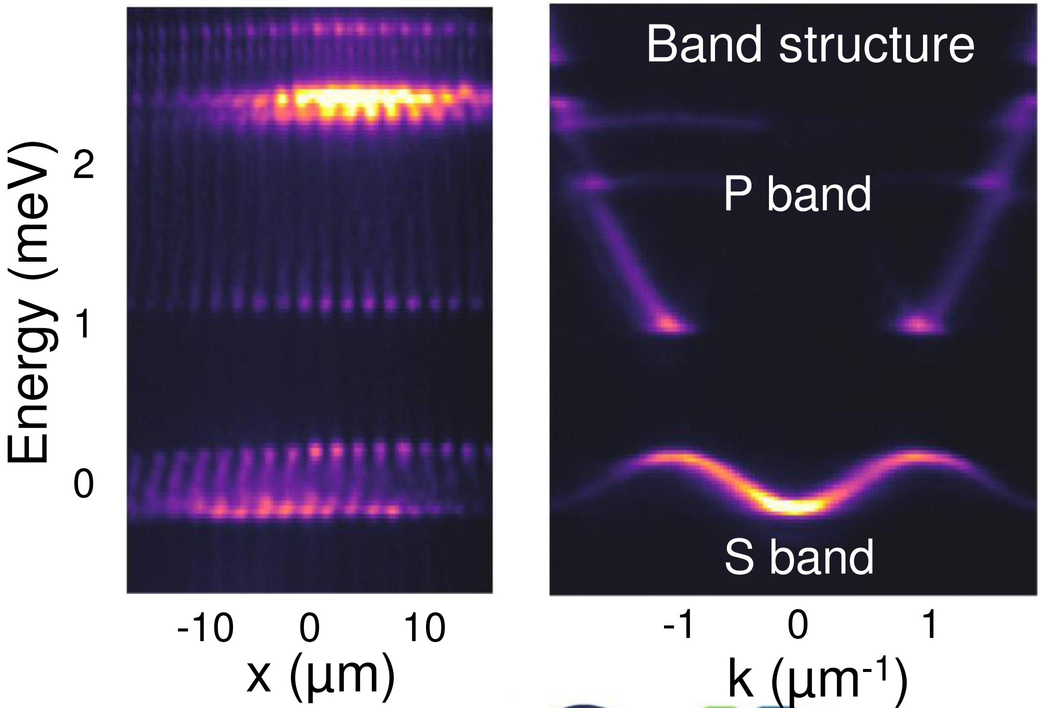


# Polariton lattices:Tight binding approach

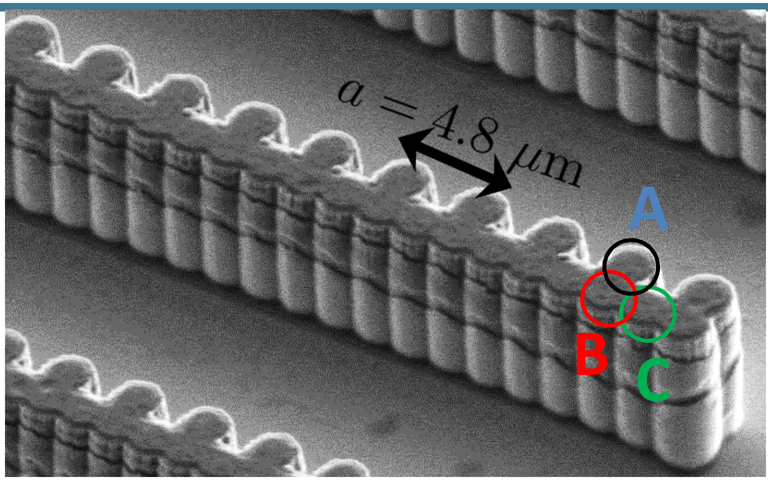


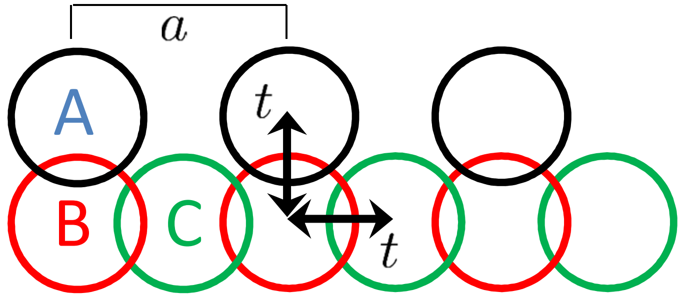


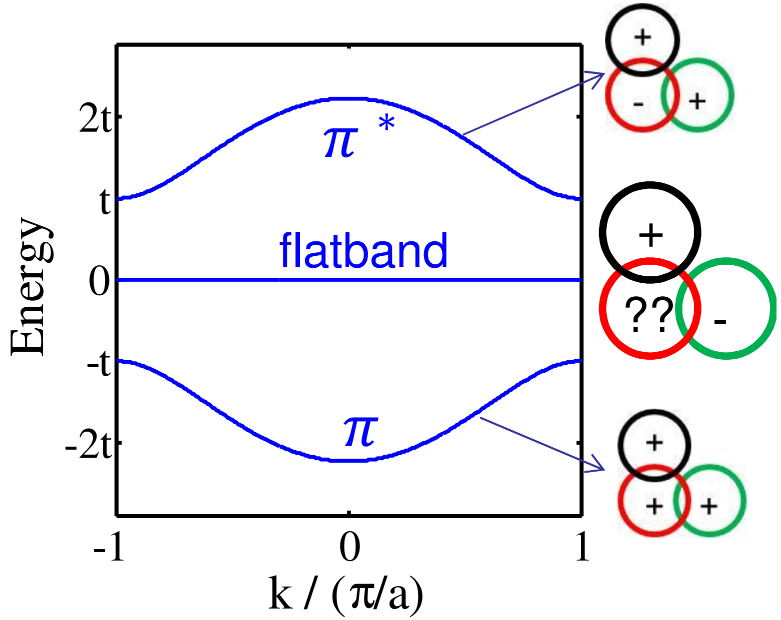



# Engineering of a 1D flatband : “comb” lattice

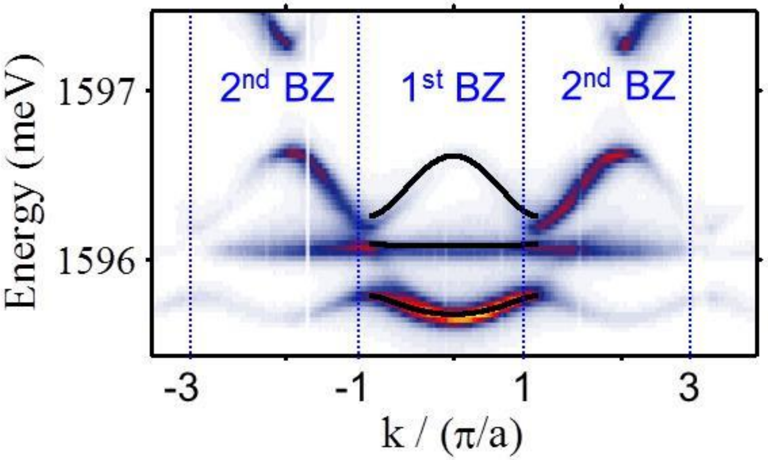



Pillar diameter = 3 µm
Interpillar distance= 2,4 µm

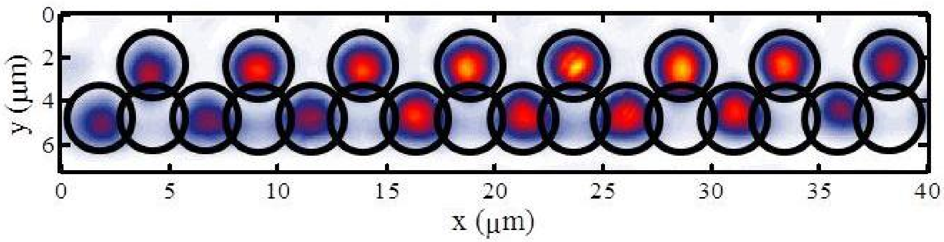



Far field emission




Emission of flat band in real space



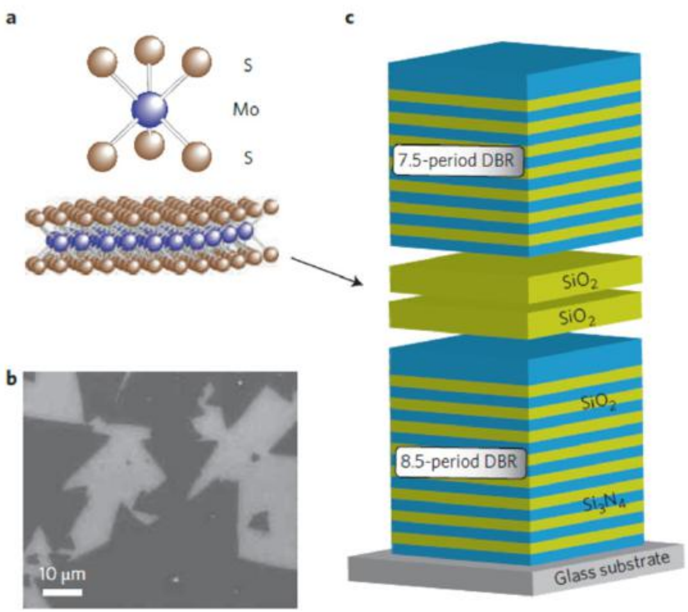

F. Baboux et al. PRL116, 066402 (2016)

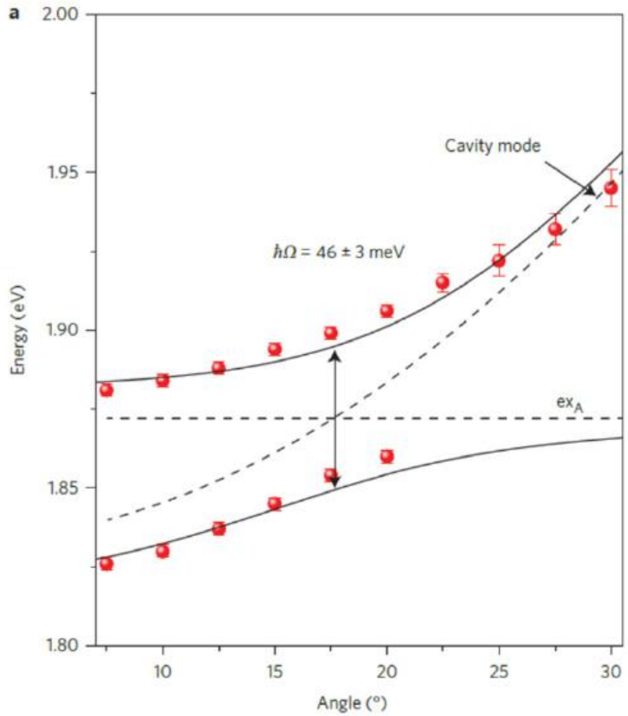
ARTICLES
PUBLISHED ONLINE: 23 DECEMBER 2014 | DOI: 10.1038/NPHOTON.2014.304

nature photonics

# Strong light–matter coupling in two-dimensional atomic crystals

Xiaoze Liu[1,2], Tal Galfsky[1,2], Zheng Sun[1,2], Fengnian Xia[3], Erh-chen Lin[4], Yi-Hsien Lee[4], Stéphane Kéna-Cohen[5] and Vinod M. Menon[1,2]*



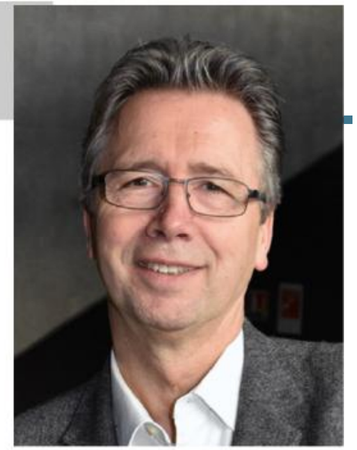
GDCh
Communications
Angewandte Chemie International Edition

Kinetics Hot Paper

International Edition: DOI: 10.1002/anie.201605504
German Edition: DOI: 10.1002/ange.201605504

# Ground-State Chemical Reactivity under Vibrational Coupling to the Vacuum Electromagnetic Field

*Anoop Thomas+, Jino George+, Atef Shalabney, Marian Dryzhakov, Sreejith J. Varma, Joseph Moran, Thibault Chervy, Xiaolan Zhong, Eloïse Devaux, Cyriaque Genet, James A. Hutchison, and Thomas W. Ebbesen**



Thomas Ebbesen
2019 CNRS Gold medal

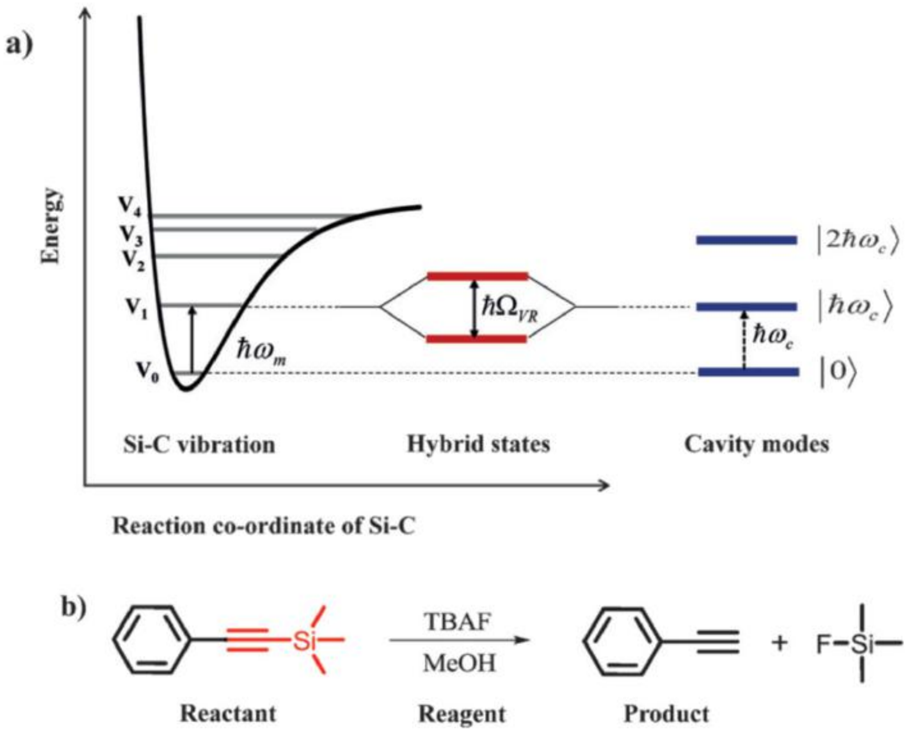



**Figure 1.** a) The light–matter strong coupling between the Si–C stretching vibrational transition and a cavity mode that results in the Rabi splitting. b) The silane deprotection reaction of 1-phenyl-2-trimethylsilylacetylene used in the present study.

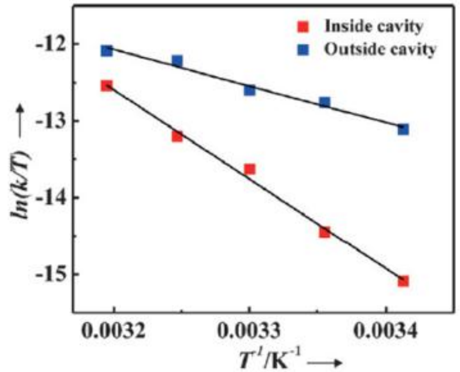
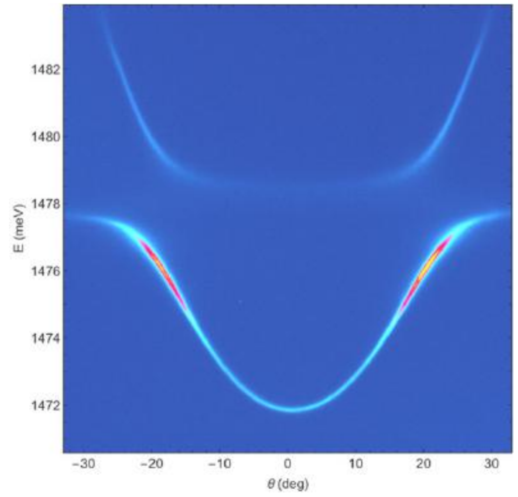



**Figure 4.** The reaction rate ([PTA] = 2.53 M, $\hbar\Omega_{VR}$ = 98 cm$^{-1}$) as a function of temperature (Eyring equation plot) for reactions inside the ON resonance cavity (red squares) and outside the cavity (blue squares).

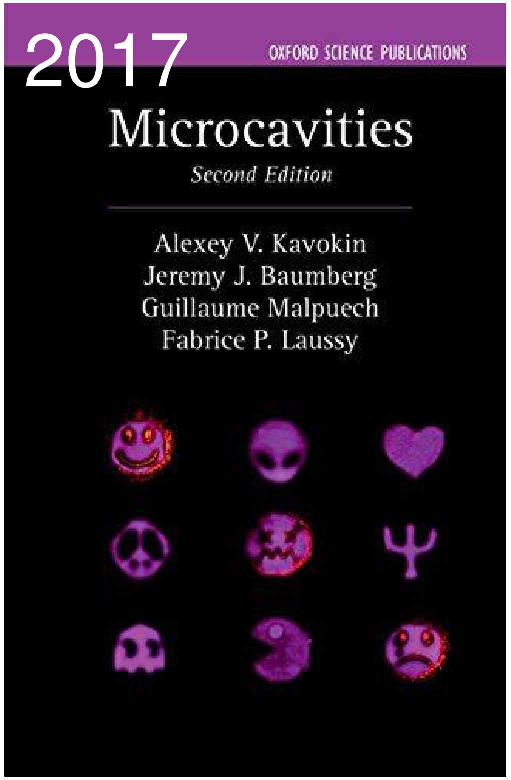
CNRS
C2N Centre de Nanosciences et de Nanotechnologies

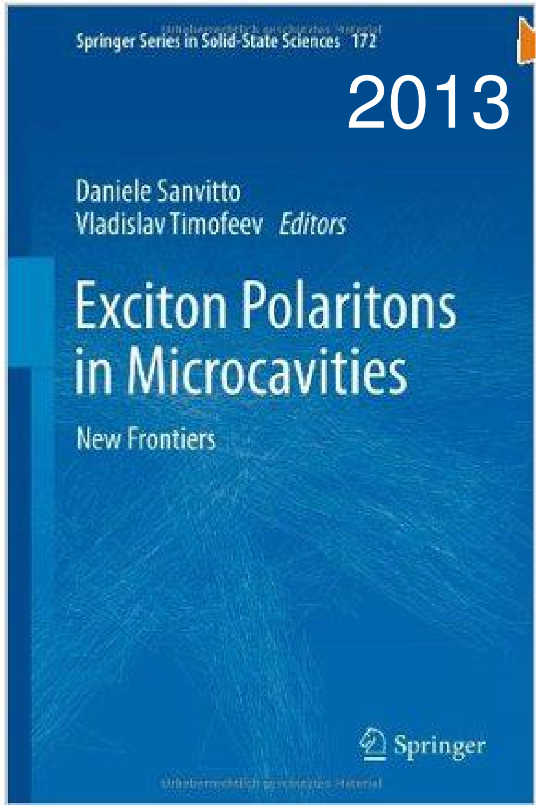
# Summary

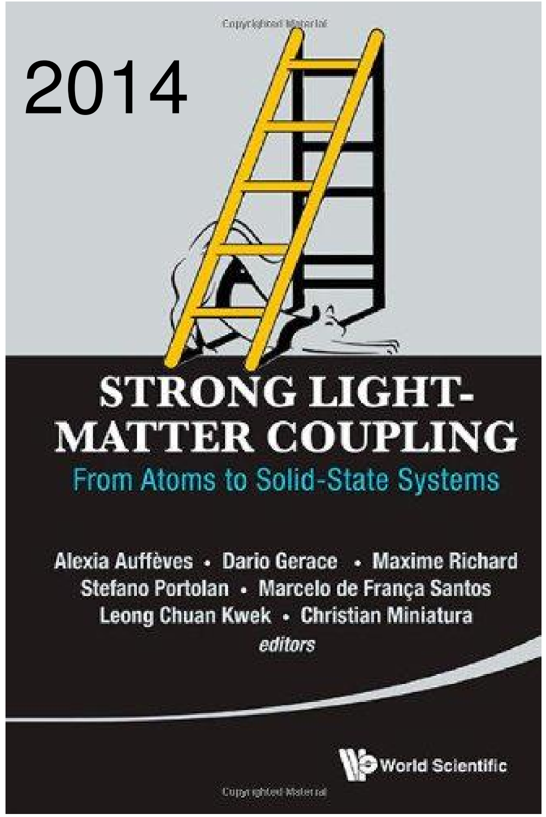
- Hybrid exciton-photon quasi-particles
- Tunable properties : effective mass, group velocity
- Lateral confinement : engineering of band structure
- Spin dependent interactions
- Optical access to all physical properties



# Reviews




C. Ciuti & I. Carusotto, *Quantum fluids of light*: Rev. Mod. Phys. **85**, 299 (2013)

A. Amo and J. Bloch, "*Exciton-polaritons in lattices: A non-linear photonic simulator*", Comptes Rendus de l'Académie des Sciences 8, 805 (2016)