Fundamental phenomena and applications of exciton-polariton condensates (I)

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LABORATOIRE DE PHOTONIQUE ET DE NANOSTRUCTURES

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FORTH

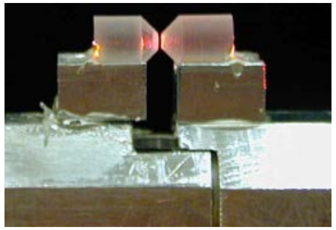
Index

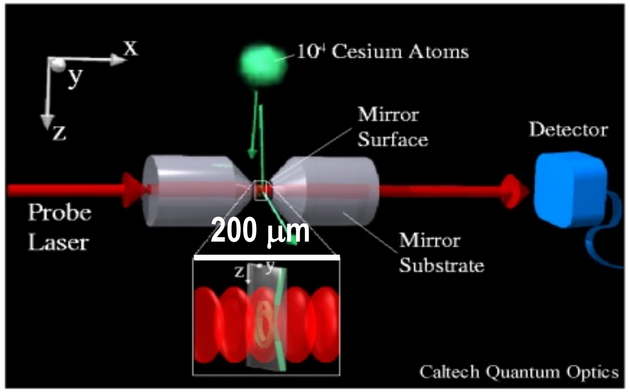
- Introduction
  - Semiconductor laser……VCSEL
  - VCSELs & microcavities
- **Polaritons**
- **Some key studies**
  - Polaritons in cavities, Rabi
  - OPO
  - BEC
  - Vortices
  - Superfluidity
  - Patterning of cavities

Quantum cavities

- Materials
  - Atoms, structured materials, **semiconductors**
- Requisites
  - Cavity size comparable to characteristic λ
  - Excellent control of sizes and compositions (n)
- Physics
  - Interactions: electronics excitations – electromagnetic modes
  - Condensation
- Aplications
  - Spontaneous emission control → decrease laser threshold
  - Thersholdless lasers
  - All optical devices
  - Quantum information

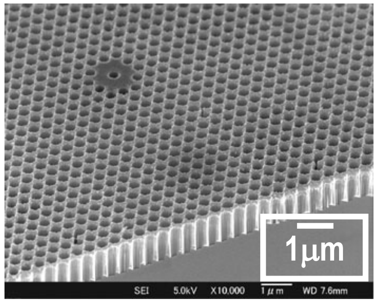
Materials





Atoms

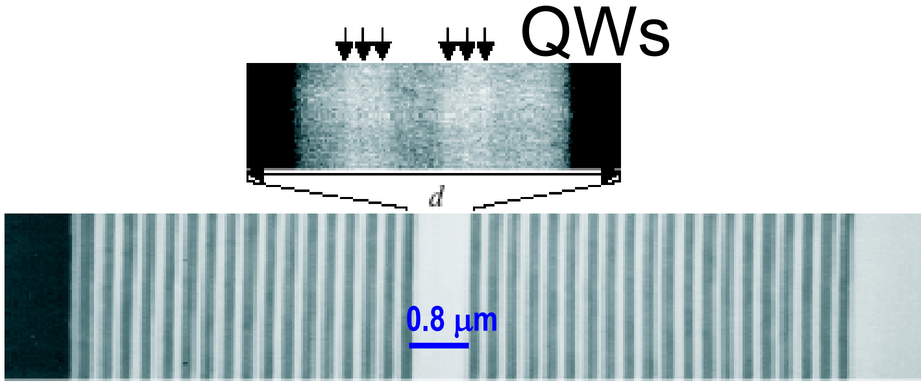
Real-Time Cavity QED with single atoms
Kimble et al. (Caltech)
Phys. Rev. Lett. **80** (1998)



Structured materials

Photonic crystal with defects

Semiconductor And Materials Company (SAMCO). Kyoto. Japan

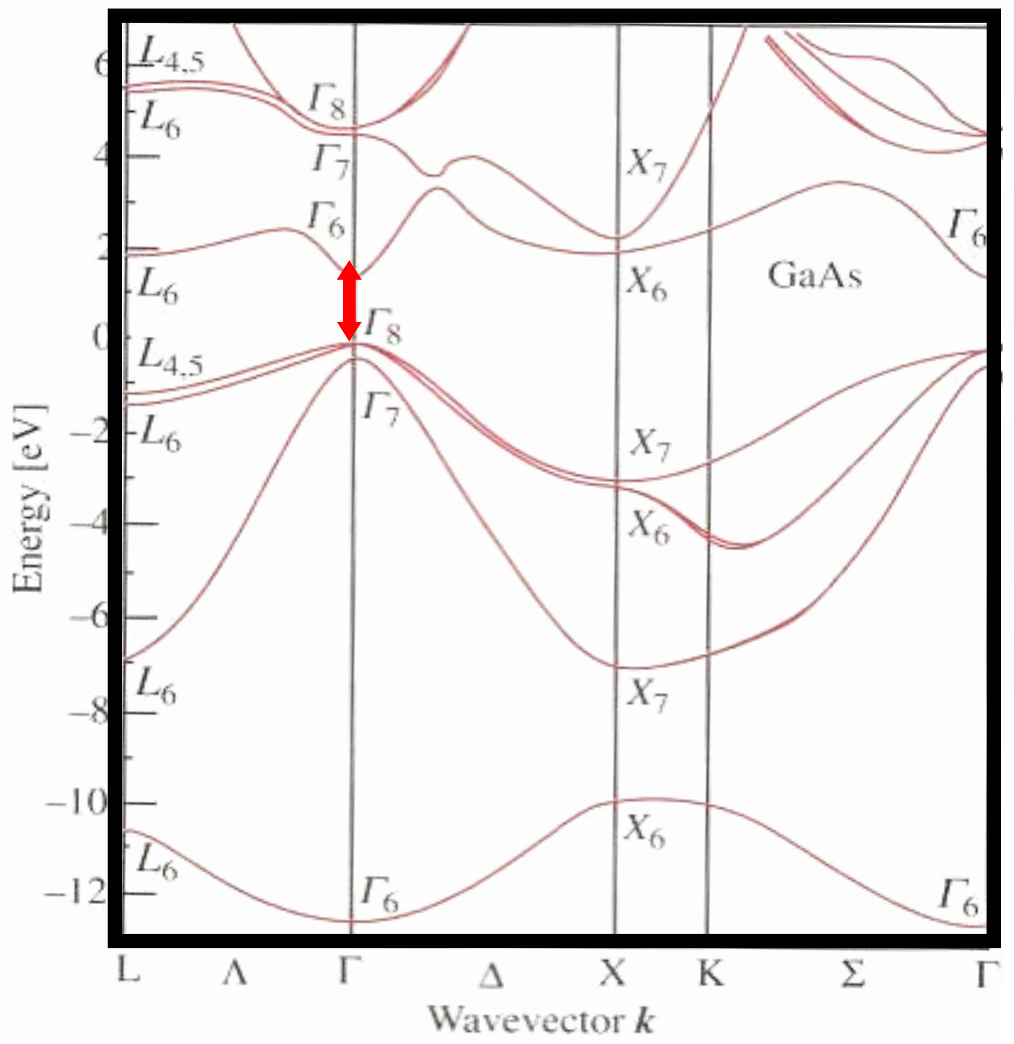


Semiconductors & QWs

R. André. *Joseph Fourier Université. Grenoble, Francia*

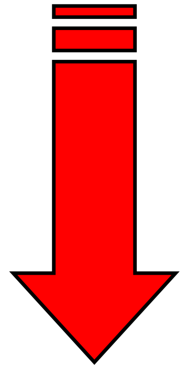
Semiconductor Laser (I)

Band structure



GaAs

Direct band gap

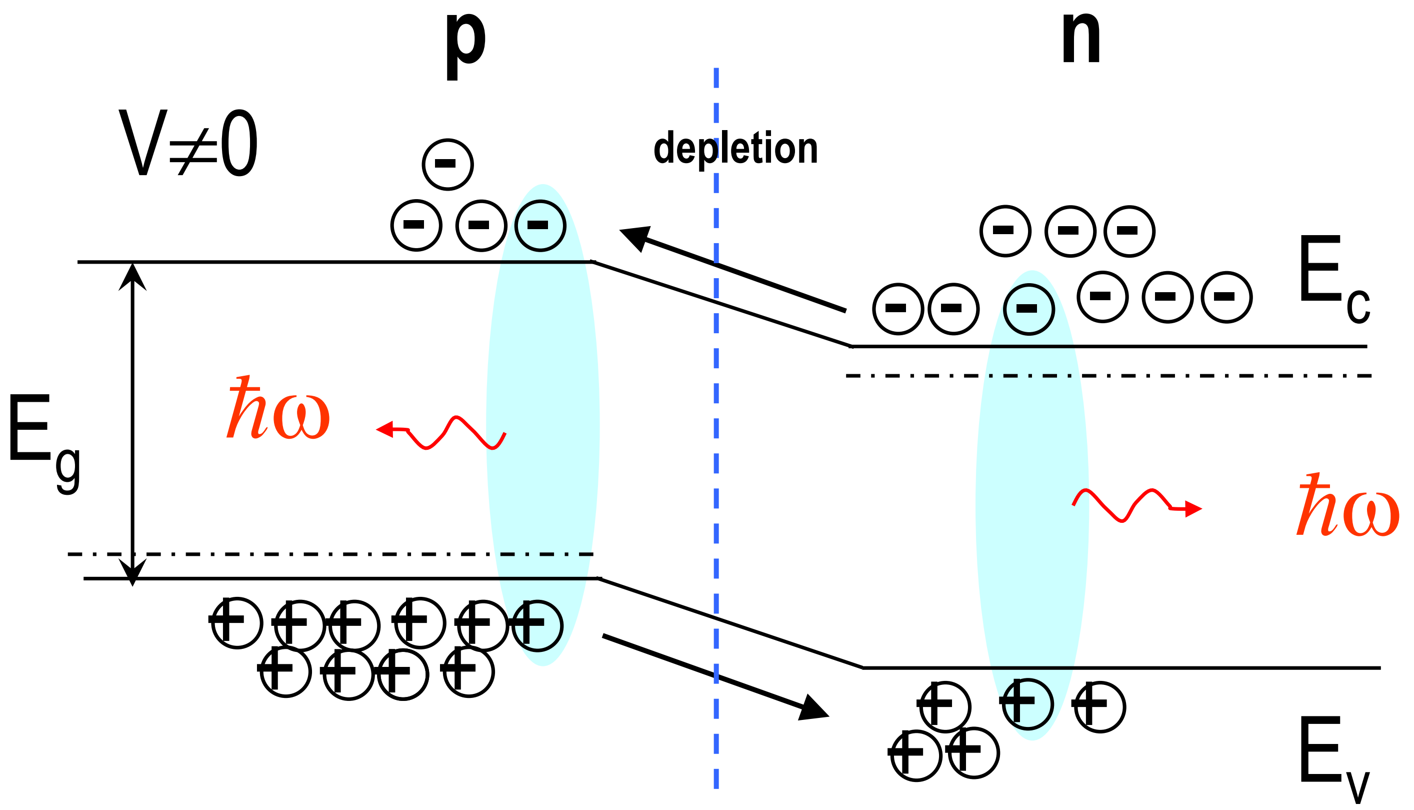


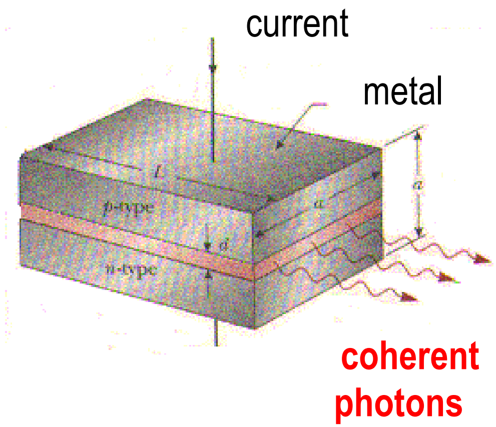
Light emission and absorption

Semiconductor Laser (II)

- Doping & carrier injection
- Homo-union

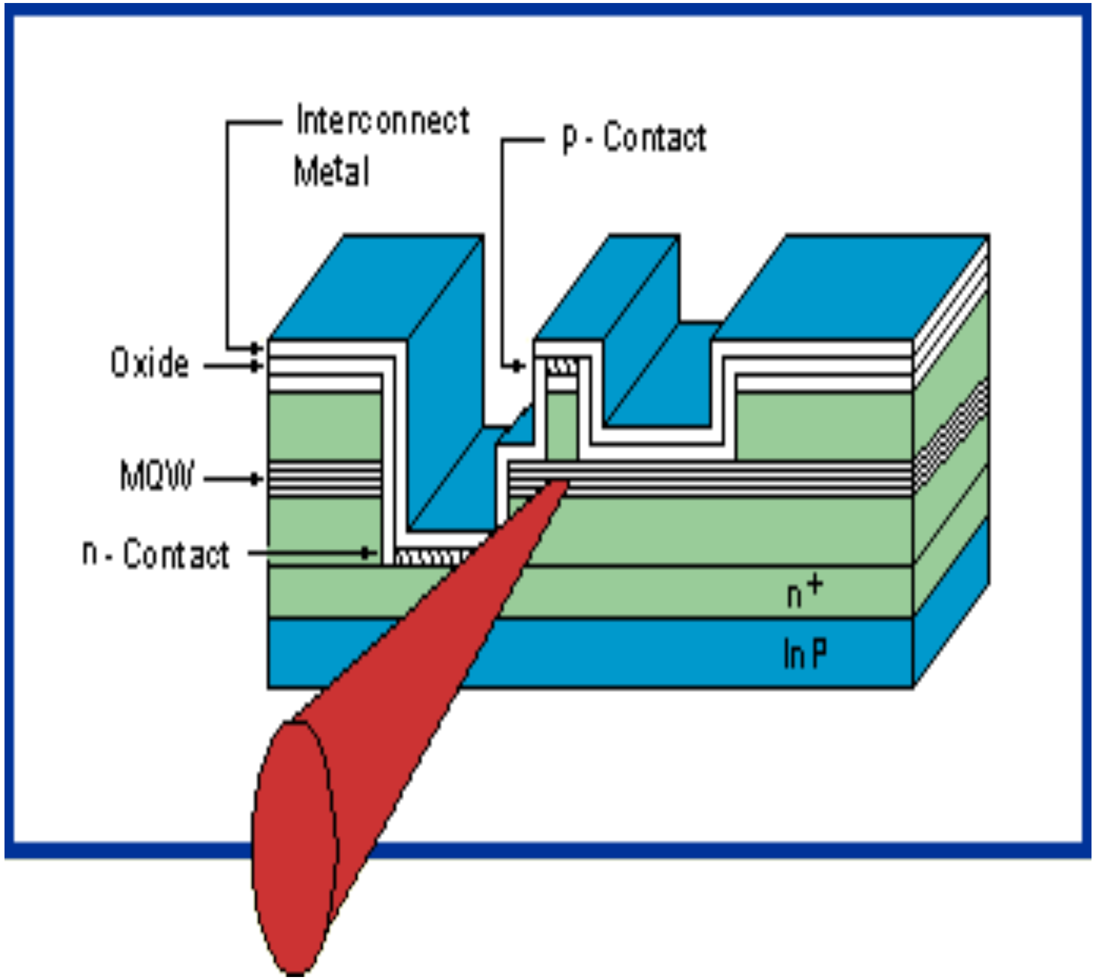
Light emission

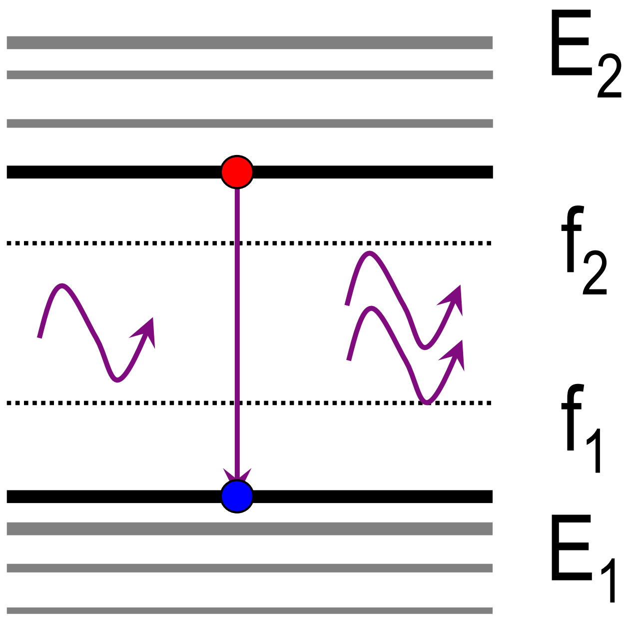




Semiconductor Laser (III)

Confinement (quantum wells)

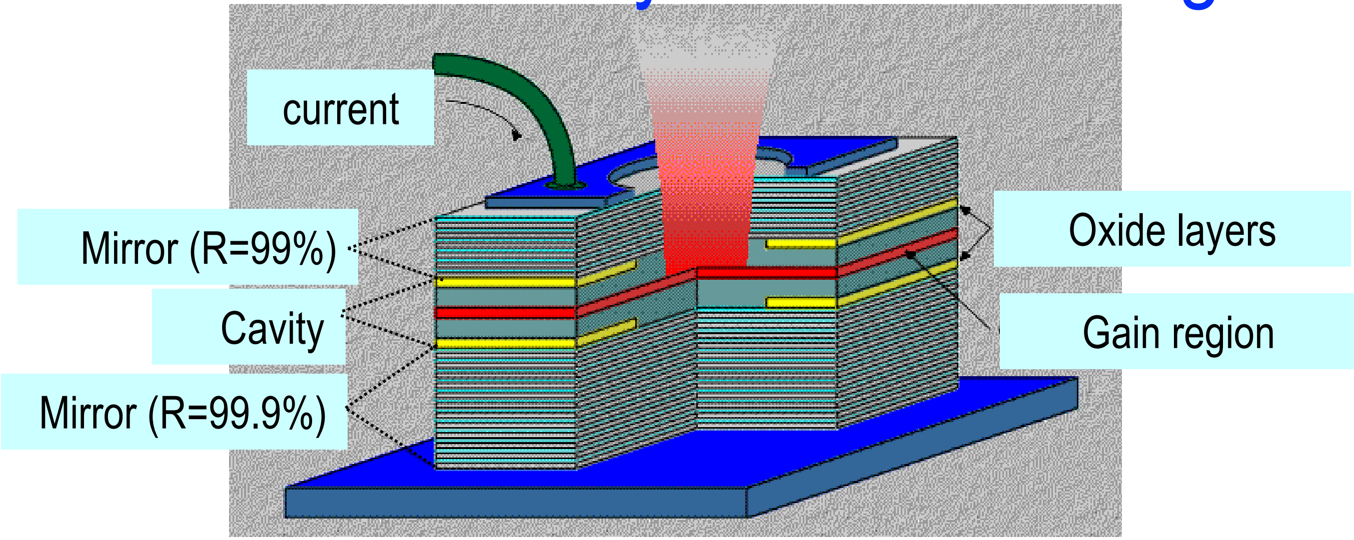


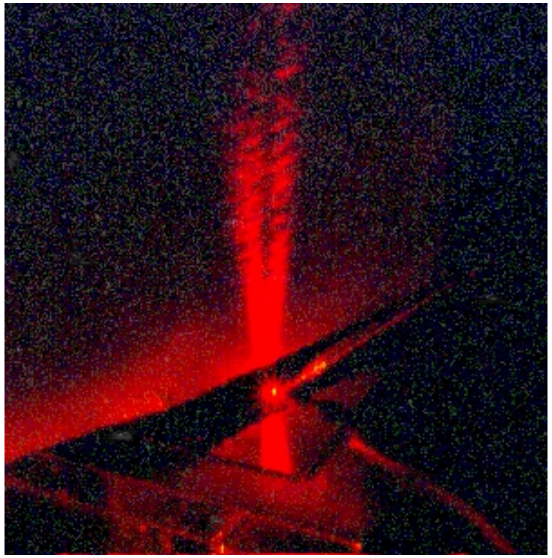


Population inversion & stimulated emission

Semiconductor Laser (IV)

Vertical cavity surface emitting laser (VCSEL)





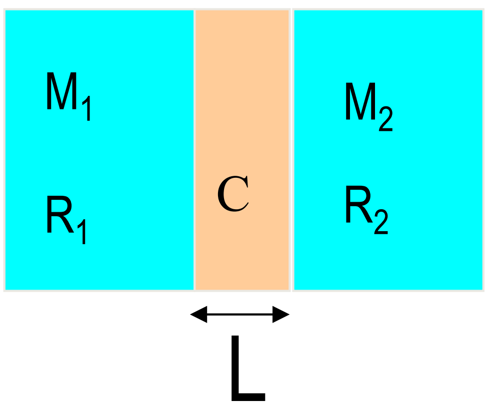
Advantages

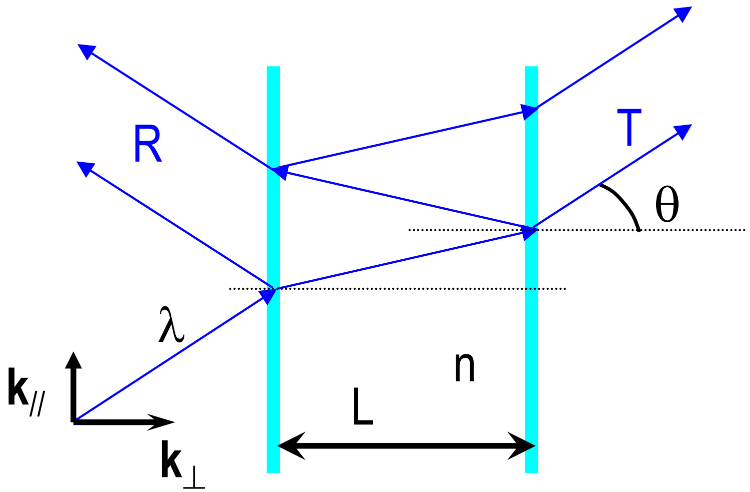
- Vertical emission
- Only a longitudinal mode
- Large efficiency/ low consumption
- Easiness of processing / testing

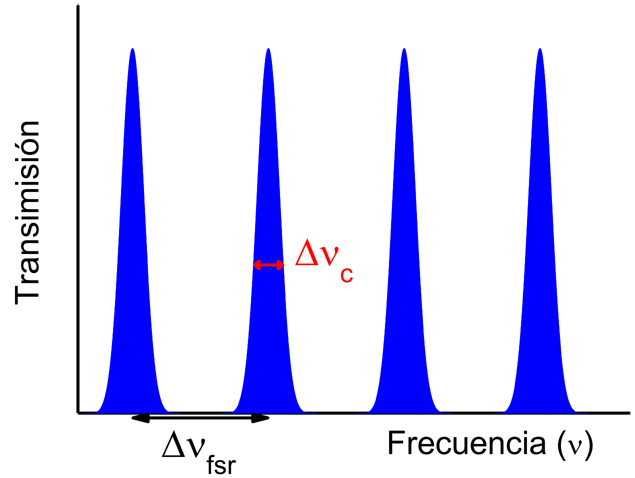
Laser cavity (I)

Fabry-Perot Resonator

- Simplest structure to confine electromagnetic fields







$$T = \frac{(1-R_1)(1-R_2)}{\left[(1-\sqrt{R_1R_2}\right]^2 + 4\sqrt{R_1R_2}\,\sin\phi^2}$$

$$\Delta\nu_{fsr} = \frac{c}{2\pi L\cos\theta}$$

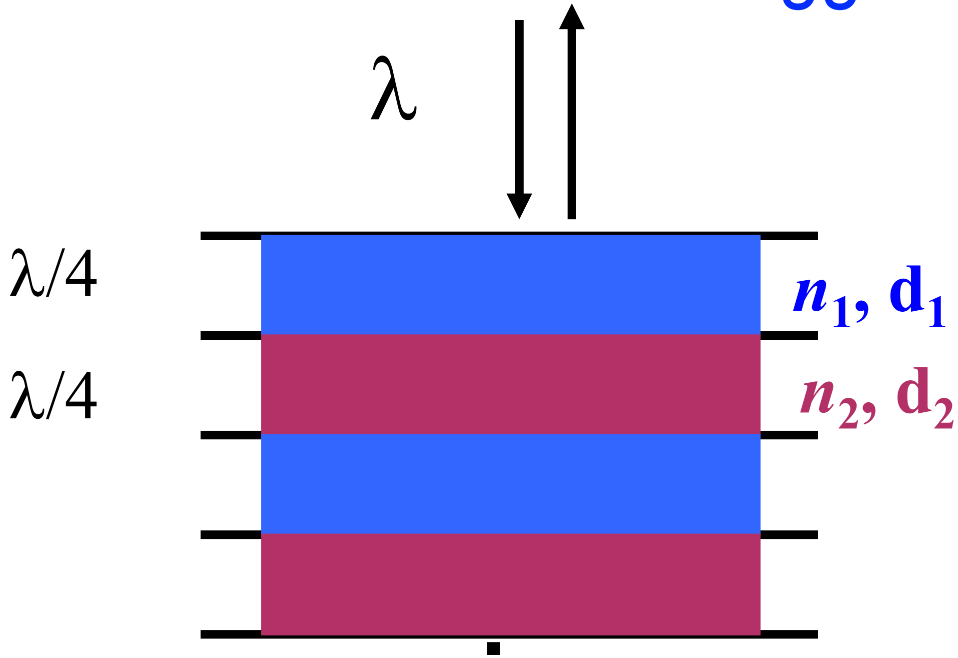
$$\Delta\nu_c = \frac{c}{2nL\cos\theta}\,\frac{1-\sqrt{R_1R_2}}{\pi(R_1R_2)^{1/4}}$$

$$\phi = \frac{2\pi nL\cos\theta}{\lambda}$$

$$Q \propto \mathrm{F} = \frac{\Delta\nu_{\mathrm{fsr}}}{\Delta\nu_{\mathrm{c}}} = \frac{\pi(R_1R_2)^{1/4}}{1-\sqrt{R_1R_2}}$$

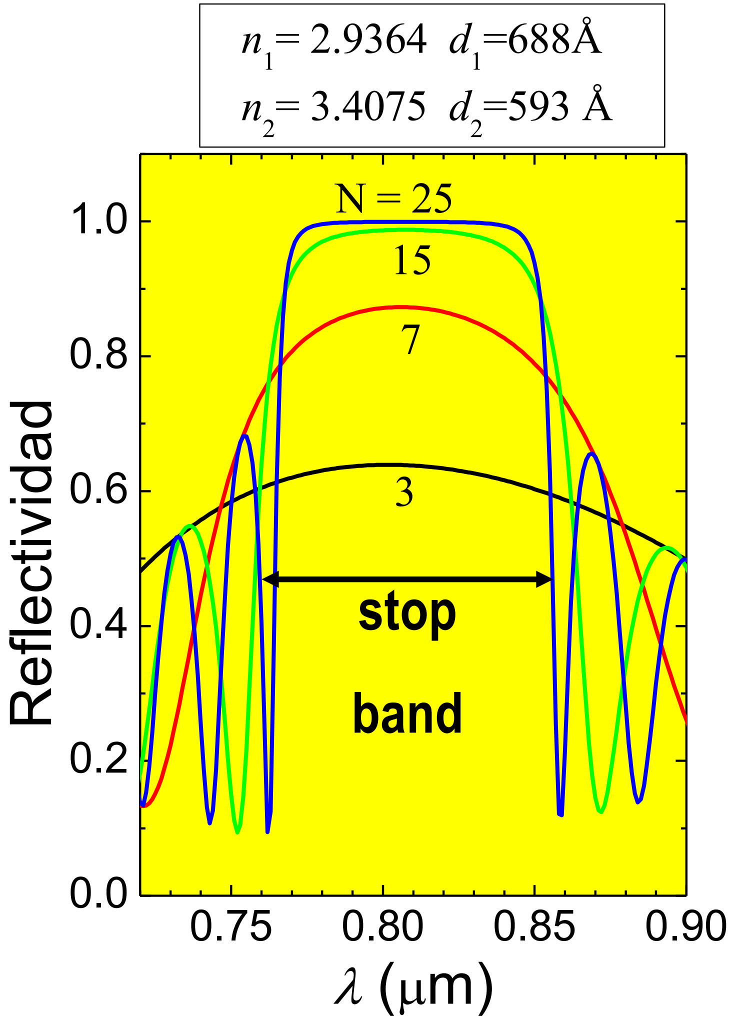
Laser cavity (II)

Distributed Bragg Reflectors (DBR)



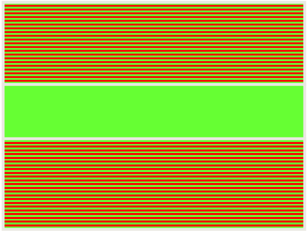
High reflectivity

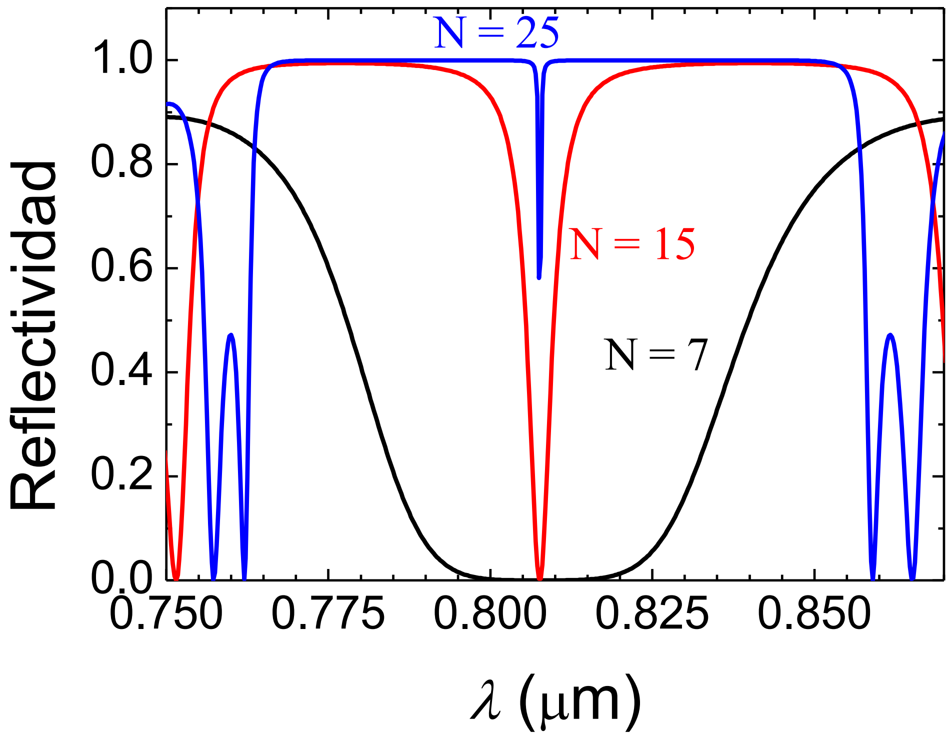
- normal incidence
- many periods



Laser cavity (III)

- "Cavity" ⟺ open a region (*d*) in-between DBR
- "Defect" ⟹ increase of transmission (**R↓**)
- *d*=λ/2 ⟹ transmission at the center of "stop"band



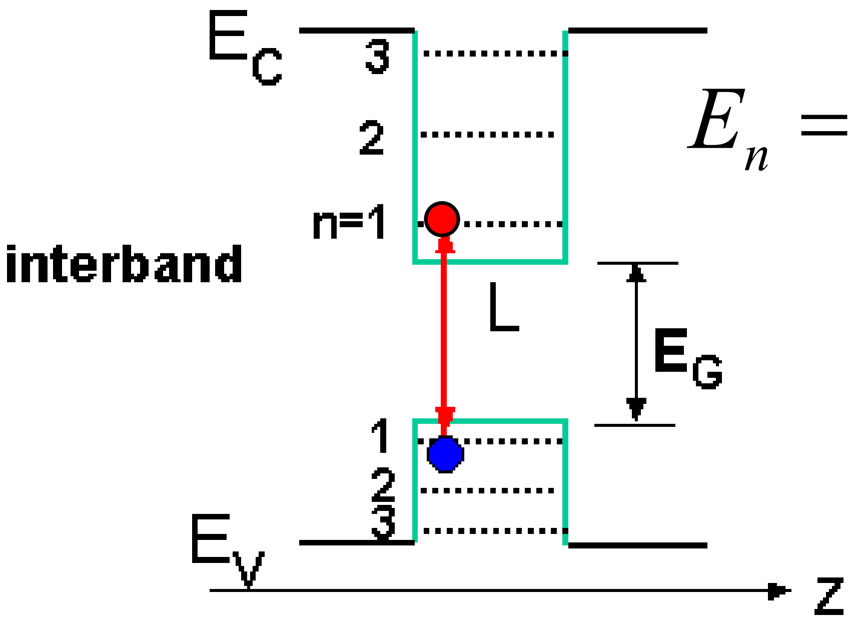


Emitter in the cavity

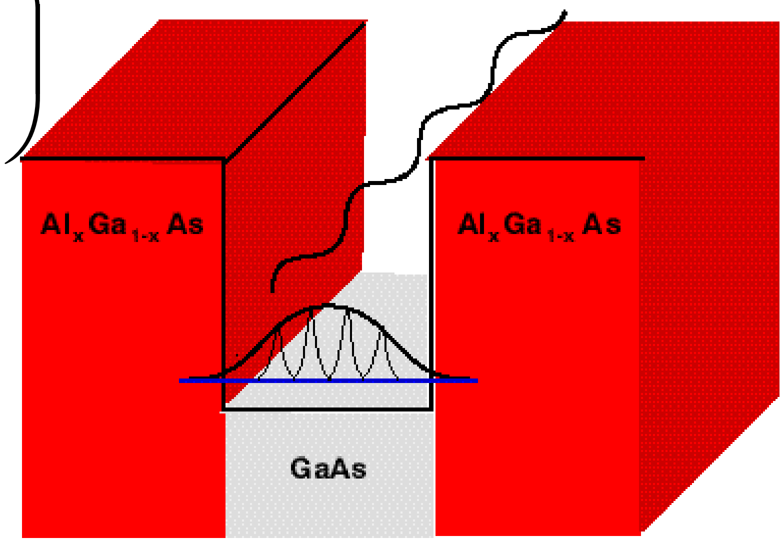
Emitter (I)

Quantum wells

- **Artificial structures**
- **Layers ~10 nm, with different "gap"**
- **Quantum confinement effects**



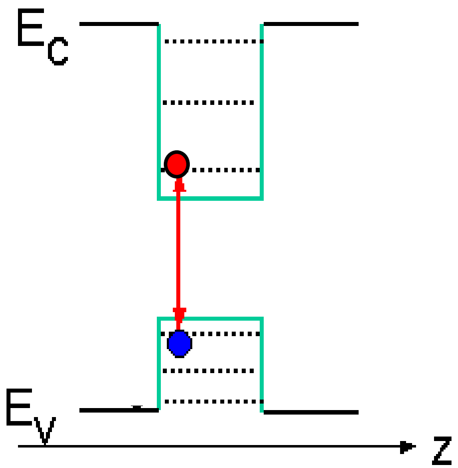
$$E_n = \frac{\hbar^2}{2m}\left(\frac{n\pi}{L}\right)^2$$



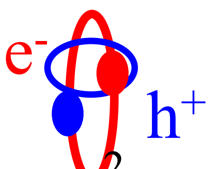
Emitter (II)

Excitons

Independent particles

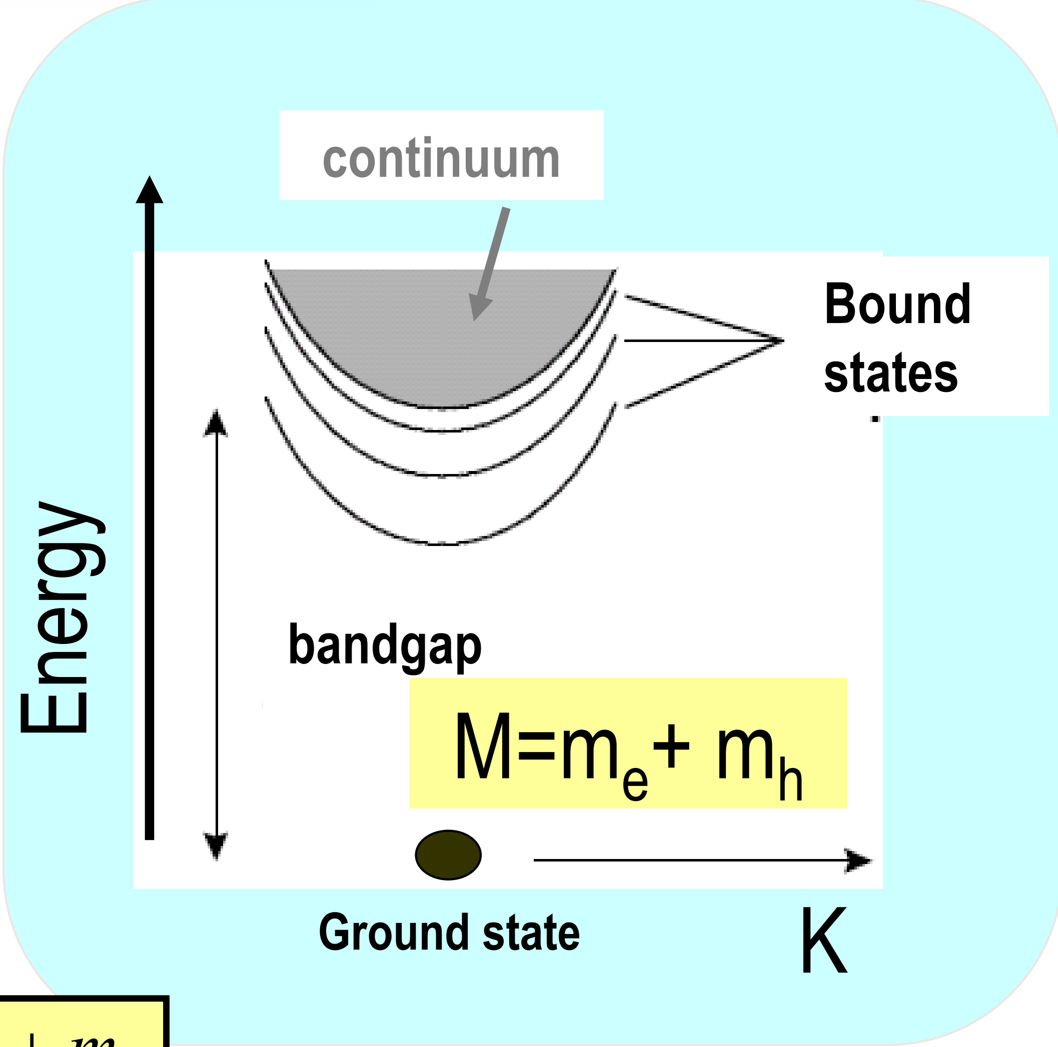


Coulomb interaction



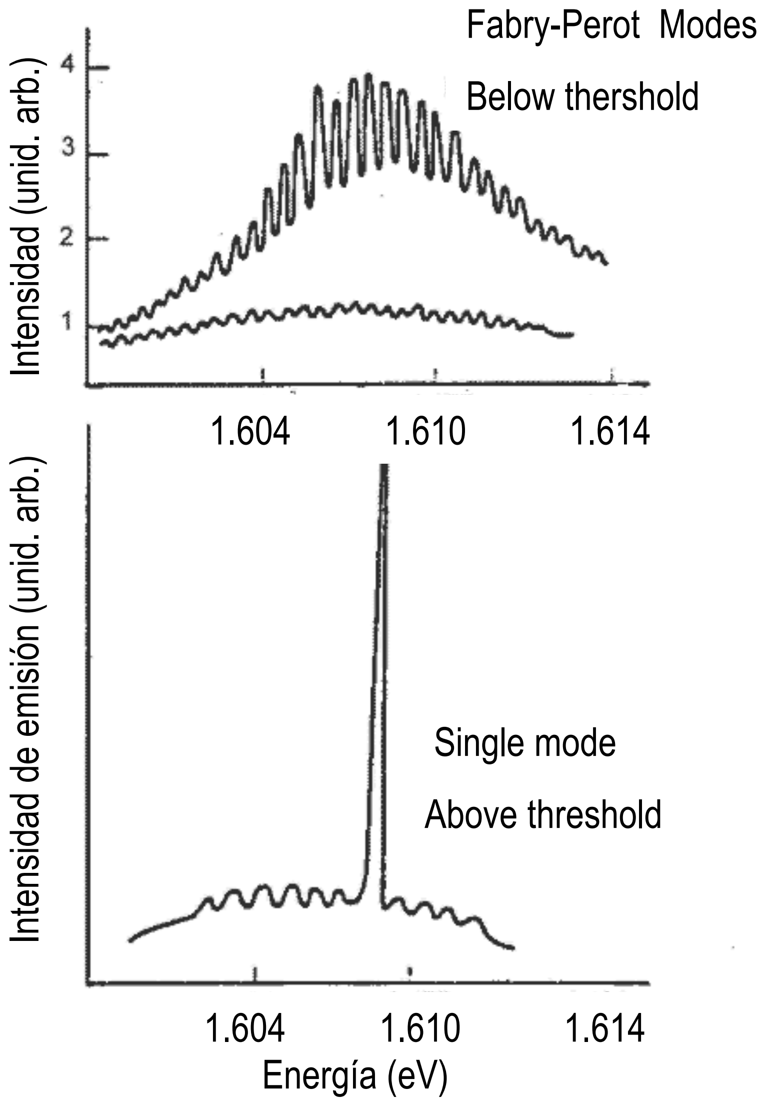
$$-\frac{e^2}{4\pi\varepsilon_r\varepsilon_o\left|\vec{r}_e-\vec{r}_h\right|}$$

$$\mu=\frac{m_e+m_h}{m_e\times m_h}$$



Integer Spin ⟹ Boson

VCSEL

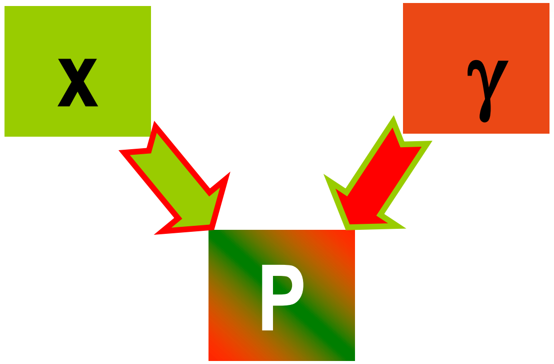


Weak coupling

- ➲Fast damping rates
- ➲Irreversible emission decay
- ➲Mode crossing

Modification of spontaneous decay rates

Exciton-Polariton (I)



$$g_0 = \vec{d} \bullet \vec{E}_0$$

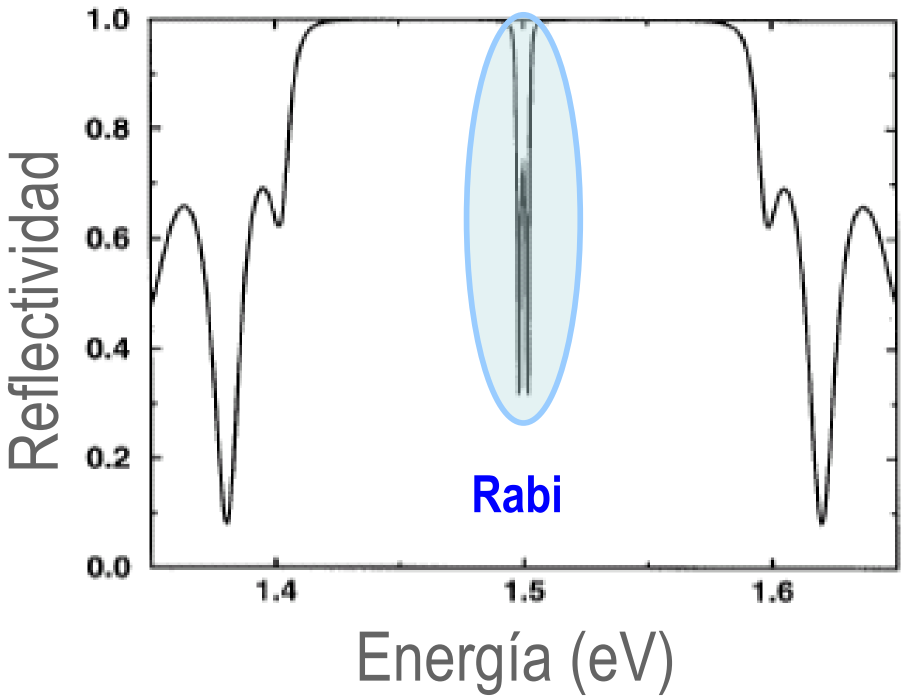
Integer Spin

⇓

Boson

Strong coupling

- Slow damping rates
- Oscillations $|X, \gamma\rangle \leftrightarrow |\gamma, X\rangle$
- Mode anticrossing ➔ Rabi



PHYSICAL REVIEW VOLUME 112, NUMBER 5 DECEMBER 1, 1958

Theory of the Contribution of Excitons to the Complex Dielectric Constant of Crystals*†

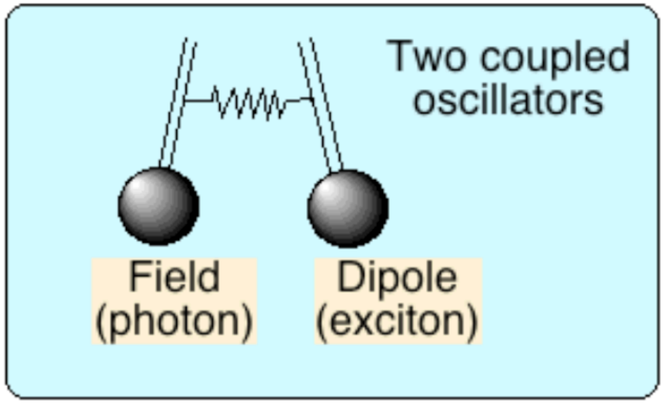
J. J. HOPFIELD‡
Physics Department, Cornell University, Ithaca, New York

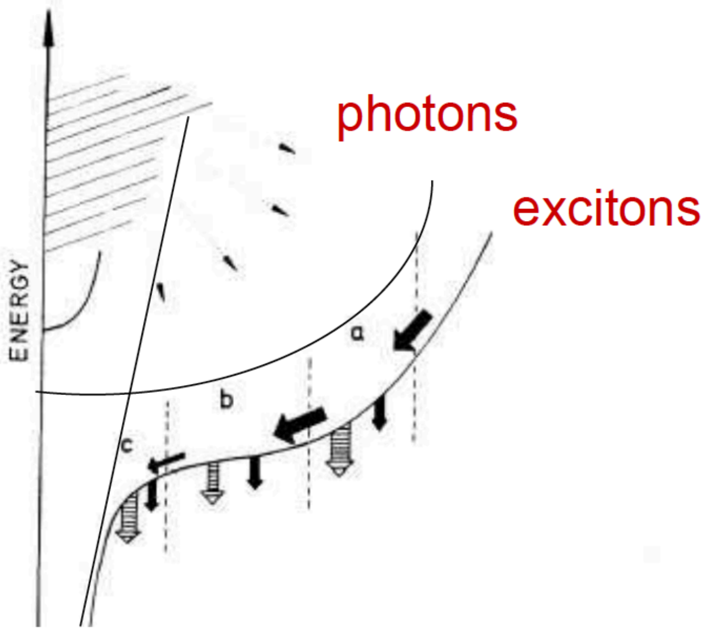
(Received July 16, 1958)

It is shown that the ordinary semiclassical theory of the absorption of light by exciton states is not completely satisfactory (in contrast to the case of absorption due to interband transitions). A more complete theory is developed. It is shown that excitons are approximate bosons, and, in interaction with the electromagnetic field, the exciton field plays the role of the classical polarization field. The eigenstates of the system of crystal and radiation field are mixtures of photons and excitons. The ordinary one-quantum optical lifetime of an excitation is infinite. Absorption occurs only when "three-body" processes are introduced. The theory includes "local field" effects, leading to the Lorentz local field correction when it is applicable. A Smakula equation for the oscillator strength in terms of the integrated absorption constant is derived.

Strongly-coupled 3D excitons and photons, excitonic polaritons are the quasi particles of the system

Exciton ω.**k** ⟷ photon ω.**k**

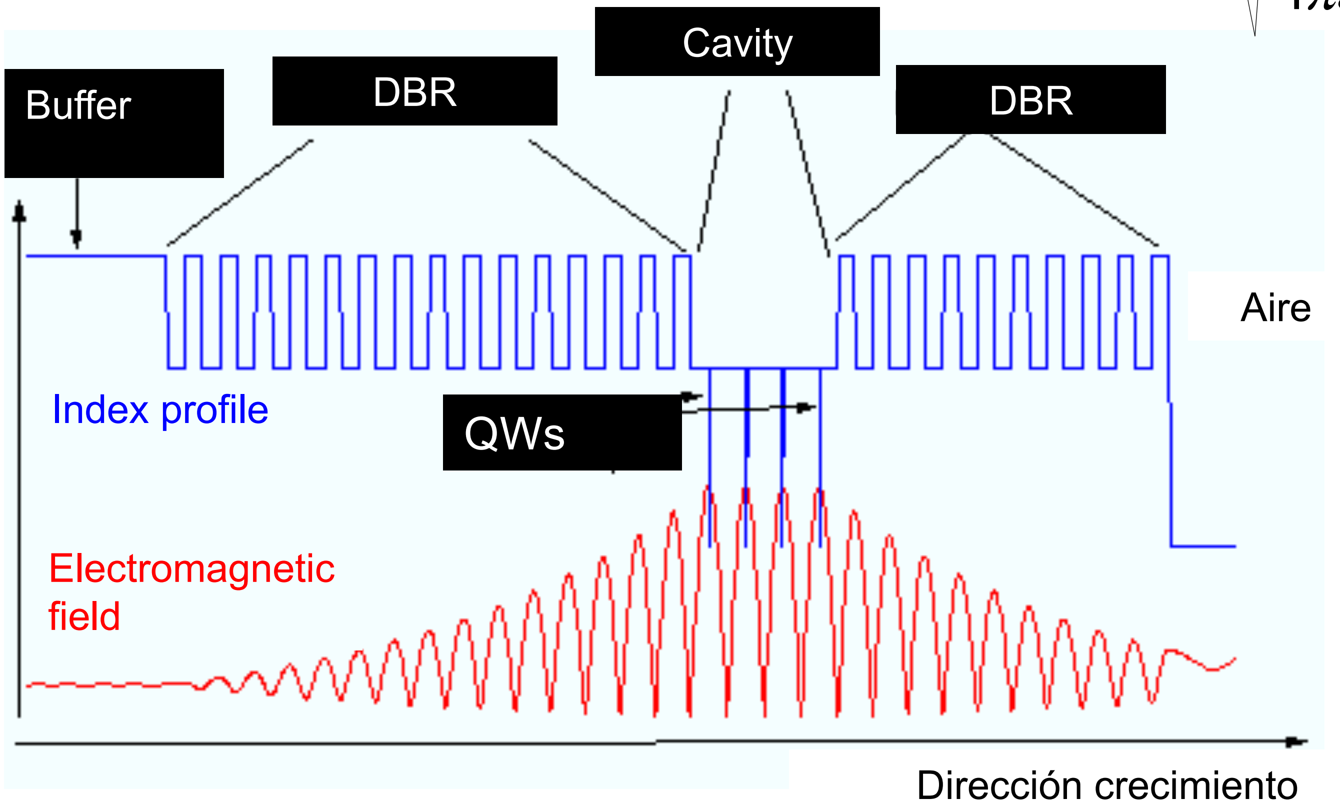




Exciton-Polariton (II)

Light-matter interaction optimization

$$\Omega = 2\sqrt{\frac{e^2}{4\pi\varepsilon_0\varepsilon_r m_0}\frac{2\pi}{L_{eff}} N f_X}$$



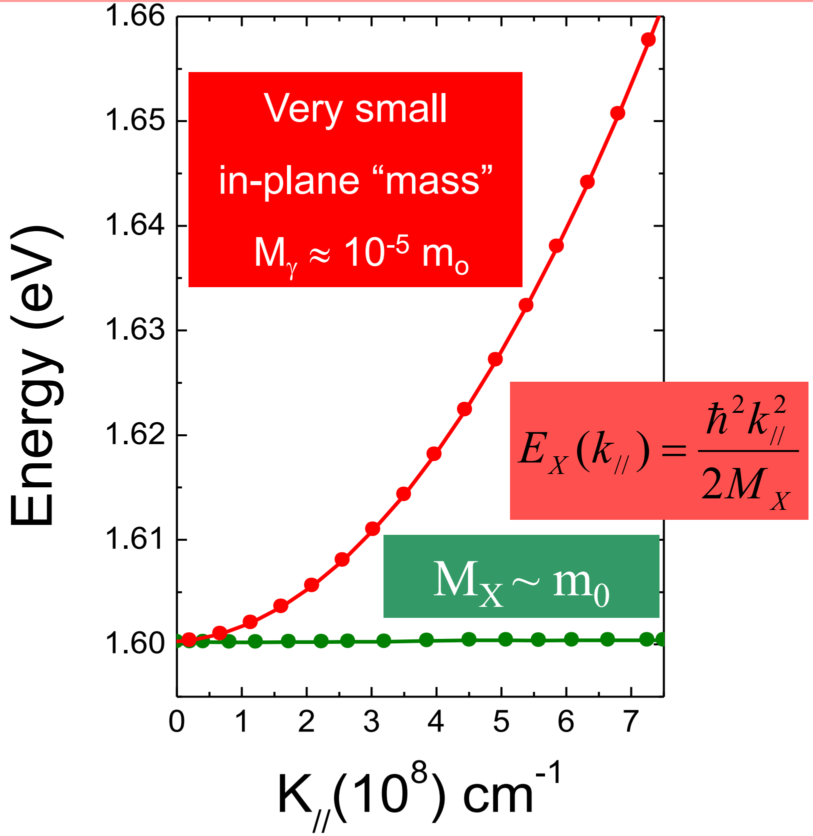
Position

Dispersion relations

Along the growth direction (confinement): $k_z = 2\pi/L$

Decoupled

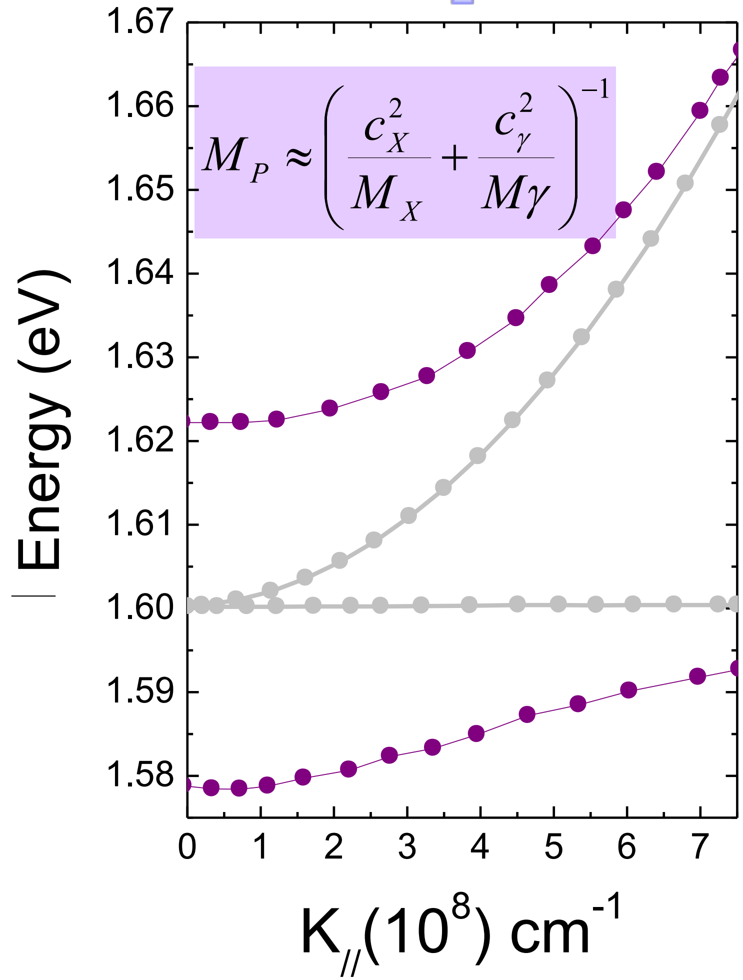
$$E_\gamma(k_{//}) = \frac{\hbar c}{n}\left[\left(\frac{2\pi}{L}\right)^2 + k_{//}^2\right]^{1/2} = E_0\left(1 + \frac{\hbar^2 c^2 k_{//}^2}{E_0^2 n^2}\right)^{1/2}$$



$$E_X(k_{//}) = \frac{\hbar^2 k_{//}^2}{2M_X}$$

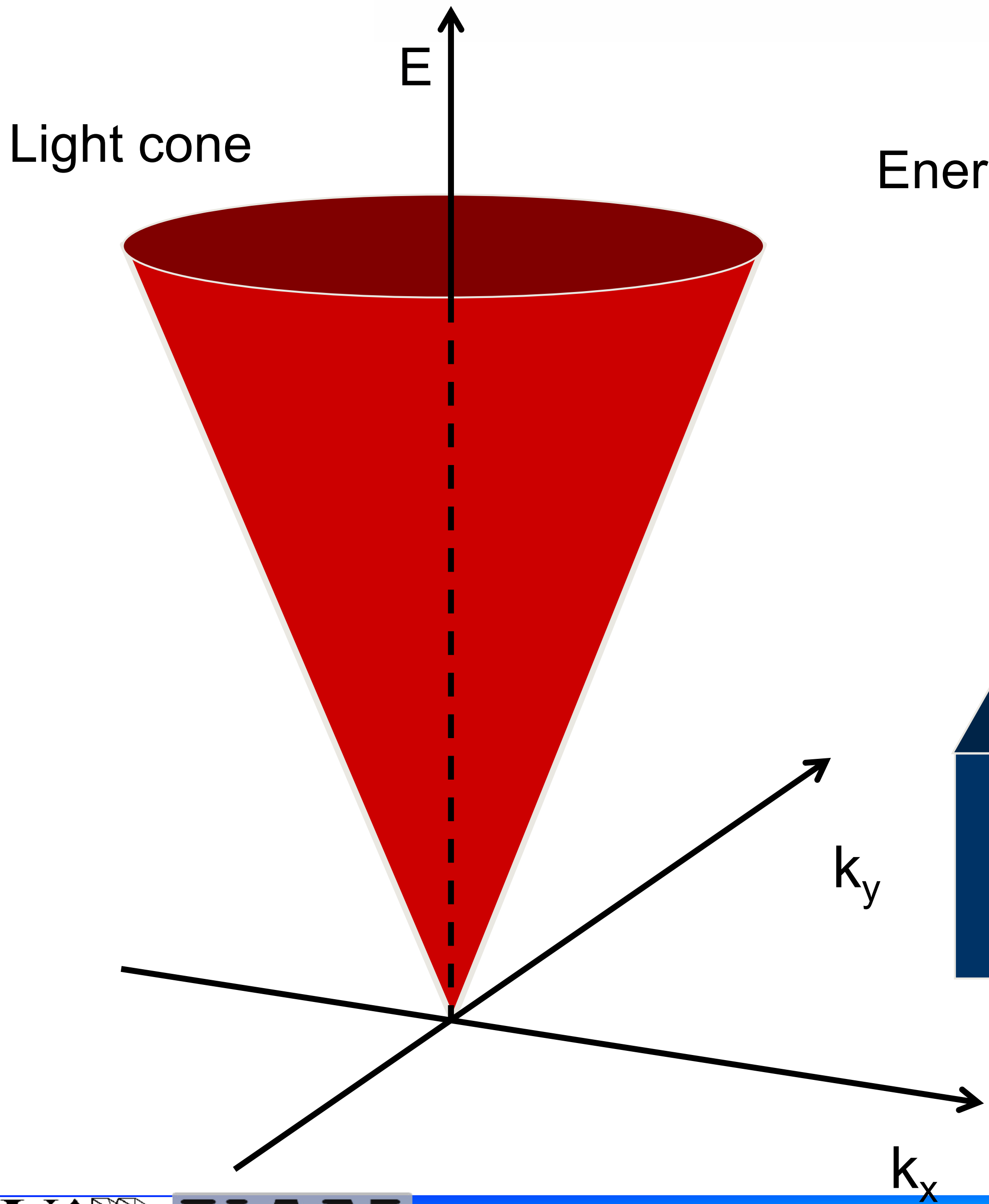
Coupled

$$M_P \approx \left(\frac{c_X^2}{M_X} + \frac{c_\gamma^2}{M\gamma}\right)^{-1}$$



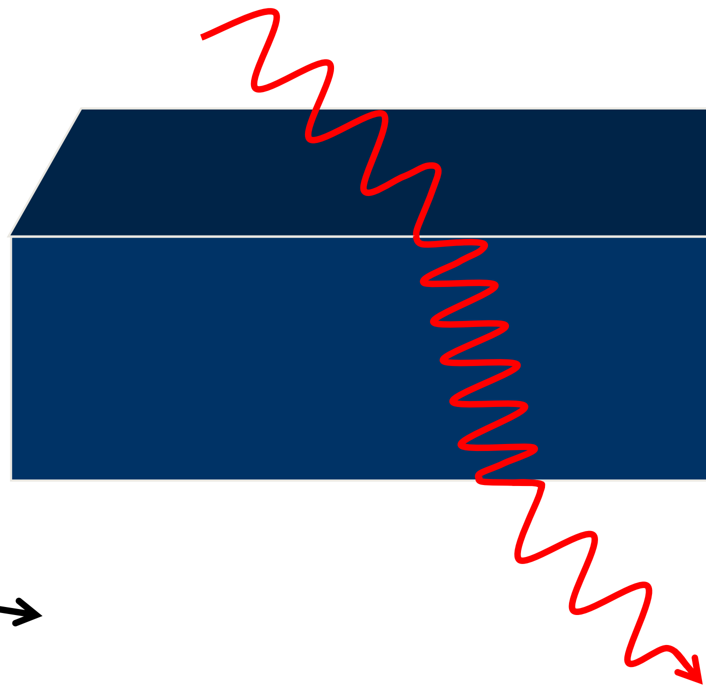
$$K_{//} = \frac{E}{\hbar c}\sin\theta$$

Semiconductor microcavities

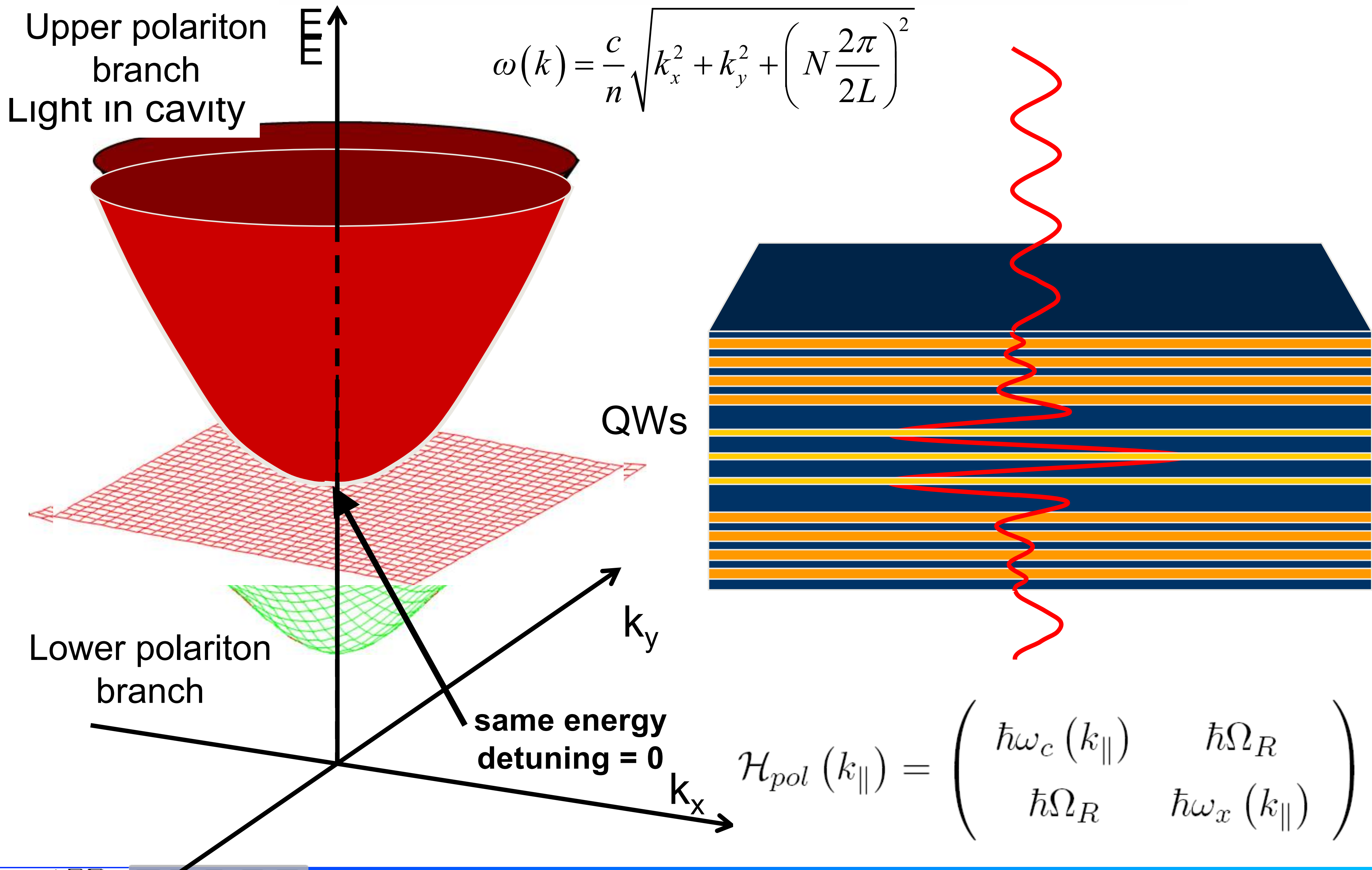


Energy dispersion for a photon in a solid

$$\omega = \frac{c}{n}\left|\vec{k}\right|$$



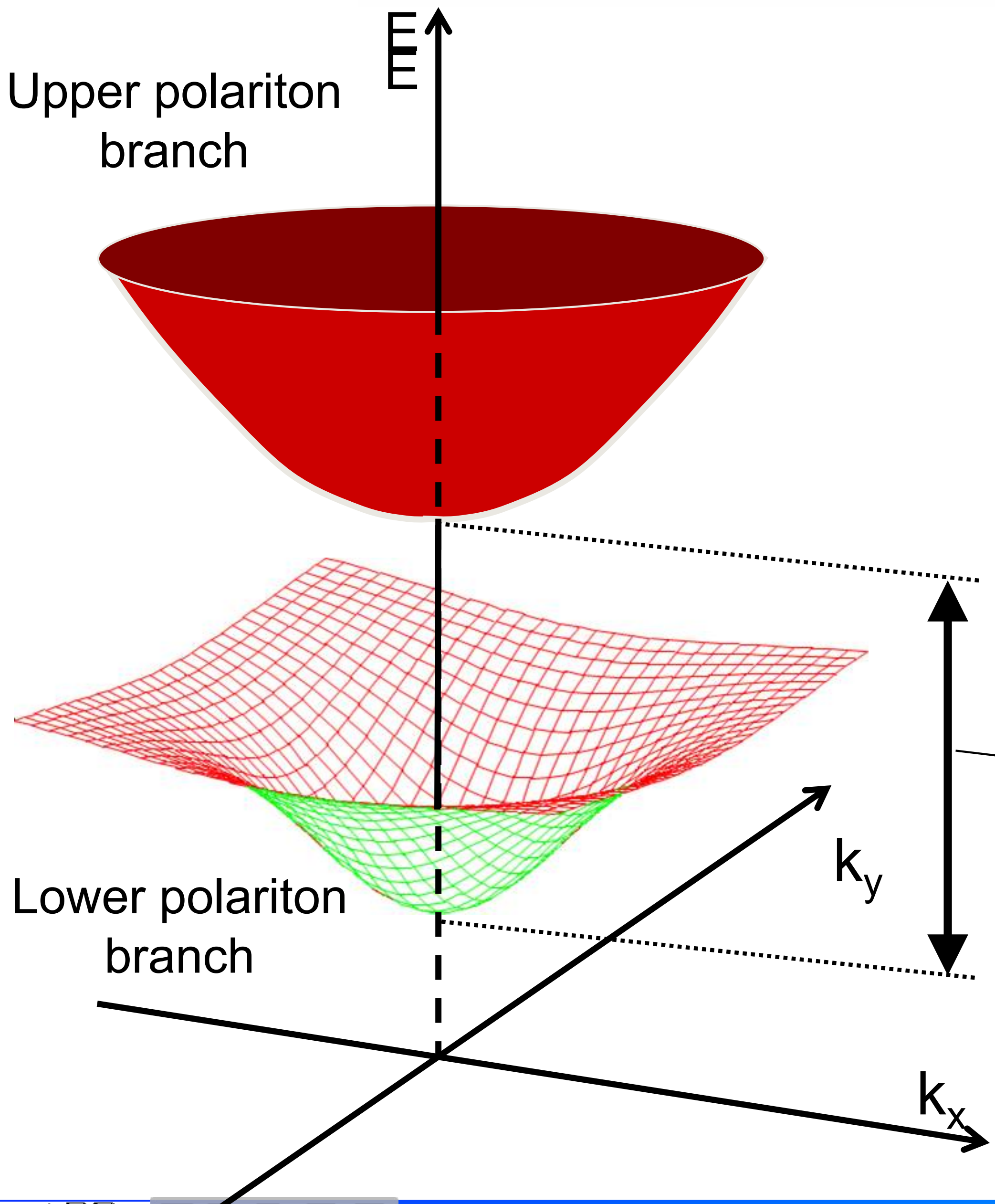
Semiconductor microcavities



$$\omega(k) = \frac{c}{n}\sqrt{k_x^2 + k_y^2 + \left(N\frac{2\pi}{2L}\right)^2}$$

$$\mathcal{H}_{pol}\left(k_{\|}\right) = \begin{pmatrix} \hbar\omega_c\left(k_{\|}\right) & \hbar\Omega_R \\ \hbar\Omega_R & \hbar\omega_x\left(k_{\|}\right) \end{pmatrix}$$

Semiconductor microcavities



Strong exciton confinement
Enhanced electromagnetic field

Strong light-matter coupling

New eigenstates
POLARITONS

$$\hat{Q}_{UPB} = c \cdot \hat{P} + d \cdot \hat{X}$$

$$\hat{Q}_{LPB} = -d \cdot \hat{P} + c \cdot \hat{X}$$

Rabi splitting

$$\Omega_R^2 = \frac{\left(1+\sqrt{R}\right)^2}{2\sqrt{R}} \frac{c\Gamma_0}{n_{cav} L_{eff}}$$

Low polariton mass

"*S*" shaped dispersion

Momentum trap

Polaritons

New eigenstates
POLARITONS

$$\hat{Q}_{UPB} = c \cdot \hat{P} + d \cdot \hat{X}$$

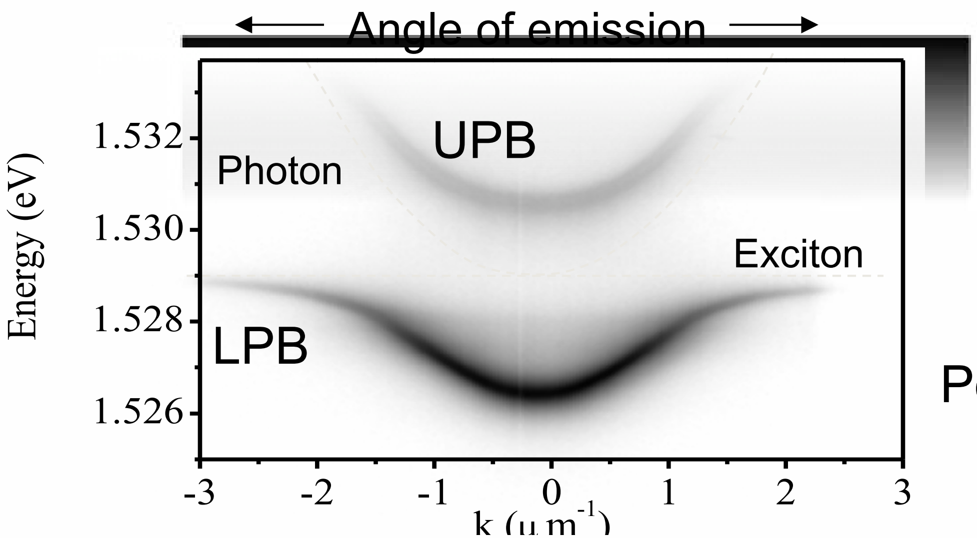
$$\hat{Q}'_{LPB} = -d \cdot \hat{P} + c \cdot \hat{X}$$

Polaritons

New eigenstates
POLARITONS

$$\hat{Q}_{UPB} = c \cdot \hat{P} + d \cdot \hat{X}$$

$$\hat{Q}_{LPB} = -d \cdot \hat{P} + c \cdot \hat{X}$$



Polariton lifetime: 2-8 ps (at k = 0)

PL experiment

Polaritons

New eigenstates
POLARITONS

$$\hat{Q}_{UPB} = c \cdot \hat{P} + d \cdot \hat{X}$$

$$\hat{Q}_{LPB} = -d \cdot \hat{P} + c \cdot \hat{X}$$

composite BOSONS

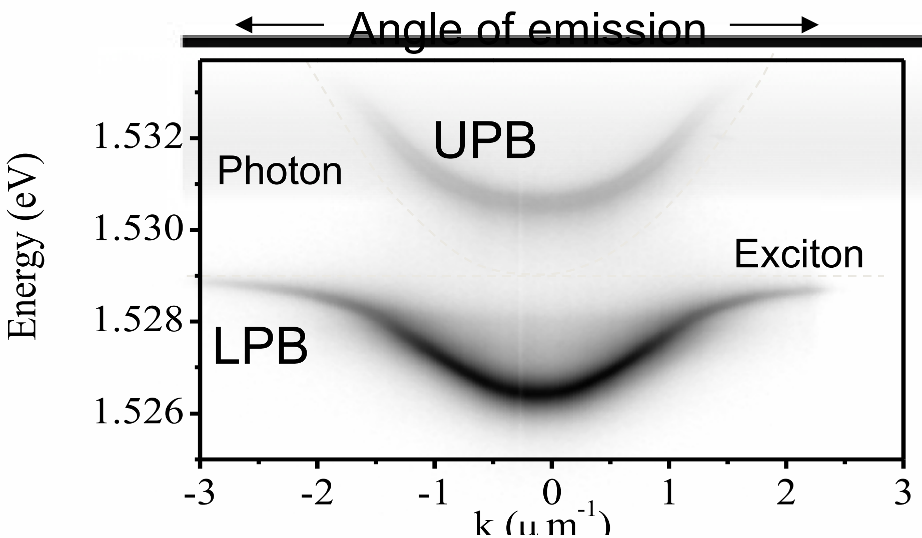
photonic content ⟷ very low mass

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

High condensation temperature

10 K -300 K

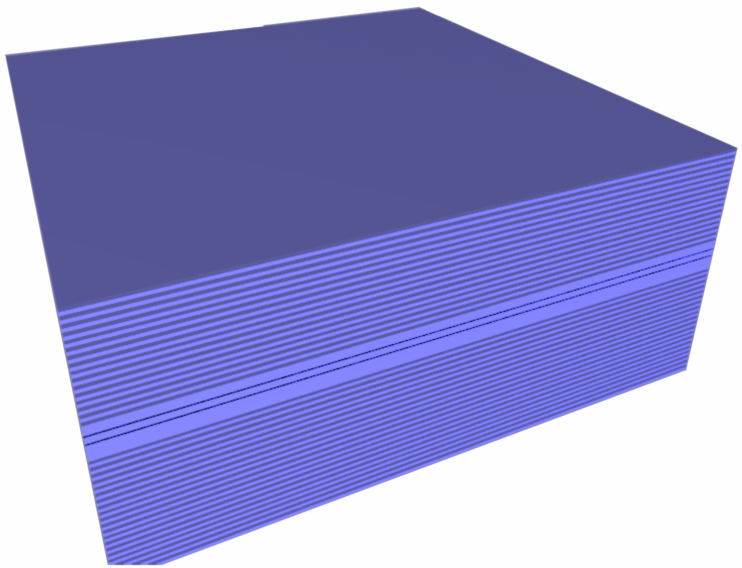
species	atomic gases	polaritons
mass m^*/m_0	10^4	10^{-5}
Bohr radius	10^{-1} Å	10^2 Å
λ_T at T_c	10^3 Å	10^4 Å
T_c	$< 1\mu$K	$10 - 300$K

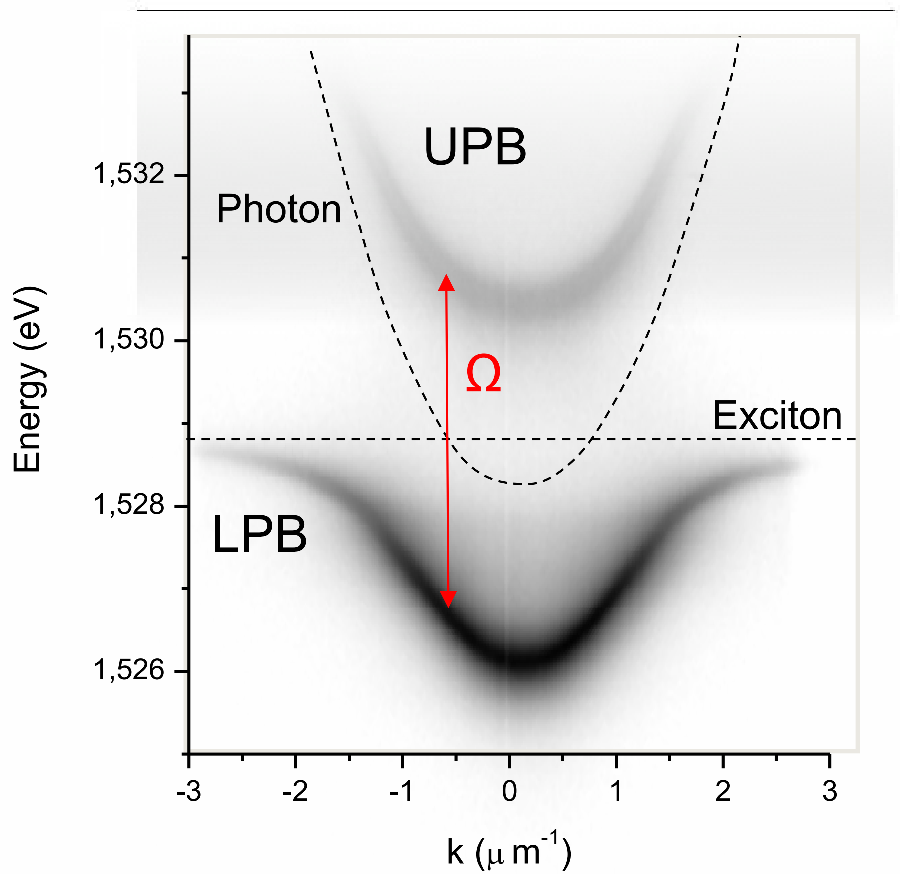


Polariton lifetime: 2-8 ps (at k = 0)

PL experiment

Polaritons





- Low mass (10^{-5} m_e) → low density of states
- Vacuum Rabi splitting: 3 meV < Ω < 30 meV (GaAs, CdTe)
- Strong non-linearities (χ^3) → polariton OPO

$$\lambda = \left(\frac{2\pi \hbar^2}{m k_B T} \right)^{\frac{1}{2}}$$

↓

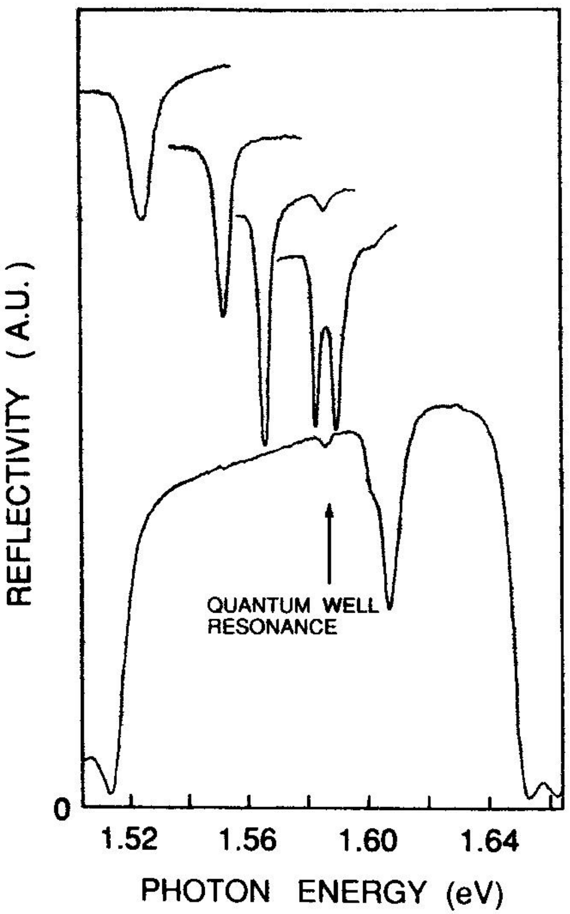
Ideal system to study interacting BEC

High condensation temperatures (10 K -300 K)

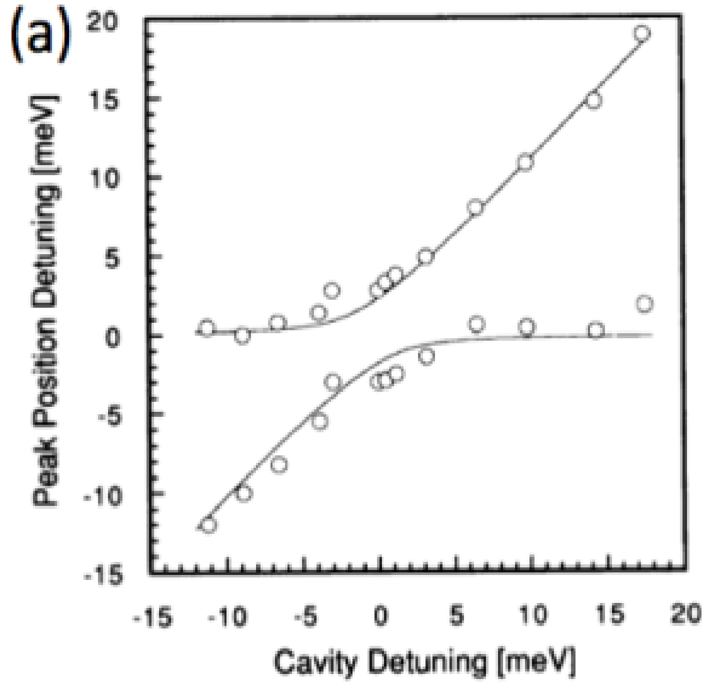
Some key studies

First report polaritons in microcavities

C. Weisbuch, *et al*., Phys. Rev. Lett. **69**, 3314 (1992).



Changing the detuning

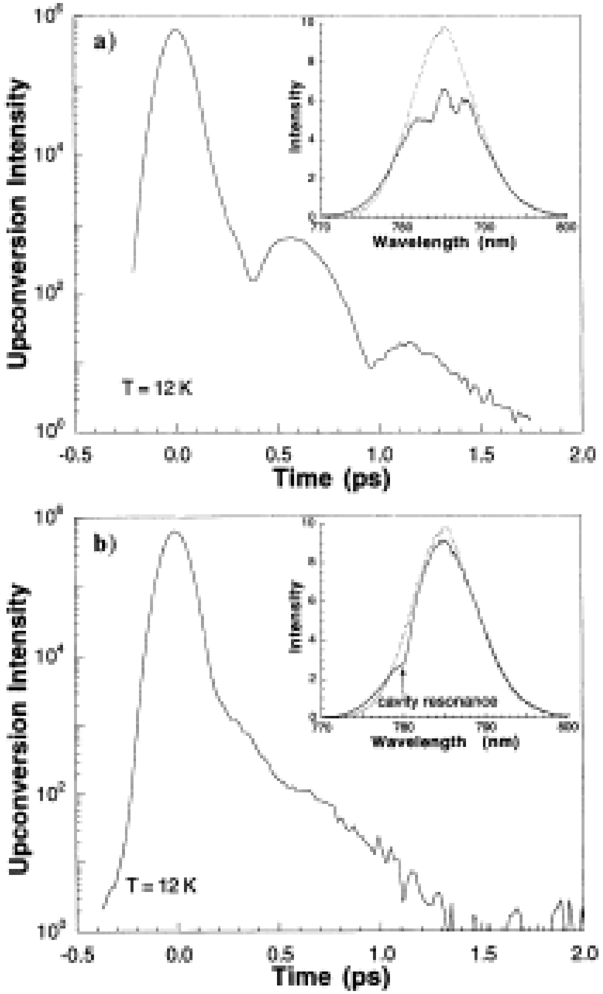


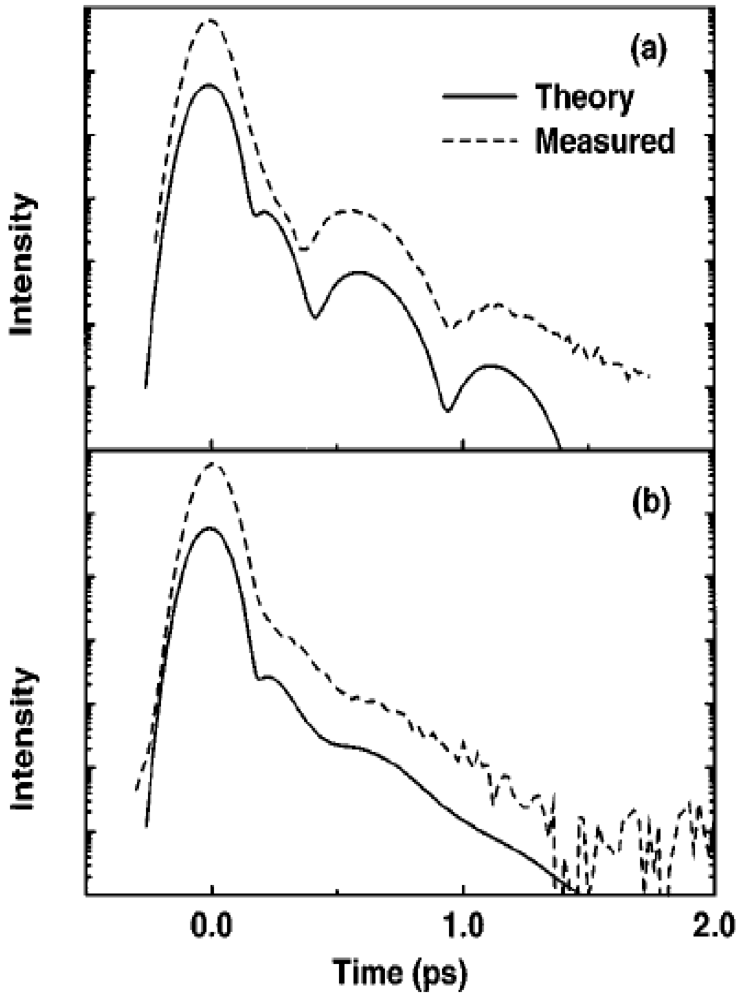
Some key studies

Vacuum Rabi oscillations

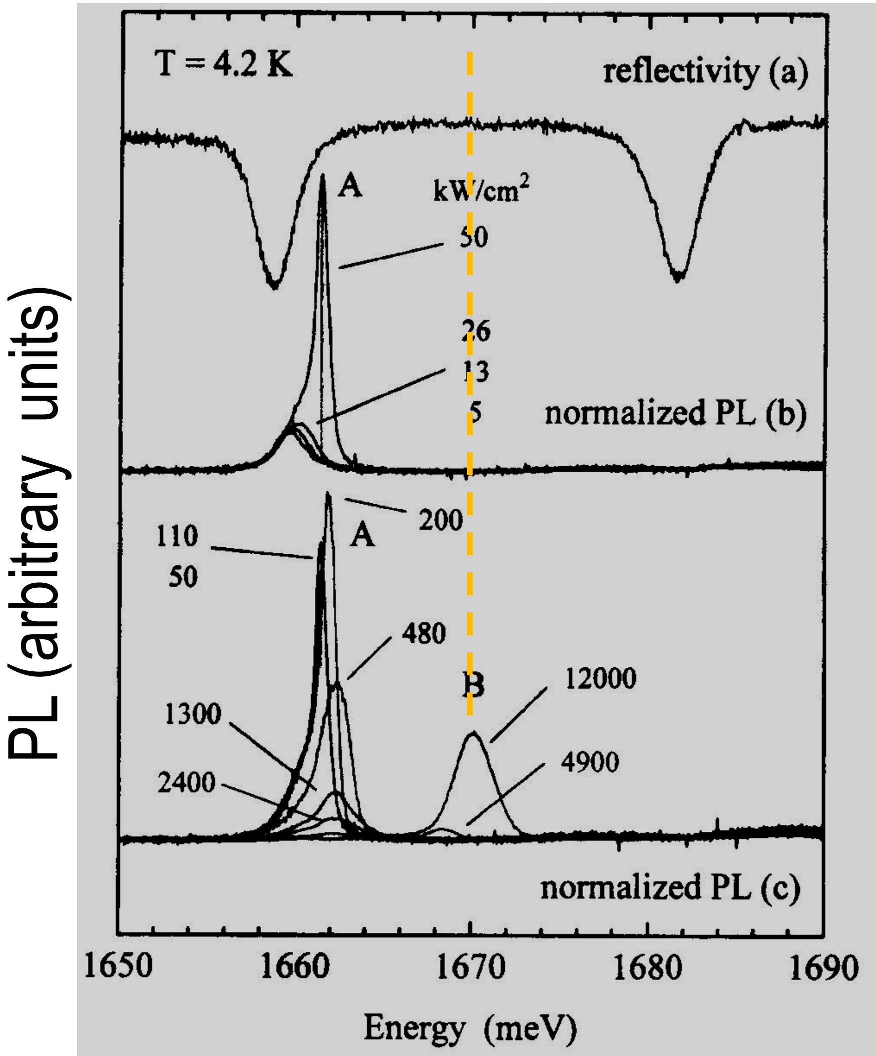
T. B. Norris, *et al.*, Phys. Rev. B **50**, 14663 (1994).

V. Savona & C. Weisbuch, Phys. Rev. B **54**, 10835 (1996)





Some key studies



PL in a non-linear regime

L.S. Dang et al., Phys. Rev. Lett. **81**, 3920 (1998)

➲Line narrowing

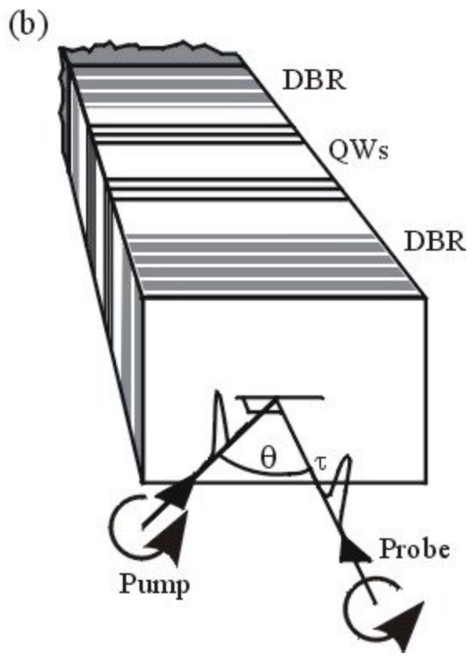
➲Non-linear intensity increase

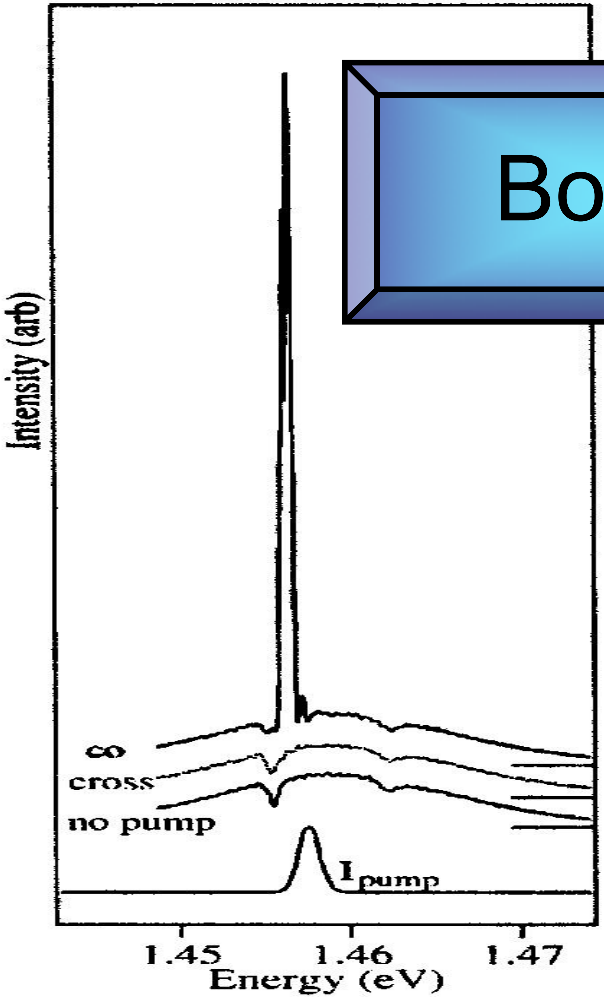
Some key studies

Amplification by stimulated polariton scattering

P.G. Savvidis et al. Phys. Rev. Lett. **84**, 1547 (2000)

Reflectivity experiments:
"Pump & probe"

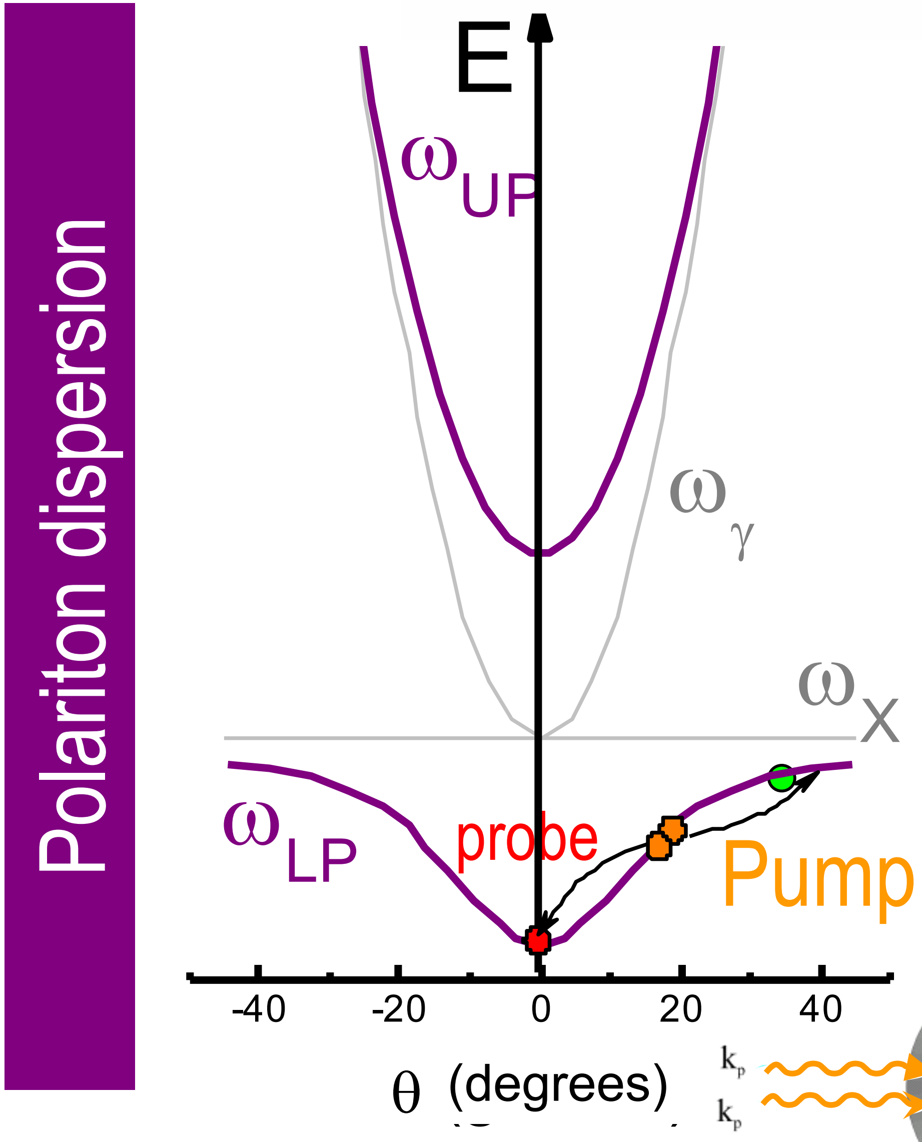


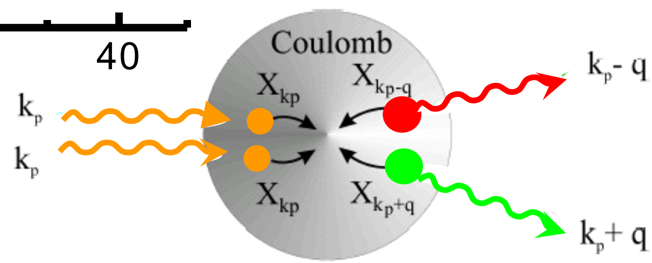


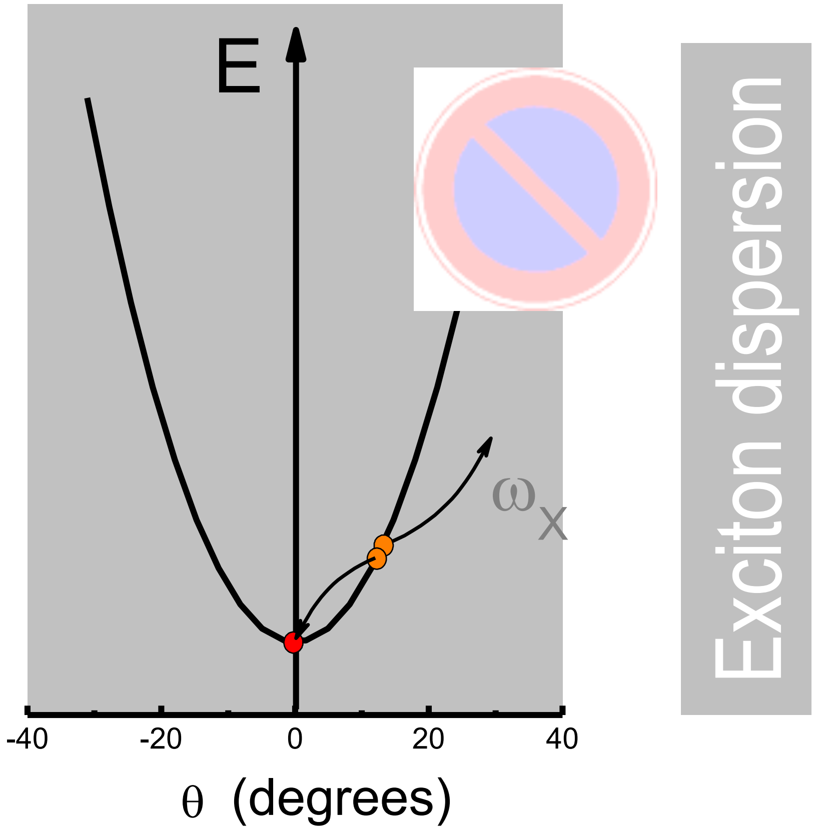
Bosons

Gain 700%

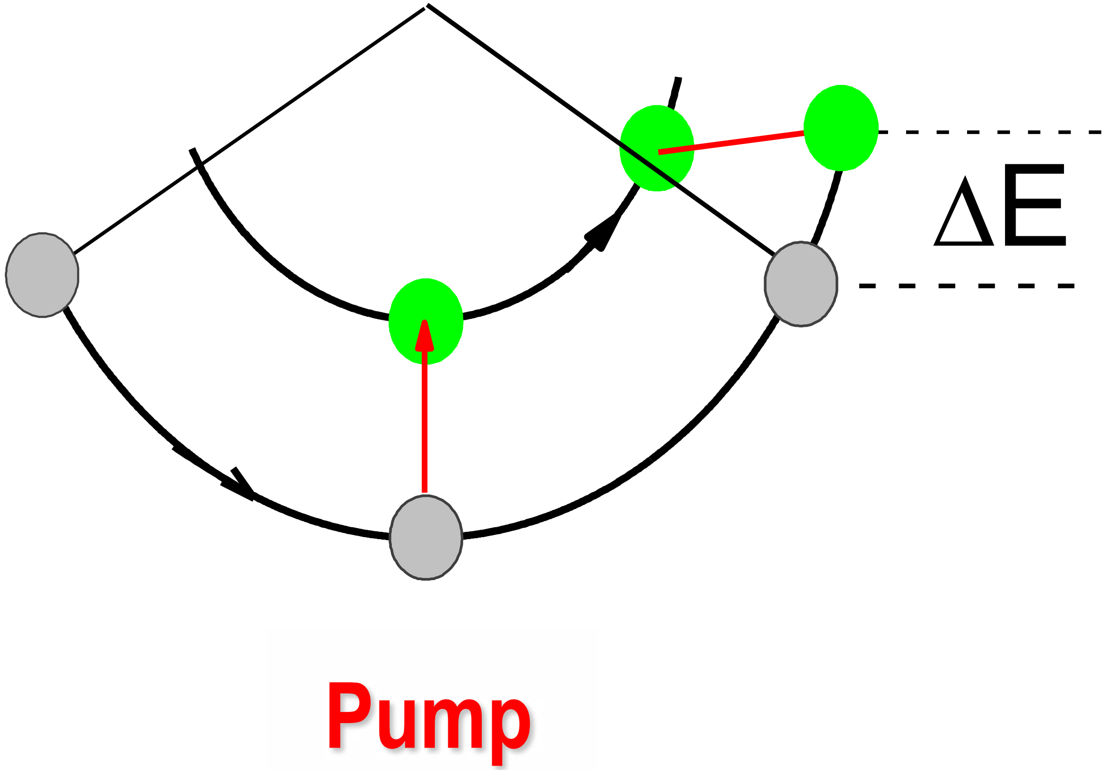
Stimulated Scattering

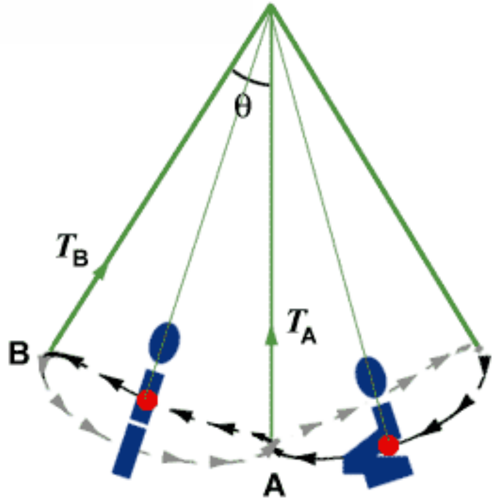




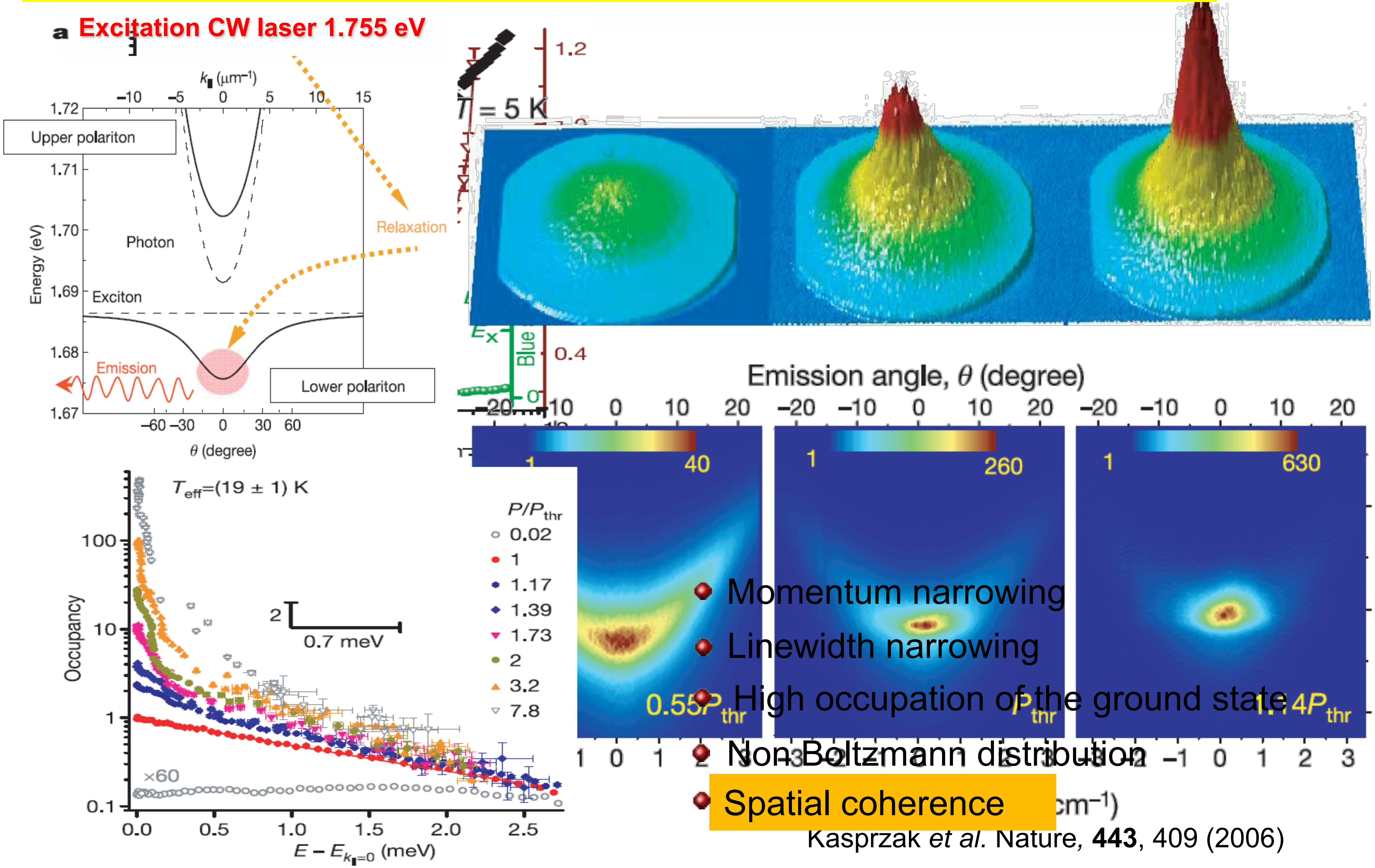


Parametric Oscillator





Some key studies BEC of polaritons

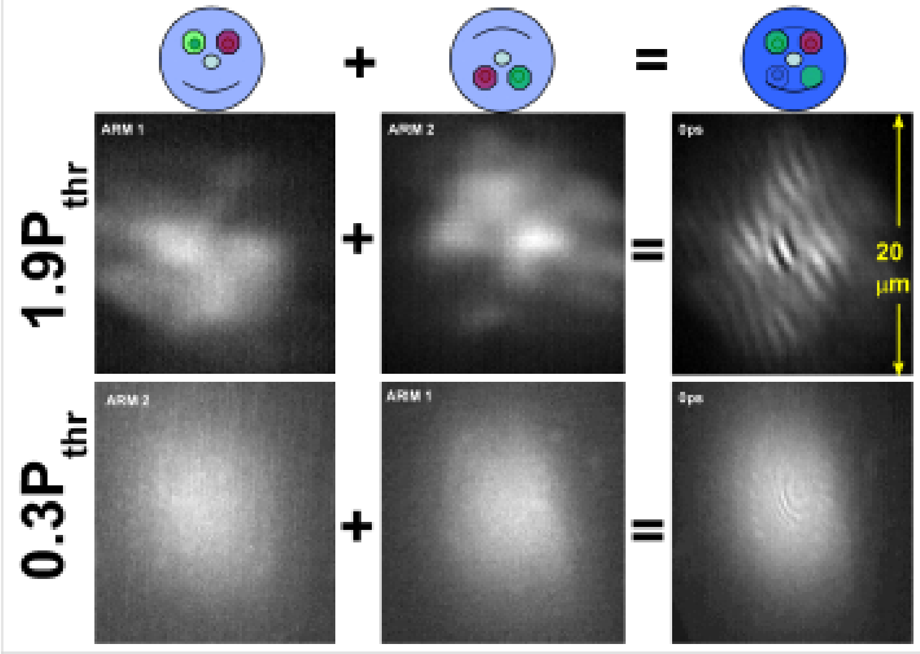


- Momentum narrowing
- Linewidth narrowing
- High occupation of the ground state
- Non-Boltzmann distribution
- Spatial coherence

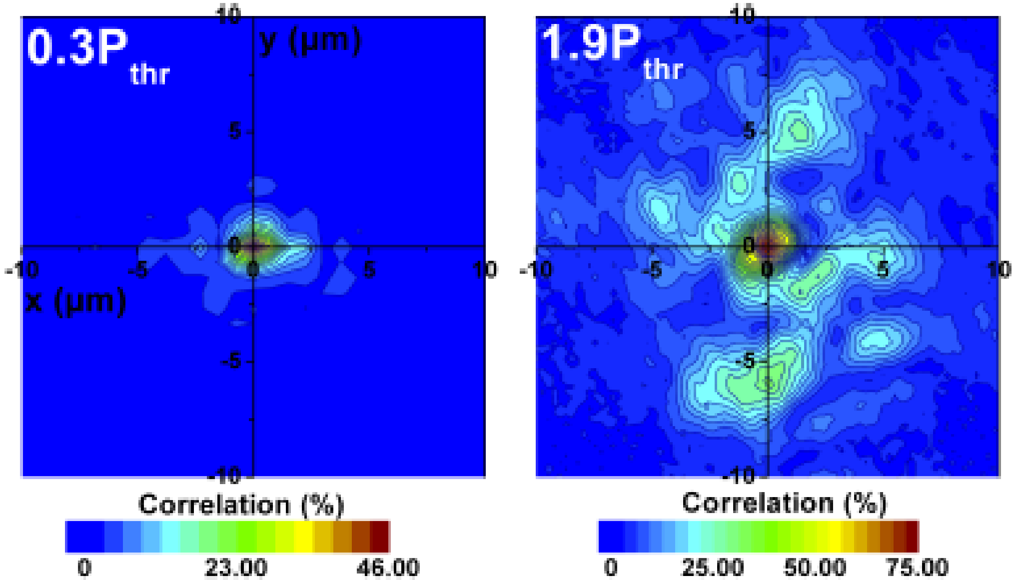
Kasprzak *et al.* Nature, **443**, 409 (2006)

Some key studies BEC of polaritons

Spatial coherence



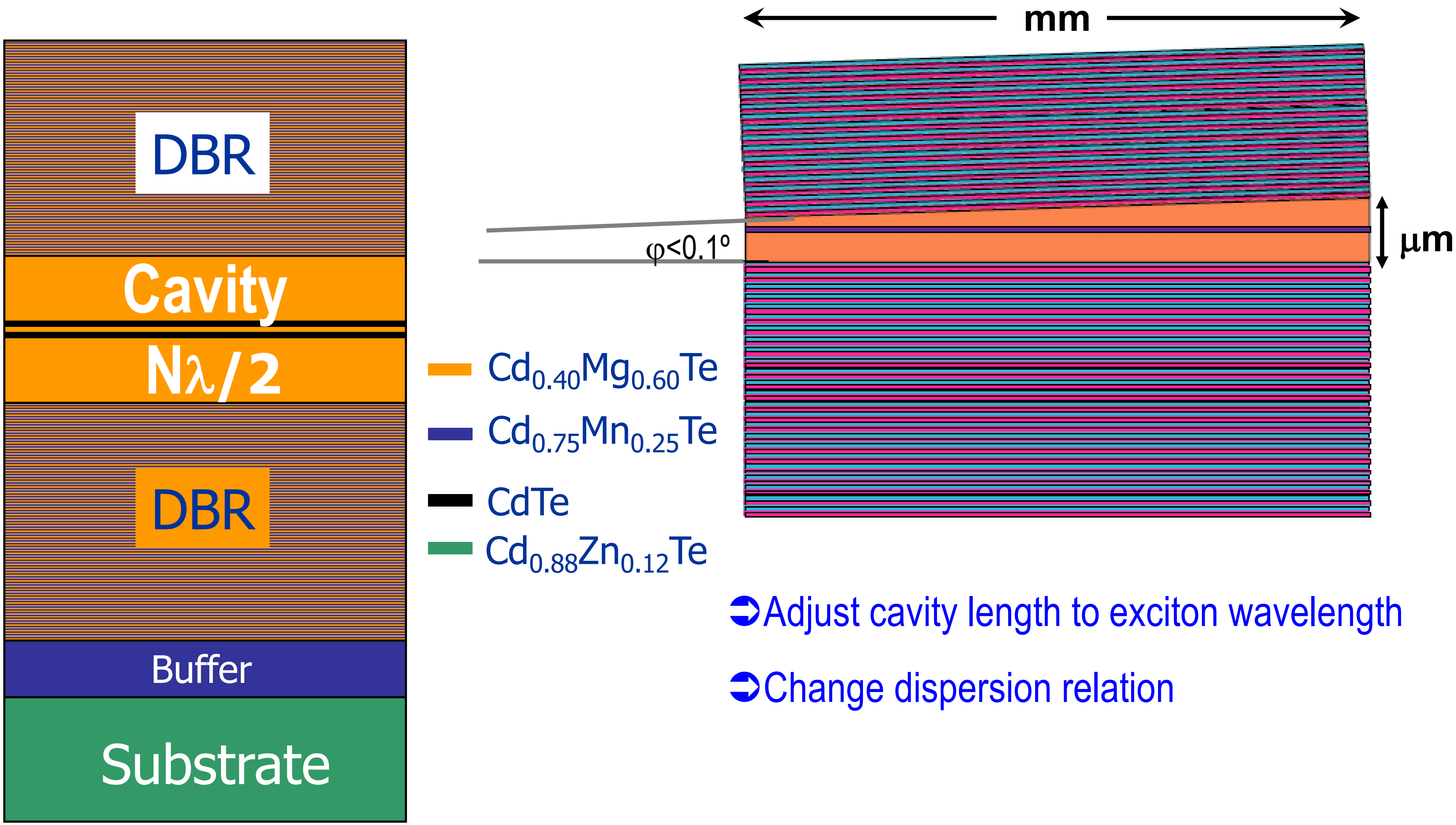
The principle of spatial correlation mapping using a Michelson interferometer



Maps of the contrast of the spatial correlations

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

Key samples for condensation



➲Adjust cavity length to exciton wavelength

➲Change dispersion relation

Why CdTe?

- Bosonic limit

$$\pi a_B^2 n_X << 1$$

a_B (CdTe) = 30 Å	<	a_B(GaAs)= 150 Å
n_X (CdTe) ~ 2 x10^{11} cm^{-2}	>	n_X (GaAs) ~ 1x10^{10} cm^{-2}

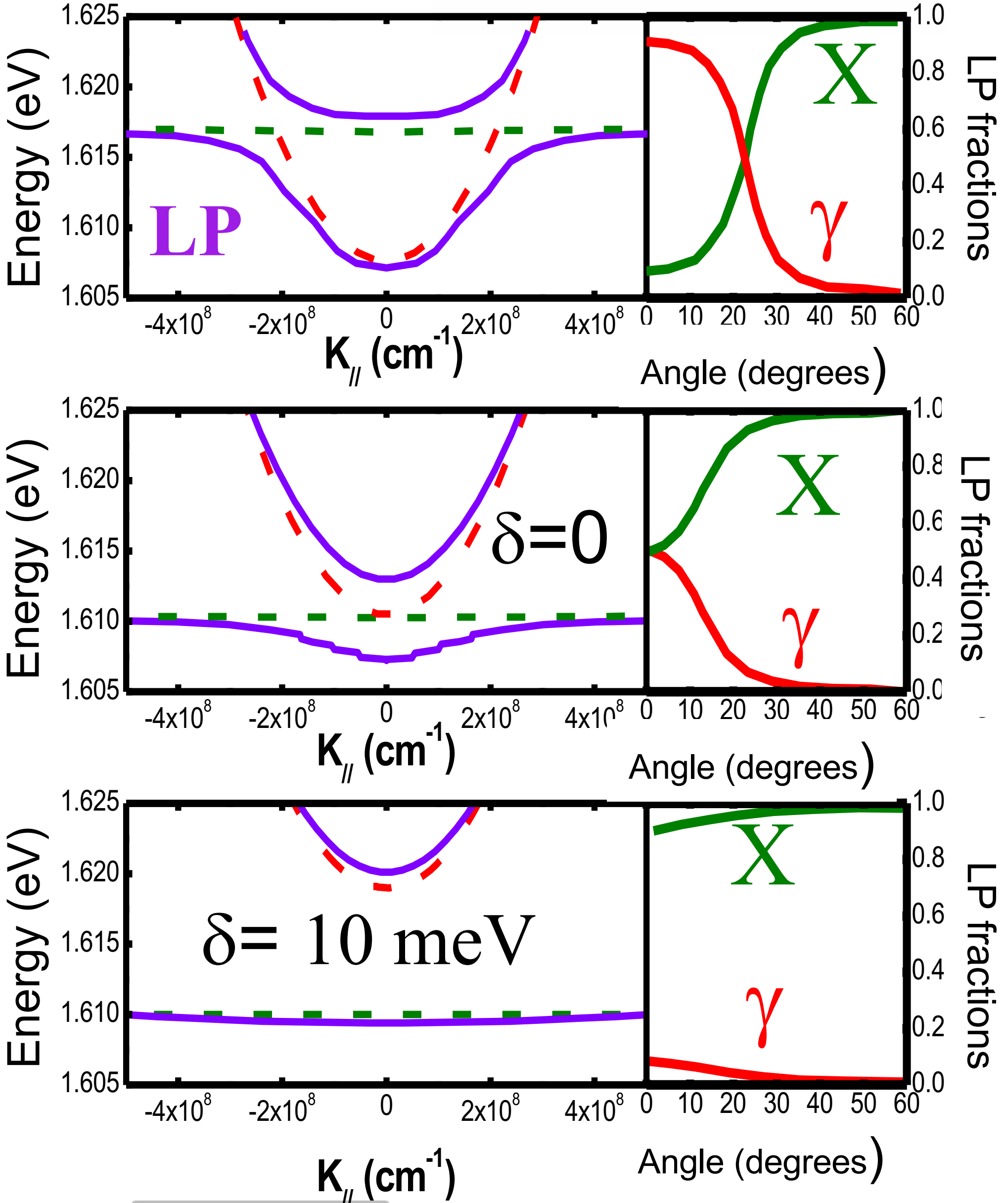
- Binding energies (polaritonic effects)

E_B(CdTe) = 25 meV	>	E_B(GaAs)= 10 meV
f_x (CdTe) = 2.3x 10^{13} cm^{-2}	>	f_x (GaAs) = 0.6x 10^{13} cm^{-2}

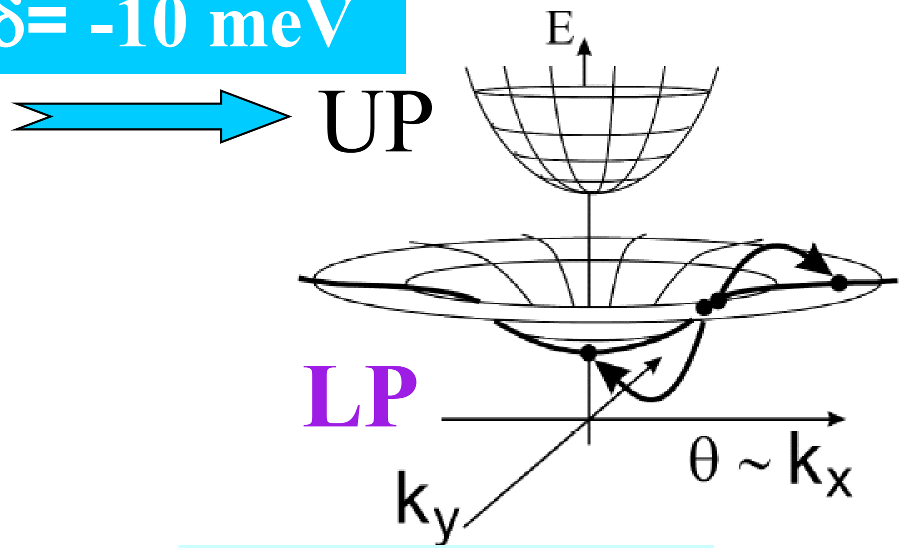
- High temperatures

- Epitaxial fabrication

Role of detuning (I)



δ= -10 meV



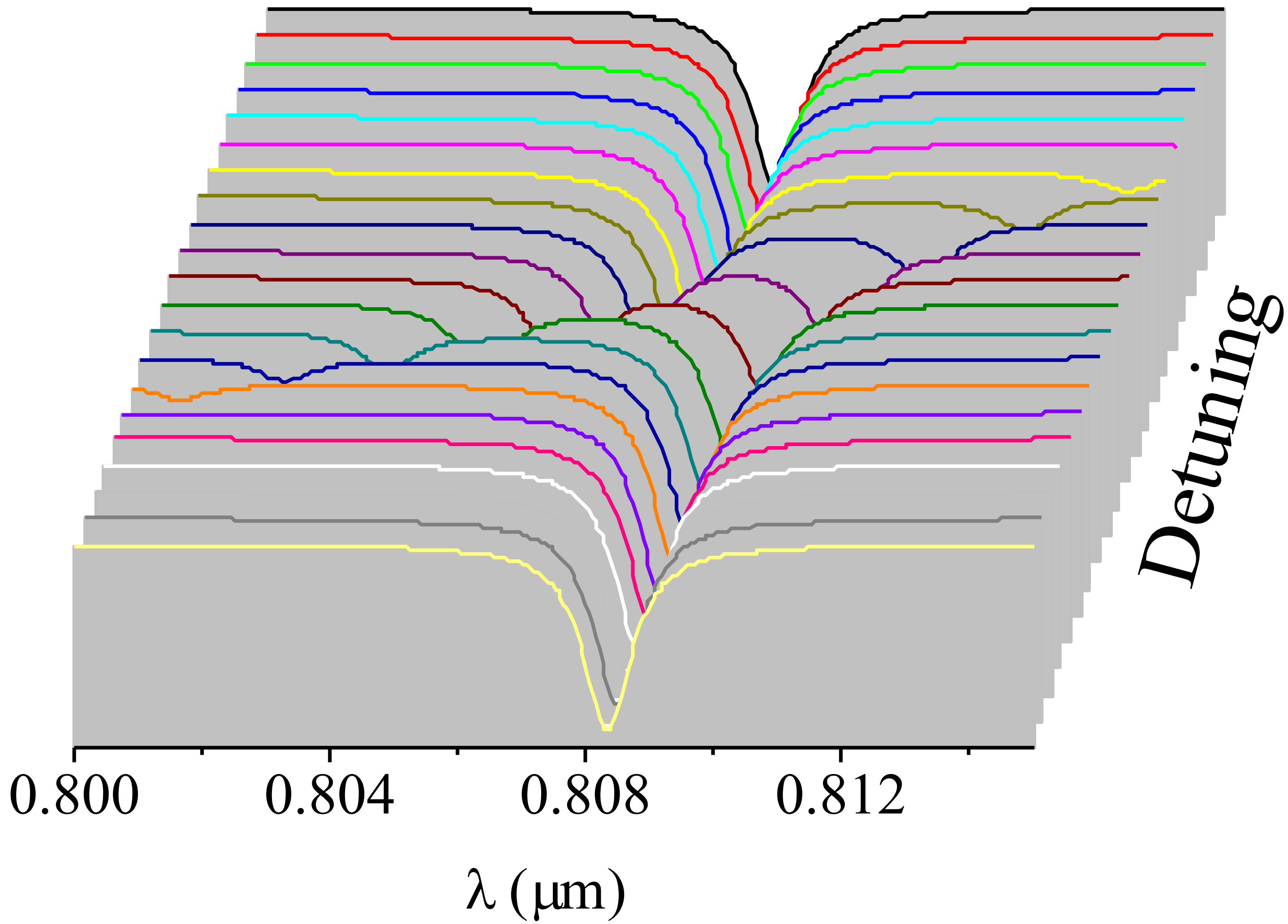
Polariton trap

Depth ⇔ Ω

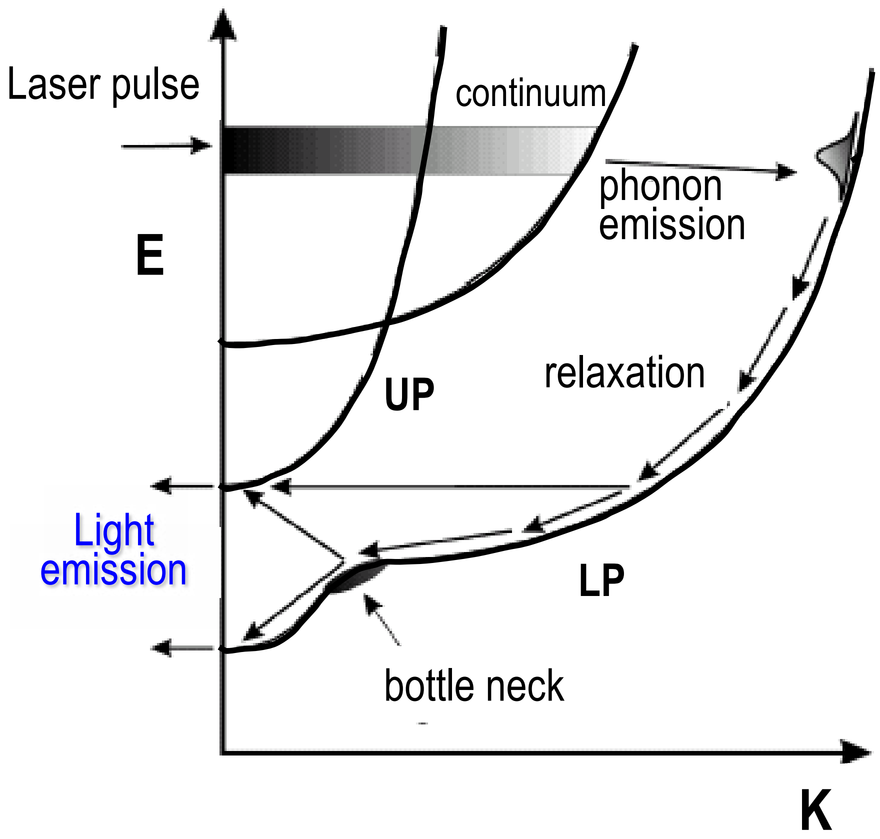
Extension ⇔ $\Delta k = \frac{\sqrt{3\varepsilon\omega_X\Omega}}{c}$

Density of states ↓

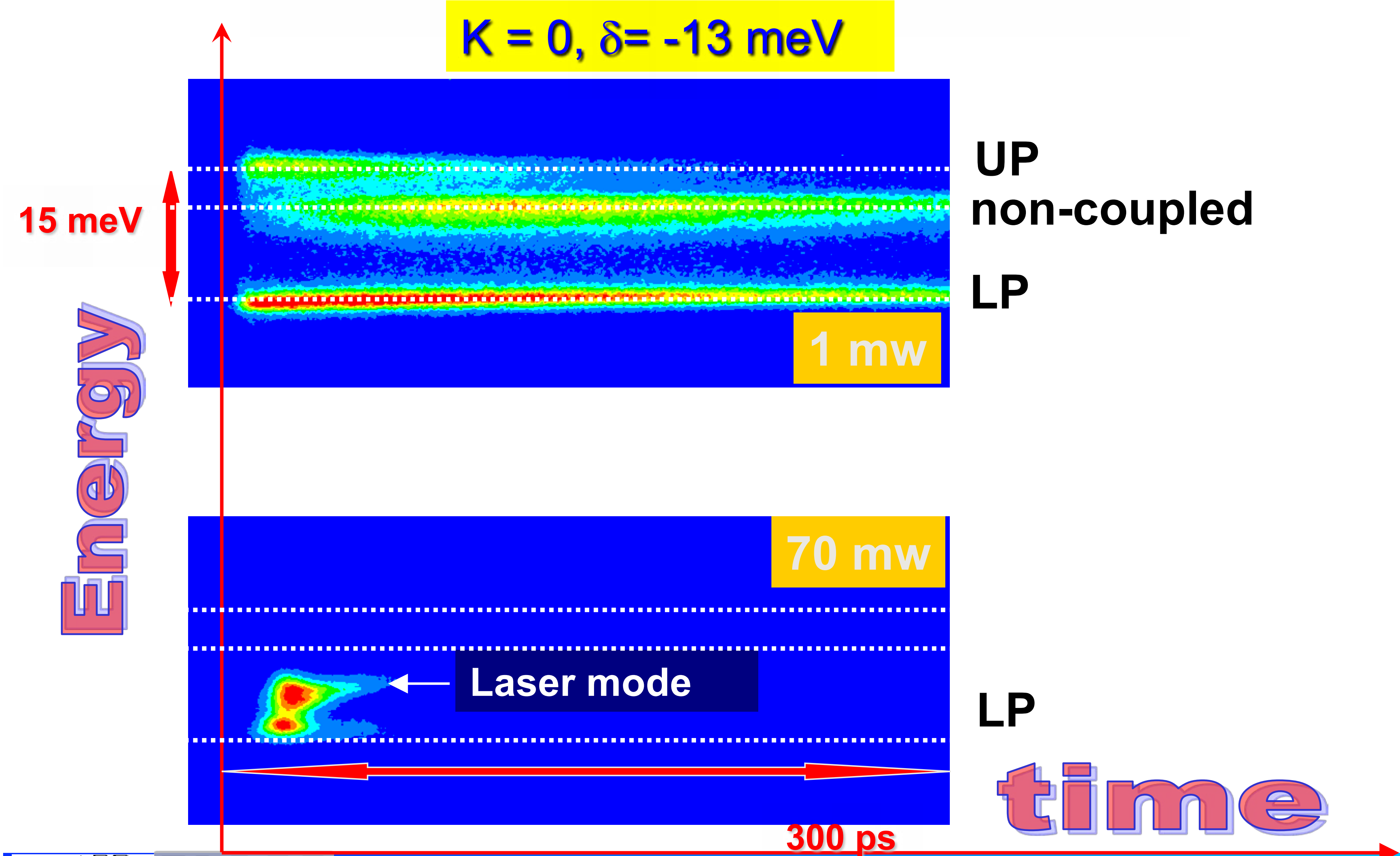
Role of detuning (II)



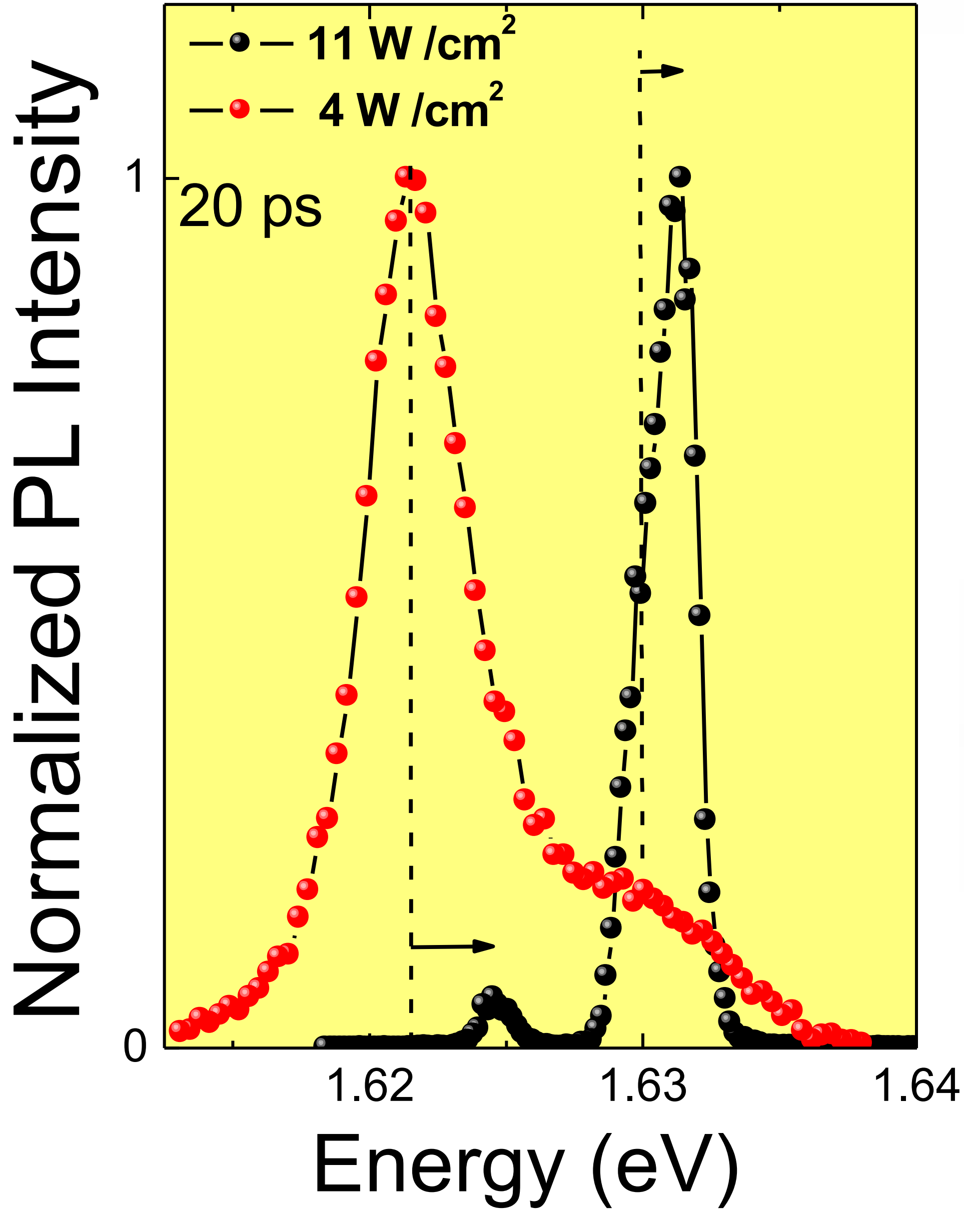
K~0


Laser pulse
continuum
phonon
emission
E
relaxation
UP
Light
emission
LP
bottle neck
K

Non-linear regime (detail)



Non-linear regime (spectra)

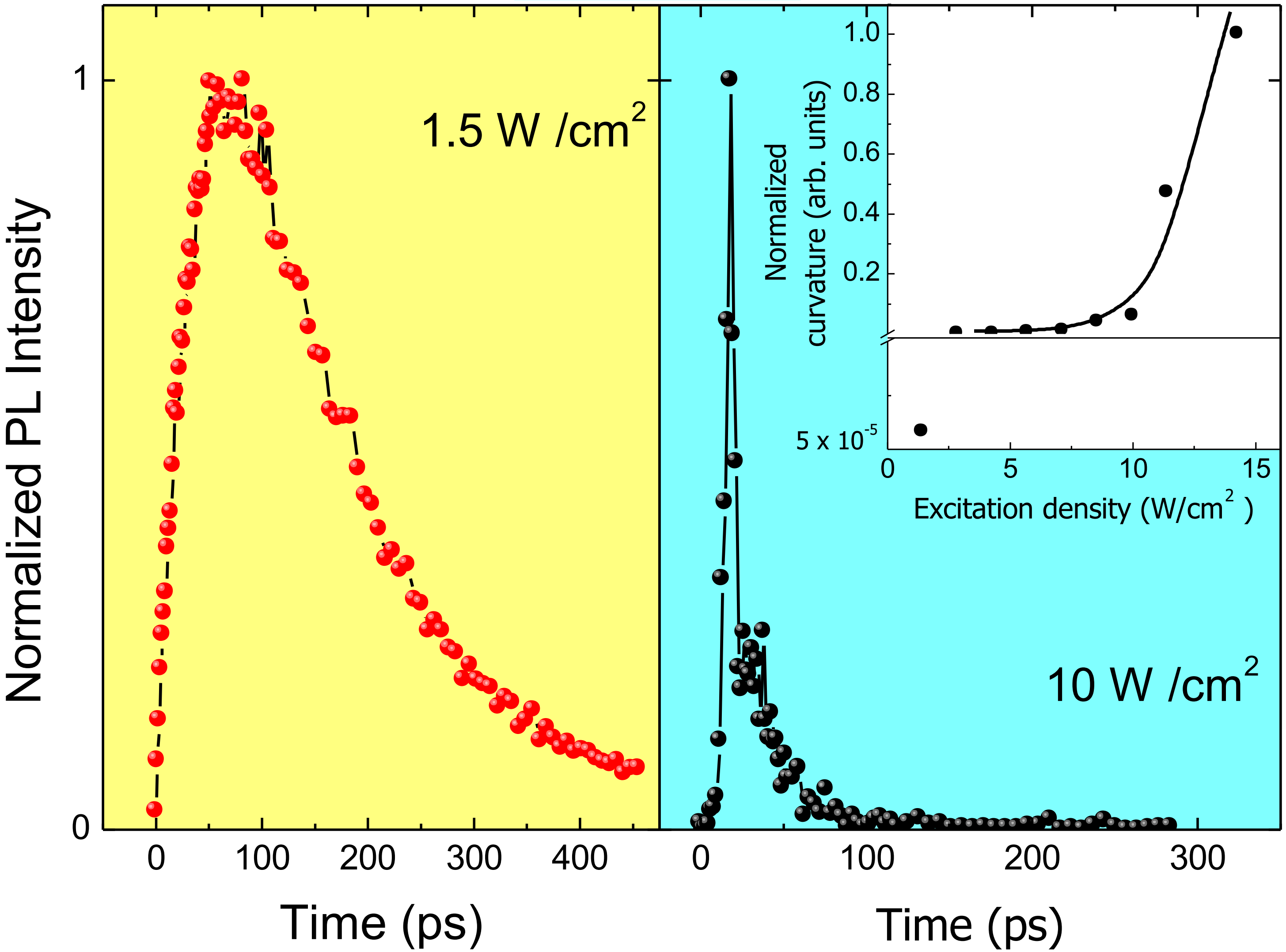


4 K

- ➲ Blue shift
- ➲ Line narrowing

Non-linear regime (dynamics 1)

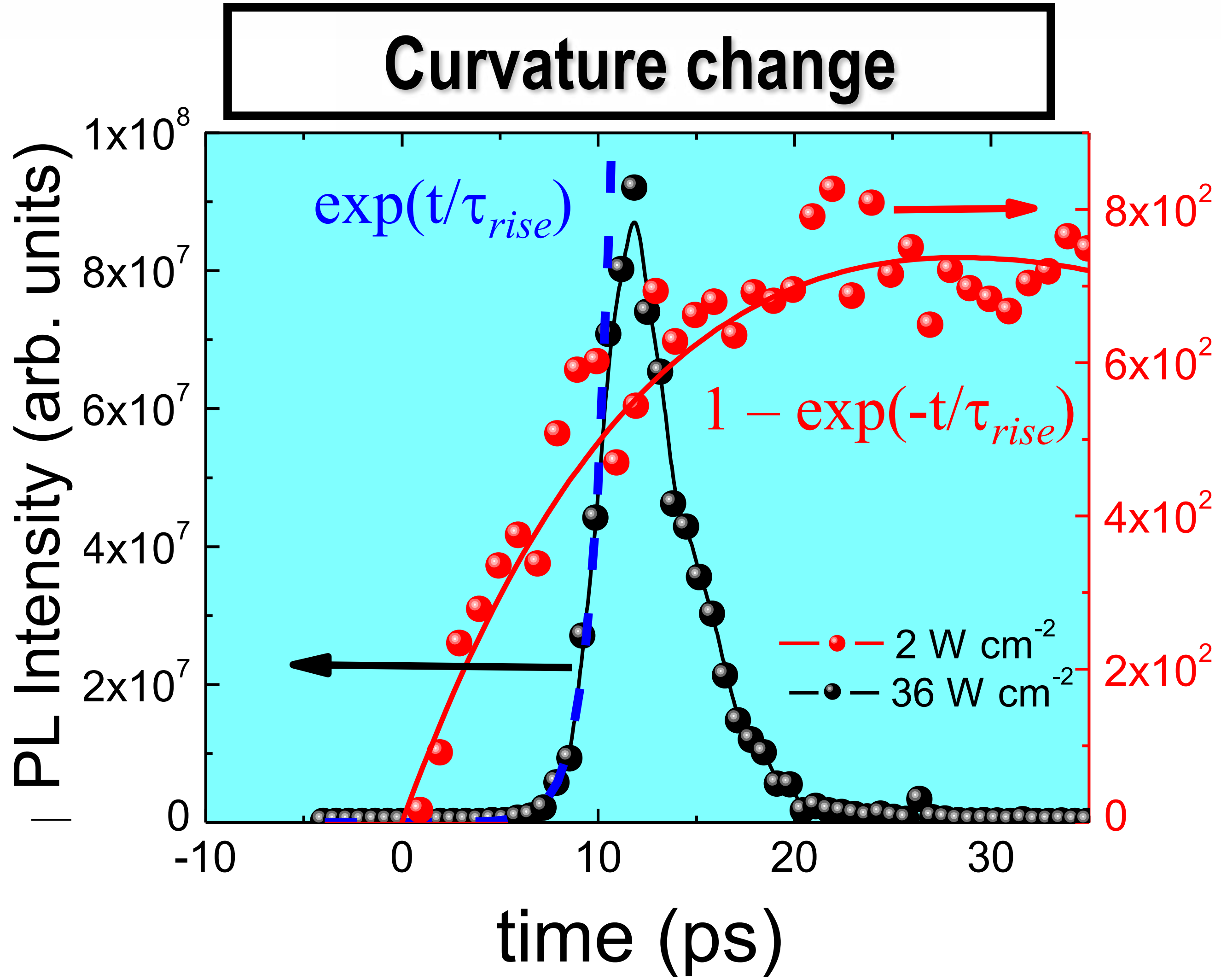
4 K



Initial curvature change

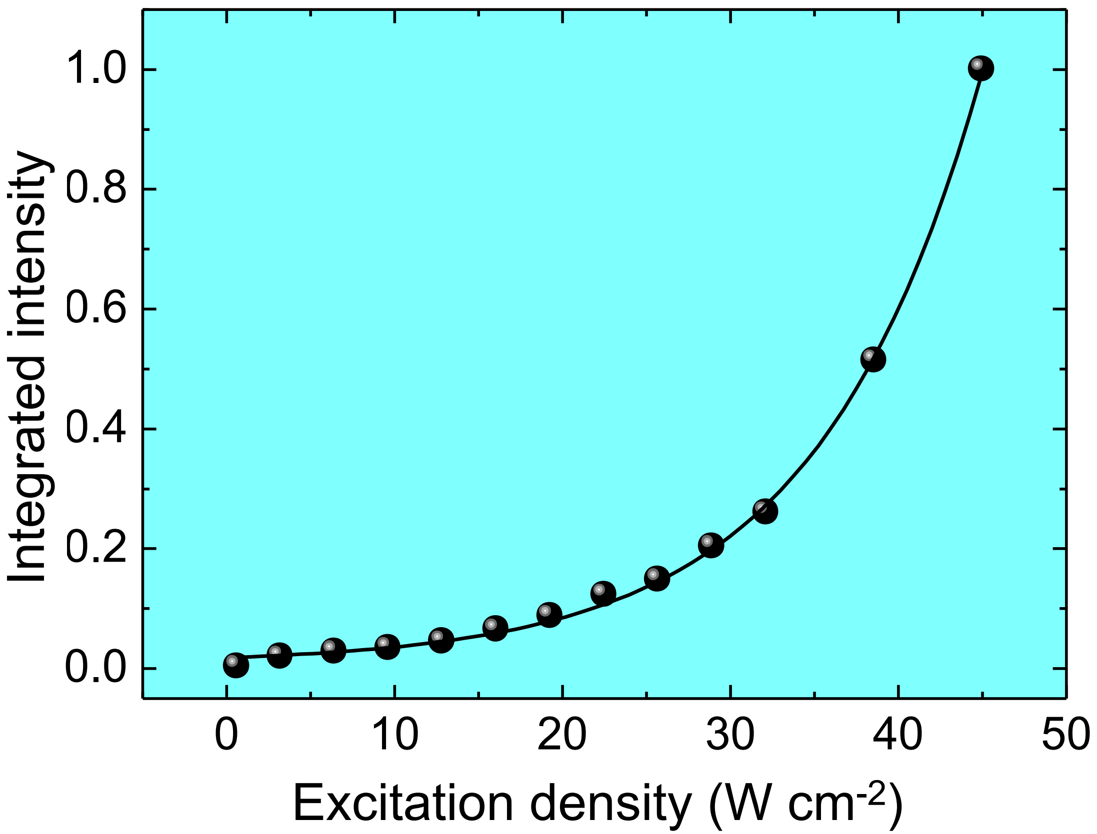
acceleration

Non-linear regime (dynamics 2)



Stimulated Scattering, exponential increase

Non-linear regime (intensities)



Stimulated Scattering

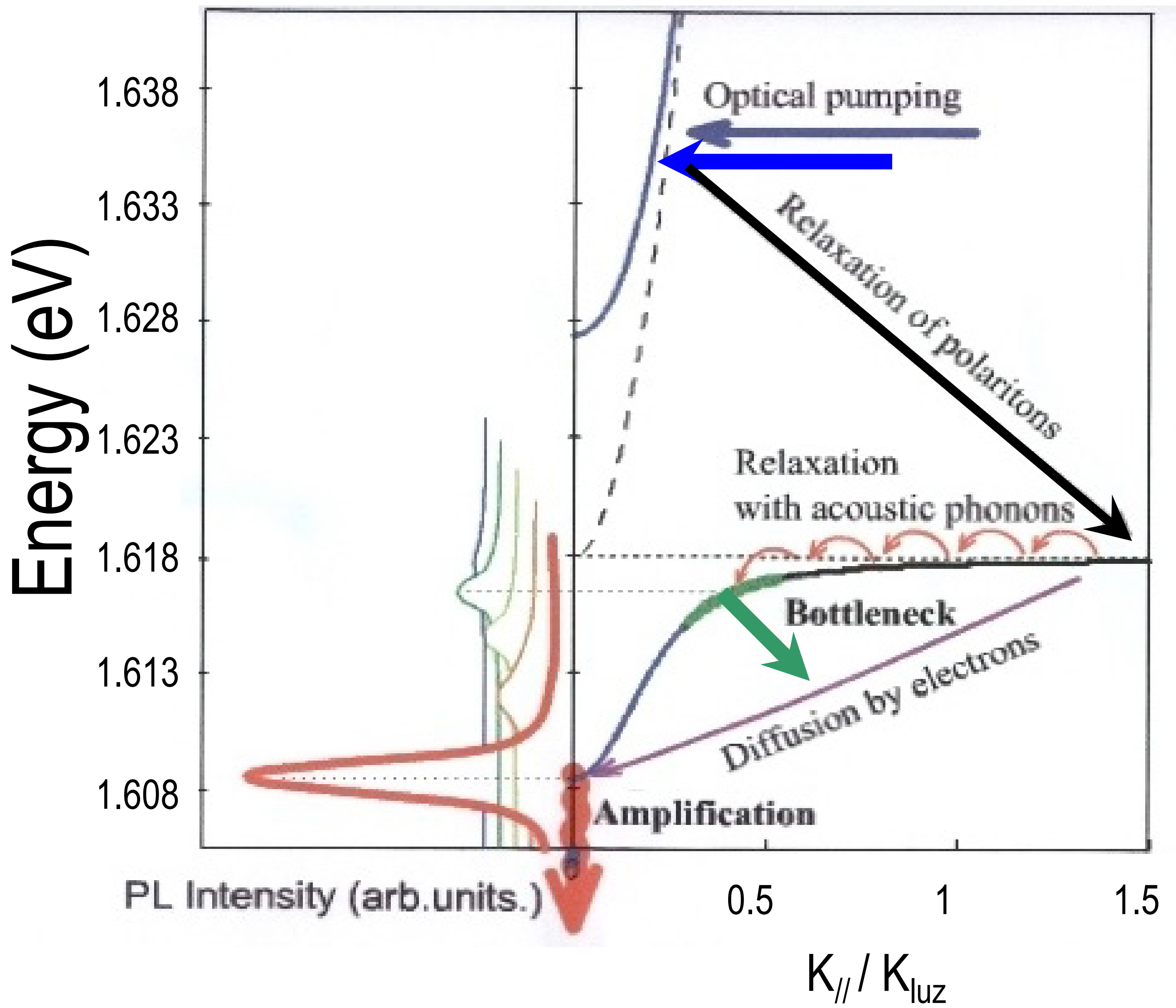
$$N_{final} \propto (1 + N_0) e^{I_{pump}}$$

Characteristics of non-linear regime

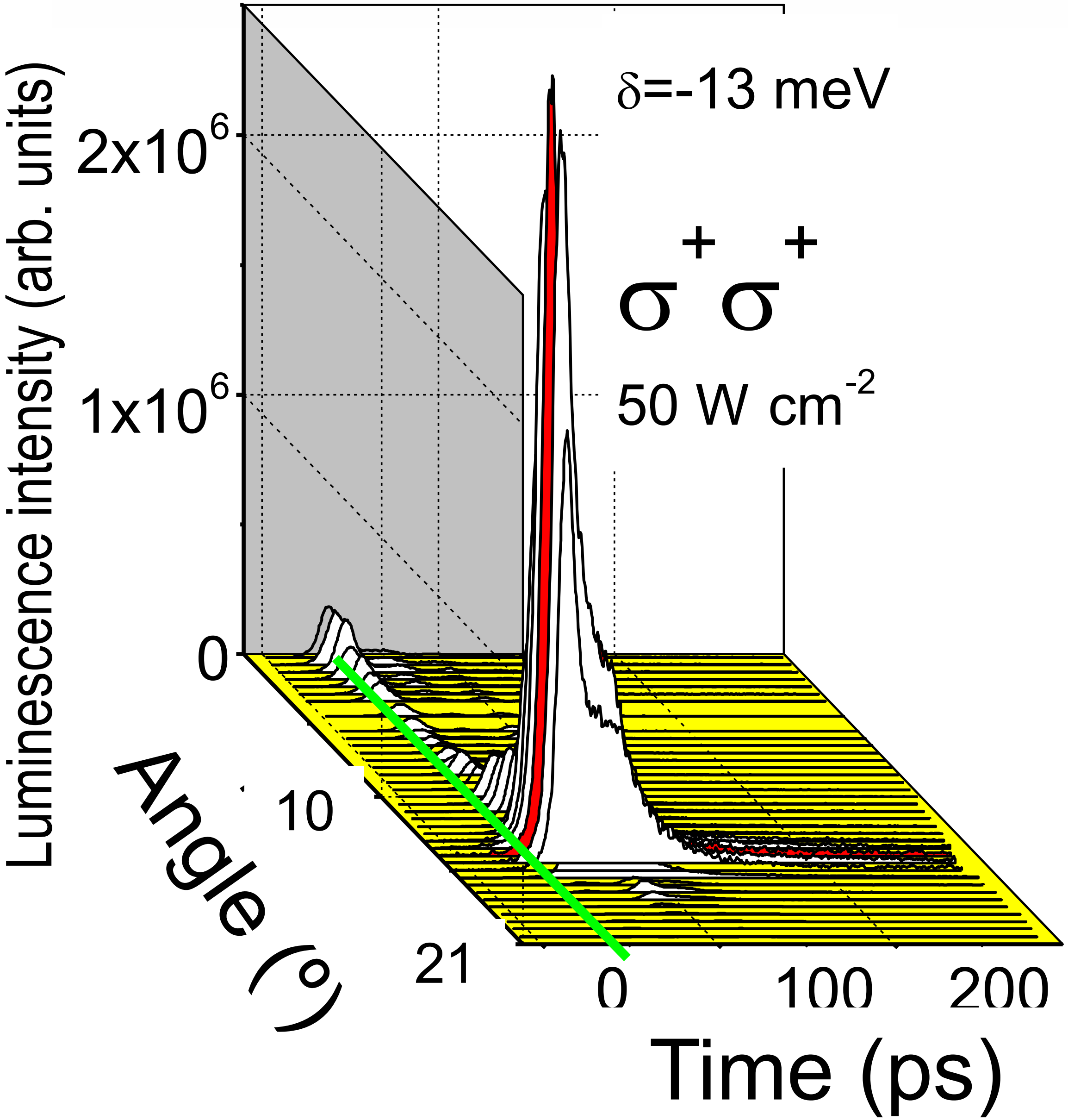
- Narrowing and shift of emission
- Acceleration of the dynamics
- Change in initial curvature
- Exponential growth

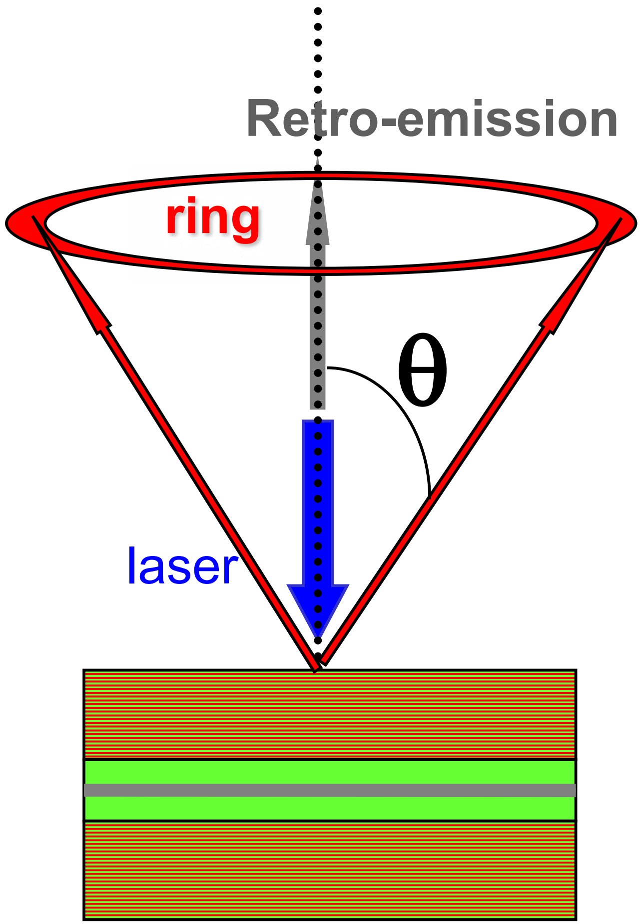
K>0

Relaxation along dispersion relation

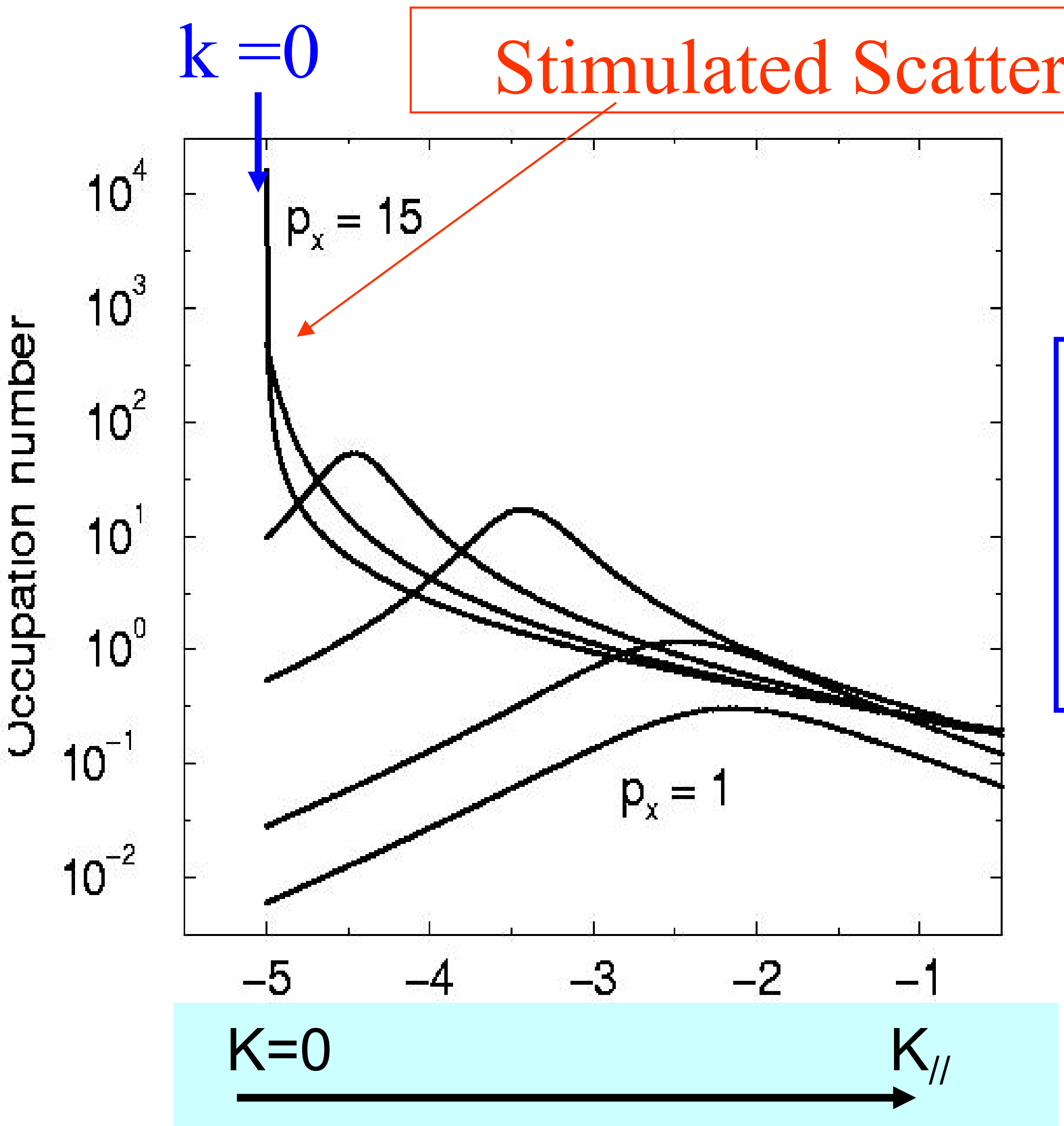


Angular dependence of emission





Occupation along dispersion



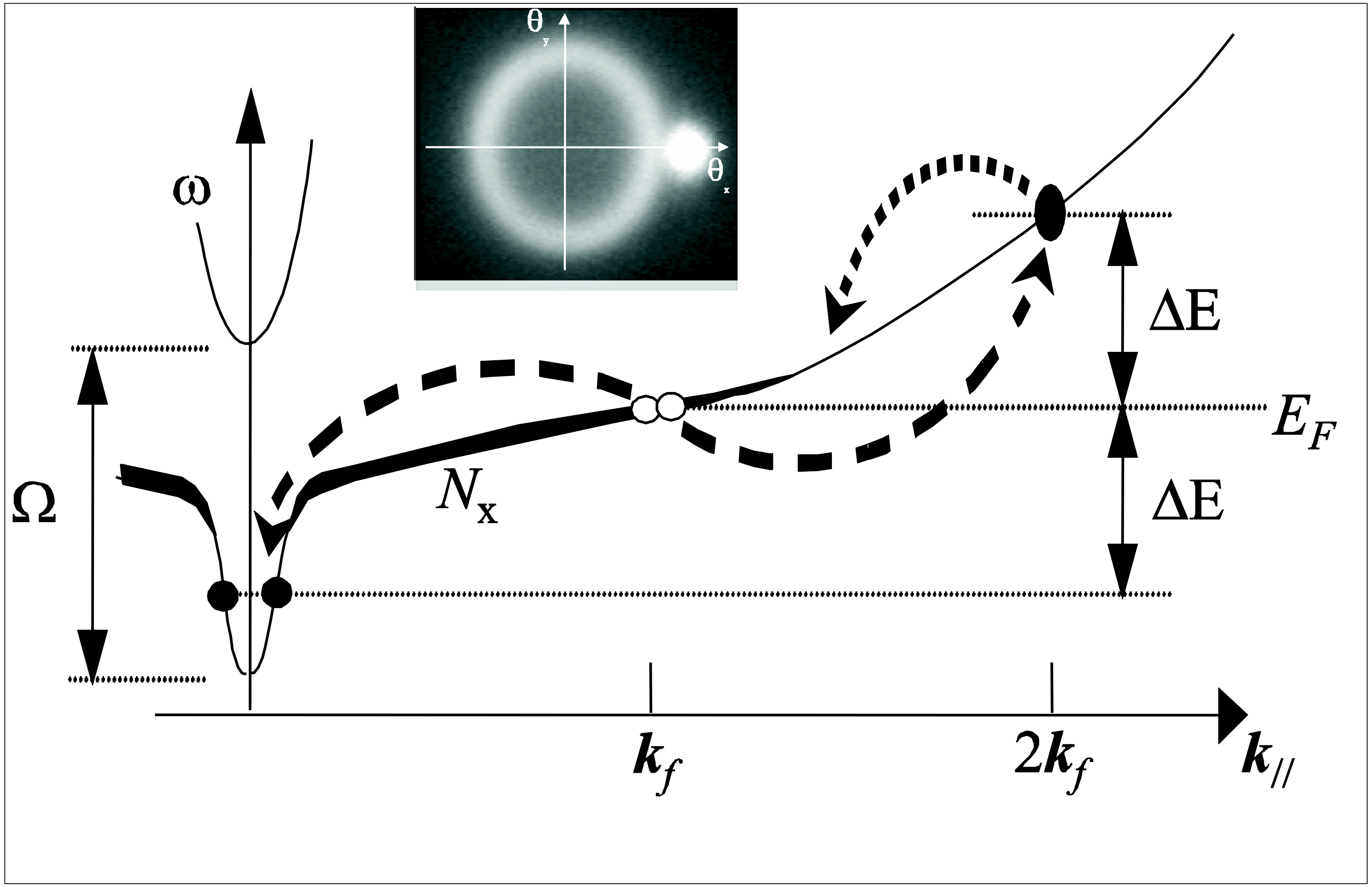
$\delta = 0$; $\Omega_P = 10$ meV

$T_L = 10$ K

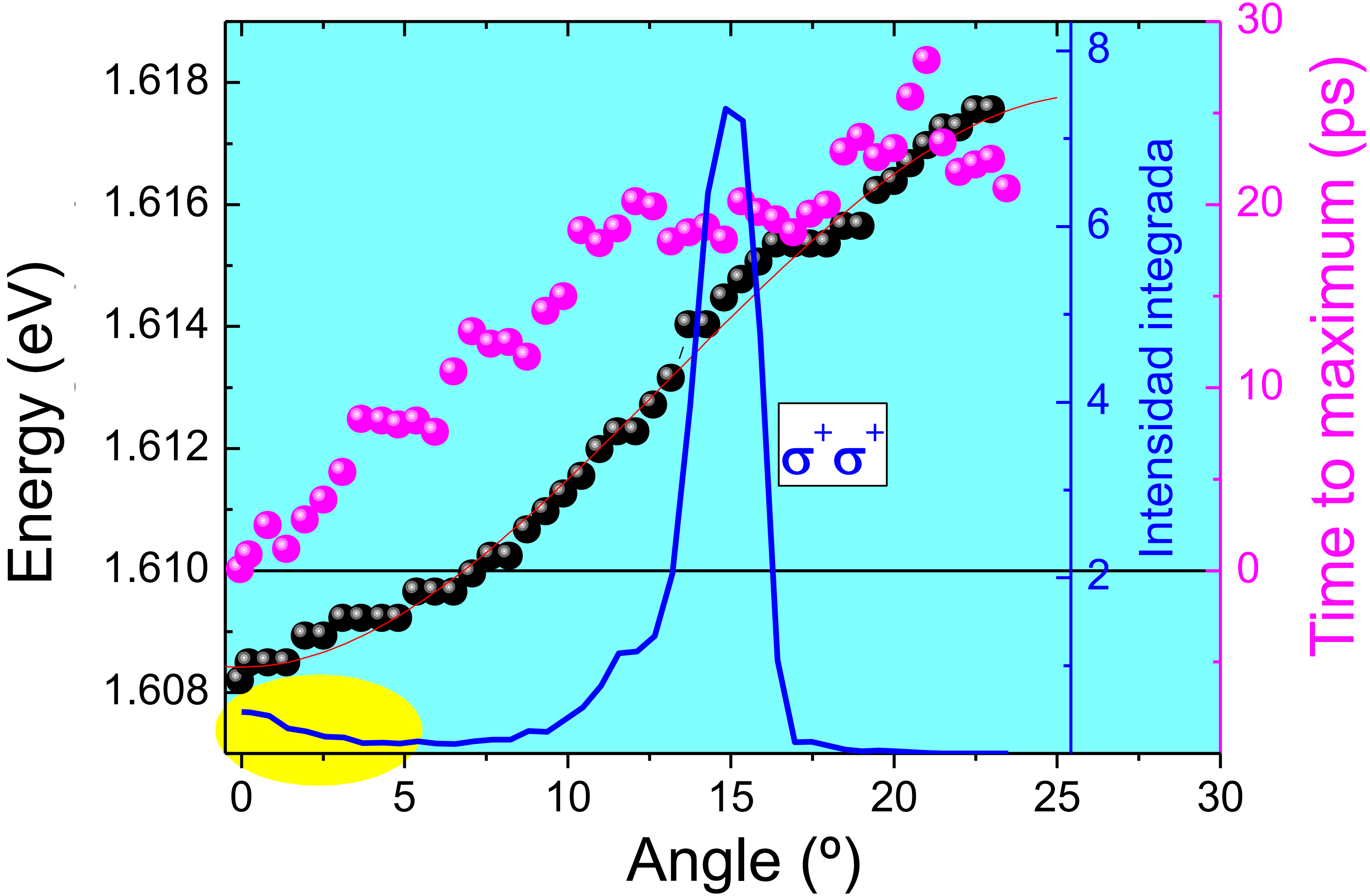
$p_x = 1,2,5,8,15\ 10^8\ cm^{-2}/ps$

D. Porras, C. Ciuti,
J. J. Baumberg, and C. Tejedor
Phys. Rev. B **66**, 085304 (2002)

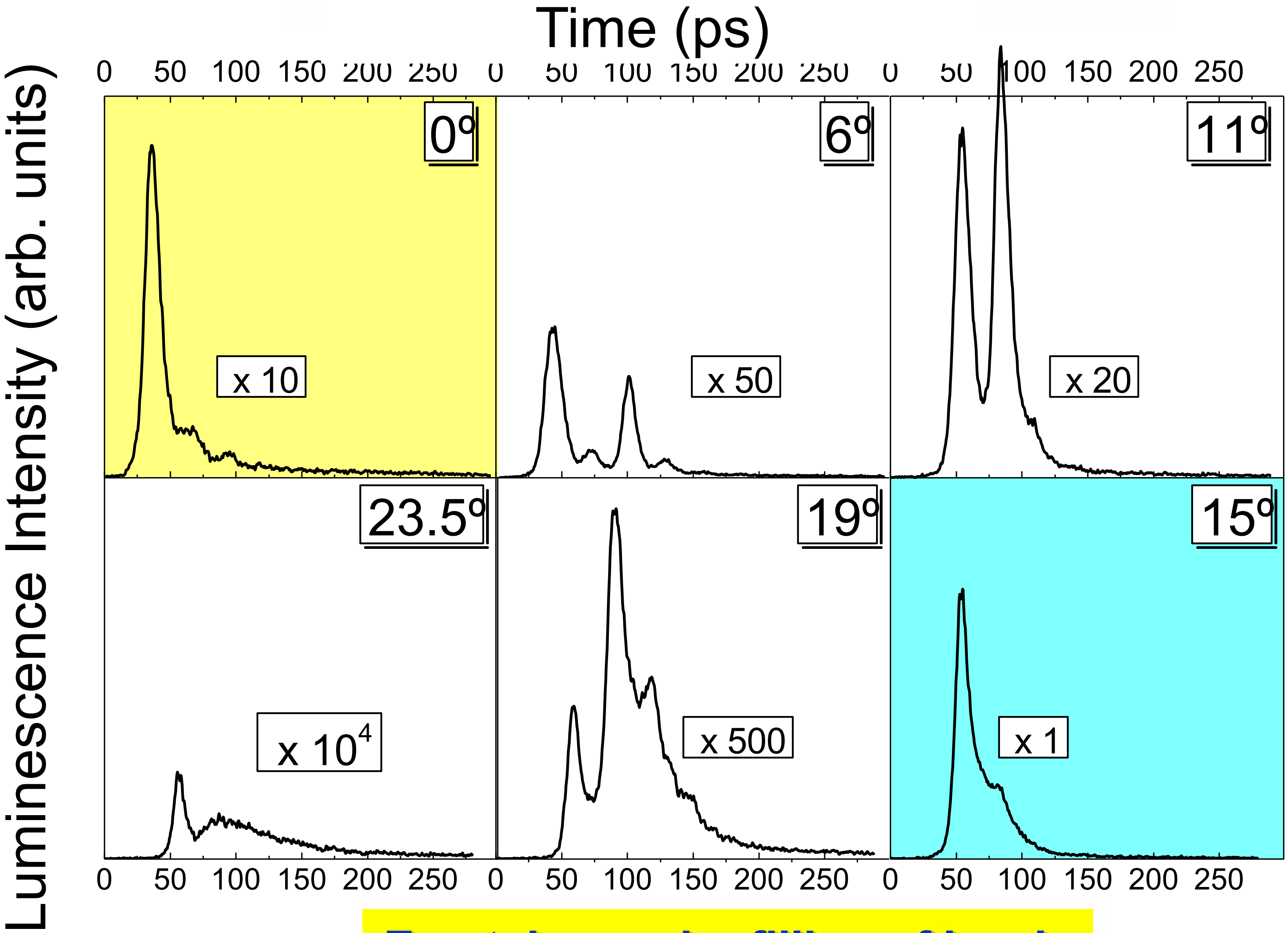
Ring formation



Ring formation dynamics



Oscillatory behavior



P e r i o d

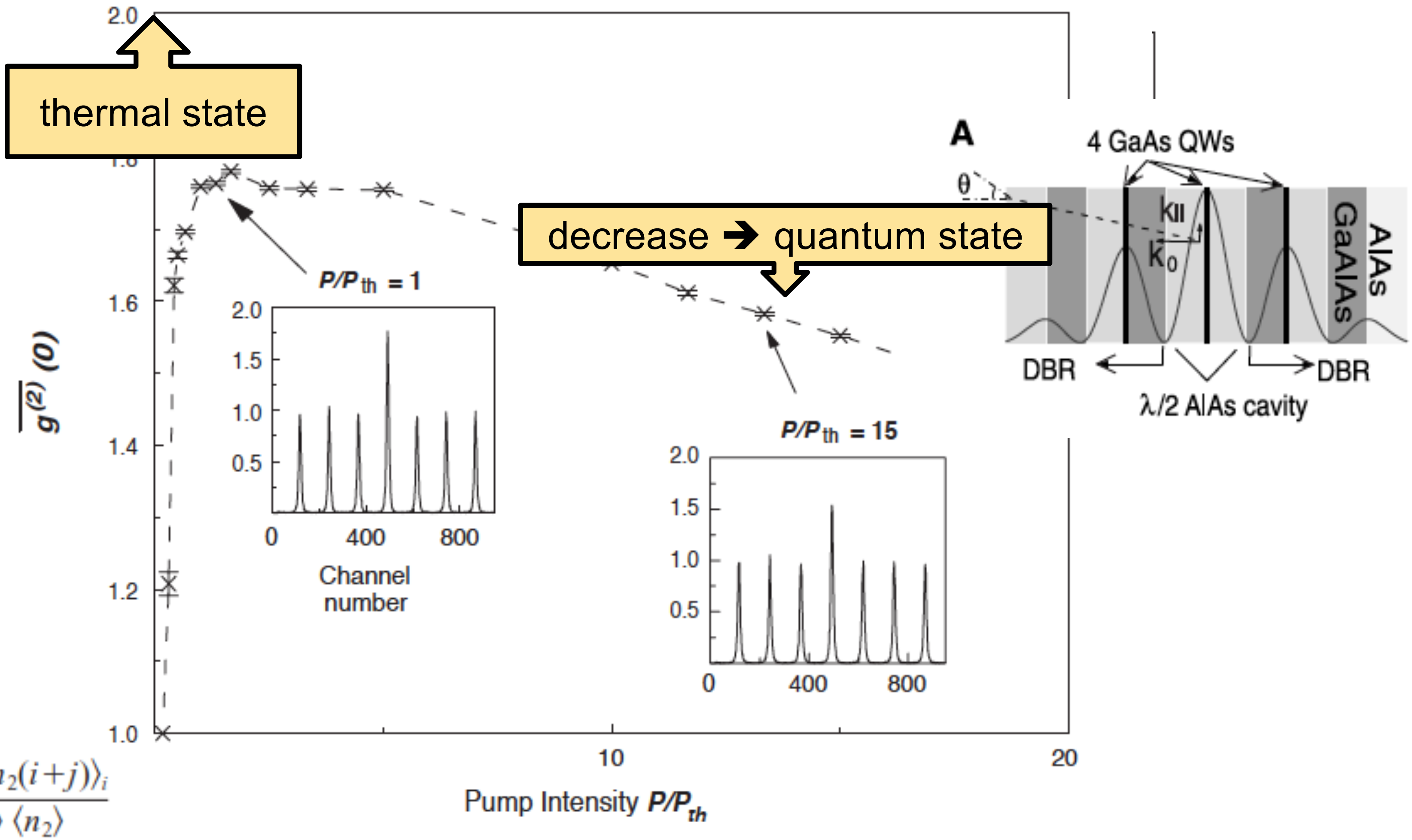
28 ps

∀θ

Emptying and refilling of levels

Some key studies

1st claim of "Condensation of Semiconductor μ-cavity Exciton Polaritons"
H. Deng, *et al*. Science **298**, 199 (2002)

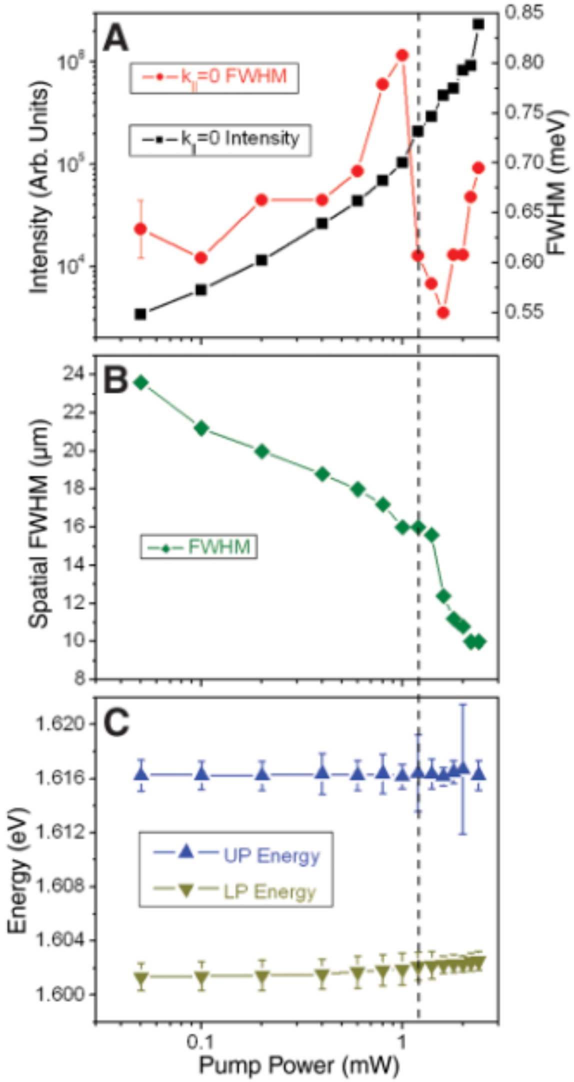


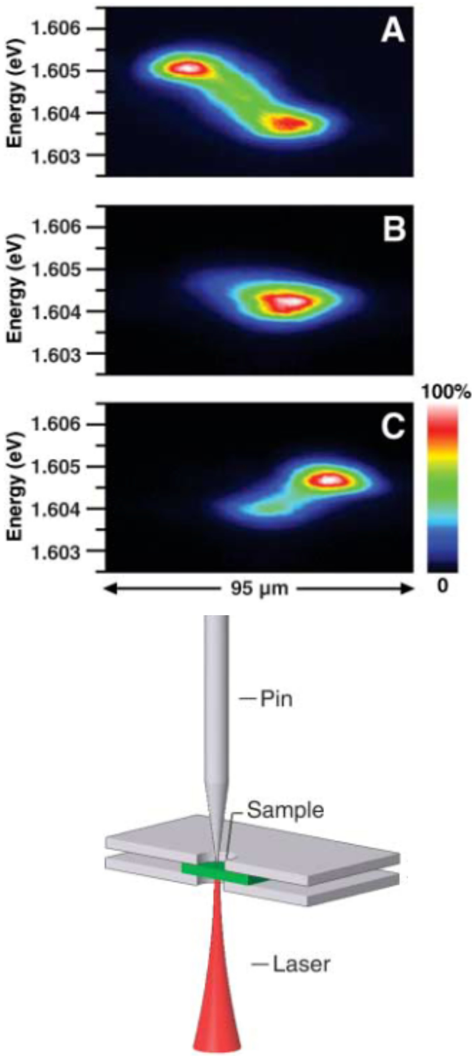
$$\overline{g^{(2)}}(j) = \frac{\langle n_1(i)\, n_2(i+j)\rangle_i}{\langle n_1\rangle \langle n_2\rangle}$$

Some key studies

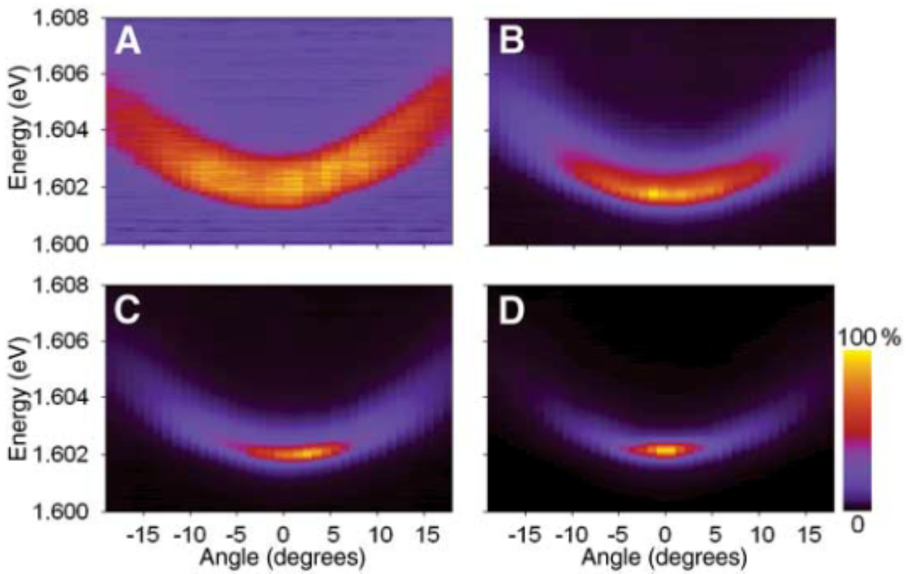
Polariton BEC in a trap

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





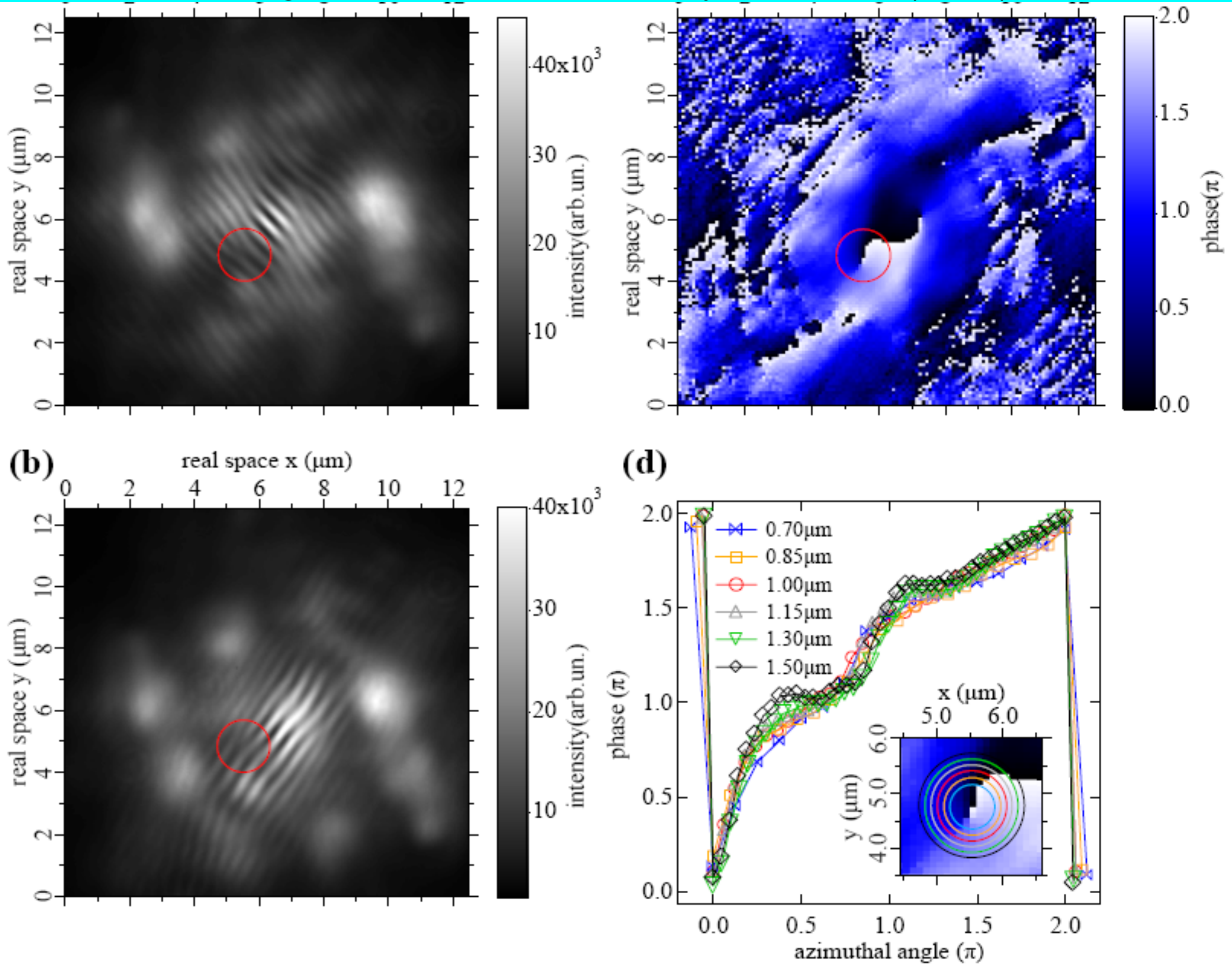
Increasing power density



Some key studies

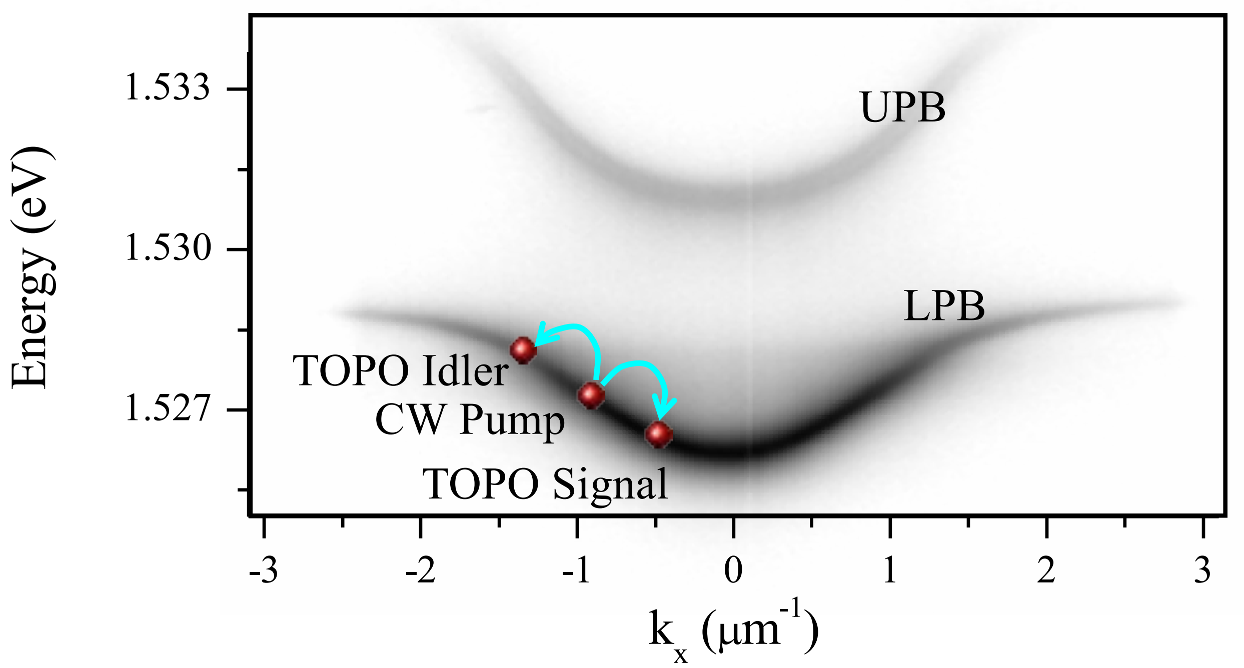
Quantized Vortices in an Exciton-Polariton Fluid

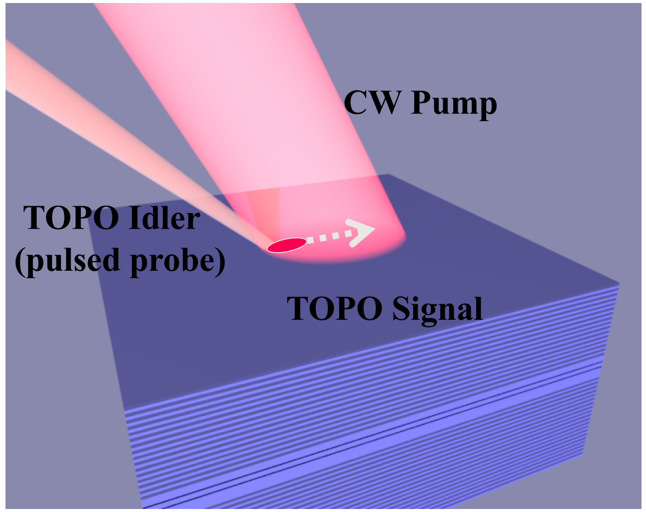
K.G. Lagoudakis, *et al*. Nature Physics **4**, 706 (2008)



Some key studies

Coherent flow of polariton condensates
A.Amo, *et al*. Nature **457** , 291 (2009)





Coexistence of **two fluids** with different velocities:

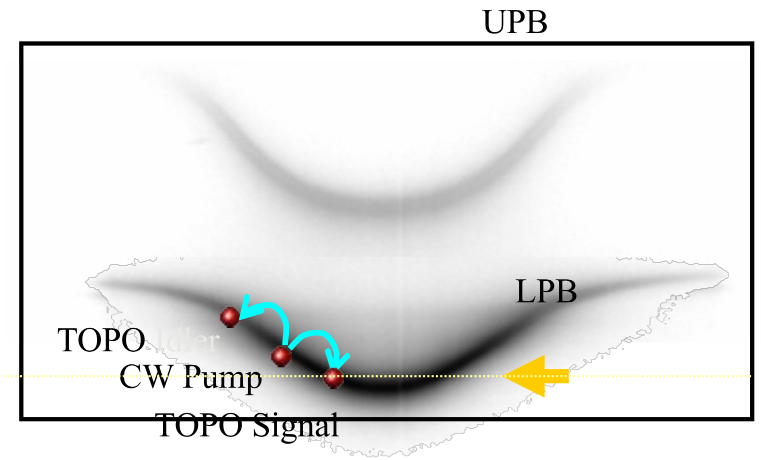
$$v_g = \frac{1}{\hbar}\frac{\partial E}{\partial k} > 0$$ →

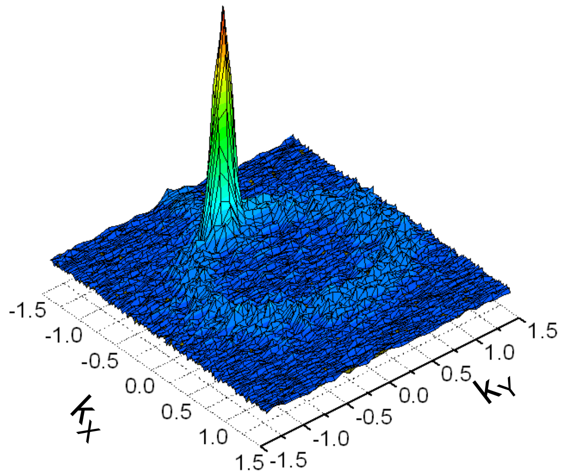
- Steady state CW (pump) ← large spot
- Triggered OPO (signal) ← small initial spot

Some key studies

Coherent flow of polariton condensates

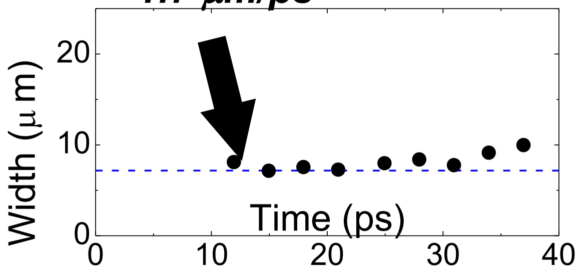
A.Amo, *et al*. Nature **457** , 291 (2009)

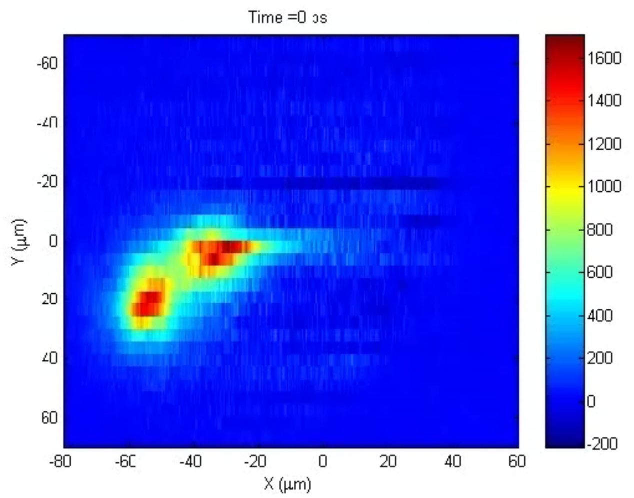




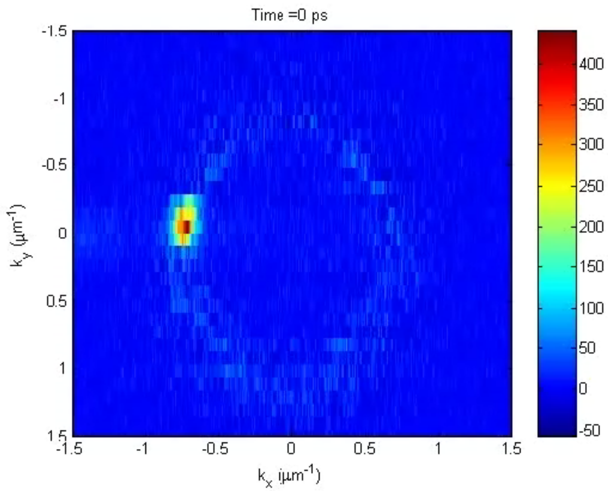
High pump power (blueshift)

- Unperturbed flow: **no expansion**
  - Well defined ***k***
  - ***1.7 μm/ps***





real space

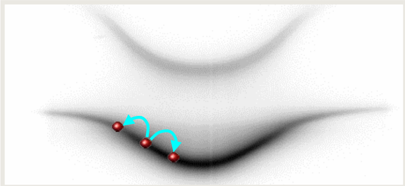


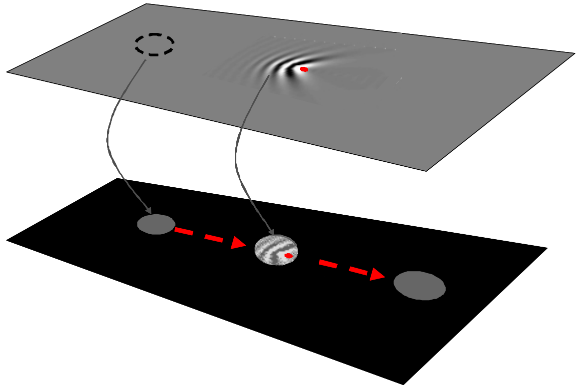
momentum space

Some key studies

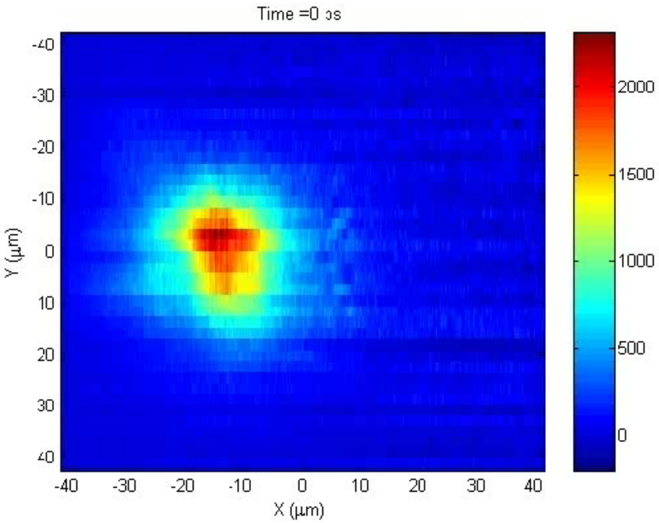
Coherent flow of polariton condensates

A.Amo, *et al*. Nature **457** , 291 (2009)



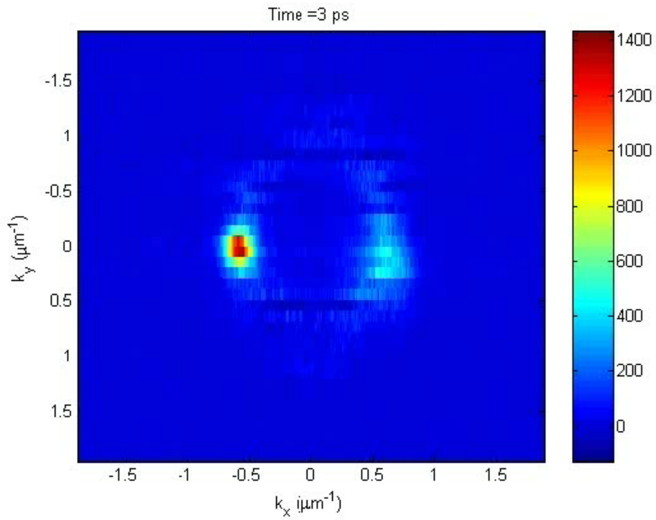


- The defect is observed through the **Čerenkov** waves present at the pump state
- Signal fluid
  no scattering with the defect
  well defined momentum



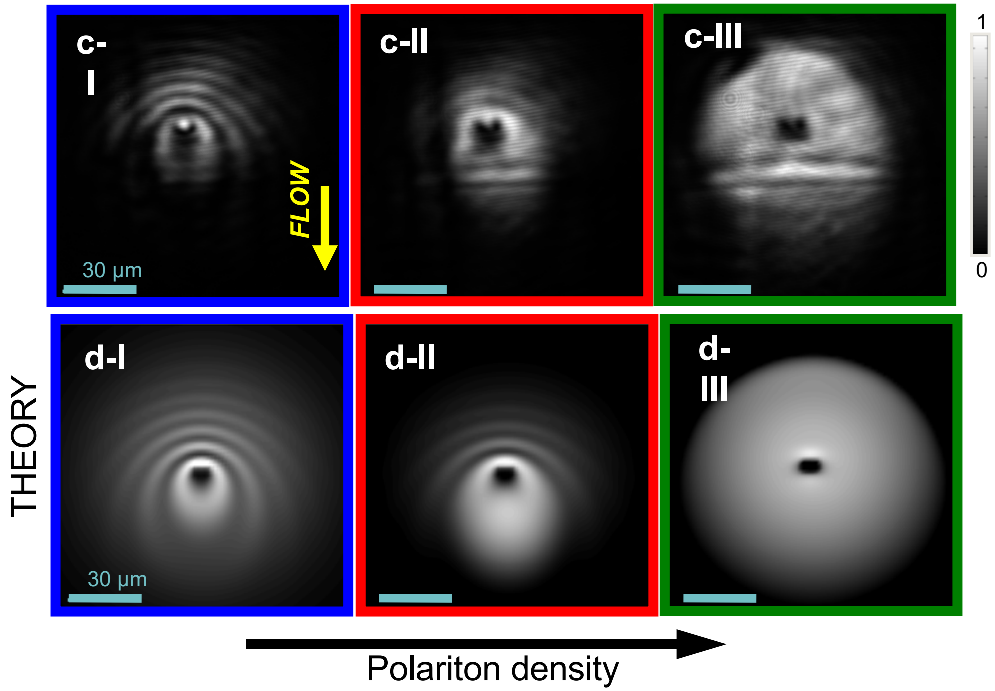
real space

momentum space



Some key studies

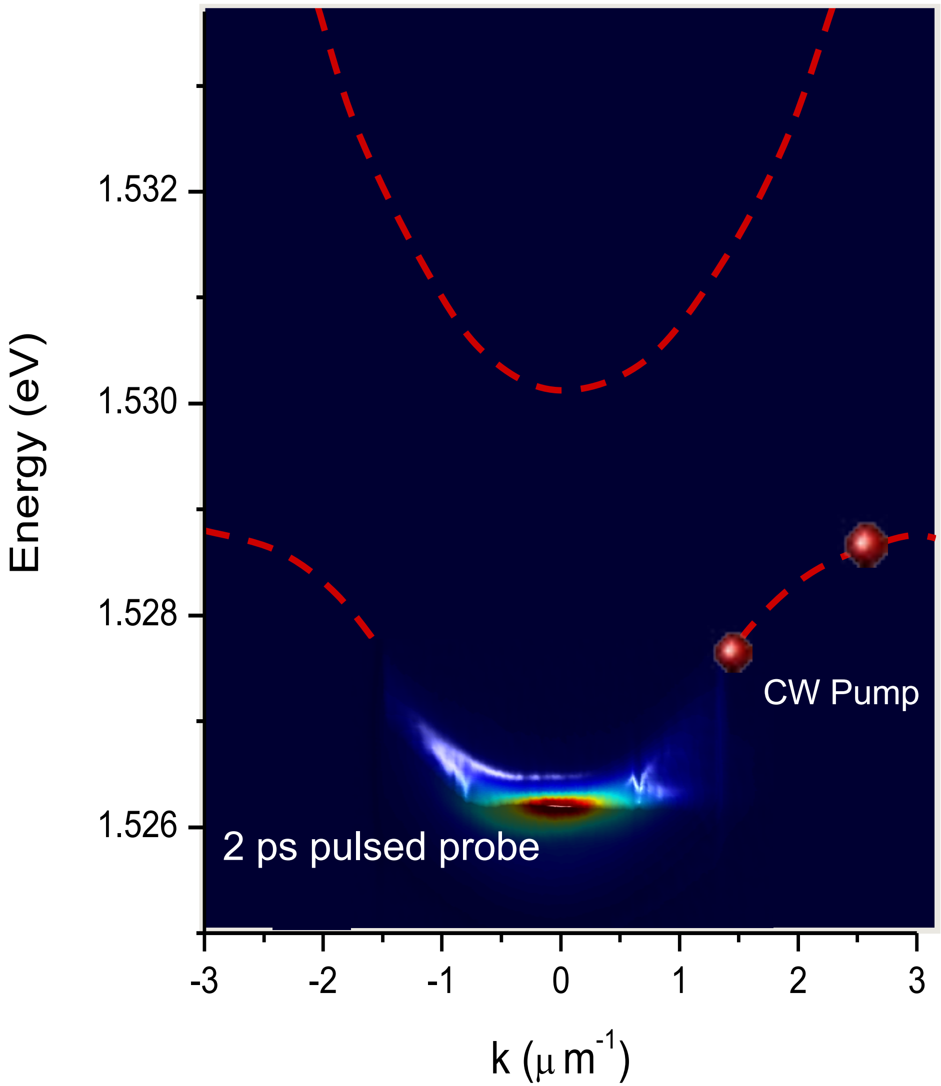
Superfluidity of polaritons in semiconductor microcavities
A. Amo, *et al*., Nature Physics **5**, 805 (2009)



Observation a pump polariton state at velocities above and below the speed of sound

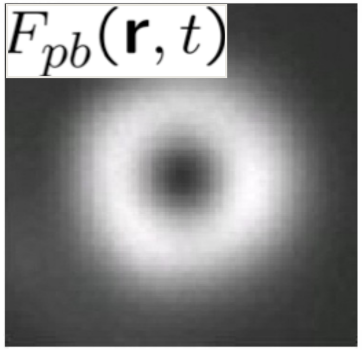
Some key studies

Vortex Dynamics in an Exciton-Polariton Fluid
D. Sanvitto, *et al.*, Nature Physics **6**, 527 (2010)

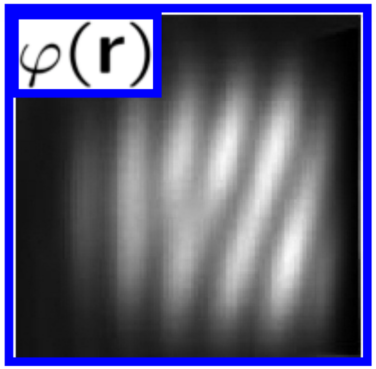


$$F_{pb}(\mathbf{r},t) = \mathcal{F}_{pb}(\mathbf{r})e^{i\varphi(\mathbf{r})}e^{-\frac{t^2}{2\sigma_t^2}}e^{i(\mathbf{k}_s\cdot\mathbf{r}-\omega_s t)}$$

Vortex state of light



Typical interferences with a mirrored image

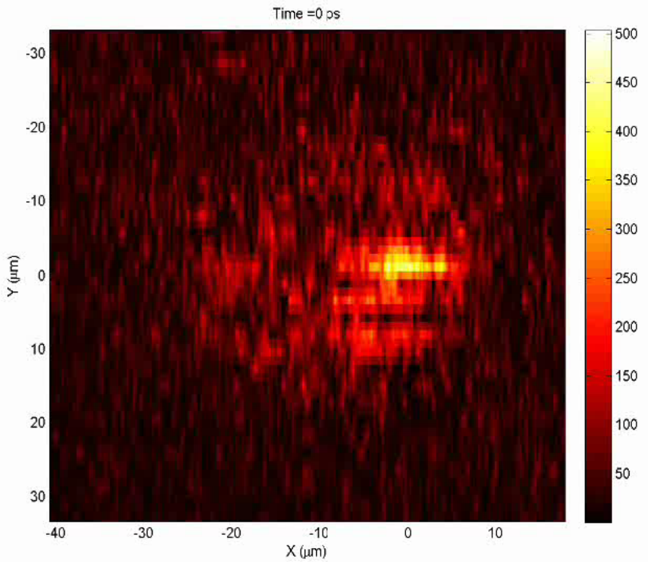


Some key studies

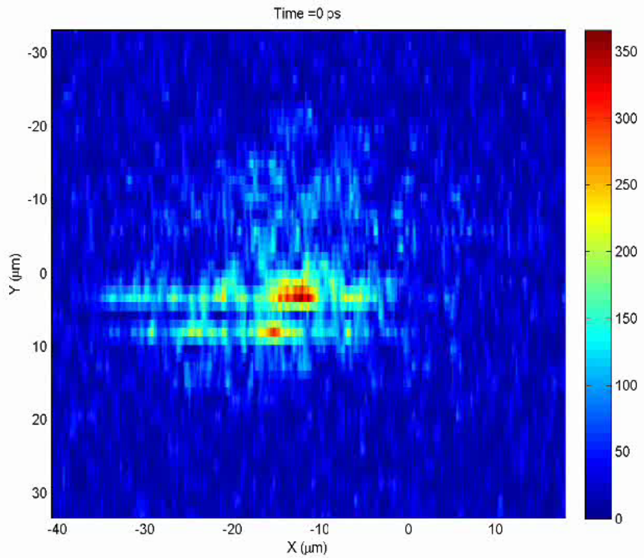
Vortex Dynamics in an Exciton-Polariton Fluid
D. Sanvitto, *et al*., Nature Physics **6**, 527 (2010)

2D Movies of the experiment injecting a m=1 vorticity

Real space image of the signal emission

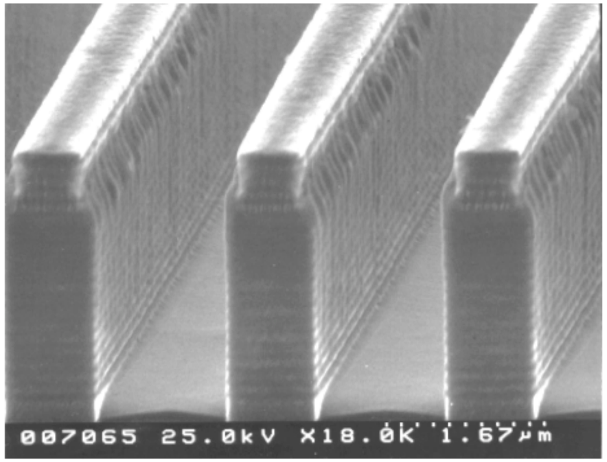


Interference pattern of the signal

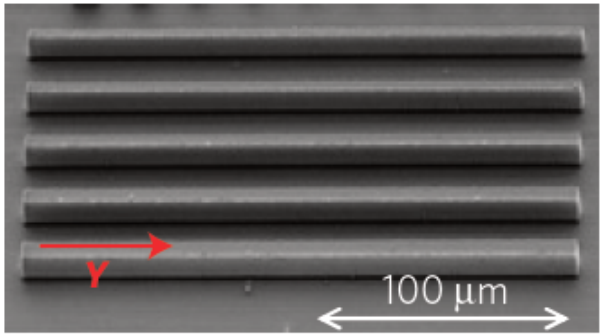


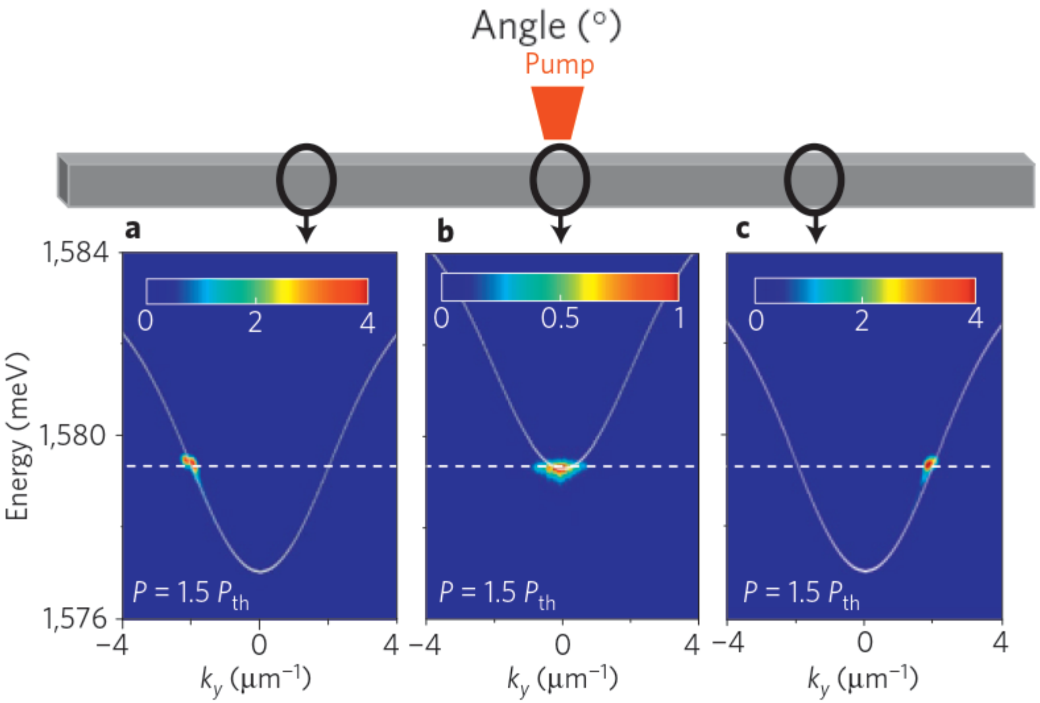
Some key studies

Patterning of μ-cavities



A. Kuther, *et al.*,
Phys. Rev. B **58**, 15744 (1998)

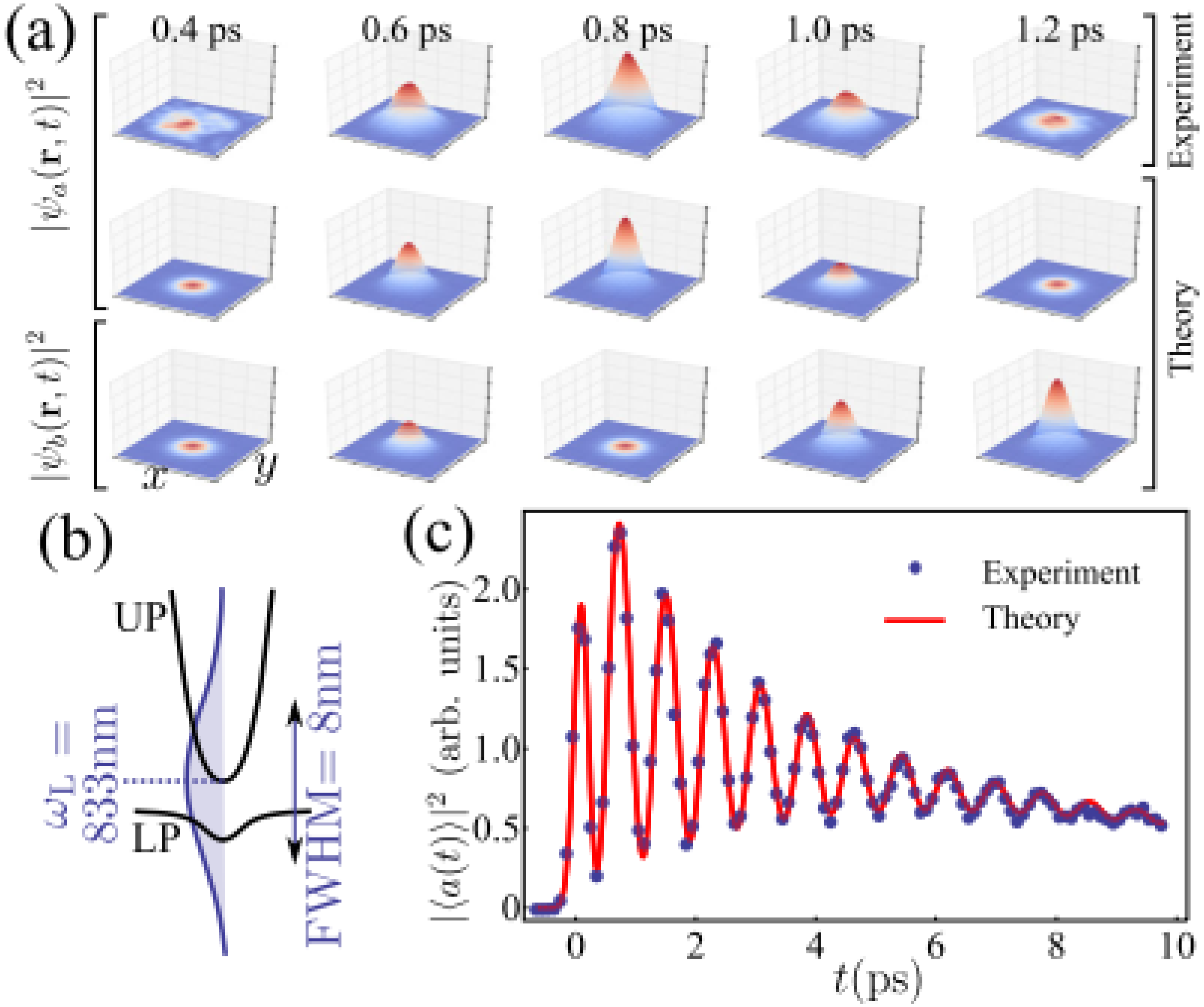


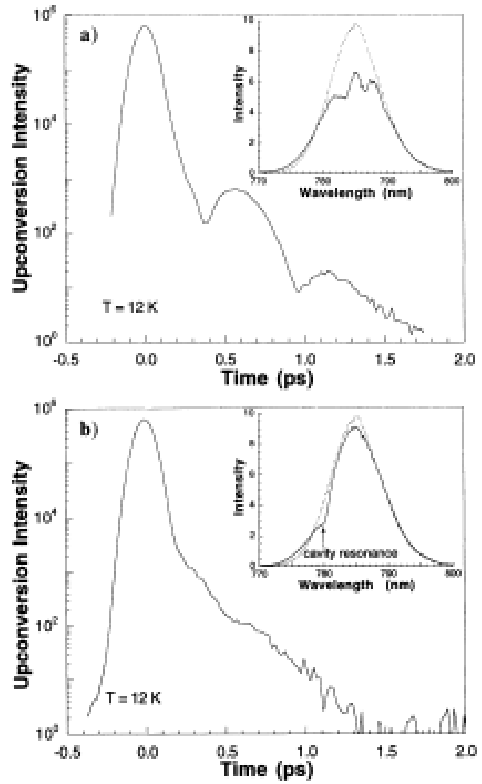


E. Wertz, *et al.*,
Nature Physics **6**, 860 (2010)

Some key studies

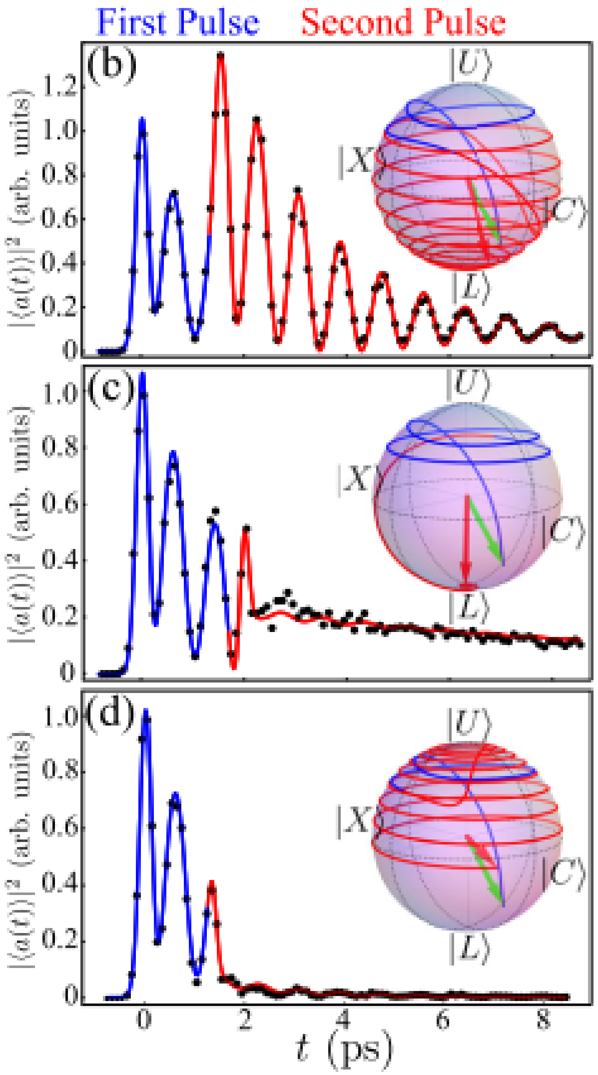
Ultrafast Control and Rabi Oscillations of Polaritons
L. Dominici, et al., Phys. Rev. Lett. **113**, 226401 (2014)





Some key studies

Ultrafast Control and Rabi Oscillations of Polaritons
L. Dominici, et al., Phys. Rev. Lett. **113**, 226401 (2014)



Amplification

From p → LP

Annihilation

More to come