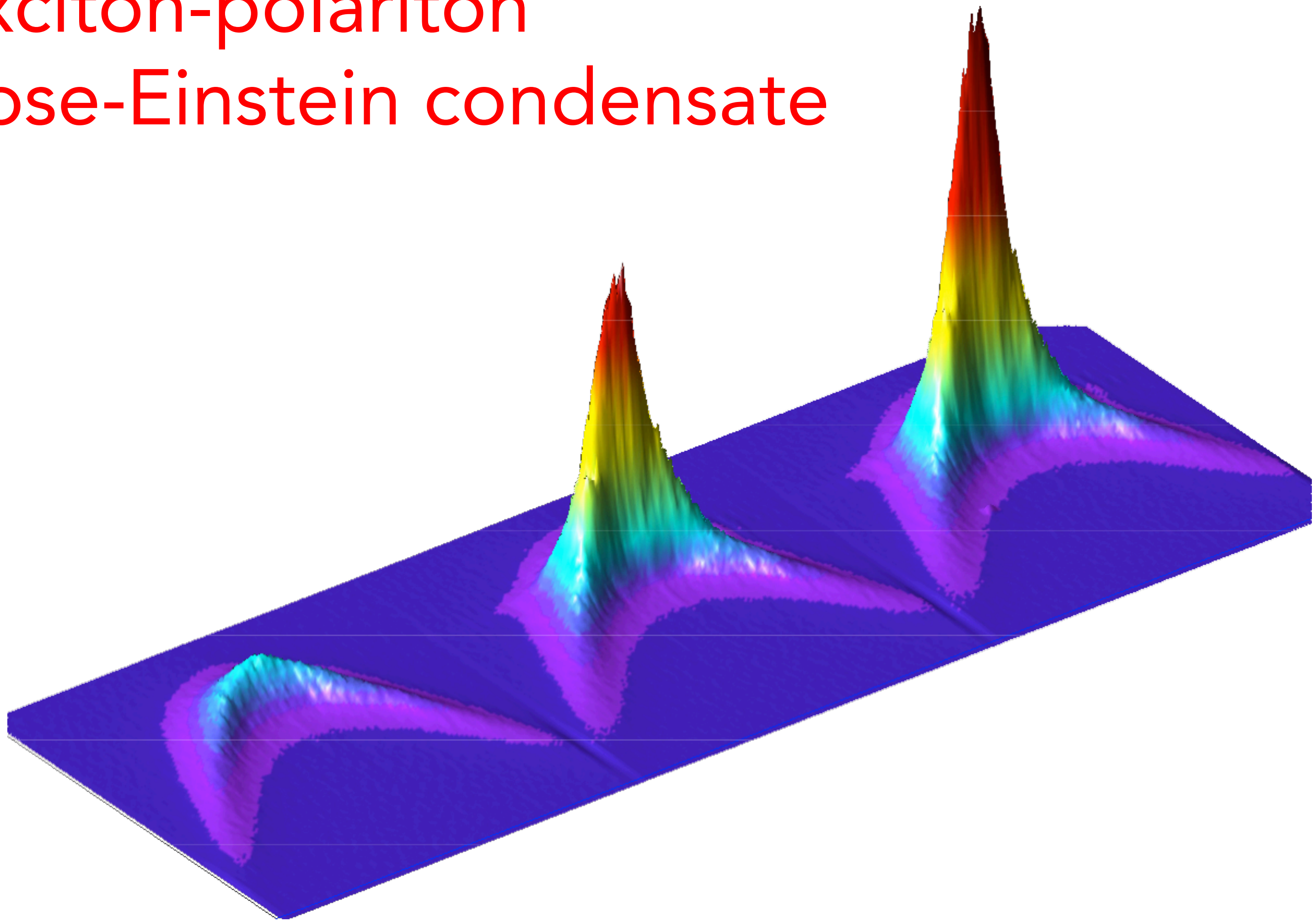
Exciton-polariton Bose-Einstein condensate



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http://polaritonbec.org

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AUSTRALIAN NATIONAL UNIVERSITY

Polariton BEC Laboratory

&

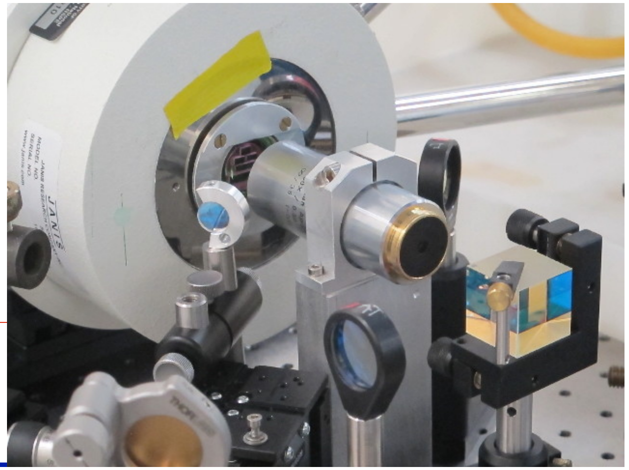
Picosecond Imaging Facility

Australian National University

ATOMIC AND MOLECULAR PHYSICS LABORATORIES

NONLINEAR PHYSICS CENTRE

established in 2013



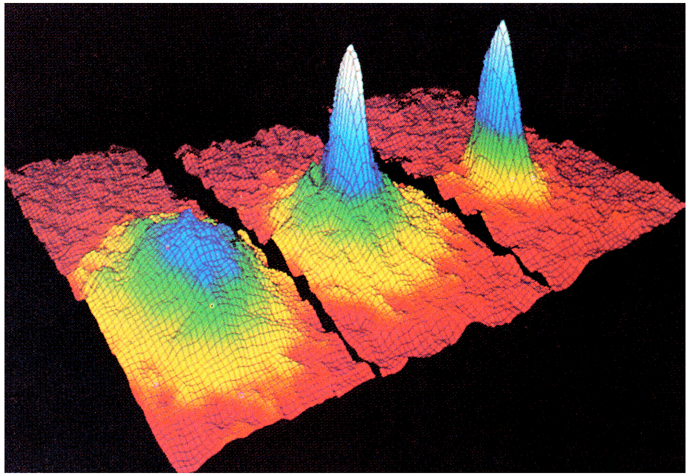
outline of the lectures

- Wannier-Mott excitons in QW
- light-matter coupling in semiconductor cavities
- (exciton-)polaritons

- condensation of polaritons
- superfluid dynamics
- vortices in pBEC

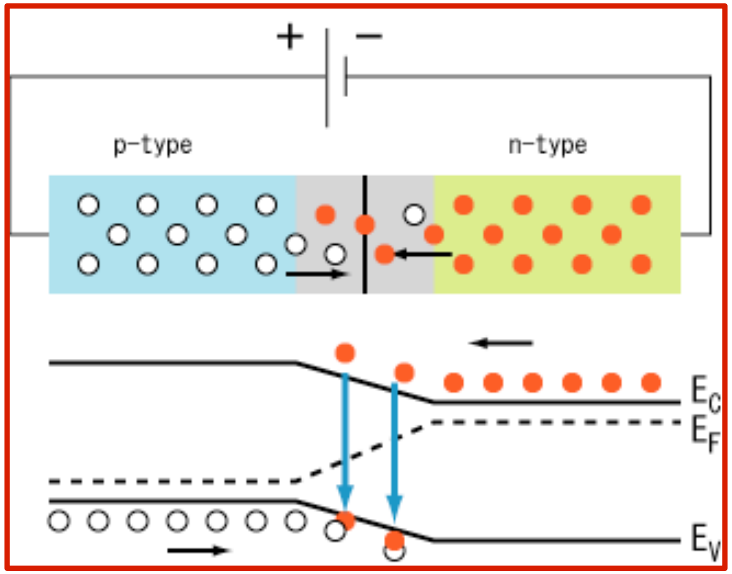
- trapping techniques
- excitonic potentials
- photonic potentials

- pBEC in periodic potentials
- polaritonic devices



The Nobel Prize in Physics 2001
Eric A. Cornell, Wolfgang Ketterle
and Carl E. Wieman

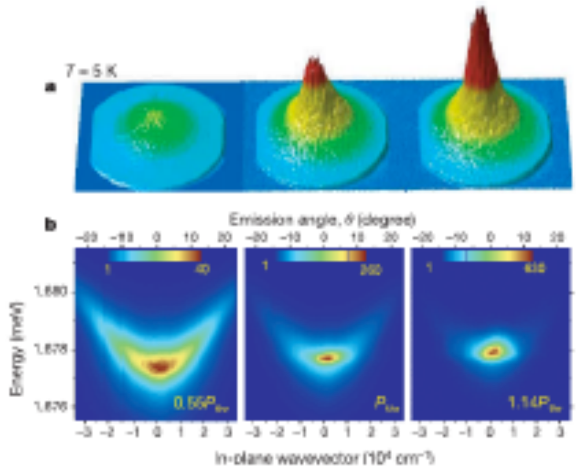
"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

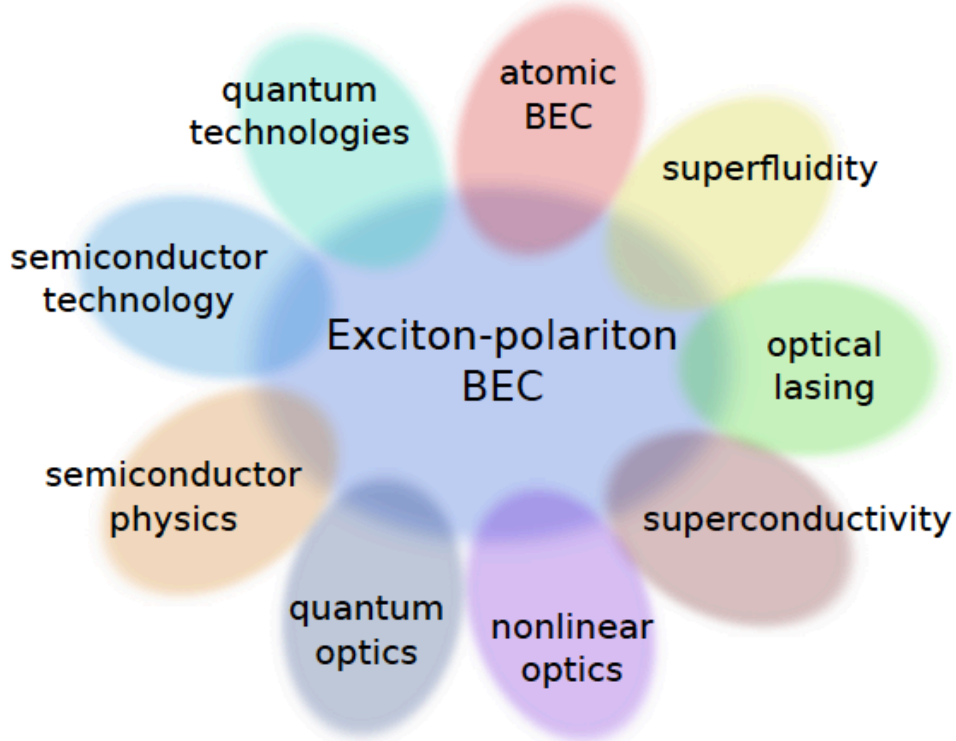


The Nobel Prize in Physics 2000
Zh. I. Alferov and H. Kroemer

"for developing semiconductor heterostructures used in high-speed- and opto-electronics"

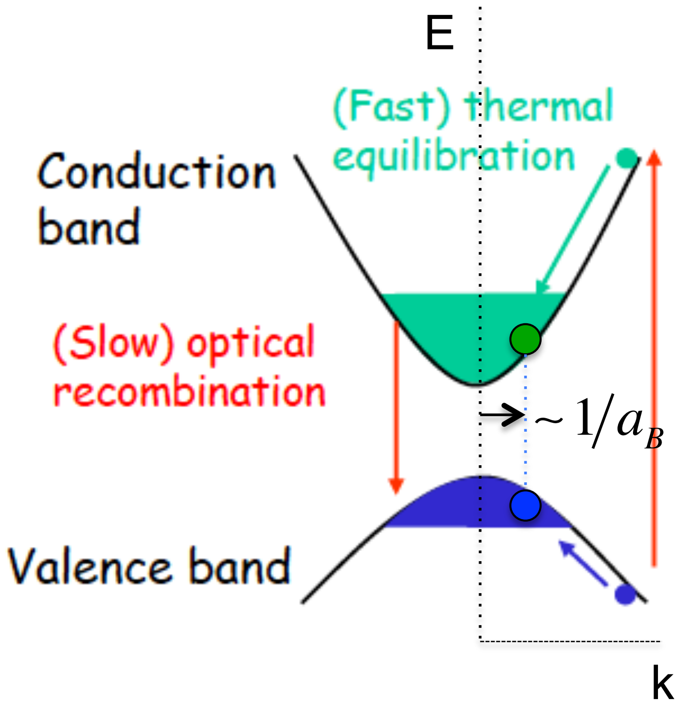
2006: Exciton-Polariton BEC





- Polariton mass 10^9 orders lighter than aton
- Transition temperature in 10s to 100s of K
- Ease of study using optical techniques
- Completely embedded within a semiconductor chip

Wannier-Mott excitons



In direct gap semiconductors, optical properties are governed by two bands above and below the Fermi level.

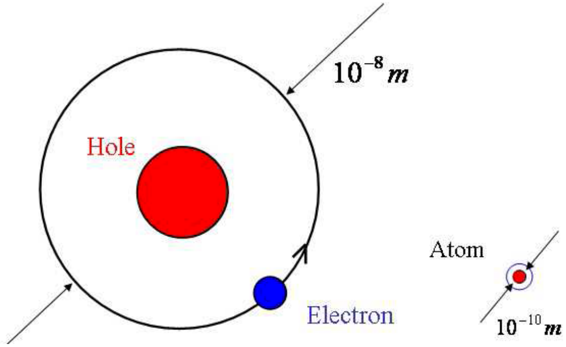
Absorption of a photon leads to electron excitation into conduction band.

Excitons are quasi-particles formed by optically-excited electrons-hole pairs bound by Coulomb attraction.

Binding is weak and their size is larger than inter-atomic distance in the solid-state lattice.

At high densities $n_{exc}a_B \sim 1$ and high temperatures electrons and holes unbind and form electron-hole plasma.

Wannier equation



Schrödinger equation for the wavefunction of the relative e-h motion

$$-\frac{\hbar^2}{2\mu}\Delta f(r)-\frac{e^2}{4\pi\varepsilon\varepsilon_0 r}f(r)=Ef(r)$$

$$\mu = m_e m_h/(m_e+m_h)$$ reduced mass

Equivalent to Schrödinger equation for a hydrogen atom with: $m_0 \to \mu, \quad e^2 \to e^2/\varepsilon$

The first bound state (1s): $f_{1s}=\frac{1}{\sqrt{\pi a_B^3}}e^{-r/a_B}$ $\quad a_0=\frac{4\pi\varepsilon_0\hbar^2}{m_e e^2}\sim 0.529\,\mathring{A}$

Exciton Bohr radius and Rydberg (SI) $\quad a_B=\frac{a_0\varepsilon}{\mu/m_e} \qquad E_B=\frac{\hbar^2}{2\mu a_B^2}$

e.g. in GaAs ($m^* \sim 0.1\ m_e$, $\epsilon = 13$)
Binding energy = 5 meV (13.6 eV for Hydrogen)
Bohr radius = 7 nm (0.05 nm for Hydrogen)

A Kavokin, J J Baumberg, G Malpuech, & F P Laussy, "Microcavities", Oxford University Press (2007)

Effective mass

$\boxed{\mu = m_e m_h/(m_e + m_h)}$

Schrödinger equation for the wavefunction of an electron in a periodic lattice potential $V(r)$ has solutions in the form of Bloch waves:

$$\Psi_{n,\mathbf{k}} = U_{n,\mathbf{k}}(\mathbf{r})e^{i\mathbf{kr}}$$

$$-\frac{\hbar^2}{2m_0}\Delta\Psi_{n,\mathbf{k}} + V(\mathbf{r})\Psi_{n,\mathbf{k}} = E_{n,\mathbf{k}}\Psi_{n,\mathbf{k}} \qquad \Delta = \nabla^2$$

Equation for Bloch amplitudes (in real space):

$$-\frac{\hbar^2}{2m_0}\Delta U_{\mathbf{k},n} + V(\mathbf{r})U_{\mathbf{k},n} + \left(\frac{\hbar^2\mathbf{k}^2}{2m_0} + \frac{\hbar}{m_0}(\mathbf{kp})\right)U_{\mathbf{k},n} = E_{\mathbf{k},n}U_{\mathbf{k},n} \qquad \mathbf{p} = -i\hbar\nabla$$

Considering ($\mathbf{kp}$) terms as perturbation, we obtain energy near k=0 of all bands:

$$E_{\mathbf{k},n} \approx E_{0,n} + \frac{\hbar^2 k^2}{2m_n*}$$

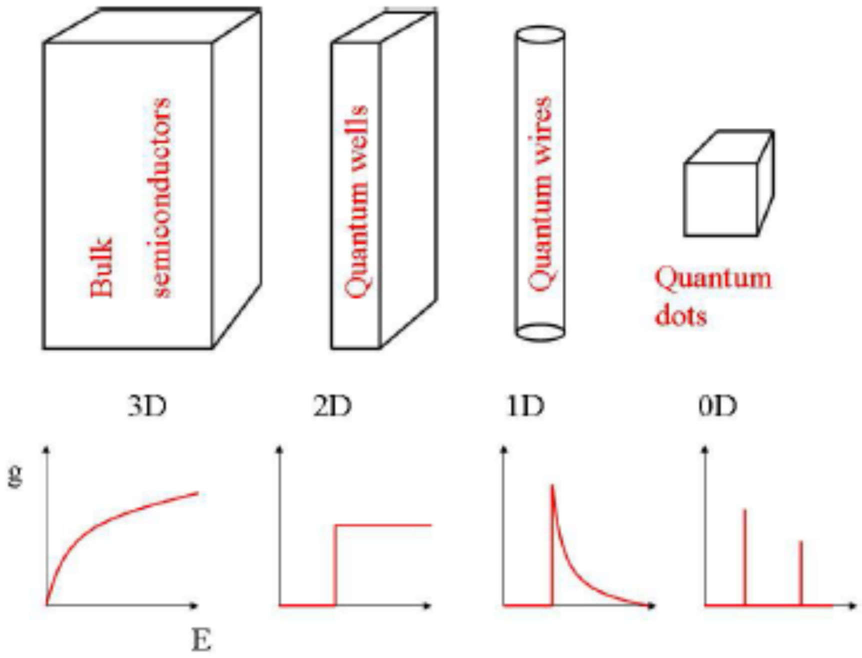
Electron's effective mass $\displaystyle \frac{1}{m_n*} = \frac{1}{m_0} + \frac{2}{m_0^2}\sum_{l\neq n}\frac{|\langle U_{0,l}|\mathbf{p}|U_{0,n}\rangle|^2}{E_{0,l} - E_{0,n}}$

In GaAs: $m_e = 0.067m_0,\ \ m_h = 0.45m_0$

Ashcroft &Mermin, 'Solid State Physics'

Spatial confinement

Semiconductor nanotechnology has enabled engineering of strongly confined electron states



density of states:

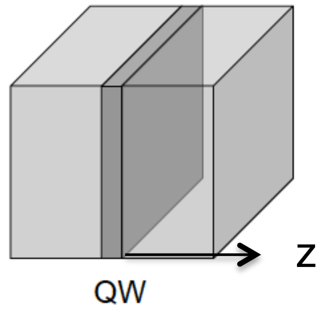
$$g = dN / dE$$

Confinement increases binding energy of excitons thus increasing their lifetime

Confinement enables strong light-matter interaction

Exciton in a quantum well

$$-\frac{\hbar^2}{2m_e}\nabla_e^2 - \frac{\hbar^2}{2m_h}\nabla_h^2 + V_e(z_e) + V_h(z_h) - \frac{e^2}{4\pi\varepsilon_0\varepsilon|\mathbf{r}_e - \mathbf{r}_h|}\Psi = E\Psi$$

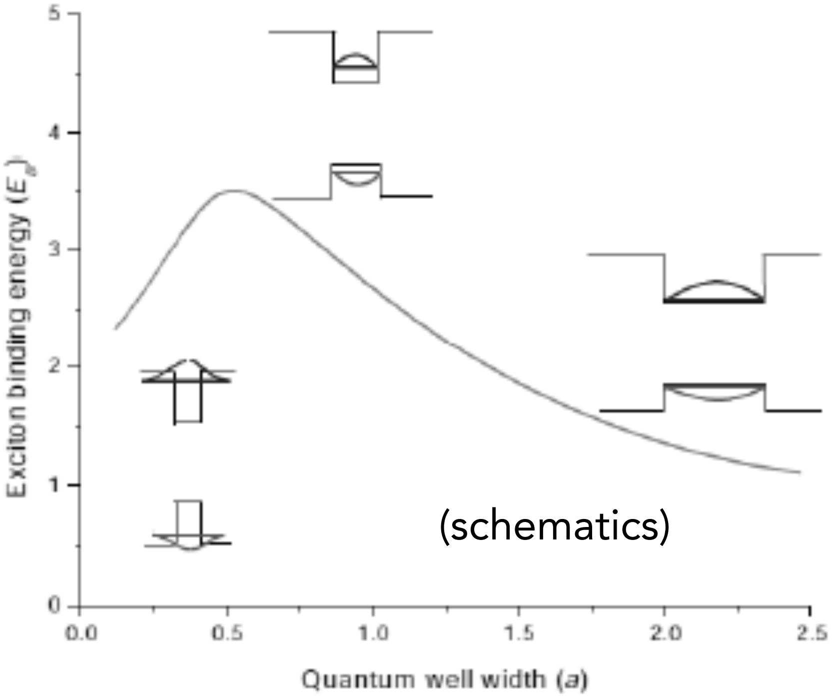


$$\boxed{\Psi(\mathbf{r}_e, \mathbf{r}_h) = F(\mathbf{R})f(\boldsymbol{\rho})U_e(z_e)U_h(z_h)}$$

$$\mathbf{R} = \frac{m_e\mathbf{r}_e + m_h\mathbf{r}_h}{m_e + m_h} \qquad \boldsymbol{\rho} = \boldsymbol{\rho}_e - \boldsymbol{\rho}_h$$

In the ideal 2D case, $|U_{e,h}(z_{e,h})|^2 = \delta(z_{e,h})$

$$\boxed{\left\{-\frac{\hbar^2}{2\mu}\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right) - \frac{e^2}{\varepsilon\rho}\right\} f(\rho) = E_B^{2D} f(\rho)}$$



Exactly solvable
hydrogen atom problem

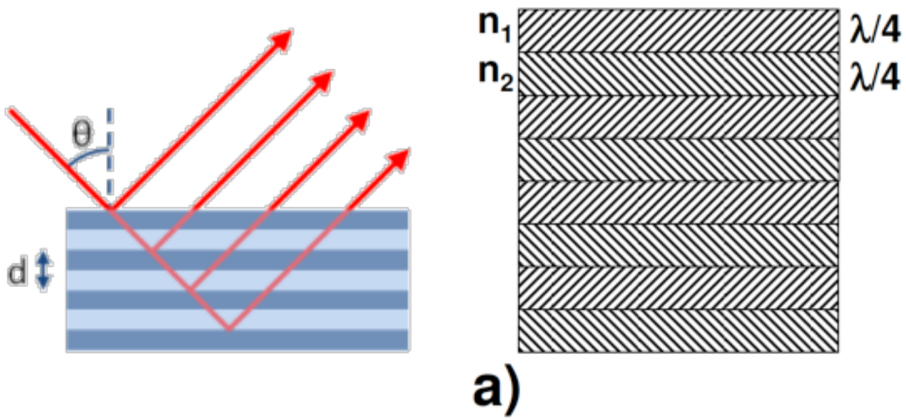
$$f_{1S}(\rho) = \sqrt{\frac{2}{\pi}}\frac{1}{a_B^{2D}}\exp(-\rho/a_B^{2D})$$

$$a_B^{2D} = \frac{a_B}{2} \qquad \boxed{E_B^{2D} = 4E_B}$$

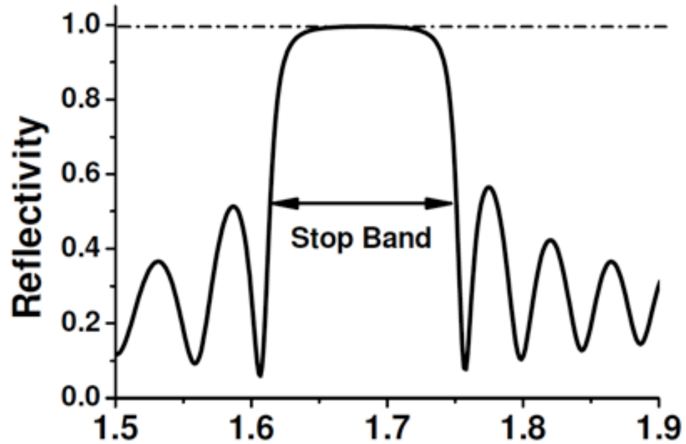
QW excitons in a semiconductor microcavity – the birth of a polariton

Mirrors: Distributed Bragg Reflectors

Alternative high and low dielectric layers with dimensions exactly $\lambda/4n$



Reflectivity is angle and wavelength dependent



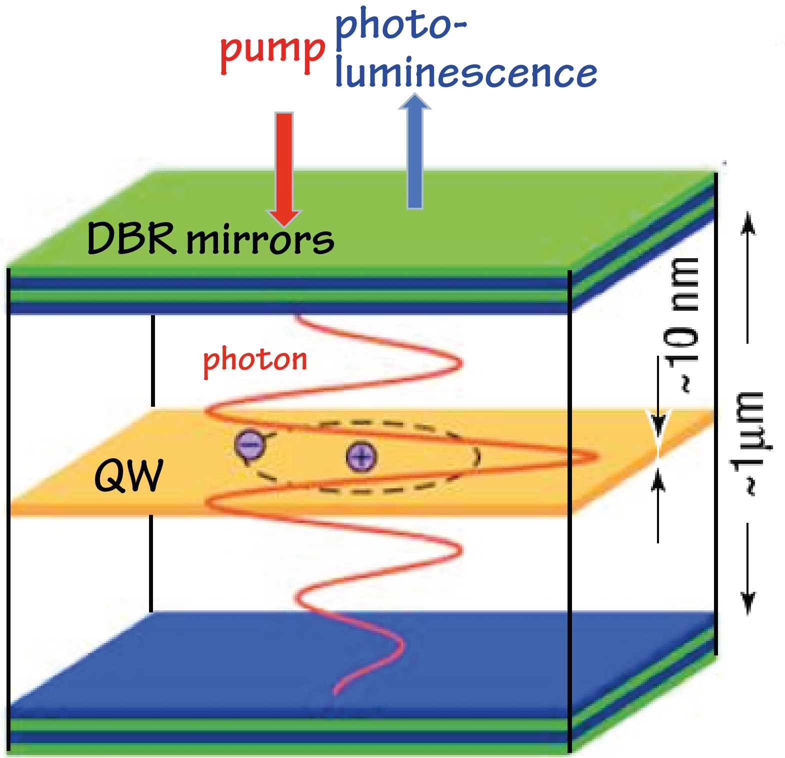
Reflectivity - depends on number of layers and index contrast

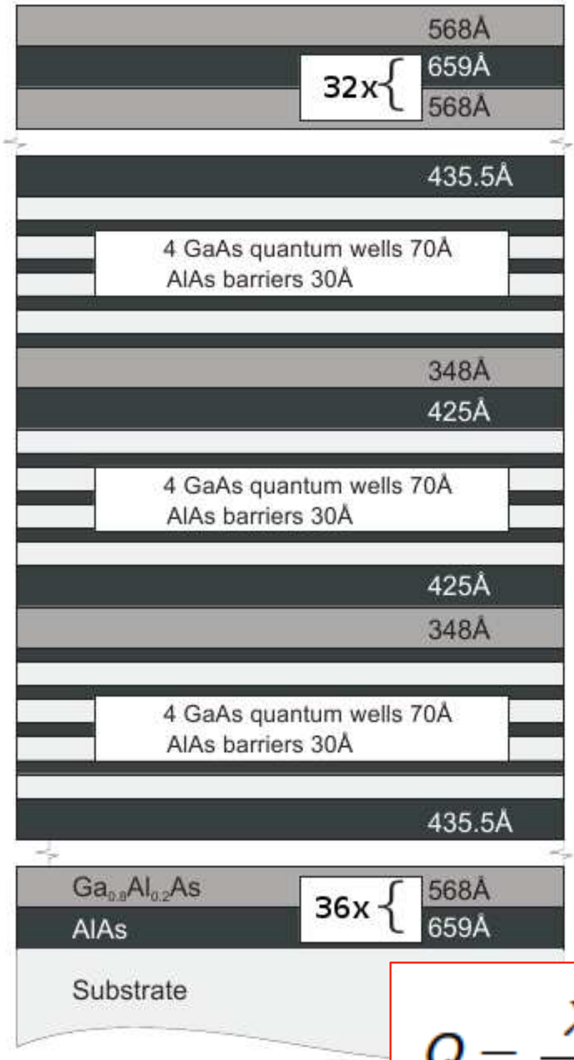
$$R = \left[\frac{n_o(n_2)^{2N} - n_s(n_1)^{2N}}{n_o(n_2)^{2N} + n_s(n_1)^{2N}} \right]^2$$

Bandwidth - fixed by index contrast

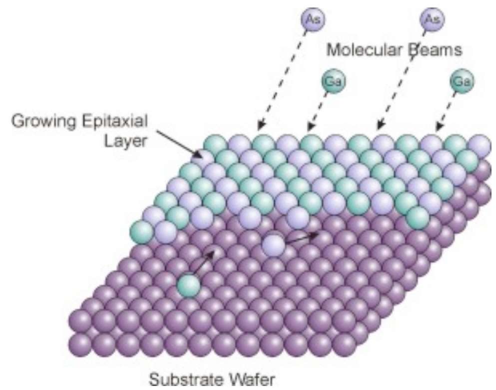
$$\Delta\lambda_0 = \frac{4\lambda_0}{\pi} \arcsin\left(\frac{n_2 - n_1}{n_2 + n_1}\right)$$

Semiconductor microcavity





Fabrication:
epitaxially grown QWs between DBR layers



DBR + QW
photon and exciton confinement

Julius-Maximilians-
UNIVERSITÄT WÜRZBURG

Heterostructure grown
at Wuerzburg University, Germany

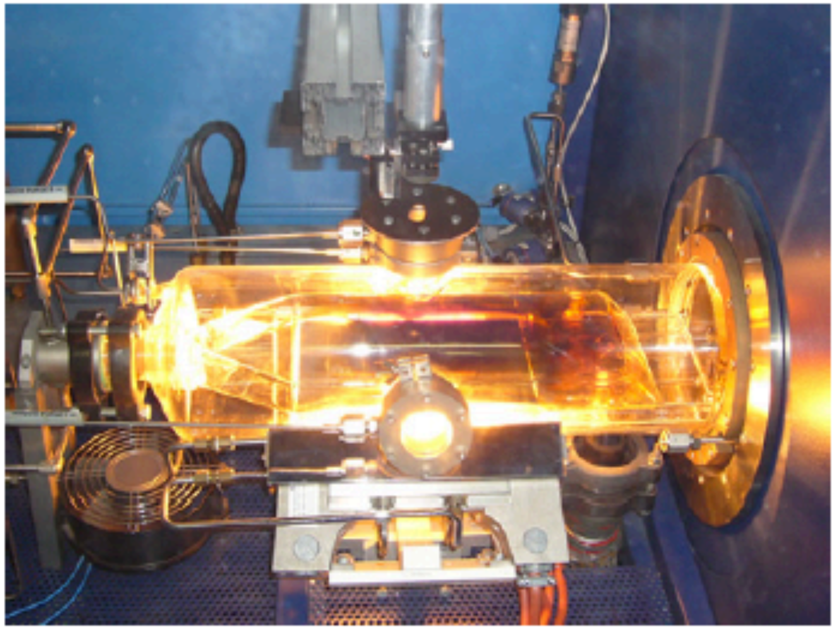
$$Q = \frac{\lambda_c}{\Delta\lambda_c} \simeq \frac{\pi (R_1 R_2)^{1/4}}{1-(R_1 R_2)^{1/2}}$$

$Q \sim 10^5 - 10^6$

Growing the geterostructures

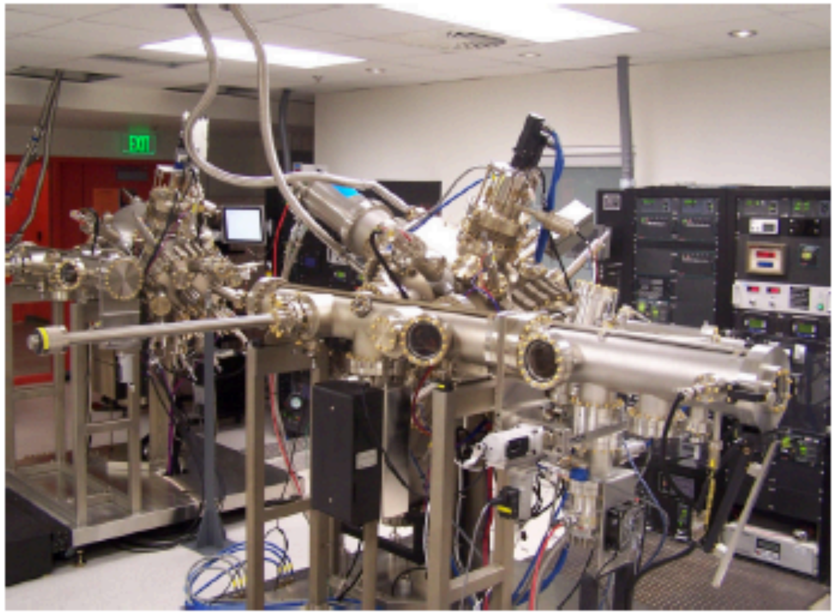
Metal-organic chemical vapour deposition (MOCVD)

- dissociation of low pressure flow of molecular gases (e.g. As_3, $(CH_3)_3Ga$)
- unwanted impurities (e.g. C, trace dopants)
- relatively fast - industry preferred



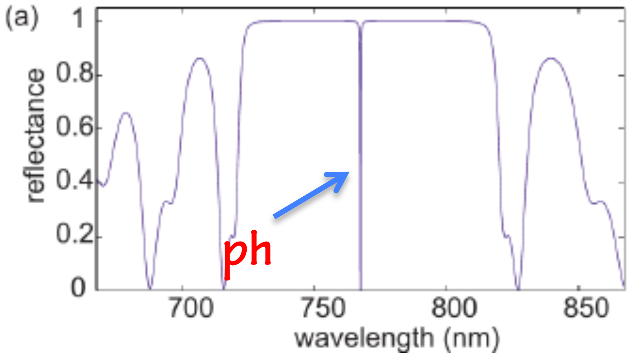
Molecular-beam epitaxy (MBE)

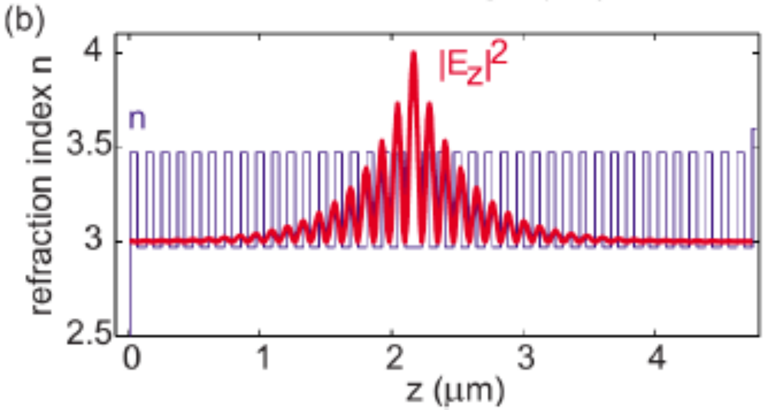
- dissociated molecular beams under UHV
- slow, but very precise
- low impurities and disorder
- method of choice for polariton microcavities



Microcavity spectrum

photon mode
in a microcavity





$$E_{\text{cav}} = \frac{\hbar c}{n_c}\sqrt{k_\perp^2 + k_\parallel^2}$$

$$k_\perp = n_c(2\pi/\lambda_c)$$

In the region $k_\parallel \ll k_\perp$, we have

$$E_{\text{cav}} \approx \frac{\hbar c}{n_c} k_\perp \left(1 + \frac{k_\parallel^2}{2k_\perp^2}\right) = E_{\text{cav}}(k_\parallel = 0) + \frac{\hbar^2 k_\parallel^2}{2m_{\text{cav}}}$$

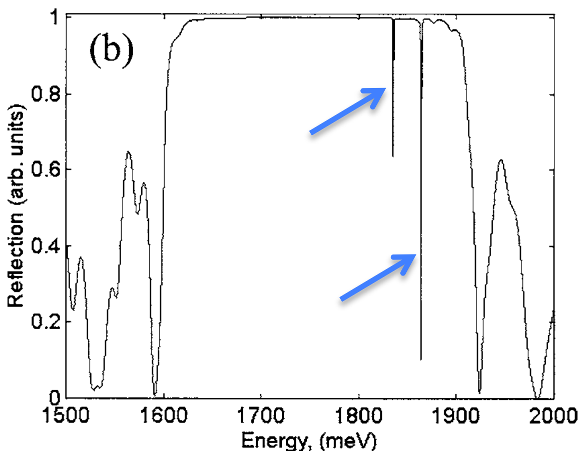
$$m_{\text{cav}} = \frac{E_{\text{cav}}(k_\parallel = 0)}{c^2/n_c^2}$$

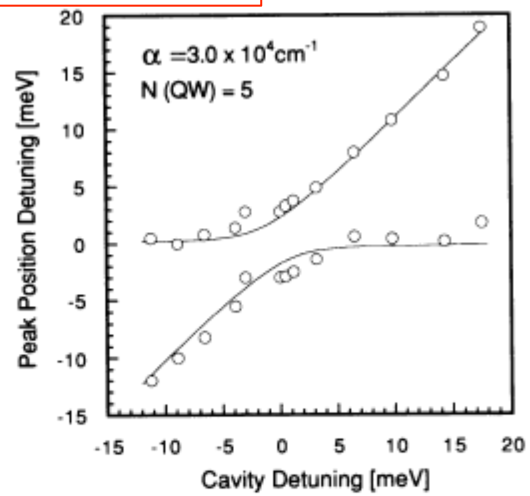
$\sim 10^{-5} m_e$

microcavity + QW:

normal mode
splitting;

avoided crossing





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

Quantum picture of light-matter coupling

The linear Hamiltonian of the system in the second-quantization form:

$$\hat{H}_{\mathrm{pol}} = \hat{H}_{\mathrm{cav}} + \hat{H}_{\mathrm{exc}} + \hat{H}_I = \sum E_{\mathrm{cav}}(k_\parallel, k_c)\hat{a}^\dagger_{k_\parallel}\hat{a}_{k_\parallel} + \sum E_{\mathrm{exc}}(k_\parallel)\hat{b}^\dagger_{k_\parallel}\hat{b}_{ky} + \sum g_0(\hat{a}^\dagger_{k_\parallel}\hat{b}_{k_\parallel} + \hat{a}_{k_\parallel}\hat{b}^\dagger_{k_\parallel})$$

$\hat{a}^\dagger_{k_\parallel}$ and $\hat{b}^\dagger_{k_\parallel}$ are photon and exciton creation operator with in-plane wavevector $k_\parallel$

$k_c = \boldsymbol{k}\cdot\hat{z}$ longitudinal wavevector defined by cavity resonance

g_0 strength of exciton-photon dipole interaction

$$\hat{P}_{k_\parallel} = X_{k_\parallel}\hat{b}_{k_\parallel} + C_{k_\parallel}\hat{a}_{k_\parallel},$$

$$\hat{Q}_{k_\parallel} = -C_{k_\parallel}\hat{b}_{k_\parallel} + X_{k_\parallel}\hat{a}_{k_\parallel}$$

Creation and annihilation operators of the new bosonic quasiparticles (eigenmodes) – upper and lower polaritons

$$\hat{H}_{\mathrm{pol}} = \sum E_{\mathrm{LP}}(k_\parallel)\hat{P}^\dagger_{k_\parallel}\hat{P}_{k_\parallel} + \sum E_{\mathrm{UP}}(k_\parallel)\hat{Q}^\dagger_{k_\parallel}\hat{Q}_{k_\parallel}$$

The Hopfield coefficients define proportion of photon/exciton in a polariton:

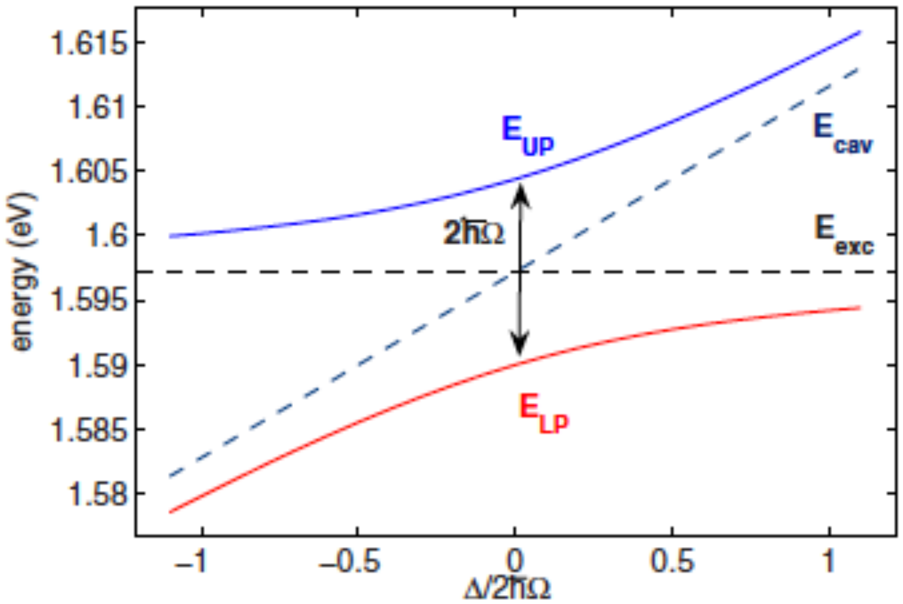
$$|X_{k_\parallel}|^2 = \frac{1}{2}\left(1 + \frac{\Delta E(k_\parallel)}{\sqrt{\Delta E(k_\parallel)^2 + 4g_0^2}}\right) \qquad |C_{k_\parallel}|^2 = \frac{1}{2}\left(1 - \frac{\Delta E(k_\parallel)}{\sqrt{\Delta E(k_\parallel)^2 + 4g_0^2}}\right)$$

$$\Delta E(k_\parallel) = E_{\mathrm{exc}}(k_\parallel) - E_{\mathrm{cav}}(k_\parallel, k_c)$$

$$|X_{k_\parallel}|^2 + |C_{k_\parallel}|^2 = 1$$

Deng, Haug, Yamamoto, Rev. Mod. Phys. 82, 1489 (2010)

Polariton: part-light and part-matter



$$E_{\mathrm{LP,UP}}(k_\parallel) = \tfrac{1}{2}[E_{\mathrm{exc}} + E_{\mathrm{cav}} \pm \sqrt{4g_0^2 + (E_{\mathrm{exc}} - E_{\mathrm{cav}})^2}]$$

Rabi (normal mode) splitting

$$E_{\mathrm{UP}} - E_{\mathrm{LP}} = 2g_0$$

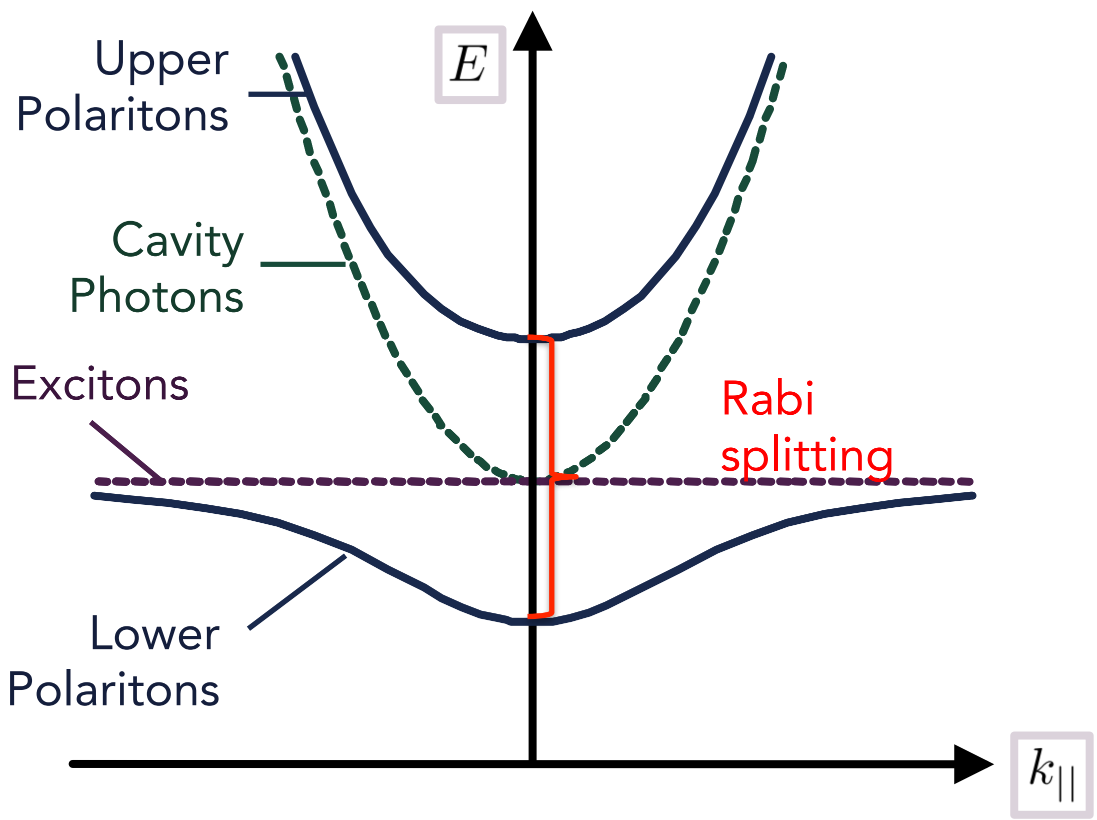
$$\hbar^2 k_\parallel^2 / 2m_{\mathrm{cav}} \ll 2g_0$$

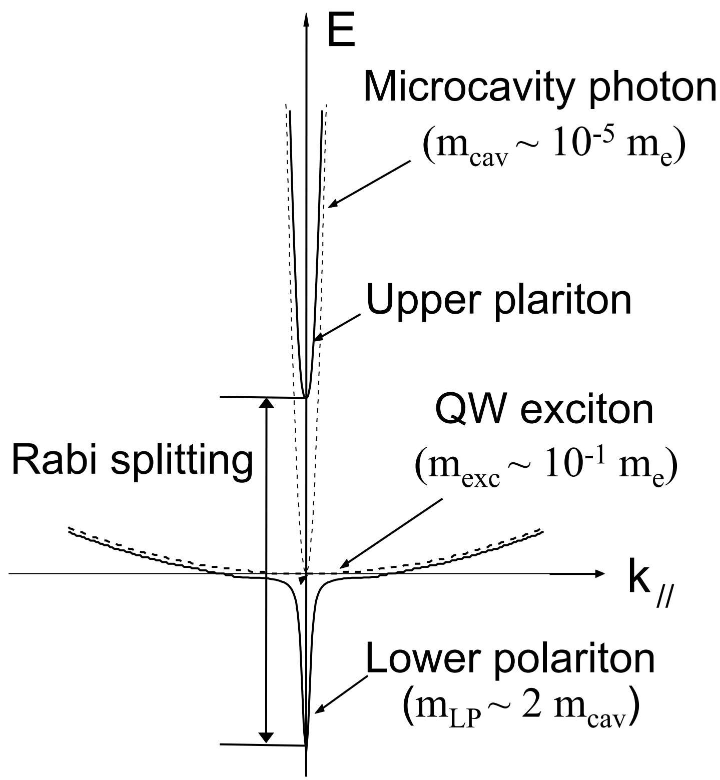
$$E_{\mathrm{LP,UP}}(k_\parallel) \simeq E_{\mathrm{LP,UP}}(0) + \frac{\hbar^2 k_\parallel^2}{2m_{\mathrm{LP,UP}}}$$

$$\frac{1}{m_{LP}} = \frac{|X|^2}{m_{exc}} + \frac{|C|^2}{m_{cav}}$$
$$\frac{1}{m_{UP}} = \frac{|C|^2}{m_{exc}} + \frac{|X|^2}{m_{cav}}$$

$$\boxed{\begin{aligned} m_{LP}(k_\parallel \sim 0) &\simeq m_{cav}/|C|^2 \sim 10^{-4} m_{exc} \\ m_{UP}(k_\parallel \sim 0) &\simeq m_{cav}/|X|^2. \end{aligned}}$$

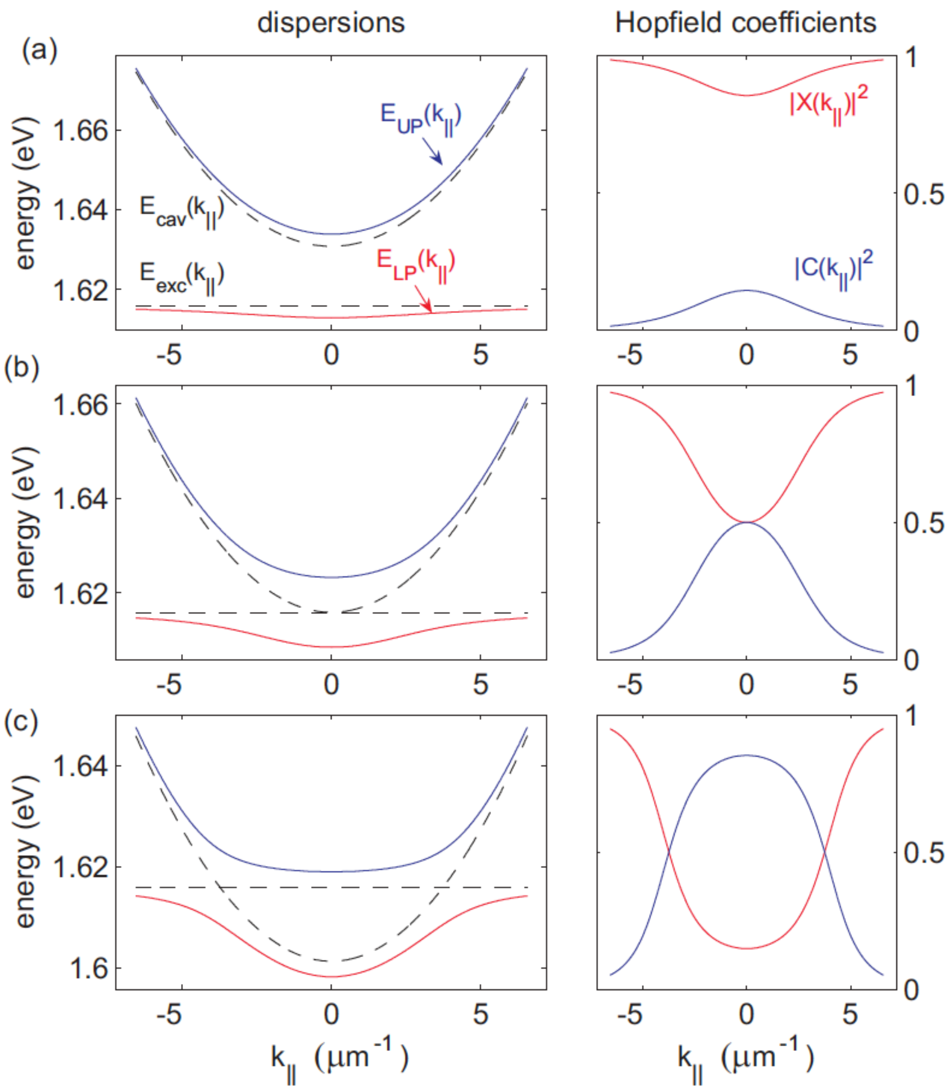
Polariton dispersion





$$E_{LP,UP}(k_{\|}) = \frac{1}{2}\left[E_{exc} + E_{cav} \pm \sqrt{4\hbar^2\Omega^2 + (E_{exc} - E_{cav})^2}\ \right]$$

(Not quite) half-light half-matter



Photon part (light):

- light effective mass (~10^{-5} m_e)
- fast propagation (~µm/ps)
- short lifetime (~ps)
- low dephasing (~ns)

Exciton part (matter):

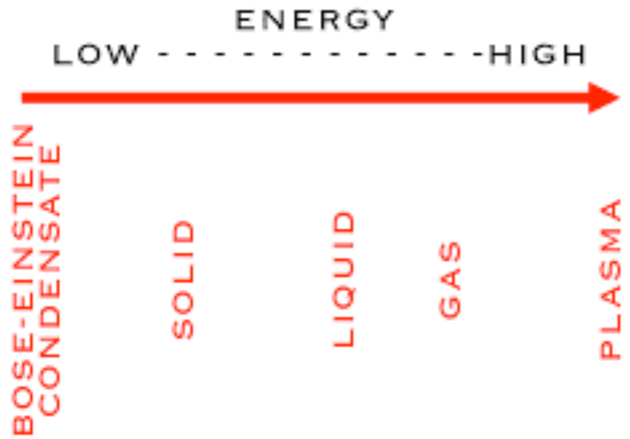
- nonlinear interactions
- electric + magnetic field dependence

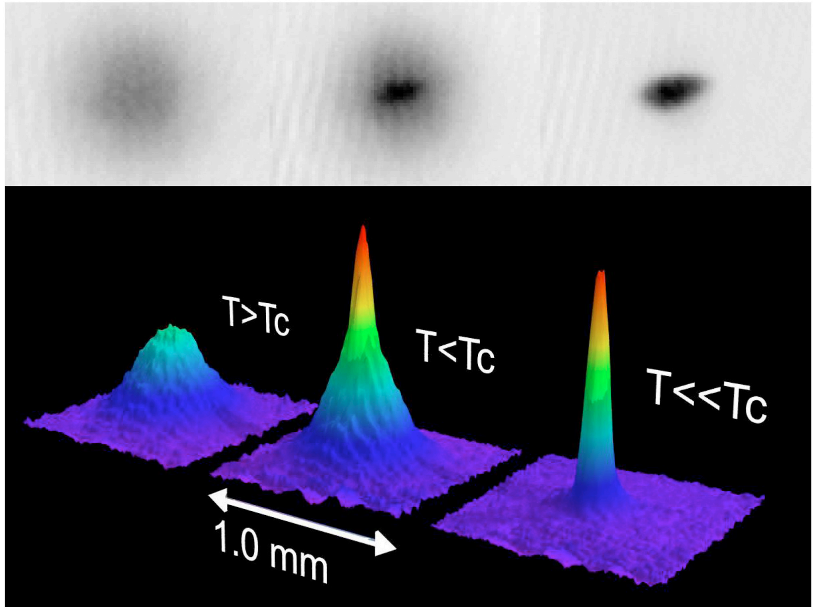
Hybrid property:

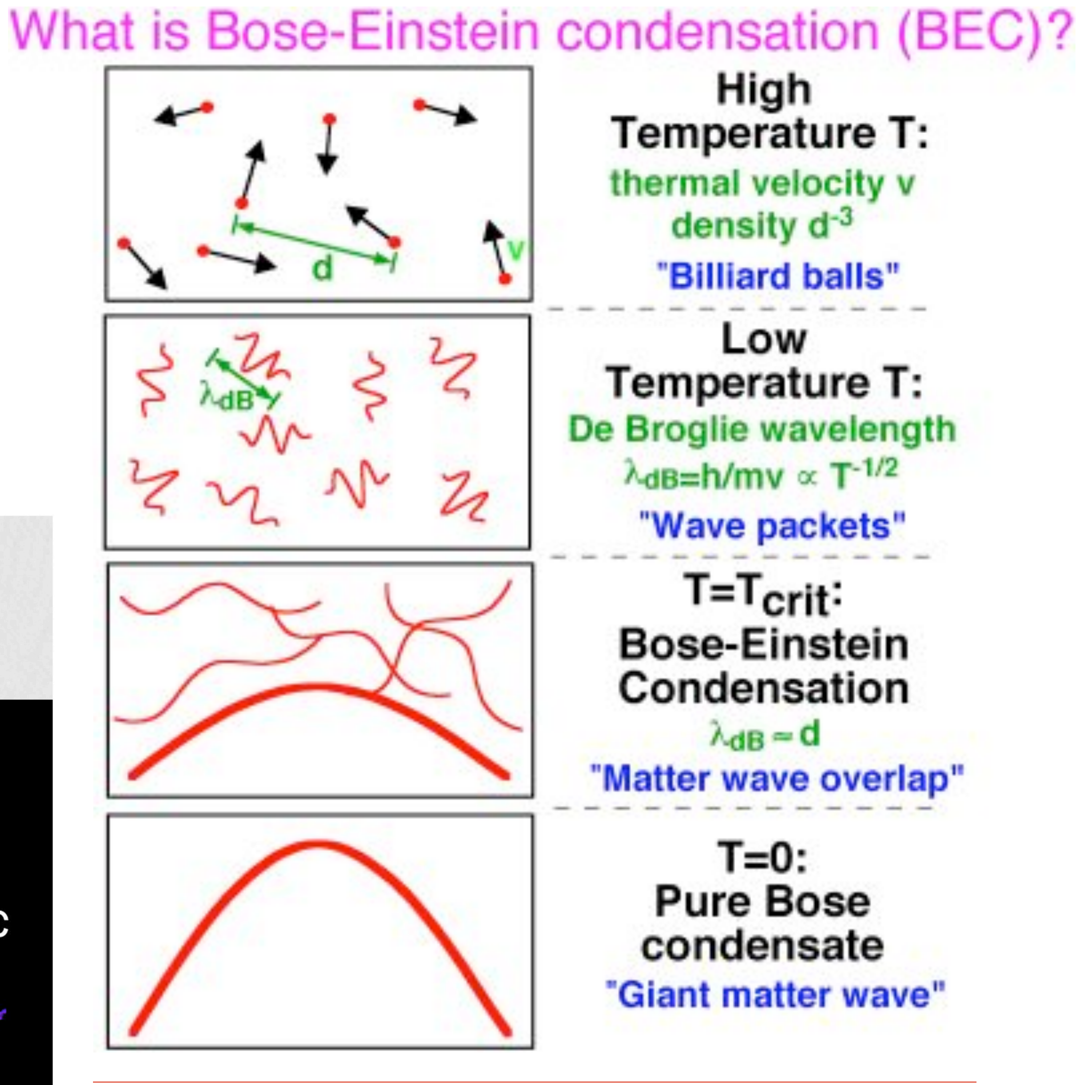
- spin degree of freedom

H. Deng et al., Rev. Mod. Phys. 82, 1489 (2010)

Bose-Einstein condensation







BEC of neutral alkaline atoms

- Created in 1995, Nobel Prize in 2001
- Access to quantum physics on a macroscopic scale
- Studies of fundamental physics (quantum many-body physics and nonlinear dynamics)
- Clean, very controllable system
- Basis for ultra-precise sensing and measurement, quantum simulation
- Atom laser
- On-chip integration (?)
- Ultracold (~nK) temperatures, ultra-high vacuum

- How does the polariton BEC compare?

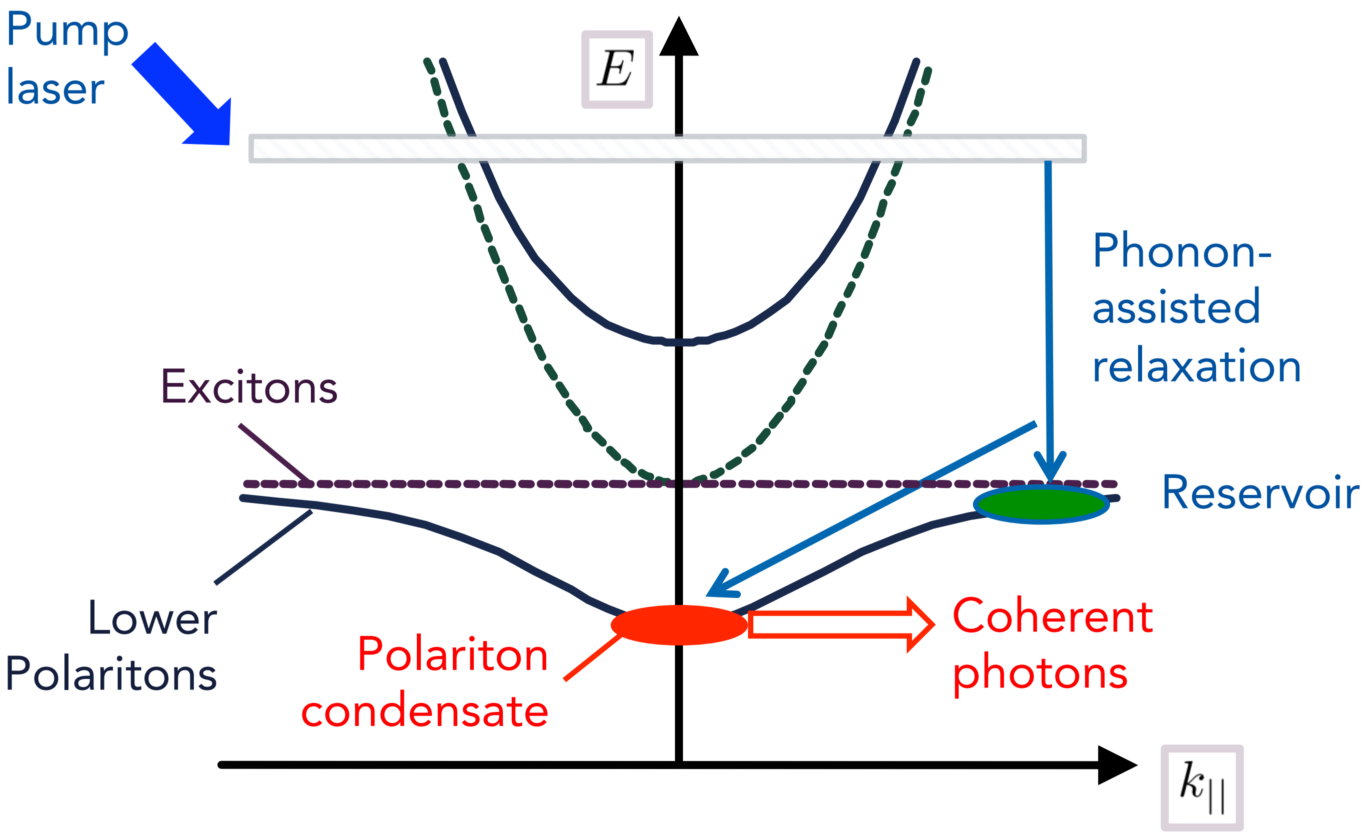
Can polaritons condense?

TABLE I. Parameter comparison of BEC systems.

Systems	Atomic gases	Excitons	Polaritons
Effective mass m^*/m_e	10^3	10^{-1}	$\boxed{10^{-5}}$
Bohr radius a_B	10^{-1} Å	10^2 Å	10^2 Å
Particle spacing: $n^{-1/d}$	10^3 Å	10^2 Å	1 μm
Critical temperature T_c	1 nK–1 μK	1 mK–1 K	$\boxed{1\text{–}>300\ \text{K}}$
Thermalization time/Lifetime	1 ms/1 s $\sim 10^{-3}$	10 ps/1 ns $\sim 10^{-2}$	(1–10 ps)/(1–10 ps)=0.1–10

Critical temperature is inversly proportional to the mass of the condensing particles!

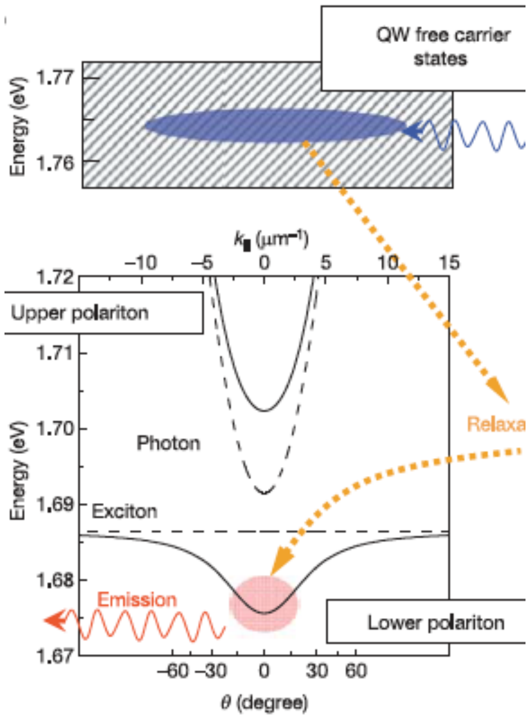
Polariton condensation

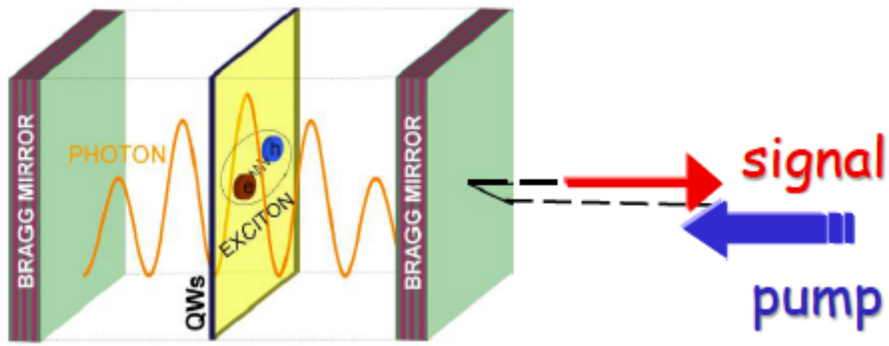


- non-resonant, incoherent pump
- LP-LP interactions
- phonon scattering
- low threshold lasing w/out population inversion

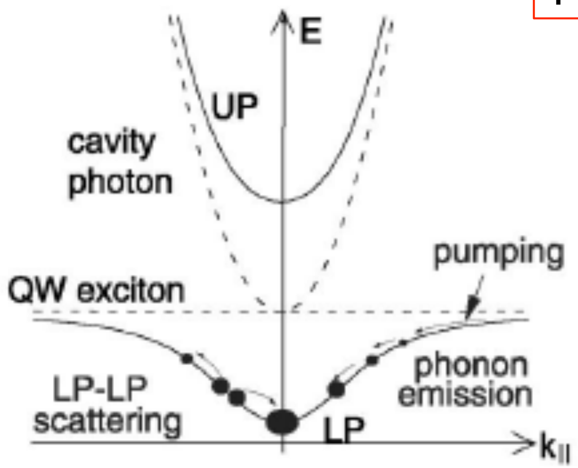
Condensate forms by stimulated scattering of polaritons from an incoherent reservoir – reservoir plays a strong role in condensate dynamics

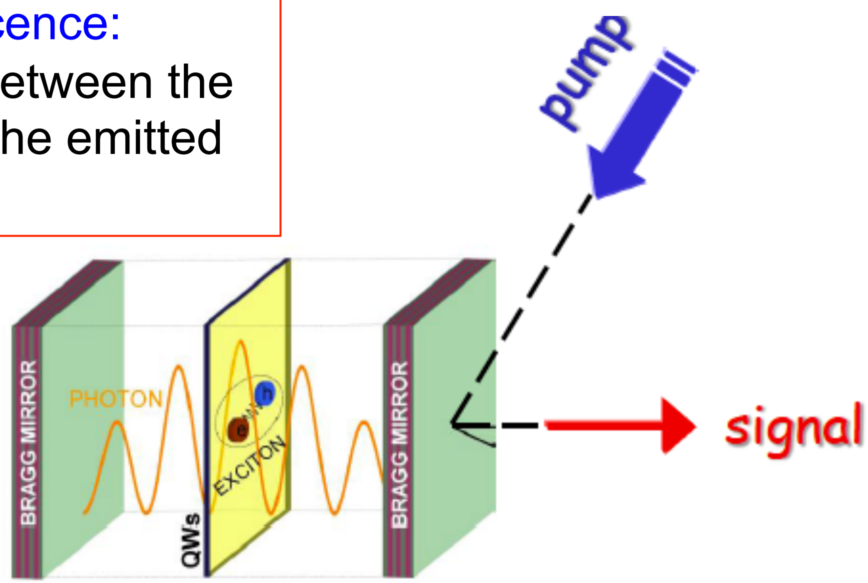
Incoherent pumping schemes



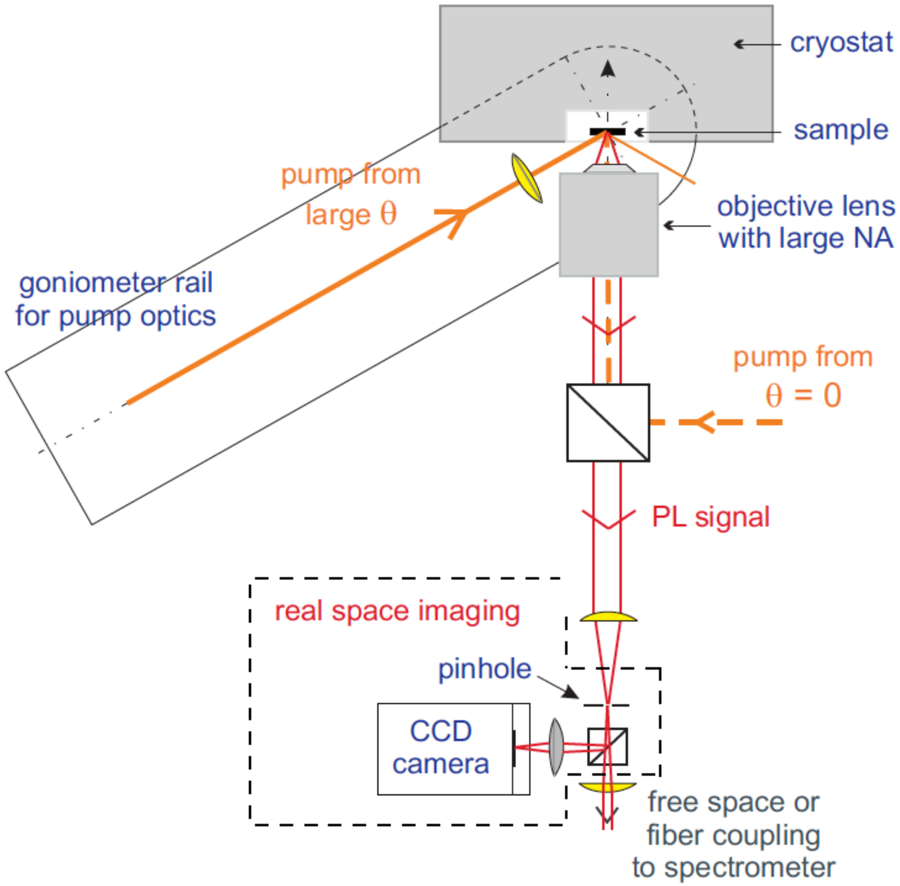


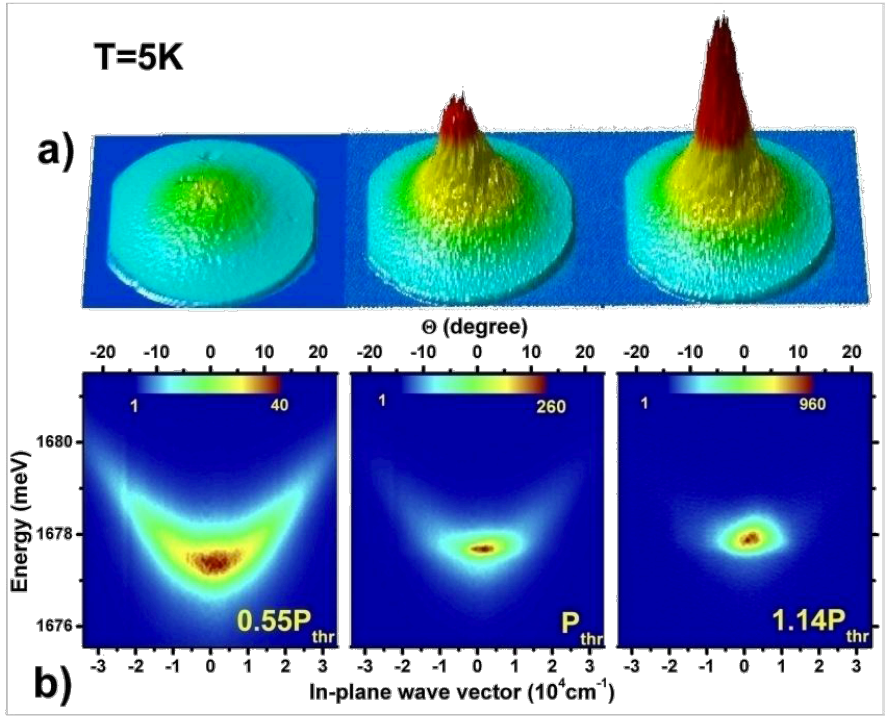
angle-resolved photoluminescence:
1:1 mapping between the polariton and the emitted photon $k_{//}$





Polariton BEC experiment





Transition to condensation with increasing laser power @ T=5K

From cavity emission we extract: energy, momentum, polarization, coherence, noise properties, spatial distribution of probability density (wavefunction)

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