Microcavity Exciton-Polariton

Neil Na (那允中)

Institute of Photonics Technologies
National Tsing-Hua University

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Outline

- Microcavity Exciton-polariton
  - QW excitons
  - Microcavity photons
  - Strong coupling regime: exciton-polariton
- Dynamic Condensation of Exciton-Polariton
  - Dynamic polariton BEC
  - Polariton laser
  - Equilibrium Polariton BEC
  - Beyond BEC
- Quantum simulator of many-body system
  - Bose-Hubbard & Fermi-Hubbard model
  - Higher-orbital state condensation
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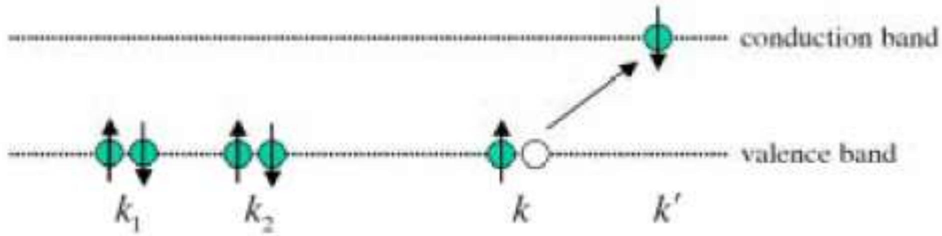
QW excitons

- Wannier exciton:



$$\hat{H} = \int d^3\boldsymbol{x}\hat{\psi}^\dagger(\boldsymbol{x})\hat{H}_0(\boldsymbol{x})\hat{\psi}^\dagger(\boldsymbol{x}) + \frac{1}{2}d^3\boldsymbol{x}d^3\boldsymbol{y}\hat{\psi}^\dagger(\boldsymbol{x})\hat{\psi}^\dagger(\boldsymbol{y})\hat{V}(\boldsymbol{x}-\boldsymbol{y})\hat{\psi}(\boldsymbol{x})\hat{\psi}(\boldsymbol{y})$$

free Hamiltonian — **screened Coulomb potential**

$$\hat{\psi}(\boldsymbol{x}) = \sum_{j=c,v;\boldsymbol{k}} \hat{a}_{\boldsymbol{k}j}\psi_{\boldsymbol{k}j}(\boldsymbol{x})$$

$$\hat{a}^\dagger_{\boldsymbol{k}v} = \hat{b}_{-\boldsymbol{k}}$$

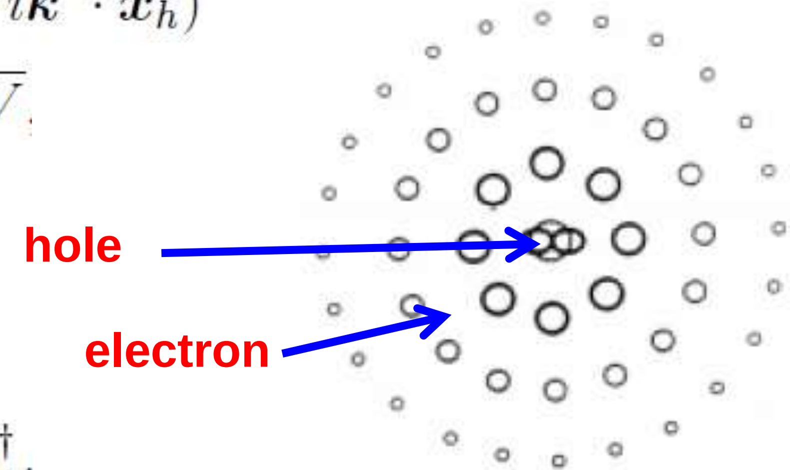
$$|p\rangle = \sum C_{\boldsymbol{k}\boldsymbol{k}'}\hat{a}^\dagger_{\boldsymbol{k}}\hat{b}^\dagger_{\boldsymbol{k}'}|vac\rangle$$

$$\hat{H}_{exc} = -\frac{\hbar^2}{2m_e}\nabla_e - \frac{\hbar^2}{2m_h}\nabla_h + E_g - \frac{e^2}{\epsilon|\boldsymbol{x}_e - \boldsymbol{x}_h|}$$

Wannier approximation

$$\phi(\boldsymbol{x}_e, \boldsymbol{x}_h) = \sum C_{\boldsymbol{k}\boldsymbol{k}'} \exp(i\boldsymbol{k}\cdot\boldsymbol{x}_e + i\boldsymbol{k}'\cdot\boldsymbol{x}_h)$$

$$\phi(\boldsymbol{x}_e, \boldsymbol{x}_h) = \phi_n(\boldsymbol{r}) \exp(i\boldsymbol{K}\cdot\boldsymbol{R})/\sqrt{V}$$

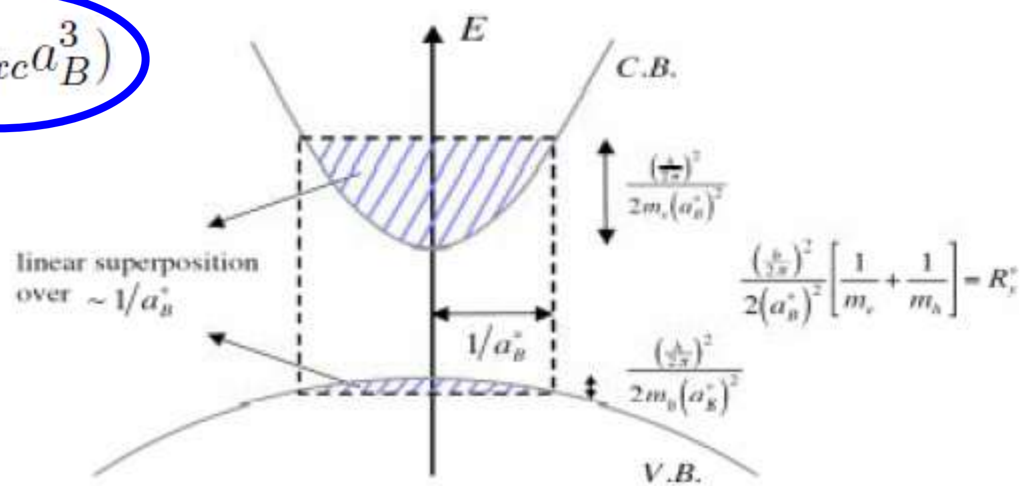


$$|p\rangle = \hat{e}^{\dagger}_{\boldsymbol{K},n}|vac\rangle$$

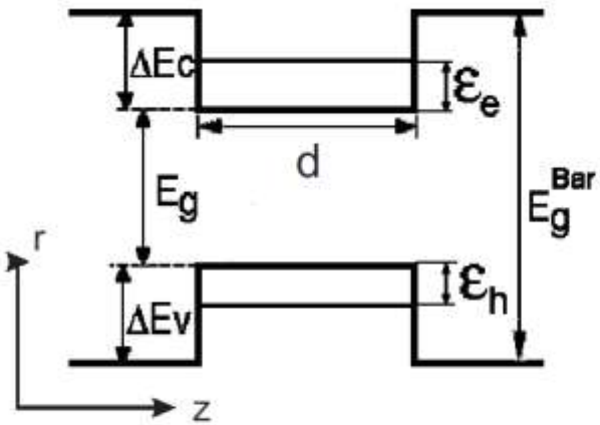
$$\hat{e}^{\dagger}_{\boldsymbol{K},n} = \sum_{\boldsymbol{k},\boldsymbol{k}'} \delta_{\boldsymbol{K},\boldsymbol{k}+\boldsymbol{k}'} \phi_n(\beta_h \boldsymbol{k} - \beta_e \boldsymbol{k}') \hat{a}^{\dagger}_{\boldsymbol{k}} \hat{b}^{\dagger}_{\boldsymbol{k}'}$$

$$[\hat{e}_{\boldsymbol{K}',n'}, \hat{e}^{\dagger}_{\boldsymbol{K},n}] = \delta_{\boldsymbol{K}\boldsymbol{K}'}\delta_{nn'} - O(n_{exc}a_B^3)$$

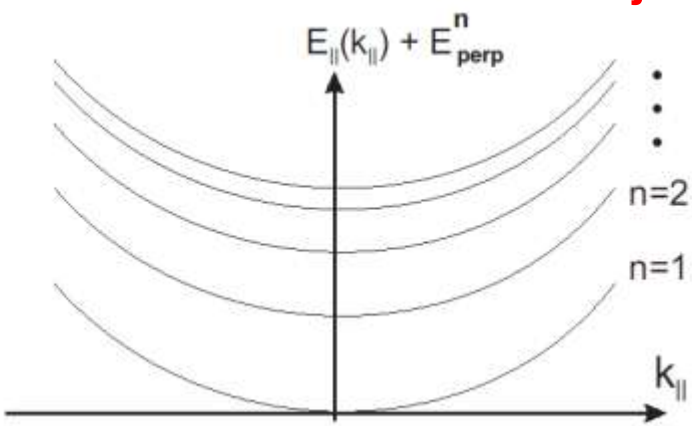
excitons are bosonic at low-density limit



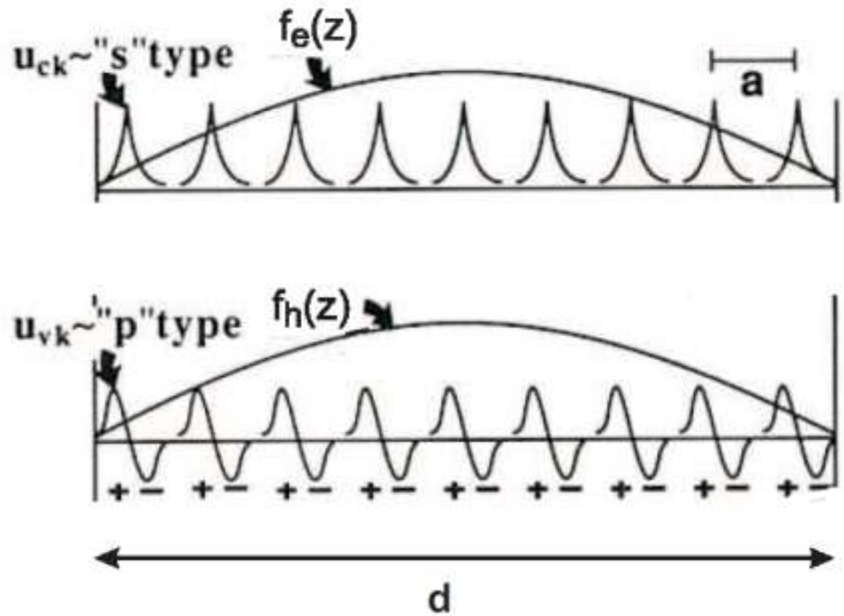
- QW interband transition



heterojunction



dispersion



we consider only interband transition in this presentation!

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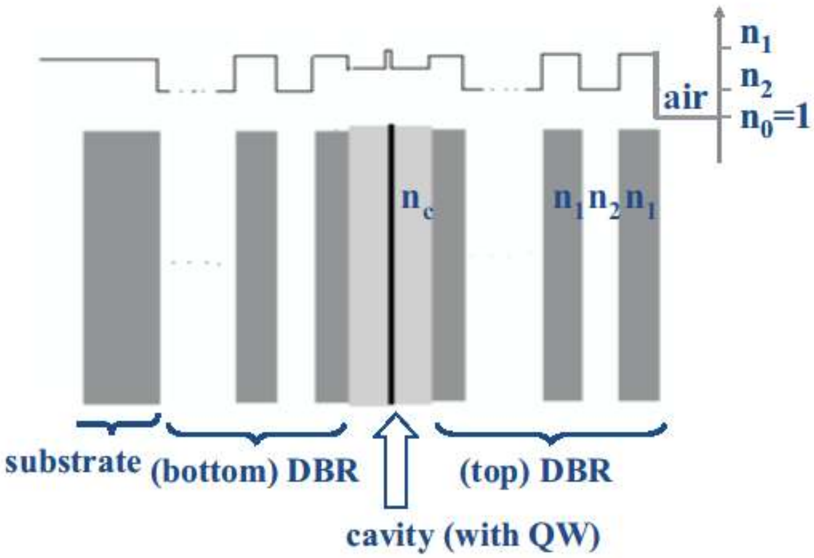
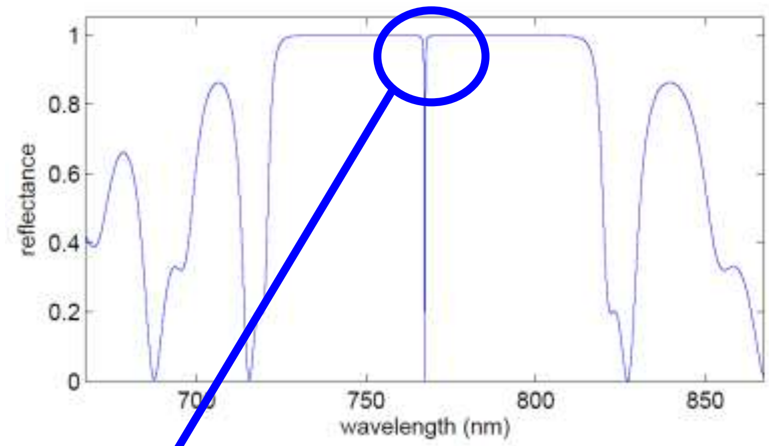
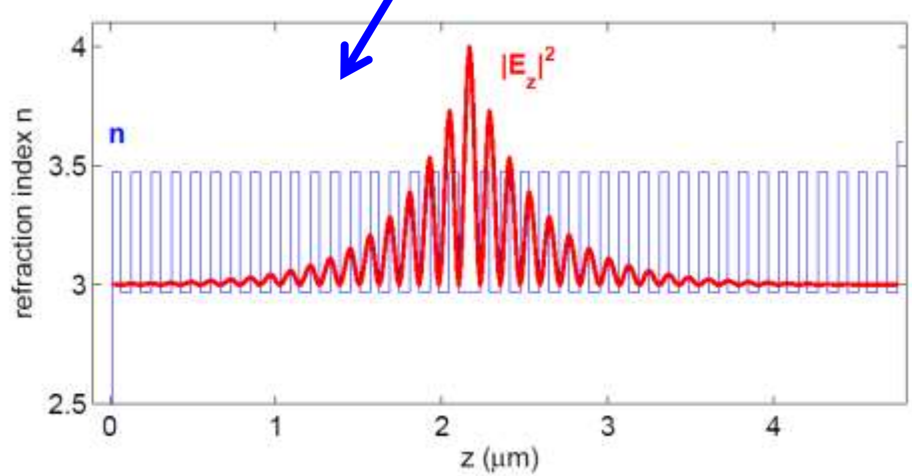
Microcavity photons

- DBR cavity:

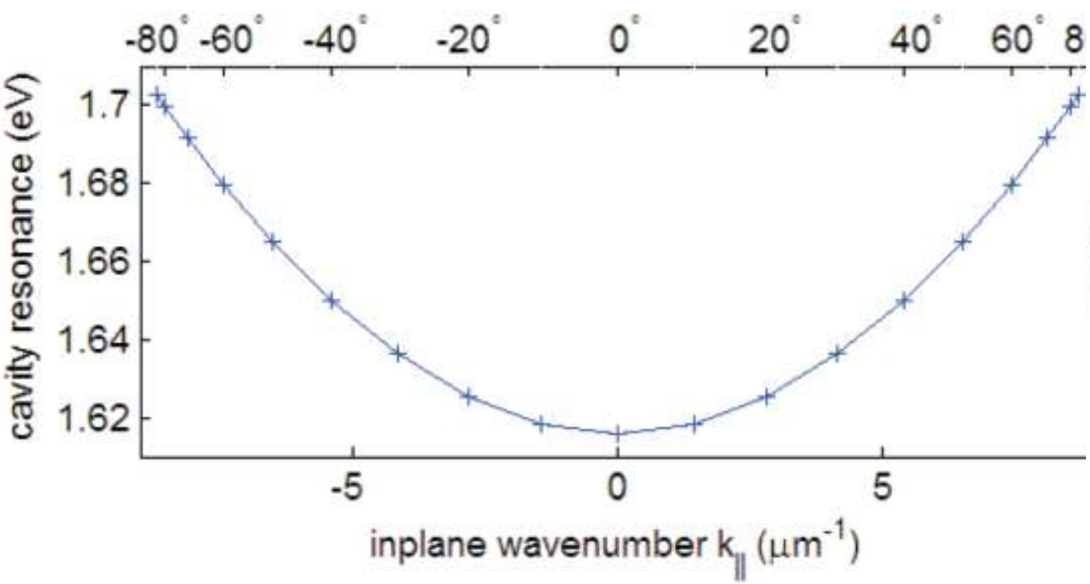


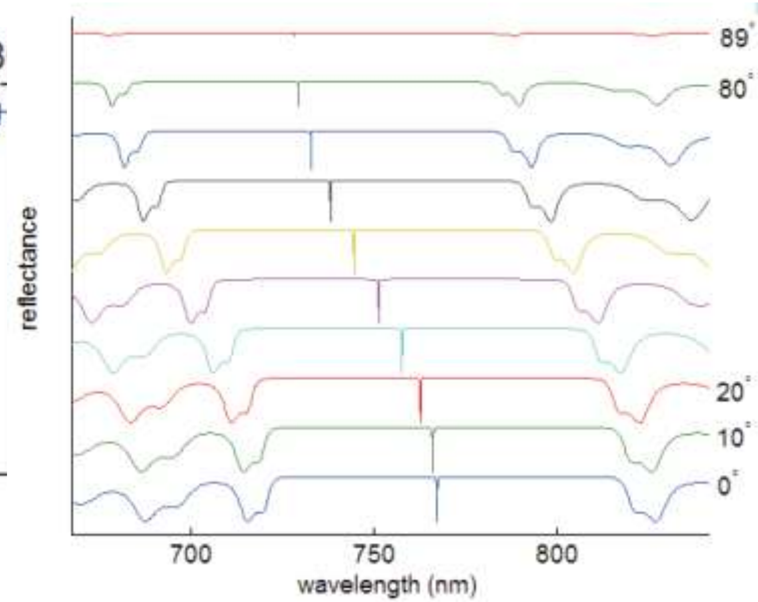




small mode volume & large quality factor can be achieved

- Dispersion & effective mass





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

$$= E_{cav}(k_\parallel = 0) + \frac{\hbar^2 k_\parallel^2}{2(2\pi\hbar/\lambda_c c)} = E_{cav0} + \frac{\hbar^2 k_\parallel^2}{2m_{cav}}$$

~$10^{-4}m_{ex}$

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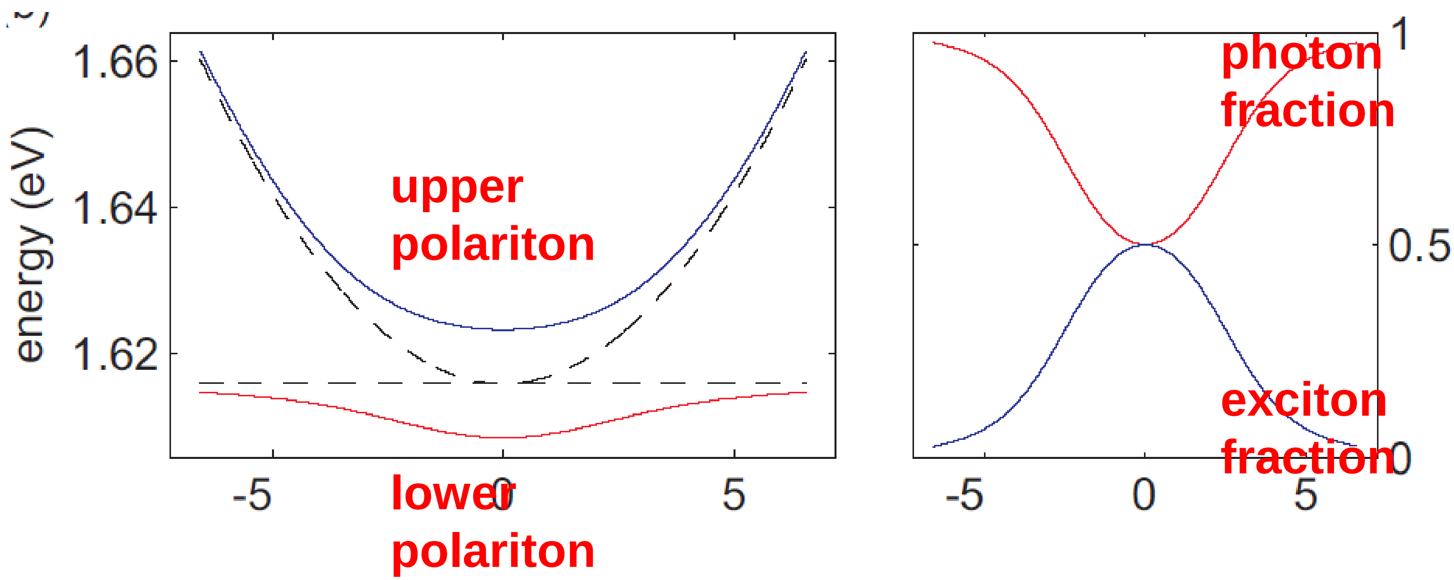
Strong coupling regime: exciton-polariton

- Strong coupling

$$\hat{H}_{pol} = \hat{H}_{cav} + \hat{H}_{exc} + \hat{H}_I$$
$$= \sum E_{cav}(k_\parallel, k_c)\hat{a}^\dagger_{\boldsymbol{k}_\parallel}\hat{a}_{\boldsymbol{k}_\parallel} + \sum E_{exc}(k_\parallel)\hat{e}^\dagger_{\boldsymbol{k}_\parallel}\hat{e}_{\boldsymbol{k}y} + \sum \hbar\Omega(\hat{a}^\dagger_{\boldsymbol{k}_\parallel, k_c}\hat{e}_{\boldsymbol{k}_\parallel} + \hat{a}_{\boldsymbol{k}_\parallel}\hat{e}^\dagger_{\boldsymbol{k}_\parallel})$$

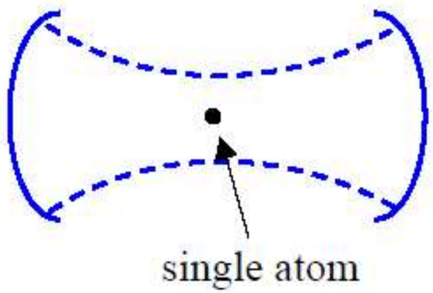
$$\hat{p}_{\boldsymbol{k}_\parallel} = X_{\boldsymbol{k}_\parallel}\hat{e}_{\boldsymbol{k}_\parallel} + C_{\boldsymbol{k}_\parallel}\hat{a}_{\boldsymbol{k}_\parallel}$$
$$\hat{q}_{\boldsymbol{k}_\parallel} = -C_{\boldsymbol{k}_\parallel}\hat{e}_{\boldsymbol{k}_\parallel} + X_{\boldsymbol{k}_\parallel}\hat{a}_{\boldsymbol{k}_\parallel}$$

$$\hat{H}_{pol} = \sum E_{LP}(k_\parallel)\hat{p}^\dagger_{\boldsymbol{k}_\parallel}\hat{p}_{\boldsymbol{k}_\parallel} + \sum E_{UP}(k_\parallel)\hat{q}^\dagger_{\boldsymbol{k}_\parallel}\hat{q}_{\boldsymbol{k}_\parallel}$$



- Comparison between atomic & polaritonic cavity QED

single-atom cavity QED



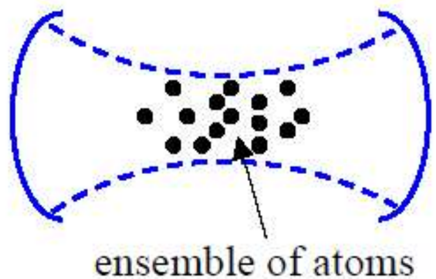
$$\Omega_R = \frac{d}{\hbar}\sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}}$$

d: atomic dipole moment
V: optical mode volume

⇩

$$\Omega_R \approx 10^3 \sim 10^6 (Hz)$$

many-atom cavity QED



eigenstate of collective angular momentum

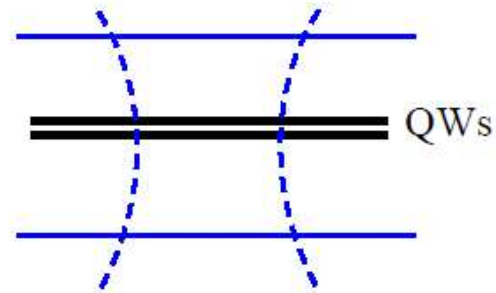
$$\hat{J}_+|J,-J\rangle = \sqrt{2J}|J,-J+1\rangle$$

($J = N/2$, N: # of atoms)

⇩

$$\Omega'_R = \Omega_R\sqrt{N}$$

exciton cavity QED



effective # of atomic oscillators:

$$N \approx \frac{S}{\pi a_B^{*2}} \approx 10^4 \sim 10^5$$

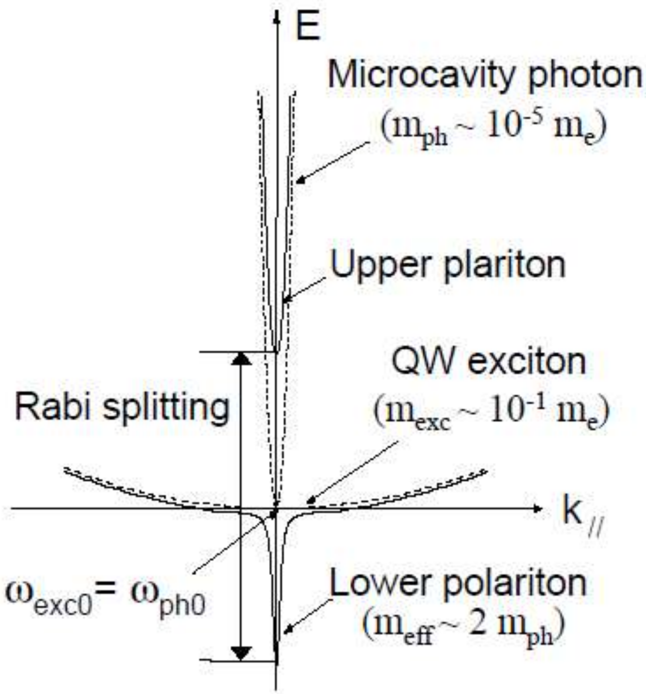
S: cavity mode area, ~2μm ϕ
a_B^*: Bohr radius, ~100A

⇩

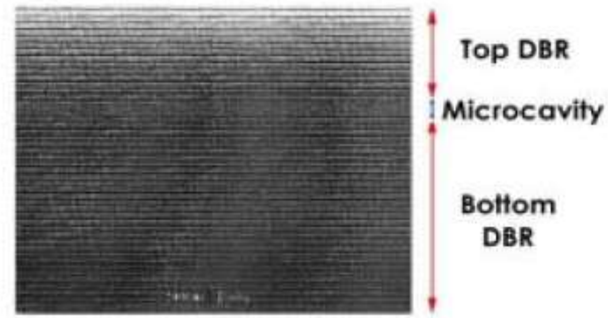
$$\Omega''_R \sim 10^{12} (Hz)$$

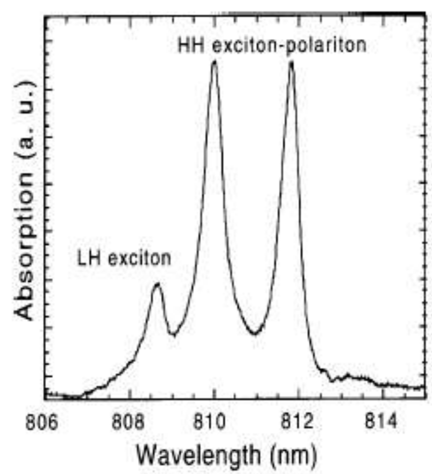
- Rabi splitting & oscillation

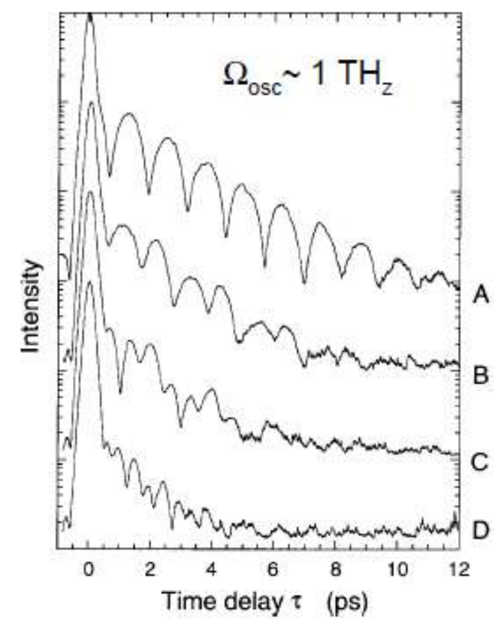
Polariton dispersion curves



C. Weisbuch, M. Nishioka, A. Ishikawa and Y. Arakawa, Phys. Rev. Lett. 69, 3314 (1992)







S. Jiang et al., Appl. Phys. Lett. 73, 3031 (1998)

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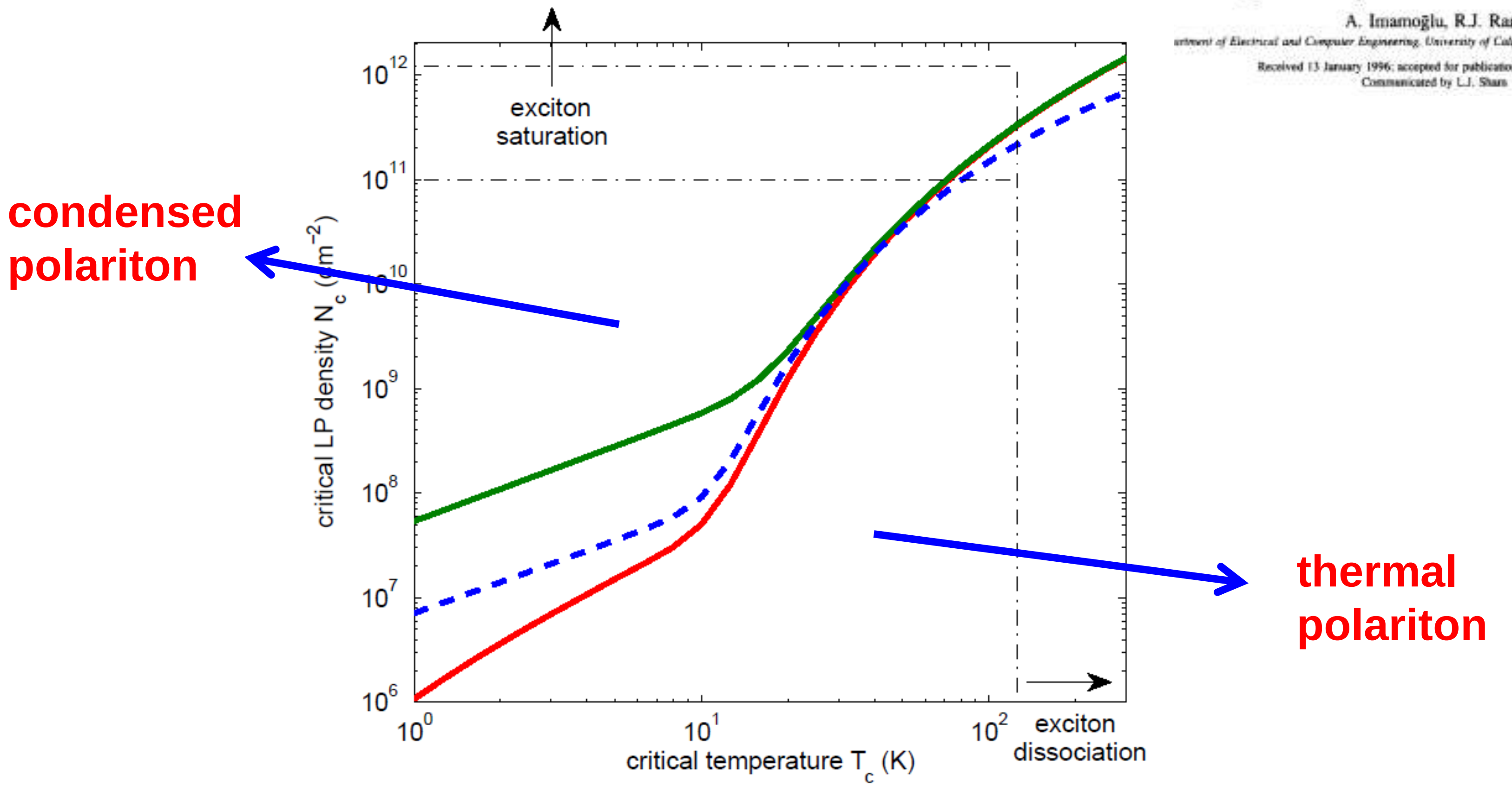
Dynamic polariton BEC

- Original proposal
  - Polariton should condense below/above critical temperature/density
  - A new type of coherent light source without population inversion

Quantum dynamics of exciton lasers

A. Imamoğlu, R.J. Ram
artment of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, USA

Received 13 January 1996; accepted for publication 29 February 1996
Communicated by L.J. Sham

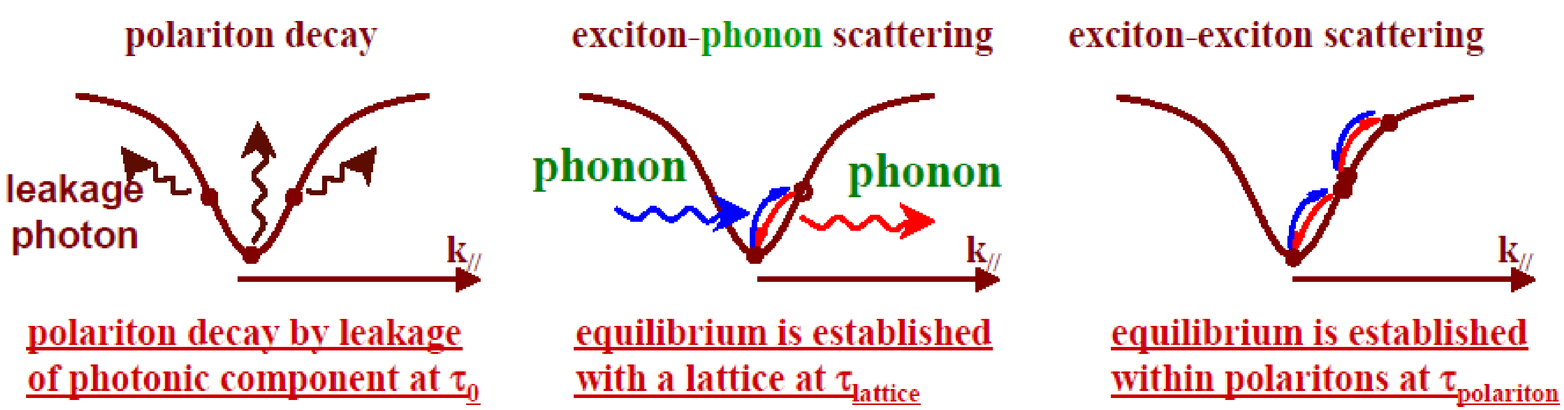


- Exciton BEC:
  - Disorder, localization (inhomogeneous broadening)
  - Dissociation of excitons (screening, phase space filling)
  - Long lifetime of indirect exciton

- Polariton BEC:
  - Extended phase coherence reinforced by a cavity field $\rightarrow$ suppression of inhomogeneous broadening
  - Binding energy enhancement by strong coupling $\rightarrow$ reduce dissociation of excitons
  - Extremely light effective mass $\rightarrow$ very high condensation temperature ($m_{polariton} \sim 10^{-4} m_{polariton} \sim 10^{-7} m_{atom}$)
  - Photonic component out-coupling from the cavity with k conservation in contrast to spontaneous decay of an un-dressed exciton $\rightarrow$ direct experimental access to internal polariton population
  - Short lifetime of microcavity photon

- Complications by time-scales

Polariton decay vs. Two relaxation processes

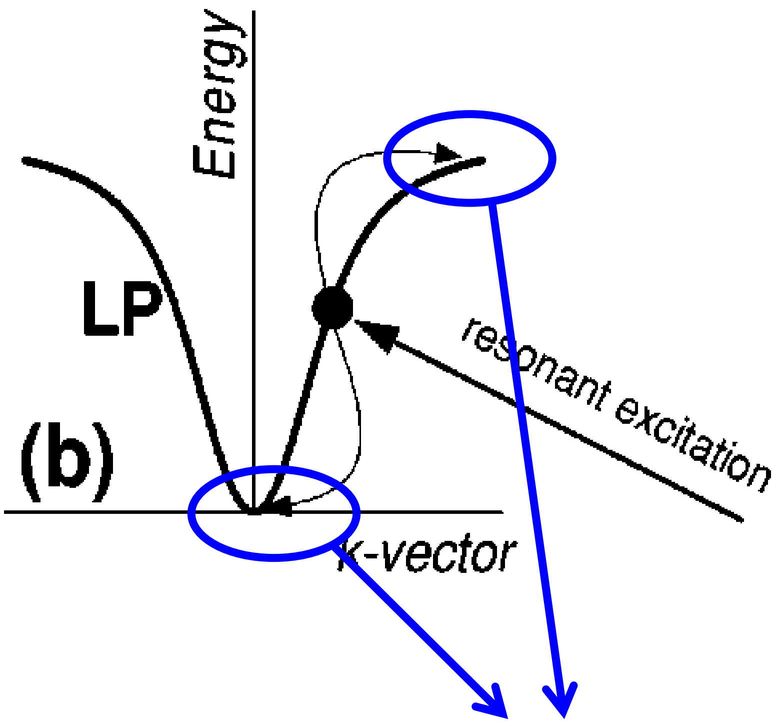


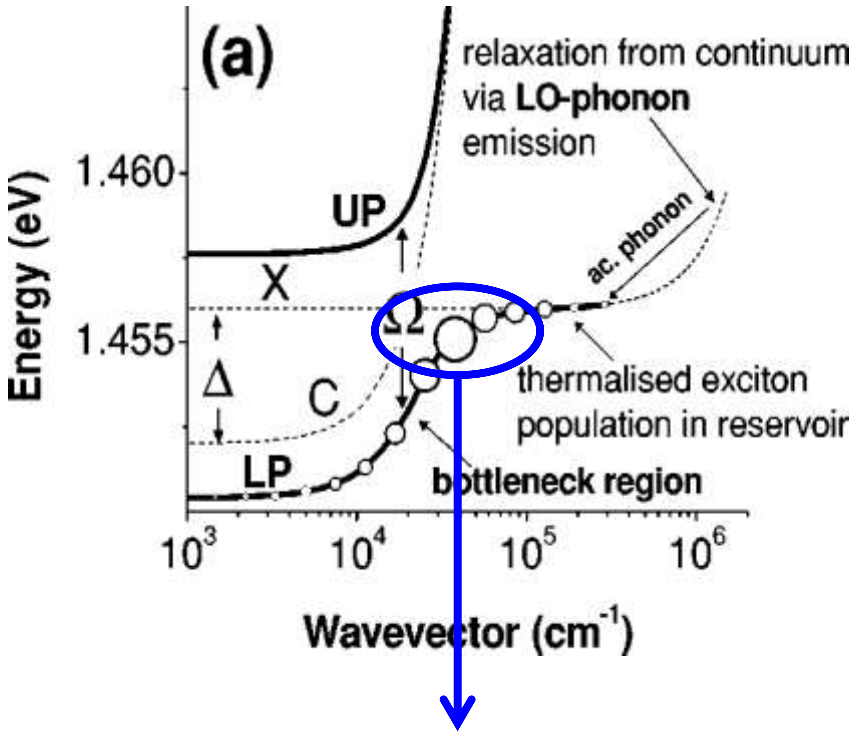
Non-equilibrium (multi-mode polariton laser)	Quasi-equilibrium (single-mode polariton laser)	Thermal equilibrium (polariton BEC)
$\tau_0 < \tau_{polariton} < \tau_{lattice}$	$\tau_{polariton} < \tau_0 < \tau_{lattice}$	$\tau_{polariton} < \tau_{lattice} < \tau_0$
$T_{polariton}$ not defined	$T_{polariton} > T_{lattice}$	$T_{polariton} = T_{lattice}$
	Fock exchange term ⇩	
Fragmentation of the condensate	Dynamic single-state condensation	Steady state single-state condensation

- Complications by excitation methods

resonant pumping

non-resonant pumping





four-wave mixing: residual coherence from external laser

relaxation bottleneck: sharp change of density of sttes

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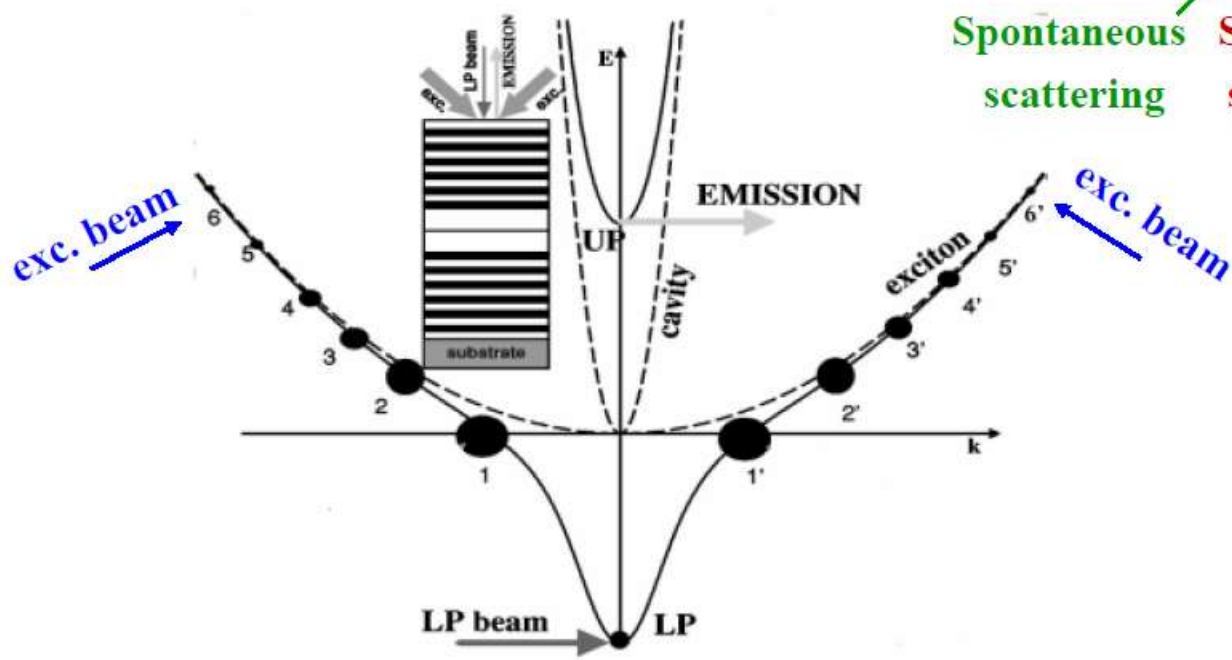
Polariton laser

- It was shown that the bosonic final state stimulation is needed to overcome the bottleneck effect, i.e., reaching polariton lasing.
- Demonstration of bosonic final state stimulation

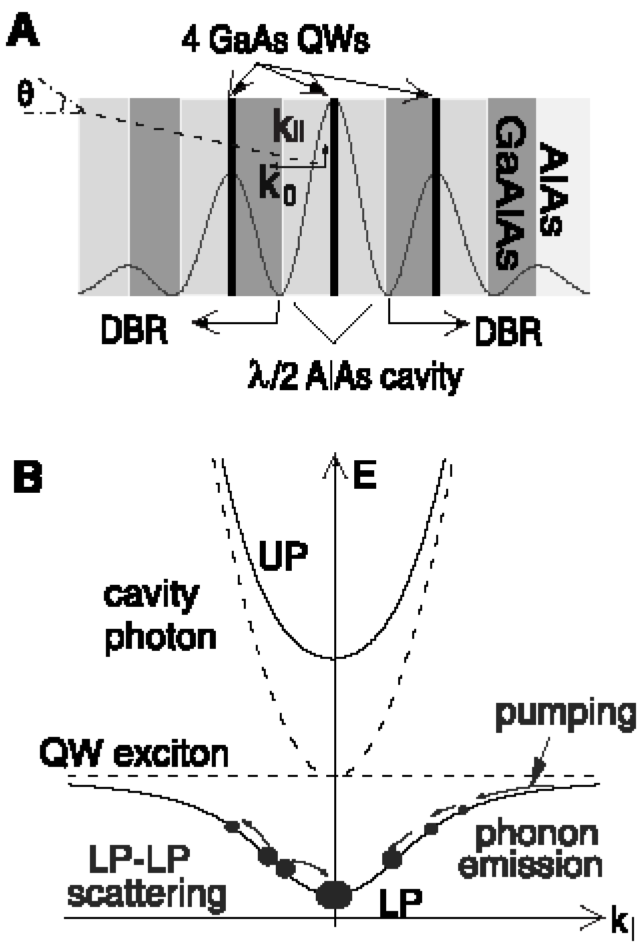
leakage from cavity — phonon scattering — exciton-exciton scattering

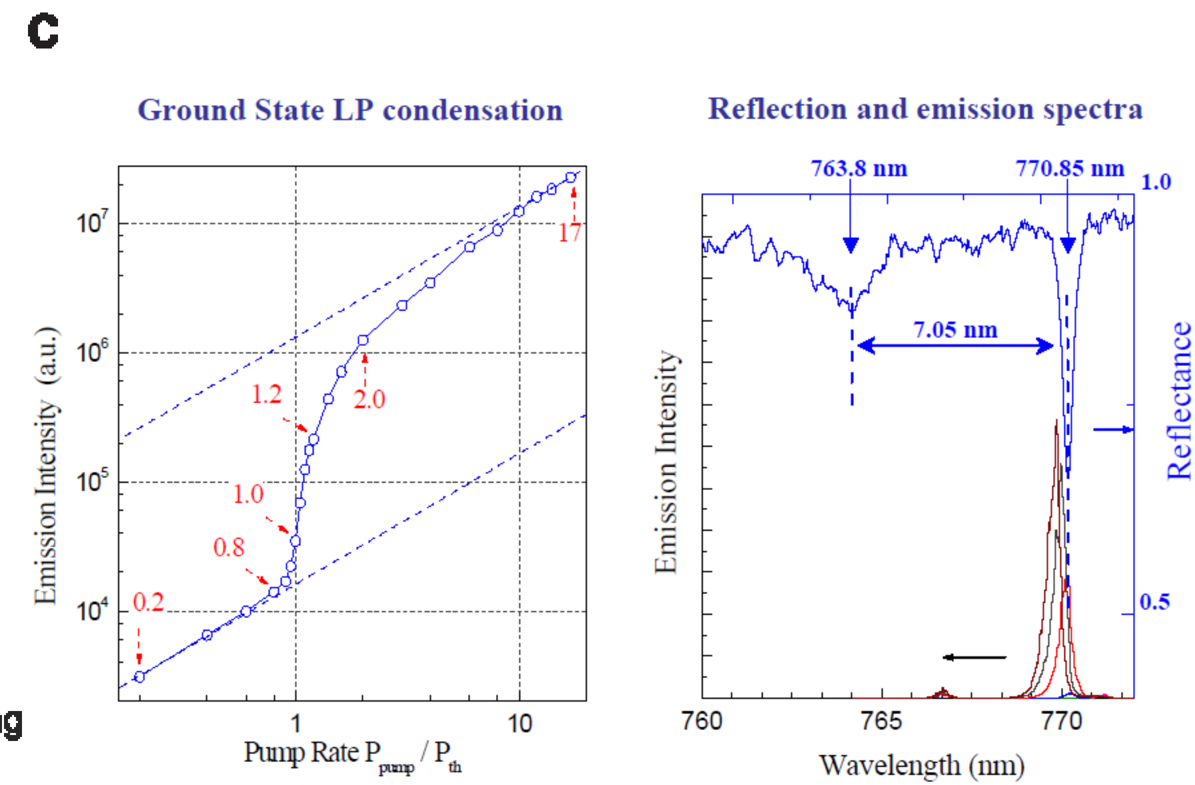
$$\frac{d}{dt}n_{UP} = -\frac{n_{UP}}{\tau_{UP}} + \sum_k a_k n_{LP,k} + b_{k_0} n_{LP,k_0} n_{LP,-k_0}(1 + n_{LP})$$

Spontaneous scattering (1) — Stimulated scattering (n_{LP})



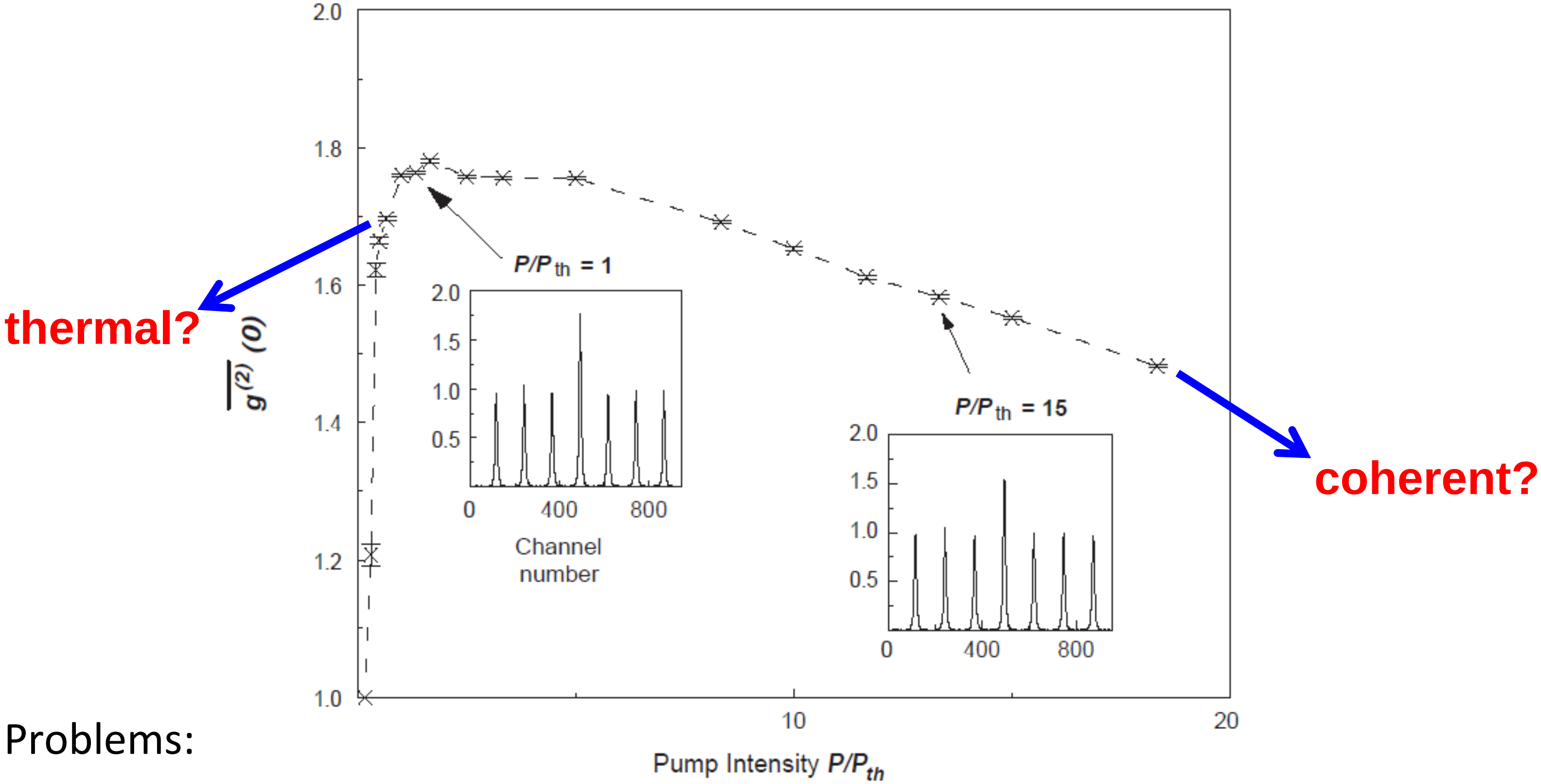
- First evidence of dynamic condensation (**Science 2002**)
  - Nonlinear threshold





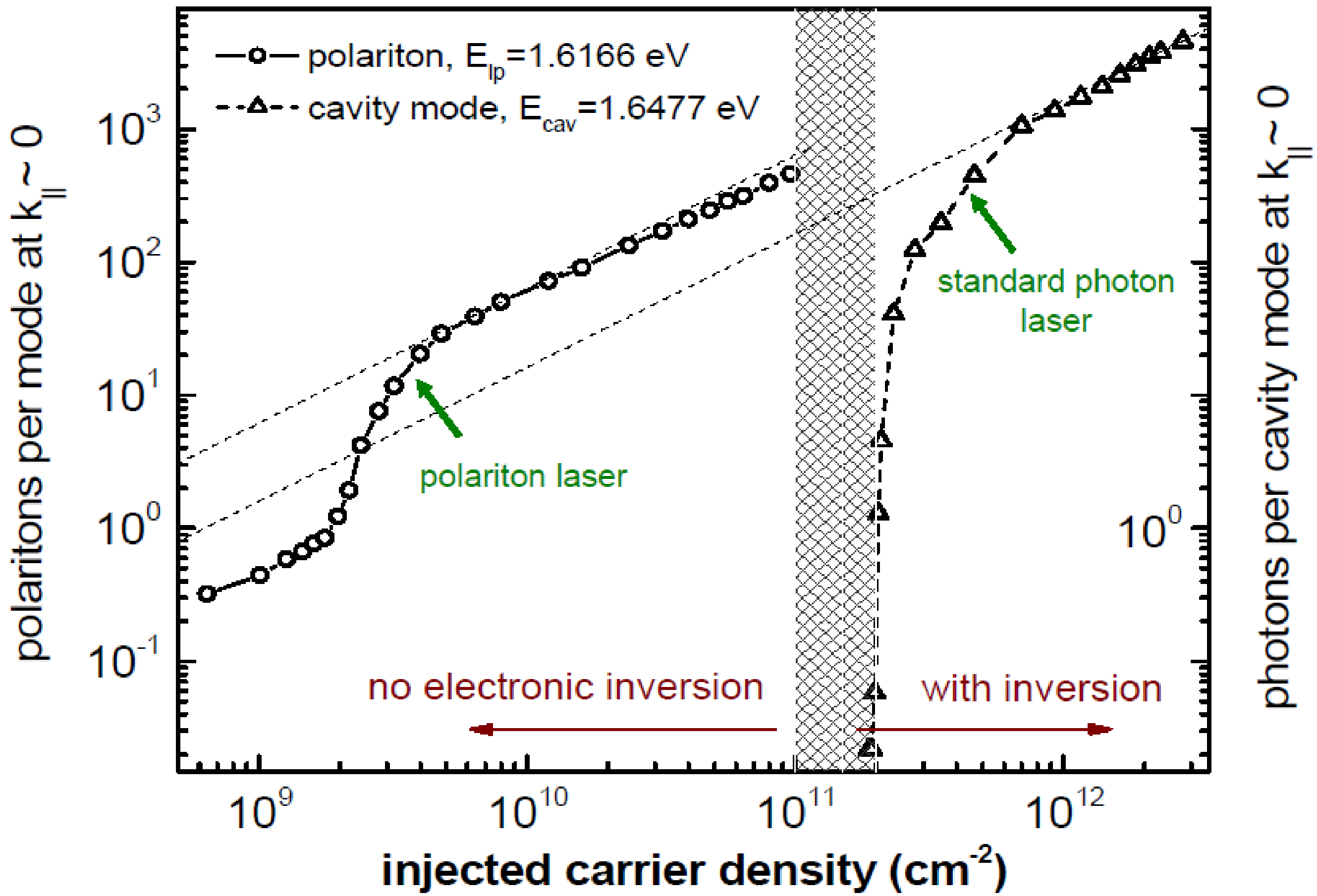
H. Deng et al., *Science*, **298**, 199 (2002)

– 2nd order coherence: $g^2(0)$ measurement



- Problems:
  - Small pump angle
  - Circular polarization
  - Multimode $g^2(0)$ measurement & quantum depletion

• Polariton laser v.s. photon laser



lasing threshold observed without electronic population inversion

H. Deng et al., *Proc. Natl. Acad. Sci.*, **100**, 15318 (2003)

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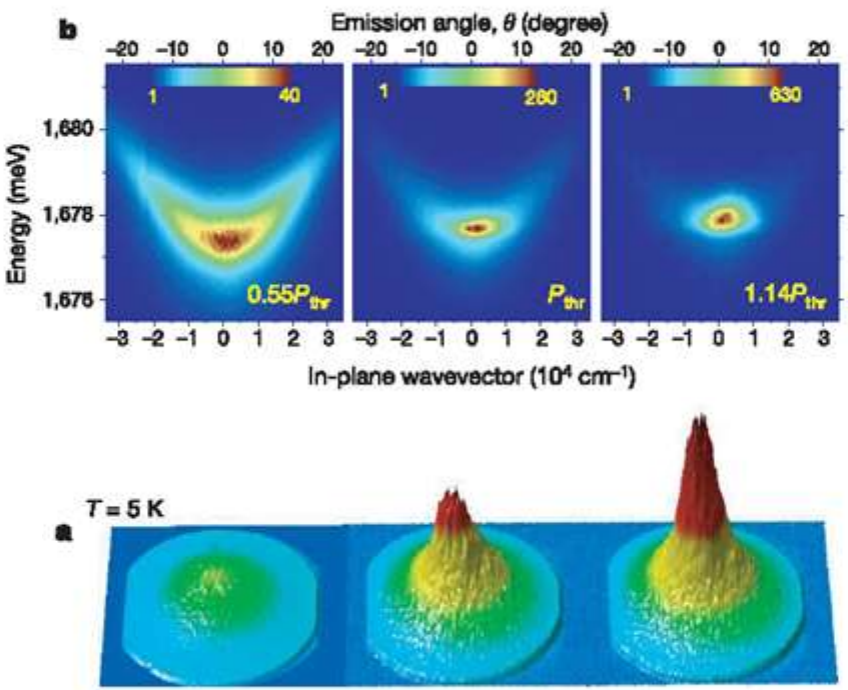
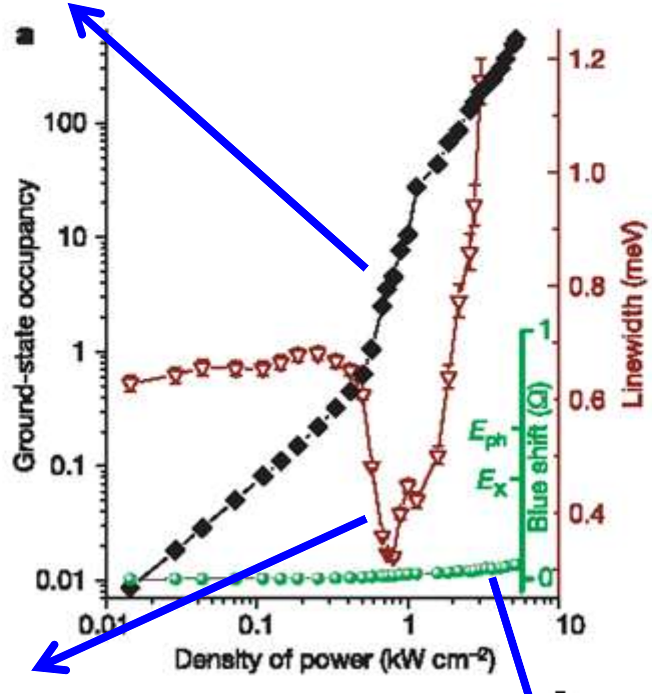
Equilibrium Polariton BEC

- First evidence of equilibrium polariton BEC (**Nature 2006**)



momentum space narrowing

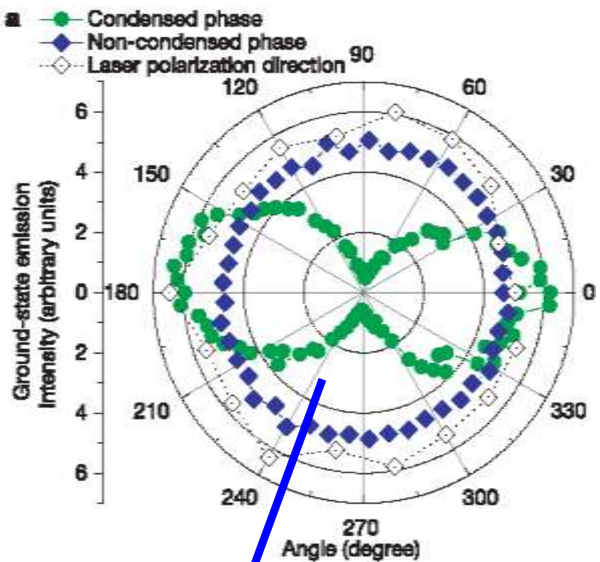
nonlinear threshold

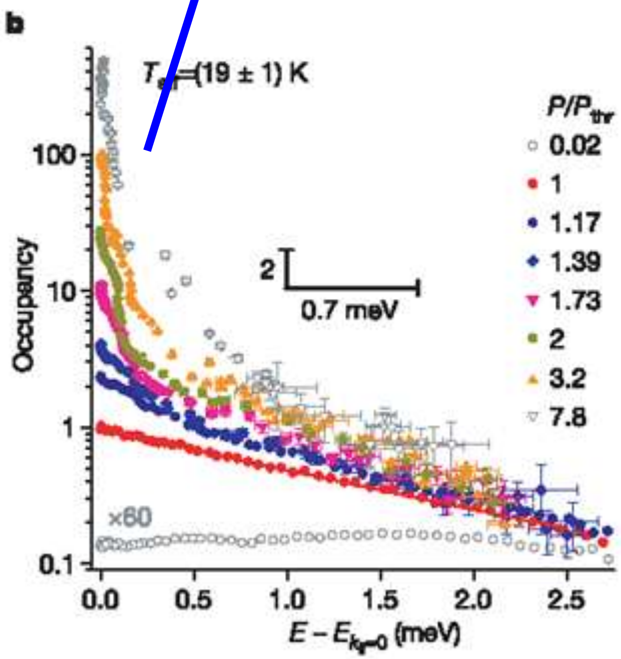


ground state coherence

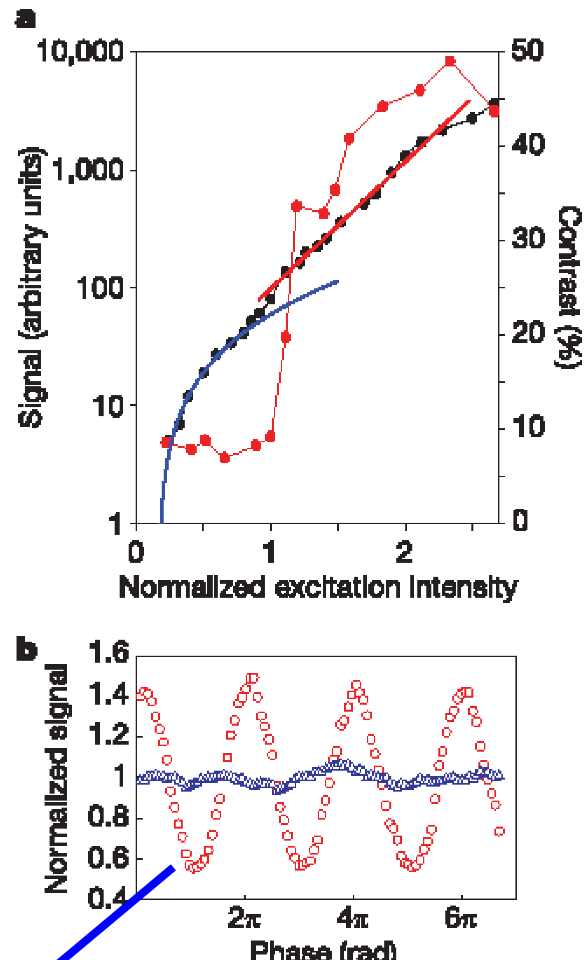
nonlinear interaction

massive occupancy





linear polarization



1st order coherence

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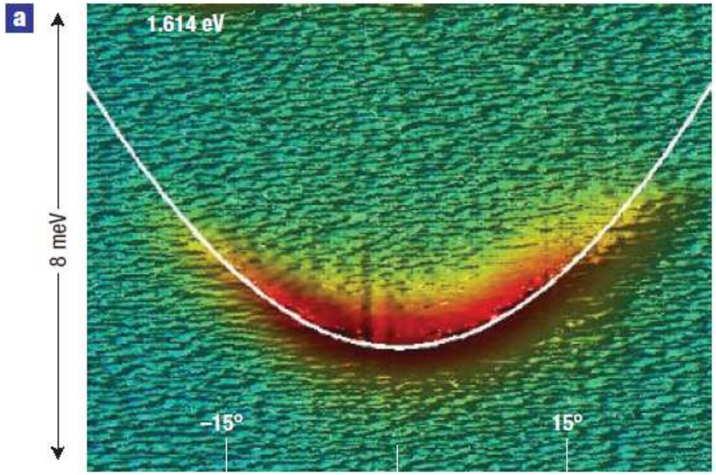
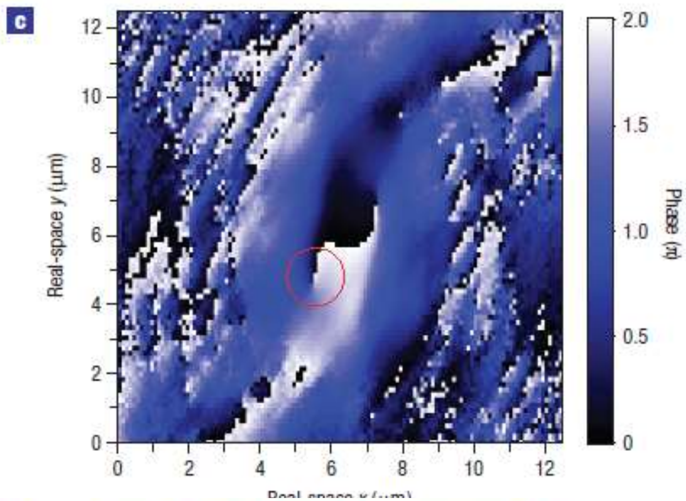
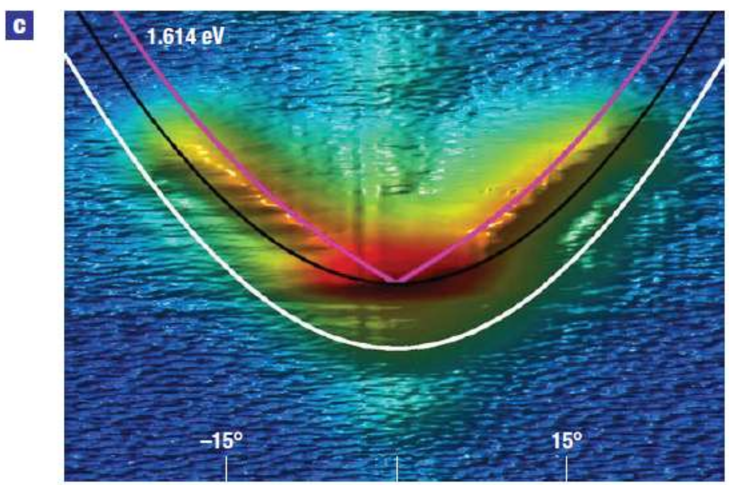
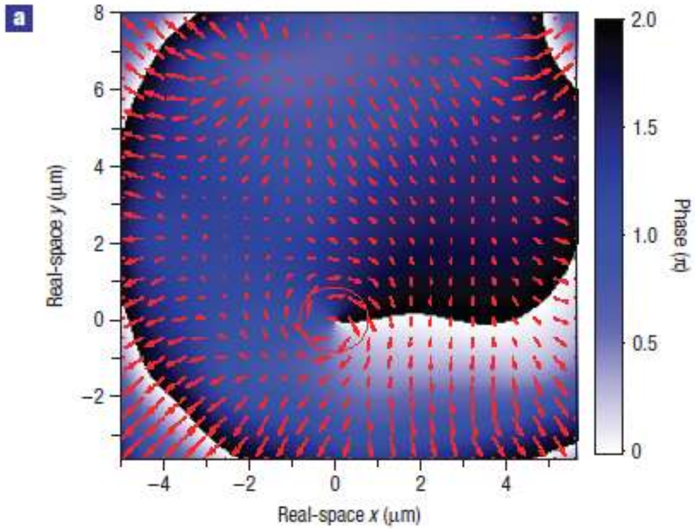
Beyond EBC

- Bogoliubov excitation (**Nature 2008**)
- Quantized vortices (**Nature 2008**)

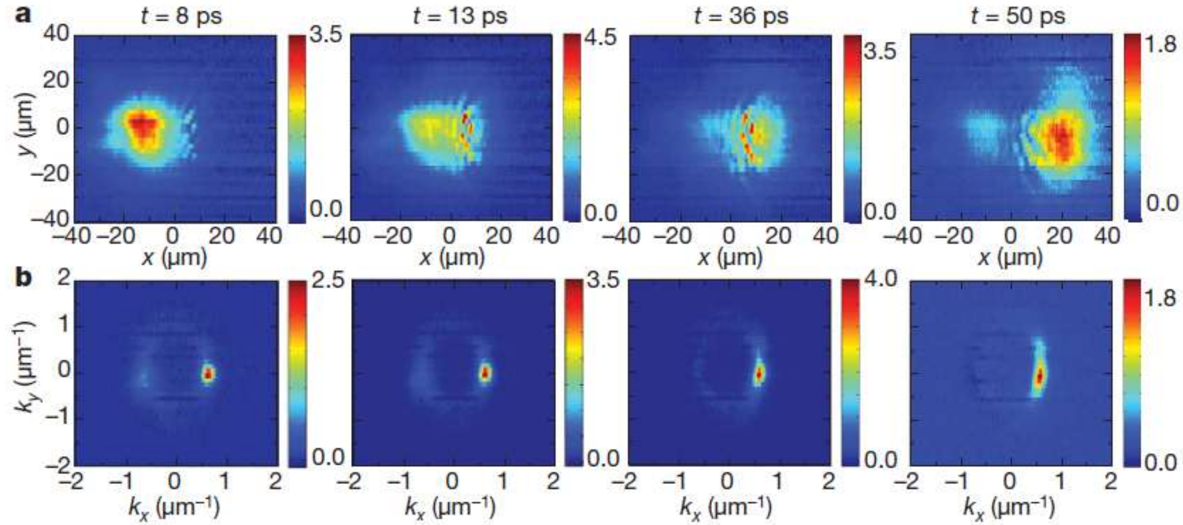




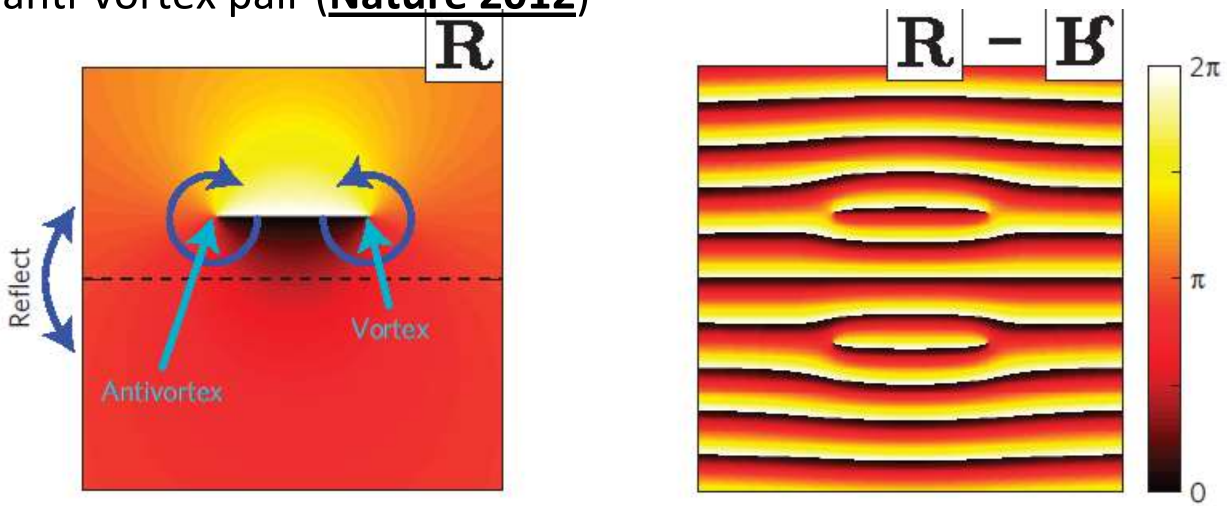




- Superfluid (**Nature 2009**)



- Vortex - anti-vortex pair (**Nature 2012**)



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Bose-Hubbard & Fermi-Hubbard model

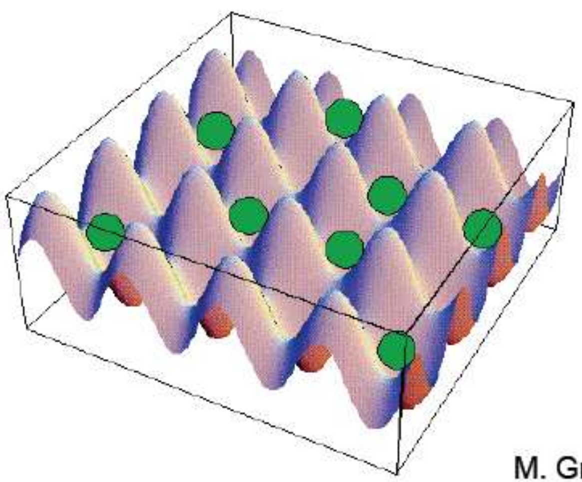
- Bose-Hubbard model

Bose – Hubbard Hamiltonian

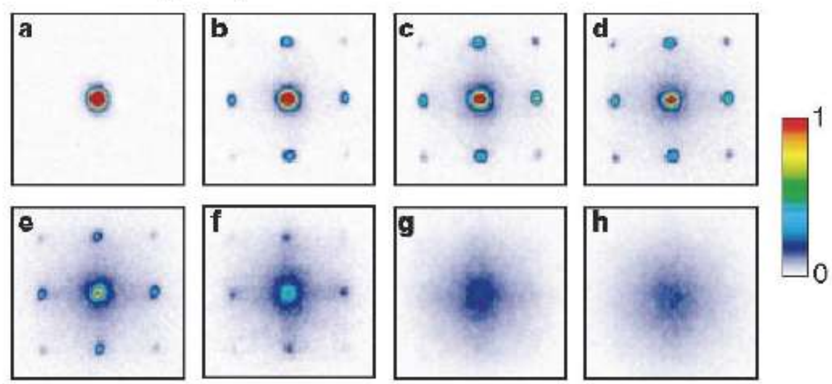
$$\hat{H} = \sum_j \epsilon_j \hat{n}_j - J \sum_{i,j} \hat{b}_i^\dagger \hat{b}_j + \frac{U}{2} \sum_j \hat{n}_j (\hat{n}_j - 1)$$

M.P.A. Fisher et al., PRB 40, 546 (1989)
D. Jaksch et al., PRL 81, 3108 (1998)

Cold atoms in 3D Optical lattice



Experimental evidence for quantum phase transition from BEC, superfluid to Mott insulator



M. Greiner et al., Nature 419, 6901 (2002)

Exciton-polaritons in 2D lattice

2D physics
Mass can be varied over four orders of magnitude
Optical input and readout

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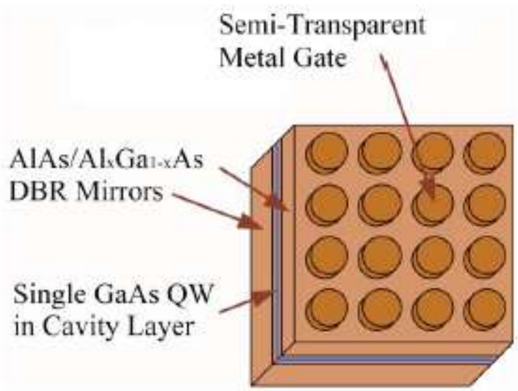
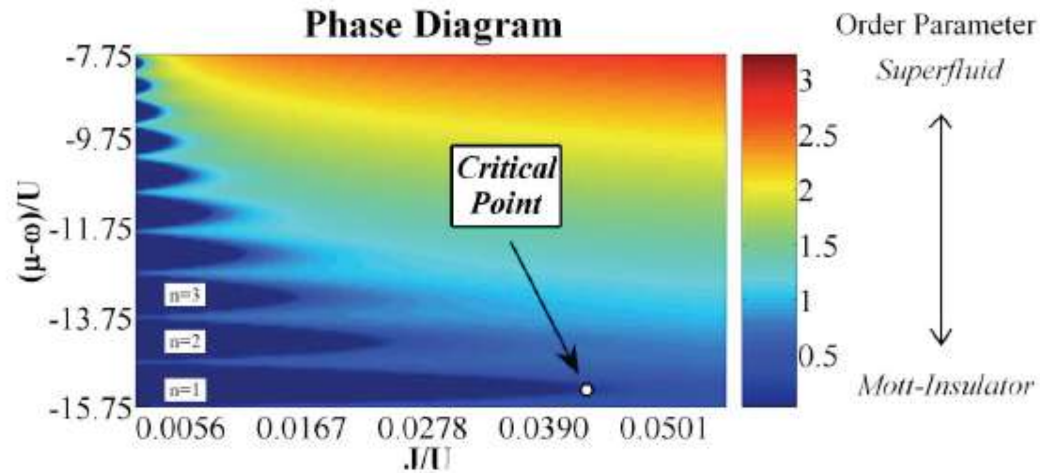
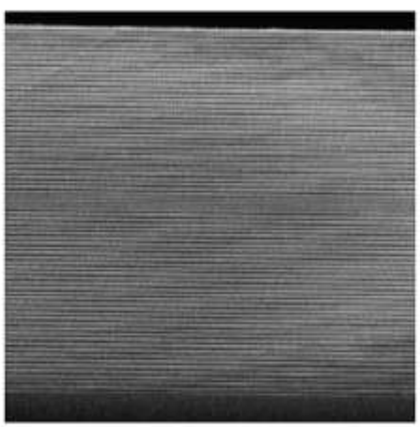
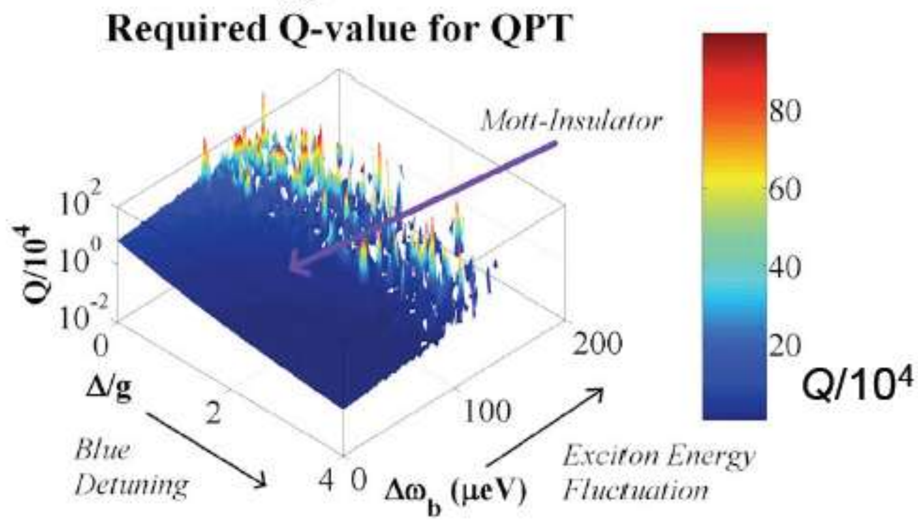




Cross-sectional SEM of the whole structure





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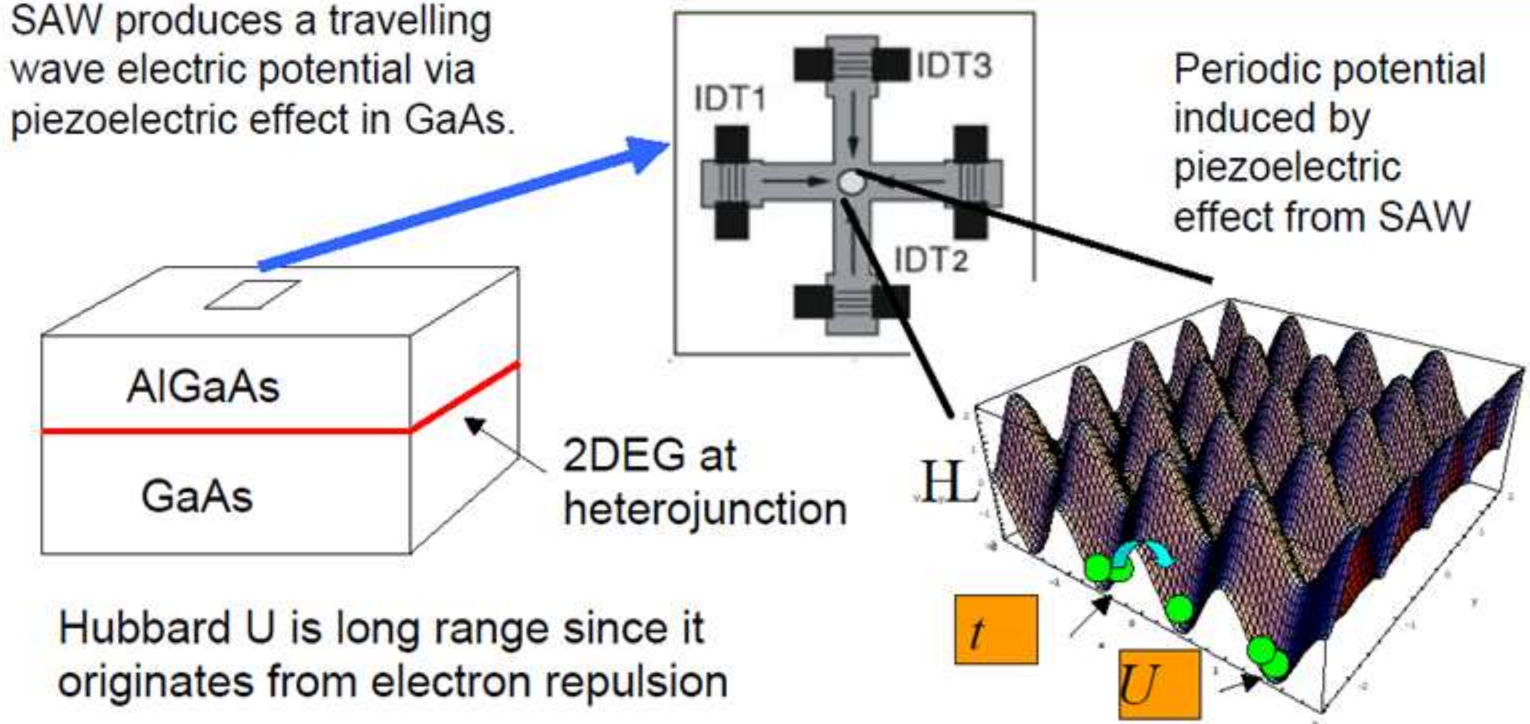
- Fermi-Hubbard model

Semiconductor version of optical lattice atom trapping using electrons.

$$H_{Hubbard} = t \sum_{<ij>,\sigma} \left(c^{+}_{i\sigma} c_{j\sigma} + c^{+}_{j\sigma} c_{i\sigma} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

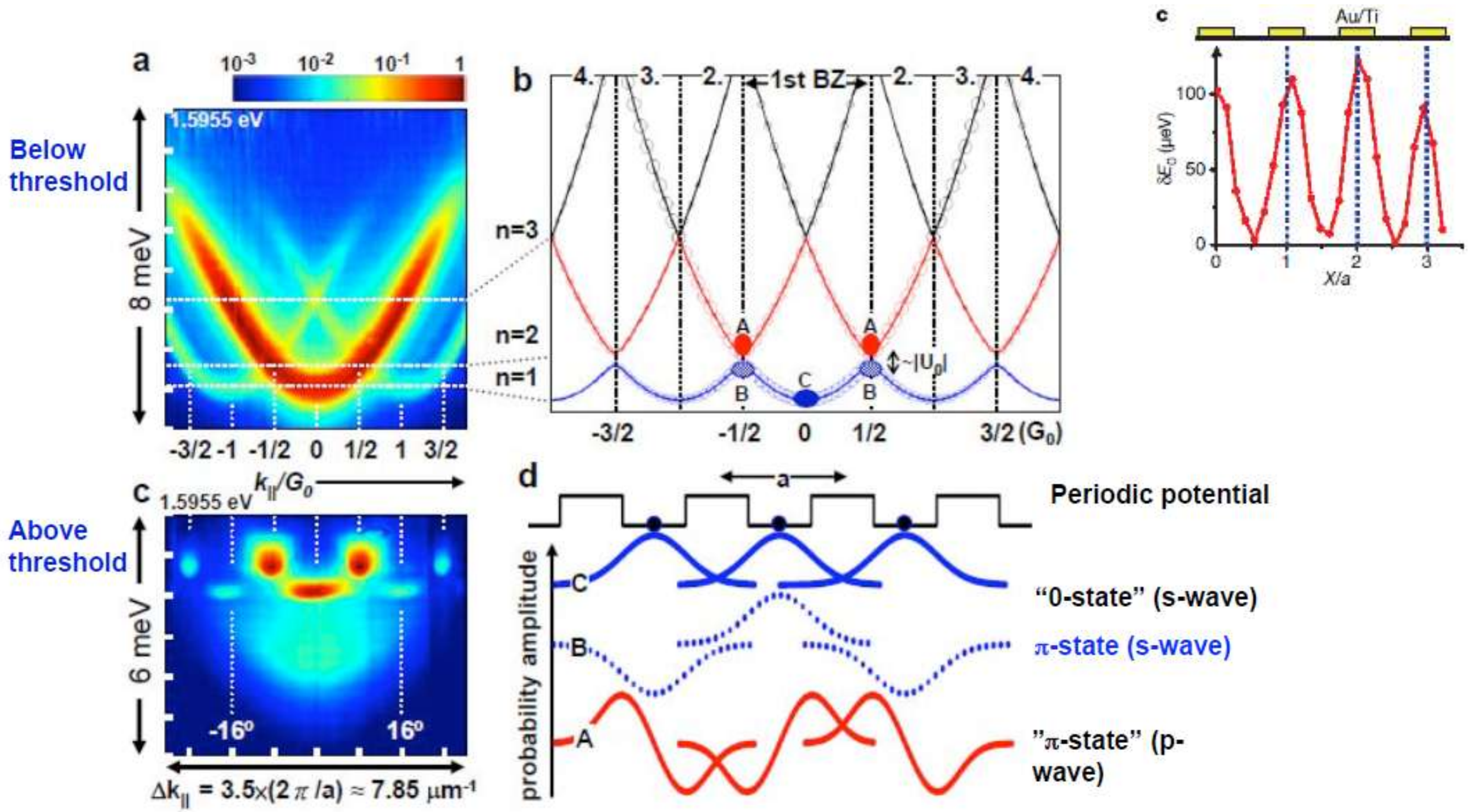


Hubbard U is long range since it originates from electron repulsion

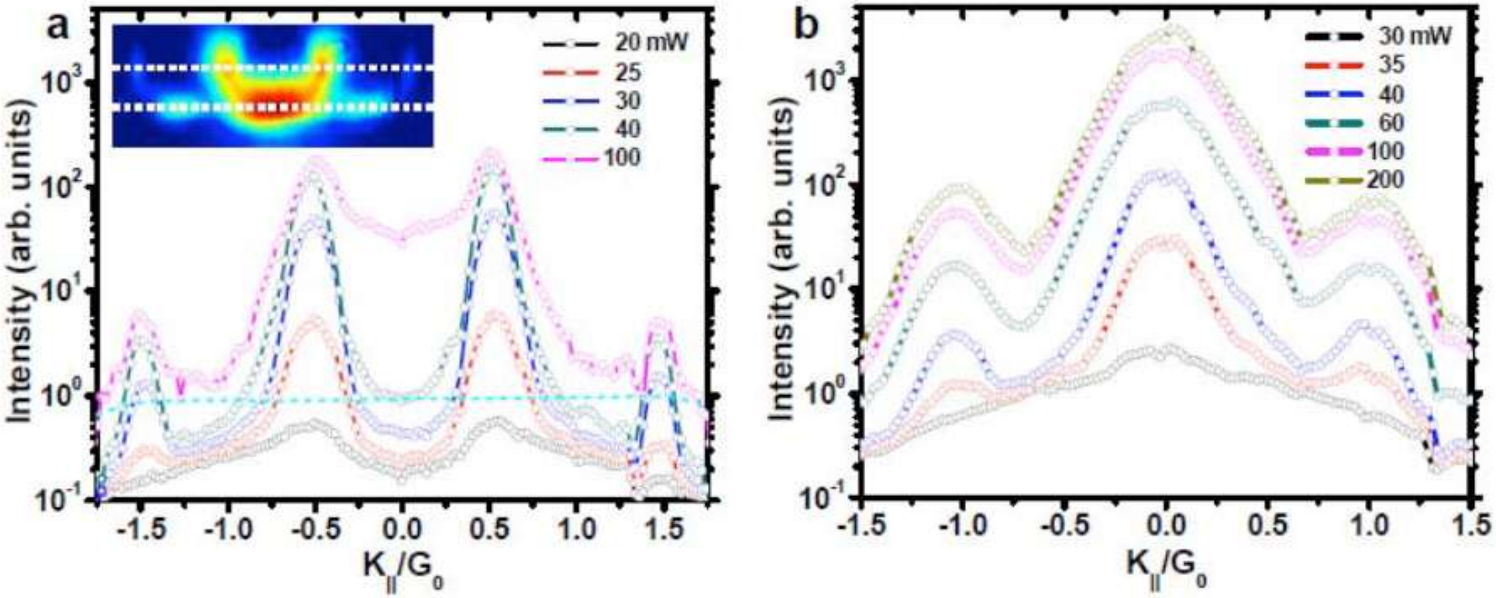
- Microcavity Exciton-polariton
  - QW excitons
  - Microcavity photons
  - Strong coupling regime: exciton-polariton
- Dynamic Condensation of Exciton-Polariton
  - Dynamic polariton BEC
  - Polariton laser
  - Equilibrium Polariton BEC
  - Beyond BEC
- Quantum simulator of many-body system
  - Bose-Hubbard & Fermi-Hubbard model
  - Higher-orbital state condensation
- Summary

Higher-orbital state condensation

- Accessing weakly interacting regime is much easier experimentally
- S & P wave condensation (**Nature 2007**)



Anti-Phased p-wave and In-Phased s-wave in One-Dimensional Exciton-Polariton Condensate Array



Excited state condensation

(π state)

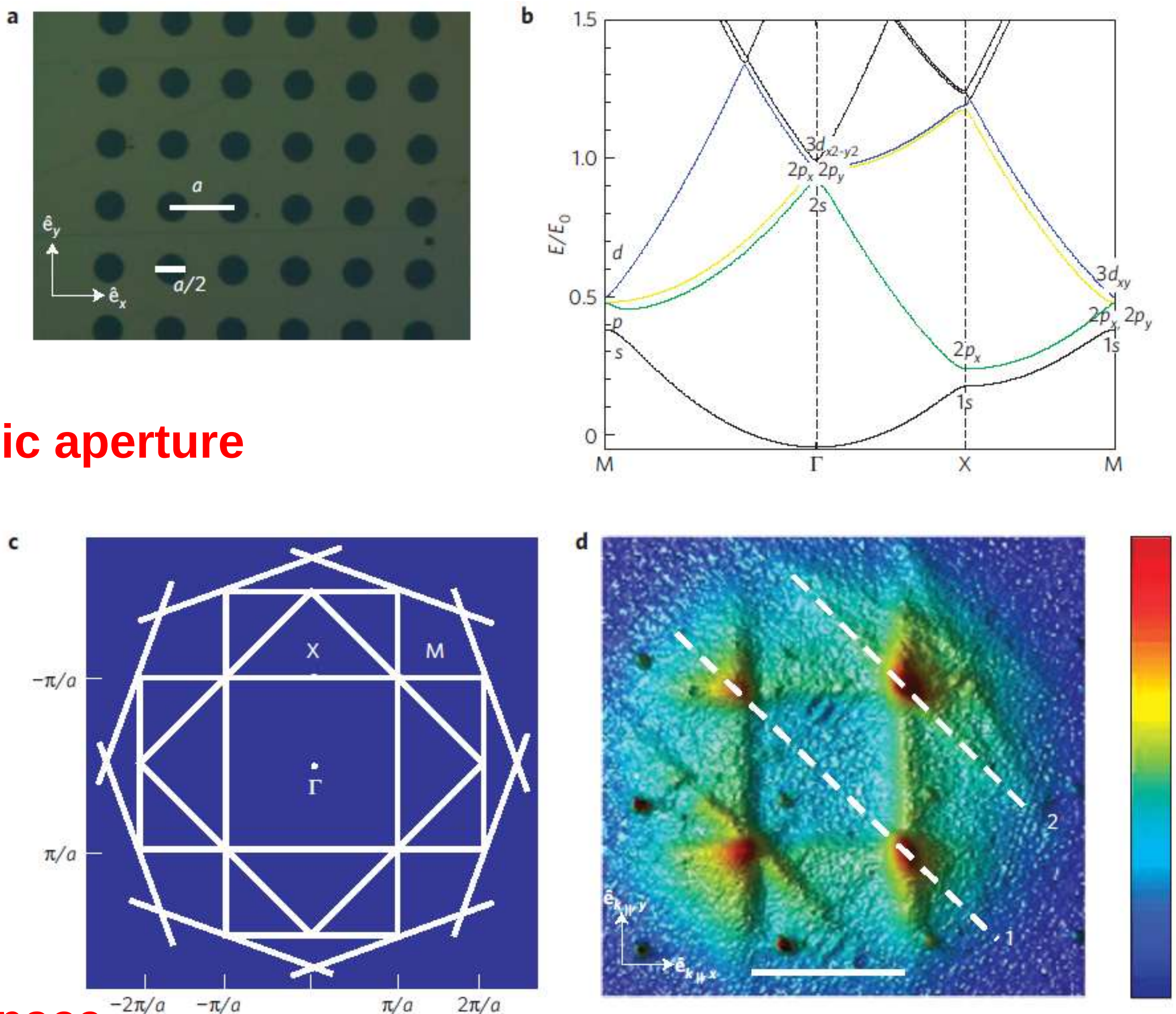
Ground state condensation

(0 state)

far field interference

- D wave condensation (**Nature 2011**)

bandstructure



metallic aperture

reciprocal space

far field image

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Summary

- The field of exciton-polariton vastly expanded in the past decade.
- Although it is an open dissipative system, many features of bosons in equilibrium can be similarly observed.
- In additional to fundamental scientific research, numerous practical applications have also been proposed.

- Future directions:
  - BEC - BCS crossover
  - Polariton meditated superconductivity
  - Polaritonics
  - THz generation
  - Nonclassical photon generation