A condensate of matter and light

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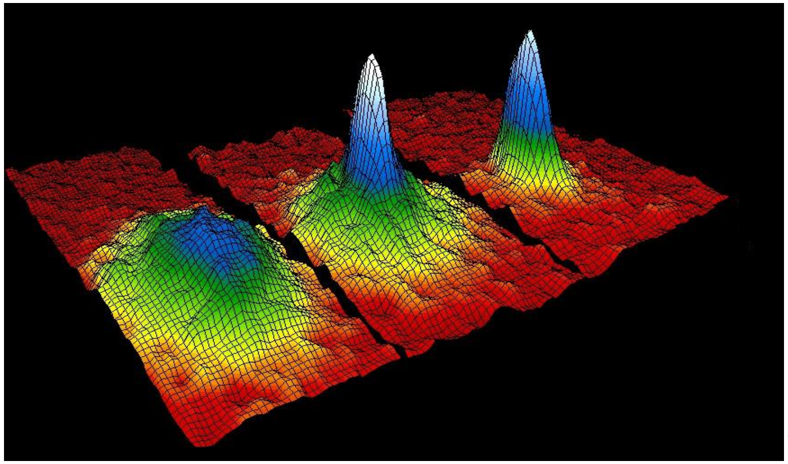
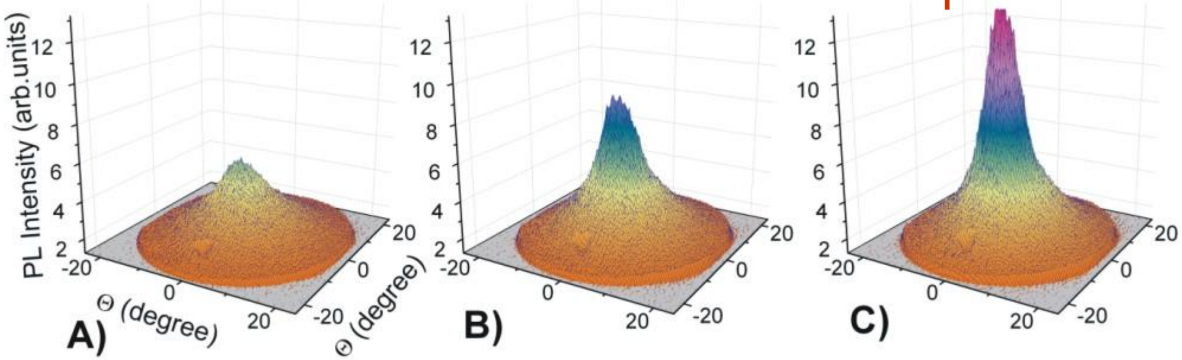


Rb atom condensate, JILA, Colorado

Momentum distribution of cold atoms

Momentum distribution of cold exciton-polaritons



Kasprzak et al Nature 443, 409 (2006)

Acknowledgements

Anson Cheung

Paul Eastham (now Trinity College Dublin)

Jonathan Keeling

Francesca Marchetti (now Madrid)

Marzena Szymanska (now Warwick)

Cavendish Laboratory

University of Cambridge

Jacek Kasprzak

Le Si Dang

Laboratoire de Spectrometrie Physique

Grenoble

Also thanks to: Gavin Brown, Alexei Ivanov, Leonid Levitov, Richard Needs, Ben Simons, Sasha Balatsky, Yogesh Joglekar, Jeremy Baumberg, Leonid Butov, David Snoke, Benoit Deveaud

Characteristics of Bose-Einstein Condensation

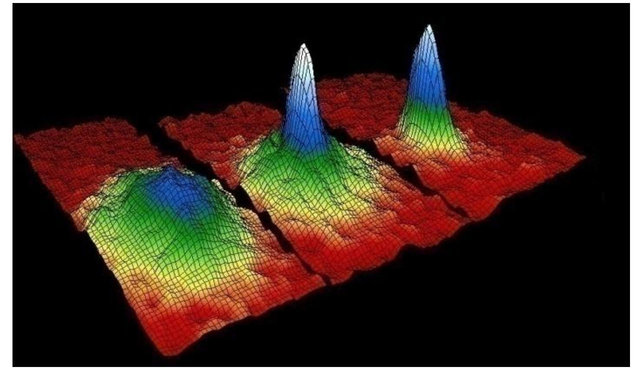
- Macroscopic occupation of the ground state
  - weakly interacting bosons

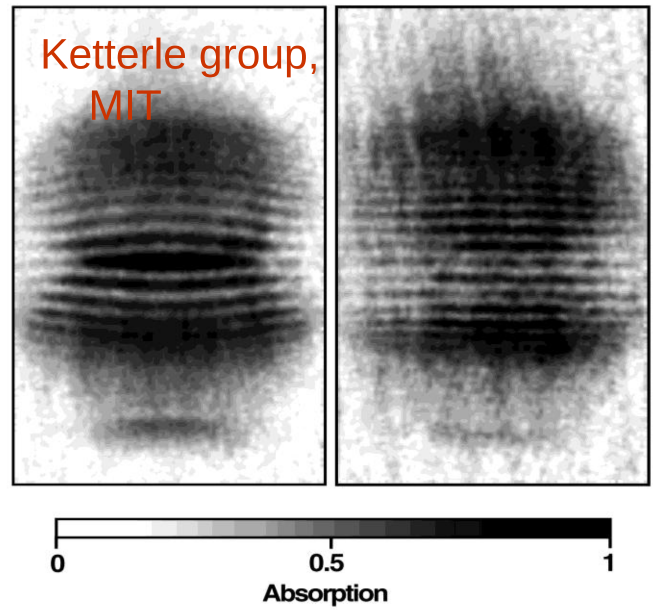
$$k_B T_0 \approx \frac{\hbar^2 n^{2/3}}{2m} \approx \frac{1.3}{r_s^2}\, Ryd$$

- Macroscopic quantum coherence
  - Interactions (exchange) give rise to synchronisation of states

$$\psi \rightarrow \psi e^{i\phi}$$

- Superfluidity
  - Rigidity of wavefunction gives rise to new collective sound mode





Christiaan Huygens 1629-95

1656 – Patented the pendulum clock

1663 – Elected to Royal Society

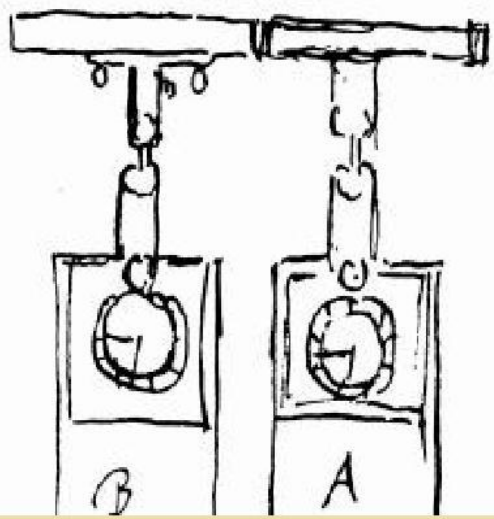
1662-5 With Alexander Bruce, and sponsored by the Royal Society, constructed maritime pendulum clocks – periodically communicating by letter

Huygens Clocks

In early 1665, Huygens discovered ``..an odd kind of sympathy perceived by him in these watches [two pendulum clocks] suspended by the side of each other."

1665.

[Fig. 75.][2])



22 febr. 1665.

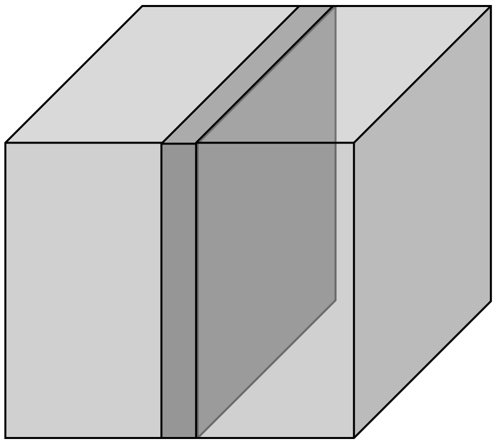
Diebus 4 aut 5 horologiorum duorum novorum in quibus catenulæ [Fig. 75], miram concordiam obſervaveram, ita ut ne minimo quidem exceſſu alterum ab altero ſuperaretur. ſed conſonarent ſemper reciprocationes utriusque perpendiculi. unde cum parvo ſpatio inter ſe horologia diſtarent, ſympathiæ quandam [3]) quasi alterum ab altero afficeretur ſuſpicari cœpi. ut experimentum caperem turbavi alterius penduli reditus ne ſimul incederent ſed quadrante horæ poſt vel ſemihora rurſus concordare inveni.

He deduced that effect came from “imperceptible movements” of the common frame supporting the clocks

"Huygens' Clocks", M. Bennett et al, Proc. Roy. Soc. A **458**, 563 (2002)

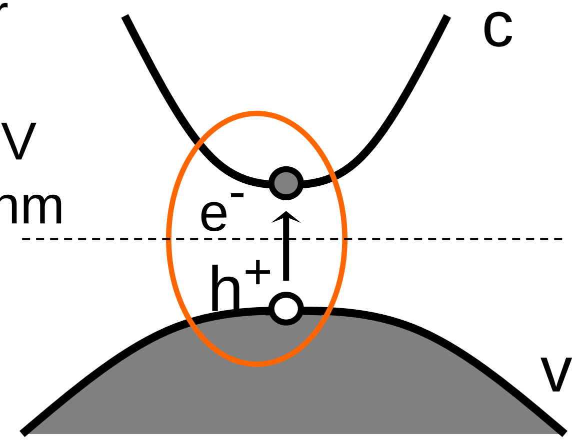
Two metronomes on a cart

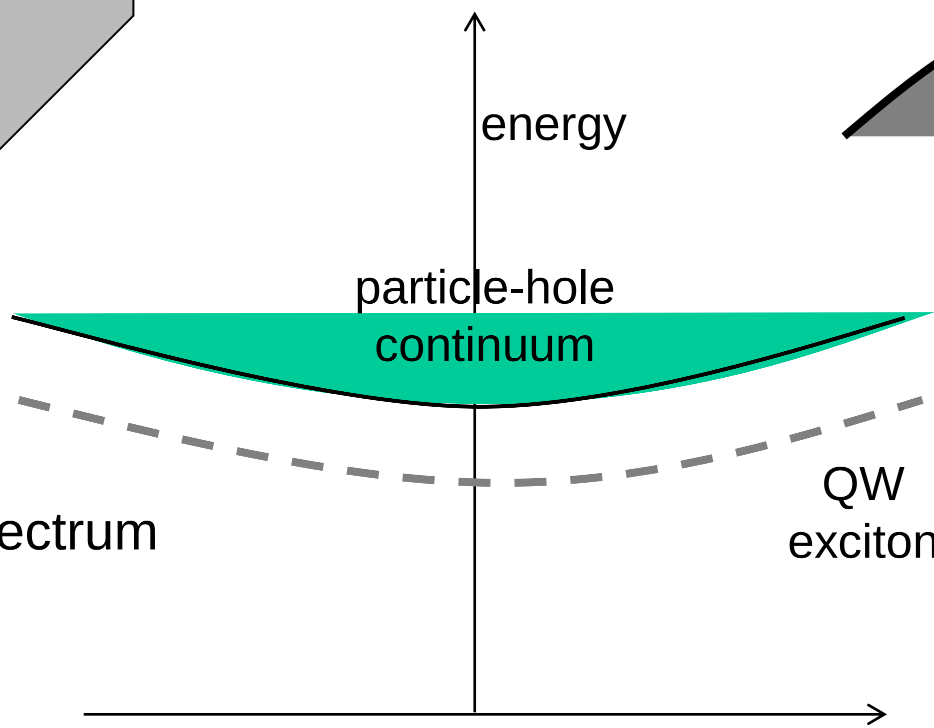
Quantum Well Excitons



QW

Weakly bound
electron-hole pair
EXCITON
Rydberg – few meV
Bohr Radius – few nm

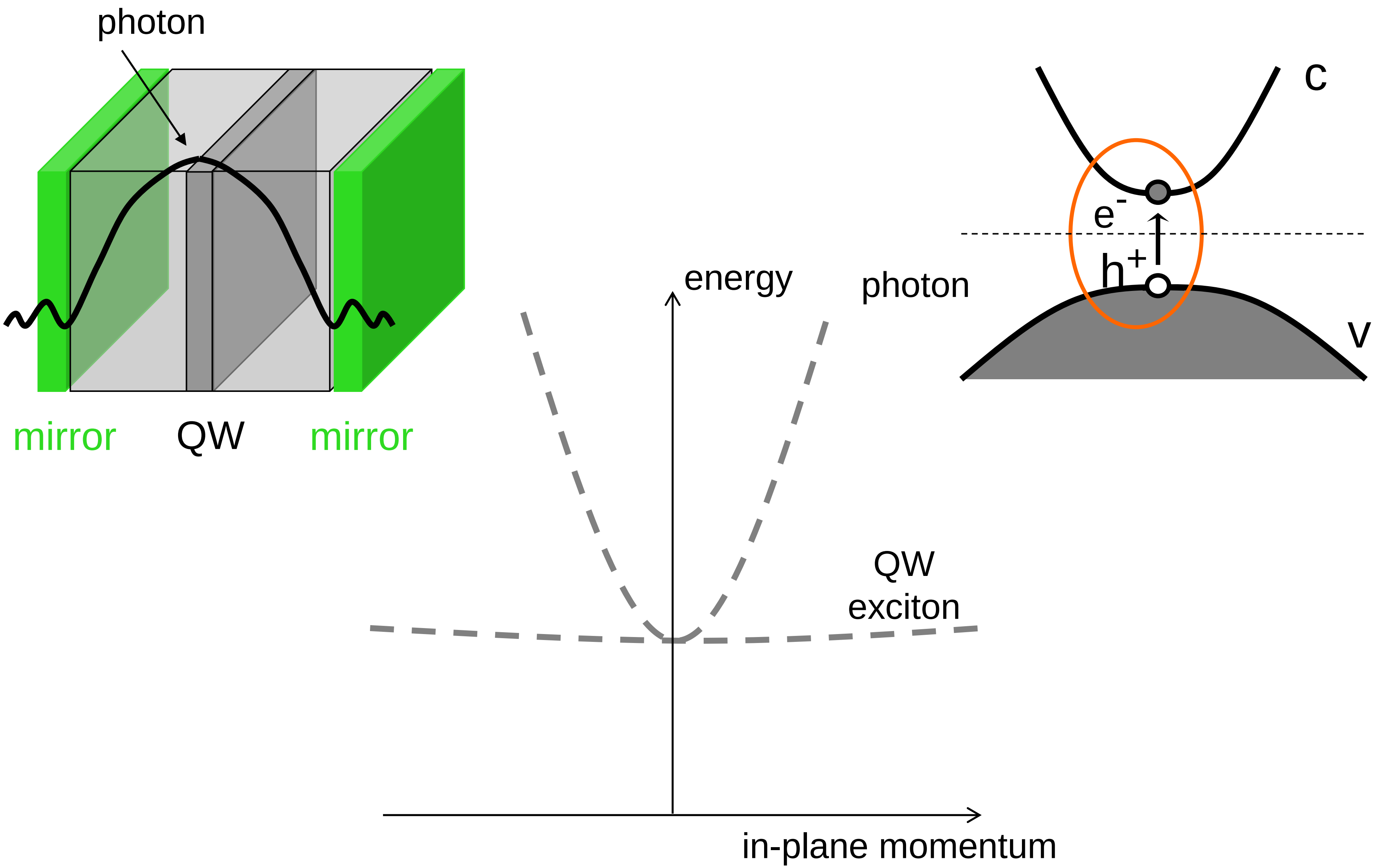




Excitation spectrum

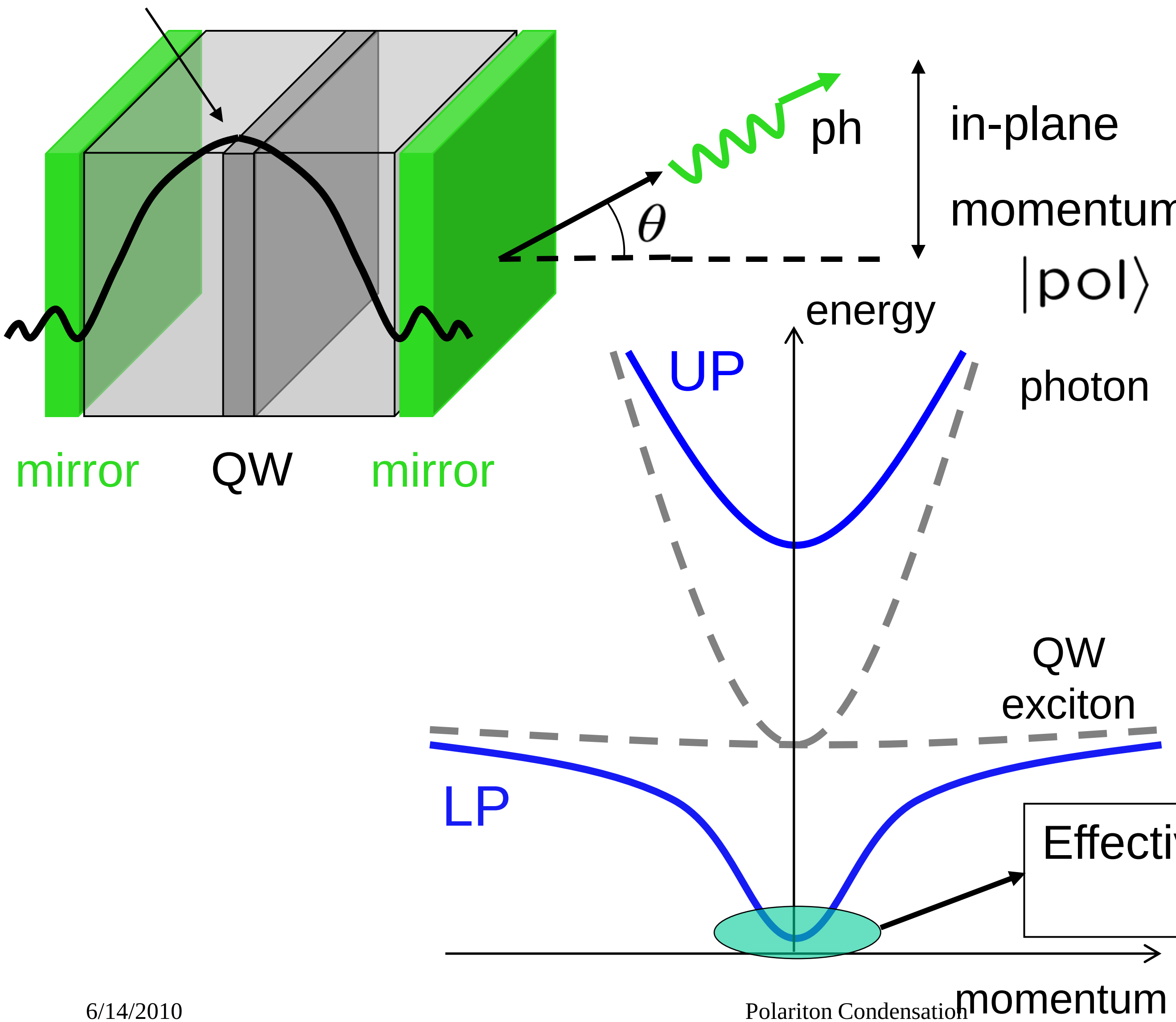
in-plane center of mass momentum

Excitons + Cavity Photons



Polaritons: Matter-Light Composite Bosons

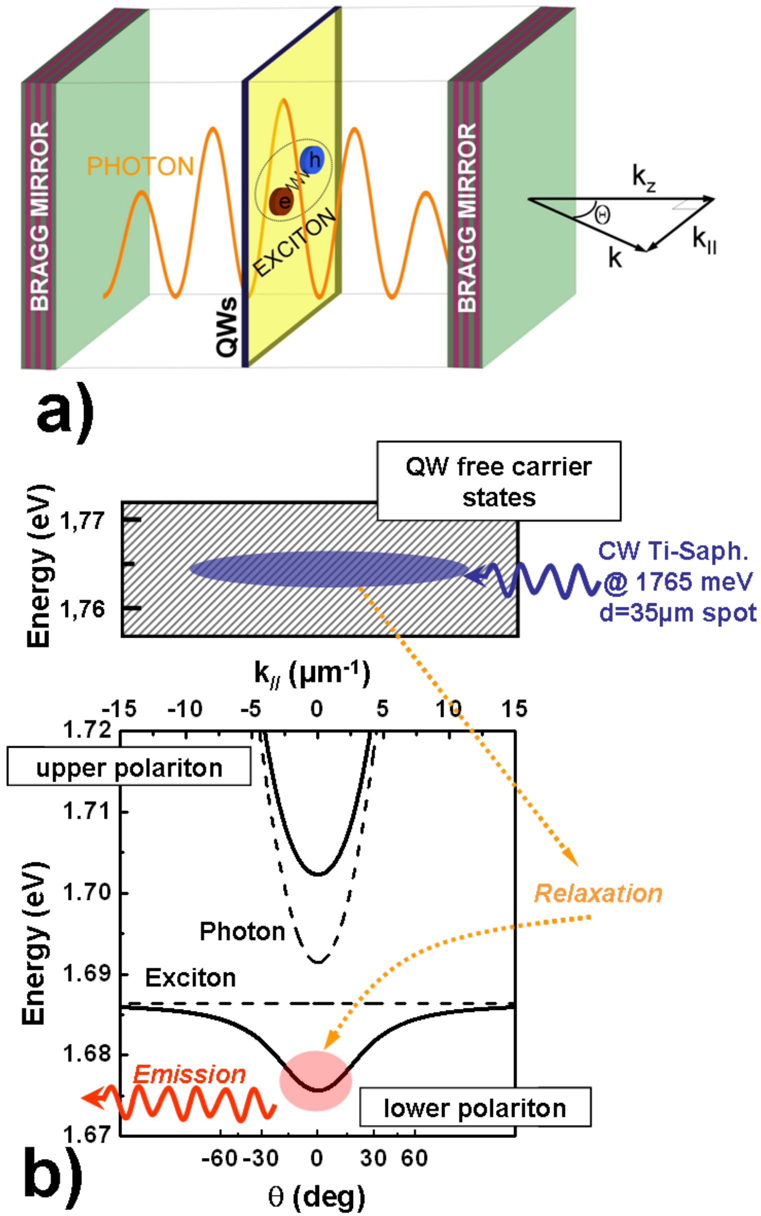
[C. Weisbuch *et al.*, *PRL* **69** 3314 (1992)]



$$|\mathrm{pol}\rangle = c_1|\mathrm{exc}\rangle + c_2|\mathrm{ph}\rangle$$

Effective Mass $m^* \sim 10^{-4}\, m_e$

$T_{BEC} \sim 1/m^*$



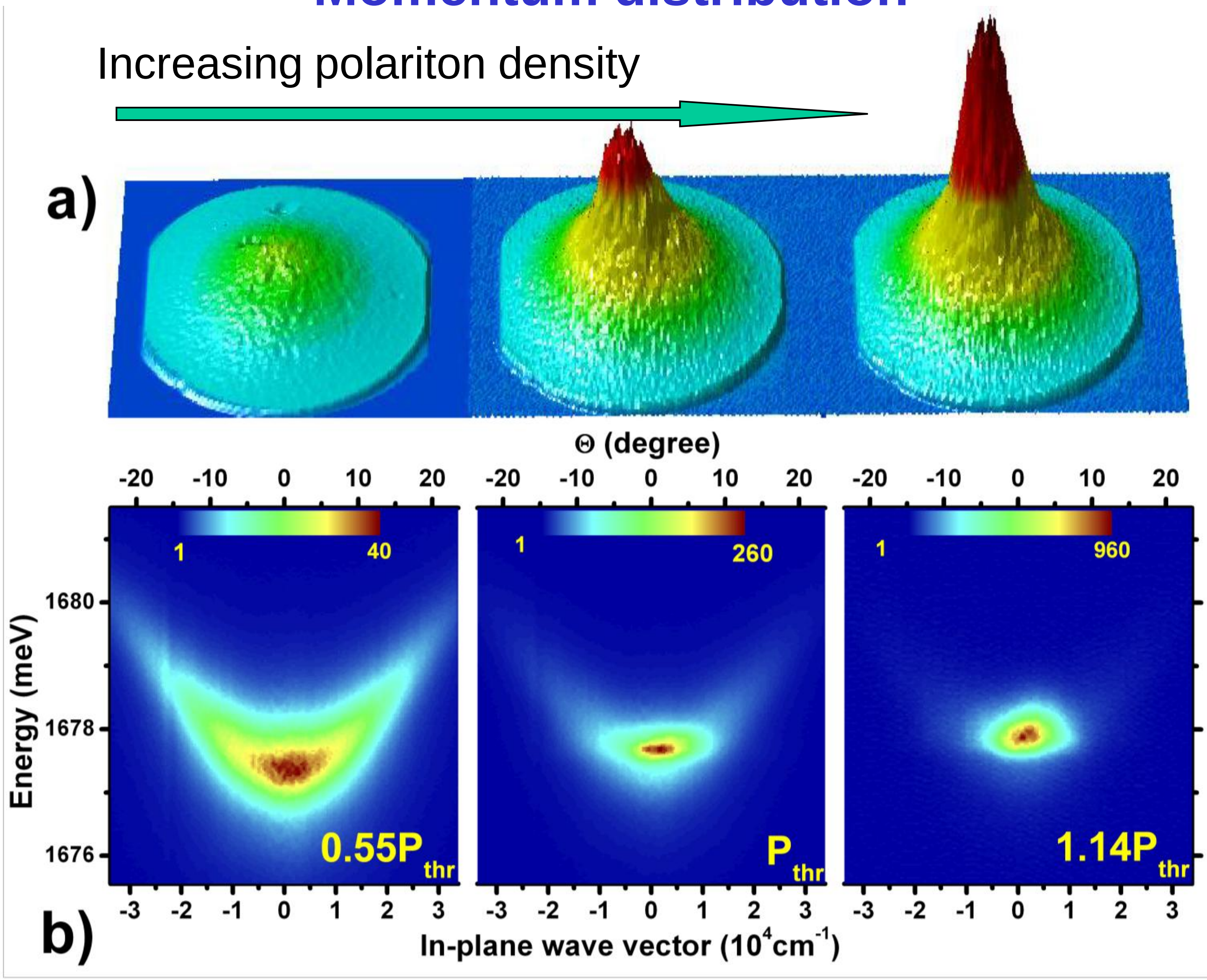
Microcavity polaritons

Experiments:
Kasprzak et al 2006
CdTe microcavities

Momentum distribution

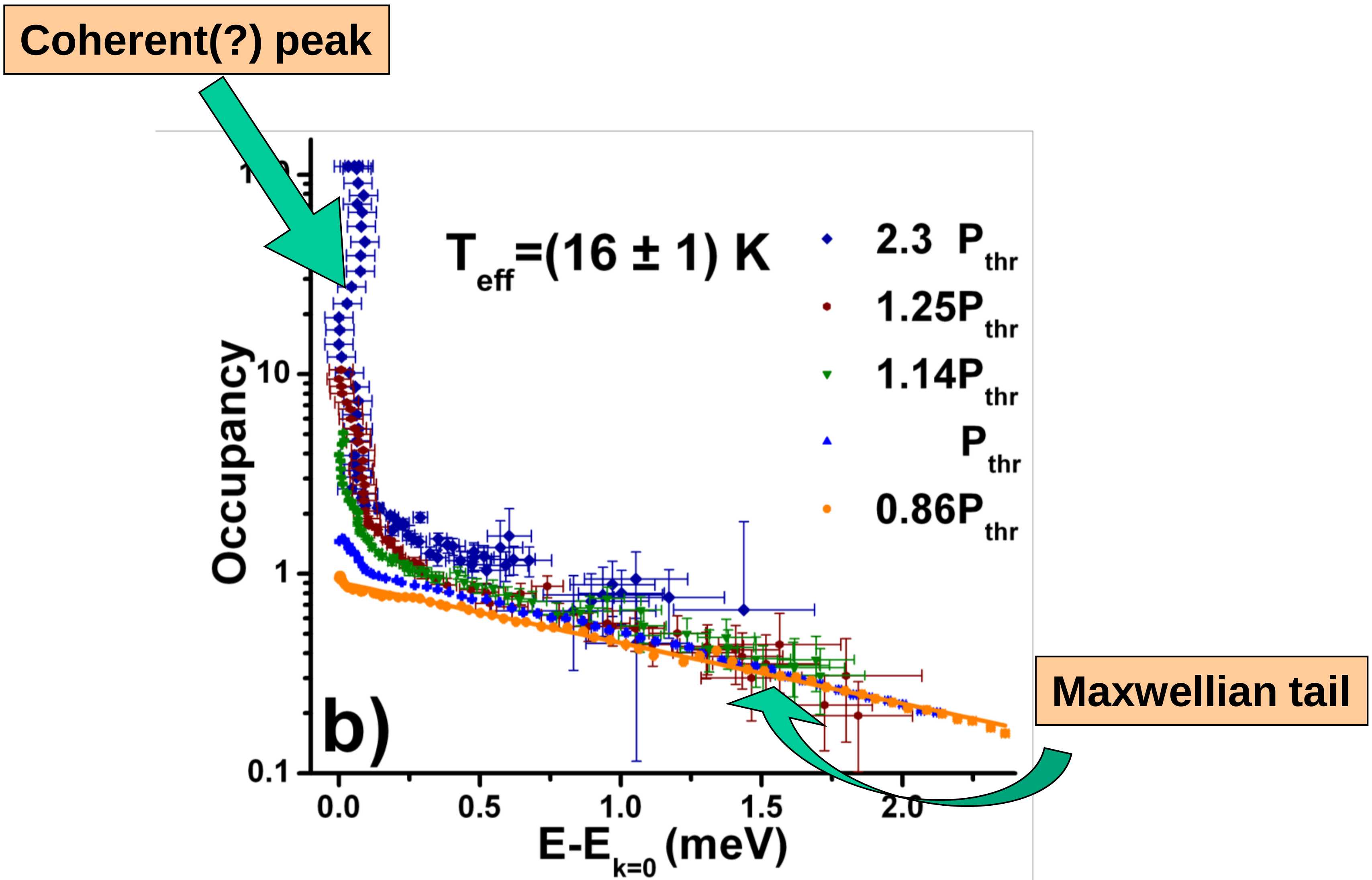
n(k)

n(k, E)

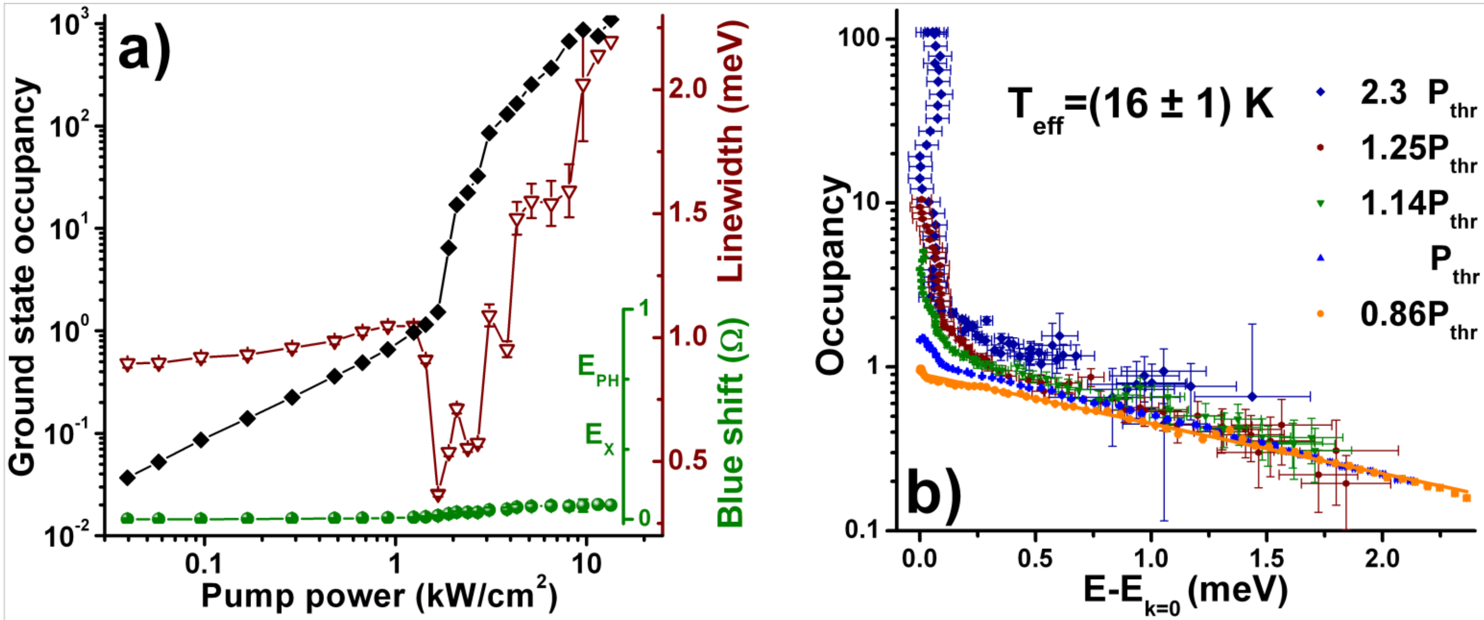


Kasprzak et al Nature 2006

Distribution at varying density

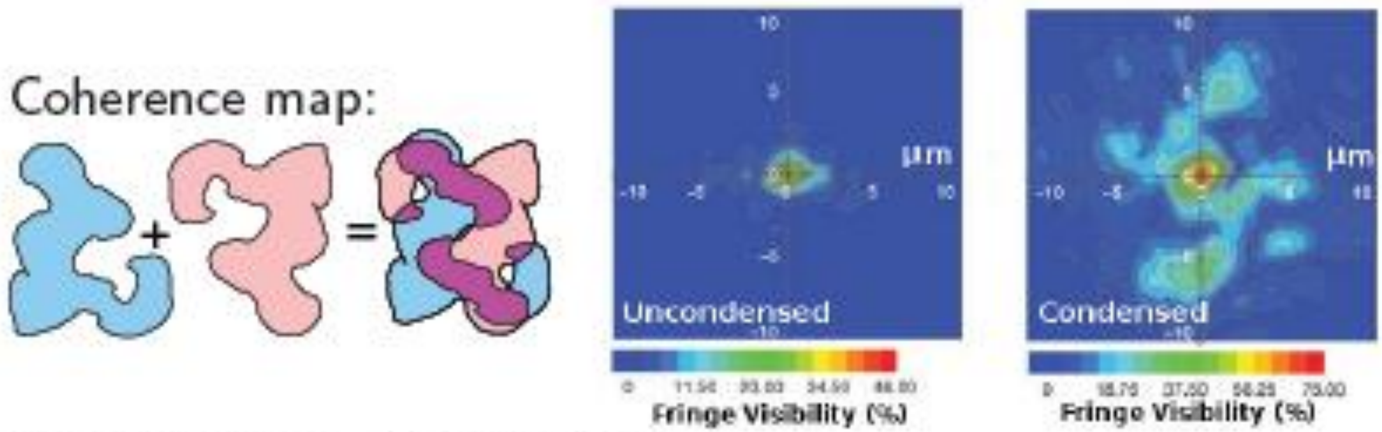


Distribution at varying density



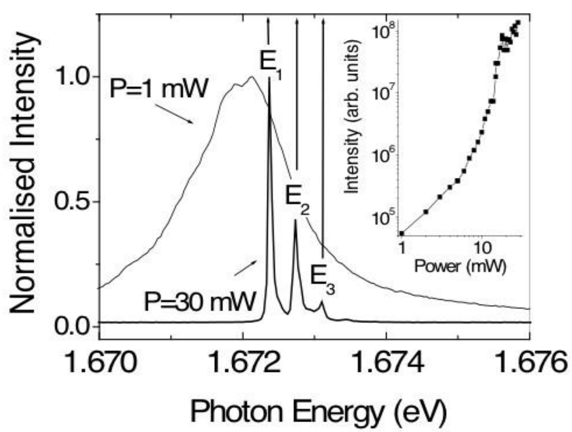
Blue shift used to estimate density
High energy tail of distribution used to fix temperature
Onset of non-linearity gives estimate of critical density
Linewidth well above transition is *inhomogeneous*

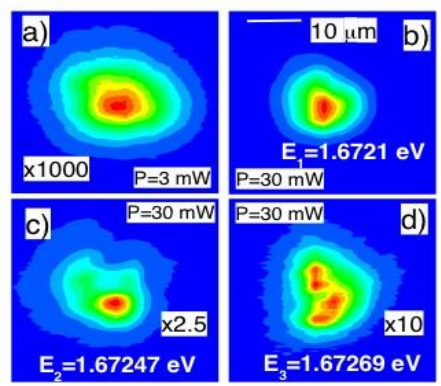
Coherence



[Kasprzak, et al., Nature, 2006]

Temporal coherence and multimode behavior

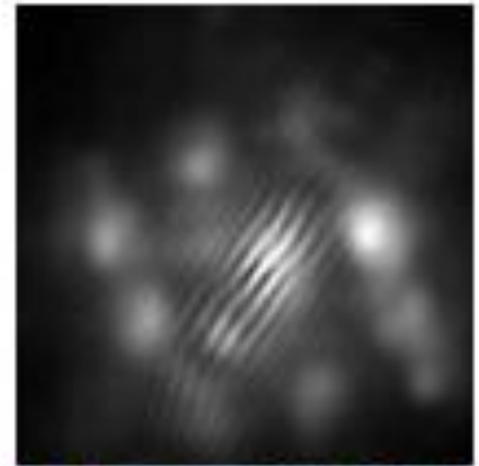


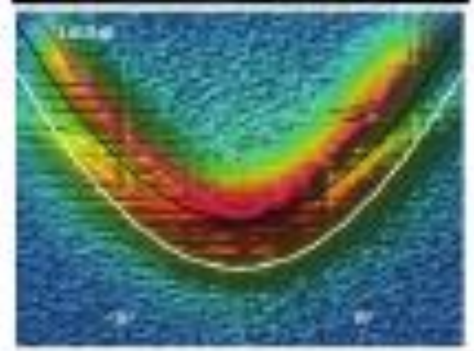


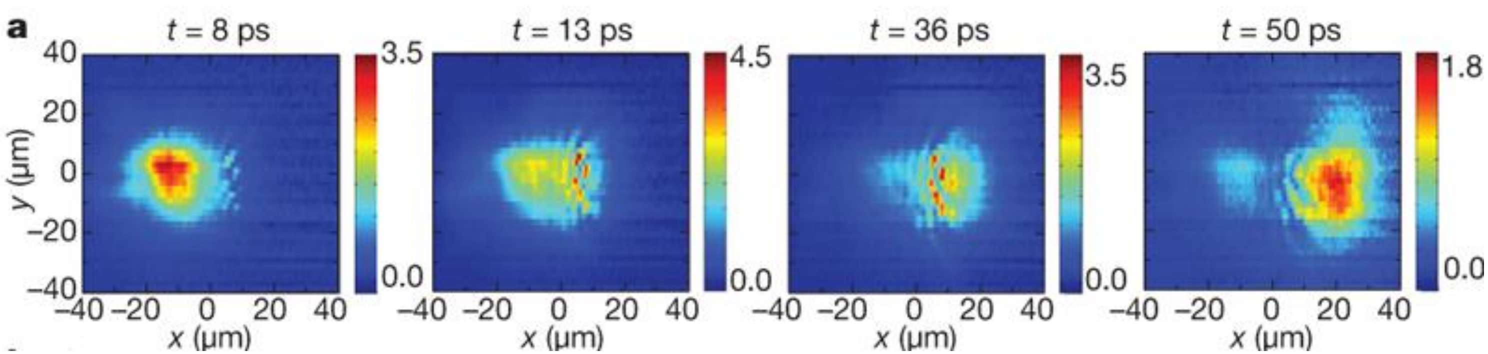
Love et al., PRL 2008

Other recent experiments

- Stress traps for polariton condensates
  - Balili et al Science 316 1007 (2007)
- Coherence and line narrowing
  - Love et al PRL 101 067404 (2008)
- Changes in the excitation spectrum
  - Utsonomiya et al Nature Physics 4 700 (2008)
- Superflow in driven condensates
  - Amo. *et al*. Nature 457, 291–295 (2009).
- Vortices and half-vortices
  - Lagoudakis et al Nature Physics 4 706 (2008)
  - Lagoudakis et al Science 326 974 (2009)







What's new about a polariton condensate ?

- Composite particle – mixture of electron-hole pair and photon
  - How does this affect the ground state ?
- Extremely light mass (~ 10^{-5} m_e) means that polaritons are large, and overlap strongly even at low density
  - BEC – “BCS” crossover ?
- Two-dimensional physics
  - Berezhinski-Kosterlitz-Thouless transition ?
- Polariton lifetime is short
  - Non-equilibrium, pumped dynamics
  - Decoherence ?
  - Relationship to the laser ?
- Can prepare out-of-equilibrium condensates
  - Quantum dynamics of many body system

Bose Condensation of Composite Bosons

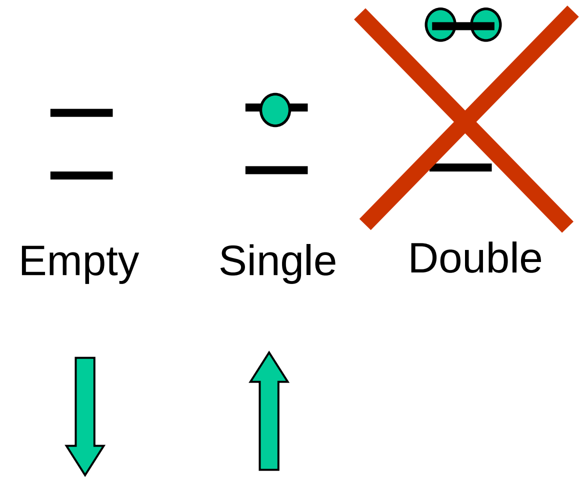
Interacting polaritons and the Dicke model

Because excitons are “heavy”, its a good enough approximation to treat them as localised two-level systems (i.e bosons with a repulsive interaction)

Photon component is “light” and mediates long range coupling

Polaritons and the Dicke Model – a.k.a Jaynes-Tavis-Cummings model

Excitons are spins



Spins are flipped by absorption/emission of photon

$$H = \omega \psi^\dagger \psi + \sum_i \epsilon_i S_i^z + \frac{g}{\sqrt{N}} \sum_i \left[S_i^+ \psi + \psi^\dagger S_i^- \right]$$

N ~ [(photon wavelength)/(exciton radius)]^d >> 1

Mean field theory – i.e. BCS coherent state – expected to be good approximation

$$|\lambda, w_i\rangle = \exp\left[\lambda \psi^\dagger + \sum_i w_i S_i^+\right] |0\rangle \qquad T_c \approx g \exp(-1/gN(0))$$

Transition temperature depends on coupling constant

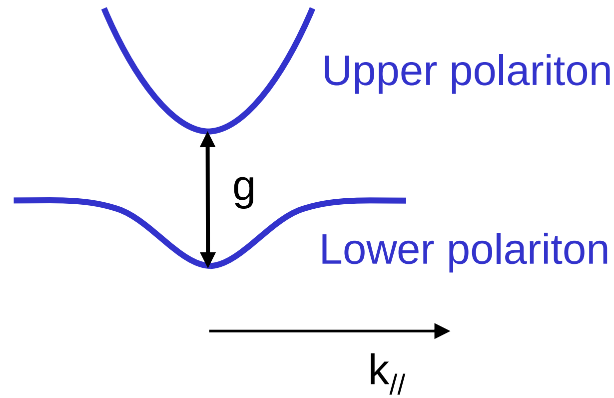
Interaction dominated physics or dilute Bose gas ?

Mean field theory – coherent state – is like BCS superconductivity, a good approximation because the polaritons are strongly overlapping

"BCS" to Bose crossover

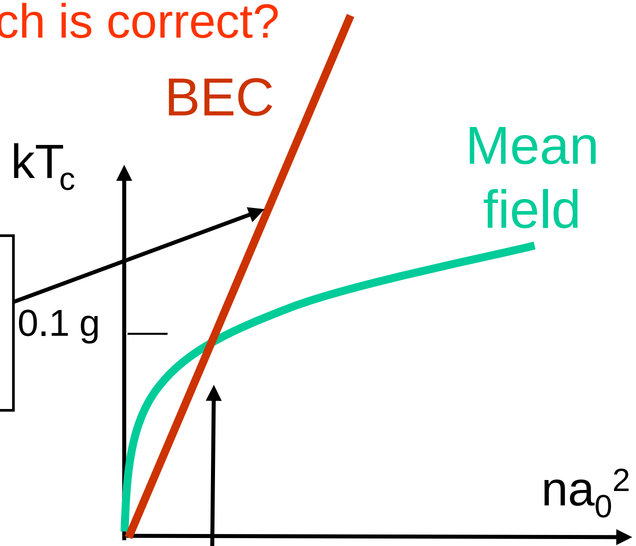
Beyond mean field: Interaction driven or dilute gas?

- Conventional "BEC of polaritons" will give high transition temperature because of light mass m^*
- Single mode Dicke model gives transition temperature ~ g



Which is correct?

$$k_B T_0 \approx \frac{\hbar^2}{2m} n$$



$$\left(\frac{g}{\hbar^2/2ma_0^2}\right) \times \left(\frac{m^*}{m}\right) \approx 10^{-4}$$

a_o = characteristic separation of excitons
a_o > Bohr radius

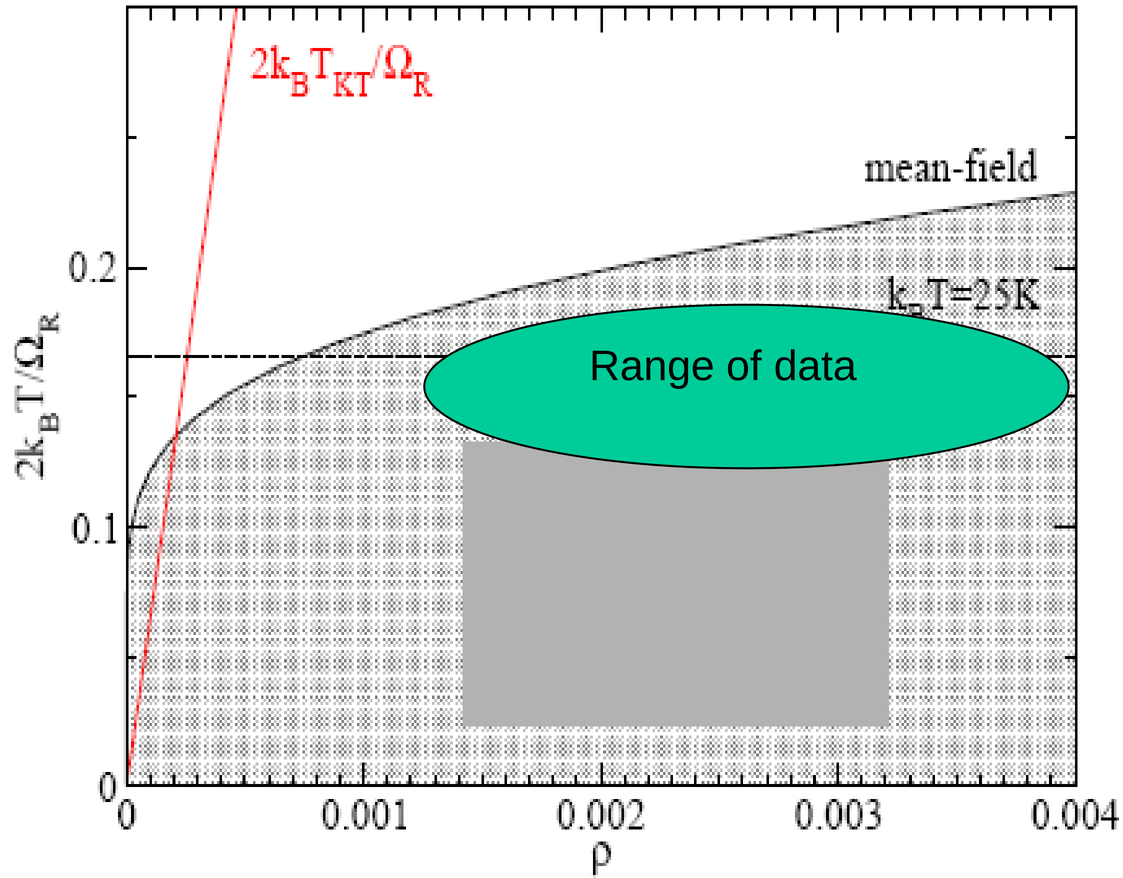
Dilute gas BEC only for excitation levels < 10^9 cm^{-2} or so

A further crossover to the plasma regime when $na_B^2 \sim 1$

Comparison to recent experiments - density

Estimate density from blueshift of polariton line

Appears to be inside mean-field regime: not a dilute Bose gas

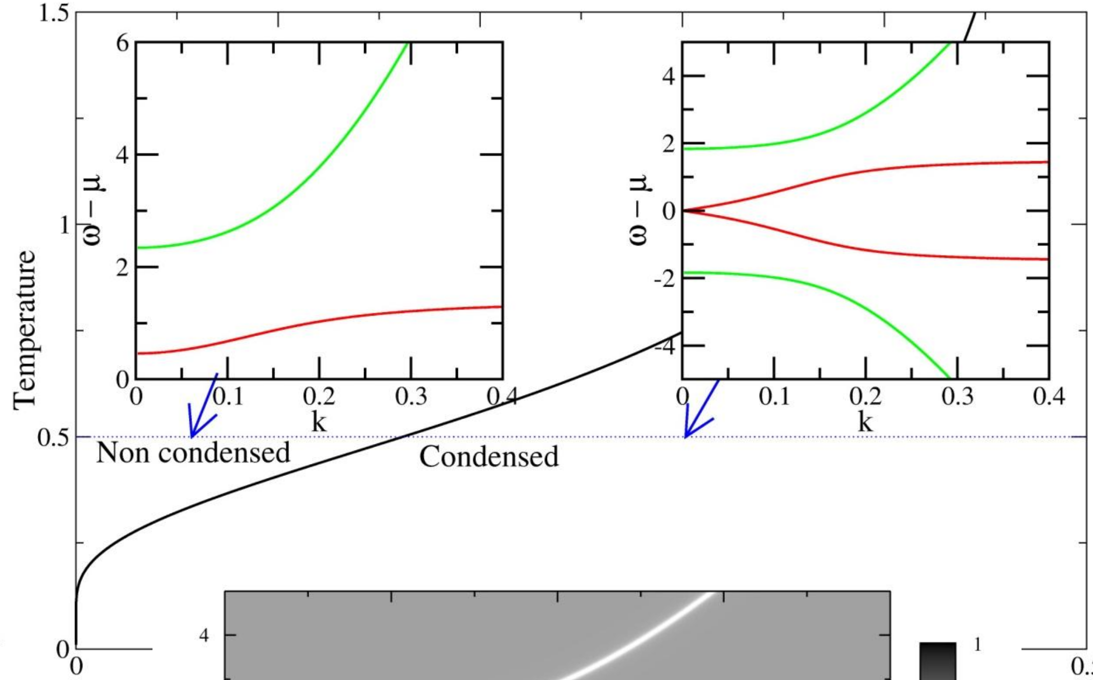


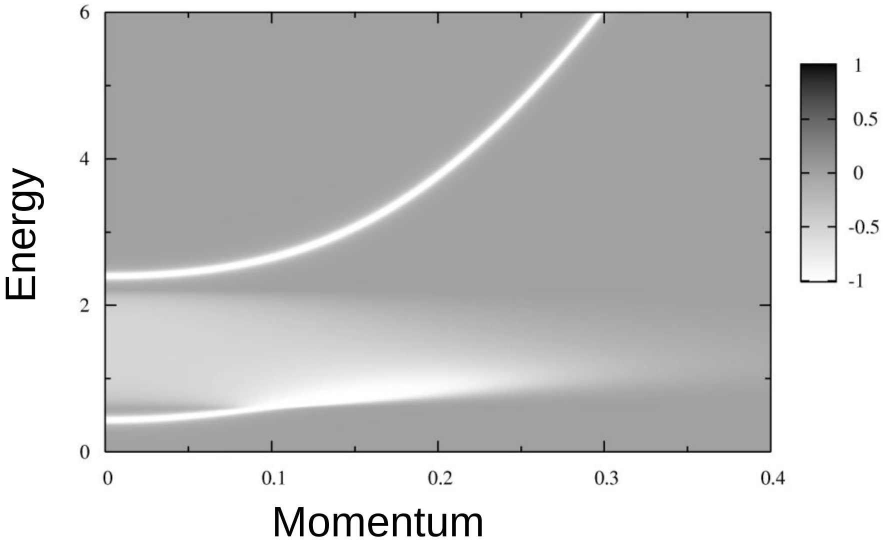
Marchetti et al Phys. Rev. B 77, 235313 (2008)

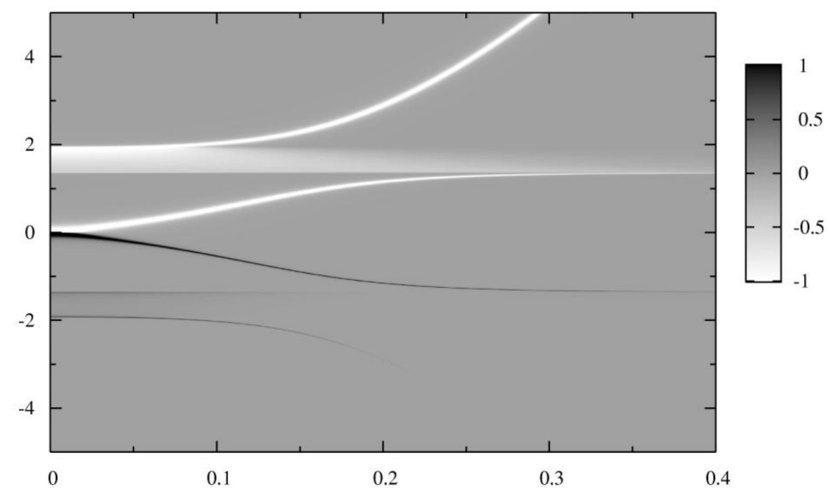
2D polariton spectrum

Keeling et al PRL 93, 226403 (2004)

- Below critical temperature polariton dispersion is linear – Bogoliubov sound mode appears
- Include disorder as inhomogeneous broadening





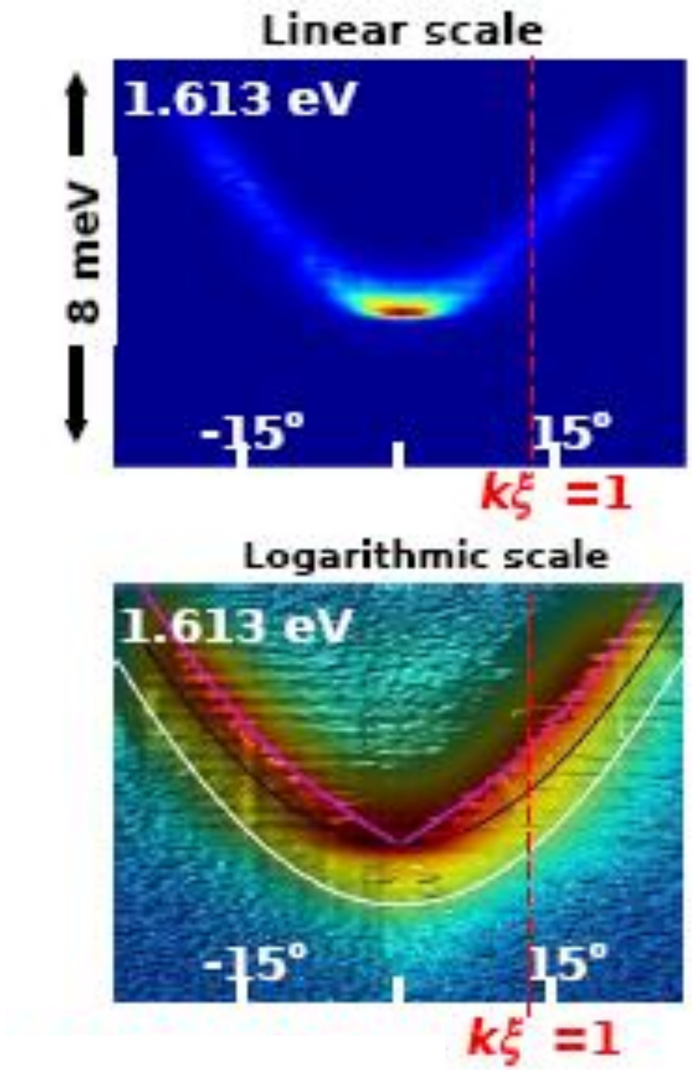


Quasiparticle spectrum above threshold

Reported observation of Bogoliubov spectrum

Utsunomiya et al, Nature Physics, 4 706 (September 2008)

But what about the effects of particle lifetimes and decoherence?



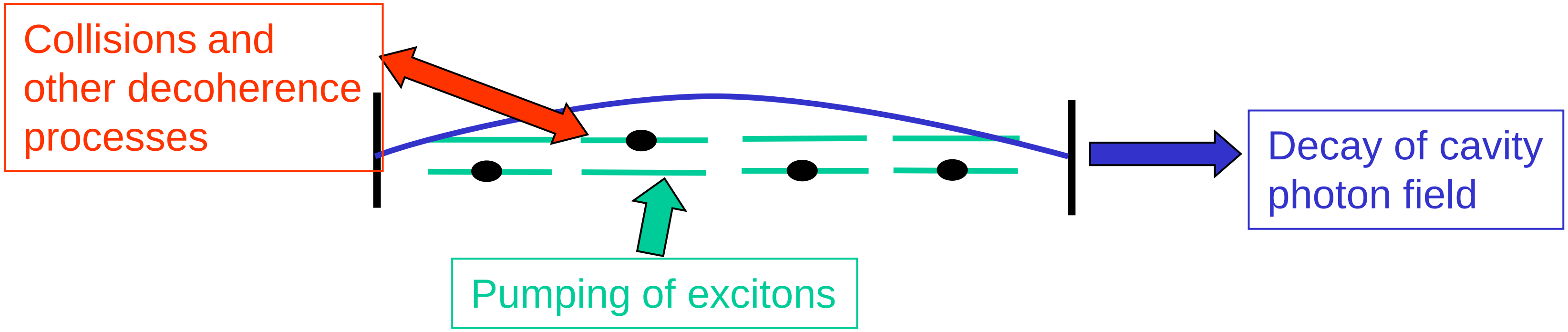
Decoherence

Despite large Q of cavity, lifetime is only a few psec

Even if a thermal distribution can be obtained, the system is non-equilibrium

Particle fluxes produce decoherence

Decoherence and the laser



Decay, pumping, and collisions will introduce “decoherence” - loosely, lifetimes for the elementary excitations - include this by coupling to bosonic “baths” of other excitations

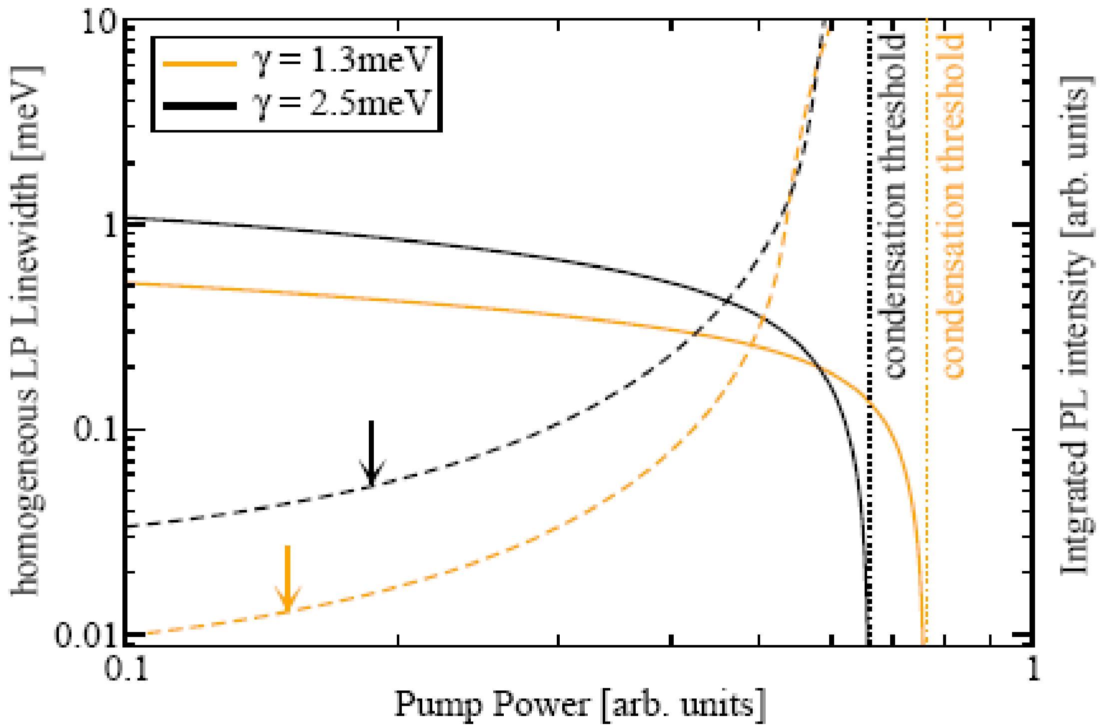
In a laser, the excitons decouple from the polaritons and become incoherent, while the photons remain coherent.

Distinguish pairbreaking (leads to electron-hole laser) from dephasing.

Szymanska, Littlewood, Simons, PRA **68**, 013808 (2003)
Szymanska, Keeling, Littlewood, PRL **96**, 230602 (2006)

Linewidth from dephasing due to pump and decay

- Calculation includes dephasing from pumping and decay
- Below threshold, linewidth narrows and intensity grows (critical fluctuations)
- Measured linewidth is consistent with dephasing that is weak enough to permit effects of condensation



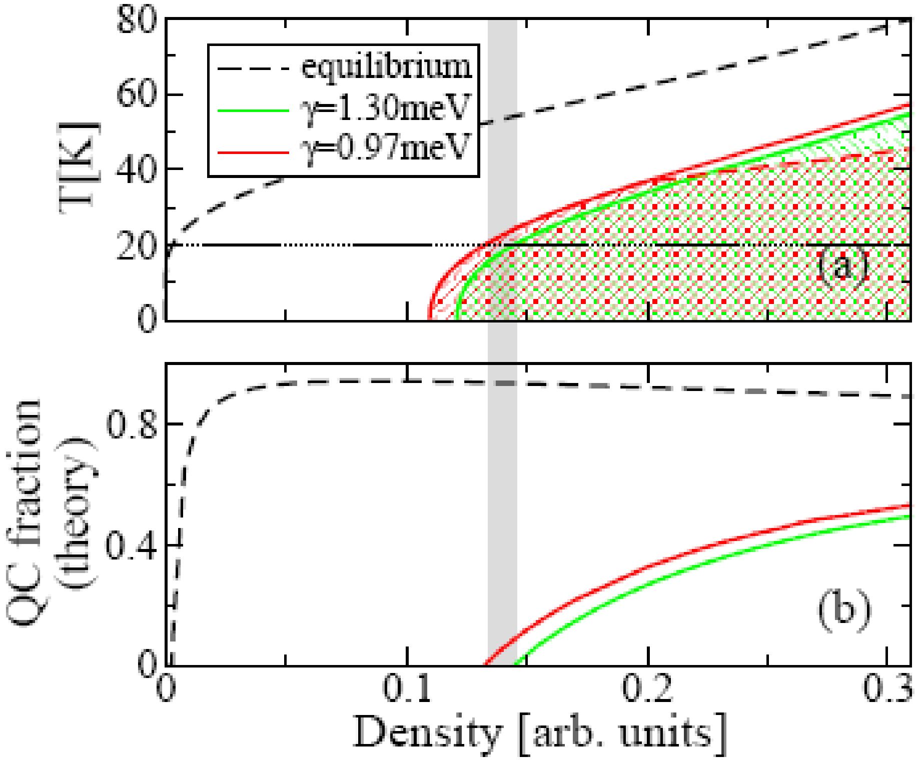
Szymanksa, Keeling, PBL PRL **96**, 230602 (2006)

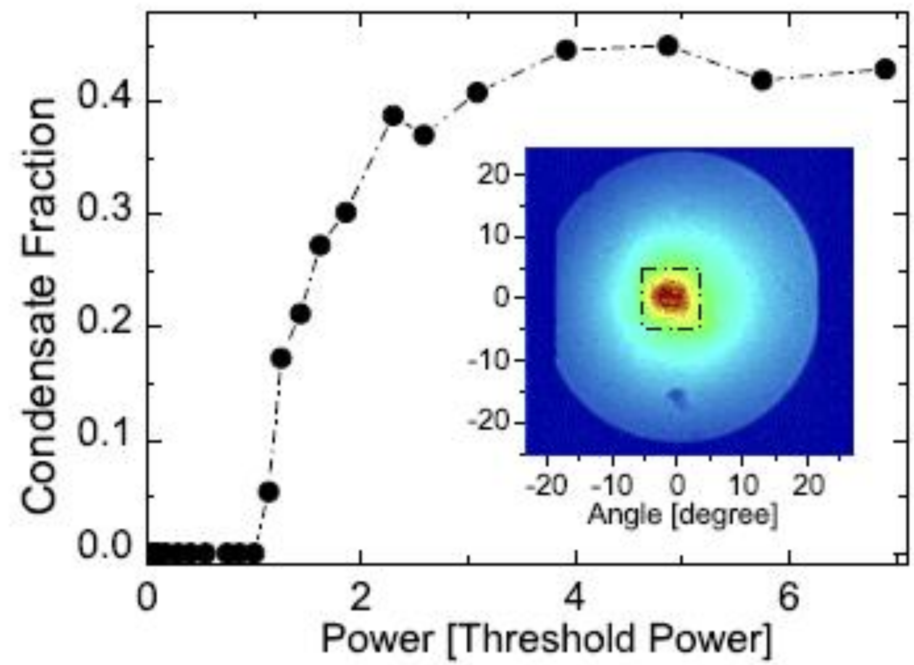
Effect of dissipation on Tc and condensate

Two parameters:

κ – photon linewidth (measured)

γ – pumping rate – unknown but bounded



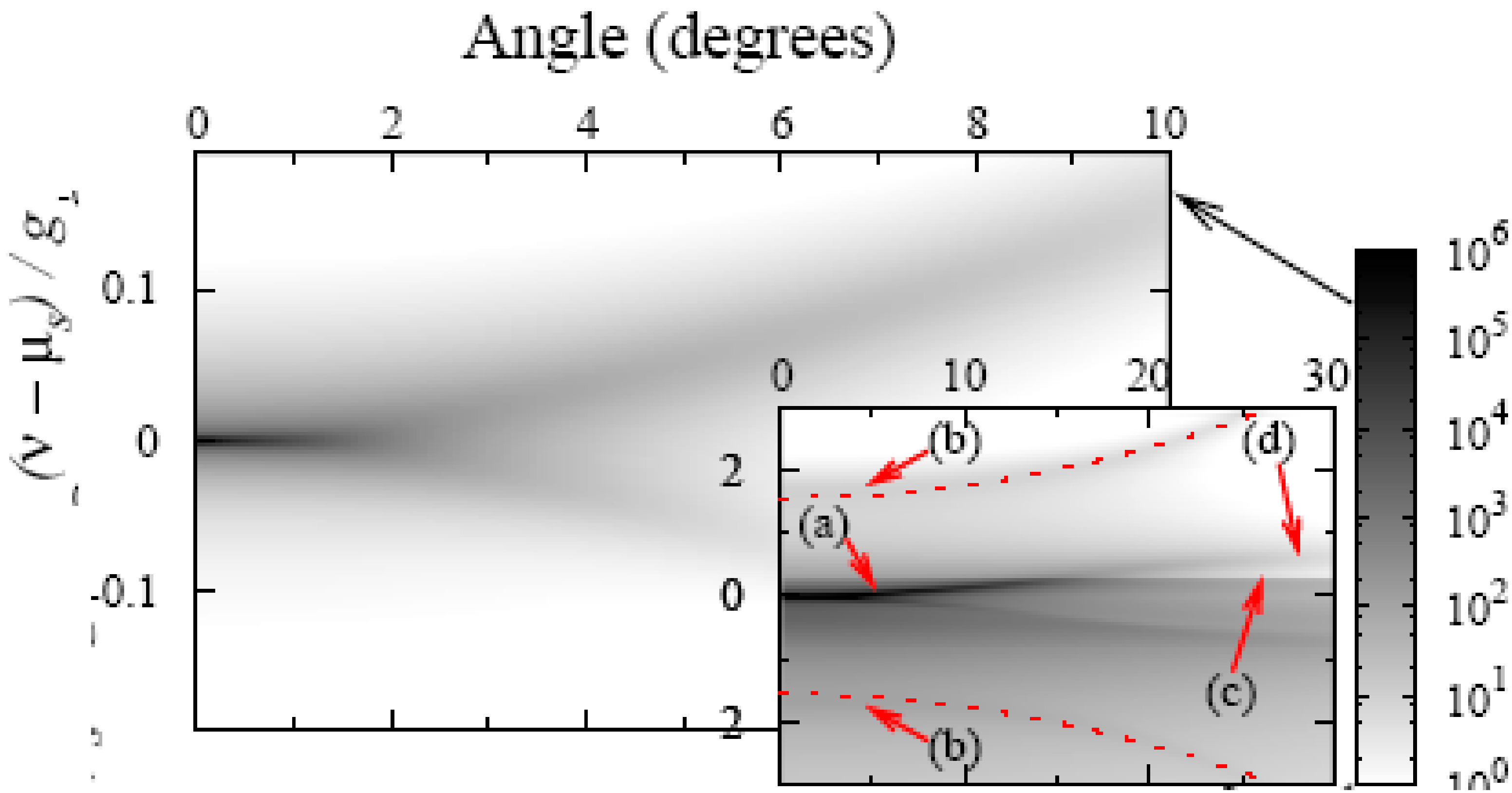


Marchetti et al Phys. Rev. B 77, 235313 (2008)

Optical emission above threshold

Szymanska et al PRL **96**, 230602 (2006)

At low momenta, Goldstone-Bogoliubov mode becomes dissipative



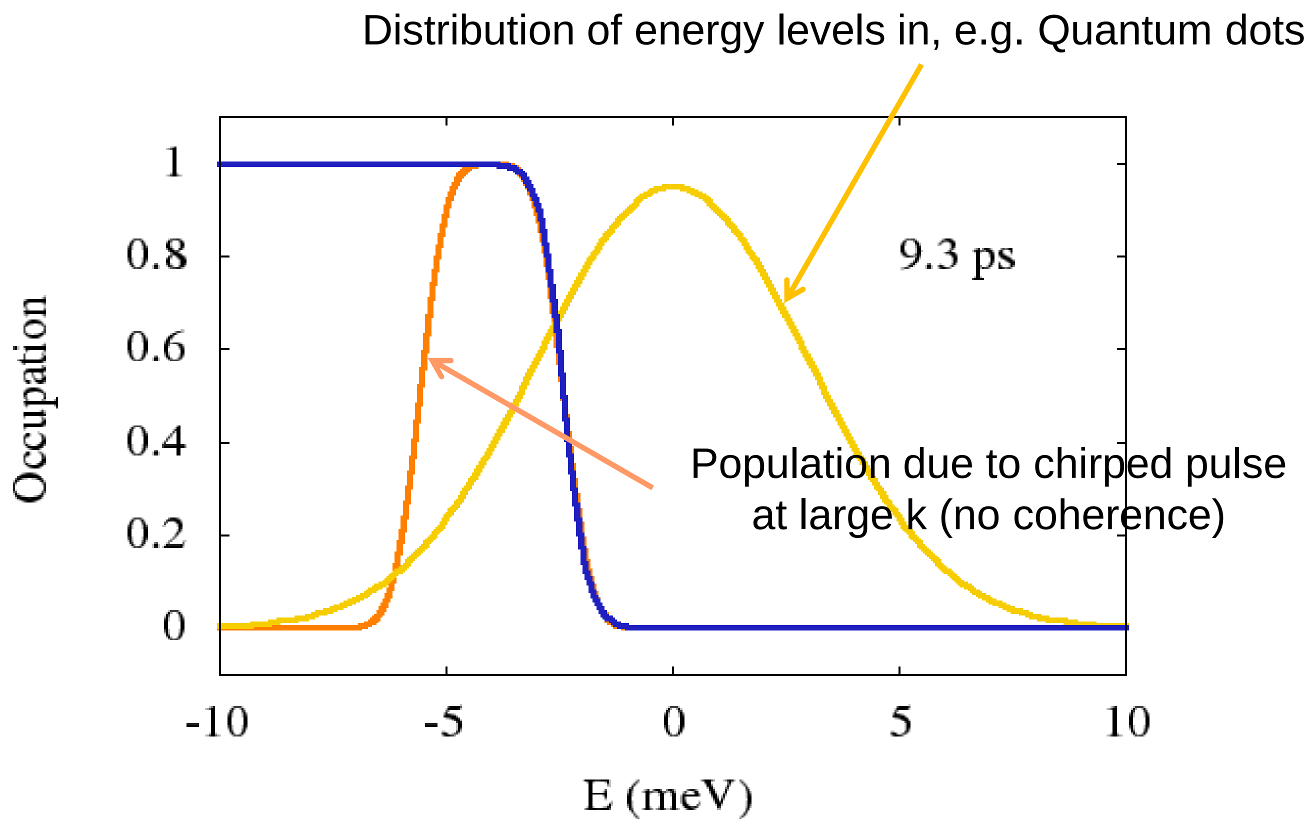
Quantum dynamics

On time scales < few psec, not in thermal equilibrium

Coupling to light allows driven dynamics

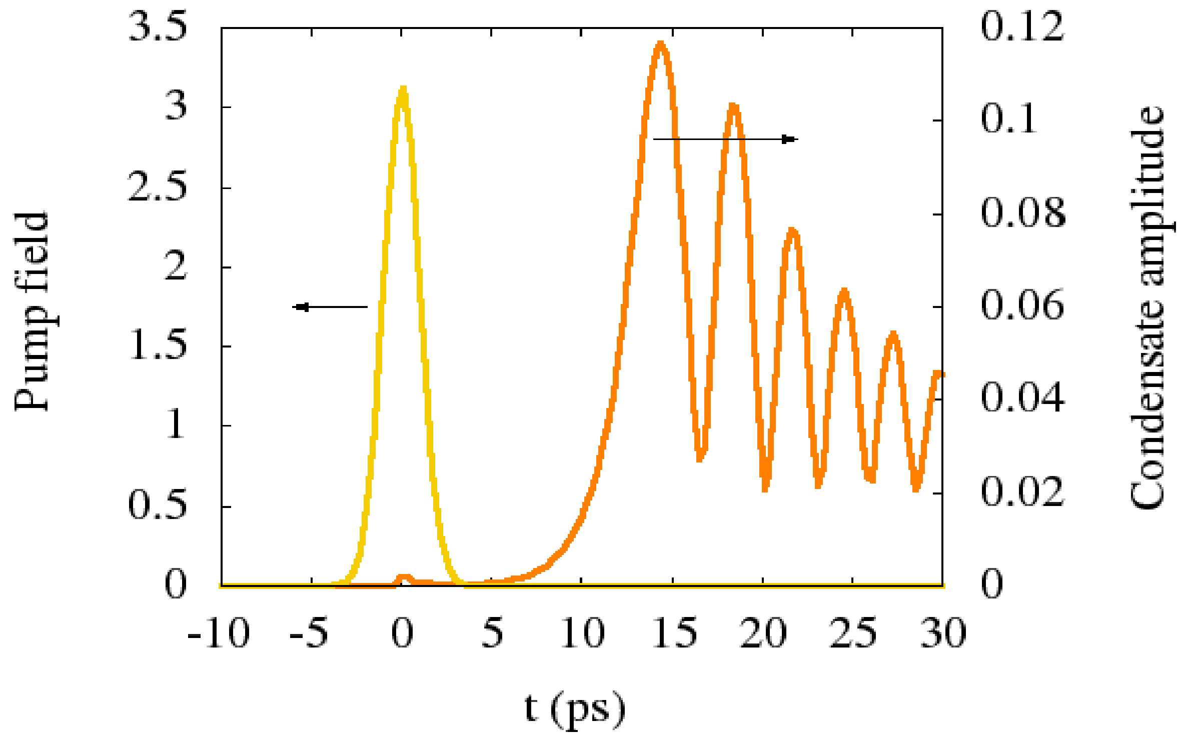
Controlled pumping of a many-particle state

P.R. Eastham and Richard Phillips; arxiv:0708.2009



- Direct creation of a *many-exciton* state
- .. equivalent to excitons in equilibrium at 0.6K

Spontaneous dynamical coherence



$\langle P_{k=0} \rangle$ are macroscopic(scaling with the number of dots $\sqrt{N}$)

$\langle \psi_{k=0} \rangle$

$\Rightarrow$ A quantum condensate of both photons and k=0 excitons

Cavity polaritons

A new correlated many body system for “cold” “atoms”