Coherent excitonic matter

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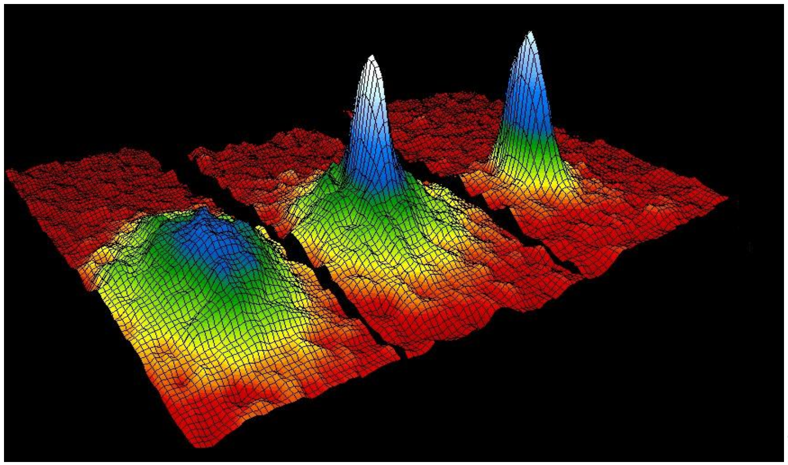
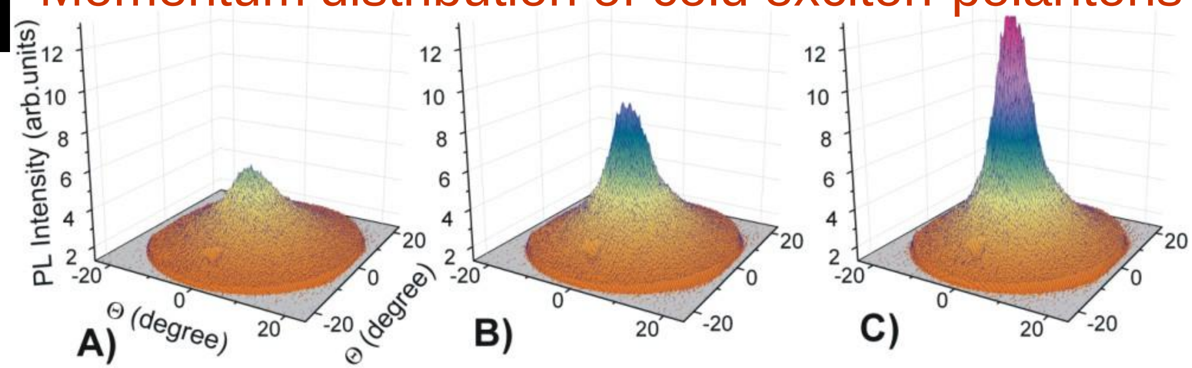


Rb atom condensate, JILA, Colorado

Momentum distribution of cold atoms

Momentum distribution of cold exciton-polaritons



Exciton condensate ?, Kasprzak et al 2006

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Characteristics of Bose-Einstein Condensation

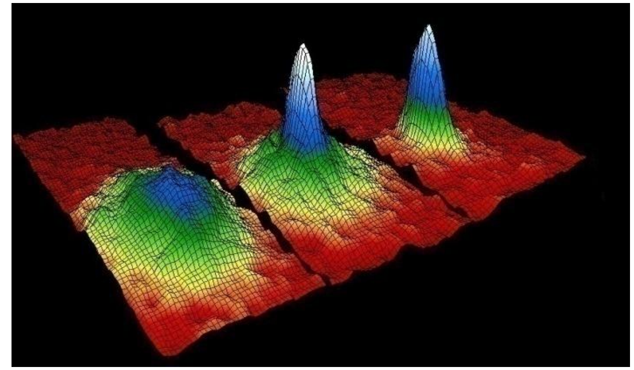
- Macroscopic occupation of the ground state
  - weakly interacting bosons

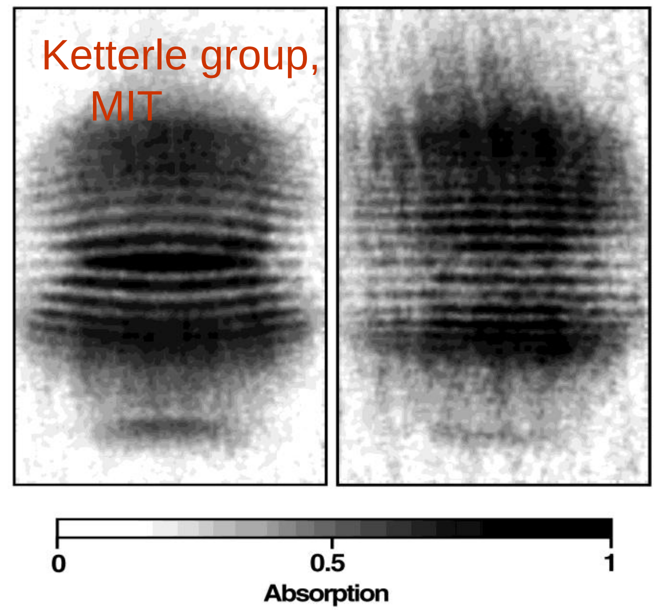
$$k_B T_0 \approx \frac{\hbar^2 n^{2/3}}{2m} \approx \frac{1.3}{r_s^2}\, Ryd$$

- 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

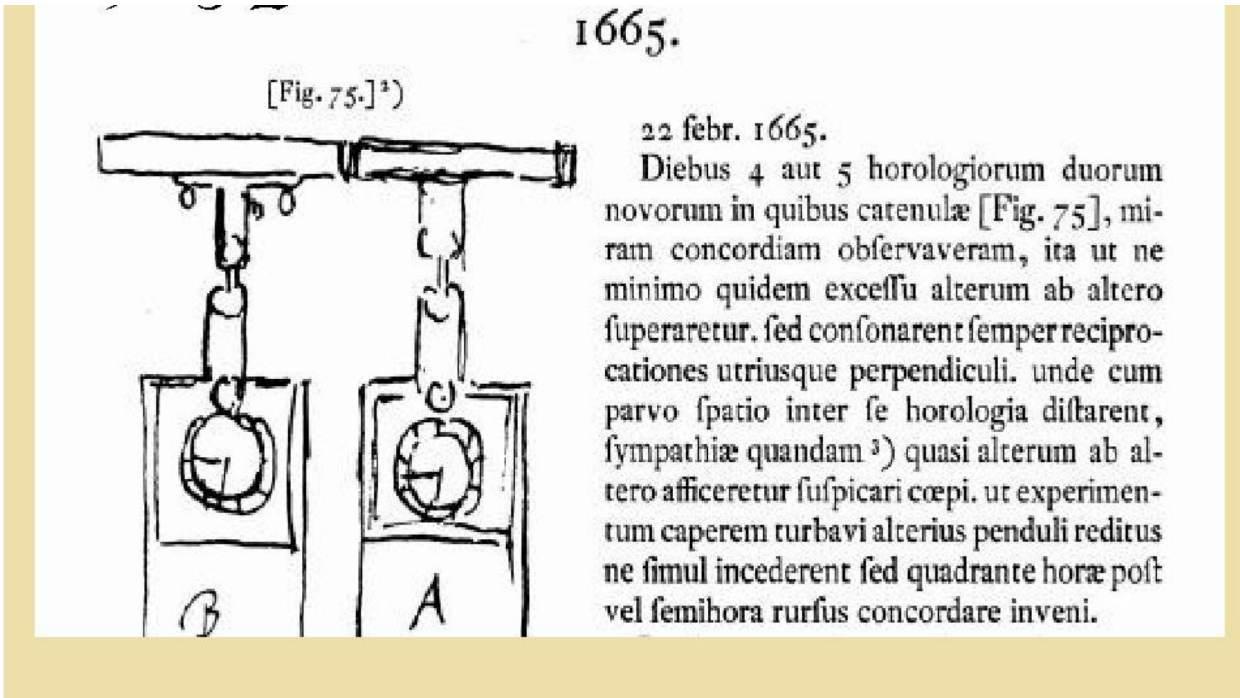
1656 – Patented the pendulum clock

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)

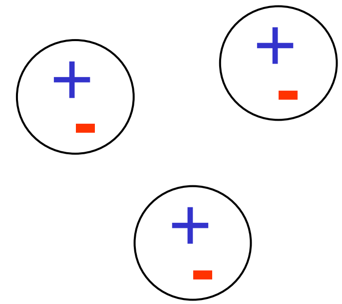
Two metronomes on a cart

Issues for these lectures

- Characteristics of a Bose condensate
- Excitons, and why they might be candidates for BEC

How do you make a BEC wavefunction based on pairs of fermions?

- BCS (interaction-driven high density limit) to Bose (low density limit) crossover

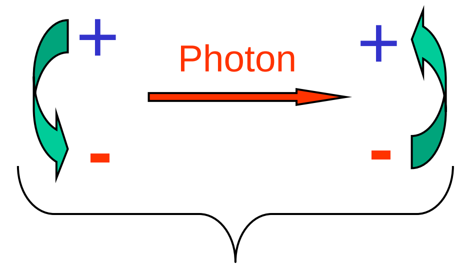


Excitons are the solid state analogue of positronium

- Excitons may decay directly into photons

What happens to the photons if the "matter" field is coherent?

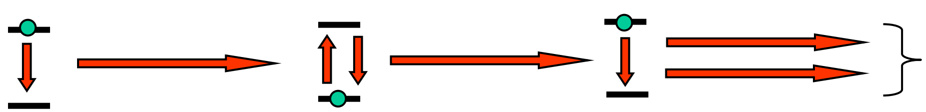
- Two level systems interacting via photons



Combined excitation is called a **polariton**

How do you couple to the environment ?

- Decoherence phenomena and the relationship to lasers



Emission

Absorption and re-emission

Stimulated emission

These photons have a fixed phase relationship

Stimulated Emission > Absorption

Laser

Outline

- General review
- Exciton condensation
  - mean field theory of Keldysh – BCS analogy
  - BCS-BEC crossover
  - broken symmetries, tunnelling, and (absence of) superfluidity
- Polaritons (coherent mixture of exciton and photon)
  - mean field theory
  - BCS-BEC crossover (again) and 2D physics
  - signatures of condensation
  - disorder
  - pairbreaking
  - phase-breaking and decoherence
- Review of Experiment intermingled (though mostly see other lectures)
- Other systems (if there is time)
  - quantum Hall bilayers
  - “triplons” in quantum spin systems
  - ultracold fermions and the Feshbach resonance

Background material and details for the lectures

I will not give detailed derivations in lectures, but they can all be found in these papers

Reviews

Bose-Einstein Condensation, ed Griffin, Snoke, and Stringari, CUP, (1995)

PB Littlewood and XJ Zhu, Physica Scripta T68, 56 (1996)

P. B. Littlewood, P. R. Eastham, J. M. J. Keeling, F. M. Marchetti, B. D. Simons, M. H. Szymanska. JPCM 16 (2004) S3597-S3620.

J. Keeling, F. M. Marchetti, M. H. Szymanska, P. B. Littlewood, *Semiconductor Science and Technology*, 22,R1-26, 2007.

D Snoke and P B Littlewood, Physics Today 2010

H. Deng, H, Haug and Y Yamamoto, Rev. Mod. Phys. 82:1489 (2010)

Basic equilibrium models:

Mean field theory (excitons): C. Comte and P. Nozieres, J. Phys. (Paris),43, 1069 (1982); P. Nozieres and C. Comte, ibid., 1083 (1982); P. Nozieres, Physica 117B/118B, 16 (1983). Y.Lozovik and V Yudson, JETP Lett. 22, 274 (1975)

Mean field theory (polaritons): P. R. Eastham, P. B. Littlewood , Phys. Rev. B 64, 235101 (2001)

BCS-BEC crossover (polaritons): Jonathan Keeling, P. R. Eastham, M. H. Szymanska, P. B. Littlewood, Phys. Rev. Lett. 93, 226403 (2004) cond-mat/0407076; Phys. Rev. B 72, 115320 (2005)

Effects of disorder: F. M. Marchetti, B. D. Simons, P. B. Littlewood, Phys. Rev. B 70, 155327 (2004)

Decoherence and non-equilibrium physics

M. H. Szymanska, P. B. Littlewood, B. D. Simons, Phys. Rev. A 68, 013818 (2003)

M. H. Szymanska, J. Keeling, P. B. Littlewood Phys. Rev. Lett. 96 230602 (2006)

F. M. Marchetti, J. Keeling, M. H. Szymanska, P. B. Littlewood, Phys. Rev. Lett. 96, 066405 (2006)

M. H. Szymanska, J. Keeling, P. B. Littlewood, *Physical Review B* 75, 195331 (2007)

M Wouters and I. Carusotto, PRL 99, 140402 (2007).

Physical signatures

Y.Lozovik and V Yudson, JETP Lett. 22, 274 (1975)

Fernandez-Rossier et al. , Solid State Commun 108, 473 (1998)

A V. Balatsky, Y N. Joglekar, PB Littlewood, Phys. Rev. Lett. 93, 266801 (2004).

JMJ Keeling, L. S. Levitov, P. B. Littlewood, Phys. Rev. Lett. 92, 176402 (2004)

I. Shelykh, F.P. Laussy, A. V. Kavokin, G. Malpuech Phys. Rev. B 73, 035315 (2006)

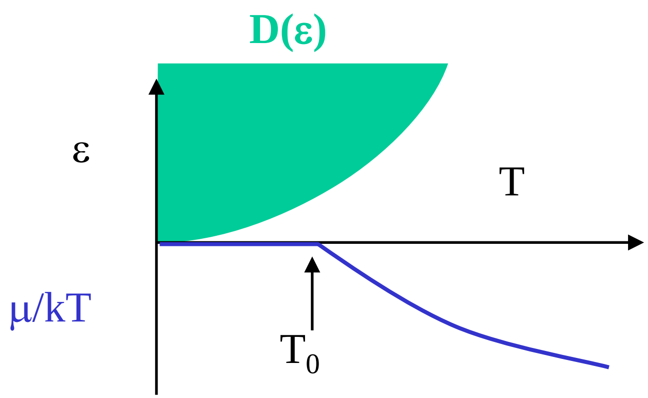
K. G. Lagoudakis, T. Ostatnicky, A.V. Kavokin, Y. G. Rubo, R. Andre, B. Deveaud-Pledran ,Science 326, 974 - 976 (2009)

Bose-Einstein condensation

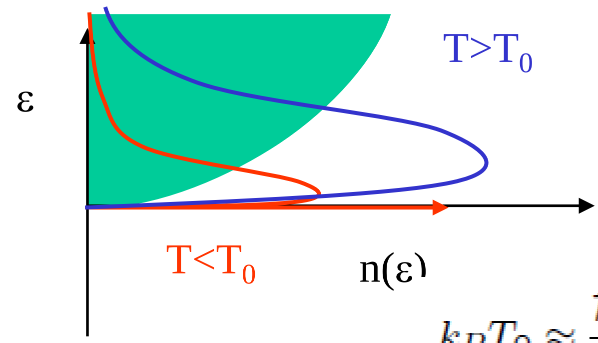
- Macroscopic ground state occupation

$$n = \int d\epsilon \frac{D(\epsilon)}{e^{\beta(\epsilon-\mu)} - 1} \sim \int d\epsilon \frac{\epsilon^{(d-2)/2}}{\beta(\epsilon - \mu)}$$

Density of states



Thermal occupation



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

- Macroscopic phase coherence

Condensate described by macroscopic wave function $\psi\, e^{i\phi}$ which arises from interactions between particles

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

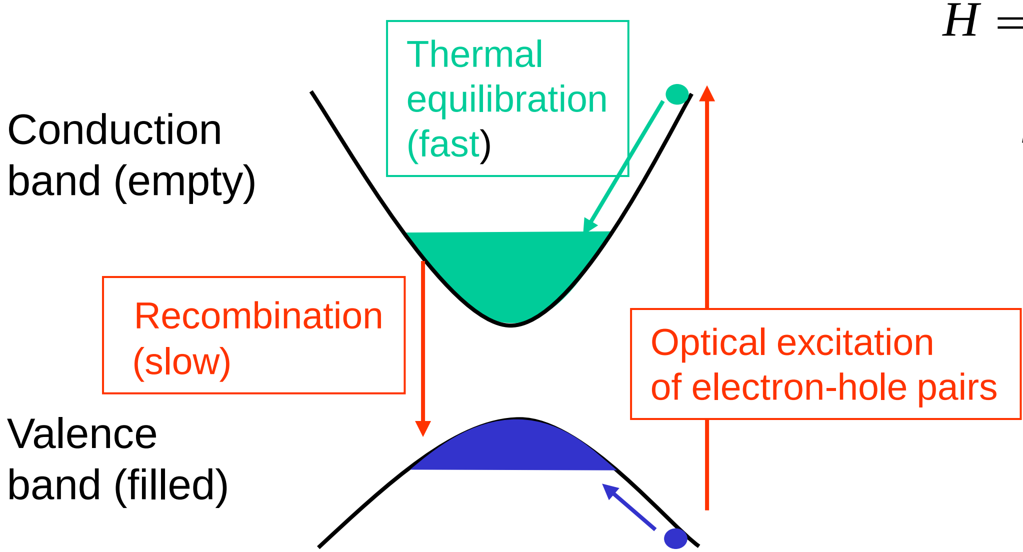
Genuine symmetry breaking, distinct from BEC

Couple to internal degrees of freedom - e.g. dipoles, spins

- Superfluidity

Implies linear Goldstone mode in an infinite system with dispersion $\omega = v_s k$ and hence a superfluid stiffness $\alpha\ v_s$

Excitons in semiconductors



$$H = \sum_i [T_i^e + T_i^h] + \sum_{i,j} [V_{ij}^{ee} + V_{ij}^{hh} - V_{ij}^{eh}]$$

$$T_i^\alpha = \frac{p_{i\alpha}^2}{2m_\alpha} \qquad V_{ij}^{\alpha\beta} = \frac{e^2}{\varepsilon |r_{i\alpha} - r_{j\beta}|}$$

At high density - an electron-hole plasma

At low density - excitons

Exciton - bound electron-hole pair (analogue of hydrogen, positronium)

In GaAs, $m^* \sim 0.1\ m_e$, $\varepsilon = 13$

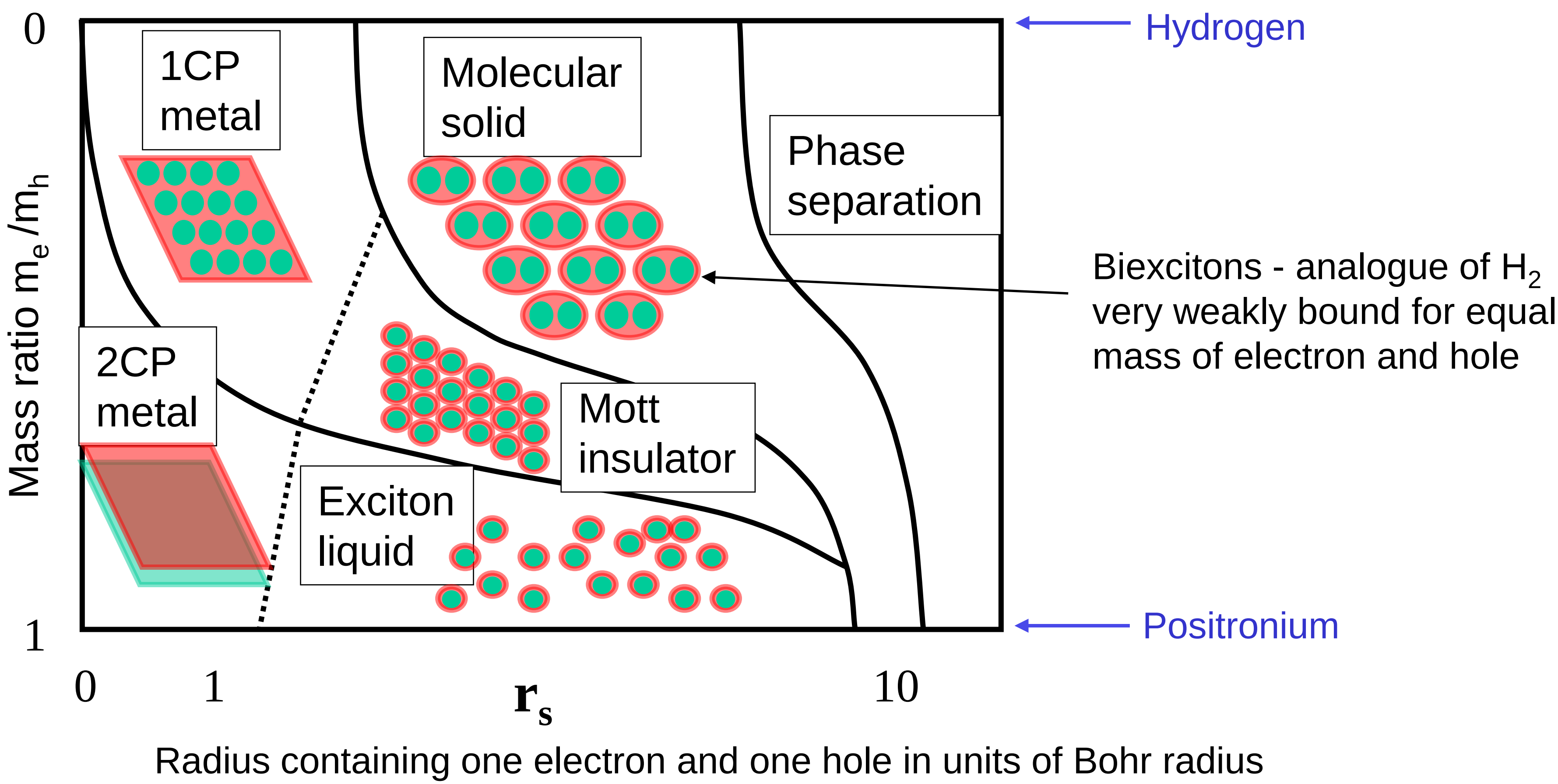
Rydberg = 5 meV (13.6 eV for Hydrogen)

Bohr radius = 7 nm (0.05 nm for Hydrogen)

Measure density in terms of a dimensionless parameter r_s - average spacing between excitons in units of a_{Bohr}

$$1/n = \frac{4\pi}{3}(a_{Bohr} r_s)^3$$

Speculative phase diagram of electron-hole system (T=0)

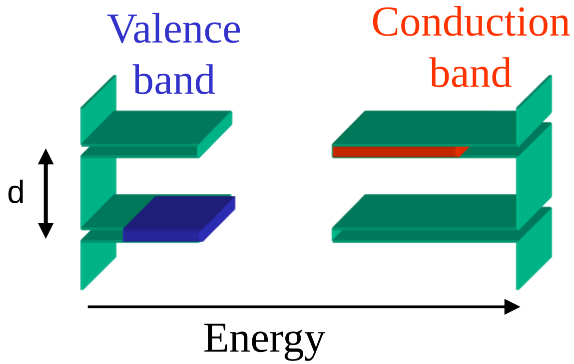


PBLittlewood and XJZhu Physica Scripta T68, 56 (1996)

Interacting electrons and holes in double quantum well

Two parabolic bands, direct gap, equal masses

Layers of electrons and holes in quantum wells spaced a distance d apart



$$H = \sum_i [T_i^e + T_i^h] + \sum_{i,j} [V_{ij}^{ee} + V_{ij}^{hh} - V_{ij}^{eh}] \qquad T_i^\alpha = \frac{p_{i\alpha}^2}{2m_\alpha} \qquad V_{ij}^{\alpha\beta} = \frac{e^2}{\varepsilon |r_{i\alpha} - r_{j\beta}|}$$

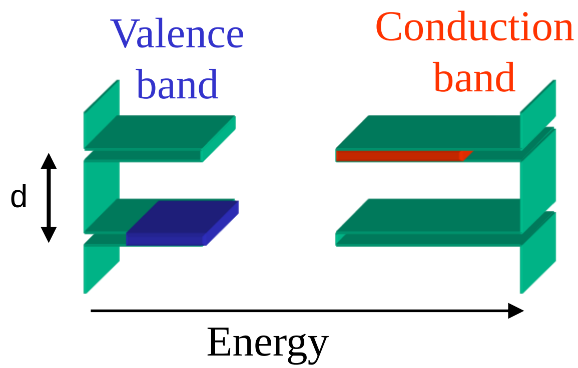
Units: density- $n = 1/\pi (r_s a_B)^2$ $\qquad a_B = \varepsilon \hbar^2 / m e^2$

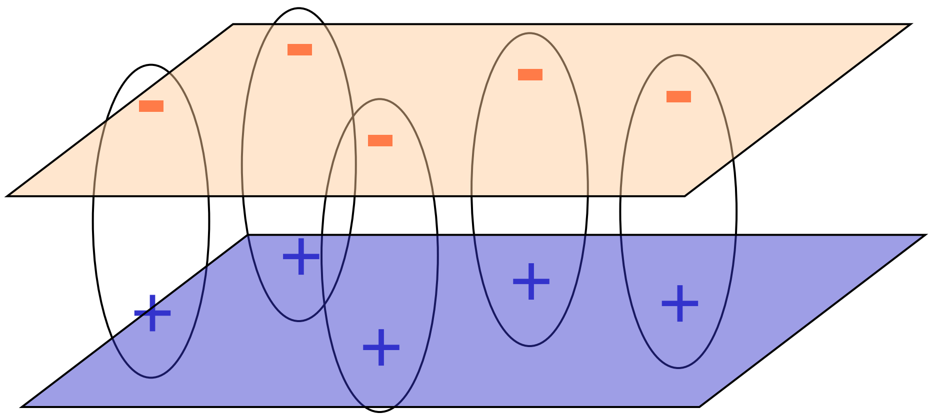
energy- Rydberg $e^2 / 2\varepsilon a_B$

Ignore interband exchange - spinless problem

Ignore biexcitons - disfavoured by dipole-dipole repulsion

Coupled Quantum Wells



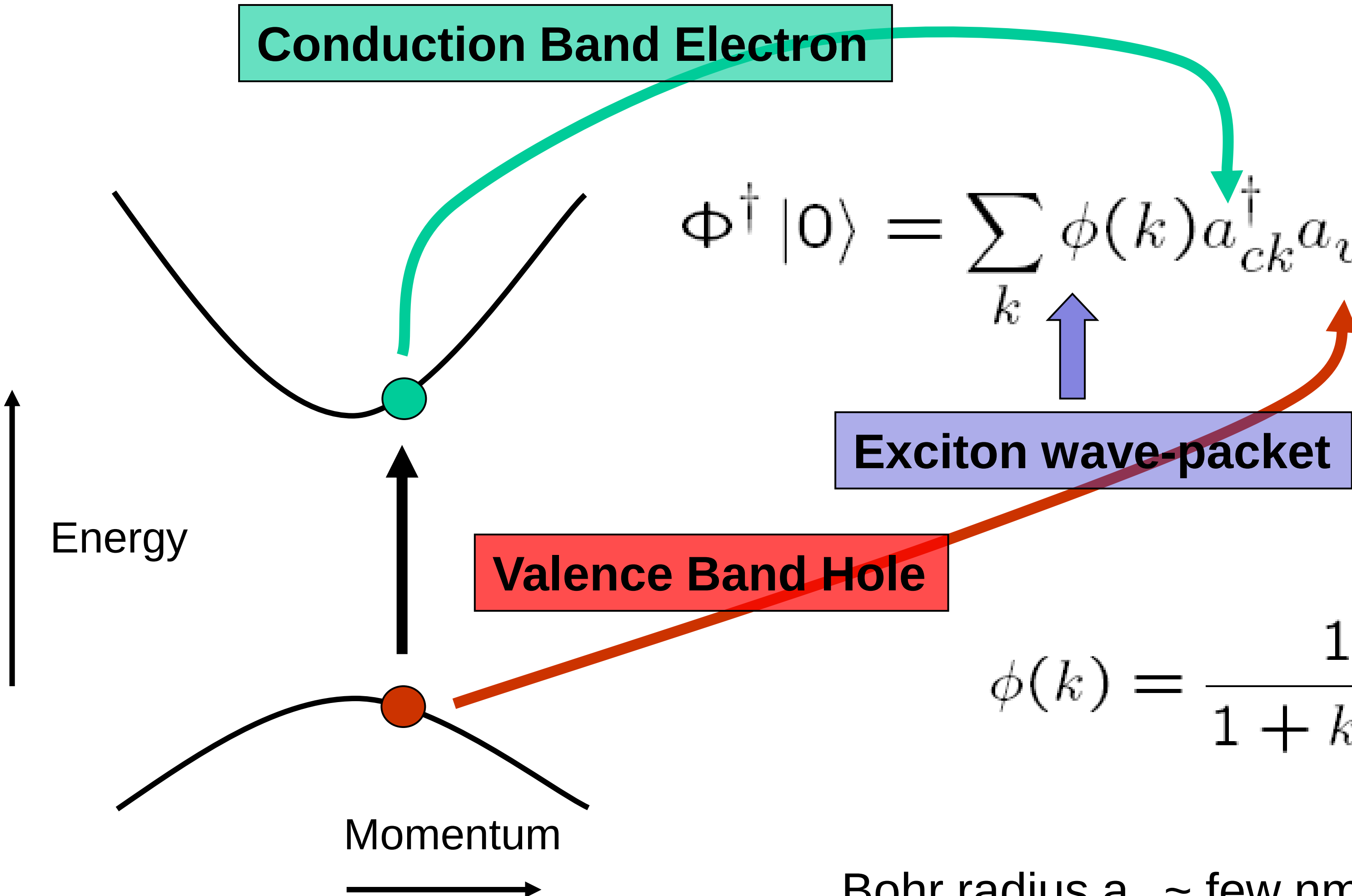


Neutral bosons with repulsive dipolar interaction in 2D

Binding energy few meV in GaAs
Bohr radius ~ 10 nm

Long lifetime up to 100 nsec – recombination by tunnelling through barrier

Excitons



$$\Phi^\dagger |0\rangle = \sum_k \phi(k) a^\dagger_{ck} a_{vk} |0\rangle$$

$$\phi(k) = \frac{1}{1 + k^2 a_B^2}$$

Bohr radius a_B ~ few nm

Mean field theory of excitonic insulator

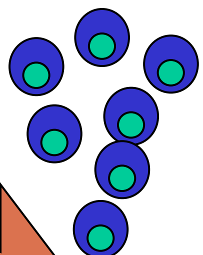
$$\Phi^\dagger |0\rangle = \sum_k \phi(k) a^\dagger_{ck} a_{vk} |0\rangle$$

Wavepacket of bound e-h pair
Composite boson

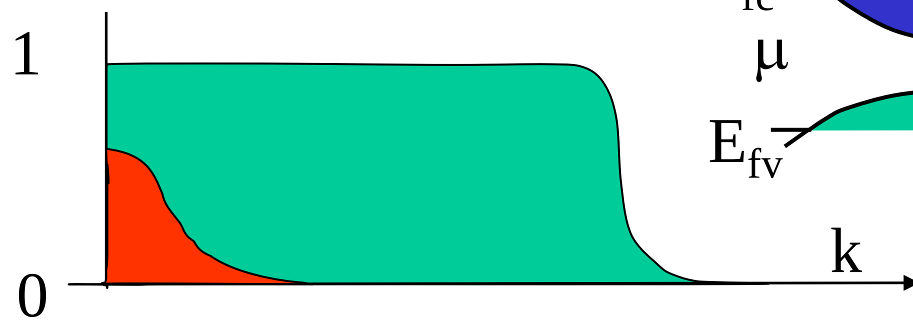
$$e^{\lambda\Phi^\dagger} |0\rangle = \prod_k \left[u(k) + v(k) a^\dagger_{ck} a_{vk} \right] |0\rangle$$

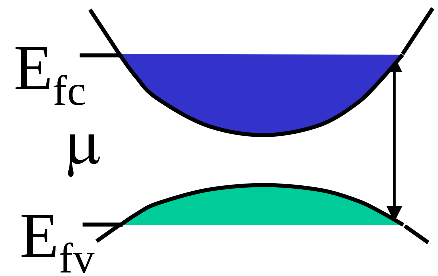
A coherent state – like a laser
Bose condensation of excitons

BCS-like instability
of Fermi surfaces



$$v(k) = \lambda\phi(k)$$





Special features: order parameter; gap

$$\langle a^+_{ck} a_{vk} \rangle = u_k v_k = (\Delta_k / 2E_k); \quad E_k = \sqrt{(\varepsilon_k - \mu)^2 + \Delta_k^2}$$

Mean Field Solution

$$H_o = \sum_k \left[\epsilon_{ck} a^\dagger_{ck} a_{ck} + \epsilon_{vk} a^\dagger_{vk} a_{vk}\right]$$

Single particle band energies

$$H_c = \frac{1}{2}\sum_q \left[V^{ee}_q \rho^e_q \rho^e_{-q} + V^{hh}_q \rho^h_q \rho^h_{-q} + 2V^{eh}_q \rho^e_q \rho^h_{-q}\right]$$

Coulomb interaction between layers separated by distance d

$$\rho^e_q = \sum_k a^\dagger_{ck+q} a_{ck} \qquad V^{ee} = V^{hh} = 2\pi/q \qquad V^{eh} = 2\pi e^{-qd}/q$$

$$\Psi_0 = e^{\lambda \sum_k a^\dagger_{ck} a_{vk}} |0\rangle = \prod_k \left[u_k + v_k a^\dagger_{ck} a_{vk}\right] |0\rangle$$

Variational “BCS” mean field solution

$$\xi_k = \epsilon_k - \mu - \sum_{k'} V^{ee}_{k-k'} n_{k'}$$

Self-energy

$$\Delta_k = 2\sum_{k'} V^{eh}_{k-k'} \left\langle a^\dagger_{ck'} a_{vk'} \right\rangle = \sum_{k'} V^{eh}_{k-k'} \Delta_{k'}/E_{k'}$$

Order parameter equation

$$E^2_k = \xi^2_k + \Delta^2_k$$

Spectrum with a gap

Excitation spectra

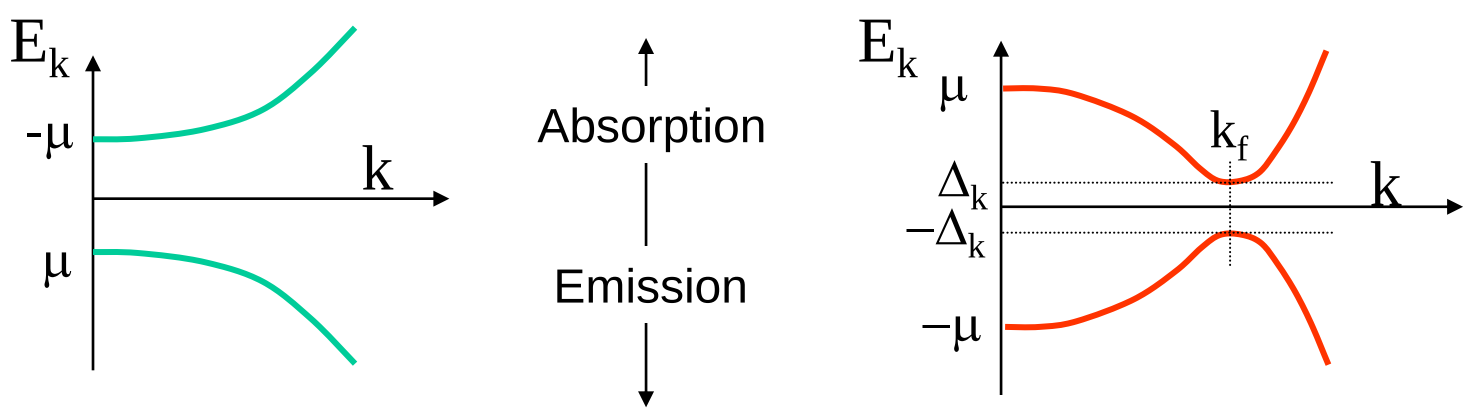
+(-)E_k is energy to add (remove) particle-hole pair from condensate (total momentum zero)

$$E_k = \sqrt{(\varepsilon_k - \mu)^2 + \Delta_k^2}$$

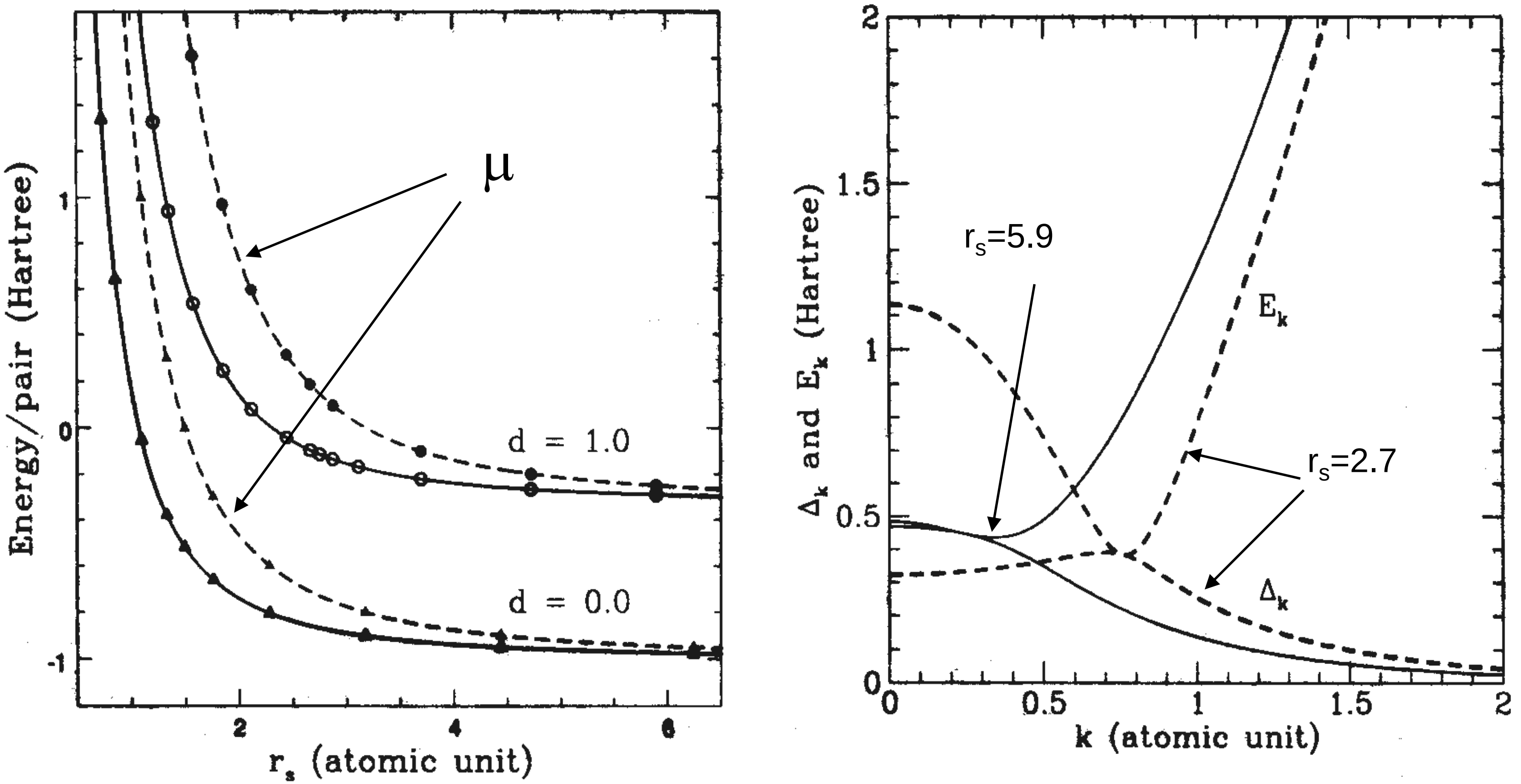
- ε_k: Band energy
- μ: Chemical potential (<0 for bound exciton)
- Δ_k: Correlation energy

Low density μ<0
Chemical potential
below band edge

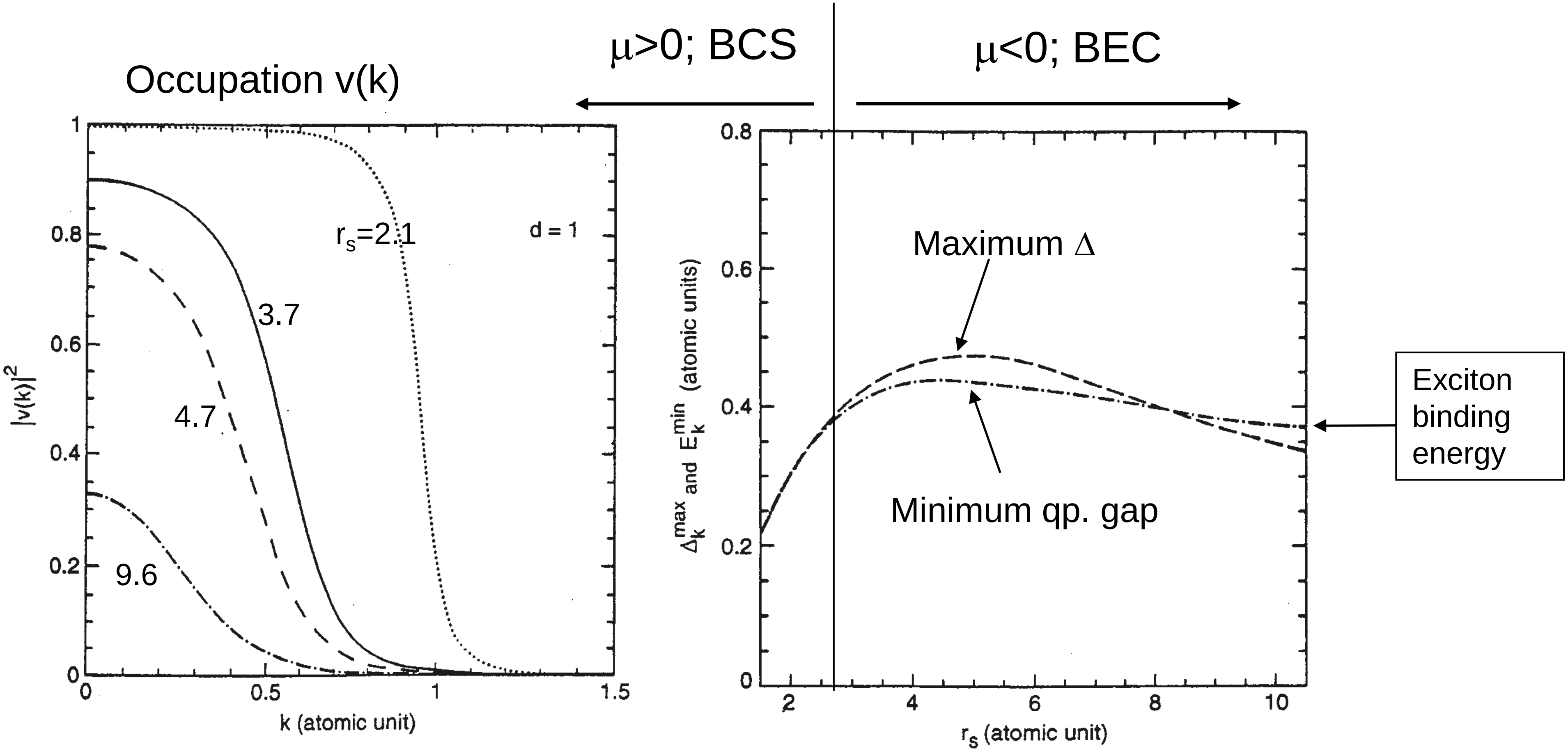
High density μ>0
No bound exciton
below band edge



2D exciton condensate: Mean field solution



Crossover from BCS to BEC



Smooth crossover between BCS-like fermi surface instability and exciton BEC

Model: 2D quantum wells separated by distance = 1 Bohr radius Zhu et al PRL 74, 1633 (1995)

Improved solution: Variational Monte Carlo

$$\Psi = \exp\left[\sum_{i\neq j} u(r_{i,e} - r_{j,e})\right] \exp\left[\sum_{i\neq j} u(r_{i,h} - r_{j,h})\right] \exp\left[\sum_{i,j} v(r_{i,e} - r_{j,h})\right] \times \Psi_0$$

Jastrow factors - smooth functions with variational parameters to add extra correlations to wavefunction

Either 2 component plasma (Slater determinant of plane waves) or BCS (Slater determinant of e-h pairs)

Zhu et al, PRB 54, 13575 (1996)

Search through variational parameter space by Monte Carlo
Output: Better energies, also pair correlation functions

Further improvements possible :

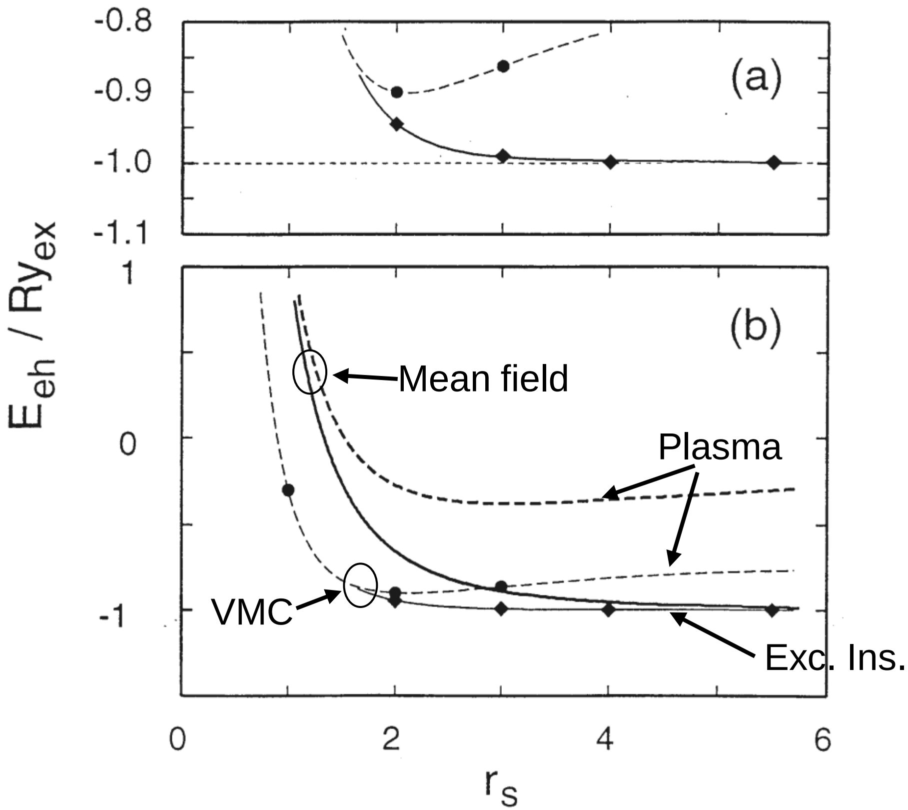
Diffusion Monte Carlo (fixed node)

Path Integral Monte Carlo (finite T)

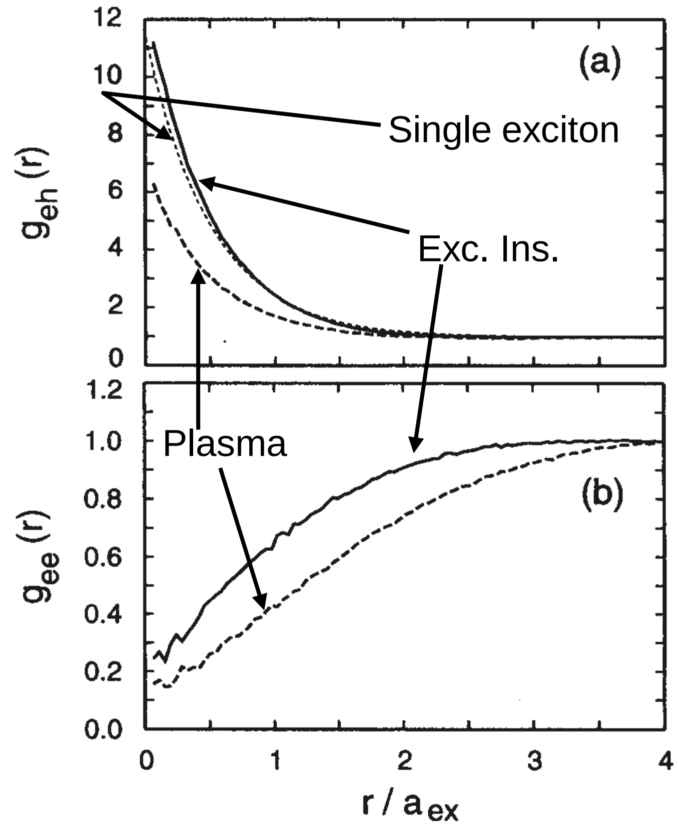
Include biexcitons, Wigner crystal phases etc...

3D exciton condensate - mean field vs VMC

Energy



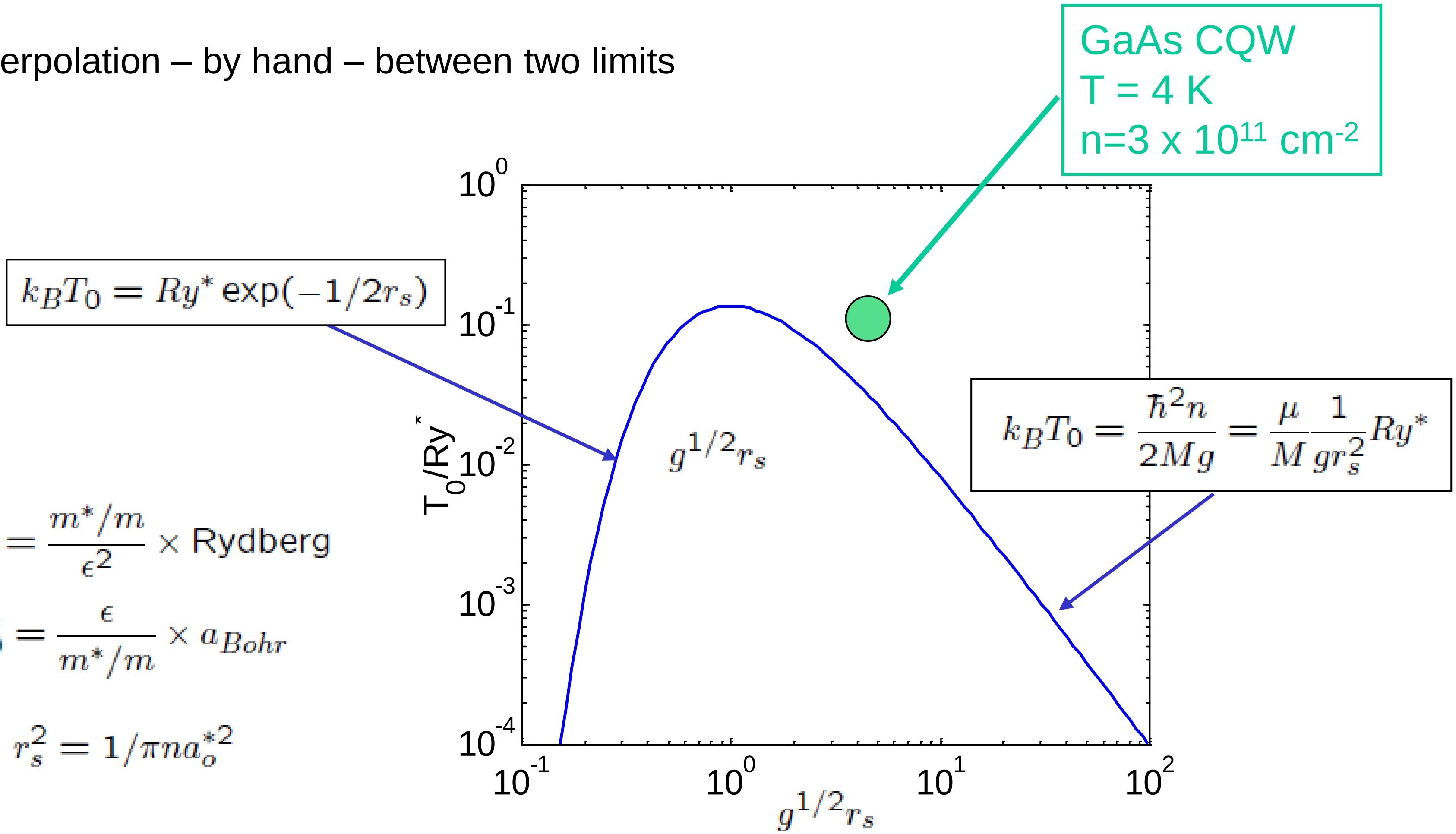
Correlation functions



Zhu et al PRB 54, 13575 (1996)

2D BEC - no confining potential

Interpolation – by hand – between two limits



$$Ry^* = \frac{m^*/m}{\epsilon^2} \times \text{Rydberg}$$

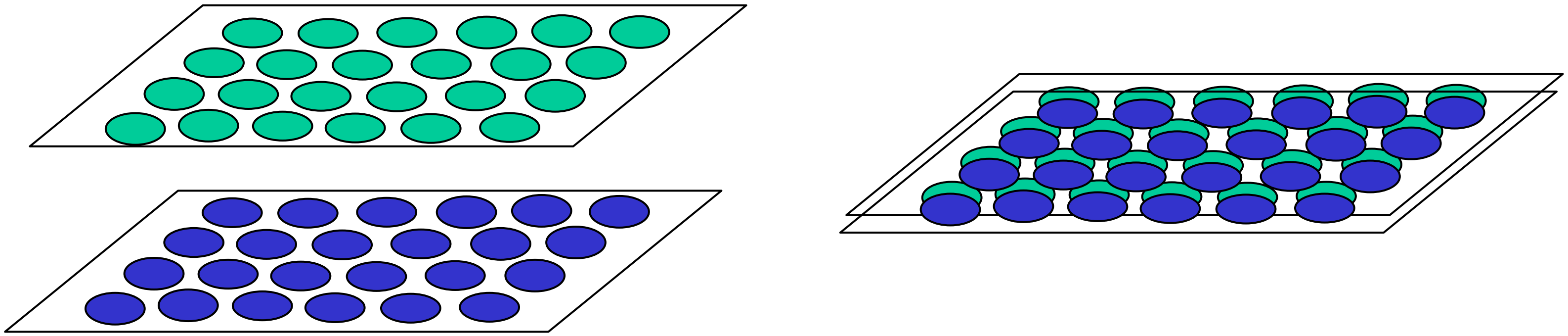
$$a_0^* = \frac{\epsilon}{m^*/m} \times a_{Bohr}$$

$$r_s^2 = 1/\pi n a_o^{*2}$$

Mean field - should be K-T transition, but OK to estimate energy scales

2D solid phases

- At low density, single layer will become a Wigner crystal
- Paired electron-hole Wigner crystal is an excitonic solid
- In 2D biexciton formation is disfavored by dipole repulsion



- Effect of crystal lattice
  - Stabilise the insulating phases to higher densities – Wigner transition turns into a Mott transition
  - Induce commensurability effects
- One component plasma (e.g. Metallic H) is believed to be a superconductor
  - In the context of excitons with localised holes and delocalised electrons this would be called excitonic superconductivity .....

Conclusions from numerics

- Condensation is a robust process
  - energy scale is fraction of exciton Rydberg (few meV in GaAs)
- No evidence for droplet formation
  - positive compressibility
  - bi-excitons ignored here, but X-X interaction repulsive in bilayers
  - contrast to multivalley bulk semiconductors like Ge, Si
- BCS-like wavefunction captures smoothly the crossover from high to low densities
- Solid phases also competitive in energy (but higher for moderate r_s)
- So it should be easy to make experimentally …..

Experimental signatures

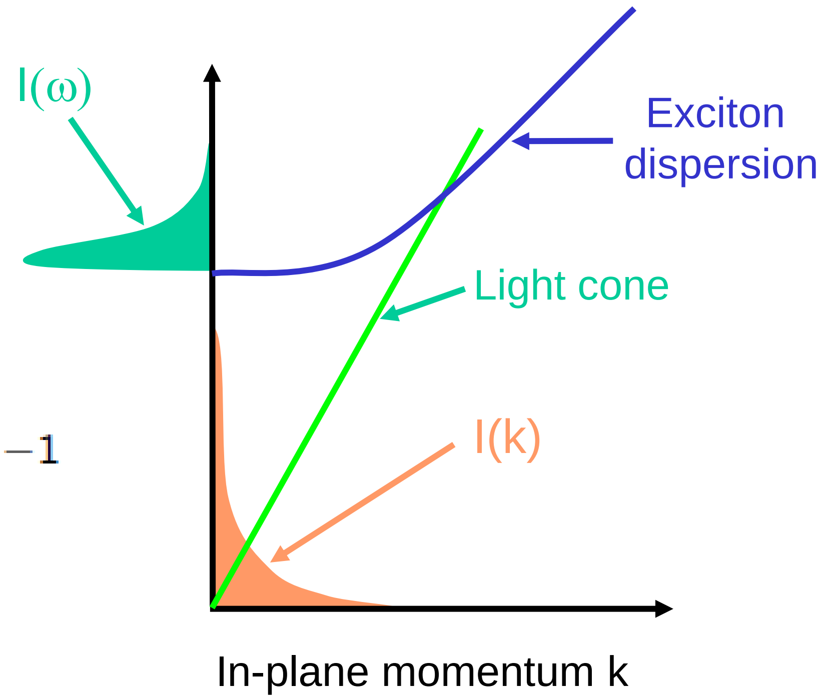
- Phase-coherent luminescence - order parameter is a macroscopic dipole
  - Should couple photons and excitons right from the start – polaritons

$$P(t) = \sum_k \left\langle a^\dagger_{ck} a_{vk} \right\rangle e^{i\mu t}$$

- Gap in absorption/luminescence spectrum
  - small and low intensity in BEC regime
- Momentum and energy-dependence of luminescence spectrum I(k,ω) gives direct measure of occupancy

$$I(k) \propto n_k = \left[e^{\beta(\epsilon_k - \mu)} - 1 \right]^{-1}$$

  - 2D Kosterlitz-Thouless transition
  - confined in unknown trap potential
  - only excitons within light cone are radiative

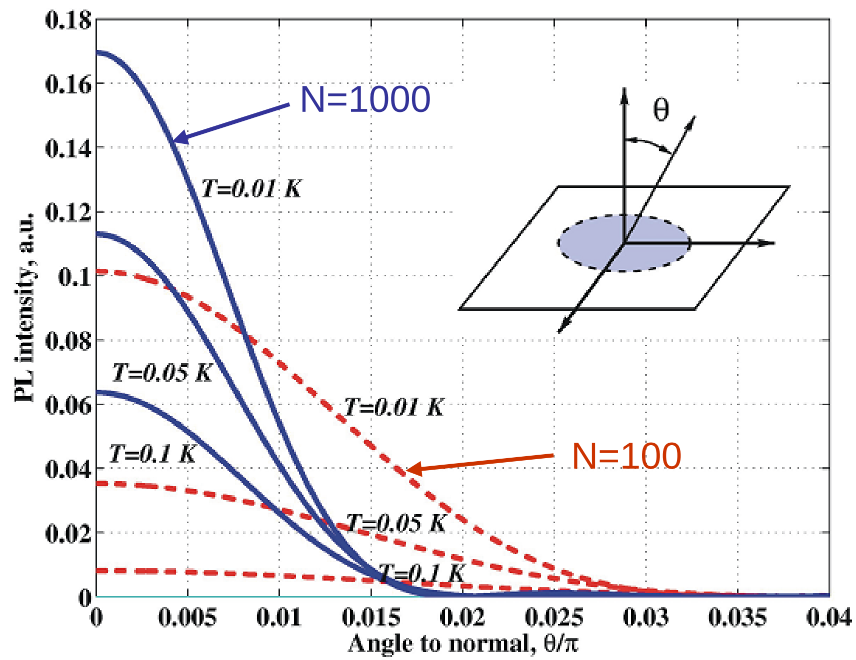


Angular profile of light emission

Keeling et al, PRL **92**, 176402 (2004)

- Emitted photon carries momentum of electron-hole pair
- Condensation (to $k_{//} \sim 0$) then has signature in sharp peak for emission perpendicular to 2D trap.
- In 2D the phase transition is of Kosterlitz-Thouless type – no long range order below T_c
- Peak suppressed once thermally excited phase fluctuations reach size of droplet

Parameters estimated for coupled quantum wells of separation ~ 5 nm; trap size ~ 10 μm; $T_{BEC} \sim 1K$

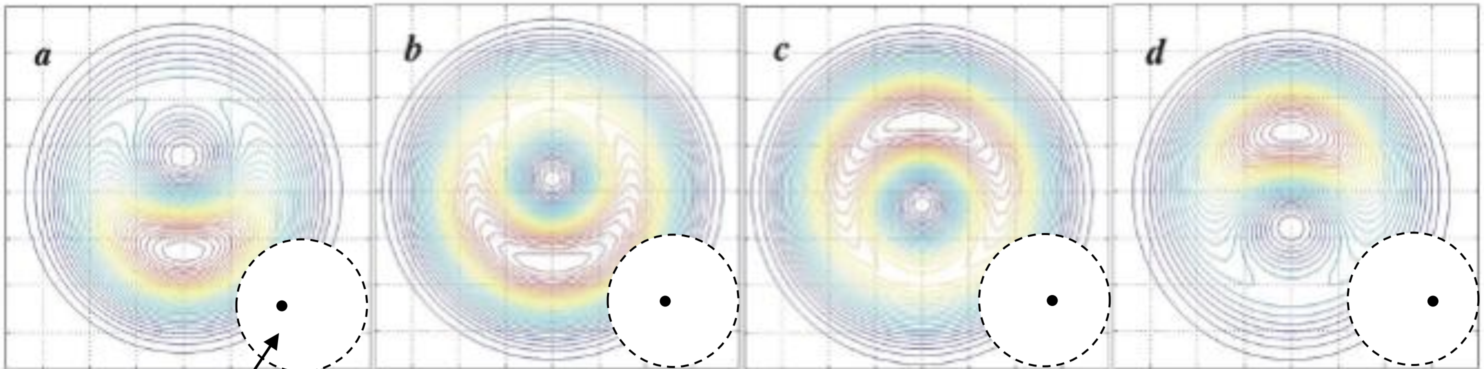


$$\xi_T = (\lambda\rho/4m)^{1/2}/k_B T$$

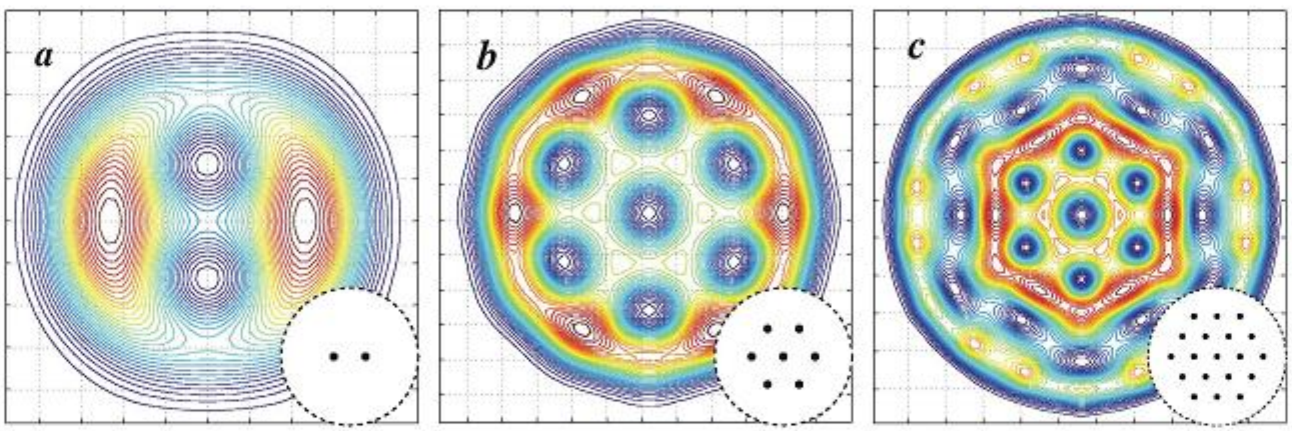
$$T \simeq T_* = T_{BEC}/\ln(R/\xi_T),$$

Vortices

Angular emission into θ_x , θ_y



Vortex position (x,y) inside droplet

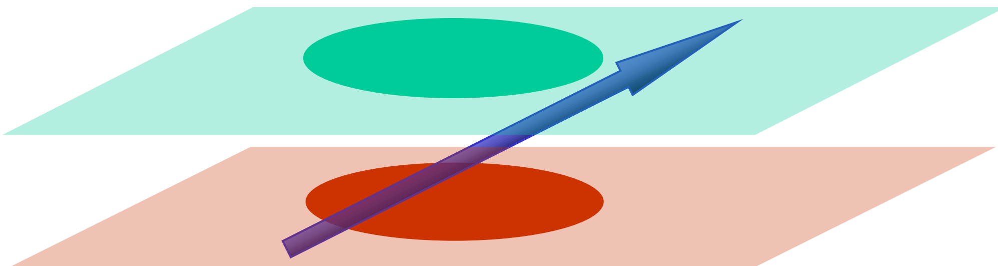


Dipolar superfluid

- What could be the superfluid response?
  - exciton transport carries no charge or mass
  - in a bilayer have a static dipole

Lozovik & Yudson 1975

Joglekar, Balatsky, PBL, 2004



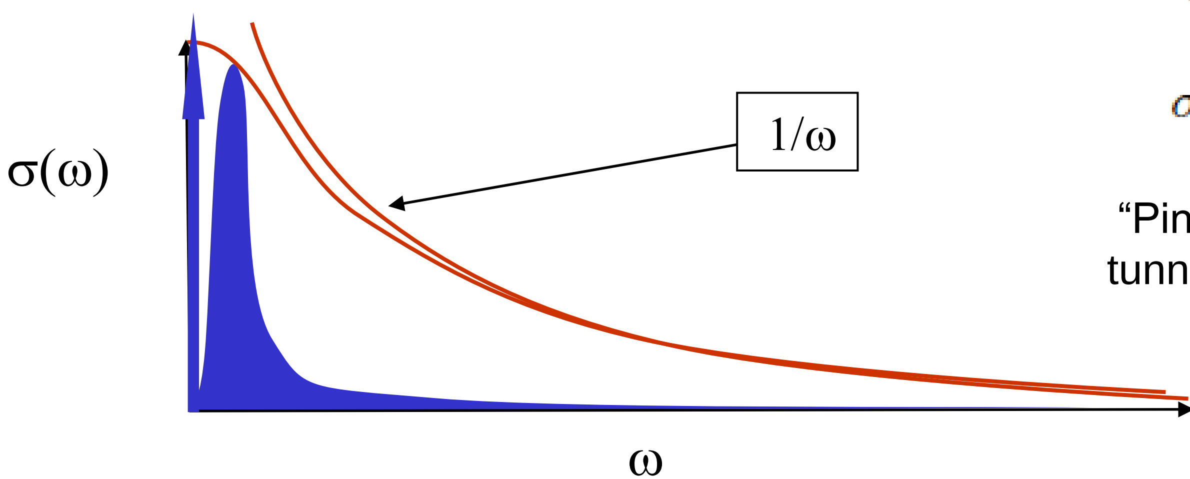
$$\mathbf{B}(t) = B_0 e^{i\omega t}\,\hat{\mathbf{y}}$$

$$\nabla \times \mathbf{E} = -\frac{\partial B}{\partial t}$$

$$F = i\omega B_0 d q\,\hat{\mathbf{x}}$$

$$\mathbf{j}_{dipole} = \sigma(\omega)\mathbf{F} = i\omega\chi(\omega)\mathbf{F}$$

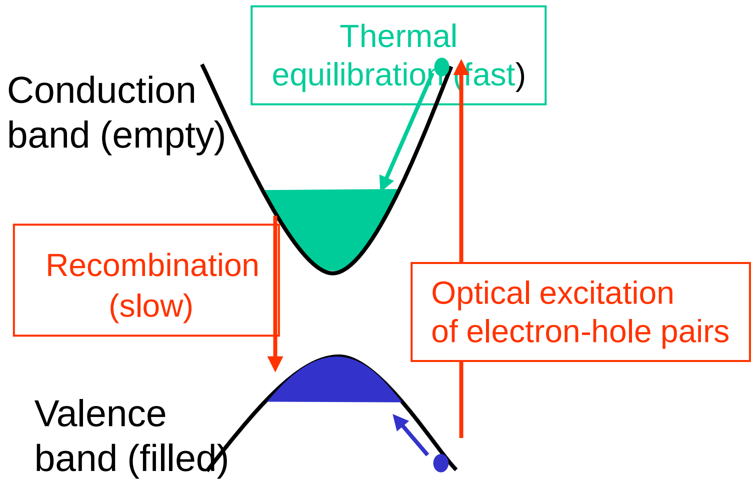
$$\sigma(\omega) = \sigma_0[\delta(\omega) + i/\omega]$$



"Pinning" of the phase by interlayer tunnelling shifts response to nonzero frequency

Recap

Exciton liquid in semiconductors



Interacting electrons and holes
Characteristic energy scale is the exciton Rydberg

$$H = \sum_k \left[\epsilon_{ck} a^\dagger_{ck} a_{ck} + \epsilon_{vk} a^\dagger_{vk} a_{vk}\right] + \frac{1}{2}\sum_q \left[V_q^{ee}\rho_q^e \rho_{-q}^e + V_q^{hh}\rho_q^h\rho_{-q}^h + 2V_q^{eh}\rho_q^e\rho_{-q}^h\right]$$

A very good wavefunction to capture the crossover from low to high density is BCS

$$\Psi_0 = e^{\lambda \sum_k a^\dagger_{ck} a_{vk}} |0\rangle = \prod_k \left[u_k + v_k a^\dagger_{ck} a_{vk}\right] |0\rangle$$

Just like a BCS superconductor, this has an order parameter, and a gap

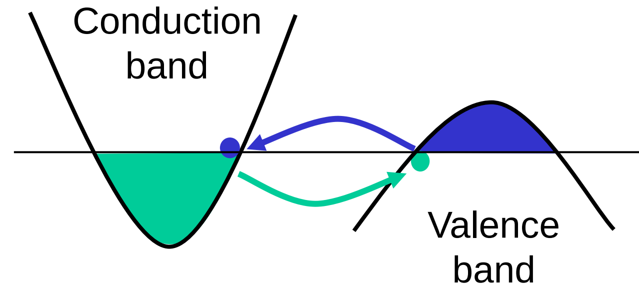
$$\langle a^+_{ck} a_{vk} \rangle = u_k v_k = (\Delta_k / 2E_k); \quad E_k = \sqrt{(\varepsilon_k - \mu)^2 + \Delta_k^2}$$

The order parameter has an undetermined phase -> superfluid.

Unfortunately, there are some terms in H that have been left out

Digression: tunnelling and recombination

- Our Hamiltonian has only included interaction between electron and hole densities, and no e-h recombination
- In a semimetal tunnelling between electron and hole pockets is allowed

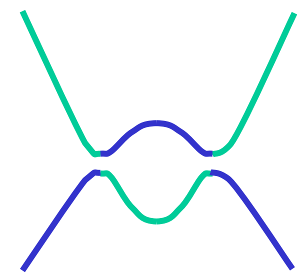


If pockets related by symmetry, generates single particle terms $t a^{\dagger}_{ck} a_{vk}$

Rediagonalise (α, β)linear combinations of (a_{ck}, a_{vk})

Introduces single particle gap

New Coulomb coupling terms $V_1 t \alpha^{\dagger} \alpha^{\dagger} \alpha \beta \quad V_2 t^2 \alpha^{\dagger} \alpha^{\dagger} \beta \beta$



If pockets are unrelated by symmetry, still the eigenstates are Bloch states

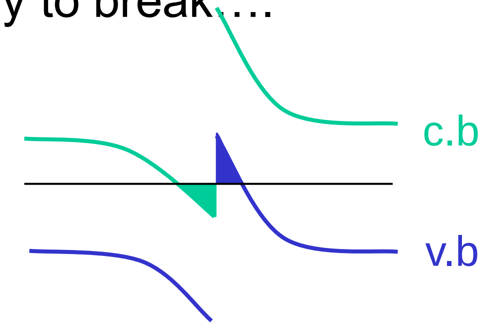
$$\hat{V} = \sum_{n_1 \ldots n_4, k_1 \ldots k_4} \langle n_1 k_1, n_2 k_2 | V | n_3 k_3 n_4 k_4 \rangle \times a^{\dagger}_{n_1 k_1} a^{\dagger}_{n_2 k_2} a_{n_3 k_3} a_{n_4 k_4},$$

In general, terms of the form $V_1 t \alpha^{\dagger} \alpha^{\dagger} \alpha \beta \quad V_2 t^2 \alpha^{\dagger} \alpha^{\dagger} \beta \beta$

Most general Hamiltonian does not separately conserve particles and holes

Tunnelling and recombination - 2

- Single particle gap - trivial physics, no extra symmetry to break….



E.g. Artificial 2D semimetal - GaSb/InAs interface
electron-hole mixing introduces gap [Lakrimi et al 1997]
In QH bilayers: tunnelling between layers -> S/AS splitting

- Consider the effect of general Coulomb matrix elements at first order

$$\psi_k = \left\langle a^\dagger_{ck} a_{vk} \right\rangle = |\Delta_k| \, e^{i\phi}$$

Complex order parameter in mean field approximation

$$\langle V_2 \rangle = V_2 \, |\Delta_k|^2 \cos 2\phi$$

→ Josephson-like term; fixes phase; gapped Goldstone mode

$$\langle V_1 \rangle = V_1 \, |\Delta_k| \cos(\phi - \phi_0)$$

→ Symmetry broken at all T; just like band-structure gap

- No properties to distinguish this phase from a normal dielectric, except in that these symmetry breaking effects may be small
- In that case, better referred to as a commensurate charge density wave
- Indeed an *excitonic insulator*

Not unfamiliar or exotic at all (but not a superfluid either)

Tunnelling and recombination - 3

- If electron and hole not degenerate, recombination accompanied by emission of a photon

$$H_{dipole} = \sum_q \omega_q \phi_q^\dagger \phi_q + \sum_{k,q} g_{q,k} \left[\phi_q^\dagger a_{vk-q}^\dagger a_{ck} + \phi_q a_{ck+q}^\dagger a_{vk} \right]$$

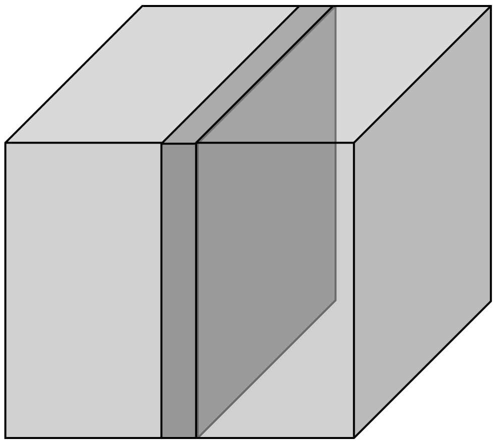
- Evaluate at zeroth order

$$\left\langle H_{dipole} \right\rangle = \sum_k g_0 \left| \Delta_k \right| \phi_0^\dagger e^{i\mu t - i\phi} + h.c.$$

- Phase of order parameter couples to phase of electric field
- Resonant radiation emitted/absorbed at frequency = chemical potential
- Behaves just like an antenna (coherent emission, not incoherent luminescence)

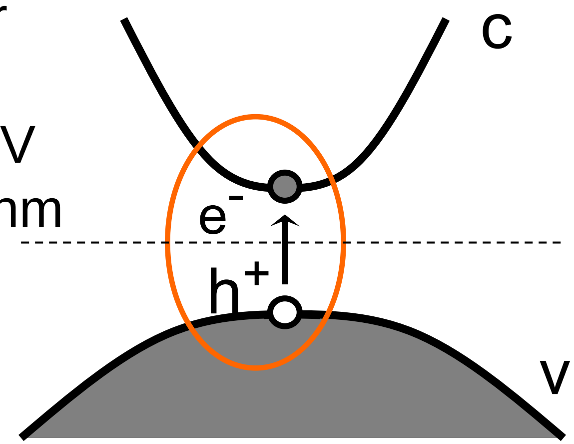
Must include light and matter on an equal footing from the start - POLARITONS

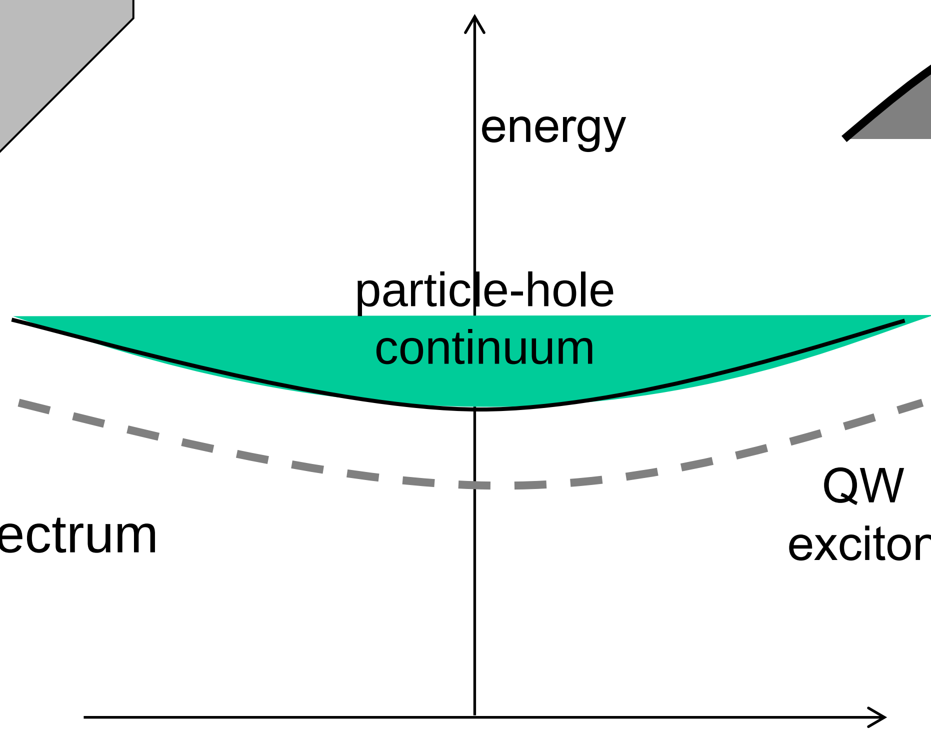
Quantum Well Excitons



QW

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

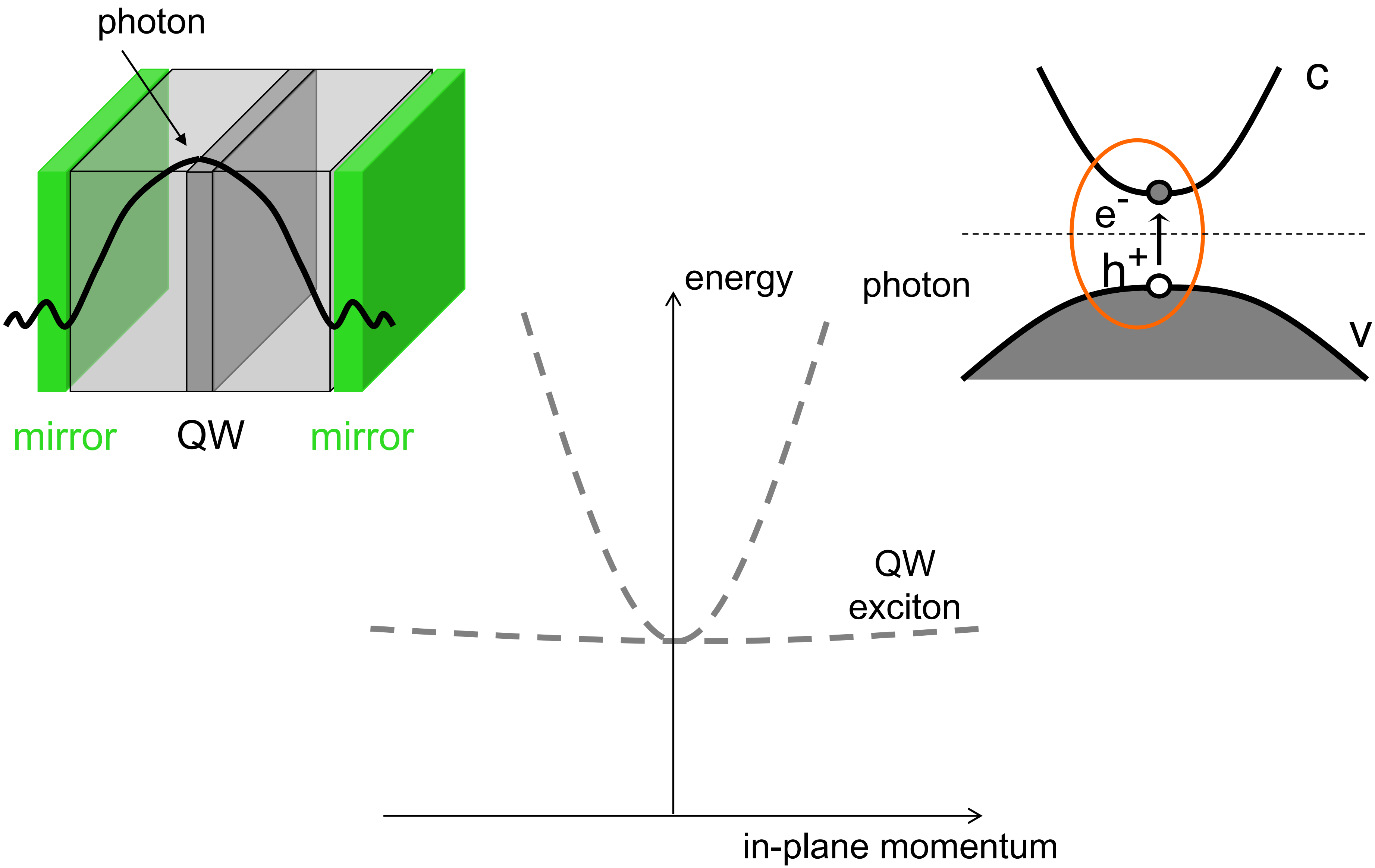




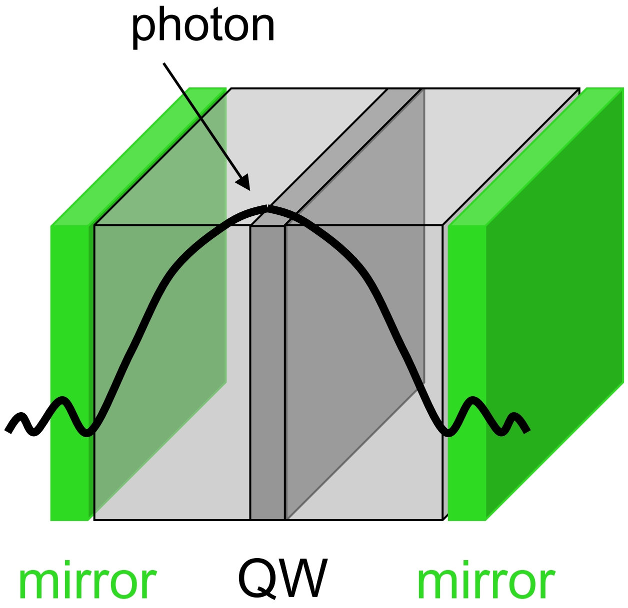
Excitation spectrum

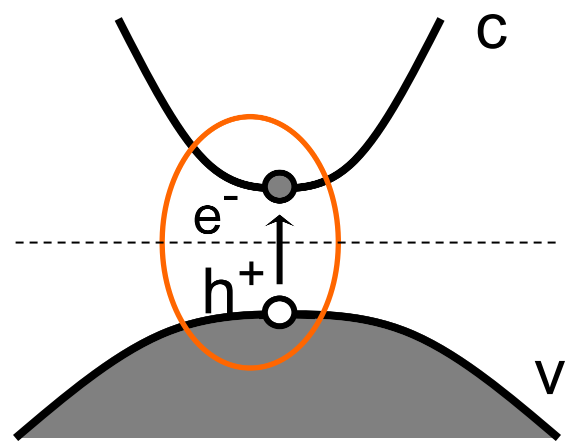
in-plane center of mass momentum

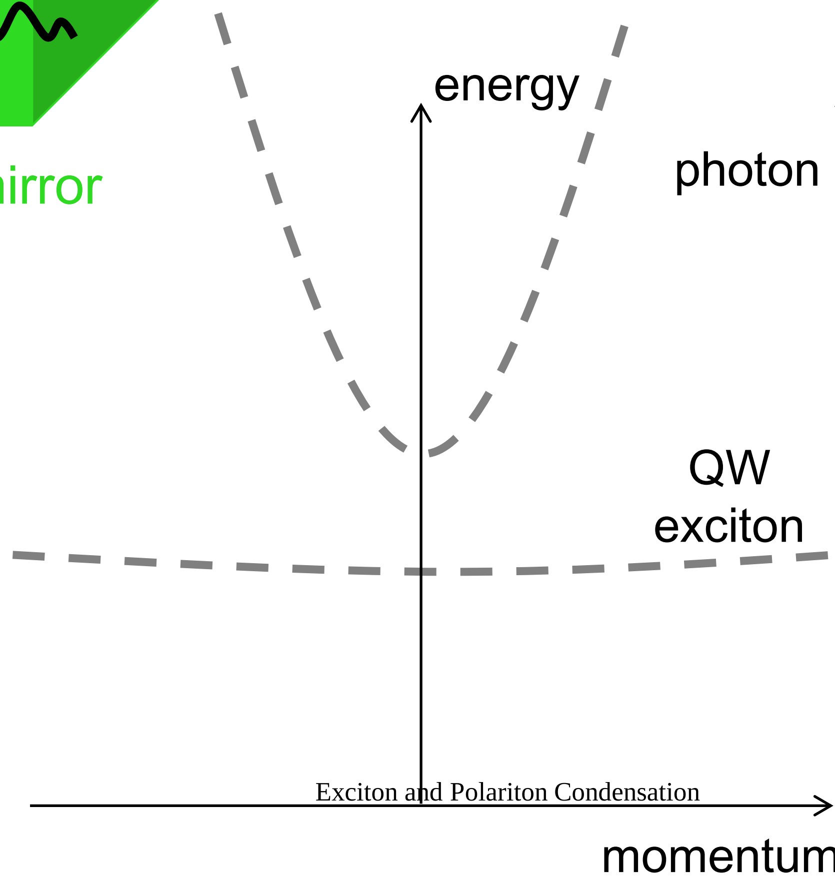
Excitons + Cavity Photons



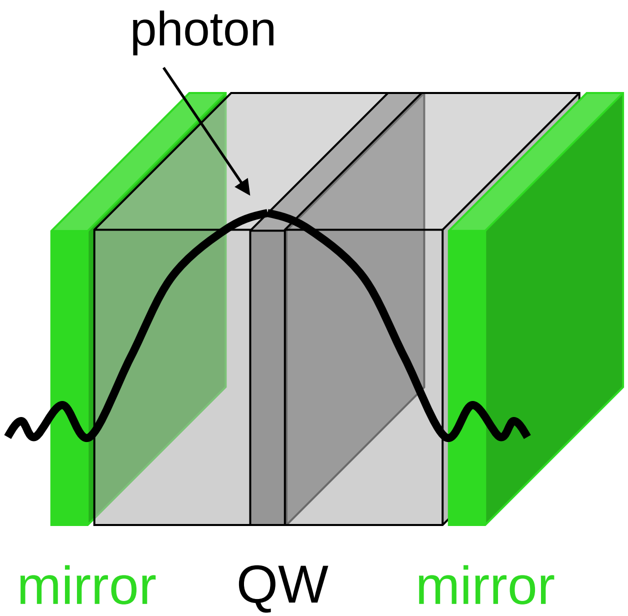
Excitons + Cavity Photons

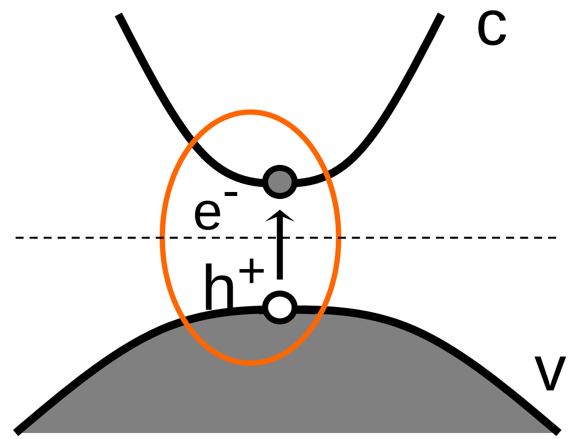


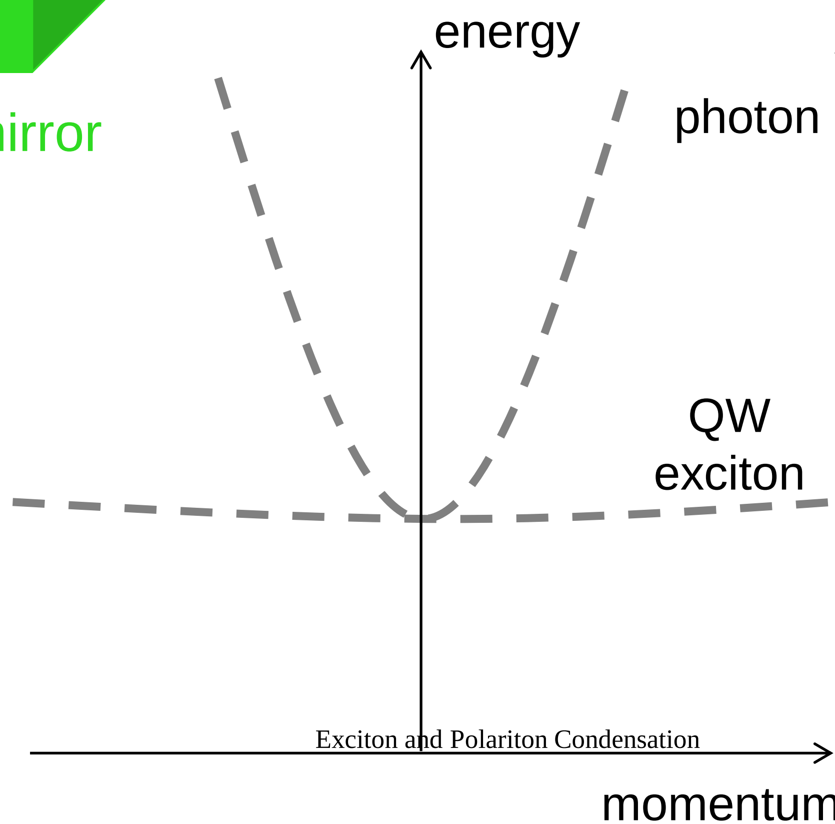




Excitons + Cavity Photons

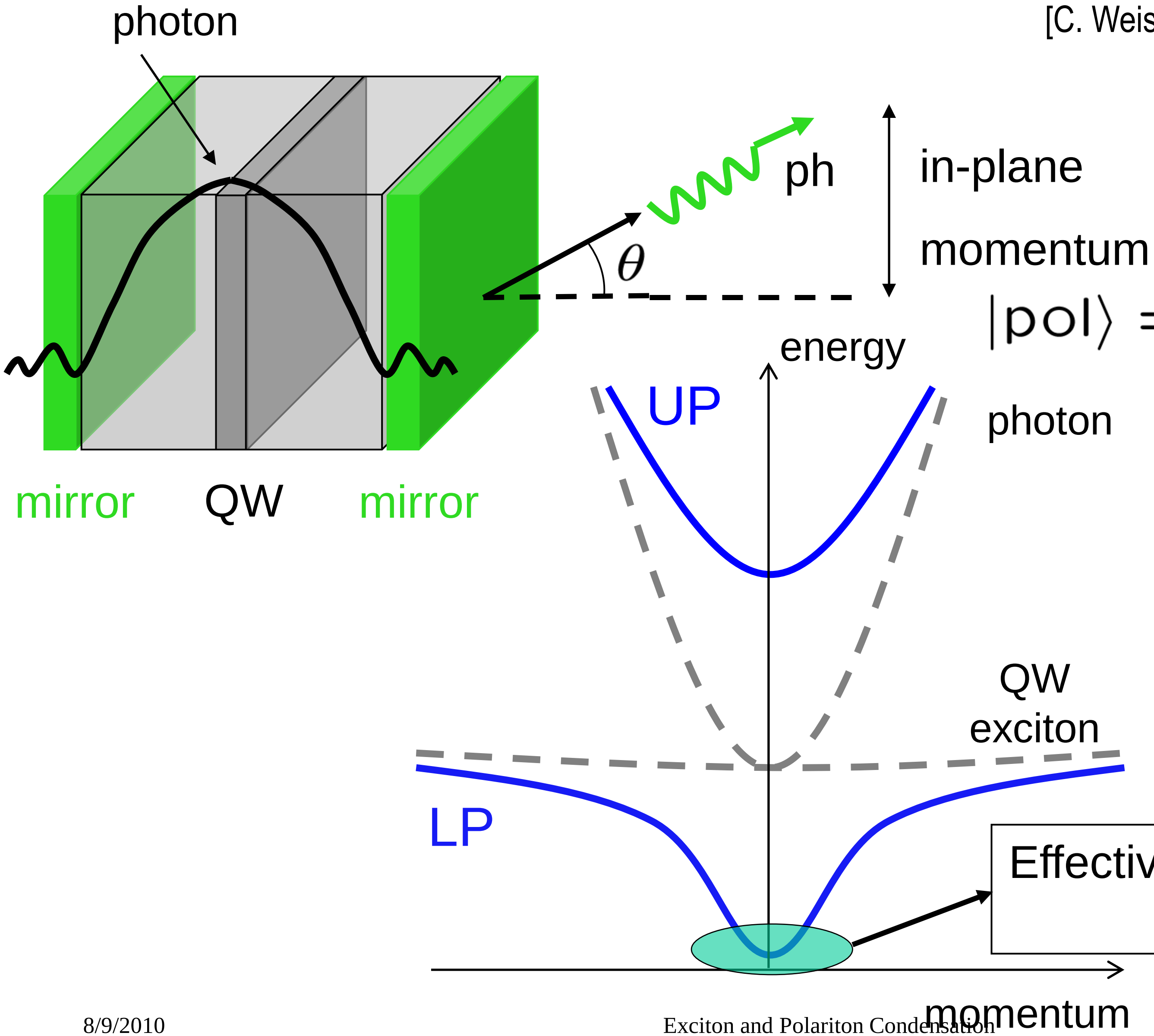






Polaritons: Matter-Light Composite Bosons

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



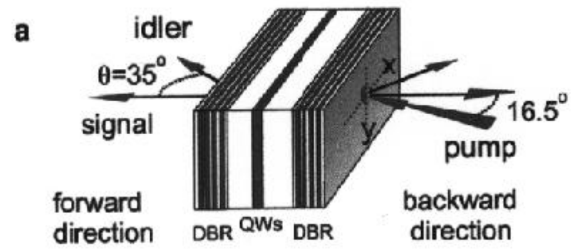
$$|\mathrm{pol}\rangle = c_1|\mathrm{exc}\rangle + c_2|\mathrm{ph}\rangle$$

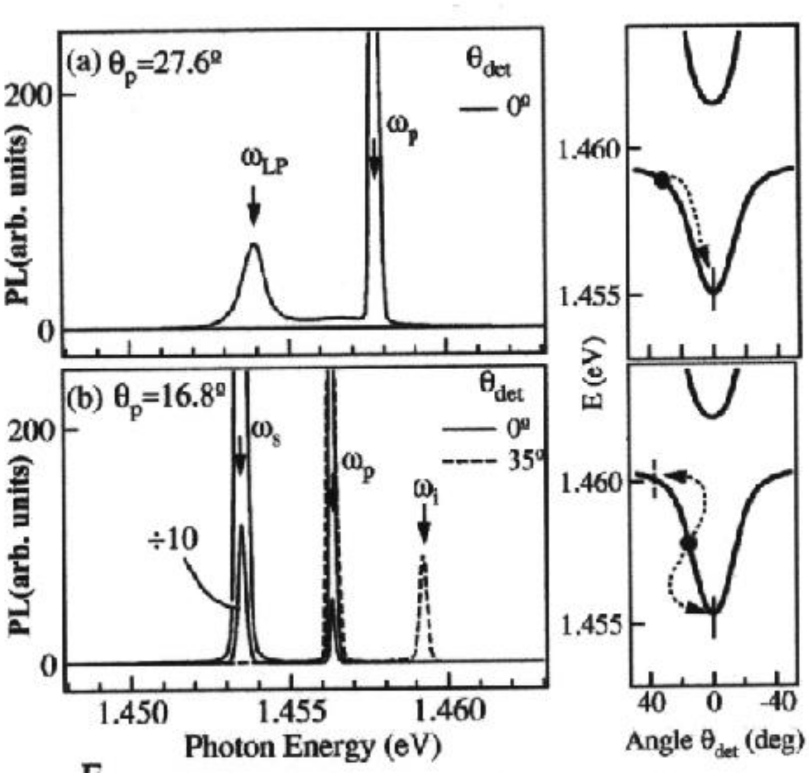
Effective Mass $m^* \sim 10^{-4}\, m_e$

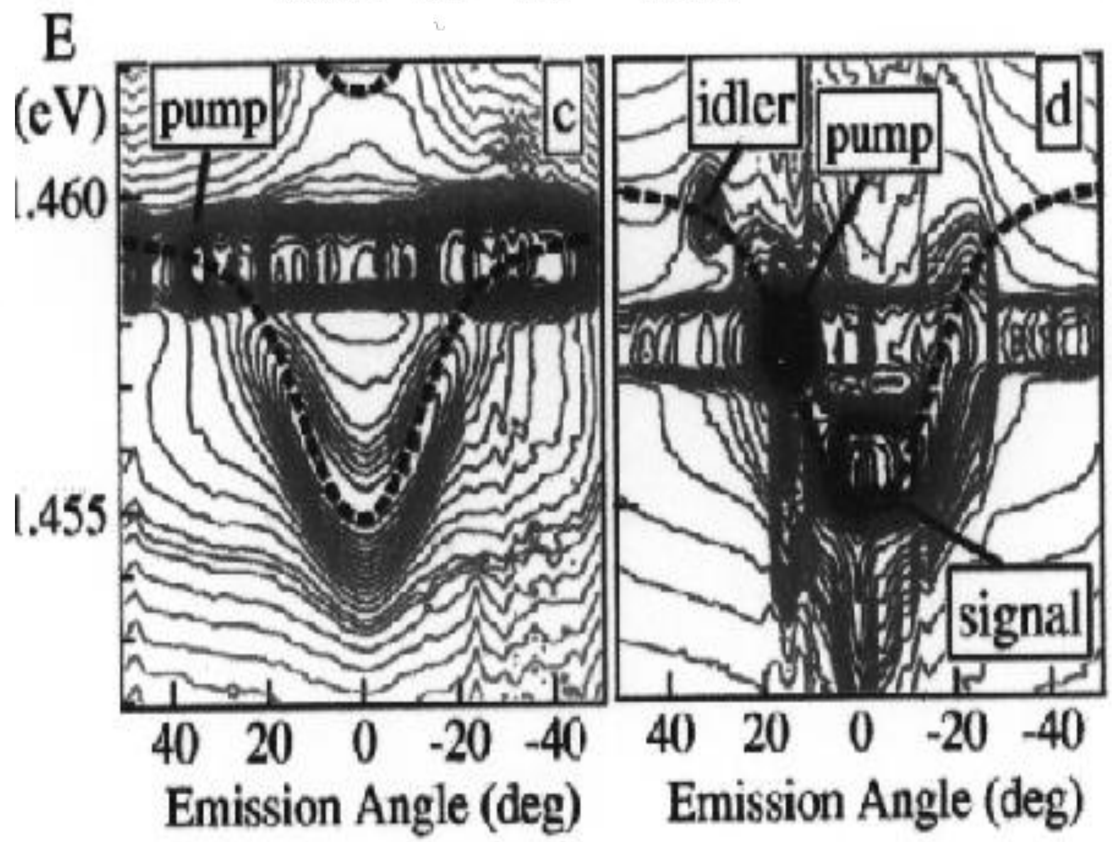
$T_{BEC} \sim 1/m^*$

Resonantly pumped microcavity

Address in plane momentum by measurement or excitation as function of angle



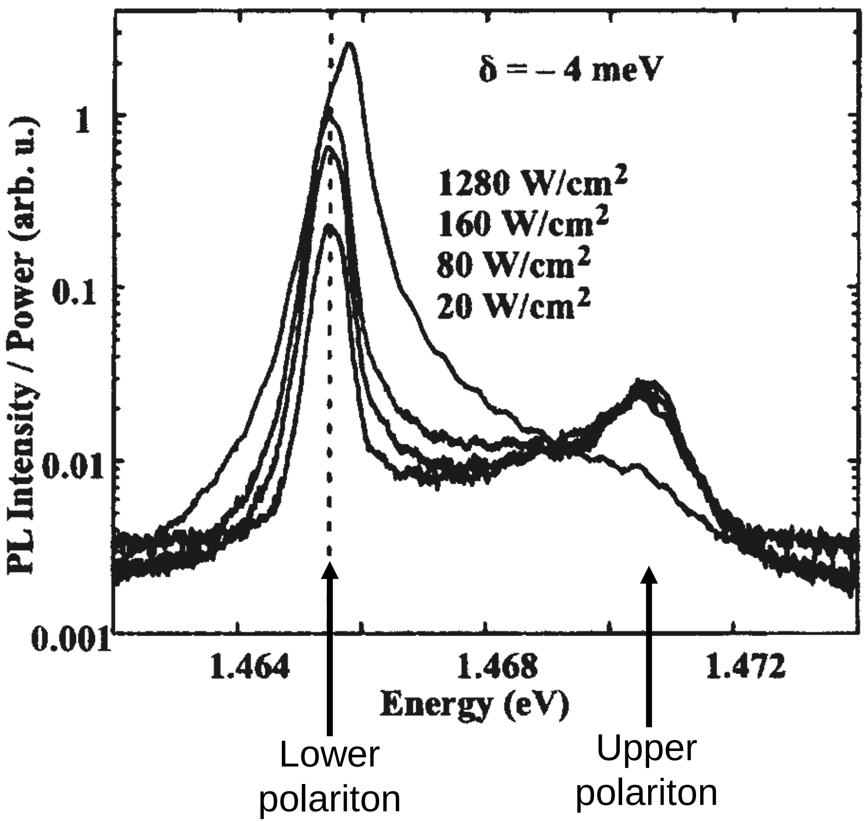


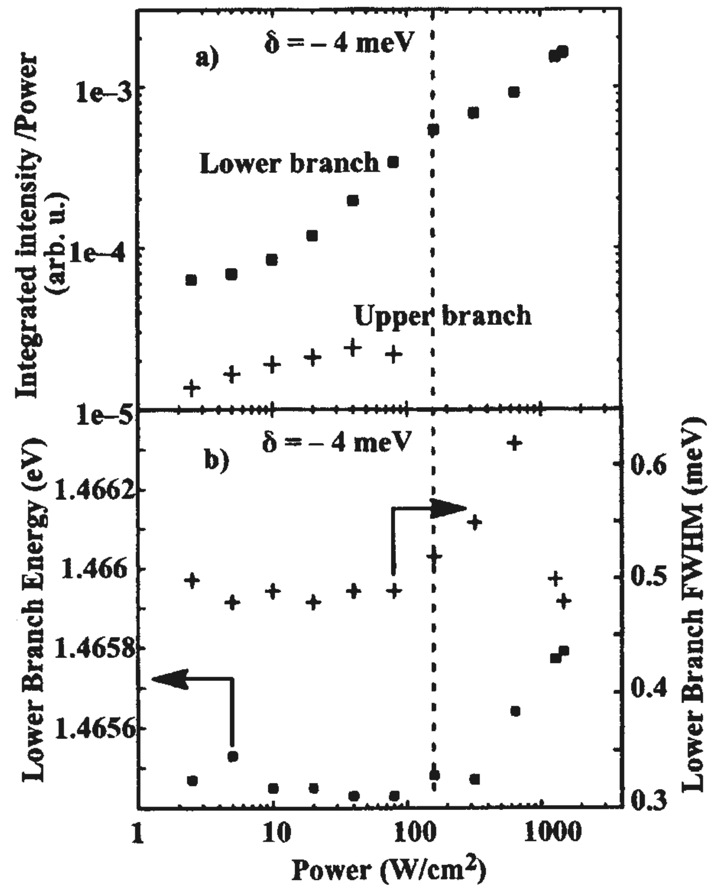


Baumberg et al Phys Rev B 62, 16247 (2000)

Photoluminescence from non-resonantly pumped microcavity

PL normalised to pump intensity



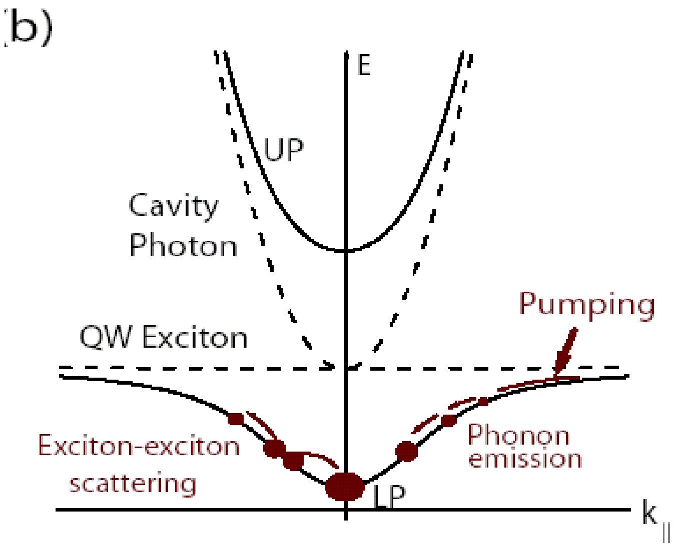


Excitation at ~ 1.7 eV

Senellart & Bloch, PRL 82, 1233 (1999)

Non-resonant(?) pumping in Lower Polariton Branch

Deng et al 2002



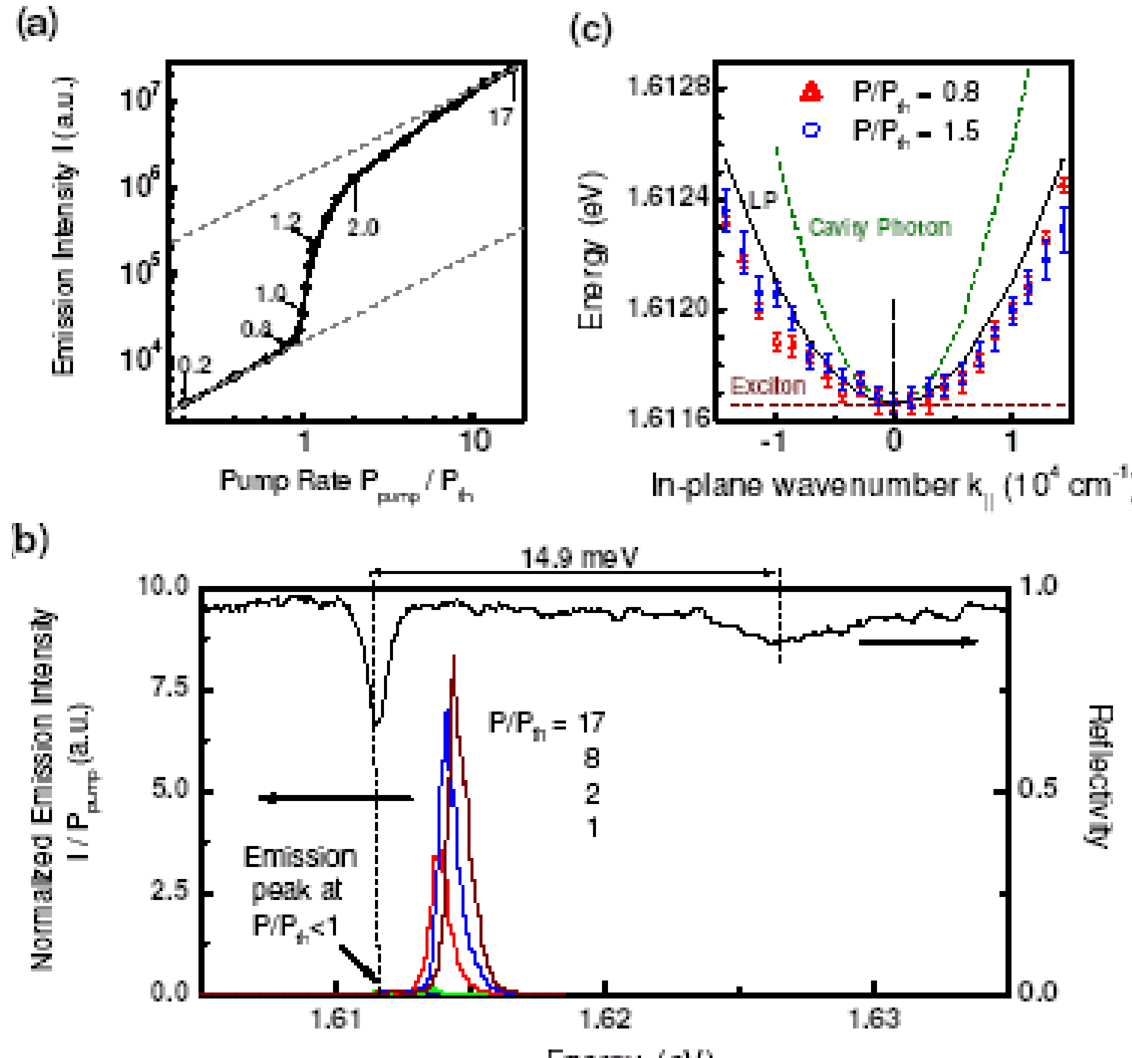
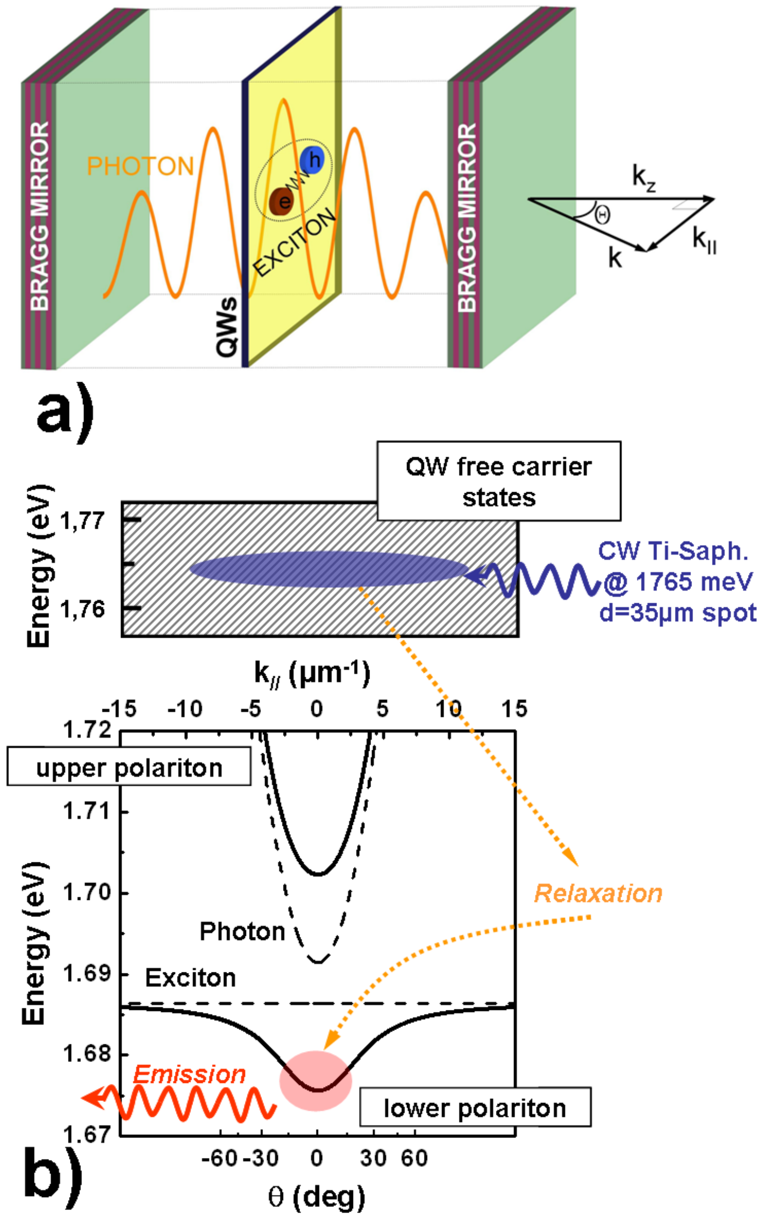


Fig.2

Substantial blue shift appears at threshold
Polariton dispersion seen above threshold

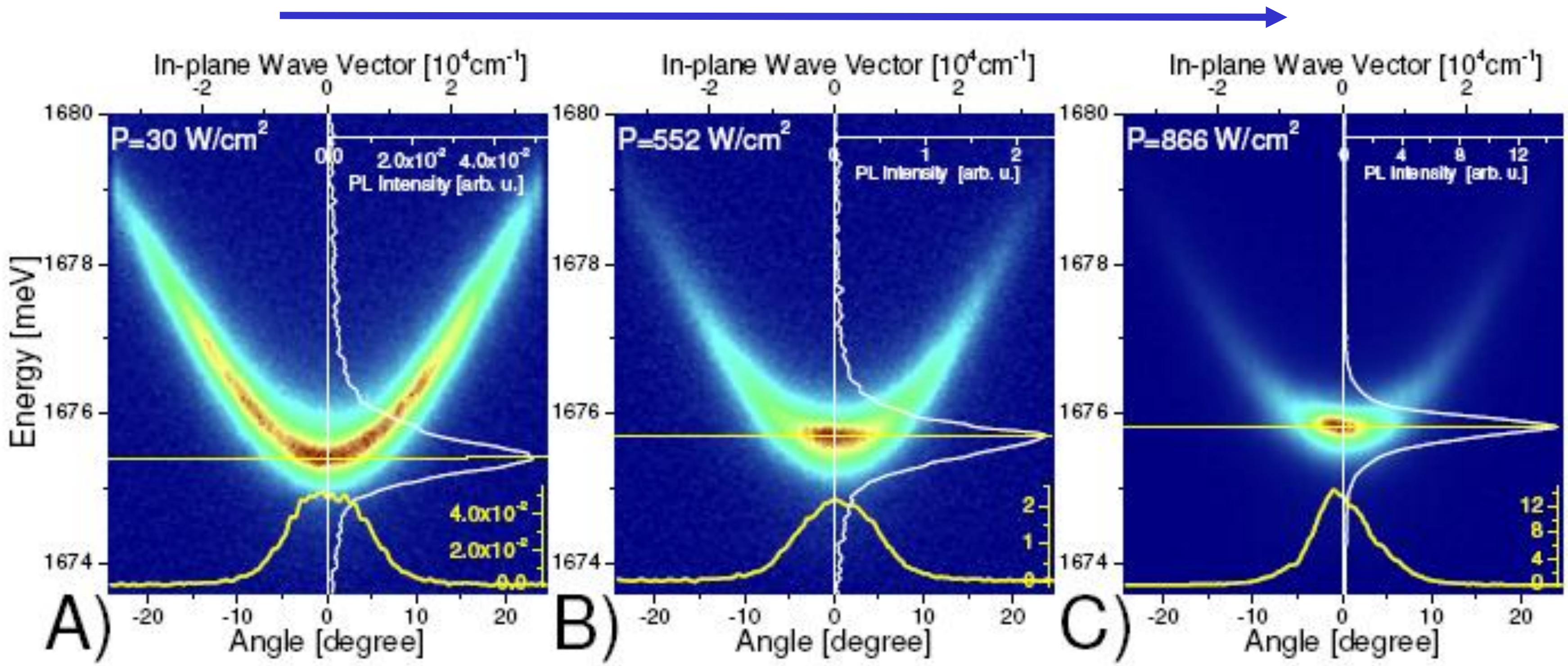


Microcavity polaritons

Experiments:
Kasprzak et al 2006
CdTe microcavities

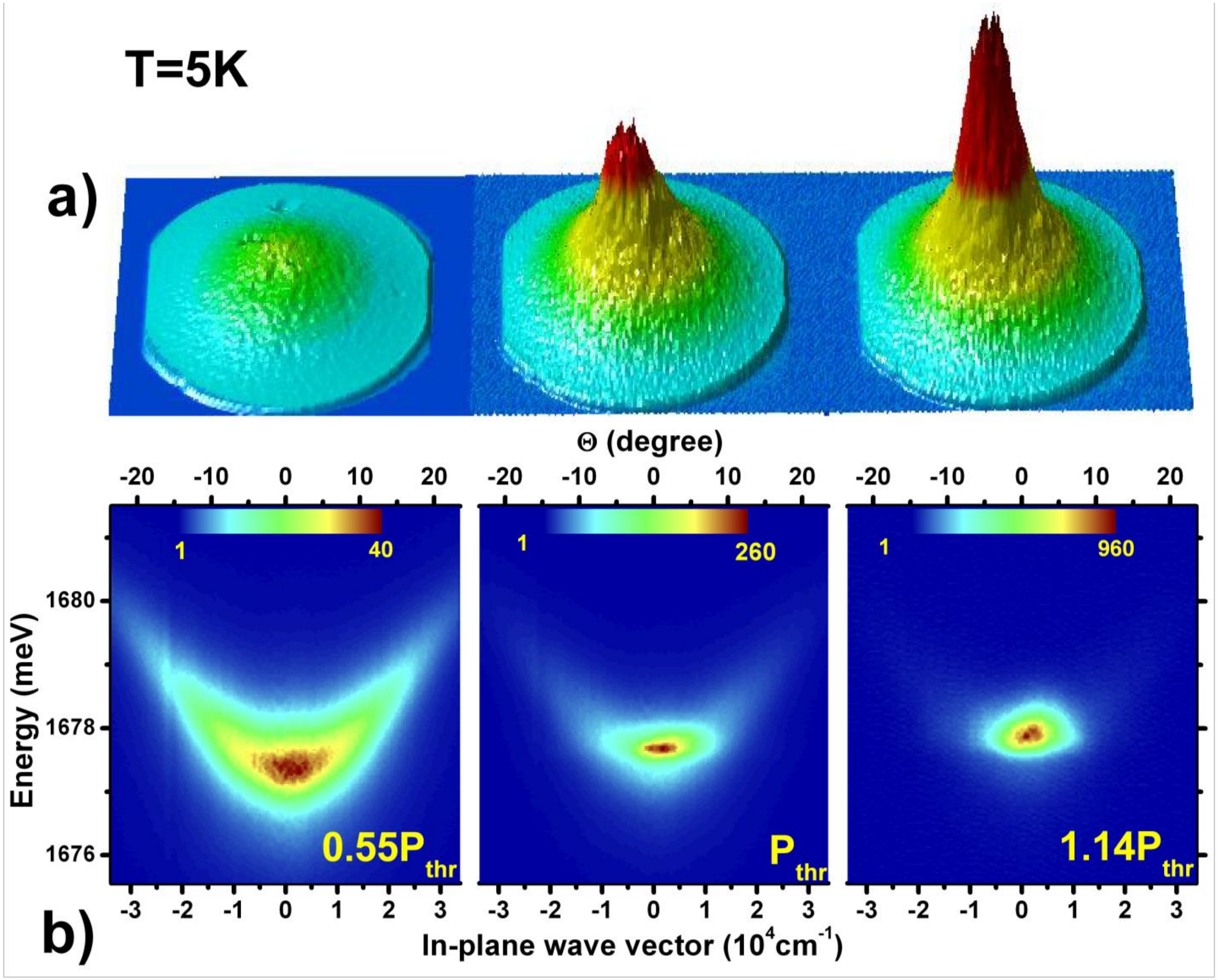
II-VI quantum well microcavities

Increasing pumping

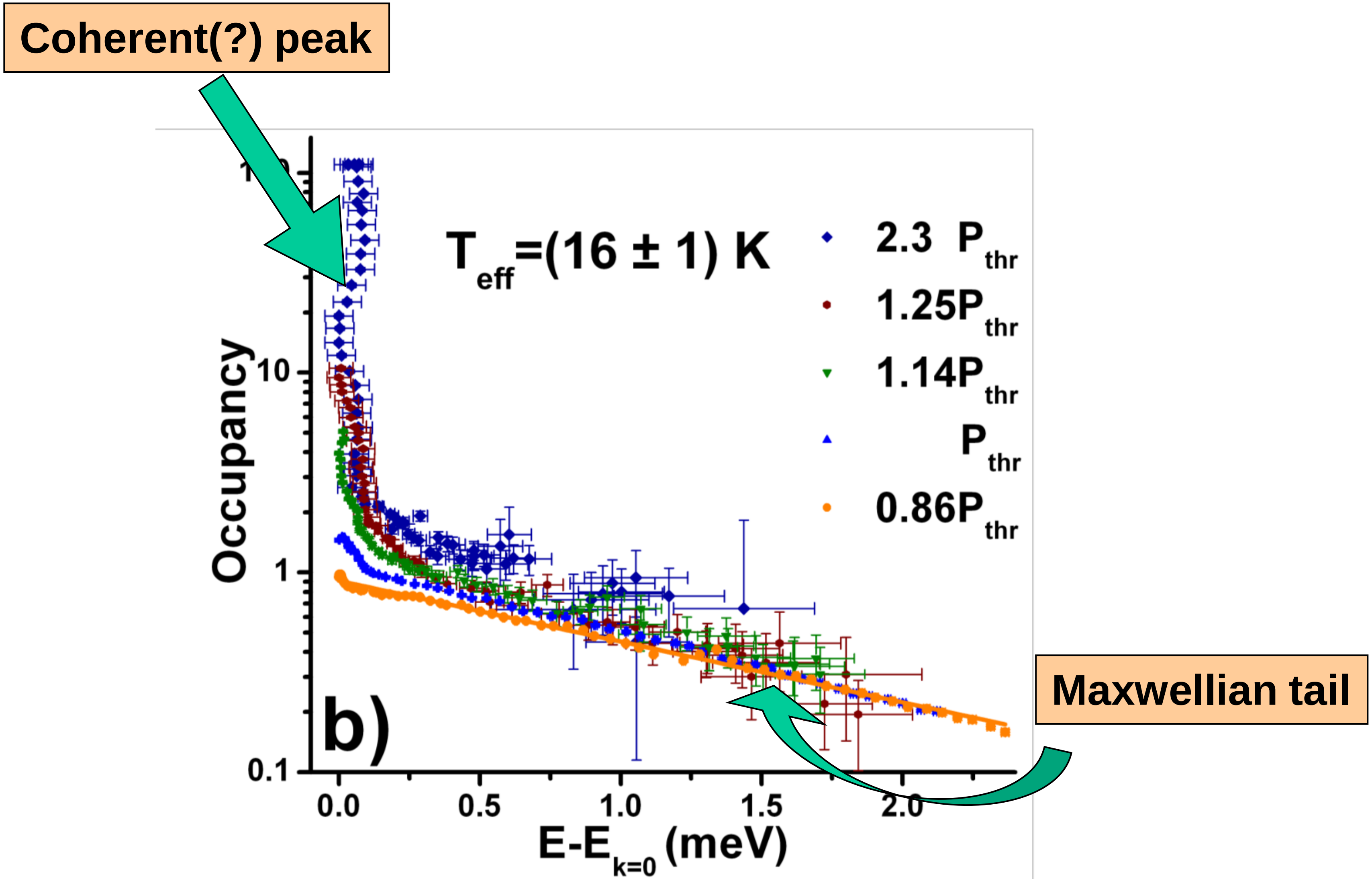


Kasprzak, Dang, unpublished

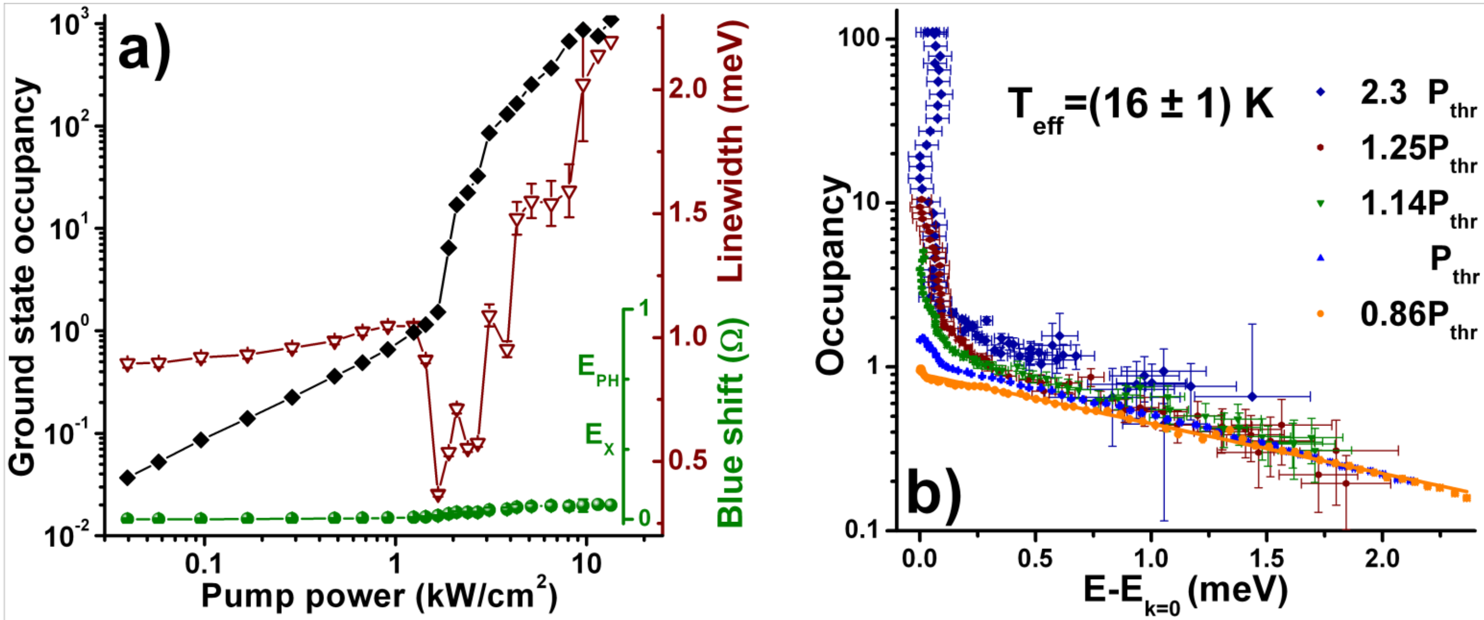
Occupancy as a function of power



Distribution at varying density



Distribution at varying density

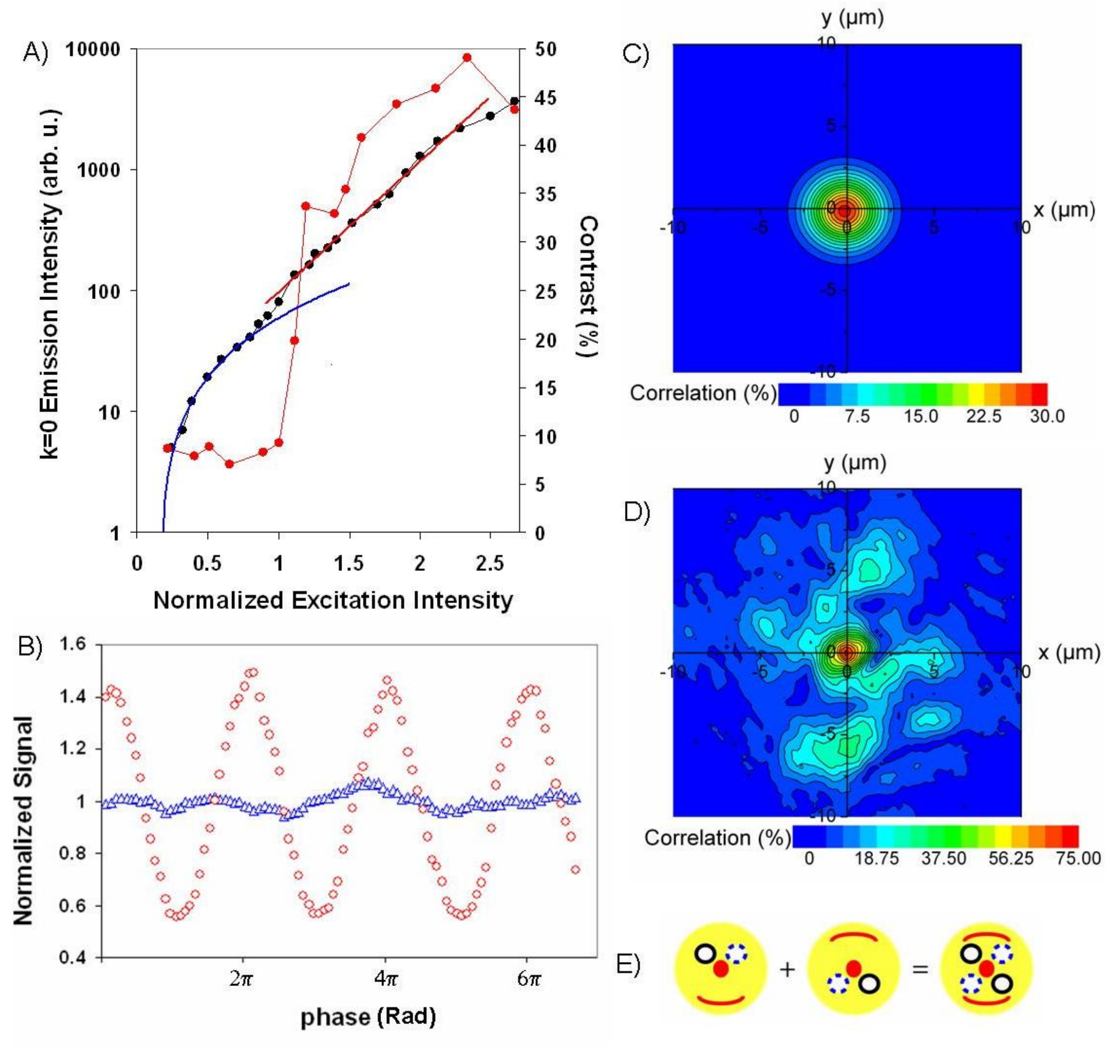


Blue shift used to estimate density
High energy tail of distribution used to fix temperature
Onset of non-linearity gives estimate of critical density
Linewidth well above transition is *inhomogeneous*

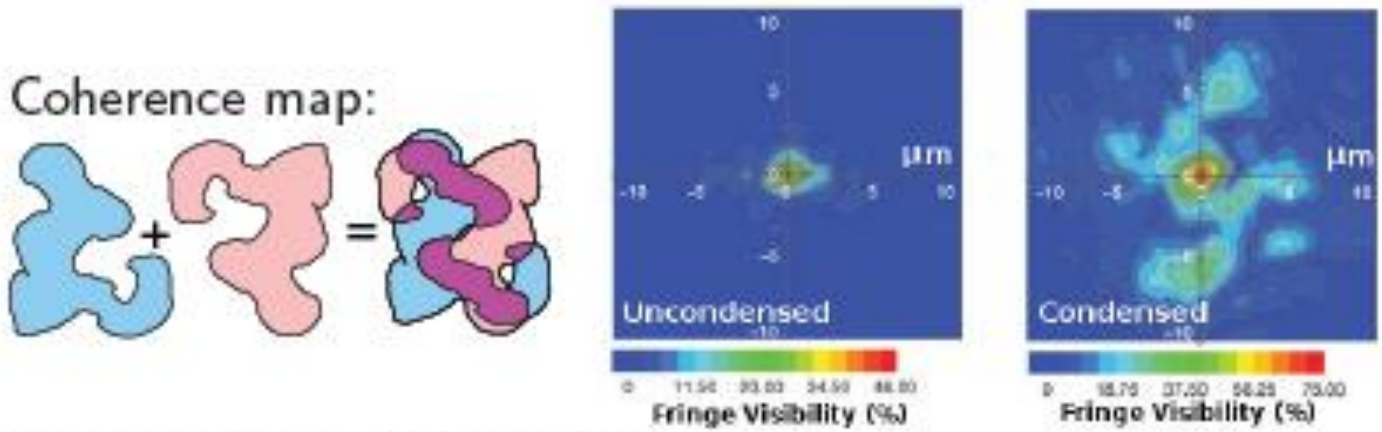
Measurement of first order coherence

Temperature and density estimates predict a phase coherence length ~ 5 μm

Experiment also shows broken polarisation symmetry

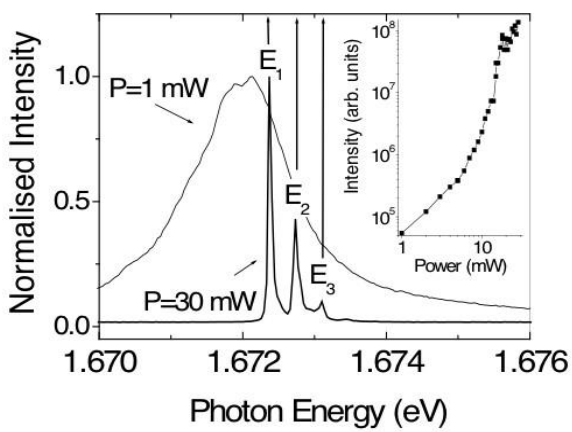


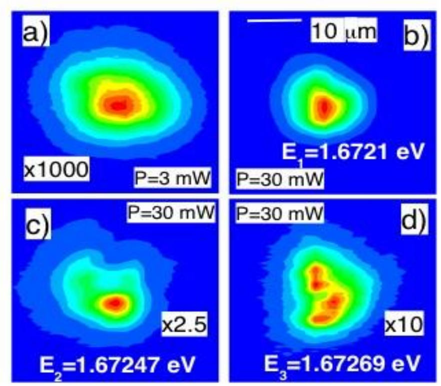
Coherence



[Kasprzak, et al., Nature, 2006]

Temporal coherence and multimode behavior

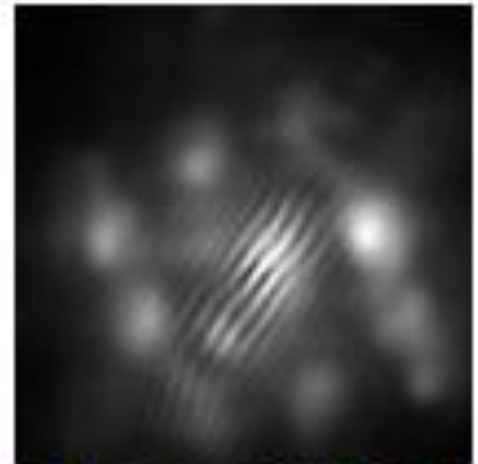


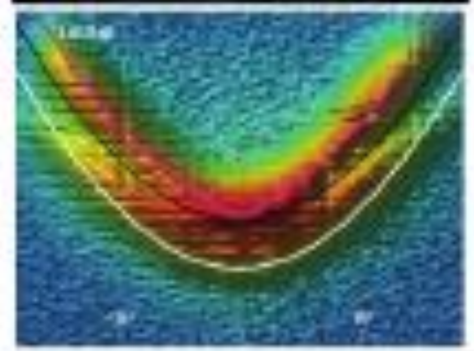


Love et al., PRL 2008

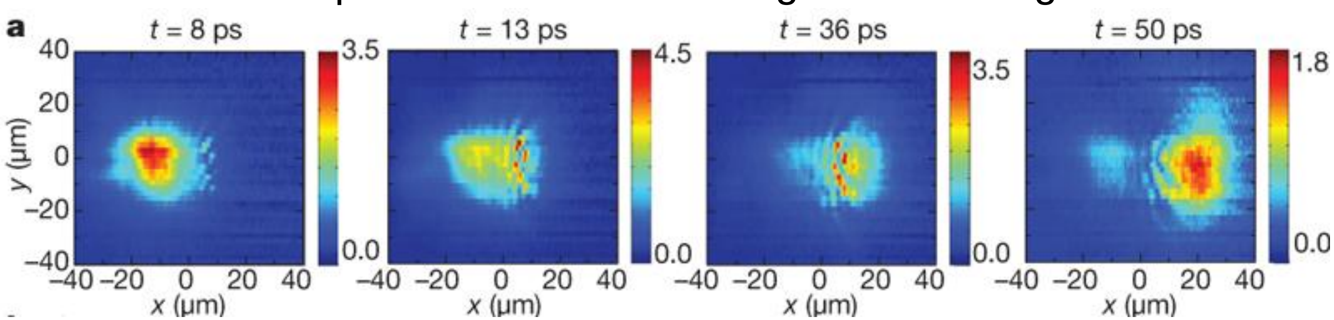
Other recent experiments

- 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)





Photon superfluid is an electromagnetic cloaking device



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

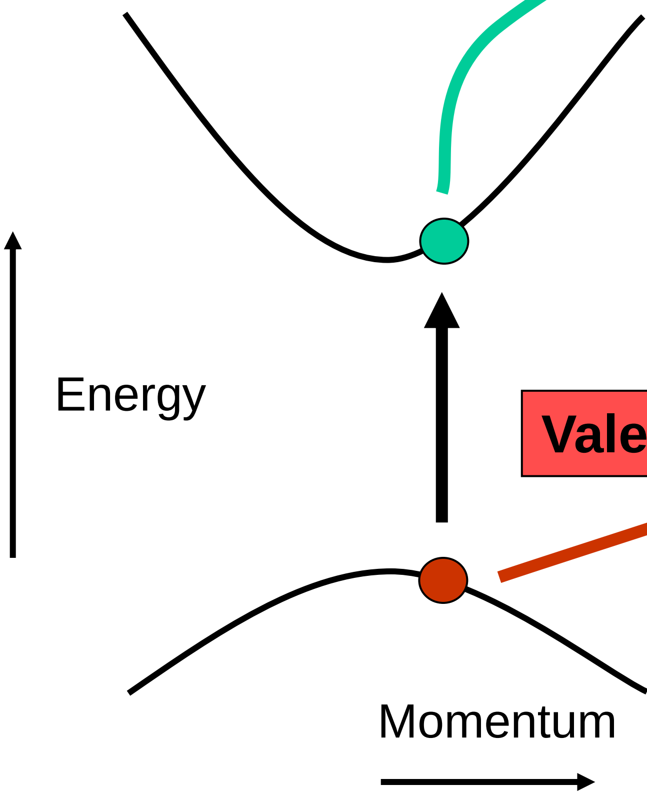
Review old picture of excitonic insulator

Interacting polaritons and the Dicke model

Analogs to other systems

Excitons

Conduction Band Electron



$$\Phi^\dagger |0\rangle = \sum_k \phi(k) a^\dagger_{ck} a_{vk} |0\rangle$$

Exciton wave-packet

Valence Band Hole

$$\phi(k) = \frac{1}{1 + k^2 a_B^2}$$

Bohr radius a_B ~ few nm

Mean field theory of excitonic insulator

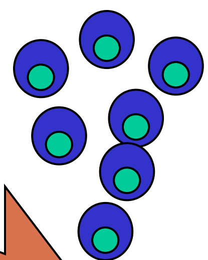
$$\Phi^\dagger |0\rangle = \sum_k \phi(k) a^\dagger_{ck} a_{vk} |0\rangle$$

Wavepacket of bound e-h pair
Composite boson

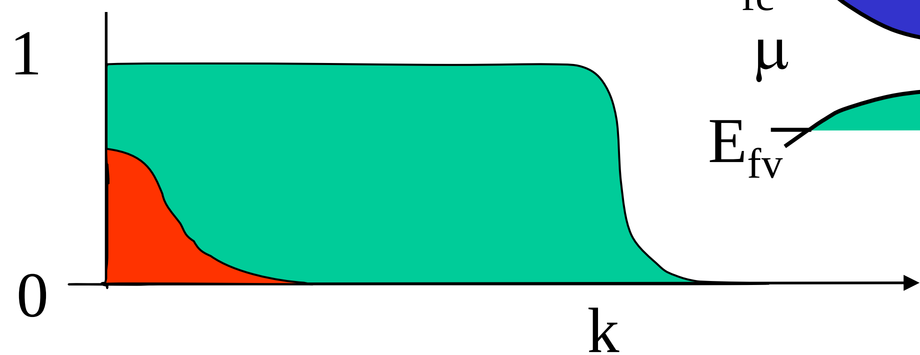
$$e^{\lambda \Phi^\dagger} |0\rangle = \prod_k \left[u(k) + v(k) a^\dagger_{ck} a_{vk} \right] |0\rangle$$

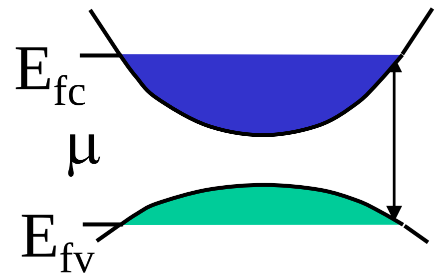
A coherent state – like a laser
Bose condensation of excitons

BCS-like instability
of Fermi surfaces



$$v(k) = \lambda \phi(k)$$





Special features: order parameter; gap

Bose Condensation of Composite Bosons

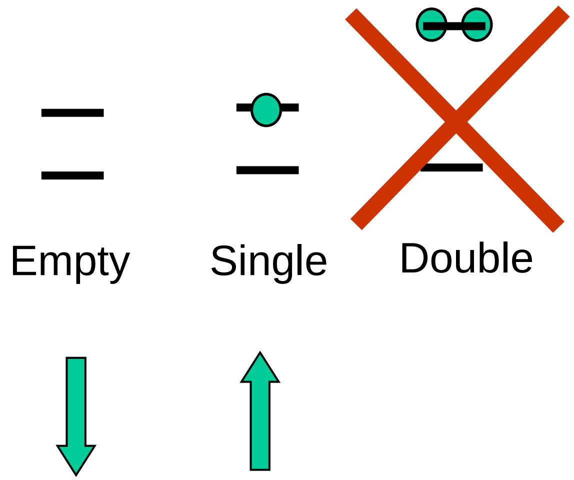
Interacting polaritons and the Dicke model

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

Localised excitons behave like 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

Two metronomes on a cart

- Modelocking – the Huygens experiment of 1665

Localized excitons in a microcavity - the Dicke model

- Simplifications
  - Single cavity mode
  - Equilibrium enforced by not allowing excitations to escape
  - Thermal equilibrium assumed (at finite excitation)
  - No exciton collisions or ionisation (OK for dilute, disordered systems)

    Work in k-space, with Coulomb added - then solution is extension of Keldysh mean field theory (used by Schmitt-Rink and Chemla for driven systems)

    Important issues are not to do with localisation/delocalisation or binding/unbinding of e-h pairs but with decoherence
- Important physics
  - Fermionic structure for excitons (saturation; phase-space filling)
  - Strong coupling limit of excitons with light
- To be added later
  - Decoherence (phase-breaking, pairbreaking) processes
  - Non-equilibrium (pumping and decay)

Mean field solution: 1. Variational method

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

Variational wavefunction $$|\lambda, w_i\rangle = \exp[\lambda\psi^\dagger + \sum_i w_i S_i^+]\,|0\rangle$$

Minimise Free Energy $$\frac{\partial}{d\lambda}, \frac{\partial}{dw_i}\left\langle \lambda, w_i \left| \hat{H} - \mu\hat{N} \right| \lambda, w_i \right\rangle = 0$$

Order parameter equation $$(\omega - \mu)\lambda = \frac{g^2\lambda}{2N}\sum_i \frac{1}{|E_i|}$$

Gap in spectrum $$E_i = \left[(\epsilon_i - \mu)^2 + g^2\lambda^2\right]^{1/2}$$

Excitation density from both photons and excitons $$\rho_{ex} = \lambda^2 - \frac{1}{2N}\sum_i \frac{\epsilon_i - \mu}{|E_i|}$$

Mean field solution: 2. Equation of motion

Conventional 2-level system notation $\langle S_z \rangle = n,\ \left\langle S^+ \right\rangle = p,\ \langle \psi \rangle = \psi.$

Semiclassical approximation to Heisenberg equations of motion for two level system in time dependent field

$$\frac{dp}{dt} = -i\epsilon p - ig\psi n$$
$$\frac{dn}{dt} = 2ig(\psi^* p - p^* \psi)$$
$$\frac{d\psi}{dt} = -i\omega\psi - igp$$

Rotating frame $\psi(t) = \psi e^{-i\mu t},\ p(t) = pe^{-i\mu t}$

Conservation: solution lies on Bloch sphere $n^2 + 4|p|^2 = 1$

$$\left.\begin{aligned} \frac{d\psi}{dt} = -i\omega\psi - igp \quad &\rightarrow \quad \psi = p/(\mu - \omega) \\ \frac{dp}{dt} = -i\epsilon p - ig\psi n \quad &\rightarrow \quad (\mu - \epsilon)p = g\psi n \end{aligned}\right\} \Rightarrow \quad p = g\psi / \sqrt{(\mu - \epsilon)^2 + 4g^2\psi^2}$$

$$\psi = \frac{sign(\epsilon - \mu)}{\omega - \mu} \frac{g^2 \psi}{\sqrt{(\mu - \epsilon)^2 + 4g^2|\psi|^2}}$$

$$\boxed{\psi = \frac{g^2\psi}{\omega - \mu} \sum_j \frac{sign(\epsilon_j - \mu)}{\sqrt{(\mu - \epsilon_j)^2 + 4g^2|\psi|^2}}}$$

Mean field solution: 3. Functional field theory

Generalise to multiple modes in area A

$$H = \sum_{j=1}^{j=nA} 2\epsilon_j S_j^z + \sum_{k=2\pi l/\sqrt{A}} \hbar\omega_k \psi_k^\dagger \psi_k \quad + \frac{g}{\sqrt{A}} \sum_{j,k} (e^{2\pi i \mathbf{k}\cdot\mathbf{r}_j} \psi_k S_j^+ + e^{-2\pi i \mathbf{k}\cdot\mathbf{r}_j} \psi_k^\dagger S_j^-)$$

Construct coherent state path integral and integrate out spins

$$S[\psi] = \int_0^\beta d\tau \sum_k \psi_k^\dagger (\partial_\tau + \hbar\tilde{\omega}_k)\psi_k + N \mathrm{Tr}\ln(\mathcal{M}) \qquad \mathcal{M}^{-1} = \begin{pmatrix} \partial_\tau + \tilde{\epsilon} & \frac{g}{\sqrt{A}} \sum_k e^{2\pi i \mathbf{k}\cdot\mathbf{r}_j} \psi_k \\ \frac{g}{\sqrt{A}} \sum_k e^{2\pi i \mathbf{k}\cdot\mathbf{r}_j} \psi_k^\dagger & \partial_\tau + \tilde{\epsilon} \end{pmatrix}$$

Minimise action around stationary uniform saddle point

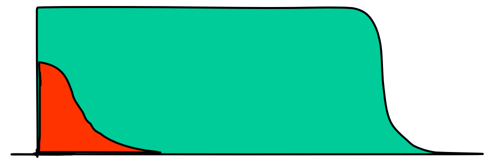
$$\hbar\tilde{\omega}_0 \psi_0 = g^2 n \frac{\tanh(\beta E)}{2E} \psi_0, \quad E = \sqrt{\tilde{\epsilon}^2 + g^2 \frac{|\psi_0|^2}{A}}.$$

$$\rho_{\mathrm{M.F.}} = \frac{|\psi_0|^2}{A} + \frac{n}{2}\left[1 - \frac{\tilde{\epsilon}}{E}\tanh(\beta E)\right]$$

Dictionary of broken symmetries

- Connection to excitonic insulator generalises the BEC concept – different guises

$$e^{\lambda \sum_k \phi_k a^\dagger_{ck} a_{vk}} = \prod_k \left[1 + \lambda \phi_k a^\dagger_{ck} a_{vk}\right]$$



- Rewrite as spin model

$$S_i^+ = a^\dagger_{ci} a_{vi} \quad ; \quad S_i^z = a^\dagger_{ci} a_{ci} - a^\dagger_{vi} a_{vi}$$

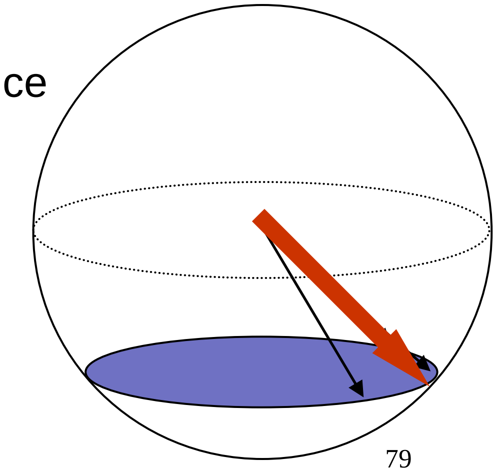
- XY Ferromagnet / Quantum Hall bilayer / BaCuSiO

$$|w_i\rangle = e^{\sum_i w_i S_i^+} |0\rangle$$

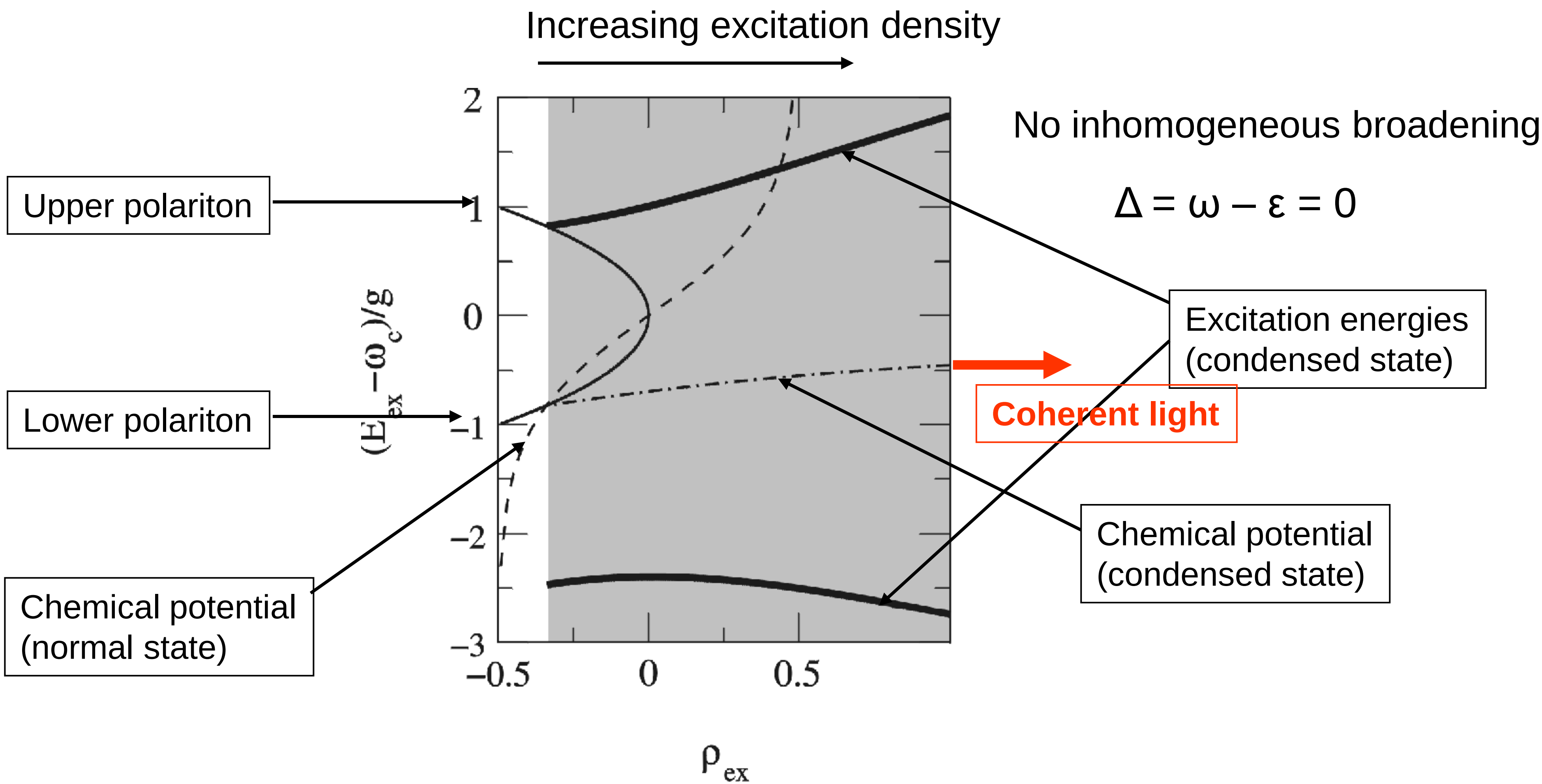
Dynamics – precession in self-consistent field

- Couple to an additional Boson mode:
  photons -> polaritons;
  molecules -> cold fermionic atoms near Feshbach resonance

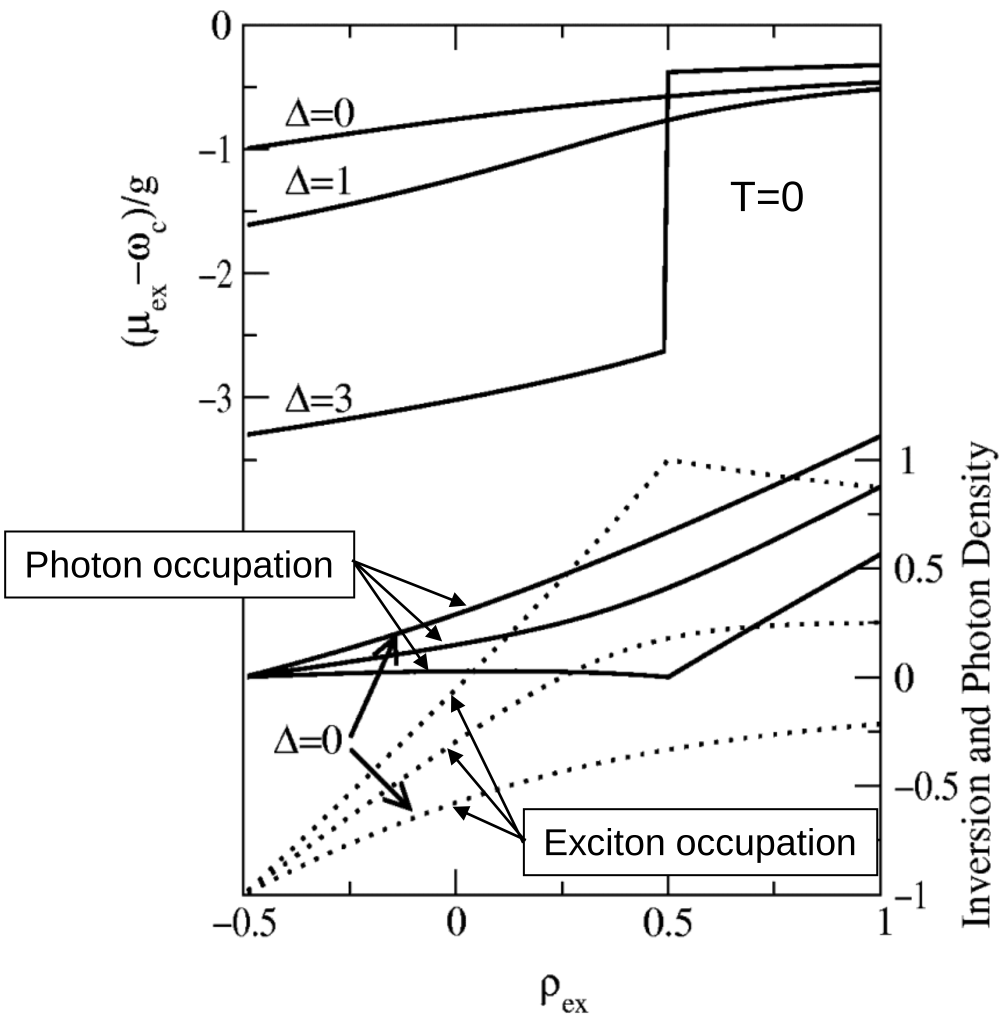
$$|\lambda, w_i\rangle = \exp[\lambda \psi^\dagger + \sum_i w_i S_i^+] |0\rangle$$



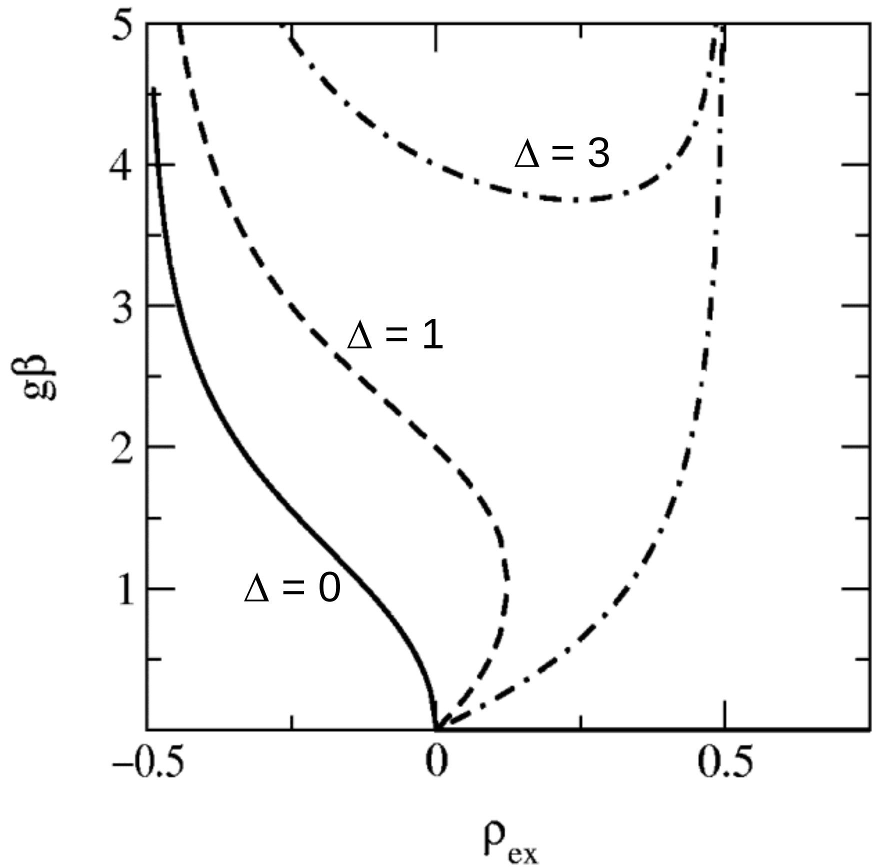
Condensation in the Dicke model (g/T = 2)



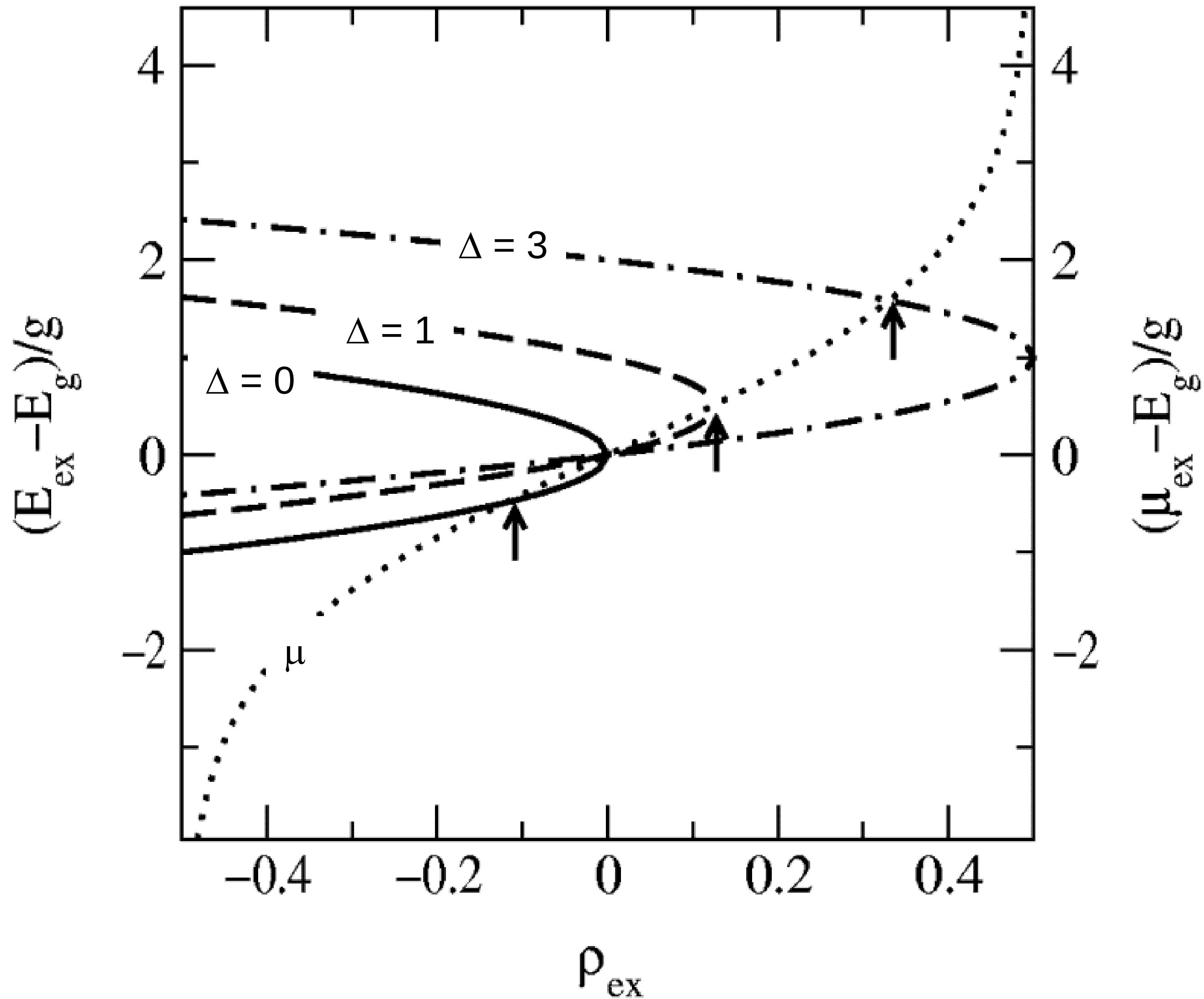
Phase diagram



Detuning $\Delta = (\omega - \varepsilon)/g$



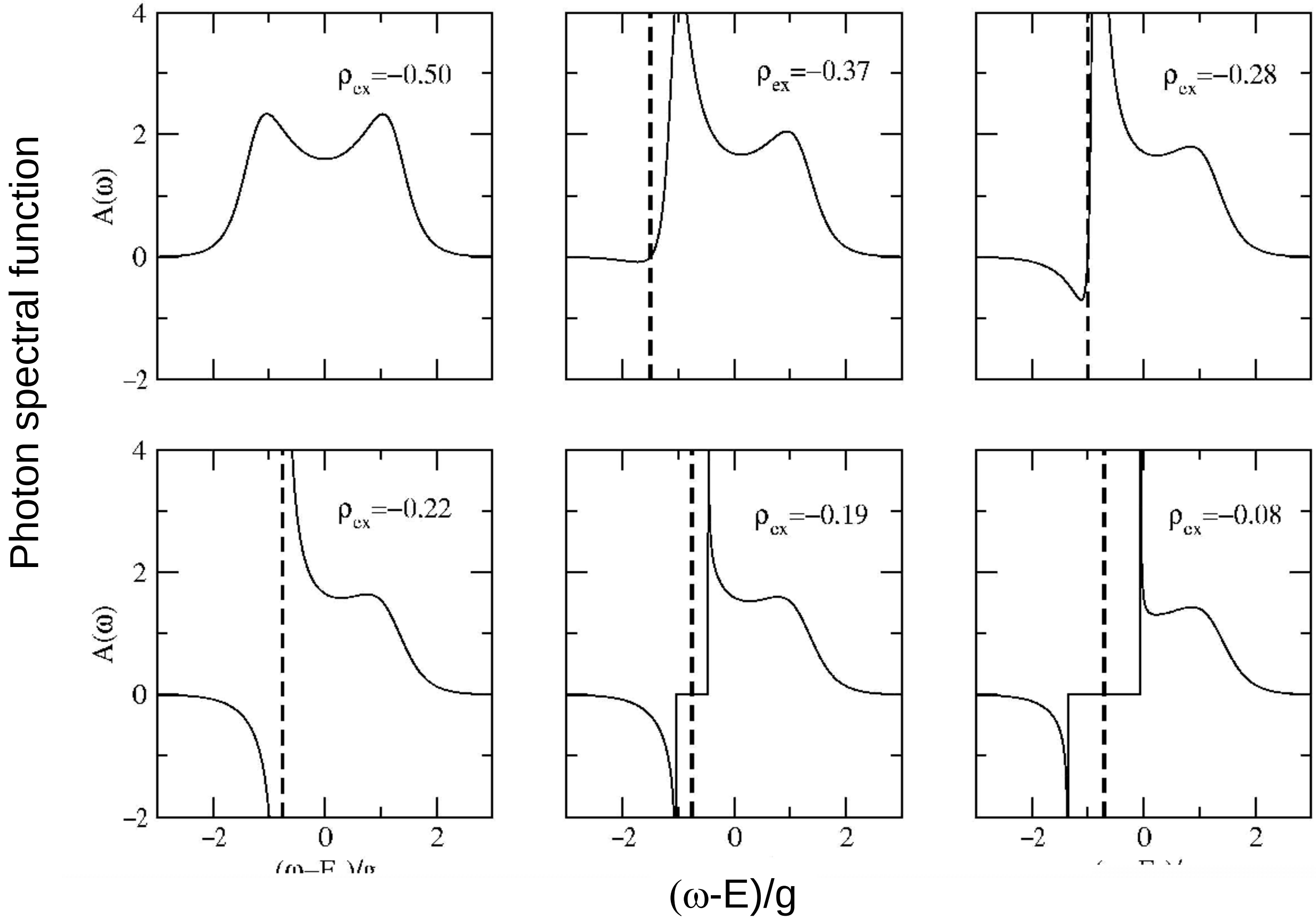
Excitation spectrum for different detunings



gβ = 1

Excitation spectrum with inhomogeneous broadening

Zero detuning: $\omega = \varepsilon$
Gaussian broadening of exciton energies σ = 0.5 g



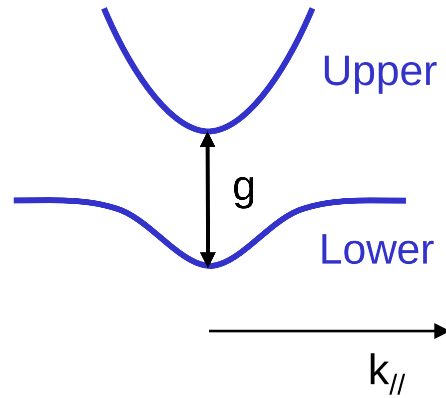
Interaction dominated physics or dilute Bose gas ?

Mean field theory – coherent state – is BCS

"BCS" to Bose crossover

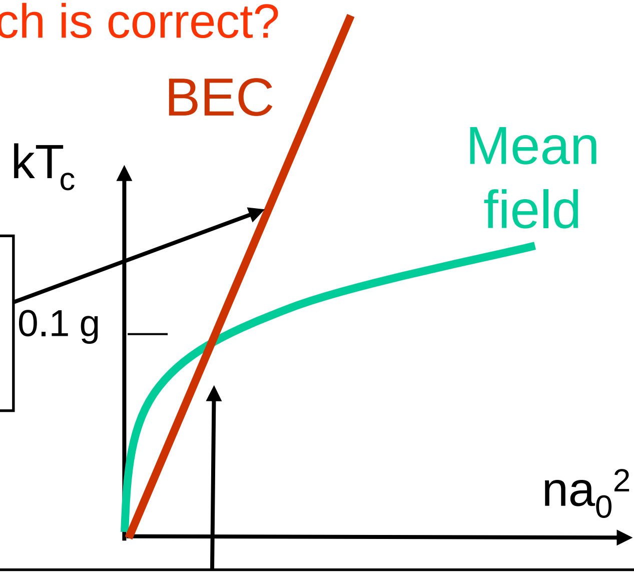
Beyond mean field: Interaction driven or dilute gas?

- 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

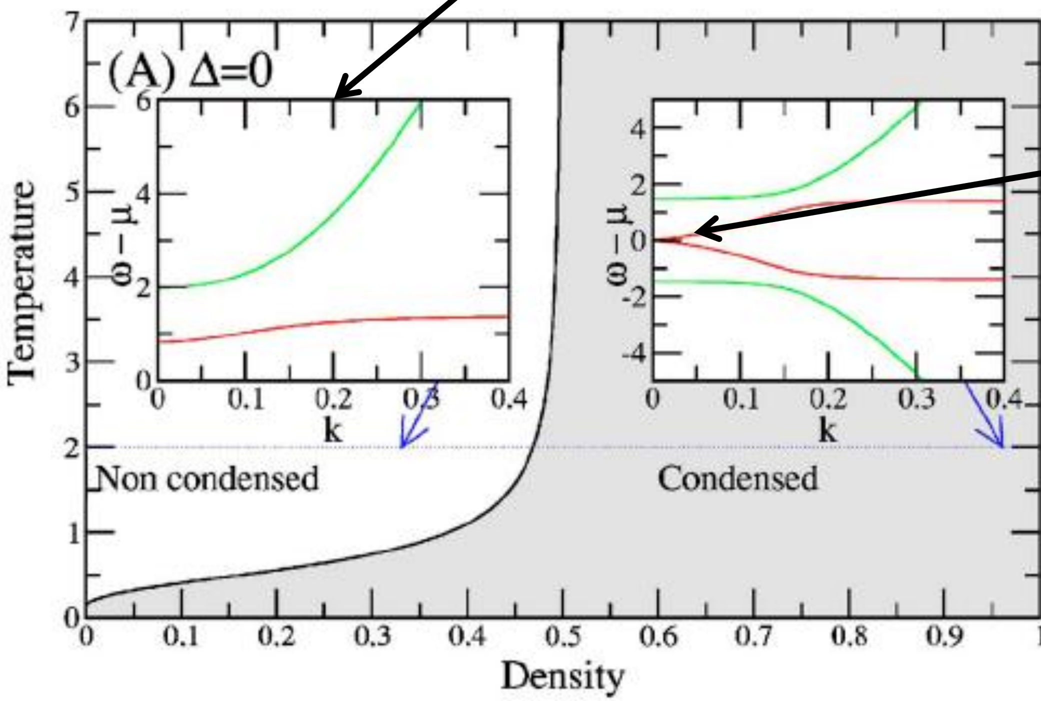
A further crossover to the plasma regime when $na_B^2 \sim 1$

Fluctuation spectrum

Expand action in quadratic fluctuations around mean field solutions, and diagonalise to determine the new collective modes.

$$E_{\pm} = \frac{1}{2}[(\hbar\tilde{\omega}_k + 2\tilde{\epsilon}) \pm \sqrt{(\hbar\tilde{\omega}_k - 2\tilde{\epsilon})^2 + 4g^2 n \tanh(\beta\tilde{\epsilon})}].$$

Conventional upper and lower polaritons



Bogoliubov sound mode

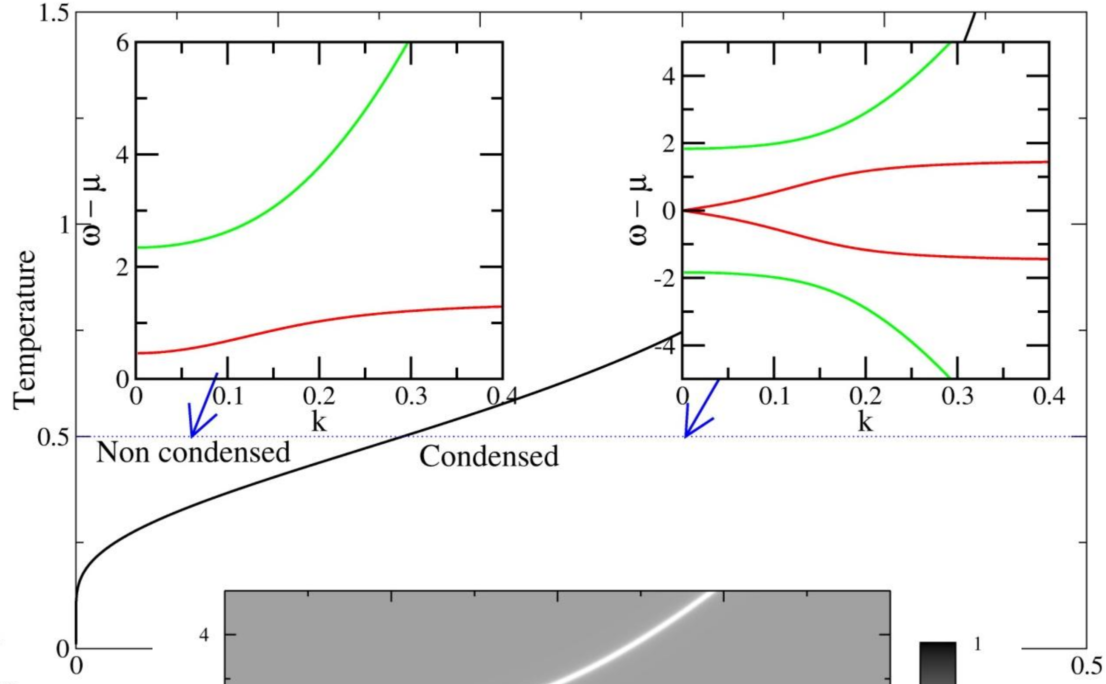
$$\xi_1 = \pm\hbar c k$$

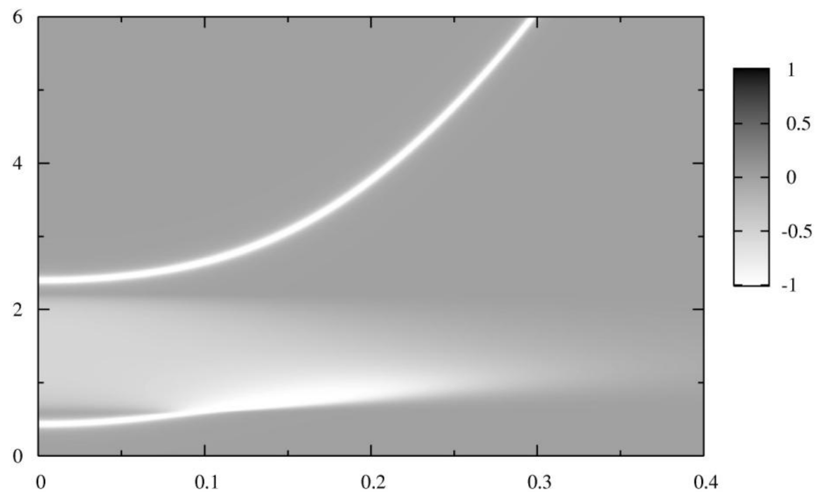
$$c = \sqrt{\frac{1}{2m}\left(\frac{4\hbar\tilde{\omega}_0 g^2 n}{\xi_2(0)^2}\right)\left(\frac{|\psi_0|^2}{N}\right)} \approx \sqrt{\frac{\lambda}{2m}\frac{\rho_0}{n}}.$$

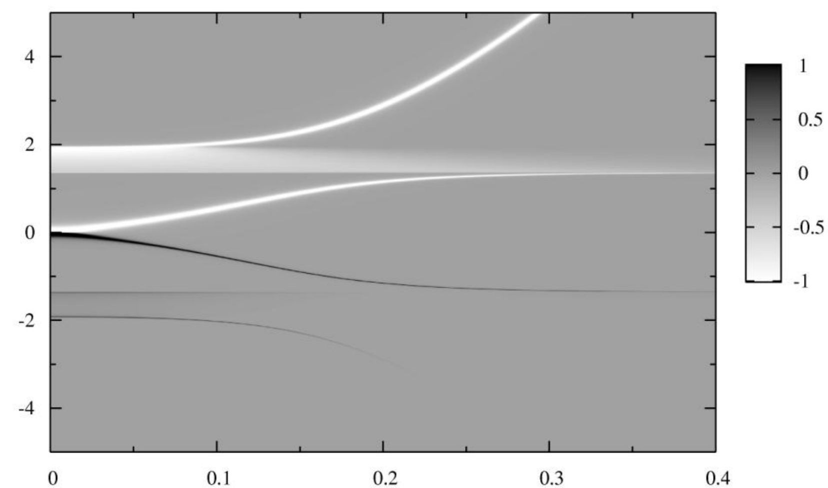
2D polariton spectrum

Keeling et al PRL 93, 226403 (2004)

- Excitation spectrum calculated at mean field level
- Thermally populate this spectrum to estimate suppression of superfluid density (one loop)
- Estimate new T_c

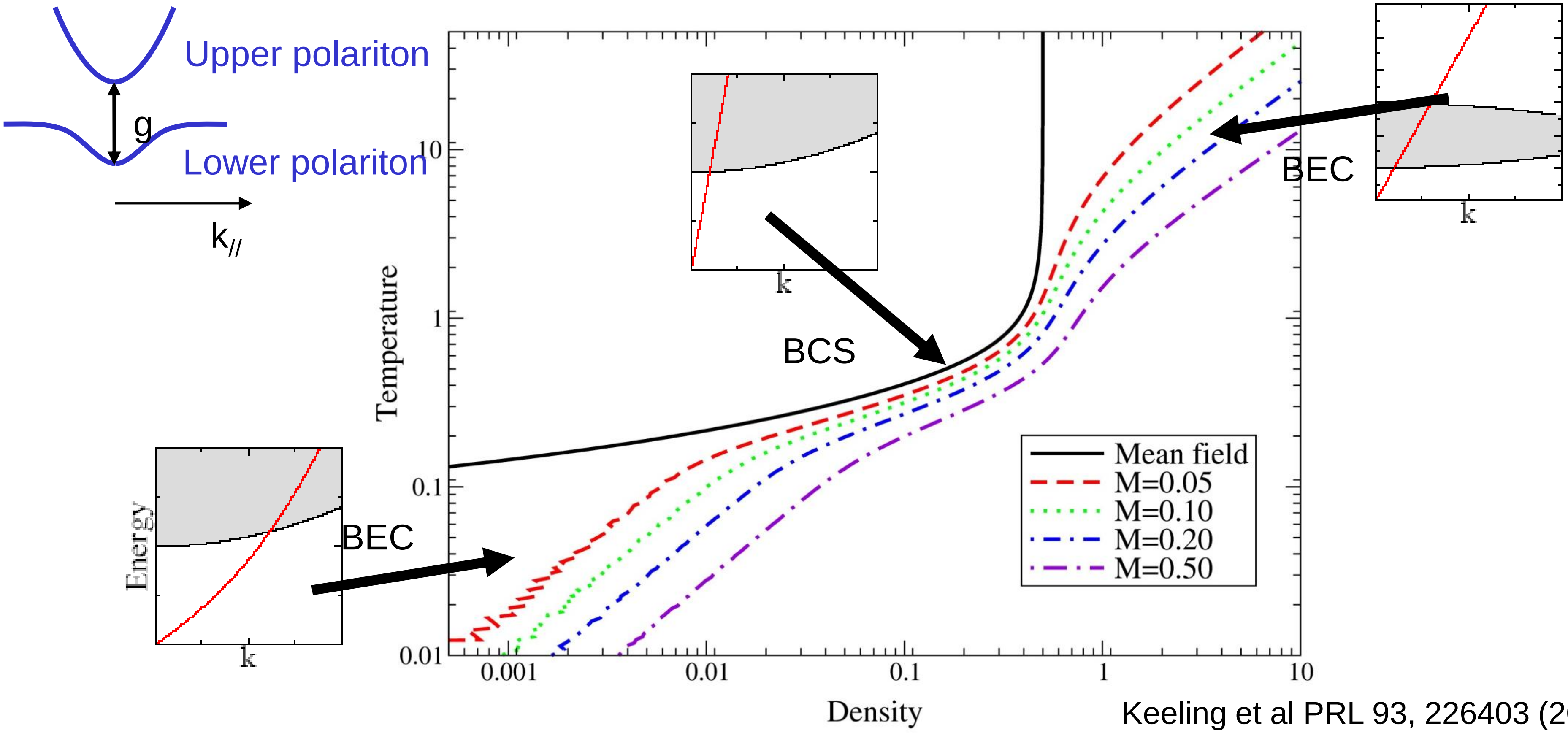






Phase diagram

- T_c suppressed in low density (polariton BEC) regime and high density (renormalised photon BEC) regimes
- For typical experimental polariton mass ~ 10^{-5} deviation from mean field is small



Keeling et al PRL 93, 226403 (2004)

2D physics

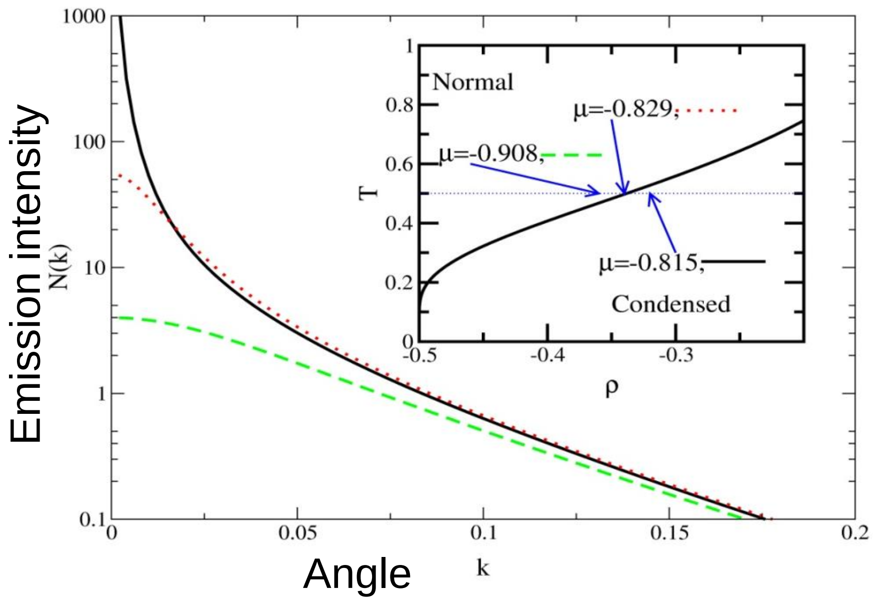
No long range order at finite temperatures

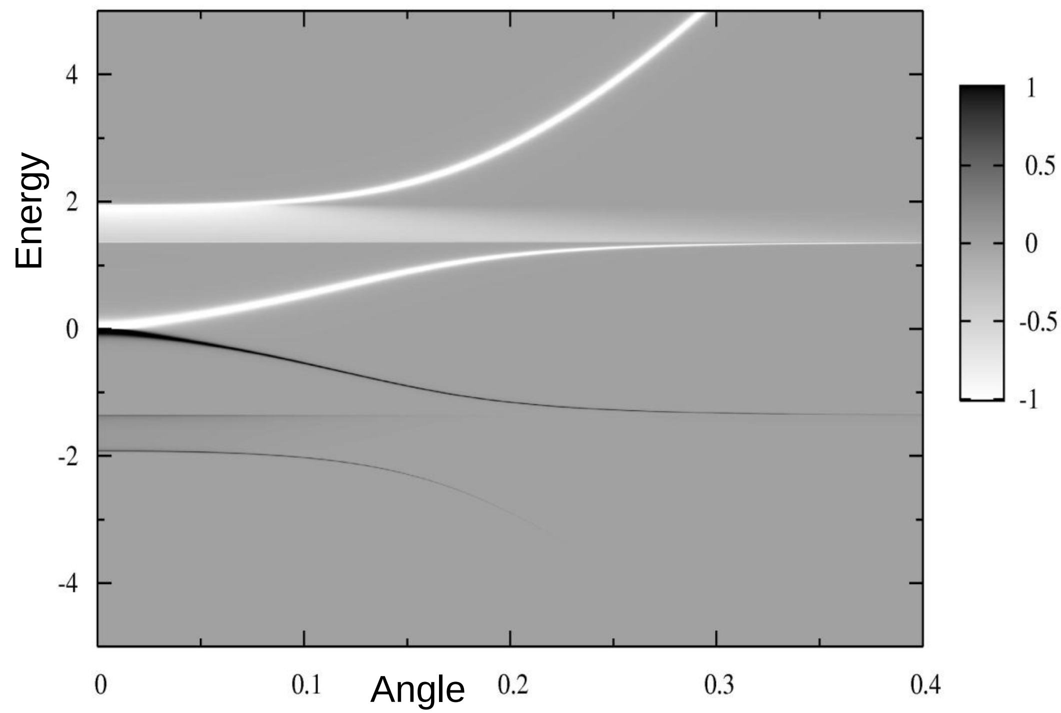
Berezhinskii-Kosterlitz-Thouless transtion

Excitation spectra in microcavities with coherence

Keeling, Eastham, Szymanska, PBL PRL 2004

Angular dependence of luminescence becomes sharply peaked at small angles
(No long-range order because a 2D system)





Absorption(white) / Gain(black) spectrum of coherent cavity

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

Conventional theory of the laser

$$b^\dagger b - a^\dagger a = S^z$$
$$b^\dagger a = S^+$$
$$a^\dagger b = S^-$$
$$b^\dagger b + a^\dagger a = 1$$

$$H = H_0 + H_{SB} + H_B$$

$$H_0 = \sum_i \epsilon_i (b_i^\dagger b_i - a_i^\dagger a_i) + \omega_c \psi^\dagger \psi + \frac{g}{\sqrt{N}} \sum_i \left[\psi^\dagger a_i^\dagger b_i + h.c. \right]$$ system

$$H_B = \sum_k \left[\omega_k d_k^\dagger d_k + \omega_{+,k} c_{+,k}^\dagger c_{+,k} + \omega_{-,k} c_{-,k}^\dagger c_{-,k} + \omega_{1,k} c_{1,k}^\dagger c_{1,k} + \omega_{2,k} c_{2,k}^\dagger c_{2,k} \right]$$ bosonic “baths”

$$H_{SB} = \sum_k g_k (\psi^\dagger d_k + d_k^\dagger \psi)$$ decay of cavity mode

$$+ \sum_{jk} \left[b_j^\dagger a_j (g_{jk}^{\gamma_+} c_{+,k}^\dagger + g_{jk}^{\gamma_-} c_{-,k}) + \mathrm{h.c} \right]$$ phase-breaking

$$+ \sum_{jk} \Gamma_{jk}^{(1)} (b_j^\dagger b_j + a_j^\dagger a_j)(c_{1,k}^\dagger + c_{1,k})$$ pair-breaking

$$+ \sum_{jk} \Gamma_{jk}^{(2)} (b_j^\dagger b_j - a_j^\dagger a_j)(c_{2,k}^\dagger + c_{2,k})$$ non-pair-breaking

From Heisenberg to Langevin equations of motion

$$\frac{d}{dt}\psi = -i\omega_c\psi - ig\sum_i a_i^\dagger b_i - i\sum_k g_k d_k$$

$$\frac{d}{dt}d_k = -i\omega_k d_k - ig_k\psi$$

$$d_k(t) = d_k(t_o)e^{-i\omega_k(t-t_o)} - g_k\int_{t_o}^{t} dt'\psi(t')e^{-i\omega_k(t-t')}$$

$$\frac{d}{dt}\psi = -i\omega_c\psi - ig\sum_i a_i^\dagger b_i - i\sum_k g_k d_k(t_o)e^{-i\omega_k(t-t_o)} - \sum_k g_k^2\int_{t_o}^{t} dt'\psi(t')e^{-i\omega_k(t-t')}$$

Markov approximation

$$\frac{d}{dt}\psi = (-i\omega_c - \kappa)\psi - ig\sum_i a_i^\dagger b_i + F(t)$$

$$\frac{d}{dt}a_j^\dagger b_j = (-i\epsilon_j - \gamma_\perp)a_j^\dagger b_j + ig\psi(b_j^\dagger b_j - a_j^\dagger a_j) + \Gamma_{j-}$$ Polarisation $S^{+,-}$

$$\frac{d}{dt}(b_j^\dagger b_j - a_j^\dagger a_j) = \gamma_{||}(d_o - b_j^\dagger b_j + a_j^\dagger a_j) + 2ig(\psi^\dagger a_j^\dagger b_j - b_j^\dagger a_j\psi) + \Gamma_{j,d}$$ Inversion S^Z

From Langevin equations to mean field

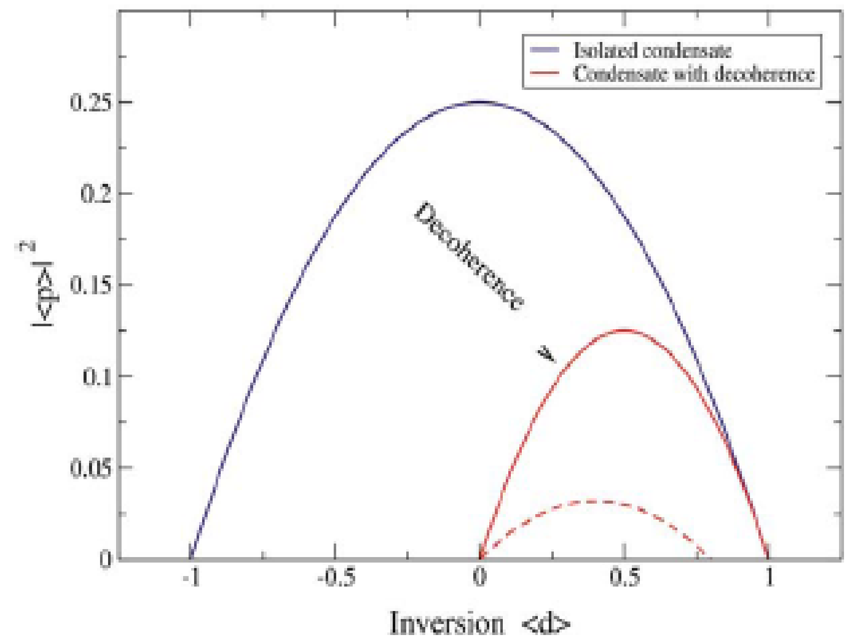
Bloch equations in a self-consistent field

$$\frac{d}{dt}\langle\psi\rangle = (-i\omega_c - \kappa)\langle\psi\rangle - ig\sum_j \left\langle S_j^- \right\rangle$$

$$\frac{d}{dt}\left\langle S_j^- \right\rangle = (-i\epsilon_j - \gamma_\perp)\left\langle S_j^- \right\rangle + ig\langle\psi\rangle\left\langle S_j^z \right\rangle$$

$$\frac{d}{dt}\left\langle S_j^z \right\rangle = \gamma_{||}(d_o - \left\langle S_j^z \right\rangle) + 2ig(\langle\psi^\dagger\rangle\left\langle S_j^- \right\rangle - \left\langle S_j^+ \right\rangle\langle\psi\rangle)$$

If decay processes are turned off, solutions are identical to BCS mean field equations – but these are unstable to infinitesimal damping



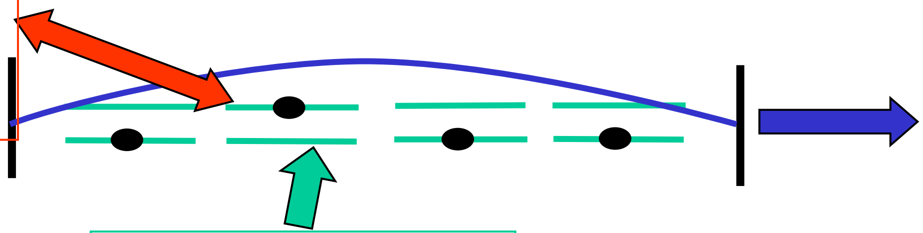
Disaster ?

Apparently arbitrarily weak decoherence destroys coherent ground state unless system is inverted, so the only solution is that of a regular laser

... but the assumption was that the noise is Markovian – uncorrelated – whereas the noise is coupled via the spectrum of the correlated ground state

....which has a gap, and a stiffness

Decoherence



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

in analogy to superconductivity, the external fields may couple in a way that is “pair-breaking” or “non-pair-breaking”

$$\sum_{i,k} g^{(1)}_{i,k} \left[b_i^\dagger b_i - a_i^\dagger a_i\right] (c^\dagger_{1,k} + c_{1,k})$$ non-pairbreaking (inhomogeneous distribution of levels)

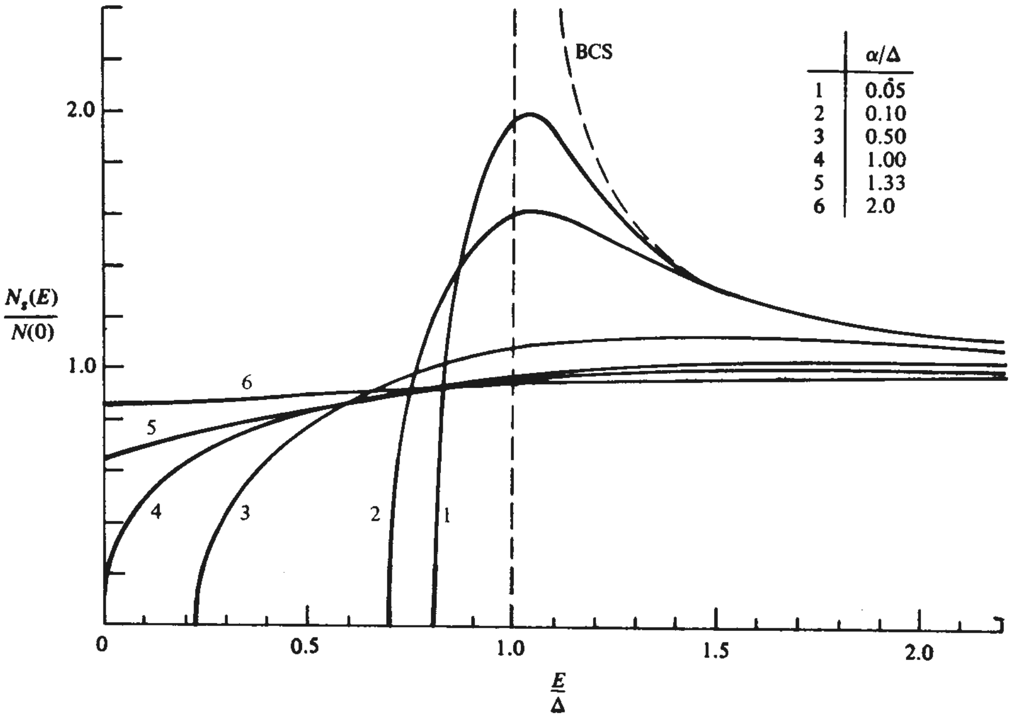
$$\sum_{i,k} g^{(2)}_{i,k} \left[b_i^\dagger b_i + a_i^\dagger a_i\right] (c^\dagger_{2,k} + c_{2,k})$$ pairbreaking disorder

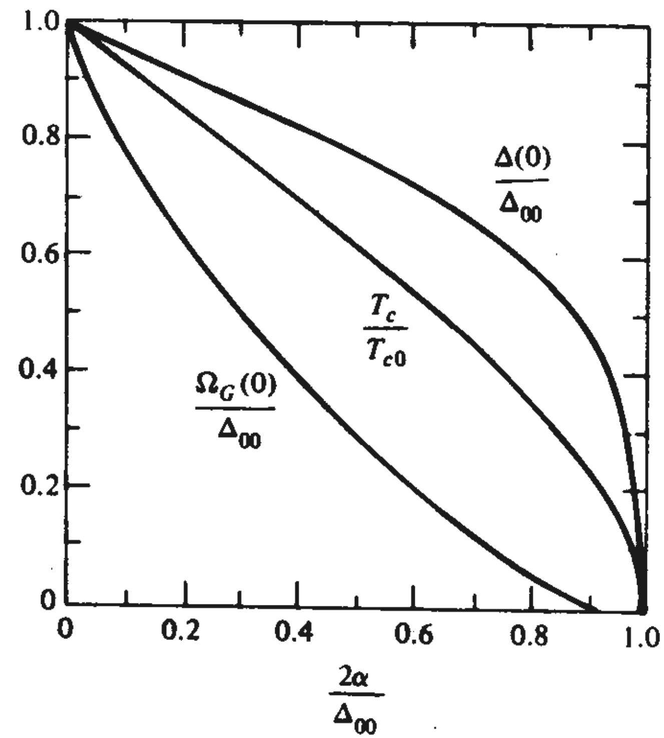
- Conventional theory of the laser assumes that the external fields give rise to rapid decay of the excitonic polarisation - incorrect if the exciton and photon are strongly coupled
- Correct theory is familiar from superconductivity - Abrikosov-Gorkov theory of superconductors with magnetic impurities

$$\sum_{i,k} g^{(3)}_{i,k} \left[b_i^\dagger a_i c^\dagger_{3,k} + a_i^\dagger b_i c_{3,k}\right]$$ symmetry breaking – XY random field destroys LRO

Detour - Abrikosov-Gorkov theory of gapless superconductivity

- Ordinary impurities that do not break time reversal symmetry are “irrelevant”. Construct pairing between degenerate time-reversed pairs of states (Anderson’s theorem)
- Fields that break time reversal (e.g. magnetic impurities, spin fluctuations) suppress singlet pairing, leading first to gaplessness, then to destruction of superconductivity
[Abrikosov & Gorkov ZETF 39, 1781 (1960); JETP 12, 12243 (1961)]





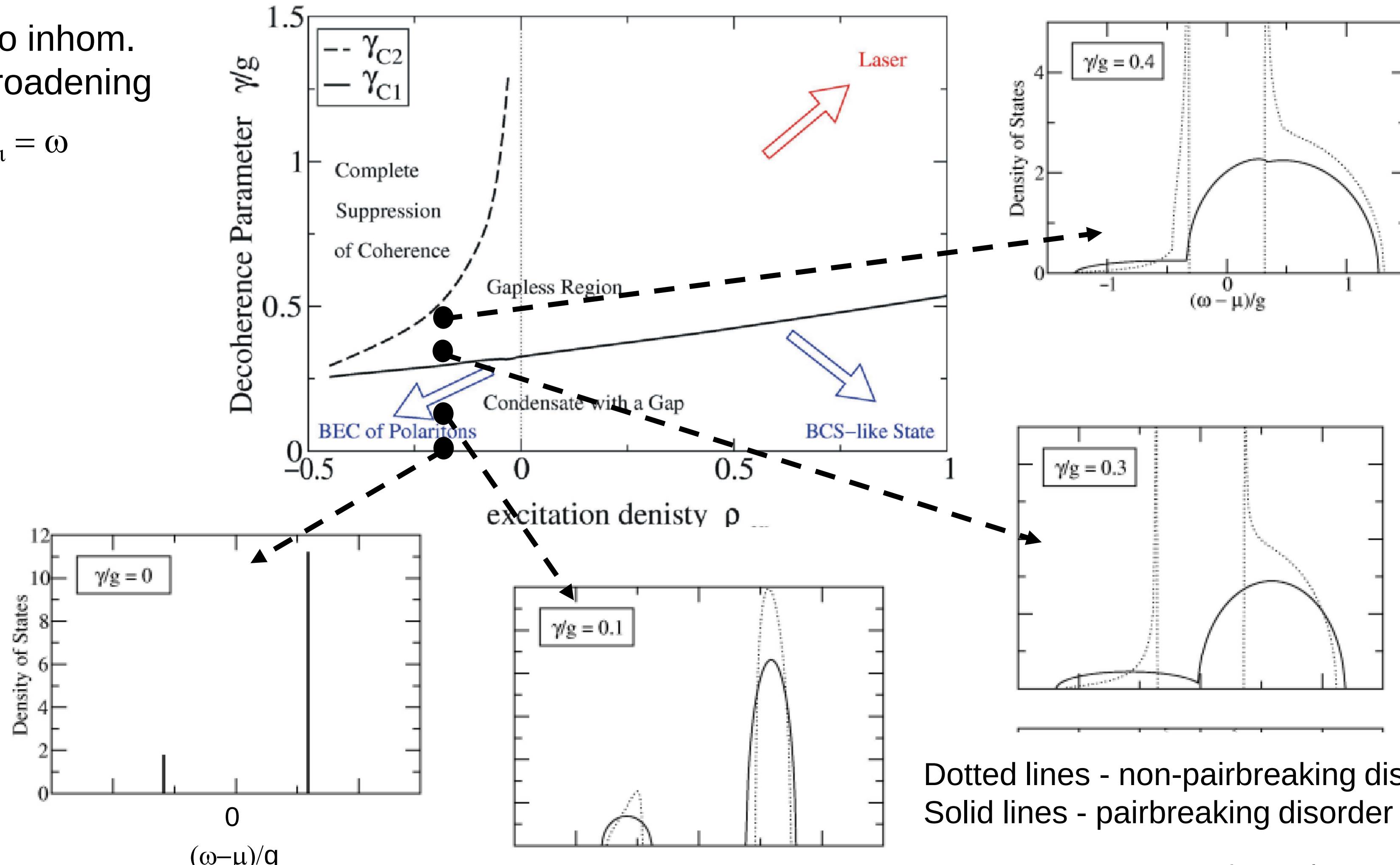
Skalski et al, PR136, A1500 (1964)

Phase diagram of Dicke model with pairbreaking

Pairbreaking characterised by a single parameter $\gamma = \lambda^2 N(0)$

No inhom. broadening

$\varepsilon_\iota = \omega$



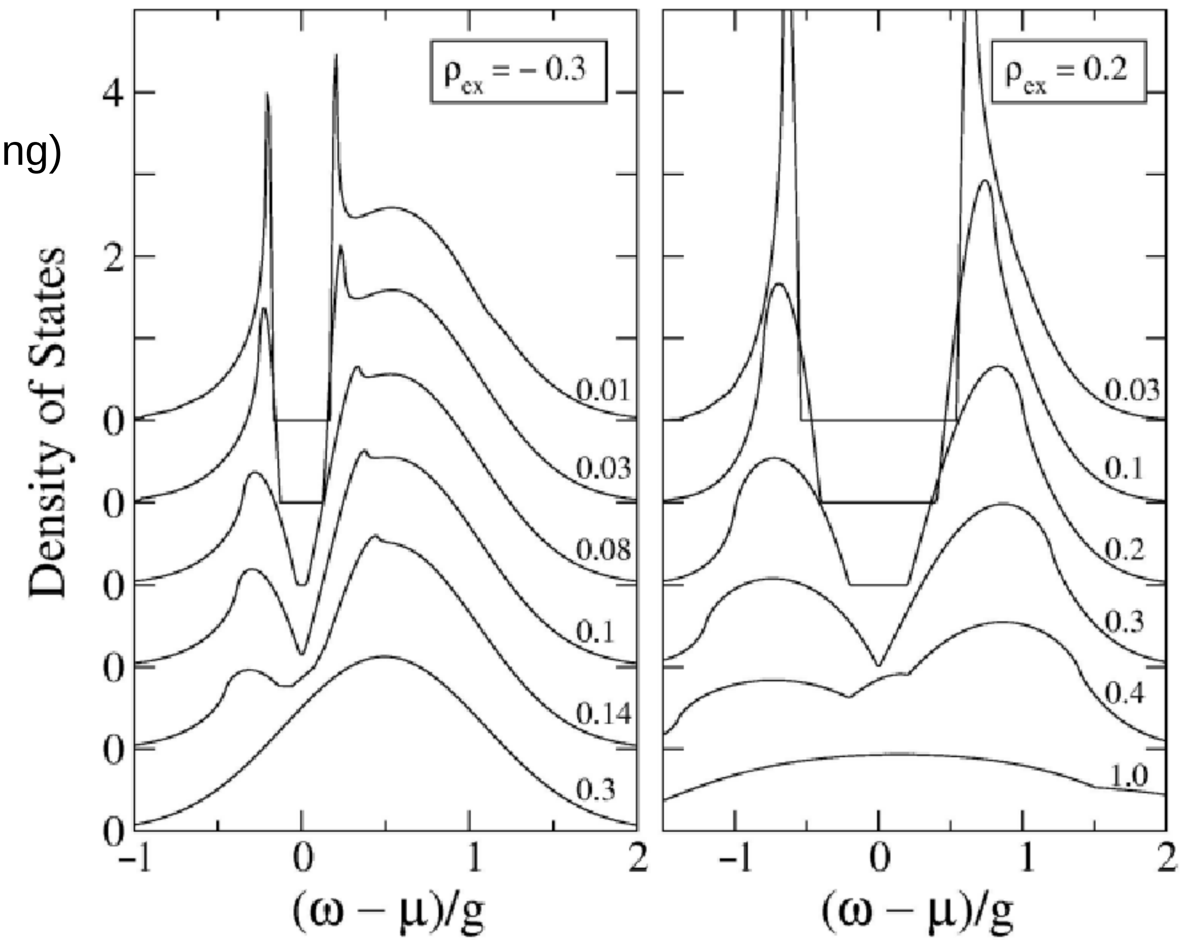
Dotted lines - non-pairbreaking disorder
Solid lines - pairbreaking disorder

MH Szymanska et al 2003

Transition to gaplessness and lasing

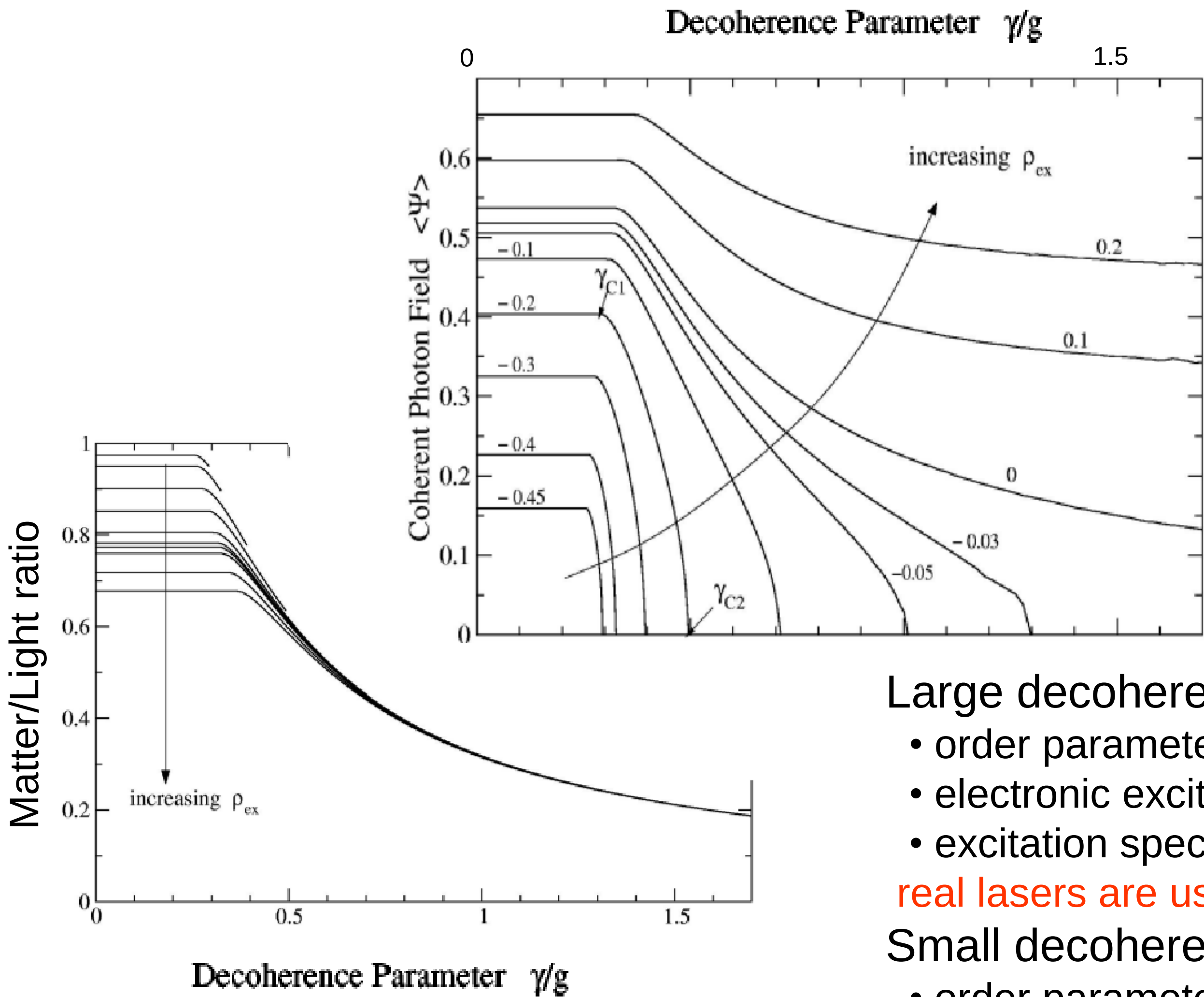
Model with both pairbreaking and non-pairbreaking (inhom. broadening)

Low density: below inversion | Higher density: above inversion



Increasing pairbreaking

Strong pairbreaking -> semiconductor laser



Large decoherence -- "laser"

- order parameter nearly photon like
- electronic excitations have short lifetime
- excitation spectrum gapless

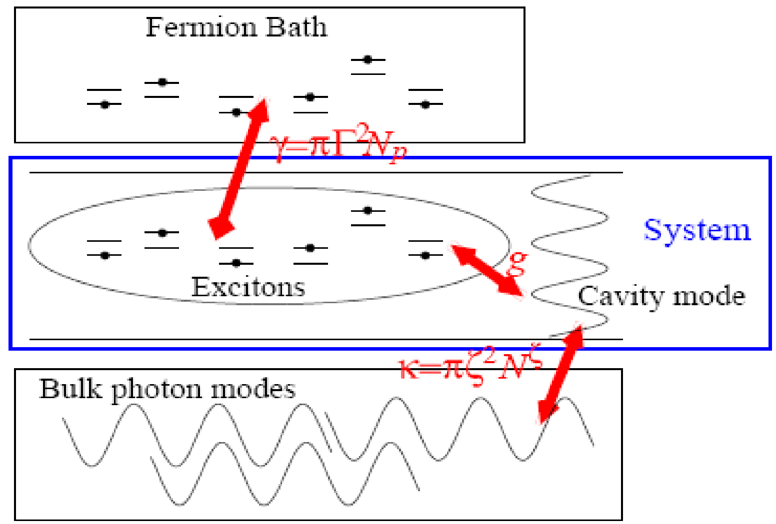
real lasers are usually far from equilibrium

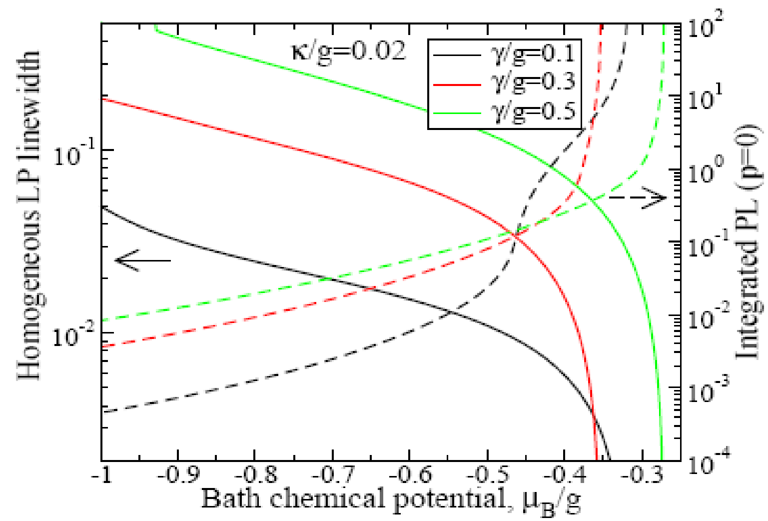
Small decoherence -- BEC of polaritons

- order parameter mixed exciton/photon
- excitation spectrum has a gap

Model for coupling to external baths

- Couple cavity photons to bulk photon modes (outside the cavity) – damping parameter κ
- Couple excitons to baths of free fermions (electrons and holes) – dampling parameter γ
- Fermions kept at a chemical potential μ_{ext}
- For fixed parameters, system reaches steady state equilibrium – increase occupation of the system by changing the external chemical potential
- Mathematically, construct non-equilibrium formulation using Keldysh method

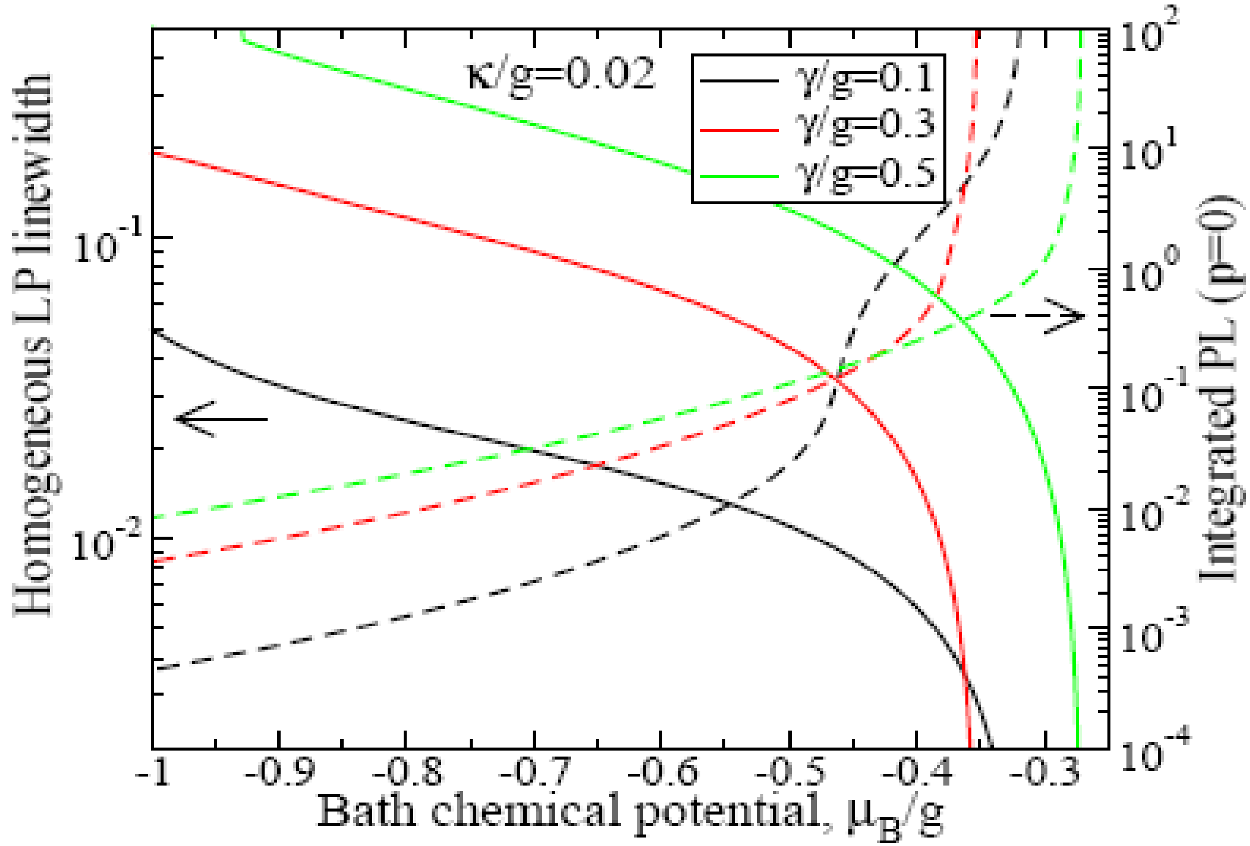




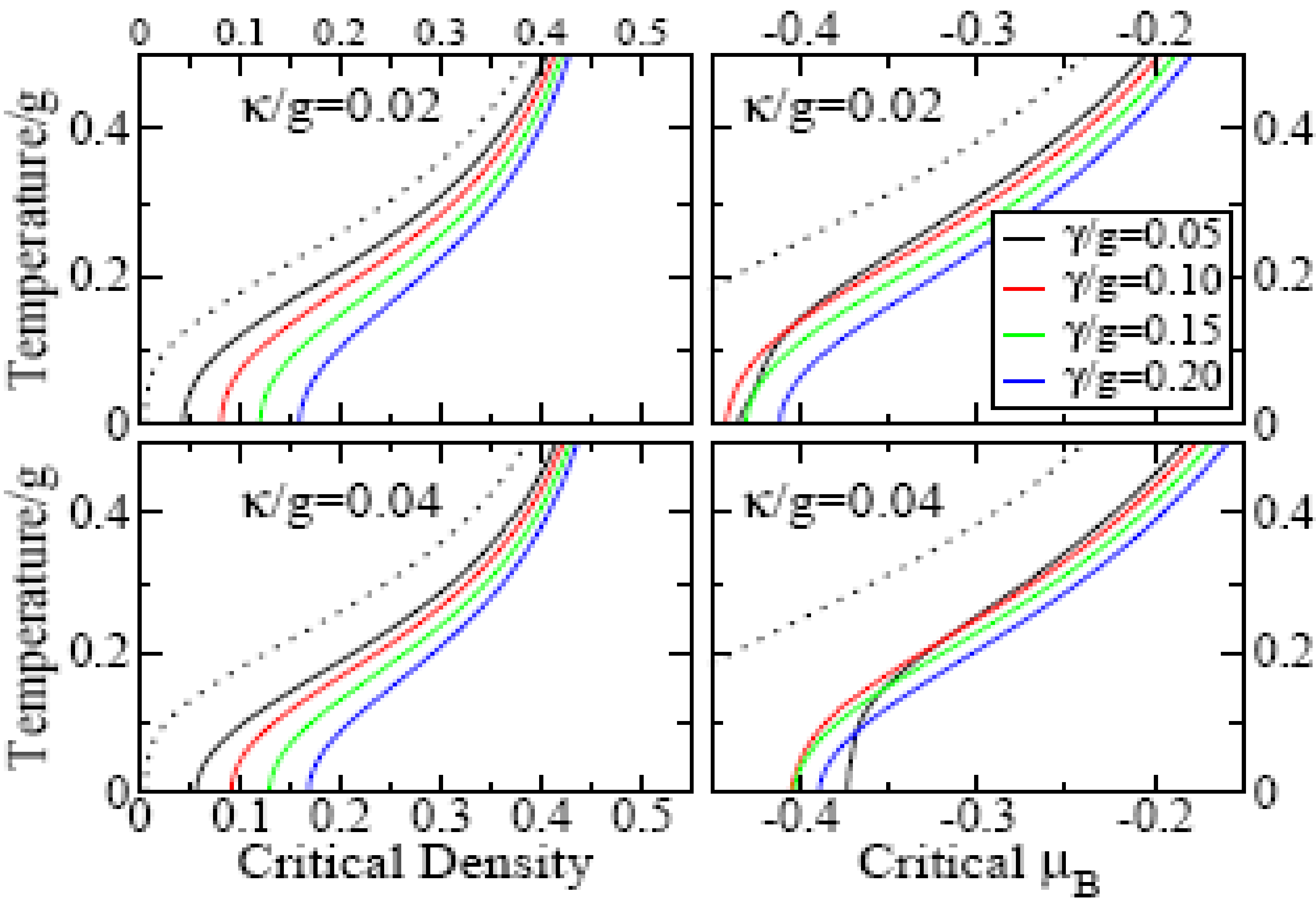
Szymanska, Keeling, Littlewood, *Physical Review B* 75, 195331 (2007)

Linewidth and luminescence

- Linewidth vanishes as transition is approached
- Luminescence – N(0) diverges at transition
- Both have mean field exponents ~ $(P_c - P)^{\pm 1/2}$

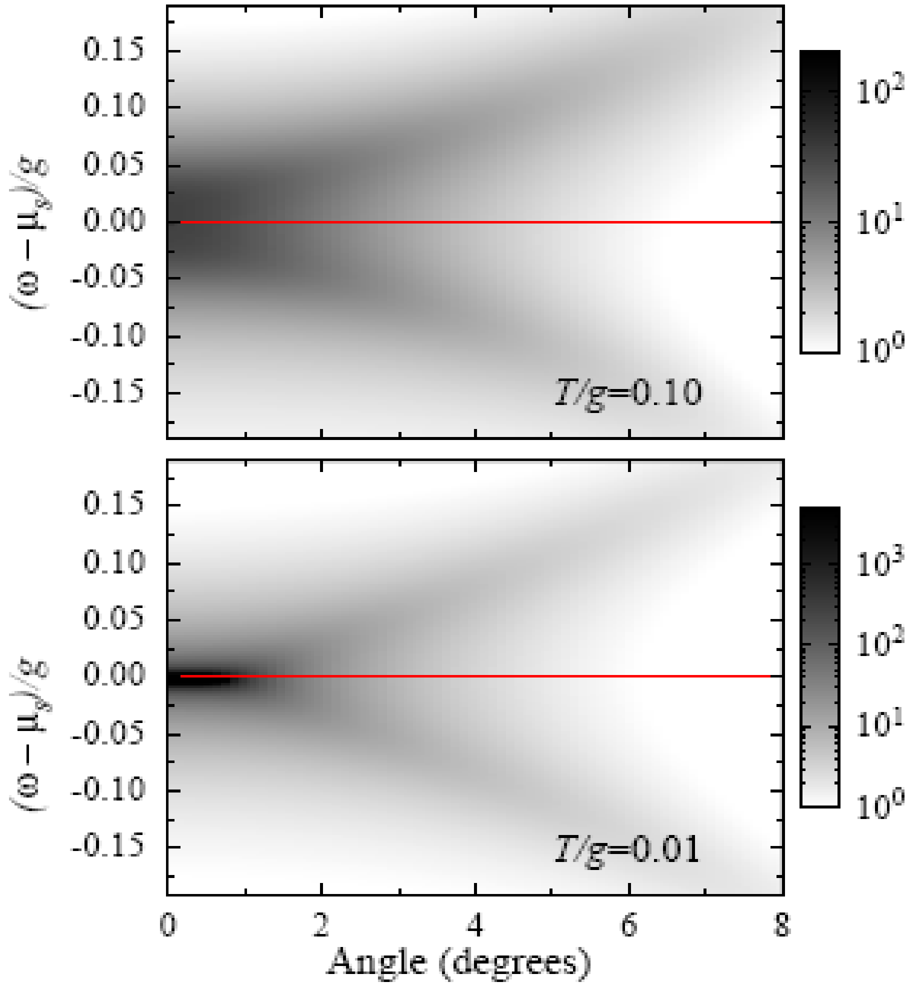


Phase boundary in presence of dissipation



Photoluminescence

- Crossover from propagating Bogoliubov mode to diffusion on lon length scales
- Crossover length determined by dissipation rate



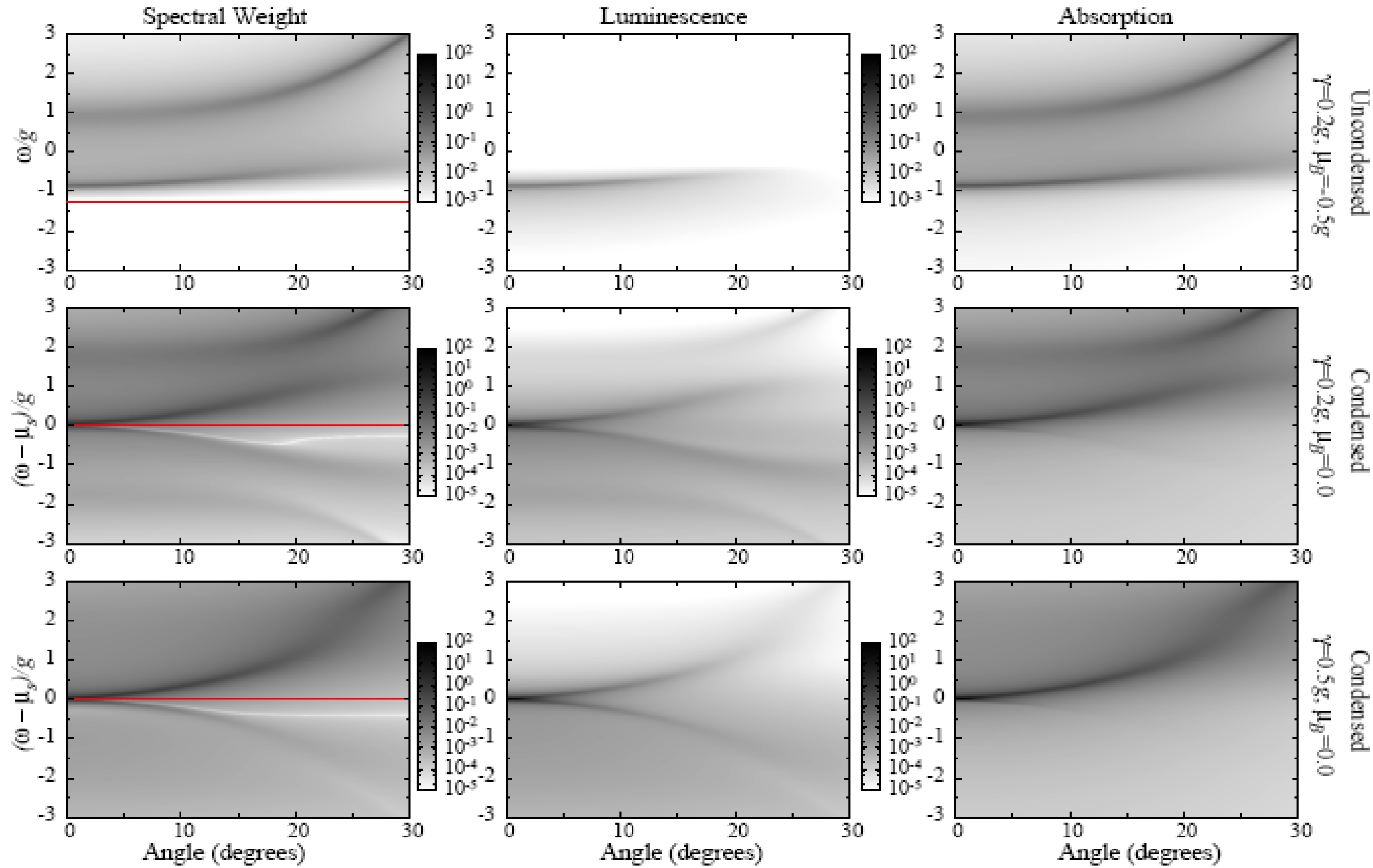


FIG. 10: Spectral weight, photoluminescence and absorption spectra, as a function of emission angle, $\tan^{-1}(cp/\omega_0)$. For all graphs, $\kappa = 0.02g$ and $T = 0.1g$. Top row: Uncondensed case, $\gamma = 0.2g, \mu_B = -0.5g$. (cf parameters in Fig. 2 and Fig. 3) Middle row: Condensed case, $\gamma = 0.2g, \mu_B = 0.0g$. Bottom row: Condensed case, $\gamma = 0.5g, \mu_B = 0.0g$ (transition to weak coupling).

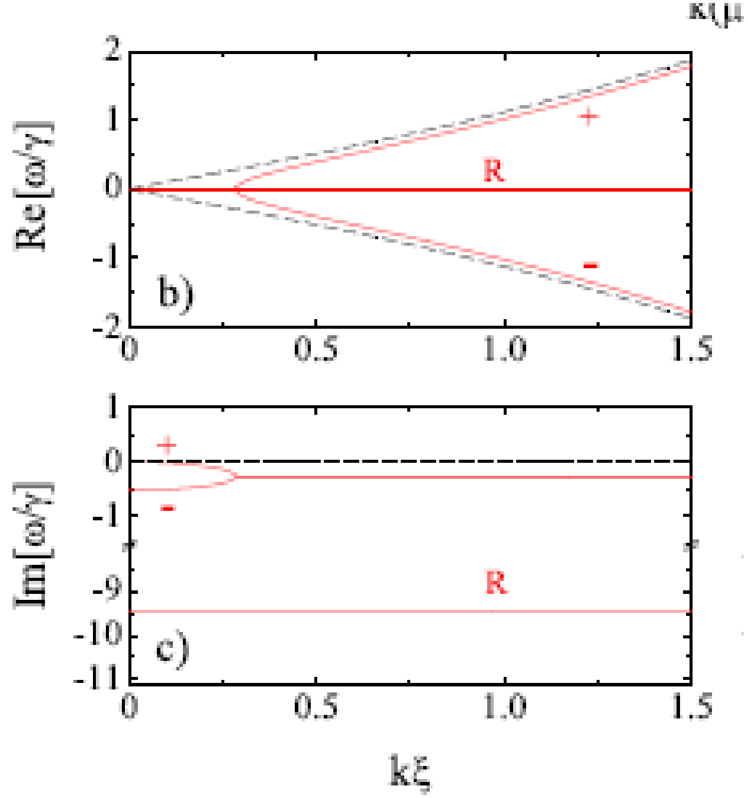
Damped, driven Gross-Pitaevski equation

- Microscopic derivation consistent with simple behavior at long wavelengths for the condensate order parameter ψ and polariton density n_R

$$i\frac{\partial\psi}{\partial t} = \left\{-\frac{\hbar\nabla^2}{2m_{LP}} + \frac{i}{2}\left[R(n_R) - \gamma\right] + g\,|\psi|^2 + 2\tilde{g}\,n_R\right\}\psi.$$

$$\frac{\partial n_R}{\partial t} = P - \gamma_R\,n_R - R\,(n_R)\,|\psi\,(x)|^2 + D\nabla^2 n_R.$$

$$\omega_\pm(k) = -\frac{i\Gamma}{2} \pm \sqrt{\omega_{Bog}(k)^2 - \frac{\Gamma^2}{4}},$$



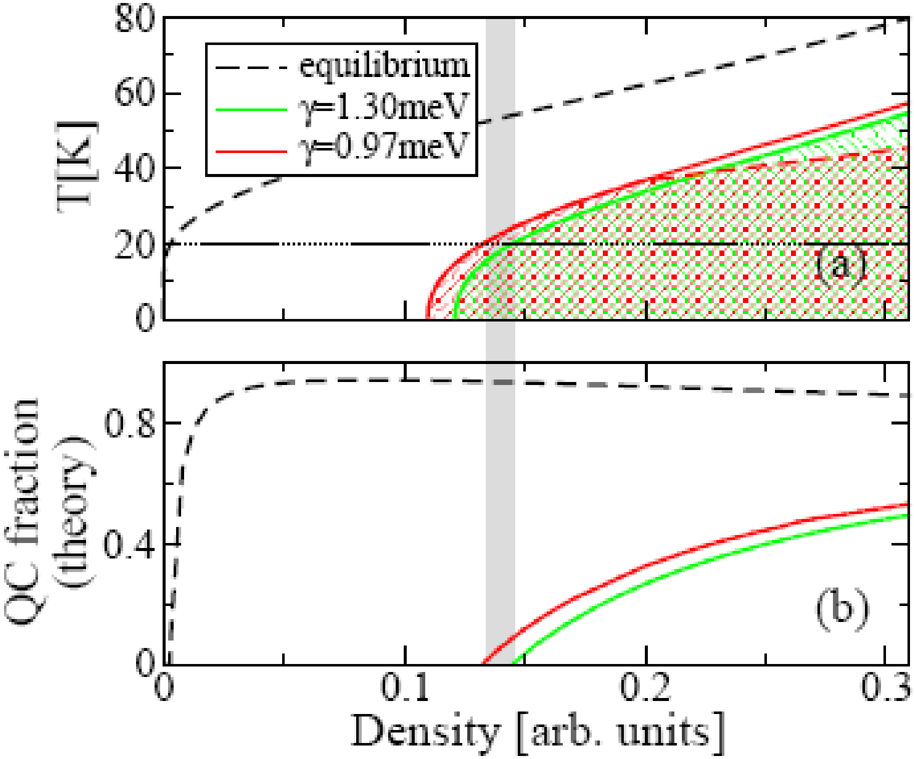
From Wouters and Carusotto 2007

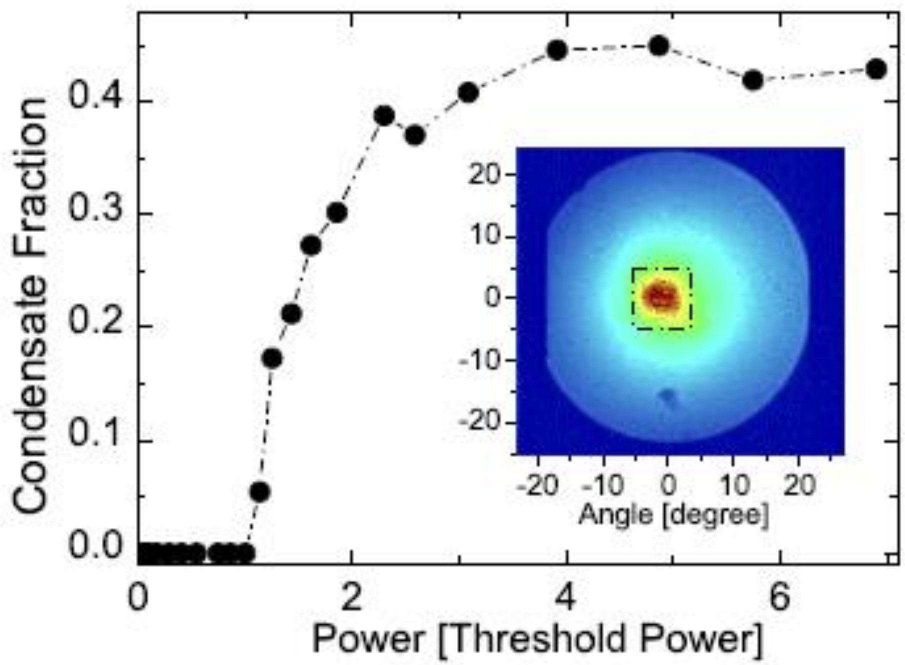
Effect of dissipation on Tc and condensate

Two parameters:

κ – photon linewidth (measured)

γ – pumping rate – unknown but bounded





Quantum dynamics

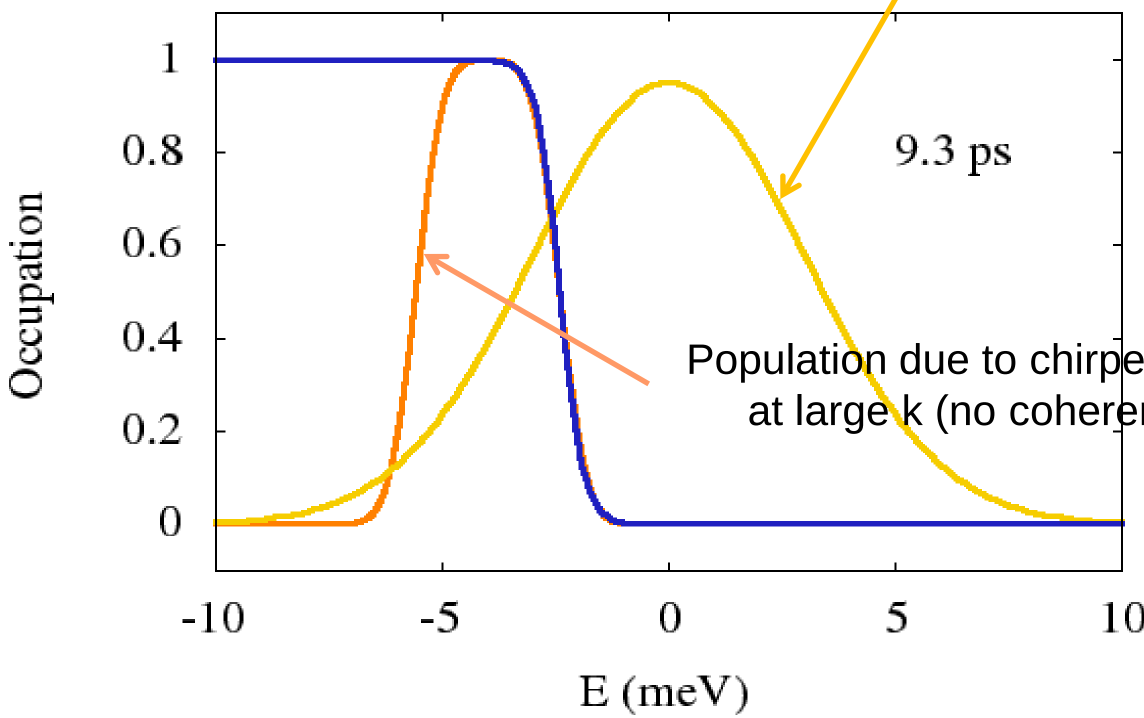
On time scales < few psec, not in thermal equilibrium

Coupling to light allows driven dynamics

Controlled pumping of a many-particle state

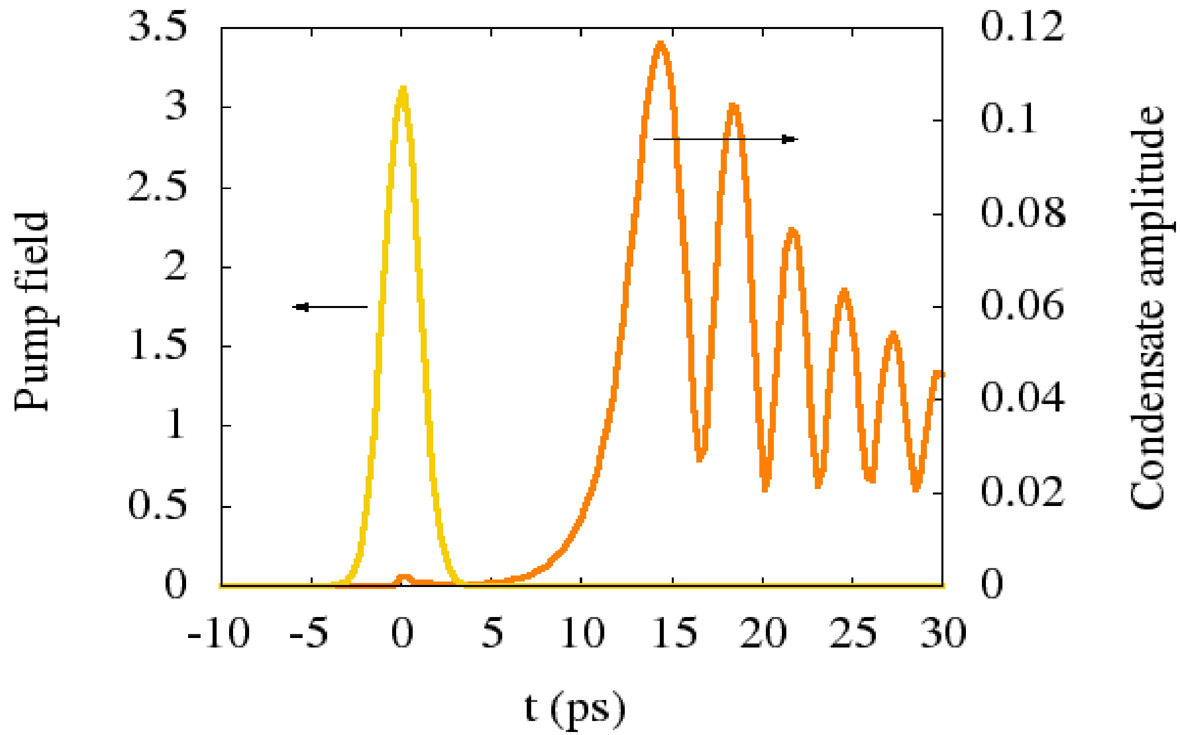
P.R. Eastham and Richard Phillips; arxiv:0708.2009

Distribution of energy levels in, e.g. Quantum dots



- 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

Conclusions

- Excitonic insulator is a broad concept that logically includes CDW's, ferromagnets, quantum Hall bilayers as well as excitonic BEC
- Polariton condensates
  - Mean field like (long range interactions)
  - Strong coupling (not in BEC limit)
- Excitonic coherence – oscillator phase-locking
  - enemy of condensation is decoherence
  - excitons are not conserved so *all* exciton condensates are expected to show coherence for short enough times only
  - condensates will either be diffusive (polaritons) or have a gap (CDW)
- Mean field+ pairbreaking or phasebreaking fluctuations gives a robust model that connects exciton/polariton BEC continuously to
  - semiconductor plasma laser (pairbreaking) or
  - solid state laser (phase breaking)
  - is a laser a condensate? – largely semantic

- Now good evidence for polariton condensation in recent experiments