Polariton Condensation and Collective Dynamics

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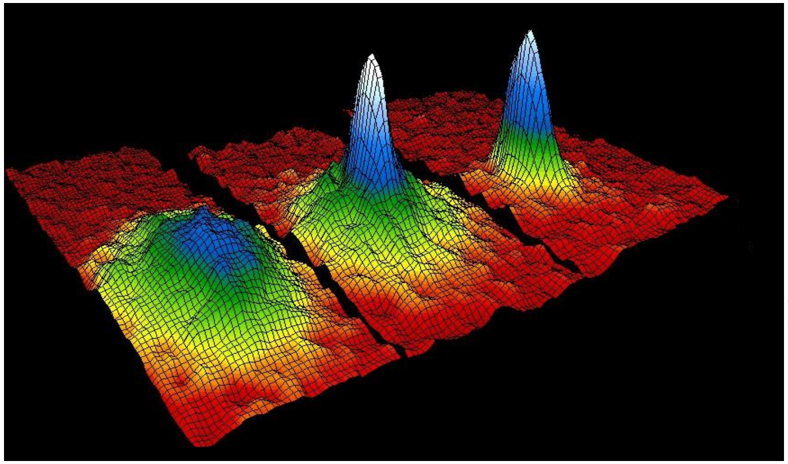
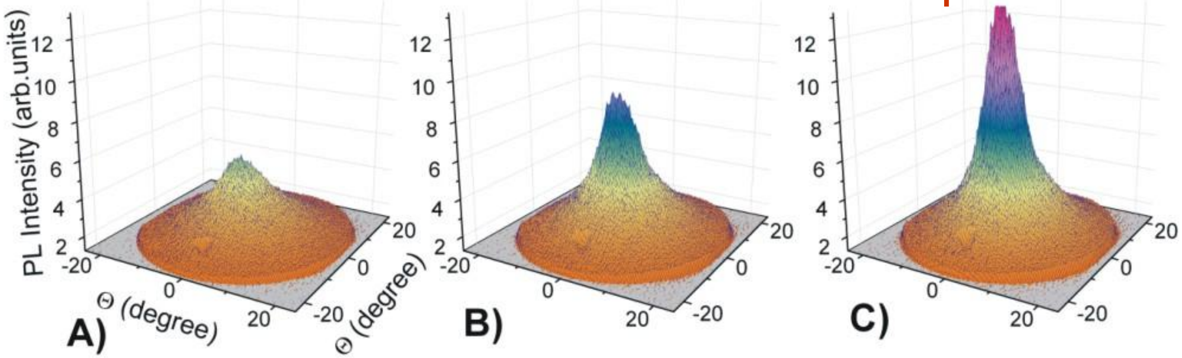


Rb atom condensate, JILA, Colorado

Momentum distribution of cold atoms

Momentum distribution of cold exciton-polaritons



Kasprzak et al Nature 443, 409 (2006)

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Characteristics of Bose-Einstein Condensation

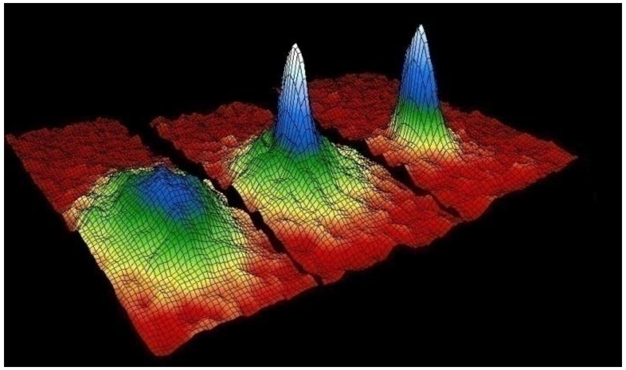
- Macroscopic occupation of the ground state
  - weakly interacting bosons

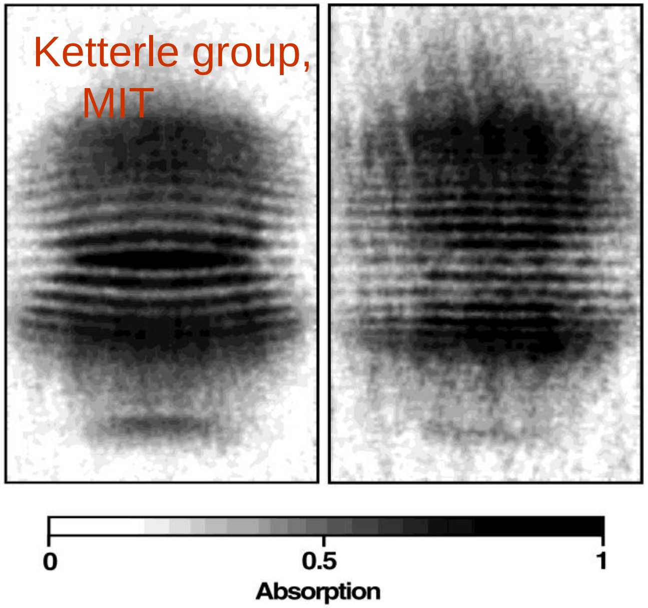
$$k_B T_0 \approx \frac{\hbar^2 n^{2/3}}{2m} \approx \frac{1.3}{r_s^2}\, Ryd$$

- 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





Ketterle group, MIT

Christiaan Huygens 1629-95

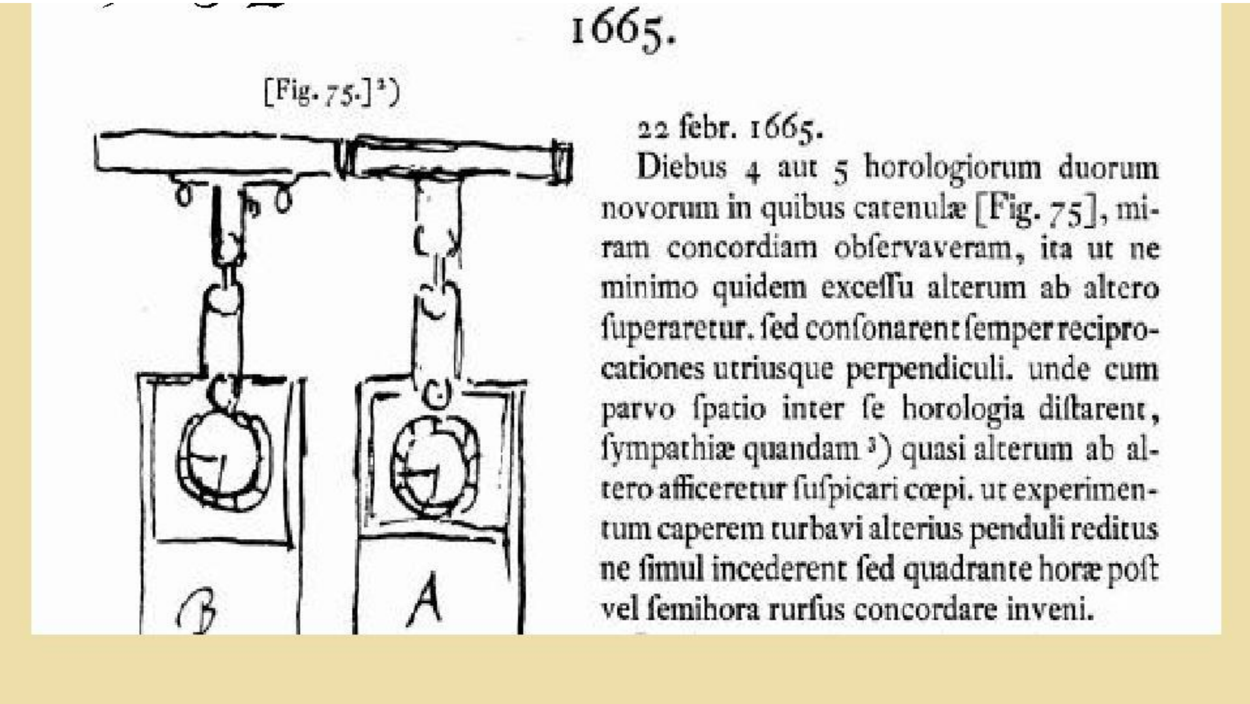
1656 – Patented the pendulum clock

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.

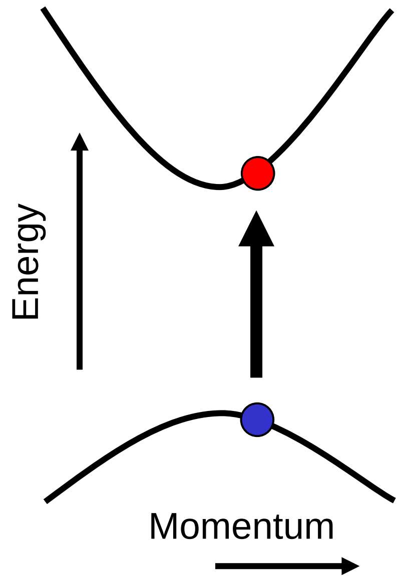
He deduced that effect came from “imperceptible movements” of the common frame supporting the clocks

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

Two metronomes on a cart

Making light atoms inside a solid

Excite electron-hole pair across a semiconductor band gap



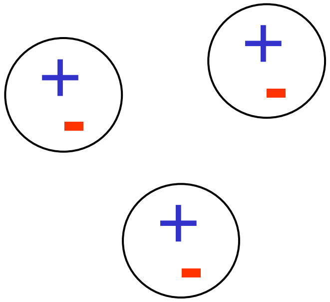
Bound by the screened Coulomb interaction to make an exciton

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

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

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

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

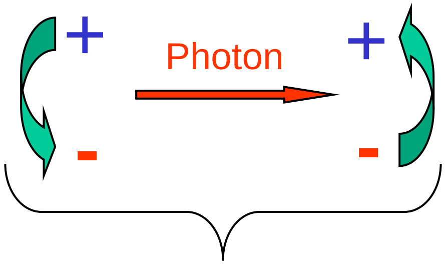


Excitons are the solid state analogue of positronium

In GaAs

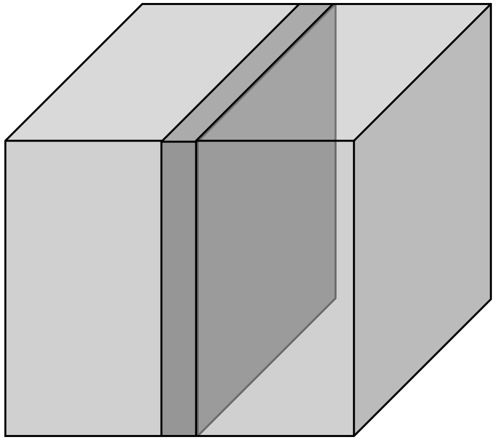
Binding energy ~ 5 meV

Bohr Radius ~ 7 nm



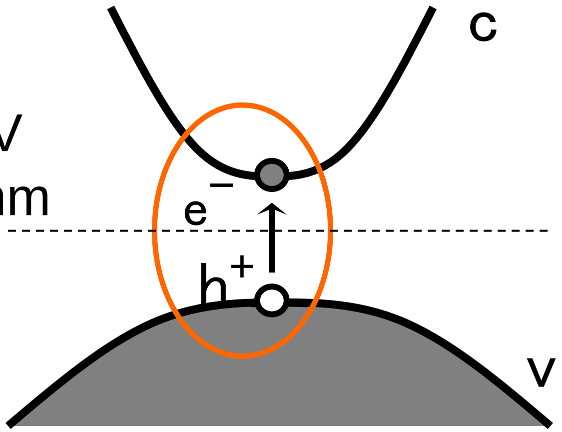
Combined coherent excitation is called a **polariton**

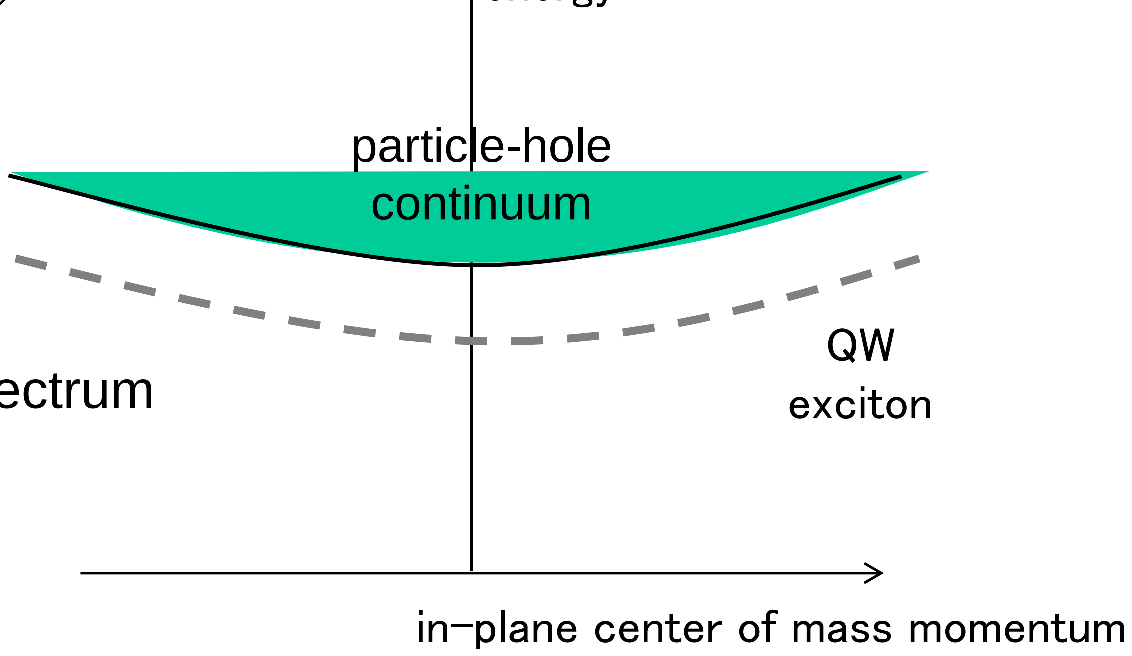
Quantum Well Excitons



QW

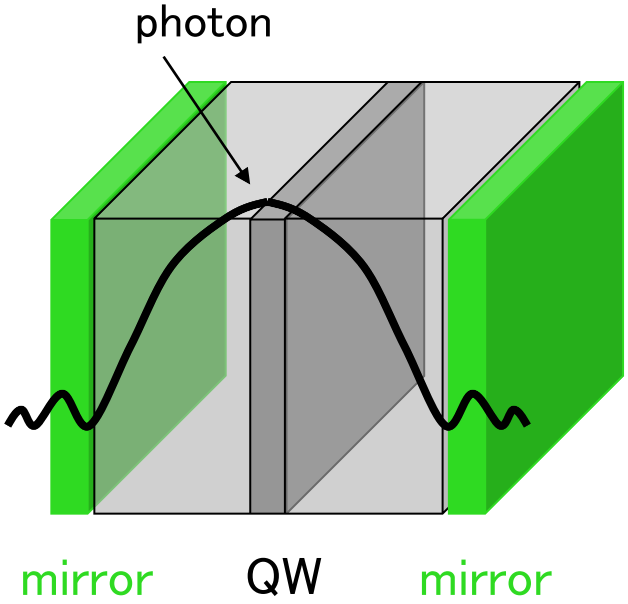
Weakly bound
electron-hole pair
EXCITON
Rydberg – few meV
Bohr Radius – few nm

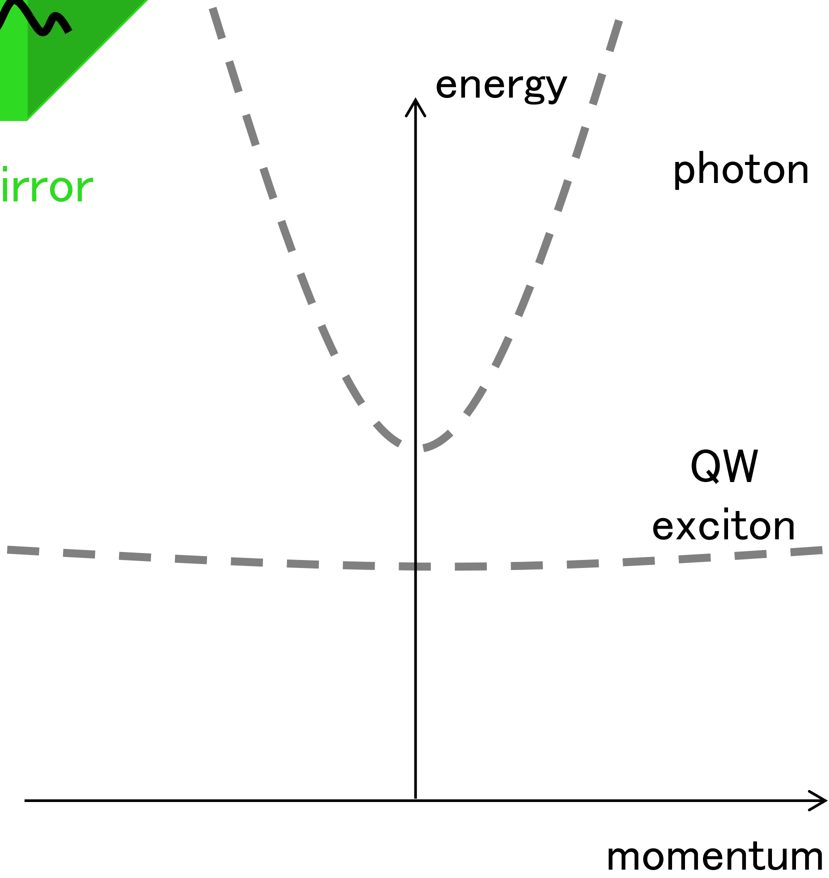


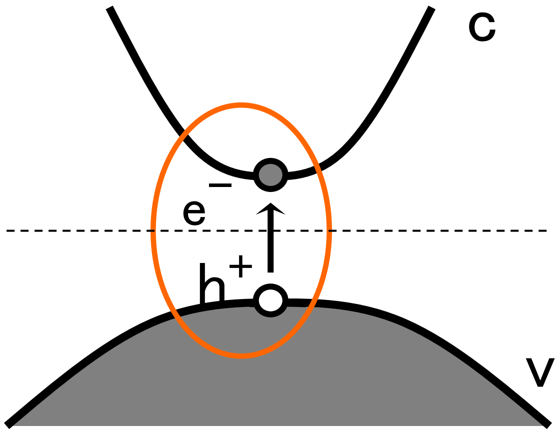


Excitation spectrum

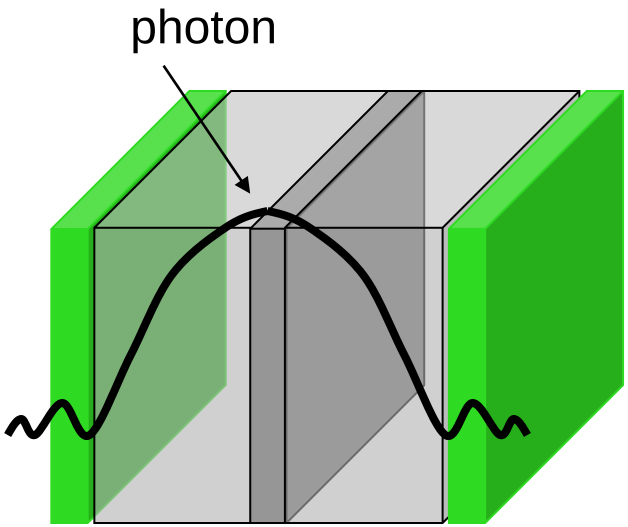
Excitons + Cavity Photons

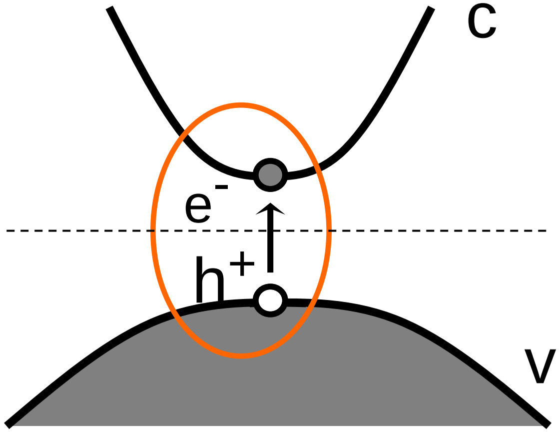


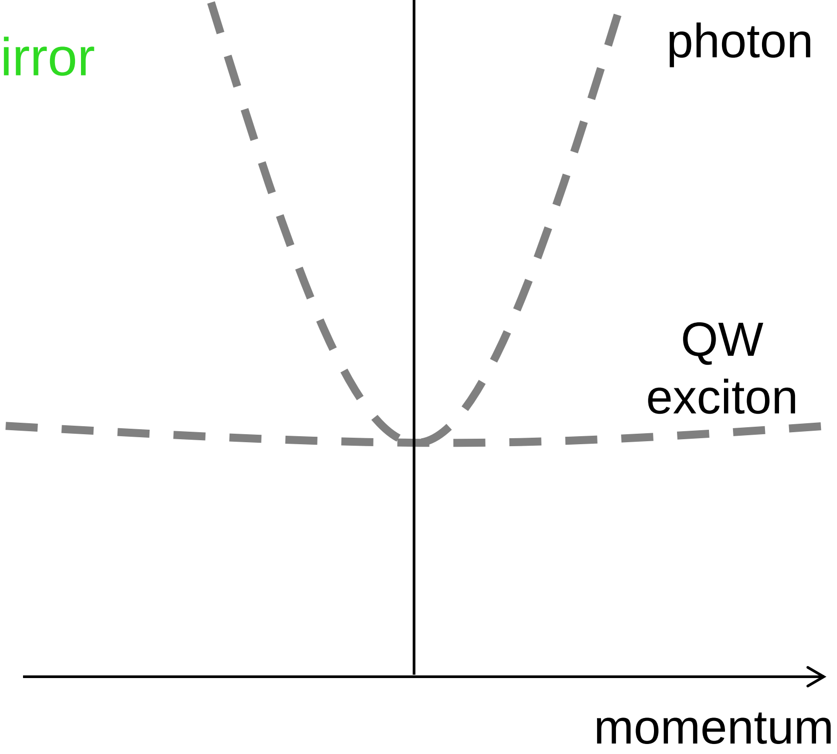




Excitons + Cavity Photons

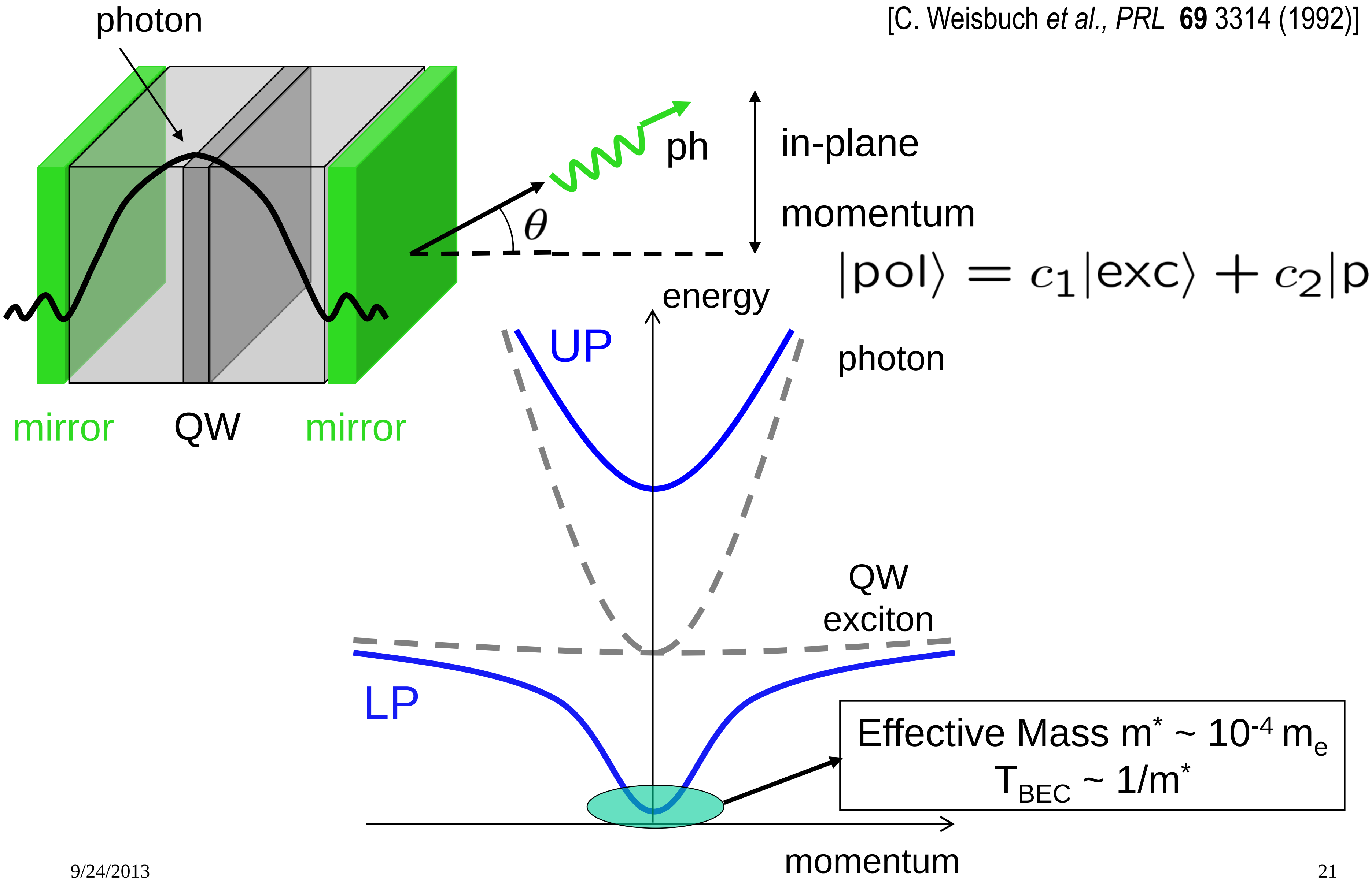






Polaritons: Matter-Light Composite Bosons

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

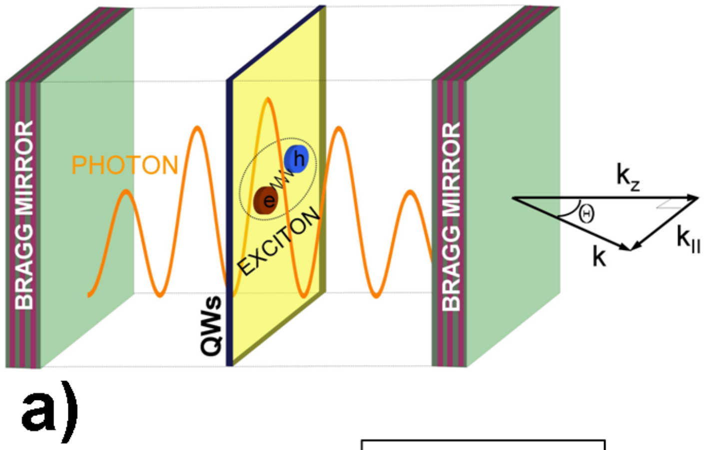


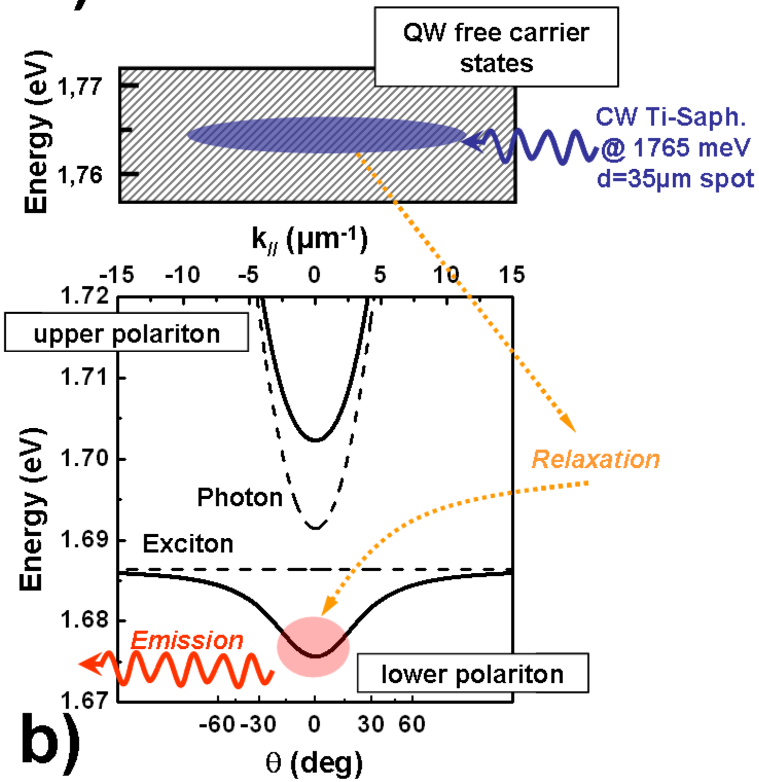
$$|\mathrm{pol}\rangle = c_1|\mathrm{exc}\rangle + c_2|\mathrm{ph}\rangle$$

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

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

Two metronomes on a cart





Microcavity polaritons

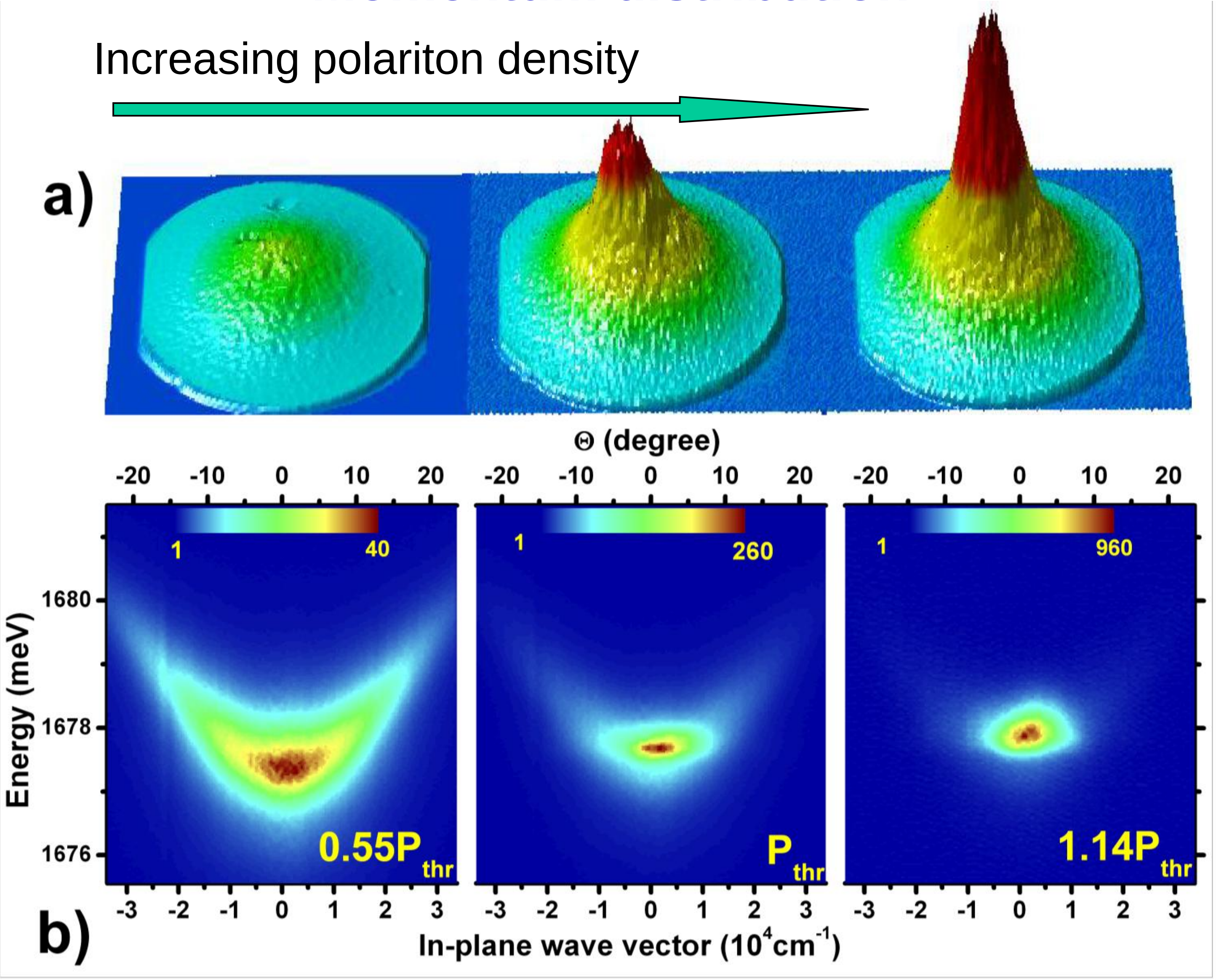
Experiments:
Kasprzak et al 2006
CdTe microcavities

Momentum distribution

Increasing polariton density

n(k)

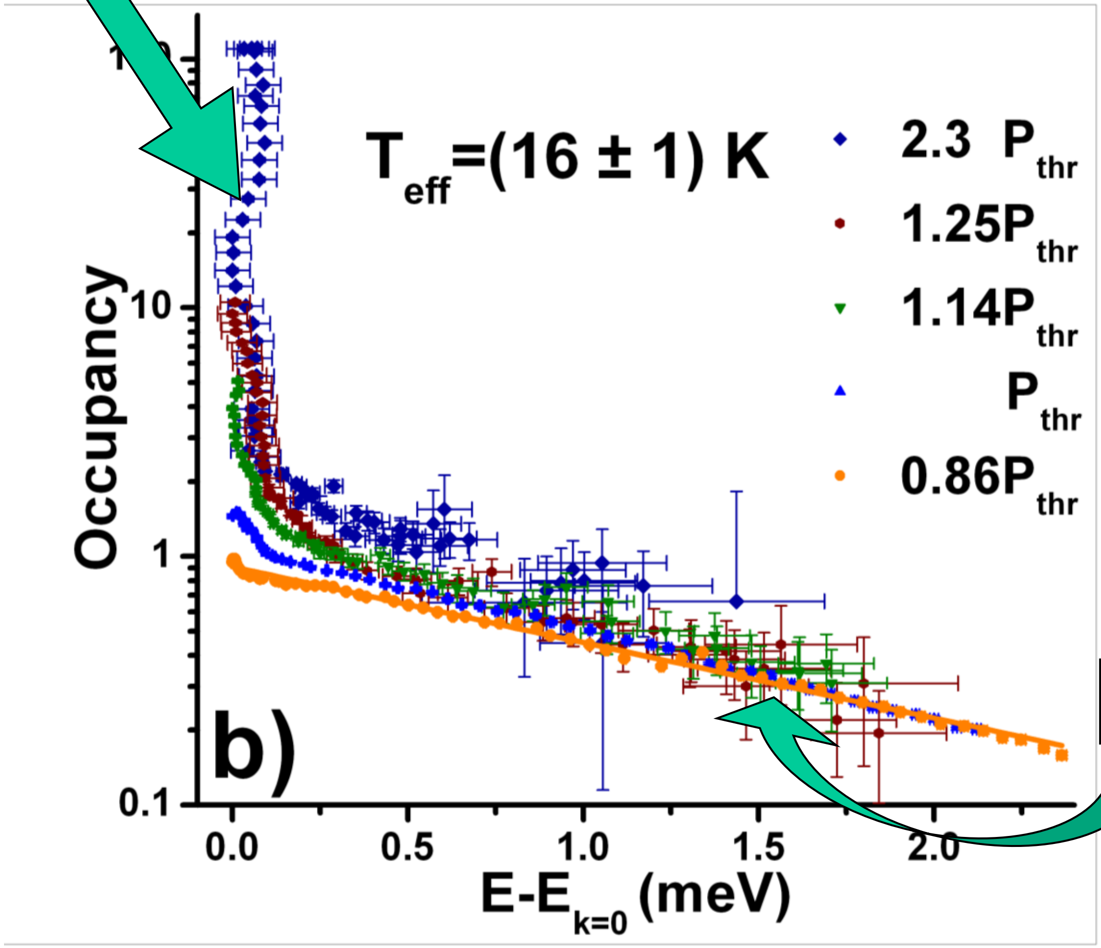
n(k, E)



Kasprzak et al Nature 2006

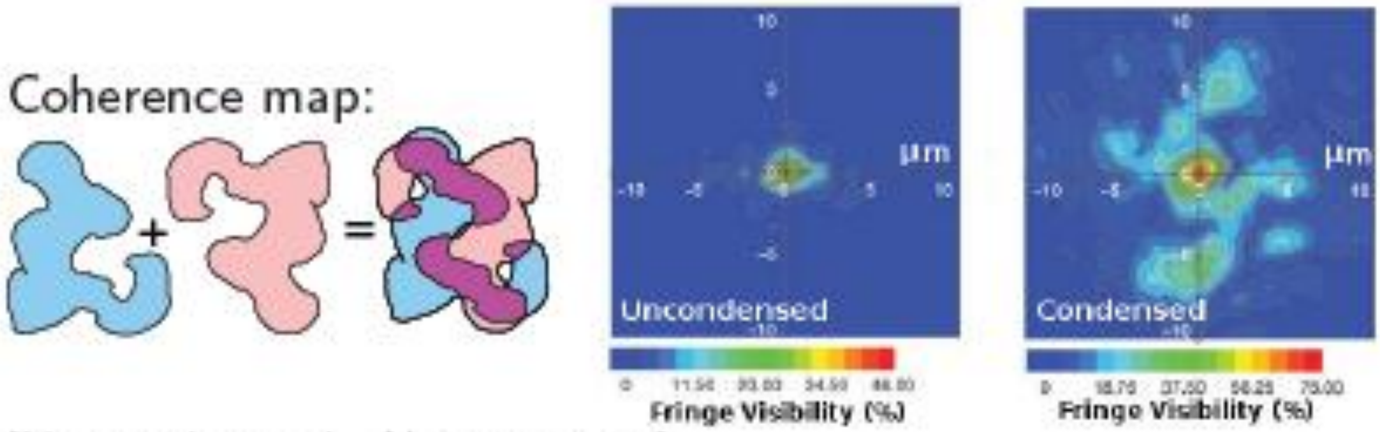
Distribution at varying density

Coherent(?) peak



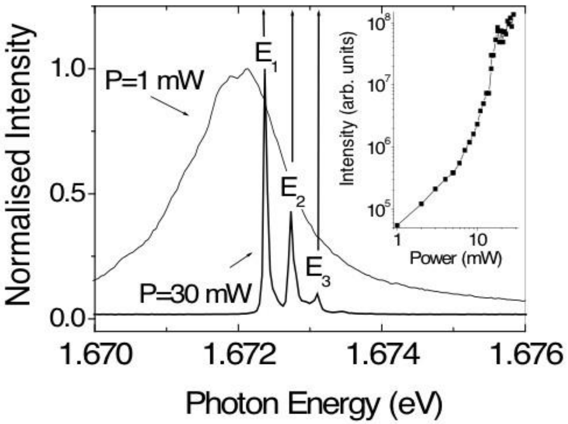
Maxwellian tail

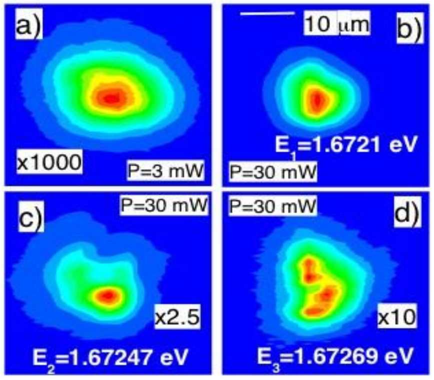
Coherence



[Kasprzak, et al., Nature, 2006]

Temporal coherence and multimode behavior

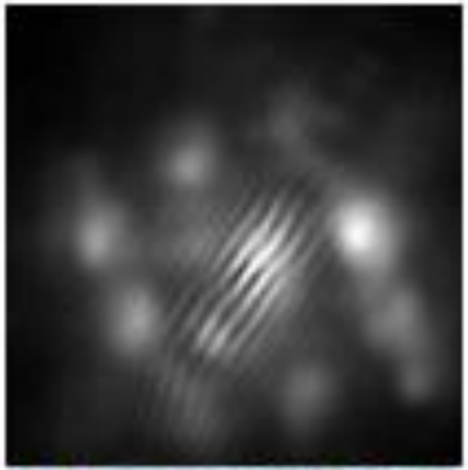


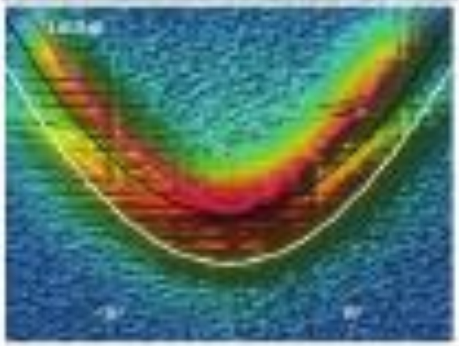


Love et al., PRL 2008

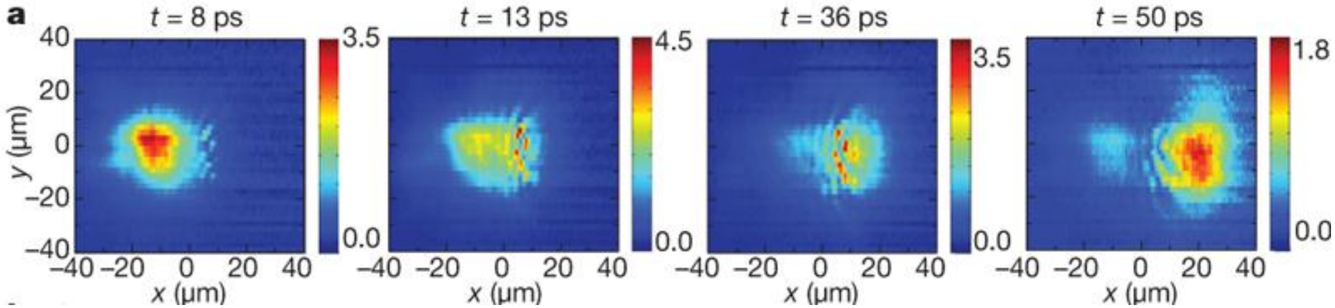
Other recent experiments

- 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)



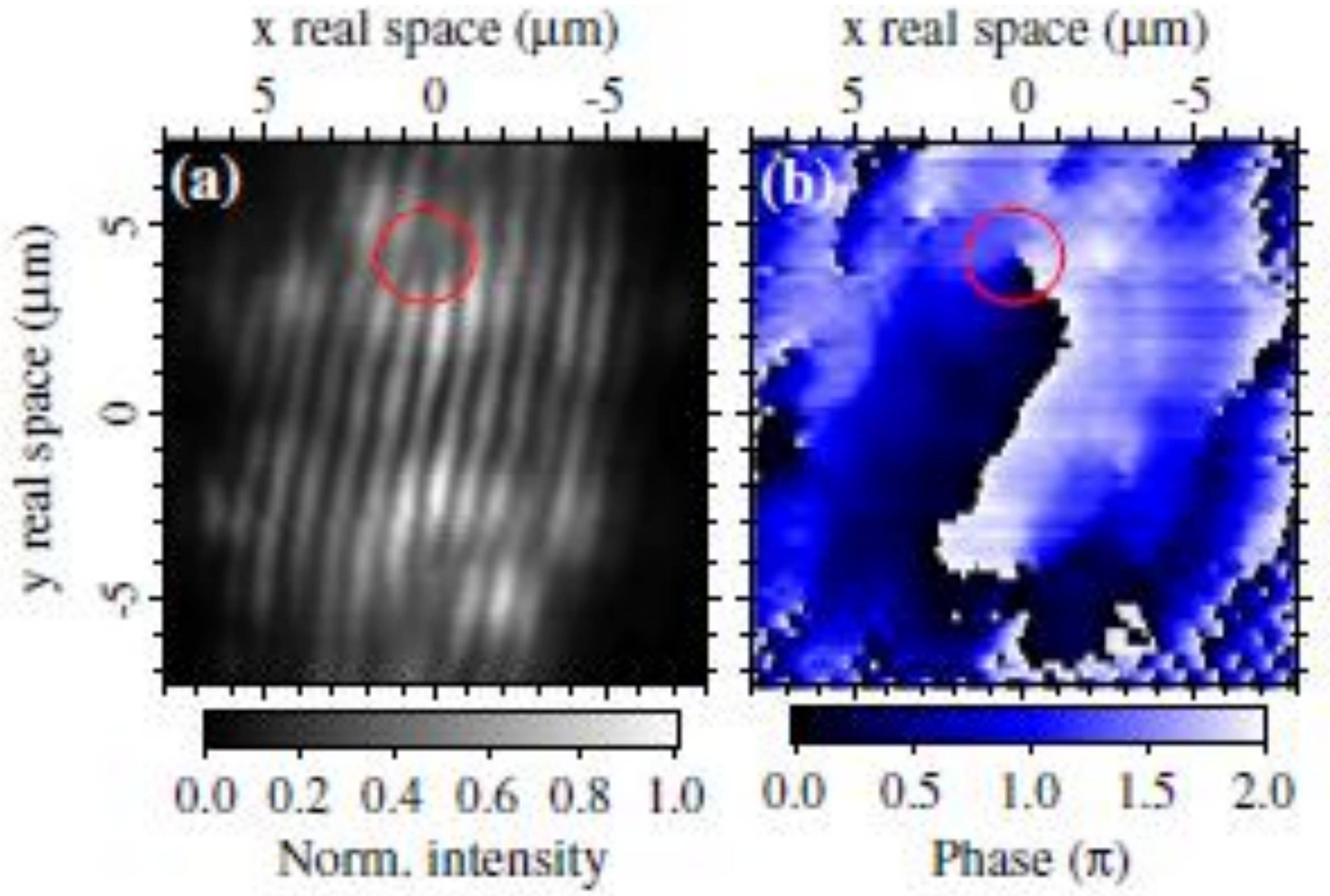


Photon superfluid is an electromagnetic cloaking device



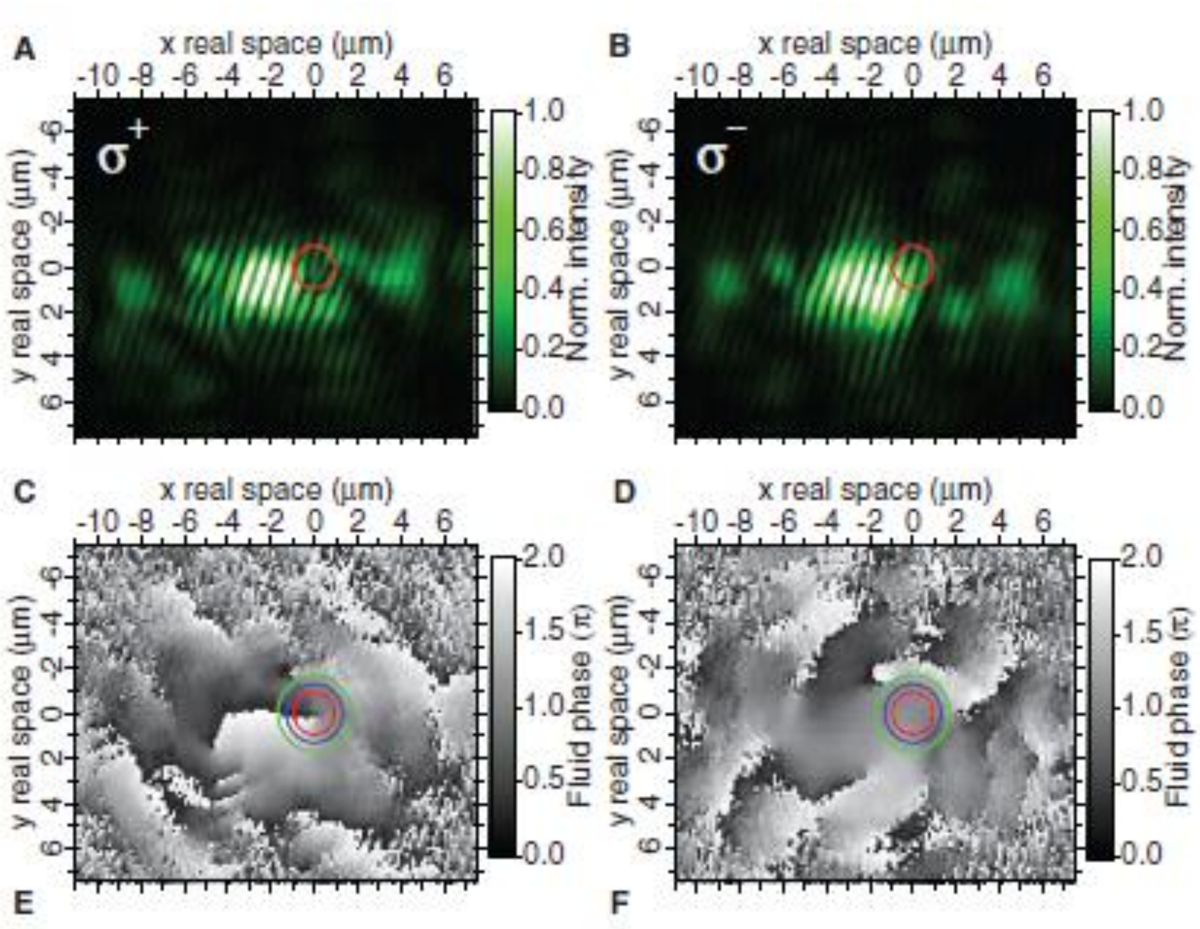
Vortex formation and dynamics

Interferogram



Lagoudakis et al. PRL 106, 115301 (2011)

Observation of Half-Quantum Vortices in an Exciton-Polariton Condensate
K. G. Lagoudakis *et al.*
Science **326**, 974 (2009);
DOI: 10.1126/science.1177980

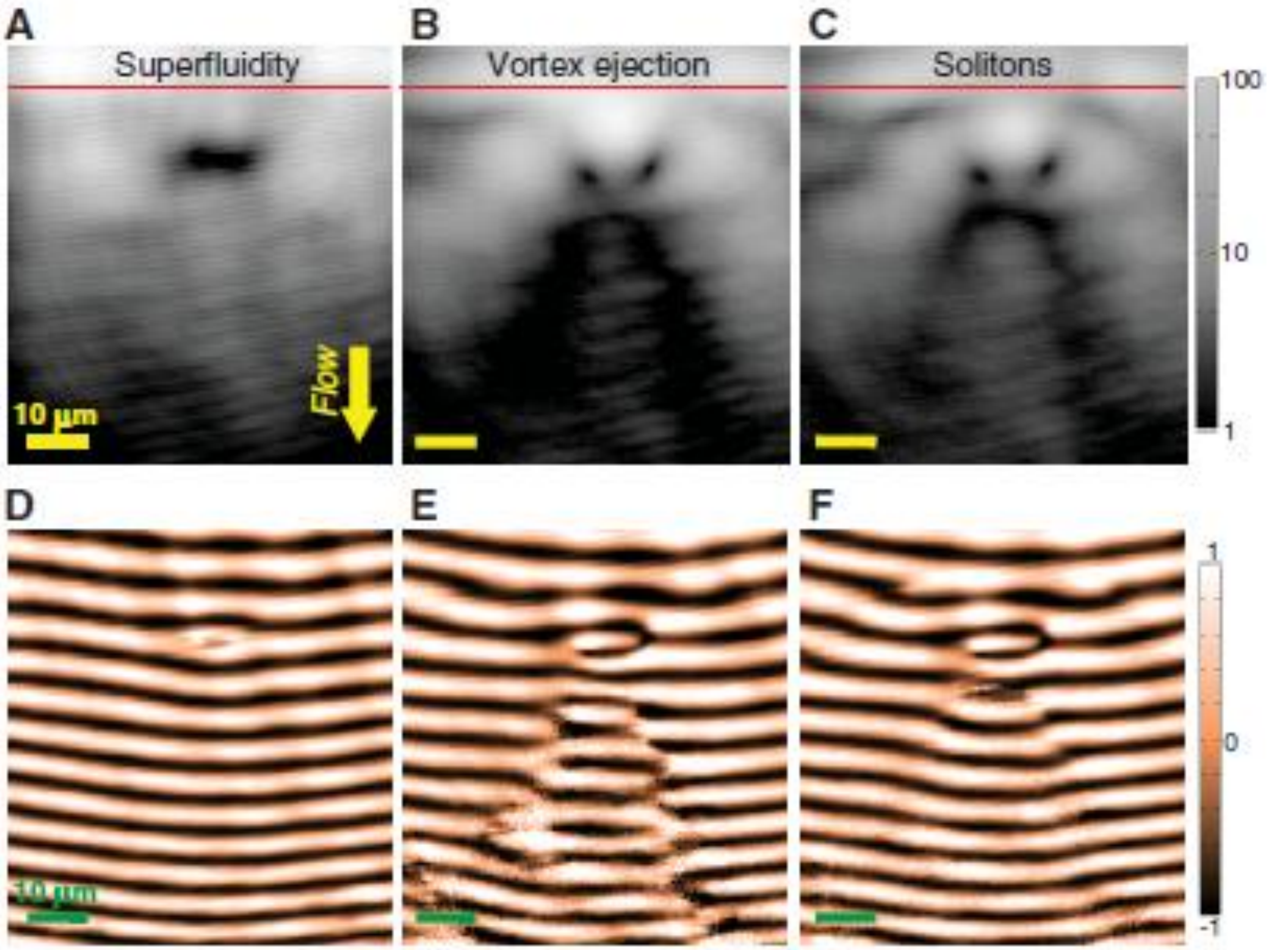


Polariton condensate is a spinor – polarisation degree of freedom (as in ^{3}He, triplet superconductors)

Half vortex in single circular polarisation possible

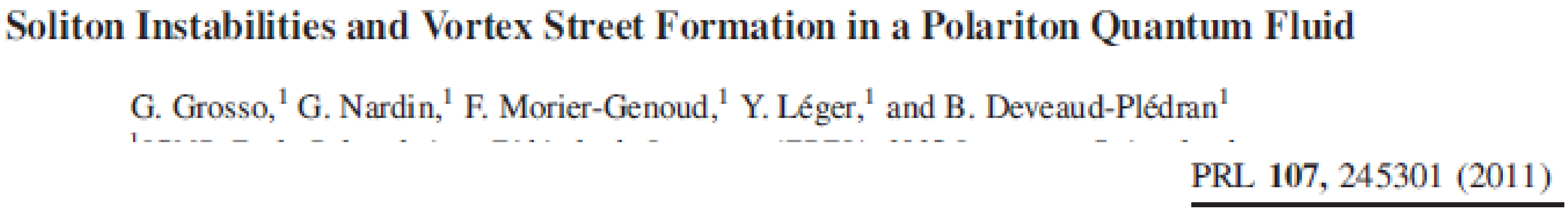
Superflow and vortex creation

Polariton Superfluids Reveal Quantum Hydrodynamic Solitons
A. Amo *et al.*
Science **332**, 1167 (2011);
DOI: 10.1126/science.1202307



High density → Lowdensity

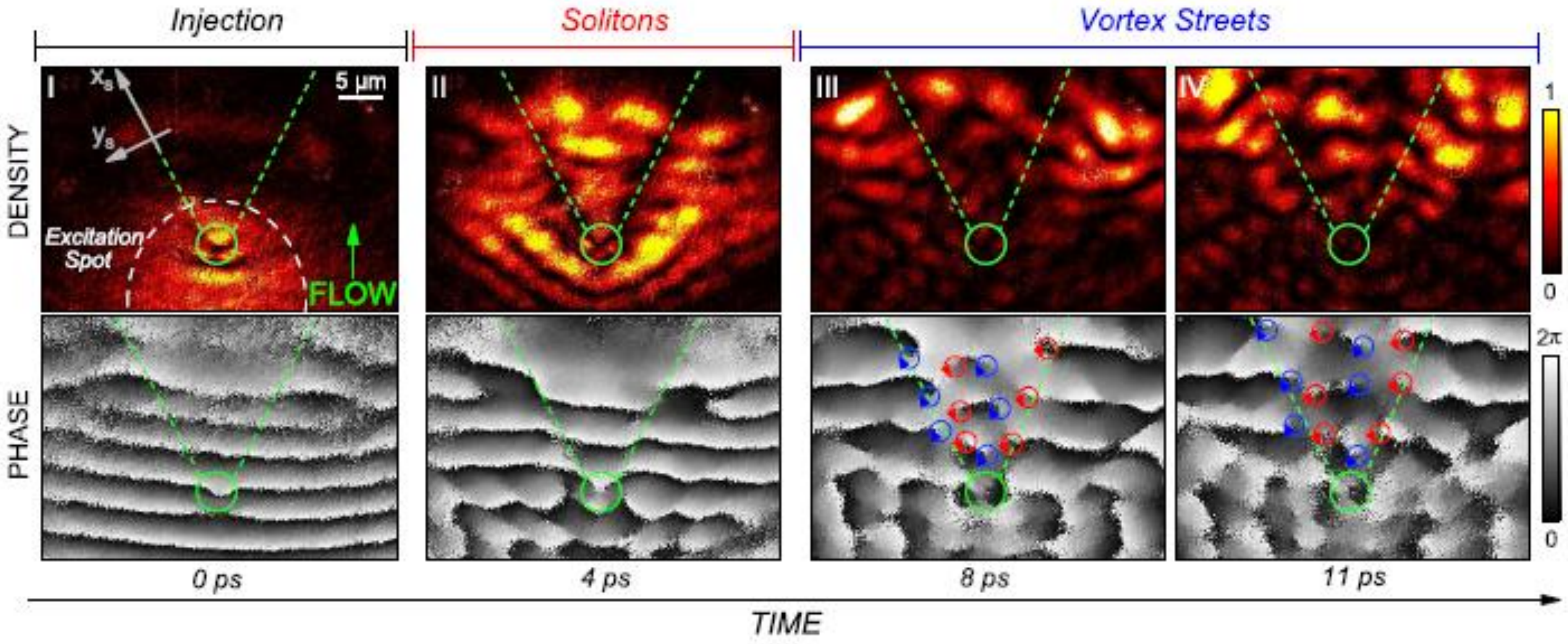
Vortex injection in superflow



Soliton Instabilities and Vortex Street Formation in a Polariton Quantum Fluid

G. Grosso,[1] G. Nardin,[1] F. Morier-Genoud,[1] Y. Léger,[1] and B. Deveaud-Plédran[1]

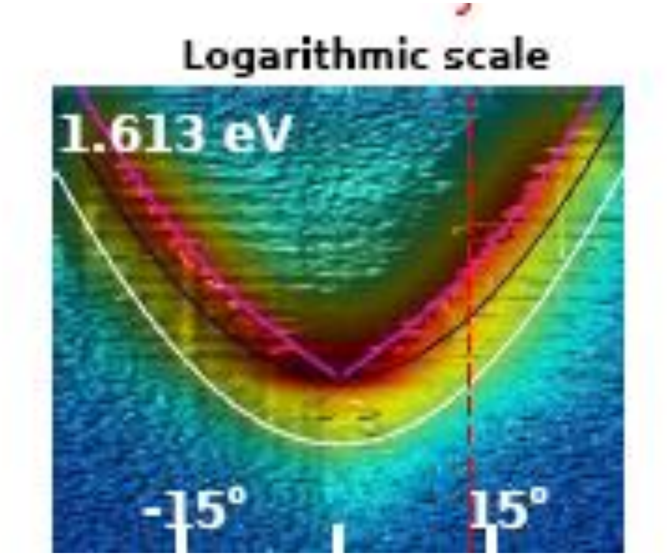
PRL **107,** 245301 (2011)



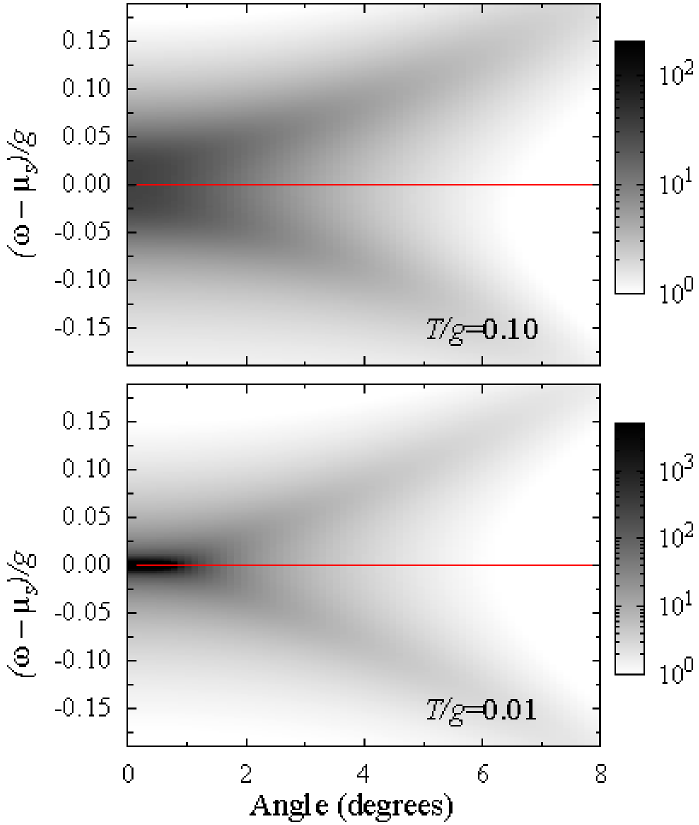
Quasiparticle spectrum above threshold

Observation of Bogoliubov spectrum

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



Including decay with effective temperature T modes become dissipative at long wavelengths



Szymanska et al, PRB 75, 195331 (2007)

Power-law decay of the spatial correlation function in exciton-polariton condensates

Georgios Roumpos[a,1,2], Michael Lohse[a,b], Wolfgang H. Nitsche[a], Jonathan Keeling[c], Marzena Hanna Szymańska[d,e], Peter B. Littlewood[f,g], Andreas Löffler[h], Sven Höfling[h], Lukas Worschech[h], Alfred Forchel[h], and Yoshihisa Yamamoto[a,i]

PNAS | April 24, 2012 | vol. 109 | no. 17 | 6467–6472

Short distance

measures "particle like" excitations

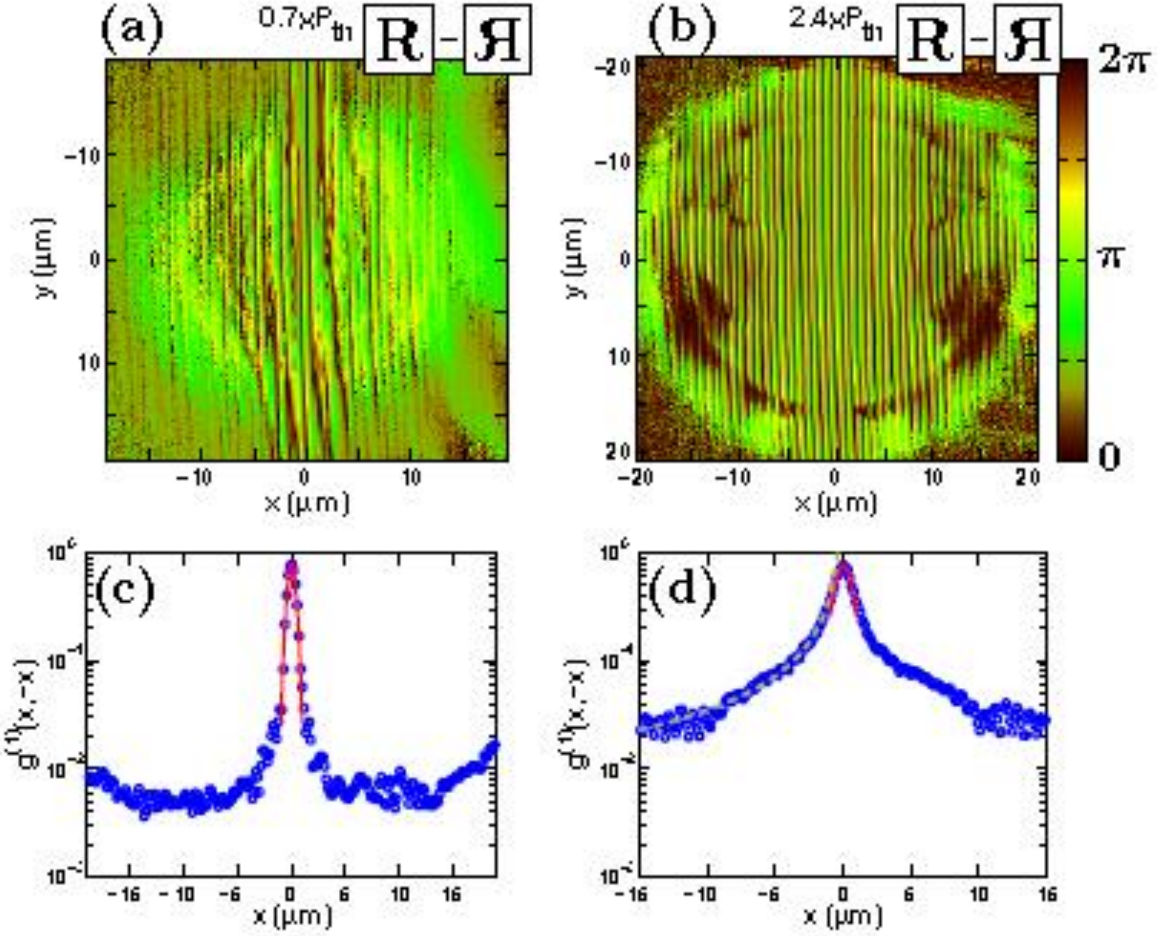
occupation at large momentum/energy –

gaussian with effective "temperature"

Long distance

measures order parameter fluctuations

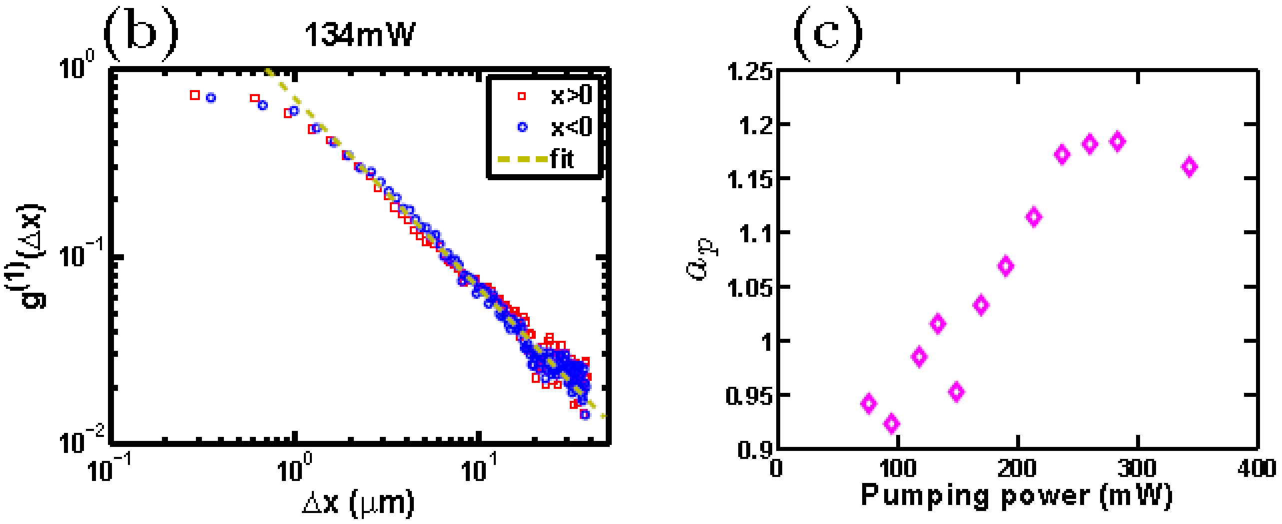
approximate power law



$$g_1(r_1, r_2, ; \tau) = \left\langle \psi^\dagger(r_1, t+\tau)\psi(r_2, t) \right\rangle_t$$

Power law correlation due to non-thermal fluctuations

Roumpos et al 2012



- Experiment shows exponent ~ 1, increasing with pump power
- BKT? Exponent < ¼, decreasing on going further into ordered state

$$a_p = mk_BT/2\pi\hbar^2 n_s \leq \frac{1}{4}$$

- Distribution is not thermal, inherited from pumping
- Non-equilibrium condensate with dynamic phase fluctuations but frozen vortices --- “shaken but not stirred”

What’s new about a polariton condensate ?

- Composite particle – mixture of electron-hole pair and photon
- Extremely light mass (~ 10^{-5} m_e) means that polaritons are large, and overlap strongly even at low density
  - crossover from dilute gas BEC to coherent state, eventually to plasma
- Two-dimensional physics
  - Berezhinski-Kosterlitz-Thouless transition ?
- Polariton lifetime is short
  - Non-equilibrium, pumped dynamics leads to decoherence on long length scales

Excellent description by damped, driven Gross-Pitaevskii equation

Wouters and Carusotto, Phys. Rev. Lett. 99, 140402 (2007)

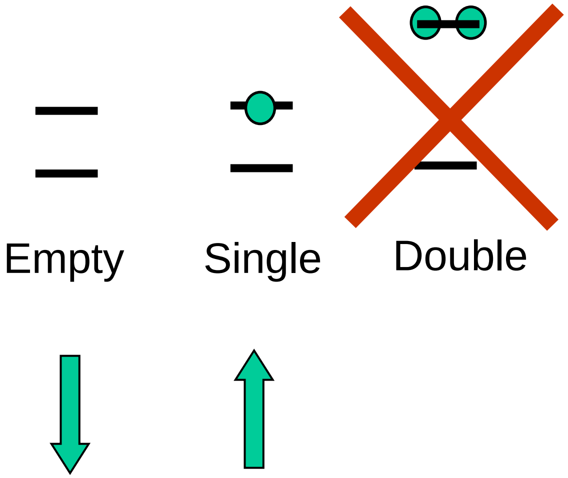
Derivable from microscopic theory [see e.g. Keeling et al Semicond. Sci. Technol. 22 R1 (2007)]

Can prepare out-of-equilibrium condensates

– Quantum dynamics of many body system

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

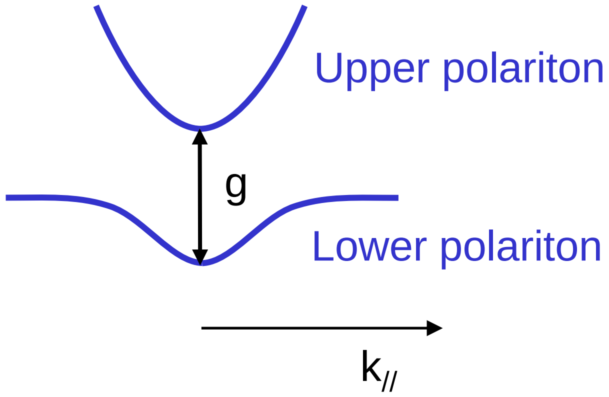
Mean field theory – i.e. BCS coherent state – expected to be good approximation

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

Transition temperature depends on coupling constant

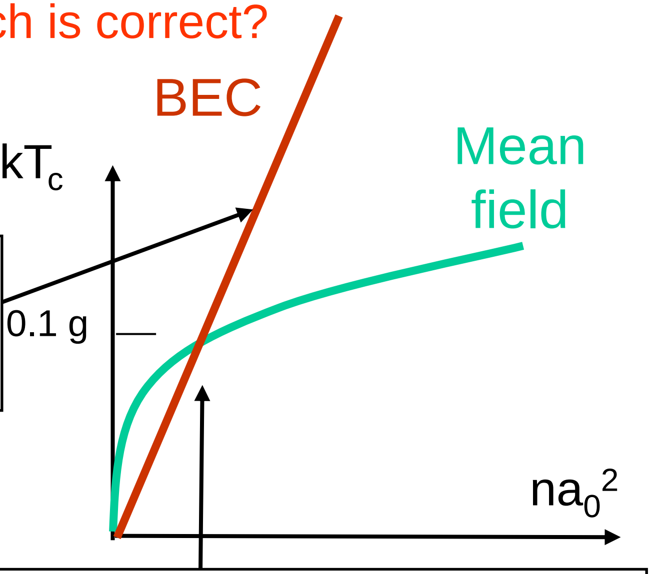
Beyond mean field: Interaction driven or dilute gas?

- 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

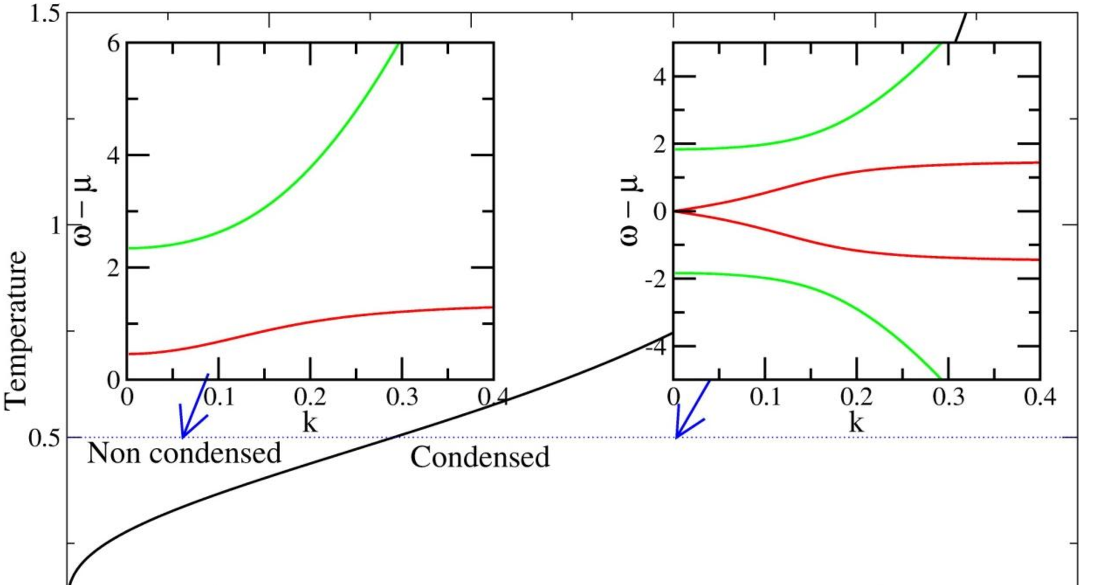
Dilute gas BEC only for excitation levels < 10^9 cm^{-2} or so

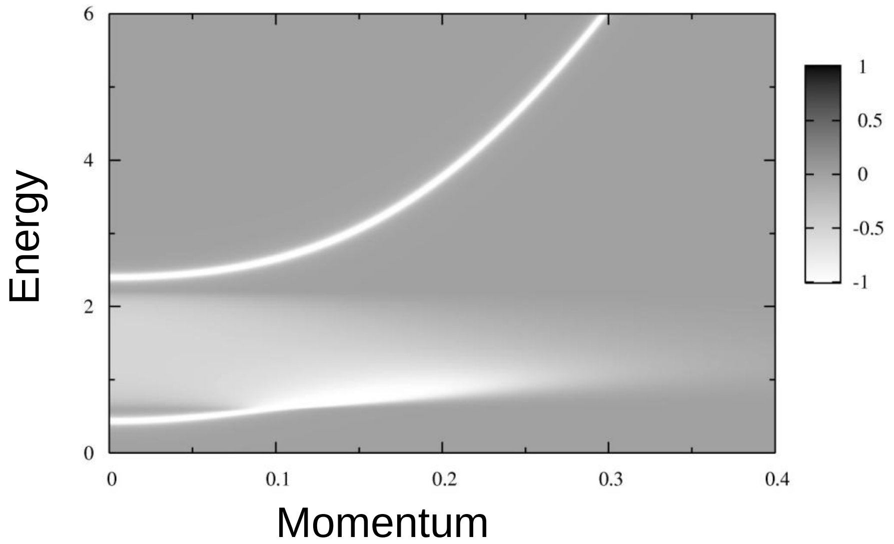
A further crossover to the plasma regime when $na_B^2 \sim 1$

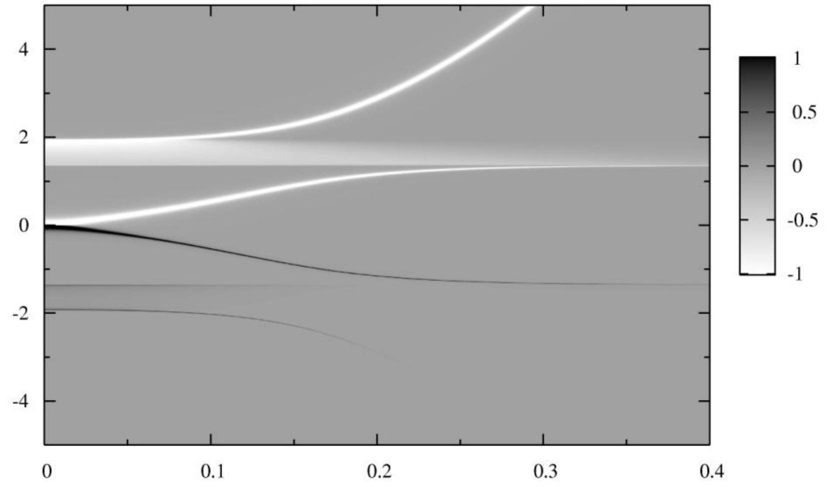
2D polariton spectrum

Keeling et al PRL 93, 226403 (2004)

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

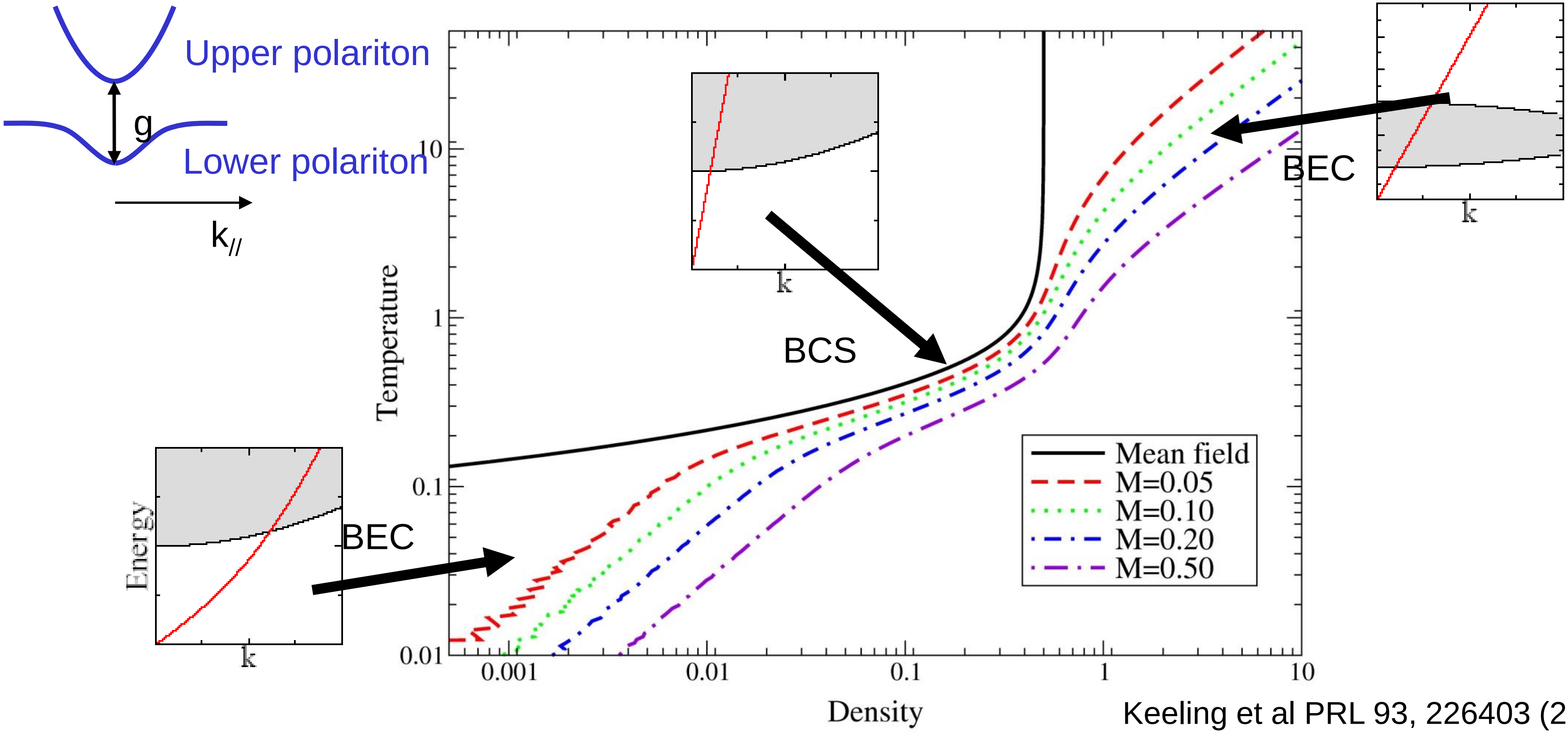






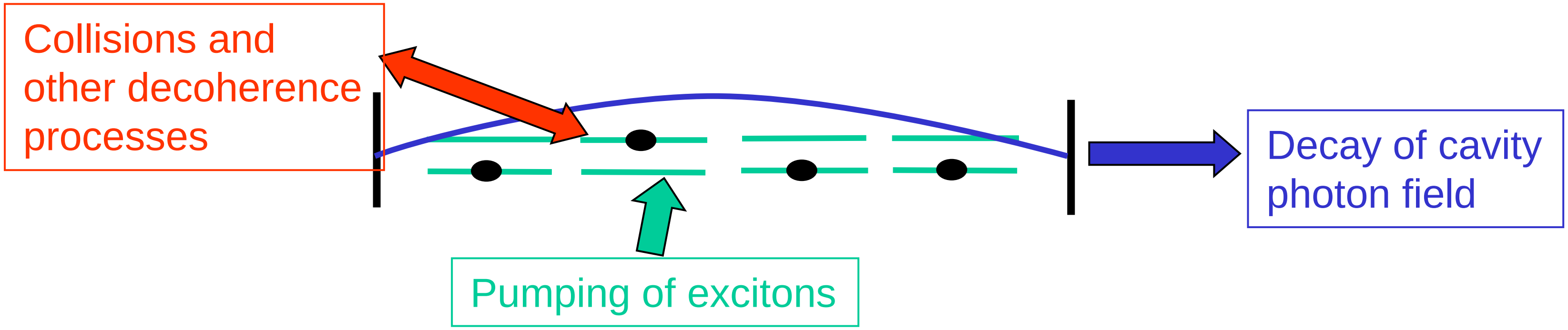
Phase diagram

- 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)

Decoherence and the laser



Collisions and other decoherence processes

Decay of cavity photon field

Pumping of excitons

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)

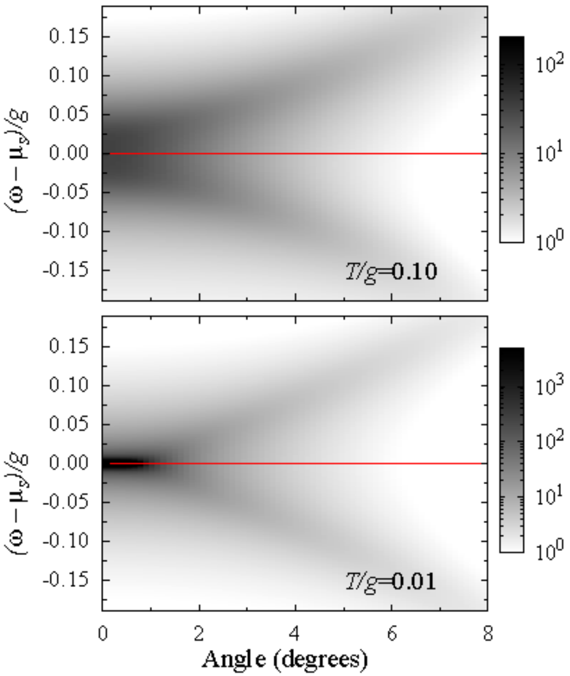
Damped, driven Gross-Pitaevski equation

Wouters and Carusotto, Phys. Rev. Lett. 99, 140402 (2007)

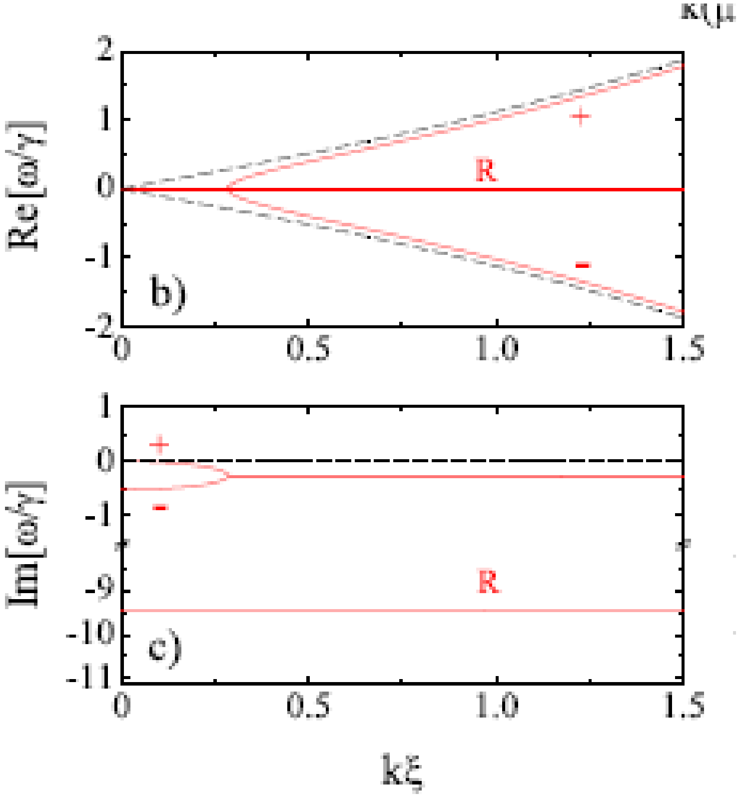
$$i\frac{\partial\psi}{\partial t} = \left\{-\frac{\hbar\nabla^2}{2m_{LP}} + \frac{i}{2}\left[R(n_R) - \gamma\right] + g\,|\psi|^2 + 2\tilde{g}\,n_R\right\}\psi.$$

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

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

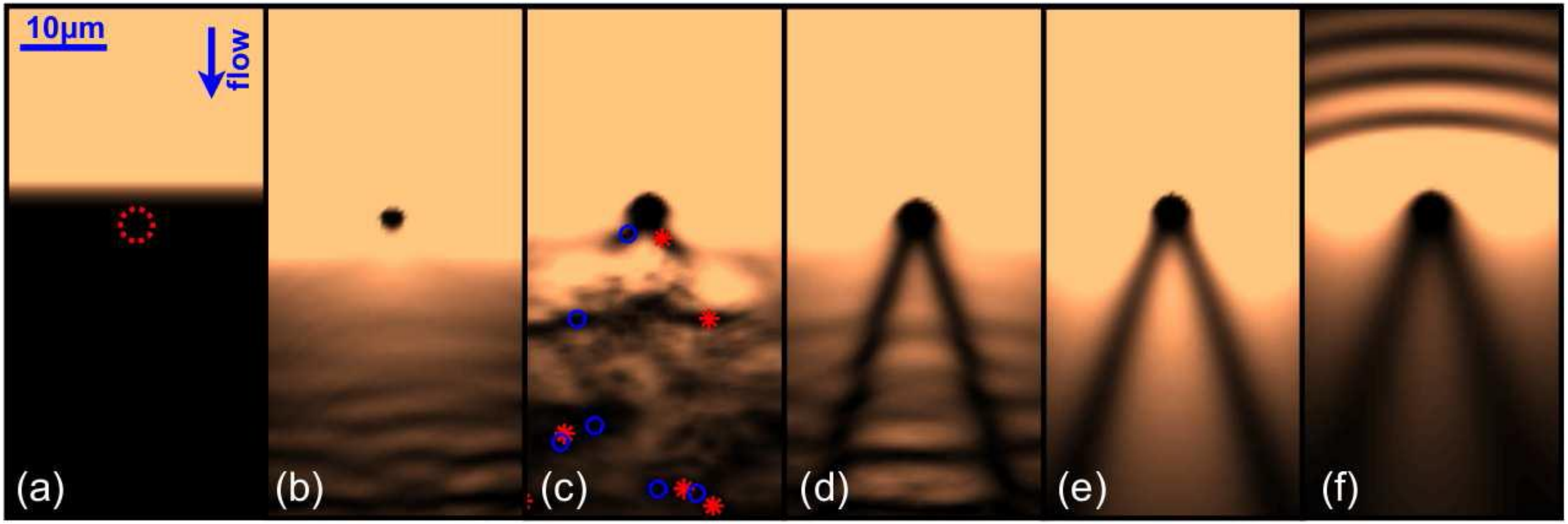


Szymanska et al PRL **96**, 230602 (2006)



Modelling of Superflow

Superflow **Vortices** **Solitons** **Cerenkov**



Pigeon, Carusotto, and Ciuti, Physical Review B 83 (2011) 144513

Quantum dynamics

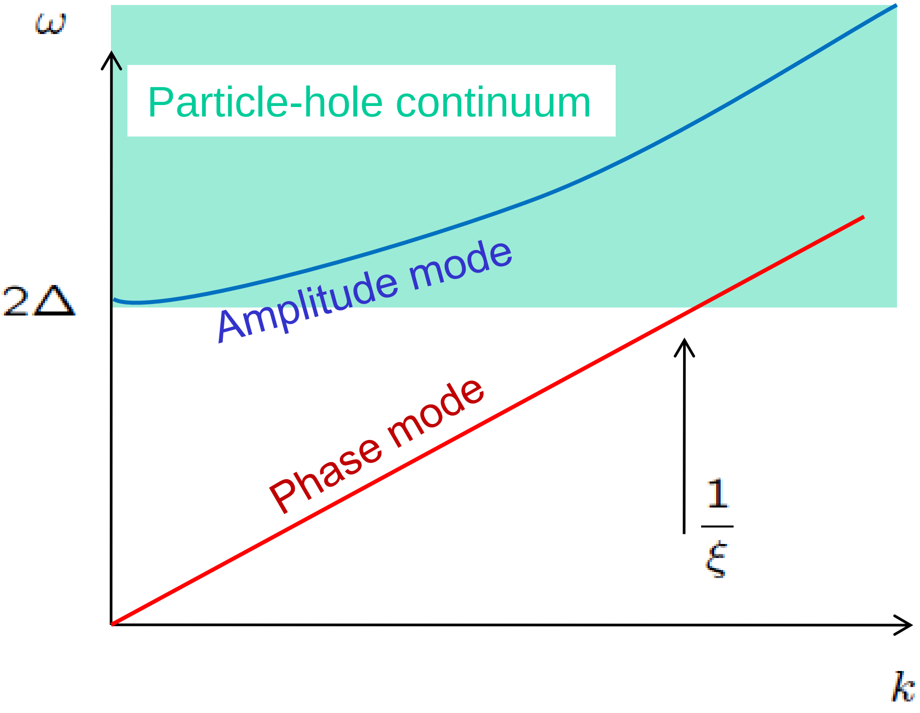
On time scales < few psec, not in thermal equilibrium

Coupling to light allows driven dynamics

Collective dynamics

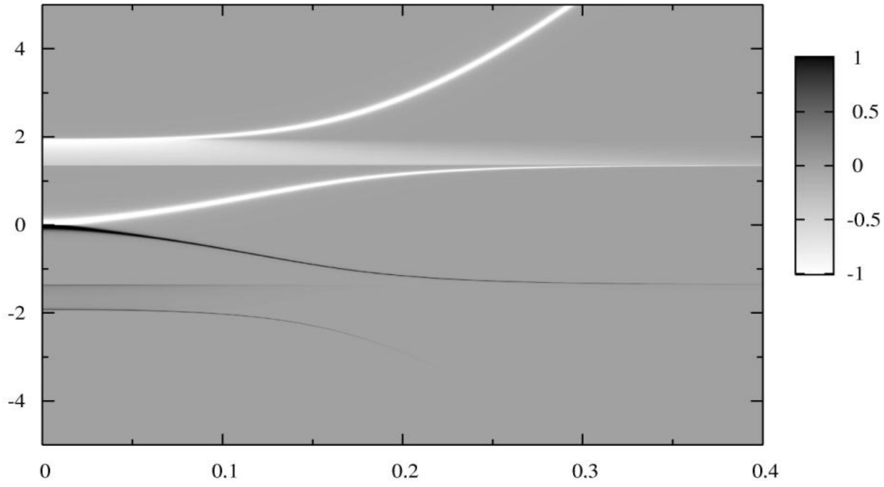
- Use pump pulse to prepare non-equilibrium population
- Follow dynamics (typically on time scales faster than dephasing times)
- Similar to a “quantum quench” – where parameters of the Hamiltonian are abruptly changed
- Project an initial state onto the exact (time-dependent) eigenstates:
  - If the perturbation is small, expect to see a linear superposition of a few excitations – separate into single-particle like, and collective (e.g. Phase/amplitude)
  - Large?

Compare condensed polaritons to superconductor



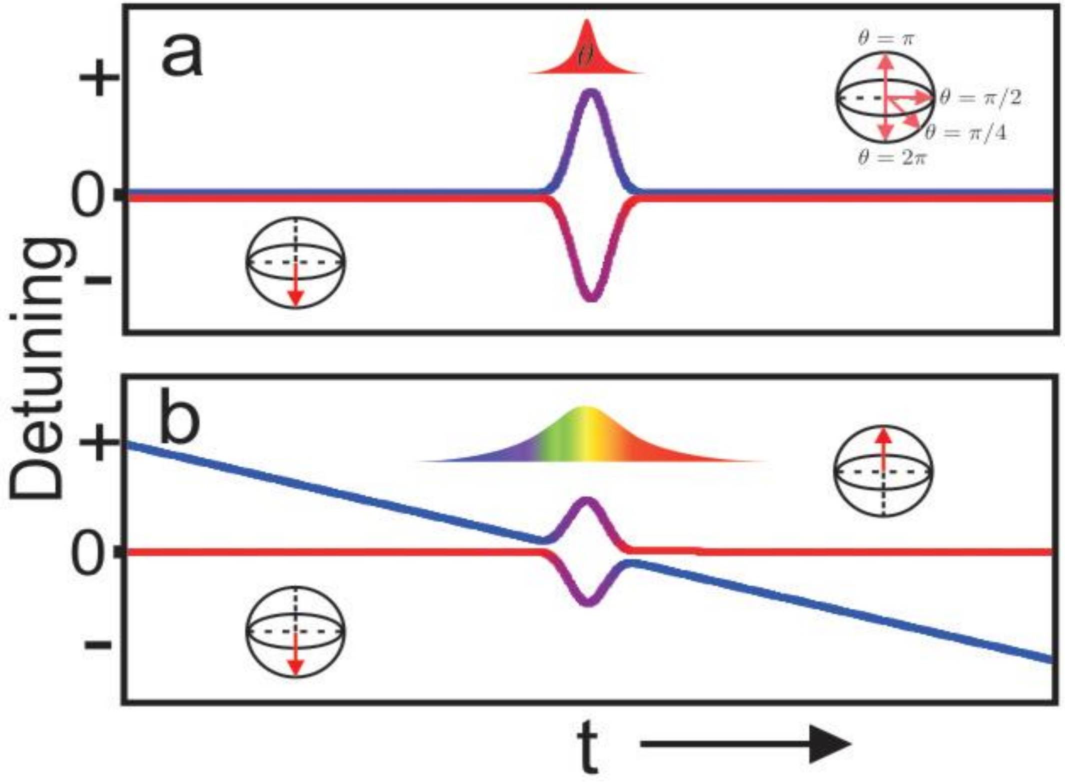
NB $2\Delta/E_F \ll 1; \quad k_F\xi \ll 1$

Keeling 2006



Phase mode – LP
Amplitude mode – UP
Continuum – inhom. broadening

Adiabatic Rapid Passage on two level system

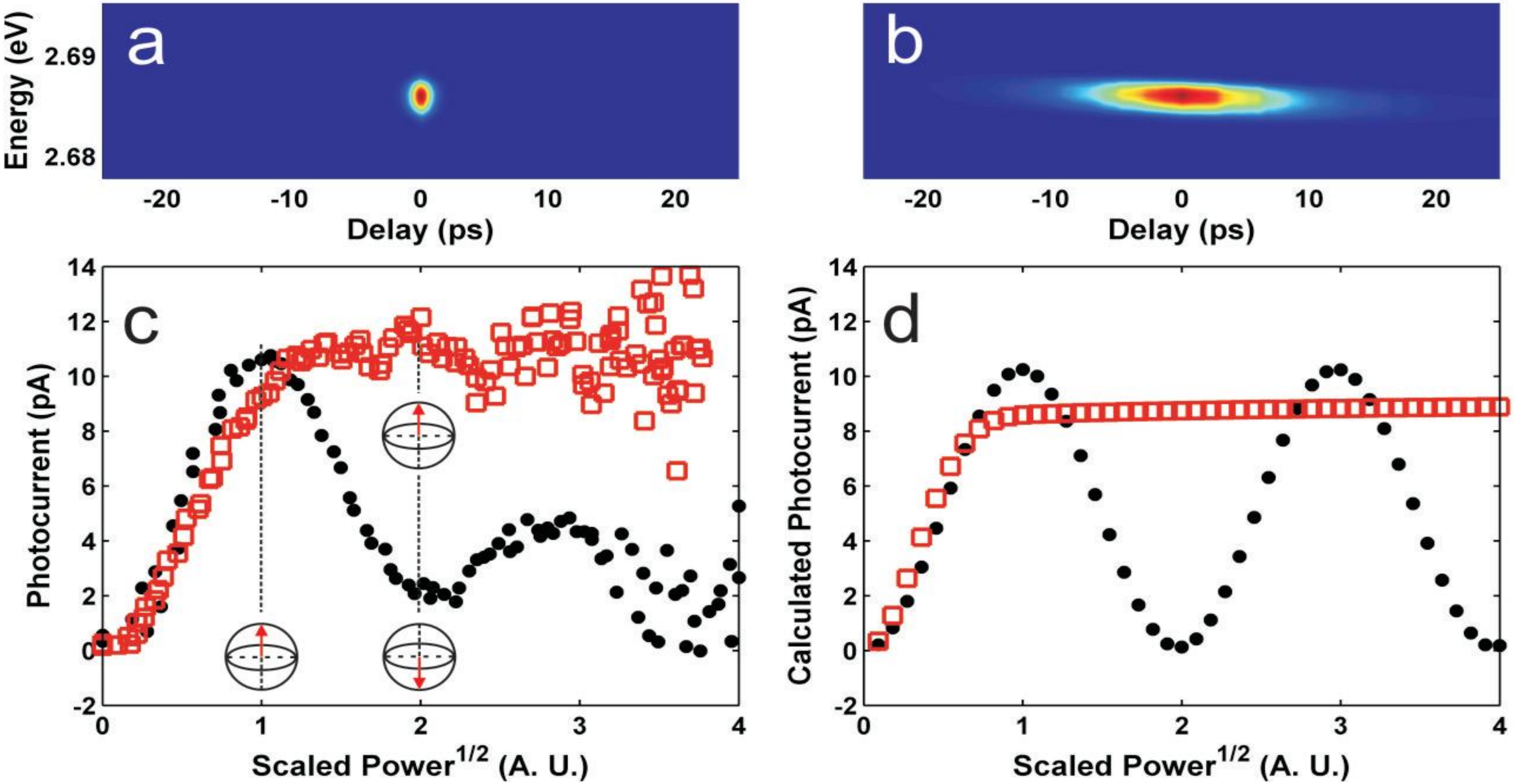


Conventional Rabi flopping requires accurate pulse areas

- Chirped pulse produces anticrossing of levels
- Weight of wavefunction transfers from one state to the other
- Robust population inversion independent of pulse area

Single Dot Experiment

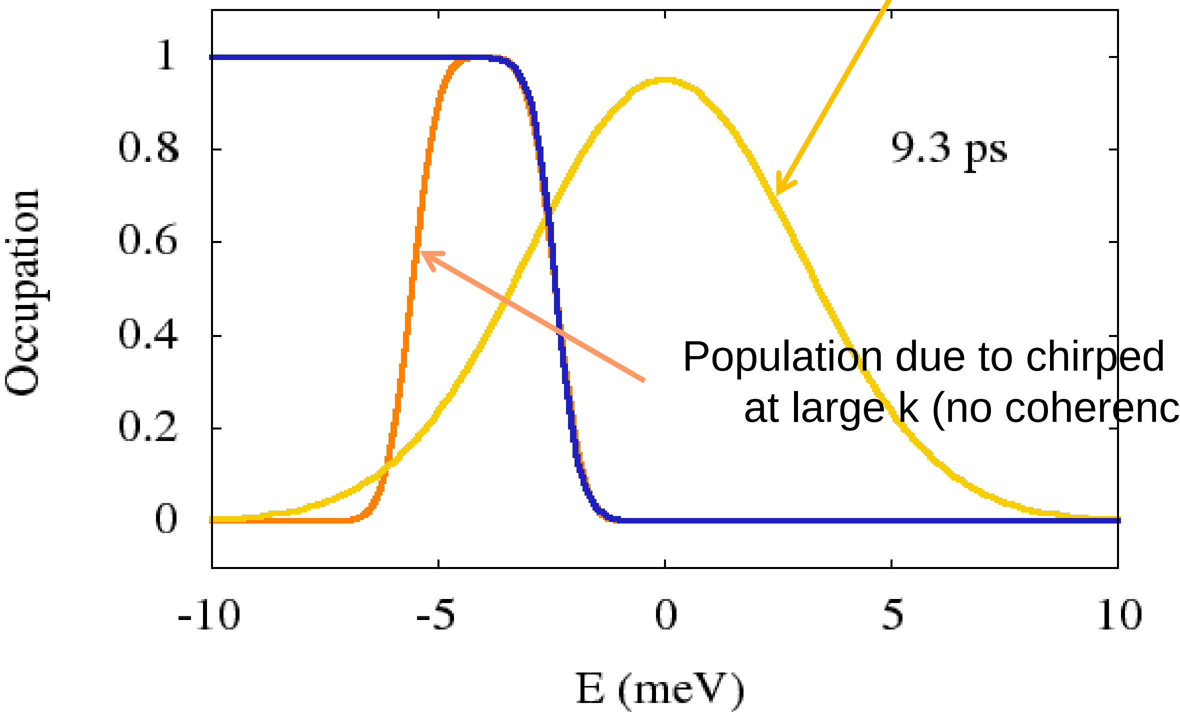
Wu et al, PRL 106 067401 (2011)



Controlled pumping of a many-particle state

Paul Eastham and Richard Phillips PRB 79 165303 (2009)

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

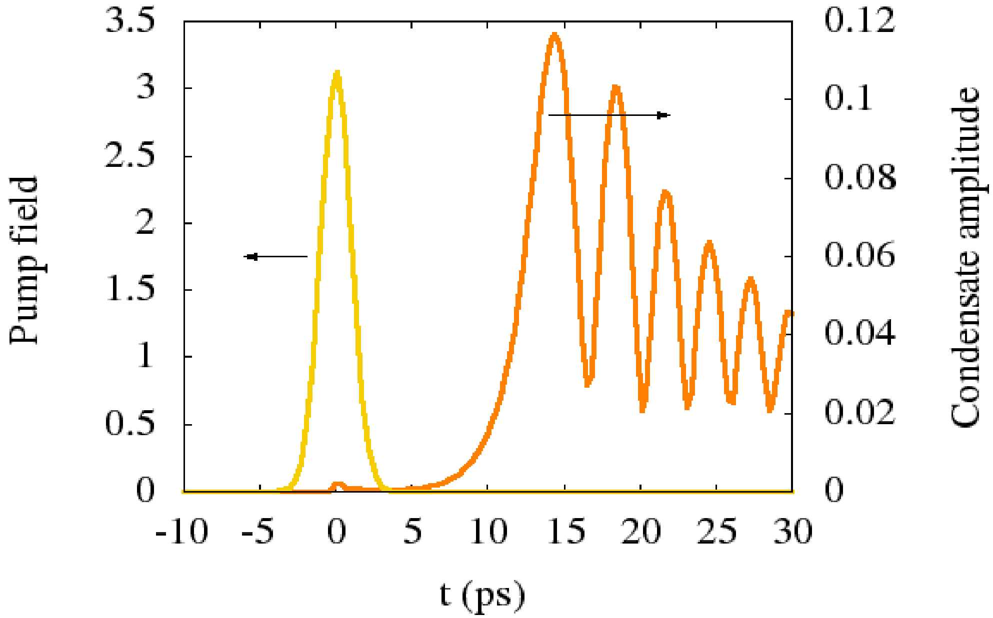


Population due to chirped pulse
at large k (no coherence)

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

Spontaneous dynamical coherence

Paul Eastham and Richard Phillips PRB 79 165303 (2009)



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

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

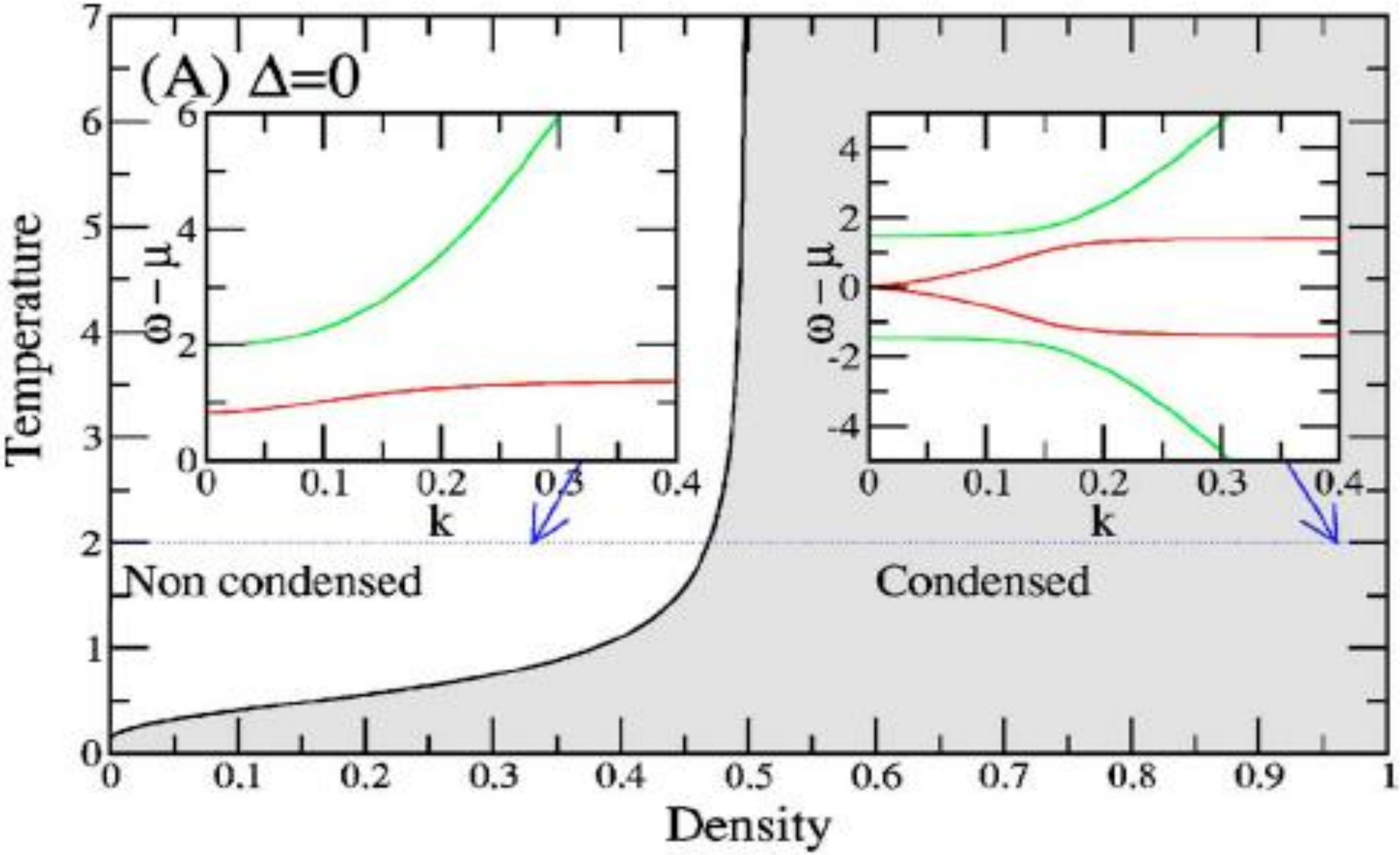
$\Rightarrow$ A quantum condensate of both photons and k=0 excitons

$\Rightarrow$ Ringing produced by dynamical amplitude oscillations

$\Rightarrow$ Mean field assumed: i.e. keep only momenta of pump and k=0

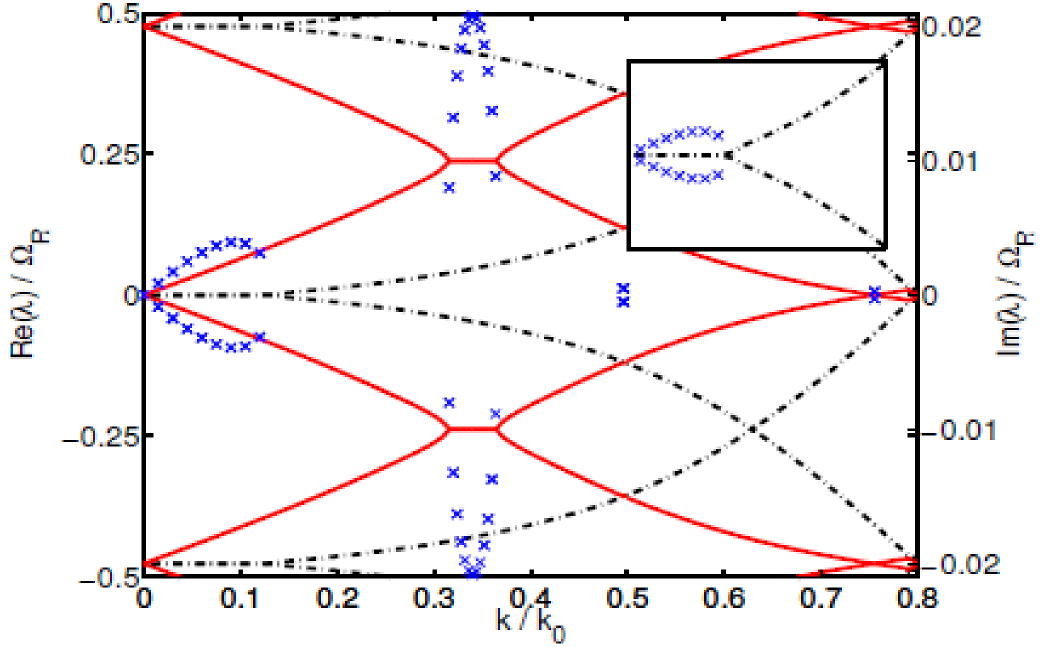
Full nonlinear semiclassical dynamics ....

Brierley, Littlewood, Eastham Phys. Rev. Lett. 107, 040401 (2011)



R,

Quasienergy spectrum of oscillating system



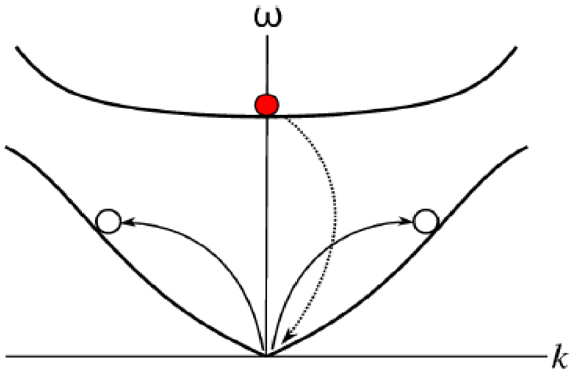
Red lines – derived from phase modes (LP)

Black lines – amplitude modes (UP)

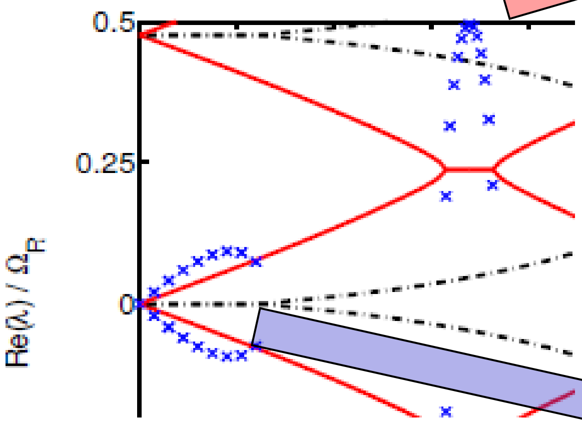
Unstable regimes when *Im λ* nonzero (Blue crosses)

Unstable regimes

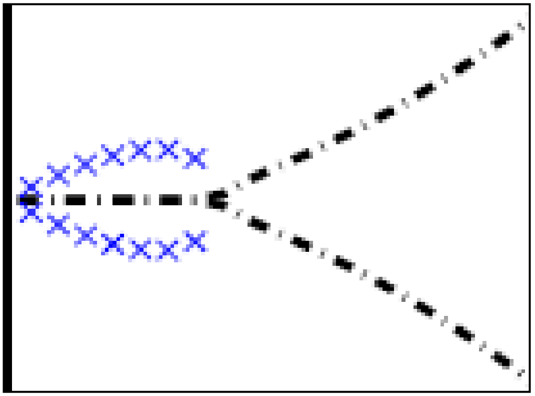
OPO – like instability
amplitude modes pump phase



Spectrum of dilute Bose gas with weak
attractive interactions



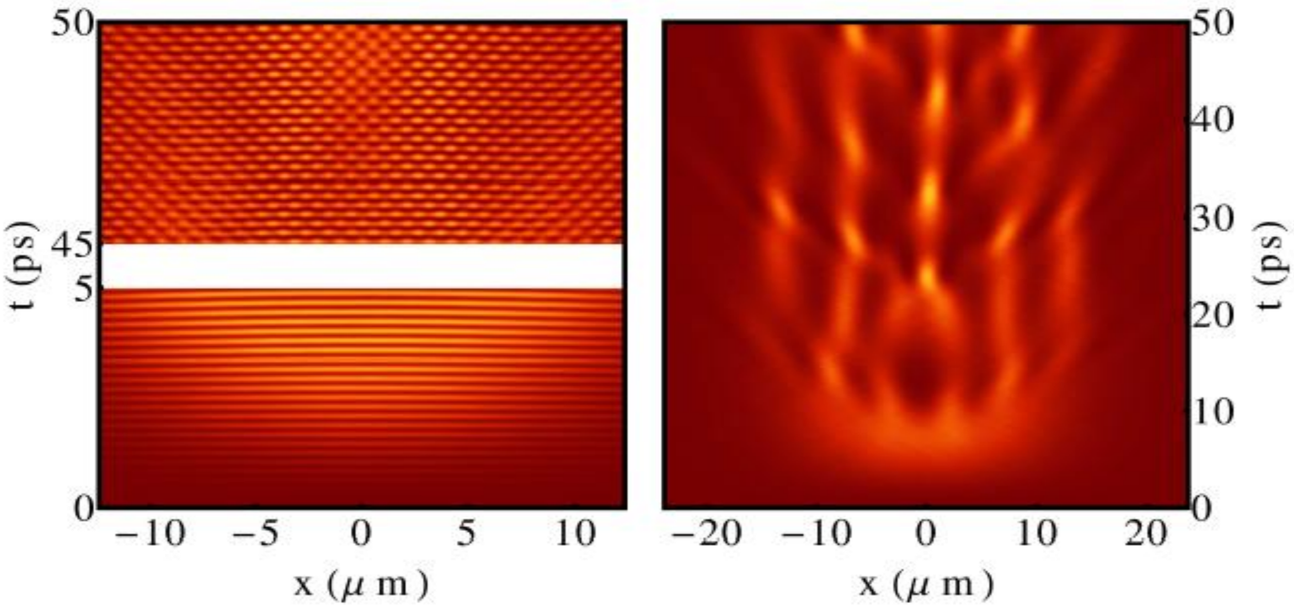
Attractive interaction between
amplitude fluctuations



Ginzburg – Landau analysis

$$i\frac{\partial\psi}{\partial t} = \left(\omega_0 - \frac{\hbar^2}{2m_{\mathrm{ph}}}\nabla^2\right)\psi + \frac{\Omega_R}{2}\left(1-\lambda|P|^2\right)P$$
$$- i\gamma\psi + \xi + F,$$

$$i\frac{\partial P}{\partial t} = EP + \frac{\Omega_R}{2}(1-\lambda|P|^2)\psi.$$

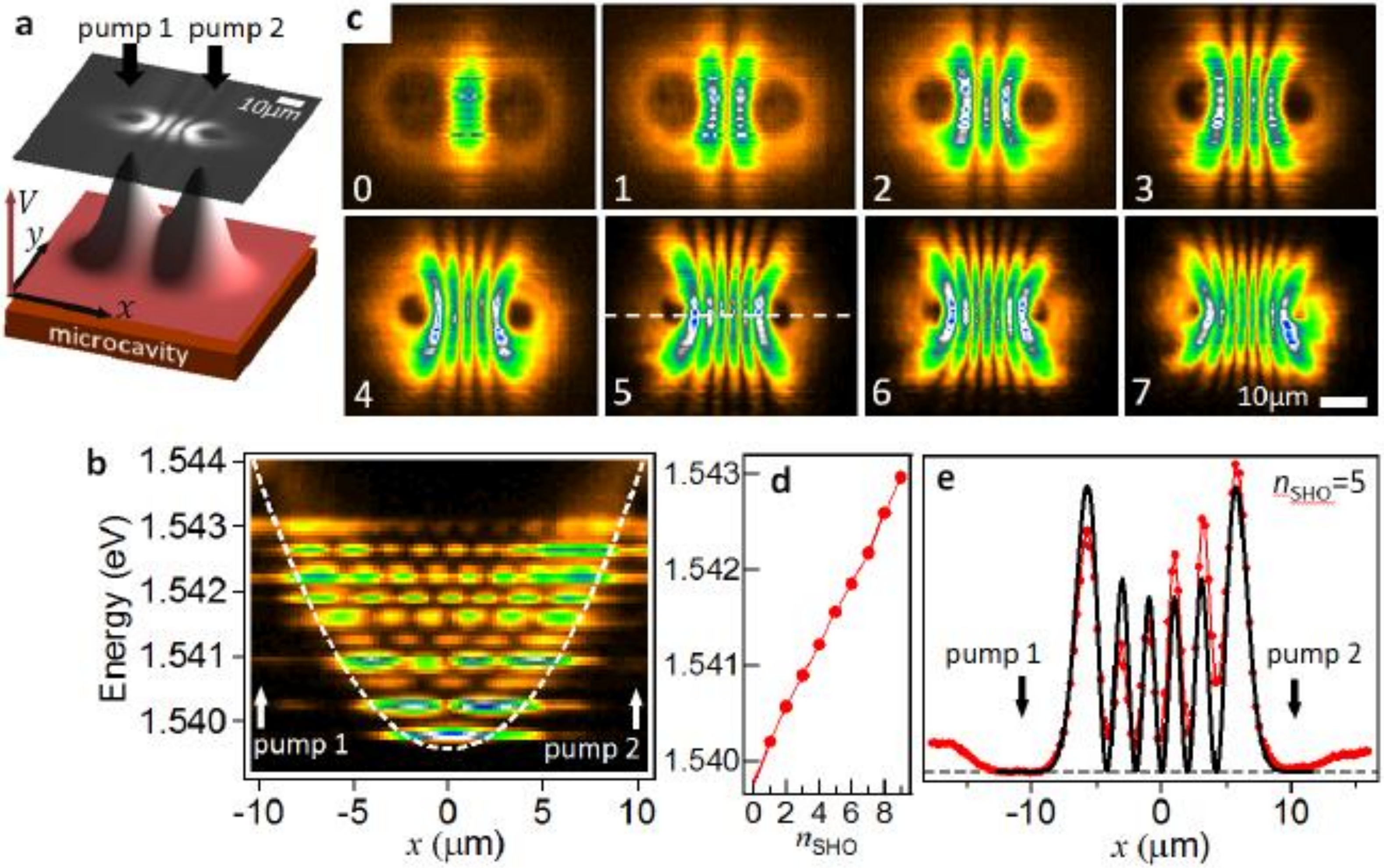


Lower and upper polariton resonantly pumped

Upper polariton resonantly pumped

Long-wavelength instability appears to develop spatio-temporal chaos

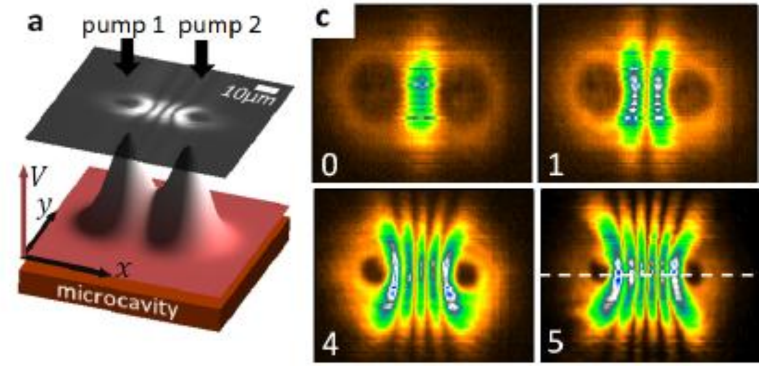
An instability of two coupled condensates



Tosi et al Nature Physics 2012

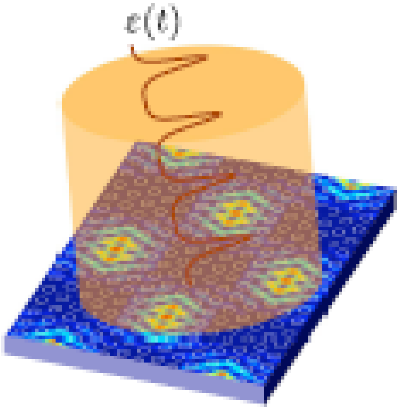
What’s next?

Coupled Condensates



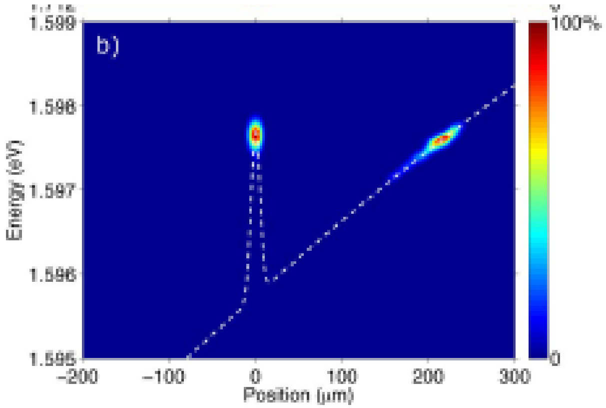
Tosi et al Nature Physics 2012

Coupled cavity arrays



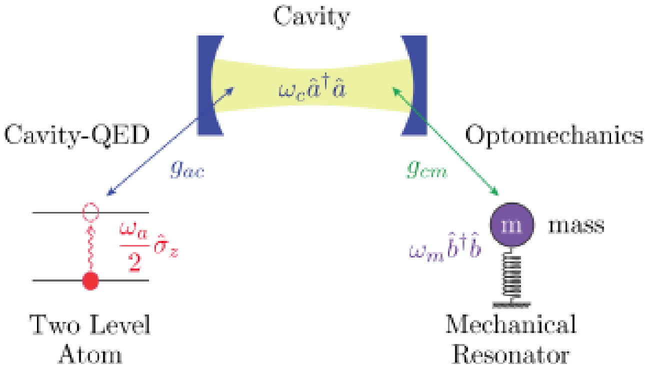
Tomadin et al., Phys. Rev. A **81**, 061801 (2010).

Ballistic transport



Nelsen et al, arXiv:1209.4573

Cavity Optomechanics



Restrepo et al, arXiv:1307.4282

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Conclusions

Cavity polaritons are a new correlated many body system for “cold” “atoms” that show condensation phenomena analogous to BEC

- Strong and long-range coupling – transition temperature set by interaction energy, not density
- Like a laser – but matter and light remain strongly coupled
- Far from equilibrium physics – quantum dynamics?
- State preparation possible using optical control