The meaning of superfluidity for polariton condensates

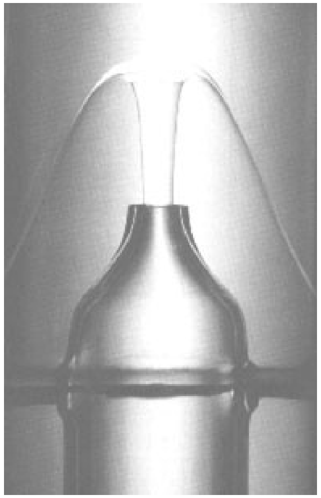
Iacopo Carusotto
BEC CNR-INFM and Università di Trento, Italy

Michiel Wouters
EPFL, Lausanne, Switzerland

Cristiano Ciuti and Simon Pigeon
MPQ, Univ. Paris VII

Some milestones of liquid He superfluidity

Liquid ^{4}He below Λ point (2.2 K):



- Λ singularity in thermodynamic functions
- Flows through narrow capillars with no viscosity

  Kapitsa; Allen and Misener (1937)

- Rotating bucket experiment: lattice of quantized vortices

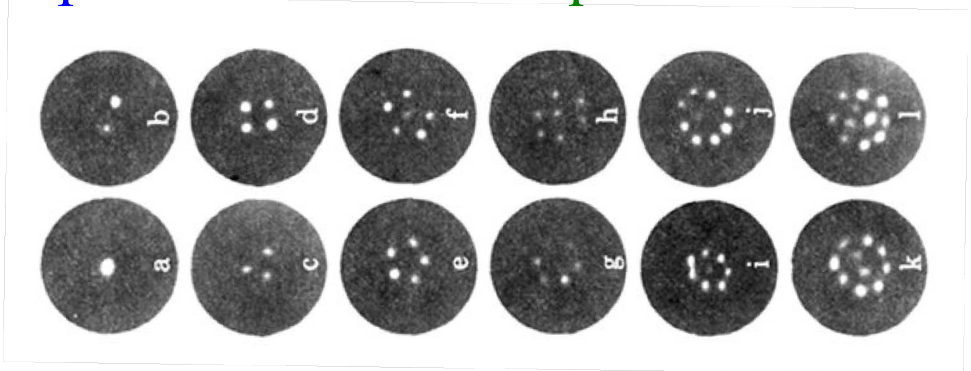


Figure from: Yarmchuk, Gordon and Packard PRL (1979)

- Fountain effect: superfluid ^{4}He climbs over container walls when heated

Several definitions of superfluidity

1 - Rotating bucket experiment, i. e. **equilibrium in rotating frame :**

- no rotation of fluid for $\Omega < \Omega_c$ (Hess-Fairbank effect)
- lattice of quantized vortices for $\Omega > \Omega_c$

2 - Meissner-like effect :

- absence of response to transverse gauge field, i.e. transverse current response
- normal, non-superfluid fraction defined as: $\lim_{q \to 0} \chi^T(q, \omega=0) = \frac{N}{m} \frac{\rho_n}{\rho}$

3 - Metastability of superflow :

- flow persists for macroscopic times even in the presence of defects

4 - Landau criterion :

- no drag force on object slowly moving through the fluid
- Landau critical velocity: $v_c = \min_k \frac{\omega(k)}{k}$

A. L. Leggett, *Superfluidity*, RMP **71**, S318 (1999) ; Stringari & Pitaevskii, *BEC*, Clarendon Press, 2003

Superfluidity in equilibrium Bose systems

	Non-interacting BEC	Interacting BEC
Rotating bucket experiment	**YES**	**YES**
Transverse current response	**YES**	**YES**
Persistent currents	**NO**	**YES**
No drag force	**NO**	**YES**

Interacting BEC : all definitions coincide !

Recent experiments with atomic BECs (I)

$v = 0.35$ mm/s $< v_c$

$v = 5.6$ mm/s $> v_c$

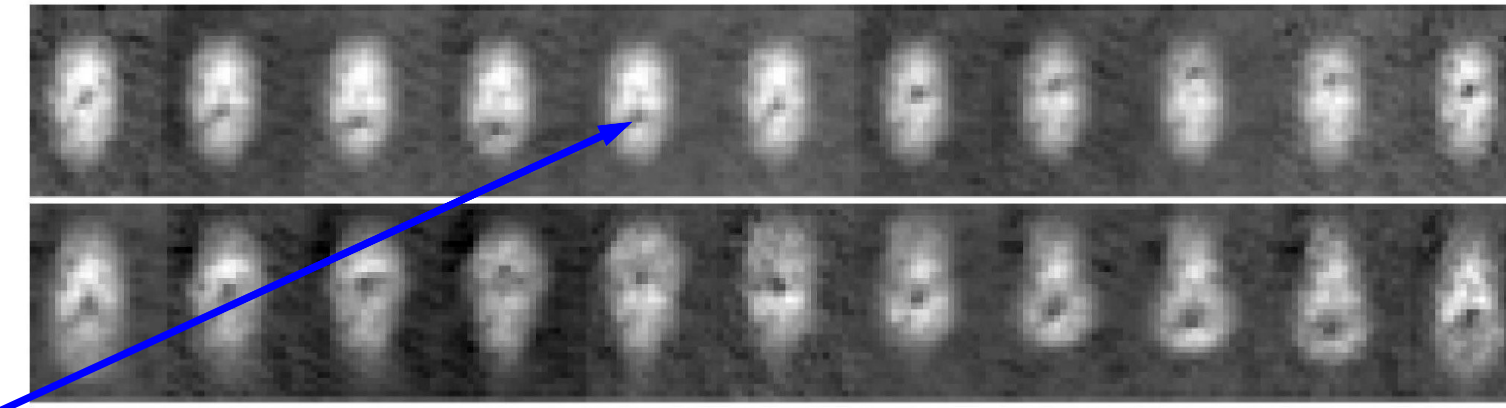
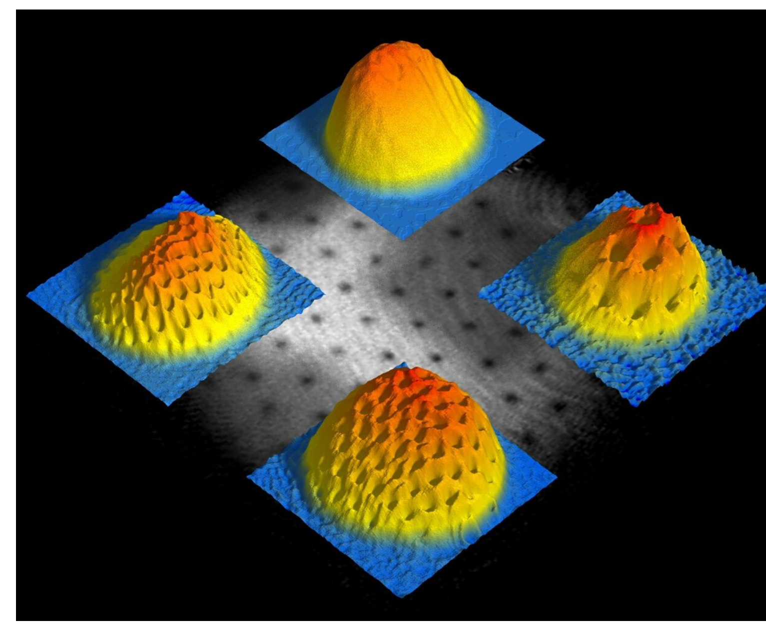


Figure: from R. Onofrio et al. PRL 85, 2228 (2000)

moving defect:

$v < v_c$: dissipationless flow

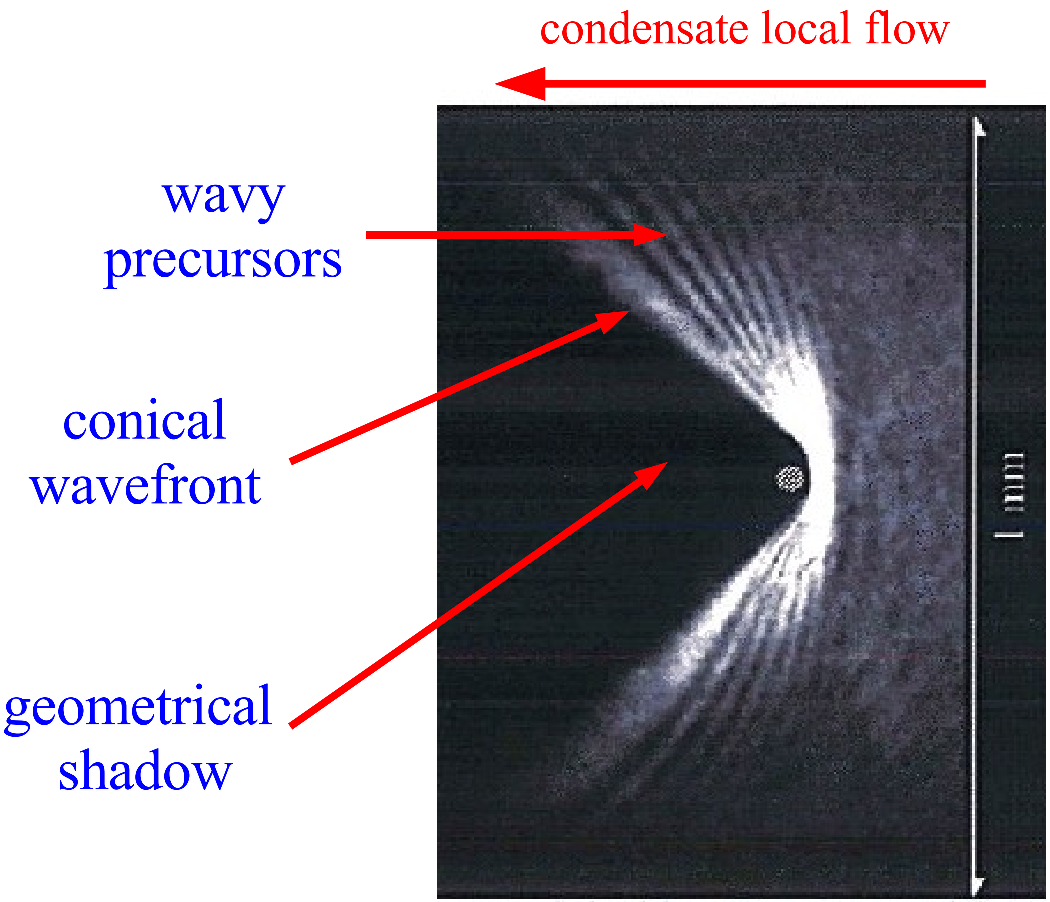
$v > v_c$: asymmetry in density profile



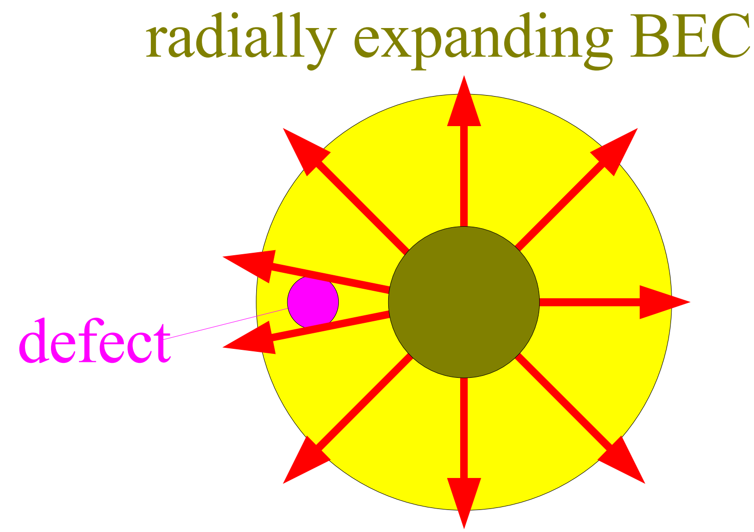
Lattice of quantized vortices in stirred BEC

Figure from: Abo-Shaeer et al., Science **292**, 476 (2001)

Recent experiments with atomic BECs (II)



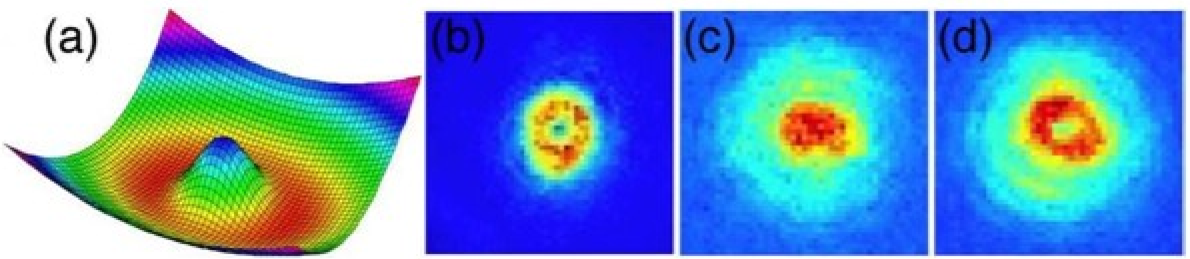
Experimental picture taken at JILA,
courtesy E. Cornell and P. Engels



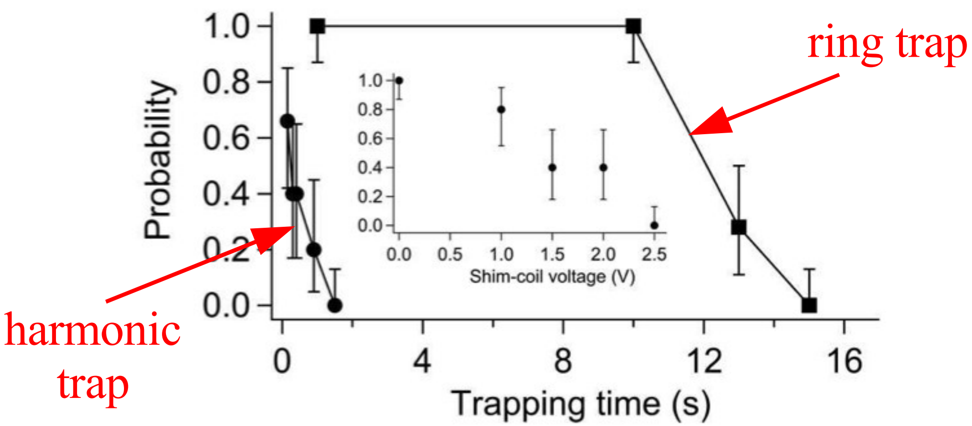
IC, S. X. Hu, L. A. Collins, A. Smerzi, *Bogoliubov-Čerenkov Radiation in a Bose-Einstein Condensate Flowing against an Obstacle*, PRL **97**, 260403 (2006).

Recent experiments with atomic BECs (III)

Metastability of supercurrents in ring traps during macroscopic times



Supercurrent survival after *t*

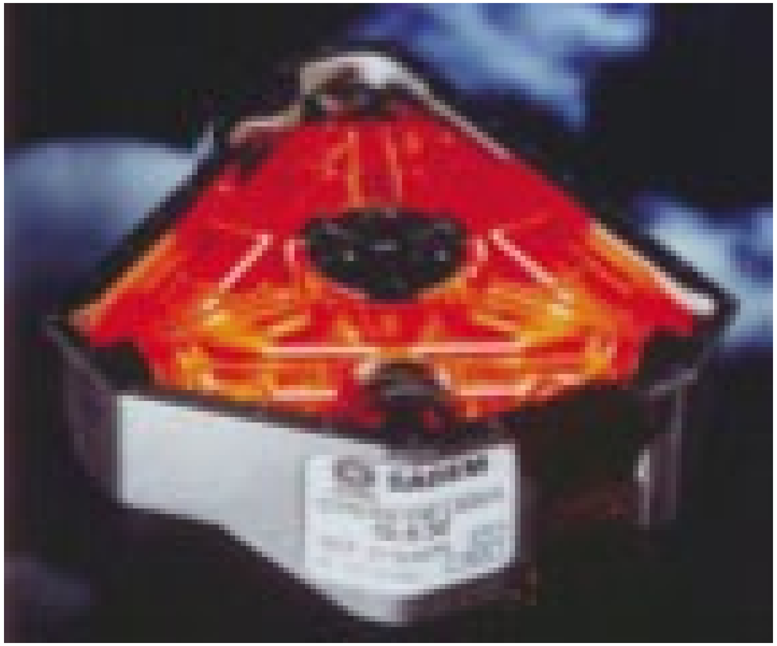


Images from:

C. Ryu, M. F. Andersen, P. Cladé, Vasant Natarajan, K. Helmerson, and W. D. Phillips PRL **99**, 260401 (2007)

What to expect in non-equilibrium systems

1 - Metastability of superflow ⟶ **YES**

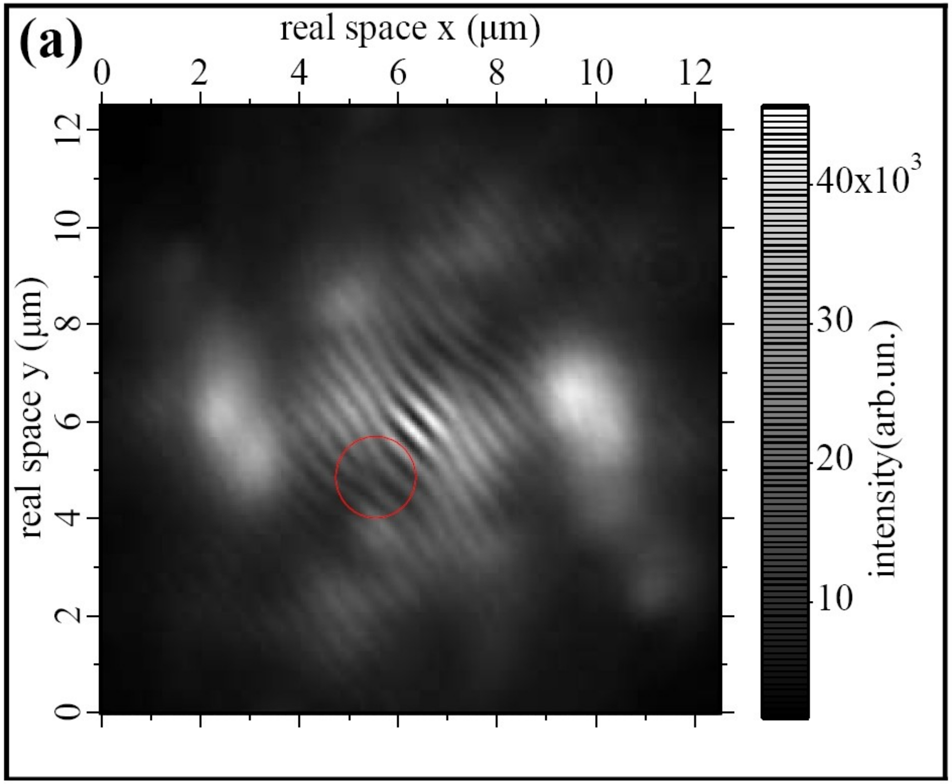


Gyrolaser for aeronautics

exploit a kind of metastable supercurrent of light

What to expect in non-equilibrium systems

2 - Quantized vortices ⟶ **YES**



Vortices can spontaneously appear even in the absence of stirring

Single-valued macroscopic wf. implies quantized winding number

Does NOT prove superfluidity

More details in talks by Wouters, Lagoudakis and Keeling

Figure taken from: K. G. Lagoudakis, M. Wouters, M. Richard, A. Baas, IC, R. André, Le Si Dang, B. Deveaud-Pledran, *Quantised Vortices in an Exciton Polariton Fluid,* preprint arXiv/0801.1916, Nature Physics (in the press)

What to expect in non-equilibrium systems

3 – Response to transverse gauge field ⟶ **YES**

- Minimal coupling Hamiltonian $H = \frac{\left[\boldsymbol{P} - e\,\boldsymbol{A}(\boldsymbol{r})\right]^2}{2\text{m}}$
- gauge field $\boldsymbol{A}(\boldsymbol{r}) = \boldsymbol{A}_0\, e^{i\,\boldsymbol{q}\cdot\boldsymbol{r}} + c.c.$
- transverse condition $\boldsymbol{q}\cdot\boldsymbol{A} = 0$
- current-current response $\boldsymbol{J}(\boldsymbol{q},\omega) = \boldsymbol{\chi}(\boldsymbol{q},\omega)\;\boldsymbol{A}(\boldsymbol{q},\omega)$
- normal, non-superfluid fraction related to transverse response:

$$\lim_{q\to 0} \chi^T(q,\omega{=}0) = \frac{N}{m}\,\frac{\rho_n}{\rho}$$

But...

- how to generate the A field acting on (neutral) polaritons ?
- for atoms: topological potentials in 3-level EIT-like configurations

What to expect in non-equilibrium systems

4 - Drag force → depends on pumping scheme

Landau criterion for superfluidity:

drag force F(v) on object moving through the quantum fluid

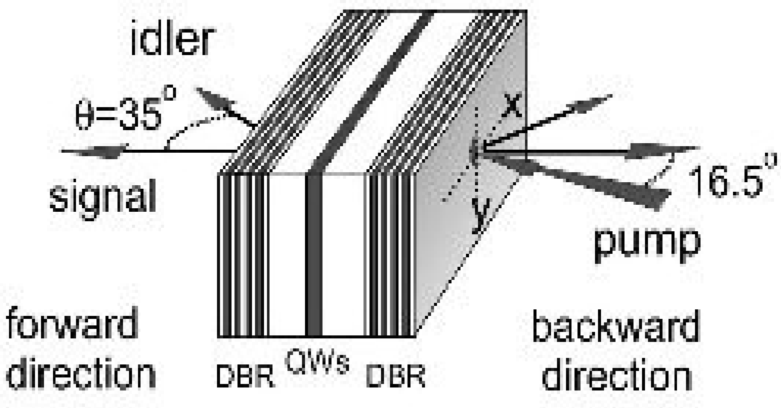
no drag force for slow objects $F(v<v_c)=0$, Landau critical velocity: $v_c = \min_k \frac{\omega(k)}{k}$

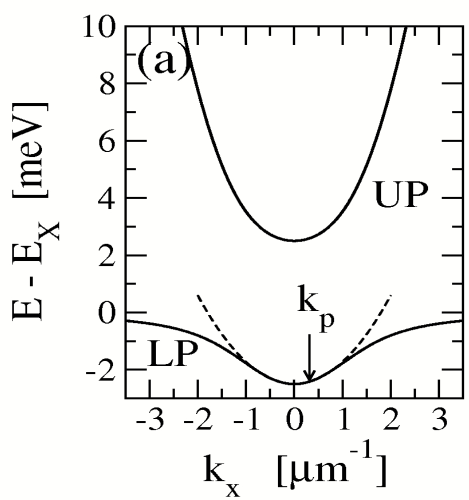
- coherent polaritons injected by resonant pump (IC, Ciuti, PRL 2004) → Landau criterion is accurate

- OPO system (Madrid expts) → complex physics, see talks by Sanvitto, Del Valle and Laussy

- polariton BEC under non-resonant pump → Landau predicts non-superfluid behaviour. But crossover still visible in F(v)

Exciton-polaritons in DBR microcavity with QWs





- DBR: stack λ/4 layers (e.g. GaAs/AlAs)
- Cavity layer → confined photonic mode, delocalized along 2D plane:

$$\omega_C(\boldsymbol{k}) = \omega_C^0 \sqrt{1 + \boldsymbol{k}^2 / k_z^{\,2}}$$

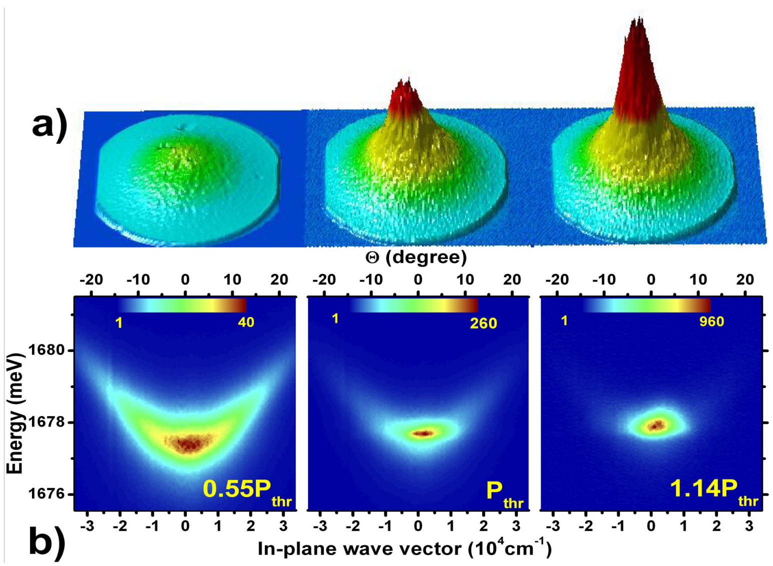
- e and h confined in QW layer (e.g. InGaAs)
- e-h pair: sort of H atom. **Exciton**
- Excitons bosons if $n_{exc}\, a^2_{Bohr} \ll 1$
- Excitons delocalized along cavity plane. Flat exciton dispersion $\omega_x(\mathbf{k}) \approx \omega_x$

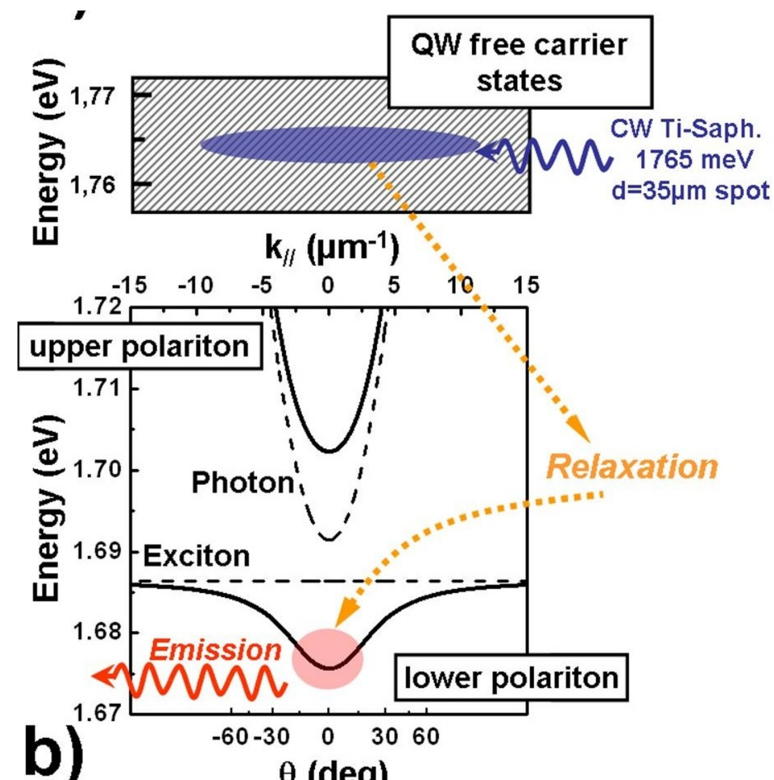
Radiative coupling between excitonic transition and cavity photon at same in-plane k

Eigenmodes: bosonic superpositions of exciton and photon, called **polaritons**

Polariton BEC under non-resonant pumping

- high-energy pump creates incoherent e-h pairs
- relaxation via polariton-polariton collisions, quasi-equilibrium condition
- at high pumping, stimulated scattering into low-energy modes
- coherence spontaneously created via BEC effect



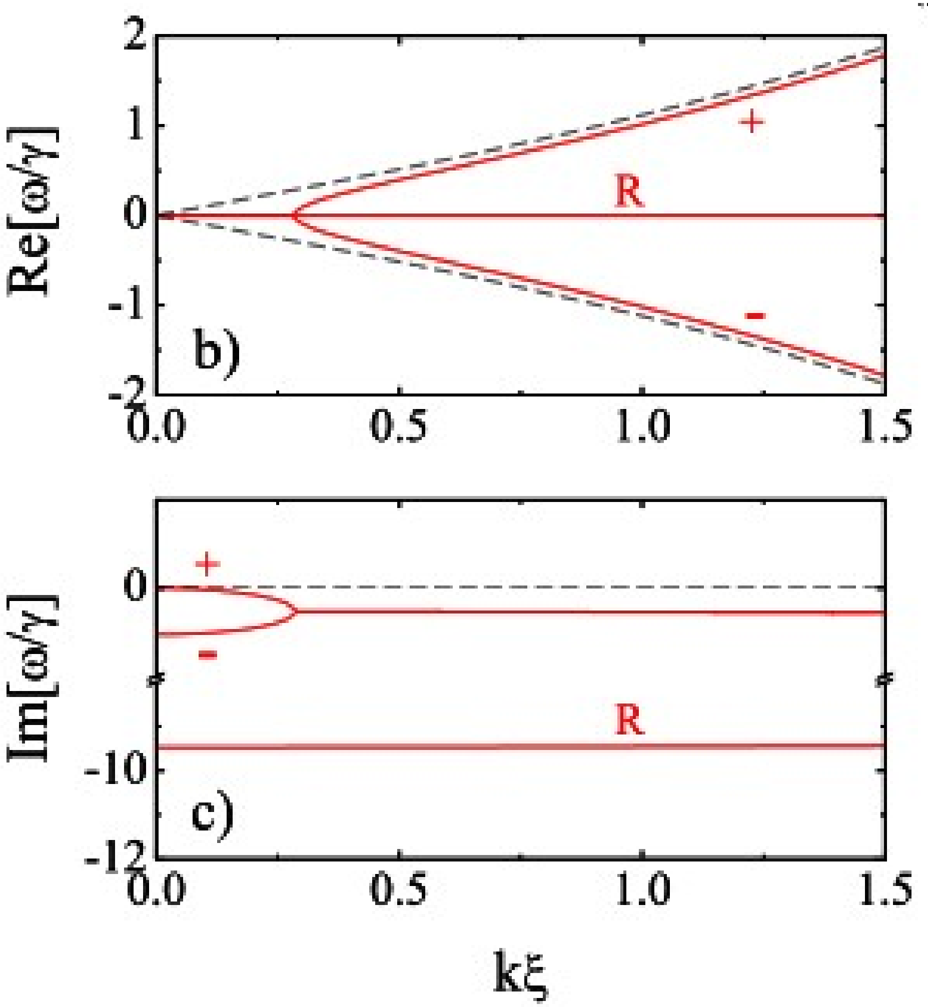


Figures from: Kasprzak et al., Nature **443**, 409 (2006)

Elementary excitations of polariton BEC

- system far from thermodynamical equilibrium
- dynamical balance of pump and losses
- + mode satisfies Goldstone theorem
- but has diffusive nature at low k

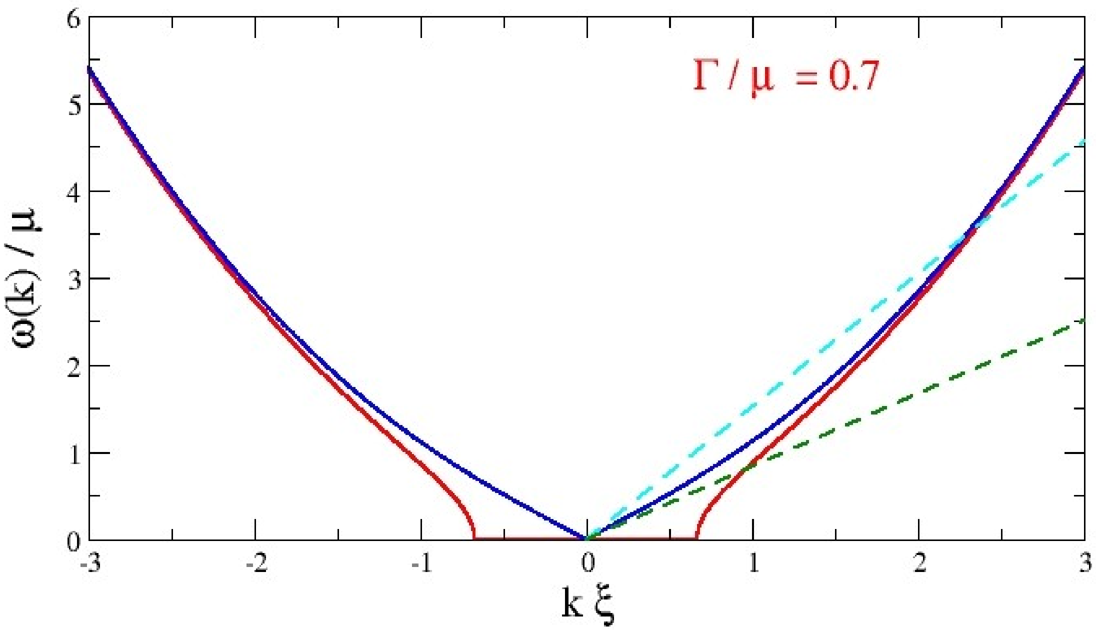
  $Re[\omega(k)] = 0, \quad Im[\omega(k)] = - a k^2$
- recovers Bogoliubov sound at high k



M. H. Szymanska, J. Keeling, P. B. Littlewood, *Nonequilibrium Quantum Condensation in an Incoherently Pumped Dissipative System*, PRL 96, 230602 (2006)

M. Wouters and IC, *Excitations in a non-equilibrium polariton BEC*, Phys. Rev. Lett. **99**, 140402 (2007)

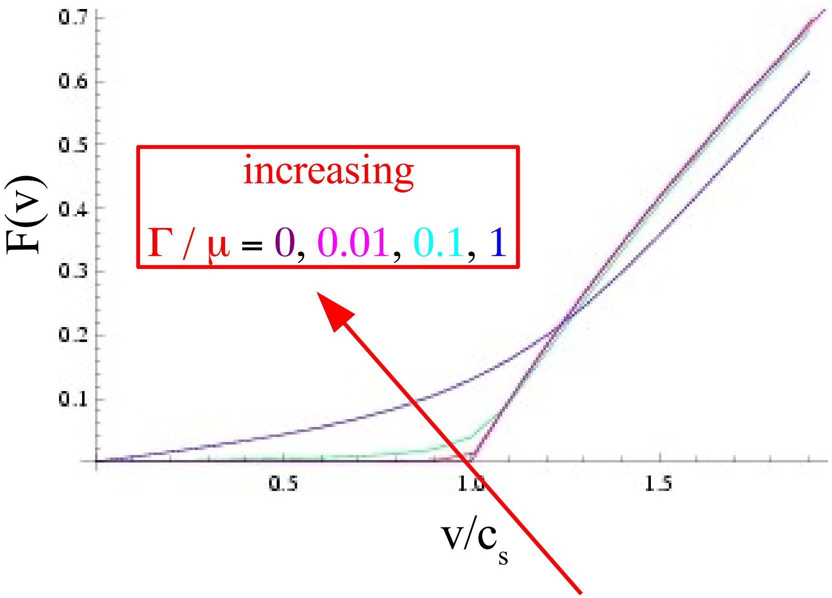
Consequences on superfluidity of polariton BECs



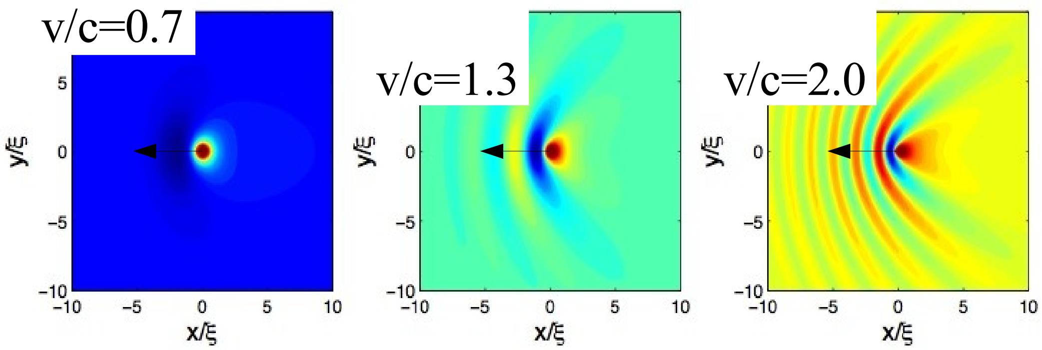
Naïf Landau argument:

- Landau critical velocity $v_c = \min_k \frac{\omega(k)}{k} = 0$ for non-equilibrium BEC
- Any moving defect expected to emit phonons

But non-equilibrium life is bit more complicate...



Γ / μ = 0.5



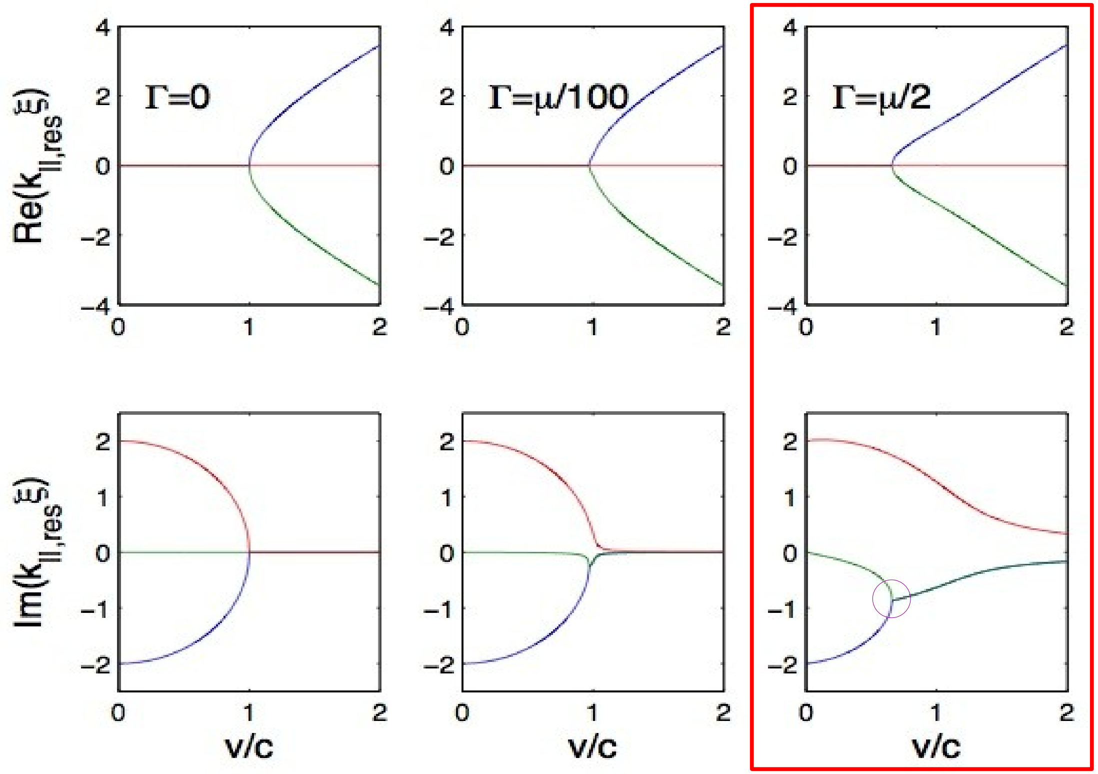
- drag force F(v): $\Gamma / \mu = 0$ recovers Landau criterion, $F(v<v_c)=0$

  $\Gamma / \mu > 0$ smoothened, still crossover behaviour

- real-space "Cerenkov" wake: localized perturbation for small v

  propagating phonons for large v

Generalized Landau criterion with complex k's



Low v :

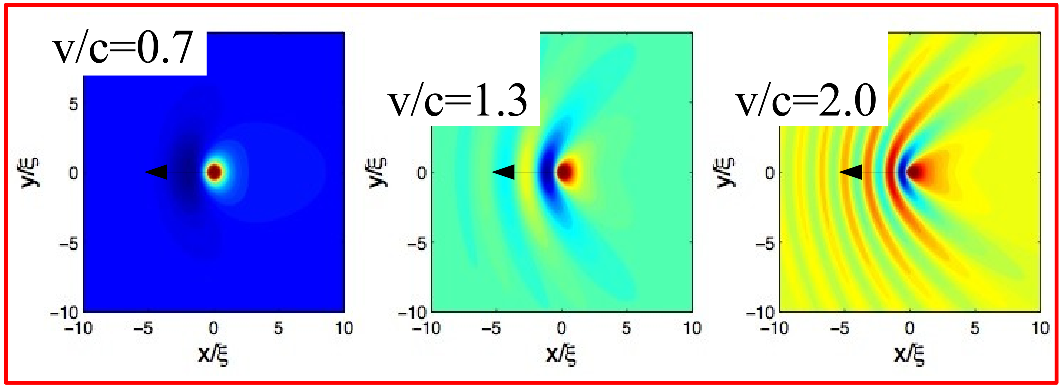
- emitted $k_{\parallel}$ purely imaginary
- no real propagating phonons
- localized perturbation around defect

Critical velocity $v_c < c$:

- corresponds to bifurcation point
- decreases with Γ / μ

High v:

- propagating phonons are emitted :
  - → Cerenkov cone
  - → parabolic precursors
- spatial damping of Cerenkov cone



M.Wouters and IC, *Excitations and superfluidity in non-equilibrium Bose-Einstein condensates of exciton-polaritons*, preprint arXiv:0707.1446.

Conclusions and outlook

A new frontier :

superfluidity effects in non-equilibrium systems

Non-equilibrium Landau superfluidity very rich world:

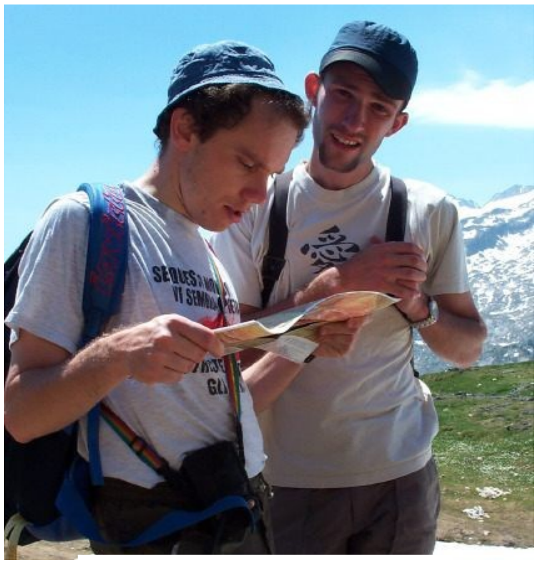
- under coherent pump: from standard Cerenkov to zebra-Cerenkov
- Non-resonantly pumped BECs :
    - → diffusive Goldstone mode
    - → zero Landau critical velocity, but remnants of superfluidity apparent

Other aspects of polariton superfluidity that remain to be explored:

- metastability of supercurrents, possible gyroscopic sensor applications
- transverse current-current fluctuations and response to gauge fields

Thanks to my brave coworkers...

free SOFTWARE FOUNDATION



Michiel Wouters

LINUX POWERED

Cristiano Ciuti

Simon Pigeon

Experimental data: linear regime

Polariton cloud expanding against a defect

Real space pattern: fringes

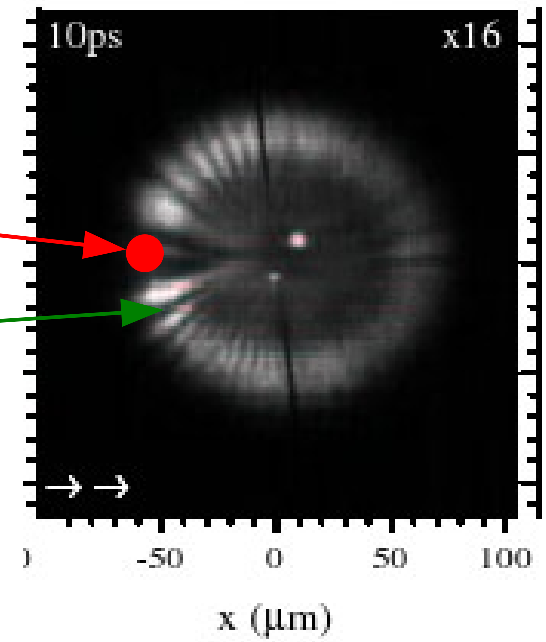


Figure from Langbein (2002)

k-space pattern
Resonant Rayleigh scattering ring

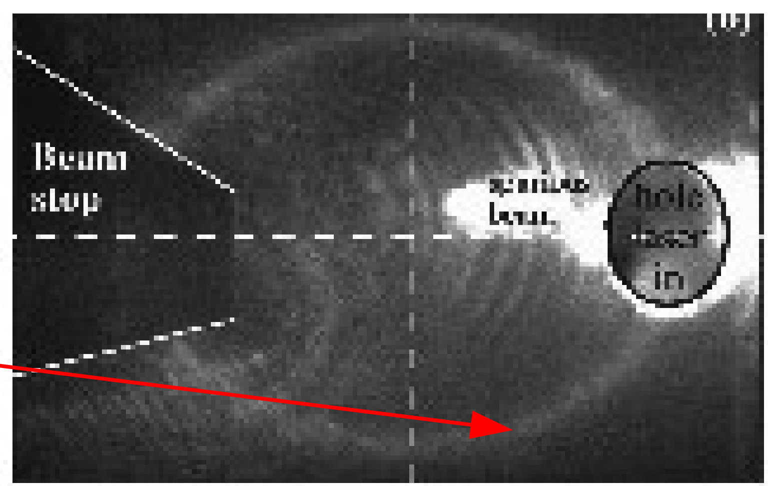
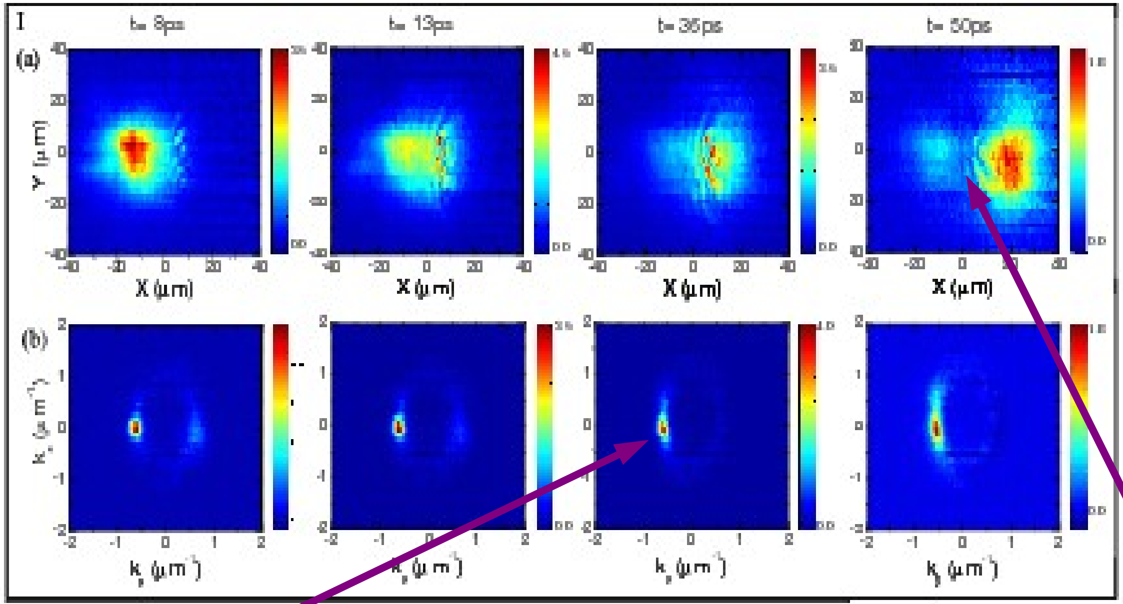


Figure from Houdré et al, PRL (2000)

Madrid experiment: a different regime

More complex OPO configuration:

- coherent pump, parametric oscillation into signal and idler modes
- defect acts on all of them
- wavepacket of signal polaritons moving against defect

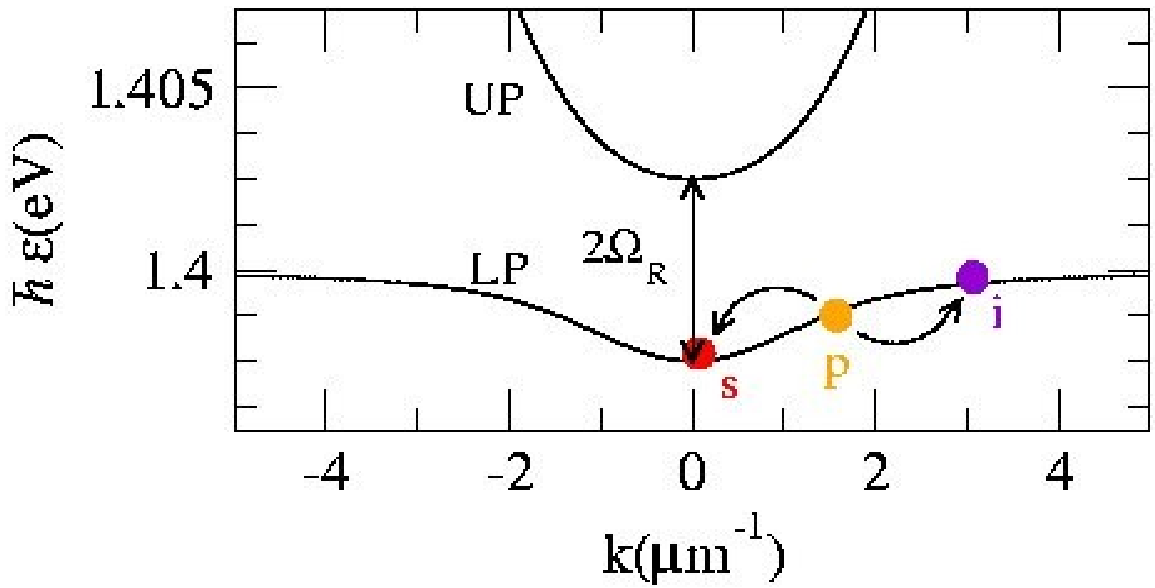


A. Amo *et al.*, arxiv/0711.1539

Weakly perturbed probe: superfluid ?

Fringes: non-superfluid pump

Basics of the OPO regime



- CW pump at k_p close to "magic angle" condition $2\omega(k_p)=\omega(k_s)+\omega(k_i)$
- Parametric oscillation: ever lasting coherent emission at $k_{s,i}$
- No need for seeding $k_{s,i}$, zero point fluctuations enough to start process
- Short pulse into $k_{s,i}$ may serve to force mode selection

Small fluctuations around OPO state

Steady-state above threshold:

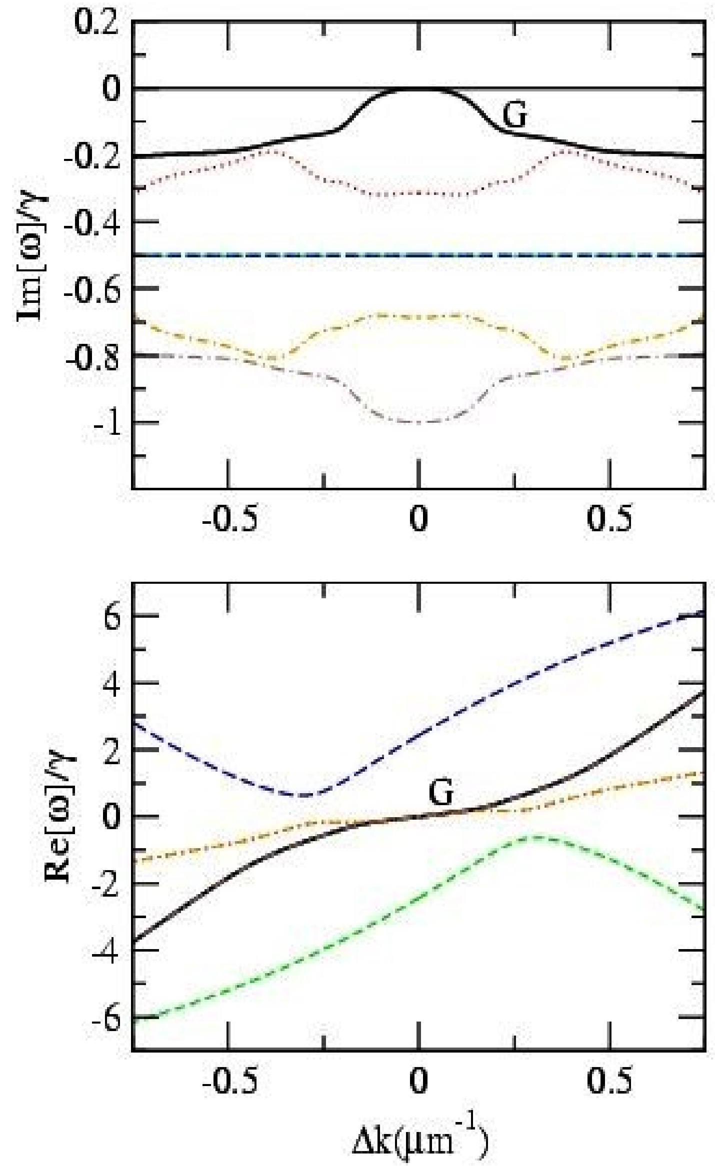
- coherent signal/idler beams
- U(1) symmetry spontaneously broken
- soft Goldstone mode $\omega_G(k) \to 0$ for $k \to 0$
- corresponds to slow signal-idler phase rotation

  → as Bogoliubov phonon at equilibrium !!!

Fundamental physical difference:

→ Goldstone mode diffusive,

not propagating like sound



M. Wouters, IC, *The Goldstone mode of planar optical parametric oscillators*, Phys. Rev. A **76**, 043807 (2007)

Consequences for superfluidity of an OPO state

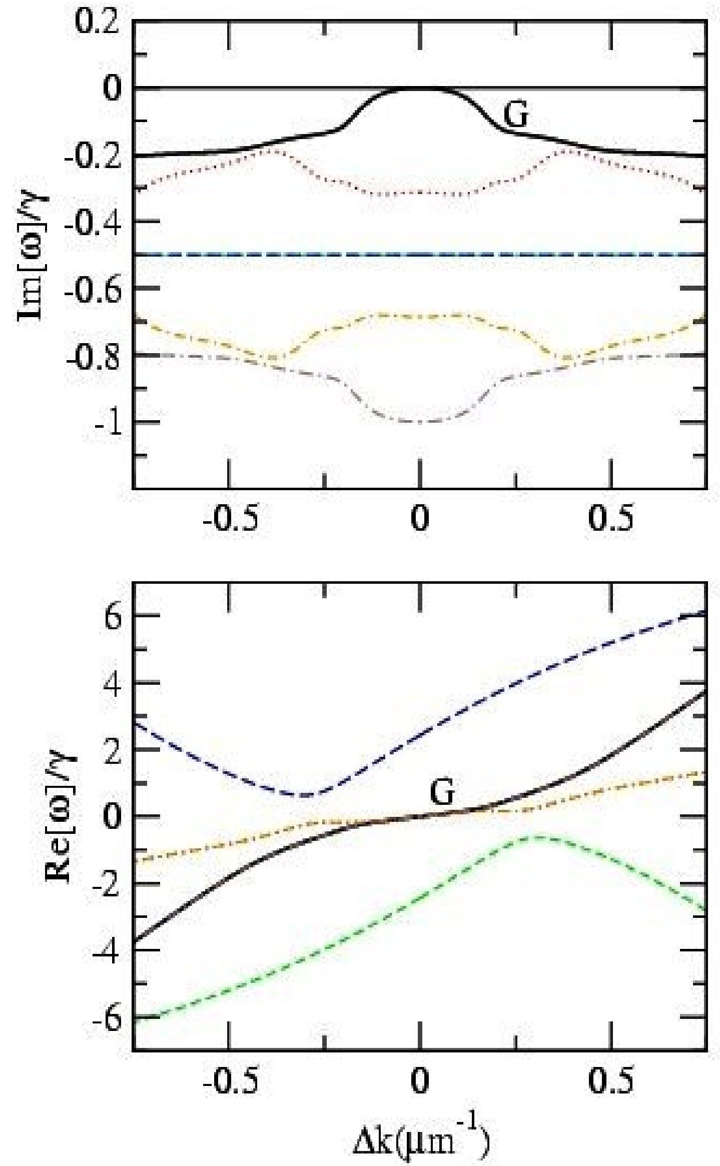
Diffusive Goldstone mode

Naif application of Landau's argument:

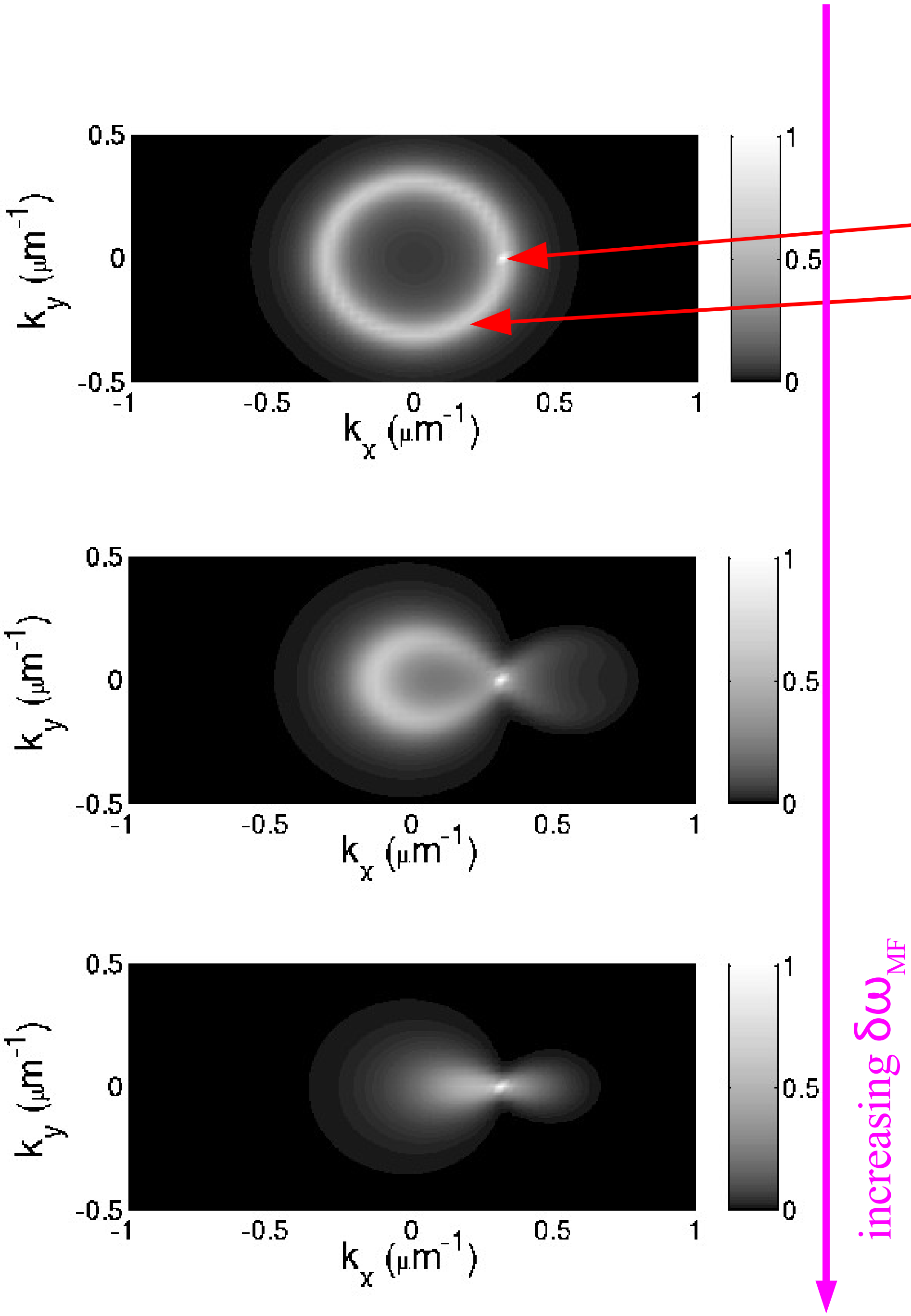
- excitations created by the defect for low speed
- no superfluidity properties

Complete calculations is in progress

- rich excitation spectrum
- pump and signal/idler modes to be identified
- all of them excited by the defect



Scattering on defect: far-field emission patterns



Linear regime:

- peak at k_p due to unscattered light
- resonant Rayleigh scattering ring

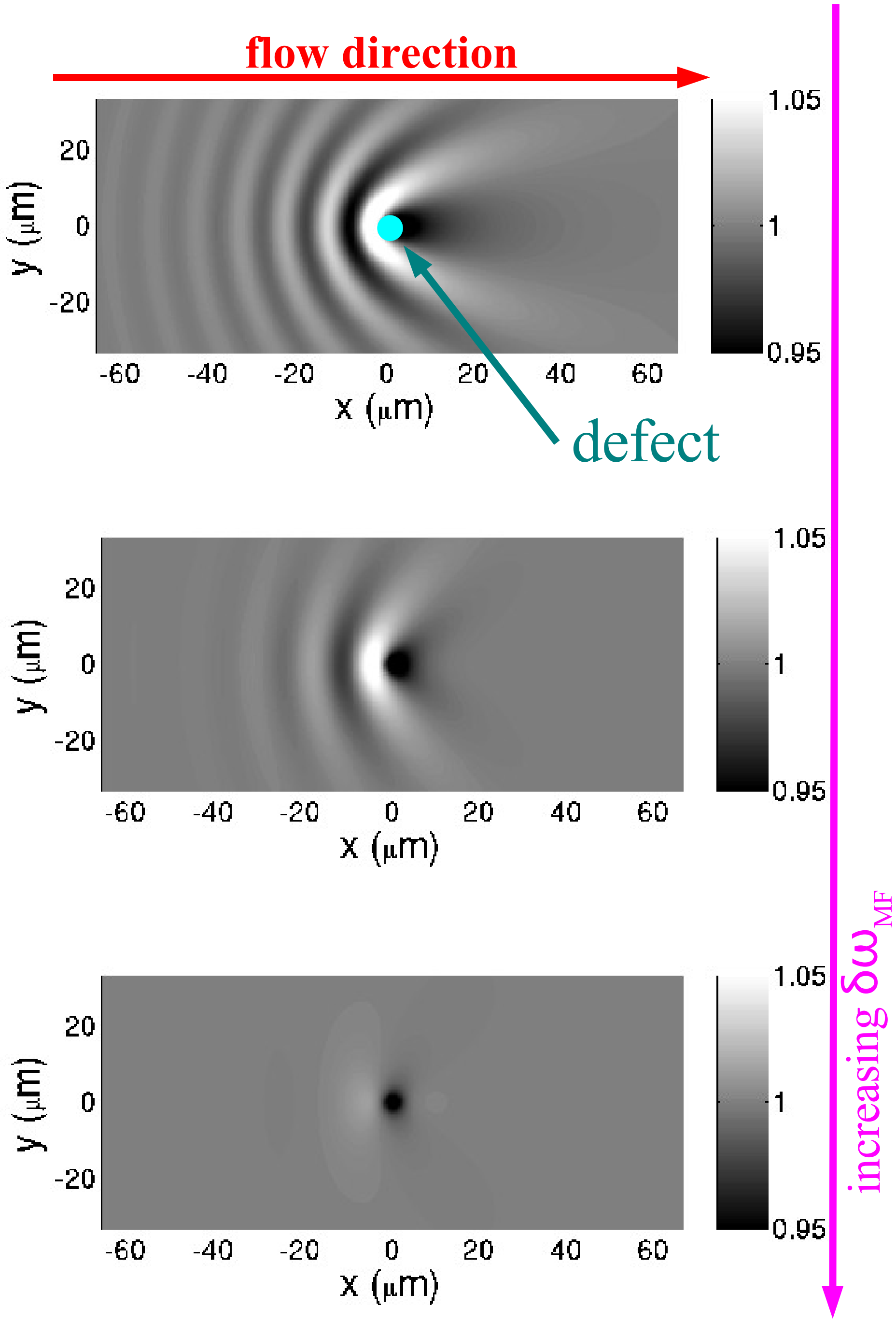
Super-sonic flow $v_p > c_s$:

- ∞ shaped pattern
- two lobes touch at k_p
- left lobe (particle) stronger than right lobe (hole)

Sub-sonic flow $v_p < c_s$:

- Landau criterion predicts superfluidity
- lobes disappear, much weaker scattering on defect

Near-field emission patterns



Linear regime:

- interference of incident and scattered field gives parabolic wavefronts

Super-sonic flow $v_p > c_s$:

- sound waves form Cerenkov cone
- aperture: $\sin\theta = c_s / v_p$
- parabolic precursors upstream

Subsonic flow $v_p < c_s$:

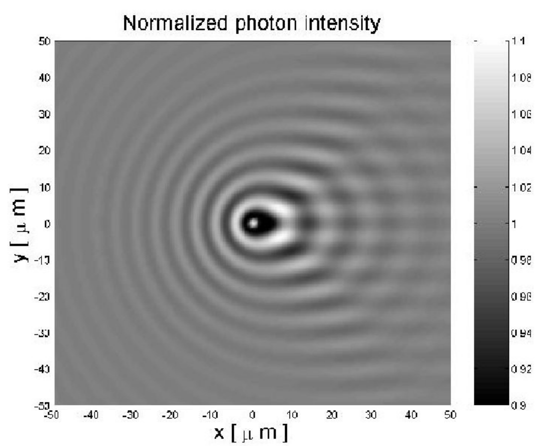
- localized perturbation
- superfluid flow around defect

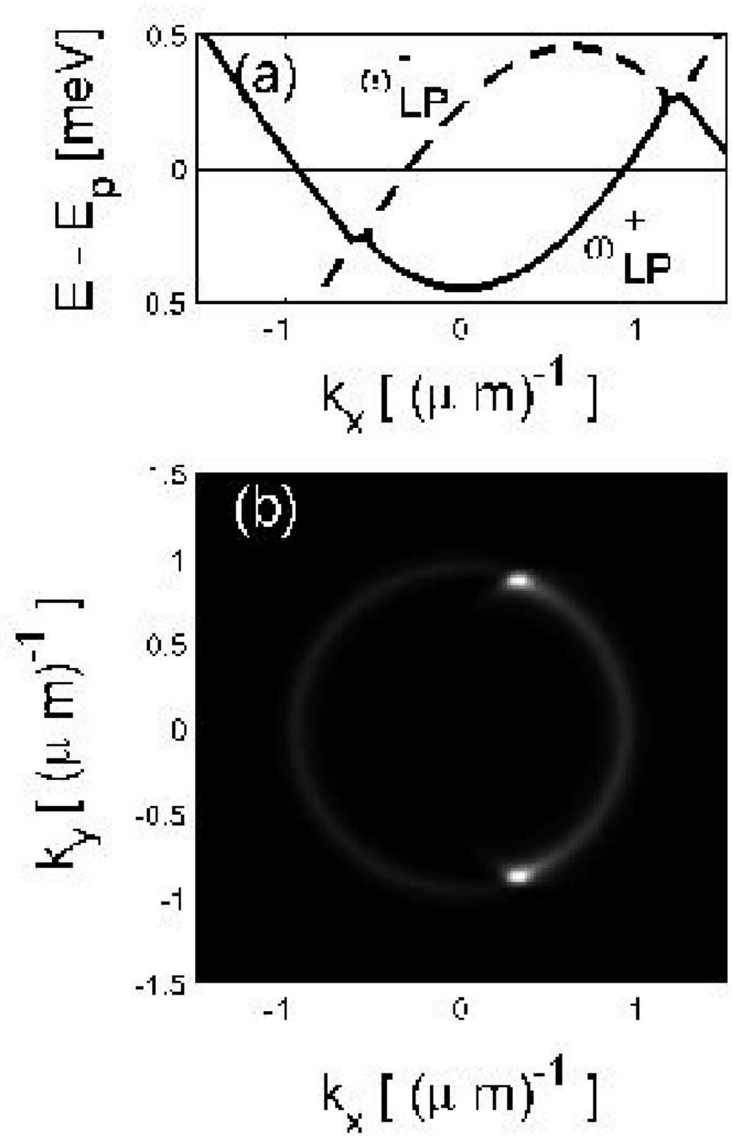
Polaritons much richer than atomic BECs

Richer phenomenology as oscillation freq. freely fixed by $\mu=\omega_p$

An example:

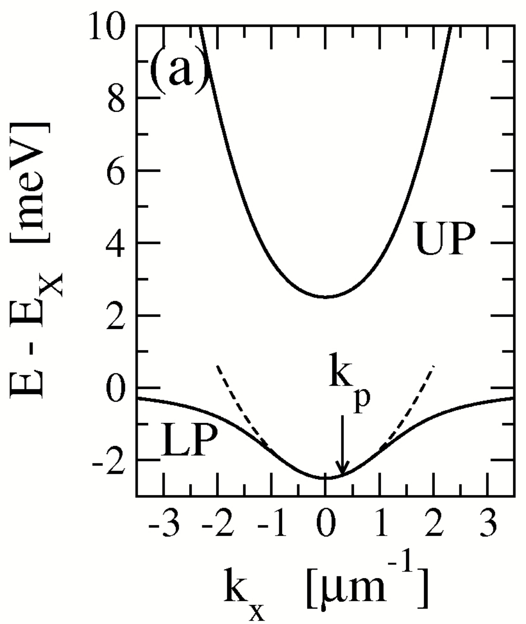
- Concentric rings: usual RRS ring
- Zebra pattern: narrow k-space peaks, precursor of parametric oscillation
- But many other shapes possible by tuning angle, frequency, intensity ...





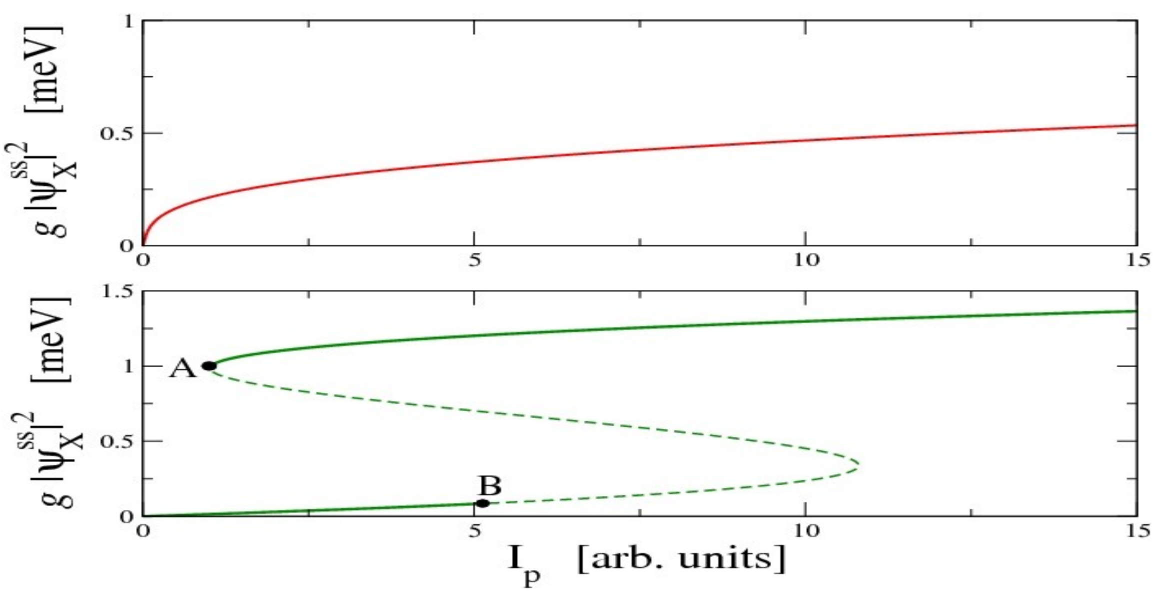
C.Ciuti and IC, *Quantum fluid effects and parametric instabilities in microcavities*, Phys. Stat. Sol. (b) **242**, 2224 (2005).

Coherently driven microcavity



Plane wave monochromatic pump

- fixes condensate $k=k_p$, finite drift velocity v_p
- oscillation frequency μ selected by ω_p, not by Eq. of state $\mu=gn$ as in equilibrium BECs
- Rich density vs. pump intensity dependence



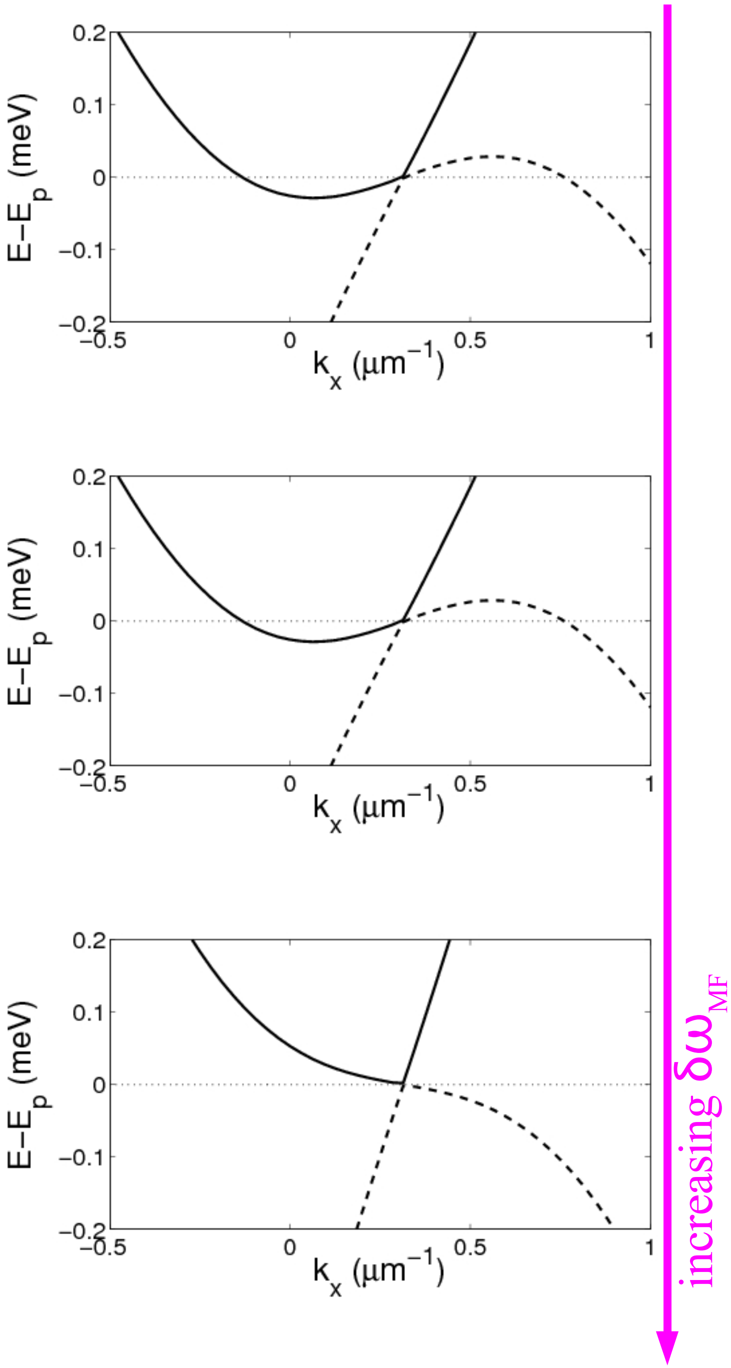
$\omega_p < \omega_{LP}(k_p)$

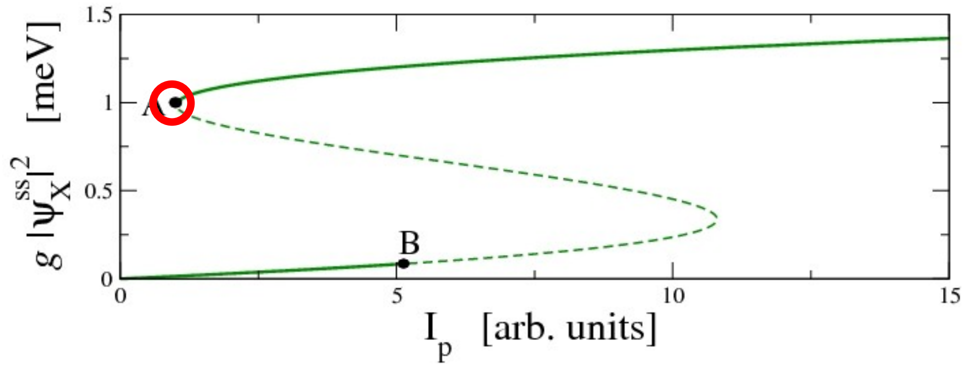
optical limiting

$\omega_p > \omega_{LP}(k_p)$

optical bistability

Resonant point: same behaviour as in atomic BEC





Gapless spectrum of Bogoliubov modes around pump-only state: tilting by v_p

For growing interactions $\delta\omega_{MF} = g|\psi_X^{ss}|^2$:

- almost parabolic dispersion for small $\delta\omega_{MF}$
- sound velocity increases with $\delta\omega_{MF}$
- sound velocity eventually changes sign and intersection with $E-E_p=0$ disappears (Landau criterion of superfluidity)