BEC and Quantum Optics

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Qian Niu	(Texas)
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G.Modugno, M.Inguscio	(LENS)

Recent publications: main research lines

Non-equilibrium BEC of polaritons

- IC and C.Ciuti, *Probing microcavity polariton superfluidity through resonant Rayleigh scattering*, PRL 93, 166401 (2004)
- C.Ciuti and IC, *Quantum fluid effects and parametric instabilities in microcavities*, Phys. Stat. Sol. (b) **242**, 2224 (2005).
- IC and C.Ciuti, *Spontaneous microcavity-polariton coherence across the parametric threshold: QMC studies*, Phys. Rev. B **72**, 125335 (2005)
- A.Verger, C.Ciuti, I. Carusotto, *Polariton quantum blockade in a photonic dot*, accept. on PRB
- M.Wouters and IC, *Absence of long-range coherence in the parametric emission from photonic wires*, cond-mat/0512464, subm. to PRL.

Dynamical Casimir effect

- C.Ciuti, G.Bastard, IC, *Quantum vacuum properties of the intersubband cavity polariton field*, PRB **72**, 115303 (2005).

Dynamical photonic structures

- Z.Gaburro, M.Ghulinyan, F.Riboli, L.Pavesi, A.Recati, IC, Photon energy lifter, cond-mat/0510043, subm. to Opt. Expr.
- F.Riboli, A.Recati, N.Daldosso, L.Pavesi, G.Pucker, A.Lui, S.Cabrini, E. DiFabrizio, *Photon recycling in Fabry-Perot microcavities based on Si_3N_4 waveguides,* Photonics and nanostructures **4**, 41 (2006)

Recent publications: other research lines and collaborations

- IC and Y.Castin, *Atom interferometrical detection of the pairing order parameter in a Fermi gas,* PRL **94**, 223202 (2005)
- IC, L.Pitaevskii, S.Stringari, G.Modugno, and M.Inguscio*, Sensitive measurement of forces at micron scale using Bloch oscillations of ultracold atoms,* PRL **95**, 093202 (2005)
- IC, *Bragg scattering and the spin structure factor of two-component atomic gases,* J. Phys. B: At. Mol. Opt. Phys. **39,** S211 (2006)
- Q.Niu, IC, A.B.Kuklov, *Imaging of critical correlations in optical lattices and atomic traps,* cond-mat/0601032, to appear on PRA
- C.Lobo, I.Carusotto, S.Giorgini, A.Recati, S.Stringari, *Pair correlations of an expanding superfluid Fermi gas*, cond-mat/0604282, submitted to PRL
- A. Recati, C. Peca, J.N.Fuchs, and W.Zwerger, *Long range interactions Casimir forces between defects in 1D quantum liquids,* PRA **72,** 023616 (2005)

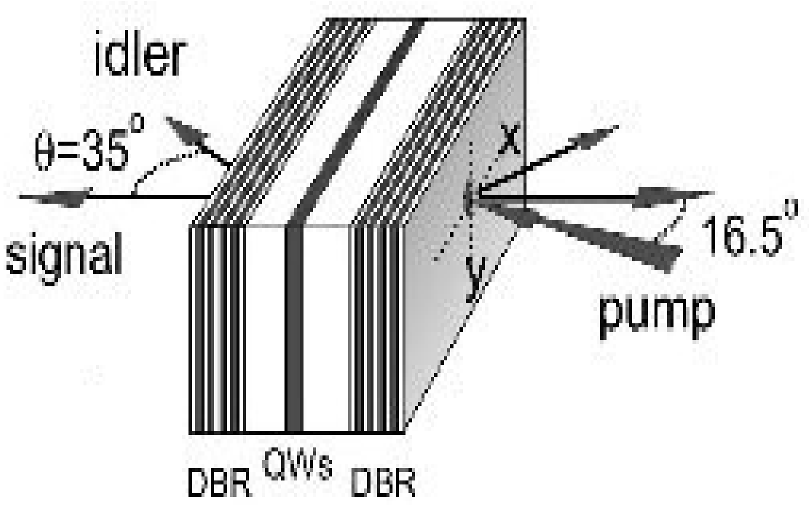
Part 1

Non-equilibrium BECs of polaritons

Michiel Wouters and Iacopo Carusotto

Collab: C.Ciuti, J.Tignon (LPA-ENS)

The physical system



Distributed Bragg Reflector planar microcavity with Quantum Wells

- DBR → λ/4 GaAs/AlAs layers
- Cavity layer confined photonic mode, delocalized along 2D plane
- In-plane photon dispersion:

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

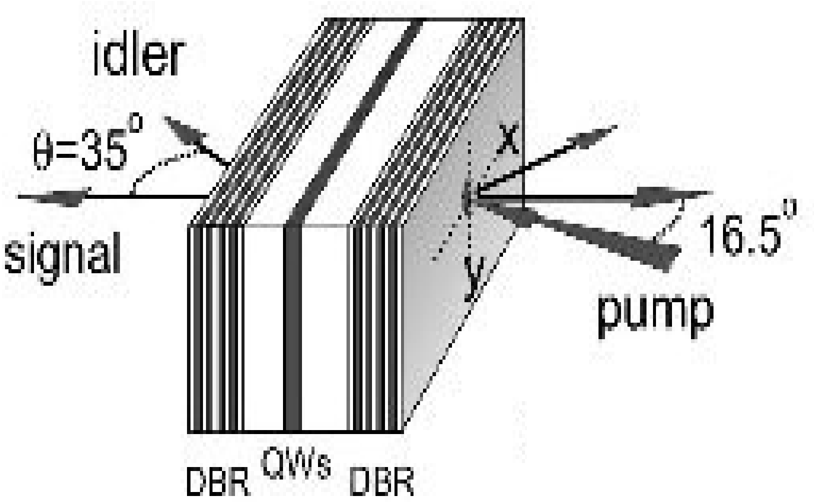
- e and h confined in InGaAs QW
- e-h pair: sort of H atom. **Exciton**
- Excitons bosons if $n_{exc}\, a_{Bohr}^2 \ll 1$
- Excitons delocalized along cavity plane. Flat exciton dispersion $\omega_X(\boldsymbol{k}) \approx \omega_X$

Exciton radiatively coupled to cavity photon at same in-plane k
No coupling to continuum, no spontaneous emission, Rabi oscillations at Ω_R
Bosonic superpositions of exciton and photon, called **polaritons**

How to create polariton BEC

Direct injection by resonant pump

- Coherence injected by pump
- Study of elementary excitations
- Superfluidity and response to defects
- Novel Cerenkov-like effects



OPO process $(k_p,k_p) \rightarrow (k_s,k_i$

- High pumping: stimulation on $k_{s,i}$ modes
- Appearance of coherence above threshold
- Non-equilibrium BEC transition
- Spontaneous breaking of U(1). (Quasi)-Long-Range order

Other experimental technique: non-resonant pumping of excitons

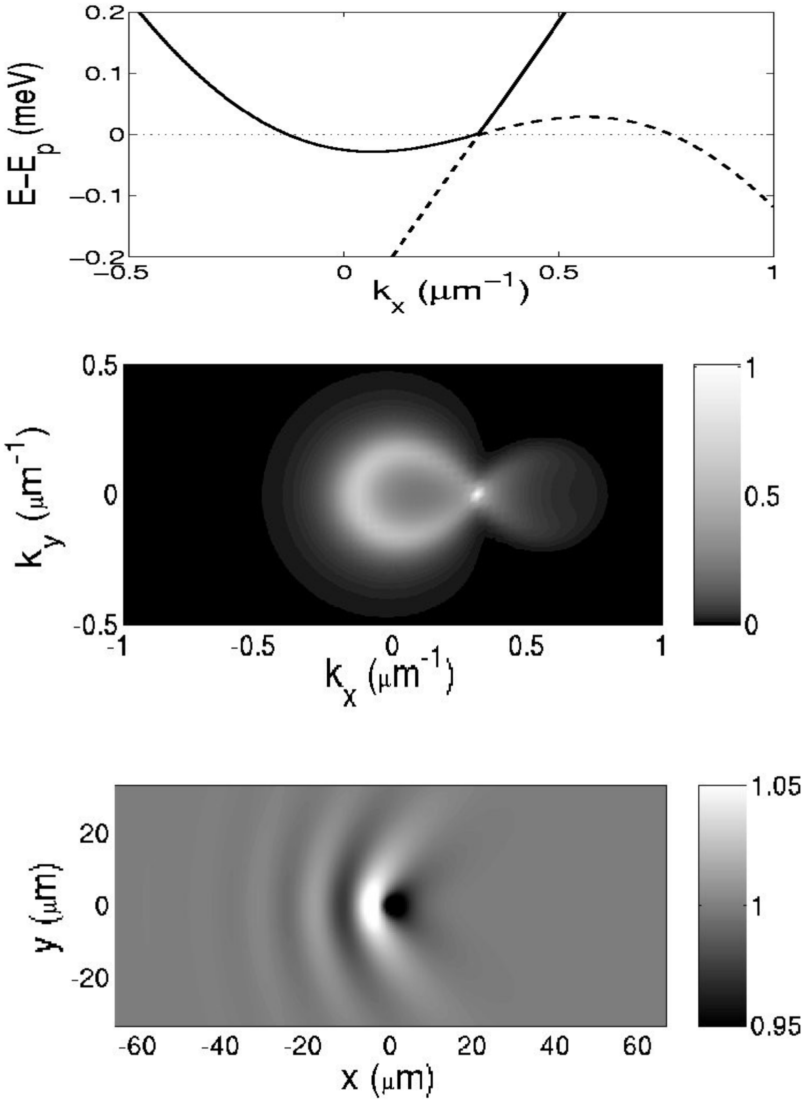
- Wait for thermalization to lattice temperature via collisions and phonons
- Closer to standard route to equilibrium BEC, but harder to model

Not considered here !

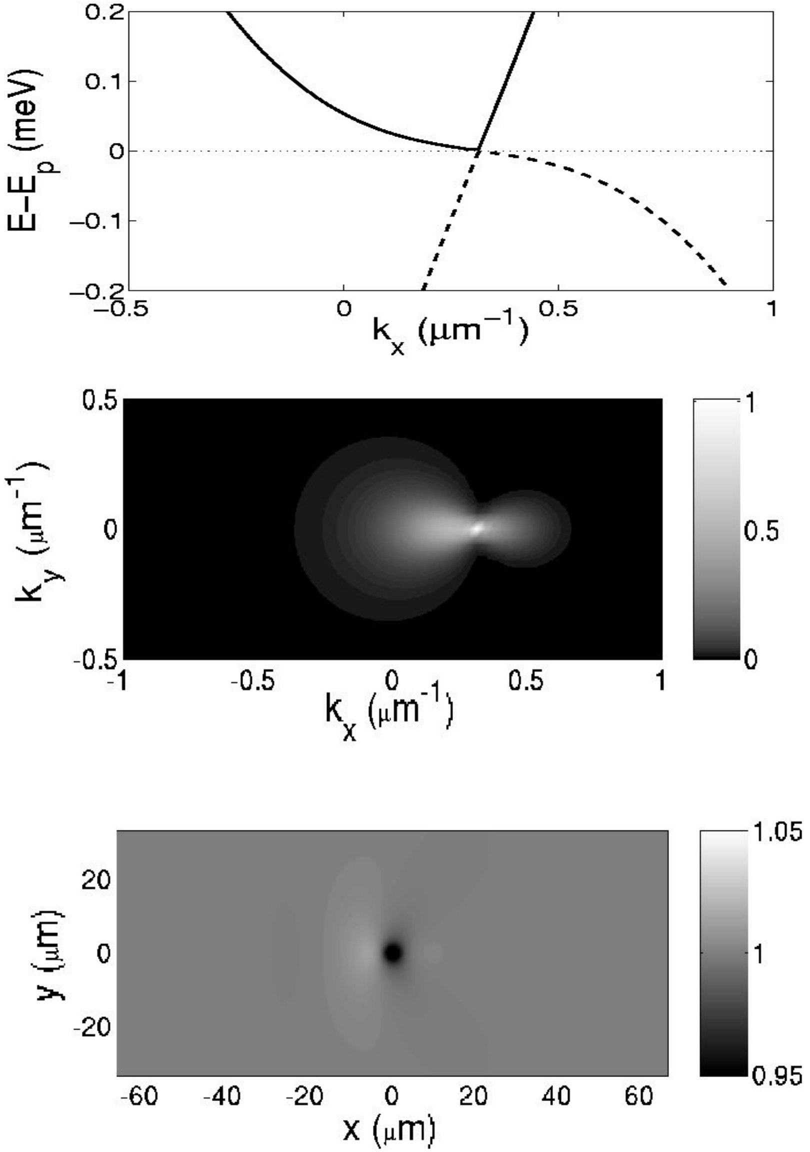
Polariton superfluidity and Cerenkov effect

Polariton BEC injected at finite k_p: flow towards right incident on defect

Super-sonic flow: $v_p > c_s$

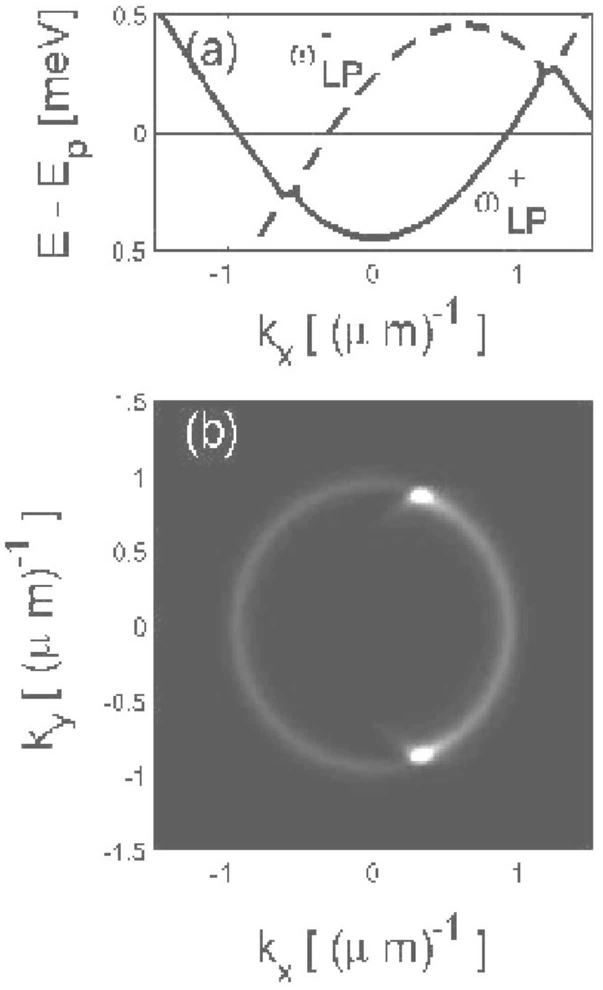


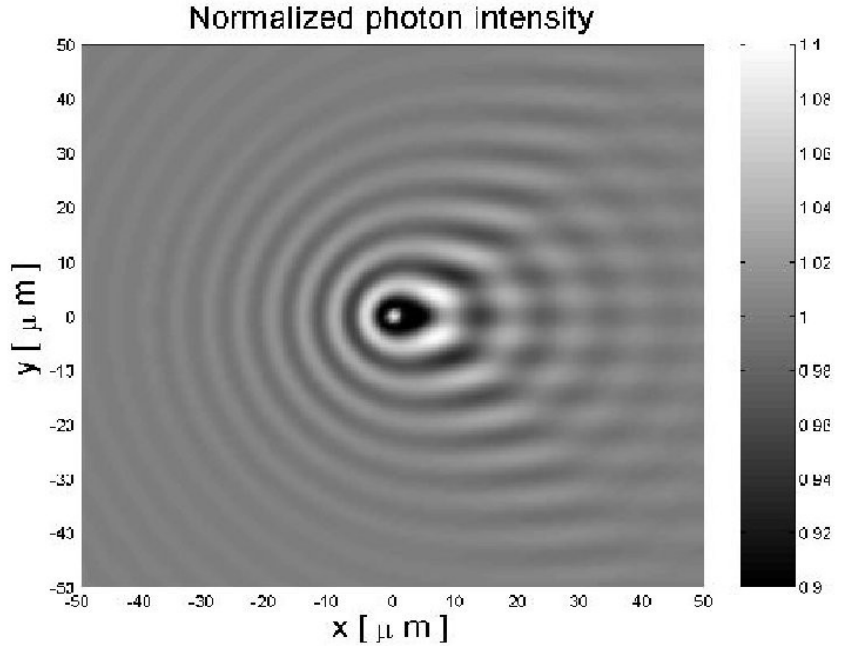
Sub-sonic flow: $v_p < c_s$



IC and C.Ciuti, PRL **93**, 166401 (2004)

Zebra-Cerenkov effect





With respect to usual quantum fluids

- chemical potential μ not fixed by equation of state
- freely chosen by pump laser frequency

⇒ much richer behavior !!!

C.Ciuti and IC, Phys. Stat. Sol. (b) **242**, 2224 (2005)

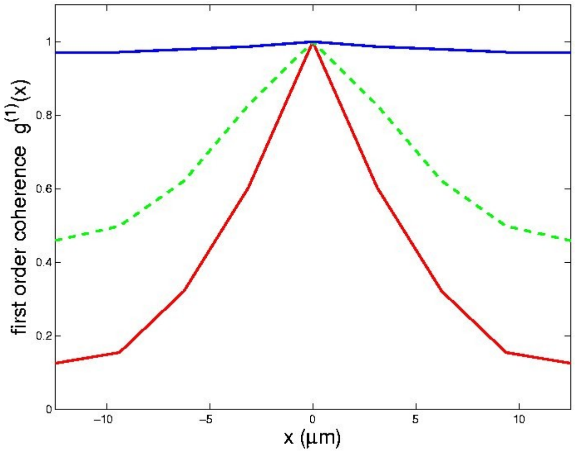
OPO threshold as a non-equilibrium BEC transition

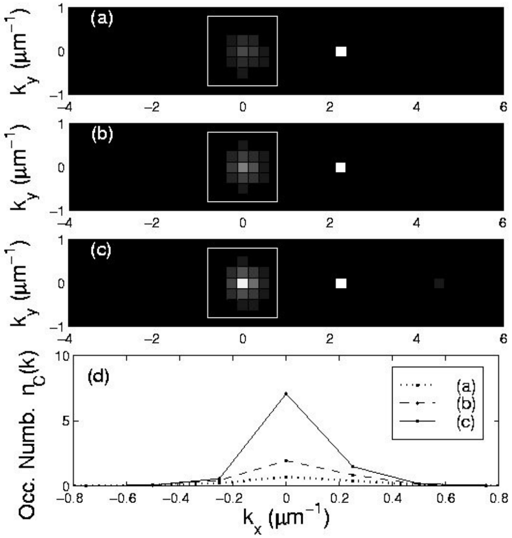
OPO process $(k_p,k_p) \rightarrow (k_s,k_i)$: $H = a_s^+ a_i^+ a_p a_p + h.c.$ Signal/idler phase free

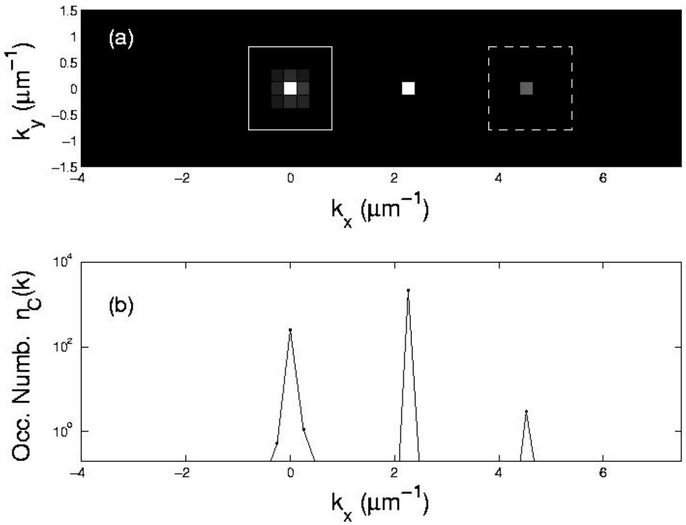
Optical coherence in parametric emission at k_s

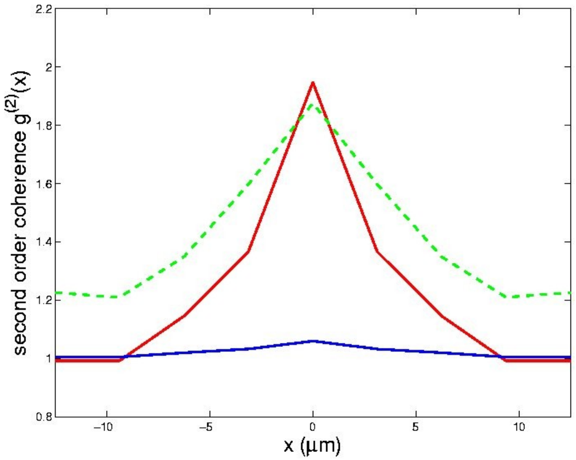
- k-space narrowing
- long-range coherence in transverse plane
- Suppressed intensity fluctuations
- U(1) spont. broken, well defined signal phase

Phenomenology similar to BEC critical point at T_c









Wigner Quantum Monte Carlo simulations

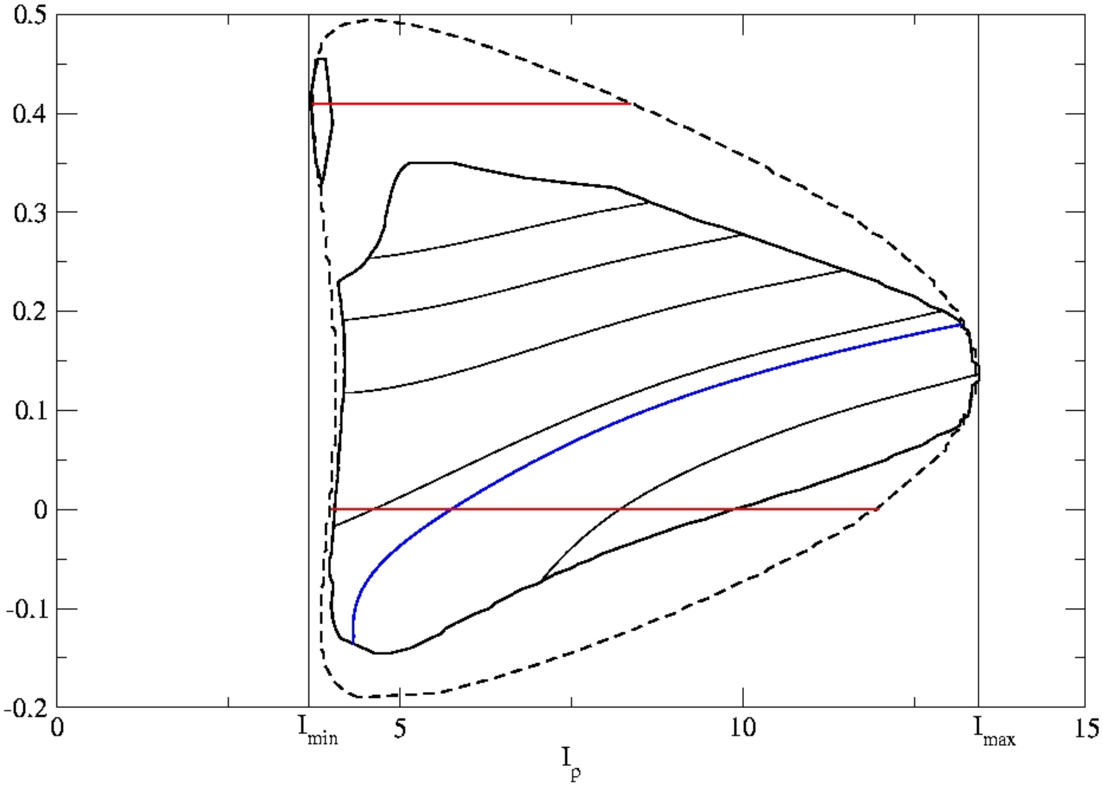
IC and C. Ciuti, Phys. Rev. B **72**, 125335 (2005)

Looking more in detail... the k_s selection problem

Equilibrium systems: BEC in lowest energy state

Non-equilibrium:

- no free energy available
- k_s dynamically selected
- Methods of pattern formation in nonlinear dynamical systems (H. Henry, A. Couairon, J.-M. Chomaz)



- Finite excitation spot: absolute vs. convective instability
- Increas. pump intens.: change in k_s
- Single ω_s, but inhomogeneous broadening of k_s
- Limits coherence length of OPO emission: important for applications!

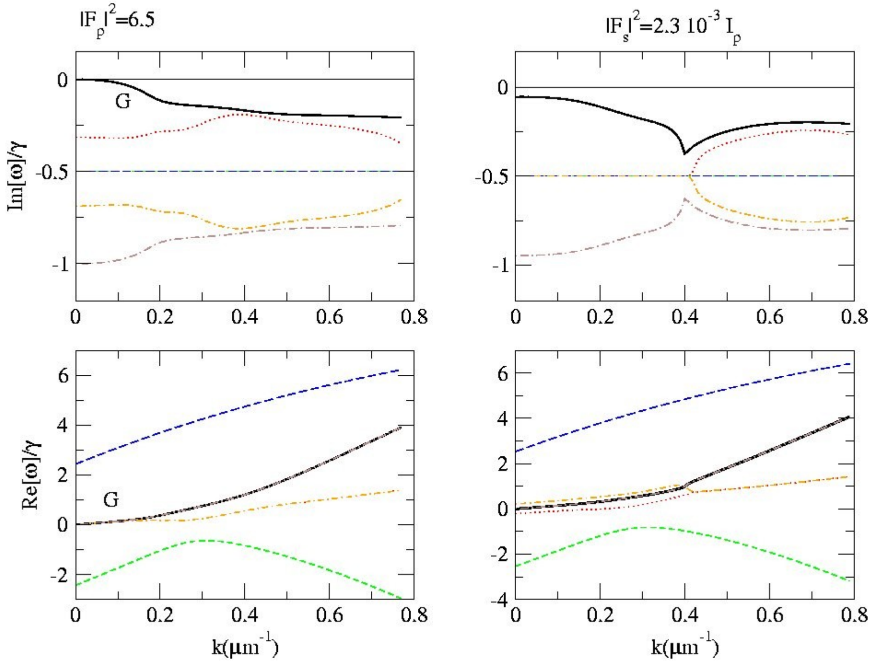
M.Wouters and IC, *Pattern formation and parametric oscillation in planar cavities*, in preparation.

Looking more in detail... the Goldstone mode

Non-equilibrium steady state
above threshold:

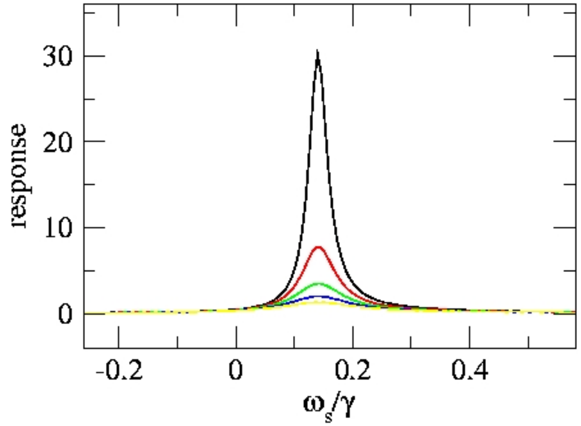
- U(1) symmetry spont. broken
- Soft Goldstone mode
- Slow rotation of signal/idler phases

all this as at equilibrium !!!



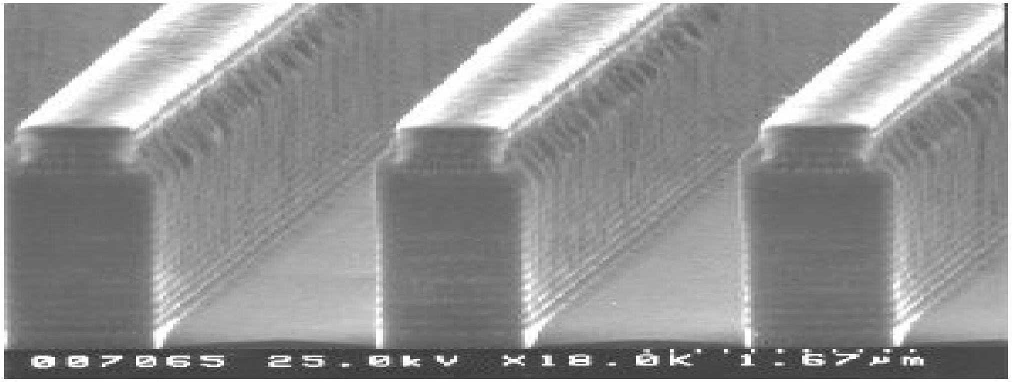
But:

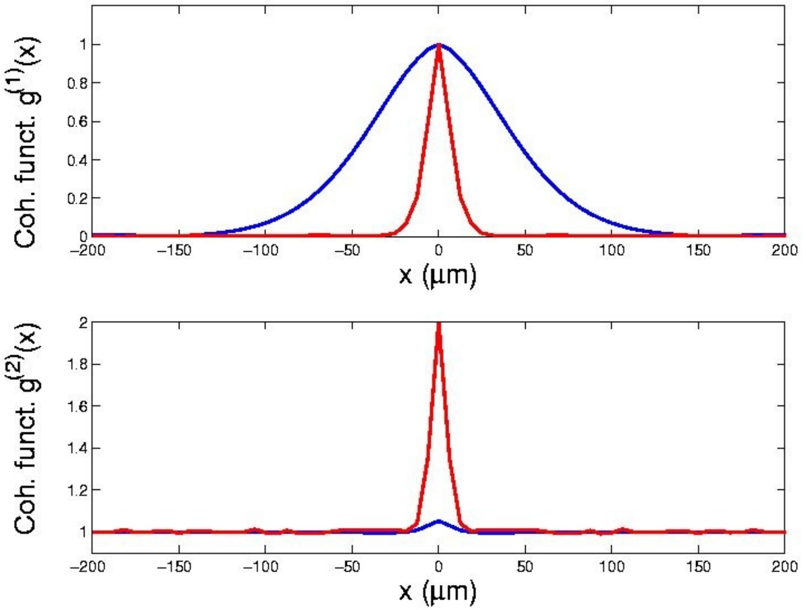
- Goldstone diffusive, not propagating
- Can be probed by additional laser
- Seeding OPO at k_s: as external B field in ferromagnet. Gap opens, peak broadened.



M.Wouters and IC, *Probing the Goldstone mode of parametric oscillation in planar cavities,* in preparation.

Looking more in detail... quasi-condensates in 1D

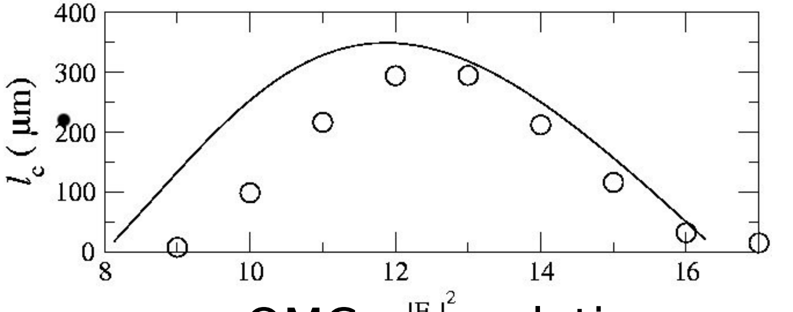




- Intensity fluctuations suppressed
- ... but phase coherence still finite range !!

Analytical calculations (Wigner)

- Quantum noise drives Bogoliubov modes.
- Effect strongest on Goldstone mode because of lowest damping
- Exponential decay: $g^{(1)}(x) \propto \exp(- x / l_c)$



QMC vs analytics

M.Wouters and IC, *Absence of long-range coherence in the parametric emission from photonic wires, cond-mat/0512464,* subm. to PRL

Experiment in progress at LPA-ENS by J.Tignon

New developments

Hawking effect with polaritons (collab. R. Balbinot)

- Polaritons directly injected by patterned laser field:

  → space-dependent density and/or flow velocity
- Sub- to super-sonic flow interface in polariton fluid
- Hawking radiation contributes to incoherent luminescence.
  - What are characterizing properties?
  - How strong it is?

Polariton-polariton interactions

- Quantitative measurements and comparison to available QMC data
- Feshbach resonances due to biexciton states

Part 2

Dynamical Casimir effect

Iacopo Carusotto, Francesco Bariani
Mauro Antezza, Germano Tessaro

Collab: C.Ciuti (LPA-ENS)

What is the Dynamical Casimir effect?

Static Casimir effect: e.m. vacuum fluctuations of exert reactive force on mirror

Dynamical Casimir effect: e.m. vacuum fluctuations exert dissipative force opposing mirror's motion. Correspondingly real photons are emitted

Emission enhanced in high-finesse optical cavity with periodically oscillating mirrors.
Parametric resonance condition $\omega_0=\omega_m+\omega_n$

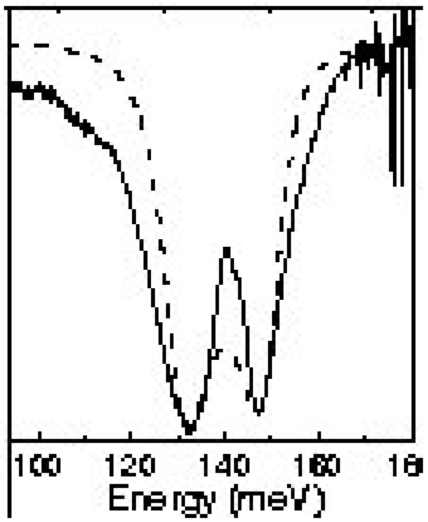
Effect still to be observed:

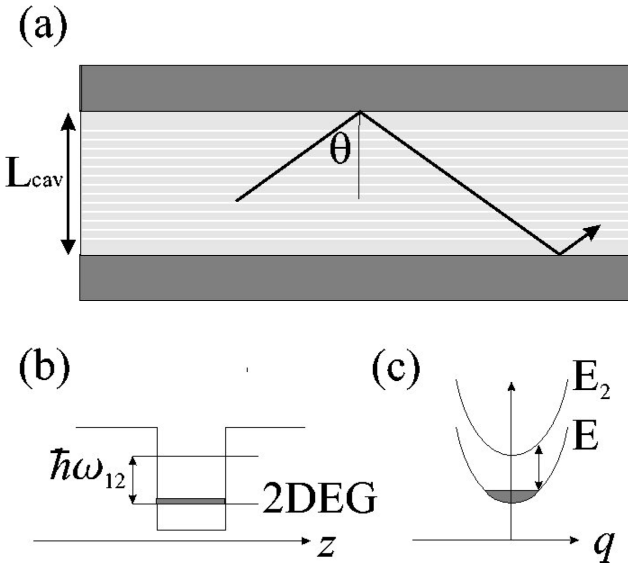
- hard to put macroscopic object in mechanical oscillation at high frequency
- better to change optical length by modulating refractive index within cavity

Our strategy: identify media with extraordinary optical properties and calculate emission intensity from first principles

- **Solid state systems**: strong light-matter coupling, but large linewidths. Intersubband transitions in QWs
- **Atomic systems**: long coherence times, fast and complete control on system parameters. Mott-insulator states in the EIT regime.

Intersubband transitions in Quantum Wells





Electronic polarization coupled to cavity photon mode

- Hopfield model of two coupled bosonic modes

$$H = \omega_X \, a_X^+ a_X + \omega_C \, a_C^+ a_C + \Omega_R (a_C + a_C^+)(a_X + a_X^+)$$

- Elementary excitations are polaritons.
- Polaritonic peaks observed in reflection spectra
- “world record” for polariton splitting: ultra-strong coupling regime

$$\omega_{X,C} \geq \Omega_R \gg \Gamma$$

Properties of the ground state and dynamical Casimir emission

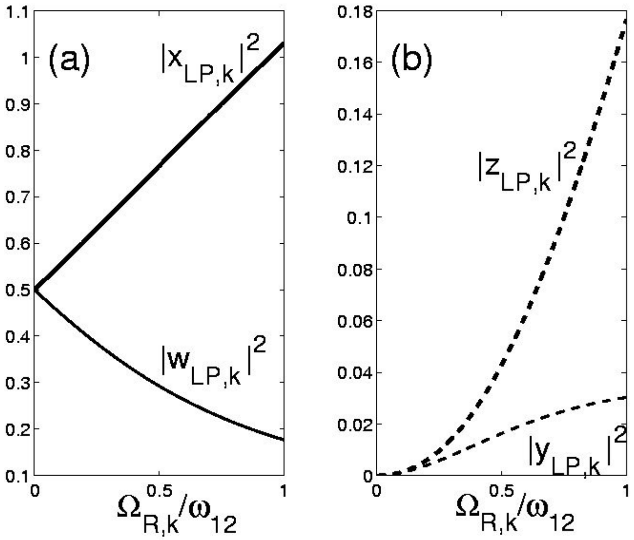
Because of anti-RWA terms in Hamiltonian:

- polariton annihilation operator:

$$p_{LP} = w\,a_C + x\,a_X + \underset{\uparrow}{y\,a_C^{+}} + \underset{\uparrow}{z\,a_X^{+}}$$

- ground state Is squeezed
- finite number of (virtual) excitations present

$$N_C^0 = \langle g | a_C^{+} a_C | g \rangle = |y|^2 + |z|^2 \sim (\Omega_R / \omega_C)^2$$



To transform them into real excitations:

→ **time-modulation** of $\omega_{X,C}$ and/or Ω_R

Simplest case: Ω_R non-adiabatically switched off

- new ground state coincides with standard vacuum
- all (virtual) photons present in the system become real and can escape as **dynamical Casimir radiation**
- effect stronger for periodic change of Ω_R resonant with cavity mode

C. Ciuti, G. Bastard, IC, *Quantum vacuum properties of the intersubband cavity polariton field*, PRB **72**, 115303 (2005).

Complete calculations

Dissipation and coupling to radiative modes to be included:

- **Input-output formalism**, quantum Langevin equations for cavity-photon and electronic polarization operators
- colored damping kernel and noise: otherwise energy not conserved
- analytical solution possible in time-independent case. Recovers previous results

General theory and time-independent applications: reflection and transmission, electroluminescence. **Technological applications**: detectors, FIR LEDs

- C.Ciuti and IC, *Input-output theory of cavities in the ultra-strong vacuum Rabi coupling regime,* to be submitted.

Time-dependent problem and **dynamical Casimir effect**: work in progress.

Encouraging results (S. De Liberato DEA work at LPA-ENS) : large Ω_R allows for strong emission even with modulation at low-frequency.

Ultra-cold atoms in optical lattices: Mott insulator states

N atoms trapped at each site. Very interesting system for **optical applications**

- Extremely regular lattice
- Deterministic mean-field shifts, no collisional decoherence
- No Doppler effect, only radiative linewidth
- Lamb-Dicke trapping suppresses recoil

Lower density, radiation-matter coupling much weaker than in solids:

- very small N_c^0 ...
- ... but very long coherence time.
- Allows to sum over many non-adiabatic kicks

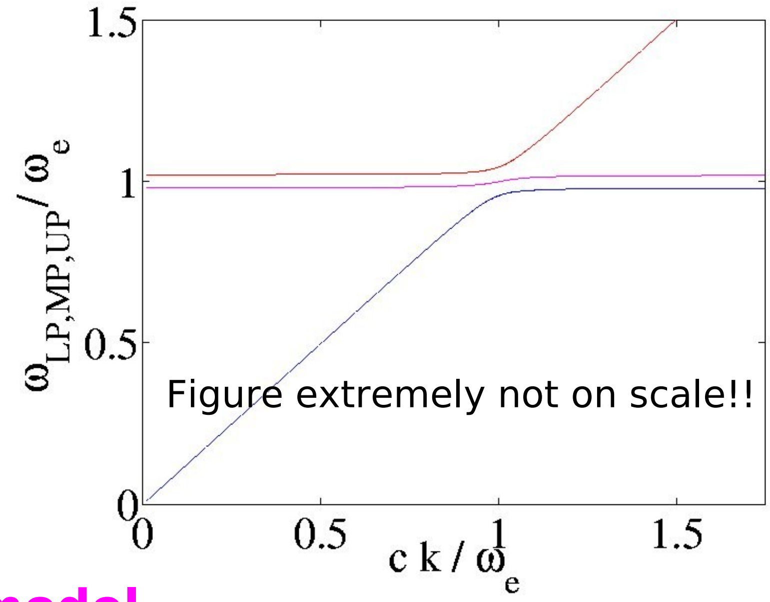


Figure extremely not on scale!!

3-level atoms, additional coupling laser:
EIT regime

- Extremely low v_g means long exit time
- low absorption at resonance

Complete calculations in progress**: EIT-Hopfield model**
EIT-polaritonic band structure in lattice: **F. Bariani's laurea**

Part 3

Dynamical photonic structures

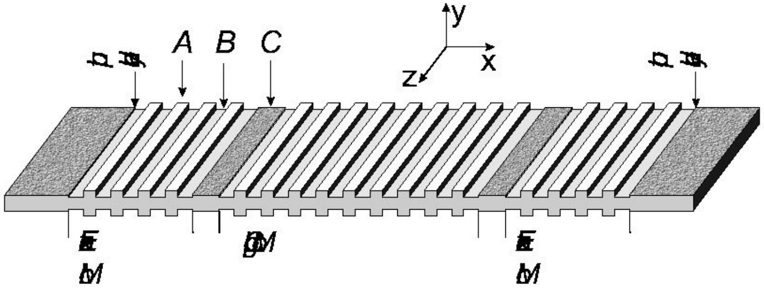
Iacopo Carusotto, Alessio Recati, Mauro Antezza

Collab: F.Riboli, M.Ghulinyan, Z.Gaburro, L.Pavesi (UniTN)
A.Trombettoni (UniPG)

Photon energy lifter

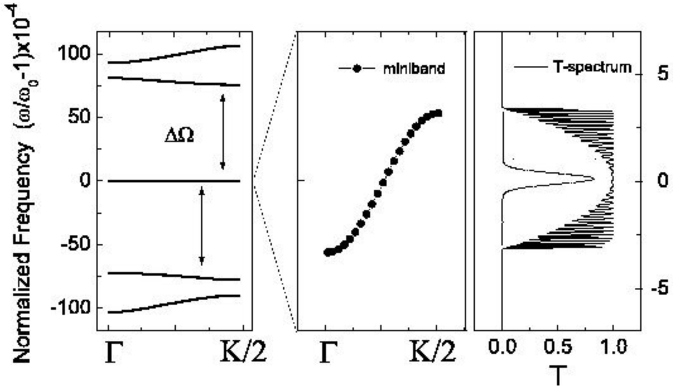
Usual time-resolved (pump-probe) spectroscopy:

- response of system depends on instantaneous value of parameters
- constant properties during propagation time



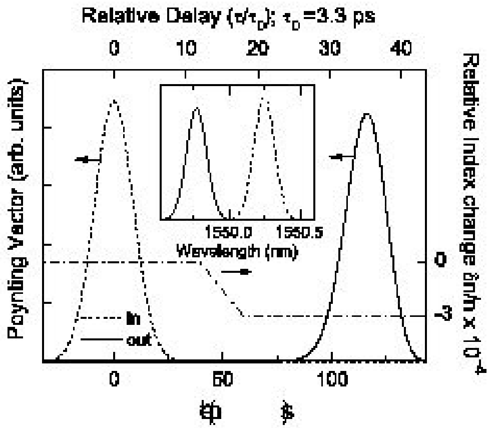
Dynamic photonic structure

- e.g. homogeneous dielectric, time-dependent n(t)
- change of n occurs while optical pulse in medium
- Transl. Invariance k conserved,
  while frequency changes ω (t)=c k / n(t)
- CROW geometry: slower light, more time to switch



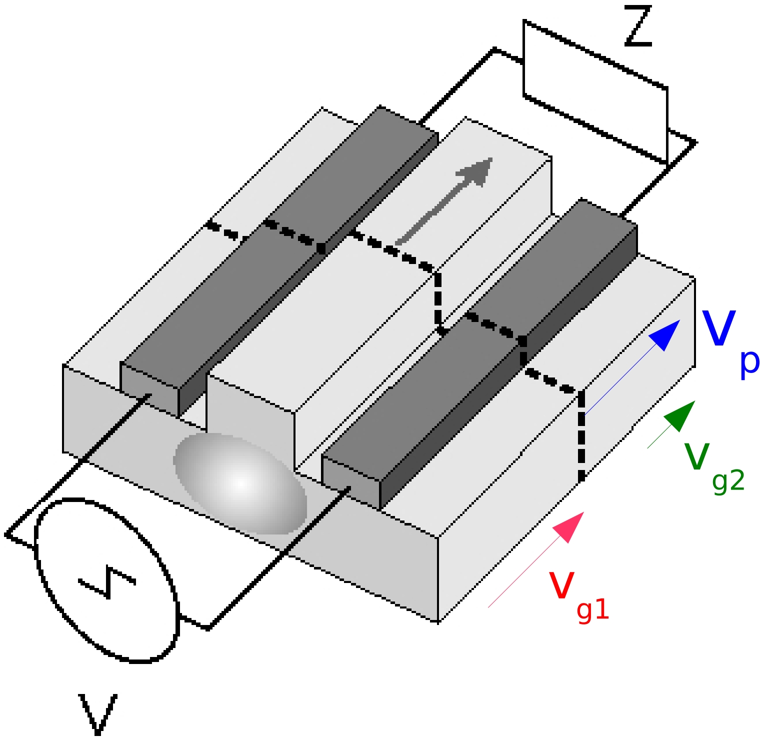
Applications

- Frequency tunable over continuous range
- Frequency conversion without affecting pulse shape
- Shift optical signal from one telecom channel to next



Z.Gaburro, M.Ghulinyan, F.Riboli, L.Pavesi, A.Recati, I.Carusotto, *Photon energy lifter*, cond-mat/0510043, subm. to Opt. Expr

Light refraction and reflection at light-induced moving interfaces



Propagating pump pulse

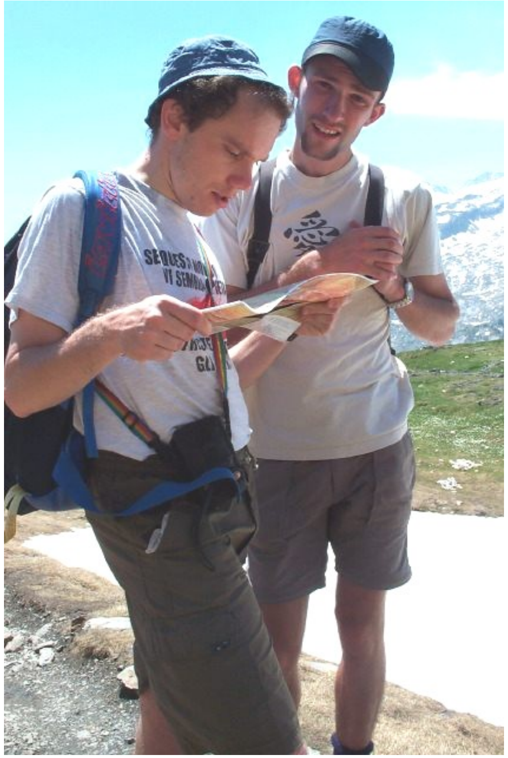
- Moving microwave front travelling at v_p
- Nonlinear electro-optic effect modifies refractive index
- Guided light refracts and reflects on **moving interface**
- Possibility of tuning v_p from **sub-** to **super-luminal**

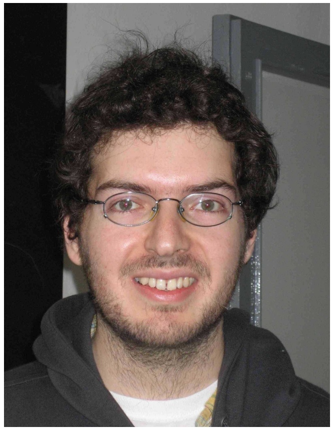
If $v_{g1} > v_p > v_{g2}$ light can not escape from interface

Black hole-like effects for real photons and quantum fluctuations

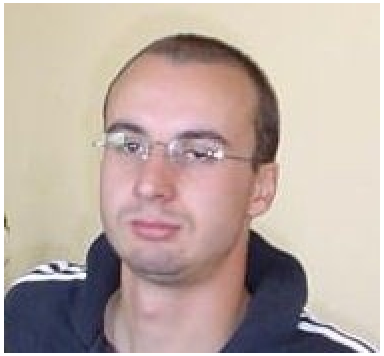
Work in progress

Non-Equilibrium Polariton BECs
Analogies and Differences with Cold Atoms





Quantum Fluctuations in E.M. vacuum
Optical Experiments
Dynamical Casimir effects



New Materials and Nanostructures
for New Optical Effects