Spectroscopy of a non-equilibrium Tonks-Girardeau gas of strongly interacting photons

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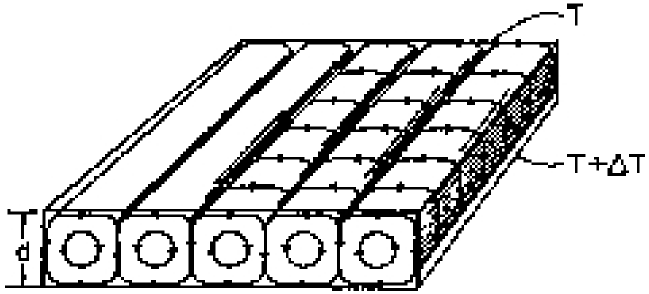
The non-equilibrium world

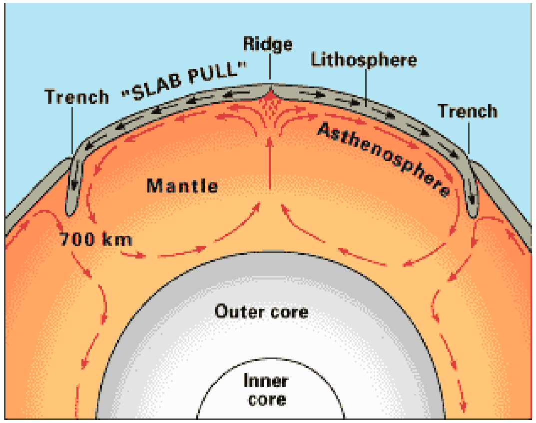
Thermodynamical equilibrium:

- Boltzmann probability distribution $\exp(-E/k_b T)$
- fluctuation-dissipation theorems of linear response theory
- general theorems on phase transitions, e.g. in low-D



Non-equilibrium steady-states:

- dynamical balance of driving and dissipation
- no Boltzmann factor, dynamics plays major role



Non-equilibrium phase transitions:

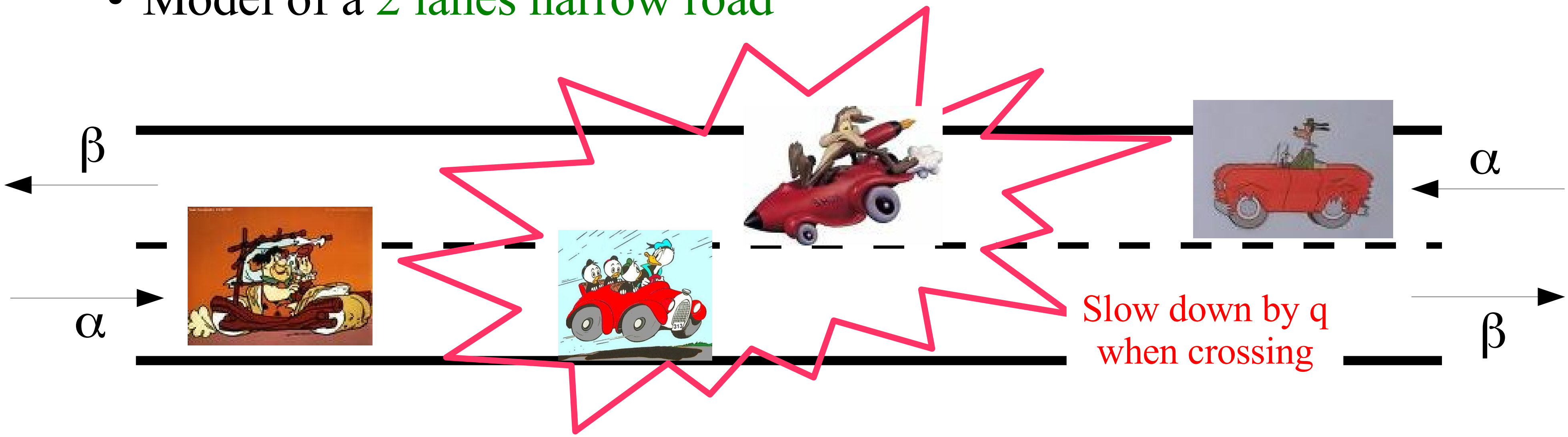
- Bénard convection cells: break translational symmetry
- driven-diffusive lattice gases: non-equilibrium Ising transition
- lasing: break U(1) symmetry, sort of non-equilibrium BEC
- interplay of quantum physics with non-equilibrium still to be explored

Non-equilibrium phase transitions in 1D systems

General theorems forbid phase transitions in 1D equilibrium systems

Non-equilibrium world richer:

- Totally asymmetric, two component exclusion process (TASEP-2)
- Model of a 2 lanes narrow road



When traffic is heavy: road turns into effectively one-way

- Spontaneous left/right symmetry breaking
- Robust against fluctuations
- Reversal time grows exponentially with length of road

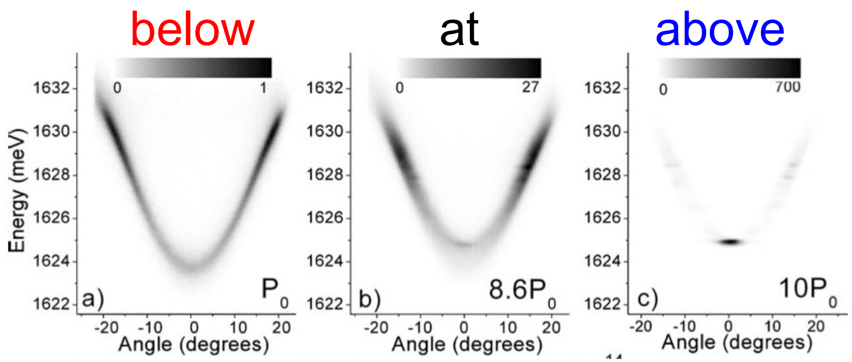
See e.g. D. Mukamel's NATO lectures, cond-mat/0003424

Non-equilibrium many-body physics with light

1 - Shape of exciton-polariton Bose-Einstein condensates

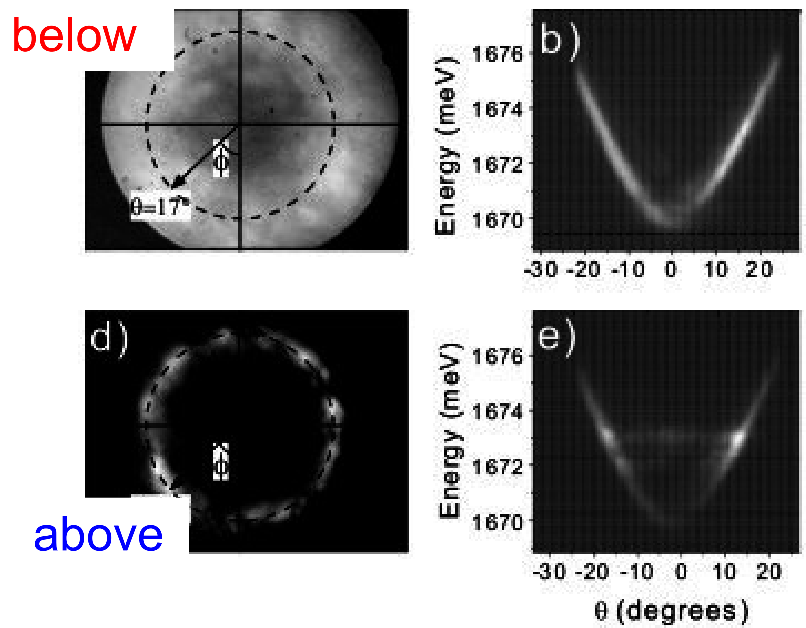
Large pump spot:

- BEC into k=0



Small pump spot:

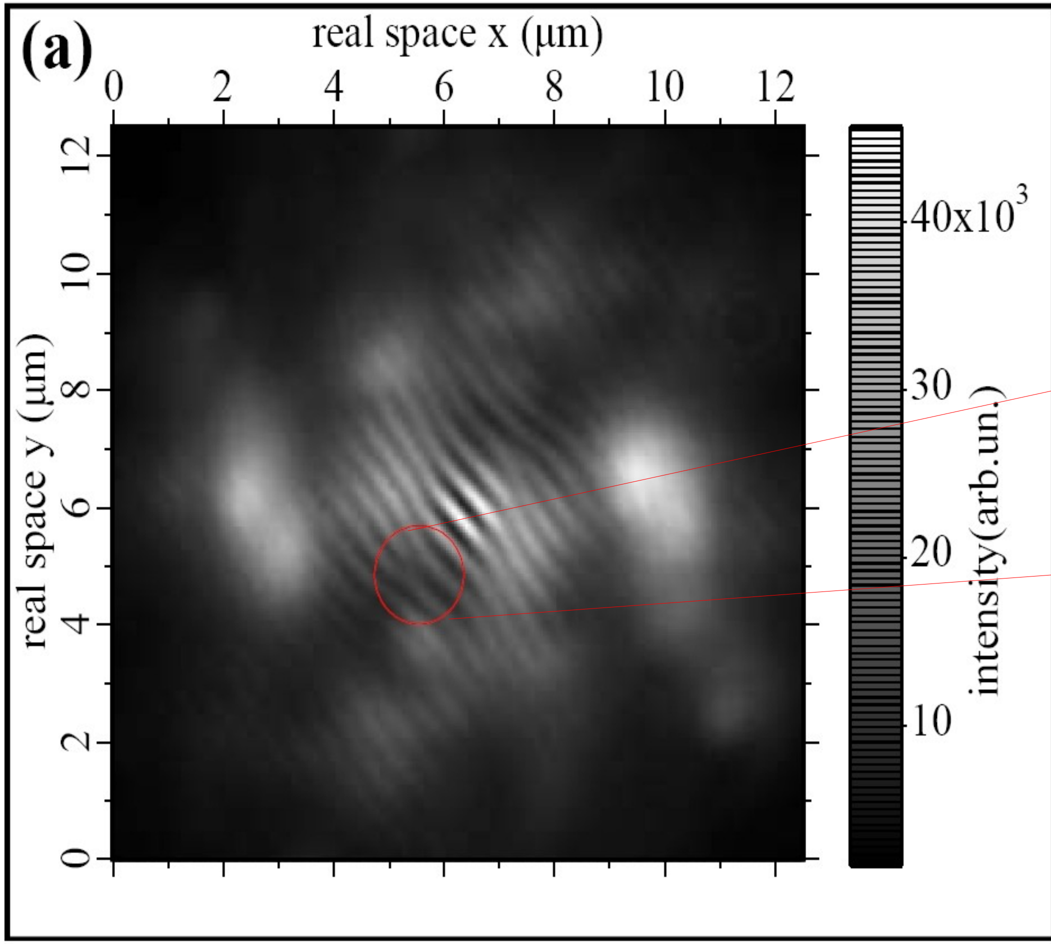
- BEC on ring in k-space
- radial flow under effect of pump and interactions
- still fully coherent BEC
- close relation with lasing and random lasing



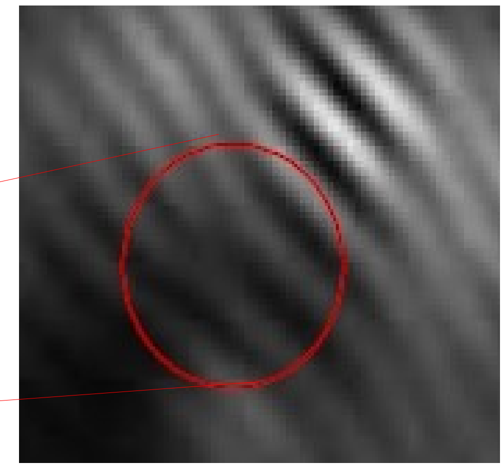
Figures from Grenoble group: M. Richard et al., PRB **72**, 201301 (2005); M. Richard et al., PRL **94**, 187401 (2005)

Theory: M. Wouters, IC, and C. Ciuti, PRB **77**, 115340 (2008)

2 – Appearance of quantized vortices



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,* Nature Phys. **4**, 706 (2008).



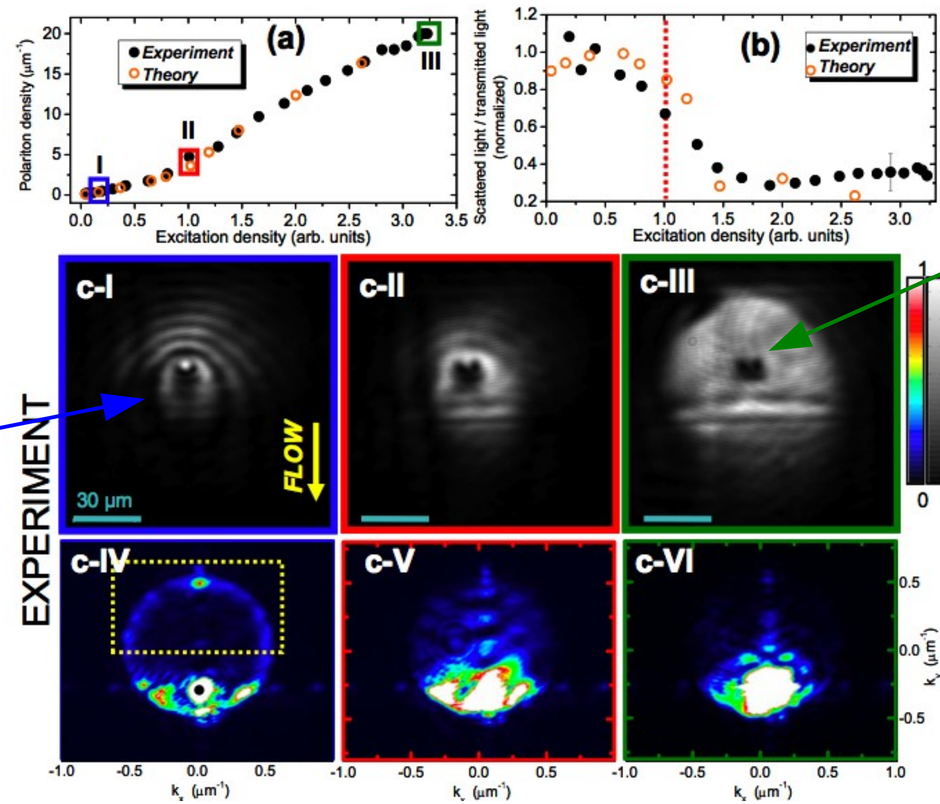
Fork dislocation in interference pattern with a plane wave

- phase singularity in macroscopic wavefunction
- appears with no need for stirring
- interplay of non-equilibrium flow, disorder and interactions

3 – Polariton superfluidity according to Landau criterion

superfluid flow

scattering
on defect



increase polariton density

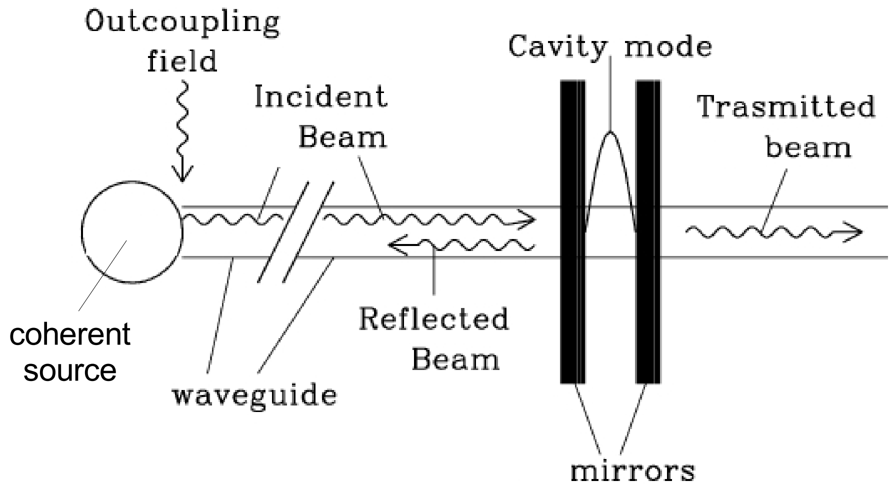
Figure from LKB-P6 group: J.Lefrère, A.Amo, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, submitted (2008)
Theory: IC and C. Ciuti, PRL **93**, 166401 (2004).

.... but all these effects are at mean-field level !!

Beyond mean-field effects

Single-mode system:

- coherent pump provides driving
- radiative losses give dissipation
- nonlinearity gives interactions.



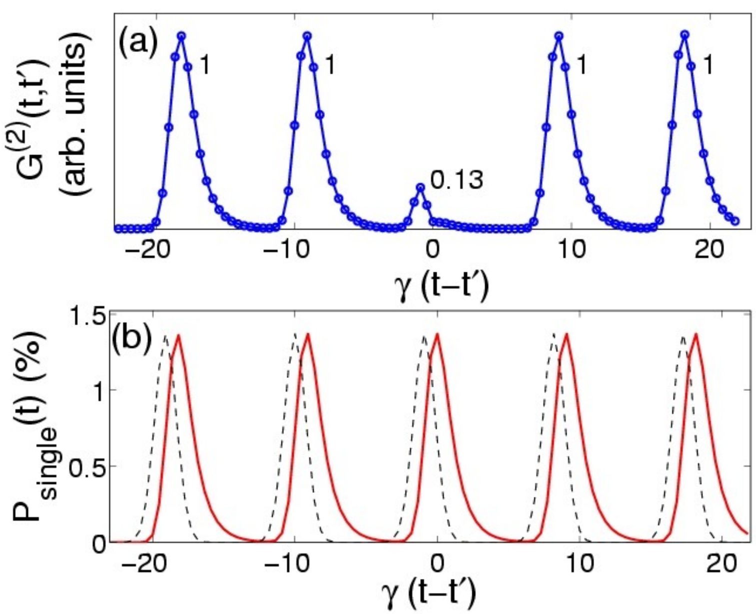
Quantum features if $U >> \gamma$

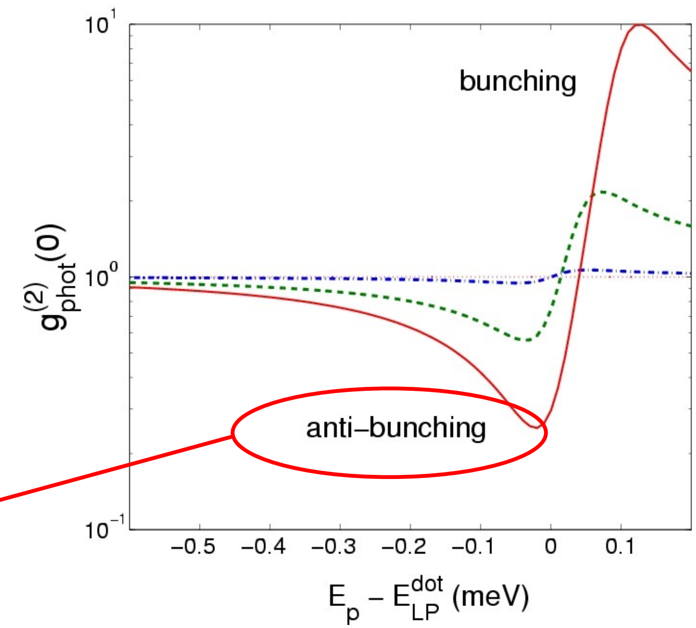
- red-detuned pump: negative feedback, antibunching $g^{(2)}(\tau=0)<1$
- blue-detuned pump: positive feedback, bunching $g^{(2)}(\tau=0)>1$

Spatially extended, many-mode systems:

- complex interplay of classical and quantum dynamics
- in-cavity quantum correlations transfer into statistics of emission

Bunching vs. anti-bunching





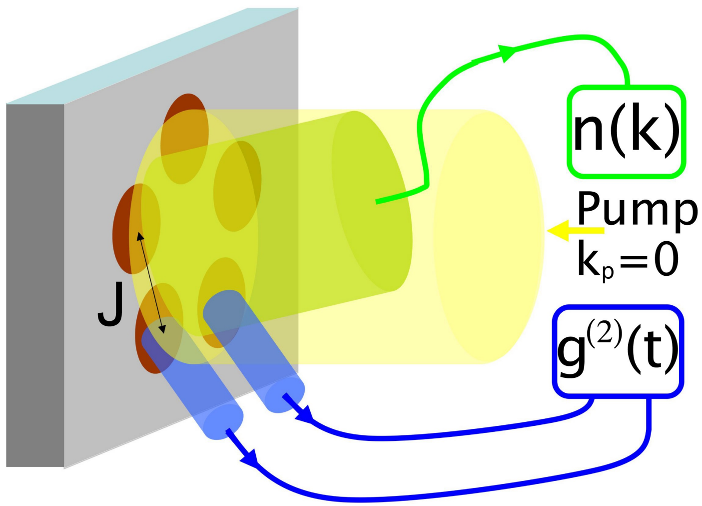
A. Imamoglu, H. Schmidt,G. Woods,M. Deutsch, Phys. Rev. Lett. **79**, 1467 (1997)
Figures here from: A.Verger, C. Ciuti, IC, Phys. Rev. B 73, 193306 (2006).

The many-cavity system: 1D array of coupled cavities

- periodic boundary conditions
- strong on-site repulsion U
- Josephson tunnel coupling J
- external driving F_p:

  monochromatic at ω_p

  plane wave shape $k_p=0$



- weak losses γ << J,U but always crucial to determine steady-state
- light collected in reflection and/or transmission geometry
- far-field emission: k-selection from orbital angular momentum
- near-field emission: spatial resolution

Impenetrable bosons ($U=\infty$): Girardeau's Bose-Fermi mapping

Many-body wavefunction in terms of non-interacting Fermions

$$\psi(x_1, x_2, \ldots) = \epsilon[\sigma(x_1, x_2, \ldots)]\, \psi_F(x_1, x_2, \ldots)$$

✓ density and density fluctuations preserved in Bose-Fermi mapping

✗ coherence function $g^{(1)}(x,x')$ and momentum distribution not preserved

Many-body states labeled by momenta q of occupied Fermi orbitals $|q_1, q_2, q_3 \ldots\rangle$

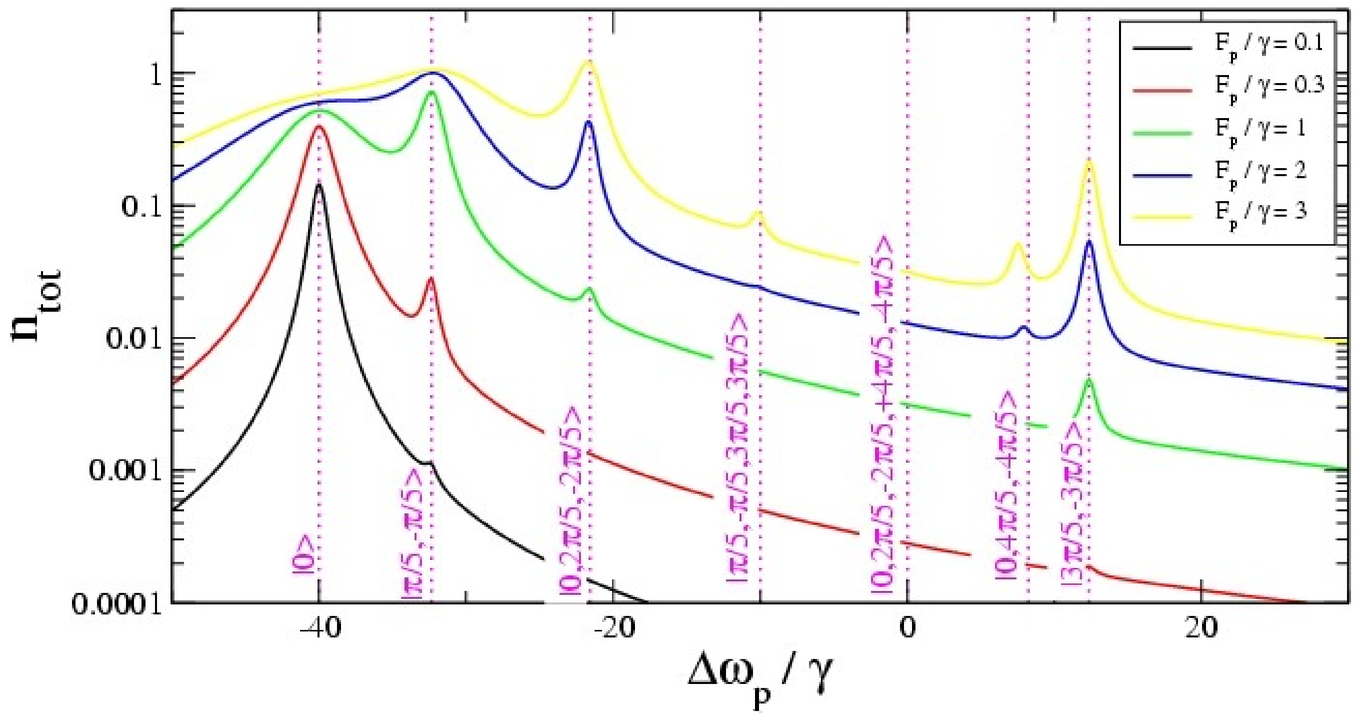
Periodic boundary cond.: Fermi orbitals satisfy PBC/anti-PBC for odd/even N

Energy (and momentum) preserved by mapping $E = \sum_i \frac{\hbar^2 q_i^2}{2m}$

Example: two-particle states $\psi(i_1, i_2) = \frac{1}{\sqrt{2L}} \sin\left(\frac{(2n+1)\pi}{L} |i_1 - i_2|\right)$

M. D. Girardeau, Phys. Rev. **1**, 516 (1960)

Impenetrable bosons (U=∞): photoluminescence



Total luminescence as a function pump frequency for fixed pump intensity:

- each peak corresponds to a many-body state $|q_1,q_2,q_3...>$
- q_i quantized according to PBC/anti-PBC depending on N=odd/even
- N-particle state excited by N photon transition
- many-body energy E corresponds to peak at $\Delta\omega_p = E / N$
- intensity of peak grows as $(I_p)^N$

Finite-U effects: analytics

Weakly-interacting limit U<<J :

- mean-field approximation + perturbation theory valid
- lowest 2-body state: peak position $\Delta\omega_p \approx -2J + U/M$
  almost factorizable wf

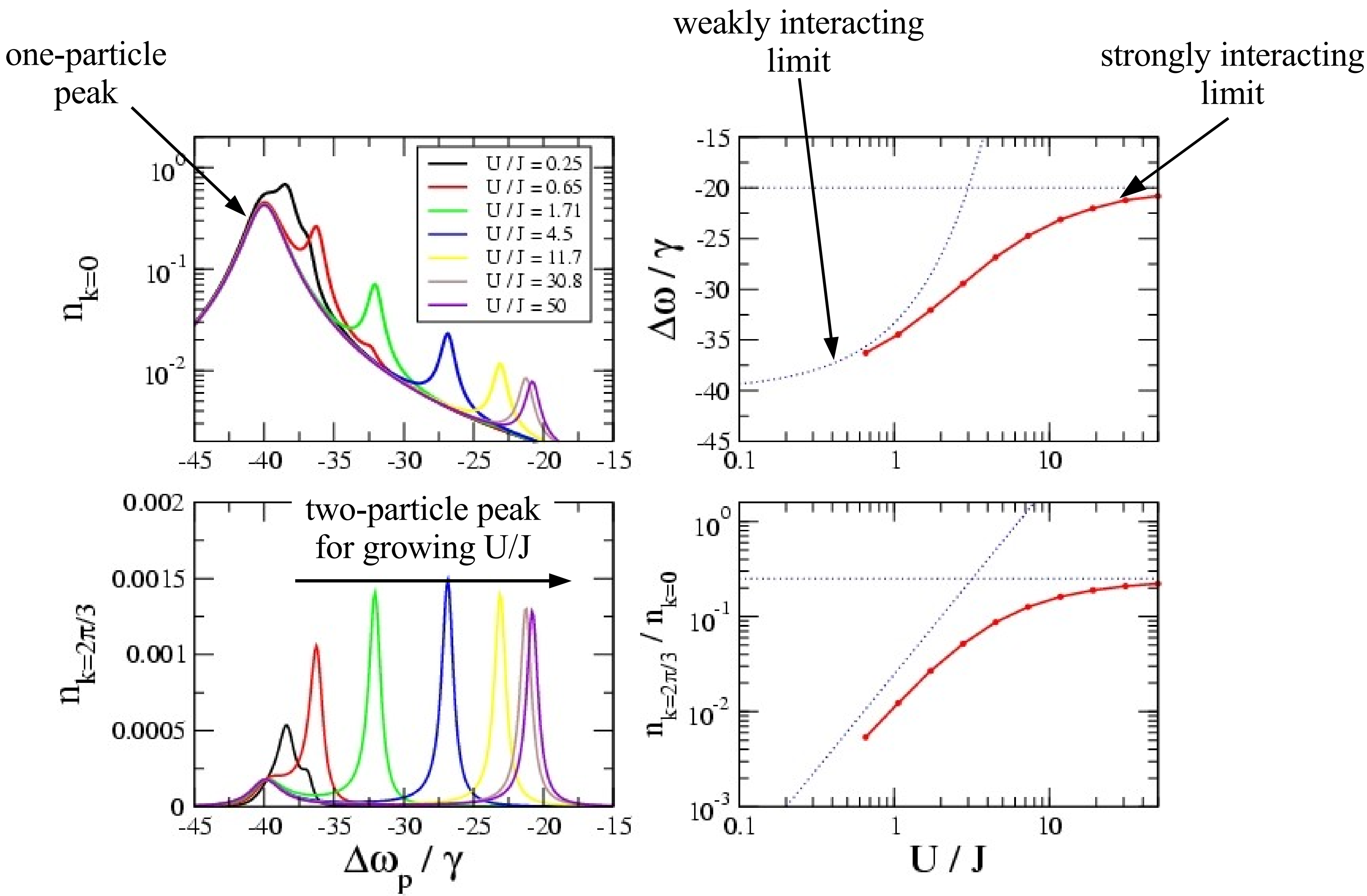
$$\psi(i_1, i_2) = \frac{1}{M}\left[1 - \frac{U}{9J}\cos\left(\frac{2\pi}{3}\,(i_1 - i_2)\right)\right]$$

Strongly-interacting limit U>>J :

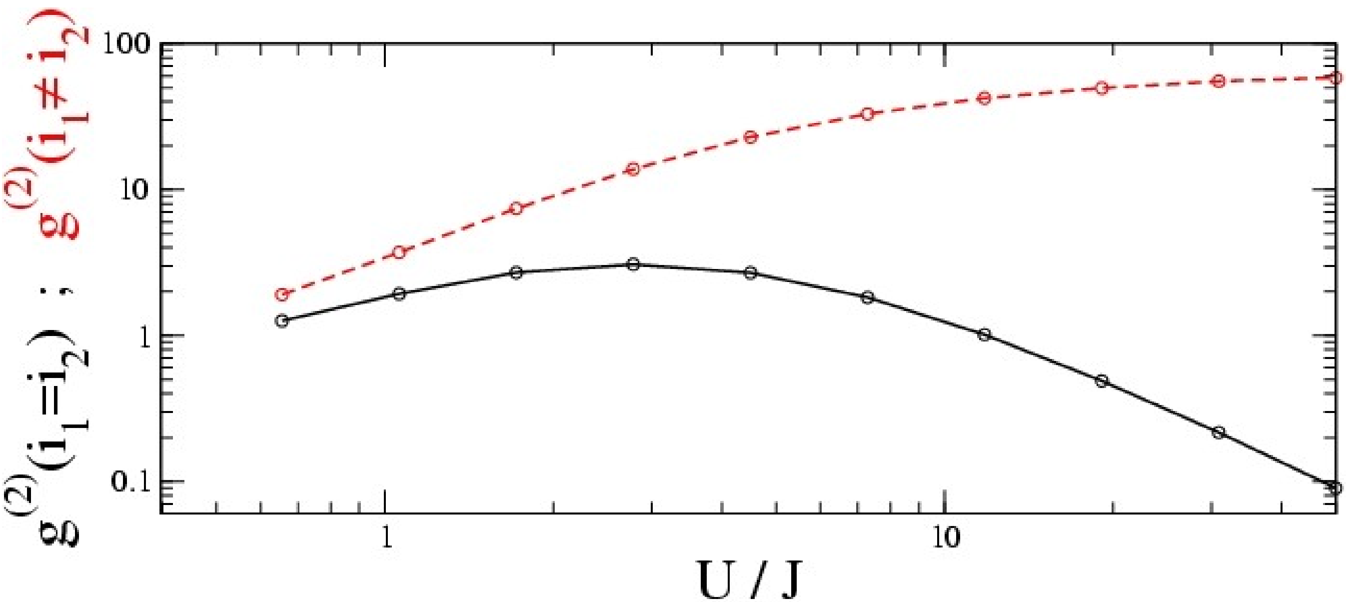
- strongly correlated Tonks-Girardeau gas
- lowest 2-body state: peak position $\Delta\omega_p \approx -J$.
  signature of anti-PBC of Fermi orbitals
  wf has many components

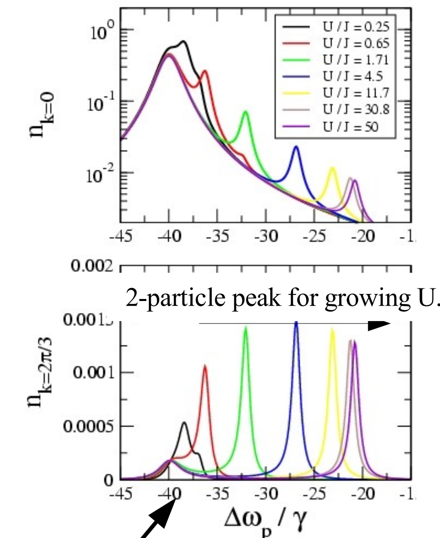
$$\psi(i_1, i_2) = \frac{1}{\sqrt{2}\,M}\sin\left(\frac{(2n+1)\pi}{L}\,|i_1 - i_2|\right)$$

Finite-U effects: k-resolved photoluminescence



Emitted light: spatial intensity correlations

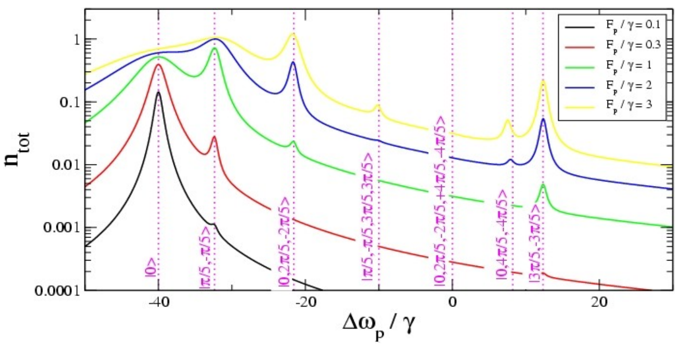


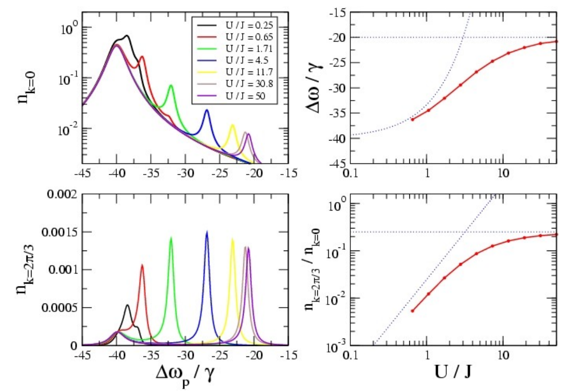


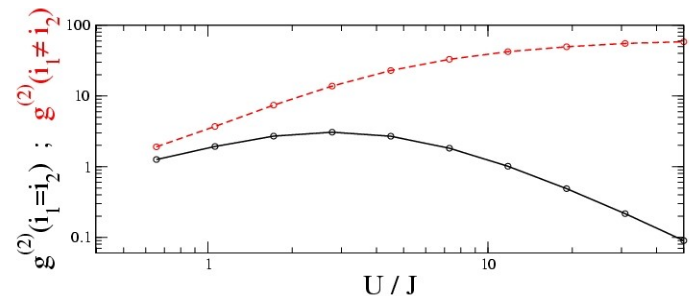
For each U/J, tune the pump laser on two-photon resonance

- intensity correlation between the emission from cavities i_1, i_2
- larger probability of having either N=0 or 2 particles than N=1
- low U<<J: bunched emission for all pairs of i_1, i_2
- large U>>J: antibunched emission from a single site
  positive correlations between different sites.

Theoretical conclusions







Many-body structure of eigenstates characterized from optical spectra

- Position of peaks gives energy of many-body eigenstates
- Peaks spectrally well resolved in mesoscopic systems
- Spectral selection via pump and/or detection identifies single state
- Intensity of peaks as a function of pump intensity gives number of particles
- Spatially-resolved intensity correlation functions of emission provide info on microscopic structure of state
- Far-field correlations provide info on momentum distribution and momentum correlations

More details: IC, D. Gerace, H. E. Türeci, S. De Liberato, C. Ciuti, A. Imamoglu, to appear soon!

Experimental requirements

- Nonlinearity at single quantum level

  strong coupling with quantum dot or quantum well exciton

  small cavity-mode volume

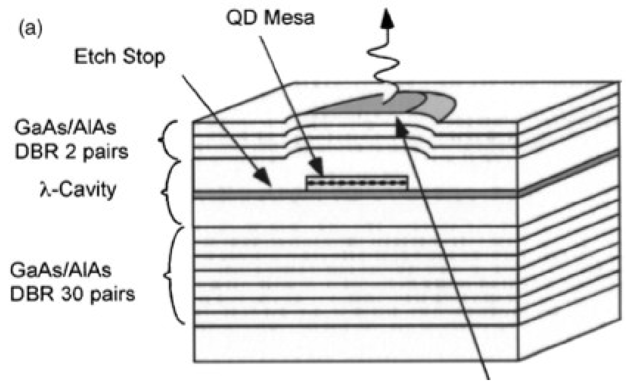
- Scalability

  growth of many identical cavities
  deterministic control of spectral position
  significant inter-cavity tunnel coupling

- Optical access and collection efficiency

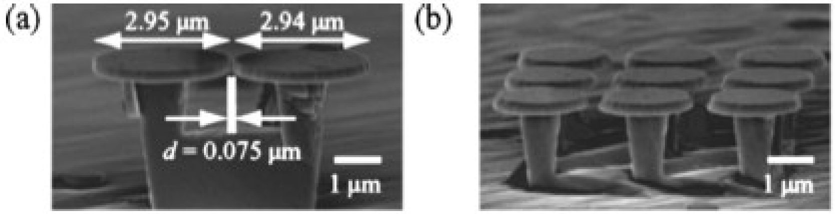
  single-site addressability
  momentum-space analysis of emission
  high collection efficiency

(Some) possible experimental routes

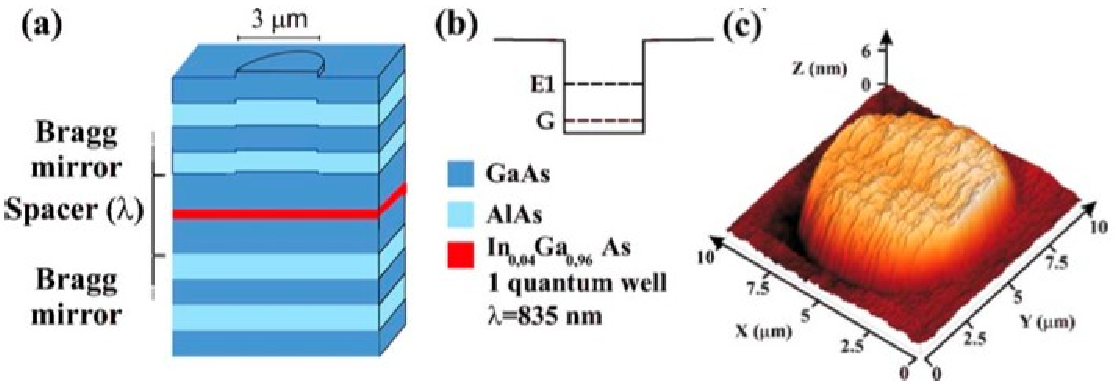


Lens-shaped cavities
Lu *et al.*, APL 87, 163105 (2005)

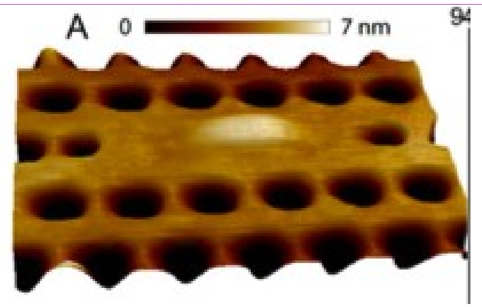
"Pisa tower" micropillars
From LPN website



Arrays of microdisks
Nakagawa *et al.*, APL 86, 041112 (2005)



Polariton boxes
El Daïf *et al.*, APL 88, 061105 (2006)



Photonic crystal cavity
Hennessy *et al.*, Nature 445, 896 (2007)

Conclusions & future steps

Non-equilibrium statistical mechanics of interacting photon gases

- a variety of correlated many-body states obtainable by spectral selection
- full microscopic characterization from intensity and statistics of emission

Phase transitions

- transition BEC ("superfluid") to thermal observed in weakly interacting systems
- some questions still open in spatially extended geometries (VCSELs, polariton BECs).
- what happens for large U/J ? Mott Insulator/superfluid transition ?

Non-equilibrium: dissipation introduces finite effective "temperature"

- predicted by several models of non-equilibrium quasi-BECs in low-D

  M. Wouters, IC, PR B **74,** 245316 (2006); M. Szymanska, J. Keeling, P. Littlewood, PRL **96**, 230602(2006).
- how general is this result ? Analytical calculations in progress using laser theory

What is meaning of superfluidity for non-equilibrium systems?

- Landau superfluidity of polaritons experimentally observed under resonant pump

  J.Lefrère, A.Amo, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, submitted (2008)
- No general consensus with other criteria, e.g. metastability of supercurrents