Swimming in a sea of light: the adventure of photon hydrodynamics

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Newton's corpuscular theory of light (“*Opticks*”, 1704)

Light is composed of material corpuscles

- different colors correspond to corpuscles of different kind
- corpuscles travel in free space along straight lines
- refraction originates from attraction by material bodies

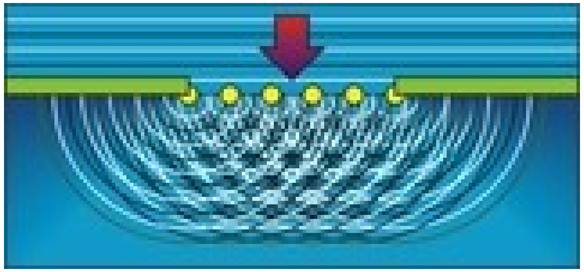
Implicit assumption: corpuscles do not interact with each other

- if they interacted via collisions, they could form a fluid like water or air
- to my knowledge, no historical trace of Newton having ever thought in these terms.

Huygens wave theory of light (“*traité de la lumière*”, 1690)

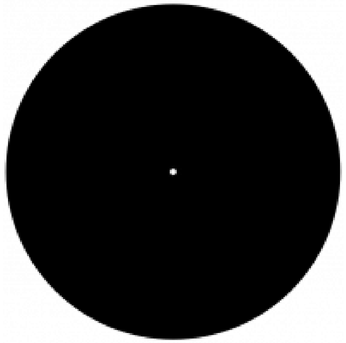
Newton's corpuscular theory soon defeated by rival wave thory of light

- Young two slit interference experiment
- diffraction from aperture:
  Huygens-Fresnel principle of secondary waves
- polarization effects



Arago-Poisson white spot

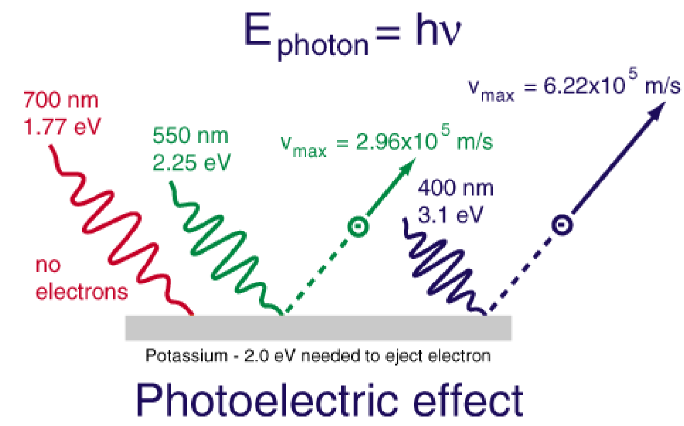
- Poisson ridiculed wave theory predicting bright spot in center of shade of circular object using Fresnel-Huygens theory of diffraction....
- … but Arago actually observed spot in early '800!!
  (actually appear to have been first observed by Maraldi in 1723)
- impossible to explain via corpuscular theory:
  strong support to wave theory



There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy

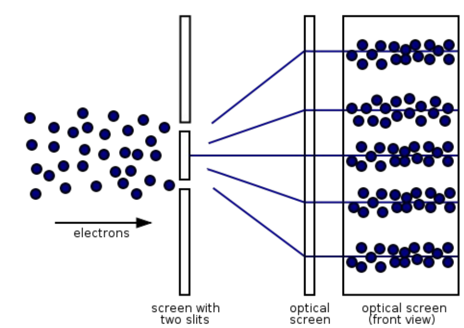
Photo-electric effect:

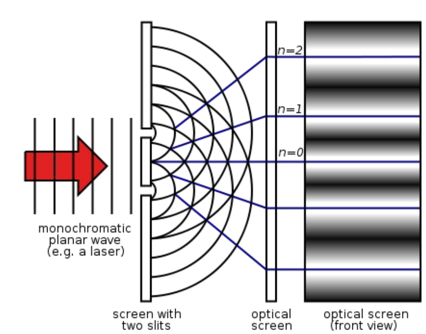
- energy of emitted electrons depends on light frequency and not intensity
- Einstein explains photoelectric effect in terms of light quanta (1905)
- concept of quantum already postulated by Planck to correct black-body catastrophe



But wavy nature of light persists:

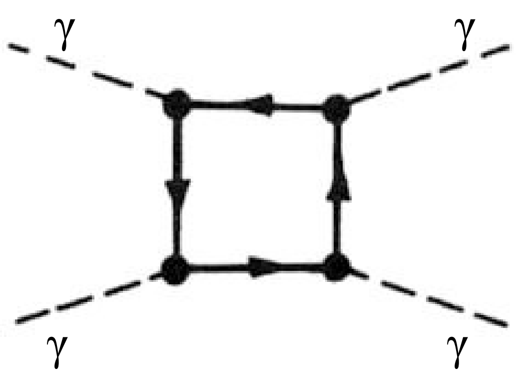
- dual wave-particle properties of photons (and electrons → de Broglie wavelength):
- Young two slit experiment:
  - every photon hits screen at random position
  - probability distribution determined by classical diffraction theory





Light-light scattering

In vacuo:



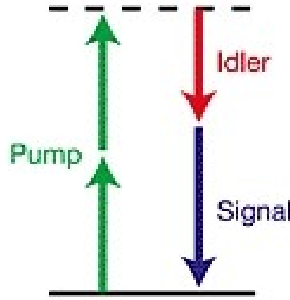
- optical photon-photon scattering mediated by (virtual) electron-positron pairs
- far off-resonance process (e^+-e^- energy ≈ MeV)
- for ħω « mc² : $\sigma \simeq \alpha^4 \frac{\hbar^2}{m^2 c^2} \left(\frac{\hbar \omega}{mc^2} \right)^6$ with ħ / mc =0.4 pm

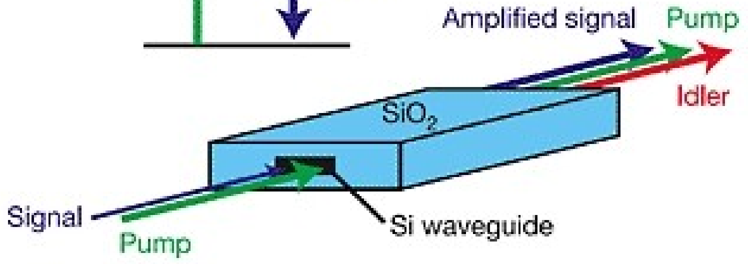
In nonlinear optical medium:

- electronic excitations available at optical energies (≈ eV)
- photon-photon scattering due to nonlinear polarization

$$P = \chi^{(1)} E + \chi^{(3)} E E E$$

Four-wave mixing:





- stimulated photon-photon collision
- still requires strong light intensity and coherence
- first observed in the '60s using laser sources

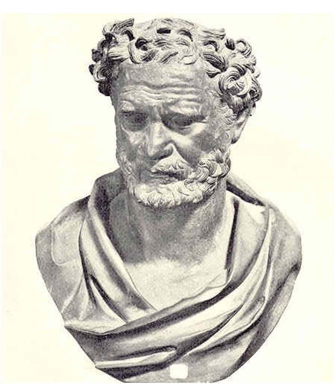
Fluids and gases: a mostly corpuscular history

Demokritus' atomistic model of matter:

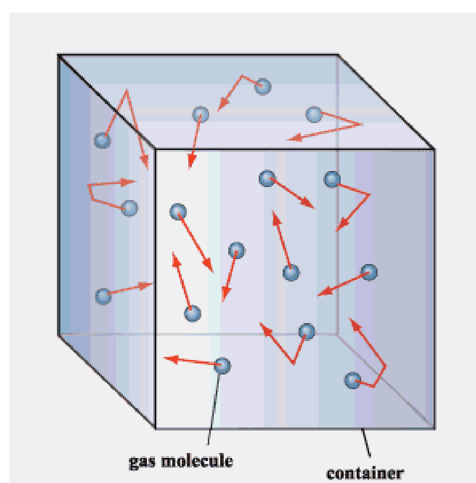
- indivisible atoms as solid objects moving in vacuo
- different material consist of different kinds of atoms
- mostly a philosophical idea, scientifically demonstrated only in modern times

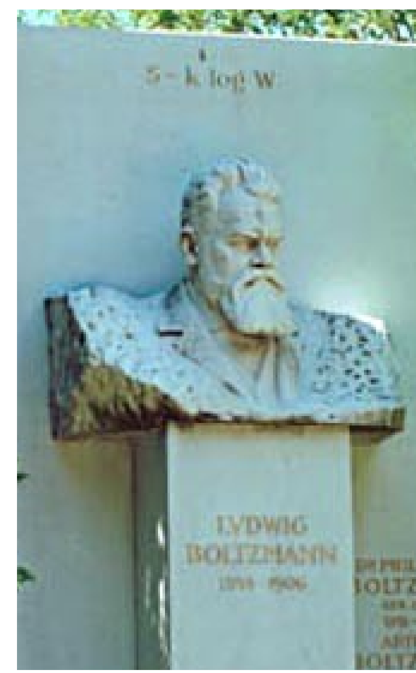
Explains in microscopic terms thermodynamics and chemistry:

- ideal gas laws, kinetic theory of gases
- fundamental laws of chemical reactions
- molecular dynamics understanding of condensed matter phenomena
- statistical fluctuations and Brownian motion



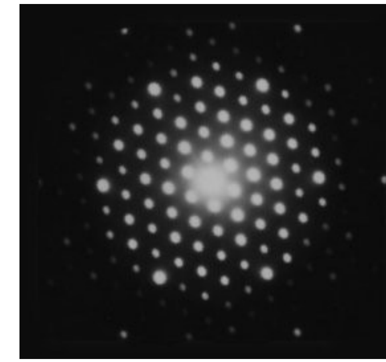
Demokritus





Quantum mechanics: wave nature of matter

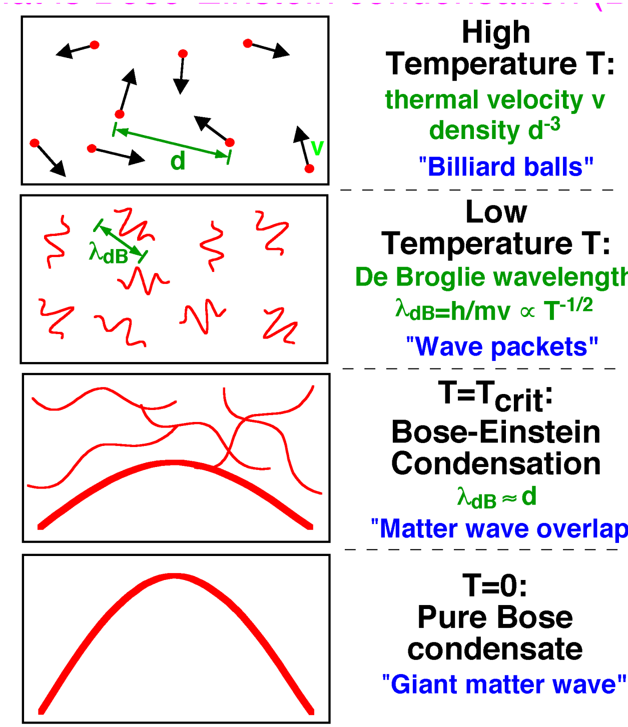
de Broglie wave (postulated in 1924):



- introduced to explain Bohr's model of atomic structure
- wavelength $\lambda = h/p$
- soon measured as interference pattern of electrons
  (Davisson and Germer, 1927)

Apparent at ultralow temperatures:

- thermal de Broglie wavelength $\lambda_{th} = (2\pi\hbar/mk_BT)^{1/2}$
  comparable to interparticle distance
- wave nature of particles starts to matter
- completely different behaviour of macroscopic systems
  depending on integer vs. half-integer spin of constituent particles



sketch from Ketterle group website

Fermions

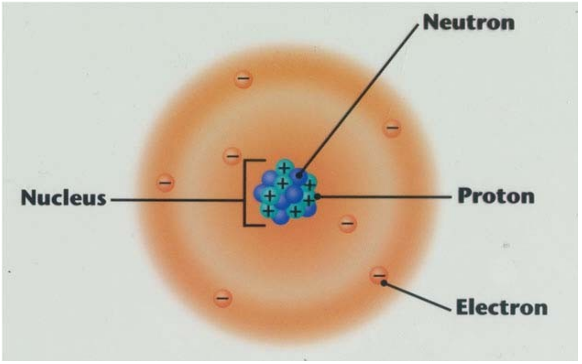
Many-body wavefunction antisymmetric under exchange of two particles

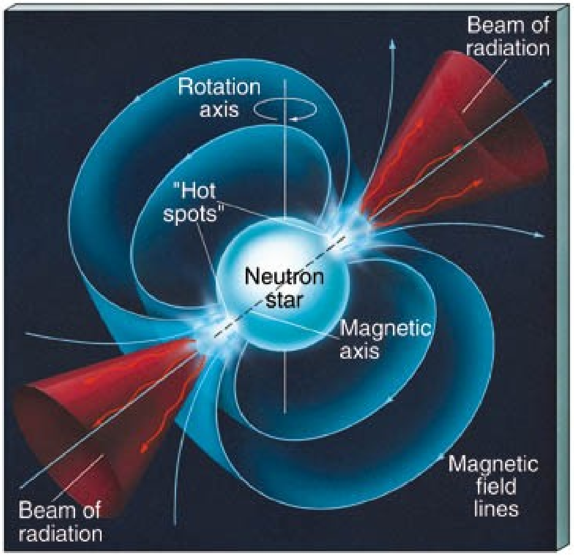
At most one particle at a time can occupy a given quantum state

Ground state: all levels filled upto to Fermi energy E_F

Fermi pressure prevents collapse and stabilizes matter:

- electrons in atoms and metals
- neutrons in neutron stars formed by gravitational collapse
  (when gravity overcomes Fermi pressure of electrons,
  i.e. for star mass above 1.44 solar masses)

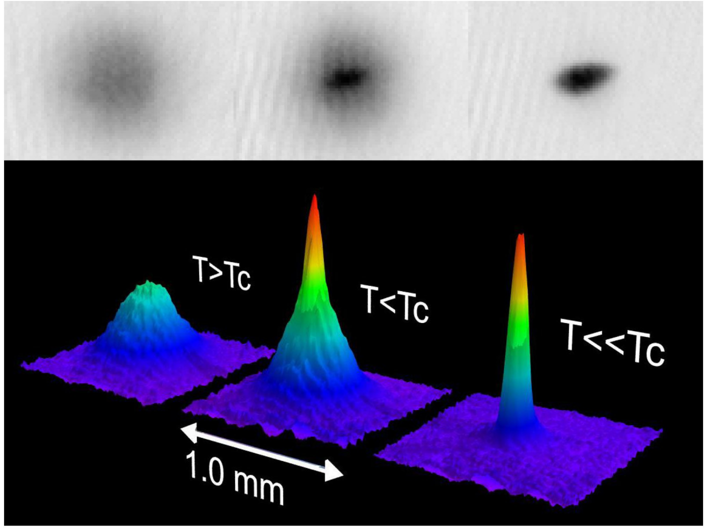




Bosons

Arbitrary number of particles occupy same quantum state:

- ground state: all boson into lowest-energy state,
  the *Bose-Einstein condensate*
- momentum-space condensation into k=0 state
- real-space condensation only in trapped geometries



Picture from Ketterle group website

Even in the presence of interactions:

- macroscopic fraction of atoms into same state
- same macroscopic wavefunction
- matter waves of all atoms "oscillate at the unison"

Macroscopic wavefunction dynamics: Gross-Pitaevskii equation:

$$i\hbar\partial_t\phi = -\frac{\hbar^2}{2m}\nabla^2\phi + V\phi + g|\phi|^2\phi$$

- independent-particle evolution: Schroedinger eq.
- atom-atom interactions responsible for nonlinear term

BEC: a coherent wave of matter

Coherent laser (or radio) e. m. field	$\leftrightarrow$	Coherent matter field of BEC
E, B fields	$\leftrightarrow$	Matter field Ψ
Coherent field $E = <\hat{E}>$	$\leftrightarrow$	Coherent field $\Psi = <\Psi>$
Maxwell equations	$\leftrightarrow$	Gross-Pitaevskii eq.
Nonlinear polarization of medium	$\leftrightarrow$	Atom-atom interactions
Light polarization	$\leftrightarrow$	Atomic spin

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 P}{\partial t^2} \quad \leftrightarrow \quad i\hbar\frac{\partial \phi}{\partial t} = -\frac{\hbar^2}{2\mathrm{m}}\nabla^2\phi + V\phi + g|\phi|^2\phi$$

Atoms of Bose-Einstein condensate effectively forget their corpuscular nature and behave as a macroscopic coherent matter wave !!

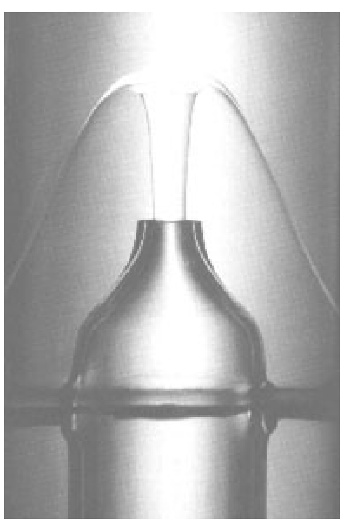
Superfluidity

Striking consequence of coherent wave nature of matter

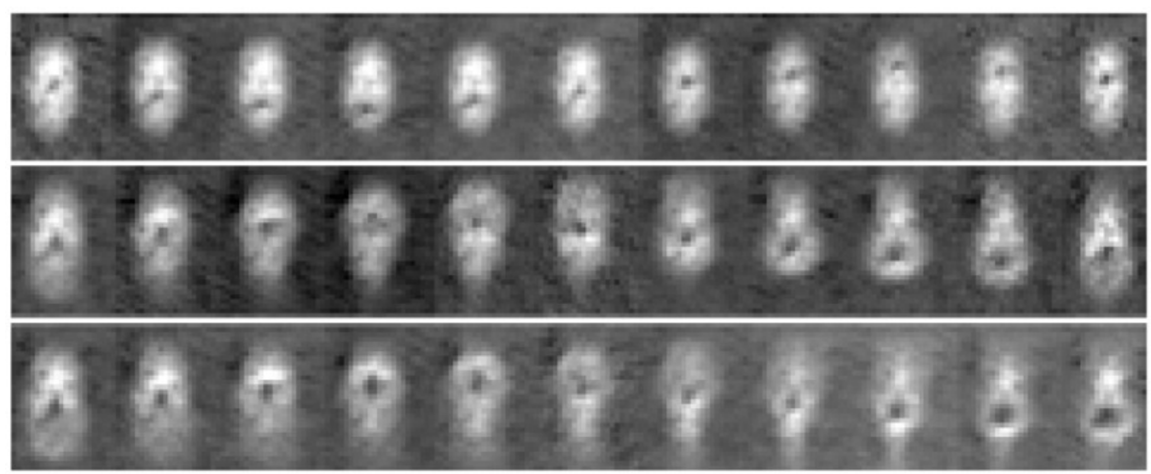
- collective behavior with all particles involved in system dynamics
- interacting Bose gas: low-energy excitations are sound modes, not single-particle ones

Impurity moving through BEC:

- no energy dissipation for $v < v_{cr}$, superfluid behaviour
- onset of friction for $v > v_{cr}$



Fountain effect in liquid He



$v < v_{cr}$

$v > v_{cr}$

R. Onofrio, *et al.* PRL **85**, 2228 (2000)

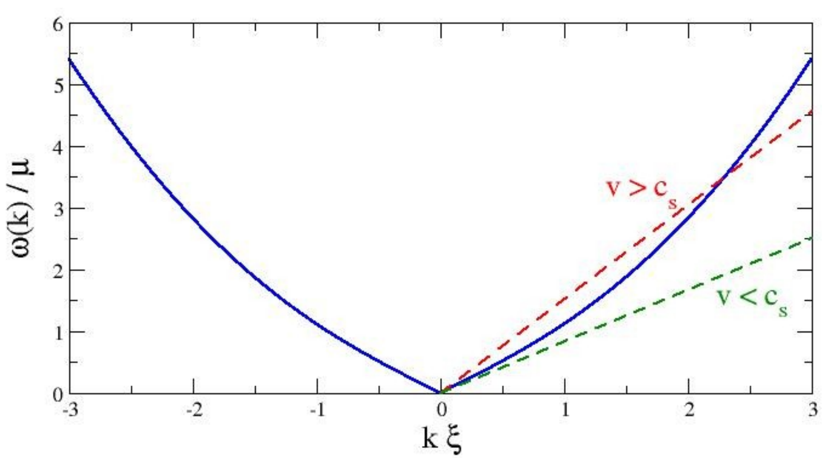
Landau interpretation

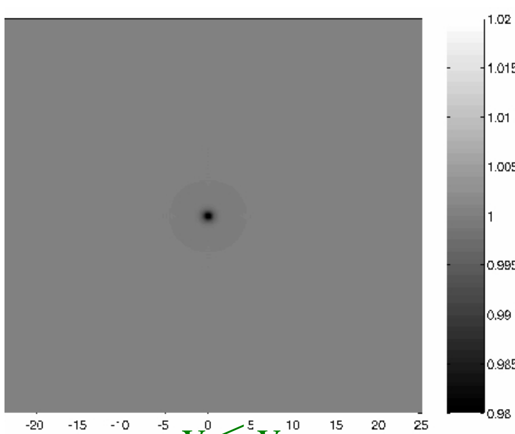
Impurity moving through BEC:

→ Landau critical speed $v_{cr} = \min_k[\omega(k)/k]$

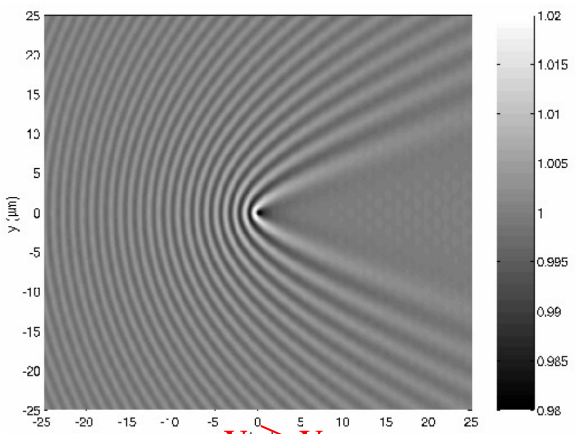
→ localized disturbance for $v < v_{cr}$, superfluid behaviour, no energy dissipation

→ complex density modulation pattern for $v > v_{cr}$
phonons radiated into modes satisfying Cerenkov condition $\omega(k) = k \cdot v$





$v < v_{cr}$



$v > v_{cr}$

In a nutshell...

So far we have seen that:

Bose-condensed bosonic atoms below T_{BEC} forget their corpuscular nature and behave as a macroscopic coherent matter wave

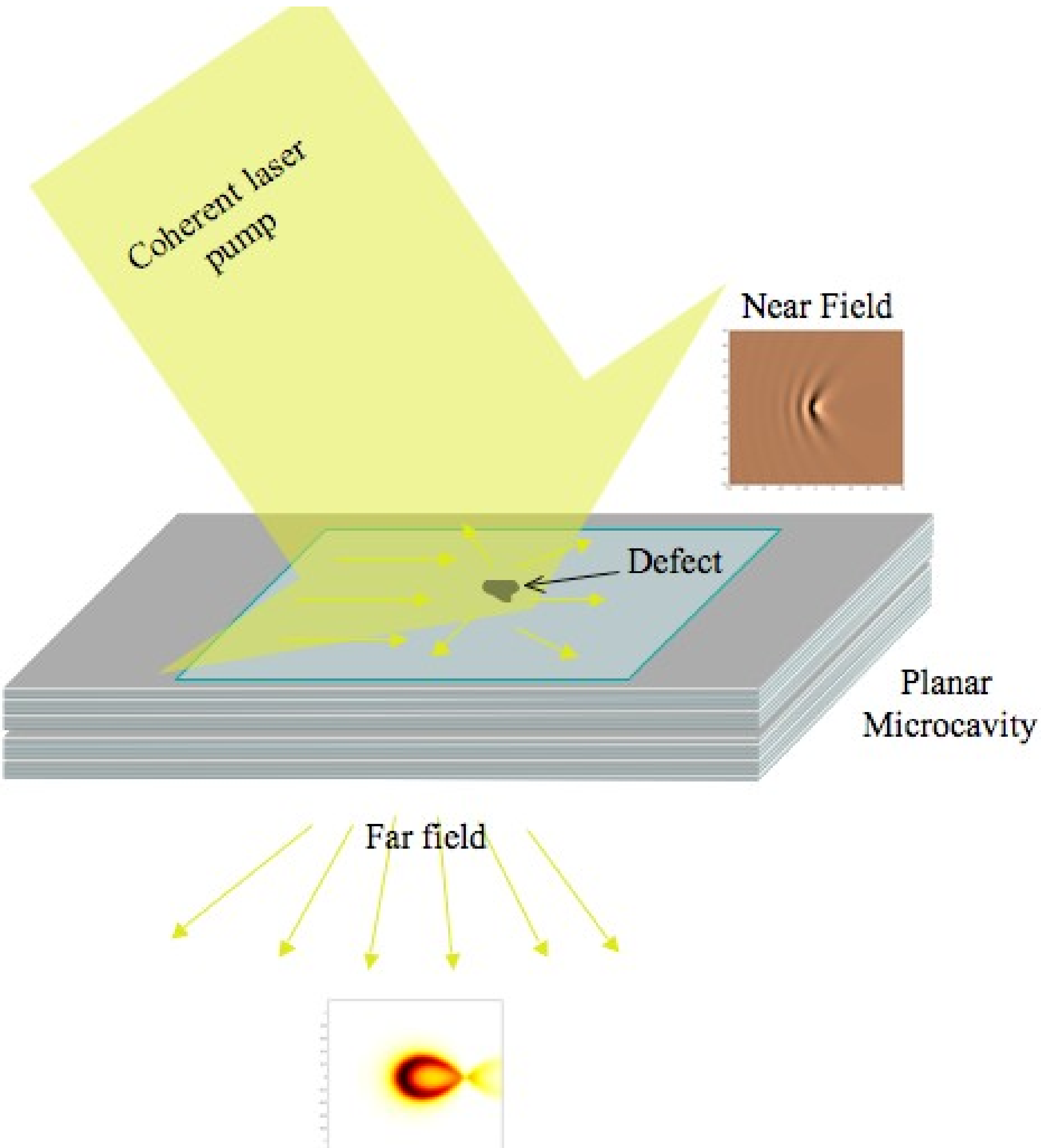
Conversely:

could one make light to forget its wave nature and behave as a hydrodynamic gas of interacting photons?

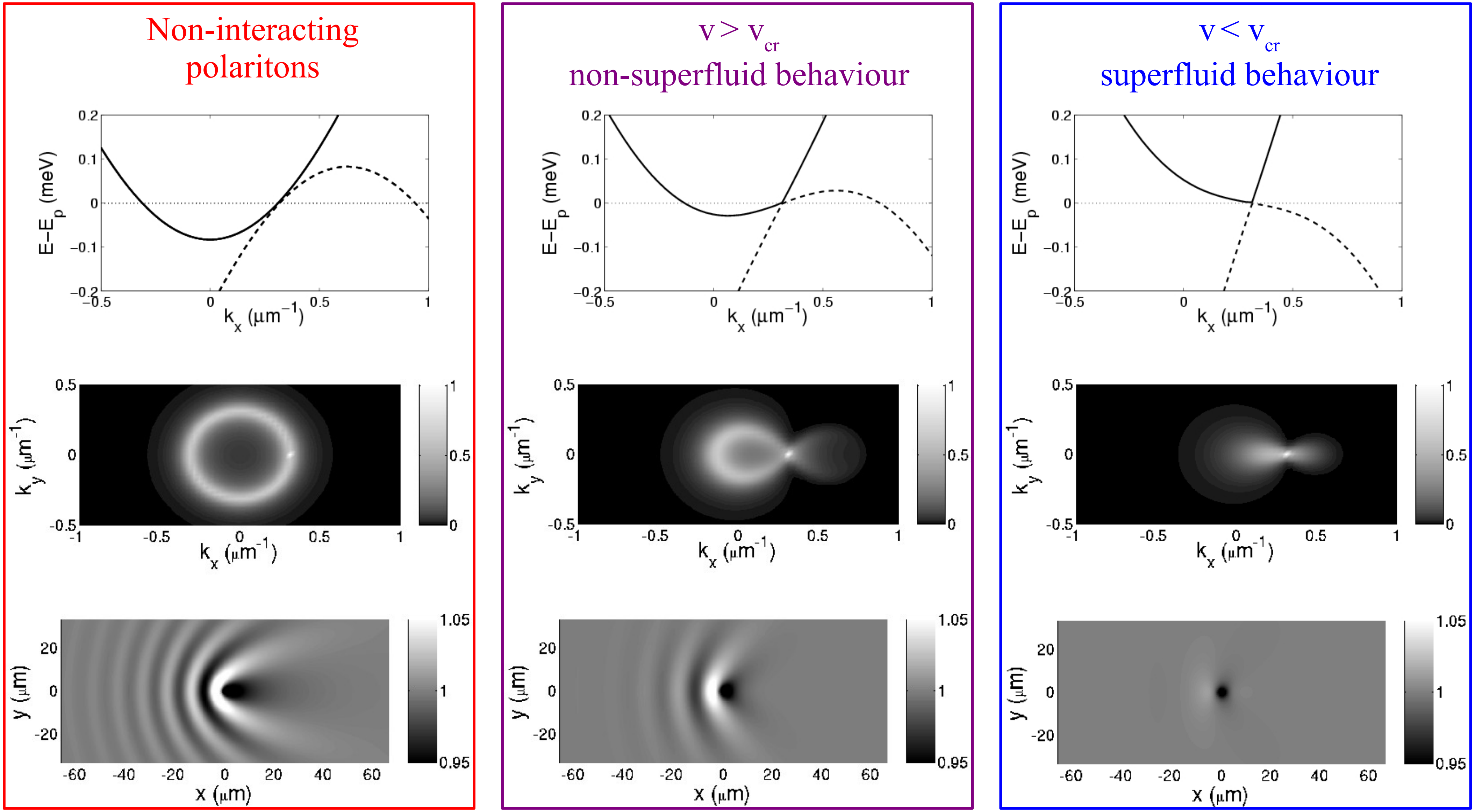
A first step:

observe superfluid behaviour in coherent light wave

The optical system under investigation



Superfluid hydrodynamics of photons



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

Experimental data: superfluid behaviour

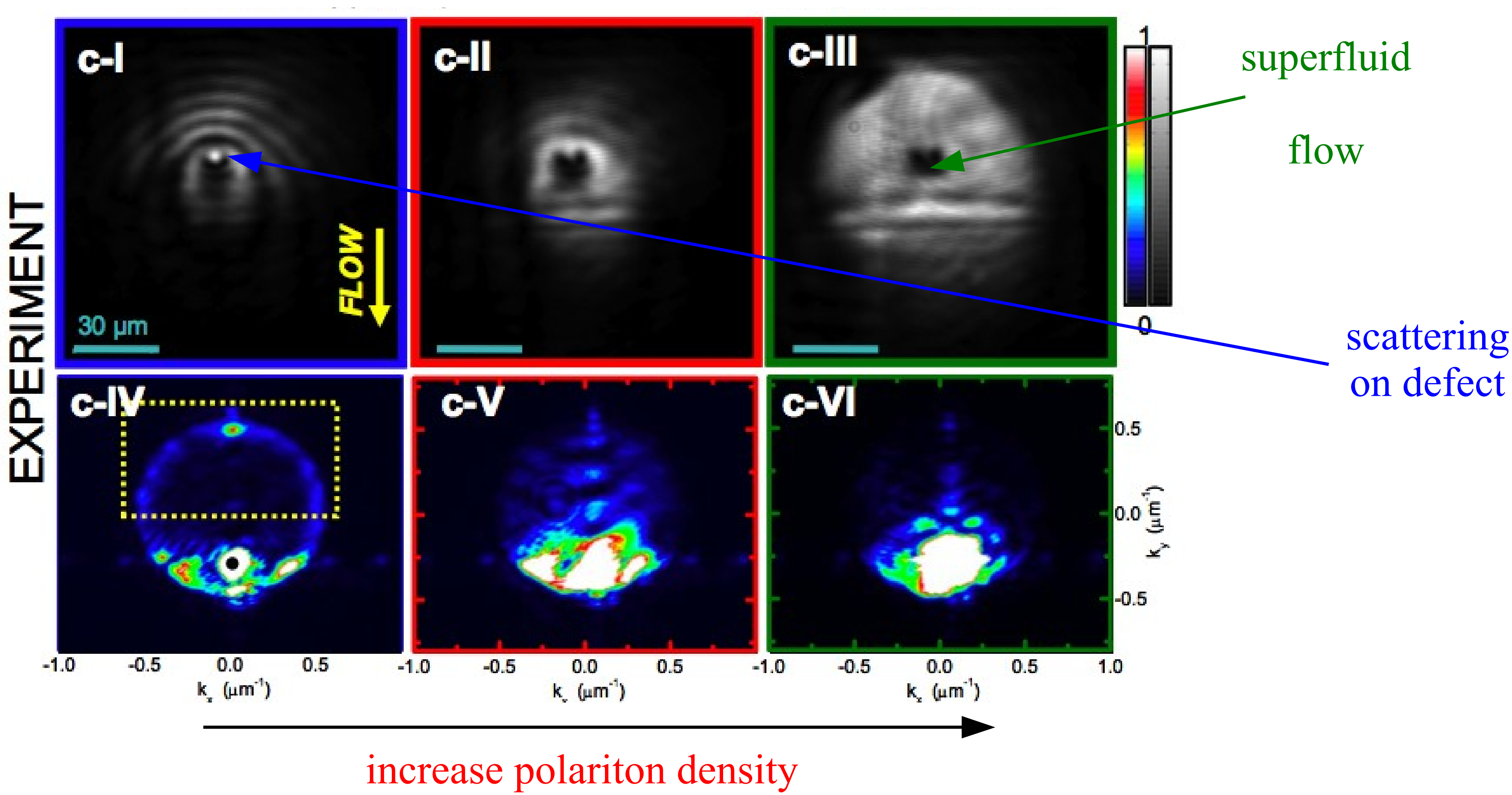
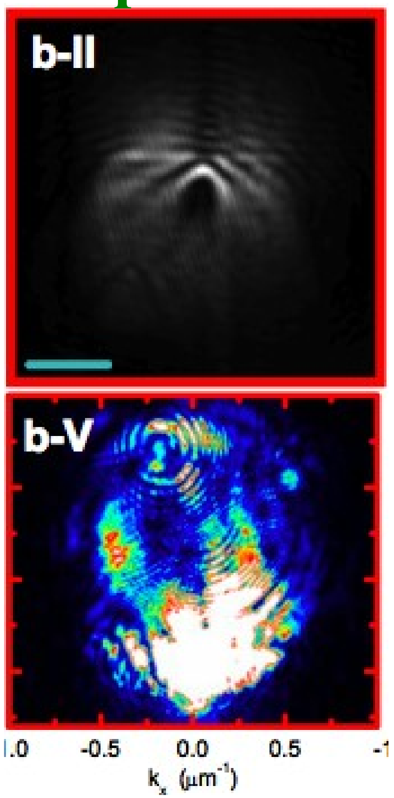


Figure from LKB-P6 group:
J.Lefrère, A.Amo, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, Nature Phys. 5, 805 (2009)

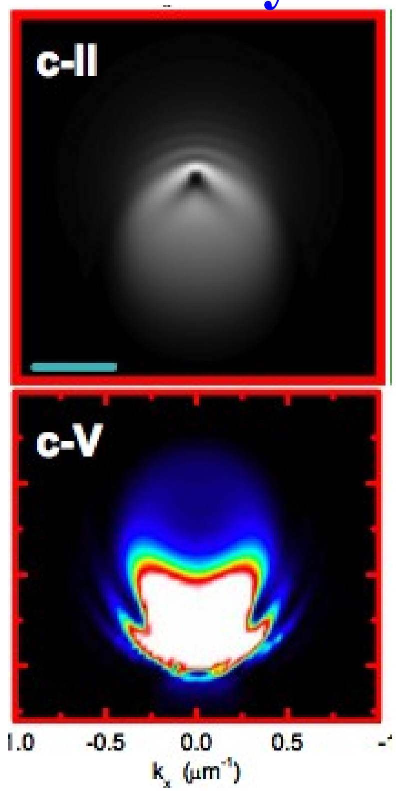
Theory: IC and C. Ciuti, PRL **93**, 166401 (2004).

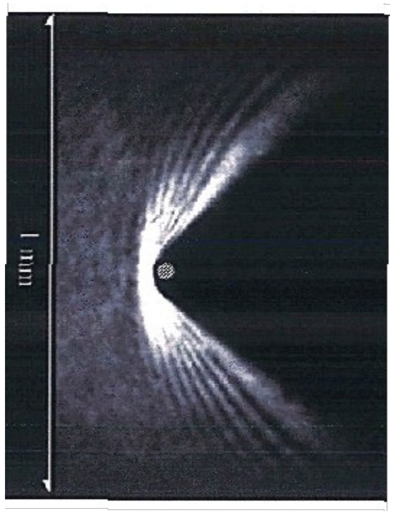
Cerenkov wake in supersonic flow

Experiment



Theory



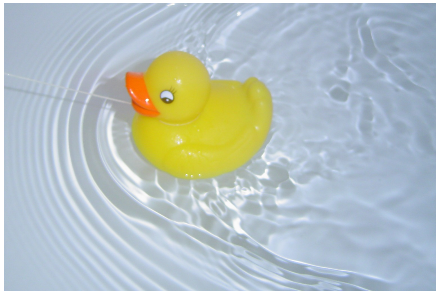


Expt with atomic BEC

Expt. image from JILA
(P. Engels, E. Cornell).
Theory IC, Hu, Collins, Smerzi,
PRL **97**, 260403 (2006)

Super-sonic flow hitting a defect:

- Cerenkov conical wave, aperture $\sin(\varphi) = c_s / v$
- single-particle parabolic precursors



Expt with duck

J.Lefrère, A.Amo, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati,Nature Phys. 5, 805 (2009); IC and C. Ciuti, PRL **93**, 166401 (2004).

Superfluid hydrodynamics observed in fluid of light!!
But still a number of open challenges...

Interactions are more effective in coherent wave state than in normal state

New frontier: hydrodynamic behaviour of light in normal gas of corpuscular photons

So far:

- ballistic propagation of photons of a thermal lamp source

Hydrodynamic behaviour:

- collisional mean-free path for photon-photon collisions shorter than wavelength of spatial modulation
- requires photon-photon interactions much stronger than in standard media

A strategy to enhance photon-photon interactions

Strongly interacting atomic gases:

- exploit Feshbach resonance effect
  on molecular intermediate state

- scattering length $a = a_{bg}\left[1 - \frac{\Delta}{B - B_0}\right]$

- scattering cross section $\sigma = 8\,\pi\, a^2$

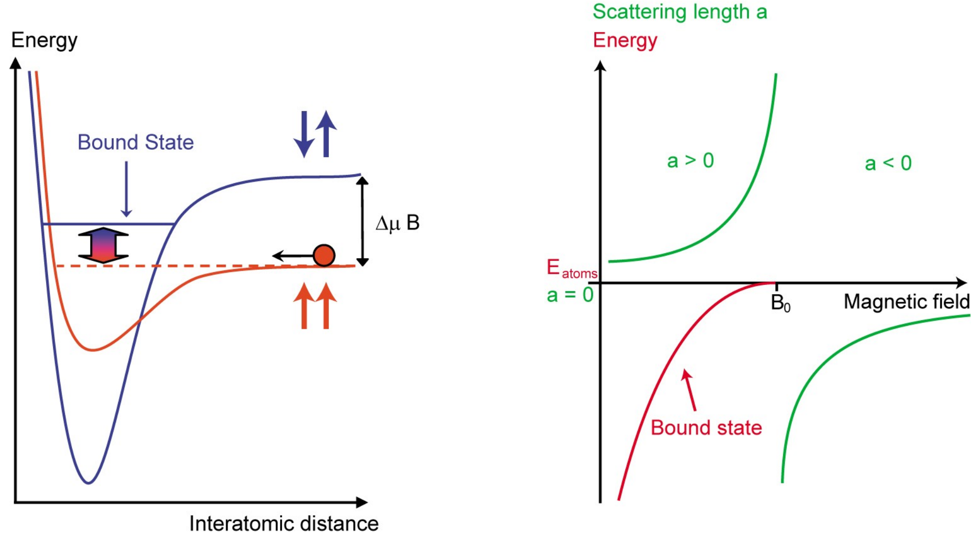


figure from Ketterle group website

Optical molecule:

- biexciton in solid-state material: 2e's+2h's complex
- can be excited via two-photon absorption

Photon-photon collisions resonant on biexciton intermediate state

In nonlinear optical terms: resonant two-photon absorption

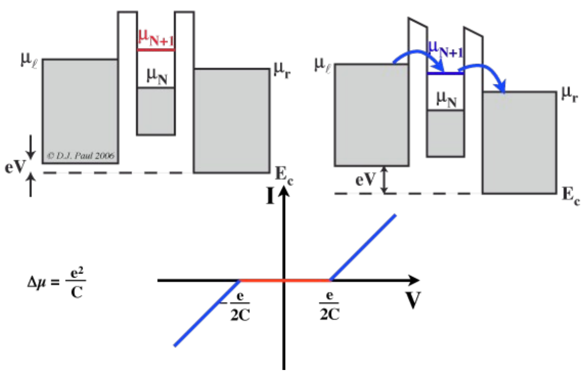
M. Wouters, Phys. Rev. B **76**, 045319 (2007); I. Carusotto, T. Volz, A. Imamoglu, arXiv:1002.2613

Photon blockade

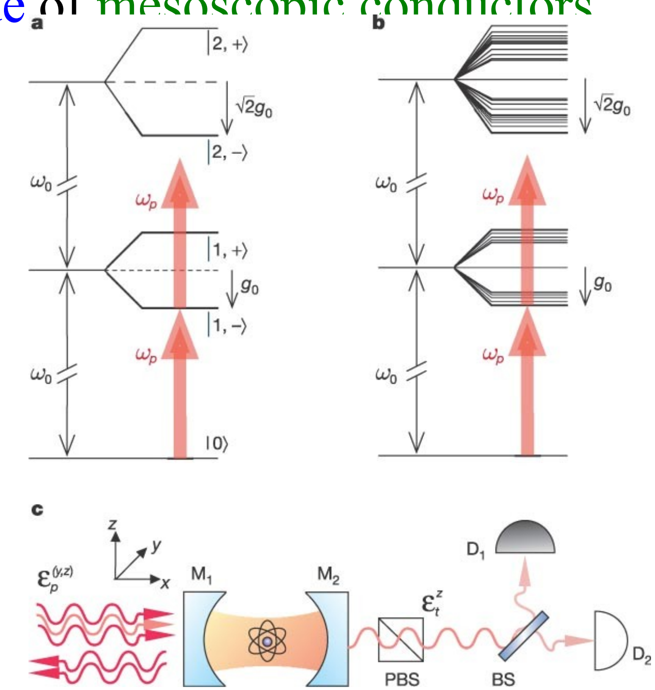
Simplest signature of photon-photon interactions at single photon level

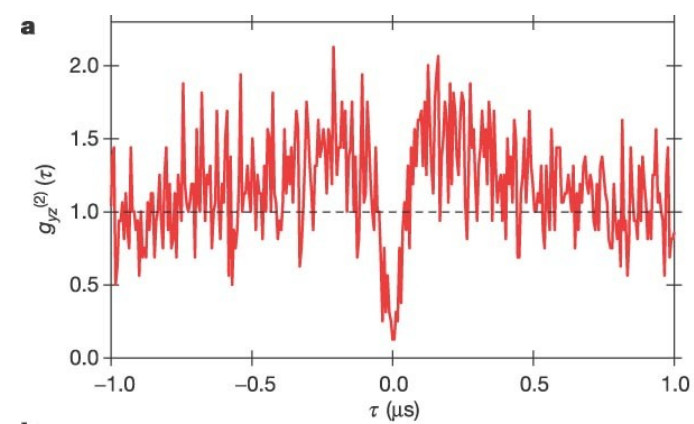
- entrance of first photon blocks entrance entrance of a second
- after one photon has exited, system has to reload.
- dead time between emitted photons, anti-bunched stream, sub-Poissonian statistics

- observed in high-finesse optical cavities with 2-level atoms, but hardly scalable
- analog of Coulomb blockade of mesoscopic conductors



Coulomb blockade
figure D. J. Paul, Cambridge, 2006





from: Birnbaum et al., Nature 436, 87 (2005)

Tonks-Girardeau gas of impenetrable bosons

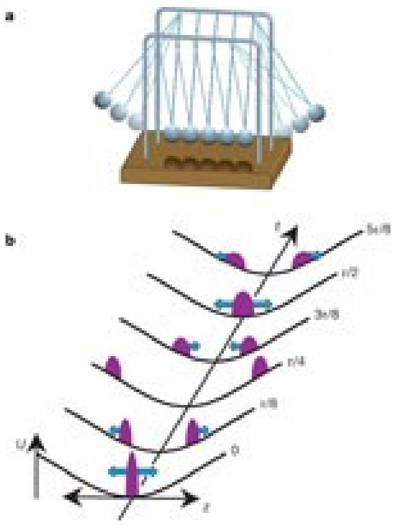
Strong interactions prevent particles from overlapping

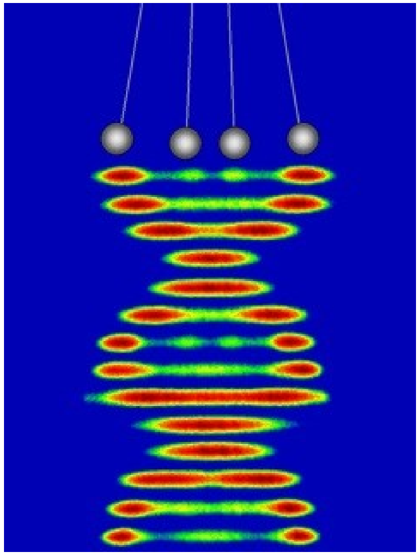
One-dimensional geometry:

- strong lateral confining potential, only axial motion
- bosons can not cross, zeros in wavefunction when overlapping
- Girardeau Bose-Fermi mapping: Bose gas inherits some fermionic properties

  e.g Fermi pressure

- dynamics: quantum Newton's craddle with ultracold atoms



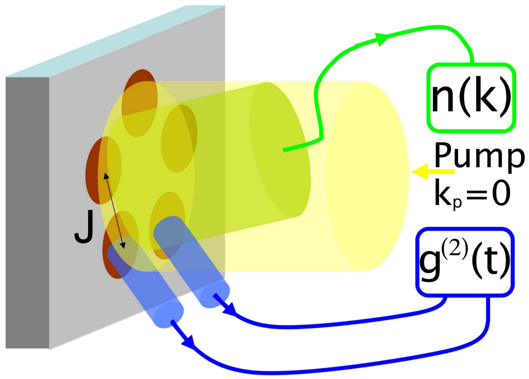


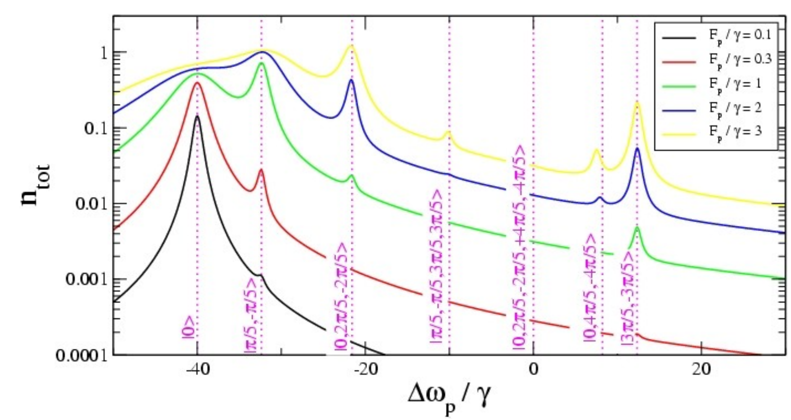
Kinoshita, Wenger, Weiss, Nature **440**, 900 (2006)

Necklace of cavities: non-equilibrium Bose-Hubbard model

Optical realization:

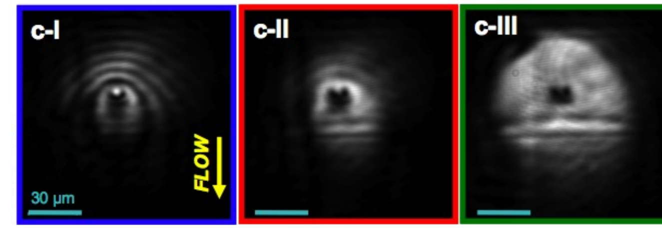
- necklace of cavities coupled by optical tunneling processes
- blockade regime: on-site nonlinearity U » tunneling J
- cavities driven by coherent pump, photons radiatively decay
- non-equilibrium state: driven-dissipative system,
  stationary state from dynamical balance of pumping and losses
- spectroscopic signature of strongly correlated many-body states
- nature of states can be inferred from photon statistics of emitted light

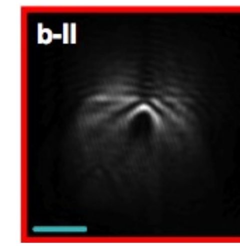




I. Carusotto, D. Gerace, H. Tureci, S. De Liberato, C. Ciuti, A. Imamoglu, Phys. Rev. Lett. 103, 033601 (2009).

Conclusions and perspectives

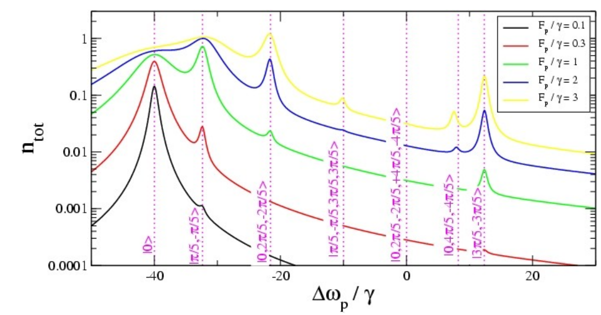




Experimental study of superfluid light:

- suppression of scattering for sub-sonic flow
- Cerenkov wake for super-sonic flow

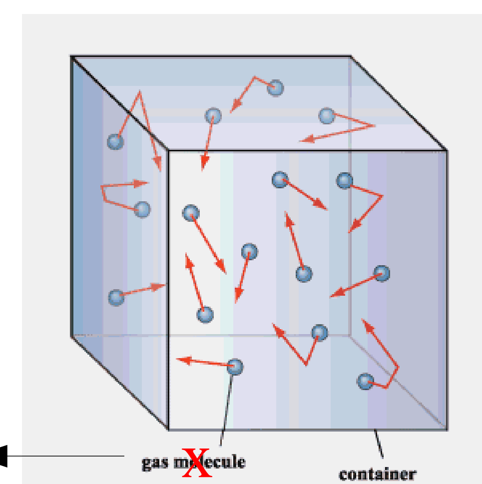
Theoretical study of strongly interacting photon gases:



- biexcitonic Feshbach resonances
- Tonks-Girardeau gas of fermionized photons in 1D

A new frontier:

- hydrodynamic behaviour in normal gas of corpuscular photons
- second sound in superfluid photon fluid at finite T
- ultimate proof of corpuscular nature of light !



photons!

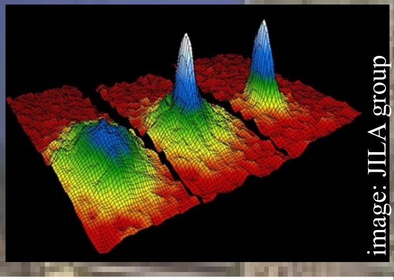
more details in a forthcoming paper on Europhysics News !!

Thanks

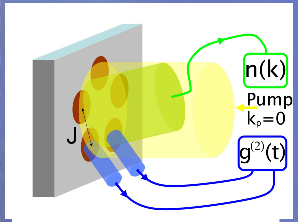
for your

attention !!!

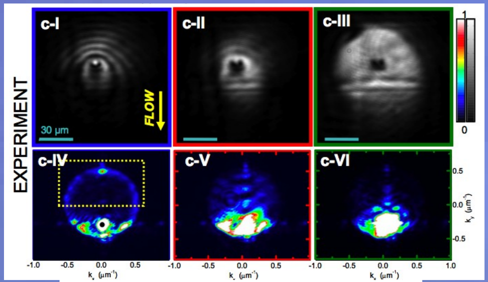
If you are a brave young researcher interested in a combination of ...



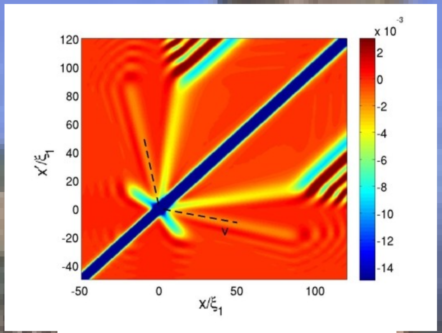
theory and experiments in ultracold atoms



quantum optics



polariton condensates



acoustic black holes

... don't hesitate, but go for BEC

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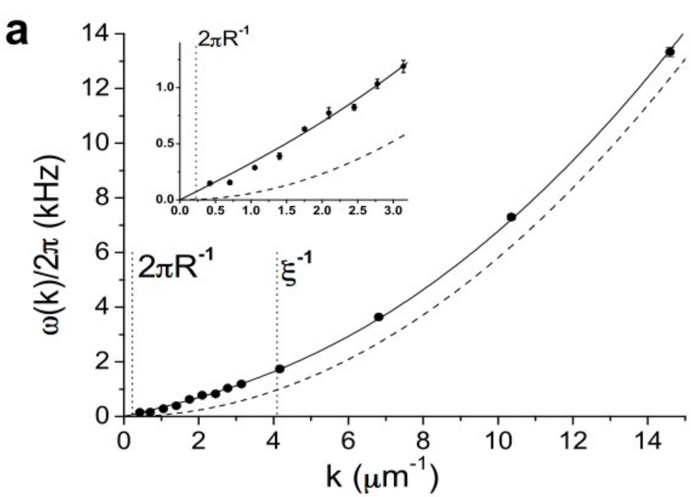
The new frontier: strongly interacting photons

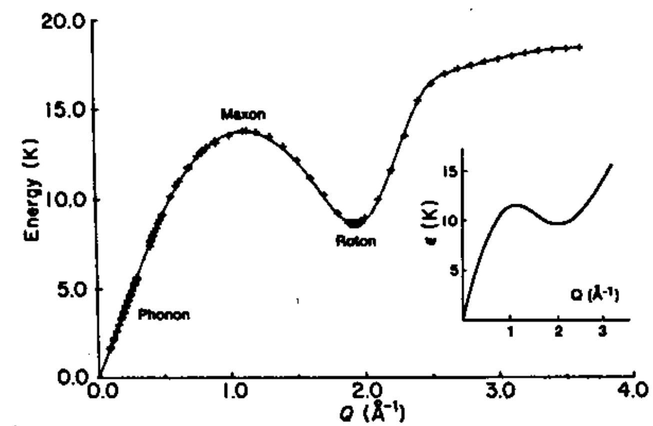
analogy between coherent light and atomic condensates based
on a weak-interaction condition
large particle involved in the dynamics, in particular mean-field interaction energy

what if small number of particles enough to give the same interaction?

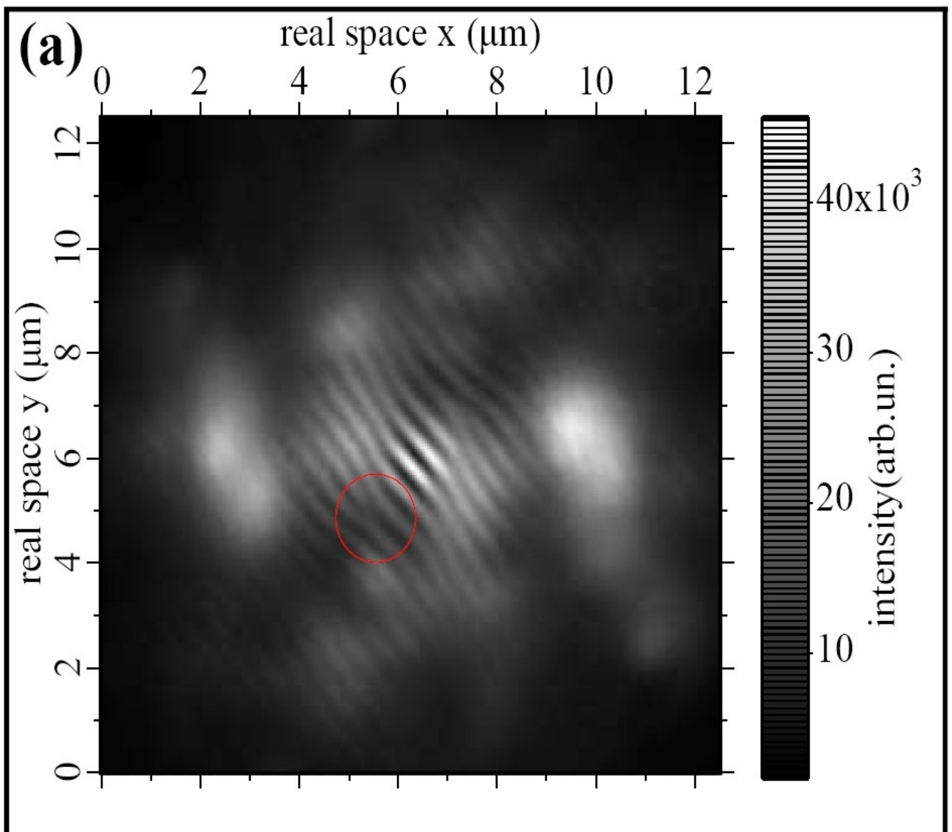
Helium vs atomic condensates

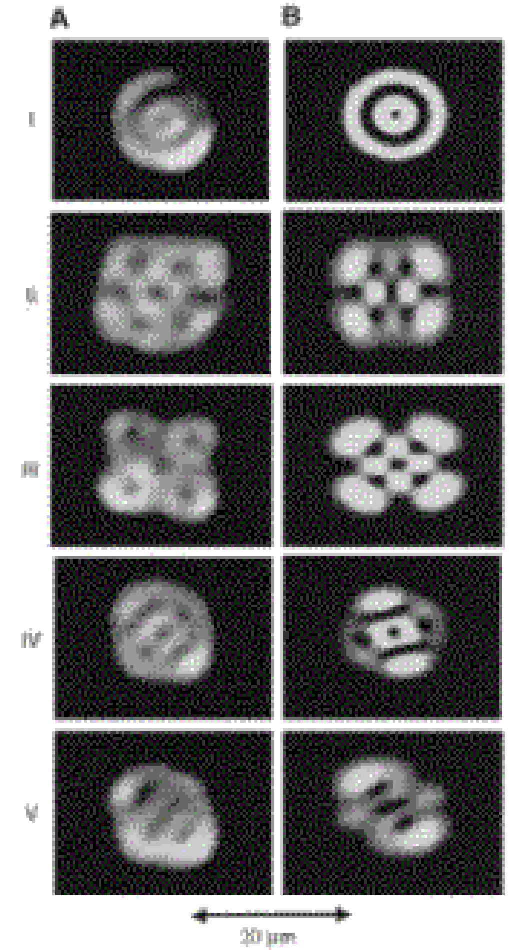


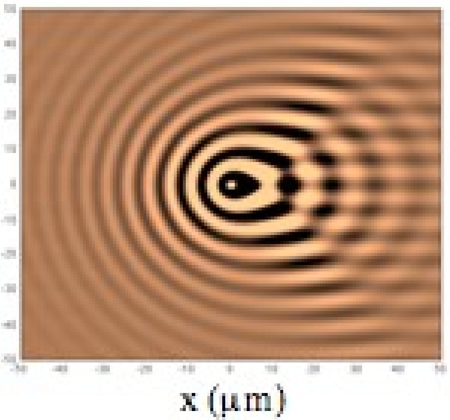
H. R. Glyde



Phonon-roton energy dispersion curve in superfluid ^{4}He at SVP and $T \simeq 1$ K (from Ref. 40) with inset from Landau 1947.


(a)
real space x (μm)
0
2
4
6
8
10
12
real space y (μm)
intensity(arb.un.)
40x10^3
30
20
10


A
B
20 μm



Non-equilibrium condition:
photons lost and reinjected continuously
stationary state: dynamical equilibrium of pumping and losses,
not thermal equilibrium
driven-dissipative system

Modified GPE

$$i\hbar\partial_t\phi = -\frac{\hbar^2}{2\mathrm{m}}\nabla^2\phi + V\phi + g|\phi|^2\phi$$

Chemical potential mu not determined by equation of state, but freely
tuned by incident laser frequency

New features: zebra Cerenkov when photon fluid is close to an instability