Ultracold Atoms
Trends and Perspectives

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Evolution of Atomic Physics

Characterized by the establishment of new fruitful links with other fields of physics

- Quantum Optics
- Molecular Physics
- Statistical Physics
- Condensed Matter Physics
- Quantum information

This evolution is a consequence of advances in our ability to manipulate atomic systems and to achieve new situations where all parameters can be controlled, providing in this way simple models for analyzing subtle problems appearing in other fields.

Purpose of this lecture

Review a few examples showing how ultracold atoms, which have become a very powerful tool in atomic physics, are contributing to this general evolution of the field.

Links with quantum optics

Atom lasers

- Extracting a beam of matter waves from a trapped BEC
- Towards a cw atom laser

Hanbury-Brown Twiss effect for bosonic matter waves

Measurement of the second order atomic correlation function

- In an expanding cloud of metastable ^{4}He atoms above and below the condensation threshold (IOTA Orsay)
- On an atom laser extracted from a BEC of ^{87}Rb (ETH)

Bunching for a thermal cloud. No correlation for a BEC

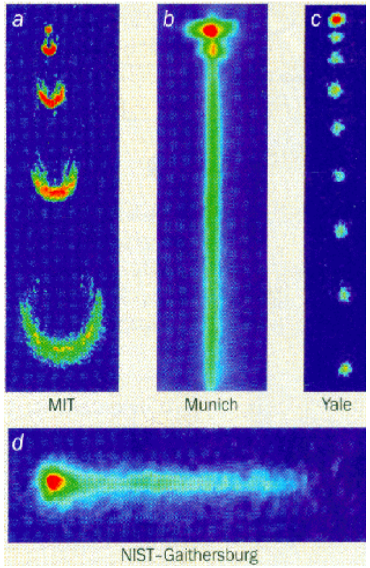
Extension to fermionic atoms

Measurement of the second order atomic correlation function

- In an expanding cloud of metastable ^{3}He atoms (IOTA Orsay + Amsterdam)
- On 40K atoms released from an optical lattice (Mainz group)

Antibunching

Atom lasers



Coherent beam of atomic de Broglie waves extracted from a trapped condensate

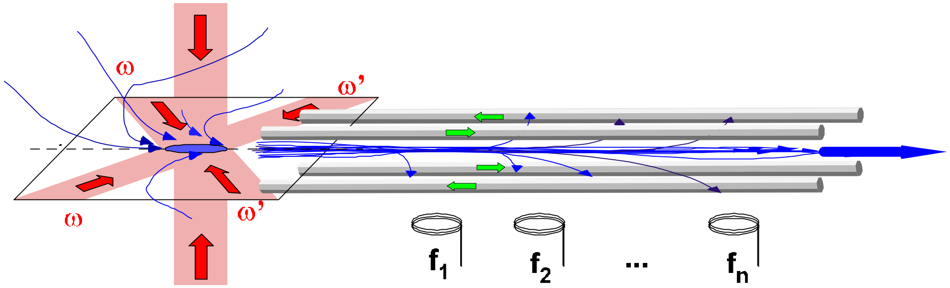
Equivalent of an optical laser where optical waves are replaced by matter waves

When the condensate is emptied, a new condensate has to be formed in the trap

The atom laser is a pulsed laser

Towards a cw atom laser

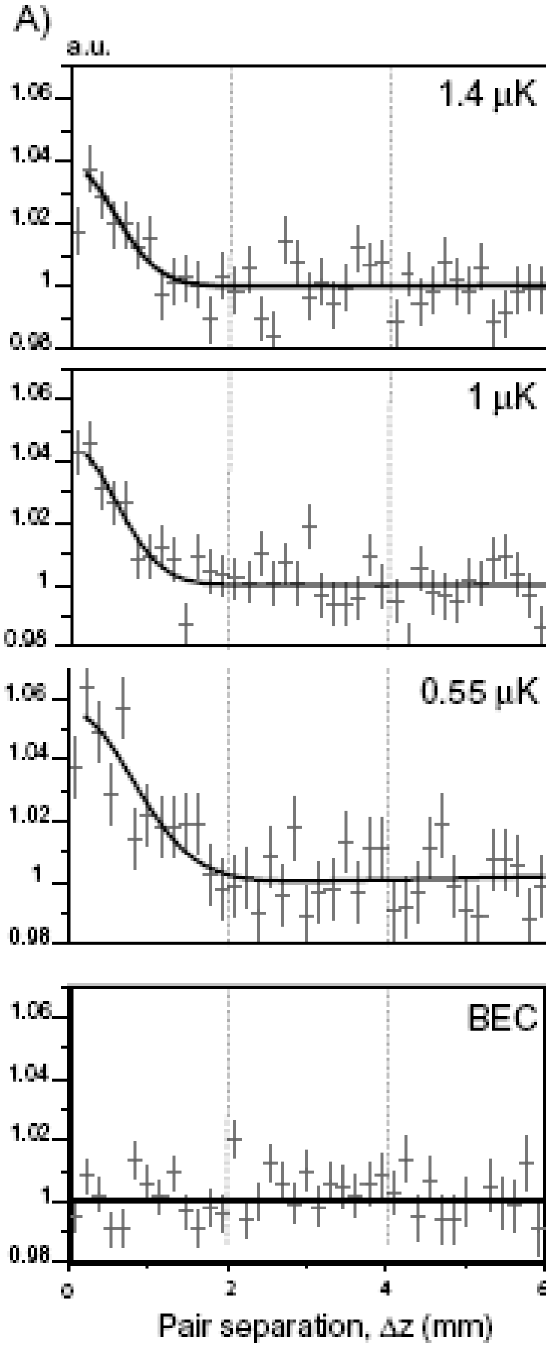
David Guéry-Odelin group
ENS Paris



Evaporative cooling of a 4.5 meter-long magnetically guided atomic beam. About 20 elastic collisions undergone by each atom during the propagation

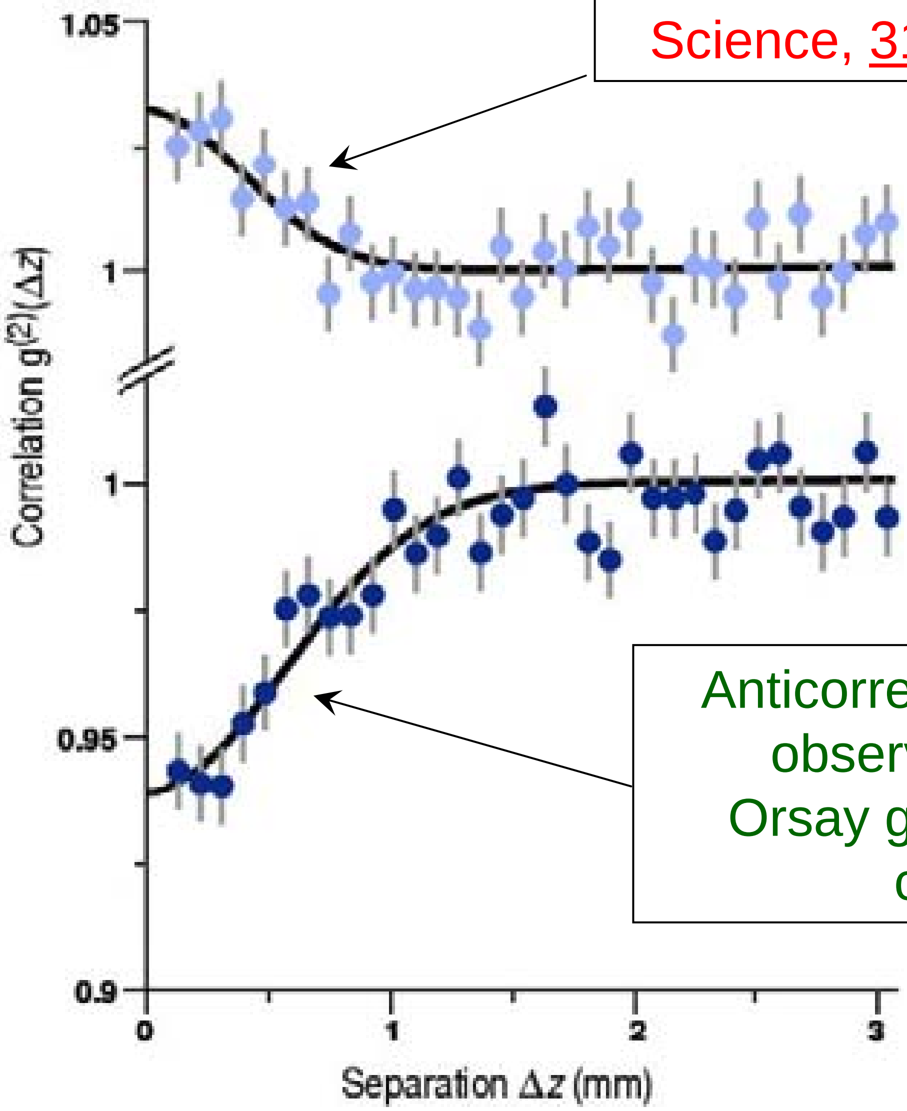
Very promising system for atom optics

Hanbury Brown Twiss effect for bosonic atoms (He_4*)
Orsay group
Science, 310, 648 (2005)



Thermal cloud

BEC



Correlation peak (Bunching)
observed for Bosons (He_4*)
Orsay group
Science, 310, 648 (2005)

Anticorrelation peak (Antibunching)
observed for Fermions (He_3*)
Orsay group + Amsterdam group
cond-mat/0612278

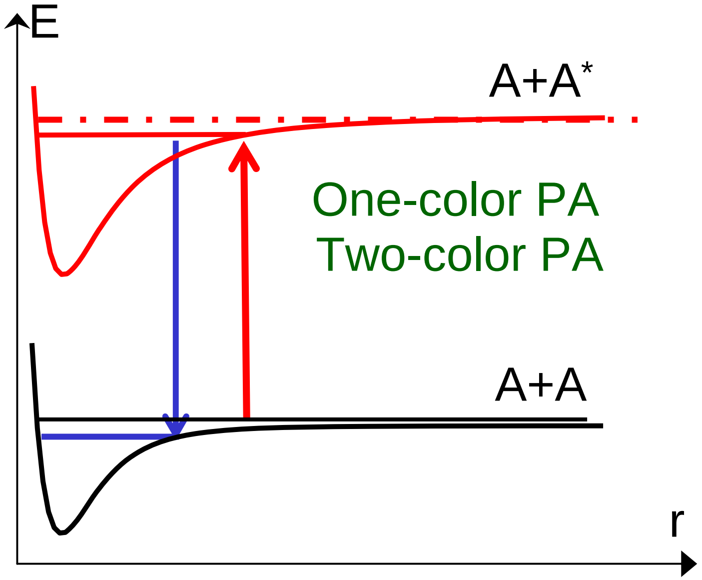
New links with Molecular Physics

How do ultracold atoms interact? Can they form molecules? Can one extend to molecules the results obtained for atoms? Trying to answer to these questions has stimulated the emergence of new fields:

- Cold collisions
- Atomic Feshbach resonances
- Ultracold molecules. Molecular BEC

Various routes towards ultracold molecules

- Evaporative cooling in a magnetic trap
- Stark deceleration of a molecular beam
- Starting from ultracold atoms and sweeping a Feshbach resonance
- Gluing 2 ultracold atoms with one or two photons Photoassociation



Two-color Photoassociation and Coherent Population Trapping

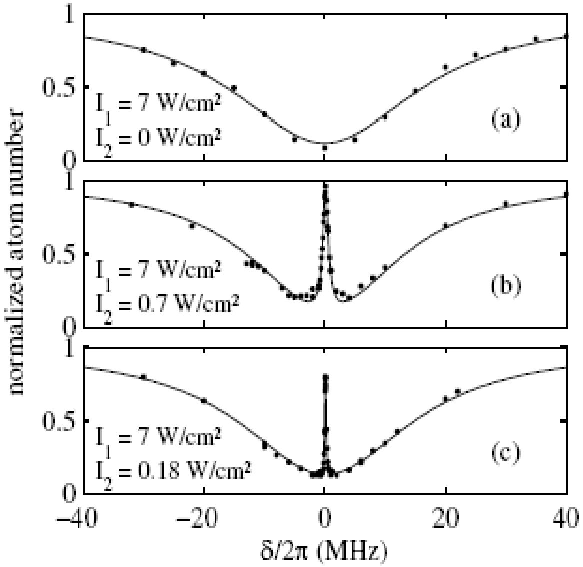
If the two lasers are coherent, they can create by stimulated Raman processes a linear superposition of 2 states

- state 1 : pair of 2 atoms
- state 2 : molecular bound state

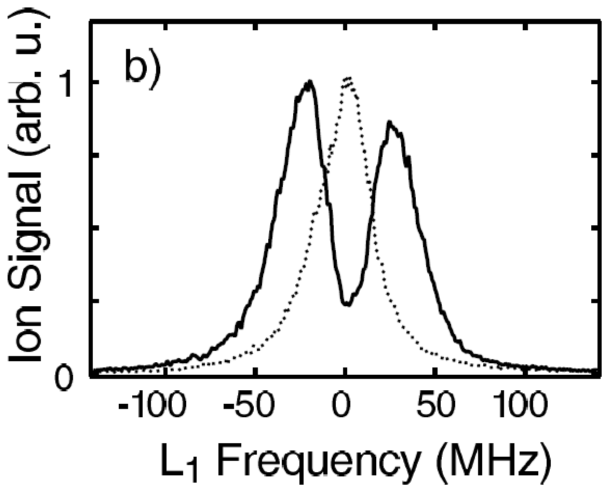
which cannot absorb light because of destructive interference

A new example of coherent population trapping which is well known in other fields of physics (EIT, subrecoil laser cooling,...) The new feature here is that CPT involves a free state and a bound state. The corresponding "dark resonance" should thus be broad but, for ultracold atoms, the energy spread of the initial free state is very narrow. By extrapolating the position of the resonance at zero temperatures one can measure very precisely the energy of the least bound state in the potential and derive an accurate value of the scattering length

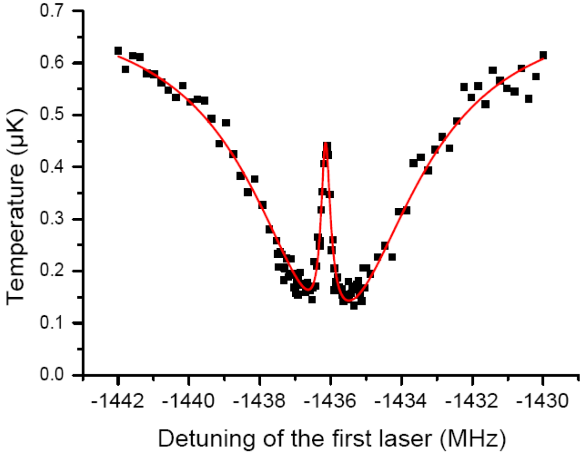
Observation of these dark resonances by 3 different groups



Innsbruck
PRL, 95, 063202 (2005)

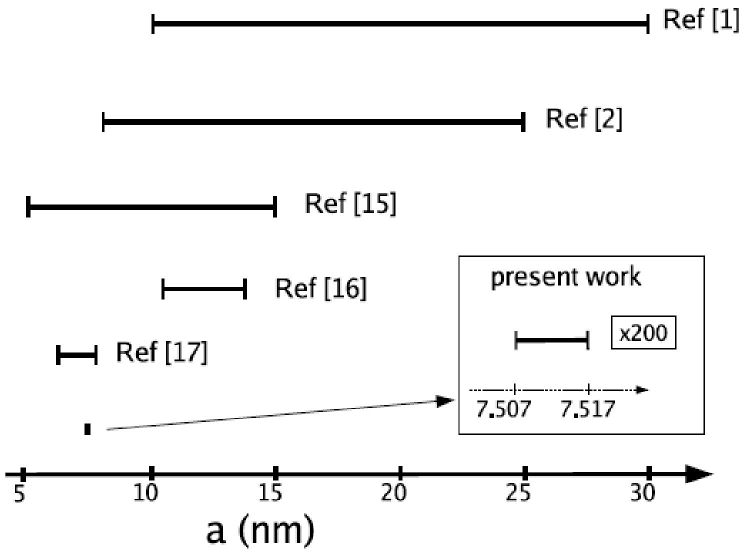


NIST
PRA, 72, 041801 (2005)



ENS Paris
PRL, 96, 023203 (2006)

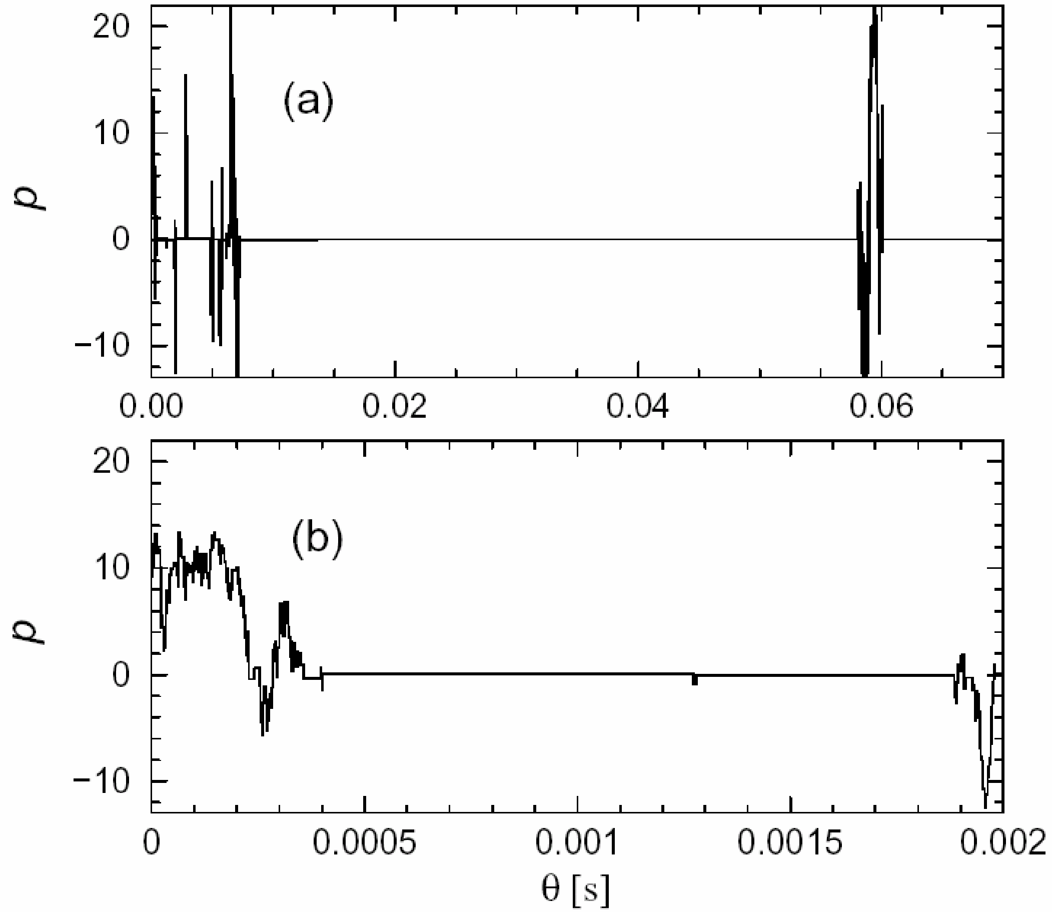
Determination of the scattering length of metastable helium atoms by the ENS group with a precision at least 150 times better than all previous measurements



New links with Statistical Physics

Certain laser cooling schemes (subrecoil cooling) use a velocity selective coherent population trapping.

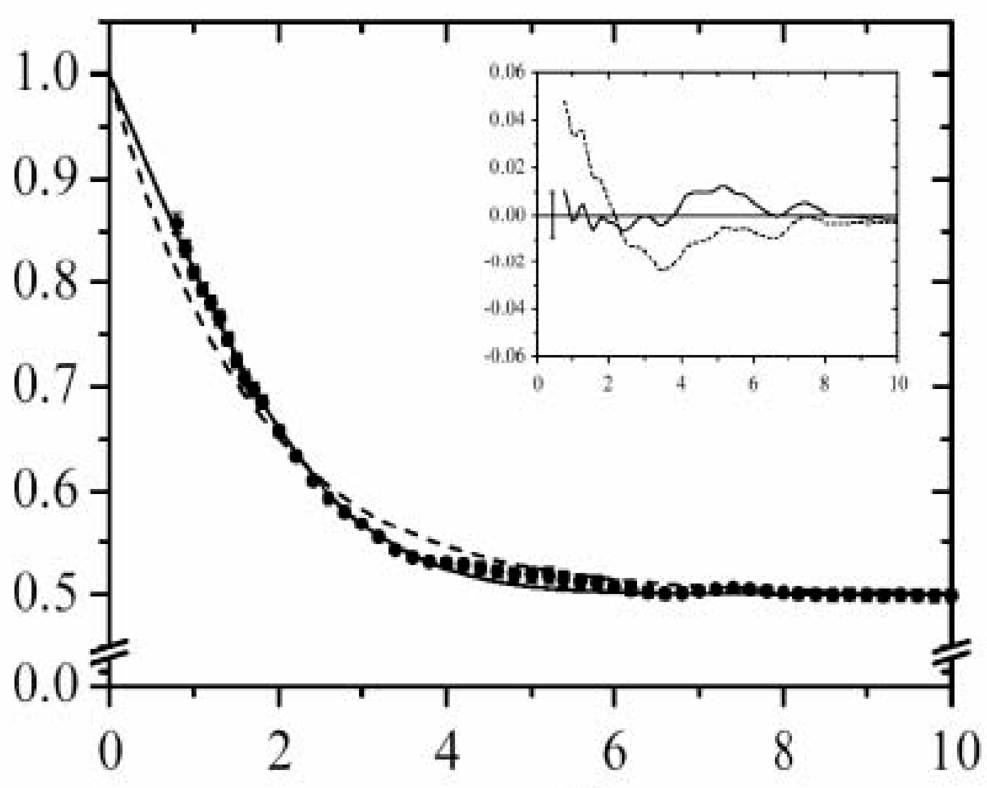
The random walk of the atom in momentum space appears anomalous and dominated by a few rare events.

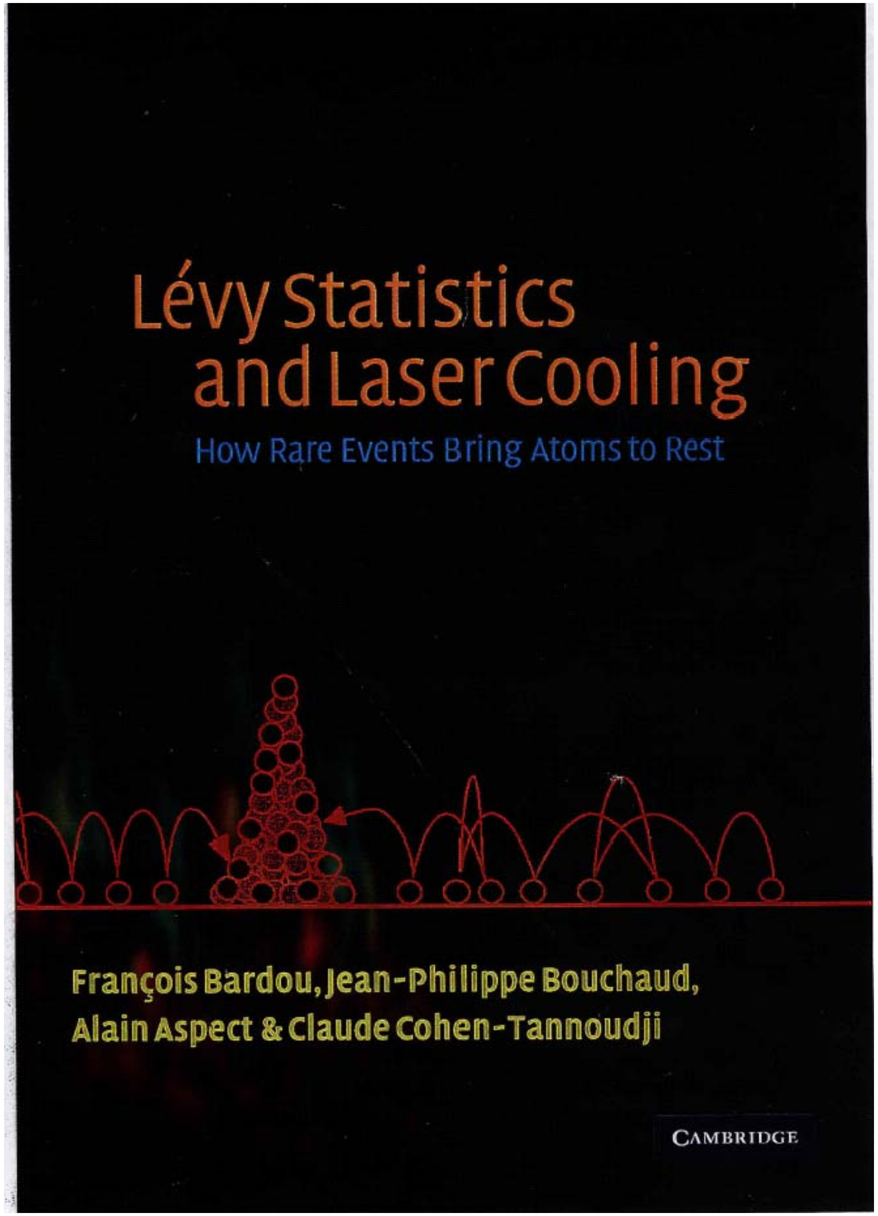


Subrecoil laser cooling and Lévy flights

Discussing with statistical physicists (J.P. Bouchaud), we realized that subrecoil cooling is one of the clearest examples of "**Lévy flights"**, involving broad distributions with power-law tails

Using Lévy statistics, it was then possible to derive analytical predictions for certain physical quantities (momentum distribution) which were hopeless to get from usual quantum optics treatments



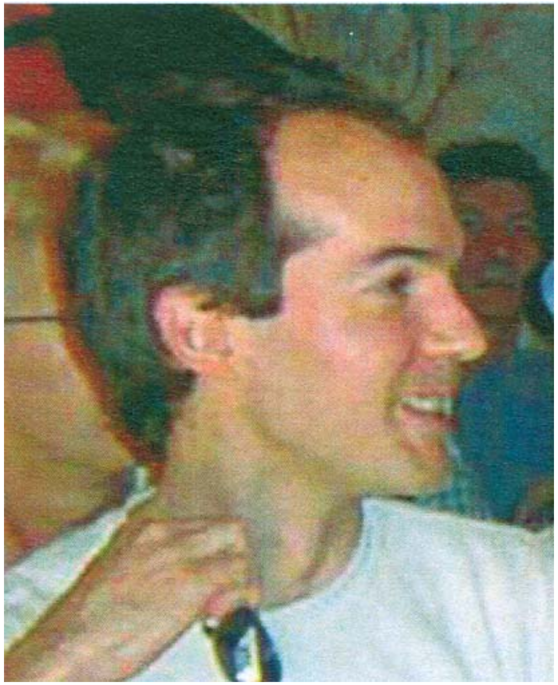


Lévy Statistics and Laser Cooling

How Rare Events Bring Atoms to Rest

François Bardou, Jean-Philippe Bouchaud, Alain Aspect & Claude Cohen-Tannoudji

CAMBRIDGE

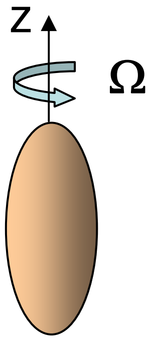


François Bardou

New links with condensed matter physics

Quantum degenerate bosonic gases

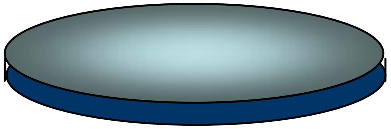
Exemple 1 : Fast rotating Bose Einstein condensates



Angular velocity Ω on the order of the radial frequency $\omega_\perp$ in the plane perpendicular to Oz

Analogy with quantum Hall physics

Exemple 2 : 2D quasi condensates



Investigation of the Berezinski Kosterlitz Thouless (BKT) transition

Quantum degenerate fermionic gases

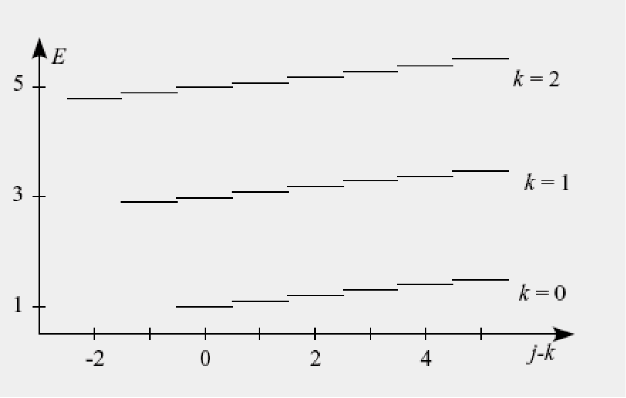
Exemple 3 : BEC-BCS crossover

Using Feshbach resonances for exploring the region between BEC of fermionic molecules and BCS-type condensates of fermion pairs

Towards a better understanding of systems of strongly correlated fermions

Fast rotating Bose Einstein condensates

Landau level structure of the single particle Hamiltonian



Manifolds of levels

- splitting between manifolds : $\omega_\perp + \Omega$
- splitting inside manifolds : $\omega_\perp - \Omega$

When $\Omega \sim \omega_\perp$, same Hamiltonian as for a charged particle in a uniform B field

Lowest Landau level (LLL)

For interacting particles with $V < \omega_\perp + \Omega$ and for $\Omega \sim \omega_\perp$, all relevant levels can be constructed from the lowest manifold

Investigation of the equilibrium shape of the condensate and of the structure of the vortex pattern (JILA Boulder, ENS Paris)

Exploration of the region $\Omega > \omega_\perp$

Adding a quartic potential to avoid the explosion of the cloud (ENS Paris)

Hope to establish a link with fractional quantum Hall effect

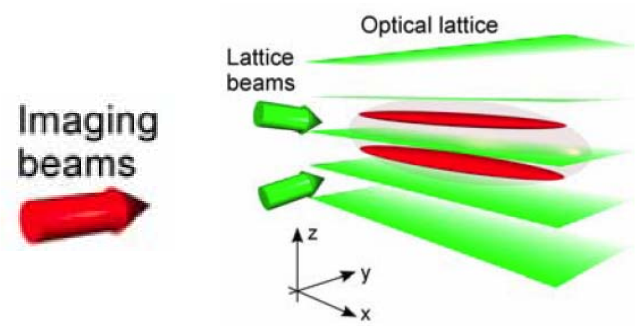
Number of vortices becoming larger than the number of particles

Strongly correlated state beyond mean field approximation

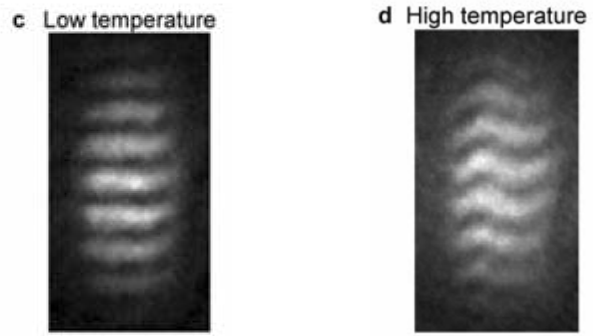
BKT crossover in a trapped 2D atomic gas

Jean Dalibard group at ENS, Nature, 441,1053 (2006)

How to prepare the 2D gas



How to detect phase coherence

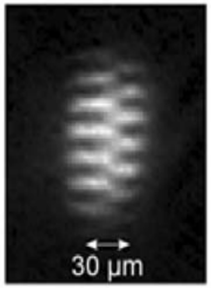


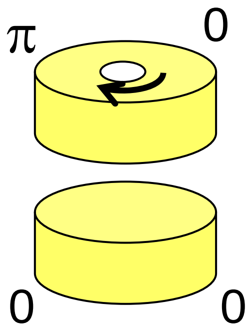
Interference fringes changing at high T (lower contrast, waviness)

Quasi-long-range order (vortex-antivortex pairs) lost at high T

Detection of the appearance of free vortices

Onset of sharp dislocations
in the interference pattern
coinciding with the loss of
long-range order

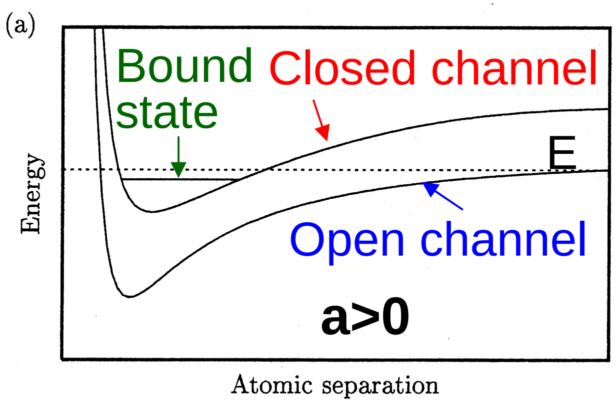


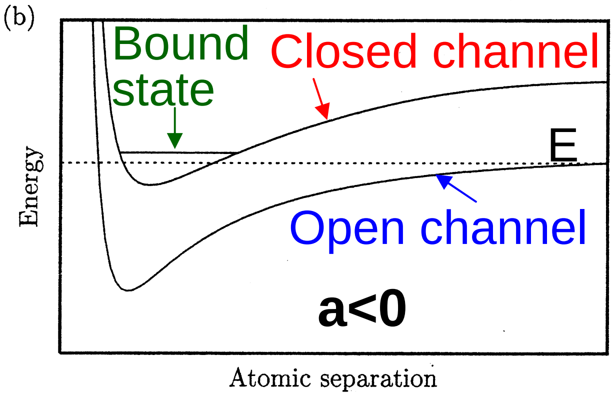


Conclusion : the mechanism of the BKT crossover is the unbinding of vortex-antivortex pairs with the appearance of free vortices

Feshbach Resonance

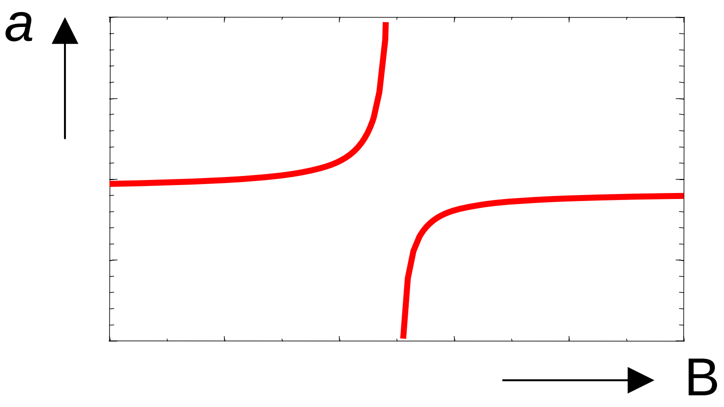
Resonance between a free state in an open channel
and a bound state in a closed channel





The 2 channels correspond to 2 different relative orientations of the spins of the 2 atoms

Their energy difference can be varied by sweeping a magnetic field B, leading to resonant variations of the scattering length *a* which fully characterizes collisions at very low T



In the region of B where the scattering length a is positive and large, the 2 atoms can form a bound state close to the threshold.

In the region where a is negative, there is a long range attractive force

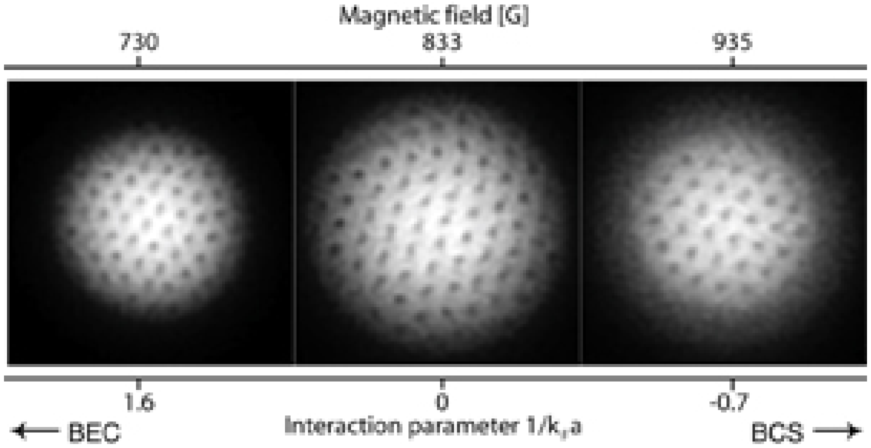
BEC-BCS crossover observed with ultracold fermions

By varying the magnetic field around a Feshbach resonance, one can explore 3 regions

- Region a>0 (strong interactions). There is a bound state in the interaction potential where 2 fermions with different spin states can form molecules which can condense in a BEC
- Region a<0 (weak interactions). No molecular state, but long range attractive interactions giving rise to weakly bound Cooper pairs which can condense in a BCS superfluid phase
- Region a=∞ (center of the resonance). Strong interactions Strongly correlated systems with universal properties.

Recent observation at MIT (W. Ketterle et al) of quantized vortices in all these 3 zones demonstrating the superfluid character of the 3 phases

Science, 435, 1047 (2005)



a>0 a=∞ a<0

Quantum information

Using entangled quantum systems with specific quantum correlations for transmitting and processing information
A domain of convergence of 2 different approaches

The “bottom-up” approach (Atomic physics)

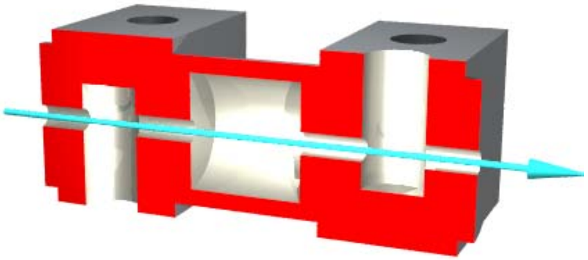
Starting from elementary quantum systems (atoms, ions, photons) which can be easily manipulated and trying to entangle an increasing number of such systems

- Atoms in microwave and optical cavities
- Chains of cooled ions. Recent entanglement of up to 6 or 8 ions (NIST Boulder and Innsbruck)
- A promising system for parallel massive entanglement: Mott insulator lattice of atoms (Mainz)

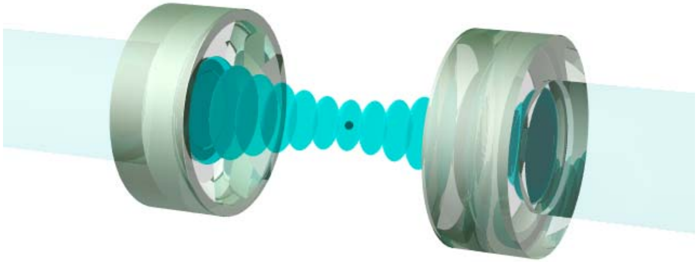
The “top-down” approach (Condensed matter physics)

Miniaturizing condensed matter systems (semiconductors, superconducting circuits) for realizing “artificial atoms”

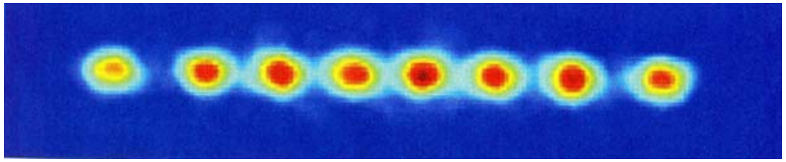
Examples of experimental realizations



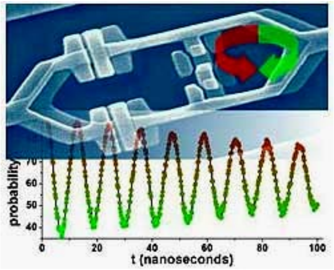
Neutral atoms in a
microwave cavity



Neutral atoms in a
optical cavity cavity



Chain of ions in a
linear trap



Superconducting qubit

Quantum information and fundamental questions

- Understanding decoherence and fighting against it
- Boundary between classical and quantum physics
- Mesoscopic “Schrödinger cats”
- Interference of beams of bigger molecules (like C_{60})
- Quantum measurement problem

A new trend : Quantum Simulators

Realizing an experimental system whose behavior reproduces as close as possible a certain class of model Hamiltonians.

Feynman's idea

Requirements for a "quantum simulator"

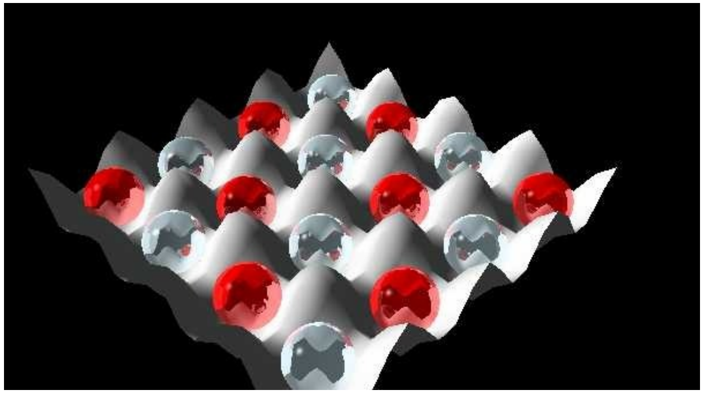
- Tailoring the potential in which particles are moving
- Controlling the interactions between particles
- Controlling the temperature, the density
- Ability to measure various properties of the system

Possibilities offered by ultracold atomic gases

- Very flexible optical potentials, with all dimensionalities, with all possible shapes (periodic, single well,…)
- Tuning the interactions with Feshbach resonances
- Various cooling schemes and measurement methods

Hope to answer in this way questions unreachable for classical computers because of memory, speed and size limitations

Example of Fermions with 2 different spin states in an optical lattice



Investigation of the transition towards a state where fermions in different spin states arrange themselves in an antiferromagnetic order (Néel transition)

Open problems

- Lattices with frustration
- p-wave pairing in BCS
- Imbalance between the 2 spin state populations
- Bose-Fermi mixtures
- Fermi Hubbard model