Online Colloquium 19 November 2020
Department of Physics, University of Pavia

Bose-Einstein Condensation in Ultra Cold Atomic Gases

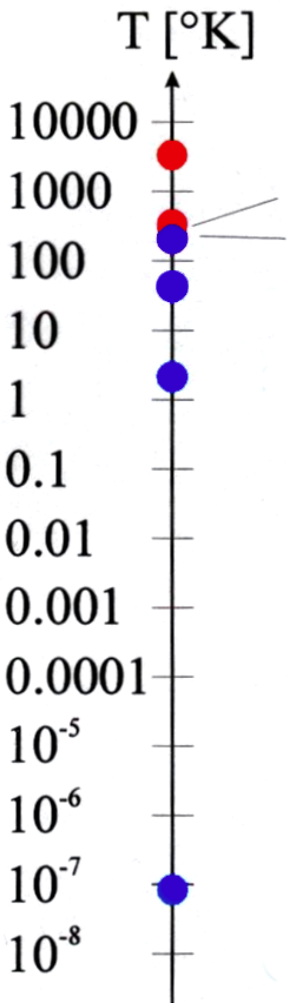
Sandro Stringari

Università di Trento

CNR-INO

Scale of temperatures

⇈ Big Bang



sun surface
boiling water
freezing water
liquid nitrogen

Standard superfluids and superconductors, cosmic radiation

↓ Doppler cooling

↓ polarisation gradient cooling

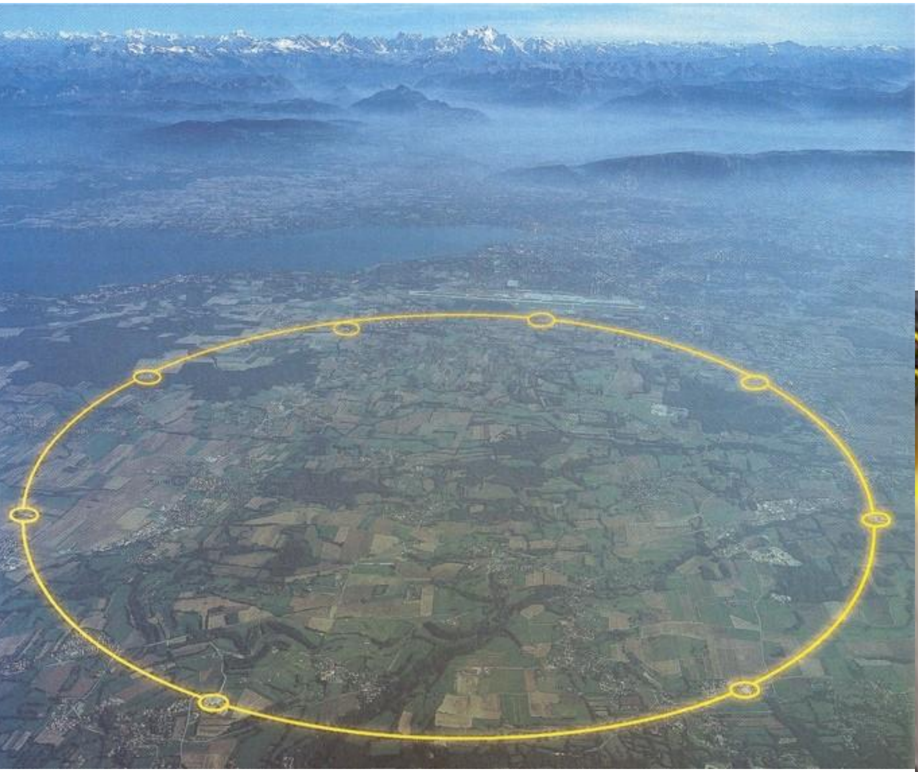
↓ evaporative cooling

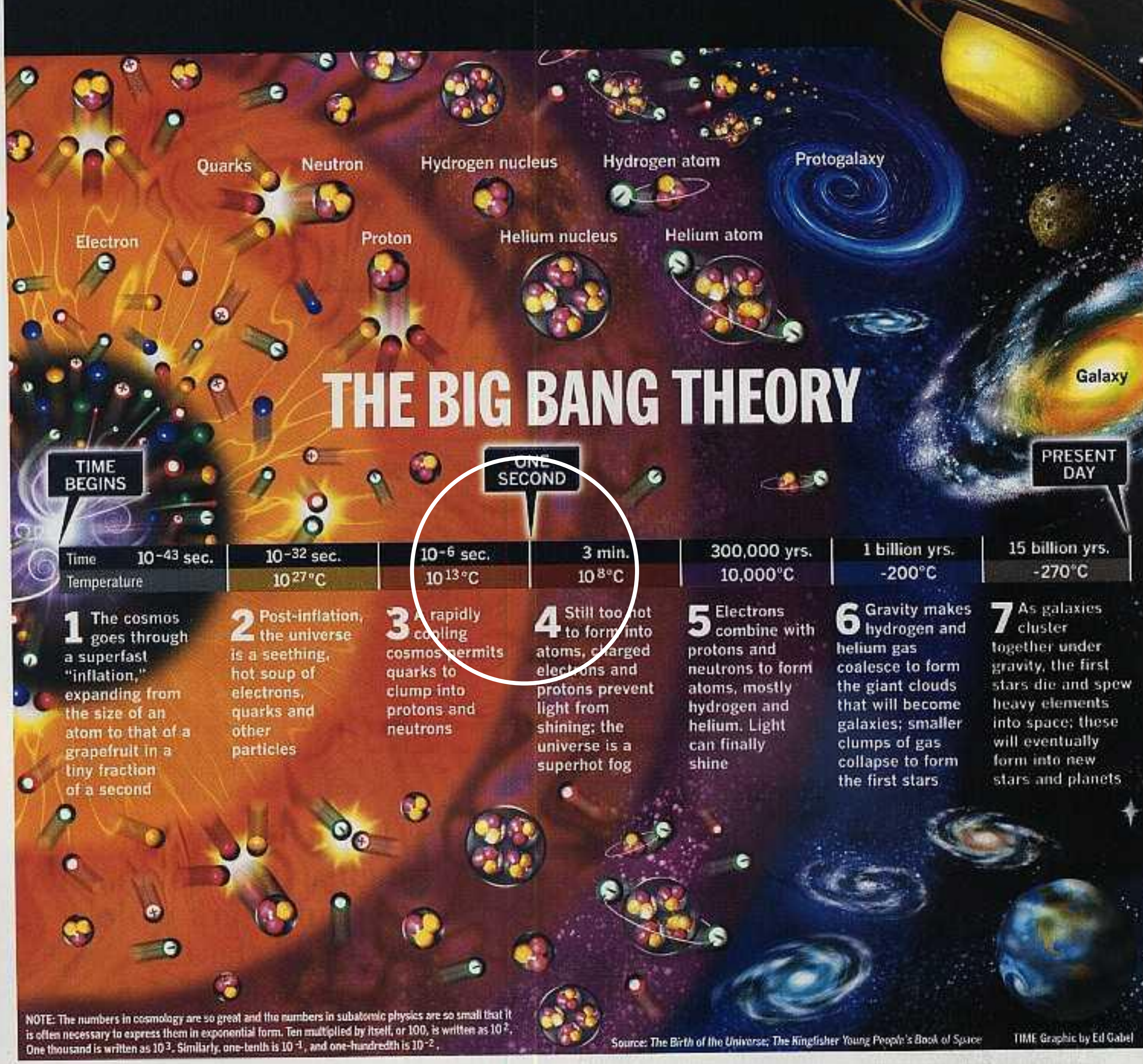
Quantum degeneracy in dilute ultacold atomic gases

The highest temperature

$$T = 4 \times 10^{12}\ K$$

Cern-Ginevra

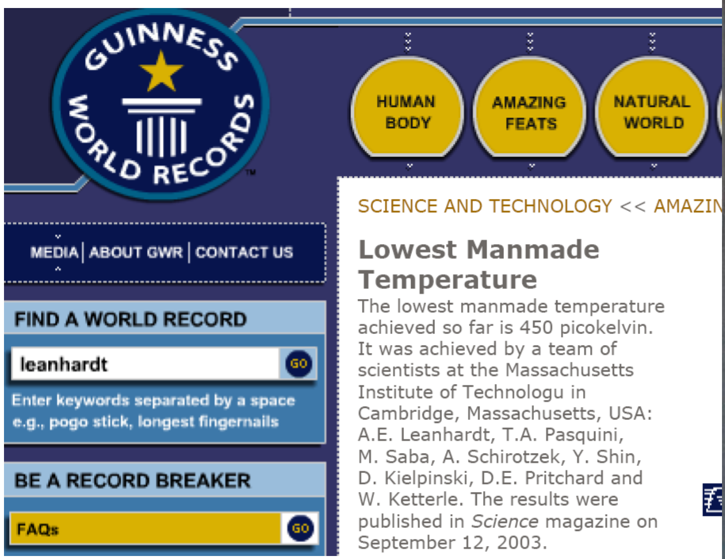


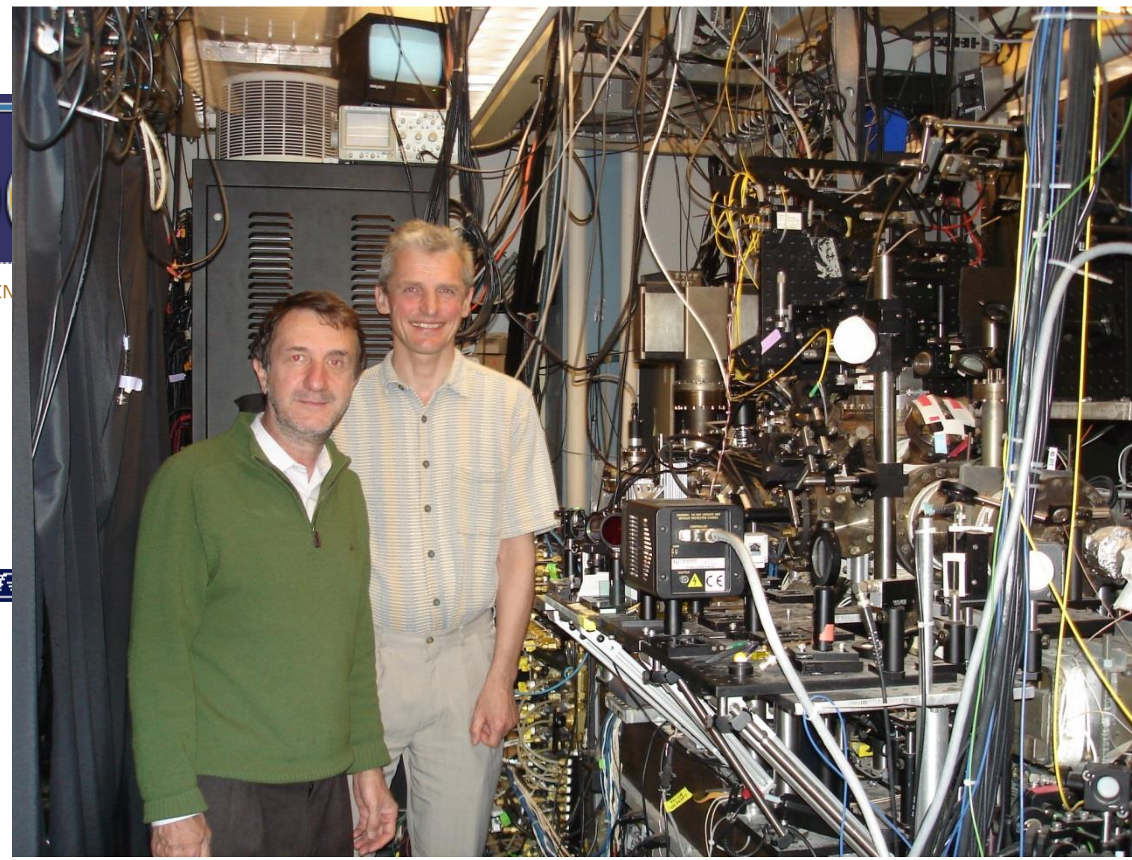

Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
THE BIG BANG THEORY
TIME BEGINS
ONE SECOND
PRESENT DAY
Time: 10-43 sec. | 10-32 sec. | 10-6 sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature: 10 27 °C | 10 13 °C | 10 8 °C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets
NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10 2. One thousand is written as 10 3. Similarly, one-tenth is 10 -1, and one-hundredth is 10 -2.
Source: The Birth of the Universe; The Kingfisher Young People's Book of Space
TIME Graphic by Ed Gabel

The lowest Temperature

$$T = 4 \times 10^{-10}\ K$$

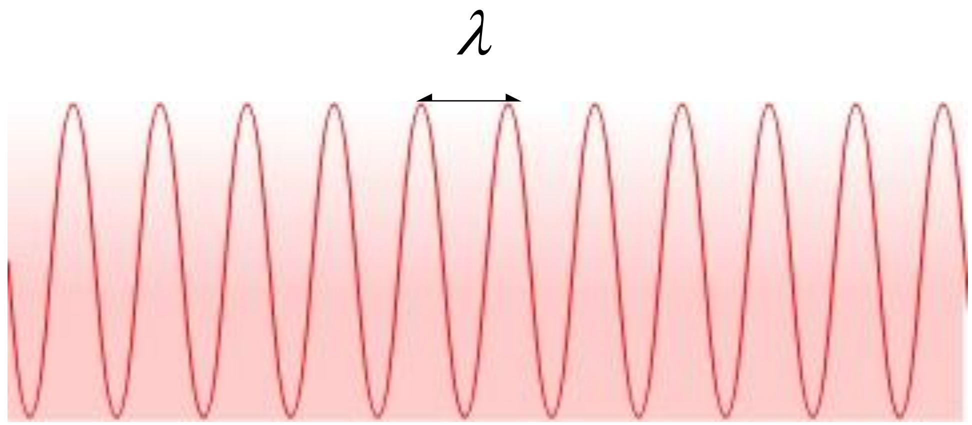
MIT-Cambridge





Why do we need extremely low temperatures to reach Bose-Einstein condensation in atomic gases ?

At low temperatures the motion of atoms is governed by the laws of quantum mechanics.



$$\lambda = \frac{h}{p}$$ de Broglie wave length

$$p = mv$$ momentum

$$h = 6.6 \times 10^{-27} g \frac{cm^2}{\sec}$$

Planck constant **(1900)**

GAS AT TEMPERATURE T

Typical value of the thermal wavelength

$$\lambda = \frac{h}{mv} \approx \sqrt{\frac{h^2}{mkT}}$$

T	v	λ
$300K$	$500m/\sec$	$10^{-8}cm$
$10^{-8}K$	$mm/\sec$	$10^{-3}cm$

Atomic radius

Typical hair thickness

When one **decreases temperature** the thermal **wave length** becomes **larger** and larger and eventually comparable to the interatomic distance.

Atoms behave like waves

and loose their identity

Nature divides elementary particles into two main classes

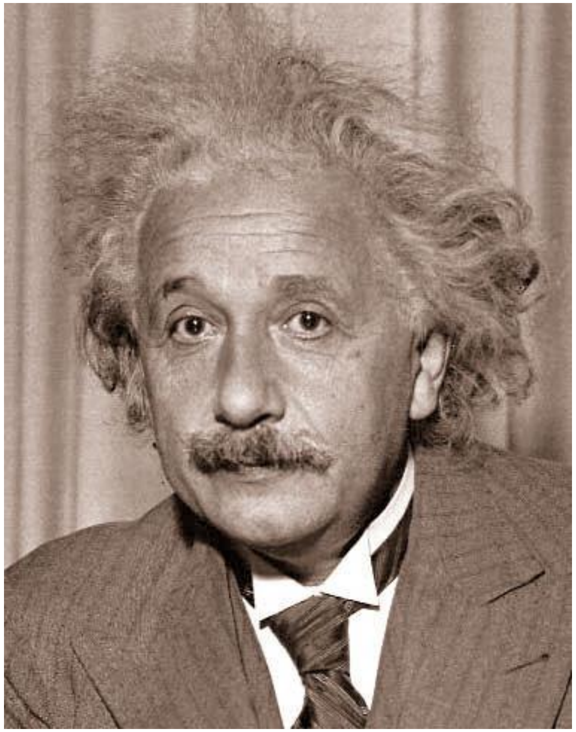
- **Fermions** (electrons, neutons, protons, atoms with odd number of fermions, like He3)

- **Bosoni** (photons, atoms with even number of fermions, like hydrogen, He4 ..)

At low temperatures quantum mechanics predicts a new phenomenon exhibited by bosons

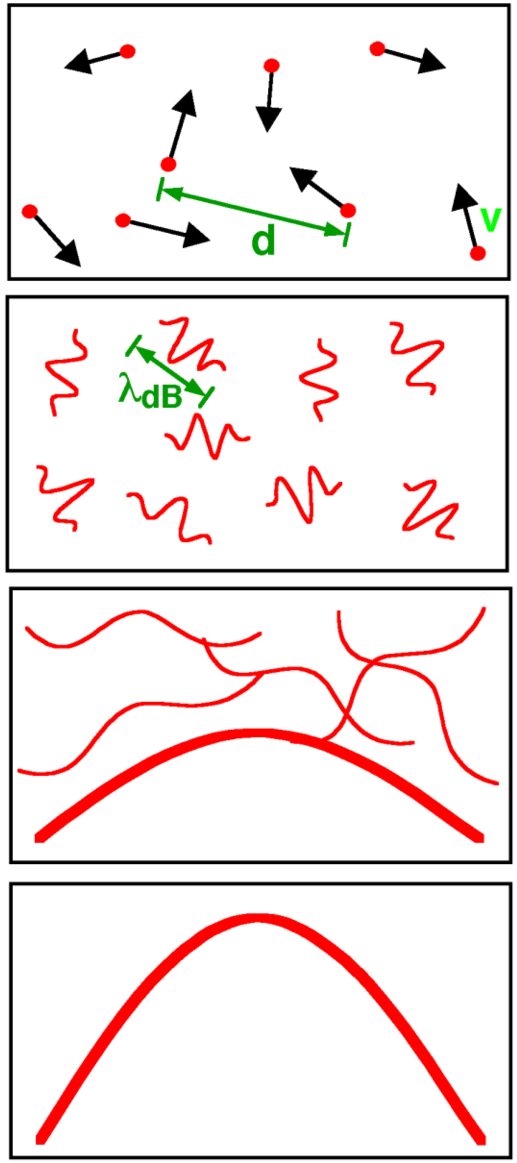
Bose-Einstein Condensation (1924-1925)

Satyendra Nath Bose



Albert Einstein

What is Bose-Einstein condensation (BEC)?



High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

Low Temperature T:

De Broglie wavelength

$\lambda_{dB}=h/mv \propto T^{-1/2}$

"Wave packets"

$T=T_{crit}$: Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

T=0: Pure Bose condensate

"Giant matter wave"

W. Ketterle

- **Bose-Einstein condensation in atomic gases has been a long sought goal for decades before 1995.**

- **At low temperature all the systems existing in nature (with the exception of liquid Helium) undergo a transition to the crystal phase.**

- **Atomic gases are not available in equilibrium at T=0**

- **Atomic gases at** $T \approx 0$ **are fortunately available in conditions of metastable equilibrium if their density is sufficiently small to avoid crystallization.**
- **This sets severe conditions for density (** $10^{13} - 10^{15} cm^{-3}$ **) and hence for temperaure (**$10^{-6} - 10^{-8} K$ **)**

Some questions

- **How can we realize such low temperatures and reach BEC ?**

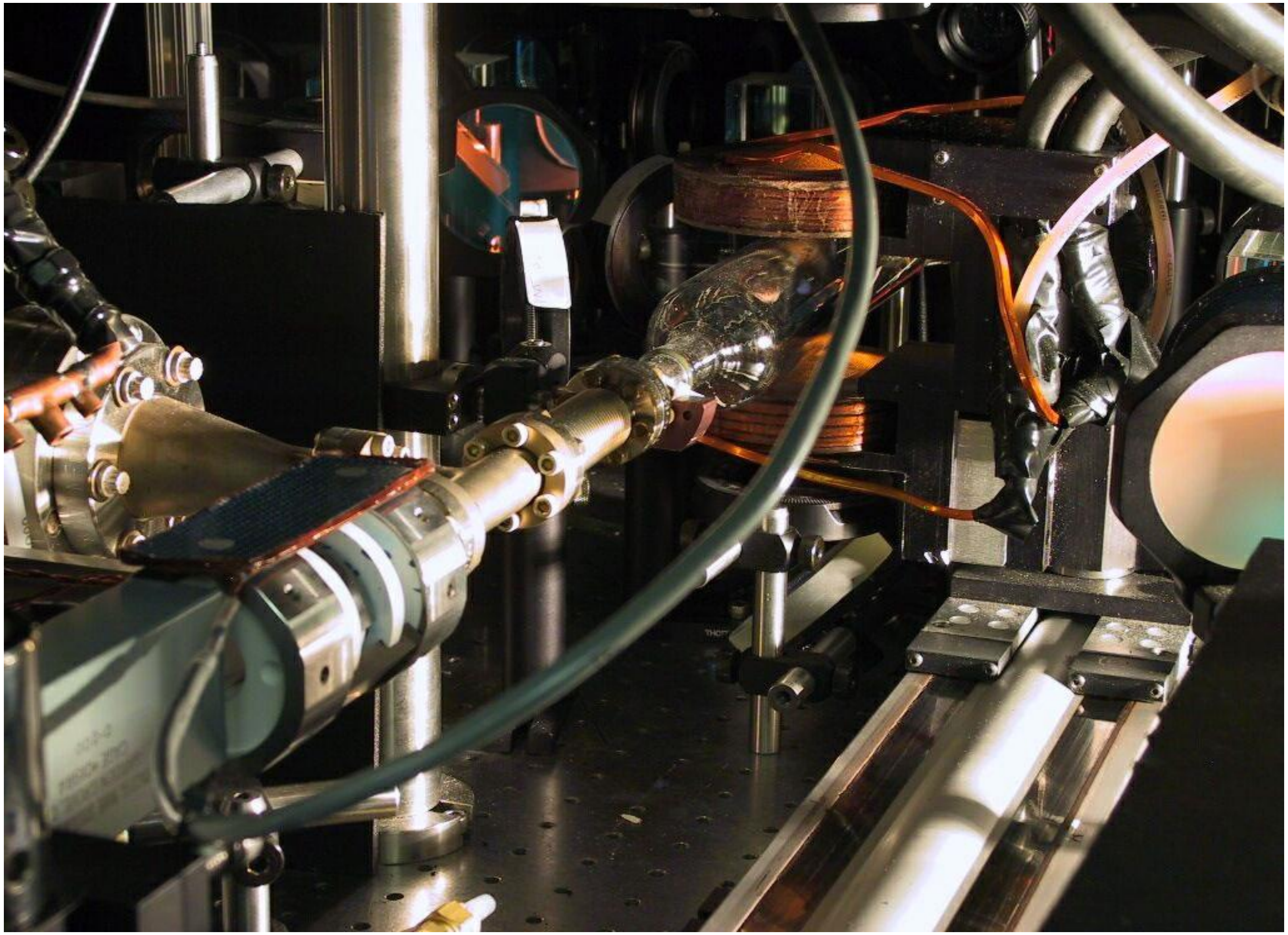
- **What are the new important features exhibited by Bose-Einstein condensates ?**

To realize BEC in atomic gases we need:

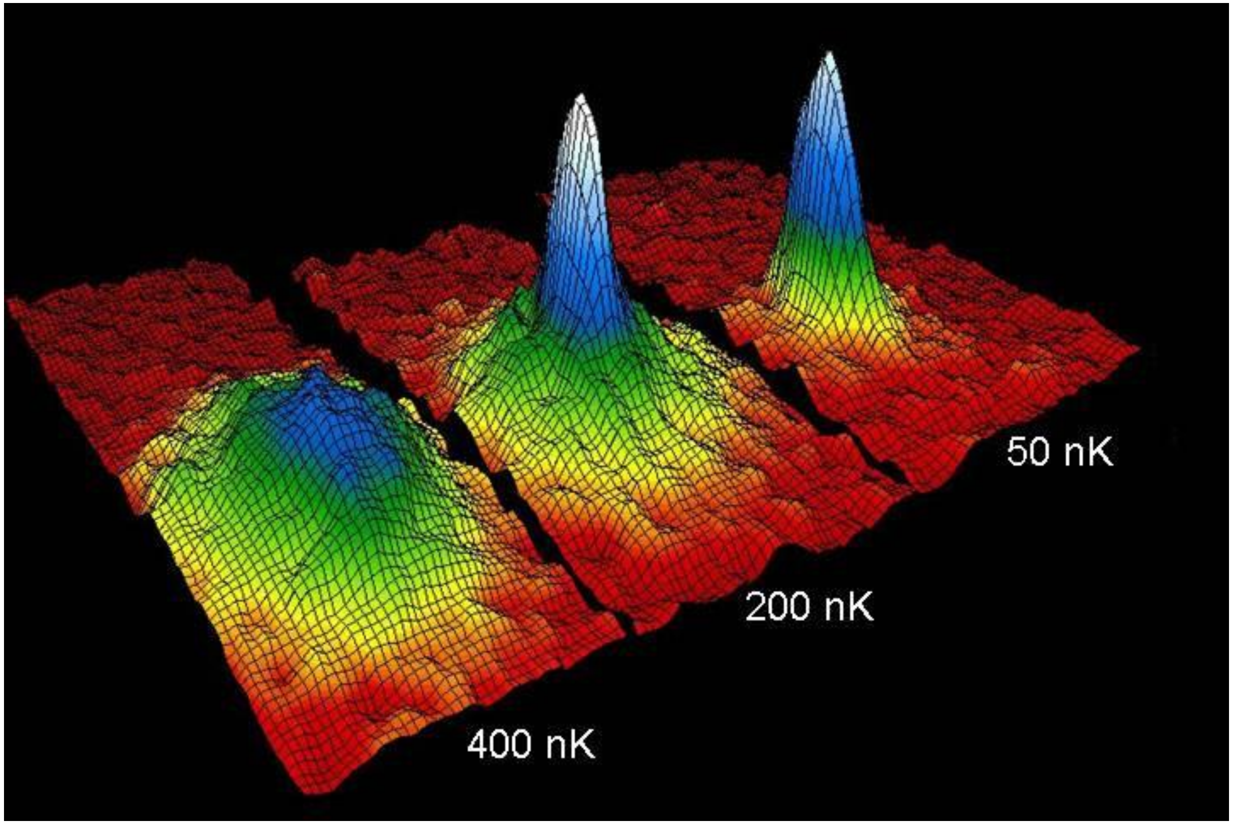
- **Trapping conditions** (keep atoms far from the walls using magnetic or optical fields)
- **Ultra-vacuum** (reduce collisions with hot atoms)
- **Very dilute gases** (avoid crystallizaion)
- **Ultra low temperatures** (new cooling techniques)

The great technological challenges of modern atomic physics !!

Experimental device used to realize BEC (JILA)



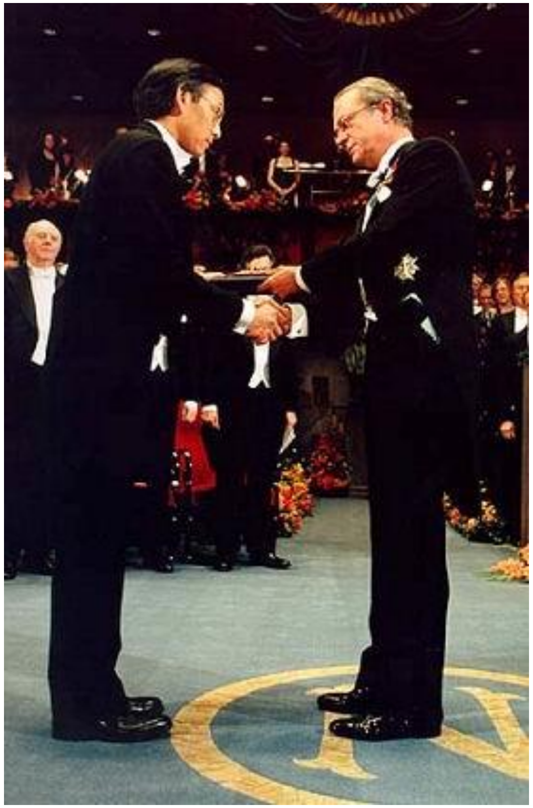
One of the first images revealing Bose-Einstein condensation (JILA 1995)

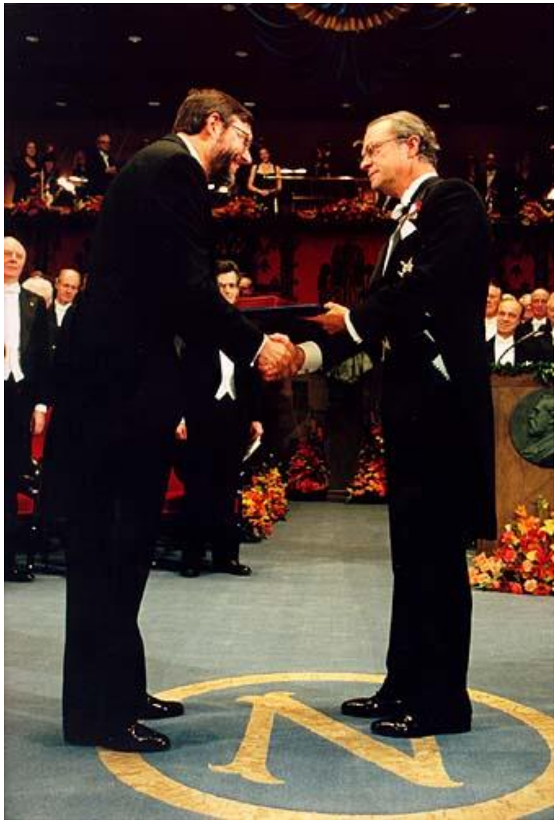


Below a certain temperature a macroscopic fraction of atoms occupies the same single particle states (Bose-Einstein condensate)

1997 NOBEL PRIZE IN PHYSICS

"for development of methods to cool and trap atoms with laser light"





Steven Chu

Claude Cohen-Tannoudji

William D. Phillips

2001 NOBEL PRIZE IN PHYSICS

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms”

Eric Cornell

Wolfgang Ketterle

Carl Wieman

- After the first realization of Bose-Einstein condensation in alkali atoms in 1995 the experimental and theoretical activity in **ultracold atomic gases** has become a well established field of research of fundamental interest for the investigation of **quantum phenomena** and involves thousands of researchers around the world.
- In Italy Bose-Einstein condensation is presently realized in Florence, Pisa and Trento

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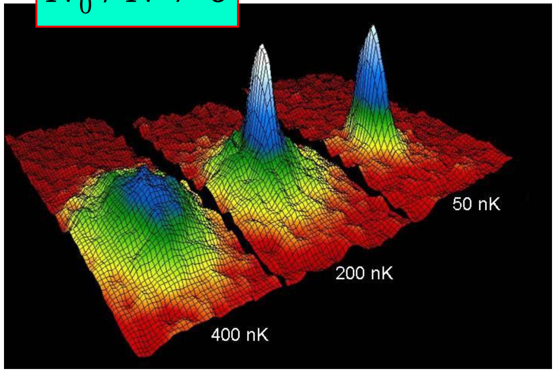
$N_0 / N \neq 0$



1995

(Jila+MIT)

Macroscopic occupation of sp state (Bose-Einstein condensation)

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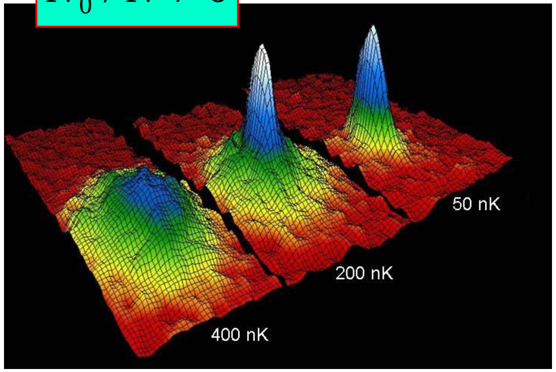

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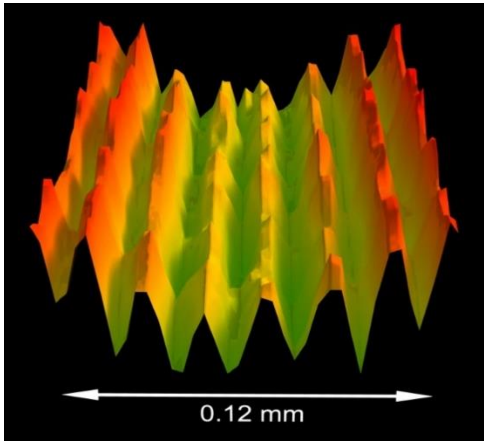
Macroscopic occupation of sp state (Bose-Einstein condensation)

1996
(MIT)

Interference and quantum coherence



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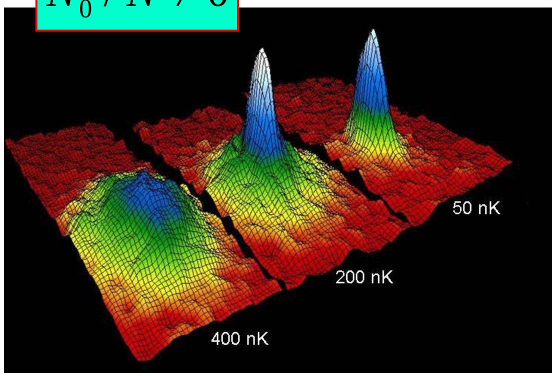

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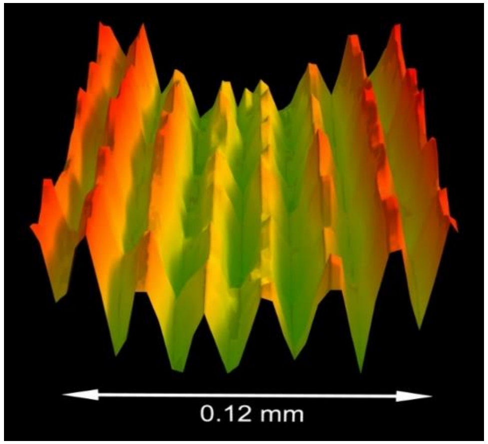
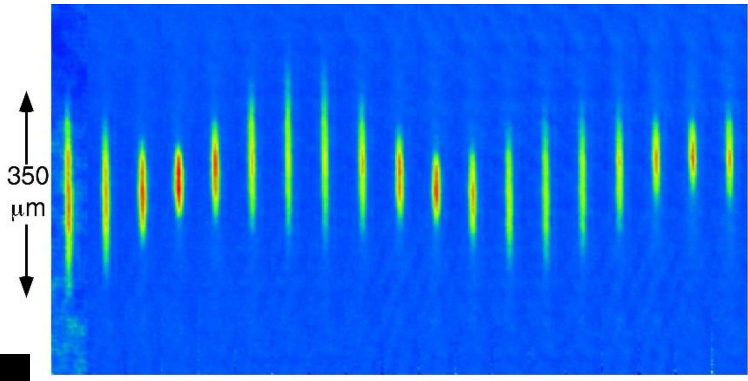
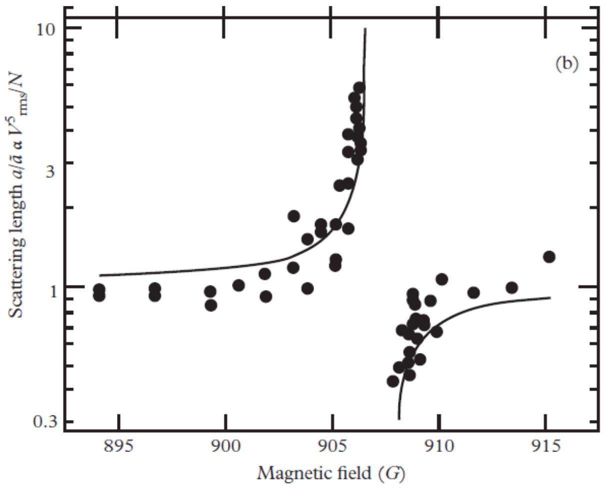




5 milliseconds per frame

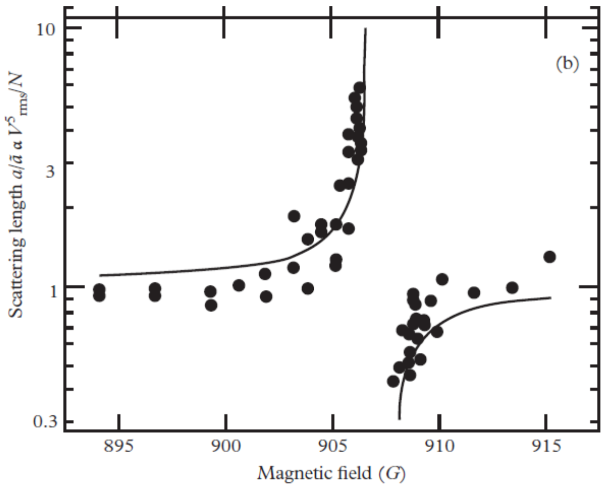
1996
(MIT)

Collective oscillations



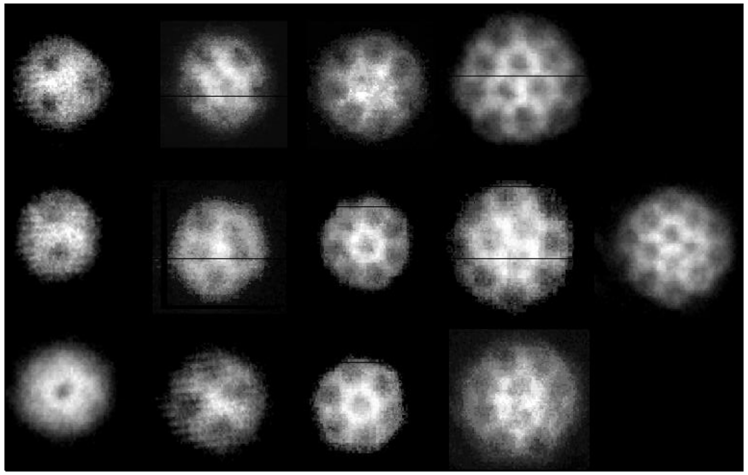
1999
(MIT)

Feshbach resonances and tuning of scattering length



2000
(ENS

Quantized vortices in BEC



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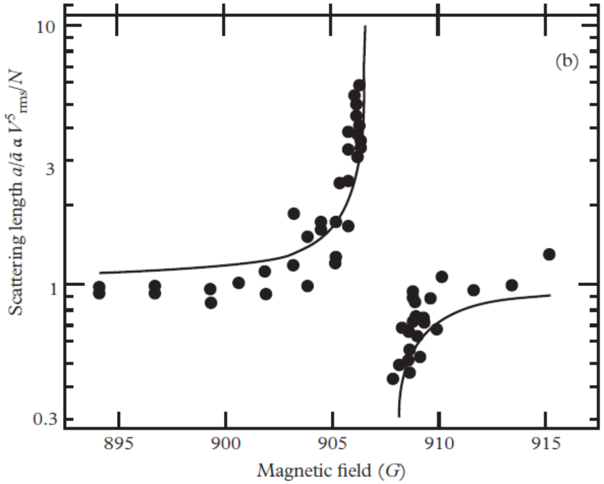

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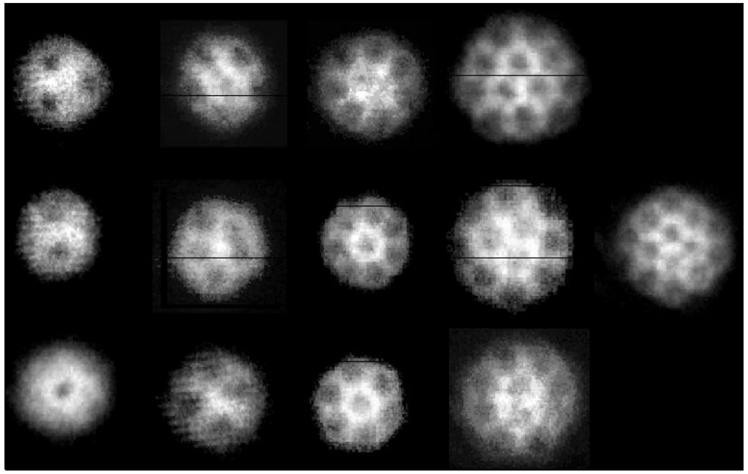
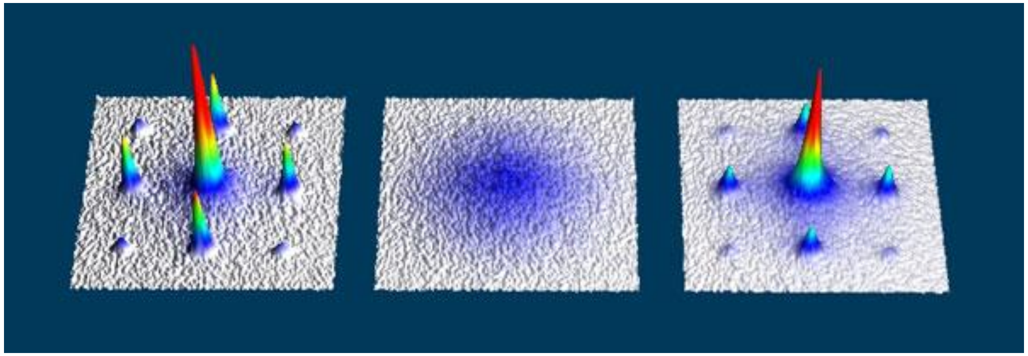
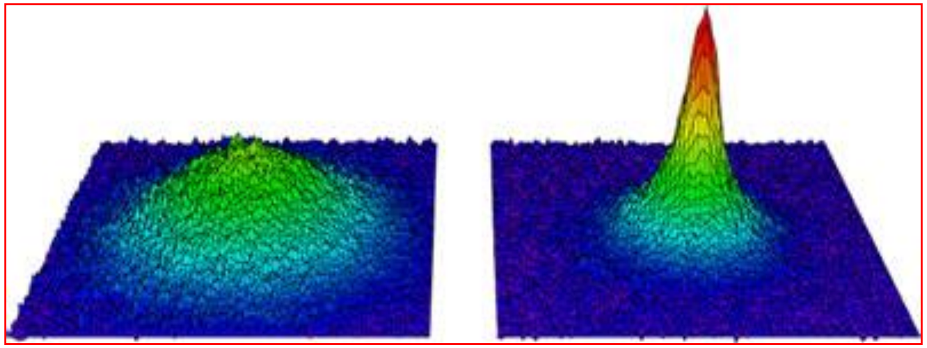




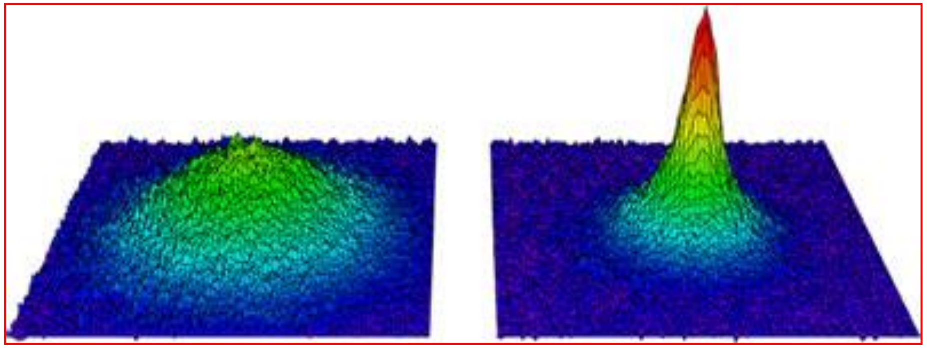
2001
(MPI Munich)

Superfluid-insulator transition



2003
(JILA-ENS-Innsbruck)

BEC of molecules emerging from Fermi sea



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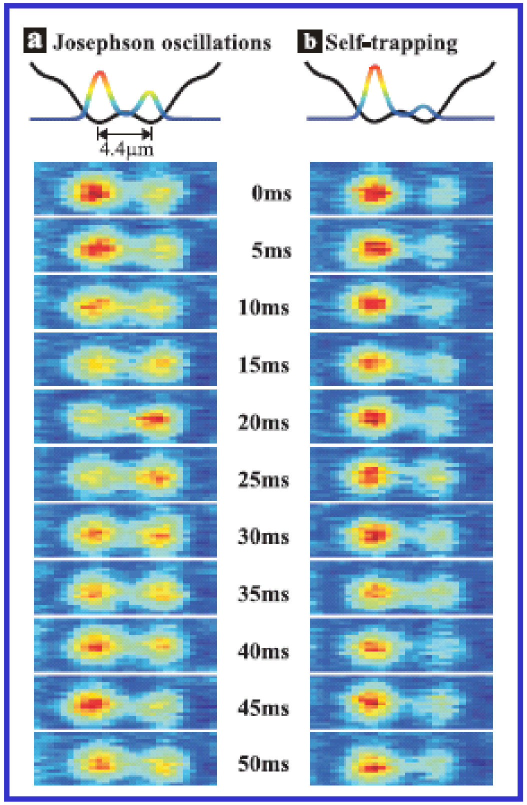
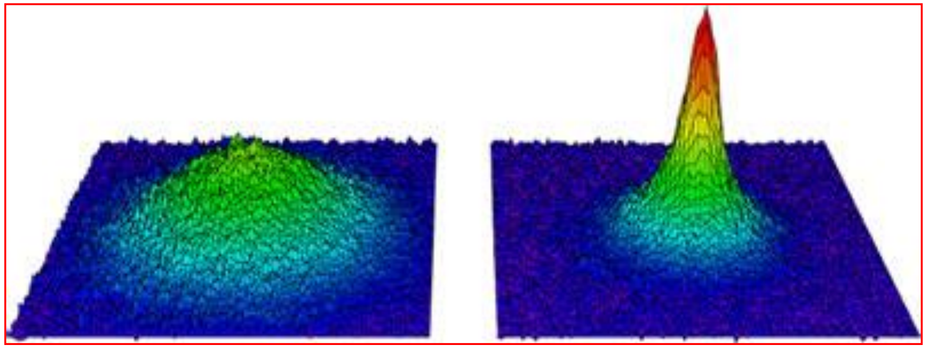


2004
(Heidelberg)

Josephson oscillation



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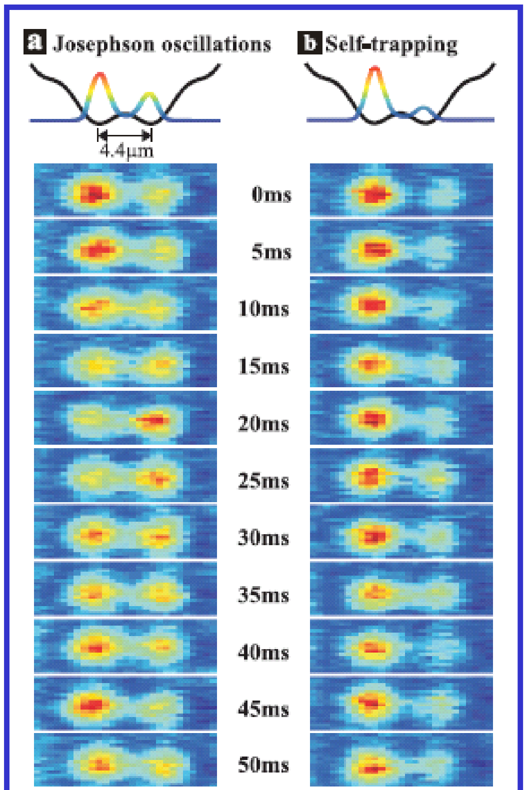

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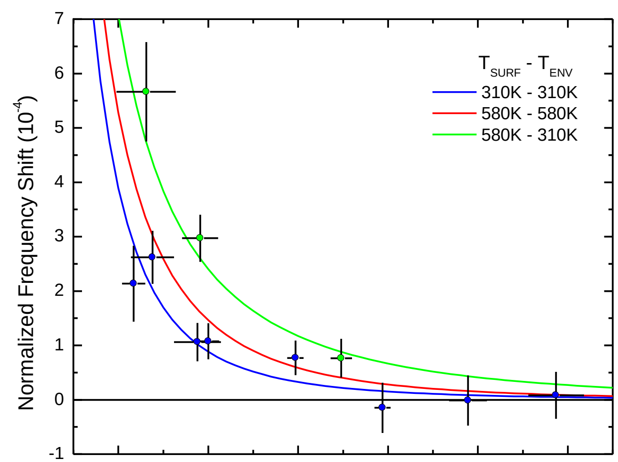
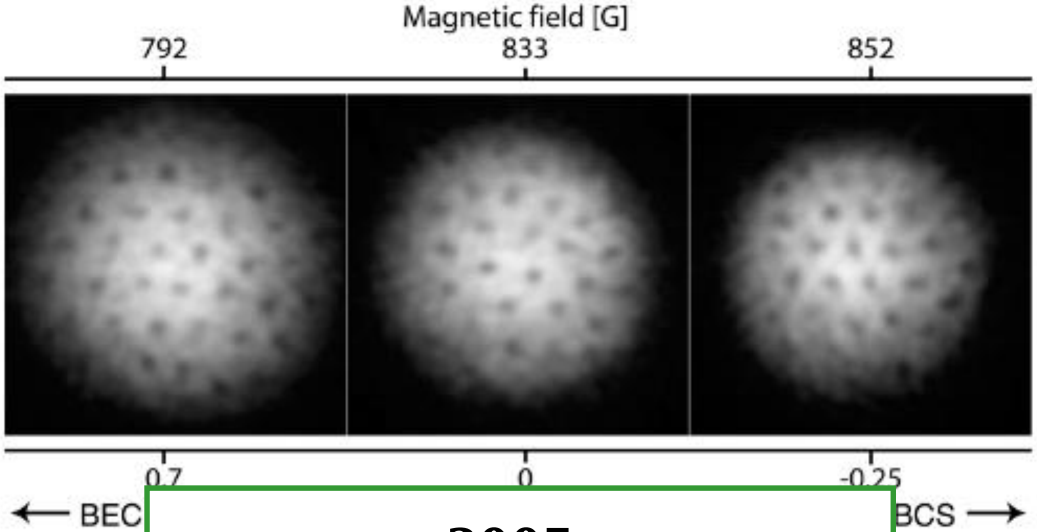


2004

(JILA)

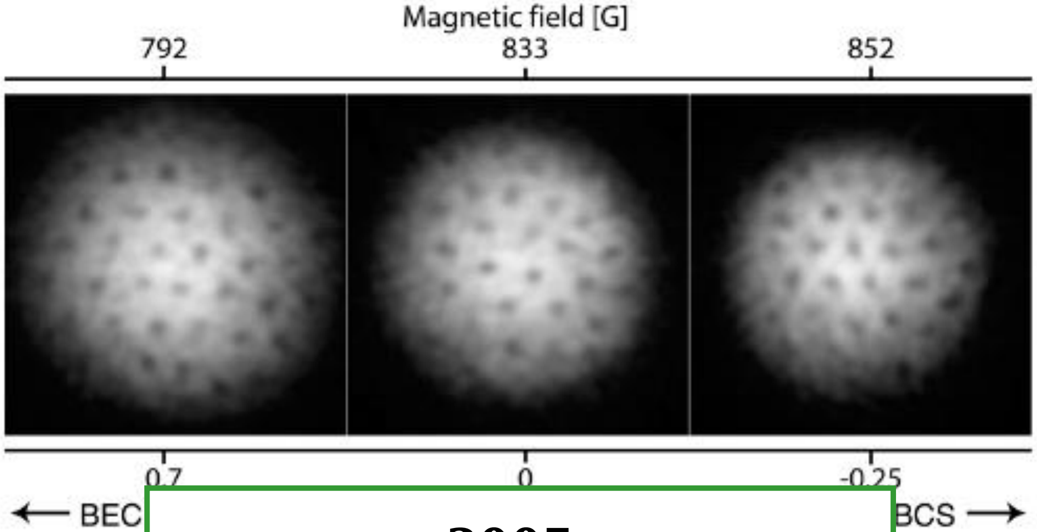
Temperature dependence of Casimir-Polder force



2005

(MIT)

Vortices in a Fermi superfluid



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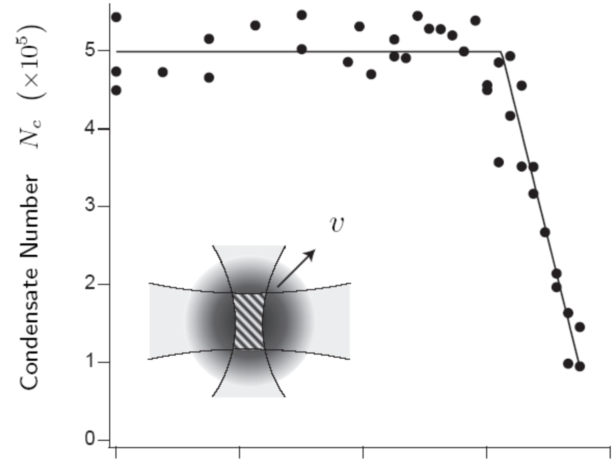
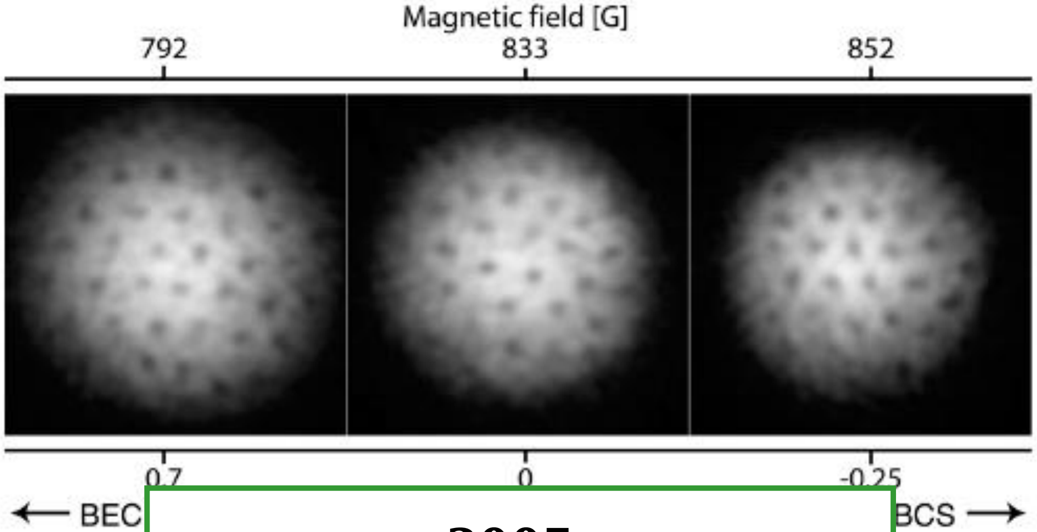


2007

(MIT)

Absence of viscosity in the unitary Fermi superfluid



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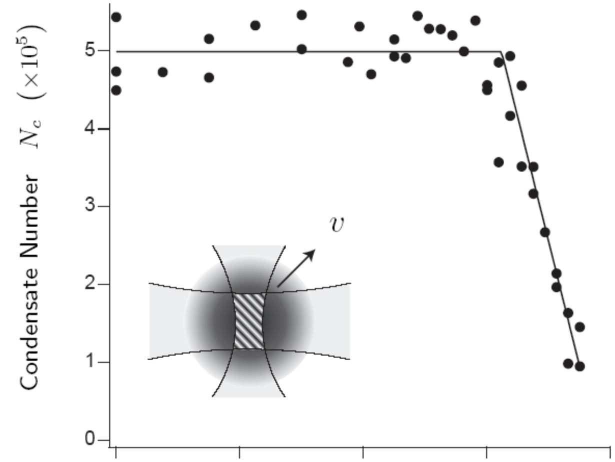

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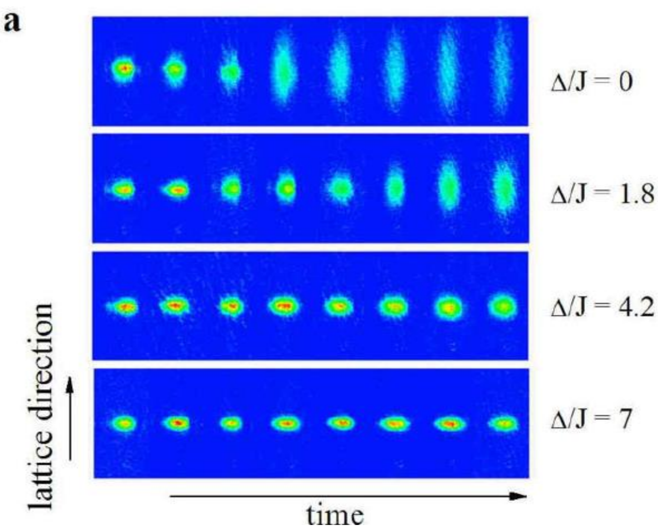
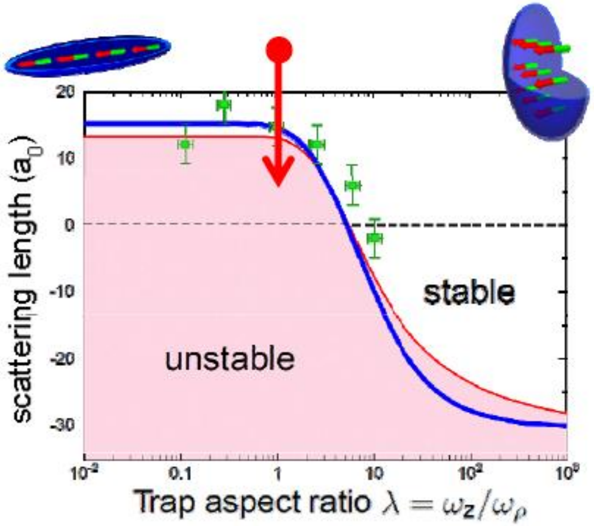


2008

(Florence-Palaiseau)

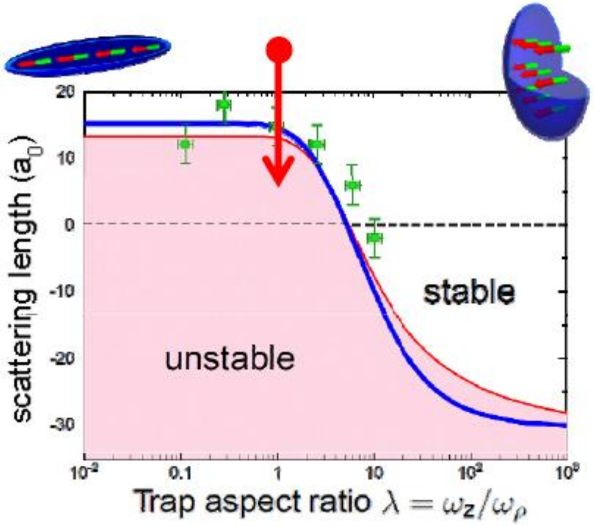
Anderson localization



2008

(Stuttgart)

BEC in
dipolar gases
(anisotropy and
long range)



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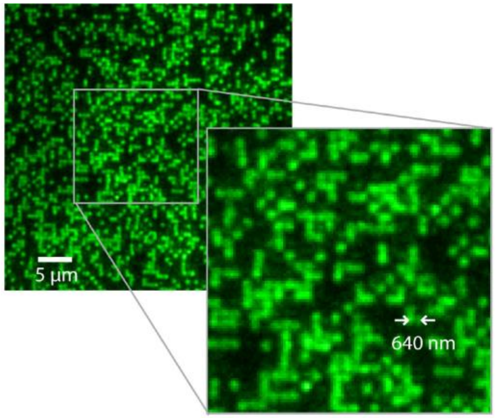
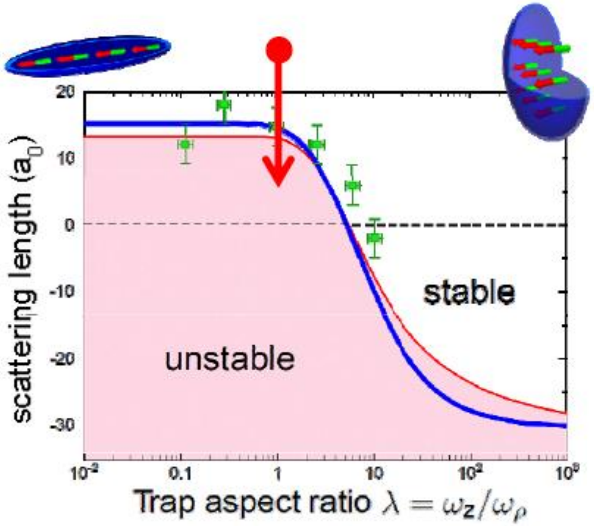


2009
(Harvard)

Quantum gas
microscope



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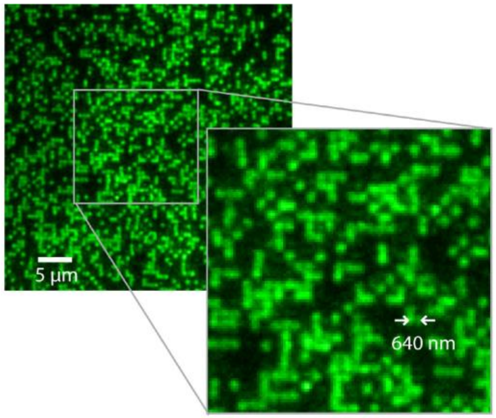

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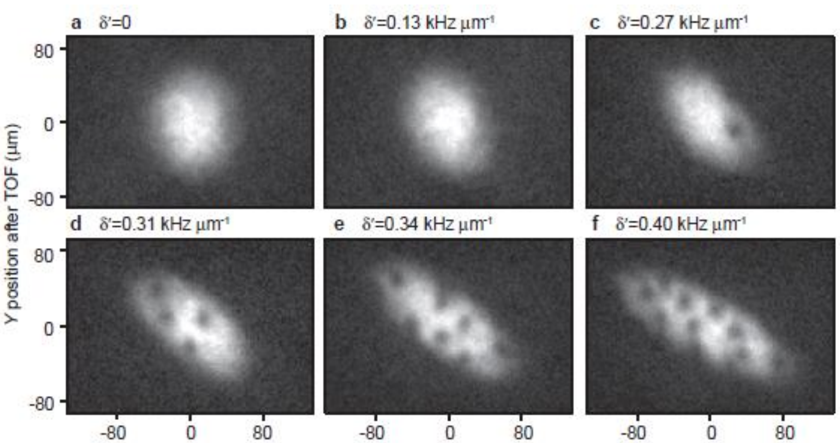
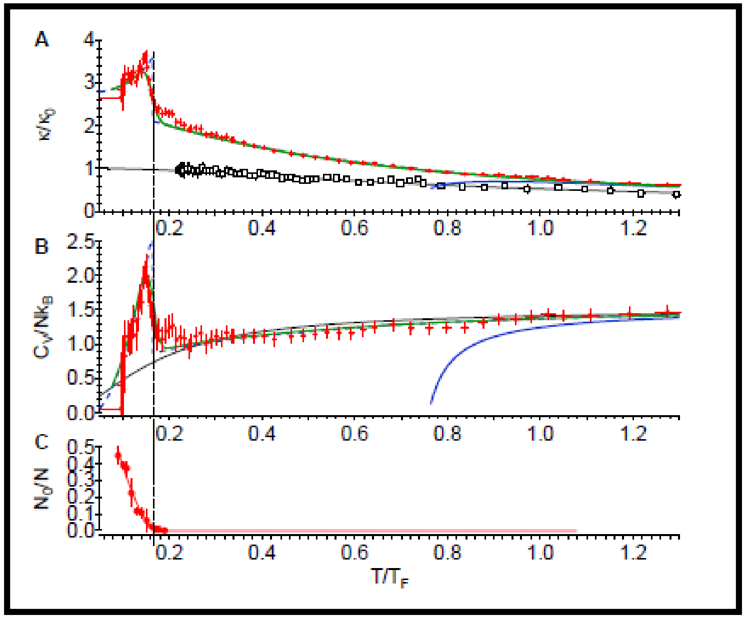
Quantum gas microscope



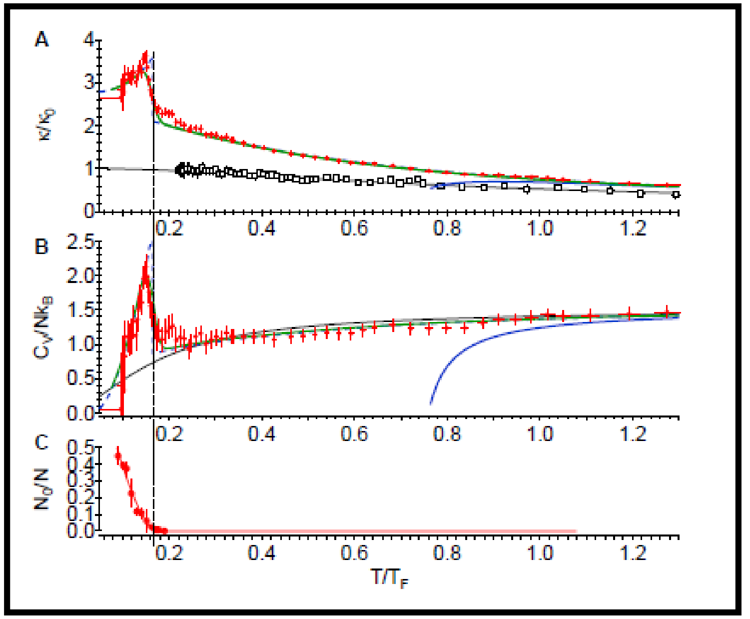
2009
(NIST)

Vortices produced with artificial gauge fields



2012
(MIT)

Lambda transition in superfluid Fermi gas



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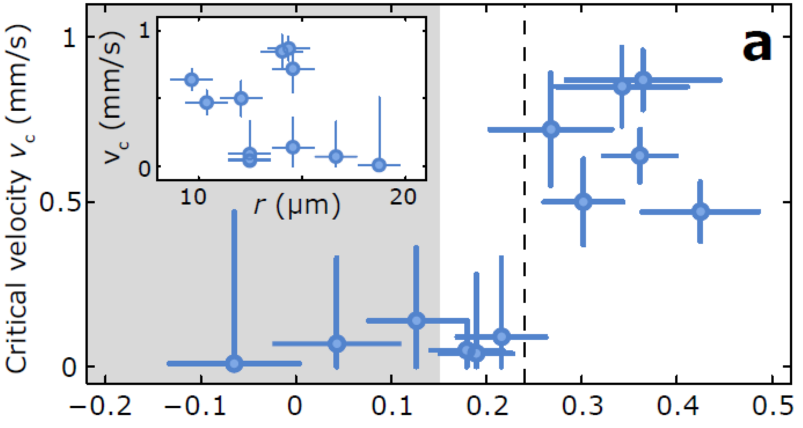
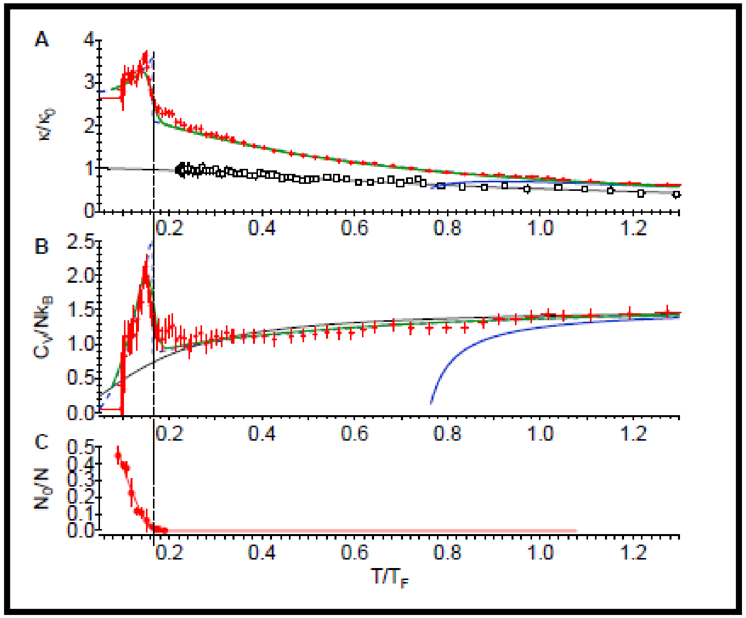


2012
(ENS)

BKT transition in 2D Bose gas

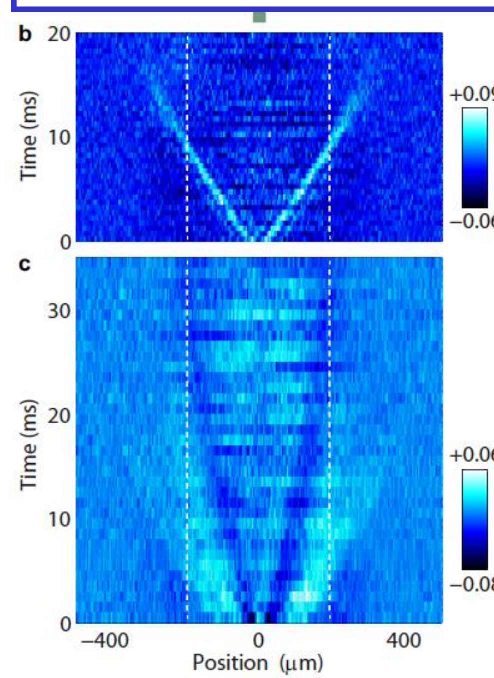


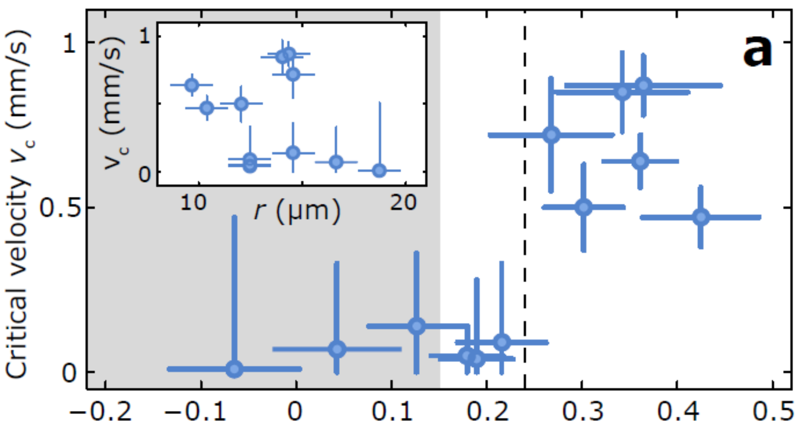
2012
(MIT)

Lambda transition in superfluid Fermi gas

2013
(Innsbruck)

Propagation of second sound in a Fermi superfluid





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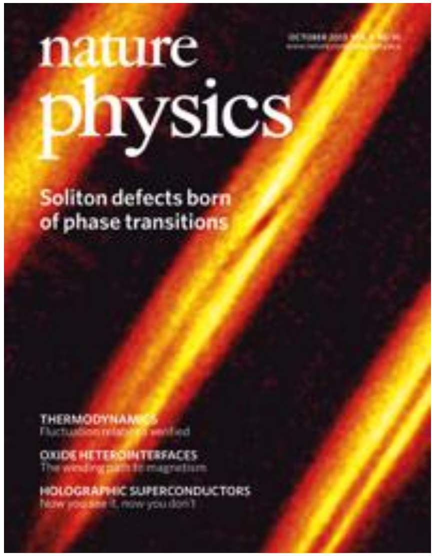
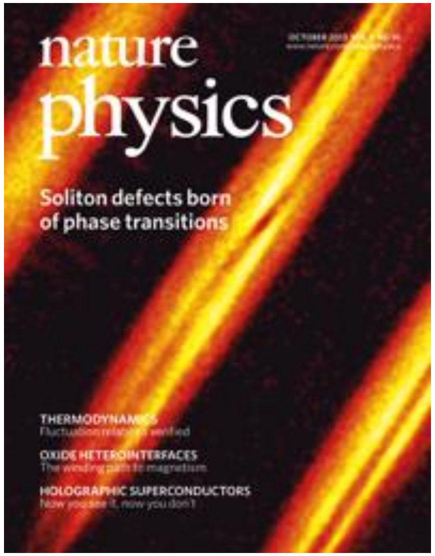


2013

(Trento)

Kibble Zurek generation of quantum defects



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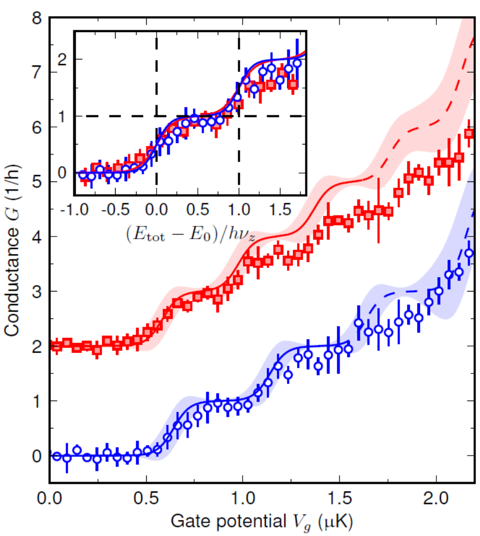
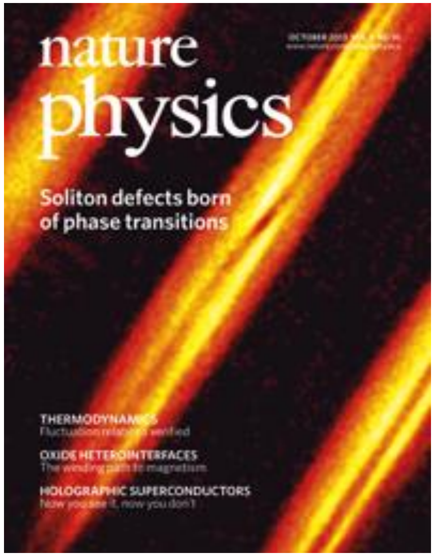


2014

(ETH Zurich)

Quantized conductance in atomic Fermi gases



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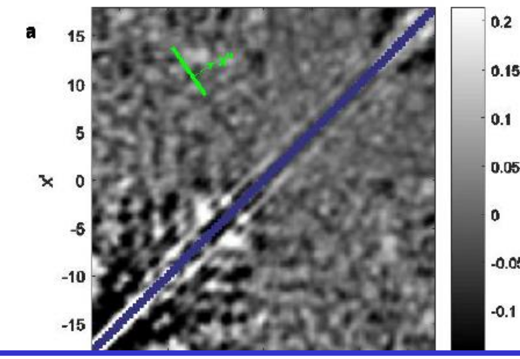
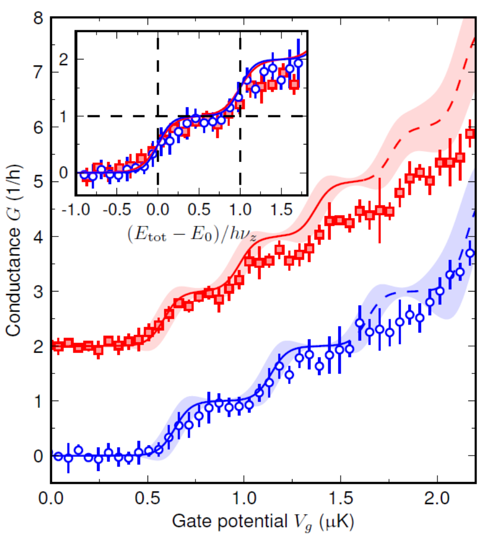


2016

(Technion)

Hawking radiation in BECs



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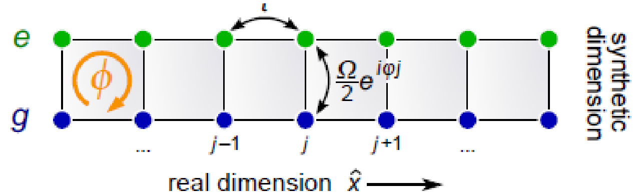
(ETH Zurich)

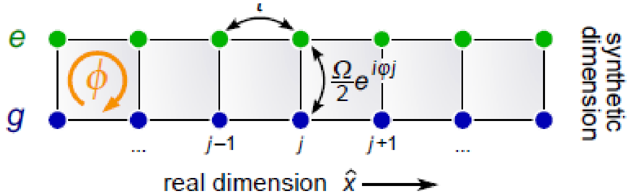
Quantized conductance in atomic Fermi gases



2016

(Florence)

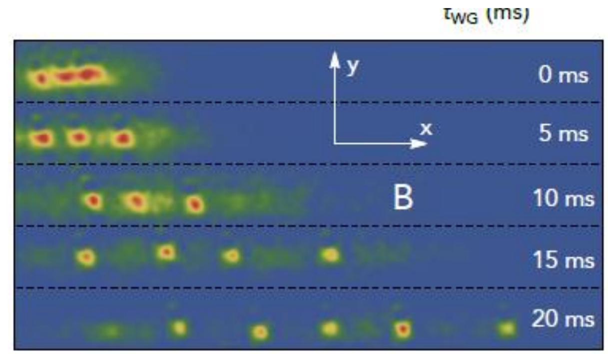
Synthetic dimensions with spin-orbit coupling



2016

(Florence)

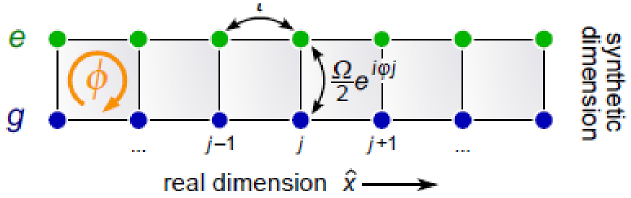
Synthetic dimensions with spin-orbit coupling



2016

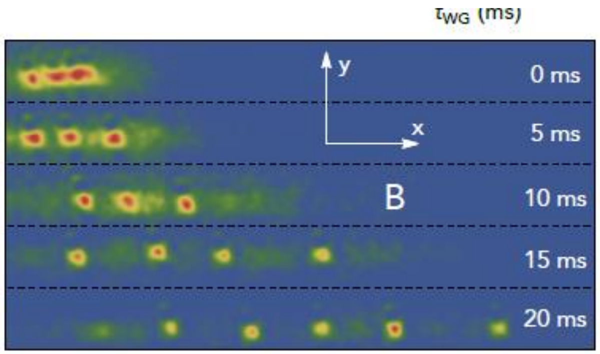
(Stuttgart)

Self-bound droplets in dipolar gases



2016
(Florence)

Synthetic dimensions with spin-orbit coupling

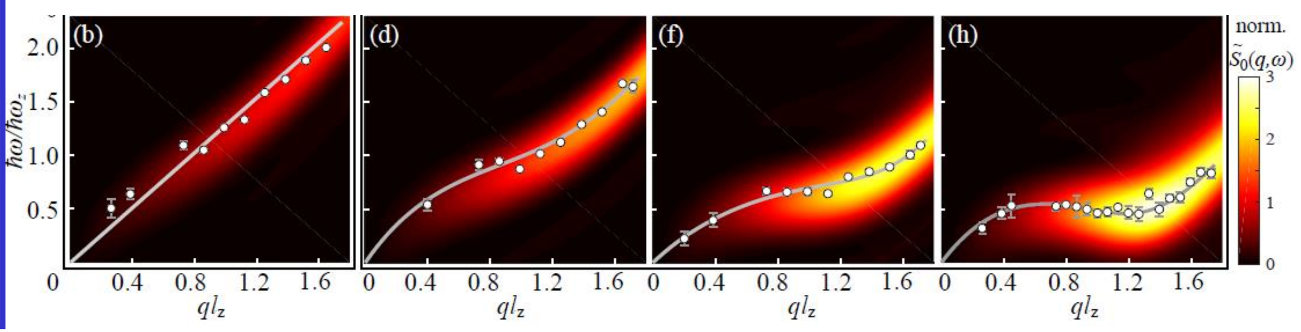


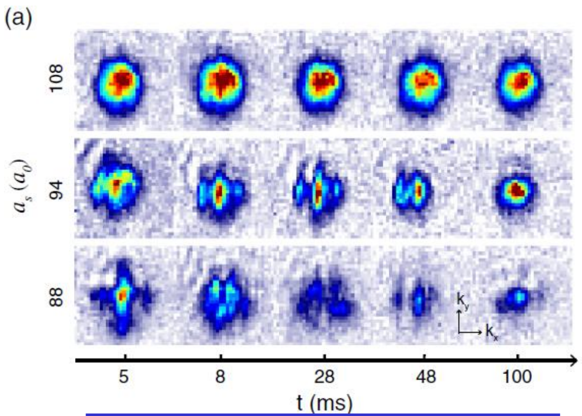
2016
(Stuttgart)

Self-bound droplets in dipolar gases

2019
(Innsbruck)

Rotons in dipolar BECs

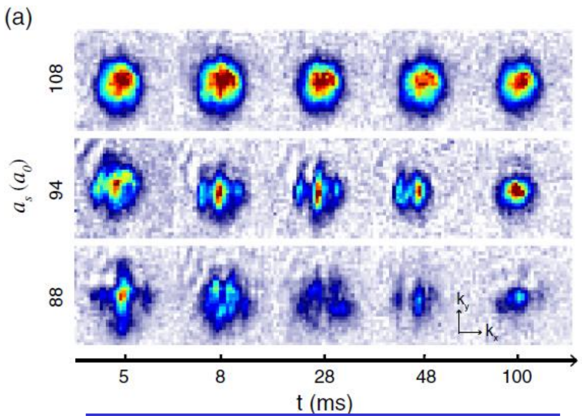




2019

(Pisa, Stuggart, Innsbruck)

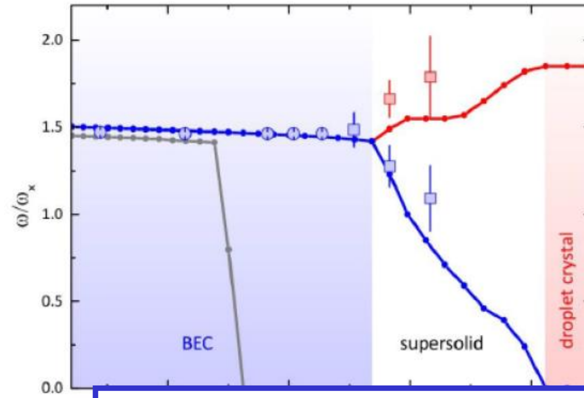
Supersolidity in dipolar BECs



2019

(Pisa, Stuggart, Innsbruck)

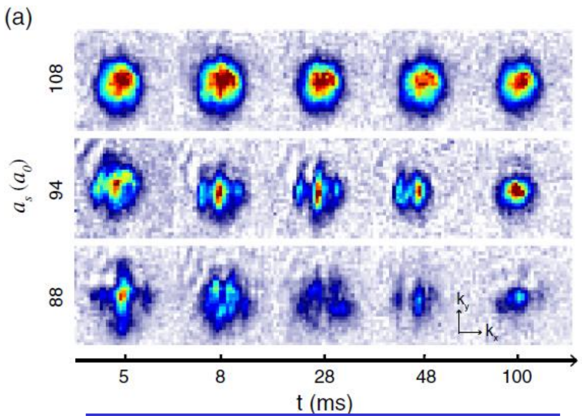
Supersolidity
in dipolar BECs



2019

(Pisa, Stuggart, Innsbruck)

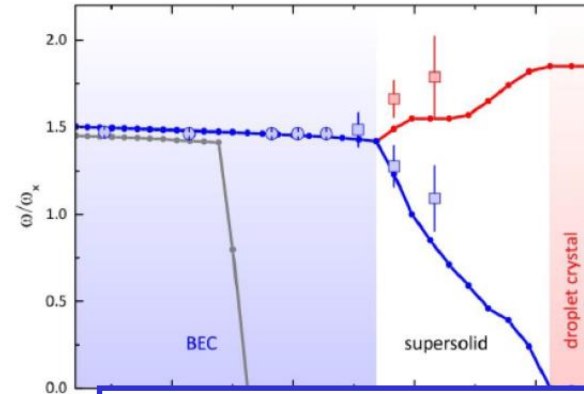
Goldstone modes
in supersolids



2019

(Pisa, Stuggart, Innsbruck)

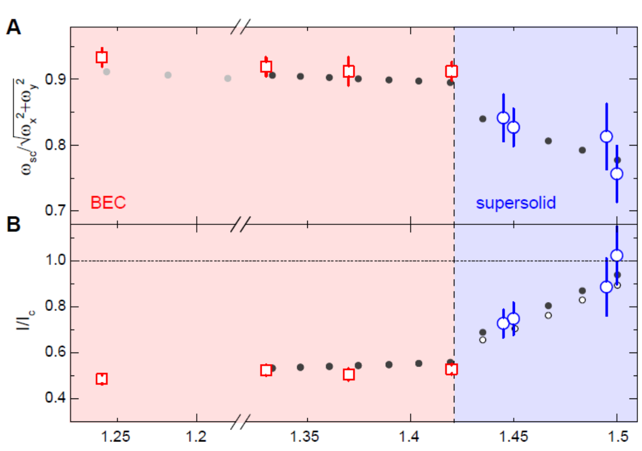
Supersolidity in dipolar BECs



2019

(Pisa, Stuggart, Innsbruck)

Goldstone modes in supersolids



2020

(Trento, Pisa)

Superfluidity of a supersolid dipolar gas

Synthetic gauge fields:

New horizons of atomic physics

Atoms are **neutral objects** and are **not sensitive to Lorentz force** which in charged systems is at the basis of important many-body phenomena (ex: Quantum Hall effect)

It is now possible to **create artificial gauge fields** which simulate in neutral systems the effect of a magnetic field on a charged particle

For a useful review see

Jean Dalibard:
Introduction to the physics of artifical gauge fields

[Proceedings of the International School of Physics "Enrico Fermi" of July 2014, "Quantum matter at ultralow temperatures“]

In the presence of a magnetic field the kinetic energy of a charged particle can be written as

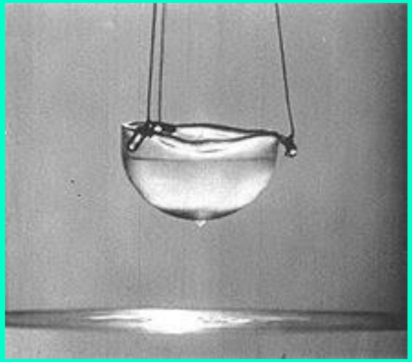
$$H = \frac{(\vec{p} - e\vec{A})^2}{2m}$$

Where p is canonical momentum operator. In the case of a uniform magnetic field oriented along the z-direction one has $A_y = Bx\,, A_x = A_z = 0$ (Landau gauge)

Can we produce similar Hamiltonians employing neutral atoms and explore the effects at the many-body level ?

The simplest example:

Rotating a trapped gas



Analogy with bucket experiment of superfluid Helium

$$H = \frac{\vec{p}^{\,2}}{2m} + \frac{1}{2} m \omega_{ho}^2 \vec{r}^{\,2} - \Omega L_z$$

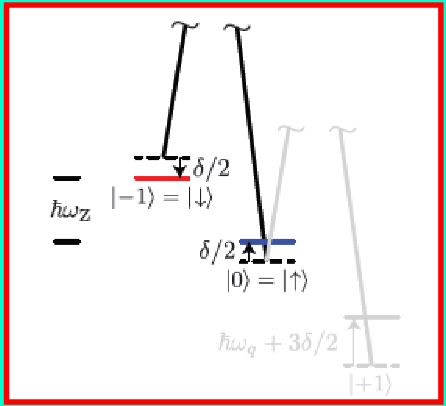
$$= \frac{(p_x - m\Omega y)^2}{2m} + \frac{(p_y + m\Omega y)^2}{2m} + \frac{1}{2} m \omega_{ho}^2 \vec{r}^{\,2} - \frac{m^2 \Omega^2 (x^2 + y^2)}{2}$$

Efficient procedure to create quantized vortices !

A more advanced example:
Spin-orbit coupling

Simplest realization in a mixture of two BECs

Two detuned and polarized laser beams + non linear Zeeman field provide Raman transitions between two spin states, give rise to new s.p. Hamitonian



$$h_0 = \frac{1}{2m}[(p_x - k_0\sigma_z)^2 + p_\perp^2] + \frac{1}{2}\hbar\Omega\sigma_x + \frac{1}{2}\hbar\delta\sigma_z$$

Spin dependent gauge field + breaking of Galilean invariance

IMPORTANT PERSPECTIVES

- **Supersolidity** with spin-orbit coupling
- **Synthetic dimensions**
- Synthetic gauge fields in **Fermi gases**
- **Non Abelian** gauge fields (Rashba Hamiltonian)
- **Simulation of lattice gauge theories**
- novel **topological properties** of quantum matter
- etc..

The Trento BEC team

Visit our web site
http://bec.science.unitn.it/