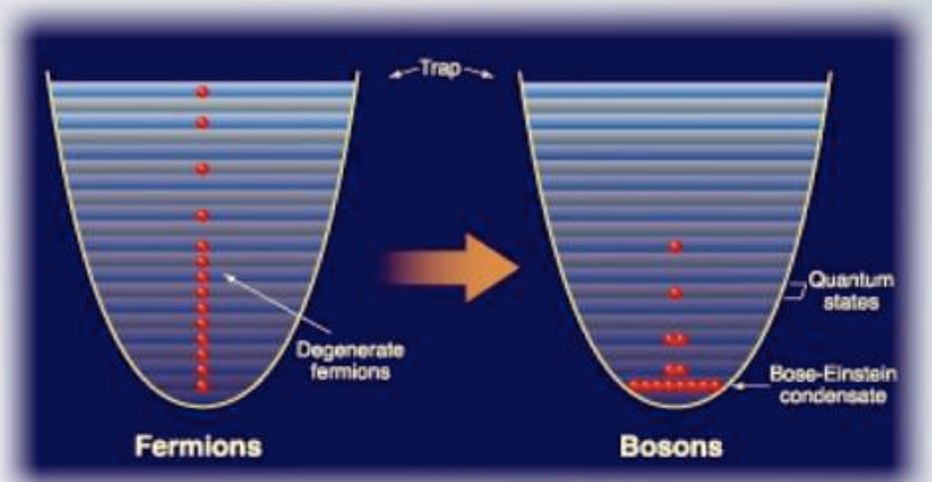
# COMMENT ON FERMIONS AND BOSONS

Only bosons can form a BEC.

Fermions cannot occupy the same ground state.




| bosons | fermions |
|---|---|
| integer spin | half-integer spin |
| Bose-Einstein distribution | Fermi-Dirac distribution<br>& Pauli exclusion principle |

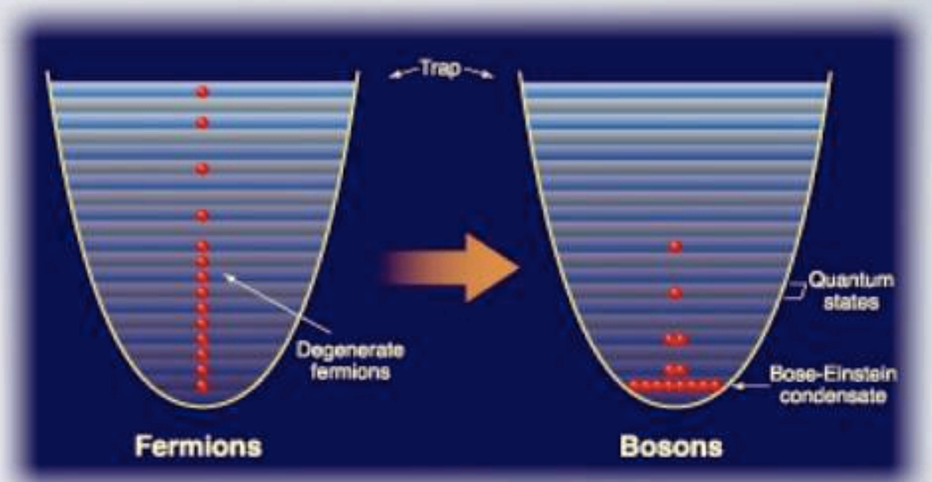
*It is supposed that any bosonic atom can condense.*

# COMMENT ON FERMIONS AND BOSONS

Only bosons can form a BEC.

Fermions cannot occupy the same ground state.

The $Z+A$ number (or number of neutrons) determines if an atom is a fermion or a boson



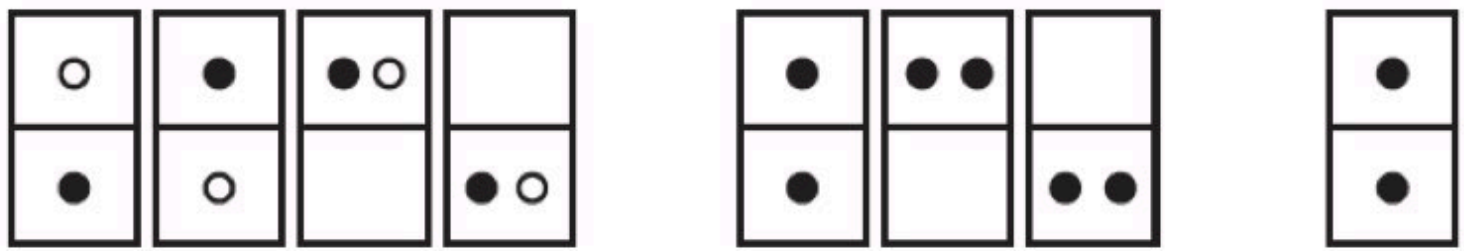

$Z$ - proton number
$A$ - nucleons number = protons+neutrons
$A=Z+N$

For alkali atoms $Z$ is an odd number

| *A* number | atom type | examples |
|---|---|---|
| odd | boson | $^{7}Li$, $^{85}Rb$, $^{23}Na$ |
| even | fermion | $^{6}Li$, $^{40}K$ |

# QUANTUM STATISTICS

- Tells how to distribute particles on possible quantum states
- Let's consider two particles distributed in two boxes
- What is a probability in each case to find two particles in a box?



*Distinguishable bosons (like classical particles)*

$$\frac{1}{2}$$

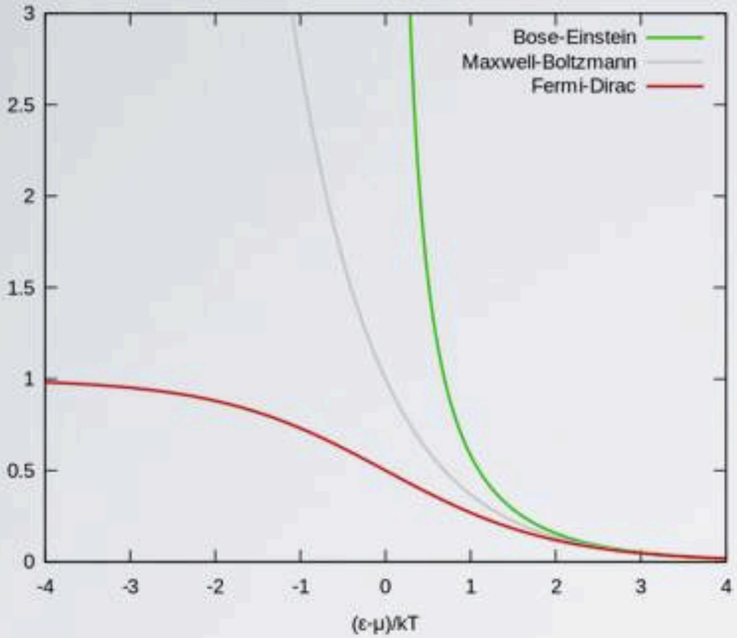
*Indistinguishable bosons (bosonic particles at quantum limit)*

$$\frac{2}{3}$$

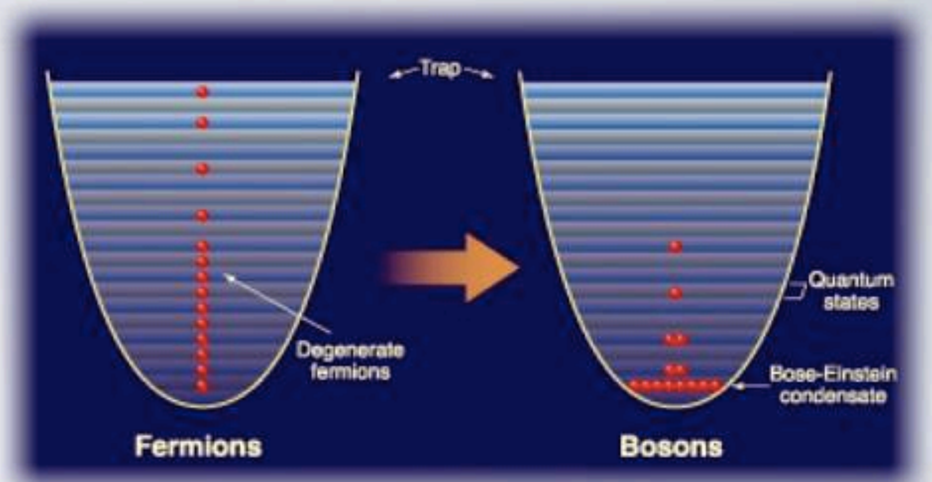
*Fermions*

$$0$$

# COMMENT ON FERMIONS AND BOSONS




for large number of particles
and low temperatures




| Boltzmann | Bose Einstein | Fermi Dirac |
|---|---|---|
| $\overline{n}_k = \dfrac{1}{\exp\left(\dfrac{\varepsilon-\mu}{k_B T}\right)}$ | $\overline{n}_k = \dfrac{1}{\exp\left(\dfrac{\varepsilon-\mu}{k_B T}\right)-1}$ | $\overline{n}_k = \dfrac{1}{\exp\left(\dfrac{\varepsilon-\mu}{k_B T}\right)+1}$ |
| indistinguishable<br>$Z=(Z_1)^N/\mathbf{N!}$<br>$n_K \ll 1$ | indistinguishable<br>integer spin 0,1,2 ... | indistinguishable<br>half-integer spin 1/2,3/2,5/2 ... |
| spin doesn't matter | bosons | fermions |
| localized particles<br>Ψ don't overlap | wavefunctions overlap<br>total Ψ symmetric | wavefunctions overlap<br>total Ψ anti-symmetric |
| gas molecules<br>at low densities | photons<br>$^4$He atoms | free electrons in metals<br>electrons in white dwarfs |
| "unlimited" number of particles per state | unlimited number of particles per state | never more than 1 particle per state |

# COMMENT ON FERMIONS AND BOSONS

Fermions :

With cooling the gas approaches to a 'Fermi sea' in which exactly one atom occupies each low-energy state.

At even lower temperatures, if the effective interaction between fermions is attractive, fermions can bind into pairs, the pairs behaving as bosons.

Because electrons and 3He atoms are fermions, this effect is responsible for the condensate-like behaviour of superconductors and superfluid 3He.

~~Lower temperature than 25% of the Fermi temperature was not acheived for atoms and the Cooper pairing and superfluidity were not observed yet.~~

# CONDENSATE ?

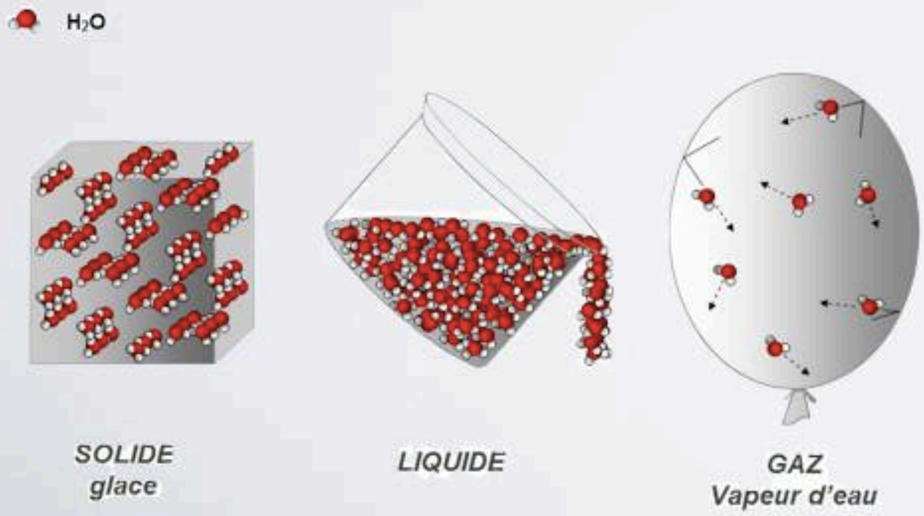
- new state of matter (bosons) at low temperature

## STATES OF MATTER:

(most common)

*phase transition* ↕

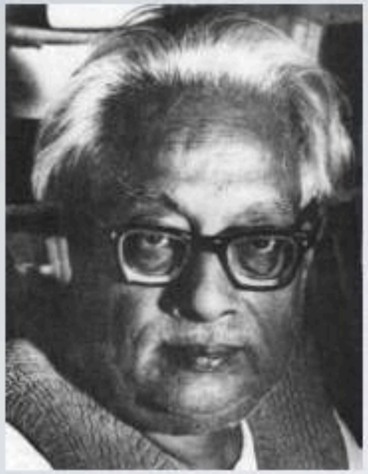
- solid
- liquid
- gas
- plasma




## BUT ALSO (less common):

- non classical states as glasses, gels, sols
- superconductors
- superfluids
- supersolids
- quantum hall effect states
- supercritical liquids
- degenerate matter
- strange matter
- Rydberg matter
- and many more...

# CONDENSATE theoretical discovery 1924 - 1925

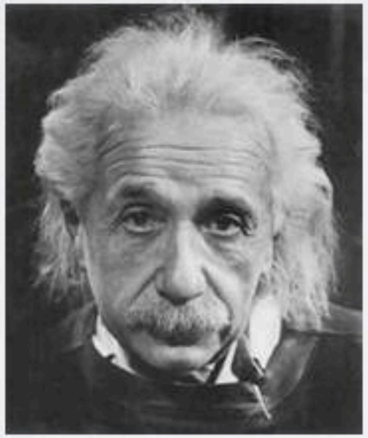


*Satyendra Natah Bose*

Quantum statistics of light quanta (photons)

S. N. Bose, Z. Phys. 26, 178 (1924)

- many photons in the same quantum state
- indistinguishability of two particles in the same quantum state



*Albert Einstein*

Not only light but also matter (bosons) may have the same properties.

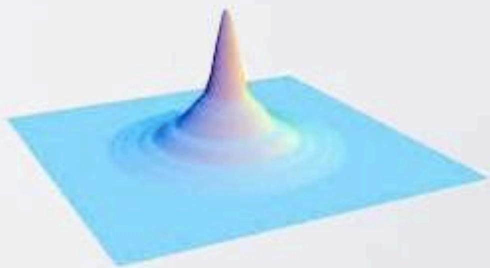
A. Einstein, Sitzungsber. Preuss. Akad. Wiss., Bericht 3, p. 18 (1925)

Recepta:

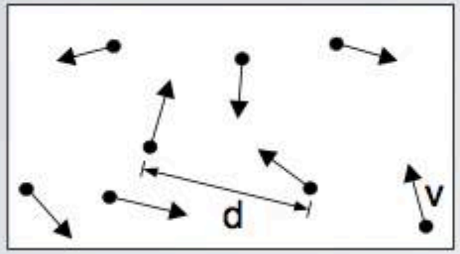
T↓ trap

→

***phase transition (second order)***



# CLASSICAL VS QUANTUM NATURE




gaz - delocalized clasical objects described within the classical thermodynamics law

quantum nature is revealed at particular conditions

# Is something considered as being material particles can sometimes behave like a wave?

*Louis de Broglie*
1923

now that it was clear that a wave can sometimes behave like particles

$$p = mv \qquad p = \frac{h}{\lambda}$$

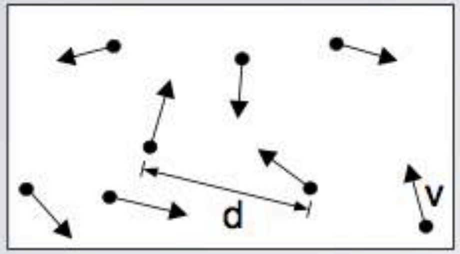
$$mv = \frac{h}{\lambda}$$

$$\lambda = \frac{h}{mv}$$

This expression allows for the calculation of wave-length of a particle in motion

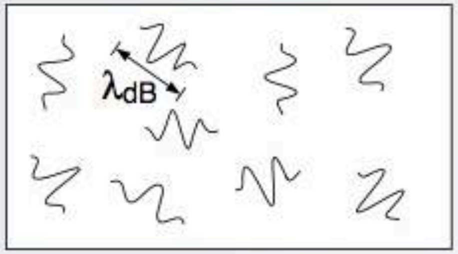
np. 0.2 kg ball moving with a speed of 15m/s has a de Broglie wavelength of 2.21e-34m

# CLASSICAL VS QUANTUM NATURE




gaz - delocalized clasical objects described within the classical thermodynamics law

quantum nature is revealed at particular conditions



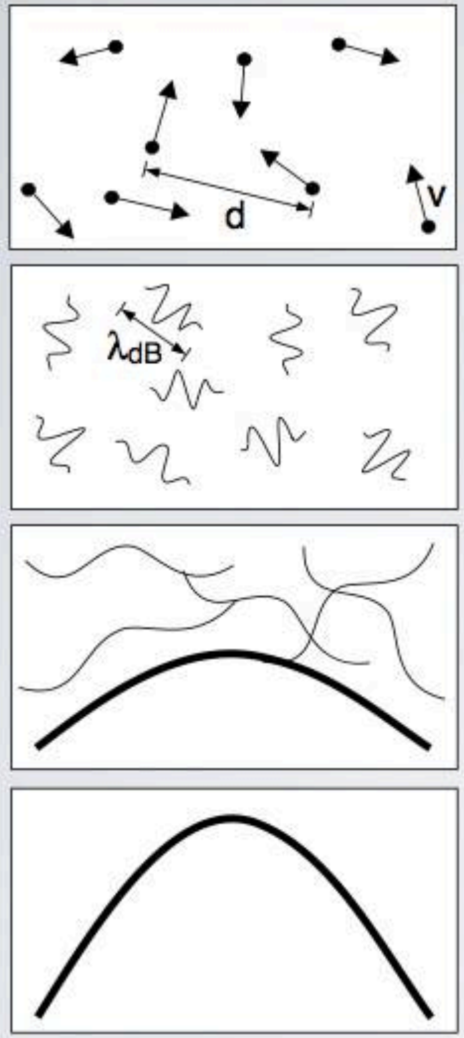
# NUMBERS

- ✓ Lowest temperatures achieved on earth
- ✓ It is possible to condense up to 90% of atoms in a trap
- ✓ Concentrations of atoms can reach up to $10^{14} cm^{-3}$
  ! which is 100 000 less than in the air !
- ✓ Typical number of atoms
  - largest - 30 milion atoms of Na, a bilion in H
  - smallest - a few hundred atoms
- ✓ Sizes of condensates : round 10 - 50 um, cigar 15 um x 300 um
- ✓ Cooling cycle time from a few seconds to several minutes

# FEW FACTS

1. Typically 1 $cm^3$ contains $10^{22}$ molecules.
2. Molecules are in motion. Av. speed 570 m/s.
3. They collide billions of times. Phenomena: sound, pressure
4. Statistical description of the system.
5. Low temperature - possibility to find all particles in a quantum state, single and of the lowest energy.
6. Diluted gas limit (to avoid three-body collisions and allow only for elastic collisions). $10^{14}$ - $10^{15}$ atoms/$cm^3$
7. B-E condensation.

# CONDENSATE (scheme)




**High Temperature T:**
thermal velocity v
density $d^{-3}$
"Billiard balls"

***Wysoka temperatura:***
**"kule bilardowe"**

**Low Temperature T:**
De Broglie wavelength
$\lambda_{dB}=h/mv \propto T^{-1/2}$
"Wave packets"

***Niska temperatura:***
**"paczka falowa"**

**$T=T_C$: BEC**
$\lambda_{dB} \approx d$
"Matter wave overlap"

***Temperatura krytyczna:***
**"przekrywanie się paczek falowych"**
"zupa kwantowa" nierozróżnialnych cząstek

**T=0: Pure Bose condensate**
"Giant matter wave"

***Zero bezwzględne:***
**"makroskopowa fala materii"**

źródło: WHEN ATOMS BEHAVE AS WAVES: BOSE-EINSTEIN CONDENSATION AND THE ATOM LASER
W. Ketterle, Nobel Lecture, December 8, 2001

# CONDENSATE

Single particle wave-function satisfies the Gross-Pitaevskii time-dependent equation:

$$i\hbar \frac{\partial \psi(\vec{r},t)}{\partial t} = \left( -\frac{\hbar^2 \nabla^2}{2m} + V_{ext}(r) + g\, n \right) \psi(\vec{r},t)$$

$$n = \left| \psi(\vec{r},t) \right|^2$$

The condensate wave-function:

$$\psi(\vec{r},t) = \sqrt{n(\vec{r},t)}\, e^{i\theta(\vec{r},t)}$$

# MACROSCOPIC QUANTUM BEHAVIOR

*phenomena*

Superconductivity

Superfluidity

Laser light

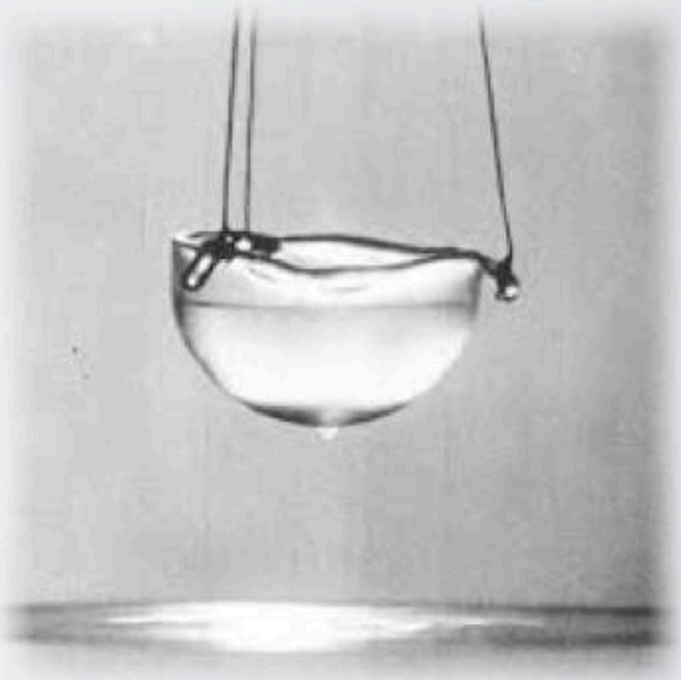
BEC of atoms

# MOST REMARKABLE EXAMPLE

First example was superfluid helium **$^4$He** (further on $^3$He)

*Fritz London (1938) & Laszlo Tisza (1938)*

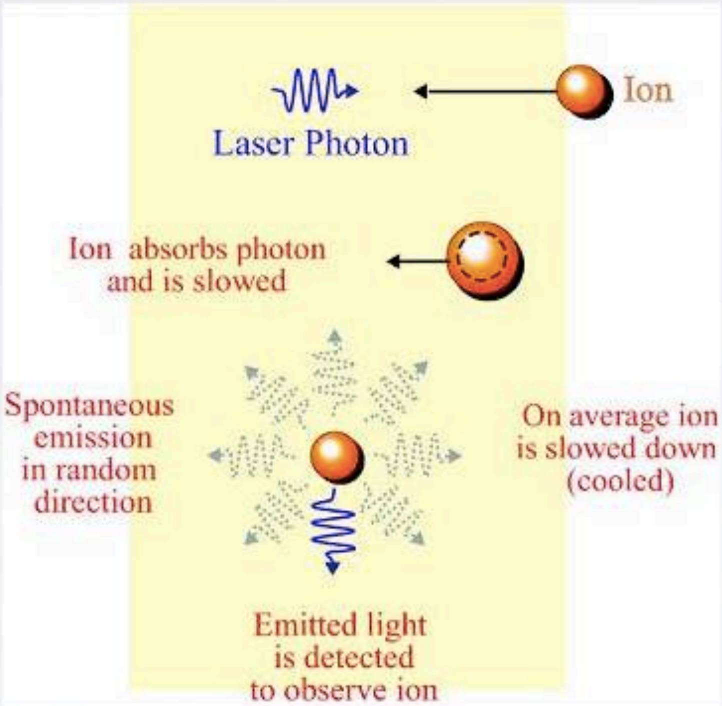
- BEC as a possible mechanism underlying superfluidity (Landau do not share this opinion)
- strongly interacting system



# LASER COOLING TECHNIQUES

## 1. Doppler coolig

from ~500 K to~100 microK
$N \sim 10^9$
further on random emission and absorption processes




http://publish.ucc.ie/boolean/2011/00/Russell/42/en

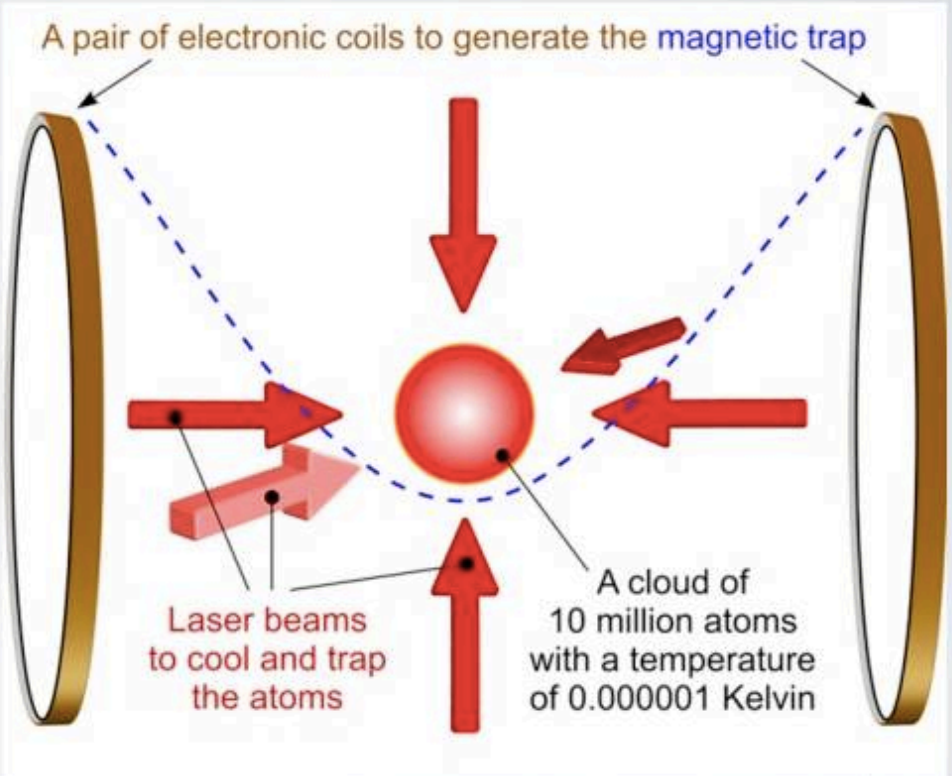
# LASER COOLING TECHNIQUES

## 2. Evaporative cooling

from ~100 microK to ~100nK
$N \sim 10^7$

rate of ellastic collisions > inellastic collisions

Magneto-optical trap (MOT).
The six laser beams cool the atoms and push them to the intersection point while the magnetic trap (generated with a pair of electronic coils) confines the atoms.




http://publish.ucc.ie/boolean/2011/00/Russell/42/en

# LASER COOLING TECHNIQUES

## 2. Evaporative cooling - advances in magnetic trap

### Atom on a chip

*Observation*:
Trapping forces are proportional to the magnetic field gradient

*Realization*:
Microchip created litographically

*Purpose*:
Wavegiuides and beamsplitters of coherent matter in restricted geometry; ultra-sensitive sensors

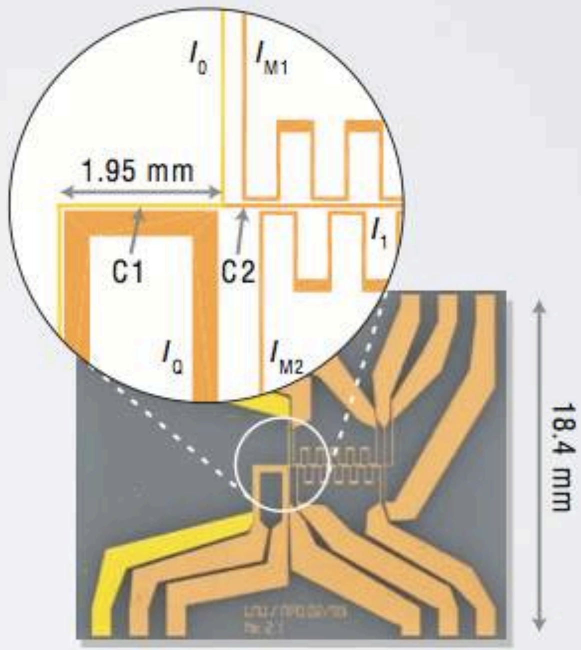



**Figure 1** Atom chip. Bose–Einstein condensates (BECs) were created in magnetic traps formed by tiny gold wires that were created lithographically on a substrate[16,17]. The figure shows the pattern used by researchers at the Ludwig-Maximilians University in Munich[17]. Atoms were trapped at positions C1 and C2.

*Bose - Einstein condensation of atomic gases*

J. R. Anglin, W. Ketterle, Nature **416**, 211 (2002)

# EXPERIMENTAL PROCEDURE

1. Atoms are released from a source. N = $10^{10}$ atoms.
2. Atoms are trapped in a magnetooptical trap. (MOT)
3. Doppler cooling. N = $10^9$ atoms. T = 100 mikroK.
4. Atoms are trapped in a magnetic trap.
5. Evaporative cooling. N = $10^7$ atoms. T = 100 nanoK.

# HISTORY of experimental realization

Steven Chu
Claude Cohen-Tannoudji
William D. Philips

*Laser cooling techniques :*
*Nobel Prize 1997*

**first works on laser cooling at 1985**

to reach temperatures as low as $10^{-7}$K = 100 nK

# HISTORY of experimental realization

Steven Chu
Claude Cohen-Tannoudji
William D. Philips

*Laser cooling techniques :*
*Nobel Prize 1997*

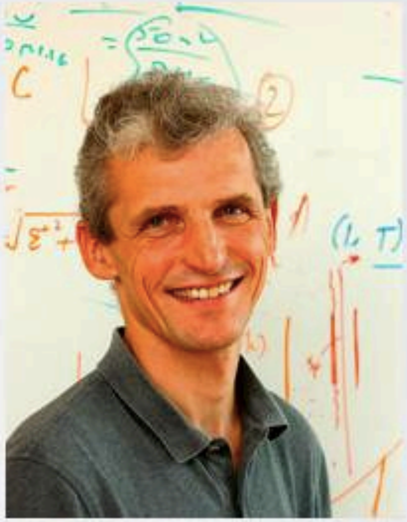
**70 years after works of Bose & Einstein... 1995**

Carl Wieman
Eric Cornell
University of Colorado
at Boulder NIST-JILA

Rubidium atom gas
cooled to 170nK !!!

**4 months later 1995**

Sodium atom gaz
(100 times more atoms)



Wolfgang Ketterle
Massachusetts Institute
of Technology

Nober Prize 2001

# HISTORY of experimental realization

VOLUME 81, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1998

## Bose-Einstein Condensation of Atomic Hydrogen

Dale G. Fried, Thomas C. Killian, Lorenz Willmann, David Landhuis, Stephen C. Moss, Daniel Kleppner, and Thomas J. Greytak

*Department of Physics and Center for Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

(Received 11 September 1998)

## Bose-Einstein Condensation of Cesium

Tino Weber, Jens Herbig, Michael Mark, Hanns-Christoph Nägerl, Rudolf Grimm

Bose-Einstein condensation of cesium atoms is achieved l
using optical trapping techniques. The ability to tune the
the ultracold atoms by an external magnetic field is
condensate and offers intriguing features for potential ap
various regimes of condensate self-interaction (attracti
interaction strength) and demonstrate properties of imp
non-interacting quantum matter

## A Bose-Einstein Condensate of Metastable Atoms

A. Robert, O. Sirjean, A. Browaeys,* J. Poupard,† S. Nowak,‡ D. Boiron, C. I. Westbrook, A. Aspect§

ate of metastable atoms
nergy of each atom with
t inelastic processes that
nough in a spin-polarized
e takes advantage of the
ns as well as of the decay
ns the way toward new
vell as in atomic quantum

VOLUME 92, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2004

## Observation of Resonance Condensation of Fermionic Atom Pairs

C. A. Regal, M. Greiner, and D. S. Jin*

*JILA, National Institute of Standards and Technology and University of Colorado, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA*

(Received 13 January 2004; published 28 January 2004)

We have observed condensation of fermionic atom pairs in the BCS-BEC crossover regime. A trapped gas of fermionic $^{40}K$ atoms is evaporatively cooled to quantum degeneracy and then a magnetic-field Feshbach resonance is used to control the atom-atom interactions. The location of this resonance is precisely determined from low-density measurements of molecule dissociation. In order to search for condensation on either side of th
atoms onto molecules; this enab
The transition to condensation o
gas temperature $T$ compared to t
and BEC sides of the resonance.

## Bose-Einstein Condensation of Molecules

S. Jochim,[1] M. Bartenstein,[1] A. Altmeyer,[1] G. Hendl,[1] S. Riedl,[1] C. Chin,[1] J. Hecker Denschlag,[1] R. Grimm[1,2*]

We report on the Bose-Einstein condensation of more than $10^5$ $Li_2$ molecules in an optical trap starting from a spin mixture of fermionic lithium atoms. During forced evaporative cooling, the molecules are formed by three-body recombination near a Feshbach resonance and finally condense in a long-lived thermal equilibrium state. We measured the characteristic frequency of a collective excitation mode and demonstrated the magnetic field–dependent mean field by controlled condensate spilling.

ber Prize

## Bose-Einstein Condensation of Potassium Atoms by Sympathetic Cooling

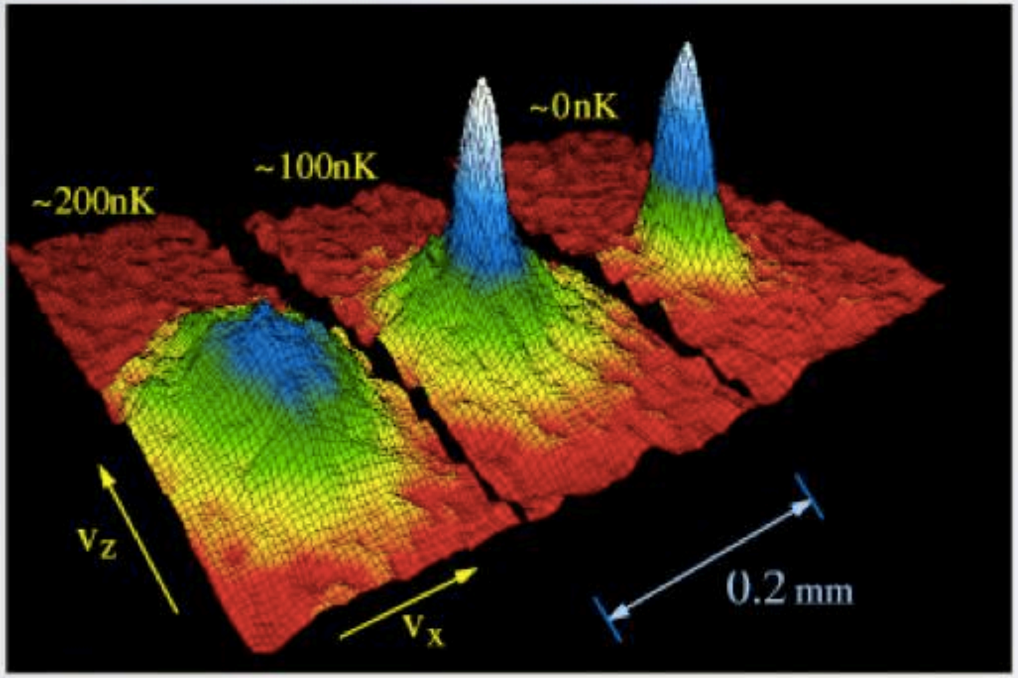
G. Modugno, G. Ferrari, G. Roati, R. J. Brecha, A. Simoni, M. Inguscio

We report on the Bose-Einstein condensation of potassium atoms, whereby quantum degeneracy is achieved by sympathetic cooling with evaporatively cooled rubidium. Because of the rapid thermalization of the two different atoms, the efficiency of the cooling process is high. The ability to achieve condensation by sympathetic cooling with a different species may provide a route to the production of degenerate systems with a larger choice of components.

# HISTORY

## experimental results

2 D velocity distributions

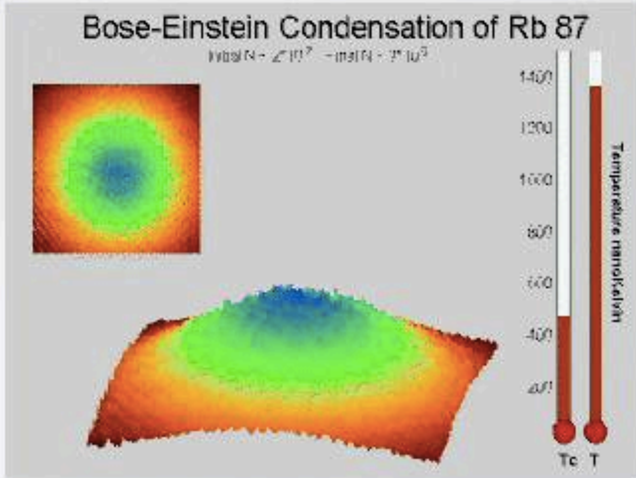



*Velocity distribution of gas of Rb atoms.*

M. H. Anderson et al., Science **269**, 198 (1995)

*E. Cornell et al. JILA, 1995*

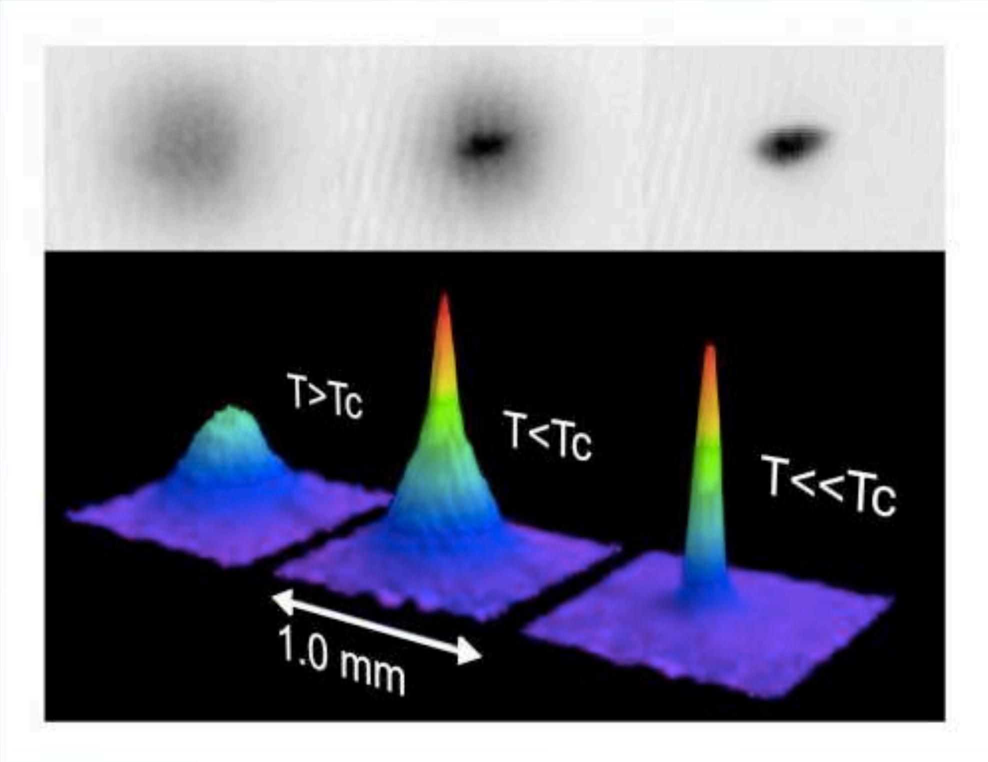
$^{87}Rb$




http://www.colorado.edu/physics/2000/bec/images/evap2.gif

# ABSORPTION IMAGING

$^{23}Na$




Expanding cloud cooled to just above the transition point; middle: just after the condensate appeared; right: after further evaporative cooling has left an almost pure condensate.

The "sharp peak" is the Bose-Einstein condensate, characterized by its slow expansion observed after 6 msec time of flight.

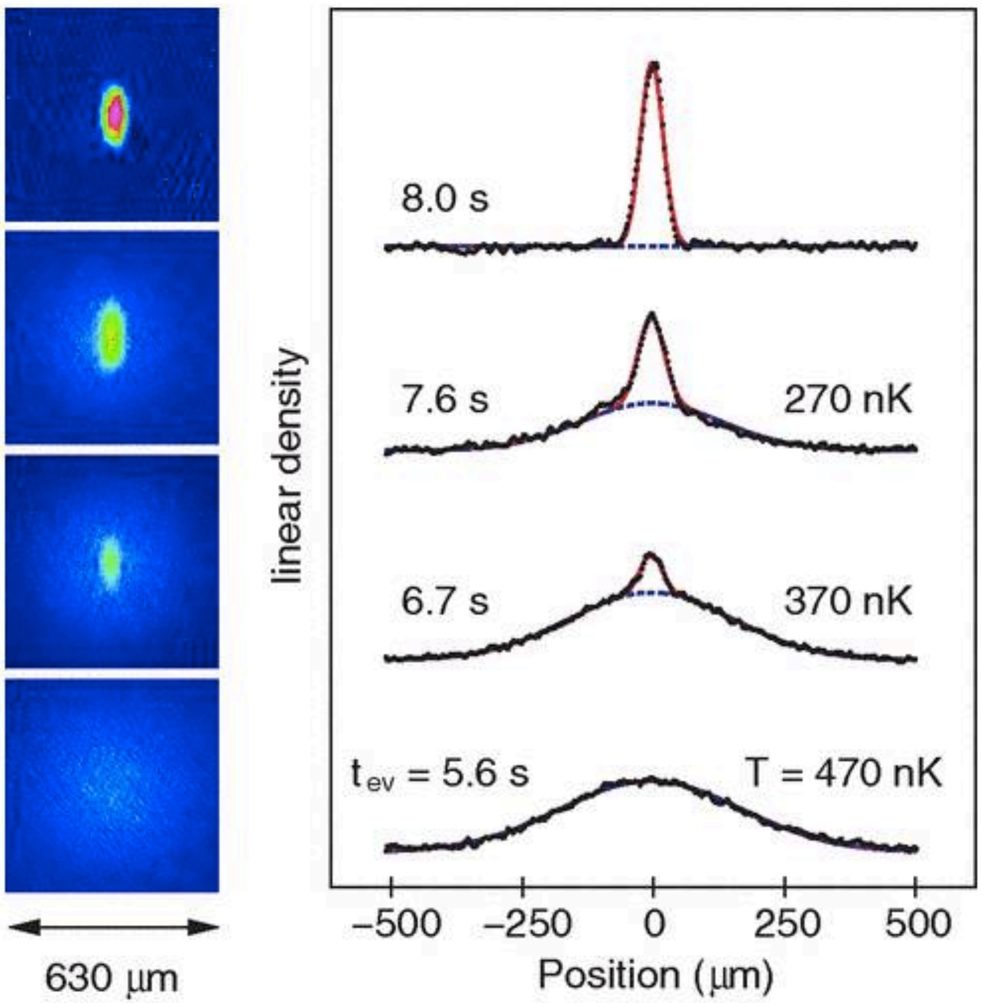
The width of the images is 1.0 mm. The total number of atoms at the phase transition is about 700,000, the temperature at the transition point is 2 microkelvin.

*W. Ketterle et al. MIT, 1995*

http://cua.mit.edu/ketterle_group/Popular_papers/Ultralow_temperatures.htm

# Bose-Einstein Condensation of Strontium

Simon Stellmer, Meng Khoon Tey, Bo Huang, Rudolf Grimm, and Florian Schreck
Phys. Rev. Lett. **103**, 200401 – Published 9 November 2009

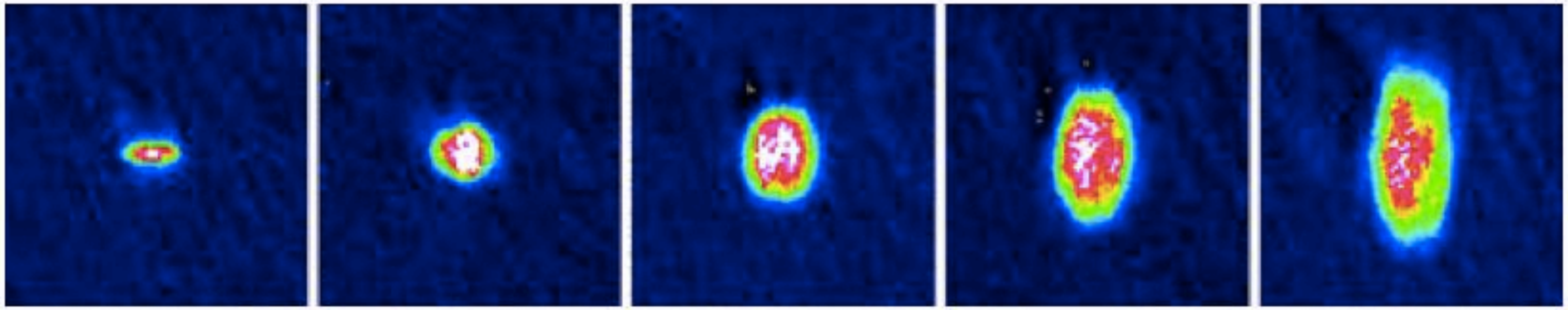



Absorption images and integrated density profiles showing the BEC phase transition for different times of the evaporative cooling ramp.

The images are along the vertical direction 25 ms after release from the trap. The solid line represents a fit with a bimodal distribution, while the dashed line shows the Gaussian-shaped thermal part, from which the given temperature values are derived.

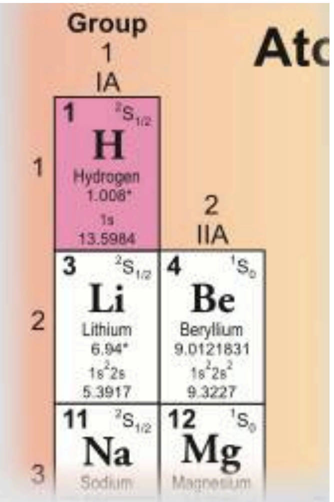
## Bose-Einstein Condensation of Strontium

Simon Stellmer, Meng Khoon Tey, Bo Huang, Rudolf Grimm, and Florian Schreck
Phys. Rev. Lett. **103**, 200401 – Published 9 November 2009

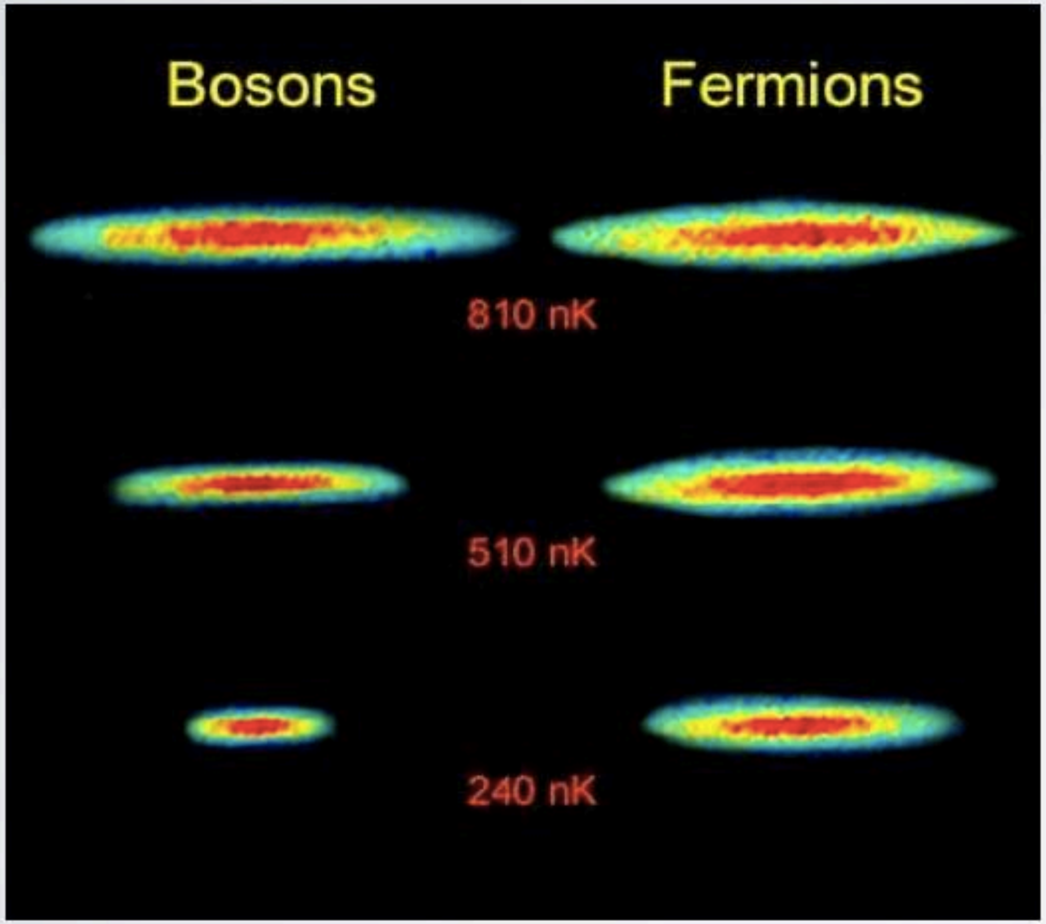


Inversion of the aspect ratio during the expansion of a pure BEC. The images (field of view 250 μm×250 μm) are taken along the vertical direction. The first image is an in situ image recorded at the time of release. The further images are taken 5, 10, 15, and 20 ms after release.

# THE QUEST FOR FERMIONIC CONDENSATE




| $^{7}Li$ | $^{6}Li$ |
|---|---|
| 3e, 3p, 4n | 3e, 3p, 3n |




The fermionic cloud cannot shrink below a certain size determined by the Pauli exclusion principle. This is the same phenomenon that prevents white dwarf and neutron stars from shrinking into black holes.

## Fermi pressure

Fermions cannot occupy the same (ground) state.

Because they cannot occupy the same state, evaporative cooling is not successful and the gas cannot rethermalize.

By mixing Lithium-6 and Lithium-7 together, it was possible to cool Lithium-7 and let it **sympathetically cool** Lithium-6.

R. Hullet. Rice University

# THE ROLE OF INTERACTIONS

Binary collisions are more frequent than three-body collisions

Separation between atoms is much larger than s-wave scattering length

$$n^{-1/3} >> a$$

$$na^3 << 1$$

Typically

$$na^3 \approx 10^{-6}$$

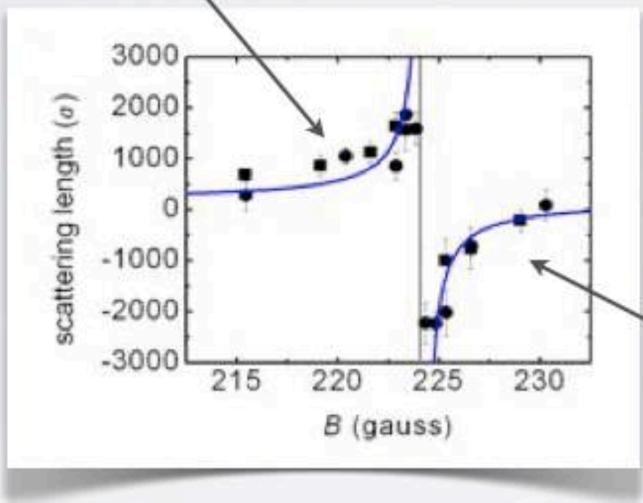
The stability of large condensates requires repulsive interactions - positive a.
For attractive interactions - negative a, the condensate becomes unstable against collapse if it grows above a certain size.

# THE ROLE OF INTERACTIONS

Feshbach resonance

if the energy of a bound state of an interatomic potential is equal to the kinetic energy of a colliding pair of atoms, the effective scattering potential is divergent.

repulsive




attractive

C. A. Regal et al., Phys. Rev. Lett. 90, 230404 (2003)

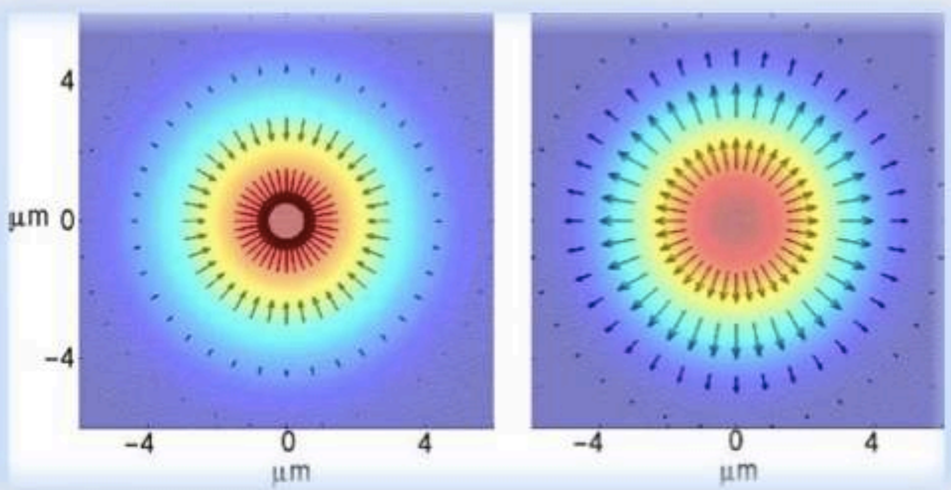
http://users.physics.harvard.edu/~greiner/fermicondensates.html

# THE ROLE OF INTERACTIONS

**Feshbach resonance is used to study the instability of condensates when atomic interactions were attractive and explore the impact on a BEC's quantum wave function when atomic interactions were large and repulsive.**

EXPERIMENT

- atoms condense (BEC)
- they interact with repulsive interactions
- external magnetic field changes the interactions from repulsive to attractive
- the attractive force leads to implosion
- the system explodes as in the Supernova

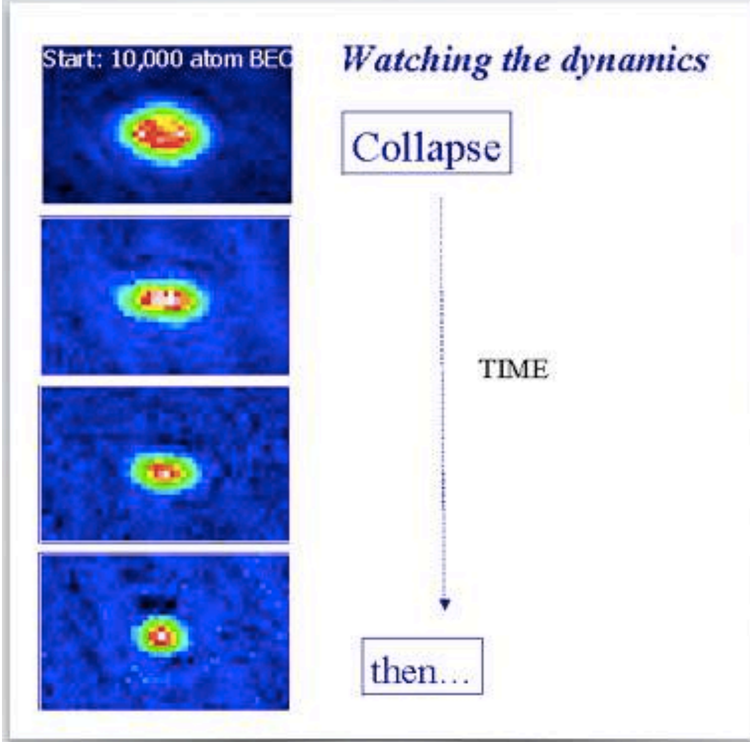


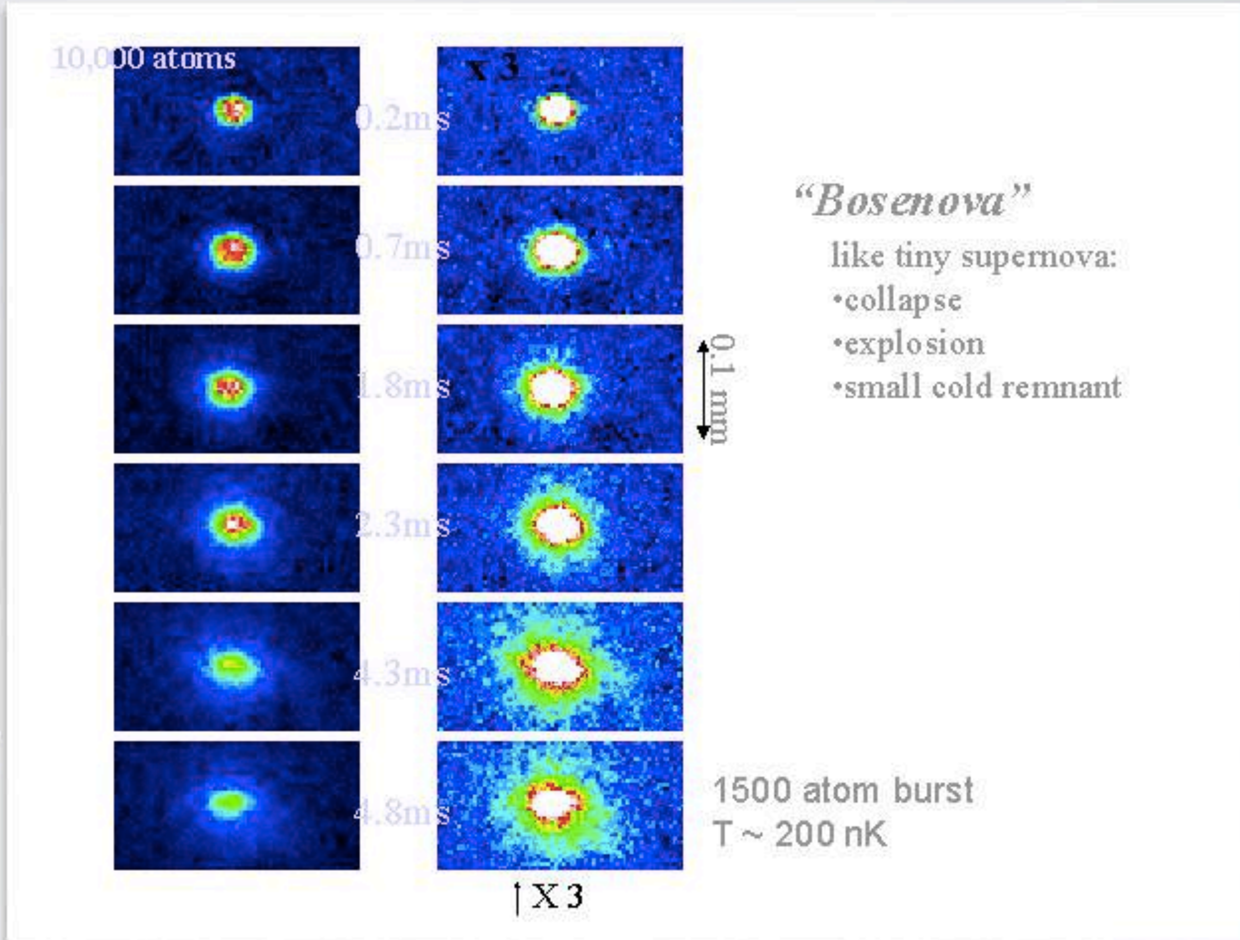

BEC implosion Burst of atom cloud

J. N. Milstein at al. New Journ. Phys. 5, 52 (2003)

# THE ROLE OF INTERACTIONS

## BOSENOVA




C. Wieman,
Colorado Univ.

http://spot.colorado.edu/~cwieman/Bosenova.html

# ORDER PARAMETER

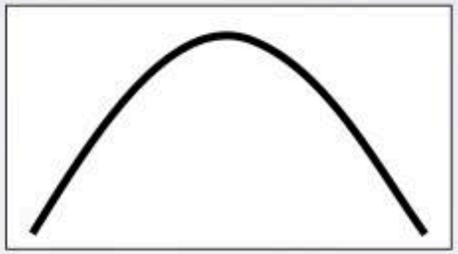
zero before the phase transition and becomes determined after phase transition

ORDER PARAMETER

$$\psi(\vec{r},t) = \sqrt{n(\vec{r},t)}\, e^{i\theta(\vec{r},t)}$$

Phase coherence!!!

**spatial and temporal:**



**T=0:**
**Pure Bose condensate**
"Giant matter wave"

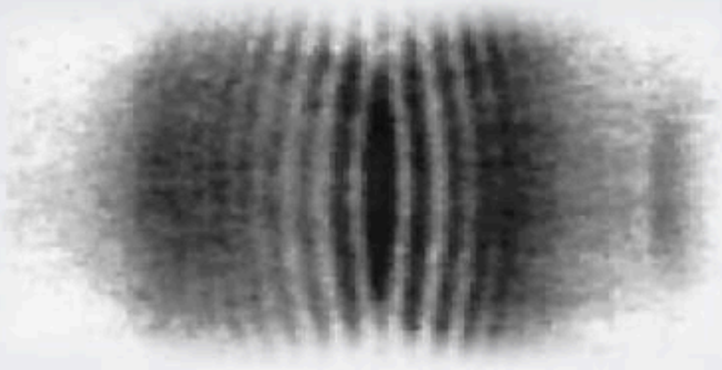
- Coherence in time
- Long-range order = spatial coherence

*during the phase transition*

**interference !!**

# INTERFERENCE BETWEEN TWO BEC

**Interference = coherence !!**

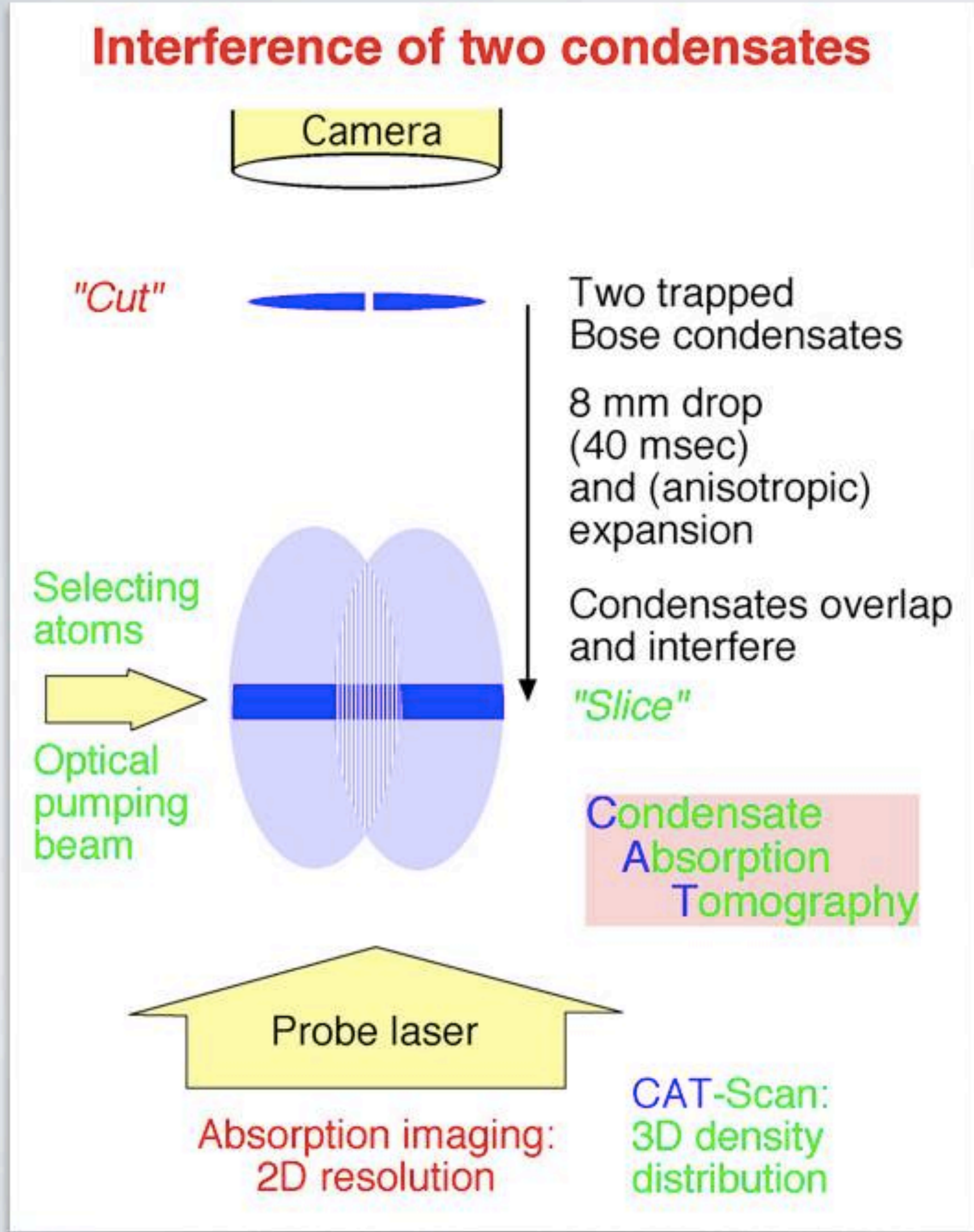


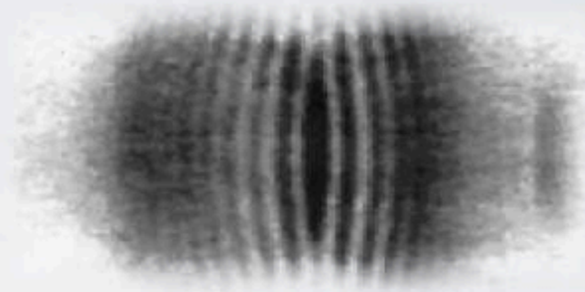
*Interference between two atomic BEC*

M. R. Andrews et al., Science **275,** 637 (1997)

! Interference of a matter wave !

# INTERFERENCE BETWEEN TWO BEC



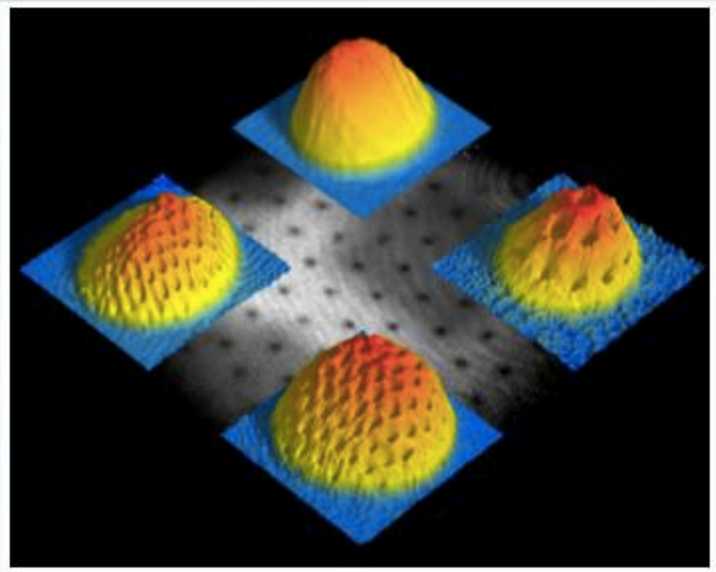



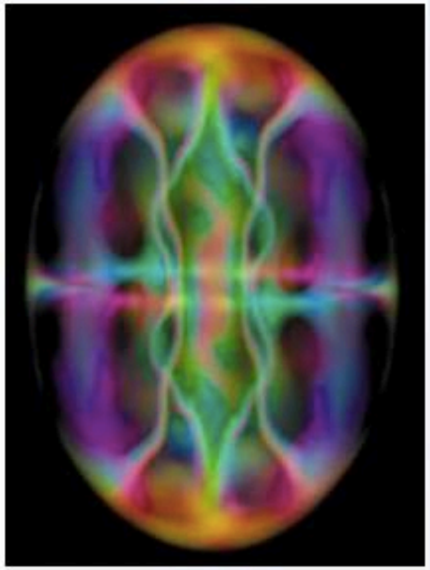
*Interference between two atomic BEC*

M. R. Andrews et al., Science **275,** 637 (1997)

# VORTICES

Condensates in a rotating trap reveal the regular array of vortices (Abrikosov type)





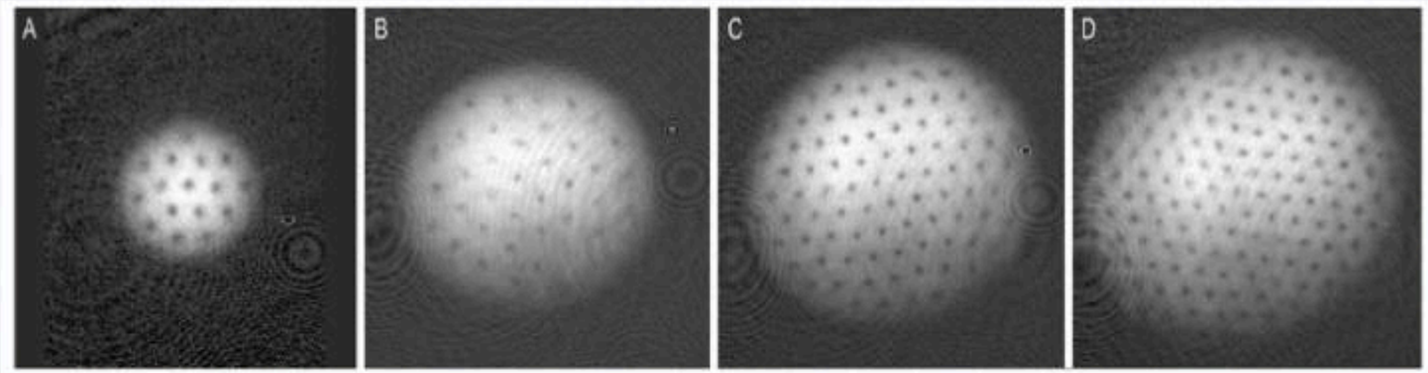
$^{23}$Na

N = 5 x10$^7$

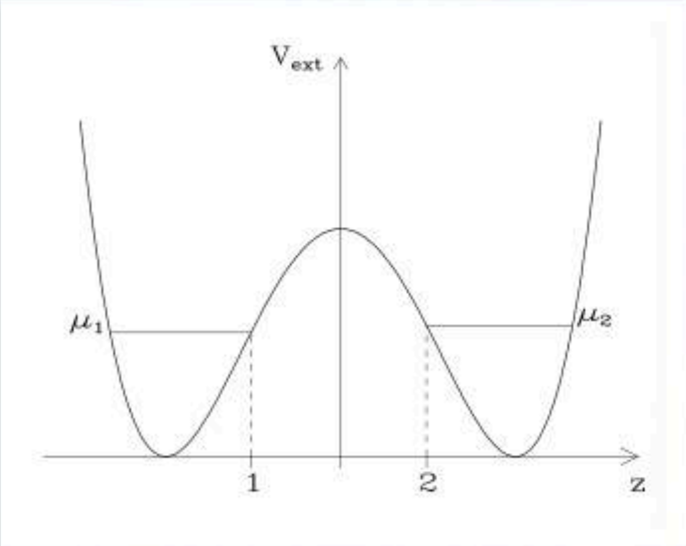
up to 130 of vortices

*W. Ketterle et al. MIT*

J. R. Abo-Shaer et al., Science **292,** 476 (2001)



# JOSEPHSON EFFECT

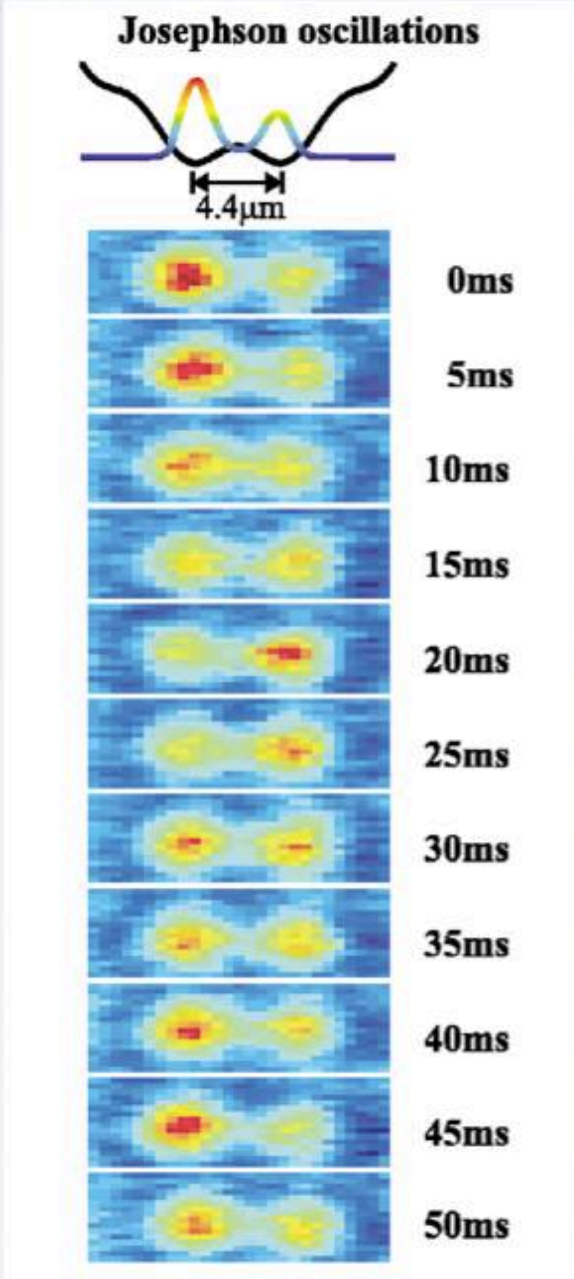



F. Dalfovo, Lp. P. Pitaevskii, S. Stringari, Rev. Mod. Phys. 71, 463 (1999)

$$\mu_1 \neq \mu_2 \quad (N_1 \neq N_2)$$

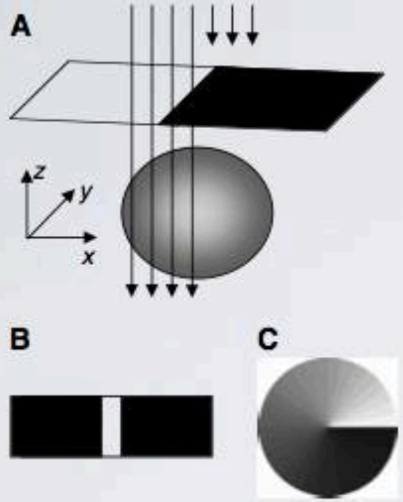
$$\theta_1 \neq \theta_2$$

$$I = I \sin \frac{(\mu_1 - \mu_2)\, t}{\hbar}$$




M. Albiez et al., PRL 95, 010402 (2005)

# SOLITONS




## Generating Solitons by Phase Engineering of a Bose-Einstein Condensate

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L. A. Collins,[3] J. Cubizolles,[1,4] L. Deng,[1] E. W. Hagley,[1]
K. Helmerson,[1] W. P. Reinhardt,[1,5] S. L. Rolston,[1] B. I. Schneider,[6]
W. D. Phillips[1]

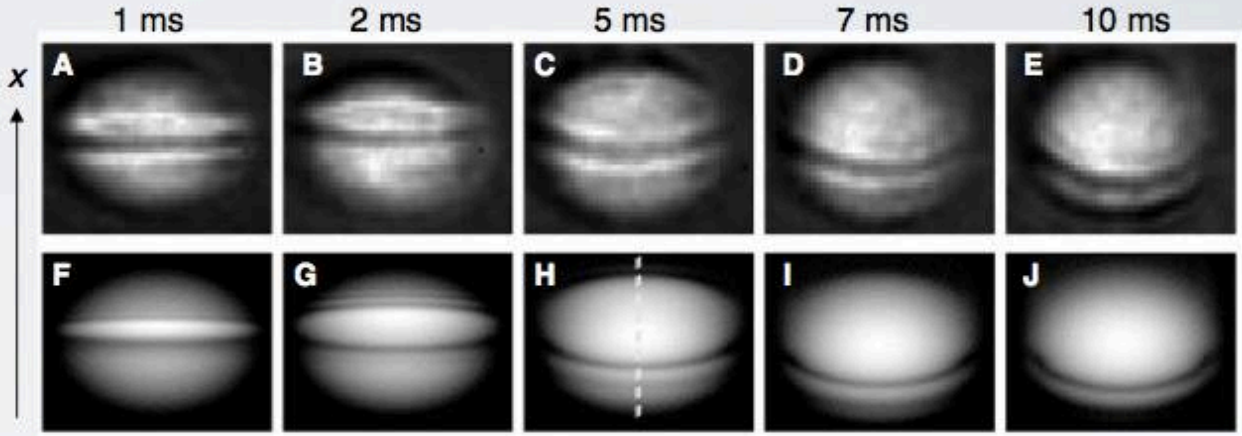
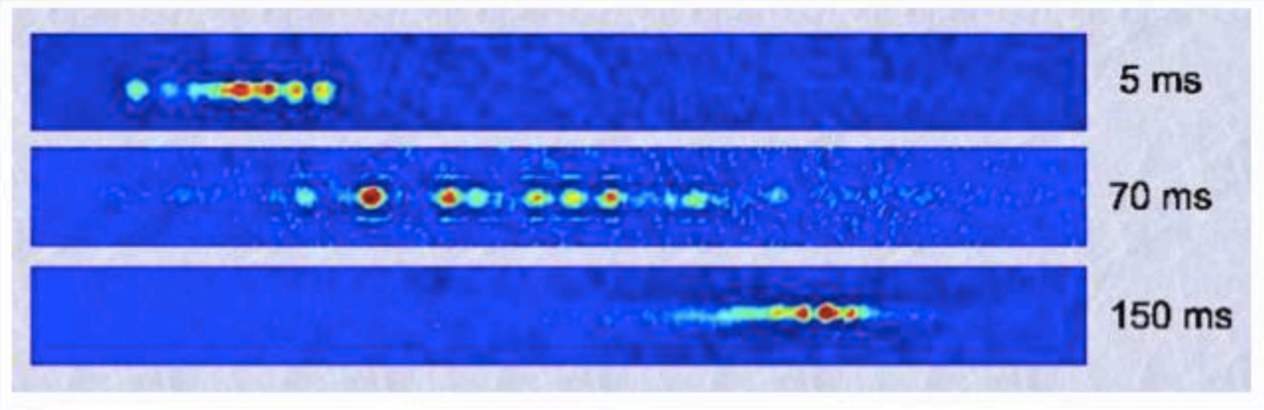



**Fig. 3.** Experimental (**A** to **E**) and theoretical (**F** to **J**) images of the integrated BEC density for various times after we imprinted a phase step of $\sim 1.5\pi$ on the top half of the condensate with a 1-μs pulse. The measured number of atoms in the condensate was 1.7 ($\pm$0.3) $\times 10^6$, and this value was used in the calculations. A positive density disturbance moved rapidly in the $+x$ direction, and a dark soliton moved oppositely at significantly less than the speed of sound. Because the imaging pulse (*27*) is destructive, each image shows a different BEC. The width of each frame is 70 μm.

# THE ROLE OF INTERACTIONS

## SOLITONIC TRAIN




$^7$Li after the change of the interaction type from repulsive to attractive exhibit solitonic train.

K. S. Strecker et al., Nature 417, 150 (2002)