An Intimate Gathering of Bosons

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Atom Optics (AOUD)

Honoursprogramma
Utrecht

September 29, 2009

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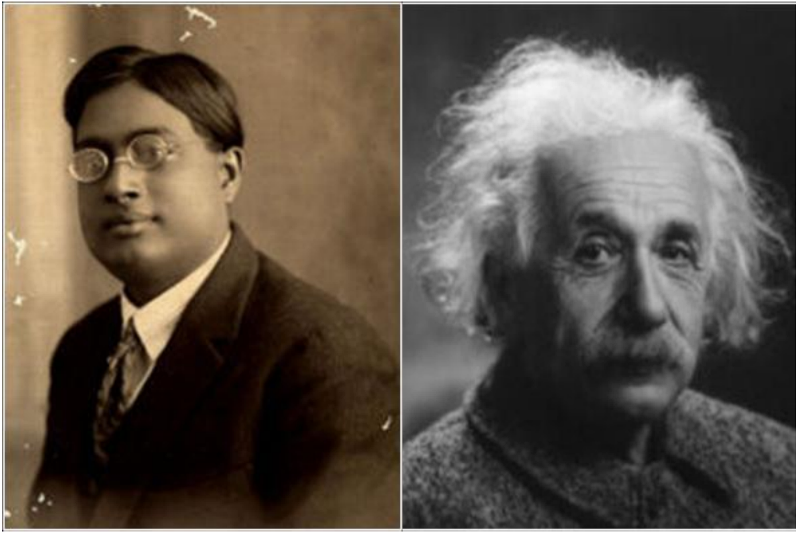
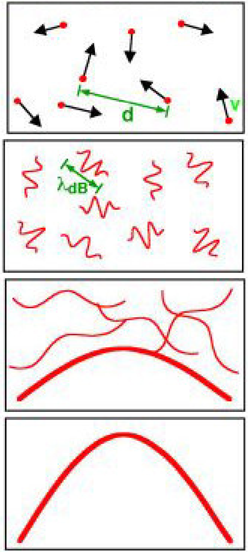
Outline

1. How to produce a Bose-Einstein condensate
   - Step 1: Light pressure
   - Step 2: Optical molasses
   - Step 3: Magnetic trapping
2. Observation of BEC
3. What to do with a Bose-Einstein condensate
   - Superradiant scattering
   - Collective excitations
   - Bosons *versus* Fermions
   - Superfluidity
   - Atom laser

Bose-Einstein condensation



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
$\lambda_{dB}=d$
"Matter wave overlap"

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

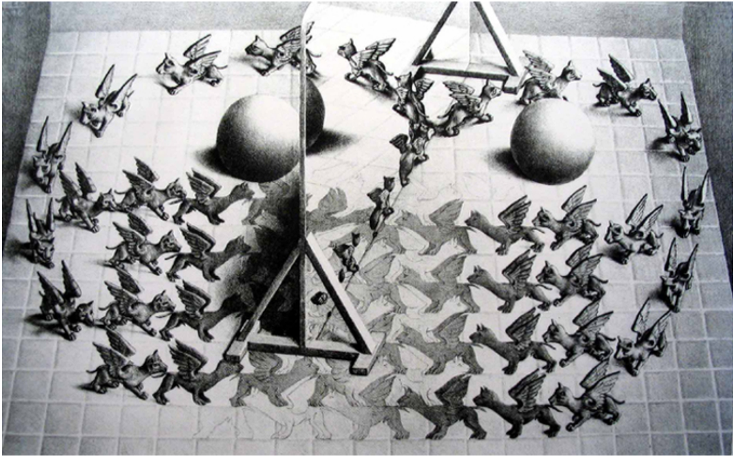
Bose-Einstein condensation

$$\rho = n\Lambda_{\mathrm{deB}}{}^3 = 2.612375349\ldots$$

with

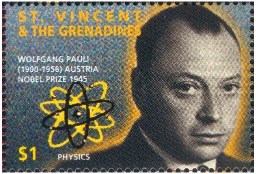
$$\Lambda_{\mathrm{deB}} = \frac{h}{\sqrt{2\pi m k_B T}}$$

Bosons and Fermions



Usual examples: electrons, protons, neutron (fermions), photon (boson)
Example: ^{3}He (I=$^1/_2$) and ^{4}He (I=0), or ^{6}Li (F=$^1/_2$,$^3/_2$) and ^{7}Li (F=1,2)

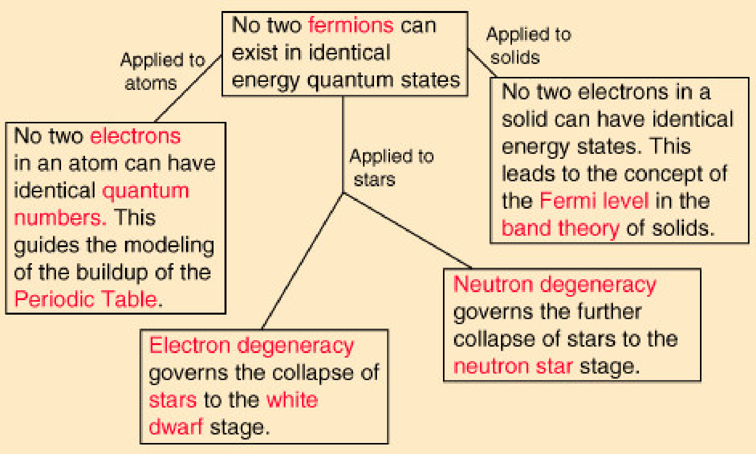
Pauli exclusion principle



The Pauli exclusion principle is a quantum mechanical principle formulated by Wolfgang Pauli in 1925. It states that no two identical fermions may occupy the same quantum state simultaneously.

A more rigorous statement of this principle is that, for two identical fermions, the total wave function is anti-symmetric. For electrons in a single atom, it states that no two electrons can have the same four quantum numbers, that is, if n, l, and ml are the same, ms must be different such that the electrons have opposite spins.
In relativistic quantum field theory, The Pauli principle follows from applying a rotation operator in imaginary time to particles of half-integer spin. It does not follow from any spin relation in nonrelativistic quantum mechanics.

Application of Pauli principle



No two fermions can exist in identical energy quantum states

Applied to atoms

No two electrons in an atom can have identical quantum numbers. This guides the modeling of the buildup of the Periodic Table.

Applied to solids

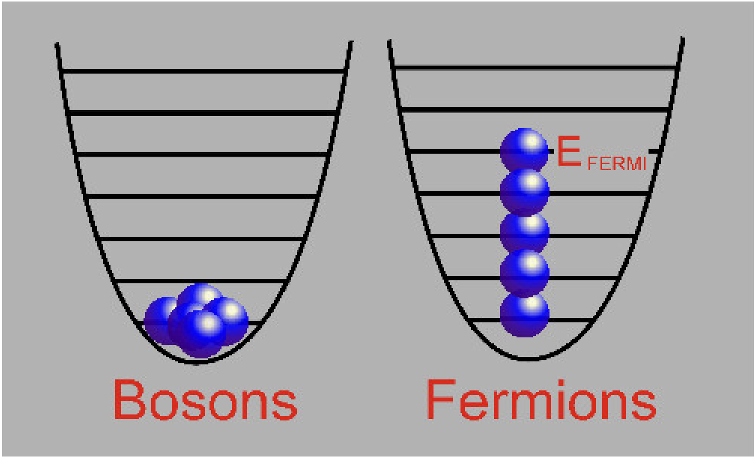
No two electrons in a solid can have identical energy states. This leads to the concept of the Fermi level in the band theory of solids.

Applied to stars

Electron degeneracy governs the collapse of stars to the white dwarf stage.

Neutron degeneracy governs the further collapse of stars to the neutron star stage.

Population of states



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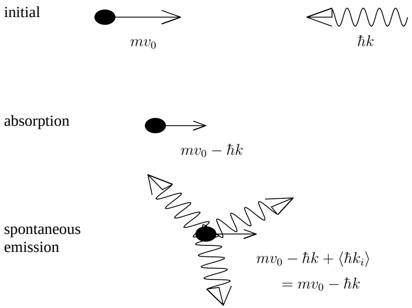
Light pressure



recoil "kick"

$$v_r = \frac{\hbar k}{m} \approx 3 \text{ cm/s (Na)}$$

thermal

$$v \approx 1000 \text{ m/s}$$

$$N_{\text{stop}} \approx 33.000 \text{ fotons}$$

lifetime

$$\tau = 16 \text{ ns}$$

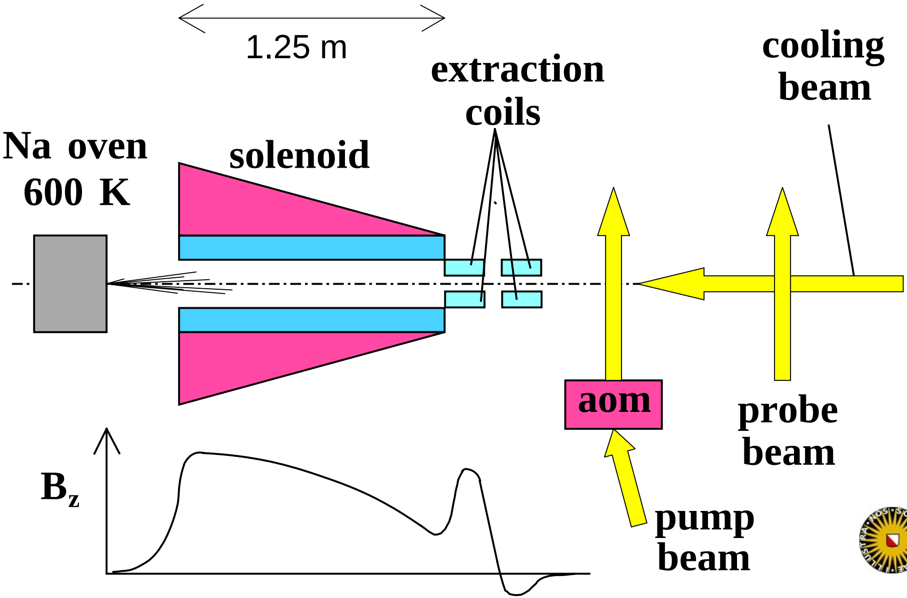
$$T_{\text{stop}} \approx 1 \text{ msec}$$

$$l_{\text{stop}} \approx 0.5 \text{ m}$$

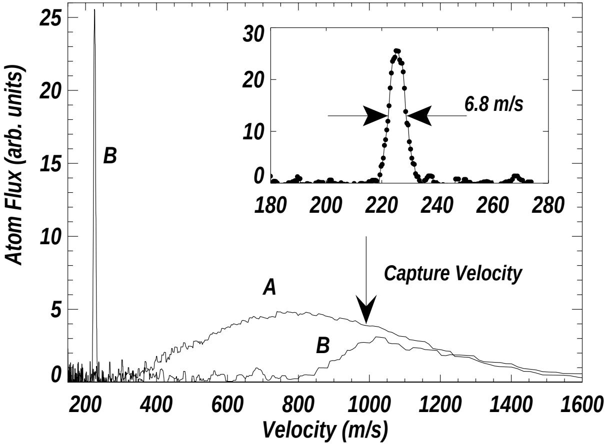
acceleration

$$a \approx 9 \times 10^5 \text{ m/s}^2$$

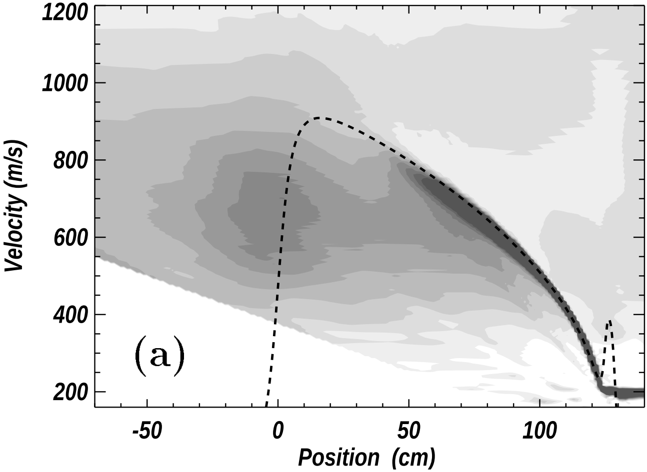
Zeeman technique



Velocity distribution

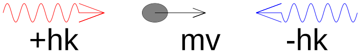


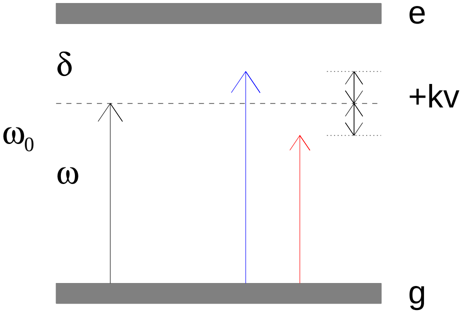
Funnel for atoms

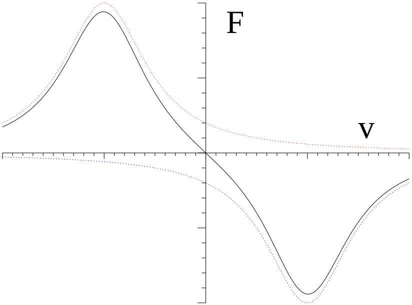


Contour map of the velocity and position of atoms in the solenoid

Laser cooling



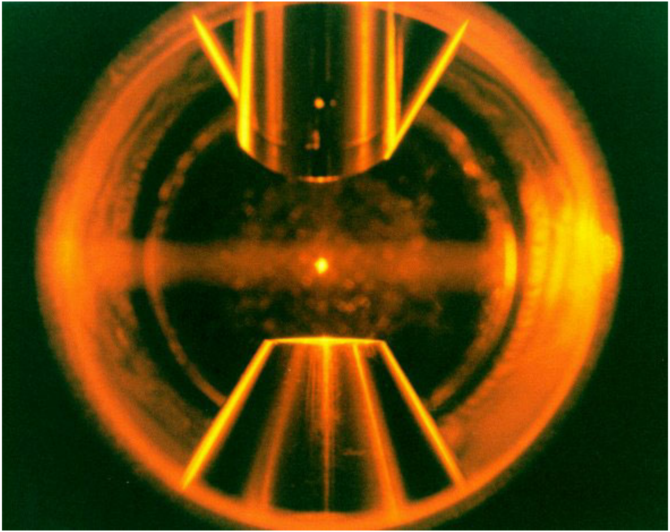




Cooling limit: Damping by Doppler tuning vs. heating by random recoil

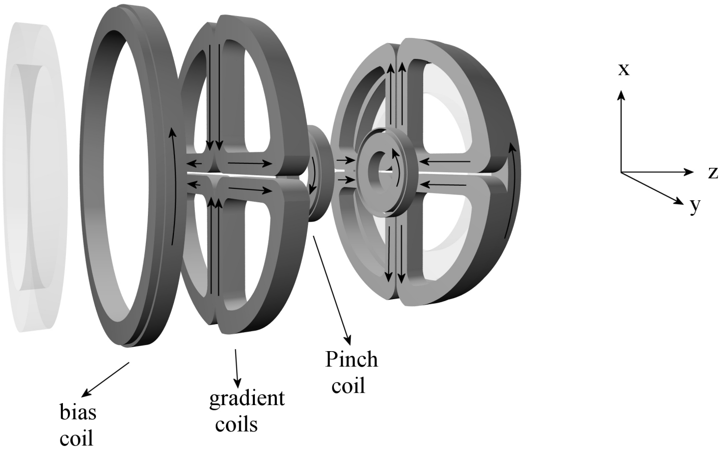
$$kT_{\mathrm{D}} = \frac{\hbar\Gamma}{2} \qquad [\mathrm{Na} : 240\mu\mathrm{K}]$$

Cold Atoms



`D:/upload/Phys2000/bec/lascool4.html`

Magnetic Trap



Cloverleaf trap

Evaporation

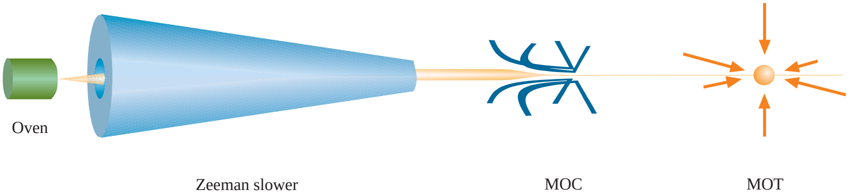
1. Cools a cup of coffee
2. Cools apples by overtree sprinkling
3. Is used in technical water coolers
4. Globular clusters do it by evaporation of stars
5. Compound nuclei do it by evaporating neutrons
6. Atom coolers love it.

Evaporative cooling of a trapped gas is based on the preferential removal of atoms with an energy higher than the average energy, followed by thermalization of the gas by elastic collisions.

In order to force the cooling to proceed at a constant rate, the evaporation threshold may be lowered as the gas cools (forced evaporation).

`D:/Upload/Phys2000/bec/xevap_cool.html`

Experimental feasibility



Properties of the trapped atoms	N	n (atoms/cm^3)	$T(\mu K)$
MOT	1.2×10^{10}	3×10^{11}	320
magnetic trap	8×10^{9}	3×10^{11}	340
evaporative cooling	1.5×10^{8}	8×10^{13}	0.3

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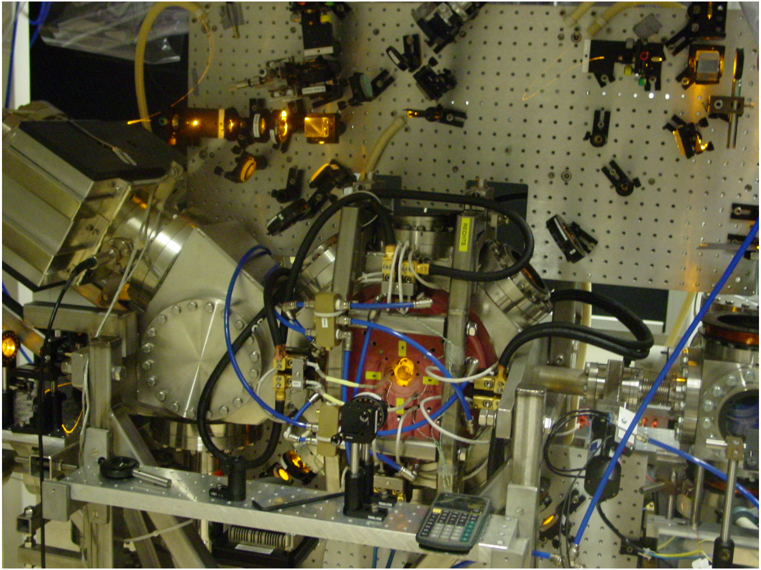
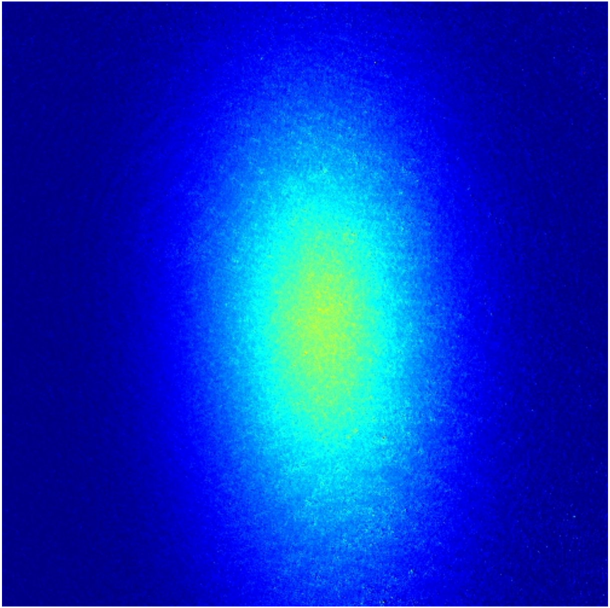
Current setup



Bose-Einstein condensation–The last stages



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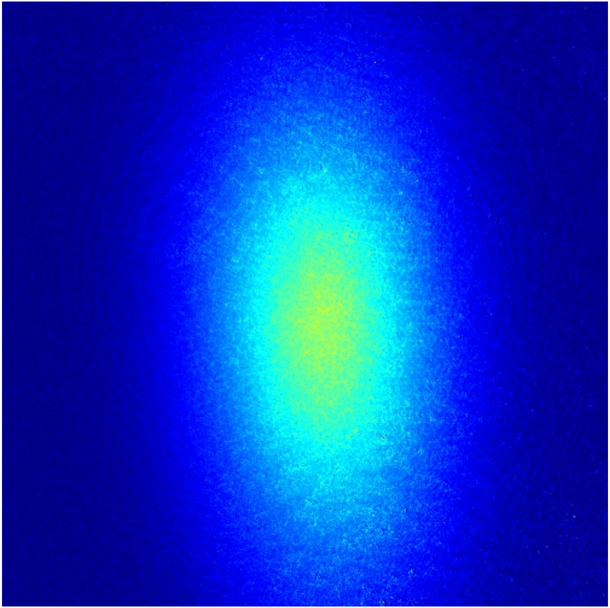

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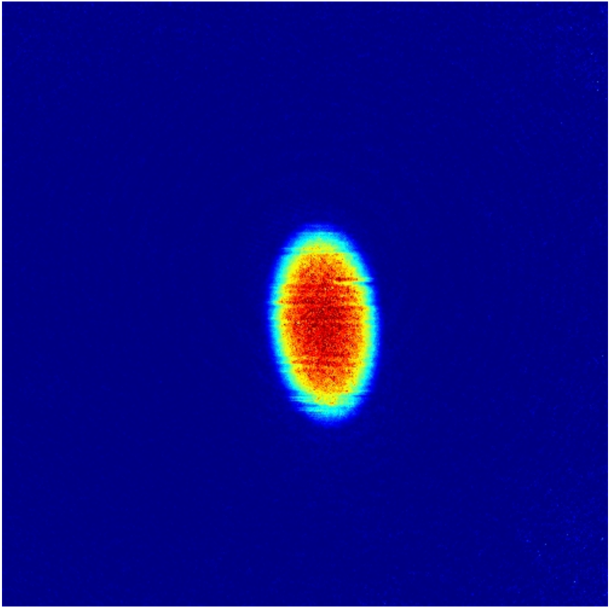

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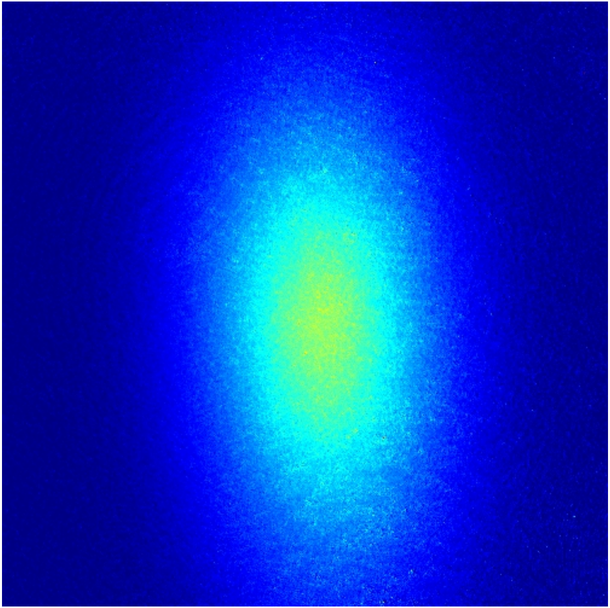

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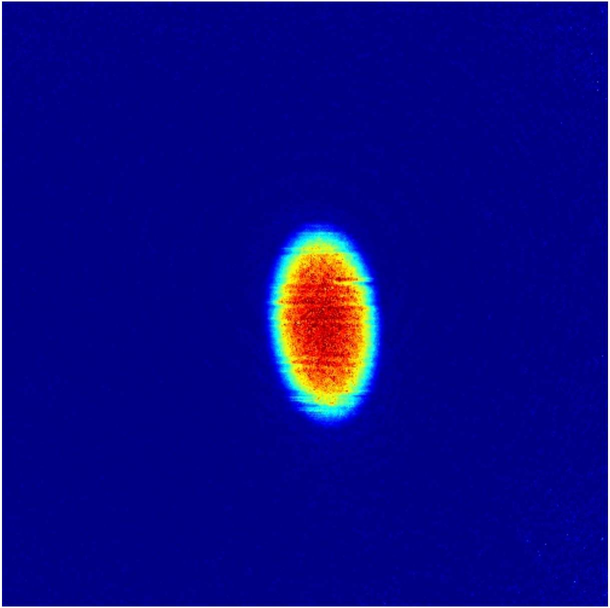

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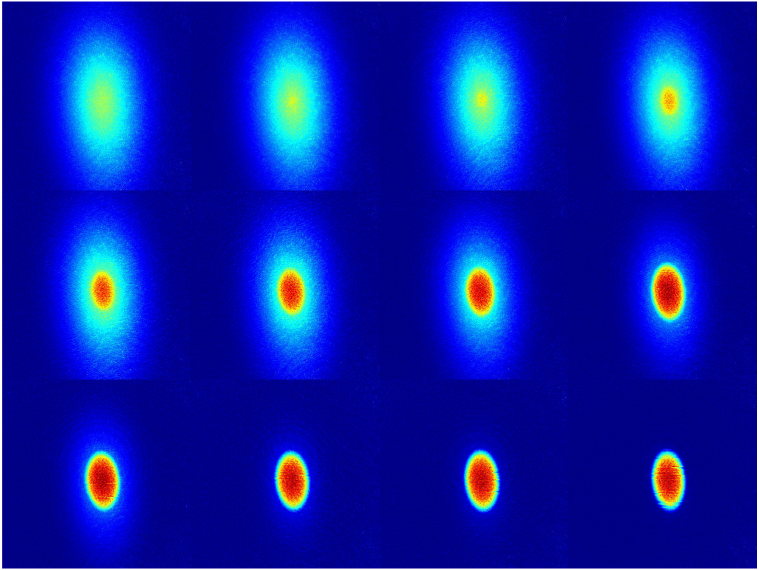
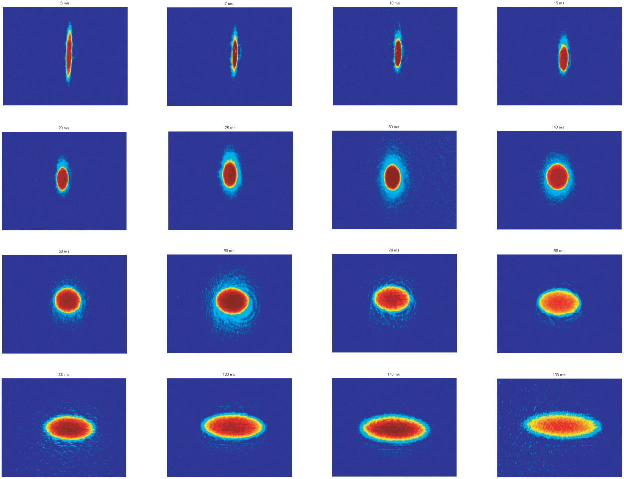
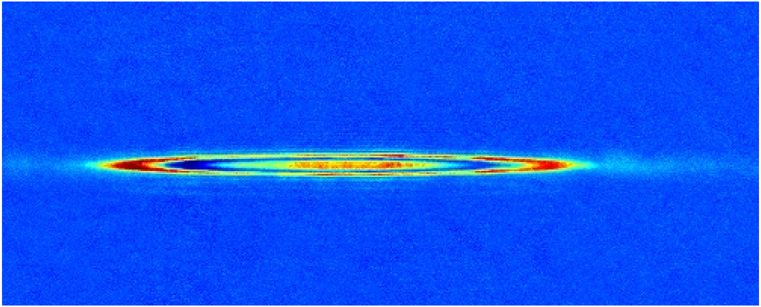


Expansion of the cloud



Phase contrast imaging, “close” to resonance



$\delta = -286$ MHz	Trap 96×4 Hz
Field-of-view 1.8×0.7 mm	“*in situ*”
$N = 1.5 \times 10^8$ atoms	

Characteristic values

Dark magneto-optical trap

Temperature	320 μK
Number of particles	1.2×10^{10} atoms
Density	3×10^{11} atoms/cm^3

Magnetic trap

Trap frequencies	ν_r=96 Hz and ν_z=16$\rightarrow$1.08 Hz
Number of particles	8×10^{9} atoms
Elastic scattering rate	10 collisions/s

Bose-Einstein condensation

Evaporation ramp	40 s
Number of particles	2.5×10^{8} atoms
Density	2.5×10^{14} atoms/cm^3
Chemical potential	3.5 kHz
Temperature	300 nK

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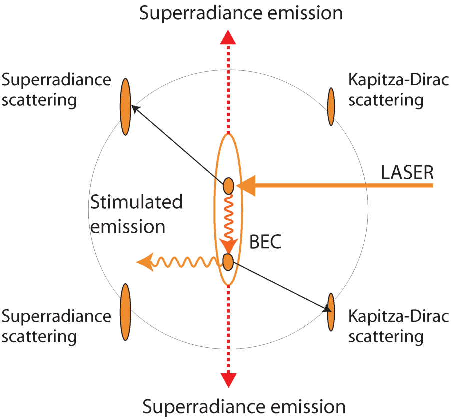
Topic One

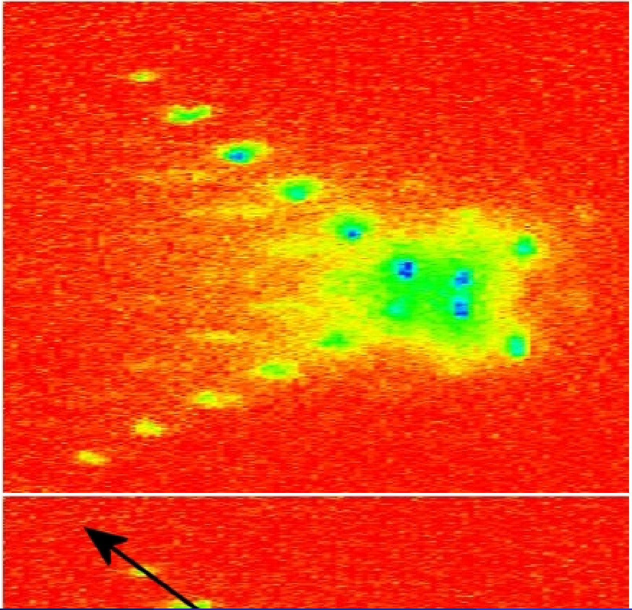
Superradiant scattering

"Collective scattering of light from a Bose-Einstein condensate"

Superradiant backscattering–Setup



Superradiant scattering–Spectrum

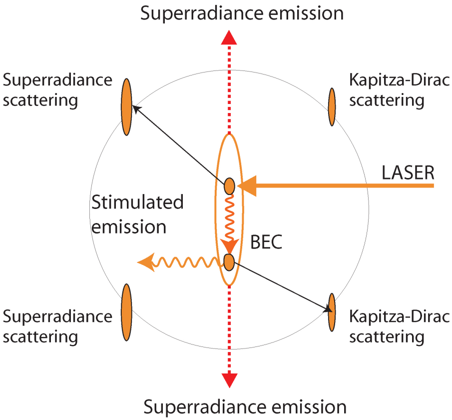


Defining Entanglement

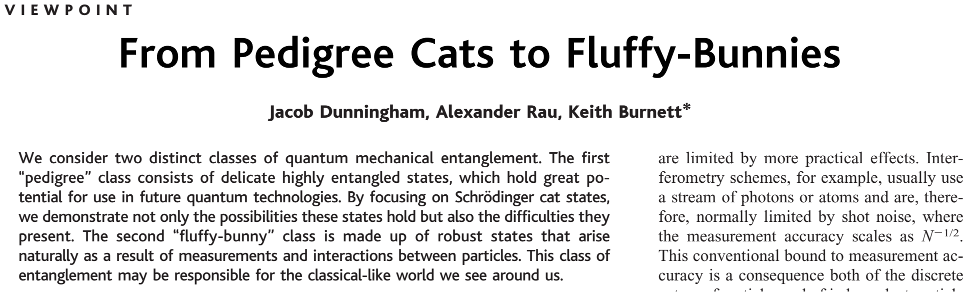
When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives [the quantum states] have become entangled.

Erwin Schrödinger, 1935

Superradiant backscattering–Entanglement



Distinguishing Entanglement



VIEWPOINT

From Pedigree Cats to Fluffy-Bunnies

Jacob Dunningham, Alexander Rau, Keith Burnett*

We consider two distinct classes of quantum mechanical entanglement. The first "pedigree" class consists of delicate highly entangled states, which hold great potential for use in future quantum technologies. By focusing on Schrödinger cat states, we demonstrate not only the possibilities these states hold but also the difficulties they present. The second "fluffy-bunny" class is made up of robust states that arise naturally as a result of measurements and interactions between particles. This class of entanglement may be responsible for the classical-like world we see around us.

are limited by more practical effects. Interferometry schemes, for example, usually use a stream of photons or atoms and are, therefore, normally limited by shot noise, where the measurement accuracy scales as $N^{-1/2}$. This conventional bound to measurement accuracy is a consequence both of the discrete

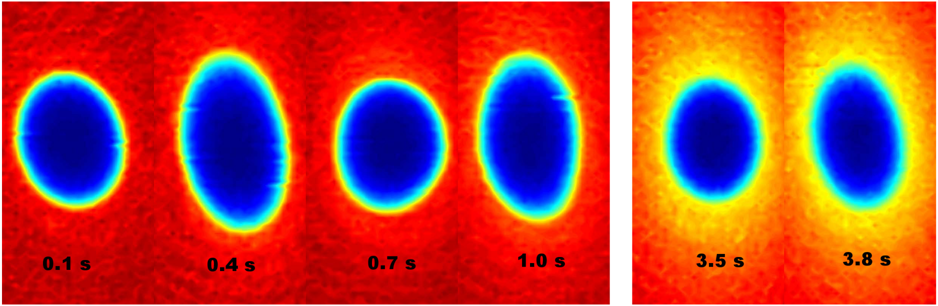
Dunningham *et al.*, Science **307**, 872 (2005)

Topic Two

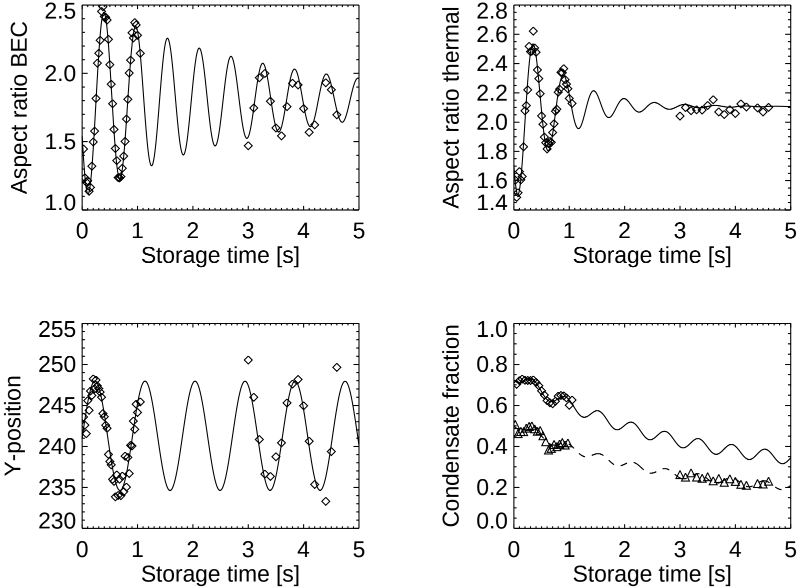
Collective excitations

"Excitation of a mode of the condensate"

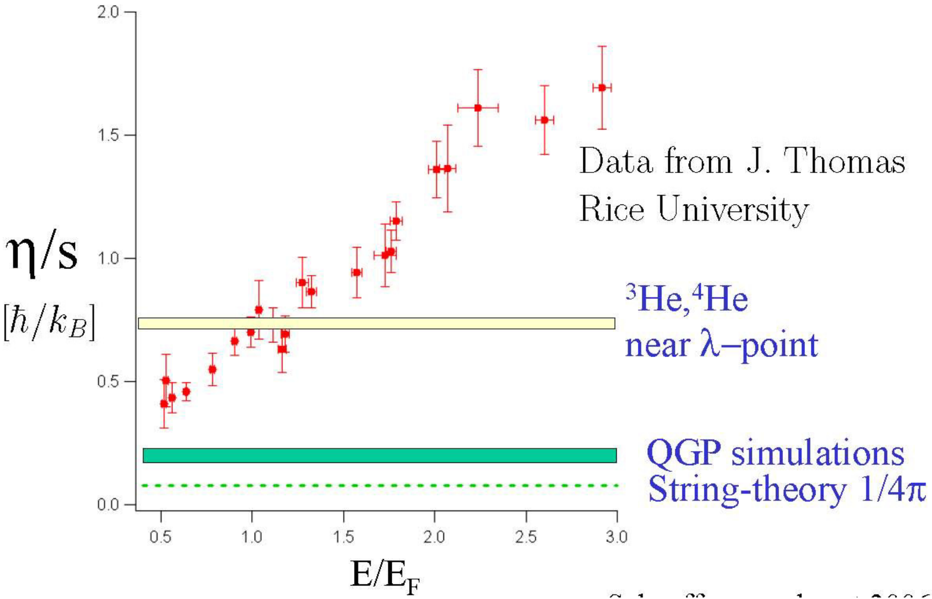
Quadrupole oscillations of a condensate



Damping of quadrupole oscillations



String theory, ^{3}He-^{4}He, quark-gluon plasma and cold atoms

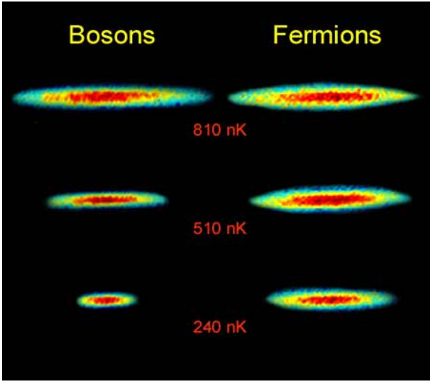


Topic Three

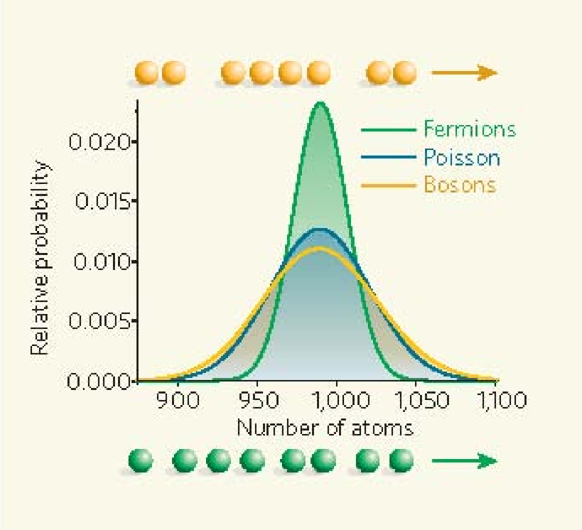
Bosons *versus* Fermions

“How quantum statistics changes everything”

“Fermi” pressure



Bunching or anti-bunching



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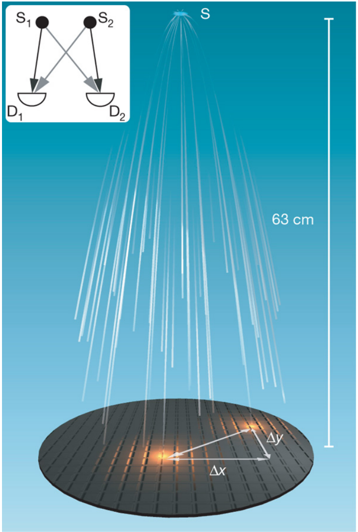

Jeltes *et al.*, Nature 2007

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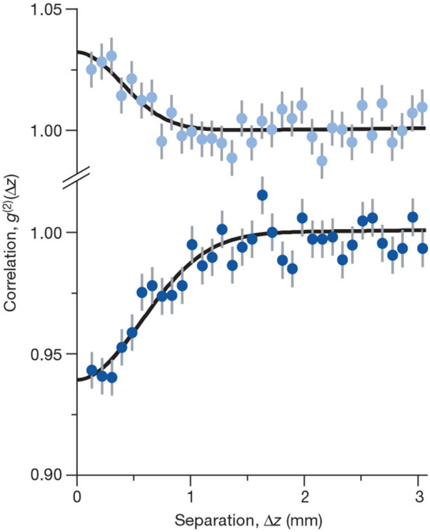


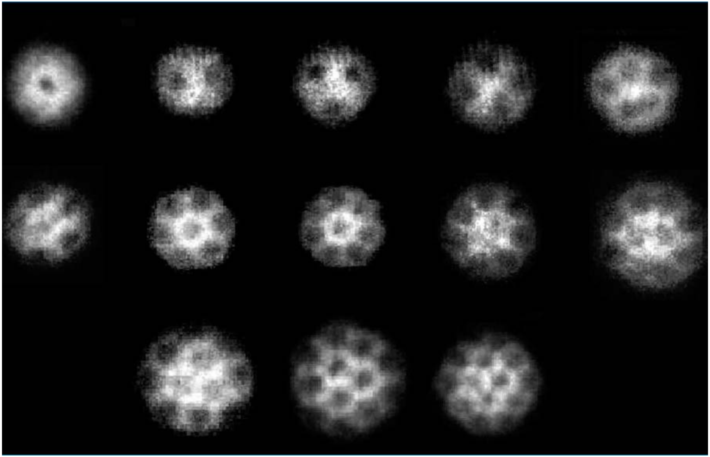
Jeltes *et al.*, Nature 2007

Topic Fout

Prove of superfluidity

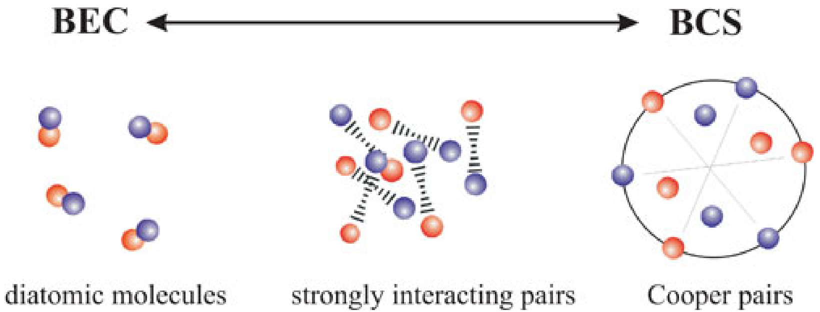
"Vortices in a quantum fluid"

Prove of superfluidity

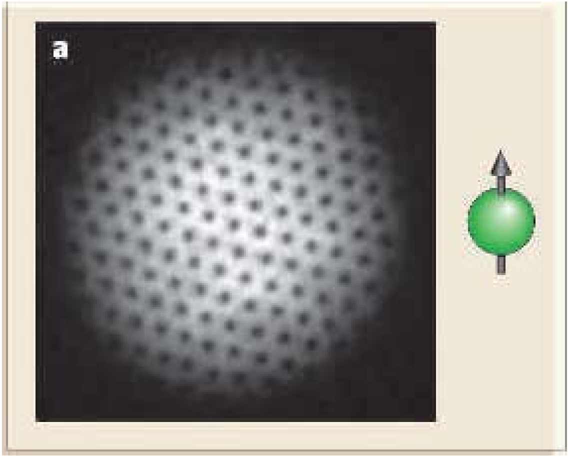


Madison *et al.*, Phys. Rev. Lett. **84**, 806 (2000)

Cross-over between bosons and fermions

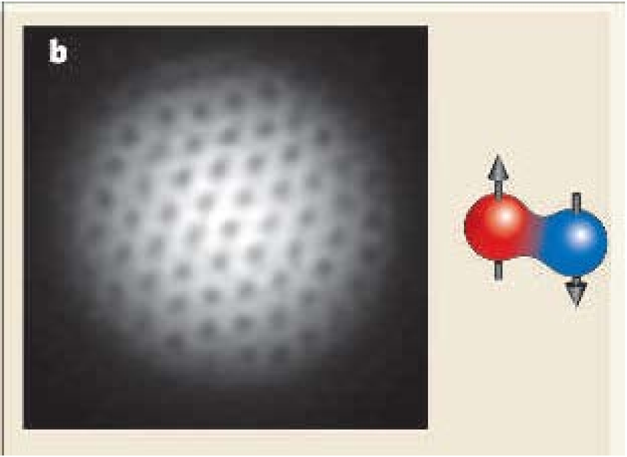


Prove of superfluidity for atoms



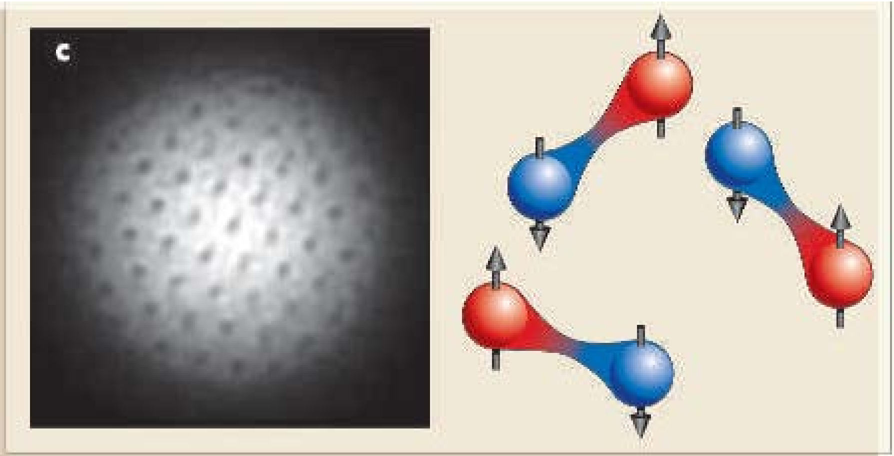
J. Abo-Shaer *et al.*, Science **292**, 476 (2001)

Prove of superfluidity for molecules



M. Zwierlein *et al.*, Nature **435**, 1047 (2005)

Prove of superfluidity for atom pairs



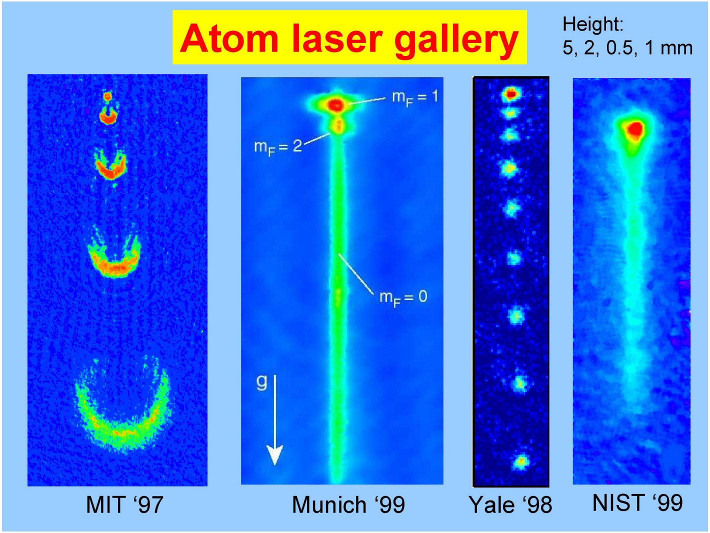
M. Zwierlein *et al.*, Nature **435**, 1047 (2005)

Topic Five

Atom laser

“The creation of a continuous flow of Bose-condensed atoms”

Atom lasers


Atom laser gallery
Height:
5, 2, 0.5, 1 mm
$m_F = 1$
$m_F = 2$
$m_F = 0$
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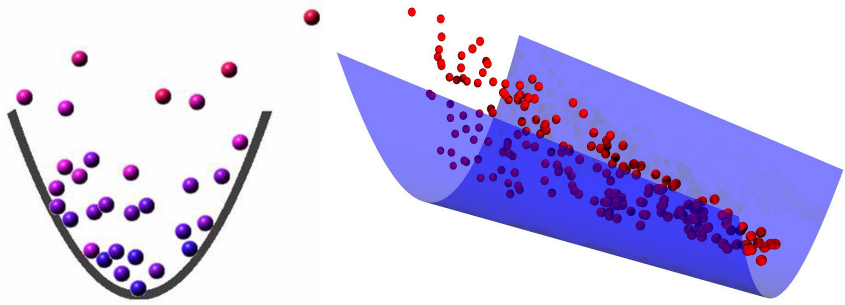
MIT '97
Munich '99
Yale '98
NIST '99

Evaporative cooling



Trap geometry *vs.* Beam geometry

“The rollercoaster”