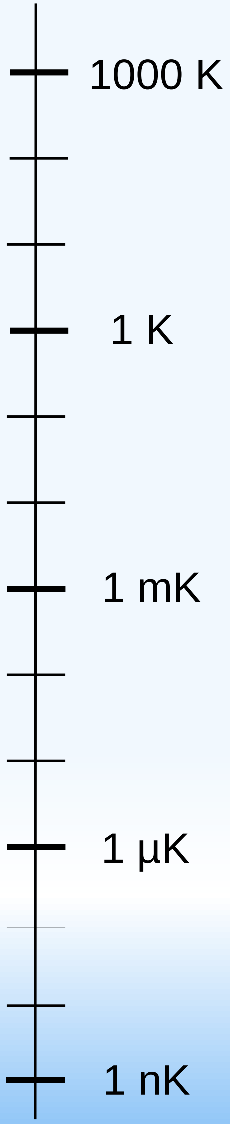
Introductory course, 10 July 2023

Cooling and trapping
Atoms, basics

Manuele Landini

"Institut für Experimentalphysik", **Innsbruck**

temperature scale



1000 K

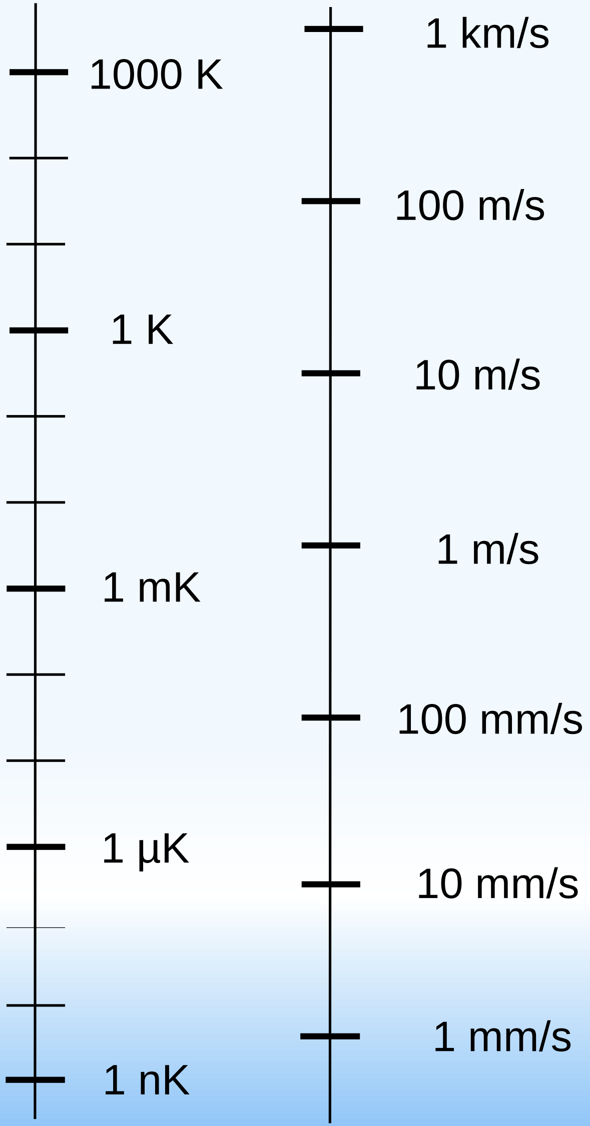
1 K

1 mK

1 μK

1 nK

temperature vs. velocity scale



1000 K

1 K

1 mK

1 µK

1 nK

1 km/s

100 m/s

10 m/s

1 m/s

100 mm/s

10 mm/s

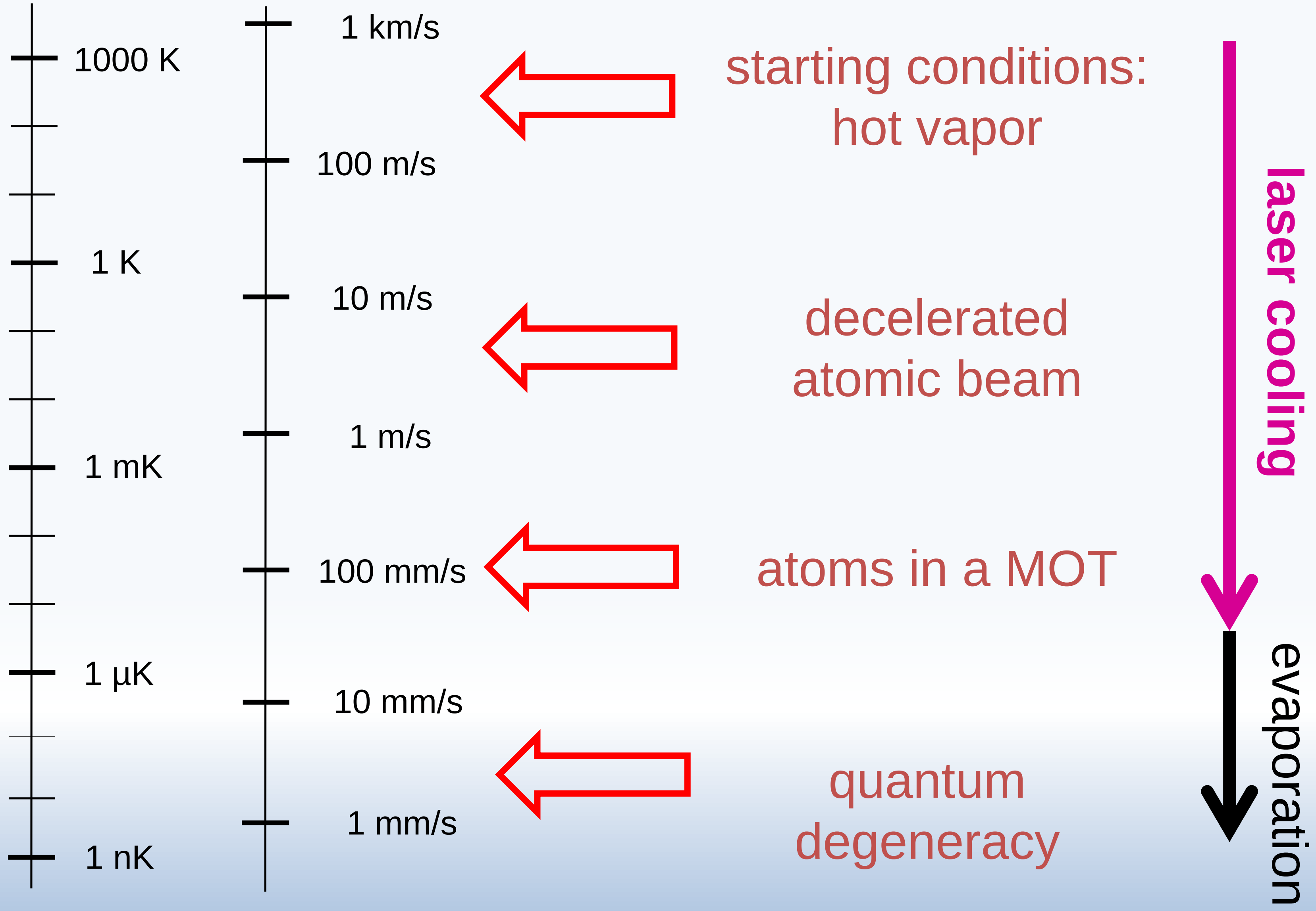
1 mm/s

$$\boxed{\frac{3}{2}k_BT = \frac{1}{2}mv_{rms}^2}$$

ideal gas:
relation between
kinetic energy and
rms velocity

we assume
m = 87 u
Rb atoms as example
(most common species)

temperature regimes



1000 K

1 K

1 mK

1 µK

1 nK

1 km/s

100 m/s

10 m/s

1 m/s

100 mm/s

10 mm/s

1 mm/s

starting conditions:
hot vapor

decelerated
atomic beam

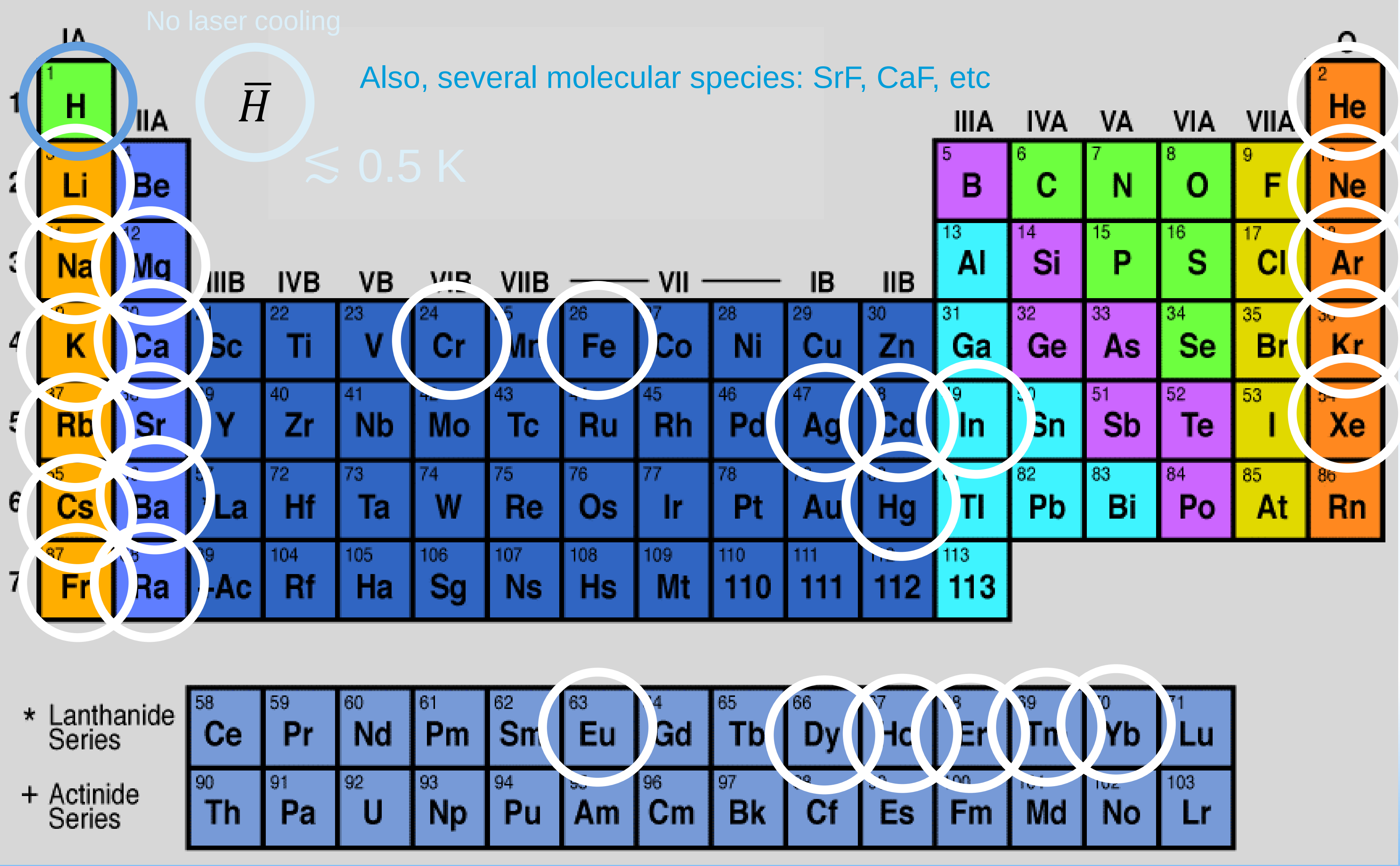
atoms in a MOT

quantum
degeneracy

laser cooling

evaporation

Ultracold atoms

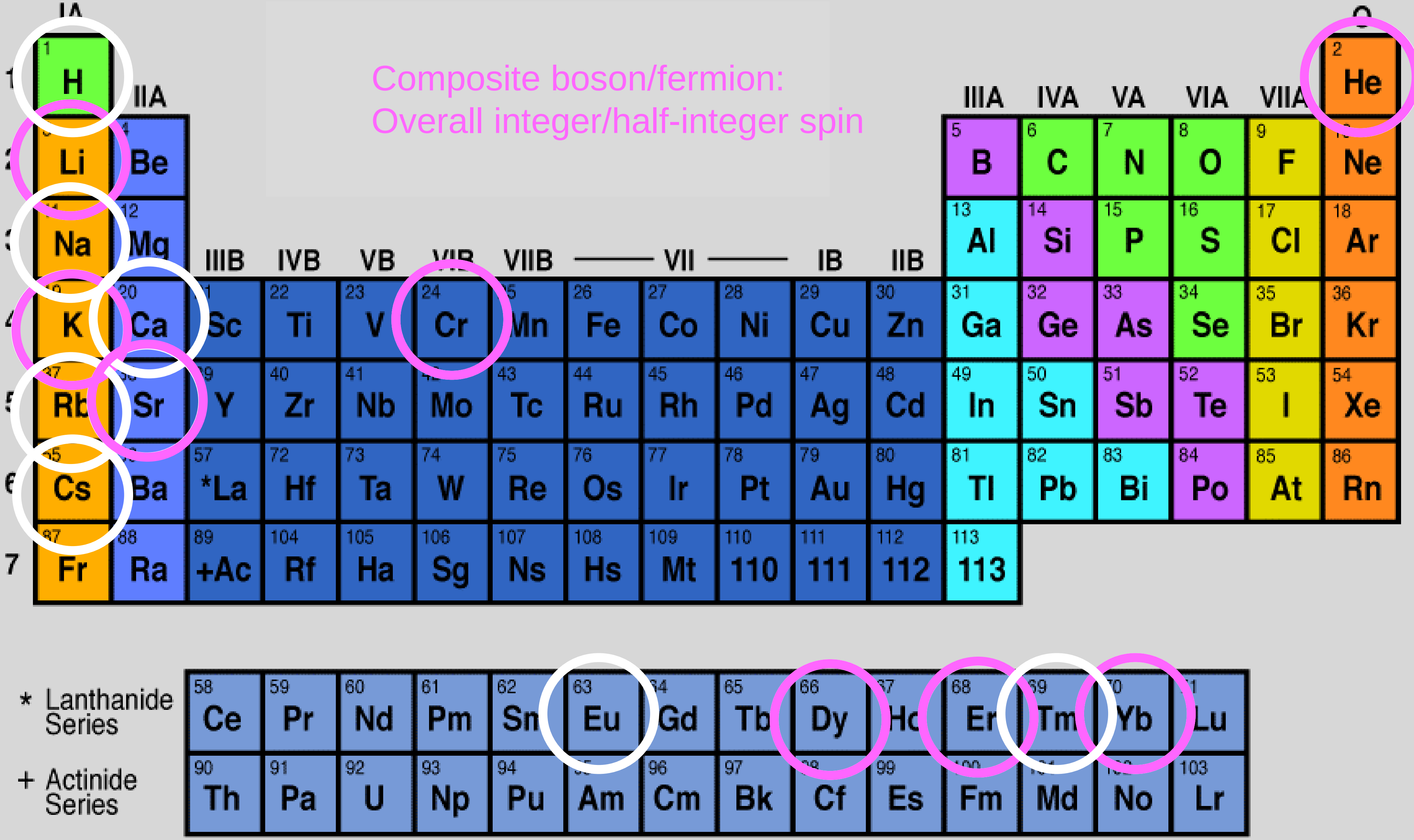


No laser cooling

$\lesssim 0.5$ K

Also, several molecular species: SrF, CaF, etc

Atomic species brought to degeneracy



Composite boson/fermion:
Overall integer/half-integer spin

More on Fermions and Bosons Today and tomorrow

Why are Fermions rare?

Spin-statistics connection:

$$S_{atom} = \sum s_e + s_p + s_n \begin{cases} \text{Integer: Boson} \\ \text{Semi-Integer: Fermion} \end{cases}$$

The atom is neutral: $Z = n_e = n_p \Rightarrow \sum s_e + s_p$ integer

Even(odd) N: B(F)

Nuclear pairing favors even N nuclear configurations

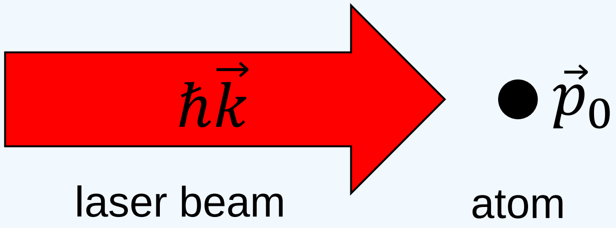
Fermionic isotopes are more unstable

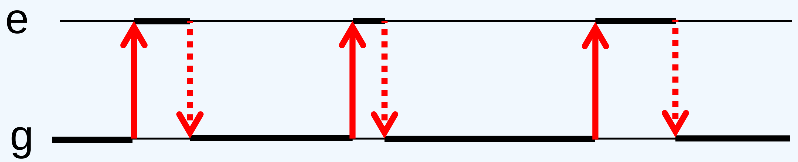
scattering force

$$\boxed{\vec{F}_{sc} = \hbar\vec{k}\,\Gamma\,\rho_e}$$

ρ_e: population of excited state

Γ: decay rate





absorption-emission cycles

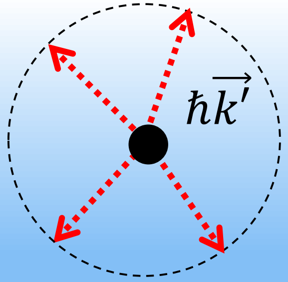
momentum transfer

absorption $\vec{p}_e = \vec{p}_0 + \hbar\vec{k}$

stimulated emission $\vec{p}_1 = \vec{p}_e - \hbar\vec{k} \quad = \vec{p}_0$ no net effect

spontaneous emission

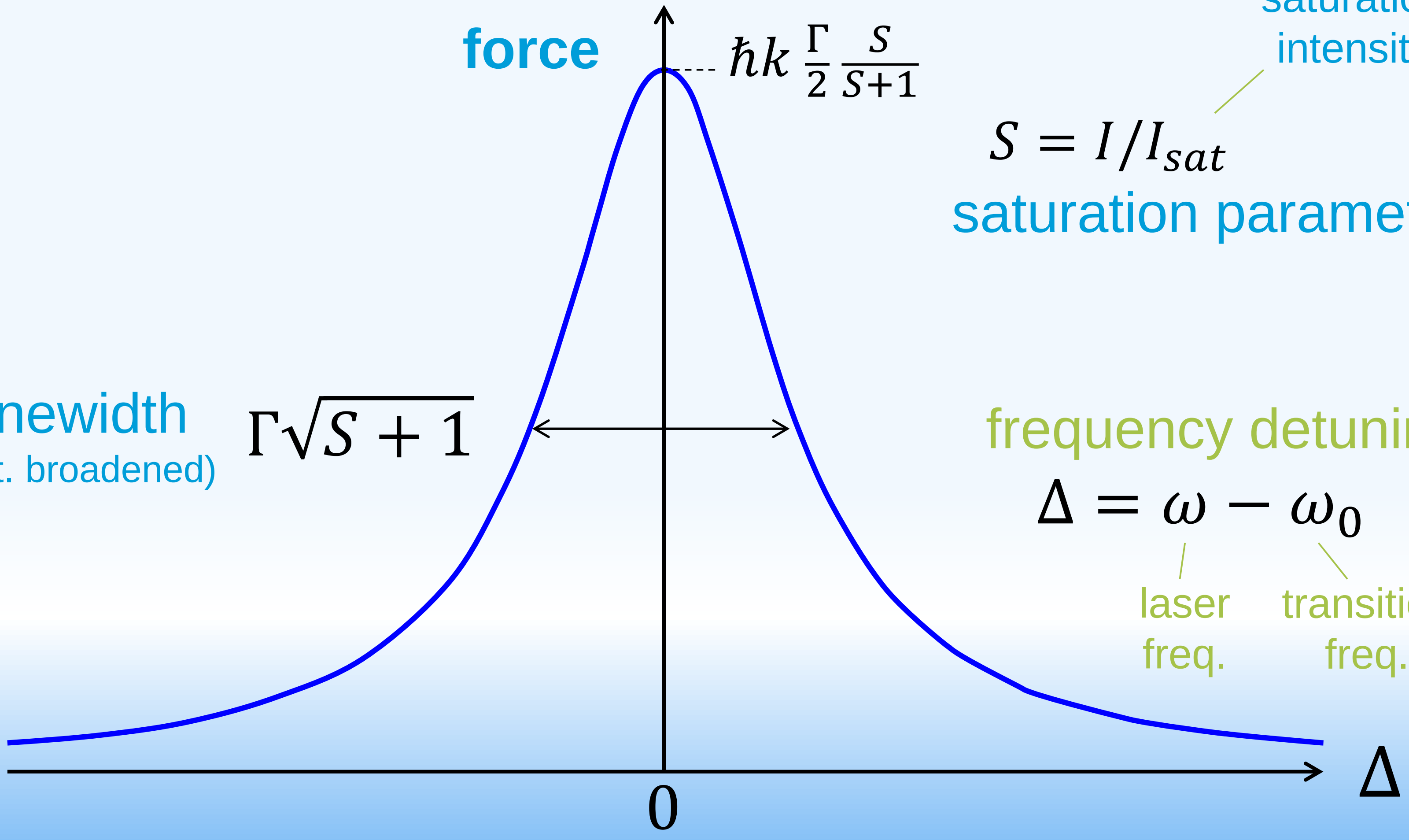
$$\vec{p}_1 = \vec{p}_e - \hbar\vec{k'}$$
$$= \vec{p}_0 + \underbrace{\hbar\vec{k}}_{\text{same in each cycle}} - \underbrace{\hbar\vec{k'}}_{\text{on average zero}}$$



resonance behavior

excited-state population

$$\boxed{\rho_e(\Delta) = \frac{1}{2}\,\frac{S}{(2\Delta/\Gamma)^2 + S + 1}}$$



force

$$\hbar k\,\frac{\Gamma}{2}\,\frac{S}{S+1}$$

linewidth

(sat. broadened)

$$\Gamma\sqrt{S+1}$$

saturation intensity

$$S = I/I_{sat}$$

saturation parameter

frequency detuning

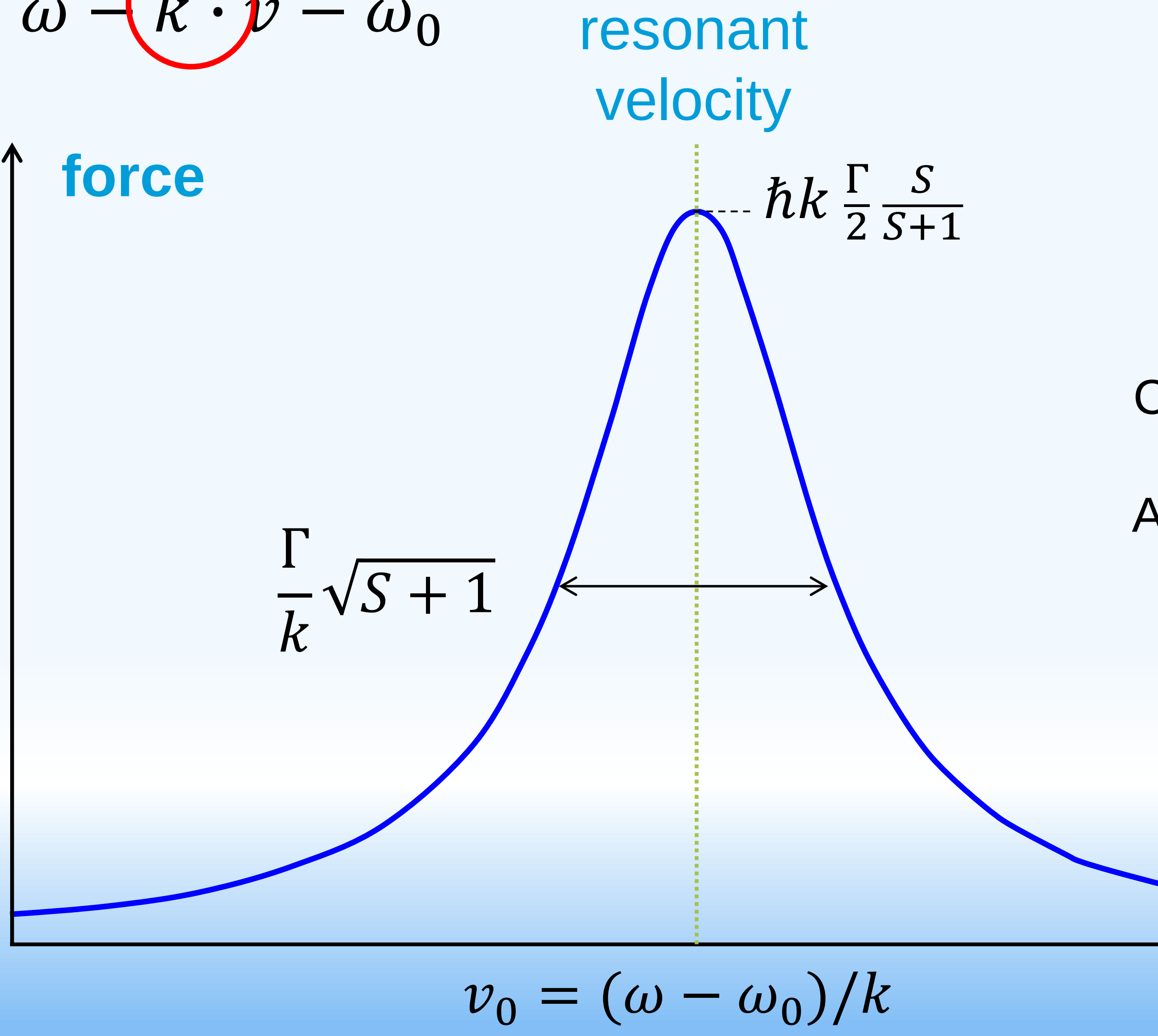
$$\Delta = \omega - \omega_0$$

laser freq.

transition freq.

Doppler effect: force depends on atomic velocity

$$\Delta = \omega - \boxed{\vec{k}} \cdot \vec{v} - \omega_0$$



Christian Doppler
(1803 – 1853)
Austrian physicist

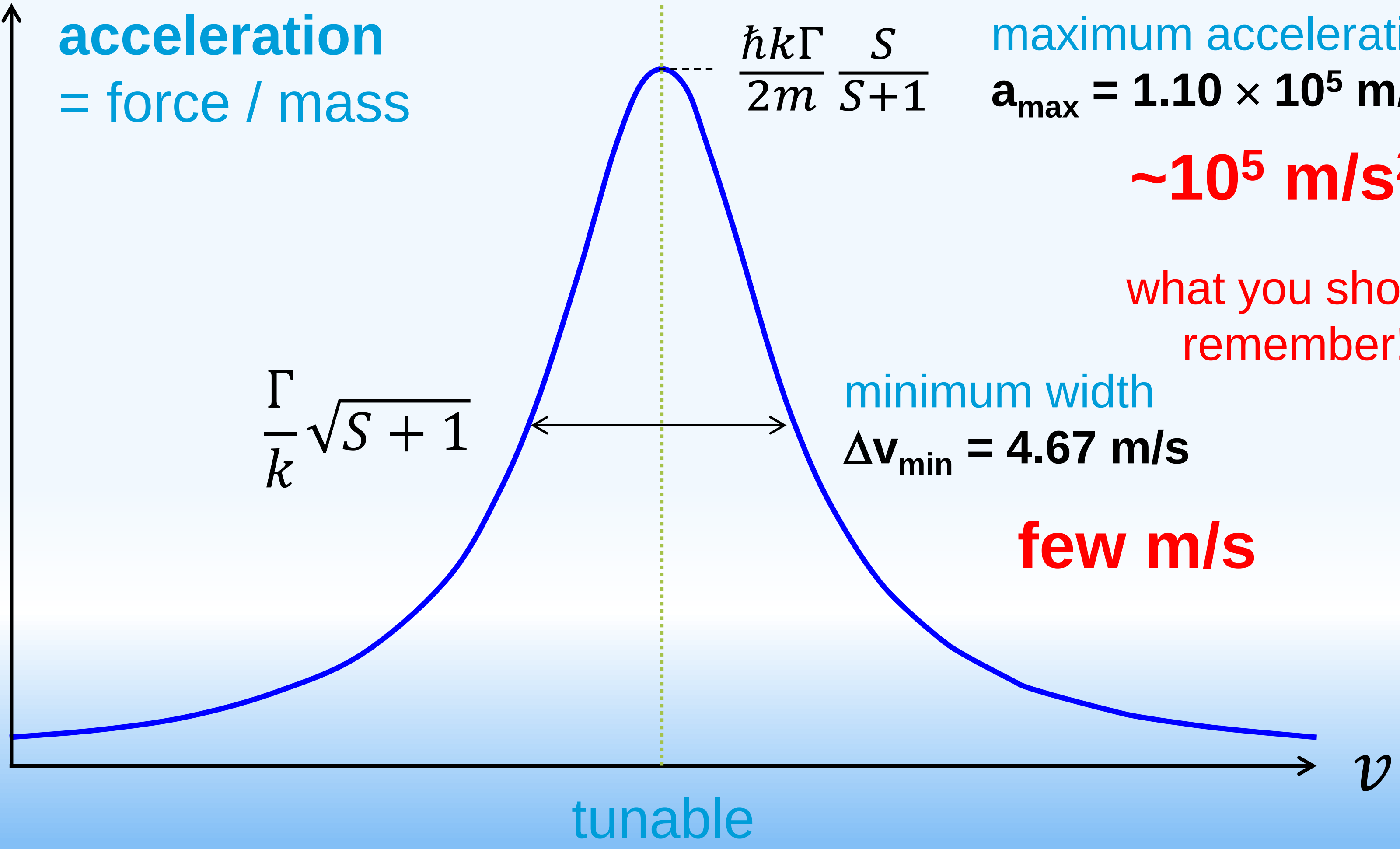
some typical numbers

$\Gamma/2\pi = 5.98$ MHz
natural linewidth

^{87}Rb

$\lambda = 780$ nm
wavelength

$I_{sat} = 1.64$ mW/cm^2
saturation intensity


acceleration
= force / mass

$$\frac{\hbar k \Gamma}{2m}\,\frac{S}{S+1}$$

$$\frac{\Gamma}{k}\sqrt{S+1}$$

maximum acceleration
a_{max} = 1.10 × 10^5 m/s^2

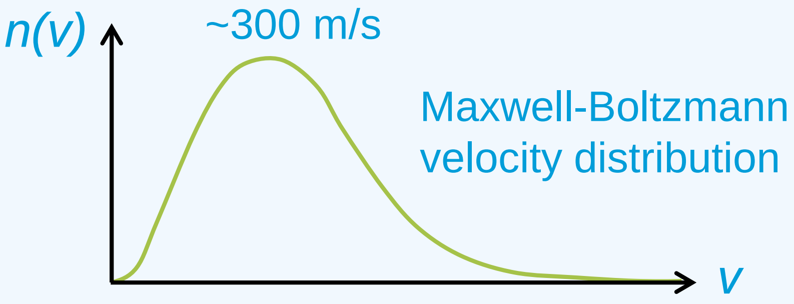
~10^5 m/s^2

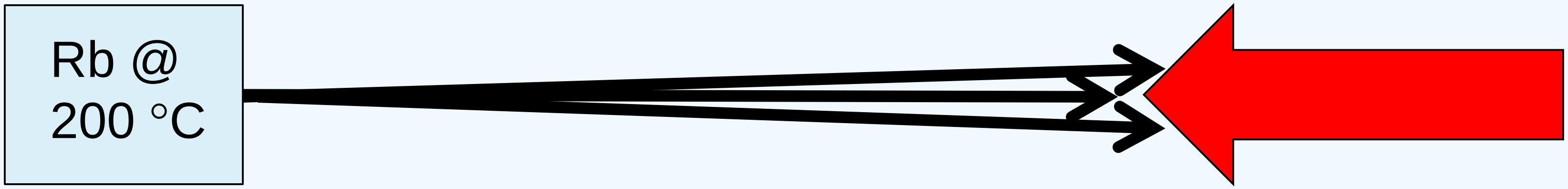
what you should
remember!

minimum width
Δv_{min} = 4.67 m/s

few m/s

decelerating an atomic beam

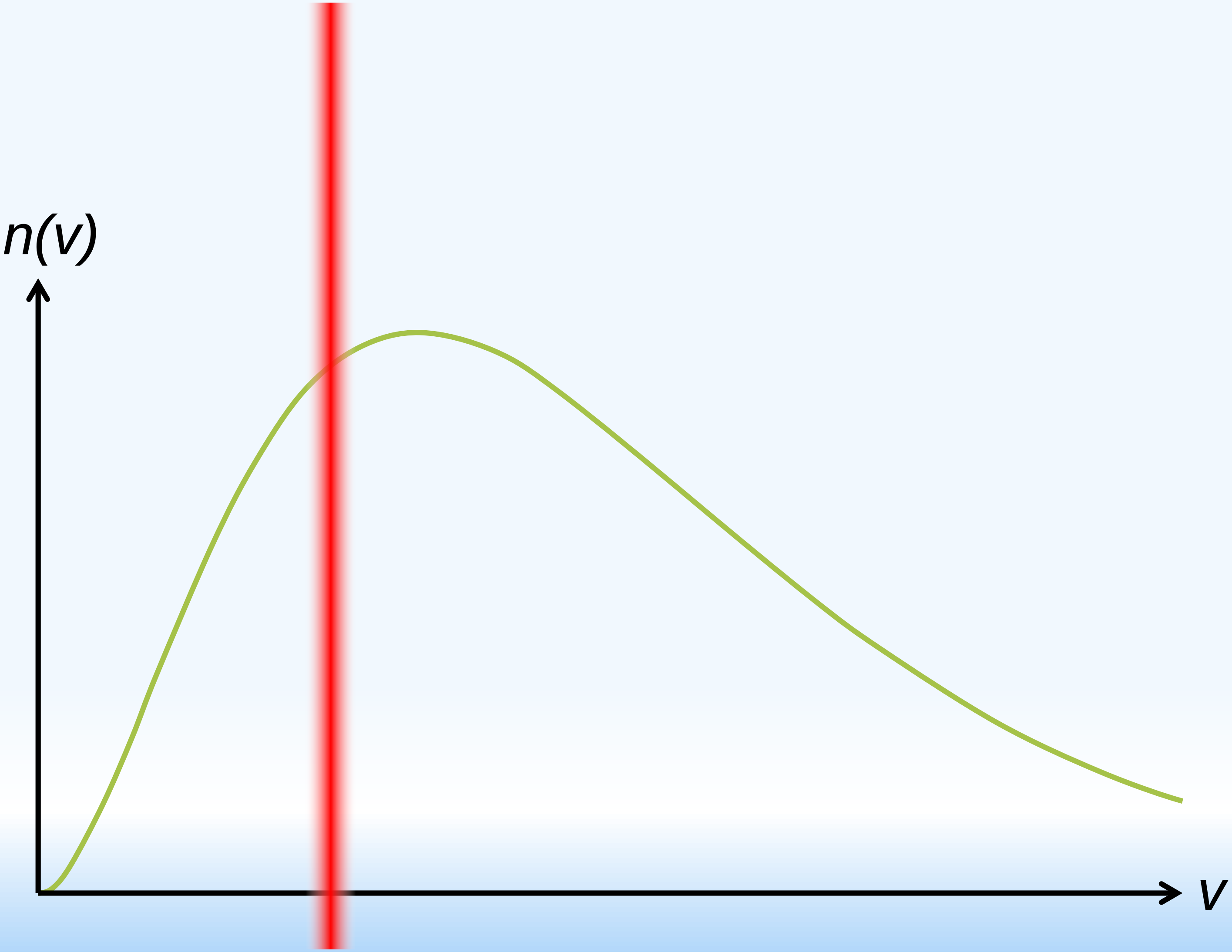




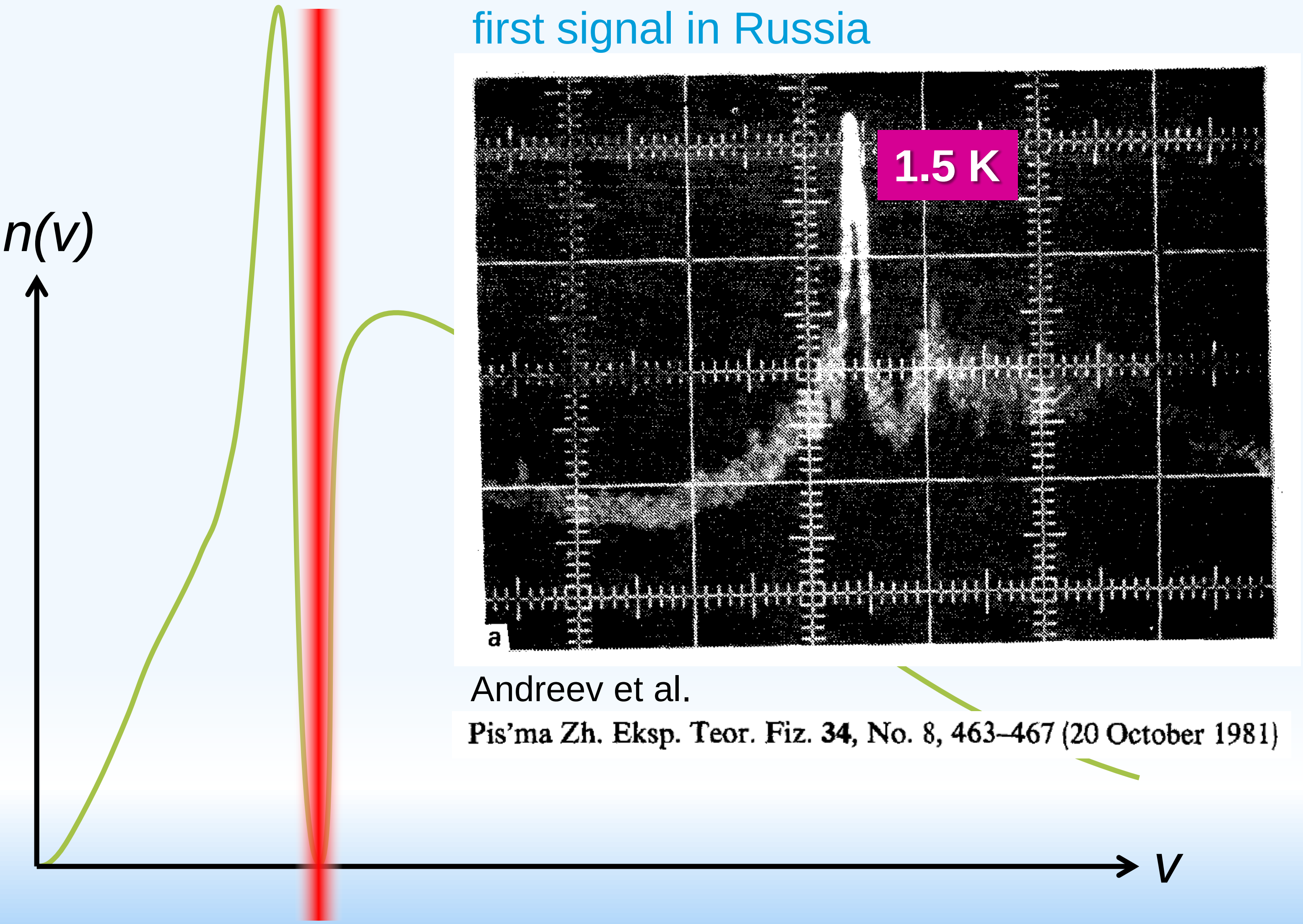
min. distance for slowing atoms from 300m/s to zero

$$L_{min} = v^2/(2a_{max}) = 41\text{cm}$$

remember Doppler



remember Doppler

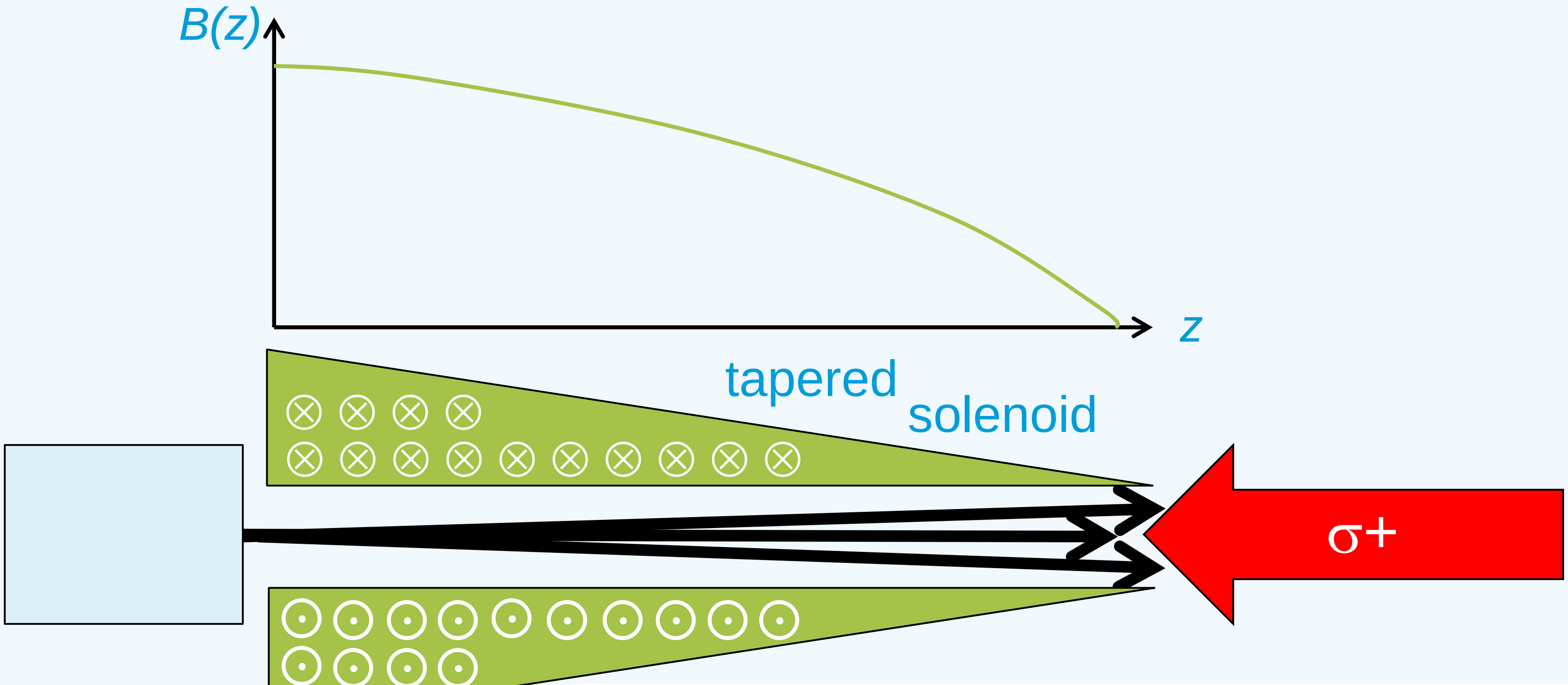


first signal in Russia

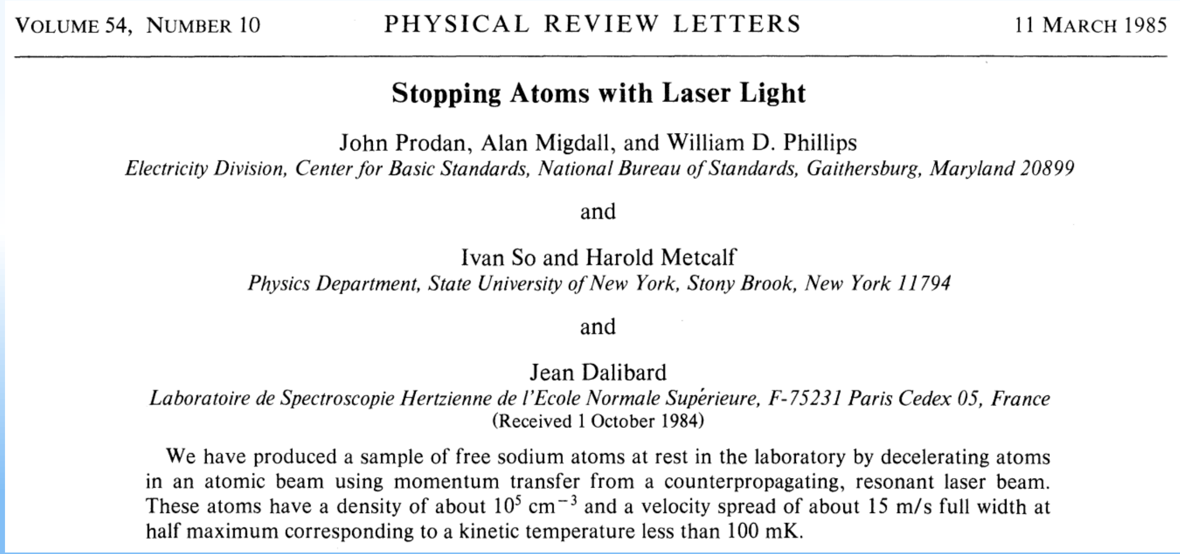
Andreev et al.

Pis'ma Zh. Eksp. Teor. Fiz. **34**, No. 8, 463–467 (20 October 1981)

Zeeman slower



Zeeman effect
compensates
for Doppler effect:
<u>continuous</u> slowing !!!



VOLUME 54, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 1985

Stopping Atoms with Laser Light

John Prodan, Alan Migdall, and William D. Phillips
Electricity Division, Center for Basic Standards, National Bureau of Standards, Gaithersburg, Maryland 20899

and

Ivan So and Harold Metcalf
Physics Department, State University of New York, Stony Brook, New York 11794

and

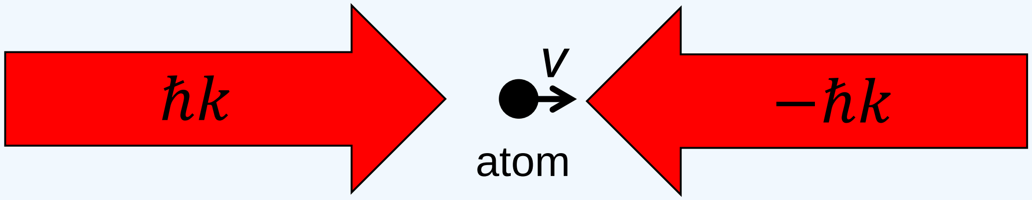
Jean Dalibard
Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, F-75231 Paris Cedex 05, France
(Received 1 October 1984)

We have produced a sample of free sodium atoms at rest in the laboratory by decelerating atoms in an atomic beam using momentum transfer from a counterpropagating, resonant laser beam. These atoms have a density of about 10^5 cm^{-3} and a velocity spread of about 15 m/s full width at half maximum corresponding to a kinetic temperature less than 100 mK.

optical molasses

recipe:

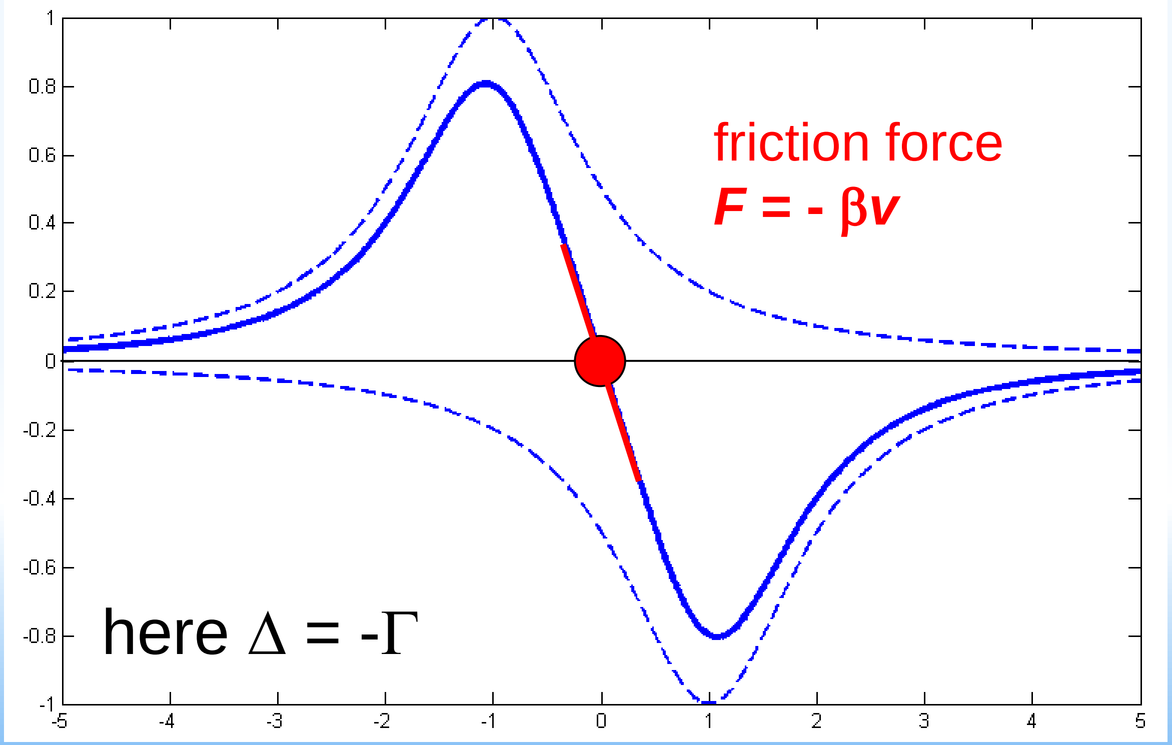
- use pair of counterpropagating laser beams
- choose detuning below resonance



force

in units of

$$\hbar k \frac{\Gamma}{2} S$$



$$S \ll 1$$

low-intensity limit

friction

friction coefficient

$$\boxed{\beta = 4\hbar k^2\, S\, \underbrace{\frac{-2\Delta/\Gamma}{[1+(2\Delta/\Gamma)^2]^2}}_{\frac{1}{4}}}$$

$S \ll 1$

$\frac{1}{4}$ for $\Delta = -\frac{\Gamma}{2}$

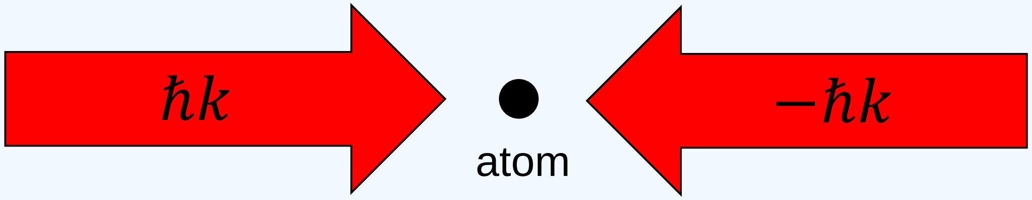
dissipation of kinetic energy

$$\boxed{\frac{d}{dt}\overset{\frac{1}{2}mv^2}{E_{kin}} = mv\frac{d}{dt}v = v\,F(\overset{-\beta v}{v}) = -\beta\, v^2 = -\frac{2\beta}{m}E_{kin}}$$

energy damping rate

typ. time scale: few µs

heating



cycles of absorption and spont. emission

25% $\rightarrow\rightarrow$ $\Delta p = +2\hbar k$ $\Delta E = 2\hbar^2 k^2/m$

25% $\rightarrow\leftarrow$ $= 0$ $= 0$

25% $\leftarrow\rightarrow$ $= 0$ $= 0$

25% $\leftarrow\leftarrow$ $= -2\hbar k$ $= 2\hbar^2 k^2/m$

average energy gain per cycle: $<\Delta E> = \boldsymbol{\hbar^2 k^2/m}$

heating rate

$$\boxed{\frac{d}{dt}E_{kin} = \frac{\boldsymbol{\hbar^2 k^2}}{\boldsymbol{m}}\underbrace{2\frac{\Gamma}{4}S}_{\text{scattering rate (both beams)}}}$$

$$\Delta = -\frac{\Gamma}{2}$$

balance between heating and cooling

$$\boxed{\frac{d}{dt}E_{kin} = -\frac{2\beta}{m}E_{kin} = -\frac{2\hbar k^2}{m}S\,E_{kin}}$$

cooling

$$\boxed{\frac{d}{dt}E_{kin} = \frac{\hbar^2 k^2}{m}\frac{\Gamma}{2}S}$$

heating

$\Delta = -\frac{\Gamma}{2}$

balance: $\boxed{E_{kin} = \frac{\hbar\Gamma}{4}}$

$\frac{1}{2}k_B T$

Rb: T_D = 146 µK

$$\boxed{T_D = \frac{\hbar\Gamma}{2k_B}}$$

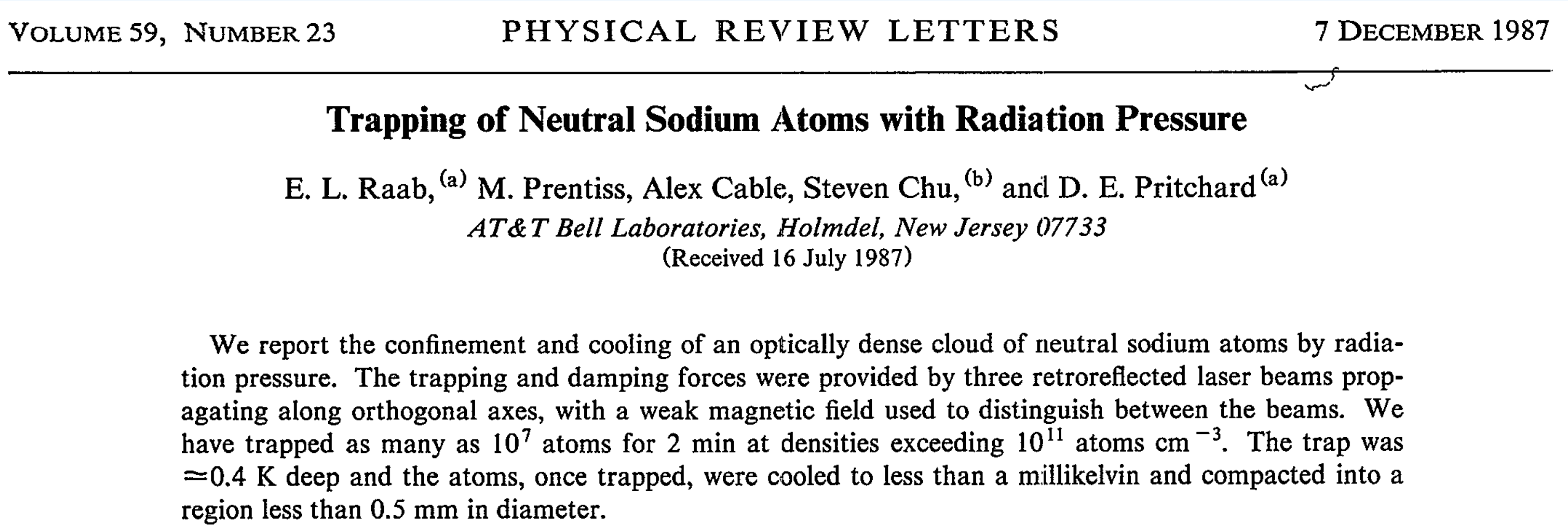
Doppler temperature

(low sat. S<<1, optimum det. $\Delta = -\Gamma/2$)

lowest attainable temperature determined by transition linewidth !

Lower temperatures are possible with multilevel atoms, sub-Doppler

landmark: magneto-optical trap



VOLUME 59, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1987

Trapping of Neutral Sodium Atoms with Radiation Pressure

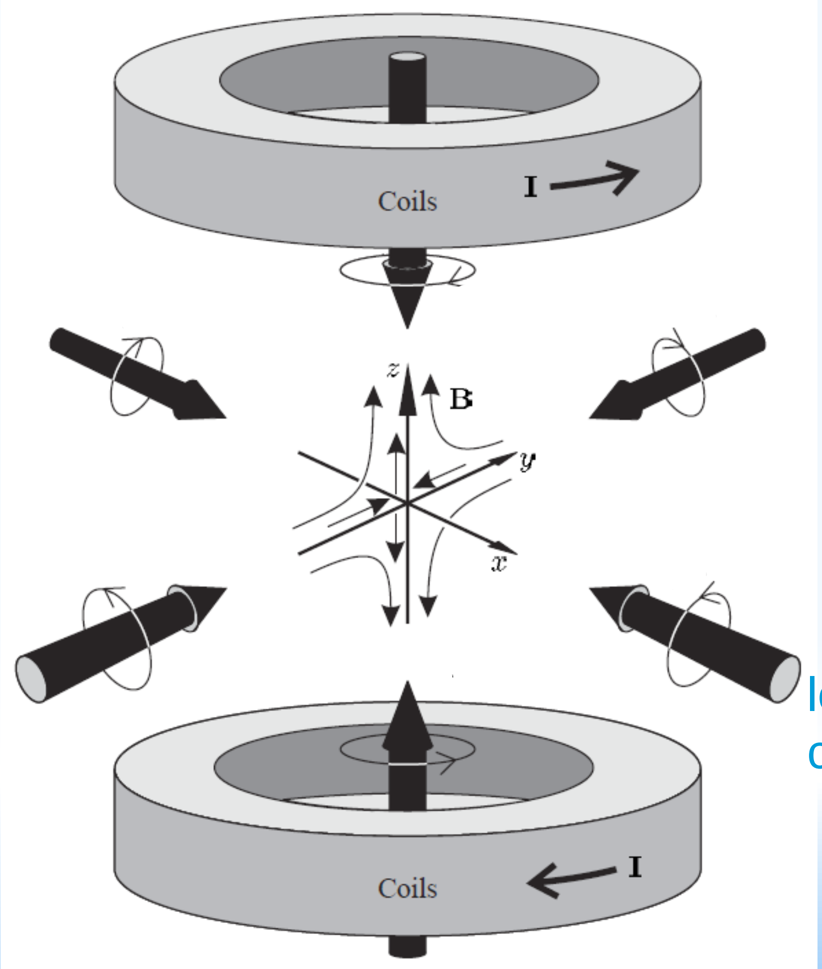
E. L. Raab,(a) M. Prentiss, Alex Cable, Steven Chu,(b) and D. E. Pritchard(a)
AT&T Bell Laboratories, Holmdel, New Jersey 07733

(Received 16 July 1987)

We report the confinement and cooling of an optically dense cloud of neutral sodium atoms by radiation pressure. The trapping and damping forces were provided by three retroreflected laser beams propagating along orthogonal axes, with a weak magnetic field used to distinguish between the beams. We have trapped as many as 10^7 atoms for 2 min at densities exceeding 10^{11} atoms cm^{-3}. The trap was $\simeq 0.4$ K deep and the atoms, once trapped, were cooled to less than a millikelvin and compacted into a region less than 0.5 mm in diameter.

magneto-optical trap (MOT)

right-hand
circular



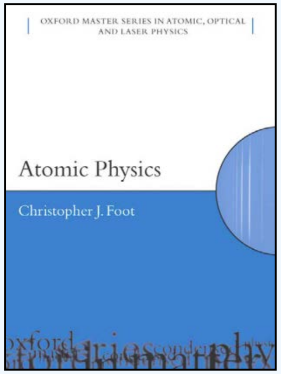
left-hand
circular

left-hand
circular

left-hand
circular

left-hand
circular

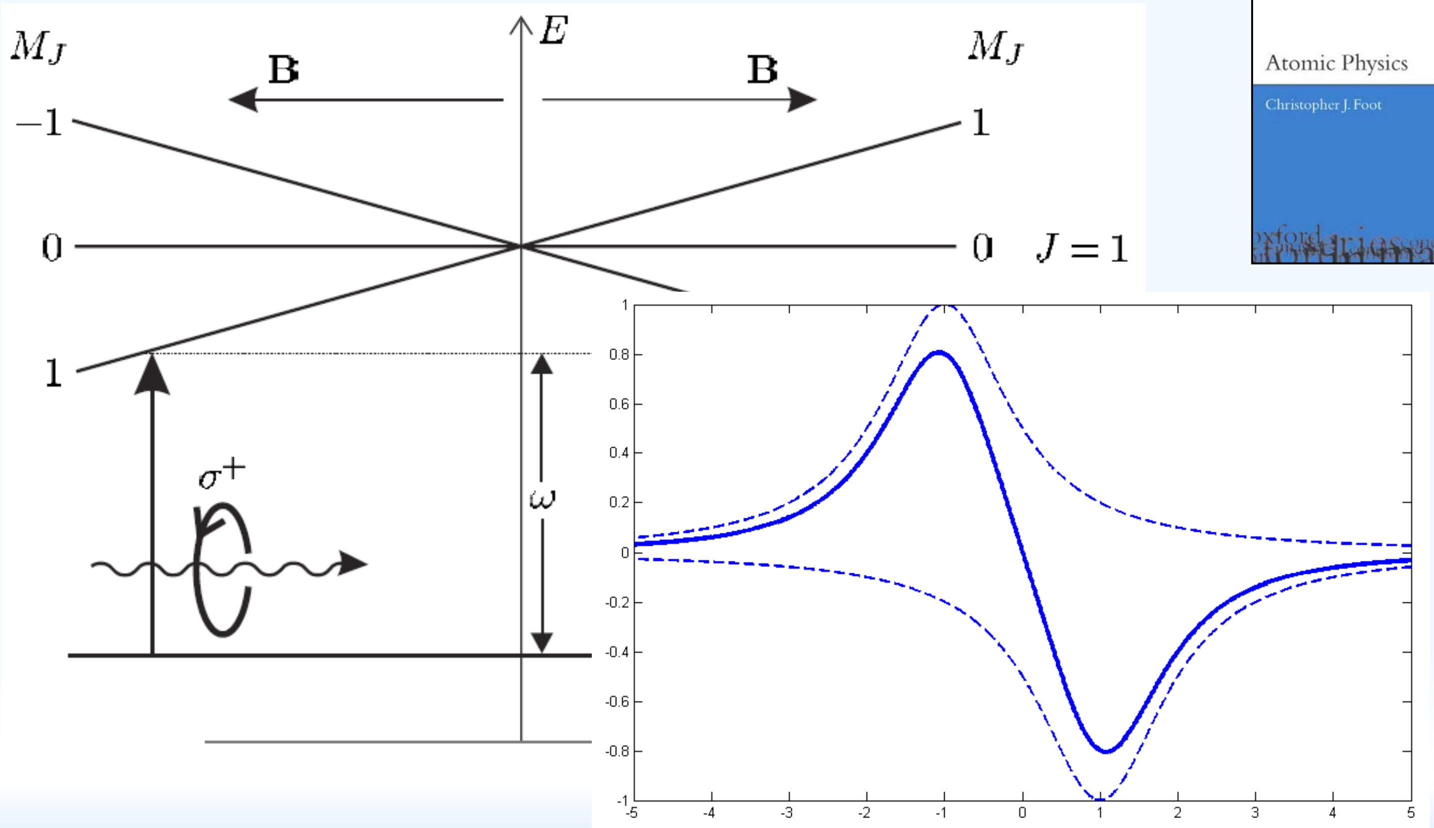
right-hand
circular

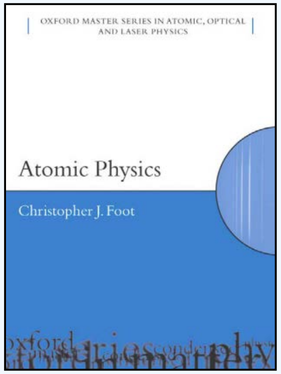

OXFORD MASTER SERIES IN ATOMIC, OPTICAL AND LASER PHYSICS

Atomic Physics

Christopher J. Foot

along z-axis

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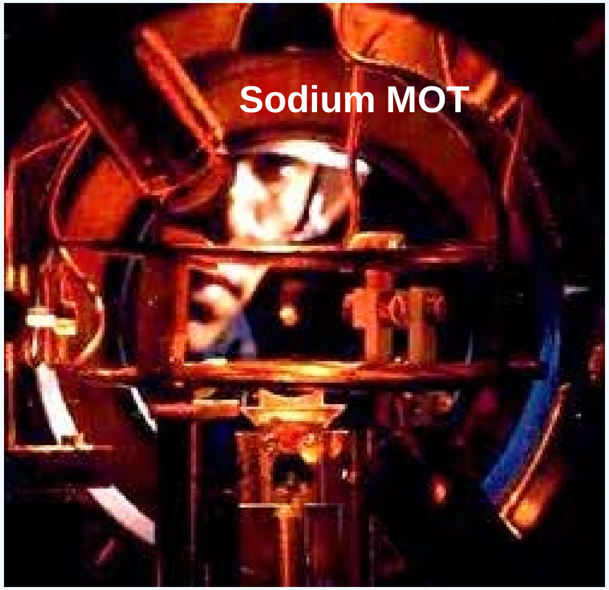
Atomic Physics

Christopher J. Foot

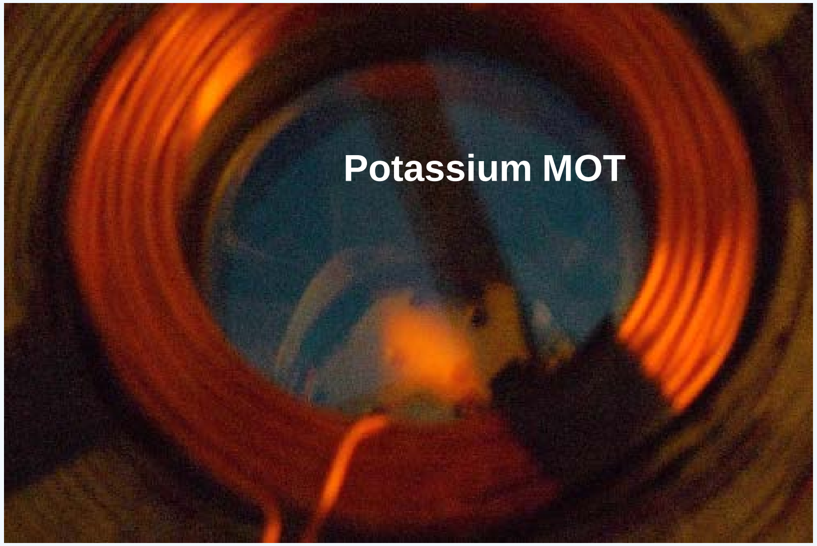
spatially restoring force: $F(z) = -\kappa z$ (lin. approx. in trap center)

(same for x-, and y-axis)

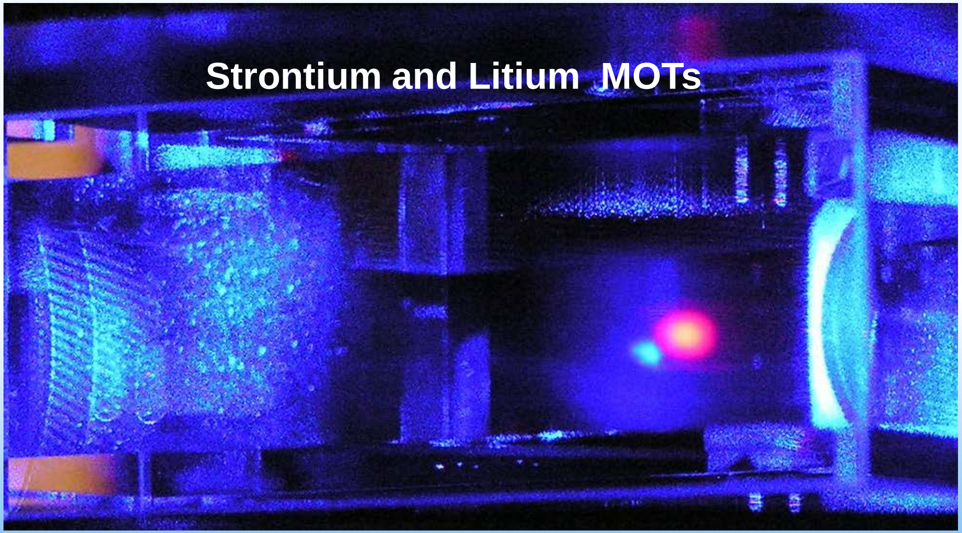
MOT Gallery



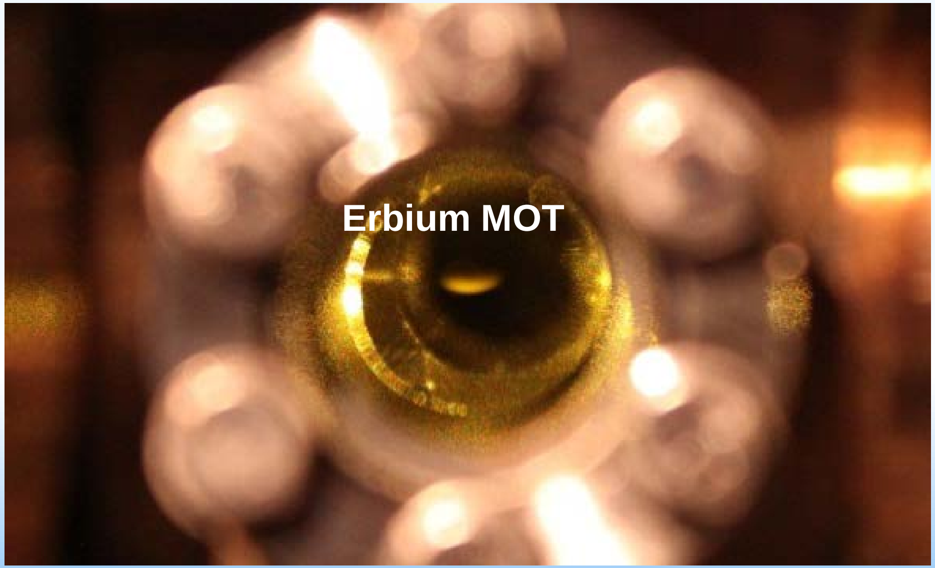
Sodium MOT



Potassium MOT



Strontium and Litium MOTs



Erbium MOT

MORE IN LAB TOUR

Cooling techniques

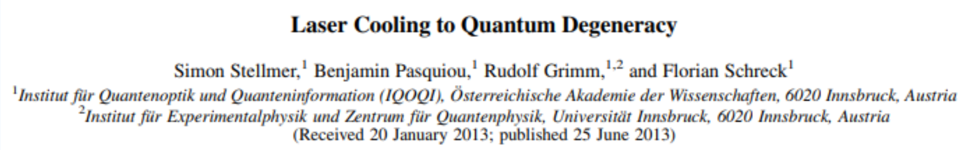
Laser cooling

✓ Large capture range

✓ High atomic flux

✓ Fast cooling rate

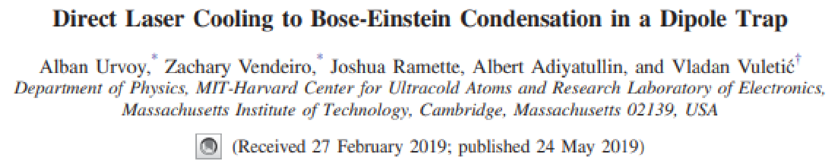
✗ Phase-space density limited to $10^{-6}...10^{-4}$ (with exceptions)



Laser Cooling to Quantum Degeneracy

Simon Stellmer,[1] Benjamin Pasquiou,[1] Rudolf Grimm,[1,2] and Florian Schreck[1]
[1] *Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[2] *Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

(Received 20 January 2013; published 25 June 2013)



Direct Laser Cooling to Bose-Einstein Condensation in a Dipole Trap

Alban Urvoy,[*] Zachary Vendeiro,[*] Joshua Ramette, Albert Adiyatullin, and Vladan Vuletić[†]
Department of Physics, MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 27 February 2019; published 24 May 2019)

Evaporative cooling

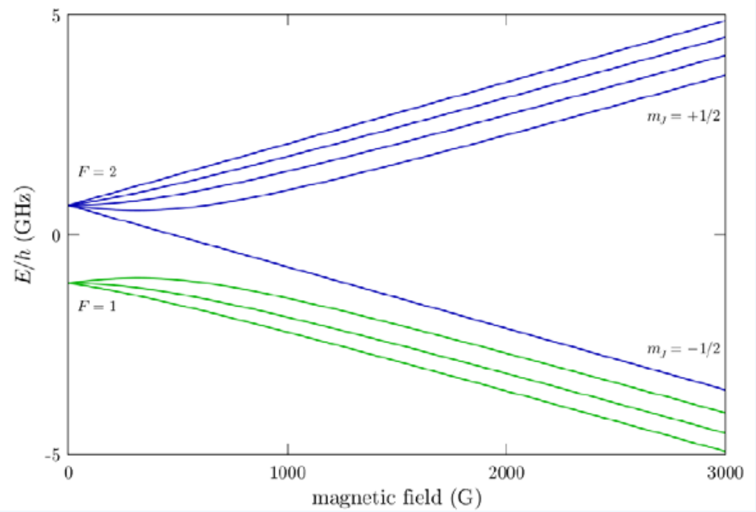
✓ No fundamental limits to the ultimate lower temperature

✓ More efficient at high spatial density

✓ Proven method to enter into the quantum degenerate regime

Magnetic Traps

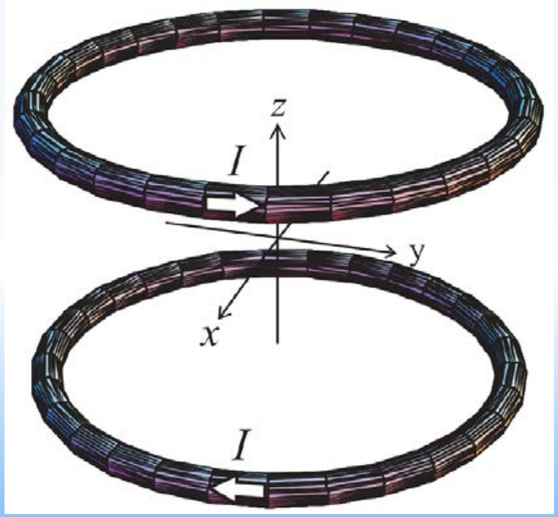
$$U(B) = -\vec{\mu}\cdot\vec{B} = m_F g_F \mu_B \left|\vec{B}\right|$$



$$\frac{d\hat{B}}{dt} \ll \frac{\mu\left|\vec{B}\right|}{\hbar} = \omega_L$$ *adiabatic condition along atomic trajectories*

$m_F g_F > 0$ *low field seeking*

$m_F g_F < 0$ *high field seeking*



$$\vec{B}(x,y,z) = B'\begin{pmatrix}-x\\-y\\2z\end{pmatrix}$$

$$\left|\vec{B}\right| = B'\sqrt{x^2+y^2+4z^2}$$

Magnetic traps

Low-field seekers would need a 3D *minimum* for $\left|\vec{B}(\vec{r})\right|$

High-field seekers would need a 3D *maximum* for $\left|\vec{B}(\vec{r})\right|$

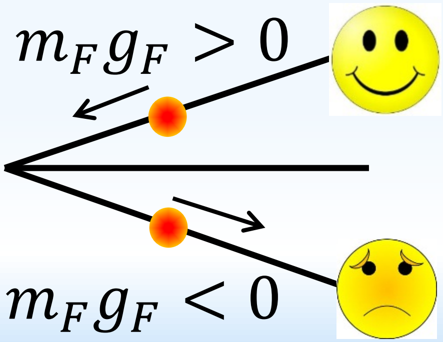
In general, one finds that

$$\vec{\nabla}^2 |\vec{B}| > 0 \text{ , i.e. } \vec{\nabla}^2 B^2 > 0$$

Earnshaw‘s theorem
for magnetic fields

As a consequence, there is *no trap* (in free space) *for high-field seekers*.

Thus:



The absolute ground-state cannot be trapped magnetically.

Solution: optical trapping

Light shift and light forces

So far, we have *neglected* the light shift (or ac Stark effect) on the atoms.

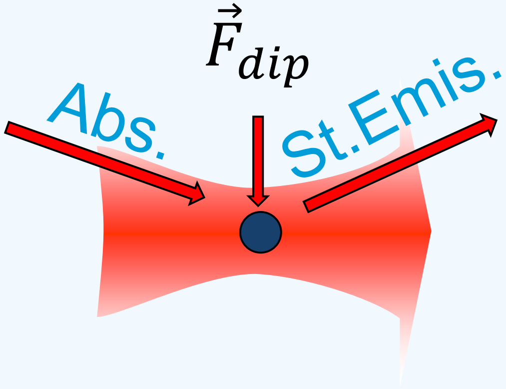
What we have done is introduce the dissipative forces simply *by hand*.

But that is only *half the truth*!

$$\boxed{\vec{F} = \vec{F}_{sc} + \vec{F}_{dip}}$$

$$\boxed{\vec{F}_{dip} = -\hbar\Delta \frac{\nabla S}{S} \rho_e}$$

$$\boxed{\vec{F}_{sc} = \hbar\vec{k}\,\Gamma\,\rho_e}$$



Note: This Force requires a varying intensity.

Not there for plane wave

Light shift and light forces

Let's take a closer look at

$$\boxed{\vec{F}_{dip} = -\hbar\Delta \frac{\nabla S}{S} \rho_e}$$

$$\boxed{\vec{F}_{dip} = -\nabla U_{dip}}$$

with
$$\boxed{U_{dip} = \frac{\hbar\Delta}{2} \ln\left(\frac{1 + S + \left(\frac{2\Delta}{\Gamma}\right)^2}{1 + \left(\frac{2\Delta}{\Gamma}\right)^2} \right)}$$
Conservative force !!!

In the limit $\Delta \gg \Gamma$ we have

$$\boxed{U_{\text{dip}} \propto \frac{I_L}{\Delta}}$$

but for the scattering rate

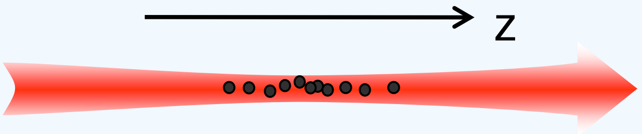
$$\boxed{\Gamma_{\text{scat}} \propto \frac{I_L}{\Delta^2}}$$

Note: U has the sign of Δ

Comment: This is the basis for optical tweezers (Nobel prize 2018)
As well as a *large* fraction of the modern cold atom experiments

Light shift and light forces

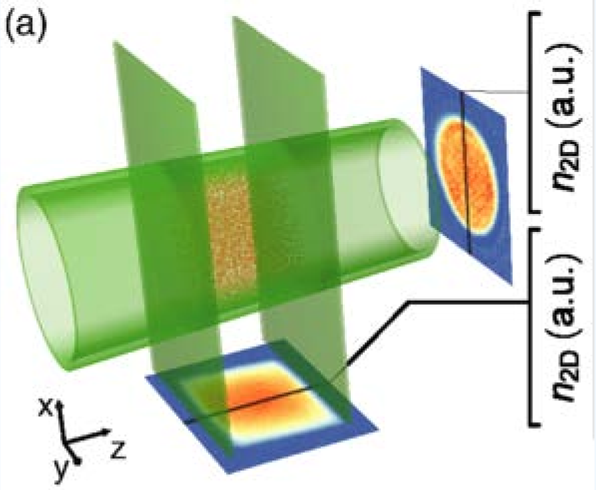
Dipole trap gallery: usually generated by far-off-resonant laser beams



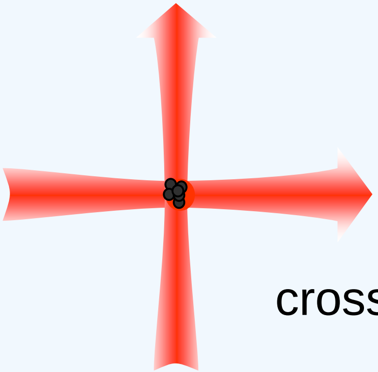
$\omega_x,\omega_y > \omega_z$

focused gaussian beam trap

Blue-detuned optical trap

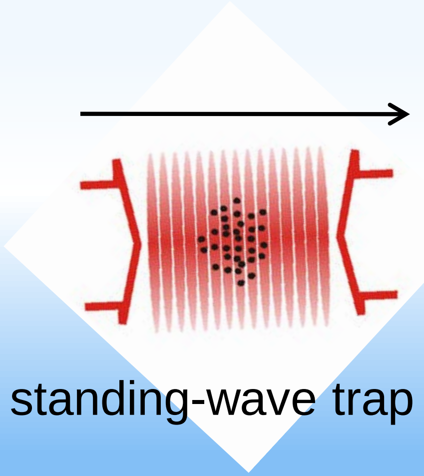


Phys. Rev. Lett. 118, 123401 (2017).



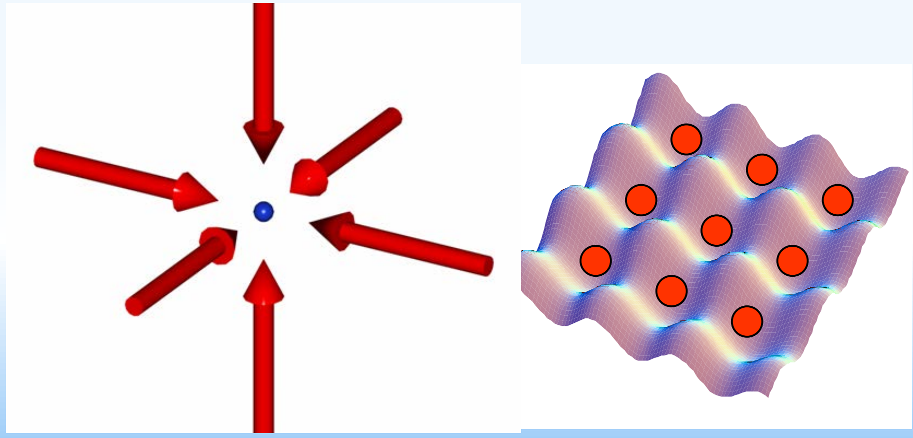
$\omega_y \approx \omega_z \approx \omega_x$

crossed-beam
trap



$\omega_z >> \omega_x$ and ω_y

standing-wave trap (1D lattice)

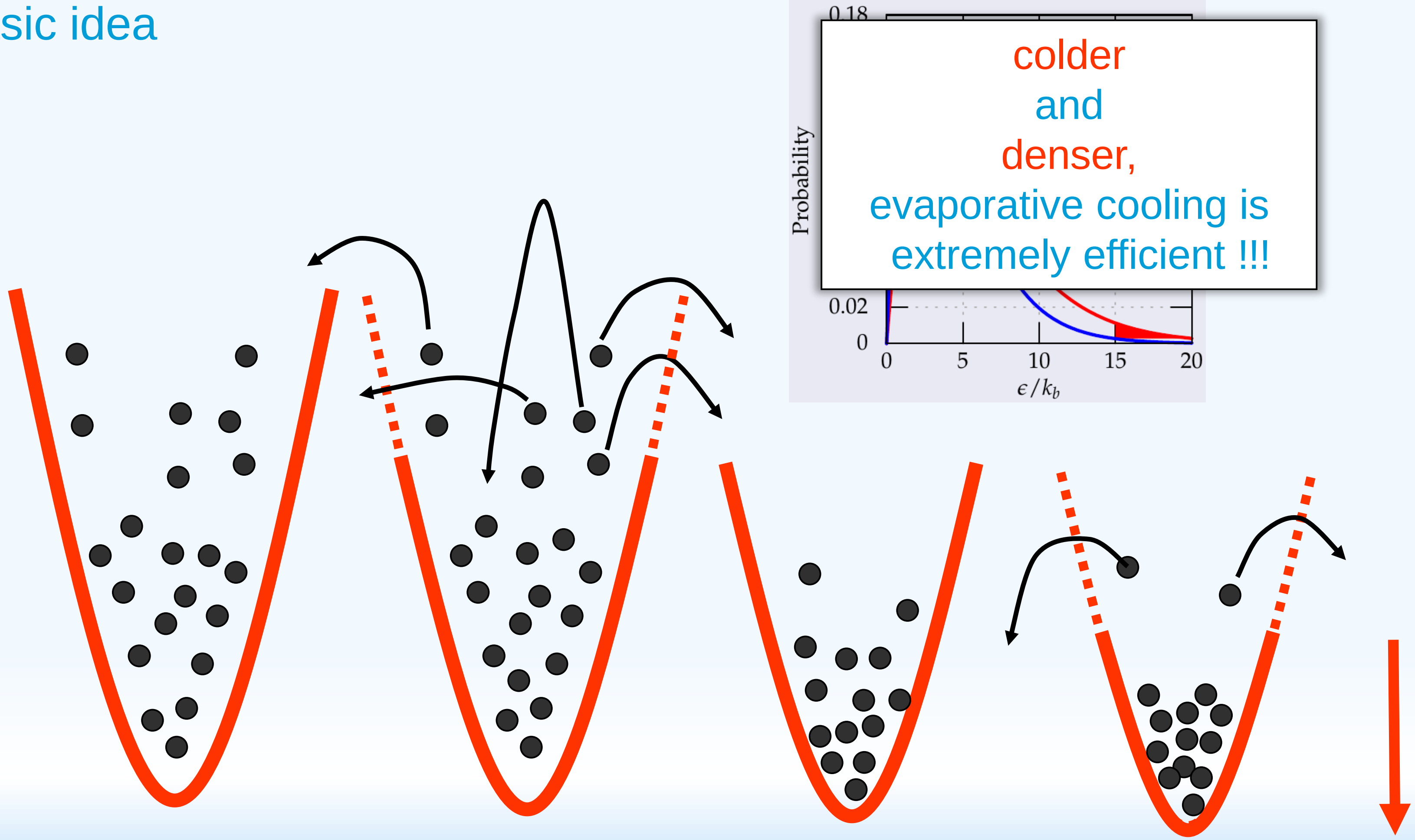


3D optical lattice (here: cubic)

More on optical lattices tomorrow

Evaporative cooling

Basic idea



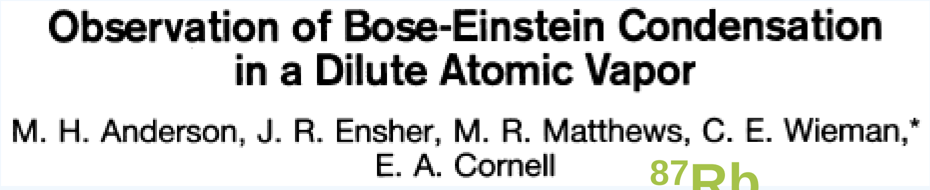
colder
and
denser,
evaporative cooling is
extremely efficient !!!

1/10 to
1/1000
typically

Thermal equilibrium via elastic collisions

More on collisional properties tomorrow

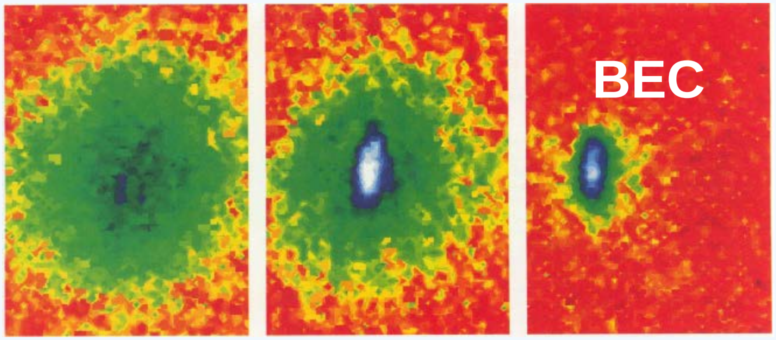
Historical highlights

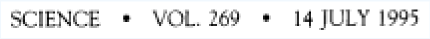


Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman,* E. A. Cornell

^{87}Rb





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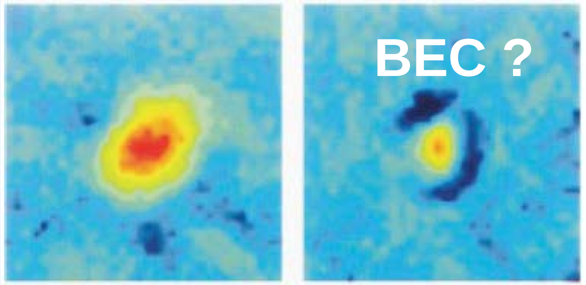
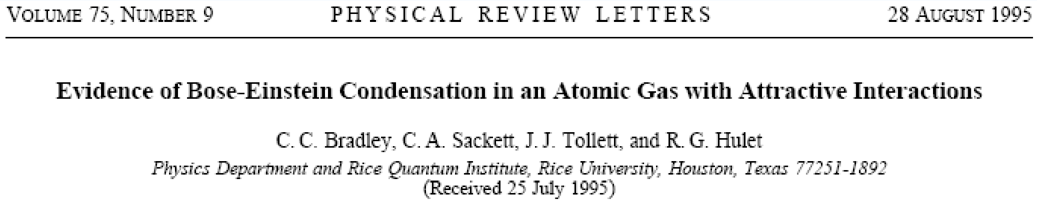
^{7}Li





VOLUME 75, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1995

Evidence of Bose-Einstein Condensation in an Atomic Gas with Attractive Interactions

C. C. Bradley, C. A. Sackett, J. J. Tollett, and R. G. Hulet

Physics Department and Rice Quantum Institute, Rice University, Houston, Texas 77251-1892

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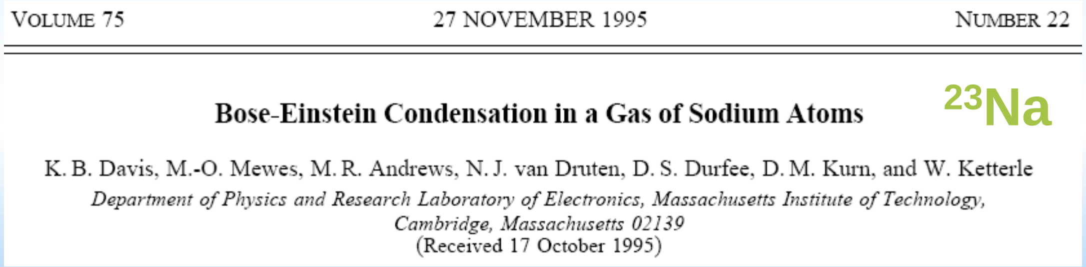
BEC confirmed in 1997



VOLUME 75 27 NOVEMBER 1995 NUMBER 22

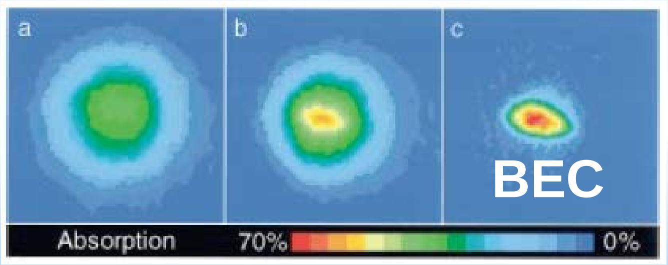
Bose-Einstein Condensation in a Gas of Sodium Atoms

^{23}Na

K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle

Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 17 October 1995)

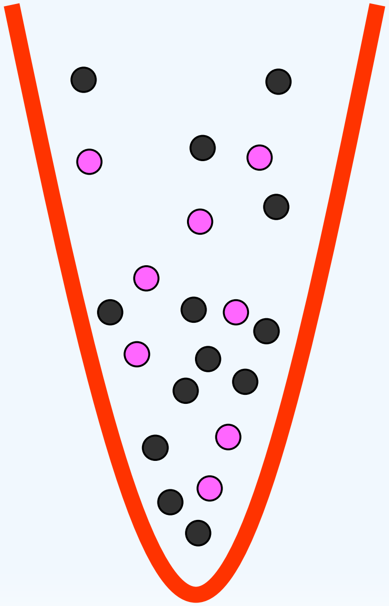


Sympathetic cooling

Evaporation not working due to bad collisional properties:

Example: spin polarized Fermi gas
Solution: Mixture

First degenerate Fermi gas: B. DeMarco, D. S. Jin, Science (1999).

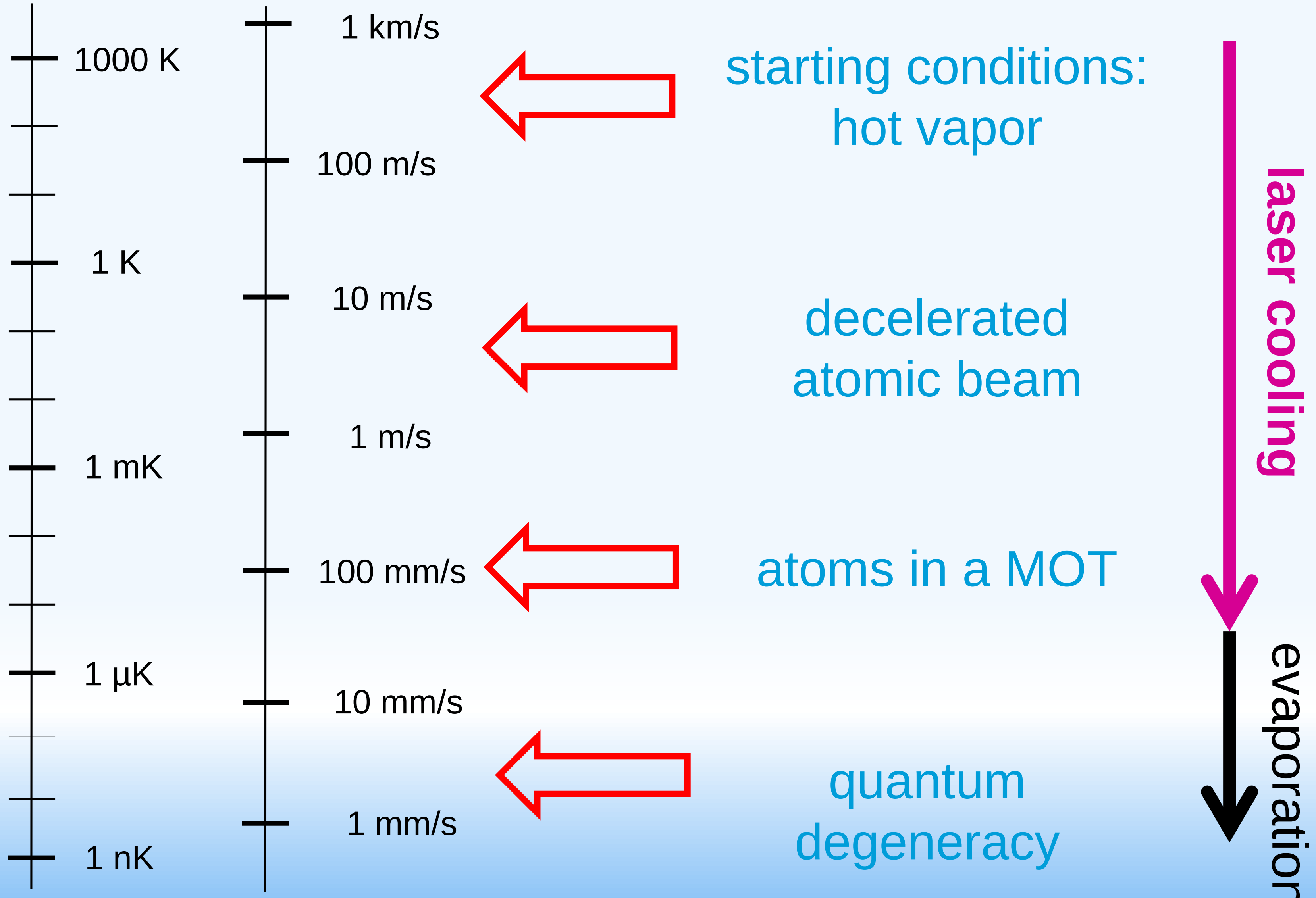


● “Spin up” fermion

● “Spin down” fermion

More on mixtures tomorrow

Conclusions:



1000 K

1 K

1 mK

1 µK

1 nK

1 km/s

100 m/s

10 m/s

1 m/s

100 mm/s

10 mm/s

1 mm/s

starting conditions:
hot vapor

decelerated
atomic beam

atoms in a MOT

quantum
degeneracy

laser cooling

evaporation

More in next lectures and labtours

Thank you

Powered by: R. Grimm, H. C. Nägerl, F. Ferlaino, G. Ferrari

Recent developments

Combination of cooling and trapping

Sub-poissonian loading of single atoms in a microscopic dipole trap

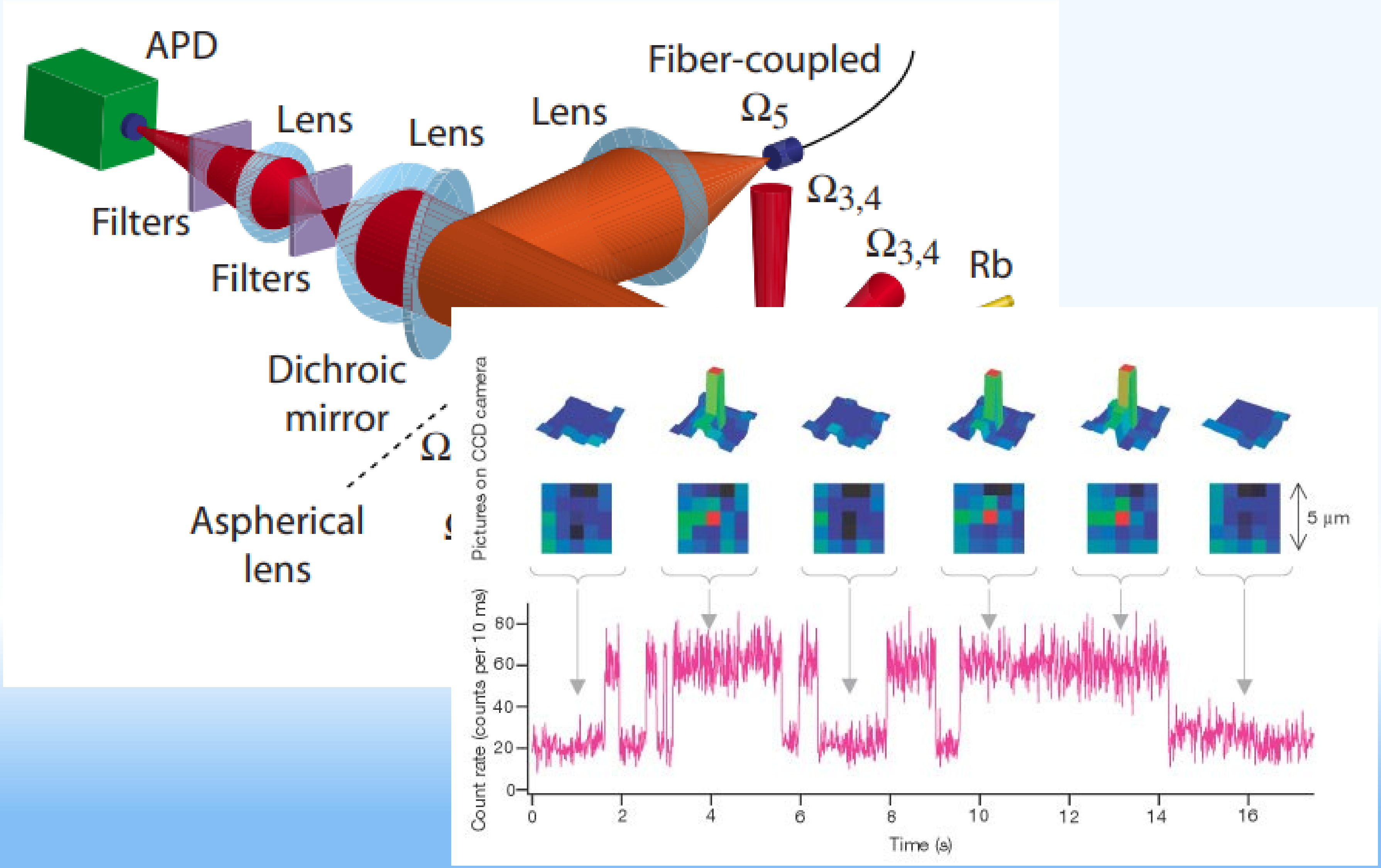
Nicolas Schlosser, Georges Reymond, Igor Protsenko & Philippe Grangier

Laboratoire Charles Fabry de l'Institut d'Optique, UMR 8501 du CNRS, BP 147, F91403 Orsay Cedex, France

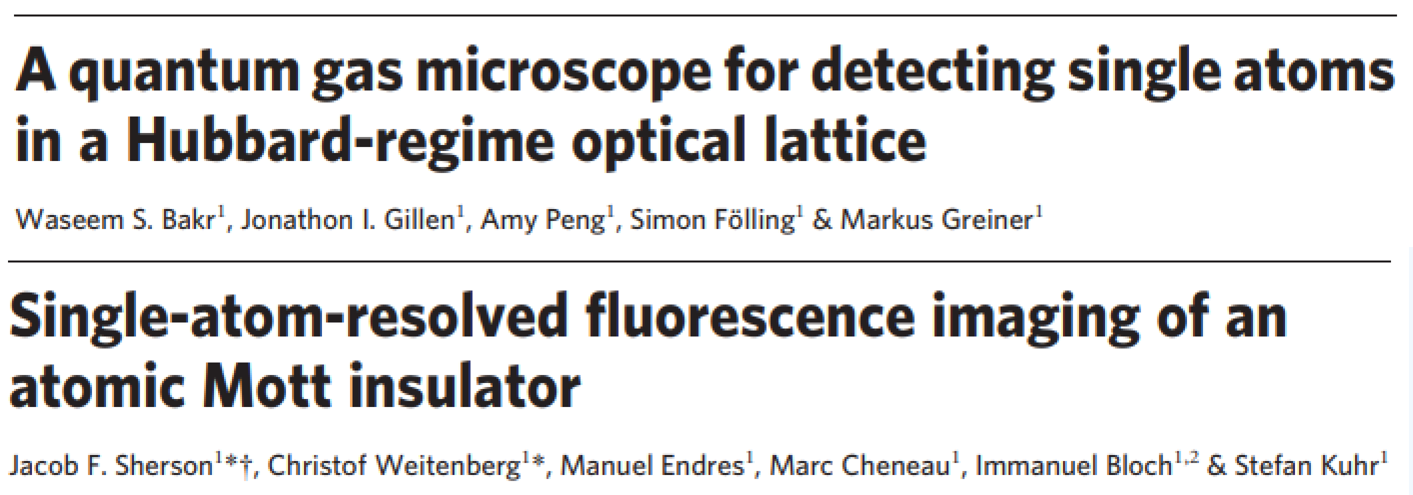
2001 single atom tweezer

Recent developments

Combination of cooling and trapping



Recent developments



A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice

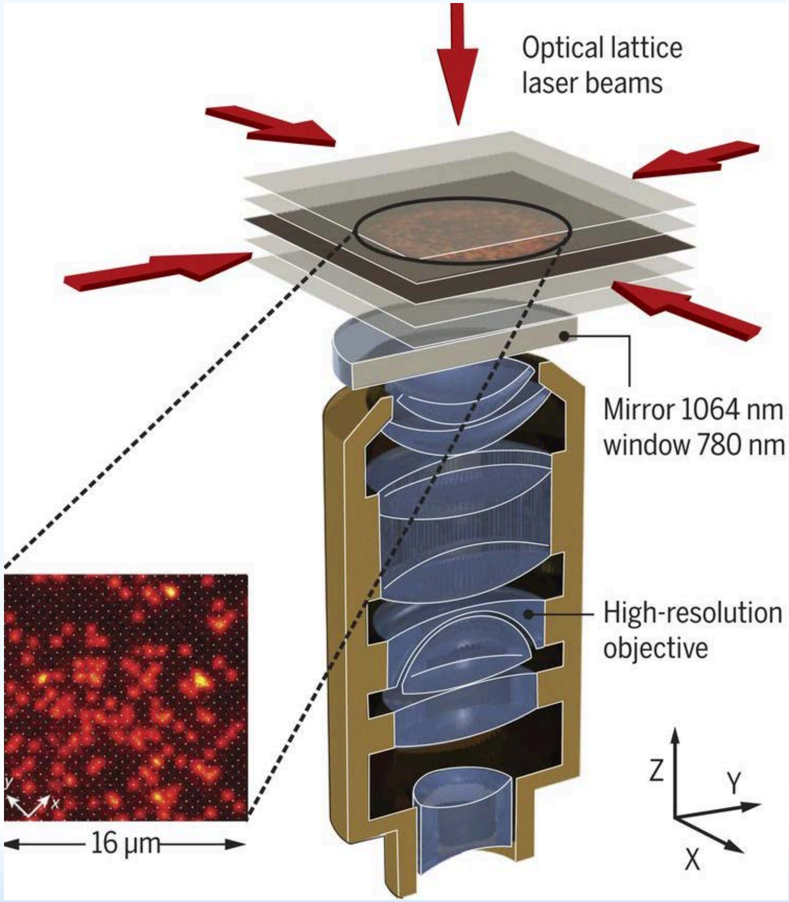
Waseem S. Bakr[1], Jonathon I. Gillen[1], Amy Peng[1], Simon Fölling[1] & Markus Greiner[1]

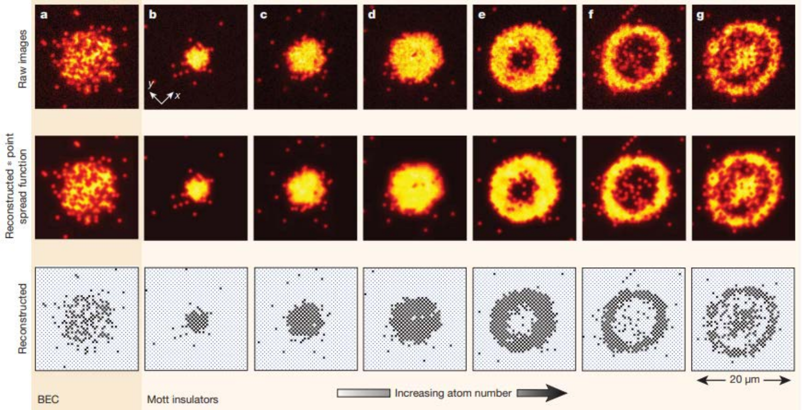
Single-atom-resolved fluorescence imaging of an atomic Mott insulator

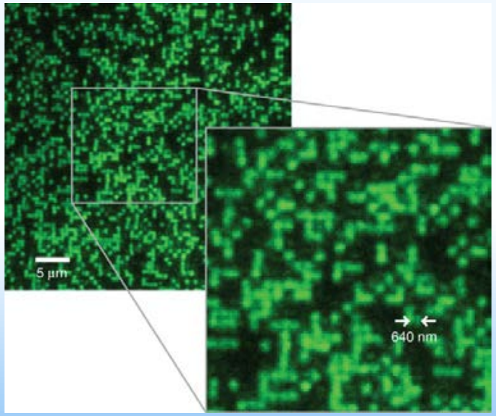
Jacob F. Sherson[1]*†, Christof Weitenberg[1]*, Manuel Endres[1], Marc Cheneau[1], Immanuel Bloch[1,2] & Stefan Kuhr[1]

2009-2010 quantum gas microscope

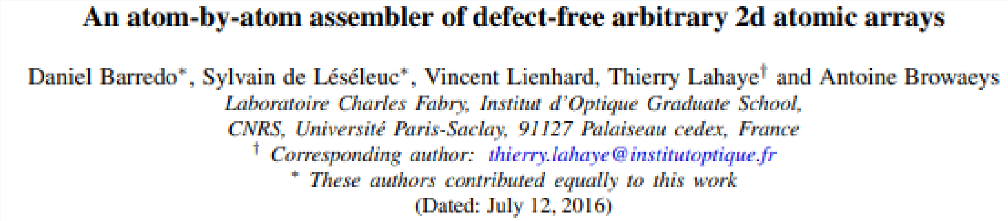
Recent developments







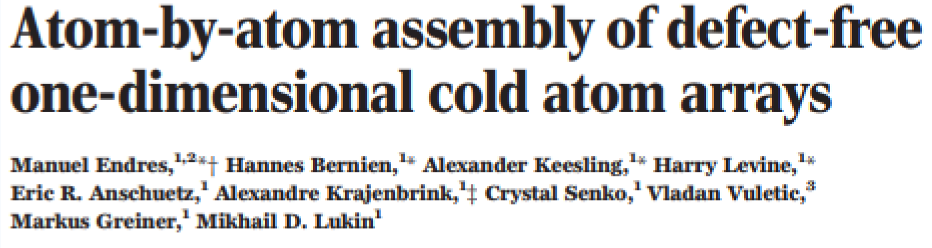
Recent developments



An atom-by-atom assembler of defect-free arbitrary 2d atomic arrays

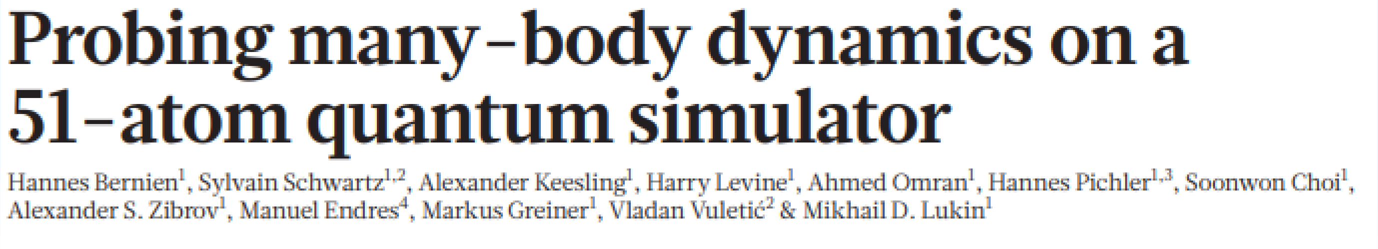
Daniel Barredo*, Sylvain de Léséleuc*, Vincent Lienhard, Thierry Lahaye† and Antoine Browaeys
Laboratoire Charles Fabry, Institut d'Optique Graduate School,
CNRS, Université Paris-Saclay, 91127 Palaiseau cedex, France
† *Corresponding author: thierry.lahaye@institutoptique.fr*
* *These authors contributed equally to this work*
(Dated: July 12, 2016)

2016 tweezer arrays



Atom-by-atom assembly of defect-free one-dimensional cold atom arrays

**Manuel Endres,[1,2]*† Hannes Bernien,[1]* Alexander Keesling,[1]* Harry Levine,[1]*
Eric R. Anschuetz,[1] Alexandre Krajenbrink,[1]‡ Crystal Senko,[1] Vladan Vuletic,[3]
Markus Greiner,[1] Mikhail D. Lukin[1]**

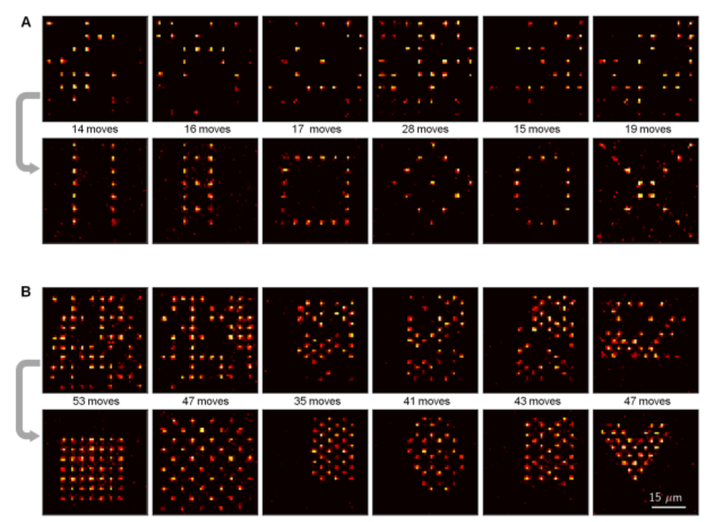


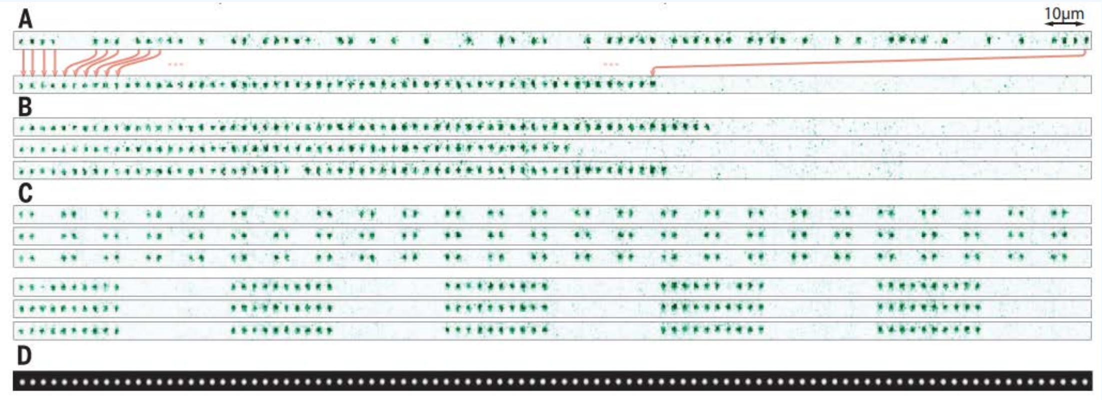
Probing many-body dynamics on a 51-atom quantum simulator

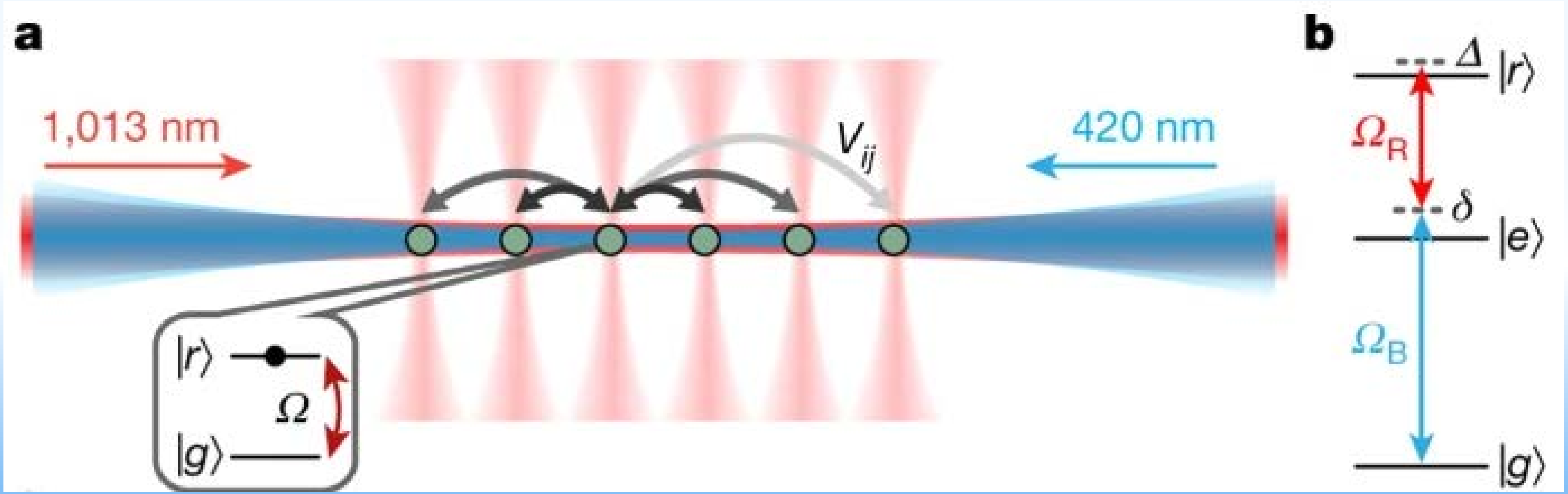
Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

2017 tweezer-based Q-simulator

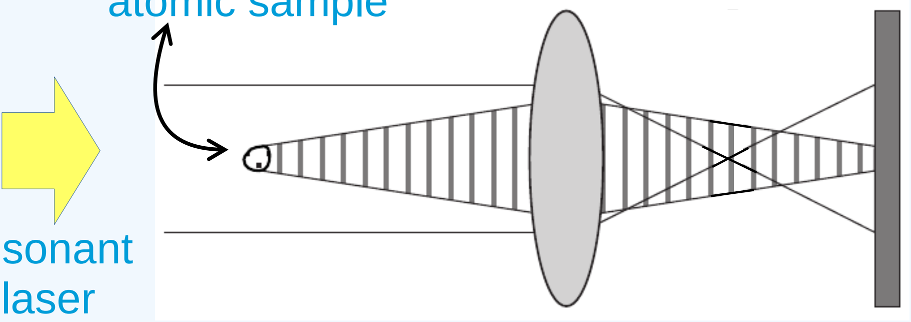
Recent developments







Imaging cold atomic gases

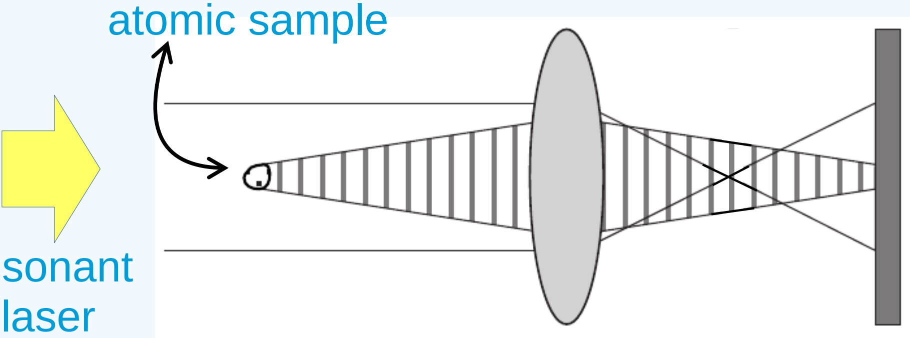


atomic sample

camera screen

resonant
laser

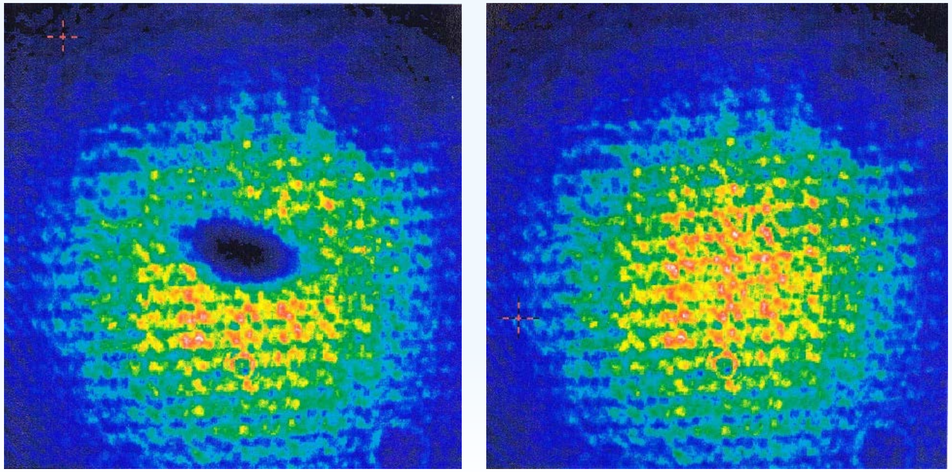
Imaging cold atomic gases

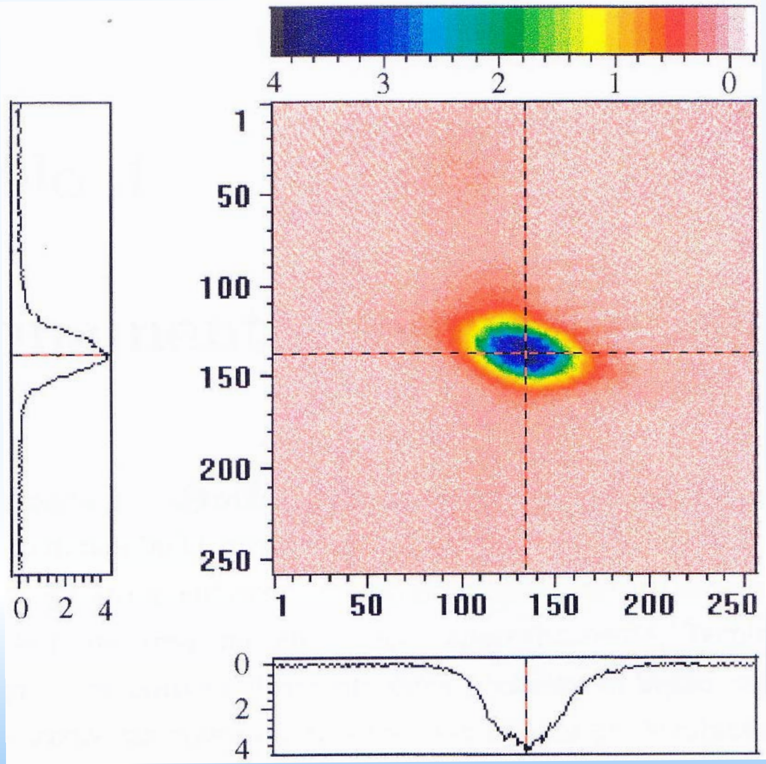


atomic sample

camera screen

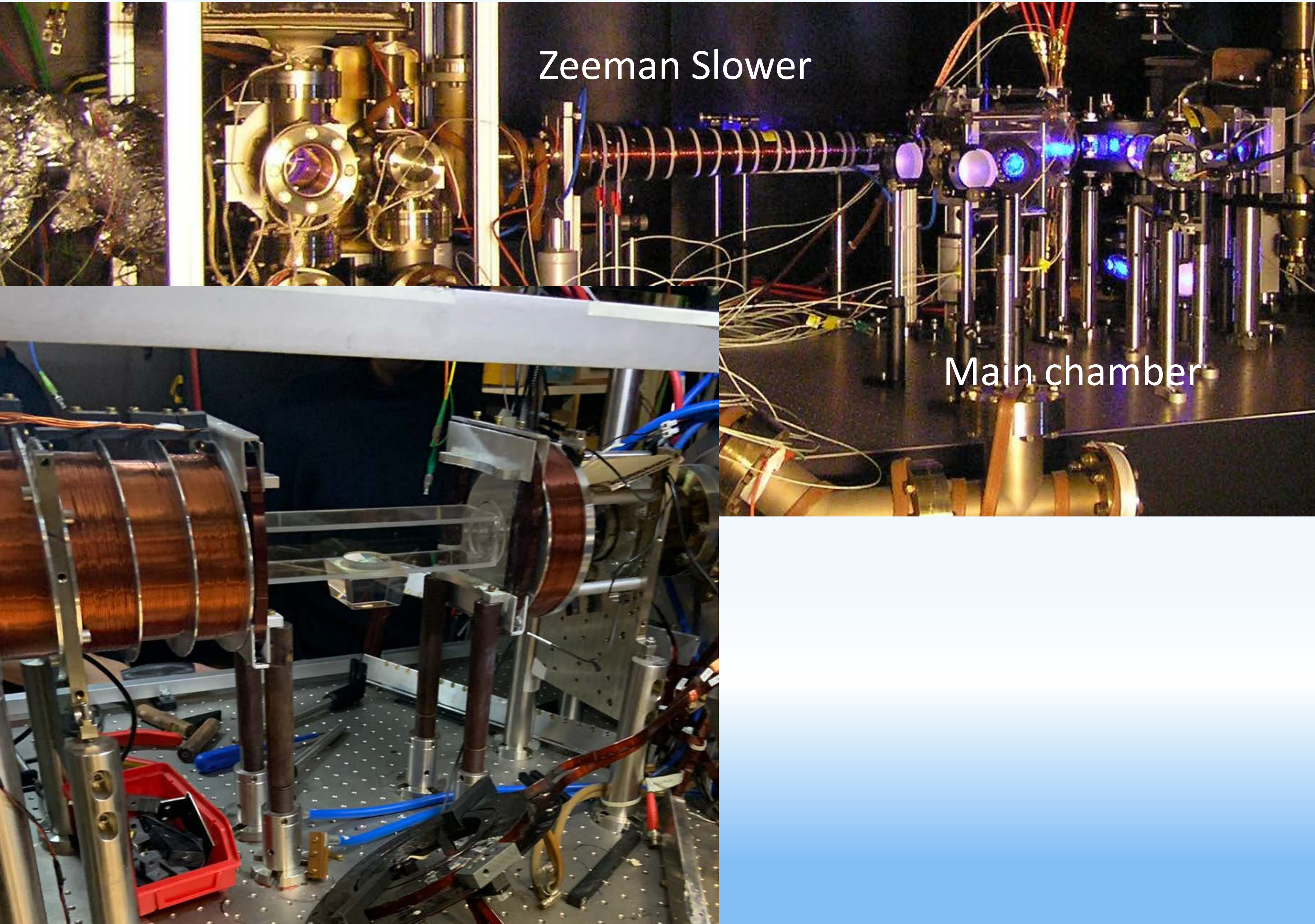
resonant laser





$$E = tE_0 e^{i\phi}$$

$$t = e^{-\tilde{D}/2} = \exp\left(-\frac{\tilde{n}\sigma_0}{2}\frac{1}{1+\delta^2}\right)$$


Zeeman Slower
Main chamber

Collisional blockade regime

$$\frac{dN}{dt} = R - \gamma N - \beta' N(N-1)$$

β' is larger for smaller trap volume

Low R: $N_{ss} \approx \frac{R}{\gamma}$

High R: $N_{ss} \approx \sqrt{\frac{R}{\beta'}}$

Crossover regime: $N_c \approx \frac{\gamma}{\beta'}$ $R_c \approx \frac{\gamma^2}{\beta'}$

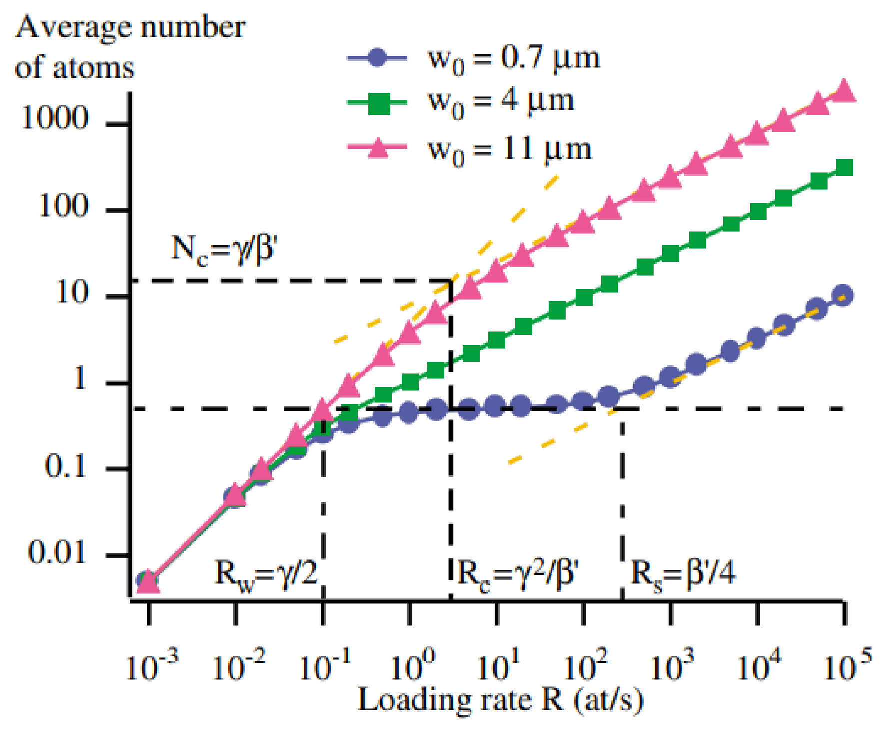
Collisional blockade regime

$N_c \gg 1$

Typical situation,
Change of slope

$N_c \ll 1$

Not physically acceptable:
collisions would play a role for N<1



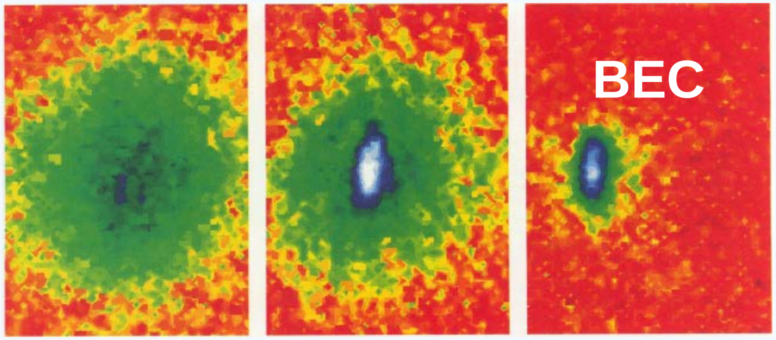
Schlosser et al. PRL **89**, 023005

Cooling & Trapping: historical highlights

Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman,*
E. A. Cornell

^{87}Rb



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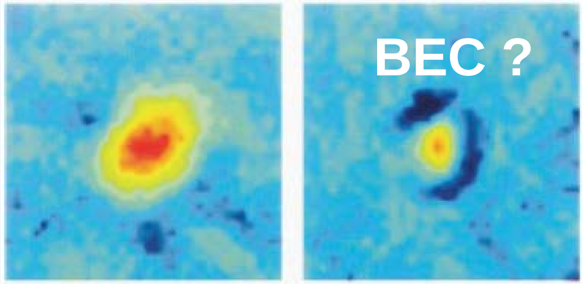
^{7}Li



VOLUME 75, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1995

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VOLUME 75 27 NOVEMBER 1995 NUMBER 22

Bose-Einstein Condensation in a Gas of Sodium Atoms

^{23}Na

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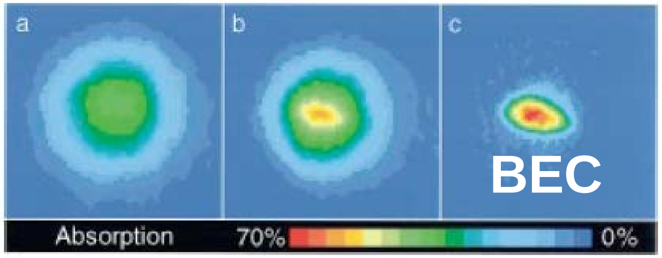
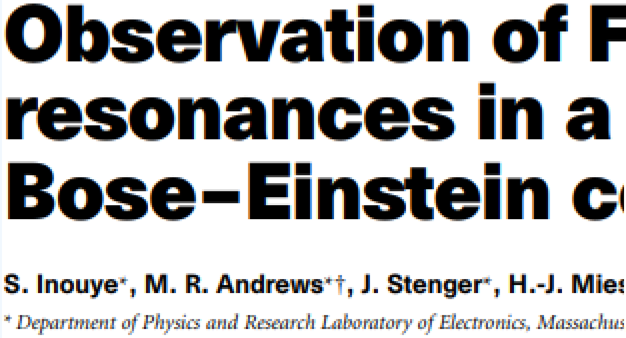


Feshbach resonances

Evaporation not working due to bad collisional properties:

Example: certain bosonic species, like Cs
Solution: Feshbach resonances

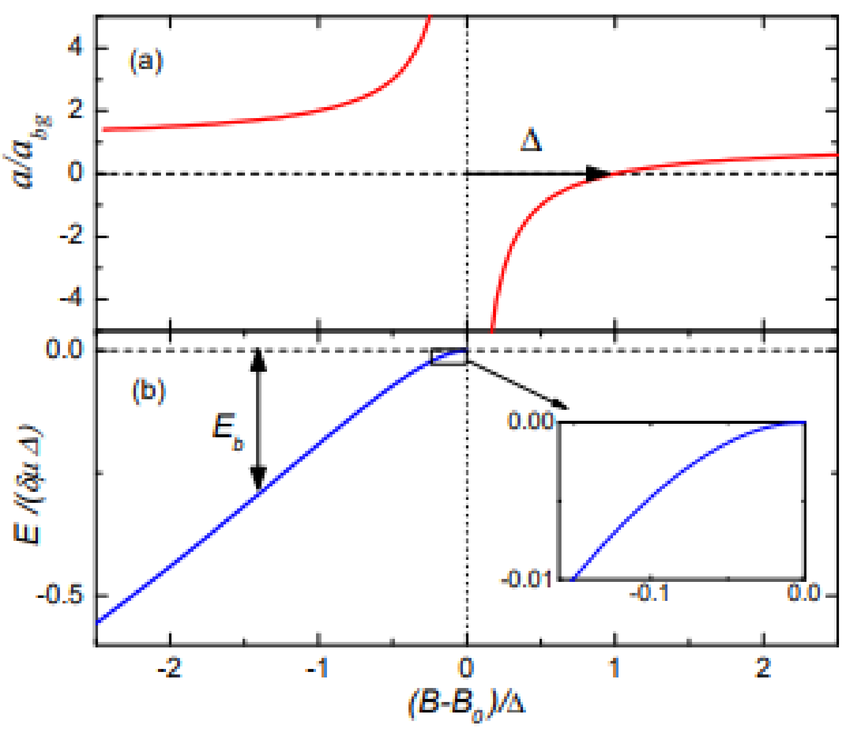


Observation of Feshbach resonances in a Bose–Einstein c

S. Inouye*, M. R. Andrews*†, J. Stenger*, H.-J. Mies

** Department of Physics and Research Laboratory of Electronics, Massachus*

1998 interaction tuning

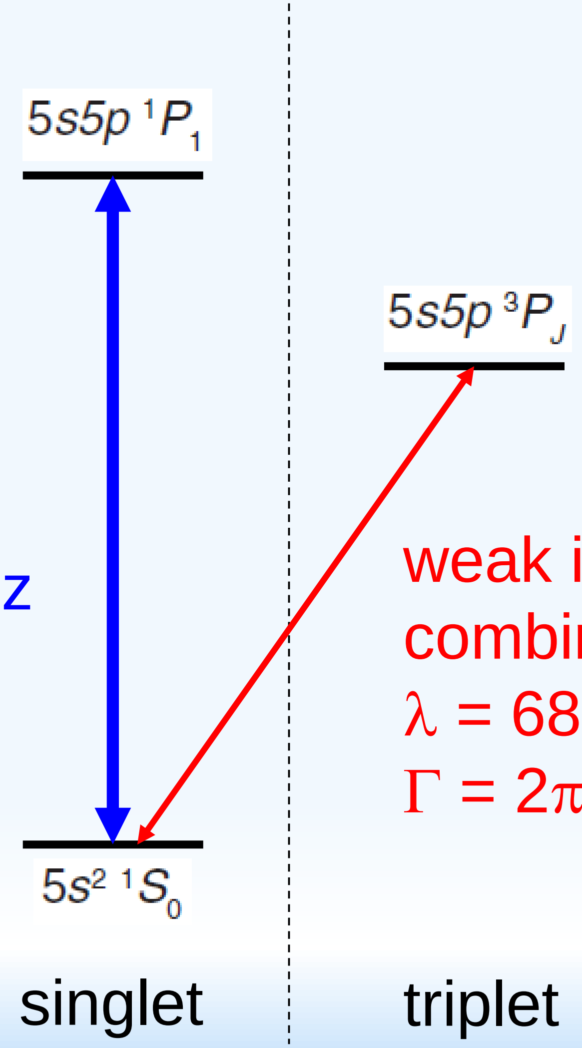


More on this tomorrow

strontium cooling transitions

$a_{max} = 1.0 \times 10^6$ m/s^2

T_D = 770 µK



strong line
λ = 461nm
$\Gamma = 2\pi \times 32$ MHz

a_{max} = 160 m/s^2

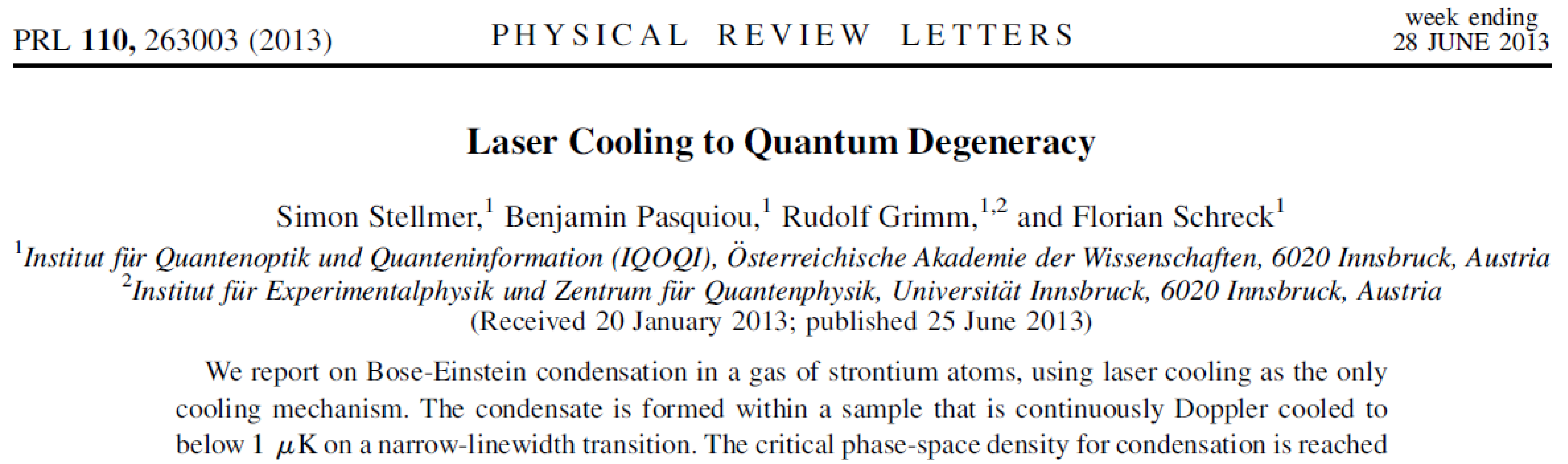
T_D = 180 nK

(T_R = 230 nK)

weak inter-combination line
λ = 689nm
$\Gamma = 2\pi \times 7.4$ kHz

atomic beam slowing
and MOT precooling (mK) ⇨ deep Doppler cooling (µK)

BEC by laser cooling !



PRL **110,** 263003 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Laser Cooling to Quantum Degeneracy

Simon Stellmer,[1] Benjamin Pasquiou,[1] Rudolf Grimm,[1,2] and Florian Schreck[1]

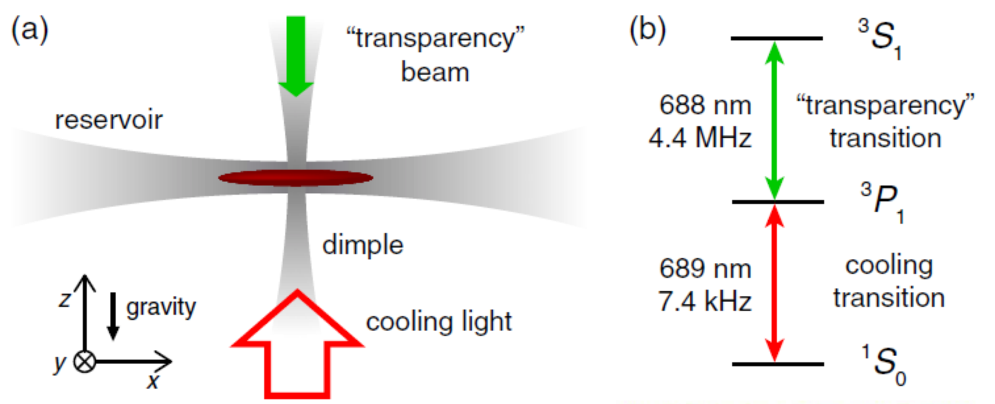
[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*

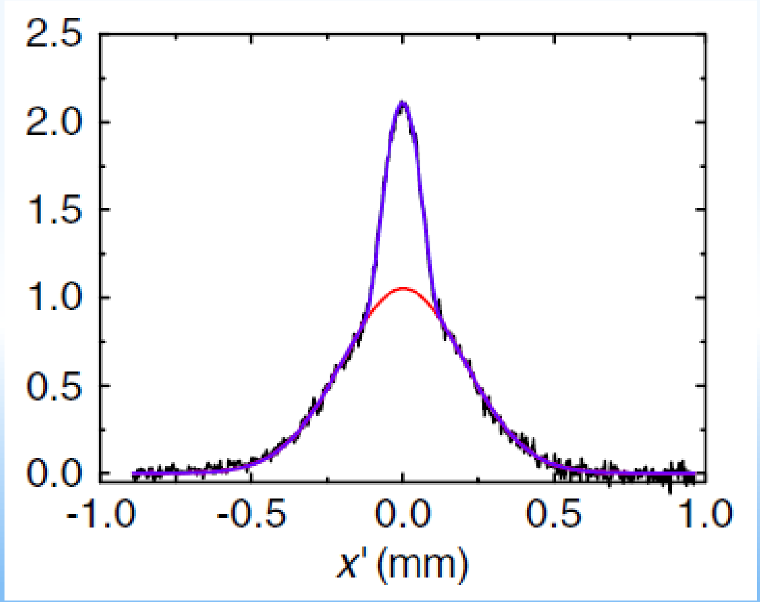
[2]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

(Received 20 January 2013; published 25 June 2013)

We report on Bose-Einstein condensation in a gas of strontium atoms, using laser cooling as the only cooling mechanism. The condensate is formed within a sample that is continuously Doppler cooled to below 1 μK on a narrow-linewidth transition. The critical phase-space density for condensation is reached

experiments continued in the Schreck group in Amsterdam





Cooling and trapping

-Laser cooling

-Magnetic trapping

-Optical trapping

-Evaporation

Cooling and trapping

-Laser cooling

-Magnetic trapping

-Optical trapping

-Evaporation

Interaction engineering

-Feshbach resonances

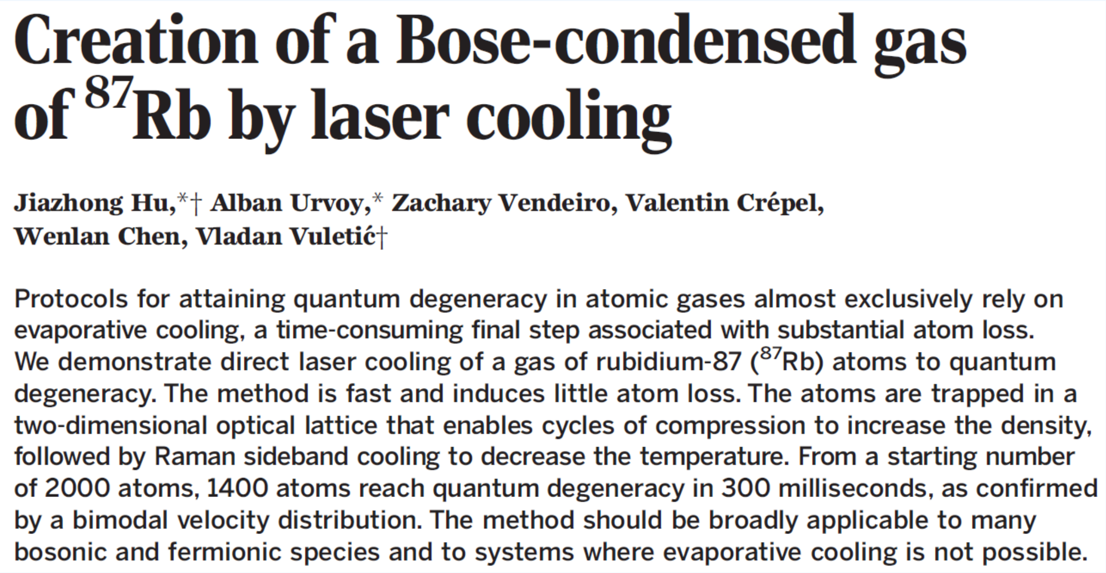
-Dipolar gases

-Polar molecules

-Rydberg gases

-Coupling to photonic structures

BEC by laser cooling !

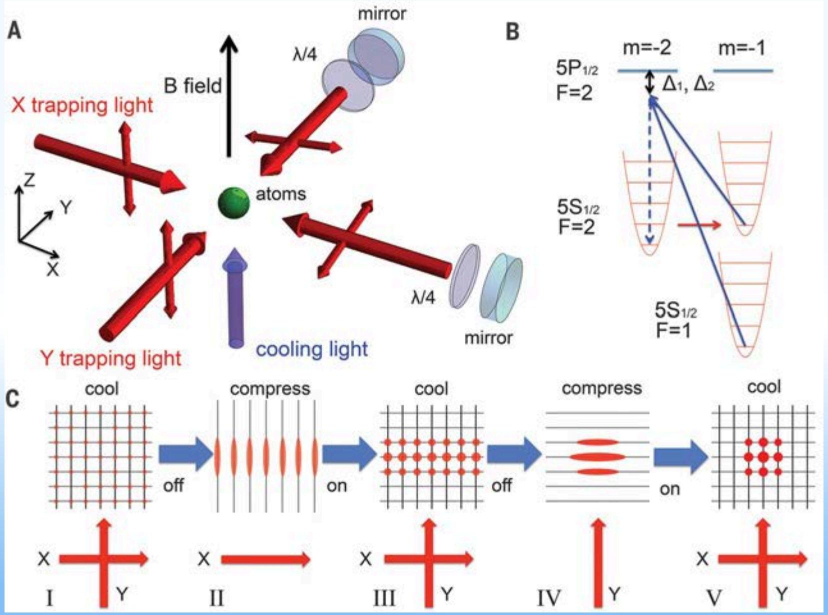


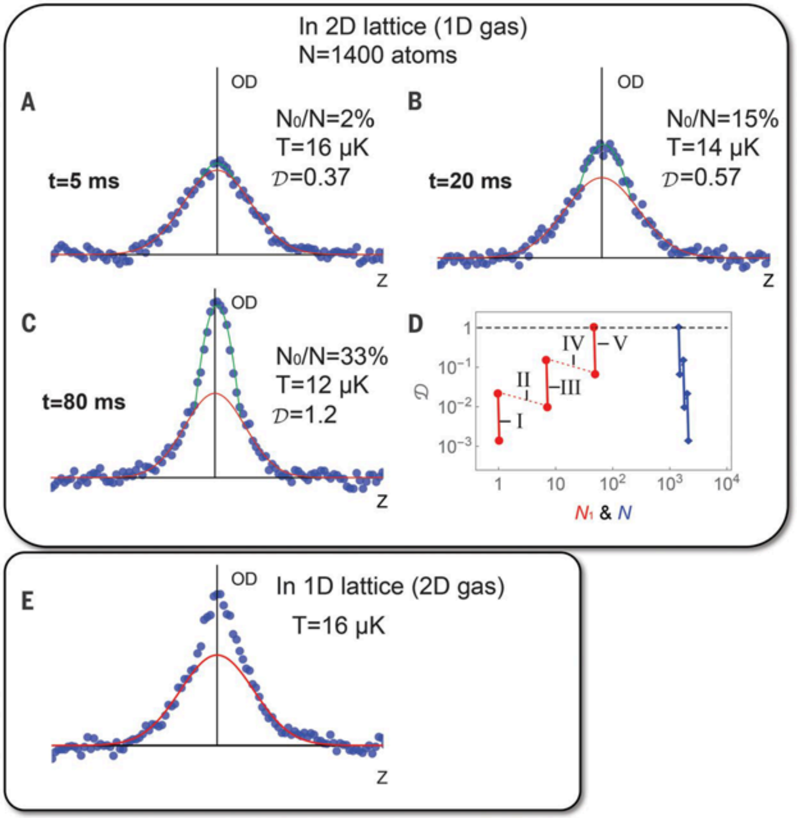
Creation of a Bose-condensed gas of ^{87}Rb by laser cooling

Jiazhong Hu,*† Alban Urvoy,* Zachary Vendeiro, Valentin Crépel,
Wenlan Chen, Vladan Vuletić†

Protocols for attaining quantum degeneracy in atomic gases almost exclusively rely on evaporative cooling, a time-consuming final step associated with substantial atom loss. We demonstrate direct laser cooling of a gas of rubidium-87 (^{87}Rb) atoms to quantum degeneracy. The method is fast and induces little atom loss. The atoms are trapped in a two-dimensional optical lattice that enables cycles of compression to increase the density, followed by Raman sideband cooling to decrease the temperature. From a starting number of 2000 atoms, 1400 atoms reach quantum degeneracy in 300 milliseconds, as confirmed by a bimodal velocity distribution. The method should be broadly applicable to many bosonic and fermionic species and to systems where evaporative cooling is not possible.

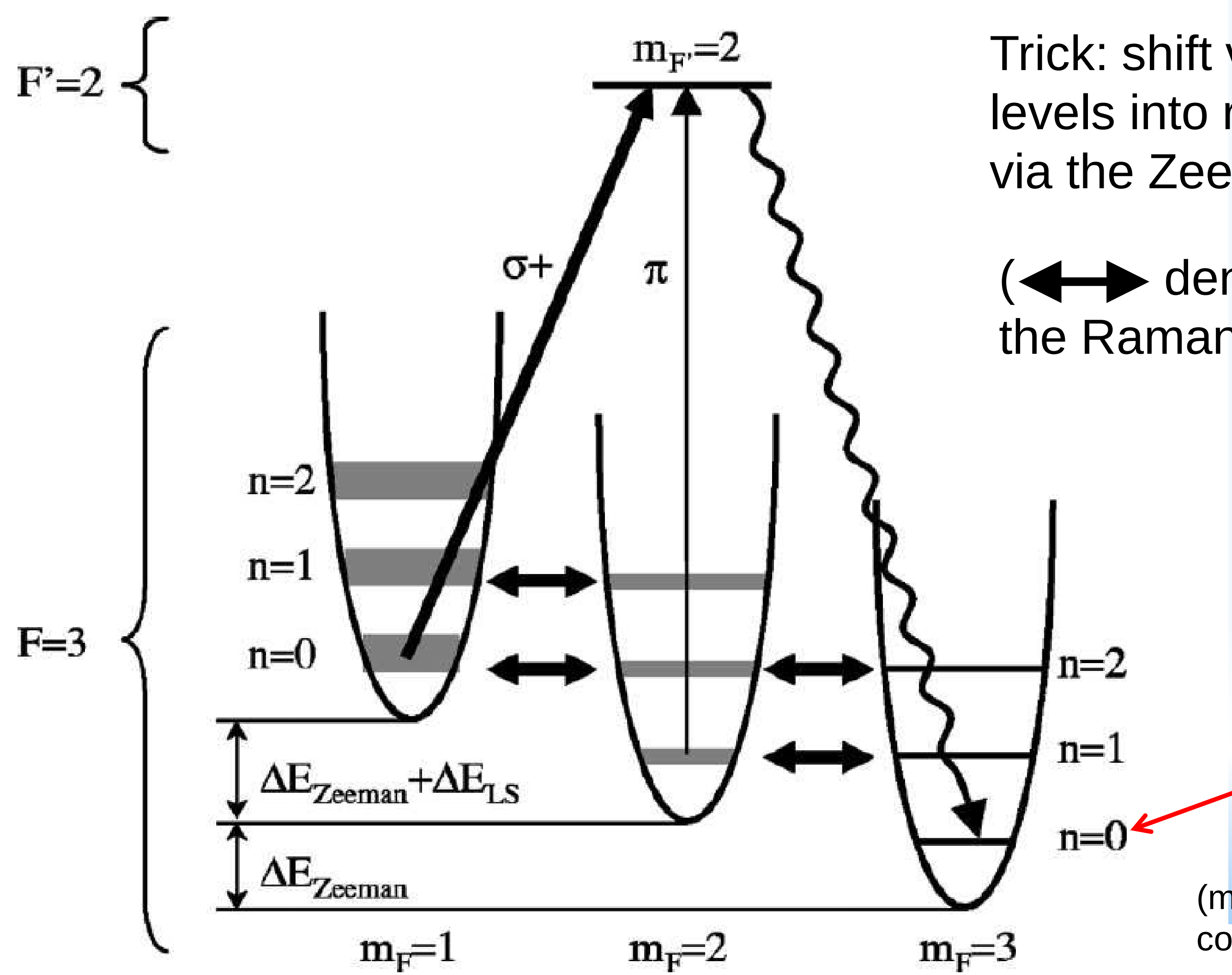
Hu et al., Science 358, 1078–1080 (2017).
With Cs in arXiv:1906.05334 (2019).





Cooling & Trapping: Raman sideband cooling

Raman sideband cooling (RSC) on (neutral) Cs in a lattice



Trick: shift vibrational levels into resonance via the Zeeman effect

(↔ denotes the Raman transition)

dark state!

(makes this type of cooling very robust)

First demonstration in 1989 (ions-1D). Group of D. Wineland, NIST Boulder, Nobel Prize 2012.

for atoms: S. E. Hamann, et al. Phys. Rev. Lett. 80, 4149–4152 (1998).

Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman,
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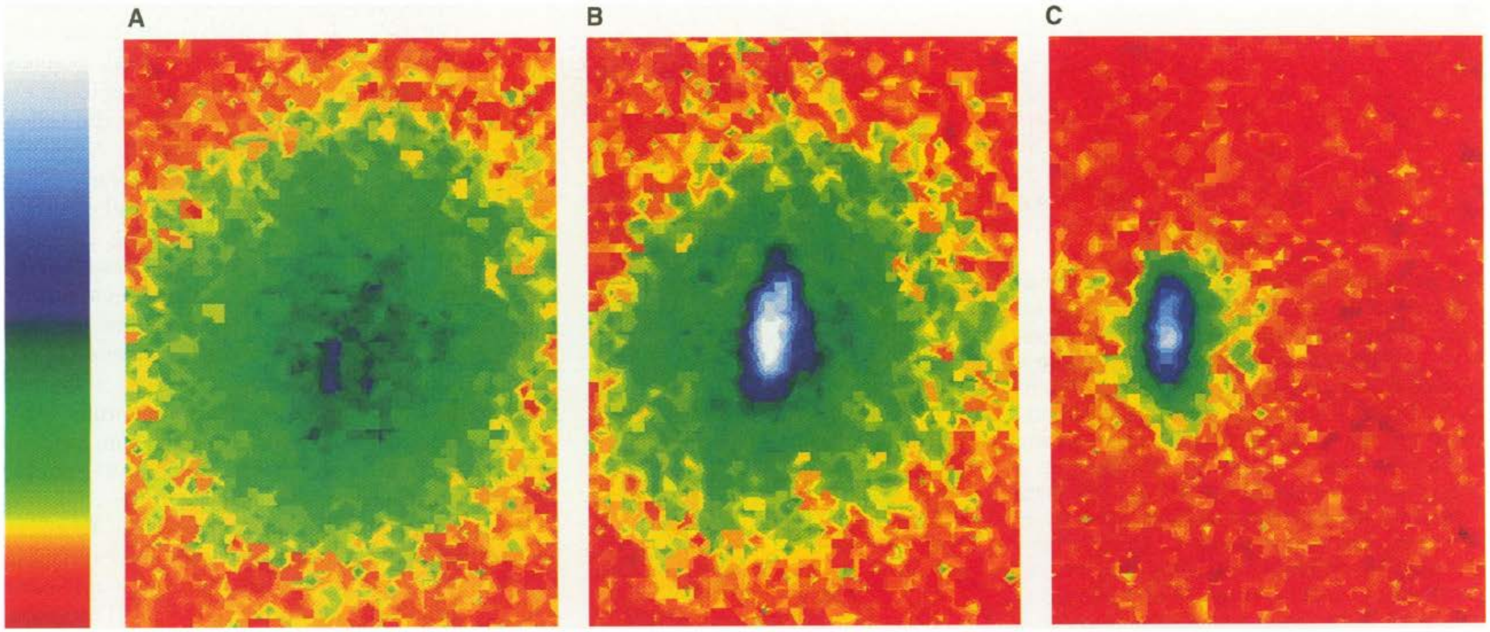

Fig. 2. False-color images display the velocity distribution of the cloud (**A**) just before the appearance of the condensate, (**B**) just after the appearance of the condensate, and (**C**) after further evaporation has left a sample of nearly pure condensate. The circular pattern of the noncondensate fraction (mostly yellow and green) is an indication that the velocity distribution is isotropic, consistent with thermal equilibrium. The condensate fraction (mostly blue and white) is elliptical, indicative that it is a highly nonthermal distribution. The elliptical pattern is in fact an image of a single, macroscopically occupied quantum wave function. The field of view of each image is 200 μm by 270 μm. The observed horizontal width of the condensate is broadened by the experimental resolution.

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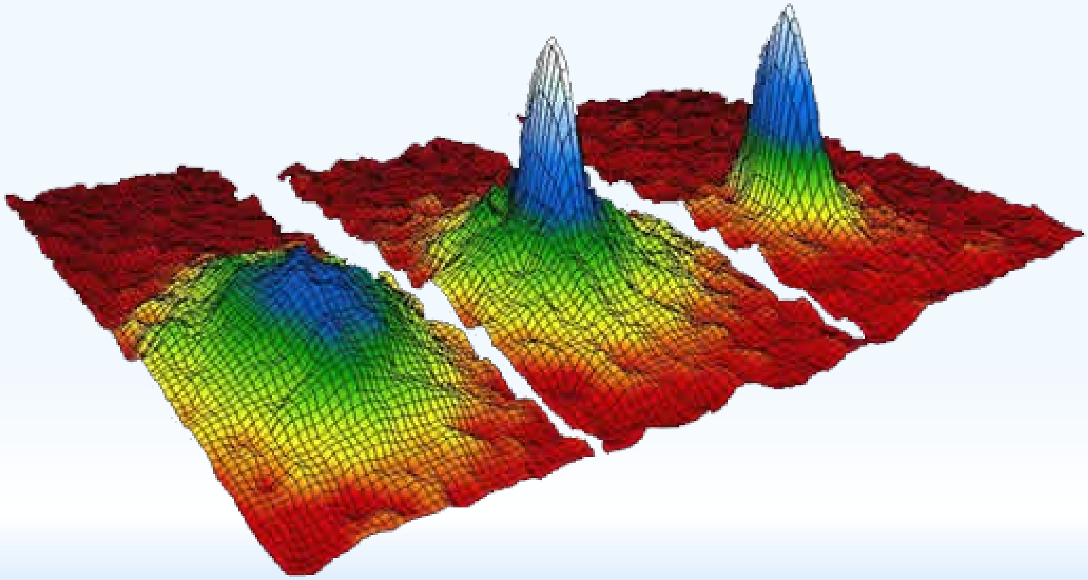

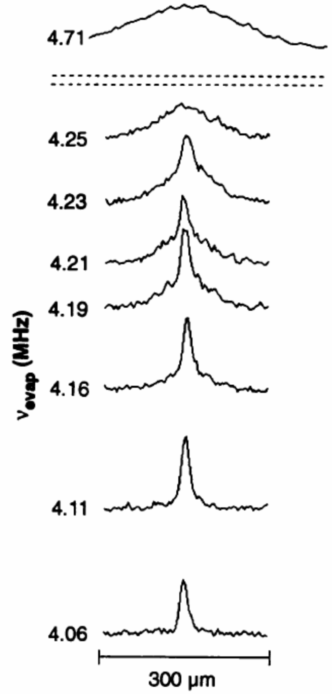

Fig. 4. Horizontal sections taken through the velocity distribution at progressively lower values of ν_{evap} show the appearance of the condensate fraction.

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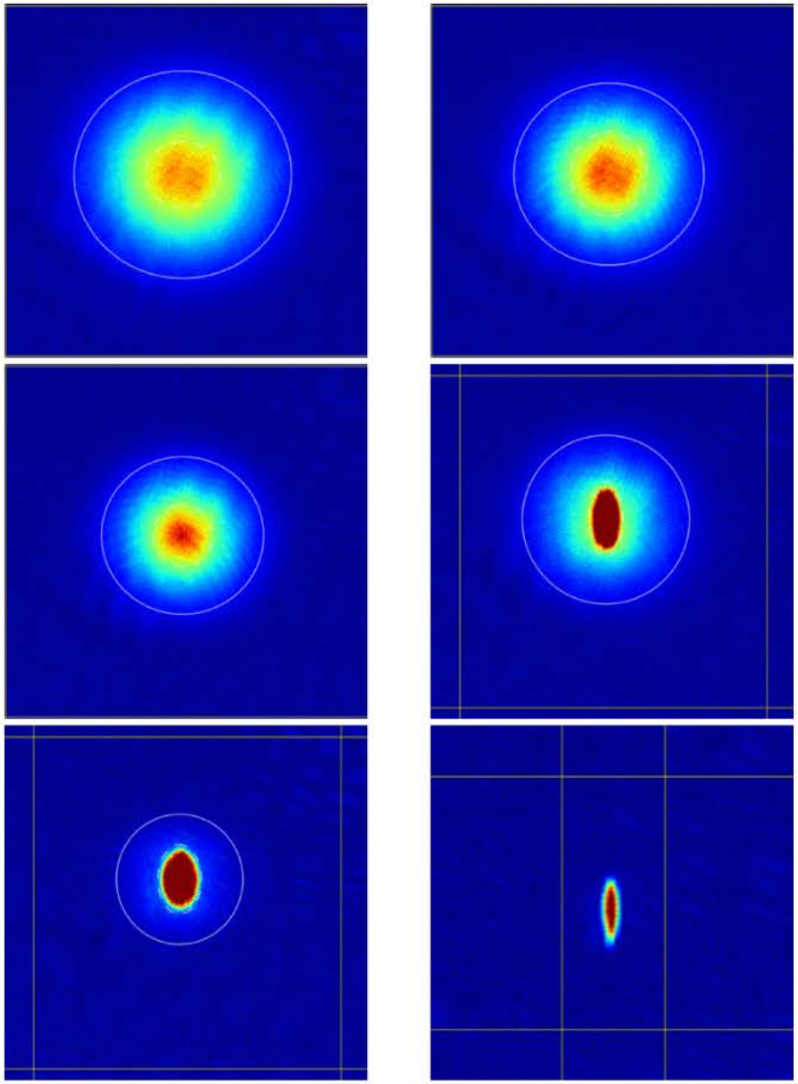


(a)
$T = 1.1(1)\,\mu\text{K}$
$N_{tot} = 2.5(2) \times 10^7$
$N_{bec} = 0$

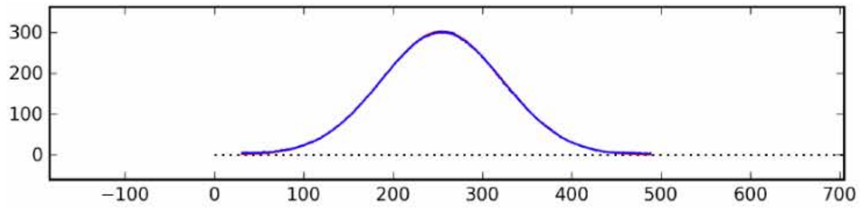
(b)
$T = 0.87(6)\,\mu\text{K}$
$N_{tot} = 2.0(1) \times 10^7$
$N_{bec} = 0$

(c)
$T = 0.65(7)\,\mu\text{K}$
$N_{tot} = 1.7(1) \times 10^7$
$N_{bec} = 0$

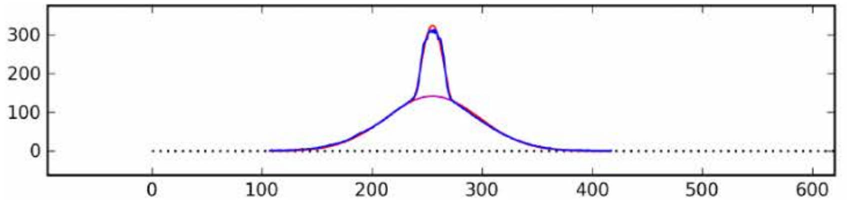
(d)
$T = 0.47(5)\,\mu\text{K}$
$N_{tot} = 1.1(5) \times 10^7$
$N_{bec} = 3.7(2) \times 10^6$

(e)
$T = 0.29(5)\,\mu\text{K}$
$N_{tot} = 7.0(2) \times 10^6$
$N_{bec} = 5.3(1) \times 10^6$

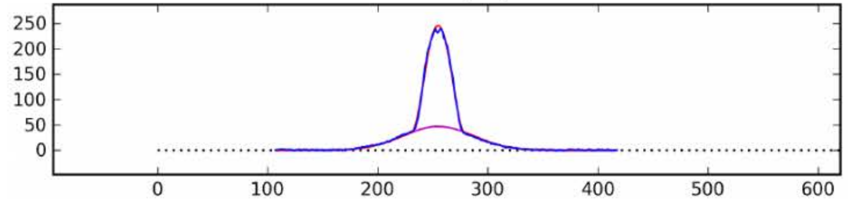
(f)
$T < 200\,\text{nK}$
$N_{tot} = 4.0(3) \times 10^6$
$N_{bec} = 4.0(3) \times 10^6$



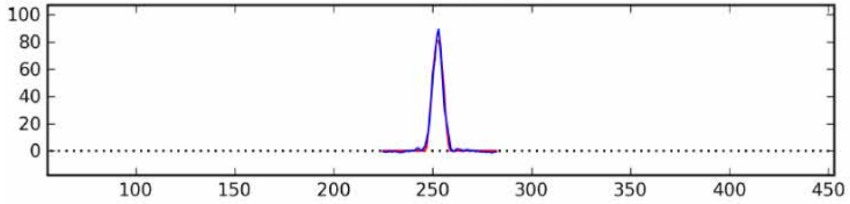
$T = 1.1(1)\,\mu\text{K}$



$T = 0.47(5)\,\mu\text{K}$



$T = 0.29(5)\,\mu\text{K}$

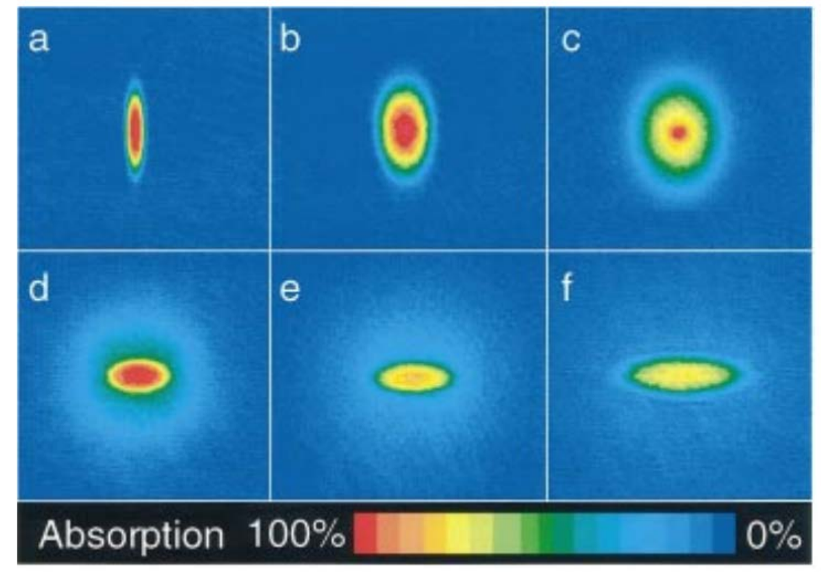


$T < 200\,\text{nK}$

VOLUME 77, NUMBER 3 416 PHYSICAL REVIEW LETTERS 15 JULY 1996

Bose-Einstein Condensation in a Tightly Confining dc Magnetic Trap

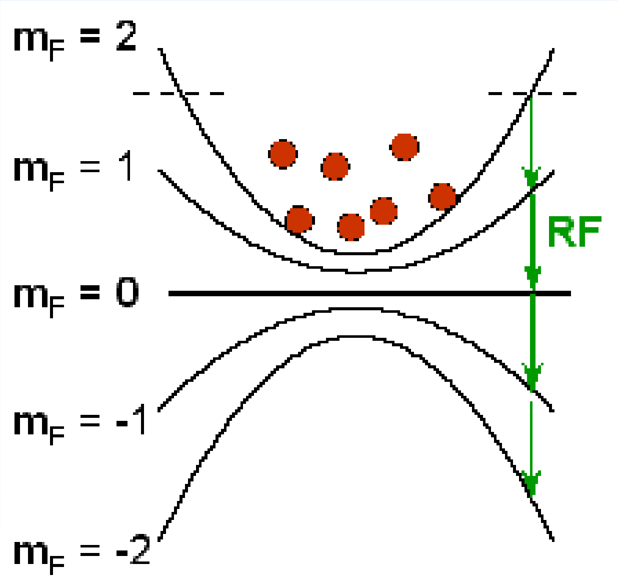
M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. M. Kurn, D. S. Durfee, and W. Ketterle



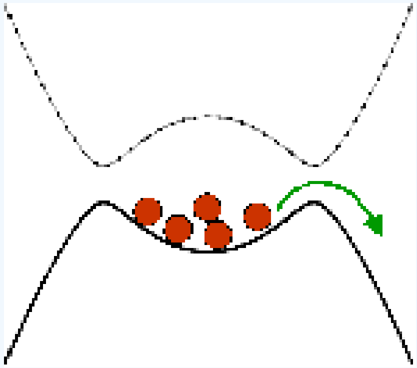
See also the theory of hydrodynamic expansion of BECs:
Y. Castin, R. Dum, PRL 77, 5315 (1996)

Evaporation in magnetic traps

- Spin-flip transitions induced by radiofrequency fields
- Frequency of the RF sets the threshold for evaporation
- Curvature of the confining potential is unaffected when reducing the trap depth



Unperturbed levels



Dressed levels

Evaporation in magnetic traps

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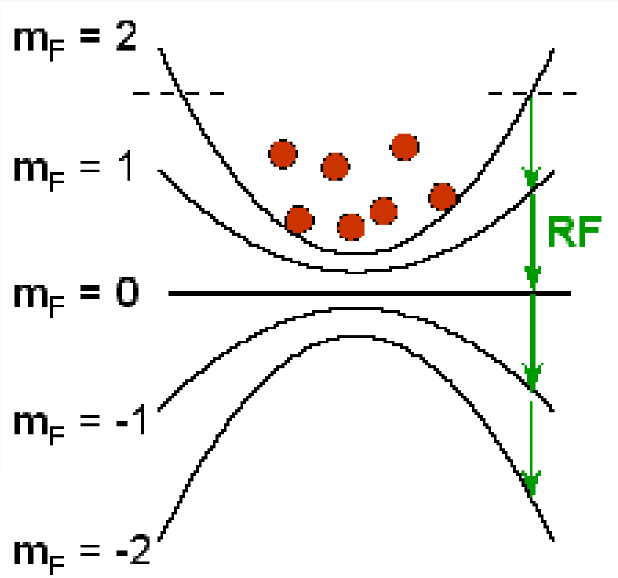
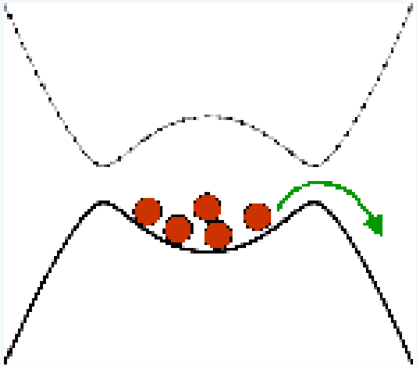
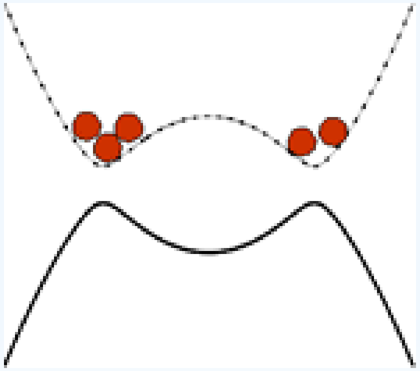


Unperturbed levels



Dressed levels

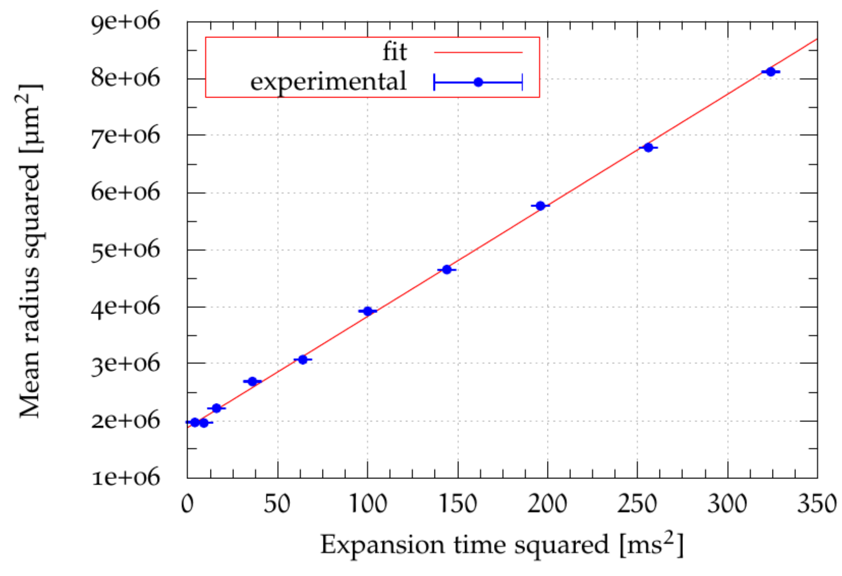


Trapped dressed atoms

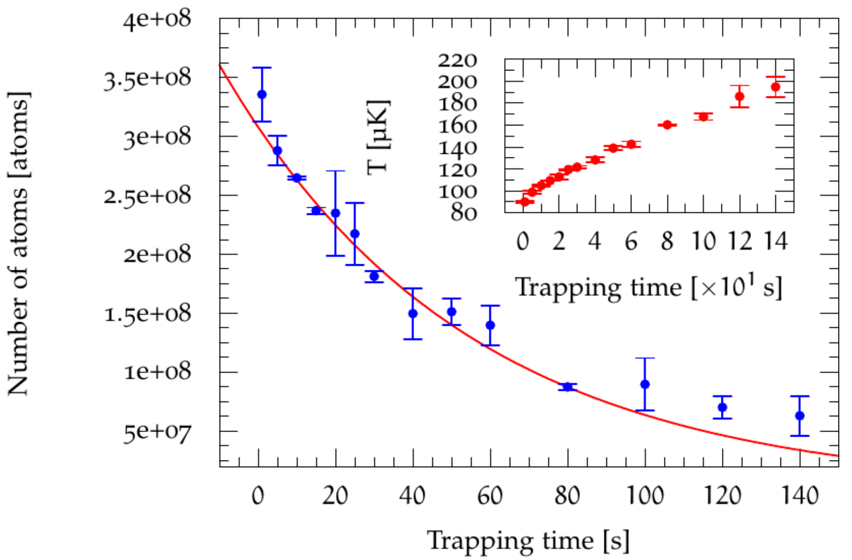
RF-dressing of Zeeman states is a versatile tool to implement exotic configurations such as

Imaging cold atomic gases

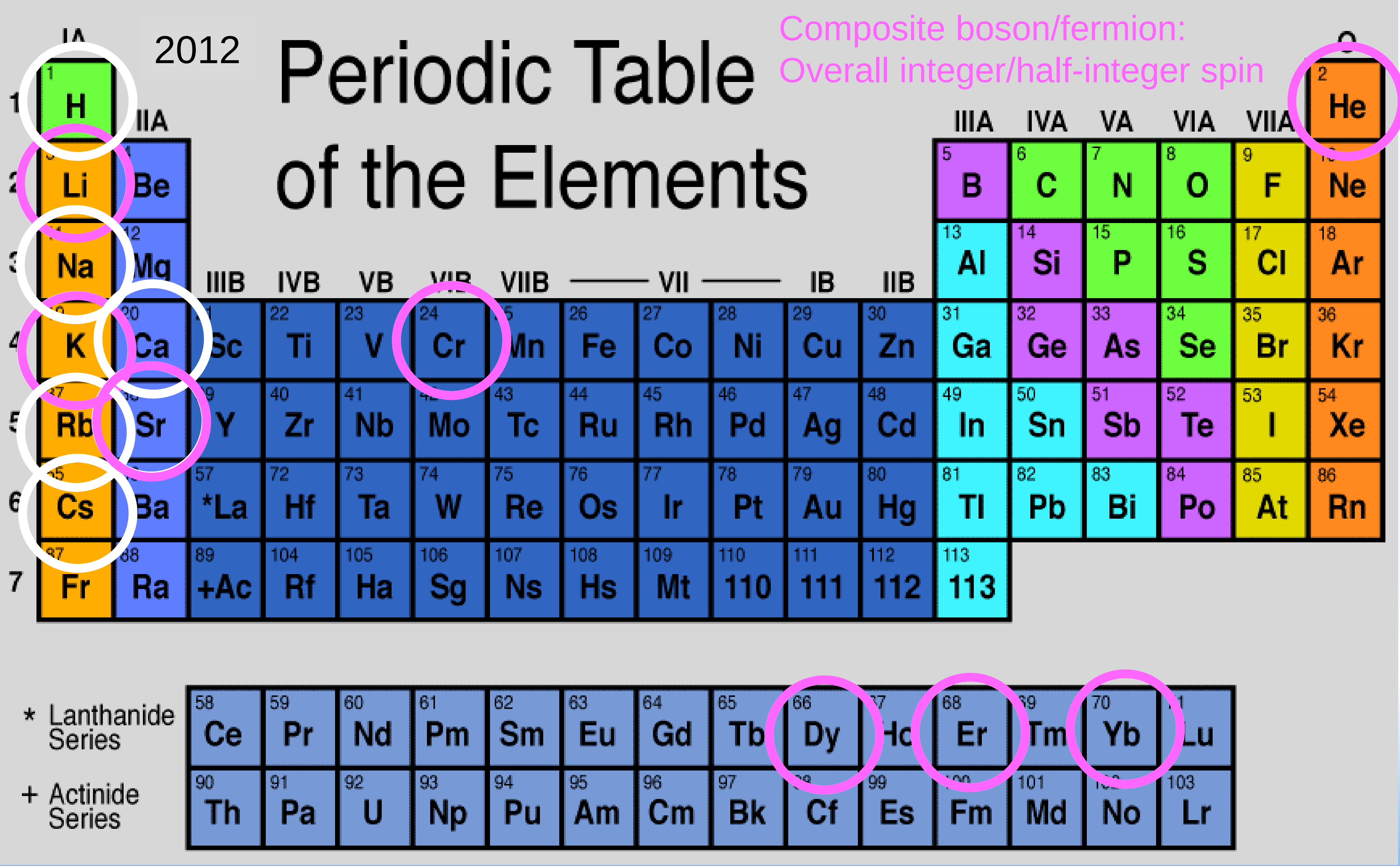
Temperature



Lifetime



Atomic species brought to degeneracy



2012

Periodic Table of the Elements

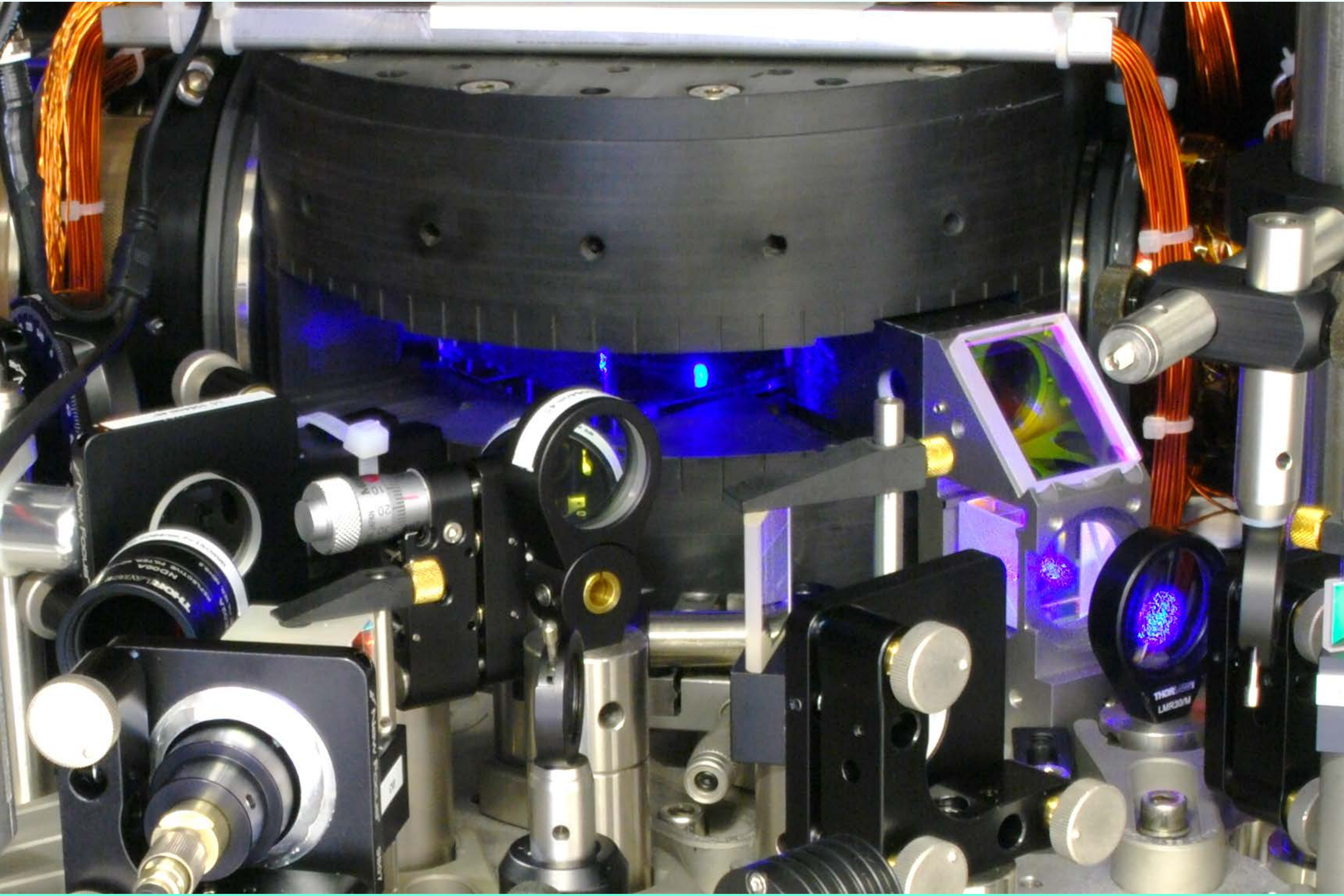
Composite boson/fermion:
Overall integer/half-integer spin

	IA	IIA	IIIB	IVB	VB	VIB	VIIB		VII		IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

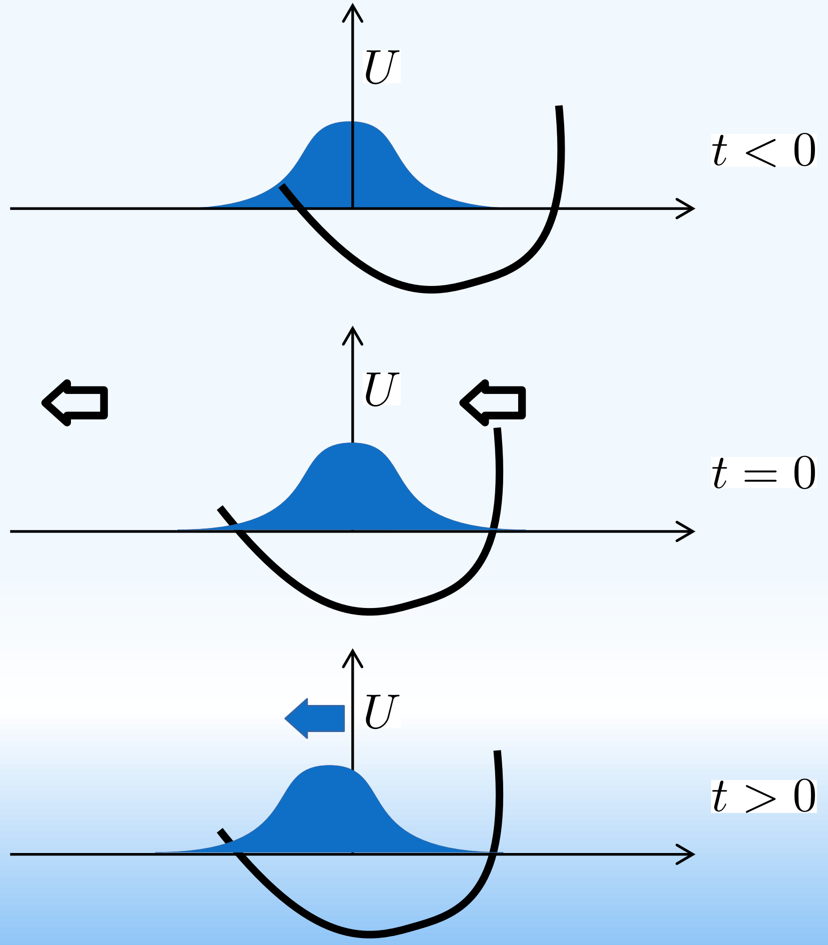
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

More on Fermions and Bosons In Today's lectures

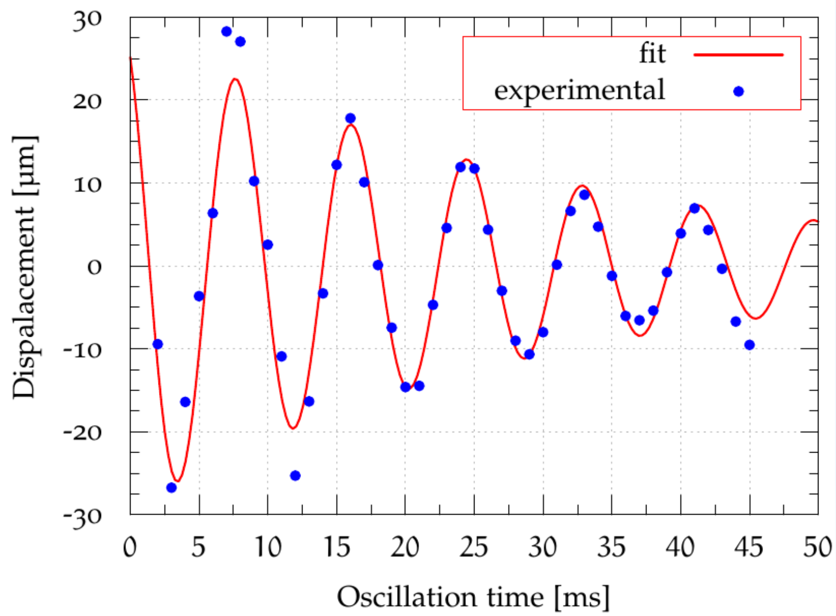
magneto-optically trapped Sr atoms (461nm)



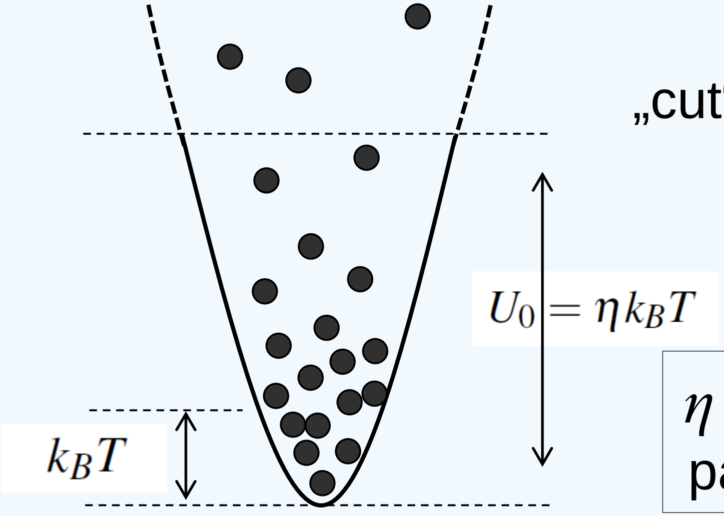
Imaging cold atomic gases



Trapping frequency



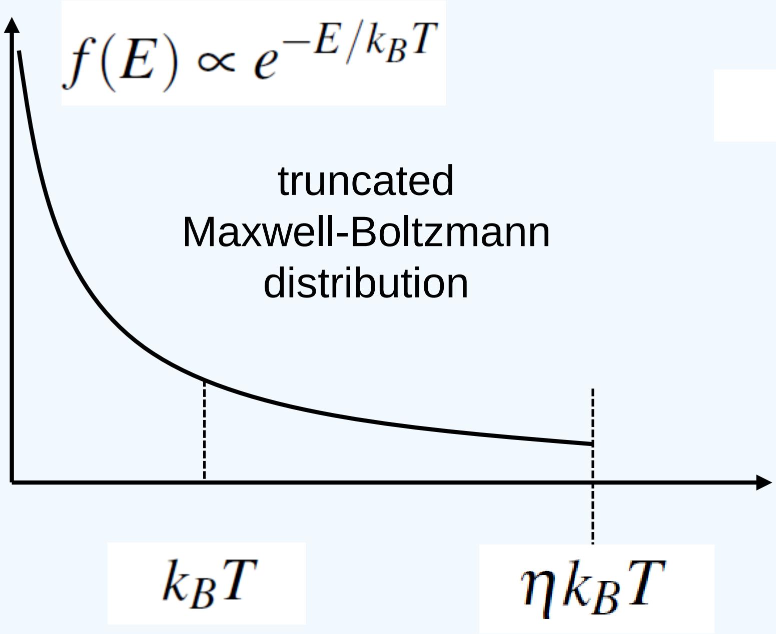
Cooling & Trapping: evaporative cooling dynamics



„cut“ trap

η = cut-off parameter

$\varepsilon = 3k_BT$ energy per particle


$f(E) \propto e^{-E/k_BT}$

truncated Maxwell-Boltzmann distribution

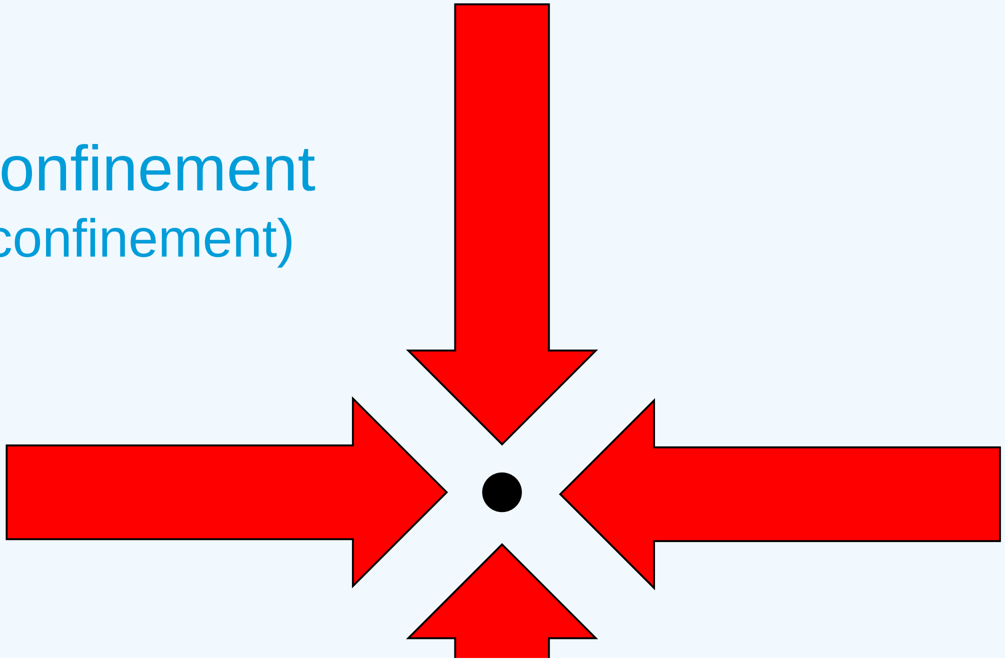
After cutting, wait for elastic collisions to re-equilibrate the system at a lower temperature

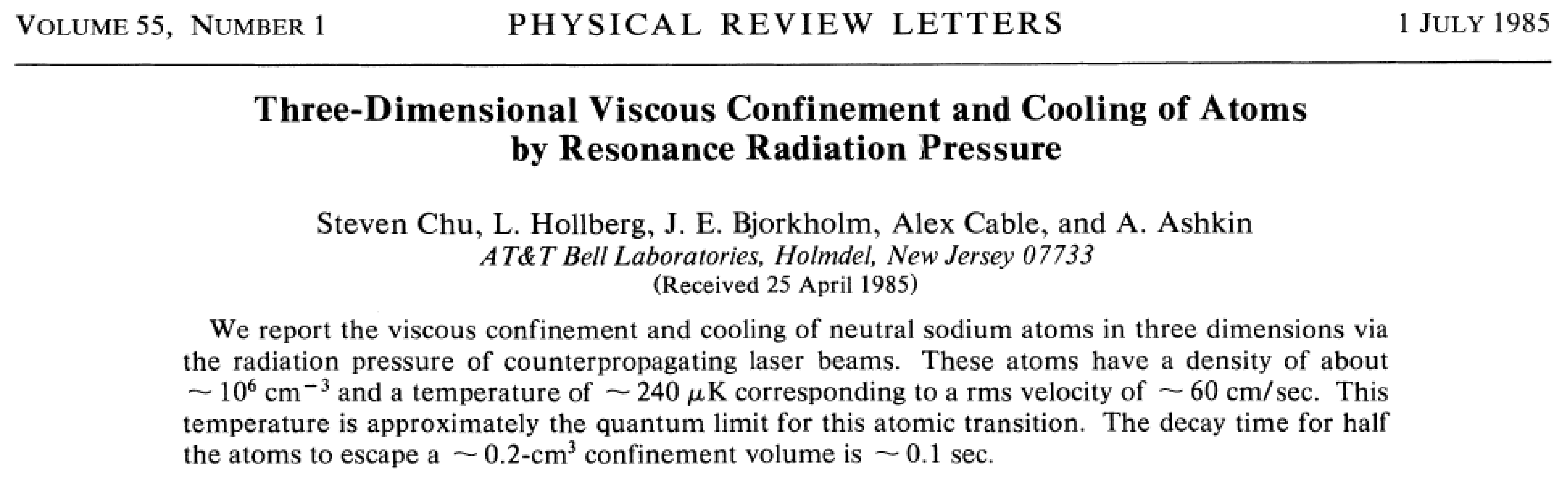
More on collisional properties tomorrow in Hanns Christoph‘s lecture

optical molasses in 3D

3D viscous confinement

(but no spatial confinement)





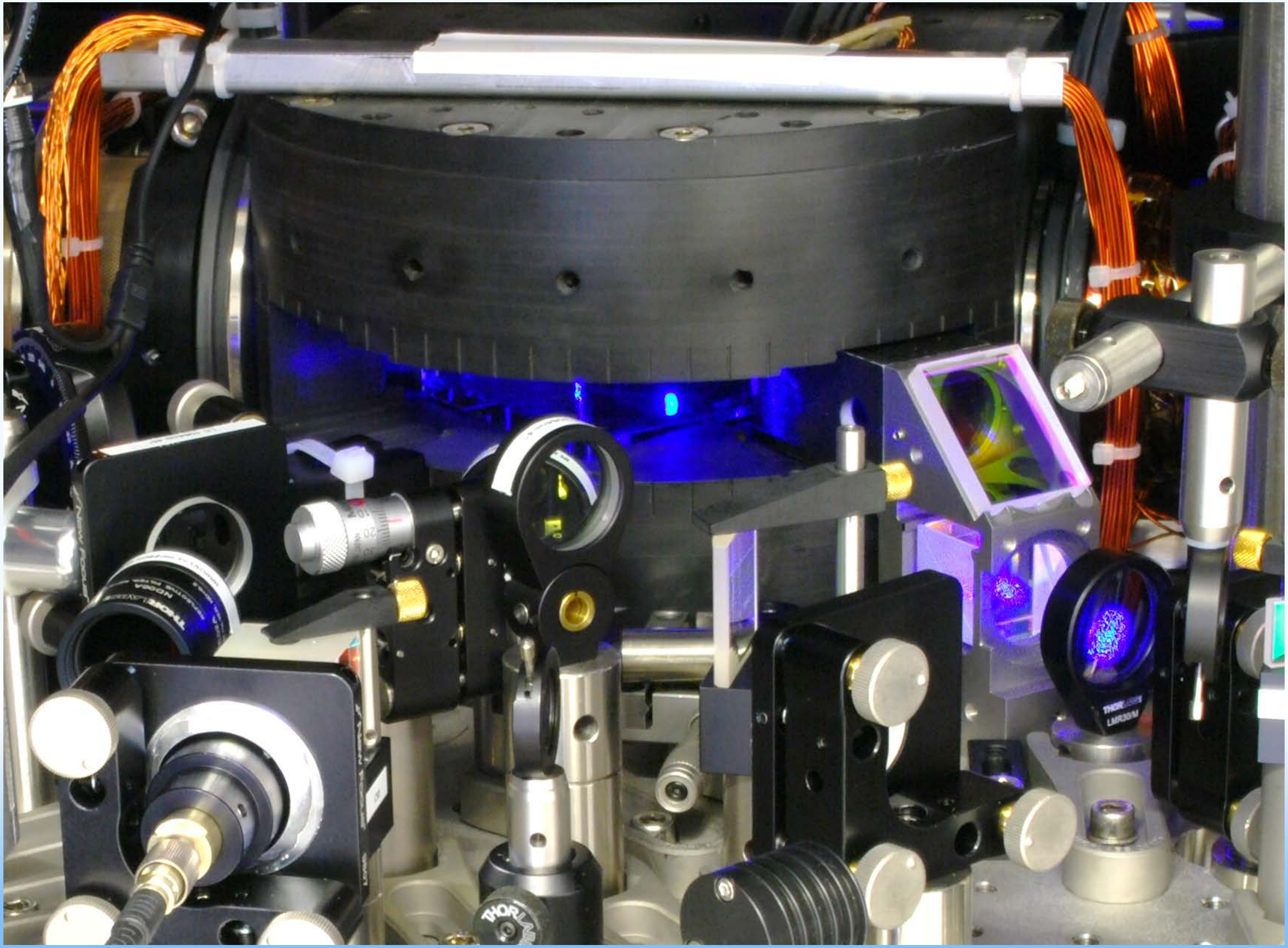
Volume 55, Number 1 PHYSICAL REVIEW LETTERS 1 July 1985

Three-Dimensional Viscous Confinement and Cooling of Atoms by Resonance Radiation Pressure

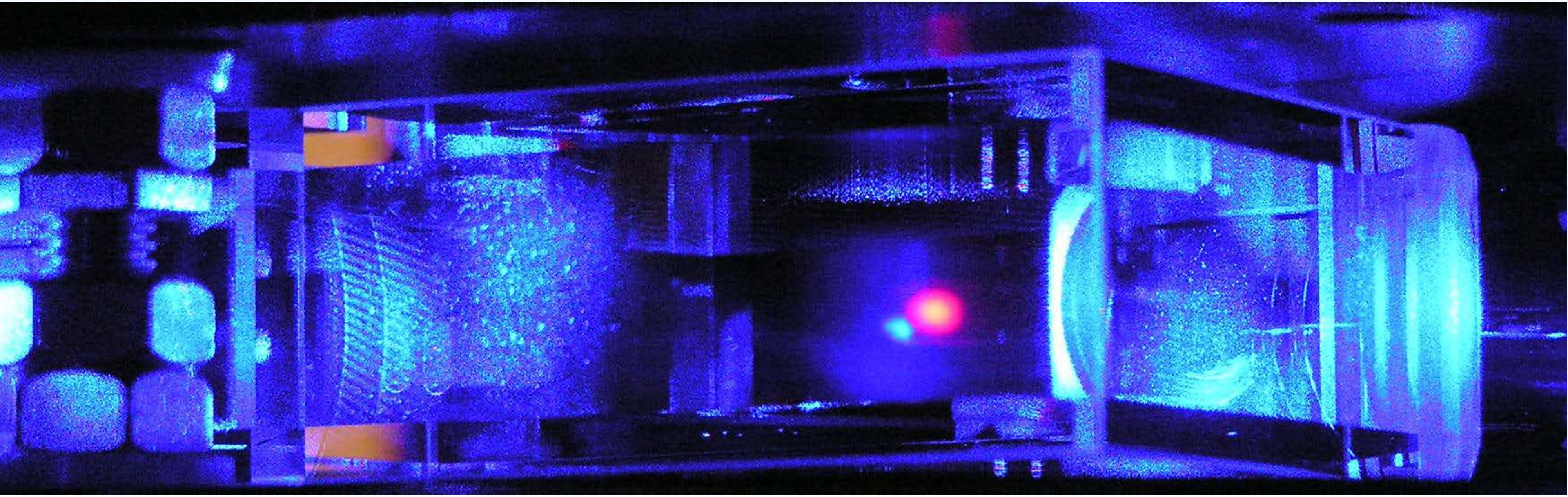
Steven Chu, L. Hollberg, J. E. Bjorkholm, Alex Cable, and A. Ashkin
AT&T Bell Laboratories, Holmdel, New Jersey 07733

(Received 25 April 1985)

We report the viscous confinement and cooling of neutral sodium atoms in three dimensions via the radiation pressure of counterpropagating laser beams. These atoms have a density of about $\sim 10^6$ cm^{-3} and a temperature of $\sim 240\ \mu$K corresponding to a rms velocity of ~ 60 cm/sec. This temperature is approximately the quantum limit for this atomic transition. The decay time for half the atoms to escape a ~ 0.2-cm^3 confinement volume is ~ 0.1 sec.



Sr and Li: two-species MOT (461nm and 671nm)



Cooling techniques

Laser cooling

- ✓ Large capture range
- ✓ High atomic flux
- ✓ Fast cooling rate

Cooling techniques

Laser cooling

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- ✓ High atomic flux
- ✓ Fast cooling rate

- ✗ Ultimate temperature limited by the photon recoil
- ✗ Spurious heating mechanisms at high spatial density
- ✗ Degraded performances in optically thick samples
- ✗ Phase-space density limited to 10^{-6}...10^{-4} (with exceptions)

Cooling techniques

Laser cooling

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✓ High atomic flux

✓ Fast cooling rate

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✗ Spurious heating mechanisms at high spatial density

✗ Degraded performances in optically thick samples

✗ Phase-space density limited to $10^{-6}...10^{-4}$ (with exceptions)

Evaporative cooling

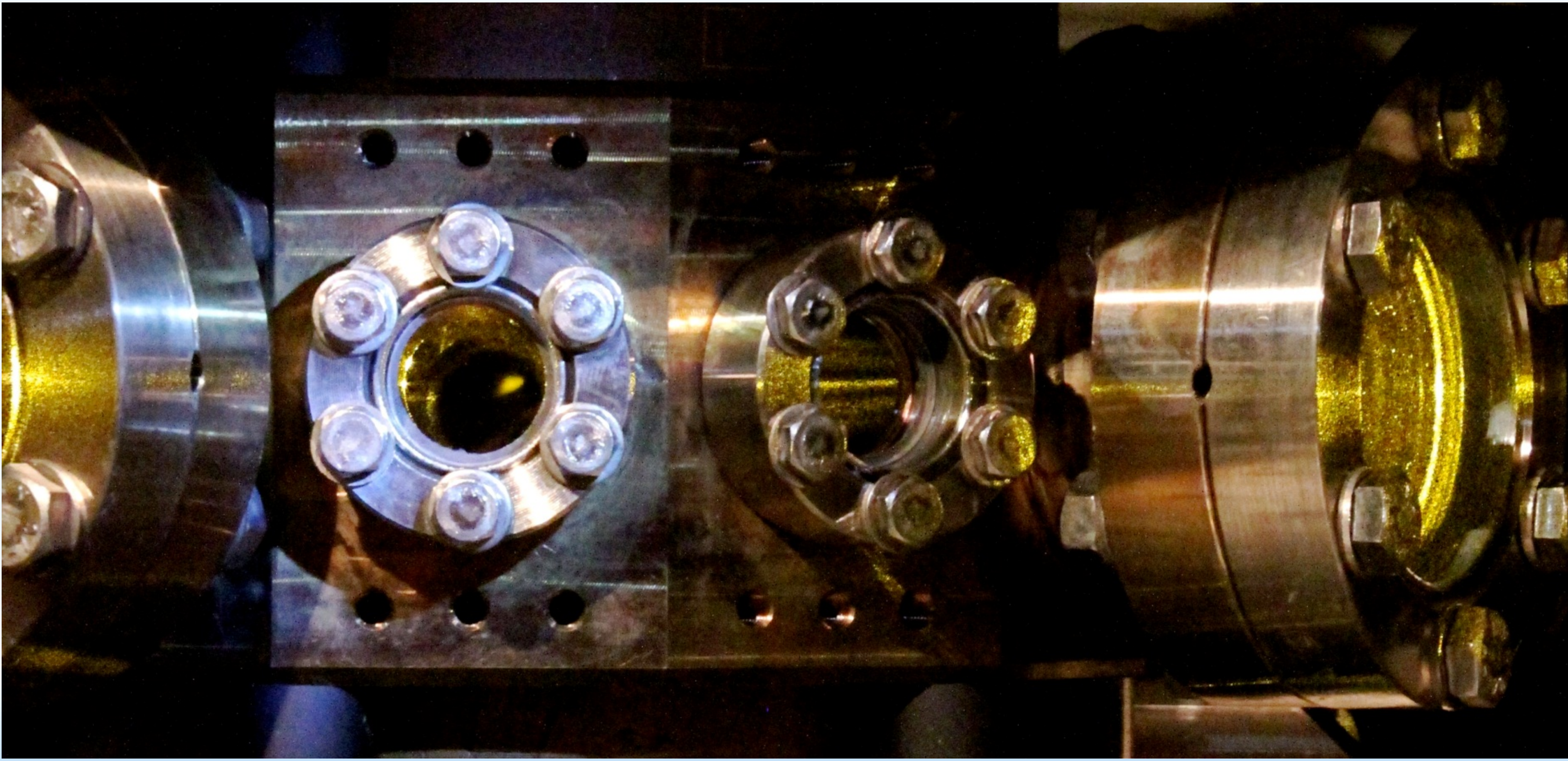
- Generally applicable in conservative traps
- Removal of most energetic particles
- Elastic collisions among remaining particles to insure thermalization at lower temperature

✓ No fundamental limits to the ultimate lower temperature

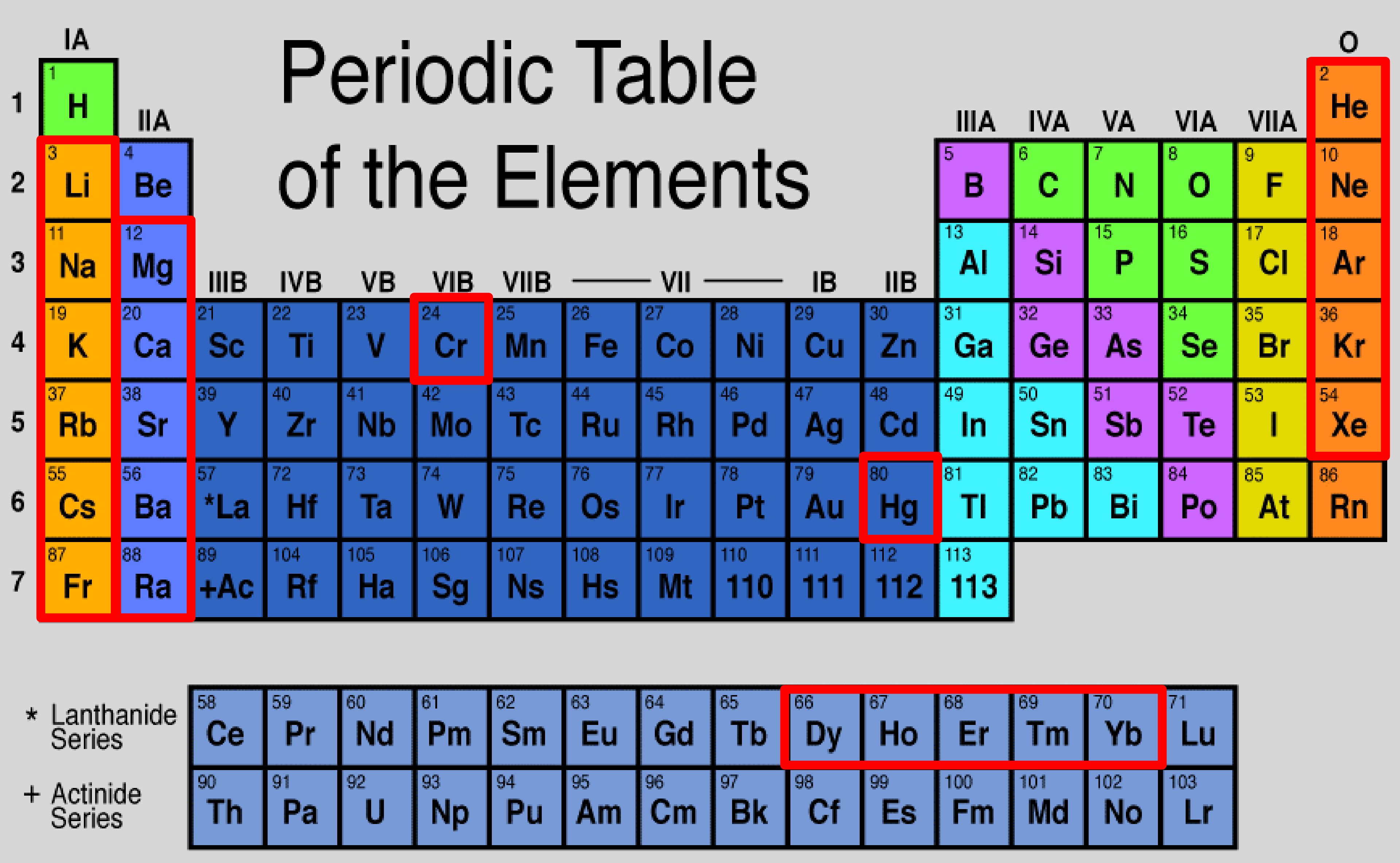
✓ More efficient at high spatial density

✓ Proven method to enter into the quantum degenerate regime

magneto-opically trapped erbium (583nm)



magneto-optically trapped atoms



Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB		VII		IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
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5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

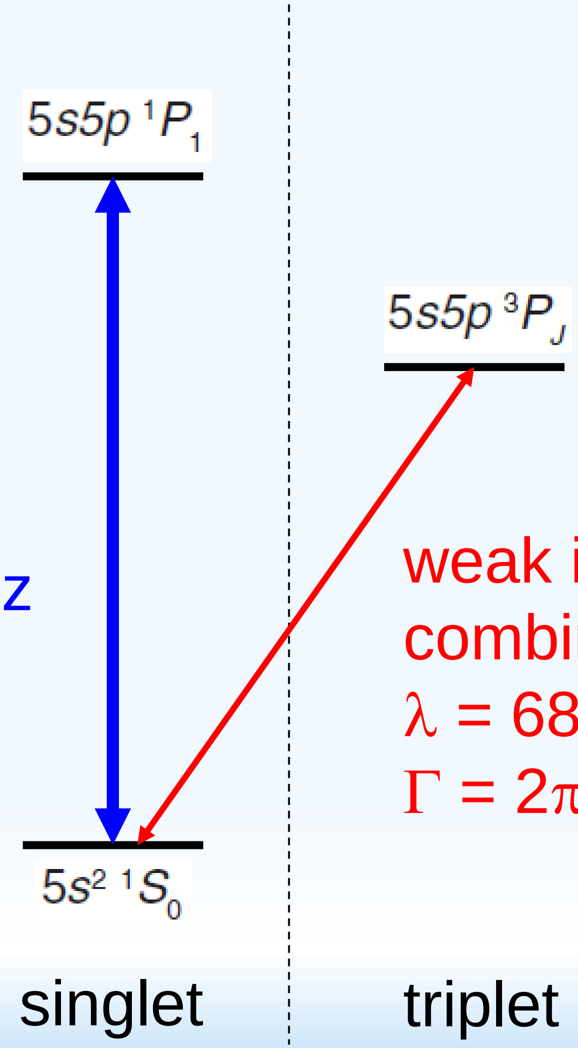
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

strontium cooling transitions

$a_{max} = 1.0 \times 10^6$ m/s^2

T_D = 770 µK

strong line
λ = 461nm
$\Gamma = 2\pi \times 32$ MHz



a_{max} = 160 m/s^2

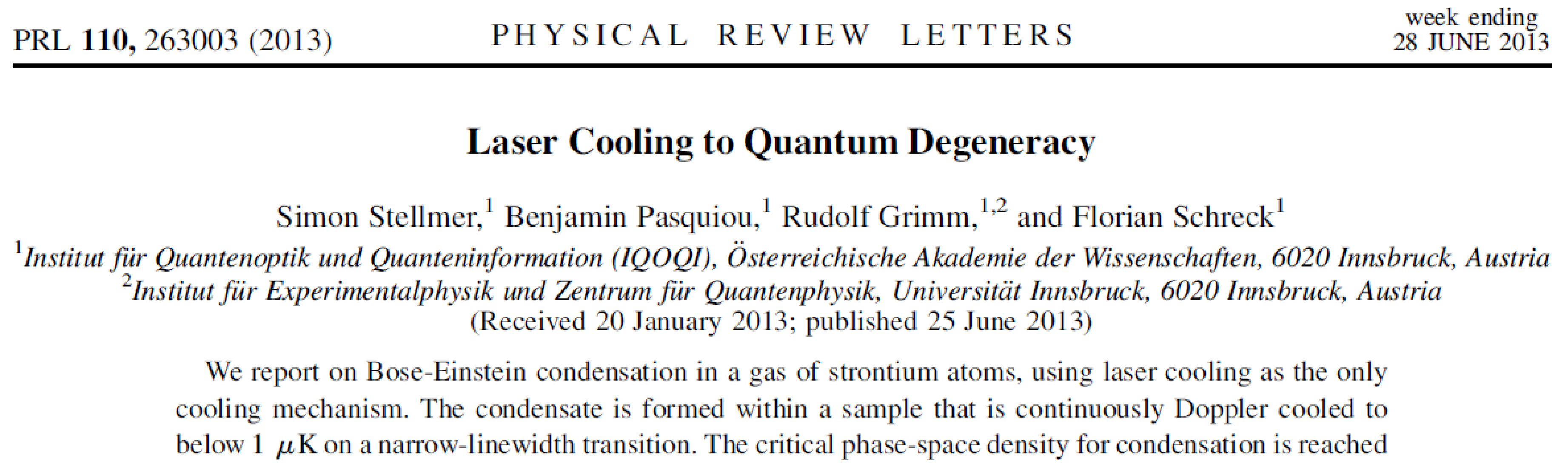
T_D = 180 nK

weak inter-combination line
λ = 689nm
$\Gamma = 2\pi \times 7.4$ kHz

extremely powerful

atomic beam slowing
and MOT precooling (mK) → deep Doppler cooling (µK)

BEC by laser cooling !



PRL **110,** 263003 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

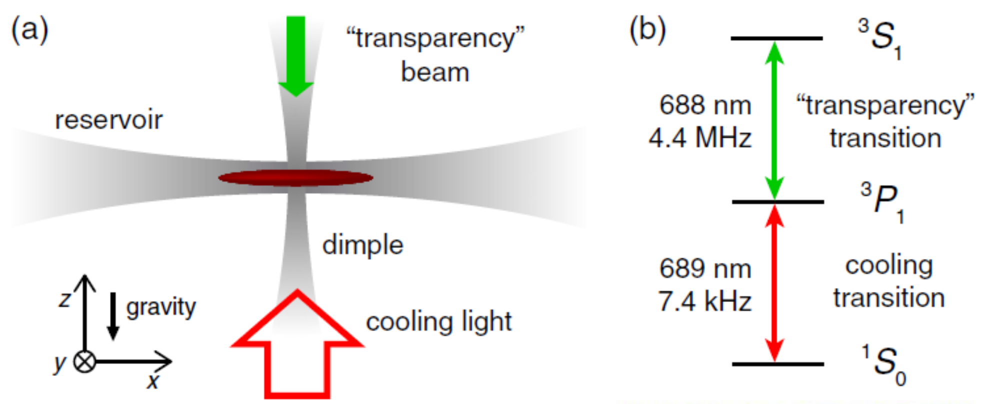
Laser Cooling to Quantum Degeneracy

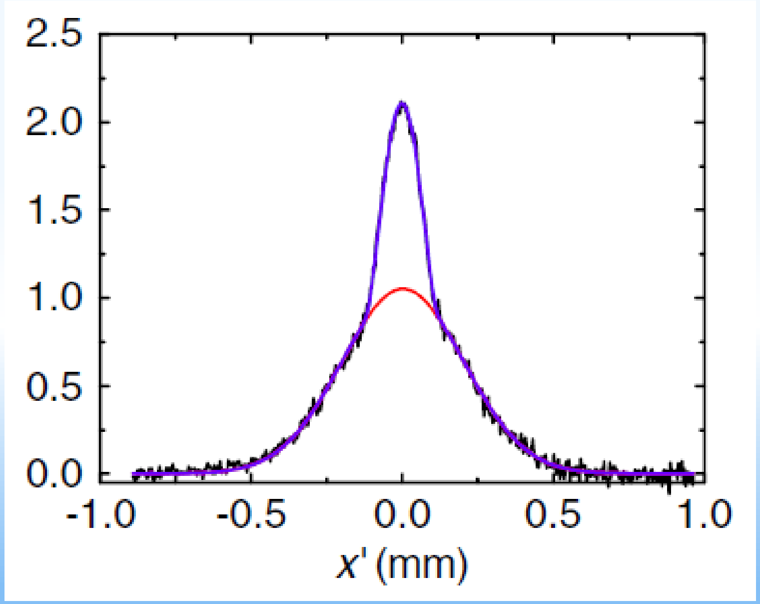
Simon Stellmer,[1] Benjamin Pasquiou,[1] Rudolf Grimm,[1,2] and Florian Schreck[1]
[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*
[2]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

(Received 20 January 2013; published 25 June 2013)

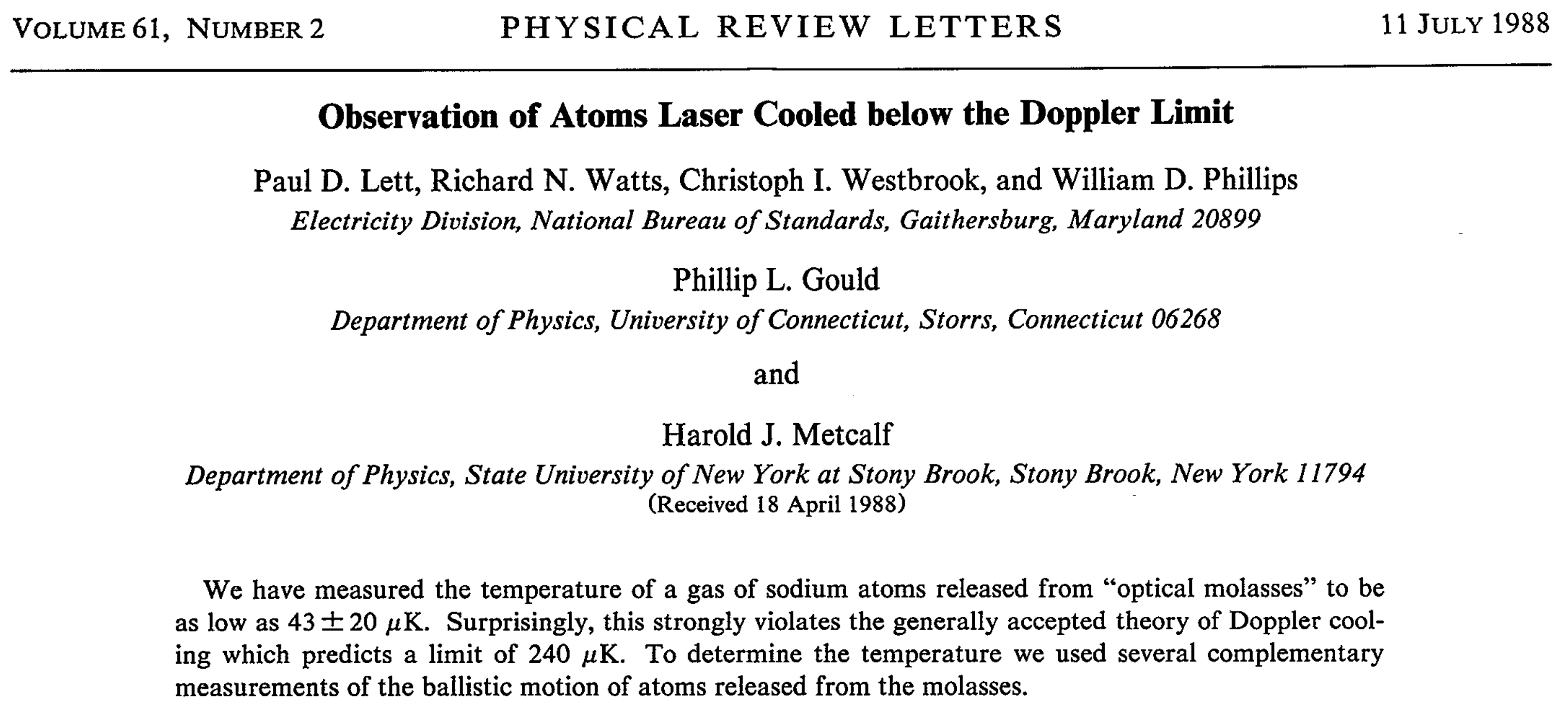
We report on Bose-Einstein condensation in a gas of strontium atoms, using laser cooling as the only cooling mechanism. The condensate is formed within a sample that is continuously Doppler cooled to below 1 μK on a narrow-linewidth transition. The critical phase-space density for condensation is reached

experiments continued in the Schreck group in Amsterdam





landmark: sub-Doppler cooling



VOLUME 61, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1988

Observation of Atoms Laser Cooled below the Doppler Limit

Paul D. Lett, Richard N. Watts, Christoph I. Westbrook, and William D. Phillips
Electricity Division, National Bureau of Standards, Gaithersburg, Maryland 20899

Phillip L. Gould
Department of Physics, University of Connecticut, Storrs, Connecticut 06268

and

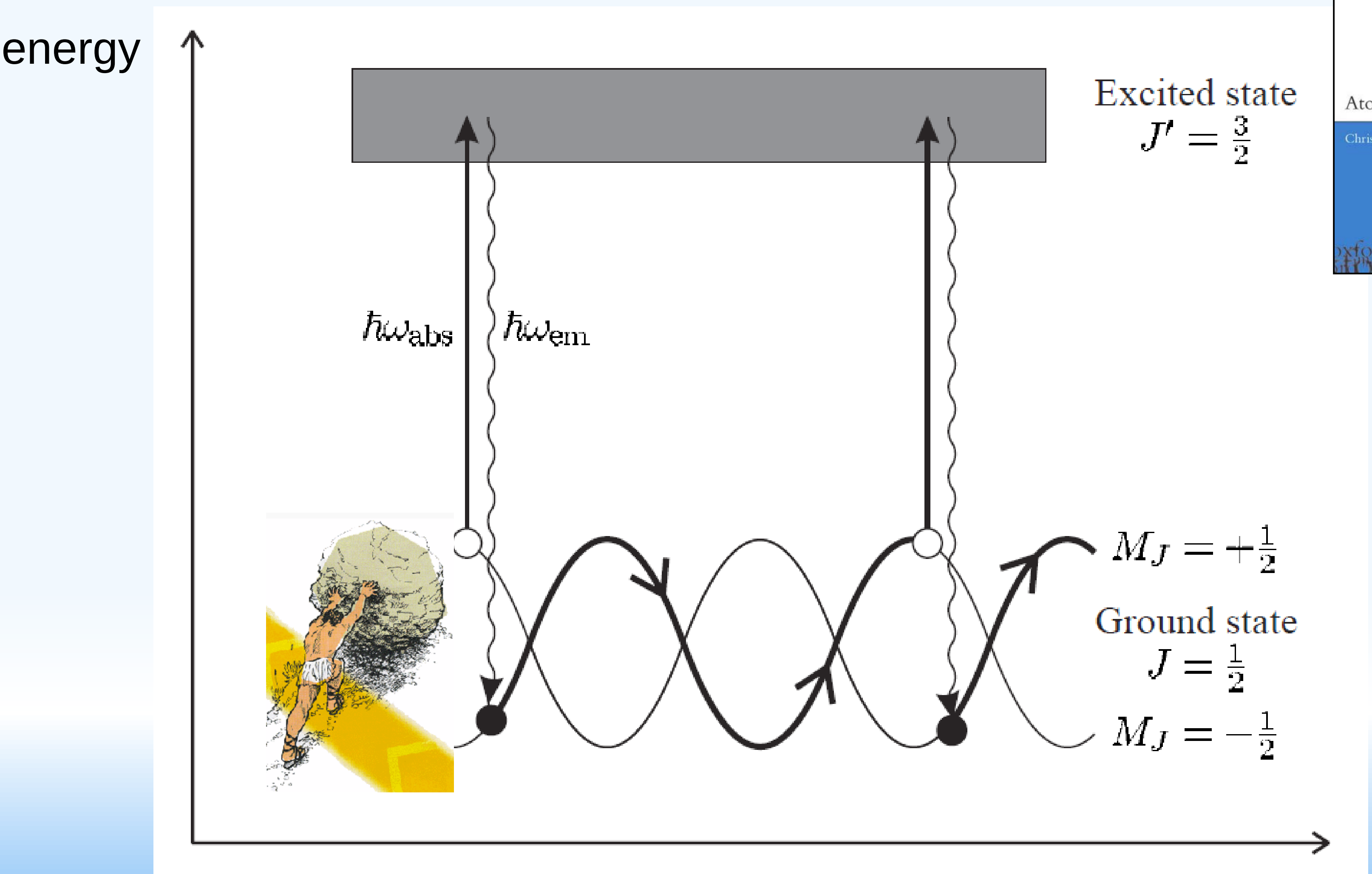
Harold J. Metcalf
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794

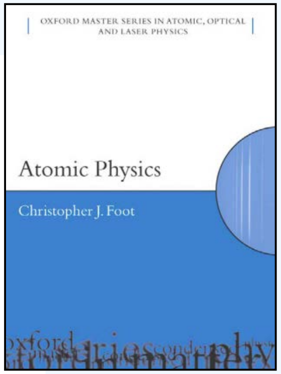
(Received 18 April 1988)

We have measured the temperature of a gas of sodium atoms released from "optical molasses" to be as low as 43 ± 20 μK. Surprisingly, this strongly violates the generally accepted theory of Doppler cooling which predicts a limit of 240 μK. To determine the temperature we used several complementary measurements of the ballistic motion of atoms released from the molasses.

very interesting story: "Sisyphus effect" in laser cooling

Sisyphus effect in laser cooling




OXFORD MASTER SERIES IN ATOMIC, OPTICAL AND LASER PHYSICS

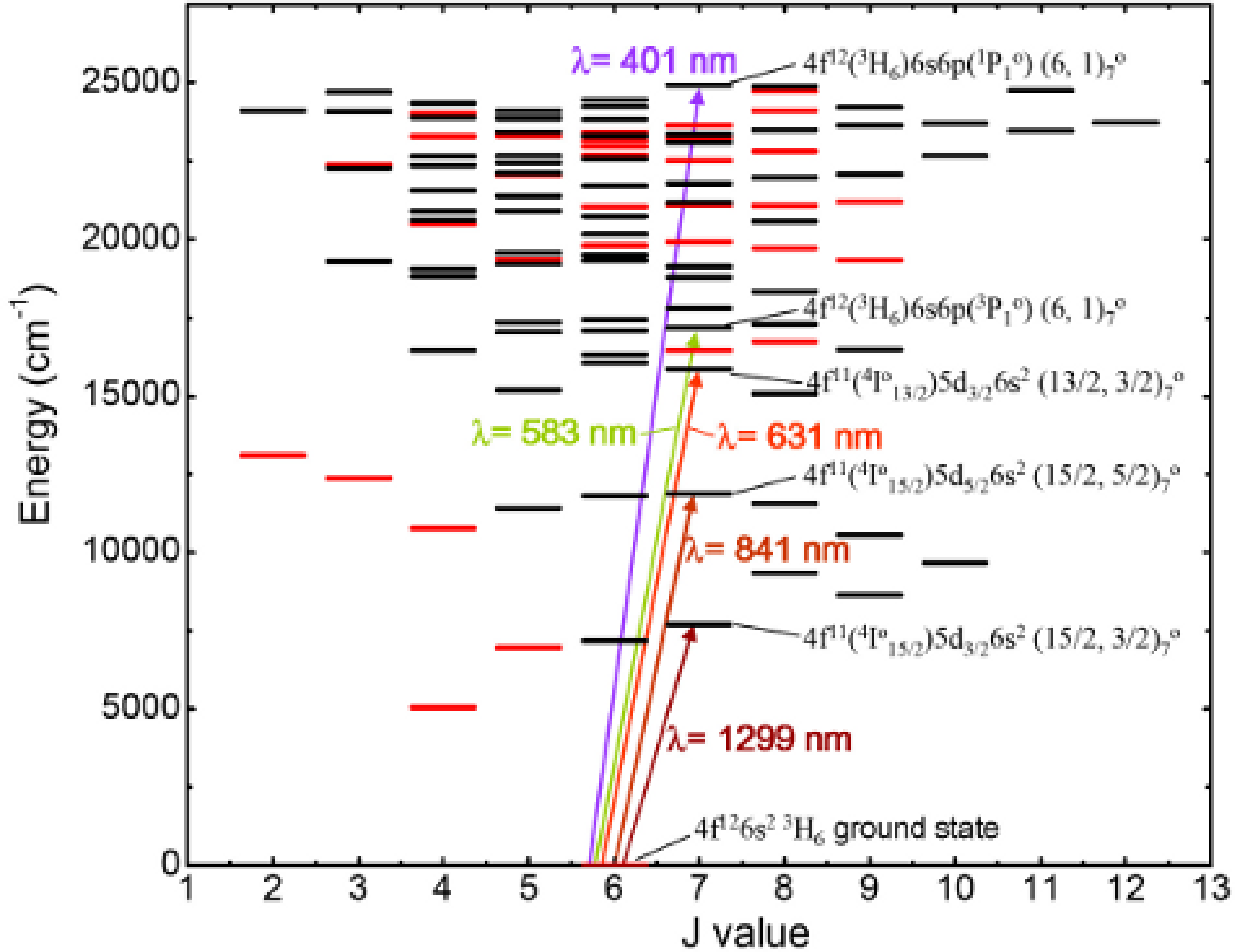
Atomic Physics

Christopher J. Foot

Recoil limited Rb: $T_R = 362$ nK

Cooling lines in lanthanides: erbium

https://www.uibk.ac.at/exphys/ultracold/projects/erbium/energyspectrum.png



Cooling lines in lanthanides: dysprosium

Dy example

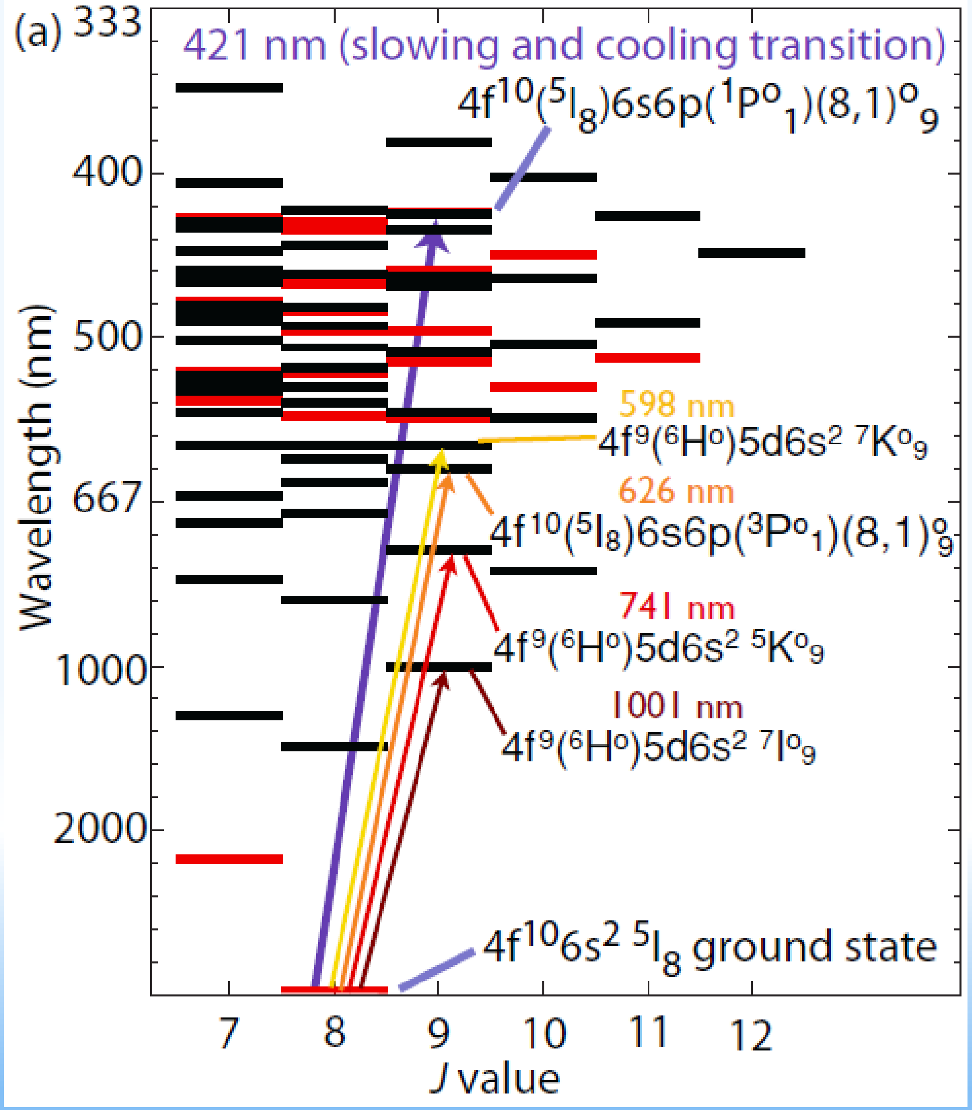
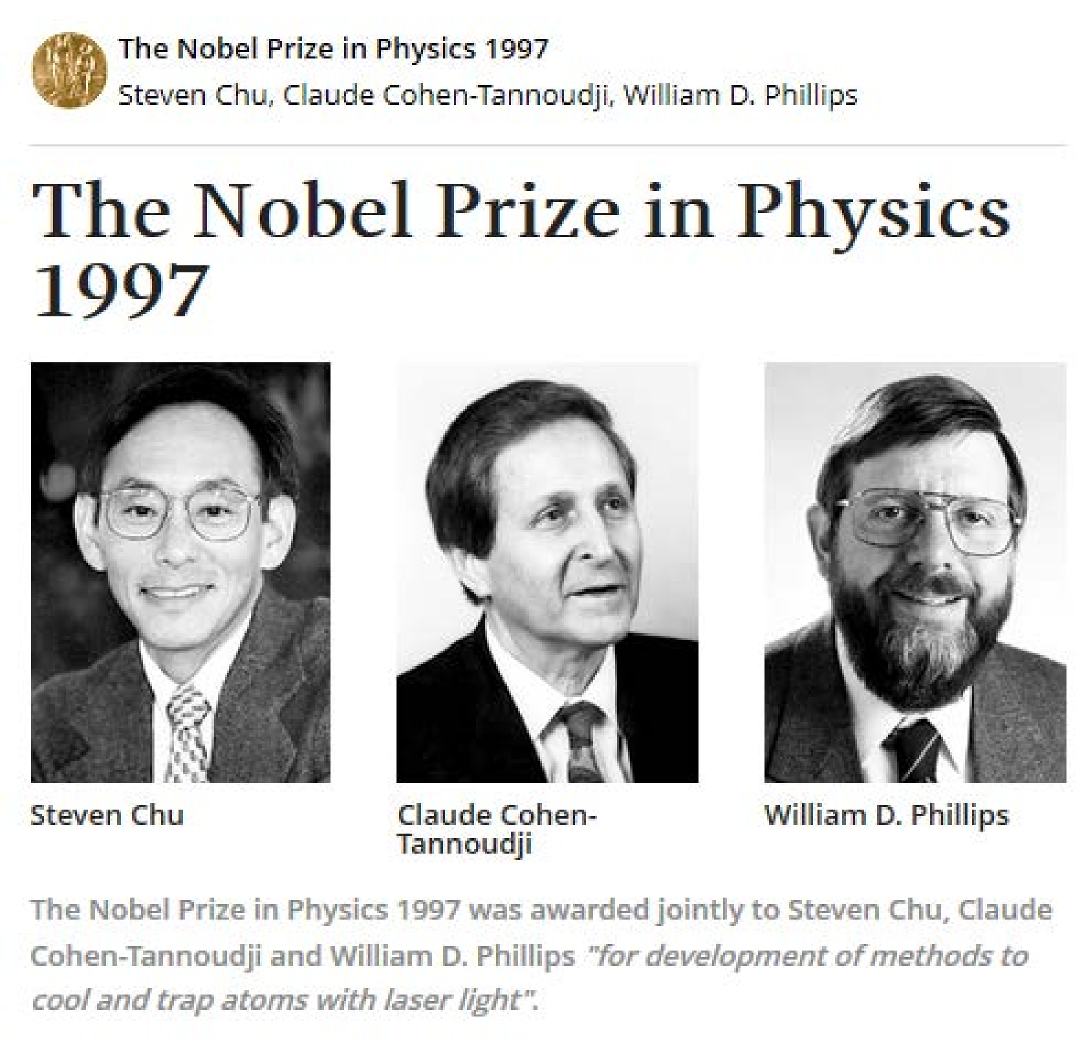


Figure from Lu et al., PRA 83, 012110 (2011)

Nobel prize in physics 1997



The Nobel Prize in Physics 1997
Steven Chu, Claude Cohen-Tannoudji, William D. Phillips

The Nobel Prize in Physics 1997

Steven Chu

Claude Cohen-Tannoudji

William D. Phillips

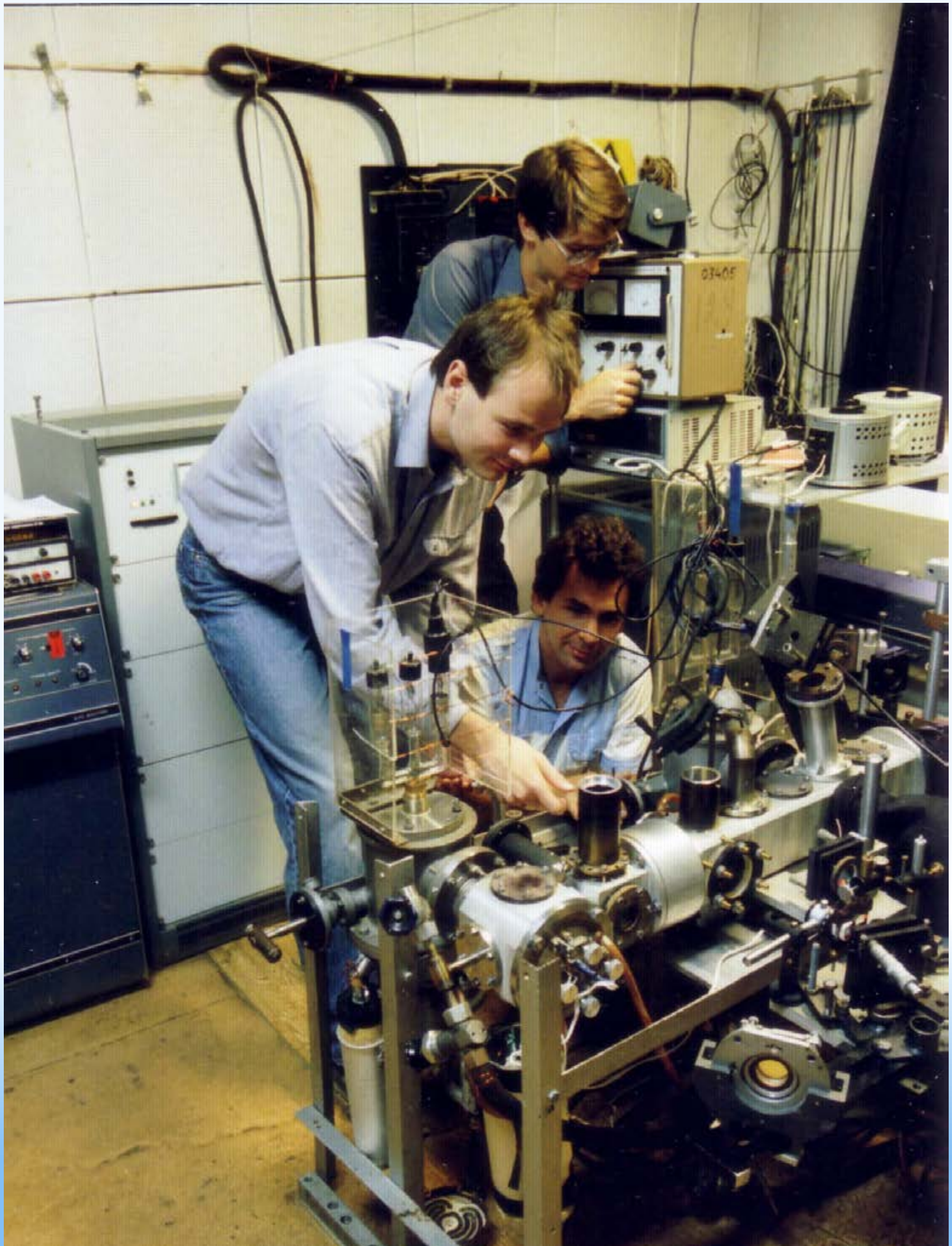
The Nobel Prize in Physics 1997 was awarded jointly to Steven Chu, Claude Cohen-Tannoudji and William D. Phillips *"for development of methods to cool and trap atoms with laser light"*.

pioneer of laser cooling who didn‘t get it

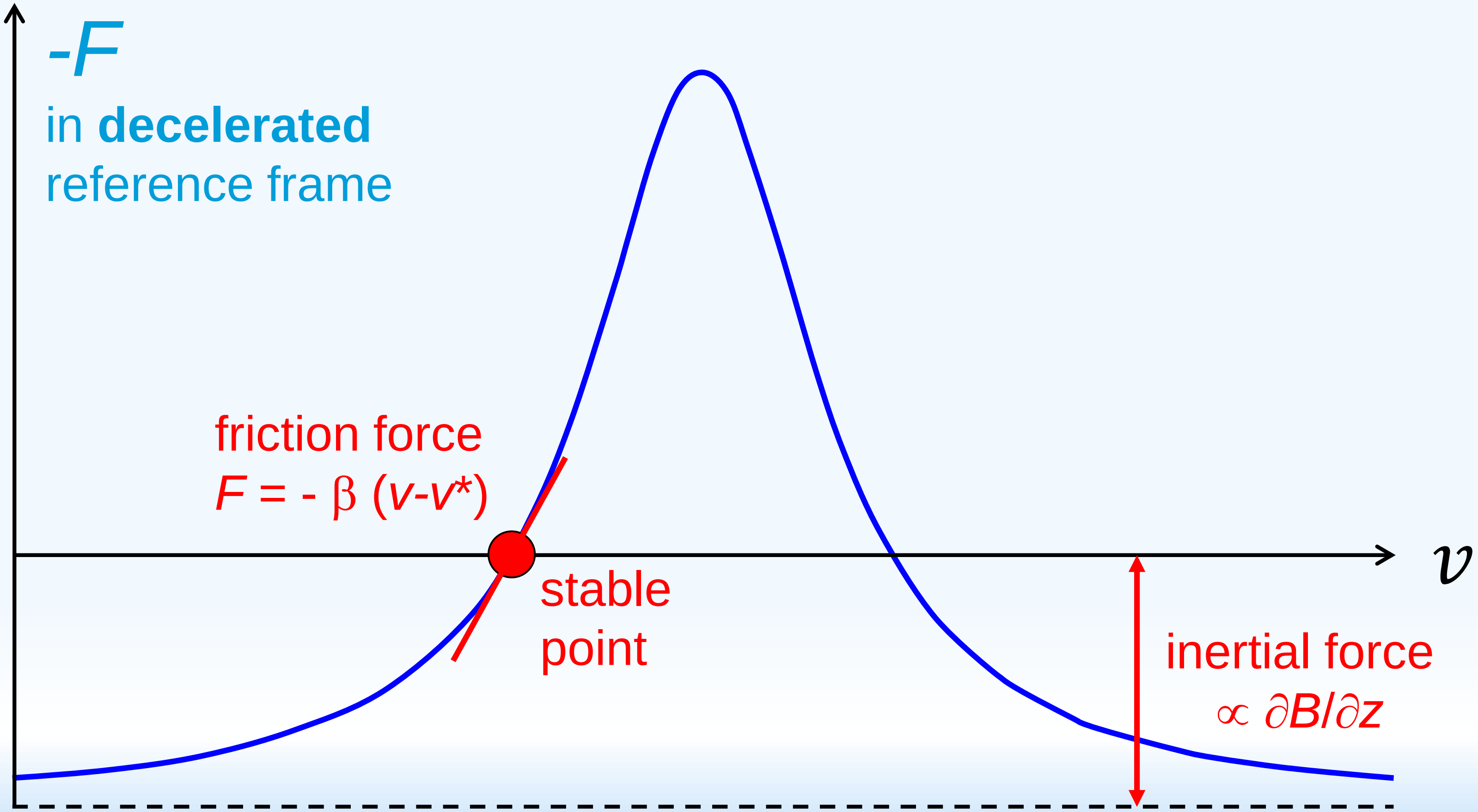
Vladilen Letokhov
(1939-2009)

Doppler cooling even much more powerful than understood at that time

RG in Troitsk (1991)



why does a Zeeman slower cool?



remarks

about 55 mins., ~ 10 min too long

MOT restoring force explained at the blackboard

introduce Isat to show that it contains hbar
(friction is classical)

Cooling & Trapping: light shift + light forces

So far, we have *neglected* the light shift (or ac Stark effect) on the atoms.

What we have done is introduce the dissipative forces simply *by hand*.

But that is only *half the truth*!

For the derivation of the optical Bloch equ‘ns above we have assumed

$$\vec{E}(\vec{r},t) = \vec{E}_0 \cos(\omega_L t)$$

for the electrical field of the laser light.
We have *neglected* any position dependence of the light field.

This is ok if we assume that the atom is *infinitely heavy* and that hence the photon recoil (in absorption and emission) plays *no role*.
Evidently, this *cannot* be correct.

In reality, we should at least assume that

$$\vec{E}(\vec{r},t) = \vec{E}_0(\vec{r},t) \cos(\vec{k}_L \vec{r} - \omega_L t)$$

Here, $\vec{r}$ is the position operator for the center-of-mass motion of the atom.

Cooling & Trapping: light shift + light forces

$$\vec{E}(\vec{r},t) = \vec{E}_0(\vec{r},t)\cos(\vec{k}_L\vec{r} - \omega_L t)$$

Or, even better:

$$\vec{E}(\vec{r},t) = \vec{\varepsilon}(\vec{r})E_0(\vec{r},t)\cos(\vec{k}_L\vec{r} - \omega_L t + \phi)$$

some phase, which might depend on time, usually not on space.

the usual sinusoidal dependence, but not only on *time*, but also in *space*.

a polarization that can vary in space as fast as given by the length scale λ_L . (quite often it does not vary at all in space)

an amplitude that varies in space, sometimes as fast as λ_L, e.g. for a standing wave (but not faster), and that has a *slow* time variation.

Note: Think of a Gaussian beam and the obvious extensions thereof (e.g. interfering Gaussian beams)

Cooling & Trapping: light shift + light forces

For now, let us assume that the field has the simple form

$$\vec{E}(\vec{r},t) = \vec{E}_0(\vec{r})\cos\left(\vec{k_L}\vec{r} - \omega_L t\right)$$

What is the force on the atom?

$$\vec{F} = \frac{d\vec{P}}{dt} = \frac{1}{i\hbar}\left[\vec{P},H\right] = -\frac{\partial H}{\partial \vec{r}}$$

Now, $H = H_{\mathrm{A}} + H_{\mathrm{AL}}$ with only $H_{\mathrm{AL}} = H_{\mathrm{AL}}(\vec{r})$ as $H_{\mathrm{AL}}(\vec{r}) = -\vec{d}\vec{E}$

Thus
$$\vec{F} = -\frac{\partial H_{\mathrm{AL}}}{\partial \vec{r}}$$

Further: We are only interested in the *averaged* steady-state values:

$\langle \vec{F} \rangle_{\mathrm{ss}} \to \vec{F}^{\mathrm{ss}}$ as a function of $\langle \vec{r} \rangle_{\mathrm{ss}} \to \vec{r}^{\mathrm{SS}}$

Note: separation of times scales! *Fast* internal, *slow* external motion.

Cooling & Trapping: light shift + light forces

Hence
$$\langle \vec{F} \rangle_{\text{ss}} = -\langle \frac{\partial H_{\text{AL}}}{\partial \vec{r}} \rangle_{\text{ss}} = \langle \vec{d} \rangle_{\text{ss}} \frac{\partial \vec{E}}{\partial \vec{r}}$$

Now
$$\langle d \rangle = \text{Tr}(\rho d) = \rho_{12} e^{-i(\vec{k}_L \vec{r} - \omega_L t)} d_{21} + \rho_{21} e^{+i(\vec{k}_L \vec{r} - \omega_L t)} d_{12}$$

(in the oscillating frame, check)

and
$$\frac{\partial \vec{E}}{\partial \vec{r}} = \frac{\partial \vec{E}_0}{\partial \vec{r}} \cos(\vec{k}_L \vec{r} - \omega_L t) - \vec{E}_0 \vec{k}_L \sin(\vec{k}_L \vec{r} - \omega_L t)$$

O.E.
$$d_{12} = d_{21} \equiv d$$

Thus
$$\langle \vec{F} \rangle_{\text{ss}} = \langle \vec{d} \rangle_{\text{ss}} \frac{\partial \vec{E}}{\partial \vec{r}} = \frac{\partial \vec{E}_0}{\partial \vec{r}} (\rho_{12}^{\text{ss}} + \rho_{21}^{\text{ss}}) \frac{d}{2} + \vec{E}_0 \vec{k}_L i (\rho_{12}^{\text{ss}} - \rho_{21}^{\text{ss}}) \frac{d}{2}$$

(the fast oscillating terms are averaged away)

Now remember
$$\rho_{12}^{\text{ss}} = \frac{\Omega/2(\Delta + i\Gamma/2)}{\Delta^2 + (\Gamma/2)^2 + \Omega^2/2}$$
and
$$\rho_{21}^{\text{ss}} = (\rho_{12}^{\text{ss}})^*$$

Cooling & Trapping: light shift + light forces

Thus

$$\langle\vec{F}\rangle_{\mathrm{ss}} = -\frac{\hbar\Delta}{2}\frac{\Omega}{\Delta^2+(\Gamma/2)^2+\Omega^2/2}\frac{\partial\Omega}{\partial\vec{r}} + \frac{\Gamma}{4}\frac{\Omega^2}{\Delta^2+(\Gamma/2)^2+\Omega^2/2}\hbar\vec{k}_L$$

I.e.

$$\boxed{\langle\vec{F}\rangle_{\mathrm{ss}} = \langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{dip}} + \langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{scat}}}$$

with

$$\boxed{\langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{dip}} = -\frac{\hbar\Delta}{2}\frac{\Omega}{\Delta^2+(\Gamma/2)^2+\Omega^2/2}\frac{\partial\Omega}{\partial\vec{r}}}$$

and

$$\boxed{\langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{scat}} = \frac{\Gamma}{4}\frac{\Omega^2}{\Delta^2+(\Gamma/2)^2+\Omega^2/2}\hbar\vec{k}_L}$$

(compare)

Cooling & Trapping: light shift + light forces

Let‘s have a closer look at

$$\langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{dip}} = -\frac{\hbar\Delta}{2}\frac{\Omega}{\Delta^2+(\Gamma/2)^2+\Omega^2/2}\frac{\partial\Omega}{\partial\vec{r}}$$

In the limit $\Delta \gg \Gamma,\ \Omega$ we have

$$\langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{dip}} = -\frac{\hbar}{4\Delta}\frac{\partial\Omega^2}{\partial\vec{r}}$$

Thus $\boxed{\langle\vec{F}\rangle^{\mathrm{ss}}_{\mathrm{dip}} = -\frac{\partial U_{\mathrm{dip}}}{\partial\vec{r}}}$ with $\boxed{U_{\mathrm{dip}} = \frac{\hbar\Omega^2}{4\Delta}}$

Conservative force !!!

Thus, in this limit we have (with *I*$_L$ the light intensity)

$\boxed{U_{\mathrm{dip}} \propto \frac{I_L}{\Delta}}$ but for the scattering rate $\boxed{\Gamma_{\mathrm{scat}} \propto \frac{I_L}{\Delta^2}}$

Comment: This is the basis for a *large* fraction of the modern cold atom exp‘ts

Cooling & Trapping: magnetic trapping

How can one generate a trap? (without the help of other means, see below)

Low-field seekers would need a 3D *minimum* for $|\vec{B}| = |\vec{B}(\vec{r})|$

High-field seekers would need a 3D *maximum* for $|\vec{B}| = |\vec{B}(\vec{r})|$

In general, one finds that

$$\vec{\nabla}^2 |\vec{B}| > 0 \text{ , i.e. } \vec{\nabla}^2 \vec{B}^2 > 0$$

Earnshaw‘s theorem for magnetic fields

As a consequence, there is *no trap* (in free space) *for high-field seekers*.

Proof: $\vec{\nabla}^2 \vec{B}^2 = \vec{\nabla}^2 \left(B_x^2 + B_y^2 + B_z^2\right) =$

$$= 2\left((\vec{\nabla} B_x)^2 + (\vec{\nabla} B_y)^2 + (\vec{\nabla} B_z)^2 + B_x \vec{\nabla}^2 B_x + B_y \vec{\nabla}^2 B_y + B_z \vec{\nabla}^2 B_z\right)$$

Now: $\vec{\nabla}^2 B_x = \vec{\nabla}^2 B_y = \vec{\nabla}^2 B_z = 0$

because $\vec{\nabla}^2 \vec{B} = \vec{\nabla}(\vec{\nabla} \cdot \vec{B}) - \vec{\nabla} \times (\vec{\nabla} \times \vec{B}) = 0$ (both terms in the brackets vanish)

Thus $\vec{\nabla}^2 \vec{B}^2 = 2\left((\vec{\nabla} B_x)^2 + (\vec{\nabla} B_y)^2 + (\vec{\nabla} B_z)^2\right) \geq 0$