TRESURES NEAR THE ABSOLUTE ZERO

Bose-Einstein Condensates and more

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PLAN

1) A quick summary of laser cooling of atoms to quantum degeneracy

2) Bose-Einstein Condensation in an optical trap for neutral atoms at TIFR

3) A short glimpse at some features of magnetic and optical trap BECs

4) Physics of atoms near the absolute zero: some examples with Bosons and Fermions

5) The larger picture

Bose-Einstein Condensation in TIFR

Some features that has attracted attention:

1) First BEC in India and the only one at present

2) One of the four or five optical trap BECs (spinor condensate) around the world

3) Perhaps the largest and the fastest condensing optical trap BEC (1 second). Might cross 10^5 atoms with some optimization. (typical optical trap BEC is 10^4 to $3x10^4$)

4) Fastest condensations in optical lattices as well (1 s) with >50,000 atoms

Bose-Einstein Condensation

Substantial accumulation in the the lowest energy state of a multi-particle system at a temperature above the absolute zero

Einstein to Ehrenfest (1925):
'From a certain temperature onwards molecules "condense" without attractive forces, that is, they accumulate at zero velocity. The theory is pretty, but is there also some truth to it?'

How did he arrive at this conclusion?

Quantentheorie des einatomigen idealen Gases

Zweite Abhandlung.

(in diesen Berichten (XXII 1924. S. 261)
In einer neulich verschienenen Abhandlung wurde unter Anwendung einer von Hrn. D. Bose zur Ableitung der Planck'schen Strahlungsformel erdachten Methode eine Theorie der „Entartung" idealer Gase angegeben.

von Hrn. D. Bose

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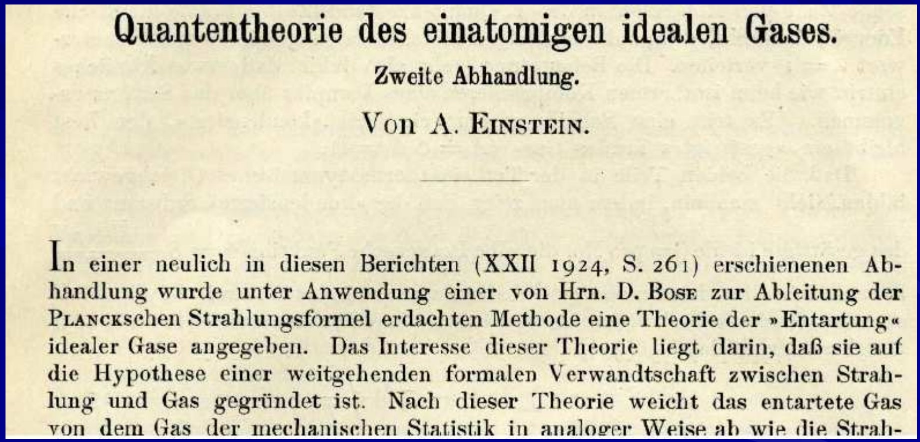
Einstein’s papers in 1924 and 1925:

E’s footnote to Bose’s paper: “In my opinion Bose’s derivation signifies an important advance. The method used here gives the quantum theory of an ideal gas as I will work out elsewhere.”

First paper (1924): The phase space of an elementary object (here of a monatomic gas and in Bose’s paper of a light quantum), associated with a given three-dimensional volume is divided into cells of volume h³…



Quantentheorie des einatomigen idealen Gases.

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$$\frac{1}{\exp\frac{\hbar\omega}{kT}-1} \rightarrow \frac{1}{\exp\frac{(\varepsilon_i-\mu)}{kT}-1}; \qquad \mu \approx -kT/N$$

Second paper in early 1925

$$\frac{1}{\exp\frac{(\varepsilon_i-\mu)}{kT}-1}; \qquad \mu \approx -kT/N$$

$$\frac{1}{\exp\frac{(\varepsilon_i-\mu)}{kT}} \quad \text{for } \varepsilon \approx 0 \rightarrow \frac{1}{\exp\frac{(\varepsilon_i+kT/N)}{kT}} \approx \frac{1}{1+\frac{\varepsilon_i}{kT}+\frac{1}{N}} \approx \frac{1}{1+O(0)} \approx 1$$

The factor is 1 for ALL low energy states without the 'minus 1' of Planck's law: Equal occupation in all low energy states near ground state

$$\frac{1}{\exp\frac{(\varepsilon_i-\mu)}{kT}-1} \approx \frac{1}{\exp\frac{(\varepsilon_i+kT/N)}{kT}-1} \approx \frac{1}{1+(1/N)-1} \approx N \text{ for } \varepsilon = 0$$

$$\frac{1}{\exp\frac{(\varepsilon_i-\mu)}{kT}-1} \approx \frac{1}{\exp\frac{(\varepsilon_i+kT/N)}{kT}-1} \approx \frac{1}{1+(\varepsilon_i/kT)+(1/N)-1} \approx \frac{kT}{\varepsilon_i} \text{ for } \varepsilon_i \neq 0$$

Most atoms (~N) in ground states at finite temperature!

Requirement for BEC

Inter-particle separation < Quantum de Broglie wavelength

Phase space density $\boxed{n\lambda^3 > 1}$

$n = N/V$ Atom number density

$$\lambda = \frac{h}{mv} \longrightarrow \lambda \approx \frac{h}{\sqrt{2k_B T m}} \quad \left(\text{since } mv^2 \approx k_B T\right)$$

De Broglie wavelength

0.02 nm @ 300 K, 60 nm @ 30 μK, 0.3 microns @ 1 μK

Inter-particle separation

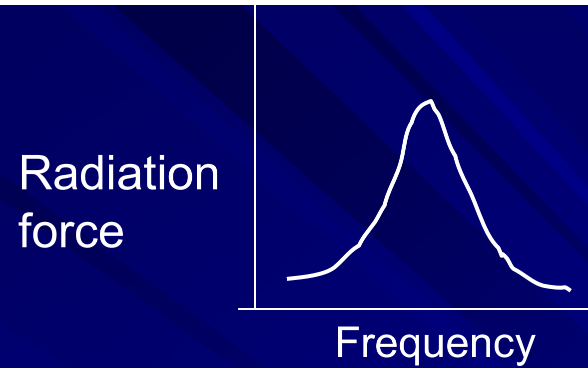
$1/n^{1/3} \approx 2$ microns@ 10^{11} atoms/cc, 0.2 microns@ 10^{14} atoms/cc

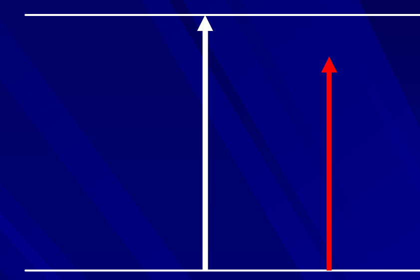
Magneto-optical trap: $n\lambda^3 = 10^{-6}$

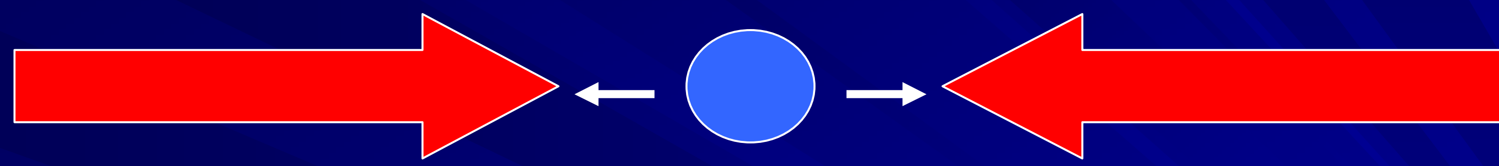
ENERGY SCALES:

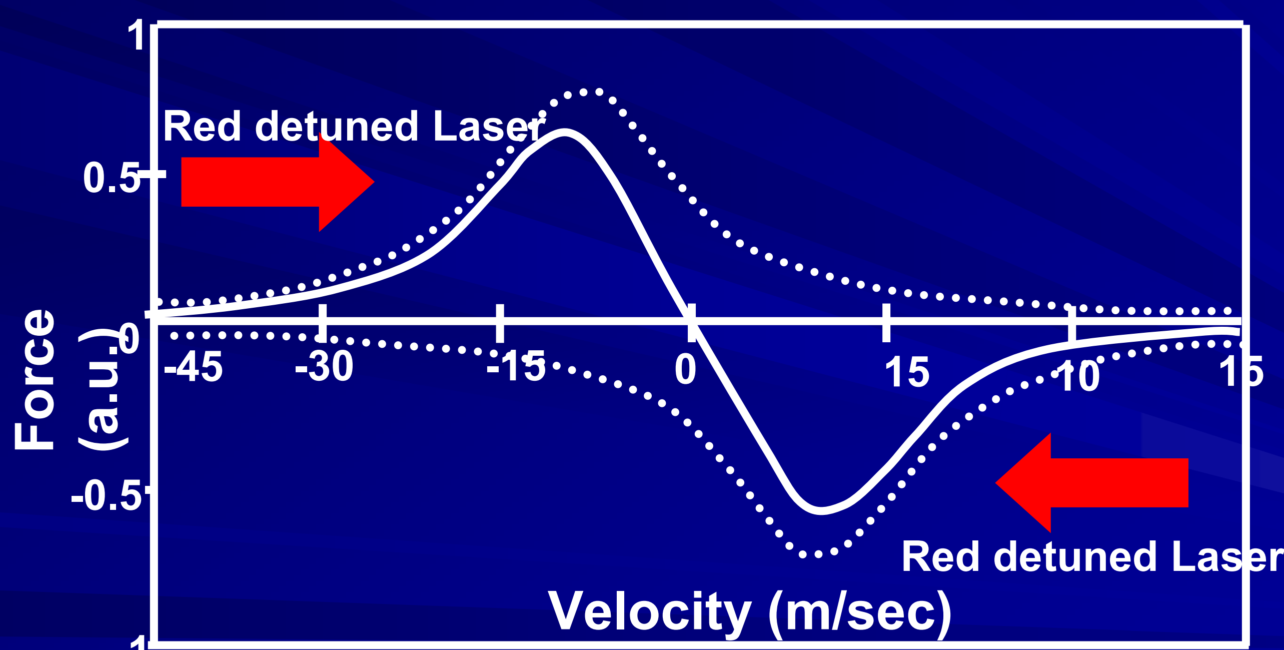
	Frequency	Equivalent temperature
Thermal atom		300 K
Electronic levels	$>3\text{x}10^{14}$	15000 K
Single photon recoil		0.1 – 0.3 μK
Line-width	6 MHz	300 μK
Hyperfine	1 GHz	50 mK
Harmonic trap	<1 kHz	<50 nK
BEC		200-1000 nK

LASER-COOLING





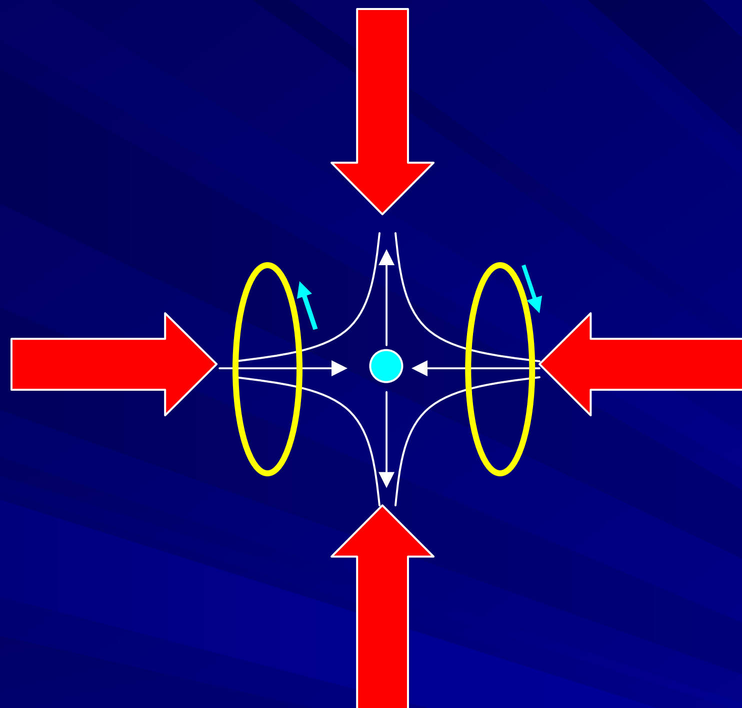




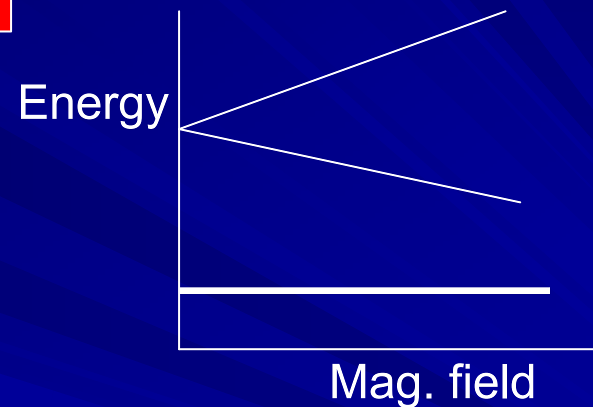
$$\vec{F} \propto -\vec{v}$$

Velocity-dependent force on atoms: Friction Damping

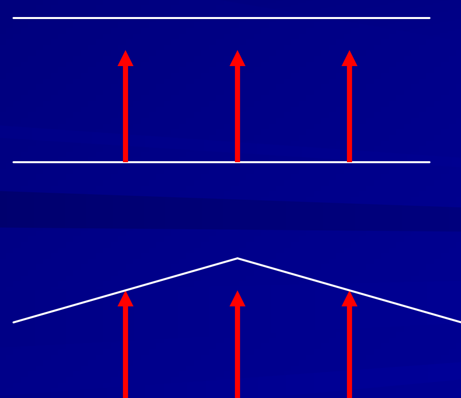
Magneto-Optical trap (MOT)



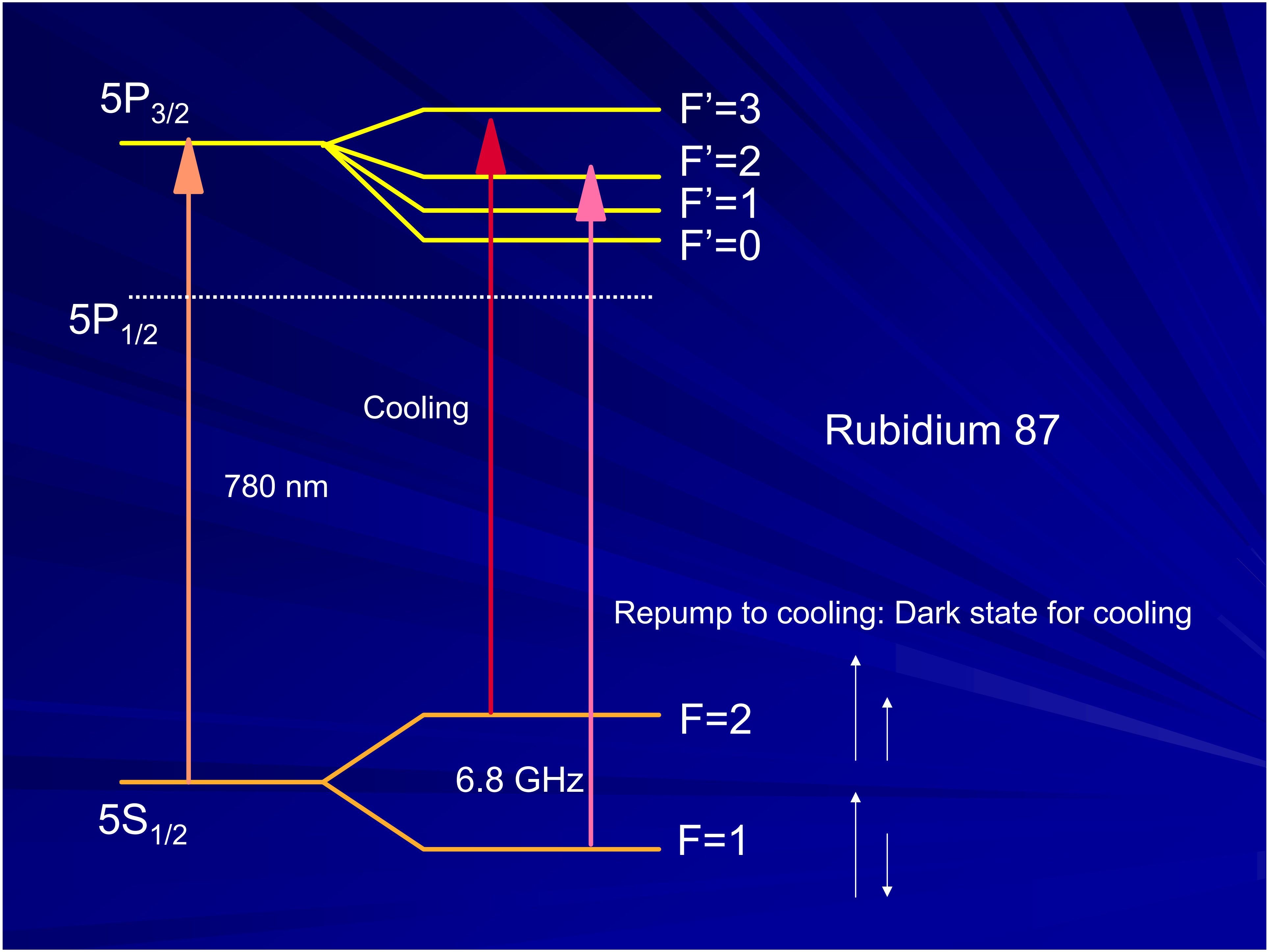
$$E(r) = -\mu \cdot B(r)$$



Energy levels

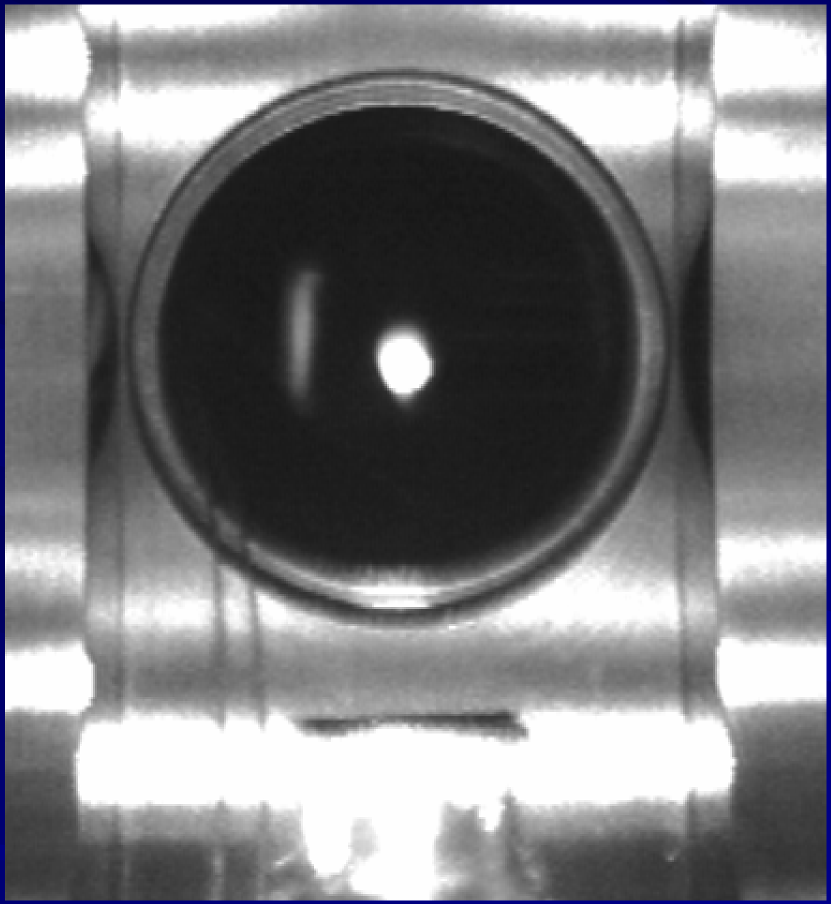


Velocity dependent force



$5P_{3/2}$
F'=3
F'=2
F'=1
F'=0
$5P_{1/2}$
Cooling
Rubidium 87
780 nm
Repump to cooling: Dark state for cooling
F=2
6.8 GHz
$5S_{1/2}$
F=1

Fluorescence Image by CCD



Cloud size ~ 1 mm

Number of atoms: $10^6 – 10^7$

Density ~ 10^{10} atoms/cc

Temperature : <100 micro-K

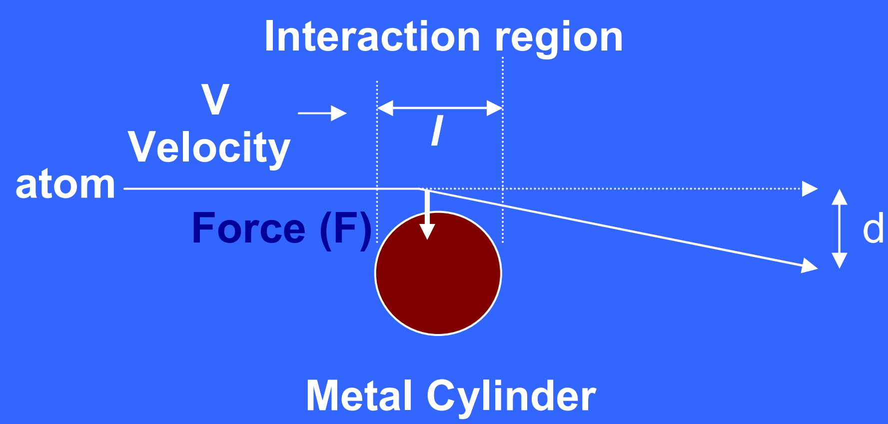
Inter-particle separation: 2 microns

De Broglie wavelength: 40 nm

$$n\lambda^3 \approx 10^{10}\ \text{atomc/cc} \cdot (45\ nm)^3 \approx 10^{-6}$$

To reach 1

$$n\lambda^3 \approx 10^{14}\ \text{atomc/cc} \cdot (300\ nm)^3 \approx 2.7$$

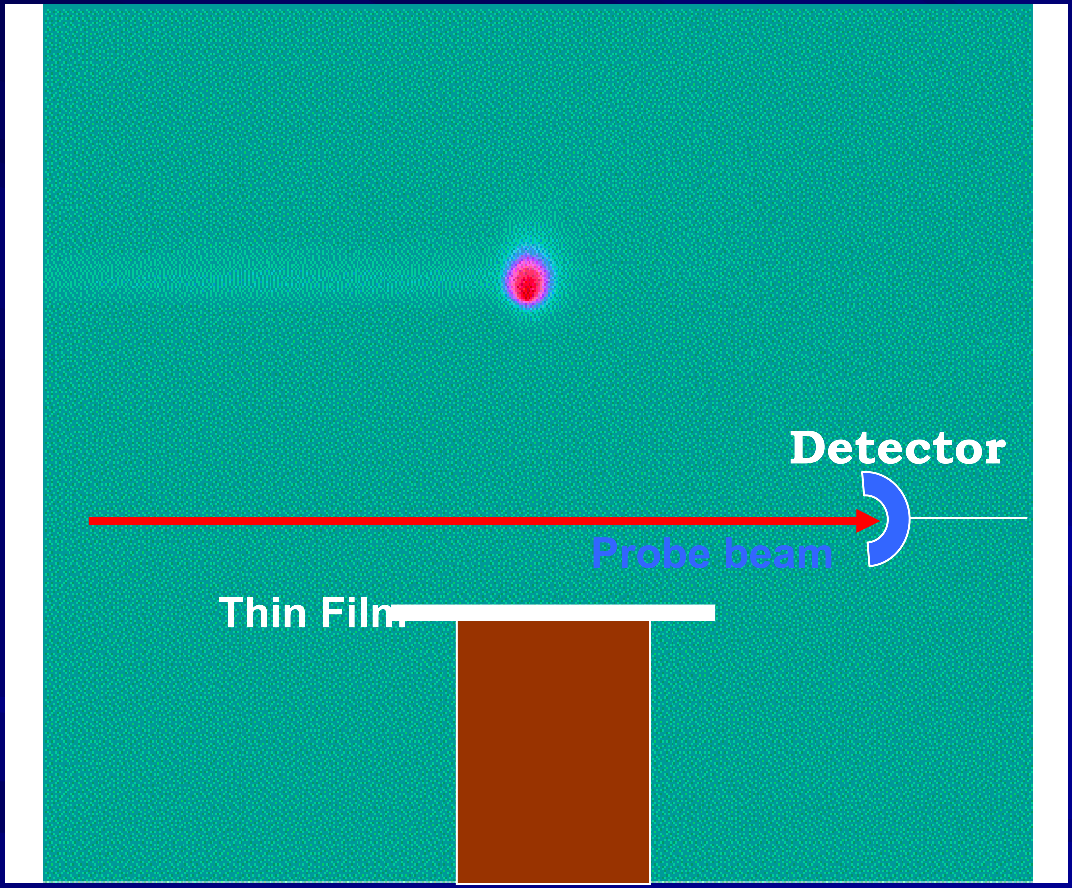


$$d : \frac{Fl^2}{mV^2}$$

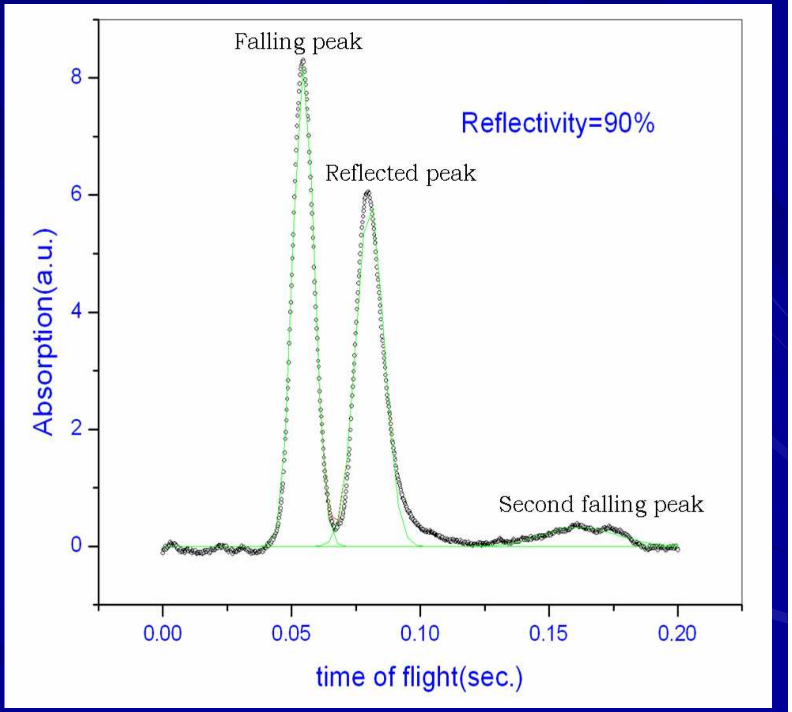
Slow laser cooled atoms at V < 1 m/s are very good for such studies since the signal increases by up to 10^6 compared to thermal beams

There are also spectral shift and phase changes, enhanced by similar factors. Great advantage for short range experiments.

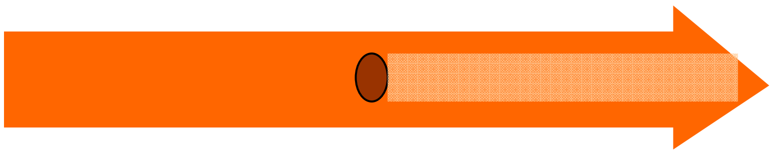
Reflection of spin-polarized ^{85}Rb atoms from magnetic thin film: Measurement of short-range forces



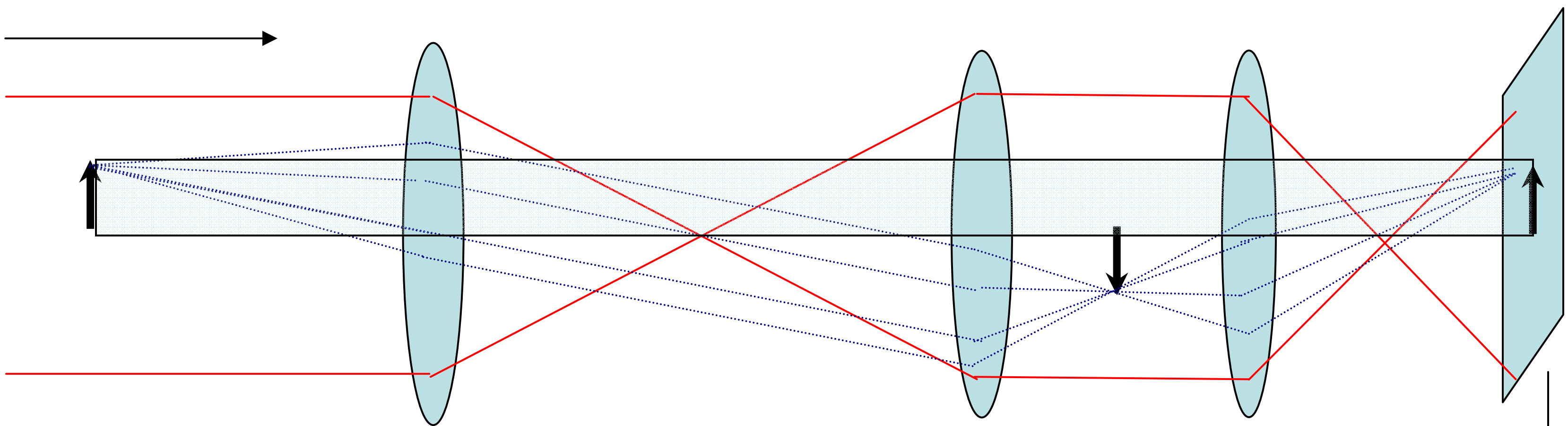
Time-of-flight signal



A. K. Mohapatra and CSU, Europhys. Lett (2006), EPJD (2007)



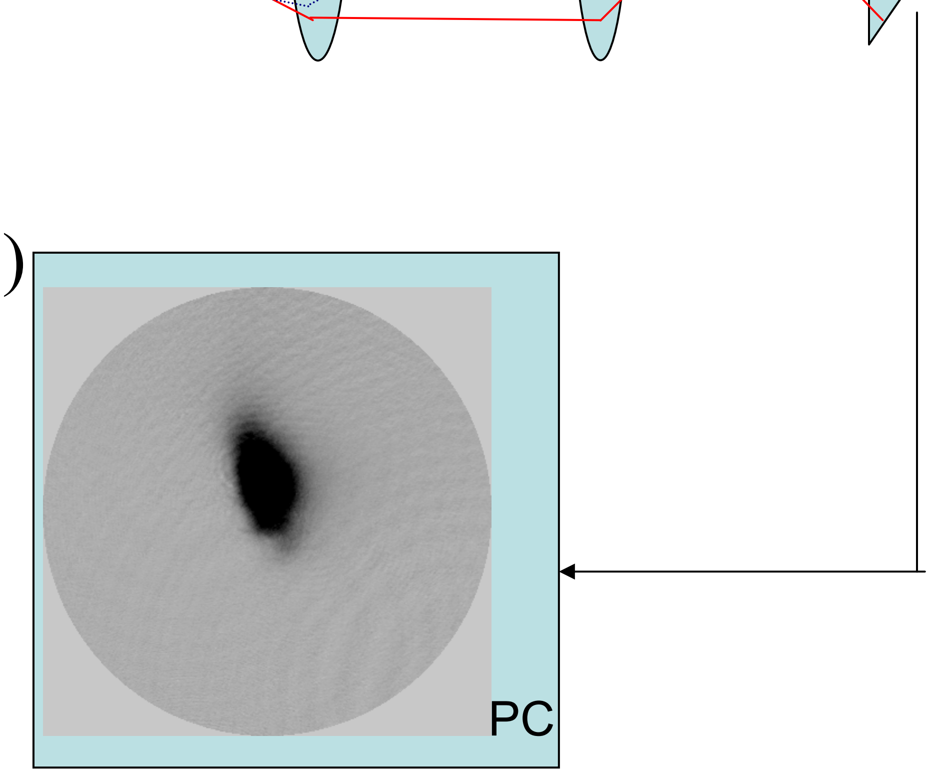
Absorption imaging



$$I = I_0 \exp(-\sigma \int n(x,y,z)dz)$$

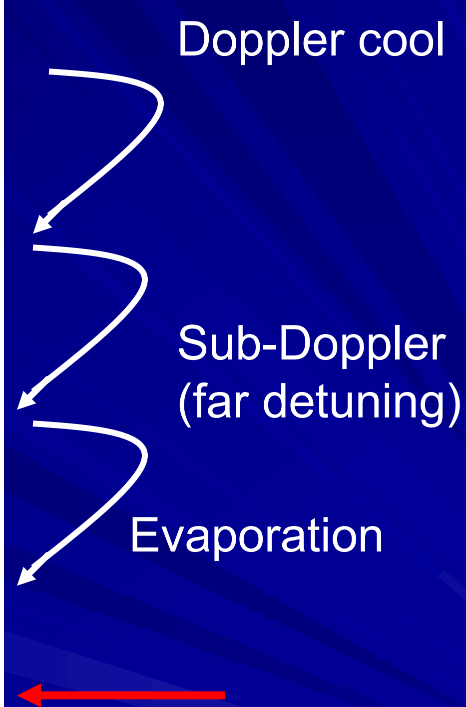
$$I / I_0 = \exp(-\sigma n_{col})$$

Optical density



Temperature and speeds

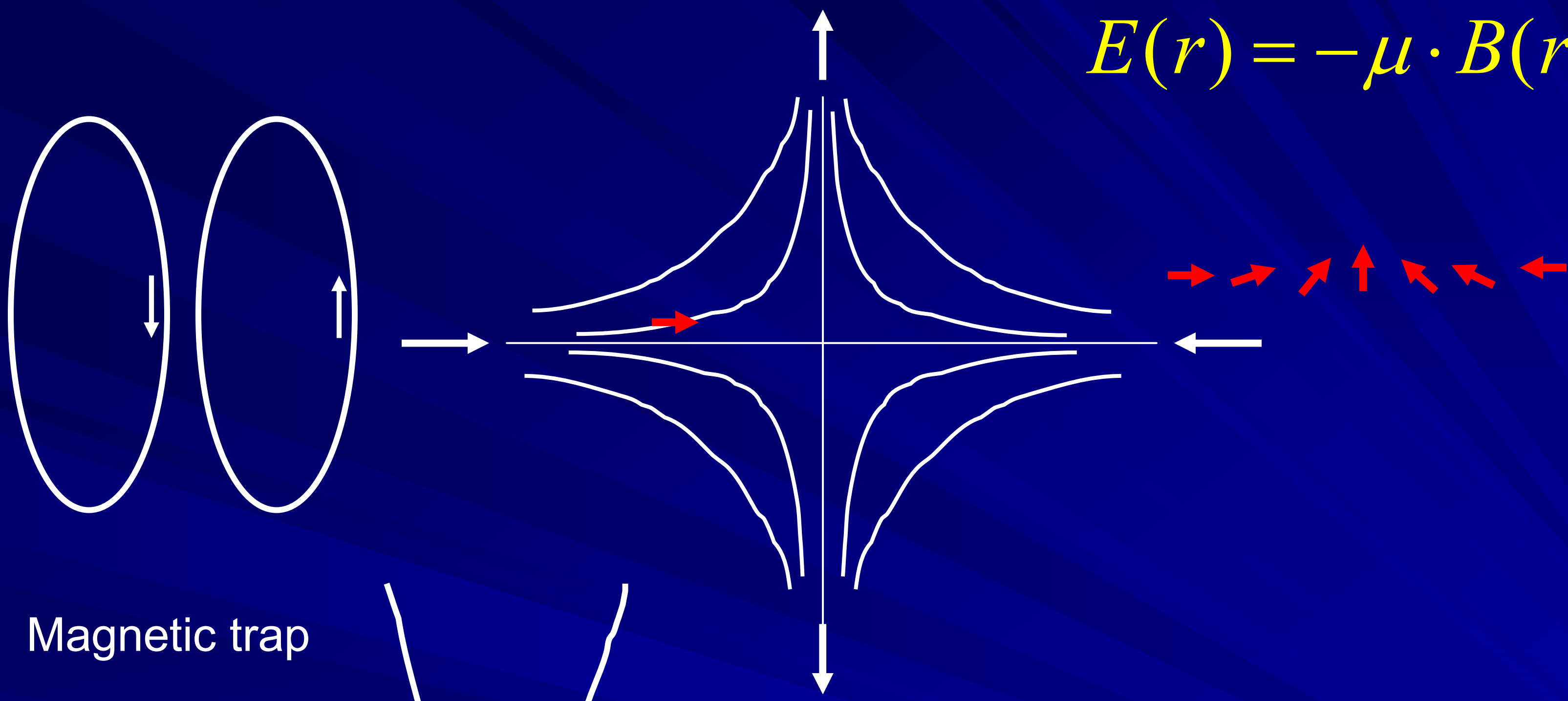
	Temperature	Velocity
Thermal atom	300 K	300 m/s
MOT	100 µK	15 cm/s
MOT with forced sub-Doppler	10 µK	5 cm/s
BEC	200-1000 nK	1 cm/s
Single photon recoil	0.1 – 0.3 µK	1 cm/s



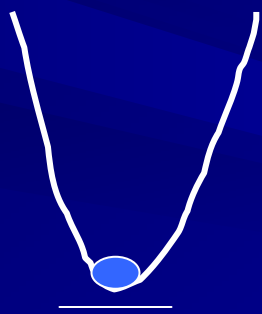
Last stage of cooling should avoid near-resonant light.

Magnetic traps

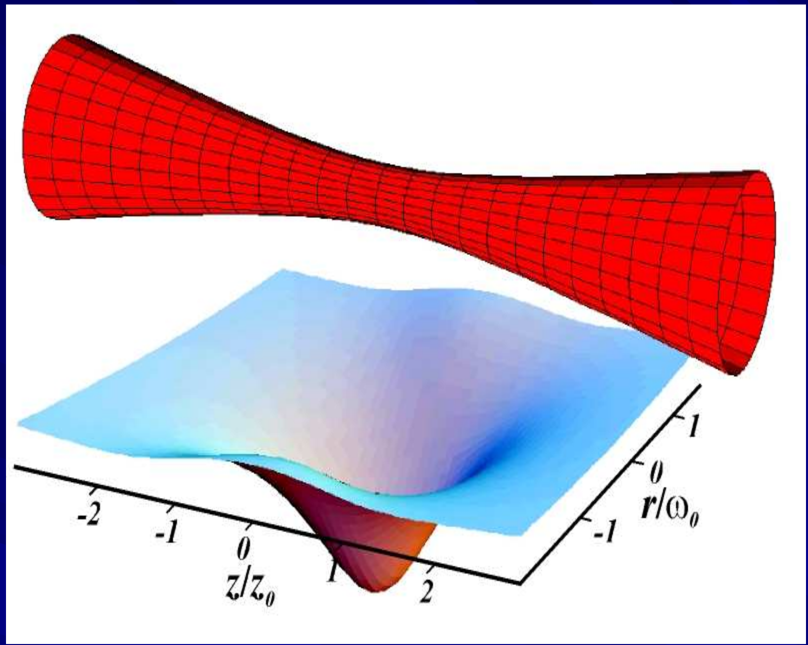
$$E(r) = -\mu \cdot B(r)$$



Magnetic trap



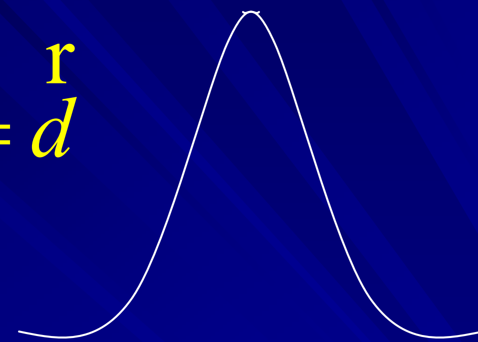
Optical Traps



Most BECs including the first ones in 1995 are produced in magnetic traps, and they are naturally magnetized (one spin-state), whereas an optical trap BEC (2001) is unmagnetized (general superposition or mixture of spin states). This technique of cooling is applicable to atoms with no magnetic moment, or to Fermions, and it allows optical lattice experiments as a simple extension, even in a magnetic field.

Atom in a laser field:

$$\frac{d^2x}{dt^2}+\omega_0^2 x = \frac{e}{m_e}E(t) \rightarrow \times e \rightarrow e\vec{x} = \vec{d}$$

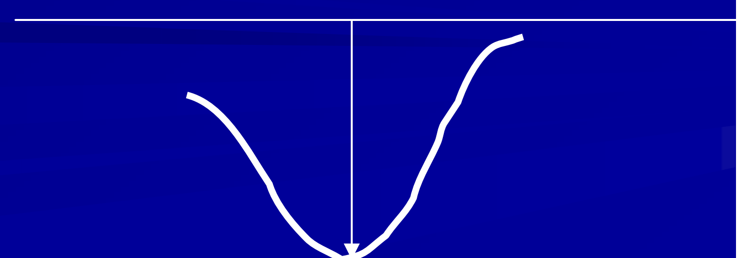


Response to an oscillating electric field,

$$\alpha(\omega) = \frac{e^2}{m_e\left(\omega_0^2-\omega^2\right)}$$

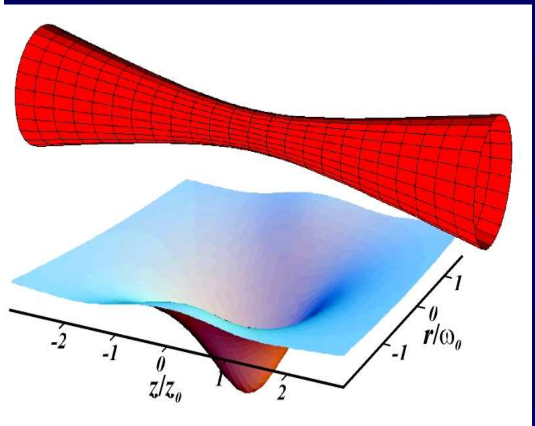
$$\text{Energy } V(r) = -\vec{d}\cdot\vec{E}_0 = -\frac{1}{2}\alpha(\omega)E_0^2 = -\frac{1}{2}\alpha(\omega)I(r)$$

The trapping potential follows the ‘shape’ of the laser beam intensity



Optical dipole trap

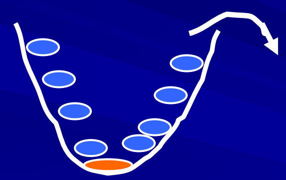
$$V(r) = -\frac{1}{2}\alpha(\omega)E_0^2 = -\frac{e^2E_0^2}{2m_e\left(\omega_0^2-\omega^2\right)}$$



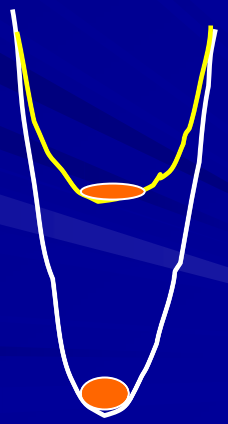
Near Resonance, $V(r) \approx -\frac{e^2E_0^2}{4m_e\omega_0\left(\delta\omega\right)} : \; -I/\delta$

$$V(r) = -\alpha_{stat} I(r)/2\varepsilon_0 c$$ (Well below res.)

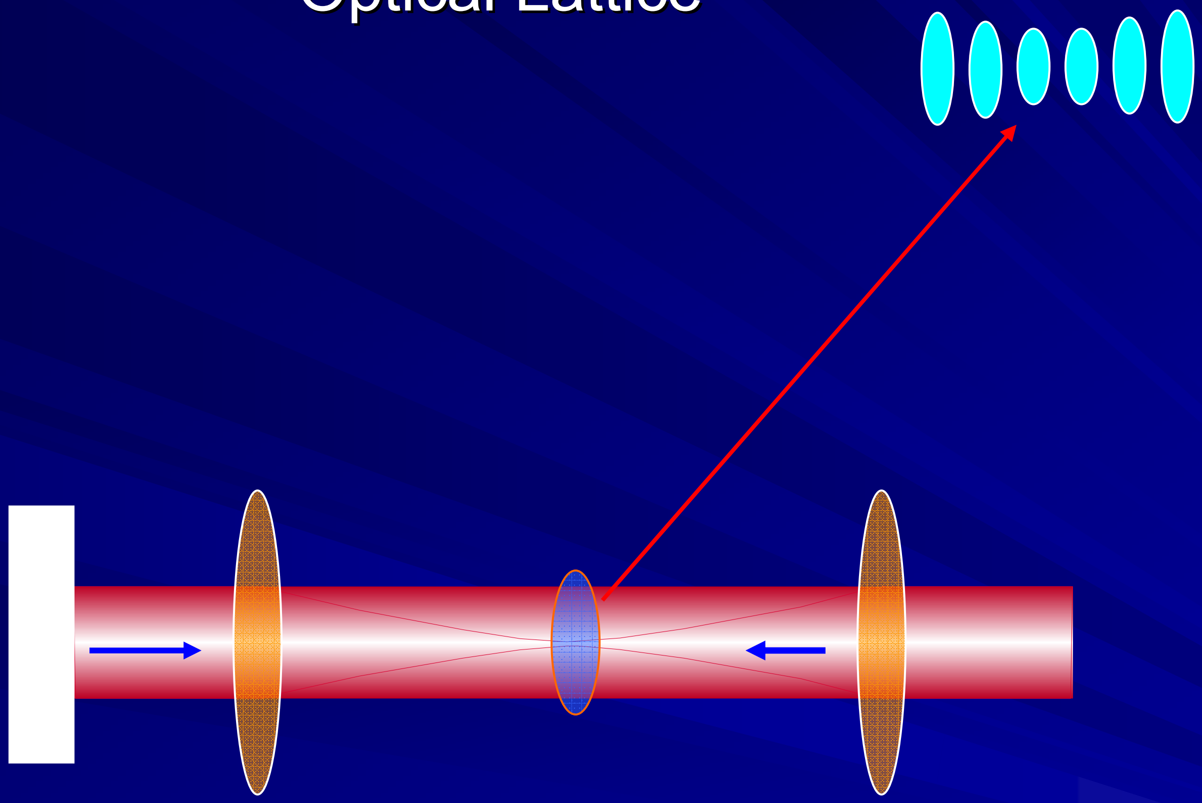
$$V_0 = \alpha_{stat} I_0/\varepsilon_0 c, \;\; I_0 = 2P/\pi w^2$$



Evaporation can be done by relaxing the trap
(Reduce the laser power)



Optical Lattice



Reflecting on itself gives a series of nodes and anti-nodes: a lattice of optical trapping potentials

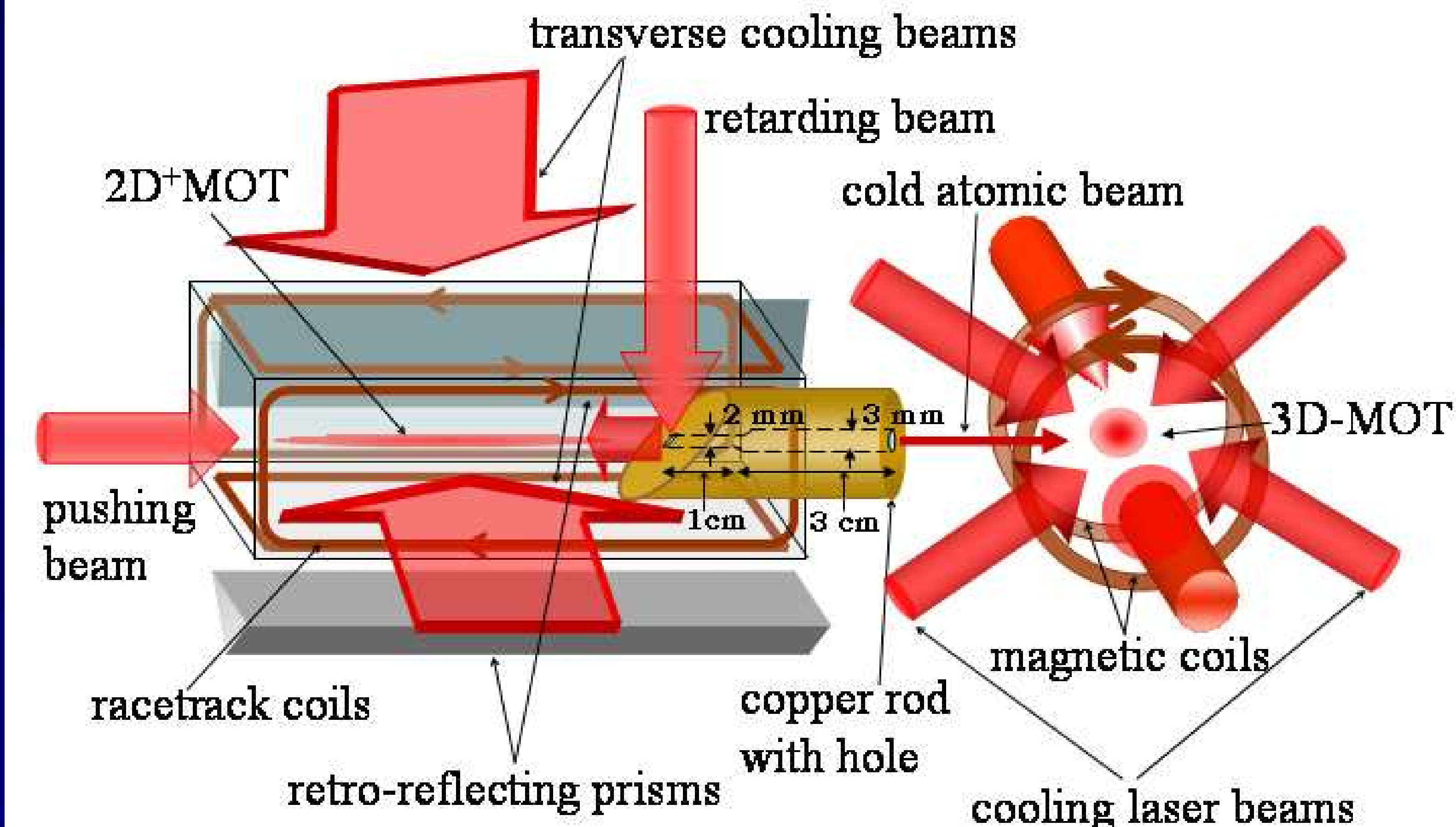
Strategy

1. Optical trap instead of the more popular magnetic trap: Conceptually simpler, better control, magnetic state – independent (and rare – only <u>one</u> when we planned in 2003; now about 5)

2. Plan for very large number of atoms in the MOT to start with : possibility to start with high density

3. Achieve BEC with moderate values for control parameters like trap light intensity (50 watts), focus (70-100 microns)

4. Naturally accommodate optical lattices (standing wave of light, and atoms can get trapped in the periodic potential)

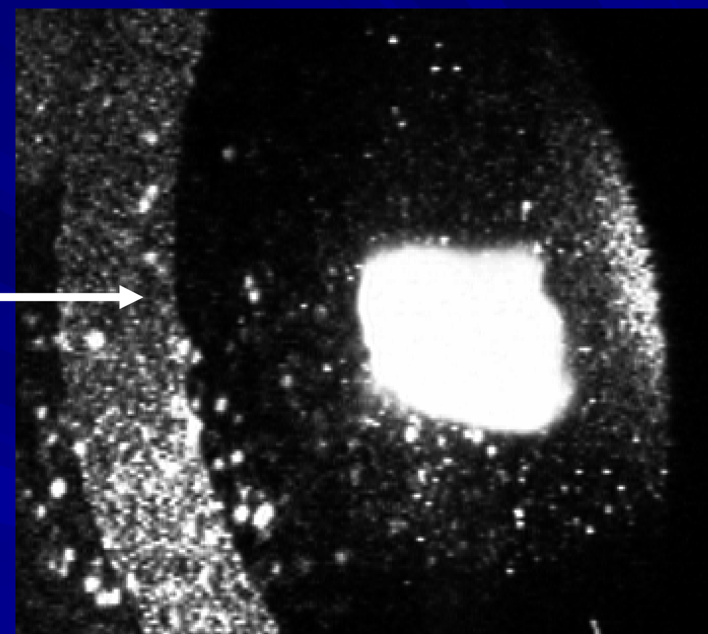


S. Chaudhuri, S. Roy, Unnikrishnan, Phys. Rev. A (2006)

Magneto-optic Trap loaded from cold atomic beam

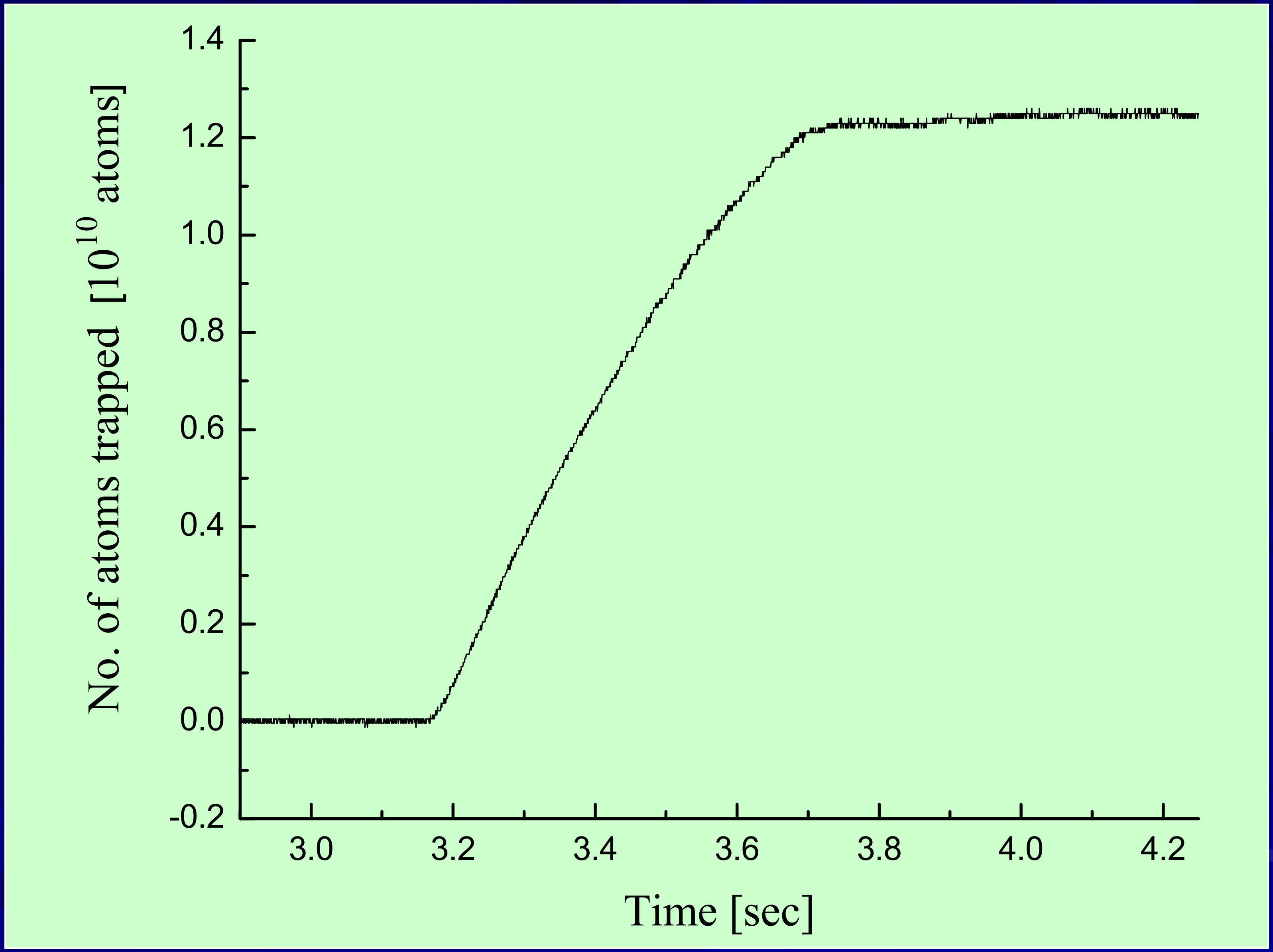
Push the atoms using light

Cold atomic beam



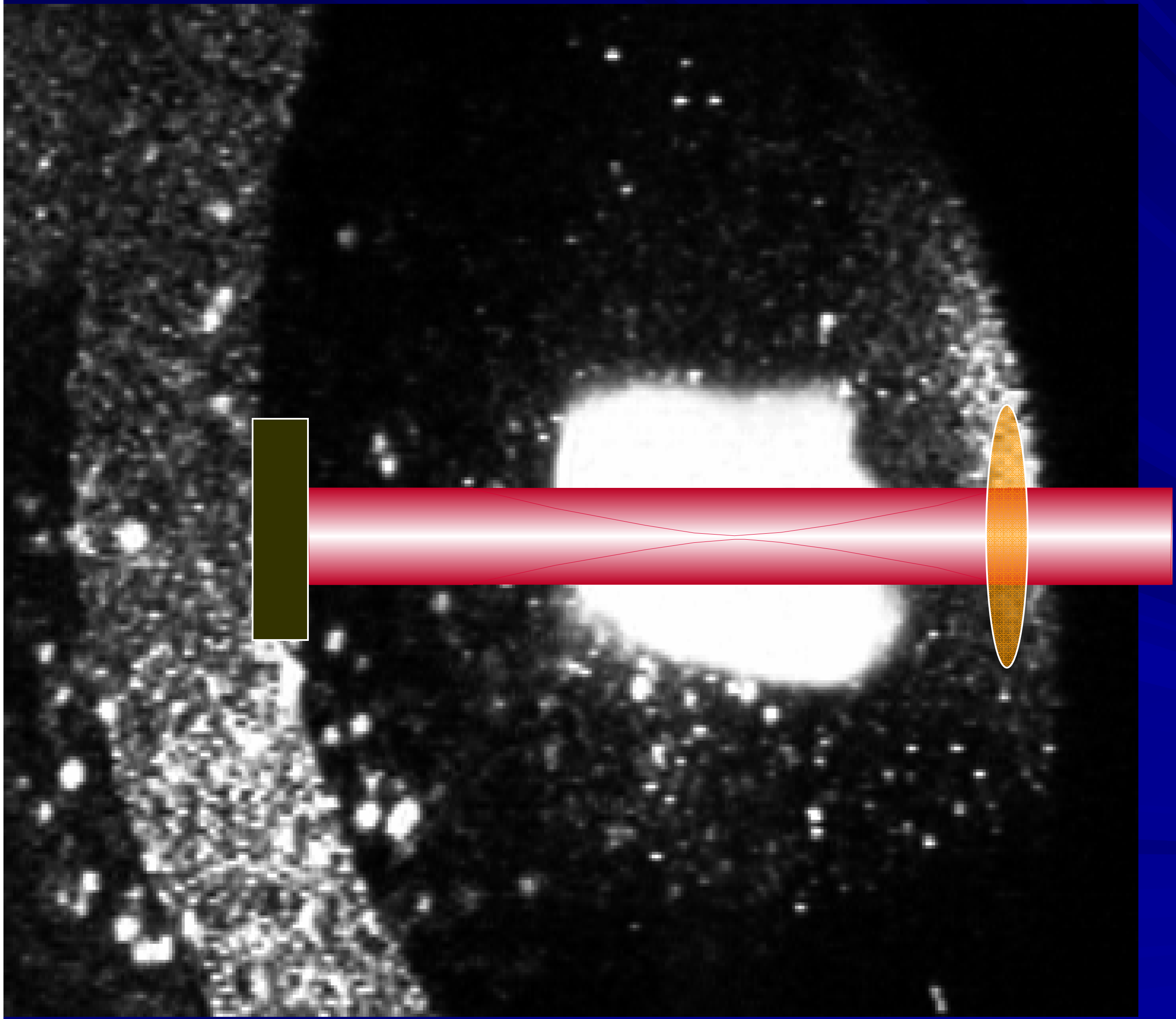
Magneto-Optic Trap

Atomic beam loaded MOT has 1000 times more atoms than background loaded MOT



> 10^{10} atoms /second loaded when optimized

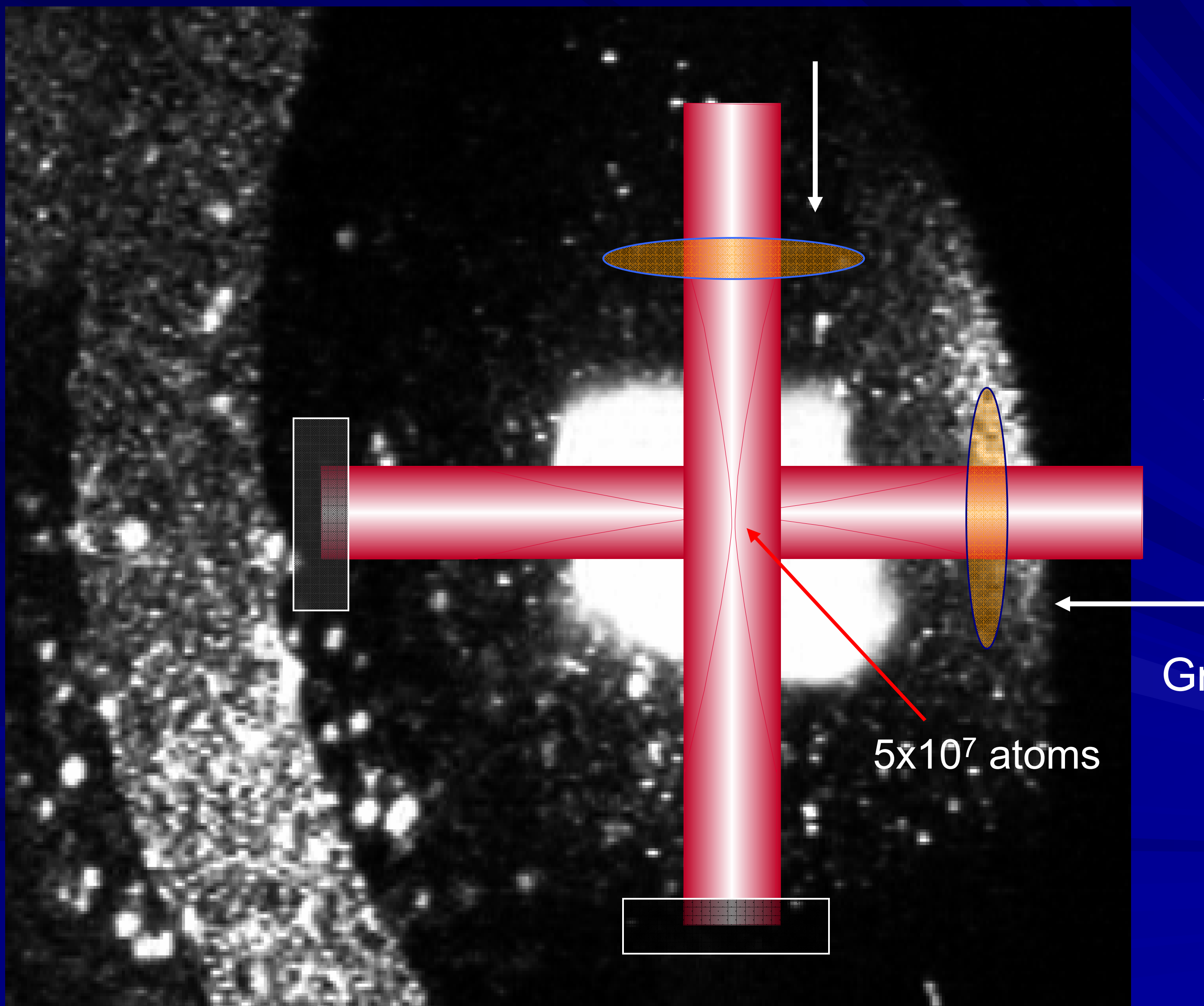
Optical dipole trap



CO_2 Laser: Quasi-Electrostatic Trap (QUEST) for atoms

C. K. N. Patel

Crossed beam optical dipole trap



Trap Depth for

P = 20W each,

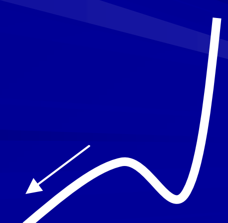
Beam waist dia. =100 micron

$\lambda = 10.6\mu m$

is

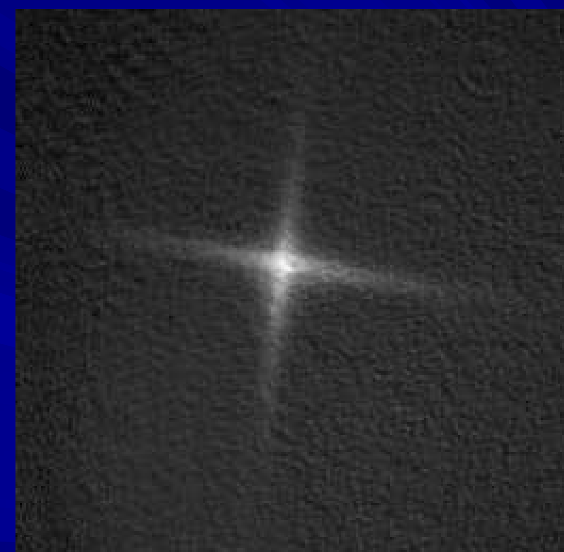
$> 400\mu K$

Gravity: 6 micro-K



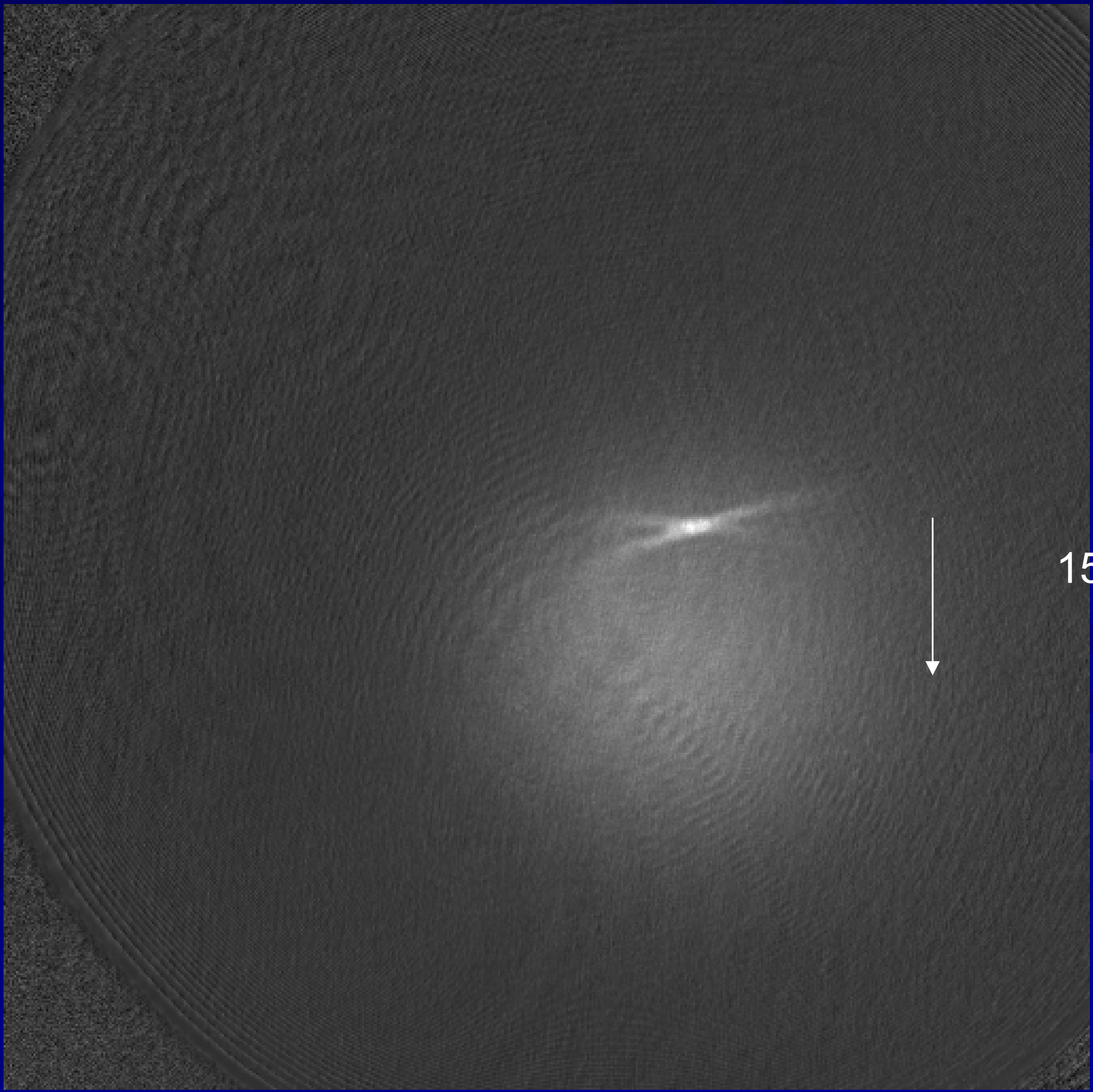
Absorption images of atoms trapped in the optical dipole trap

2 mm



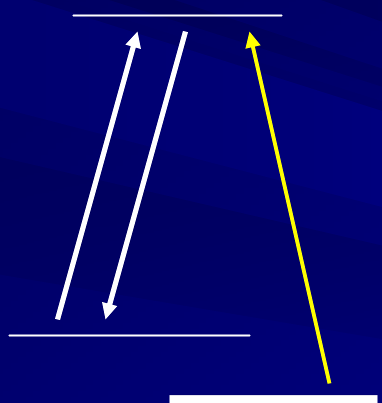
Number of atoms in the dipole trap ~ 10^6 - 10^8

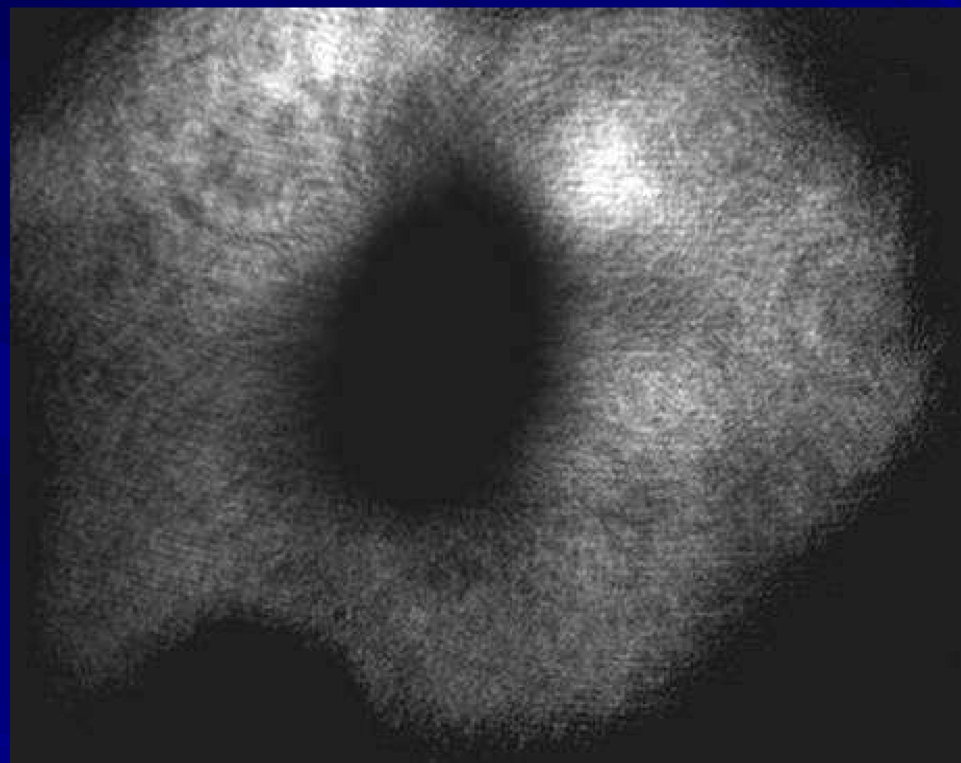
Crossed optical trap and the falling cloud from MOT



15 ms of free fall

Enhancing the density with darkness



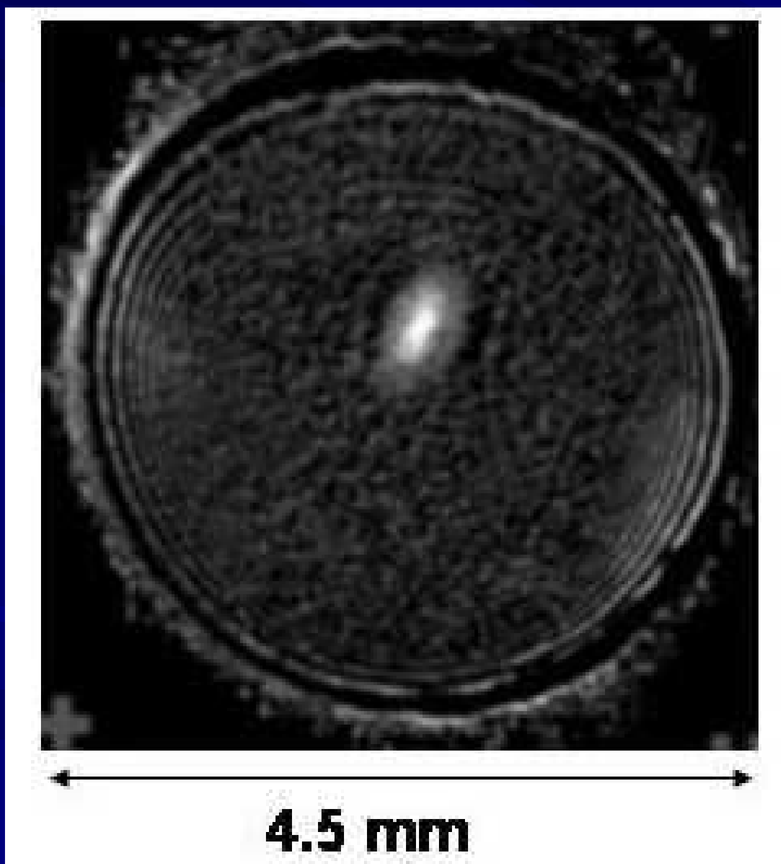


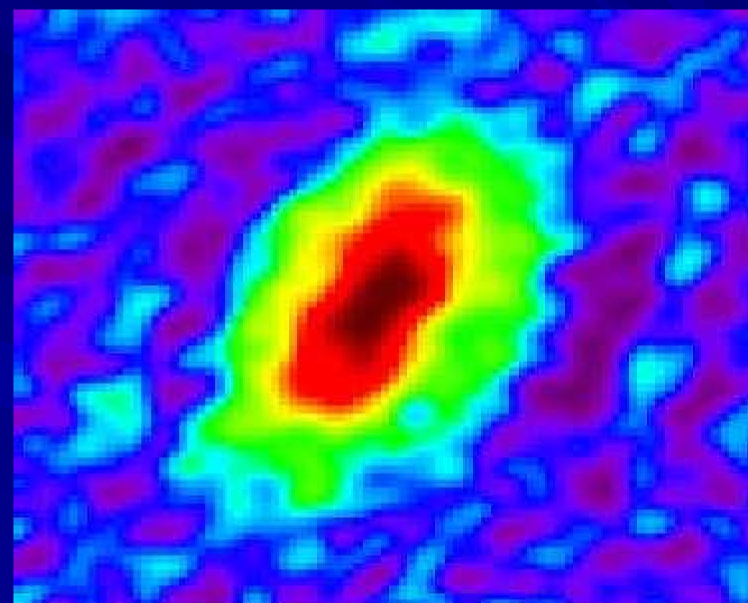
Temperature: $40\mu K$

Dark MOT

Atom no. density $\approx 5 \times 10^{12}$ atoms/cc

Atoms in the crossed dipole trap
(25 micro-K)



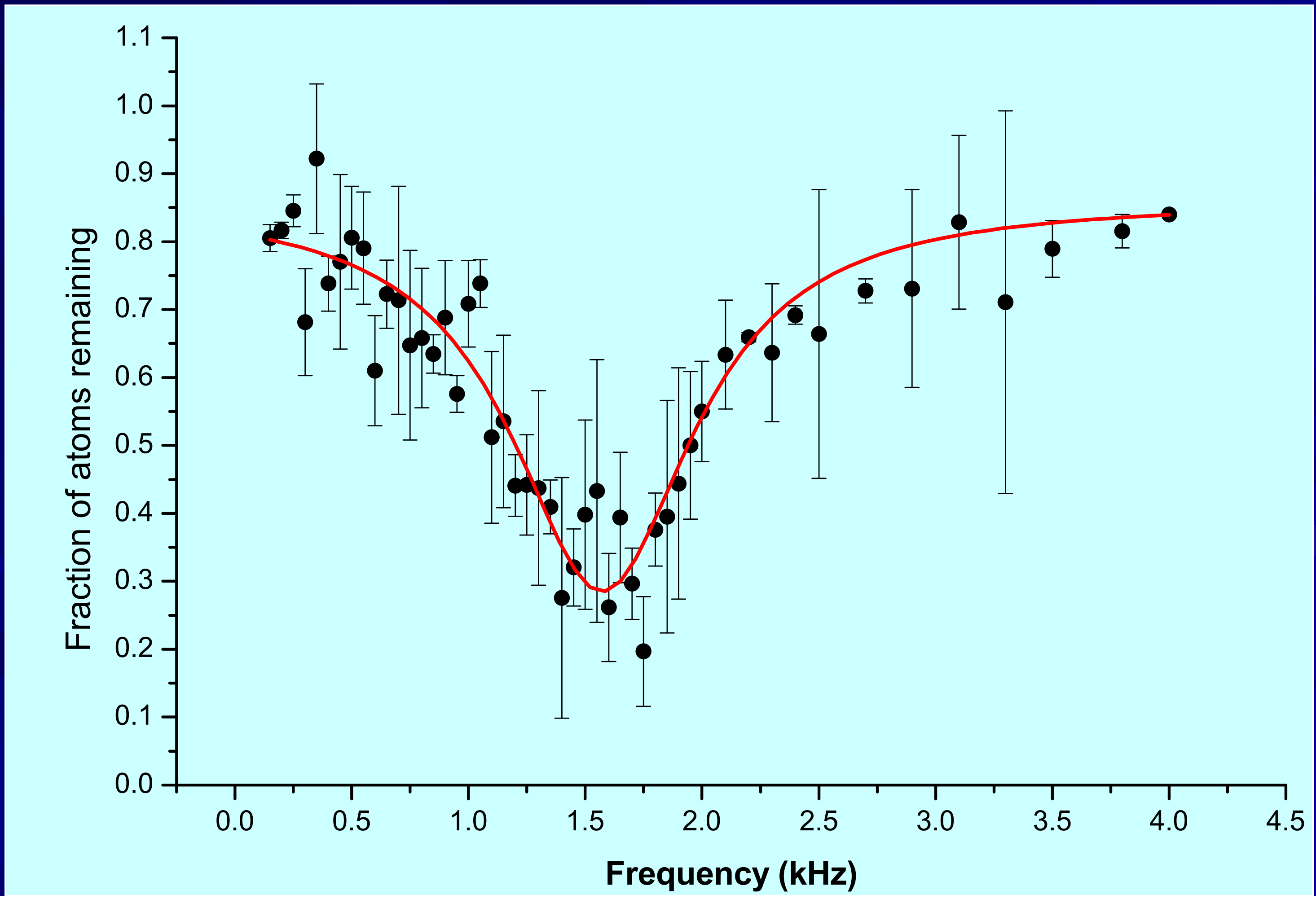


350 microns

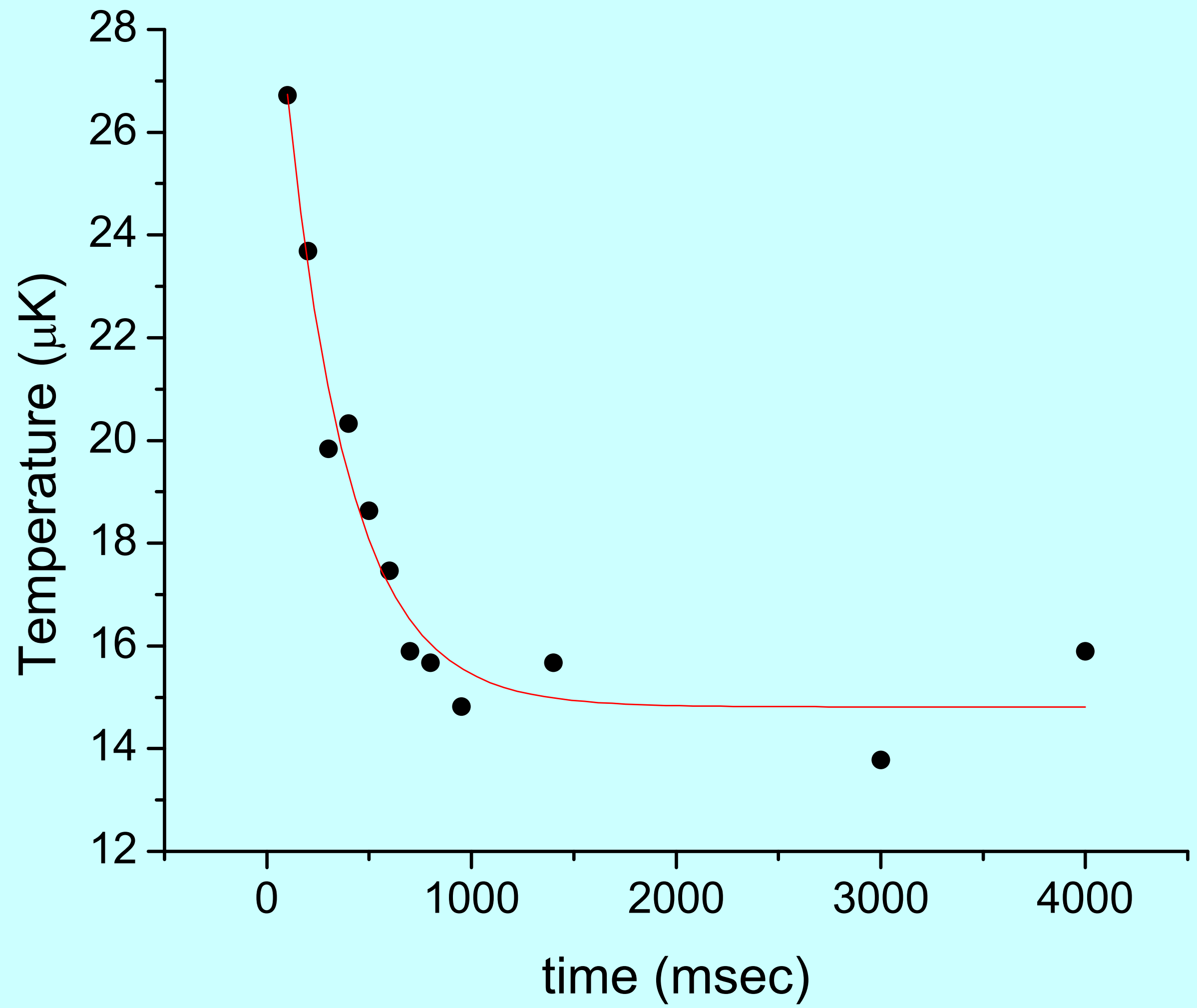
Peak density > 10^{14} atoms/cc

Single beam trap depth (frequency) from parametric resonance

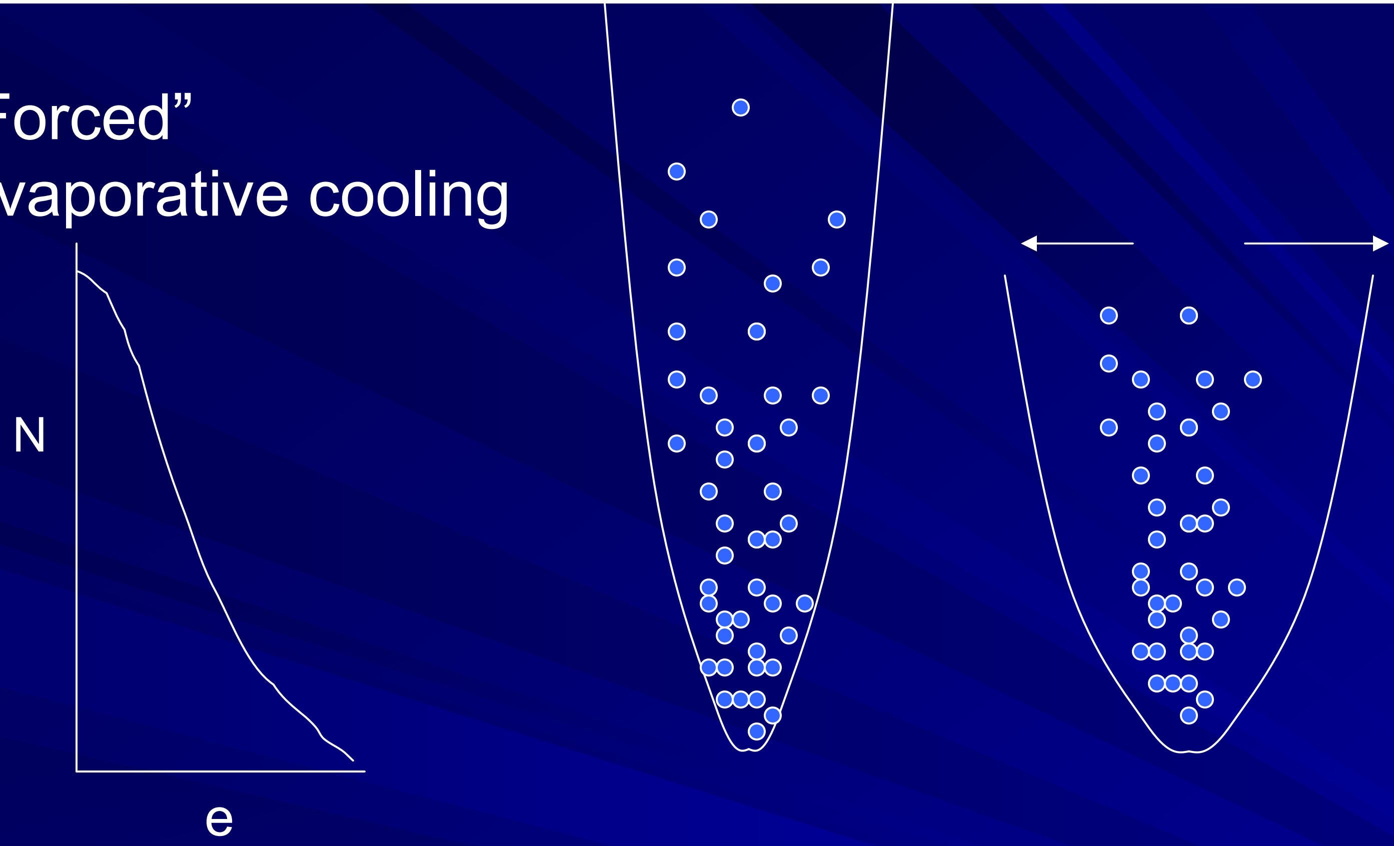
Radial frequency $\omega_r = \sqrt{\dfrac{4U_0}{mw^2}}; \quad U_0 \sim I_0$



Cooling by spontaneous evaporation



“Forced”
Evaporative cooling



$$T = N^{\alpha}, \alpha : 1-2$$

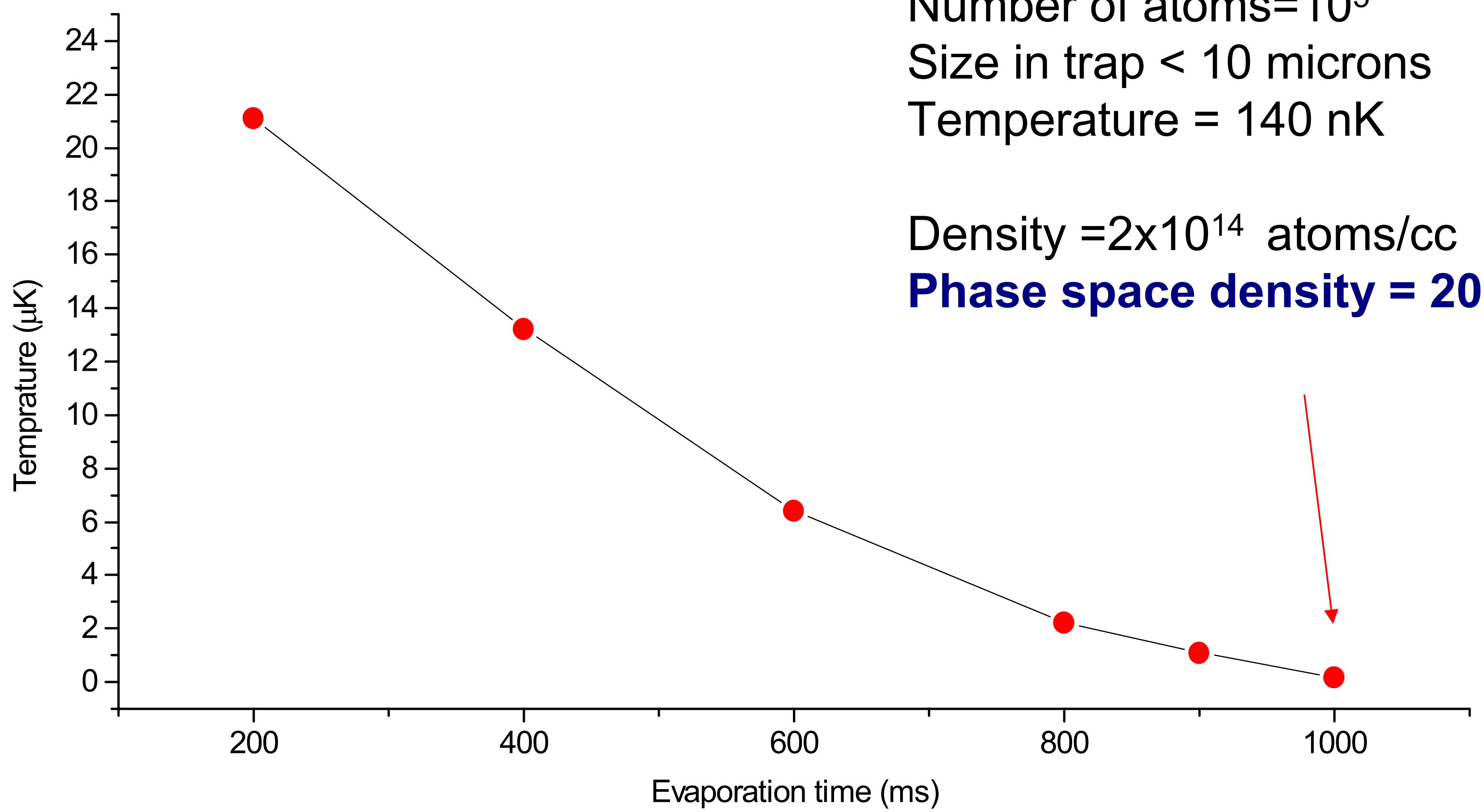
‘Efficient’ even with T ~ N

Phase space density $$n\lambda^3 > 1$$

In a harmonic trap $$T_c \approx \frac{\hbar\omega_0 N^{1/3}}{k_B} \rightarrow 10^{-11}\omega_0 N^{1/3}$$

When density is more or less constant, PSD increases as $1/T^{3/2}$

Evaporative cooling to BEC transition



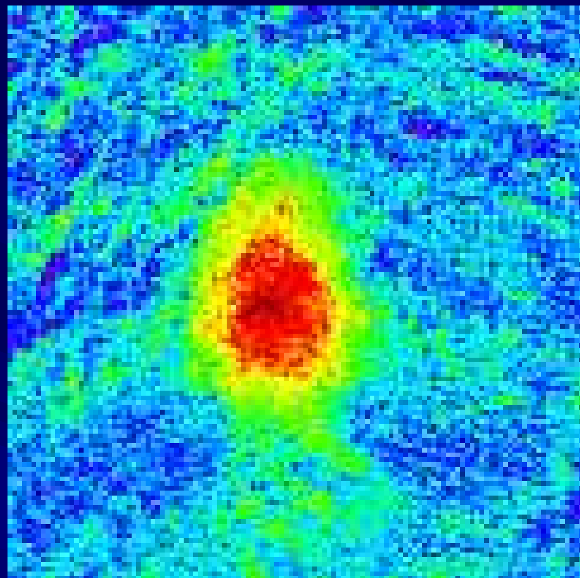
Number of atoms=10^5
Size in trap < 10 microns
Temperature = 140 nK

Density =$2x10^{14}$ atoms/cc
Phase space density = 20

Thermal de Broglie wavelength=0.4 microns;
Inter-particle separation=0.15 microns

Evaporative cooling to BEC

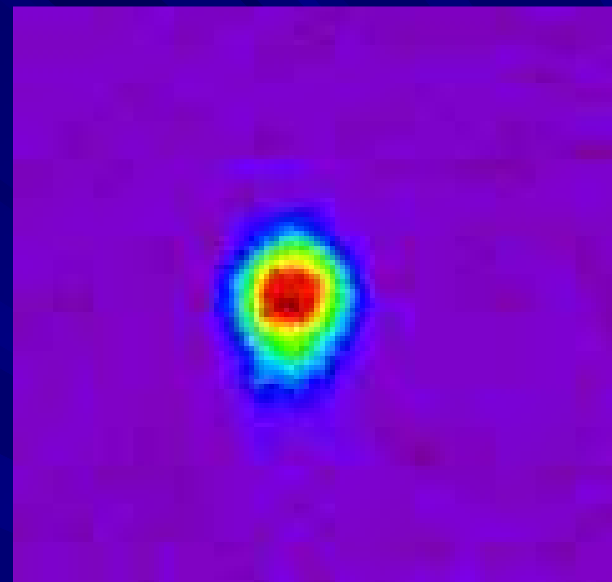
300 micron



200 ms

T=18 μK

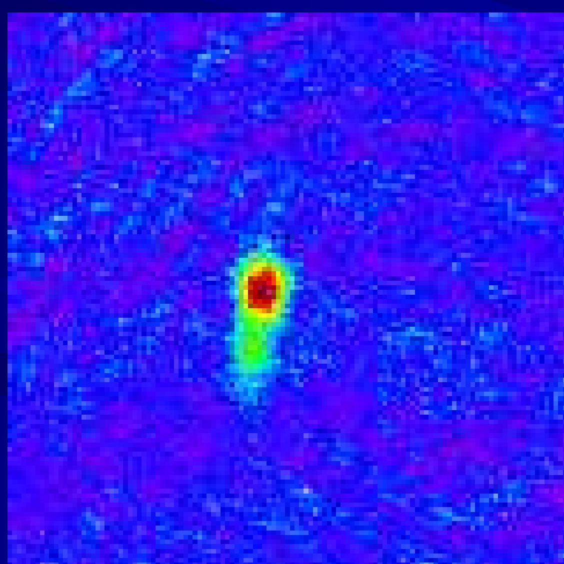
$\Lambda > 0.013$



600 ms

T= 1 μK

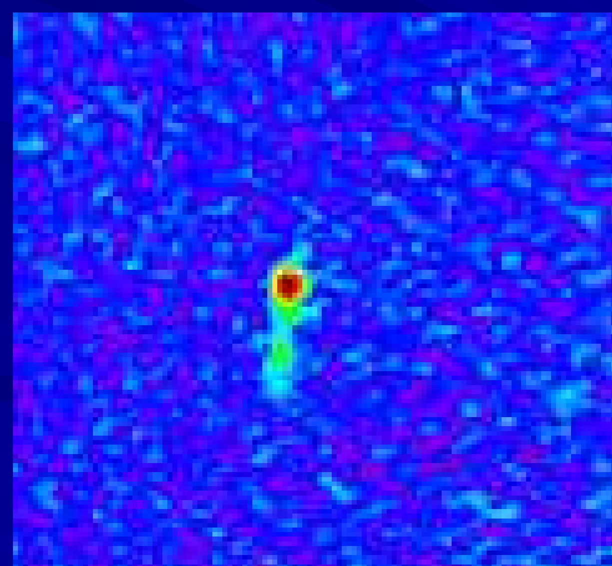
$\Lambda \approx 0.3$



900 ms

T= 400 nK

$\Lambda \approx 4$

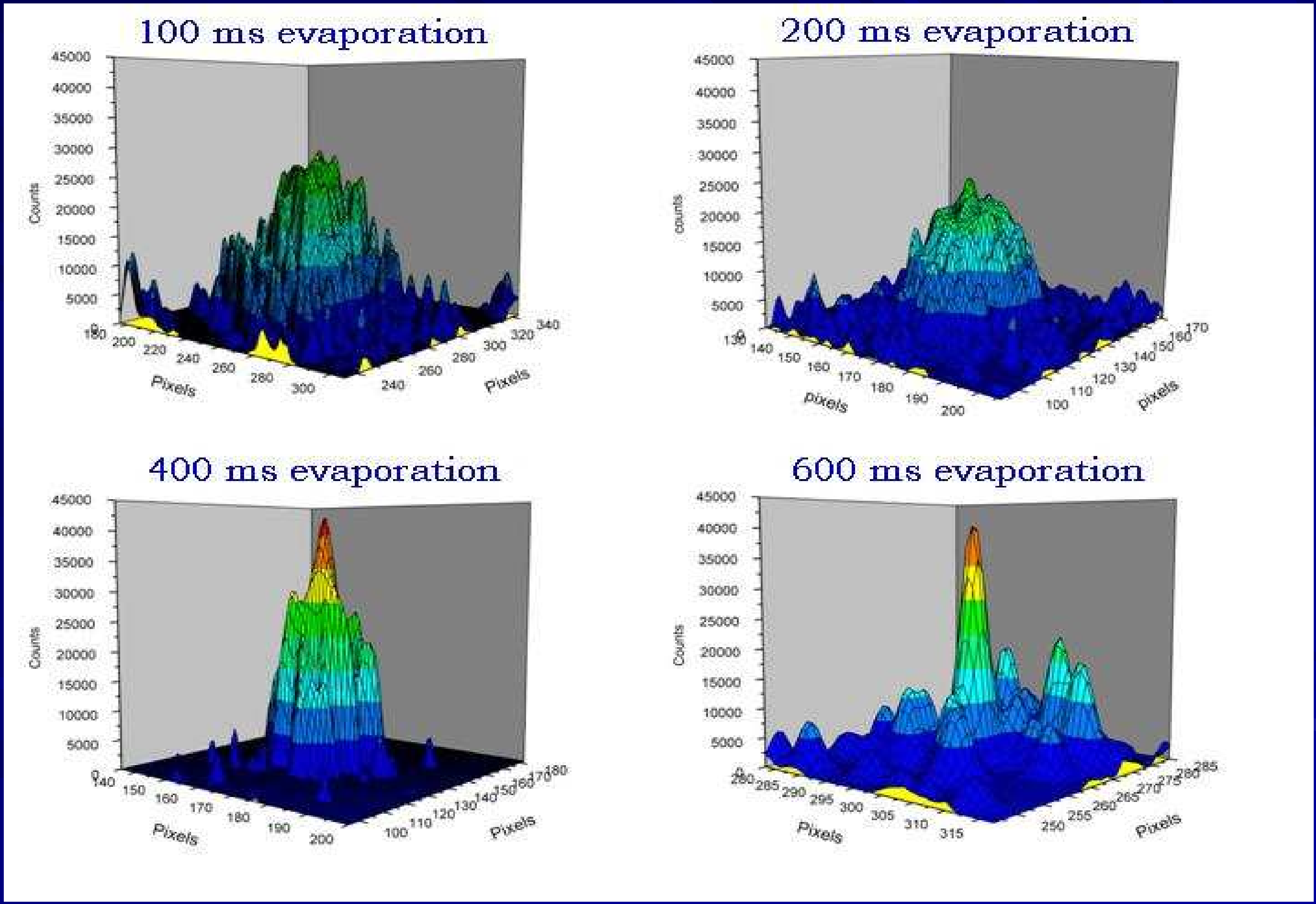


1000 ms

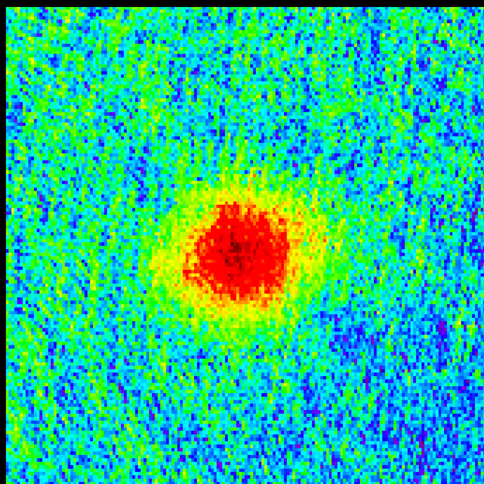
T=140 nK

$\Lambda \approx 20$

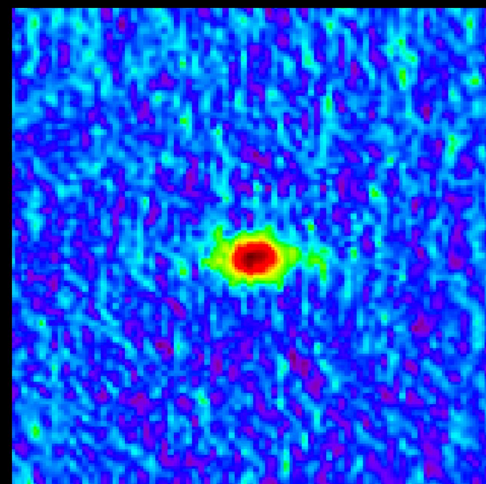
BEC Phase transition



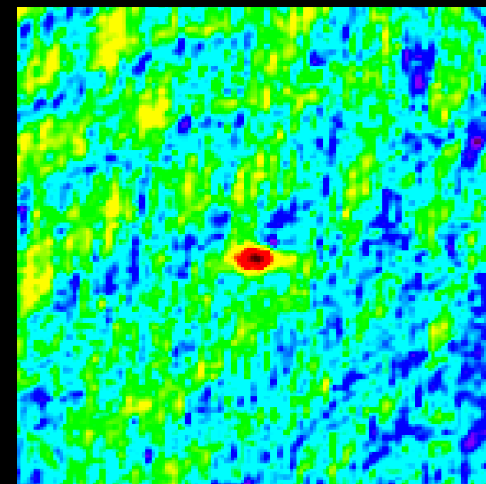
BEC in crossed Optical dipole trap



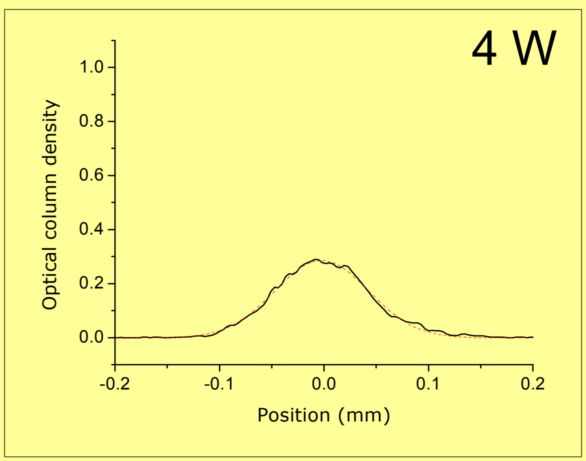
700 nK

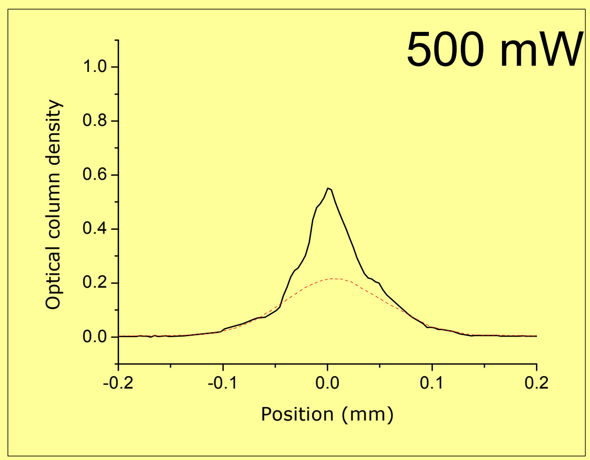


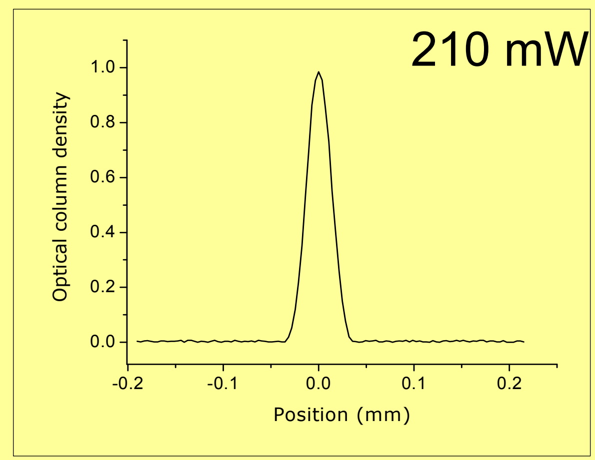
250 nK



140 nK



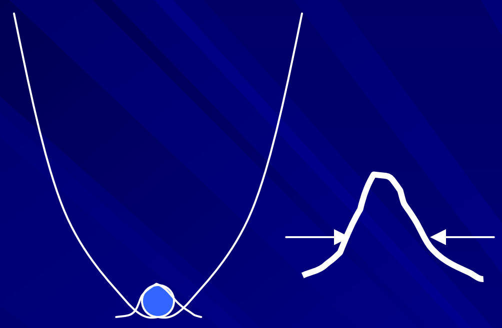




Size of the condensate

$$a_h = \left(\frac{\hbar}{m\omega_0} \right)^{1/2}$$

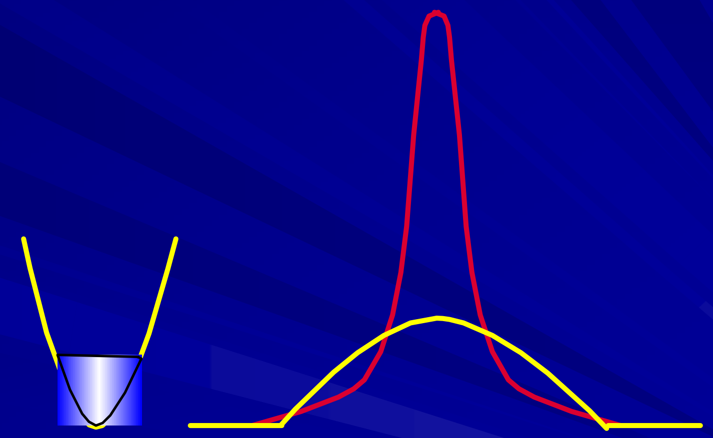
1 micron



Interactions between the atoms change the equilibrium size

$$R_{BEC} \approx a_h \left(\frac{Na}{a_h} \right)^{1/5} \approx 10 a_h$$

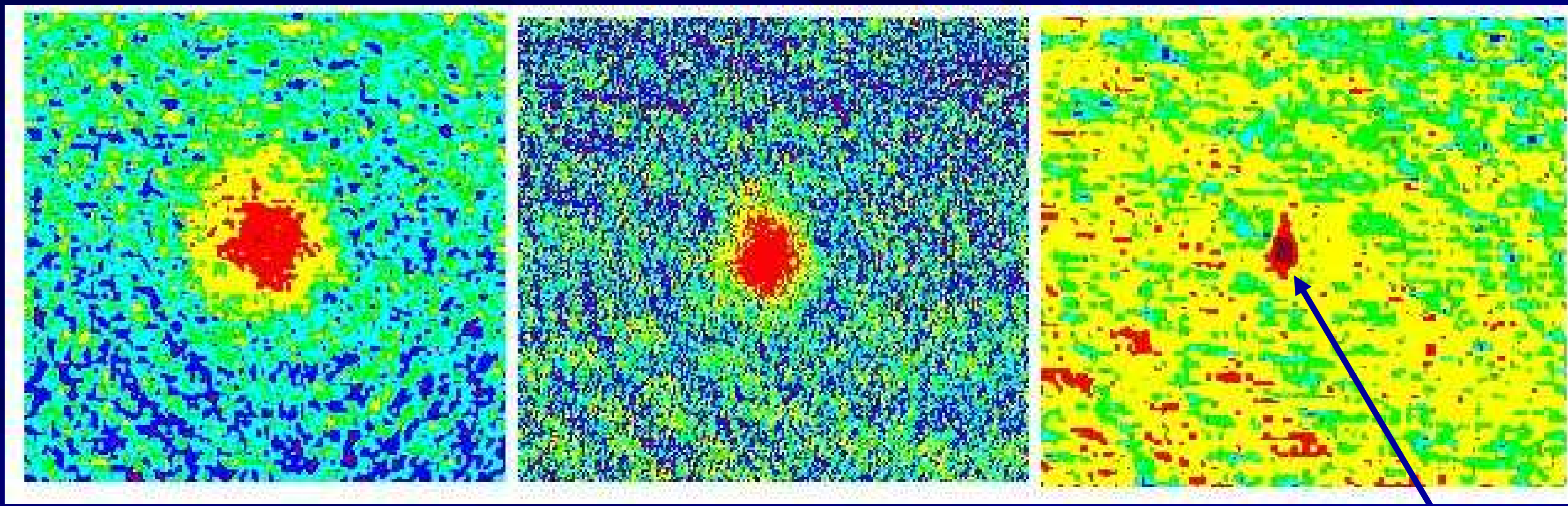
10 microns

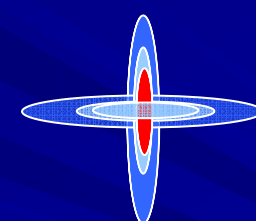


Expansion after releasing from the trap:

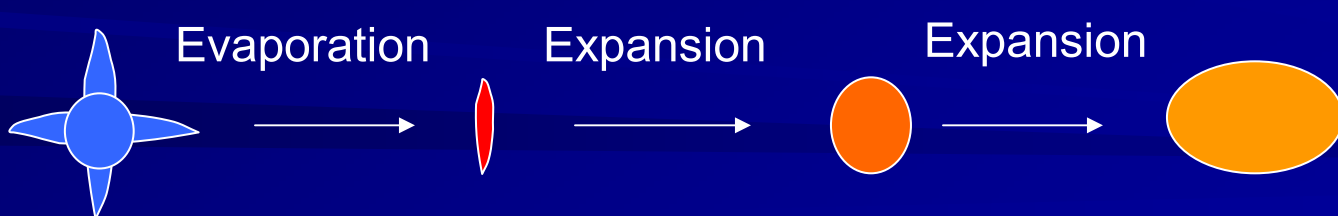
$$R^2 = R_0^2 (1 + \omega_0^2 t^2) \rightarrow R_0^2 \omega_0^2 t^2$$

1 cm/s in our trap

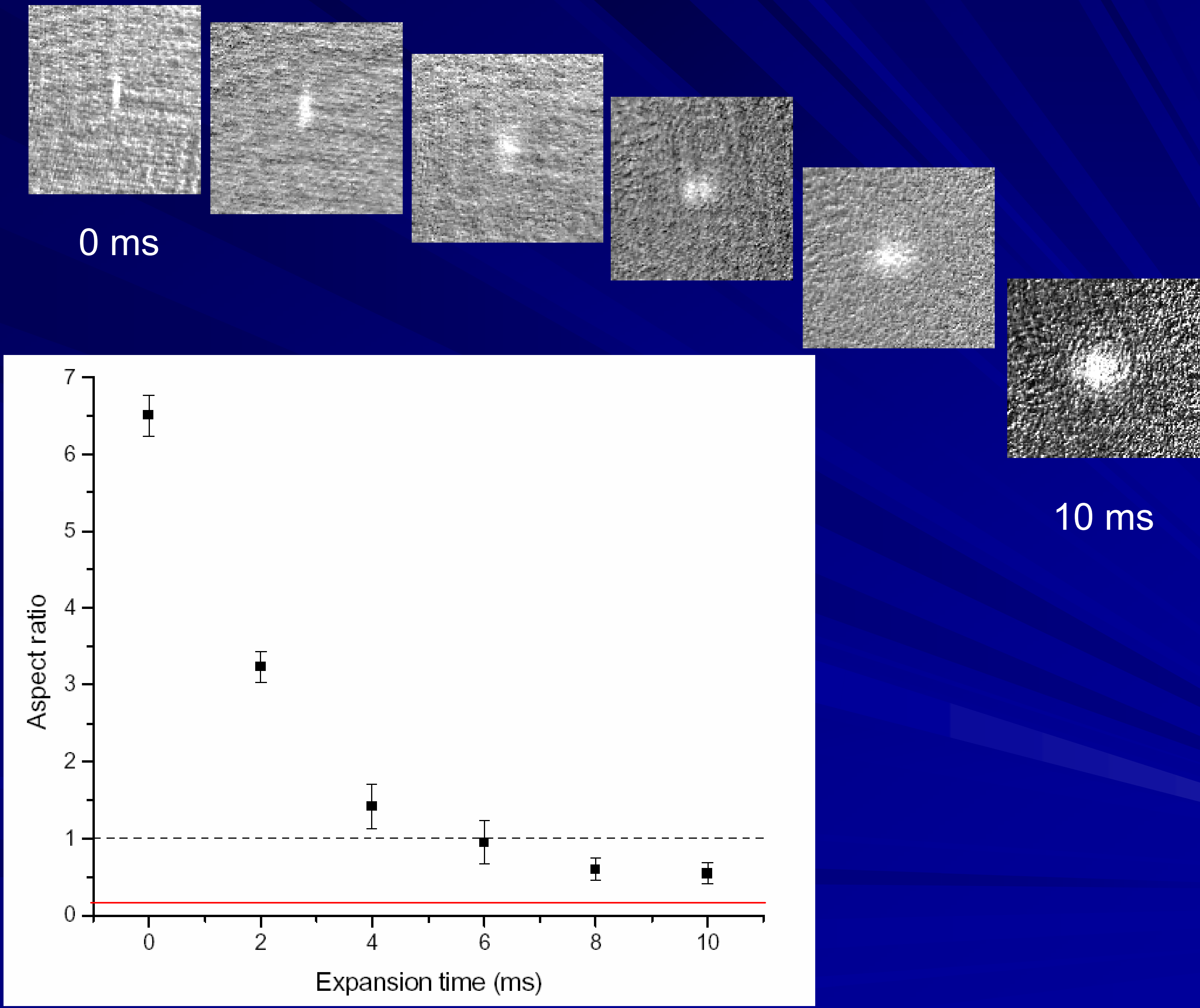




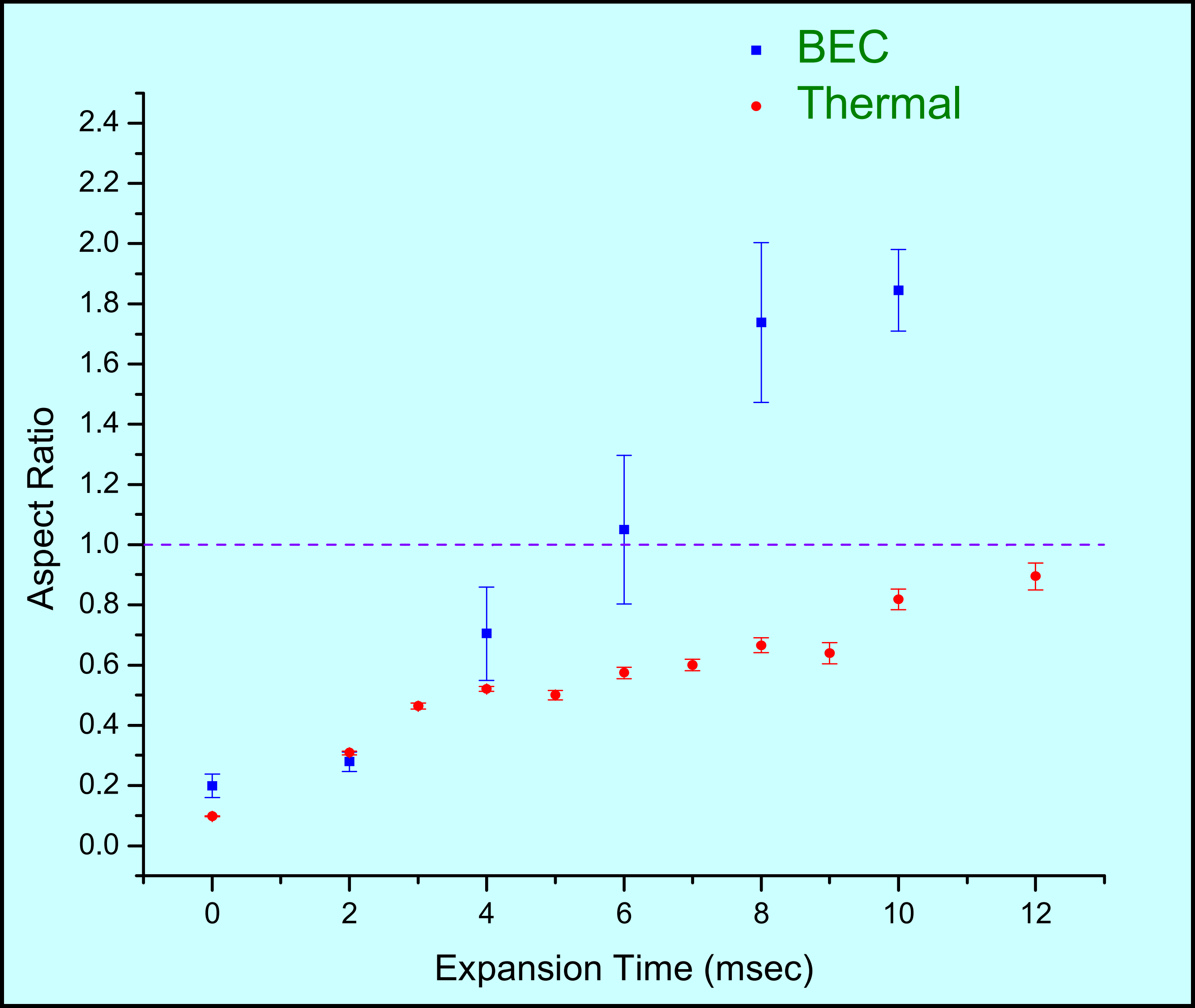
HOW TO PROVE IT?



Inversion of ellipticity


0 ms
10 ms
Aspect ratio
Expansion time (ms)
0
1
2
3
4
5
6
7
0
2
4
6
8
10

Inversion of Aspect ratio



Nonlinear

Description as a phase coherent ‘wave’

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(r)+V(r)\Psi(r)+U_0(a)\left|\Psi(r)\right|^2\Psi(r)=\mu\Psi(r)$$

$$n(r)=\left|\Psi(r)\right|^2$$

Tunable with magnetic field, light…

$$i\hbar\frac{\partial\Psi(r,t)}{\partial t}$$

Interference effects,
Nonlinear effects (four-wave mixing, amplification…)
Quantized vortices,
Coherent beams (atom lasers)
Superfluidity
.
.
.

Spinor condensates:

BEC of atoms that can assume any of the several possible ground states, either of the hyperfine levels, or of the magnetic sub-levels (projections, including $m_F=0$). This occurs naturally in an optical trap, whereas magnetic trap BEC are usually in a single state (weak field seeking state) that can be trapped well in the magnetic trap.

Magnetically Tunable

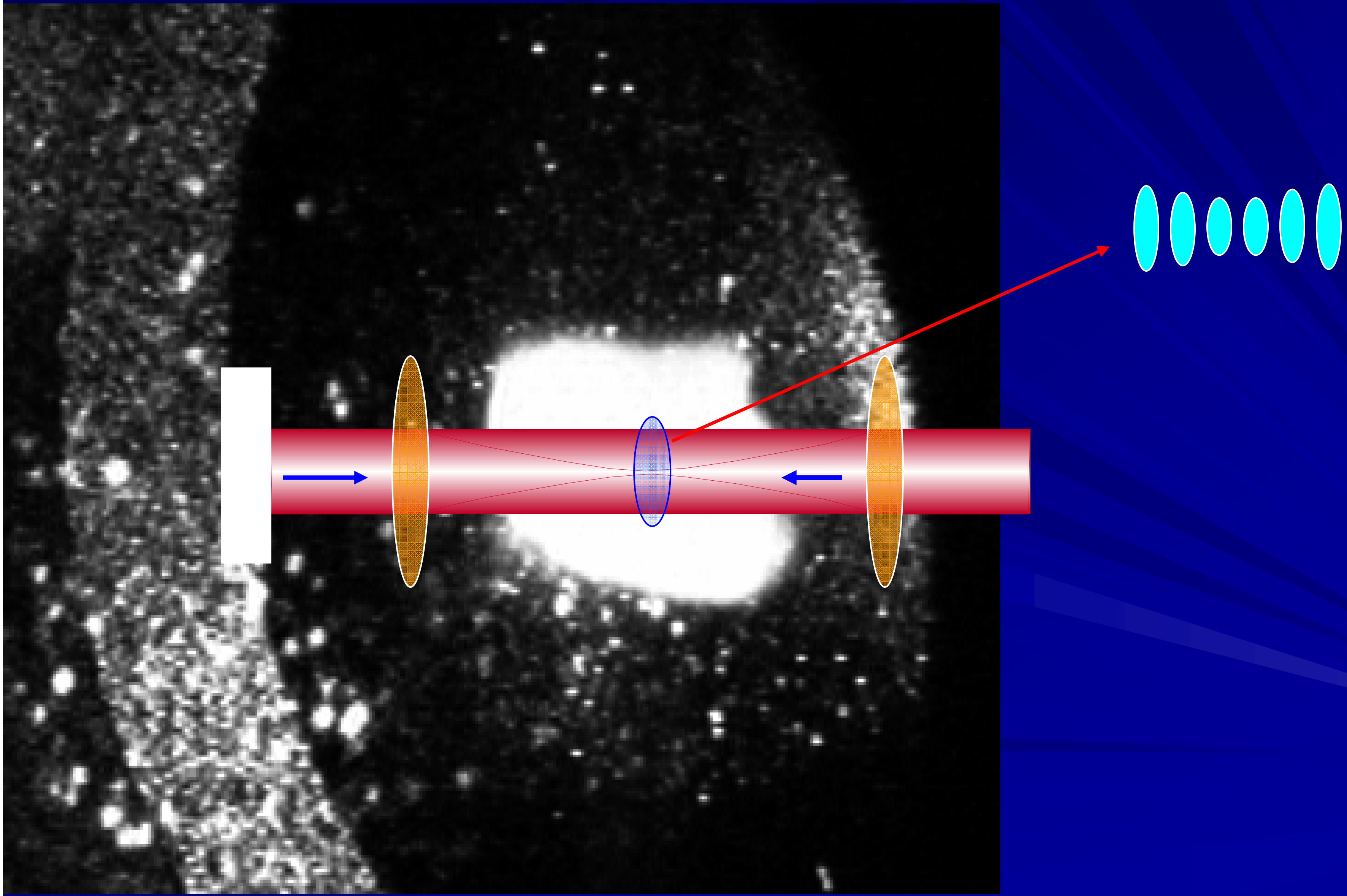
$$E=\sum_i p_i^2/2m+U(r_i)+\sum\delta(r_i-r_j)\left(\frac{4\pi\hbar^2\bar{a}}{m}+c_s\vec{f}_i\cdot\vec{f}_j\right)$$

C_s negative -> Ferromagnetic order
C_s positive -> Anti-ferromagnetic order

For Rb, F=1, c_s is about -3×10^{-14} Hz.cm^3

Optical Lattice

Operational now



Effect of AC Stark shift in 1D optical lattice

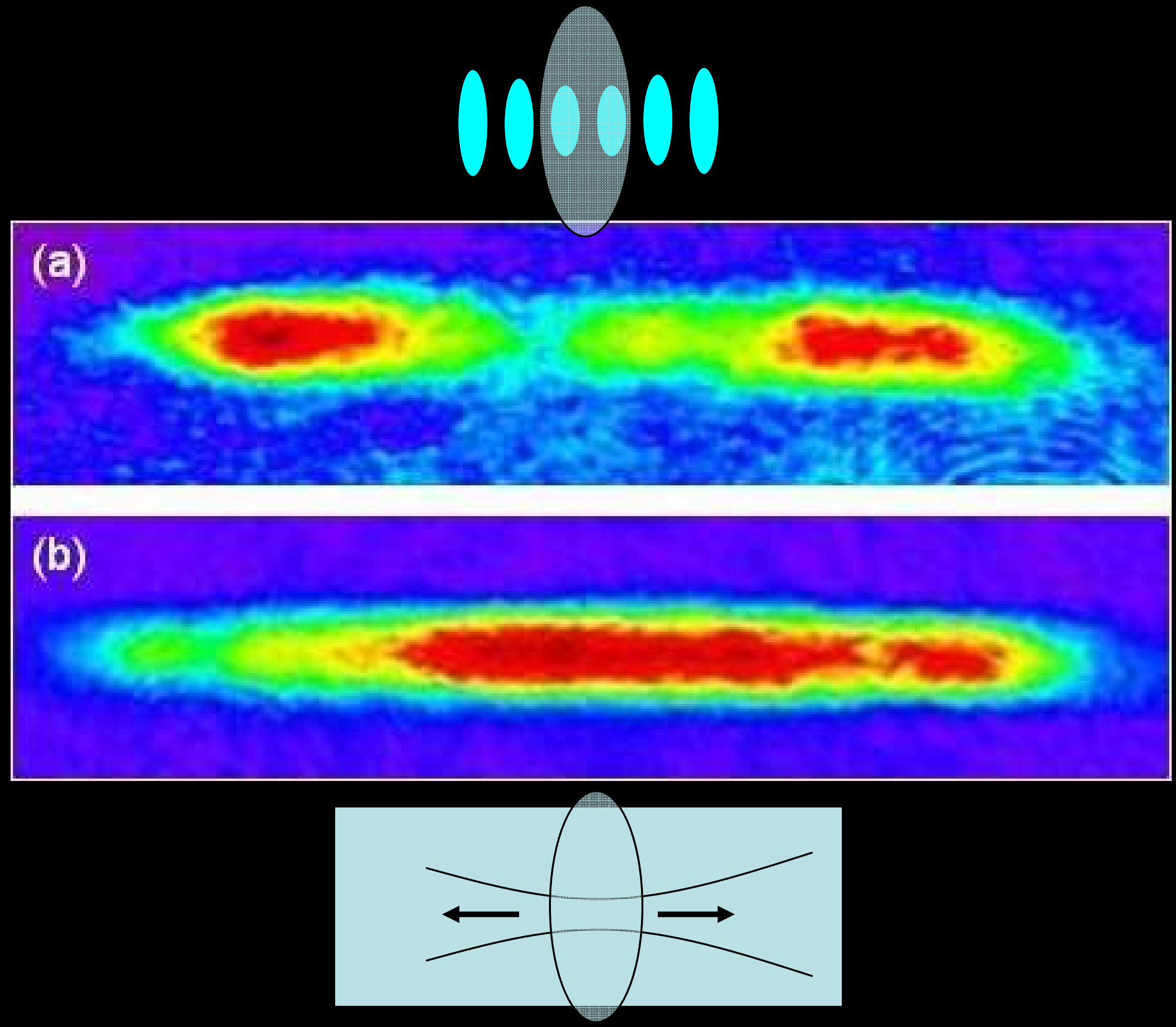


Image of rubidium atoms trapped in (a) one-dimensional CO_2 laser Optical lattice (b) single beam dipole trap.

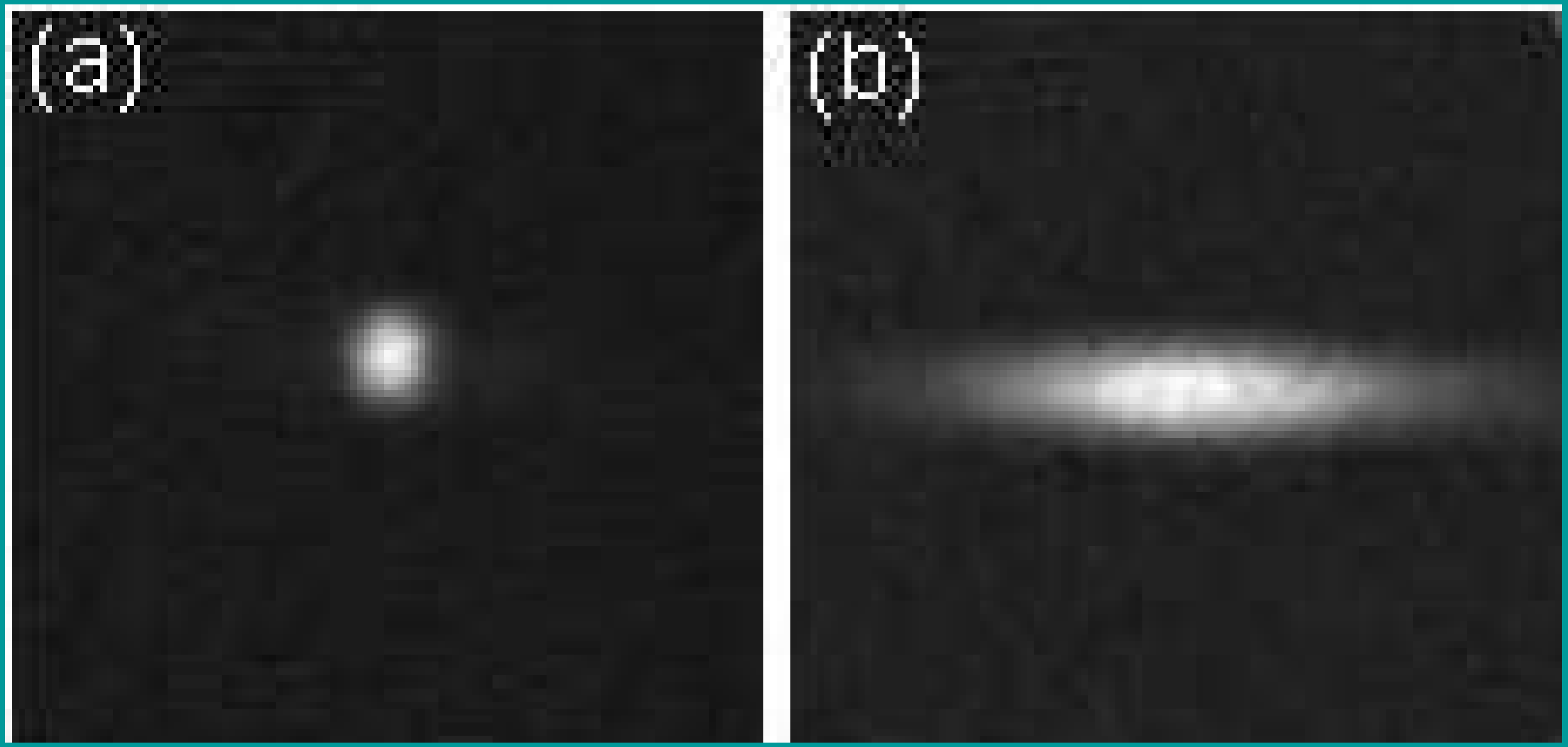
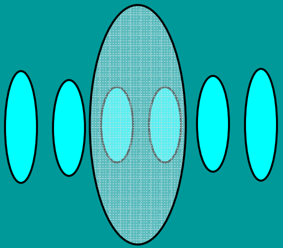
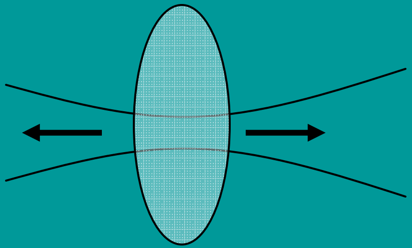


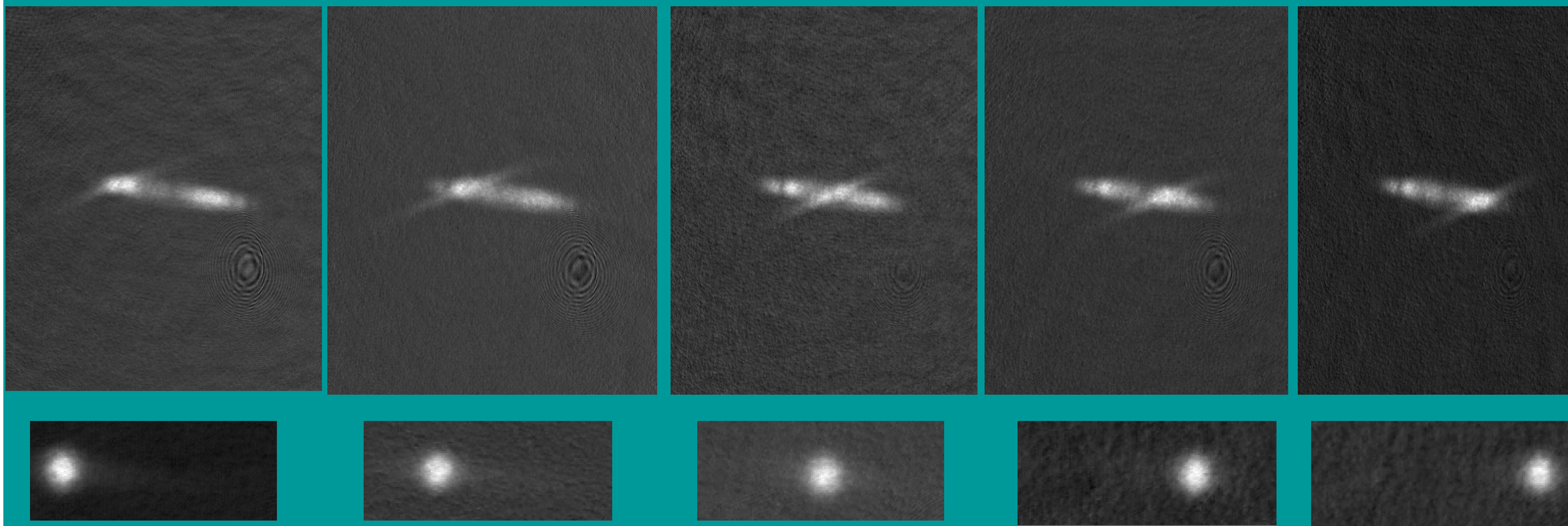
Image of rubidium atoms trapped in (a) one-dimensional CO_2 laser Optical lattice

(b) single beam dipole trap, after being transferred from an orthogonal single beam dipole trap.



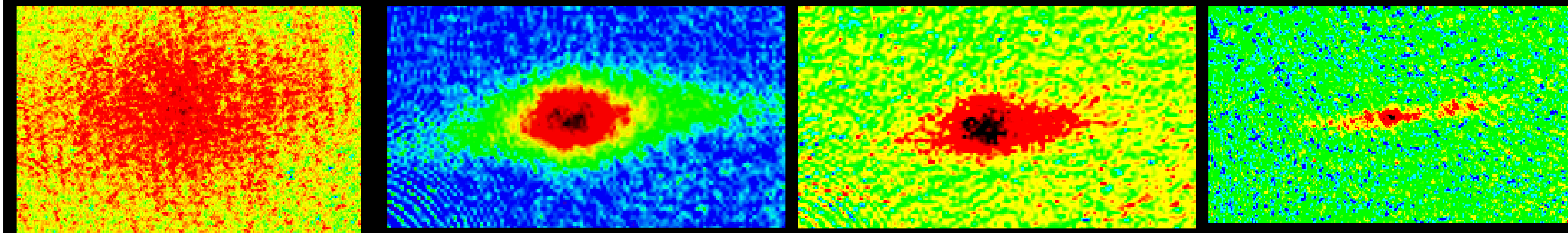


Loading at will – evidence for optical lattice

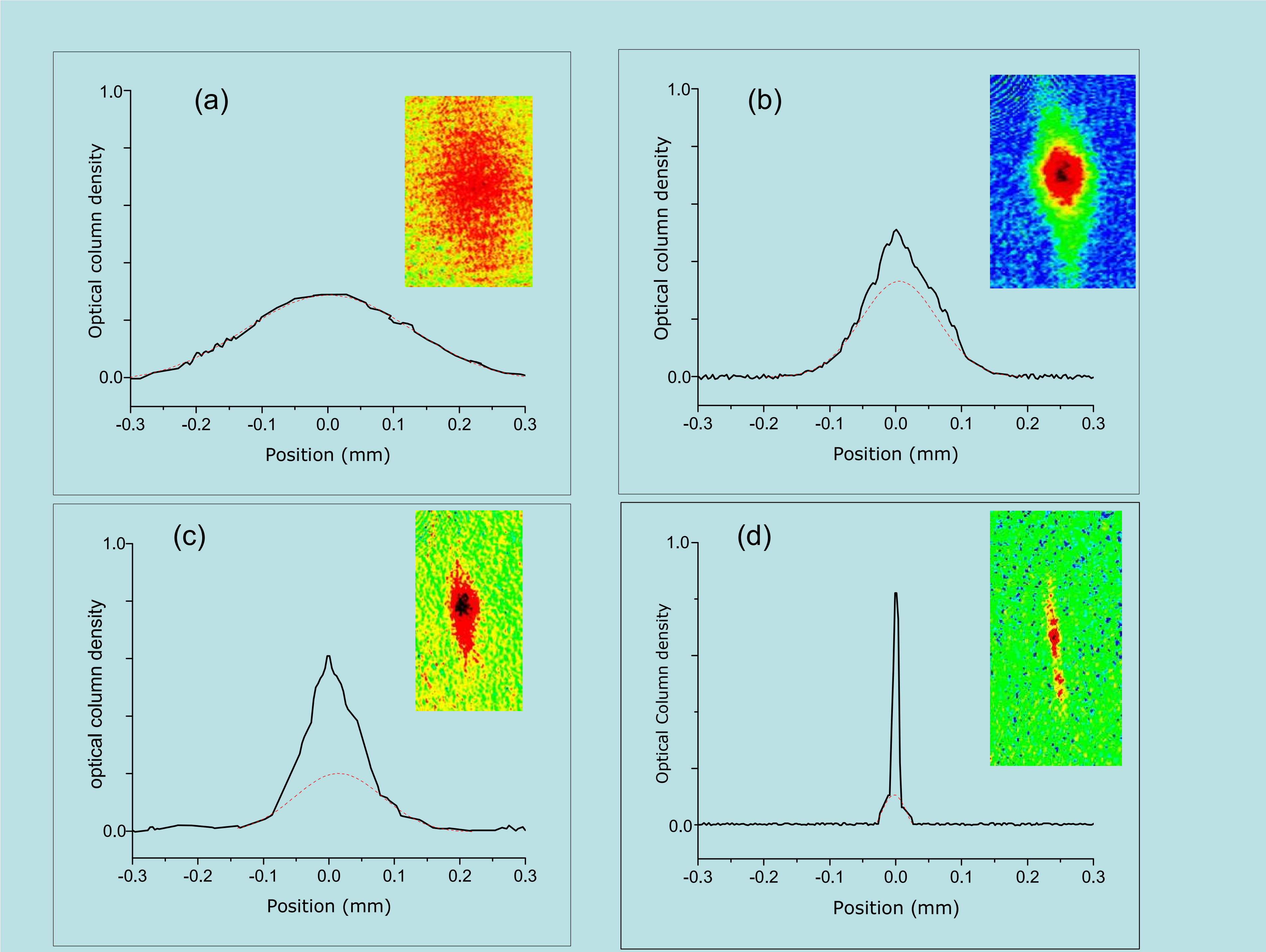


Loading without lattice

Evaporative cooling in Optical lattice crossed with single beam dipole trap



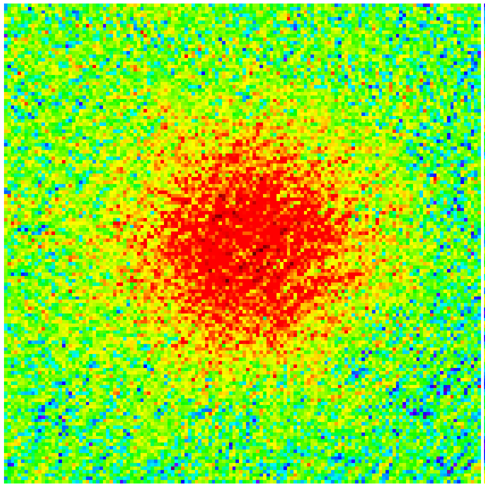
900 nK 410 nK 250 nK 150 nK



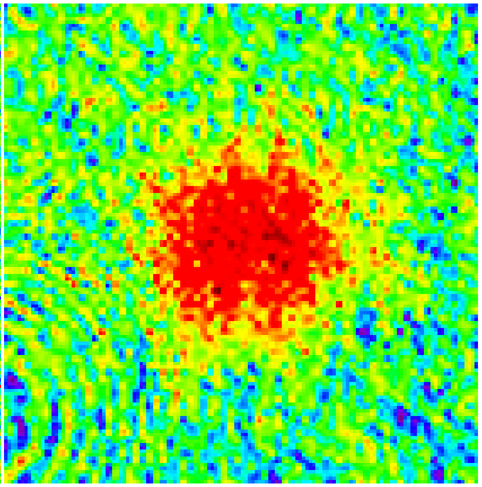
(a)
Optical column density
1.0
0.0
-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3
Position (mm)
(b)
Optical column density
1.0
0.0
-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3
Position (mm)
(c)
optical column density
1.0
0.0
-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3
Position (mm)
(d)
Optical Column density
1.0
0.0
-0.3 -0.2 -0.1 0.0 0.1 0.2 0.3
Position (mm)

Evaporative cooling in Optical lattice

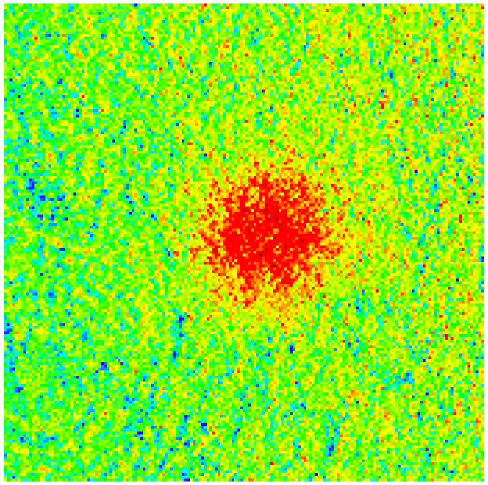
Expansion time = 4ms



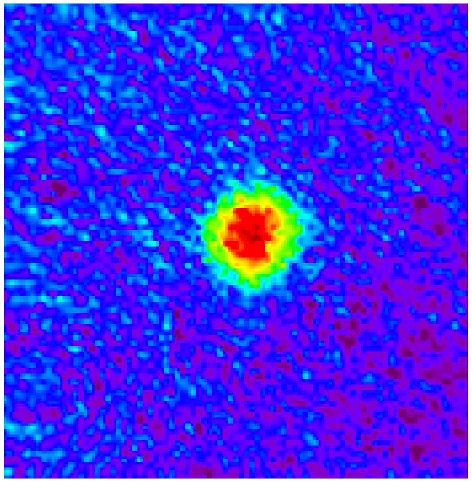
300 ms



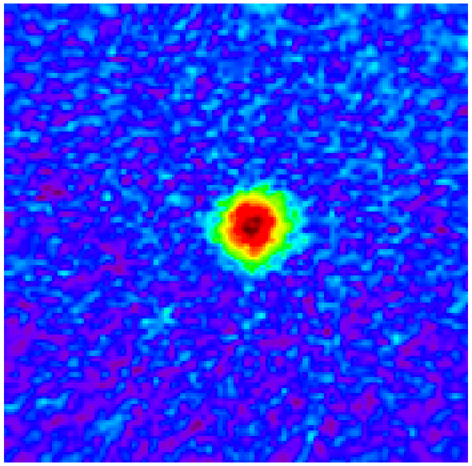
600 ms



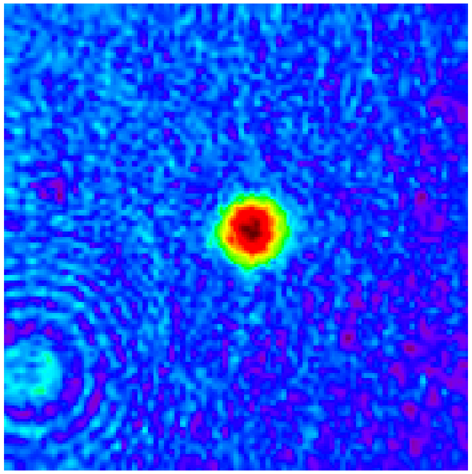
700 ms



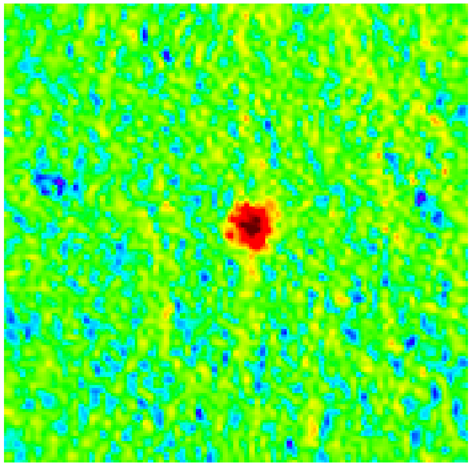
900 ms



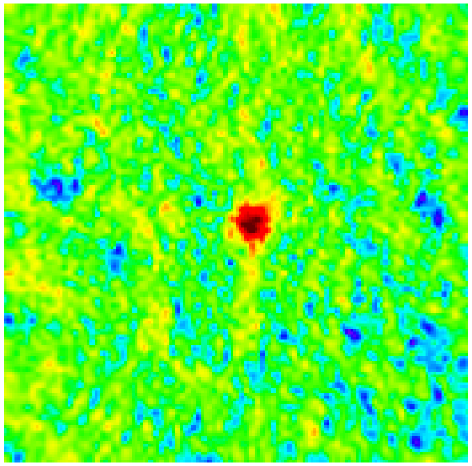
950 ms



970 ms

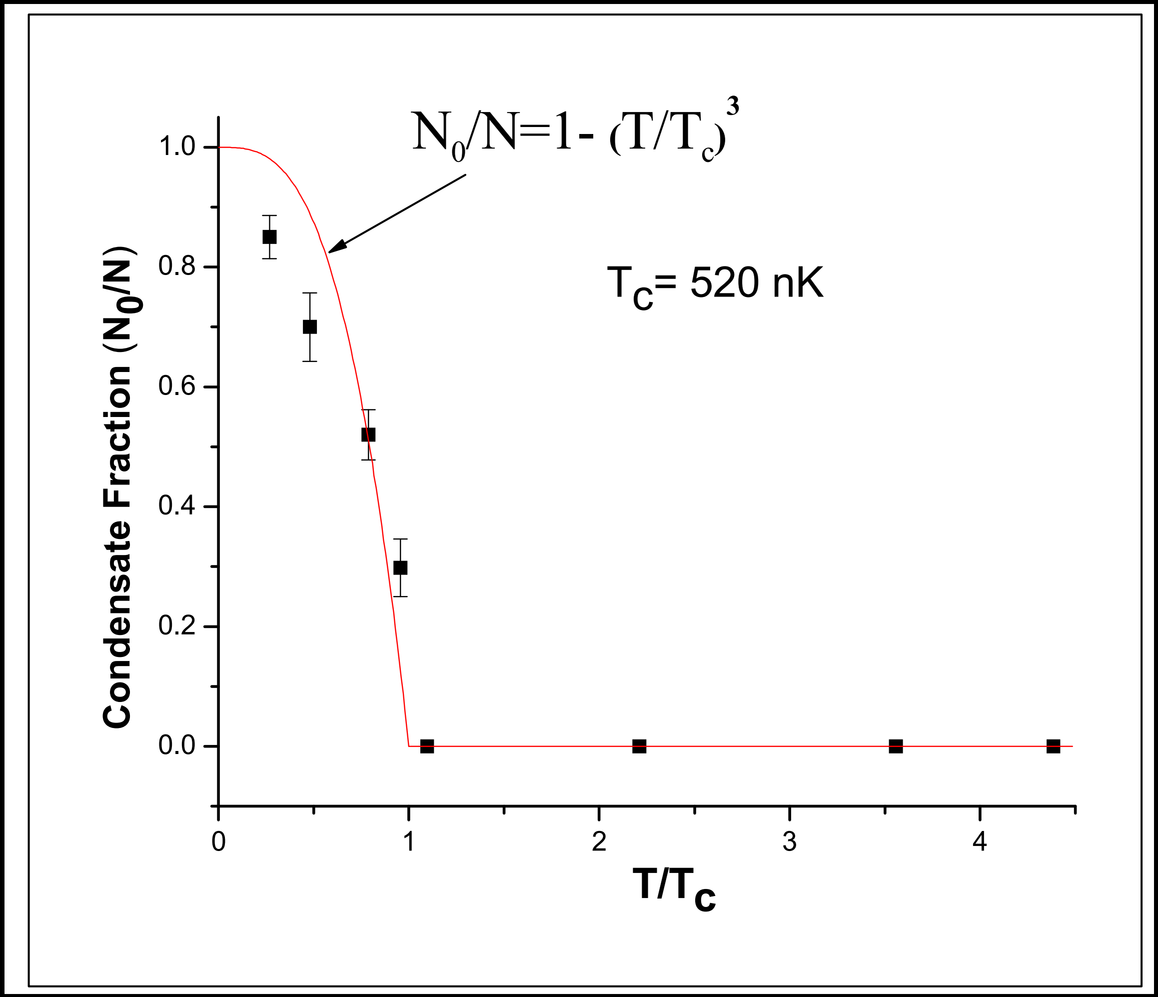


1000 ms

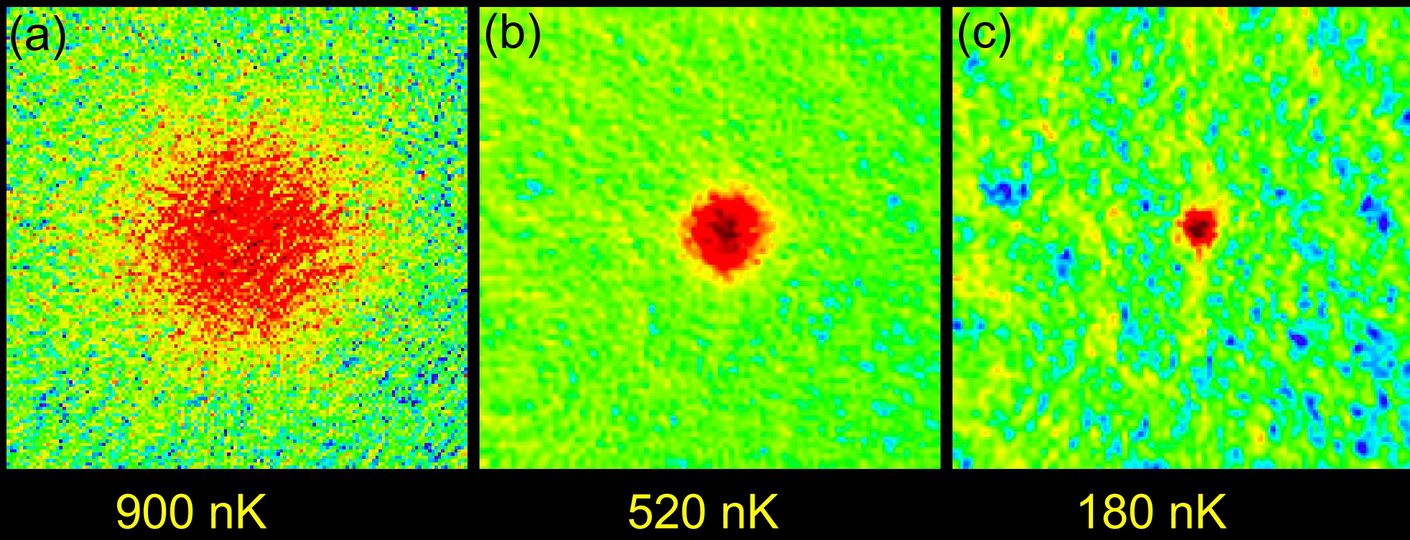


1020 ms

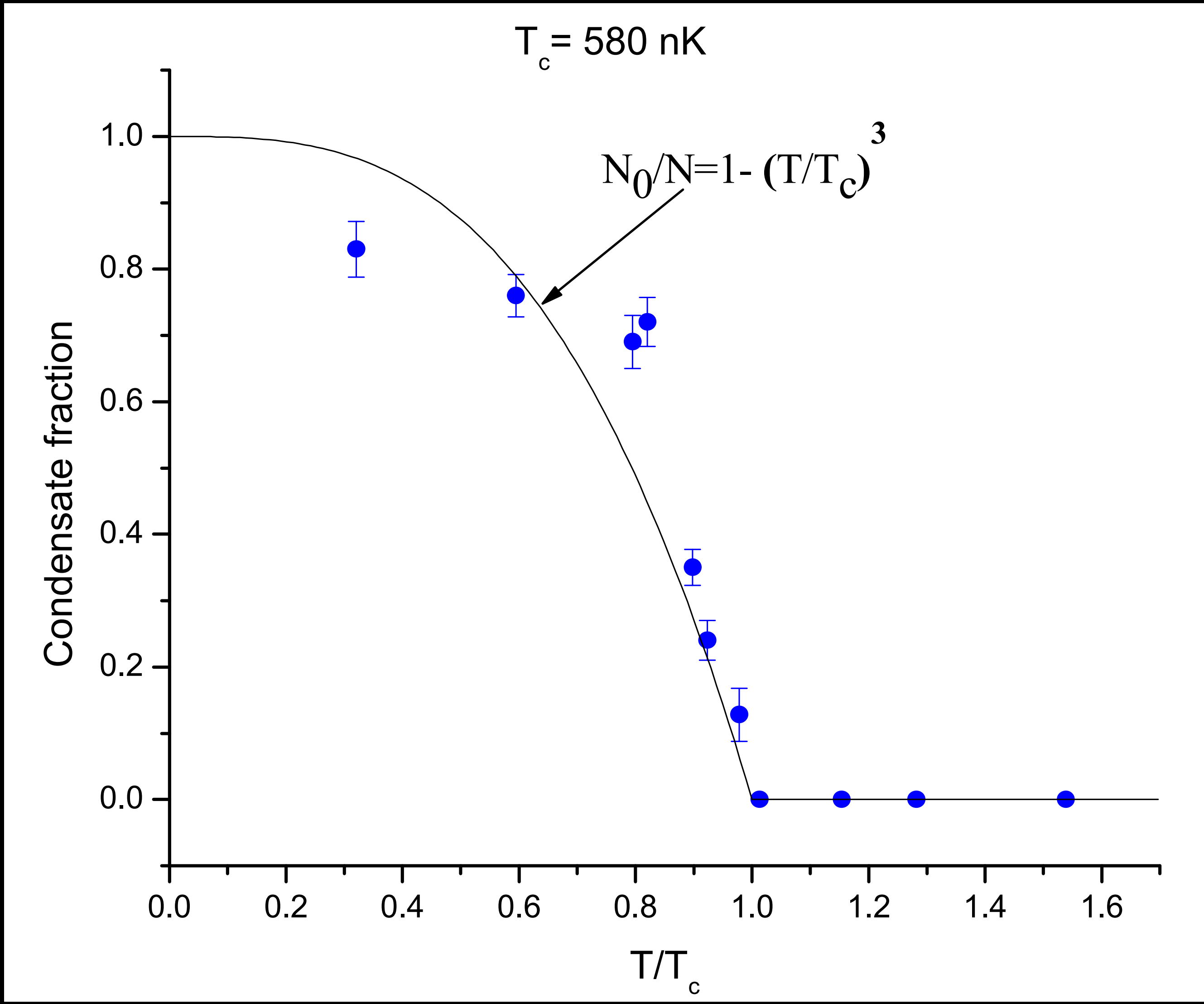
BEC Phase transition in Optical Lattice crossed with dipole trap



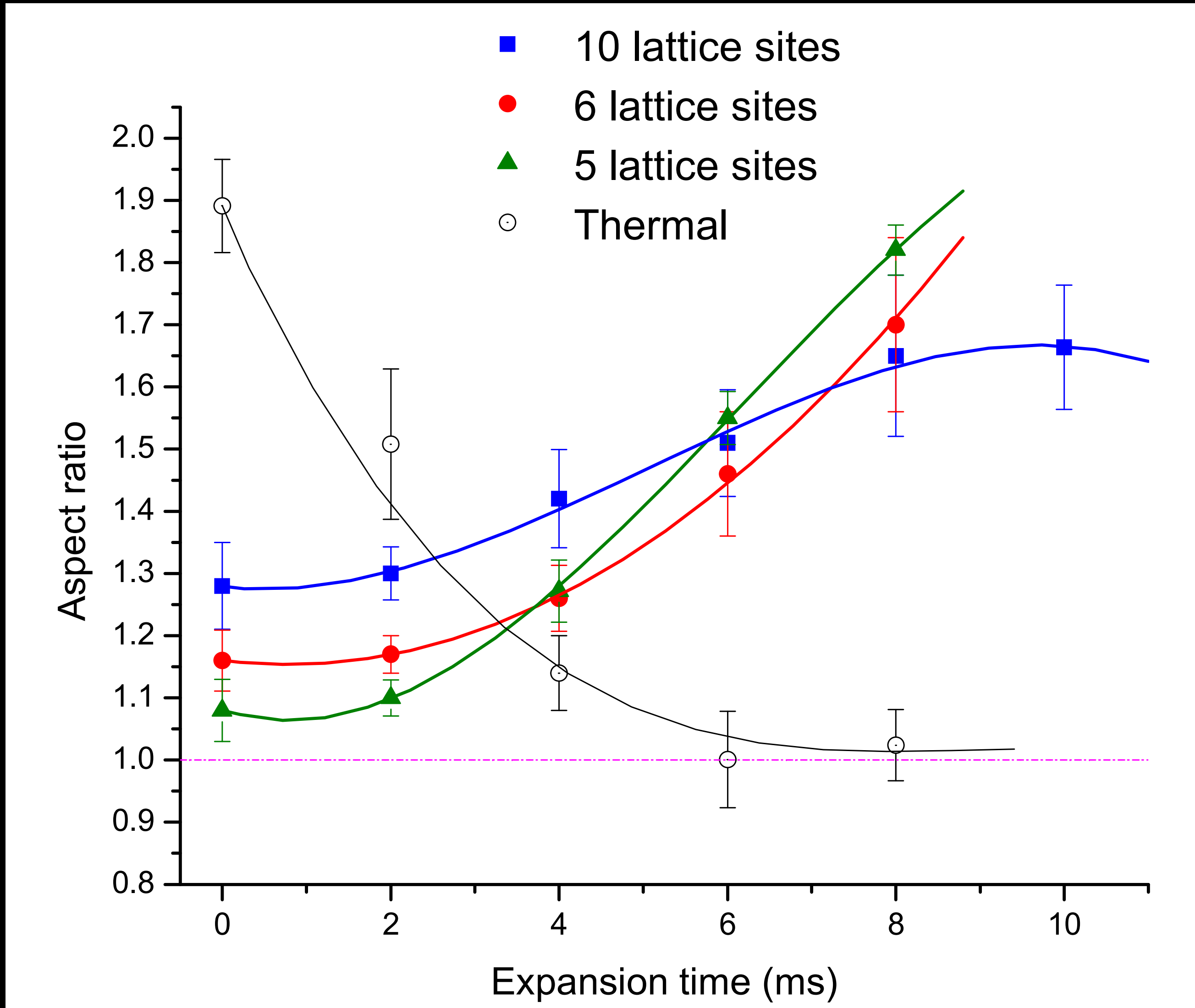
Evaporative cooling in Optical lattice



BEC Phase transition in Optical Lattice



Experimental data for aspect ratio of BEC produced in Optical lattice



New Experiments (2008-2012):

1) Atom-Atom correlations in 2-atom or few atom experiments (QED, molecular, spin-statistics etc.)

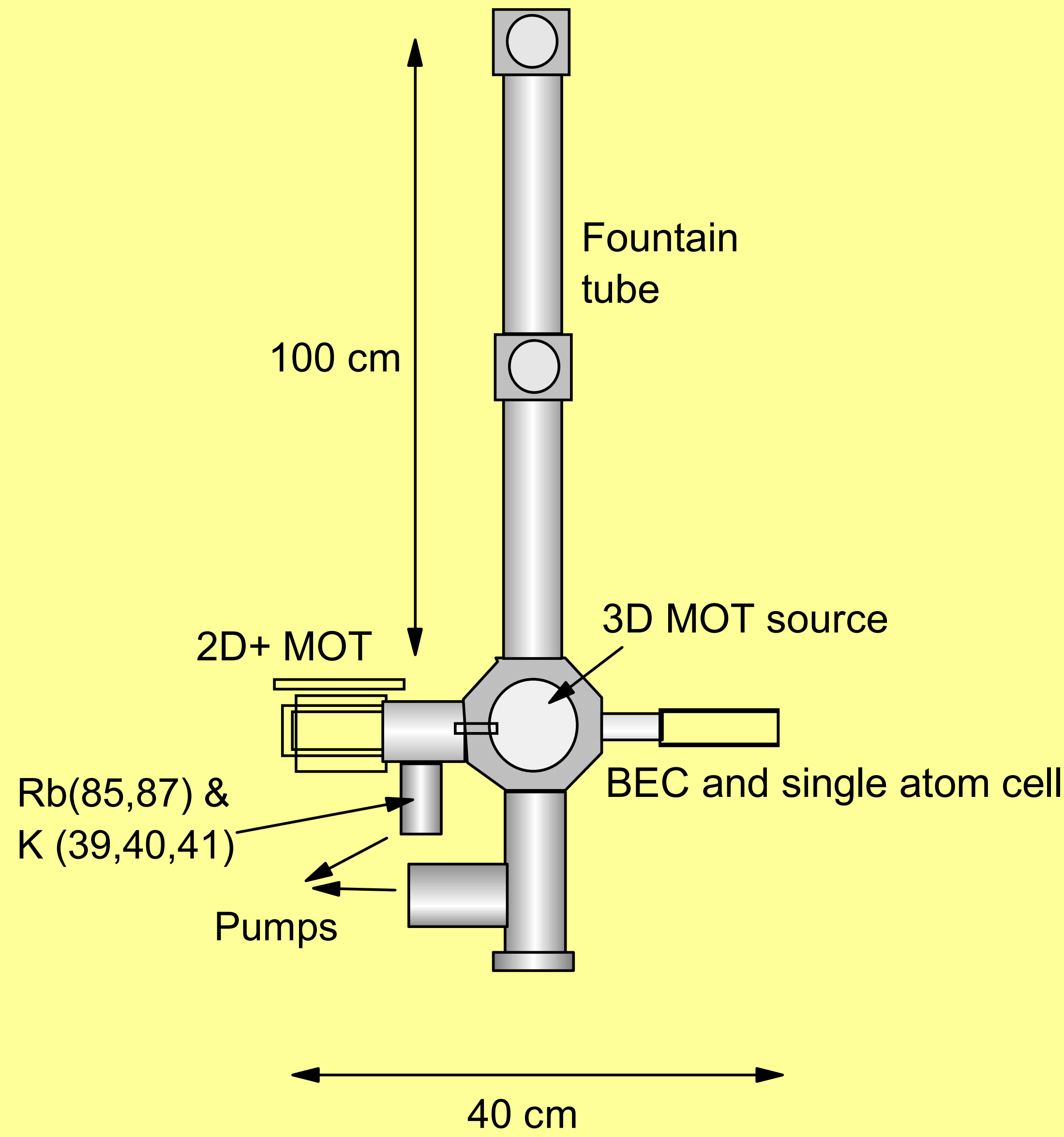
2) Fountain based measurements (atom interferometry/gravity)

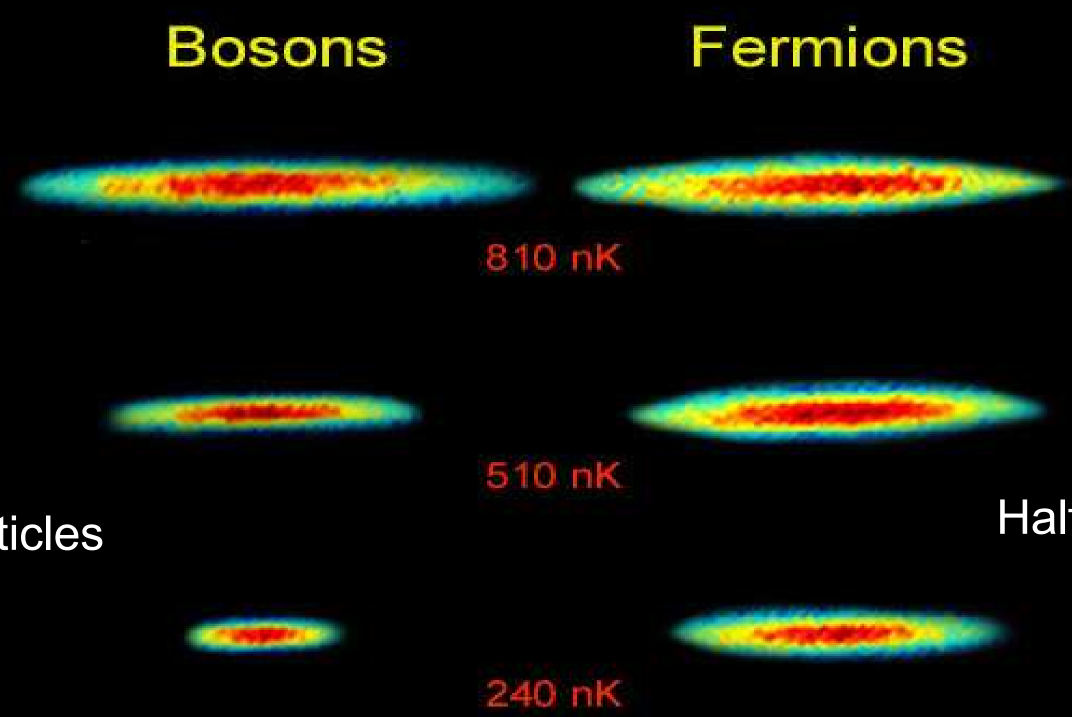
3) Fermion physics

4) Optical lattice physics

5) Short range forces

6) Physics of quantum entanglement and decoherence





Integer-spin particles

Half-integer-spin particles

$$S = nh/2\pi, \quad n = 1, 2, 3\ldots$$

$$S = \frac{n}{2}(h/2\pi), \; n = 1, 3, \ldots$$

Photon, atoms with total even number of electrons+nucleons Rb87, Rb85, K39, He4, Li7, H….

Most of fundamental particles

$$\frac{1}{\exp\frac{(\varepsilon_i - \mu)}{kT} - 1}$$

$$\frac{1}{\exp\frac{(\varepsilon_i - \mu)}{kT} + 1}$$

THE SPIN-STATISTICS CONNECTION

Particles with integer spin are bosons and obey the Bose-Einstein statistics (laser, BEC…)

Particles with half-integer spin are fermions and obey the Fermi-Dirac statistics (Pauli exclusion – neutron stars…)

"It appears to be one of the few places in physics where there is a rule that can be stated very simply, but for which no one has found a simple and easy explanation…This probably means that we do not have a complete understanding of the fundamental principle involved."

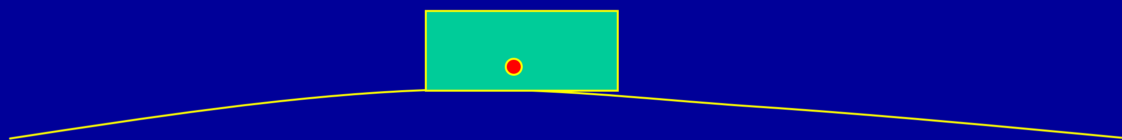
R. P. Feynman, FLP III

We now know what might be the fundamental principle involved here!

There is in fact a cosmic connection that is gravitational !

Unnikrishnan, Cosmic Relativity gr-qc/0406023
gr-qc/0406043

Gravitational potential “here”

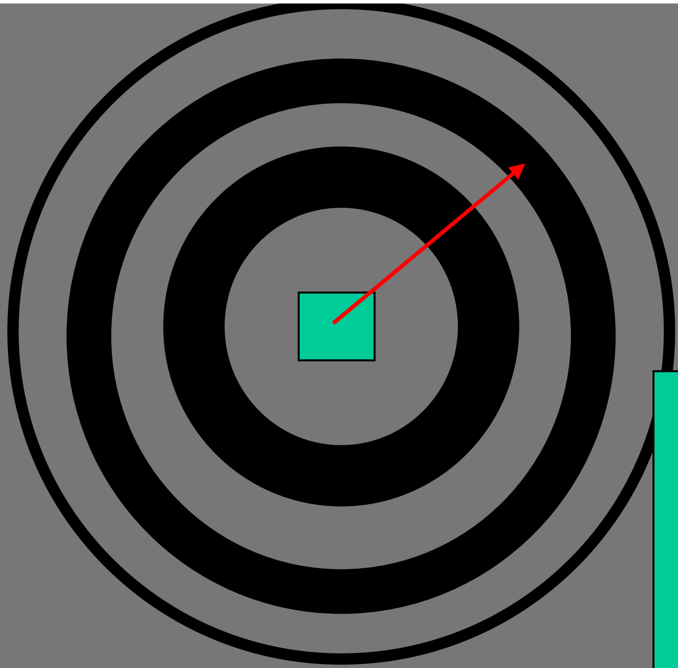


Earth: $\dfrac{GM_E}{c^2 R_E} < 10^{-9}$

Sun: $\dfrac{GM_S}{c^2 R_S} \; ; \; 10^{-8}$

Galaxy: 10^{-6}

Distant masses dominate!



$$\Phi_U : \int_{Over\,all\,Galaxies} G \cdot (4\pi\rho R^2 dR) / Rc^2$$

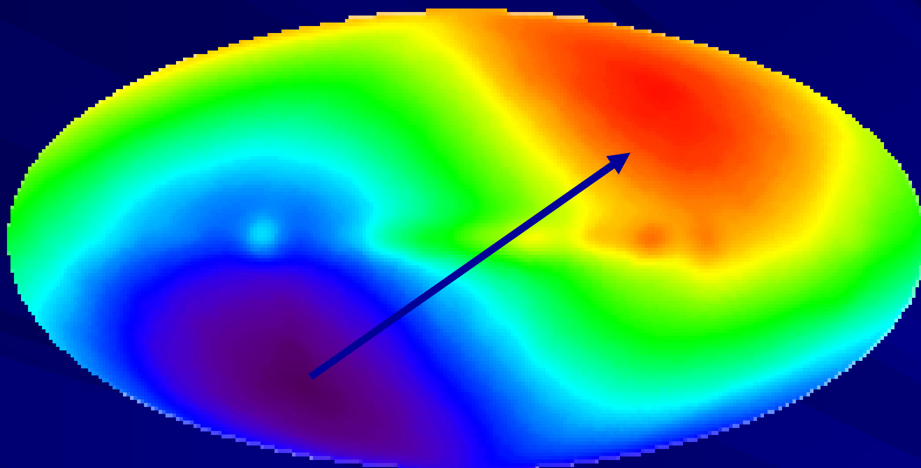
$$: 2\pi G\rho R^2{}_H / c^2 \approx 1$$

$$\Phi_U \approx c^2$$

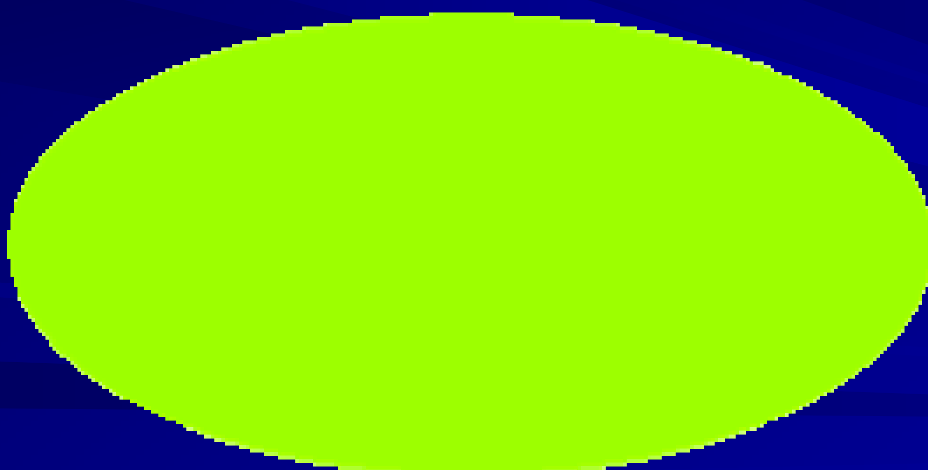
Our interaction energy with the matter in the Universe is billion time larger than our interaction energy with the Earth!!

What can this large potential do?

Moving through the microwave background

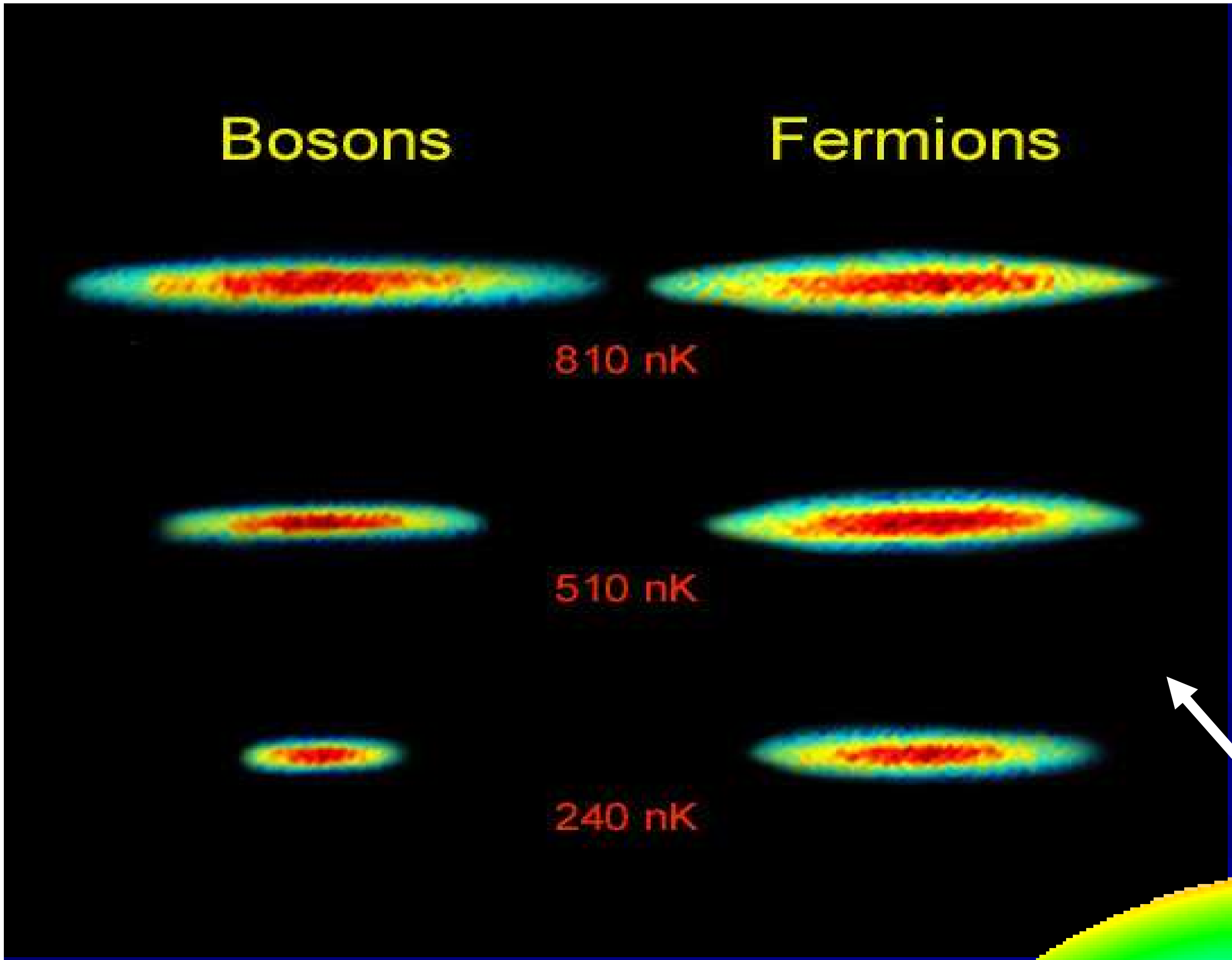


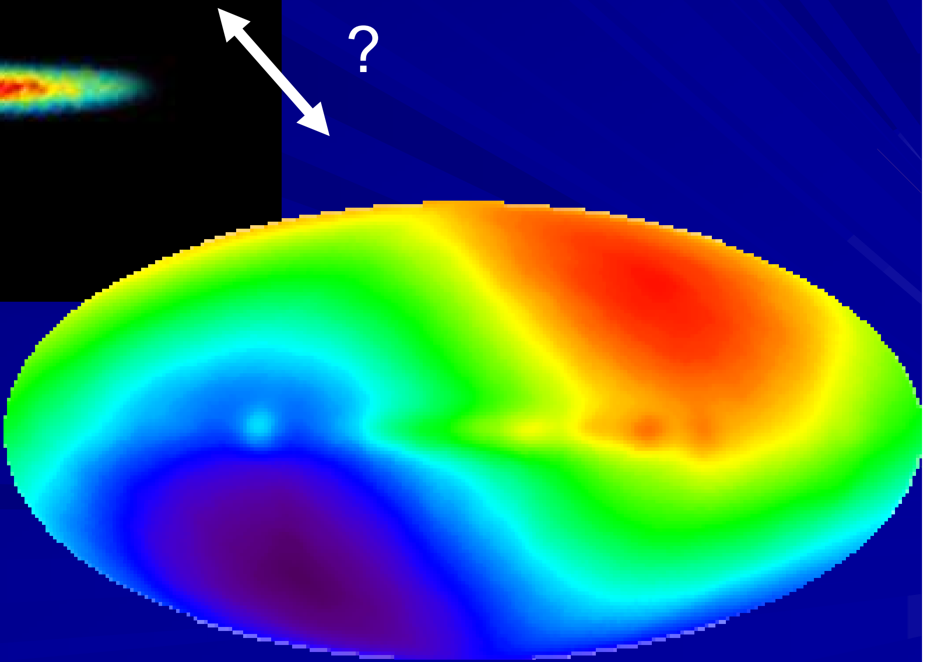
Absolute velocity



Absolute time
Same as average T

Universe is NOT Lorentz invariant


Bosons
Fermions
810 nK
510 nK
240 nK


?

What can these large potentials do?

In fact a lot! All kinematical effects we know of, including Newton's pseudo-forces, ALL relativistic effects wrongly attributed to motion relative to each other (time dilation etc. special relativity), and many quantum effects like finer-structure splitting…

In fact, Newton's law of motion itself, and the equivalence between gravitational and inertial mass are consequences

Cosmic Relativity
gr-qc/0406023

But, let us get back to spins…

Classical and quantum Spins in the real non-empty Universe

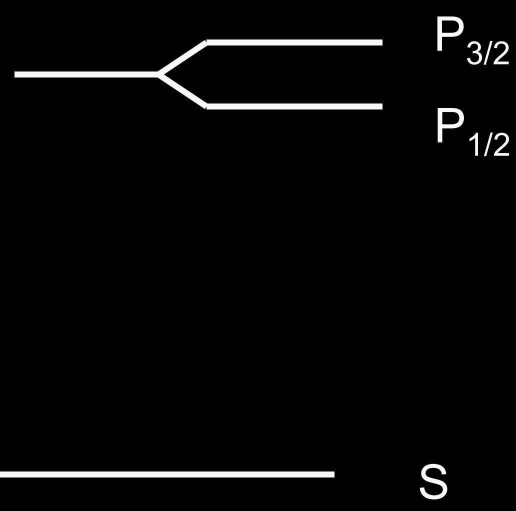
Cosmic Relativity gr-qc/0406023

Universe in rotating frame

Gravitomagnetism $$B_g = \frac{\Phi_g}{c^2} \nabla \times \vec{v} \approx 2\Omega$$

(this gives the Coriolis force as a gravitational Lorentz force)

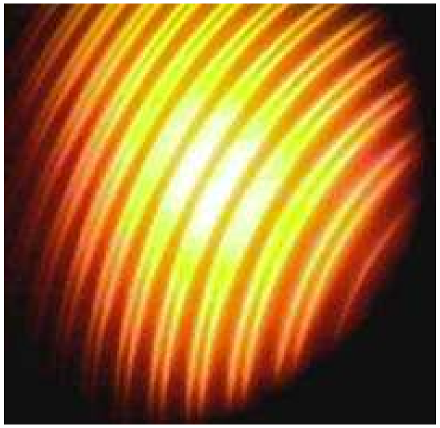
$$F_C = \vec{v} \times \vec{B}_g = 2\vec{v} \times \vec{\Omega}$$

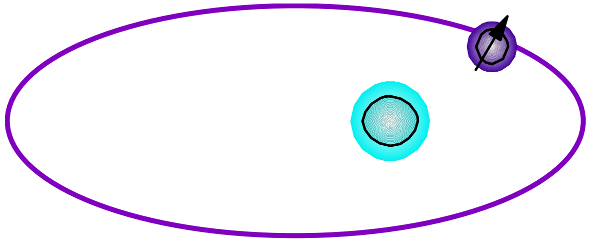


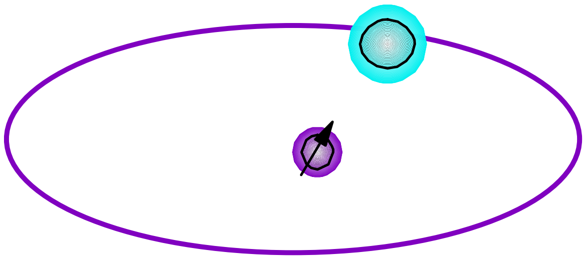
Magnetic LS coupling gives 2 times the observed value. The kinematic, relativistic ‘Thomas precession’ corrects this with a ‘-1’ and the fine structure is explained.

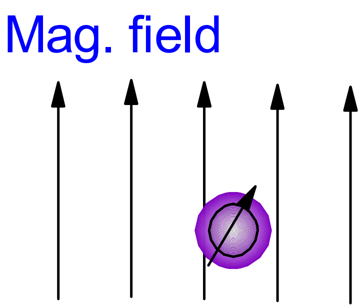
Physics of Fine Structure in atomic spectra

1) Spin-Orbit coupling

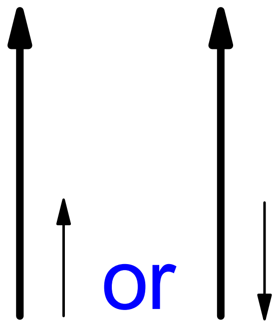




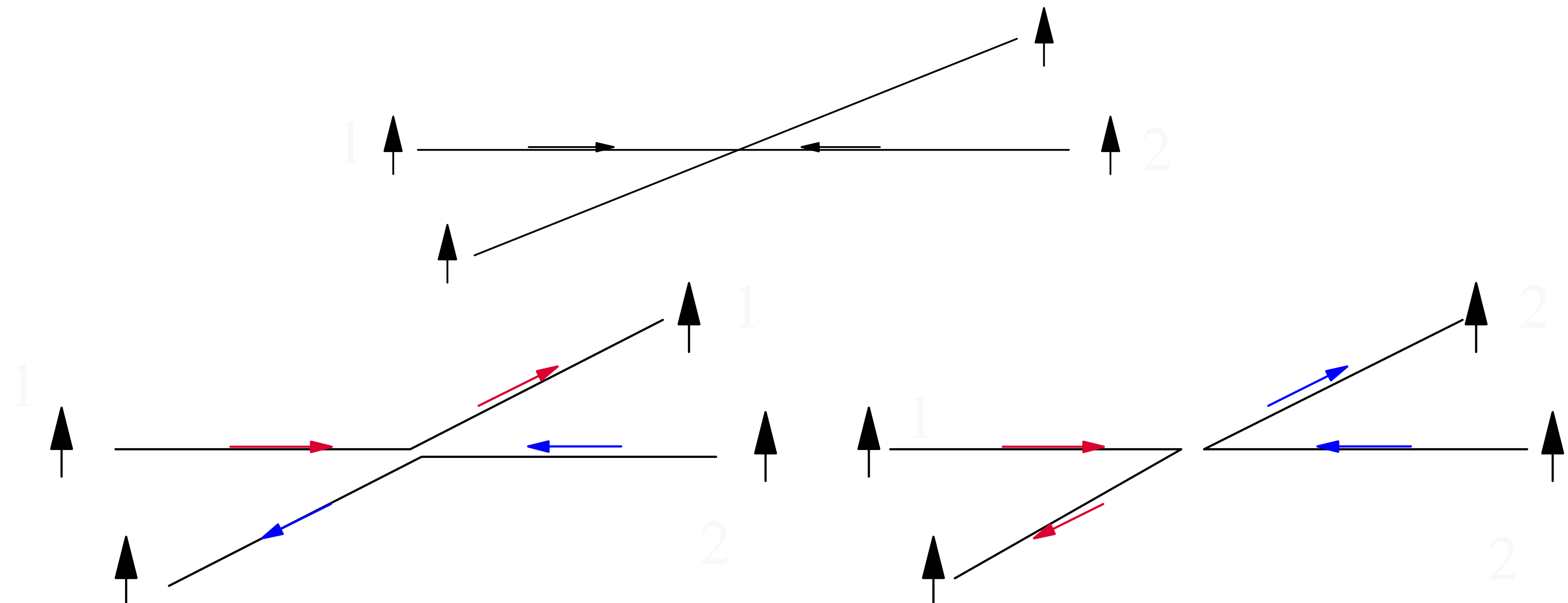




l.s can be positive or negative



THE SPIN-STATISTICS CONNECTION



small angle deflection

large angle deflection

Amplitude 1 $f(\theta)$

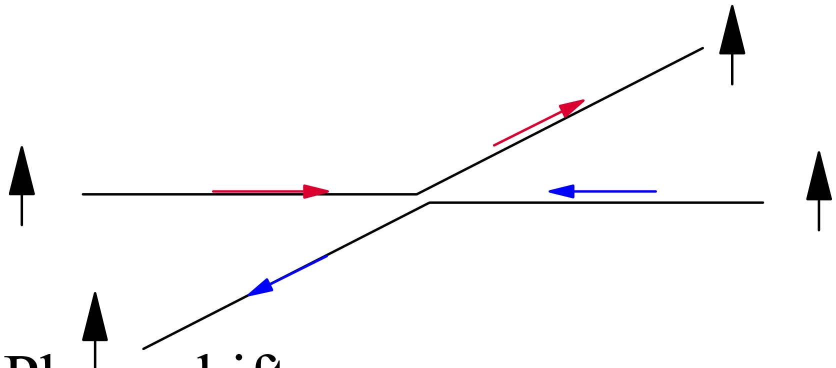
Amplitude 2 $e^{i\delta} f(\pi + \theta)$

$$\text{Probability for the process} = \left|(A1 + e^{i\delta} A2)\right|^2$$

Either Amplitude 1+ Amplitude 2 or

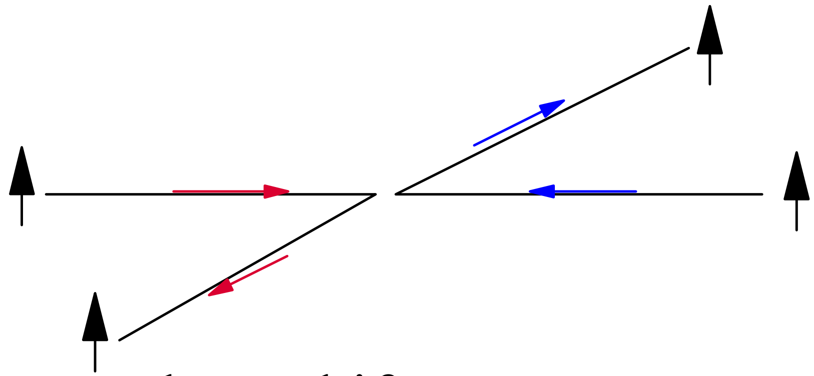
Amplitude 1– Amplitude 2

The Origin of the Spin-Statistics Connection



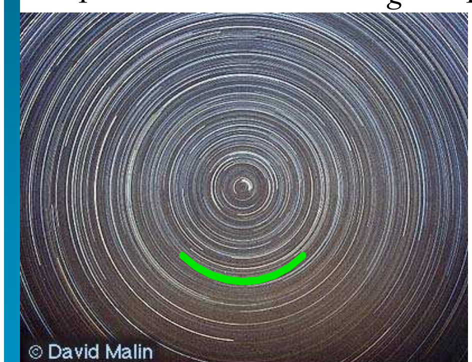
Phase shift

$$\delta_1 = 2 \times \tfrac{1}{2}\vec{s} \cdot \vec{B}_g \delta t_1 = 2s\Omega t_1 = 2s\theta_1$$



Phase shift

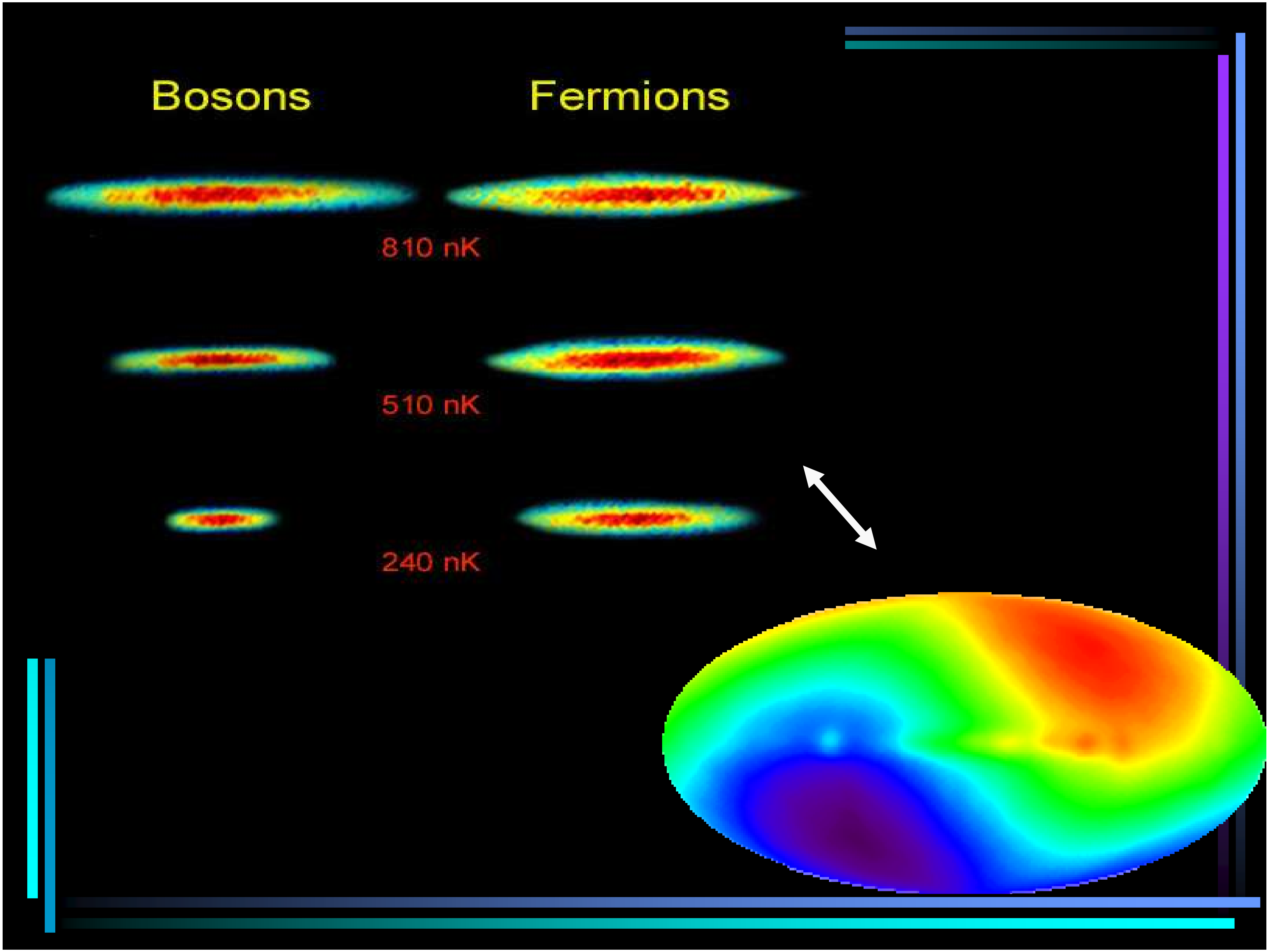
$$\delta_2 = s \cdot B_g \delta t_2 = 2s\theta_2$$



Phase difference

$$2s(\theta_2 - \theta_1) = s \cdot 2\pi$$

There is most certainly a cosmic connection to the spin-statistics connection


Bosons
Fermions
810 nK
510 nK
240 nK

Our experiments with laser-cooled atoms and BECs and the future experiments with Fermionic atoms are all planned in the frame work of our fundamental contribution to relativity, gravity and spin-statistics connection. This is the focal point, and also the main theme. For the present I expect, with good reasons, that my finding that cosmic gravity is responsible for all physical effects usually attributed to kinematics (relativistic effects, laws of motion, spin-stat. connection…) will stand on the long run.

It also provides one of the most versatile laboratory systems at present for studying fundamental interactions, especially short range interactions, and for making precision measurements in atomic physics, condensed matter physics, quantum optics, and atom-light interactions.

With cold atoms and BECs, we can probe fundamental physics from 10^{-9} m to 10^{25} m

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