Laser cooling and trapping IV

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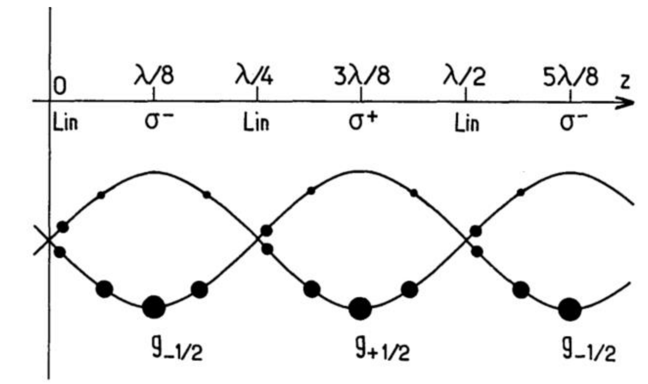
Cold Atom Predoc School
Quantum simulations with ultracold atomic gases
Les Houches, 13-24 September 2021

A wealth of cooling methods

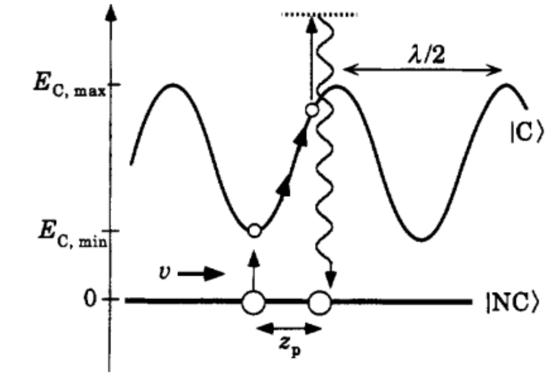
Previous courses:

Different cooling methods based on radiative forces:



- sub-Doppler cooling in « bright » molasses

Recoil limited temperature,
due to the continuous scattering of photons
Deleterious impact of multiple absorption at high atomic densities
(increase of T, increase of MOT size …)

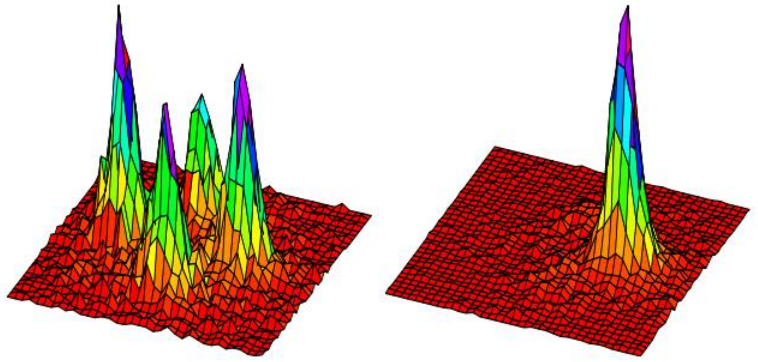


- sub-Doppler cooling in « grey » molasses

Atoms mainly in dark states, reduced photon scattering

- sub-recoil cooling

Cooling schemes (VSCPT and Raman cooling)
Rely on trapping atoms in « dark » states.
Temperatures are well below the recoil limit



Phase space densities generally still < 1
A key limitation is spontaneous emission. Can we get rid of it?

Organization of the lecture

1 : Conservative traps

2 : Evaporative cooling

3 : Bose-Einstein condensation

4 : Miscellaneous

Organization of the lecture

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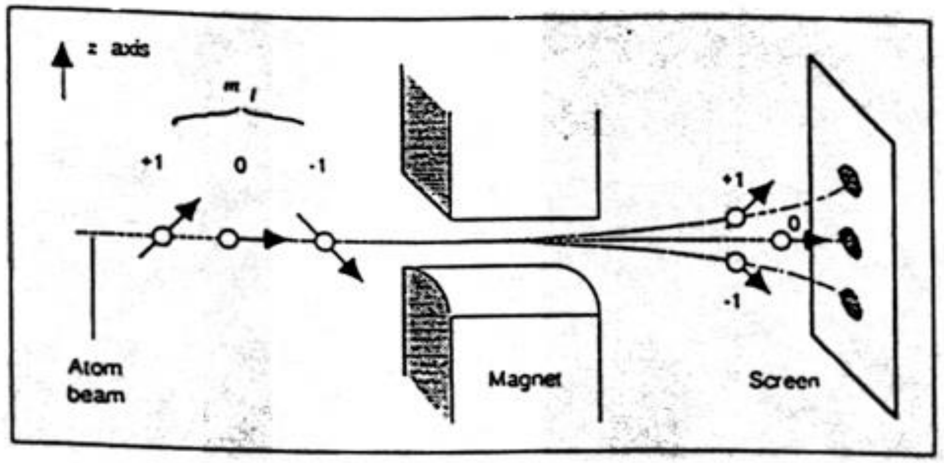
Magnetic traps

Atoms or paramagnetic molecules (ie having a permanent magnetic moment) do interact with gradients of static magnetic fields

Example: an atom in a Zeeman state $m \neq 0$ has an energy $E(B) \propto \mu B$ with $\mu \propto m\mu_B$

In a gradient, it feels a force $F \propto -\nabla E(B)$

This is what gives rise to the Stern Gerlach effect



NOTE:
B might vary not only in amplitude but also in direction.
Zeeman eigenstates thus depend on the position.
But if the rate at which the direction of B rotates is slower than the Larmor frequency, $\mu B/\mathrm{h}$ the spin will remain aligned on the field.
It will stay adiabatically in the same state m.

→ Only the spatial variations of $|B|$ matter

Magnetic traps

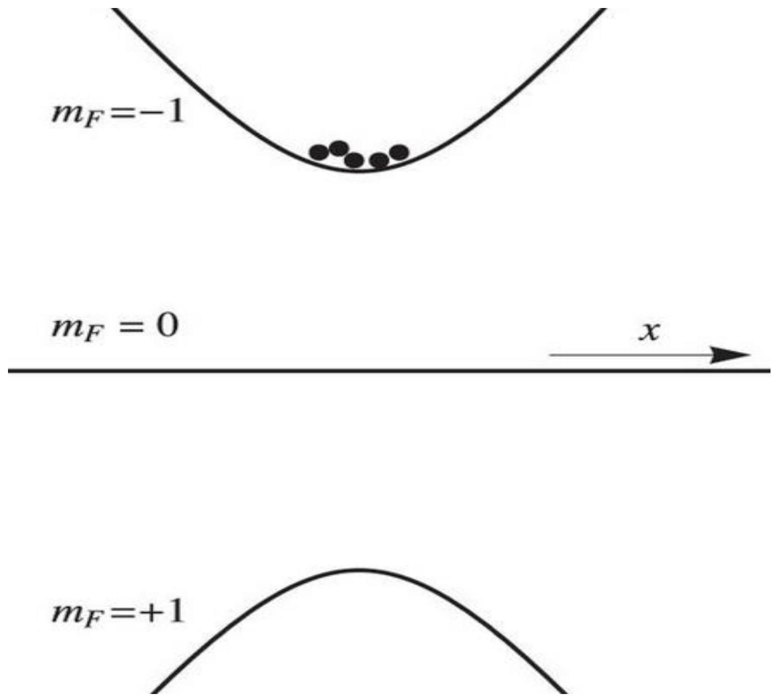
Atoms can be

- « low field seekers » (the energy increases with B)
- « high field seekers » (the energy decreases with B)

One could thus think of trapping
« low field seekers » at a minimum of B
« high field seekers » at a maximum of B

Wing theorem: the modulus of a magnetic (or an electric) field cannot have a maximum in a region free of charges and currents.
This is a consequence of Maxwell equations.

Example: atoms with $J = 1$



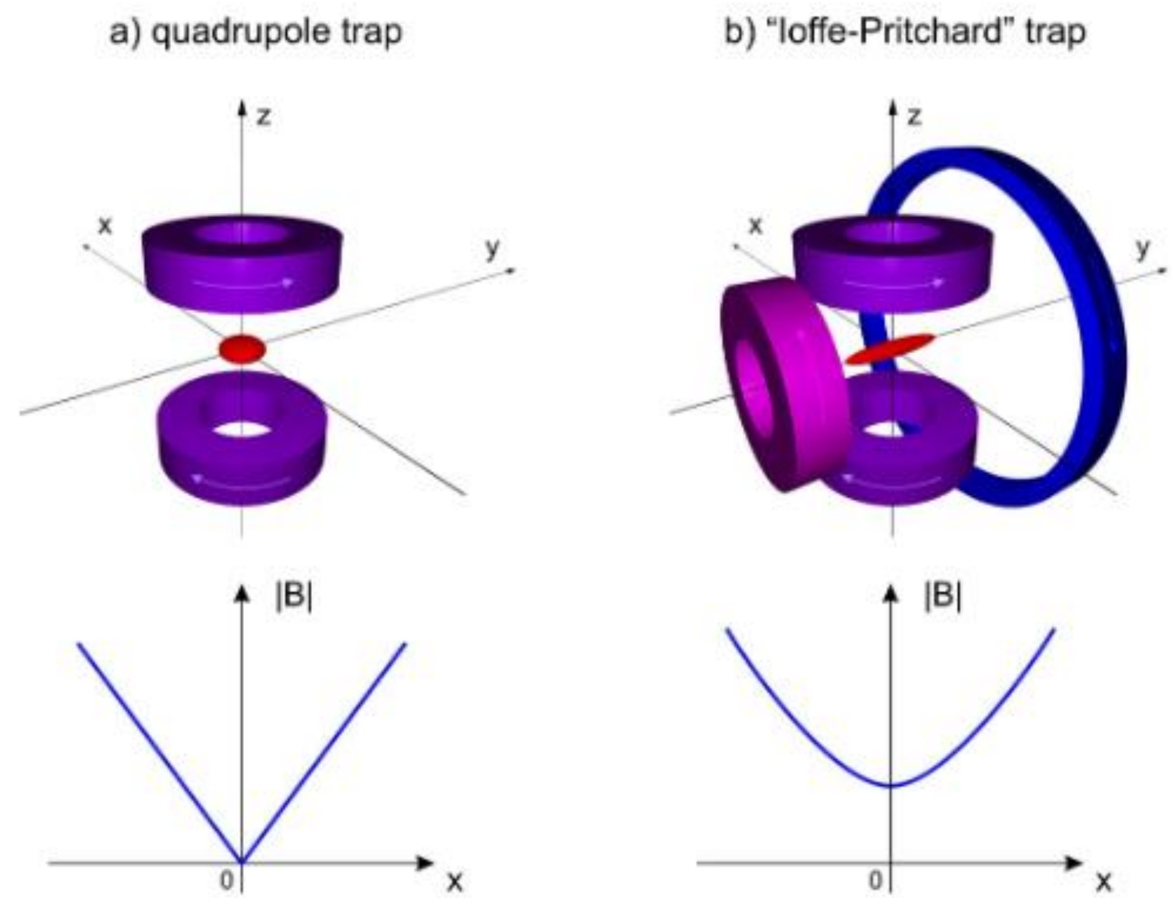
→ Only « low field seekers » can
be trapped by static magnetic fields

→ Atoms cannot be trapped
in their fundamental (lowest energy) state.

→ Inelastic collisions are exothermic
which leads to losses

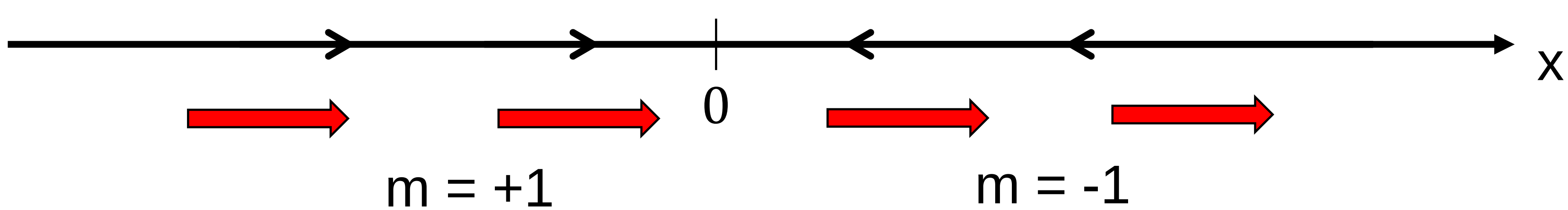
Magnetic traps

Popular trap configurations:



Massimo Inguscio
Majorana "spin-flip" and ultra-low temperature atomic physics

Problem with quadrupole traps: « Majorana spin flips »
The direction of the field reverses when crossing the zero,
and the spin cannot follow adiabatically



This leads to losses to untrapped states, which increase when decreasing the temperature

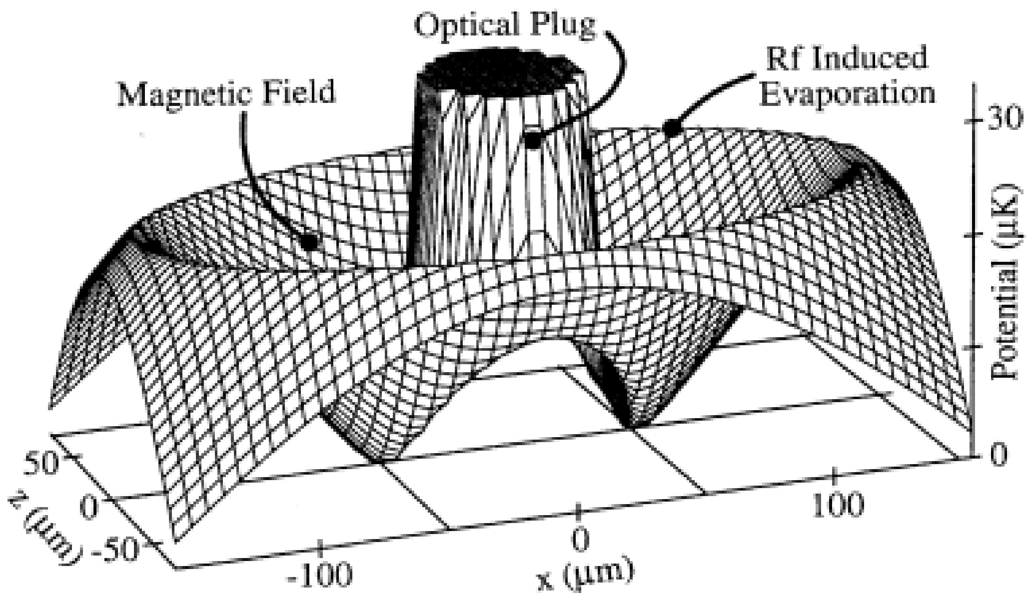
Magnetic traps

How to supress Majorana losses ?

Trick #1: Optical plugged quadrupole trap
Davis et al., PRL 75, 3969 (1995)

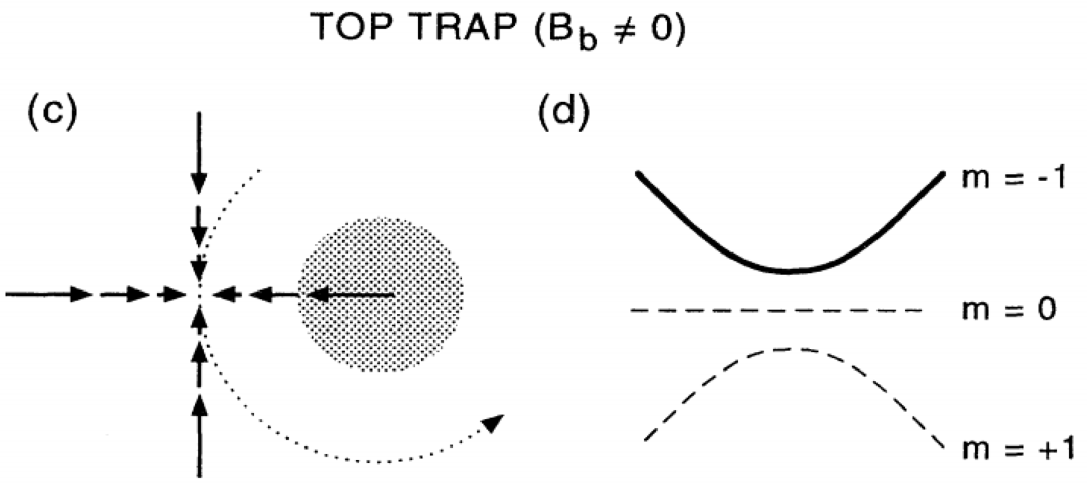
Adding a repulsive potential
around the zero, « plugging » the hole

3.5 W Ar+ laser
30 µm waist



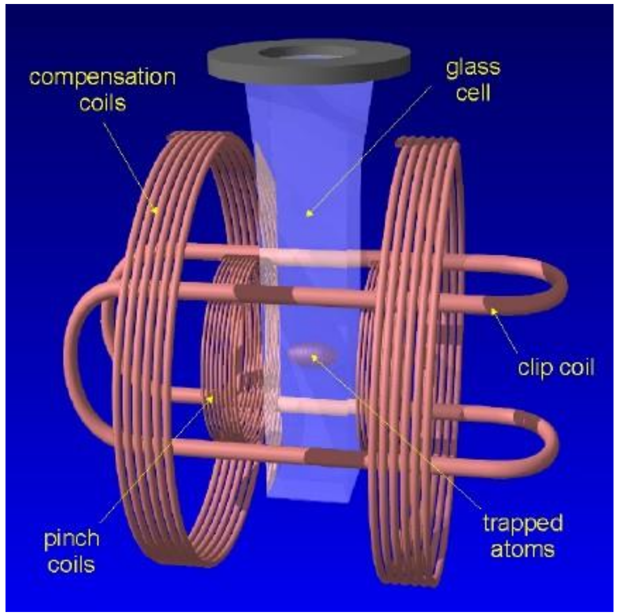
Trick #2: TOP trap
W. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, Phys. Rev. Lett. 74, 3352 (1995).

Adding a small rotating transverse field
Shifts the zero, which rotates over a circle
Time averaged potential has a non-zero minimum

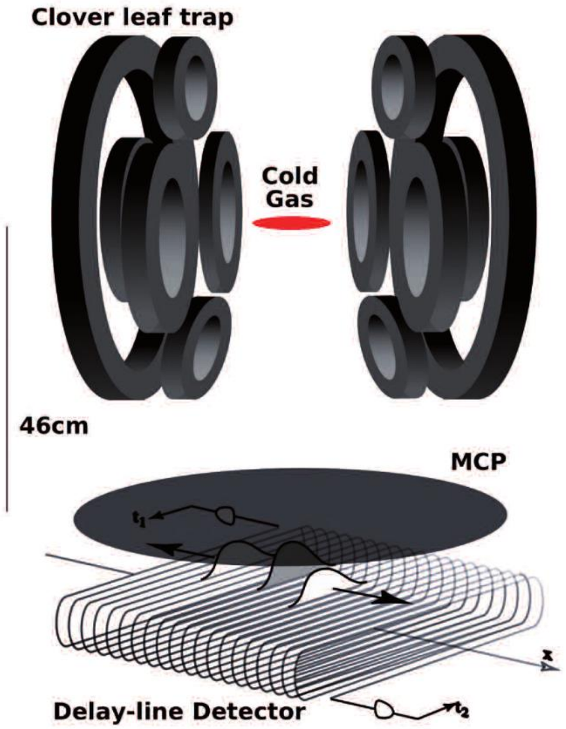


Magnetic traps

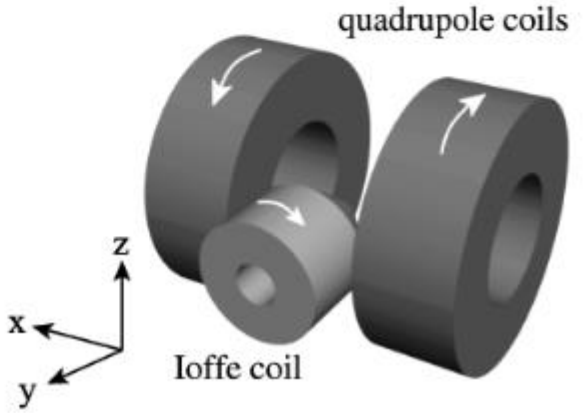
Ioffe Pritchard traps: 3D harmonic traps



Ioffe Pritchard

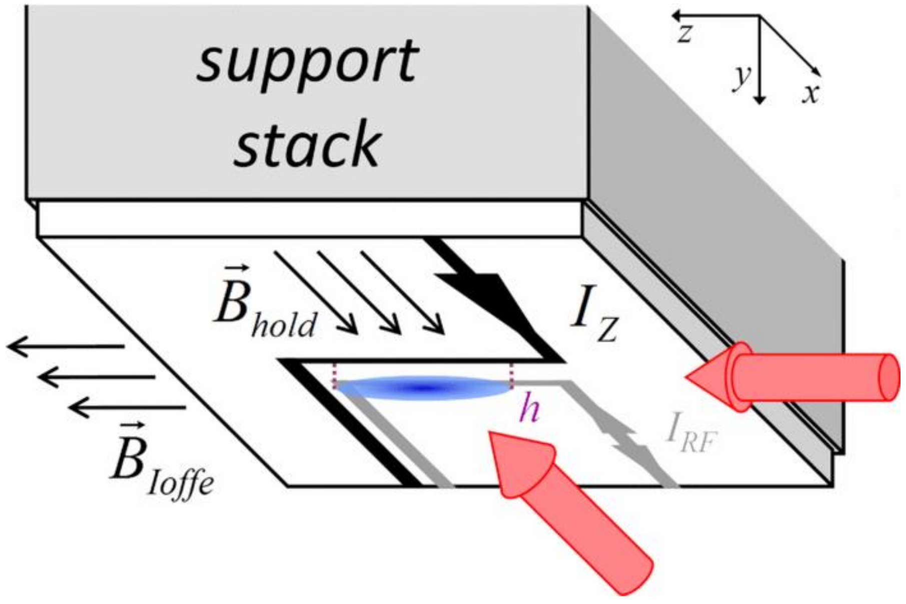


Cloverleaf trap
He, Institut d'optique



QUIC trap
Esslinger et al, PRA 58, R2664 (1998)

Z trap
on an atom chip



*Ivory et al, RSI **85**, 043102 (2014)*

Magnetic traps

Typically, atoms are transfered from a MOT or a molasses in the magnetic trap

- Optical pumping in the « low field seeking » states increase loading efficiency

- « Mode matched » transfer in the quadrupole trap requires

$$E = \mu b \sigma = \mathrm{kT}$$

For typical parameters (MOT size: $\sigma \sim 1\ mm,$ Temperature: $\mathrm{T} \sim 10\ \mu K$) and with $\mu \sim \mu_B \sim \hbar \times 1.4\ \mathrm{MHz/G}$, we find $b \sim 10\ \mathrm{G/cm}$

- Compression of the cloud by ramping up b up to few $100\ \mathrm{G/cm}$

To produces such gradients, one needs:

- for coils of ~ 10 cm diameter, I ~ 10s A with 10s turns
- for a few µm wide single wire, I ~ 1 A

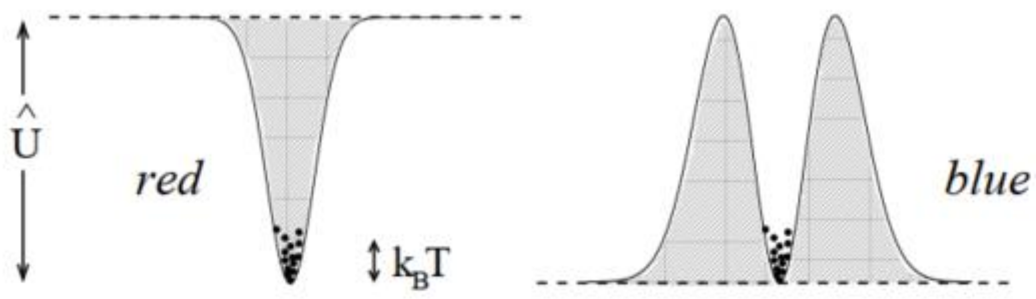
Dipole traps

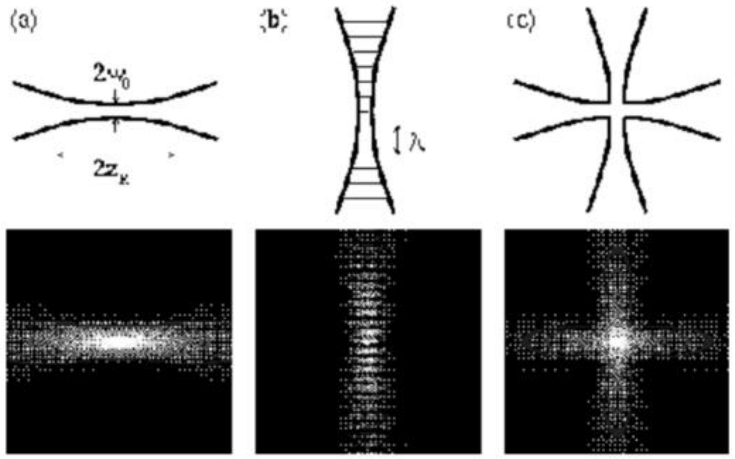
Use of far off resonance lasers

Potential depth $U \sim \frac{I}{\Delta}$ while scattering rate $\Gamma \sim \frac{I}{\Delta^2}$, so that $\frac{\Gamma}{U} \sim \frac{1}{\Delta}$

→ Spontaneous emission can be neglected at very large detunings

Red or blue detuned lasers





A large variety of trap configurations : single, lattice, crossed

Grimm et al,
Advances In Atomic, Molecular, and Optical Physics 42, 95-170 (2000)

Typical parameters: $\Delta \sim 100$ nm, $P \sim 10$s of Watts, $w_0 \sim$ 10-100 µm
Depth $U/k \sim 1$ mK
Scattering rate $\Gamma' \sim 0.01$ photon/s

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3 : Bose Einstein Condensation

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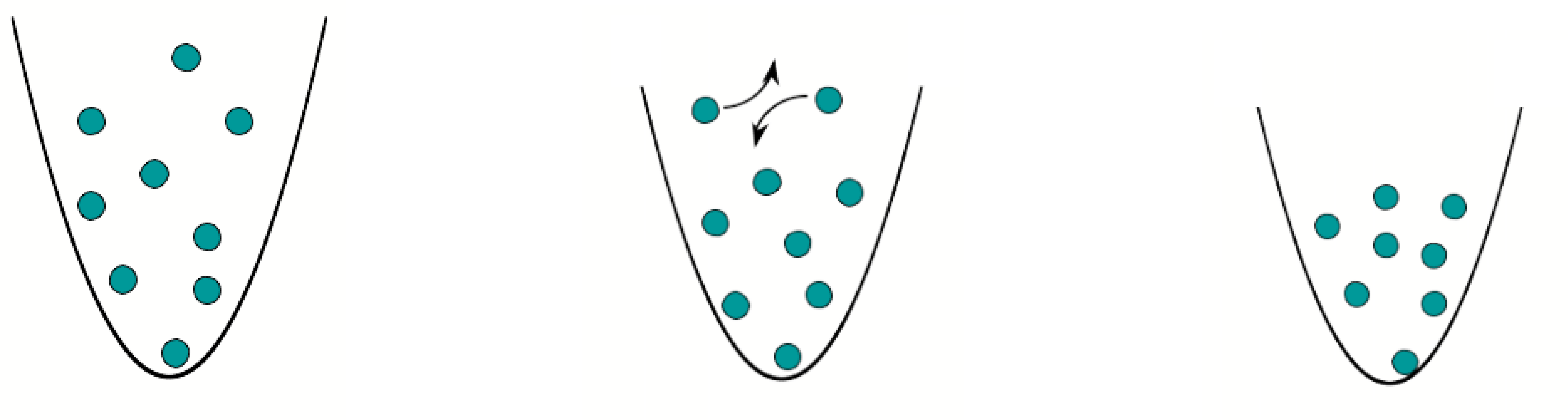
Evaporative cooling

Principle:



1) 2) 3)

Credit: H. Perrin

1) Atoms initially at thermal equilibrium at a temperature T_i in a trap of depth $U_i >> kT_i$

2) The potential height is reduced down to U_t.
Elastic collisions between atoms in the trap redistribute the energies of atom pairs.
Most energetic atoms escape the trap

3) Least energetic atoms remain in the trap.
They thermalize down to $T_f < T_i$

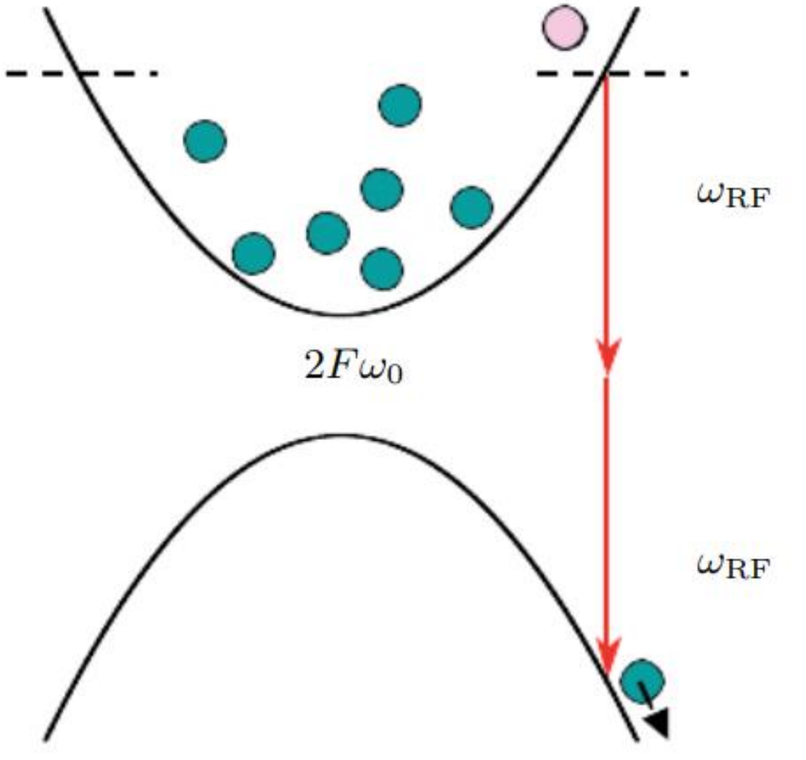
Evaporative cooling

How to reduce the potential height?

<u>Magnetic Trap</u>

→ Use of an « RF knife »
= a radiofrequency wave at frequency ω_{RF}

Leads to transitions to untrapped states selective in position



Credit: H. Perrin

<u>Dipole Trap</u>

→ Reduction of the laser intensity

Disadvantage: reduction of the confinement

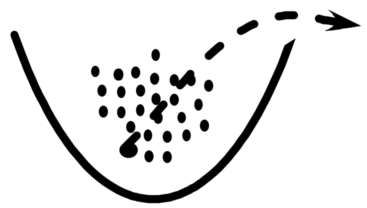
Evaporative cooling

A simple model

Note: For U_t infinite and thermal equilibrium, the energy is given by

$$E = E_c + E_p = \frac{3}{2}k_B T + \frac{3}{2}k_B T = 3k_B T$$

Let us choose $U_t = \eta k_B T$, with $\eta \gg 1$



Let us consider dN atoms that leave the trap after a collision
They carry an energy of $(\eta + \kappa)k_B T$, with $\kappa \ll \eta$

These atoms have received from the atoms that remained in the trap an energy

$$dE = dN((\eta + \kappa)k_B T - 3k_B T)$$

The $N - dN$ remaining atoms, which have given dE, thermalize at a temperature $T - dT$

Conservation of energy: $3(N - dN)k_B T - dE = 3(N - dN)k_B(T - dT)$

Evaporative cooling

$$\begin{cases} 3(N-dN)k_BT - dE = 3(N-dN)k_B(T-dT) \\ dE = dN((\eta+\kappa)k_BT - 3k_BT) \end{cases}$$

$\rightarrow \quad \frac{dT}{T} = \alpha \frac{dN}{N}$, with $\alpha = \frac{\eta+\kappa}{3} - 1$ which gives $\boxed{T \propto N^{\alpha}}$

Since $\eta \gg 1$, α can also be $\gg 1$

For a loss of a factor 10 in N, one reduces the temperature by $10^{\alpha} \gg 10$

The evaporation is a very efficient process

Evaporative cooling

Scaling of relevant parameters:

- Temperature: $T \propto N^{\alpha}$

- Volume of the atomic cloud: $V \propto N^{3\alpha/2}$

(in an harmonic trap $\frac{1}{2}m\omega^2\sigma^2 = \frac{1}{2}k_B T$, $V \propto \sigma^3 \propto T^{3/2}$)

- Velocity: $v \propto T^{1/2} \propto N^{\alpha/2}$

- Density: $\mathrm{n} \propto \frac{N}{\sigma^3} = N^{1-\frac{3\alpha}{2}}$

This gives:

- Elastic collision rate $\gamma = nv\sigma_{el} \propto N^{1-\alpha}$,

since $\sigma_{el} = 8\pi a^2$, independent of T, with a the scattering length.

- Phase space density $\rho = n\Lambda^3 \propto n/T^{3/2} \propto N^{1-3\alpha}$

For $\alpha > 1$, γ and ρ increase while N decreases

→ « Runaway » regime of evaporation

→ Eventually reach quantum degeneracy $\rho \sim 1$

Evaporative cooling

Optimization of the evaporation: kinetic aspects

Choice of U_t: high (η high) for efficient cooling

BUT the rate of « good events » is low and decreases as the temperature T decreases

→ Reduce progressively U_t in order to keep the process efficient

Choice of $\dot{U}_t$:

An optimum has to be found as

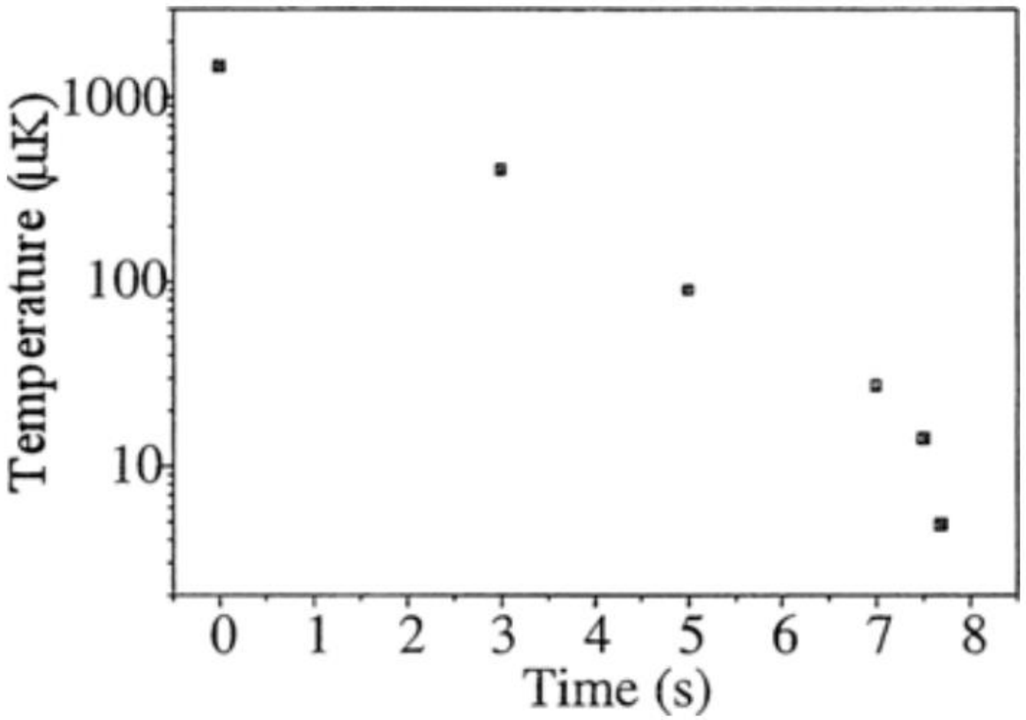
- if too slow, inelastic losses, such as due to background collisions, become important
- if too fast, no time for thermalization, atoms will end up spilling out of the trap

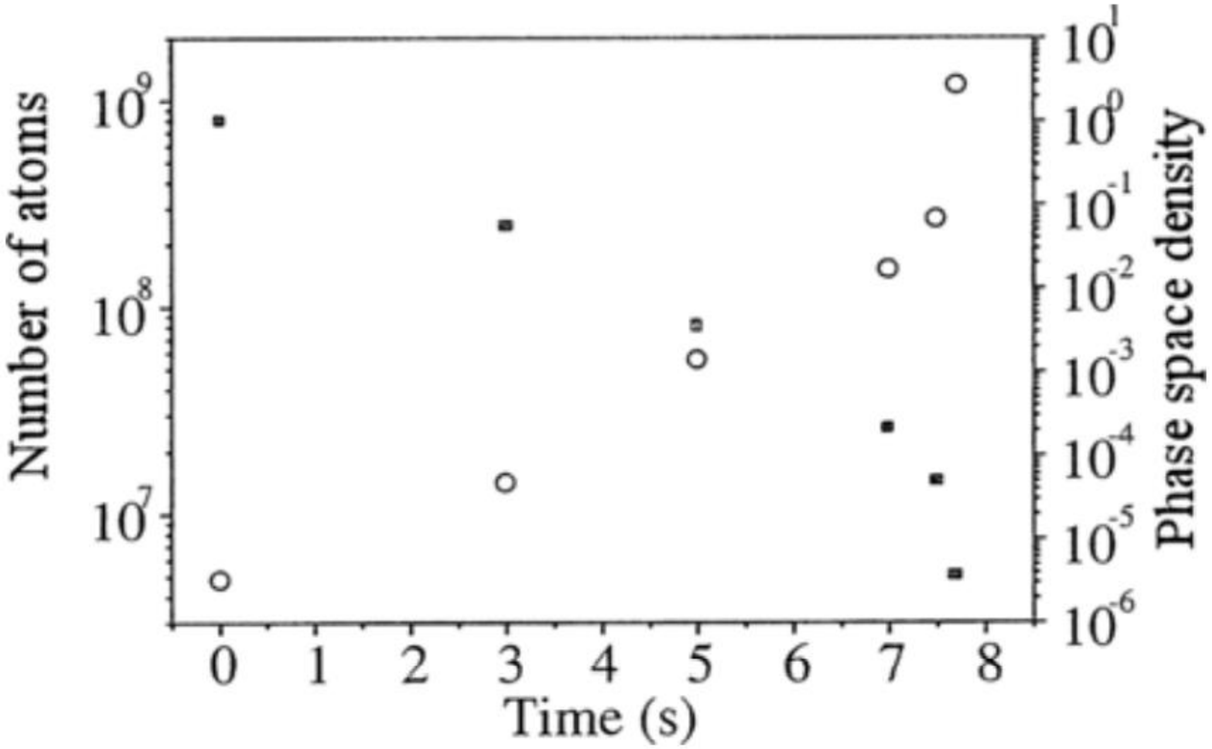
→ one need a high enough rate of elastic collisions

→ Importance of a large enough scattering length

Evaporative cooling

Typical behaviour for T, N and ρ



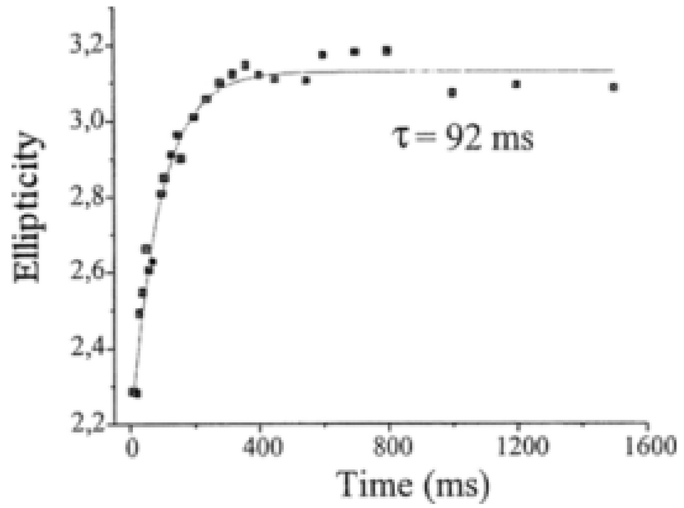


Metastable He in a magnetic trap
F. Pereira dos Santos et al, EPJD 19, 103 (2002)

For a loss in N of 2 of magnitude, gain on ρ is 6 orders of magnitude

What about $\gamma(0)$?

Induce a change of trap geometry and measure the evolution of the shape of the cloud



$\gamma(0) \sim 2.7/\tau \sim 30/s$

Evaporative cooling

Typical parameters

Magnetic trap

Initial parameters:

$N \sim 10^9$
$T \sim 1$ mK
$\omega/2\pi \sim 0.1 - 1$ kHz
$\gamma \sim 10 - 100/\text{s}$

$\tau \sim 10 - 100$ s

Final parameters:

$N \sim 10^6$ - 10^7
$T \sim 1$ µK
$\gamma \sim 1000/\text{s}$

Dipole trap

Initial parameters:

$N \sim 10^7$ ← Smaller trapping volume
$T \sim 1$ mK
$\omega/2\pi \sim 1 - 10$ kHz ← Tighter confinement
$\gamma \sim 1000/\text{s}$

$\tau \sim 1 - 10$ s

Final parameters:

$N \sim 10^5$
$T \sim 1$ µK
$\omega/2\pi \sim 10 - 100$ Hz ← Reduction of confinement
$\gamma \sim 10/\text{s}$ ← Decrease of the collisional rate; No runaway evaporation

Evaporative cooling

TABLE III
OVERVIEW OF EVAPORATIVE COOLING EXPERIMENTS

Atom	N^a	$n_0{}^a$ (cm^{-3})	T^a (K)	D^a	$\tau_{el}^{-1\,a}$ (sec^{-1})	t^b (sec)	$\gamma_{tot}{}^c$
^{1}H^d	2×10^{12} 3×10^{11}	5×10^{12} 8×10^{12}	0.05 3×10^{-3}	2×10^{-6} 2×10^{-4}	20 7	200	2.5
^{1}H^e	7×10^{12} 3×10^{11}	2×10^{13} 8×10^{13}	1.1×10^{-3} 1×10^{-4}	2×10^{-3} 0.4	9 13	250	1.6
^{1}H^f	5×10^{11} 4×10^{10}	3×10^{11} 4×10^{11}	0.2 0.06	2×10^{-8} 1.5×10^{-7}	2 2	100	0.8
^{1}H^g	8×10^{10} 7×10^{9}	5×10^{12} 4×10^{12}	0.011 3×10^{-3}	2×10^{-5} 1.3×10^{-4}	8 4	40	0.8
^{7}Li^h	2×10^{8} 1×10^{5}	7×10^{10} 1.4×10^{12}	2×10^{-4} 4×10^{-7}	7×10^{-6} 2.6^l	3 2	300	1.7
^{23}Na^i	5×10^{3} 5×10^{2}	4×10^{12} 6×10^{11}	1.4×10^{-4} 4×10^{-6}	1.2×10^{-4} 4×10^{-3}	8×10^{2} 20	2	1.5
^{23}Na^j	1×10^{9} 7×10^{5}	1×10^{11} 1.5×10^{14}	2×10^{-4} 2×10^{-6}	2×10^{-6} 2.6^l	23 3×10^{3}	7	1.9
^{87}Rb^k	4×10^{6} 2×10^{4}	4×10^{10} 3×10^{12}	9×10^{-5} 1.7×10^{-7}	3×10^{-7} 2.6^l	5 15	70	3.0

[a] Upper row: initial value, lower row: final value, for number of atoms N, peak density n_0, temperature T, phase space density D, and peak elastic collision rate τ_{el}^{-1}.
[b] Duration of forced evaporation sweep t.
[c] The overall efficiency of evaporation $\gamma_{tot} = \log(D_f/D_i)/\log(N_i/N_f)$.
[d] Masuhara *et al.* (1988), MIT, cryogenic Ioffe–Pritchard (IP) trap, saddle-point evaporation.
[e] Doyle *et al.* (1991), MIT, cryogenic IP trap, saddle-point evaporation.
[f] Luiten *et al.* (1993), Amsterdam, cryogenic IP trap, saddle-point evaporation.
[g] Setija *et al.* (1993), Amsterdam, cryogenic IP trap, light-induced evaporation.
[h] Bradley *et al.* (1995), Rice, permanent-magnet IP trap, rf-induced evaporation.
[i] Adams *et al.* (1995), Stanford, crossed-dipole trap, evaporation by lowering the trap potential.
[j] Davis *et al.* (1995b), MIT, optically plugged, linear magnetic trap, rf-induced evaporation.
[k] Anderson *et al.* (1995), JILA, time-averaged, orbiting potential trap, rf-induced evaporation.
[l] Bose–Einstein condensation was reached; the number in this row reflect the situation at the transition point.

Evaporative Cooling of Trapped Atoms
W. Ketterle, N.J. VanDruten
Advances In Atomic, Molecular, and Optical Physics
37, 181-236 (1996)

Magnetically trapped hydrogen
First evaporative cooling in 1998

3 pioneer BEC experiments in 1995
RF evaporation in magnetic traps

Evaporation in a dipole trap

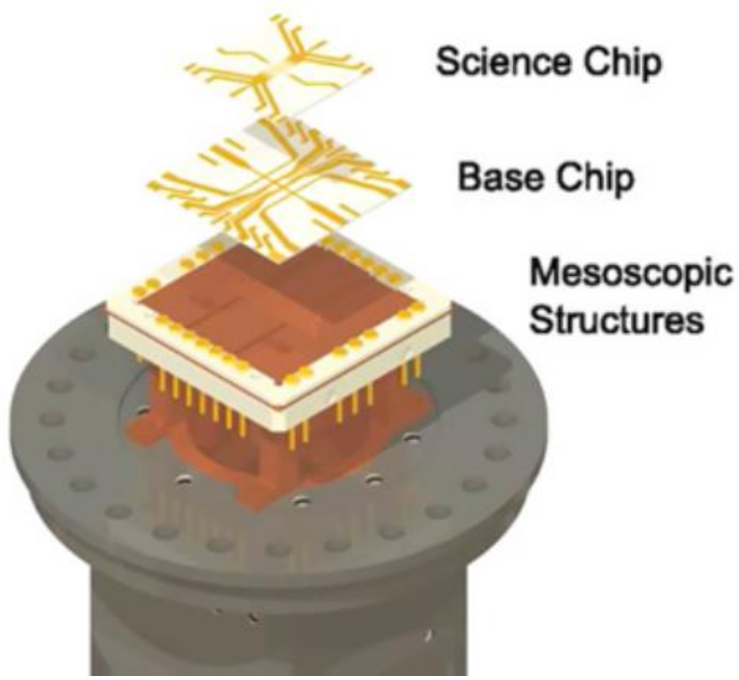
Efficiency of evaporation

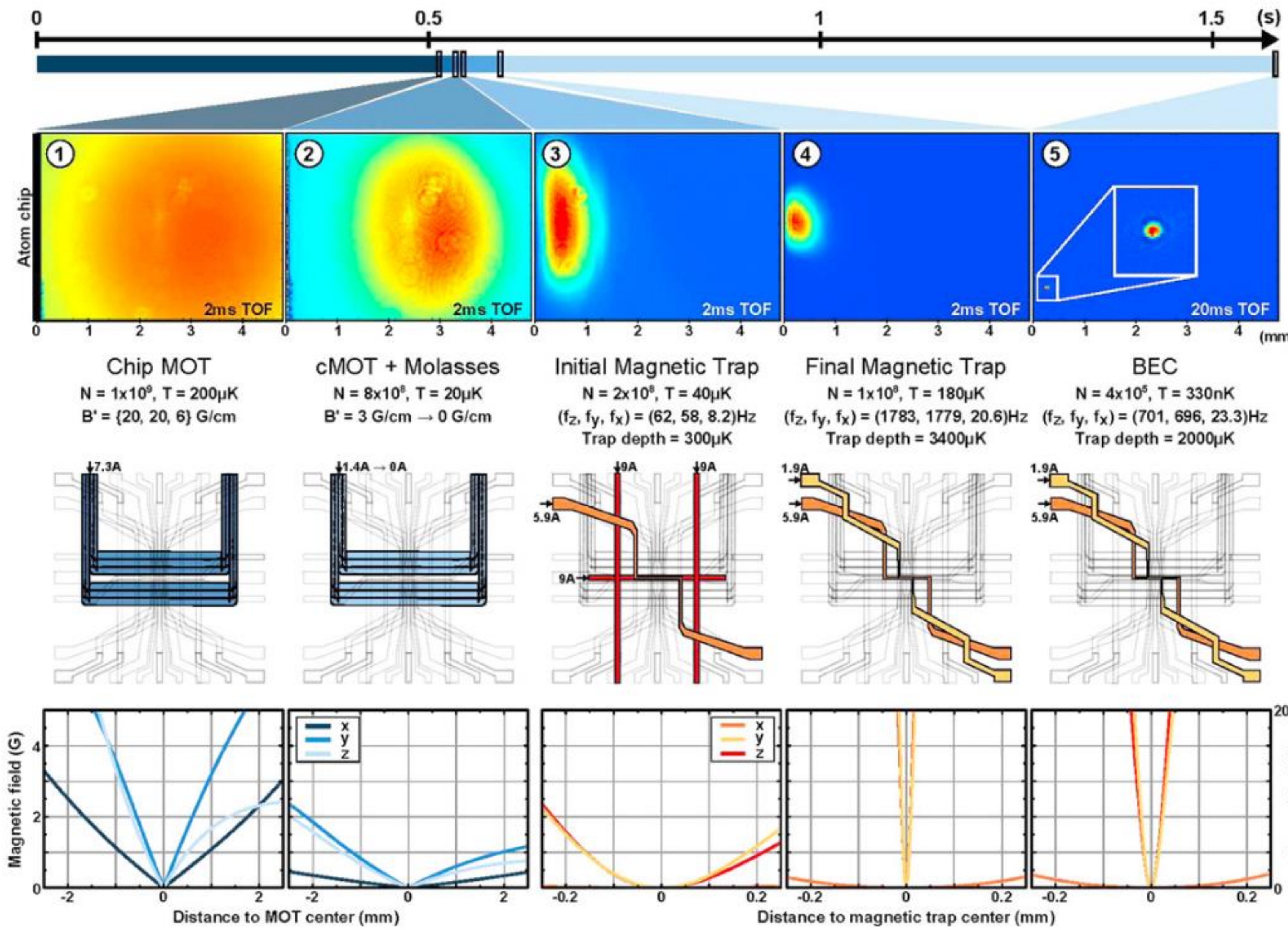
$$\frac{\mathrm{Log}\left(\frac{\rho_f}{\rho_i}\right)}{\mathrm{Log}\left(\frac{N_i}{N_f}\right)} = 3\alpha - 1 = 3\left(\frac{\eta+\kappa}{3} - 1\right) - 1 \simeq \eta - 4$$

Evaporative cooling

How to speed it up ?

Use for tight potentials : magnetic traps on atom chips or dipole traps





Optimized atom chip structure
with a two-layer chip
and mesoscopic structures

Jan Rudolph et al, New J. Phys. 17, 065001 (2015)

Evaporative cooling

How to speed it up ?

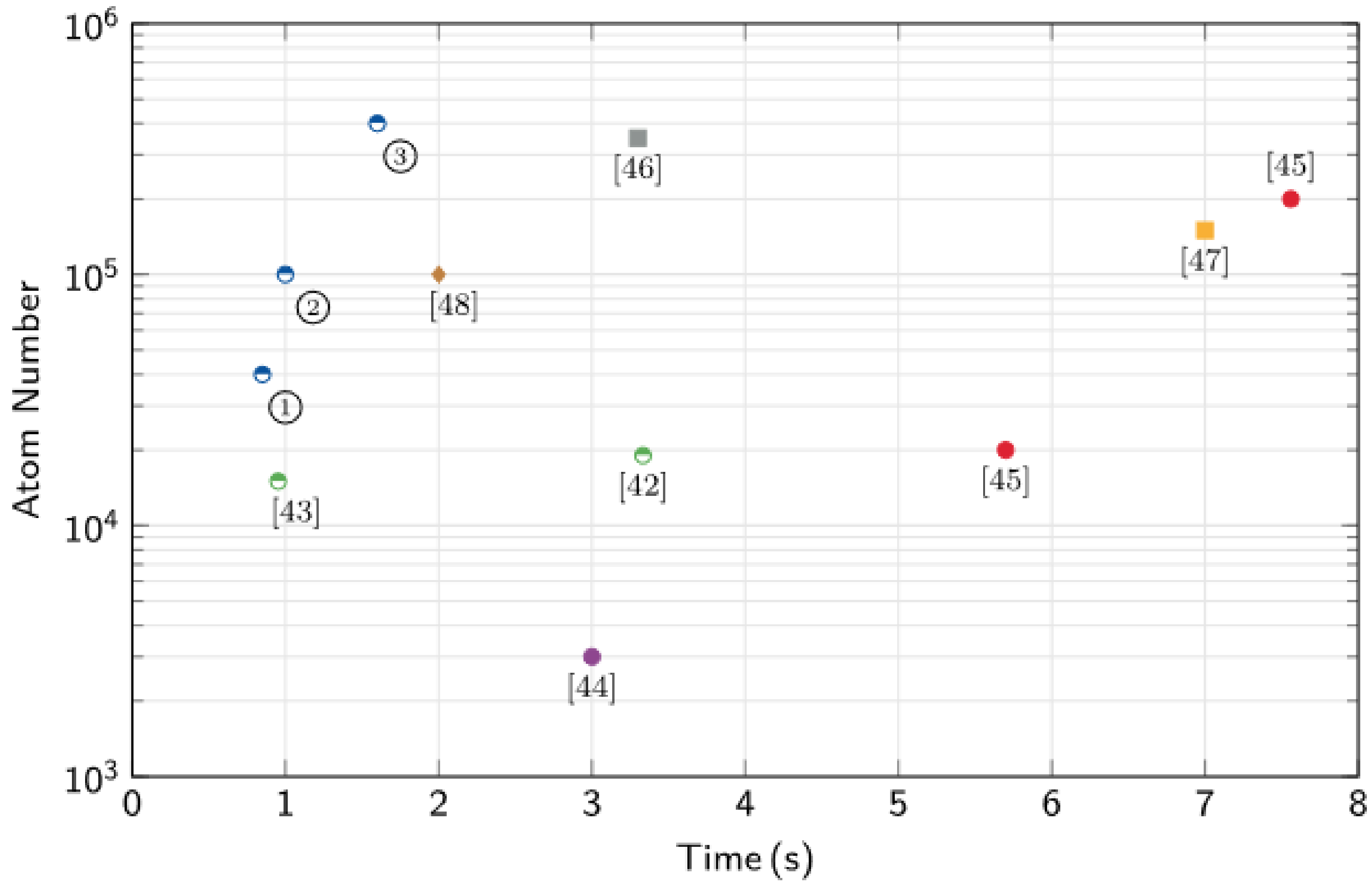


Figure 6. Comparison of the fastest BEC machines. Circles denote atom chip based experiments [42–45], squares indicate experiments using dipole traps [46, 47]. The diamond symbol indicates a Sr experiment reported in [48]. Semi-filled symbols mark compact and transportable setups. The results of this work are represented by three cases, ①–③.

Production of a BEC in less than a second (loading of the MOT + evaporation in chip traps)

BEC with 3 10^5 atoms in 1.6 s

Evaporative cooling

And in dipole traps ?

M. D. Barrett, J. A. Sauer, and M. S. Chapman, Phys. Rev. Lett. 87 (2001)

2 crossed CO_2 lasers (very very far detuned, wavelength 10 µm)
Quasi-electrostatic traps, spontaneous emission completely negligible

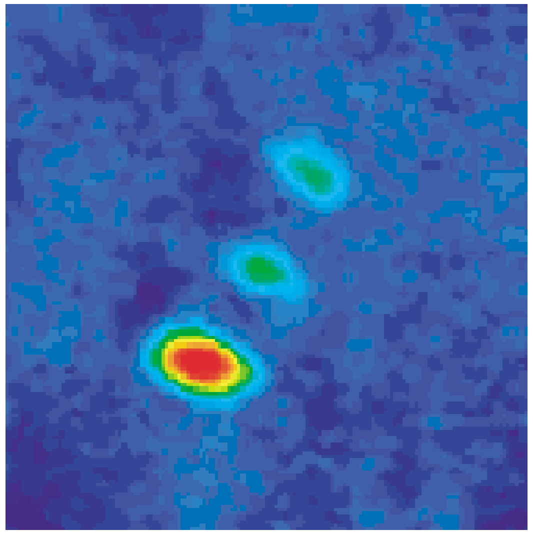
12 W per beam, with 50 µm waists, trapping frequency 1.5 kHz

Loading from subDoppler MOT:
initial density 2 10^{14} at/cm^3, initial Phase space density 1/200
Initial collisional rate : 12 kHz!

Evaporation:

- 2.5 s of evaporation led to the creation of a BEC
- Thermalization rate dops by a factor 50

A notable difference with respect to magnetic traps:
All spin states are simultaneously cooled

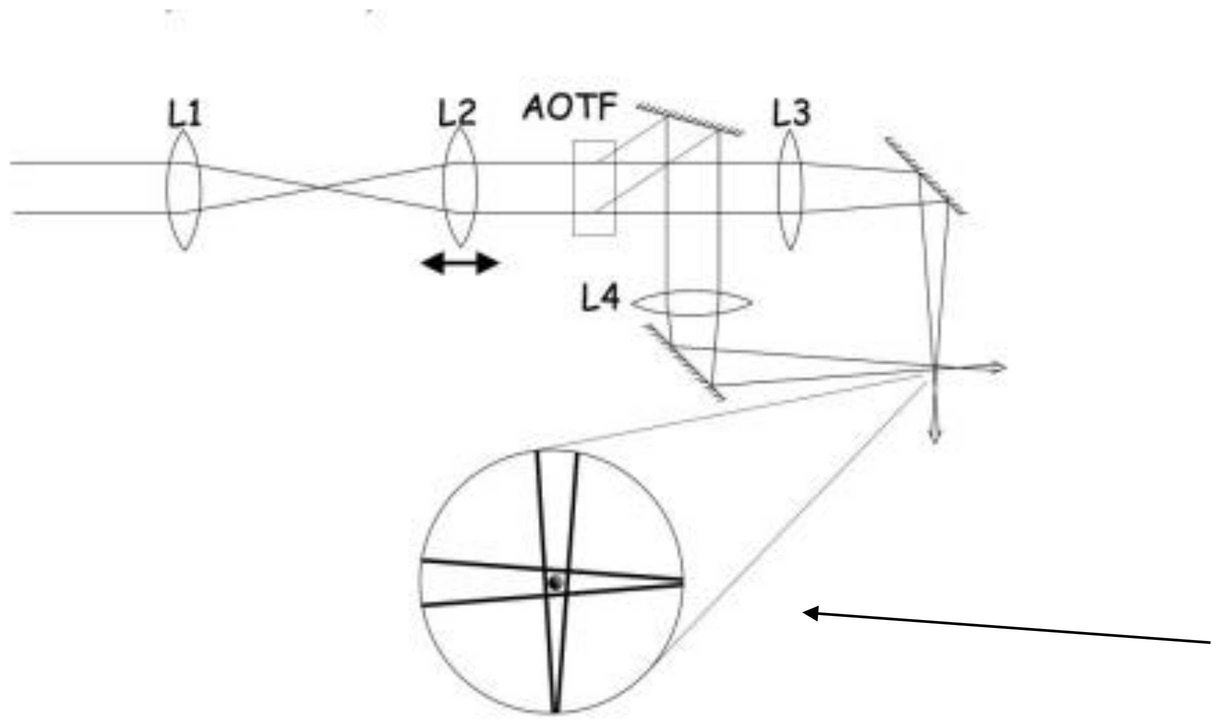


Time of flight
after 10 ms of Stern Gerlach gradient
F=1, m_F={-1,0,1}

Evaporative cooling

Dipole traps: how to circumvent the loss in collisional rate ?

Trick #1 : shift dynamically the waist positions



Crossing point can be shifted

→ Large volume for the loading

→ Compression of the cloud

→ Increase of collisional rate

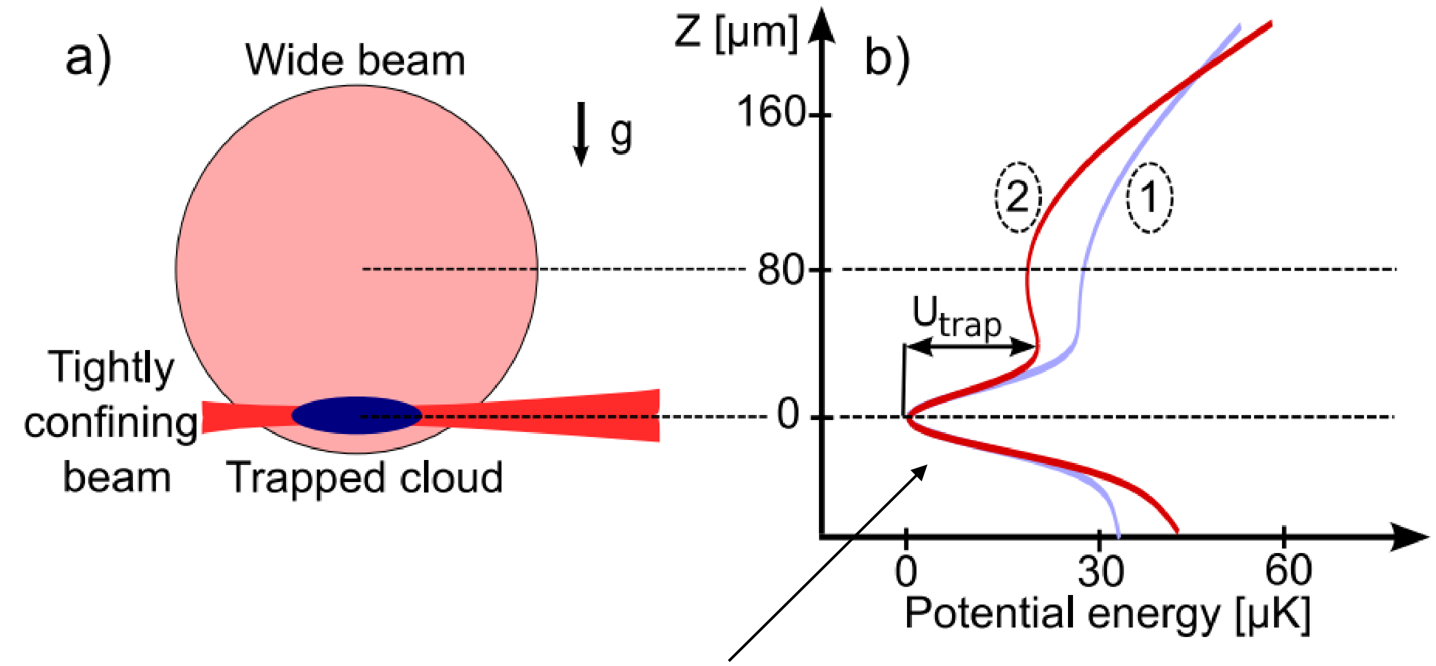
→ Depth/confinement adjustable

Kinoshita et al, PRA A 71, 011602(R) (2005)

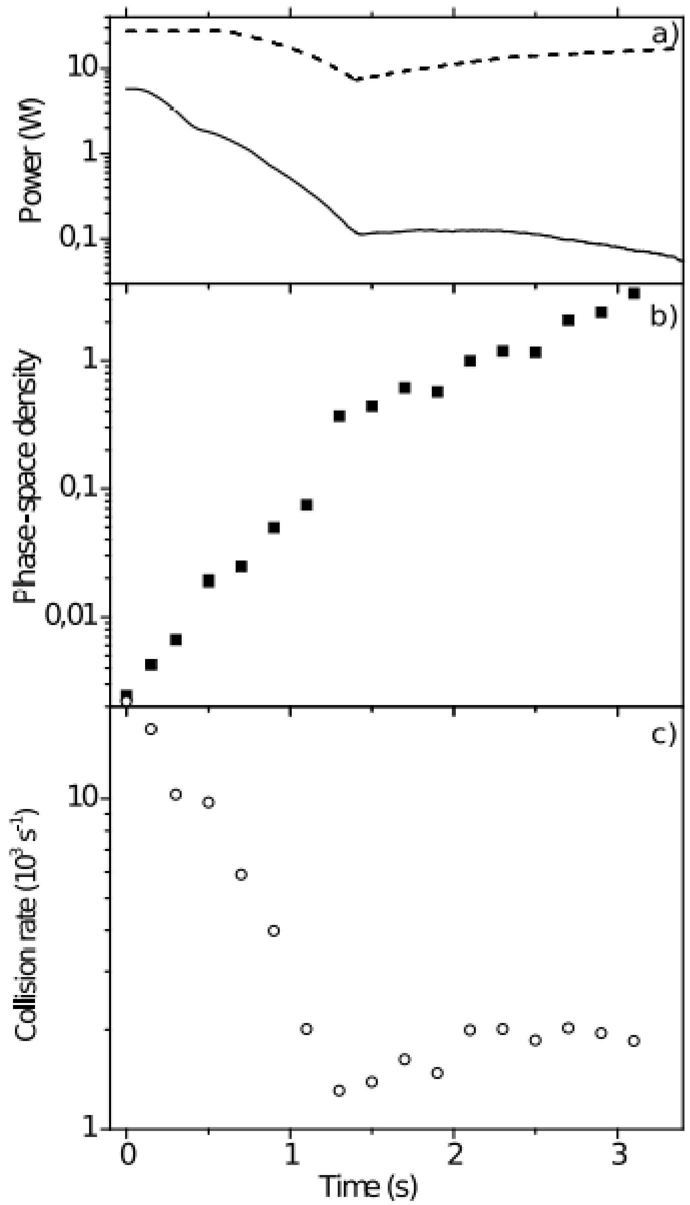
Evaporative cooling

Trick #2:

Shift the crossing point downwards



Depth reduces but not confinement



Collisional rate increases at the end
→ Runaway regime

J. F. Clément et al, PRA 79, 061406(R) (2009)

Organization of the lecture

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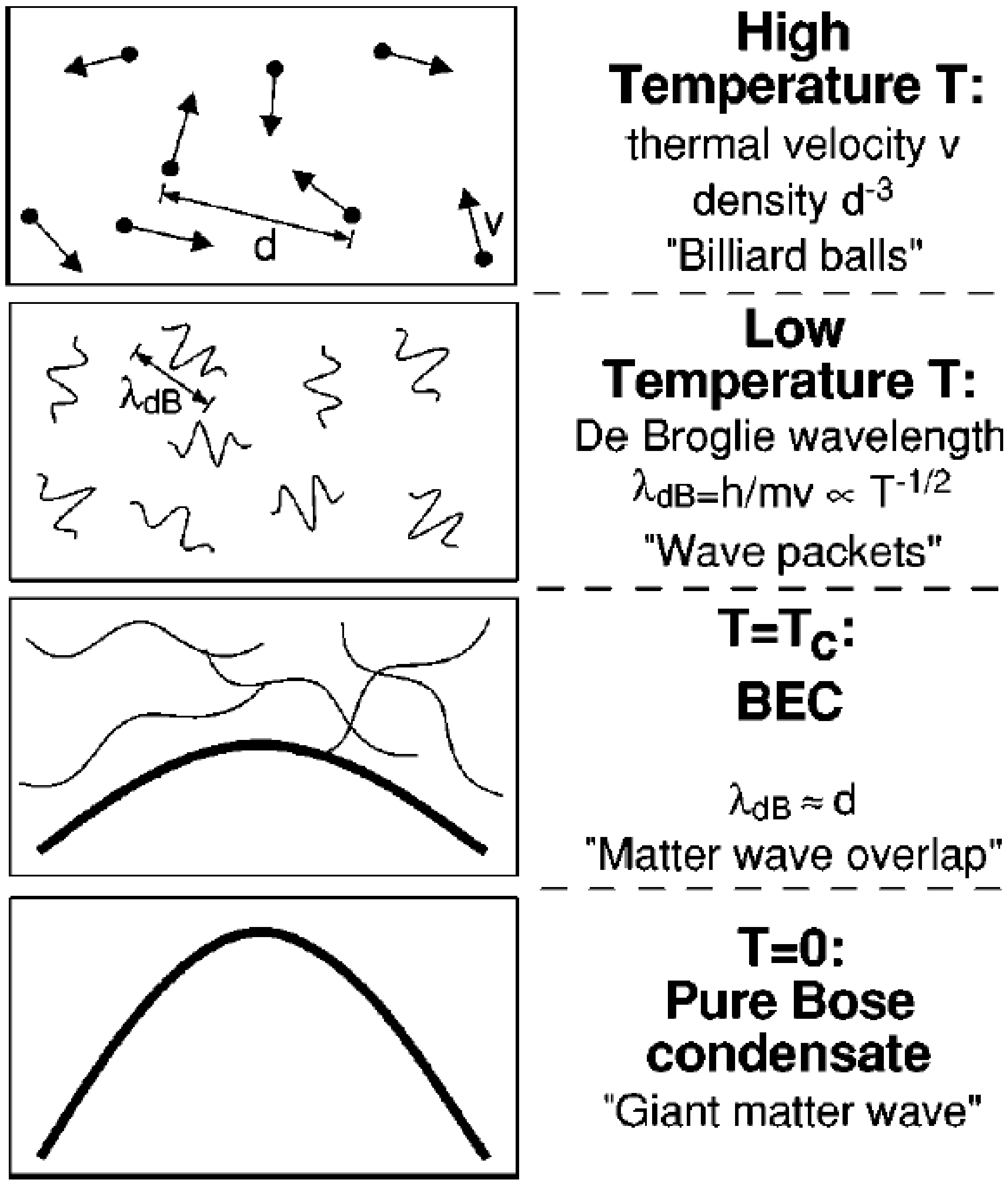
Bose Einstein condensation



MOT MOLASSES

$n\Lambda^3 \sim 10^{-7}$

Evaporative cooling

$n\Lambda^3 \sim 1$

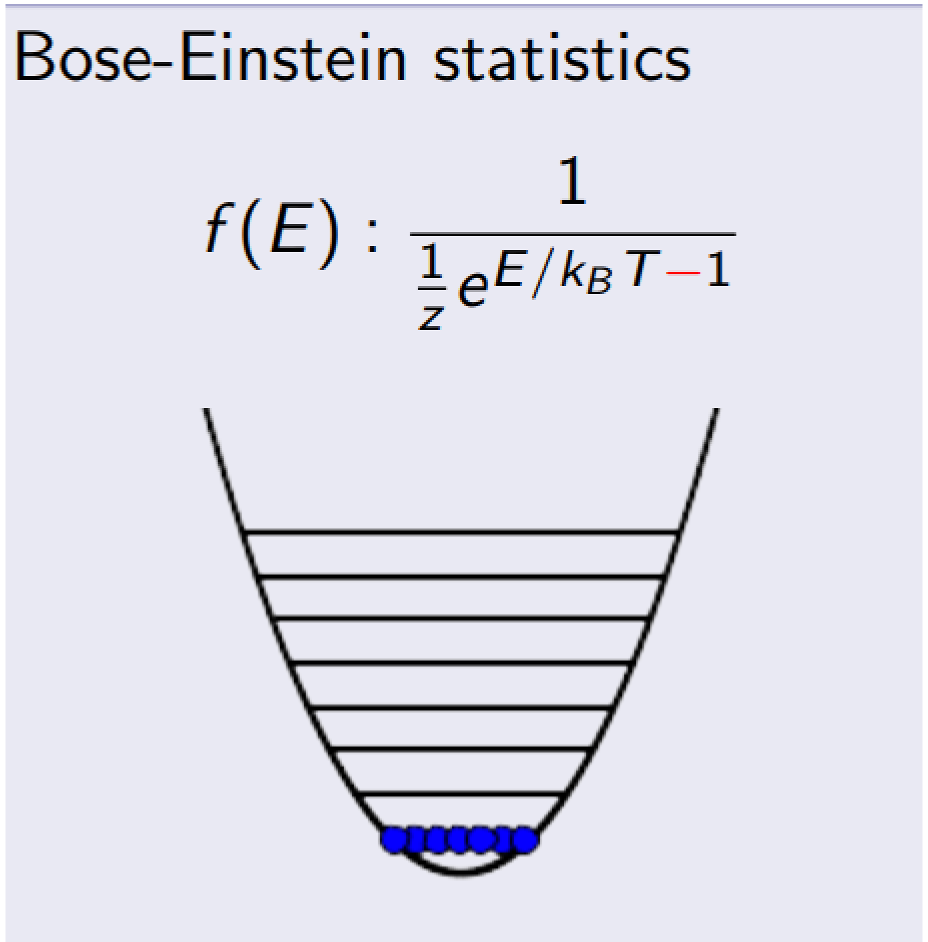
Bose Einstein condensation

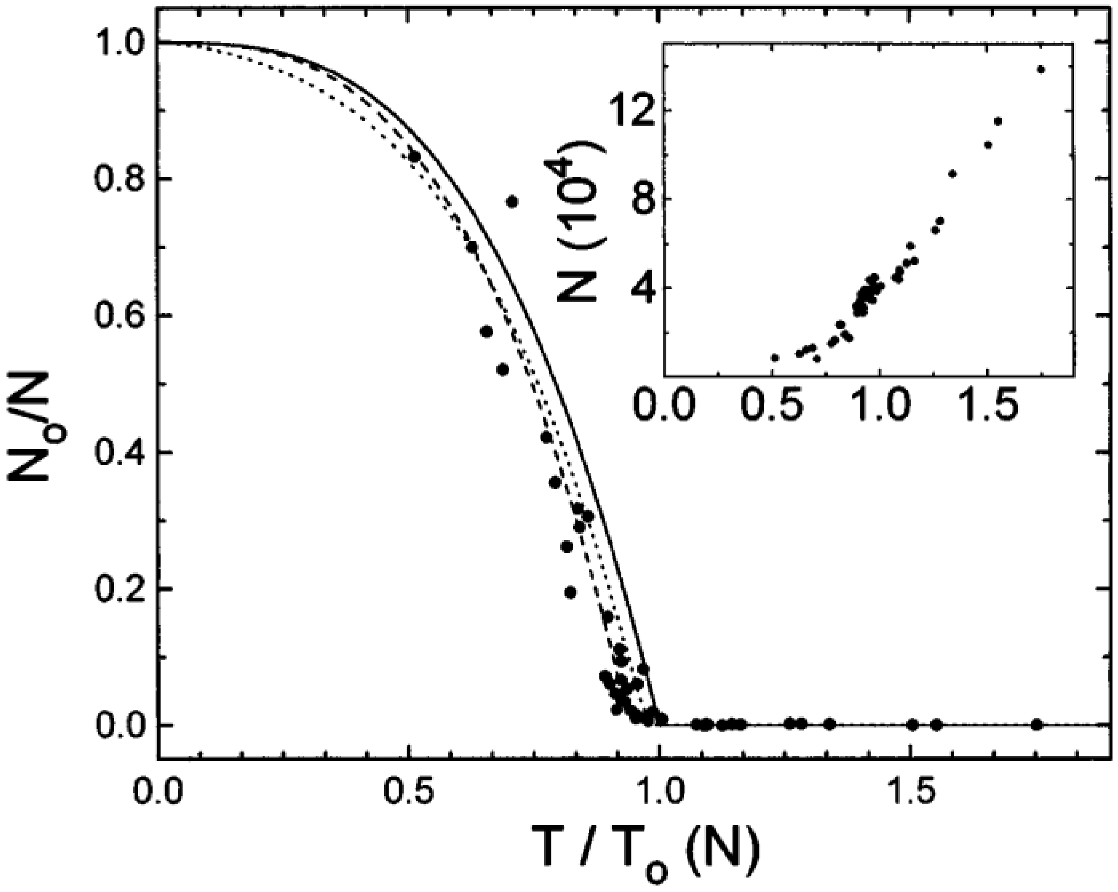
BEC is a consequence of Bose-Einstein statistics

For a given number of atoms, the number of atoms in excited states is bounded

Below a critical temperature, the ground state becomes macroscopically populated $N_0 \sim N$

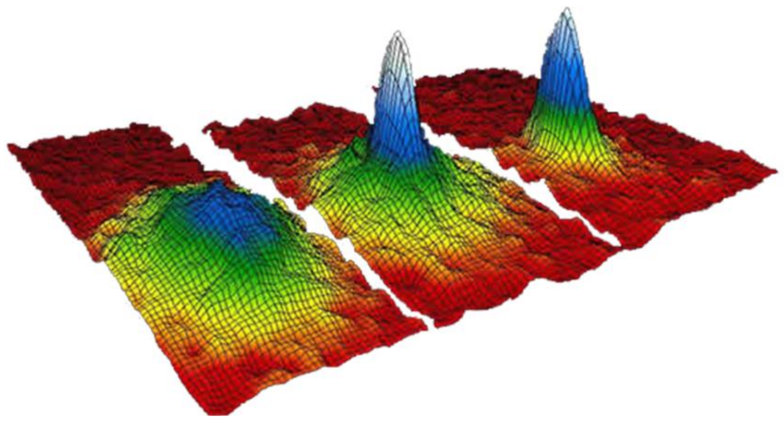
T_c corresponds to $n\Lambda^3 \sim 1$, where $\Lambda = h/\sqrt{2\pi mkT}$





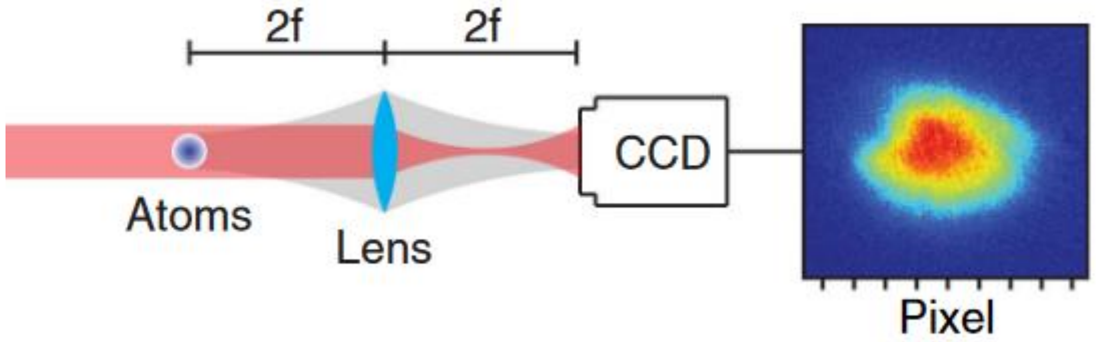
J. R. Ensher, D. S. Jin, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Phys. Rev. Lett. 77, 4984 (1996)

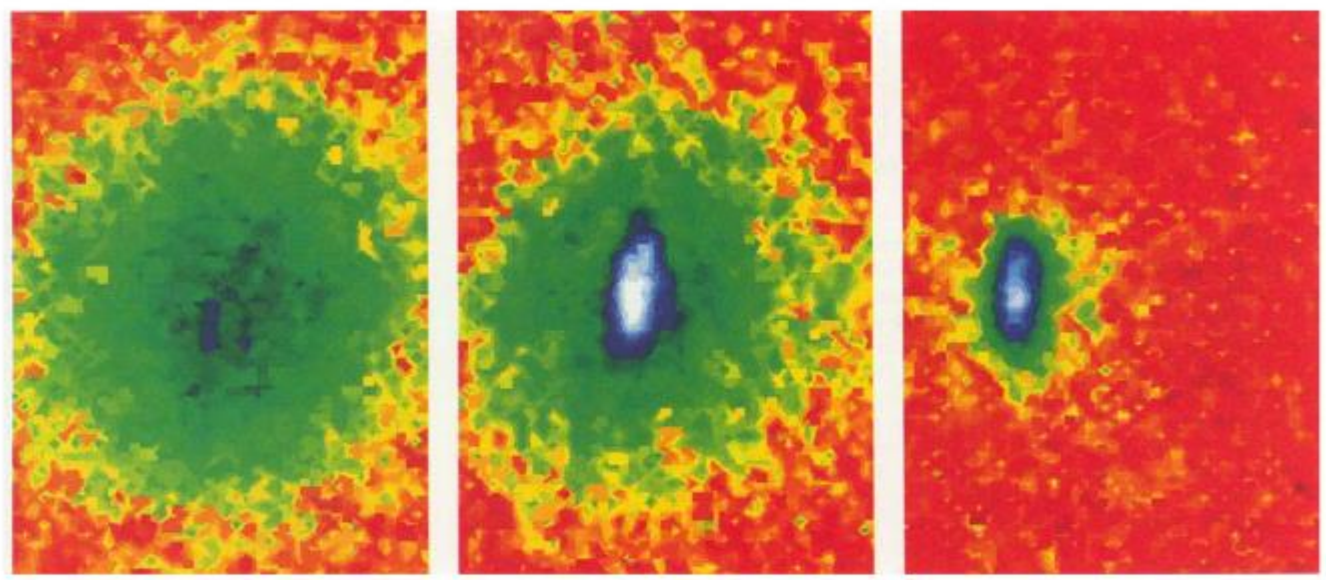
Bose Einstein condensation



M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, E.A. Cornell, Science 269, 198–201 (1995)

Time of flight in absorption imaging





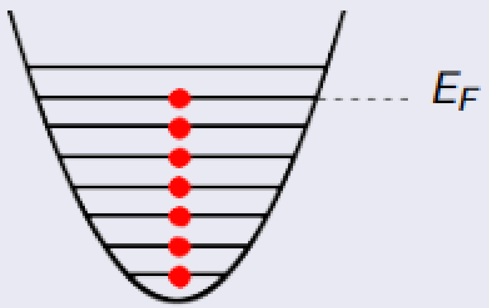
Characteristic ellipticity of the BEC
Signature of interactions

And for fermions?

fermions

Fermi-Dirac statistics

$$f(E) : \frac{1}{\frac{1}{z}e^{E/k_BT}+1}$$

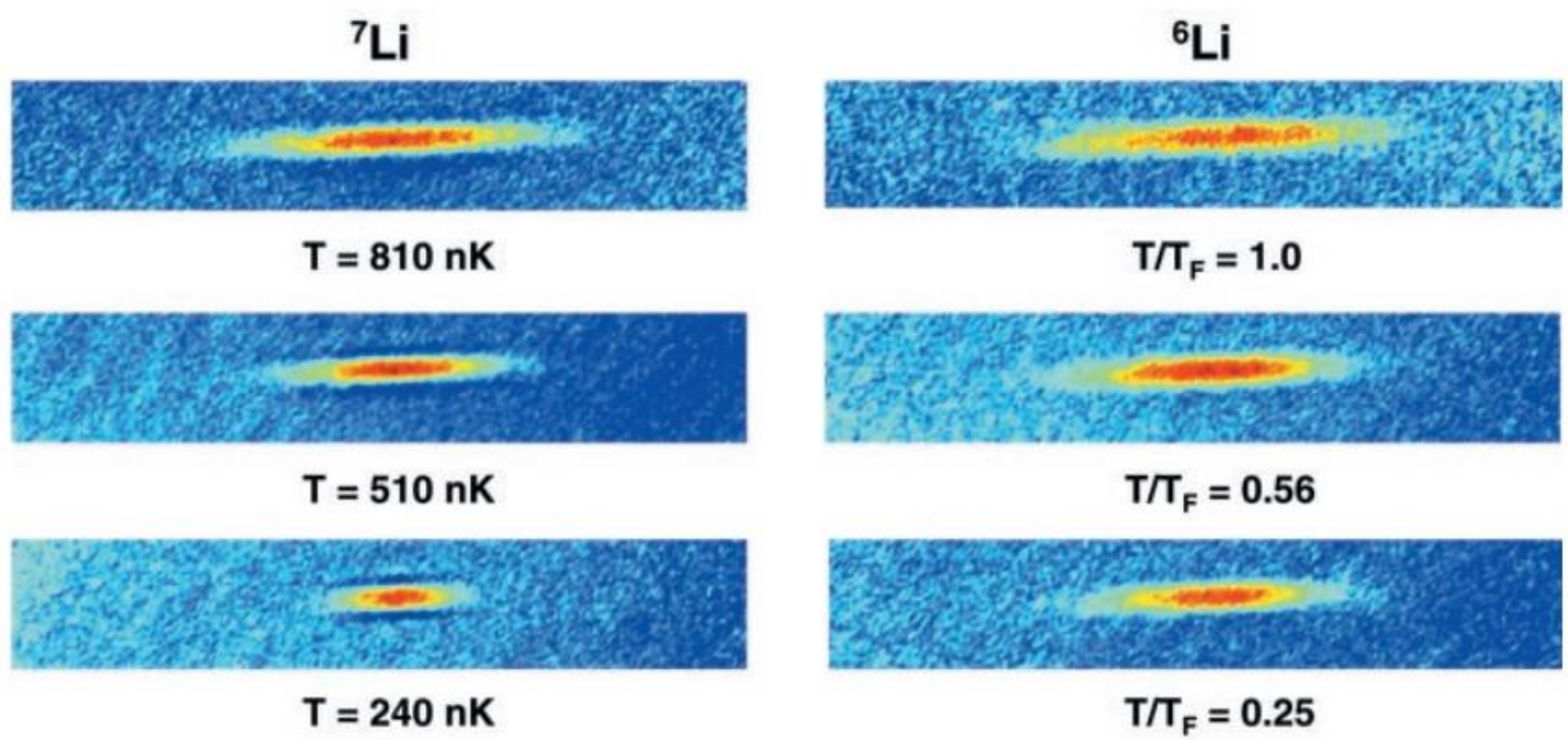


$0 \leq f \leq 1$ at most 1

A different statistics

At most one fermion per state

Pb: no (s-wave) collisions at low temperature
Evaporative cooling does not work



Use a mixture:
Cool two spin states of 40K
B. DeMarco and D. S. Jin,
Science 285, 1703 (1999)

Sympathetic cooling:
Cool ^{7}Li (boson) and 6Li (fermion) in the same trap
Truscott et al, Science 291, 2570 (2001)
BEC + « Fermi sea »

Fermi pressure limits
the minimal size of the cloud

Organization of the lecture

1 : Conservative traps

2 : Evaporative cooling

3 : Bose-Einstein condensation

4 : Miscellaneous

Delta Kick collimation

Hubert Ammann and Nelson Christensen, PRL 78, 2088 (1997)

1) Free expansion
2) Subsequent application of a pulsed potential

→ narrows the momentum distribution (provided the atoms were initially well localized)

$$t < 0: H = \frac{p^2}{2m} + U(x)$$

At t=0, turn off the potential, and apply after a free evolution time a Gaussian pulse (of the very same potential)

$$t > 0: H = \frac{p^2}{2m} + U(x)e^{\left(-\frac{t-T}{2\tau_p{}^2}\right)} \approx \frac{p^2}{2m} + V(x)\delta(t-T)$$

with $V(x) = \sqrt{2\pi}\tau_p U(x)$

Delta Kick collimation

After a (long enough) free evolution, the momentum of the atom is linear with position

$p = mx/T$ (principle of the time of flight)

With $U(x) = \frac{1}{2}m\omega^2x^2$, a kick changes the momentum of the atoms by $\Delta p \propto \nabla U \propto x \propto p$

Atom is at rest after the pulse for $\Delta p = p$, which leads to $\sqrt{2\pi}\tau_p\omega^2 T = 1$

Limitations:

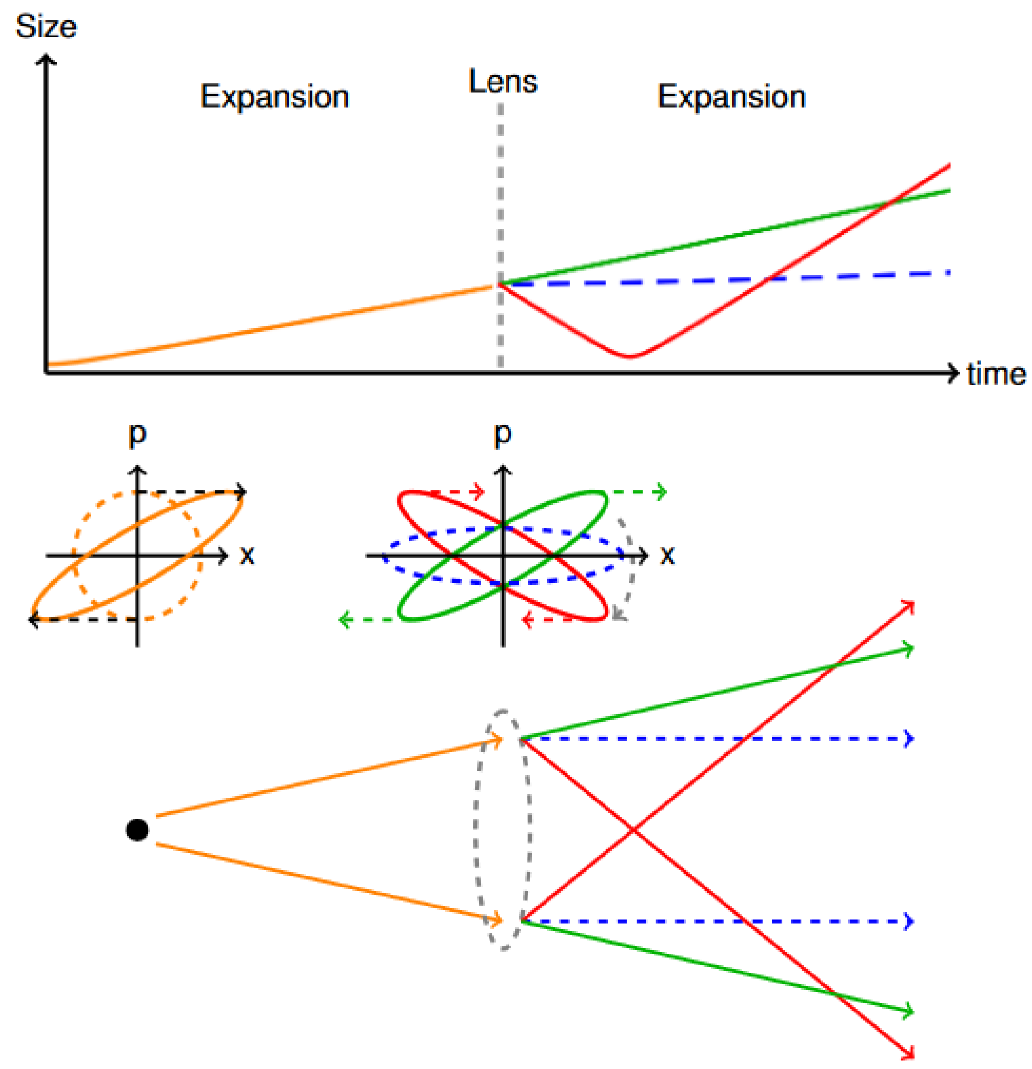
- the atomic cloud has a finite initial size $\rightarrow T$ shall not be too short
- the potential might not be perfectly harmonic far off the center $\rightarrow T$ shall not be too long

$\rightarrow$ trade-off for T

Actually, the remperature ratio $\eta = \frac{{\sigma_{p_l}}^2}{{\sigma_{p_i}}^2}$ is bounded by $\eta_c = \frac{{\sigma_{x_i}}^2}{{\sigma_{x_l}}^2}$

Delta Kick collimation

DKC acts as a lens for matter waves

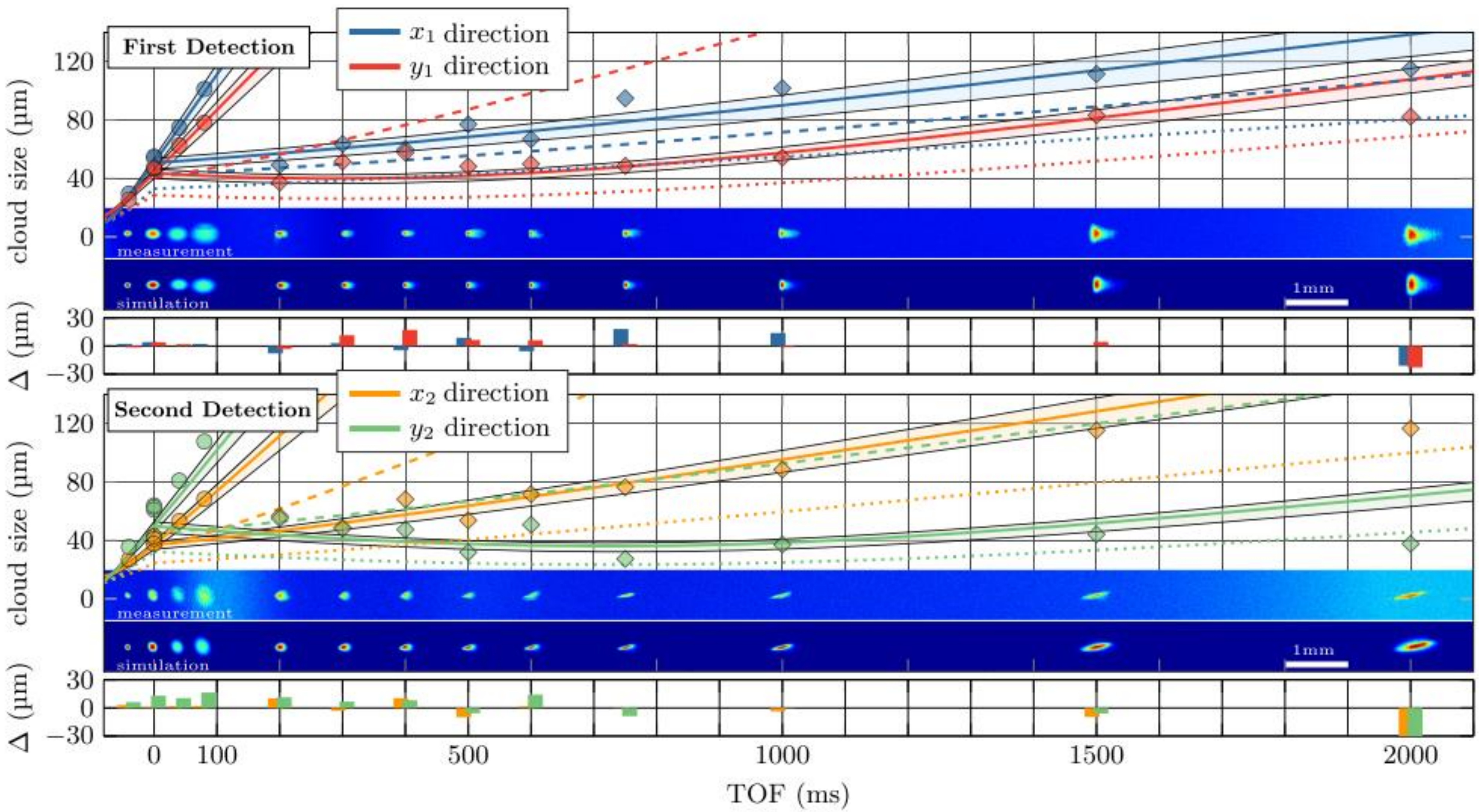


Interferometry with BEC in Microgravity
H. Müntinga et al., PRL 110, 093602 (2013)
~ 1 nK in 3D

Matter Wave Lensing to Picokelvin Temperatures
Tim Kovachy et al, PRL 114, 143004 (2015)
~ 50 pK in 2D

Delta Kick collimation

Collective-Mode Enhanced Matter-Wave Optics
Christian Deppner et al, PRL 127, 100401 (2021)
~ 40 pK in 3D



Some applications of laser cooling and trapping

- high-resolution spectroscopic measurements

frequency standards: atomic fountain MW clocks, optical clocks

- study of ultracold quantum gases

BEC physics and much more

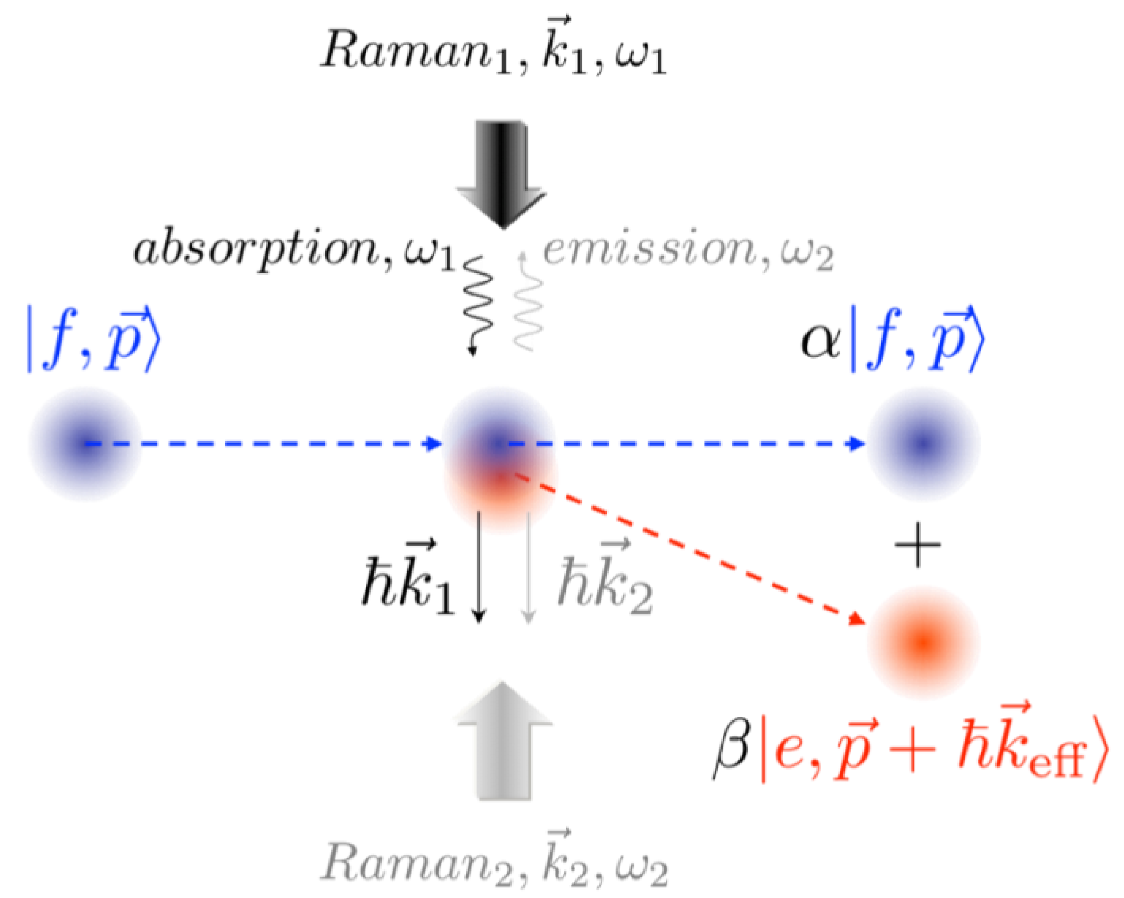
- quantum optics research and applications in quantum information technology

quantum computing, quantum simulation

- ultraprecise inertial sensors

gravimeters, gyrometers …

Atom interferometry



Beamsplitters for matter waves

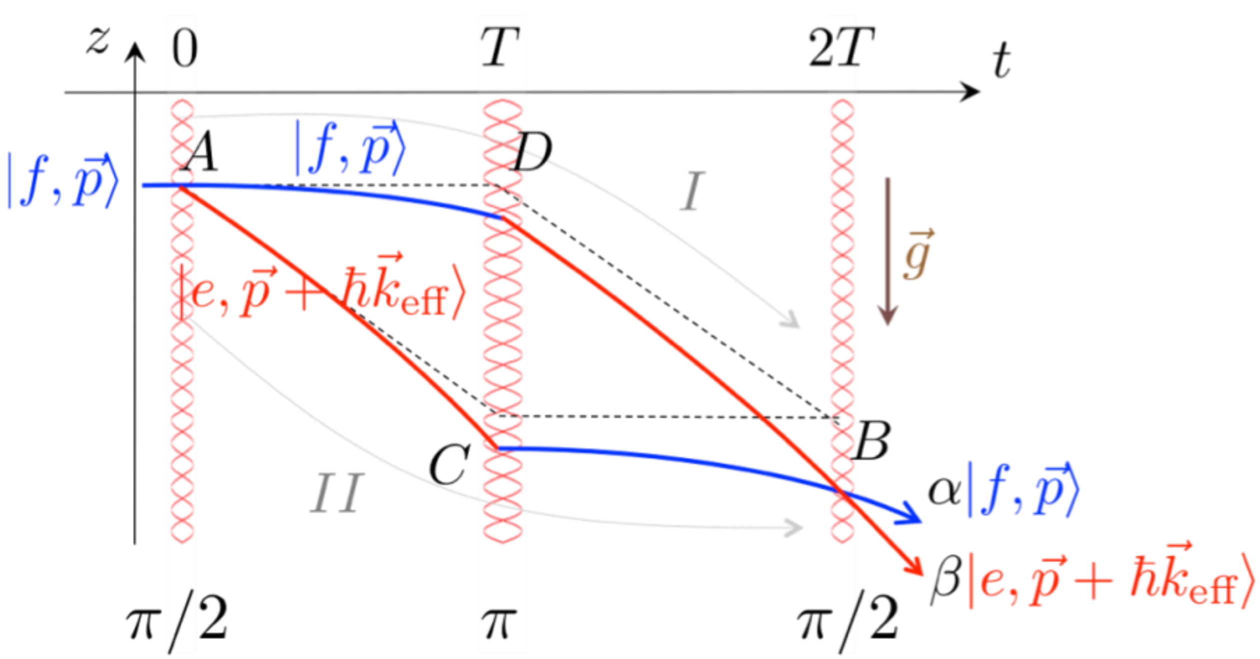
Stimulated Raman transitions are used to manipulate the atomic wave packets

They realize mirrors and beamsplitters for atomic waves

Interferometer

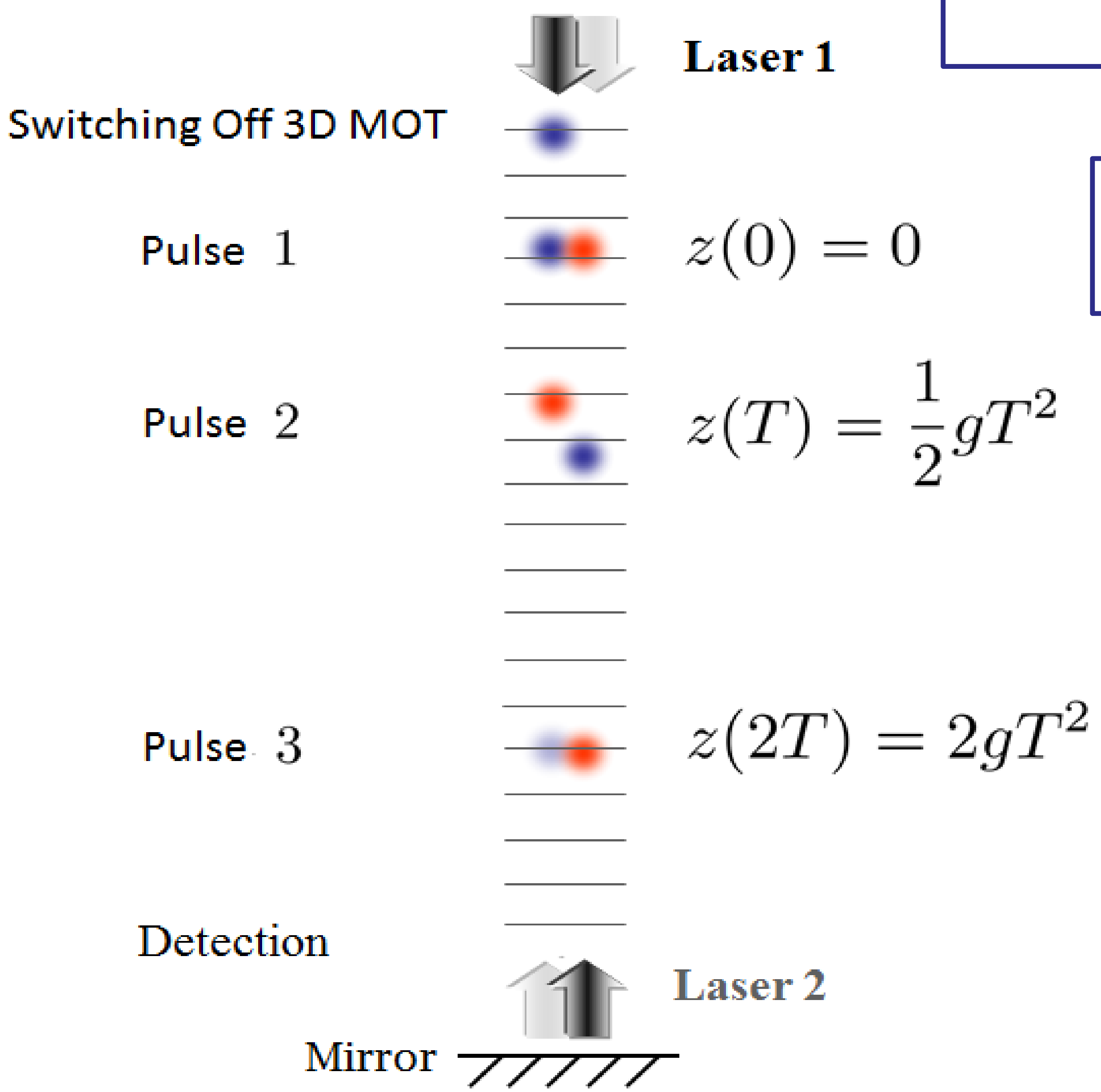
Sequence of three lasers pulses separated by a free evolution time T

Populations in the output port depend on the phase difference between the two arms



$$P_{|\vec{p}\rangle \rightarrow |\vec{p}+\hbar\vec{k}_{\rm eff}\rangle} = \frac{1}{2}(1 - C cos \Delta\Phi)$$

Cold atom gravimeter



The interferometer phase is related to the interaction between atoms and light beamsplitters

The laser phase gets imprinted onto the atomic wavepacket at each pulse

$$\Delta\Phi = \Phi_{II} - \Phi_{I}$$
$$\Delta\Phi = \varphi(0) - 2\varphi(T) + \varphi(2T)$$

Since $\varphi(t) = \vec{k}.\vec{z}(t)$, one has:

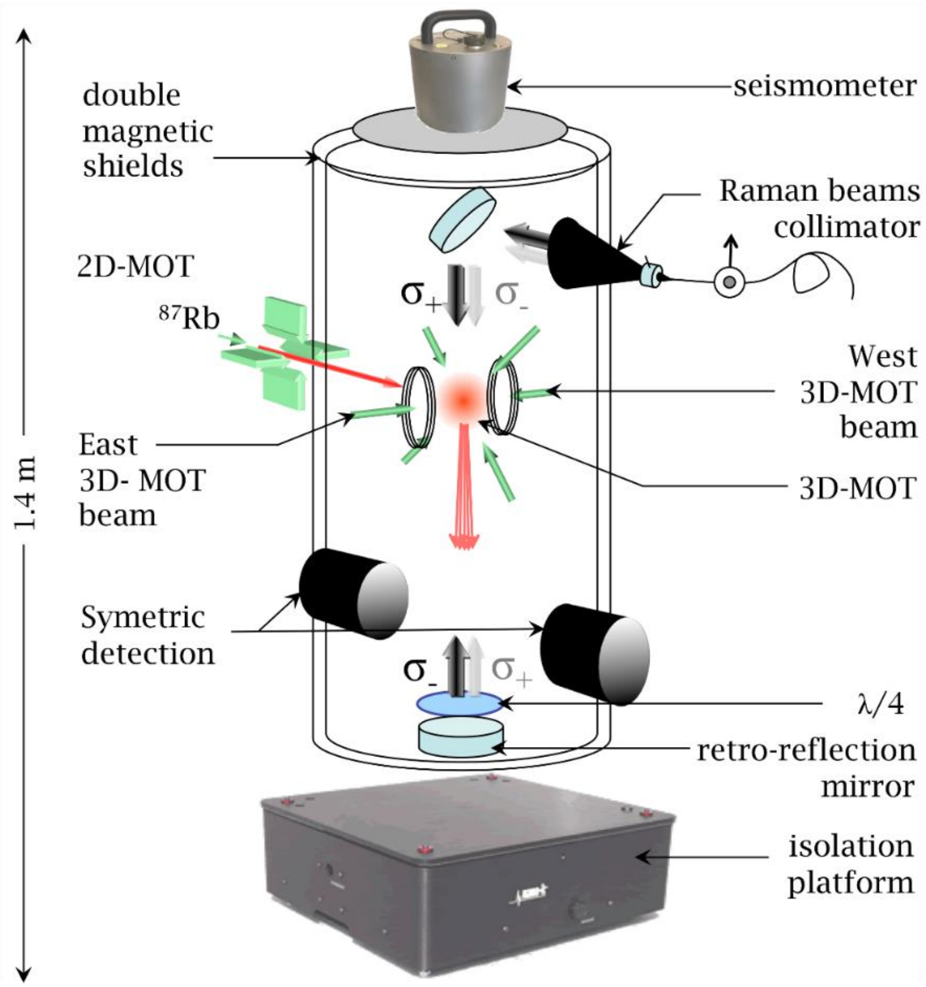
$$\Delta\Phi = k\,(z(0) - 2z(T) + z(2T))$$

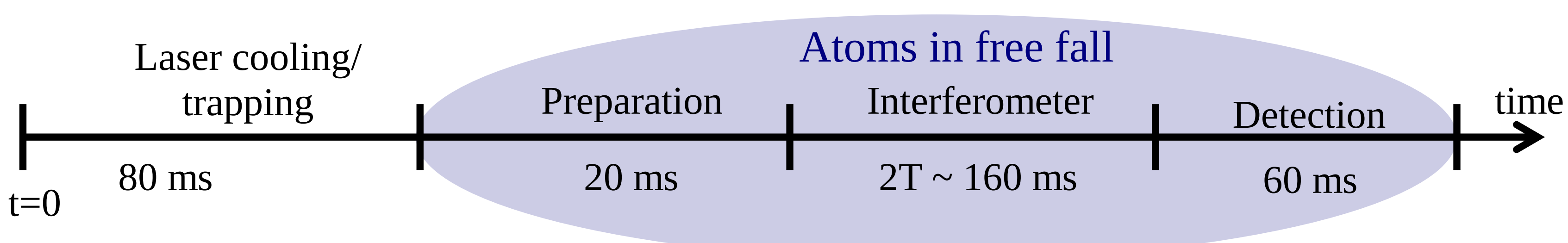
$$z(t) = \frac{1}{2} g\, t^2 \Rightarrow \Delta\Phi = k\, g\, T^2$$

measurement of g is
a measurement of the relative acceleration of the atoms with respect to the lasers equiphase

Benefit from cold atoms → increase the interferometer duration $2T$ → Increase the sensitivity

Cold atom gravimeter





Performances

Best short term stability

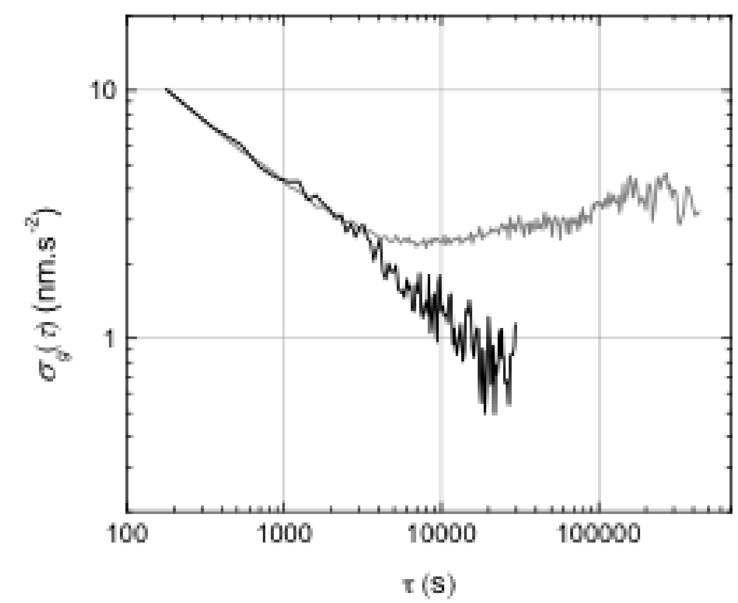
~ 6 10^{-9}g @ 1s

Typical long term stability

2-3 10^{-10}g @ 1 day

Best long term stability

~ 5 10^{-11}g



Cold atom gravimeter

Accuracy budget

Effect	Bias µGal	u µGal
Alignments	0.3	0.5
Frequency reference	0.5	<0.1
RF phase shift	0.0	<0.1
vgg	-13.4	<0.1
Self gravity effect	-2.1	0.1
Coriolis	-5.3	0.8
Wavefront aberrations	-5.6	1.3
LS1	0.0	<0.1
Zeeman	0.0	<0.1
LS2	-3.6	0.8
Detection offset	0.0	0.5
Optical power	0.0	0.5
Cloud indice	0.4	<0.1
Cold collisions	<0.1	<0.1
CPT	0.0	<0.1
Raman α LS	0.3	<0.1
Finite Speed of Light	0.0	<0.1
TOTAL	**-28.5**	**2.0**

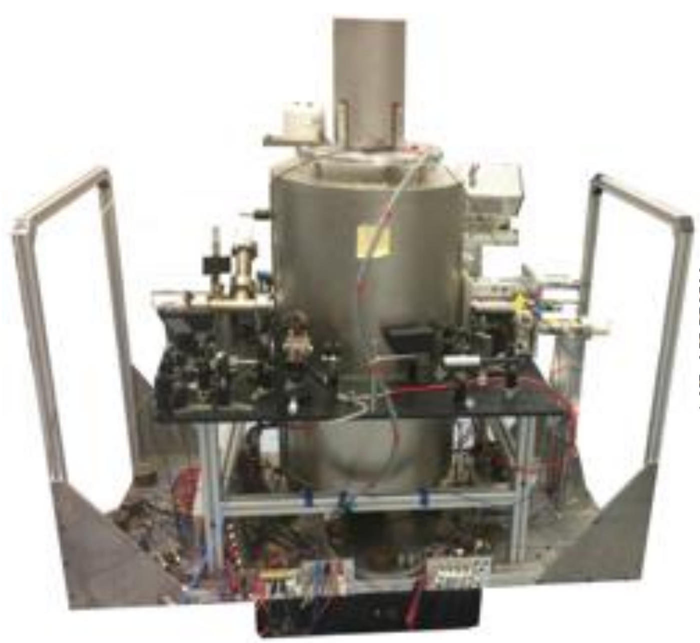
1 µGal ≈ 10^{-9}g

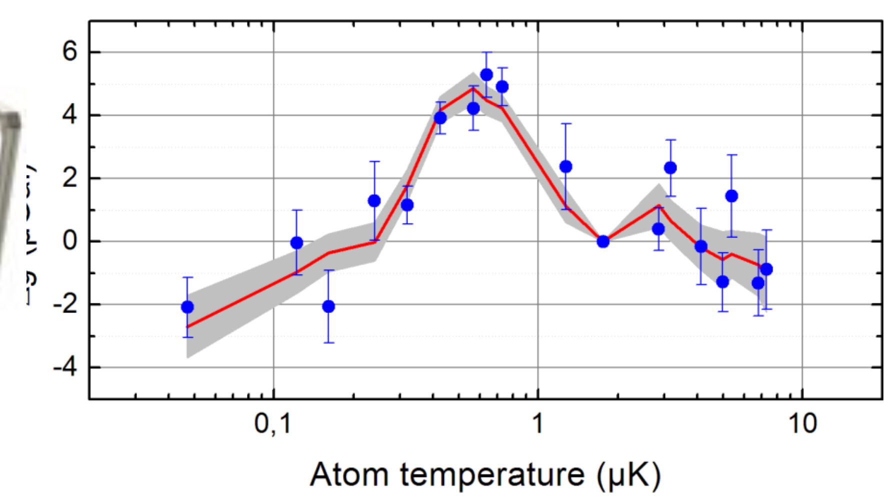
Evaluation of all systematic effects

Accuracy = combined uncertainty on the evaluation of all systematics

Dominant systematic effect: Wavefront aberrations

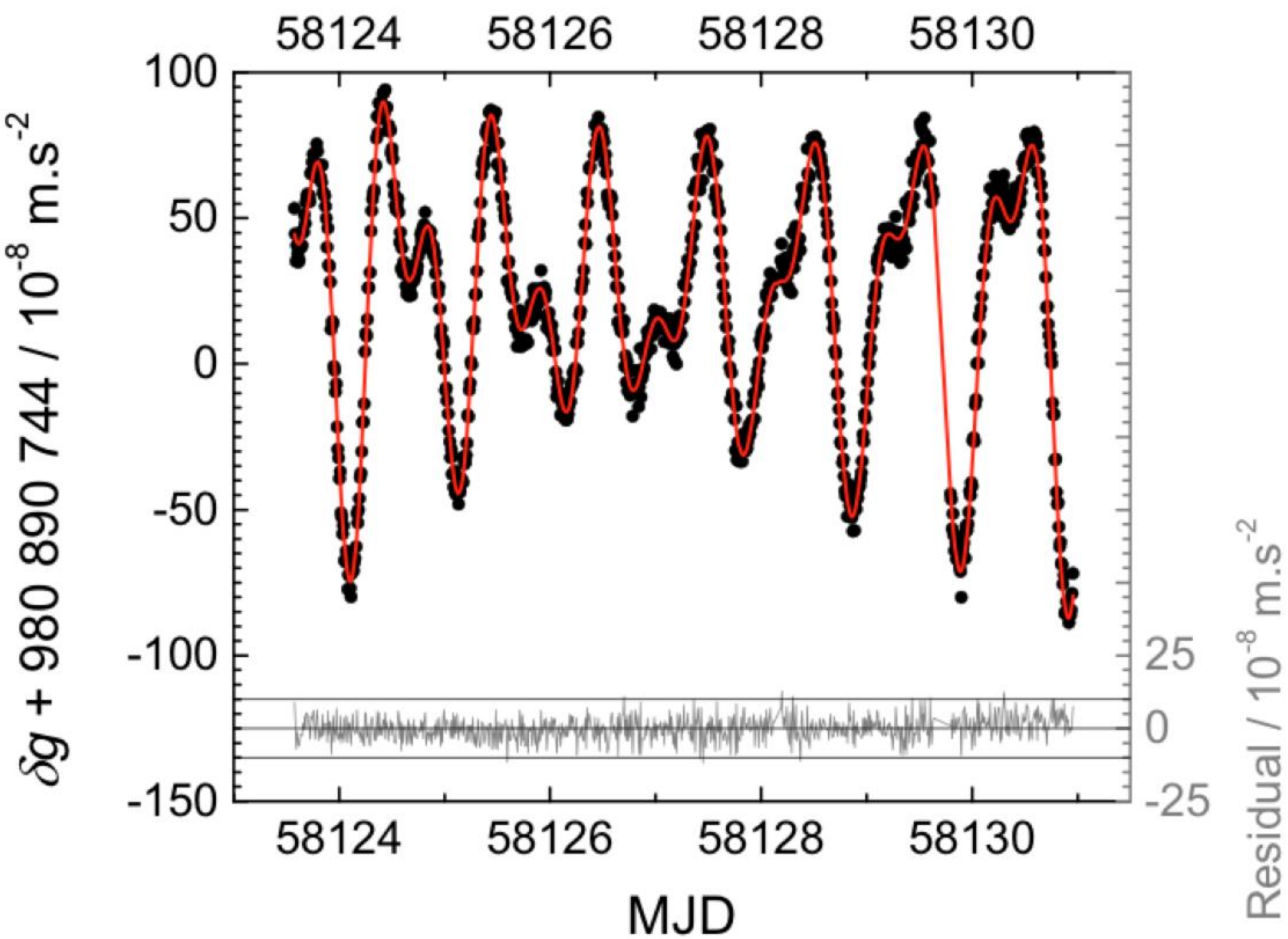
Ultracold (evaporatively cooled) atoms were instrumental for the precise evaluation of this bias

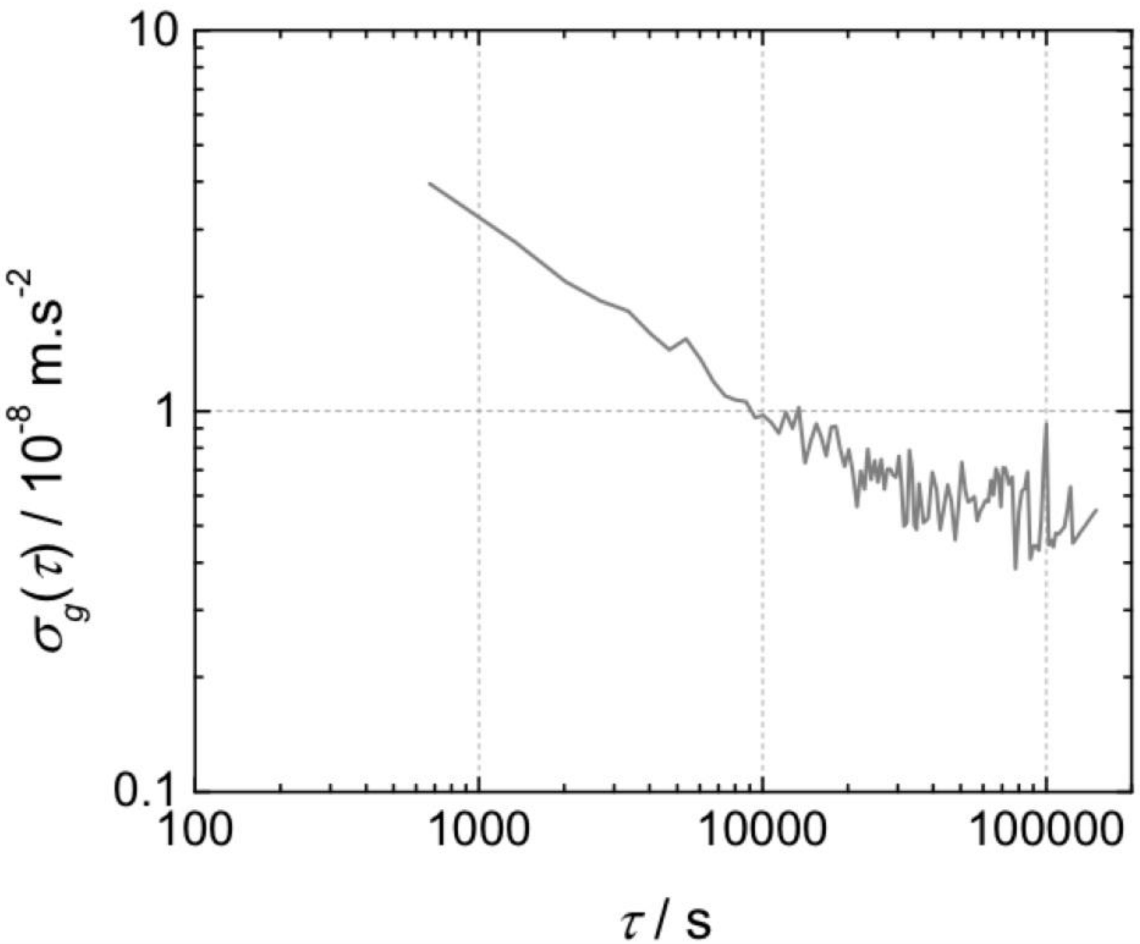




Cold atom gravimeter

Continuous gravity measurements with ultracold atoms over a week





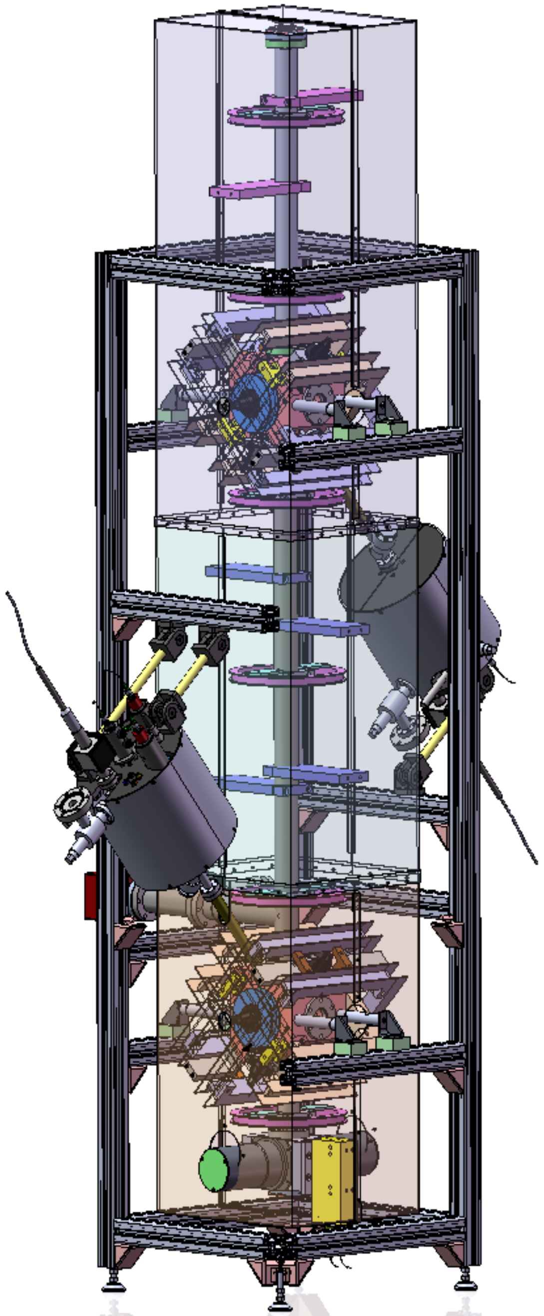
Stability: 10^{-9}g @ 10000 s

Cycle time increased from 360 ms to 4.6 s
Atom number reduced from 10^6 to 10^4

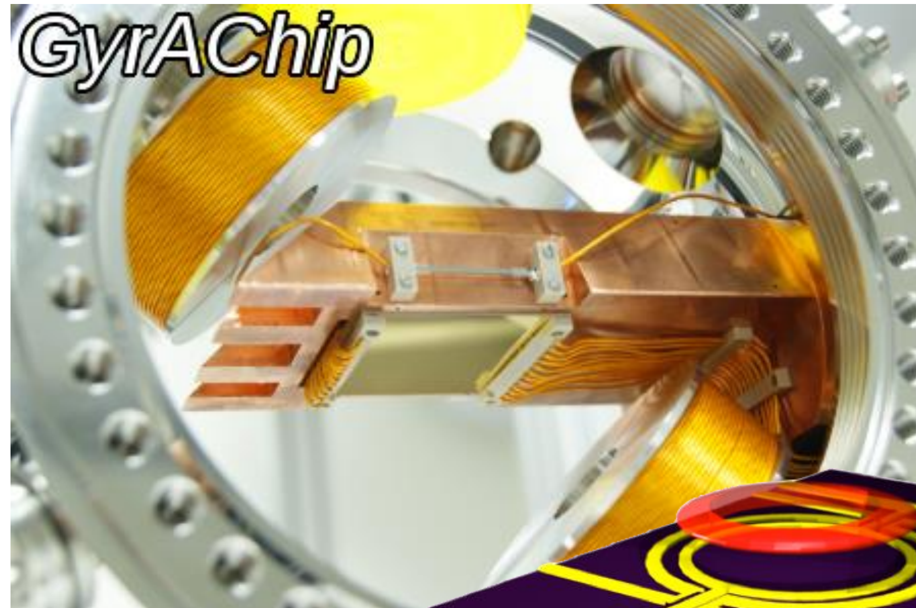
⇒ Stability degraded by a factor 5 to 10

Schemes for fast production of ultracold are needed

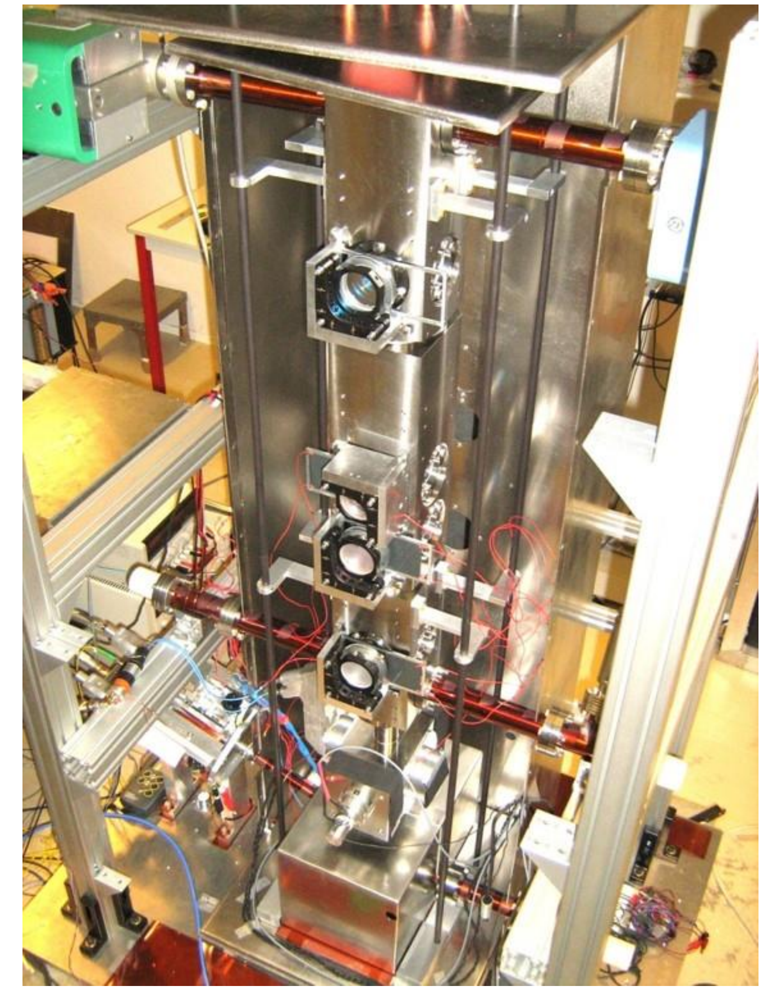
More cold atom inertial sensors at SYRTE



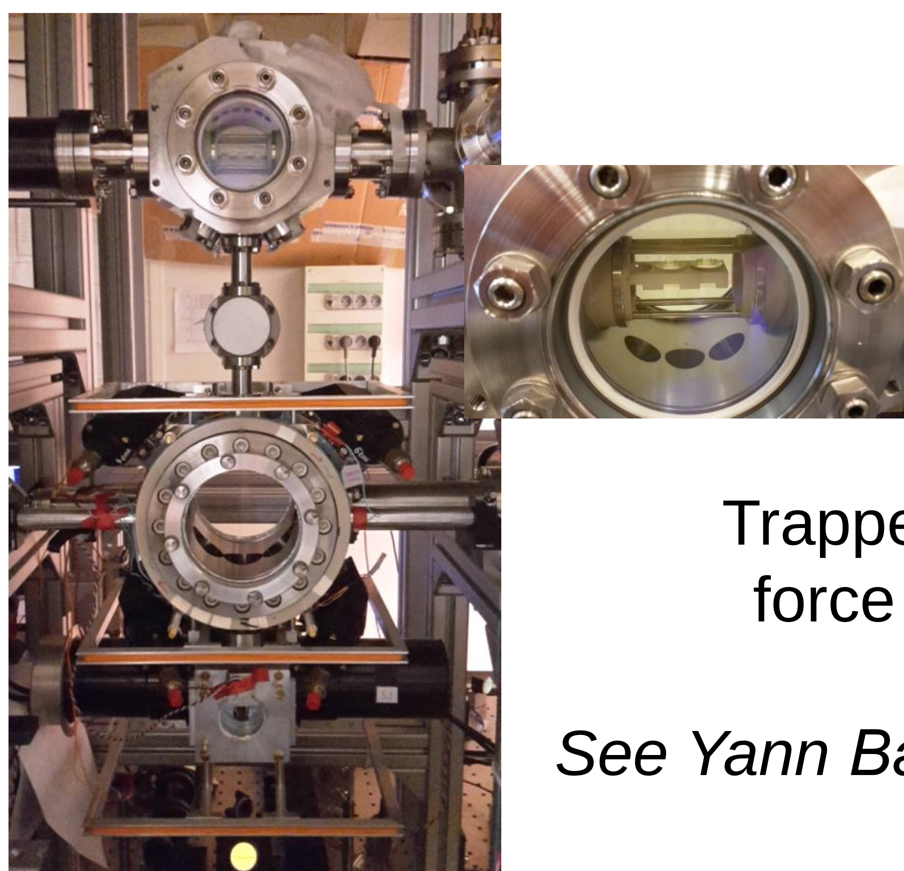
Gravity gradiometer



Gyrometer on a chip



Ultrasensitive atom gyrometer
Stability 0.2 nrad/s



Trapped atom
force sensor

See Yann Balland's poster

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