

lecture 17.11.2011

we had last week:

- atom beam - surface diffraction
- radiation pressure as means to cool atom ensembles

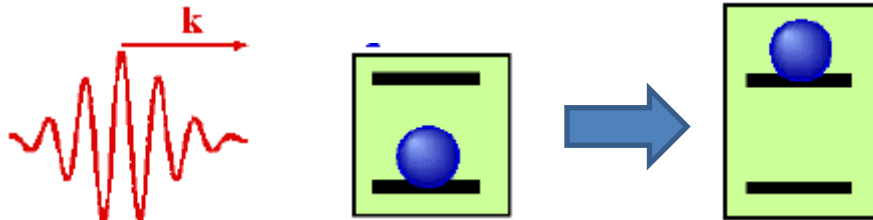
today:

- Doppler cooling
- optical molasses
- Bose Einstein condensation
- trapping of ions

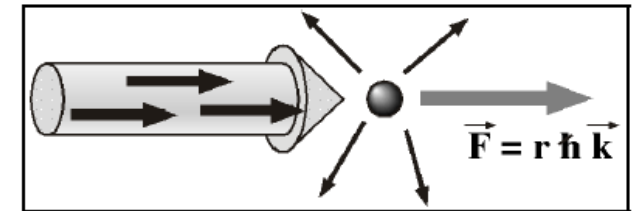
Light forces

quantum mechanically: transfer of momentum and energy of the photon

$$E = \hbar\omega, p = \hbar k$$



absorption is directed, emission isotropic.
So the emission leads to no net force and thus
can be neglected in a theoretical description.



$F = r \hbar k$, with r : the absorption rate

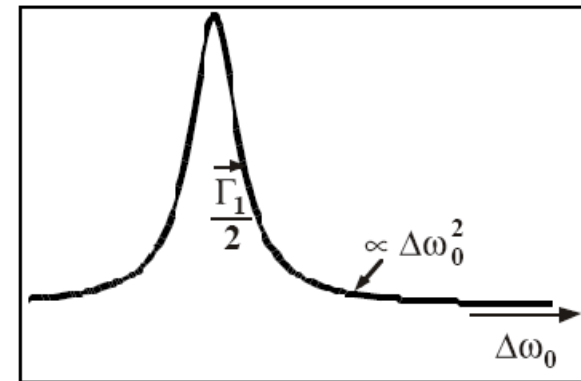
$$r = \Gamma_1 \omega_x^2 / (\Gamma_1^2 + 4 \Delta\omega^2)$$

ω_x^2 proportional to laser intensity

Γ : inverse life time

$\Delta\omega$: $\omega_{\text{laser}} - \omega_0$, i.e. the laser detuning from
the atomic resonance ω_0 .

You know the Lorentzian absorption curve from the theoretical lessons.



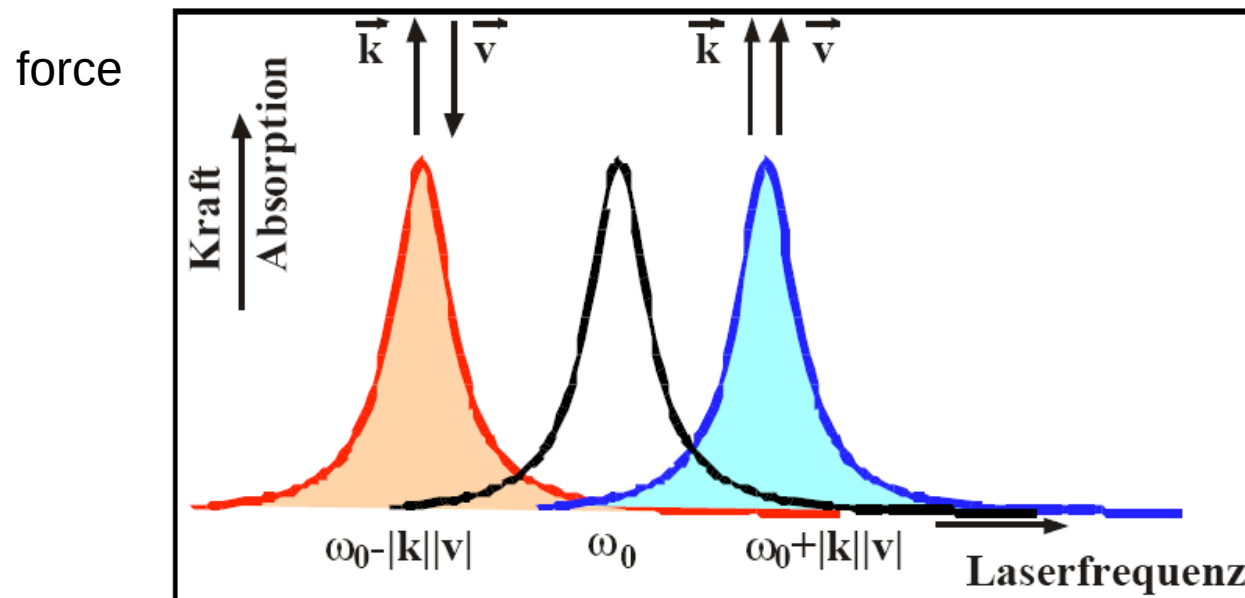
influence of the Doppler effect

for an atom moving with velocity $\mathbf{v}$: $\Delta \omega \rightarrow \Delta \omega + \mathbf{k} \mathbf{v}$, with $\mathbf{k}$: wave vector
 thus the rate r changes to

$$r = \Gamma_1 \frac{\omega_x^2}{\Gamma_1^2 + 4(\Delta\omega_0 + \mathbf{k} \mathbf{v})^2}$$

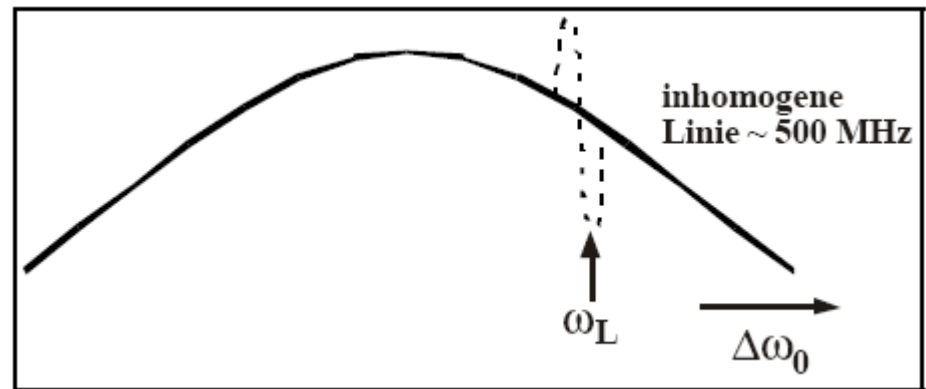
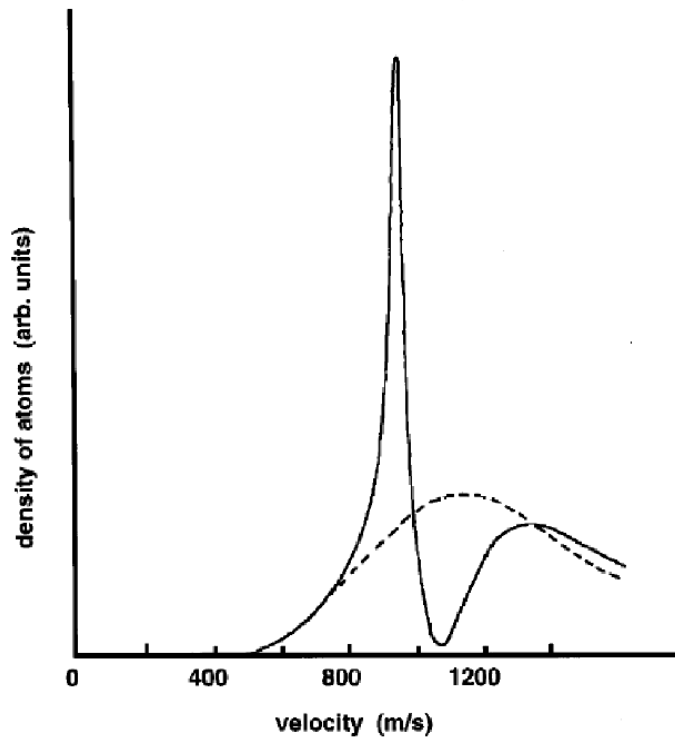
Force $F = r \hbar \mathbf{k}$ $F = \hbar k \Gamma_1 \frac{\omega_x^2}{\Gamma_1^2 + 4(\Delta\omega_0 + \mathbf{k} \mathbf{v})^2}$ has maximum if $v = -\Delta \omega_0 / k$

this means the Doppler shift drives the spectrum into resonance.



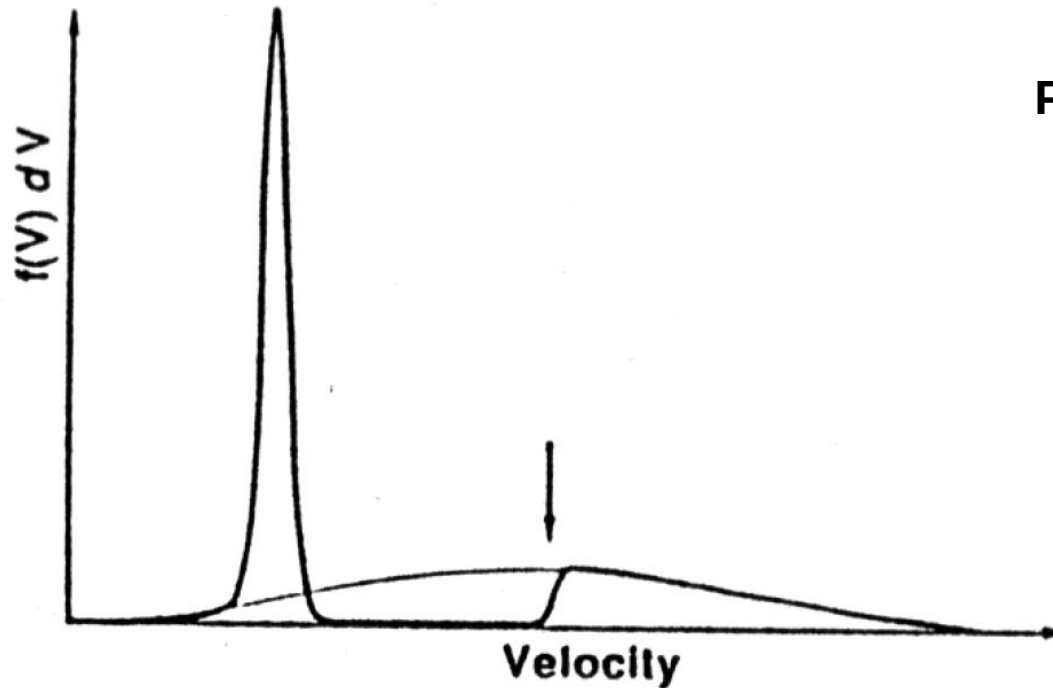
→ slowing down is possible!

velocity distribution after irradiation with fixed frequency



problem with fixed frequency: a hole is burned into the velocity distribution

velocity distribution after irradiation with chirped frequency



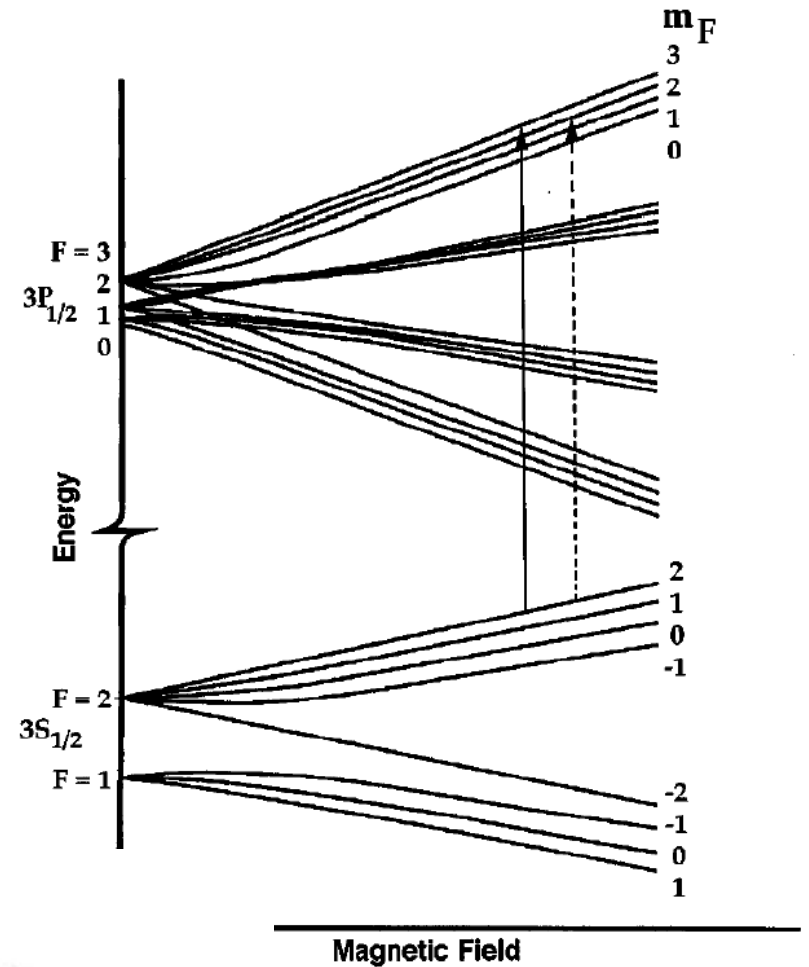
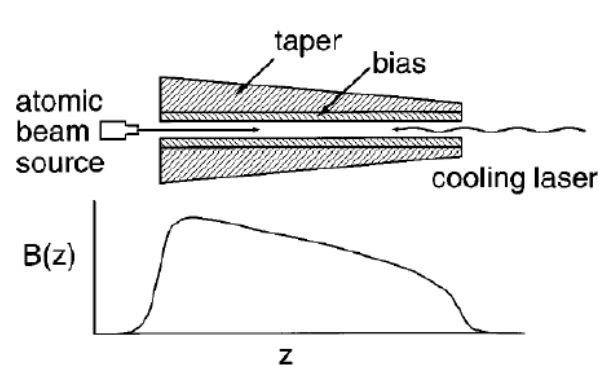
Phillips RMP 1998

a chirped, i.e. temporally tuned frequency can shift a significant part of the velocity distribution and thus cool the atom ensemble.

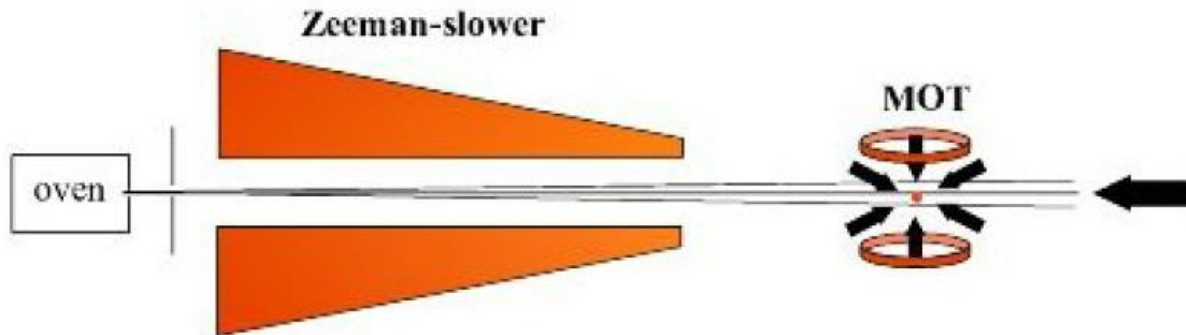
Problem: it is difficult to create such chirped laser radiation.

Solution: we do not tune the laser but the atomic resonance

Zeeman cooler: deceleration to identical v possible

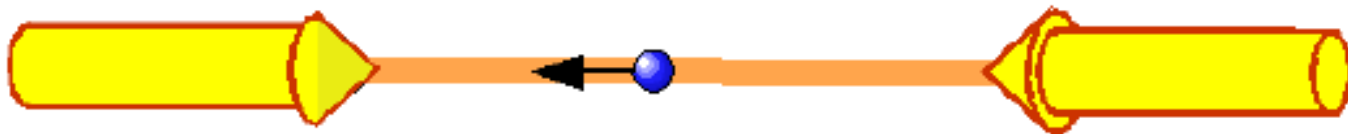
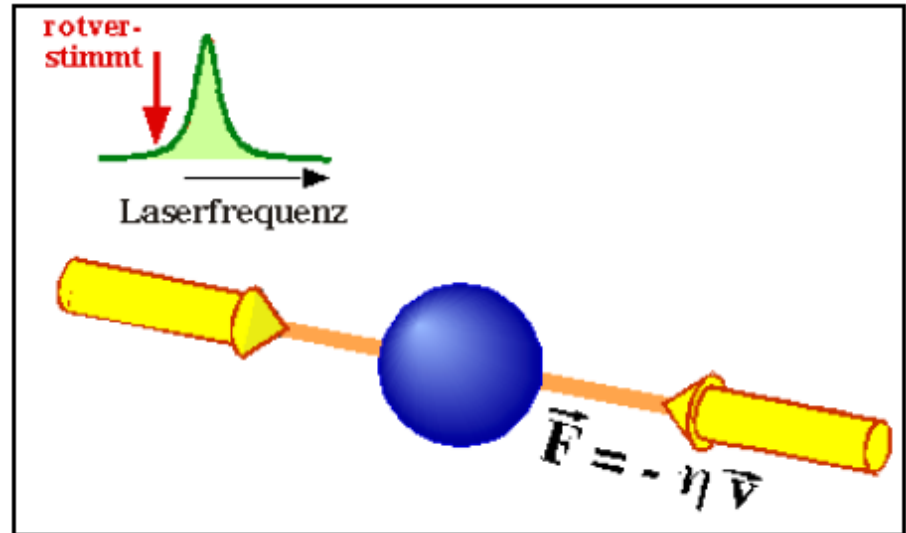
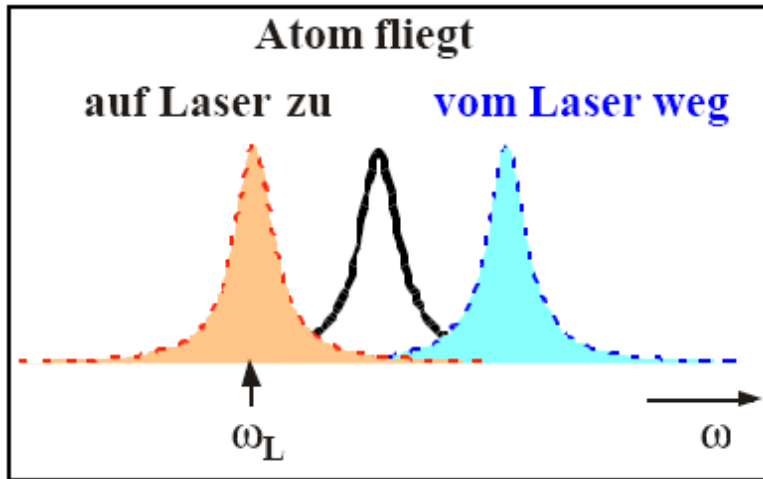


- ▶ Zirkular polarisiertes Licht σ^+
- ▶ Übergang:
 $3S_{1/2}(m_F = 2) \leftrightarrow 3P_{3/2}(m_F = 3)$
- ▶ Wahrscheinlichkeit für falschen Übergang extrem gering



Phillips RMP 1998

Doppler cooling to stop the atom



resonant for laser

→ **strong absorption**

→ **strong force**

not resonant for laser

→ **weak absorption**

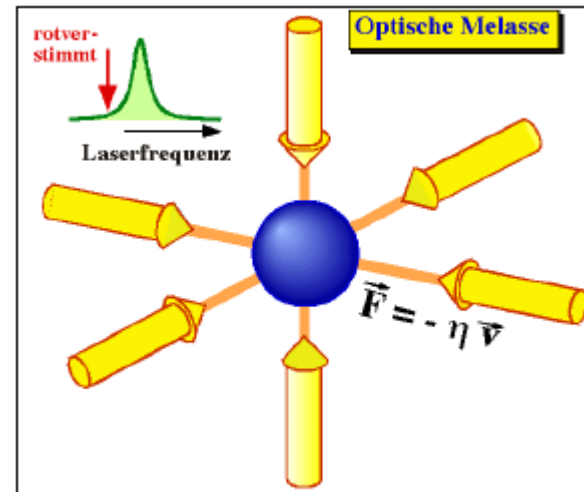
→ **weak force**

Doppler cooling

it can be shown: $F \sim -v$, i.e. $F = -\eta v$

η being a viscosity!

so in three dimensions such a setup is called **optical molasses** ('Melasse')



calculating the force:

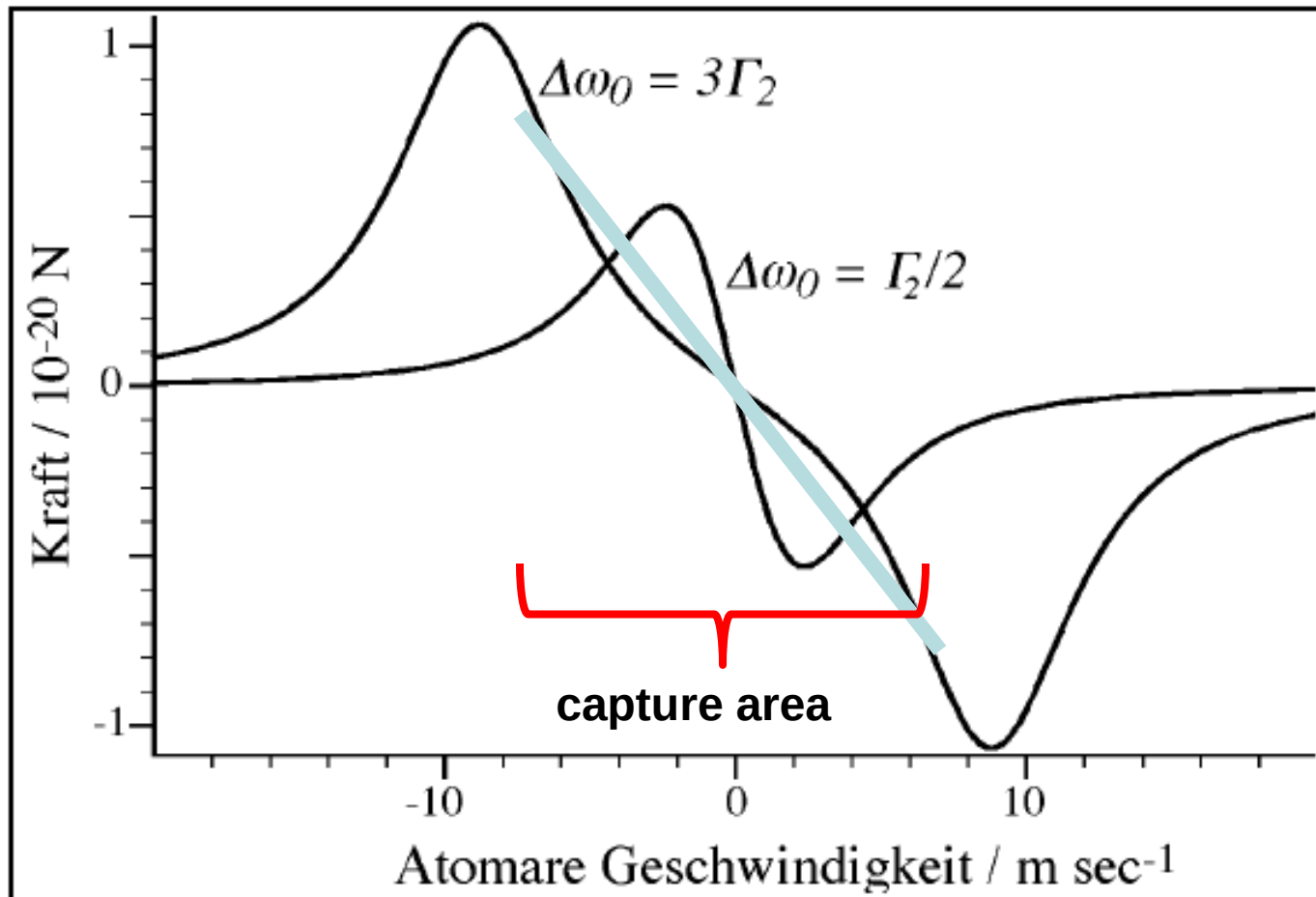
$$F_{+/-} = \hbar k_{+/-} \frac{\Gamma_1 \omega_x^2}{\Gamma_1^2 + 4(\Delta\omega_0 \pm kv)^2}$$

inserting $\rightarrow$
$$F_{om} = \hbar k \Gamma_1 \omega_x^2 \left(\frac{1}{\Gamma_1^2 + 4(\Delta\omega_0 + kv)^2} - \frac{1}{\Gamma_1^2 + 4(\Delta\omega_0 - kv)^2} \right)$$

force in an optical molasses

force in the optical molasses

force



velocity

two red detunings

$$v_{\text{capture}} \leq \Delta \omega_0 / k$$

viscosity

$$\mathbf{F} = -\eta \mathbf{v} \quad \eta \text{ being the viscosity}$$

$$\text{determining } \eta: \quad \eta = - \frac{dF_{\text{om}}}{dv} \bigg|_{v=0}$$

absorption rate in rest:

$$r_0 = \frac{\Gamma_1 \omega_x^2}{\Gamma_1^2 + 4\Delta\omega_0^2}$$

thus we obtain for the viscosity

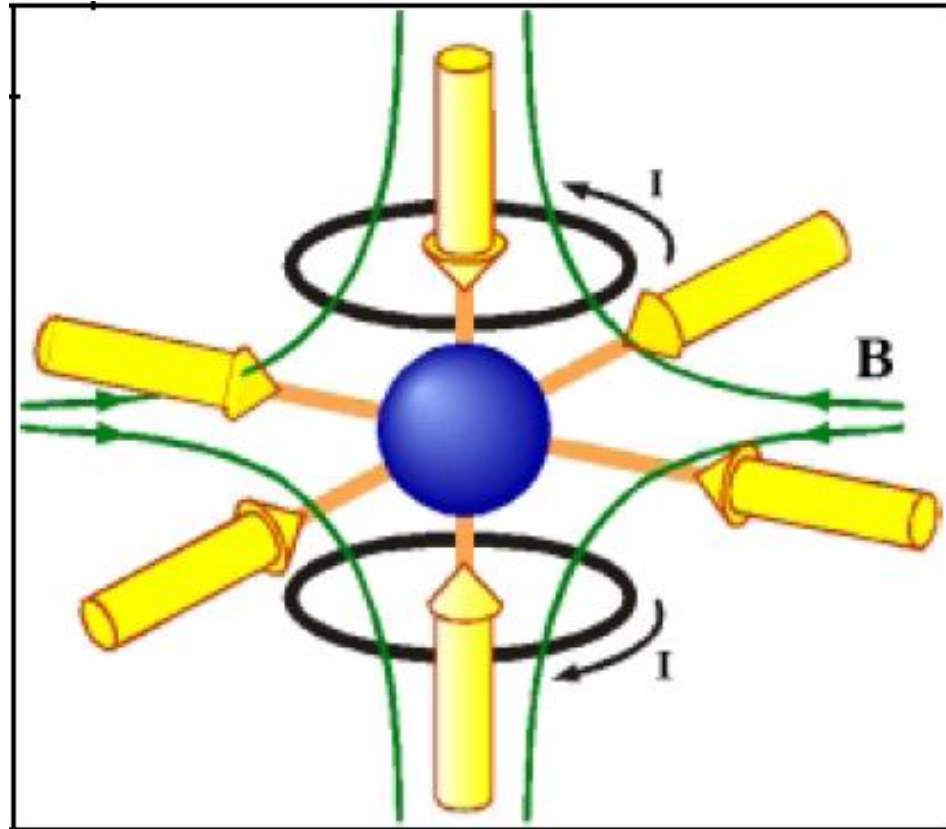
$$\eta = 16 r_0 \hbar k^2 \frac{\Delta\omega_0}{\Gamma_1^2 + 4\Delta\omega_0^2}$$

η has a dispersion-like dependence on laser detuning,
it changes sign when $\Delta\omega_0$ goes through zero

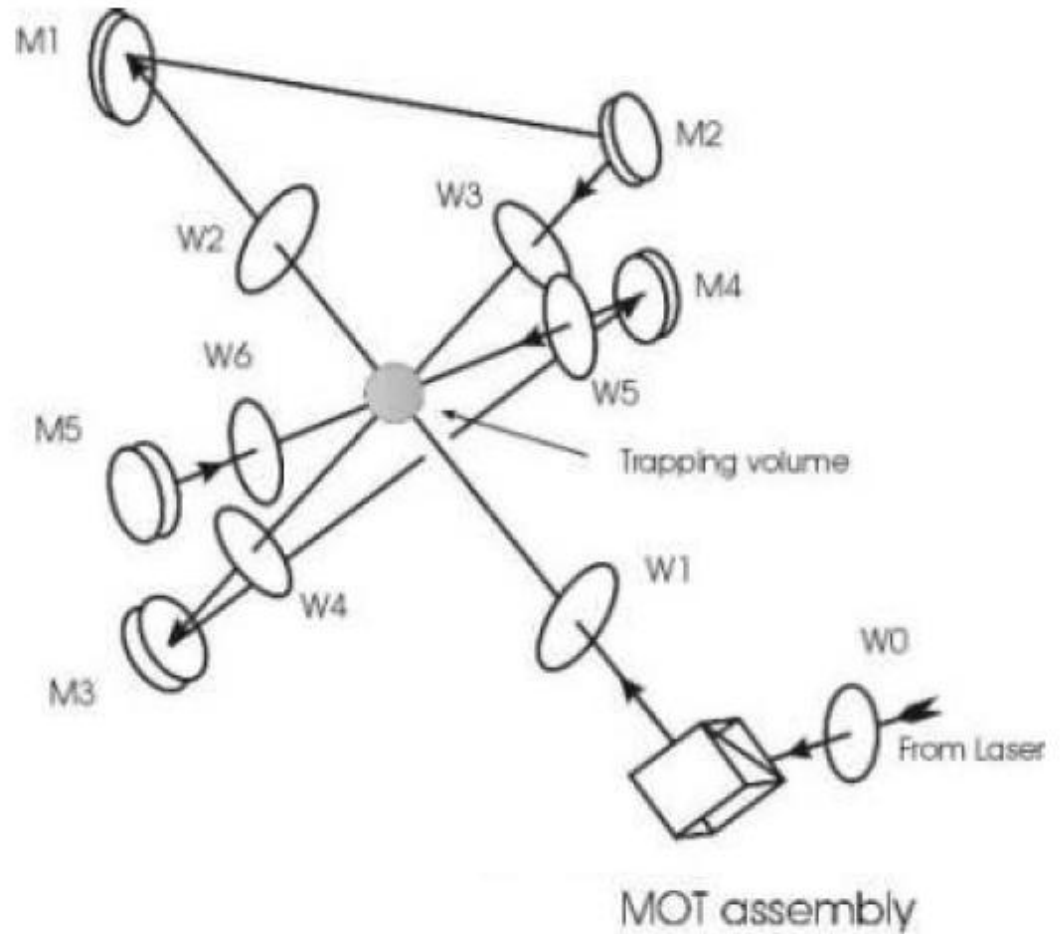
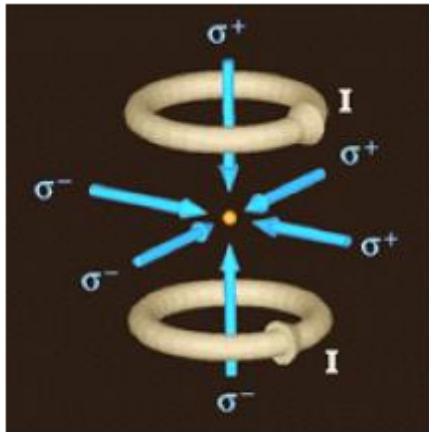
technical realization of a molasses with magneto optical trap (MOT)

trapping lasers

B-field gradient made
with two Helmholtz
coils: field zero in the
center, linear gradient
to the outside



technical realization of a molasses



experimental realization
FOM Amsterdam

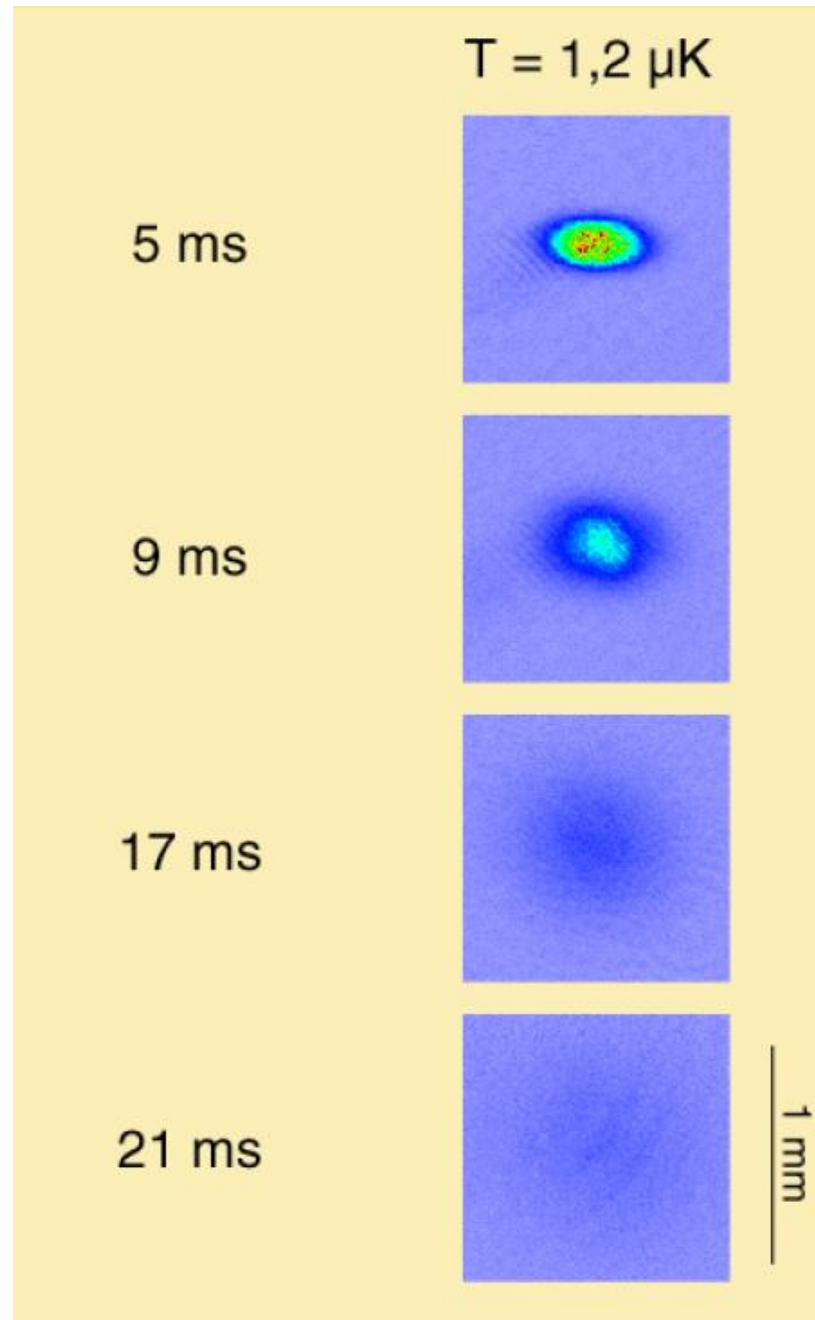


how to measure temperatures in the μK - range?

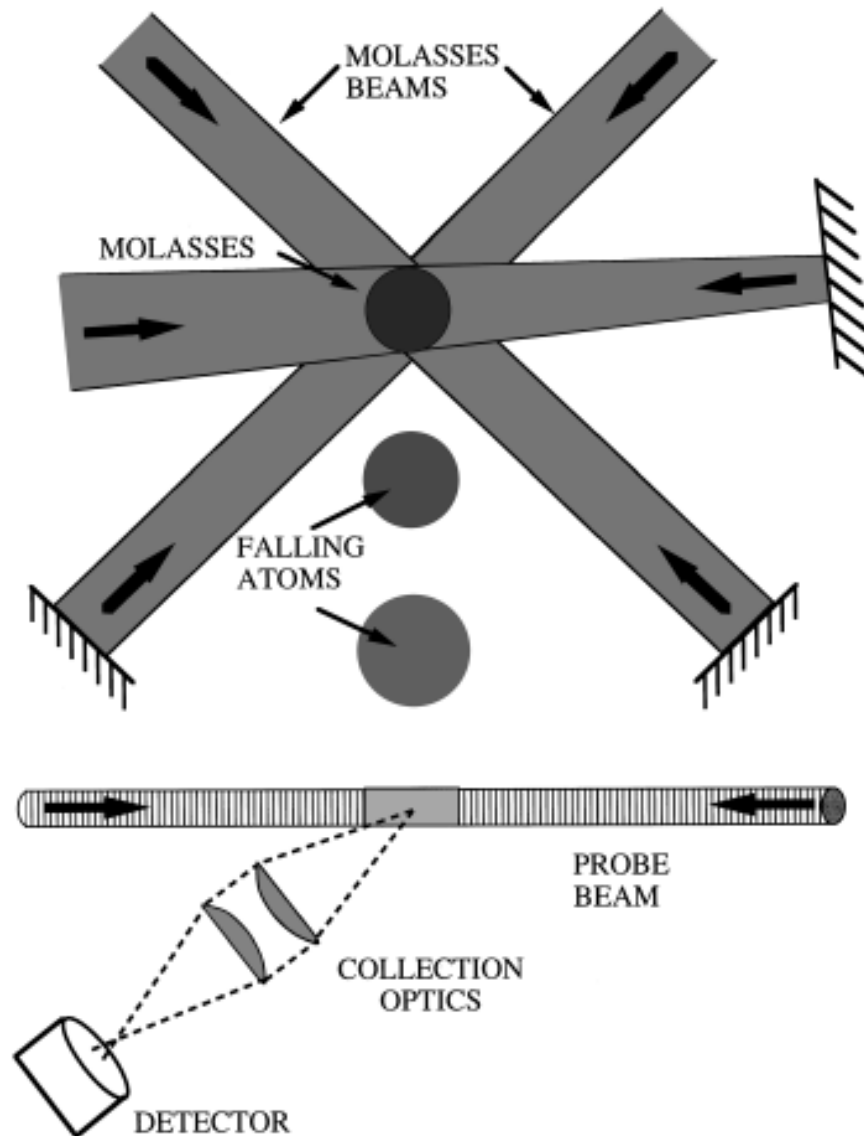
switching off the trap potential

free expansion of the ultracold gas

expansion velocity depends on temperature



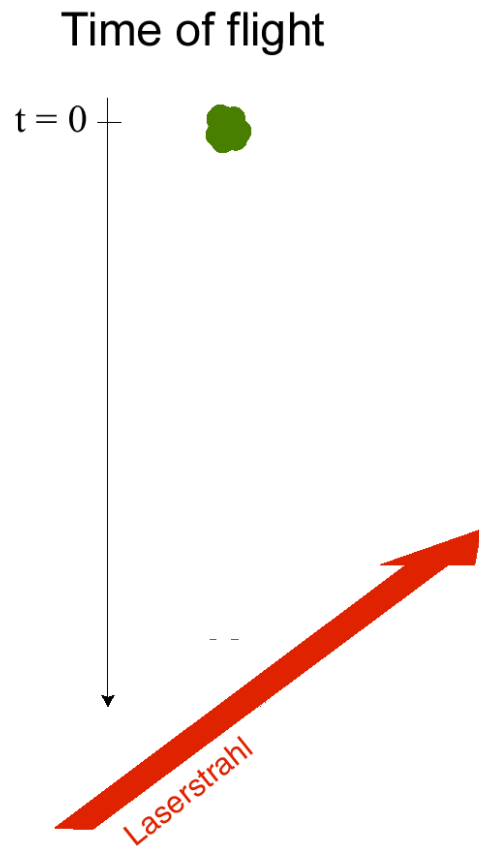
how to measure the temperature



Phillips RMP 1998

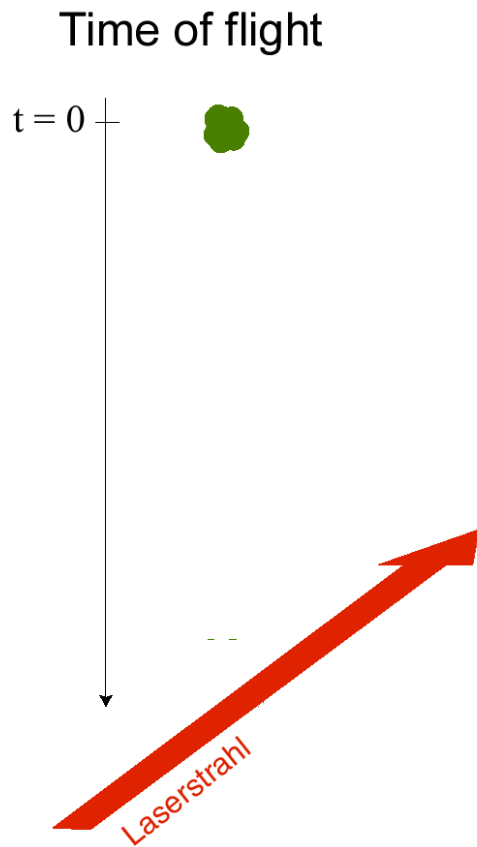
how to measure temperatures in the μK - range?

or by a time-of-flight measurement



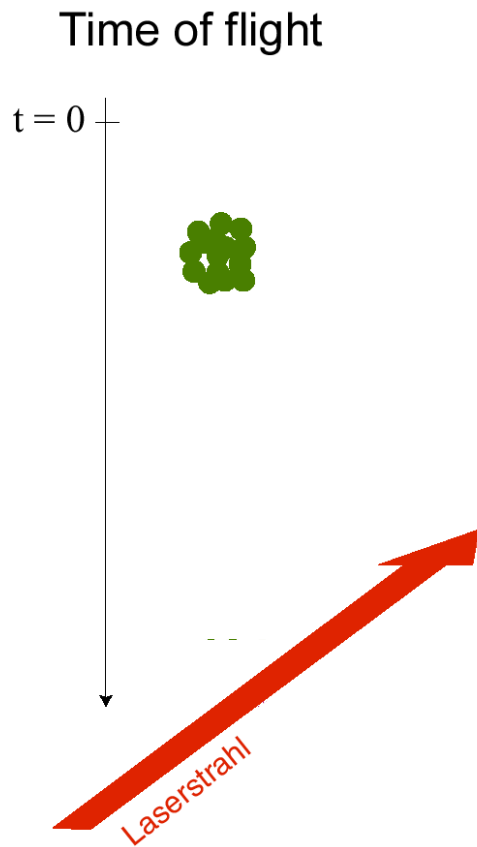
how to measure temperatures in the μK - range?

or by a time-of-flight measurement



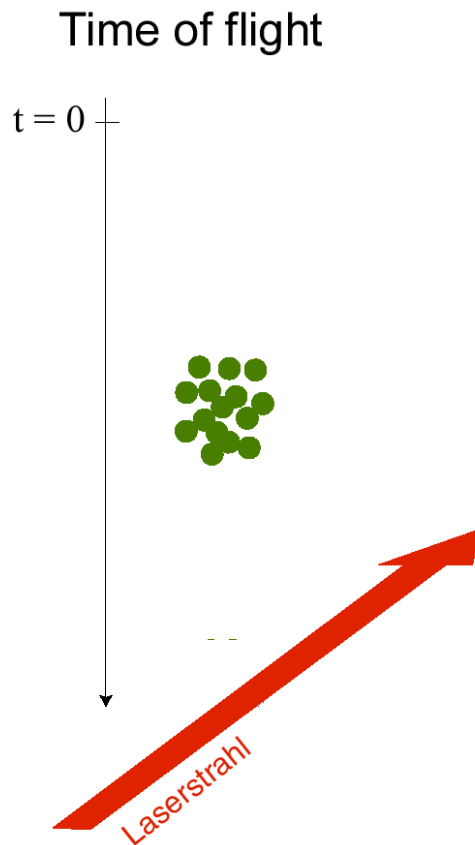
how to measure temperatures in the μK - range?

or by a time-of-flight measurement



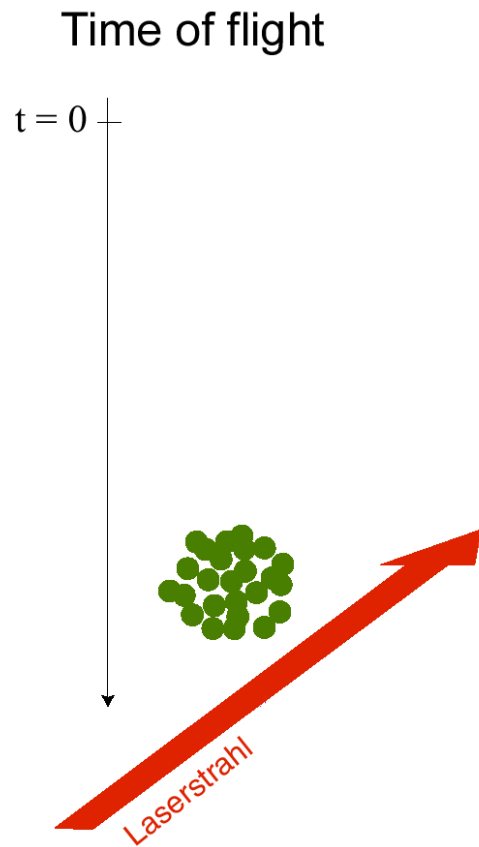
how to measure temperatures in the μK - range?

or by a time-of-flight measurement



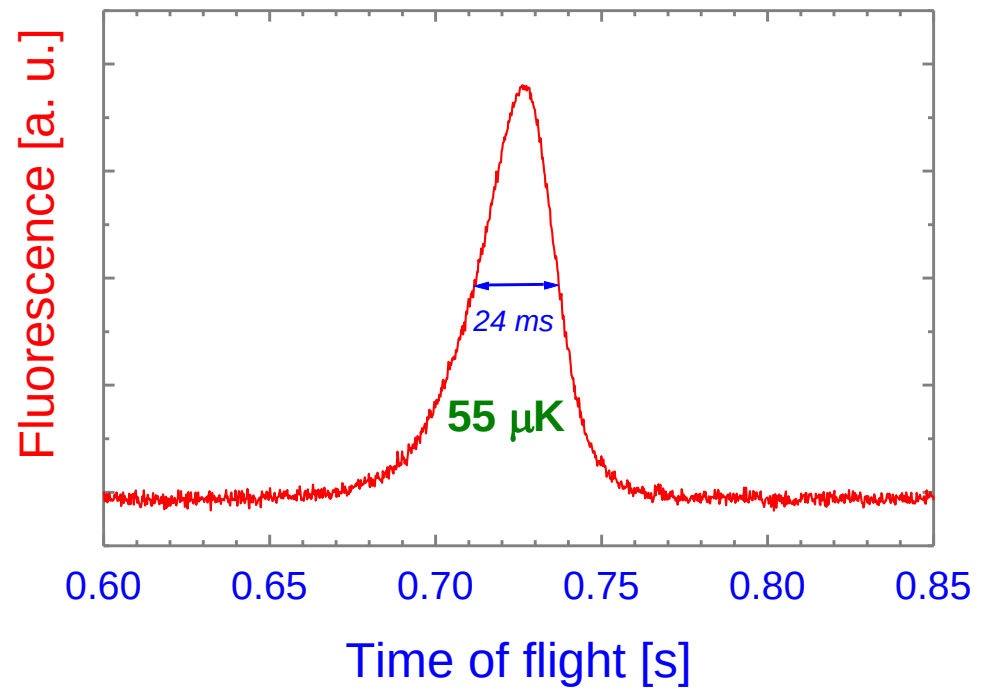
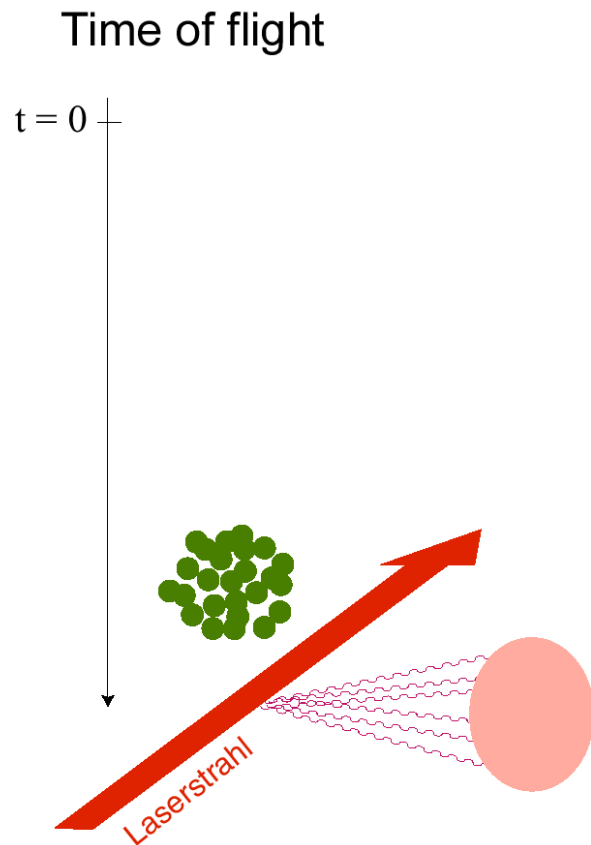
how to measure temperatures in the μK - range?

or by a time-of-flight measurement



how to measure temperatures in the μK - range?

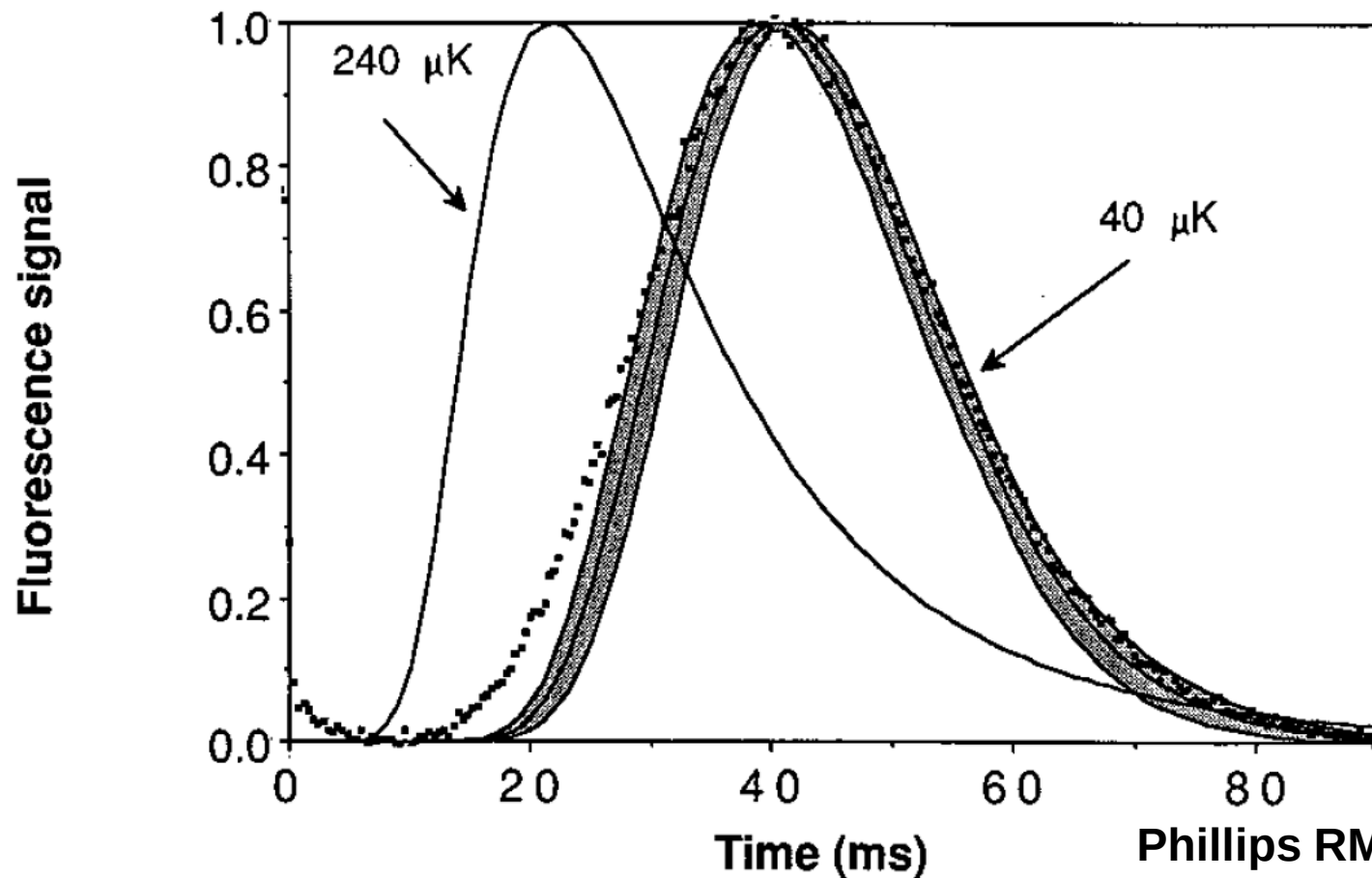
or by a time-of-flight measurement



temperature distribution from time-of-flight measurement

exp.: points, curves: theory.

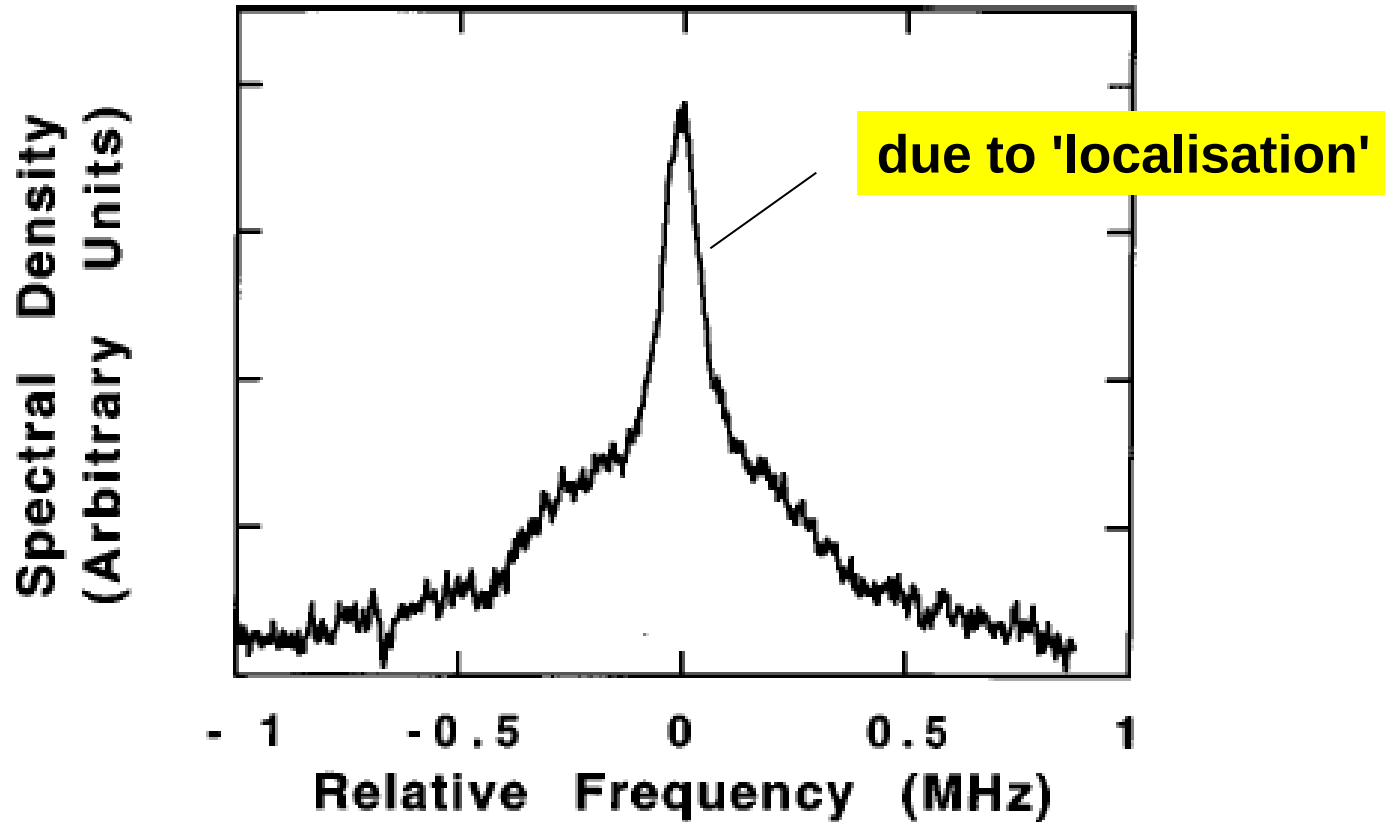
40 μK curve: theoretical limit of Doppler cooling (discrete nature of the radiation field, Brownian motion of the atoms)



Phillips RMP 1998

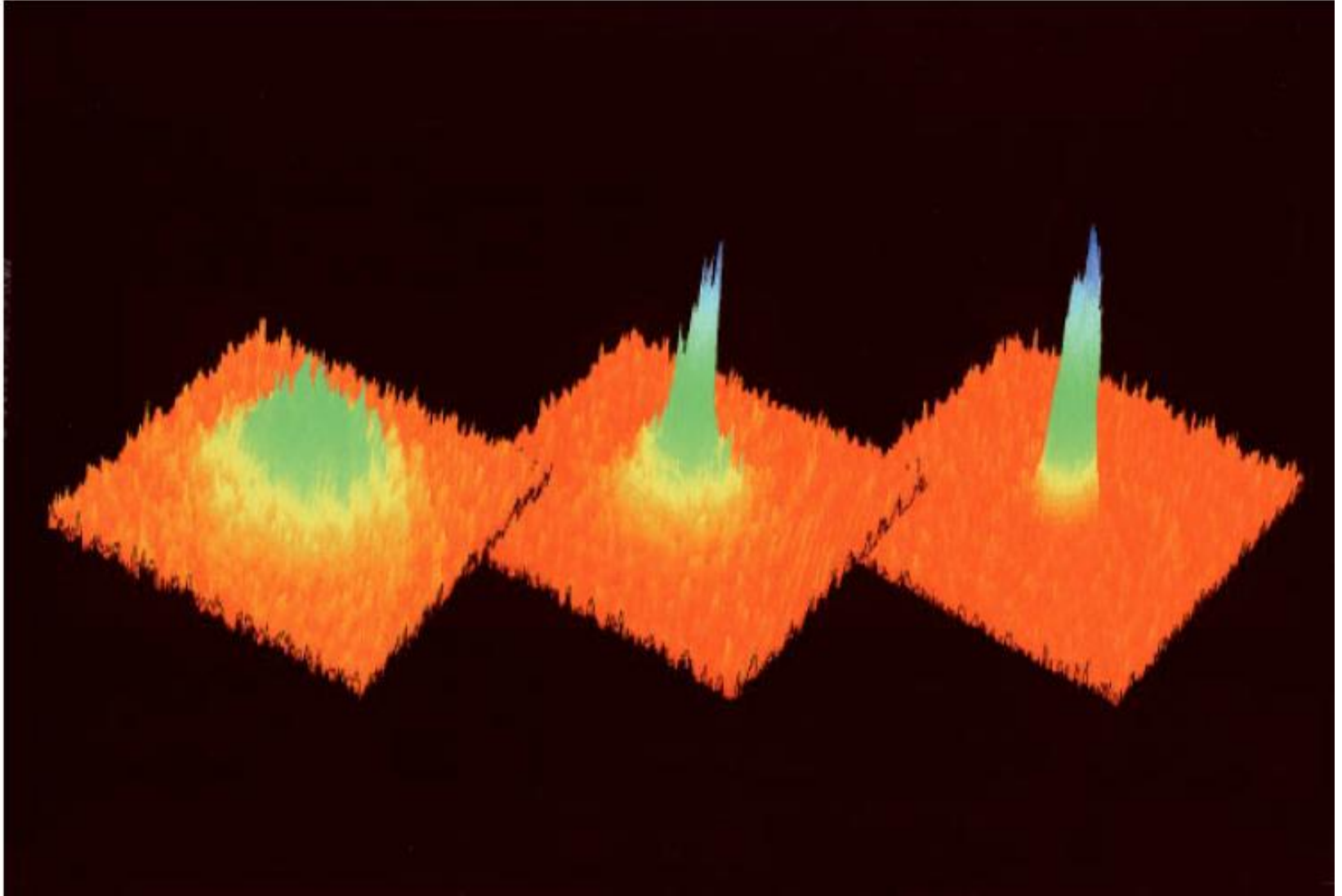
sub-Doppler cooling by evaporation

broad component: 84 μK thermal contribution



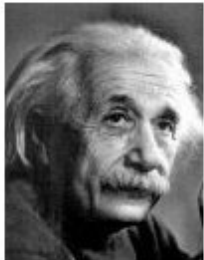
Phillips RMP 1998

2D velocity distribution of Na atoms at different stages of evaporative cooling



a short history of Bose-Einstein condensation

Predicted 1924...



A. Einstein



S. Bose

- **1924** Bose schickt Einstein seine Arbeit über die Statistik von Photonen. Einstein übersetzt diese Arbeit.

- **1924** Nur acht Tage später hat Einstein seine „Quantentheorie der einatomigen idealen Gase“ fertiggestellt.

- **1925** Einstein setzt seine Arbeit über das ideale Gas mit Bose-Statistik fort und entdeckt zum ersten Mal das Phänomen der „Bose-Einstein-Kondensation“

- **1995** Bose-Einstein-Kondensation in einem verdünnten Gas von ^{87}Rb Atomen wird zum ersten Mal von Eric Cornell und Carl Wieman (JILA) erzielt und wenige Monate später in ^{23}Na von Wolfgang Ketterle (MIT)



University of Colorado at Boulder



University of Colorado at Boulder



EPN/MPRE



Nobelpreis
2001 !

Eric Cornell has been in Rostock on the occasion of the DPG spring meeting 1996

SITZUNGSBERICHTE
DER PREUSSISCHEN
AKADEMIE DER WISSENSCHAFTEN.

1925.

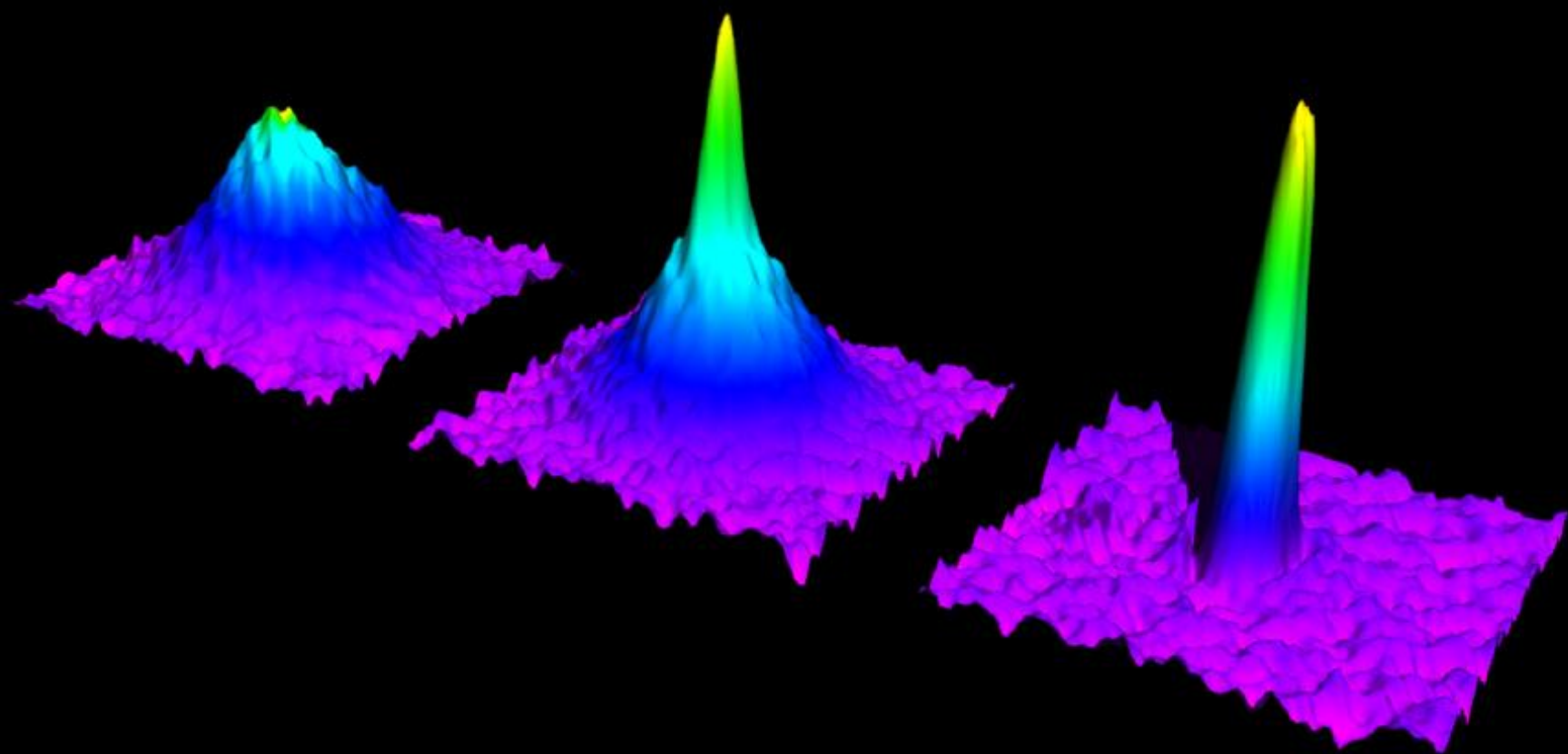
I

Sitzung der physikalisch-mathematischen Klasse vom 8. Januar.

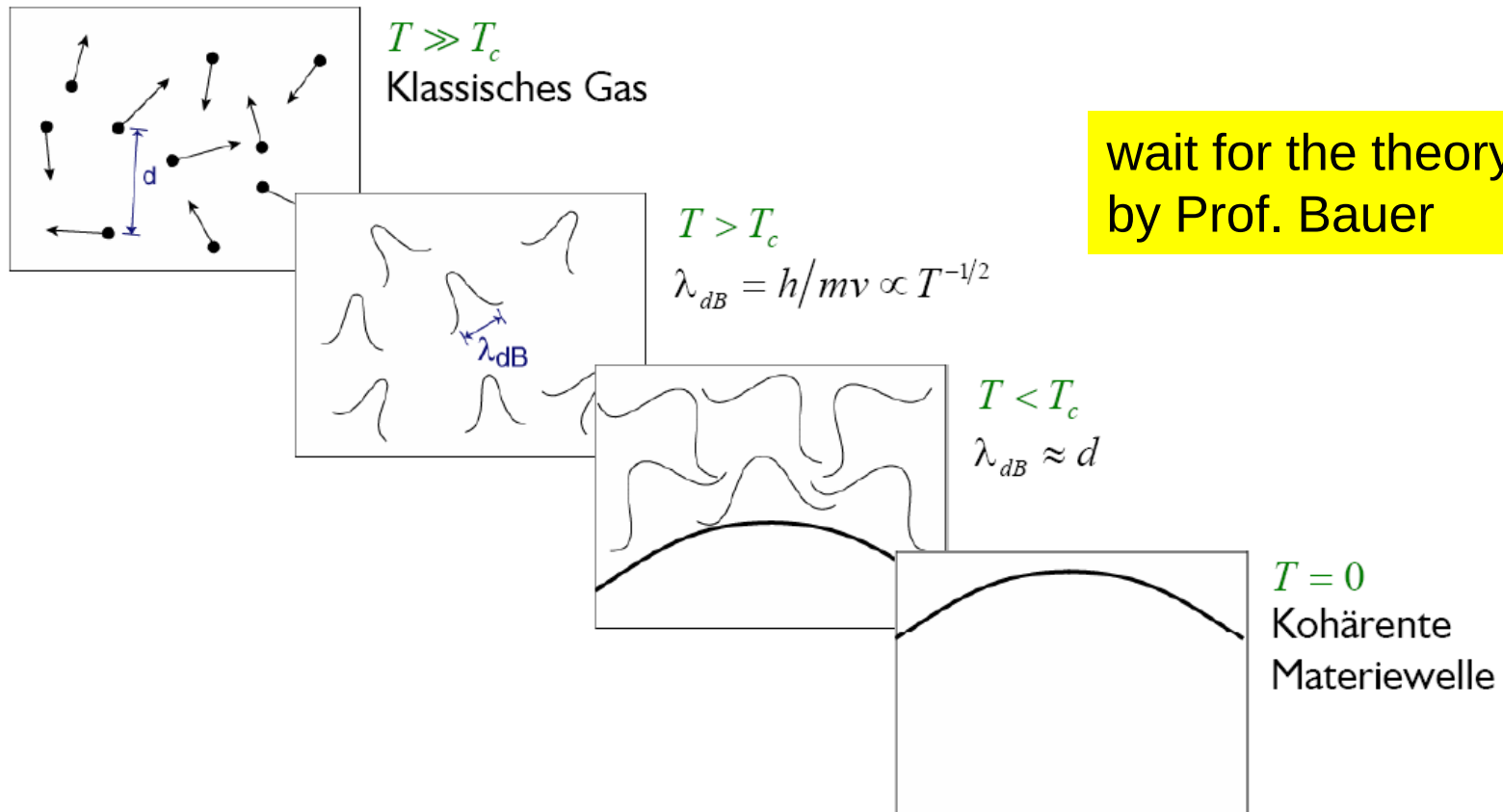
Quantentheorie des einatomigen idealen Gases.

Zweite Abhandlung.

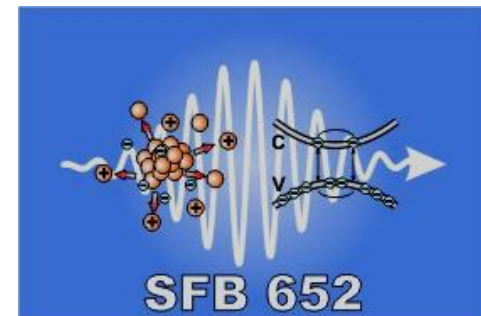
Von A. EINSTEIN.



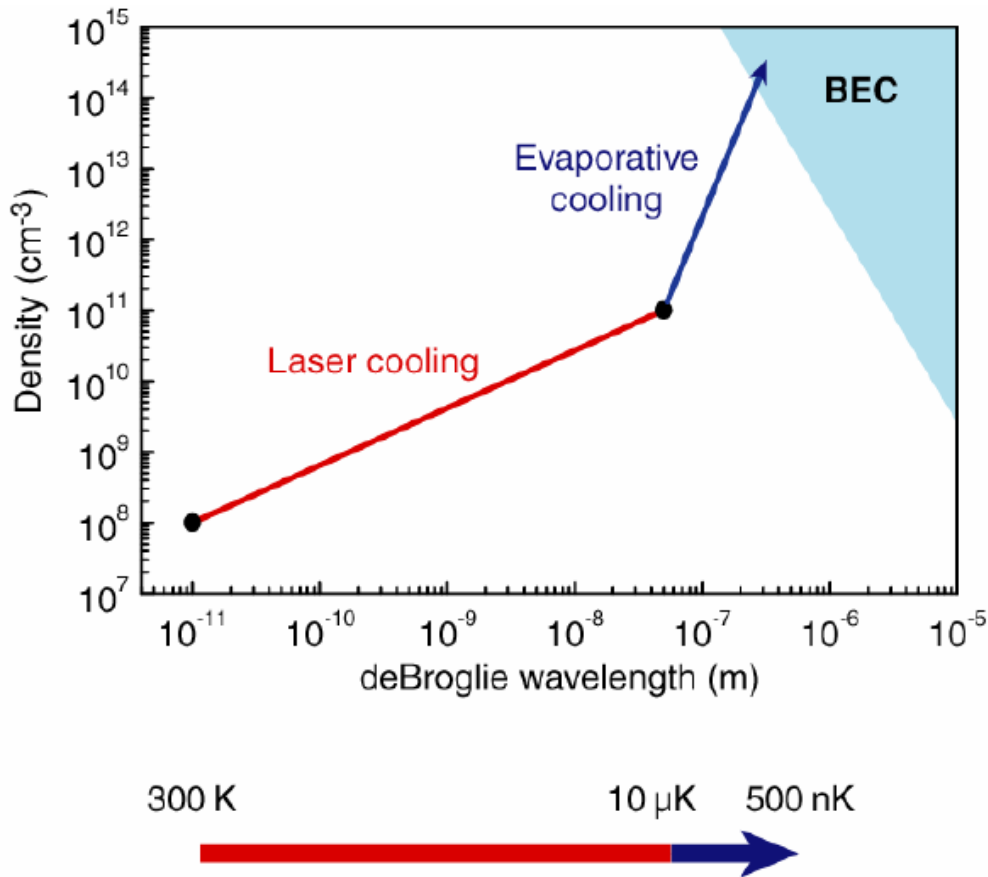
from a classical gas to a Bose-Einstein condensate



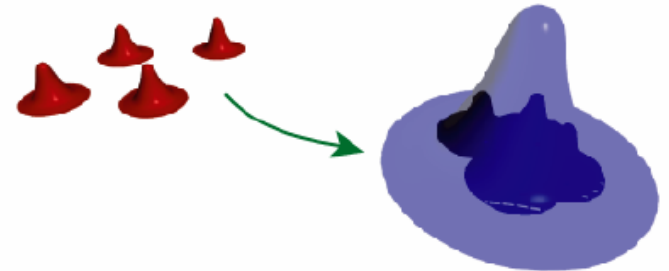
side remark: there can also be Bose-Einstein condensation of excitons in a semiconductor
→ work of Prof. Stolz in the SFB 652
(collaborative research center)



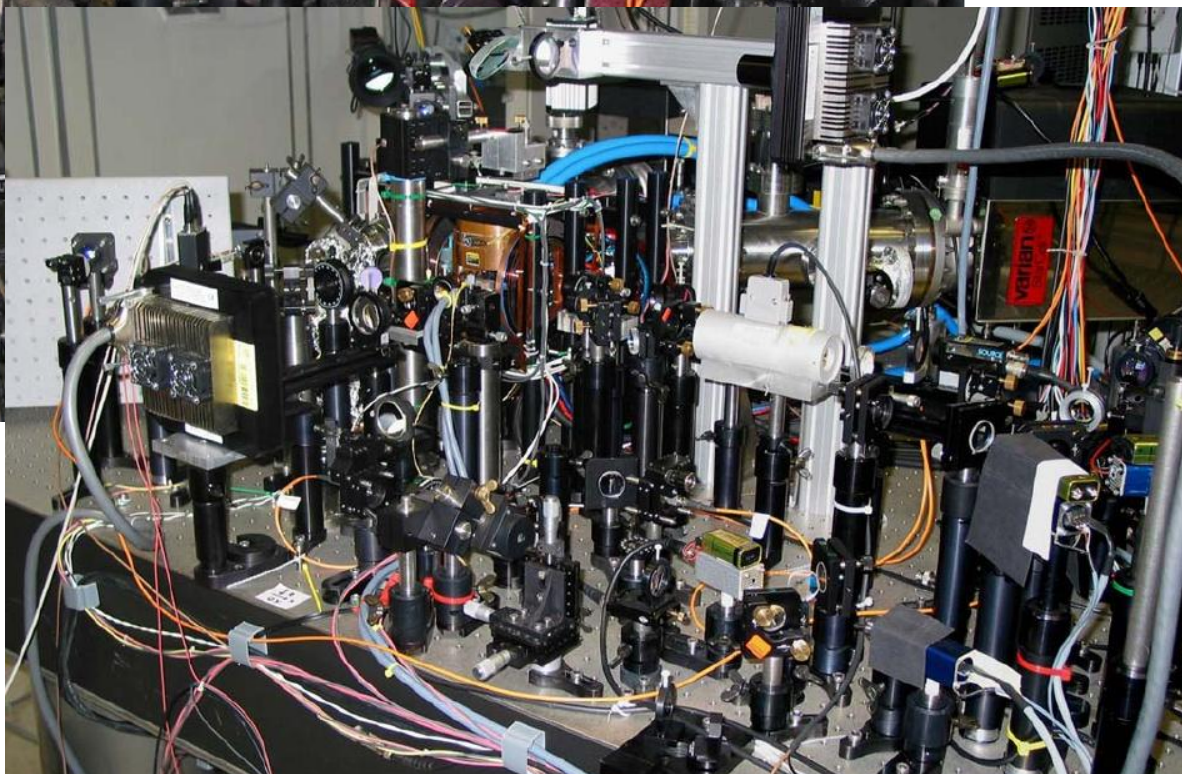
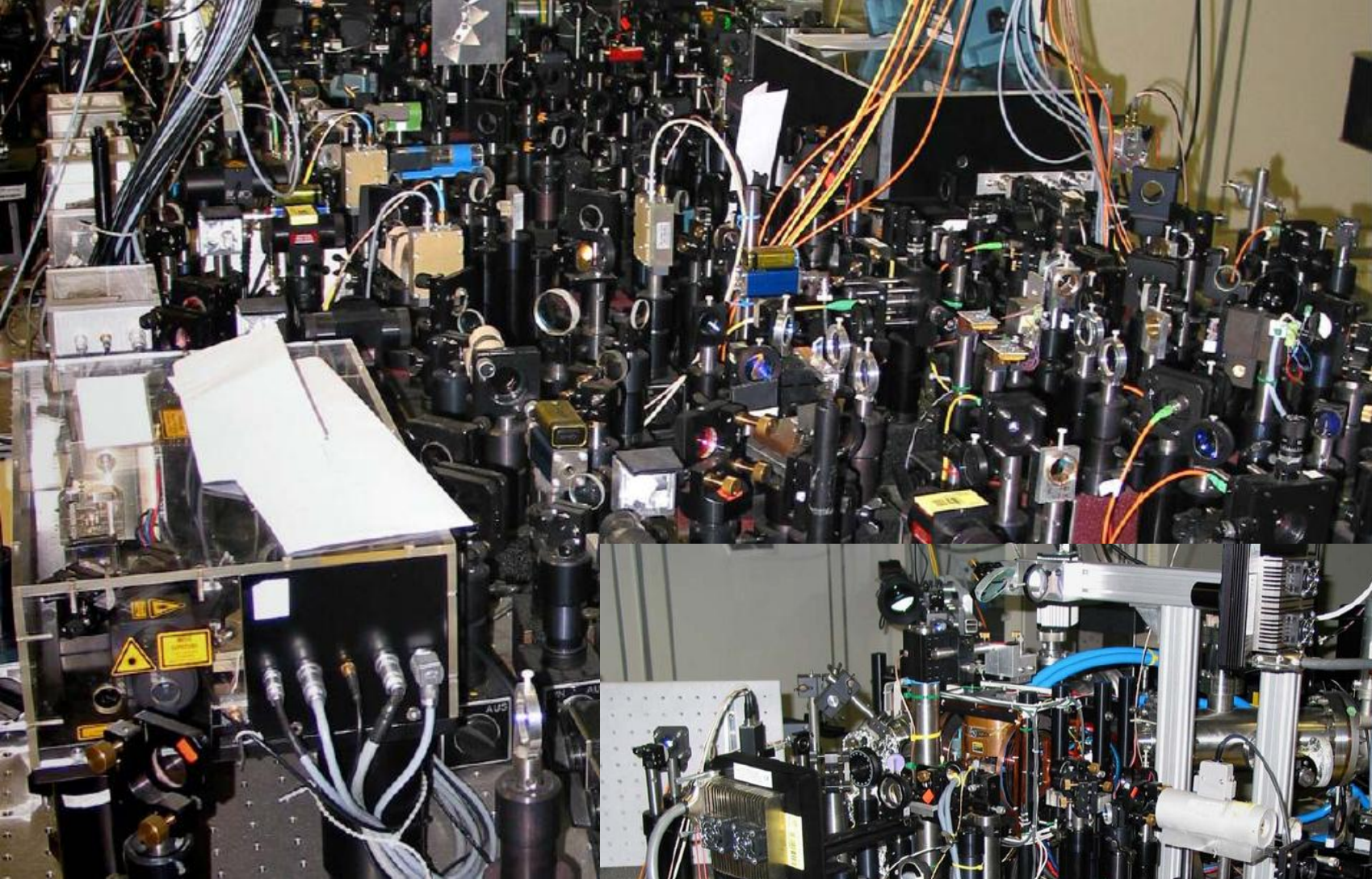
the long experimental way to BEC



$$n \cdot \lambda^3 \approx 1$$

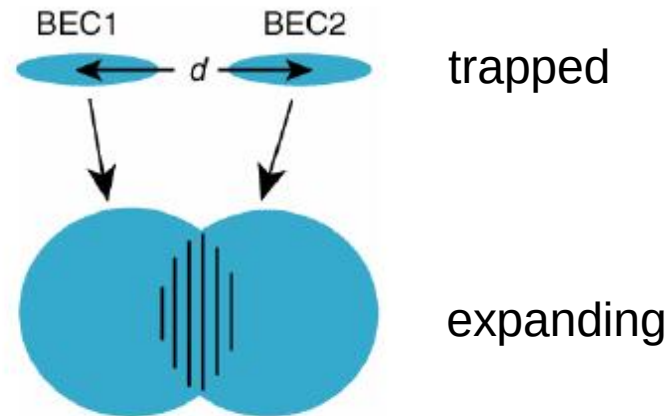


all the tools of atom cooling have to be used!

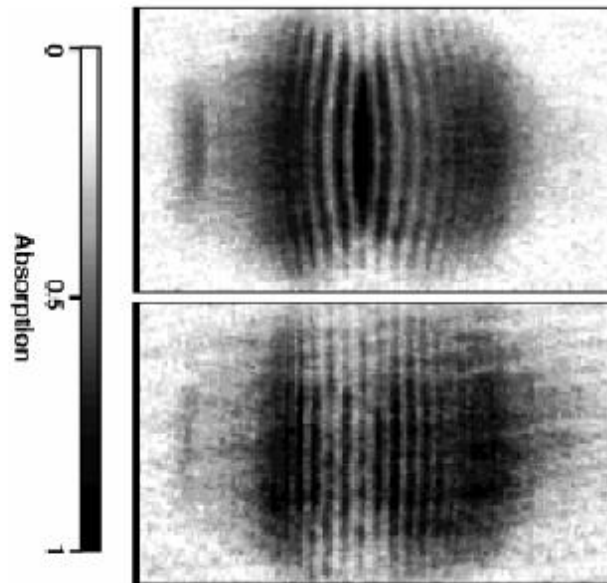


further studies of the BEC

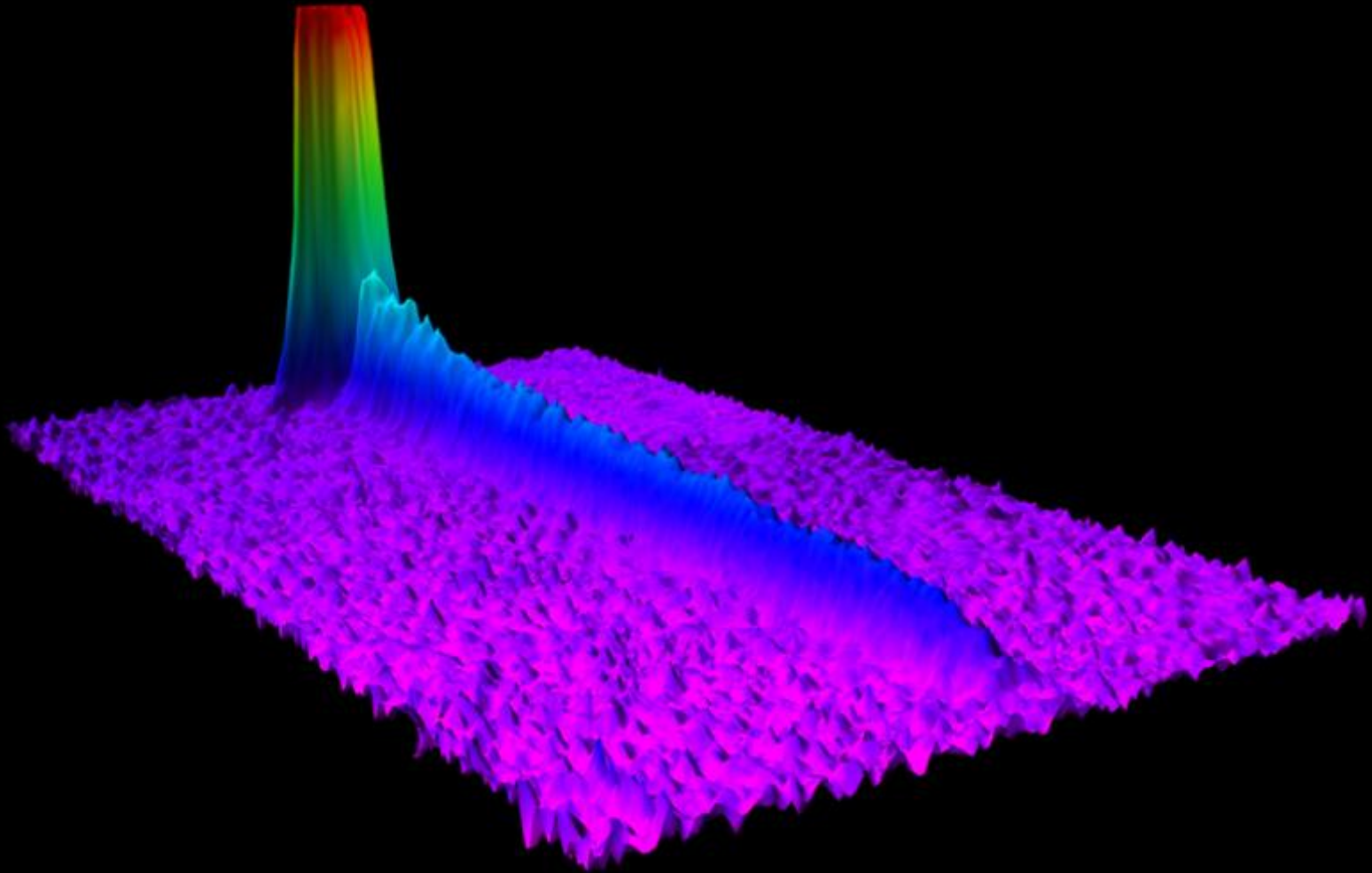
BEC can show interference



Andrews et al.,
Science 275, 637 (1997)



towards an atom laser



atom lasers

物理科学雑誌

parity

第11巻第9号
September 1999
毎月10日11日発行
ISSN 0911-4015
PHYSICS TODAY 提携

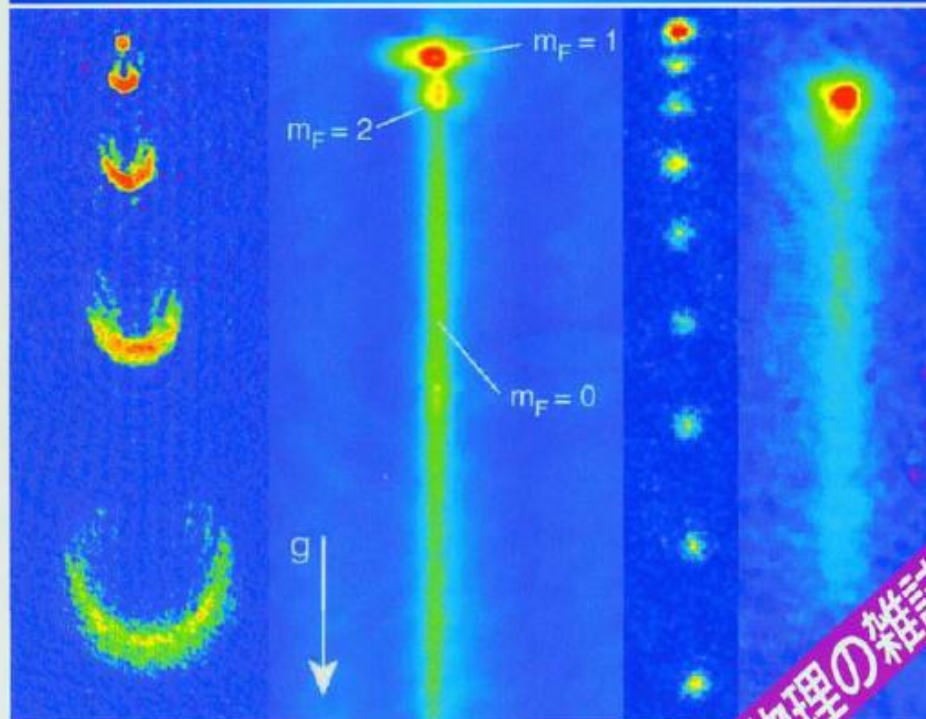
パリティ

1999
09

座談会:ボース-アインシュタイン凝縮をめぐる
ストロンチウム原子のレーザー冷却とその応用 | 原子線ホログラフィー
原子波レーザー | スピン自由度とBEC | 水素原子の陰と陽 | ボース凝縮体のコヒーレンス

特集: 打ち寄せる原子のさざ波

——レーザー冷却とボース-アインシュタイン凝縮——

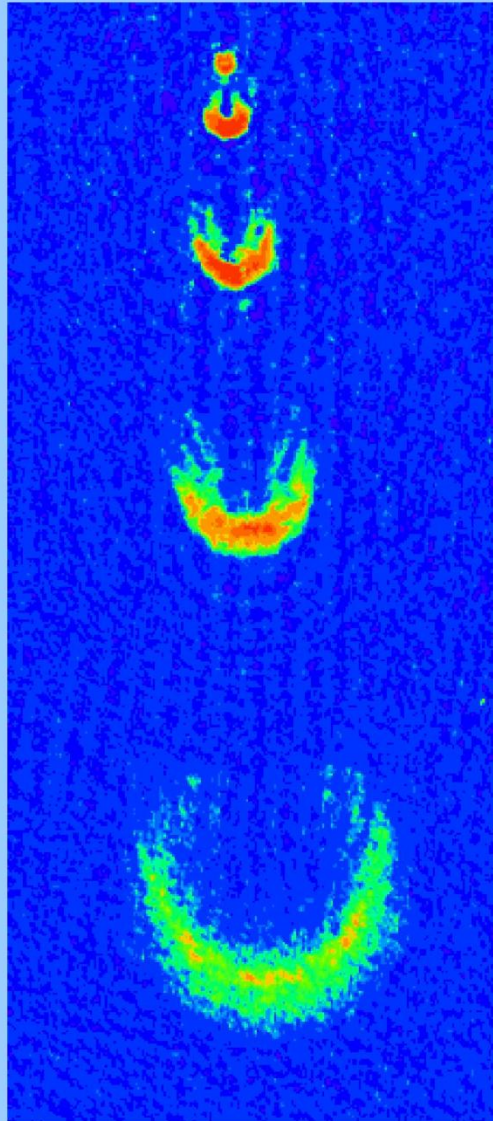


MARUZEN

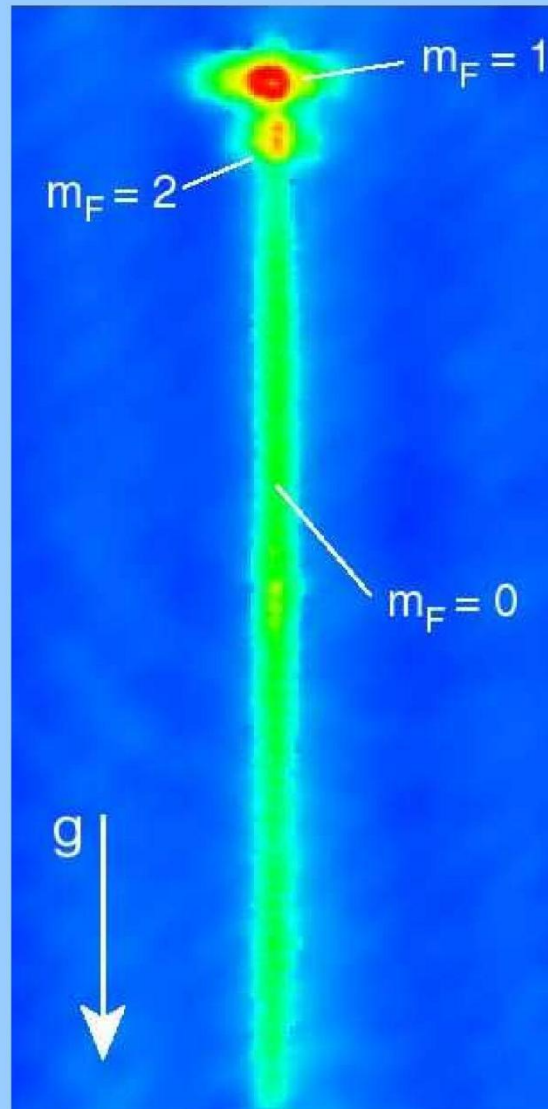
物理の雑誌

Atom laser gallery

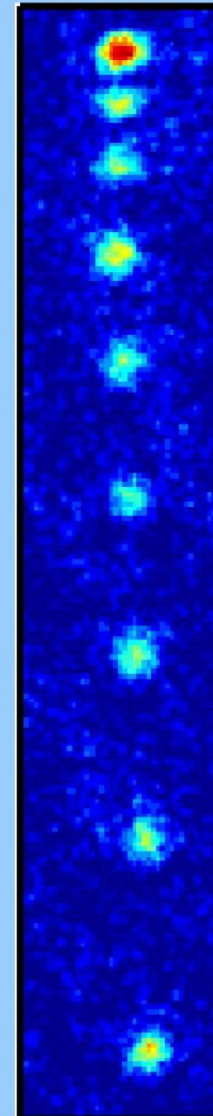
Height:
5, 2, 0.5, 1 mm



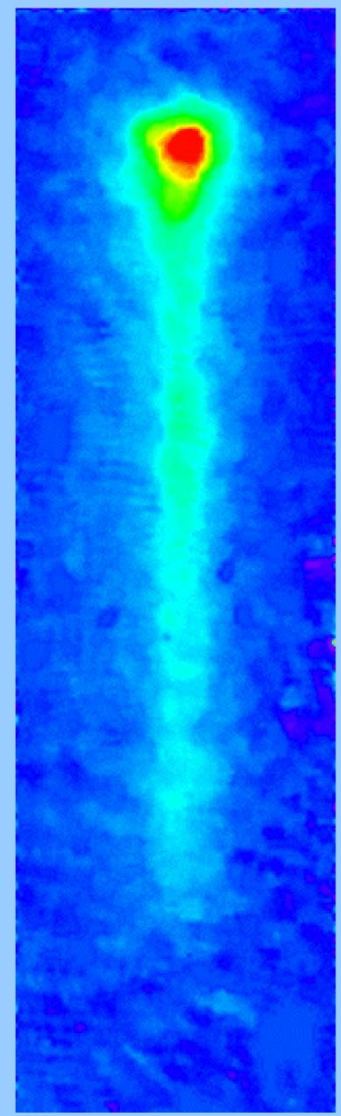
MIT '97



Munich '99

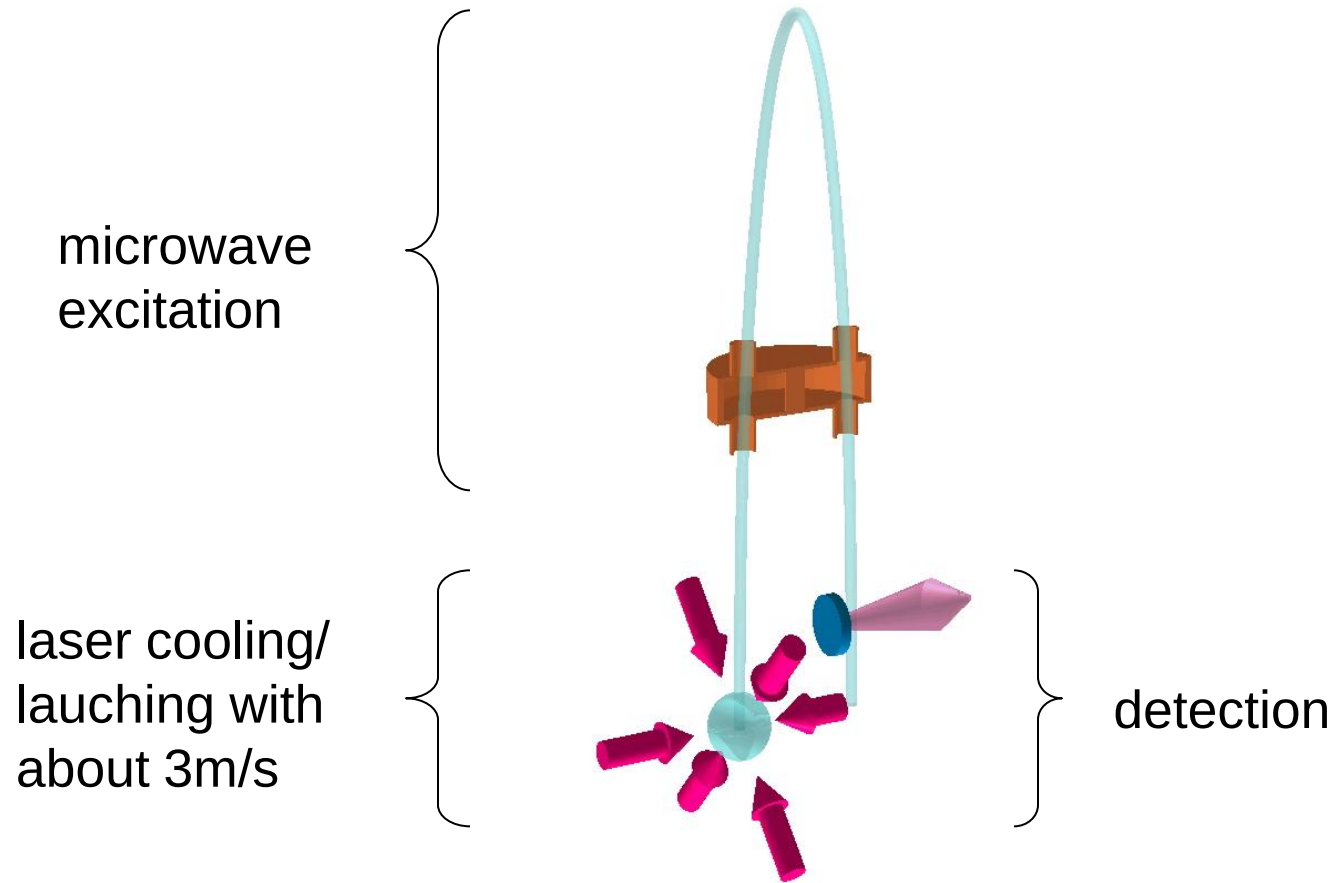


Yale '98

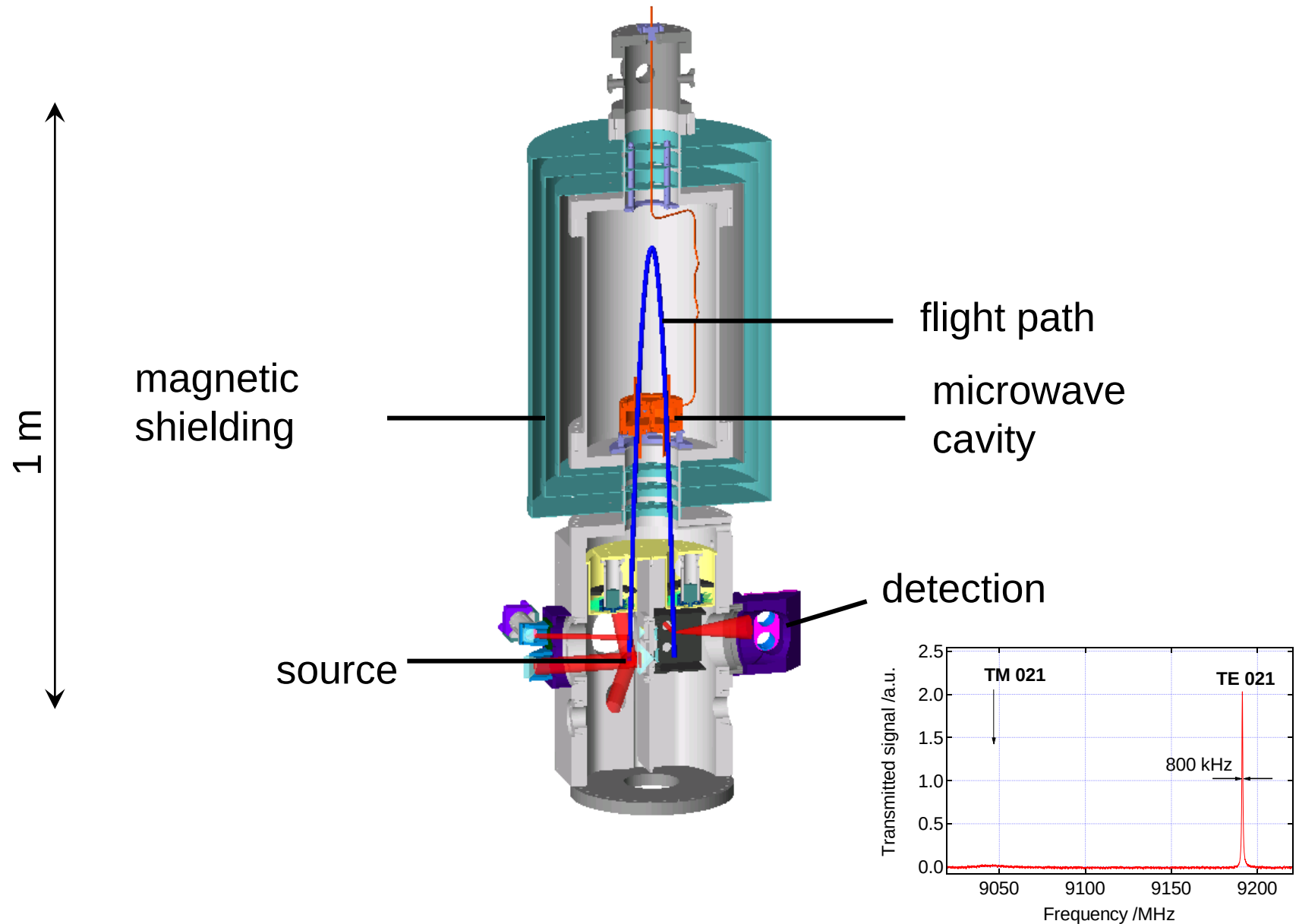


NIST '99

**one application: ultra-precise experiments
with an atomic fountain
e.g., for frequency standards**



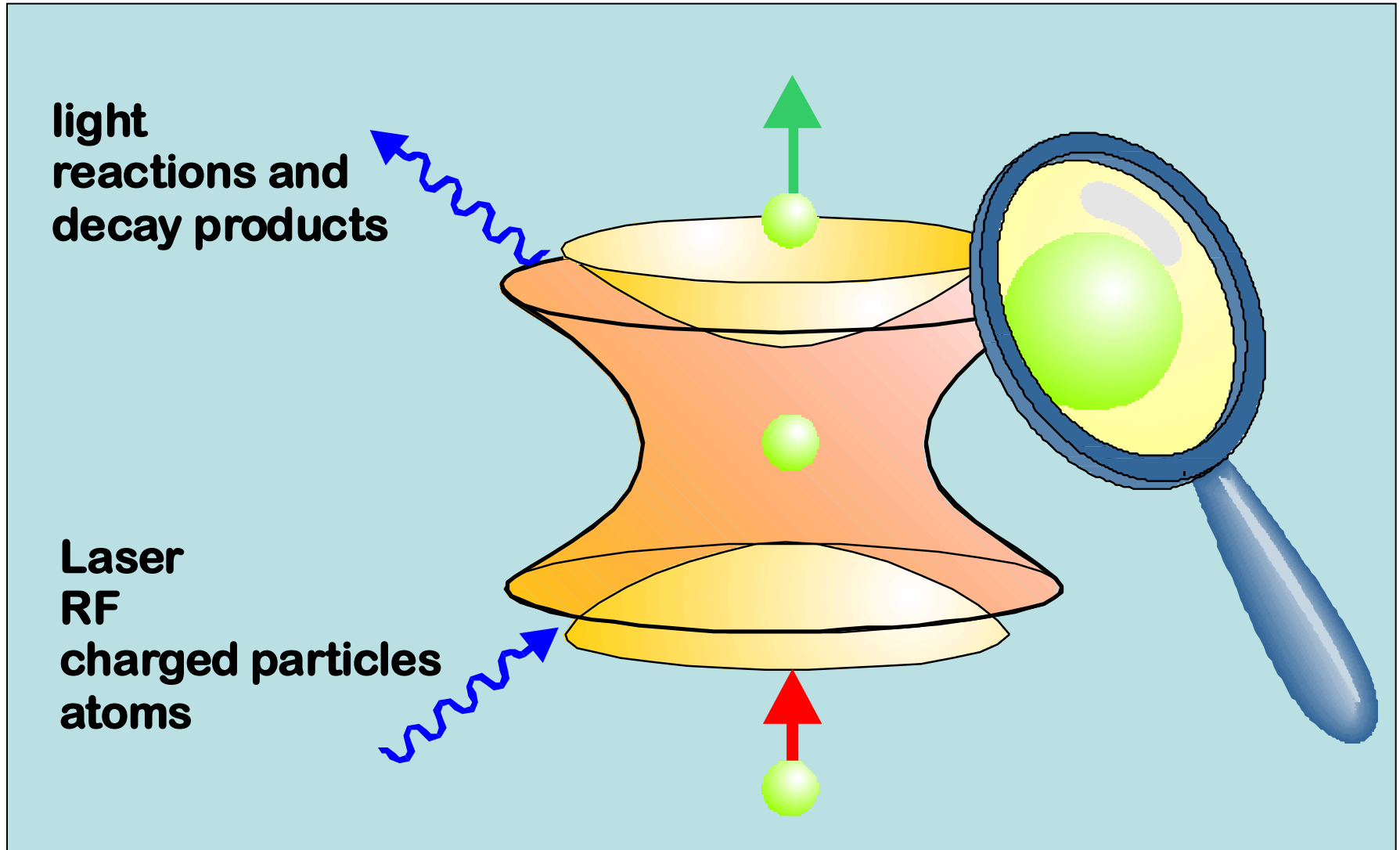
atom fountain: realization



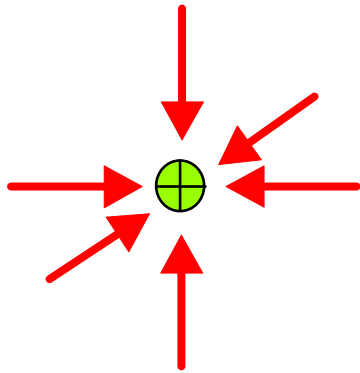
so far: trapping of neutral atoms

now: trapping of ions

Ion traps: store, select and investigate particles in 'free' space

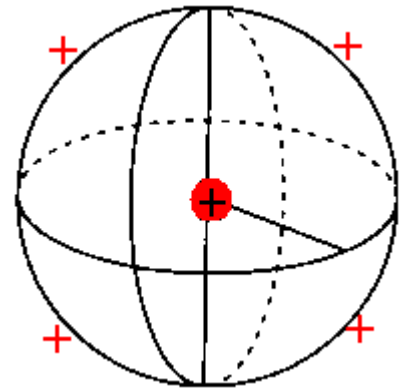


How to trap ions? Need potential minimum in 3 D

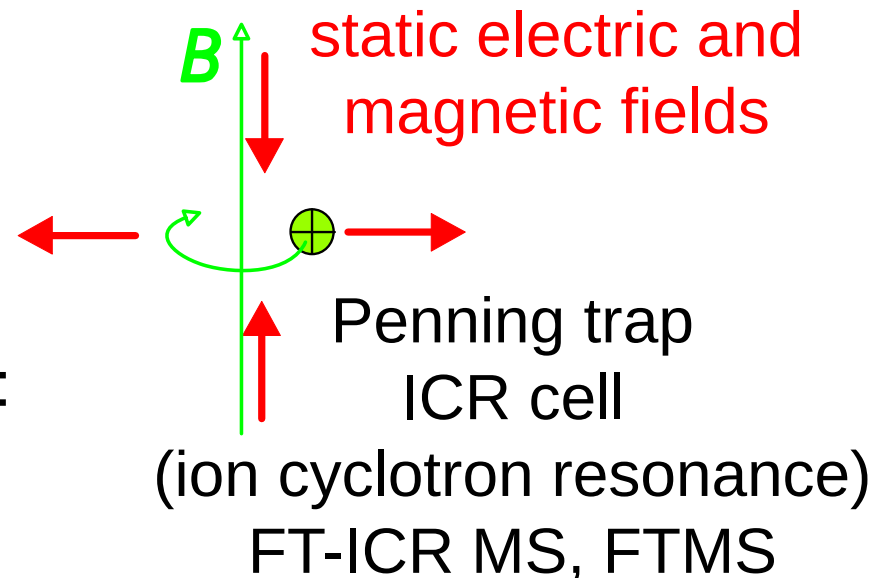
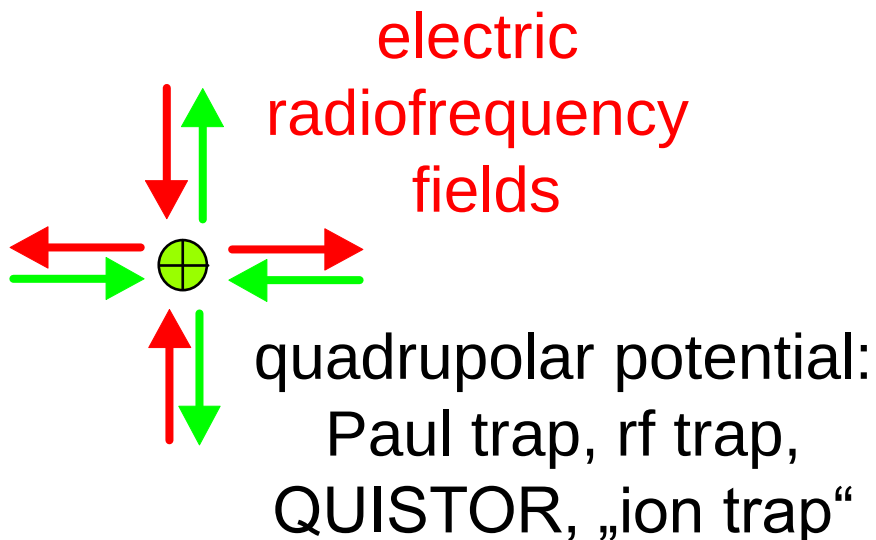


~~electrostatic trapping~~

not possible due to
Laplace: $\Delta\phi = 0$

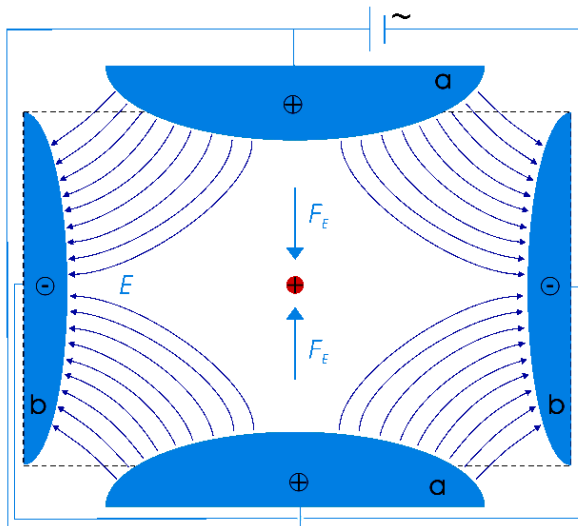


no field inside!



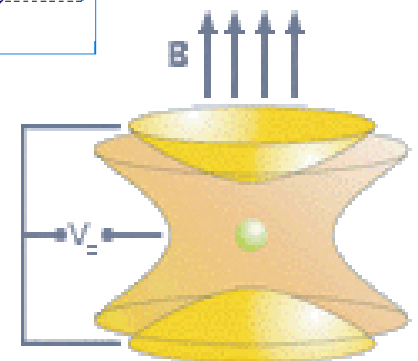
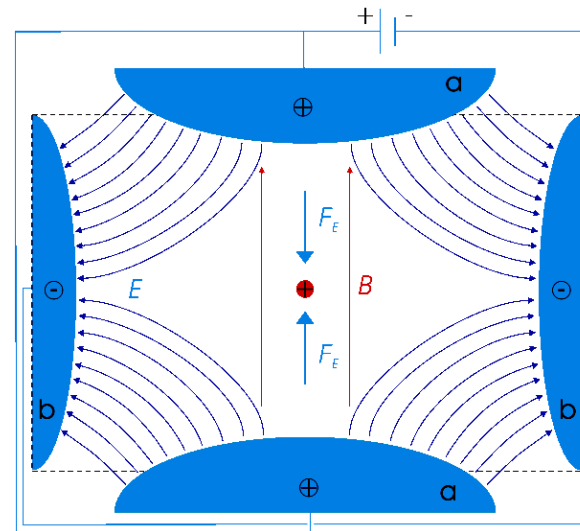
Paul trap

principle: electric
alternating field



Penning trap

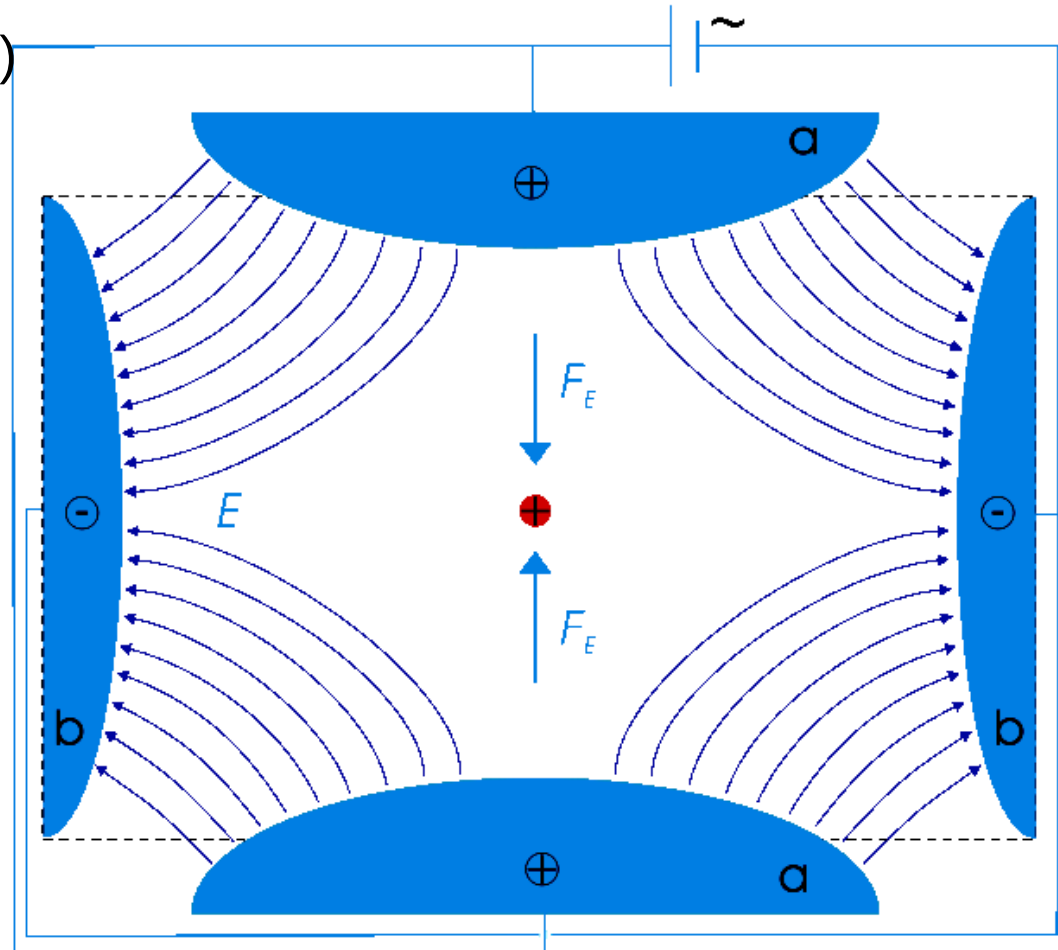
principle:
superposition of
a magnetic field



the Paul trap

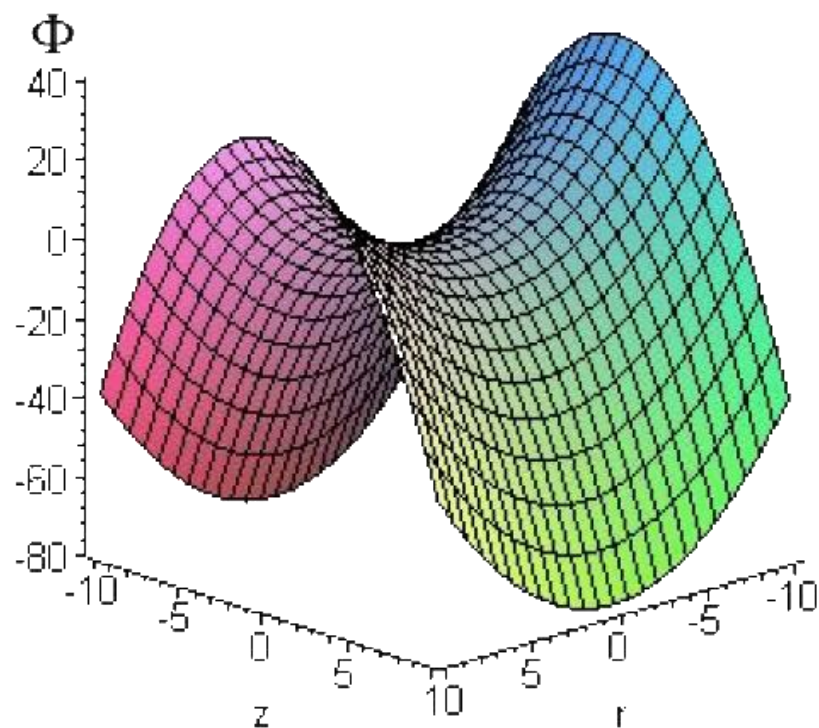
developed by
Wolfgang Paul (1913-1993)
in the 1950ies

Nobel price
in physics 1989



Electrically alternating field creates a static
pseudopotential

the potential of the Paul trap



$$\Phi(x, y, z, t) = \frac{U_0 \cdot \sin \omega t}{2r_0^2} \cdot (x^2 + y^2 - 2z^2)$$

operation of a Paul trap with charged dust particles

see Youtube <http://www.youtube.com/watch?v=bkYXNeJ8IP0>

