The World of Quantum Matter

ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

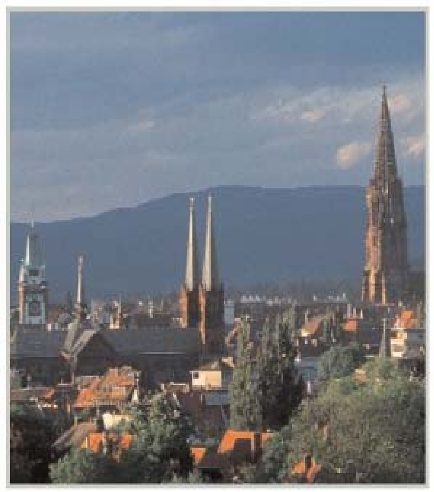
Atomic and Molecular Quantum Dynamics

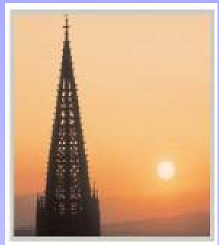
founded 1457

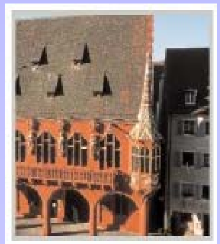
Matthias Weidemüller

Albert-Ludwigs-Universität Freiburg

Atomare und Molekulare Quantendynamik







€€€: **DFG** *(SPP 1116)*
EU *(TMR Network „Cold Molecules“)*
Landesstiftung BW
(Quanteninformation/Eliteförderung)

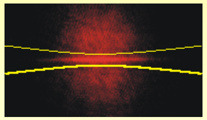
http://quantendynamik.physik.uni-freiburg.de

Matthias Weidemüller

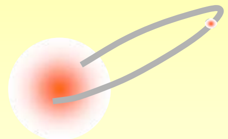
Roland Wester

Helga Müller (Sekr.)
Ulrich Person (Ing.)
Hartmut Götz (Ing.)

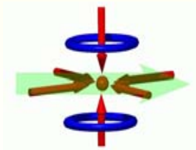
- Mixtures of ultracold atoms and cold molecules
  - Stephan Kraft *(Doct)*
  - Jörg Lange *(Doct)*
  - Peter Staanum *(PostDoc)*
  - Benjamin Müller *(Dipl)*
  - Christian Giese *(Dipl)*



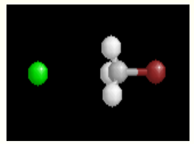
- Ultracold Rydberg gases and plasmas
  - Markus Reetz-Lamour *(Dokt)*
  - Thomas Amthor *(Doct)*
  - Johannes Deiglmayr *(Dipl)*
  - Sebastian Westermann *(Dipl)*
  - André de Oliveira *(GuestSci)*



- Cold atom targets /coherent control with femtosecond pulses
  - Wenzel Salzmann *(Doct)*
  - Ulrich Poschinger *(Dipl)*
  - Judith Eng *(Dipl)*



- Quantum dynamics of ion-molecule reactions
  - Roland Wester *(PI)*
  - Jochen Mikosch *(Doct)*
  - Sebastian Trippel *(Doct)*
  - Raphael Berhane *(Dipl)*



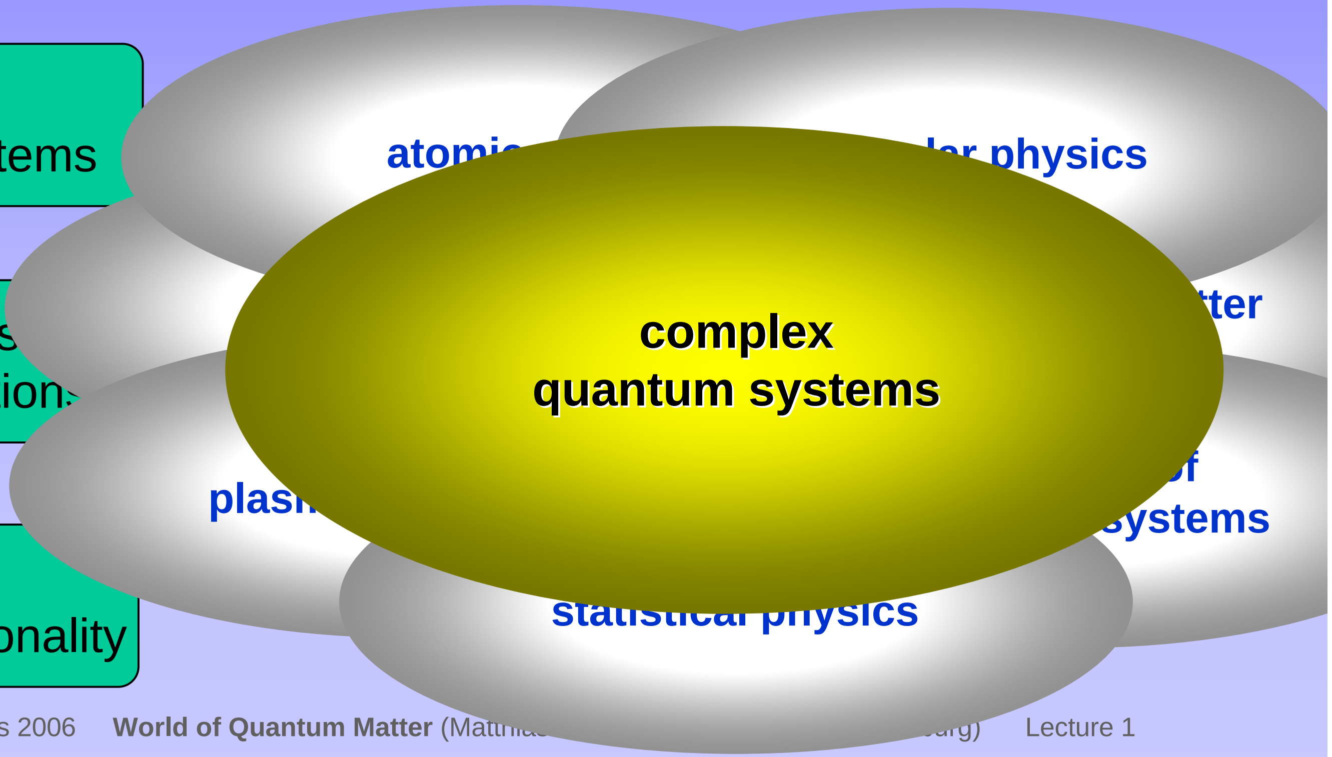
The new era of quantum mechanics

Quantum Physics
is undergoing the transition from
the *Analytical* Era
to
the *Synthetic* Era

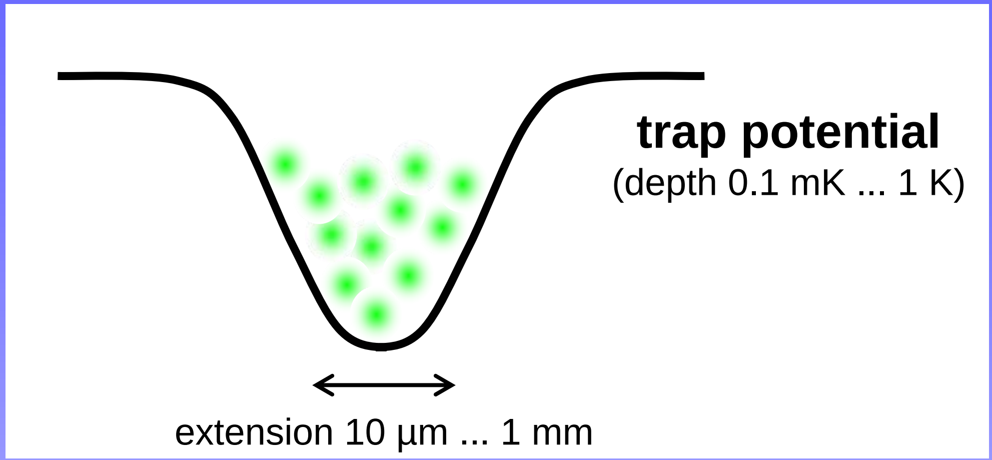
coherent control
of simple quantum systems

many-body systems
with controlled interactions

control of
geometries and dimensionality



Ultracold atoms in traps

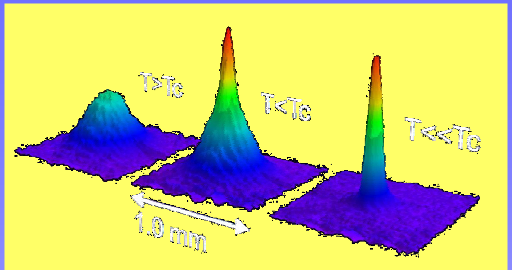


- **Negligible thermal energy** (**$k_B T$ ~ neV**)
  dynamics determined by interactions, strong correlations
- **Large deBroglie wavelength** (**λ_{dB} ~ mm**)
  quantum degeneracy, scattering resonances
- **Very long observation times** (**t_{obs} ~ min**)
  ultrahigh resolution, observable effects of weak interactions

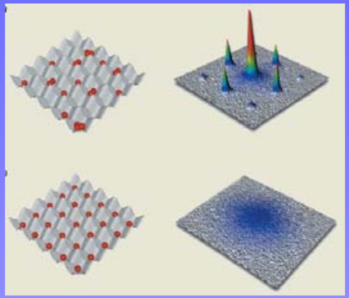
FULL CONTROL over
INTERNAL and EXTERNAL degrees of freedom

Systems under investigation (selection)

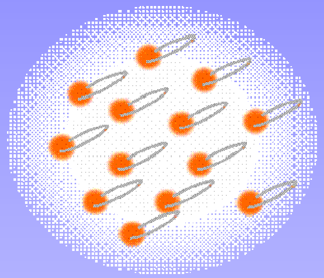
Bose-Einstein condensates



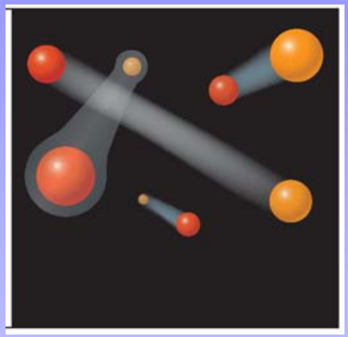
ultracold gases in optical lattices



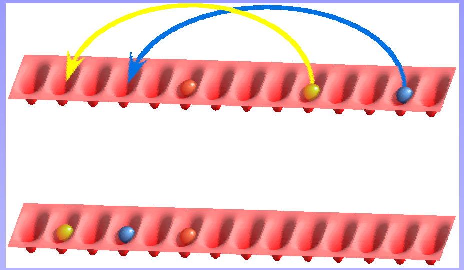
Rydberg gases



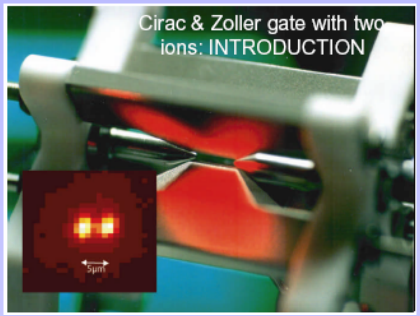
quantum-degenerate Fermi gases



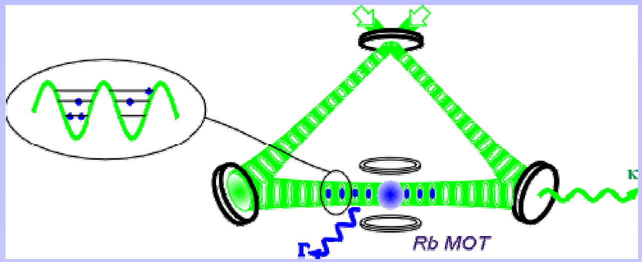
single atoms



trapped ions



atoms in high-finesse resonators



The World of Quantum Matter

Applications and Fundamental Concepts

Atomic, Molecular and Optical Physics

Statistical Physics

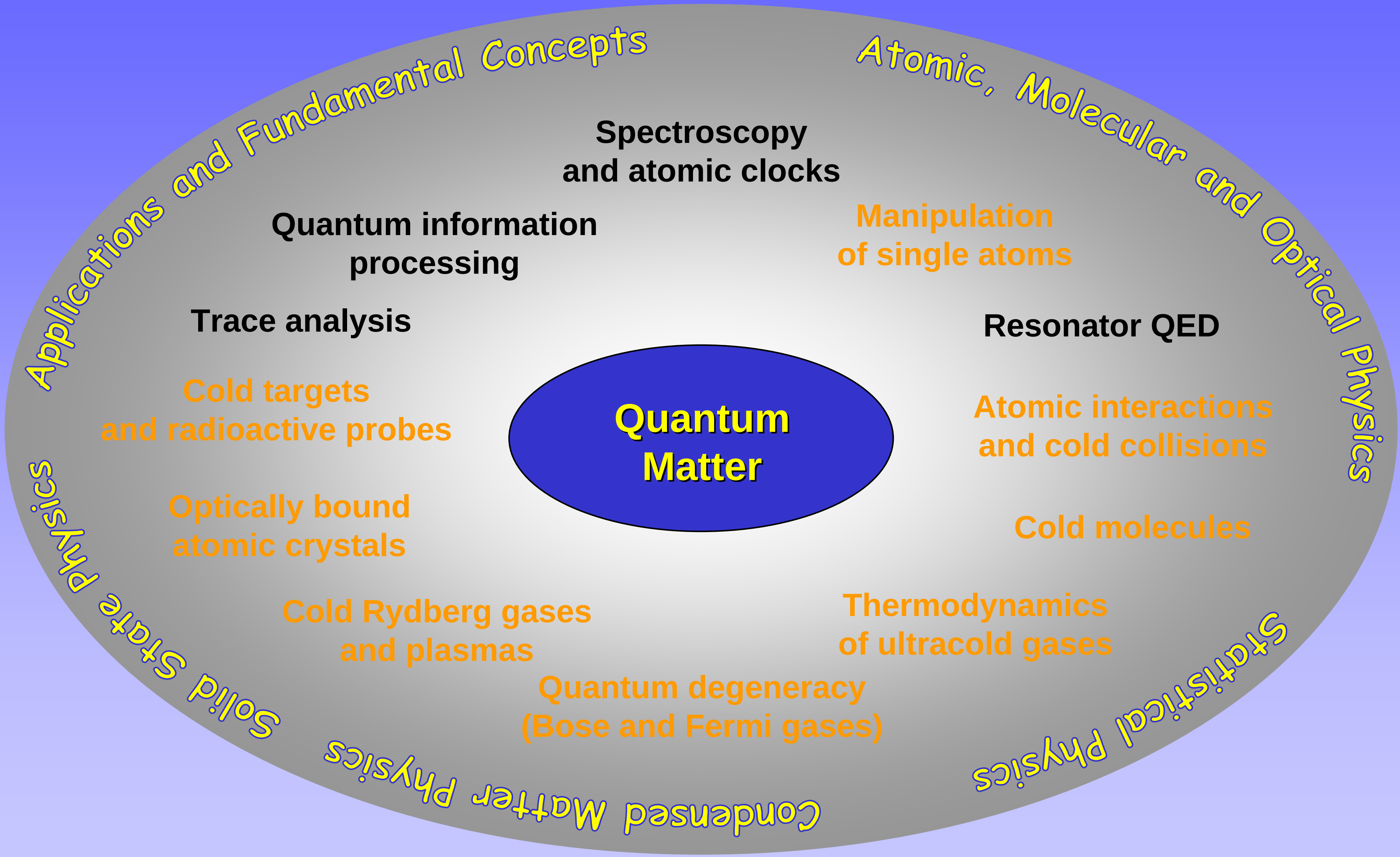
Condensed Matter Physics

Solid State Physics

Quantum Matter

- Spectroscopy and atomic clocks
- Manipulation of single atoms
- Resonator QED
- Atomic interactions and cold collisions
- Cold molecules
- Thermodynamics of ultracold gases
- Quantum degeneracy (Bose and Fermi gases)
- Cold Rydberg gases and plasmas
- Optically bound atomic crystals
- Cold targets and radioactive probes
- Trace analysis
- Quantum information processing

The World of Quantum Matter



Contents of the lectures

0. Primer on light-matter interactions
1. The way to absolute zero – cooling and trapping methods for atoms
2. Cold collisions
3. Bose-Einstein condensation
4. Degenerate Fermi gases
5. Cold Rydberg gases and plasmas
6. Ultracold molecules
7. Manipulation of single atoms
8. Cold atoms as targets for photon and particle beams

Lecture 1

Lecture 2

Lecture 3

Lecture 4

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Lecture 1 (items 0–2)

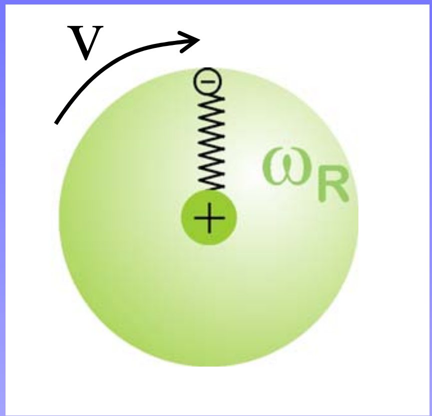
Lecture 2 (items 3–4)

Lecture 3 (items 5–6)

Lecture 4 (items 7–8)

Different look at light-matter interactions

Lorentz atom



- **magnetic dipole moment**
  through ring current
- **no electric dipole moment**
  through symmetry

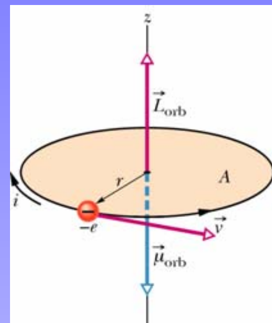
Interaction with external fields

magnetic fields

$$E_{\mathrm{mag}} = -\vec{\mu} \cdot \vec{B}$$

magnetic moment

$$\vec{\mu} = -\frac{e}{2m_e}\vec{L}_{\mathrm{orbit}}$$



electric fields

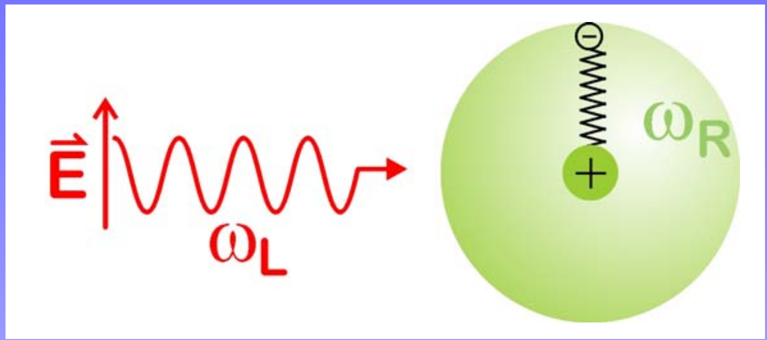
$$E_{\mathrm{el}} = -\vec{\wp}_{\mathrm{ind}} \cdot \vec{\mathcal{E}}$$

induced dipole moment

$$\vec{\wp}_{\mathrm{ind}} = \underline{\underline{\alpha}}\,\vec{\mathcal{E}}$$

Different look at light-matter interactions

Electric polarizability



Equation of motion

$$\ddot{\wp} + \Gamma_\omega \, \dot{\wp} + \omega_0 \, \wp = -\frac{e^2}{m_e} \mathcal{E}(t)$$

classical damping rate

$$\Gamma_\omega = \frac{e^2 \, \omega^2}{6\pi\varepsilon_0 \, m_e \, c^3}$$

Polarizability

$$\alpha = 6\pi\varepsilon_0 c^3 \frac{\Gamma/\omega_0^2}{\omega_0^2 - \omega^2 - i\,(\omega^3/\omega_0^2)\,\Gamma}$$

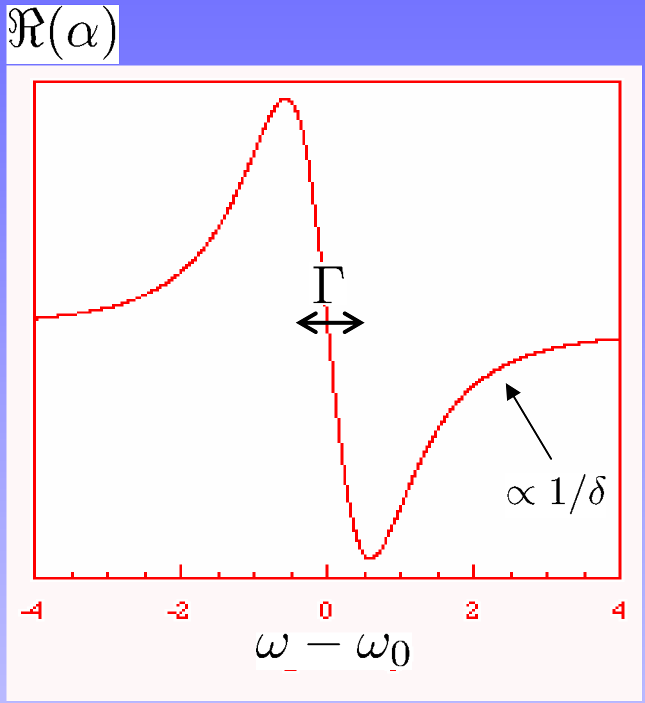
with $\Gamma \equiv \Gamma_{\omega_0}$

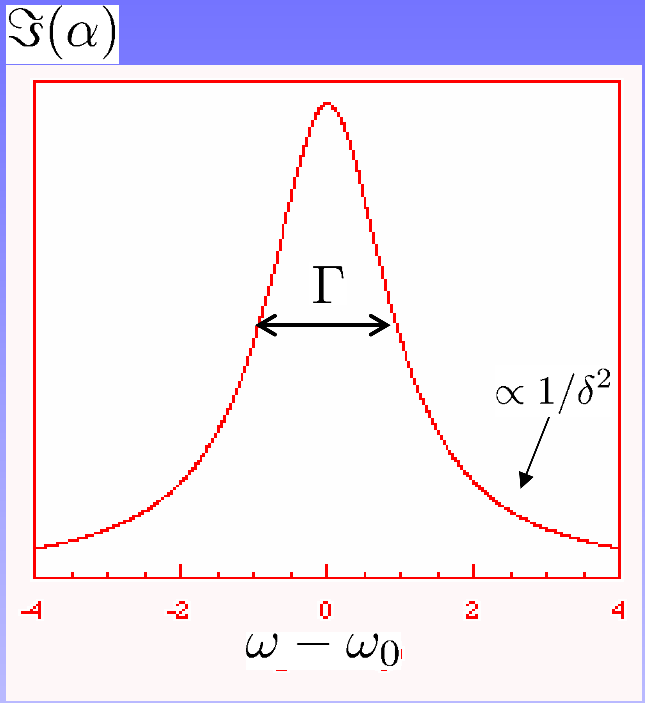
Susceptibility

$$\chi_{\rm el} = \mathcal{N} \, \alpha \, / \varepsilon_0$$

Different look at light-matter interactions

Electric polarizability (cont‘d)

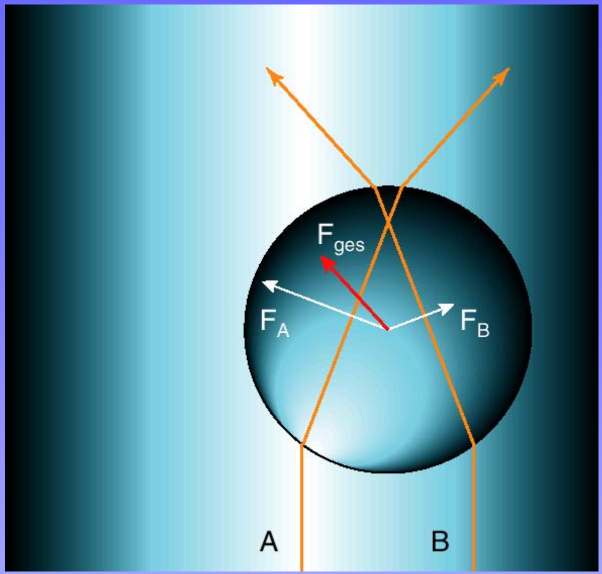




Refractive index (small χ)

$$n \simeq 1 + \frac{1}{2}\chi_{\mathrm{el}} = 1 + \frac{1}{2}\mathcal{N}\,\alpha\,/\varepsilon_0$$

Different look at light-matter interactions



Dipole force

Interaction potential

$$U_{\rm dip} = -\frac{1}{2}\langle \vec{\wp}_{\rm ind} \cdot \vec{\mathcal{E}} \rangle = -\frac{1}{2\varepsilon_0 c}\Re(\alpha)\, I$$

Dipole force

$$\vec{F}_{\rm dip} = -\vec{\nabla} U_{\rm dip} = \frac{1}{2\varepsilon_0 c}\Re(\alpha)\, \vec{\nabla} I$$

Scattering force (light pressure)

Scattering rate

$$\Gamma_{\rm sc} = P_{\rm abs}/\hbar\omega = -\frac{1}{\varepsilon_0 \hbar c}\Im(\alpha)\, I$$

Scattering force

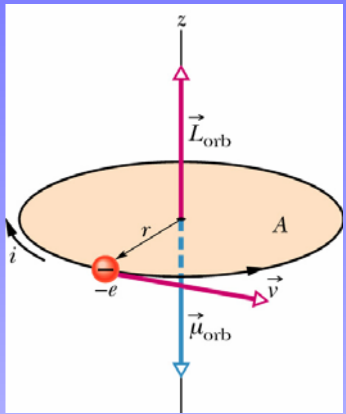
$$\vec{F}_{\rm sc} = \hbar\, \vec{k}\, \Gamma_{\rm sc} = \frac{1}{\varepsilon_0 c}\Im(\alpha)\, I\, \vec{k}$$

Different look at atom-field interactions

Why does the classical picture work so well?

Magnetic dipole moment

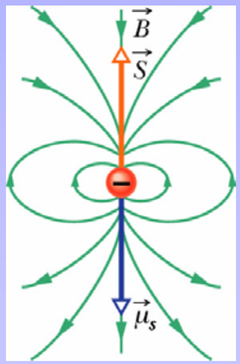
Orbital momentum



$$\vec{\mu}_{\rm Bahn} = -\frac{e}{2m_e}\vec{L}_{\rm Bahn}$$

$$|\vec{\mu}_{\rm Bahn}| = -\mu_{\rm Bohr}\frac{|\vec{L}|}{\hbar}$$

Electron spin



$$\vec{\mu}_S = -\frac{e}{m_e}\vec{S}$$

$$|\vec{\mu}_S| = \pm\frac{1}{2}\hbar\,\frac{e}{m_e} \equiv \pm\mu_{\rm Bohr}$$

$$\mu_{\rm Bohr} = 9.72\times 10^{-24}\ {\rm J/T}$$

Current operator

$$\vec{J}(\vec{r}) = \frac{\hbar}{2\mu i}\,\psi^*(\vec{r})\,\vec{\nabla}\,\psi(\vec{r}) + {\rm c.c.}$$

For wavefunction n,l,m:

$$\vec{J}_{n\ell m}(\vec{r}) = \frac{\hbar}{\mu}\,m\,\frac{\rho_{n\ell m}(\vec{r})}{r\sin\vartheta}\,\vec{e}_\varphi(\vec{r})$$

$$\rho(\vec{r}) = |\psi(\vec{r})|^2$$

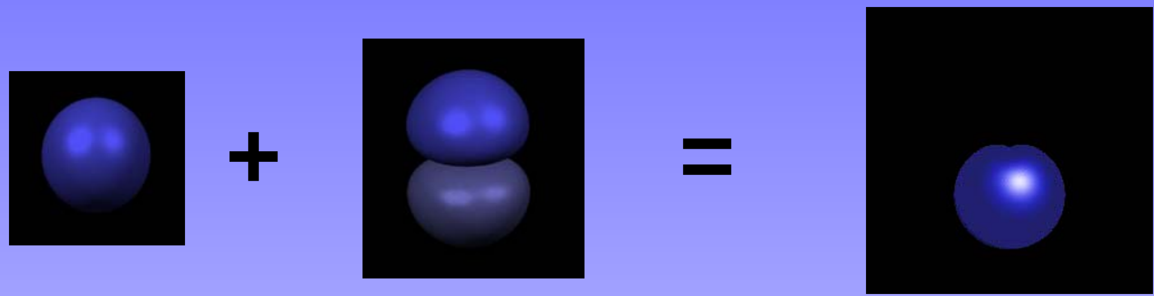
$$\langle\,\vec{\mu}_{\rm mag}\,\rangle_{n\ell m} = -m\,\frac{e\hbar}{2\mu}\,\vec{e}_z$$

Different look at light-matter interactions

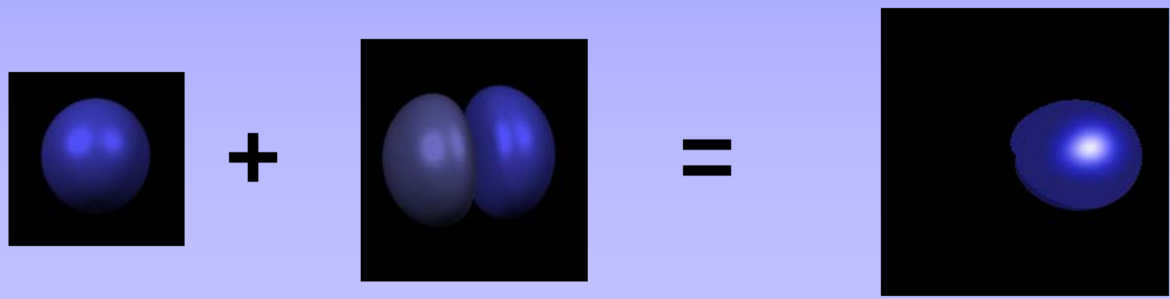
Why does the classical picture work so well?

Electric dipole moment

Superposition of eigenfunctions (ex. s- and p-orbitals)



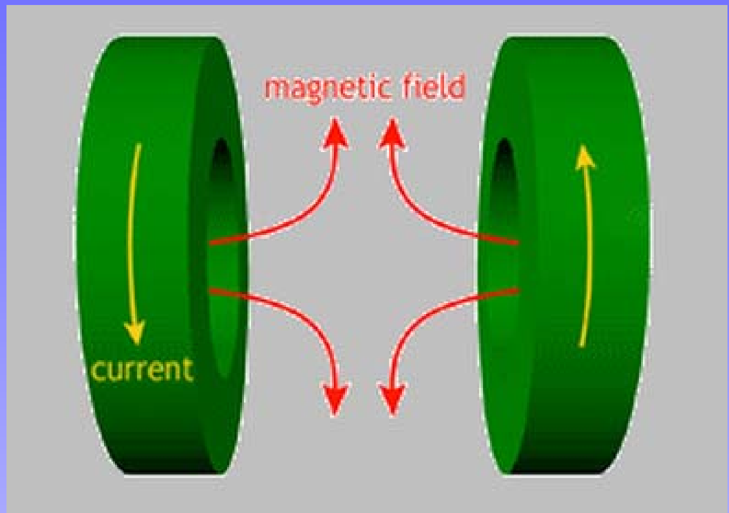
n=0,l=0,m=0 n=1,l=1,m=0



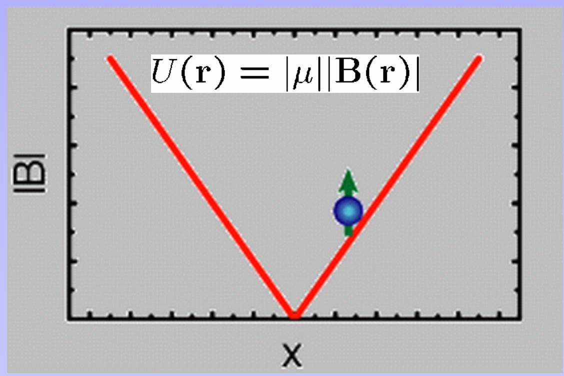
n=0,l=0,m=0 n=1,l=1,m=1

The trap zoo: magnetic traps

Quadrupole trap



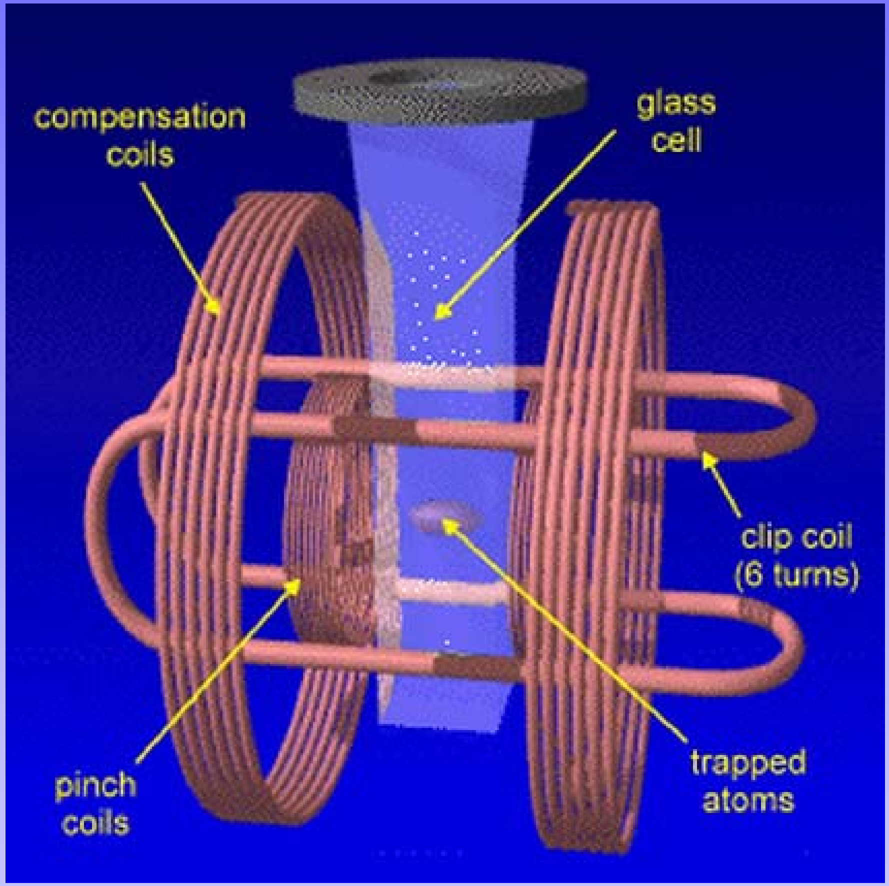
Potential



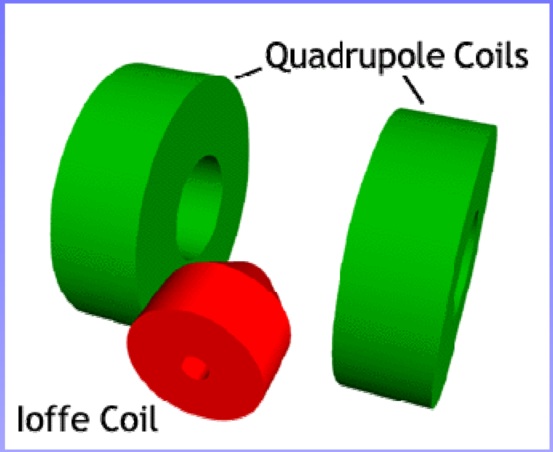
Problem:
Spin flips close to zero field
(Majorana flip)

The trap zoo: magnetic traps

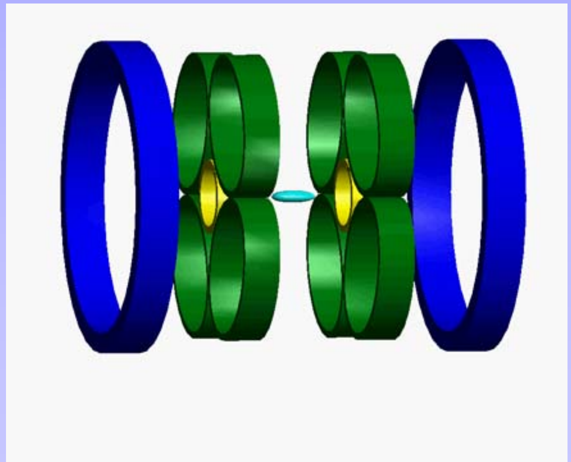
Joffe-Pritchard trap



QUadrupole **I**offe **C**onfiguration

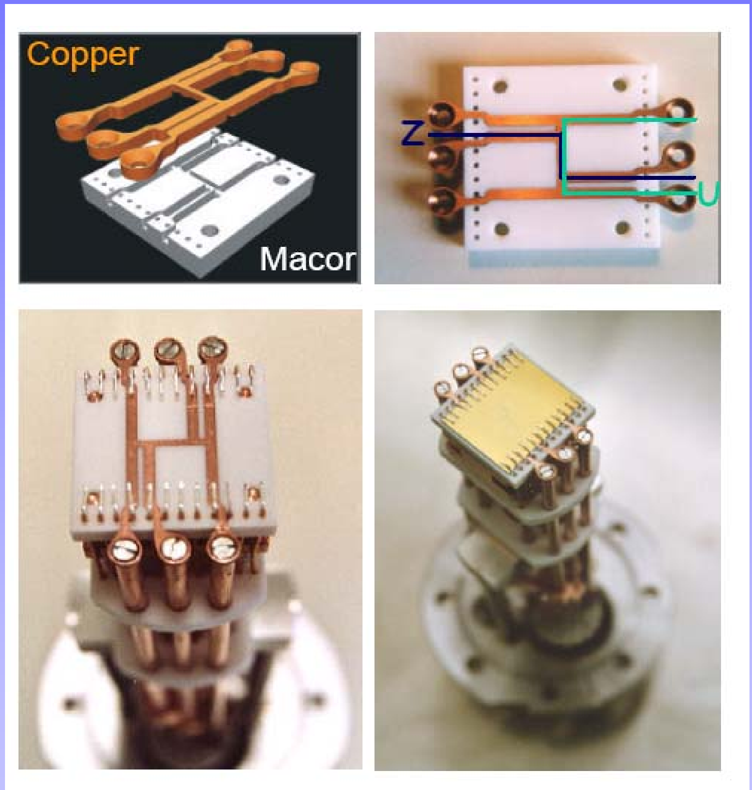


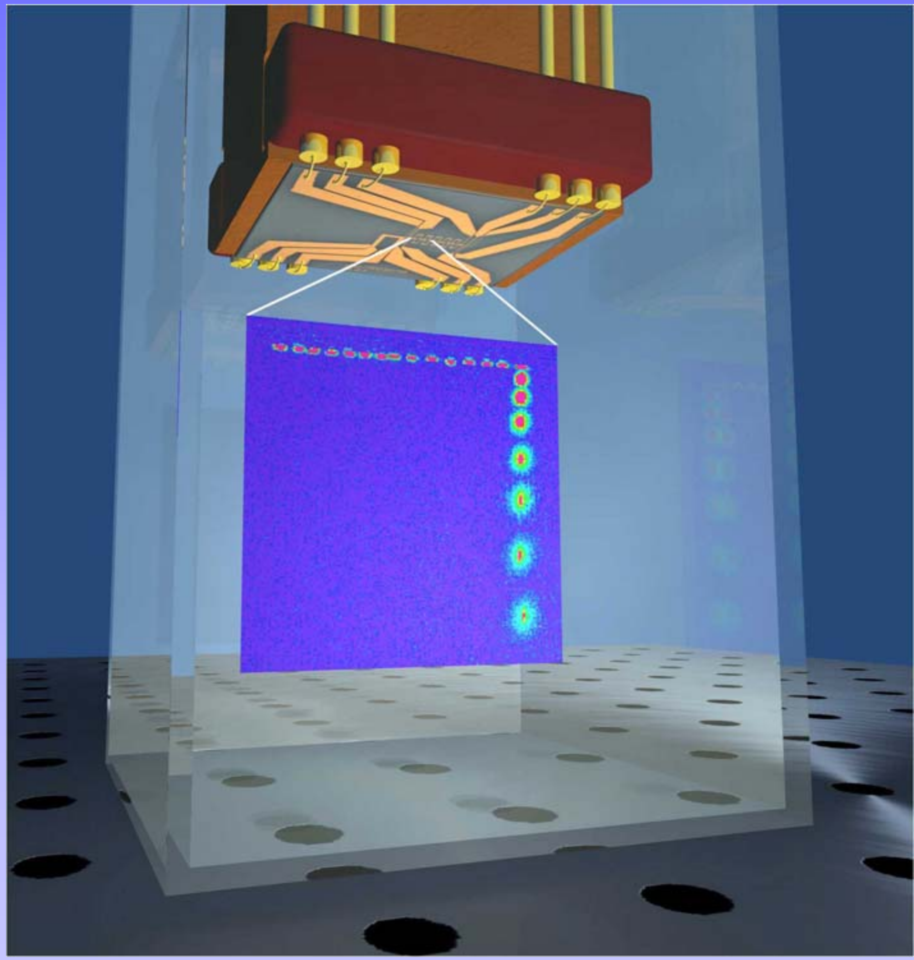
Cloverleaf configuration



The trap zoo: magnetic traps

Chip traps



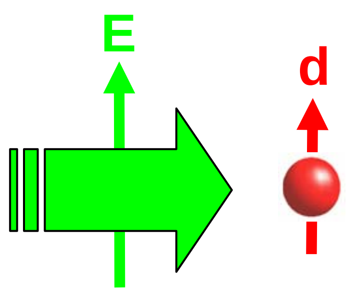


courtesy J. Reichel (ENS Paris)

The trap zoo: optical dipole traps

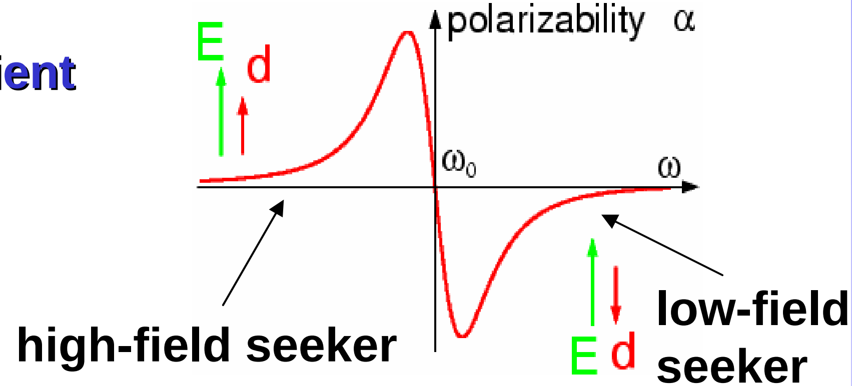
Laser light *far-detuned from resonance*
induces an oscillating **atomic dipole**

$$\mathbf{d} = \underline{\underline{\alpha}}\,\mathbf{E}$$



Dipole experiences force prop. to the **polarizability** and the **intensity gradient**

$$\mathbf{F}_{\text{dip}} = -\nabla(\mathbf{d}\cdot\mathbf{E}) \propto -\underline{\underline{\alpha}}\,\nabla I \equiv -\nabla U_{\text{dip}}$$

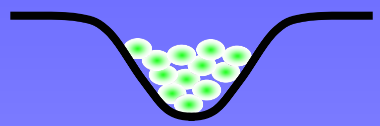


The trap zoo: optical dipole traps

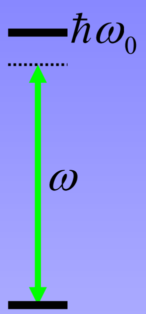
optical dipole force

$$F_{\text{dip}} = -\nabla U_{\text{dip}}$$

optical dipole potential



R. Grimm, M. Weidemüller, Yu.B. Ovchinnikov, Adv. At. Mol. Opt. Phys. **42**, 95 (2000)



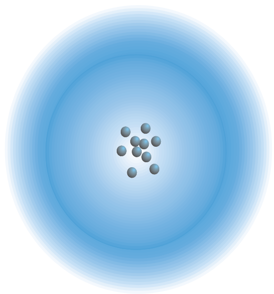
$$U_{\text{dip}}(\mathbf{r}) = -\frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\omega_0-\omega}+\frac{\Gamma}{\omega_0+\omega}\right) I(\mathbf{r})$$

dipole potential

$$\Gamma_{\text{sc}}(\mathbf{r}) = -\frac{3\pi c^2}{2\hbar\omega_0^3}\left(\frac{\omega}{\omega_0}\right)^3\left(\frac{\Gamma}{\omega_0-\omega}+\frac{\Gamma}{\omega_0+\omega}\right)^2 I(\mathbf{r})$$

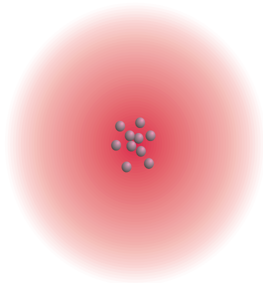
scattering rate

„**blue**“ detuning ($\omega>\omega_0$)



repulsion

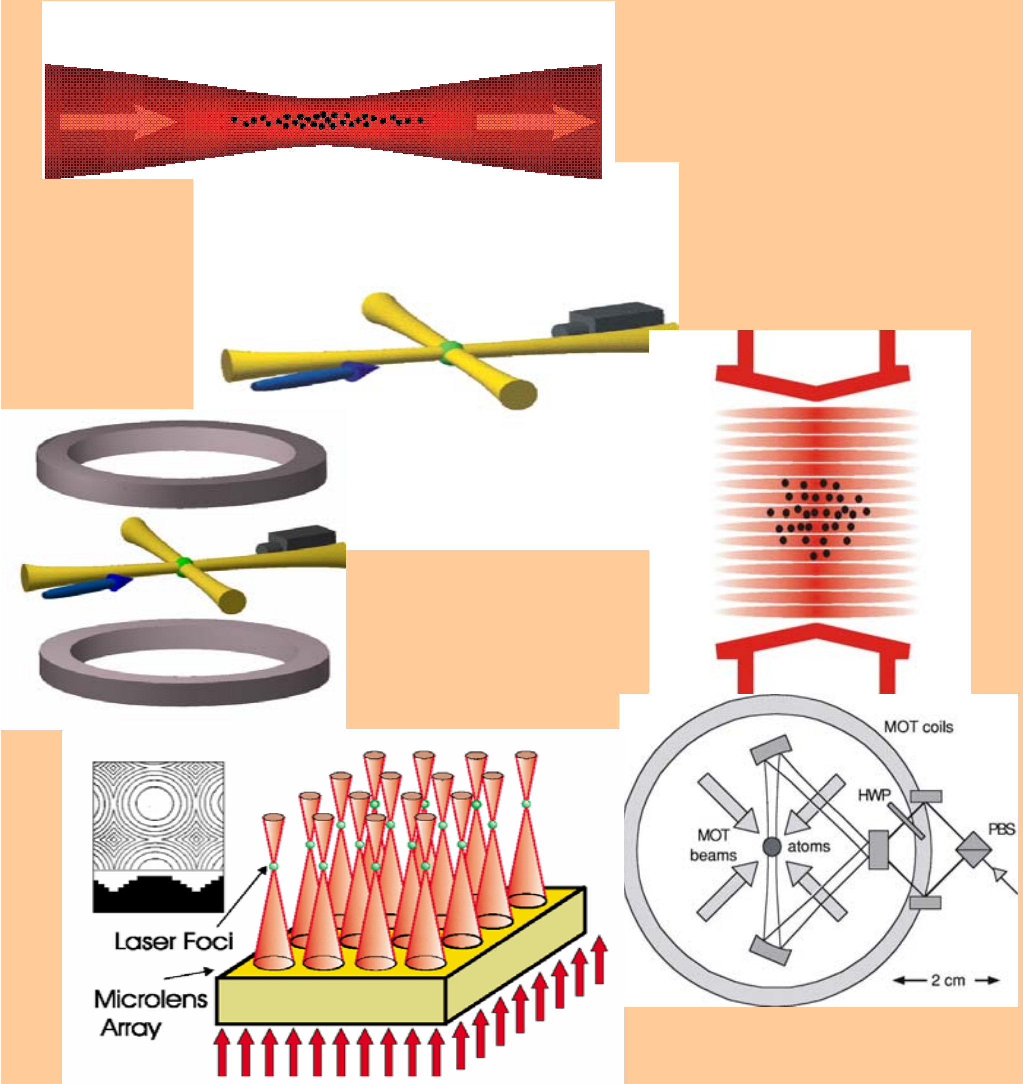
„**red**“ detuning ($\omega<\omega_0$)



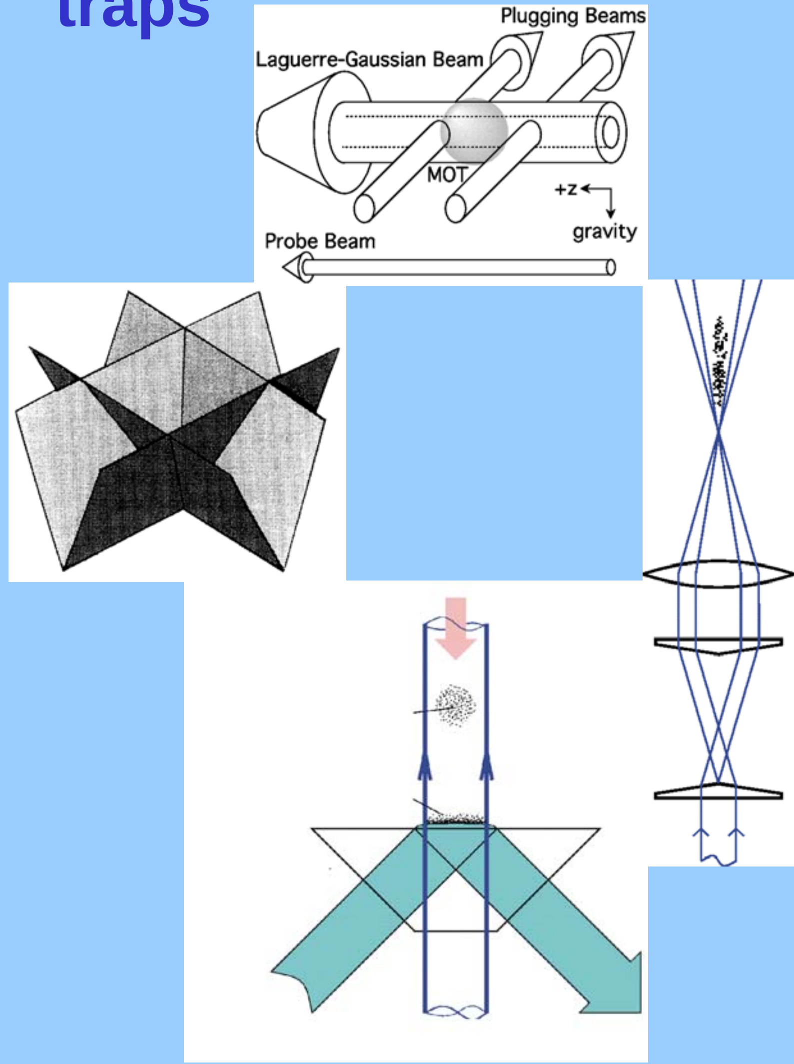
attraction

The “zoo” of dipole traps

- **Red-detuned dipole traps**

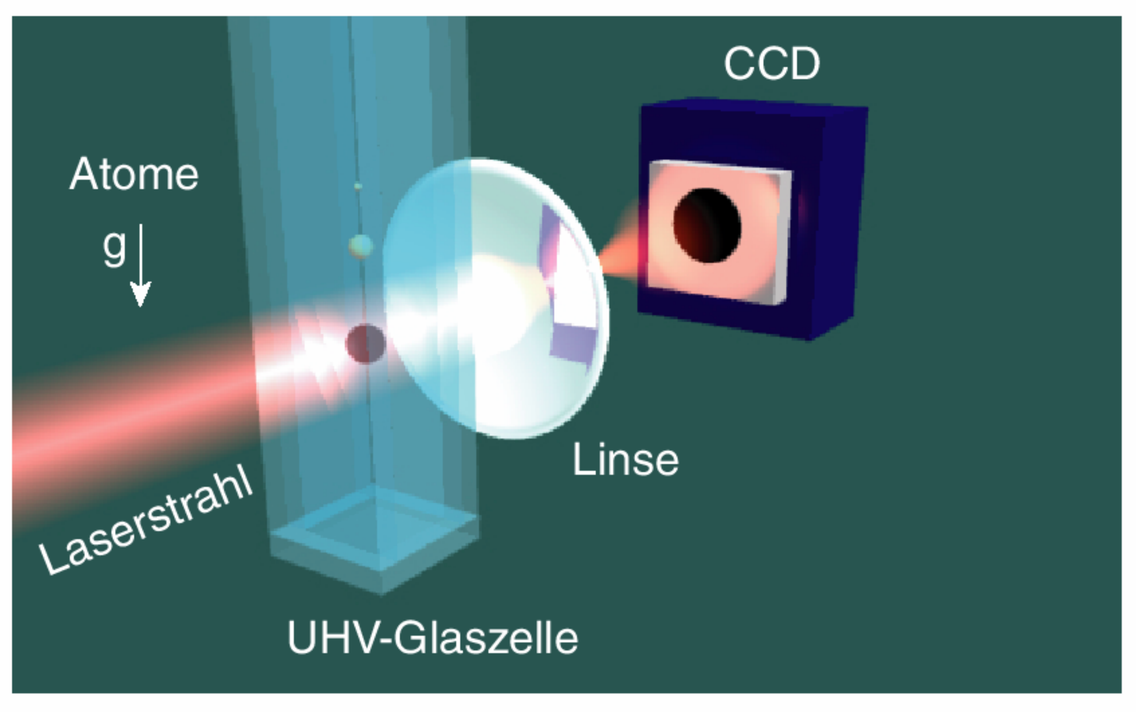


- **Blue-detuned dipole traps**

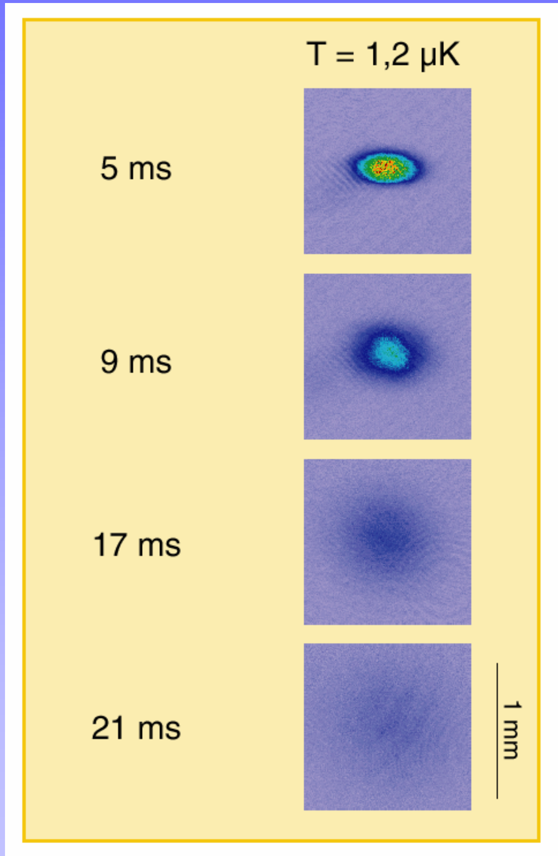


Diagnostics

Absorption imaging of the atom cloud



CCD camera pictures

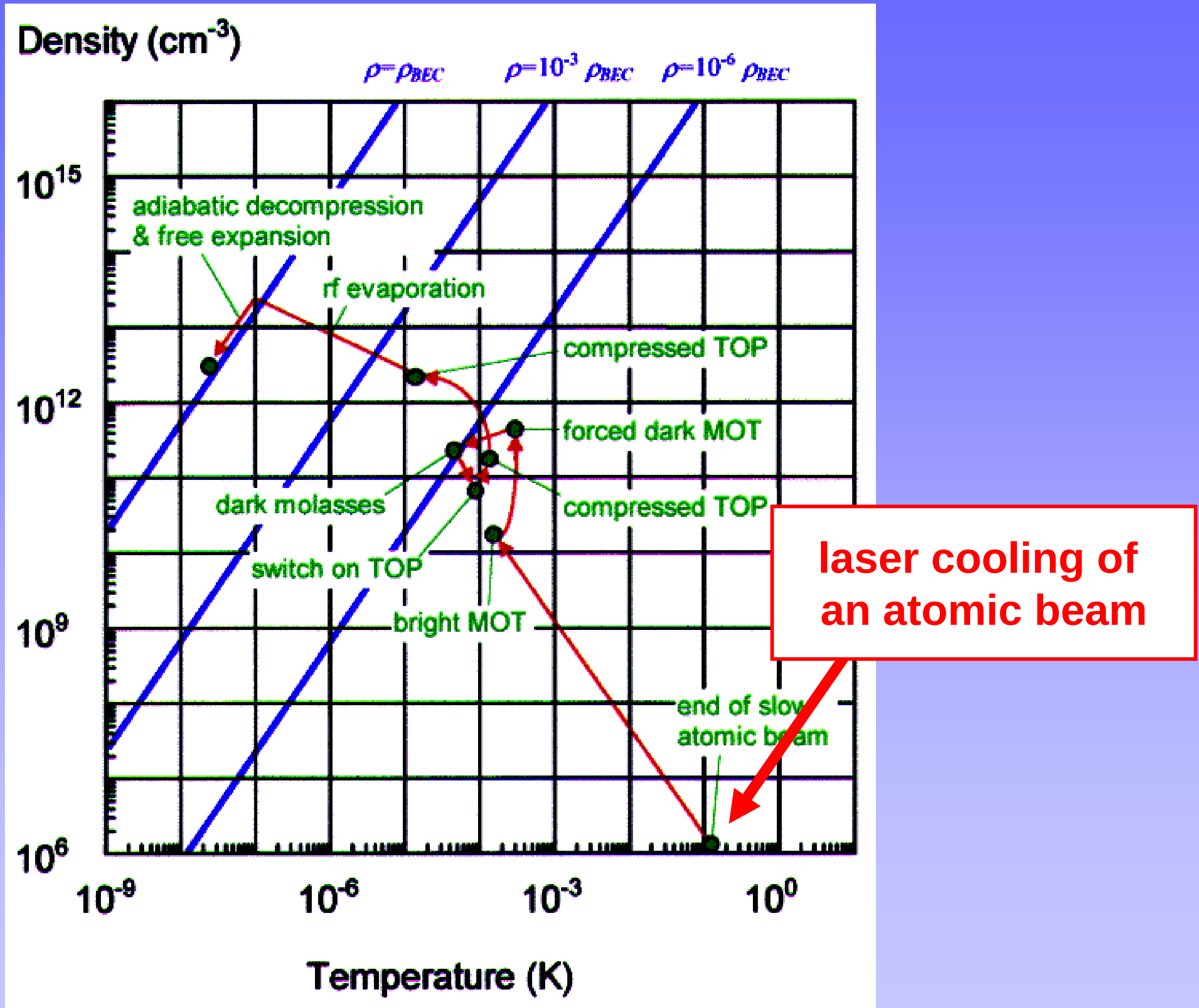


I. Bloch, T.W. Hänsch *et al.* @ Universität München

Contents of the lectures

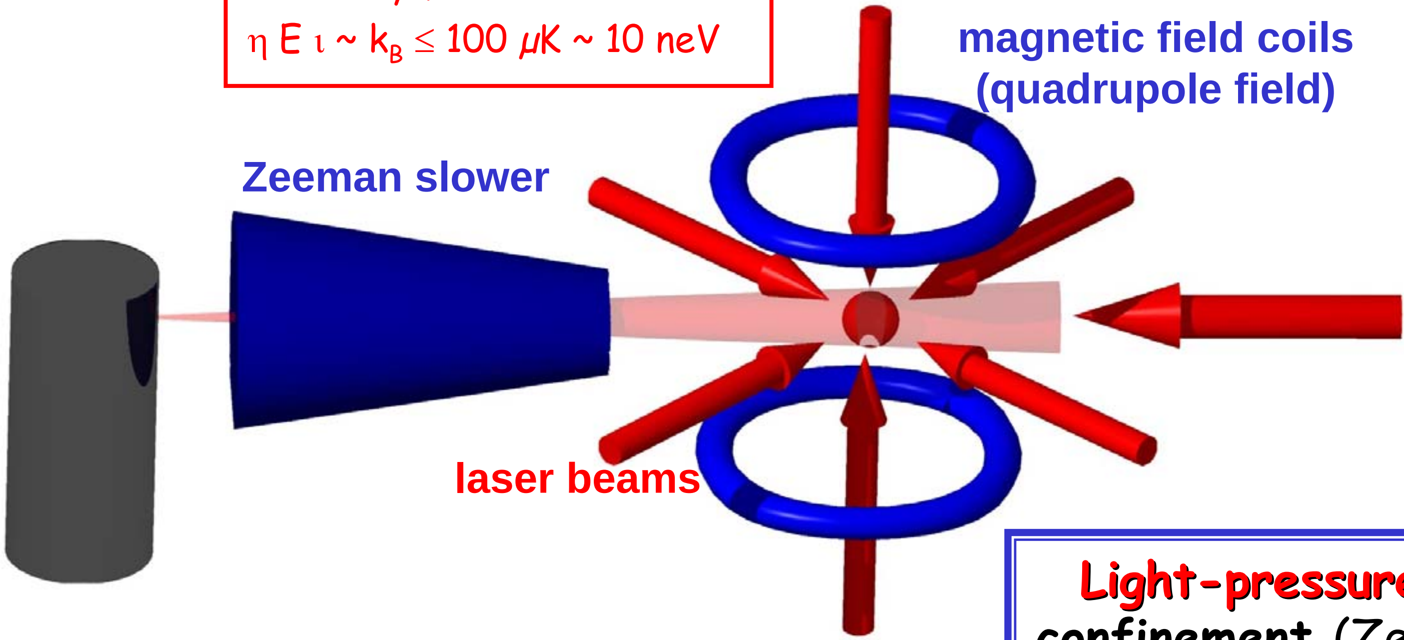
0. Primer on light-matter interactions
1. **The way to absolute zero – cooling and trapping methods for atoms** — **Lecture 1**
2. Cold collisions
3. Bose-Einstein condensation — **Lecture 2**
4. Degenerate Fermi gases
5. Cold Rydberg gases and plasmas — **Lecture 3**
6. Ultracold molecules
7. Manipulation of single atoms — **Lecture 4**
8. Cold atoms as targets for photon and particle beams

The long, long road to the Ultracold



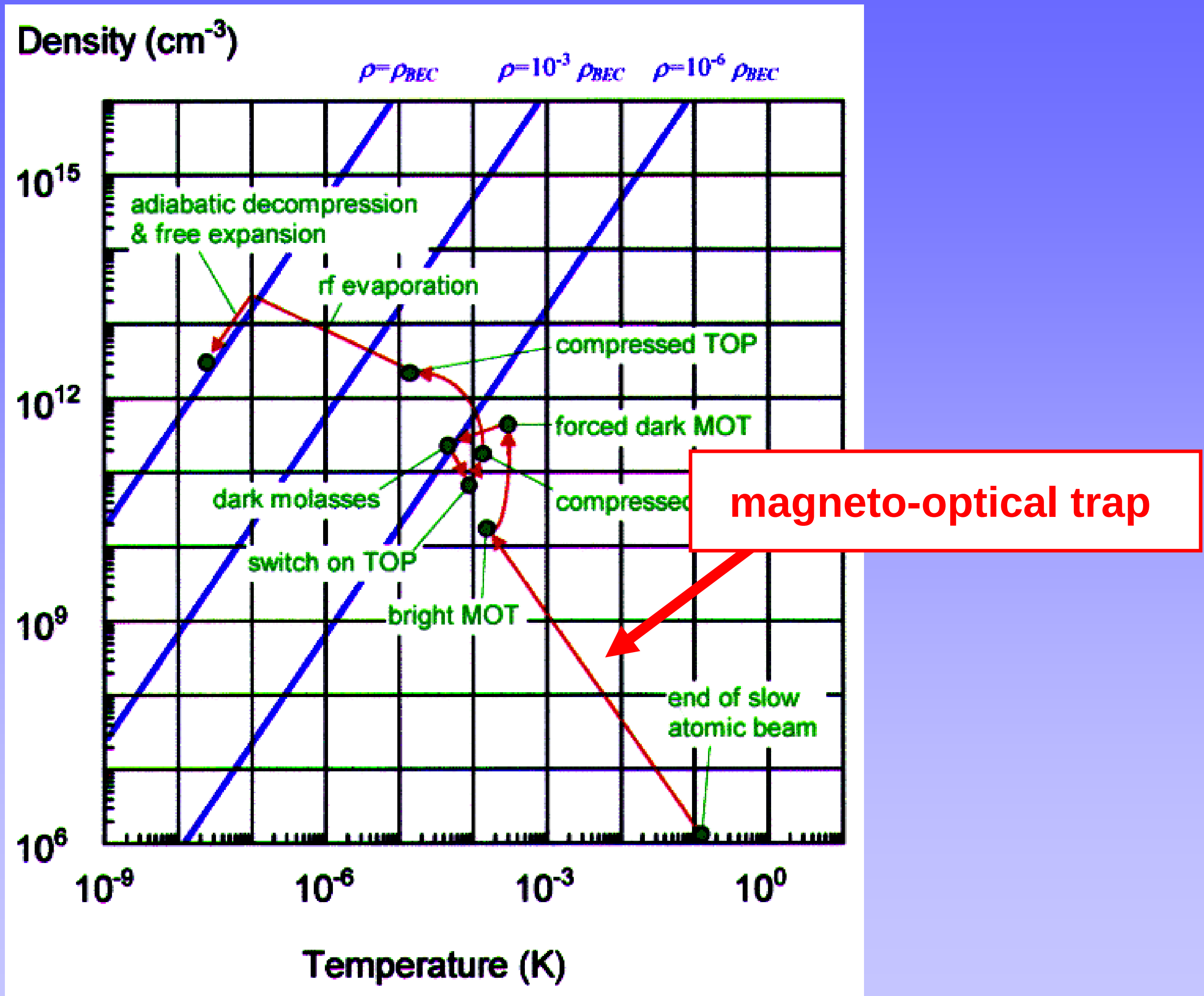
Magneto-optical trap

$10^7 \ldots 10^9$ stored atoms
10^{11} atoms / cm^3
Ø ~ 100 μm
η E ι ~ $k_B \leq 100\ \mu K \sim 10$ neV

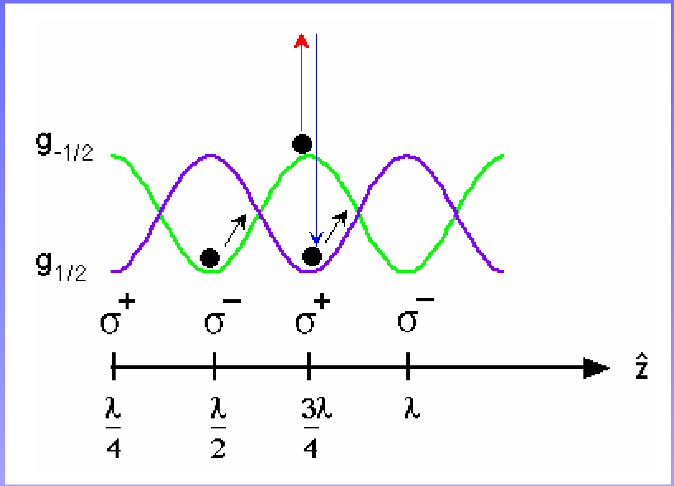


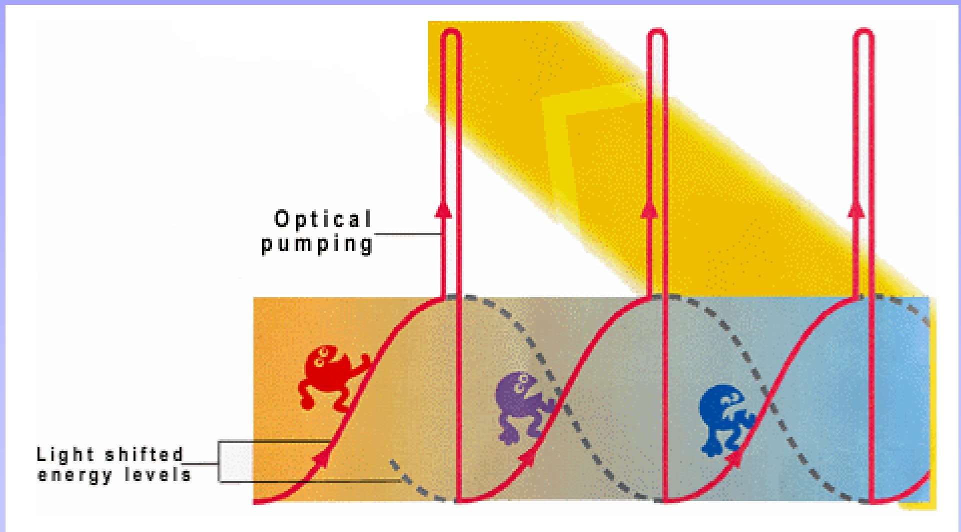
Light-pressure force for
confinement (Zeeman effect)
and
cooling (Doppler effect)

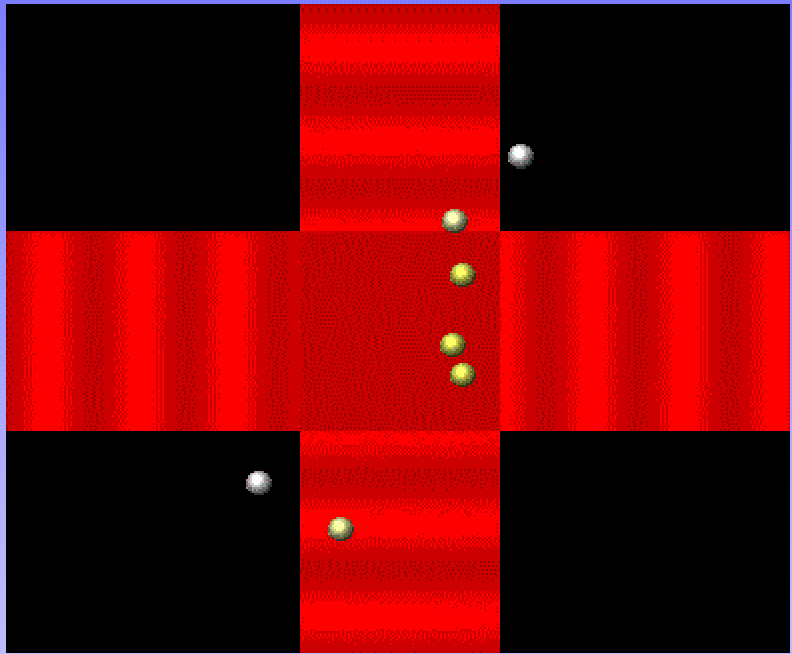
The long, long road to the Ultracold



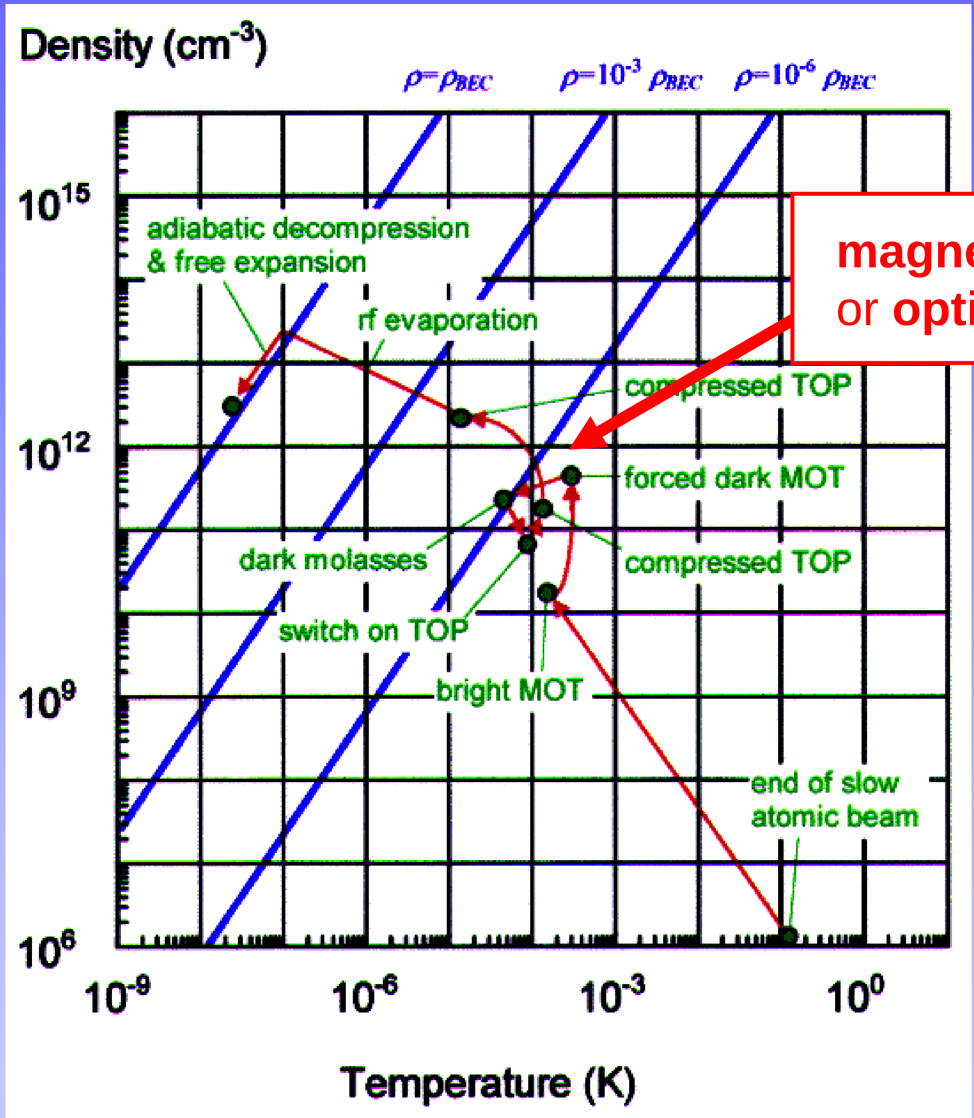
Optical molasses







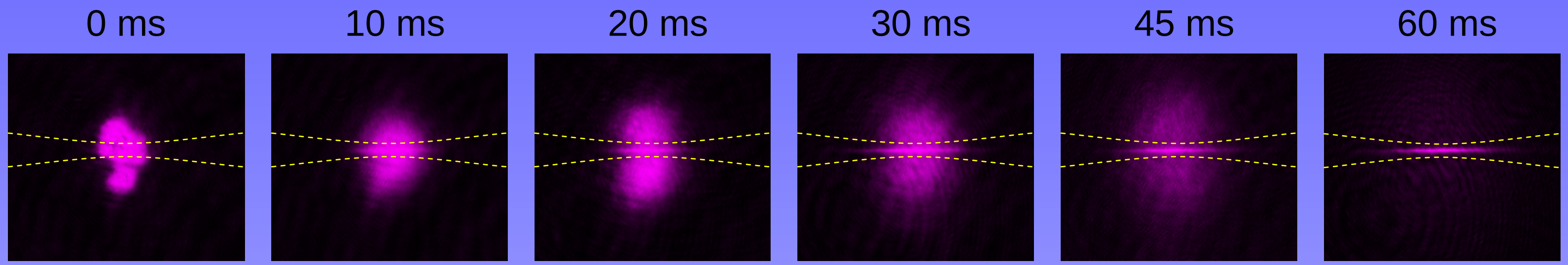
The long, long road to the Ultracold



magnetic trap or **optical trap**

Transfer into optical dipole trap

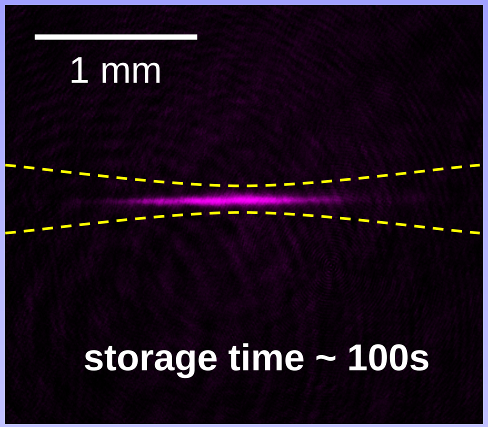
Transfer into the optical dipole trap (absorption images)



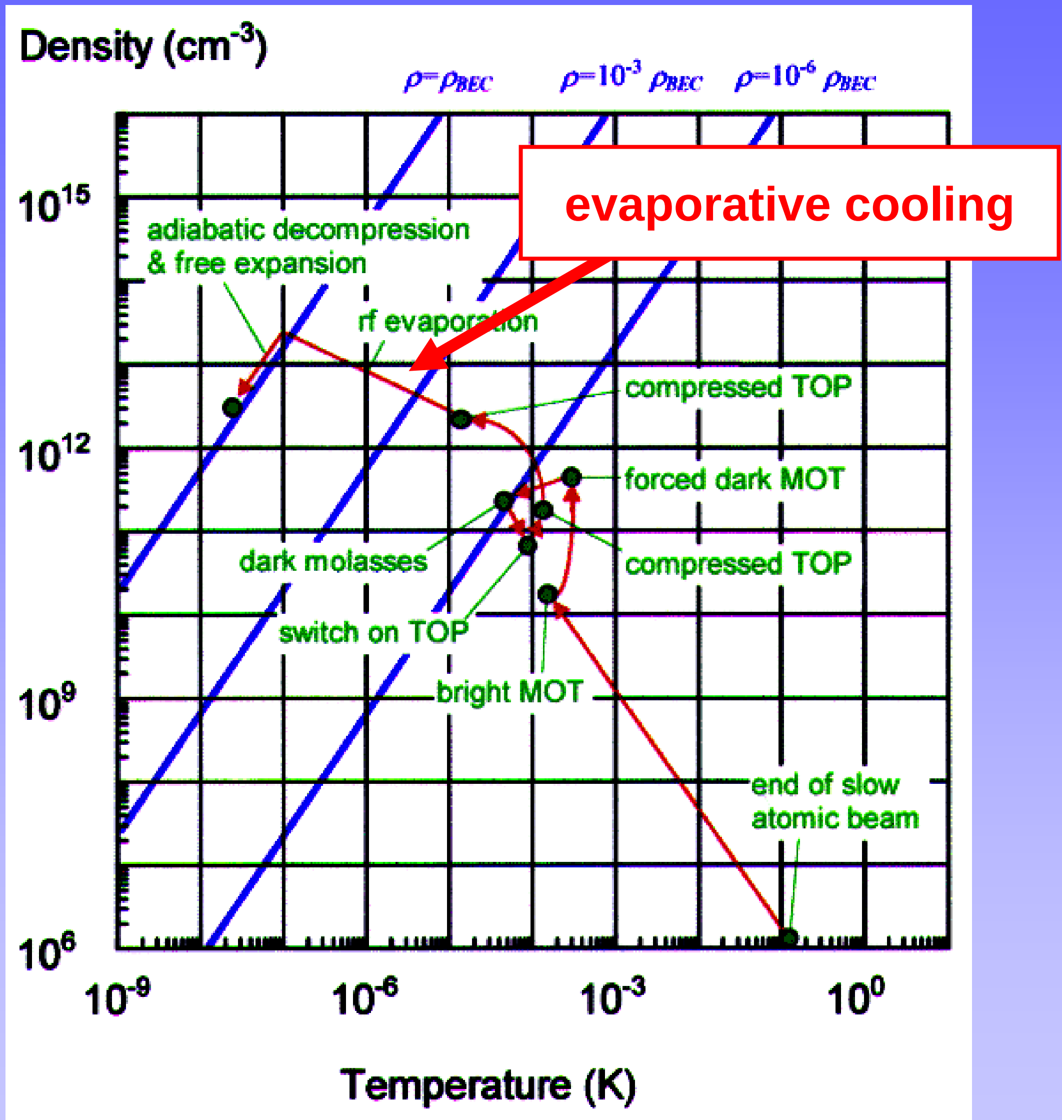
Trap parameters

	Cs	Li
trap depth	1000 μK	400 μK
eff. temperature	30 μK	~ 100 μK
# of stored atoms	~ 10^6	~ 10^5
transfer efficiency	7%	0.03%
peak density	~ 10^{12} cm^{-3}	~ 10^{10} cm^{-3}

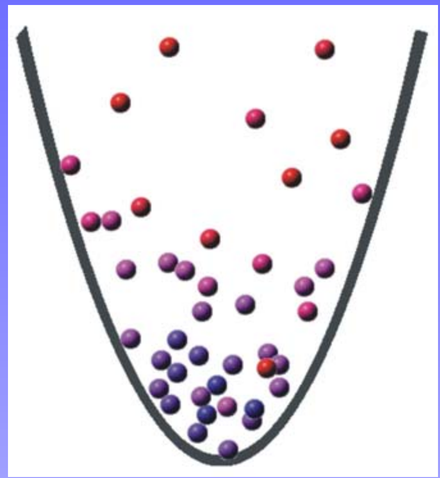
density distribution

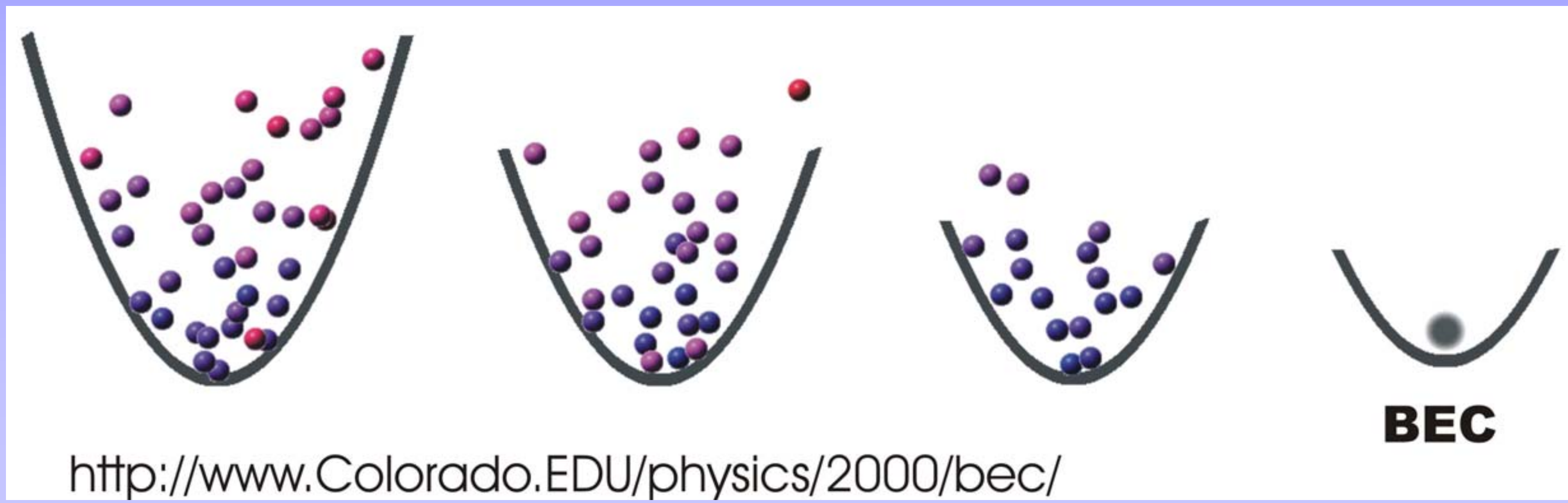


The long, long road to the Ultracold



Evaporative cooling





Contents of the lectures

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1. The way to absolute zero – cooling and trapping methods for atoms
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3. Bose-Einstein condensation
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4. Degenerate Fermi gases
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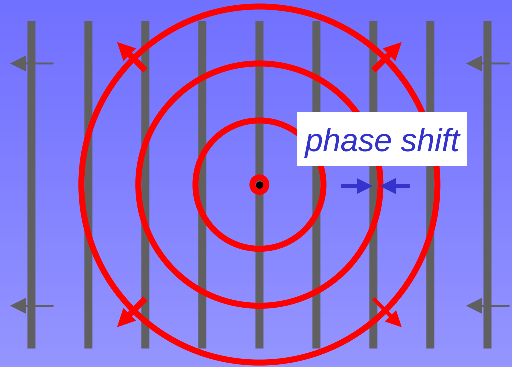
Short reminder on binary collisions

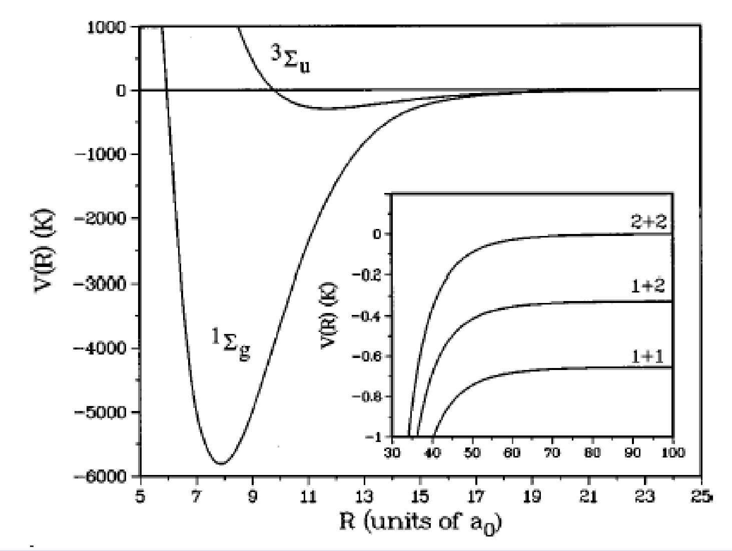
Cross section

$$\sigma(E) = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)|T_\ell(E)|^2 = \frac{4\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)\sin^2\eta_\ell$$



phase shift induced by interaction potential

Rb$_2$



Effective potential
(incl. centrifugal energy):

$$V_{\rm eff}(R) = V_g(R) + \frac{\hbar^2\ell(\ell+1)}{2\mu R^2}$$

centrifugal barrier

Cold collisions

Scaling laws

For small energies, all partial waves (except $\ell=0$) freeze out due to centrifugal barrier
$\longrightarrow$ **pure s-wave scattering**

Inelastic scattering:
(**bad** collisions)

$$\sigma_{\rm inel}(E) \propto 1/k$$

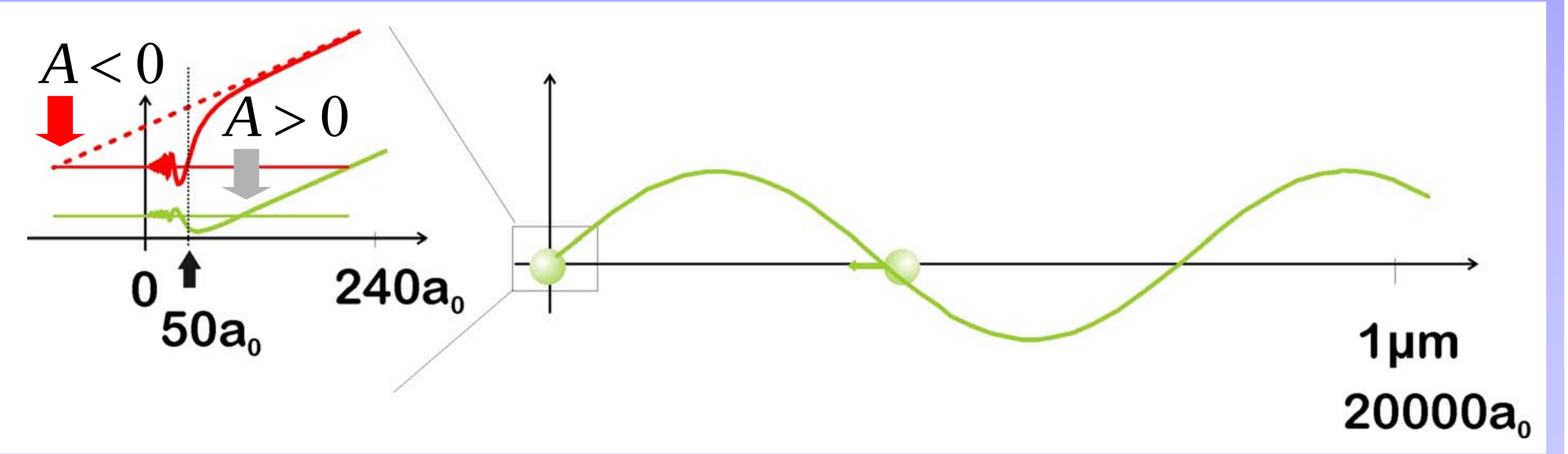
(Wigner 1/v-law)

Elastic scattering:
(**good** collisions)

$$\sigma_{\rm el}(E) \simeq 4\pi\, A^2$$

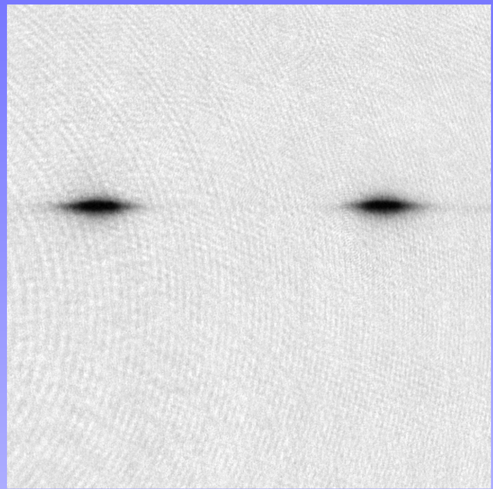
scattering length

(identical particles: $\sigma_{\rm el}(E) \simeq 8\pi\, A^2$)

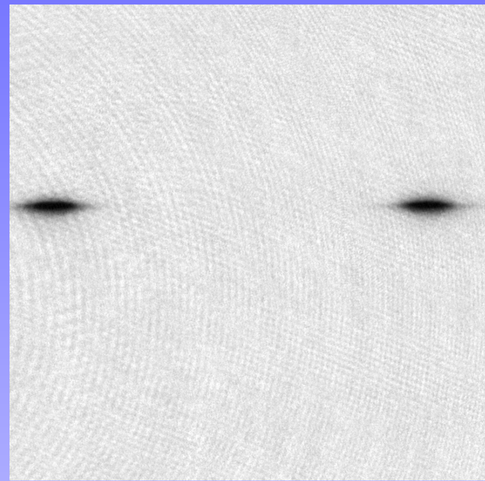


Direct imaging of elastic scattering

Collision of two ultracold clouds



E_c/k_B=138 μK



E_c/k_B=1230 μK

courtesy Jook Walraven (University of Amsterdam)

Ch. Buggle, *et al.*, Phys. Rev. Lett. **93**, 173202 (2004)
N. R. Thomas, *et* al., Phys. Rev. Lett. **93**, 173201 (2004)

Sympathetic cooling

Mean energy transfer per collision:

$$\Delta E = k_B \, \Delta T \, \frac{4 \, m_{\mathrm{Li}} \, m_{\mathrm{Cs}}}{(m_{\mathrm{Li}} + m_{\mathrm{Cs}})^2}$$

Collision rate:

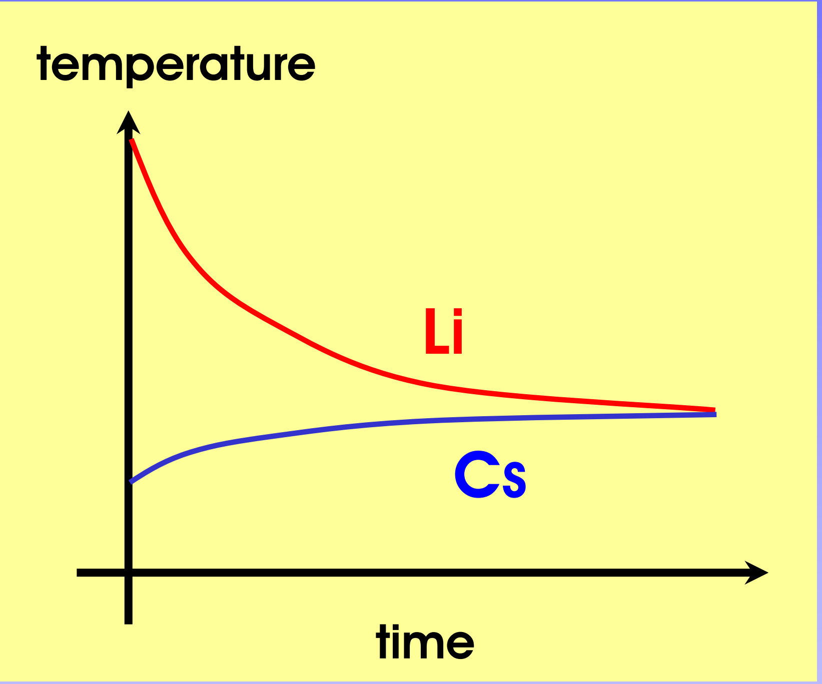
$$\Gamma_{\mathrm{coll}} = \frac{N_{\mathrm{Li}} N_{\mathrm{Cs}}}{V_{\mathrm{eff}}} \, \sigma_{\mathrm{LiCs}} \, \bar{v}$$

Thermalization rate:

$$\Gamma_{\mathrm{therm}} \simeq \Gamma_{\mathrm{coll}} \, \frac{\Delta E}{\Delta T} \, / \, C_V$$

Heat capacity in harmonic trap:

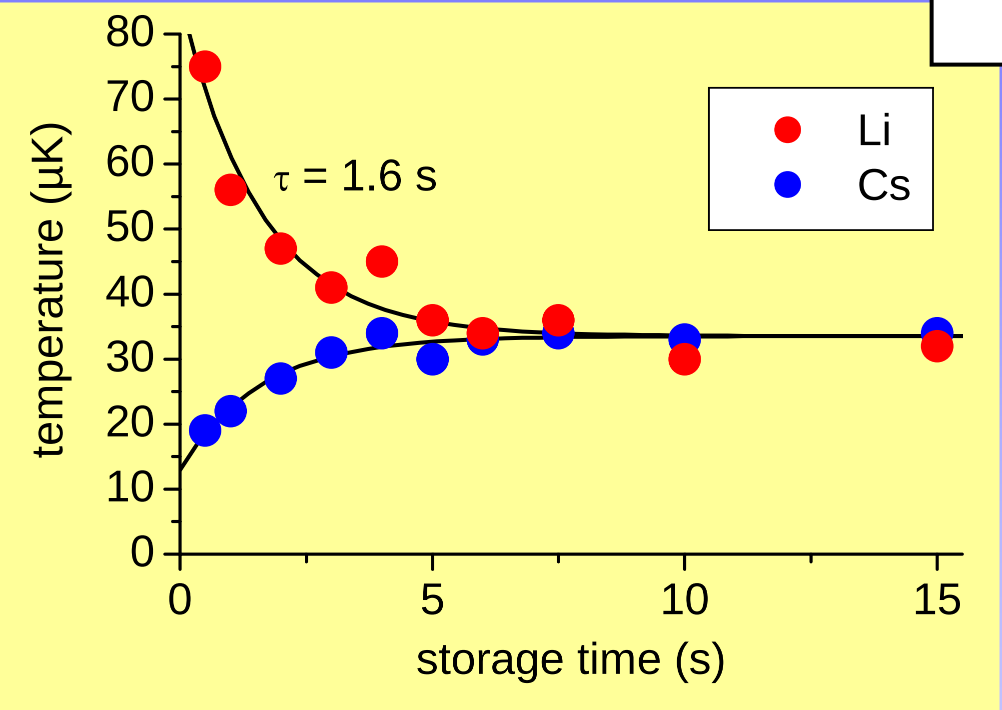
$$C_V = 3 \, N \, k_B$$



Sympathetic cooling

$$\frac{d(T_{\text{Li}} - T_{\text{Cs}})}{dt} = -\Gamma_{\text{therm}}(T_{\text{Li}} - T_{\text{Cs}})$$

$$[\,\Gamma_{\text{therm}} \propto \sigma_{\text{LiCs}}\,]$$



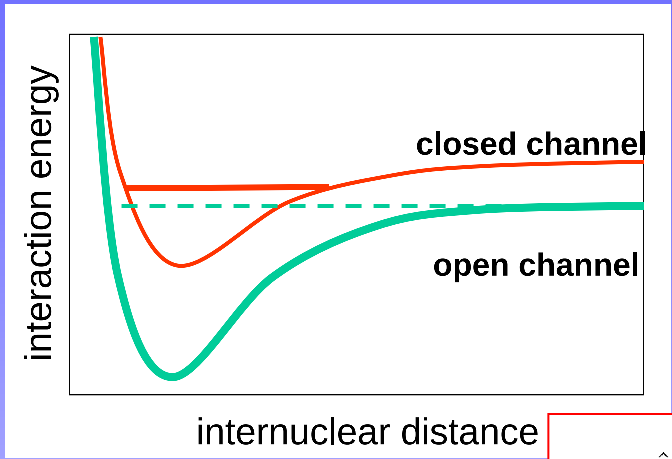
Sympathetic cooling takes place on a timescale of ~ **1 s**

large cross section σ_{LiC} ~ (300 Å)^2

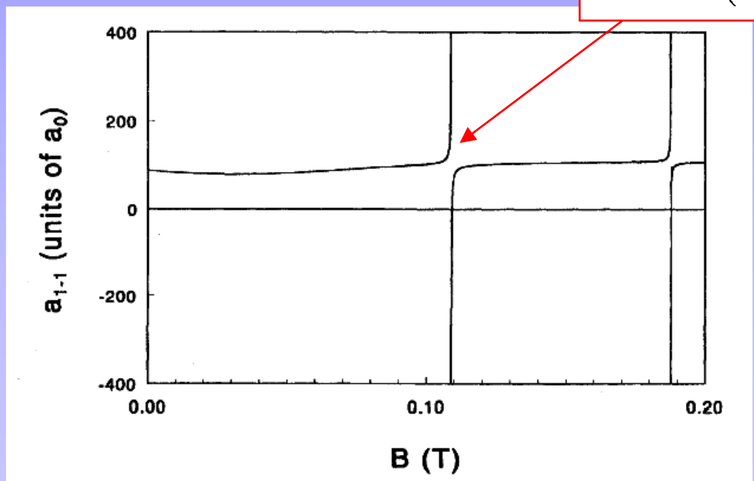
M. Mudrich *et al.*, Phys. Rev. Lett. **88**, 253001 (2002)

Controlling the scattering length

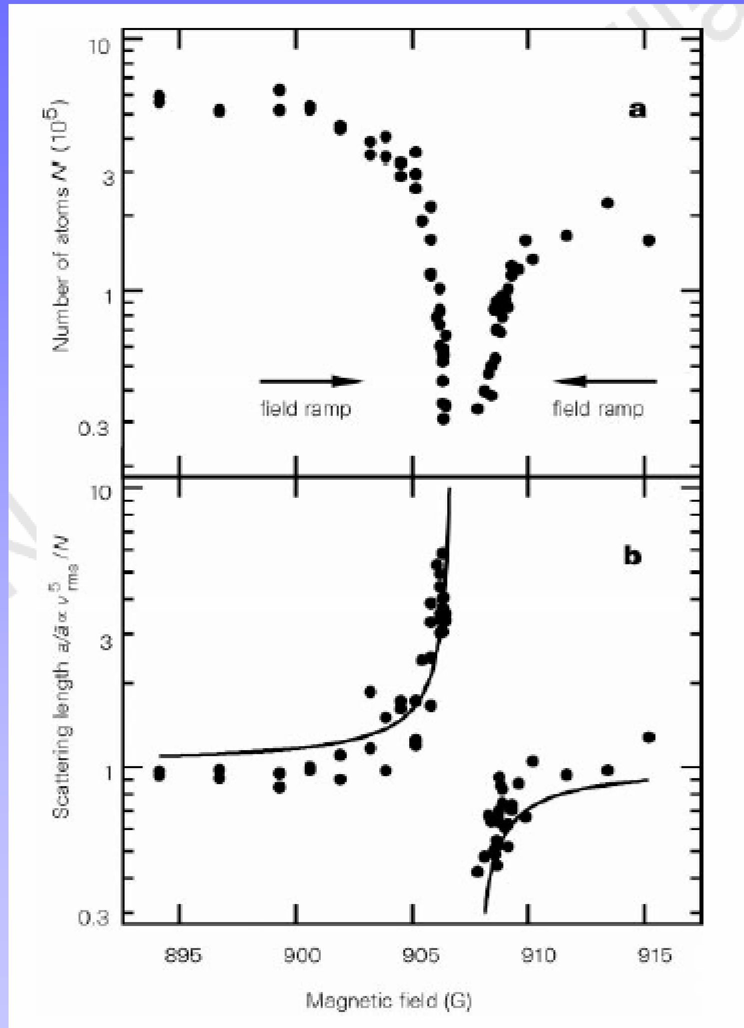
Feshbach resonance



$$A = \hat{A}\left(1 - \frac{\Delta}{B - B_0}\right)$$



A.J. Moerdijk *et al.*, Phys. Rev. A **51**, 4852 (1995)



S. Inouye *et al.*, Nature **392**, 151 (1998)

Summary of Lecture 1

- **Lorentz atom and forces on atoms**
  - force in a magnetic field
  - force in an oscillating electric field (optical dipole force)

- **Magnetic traps and optical dipole traps**
  - quadrupole, Joffe-Pritchard and chip traps
  - FORT and QUEST, blue- and red-detuned traps

- **Cooling techniques and increase of phase-space density**
  - laser cooling and optical molasses
  - evaporative cooling
  - sympathetic cooling

Summary of Lecture 1 (cont'd)

➢ Cold collisions

- pure s-wave collisions at ultralow temperatures
- inelastic collisions → trap loss and heating
- elastic collisions → thermalization and momentum exchange
- control of the elastic scattering cross section (Feshbach resonance)

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Lecture 1

Lecture 2

Lecture 3

Lecture 4