Taming the dragon Chromium

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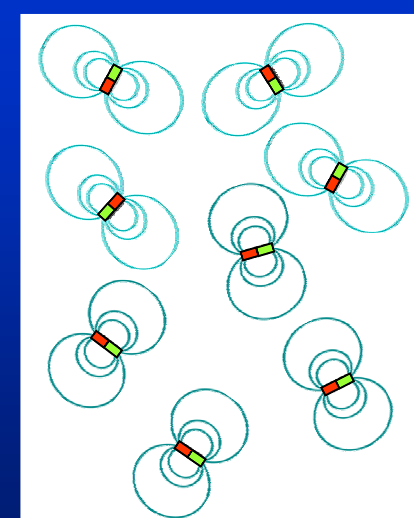
12.10.04 @ MPIPKS

5. Physikalisches Institut

STUTTGART

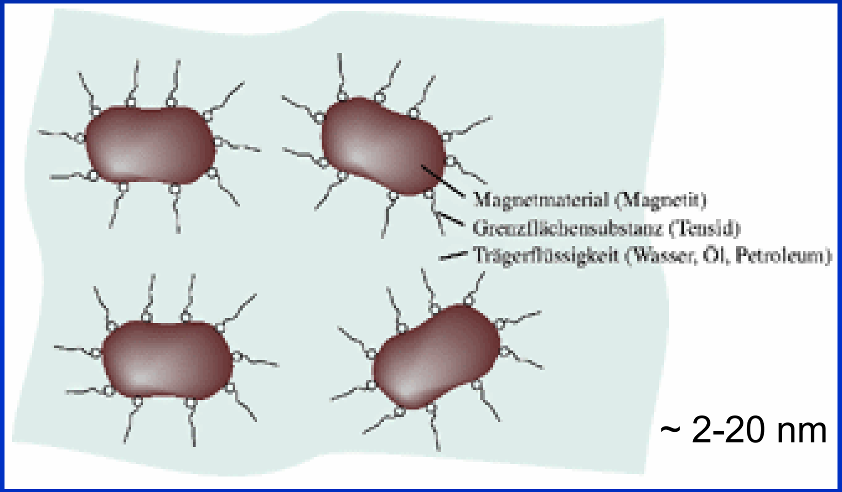

•READ•SAVE•COLLECT•# 10634 OF 20,000
THE CHROMIUM MAN
$2.50 USA
0
Science Fiction
Action Adventure
SUPER
MAX

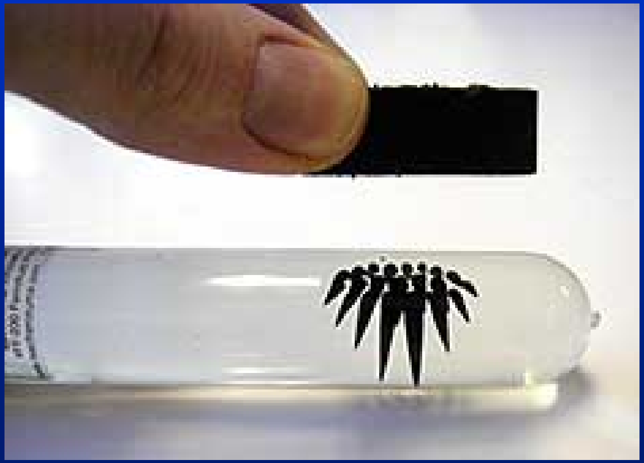
Why bother?



Dipolar coupling in fluids

Ferrofluids





Application:
rotary seals in disk drives
dampers for audio speakers

Dipolar coupling in gases?

$$k_B T_c \approx V_{DD} \sim \frac{1}{r^3} \sim n$$

solid	$n \sim 10^{23}/cm^3$	$T_c \sim 1K$ ($T^{ex}_c \sim 100\text{-}1000K$)	
air	$n \sim 10^{19}/cm^3$	$T_c \sim 0.1$ mK	
ultracold gas	$n \sim 10^{14}/cm^3$	$T_c \sim 1$ nK	

Weak interaction:

$$n \ll \left(\frac{12\pi\hbar^2}{\mu_0 \mu^2 M} \right)^3$$

magnetic dipoles
$n \ll 10^{21}/cm^3$

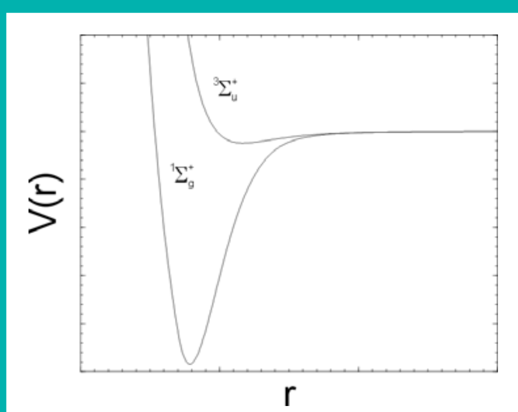
electric dipoles
$n \ll 10^{9}/cm^3$

Contact and Long Range Interaction

Contact interaction

$$U_{\text{eff}}(r) = \frac{4\pi\hbar^2 a}{m}\delta(r)$$

- isotropic
- short range

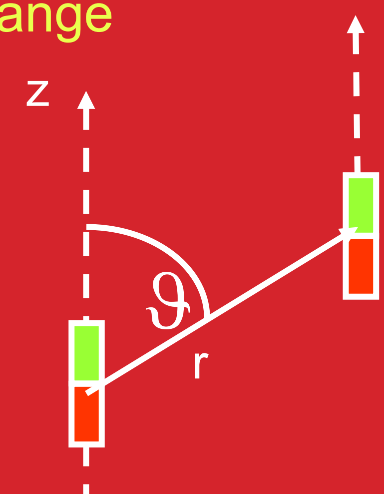


nonlinear matter wave optics
strong correlations: Bose Hubbard...

Dipolar interaction

$$U_{dd}(\vartheta, r) = -\frac{\mu_0\mu^2}{4\pi}\frac{(3\cos^2\vartheta - 1)}{r^3}$$

- anisotropic
- long range



stability and ground state of BEC
magnetism: Heisenberg, Ising, frustrated lattices...

How strong is the dipolar interaction?

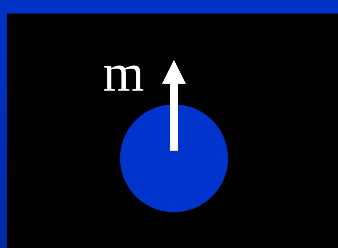
dipole strength (tunable)

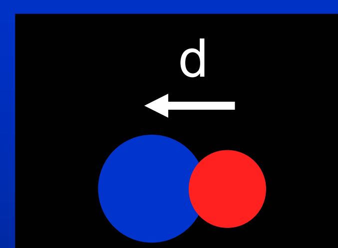
compare to
contact interaction:

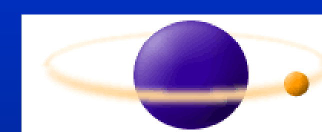
$$\varepsilon_{dd} = \frac{\mu_0 \mu^2 M}{12\pi\hbar^2 a}$$

scattering length (tunable)

atoms | heteronuclear molecules | Rydberg atoms







Cr ε_{dd}=0.1..0.3
Rb ε_{dd}=0.007
Na ε_{dd}=0.003

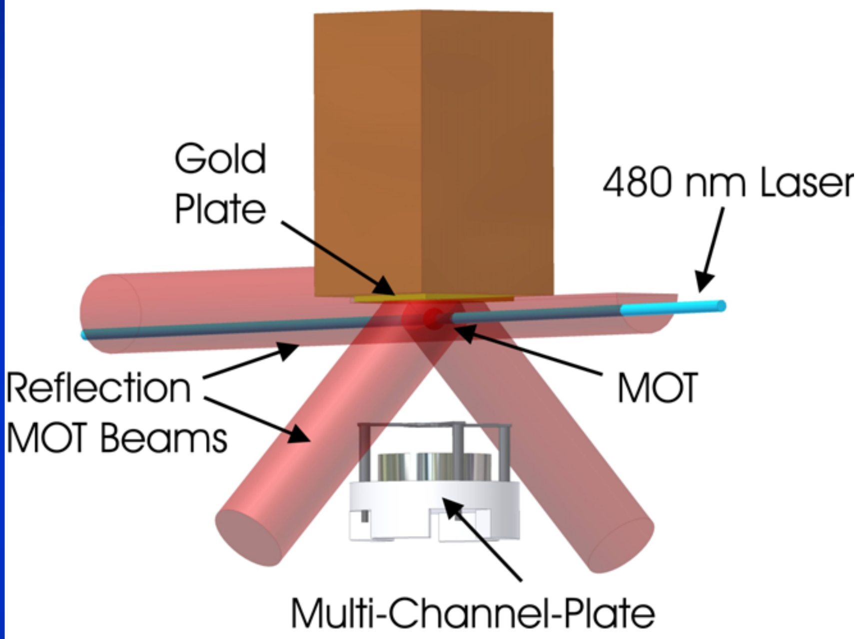
magnetic dipoles

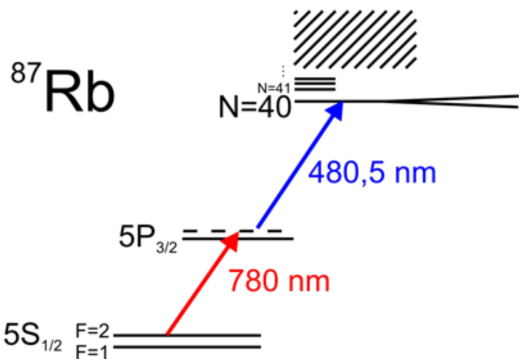
e.g.: CaH, NH_3, CrRb
$\varepsilon_{dd}\sim100$

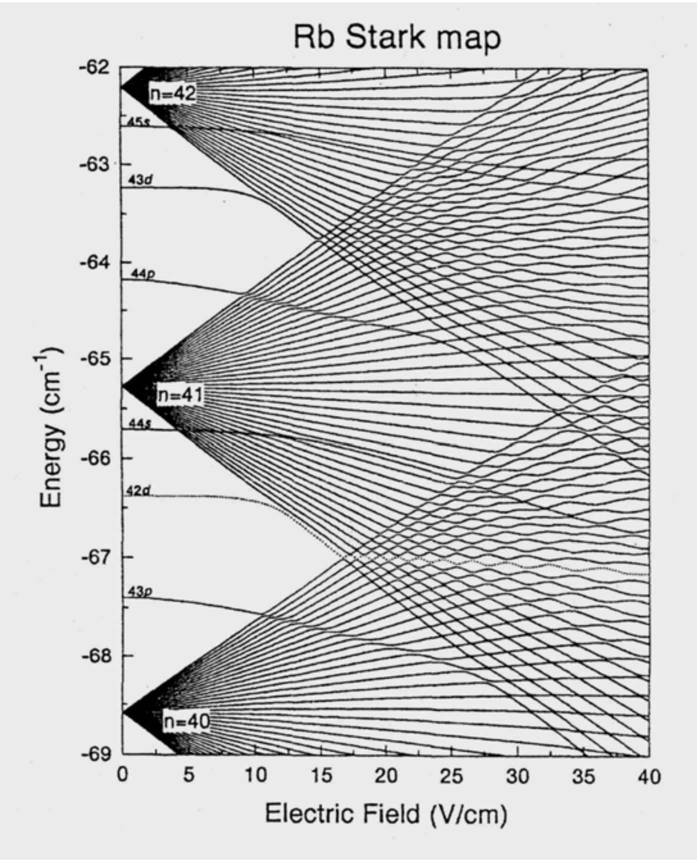
e.g.: Rb (n=40)
$\varepsilon_{dd}\sim10^8$

electric dipoles

Rydberg Excitation of Rubidium Atoms

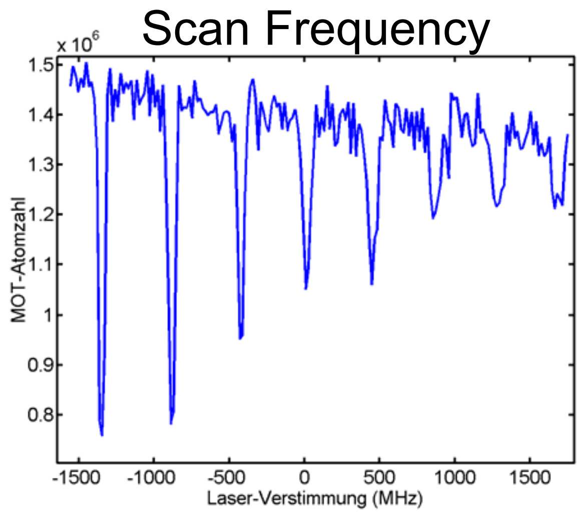


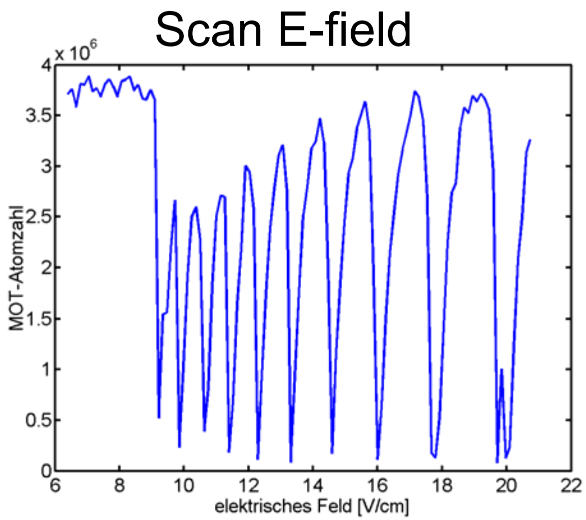


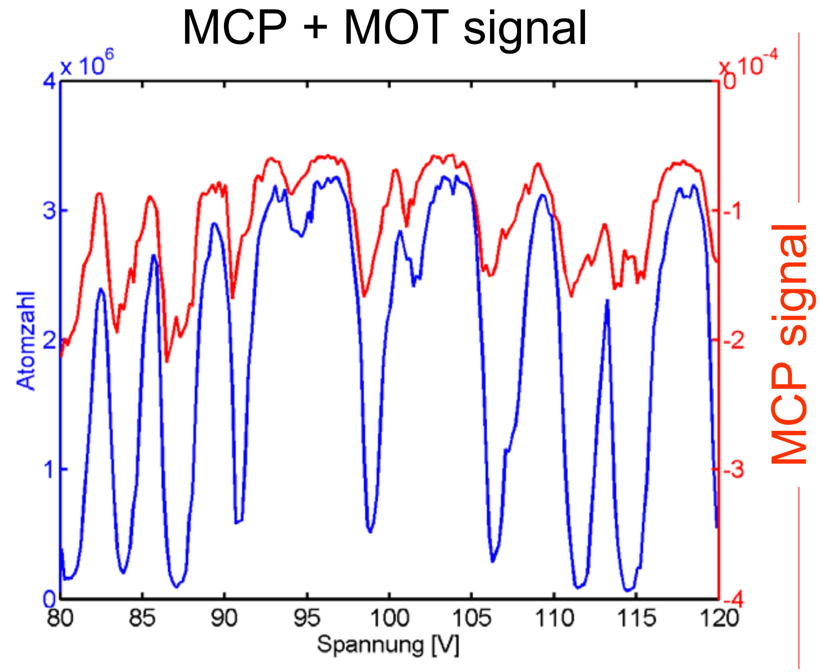


Rydberg excitation of cold atoms

MOT fluorescence

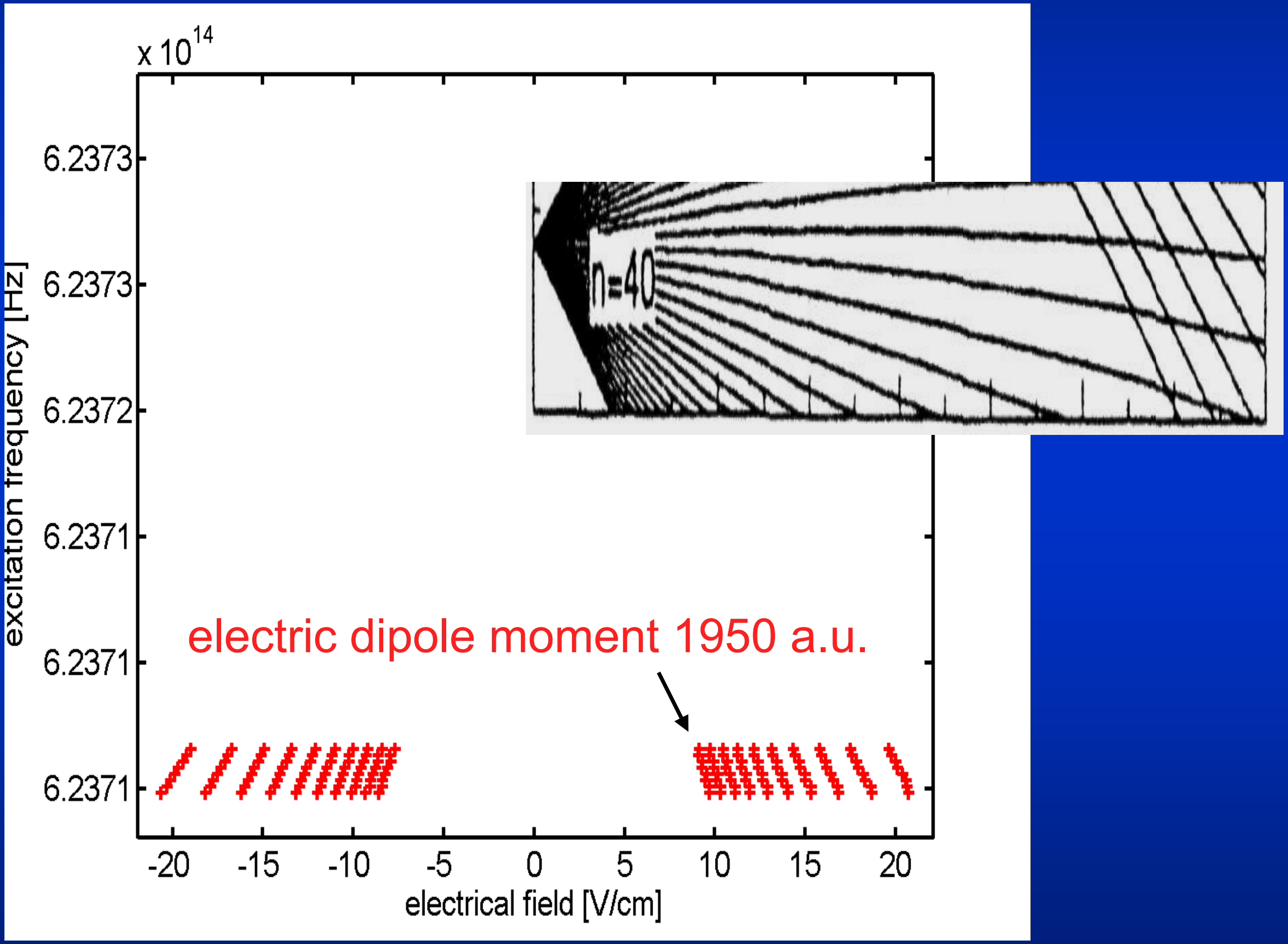






Results: Stark maps

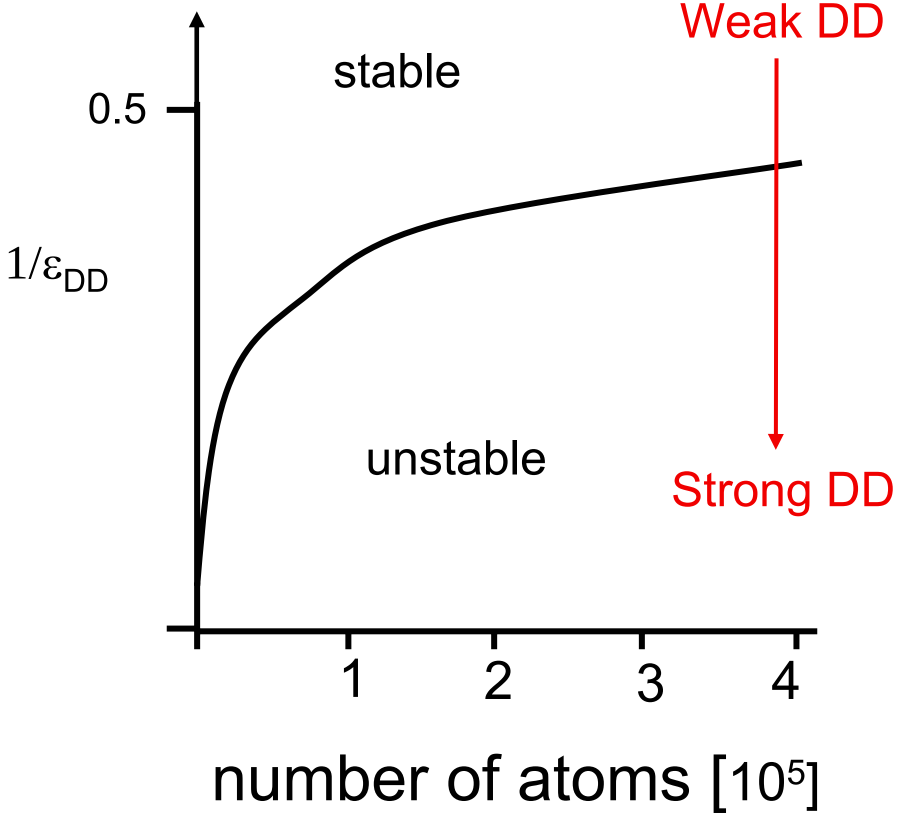
E-field Scan

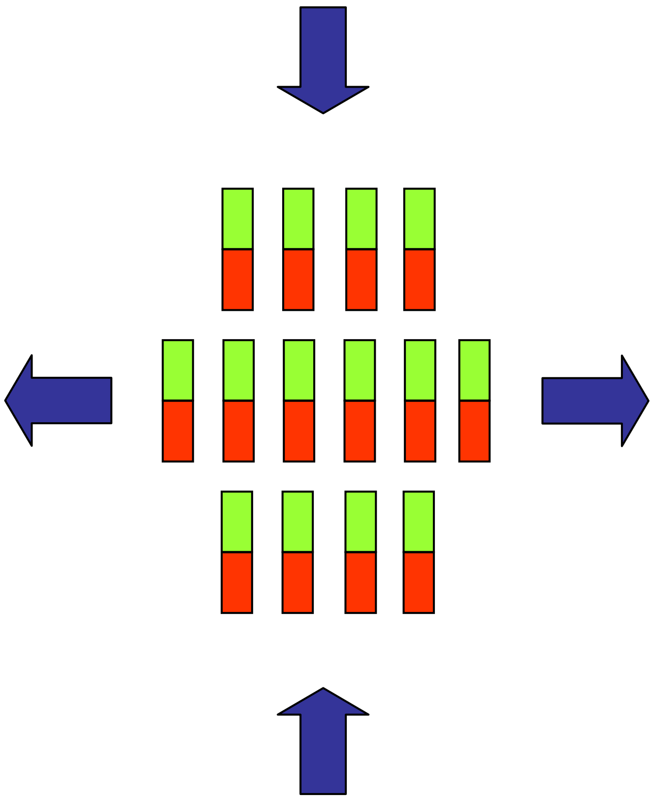


A. Grabowski
R. Heidemann
J. Bauer
J. Stuhler

Stability of dipolar condensates

Here: Cr atoms; $\omega_0 = 2\pi$ 150 Hz





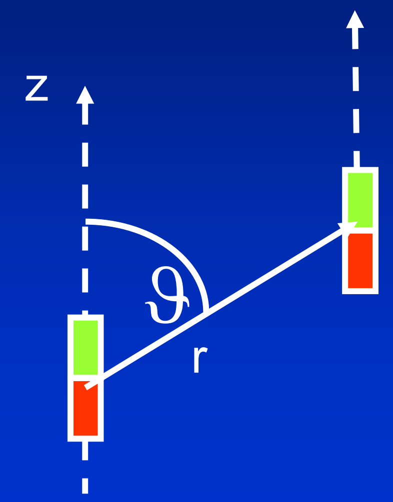
K. Góral, K. Rzazewski, T.P.;
Phys. Rev. A, **61**, 051601 (R) (2000)

Stabilization?

polarized sample

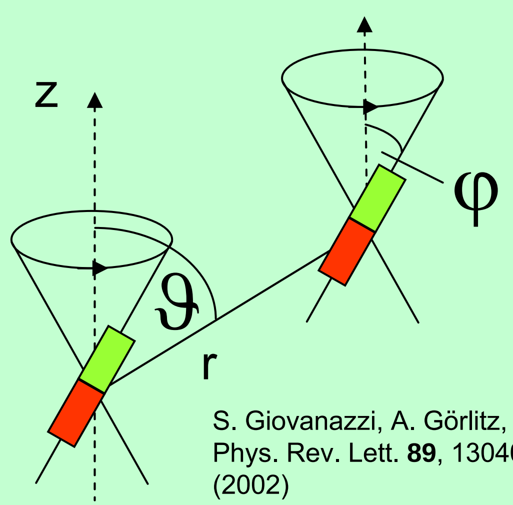
$$V_{dd}(r) \propto \frac{m^2}{r^3}(1-3\cos^2\vartheta)$$

anisotropic



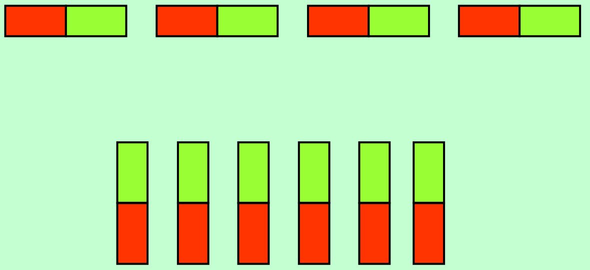
tunable interaction

spinning polarization



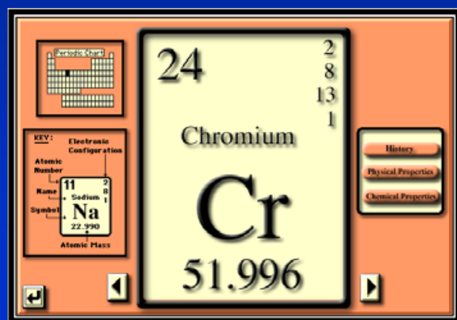
S. Giovanazzi, A. Görlitz, T.P.
Phys. Rev. Lett. **89**, 130401 (2002)

trap shape



K. Góral, K. Rzazewski, T.P.;
PRA**, 61**, 051601 (R) (2000)
L. Santos, et al.; PRL **85**, 1791(2000)

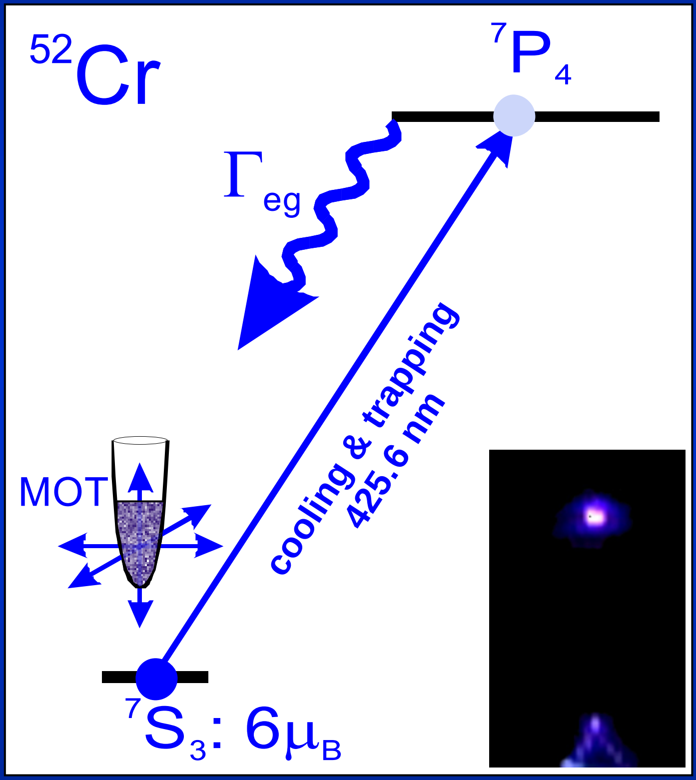
How to tame Chromium

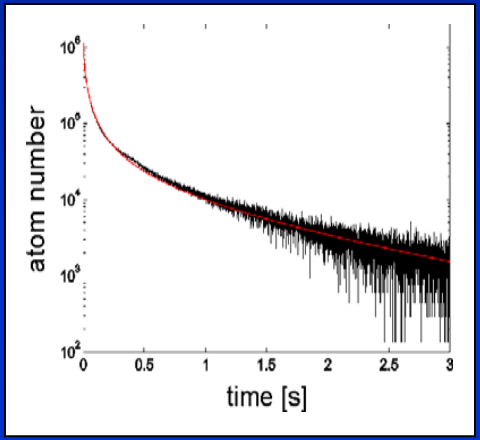


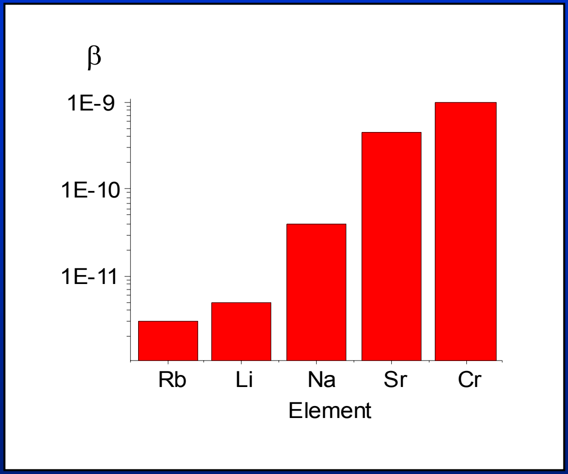
4 stable isotopes:

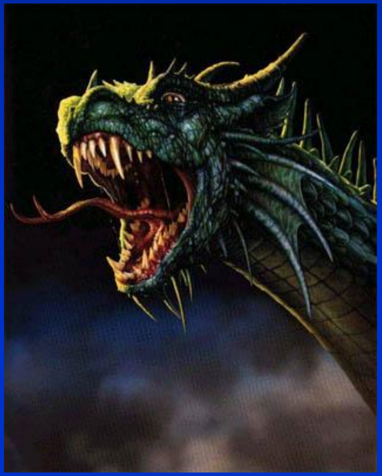
	Bosons		Fermion
^{52}Cr	^{50}Cr	^{54}Cr	^{53}Cr
83.8%	4.3%	2.4%	9.5%

Magneto-optical Trap







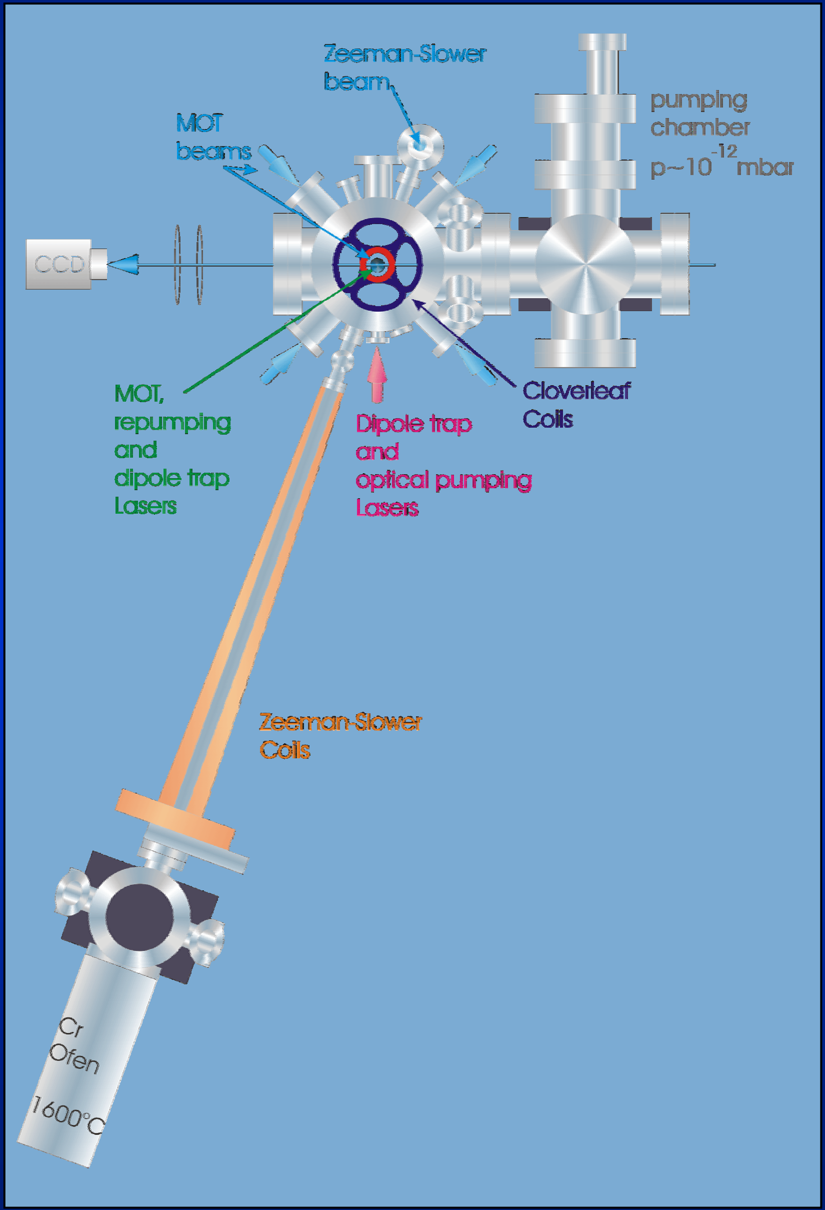


N ~ 10^6 atoms

T=70 μK

A. S. Bell, J. Stuhler, S.Locher, S. Hensler, J. Mlynek, T. Pfau, *Europhys. Lett.* **45**, 156 (1999)

Preparation of an ultracold Cr sample:



• Continously loaded Ioffe Pritchard trap (CLIP-trap)

J. Stuhler, et al., Phys. Rev. A **64**, 031405 (2001)

P. O. Schmidt, et al., J. *Opt. B* ***5**, S170 (2003)*

• Compress IP-trap

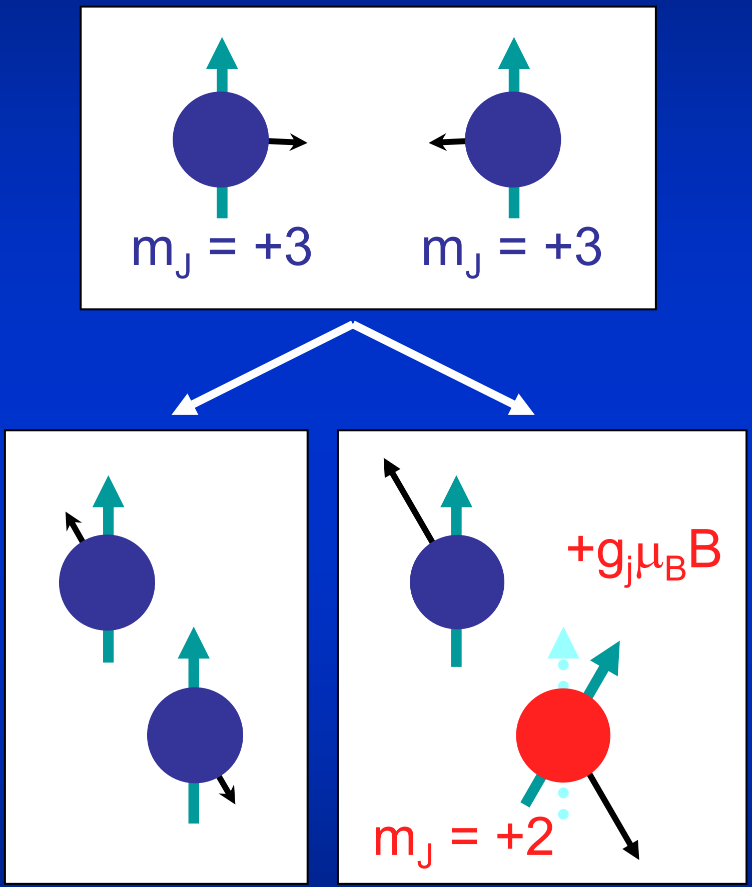
• Doppler cooling in the IP-trap at high offset field

P. O. Schmidt, et al., J. *Opt. Soc. Am. B* ***20**, 5 (2003)*

2×10^8 atoms in the ground state
phase space density $\rho \sim 10^{-7}$

• Temperature is adjusted by evaporation

Collisions



Short range

P. O. Schmidt, S. Hensler,
J. Werner, A. G[...]maier,
A. Görlitz, T[...]
and A. S[...]
PRL

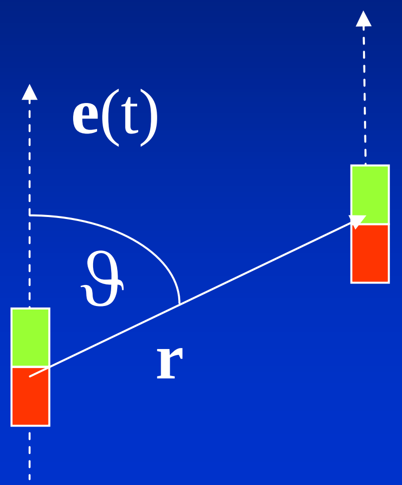
New:
14 Feshbach
resonances
observed

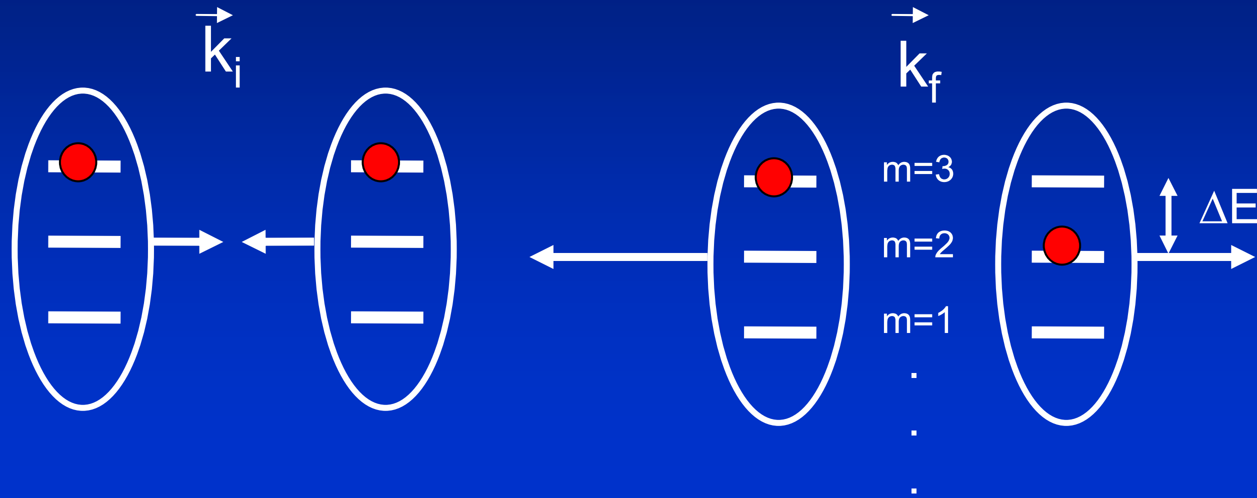
elastic
Collision
GOOD

dipolar
Relaxation
BAD

Long range

Dipole-dipole scattering in magnetic fields





no spin flip (elastic):

$$\sigma_0 = \tfrac{16\pi}{45} S^4 \left(\frac{\mu_0 (g_S \mu_B)^2 m}{4\pi\hbar^2} \right)^2 \left(1 + h(1)\right)$$

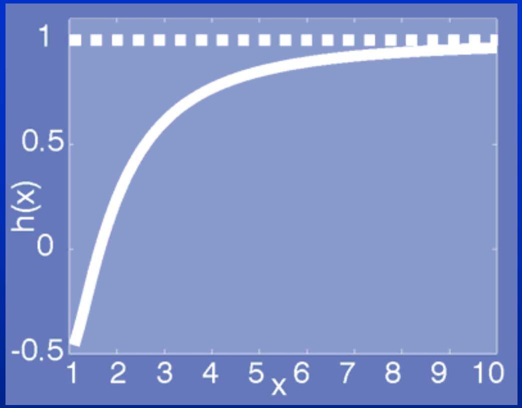
Cr: S=3

single spin flip:

$$\sigma_1 = \tfrac{8\pi}{15} S^3 \left(\frac{\mu_0 (g_S \mu_B)^2 m}{4\pi\hbar^2} \right)^2 \left(1 + h\left(k_f/k_i\right)\right) k_f/k_i$$

double spin flip:

$$\sigma_2 = \tfrac{8\pi}{15} S^2 \left(\frac{\mu_0 (g_S \mu_B)^2 m}{4\pi\hbar^2} \right)^2 \left(1 + h\left(k_f/k_i\right)\right) k_f/k_i$$

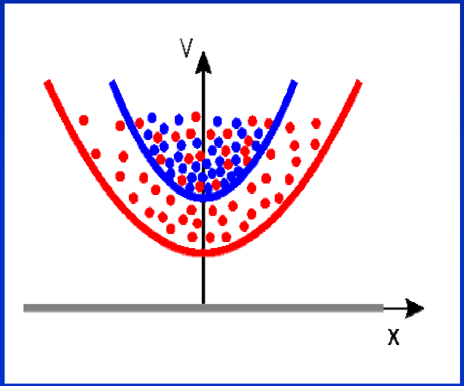


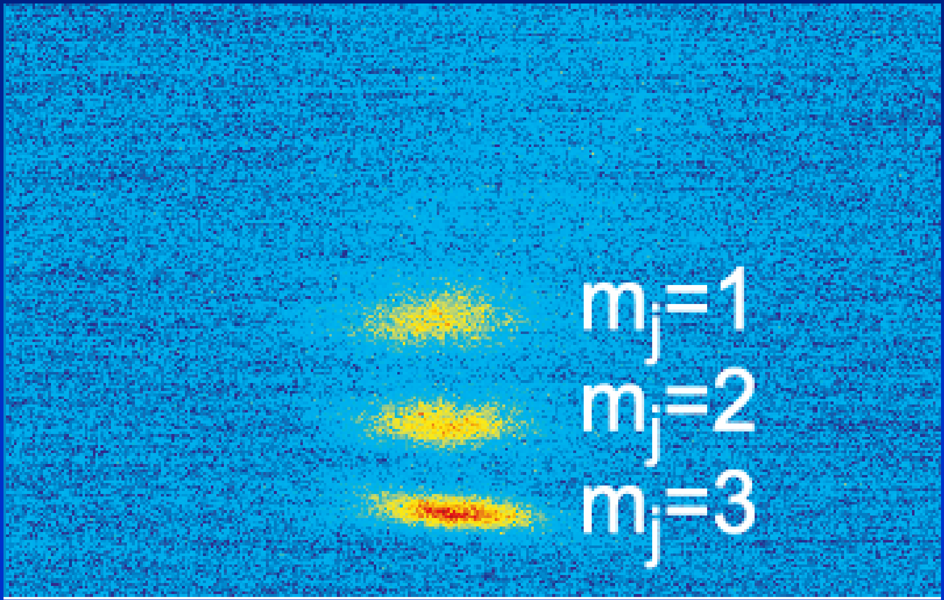
Calculation by Stefano Giovanazzi: Appl. Phys. **B 77**, 765-772 Hensler et al. (2003)

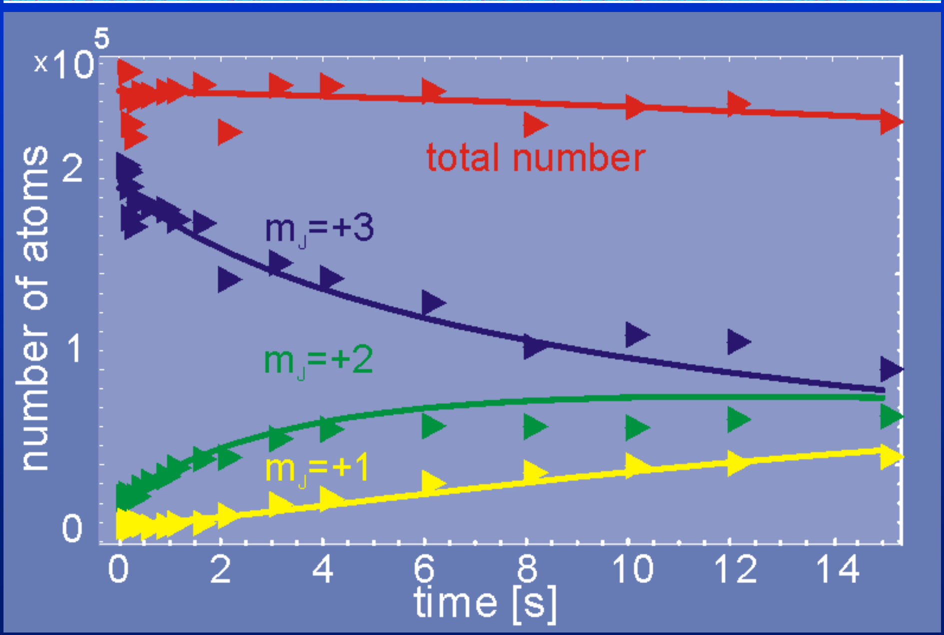
Measuring the cross sections

Experiment 1:

Stern-Gerlach experiment:





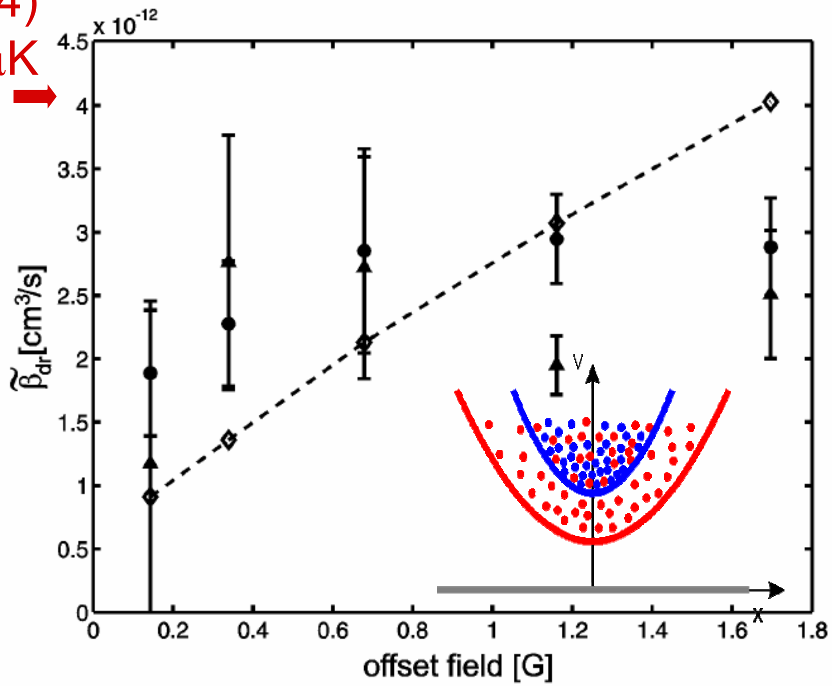


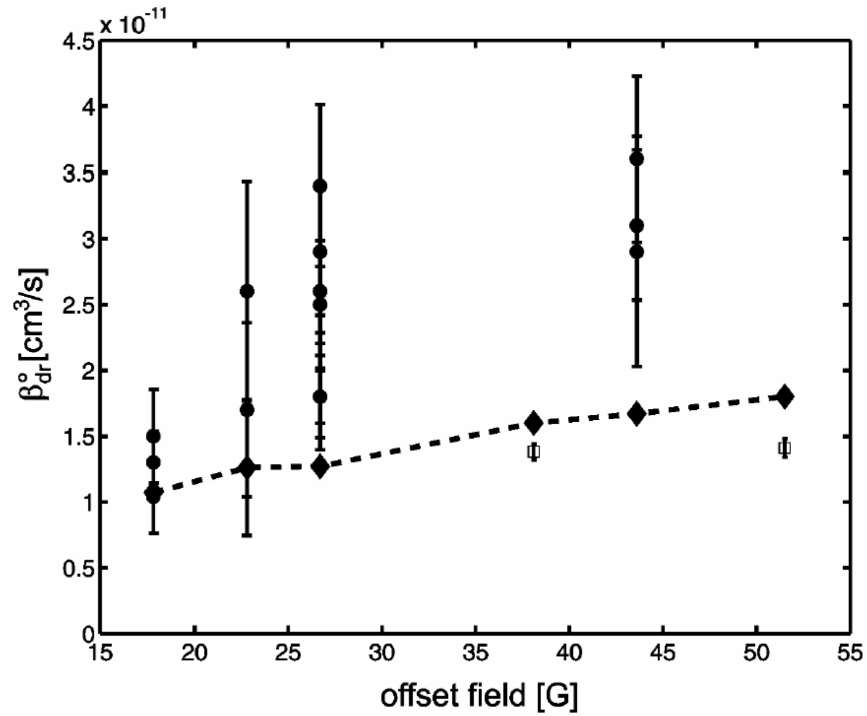
• Very good agreement between theory and experiment

Dipolar relaxation: theory vs exp.

$$\sigma_{inel} = \frac{k_{final}}{k_{initial}} \sigma_0 \sim \mu^3 \sqrt{\tilde{c} \cdot B_0/T + 1}, \quad \mu(\text{Cr}) = 6\mu_B$$

Cs(F=4)
@ 8 μK

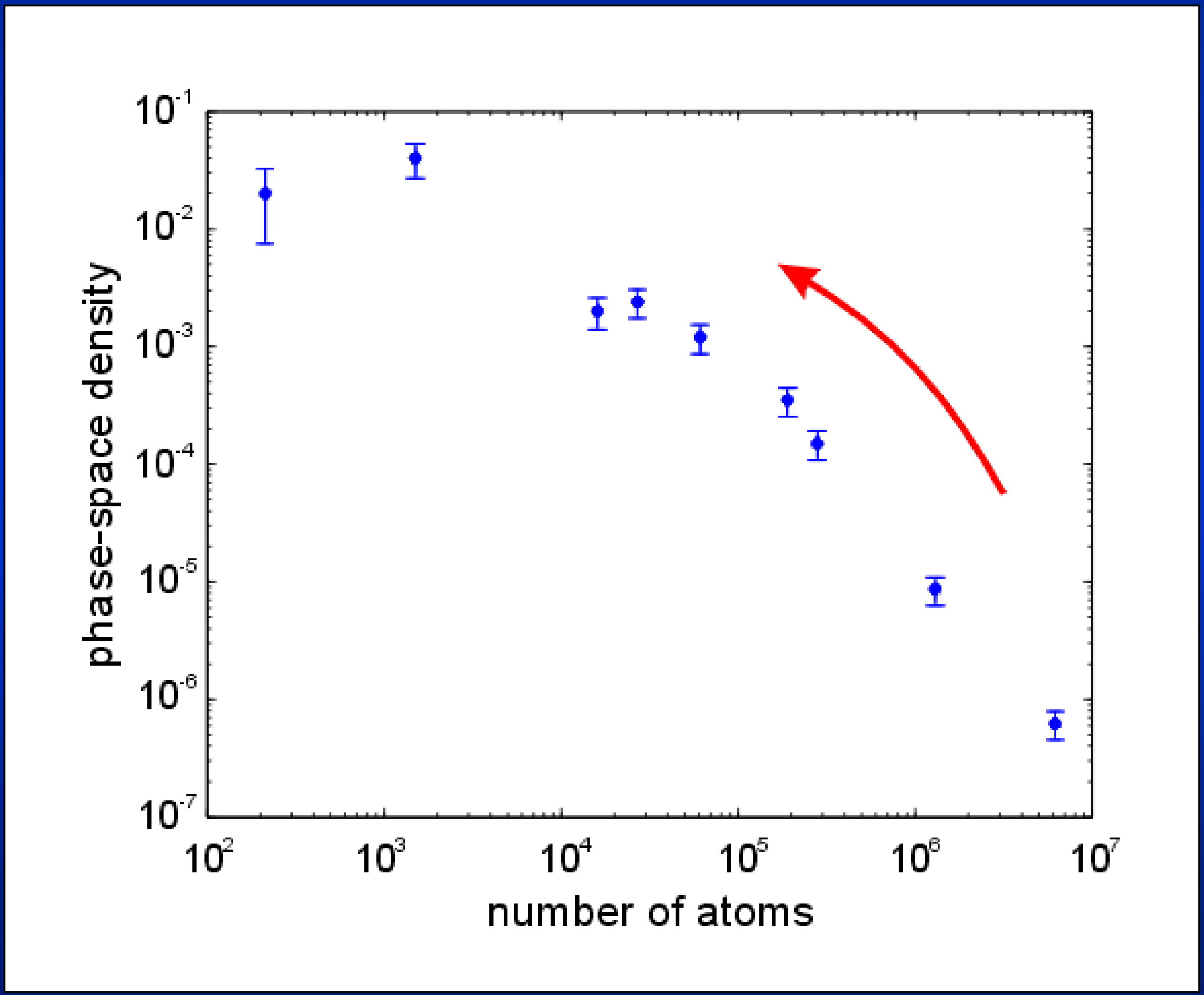




S. Hensler, J. Werner, A. Griesmaier, P.O. Schmidt,
A. Görlitz, T. Pfau, S. Giovanazzi, K. Rzazewski
Appl. Phys. B. (2003)

Loss independent of molecular potentials
Born approximation confirmed

Optimization of Rf-Ramp



$$B_0 \approx 150\,\mathrm{mG}$$

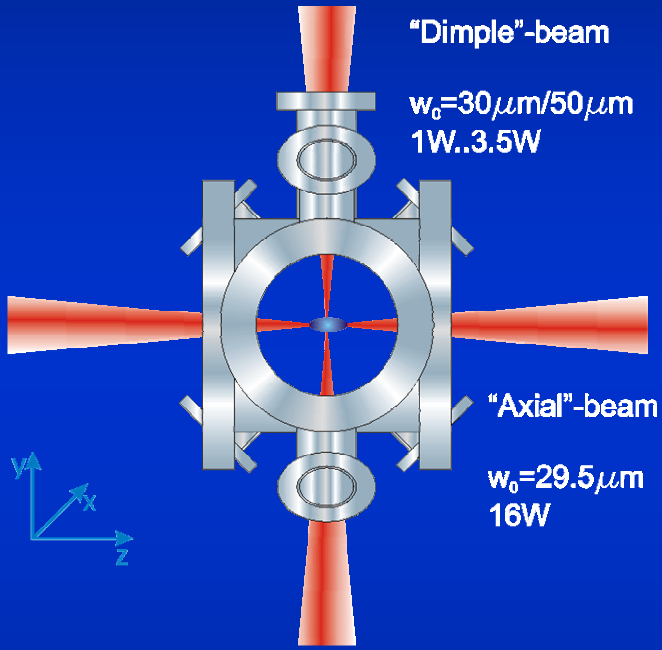
$$\varrho_{\max} = \frac{1}{25}$$

$$n_0 = 6.5 \times 10^{11}\ \mathrm{cm}^{-3}$$

$$T = 370\ \mathrm{nK}$$

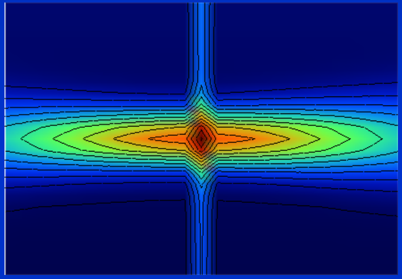
Taming Part II:
Transfer atoms into an optical trap

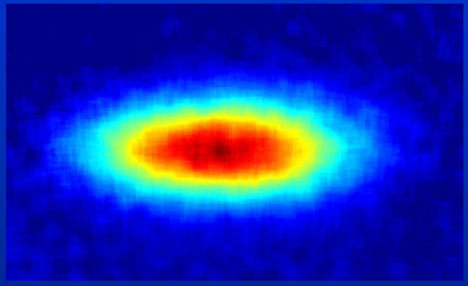
- Optical Dipole trap: 20W fibre Laser @ λ=1064 nm



1st beam: - U_{max}~210μK

2nd beam: - U_{max}~7.5..16μK



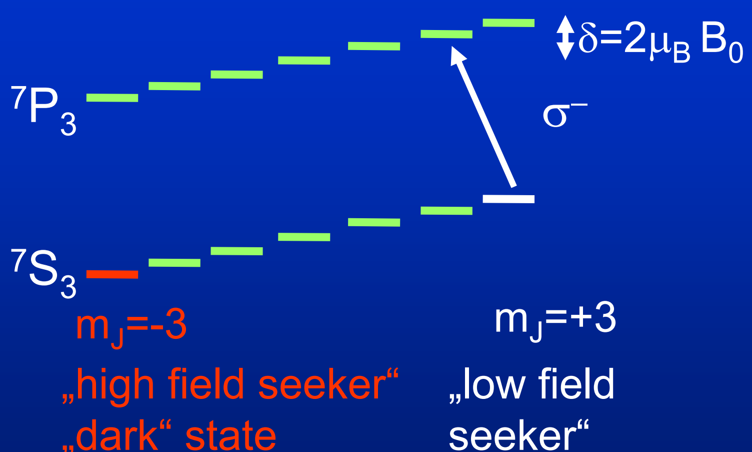


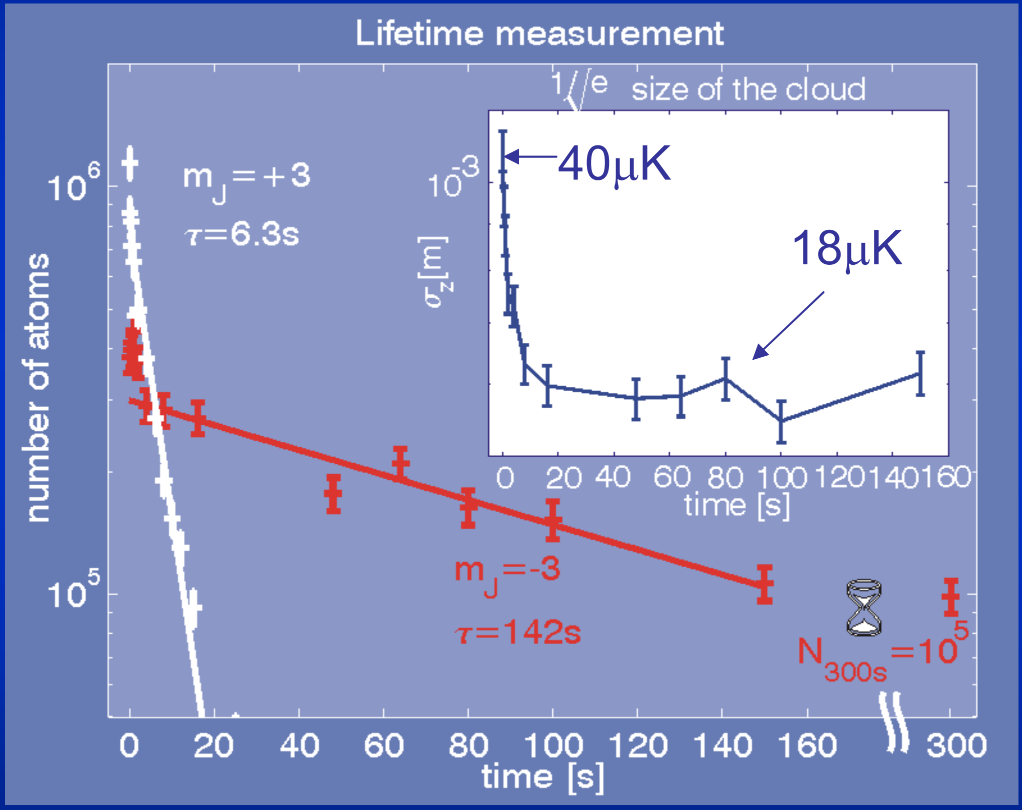
Advantage:
- all magnetic substates trapable
- use „dimple trick“

- Problem : Sample still mainly polarized in m_J=+3

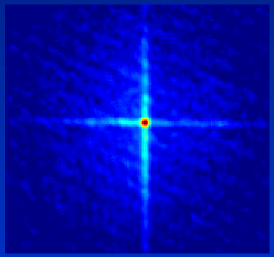
Polarize by optical pumping

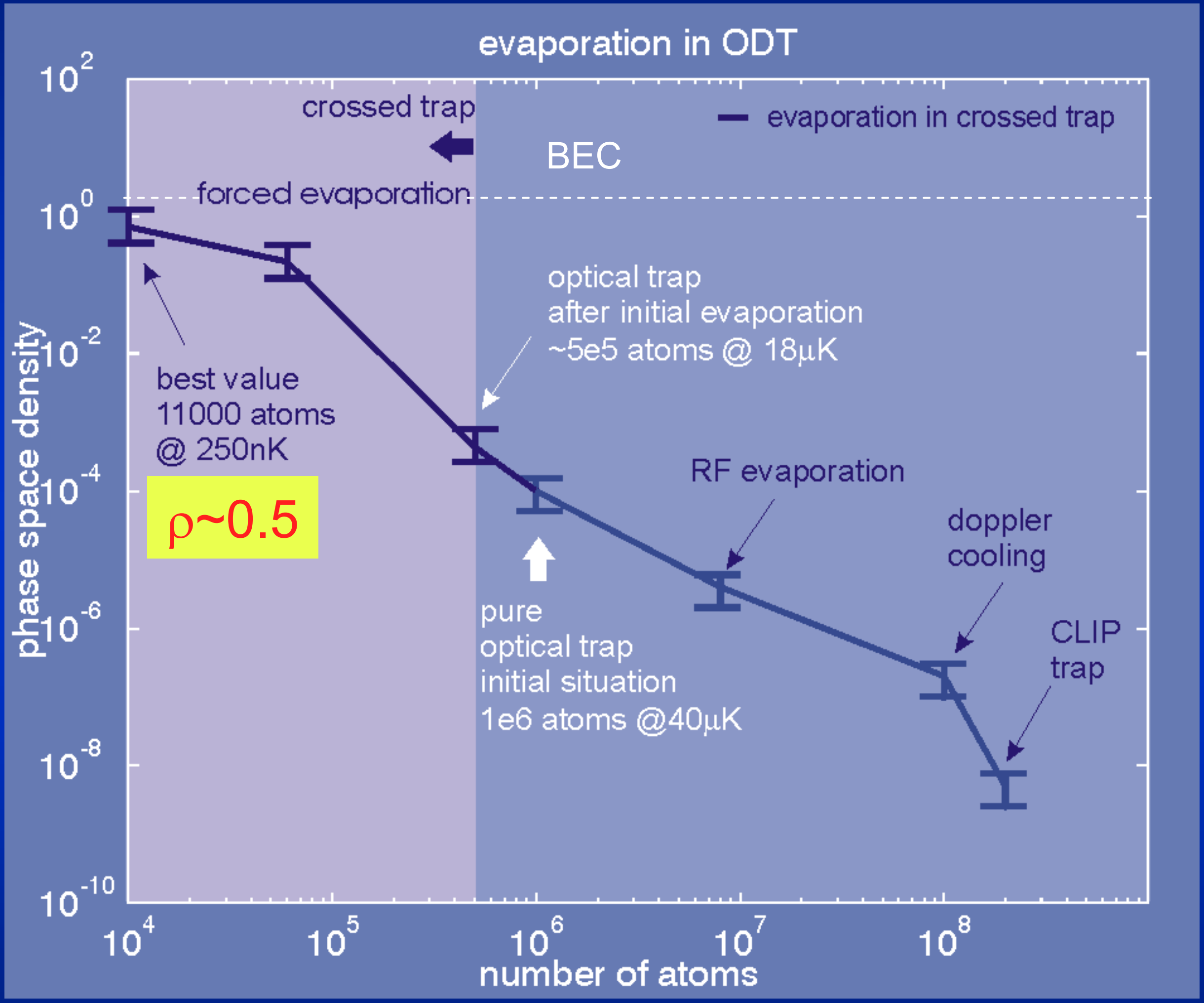
- Optically pump atoms to magnetic ground state:



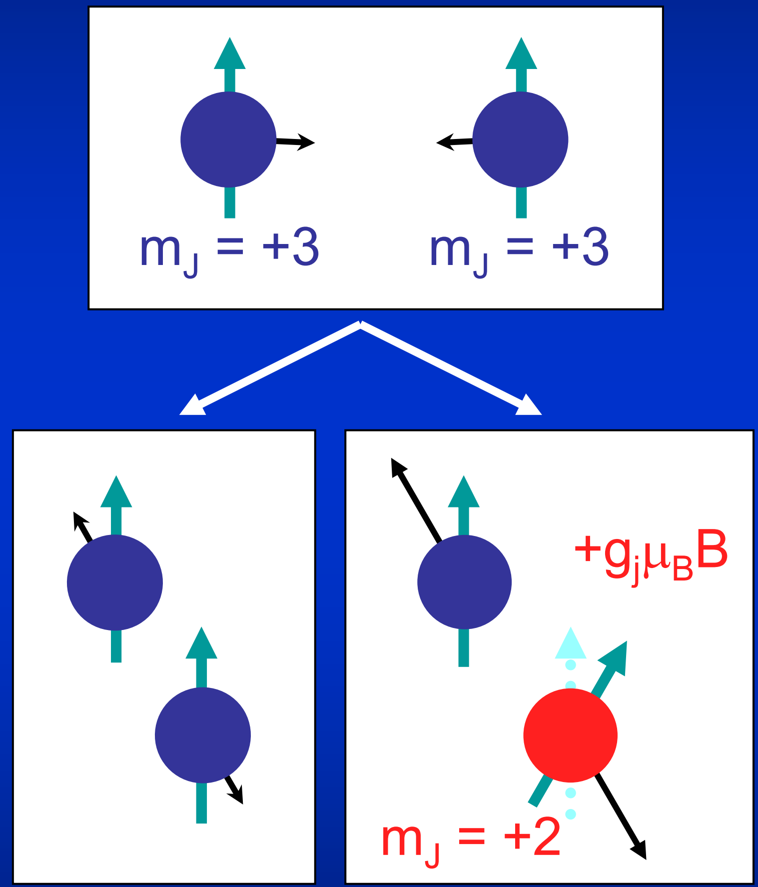


Evaporation in crossed trap





Collisions



Short range

Long range

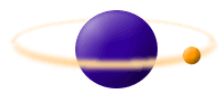
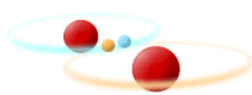
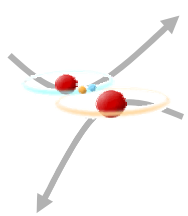
New:
14 Feshbach
resonances
observed

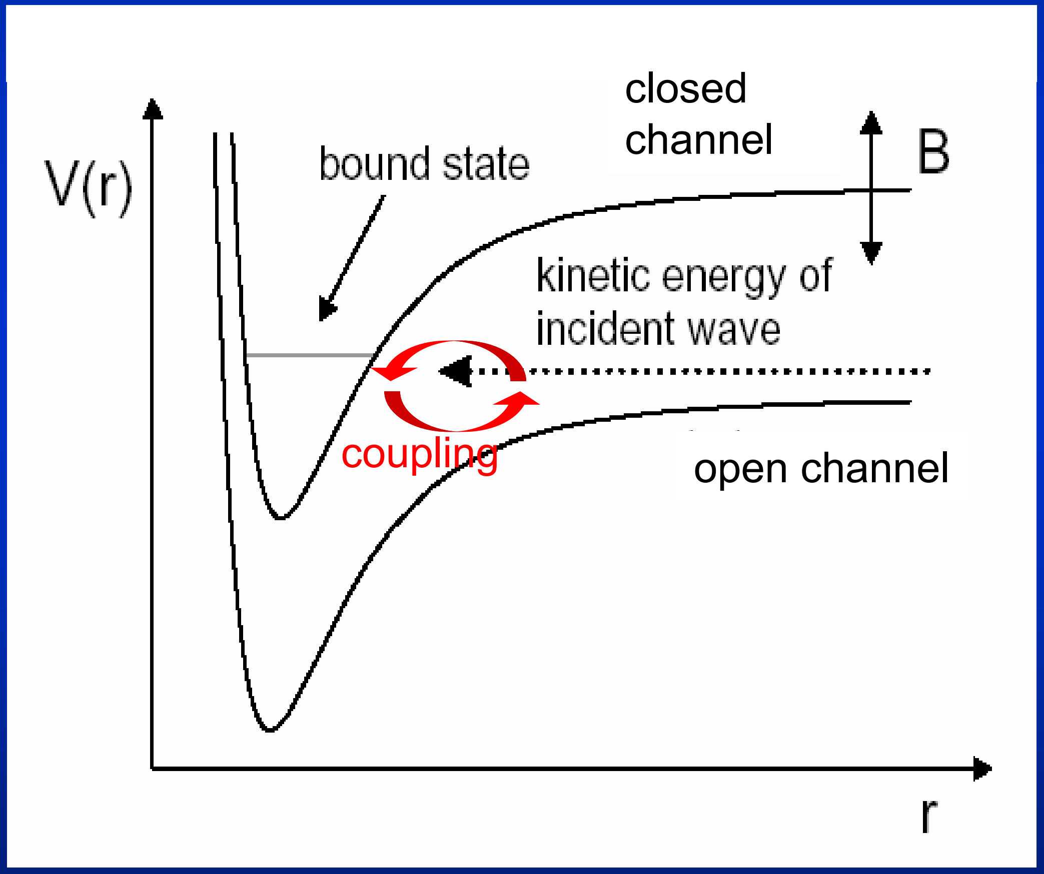
elastic
Collision
GOOD

dipolar
Relaxation
BAD

Feshbach resonances I

Quantum numbers - notation

atomic electrons	s,l	
molecular electrons	S,L	
molecular nuclei	ℓ	



Feshbach resonances II

Possible couplings:

2nd order

Spin - Orbit $\propto \vec{l}.\vec{s} \propto Y_{2q}$

Spin - Spin $\propto \vec{s}.\vec{s} \propto Y_{2q}$

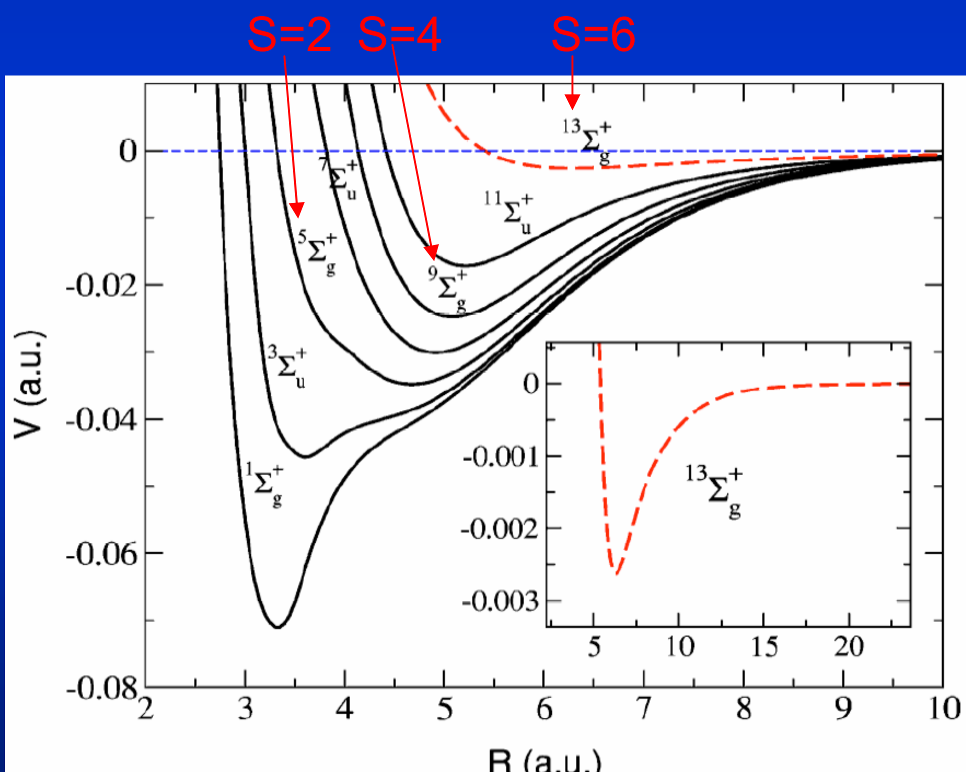
Selection rules:

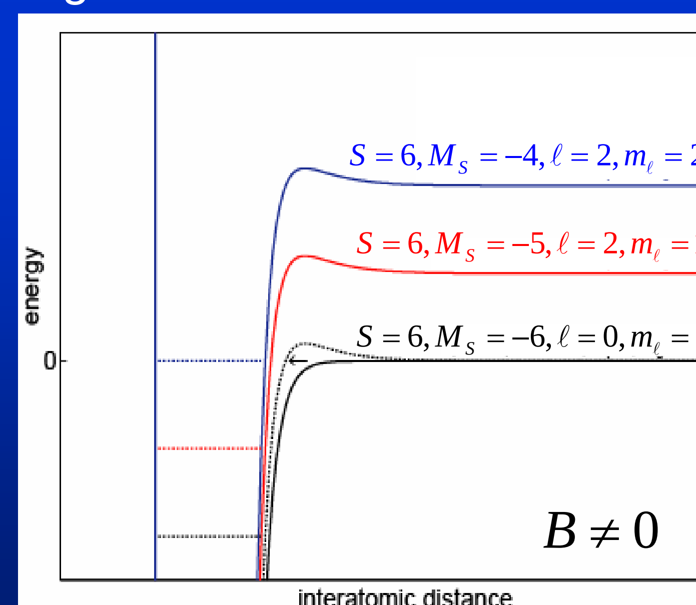
first order	second order
$\Delta S = 0,\pm 2$	$\Delta S = 0,\pm 2,\pm 4$
$\Delta \ell = 0,\pm 2;\ \Delta m_\ell = 0,\pm 1,\pm 2$	$\Delta \ell = 0,\pm 2,\pm 4;\ \Delta m_\ell = 0,\pm 1,\pm 2,\pm 3,\pm 4$

Momentum conservation:

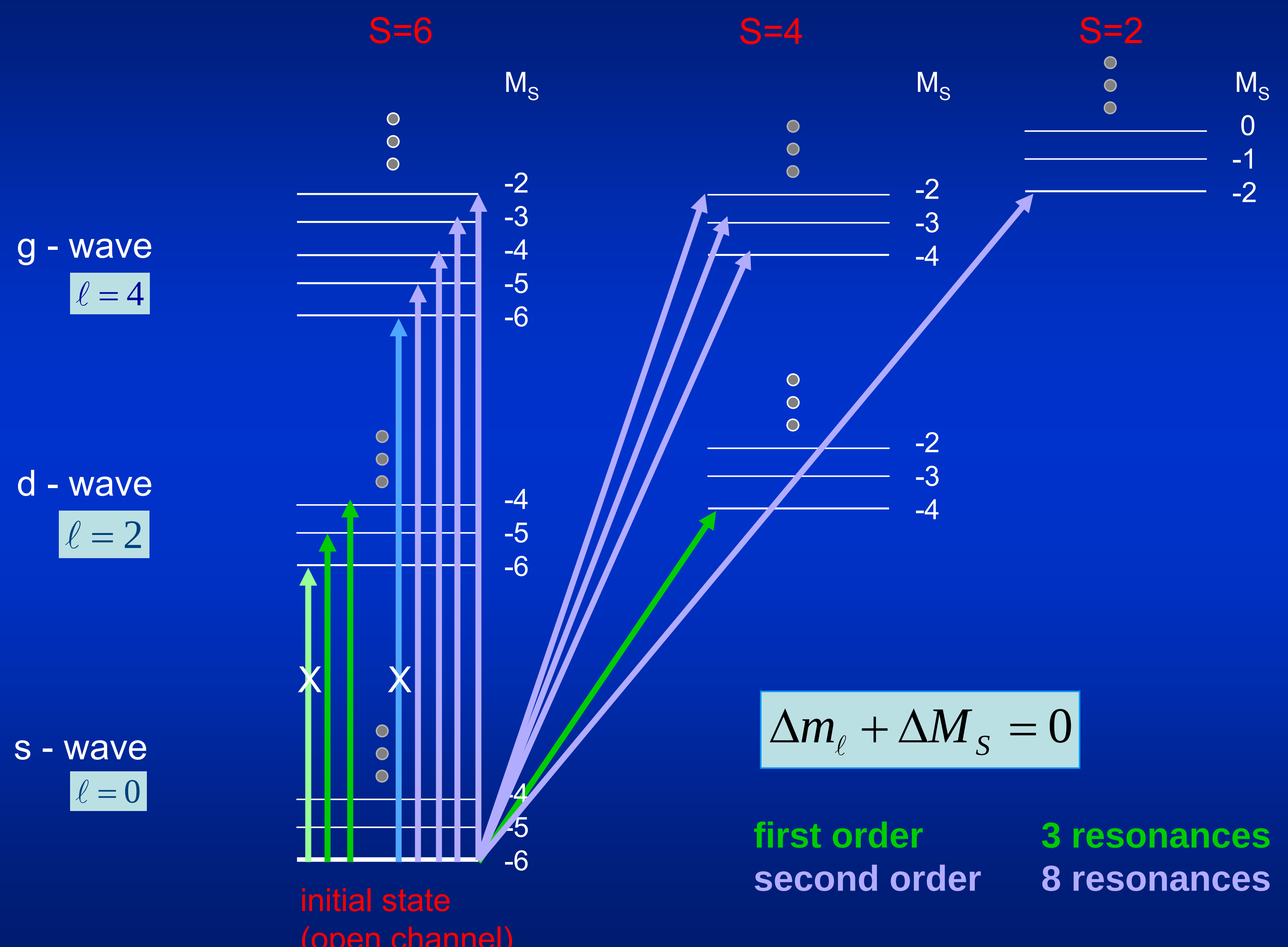
$$\Delta m_\ell + \Delta M_S = 0$$

e.g.

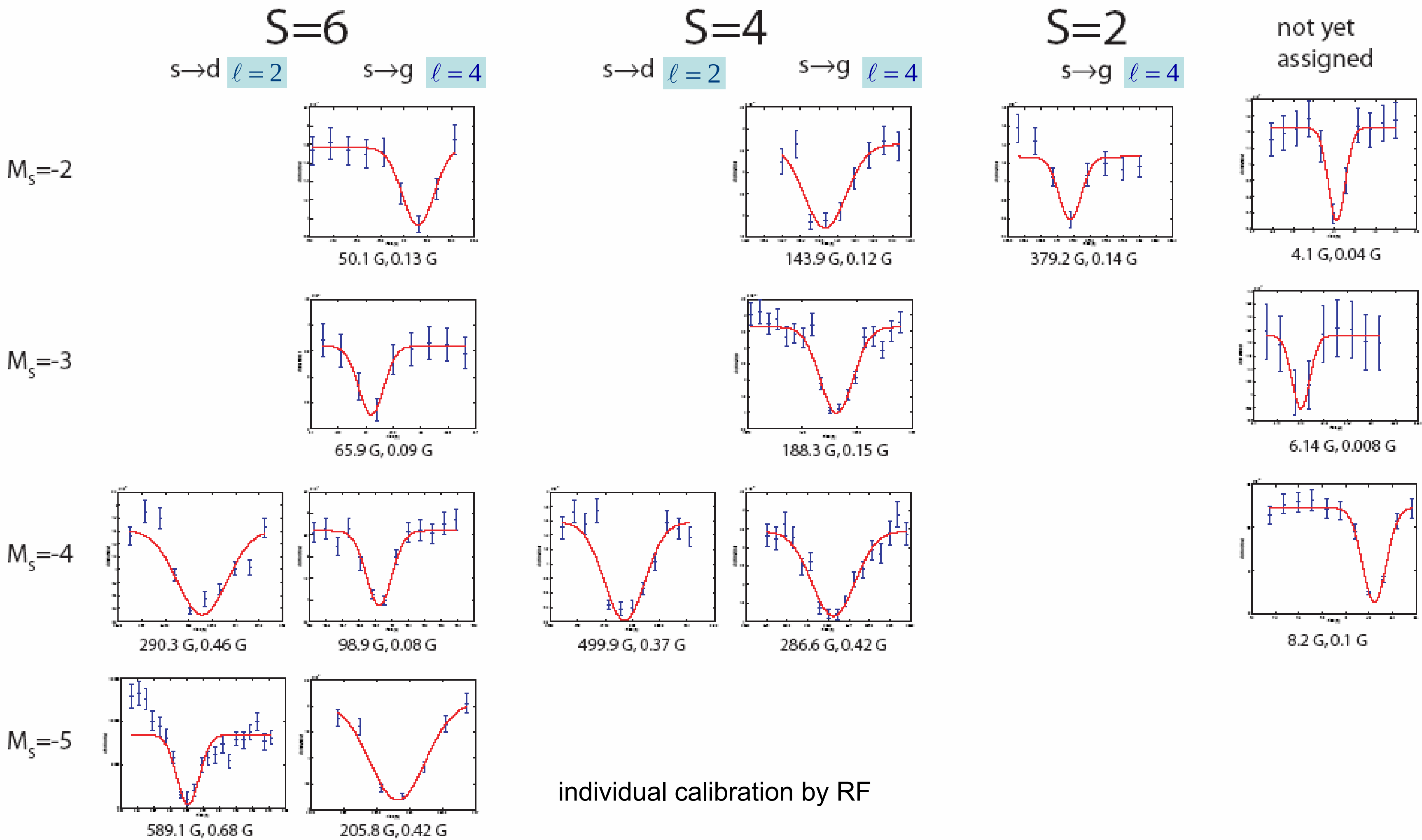




Cr_2 from:
Z. Pavlovic, B. O. Roos, R. Côté, and H. R. Sadeghpour
Phys. Rev. A **69**, 030701 (2004)


S=6
S=4
S=2
M_S
g - wave
$\ell = 4$
d - wave
$\ell = 2$
s - wave
$\ell = 0$
-2
-3
-4
-5
-6
0
-1
X
X
initial state
(open channel)
$\Delta m_\ell + \Delta M_S = 0$
first order
3 resonances
second order
8 resonances

Our 14 resonances

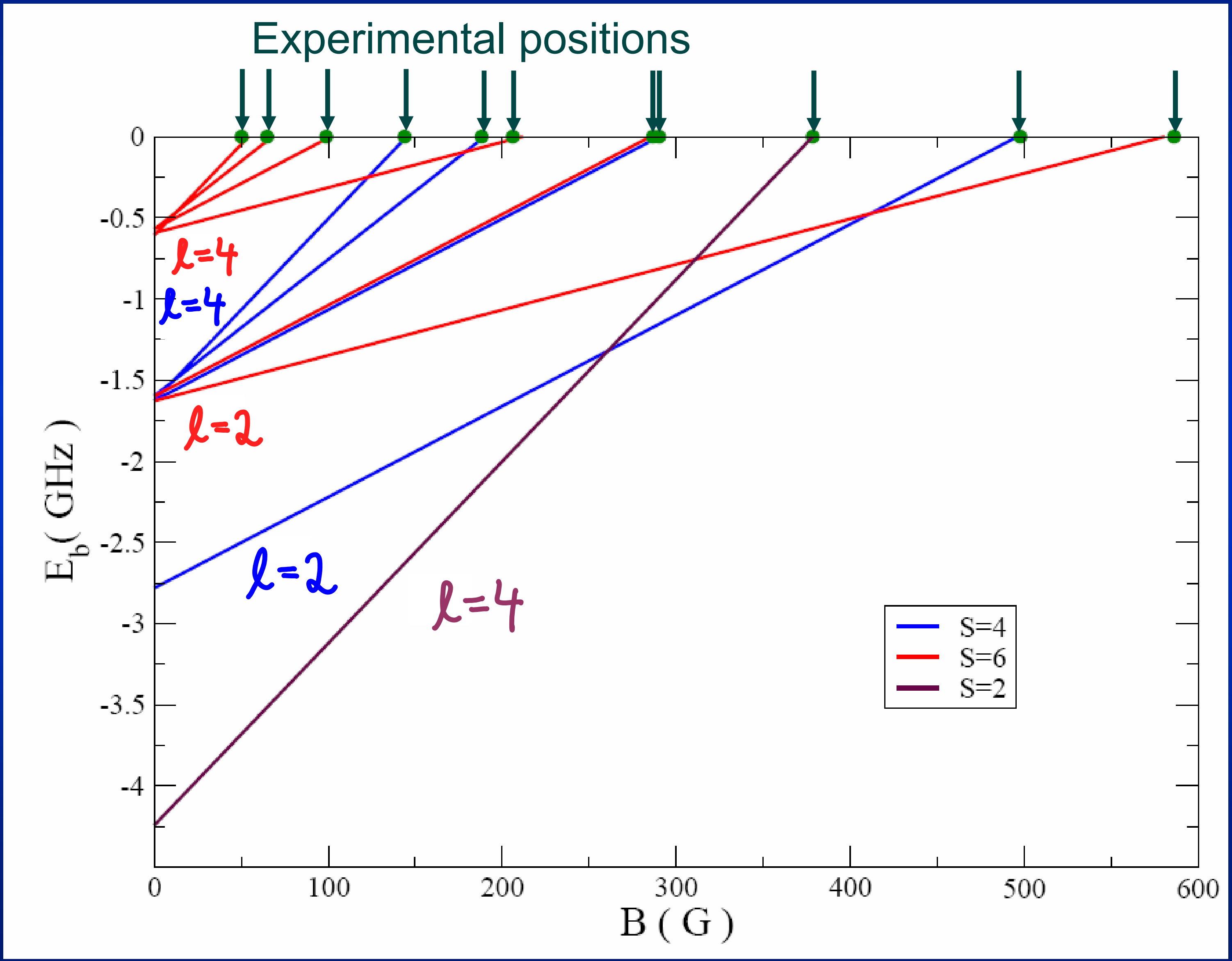


individual calibration by RF

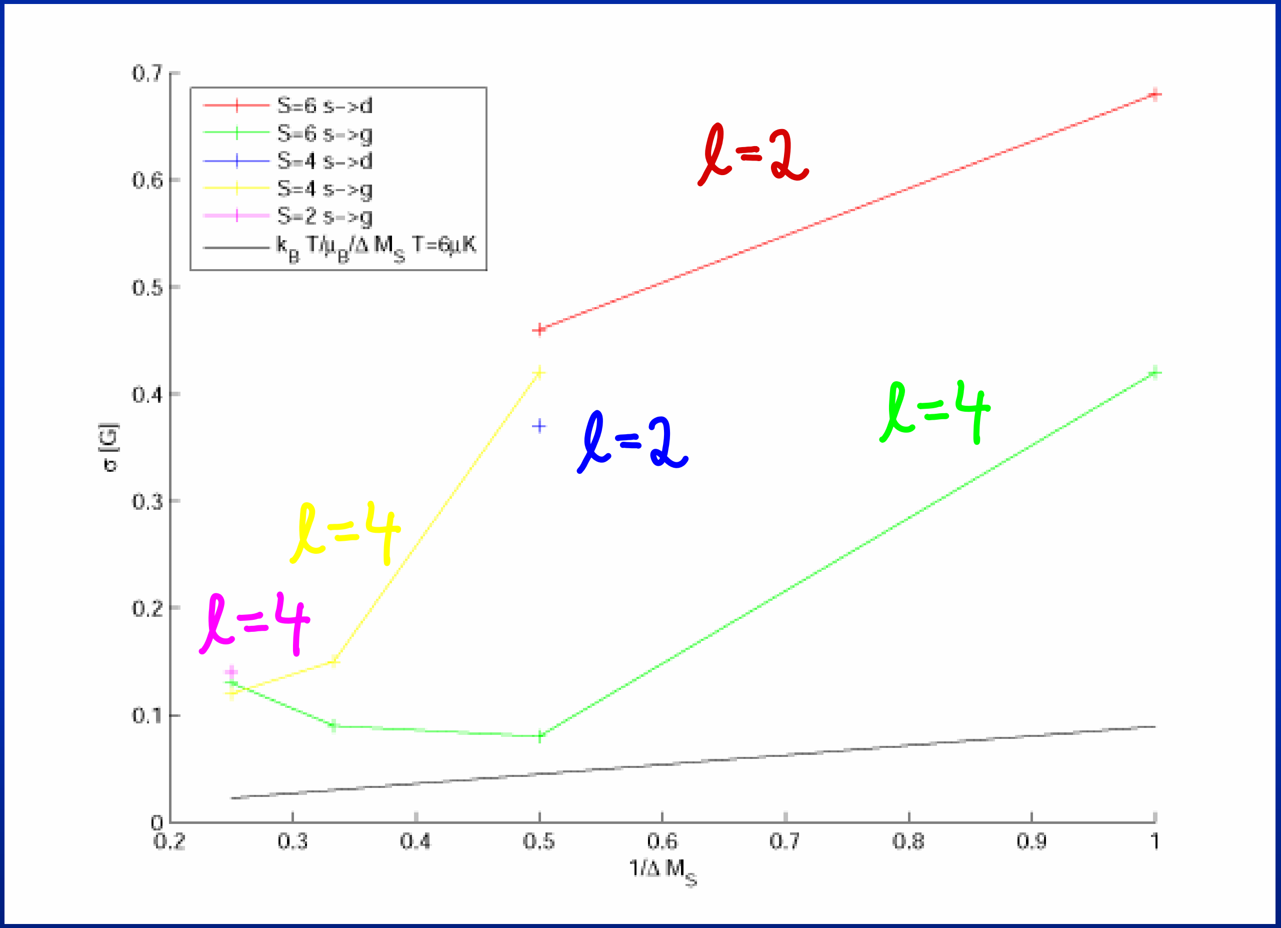
Comparison exp vs. theory (preliminary)

Theory:
A. Simoni
E. Tiesinga
NIST

a_6=+105(4) a_0
a_4= +54(3) a_0
a_2= -21(9) a_0
C_6=798(25) a.u.
C_8< 6 10^5 a.u.

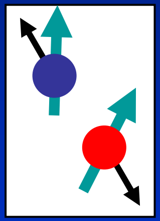


Width vs $1/\Delta M_S$

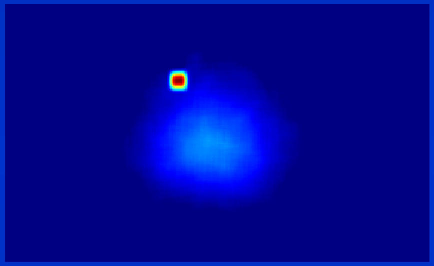


Status of taming

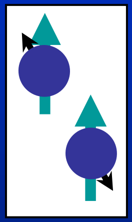
- dipolar relaxation (pure long range)



- transfer into an ODT



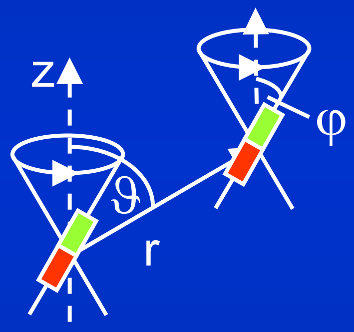
- Optical pumping & evaporation to $\rho \sim 0.5$ @250nK & 10^4 atoms
- 14 Feshbach resonances



Outlook

BEC at last

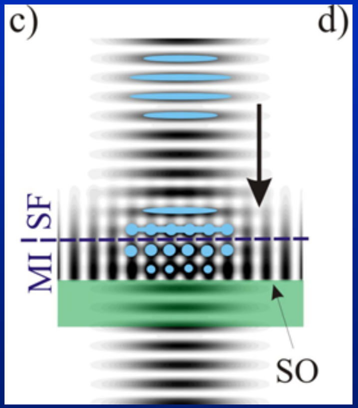
Tune contact interaction using Feshbach resonances (√)
Tune dipole-dipole interaction using NMR-techniques



Play the dipolar game (stability, optical lattices, roton, ...)

Cr_2 molecules (12 μ_B)

Continuous loading of magnetic wave guide



Trap fermion

Lithography: controlled single atom deposition

The Dragontamers

Postdoc wanted!

Former members
P.O.Schmidt
A. Görlitz

Theory:
K. Rzazewski
S. Giovanazzi
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