The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
Energy Agency

SMR 1666 - 24

SCHOOL ON QUANTUM PHASE TRANSITIONS
AND
NON-EQUILIBRIUM PHENOMENA IN COLD ATOMIC GASES

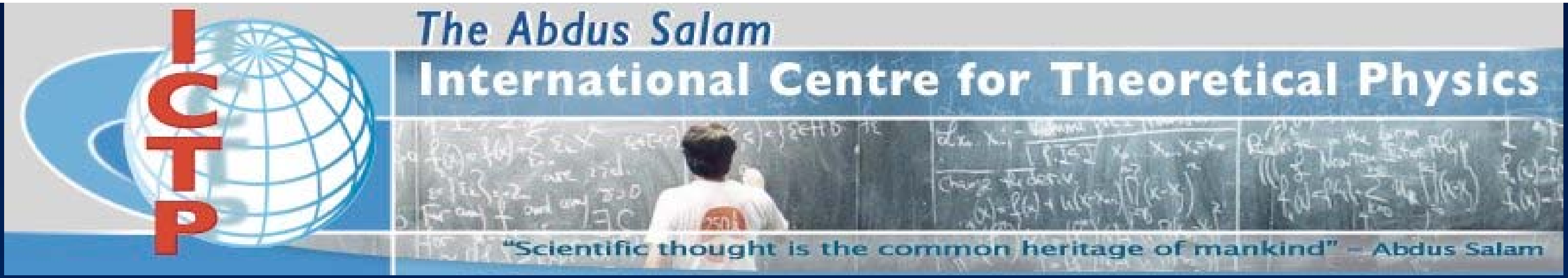
11 - 22 July 2005

Dipolar gases: Experiments

Presented by:

Jürgen Stuhler

University of Stuttgart, Germany



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"Scientific thought is the common heritage of mankind" – Abdus Salam

School on Quantum Phase Transitions and Non-Equilibrium Phenomena in Cold Atomic Gases

Dipolar gases: Experiments

Jürgen Stuhler
Universität Stuttgart
5. Physikalisches Institut (Tilman Pfau)
www.physik.uni-stuttgart.de/institute/pi/5/

outline

- motivation & dipolar systems “in the game”
- production of cold molecules
- BEC of atoms with high magnetic moments (Cr)
- first observation of dipole-dipole interaction in a degenerate quantum gas

dipole-dipole vs. contact interaction

interactions make life interesting!

contact interaction

short range

$$U_{\text{eff}}(r) = g\,\delta(r)$$

isotropic

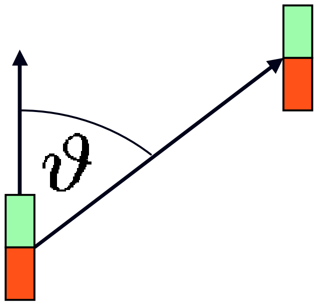
$$g = \frac{4\pi\hbar^2 a}{m}$$

dipole-dipole interaction

anisotropic

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

long range



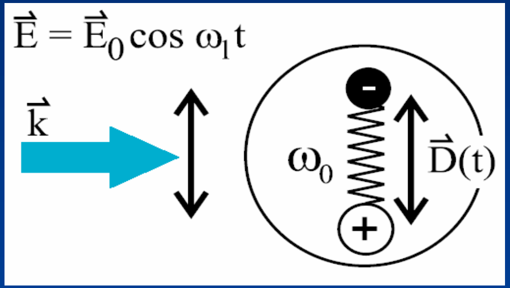
$$C_{dd} = \mu_0\mu^2 = p^2/\varepsilon_0$$

dipolar systems “in the game”

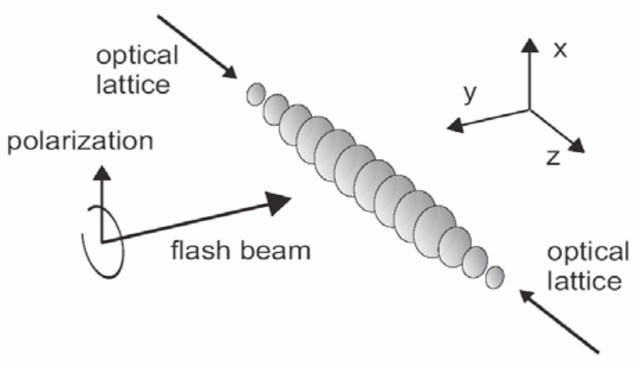
electric dipoles p

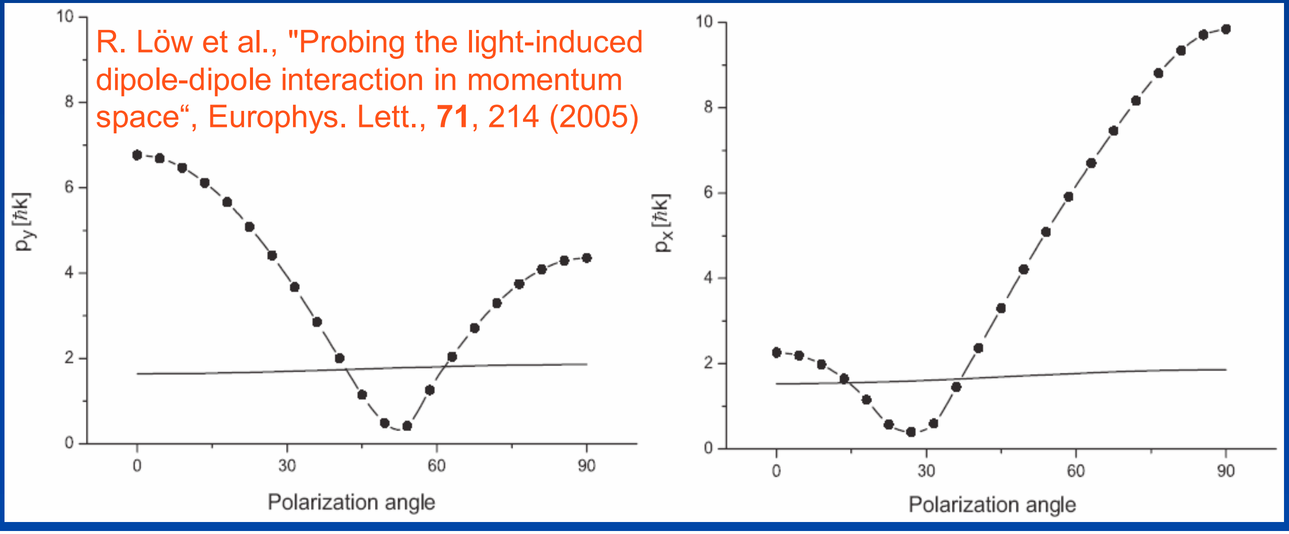
[p] = 1 Debye = 1 D = 3.33564×10^{-30} Cm
e.g.: p^+, e^- @ a_0 ~ 2.5 D

light-induced
dipoles



- oscillating dipoles
- large amplitudes p ~ 5 D
- retardation effects




R. Löw et al., "Probing the light-induced dipole-dipole interaction in momentum space“, Europhys. Lett., **71**, 214 (2005)

dipolar systems “in the game”

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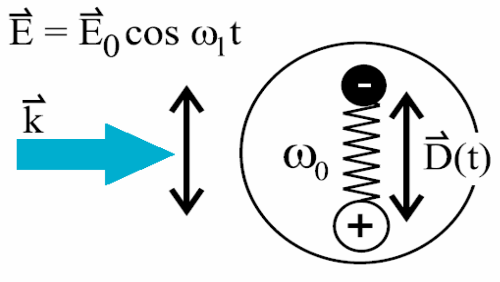
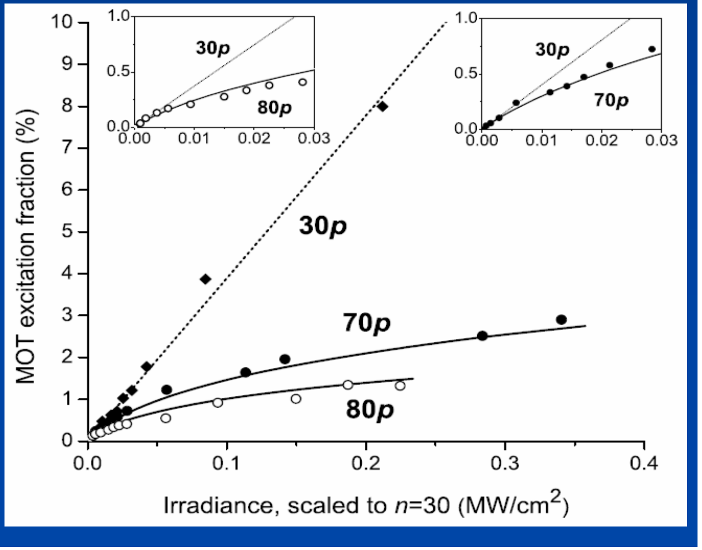


- oscillating dipoles
- large amplitudes p ~ 5 D
- retardation effects

Rydberg atoms

- static dipoles (E-field)
- $p \propto n^2$, p(n=40) ~ 2000 D !
- fragile, difficult to prepare (1- or 2-photon excitation)
- dipole blockade, QC$^{1)}$
- van der Waals blockade$^{2)}$

1) Jaksch et al., PRL **85**, 2208 (2000)
2) Tong et al., PRL **93**, 063001 (2004)
groups: Gallagher, Gould, Pillet, Weidemüller, Raithel, Walker, Shaffer, Pfau

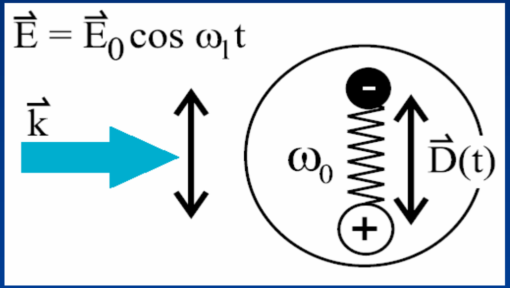


dipolar systems “in the game”

electric dipoles p

$[p]$ = 1 Debye = 1 D = 3.33564×10^{-30} Cm
e.g.: p^+, e^- @ $a_0 \sim 2.5$ D

light-induced dipoles



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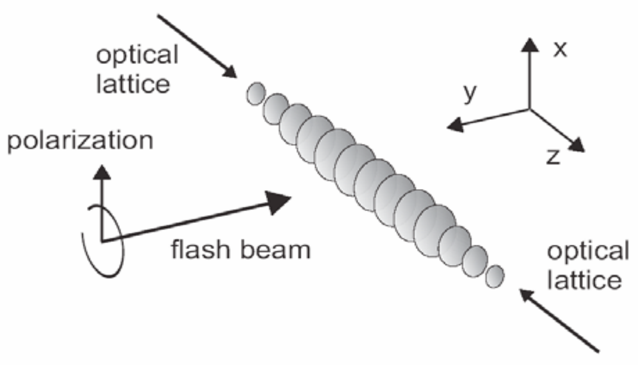

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heteronuclear molecules

- large dipoles $p \sim$ several D
- starting from molecules: cooling difficult
- starting from atoms: formation, ground state, stability ?

dipolar systems “in the game”

electric dipoles p

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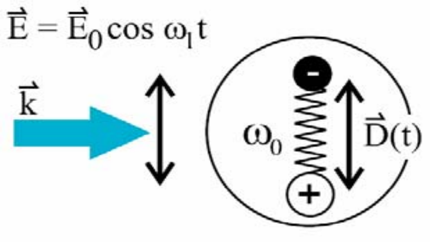
e.g.: p^+, e^- @ $a_0 \sim 2.5$ D

light-induced dipoles



Rydberg atoms

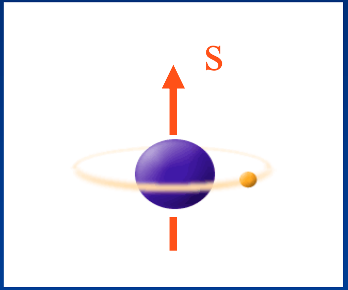
heteronuclear molecules

- large dipoles p ~ several D
- starting from molecules: cooling difficult
- starting from atoms: formation, ground state, stability ?

magnetic dipoles μ

[μ] = 1 Bohr magneton = 1 μ_B
= $\hbar e/2m_e$ = 9.2742×10^{-24} Jm^2/Vs

atoms with magn. moment



- BEC & deg. fermi gas
- typ. small dipoles $\mu \sim 1\mu_B$
- exceptions:
  Er $\mu \sim 7\mu_B$ (MOT, McClelland, NIST)
  Cr $\mu \sim 6\mu_B$ (BEC)

strength of dipole-dipole interaction

$$C_{dd} = \mu_0 \mu^2 = p^2/\varepsilon_0 \qquad U_{dd}(r) \sim C_{dd}/4\pi r^3$$

n ~ 10^{15} cm^{-3} → r ~ 100 nm

p = 1 D → U_{dd} ~ 10 μK

μ = 1 μ_B → U_{dd} ~ 1 nK

compare to
contact interaction:

$$\varepsilon_{dd} = \frac{C_{dd}}{3g} = \frac{\mu_0 \mu^2 M}{12\pi\hbar^2 a}$$

dipole interaction

contact interaction

atoms	
Rb	$\varepsilon_{dd}=0.007$
Na	$\varepsilon_{dd}=0.003$
Cr	$\varepsilon_{dd}=0.15$

molecules

CaH, NH_3, ...
di-alkalis
$\varepsilon_{dd} \sim 100$

strength of dipole-dipole interaction

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compare to
contact interaction:

$$\varepsilon_{dd} = \frac{C_{dd}}{3g} = \frac{\mu_0 \mu^2 M}{12\pi\hbar^2 a}$$

dipole interaction
tunable!
contact interaction

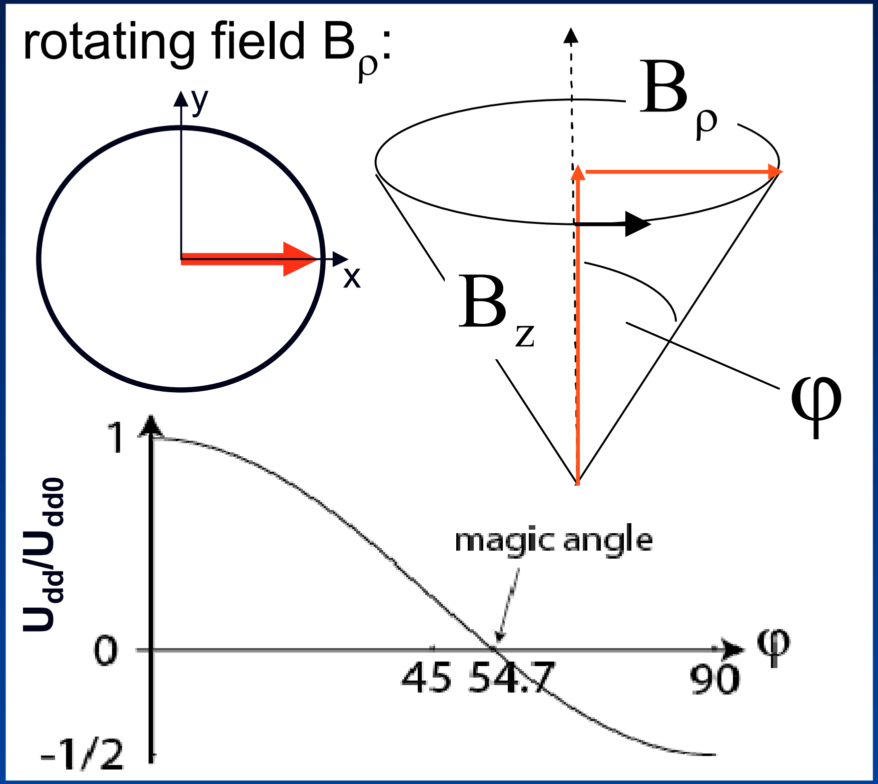
atoms

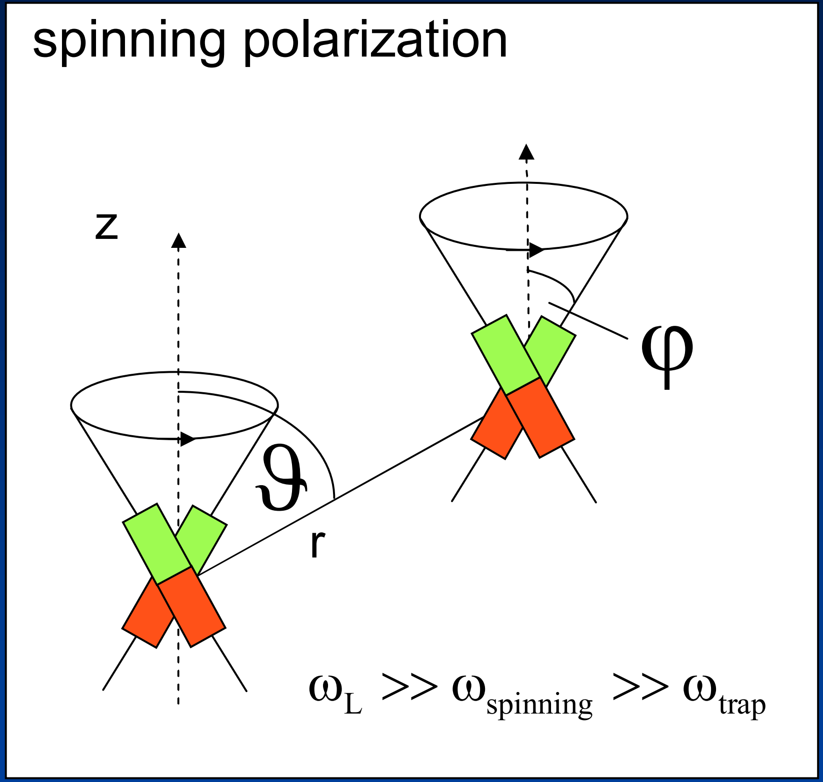
Rb $\varepsilon_{dd}=0.007$
Na $\varepsilon_{dd}=0.003$
Cr $\varepsilon_{dd}=0.15$

tuning

Feshbach resonance	spinning polarization
J. Werner et al. PRL **94**, 183201 (2005)	S. Giovanazzi et al. PRL **89**, 130401 (2002)

tuning the dipole-dipole interaction





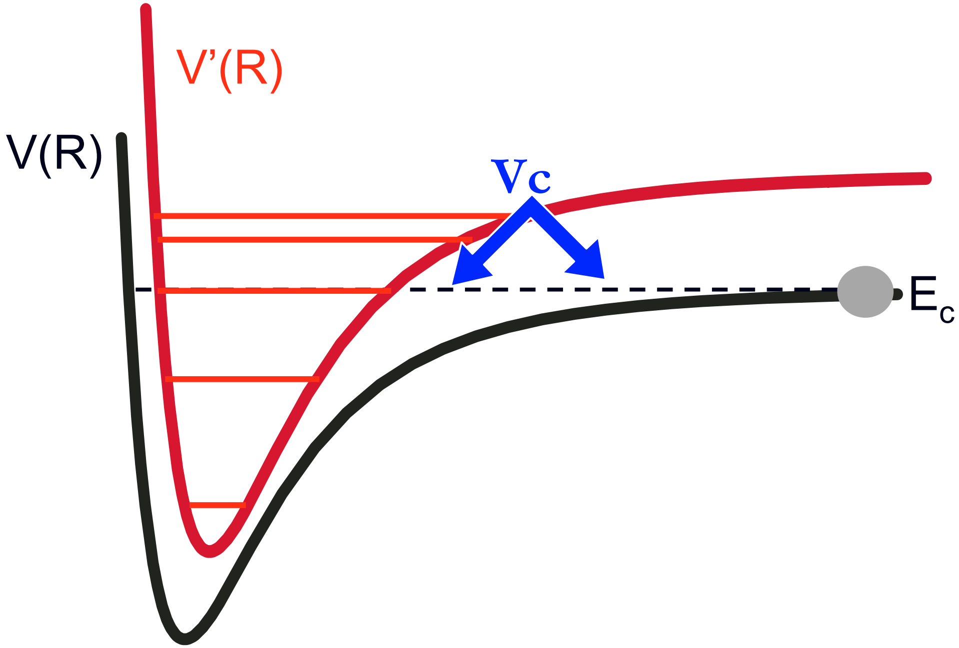
$$\langle U_{dd}(\vec{r})\rangle = -\frac{\mu_0\mu^2}{4\pi}\left(\frac{3\cos^2\vartheta - 1}{r^3}\right)\left(\frac{3\cos^2\varphi - 1}{2}\right)$$

$[-^1/_2, 1]$

tuning a with Feshbach resonances

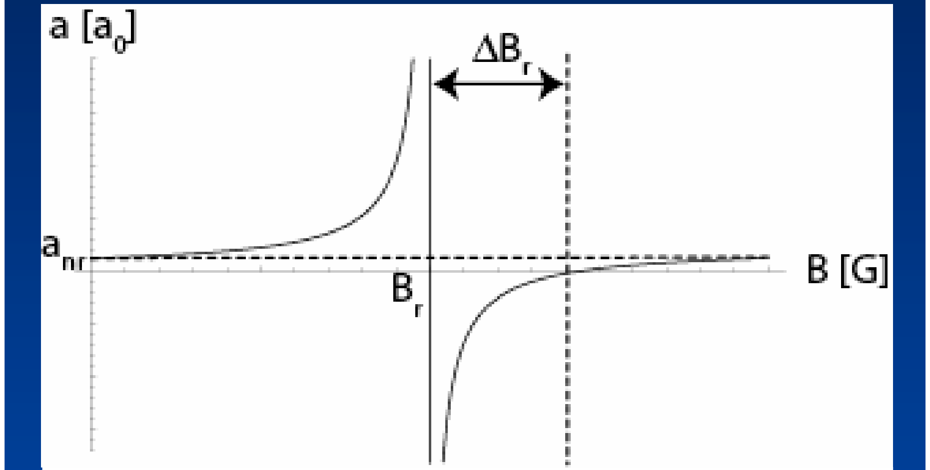
collision with molecular potential V(R):

V'(R) with $M_{s'} \neq M_s$ + B-field + coupling:



⇒ a describes scattering @ low T

⇒ a is modified !

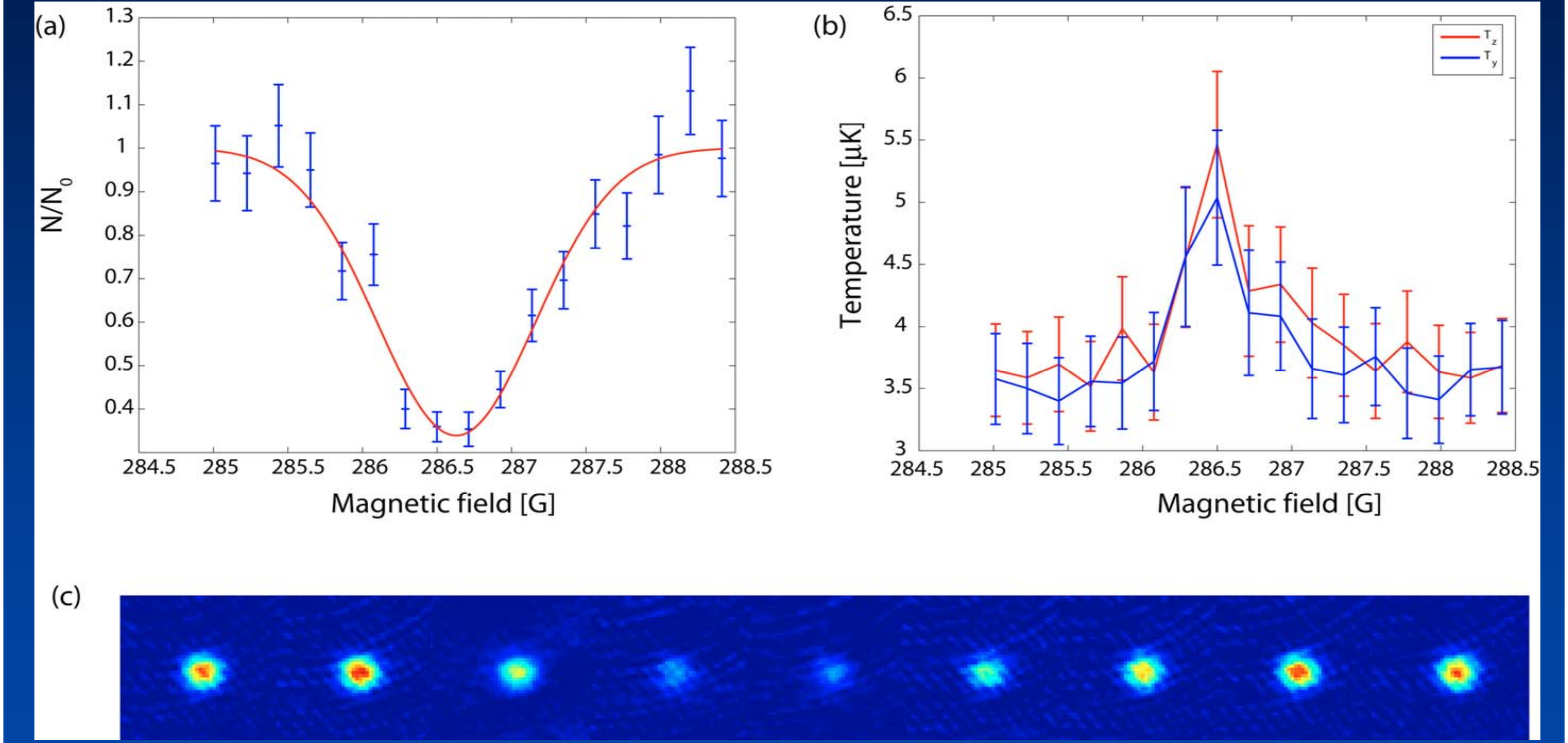


$$a_{FB}(B) = a_{nr}\left(1 - \frac{\Delta B_r}{B - B_r}\right)$$

scattering length a can be tuned with B-field !

detection of Feshbach resonances in ^{52}Cr

atom loss measurement in crossed ODT typical result:

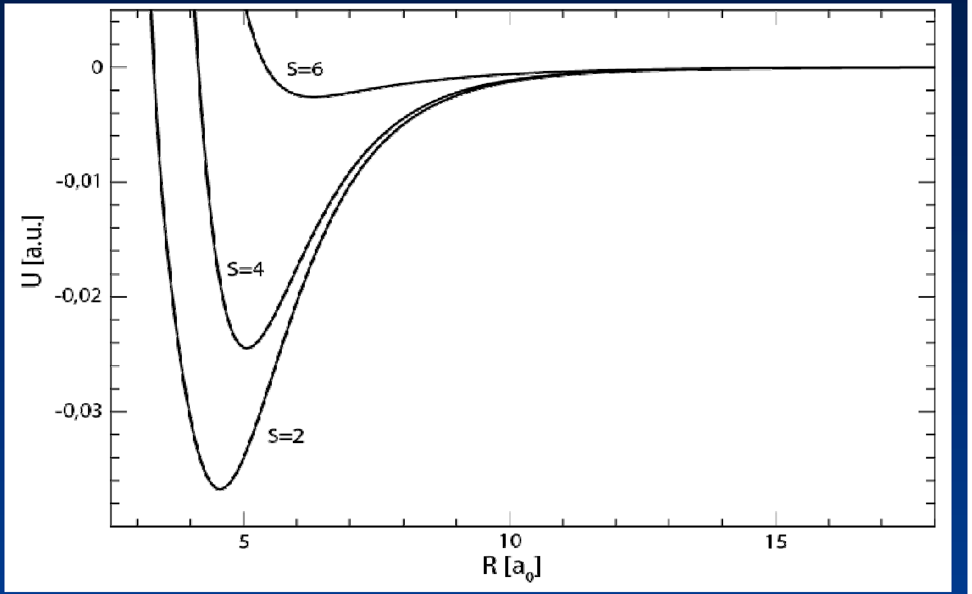


observed all 11 expected FRs

theory – multichannel calculations

- parametrize potential
- start with 5 adjustable parameters C6, C8, a6, a4, a2
- integrate Schrödinger eq. incl. spin-spin dipole interaction
- get theo. resonance positions
- compare to exp./compute χ^2
- vary parameters…

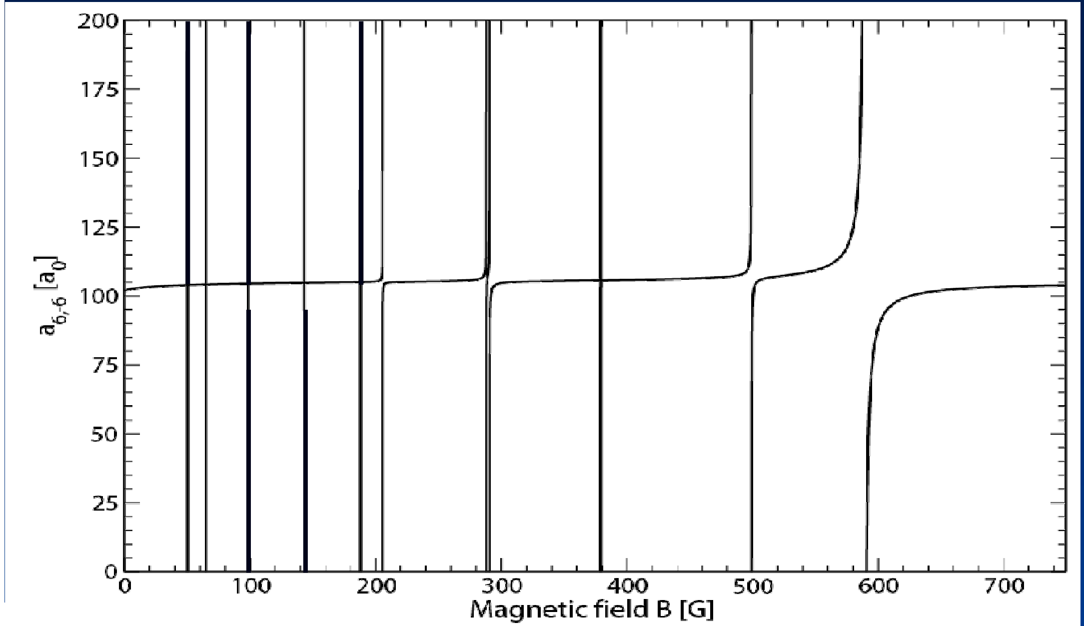
until χ^2 is minimal!

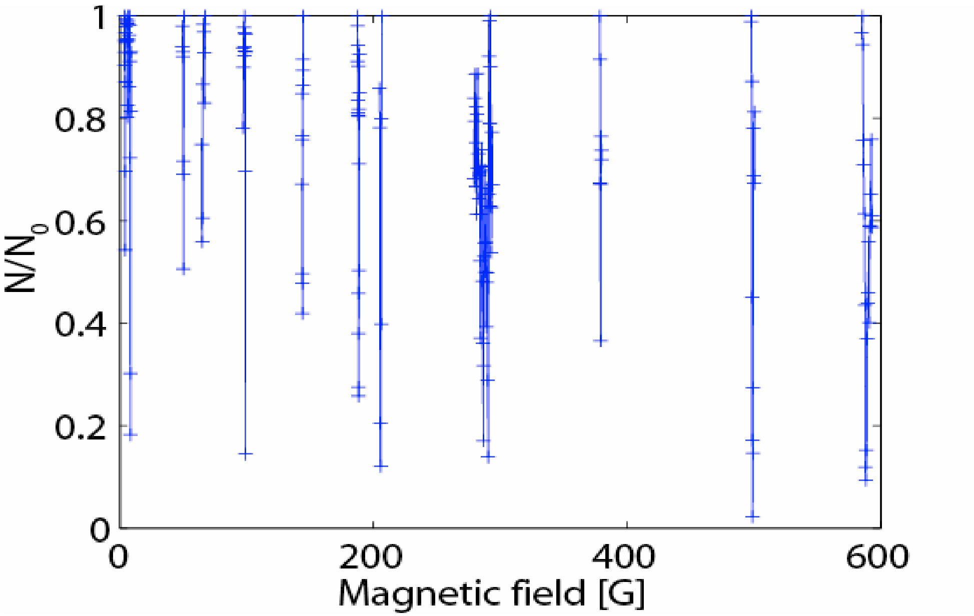


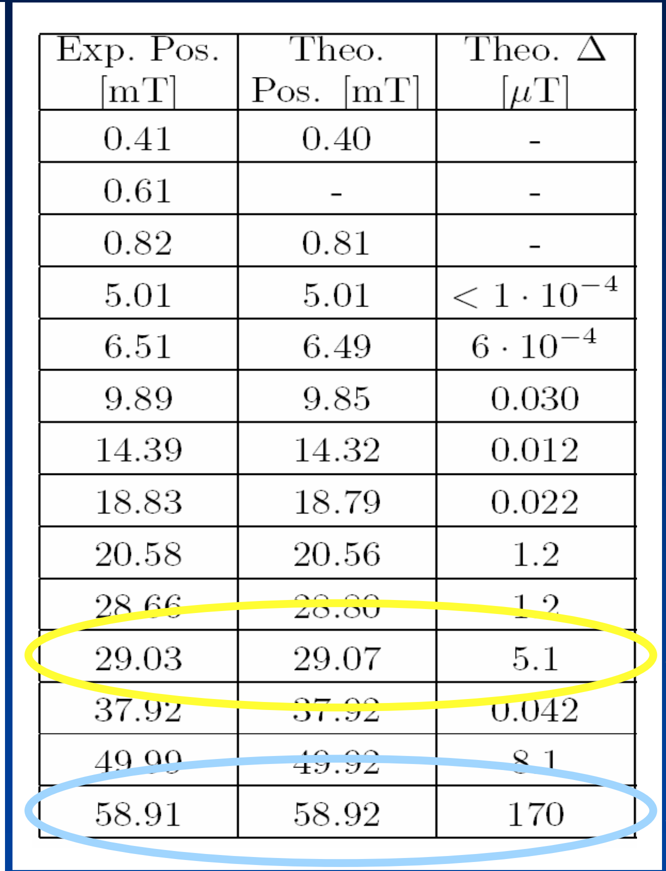
A. Simoni, E. Tiesinga
NIST Gaithersburg (USA)

a_6= 112(14) a0
a_4= 58(6) a0
a_2= -7(20) a0
C_6= 733(70) a.u.
C_8= 75(+90/-75)10^3 a.u.

FB-resonances: exp. vs. theory







Exp. Pos. [mT]	Theo. Pos. [mT]	Theo. Δ [μT]
0.41	0.40	-
0.61	-	-
0.82	0.81	-
5.01	5.01	$< 1 \cdot 10^{-4}$
6.51	6.49	$6 \cdot 10^{-4}$
9.89	9.85	0.030
14.39	14.32	0.012
18.83	18.79	0.022
20.58	20.56	1.2
28.66	28.80	1.2
29.03	29.07	5.1
37.92	37.92	0.042
49.99	49.92	8.1
58.91	58.92	170

$\Delta/B_r \sim 2\times10^{-4}$

$\Delta/B_r \sim 0.003$

Cr is textbook element:

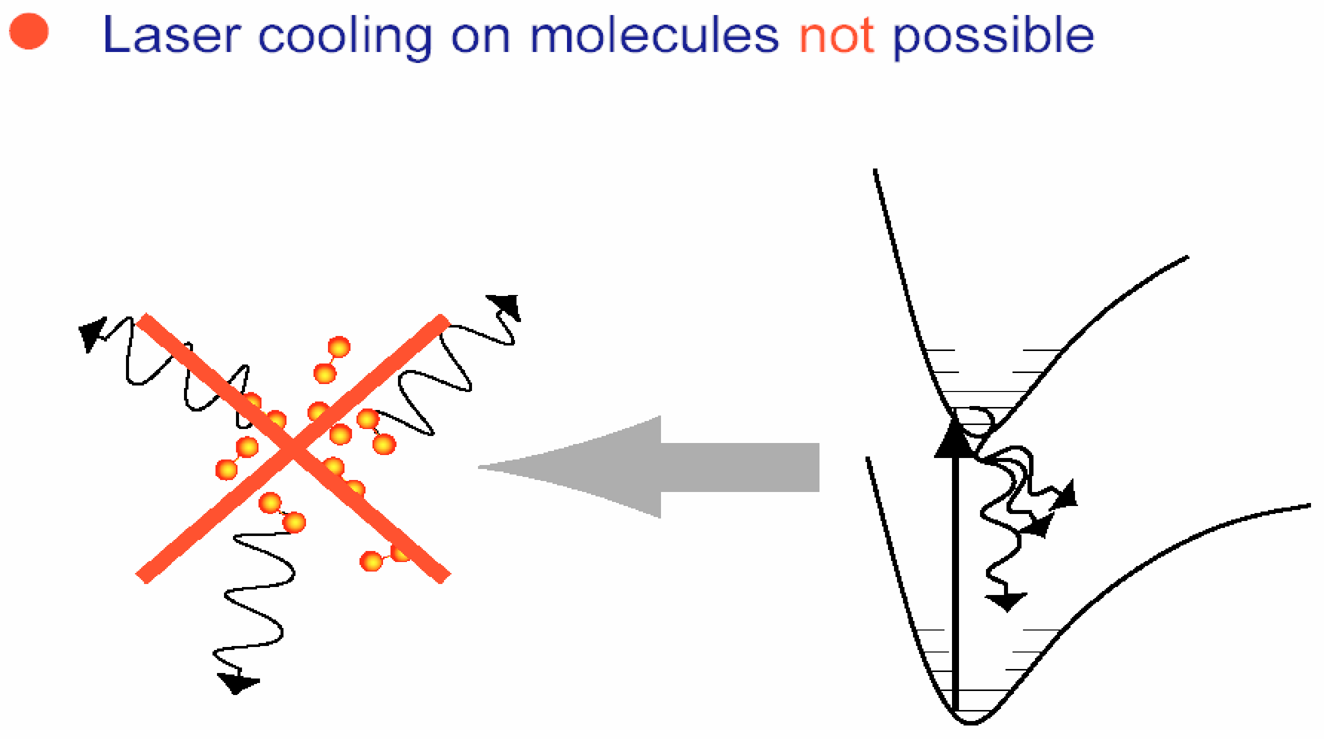
- **no hyperfine interaction (I=0)**
- **dipole-dipole interaction is dominant coupling mechanism**
- **<0.6 G av. agreement !**

outline & first summary

- motivation & dipolar systems "in the game"
    - atoms
        - light-induced electric dipoles (oscillating, retardation)
        - static electric dipoles (Rydberg atoms in E-field)
        - magnetic dipoles (weak, but stronger for Cr, tuning possible)
    - heteronuclear molecules
        - large static electric dipoles
- production of cold molecules Eur. Phys. J. D **31** iss. **2** (2004)
    - slowing & cooling of molecules (direct production)
    - making molecules out of cold atoms (indirect production)
    - trapping dipolar molecules
- BEC of atoms with high magnetic moments (Cr)
- first observation of dipole-dipole interaction in a degenerate quantum gas

direct production of cold molecules

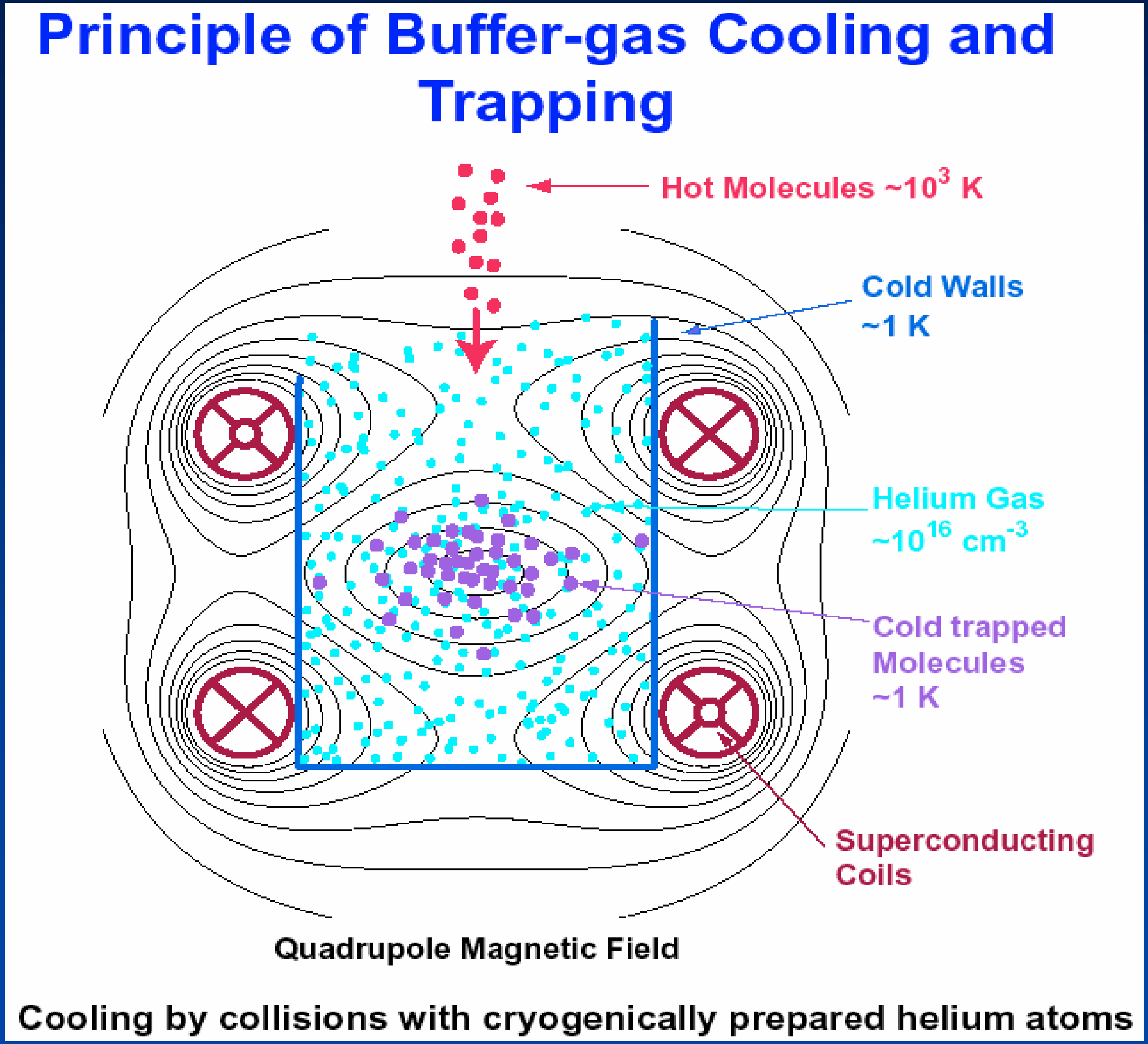
How to get cold molecules ???



- Laser cooling on molecules not possible

- select cold molecules out of beam (Pinkse/Rempe)
- buffer gas cooling
- slow down molecules of a beam

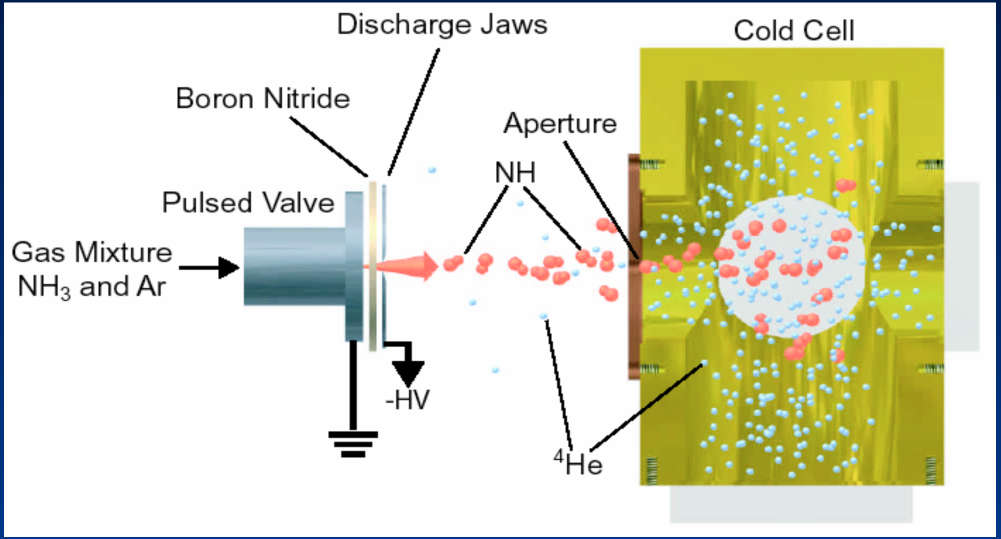
buffer gas cooling

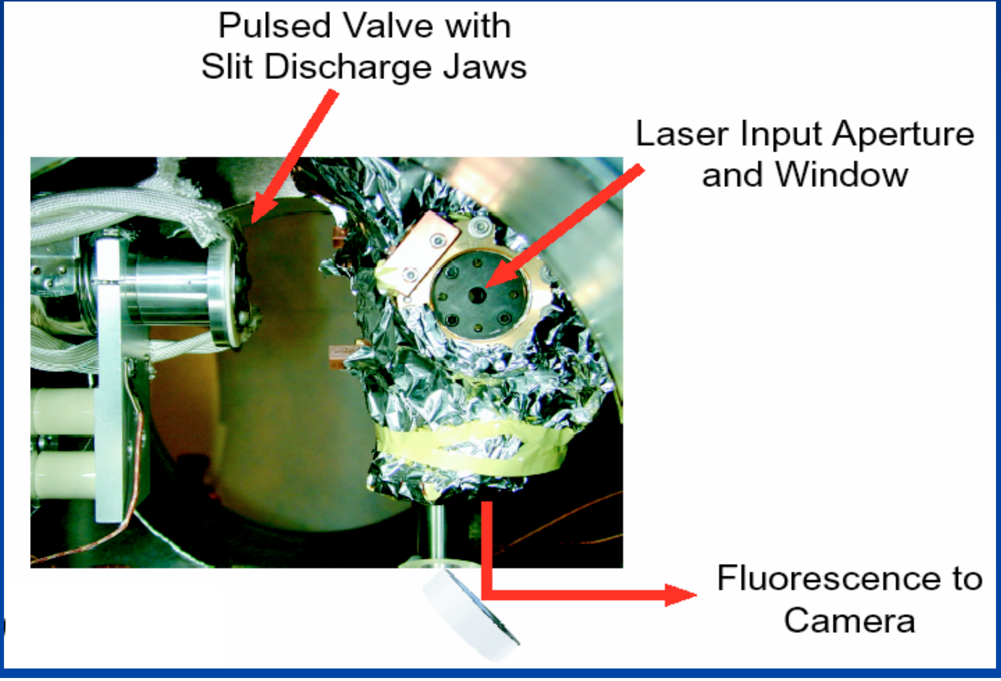


Cooling by collisions with cryogenically prepared helium atoms

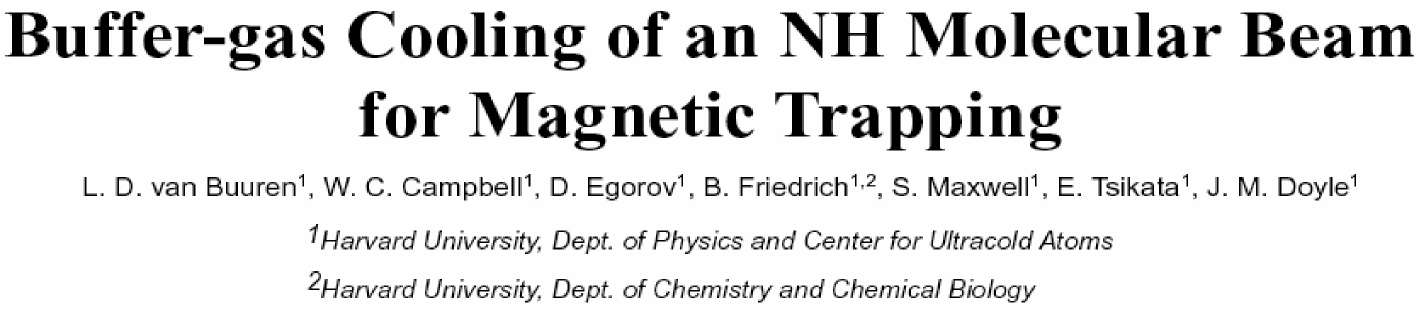
J. M. Doyle et al. PRA **52**, R2515 (1995)

buffer gas cooling





buffer gas cooling

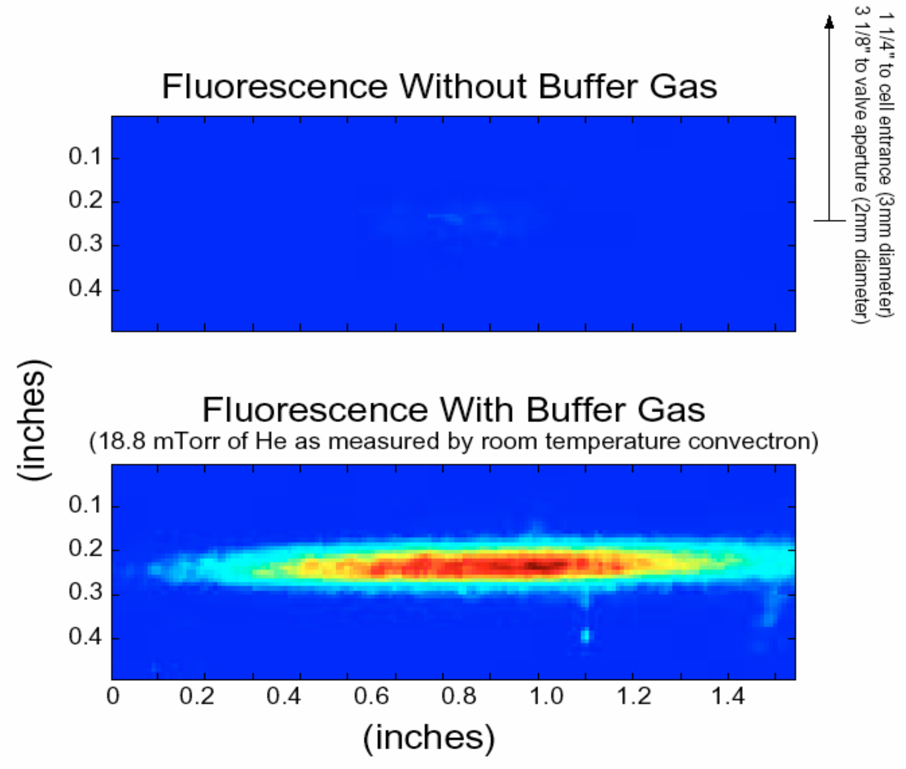


Buffer-gas Cooling of an NH Molecular Beam for Magnetic Trapping

L. D. van Buuren[1], W. C. Campbell[1], D. Egorov[1], B. Friedrich[1,2], S. Maxwell[1], E. Tsikata[1], J. M. Doyle[1]

[1] *Harvard University, Dept. of Physics and Center for Ultracold Atoms*

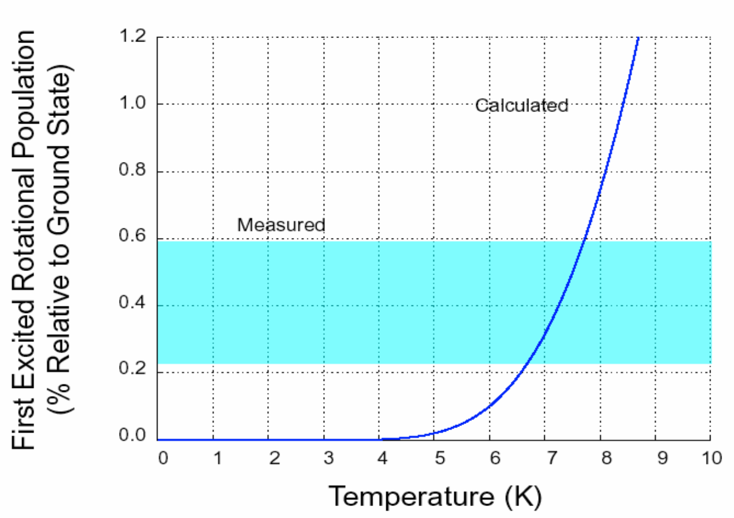
[2] *Harvard University, Dept. of Chemistry and Chemical Biology*



$N \sim 10^{11}$-10^{12}, $n \sim 3\times10^{9}$ cm^{-3}, $T \sim 10$ K

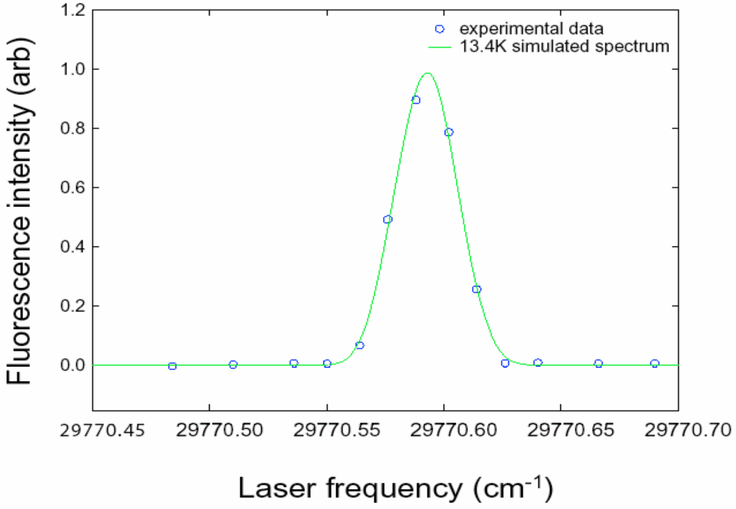
buffer gas cooling

Rotational Temperature Determination



Translational Temperature Determination

Scan over line profile of buffer gas cooled NH



Average Ground State NH Density in Cold Cell

$n \approx 3 \times 10^{9}$ cm^{-3}

Total Number of Ground State NH Radicals in Cold Cell

$N = 10^{11} - 10^{12}$

Cell Temperature

$8\ K < T_{cell} < 12\ K$

NH Rotational Temperature from State Distribution

$T_{rot} = 7.2 \pm 0.5\ K$

NH Translational Temperature from Doppler Width

$T_{trans} = 13 \pm 5\ K$

NH Mean-Free Path in Cold Cell

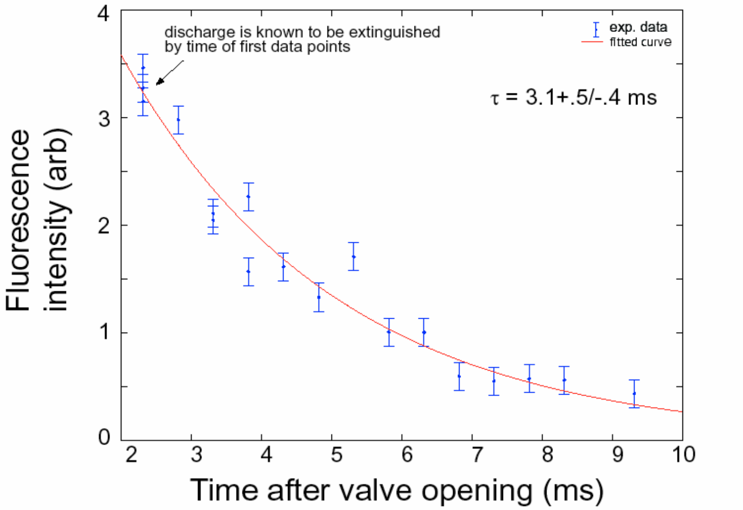
$\lambda = 350^{+300}_{-200}\ \mu m$

Diffusion Lifetime in Cold Cell at He density 3 x 10^{16} cm^{-3}

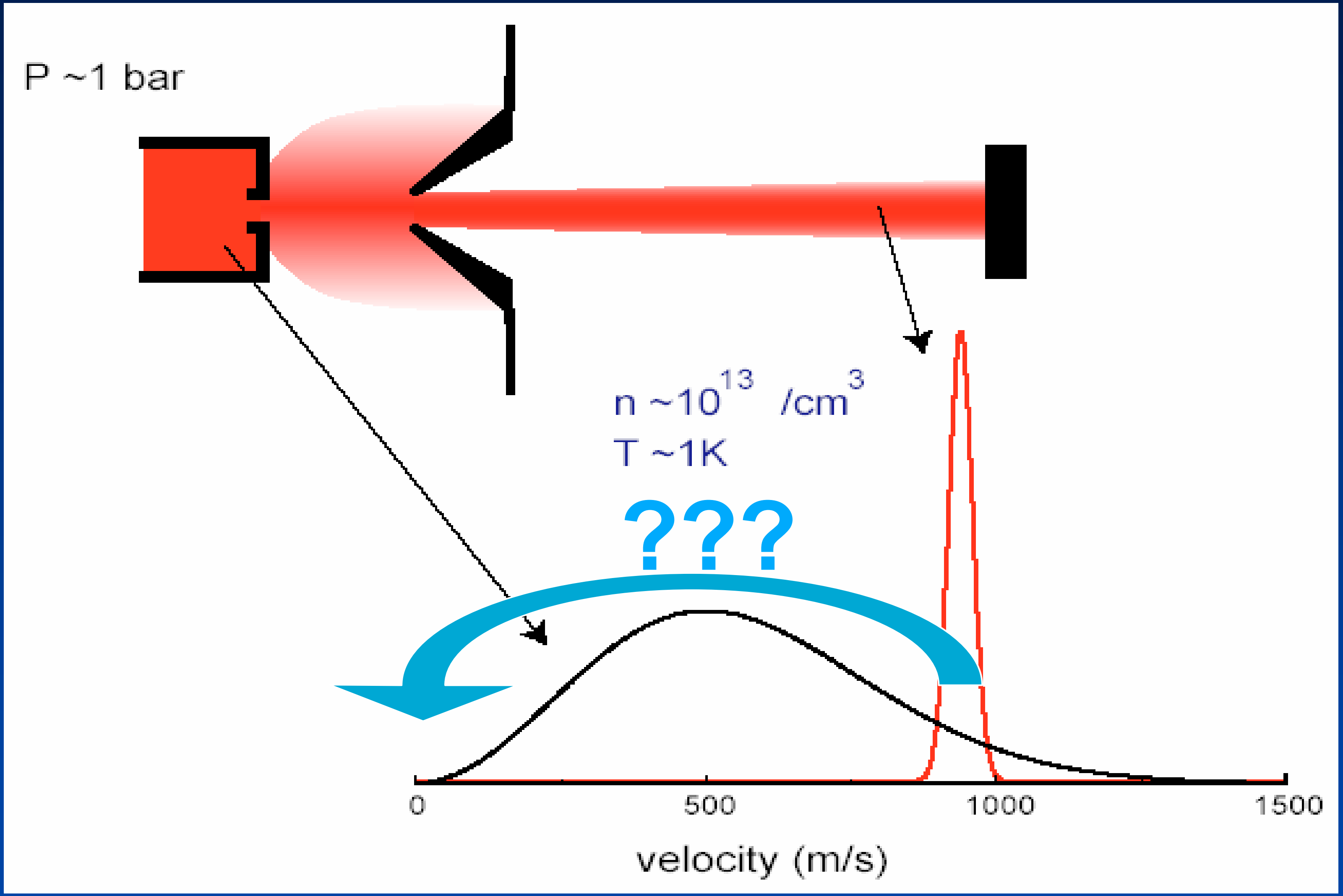
$\tau_{cell} = 3.1^{+0.5}_{-0.4}$ ms

Measurement of lifetime of NH in buffer gas cell

with 9.4-9.6 mTorr of He as measured by room temperature convectron

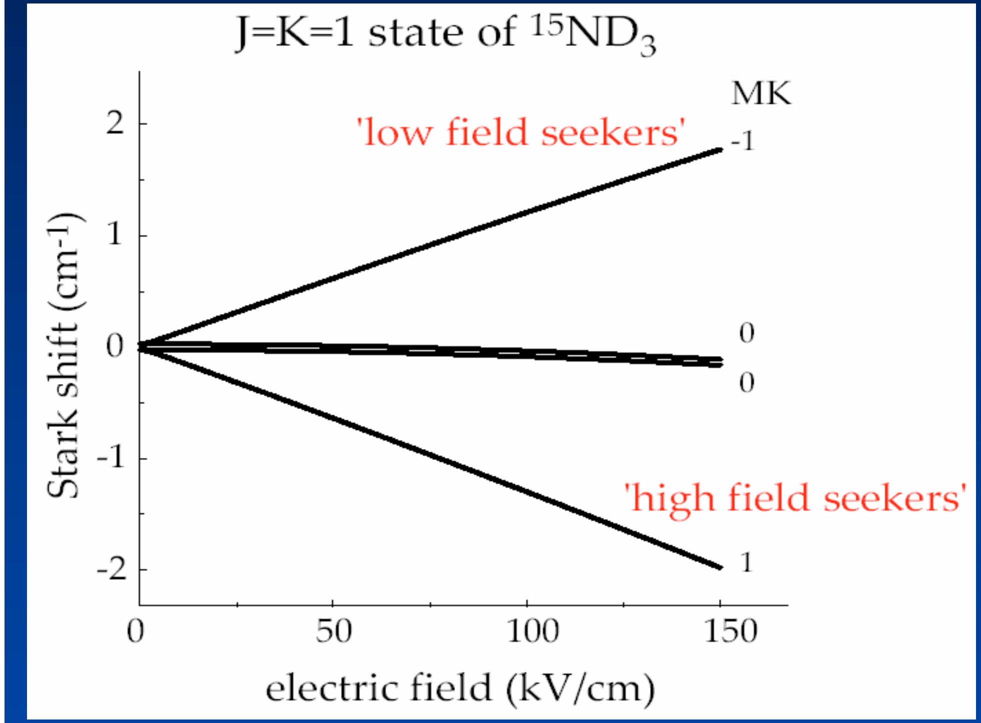


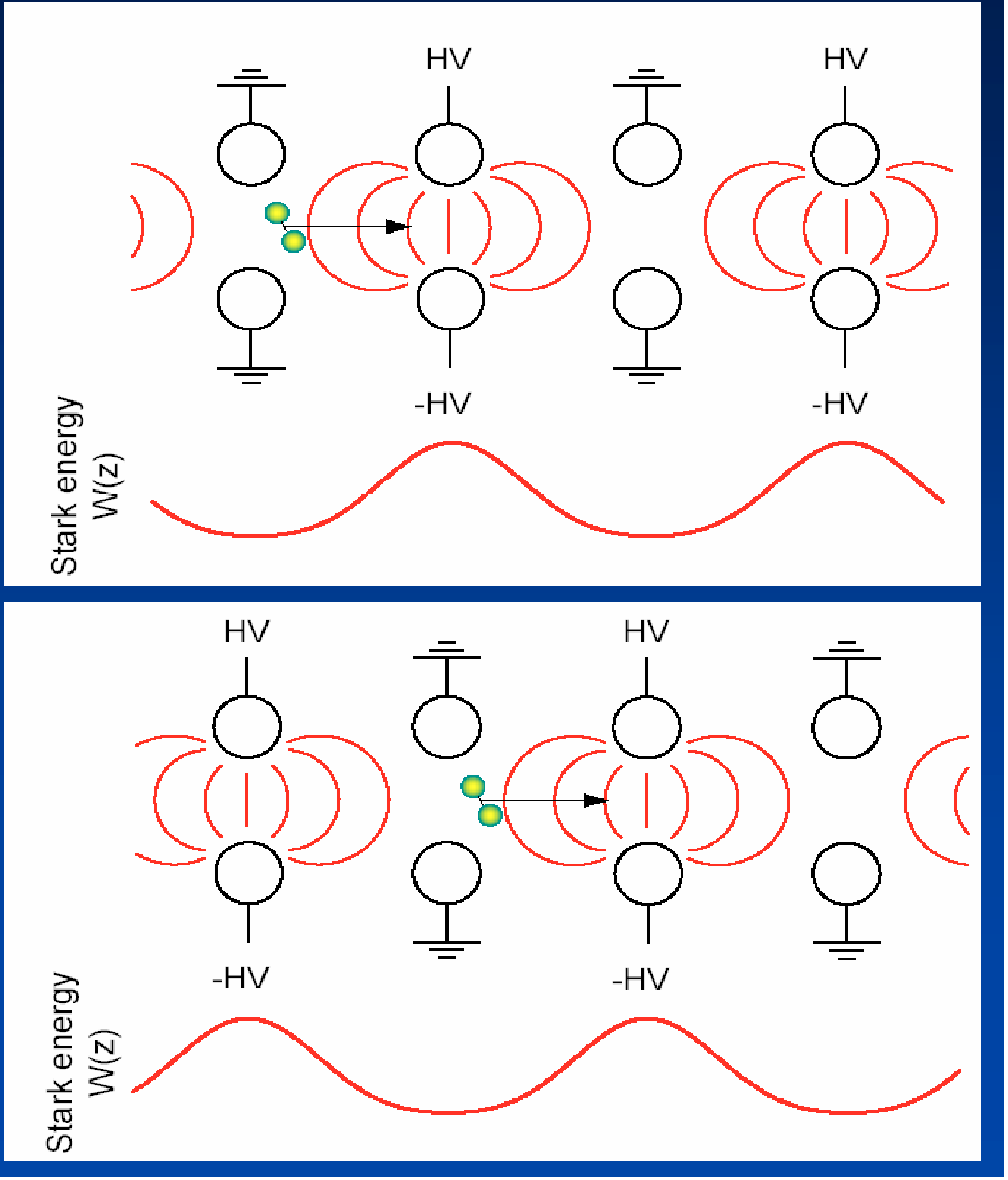
stark slowing of polar molecules



stark slowing of polar molecules

use stark shift!!!





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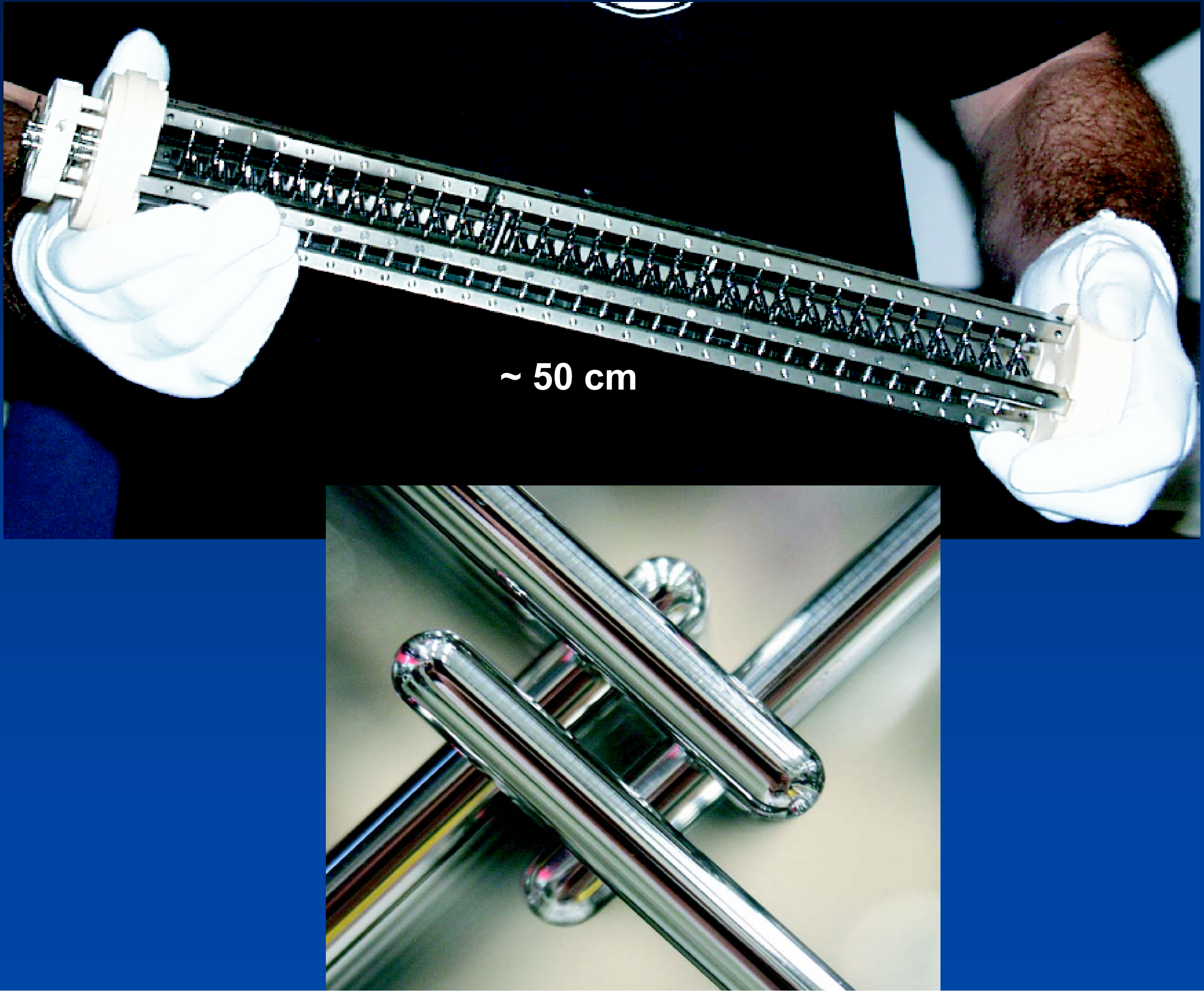
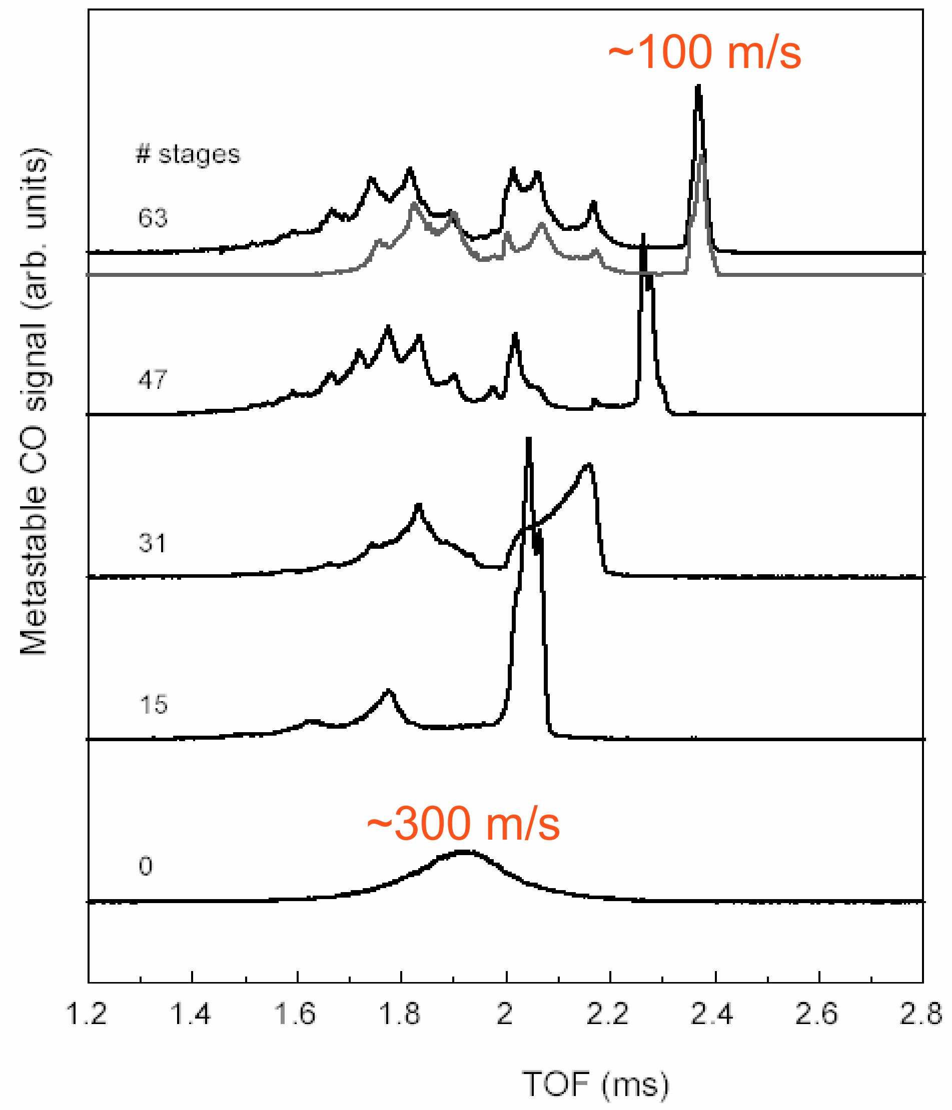


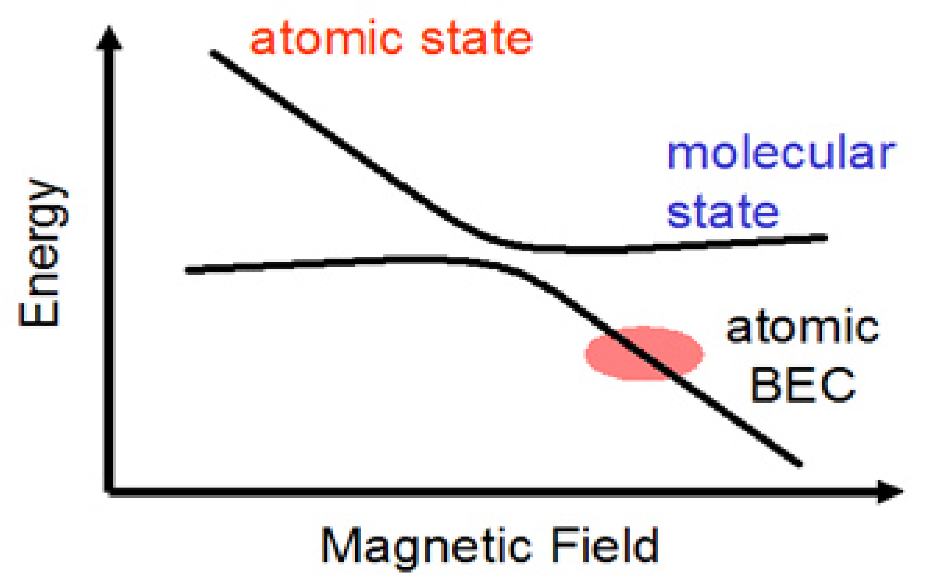
stark slowing of polar molecules

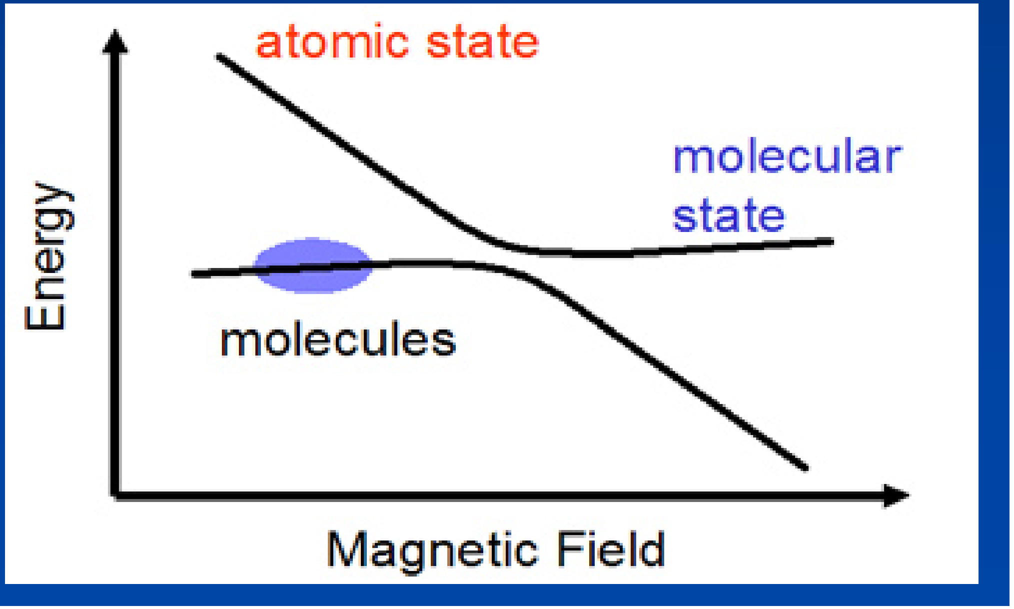
first results:



indirect production of cold molecules

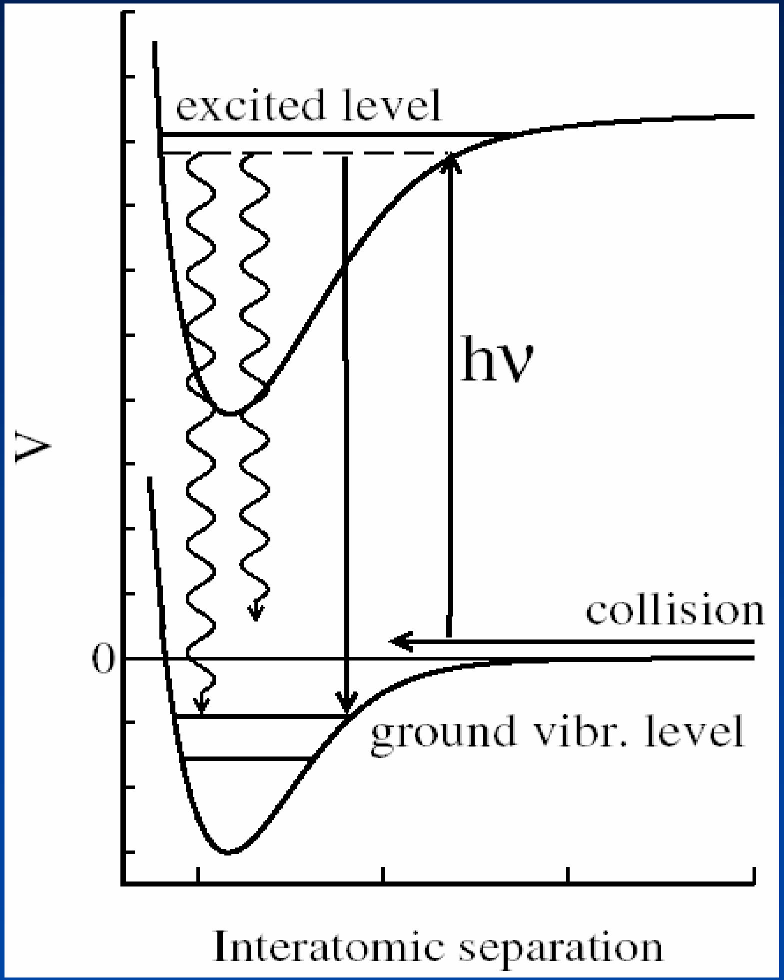
- use interspecies Feshbach resonance
  - Li-Na (Stan et al., PRL 93, 143001 (2004)), Rb-K (Simoni et al., PRL 60, 163202 (2003))
  - molecules have very short lifetime; exception: dimers of fermionic atoms (Petrov et al., J. Phys. B: At. Mol. Opt. Phys. 38, 645 (2005))
  - high vibrational states ⇒ negligible dipole moment





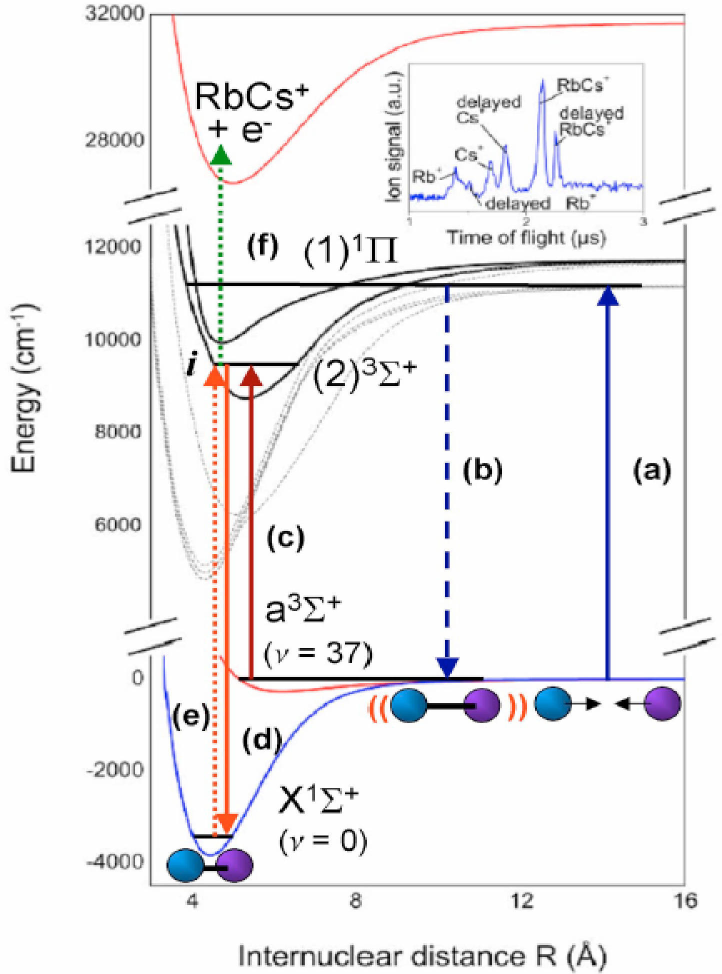
indirect production of cold molecules

- **photoassociation**



eg. Rb-K, Wang et al.,
arXiv:physics/0506232

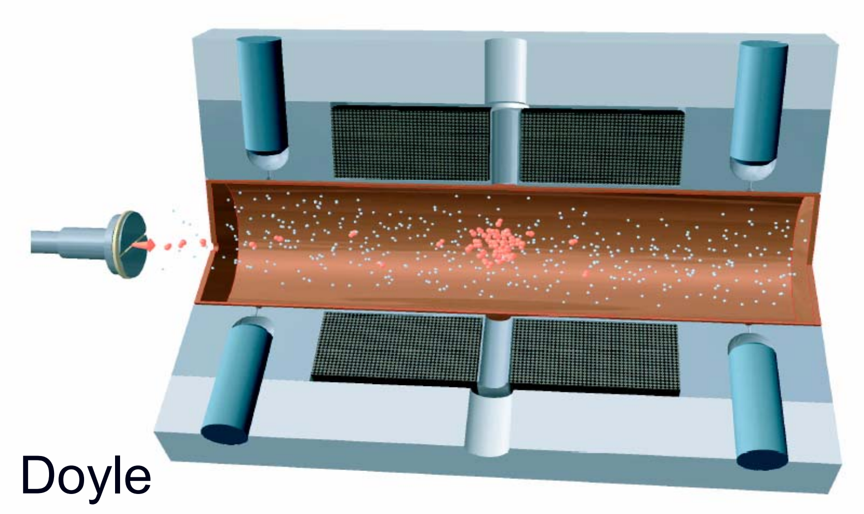
multistep process



Rb-Cs ground state molecules (500/s)
Sage et al., PRL 94, 203001 (2005)

trapping of cold molecules I

magnetic trapping:



Trapping Magnet

Anti-Helmholtz quadrupole trapping field

Superconducting NbTi windings

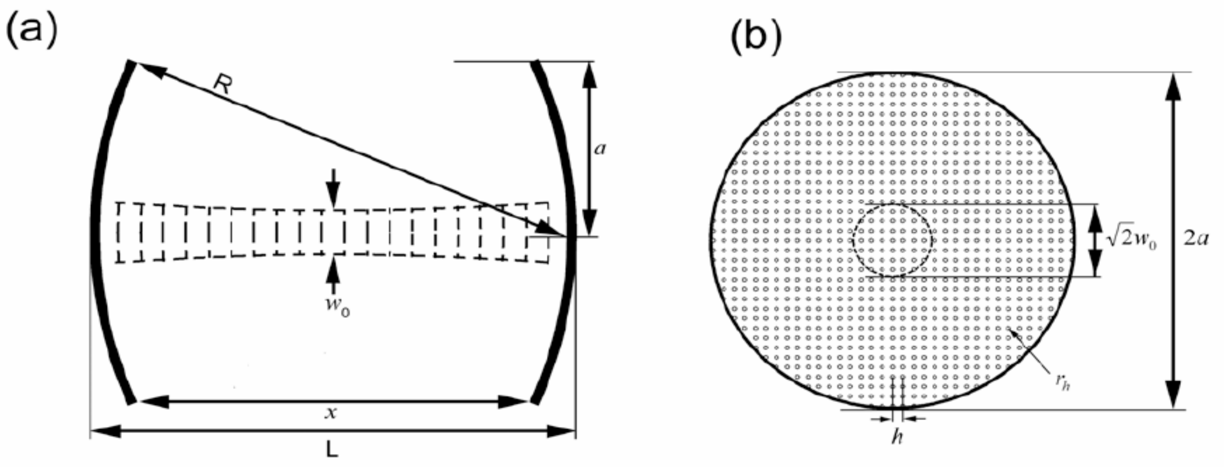
Large magnet bore (3") for loading and trapping

Current can be ramped for evaporative cooling

Magnet to operate in vacuum

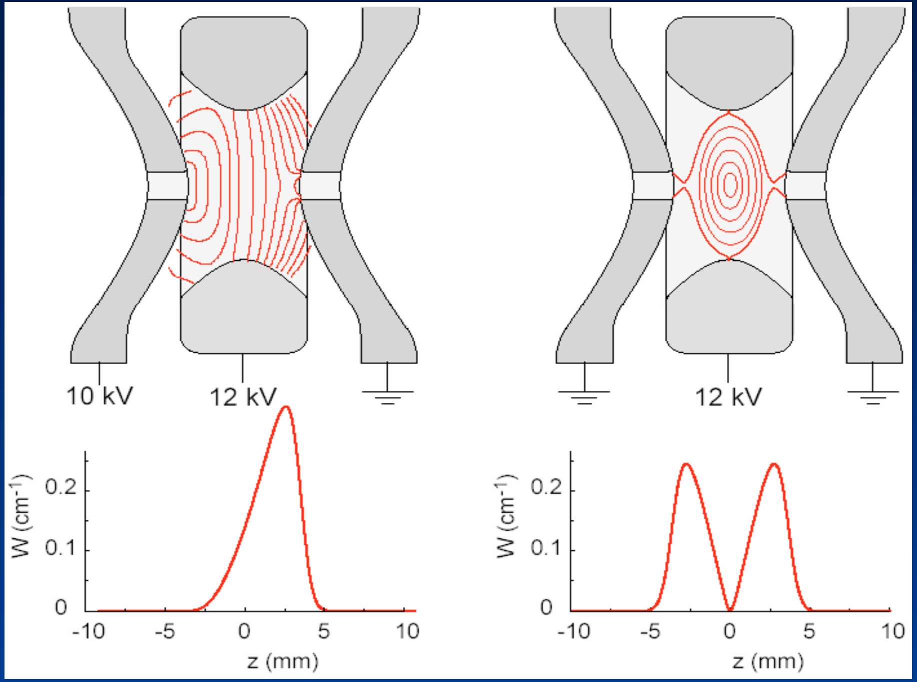
Trap Depth = 6 K for $2\mu_B$ at 4.5 Tesla

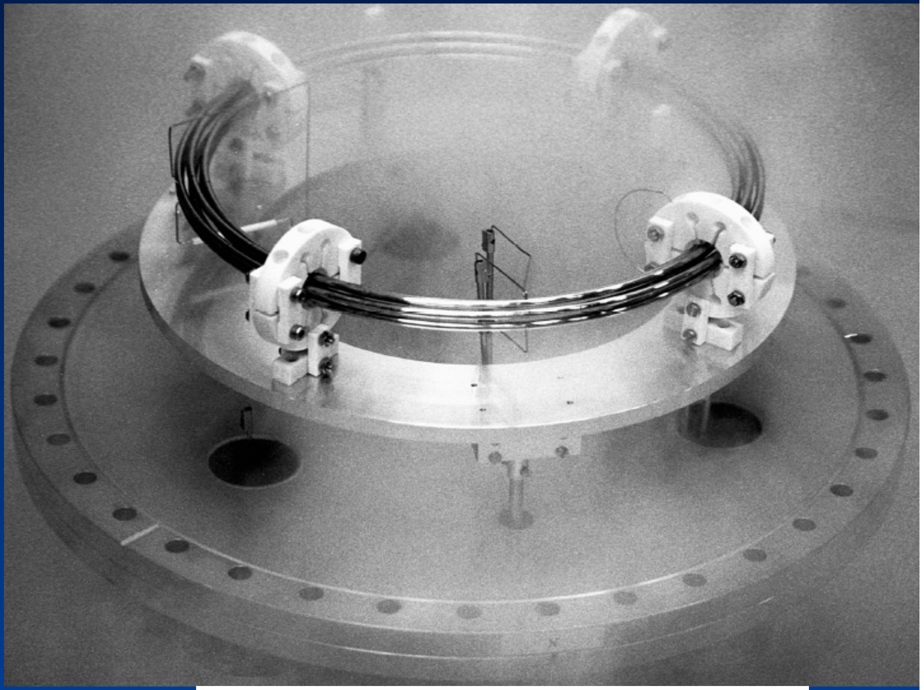
quasi-electrostatic trapping:

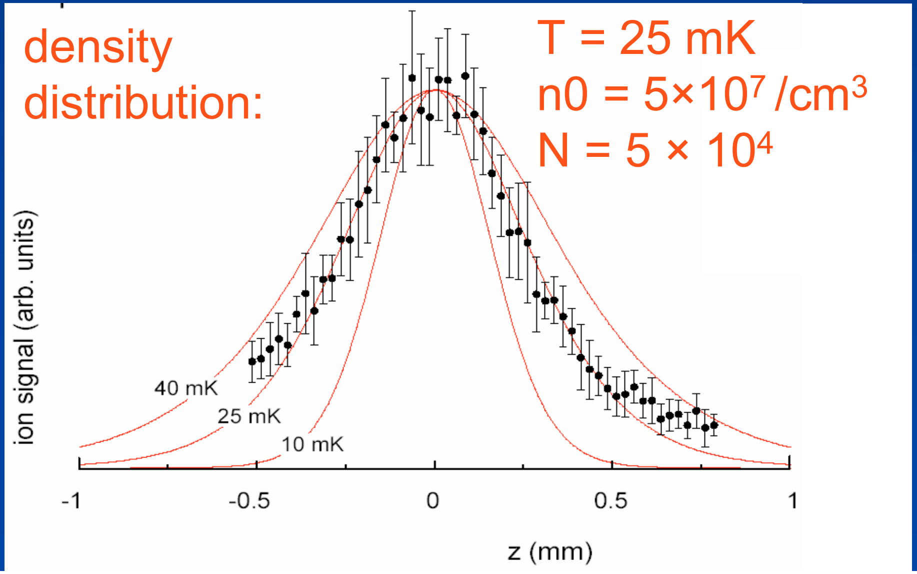


D. DeMille, D.R. Glenn, and J. Petrick, „Microwave traps for cold polar molecules”. Eur. Phys. J. D **31**, 375 (2004)

electrostatic trapping of cold molecules





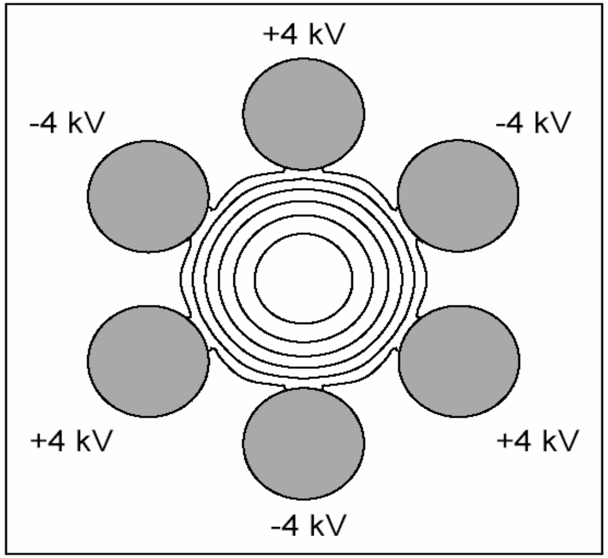


density distribution:

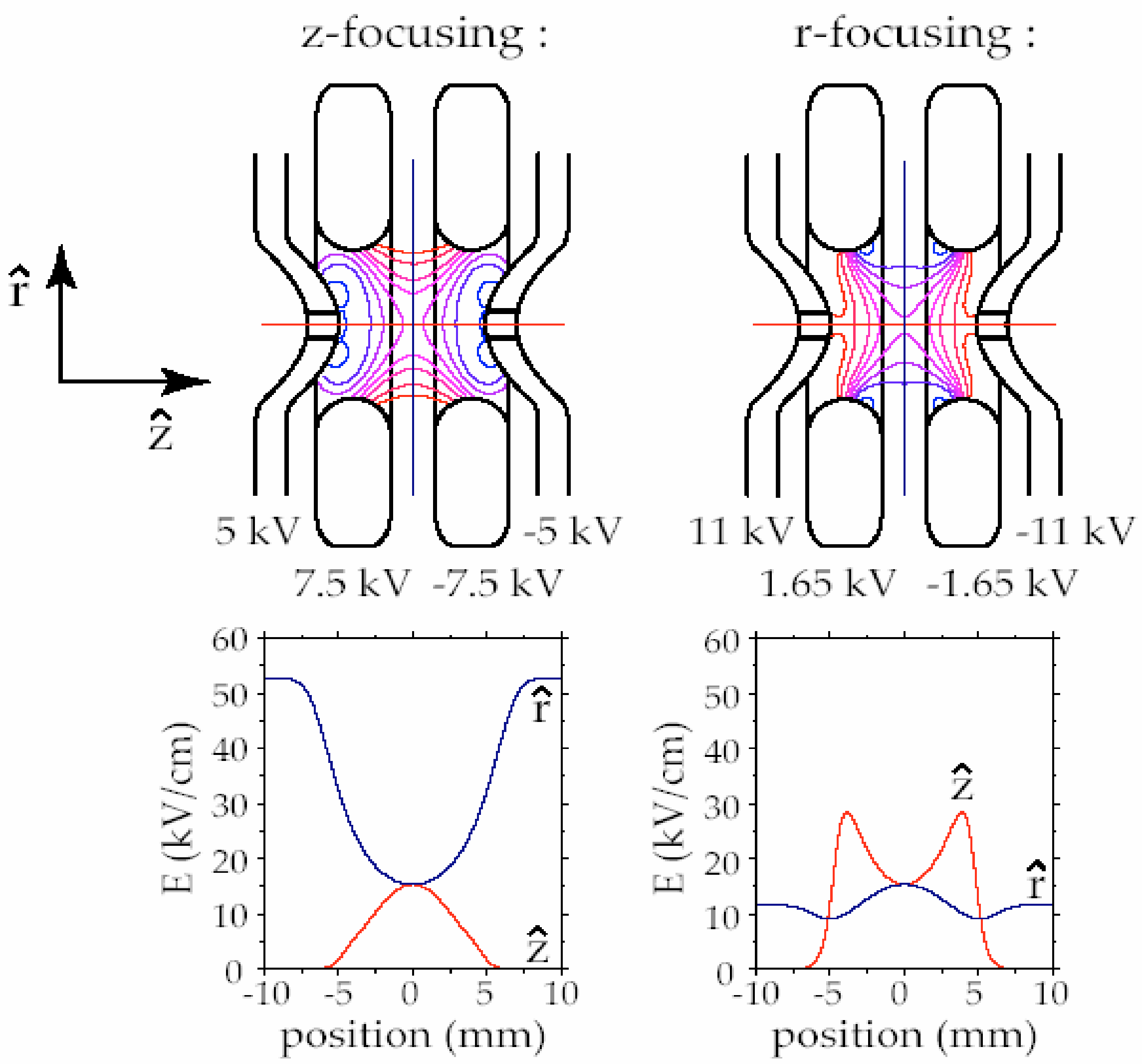
T = 25 mK

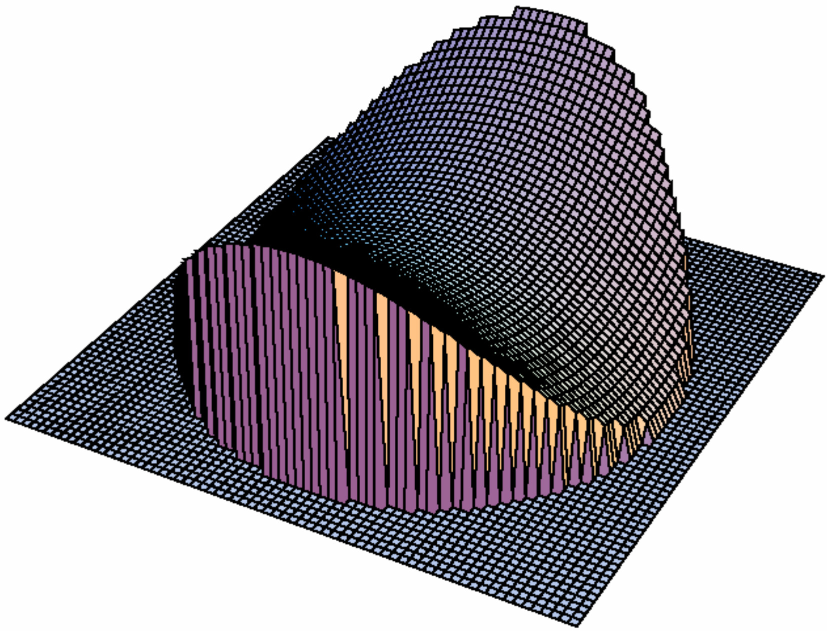
$n0 = 5 \times 10^7 /cm^3$

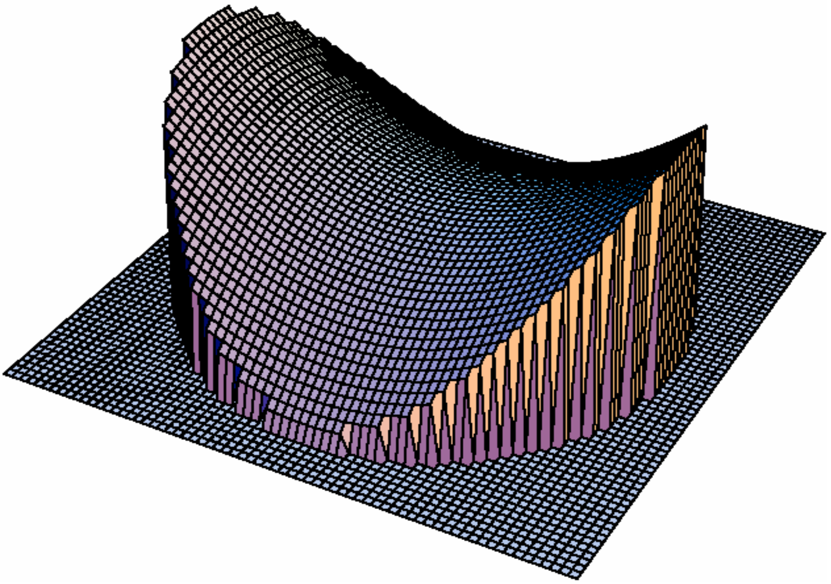
$N = 5 \times 10^4$



electrodynamic trapping of cold molecules





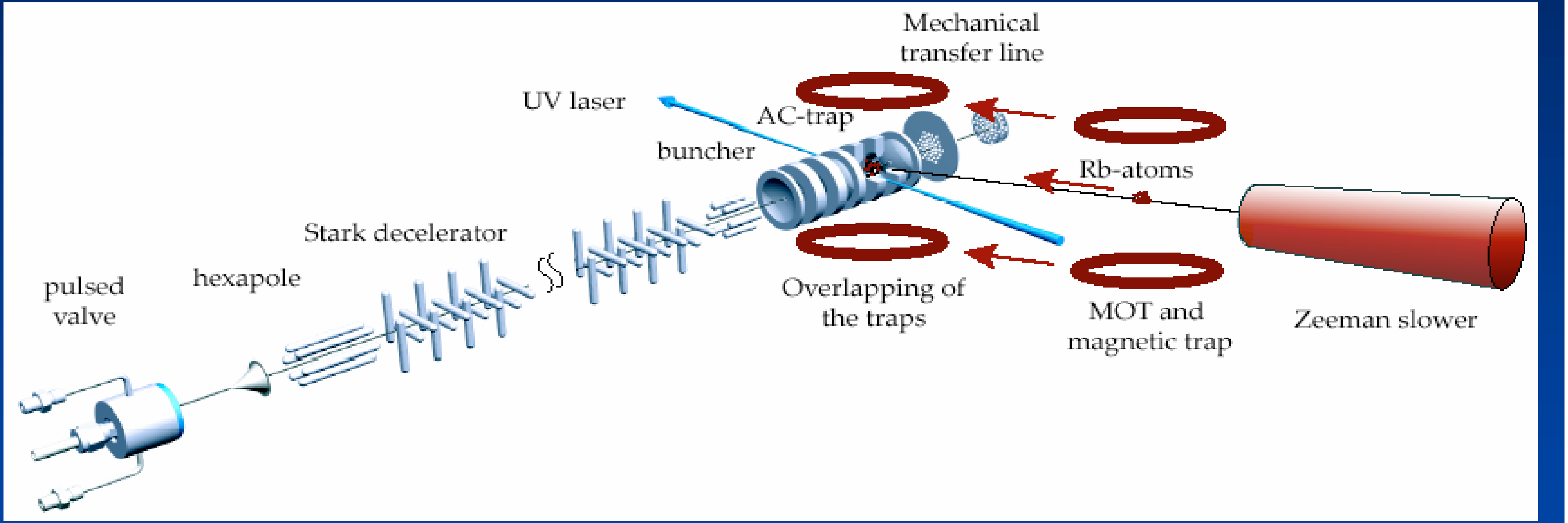


J. v. Veldhoven et al., PRL **94**, 083001 (2005)

T~1mK, $N=10^4$ in $V=0.02\,cm^3$, $n=5\times10^5\ cm^{-3}$

from cold to ultracold molecules

further cooling plans: sympathetic cooling of molecules using MOT (Rb)

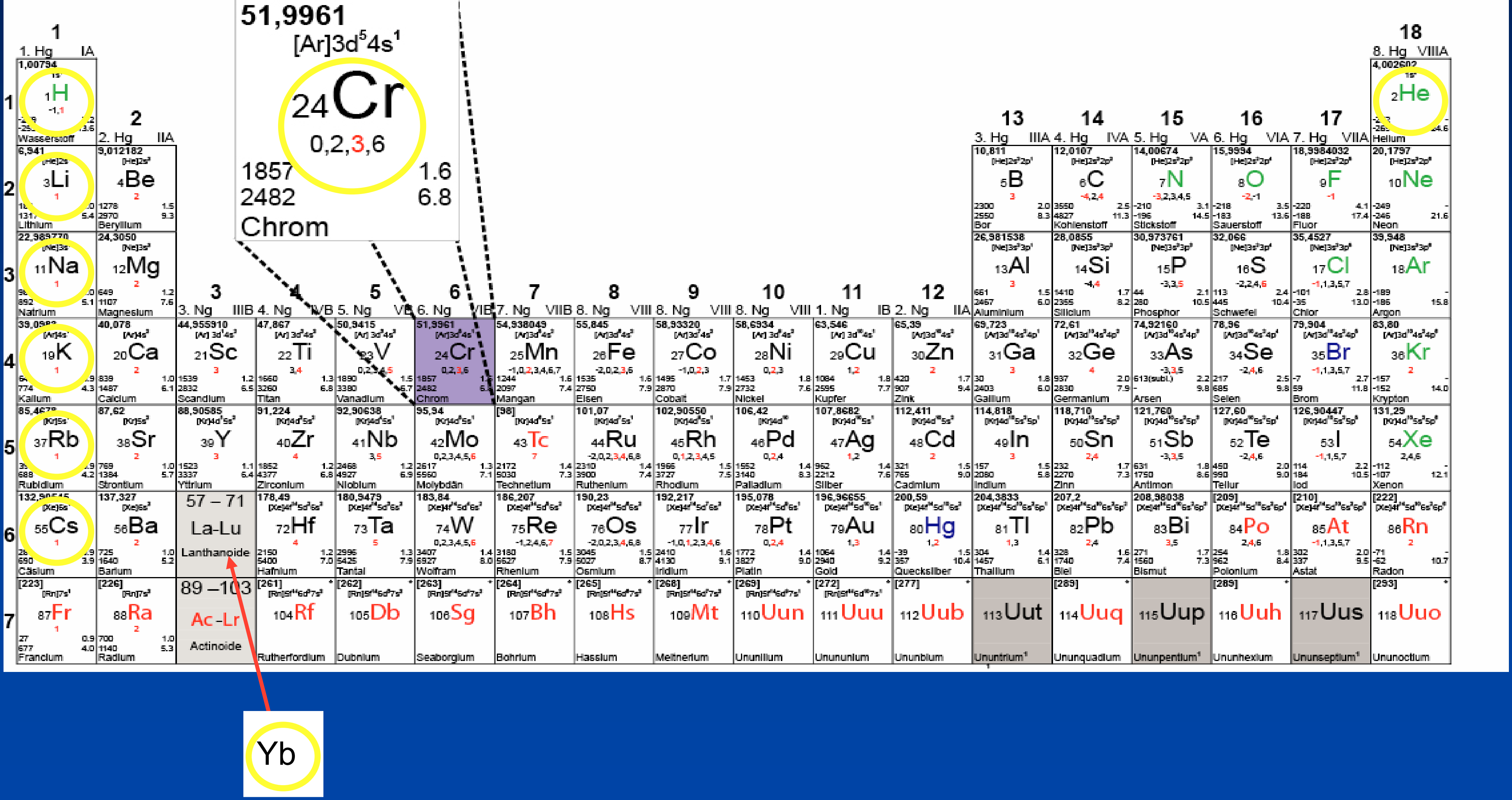


Gerard Meijer, Berlin

outline & second summary

- motivation & dipolar systems “in the game”
  - atoms (magnetic dipoles, small, tuning possible)
  - heteronuclear molecules (large static electric dipoles)
- production of cold molecules
  - slowing & cooling of molecules (direct production)
  - making molecules out of cold atoms (indirect production)
  - trapping dipolar molecules
  - strong effort, many groups, promising results, not yet there
- BEC of atoms with high magnetic moments (Cr)
  - what is special about Cr?
  - how to get BEC... problems & solutions
- first observation of dipole-dipole interaction in a degenerate quantum gas

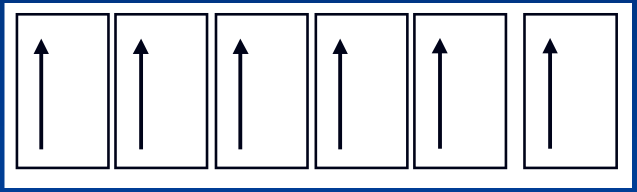
Cr in periodic table of elements



motivation – Cr properties

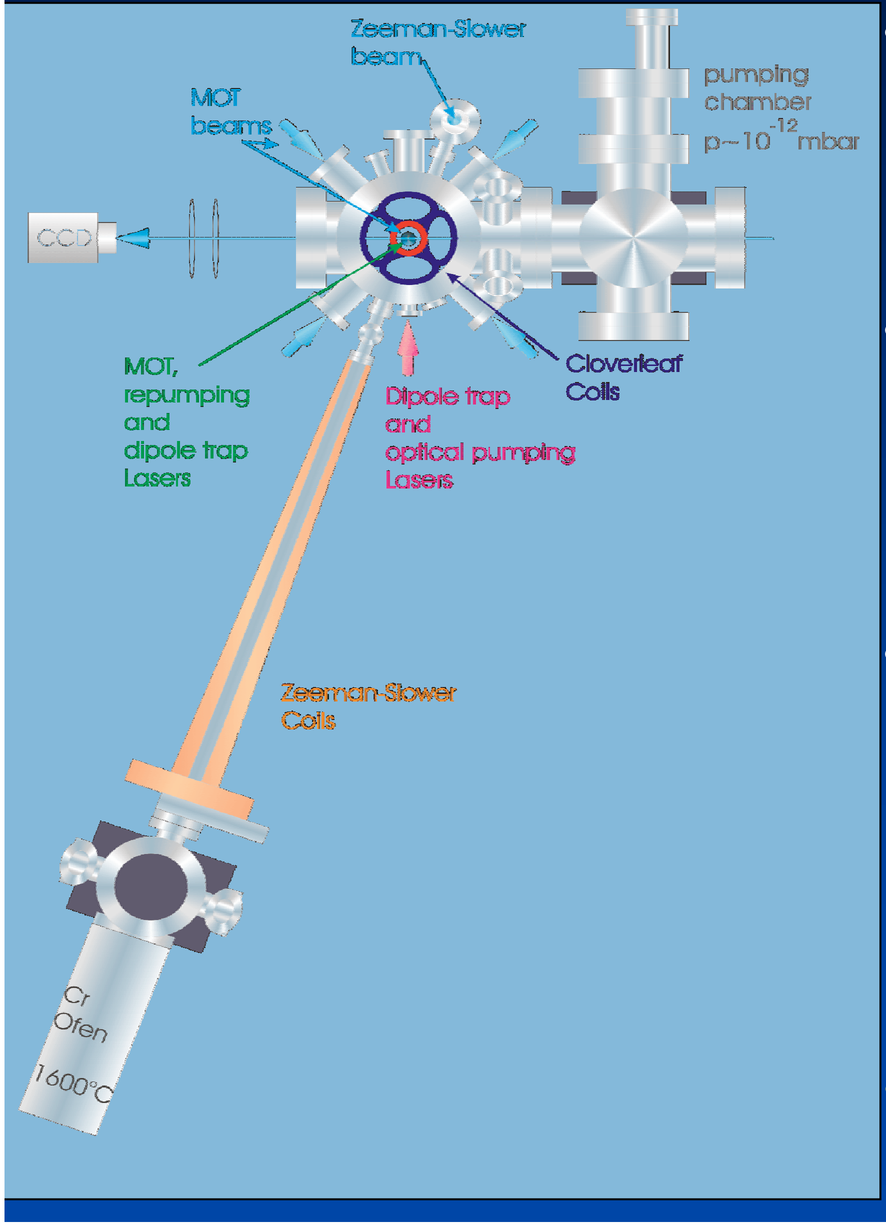
51,9961
[Ar]$3d^5 4s^1$
$_{24}$Cr
0,2,3,6
1857 1.6
2482 6.8
Chrom

- isotopic distribution
  - Bosons (I=0): ^{52}Cr (83.8%), ^{50}Cr (4.3%), ^{54}Cr (2.4%)
  - Fermion (I=3/2): ^{53}Cr (9.5%)
- versatile level scheme
- electronic configuration
  - [Ar]$3d^5 4s^1$ $\Rightarrow$ **S=3**



- large magnetic moment ***$\mu = 6\,\mu_B$!***

preparation of cold & dense Cr cloud



- continously loaded Ioffe Pritchard trap (CLIP-trap)

  J. Stuhler et al. PRA **64**, 031405 (2001); P. O. Schmidt et al. J. Opt. B **5**, S170 (2003)

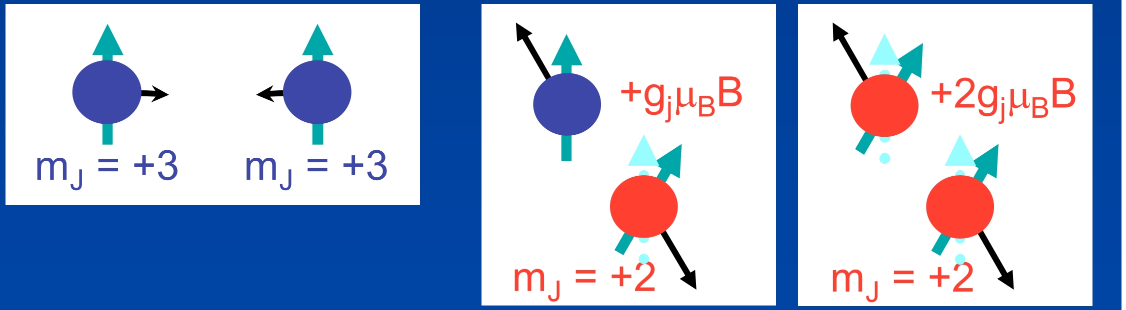
- Doppler cooling in compressed IP-trap

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

  2×10^8 atoms in the ground state

  phase space density $\rho \sim 10^{-7}$

- rf-evaporation → stop by dipolar relaxation



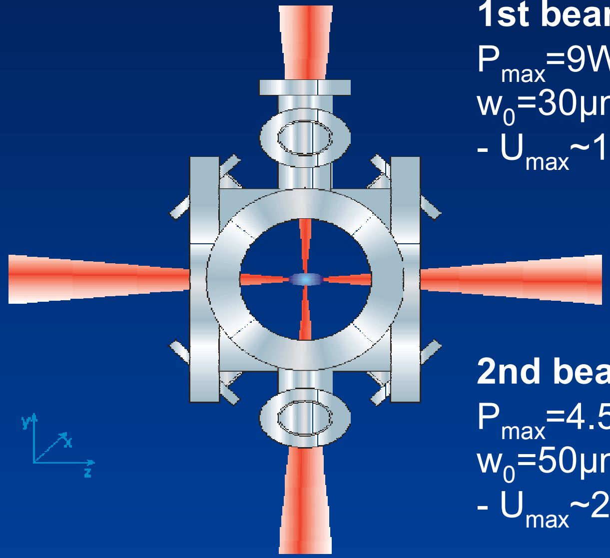
- no BEC in MT! ($\beta > 10^{12}$ cm^3/s)

  S. Hensler et al., Appl. Phys. B **77**, 765 (2003)

the way out

- optical dipole trap:

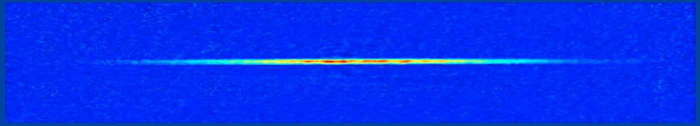
20W fibre Laser @ λ=1064 nm



1st beam:
P_{max}=9W
w_0=30μm
- U_{max}~130μK

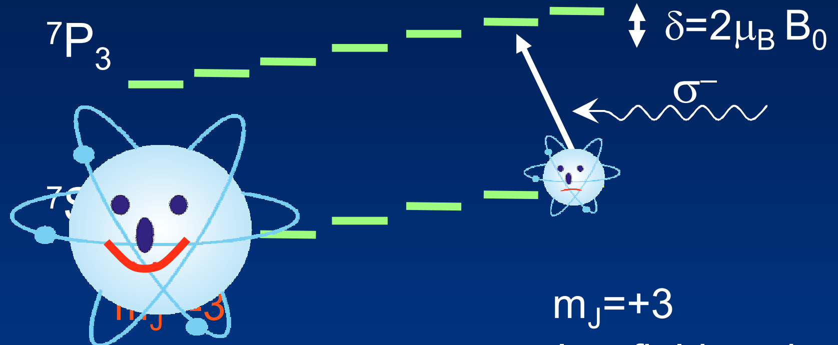
2nd beam:
P_{max}=4.5W
w_0=50μm
- U_{max}~22μK

advantages:
- operation at any offset field
- all magnetic substates trapable



problem:
- sample still mainly polarized in m_J=+3

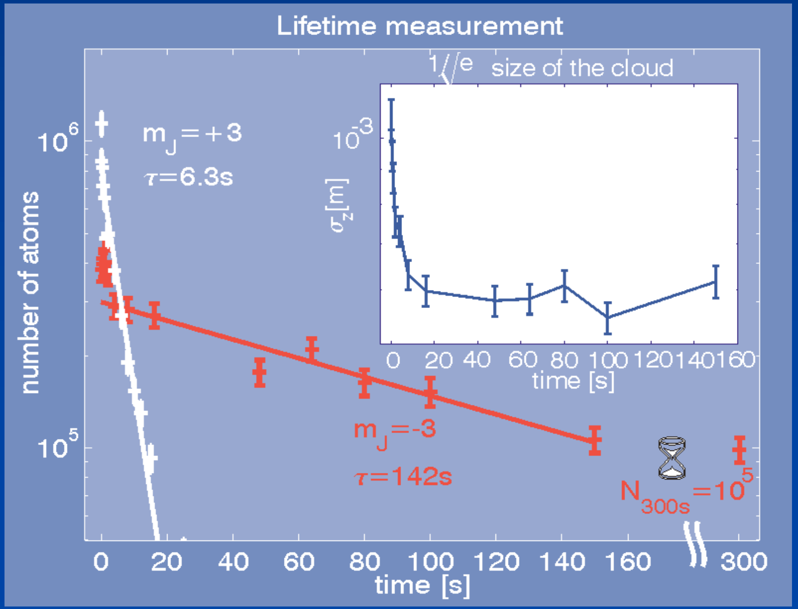
- pumping the atoms to magnetic ground state:



m_J=+3
„high field seeker“

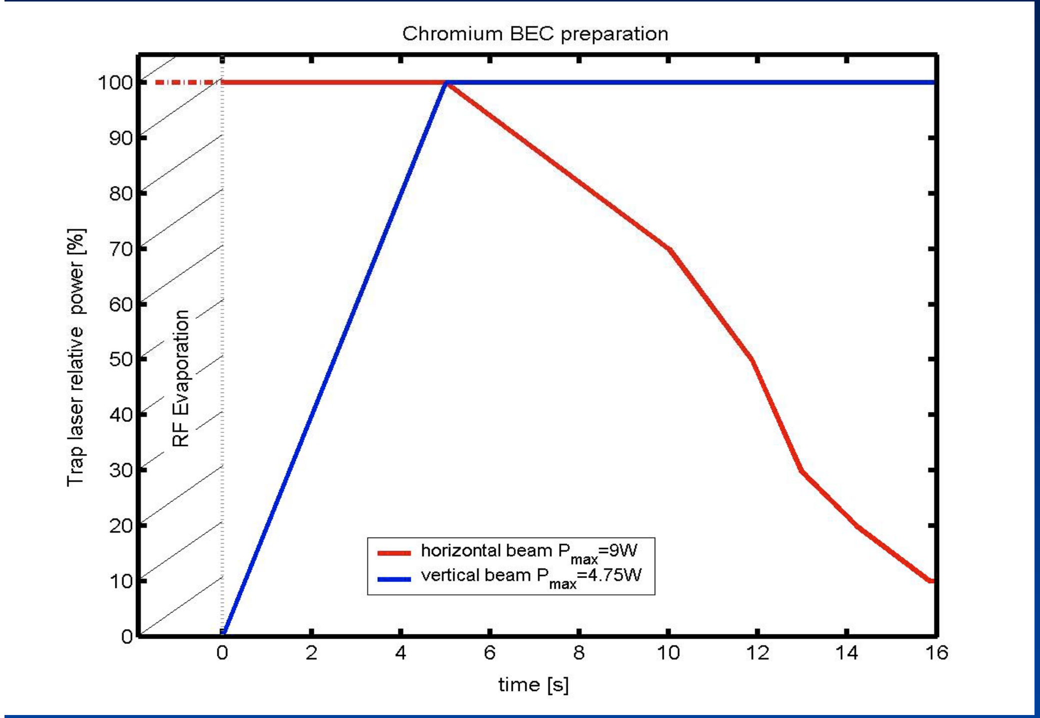
„low field seeker“

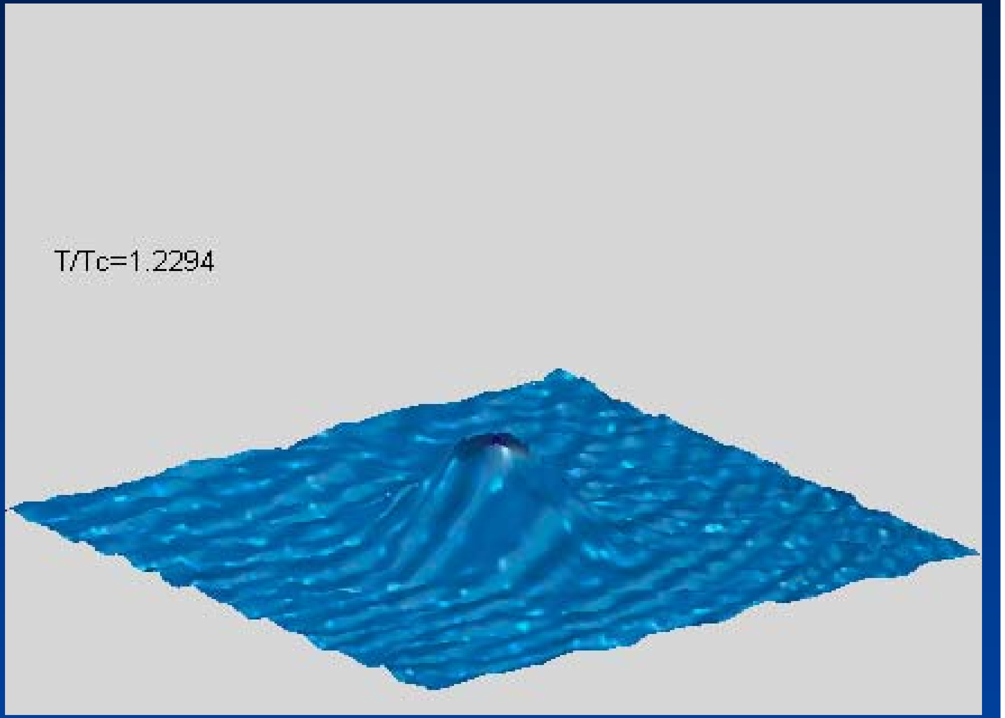
- dipolar relaxation suppressed



the final step to BEC of Cr

evaporation in crossed ODT

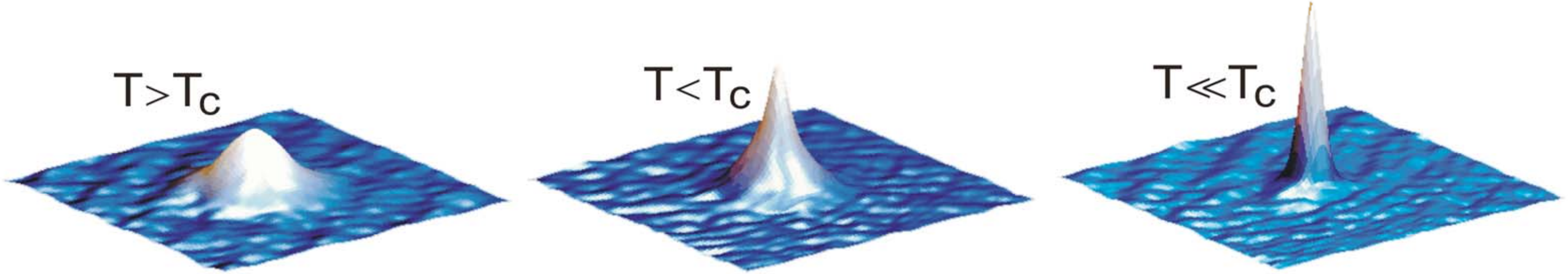




⇒ **BEC**

A. Griesmaier et al., PRL 94, 160401 (2005)

Cr-BEC

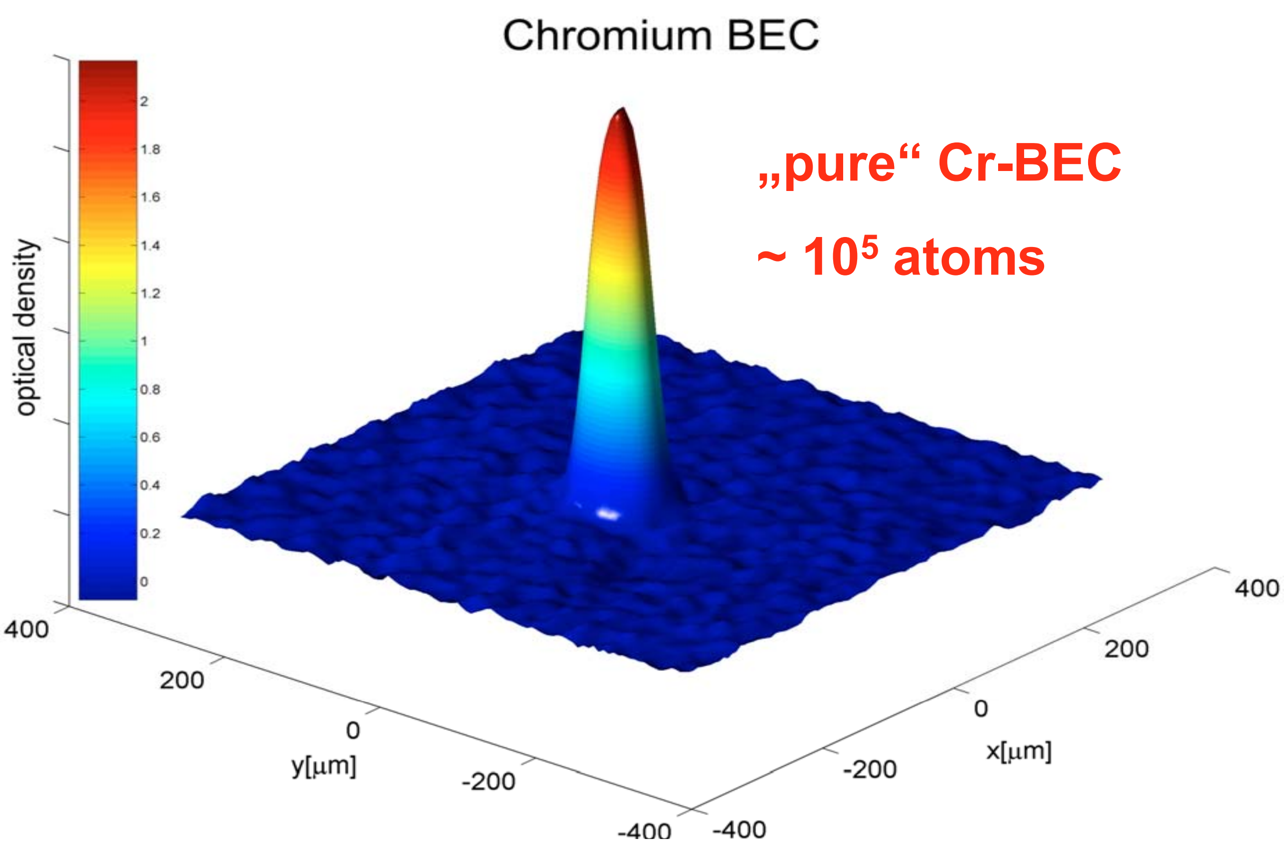


T_c~700 nK

ν_x=581 Hz

ν_y=406 Hz

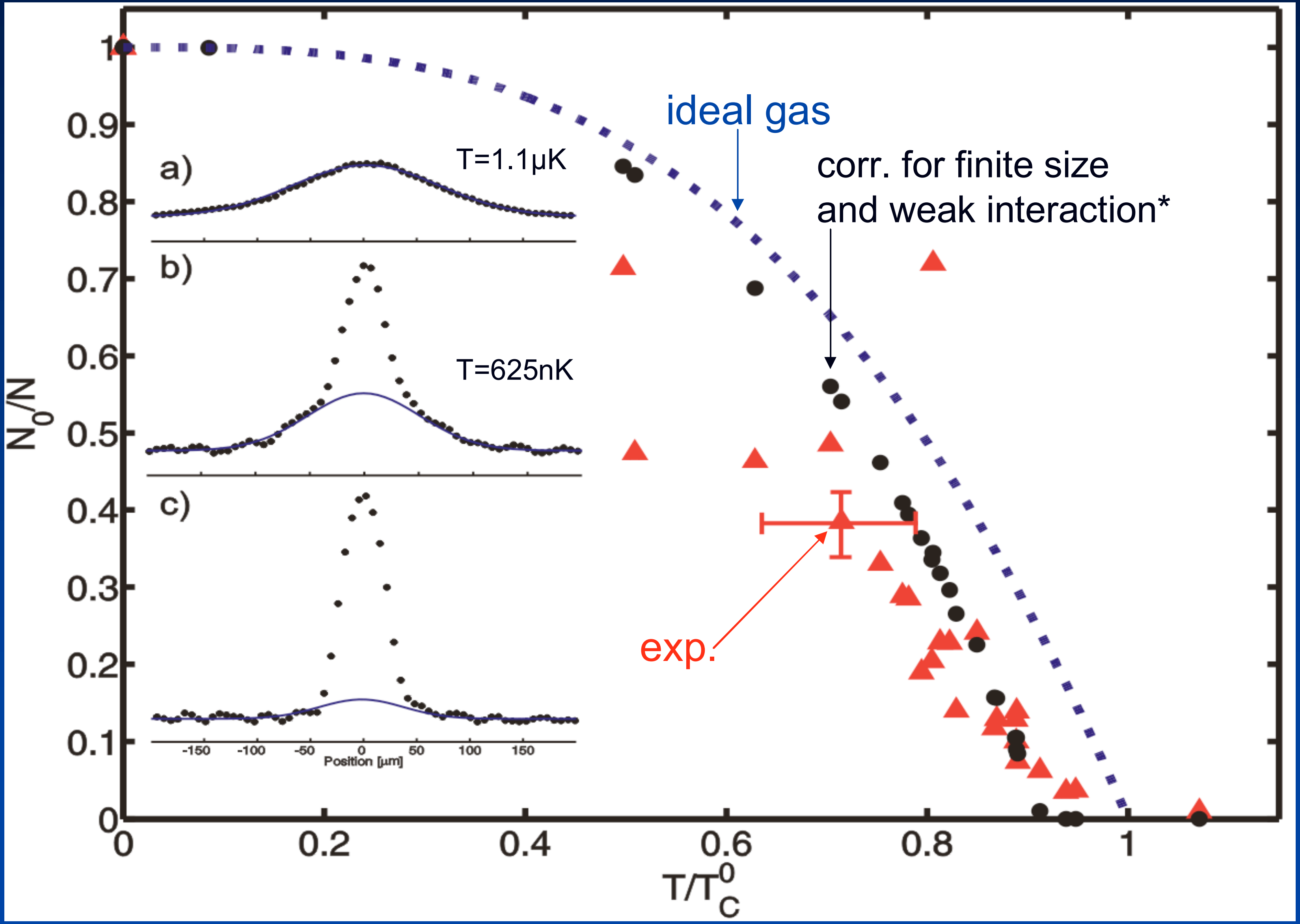
ν_z=138 Hz



„pure“ Cr-BEC

~ 10^5 atoms

Cr-BEC & phase transition



ν_x=581 Hz
ν_y=406 Hz
ν_z=138 Hz

T_c~700 nK

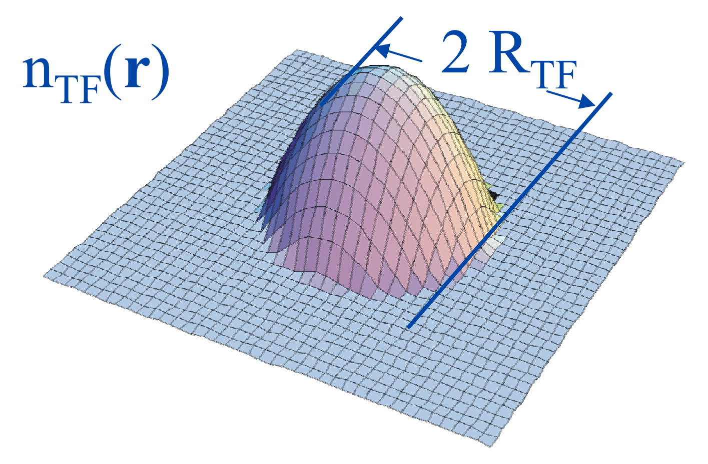
* S. Giorgini, L. P. Pitaevskii, and S. Stringari, Phys. Rev. A 54, R4633 (1996)

outline & third summary

- motivation & dipolar systems “in the game”
  - atoms (magnetic dipoles, small, tuning possible)
  - heteronuclear molecules (large static electric dipoles)
- production of cold molecules
  - slowing & cooling of molecules (direct production)
  - making molecules out of cold atoms (indirect production)
  - trapping dipolar molecules
  - strong effort, many groups, promising results, not yet there
- BEC of atoms with high magnetic moments (Cr)
  - not easy but achieved, ready to go!
- first observation of dipole-dipole interaction in a degenerate quantum gas
  - dipole-dipole interaction modifies BEC expansion

dipole-dipole interaction as perturbation

- BEC without dipoles in an
- isotropic harmonic trap
- in Thomas-Fermi limit

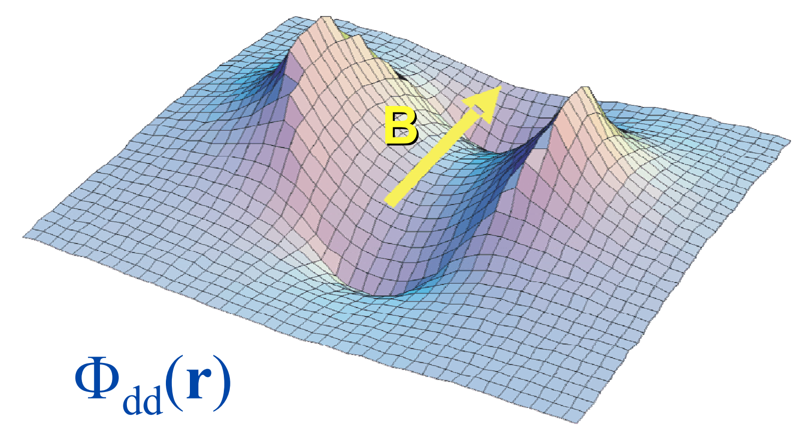


perturbation by dipole interaction:

⇒ parabolic density profile

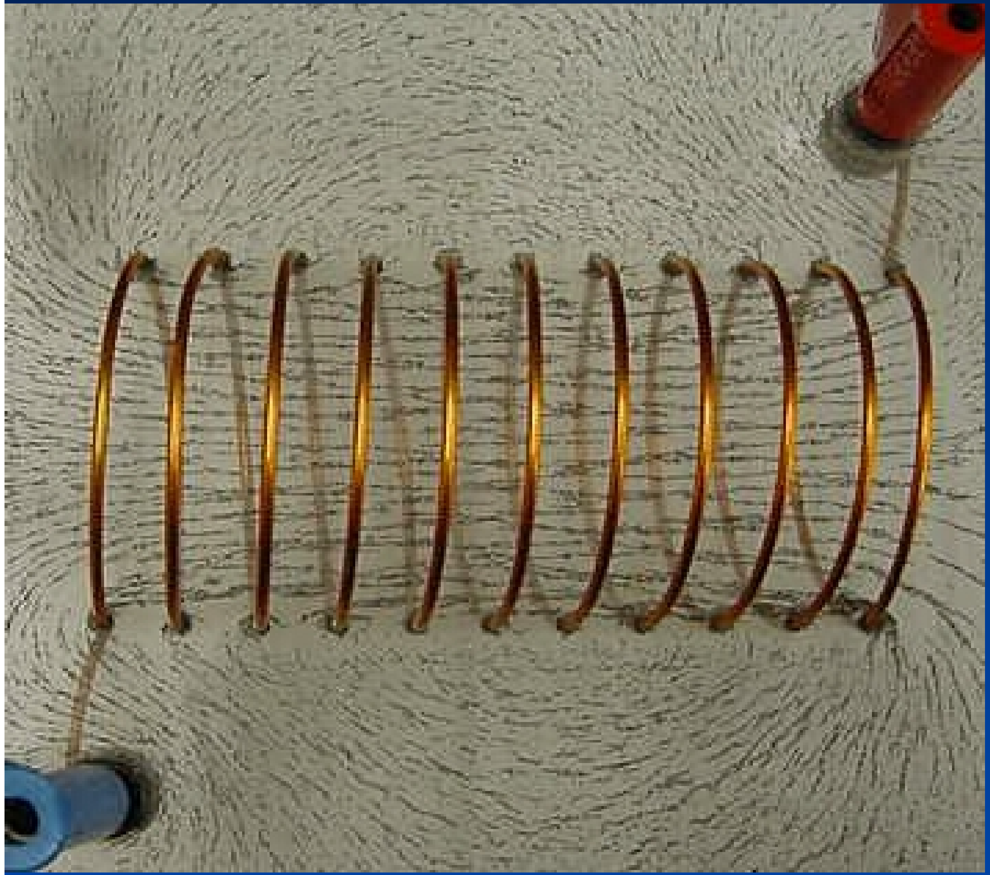
$$\Phi_{dd}(\mathbf{r}) = \int n_{TF}(\mathbf{r}')U_{dd}(\mathbf{r}-\mathbf{r}')d\mathbf{r}'$$

$$= -\frac{\varepsilon_{dd} m\omega_0^2}{5}\left[3\cos^2\vartheta - 1\right] r^2; \qquad r < R_{TF}$$



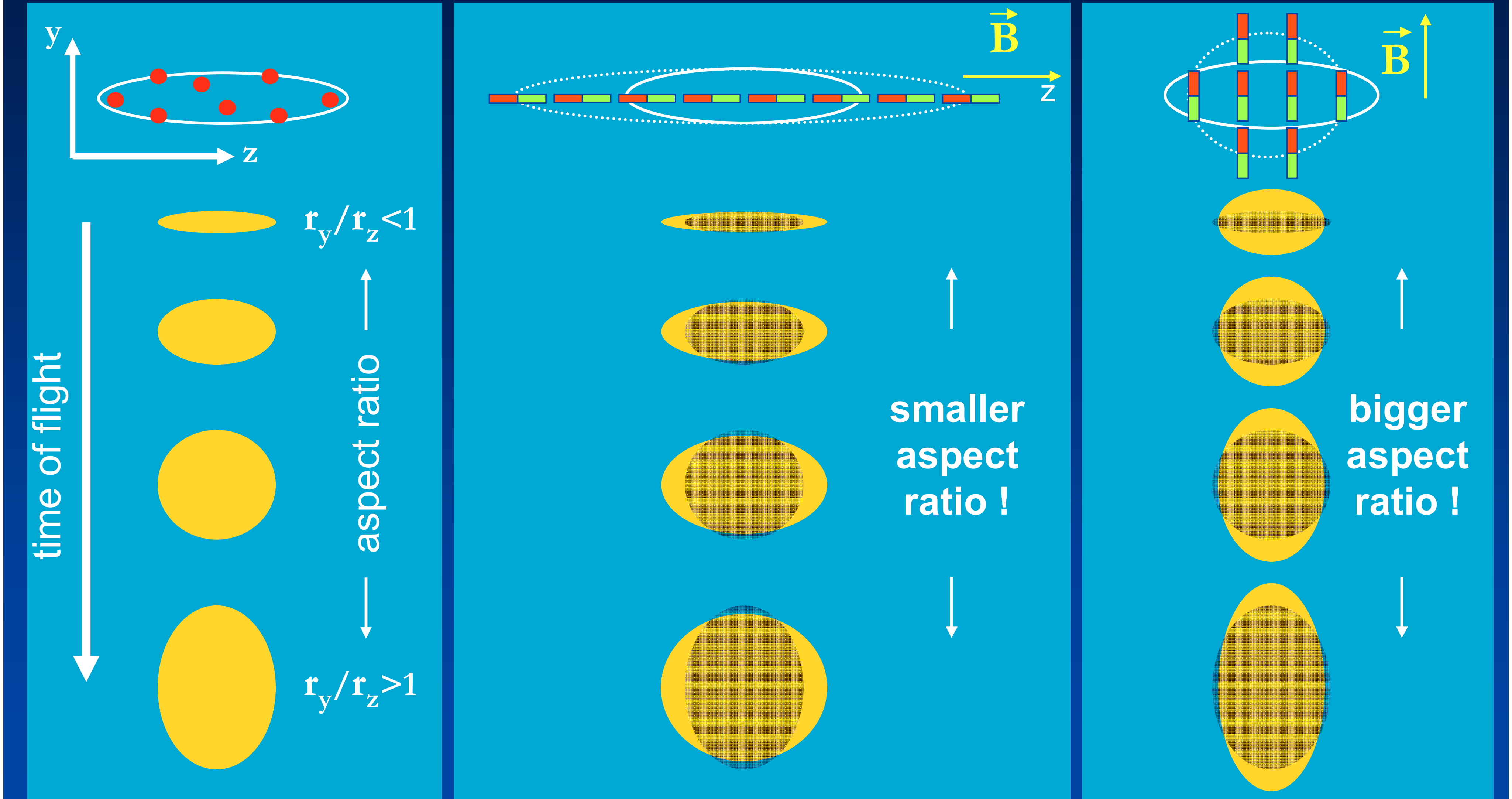
similar behaviour with solids and liquids

iron particles:



ferrofluids:

dipole-dipole interaction & aspect ratio

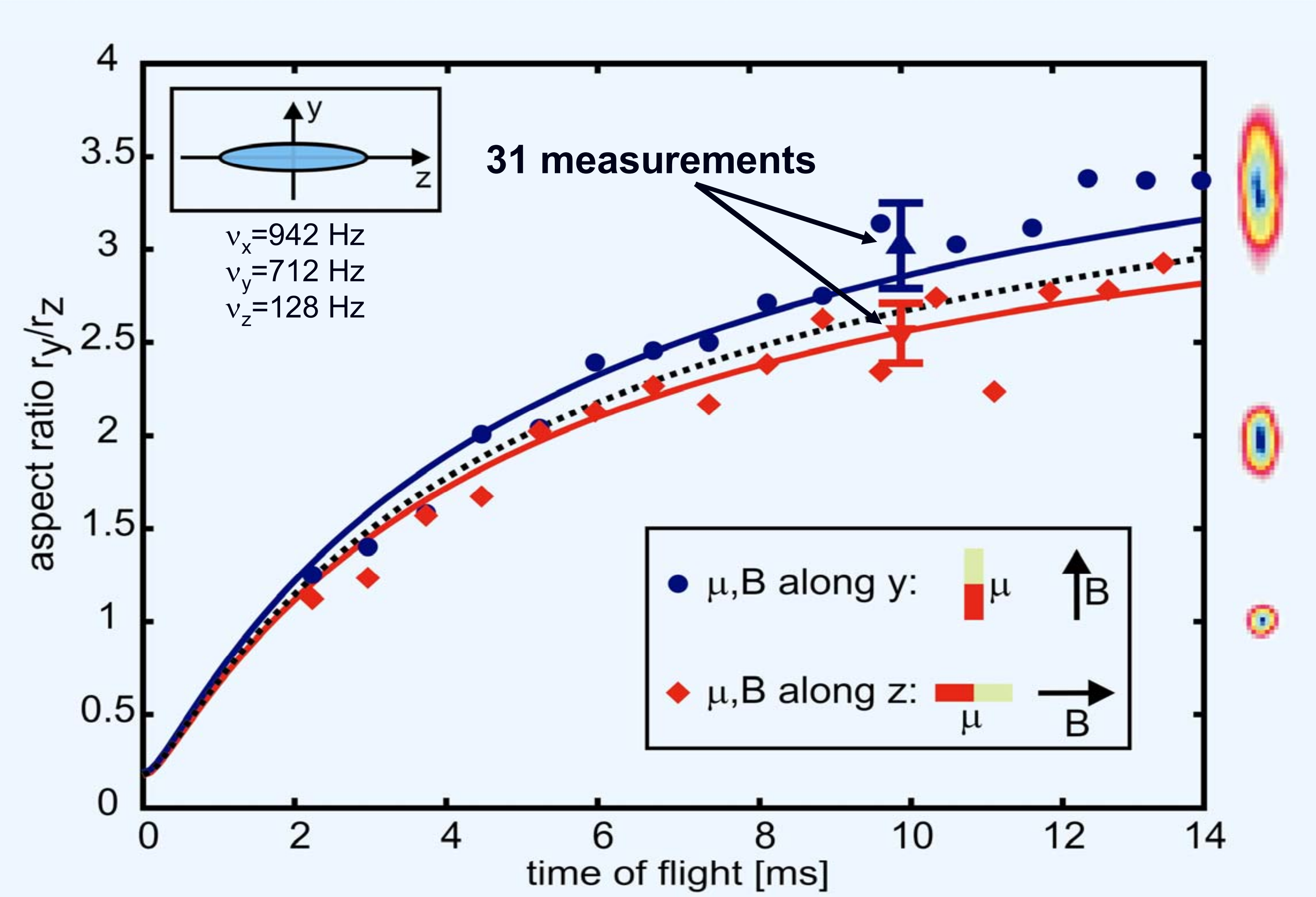


smaller aspect ratio !

bigger aspect ratio !

Magnetostriction!

magnetostriction/dipolar expansion



theory – no free parameters! S. Giovanazzi , P. Pedri, L. Santos

final summary

- motivation & dipolar systems “in the game”
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  - trapping dipolar molecules
  - strong effort, many groups, promising results, not yet there
- BEC of atoms with high magnetic moments (Cr)
- first manifestation of dipole-dipole interaction in a degenerate quantum gas
  - dipole-dipole interaction modifies BEC expansion (magnetostriction)