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Condensation du chrome et collisions assistées par champs radio-fréquence

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Chromium : S=3 ↑↑↑↑↑↑

Large sensitivity to (rf) magnetic fields

$g_J = 2$ $m_S = 3,\ldots,-3$

Initial motivation for chromium: strong magnetic traps

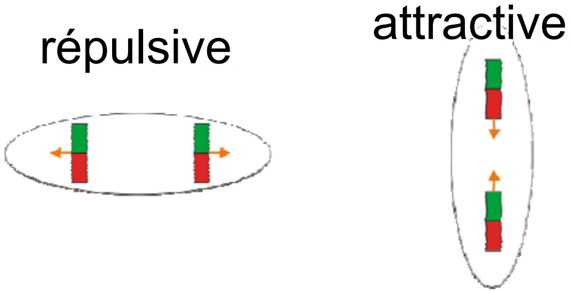
Doyle, Phys. Rev. A **57**, R3173 (1998)

No hyperfine structure

Simplification (?) for MOT

Purely linear Zeeman effect; simple description of rf-dressed states

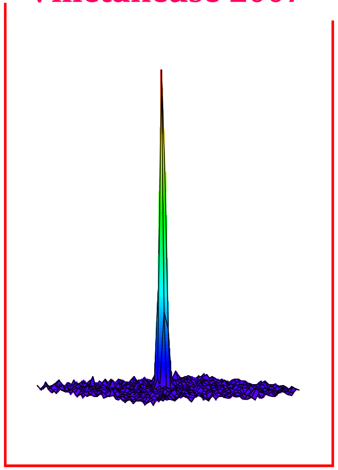
Large magnetic dipole-dipole interactions



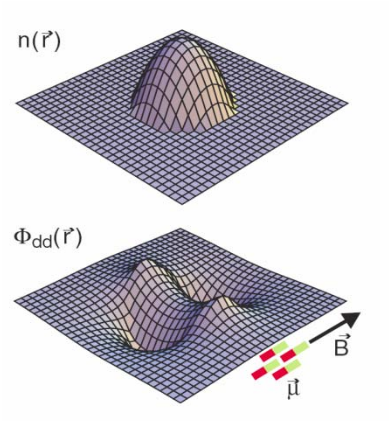
$$\varepsilon_{dd} = \frac{V_{dipolaire}}{V_{contact}} = 0.16$$

BEC: Stuttgart 2004

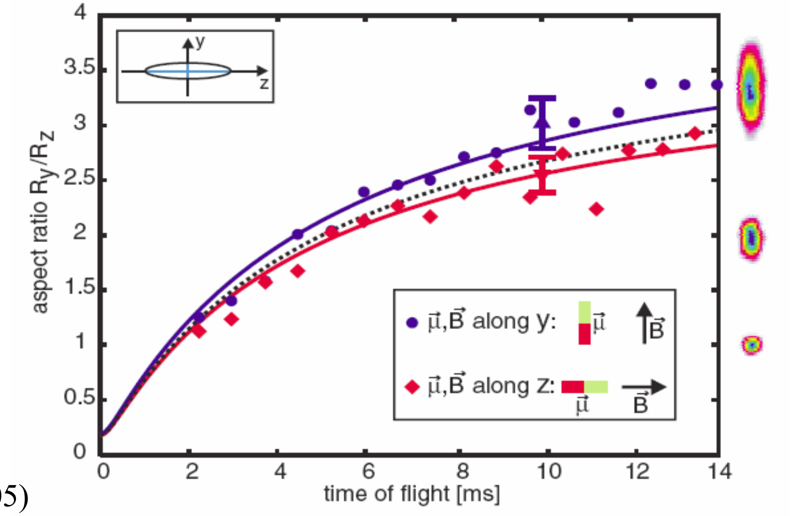
Villetaneuse 2007



Stuttgart: modification of self-similar expansion

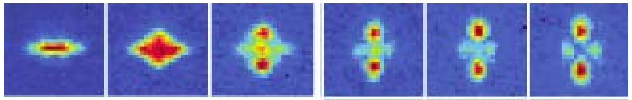


Pfau, PRL 95, 150406 (2005)



Tune contact interactions using Feshbach resonances: dipolar interaction larger than Van-der-Waals interaction **Nature. <u>448</u>, 672 (2007)**

Stuttgart: d-wave collapse



Pfau, PRL 101, 080401 (2008)

And… collective excitations, Tc, solitons, vortices, Mott physics, 1D or 2D physics…

Large inelastic losses

Large dipole-dipole interactions

+

No hyperfine interactions

=

a nice system to study inelastic collisions

$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \frac{1-3\cos^2(\theta)}{R^3}$$

Anisotropic dipole-dipole interactions

↓

Different partial waves are coupled

$$\Delta l = 2$$

→ Control of inelastic collisions (energy of output channel, geometry)

Pfau, Appl. Phys. B, **77**, 765 (2003)

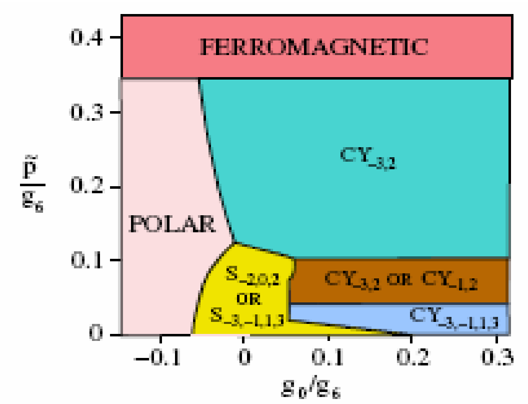
Pfau, Nature Physics **2** , 765 (2006)

- Feshbach resonances due to dipole-dipole interactions

Rich spinor physics

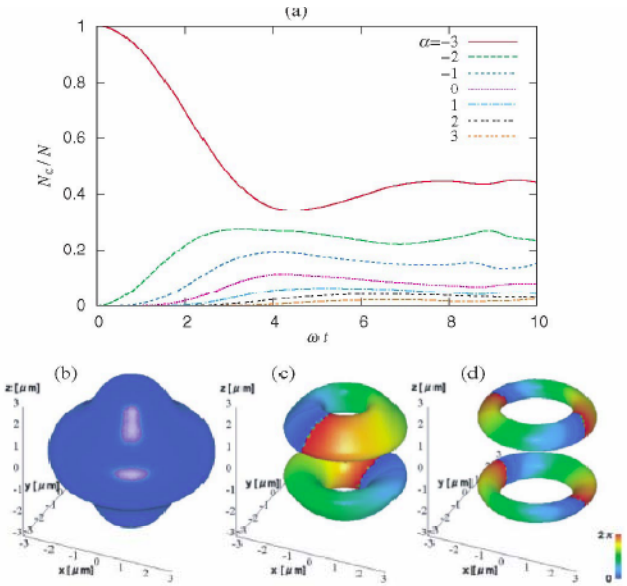
An new phase diagram:

Santos and Pfau
PRL 96, 190404 (2006)



Effect of dipole-dipole interactions: collisions with change of total magnetization (Einstein-de-Haas effect)

Ueda,
PRL **96**, 080405 (2006)



$$\Delta E = \Delta m_S \mu_B B$$

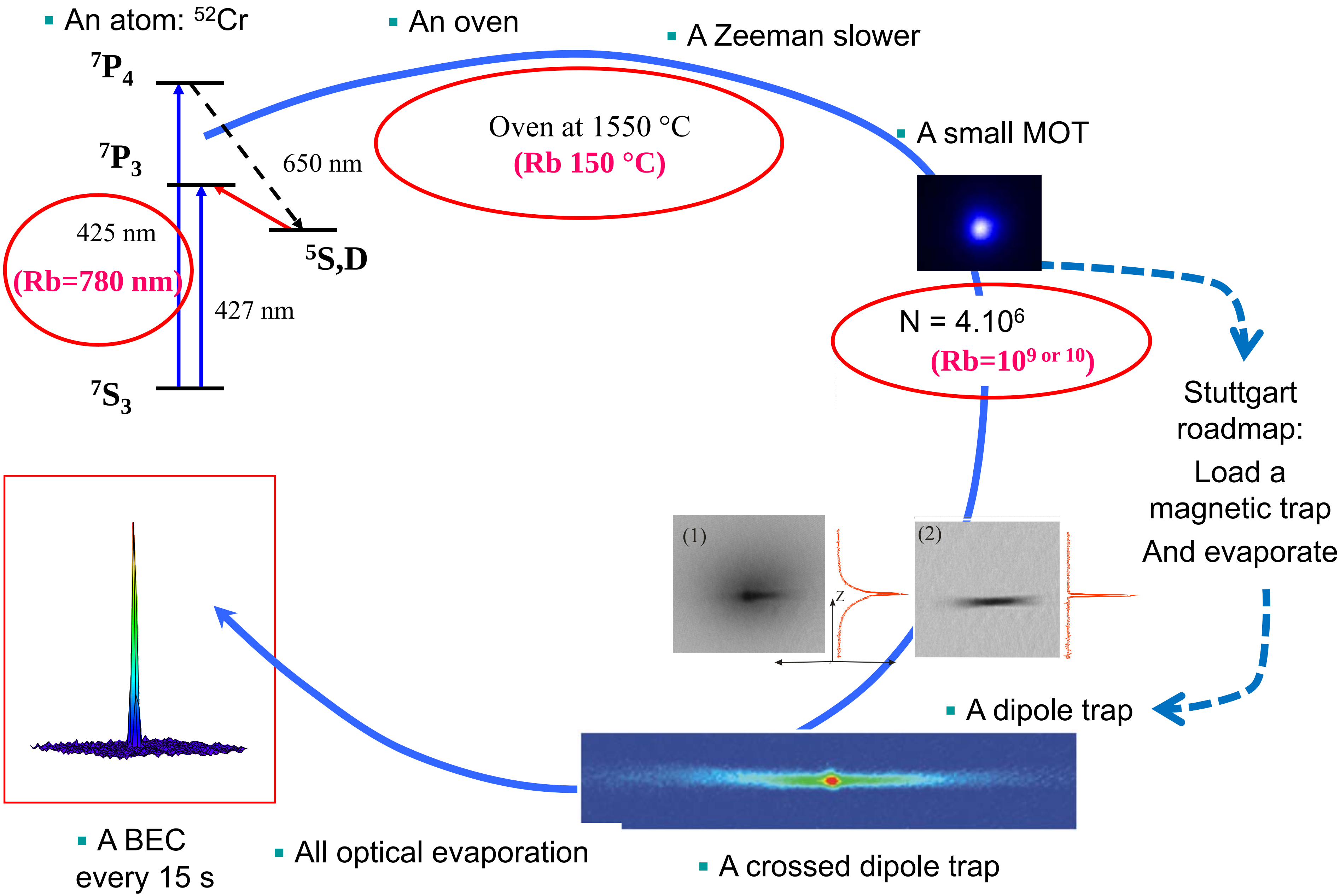
Need of an extremely good control of B (or of the difference of energy between Zeeman substates)

I Condensation tout-optique du chrome

II Contrôle de collisions inélastiques par champs radio-fréquence

- -Relaxation dipolaire
- -Association de molécules

III Contrôle du facteur de Landé par champs radio-fréquence

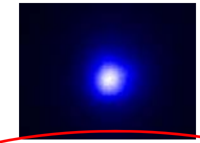


An atom: 52Cr
7P4
7P3
650 nm
425 nm
(Rb=780 nm)
427 nm
5S,D
7S3
An oven
Oven at 1550 °C
(Rb 150 °C)
A Zeeman slower
A small MOT
N = 4.10^6
(Rb=10^9 or 10)
Stuttgart roadmap:
Load a magnetic trap
And evaporate
(1)
(2)
Z
A dipole trap
A crossed dipole trap
All optical evaporation
A BEC every 15 s

Cr Magneto-optical traps

R. Chicireanu et al.Phys. Rev. A **73**, 053406 (2006)

- ^{52}Cr



N = 4.10^6 bosons

Loading rate = 3.5 10^8 atoms/s

- ^{53}Cr

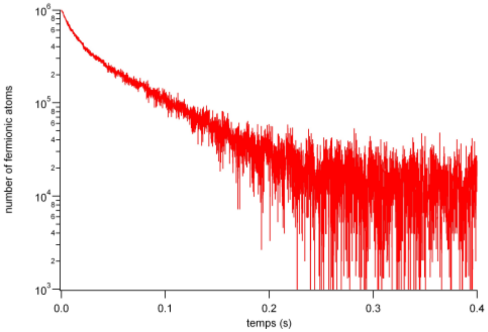
N = 5.10^5 fermions

Loading rate = 10^7 atoms/s

Very short loading times (10 à 100 ms) and small number of atoms :

• decay towards metastable states → repumpers (laser diodes at 663 and 654 nm)

• **Inelastic collisions (dominant process)**

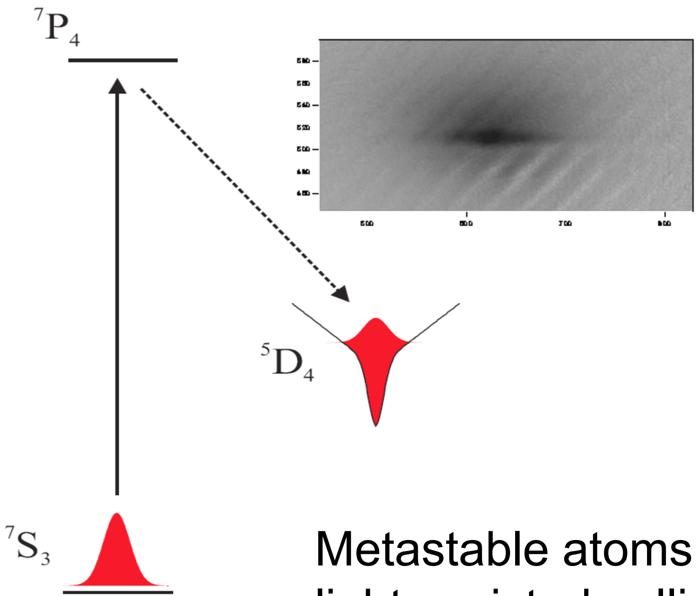


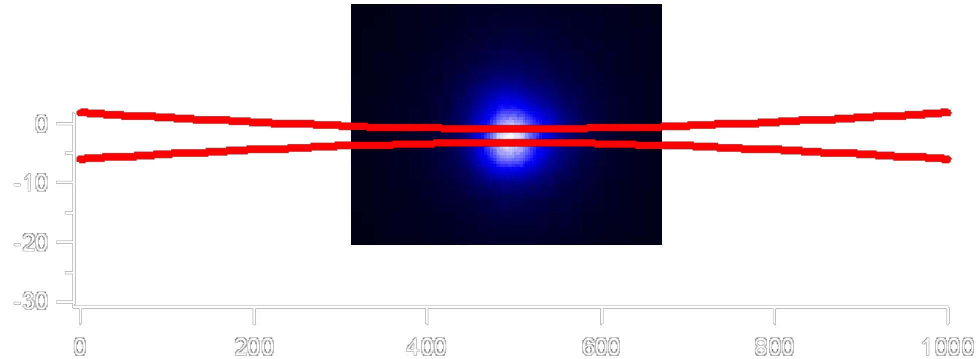
$$\beta \approx \left(\frac{\lambda}{2\pi}\right)^2 \bar{v}$$

2 to 3 orders of magnitude than alkalis

Comparable values for He*.

Our approach: cw accumulation of metastable atoms in an optical trap





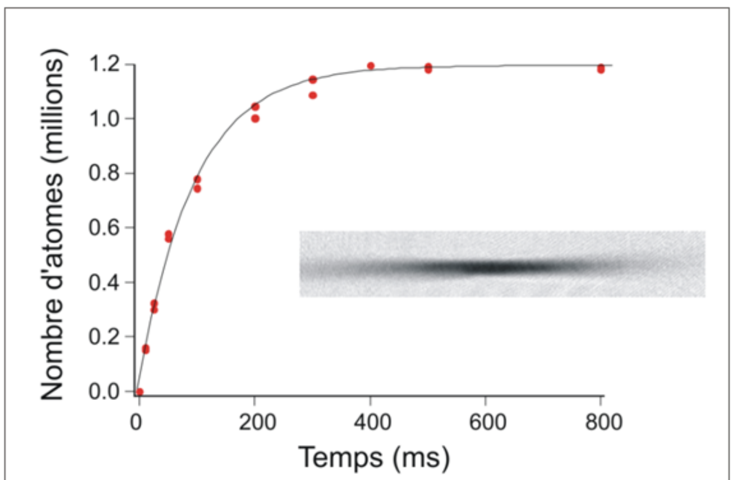
Metastable atoms shielded from light assisted collisions

- <u>The optical trap:</u>
  - IPG fiberized laser – 50W @ 1075 nm
  - Horizontal beam - ~40 μm waist

<u>Depth :</u> ~ 500μK

(parametric excitations)

R Chicireanu et al., Euro Phys J D **45**, 189 (2007)

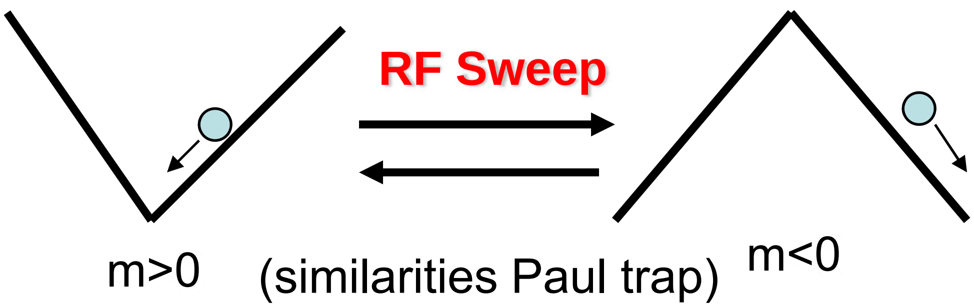


Two improvements:

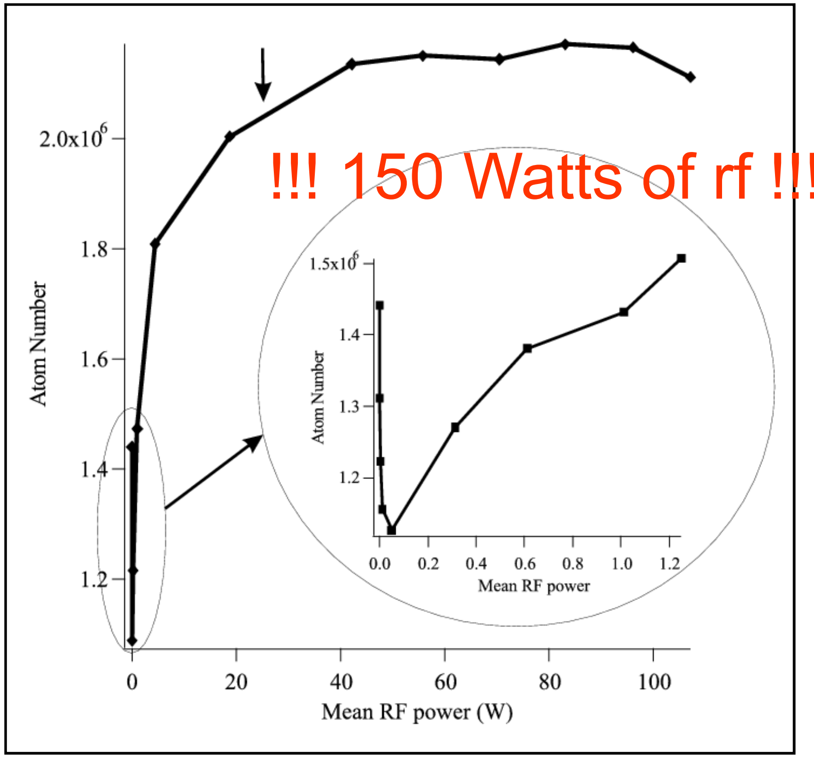
(i) Cancel magnetic forces with an rf field

- What for : Load all magnetic sublevels, and limit inelastic collisions by reducing the peak atomic density

- How : During loading of the OT, magnetic forces are averaged out by rapidly spin flipping the atoms

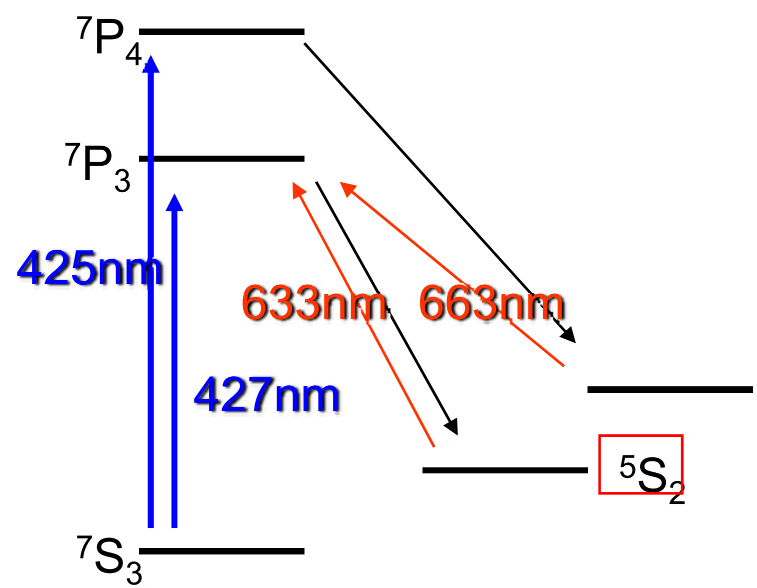


(similarities Paul trap)



(ii) Depump towards metastable state : $^5S_2$

- What we expect :
  - A lower inelastic loss parameter ?
  - A larger loading rate ?



Loading a dipole trap: Summary

- Load $^5D_4$ et $^5D_3$:

  → **1,2 million atoms**

  Loading rate : 10^7 s^{-1}

- (i) RF Sweeps :

  → **2 million atoms**

  Loading rate : 2 10^7 s^{-1}

Q. Beaufils et al., Phys. Rev. A **77**, 053413 (2008)

- (i)*(ii) Load $^5D_4$ et $^5S_2$ and rf sweeps

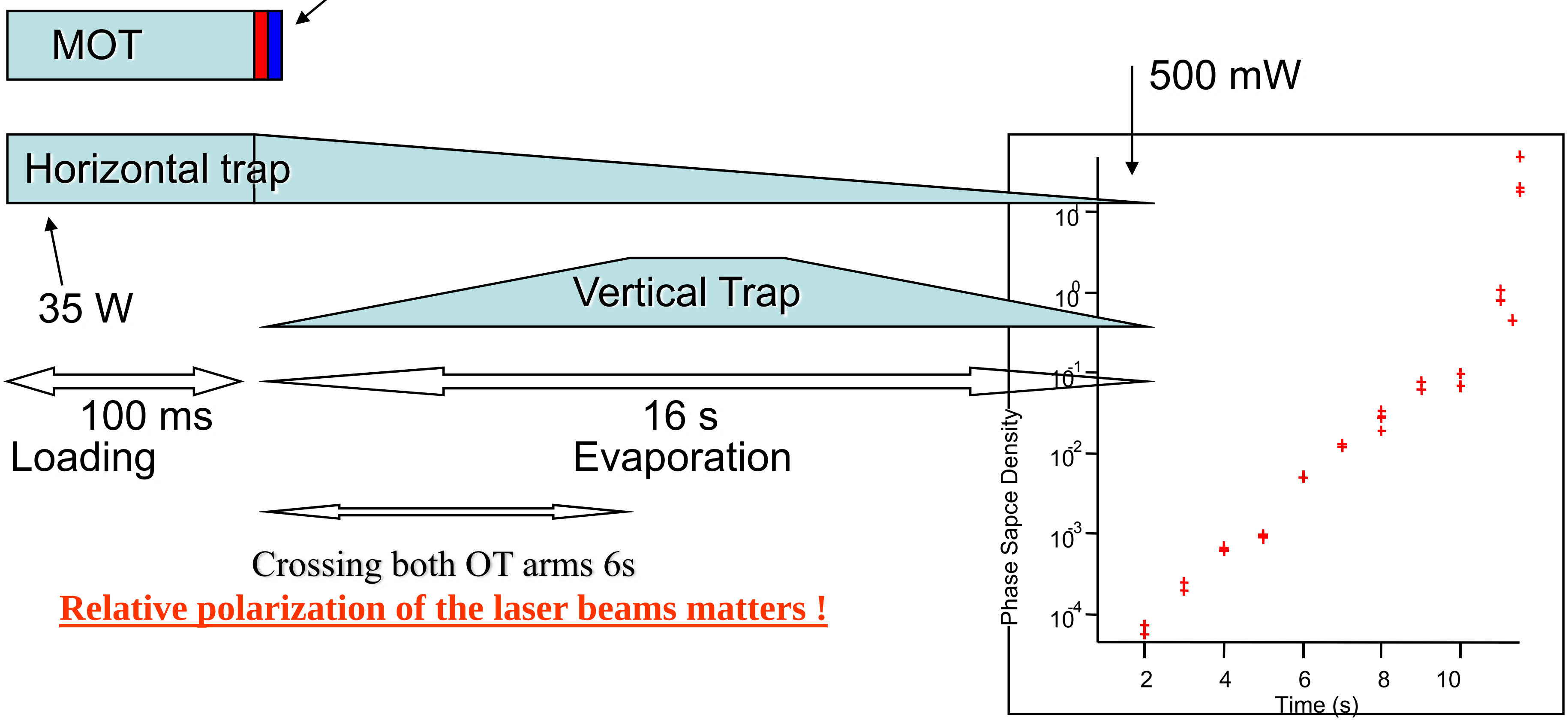
  → **5 to 6 million atoms**

  Loading rate : $1.5 10^8$ s^{-1}

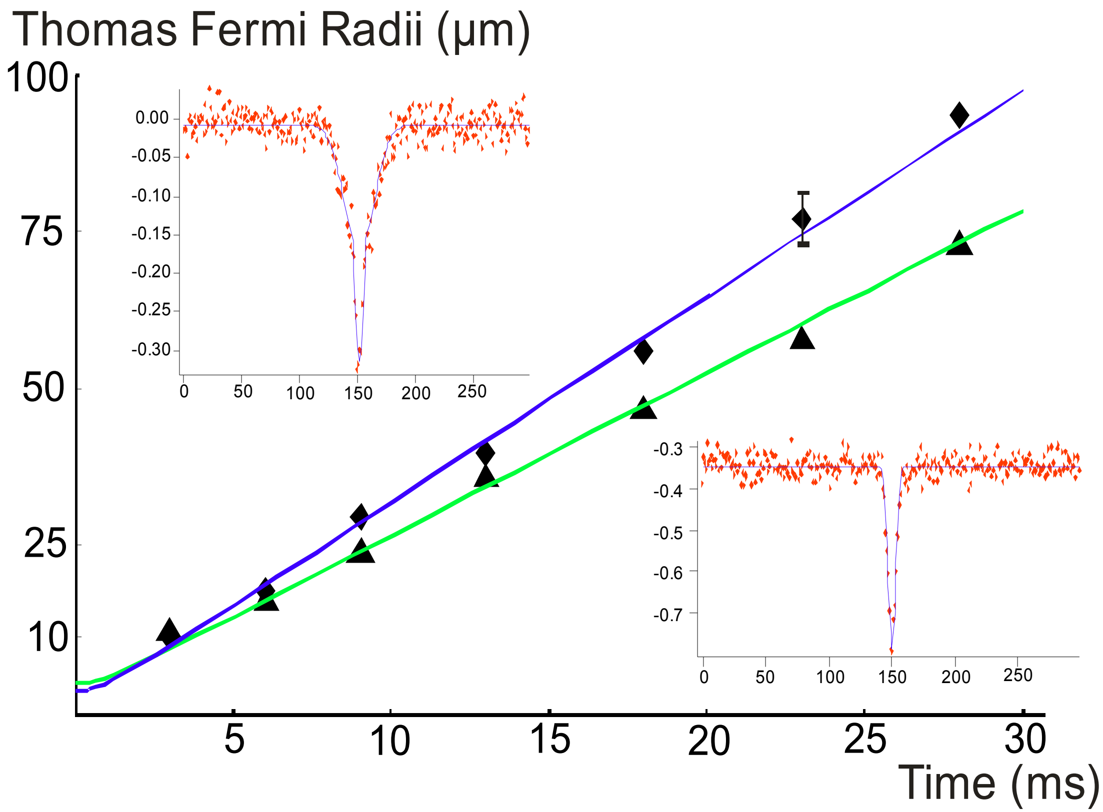
Loading rate = ¼ MOT loading rate

But… phase-space density ~10^{-6}

Repump in $^7S_3$ and polarize in m=-3
(suppression of all two-body losses)



Relative polarization of the laser beams matters !



Tc=150 nK

Pure BEC:

10 000 to

20 000 atoms

Chemical potentential of about 1 kHz ⟶ 4 kHz (recompressed trap)
In situ TF radii 4 and 5 microns
Density : 6.10^{13} at/cm^3 ⟶ 2.10^{14} at/cm^3
Condensates lifetime: a few seconds.

Q. Beaufils et al., Phys.Rev. A **77**, 061601(R) (2008)

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What is dipolar relaxation ?

Dipole-dipole interactions

$$V_{dd} = \frac{\mu_0}{4\pi}(g_J\mu_B)^2 \frac{S_1.S_2 - 3(S_1.\vec{u}_R)(S_2.\vec{u}_R)}{R^3}$$

$$S_{1z}S_{2z} + \frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$ exchange

$$-\frac{3}{4}\left(2zS_{1z} + r_-S_{1+} + r_+S_{1-}\right).$$ rotation ! $\left(r_+ = x + iy\right)$

$$\left(2zS_{2z} + r_-S_{2+} + r_+S_{2-}\right)$$

- Only two channels for dipolar relaxation in m=3 (no relaxation in m=-3):

In the Born approximation Pfau, Appl. Phys. B, **77**, 765 (2003)

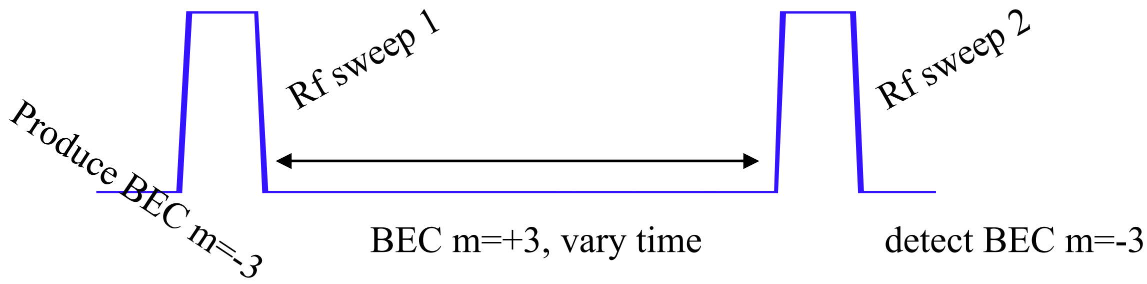
$$|3,3\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|3,2\rangle + |2,3\rangle\right) \qquad V_{dd} = \frac{8\pi}{15}S^3\left(\frac{\mu_0(g_J\mu_B)^2 m}{4\pi\hbar^2}\right)\left(1 + h\left(\frac{k_f}{k_i}\right)\right)\frac{k_f}{k_i} \qquad \Delta E = g_J\mu_B B$$

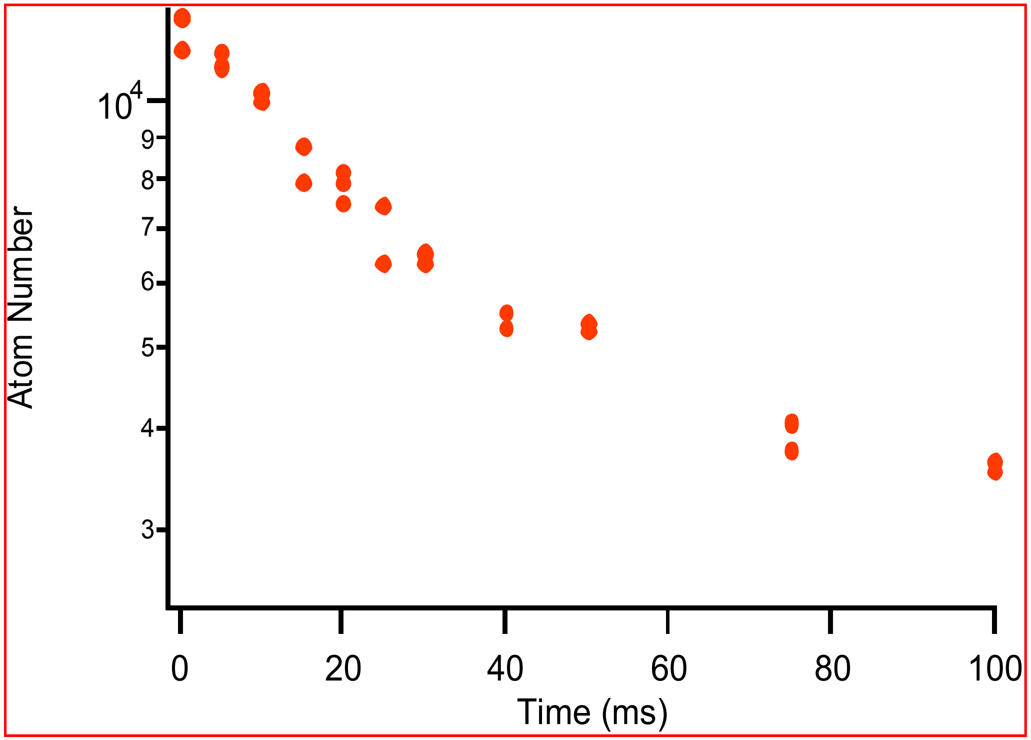
$$|3,3\rangle \rightarrow |2,2\rangle \qquad \Delta l = 2 \qquad V_{dd} = \frac{8\pi}{15}S^2\left(\frac{\mu_0(g_J\mu_B)^2 m}{4\pi\hbar^2}\right)\left(1 + h\left(\frac{k_f}{k_i}\right)\right)\frac{k_f}{k_i} \qquad \Delta E = 2g_J\mu_B B$$

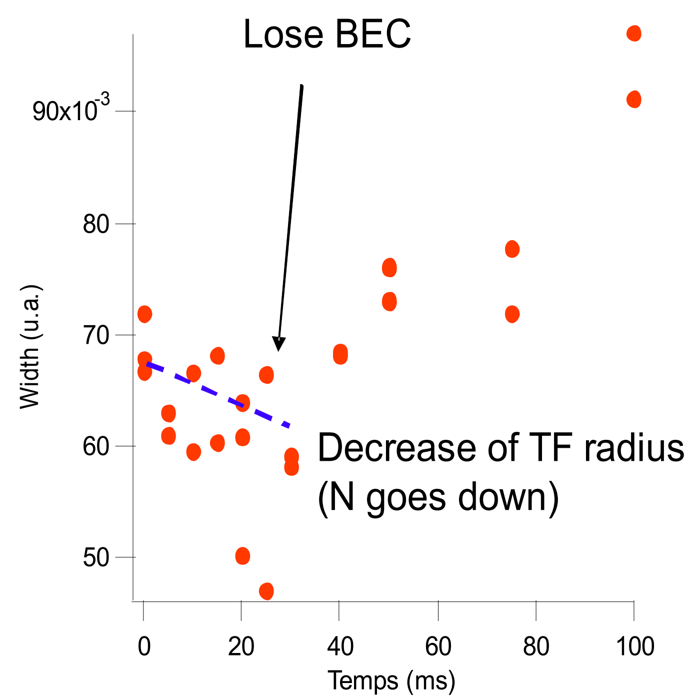
→ Control of inelastic collisions (energy of final state, geometry)

→ $\Delta l = 2$ Rotate the BEC ? (Einstein-de-Haas)

Experimental procedure; typical results





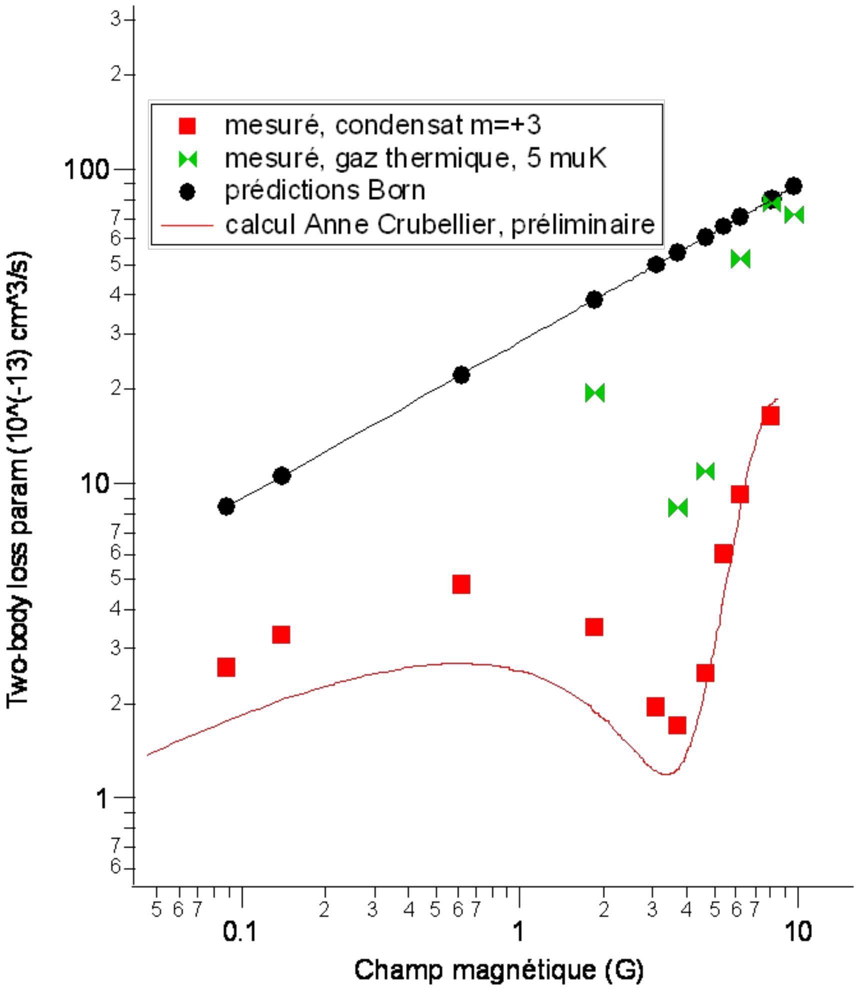


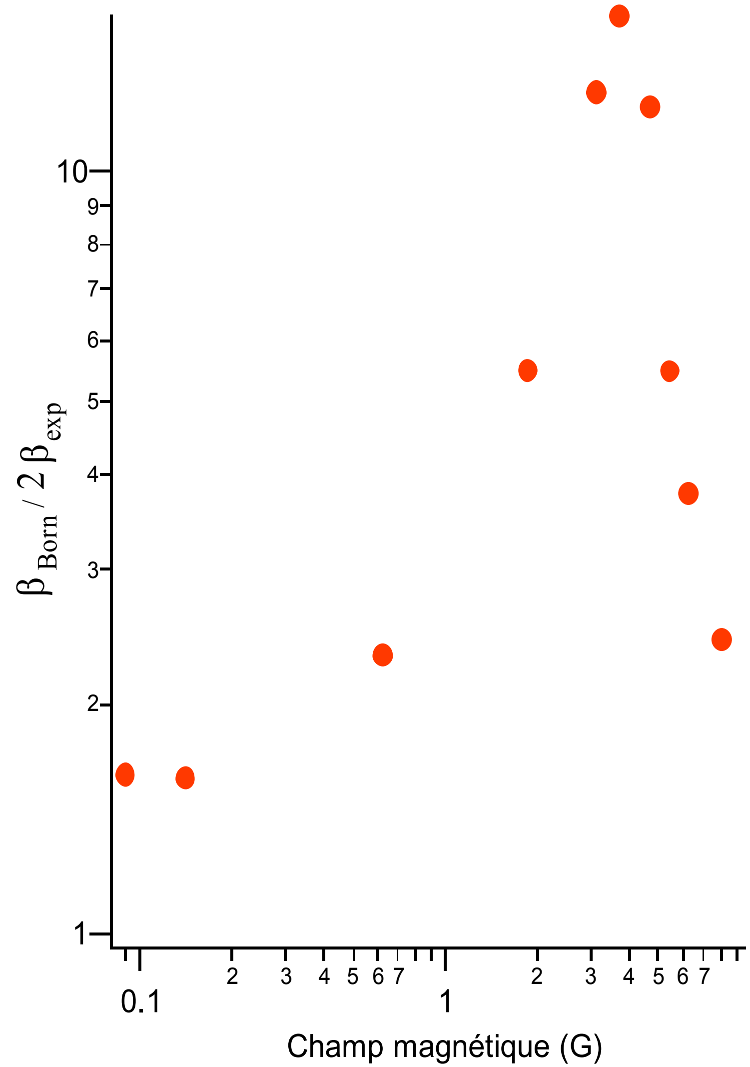
$$\frac{dn}{dt} = -\beta n^2 - \Gamma n$$

$$\frac{dN}{dt} = -\Gamma N - \beta \frac{15^{2/5}}{14\pi}\left(\frac{m\overline{\omega}}{\hbar\sqrt{a}}\right)^{6/5} N^{7/5}$$

Fit gives β

Comparison theory / experiment

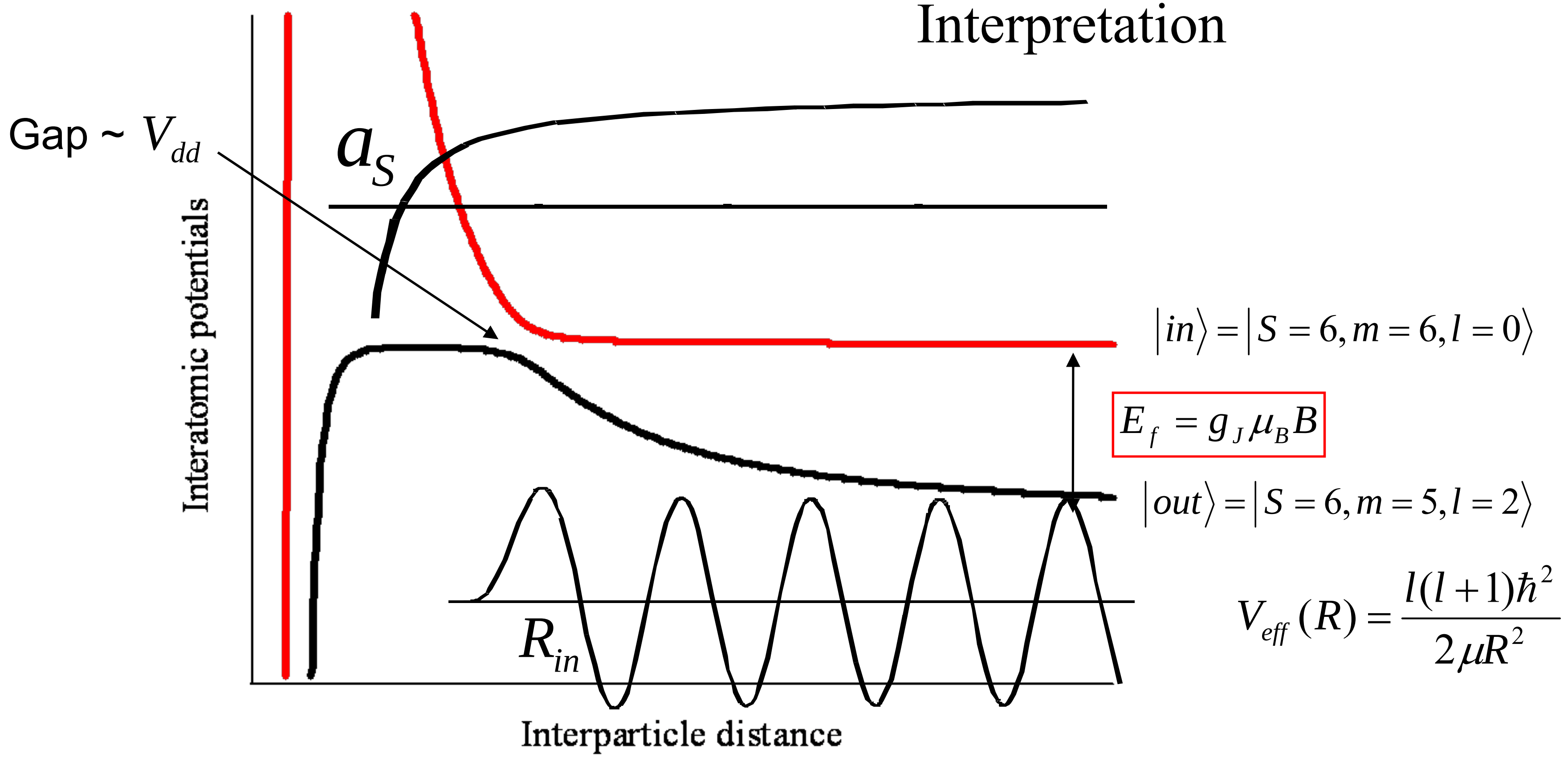




It has been shown (Pfau, Appl. Phys. B, **77**, 765 (2003) that the Born approximation is ok for B<1G and B> 10 G… not in between !

(see Shlyapnikov, PRA **53**, 1447 (1996))

Interpretation



$R_{in} = a_S$ ⟶ **Zero coupling**

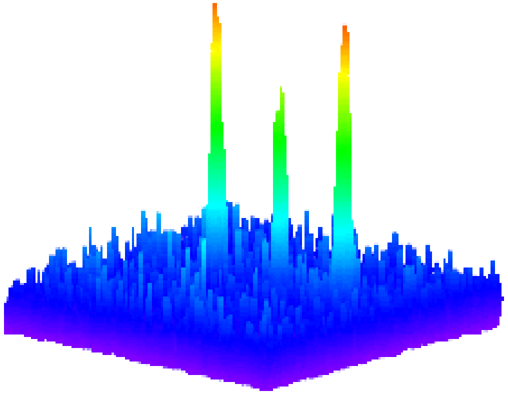
Determination of scattering lengths S=6 and S=4 (in progress, Anne Crubellier)

NB: two output channels (Δm=1, Δm=2), with two different output energies.

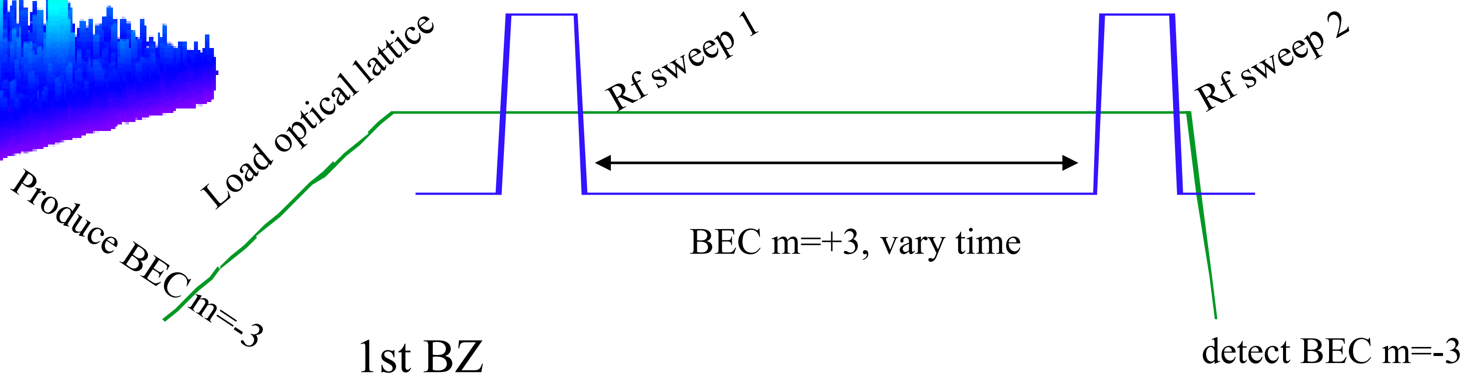
Selective cancellation of a given channel for a given magnetic field !

Perspectives: dipolar relaxation in reduced dimension (2D gaz)

1D Lattice (retro-reflected Verdi laser)



Cr BEC diffracted by lattice



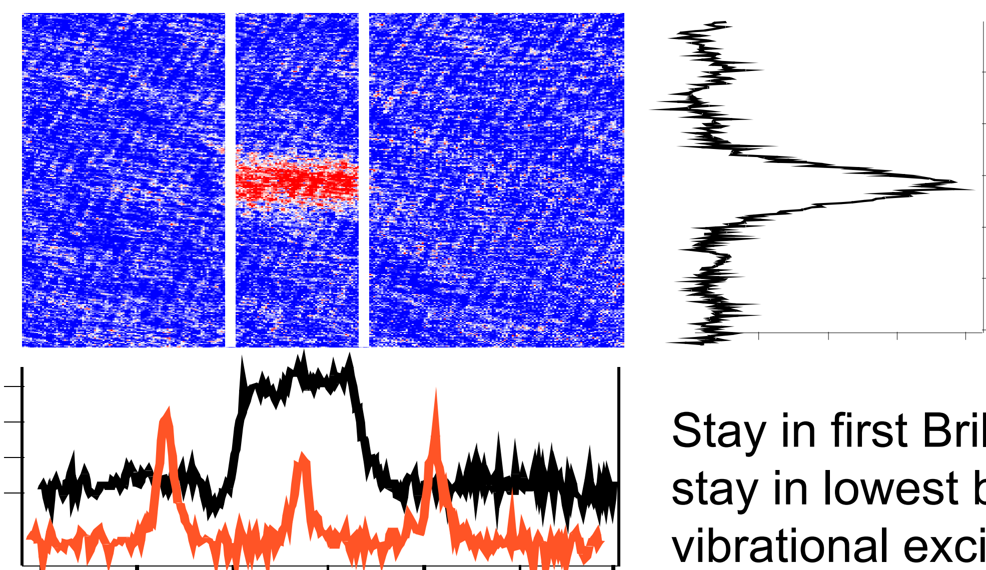
1st BZ

$$\Delta m g_J \mu_B B < \hbar \omega_L$$

Band mapping

↓

Dipolar relaxation in reduced dimension (2D)



Lose BEC
(2D thermal gas)

Stay in first Brillouin zone, i.e., stay in lowest band : no vibrational excitation in lattice !

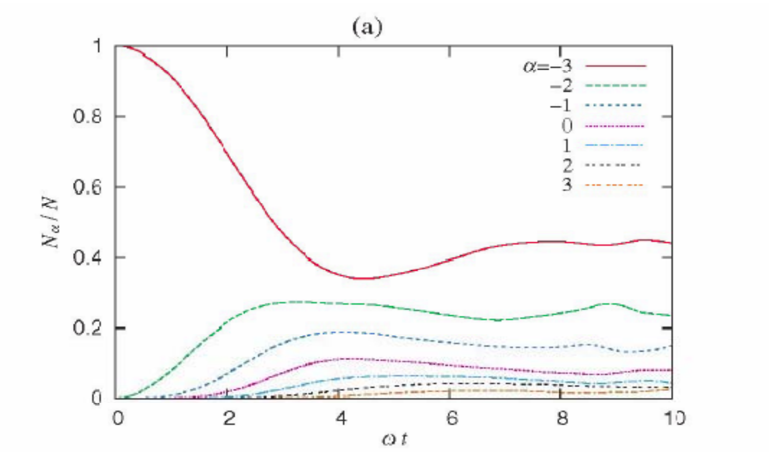
Conclusions:

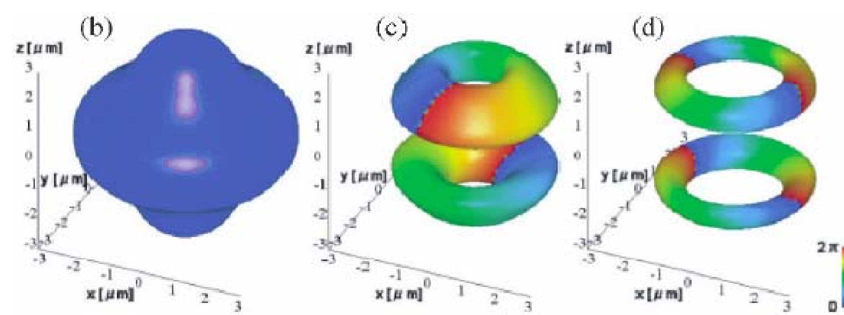
- Rates are well understood .
- Typical output (Zeeman) energy much larger than chemical potential

$$|3,3\rangle, l=0 \rightarrow \frac{1}{\sqrt{2}}\left(|3,2\rangle + |2,3\rangle\right), l=2 \qquad \Delta E = g_J \mu_B B$$

$$|3,3\rangle, l=0 \rightarrow |2,2\rangle, l=2 \qquad \Delta E = 2 g_J \mu_B B$$

The spin magnetic moment is transferred into orbital interatomic moment. Can we measure this rotation ?





Ueda, PRL **96**, 080405 (2006)

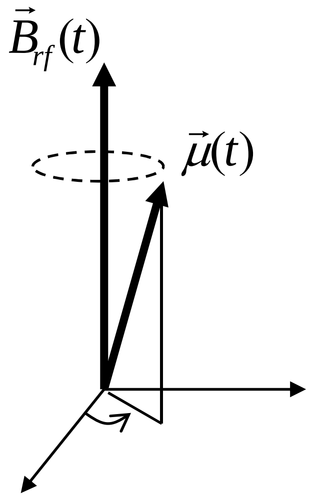
Can we « store » the produced energy ?

- Into a vibration excitation of the lattice: apparently not
- **Use rf-dressed states : dipolar relaxation between manyfolds**

Collision properties of off-resonantly rf dressed states :

Elastic s-wave collisions:

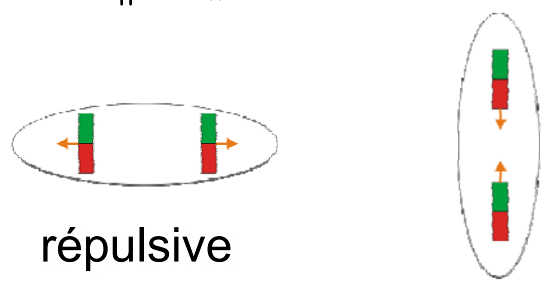
Rf does not couple different molecular potentials -> s-wave elastic collisions should be unchanged.



$$\frac{d\vec{\mu}}{dt} = -g_J \vec{\mu} \times \vec{B}_{rf}(t)$$

$$\left\| \vec{\mu} \right\| = cste$$

Dipolar interactions:

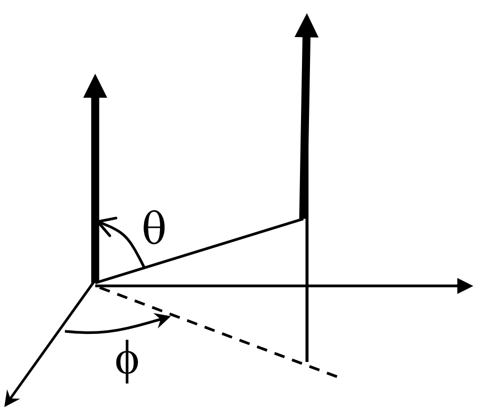


répulsive

attractive

No rf

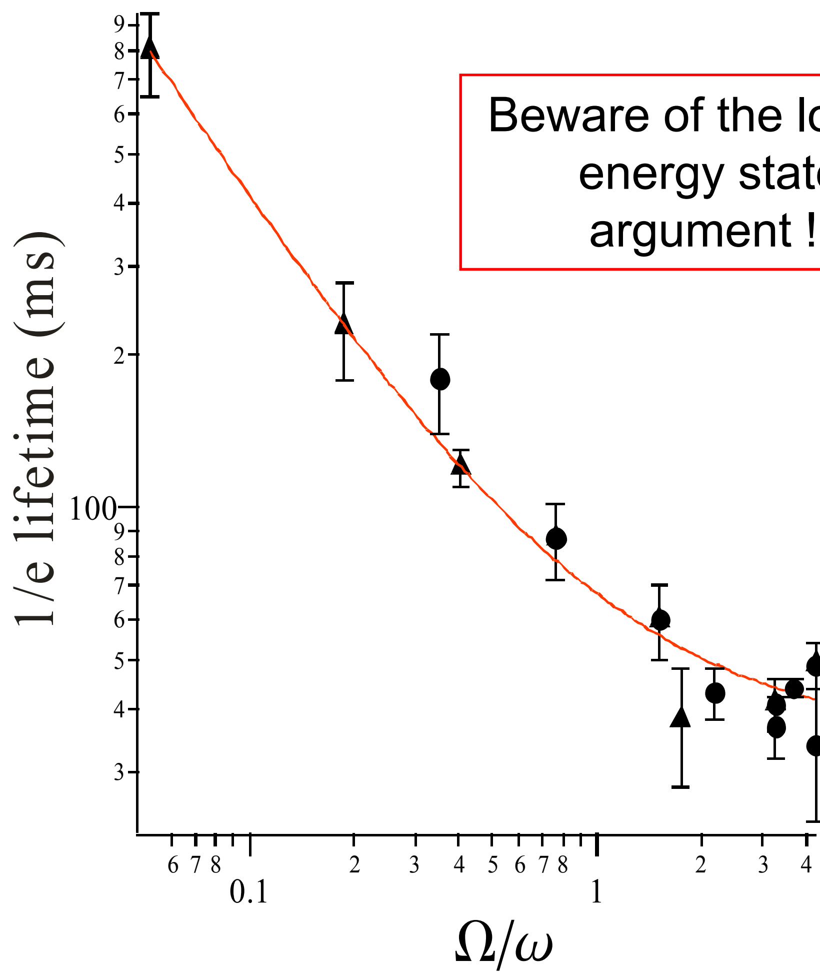
$$1 - 3\cos^2(\theta)$$



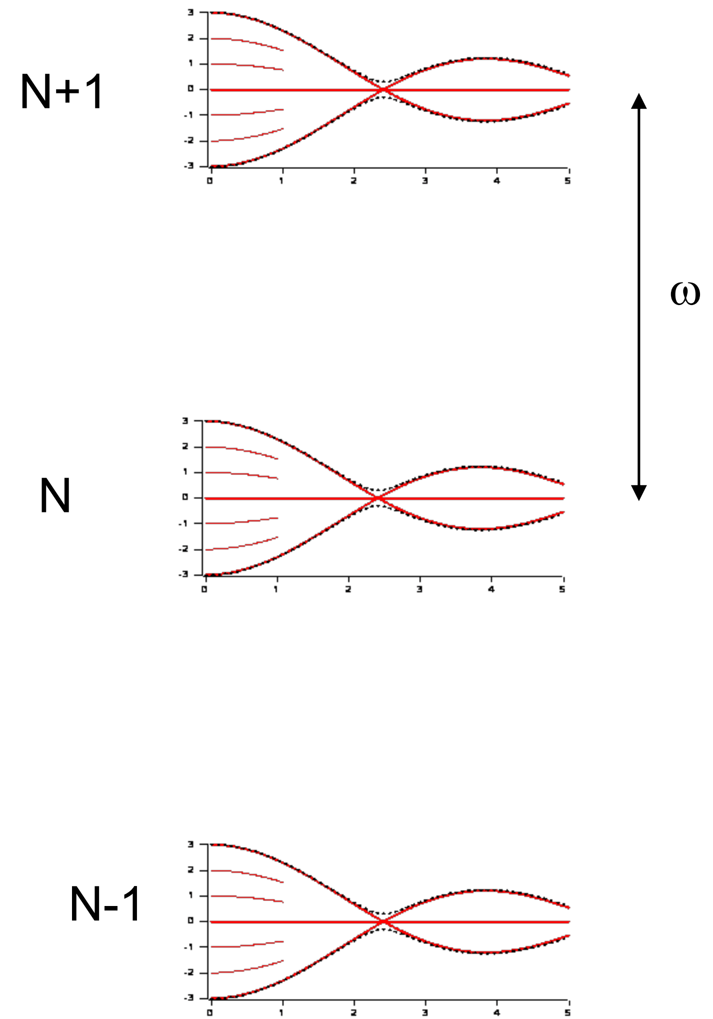
Rf perpendicular to static field : a new geometrical dependence !

$$1 - 3\cos^2(\theta)\left(\frac{1}{2} + \frac{1}{2} J_0\left(2\frac{\Omega}{\omega}\right)\right) - 3\cos^2(\theta)\sin^2(\theta)\cos^2(\phi)\left(\frac{1}{2} - \frac{1}{2} J_0\left(2\frac{\Omega}{\omega}\right)\right)$$

Inelastic collision properties of off-resonantly rf dressed states :

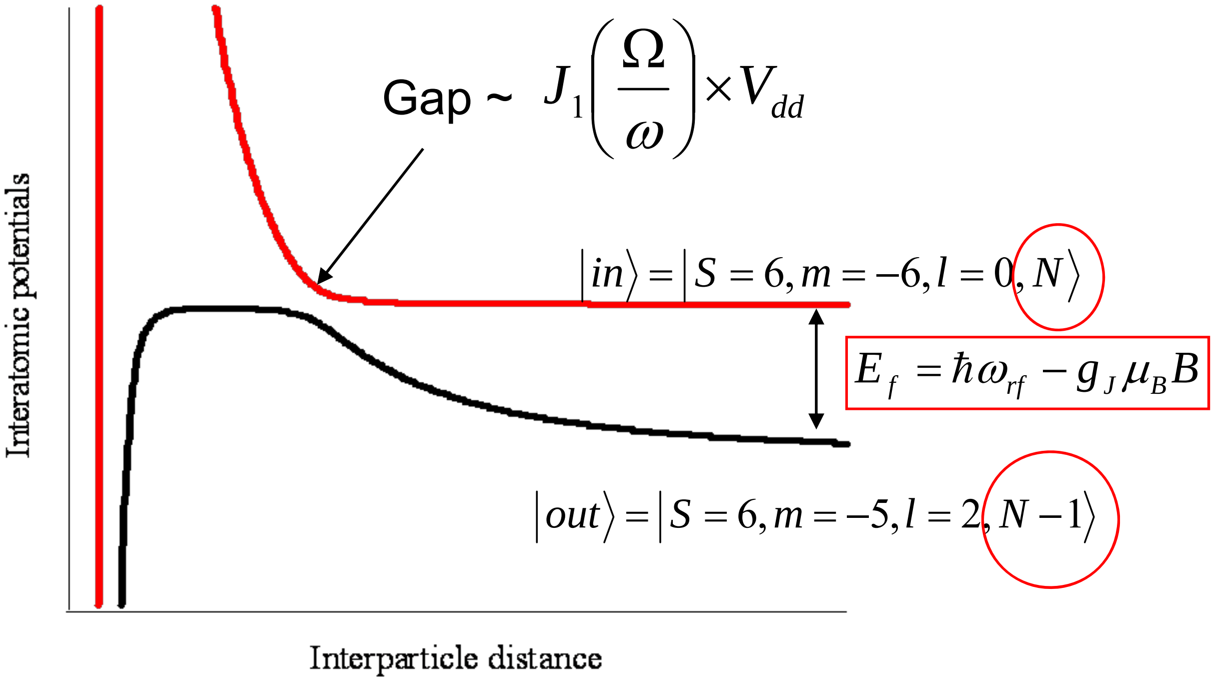


Beware of the lowest energy state argument !!



See also Verhaar, PRA, **53**, 4343 (1996)

Interpretation: an rf-assisted dipolar relaxation



Similar mechanism than dipolar relaxation

$$|in\rangle = |S=6, m=+6, l=0\rangle$$

$$\downarrow$$

$$|out\rangle = |S=6, m=+5, l=2\rangle$$

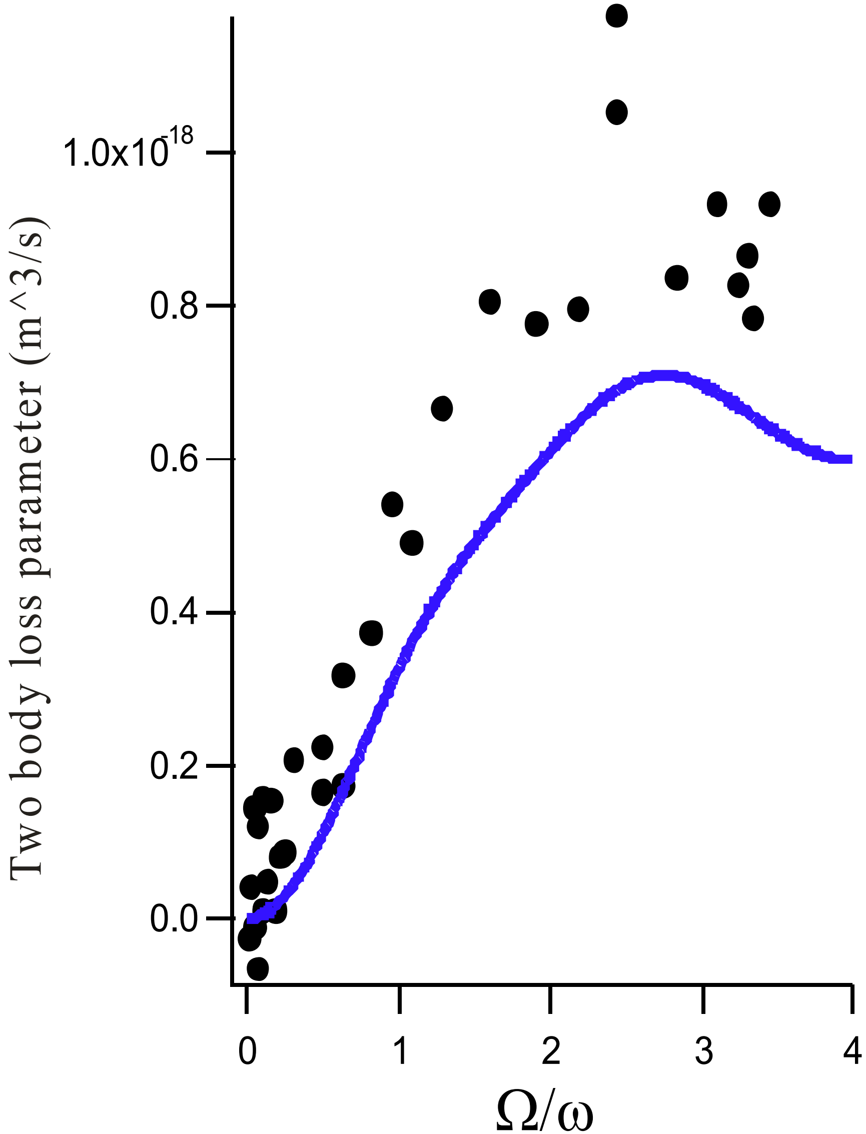
Within first order Born approximation:

$$\sigma^{rf}_{N\to N',m\to m'} = \left| J_{N-N'}\left((m-m')\frac{\Omega}{\omega}\right)\right|^2 \sigma^{dipolarrelaxation}_{m\to m'}\left(E_f = (m-m')g_J\mu_B B - (N-N')\hbar\omega_{rf}\right)$$

In collaboration with Anne Crubellier (LAC – Ifraf) and Paolo Pedri (Ifraf postdoc in our group)

(B_{rf} parallel to B)

$$\sigma^{rf}_{N\to N',m\to m'} = \left| J_{N-N'}\left((m-m')\frac{\Omega}{\omega}\right)\right|^2 \sigma^{dipolarrelaxation}_{m\to m'}\left(E_f = (m-m')g_J\mu_B B - (N-N')\hbar\omega_{rf}\right)$$



Analytic calculation by Paolo Pedri, no adjustable parameter

Dipolar relaxation between dressed states:

Control:

Coupling

$$\left| J_{N-N'}\left((m-m')\frac{\Omega}{\omega}\right)\right|^2$$

Output energy:

$$E_f = (m-m')g_J\mu_B B - (N-N')\hbar\omega_{rf}$$

Why Bessel functions ?

$$\vec{B}_{rf} \,//\, \vec{B}_0$$

$$H = H_{mol} + \hbar\omega_0 S_z + \hbar\omega a^+ a + \lambda S_z (a^+ + a)$$

Analytical expression for dressed state (from C. Cohen-Tannoudji)

$$\left|\overline{M,N}\right\rangle = \exp\left(-\frac{m\lambda}{\hbar\omega}(a - a^+)\right)\left|M,N\right\rangle$$

$$+ H_{dd}$$

First order perturbation theory:

$$K_2(\omega,\Omega) = K_2(0)\left(J_1\left(\frac{\Omega}{\omega}\right)\right)^2$$

Another equivalent approach (Floquet analysis)

Modulate the eigenenergy of an eigenstate:

$$i\hbar\frac{d\Psi_m}{dt} = \left(H + m\Delta H \cos\left(\omega_{rf} t\right)\right)\Psi_m$$

e.g. different Zeeman states

$$\left|\Psi_1(t)\right\rangle = \left|\Psi_1\right\rangle \exp\left(i\left(\omega_0 t + \frac{\Omega}{\omega_{rf}}\sin(\omega_{rf} t)\right)\right) = \left|\Psi_1\right\rangle \sum_n (i)^n J_n\left(\frac{\Omega}{\omega_{rf}}\right)\exp\left(i\left(\left(\omega_0 + n\omega\right)t\right)\right)$$

Resonant coupling between m=1 and m=0 with echange of N photons ⟶ $J_N\left(\frac{\Omega}{\omega_{rf}}\right)$

Une proposition pour voir l'effet Einstein de Haas:
Mettre en rotation le condensat par relaxation dipolaire – assistée par photons rf !

→ On sait faire des condensats de chrome

→ La relaxation dipolaire crée du moment orbital, mais aussi une énergie magnétique >> μ

→ On sait contrôler la relaxation dipolaire par champs rf:

-l'amplitude de transition

$$\left| J_{N-N'}\left((m-m')\frac{\Omega}{\omega} \right) \right|^2$$

-l'énergie dans le canal de sortie !

$$E_f = (m-m')g_J \mu_B B - (N-N')\hbar\omega_{rf}$$

On veut

$$E_f \approx \mu$$

→ Contrôle de B au voisinage de 0 au kHz près (difficile)

→ Contrôle de B au voisinage de 100 kHz au kHz près (facile) + rf

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III Contrôle du facteur de Landé par champs radio-fréquence

(digression)
Un autre cas de collision inélastique en présence de champ rf: l'association rf de molécules

Un champ magnétique est modulé au voisinage d'une résonance de Feshbach

⟶ Production résonante de molécules froides quand $\hbar\omega_{rf} = E_b$

Énergie de liaison

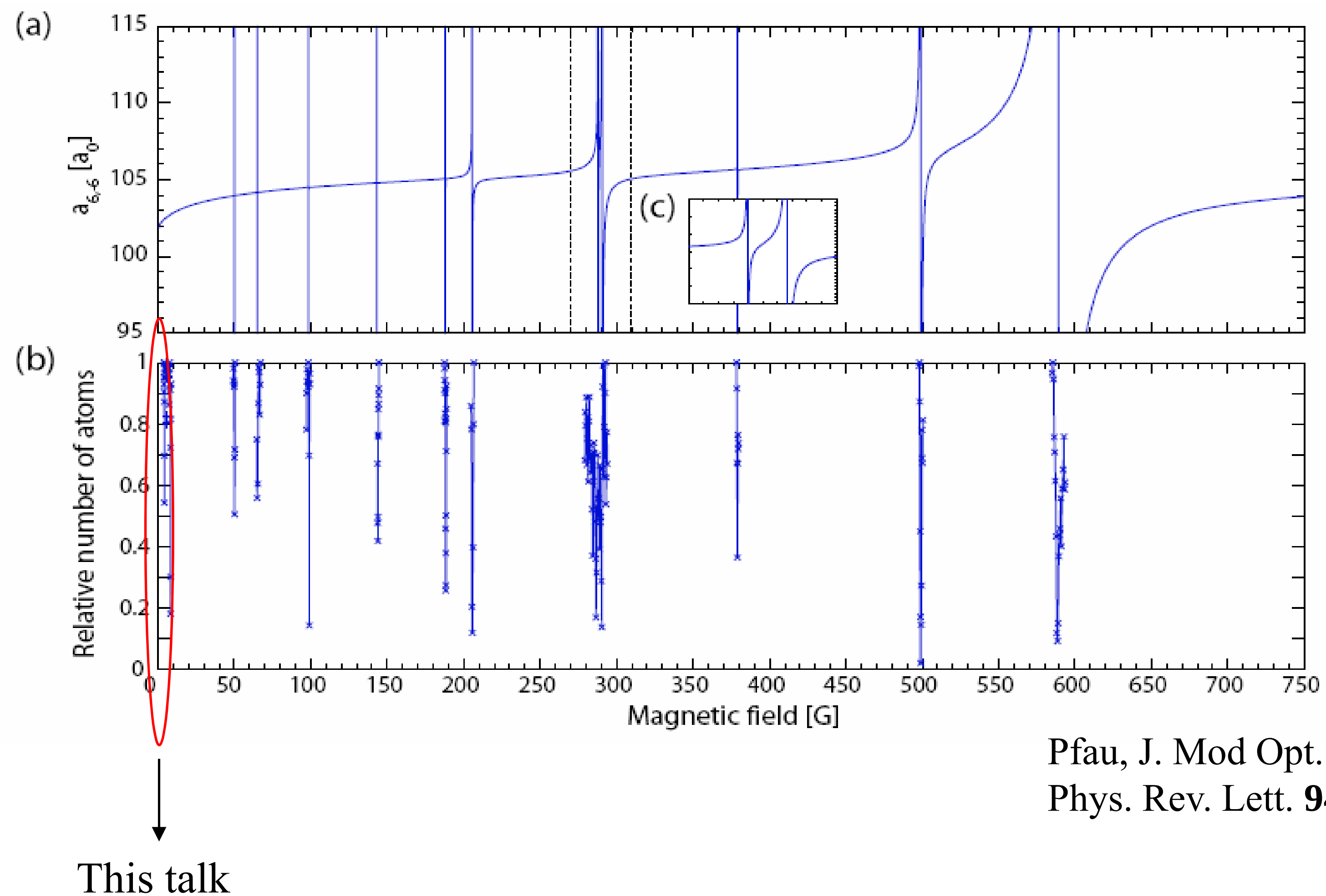
Mais… la rf ne couple pas deux potentiels moléculaires différents ! (règle de sélection)
Ni deux états vibrationnels d'un même potentiel (orthogonalité)

C'est l'opérateur qui couple les spins (dipôle-dipôle, hyperfin) qui couple les états. La résonance est assurée par l'émission ou l'absorption d'un photon rf.

See also: S. T. Thomson et al., PRL 190404 (2005), C. Ospelkaus et al., PRL 97, 120402 (2006), F. Lang et al., Nature Physics 4, 223 (2008), T. M. Hanna et al., PRA, 013606 (2007), C. Weber et al., PRA 78, 061601(R) (2008), C. Klempt et al., PRA 78, 061602(R) (2008)

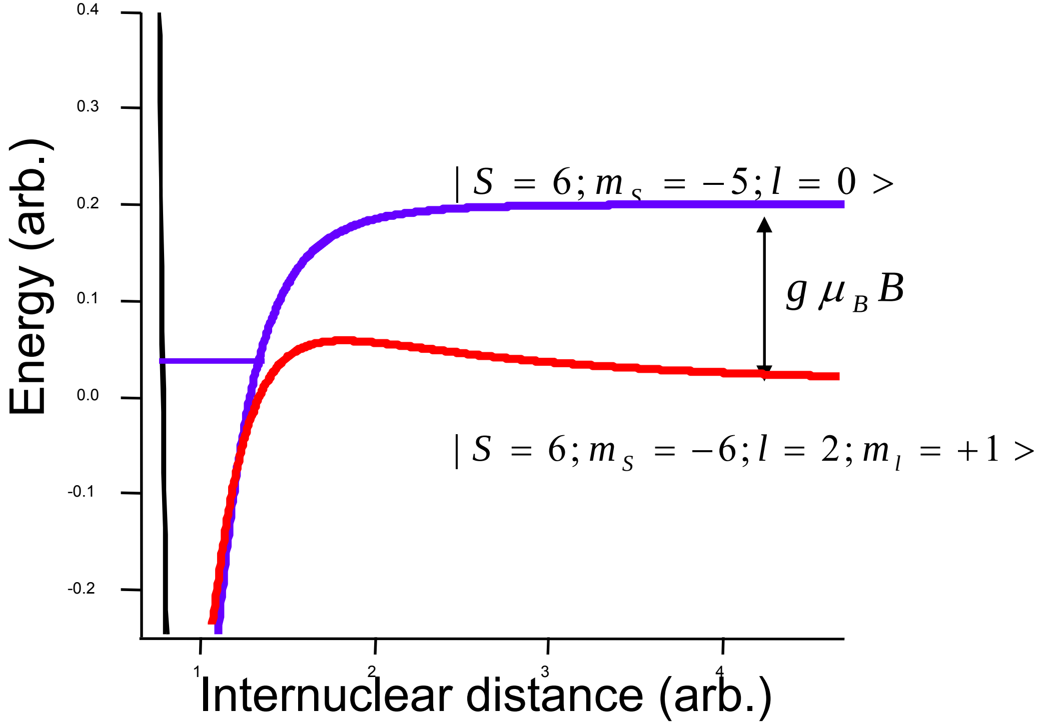
Notre contribution : une interprétation en terme d'atomes habillés, et une formule universelle pour l'association de molécules.

Feshbach resonances in chromium



Pfau, J. Mod Opt. **54**, 647 (2007),
Phys. Rev. Lett. **94**, 183201 (2005)

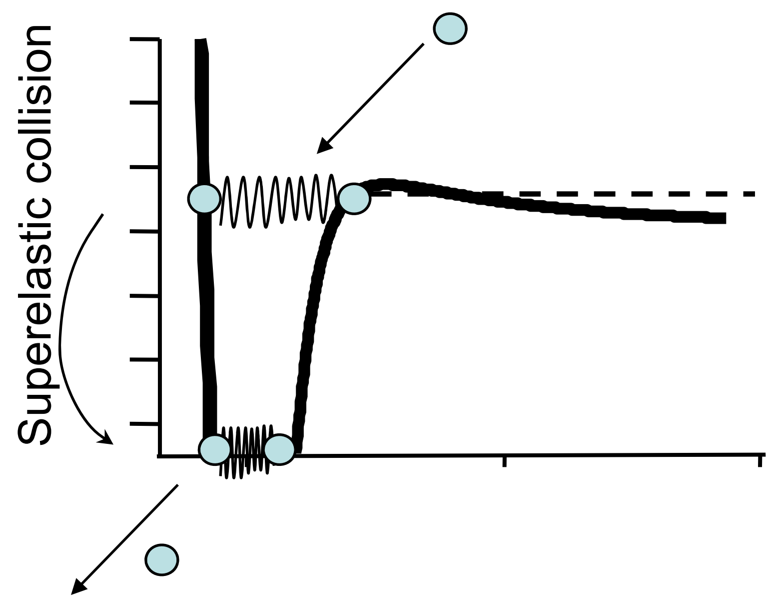
A Feshbach resonance in d-wave collisions



At ultra-low temperature scattering is inhibited in l>0, because atoms need to tunnel through a centrifugal barrier to collide: collisions are « s-wave ». In a « d-wave » Feshbach resonance, tunneling is resonantly increased by the presence of a bound molecular state.

To probe a feshbach resonance:
3 body losses

Tunneling to short internuclear distance is increased by a Feshbach resonance. A third atom triggers superelastic collisions, leading to three-body losses, as the kinetic gained greatly exceeds the trap depth



Interpretation

$$\sigma(k) = \frac{\pi}{k^2} \frac{\Gamma_m(\varepsilon)\Gamma_d}{(\varepsilon - \varepsilon_0)^2 + (\Gamma_m(\varepsilon) + \Gamma_d)^2 / 4}$$

$$\Gamma_m(\varepsilon) = 2\pi \left| \langle \Psi_{bound} | V_{dd} | \Psi_\varepsilon \rangle \right|^2 \propto \varepsilon^{(2l+1)/2} \qquad \Gamma_d = n\gamma_d$$

Feshbach coupling — Superelastic rate

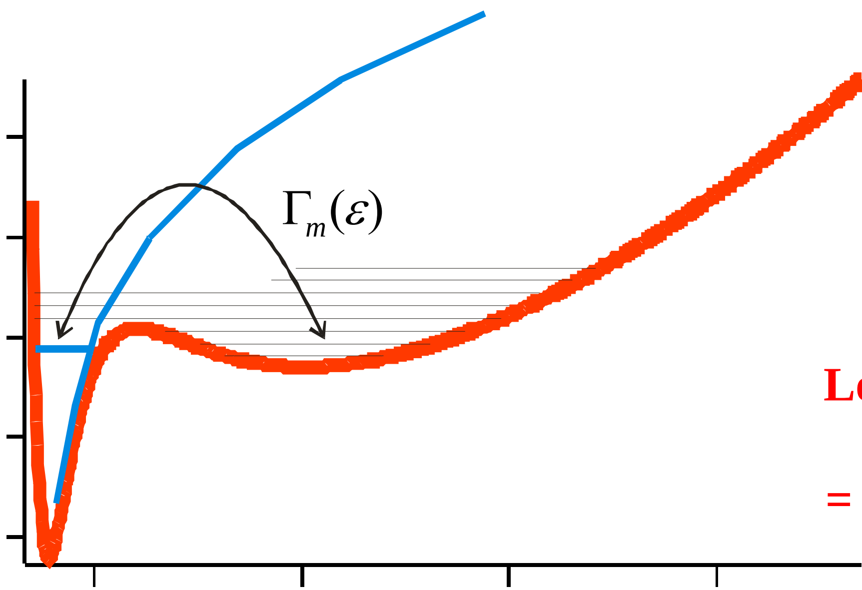
F. H. Mies et al., PRA, 61, 022721 (2000)
P. S. Julienne and F. H. Mies, J. Opt. Soc. Am. B. 6, 2257 (1989).

Thermal averaging, when

$$\Gamma_m(\varepsilon_0) << \Gamma_d << k_B T$$

$$K_2(T) = \frac{2\pi(2l+1)}{hQ_T} \Gamma_m(\varepsilon_0) \exp\left(\frac{-\varepsilon_0}{k_B T} \right)$$

Calculation with no adjustable parameter (adiabatic elimination of Γ_d) (Anne Crubellier LAC)



$$\dot{n} = -\alpha \Gamma_m \left(n \Lambda_{dB}^3 \right) \times n$$

psd

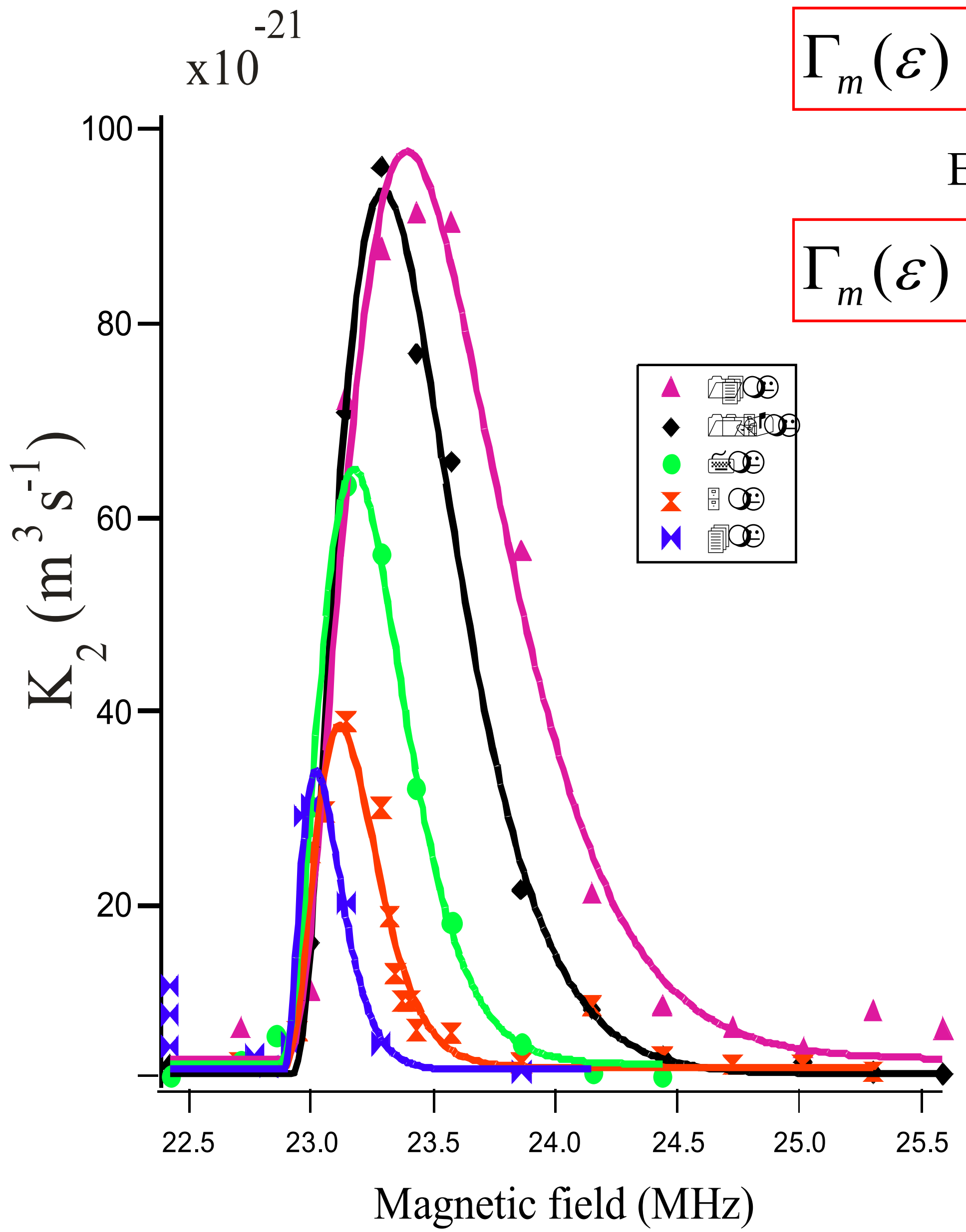
Losses = Rate of coupling to the molecular bound state
= Rate of association through the barrier

Theory

$$\Gamma_m(\varepsilon) = 7.3\times10^{-5}\, k_B T \; @ \; T = 8\mu K$$

Experiment

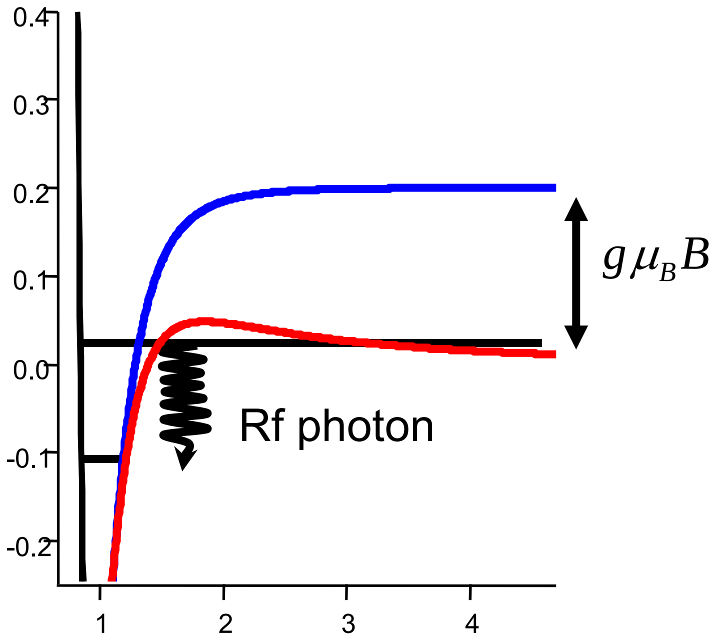
$$\Gamma_m(\varepsilon) = (5.5\pm3)\times10^{-5}\, k_B T \; @ \; T = 8\mu K$$

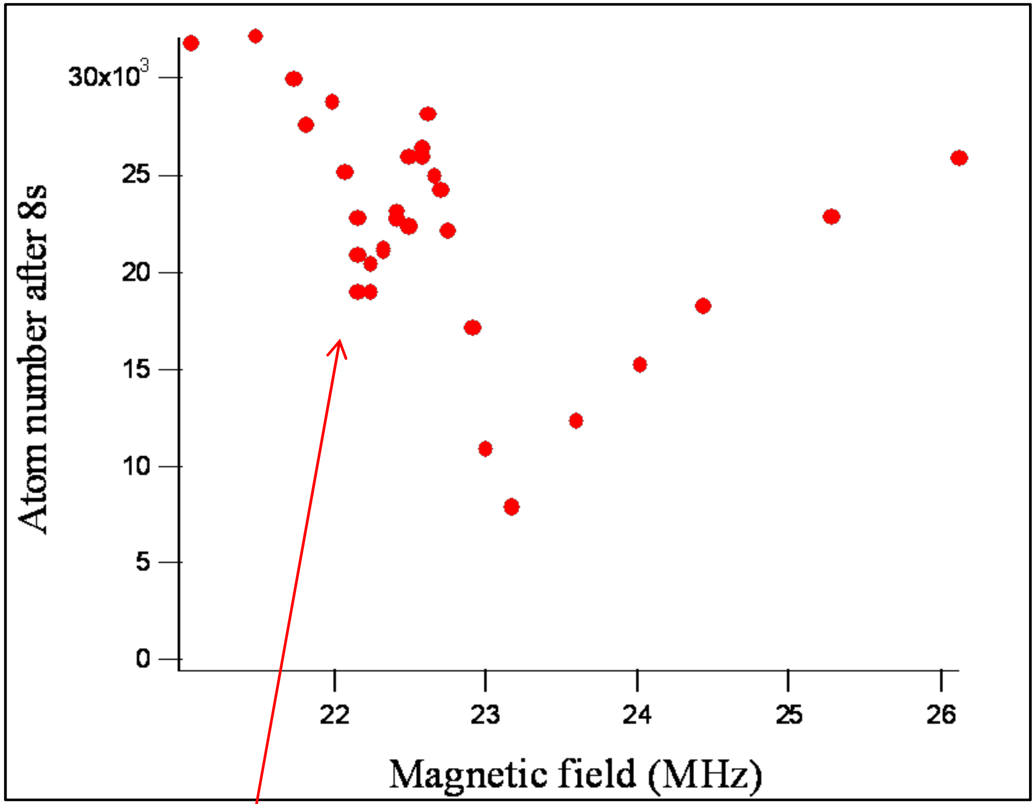


Three-body losse parameter strongly depends on T
Width of resonant losses strongly depends on T

Q. Beaufils et al., arXiv:0811.4282

Rf in the vicinity of the Feshbach resonance



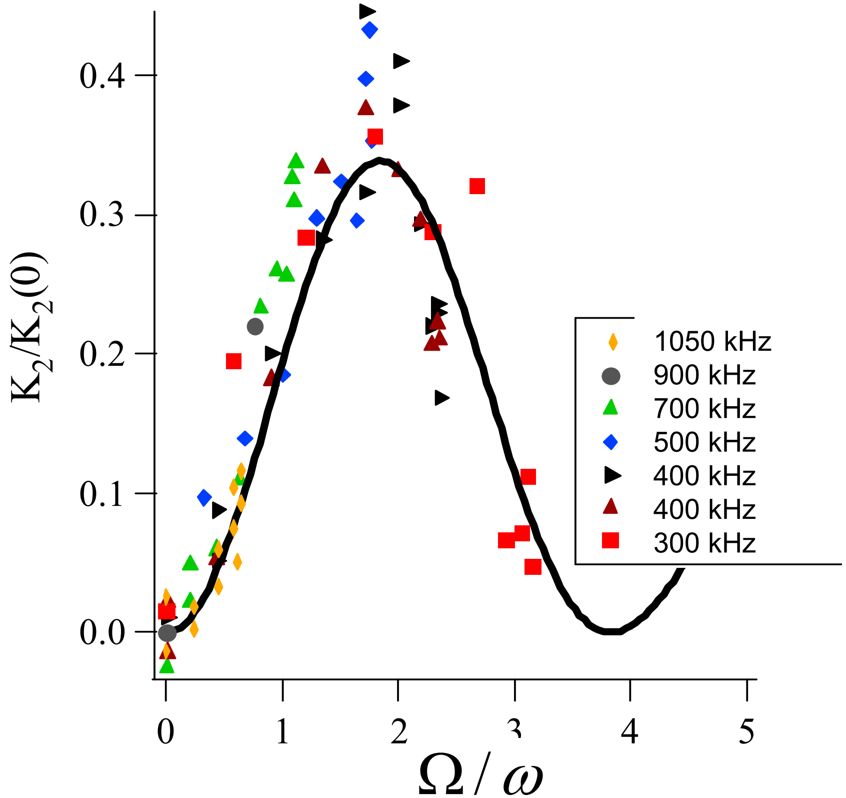


We modulate the magnetic field close to the Feshbach resonance. The colliding pair of atoms emits a photon while it is colliding, and the pair of atoms is transfered into a bound molecule

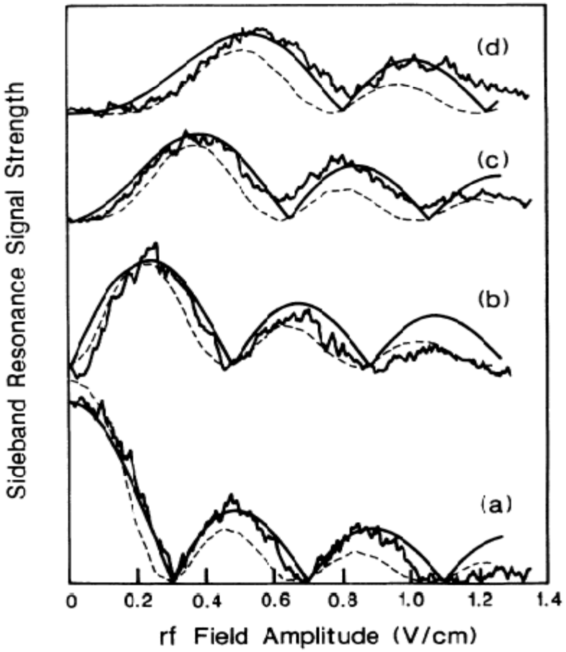
Resonant losses when $\omega = E_b - E_i$

Loss analysis in the dressed molecule approach:

$$K_2(\omega,\Omega) = K_2(0)\left(J_1\left(\frac{\Omega}{\omega}\right)\right)^2$$



Analogy with dipolar collisions of Rydberg atoms in a micro-wave field
Pillet Phys. Rev. A, 36, 1132 (1987)
Gallagher Phys. Rev. A, 45, 358 (1992)



Q. Beaufils et al., arXiv:0812.4355

Association rf of molecules = a Feshbach resonance between dressed states

I Condensation tout-optique du chrome

II Contrôle de collisions inélastiques par champs radio-fréquence

- Relaxation dipolaire
- Association de molécules

III Contrôle du facteur de Landé par champs radio-fréquence

Another use of rf for spinor physics:

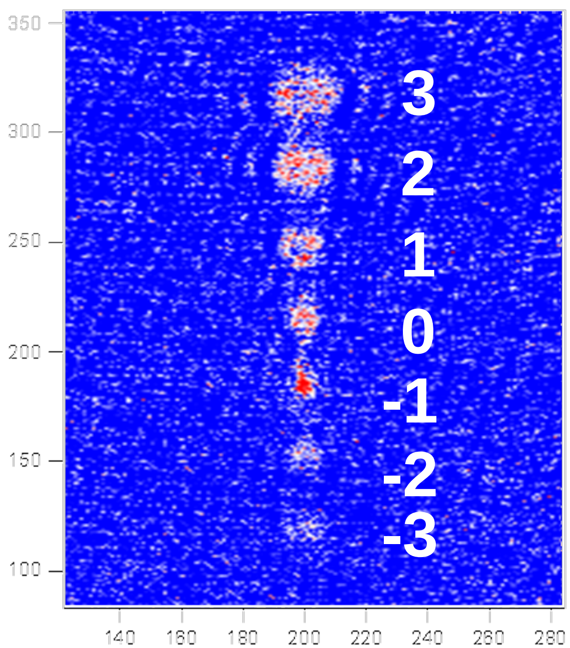
rf control of the Landé factor

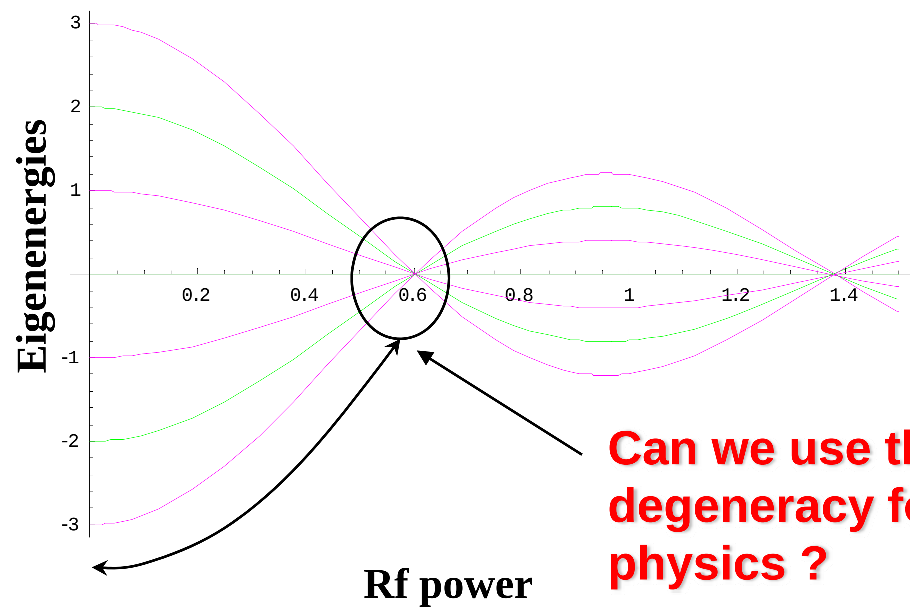
A spinor is a multicomponent BEC (with degenerate components): the magnetic fields needs to be small (interaction energy > Zeeman energy) < 1 mG !!...

Modify the Landé factor of the atoms g_J with very strong off resonant rf fields.
If the RF frequency ω is larger than the Larmor frequency ω_0, then:

$$g_J(\omega,\Omega) = g_J J_0\left(\frac{\Omega}{\omega}\right)$$

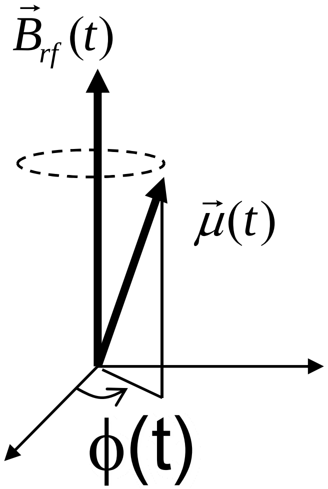
- Serge Haroche thesis
- S.Haroche, et al., PRL 24 16 (1970)
- True in 2D… Generalization in 3D ?





Can we use this degeneracy for spinor physics ?

Classical interpretation



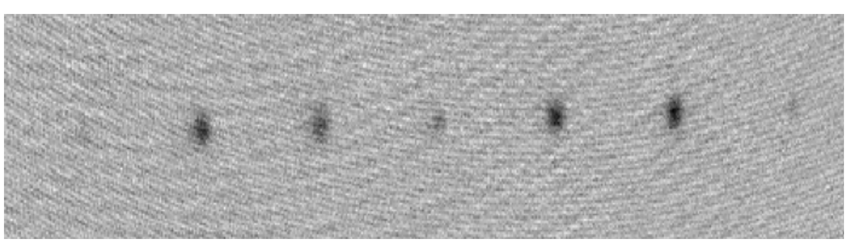
$$\frac{d\vec{\mu}}{dt} = -g_J \vec{\mu} \times \vec{B}_{rf}(t)$$

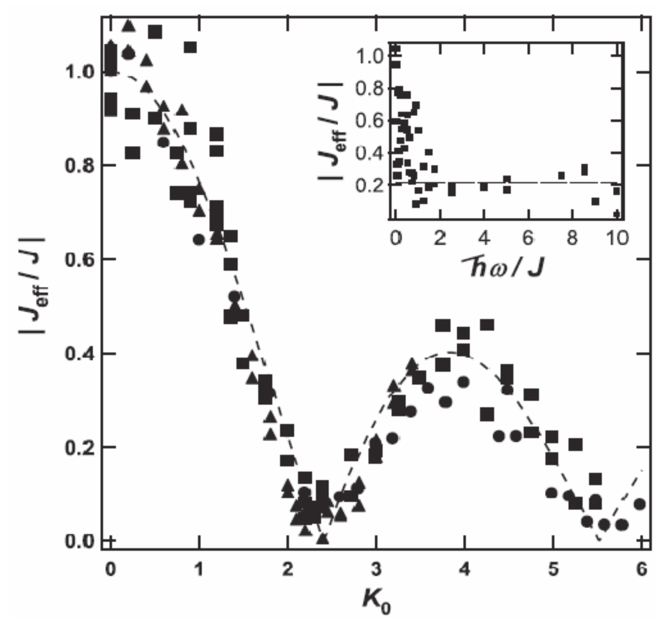
$$\frac{d\Phi}{dt} = \Omega_{rf} \cos(\omega_{rf} t)$$

$$\overline{\mu_x} \propto \frac{1}{T} \int_0^T dt \cos(\Phi(t)) = J_0\left(\frac{\Omega_{rf}}{\omega_{rf}}\right)$$

Phase modulation -> Bessel functions

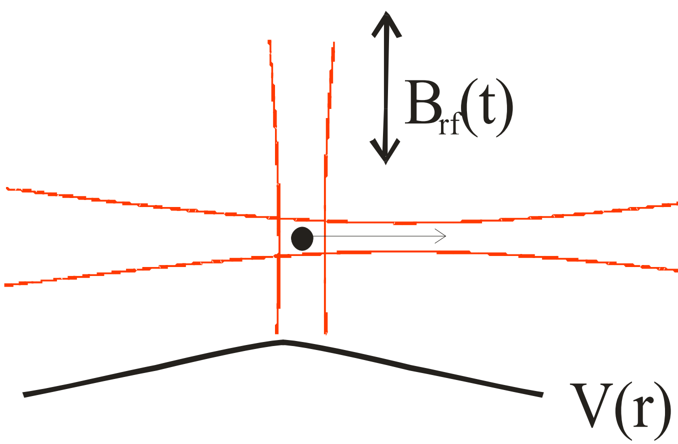
e.g. side-bands in frequency modulation;
tunneling in modulated lattice (Arimondo PRL 99 220403 (2007))…
light or matter diffraction



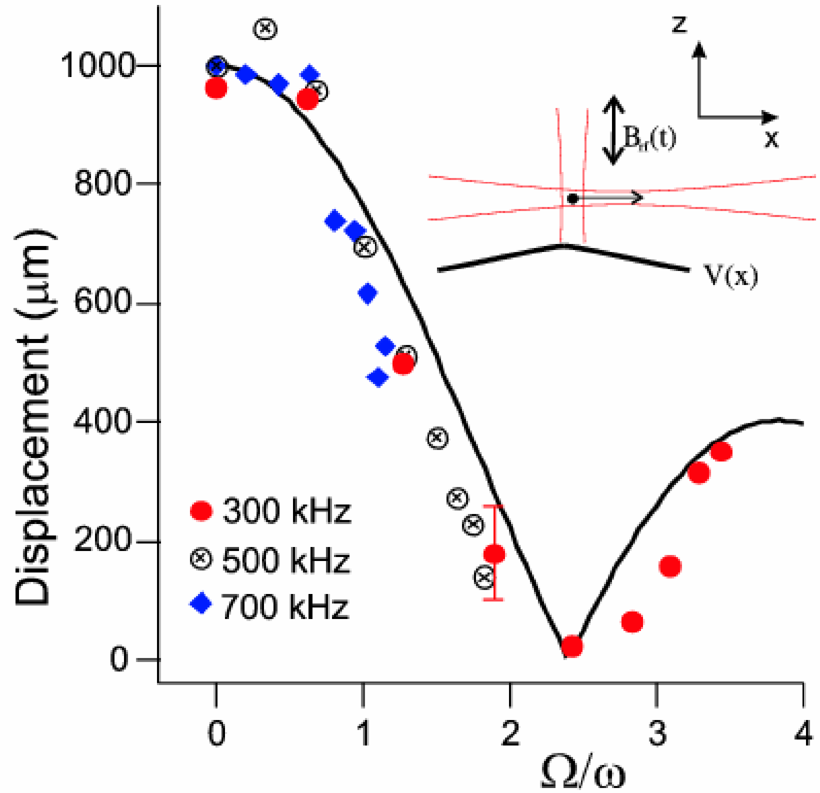


Control magnetism

- We apply blue detuned rf fields to a Cr BEC in a one beam optical trap, plus a magnetic field gradient.
- B = 0 at the center of the trap. The atoms, high field seekers, leave the center of the trap.
- RF modifies the effect of such a gradient:



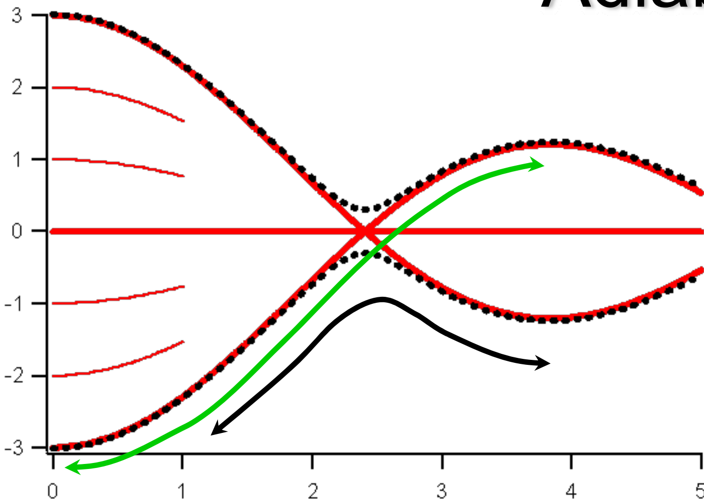
$$\Delta = \frac{1}{2}\frac{m_S g_J(\omega,\Omega)\mu_B B'}{m}t^2$$

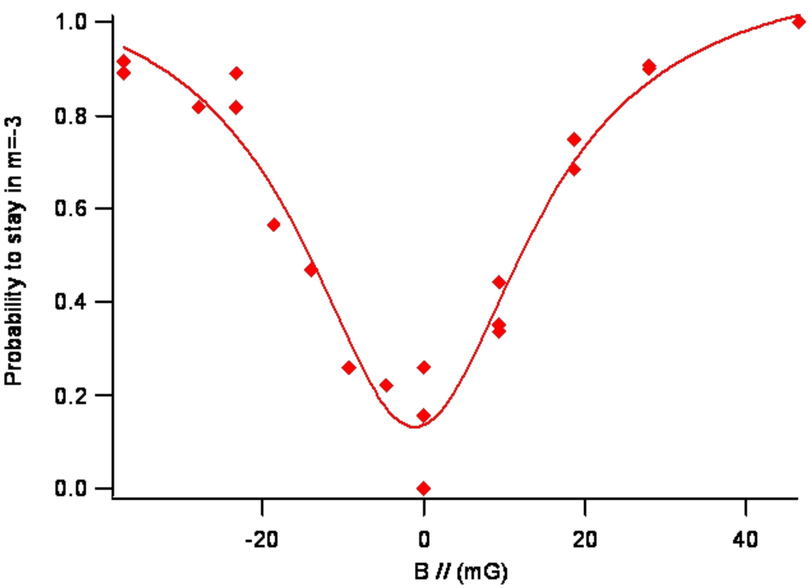


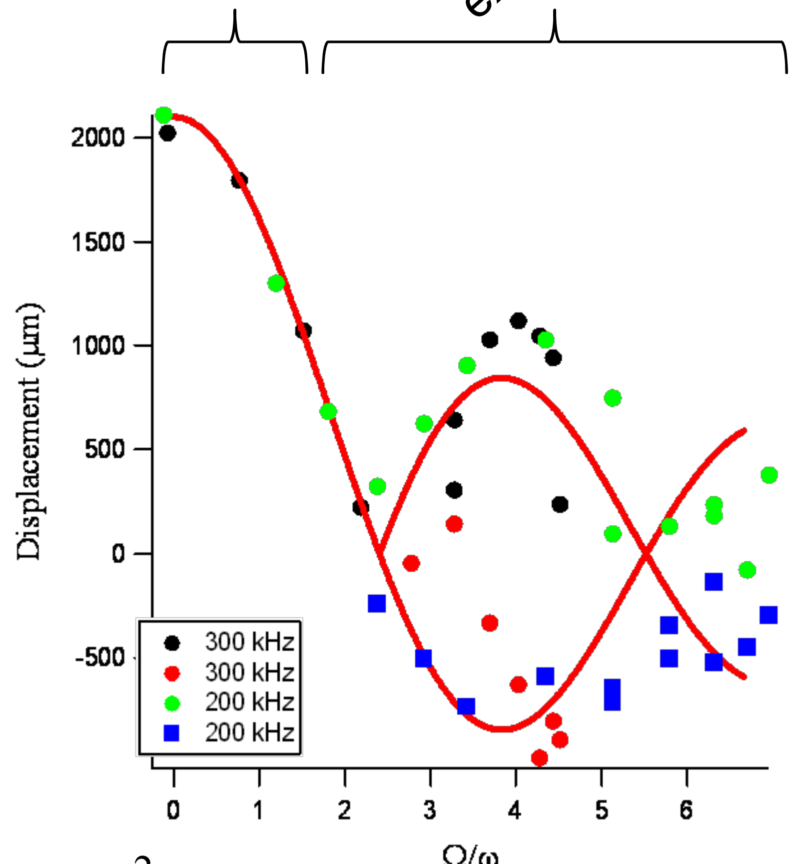
Rf dressing is reversible (adiabatic)

Q. Beaufils et al., Phys. Rev. A **78**, 051603 (2008)

Adiabaticity issues

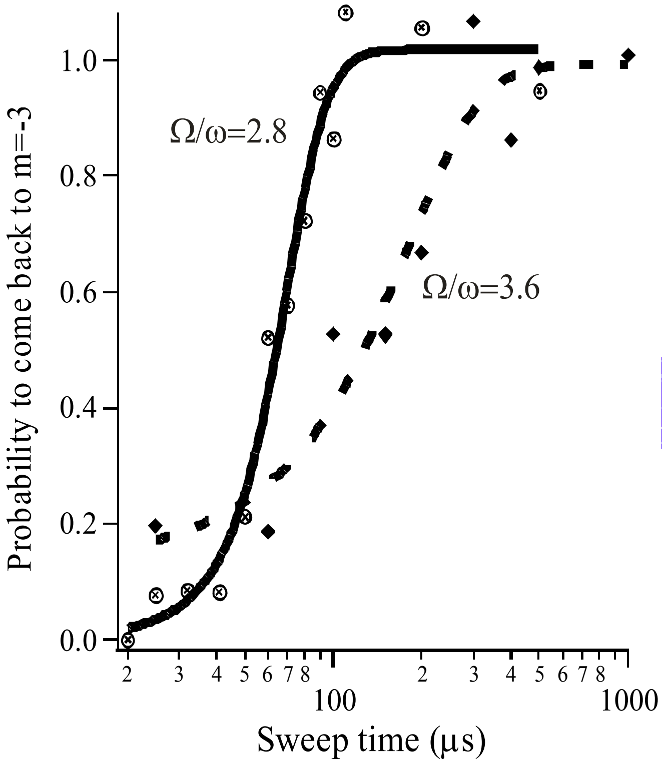


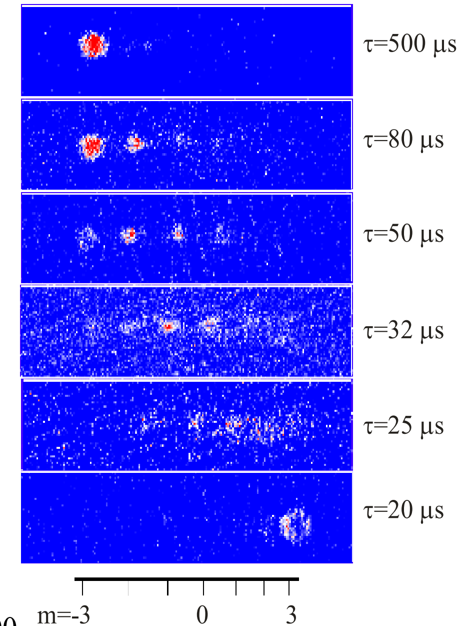


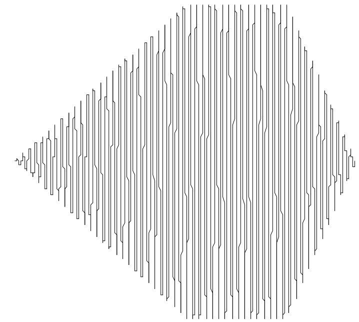


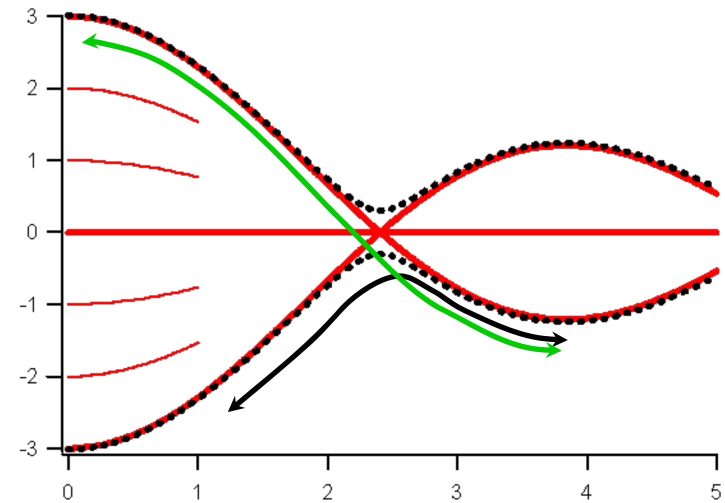
Adiabaticity depends on B_{par} : $\frac{d\Omega}{dt} << \omega_{par}^2$

A reversible dressing









If rf is applied and removed sufficiently slowly, the atoms come back to the initial Zeeman substate state.

Q. Beaufils et al., Phys. Rev. A **78**, 051603 (2008)
NB see also Phys. Rev. Lett. **24**, 974 (1970) :
Control Rb-Cs spin exchange

Perspectives for spinor physics:

Be B-independent

3D control

inelastic collisions

Conclusion

On sait produire des condensats de chrome

On a analysé la relaxation dipolaire (contrôle par champ magnétique et par confinement)

On sait contrôler par champs rf la relaxation dipolaire

Les champs rf peuvent aussi modifier le facteur de Landé des atomes

On a analysé l'association rf de molécules

Perspectives

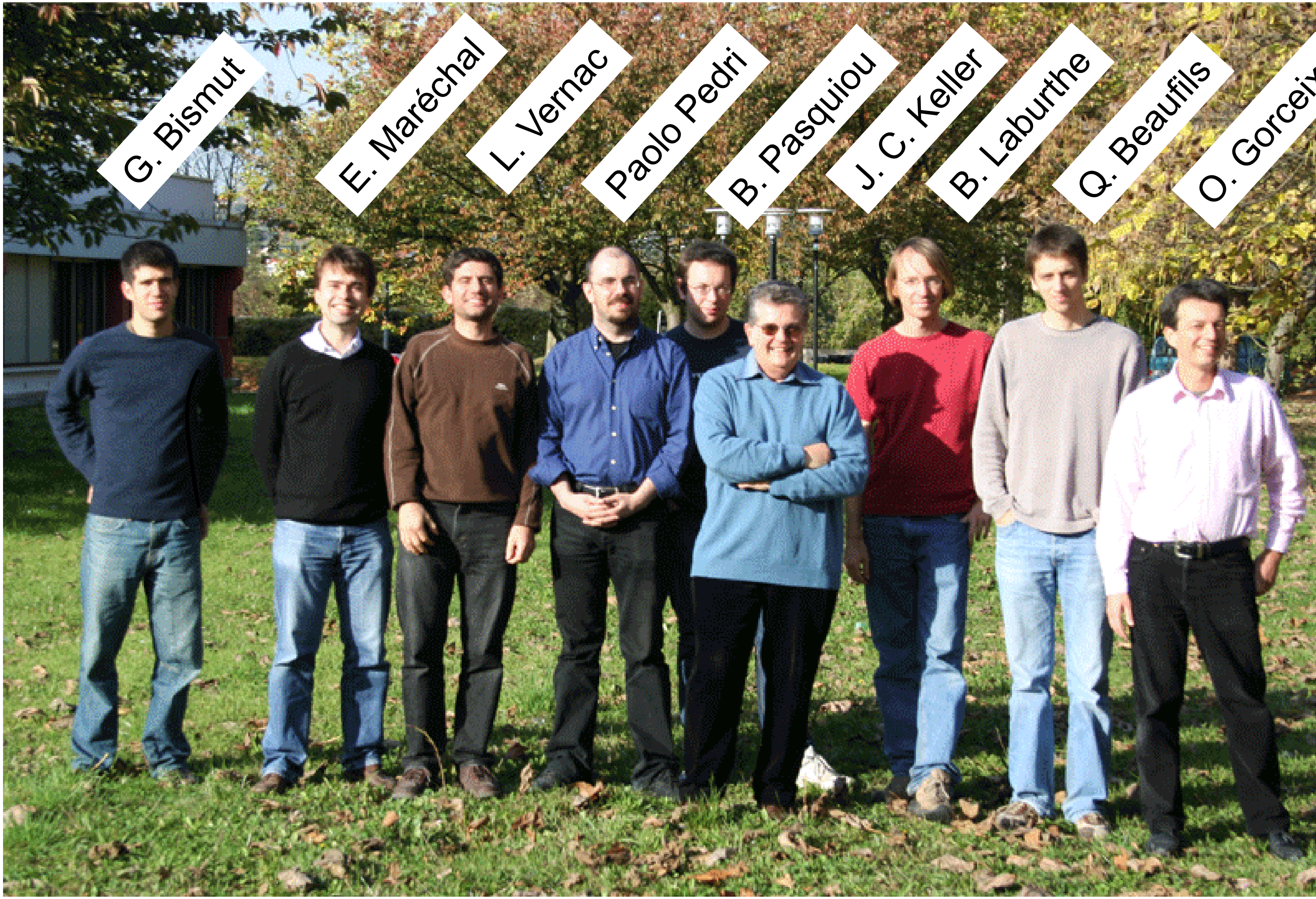
Vers l'observation de l'effet Einstein-de-Haas

Expériences dans les réseaux optiques

Produire des champs magnétiques élevés pour contrôler la longueur de diffusion

Annulation du facteur de Landé à trois dimensions, et physique des spinors

Fermions



Have left: T. Zanon, R. Barbé, A. Pouderous, R. Chicireanu

Collaboration: Anne Crubellier (Laboratoire Aimé Cotton)