Dipolar chromium BECs, and magnetism

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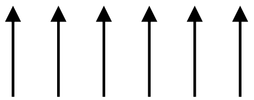
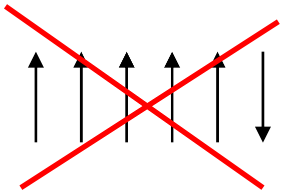
Chromium : an artificially large spin (S=3):



$$d = 6\mu_B$$

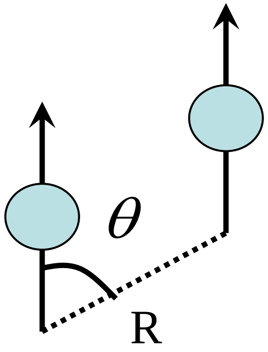


(magnetic) dipole-dipole interactions

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

Long range

Anisotropic



Van-der-Waals (contact) interactions

$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi\hbar^2}{m} a_S \delta(R)$$

Short range

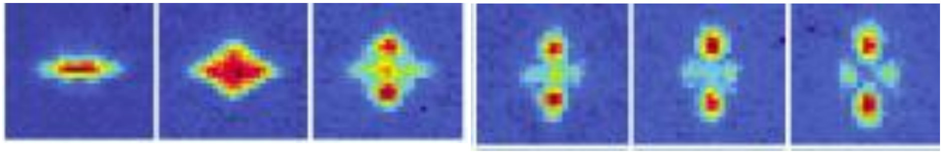
Isotropic

Relative strength of dipole-dipole and Van-der-Waals interactions

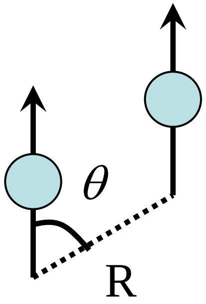
$\varepsilon_{dd} > 1$ Spherical BEC collapses

$$\varepsilon_{dd} = \frac{\mu_0 \mu_m^2 m}{12\pi\hbar^2 a} \propto \frac{V_{dd}}{V_{VdW}}$$

Stuttgart: Tune contact interactions using Feshbach resonances (Nature. 448, 672 (2007))



Anisotropic explosion pattern reveals dipolar coupling.



Stuttgart: d-wave collapse, PRL **101**, 080401 (2008)
See also Er PRL, **108**, 210401 (2012)
See also Dy, PRL, **107**, 190401 (2012)
and Dy Fermi sea PRL, **108**, 215301 (2012) … and **heteronuclear molecules**…

$\varepsilon_{dd} < 1$ BEC stable despite attractive part of dipole-dipole interactions

Cr:
$\varepsilon_{dd} = 0.16$

Small (but interesting) effects observed – at the % level :
- **Striction** – Stuttgart, PRL **95**, 150406 (2005)
- **Collective excitations** - Villetaneuse, PRL **105**, 040404 (2010)
- **Anisotropic speed of sound**, Villetaneuse, PRL **109**, 155302 (2012)

Polarized (« scalar ») BEC
Hydrodynamics
Collective excitations, sound, superfluidity

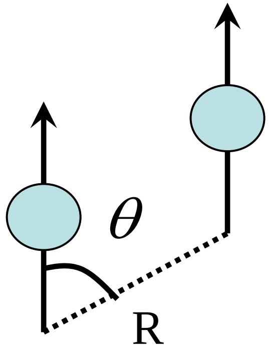
Multicomponent (« spinor ») BEC
Magnetism
Phases, spin textures…

Chromium (S=3): involve dipole-dipole interactions

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

Long-ranged

Anisotropic



Hydrodynamics:
non-local mean-field

Magnetism:
Atoms *are* magnets

Interactions couple **spin** and
orbital degrees of freedom

Key idea:

Study magnetism with large spins (S=3, S=6…)

This talk:

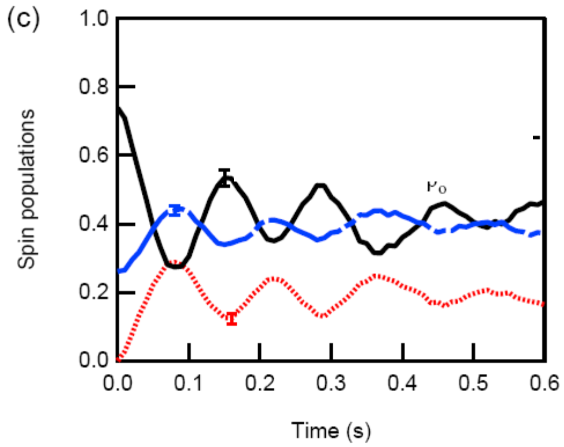
0 Introduction to spinor physics

1 Spinor physics of a Bose gas with free magnetization

2 (Quantum) magnetism in opical lattices

Introduction to spinor physics

Exchange energy
Coherent spin oscillation



Chapman,
Sengstock…

Quantum effects!

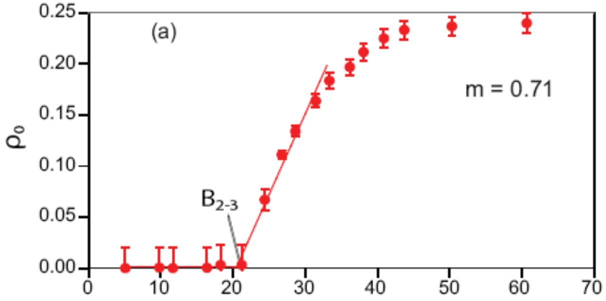
$$|0,0\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(|1,-1\rangle + |-1,1\rangle\right)$$

Klempt
Stamper-Kurn

Domains, spin textures, spin waves, topological states

Stamper-Kurn, Chapman,
Sengstock, Shin…

Quantum phase transitions



Stamper-Kurn,
Lett,
Gerbier

Main ingredients for spinor physics

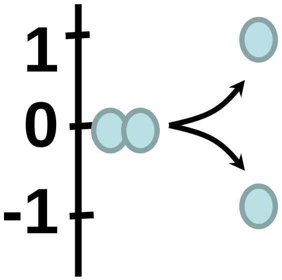
S=1,2,…

Spin-dependent contact interactions

Spin exchange

$$\left| m_S = 0, m_S = 0 \right\rangle = \sqrt{\frac{2}{3}} \left| S = 2, m_{tot} = 0 \right\rangle - \sqrt{\frac{1}{3}} \left| S = 0, m_{tot} = 0 \right\rangle$$

$$\boxed{\hbar\Gamma \propto \left(\frac{4\pi\hbar^2 (a_2 - a_0}{m} \right)}$$



Quadratic Zeeman effect

Main new features with Cr

S=3

7 Zeeman states

4 scattering lengths

New structures

Strong spin-dependent contact interactions

Purely linear Zeeman effect

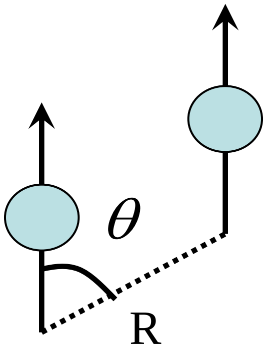
And

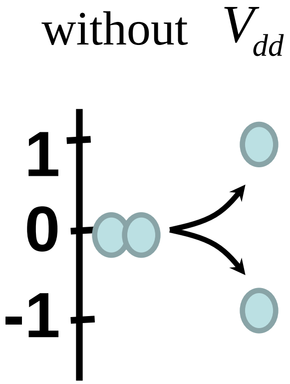
Dipole-dipole interactions

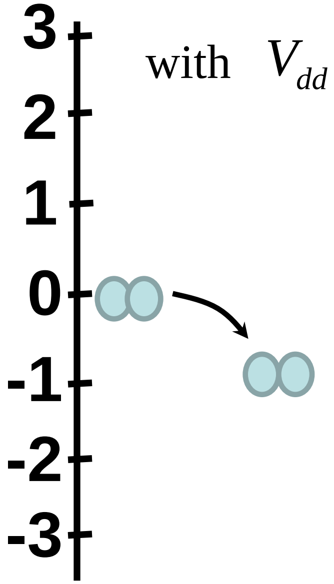
Dipolar interactions introduce magnetization-changing collisions

Dipole-dipole interactions

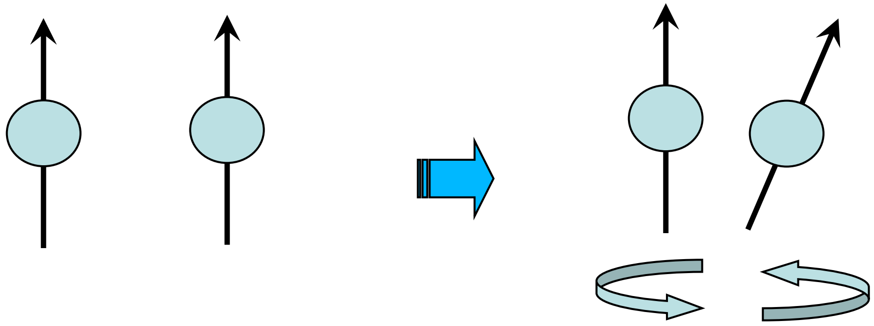
$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \left(1 - 3\cos^2(\theta)\right) \frac{1}{R^3}$$







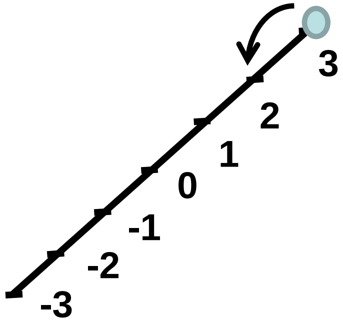
Dipolar relaxation, rotation, and magnetic field



Angular momentum conservation

$$\Delta m_S + \Delta m_l = 0$$

$$|3,3\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|3,2\rangle + |2,3\rangle\right)$$



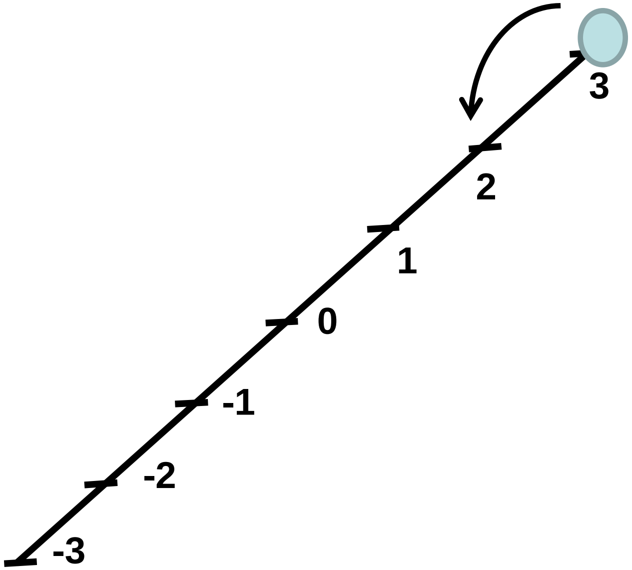
$$\Delta \ell = 2$$

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

Rotate the BEC ?
Spontaneous creation of vortices ?
Einstein-de-Haas effect

Important to control magnetic field

Ueda, PRL **96**, 080405 (2006)
Santos PRL **96**, 190404 (2006)
Gajda, PRL **99**, 130401 (2007)
B. Sun and L. You, PRL **99**, 150402 (2007)



B=1G
→ Particle leaves the trap

B=10 mG
→ Energy gain matches band excitation in a lattice

B=.1 mG
→ Energy gain equals to chemical potential in BEC

S=3 Spinor physics with free magnetization

1 Spinor physics of a Bose gas with free magnetization (bulk)

2 (Quantum) magnetism in optical lattices

Technical challenges :

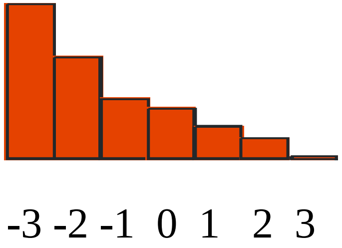
Good control of magnetic field needed (down to 100 μG)
Active feedback with fluxgate sensors

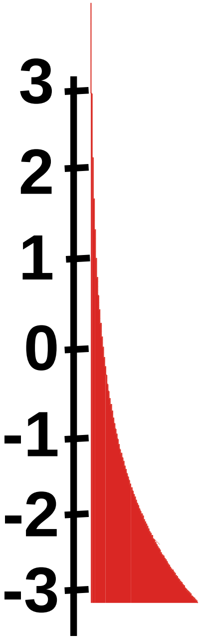
Low atom number – 10 000 atoms in 7 Zeeman states

Spin temperature equilibriates with mechanical degrees of freedom

At low magnetic field: spin thermally activated

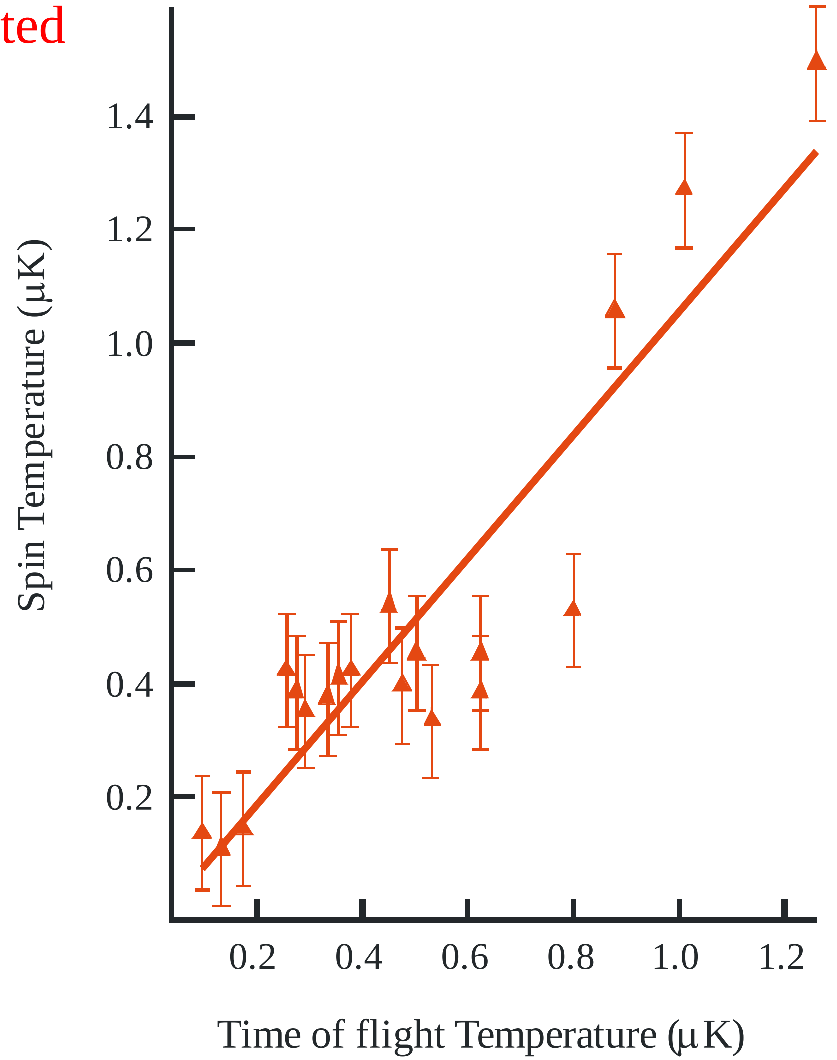
$$g\mu_B B \approx k_B T$$



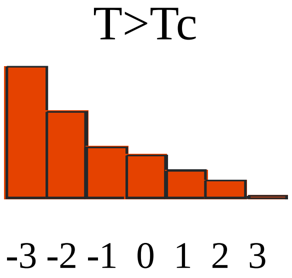


We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)

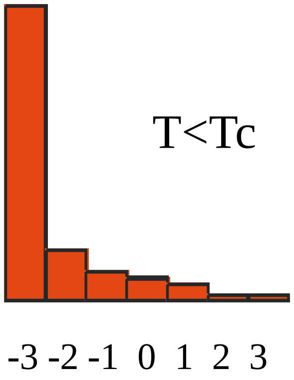
Related to Demagnetization Cooling expts, Pfau, *Nature Physics* **2**, *765 (2006)*



Spontaneous magnetization due to BEC



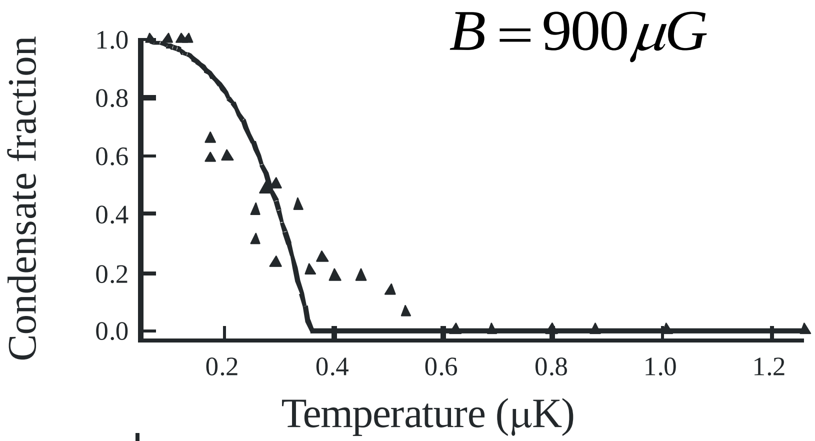
Thermal population in Zeeman excited states

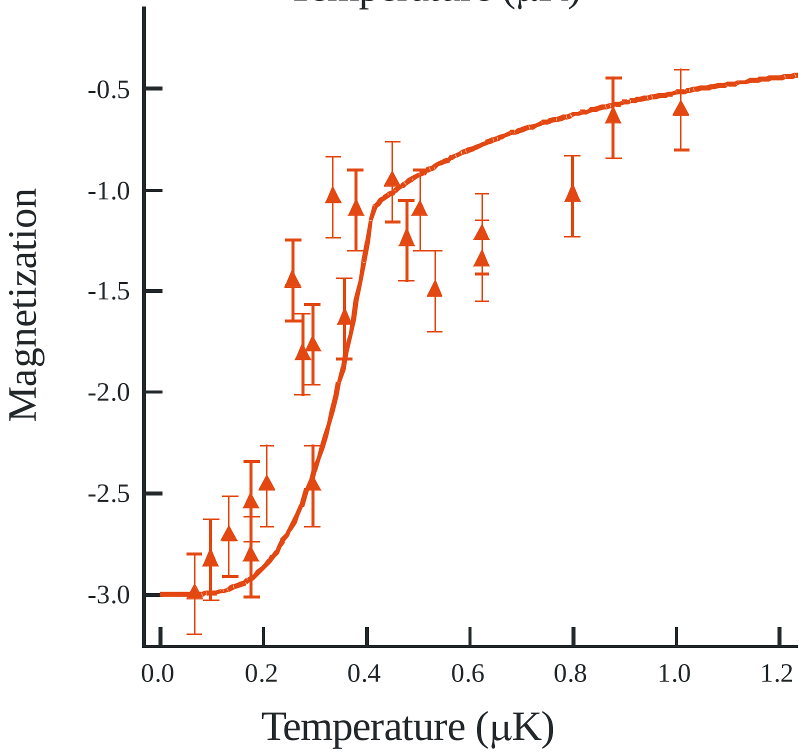


a bi-modal spin distribution

BEC only in m_S=-3 (lowest energy state)

Cloud spontaneously polarizes !



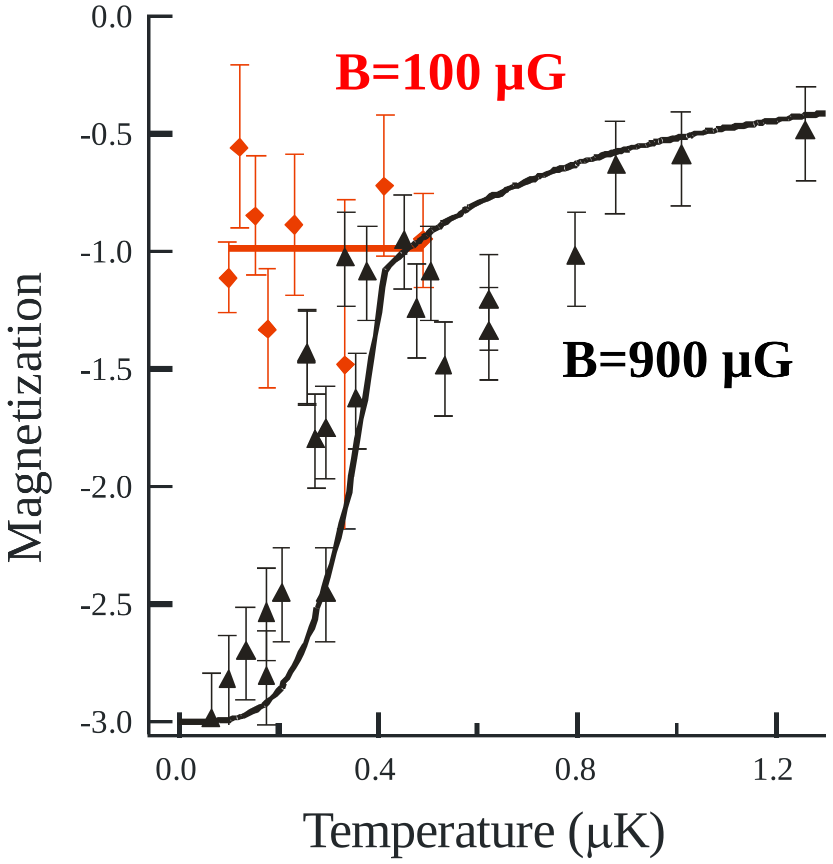


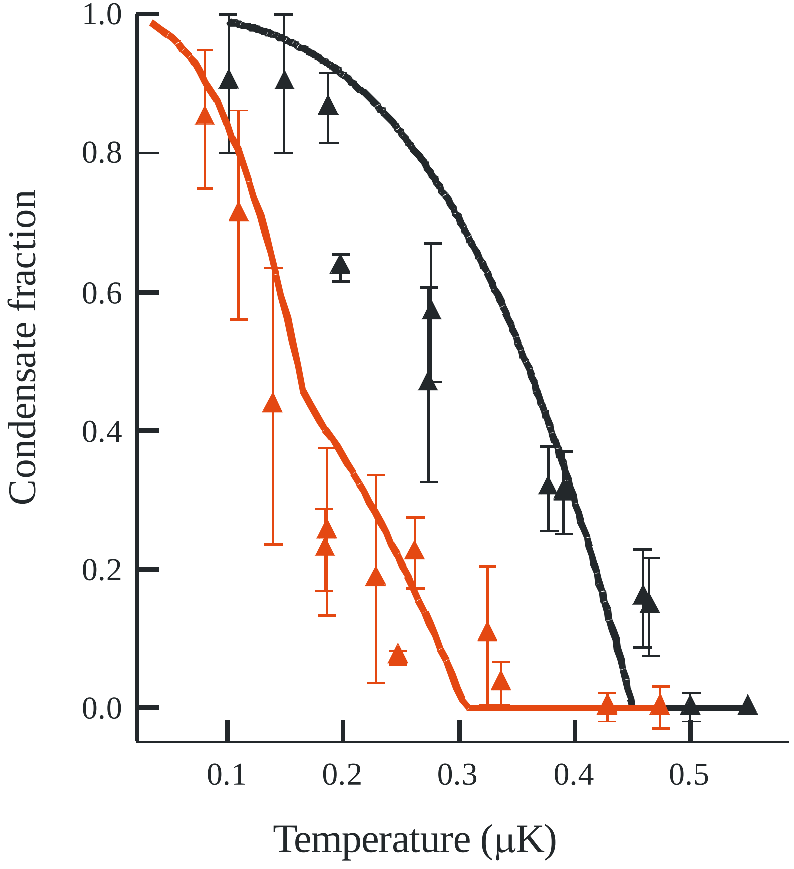
A non-interacting BEC is ferromagnetic

New magnetism, differs from solid-state

PRL **108**, 045307 (2012)

Below a critical magnetic field: the BEC ceases to be ferromagnetic !



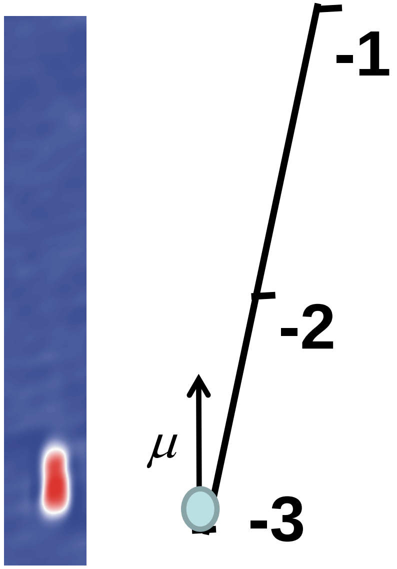


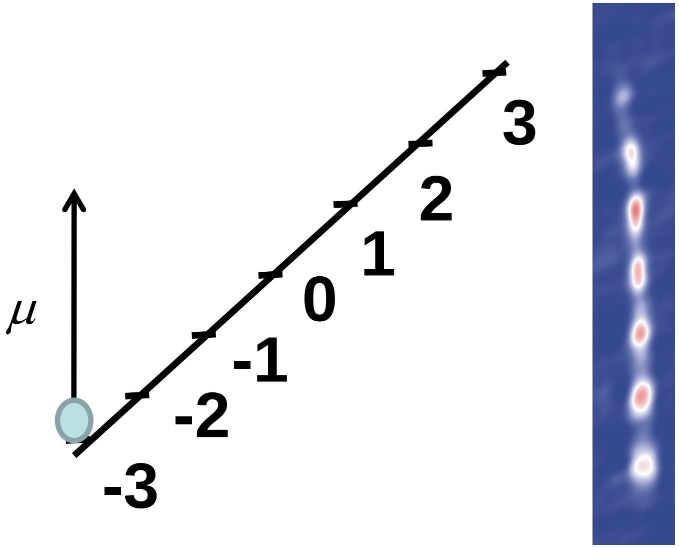
-Magnetization remains small even when the condensate fraction approaches 1
!! Observation of a depolarized condensate !!

Necessarily an interaction effect

PRL **108**, 045307 (2012)

Cr spinor properties at low field





Large magnetic field : ferromagnetic

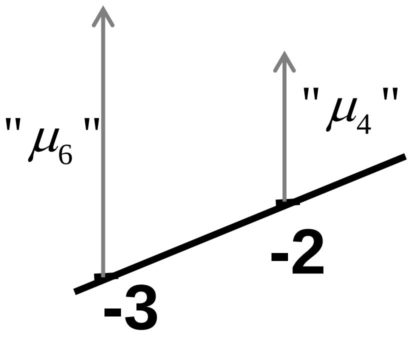
Low magnetic field : polar/cyclic

$$\left|m_S=-2, m_S=-2\right\rangle =$$

$$\sqrt{\frac{6}{11}}\left|S=6, m_{tot}=-4\right\rangle - \sqrt{\frac{5}{11}}\left|S=4, m_{tot}=-4\right\rangle$$

$$\boxed{g_J \mu_B B_c \approx \frac{2\pi\hbar^2 n_0\left(a_6-a_4\right)}{m}}$$

PRL **106**, 255303 (2011)

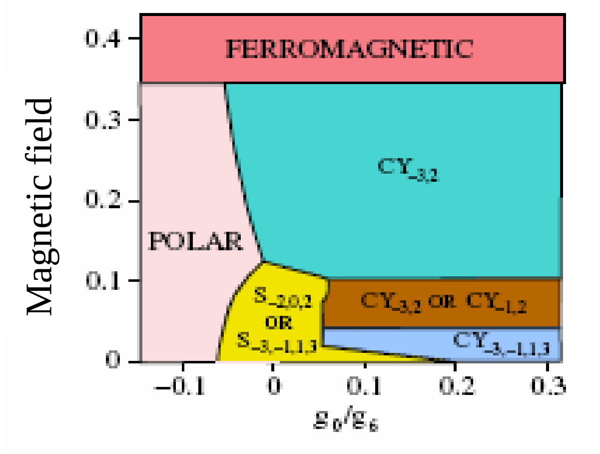


Santos PRL **96**, 190404 (2006)

Ho PRL. **96**, 190405 (2006)

Good agreement between field below which we see demagnetization and Bc

Open questions about equilibrium state

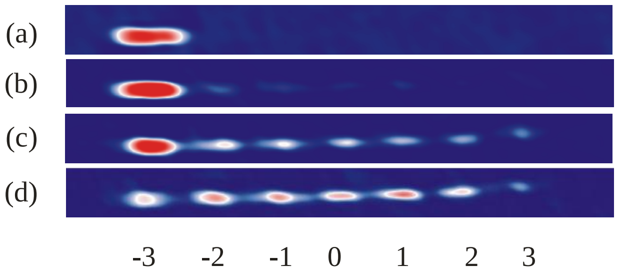


Santos and Pfau
PRL **96**, 190404 (2006)
Diener and Ho
PRL. **96**, 190405 (2006)
Demler et al.,
PRL **97**, 180412 (2006)

Phases set by contact interactions, magnetization dynamics set by dipole-dipole interactions

Polar

$$\frac{1}{\sqrt{2}}\left(1,0,0,0,0,0,1\right)$$



Cyclic

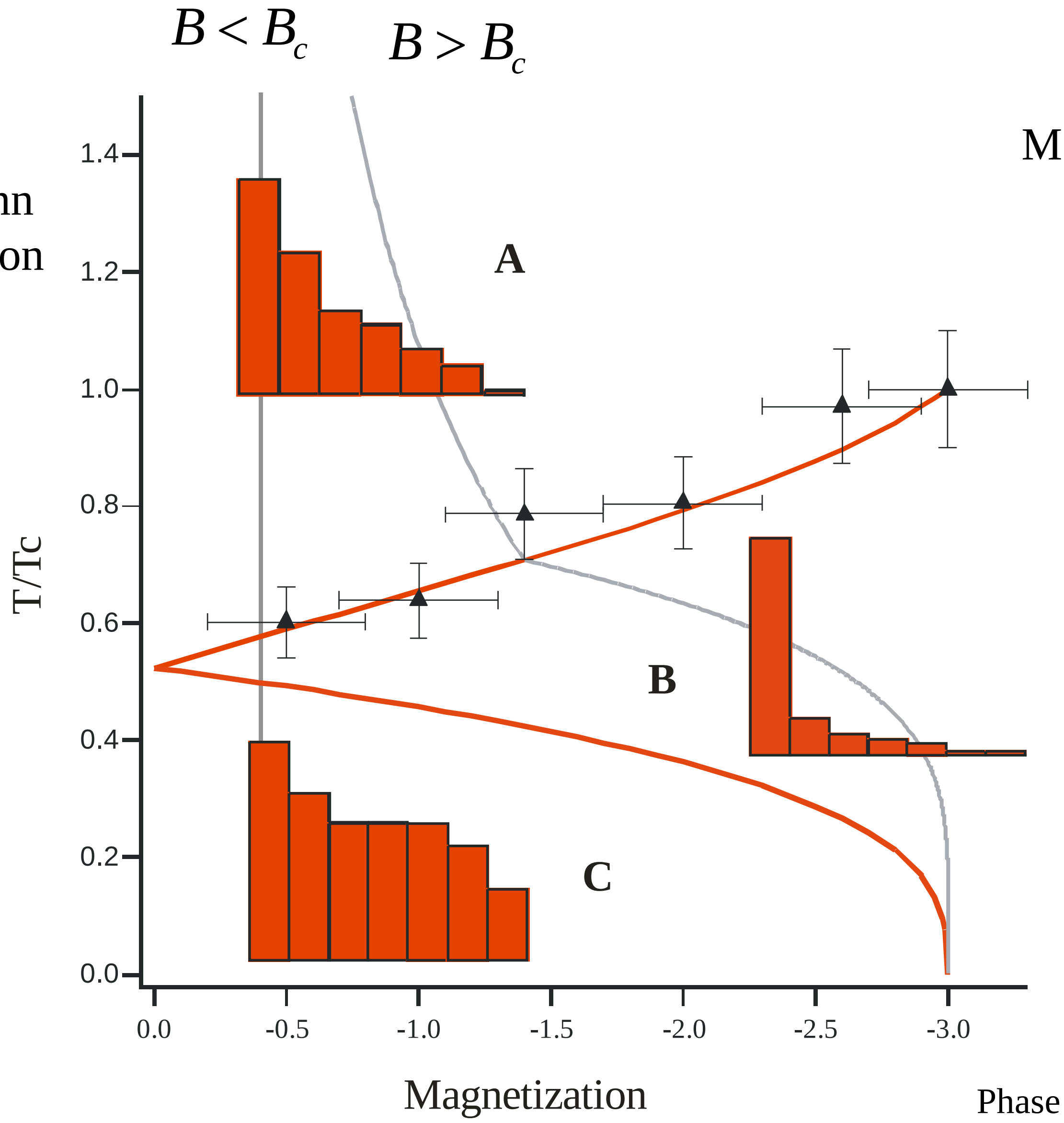
$$\frac{1}{\sqrt{2}}\left(1,0,0,0,0,1,0\right)$$

!! Depolarized BEC likely in metastable state !!

- Operate near B=0. Investigate absolute many-body ground-state
-We do not (cannot ?) reach those new ground state phases
-Quench should induce vortices…
-Role of thermal excitations ?

Magnetic phase diagram

Quasi-
Boltzmann
distribution



Measure $T_c(B)$ and $M(T_c,B)$
for different magnetic
fields B
Get $T_c(M)$

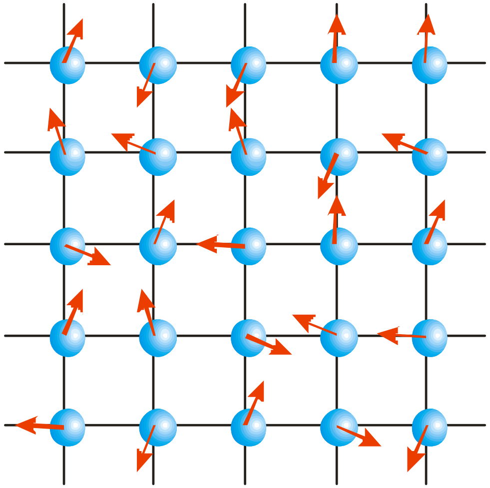
Bi-modal spin
distribution

Phase diagram adapted from J. Phys. Soc.
Jpn, **69,** 12, 3864 (2000)
See also PRA, **59**, 1528 (1999)

0 Introduction to spinor physics

1 Spinor physics of a Bose gas with free magnetization

2 (Quantum) magnetism in opical lattices



Study quantum magnetism with dipolar gases ?

Hubard model at half filling, Heisenberg model of magnetism **(effective spin model)**

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

Dipole-dipole interactions between real spins

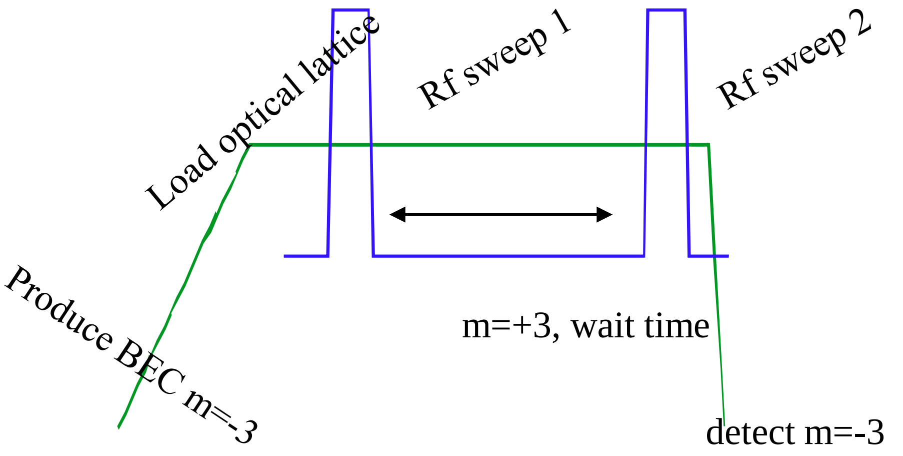
$$V_{dd}=\frac{\mu_0}{4\pi}\left(g_J\mu_B\right)^2\frac{S_1.S_2-3(S_1.\vec{u}_R)(S_2.\vec{u}_R)}{R^3}$$

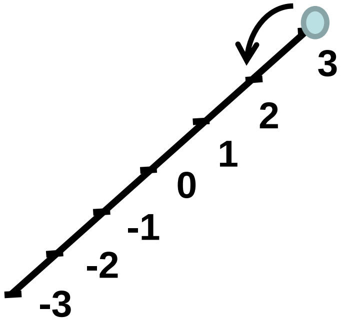
$$\begin{aligned}&S_{1z}S_{2z}+\frac{1}{2}\left(S_{1+}S_{2-}+S_{1-}S_{2+}\right)\\&-\frac{3}{4}\left(2zS_{1z}+r_-S_{1+}+r_+S_{1-}\right).\\&\left(2zS_{2z}+r_-S_{2+}+r_+S_{2-}\right)\end{aligned}$$

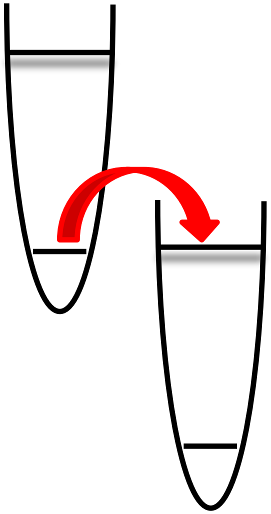
Magnetization changing collisions

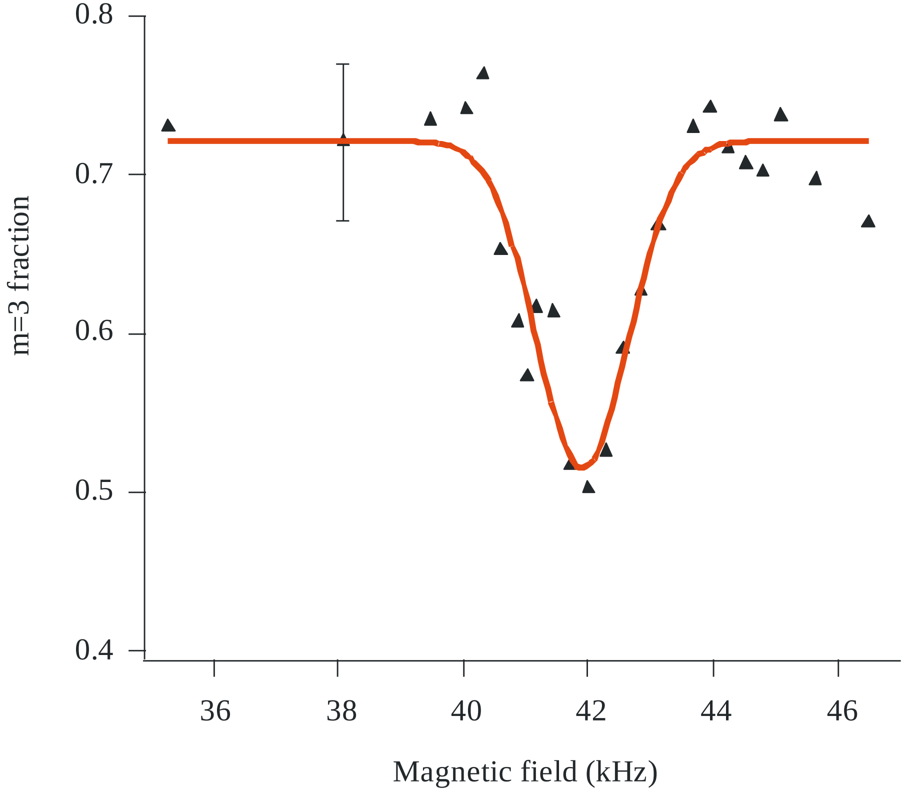
$$S_1^-S_2^-$$

Magnetization dynamics resonance for a Mott state with two atoms per site (~15 mG)





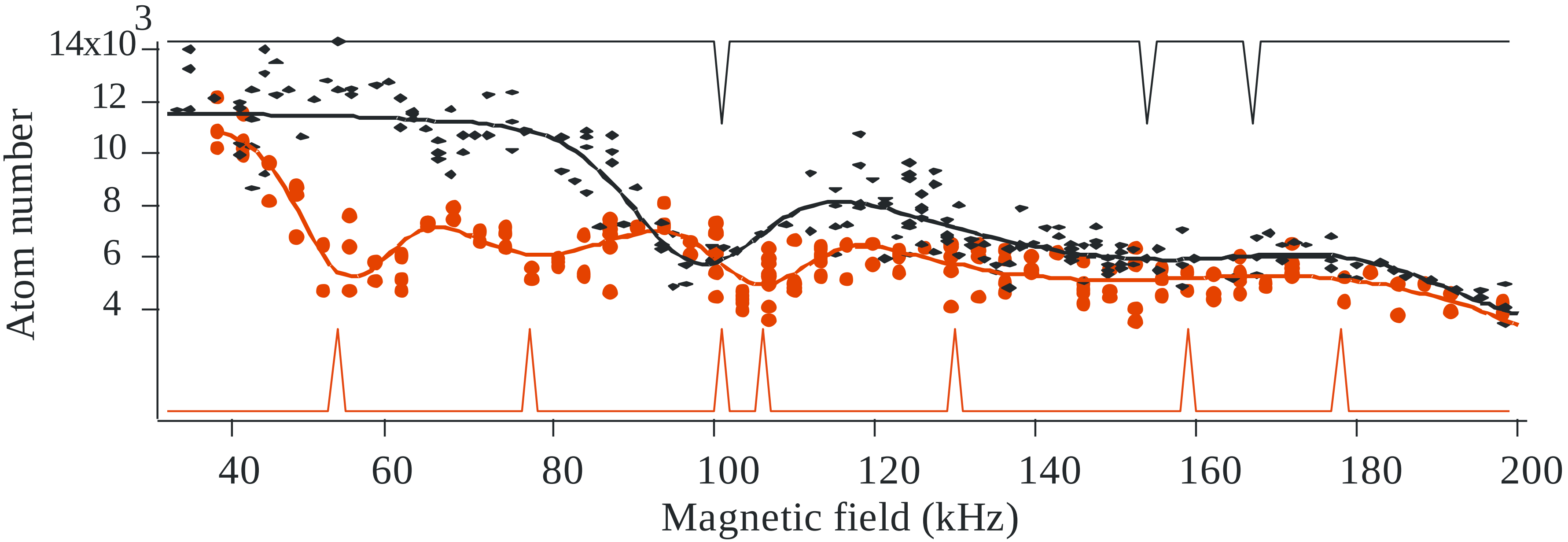




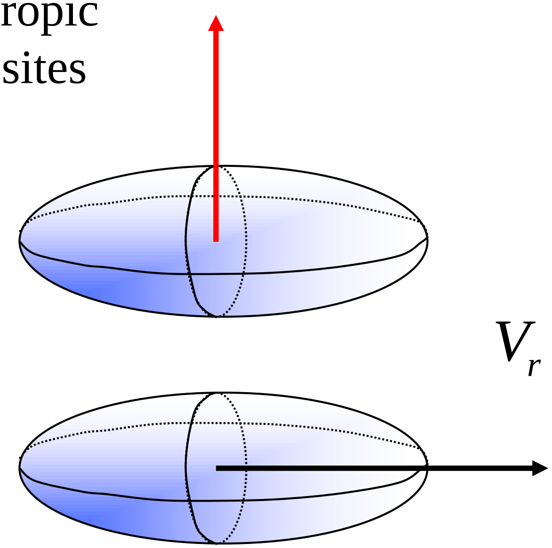
Dipolar resonance when released energy matches band excitation

Mott state locally coupled to excited band

Direct manifestation of anisotropic interactions : Strong anisotropy of dipolar resonances



Anisotropic lattice sites



$$V_r = \frac{3}{2} S d^2 \frac{(x+iy)^2}{r^5}$$

May produce vortices in each lattice site (Einstein-de-Haas effect)

See also PRL **106**, 015301 (2011)

From now on : stay away from dipolar magnetization dynamics resonances,

Spin dynamics at constant magnetization (<15mG)

Magnetization changing collisions Can be suppressed in optical lattices

$$\xcancel{S_1^- S_2^-}$$

$$S_{1z}S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

Differs from Heisenberg magnetism:

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

Related research with polar molecules:

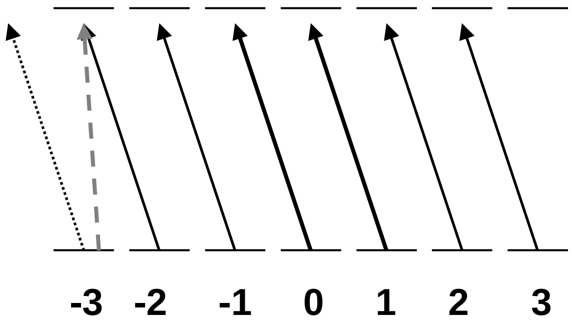
$$\alpha S_{1z}S_{2z} + \beta\frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

A. Micheli et al., Nature Phys. **2**, 341 (2006).
A.V. Gorshkov et al., PRL, **107**, 115301 (2011),
See also D. Peter et al., PRL. **109**, 025303 (2012)

Other differences from Heisenberg magnetism:

Bosons… Not a spin ½ system: S=3… Anisotropy…-1/r^3 dependence…
Does not rely on Mott physics… Can have more than one atom per site

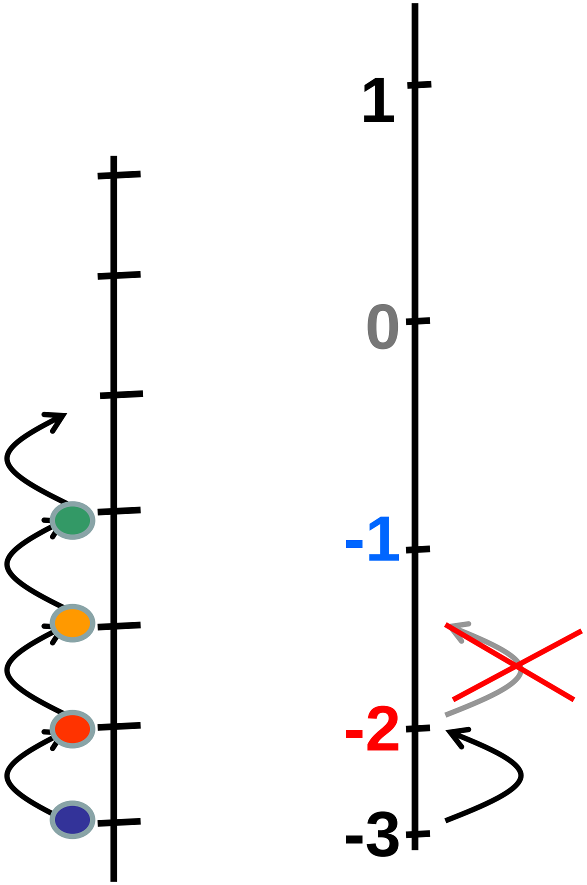
Control the initial state by a tensor light-shift



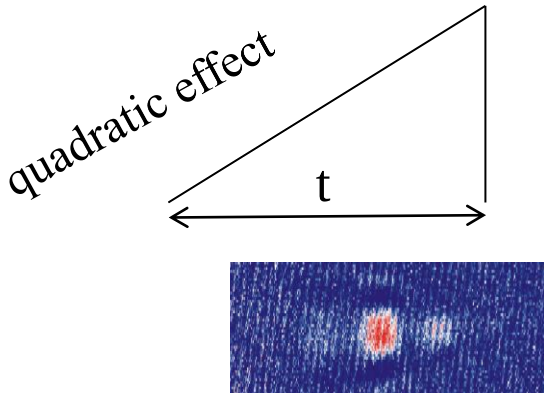
A σ– polarized laser
Close to a J→J transition
(100 mW 427.8 nm)

$$\boxed{\Delta=\alpha\, m_S^2}$$

Quadratic effect allows state preparation



Adiabatic state preparation in 3D lattice



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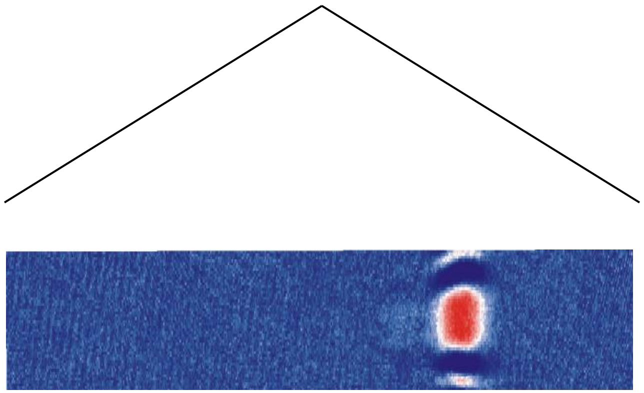
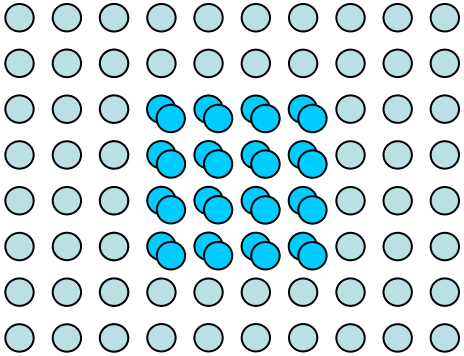
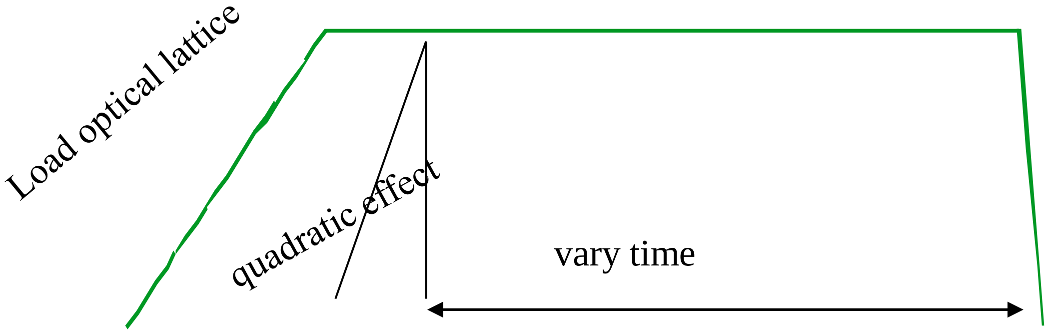


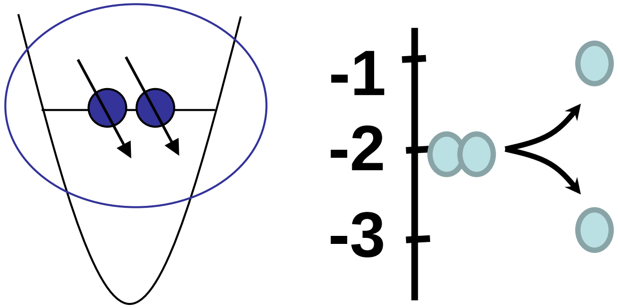
-3

Initiate spin dynamics by removing quadratic effect

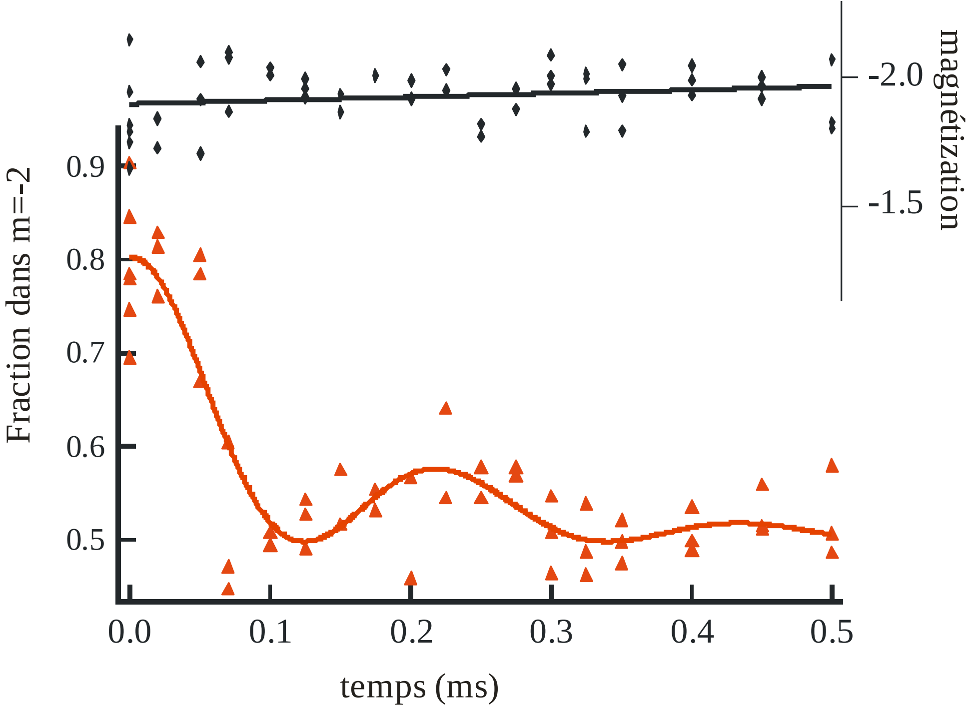




Short times : fast oscillations due to spin-dependent contact interactions



$$\left|m_S=-2, m_S=-2\right\rangle = \sqrt{\frac{6}{11}}\left|S=6, m_{tot}=-4\right\rangle - \sqrt{\frac{5}{11}}\left|S=4, m_{tot}=-4\right\rangle$$



(period ↔ 220 μs)

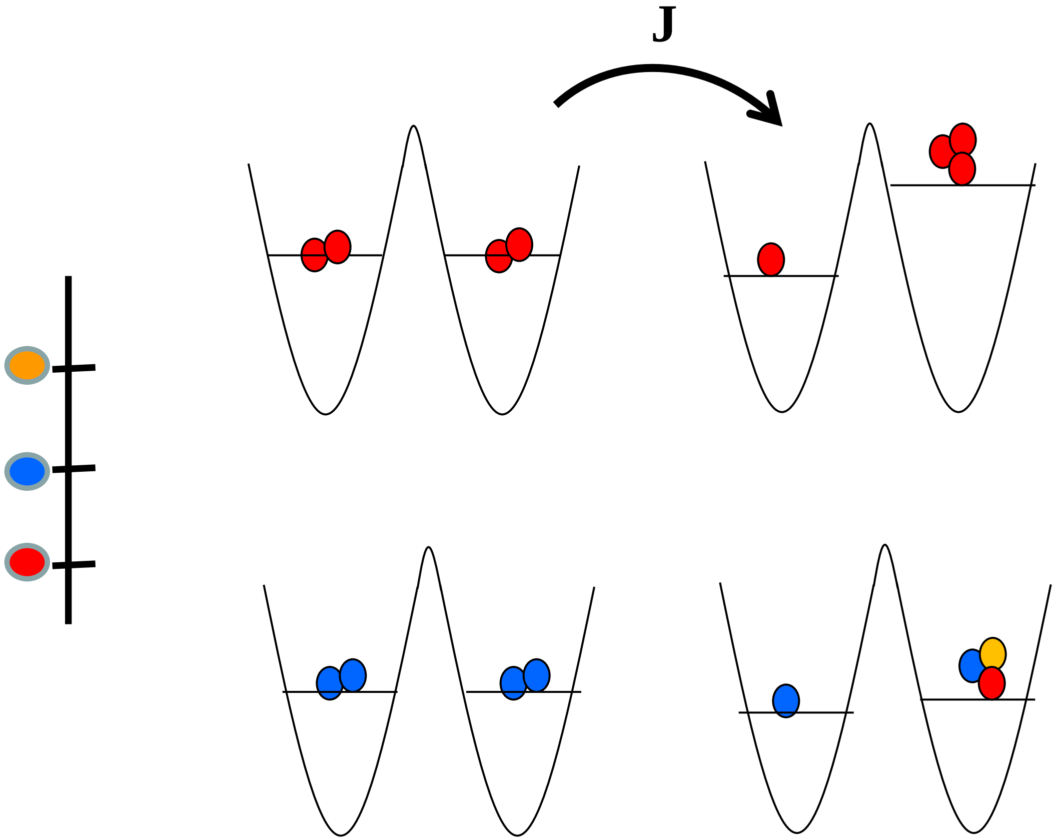
PRELIMINARY

$$\boxed{\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)}$$

(↔ 250 μs)

Up to now unknown source of damping (sudden melting of Mott insulator ?)

(sudden melting of Mott insulator ?)



All atoms in m_S=-3

Mott gap U~10kHz

U/J~100

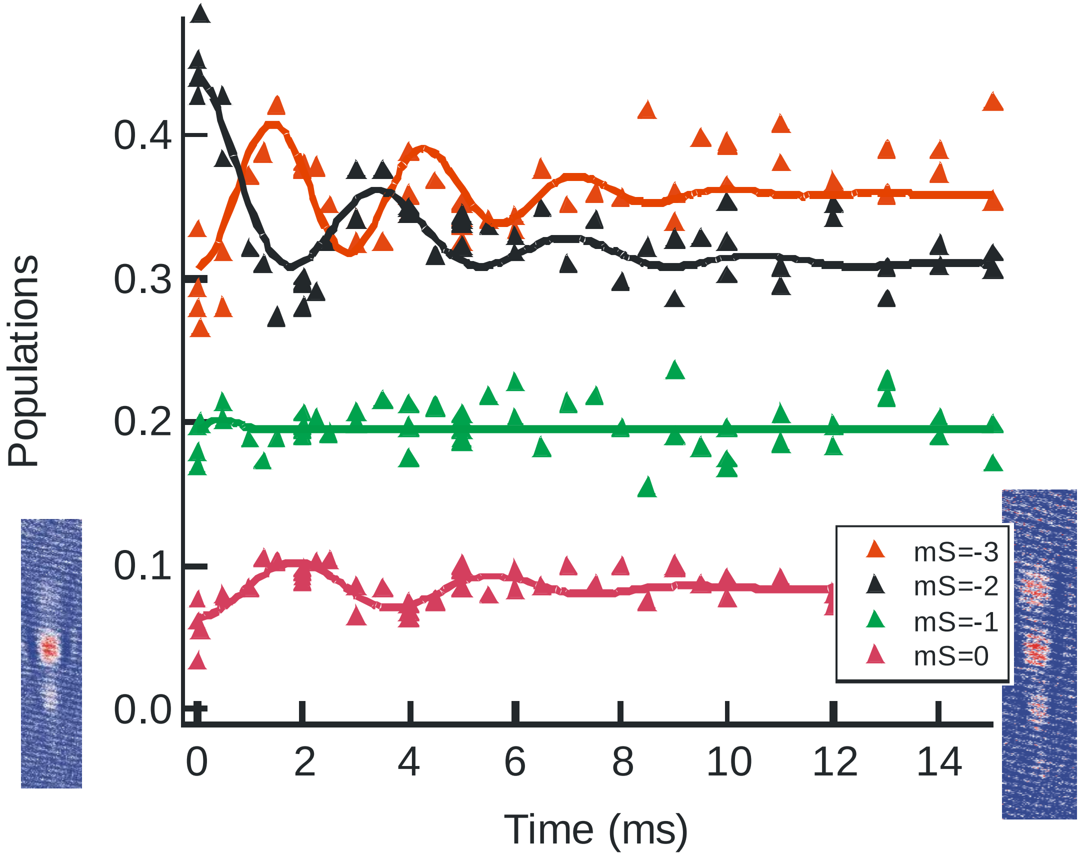
Atoms in m_S=-2

Gap ΔU~ .5 kHz

ΔU/J ~ 5

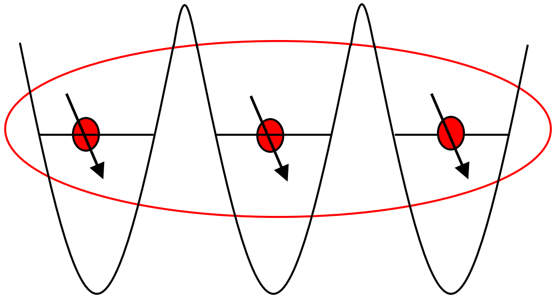
PRELIMINARY

Long time-scale spin dynamics in lattice : intersite dipolar exchange



Magnetization is constant

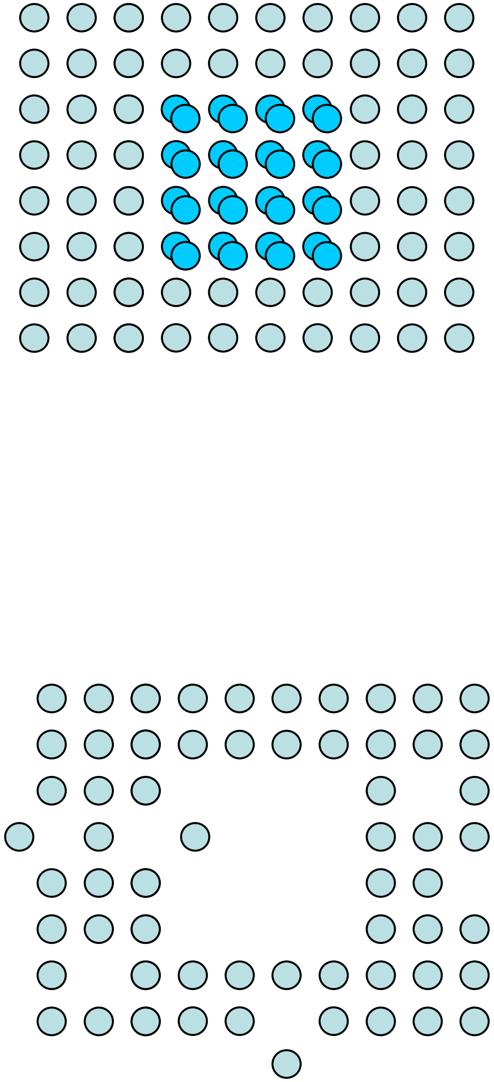
Sign for intersite dipolar interaction
(much slower than on-site dynamics)

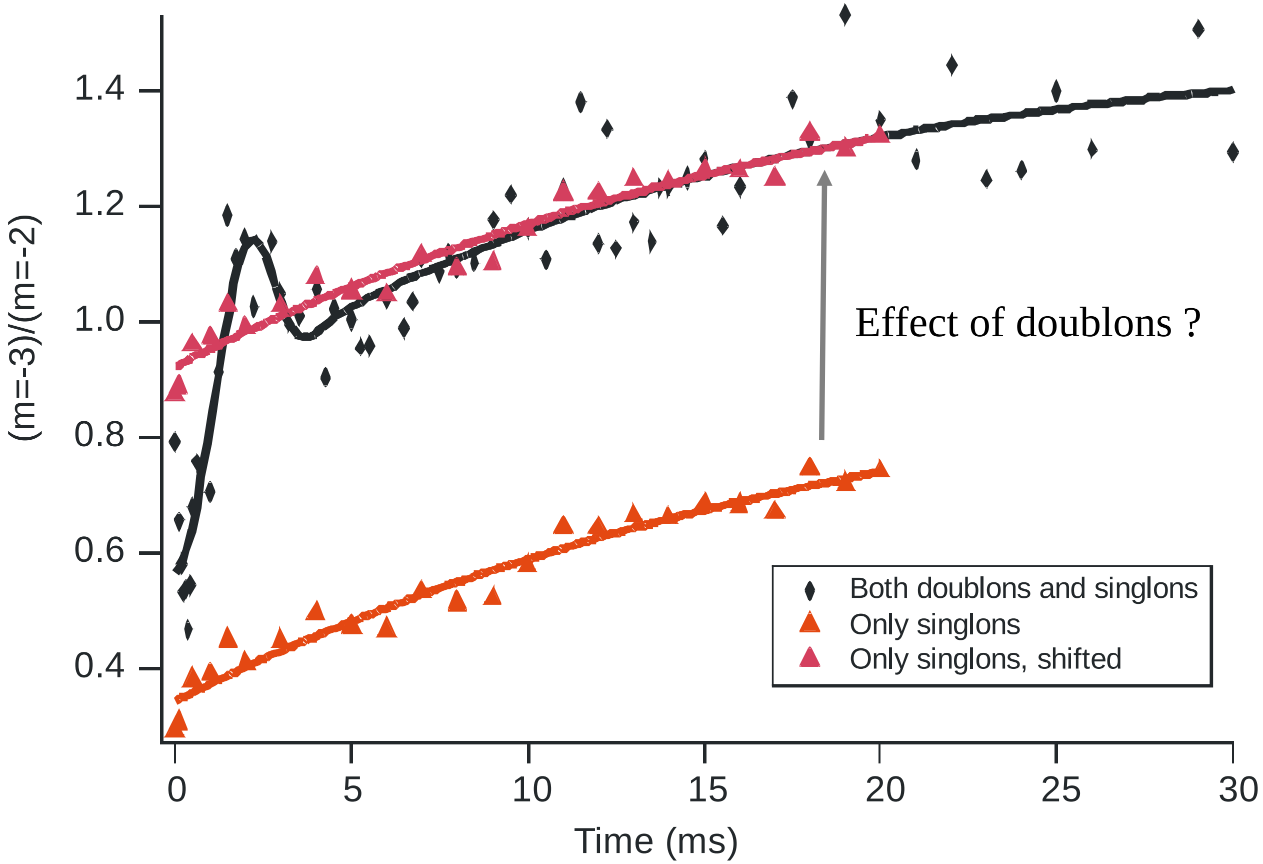


$$\frac{1}{2}\left(S_{1+}S_{2-}+S_{1-}S_{2+}\right)$$

PRELIMINARY

Oscillations arise from interactions between doubled-occupied sites





Effect of doublons ?

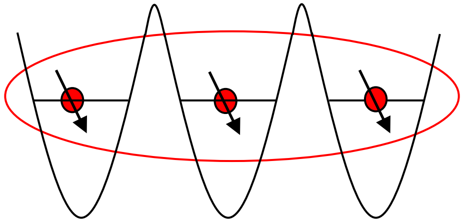
PRELIMINARY

Very slow spin dynamics for one particle per site: Intersite dipole-dipole coupling

Our current understanding:

$$S_{1z}S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

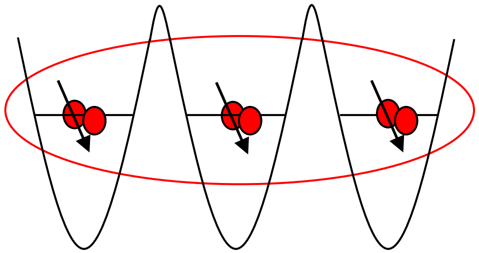
(Very) long time-scale dynamics due to inter-site dipolar exchange between singlons



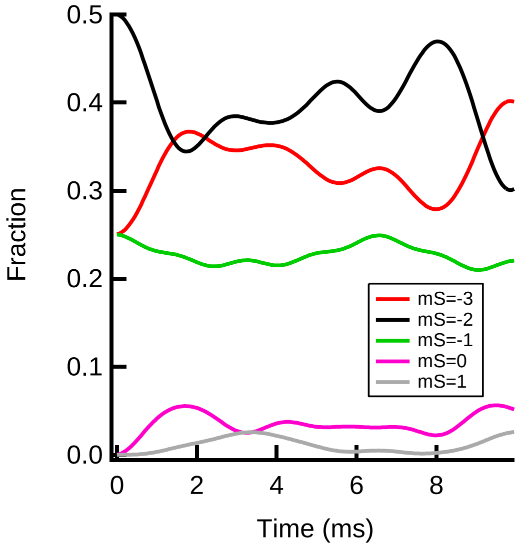
1/e timescale = 25 ms

Theoretical estimate : 2 atoms, 2 sites : exchange timescale = 50 ms

Spin oscillations due to inter-site dipolar exchange between doublons



Timescale = 4 ms

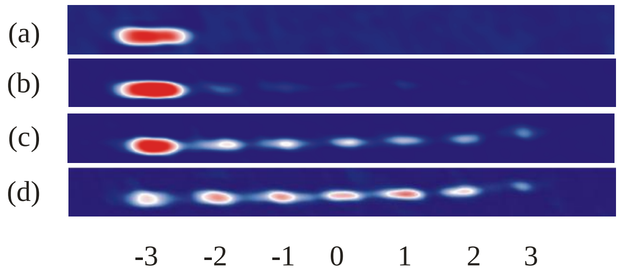


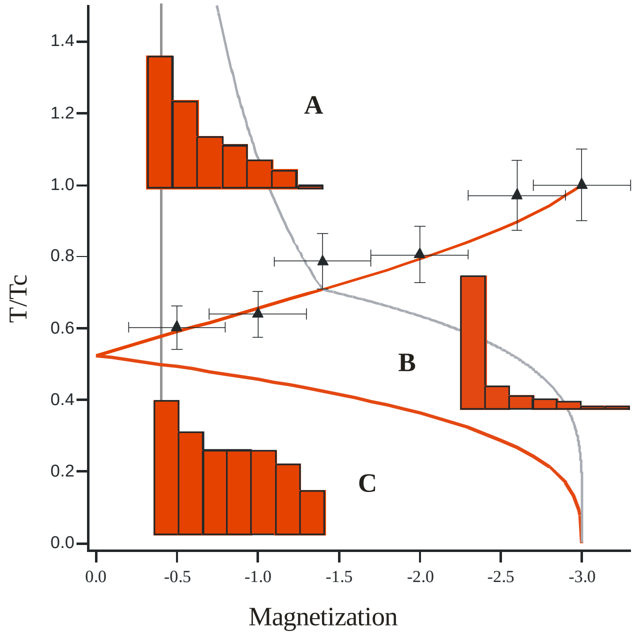
Exact diagonalization 2 pairs, 2 sites
Faster coupling because larger effecive spin

Conclusions

Bulk Magnetism:

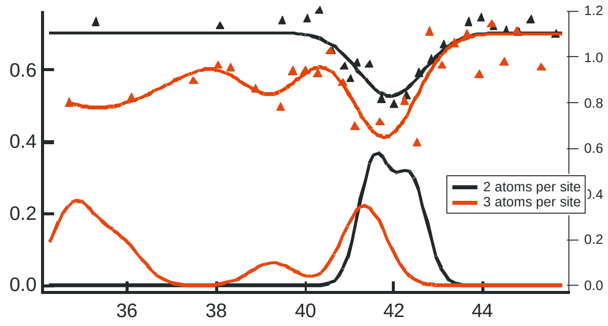
spinor physics with free magnetization



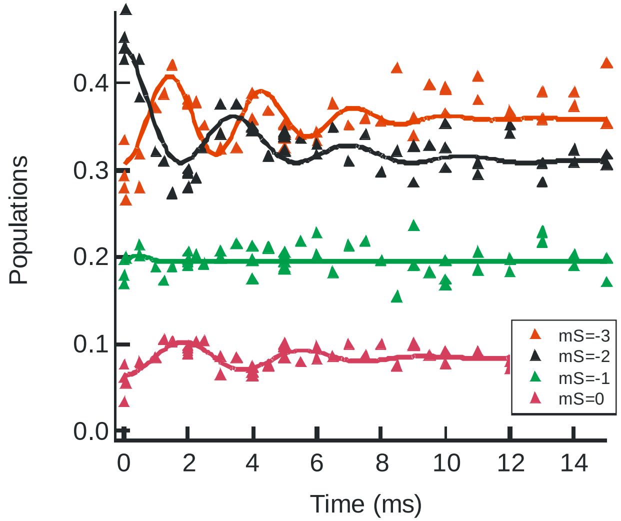


New spinor phases at extremely low magnetic fields

Lattice Magnetism:



Magnetization dynamics is resonant



Intersite dipolar spin-exchange

A. de Paz, A. Chotia, A. Sharma B. Pasquiou, G. Bismut,
B. Laburthe-Tolra, E. Maréchal, L. Vernac,
P. Pedri, M. Efremov, O. Gorceix

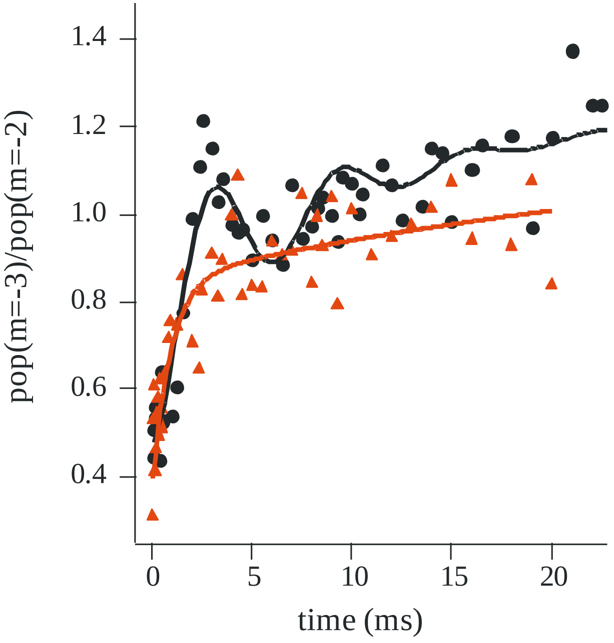
Magnetism in lattice

Resonant magnetization dynamics

Towards Einstein-de-Haas effect

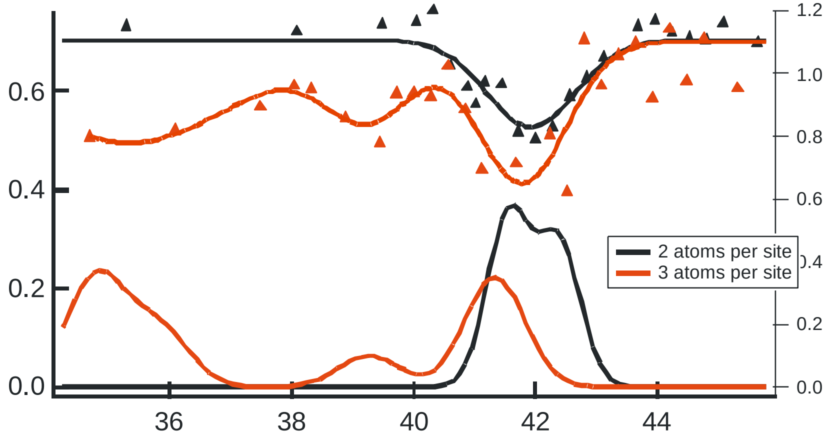
Anisotropy

Few body vs many-body physics



Spontaneous depolarization at low magnetic field

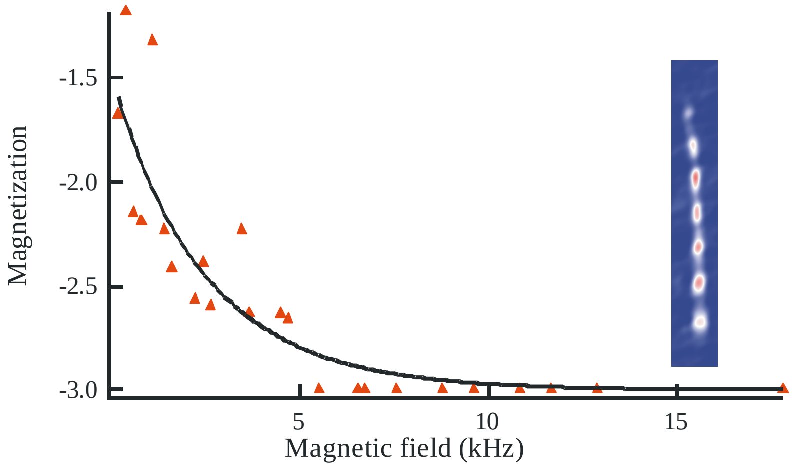
Towards low-field phase diagram



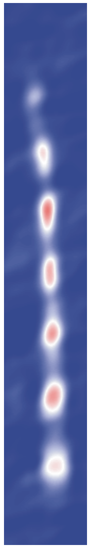
Away from resonances: spin oscillations

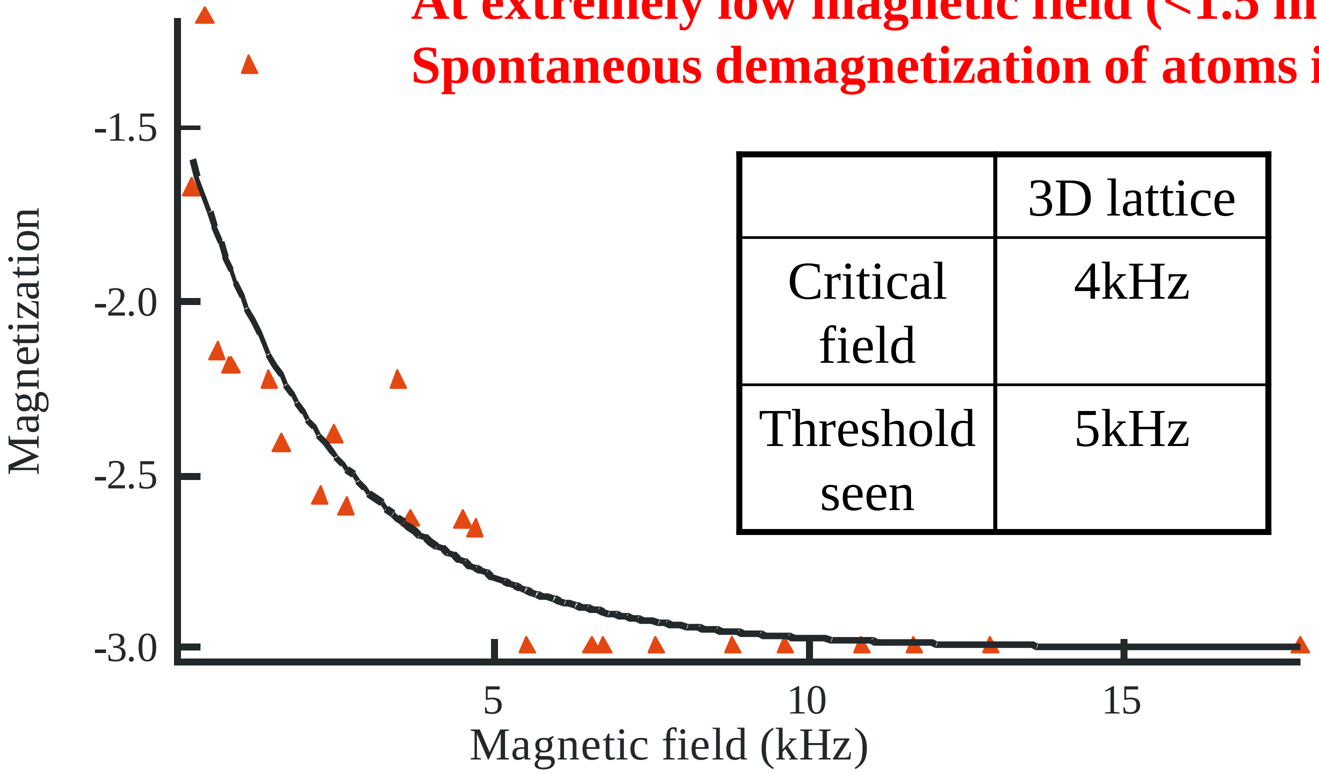
Spin-exchange

Dipolar exchange



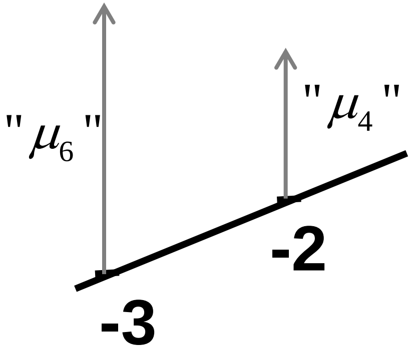
At extremely low magnetic field (<1.5 mG): Spontaneous demagnetization of atoms in a 3D lattice



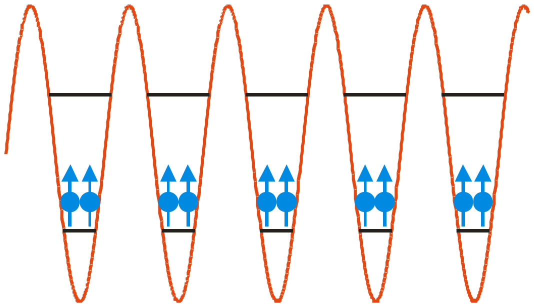


	3D lattice
Critical field	4kHz
Threshold seen	5kHz

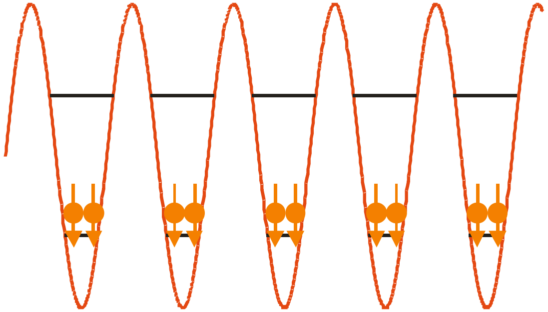
$$g_J \mu_B B_c \approx \frac{4\pi\hbar^2 n_0 \left(a_6 - a_4\right)}{m}$$



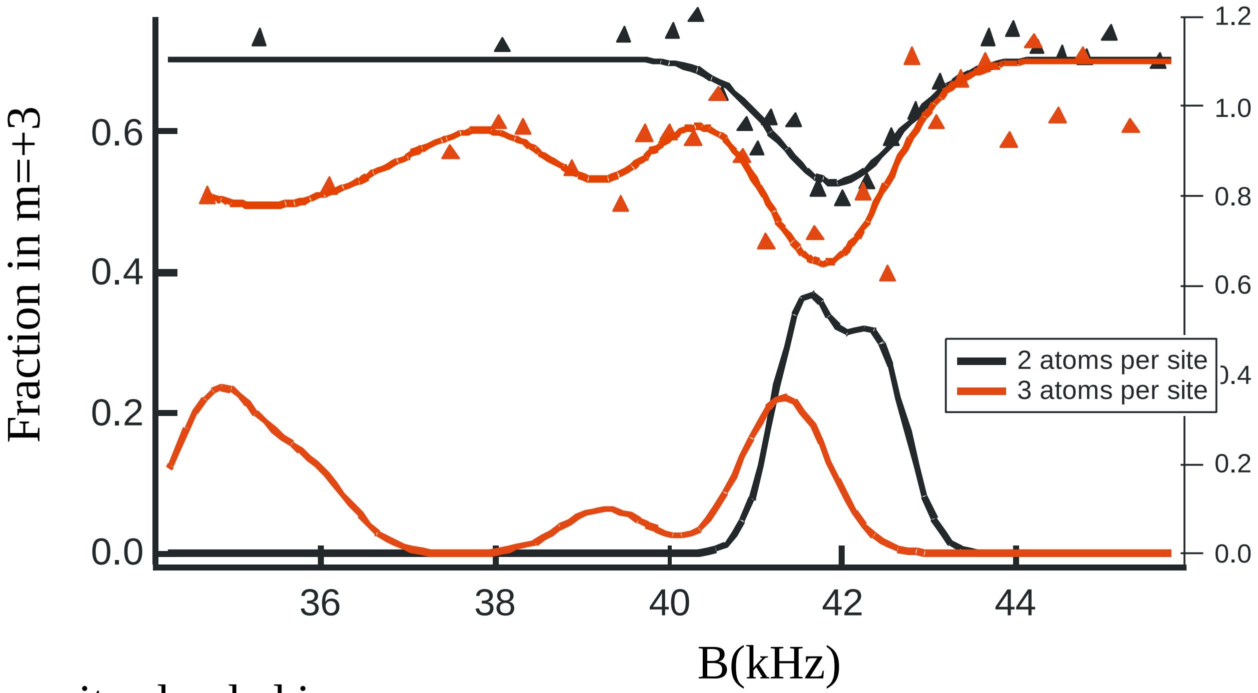
$$\left| S = 6, m = -6 \right\rangle$$



$$\left| S = 4, m = -4 \right\rangle$$



Note: Lineshape of dipolar resonances probes number of atoms per site



3 and more atoms per sites loaded in lattice for faster loading

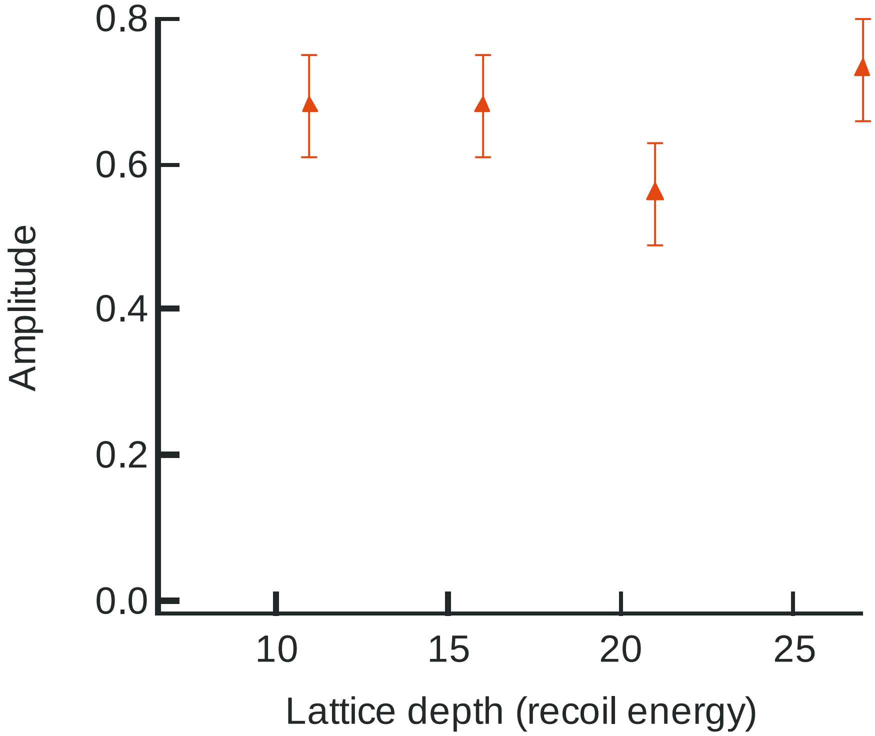
Probe of atom squeezing in Mott state

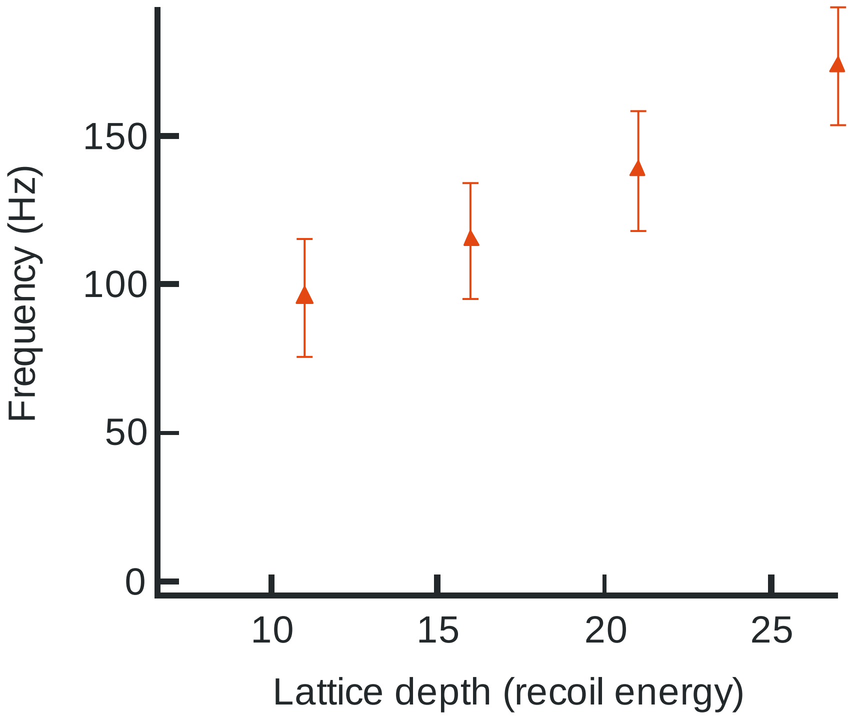
$$|3,3,3\rangle \otimes |0,0,0\rangle \rightarrow \sum |2,3,3\rangle \otimes |2,0,0\rangle$$

spin orbit

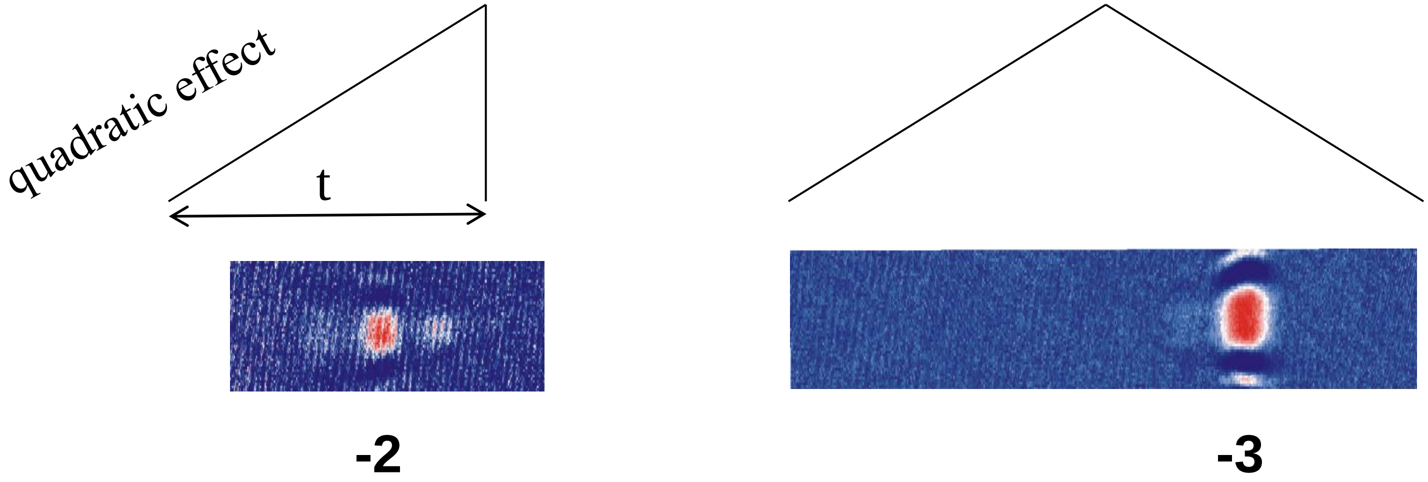
Few-body physics !

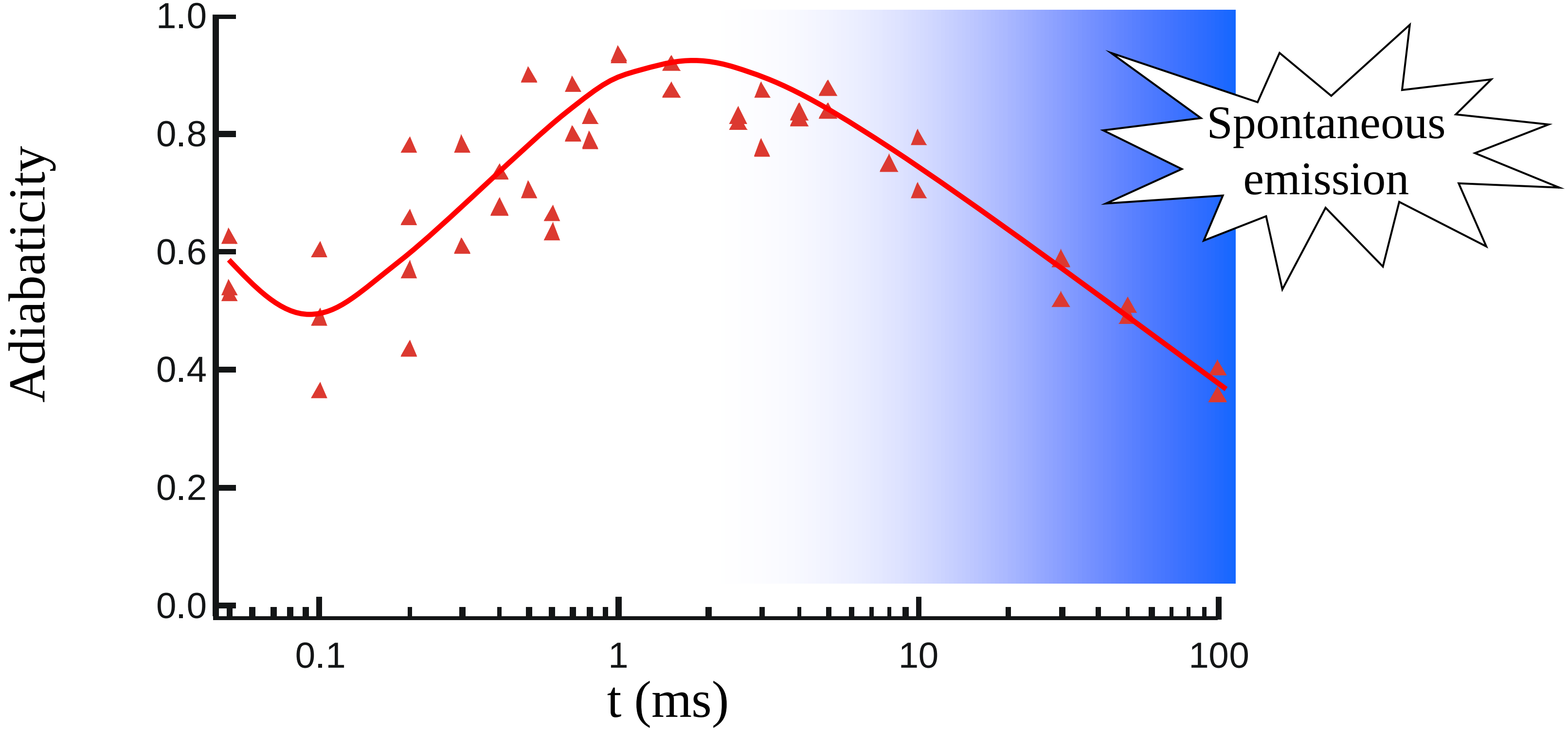
The 3-atom state which is reached has **entangled** spin and orbital degrees of freedom


Amplitude
0.8
0.6
0.4
0.2
0.0
10
15
20
25
Lattice depth (recoil energy)

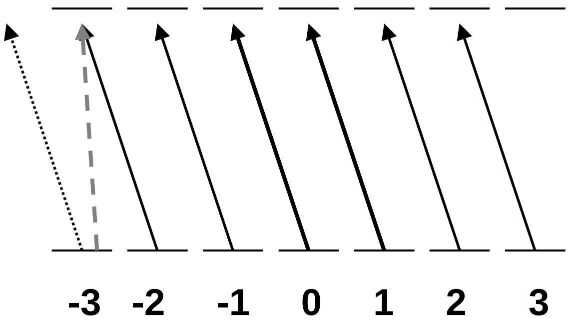

Frequency (Hz)
150
100
50
0
10
15
20
25
Lattice depth (recoil energy)

Adiabatic (reversible) change in magnetic state **(unrelated to dipolar interactions)**





A tool to study spin dynamics in the lattice : a light-induced effective Quadratic Zeeman effect

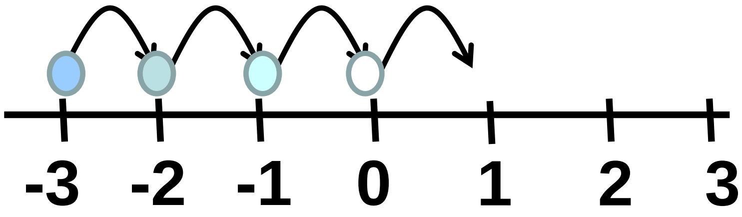


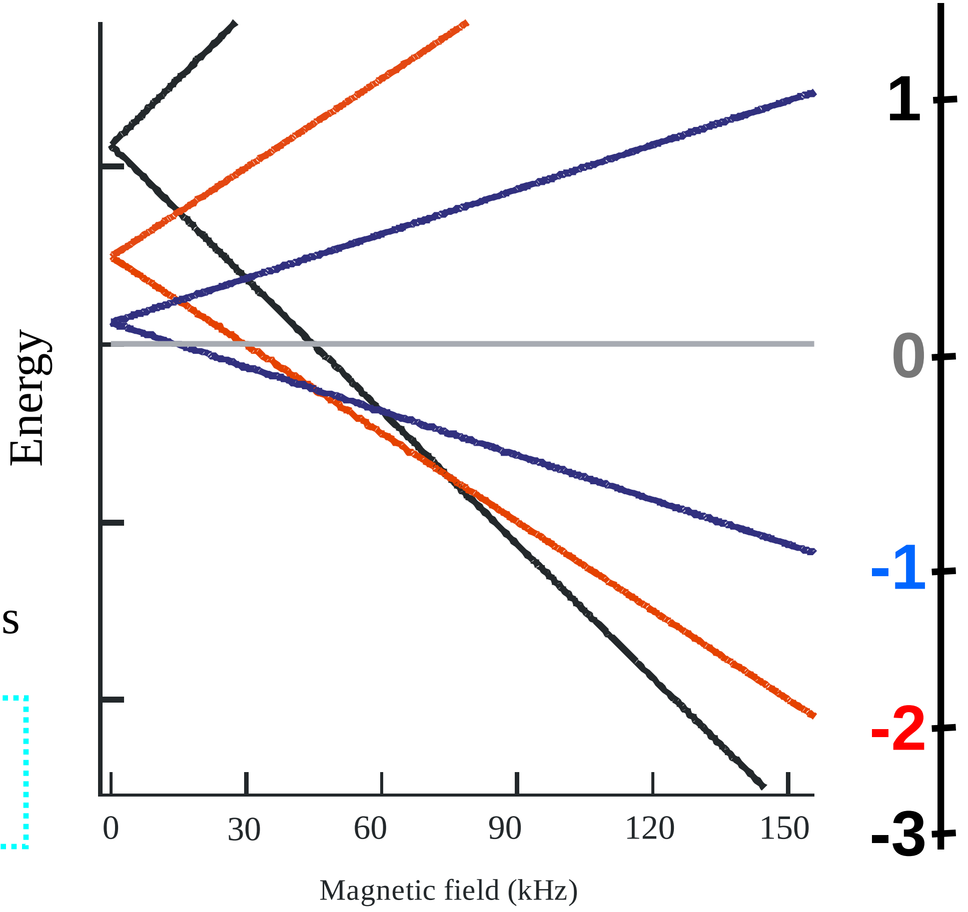
A σ− polarized laser
Close to a J→J transition
(100 mW 427.8 nm)

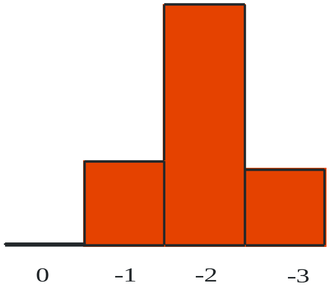
In practice, a π component couples m_S states

Note : The effective Zeeman effect is crucial for good state preparation

No two level system for a pure Zeeman effect:

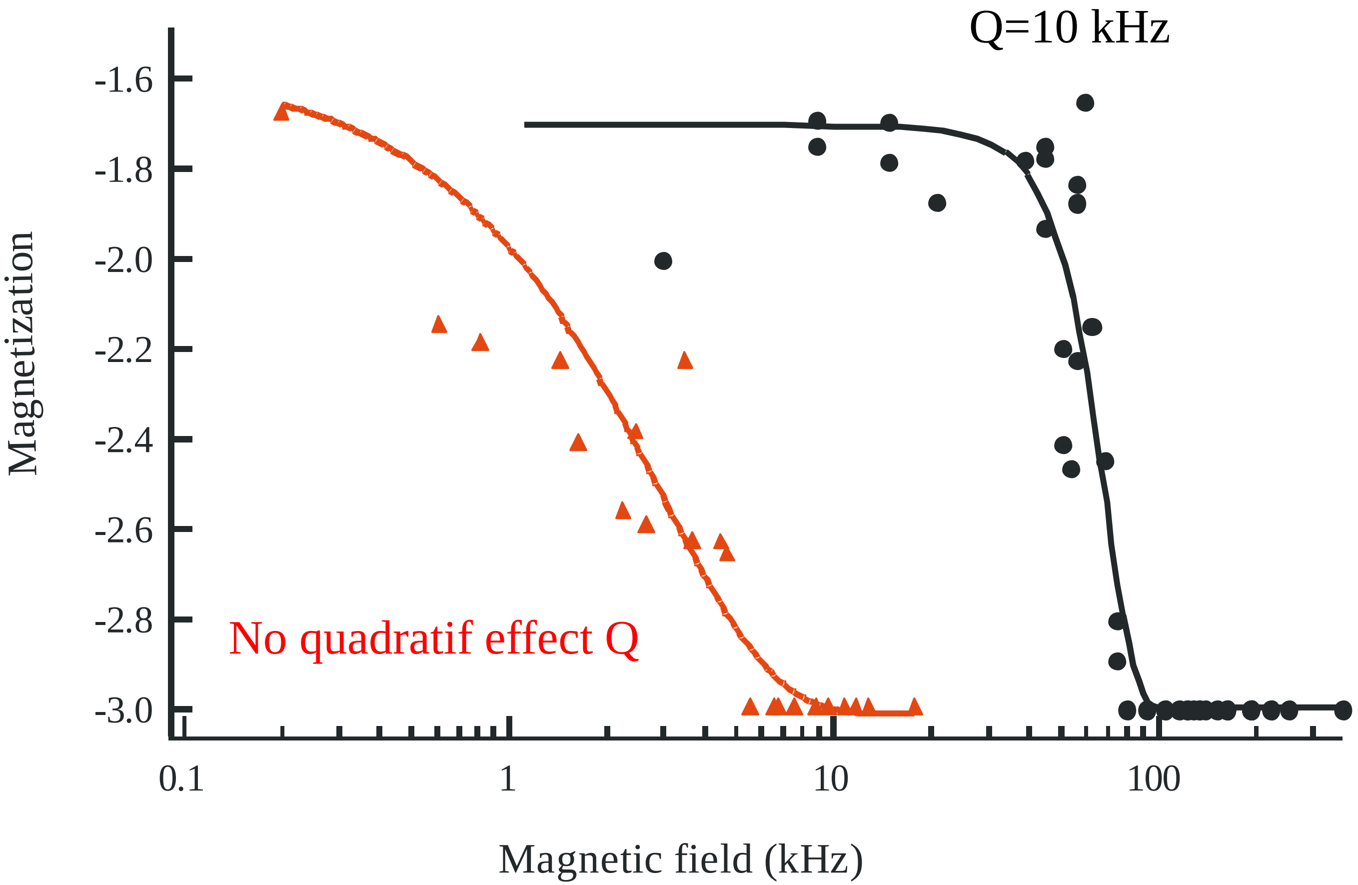




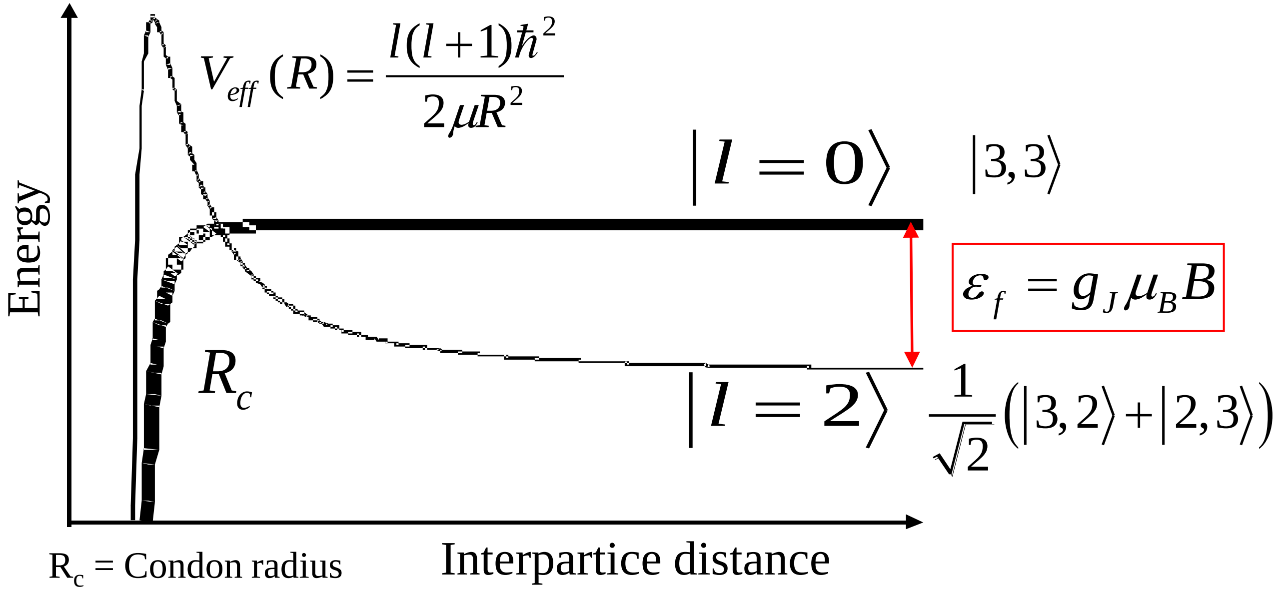


Typical eigenstate
at 50 kHz

A transition at much higher magnetic field…



From the molecular physics point of view



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

$$|l=0\rangle \qquad |3,3\rangle$$

$$\boxed{\varepsilon_f = g_J \mu_B B}$$

$$R_c$$

$$|l=2\rangle \qquad \frac{1}{\sqrt{2}}\left(|3,2\rangle + |2,3\rangle\right)$$

$\mathrm{R_c}$ = Condon radius

$$R_C \approx \sqrt{\frac{l(l+1)\hbar^2}{m g_S \mu_B B}}$$

$$\Gamma \propto |\Psi_{in}(R_c)|^2$$

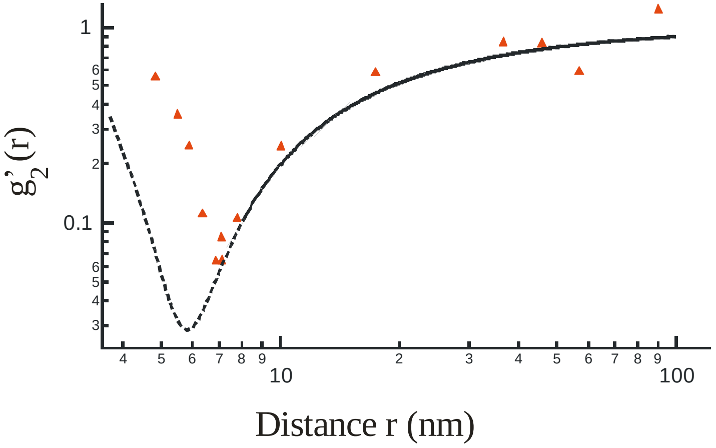
PRA **81**, 042716 (2010)

Larger and larger magnetic fields probes smaller and smaller interatomic distances

$$B = 3\ \mathrm{G}$$

$$R_c = R_{vdW}$$

2-body physics

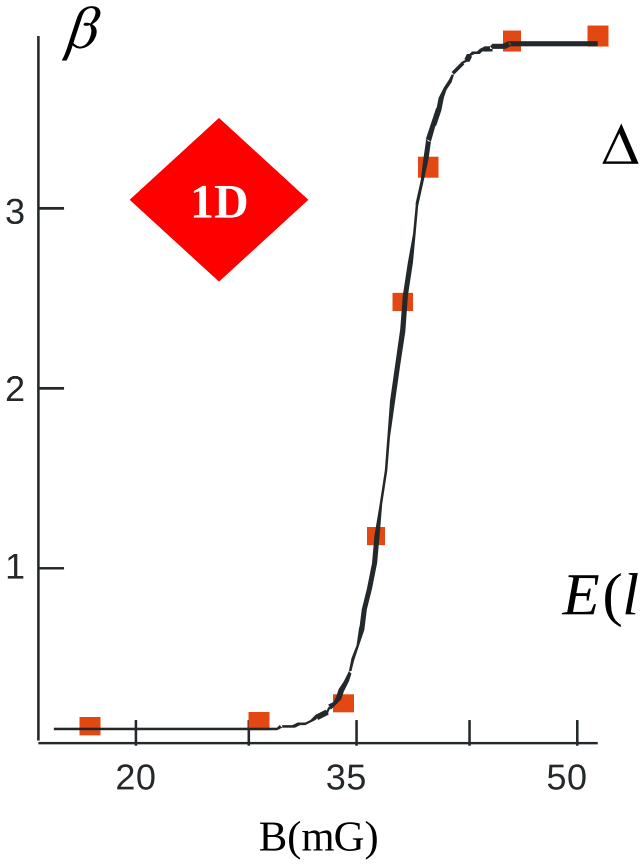


$$B = .3\ \mathrm{mG}$$

$$R_c = n^{-1/3}$$

many-body physics

(almost) complete suppression of dipolar relaxation in 1D at low field: a threshold consequence of angular momentum conservation



$$\Delta m_S + \Delta m_l = 0$$

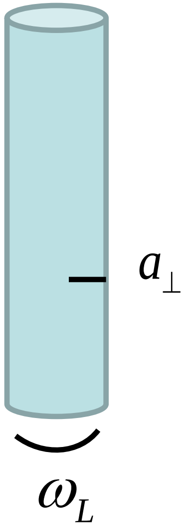
$$\Delta m_S = -1$$

⇓

$$g\mu_B B = \Delta E$$

$$>$$

$$E(l=2) = \frac{\hbar^2}{m a_L^2} = \hbar\omega_L$$



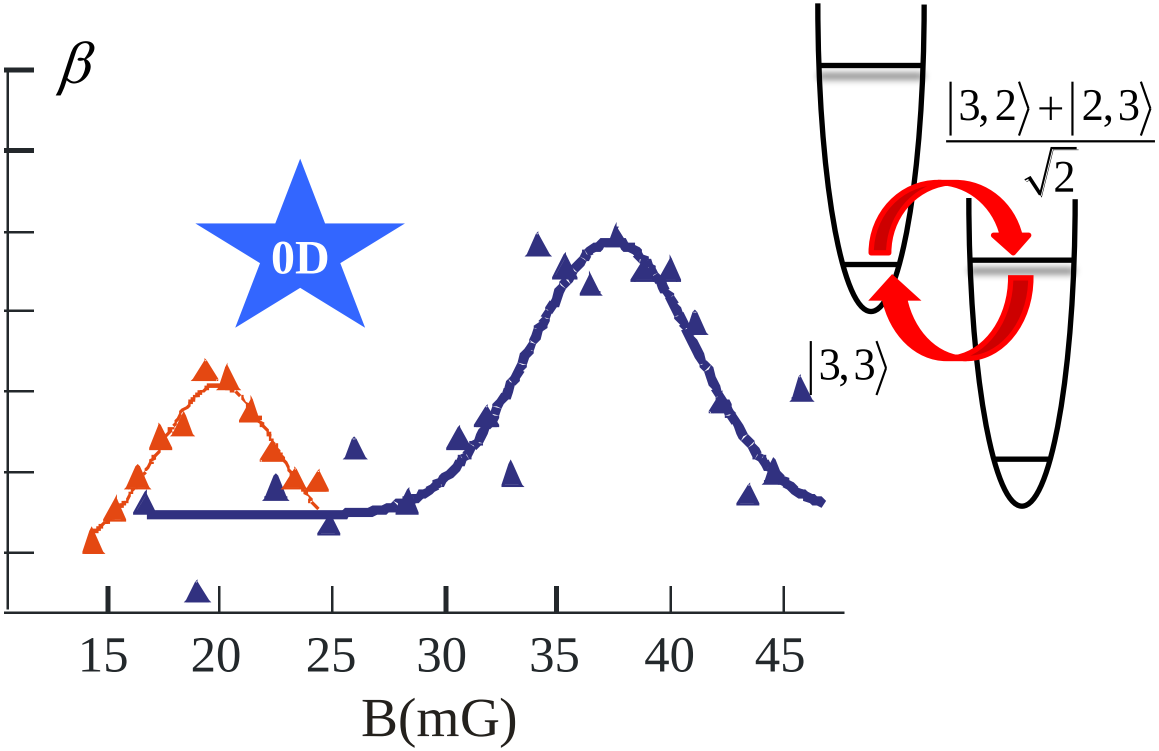
Below threshold:

a (spin-excited) metastable 1D quantum gas ;

Interest for spinor physics, spin excitations in 1D…

B. Pasquiou et al., PRL **106**, 015301 (2011)

0D: a resonance due to energy conservation



Collab. Group of Mariusz Gajda

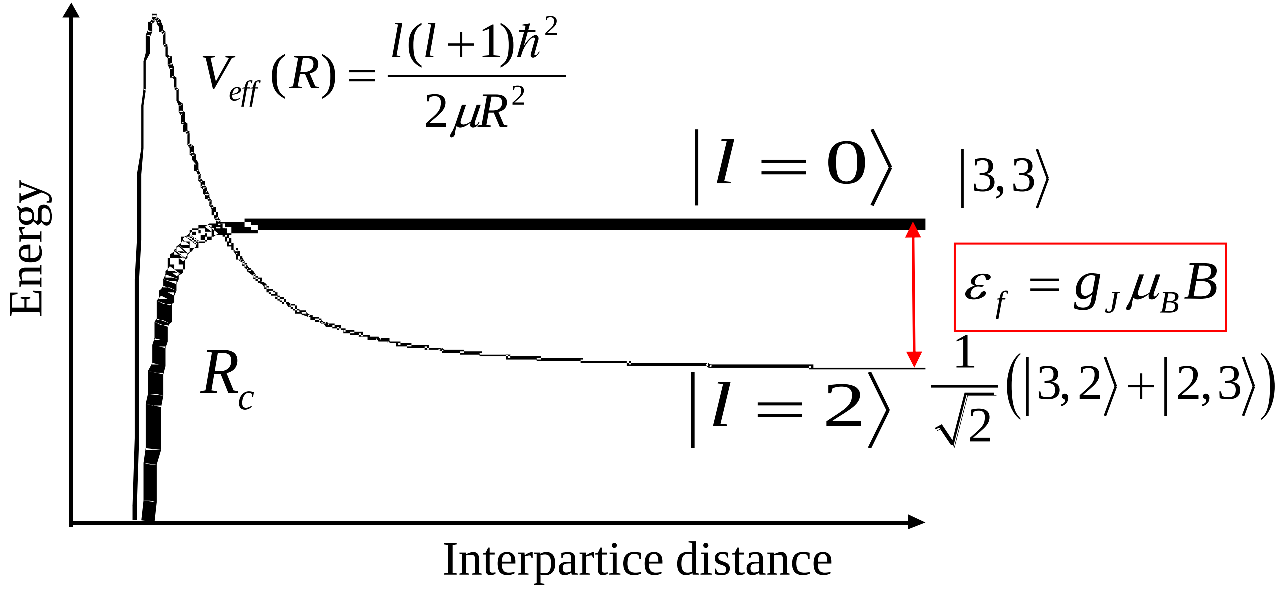
<u>At resonance</u>

should produce vortices in each lattice site (EdH effect)
(problem of tunneling)

Towards coherent excitation of pairs into higher lattice orbitals ?
(Rabi oscillations)

Mott state locally coupled to excited band

From the molecular physics point of view



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

$|l=0\rangle$ $\quad |3,3\rangle$

$$\varepsilon_f = g_J \mu_B B$$

$|l=2\rangle$ $\quad \frac{1}{\sqrt{2}}\left(|3,2\rangle + |2,3\rangle\right)$

$$R_C \approx \sqrt{\frac{l(l+1)\hbar^2}{m g_S \mu_B B}}$$

$$\Gamma \propto |\Psi_{in}(R_c)|^2$$

PRA **81**, 042716 (2010)

R_c = Condon radius

Larger and larger magnetic fields probes smaller and smaller interatomic distances

B = 3 G $\longleftrightarrow$ $R_c = R_{vdW}$

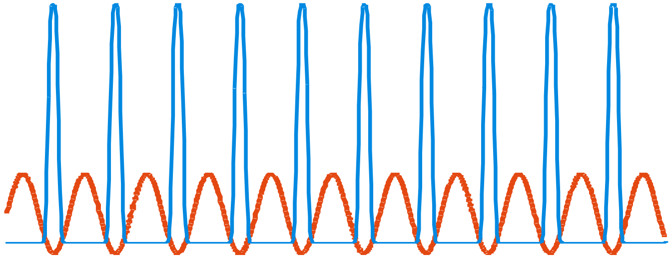
2-body physics

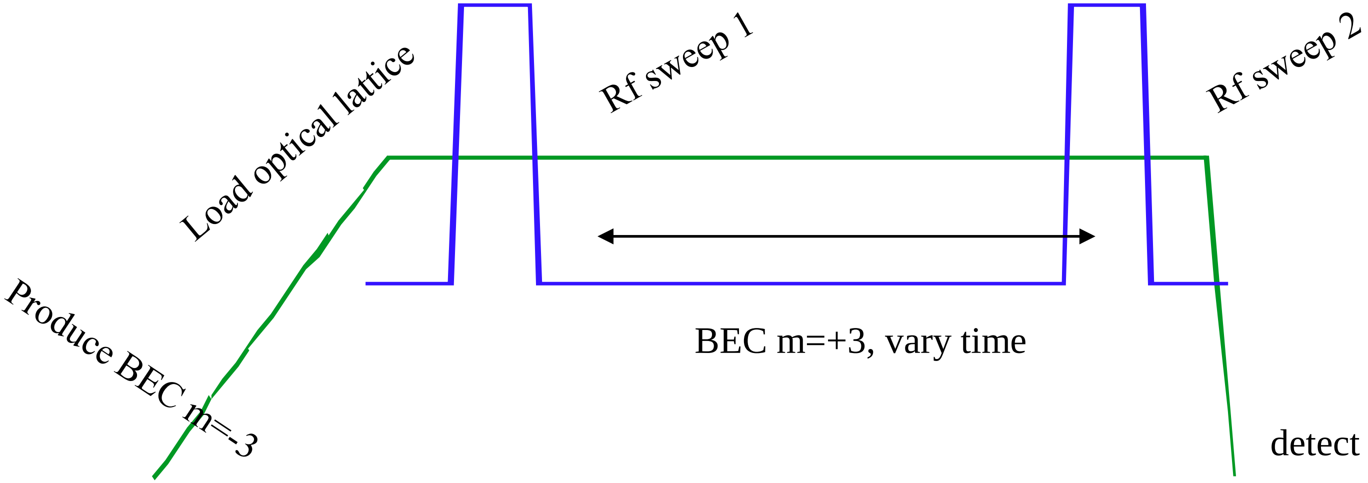
B = .3 mG $\longleftrightarrow$ $R_c = n^{-1/3}$

many-body physics

Reduction of dipolar relaxation in optical lattices

Load the BEC in a 1D, 2D or 3D Lattice





Load optical lattice

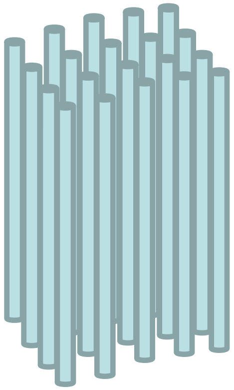
Rf sweep 1

Rf sweep 2

Produce BEC m=-3

BEC m=+3, vary time

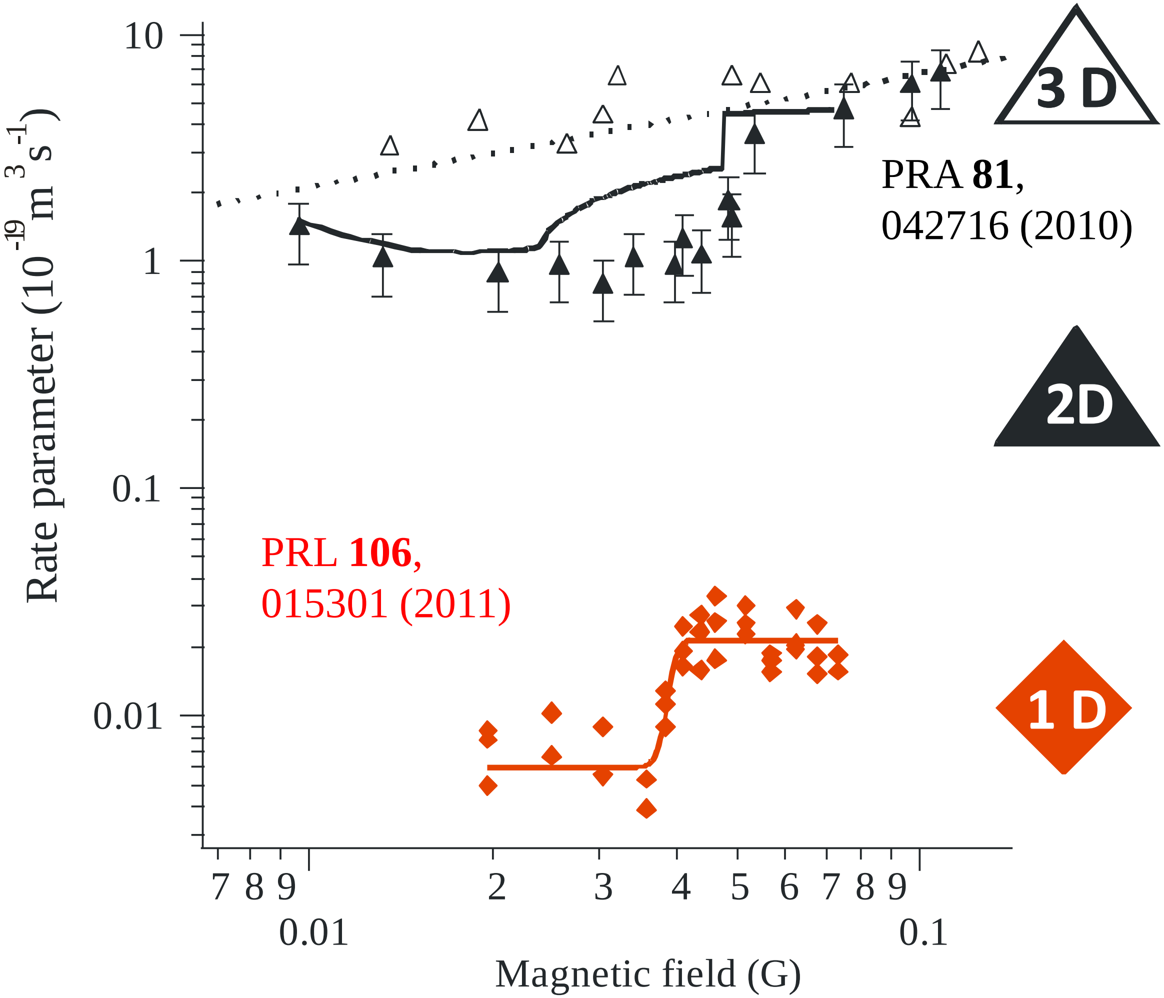
detect m=-3



$$\hbar\Gamma \approx \left|V_{dd}\right|^2 \rho\left(\varepsilon_f\right)$$

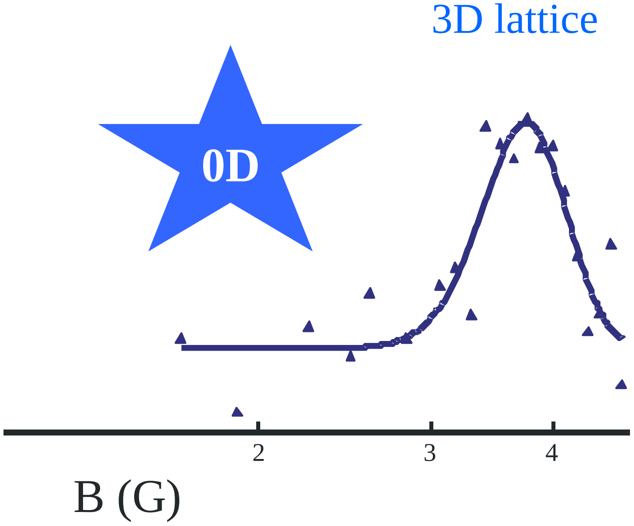
One expects a reduction of dipolar relaxation, as a result of the reduction of the density of states in the lattice

Dipolar relaxation in optical lattices

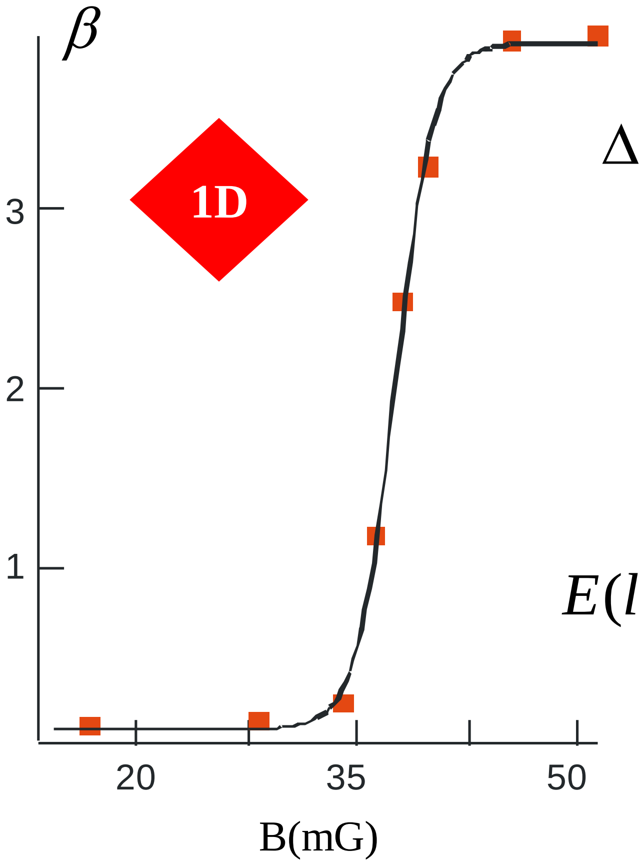


PRA **81**, 042716 (2010)

PRL **106**, 015301 (2011)



(almost) complete suppression of dipolar relaxation in 1D at low field: a threshold consequence of angular momentum conservation



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$$\Delta m_S = -1$$

⇓

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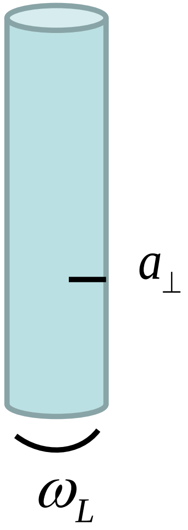

<u>Below threshold:</u>

a (spin-excited) metastable 1D quantum gas ;

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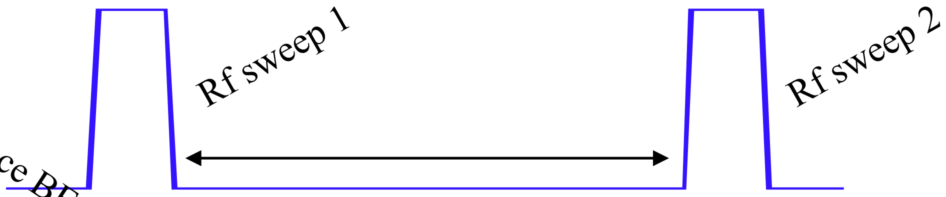
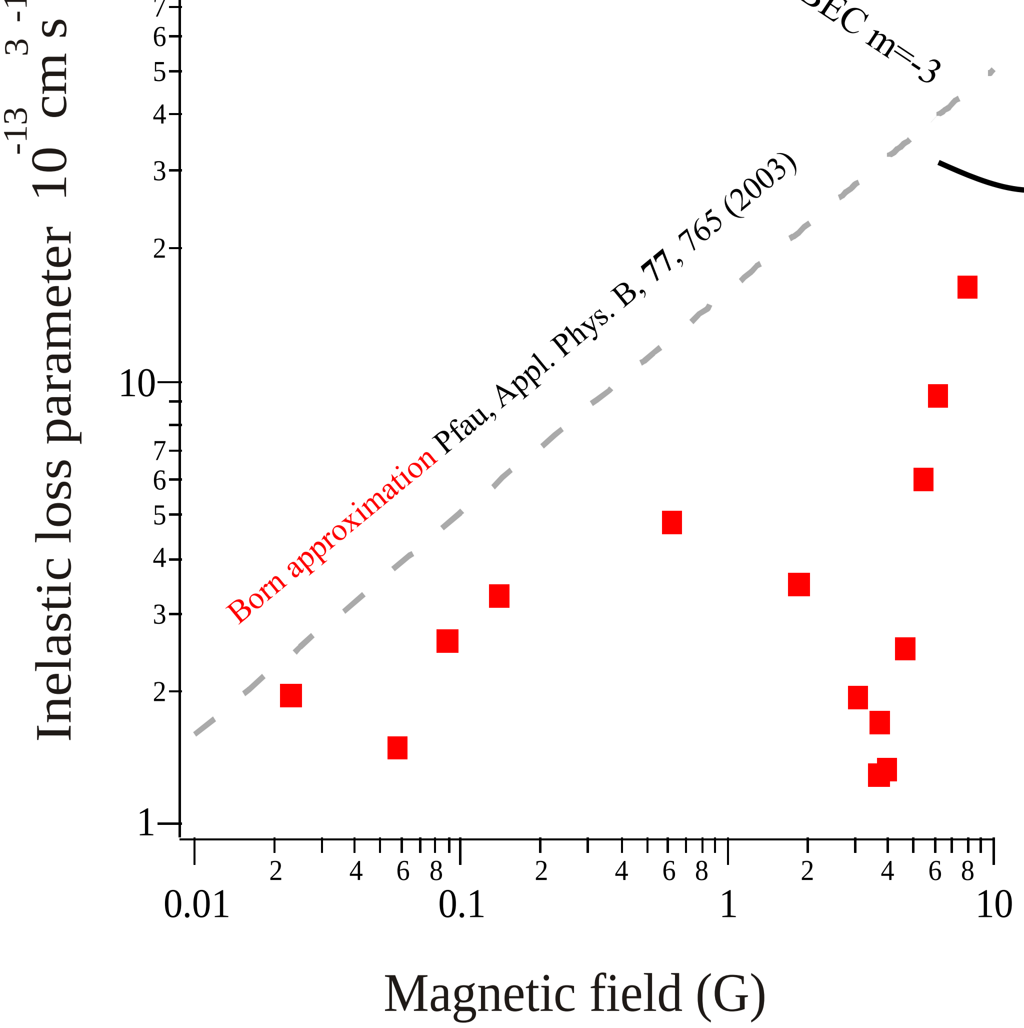
B. Pasquiou et al., PRL **106**, 015301 (2011)

Dipolar relaxation in a Cr BEC





Fermi golden rule

$$\hbar\Gamma \approx \left|V_{dd}\right|^2 \rho\left(\varepsilon_f\right)$$

$$\varepsilon_f = g_J \mu_B B$$

$$\boxed{\Gamma \propto \left|\Psi_{in}(R_c)\right|^2}$$

A measurement of scattering length

$a_6 = 103 \pm 4\ a_0$.

PRA **81**, 042716 (2010)

See also Shlyapnikov PRL **73**, 3247 (1994)

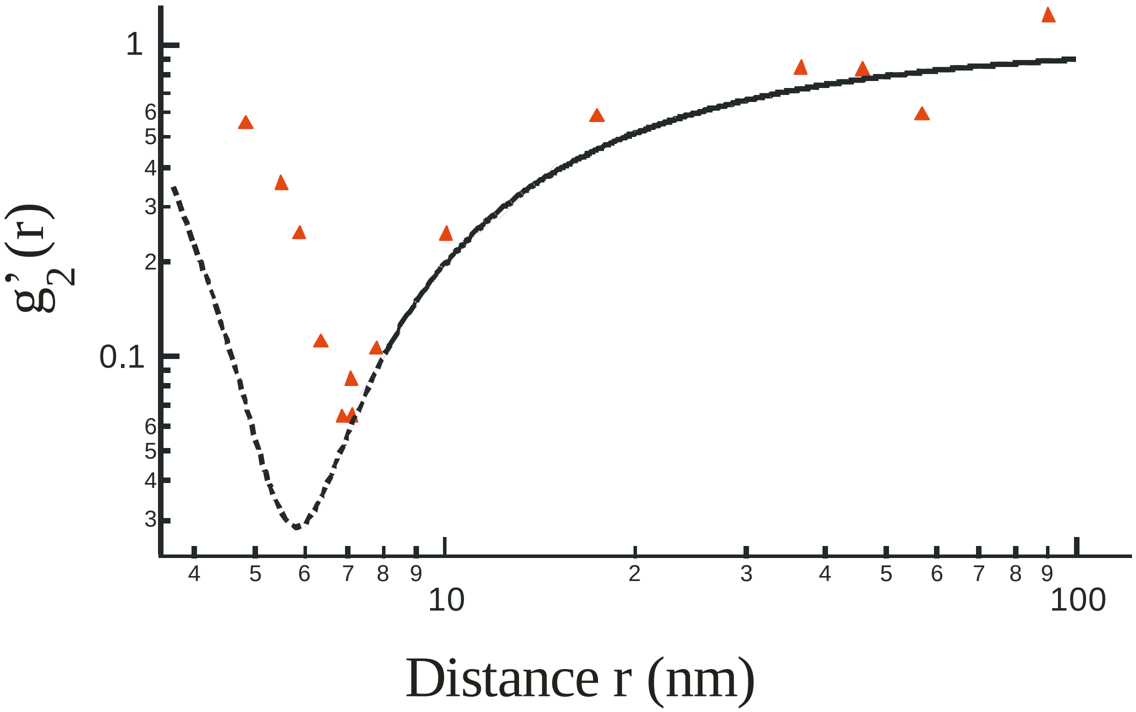
Dipolar relaxation: measuring non-local correlations

Measure dipolar relaxation
at magnetic field B

=

Measure the second order
correlation function at:

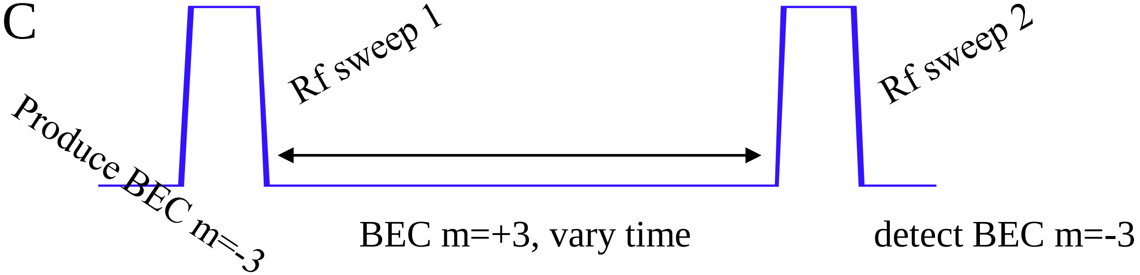
$$R_C \approx \sqrt{\frac{l(l+1)\hbar^2}{m g_S \mu_B B}}$$



$g_2(r) \square \left(1-a/r\right)^2$ $r >> R_{VdW}$ L. H. Y. Phys. Rev. **106**, 1135 (1957)

A probe of non-local correlations :
here, a mere two-body effect, yet unacounted for in a mean-field « product-ansatz » BEC model

Dipolar relaxation in a Cr BEC



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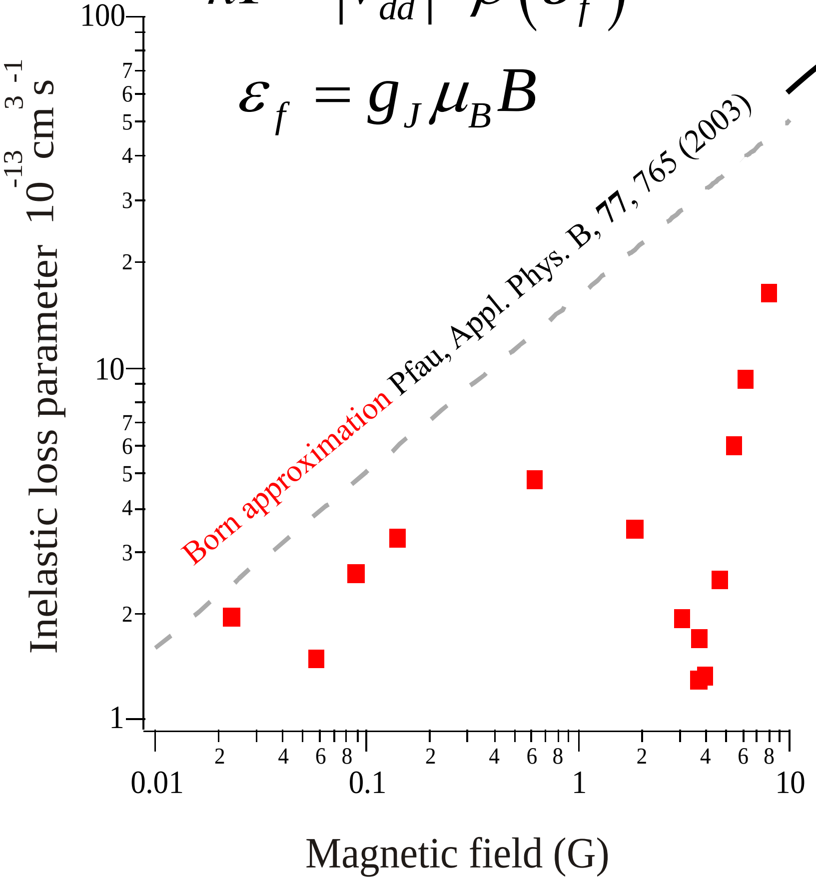

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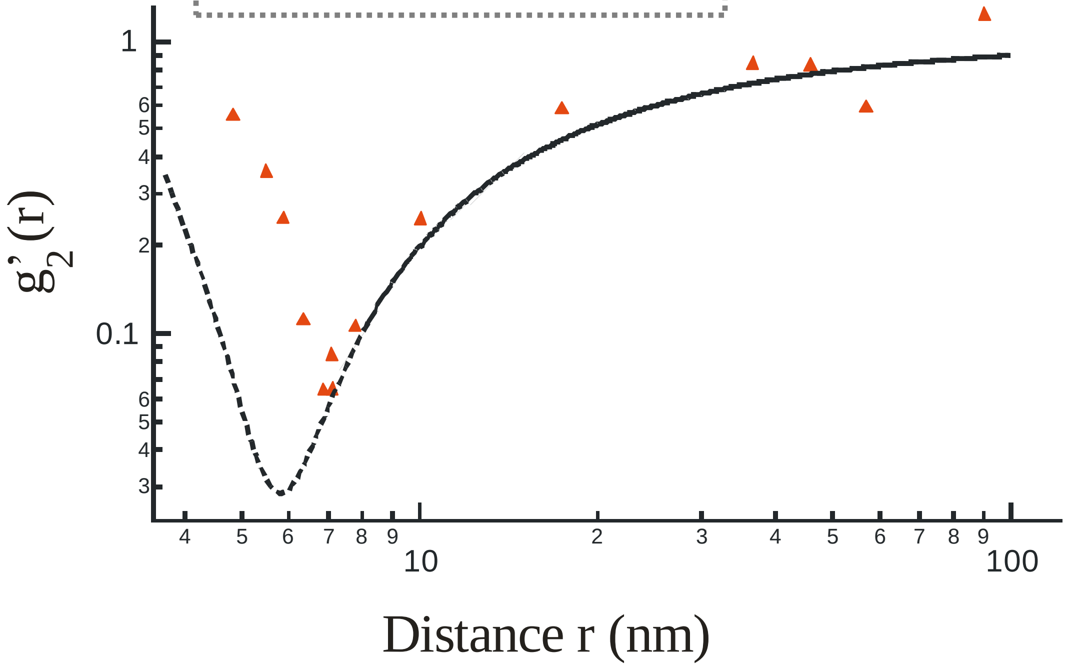

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$a_6 = 103 \pm 4\ a_0$.

PRA **81**, 042716 (2010), see also PRL **73**, 3247 (1994)

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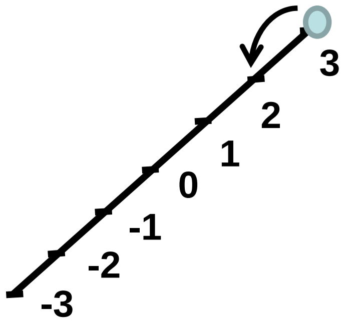
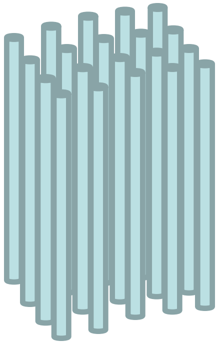


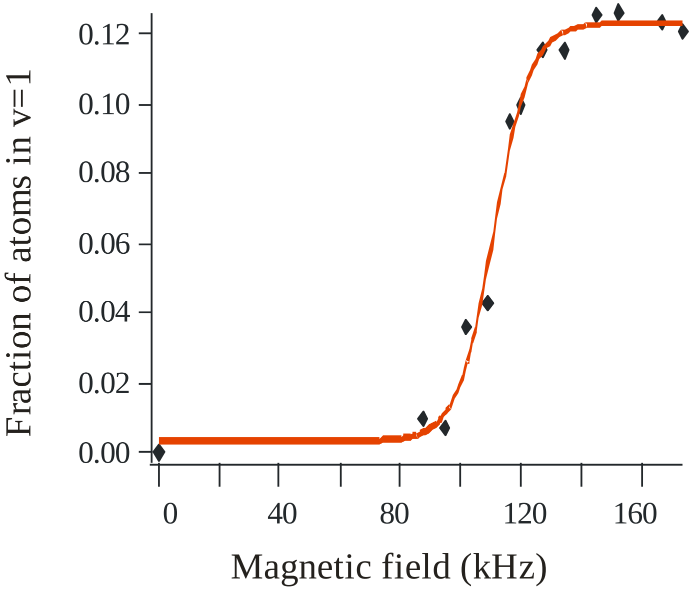
Energy released

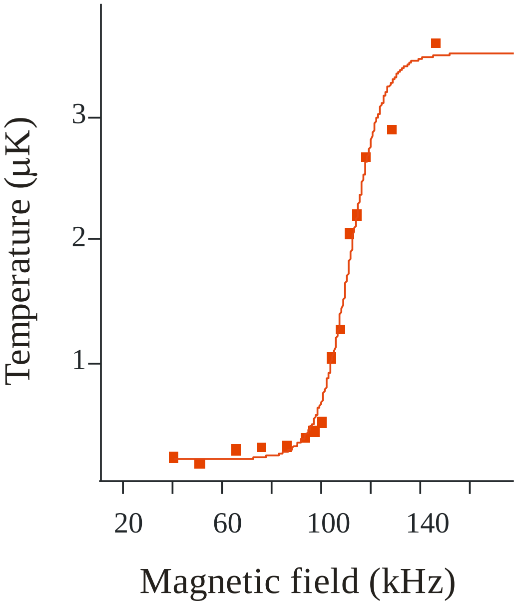
$$\varepsilon_f = g_J \mu_B B$$

Band excitation

Kinetic energy along tubes

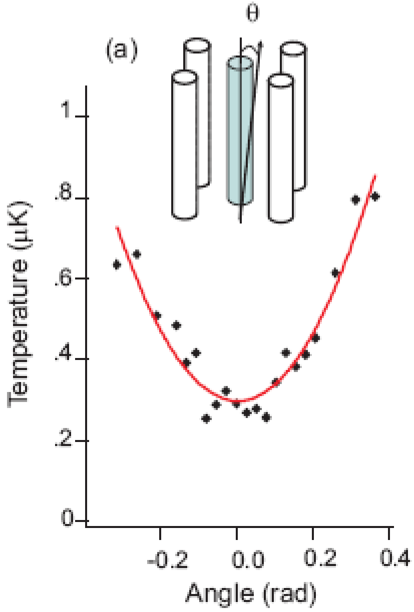






B. Pasquiou et al., Phys. Rev. Lett. **106**, 015301 (2011)

(almost) complete suppression of dipolar relaxation in 1D at low field in 2D lattices: a consequence of angular momentum conservation

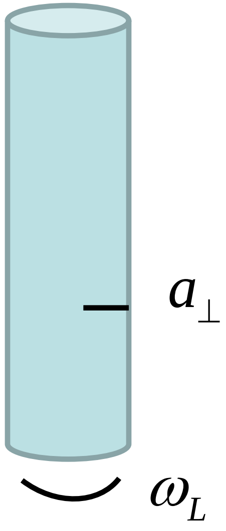


$$\Delta m_S + \Delta m_l = 0$$

$$\Delta m_S = -1$$

⇓

$$g\mu_B B = \Delta E > E(l=2) = \frac{\hbar^2}{m a_L^2} = \hbar\omega_L$$



Below threshold:

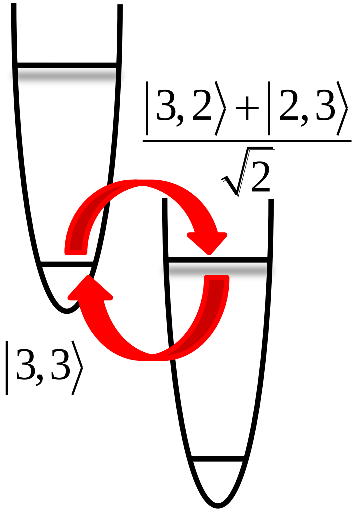
a (spin-excited) metastable 1D quantum gas ;

Interest for spinor physics, spin excitations in 1D…

Above threshold :

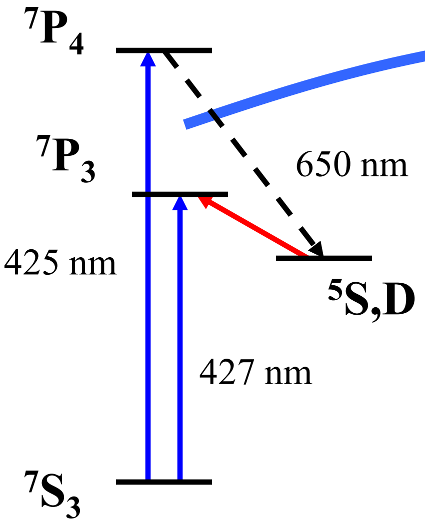
should produce vortices in each lattice site (EdH effect)
(problem of tunneling)

Towards coherent excitation of pairs into higher lattice orbitals ?
(Rabi oscillations)



How to make a Chromium BEC

- An atom: ^{52}Cr

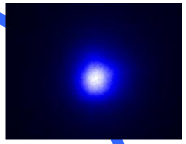


- An oven

Oven at 1425 °C

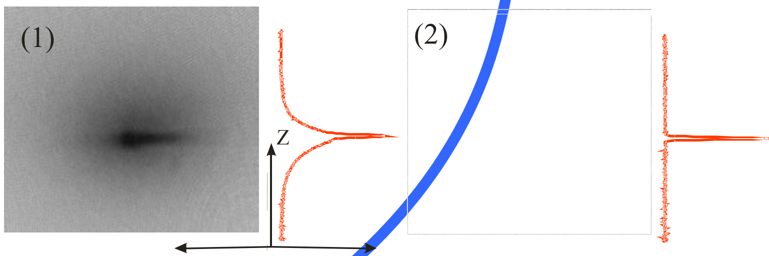
- A Zeeman slower

- A small MOT

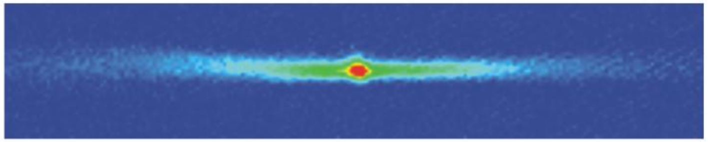


N = 4.10^6

T=120 μK

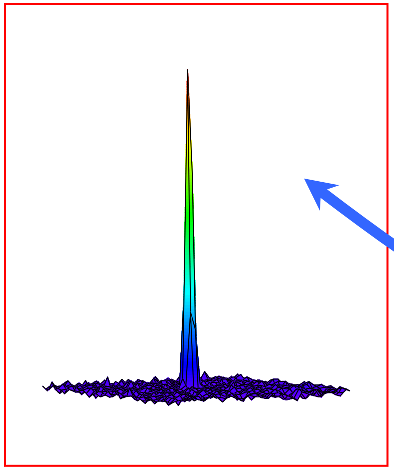


- A dipole trap



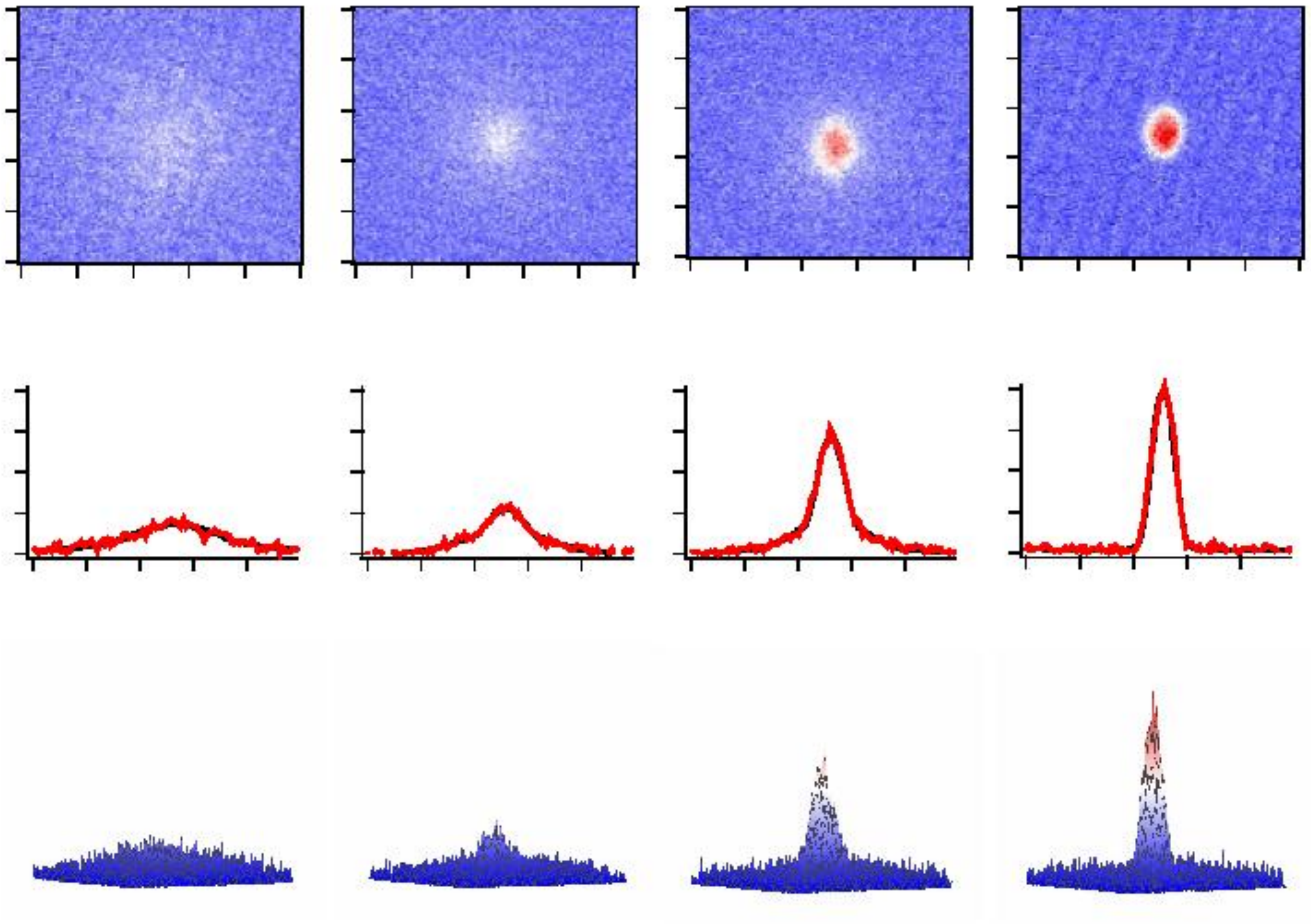
- A crossed dipole trap

- All optical evaporation



- A BEC

BEC with Cr atoms in an optical trap

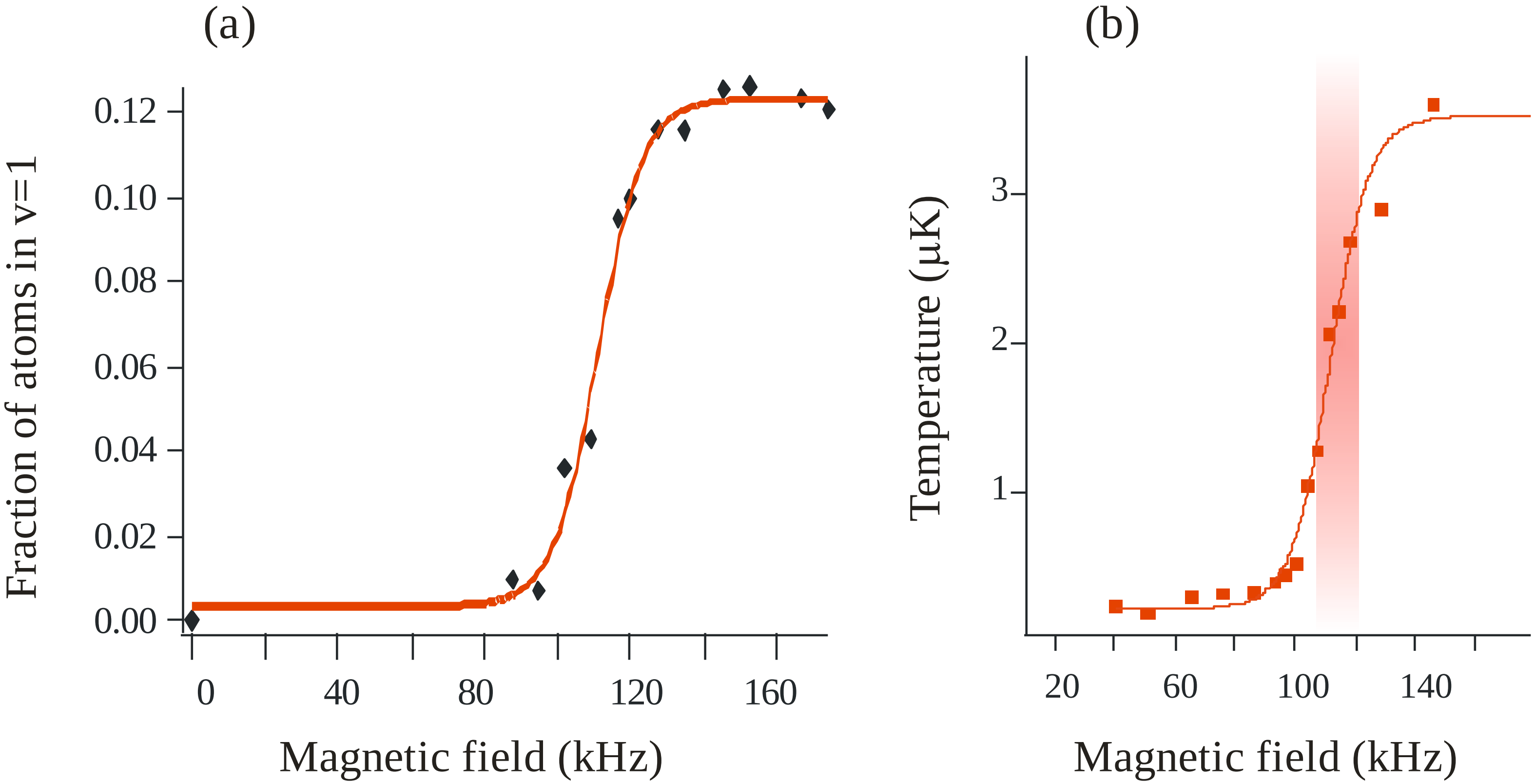


PRA **73**, 053406 (2006)

PRA **77**, 053413 (2008)

PRA **77**, 061601(R) (2008)

Threshold for dipolar relaxation in 1D:

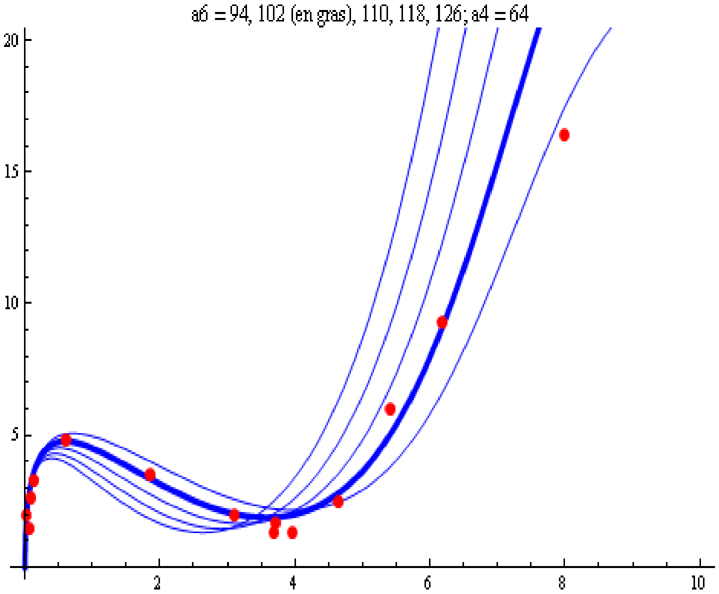


(almost) complete suppression of dipolar relaxation in 1D at low field in 2D lattices

B. Pasquiou et al., Phys. Rev. Lett. **106**, 015301 (2011)

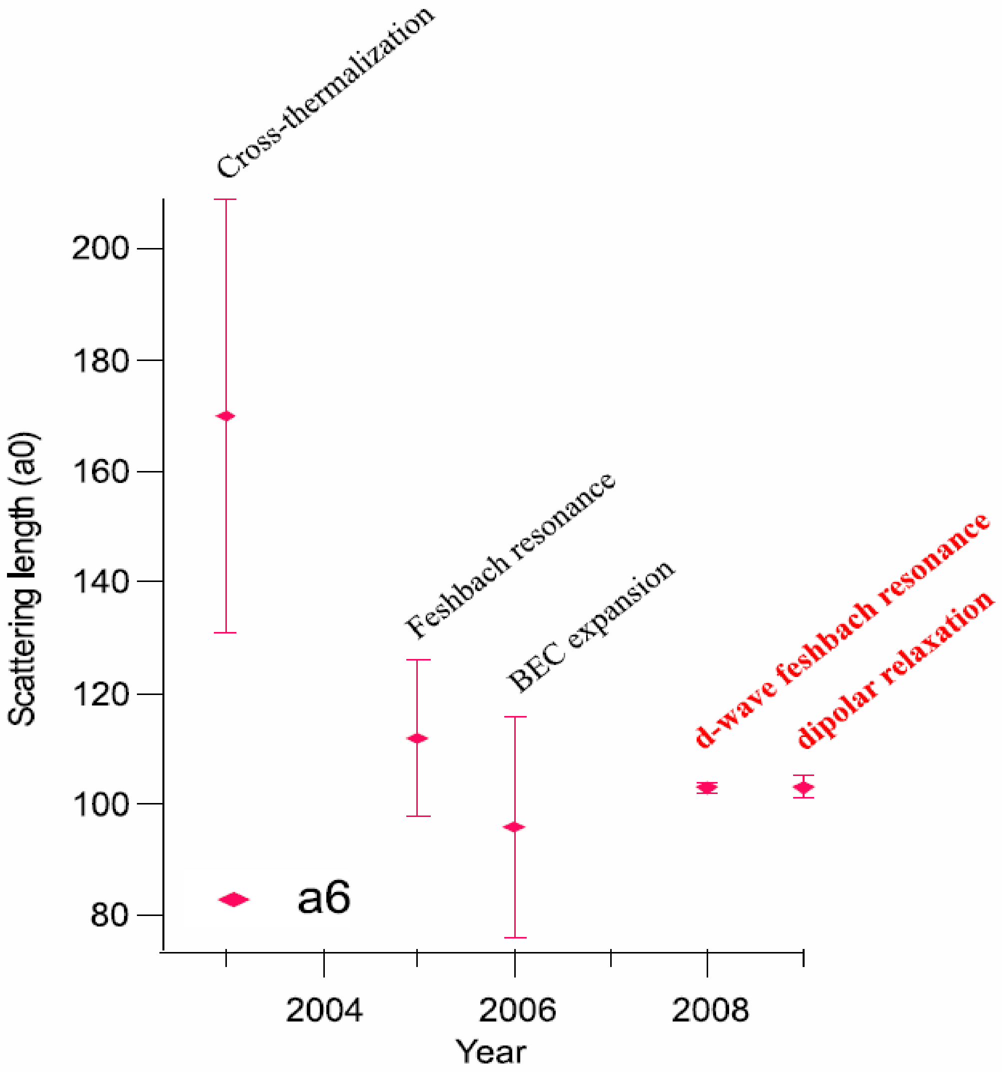
New estimates of Cr scattering lengths

Collaboration Anne Crubellier



PRA **81**,
042716 (2010)

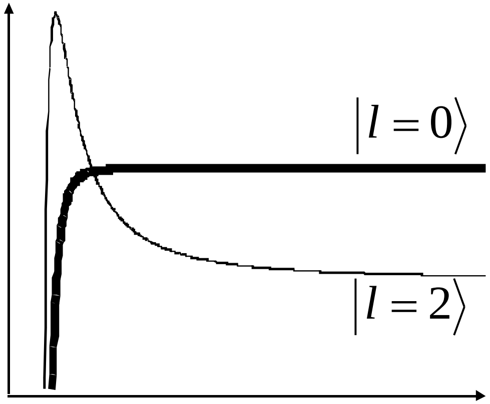
$a_6 = 103 \pm 4\ a_0.$



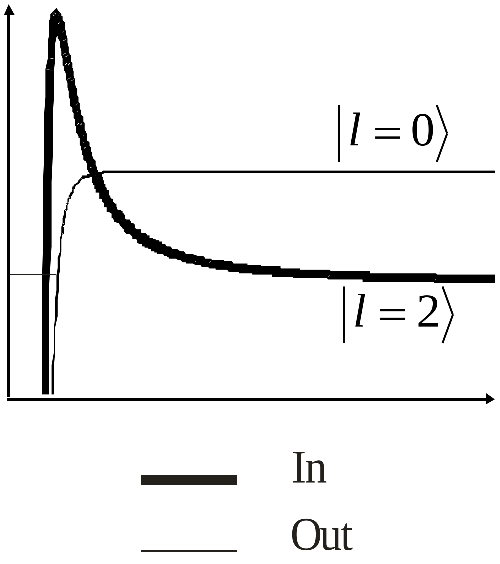
$a_6 = 102.5 \pm 0.4\ a_0$ Feshbach resonance in d-wave PRA **79**, 032706 (2009)

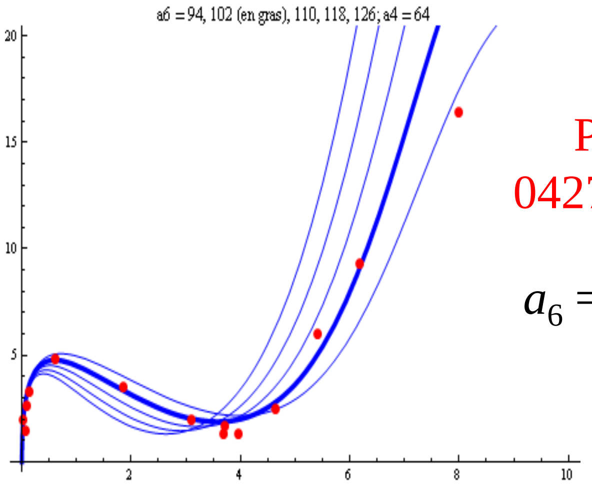
New estimates of Cr scattering lengths

(a) Dipolar relaxation



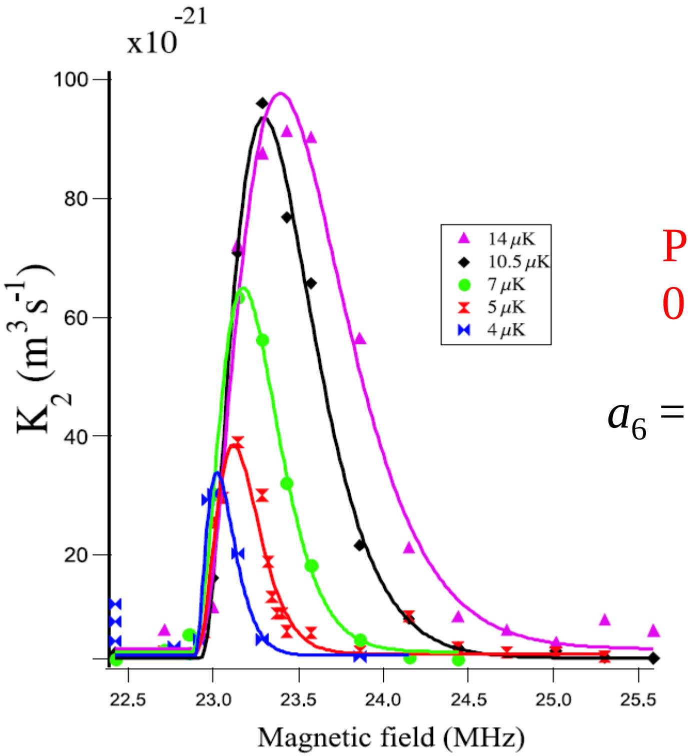
(b) Feshbach resonance





PRA **81**,
042716 (2010)

$a_6 = 103 \pm 4\ a_0$.

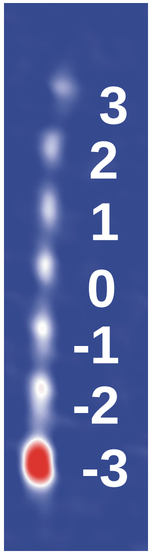


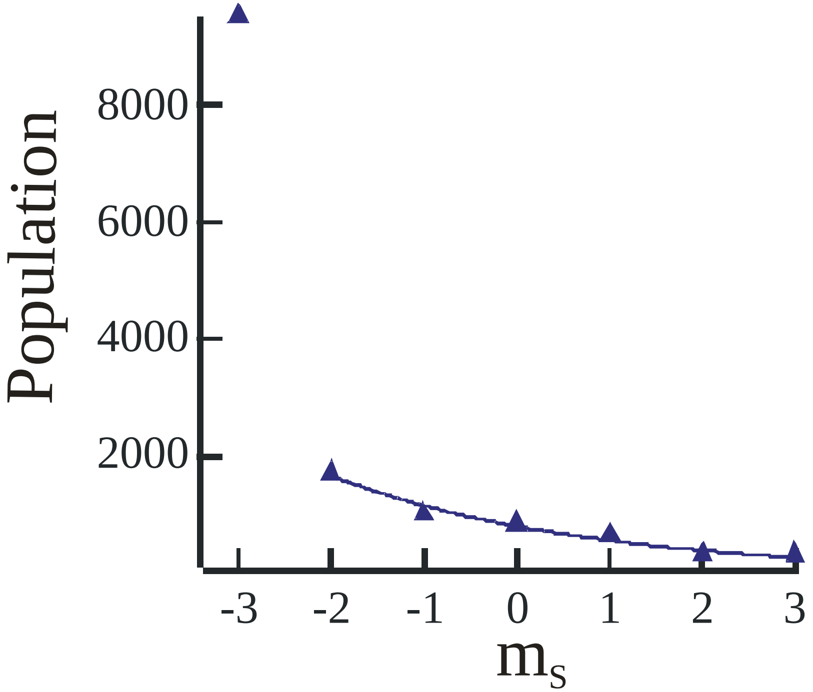
PRA **79**,
032706 (2009)

$a_6 = 102.5 \pm 0.4\ a_0$

Collaboration Anne Crubellier (LAC)

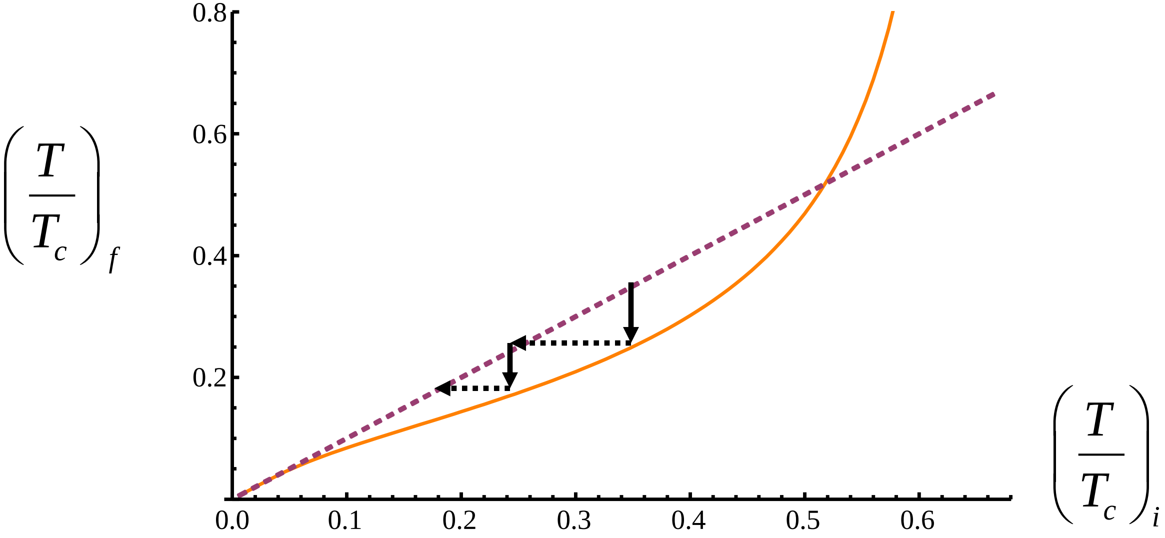
Prospect : new cooling method using the spin degrees of freedom





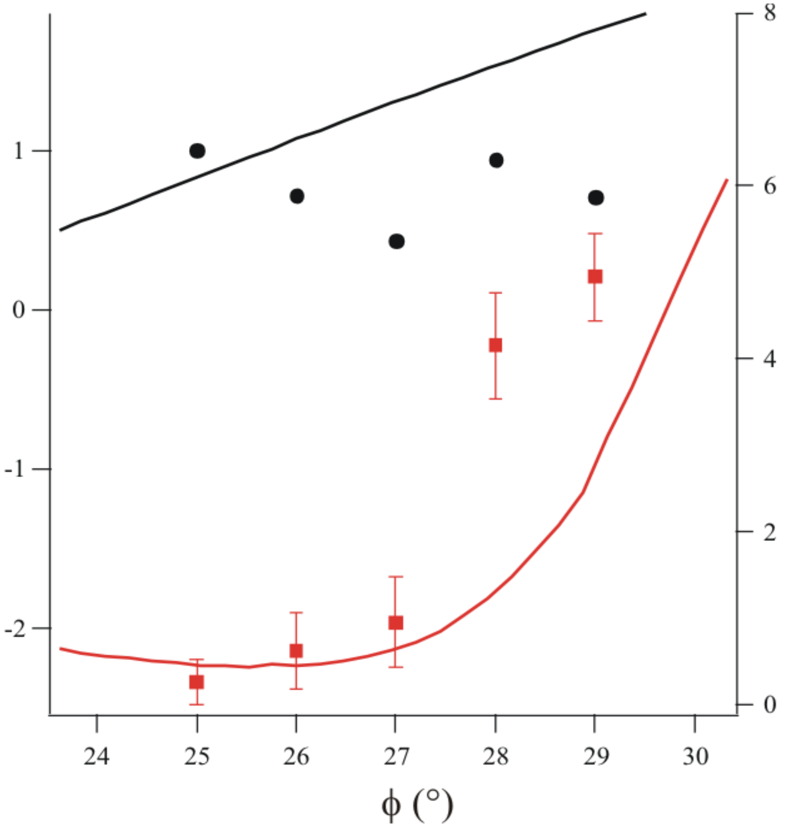
Only thermal gas depolarizes…

get rid of it ?
(field gradients)



A consequence of anisotropy :
trap geometry dependence of the frequency shift

Shift of the quadrupole mode frequency (%)



Shift of the aspect ratio (%)

Sign of dipolar mean-field depends on trap geometry
(oblate / elongated)

- **Related to the trap anisotropy**

Good agreement with Thomas-Fermi predictions

Phys. Rev. Lett. **105**, 040404 (2010)

Eberlein, PRL **92**, 250401 (2004)

Bragg spectroscopy

Probe dispersion law

$$E(k) = ck$$

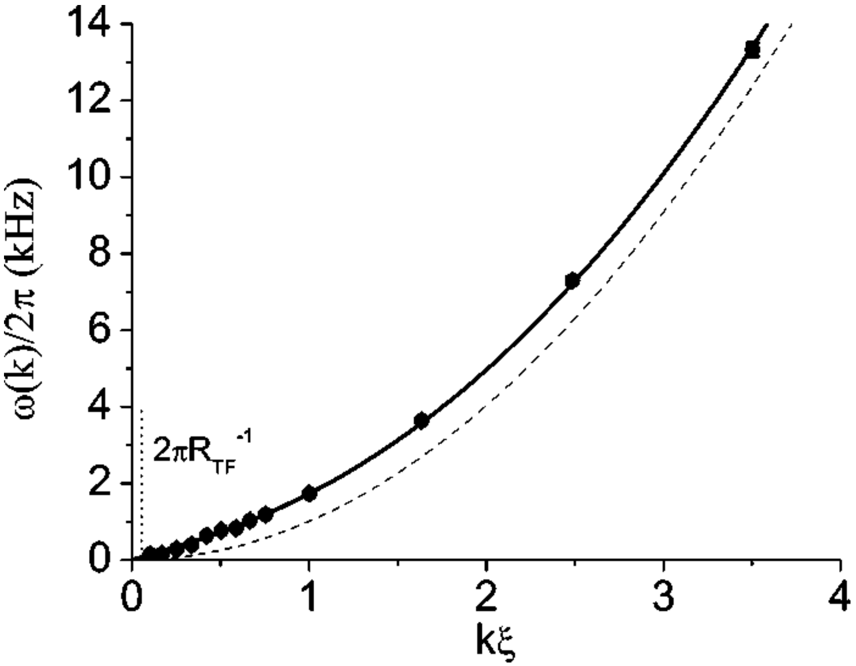
Quasi-particles, phonons

$$k\xi << 1$$

c is sound velocity

c is also critical velocity

Landau criterium for superfluidity

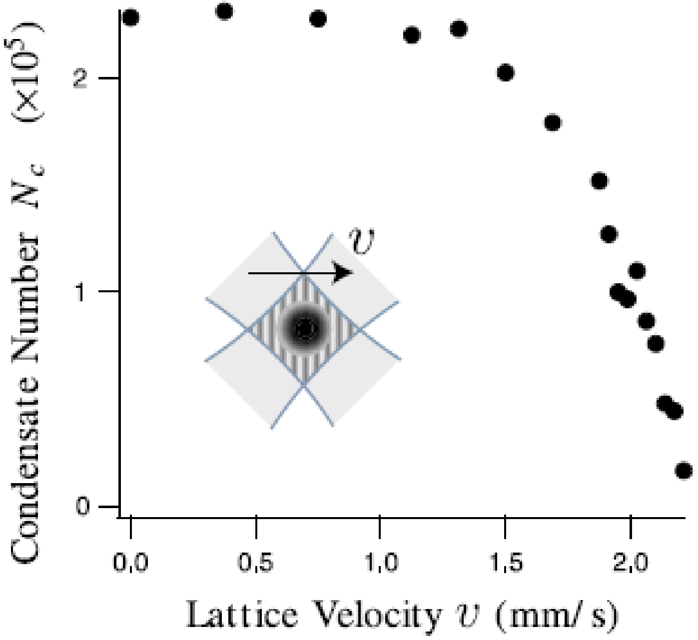


ξ healing length

Rev. Mod. Phys. **77**, 187 (2005)

Bogoliubov spectrum

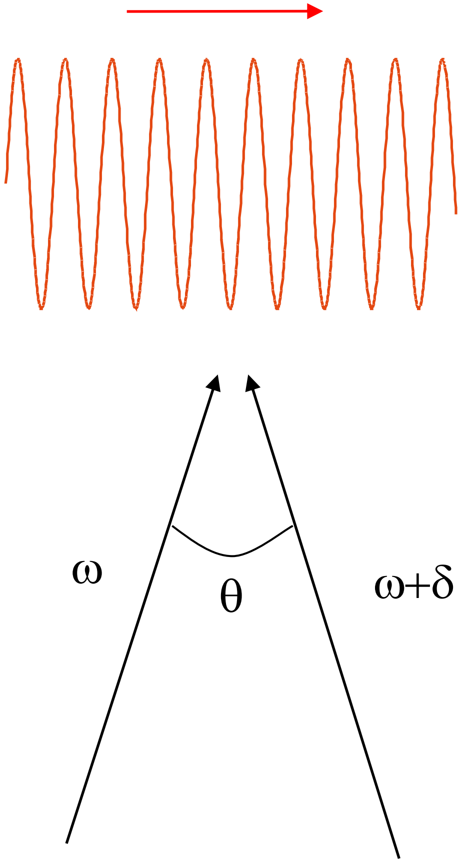
$$\varepsilon_k = \sqrt{E_k(E_k + 2n_0 g_c)}$$



Phys. Rev. Lett. **99**, 070402 (2007)

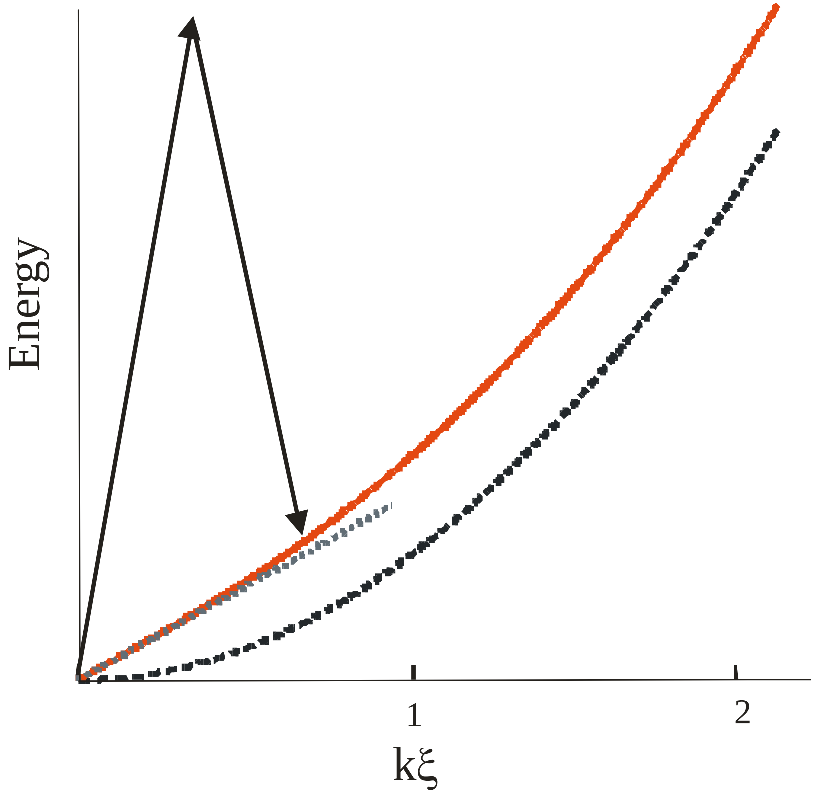
Bragg spectroscopy of an anisotropic superfluid

Moving lattice on BEC



Lattice beams with an angle.
Momentum exchange

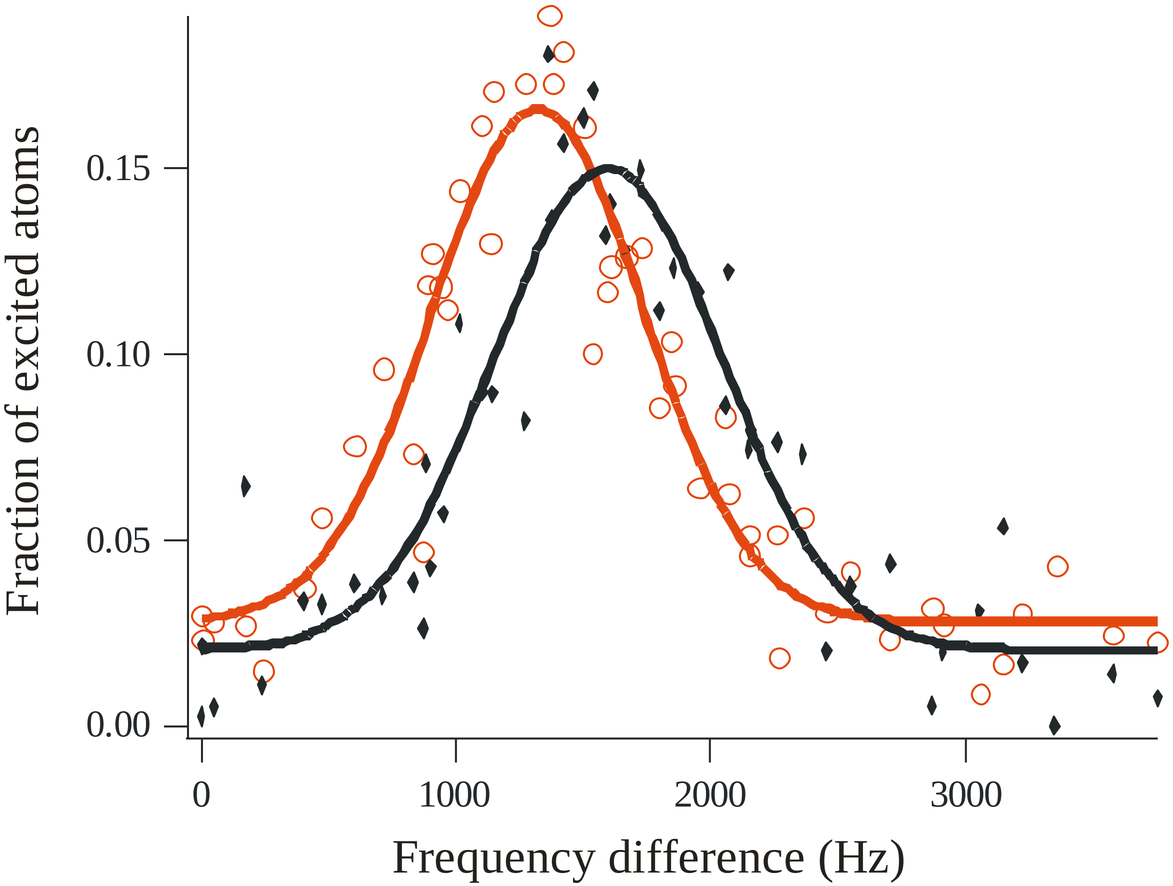
$$\hbar k = 2\hbar k_L \sin(\theta / 2)$$

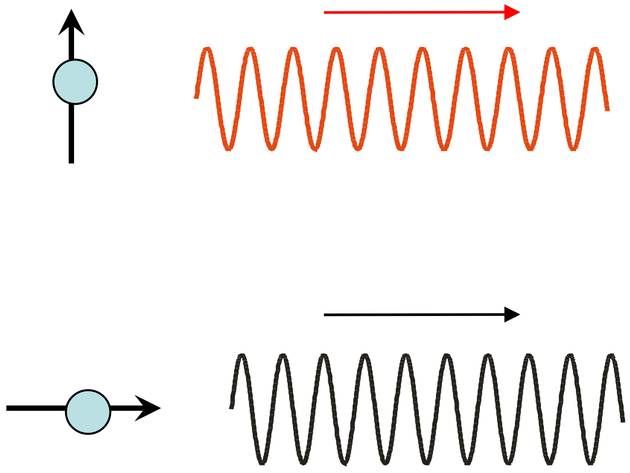


$$k\xi = 0.8$$

Resonance frequency gives speed of sound

Anisotropic speed of sound



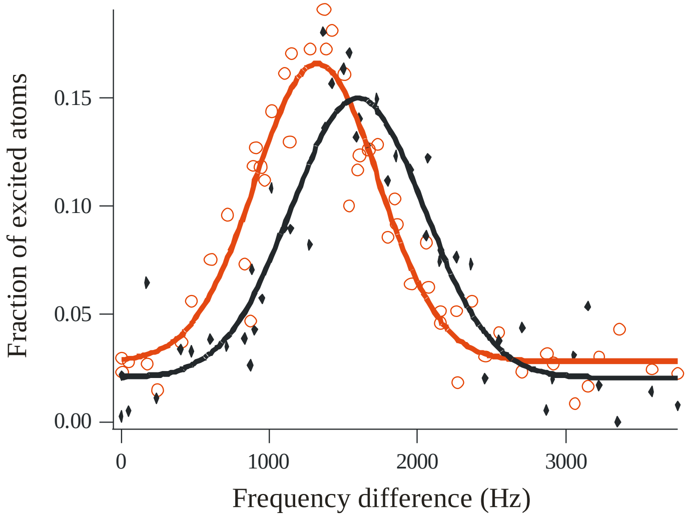


Width of resonance curve: finite size effects (inhomogeneous broadening)

Speed of sound depends on the relative angle between spins and excitation

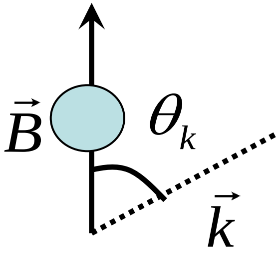
Anisotropic speed of sound

A 20% effect, much larger than the (~2%) modification of the mean-field due to DDI



An effect of the momentum-sensitivity of DDI

$$\tilde{V}(k) = \frac{4\pi d^2}{3}(3\cos^2\theta_k - 1)$$



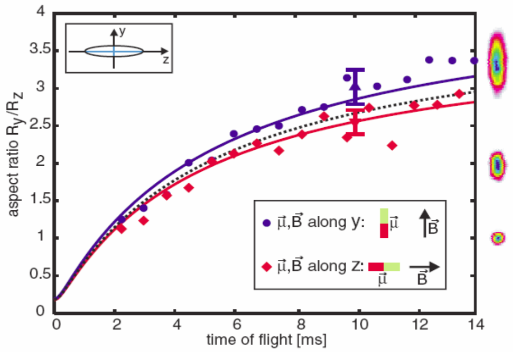
$$\varepsilon_k = \sqrt{E_k(E_k + 2n_0(g_c + g_d(3\cos^2\theta_k - 1))}$$

Good agreement between theory and experiment:

	Theo	Exp
Parallel	3.6 mm/s	3.4 mm/s
Perpendicular	3 mm/s	2.8 mm/s

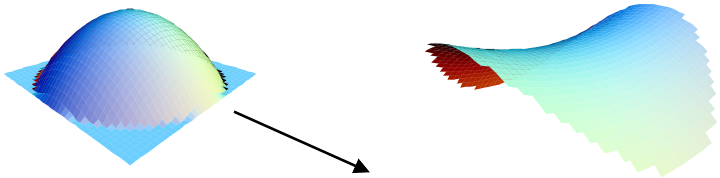
(See also prediction of anisotropic superfluidity of 2D dipolar gases : Phys. Rev. Lett. **106**, 065301 (2011))

Hydrodynamic properties of a BEC with weak dipole-dipole interactions



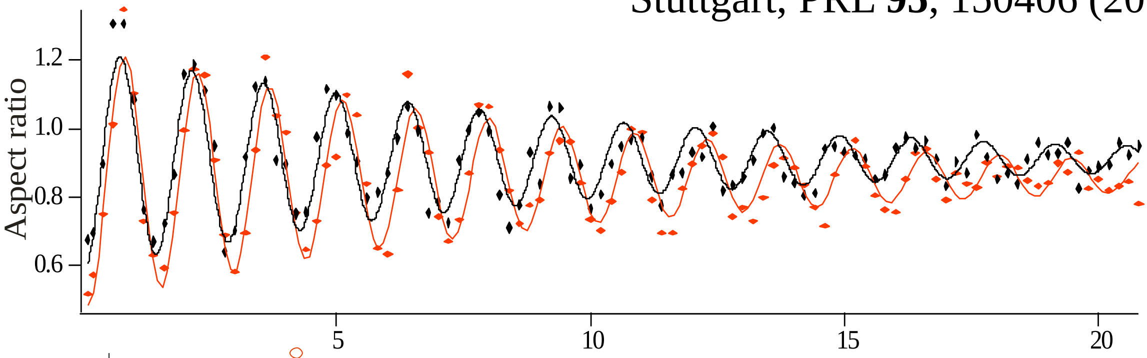
Stuttgart, PRL **95**, 150406 (2005)

Striction

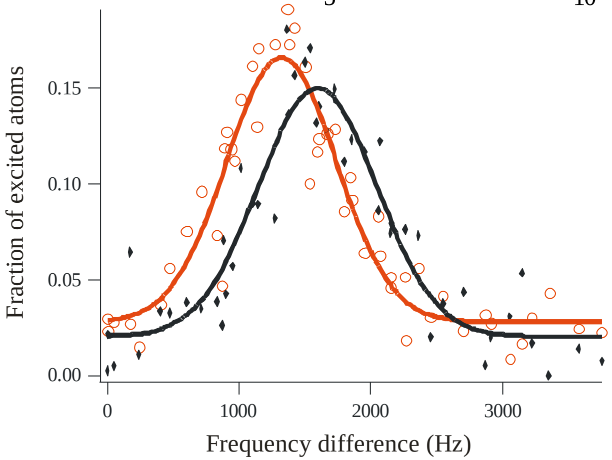


Collective excitations

Villetaneuse,
PRL **105**, 040404 (2010)



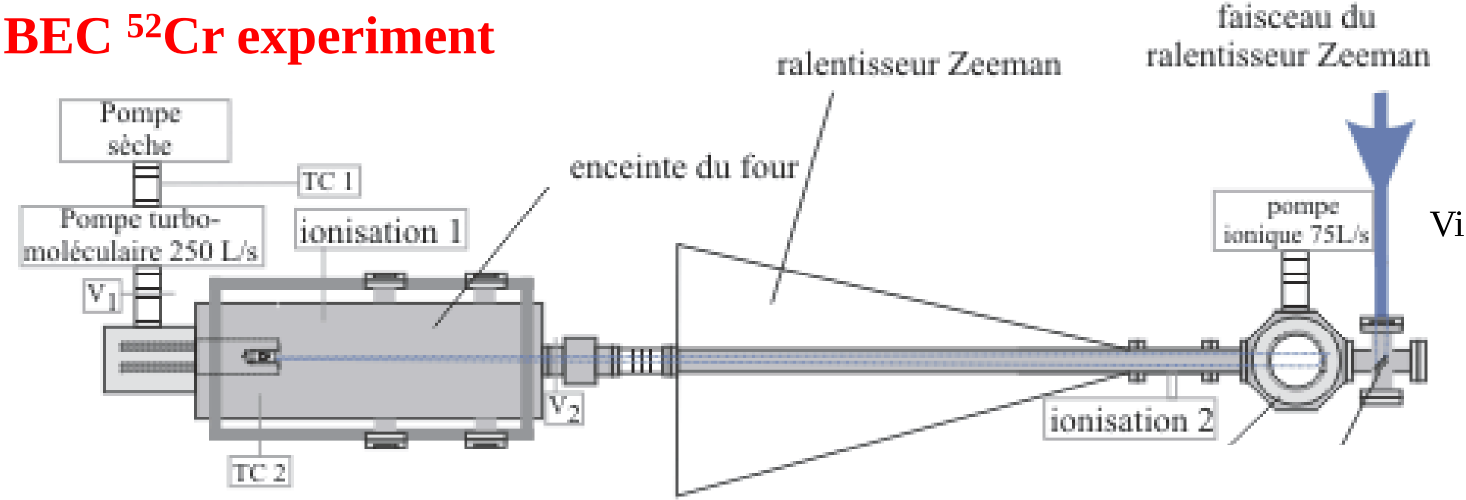
Anisotropic speed of sound



Bragg spectroscopy
Villetaneuse
arXiv: 1205.6305 (2012)

Interesting but weak effects in a scalar Cr BEC

BEC ^{52}Cr experiment



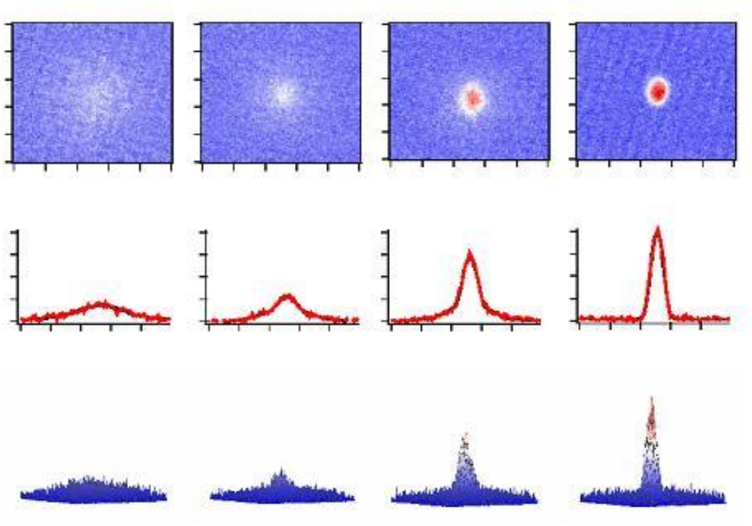
Vide 4 10^{-11} mbar

Oven 1500 °C

Zeeman slower

MOT
100 µK
10^6 atomes

Evaporative cooling
100 nK
10^4 atoms



Small condensates (10^4 atomes)

Oven at 1500 °C

Many lasers !

Magnetic field controlled to 100 µG

Quantum gases

Density : 10^{12} à 10^{15} at/cm^3 (↔10^{22} at/cm^3 for liquid He)

Temperature : 1 nK à 1µK

de Broglie wavelength > 100 nm

Interparticle distance ~ 100 nm

Van-der-Waals (contact) interactions

$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi\hbar^2}{m} a_S \delta(R)$$

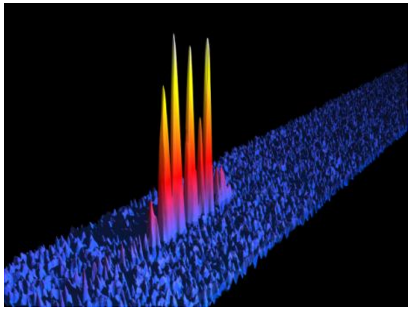
Short range
Isotropic

a_S ~ 5 nm - can be tuned via Feshbach resonances

Effect of interactions on condensates

Attractive interactions

Implosion of BEC for large atom number

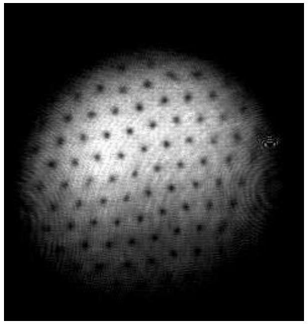


Small solitons

Rice…

Repulsive interactions

Stable condensate
Phonon spectrum



Superfluidity

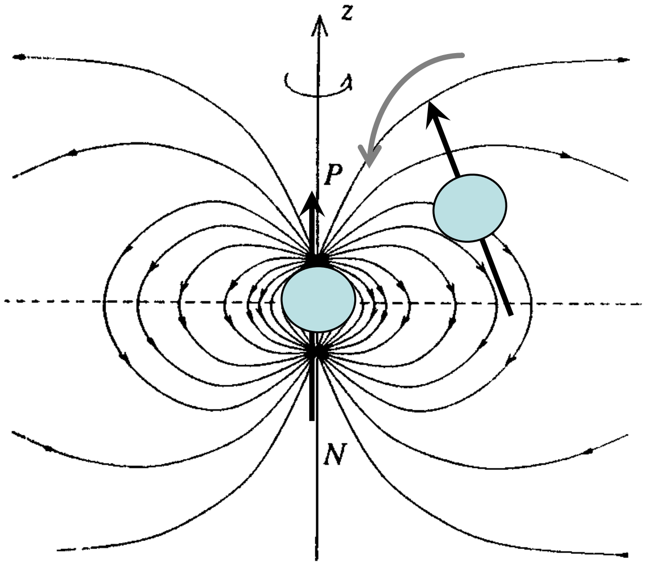
ENS, JILA…

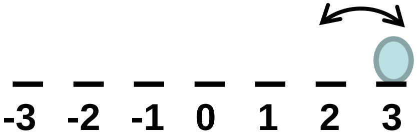
Spin dependent interactions

Berkeley…

Magnetism

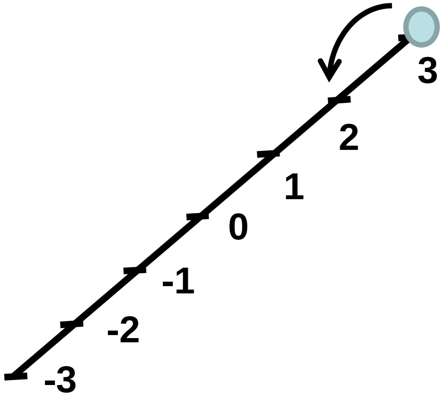
B=0: Rabi





$$\hbar\Gamma \approx V_{dd}$$

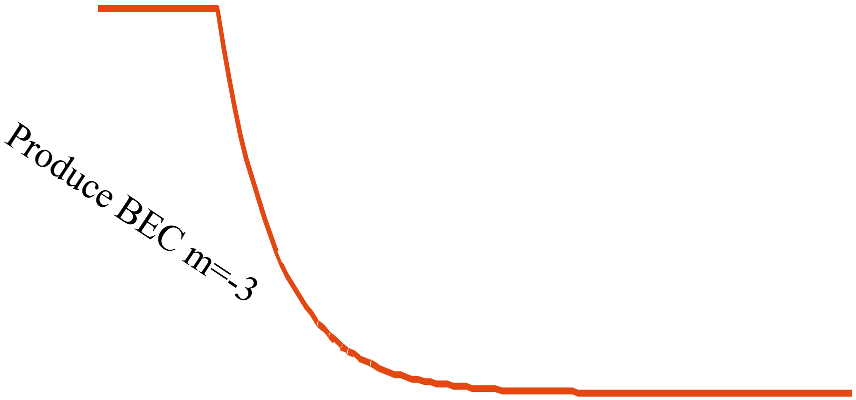
In a finite magnetic field: Fermi golden rule (losses)



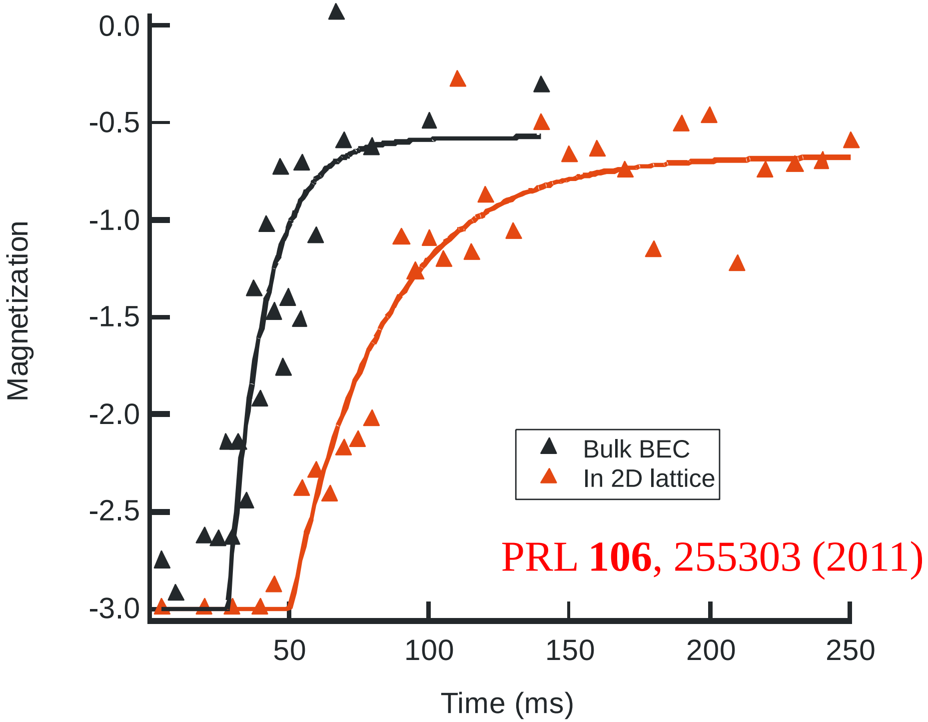
$$\hbar\Gamma \approx \left|V_{dd}\right|^2 \rho\left(\varepsilon_f = g\mu_B B\right)$$

(x1000 compared to alkalis)

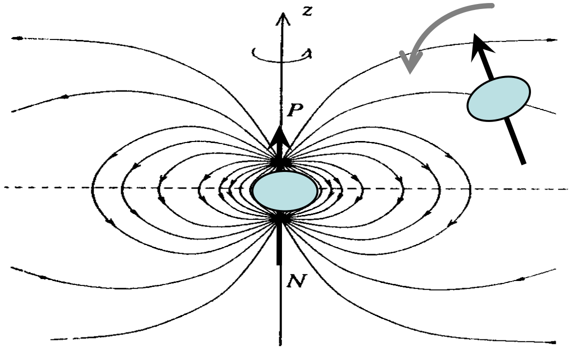
Dynamics analysis



Rapidly lower magnetic field



PRL **106**, 255303 (2011)



Meanfield picture :
Spin(or) precession

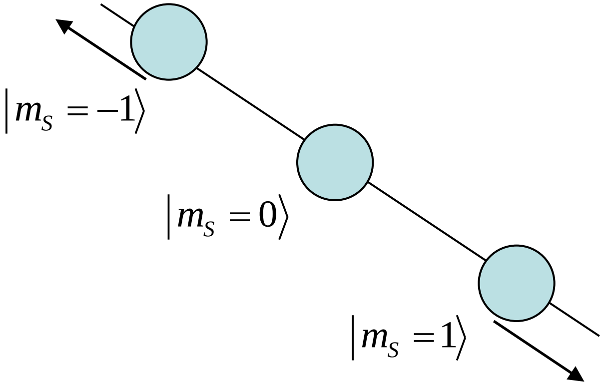
Ueda, PRL **96**,
080405 (2006)

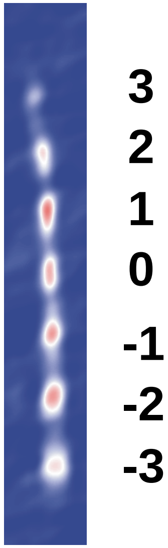
Natural timescale for depolarization:

$$V_{dd}\left(r = n^{-1/3}\right) \propto \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 n$$

Detecting spin properties with cold atoms:

Stern-Gerlach separation:
(magnetic field gradient)



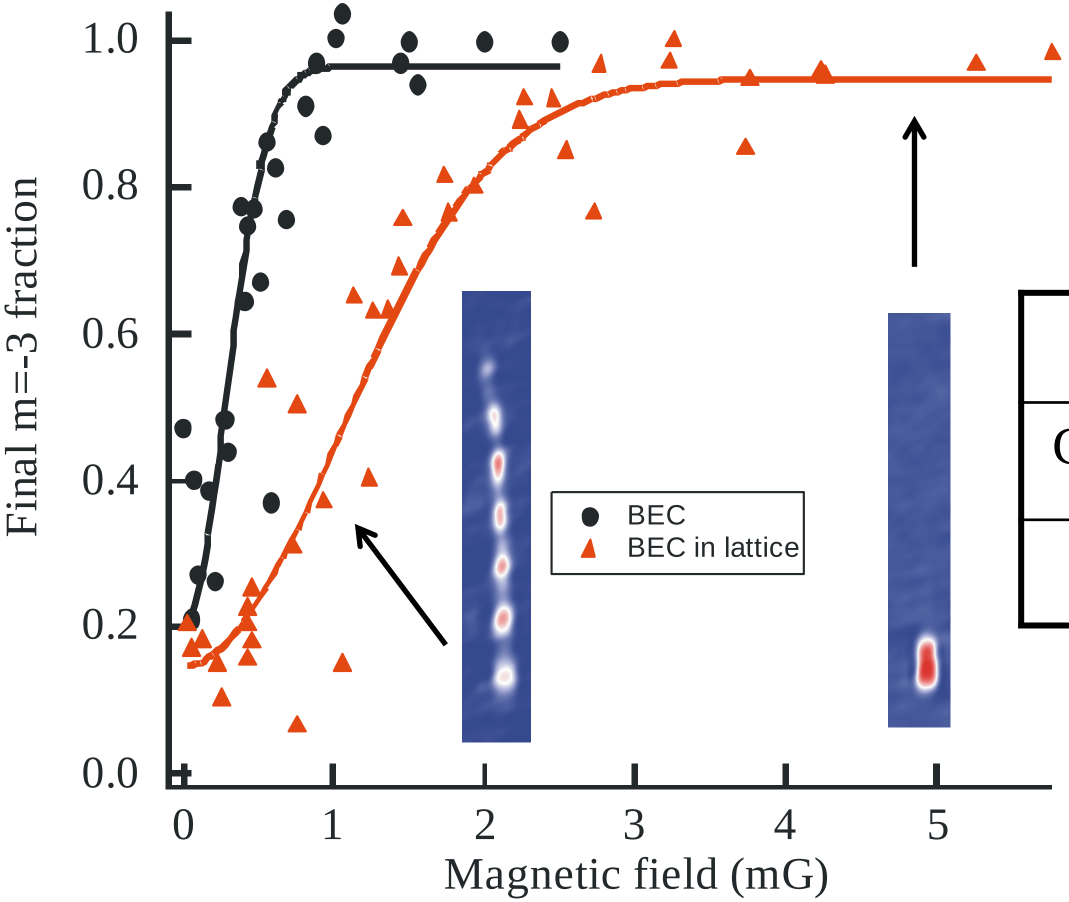


Spin-sensitive imaging:
(e.g. Faraday rotation)

See D. Stamper-Kurn,
Full 3D reconstruction of
spin vector

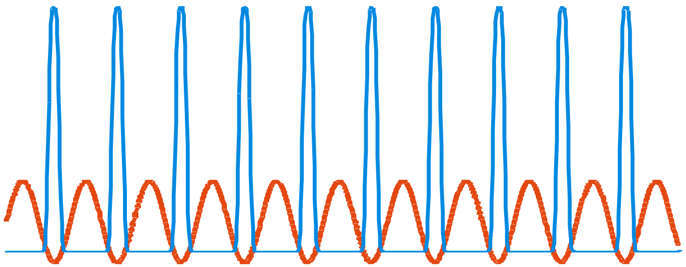
(we do not (yet) do this)

Density dependent threshold



$$g_J \mu_B B_c \approx \frac{2\pi\hbar^2 n_0 \left(a_6 - a_4\right)}{m}$$

	BEC	Lattice
Critical field	0.26 mG	1.25 mG
1/e fitted	0.3 mG	1.45 mG

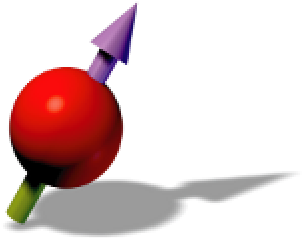


Load into deep 2D optical lattices to boost density.
Field for depolarization depends on density

Note: Possible new physics in 1D: Polar phase is a singlet-paired phase Shlyapnikov-Tsvelik NJP, 13, 065012 (2011)

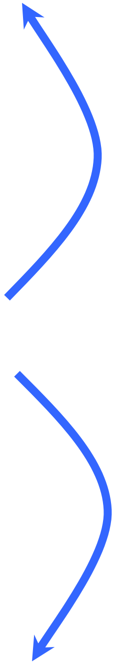
Different dipolar systems

« Magnetic atoms »

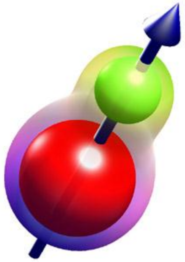


$$d = (1-10)\mu_B$$

Dipole-dipole interactions



$$\times\alpha^2 = \frac{1}{137^2}$$



Hetero-nuclear molecule with (field induced-) electric dipole moment

$$d \approx ea_0$$

$$\times n^4 = 10^8$$

Rydberg atoms

$$d = n^2 ea_0$$

$$\boxed{\left(S_{1z}.S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)\right)\left(1-3z^2\right)}$$

Other differences from Heisenberg magnetism:

-Bosons…

-Not a spin ½ system: S=3

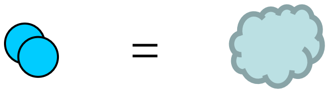
-Anisotropy

--1/r^3 dependence

-Does not rely on Mott physics

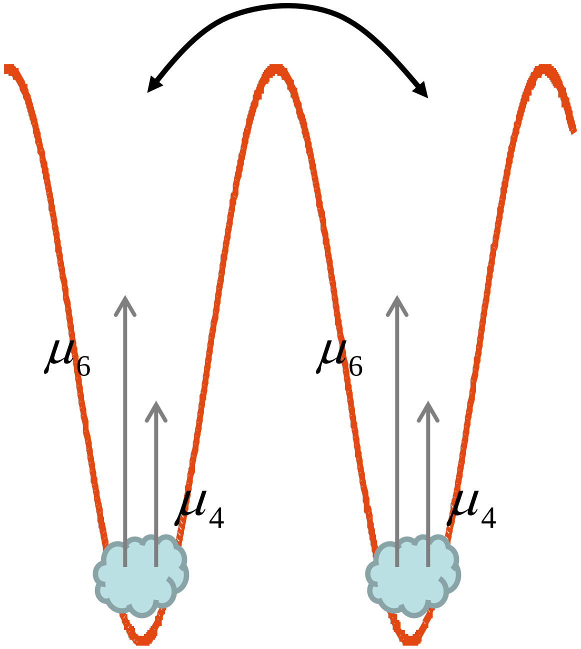
- Can have more than one atom per site

$$\left(S=3\right)+\left(S=3\right)=\left(S_t=6,4,2,0...\right)$$

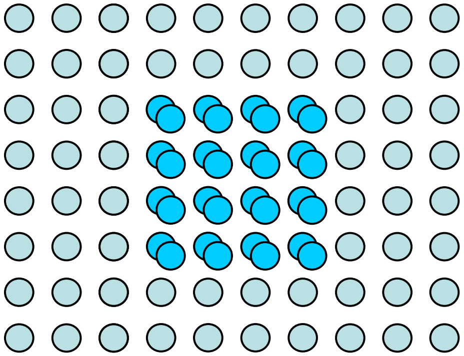


Effective S$_t$

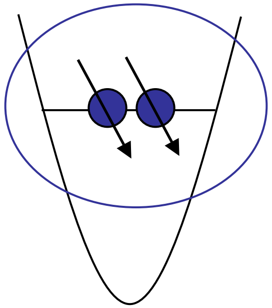
$$V_{dd} << \mu_6 - \mu_4$$

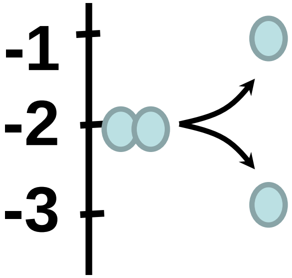


Dipolar chromium atoms in 3D optical lattices –Interactions

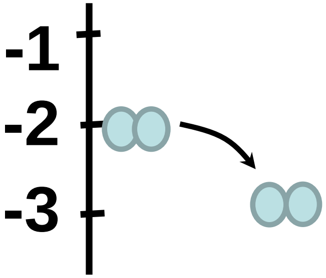


- Spin-dependent contact interactions in doubly-occupied sites



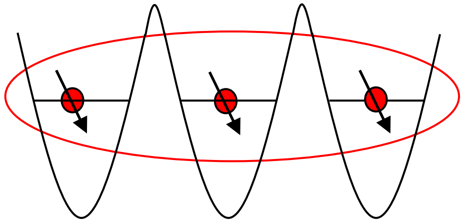


- Dipolar relaxation



- Intersite dipolar interactions

*** Between singlons**



*** Between doublons**