Dipolar chromium BECs, and magnetism

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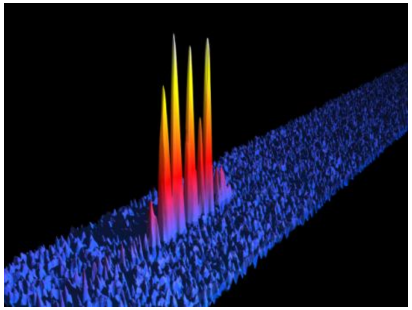
Effect of interactions on condensates

Attractive interactions

Implosion of BEC for large atom number

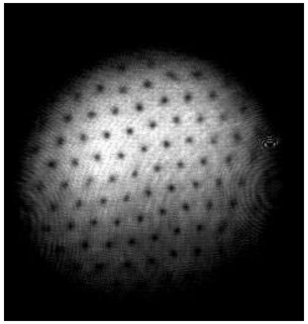


Small solitons

Rice…

Repulsive interactions

Stable condensate
Phonon spectrum



Superfluidity

ENS, JILA…

Spin dependent interactions

Berkeley…

Magnetism

Chromium (S=3): Van-der-Waals plus dipole-dipole interactions

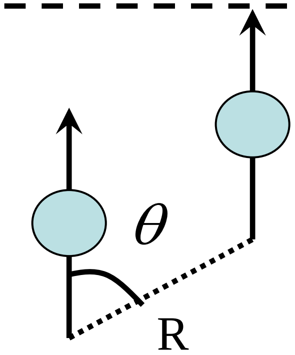
$$d = 6\mu_B$$

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



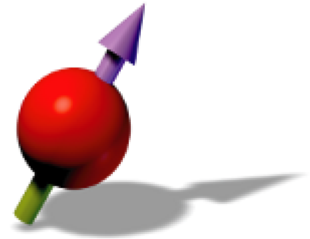
Partially **attractive**, partially **repulsive**

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

Different dipolar systems

« Magnetic atom »

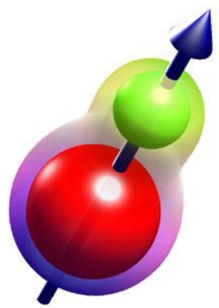
$$d \approx \mu_B$$



Dipole-dipole interactions

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

Molecule with (field induced-) electric dipole moment



$$d \approx e a_0$$

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

Rydberg atoms

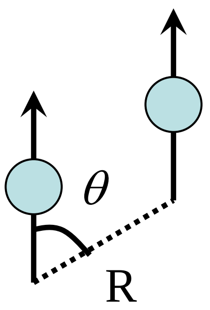
$$d = n^2 e a_0$$

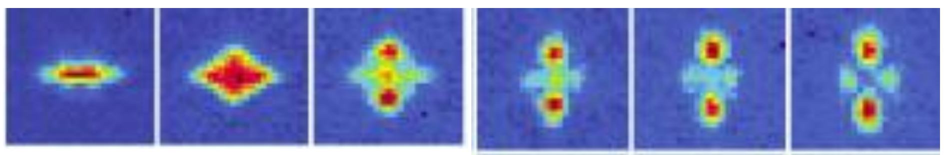
Relative strength of dipole-dipole and Van-der-Waals interactions

$\varepsilon_{dd} > 1$ 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: $\varepsilon_{dd} = 0.16$

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

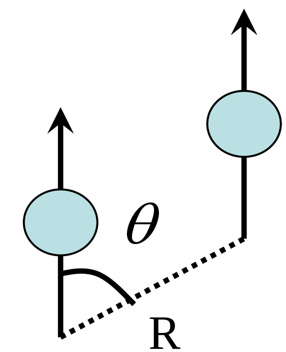
Multicomponent (« spinor ») BEC
Magnetism
Phases, spin textures…

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

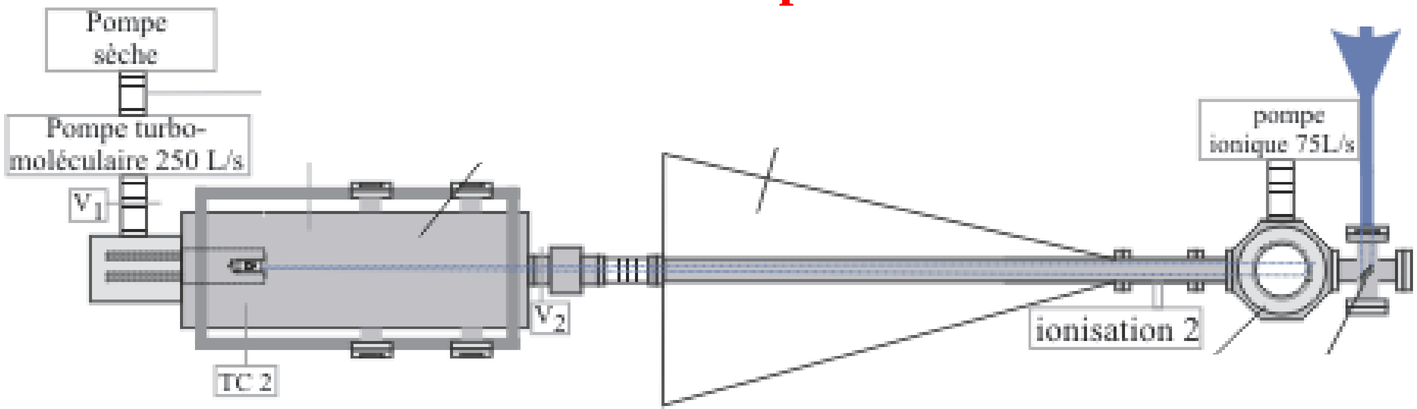
Anisotropic



Hydrodynamics:
non-local mean-field

Magnetism:
Atoms *are* magnets

^{52}Cr BEC experiment



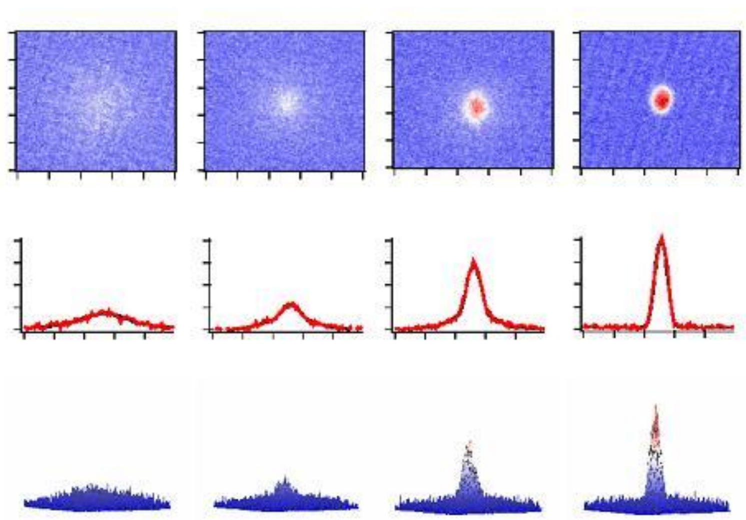
Vacuum
4 10^{-11} mbar

Oven at 1500 °C

Zeeman slower

MOT
100 µK
10^6 atoms

Evaporative cooling
100 nK
10^4 atoms



Small condensates (10^4 atoms)

Oven at 1500 °C

Many lasers !

Magnetic field control < 100 µG

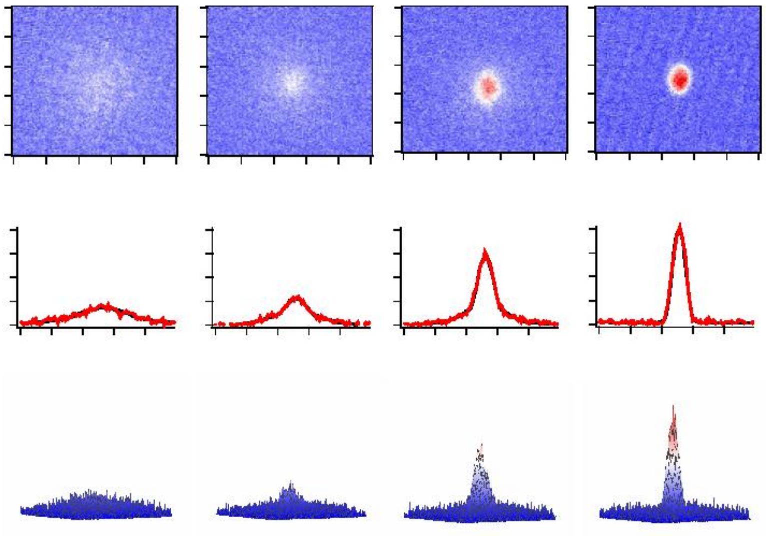
1 – Hydrodynamic properties of a weakly dipolar BEC

- ***Collective excitations***
- ***Bragg spectroscopy***

2 – Magnetic properties of a dipolar BEC

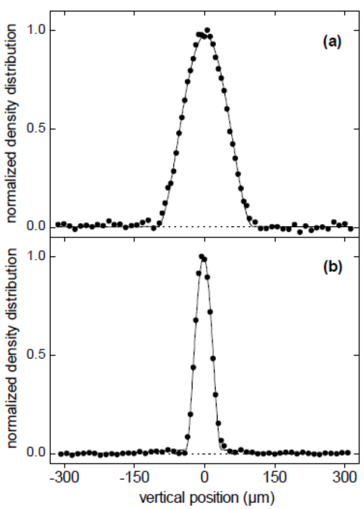
- ***Spinor physics of a Bose gas with free magnetization***
- ***(Quantum) magnetism in opical lattices***

Interaction-driven expansion of a BEC



A lie:

Imaging BEC after time-of-fligth is a measure of in-situ momentum distribution



Cs BEC with tunable interactions (from Innsbruck))

Self-similar, (interaction-driven) Castin-Dum expansion

Phys. Rev. Lett. **77**, 5315 (1996)

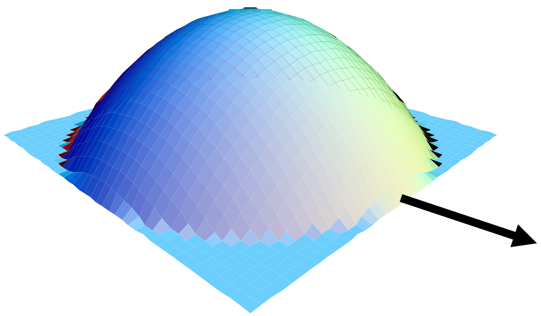
$$R_j(t) = \lambda_j(t) R_j(0)$$

$$\ddot{\lambda}_j = \frac{\omega_j^2(0)}{\lambda_j \lambda_1 \lambda_2 \lambda_3} - \omega_j^2(t) \lambda_j$$

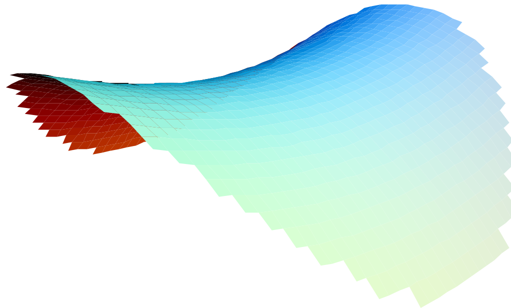
TF radii after expansion related to interactions

Modification of BEC expansion due to dipole-dipole interactions

TF profile

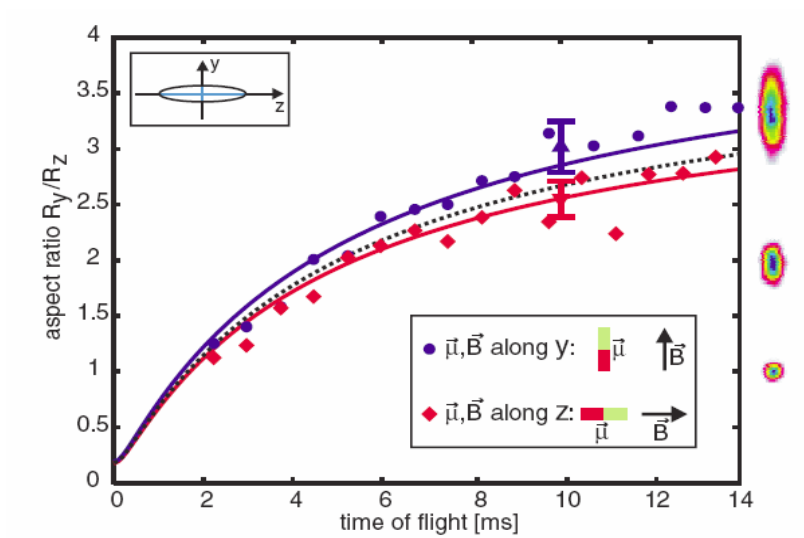


$$\Phi_{dd}(\vec{r}) = \int V_{dd}(\vec{r}-\vec{r}\,')n(\vec{r}\,')d^3\vec{r}\,'$$



Striction of BEC
(non local effect)

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



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

(similar results in our group)

Frequency of collective excitations

(Castin-Dum)

$$\ddot{\lambda}_j = \frac{\omega_j^2(0)}{\lambda_j \lambda_1 \lambda_2 \lambda_3} - \omega_j^2(t)\lambda_j$$

Consider small oscillations, then

$$\frac{d^2\vec{\lambda}}{dt^2} = H.\vec{\lambda}$$

with

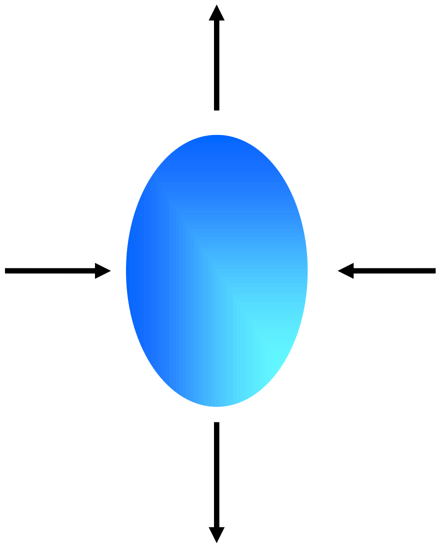
$$H = \begin{pmatrix} -3\omega_1^2 & -\omega_1^2 & -\omega_1^2 \\ -\omega_2^2 & -3\omega_2^2 & -\omega_2^2 \\ -\omega_3^2 & -\omega_3^2 & -3\omega_3^2 \end{pmatrix}$$

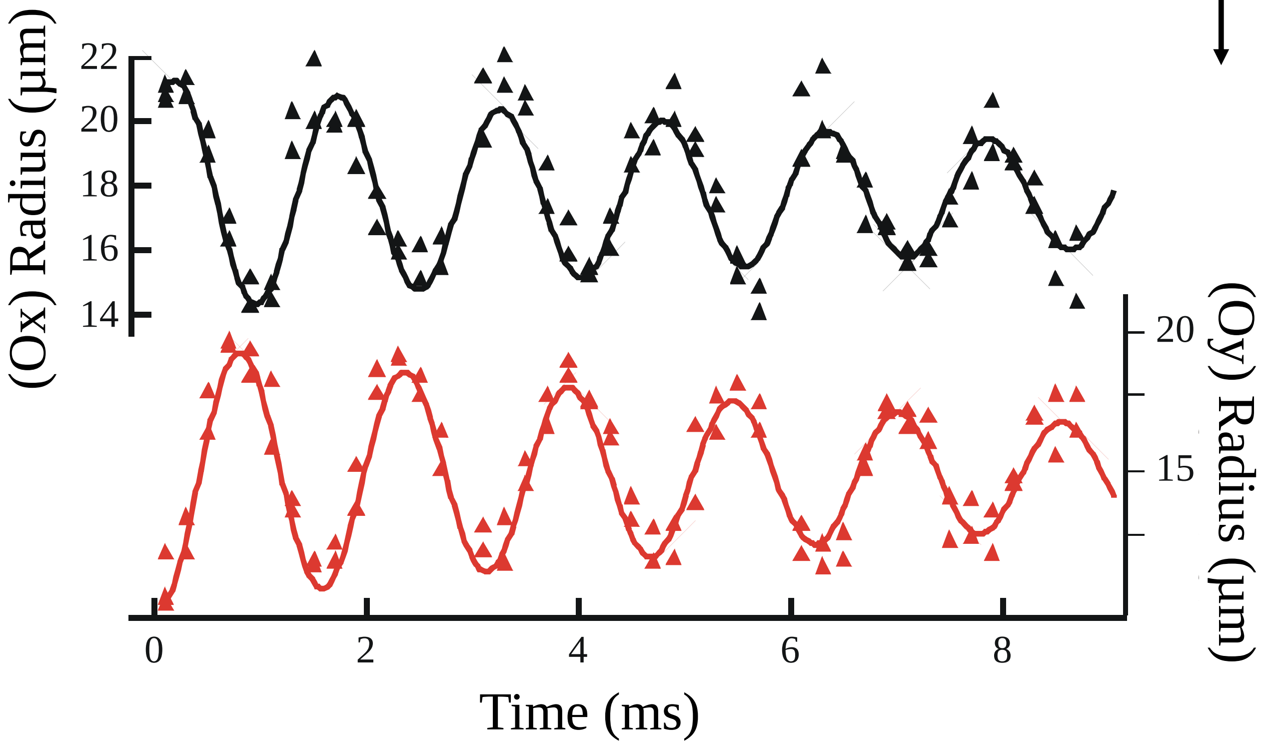
In the Thomas-Fermi regime, collective excitations frequency independent of number of atoms and interaction strength:

Pure geometrical factor

(solely depends on trapping frequencies)

Observation of one collective mode





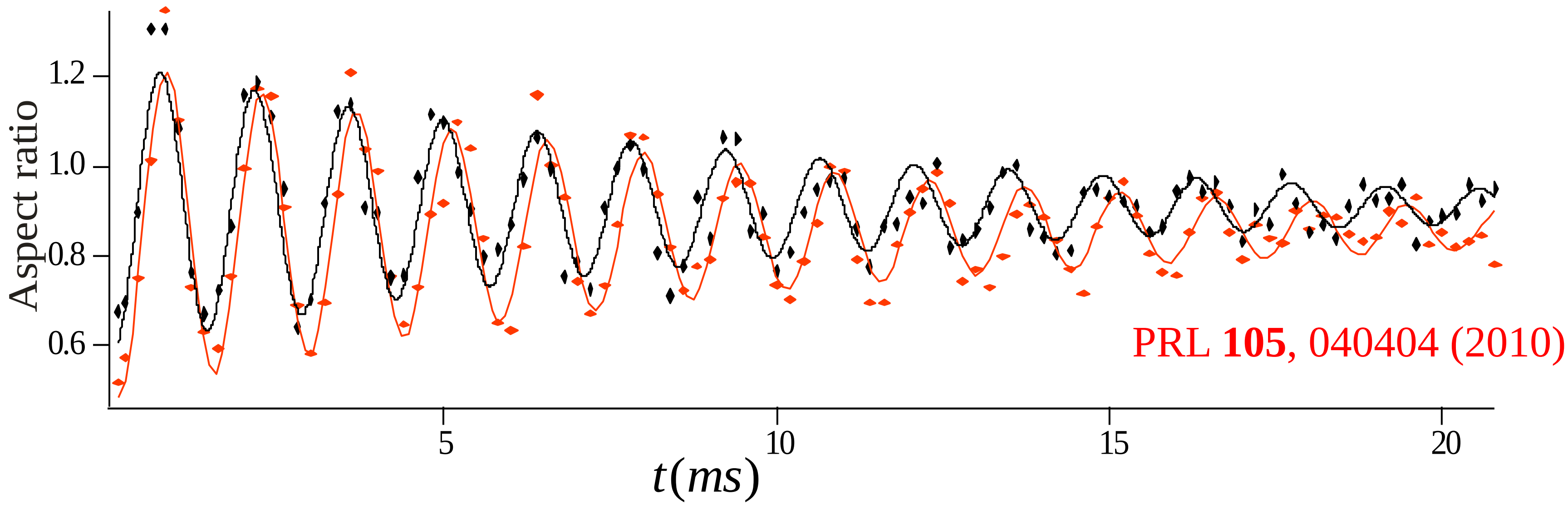
(parametric excitation)

Collective excitations of a dipolar BEC

Due to the anisotropy of dipole-dipole interactions, the dipolar mean-field depends on the relative orientation of the magnetic field and the axis of the trap

Parametric excitations

Repeat the experiment for two directions of the magnetic field (differential measurement)



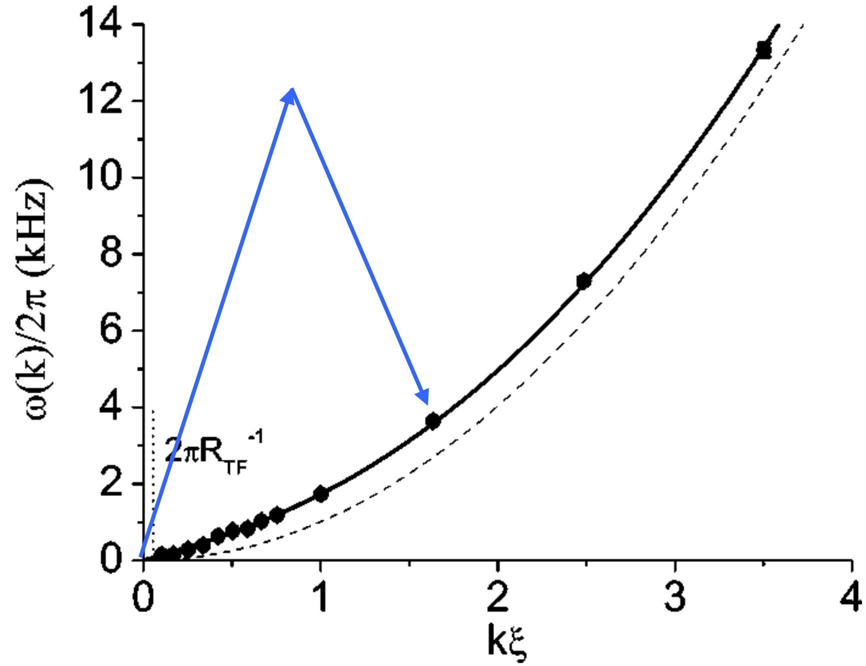
A small, but qualitative, difference (geometry is not all) $\frac{\Delta\nu}{\nu} \propto \varepsilon_{dd}$

Note : dipolar shift very sensitive to trap geometry : a consequence of the anisotropy of dipolar interactions

Bragg spectroscopy

Probe dispersion law $E(k) = ck$ — c is sound velocity; c is also critical velocity

Quasi-particles, phonons $k\xi \ll 1$ — Landau criterium for superfluidity



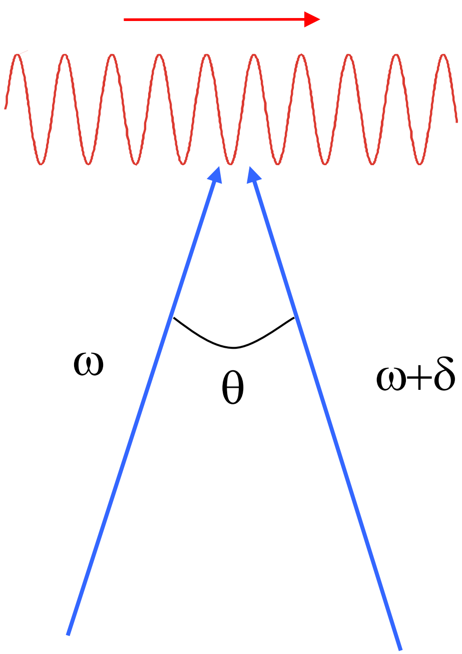
ξ healing length

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

Bogoliubov spectrum

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

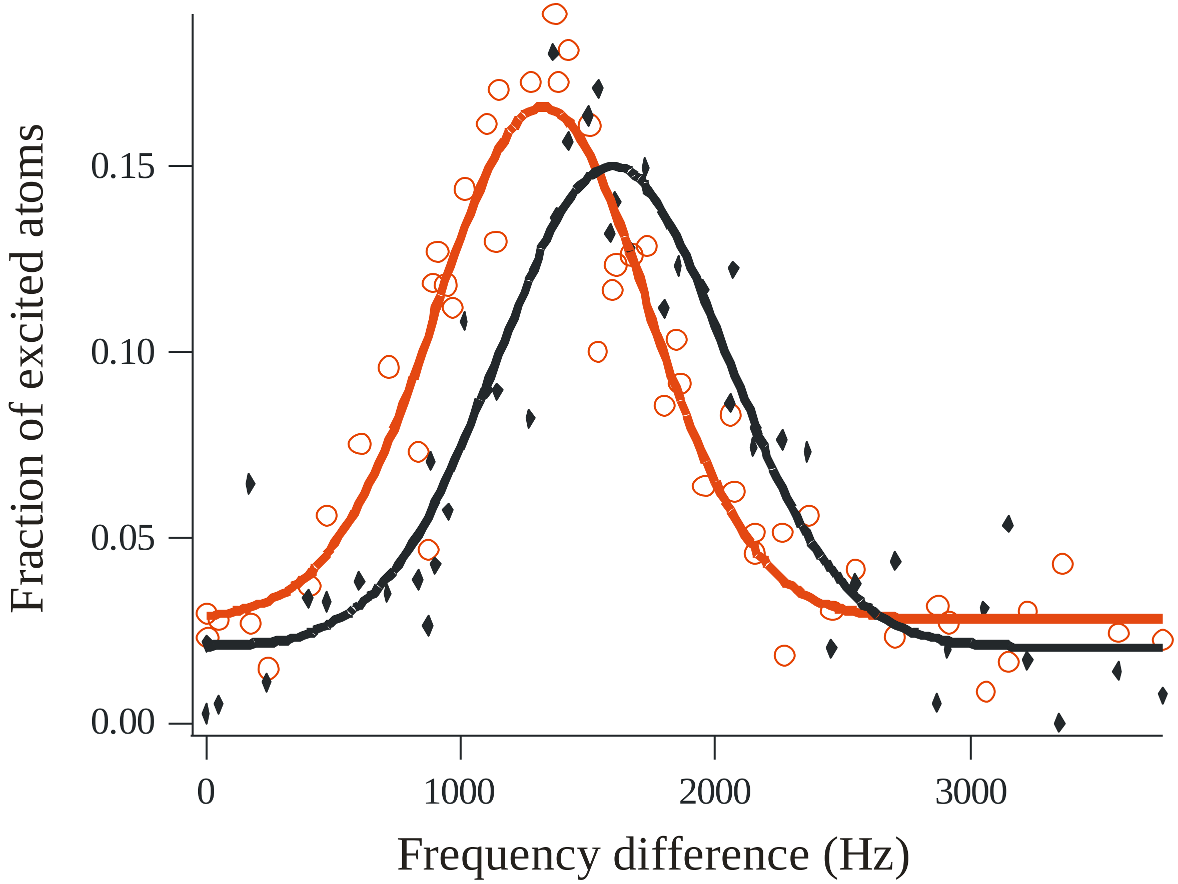
Moving lattice on BEC

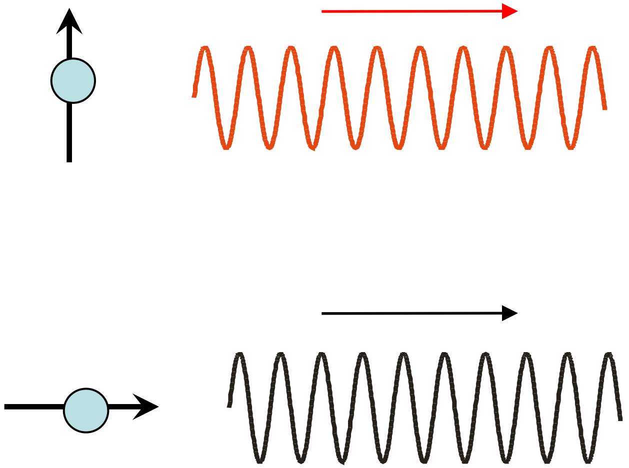


Lattice beams with an angle.
Momentum exchange

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

Anisotropic speed of sound





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

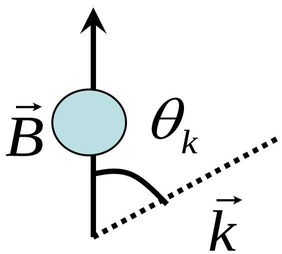
Speed of sound depends on the relative angle between spins and excitation

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

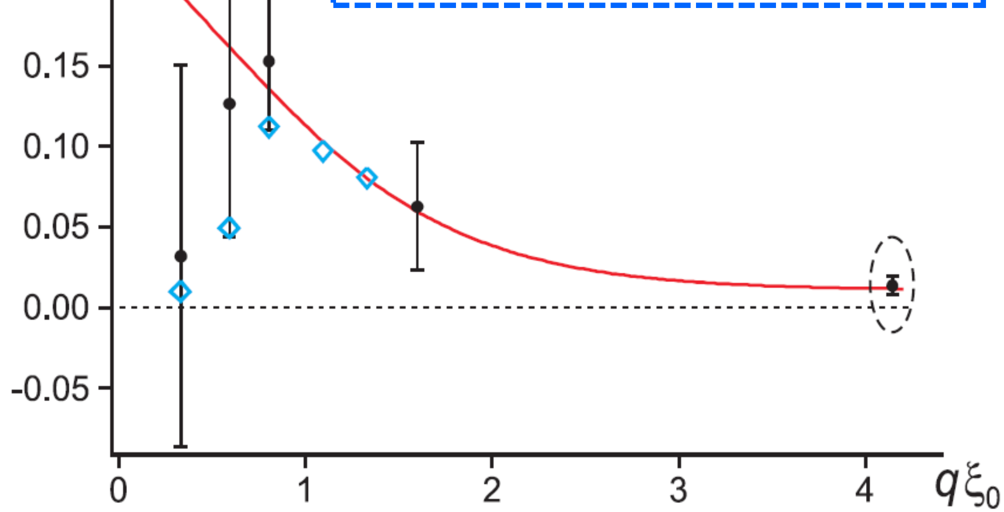
$$\tilde{V}(k) = \frac{4\pi d^2}{3}(3\cos^2\theta_k - 1) \qquad \varepsilon_k = \sqrt{E_k(E_k + 2n_0(g_c + g_d(3\cos^2\theta_k - 1))}$$



c (mm/s)	Theo	Exp
Parallel	3.6	3.4
Perpendicular	3	2.8

Good agreement between theory and experiment;

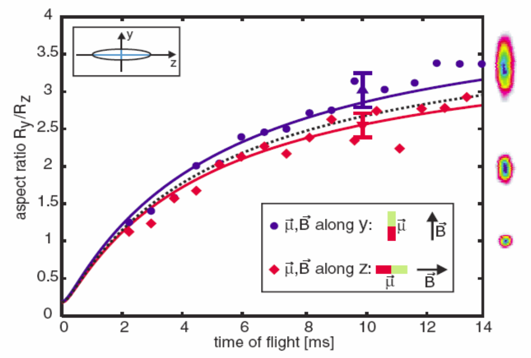
Finite size effects at low q



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

Conclusions (1) Hydrodynamic properties with weak dipole-dipole interactions

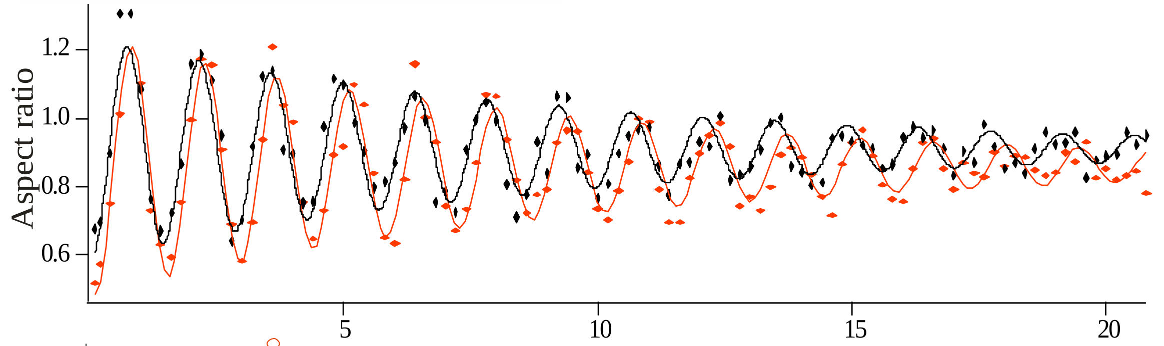
Striction



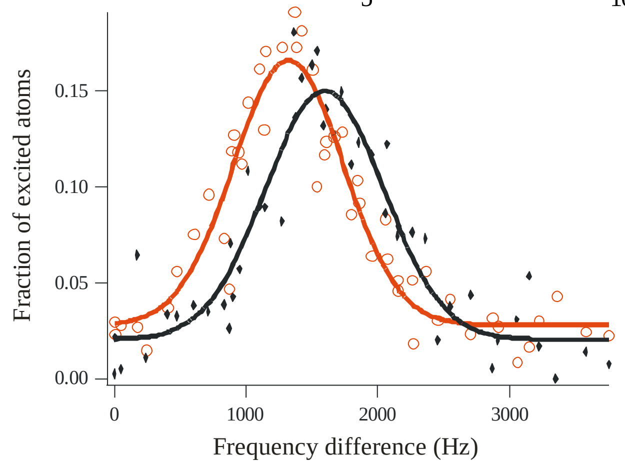
Stuttgart, PRL **95**, 150406 (2005)

Collective excitations

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



Anisotropic speed of sound



Bragg spectroscopy
Villetaneuse
Accepted in PRL (2012)

Interesting but weak effects in a scalar Cr BEC (far from Feshbach resonance)

Much more to come with…

Cr ? Er ? Dy ?
Molecules ?
Induced dipoles (Rydberg atoms) ?

Examples:

- rotonic excitation spectrum, associated instabilities
- solitons
- New vortex lattice structures
- New quantum phases in optical lattices (supersolidity, checkerboard)
- …

1 – Hydrodynamic properties of a weakly dipolar BEC

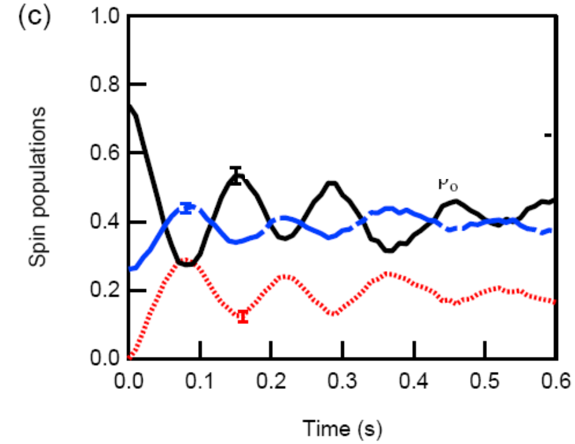
- ***Collective excitations***
- ***Bragg spectroscopy***

2 – Magnetic properties of a dipolar BEC

- ***Spinor physics of a Bose gas with free magnetization***
- ***(Quantum) magnetism in opical lattices***

Introduction to spinor physics

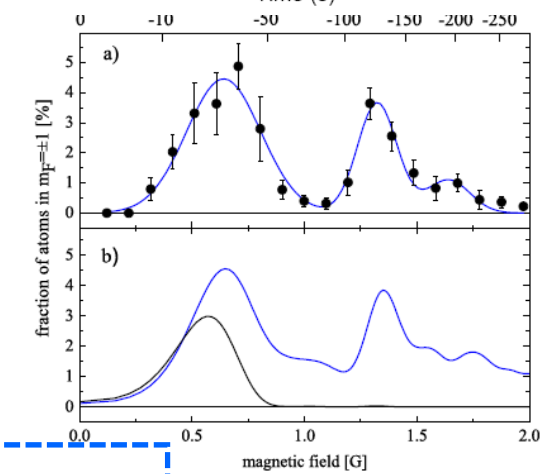
Exchange energy
Coherent spin oscillation



Chapman, Sengstock…

Quantum effects!

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

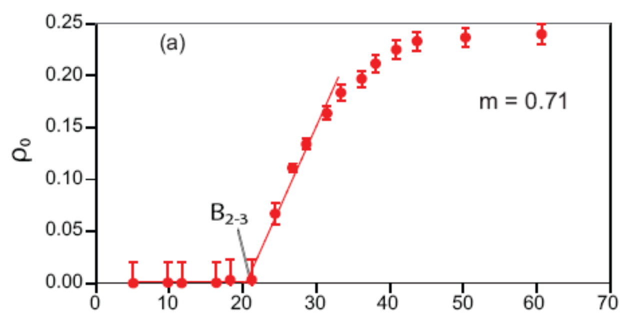


Klempt Stamper-Kurn

Domains, spin textures, spin waves, topological states

Stamper-Kurn, Chapman, Sengstock, Shin…

Quantum phase transitions



Stamper-Kurn, Lett

Main ingredients for spinor physics

S=1,2,…

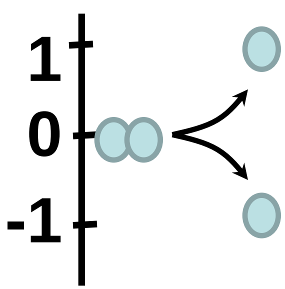
Spin-dependent contact interactions

Spin exchange

$$\left| m_S = 0, m_S = 0 \right\rangle =$$

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

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



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

Engineer artificial quadratic effect using tensor light shift

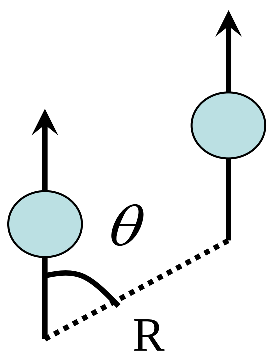
And

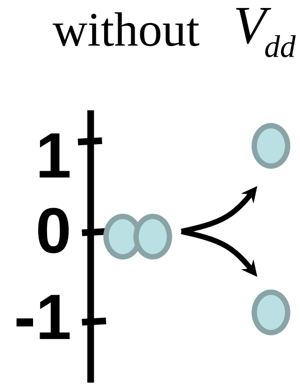
Dipole-dipole interactions

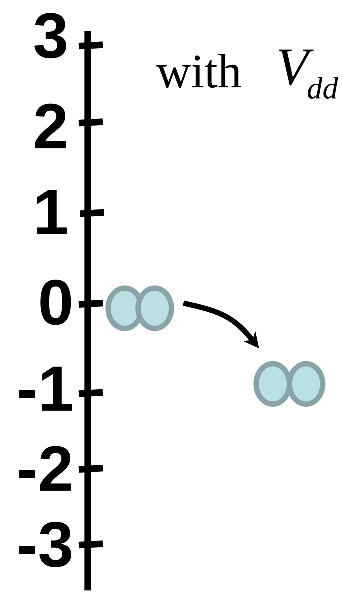
Dipolar interactions introduce magnetization-changing collisions

Dipole-dipole interactions

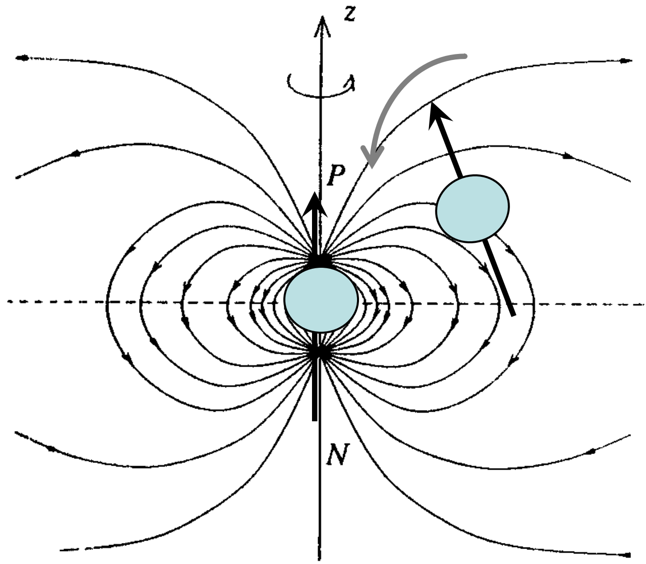
$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \left(1 - 3\cos^2(\theta)\right) \frac{1}{R^3}$$

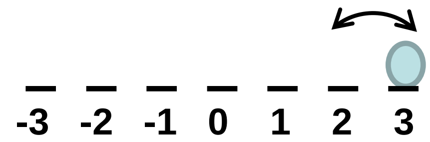






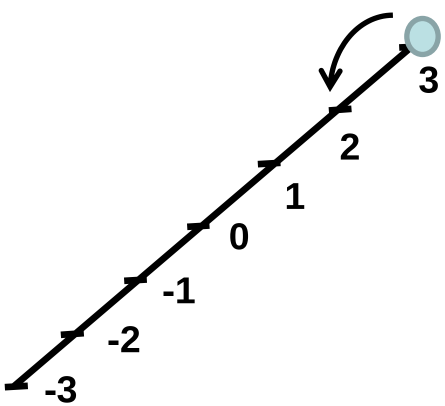
B=0: Rabi





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

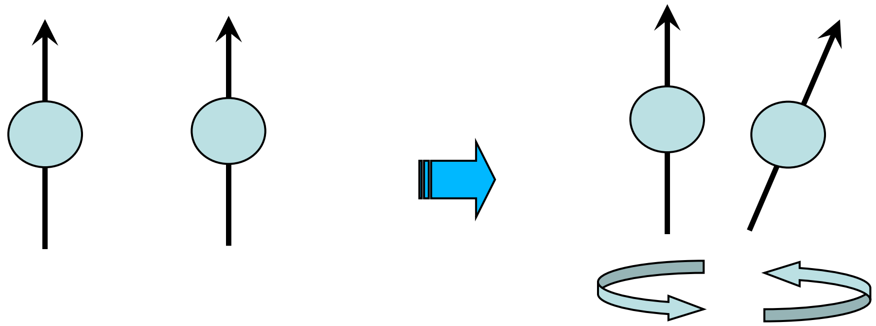
In a finite magnetic field: Fermi golden rule (losses)



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

(x1000 compared to alkalis)

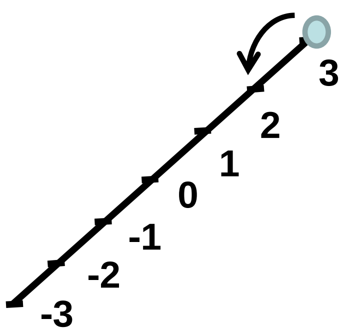
Dipolar relaxation and rotation



Angular momentum conservation

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

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



$$\Delta \ell = 2$$

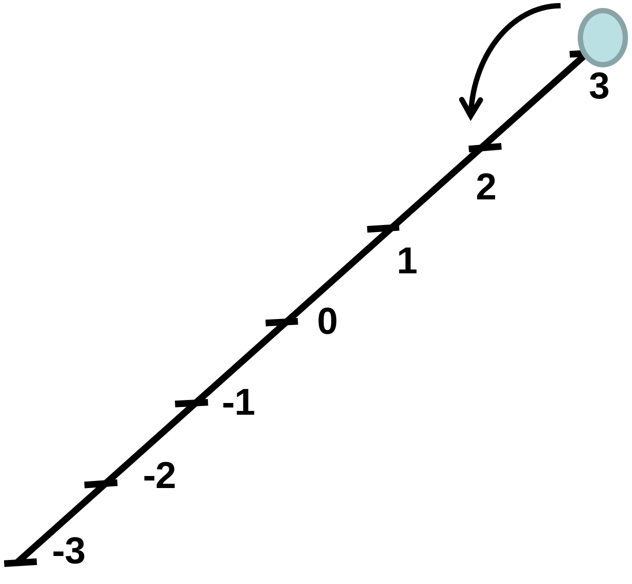
$$\Delta E = \Delta m_S g \mu_B B$$

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)

Magnetic field



B=1G

→Particle leaves the trap

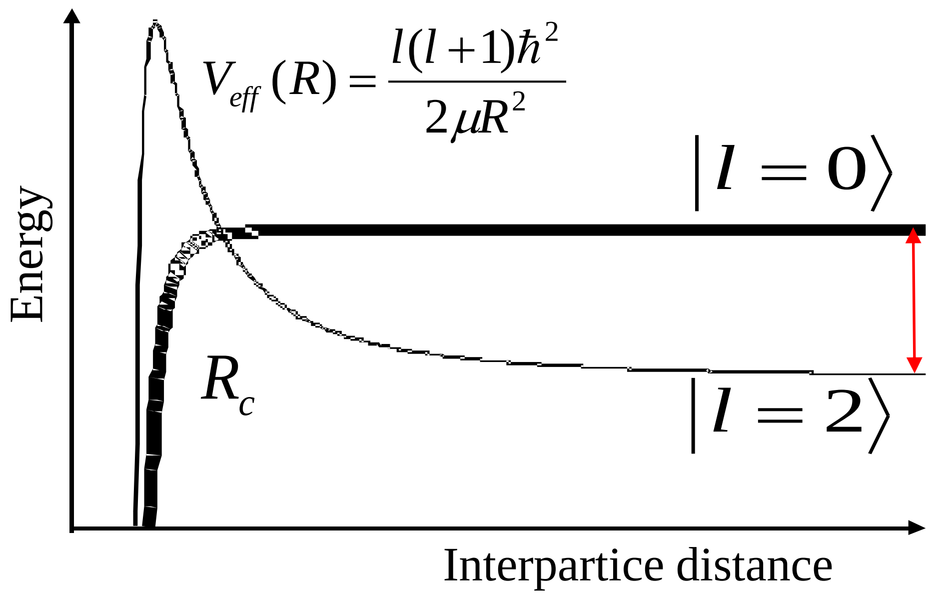
B=10 mG

→Energy gain matches band excitation in a lattice

B=.1 mG

→Energy gain equals to chemical potential in BEC

From the molecular physics point of view: a delocalized probe



$|3,3\rangle$

$\varepsilon_f = g_J \mu_B B$

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

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

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

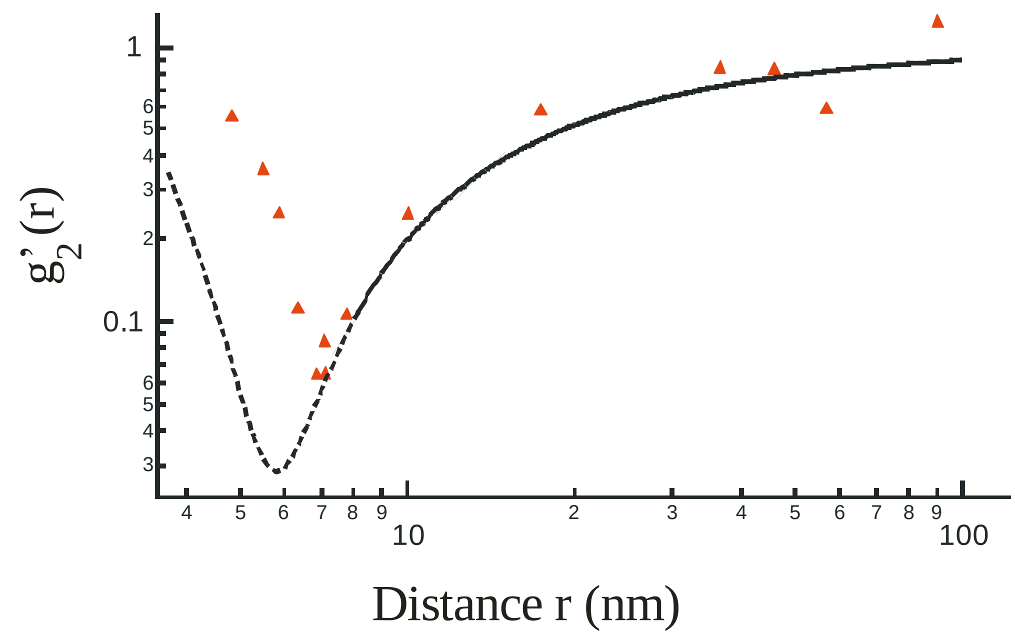
PRA **81**, 042716 (2010)

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

2-body physics

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

many-body physics



S=3 Spinor physics with free magnetization

Alkalis :

- S=1 and S=2 only
- Constant magnetization (exchange interactions)

→ Linear Zeeman effect irrelevant

New features with Cr:

- S=3 spinor (7 Zeeman states, four scattering lengths, a_6, a_4, a_2, a_0)
- No hyperfine structure
- Free magnetization

Magnetic field matters !

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

S=3 Spinor physics with free magnetization

Alkalis :

- S=1 and S=2 only
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$\rightarrow$ Linear Zeeman effect irrelevant

New features with Cr:

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- No hyperfine structure
- Free magnetization

Magnetic field matters !

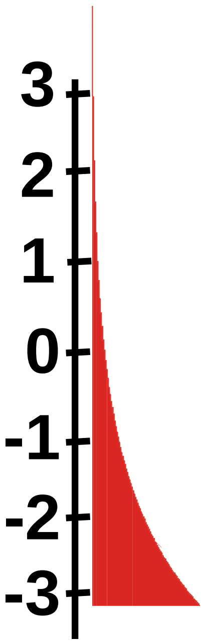
1 Spinor physics of a Bose gas with free magnetization

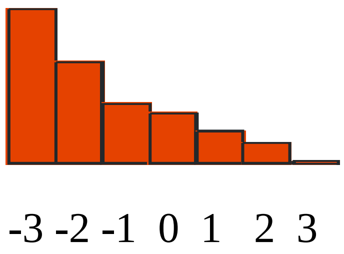
2 (Quantum) magnetism in opical lattices

Spin temperature equilibriates with mechanical degrees of freedom

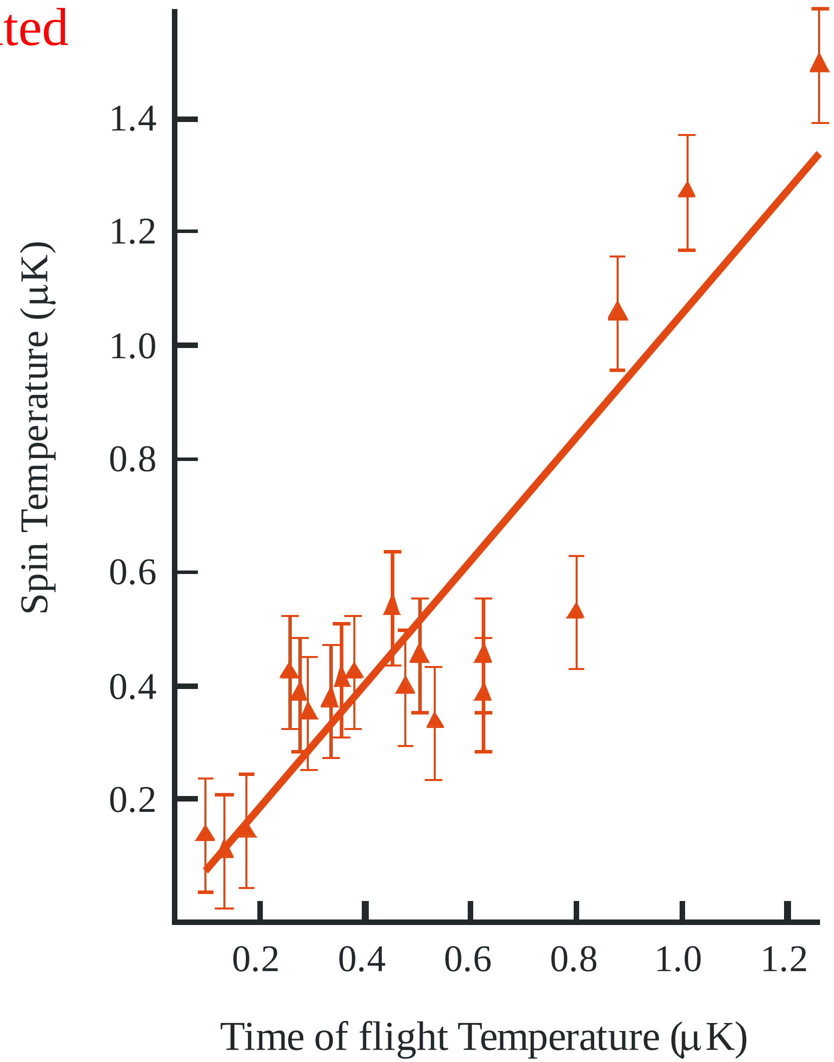
At low magnetic field: spin thermally activated

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



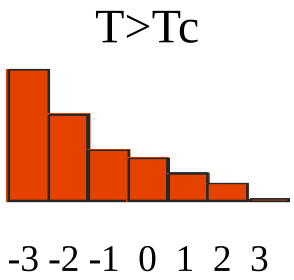


We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)

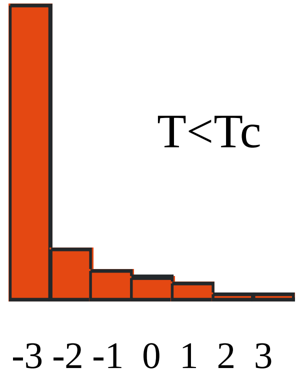


Related to Demagnetization Cooling expts, Pfau, *Nature Physics* **2**, *765 (2006)*

Spontaneous magnetization due to BEC



Thermal population in Zeeman excited states



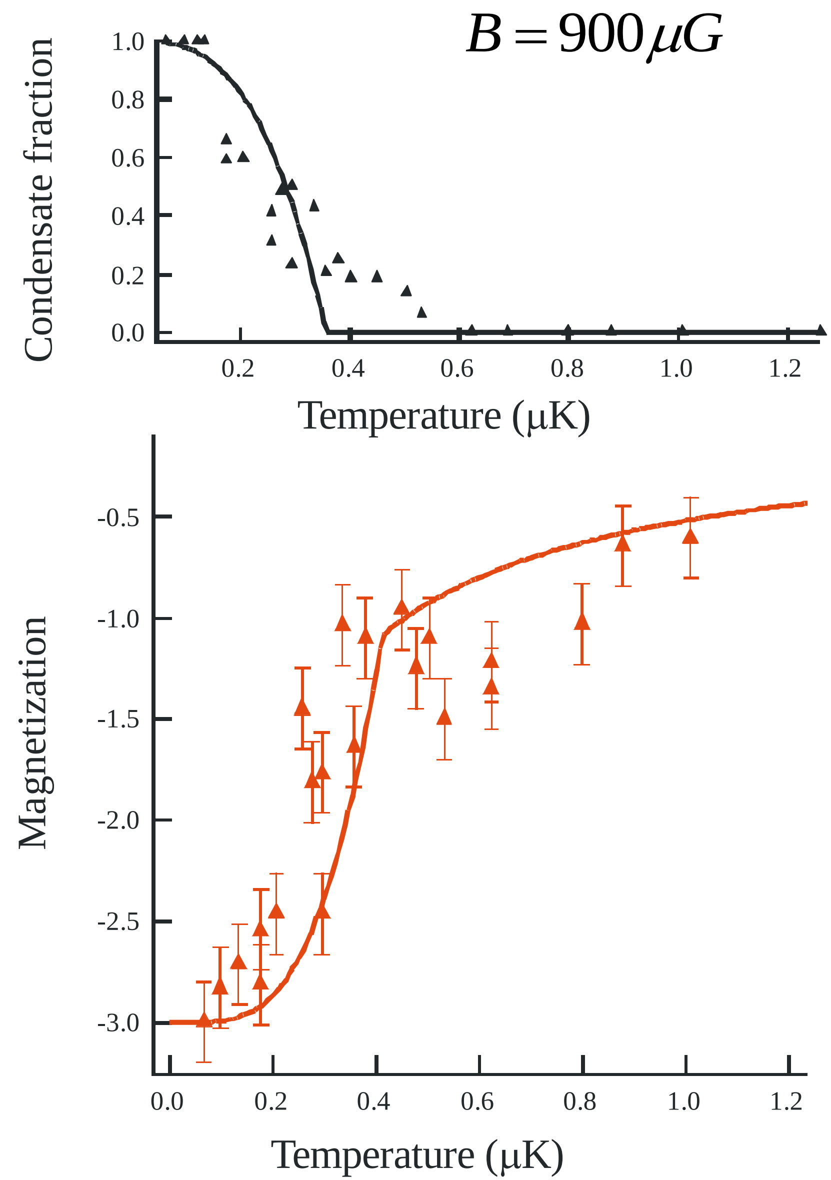
a bi-modal spin distribution

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

Cloud spontaneously polarizes !

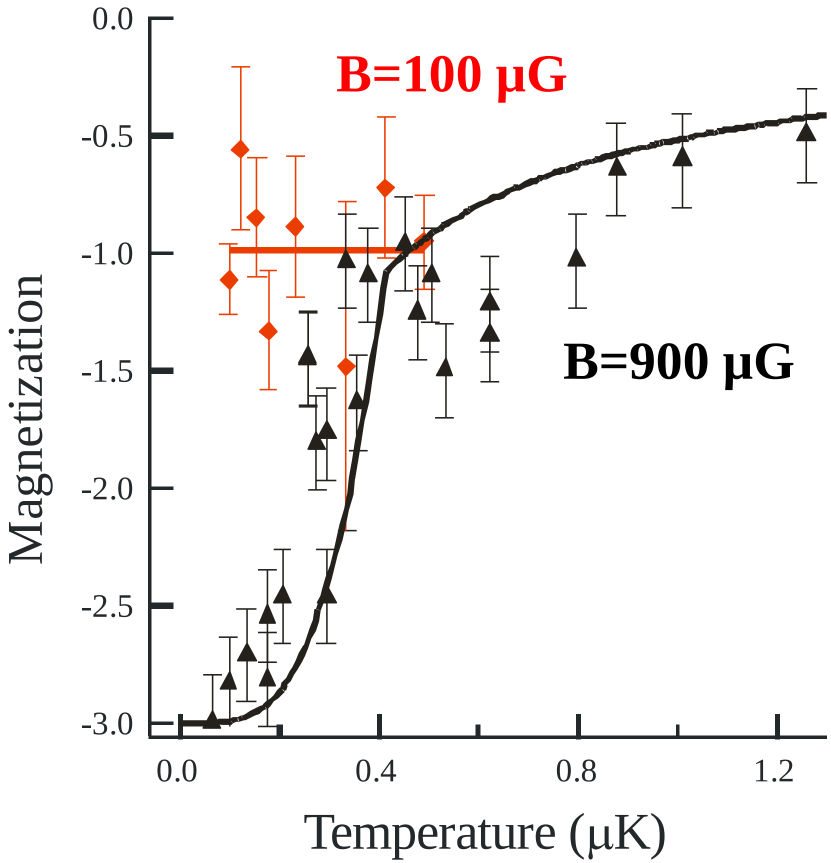
A non-interacting BEC is ferromagnetic

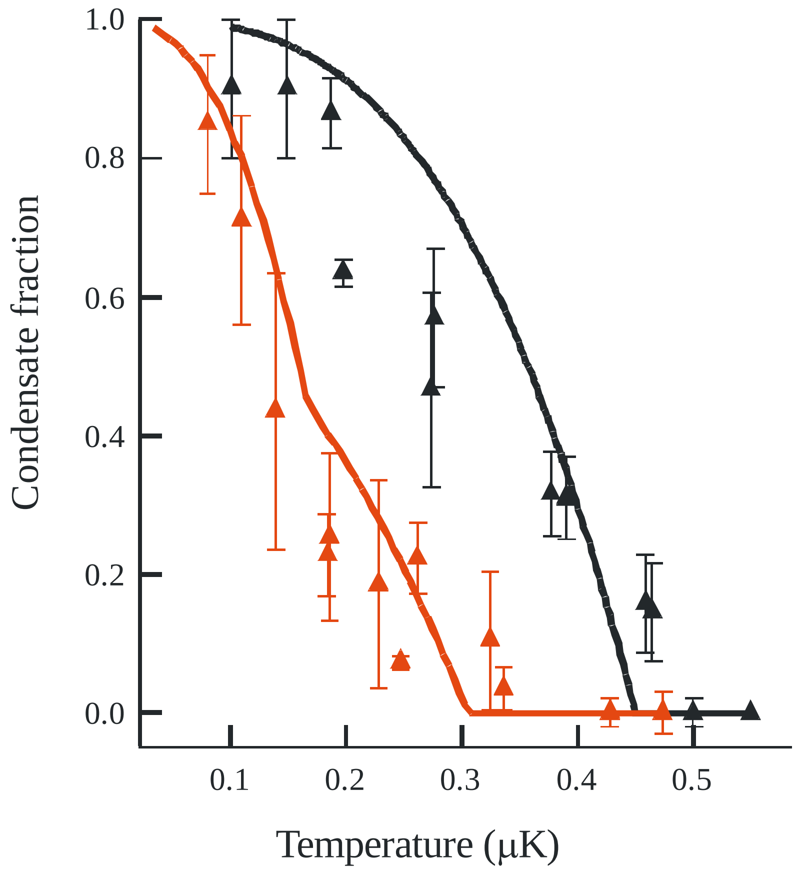
New magnetism, differs from solid-state (singlet pairing)



PRL **108**, 045307 (2012)

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





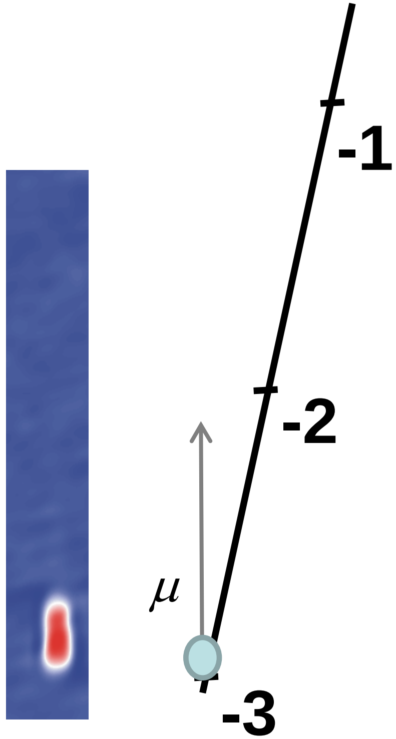
-Magnetization remains small even when the condensate fraction approaches 1

!! Observation of a depolarized condensate !!

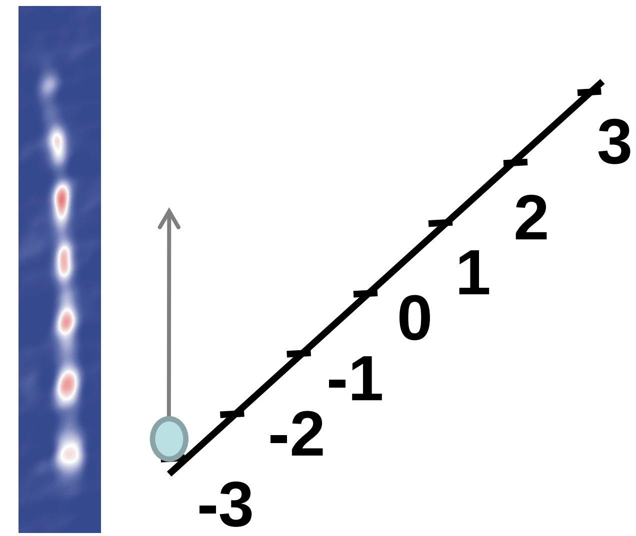
Necessarily an interaction effect

PRL **108**, 045307 (2012)

Cr spinor properties at low field

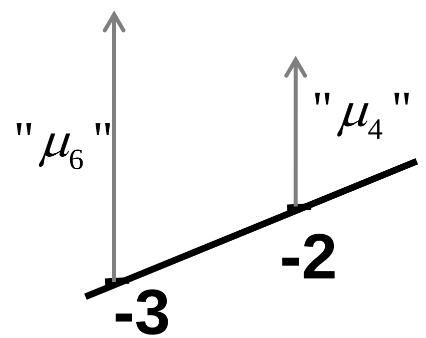


Large magnetic field : ferromagnetic



Low magnetic field : polar/cyclic

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

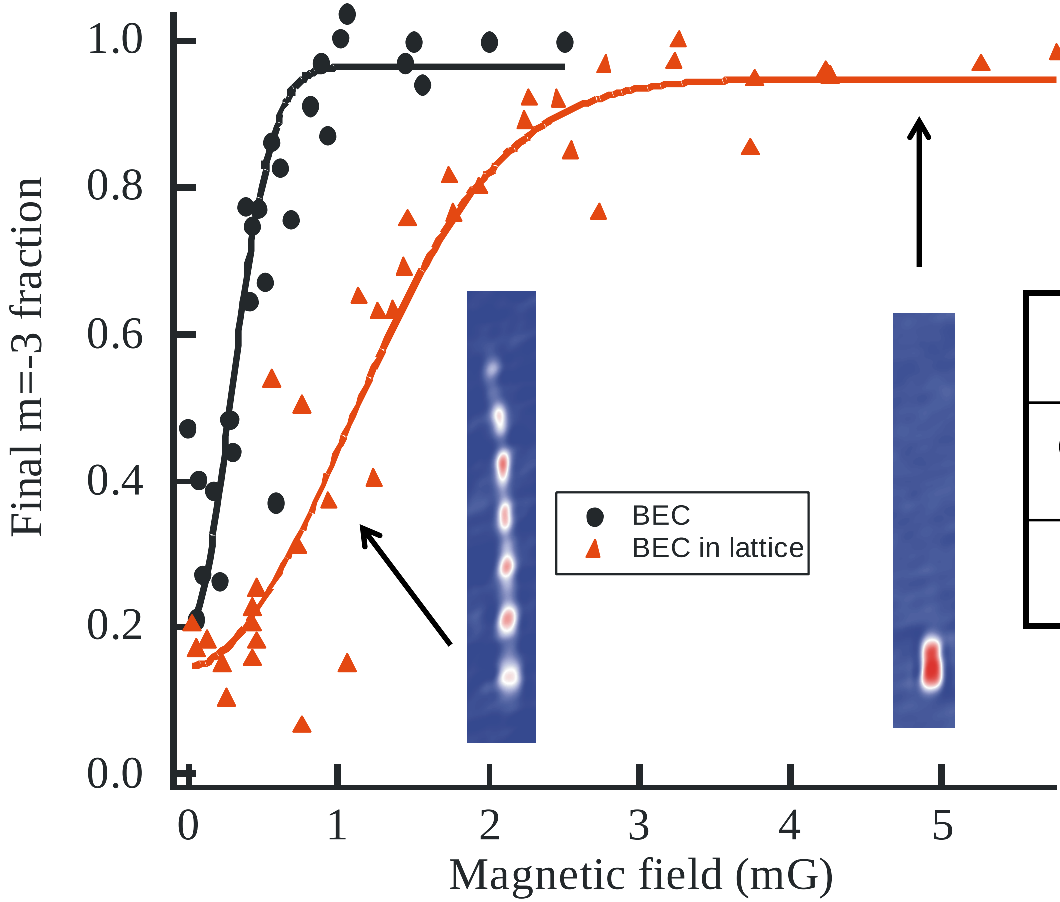


Santos PRL **96**, 190404 (2006)

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

PRL **106**, 255303 (2011)

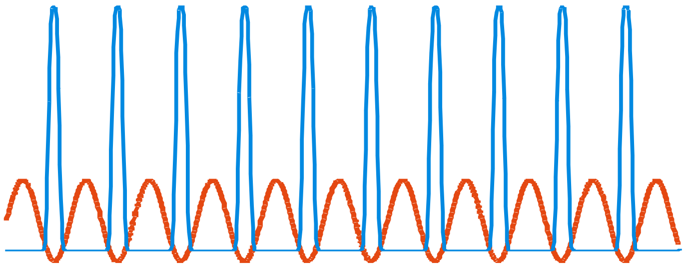
Density dependent threshold



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

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

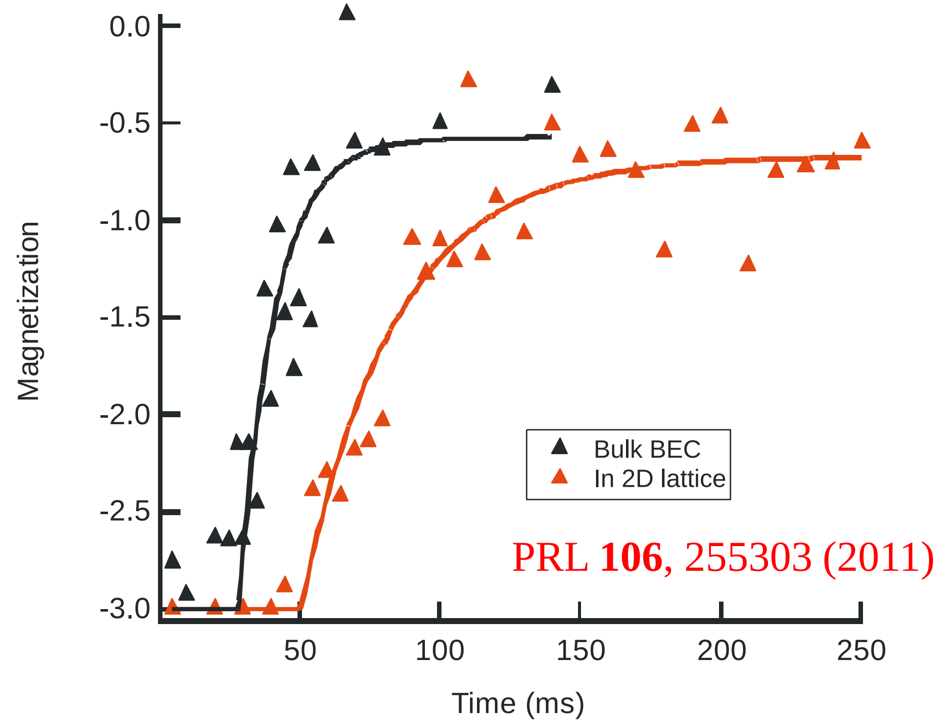
On-going discussions with
M. Brewczyk and M. Gajda



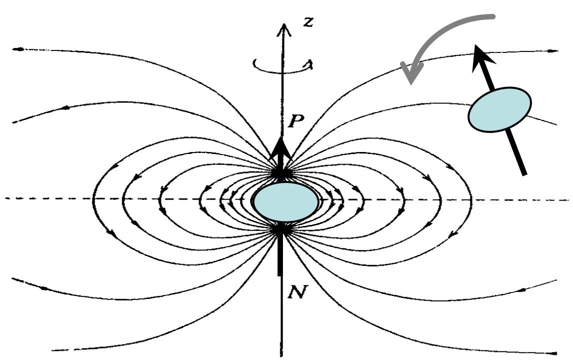
Load into deep 2D optical lattices to boost density.
Field for depolarization depends on density

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

Dynamics analysis



PRL **106**, 255303 (2011)

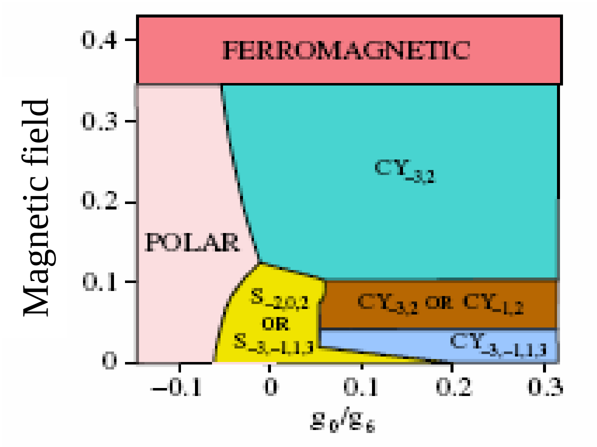


Meanfield picture :
Spin(or) precession

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

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

Open questions about equilibrium state



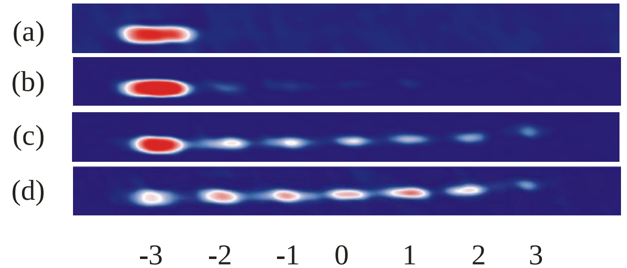
Santos and Pfau
PRL **96**, 190404 (2006)
Diener and Ho
PRL. **96**, 190405 (2006)
Demler et al.,
PRL **97**, 180412 (2006)

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

- 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 ?

Polar

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



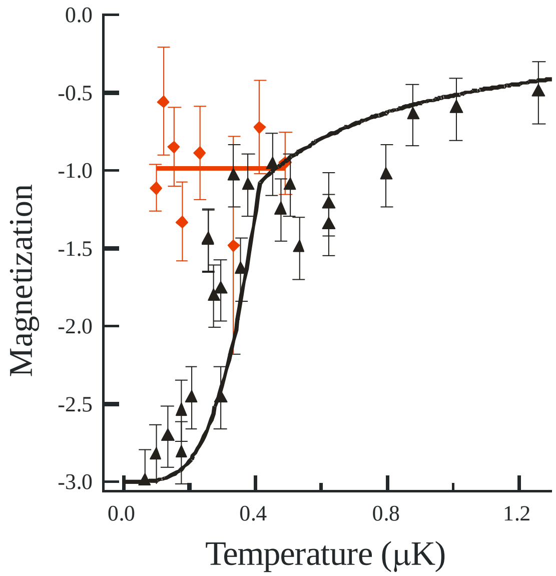
Cyclic

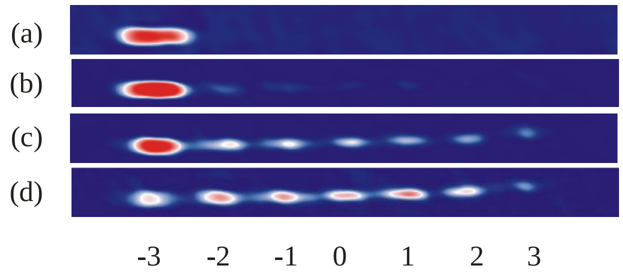
$$\frac{1}{\sqrt{2}}(1,0,0,0,0,1,0)$$

!! Depolarized BEC likely in metastable state !!

Conclusions (2)
Spinor physics with free magnetization

Spontaneous Magnetization of the cloud at BEC
New magnetism



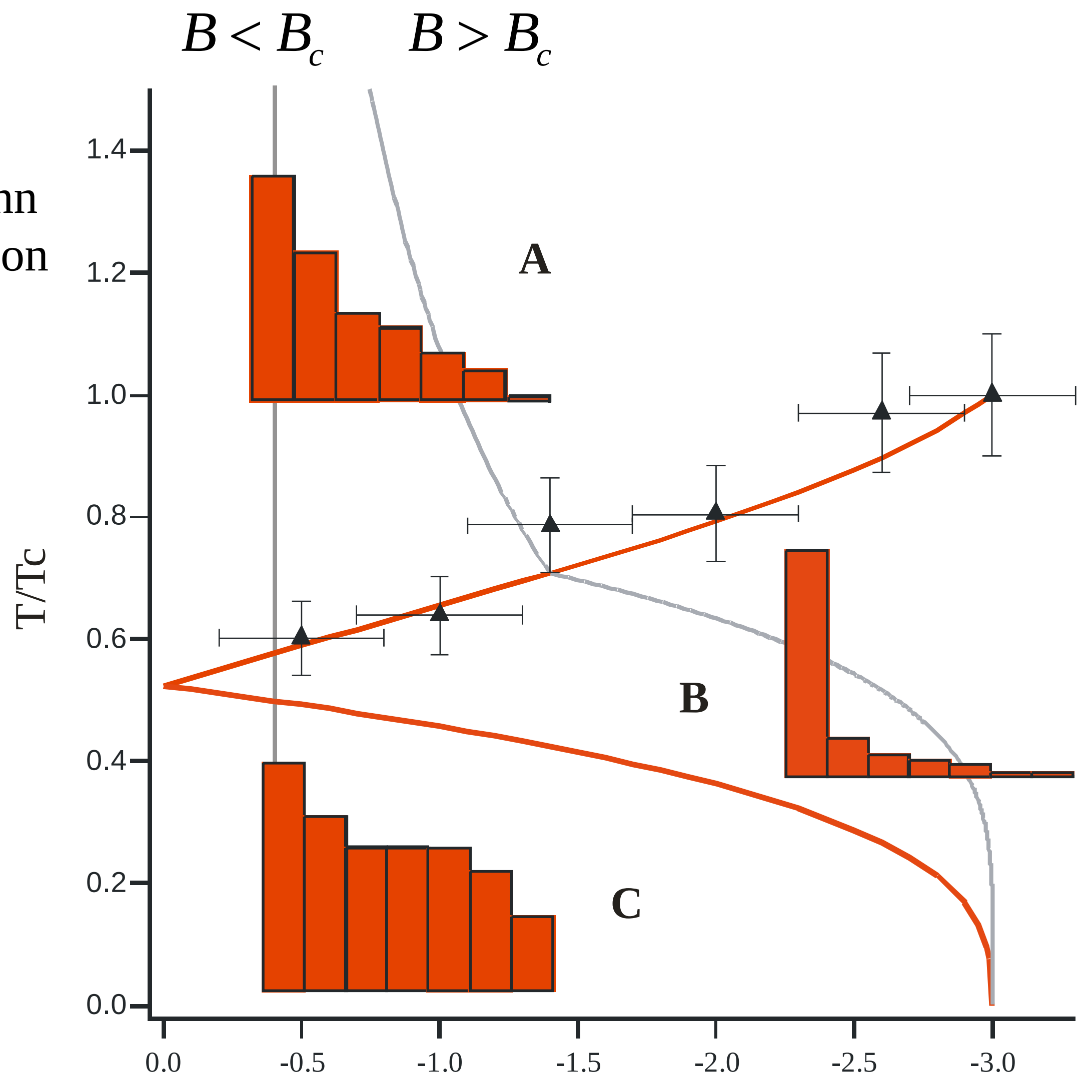


New spinor phases at extremely low magnetic fields
Interplay between magnetic field, contact interactions and dipolar interactions

Magnetism !

Phase diagram

Quasi-Boltzmann distribution



Bi-modal spin distribution

Spinor condensate

Magnetization

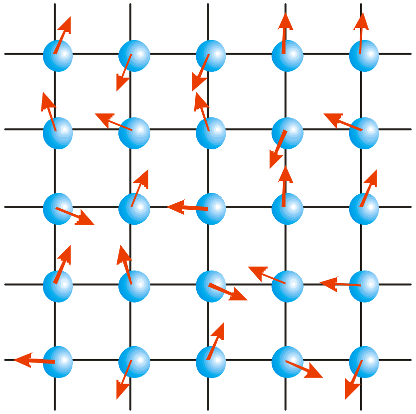
Phase diagram adapted from J. Phys. Soc. Jpn, **69,** 12, 3864 (2000)
See also PRA, **59**, 1528 (1999)

1 Spinor physics of a Bose gas with free magnetization

- *Thermodynamics: Spontaneous magnetization of the gas due to ferromagnetic nature of BEC*
- *Spontaneous depolarization of the BEC due to spin-dependent interactions*

2 Magnetism in 3D optical lattices

- *Spin and magnetization dynamics*
- *Depolarized ground state at low magnetic field*



Study quantum magnetism with dipolar gases ?

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

$$H = \frac{1}{2}\sum_{i<j} J_{ij}(\vec{S}_i.\vec{S}_j - \frac{n_i n_j}{4})$$

$$H^{zz} = \frac{1}{2}\sum_{i<j} J_{ij}(S_i^z.S_j^z)$$

$$H^{xy} = \frac{1}{2}\sum_{i<j} J_{ij}(S_i^+.S_j^- + S_i^-.S_j^+)$$

Dipole-dipole interactions between real spins

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

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

Anisotropy

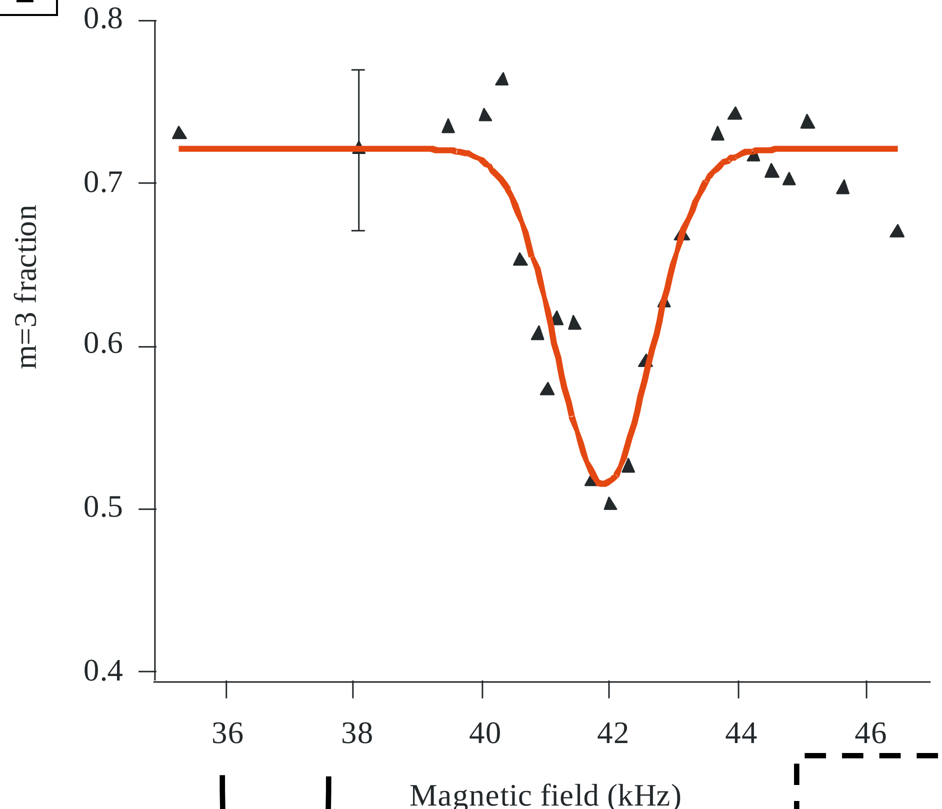
Does not rely on Mott physics

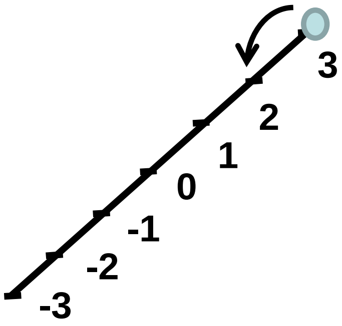
Magnetization changing collisions

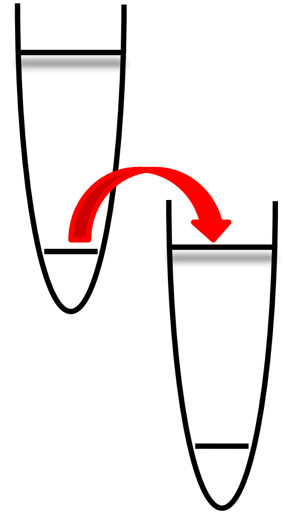
$$S_1^- S_2^-$$

$S_1^- S_2^-$

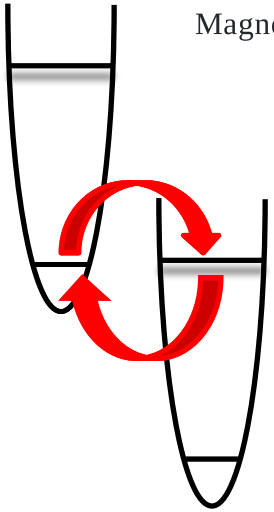
Magnetization dynamics resonance for two atoms per site (~15 mG)







Dipolar resonance when released energy matches band excitation

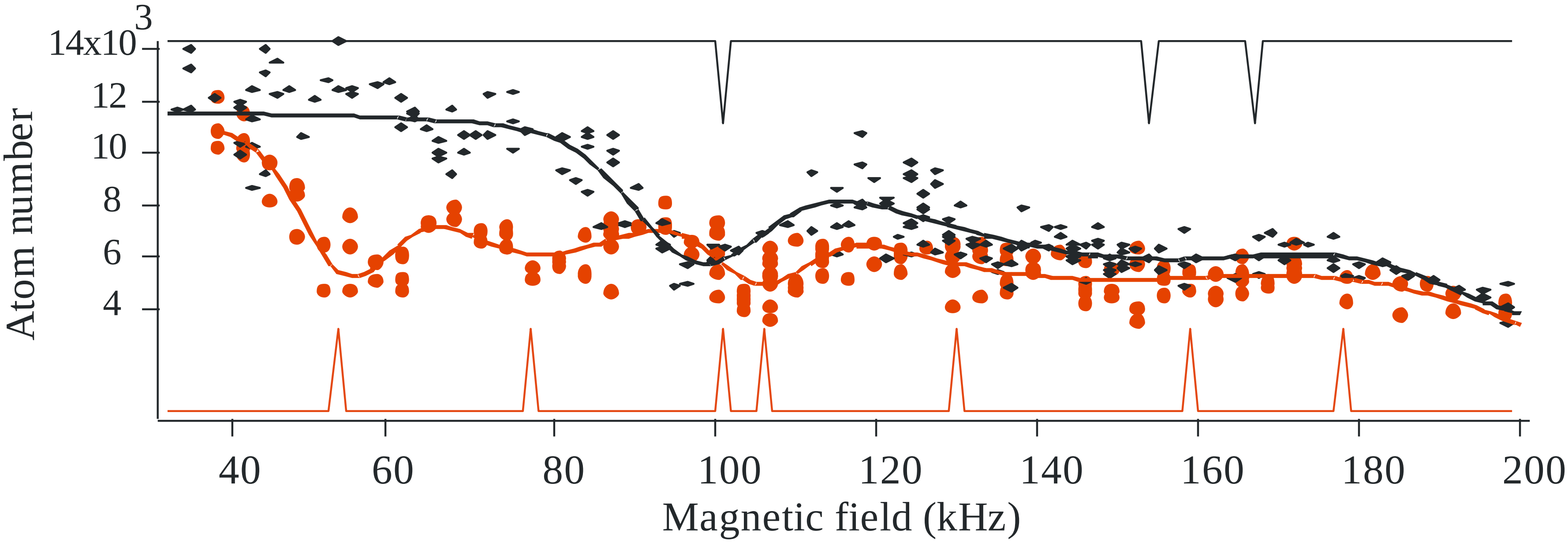


Towards coherent excitation of pairs into higher lattice orbitals ?
(Rabi oscillations)

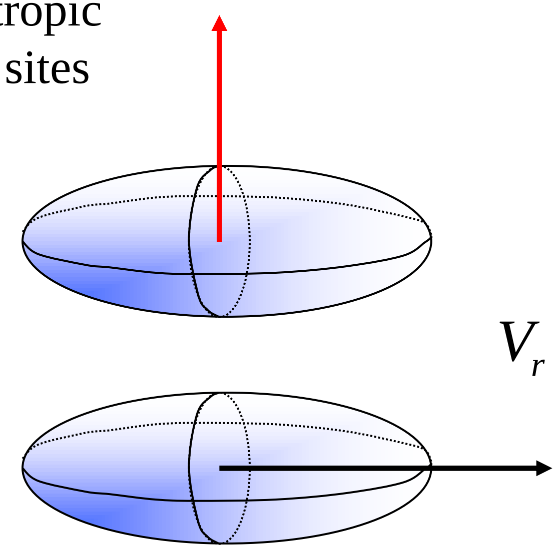
Mott state locally coupled to excited band

$S_1^- S_2^-$

Strong anisotropy of dipolar resonances



Anisotropic lattice sites



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

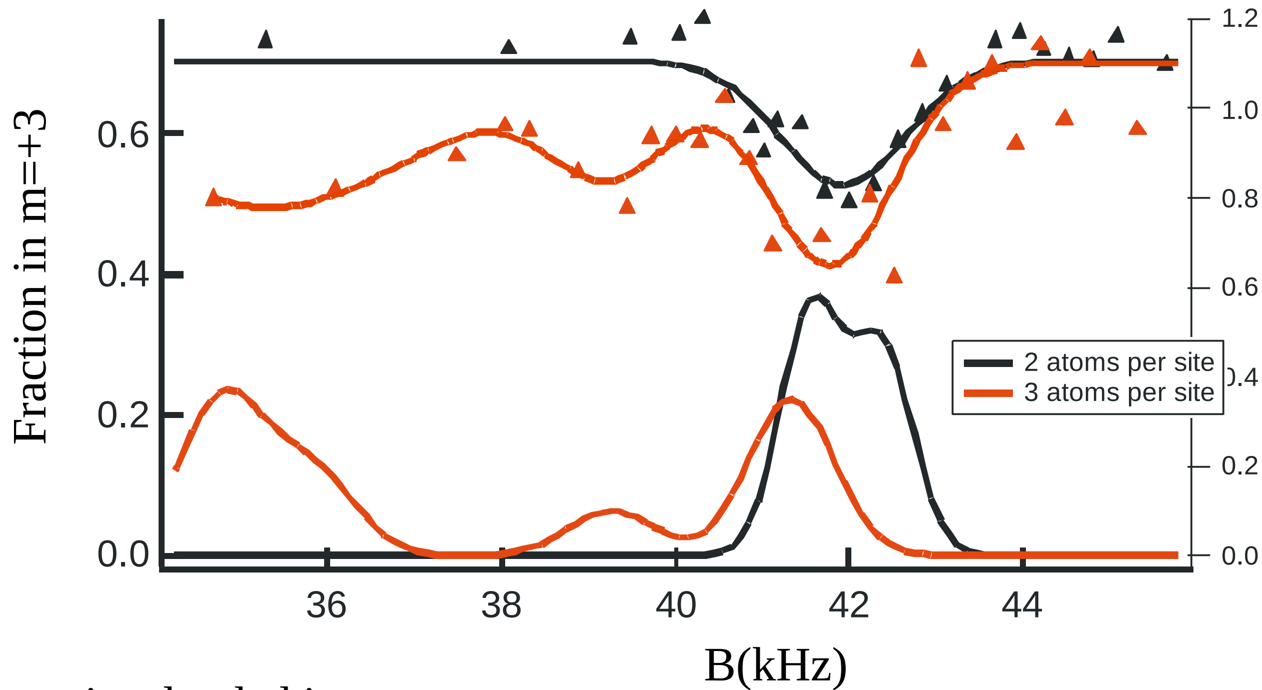
At resonance

May produce vortices in each lattice site (Einstein-de-Haas effect)
Coll. M. Gajda
(problem of tunneling)

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

$S_1^- S_2^-$

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

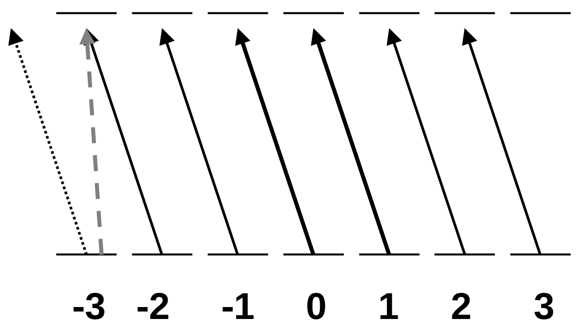
Few-body physics !

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

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

Spin dynamics at constant magnetization (<15mG)

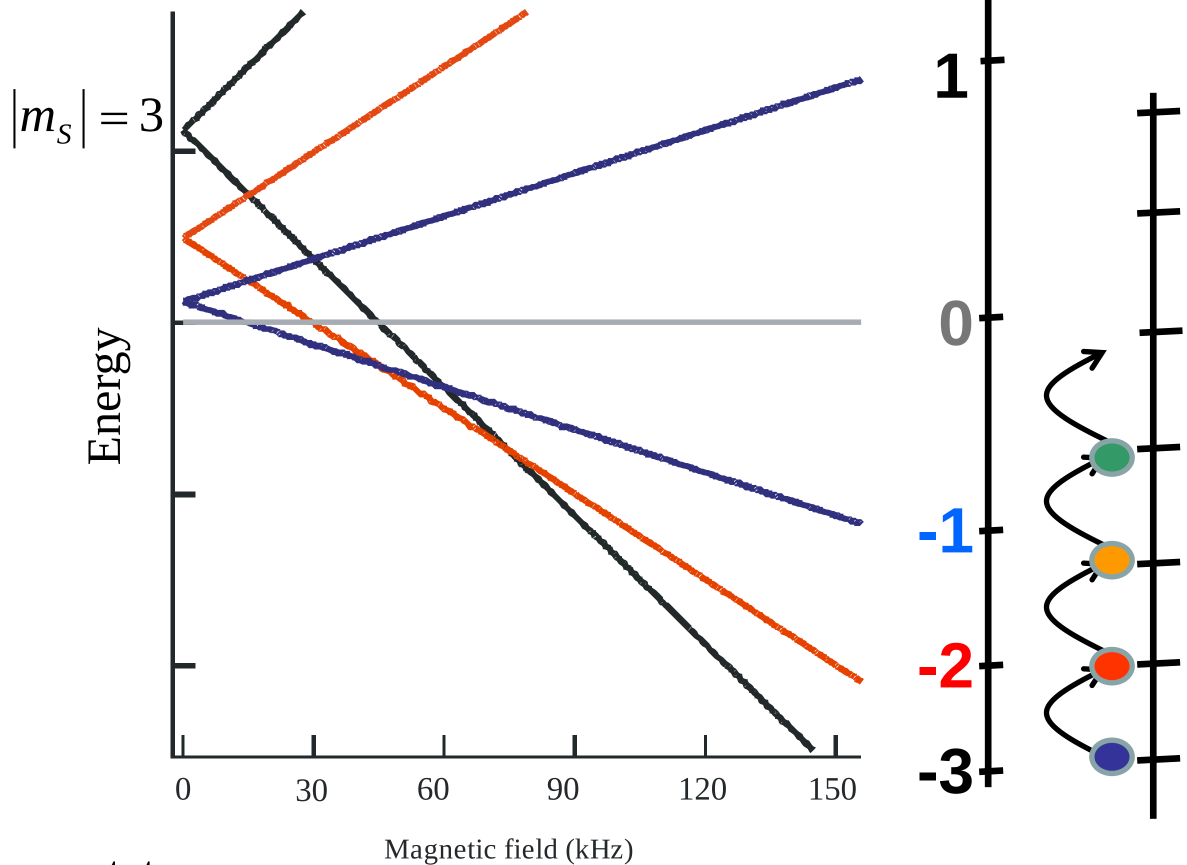
Control the initial state by a tensor light-shift



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

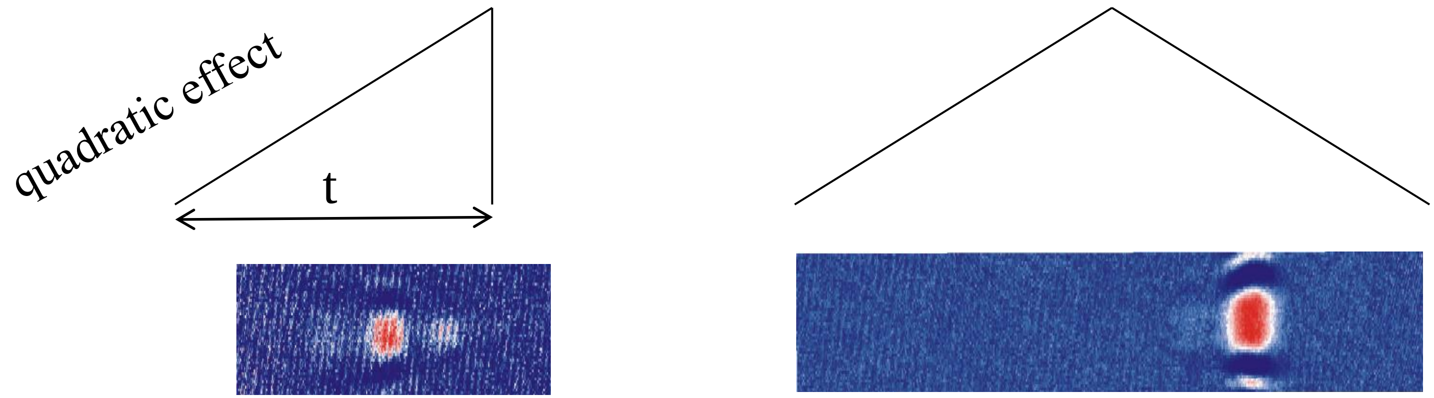
$$\Delta=\alpha\, m_S^2$$

Quadratic effect allows state preparation



In practice, a π component couples m_S states

Adiabatic state preparation in 3D lattice



-2 **-3**

(2 atomes / site)

Initiate spin dynamics by removing quadratic effect

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

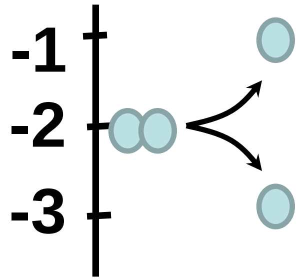
$$\sqrt{\frac{6}{11}}\left|S=6,m_{tot}=-4\right\rangle-\sqrt{\frac{5}{11}}\left|S=4,m_{tot}=-4\right\rangle$$

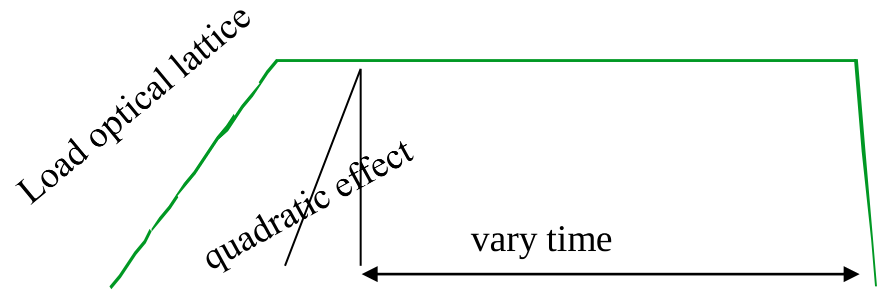
$$\left|-2,-2\right\rangle\leftrightarrow\frac{1}{\sqrt{2}}\left(\left|-3,-1\right\rangle+\left|-1,-3\right\rangle\right)$$

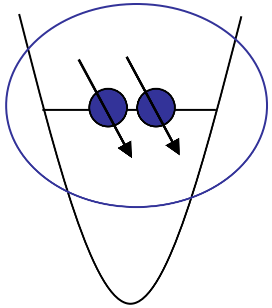
$$\Gamma=\frac{4\pi\hbar^2}{m}n\left(a_6-a_4\right)$$

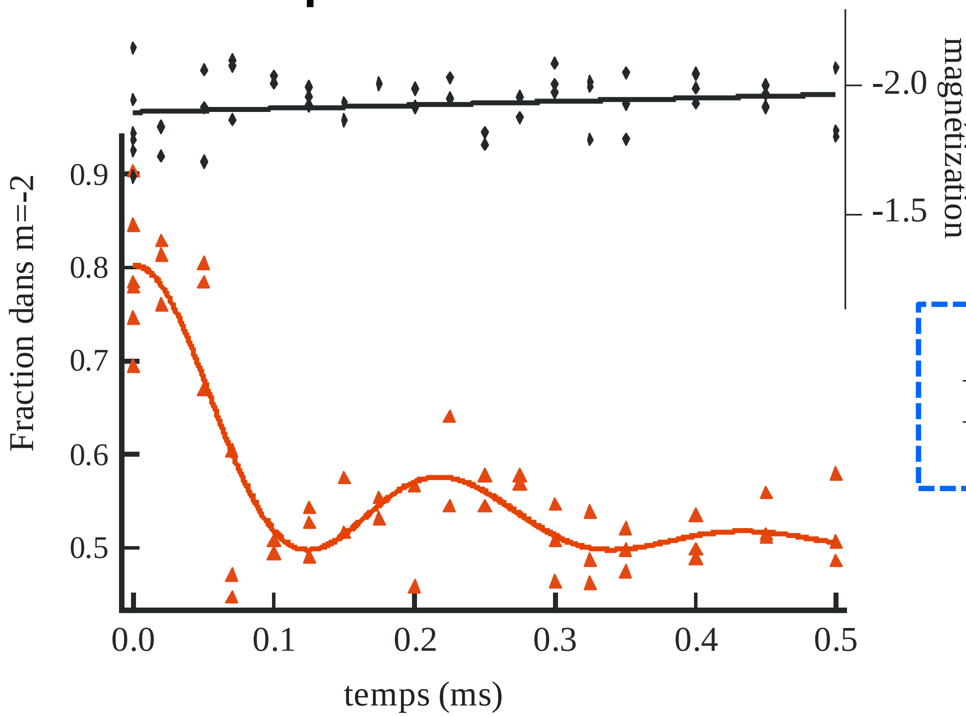
On-site spin oscillations

(due to contact oscillations)









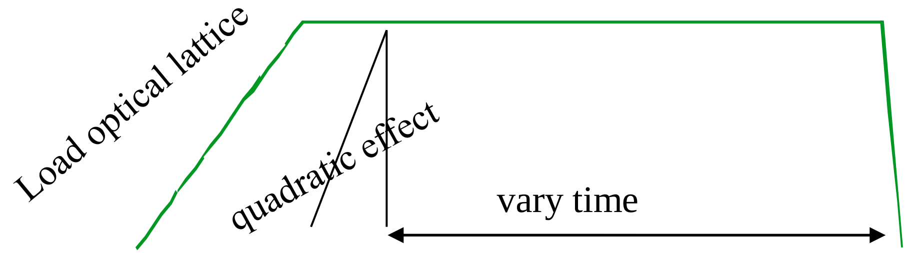
$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

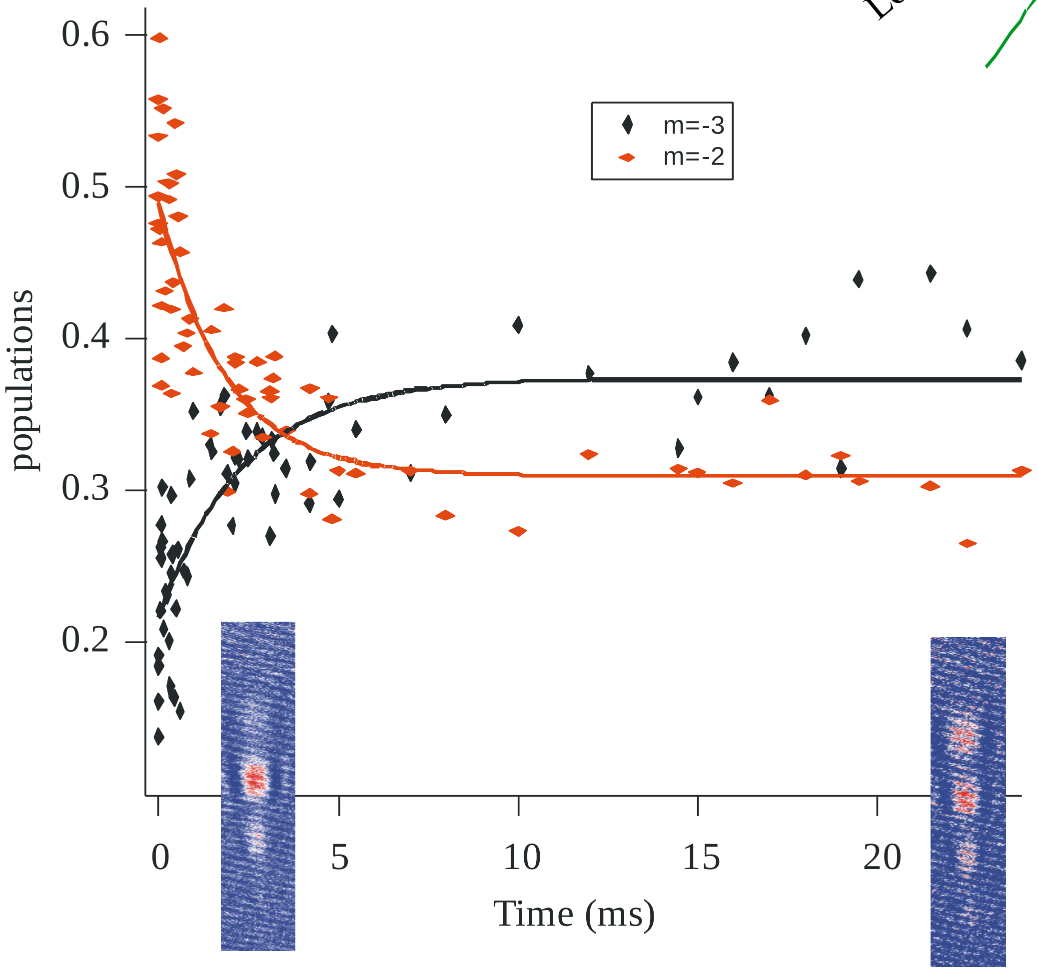
(perdiod ↔ 220 µs)

(↔ 250 µs)

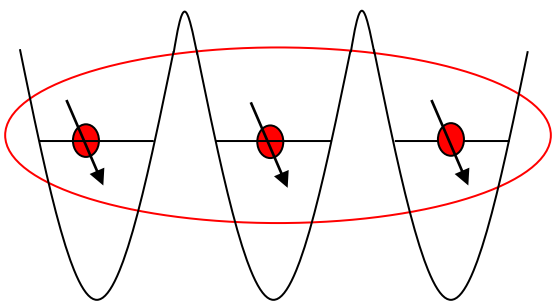
Up to now unknown source of damping

Long time-scale spin dynamics in lattice



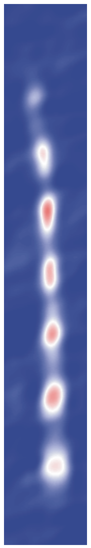


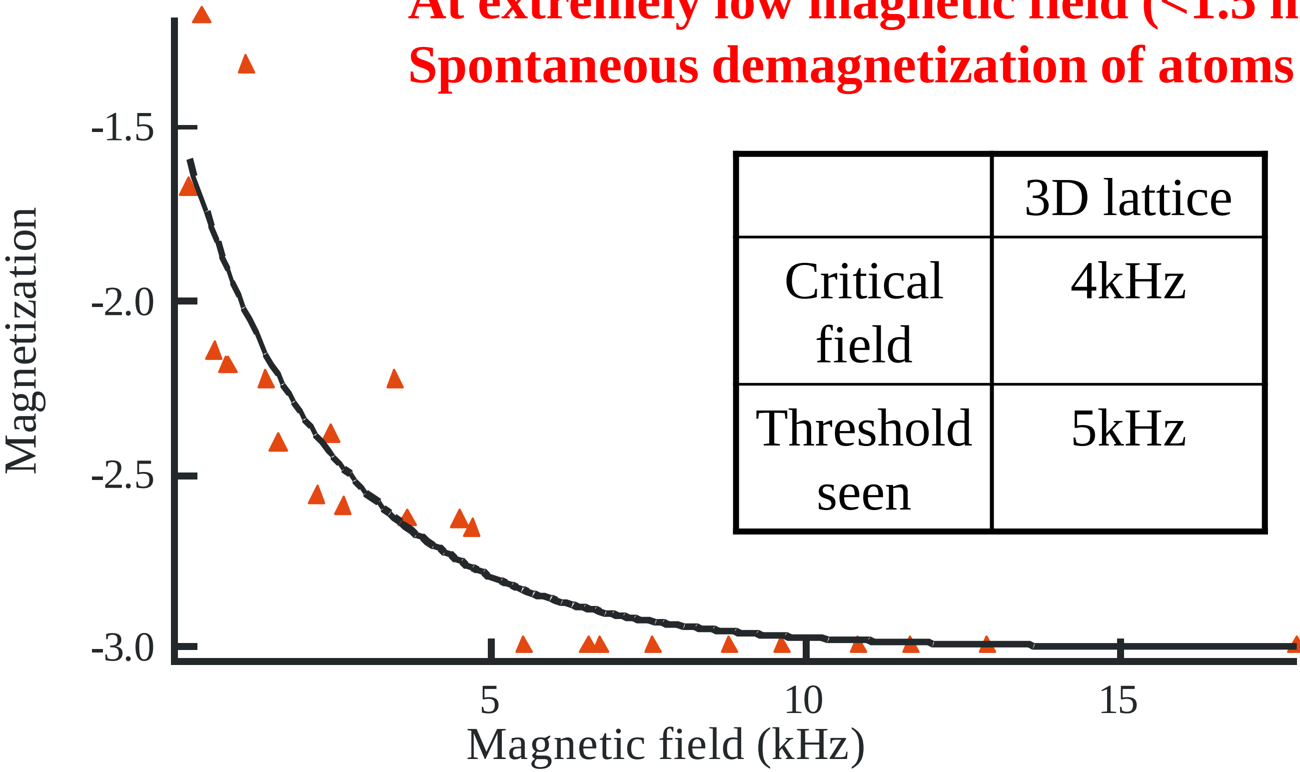
Sign for intersite dipolar interaction ?
(two orders of magnitude slower than on-site dynamics)



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

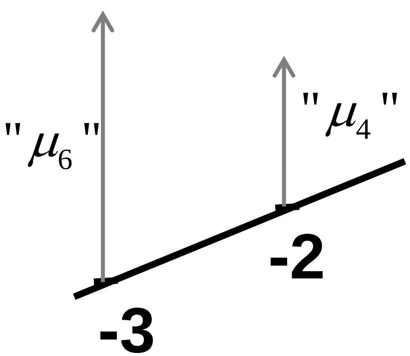
At extremely low magnetic field (<1.5 mG):
Spontaneous demagnetization of atoms in a 3D lattice



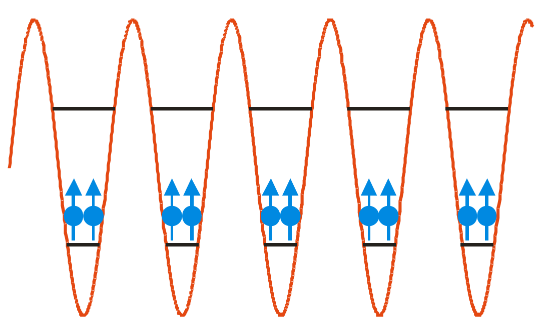


	3D lattice
Critical field	4kHz
Threshold seen	5kHz

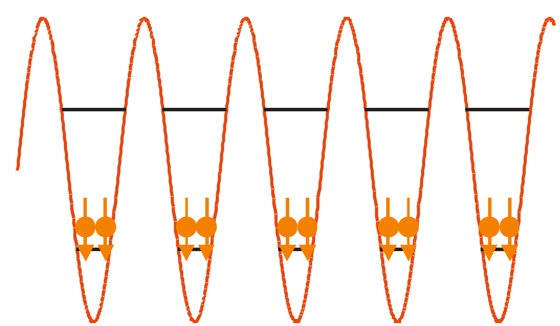
$$g_J \mu_B B_c \approx \frac{4\pi\hbar^2 n_0 \left(a_6 - a_4\right)}{m}$$



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

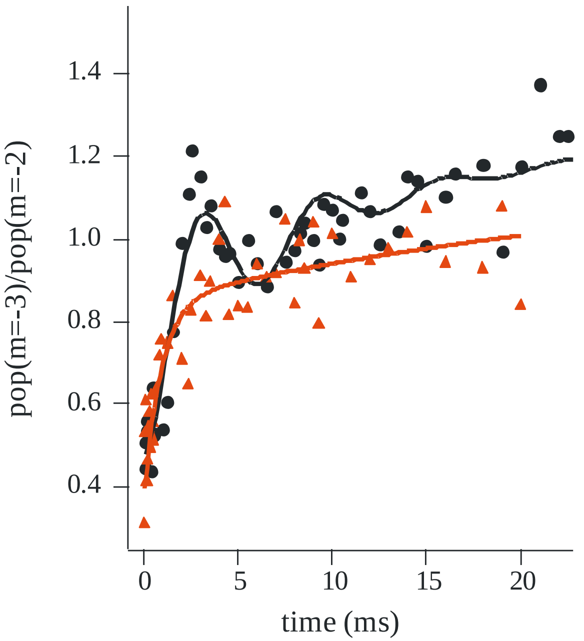


$\left| S = 4, m = -4 \right\rangle$

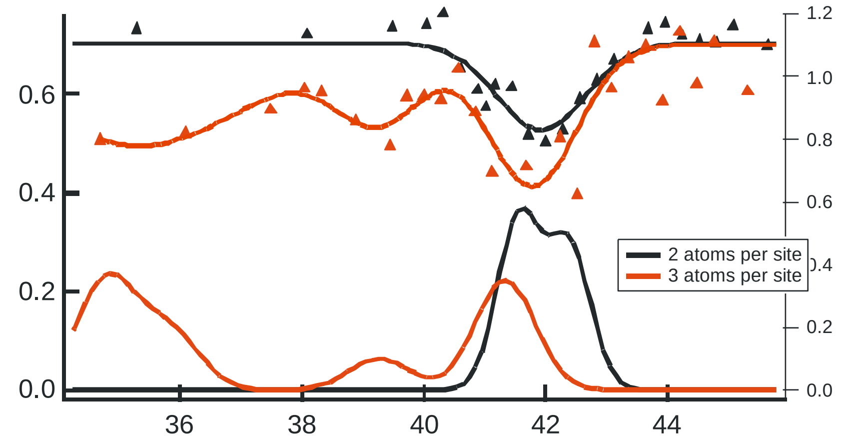


Conclusions (3) Magnetism in optical lattices

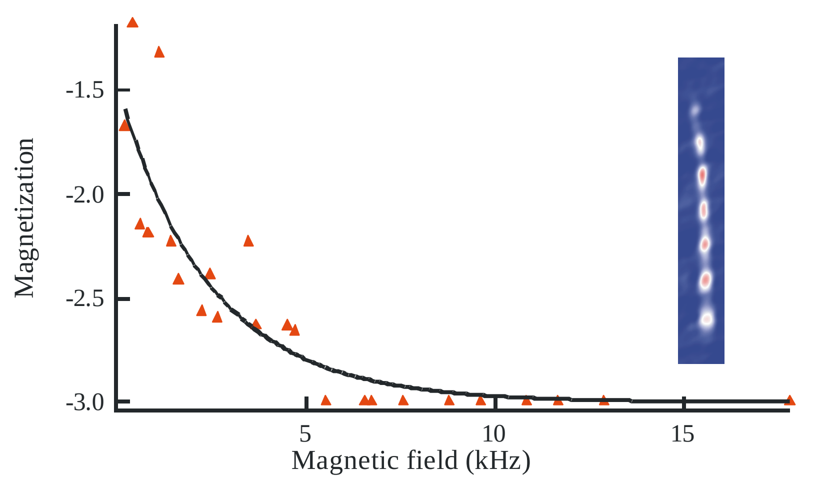
Resonant magnetization dynamics
Towards Einstein-de-Haas effect
Anisotropy
Few body vs many-body physics



Spontaneous depolarization at low magnetic field
Towards low-field phase diagram



Away from resonances: spin oscillations at constant magnetization
Spin-exchange
Dipolar exchange



Dipolar BECs:

A non-standard superfluid
Anisotropic properties

Spinor Dipolar BECs:

Study magnetism
New spinor phases

Spins in lattices

Study quantum magnetism
Spin dynamics

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