Dipolar chromium BECs, and magnetism

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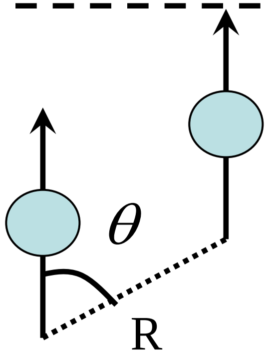
Chromium (S=3): Van-der-Waals plus dipole-dipole interactions

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



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

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

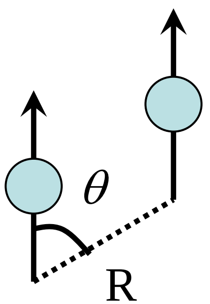
Cr: $\varepsilon_{dd} = 0.16$

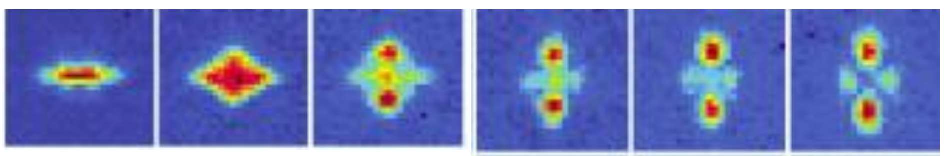
Relative strength of dipole-dipole and Van-der-Waals interactions

$\varepsilon_{dd} > 1$ 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.

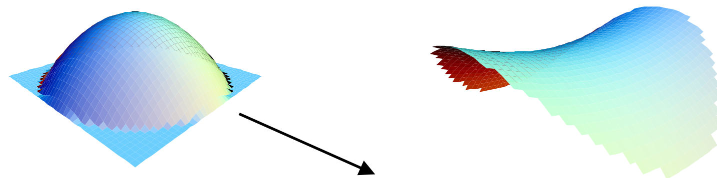
Stuttgart: d-wave collapse, PRL **101**, 080401 (2008)
See also Er PRL, 108, 210401 (2012)
See also Dy, PRL, 107, 190401 (2012)
… and Dy Fermi sea PRL, 108, 215301 (2012) … and heteronuclear molecules…

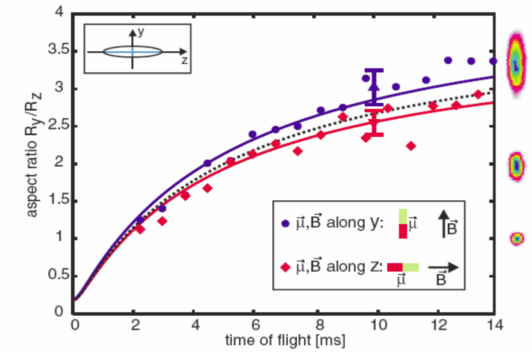
$\varepsilon_{dd} < 1$ BEC stable despite attractive part of dipole-dipole interactions

Cr: $\varepsilon_{dd} = 0.16$

Hydrodynamic properties of a BEC with weak dipole-dipole interactions

Striction

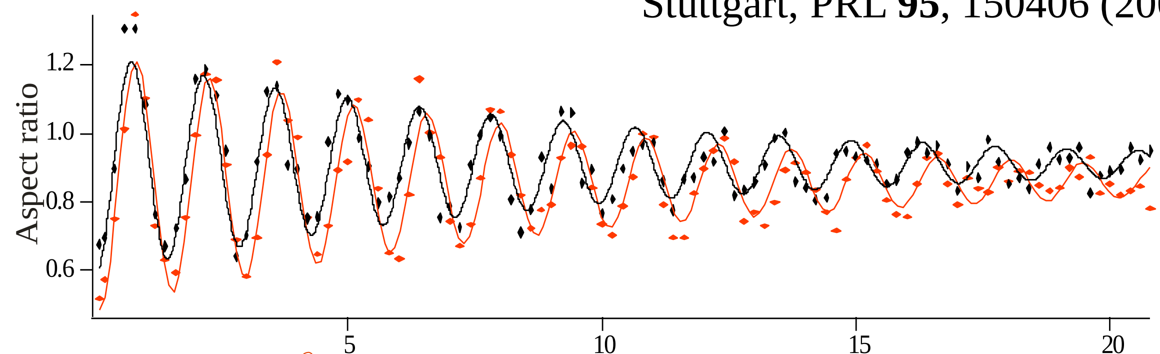




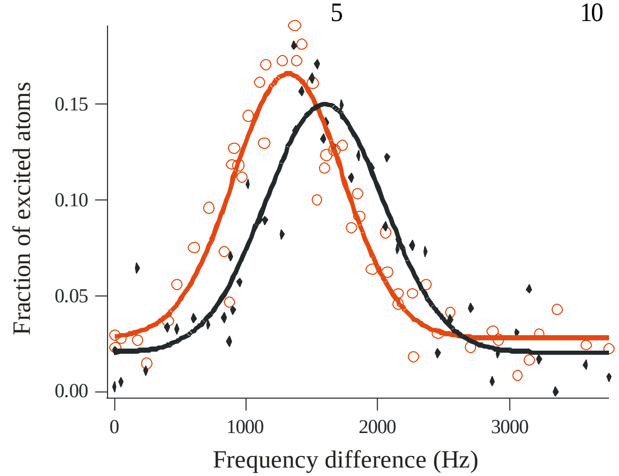
Stuttgart, PRL **95**, 150406 (2005)

Collective excitations

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



Anisotropic speed of sound



Bragg spectroscopy
Villetaneuse
arXiv: 1205.6305 (2012)

Interesting but weak effects in a scalar Cr BEC

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

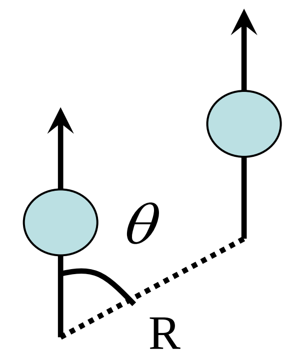
Multicomponent (« spinor ») BEC
Magnetism
Phases, spin textures…

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

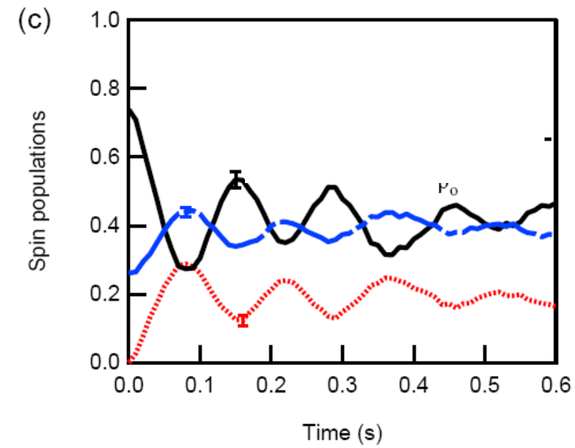


Hydrodynamics:
non-local mean-field

Magnetism:
Atoms *are* magnets

Introduction to spinor physics

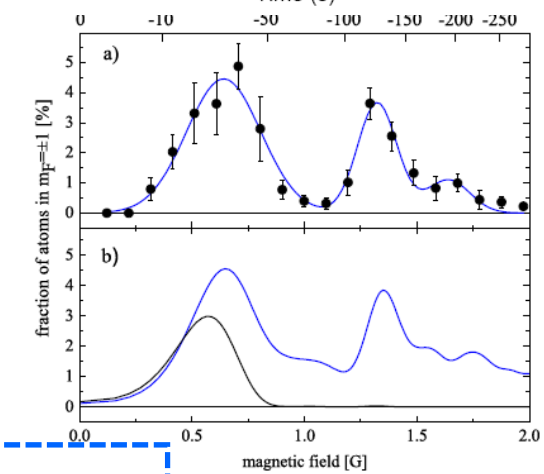
Exchange energy
Coherent spin oscillation



Chapman, Sengstock…

Quantum effects!

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

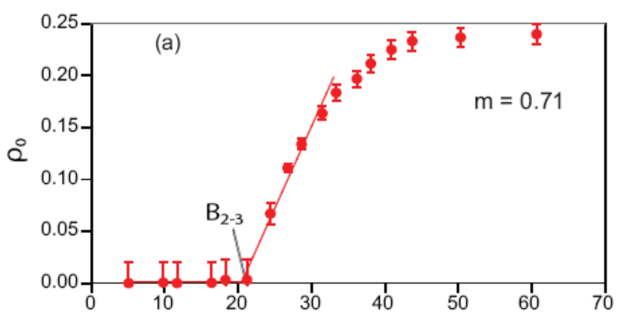


Klempt Stamper-Kurn

Domains, spin textures, spin waves, topological states

Stamper-Kurn, Chapman, Sengstock, Shin…

Quantum phase transitions



Stamper-Kurn, Lett

Main ingredients for spinor physics

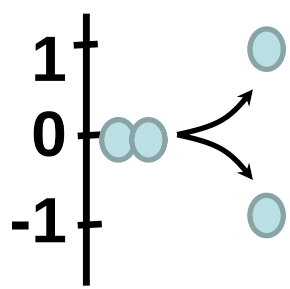
S=1,2,…

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

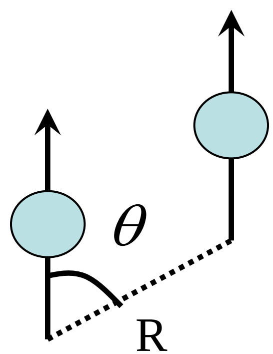
And

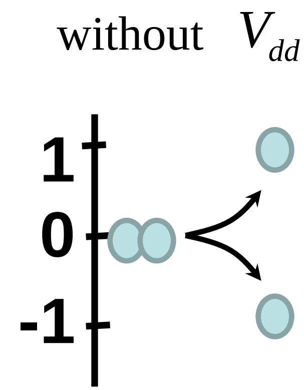
Dipole-dipole interactions

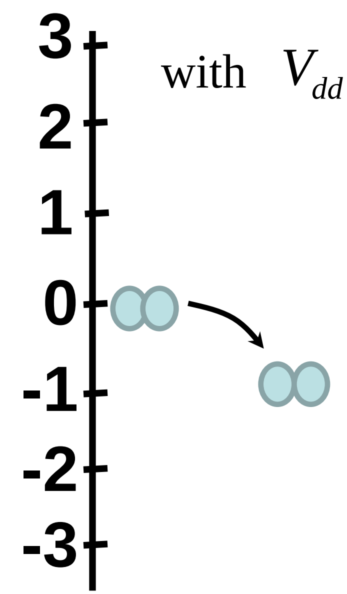
Dipolar interactions introduce magnetization-changing collisions

Dipole-dipole interactions

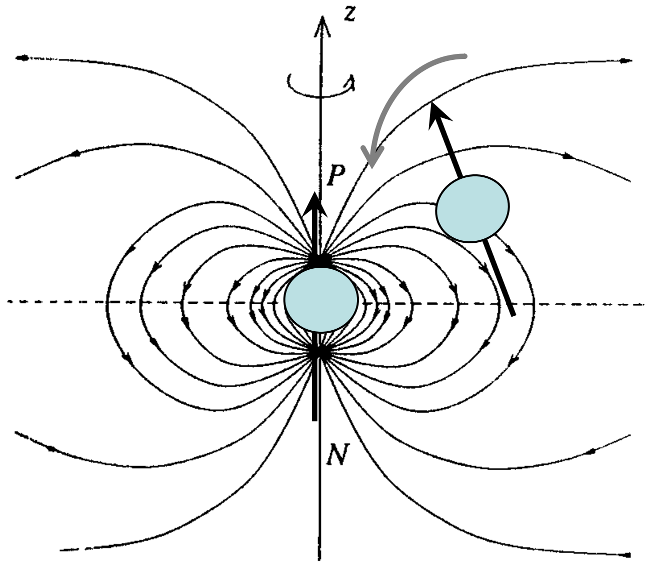
$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \left(1 - 3\cos^2(\theta)\right) \frac{1}{R^3}$$

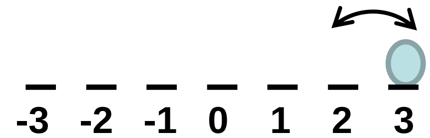






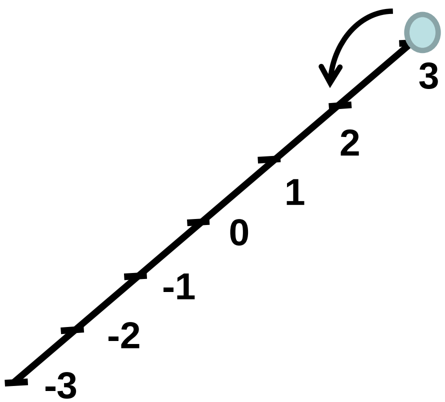
B=0: Rabi





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

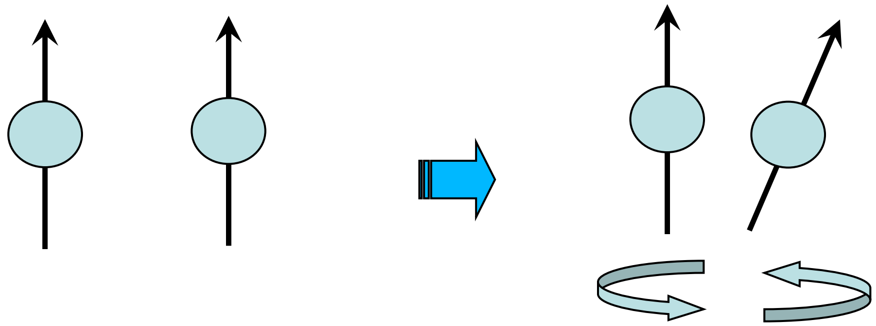
In a finite magnetic field: Fermi golden rule (losses)



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

(x1000 compared to alkalis)

Dipolar relaxation, rotation, and magnetic field



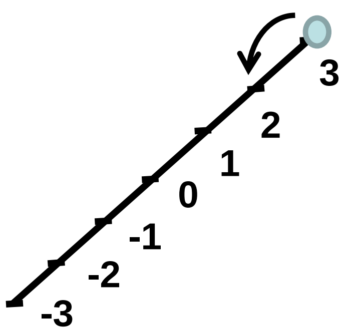
Angular momentum conservation

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

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

$$\Delta \ell = 2$$

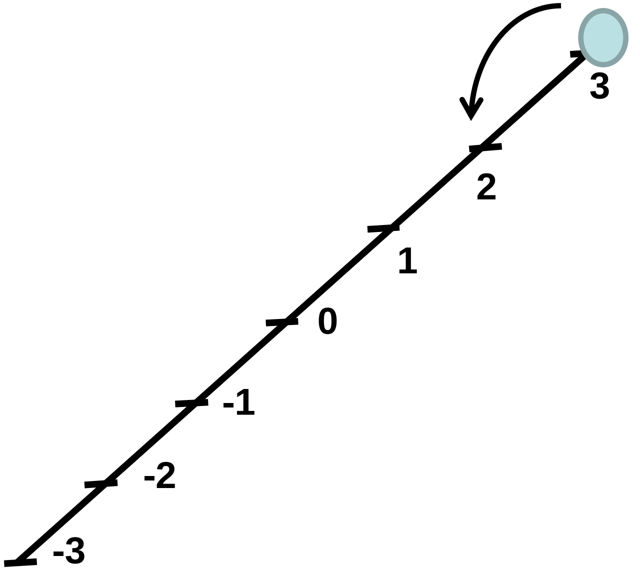
$$\Delta E = \Delta m_S g \mu_B B$$



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

Alkalis :

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

$\rightarrow$ 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
- Constant magnetization
(exchange interactions)
→ Linear Zeeman effect irrelevant

New features with Cr:

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- No hyperfine structure
- Free magnetization

Magnetic field matters !

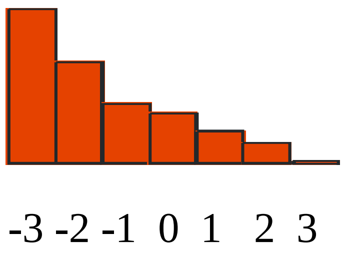
1 Spinor physics of a Bose gas with free magnetization

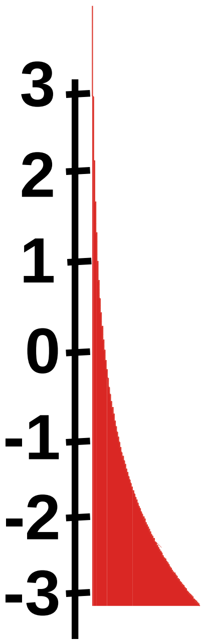
2 (Quantum) magnetism in opical lattices

Spin temperature equilibriates with mechanical degrees of freedom

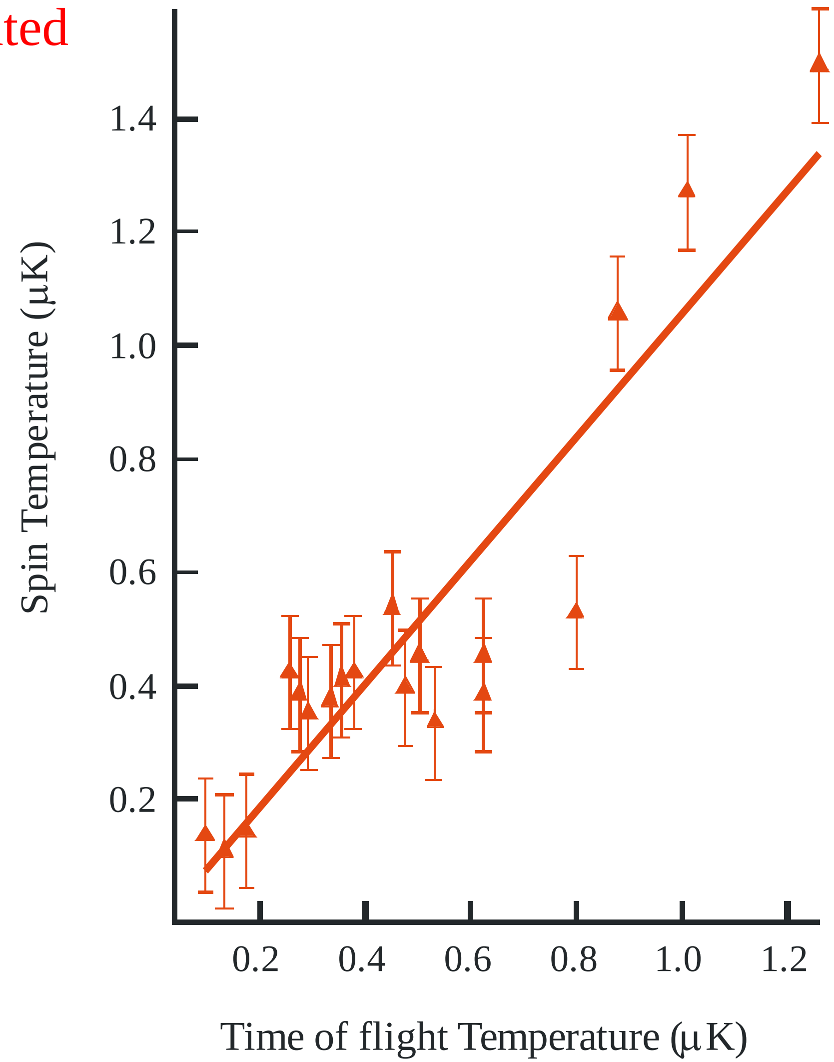
At low magnetic field: spin thermally activated

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



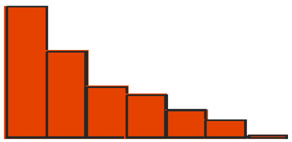


We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)

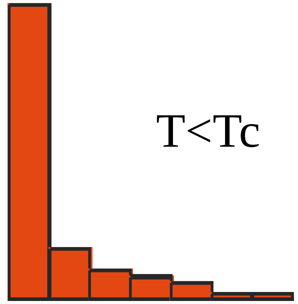


Related to Demagnetization Cooling expts, Pfau, *Nature Physics* **2**, *765 (2006)*

Spontaneous magnetization due to BEC

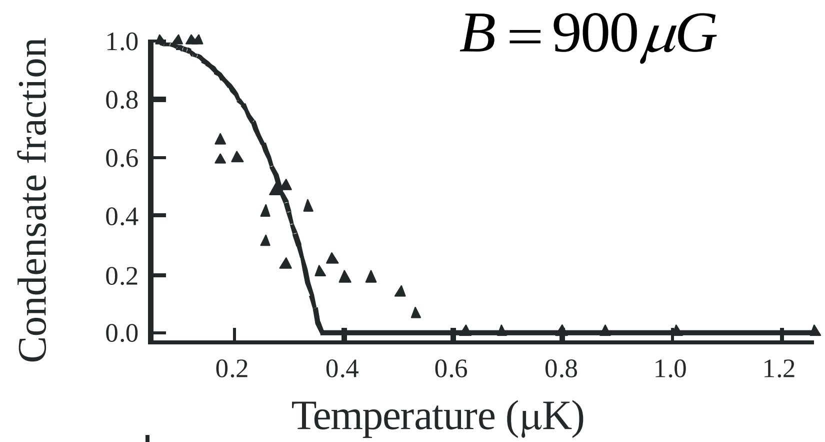


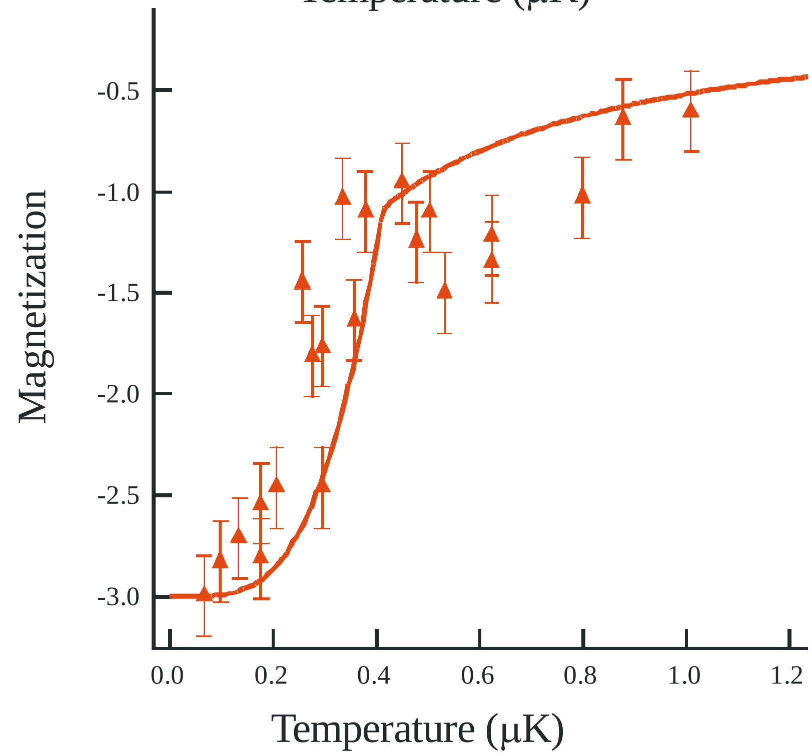
Thermal population in Zeeman excited states



a bi-modal spin distribution

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





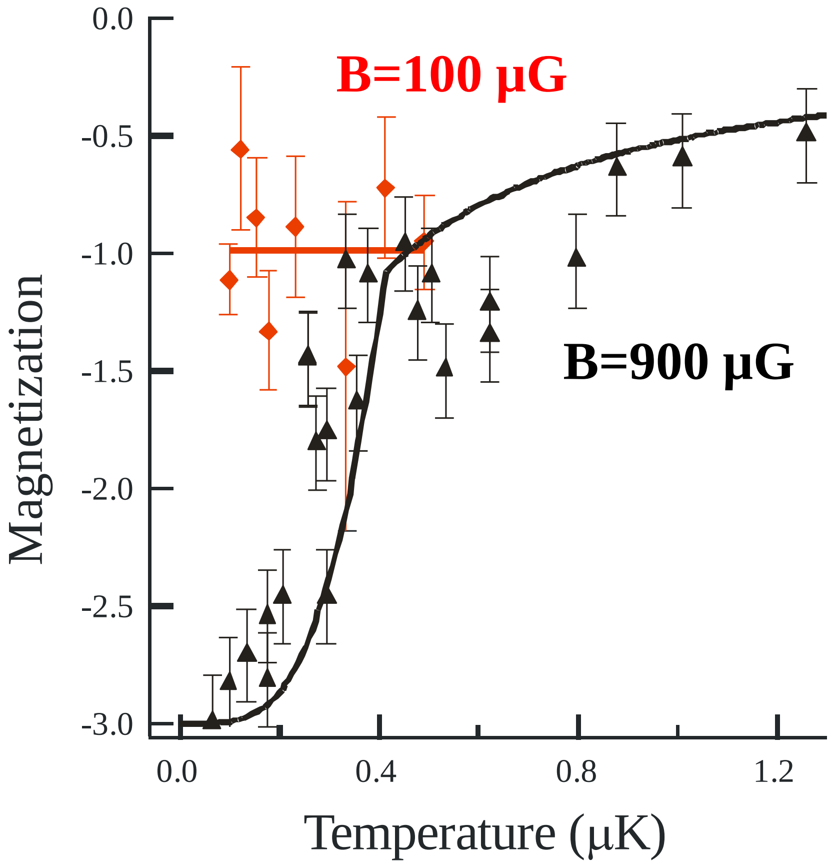
Cloud spontaneously polarizes !

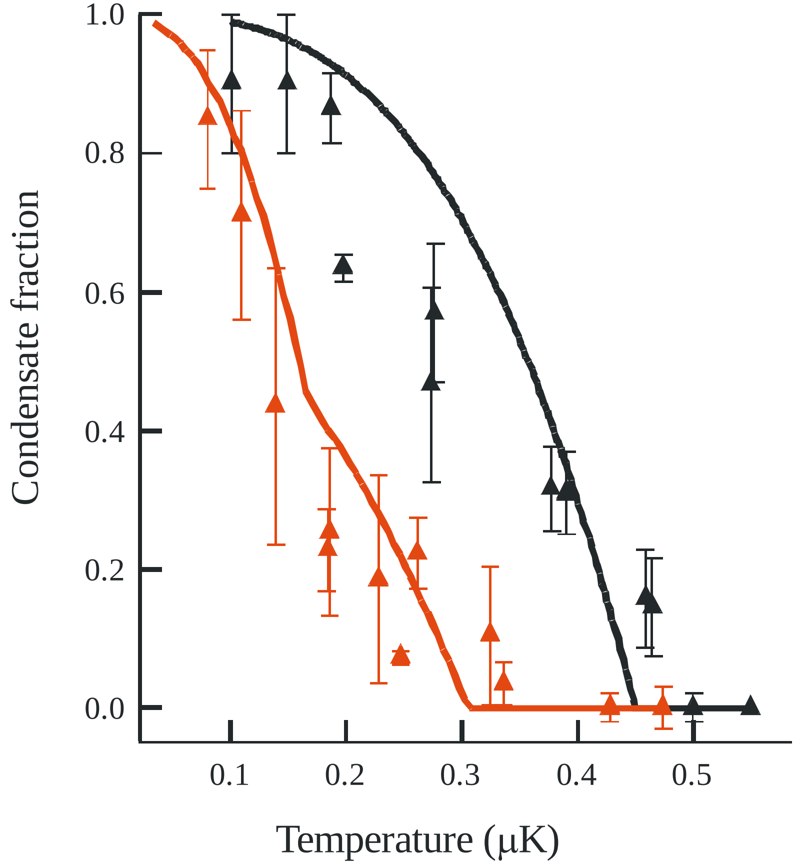
A non-interacting BEC is ferromagnetic

New magnetism, differs from solid-state

PRL **108**, 045307 (2012)

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





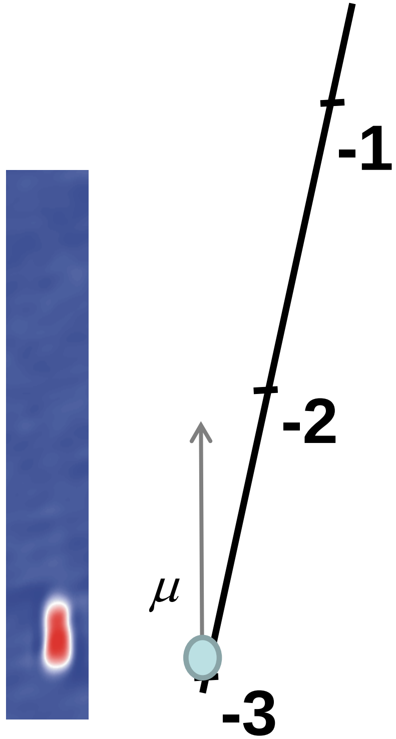
-Magnetization remains small even when the condensate fraction approaches 1

!! Observation of a depolarized condensate !!

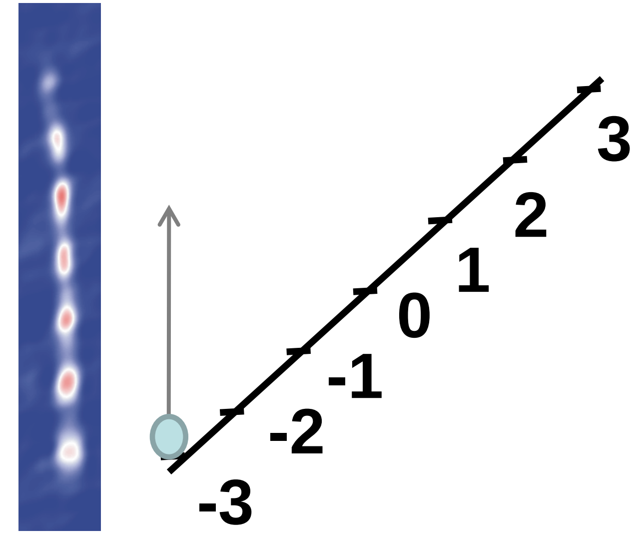
Necessarily an interaction effect

PRL **108**, 045307 (2012)

Cr spinor properties at low field

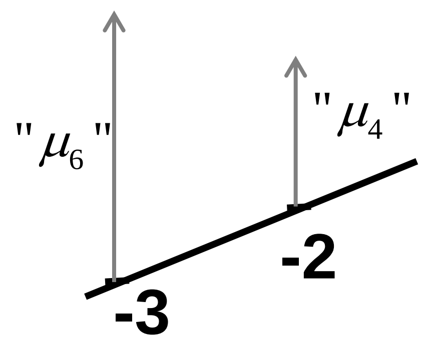


Large magnetic field : ferromagnetic



Low magnetic field : polar/cyclic

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

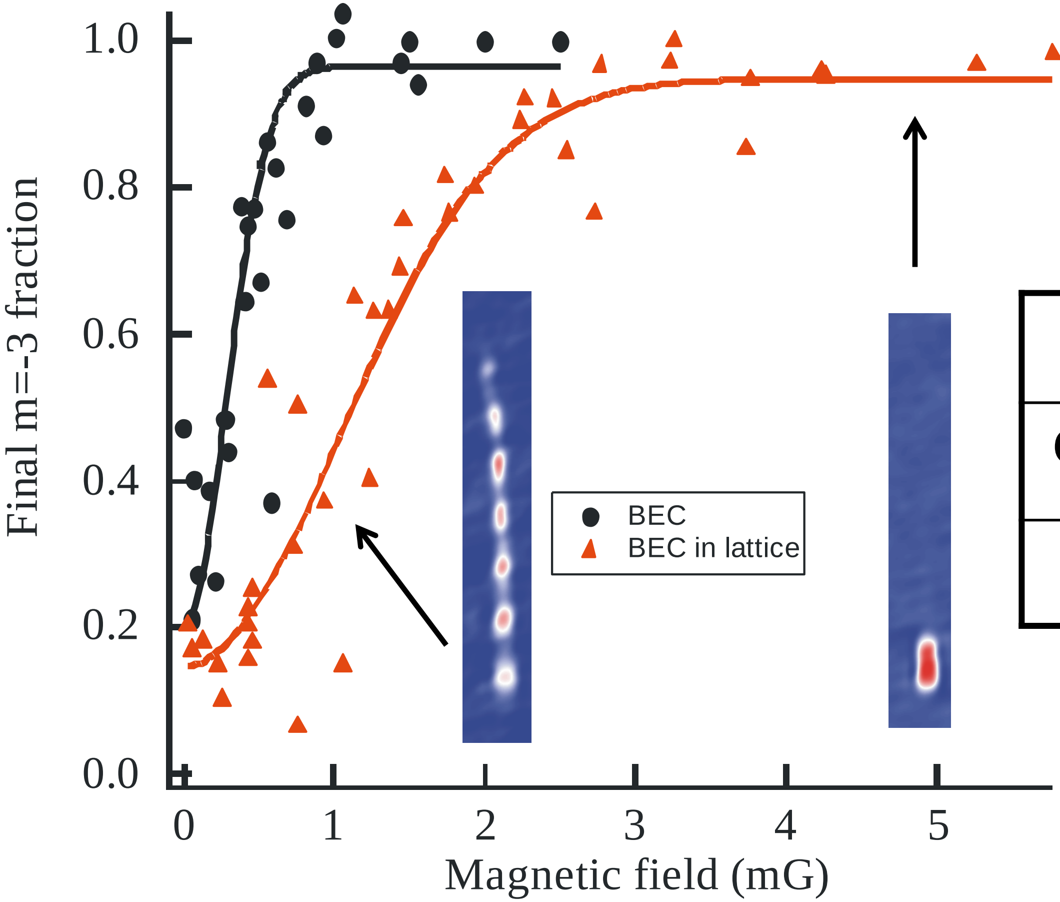


Santos PRL **96**, 190404 (2006)

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

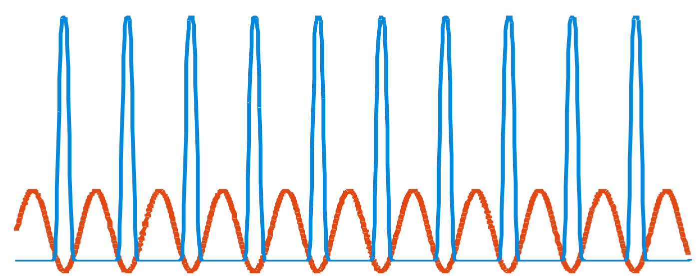
PRL **106**, 255303 (2011)

Density dependent threshold



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

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

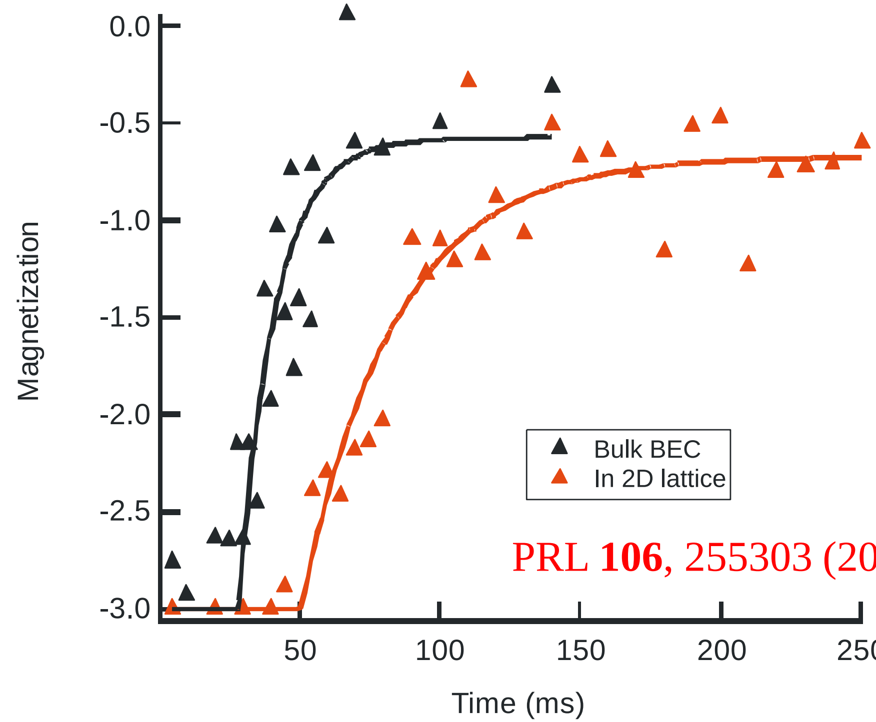


Load into deep 2D optical lattices to boost density.
Field for depolarization depends on density

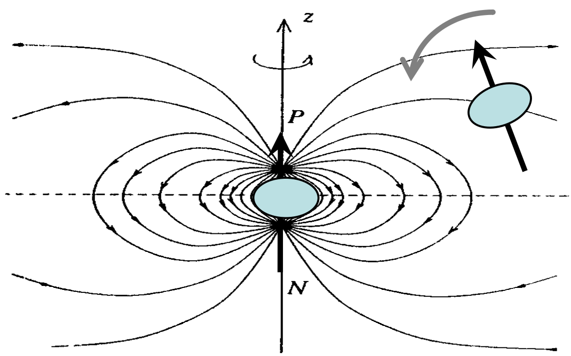
Note: Possible new physics in 1D: Polar phase is a singlet-paired phase Shlyapnikov-Tsvelik NJP, 13, 065012 (2011)

Dynamics analysis

Rapidly lower magnetic field



PRL **106**, 255303 (2011)



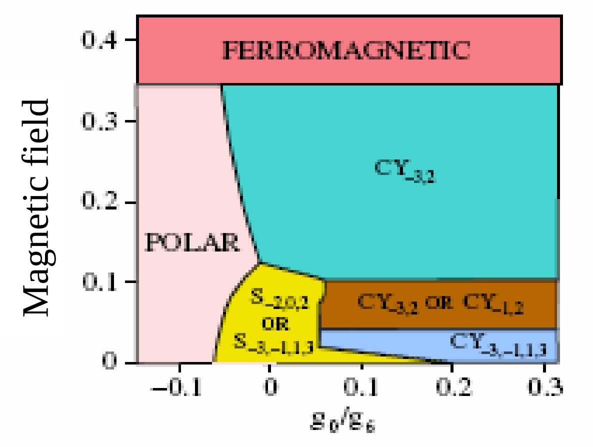
Meanfield picture :
Spin(or) precession

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

Natural timescale for depolarization:

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

Open questions about equilibrium state



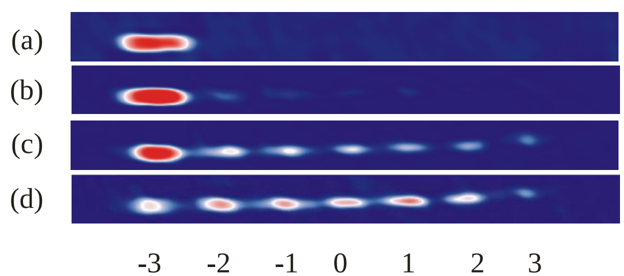
Santos and Pfau
PRL **96**, 190404 (2006)
Diener and Ho
PRL. **96**, 190405 (2006)
Demler et al.,
PRL **97**, 180412 (2006)

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

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



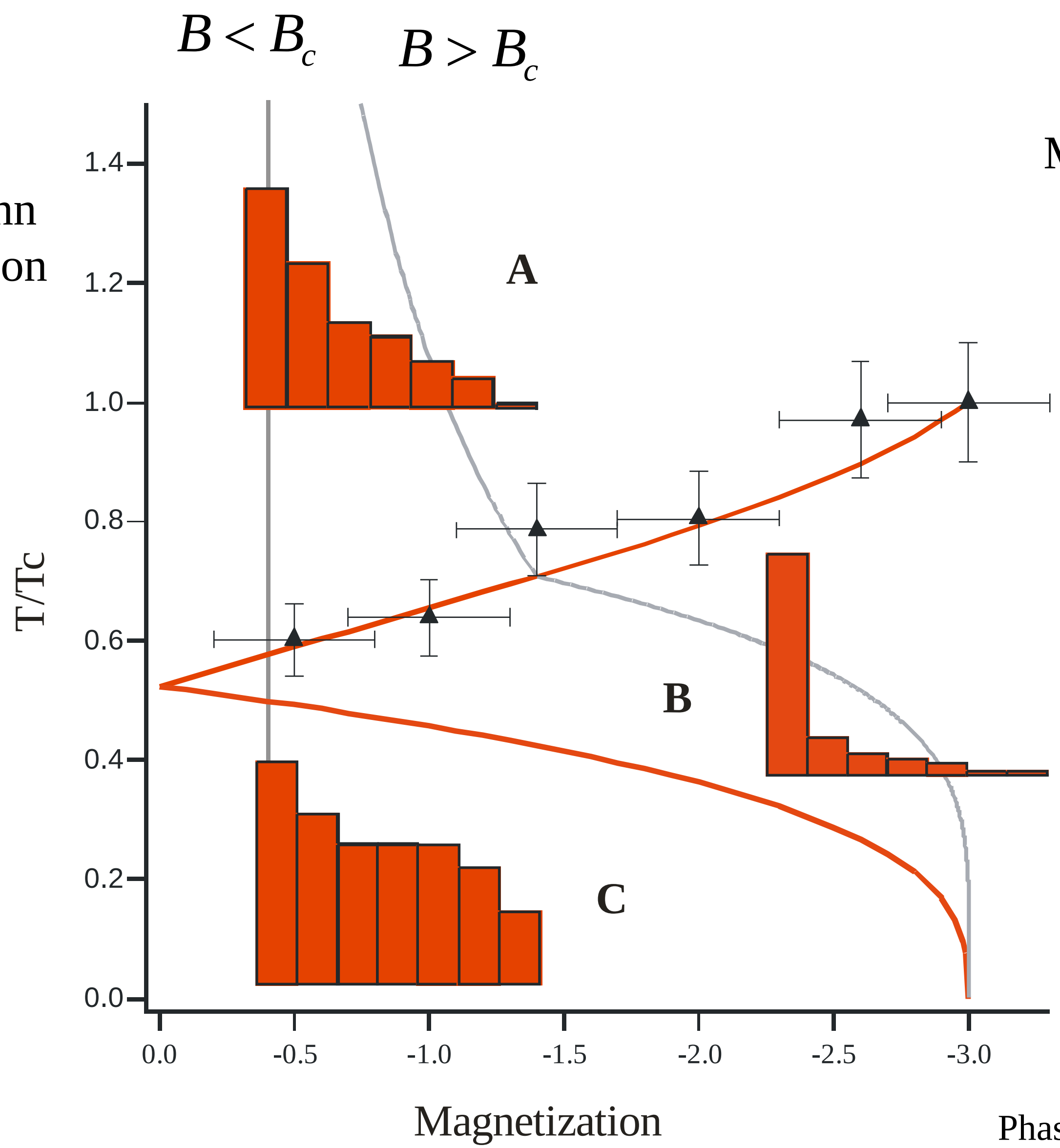
Cyclic

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

!! Depolarized BEC likely in metastable state !!

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

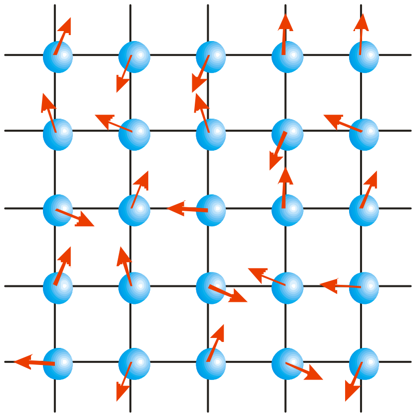
Phase diagram adapted from J. Phys. Soc. Jpn, **69,** 12, 3864 (2000)
See also PRA, **59**, 1528 (1999)

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

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

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

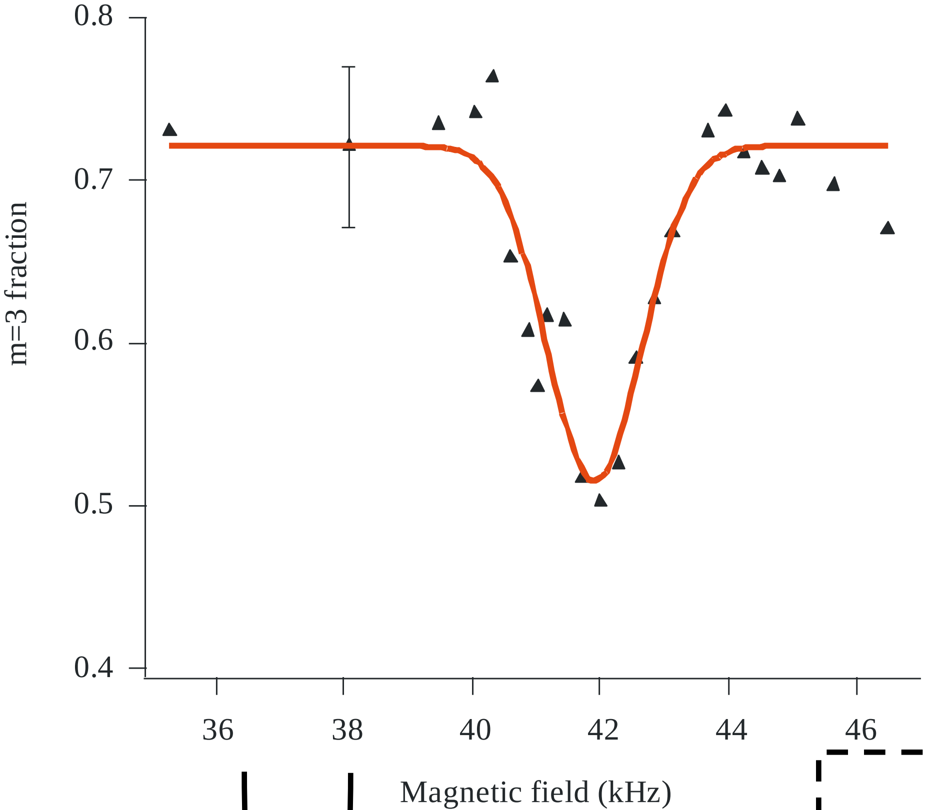
Anisotropy

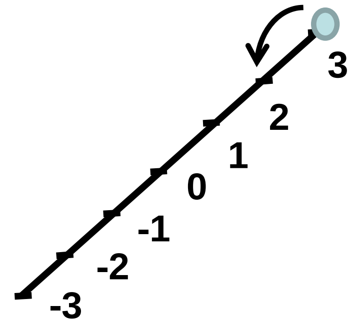
Does not rely on Mott physics

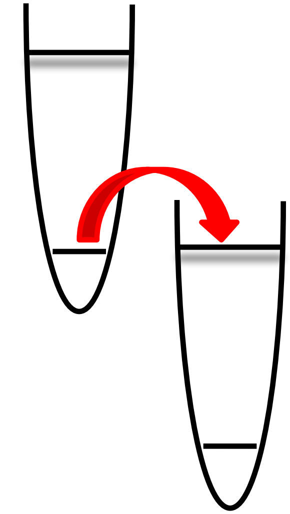
Magnetization changing collisions

$$S_1^- S_2^-$$

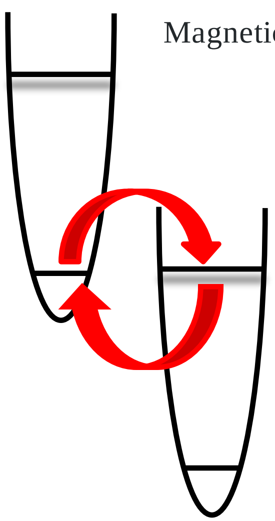
Magnetization dynamics resonance for two atoms per site (~15 mG)







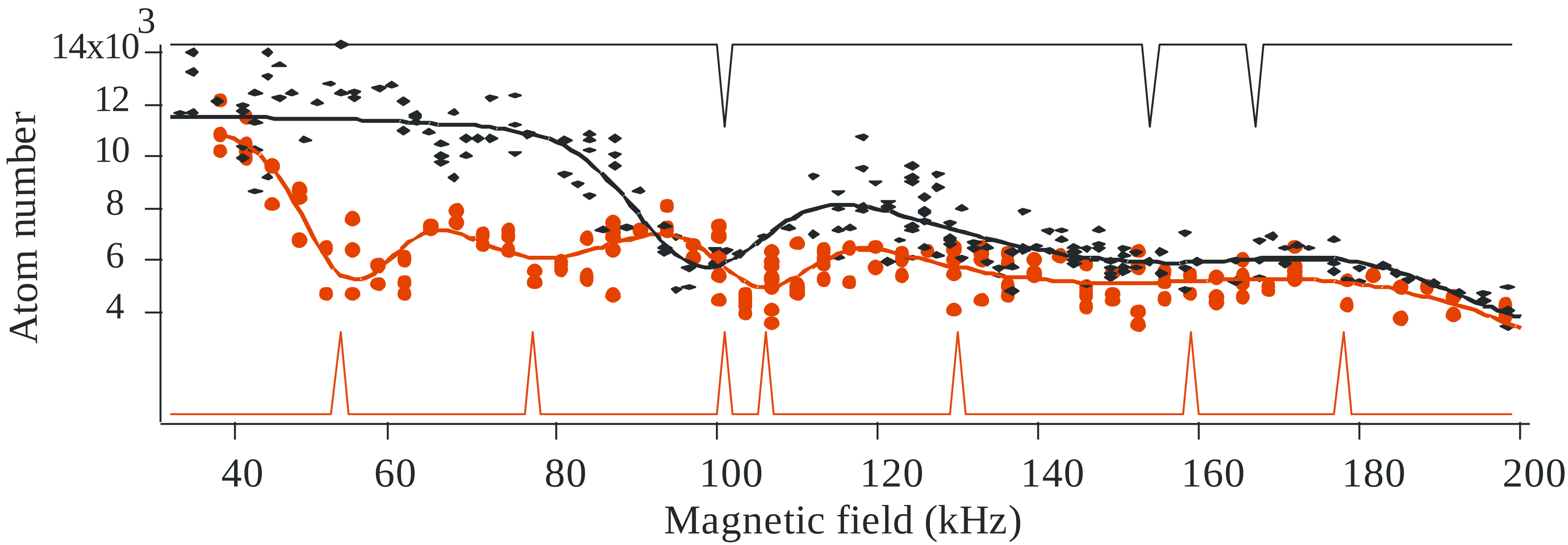
Dipolar resonance when released energy matches band excitation



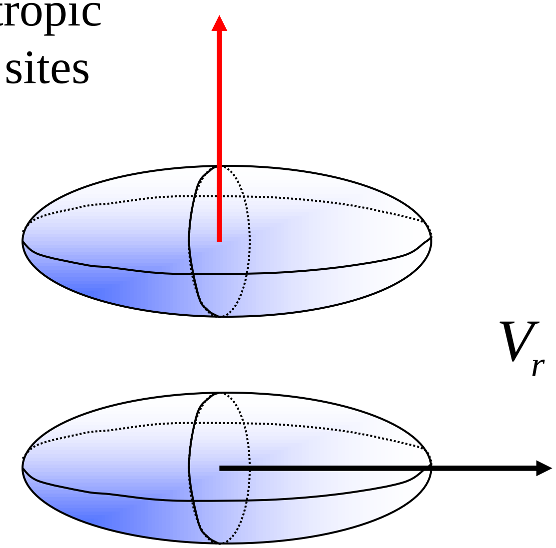
Towards coherent excitation of pairs into higher lattice orbitals ?
(Rabi oscillations)

Mott state locally coupled to excited band

Strong anisotropy of dipolar resonances



Anisotropic
lattice sites



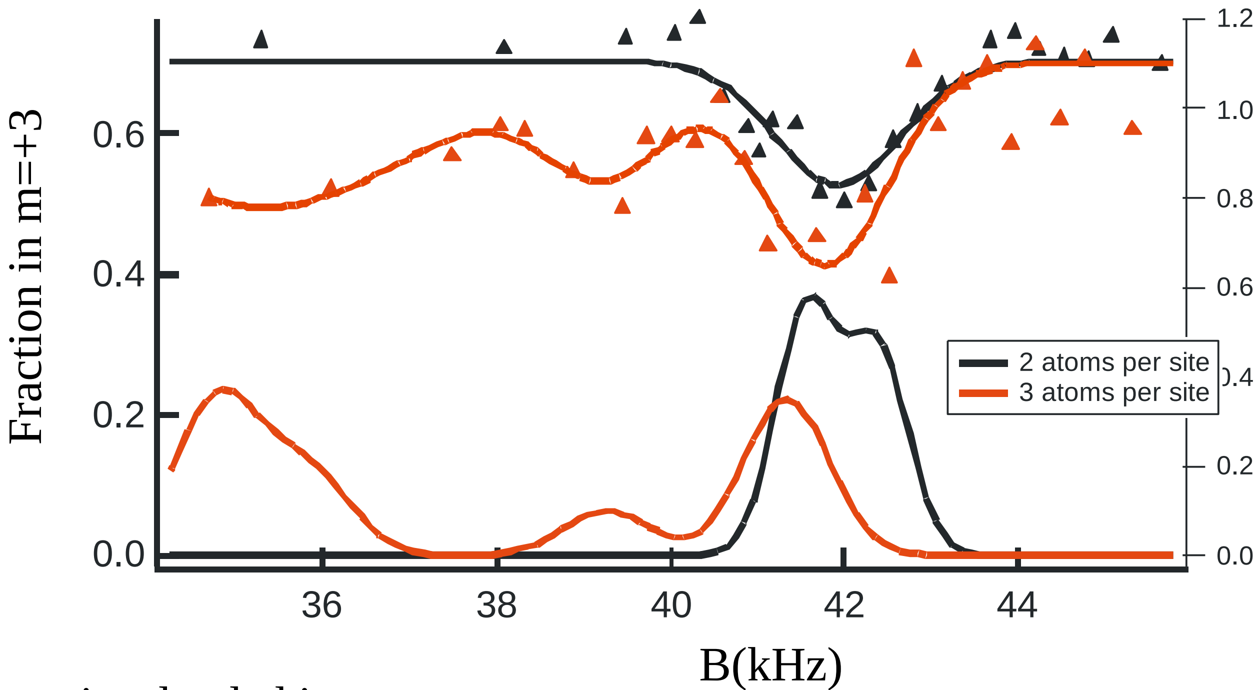
$$V_r = \frac{3}{2} S d^2 \frac{(x+iy)^2}{r^5}$$

<u>At resonance</u>

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

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

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

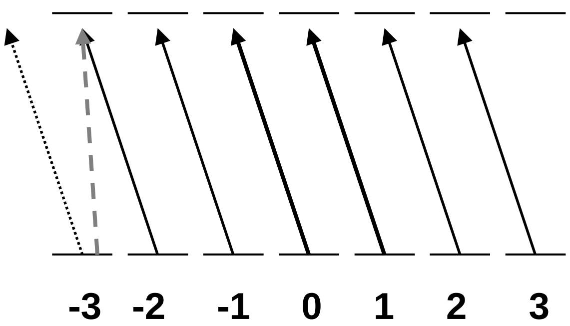
Few-body physics !

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)

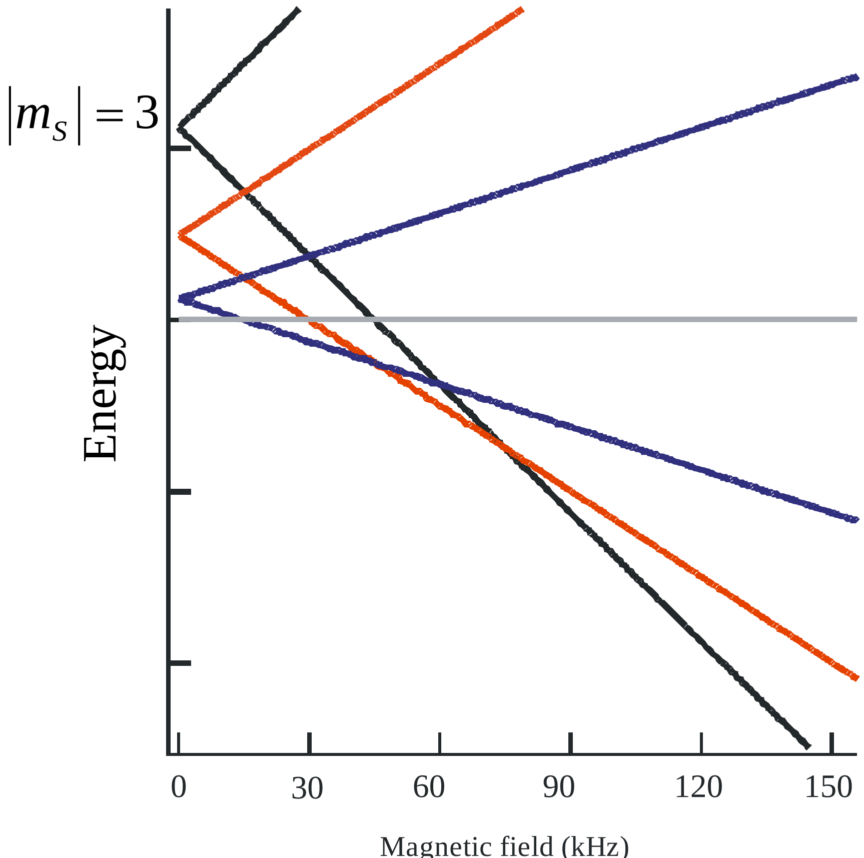
Control the initial state by a tensor light-shift

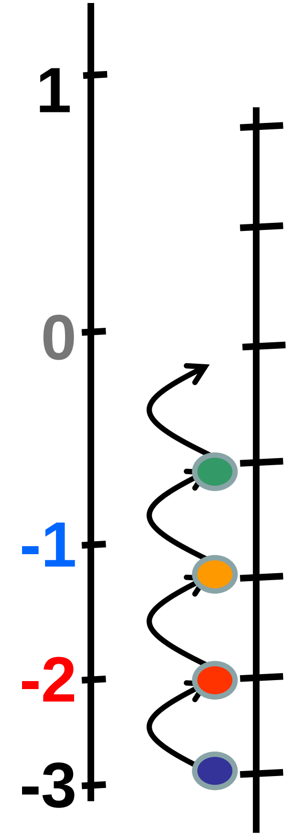


A σ– polarized laser
Close to a J→J transition
(100 mW 427.8 nm)

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

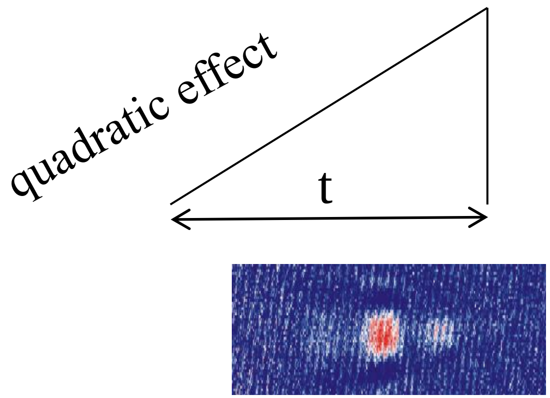
Quadratic effect allows state preparation



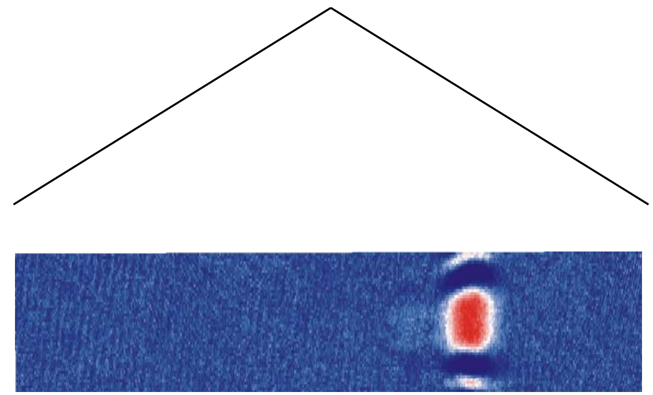


In practice, a π component couples m_S states

Adiabatic state preparation in 3D lattice



-2



-3

(2 atomes / site)

Initiate spin dynamics by removing quadratic effect

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

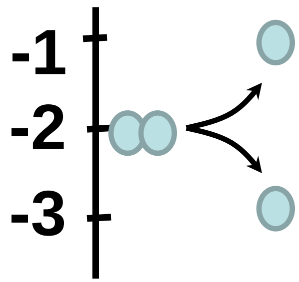
$$\sqrt{\frac{6}{11}} \left| S = 6, m_{tot} = -4 \right\rangle - \sqrt{\frac{5}{11}} \left| S = 4, m_{tot} = -4 \right\rangle$$

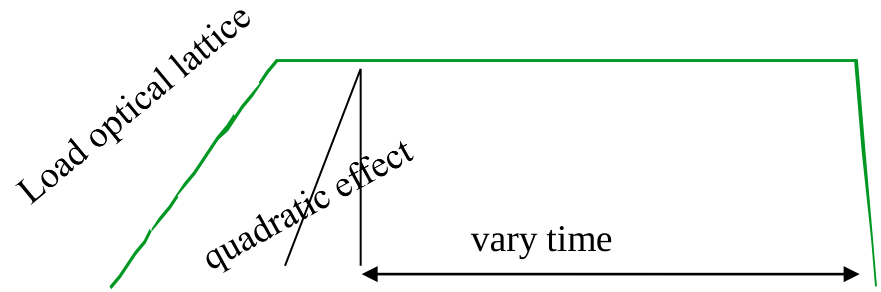
$$\left| -2, -2 \right\rangle \leftrightarrow \frac{1}{\sqrt{2}} \left(\left| -3, -1 \right\rangle + \left| -1, -3 \right\rangle \right)$$

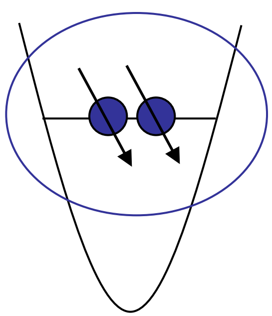
$$\Gamma = \frac{4\pi\hbar^2}{m} n \left(a_6 - a_4 \right)$$

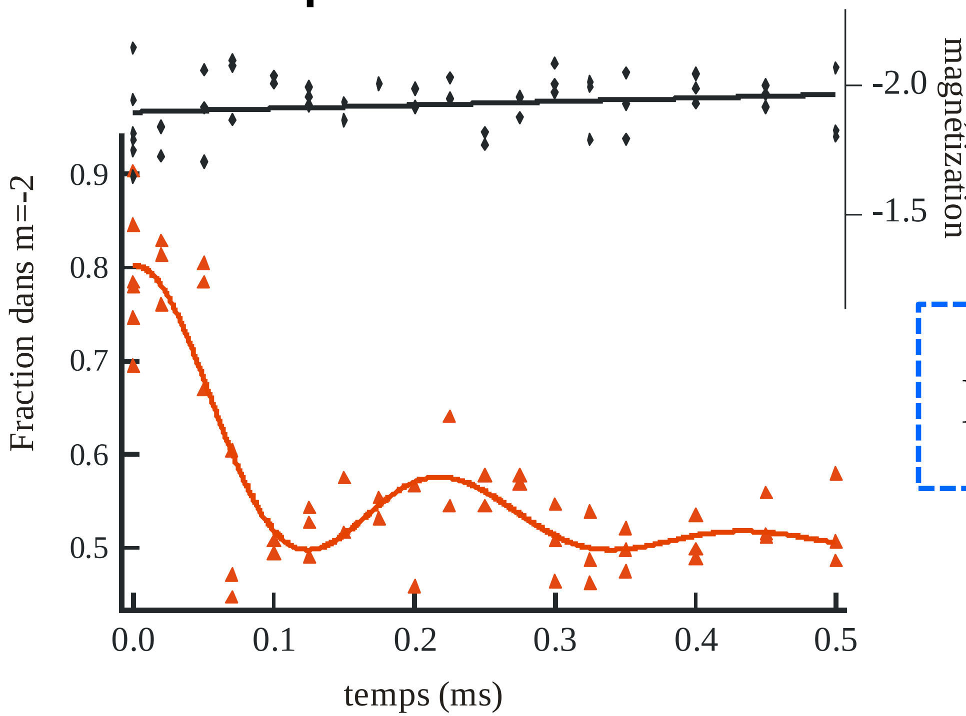
On-site spin oscillations

(due to contact oscillations)









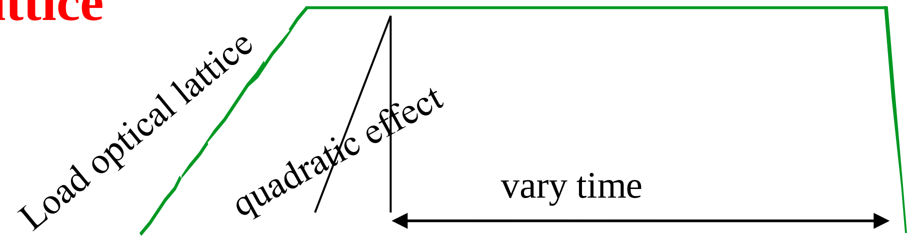
$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

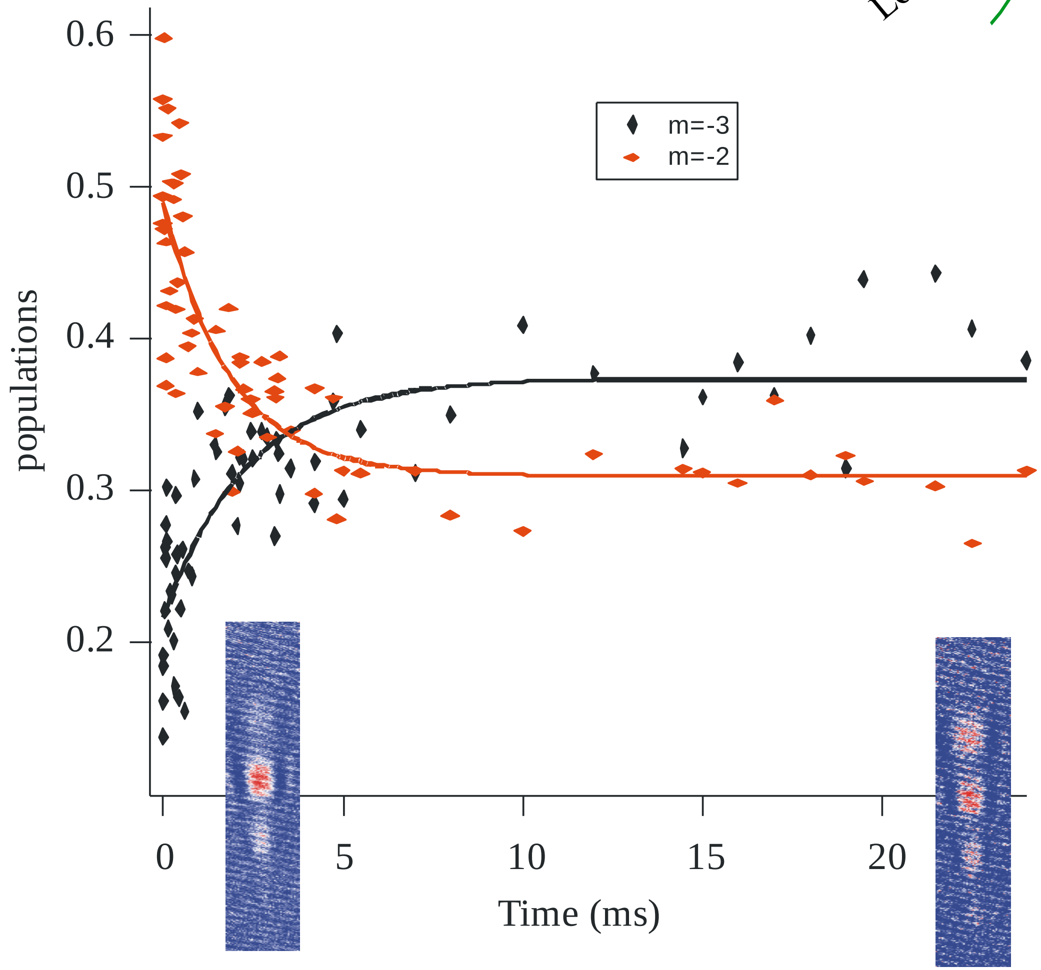
(perdiod ↔ 220 μs)

(↔ 250 μs)

Up to now unknown source of damping

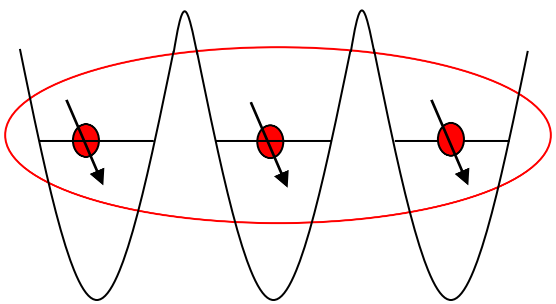
Long time-scale spin dynamics in lattice





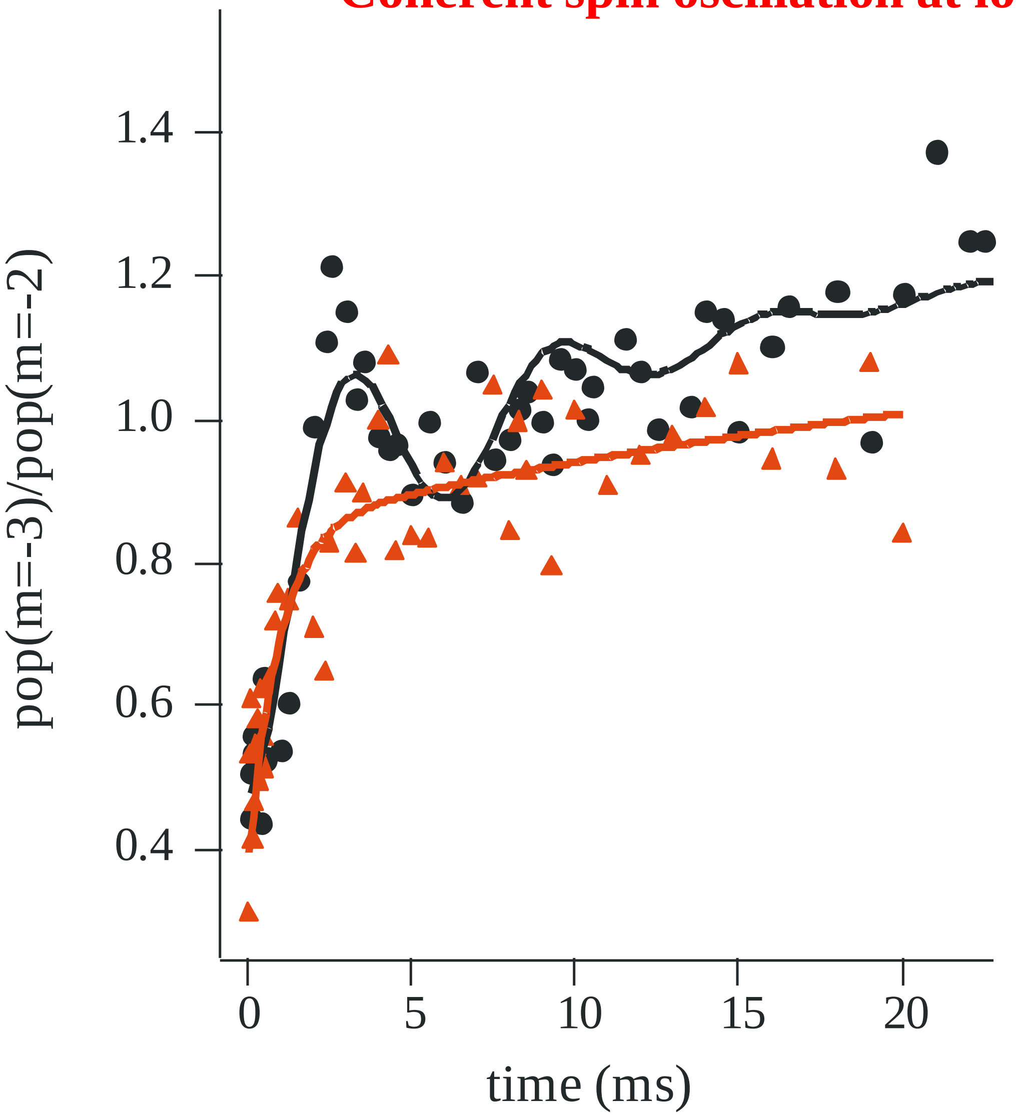
Sign for intersite dipolar interaction ?

(two orders of magnitude slower than on-site dynamics)

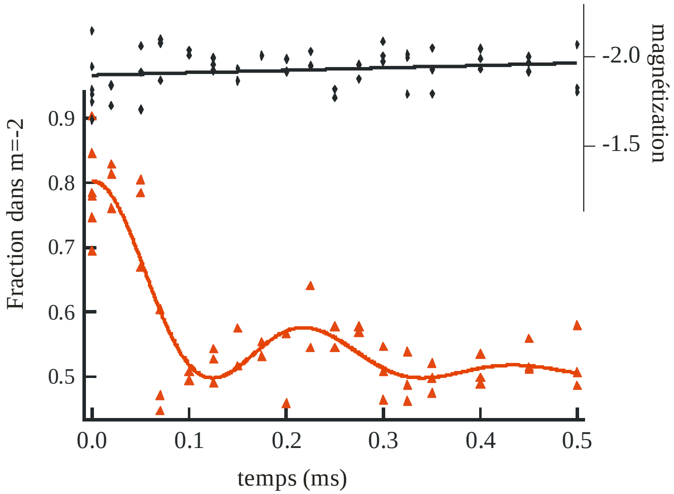


$$\frac{1}{2}\left(S_{1+}S_{2-}+S_{1-}S_{2+}\right)$$

Coherent spin oscillation at lower lattice depth

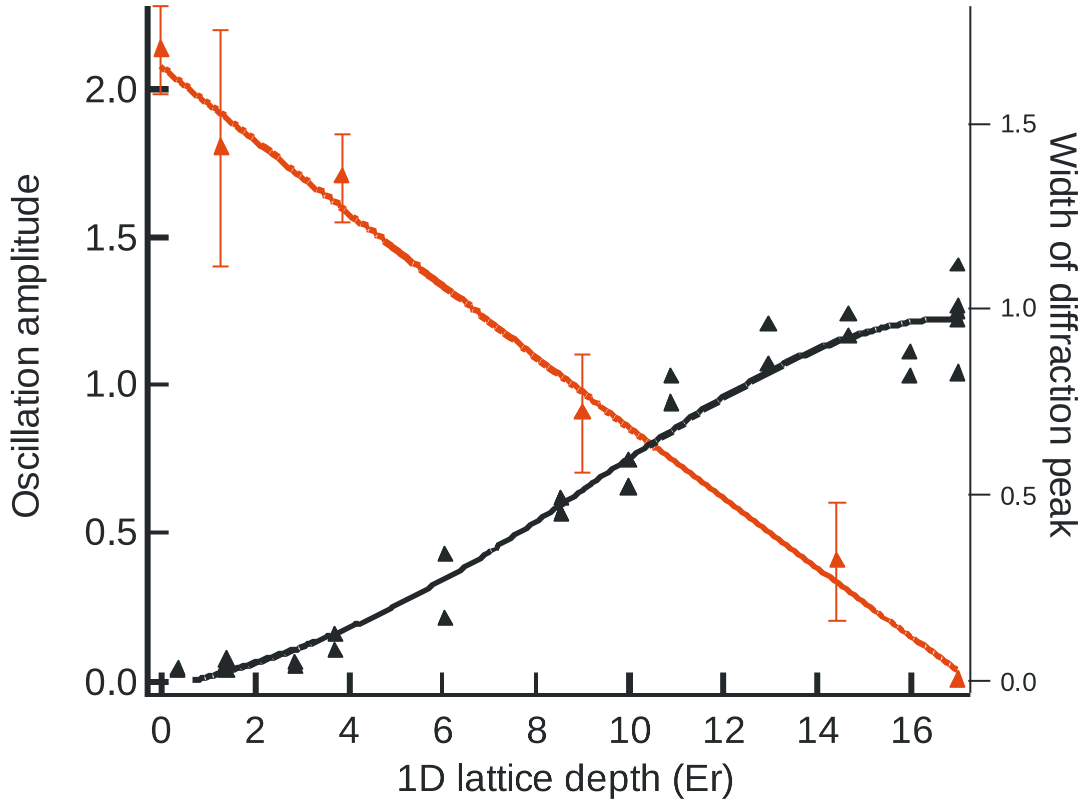


The very long time scale excludes on-site oscillations where spin-exchange collisions dominate



Probing spin oscillations from superfluid to Mott

(probes coherent spin oscillations)



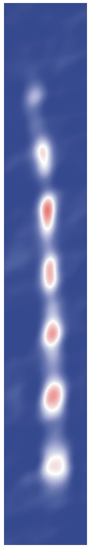
(Probes coherence length)

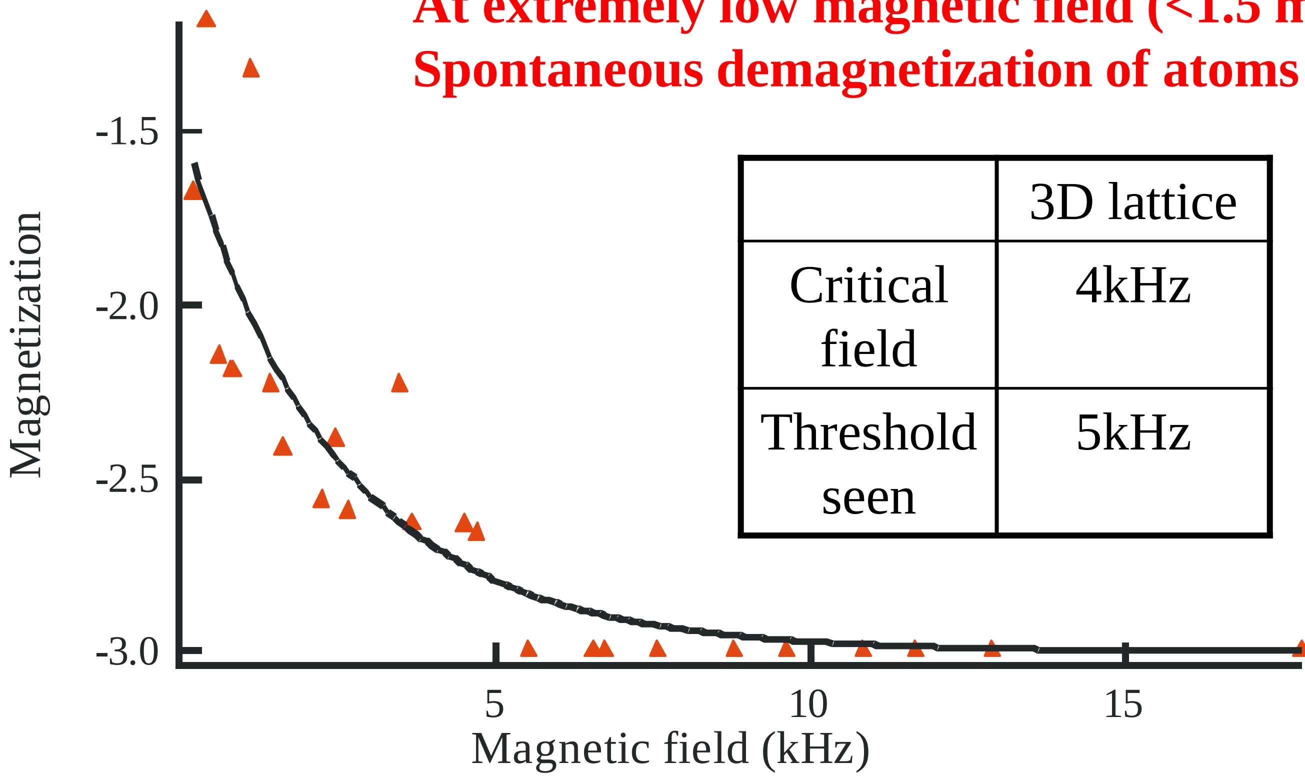
Intersite coherent spin oscillation seems to need phase coherence between sites

Superfluid more robust

Probes magnetism from superfluid to insulator

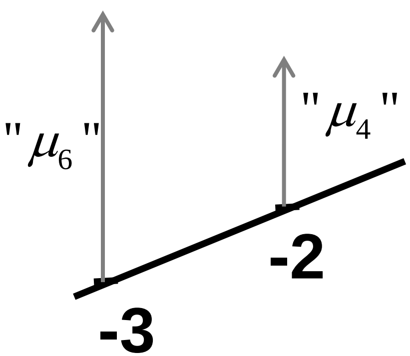
At extremely low magnetic field (<1.5 mG): Spontaneous demagnetization of atoms in a 3D lattice



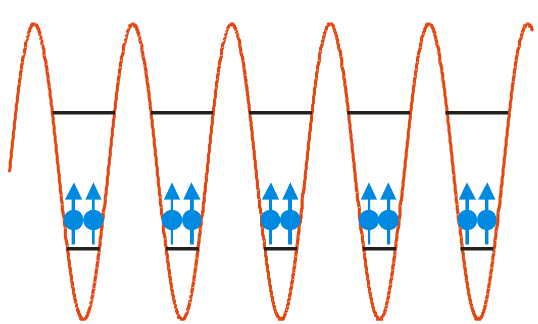


	3D lattice
Critical field	4kHz
Threshold seen	5kHz

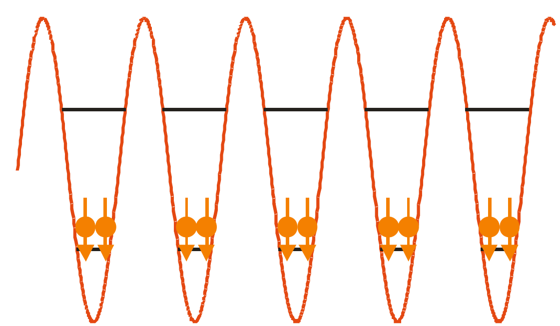
$$g_J \mu_B B_c \approx \frac{4\pi\hbar^2 n_0 (a_6 - a_4)}{m}$$



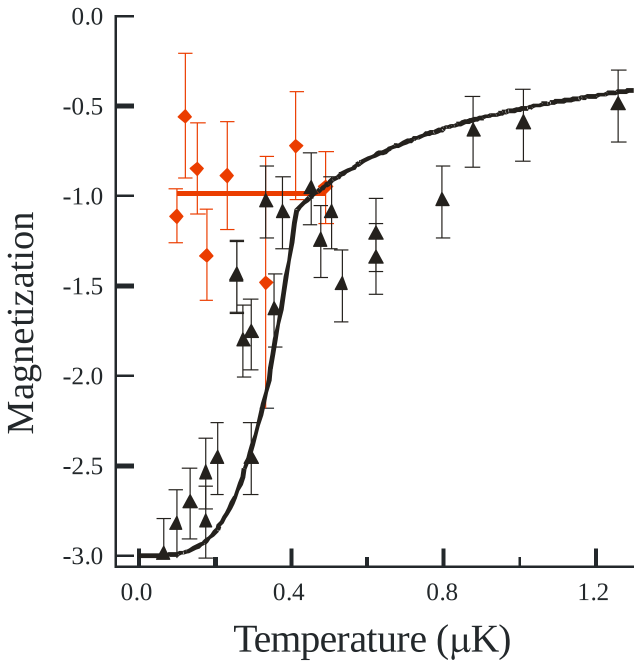
$|S=6, m=-6\rangle$



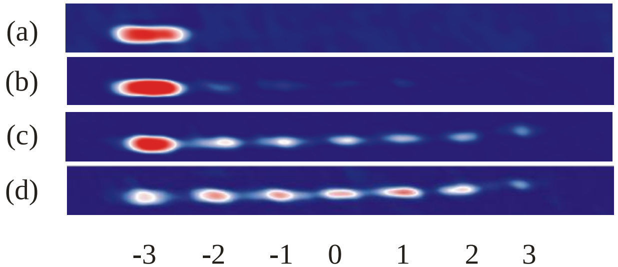
$|S=4, m=-4\rangle$



Conclusions

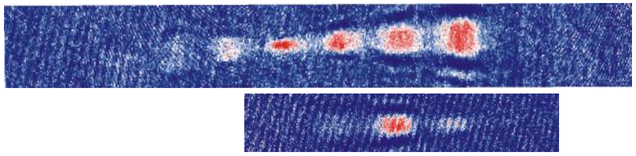


Magnetization changing dipolar collisions introduce the spinor physics with free magnetization



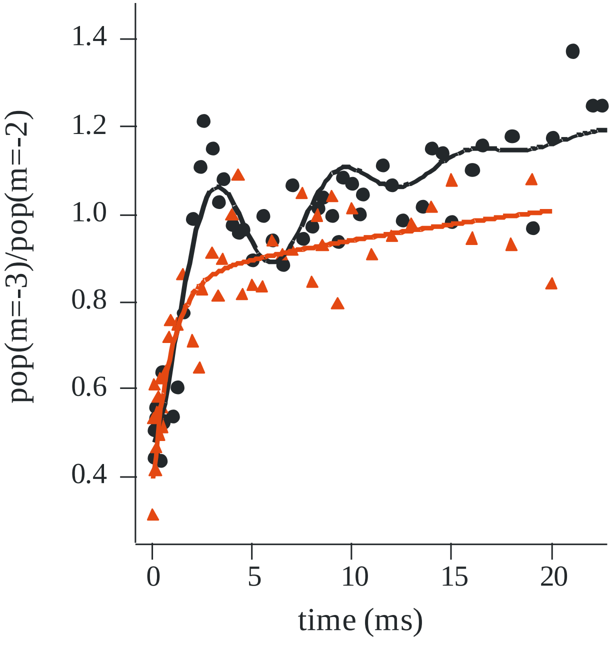
New spinor phases at extremely low magnetic fields

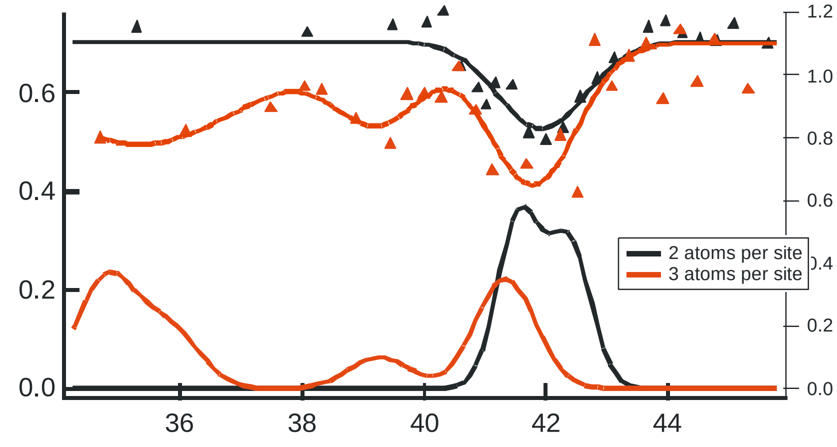
Tensor light-shift allow to reach new quantum phases



Magnetism in lattice

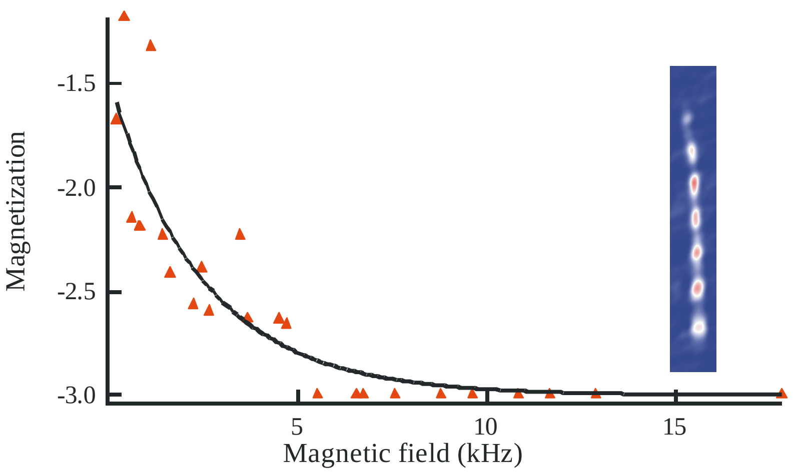
Resonant magnetization dynamics
Towards Einstein-de-Haas effect
Anisotropy
Few body vs many-body physics





Away from resonances: spin oscillations
Spin-exchange
Dipolar exchange
Not robust in Mott regime

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



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