Dipolar chromium BECs, and magnetism

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Quantum gases

Density : 10^{12} à 10^{15} at/cm^3 ($\leftrightarrow 10^{22}$ 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

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

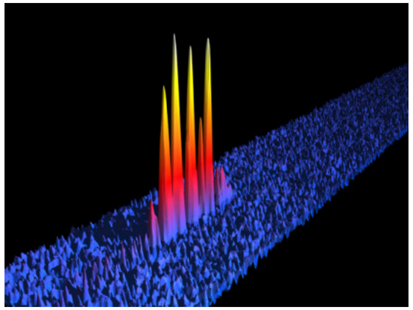
Short range
Isotropic

a_S ~ 5 nm - can be tuned via Feshbach resonances

Effect of interactions on condensates

Attractive interactions

Implosion of BEC for large atom number

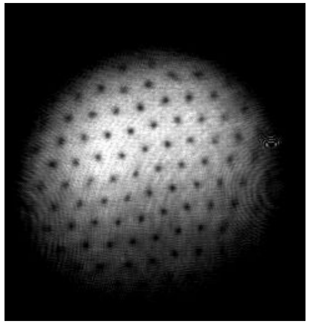


Small solitons

Rice…

Repulsive interactions

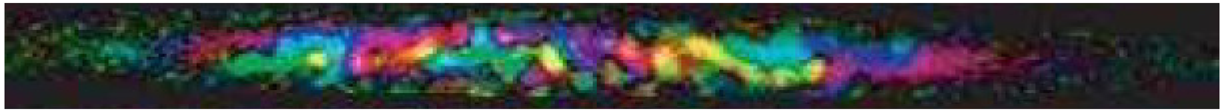
Stable condensate
Phonon spectrum



Superfluidity

ENS, JILA…

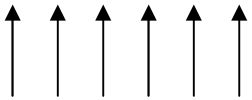
Spin dependent interactions



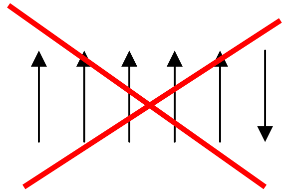
Berkeley…

Magnetism

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



$$d = 6\mu_B$$

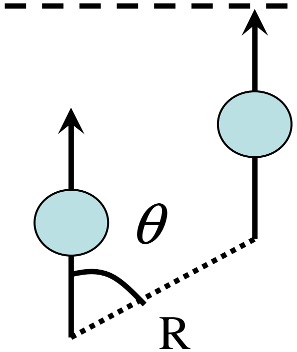


Dipole-dipole interactions

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

Long range

Anisotropic



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

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

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

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

Dipole-dipole interactions

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

Long range

Anisotropic

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

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

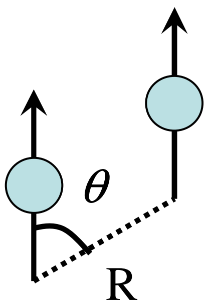
Cr: $\varepsilon_{dd} = 0.16$

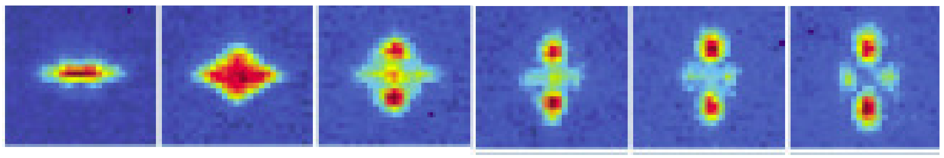
Relative strength of dipole-dipole and Van-der-Waals interactions

$\varepsilon_{dd} > 1$ 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.

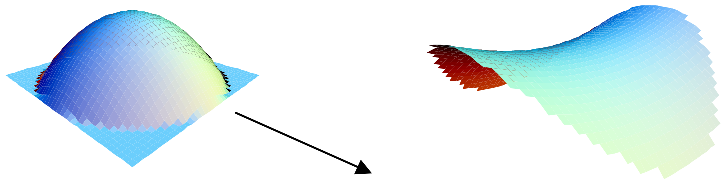
Stuttgart: d-wave collapse, PRL **101**, 080401 (2008)
See also Er PRL, 108, 210401 (2012)
See also Dy, PRL, 107, 190401 (2012)
… and Dy Fermi sea PRL, 108, 215301 (2012) … and heteronuclear molecules…

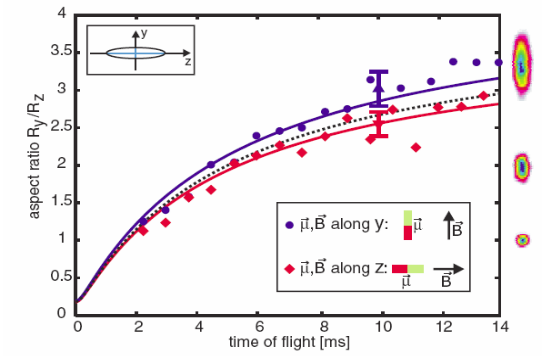
$\varepsilon_{dd} < 1$ BEC stable despite attractive part of dipole-dipole interactions

Cr: $\varepsilon_{dd} = 0.16$

Hydrodynamic properties of a BEC with weak dipole-dipole interactions

Striction

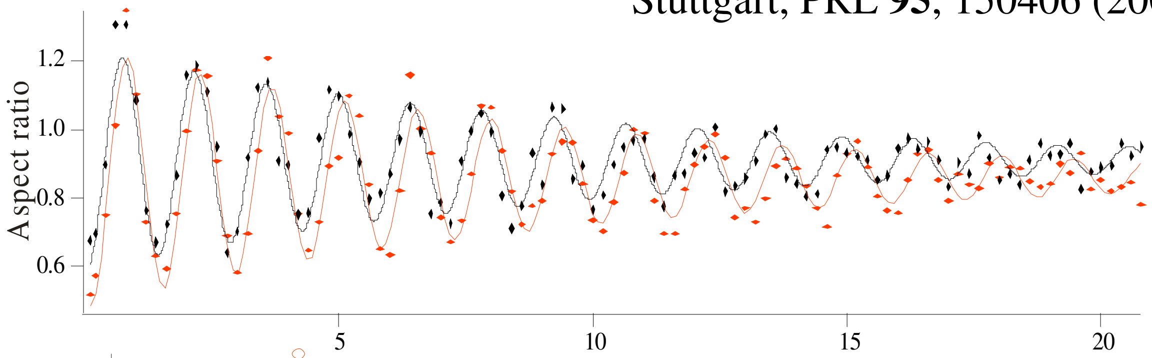




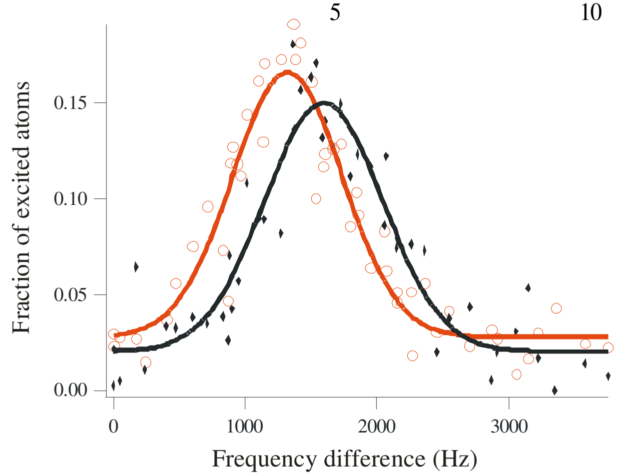
Stuttgart, PRL **95**, 150406 (2005)

Collective excitations

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



Anisotropic speed of sound



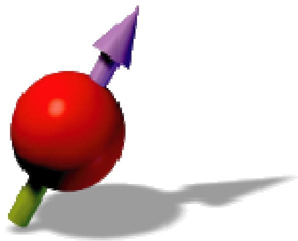
Bragg spectroscopy
Villetaneuse
PRL **109**, 155302 (2012)

Interesting but weak effects in a scalar Cr BEC

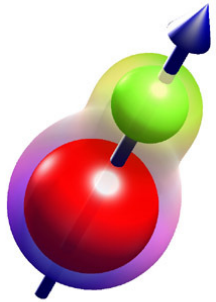
Different dipolar systems

« Magnetic atom »

$d \approx \mu_B$



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



$d \approx e a_0$

Rydberg atoms

$d = n^2 e a_0$

Dipole-dipole interactions

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

$\times n^4 = 10^8$

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

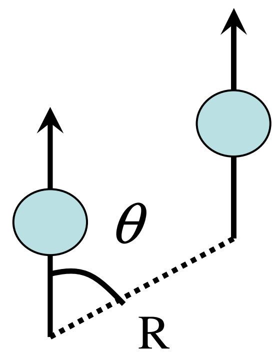
Multicomponent (« spinor ») BEC
Magnetism
Phases, spin textures…

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

Key idea:

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

This talk:

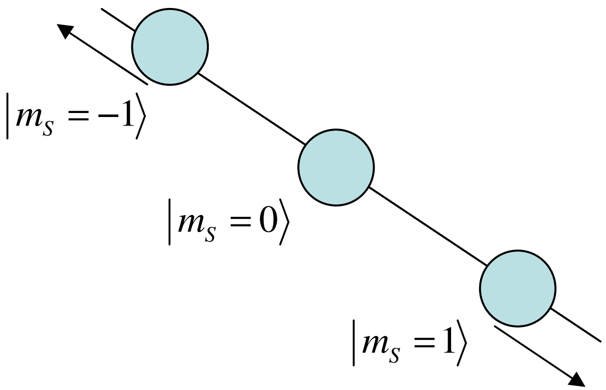
0 Introduction to spinor physics

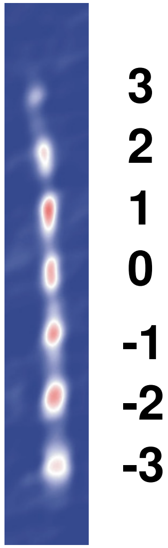
1 Spinor physics of a Bose gas with free magnetization

2 (Quantum) magnetism in opical lattices

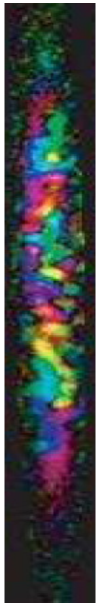
Detecting spin properties with cold atoms:

Stern-Gerlach separation:
(magnetic field gradient)





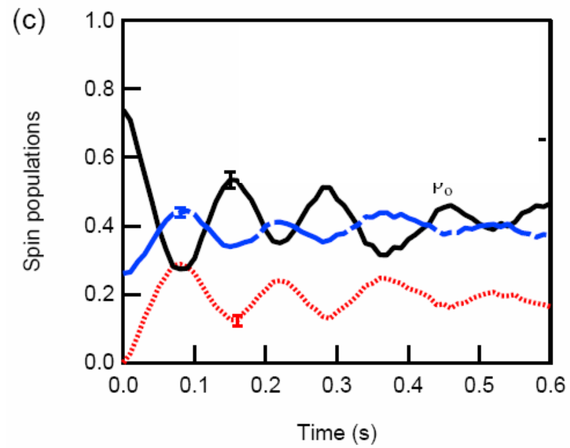
Spin-sensitive imaging:
(e.g. Faraday rotation)



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

(we do not (yet) do this)

Introduction to spinor physics

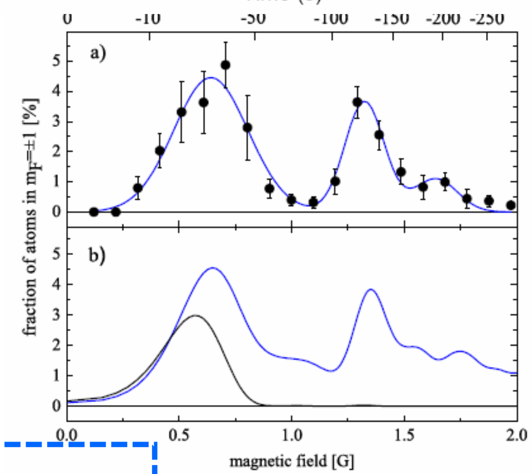


Exchange energy
Coherent spin oscillation

Chapman, Sengstock…

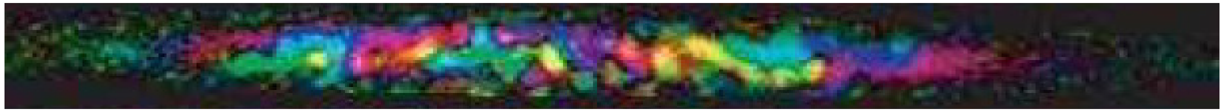
Quantum effects!

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



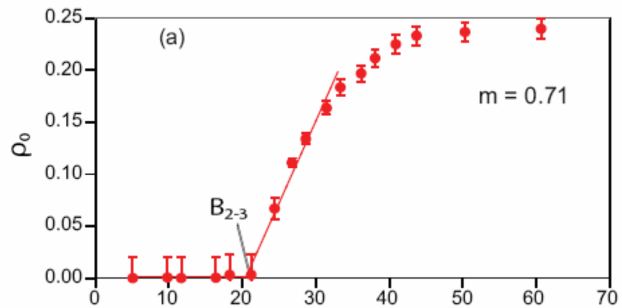
Klempt Stamper-Kurn

Domains, spin textures, spin waves, topological states



Stamper-Kurn, Chapman, Sengstock, Shin…

Quantum phase transitions



Stamper-Kurn, Lett

Main ingredients for spinor physics

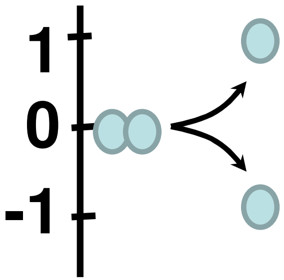
S=1,2,…

Spin-dependent contact interactions

Spin exchange

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

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



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

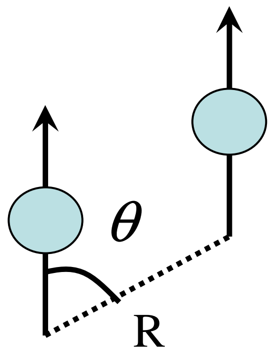
And

Dipole-dipole interactions

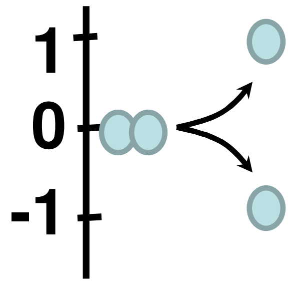
Dipolar interactions introduce magnetization-changing collisions

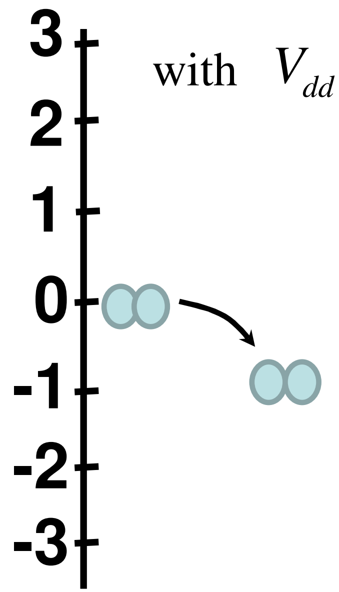
Dipole-dipole interactions

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

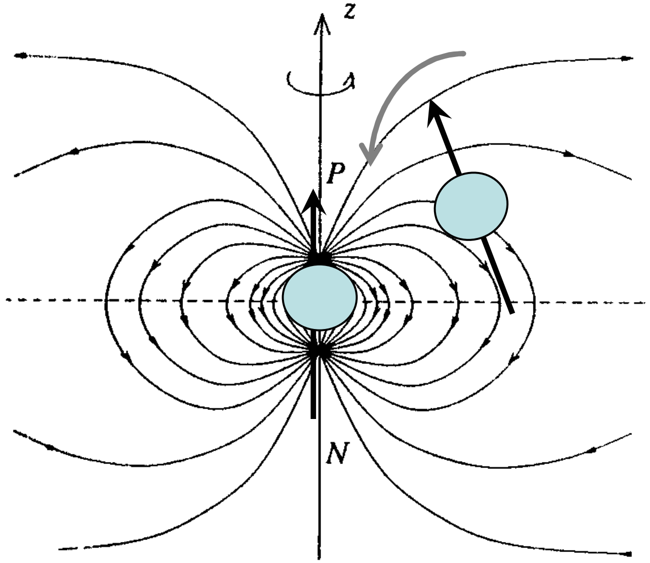


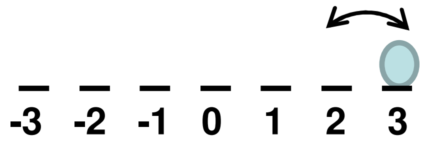
without V_{dd}





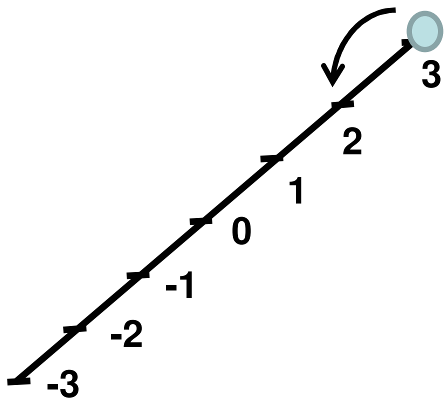
B=0: Rabi





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

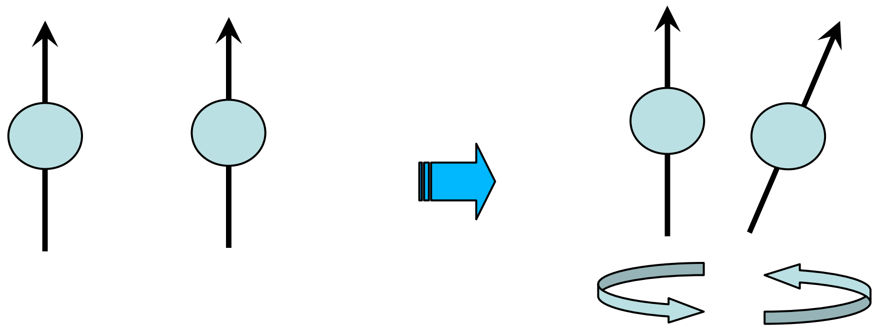
In a finite magnetic field: Fermi golden rule (losses)



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

(x1000 compared to alkalis)

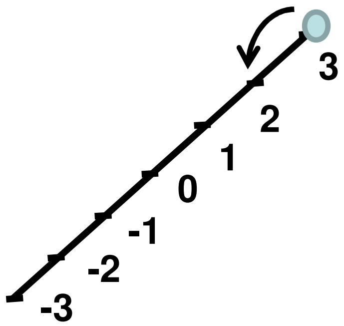
Dipolar relaxation, rotation, and magnetic field



Angular momentum conservation

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

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



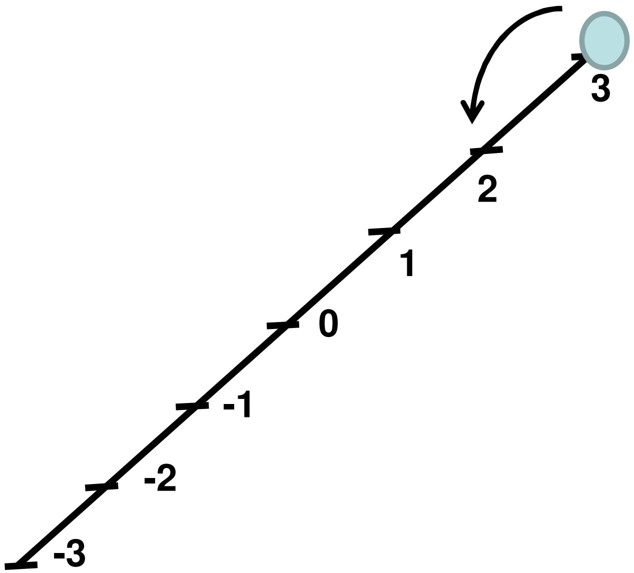
$$\Delta \ell = 2$$

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

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

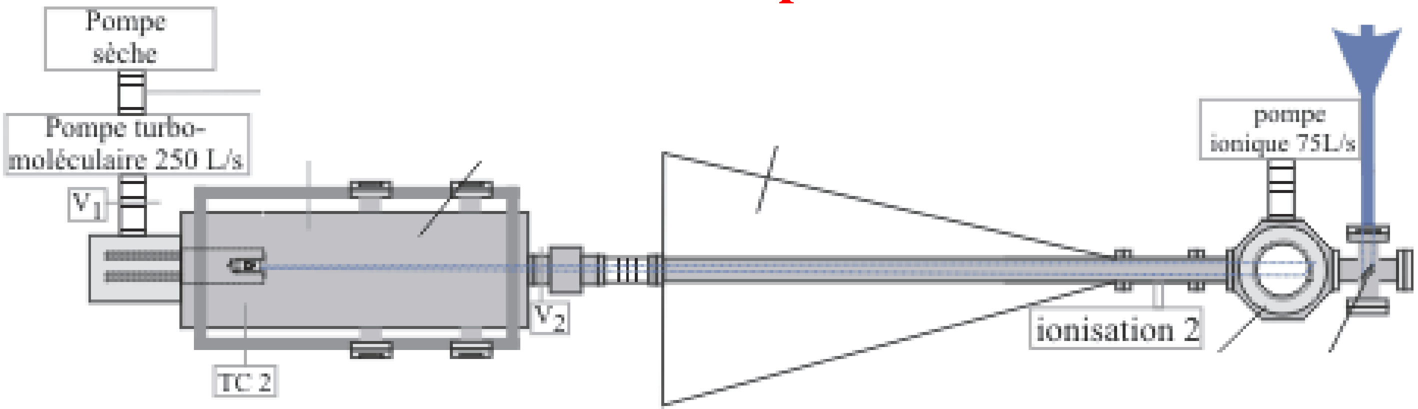
- Free magnetization

Magnetic field matters !

1 Spinor physics of a Bose gas with free magnetization

2 (Quantum) magnetism in opical lattices

^{52}Cr BEC experiment



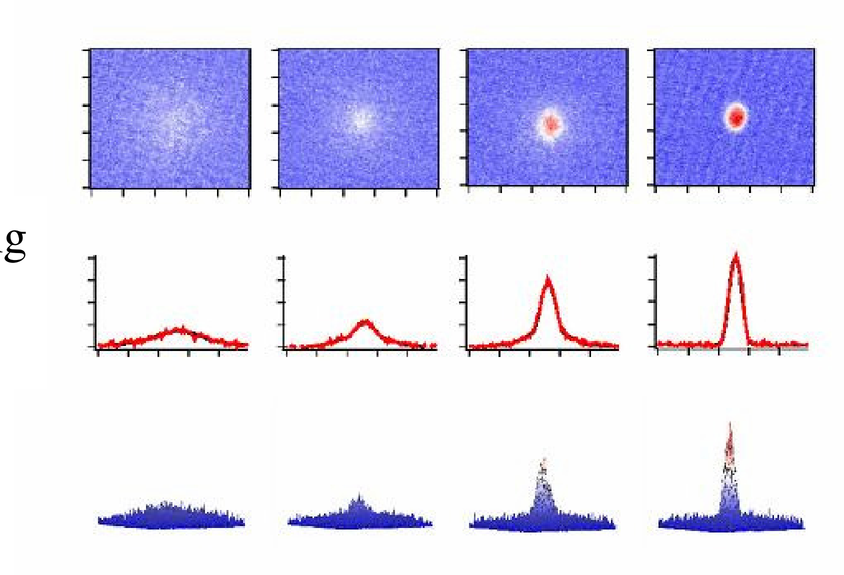
Vacuum
$4\ 10^{-11}$ mbar

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

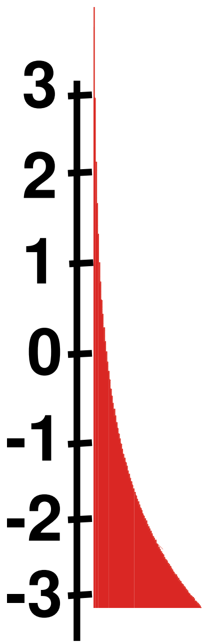
Many lasers !

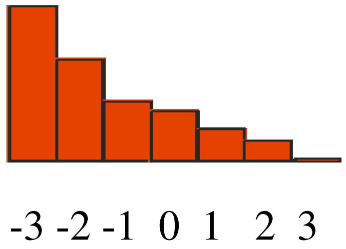
Magnetic field control < 100 μG

Spin temperature equilibriates with mechanical degrees of freedom

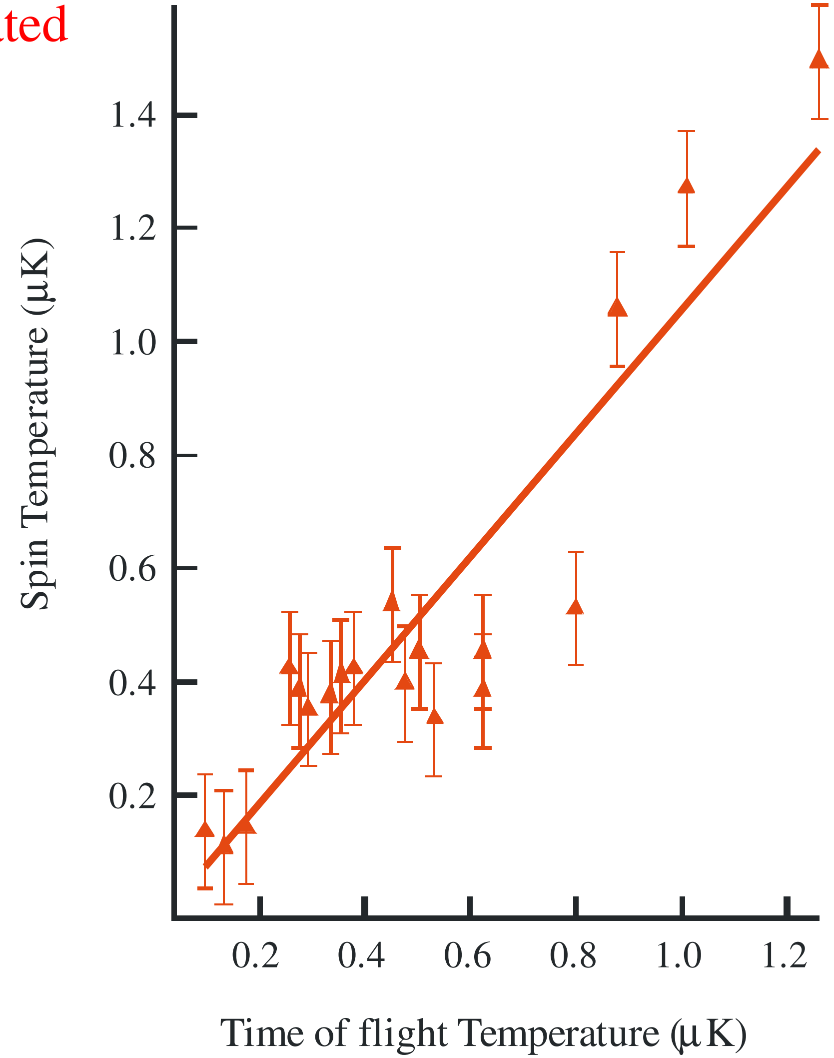
At low magnetic field: spin thermally activated

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



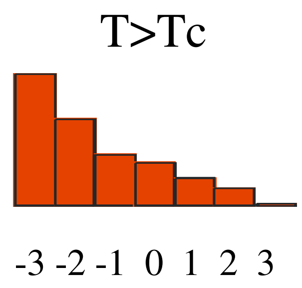


We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)

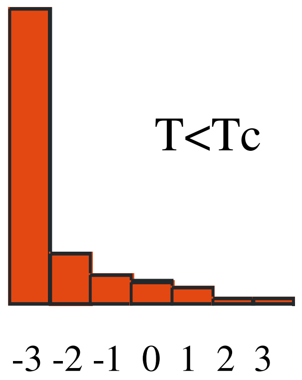


Related to Demagnetization Cooling expts,
Pfau, *Nature Physics* ***2****, 765 (2006)*

Spontaneous magnetization due to BEC

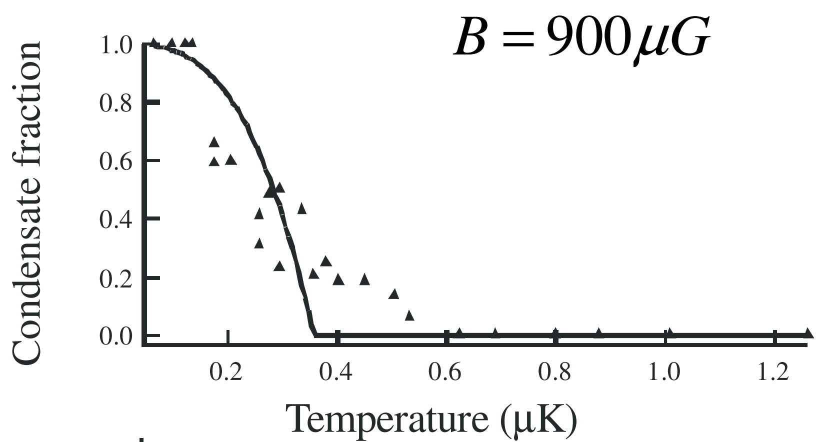


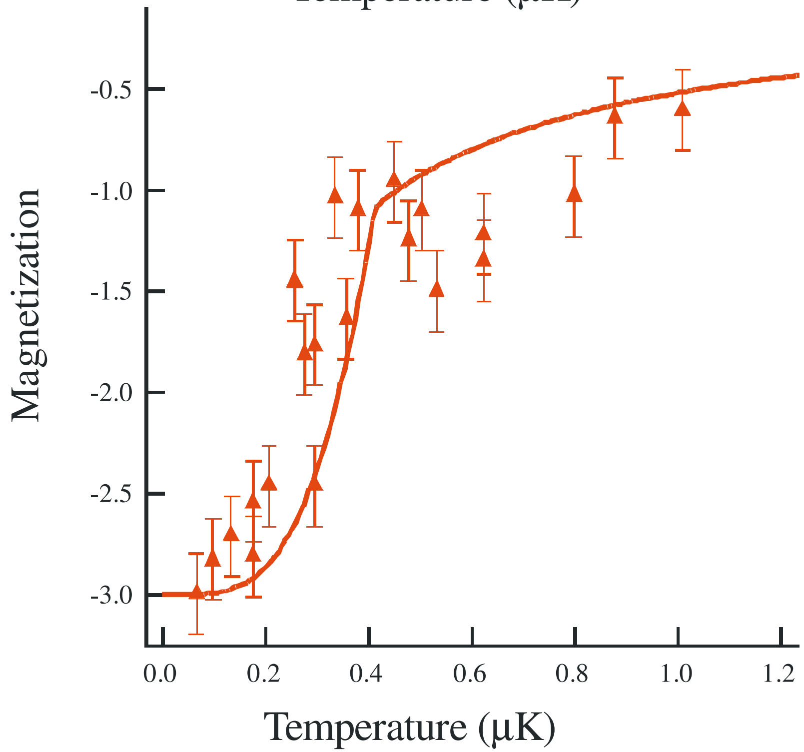
Thermal population in Zeeman excited states



a bi-modal spin distribution

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



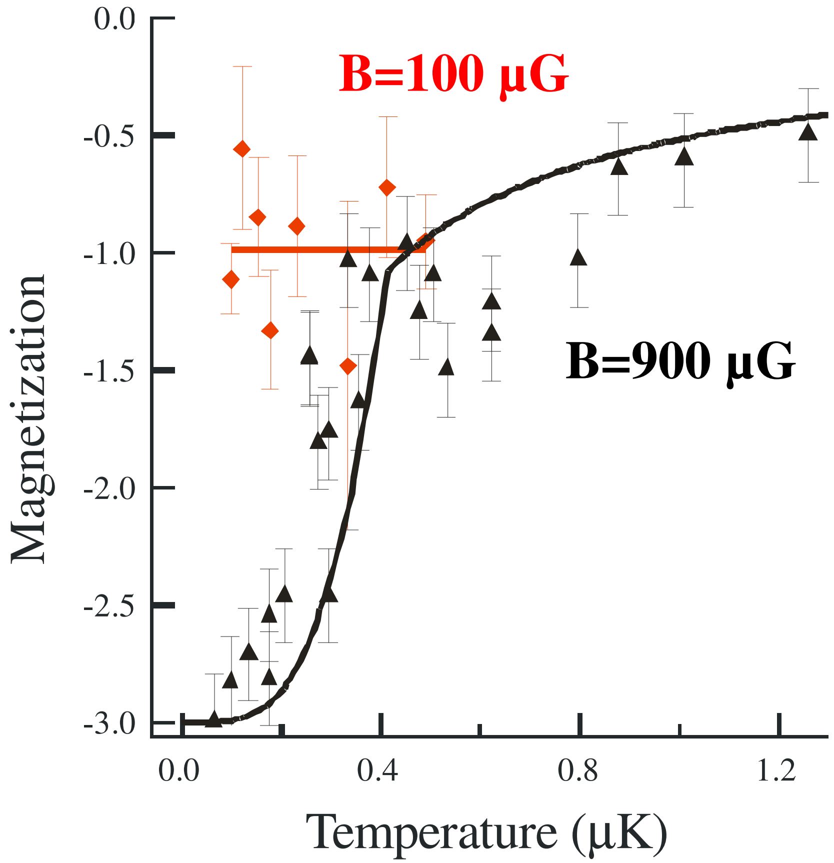


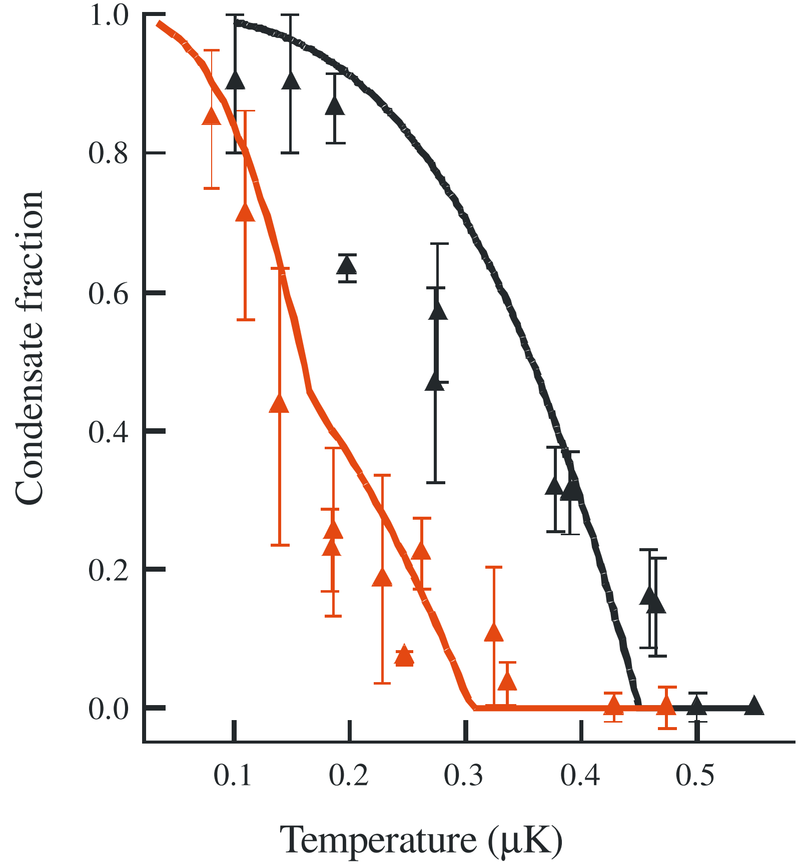
Cloud spontaneously polarizes !

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 !





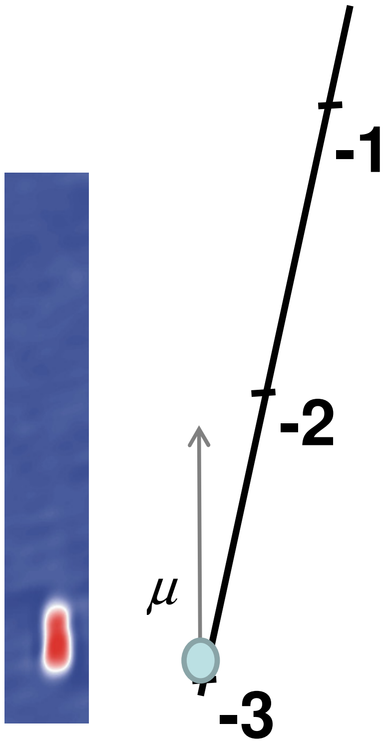
-Magnetization remains small even when the condensate fraction approaches 1

!! Observation of a depolarized condensate !!

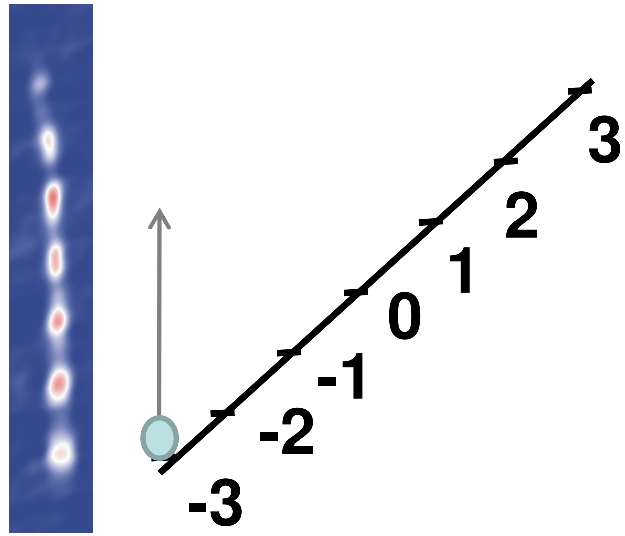
Necessarily an interaction effect

PRL **108**, 045307 (2012)

Cr spinor properties at low field

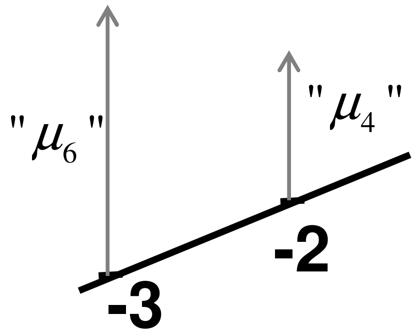


Large magnetic field : ferromagnetic



Low magnetic field : polar/cyclic

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

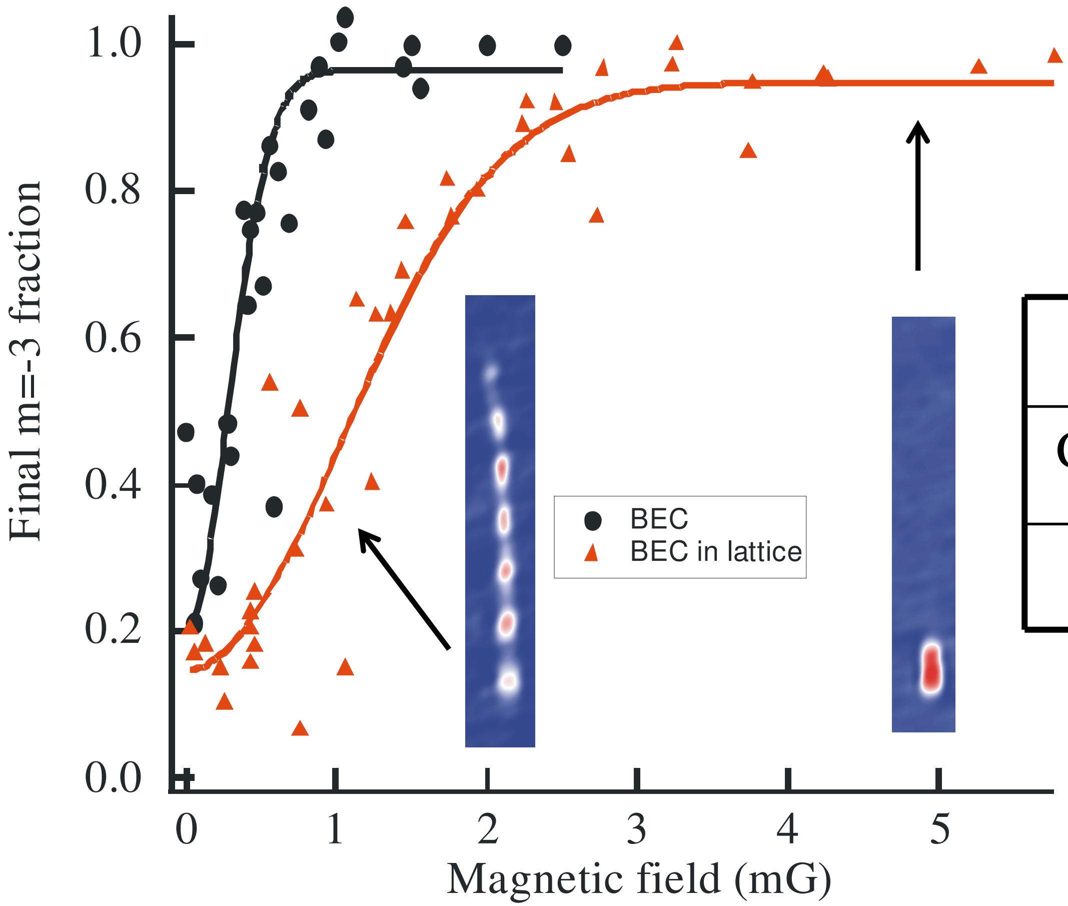


Santos PRL **96**, 190404 (2006)

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

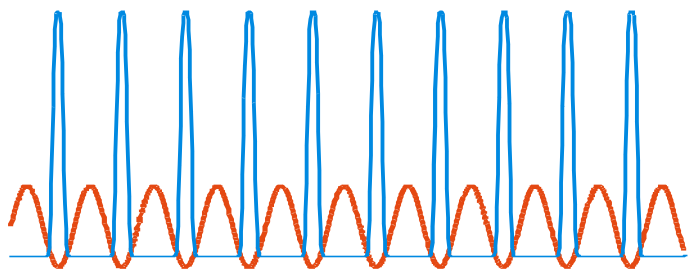
PRL **106**, 255303 (2011)

Density dependent threshold



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

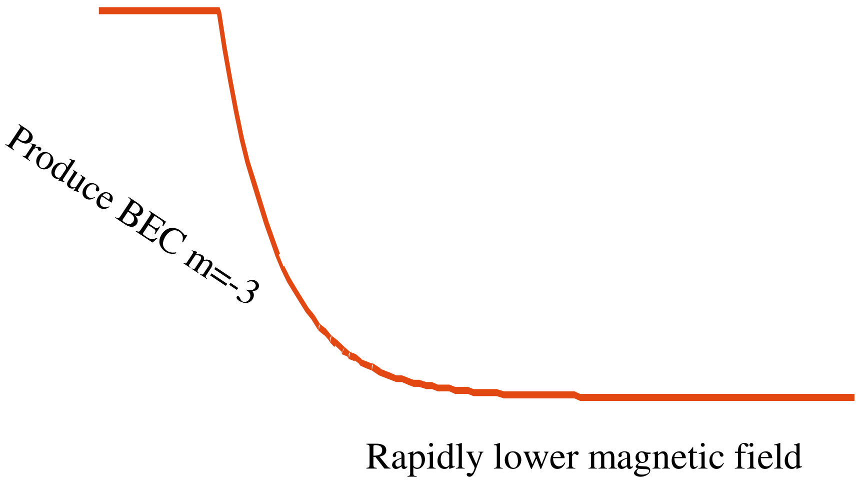
	BEC	Lattice
Critical field	0.26 mG	1.25 mG
1/e fitted	0.3 mG	1.45 mG

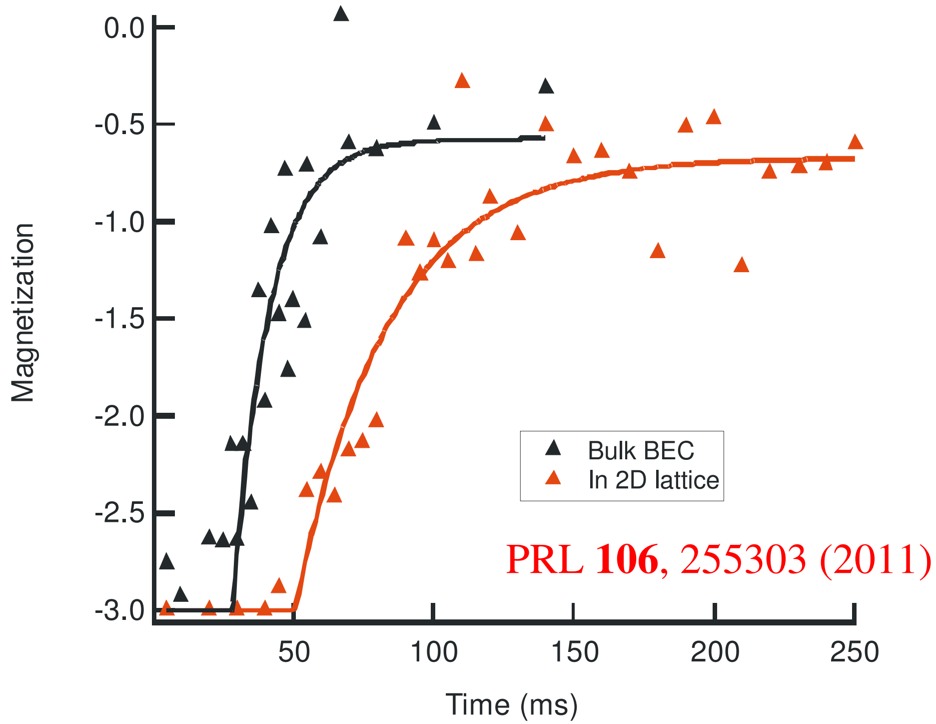


Load into deep 2D optical lattices to boost density.
Field for depolarization depends on density

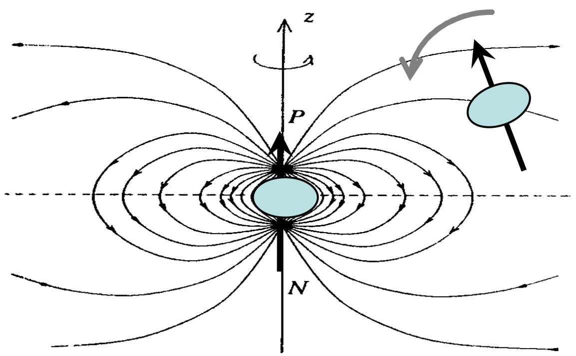
Note: Possible new physics in 1D: Polar phase is a singlet-paired phase Shlyapnikov-Tsvelik NJP, 13, 065012 (2011)

Dynamics analysis





PRL **106**, 255303 (2011)

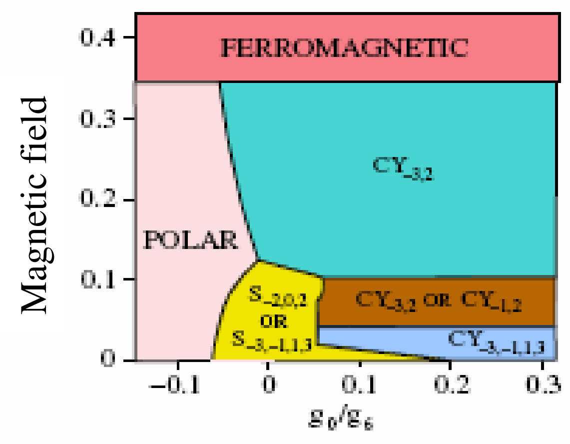


Meanfield picture :
Spin(or) precession

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

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

Open questions about equilibrium state



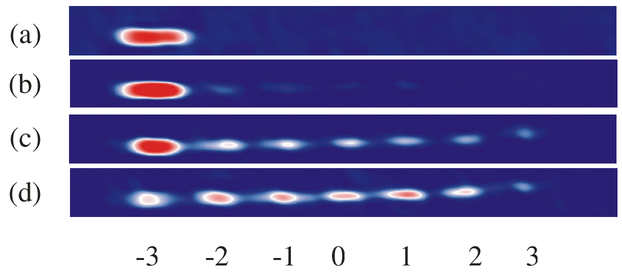
Santos and Pfau
PRL **96**, 190404 (2006)
Diener and Ho
PRL. **96**, 190405 (2006)
Demler et al.,
PRL **97**, 180412 (2006)

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

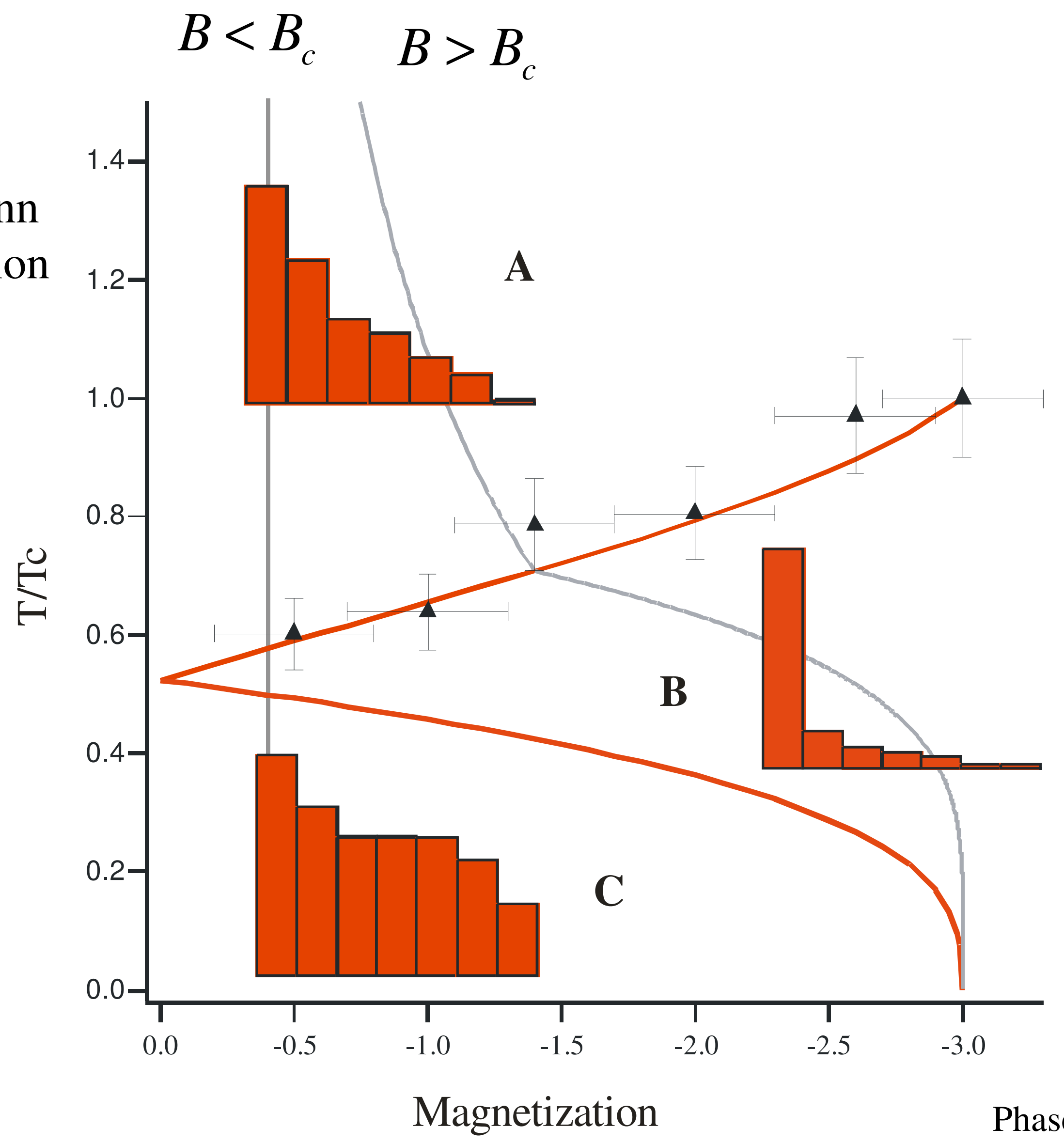
$$\frac{1}{\sqrt{2}}(1,0,0,0,0,1,0)$$

!! 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

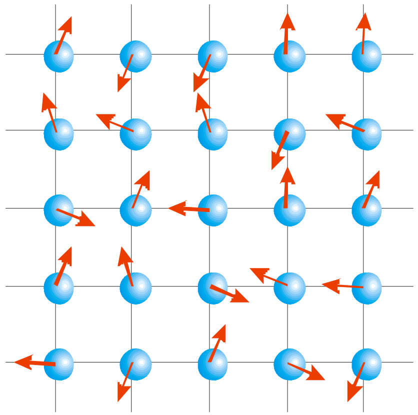
-Thermodynamics: Spontaneous magnetization of the gas due to ferromagnetic nature of BEC

-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

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

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

Anisotropy

Does not rely on Mott physics

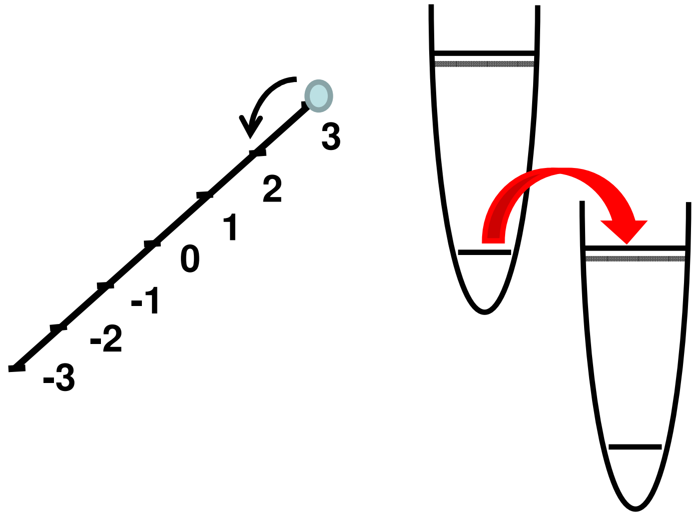
Magnetization changing collisions

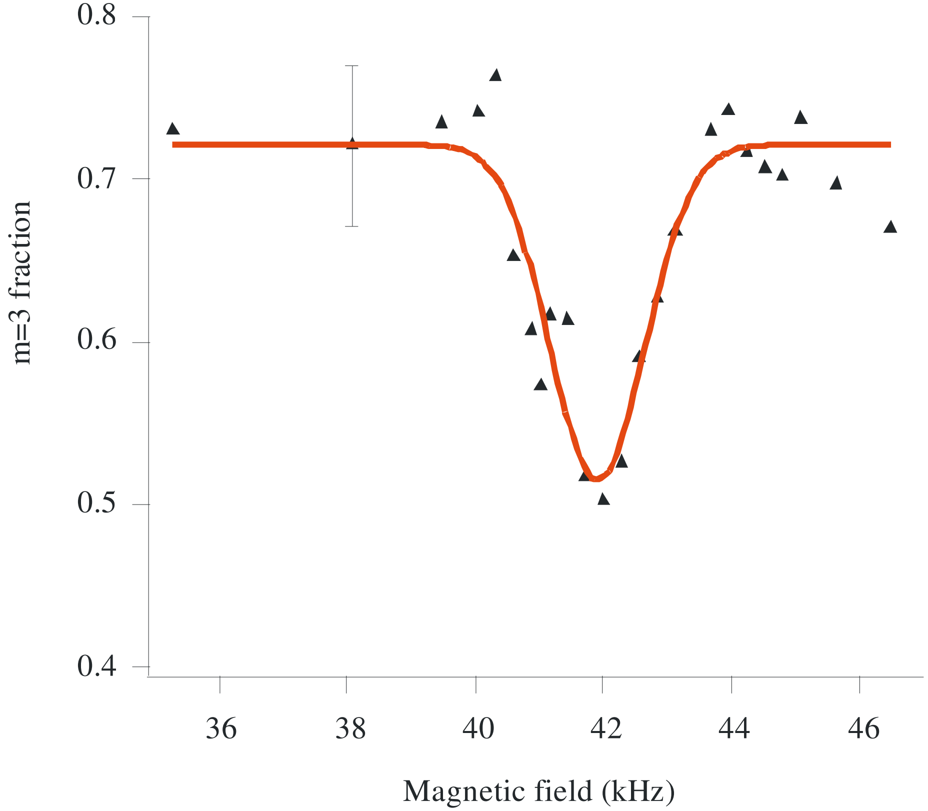
$$S_1^- S_2^-$$

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

Magnetization changing collisions

$$S_1^- S_2^-$$



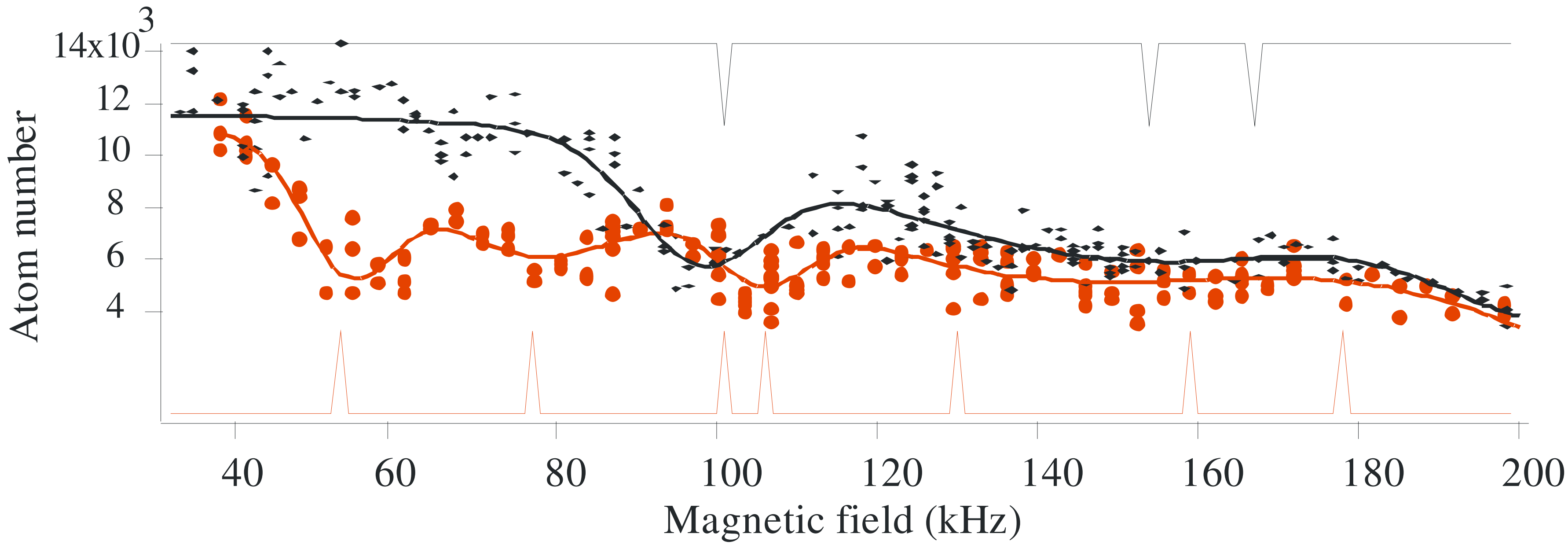


Dipolar resonance when released energy matches band excitation

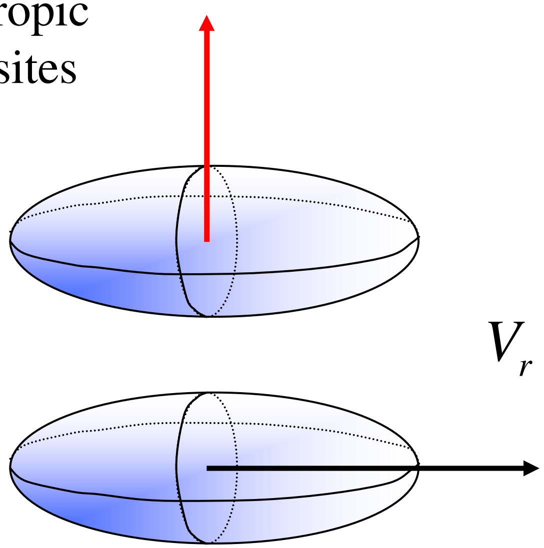
Towards coherent excitation of pairs into higher lattice orbitals ?
(Rabi oscillations)

Mott state locally coupled to excited band

Strong anisotropy of dipolar resonances



Anisotropic lattice sites



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

At resonance

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

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

$$S_1^- S_2^-$$

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

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)

Spin dynamics at constant magnetization

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

Other differences from Heisenberg magnetism:

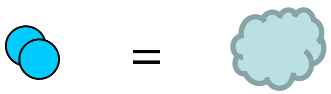
-Bosons…

-Not a spin ½ system: S=3

-Does not rely on Mott physics

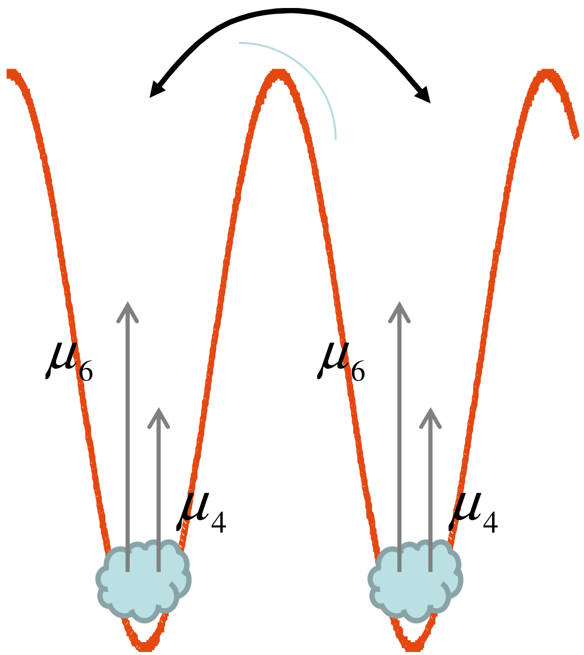
- Can have more than one atom per site

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

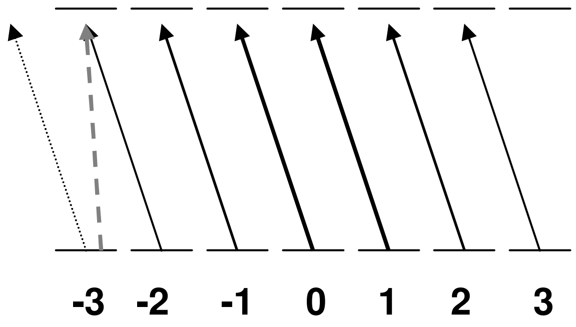


Effective S_t

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



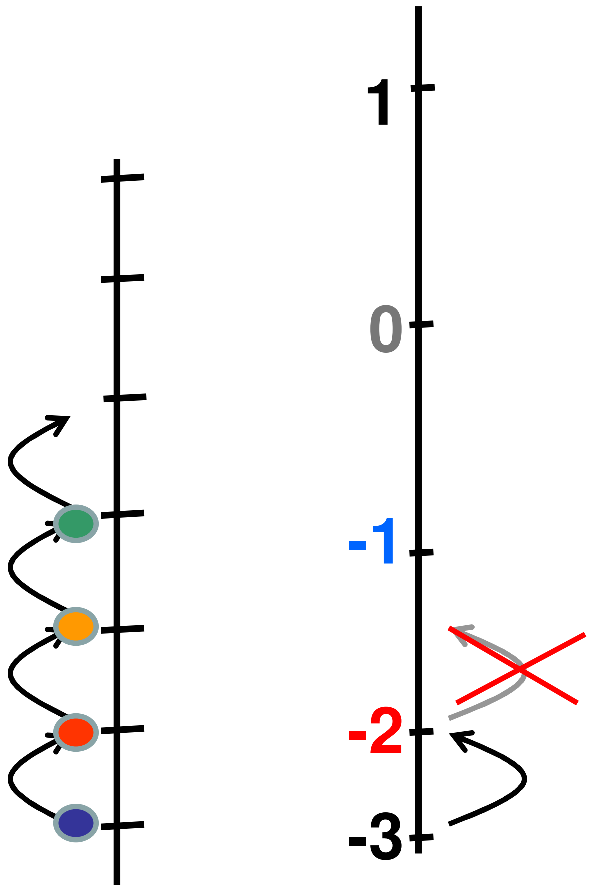
Control the initial state by a tensor light-shift



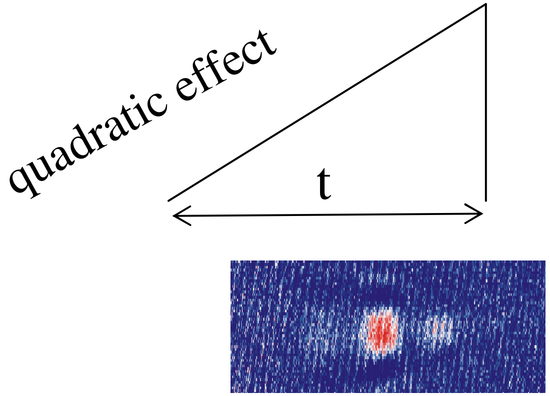
A σ− polarized laser
Close to a J→J transition
(100 mW 427.8 nm)

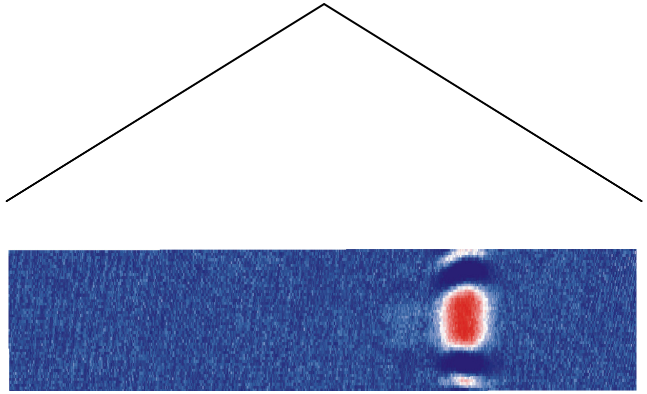
$$\Delta=\alpha\, m_S^2$$

Quadratic effect allows state preparation



Adiabatic state preparation in 3D lattice





-2 **-3**

(2 atomes / site)

Initiate spin dynamics by removing quadratic effect

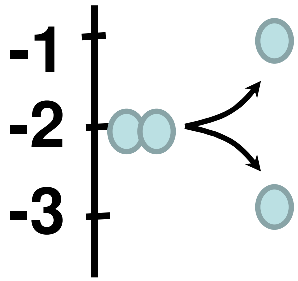
$$\left|m_S=-2, m_S=-2\right\rangle =$$
$$\sqrt{\frac{6}{11}}\left|S=6, m_{tot}=-4\right\rangle - \sqrt{\frac{5}{11}}\left|S=4, m_{tot}=-4\right\rangle$$

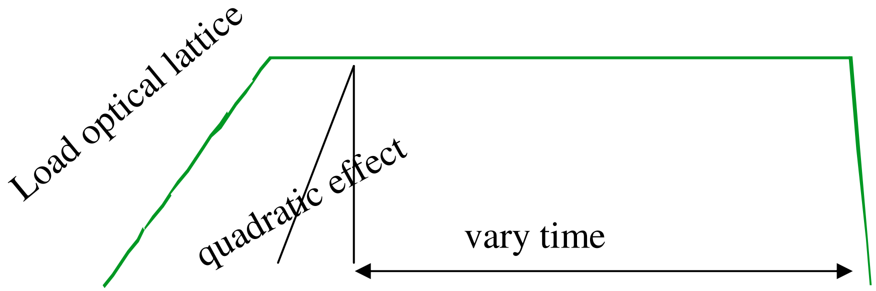
$$\left|-2,-2\right\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(\left|-3,-1\right\rangle + \left|-1,-3\right\rangle\right)$$

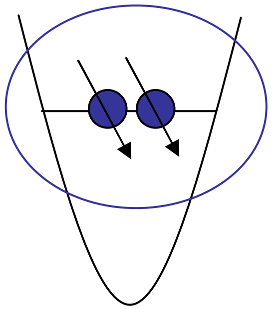
$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

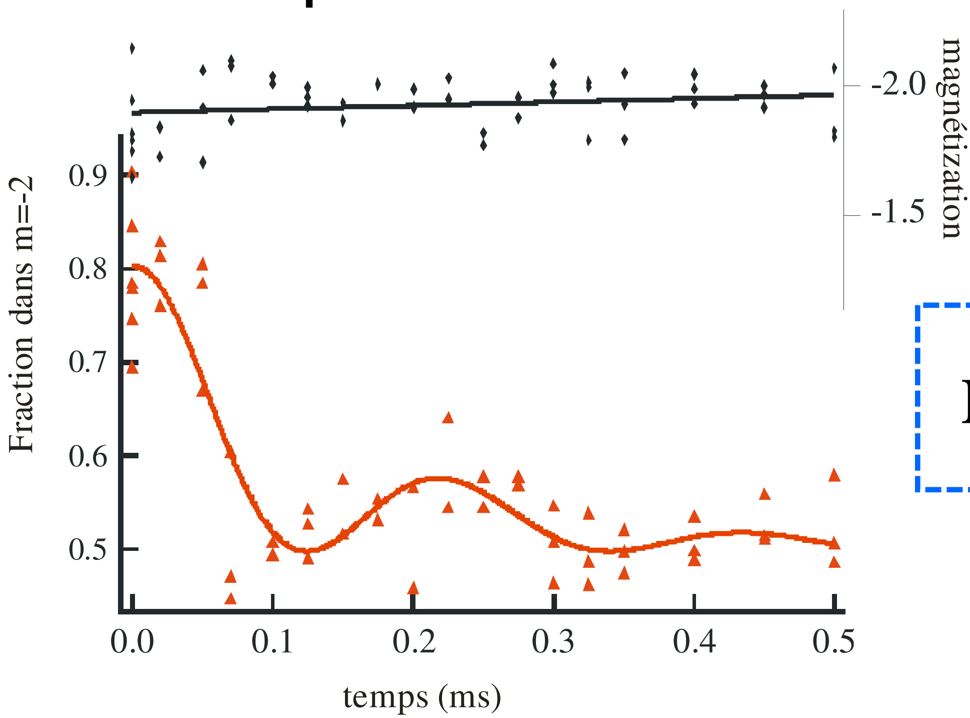
On-site spin oscillations

(due to contact oscillations)









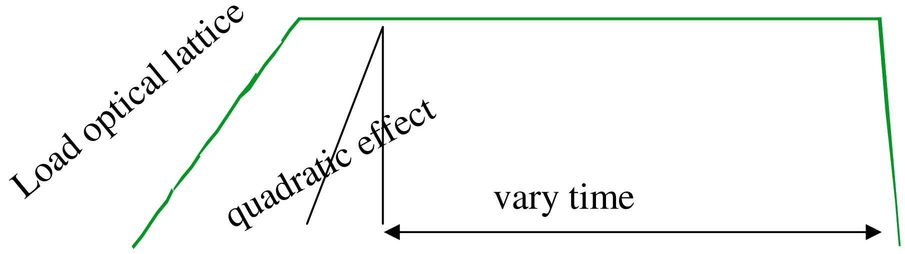
$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

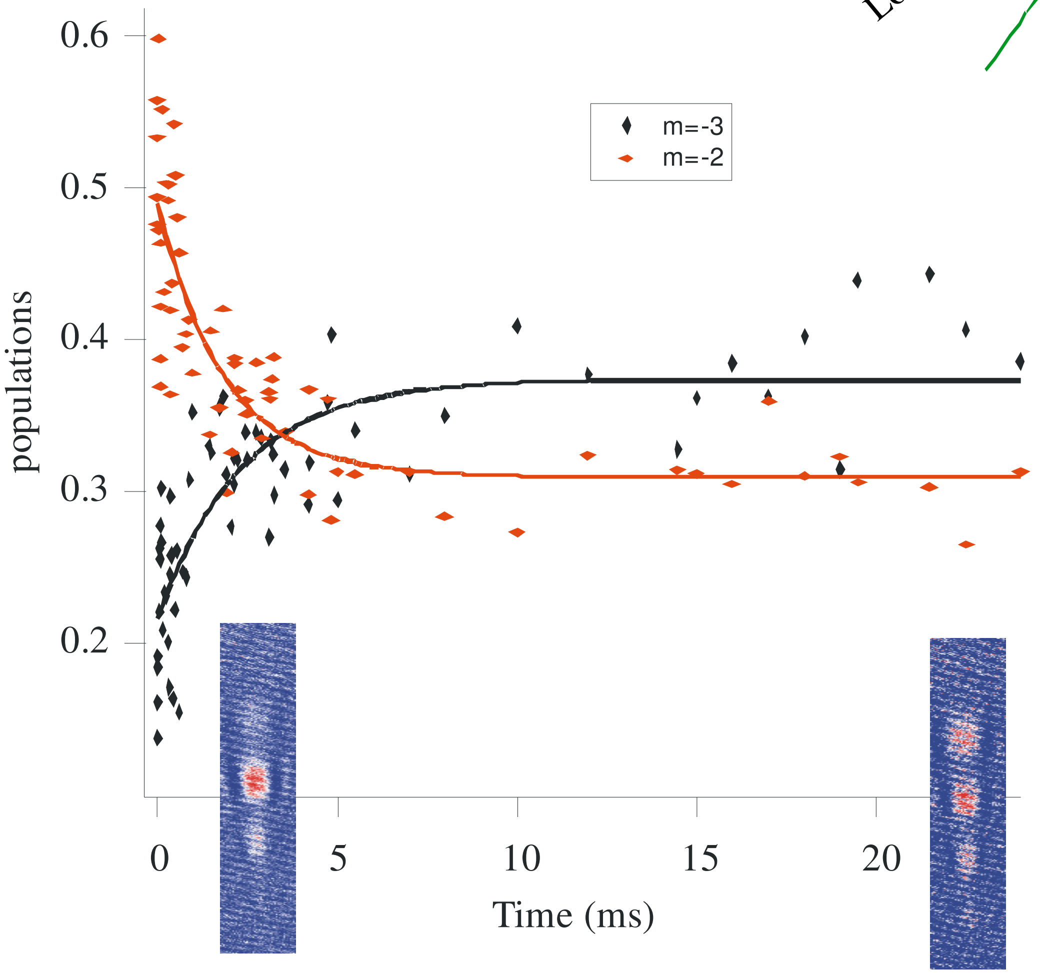
(perdiod ↔ 220 µs)

(↔ 250 µs)

Up to now unknown source of damping

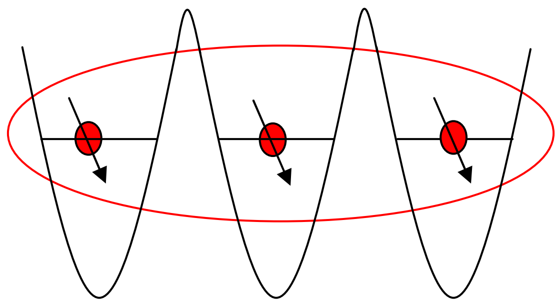
Long time-scale spin dynamics in lattice





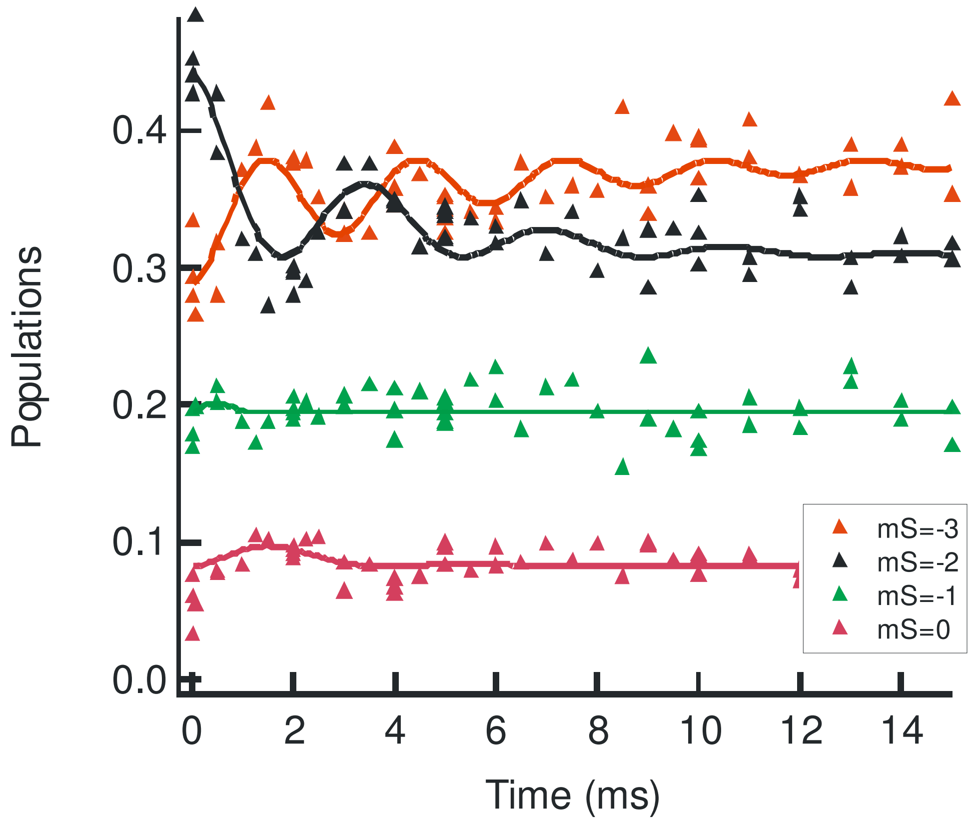
Sign for intersite dipolar interaction ?

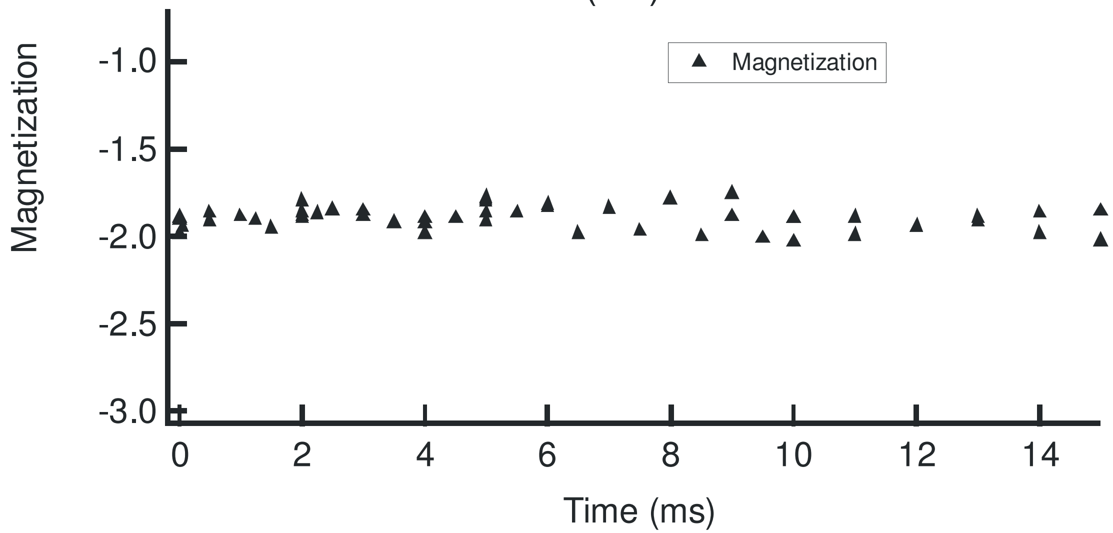
(two orders of magnitude slower than on-site dynamics)



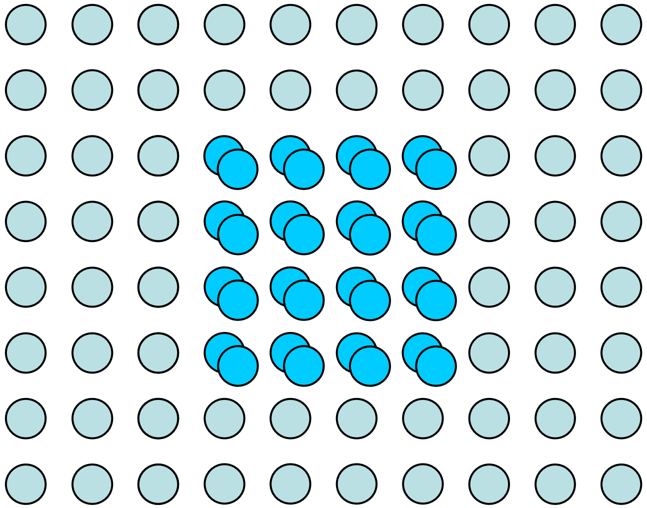
$$\frac{1}{2}\left(S_{1+}S_{2-}+S_{1-}S_{2+}\right)$$

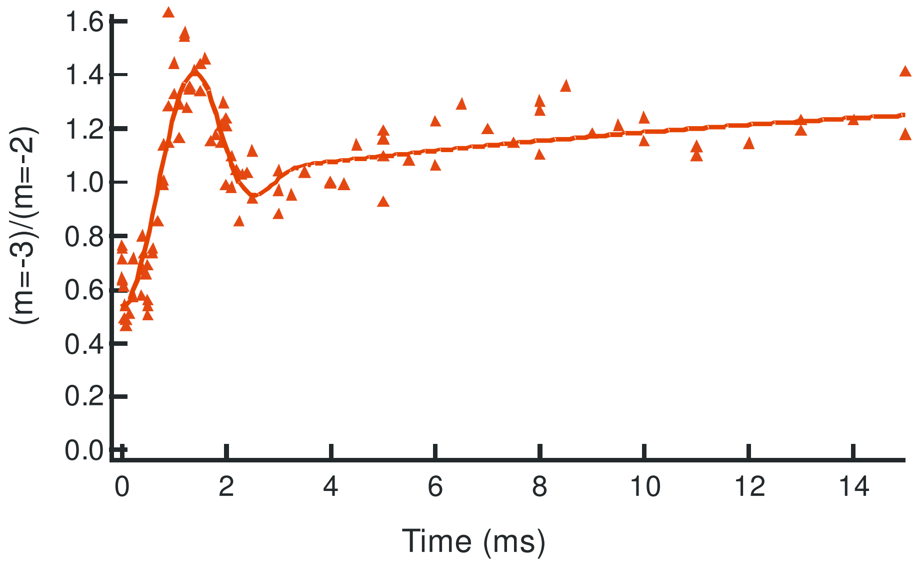
Observation of spin oscillations at constant magnetization

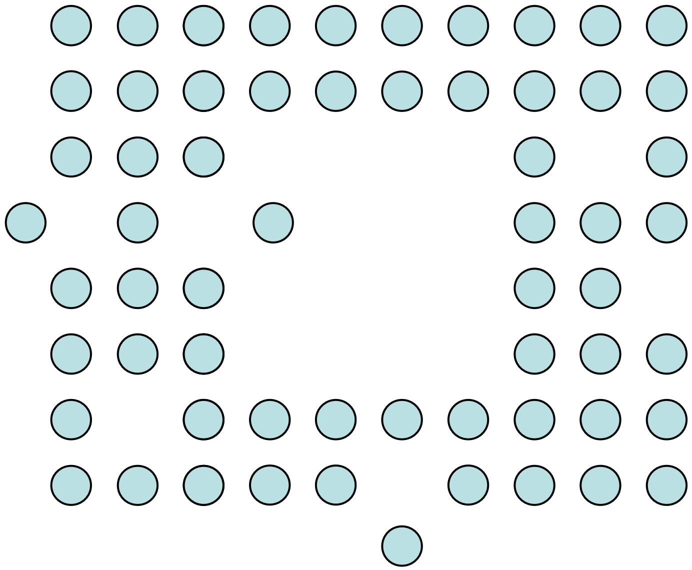


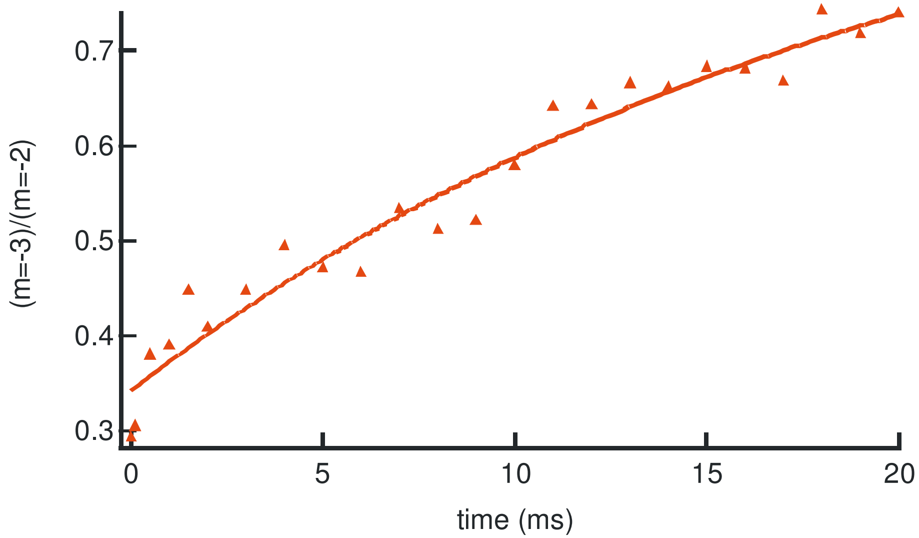


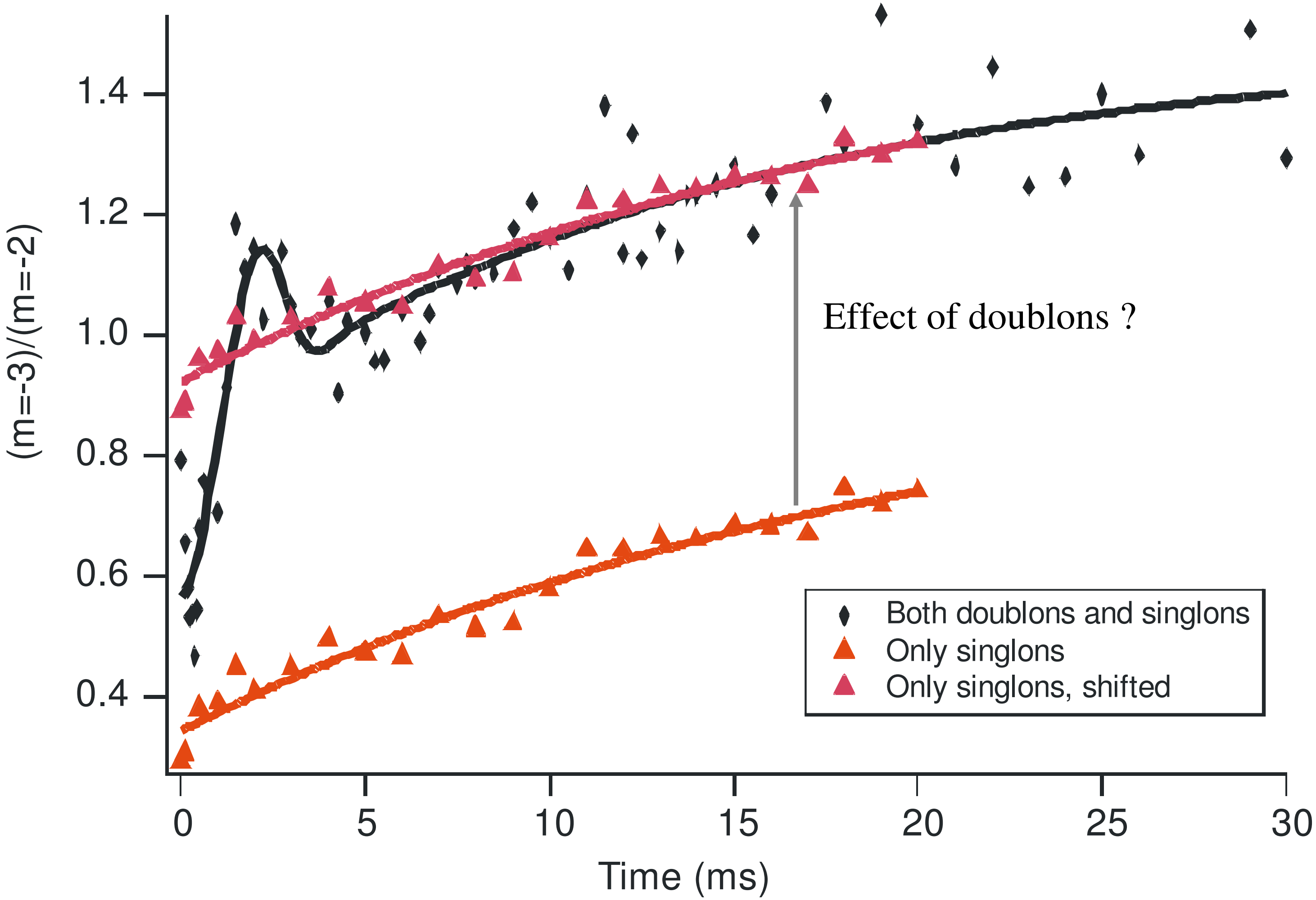
Oscillations arise from interactions between doubled-occupied sites









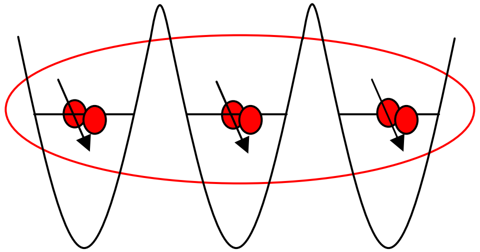


(m=-3)/(m=-2)
1.4
1.2
1.0
0.8
0.6
0.4
0
5
10
15
20
25
30
Time (ms)
Effect of doublons ?
Both doublons and singlons
Only singlons
Only singlons, shifted

Our current understanding:

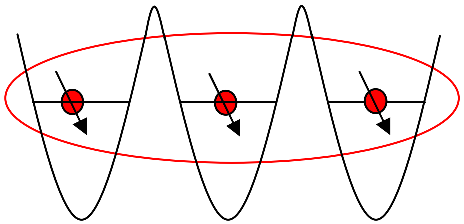
$$S_{1z}S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

Spin oscillations due to inter-site dipolar exchange between doublons



Timescale = 6 ms

Long time-scale dynamics due to inter-site dipolar exchange between singlons



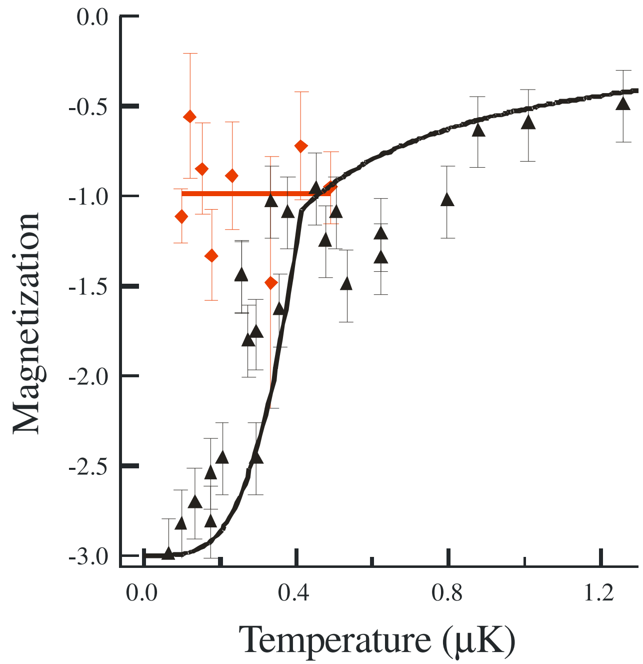
1/e timescale = 25 ms

Current theoretical modelling:

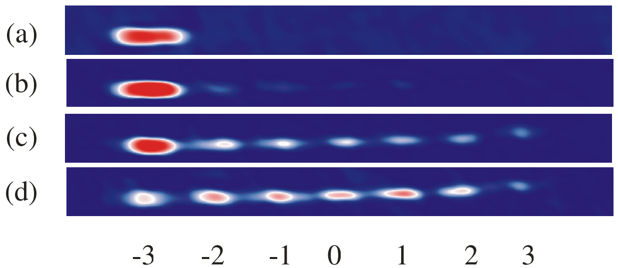
Exact diagonalization 2 pairs, 2 sites : exchange timescale = 15 ms

Exact diagonalization 2 atoms, 2 sites : exchange timescale = 50 ms

Conclusions

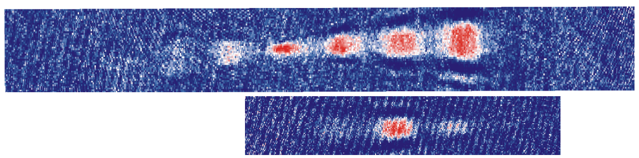


Magnetization changing dipolar collisions introduce the spinor physics with free magnetization



New spinor phases at extremely low magnetic fields

Tensor light-shift allow to reach new quantum phases



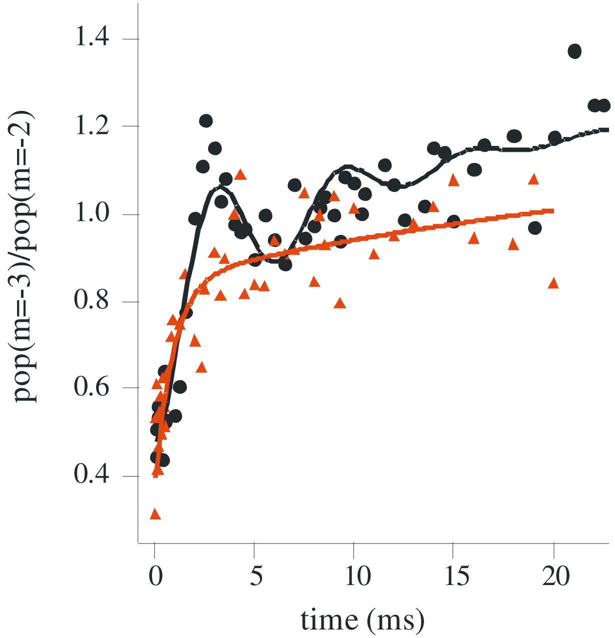
Magnetism in lattice

Resonant magnetization dynamics

Towards Einstein-de-Haas effect

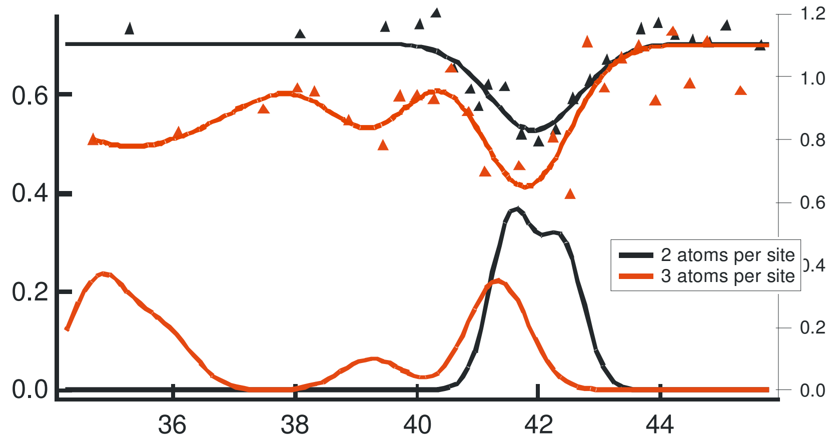
Anisotropy

Few body vs many-body physics



Spontaneous depolarization at low magnetic field

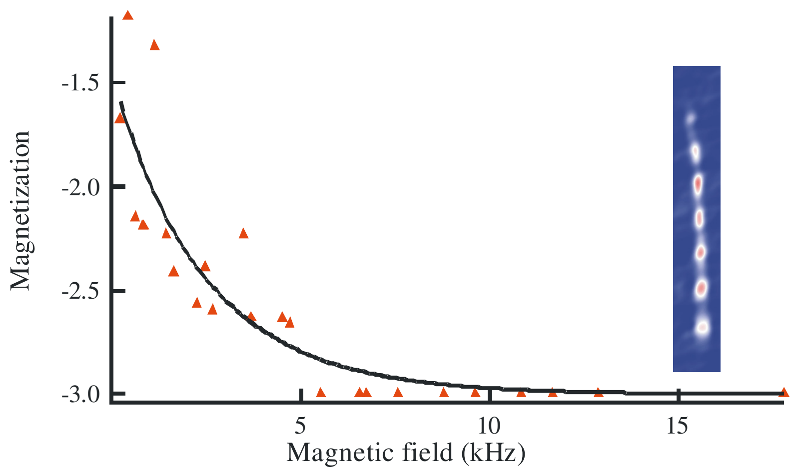
Towards low-field phase diagram



Away from resonances: spin oscillations

Spin-exchange

Dipolar 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