Non-equilibrium physics of many interacting large spins

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Collaborators: Johnny Huckans, Perola Milman, Rejish Nath,

I am against any nationalism, even in the guise of mere patriotism. - Albert Einstein

Atoms are composite objects, whose spin can be larger than 1/2

$$\vec{F} = \vec{S} + \vec{I}$$

Large spin magnetism

Spinor condensates
Stamper-Kurn, Lett, Klempt, Chapman, Sengstock, Shin, Gerbier

e.g. Na, Rb

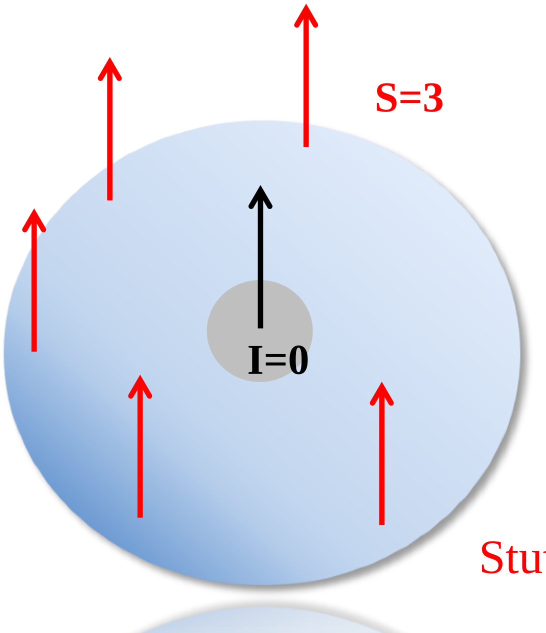
F=0,2

Alkali: spin arrises both from nuclear and electronic spins
Spin-dependent interactions

SU(N) magnetism
Bloch, Fallani, Ye, Takahashi,…

e.g. Sr, Yb

Alkaline-earth: spin is purely nuclear
Spin-independent interactions



« magnetic atoms »: spin is purely electronic

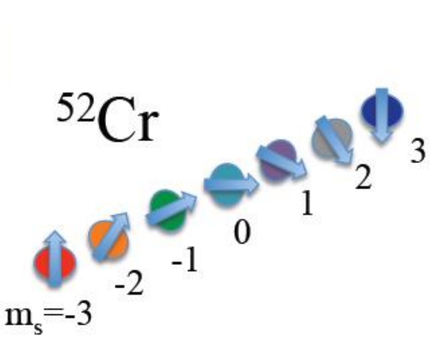
e.g. Cr, Er, Dy

Strong dipole-dipole interactions

Stuttgart, Paris, Innsbruck, Stanford

This seminar: magnetism with large spin cold atoms (Chromium atoms)

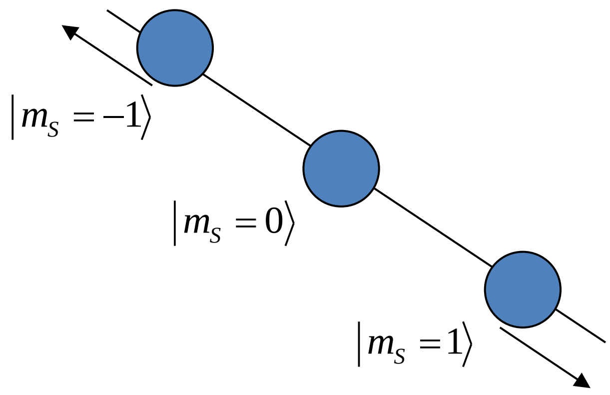
Optical dipole traps equally trap all Zeeman state of a same atom

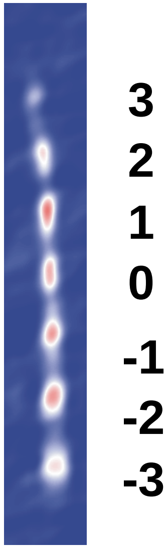


Linear (+ Quadratic)
Zeeman effect

$$E(m_S) = m_S g \mu_B B\left(+\alpha B^2\right)$$

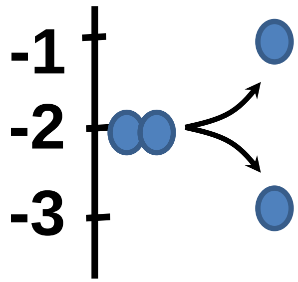
Stern-Gerlach separation:
(magnetic field gradient)



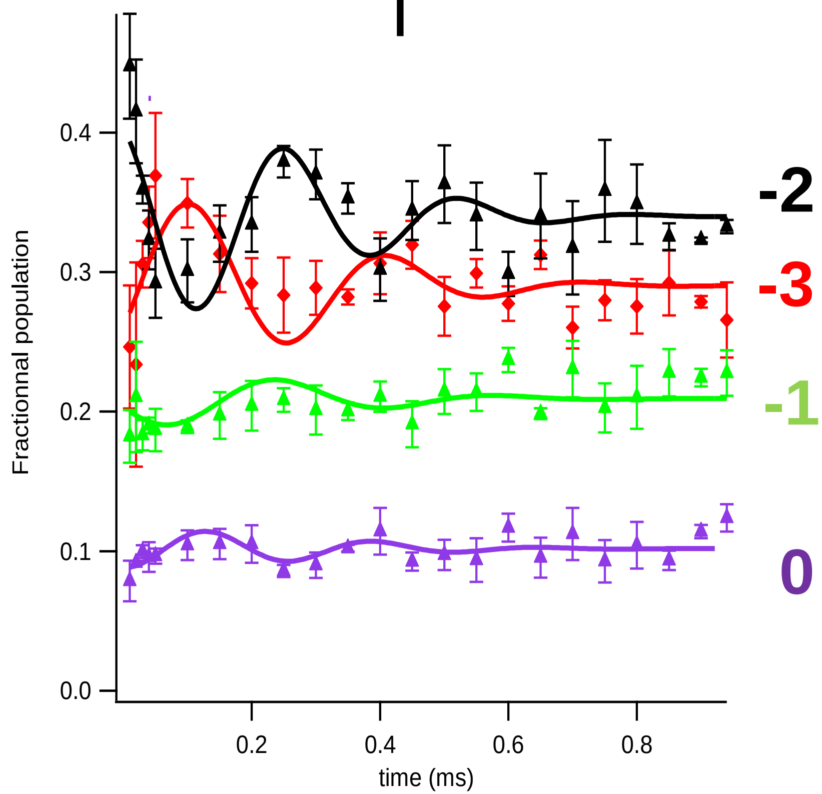


Two main players for magnetism and spin dynamics (1):

Spin-dependent contact interaction:
scattering length depends on molecular channel



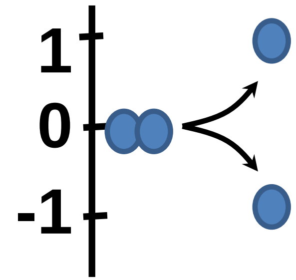
Contact exchange

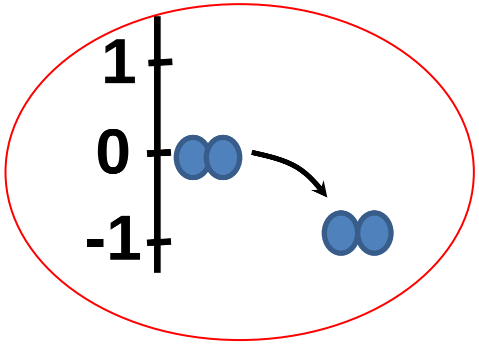


$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

Second main player:

Dipolar Exchange **Relaxation**





Dipole-dipole interactions

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

Heisenberg model of magnetism

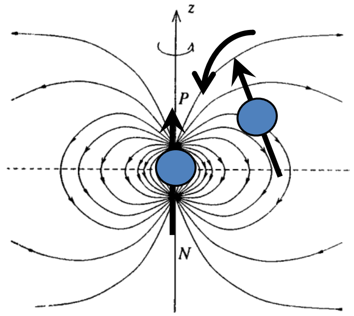
$$\Gamma \propto \frac{t^2}{U} \boxed{S_{1z} S_{2z} + \frac{1}{2}\left(S_{1+} S_{2-} + S_{1-} S_{2+}\right)}$$

Ising Exchange

Super- Exchange

Nuclear Magnetic Resonance

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



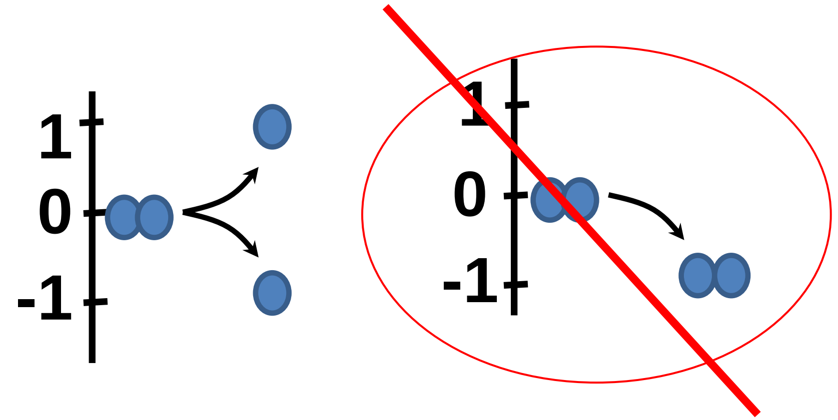
!!! Anisotropy !!! Long Range !!! Large Spin !!!

Second main player:

Dipole-dipole interactions

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

Dipolar Exchange **Relaxation**



Heisenberg model of magnetism

$$\Gamma \propto \frac{t^2}{U} \left[S_{1z} S_{2z} + \frac{1}{2}\left(S_{1+} S_{2-} + S_{1-} S_{2+}\right) \right]$$

Ising Exchange

Nuclear Magnetic Resonance

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

Ising Exchange

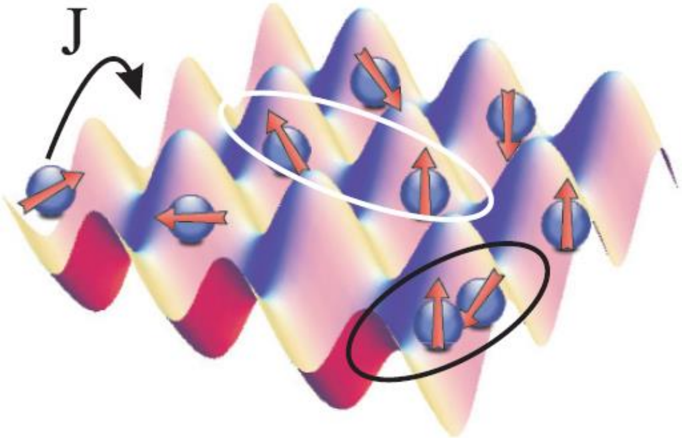
!!! Non-Heisenberg !!! Anisotropy !!! Long Range !!! Large Spin !!!

This Experiment

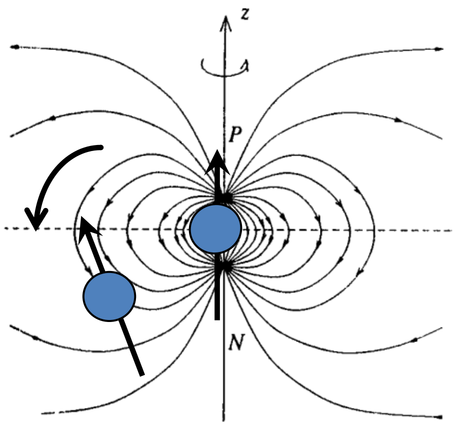
I – Excite the spins

II – Free evolution under the effect of interactions

Questions: Under which conditions is there spin dynamics ?
Do quantum correlations develop?



Under which conditions correlations develop? – Classical vs Quantum magnetism

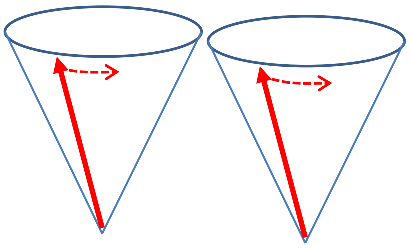


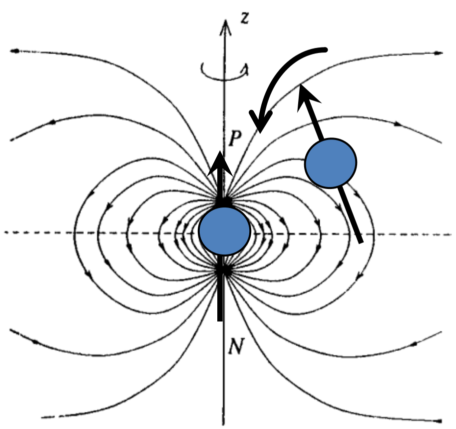
$$\vec{B}_A(B) = \vec{B}_B(A)$$

Classically:

These two atoms undergo identical precession

Total spin conserved

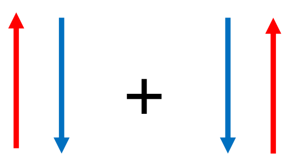




Quantum-mechanically:

Possibility for entanglement

Total spin is NOT conserved

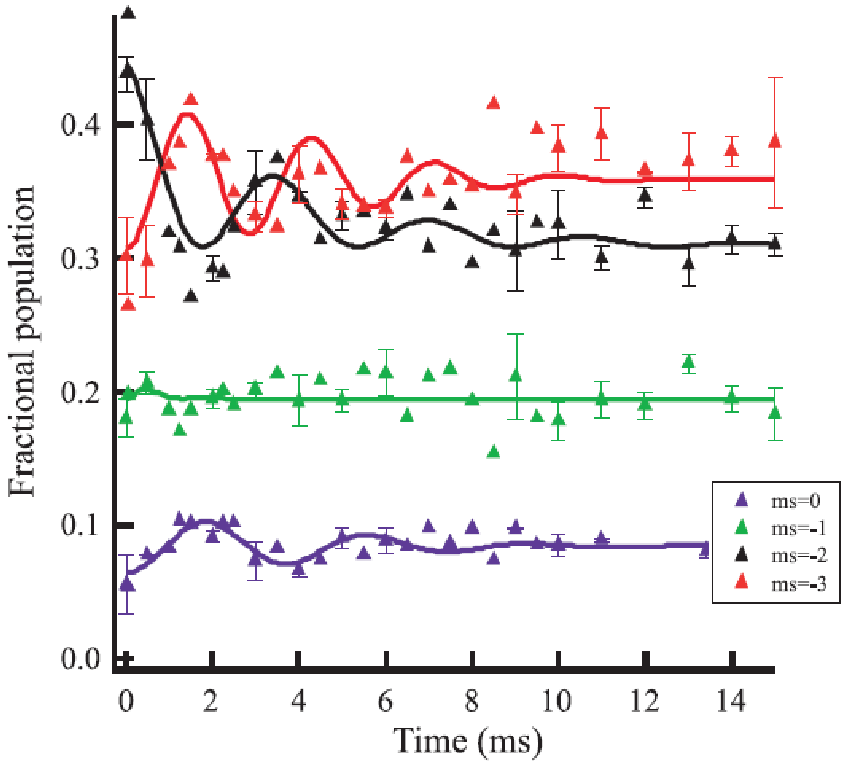


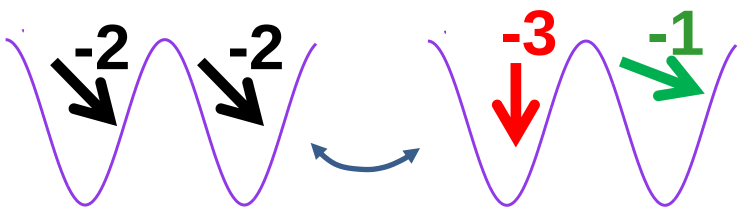
From classical to quantum: dipolar interactions may create correlations

Observation of intersite spin-exchange due to dipolar interactions

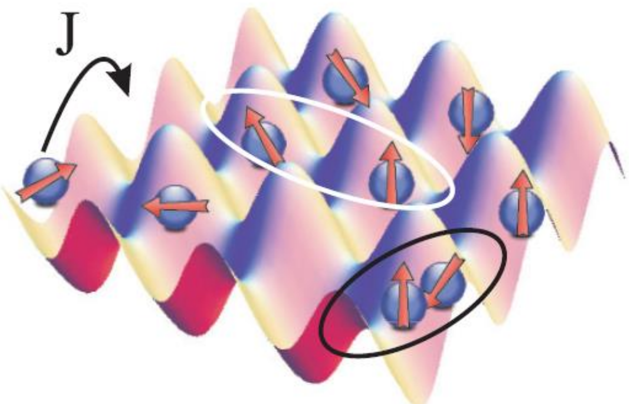
$$\Psi(0) = \left|2,2,....,2,2\right\rangle$$

Start with one atom in each site of a 3D optical lattice in one Zeeman state $m_s=2$



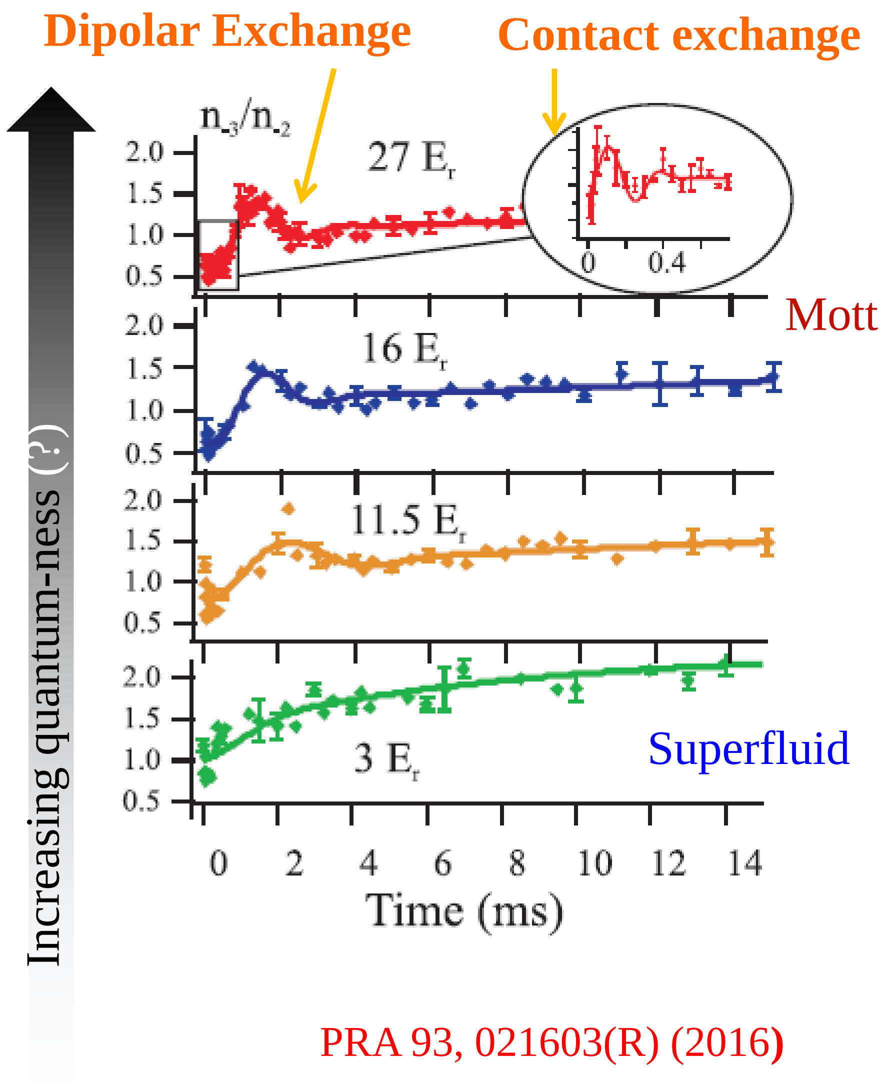


Dynamics inherently many-body
Mean-field theories fails



PRL, 111, 185305 (2013) see also Ye/Jin, Nature 2013

Exotic quantum magnetism of large spin, from Mott to superfluid



PRA 93, 021603(R) (2016)

An exotic magnetism driven by the competition between three types of exchange

Super- Exchange (I)
(nearest neighbor)

$$\Gamma \propto \frac{t^2}{U}$$

Dipolar exchange (II)
(true long range)

$$V_{dd}$$

Contact exchange (III)
(short range)

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

Mean-field theories fail; exact diagonalization techniques unrealistic…

But perturbation theory helps (a little)

$$\Psi_0 = \left|2,2,....,22\right\rangle \to \Psi_1 \propto \sum_{(i,j)} V_{(i,j)} \left|2,2,...2,\underset{(i)}{1},2,...2,\underset{(j)}{3},2,2\right\rangle$$

$$\Gamma = \sqrt{\sum_{(i,j)} \left(V_{(i,j)}{}^2\right)} \qquad \left[= \left\langle \Psi_0 \left| \sum V_{(i,j)} \right| \Psi_1 \right\rangle \right]$$

$$\left[\neq \int dr' V_{dd}(r-r') n(r') \right]$$

Good agreement with data, see: PRA 93, 021603(R) (2016)

Example 2 : tilt atom with an rf pulse

$$\left|S_\perp\right|(t) \underset{t\to 0}{\approx} \left|S_\perp\right| \left(1 - t^2 \left[\Delta B^2 + \frac{1}{N} \sum V_{i,j}^2 \right] \right)$$

PRL 110, 075301 (2013)

Classical inhomogeneous precession (↔variance of mean-field)

Beyond mean-field

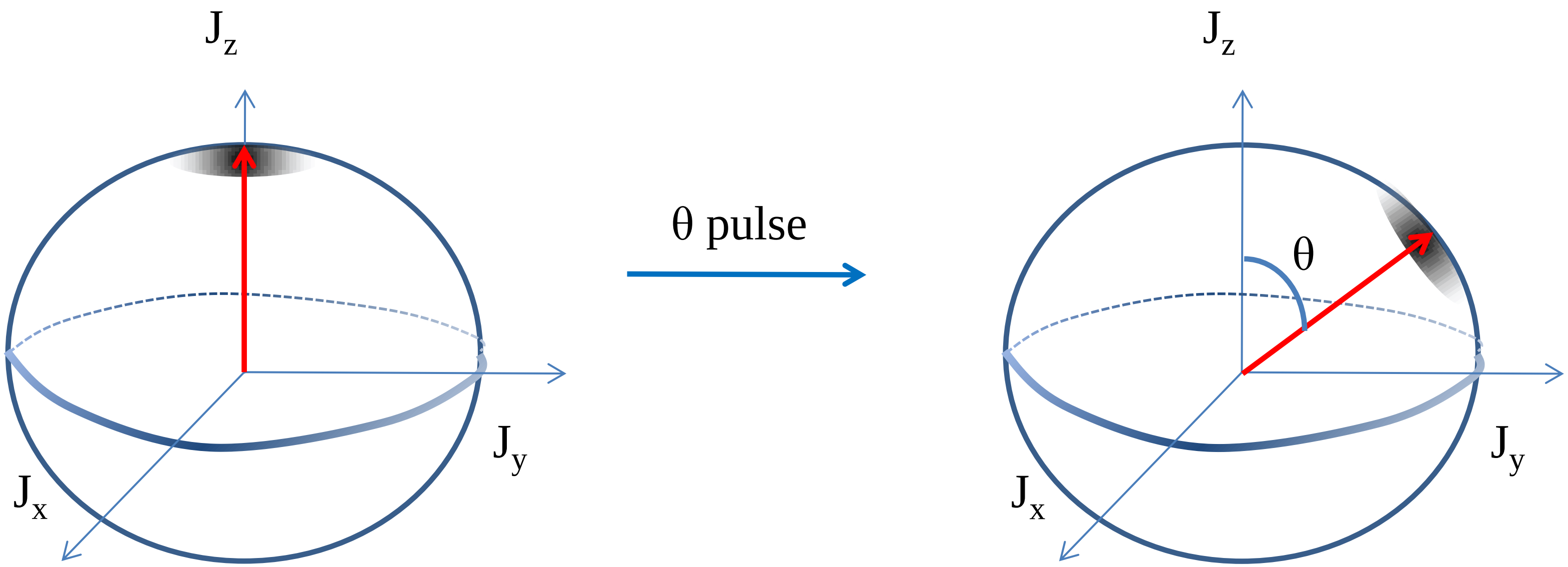
Outline

Spin dynamics after tilting spins
(rf pulse)

I BEC case

II Lattice case

Dynamics after tilting the spins



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

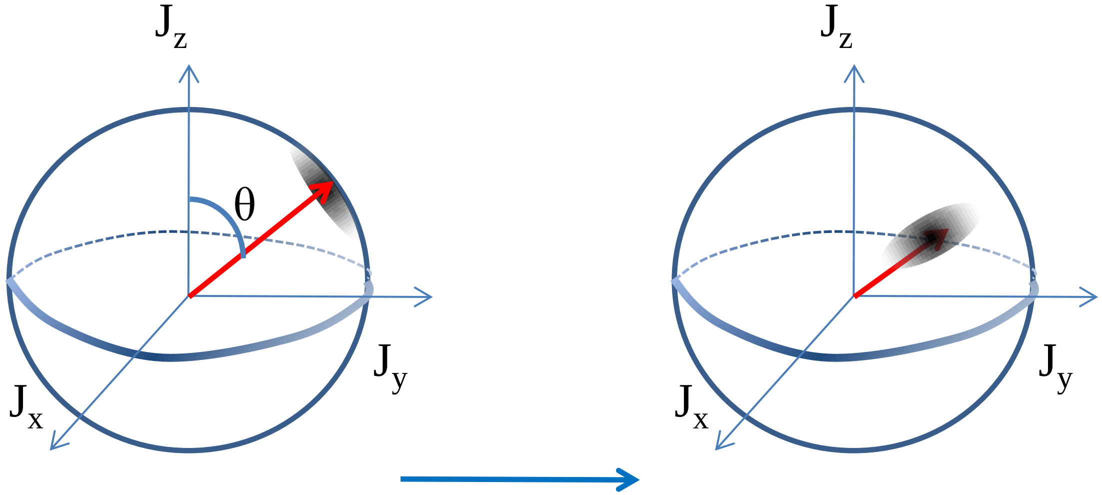
Prediction (Ana Maria Rey):

θ small → classical precession
θ large → entanglement grows

See also E. Witkowska, PRA 93, 023627 (2016)

Note !! Spin-dependent contact interactions trigger NO spin dynamics !!
The initially stretched state remains stretched after any rf pulse

After tilting the spin: from classical to quantum



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

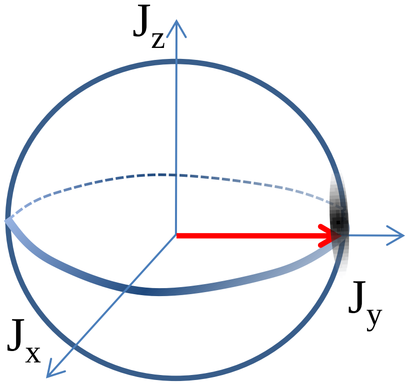
Interpretation: **dynamics comes from the difference to the Heisenberg Hamiltonian**

$$-\frac{1}{2}\left[S_{1z}S_{2z} + \frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)\right] = -\frac{1}{2}\vec{S}_1.\vec{S}_2$$

$$\delta H \propto S_{1z}S_{2z} \underset{t\to 0}{\approx} S_z^2$$

Squeezing ↔ Variance (S_z)

The specific case of π/2 pulse: mean-field dynamics vanishes



$$\vec{B}_{dd}(r) = \gamma \int dr' \frac{1-3r_z^2}{|\vec{r}-\vec{r}'|^3}\left(3S_z(\vec{r}')\vec{z} - \vec{S}(\vec{r}')\right)$$

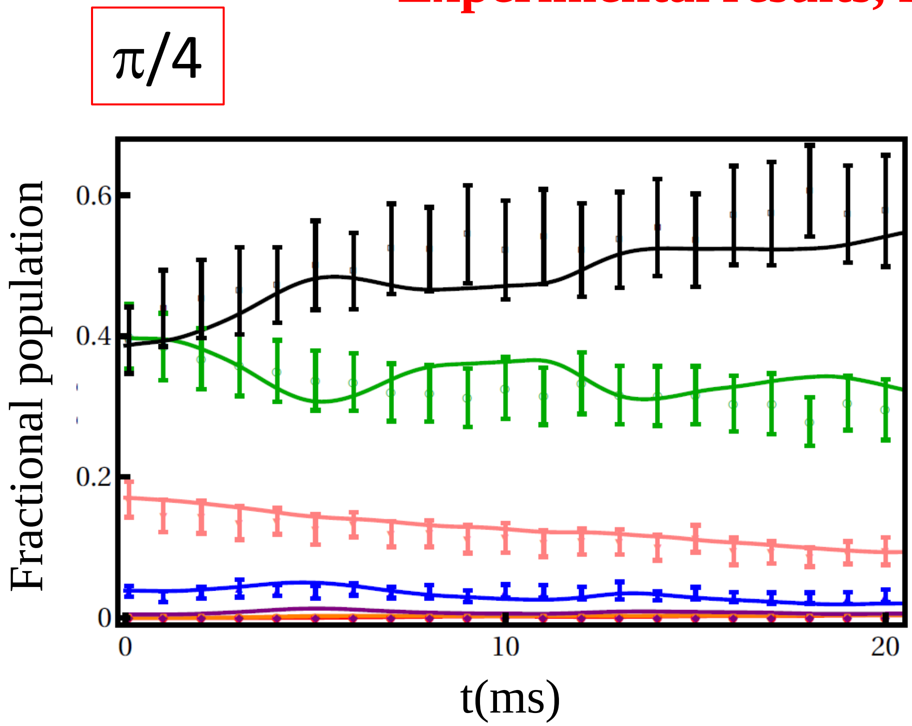
$$\Gamma \propto \vec{B} \times \vec{S}$$

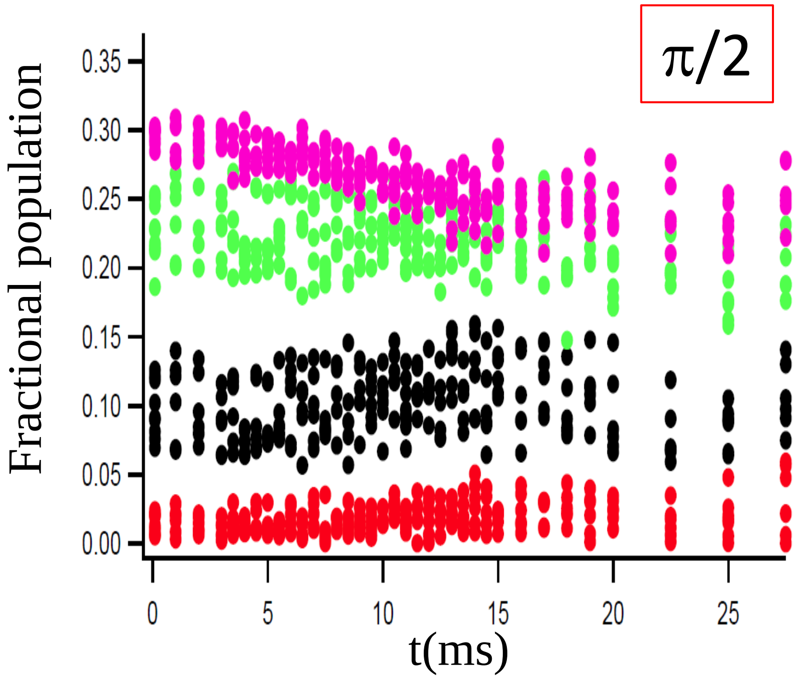
At π/2 S_z=0

Assuming a BEC initially polarized in ms=3, mean-field theory predicts **no spin dynamics!**

In principle, any dynamics seen is a beyond-mean-field effect (or is it ?)

Experimental results, BEC case…





Dynamics entirely triggered by dipolar interactions!

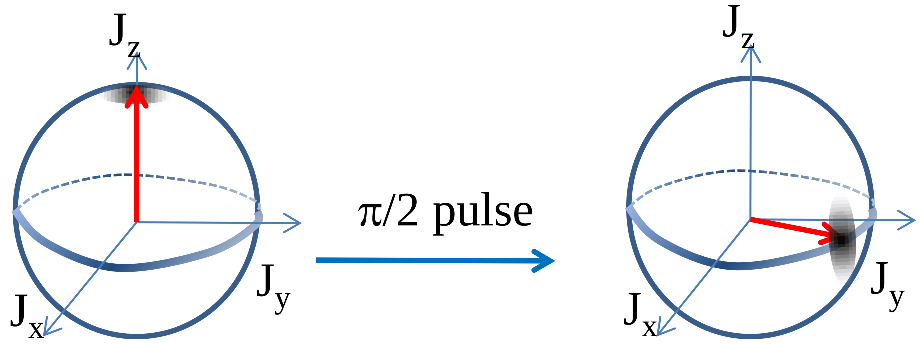
Theory
Pedri/Kechadi
Zhu/Rey

Dynamics vanishes for large angles close to π/2

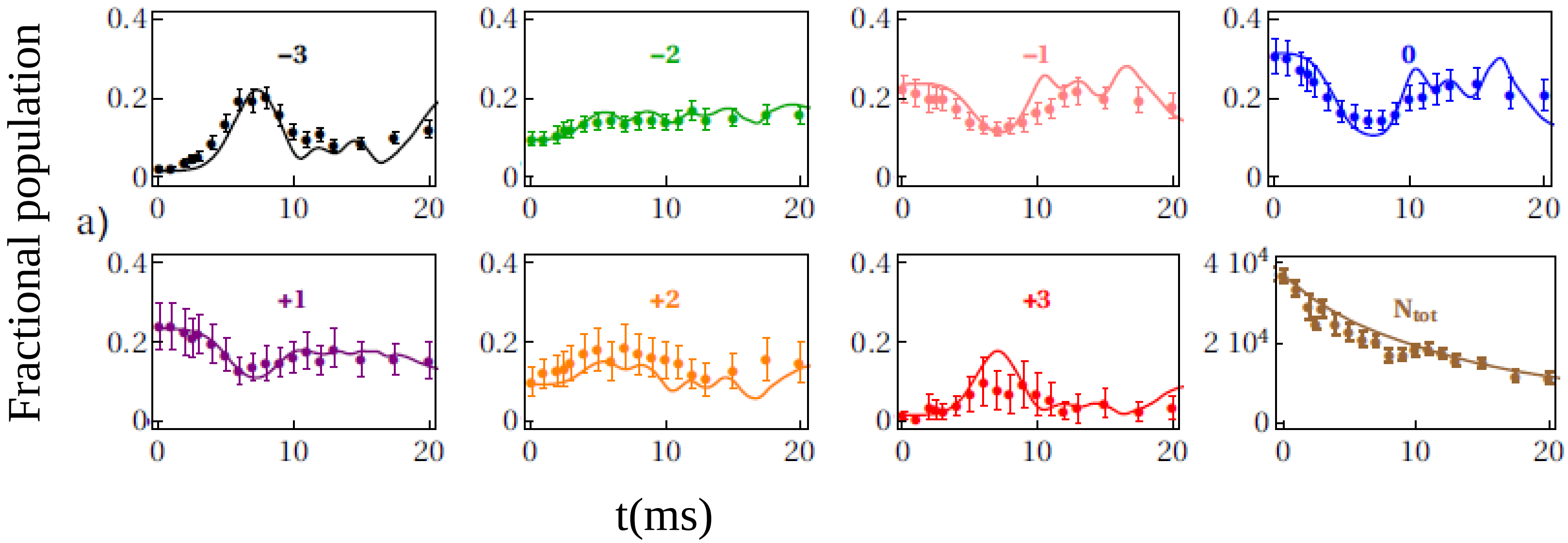
Beyond mean-field effects too small to be observed ??

Which would be the conditions ? $\left[\sqrt{\sum_{(i,j)} \left(V_{(i,j)}{}^2\right)} \Leftrightarrow 10ms\right]$

Trigger spin dynamics using magnetic field gradients



GP- Theory :
Pedri/Kechadi
Zhu/Rey

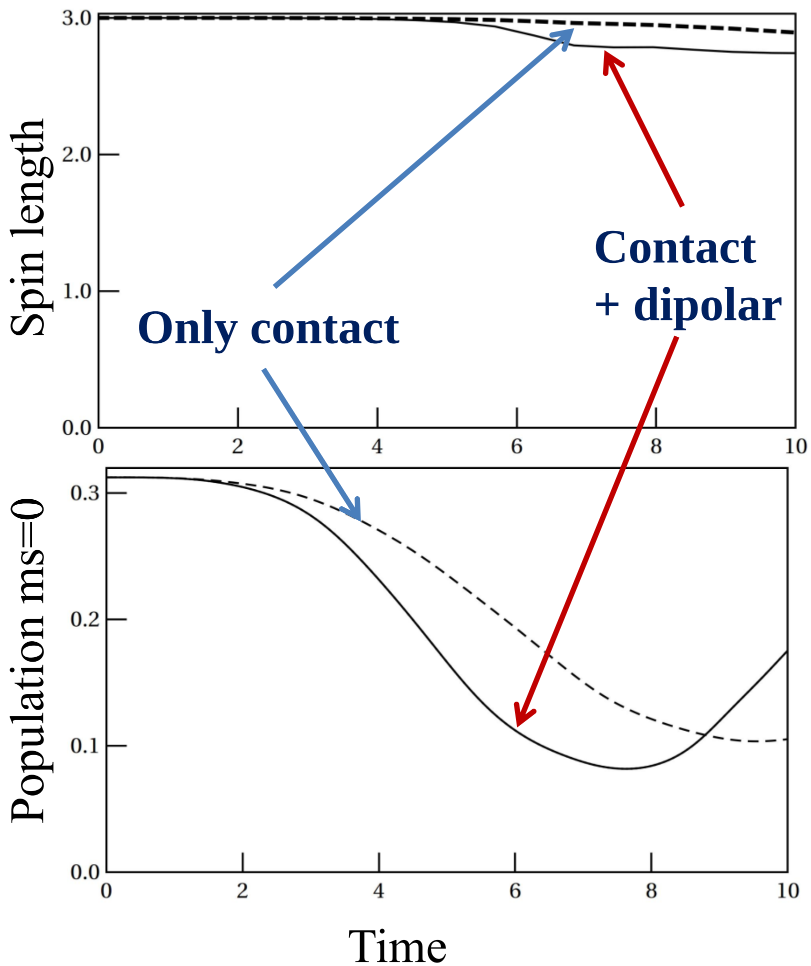


Dynamics is triggered by the existence of a B-field gradient

Dynamics reproduced by mean-field theory!

The unexpected ferromagnetic behavior of an anti-ferromagnetic gas

The spinor remains almost locally locked to total spin 3

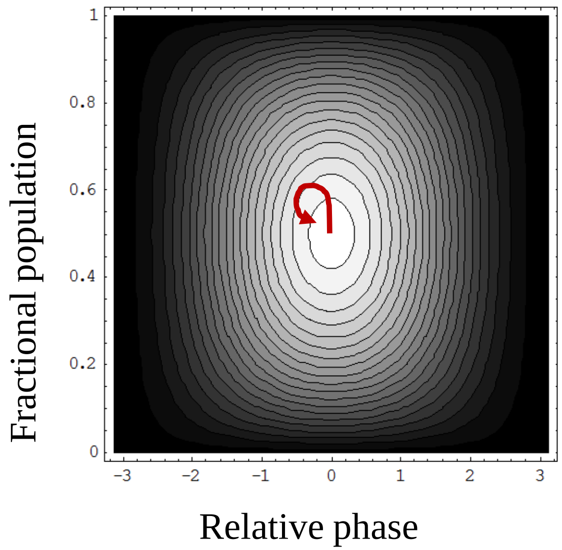


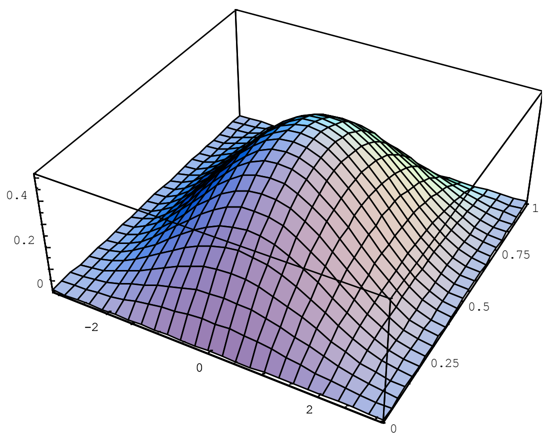
(Spin length characterizes the local polarized character)

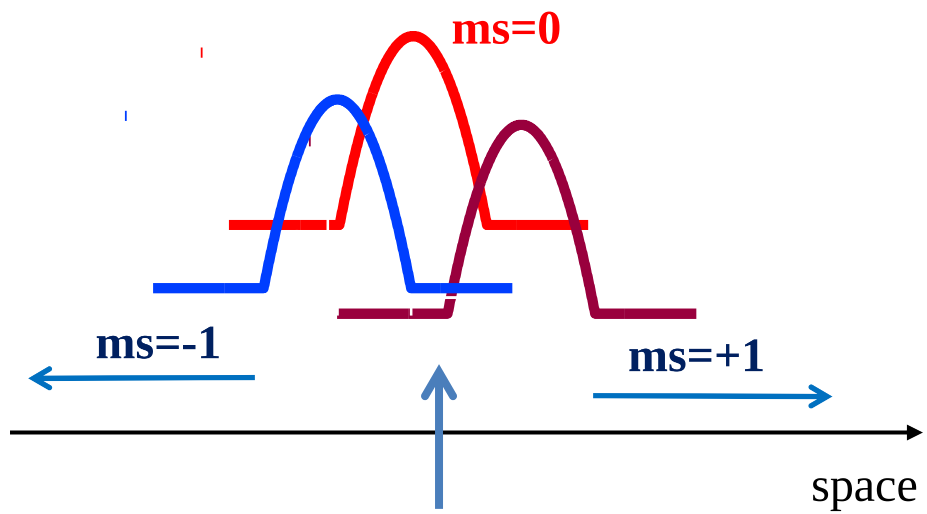
Atoms remain locally polarized in a stretched state (and therefore interact through S=6)

This is a surprise because $a_6 > a_4 \rightarrow$ equilibrium favors depolarization

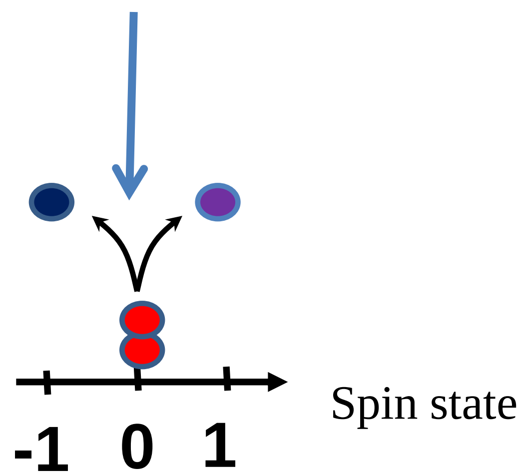
Interpretation: locally, spinor is at a maximum of the interaction energy. Magnetic field gradients cannot change the spinor structure without violating energy conservation







Local structure of spinor
- modified by gradient
- Restaured by spin-exchange



A simplistic and general equation describes spin-dynamics

gradient

$$\frac{p_{m_s}(t)}{p_{m_s}(0)} = 1 + \left(\frac{g\mu_B b}{2Mw}\right)^2 \left(m_s^2 - \sum_{m_{s'}} m_{s'}^2 p_{m'_s}(0)\right) t^4$$

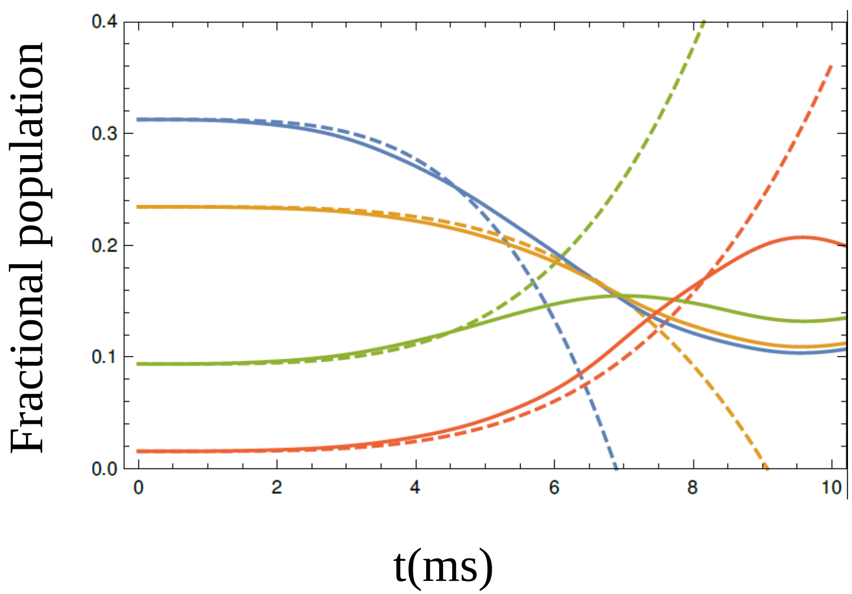
Radius BEC

(in practice independent of spin-dependent interactions)

All the spin-dependent interactions do is undo whatever population imbalance the magnetic field gradient creates !

Natural timescale

$$\tau = \left(\frac{2Mw}{g\mu_B b'}\right)^{1/2}$$



Speculation on why we do not observe beyond mean-field effects

??? Can beyond mean-field effect be observed if strong spin-dependent interactions favor ferromagnetism ???

Outline

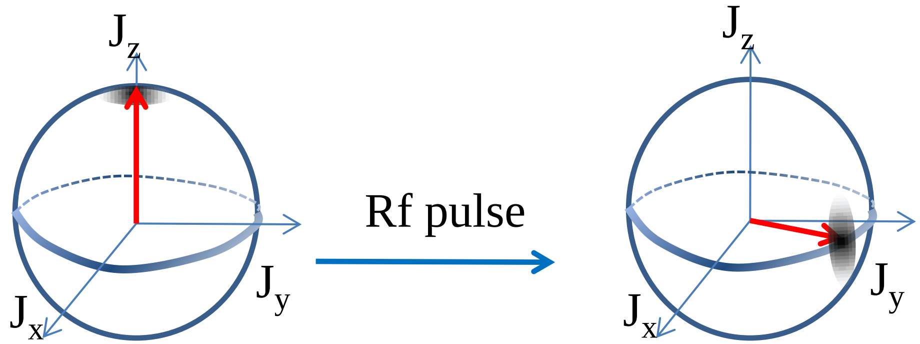
Spin dynamics after tilting spins
(rf pulse)

I BEC case

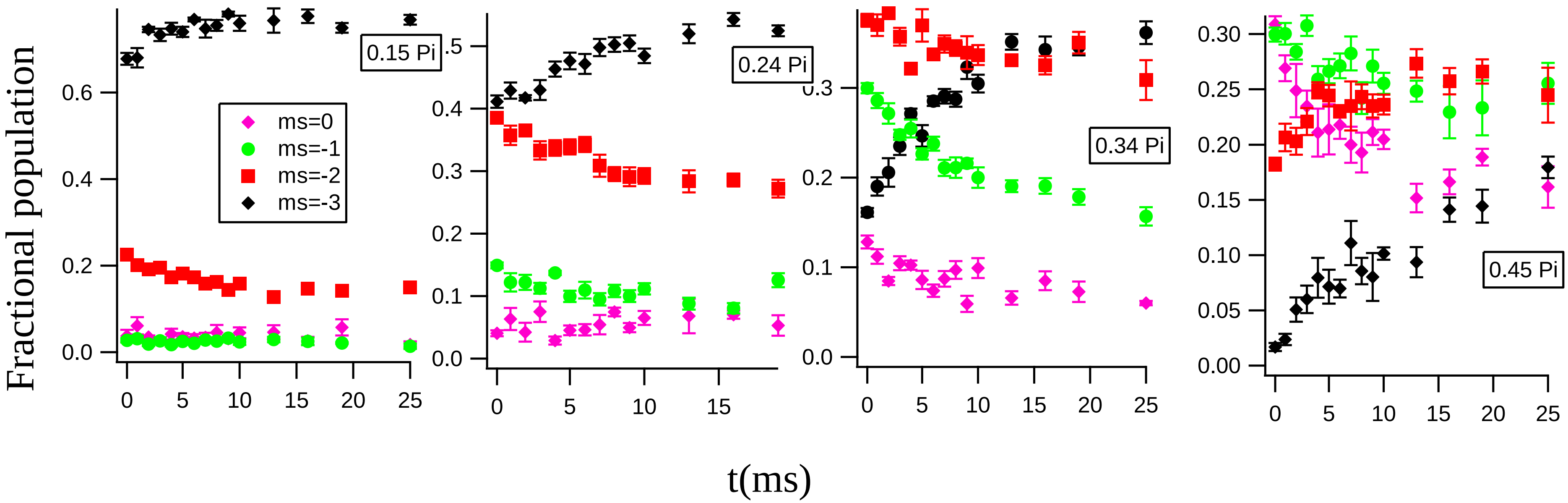
II Lattice case

Mott state, one atom per lattice site

Experimental results, lattice case…



Preliminary

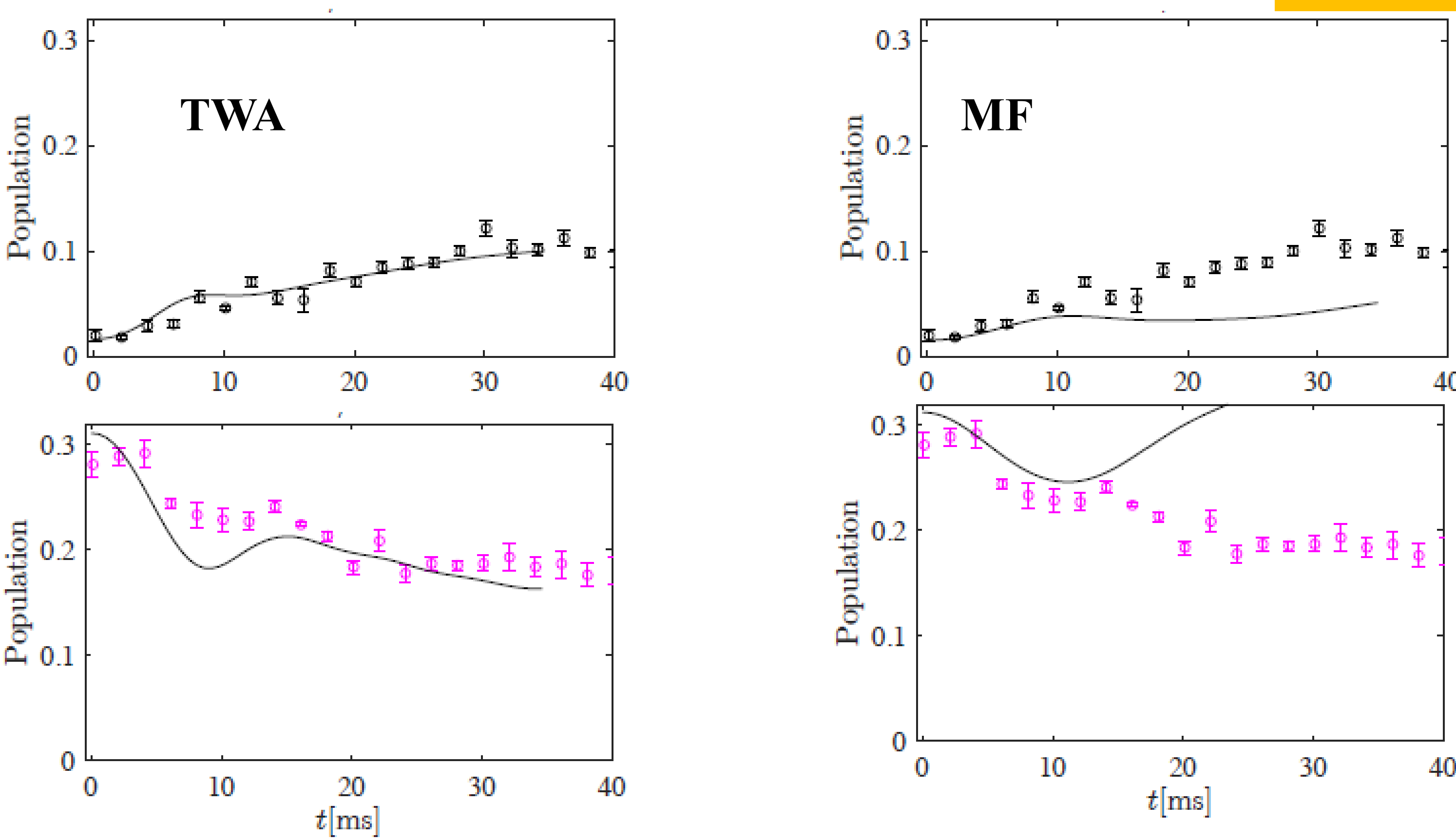


Increasing quantum-ness is expected

How to probe for beyond mean-field effects?

new numerical models being developped in A. M. Rey's group (TWA)
(J. Schachenmayer, B. Zhu).

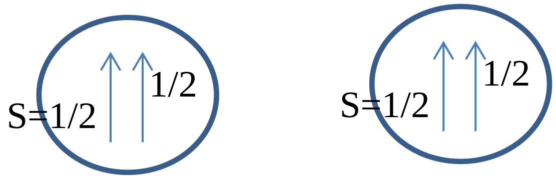
Preliminary



Beyond mean-field theory agrees significantly better
A very good test of the theory for large atom numbers
(no plaquette simulation available)

How to probe for beyond mean-field effects?
(when theory not available)

Measure spin fluctuations?



Associated to correlations ??
How to reveal entanglement ?
(Entanglement witness quest - collaboration Perola Milman; Paris 7 University)

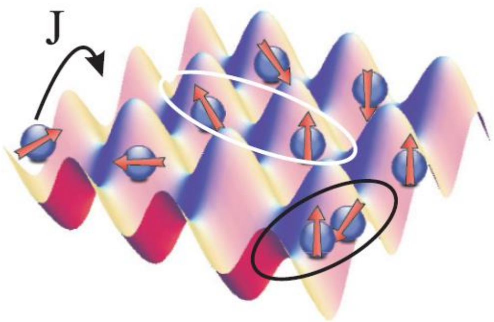
Large Spins are tricky for EWs!!

!! For example: squeezing is NOT an entanglement witness for large spins !!

See papers by Toth…

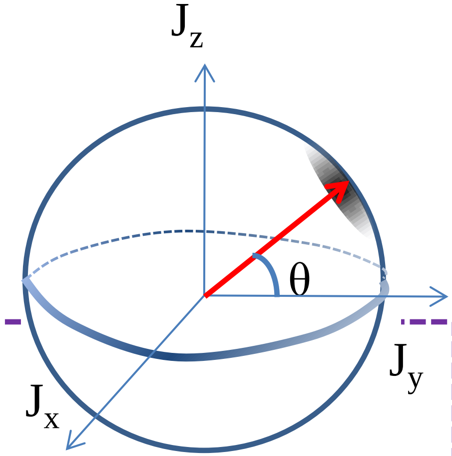
Local probes?

Bi-partite entanglement? (discussions Tommaso Roscilde)



Summing up

Spin dynamics after tilting the spin by rf



- **In the BEC phase**

- **Spin dynamics triggered by dipolar interactions for θ≠π/2**
- **When spin dynamics is triggered by magnetic field gradients, BEC remains locally almost ferromagnetic**
- **Correlations could arise without a lattice but are not seen**

- **In the lattice**

- **Correlations develop – How to prove this directly?**
- **Correlations increase with** $\Delta S_z\big|_0$ **(specific to non-Heisenberg Hamiltonian)**

- **What happens when super-exchange and dipolar interactions compete?**

Thank you

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M. Robert-de-St-Vincent,
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Paris 13 University
LPL

L. Santos

- Hannover University

A. M. Rey
J. Schachenmayer
B. Zhu

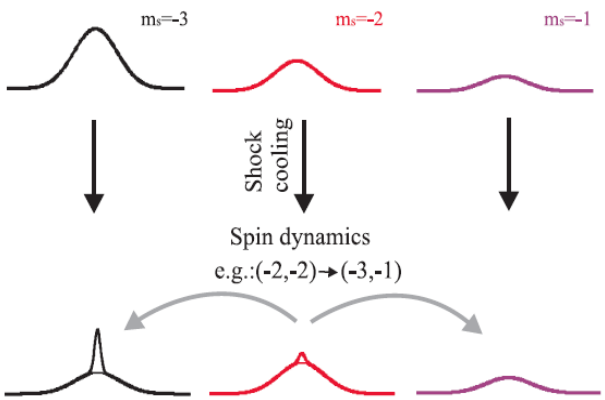
- JILA,
- University Boulder-Colorado

M. Brewczyk
M. Gajda

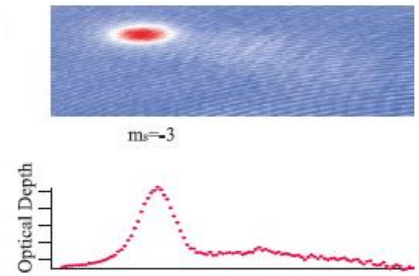
- Bialymstoku University
- Polish Academy of sciences

Other things which are being studied in the lab, but were not discussed in this talk

- Dynamics of BEC in presence of the spin degrees of freedom



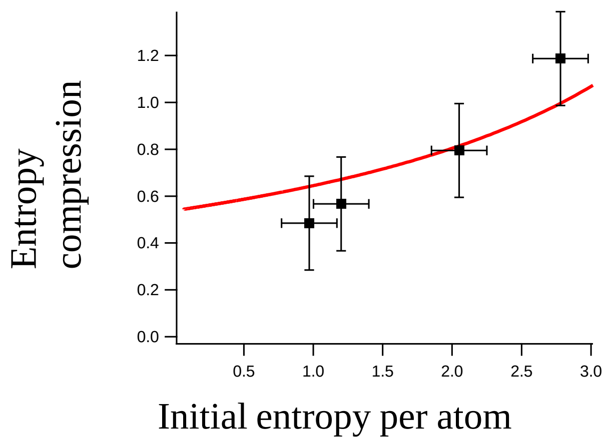
We observe a partially thermalized spin degrees of freedom, and interplay between spin-dynamics and BEC, which results in a difficulty to produce depolarized BECs.



Phys. Rev. Lett. **117**, 185302 (2016)

- Using the spin degrees of freedom to remove entropy in a BEC

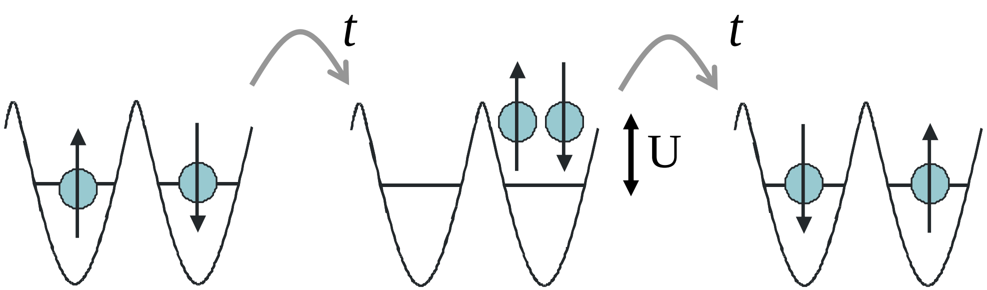
At thermodynamic equilibrium, a BEC is polarized in the lowest energy spin state. Filtering out spin excited states is therefore a very good way to remove entropy from the gas.



Phys. Rev. Lett. **115**, 243002 (2015)

Exotic quantum magnetism of large spin, from Mott to superfluid

An exotic magnetism driven by the competition between three types of exchange

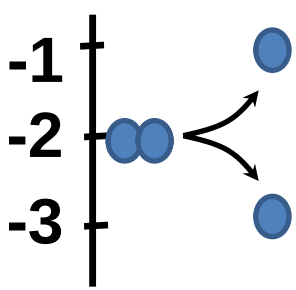


$$\Gamma \propto \frac{t^2}{U}$$

Super- Exchange (I)
(nearest neighbor)
decreases with lattice depth

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

Dipolar exchange (II)
(true long range)
independent from lattice depth



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

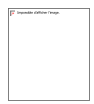
Contact exchange (III)
(short range)
Increases with lattice depth

One speculative slide - Which criterion for beyond-mean-field effects?

$$\left|S_\perp\right|(t) \underset{t\to 0}{\approx} \left|S_\perp\right|\left(1 - t^2\left[\Delta B^2 + \frac{1}{N}\sum V_{i,j}^2\right]\right)$$

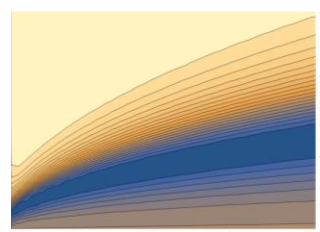
PRL 110, 075301 (2013)

$\left|\left\langle \vec{S}(t)\right\rangle\right|$ Measure size of total spin: a good indication for beyond-meand-field effects … at least for homogeneous systems!

Squeezing by 

$\left\langle S^2(t)\right\rangle$ In a lattice, energy of two nearby atoms is: $U = -\dfrac{J^2}{U_S}$ S: molecular potential

$$V_{dd} > \left|\frac{J^2}{U_{S+2}} - \frac{J^2}{U_S}\right|$$



Remember: Classically:
atoms undergo identical precession;
total spin is conserved in time

Speculation: something interesting might happen due to competition between dipolar interaction and super-exchange

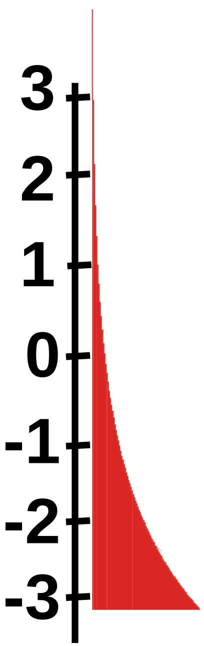
Spin temperature equilibriates with mechanical degrees of freedom

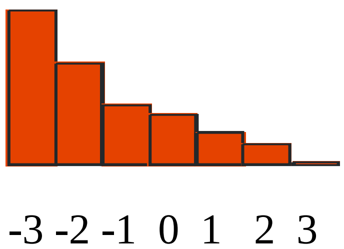
(due to magnetization changing collisions)

At low magnetic field: spin thermally activated

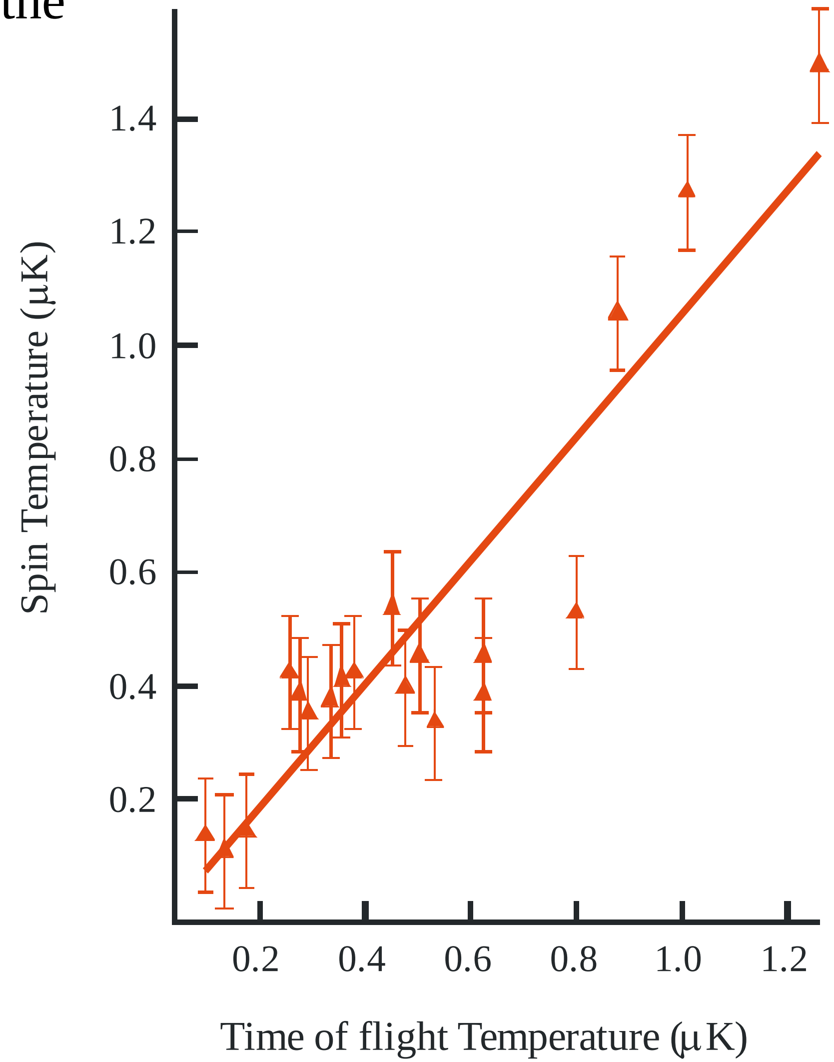
Magnetization adpats to temperature due to the presence of dipolar interactions

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



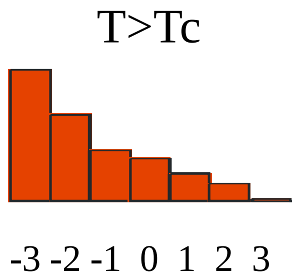


We measure spin-temperature by fitting the m_S population (separated by Stern-Gerlach technique)

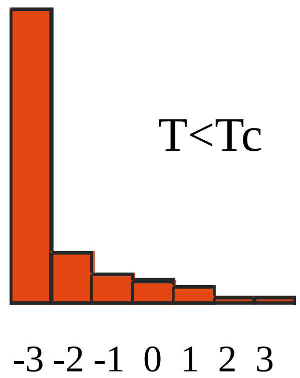


Related to Demagnetization Cooling expts,
T. Pfau, *Nature Physics* ***2****, 765 (2006)*

The BEC always forms in the m_s=-3

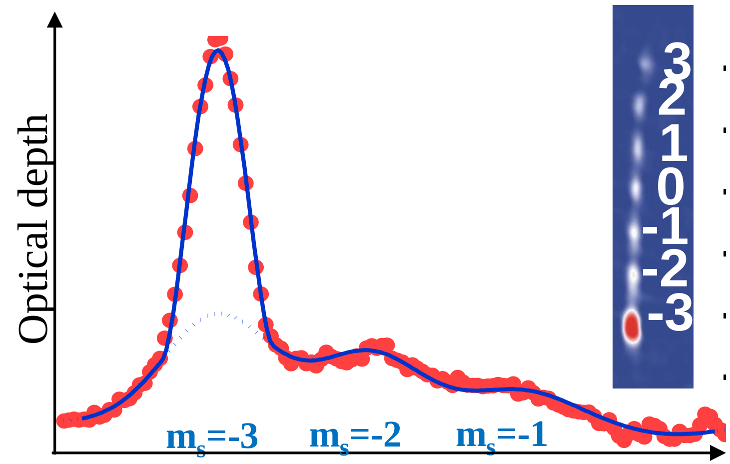


Thermal population in Zeeman excited states



a bi-modal spin distribution

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

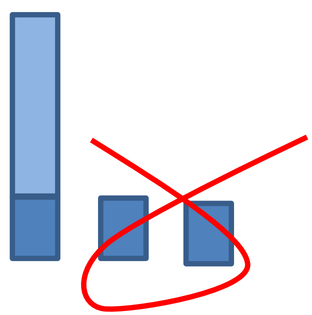


Momentum distribution in the different Zeeman states

PRL **108**, 045307 (2012)

One idea: Kill spin-excited states ?

Provides a loss specific for thermal fraction



Should lead to purification of the BEC, thus cooling

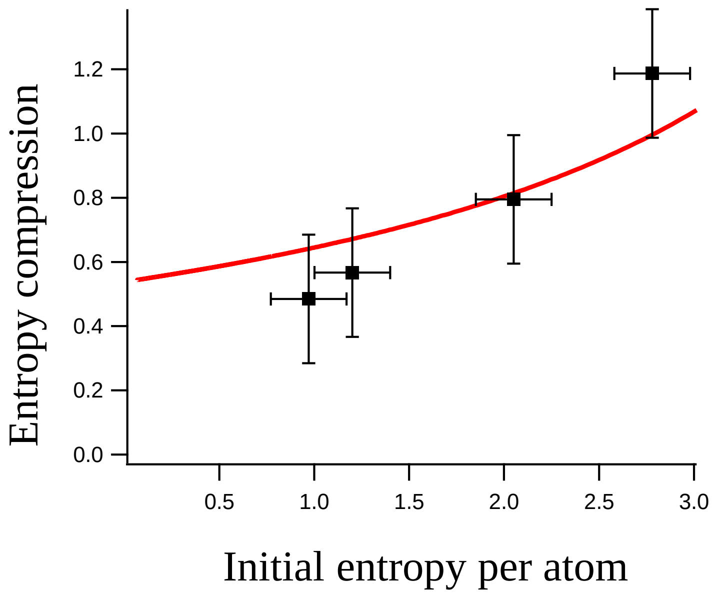
(and this process can be repeated after waiting for more depolarization)

Cooling efficiency

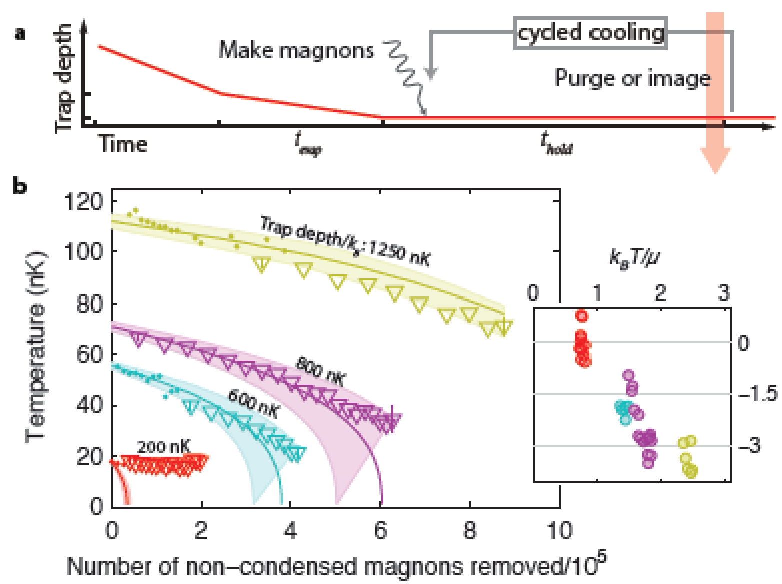
All the entropy lies in the thermal cloud

Thus spin filtering is extremely efficient!

In principle, cooling efficiency has no limitation



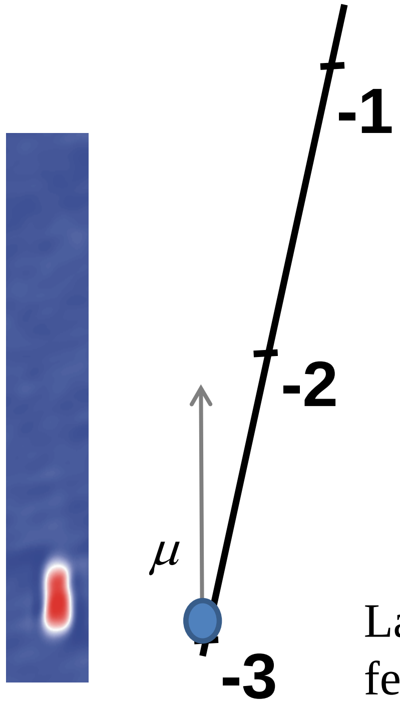
Chromium, LPL, Phys. Rev Lett. (2015)



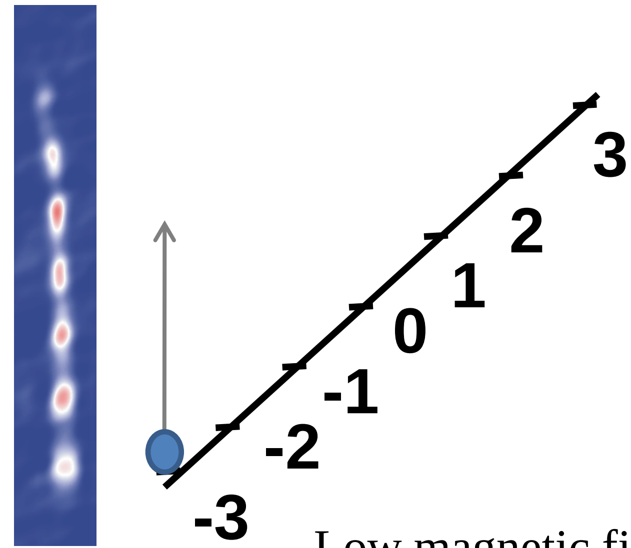
Rb, Stamper Kurn, Nature Physics (2015)

Use spin to store and remove entropy

New magnetic phases at low field

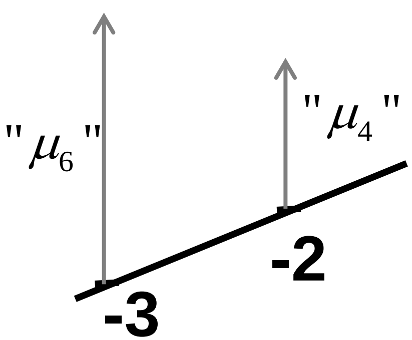


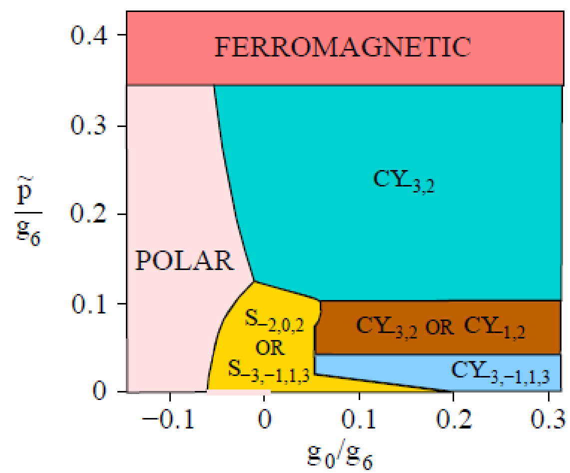
Large magnetic field : ferromagnetic



Low magnetic field : polar/cyclic

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





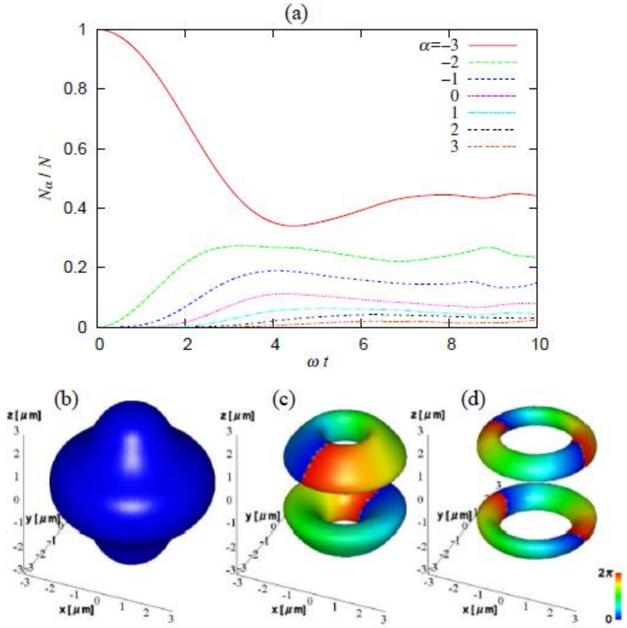
Santos PRL **96**, 190404 (2006)

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

Depolarization observed (Phys. Rev. Lett. **106**, 255303 (2011) ; phases remain to be studied

Two interesting proposals:

Einstein-de Haas effect



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

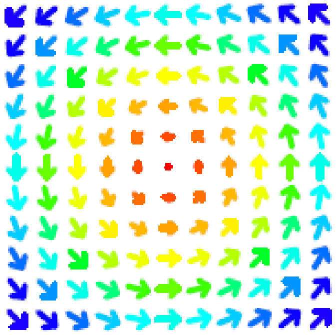
Ho PRL. **96**, 190405 (2006)

Spontaneous circulation in the ground state

$$\tilde{V}_{dd} \propto \int d^3\vec{k}\left[3\left|\vec{F}(\vec{k}).\vec{k}/k\right|^2 - \left|\vec{F}(\vec{k})\right|^2\right]$$

$\vec{F}(\vec{k})$ Fourier transform of magnetization vector

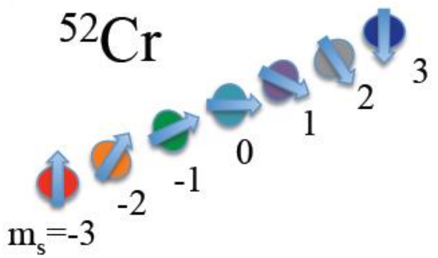
Maximize $\left|\vec{F}(\vec{k})\right|$ and $\vec{F} \perp \vec{k}$



Ueda PRL **97**, 130404 (2006)
S. Yi and H. Pu, PRL **97**, 020401 (2006)

This seminar: magnetism with large spin cold dipolar atoms

Optical dipole traps equally trap all Zeeman state of a same atom

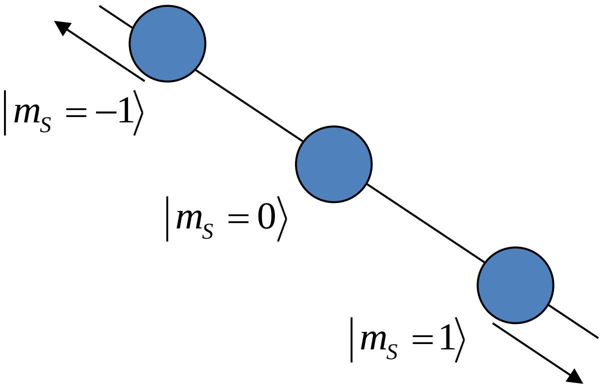


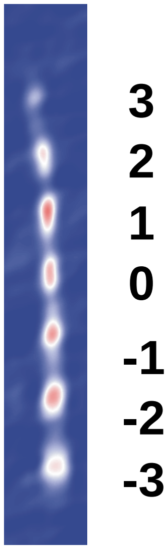
Linear (+ Quadratic)
Zeeman effect

$$E(m_S) = m_S g \mu_B B\left(+\alpha B^2\right)$$

Stern-Gerlach separation:
(magnetic field gradient)

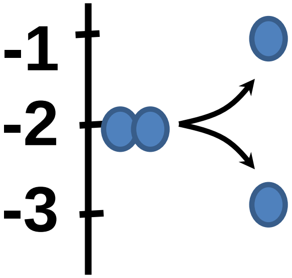
Simultaneously measure spin and momentum distribution





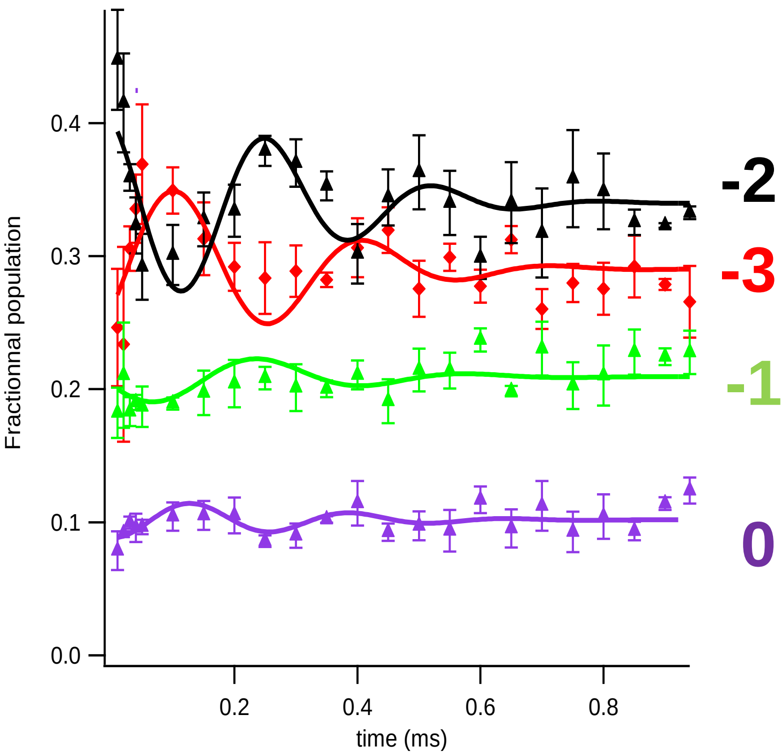
Two main players for magnetism and spin dynamics:

Spin-dependent contact interaction



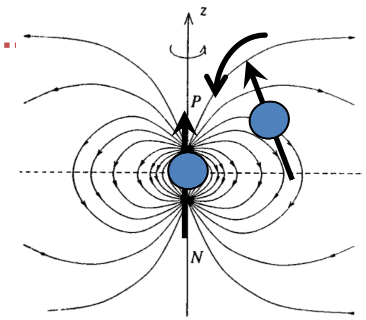
Contact exchange (I)

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

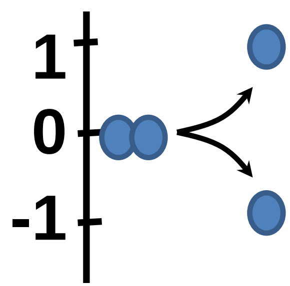


Dipole-dipole interactions

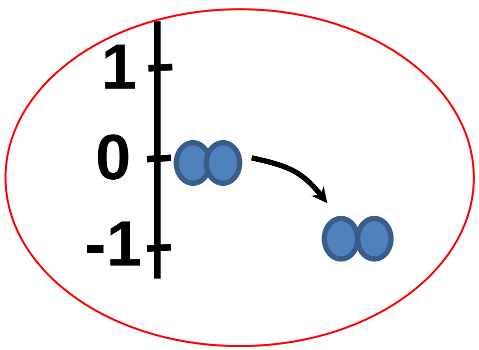
$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \left(1 - 3\cos^2(\theta)\right) \frac{1}{R^3}$$



Dipolar Exchange (II)



Relaxation

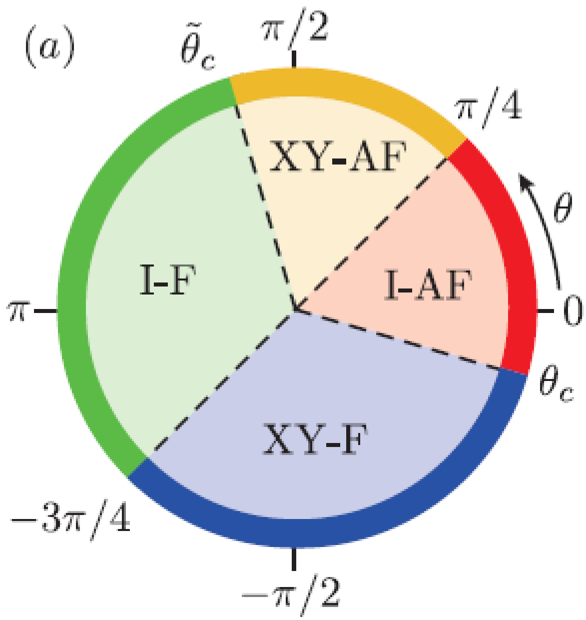


Unique!

Other consequences, due to long range character and anisotropy

Anomalous spin behavior

long range character



$$H = \frac{Ja^3}{\hbar^2} \sum_{i \neq j} \frac{\cos\theta \, S_i^z S_j^z + \sin\theta \left(S_i^x S_j^x + S_i^y S_j^y \right)}{|\mathbf{R}_i - \mathbf{R}_j|^3}$$

Possibility of long-range ferromagnetic order in 2D (in contrast to Mermin Wagner theorem for short-range interactions)

Buchler PRL **109**, 025303 (2012)

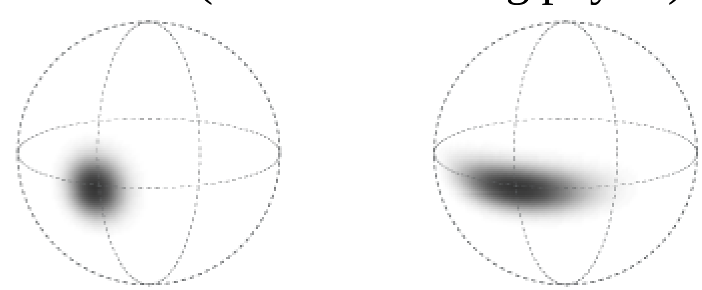
XYZ Hamiltonian
Spin-orbit coupling when magnetization is free (anisotropy)

(Rey, Buchler, Zoller, Karr, Lev…)

Needs to engineer two degenerate states of different magnetization

How correlations develop and spread

(Non-Heisenberg phyics)

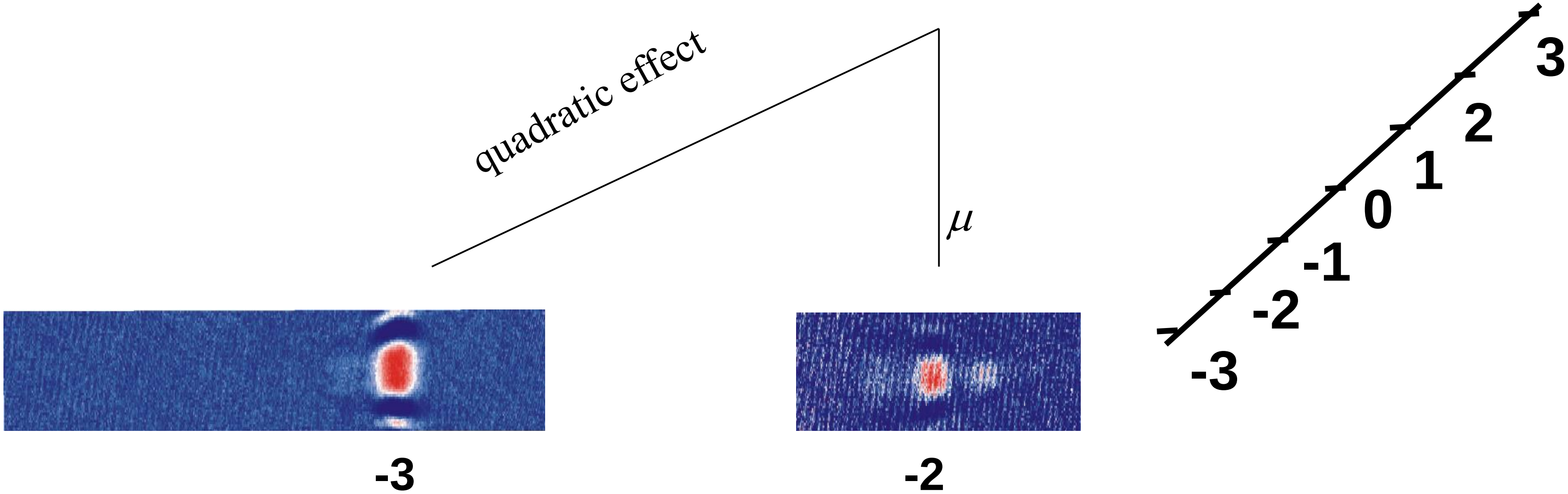


(on-going collaboration with A. M. Rey)

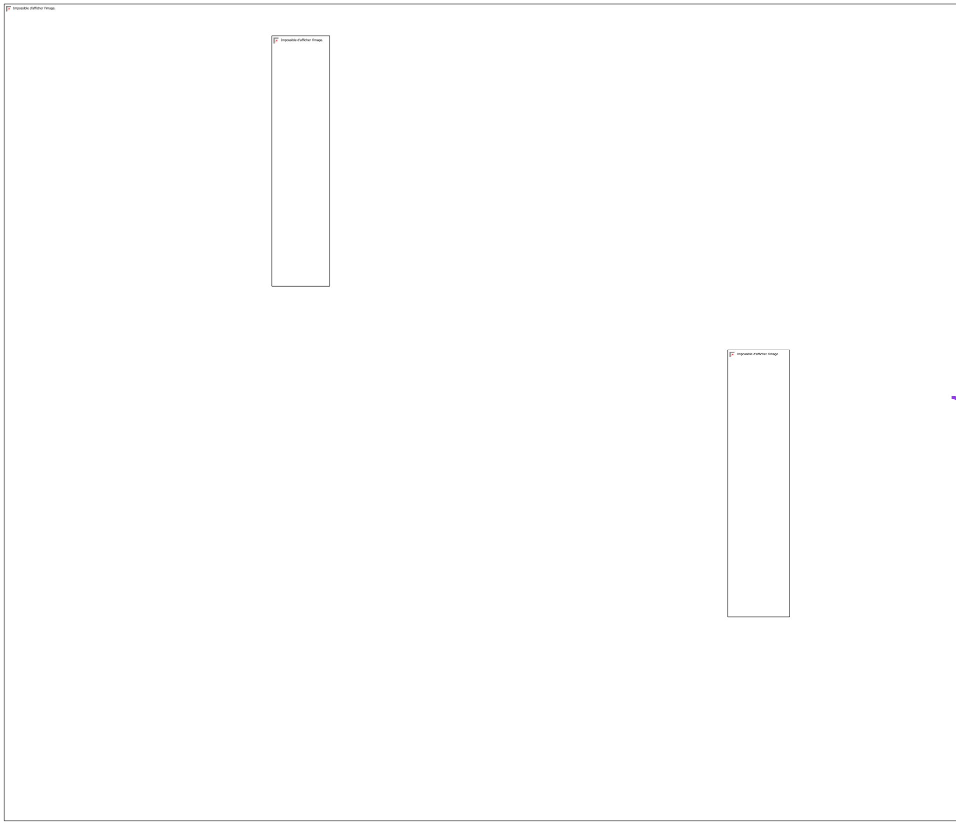
First case: prepare all atoms in a well-defined Zeeman state

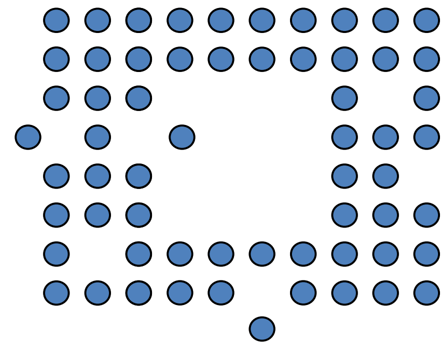
$$\Psi(0) = \left| 2,2,\ldots.,2,2 \right\rangle$$

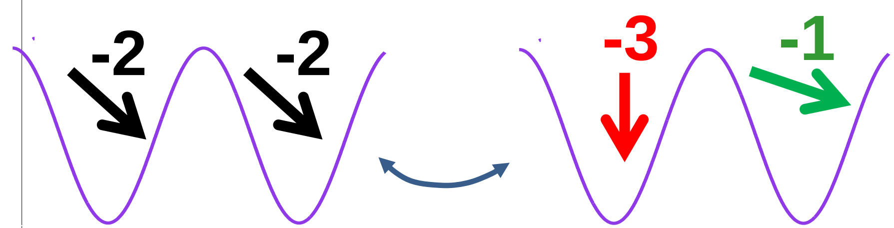
(each site contains one atom in state m_s=-2)



Spin dynamics after emptying doubly-occupied sites: A proof of inter-site dipole-dipole interaction







Magnetization is constant

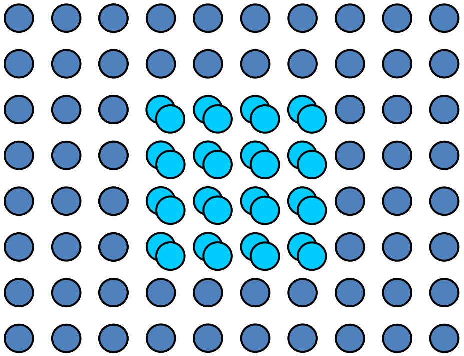
Timescale for spin dynamics = 20 ms
Tunneling time = 100 ms
Super-exchange > 10s

Experiment: spin dynamics after the atoms are promoted to ms=-2

Theory: exact diagonalization of the t-J model on a 3*3 plaquette (P. Pedri, L. Santos)

!! Many-body dynamics !!
(each atom coupled to many neighbours)
Mean-field theories fail

Phys. Rev. Lett., 111, 185305 (2013)

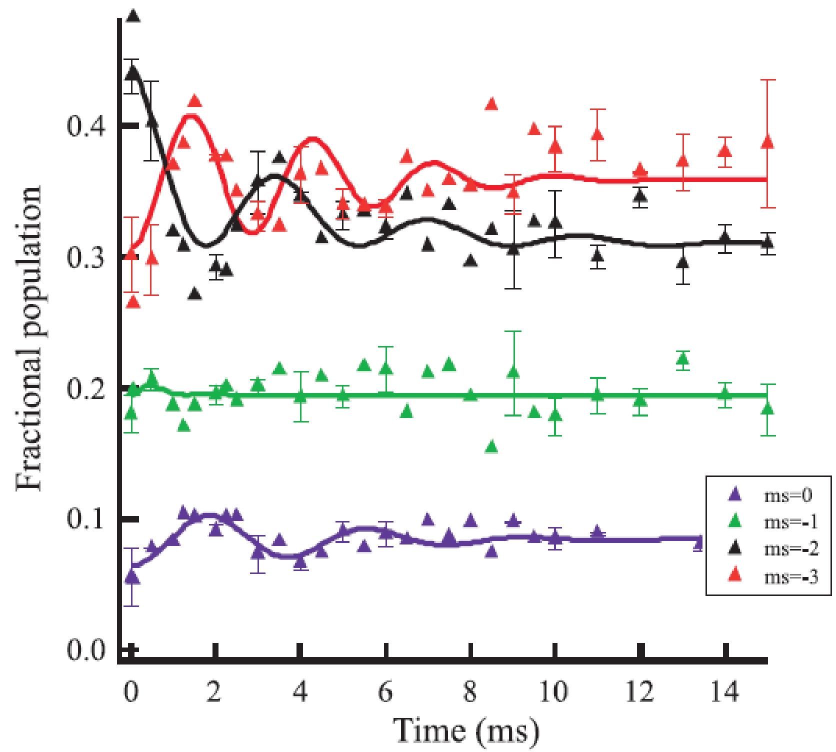


1- At large lattice depths (Mott regime)

In presence of doubly-occupied sites:

A complex oscillatory behavior dispplaying two distinc frequencies

Phys. Rev. Lett., 111, 185305 (2013)



Contact exchange (III)

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

Dipolar Exchange (II)

Exact diagonalization is excluded with two atoms per site

(too many configurations for even a few sites)

A toy many-body model for the dynamics at large lattice depth

Exact diagonalization is excluded with two atoms per site
(too many configurations for even a few sites)

Perturbative theory for singlons

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

$$\left|2,2,....,22\right\rangle \rightarrow \propto \sum_{(i,j)} V_{(i,j)} \left|2,2,...2,1,2,...2,3,2,2\right\rangle$$

(i) (j)

$$\Gamma = 2\pi\sqrt{\sum_{(i,j)}\left(V_{(i,j)}{}^2\right)}$$

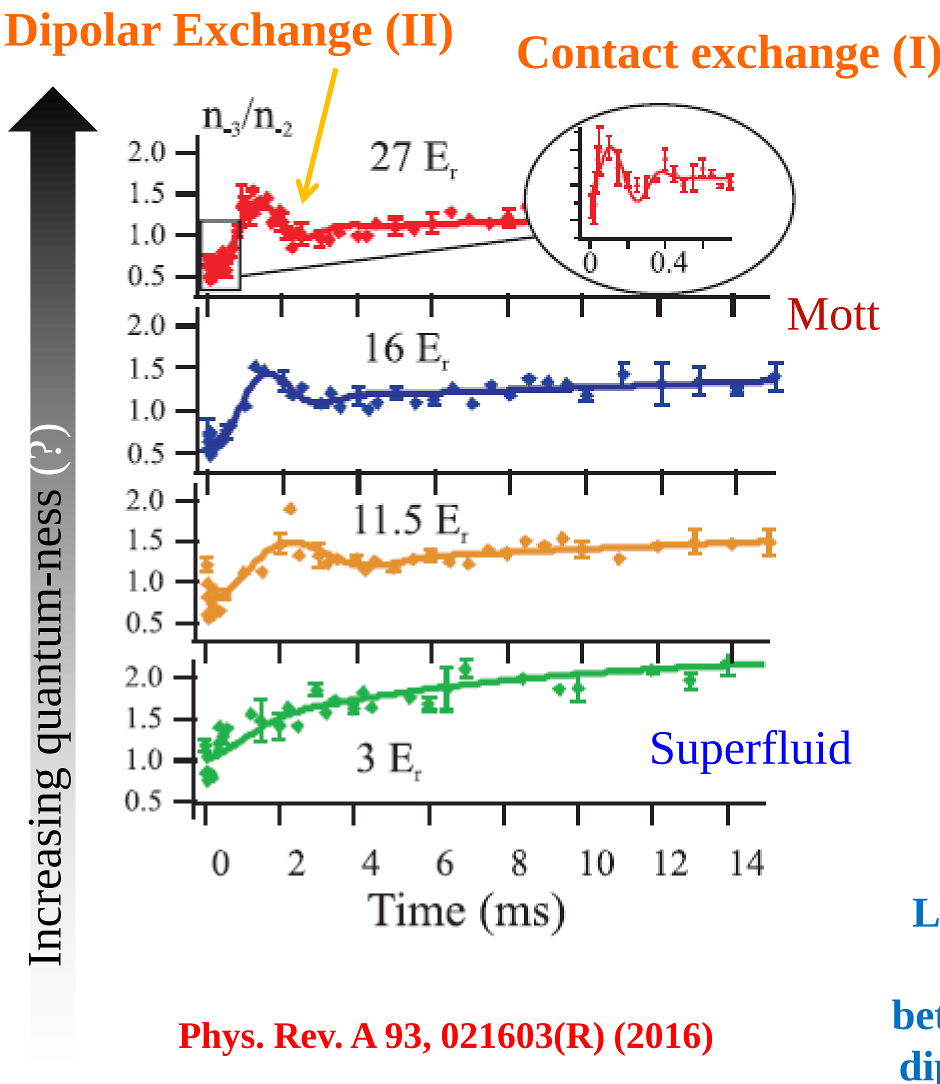
Toy model for doublons: replace S=3 by S=4 or S=6

Measured frequency: 300 Hz
Calculated frequency: S=4: 220 Hz
S=6: 320 Hz

4th order correction included

Toy models seems to qualitatively reproduce oscillation;
see related analysis in Porto, Science, (2015)

2- Spin dynamics as a function of lattice depth



Phys. Rev. A 93, 021603(R) (2016)

Large lattice depth:
dipolar exchange and contact exchange contribute on different timescales (~qualitatively well understood)

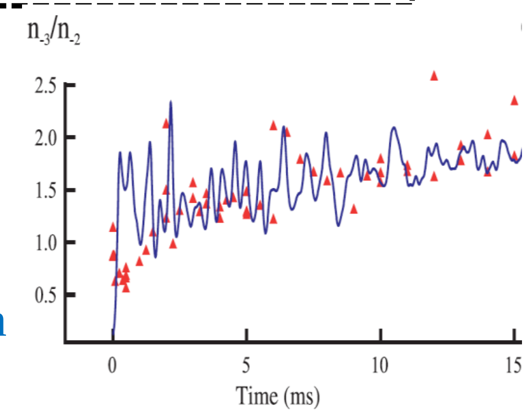
Intermediate lattice depth:
super-exchange may occur and compete

No theoretical model yet
All three exchange mechanisms contribute

A unique and exotic situation!!

Low lattice depth:
An interplay between contact and dipolar interactions

« Good » agreement with GP (P. Pedri)



Similarities and differences

Our Hamiltonian =
NMR Secular Hamiltonian
+ magnetization-changing collisions

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

Heisenberg hamiltonian

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

Magnetization-changing collisions $S_{1-}S_{2-}$

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

Anisotropy $\left(1-3\cos^2\theta\right)$

Long Range

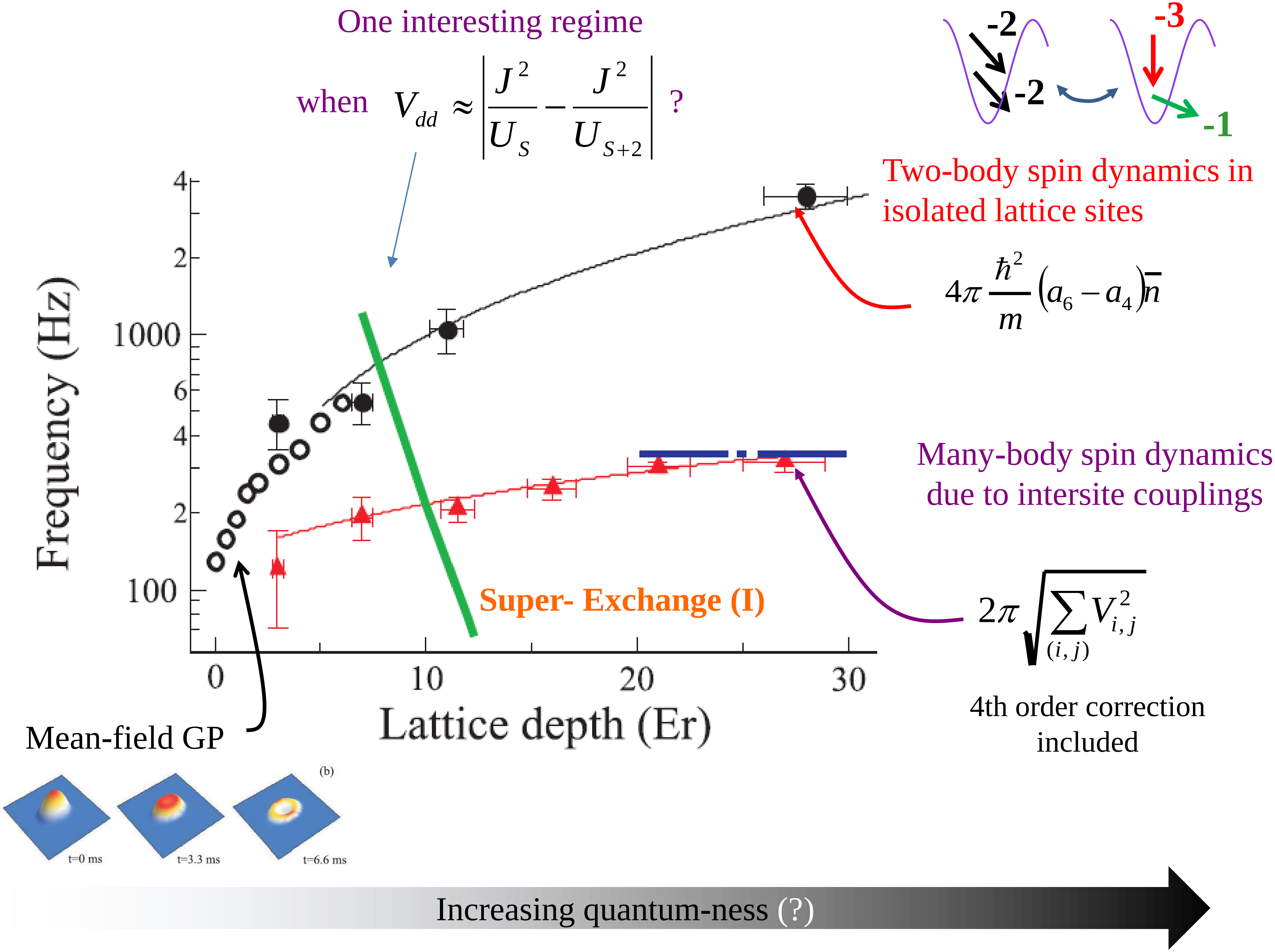
Tunneling

Large Spin

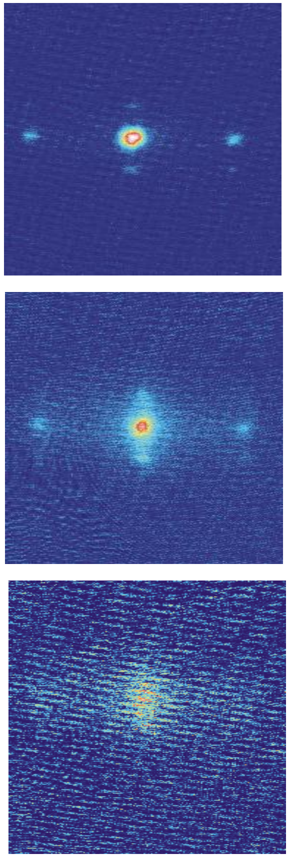
NMR Secular hamiltonian

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

Dipolar exchange (II)


One interesting regime
when $V_{dd} \approx \left| \frac{J^2}{U_S} - \frac{J^2}{U_{S+2}} \right|$?
-2
-2
-3
-1
Two-body spin dynamics in isolated lattice sites
$4\pi \frac{\hbar^2}{m}(a_6 - a_4)\bar{n}$
Many-body spin dynamics due to intersite couplings
$2\pi \sqrt{\sum_{(i,j)} V_{i,j}^2}$
4th order correction included
Super- Exchange (I)
Frequency (Hz)
4
2
1000
6
4
2
100
0
10
20
30
Lattice depth (Er)
Mean-field GP
(b)
t=0 ms
t=3.3 ms
t=6.6 ms
Increasing quantum-ness (?)

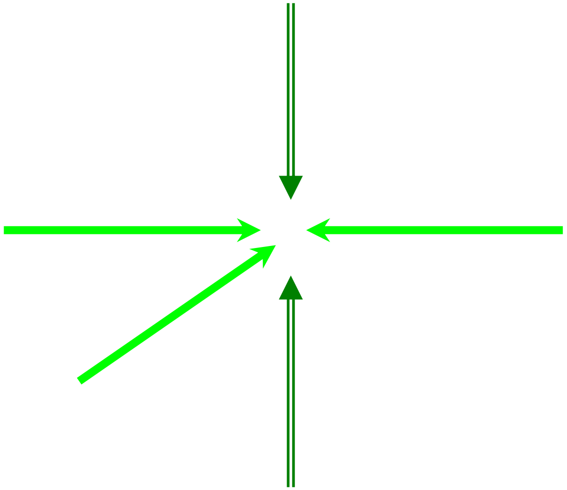
A ^{52}Cr BEC in a 3D optical lattice

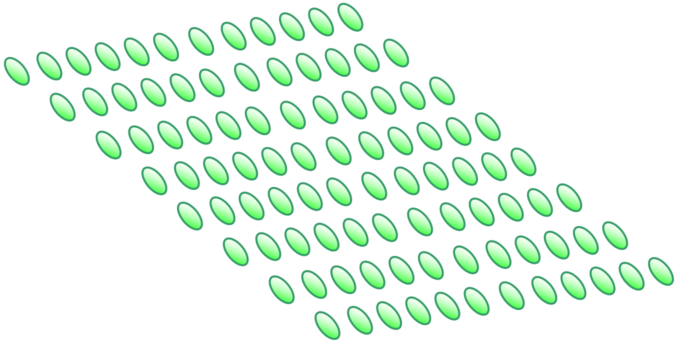


Optical lattice: Perdiodic potential made by a standing wave

Our lattice architecture:

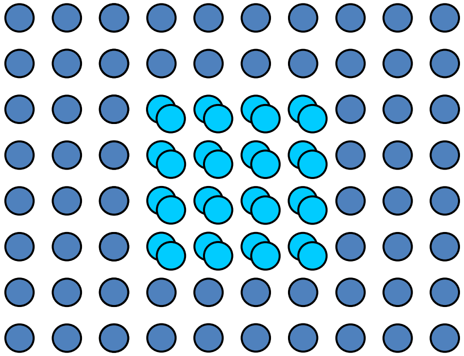
(Horizontal 3-beam lattice) x (Vertical retro-reflected lattice)





Rectangular lattice of anisotropic sites

3D lattice → Strong correlations, Mott transition…



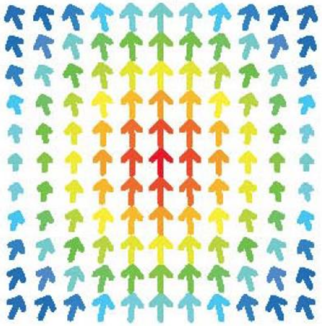
From 2 to N atoms (interacting through dipolar interactions)

$$\frac{dS}{dt} = \gamma S \times (B + \sum_j B_j)$$

$\vec{B}_j$ **Field created by atom j**

$$\frac{d\langle S\rangle}{dt} = \gamma \left\langle S \times (B + \sum_j B_j) \right\rangle$$
$$= \gamma \langle S\rangle \times (B + \sum_j \langle B_j\rangle)$$

Neglect correlations



$$\Gamma(r) = \int dr' V_{dd}(r - r')n(r')$$

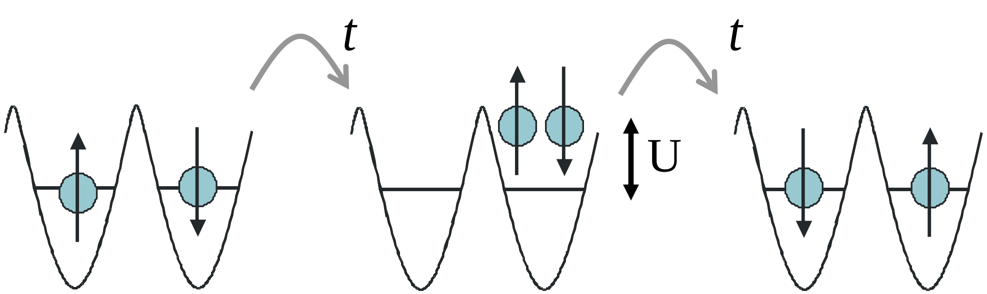
Mean-field interaction ↔ Gross-Pitaevskii equation

In the mean-field approximation, atoms undergo (classical) precession around dipolar field

Mean-field may be inhomogeneous, and total spin may not be conserved

Exotic quantum magnetism of large spin, from Mott to superfluid

An exotic magnetism driven by the competition between three types of exchange

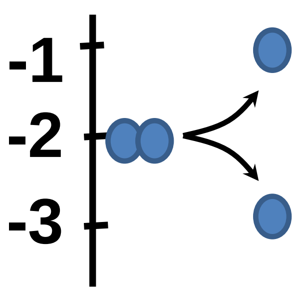


$$\Gamma \propto \frac{t^2}{U}$$

Super- Exchange (I)
(nearest neighbor)
decreases with lattice depth

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

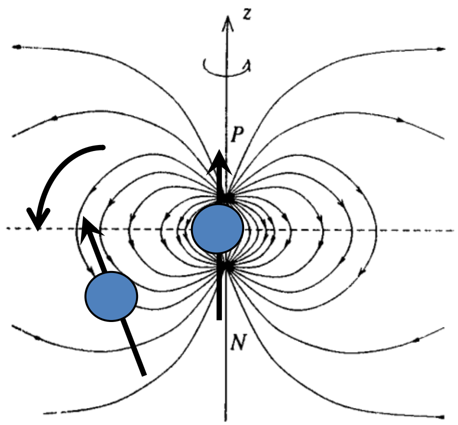
Dipolar exchange (II)
(true long range)
independent from lattice depth



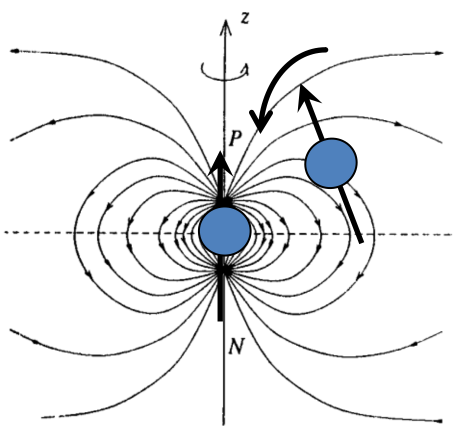
$$\Gamma = \frac{4\pi\hbar^2}{m} n\left(a_6 - a_4\right)$$

Contact exchange (III)
(short range)
Increases with lattice depth

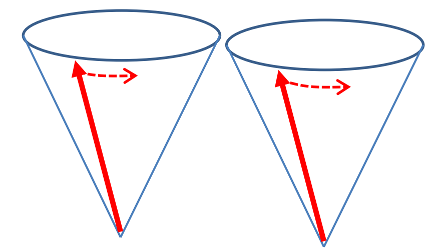
Under which conditions correlations develop? – Classical vs Quantum magnetism



$$\vec{B}_A(B) = \vec{B}_B(A)$$



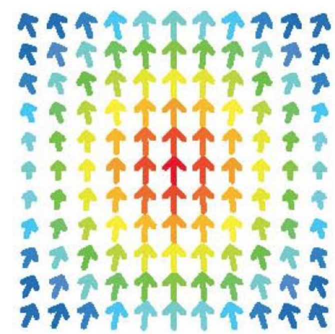
Classically:



These two atoms undergo identical precession

Total spin conserved

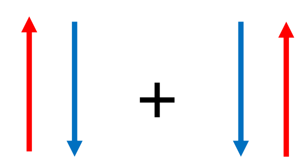
In the mean-field approximation, atoms undergo (classical) precession around dipolar field (may be inhomogeneous) ↔ GP equation



Quantum-mechanically:

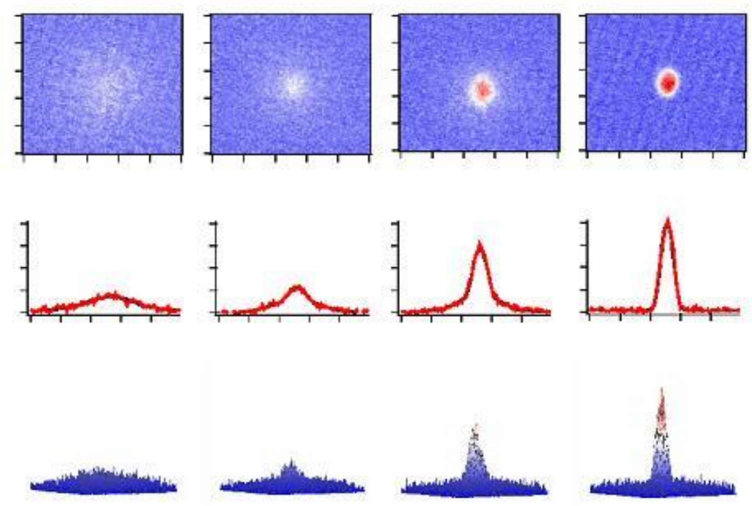
Possibility for entanglement

Total spin is NOT conserved



This experiment: chromium quantum gases

Nov 2007 : Chromium BEC



S=3

4.10^4 atoms

April 2014 : Chromium Fermi sea

F=9/2

10^3 atoms

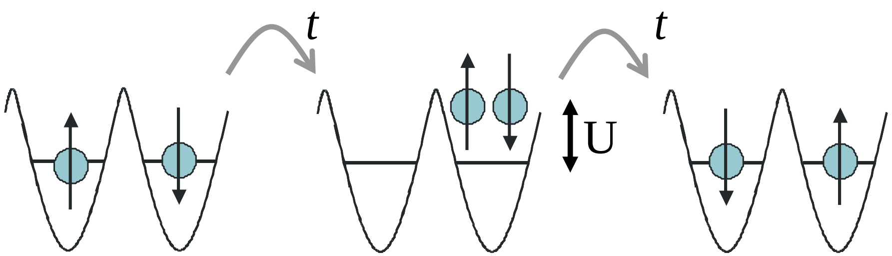
(from only 3.104 atoms in dipole trap !)
Phys. Rev. A 91, 011603(R) (2015)

Chromium: unusually large dipolar interactions

(only few experiments worldwide with non-negligible dipolar interactions
-, Boulder, Boston, Hong-Kong,…)

Quantum magnetism, some paradigms from solid-state physics
Strongly correlated (s=1/2) electrons

Condensed-matter: effective spin-spin interactions due to exchange interactions



Magnetism is driven by super-exchange

Super- Exchange

$$\Gamma \propto \frac{t^2}{U}$$

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

Ising Exchange

Heisenberg model of magnetism
(real spins, effective spin-spin interaction)

Cold atoms offer to revisit paradigms from solid-state physics experimentally
… and go beyond ?...