EGAS 46
Lille – July 2, 2014

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Quantum magnetism within a dipolar Bose-Einstein Condensate

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Two types of interactions between cold atoms

Interactions Van der Waals / contact :

short range and isotropic

Effective potential **$a_S\ \delta(R)$** , where a_S = scattering length,

Dipole-dipole interactions : **long range and anisotropic**

magnetic atoms **Cr, Er, Dy** ; *dipolar* ***molecules*** *;* ***Rydberg*** *atoms*

Chromium atoms carry a permanent magnetic moment of $6\mu_B$

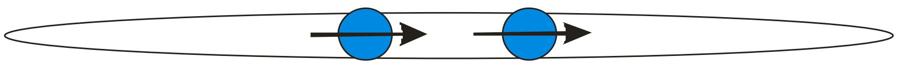
MDDI are 36 times greater than in alkali BECs

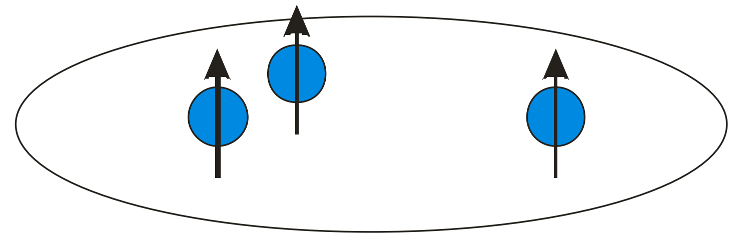
ε_{dd} = ratio : dipolar interactions / contact interactions

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

ε_{dd} (Cr)=0,159 *compared to ε_{dd} (Rb)=0,0044*

a good platform to study the **interplay between the two interactions** *head to tail attraction*



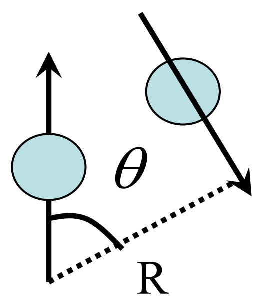


Side to side repulsion

Long range **magnetic** dipole-dipole interactions

$$V_{dd}(\vec{r}) = \frac{\mu_0 \left(g_J \mu_B\right)^2}{4\pi} \frac{\hat{s}_1 \cdot \hat{s}_2 - 3\left(\hat{s}_1 \cdot \vec{u}_r\right)\left(\hat{s}_2 \cdot \vec{u}_r\right)}{r^3}$$

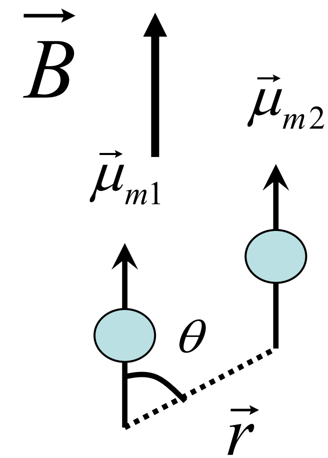
Links with **magnetism**, liquid crystal physics, rich **phase diagrams**, quantum info processing.



Coupling between spin and rotation

The two relevant interactions in a Cr condensate

$$-\frac{\hbar^2}{2m}\Delta\psi + \left(V_{ext} + g_c|\psi|^2 + \phi_{dd}\right)\psi = \mu\,\psi$$



contact interaction

$$g_c = \frac{4\pi\,\hbar^2}{m}a_s$$

Local
mean field

dipole-dipole interaction

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

$$V_{dd}(\vec{r}) = \frac{\mu_0}{4\pi}\mu_m{}^2\,\frac{1-3\cos^2\theta}{r^3}$$

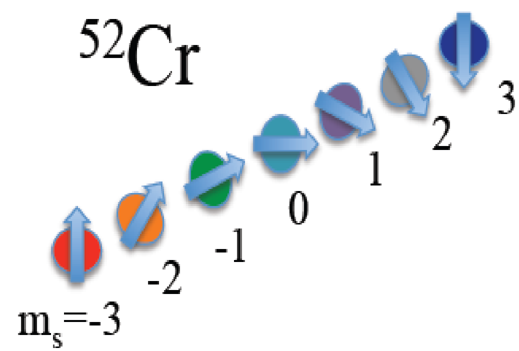
$$\mu_m = J\;g_J\mu_B$$

Non local
Anisotropic
mean field

Non-linear non-local and anisotropic terms

For ^{52}**Cr** atoms have a large **spin**

S = 3 - Ψ comprises 7 spin components



Dipolar induced spin dynamics

$$V_{dd}(\vec{r}) = \frac{\mu_0 \left(g_J \mu_B\right)^2}{4\pi} \frac{\hat{s}_1 \cdot \hat{s}_2 - 3\left(\hat{s}_1 \cdot \vec{u}_r\right)\left(\hat{s}_2 \cdot \vec{u}_r\right)}{r^3}$$

Various terms:

ISING

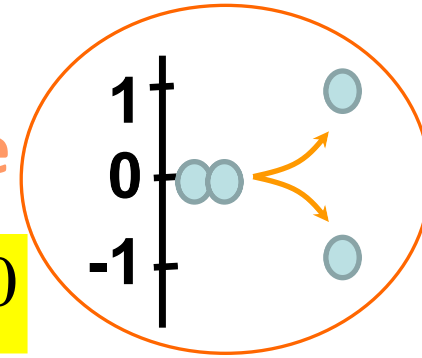
XY/ flip-flop / Spin Exchange

Elastic collisions

$$S_{1z}S_{2z} + \frac{1}{2}\left(S_1^+ S_2^- + S_1^- S_2^+\right)$$

$$-\frac{3}{4r}\left(2\, zS_{1z} + r_- S_1^+ + r_+ S_1^-\right) \otimes \left(2zS_{2z} + r_- S_2^+ + r_+ S_2^-\right)$$

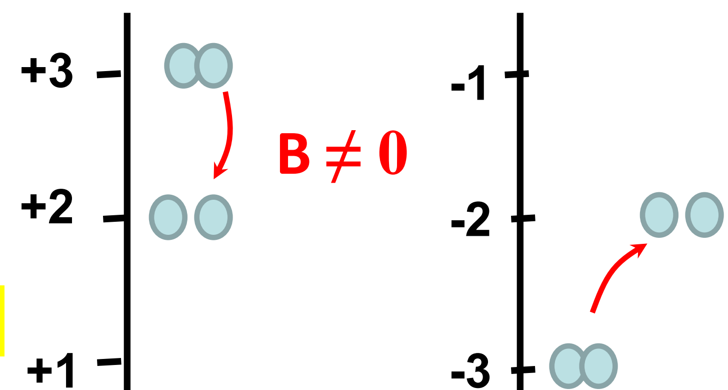
$$\Delta m_{S\ tot} = 0$$



Inelastic collisions

$$\Delta m_{S\ tot} = \pm 1, \pm 2$$

$$r_{+/-} = x \pm iy$$



Cr BEC M= 3

FORBIDDEN **or not** energetically (depending on T)

Inelastic collisions change magnetization $\Rightarrow$ **Strong heating**

Coherent Spin dynamics in a Cr BEC

When inelastic terms are prohibited

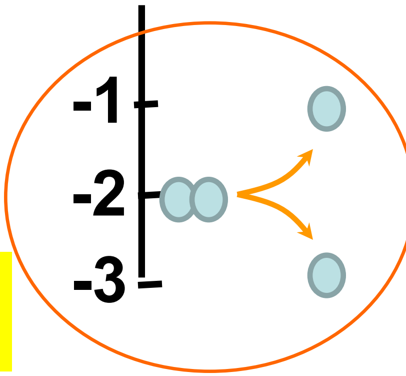
Spin operators reduce to :

ISING

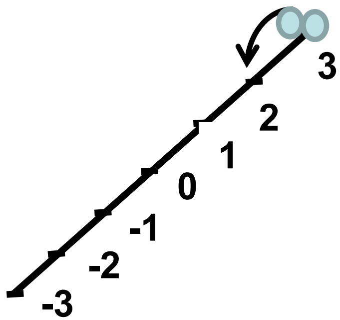
XY / Spin Exchange

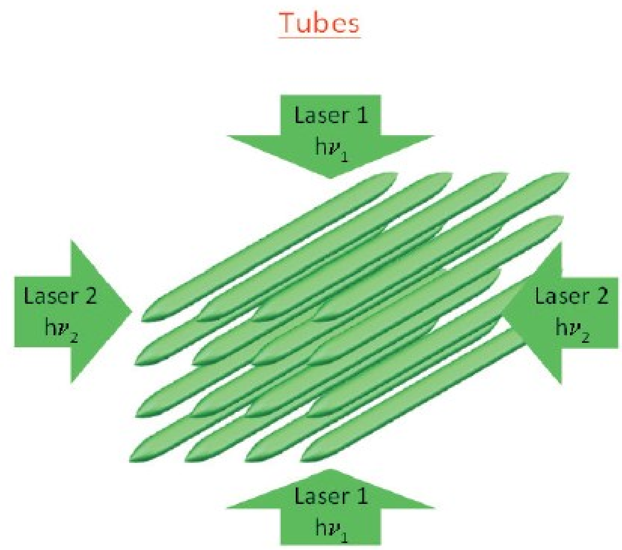
$$S_{1z}S_{2z} + \frac{1}{2}\left(S_1^{+}S_2^{-} + S_1^{-}S_2^{+}\right)$$

$$\Delta m_{S\ tot} = 0$$



First experimental study of **spin-3 spinor physics**

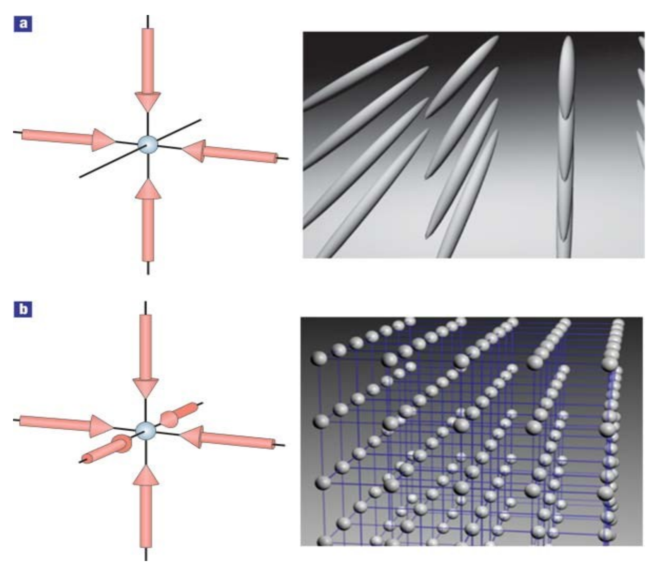




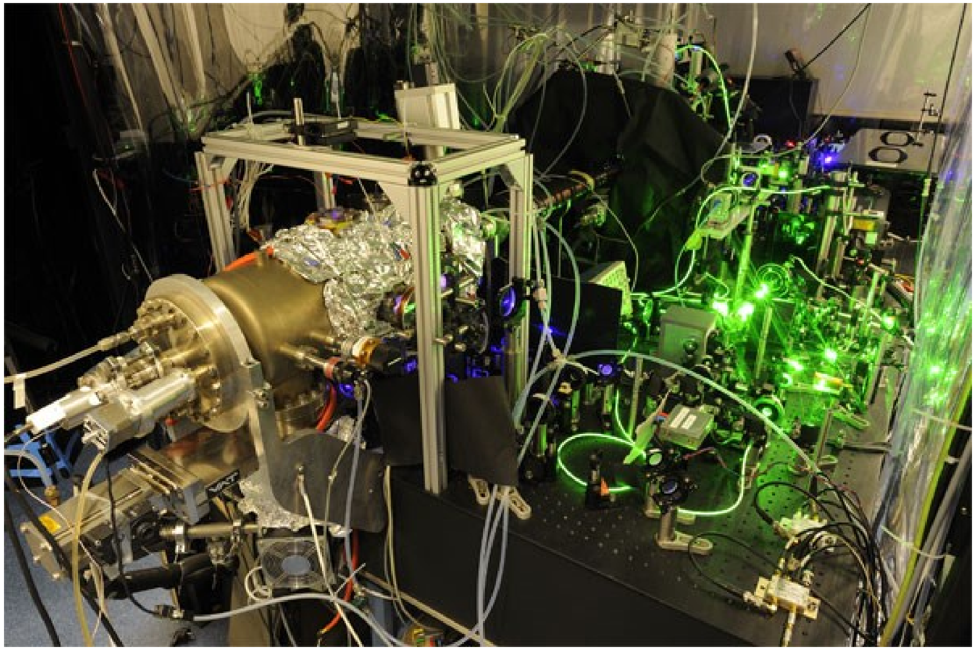
INHIBITION OF DIPOLAR RELAXATION

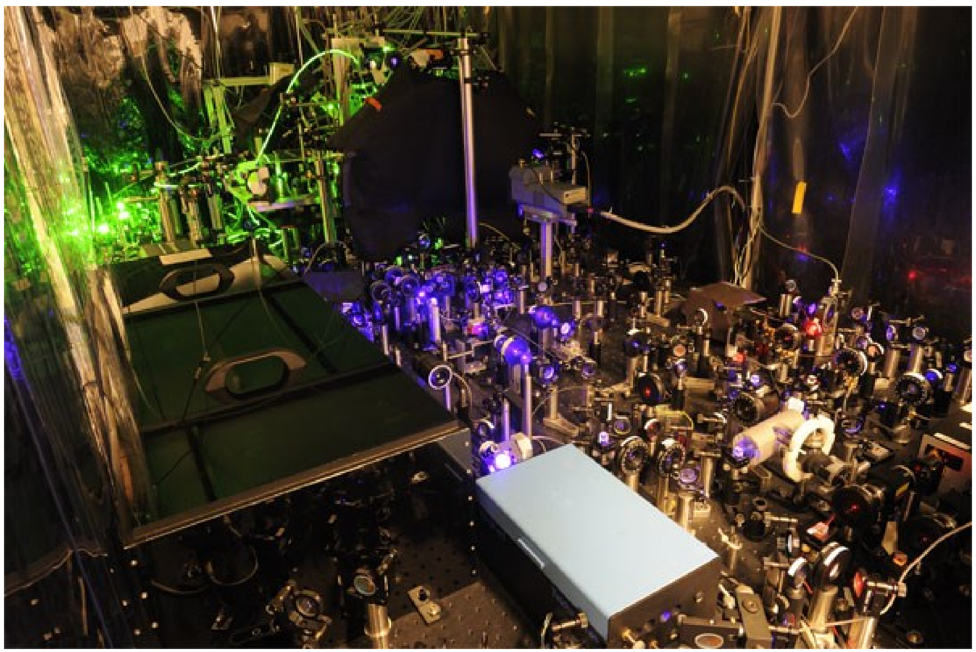
Collisional stabilisation
of the **spinor quantum gas**

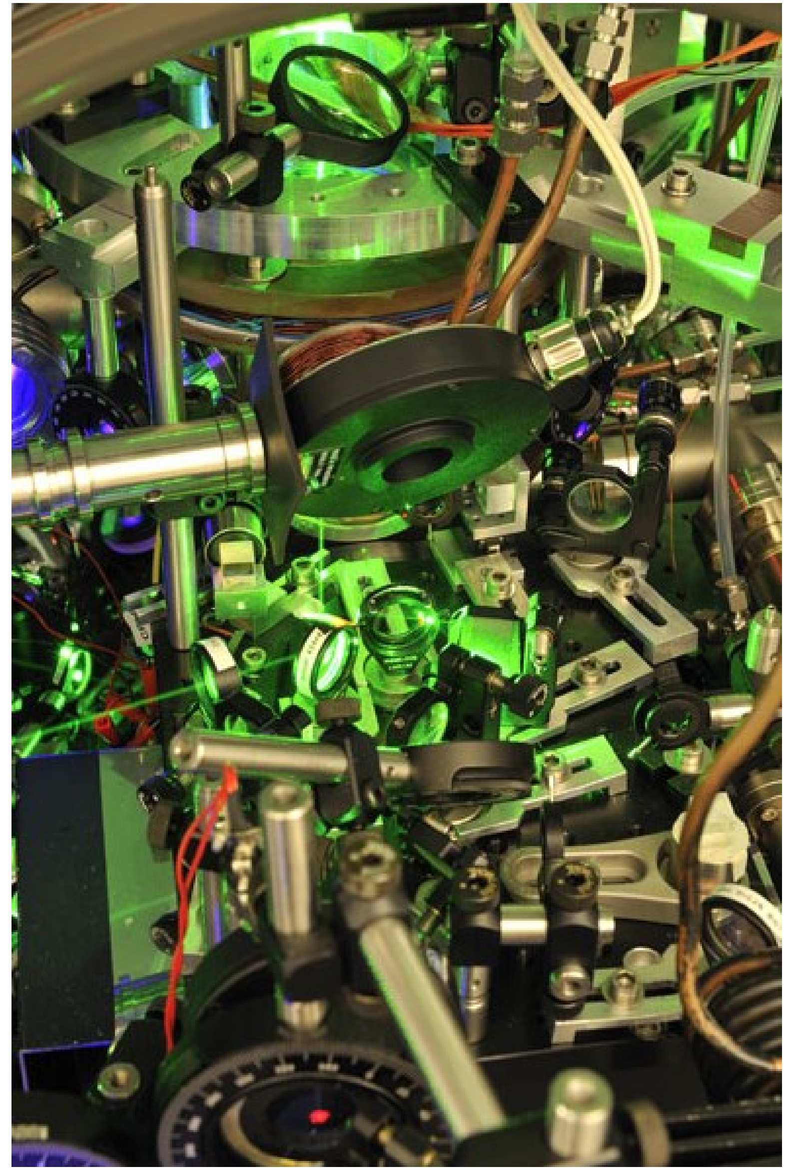
by confinement
in optical lattices



The experimental setup







… well … Part of it !!…

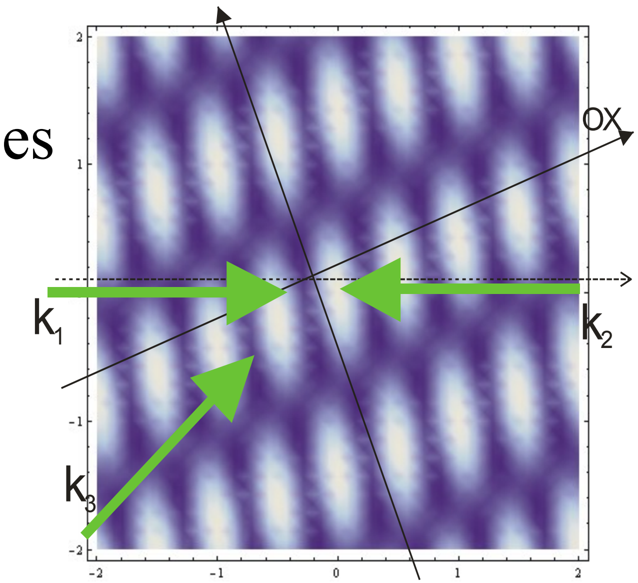
Magnetism in a 3D optical lattice

- *Coherent and incoherent spin dynamics*

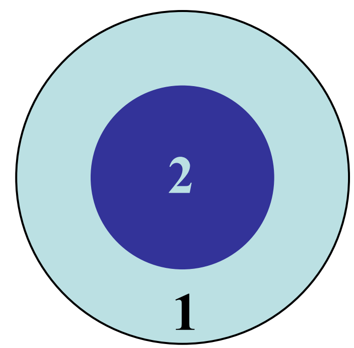
Tight confinement in
an anisotropic 3D lattices

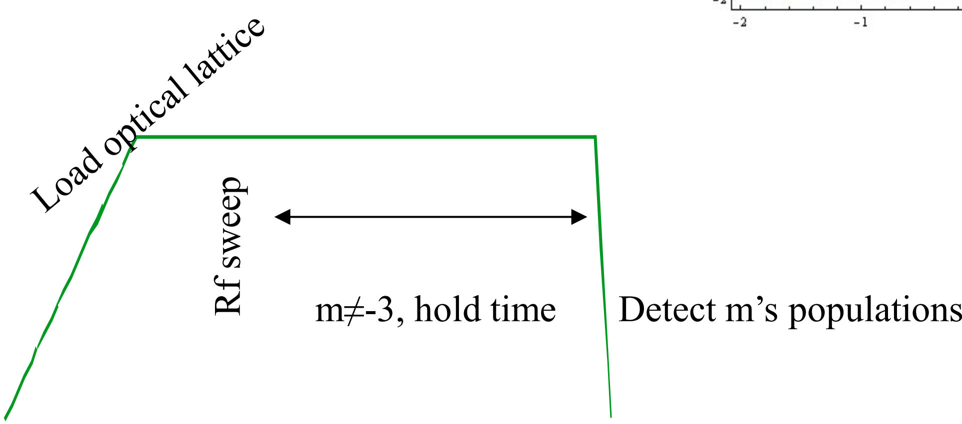
Green 532nm light

Typical parameters
Depth 30 E_{rec}
Band gaps: 60 to 200 kHz
U / 2π about 10 kHz
J / 2π about 10 Hz

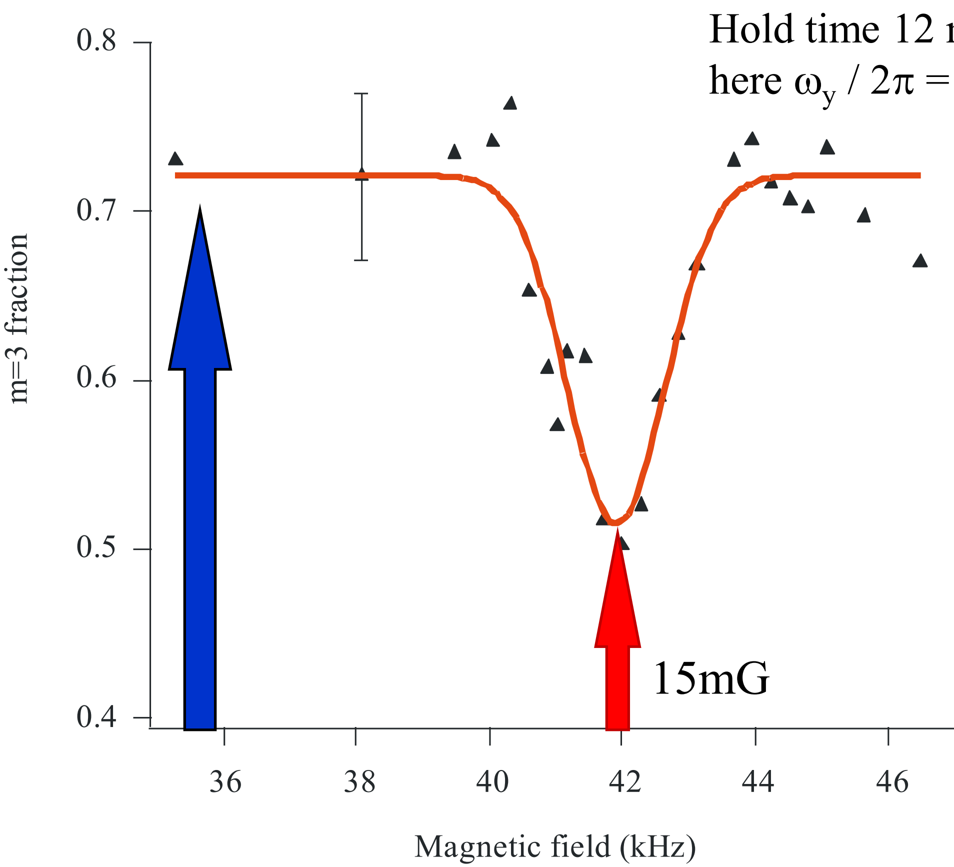


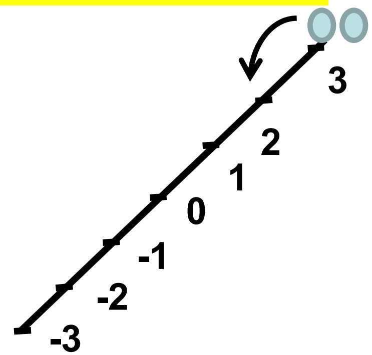
up to 20 000 atoms
Mott state :
a core of doublons
+ a shell of singlons

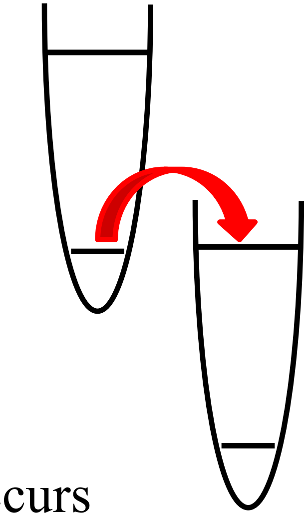




Dipolar relaxation resonance with 2 atoms per site



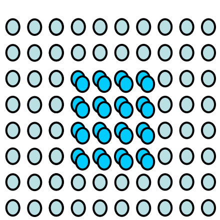


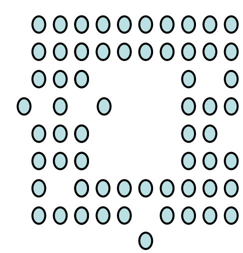


Dipolar relaxation occurs **when** the released energy matches the band excitation

$$g\mu_B B = \hbar\omega_L$$

B values to inhibit inelastic processes and to get rid of doublons…





S = 3 Spinor physics

From now on, we forbid dipolar relaxation
By setting B below 15 mG (lowest resonance in the lattice)

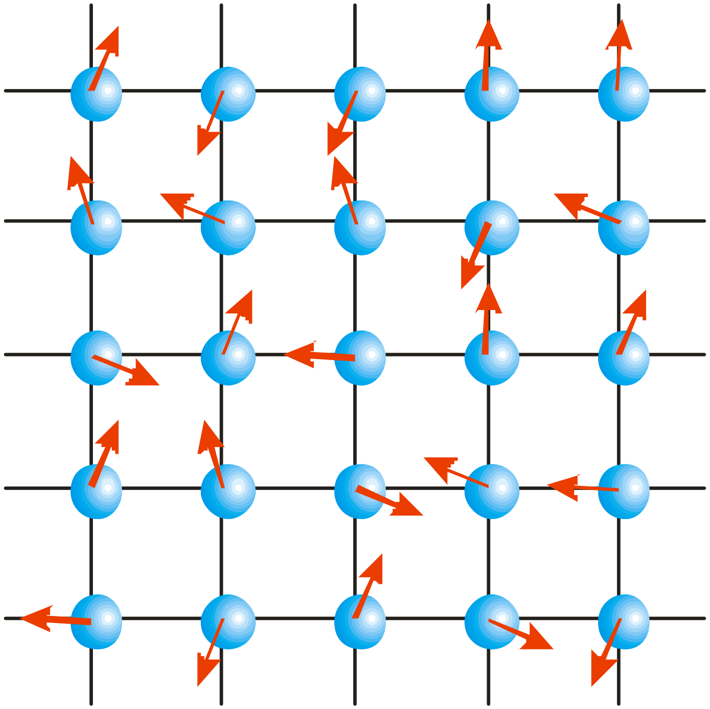
Magnetization remains constant

All interactions are elastic

Spin dynamics is coherent

We study a S=3 spinor
in a 3D lattice
with
Vdd @ 266 nm equal to h * **25 Hz**

Super-exchange 0.1 Hz



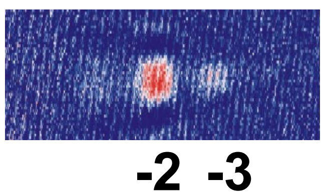
Typically 40 x 40 x 40 sites

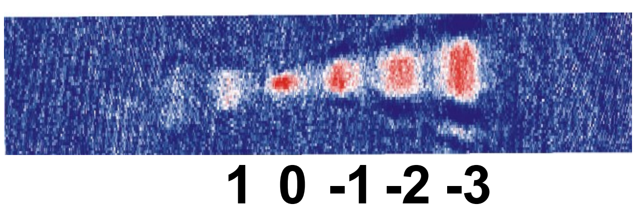
Adiabatic preparation of a condensate in m = -2

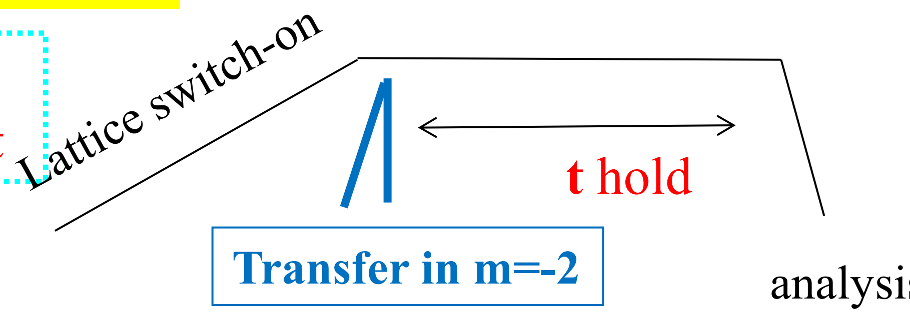
Two-photon Raman coupling
in level crossing induced
by a quadratic light shift

Out of equilibrium - Spin dynamics

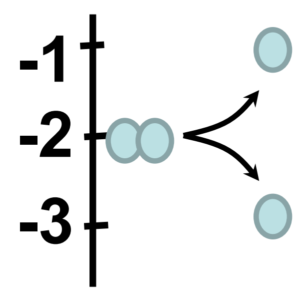
Starting from almost pure m= -2
we monitor spin composition vs hold time **t**







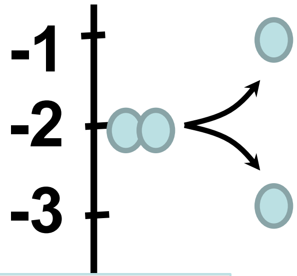
Interactions redistribute populations

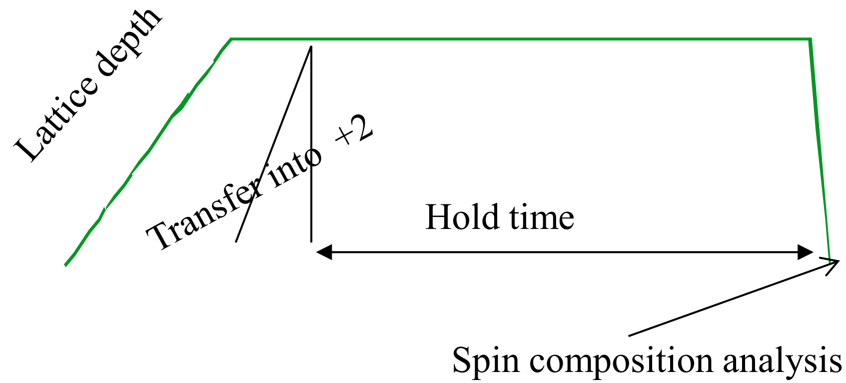


Final stages - after release : Stern Gerlach separation + TOF + absorption imaging

S= 3 spin exchange within doubly occupied sites

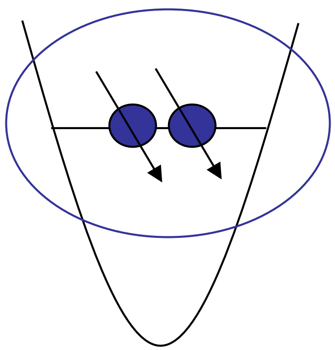
Fast dynamics
due to contact
interactions

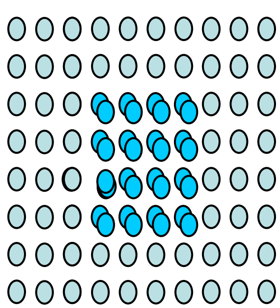


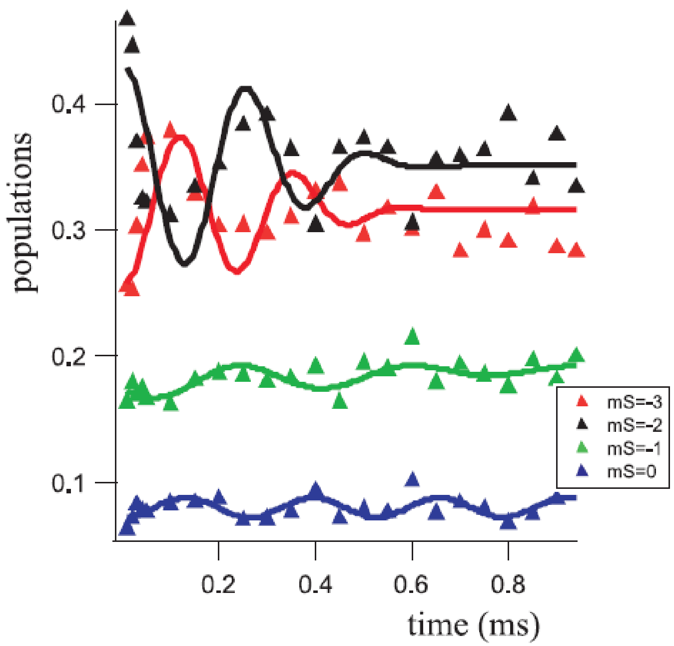


Preparation : 2 atoms in M = -2 per site

$$|-2\,;-2\rangle_{atom} = \alpha\,|6,-4\rangle_{mol} + \beta\,|4,-4\rangle_{mol}$$







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

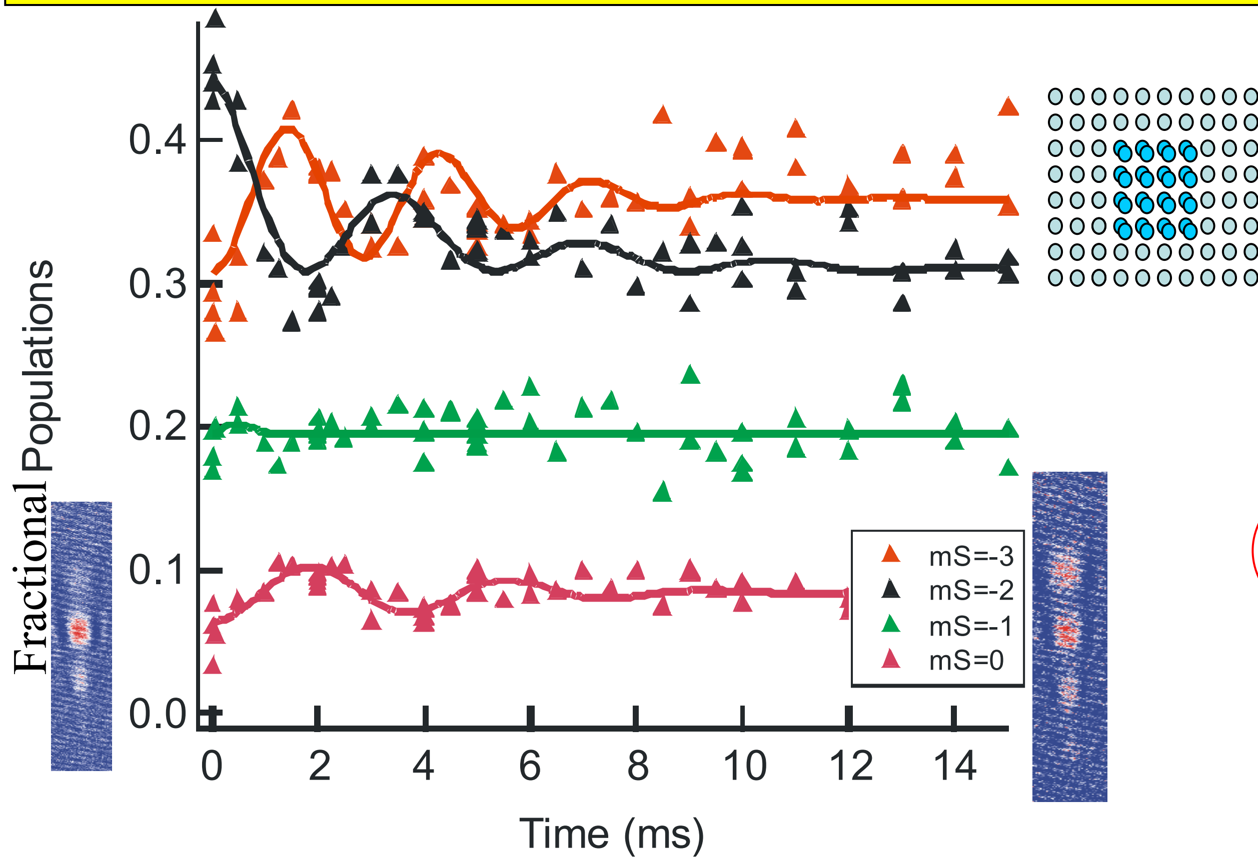
$a_6 = 102\ a_0$
differs greatly from
$a_4 = 58\ a_0$

(**exp period ↔ 320 µs**) (theory $1/\Gamma = 280$ µs)

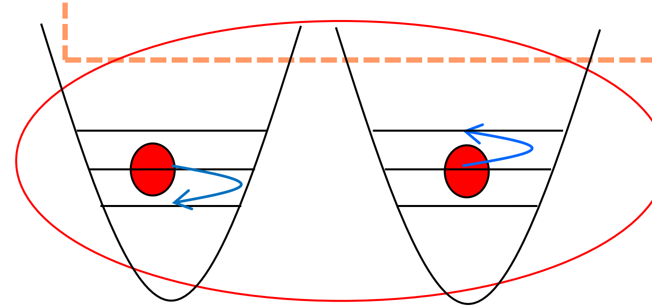
Tunneling causes damping + imperfect starting conditions

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

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

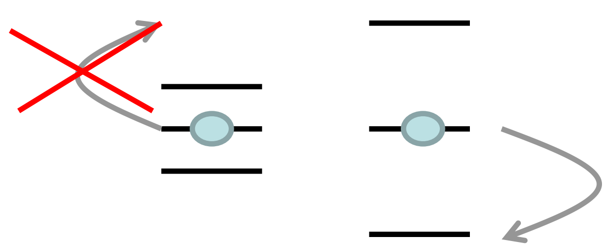


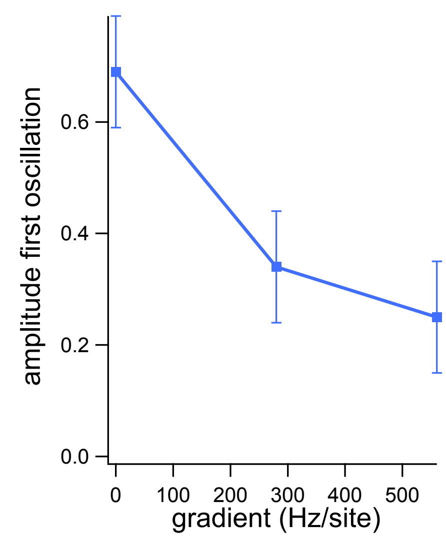
Intersite dipolar interaction induces 4 ms period oscillations
(much slower than on-site oscillations with period 0.3ms)



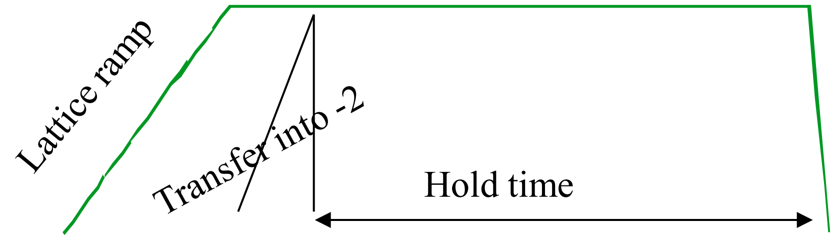
Magnetization is constant

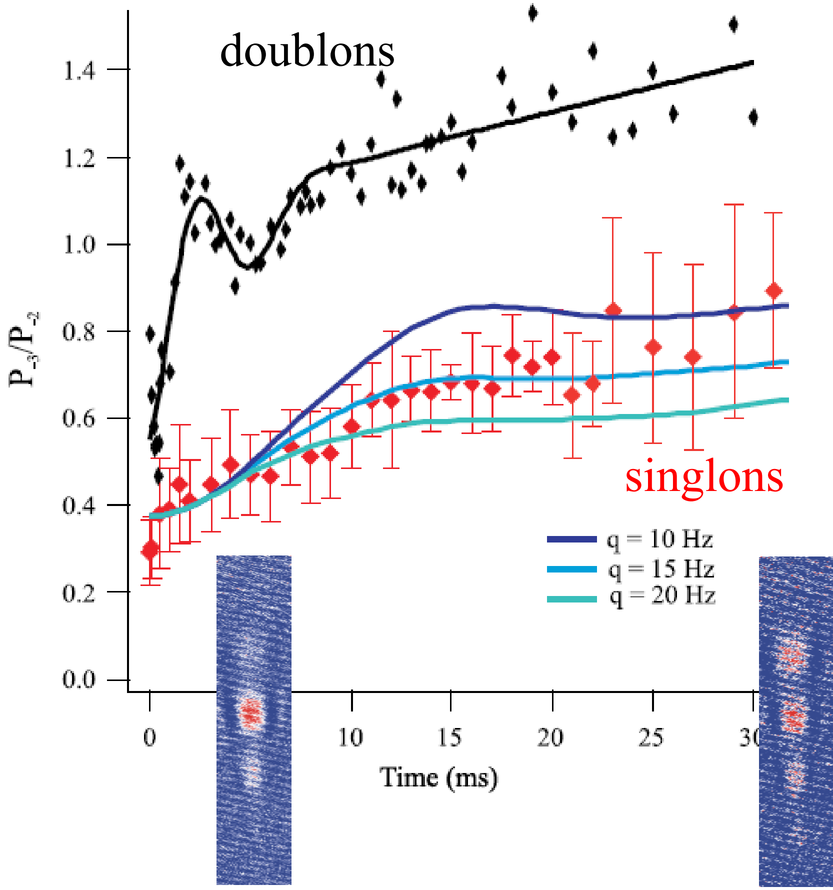
Intersite dynamics disappears in presence of a gradient

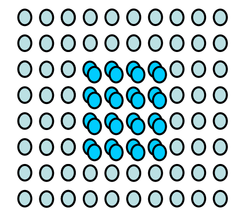


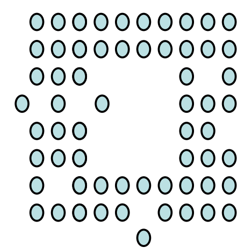


Spin dynamics in a 3D lattice with 1 or 2 atoms per site (or less)



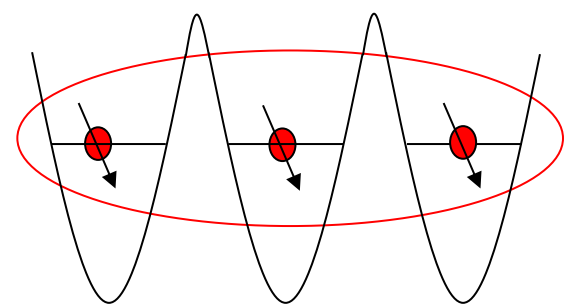






Intersite spin exchange

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



Singlon dynamics :
Good agreement with
3 x 3 plaquette simulation
(L Santos, P Pedri)

(**time scale ↔ 5 to 30 ms**)

*de Paz et al , PRL **111**, 185305 (2013)*

Summary

SPINOR physics with S = 3

Coherent spin dynamics - **evidence for inter-site dipolar interactions**

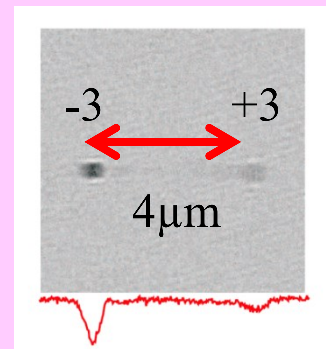
*de Paz et al, PRL **111**, 185305 (2013) and PRA **87**, 051609 R (2013)*

Past results -**Spontaneous demagnetization** at low field**;**

-**Phase transition** *PRL **106**, 255303;*

-a spin 3 gas with **free magnetization** *PRL **108**, 045307*

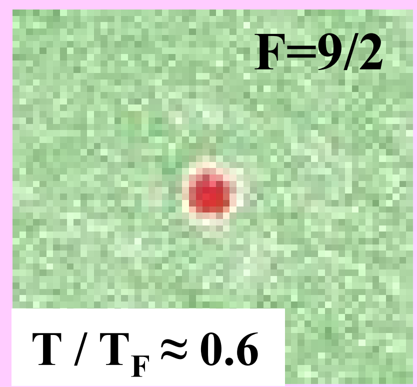
Recent results + Outlook



Double well trap with opposite polarizations

A dipolar Fermi sea ^{53}Cr

a few 10^3 atoms – April 2014



+ (just starting)

^{87}Sr in optical lattices for quantum magnetism

Cold Atom Team (GQD) in Villetaneuse - Paris Nord

LPL
Laboratoire de physique des lasers

PhD students :

Aurélie de Paz and Bruno Naylor

Post-docs :

Amodsen Chotia (now at Univ Paris - Descartes)

Arijit Sharma (now in Singapore)

Permanent members :

Bruno Laburthe-Tolra, Etienne Maréchal, Paolo Pedri (theory), Laurent Vernac and O. G.

Collaborations :

Johnny Huckans and Luis Santos

Dipolar Quantum Gas Team

www-lpl.univ-paris13.fr:8082

OG, L. Vernac, J. Huckans (invited), P. Pedri, B. Laburthe, A. de Paz (PhD),
A. Chotia (postdoc), A.Sharma (postdoc), E.Maréchal
+ L Santos (theory) + B. Naylor (PhD)