Emergent Quantum Phenomena
Heidelberg - March 11, 2014

Olivier GORCEIX

Spin dynamics in a dipolar lattice gas

Laboratoire de Physique des Lasers
Université Paris 13, Sorbonne Paris Cité
Villetaneuse - France

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 $6\mu_B$

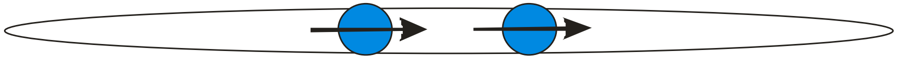
MDDI are 36 times greater than in alkali BECs

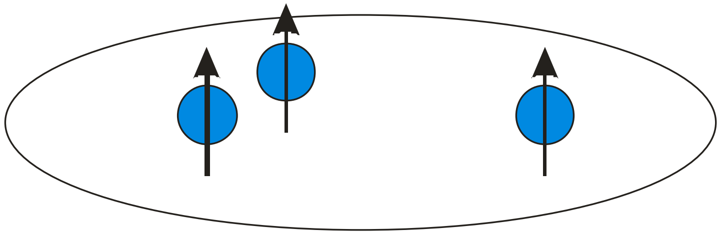
ε_{dd} = *ratio : dipolar interactions / contact interactions*

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

$\varepsilon_{dd}(Cr)=0{,}159$ *compared to* $\varepsilon_{dd}(Rb)=0{,}0044$

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



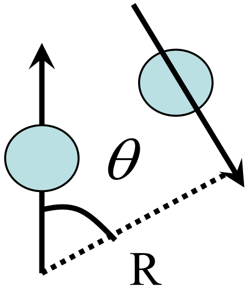


Side to side repulsion

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.

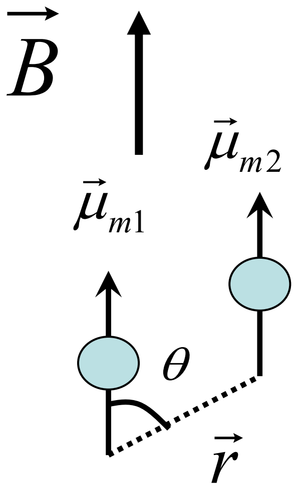


Coupling between spin and rotation

The two types of interactions in a Cr condensate

GPE / **NLSE**:

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



Contact interaction

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

Local
mean field

dipole-dipole interactions

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

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

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

Non local
Anisotropic
mean field

Non-linear non-local and anisotropic
terms enlarge the possible research opportunities.

For **Cr BECs** with **spin S = 3,**

Ψ comprises 2 S + 1 = 7 spin components

Spin dynamics in a Cr BEC

driven by dipole-dipole interactions

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

Various terms:

ISING

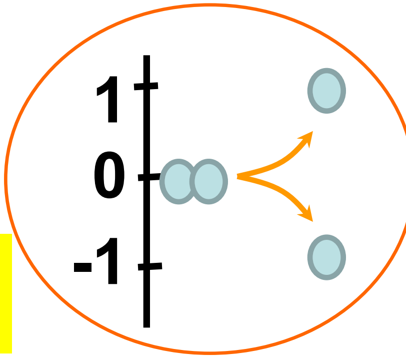
XY / Spin Exchange

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

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

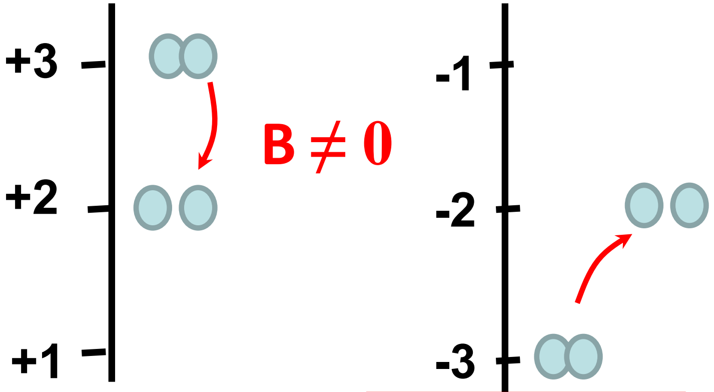
$$\otimes\left(2zS_{2z} + r_- S_2^+ + r_+ S_2^-\right)$$

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



Inelastic collisions

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



Cr BEC M= 3

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

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

Inelastic collisions change magnetization ⇒ **Strong heating**

Coherent Spin dynamics in a Cr BEC

When inelastic terms are prohibited

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

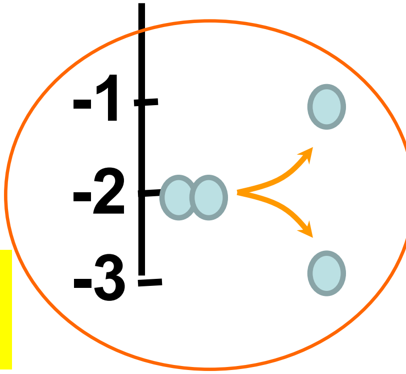
Spin operators reduce to :

ISING

XY / Spin Exchange

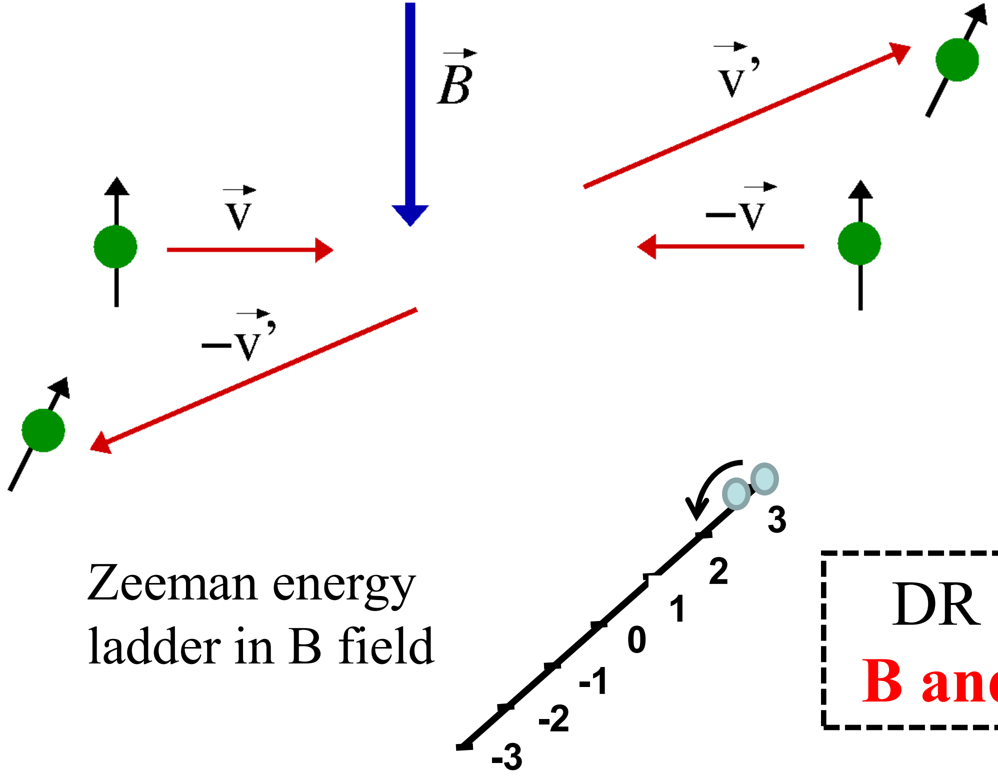
$$S_{1z}S_{2z} + \frac{1}{2}\left(S_1^{+}S_2^{-} + S_1^{-}S_2^{+}\right)$$

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



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

Control of inelastic collisions – dipolar relaxation



Zeeman energy ladder in B field

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

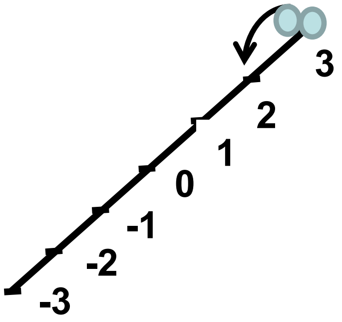
DR causes heating and losses ;
B and geometry control DR rate

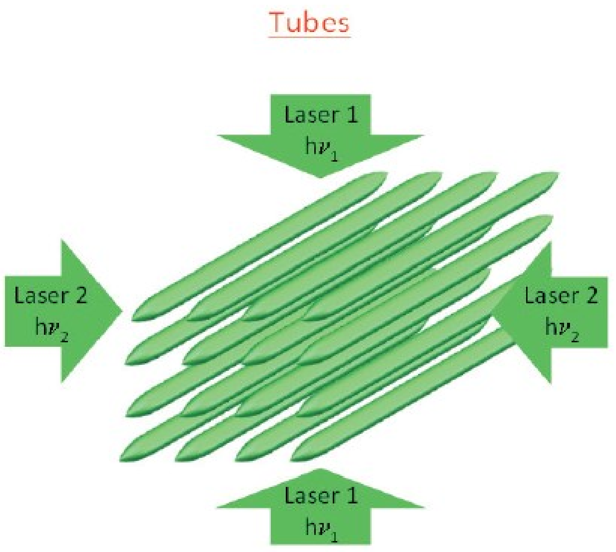
To start with **one must** produce the Cr BEC in m = -3.
When atoms are **brought to +3**
or any combinaison of **m's > -3**, one loses the BEC in a few milli-seconds ?

How do we get a stable S=3-spinor ?

Set **B extremely low** (< 0,5 mG = 5 nT) see our work in PRL 2012

Or trap the BEC in **optical lattices** (2D , 1D or even 0D ie at the nodes of 3D OLs)

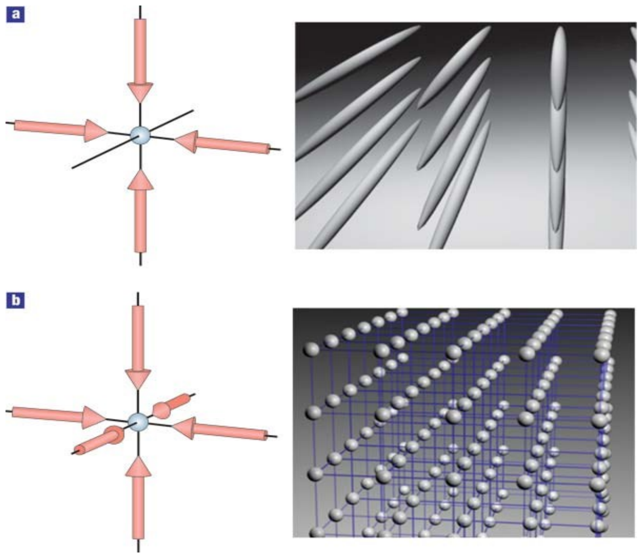




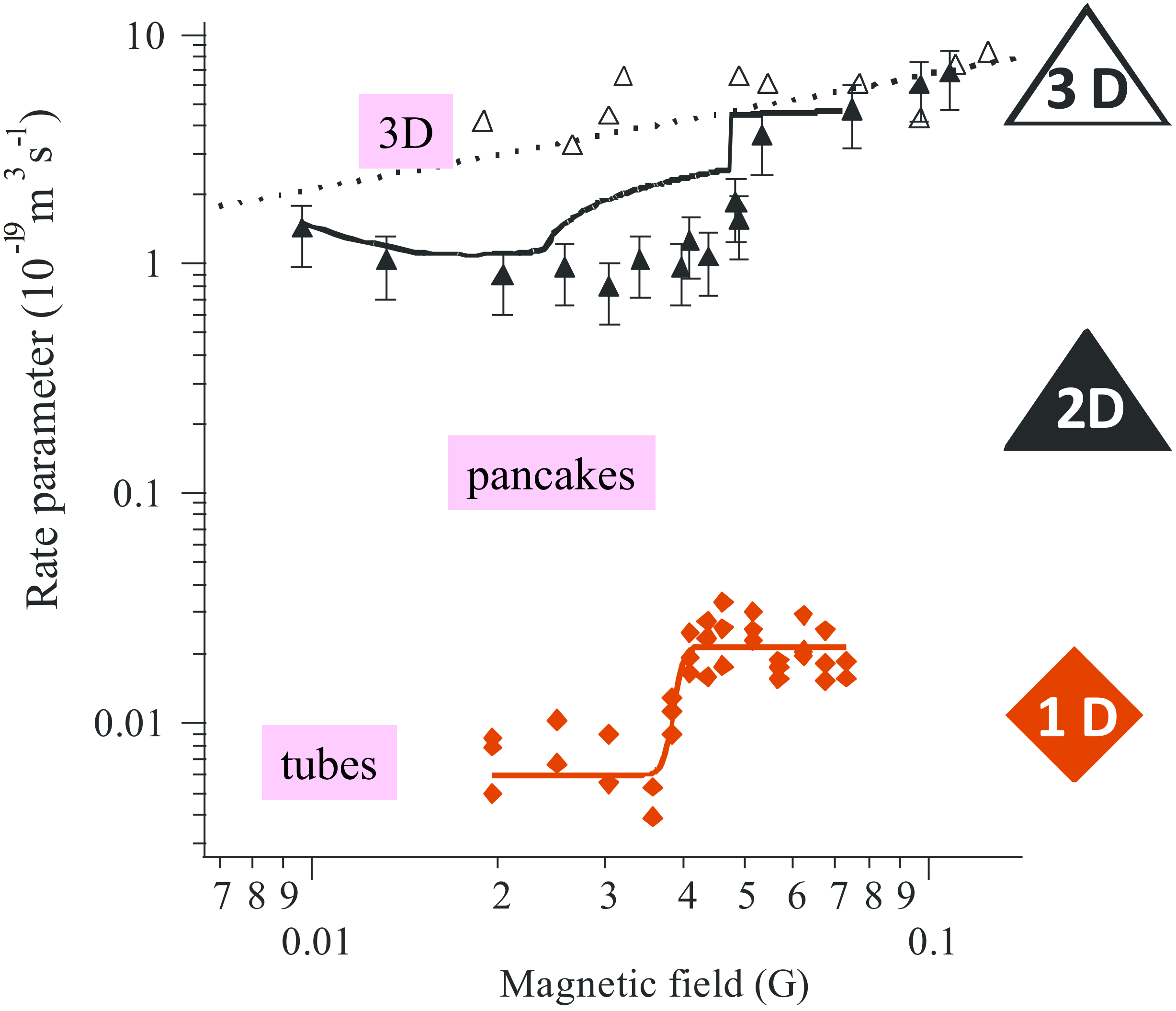
INHIBITION OF DIPOLAR RELAXATION

Collisional stabilisation
of the **spinor quantum gas**

by confinement
in optical lattices



Loss rate in log Scale !!



PRA **81**, 042716

Phys. Rev. Lett. **106**, 015301

Below **threshold**: **a metastable quantum gas in a spin excited state (energy >> chemical potential) is produced** ;
Spinor Physics can be explored with S=3

Relaxation and band excitation – Inhibition mechanism

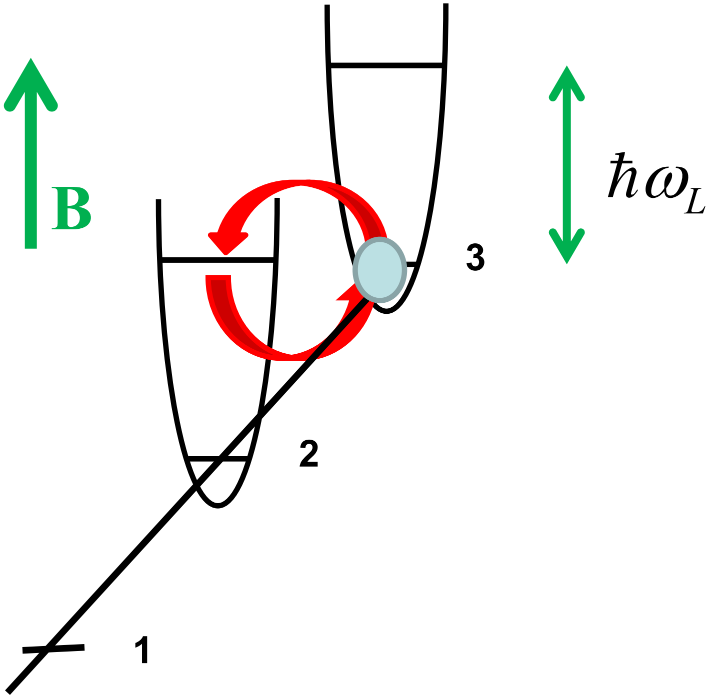
B ≈ 40 mG

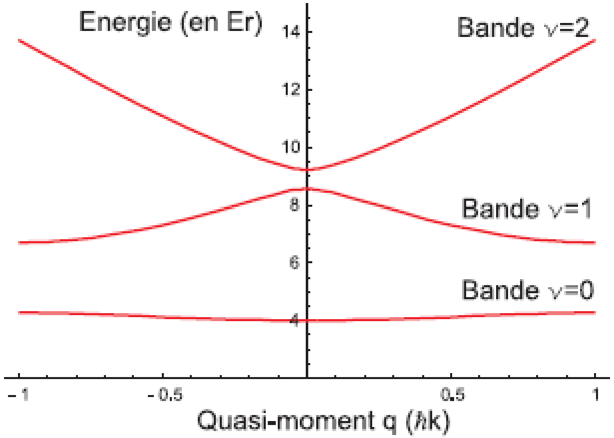
bandgap about 120kHz

Atoms whose spin flips are promoted
from the fondamental band to the excited band
as B becomes greater than the threshold value set by

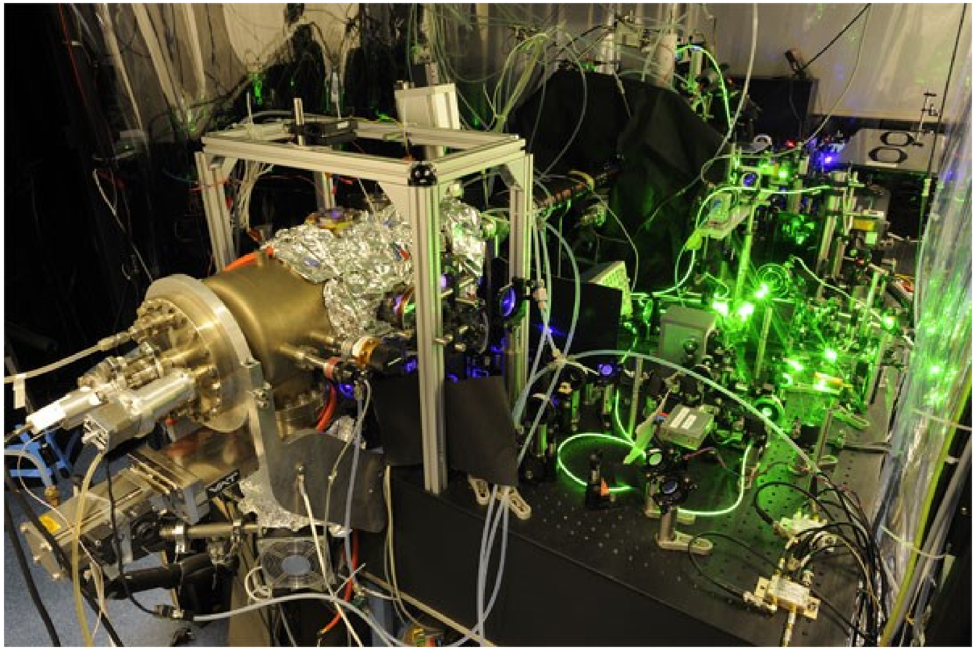
$$g\mu_B B = \hbar\omega_L$$

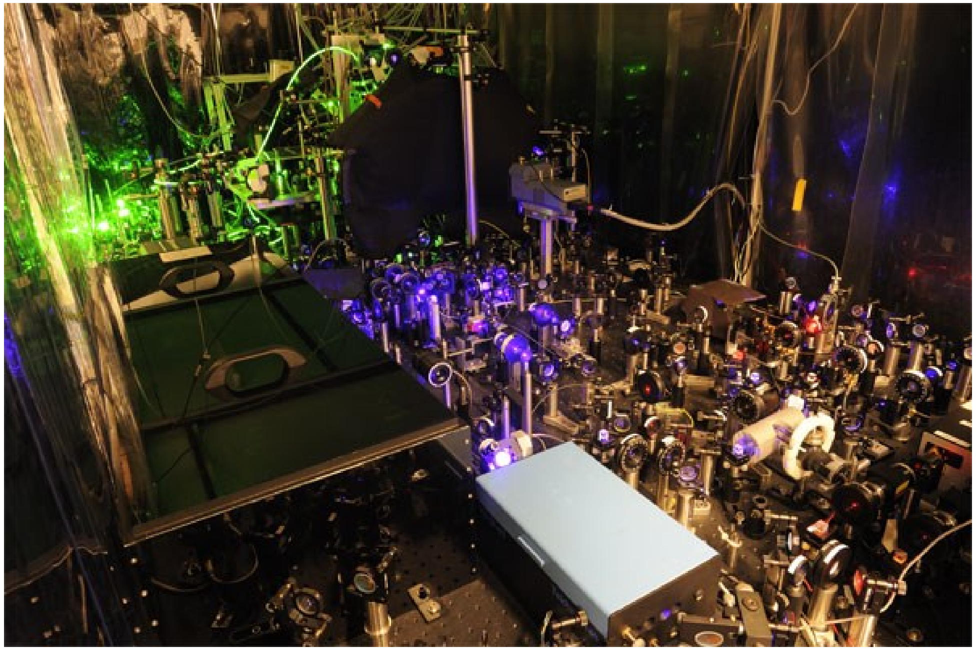
Below relaxation is energetically forbidden.

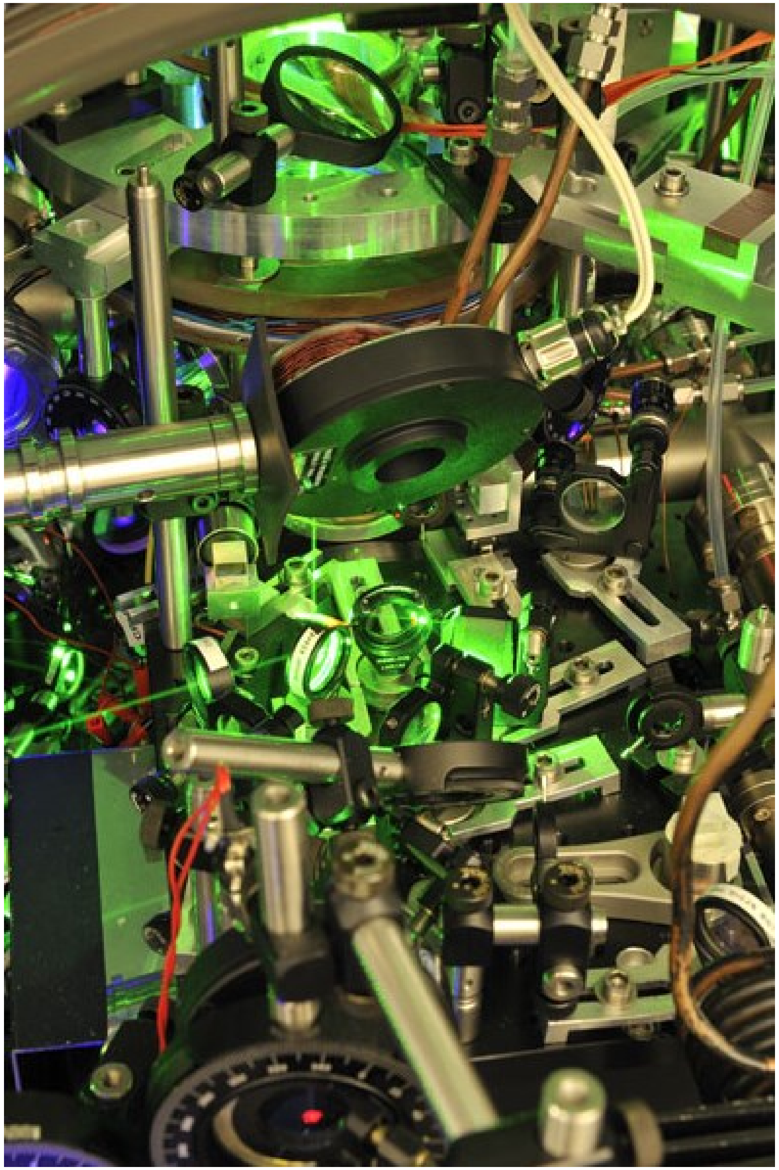




Half-time slide: The experimental setup



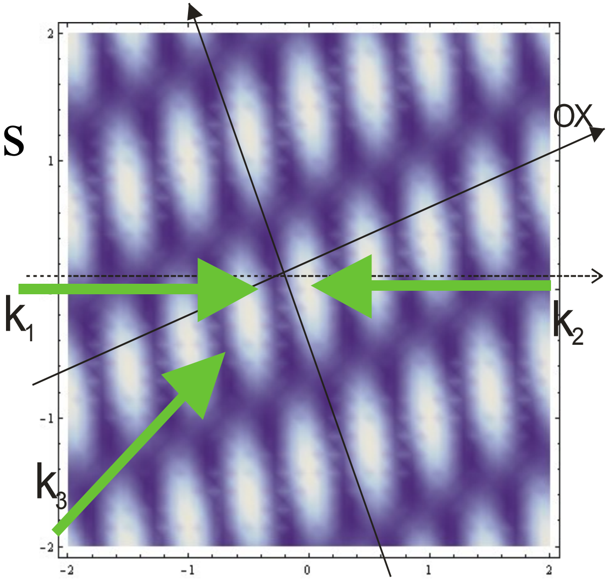




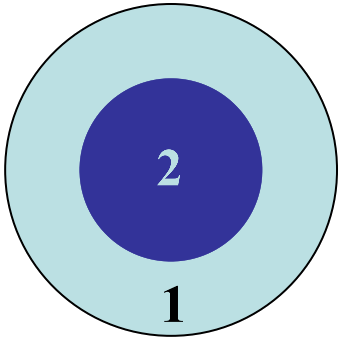
… well … Part of it !!…

Magnetism in a 3D optical lattice
- *Coherent and incoherent spin dynamics*

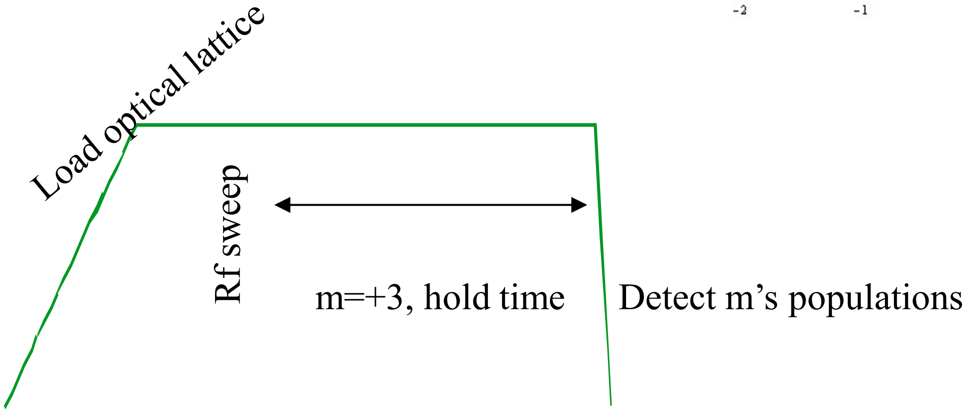
Tight confinement in
an anisotropic 3D lattices
Green 532nm light



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



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



Load optical lattice

Rf sweep

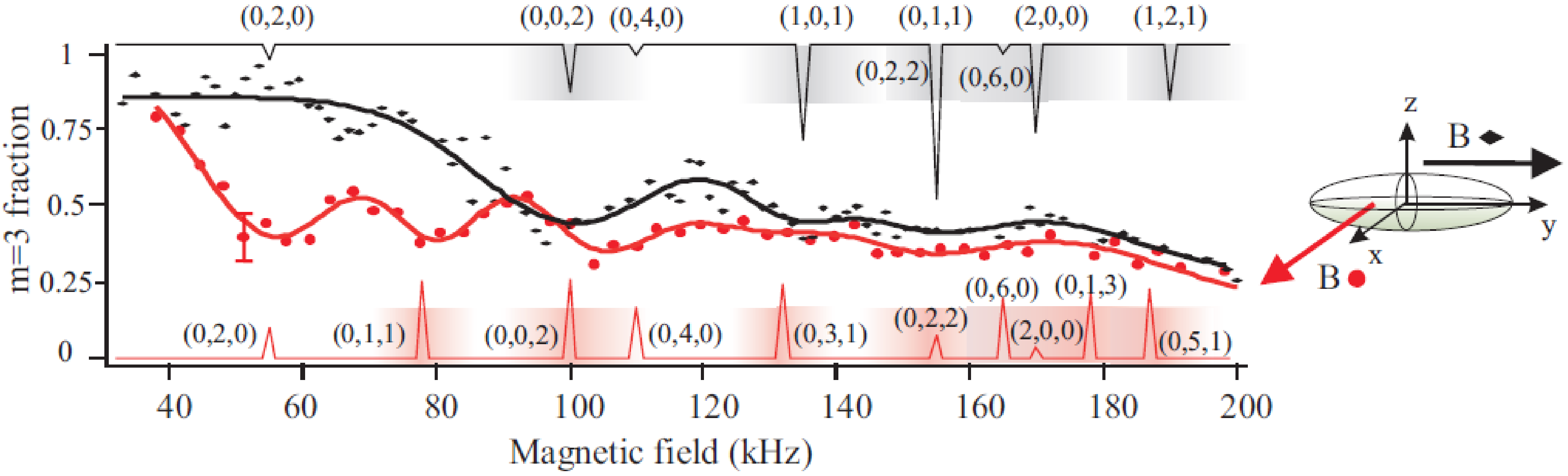
m=+3, hold time

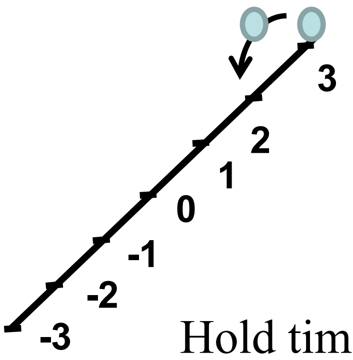
Detect m’s populations

Another dipolar effect in a dilute medium

Dipolar relaxation resonances with 2 (or more) atoms in m = +3 per site

The combined anisotropies of the lattice and of the dipolar interaction account for the anisotropy of the relaxation spectra = remaining atoms vs **B for two orthogonal orientations**





Hold time 30 ms

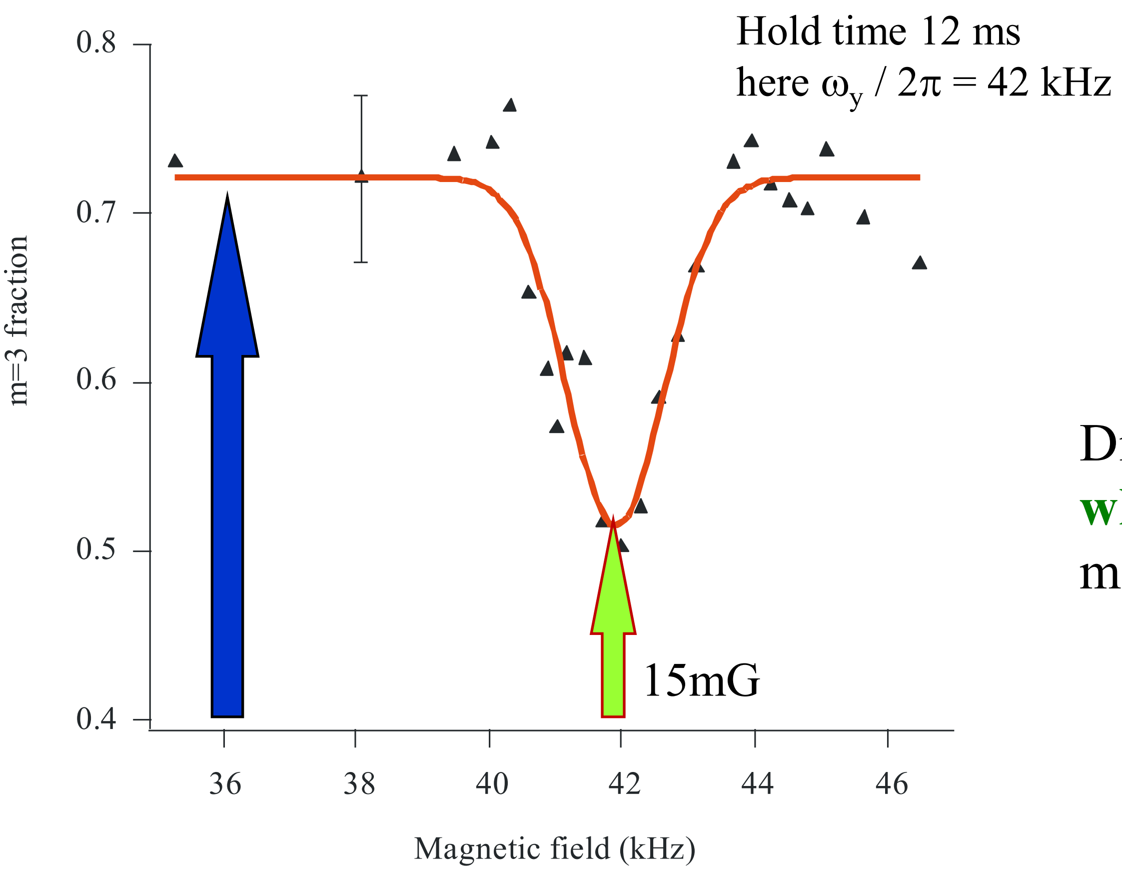
Here $\omega_y / 2\pi = 55$ kHz

Dipolar relaxation occurs when the released energy matches a band excitation.

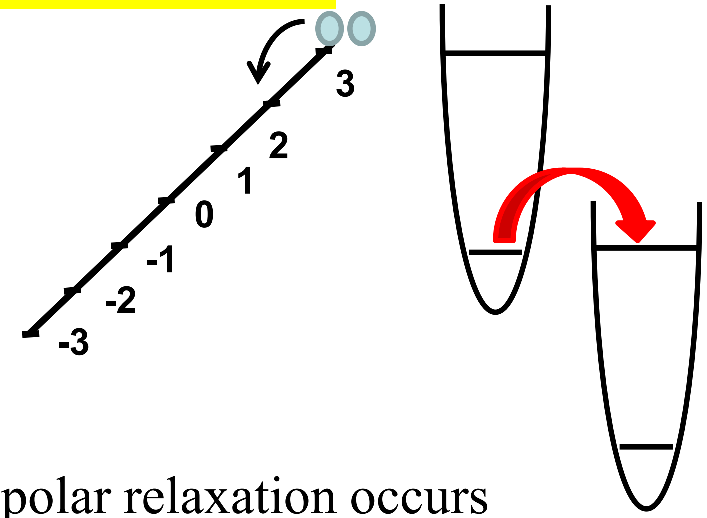
It couples |-3, -3> to **different bands depending on B orientation .**

de Paz et al, PRA 87, 0516090 (2013)

Dipolar relaxation resonance with 2 atoms per site



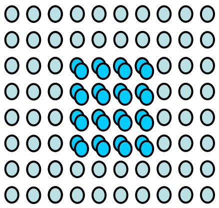
Hold time 12 ms
here $\omega_y / 2\pi = 42$ kHz

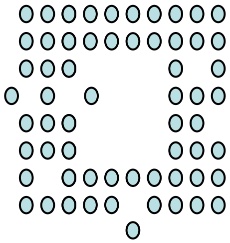


Dipolar relaxation occurs **when** the released energy matches the band excitation

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

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





S = 3 Spinor physics

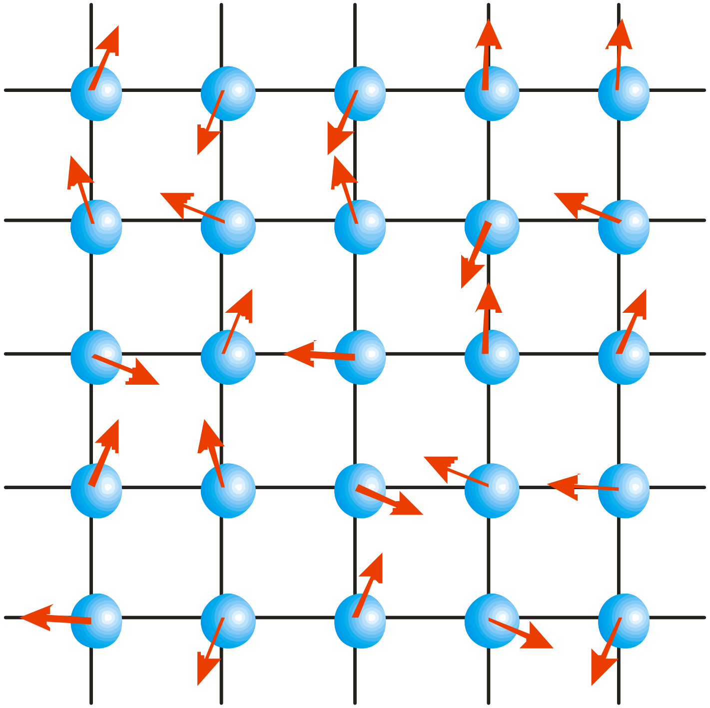
From now, we forbid dipolar relaxation

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

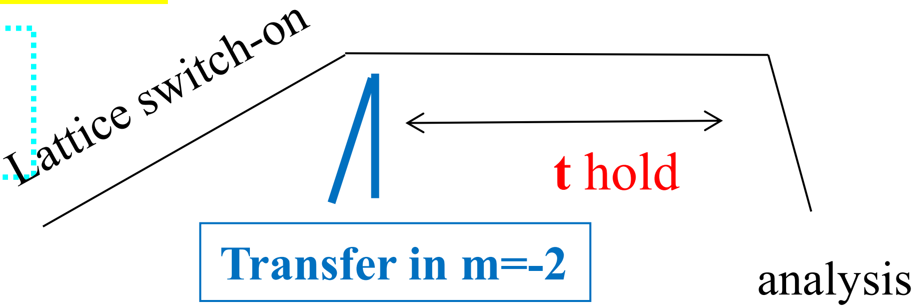
Typically 40 x 40 x 40 sites

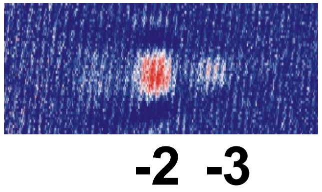
Adiabatic preparation of a condensate in m = -2

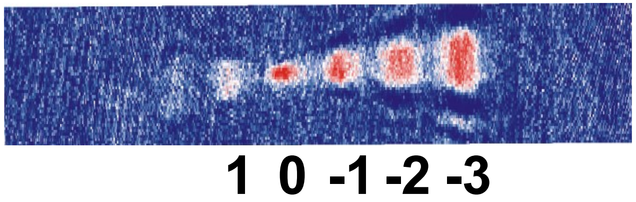
Two-photon Raman coupling in level crossing induced by a quadratic light shift

Out of equilibrium - Spin dynamics

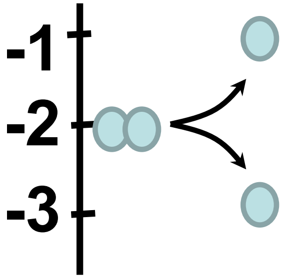
Starting from almost pure m= -2
we monitor spin composition vs hold time **t**







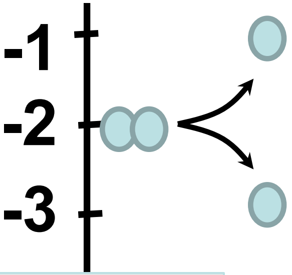
Interactions redistribute populations

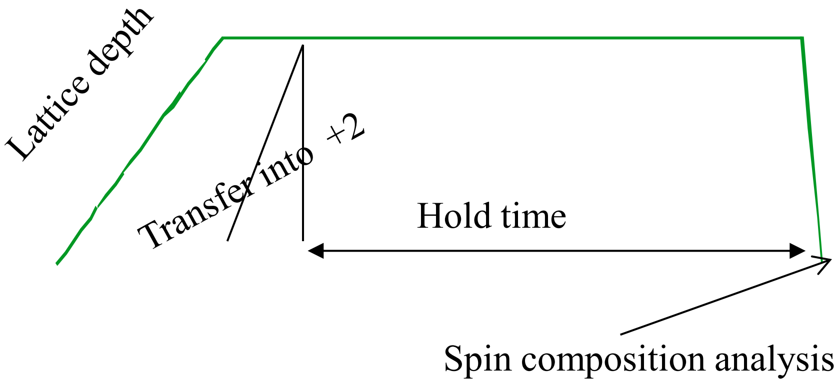


Final stages - after release : Stern Gerlach separation + TOF + absorption imaging

S= 3 spin exchange within doubly occupied sites

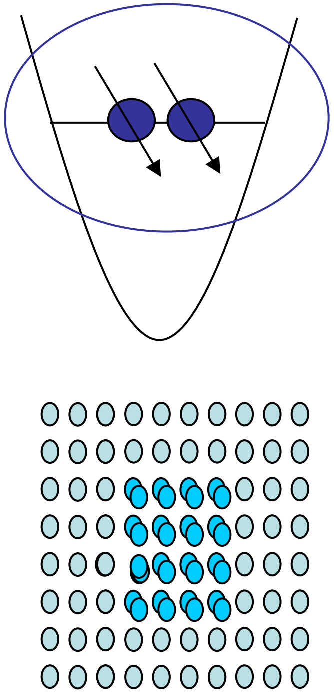
Fast dynamics
due to contact
interactions

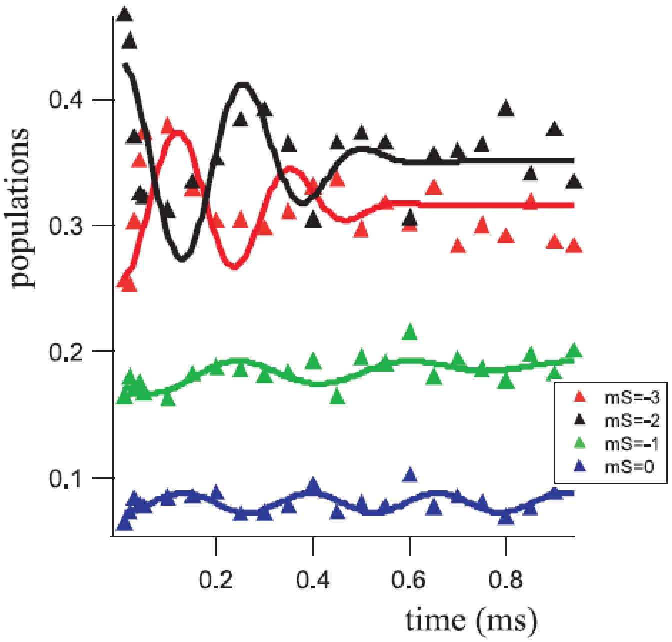




Preparation : 2 atoms in M = -2 per site

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





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

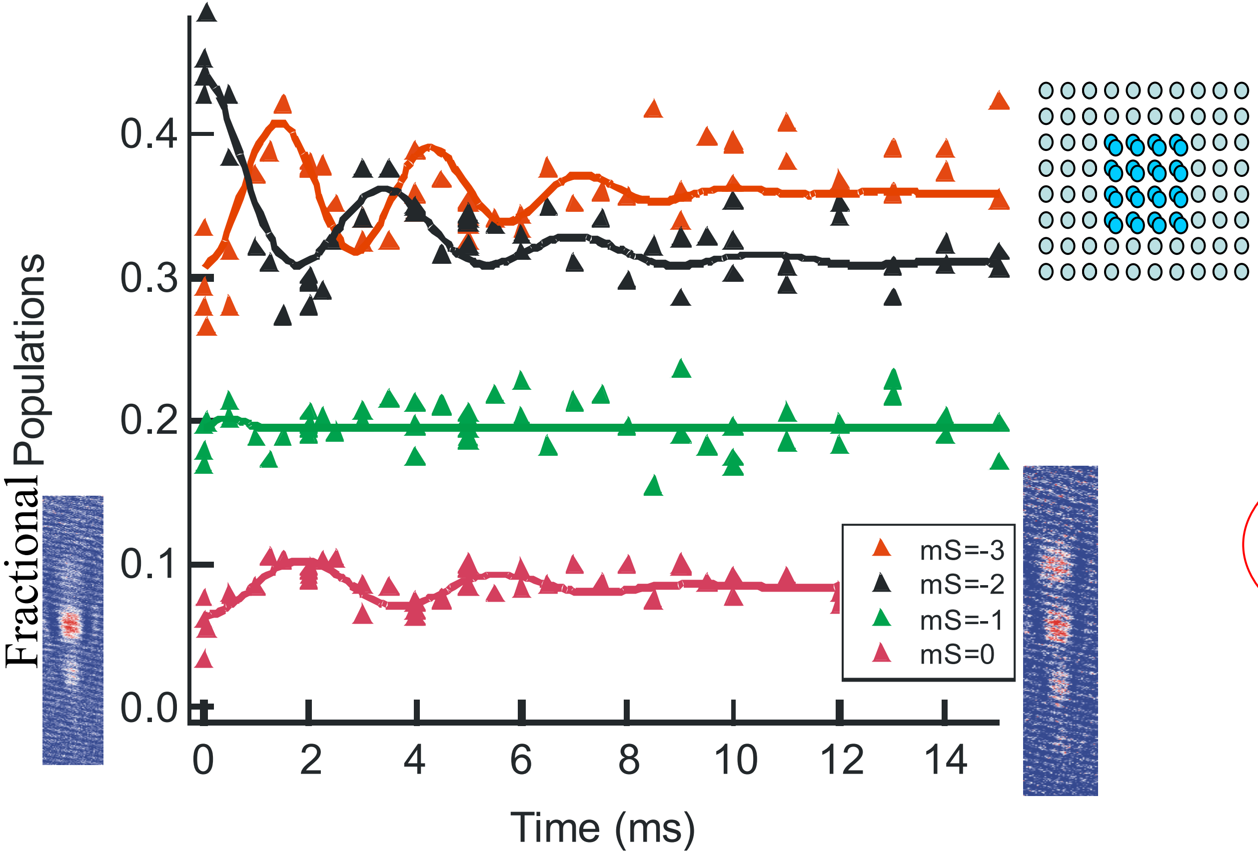
$a_6 = 102\ a_0$
differs greatly from
$a_4 = 58\ a_0$

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

Tunneling causes damping + imperfect starting conditions

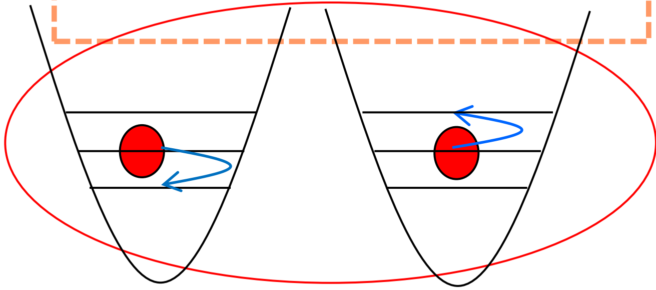
Long time-scale spin dynamics in lattice : **intersite dipolar exchange** with doublons

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

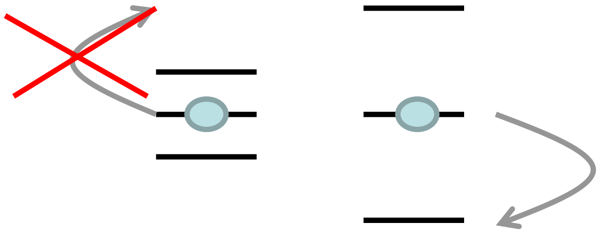


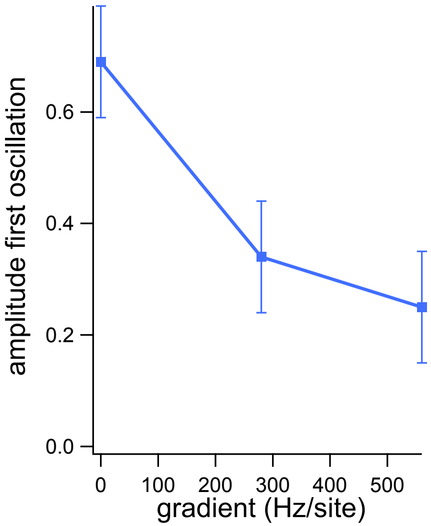
Magnetization is constant

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

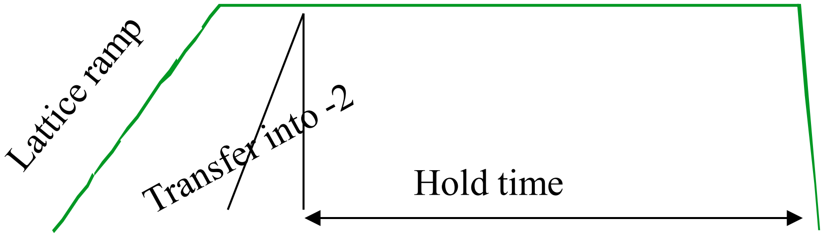


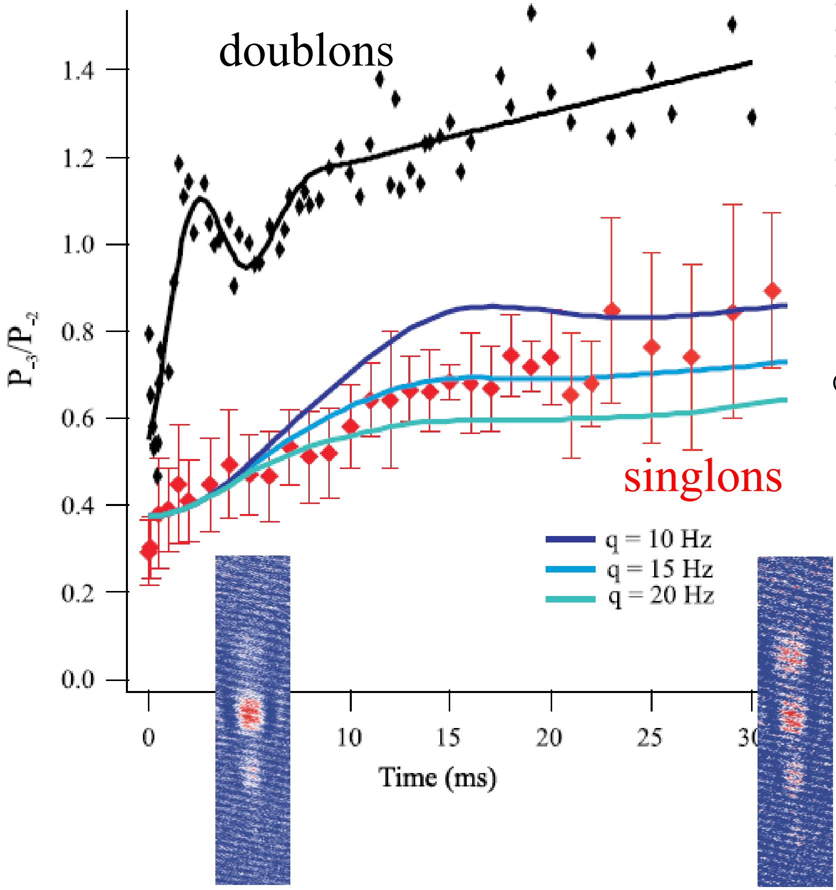
Intersite dynamics disappears in presence of a gradient

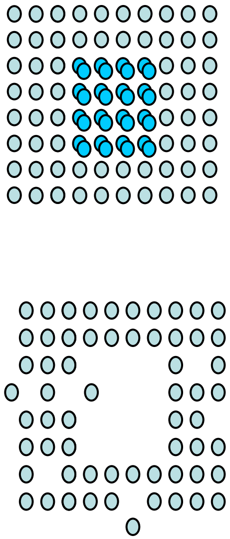




Spin dynamics in a 3D lattice with 1 or 2 atoms per site (or less)

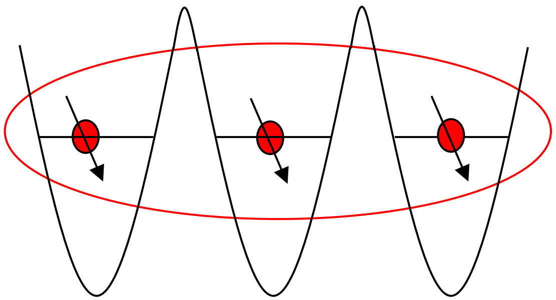






Intersite spin exchange

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



Singlon dynamics :
Good agreement with
3 x 3 plaquette simulation

(**time scale ↔ 5 to 30 ms**)

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

Summary

Inhibition of Dipolar Relaxation in reduced dimensions –

→→ **SPINOR physics with S = 3**

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

Other past results

Spontaneous demagnetization at low field

-phase transition;

-thermodynamics of a spin 3 gas with free magnetization

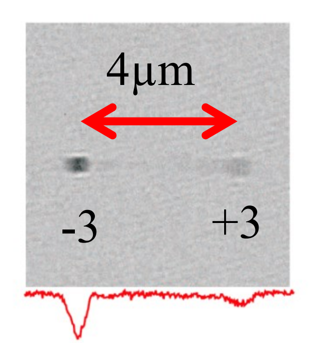
Outlook - our current on-going projects

In situ imaging – **Spin Textures** – dynamics of **magnetic domains**

→→ **quantum magnetism simulation** (in 2D + lattice)

Double well trap with opposite polarizations

Production of a dipolar **Fermi sea with ^{53}Cr**



+ **(just starting)**

87Sr 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 and Arijit Sharma

Permanent members :

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

Collaborations :

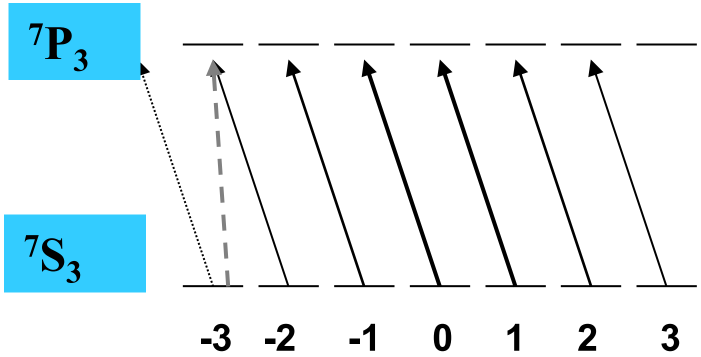
Johnny Huckans, Mariusz Gajda and Luis Santos

Dipolar Quantum Gas Team

www-lpl.univ-paris13.fr:8082

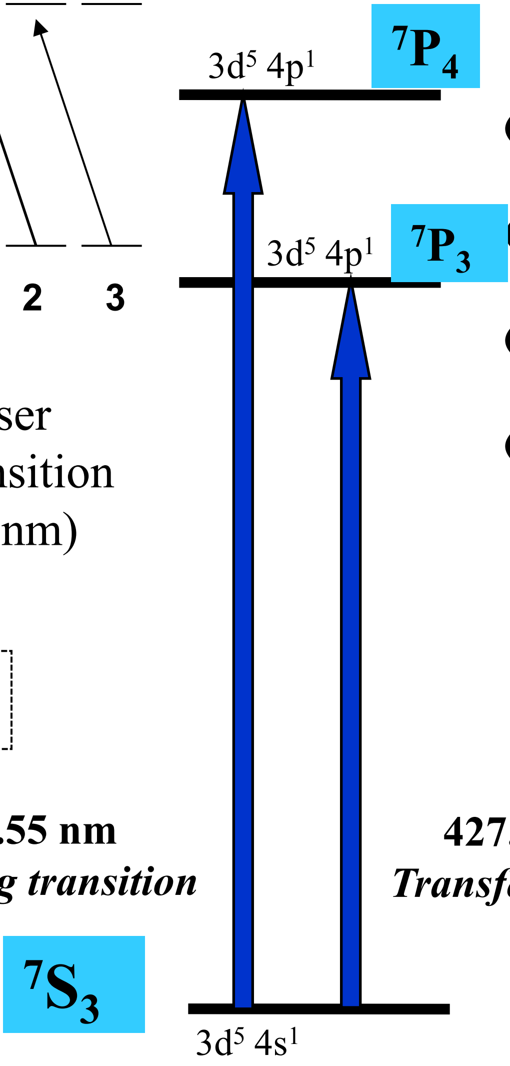
OG, L. Vernac, J. Huckans (invited), P. Pedri, B. Laburthe, A. de Paz (PhD), A. Chotia (postdoc), A.Sharma (postdoc), E.Maréchal

State preparation in m = -2



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

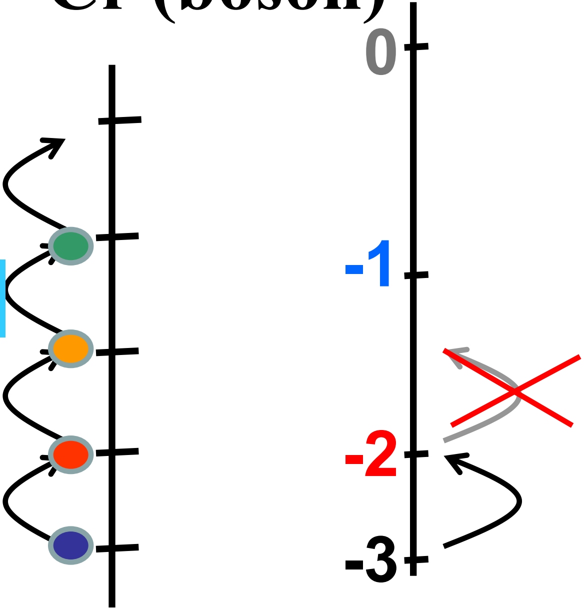
$$\boxed{\Delta=\alpha\, m_S^{\,2}}$$



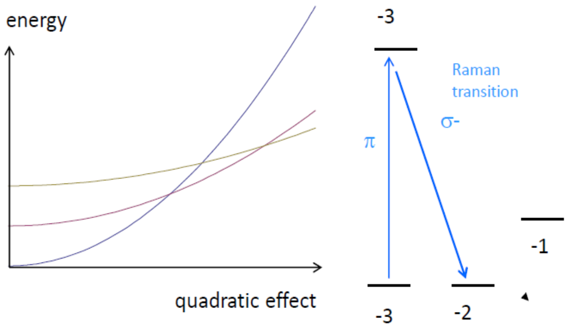
425.55 nm
Cooling transition

427.85 nm
Transfer laser

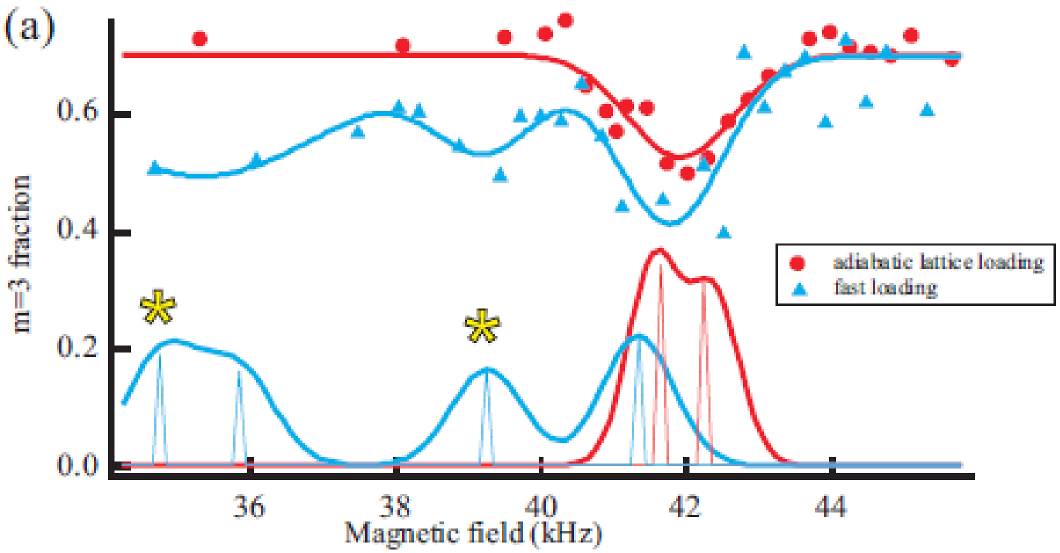
^{52}Cr (boson)

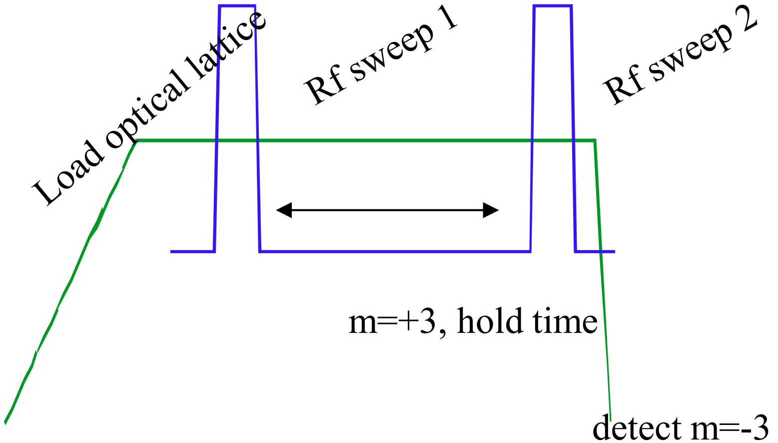


Quadratic effect allows state preparation



Dipolar relaxation resonance with 2, 3 or more atoms per site





Load optical lattice

Rf sweep 1

Rf sweep 2

m=+3, hold time

detect m=-3