CLEO Europe - IQEC
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# Exploring quantum magnetism in a Chromium Bose-Einstein Condensate

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# Contact interactions in a standard condensate (one single internal state)

GPE / **NLSE**:

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

Van der Waals Interaction

Local mean field description

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

The **non-linear** term spawns various interesting effects
**vortex,**
**solitons**, **Josephson**-like physics, **squeezing**,
**non-linear** (atomic) **optics** …

# 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 magnetic moment of $6\mu_B$**

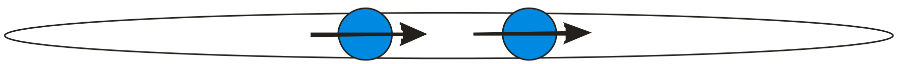
*MDDI are 36 times greater than in alkali BECs*

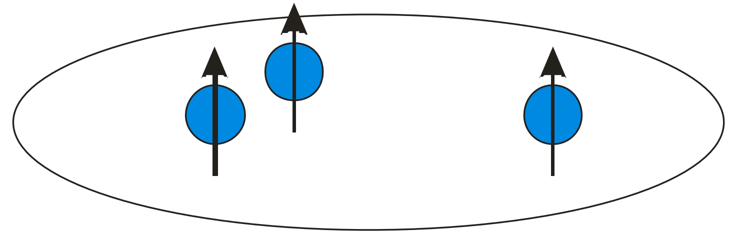
$$\varepsilon_{dd} = \frac{\mu_0 \mu_m^2 m}{12\pi\hbar} \propto \frac{V_{dd}}{V}$$

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

$\varepsilon_{dd}$ = *ratio : dipolar interactions / contact interactions*

if $\varepsilon_{dd} > 1$ a 3D condensate is **unstable** *head to tail attraction*





*Side to side repulsion*

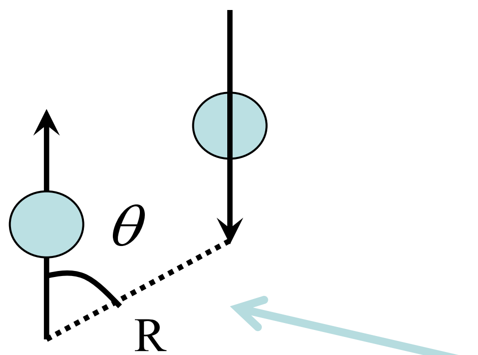
Dipole-dipole interactions

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

Links with **magnetism**,

Phases,

**Frustration**, …




Least energy configuration

**Coupling Between spin and rotation**

# The two types of interactions in a single state condensate

GPE / **NLSE**:

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

Contact interaction

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

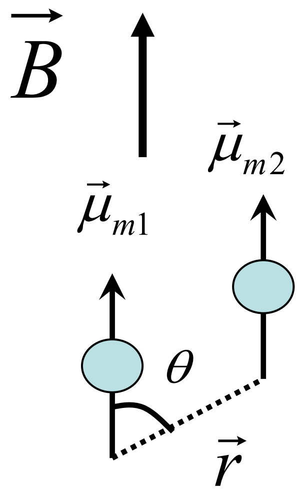
Local
mean field

**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.

# Spin Exchange and dipolar relaxation DR in a multi-component *condensate - SPINOR*

dipole-dipole interaction and spin operators :

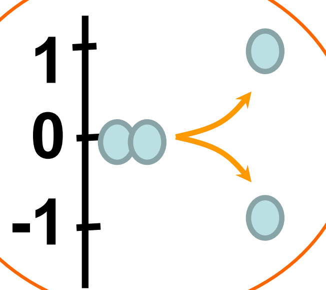
$$V_{dd}(\vec{r}) = \frac{\mu_0 (g_J \mu_B)^2}{4\pi} \frac{\hat{s}_1 \cdot \hat{s}_2 - 3(\hat{s}_1 \cdot \vec{u}_r)(\hat{s}_2 \cdot \vec{u}_r)}{r^3}$$

**Various types of collisions:**

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

**Elastic collisions**

**Spin Exchange** $\Delta m_{S\ tot} = 0$

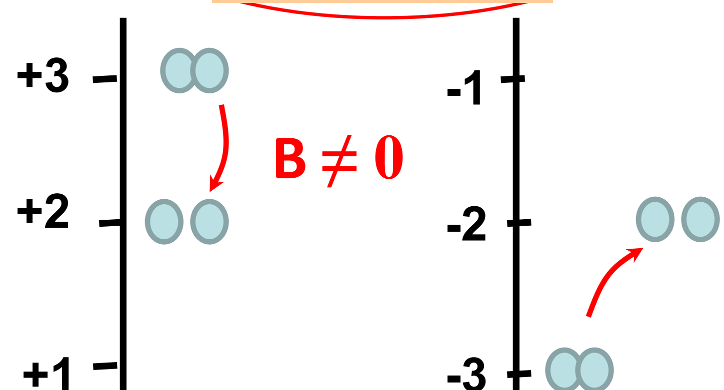



**Inelastic collisions** $\Delta m_{S\ tot} = \pm 1, \pm 2$

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

**Magnetisation is constant except for inelastic collisions**

$$\Delta m_{S\ tot} = \left(m_{S1} + m_{S2}\right)_f - \left(m_{S1} + m_{S2}\right)_i$$

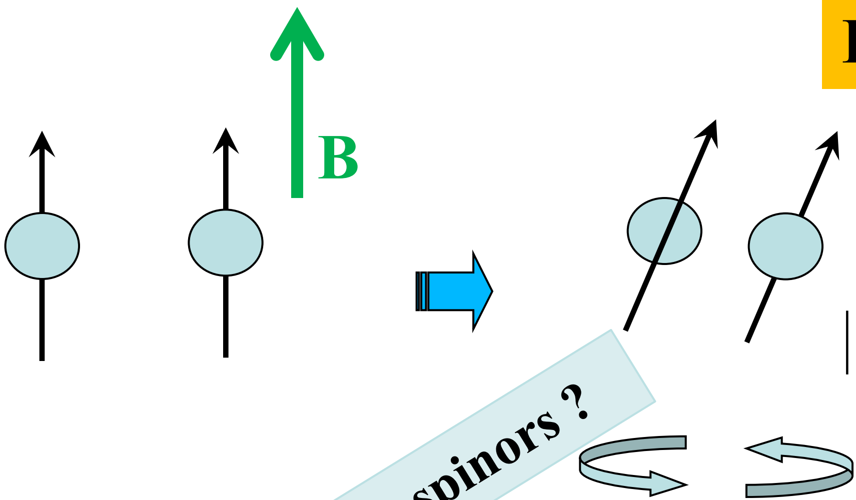



Cr BEC M= 3

$\Rightarrow$ **Strong heating**

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

# Inelastic Collisions – Induced rotation




Why do we care for spinors ?

Two channels are open for
two atoms in m = +3

$$\left|3,3\right\rangle \rightarrow \frac{1}{\sqrt{2}}\left(\left|3,2\right\rangle + \left|2,3\right\rangle\right) \quad with \quad \Delta m_S = -1$$

$$\left|3,3\right\rangle \rightarrow \left|2,2\right\rangle \quad with \quad \Delta m_s = -2$$

$$\Delta \ell = 1 \quad or \quad 2$$

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

Angular momentum conservation
implies rotation?

Spontaneous creation of **vortices** ?
**Einstein-de-Haas effect**

## Why do we care for spinors ?

« **spinor** » physics:

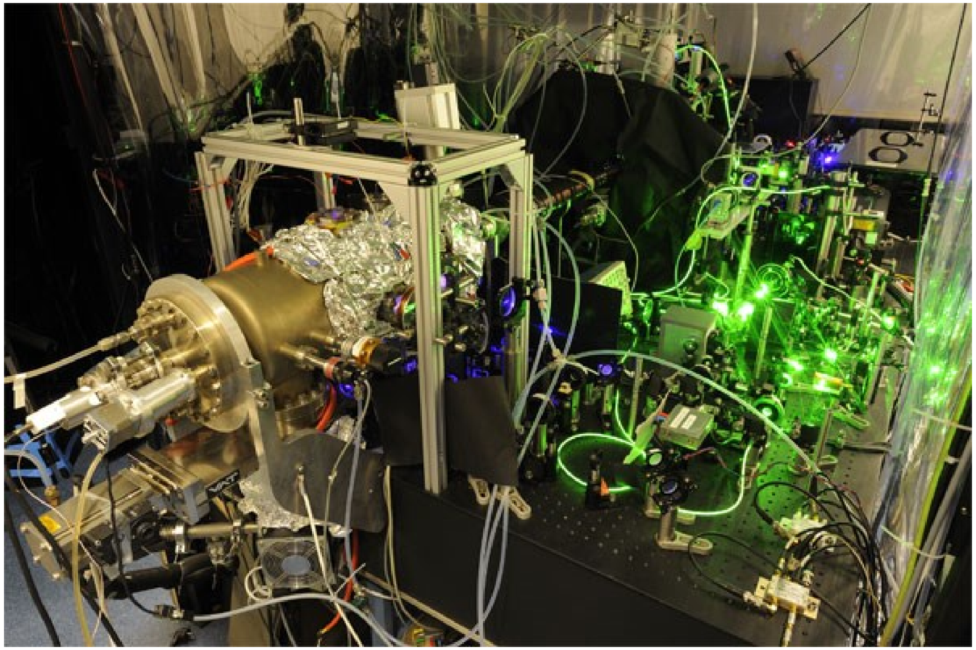
**combines**

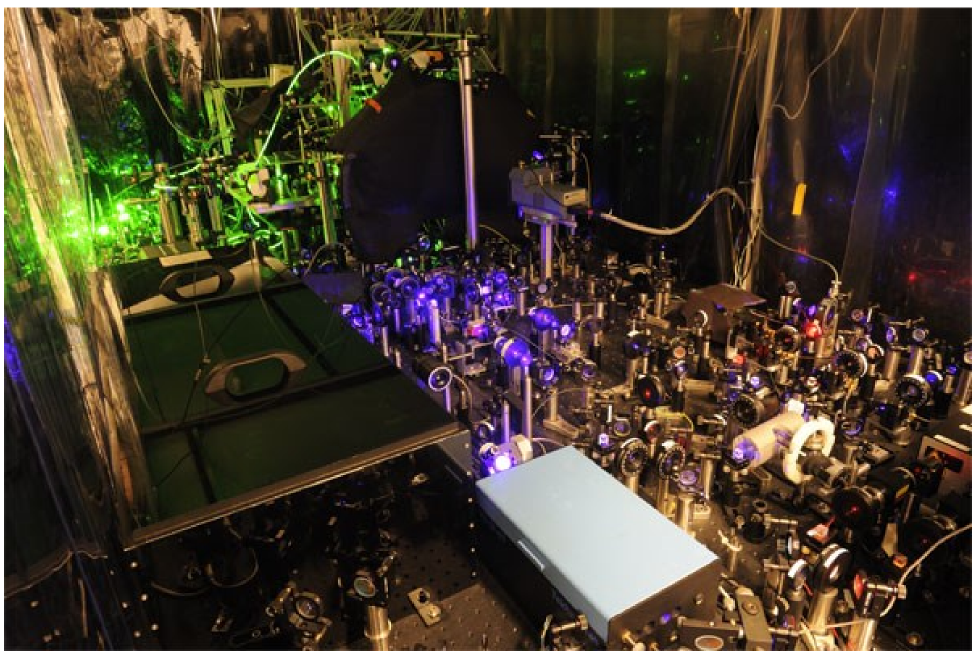
**On one hand, superfluidity**

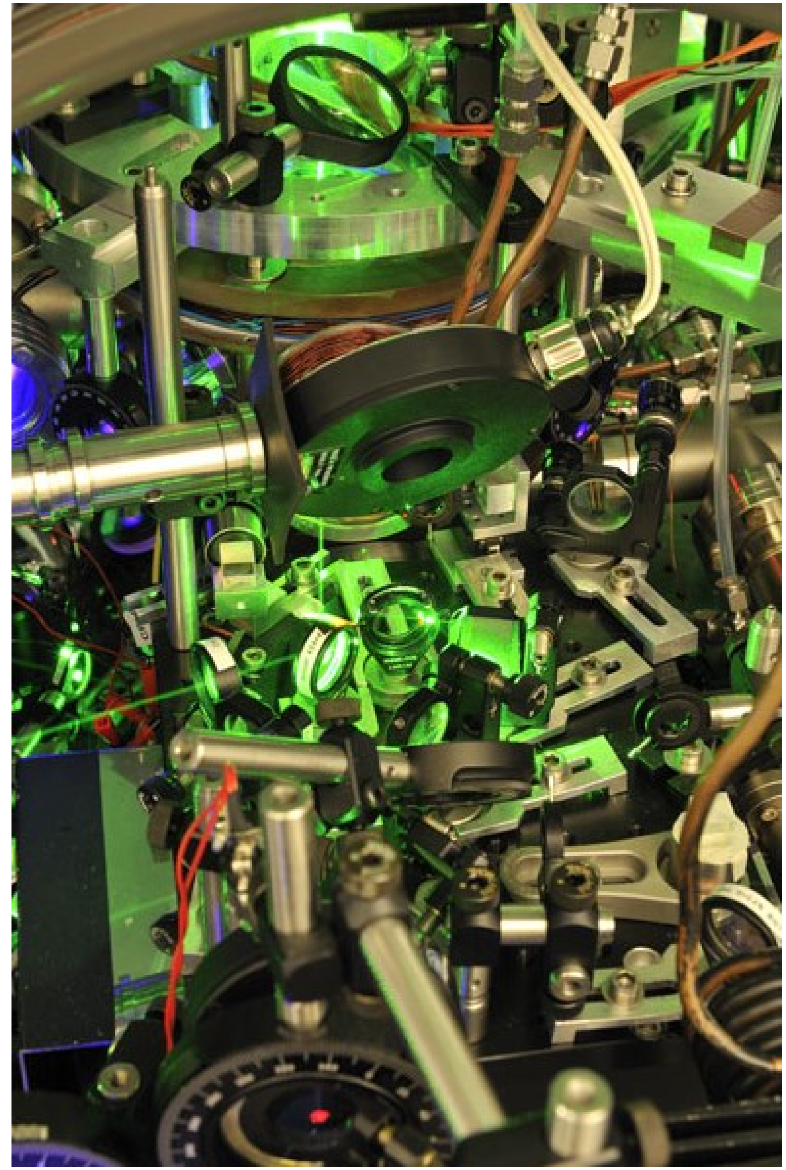
**and**

**On the other hand, magnetism**

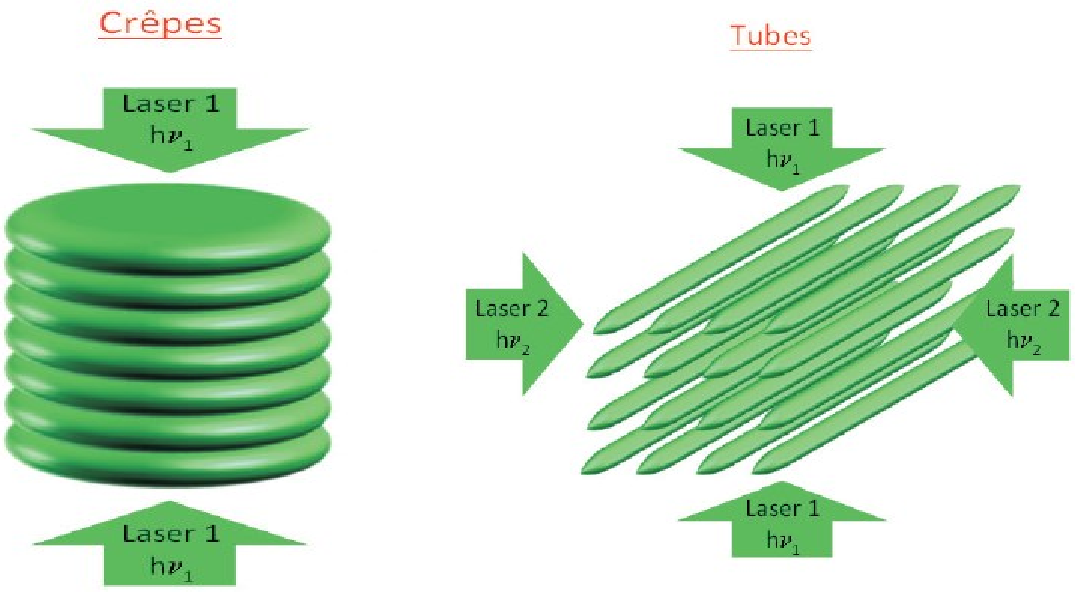
# The experimental setup





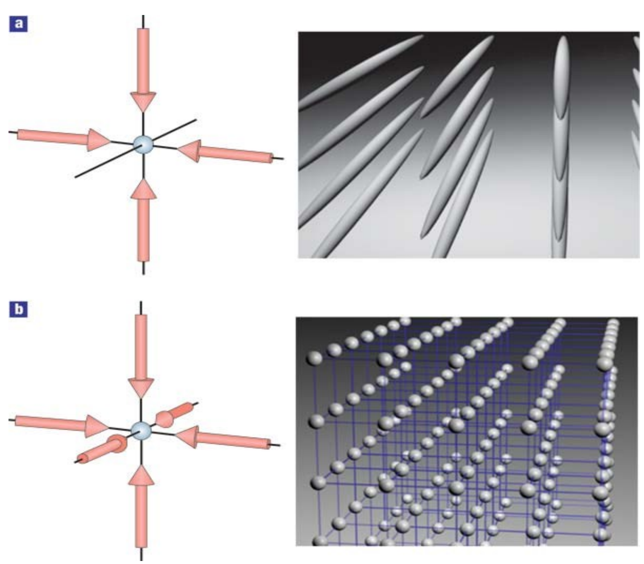


... well ... Part of it !!...

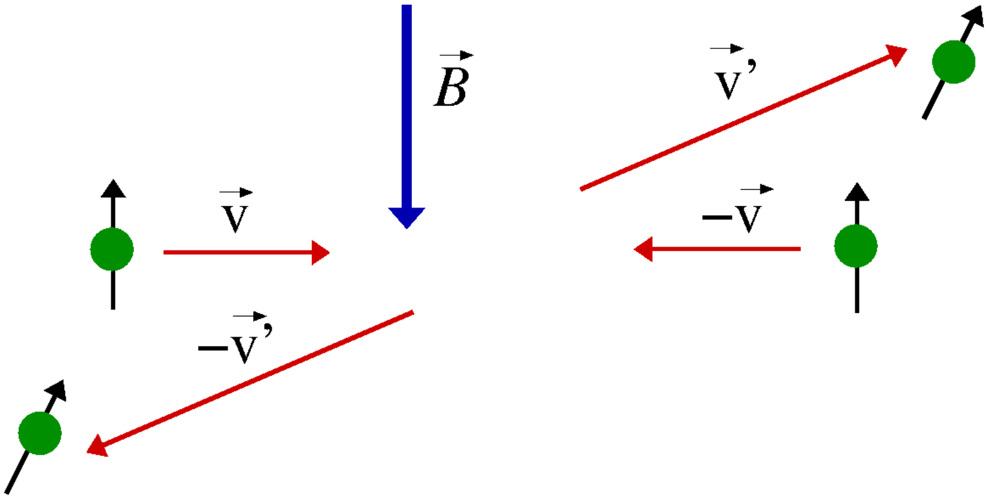



# INHIBITION OF DIPOLAR RELAXATION

**Stabilisation** of the **spinor** gas
by confinement
in optical lattices



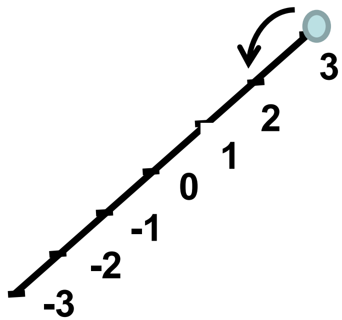
# Inelastic Collisions – dipolar relaxation DR




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

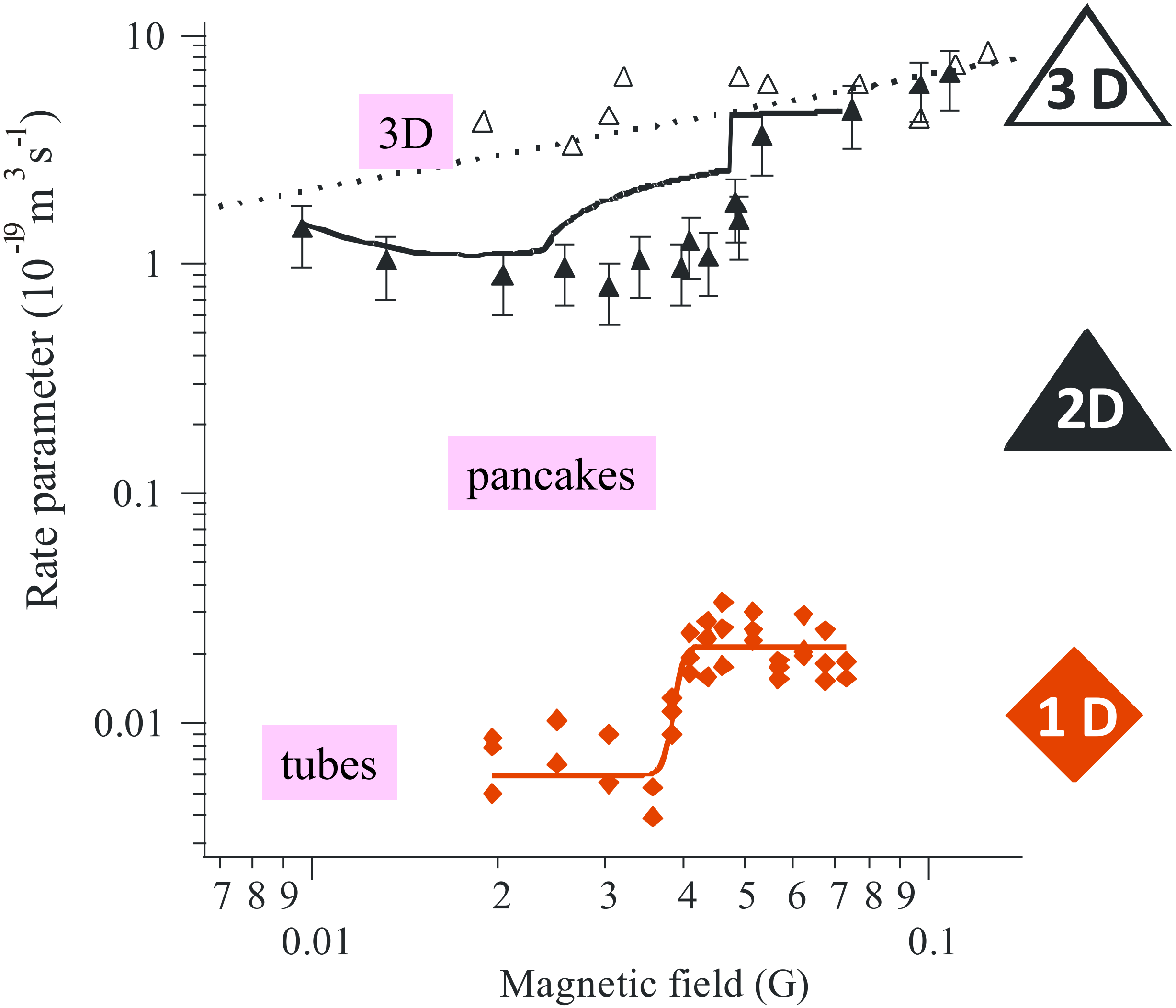
DR causes heating and losses ;
B controls DR rate

Zeeman energy
ladder in B field




To start with **one must** prepare BEC in m = -3.
When atoms are **brought to +3**
or any combinaison of m's > -3, one loses the BEC in a few milliseconds ?
**<u>How could we get a stable spinor ?</u>** Set **B extremely low** (< 0,5 mG = 5 nT)
Or **trap** the BEC in **optical lattices** (2D , 1D or even 0D ie at the nodes of 3D OL) ?

**Loss rate in log Scale !!**




PRA **81**, 042716

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

<u>Below **threshold**: </u>**a metastable quantum gas in a spin excited state (energy >> chemical potential) is produced** ;
Spinor Physics, spin excitations in 1D…

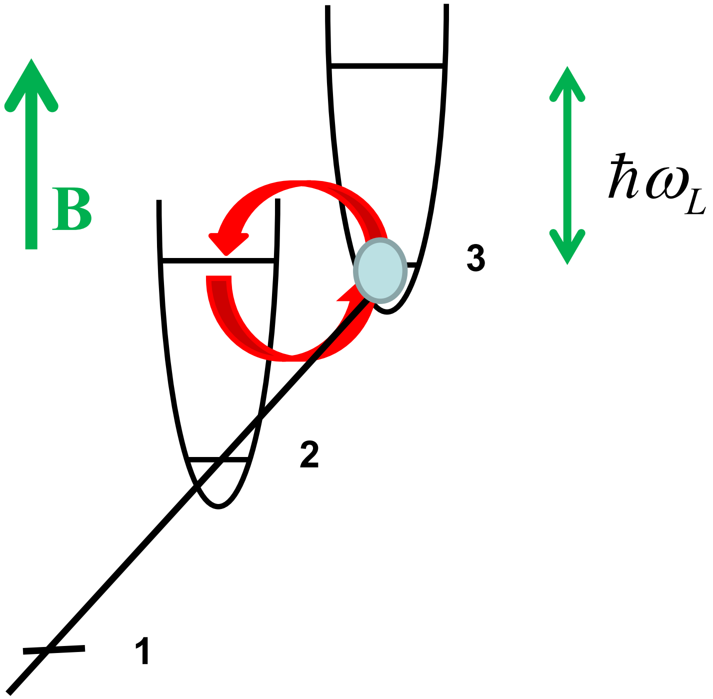
# Relaxation and band excitation – Inhibition mechanism

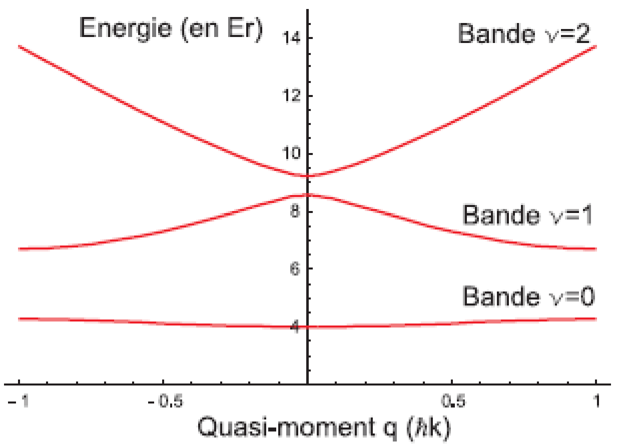
B ≈ 40 mG

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 forbidden.

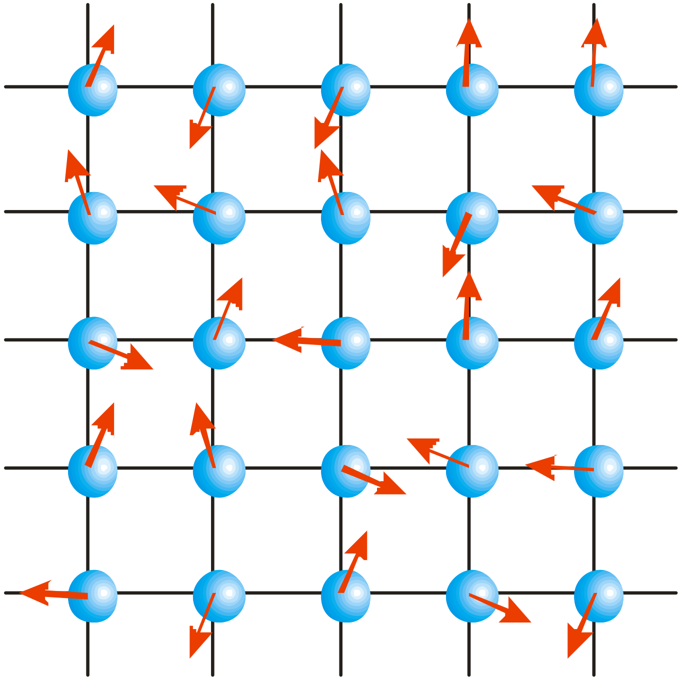


# Magnetism in a 3D optical lattice

- *Coherent vs incoherent spin dynamics*

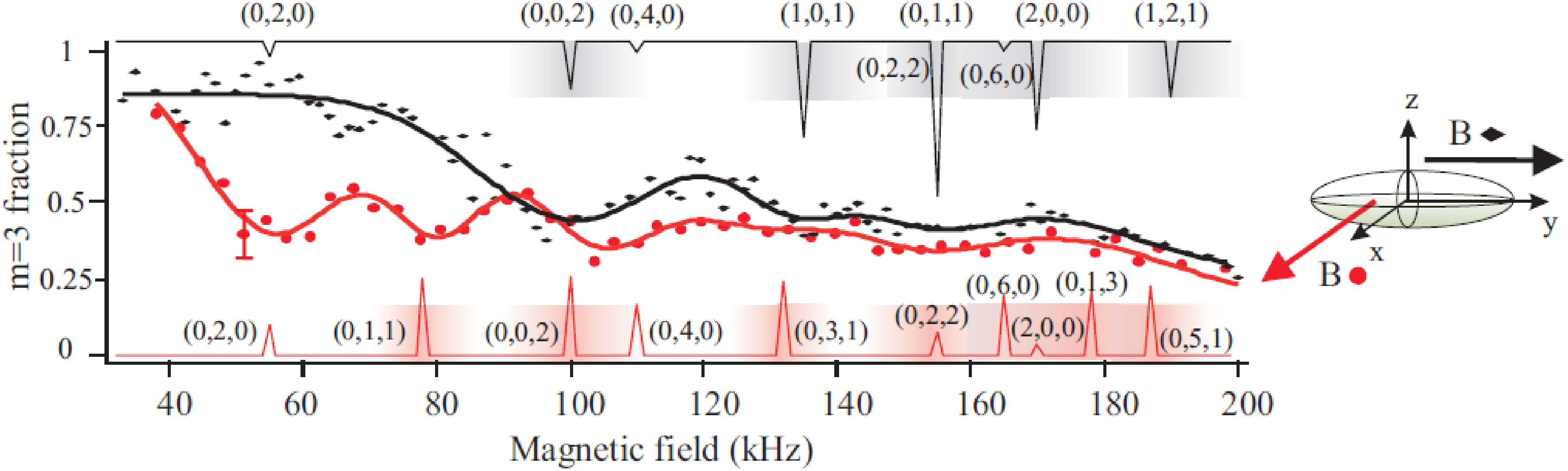
We load the BEC into anisotropic 3D lattices

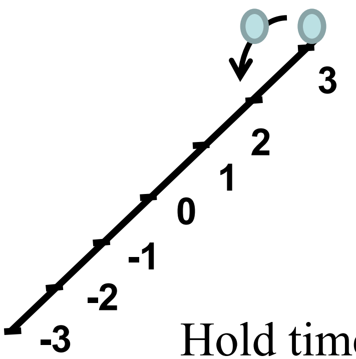


# A NEW dipolar effect

**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**



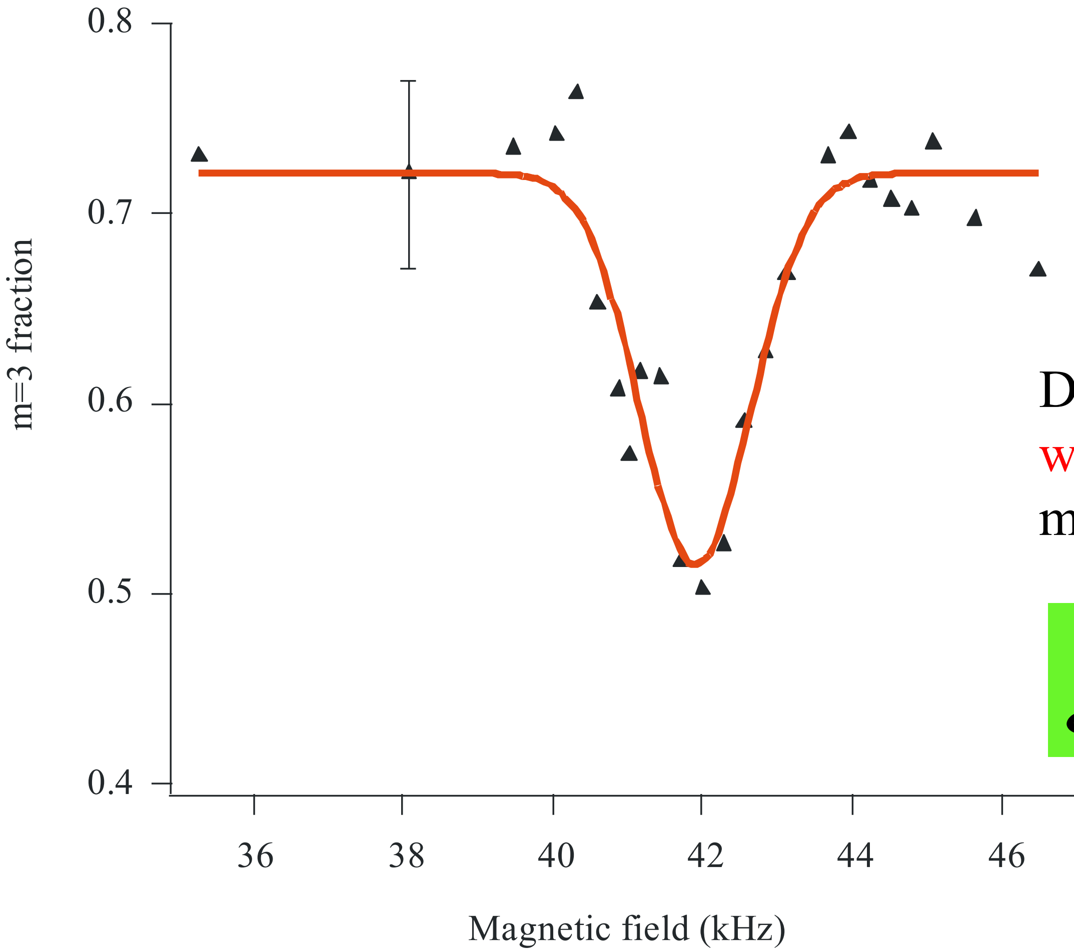

Hold time 30 ms

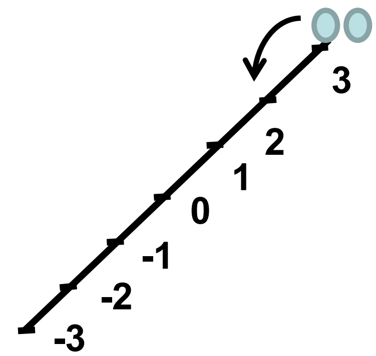
Here $\omega_y / 2\pi = 55$ kHz

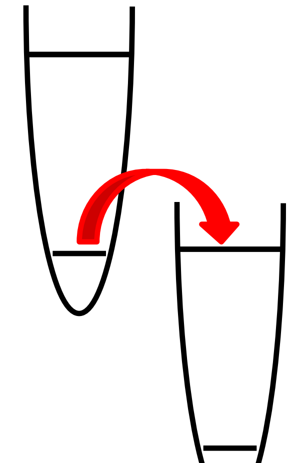
Dipolar relaxation occurs when the released energy matches a band excitation.

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

# Dipolar relaxation resonance with 2 atoms per site



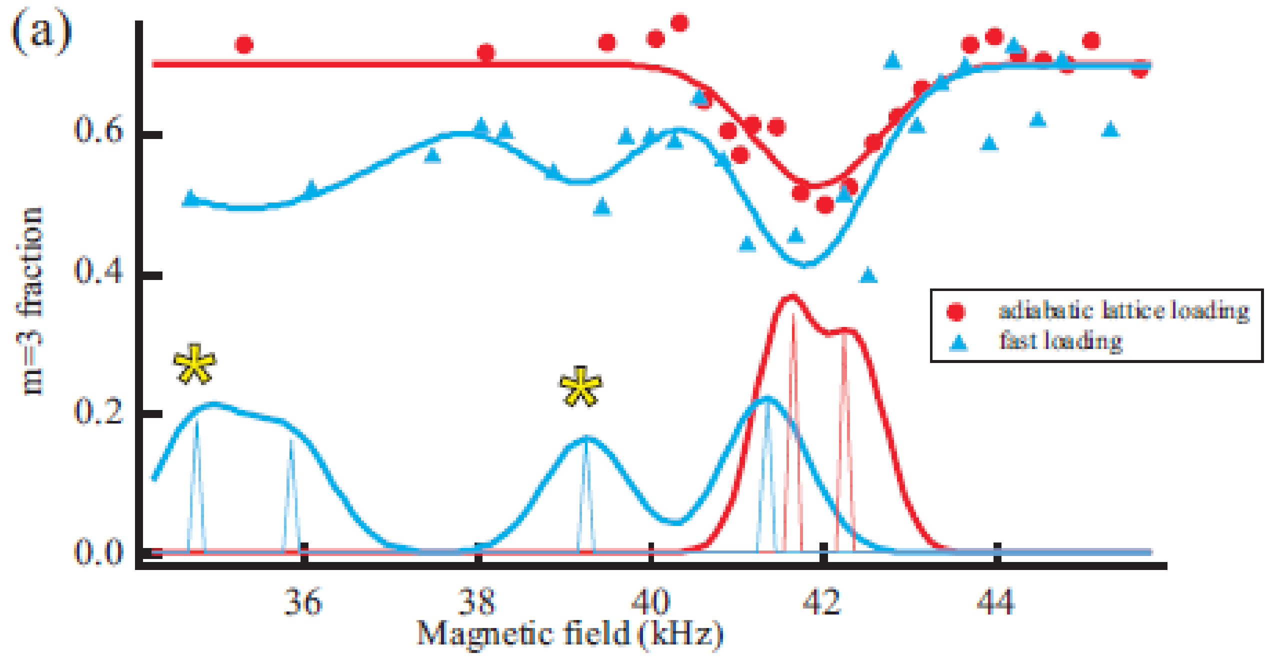



Dipolar relaxation occurs when the released energy matches the band excitation

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

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

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



# S = 3 Spinor physics

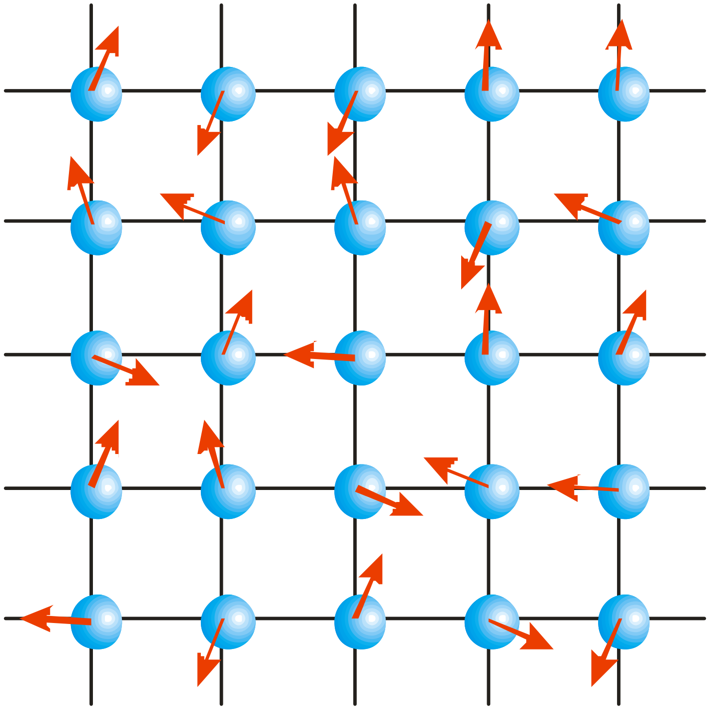
**From now, we forbid dipolar relaxation**
**By setting B below 15 mG (lowest resonance in the deep OL)**

**Magnetization remains constant**

**All interactions are elastic**

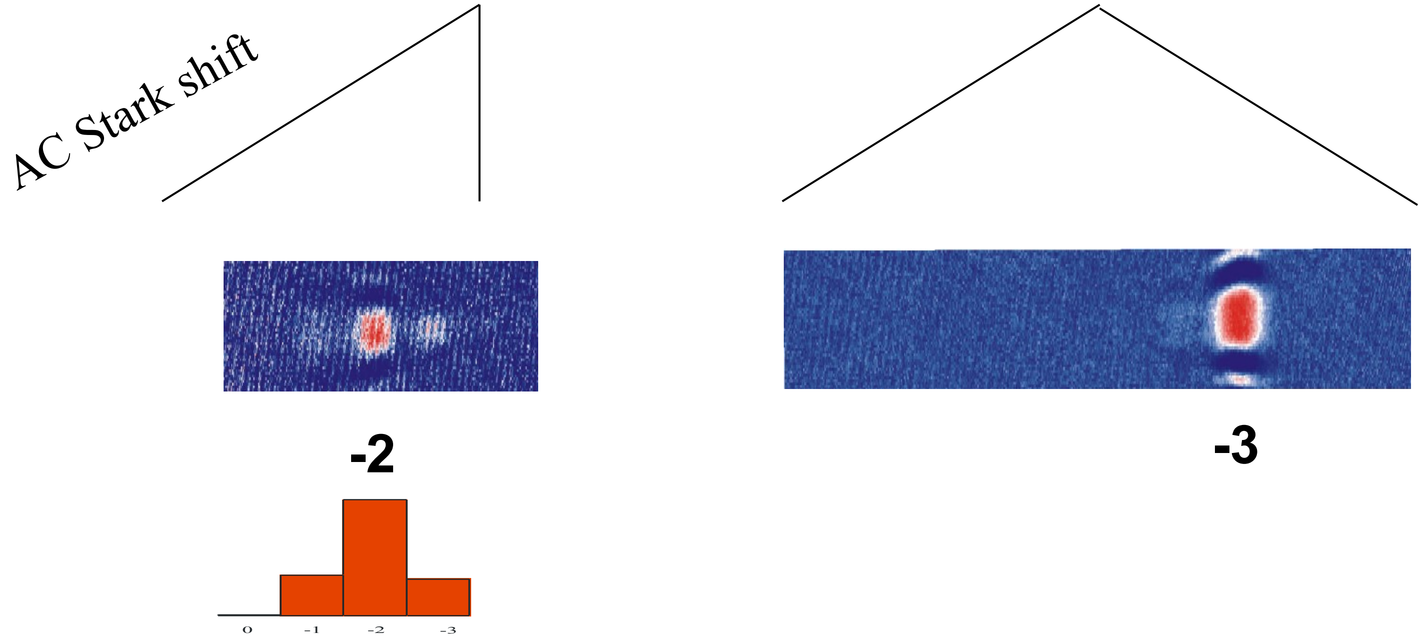
**Spin dynamics is coherent**

**We study a S=3 spinor in a 3D lattice**

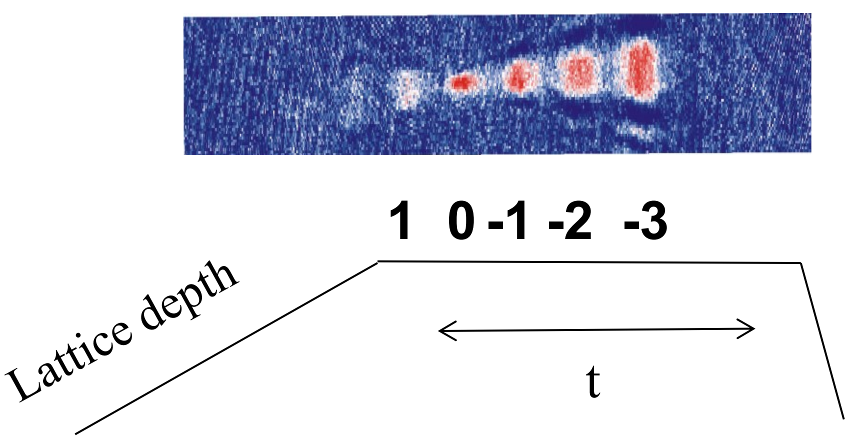


Typically 40 x 40 x 40 sites

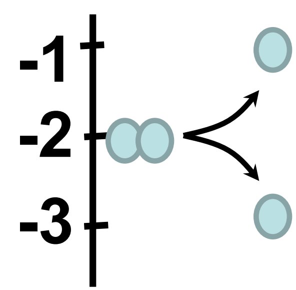
# **Adiabatic preparation** of a condensate **in m = -2** with two atoms par site




We monitor spin composition as time goes

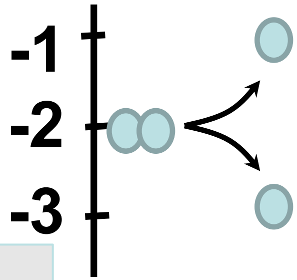


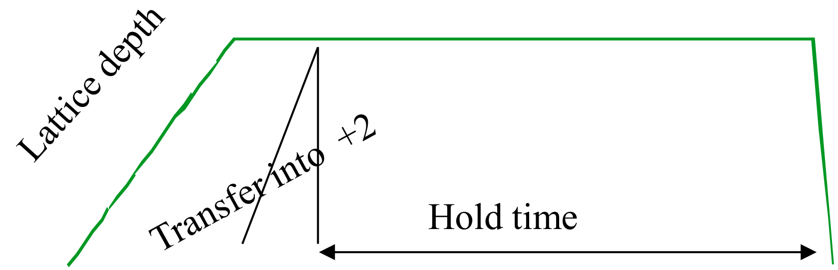

**Interactions redistribute populations**



# Spin Exchange
# within doubly occupied sites

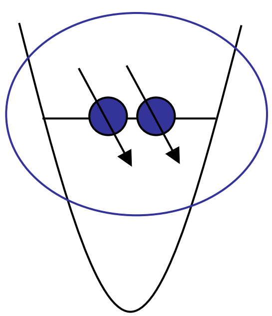
due to contact interactions

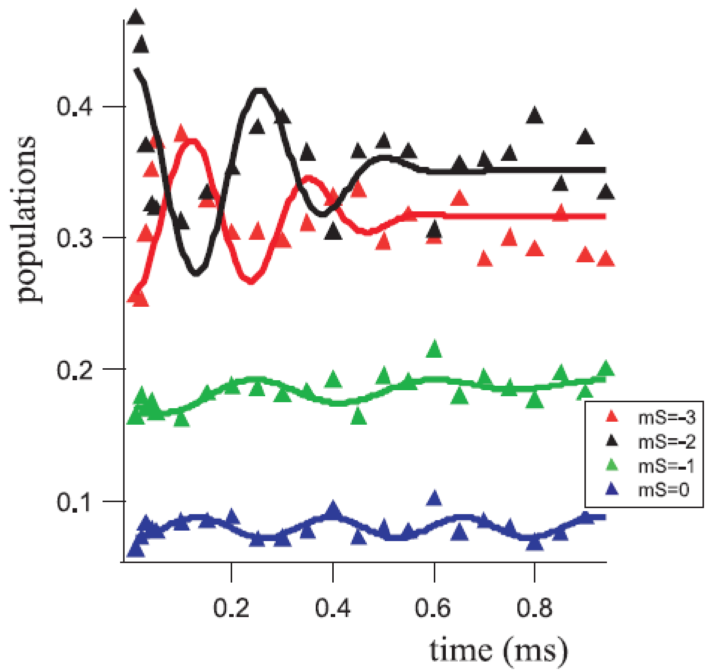



**Preparation : 2 atoms per site**

| -2 ; -2> = α|6, -4> + β | 4, -4>



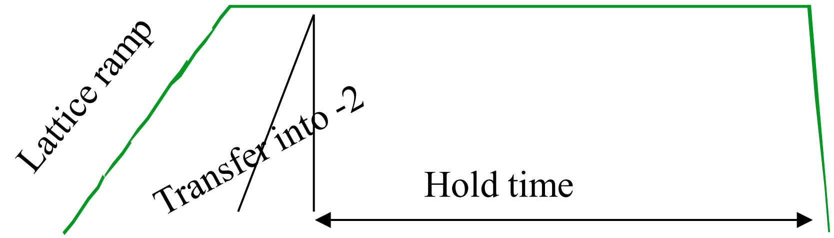


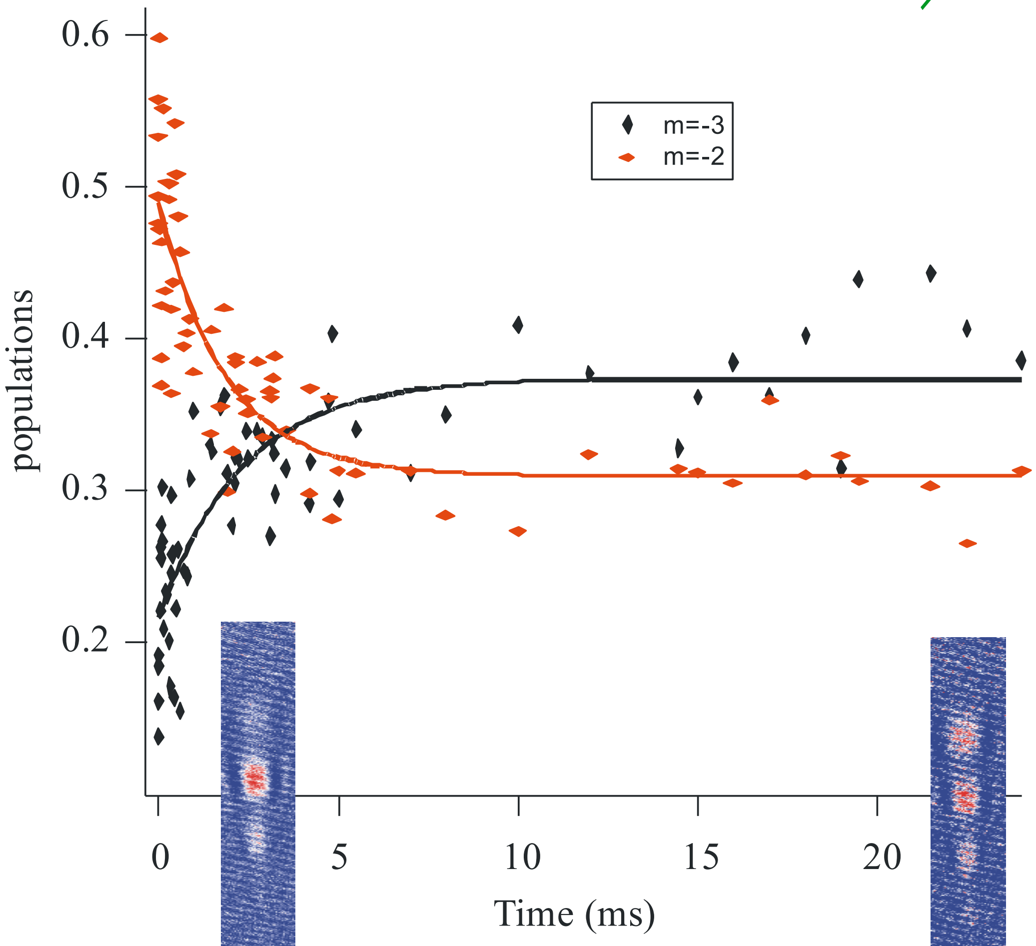

$$\Gamma = \frac{4\pi\hbar}{m} n\left(a_6 - a_4\right)$$

(**period ↔ 220 μs**) (theory 250 μs)

**Tunneling causes damping (still to fully analyse)**

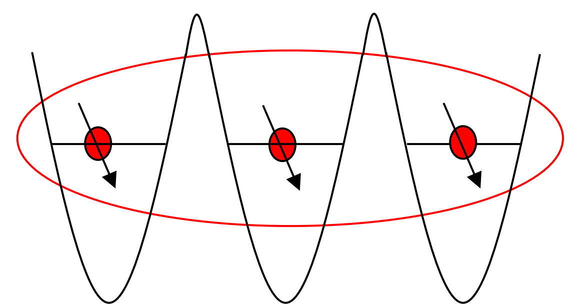
# Spin dynamics in a 3D lattice with 1 single atom per site (or less)

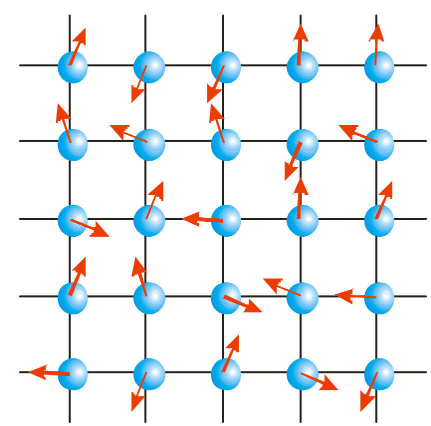



**Intersite spin redistribution**

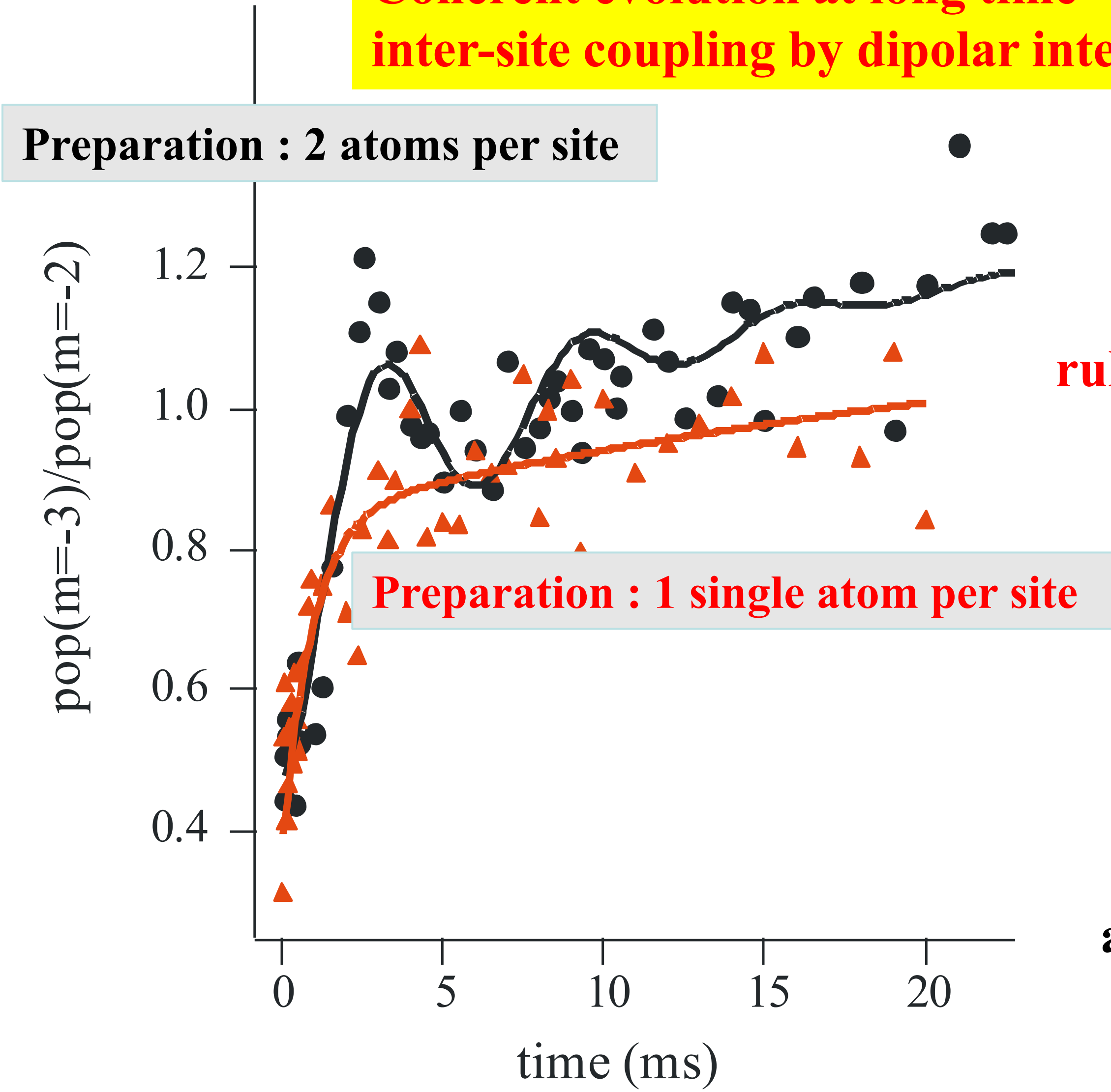
$$\frac{1}{2}\left(S_{1+}S_{2-}+S_{1-}S_{2+}\right)$$





(**time scale ↔ 5 to 10 ms**)

**Coherent evolution at long time –**
**inter-site coupling by dipolar interaction**




**For doublons**
**the oscillation time scale**
**rules out intra-site interactions**

**A toy model**
**with 2 atoms in 2 wells**
**+ dipolar interaction**
**accounts for this time scale**

## Summary

Inhibition of **Dipolar Relaxation** in reduced dimensions –

→→ **SPINOR Physics with S = 3**

**Coherent spin dynamics + inter-site dipolar interactions**

**Spontaneous demagnetization**

-**phase transition**;

-thermodynamics of a spin 3 gas with free magnetization

## Outlook

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

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

**Einstein-de-Haas effect in a gas**

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

**New exotic magnetic phases**

# Cold Atom Team (GQD) in Villetaneuse - Paris Nord

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Post-docs:

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Permanent members:

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

Collaborations:

Mariusz Gajda and Luis Santos

# Dipolar Quantum Gas Team

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