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Olivier GORCEIX

# Quantum magnetism within a dipolar Bose-Einstein Condensate

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 **$a_S$ δ(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$\mu_B$**

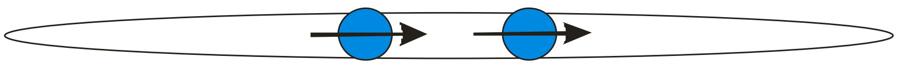
*MDDI are 36 times greater than in alkali BECs*

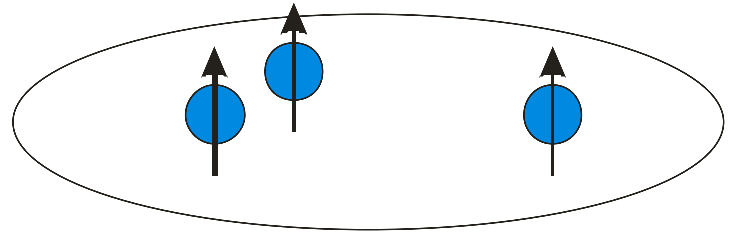
$$\varepsilon_{dd} = \frac{\mu_0 \mu_m^2 m}{12\pi\hbar} \propto \frac{V_{dd}}{V}$$

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

***$\varepsilon_{dd}$ (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*



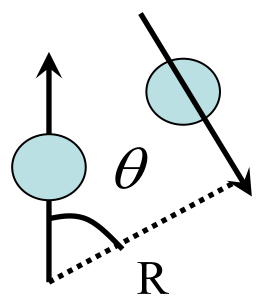


*Side to side repulsion*

Long range **magnetic** dipole-dipole interactions

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

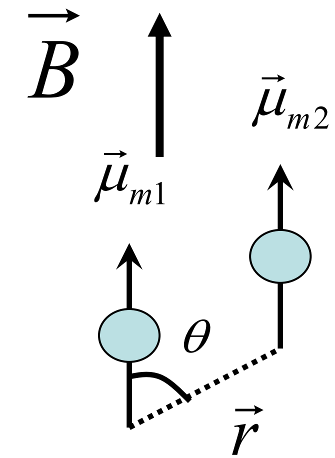
Links with **magnetism**,
liquid crystal physics,
rich **phase diagrams**,
quantum info processing.




**Coupling between spin and rotation**

# The two 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**

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

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

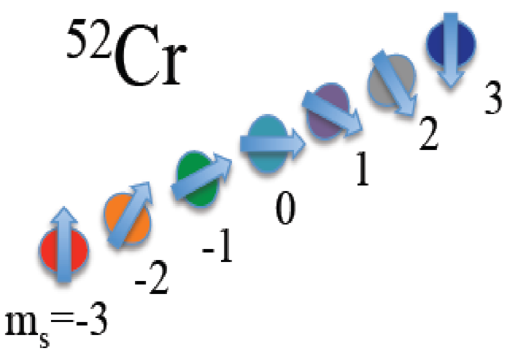
$$\mu_m = J\;g_J\mu_B$$

Non local
Anisotropic
mean field

**Non-linear** **non-local and anisotropic** terms

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

**S = 3 -** $\Psi$ comprises 7 spin components



# Dipolar induced spin dynamics

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

**Various terms:**

**ISING**

**XY/ flip-flop / Spin Exchange**

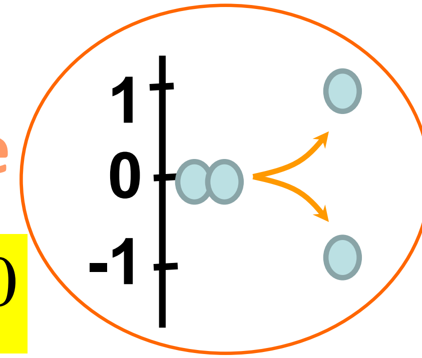
**Elastic collisions**

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

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

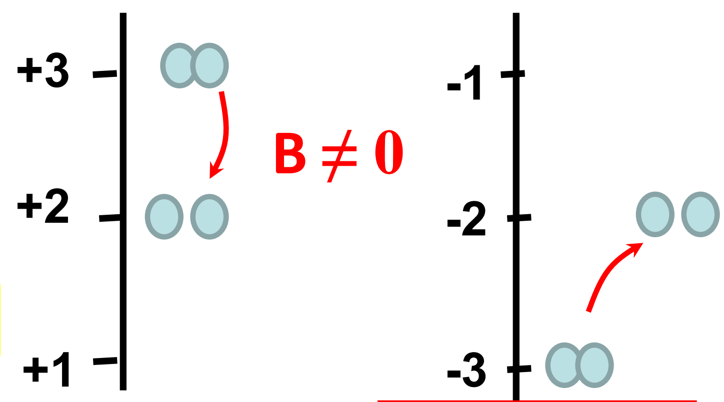
$$r_{+/-} = x \pm iy$$

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




**Inelastic collisions**

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




Cr BEC M= 3

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

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

# Coherent Spin dynamics in a Cr BEC

When inelastic terms are prohibited

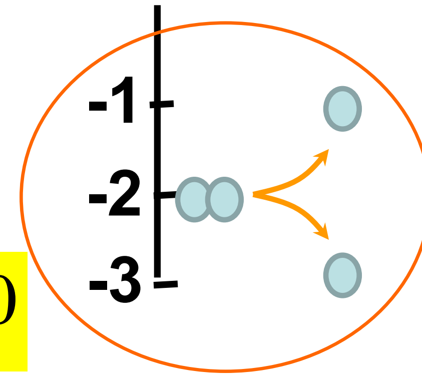
**Spin operators reduce to :**

**ISING**

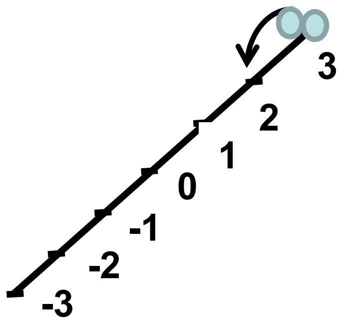
**XY / Spin Exchange**

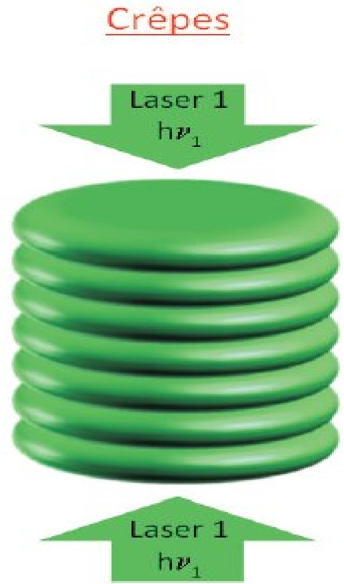
$$S_{1z}S_{2z} + \frac{1}{2}\left(S_1^+ S_2^- + S_1^- S_2^+\right)$$

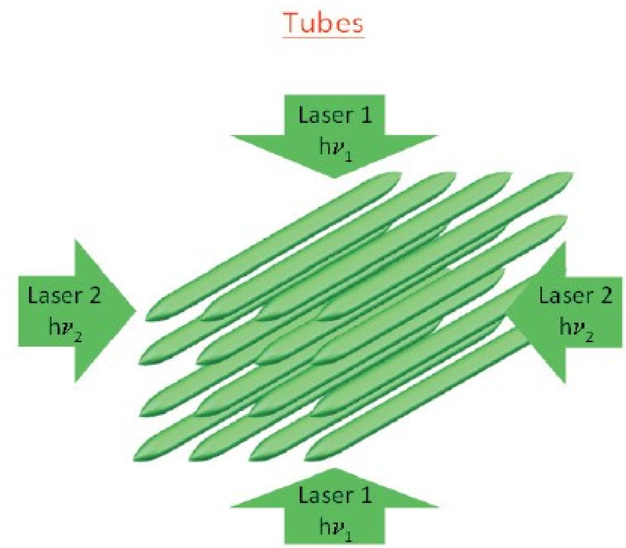
$$\Delta m_{S\ tot} = 0$$




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



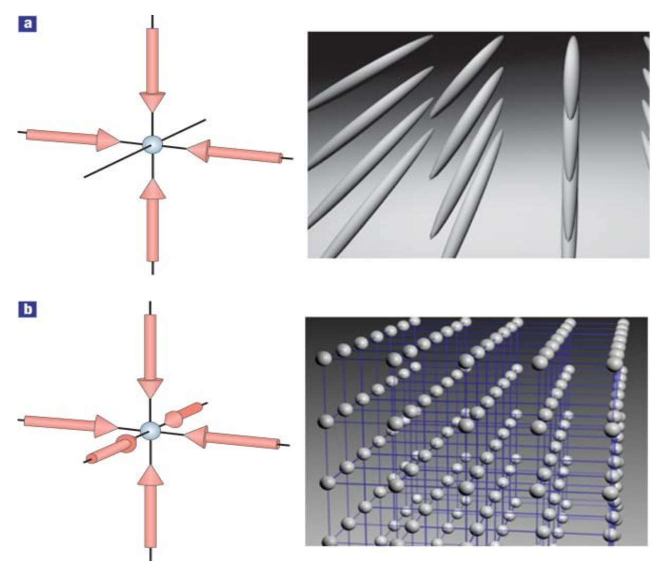




# INHIBITION OF DIPOLAR RELAXATION

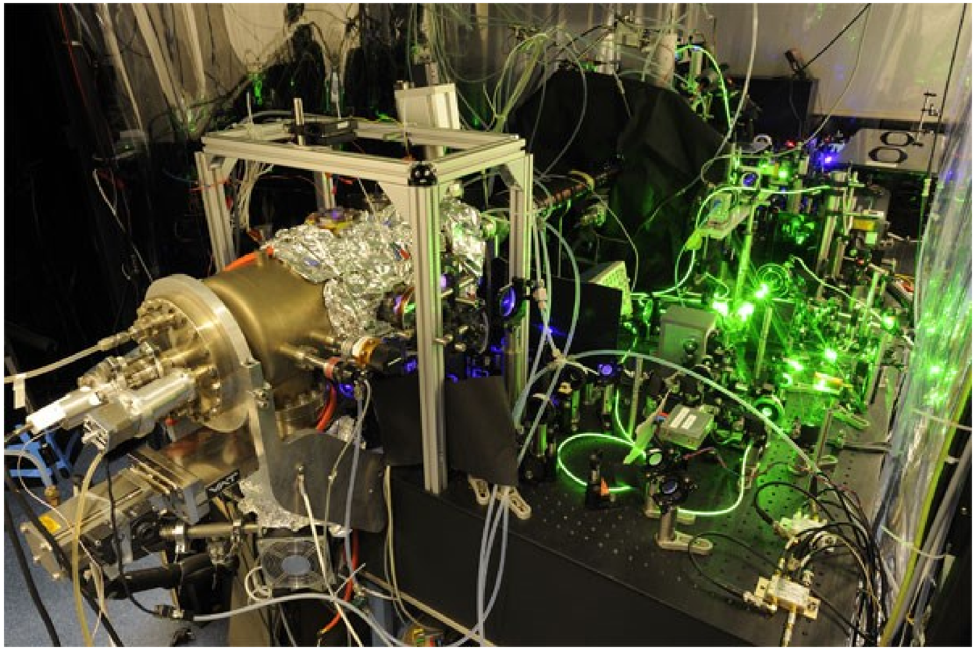
**Collisional stabilisation**

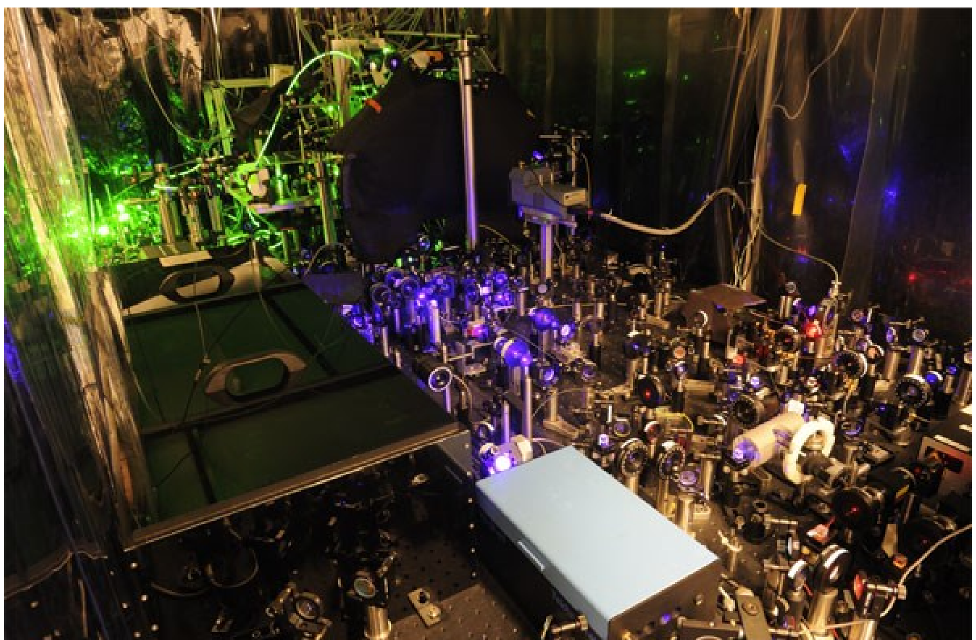
of the **spinor quantum gas**

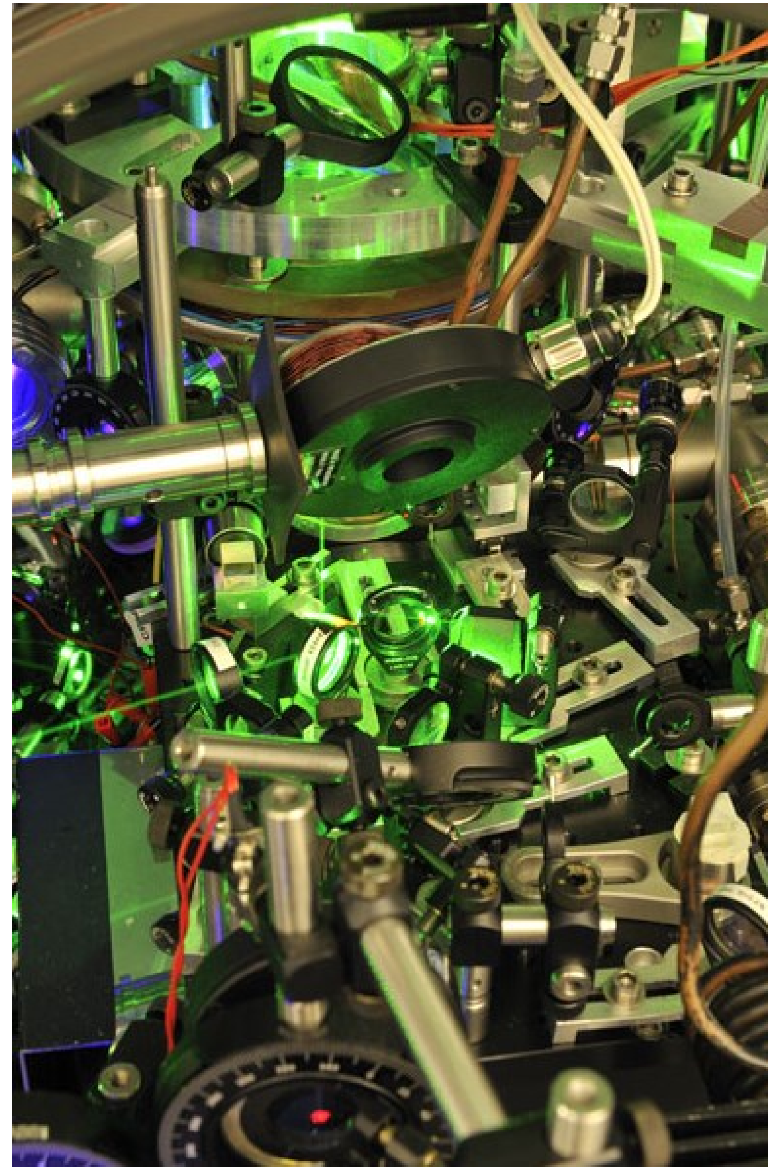
by confinement
in optical lattices



# The experimental setup





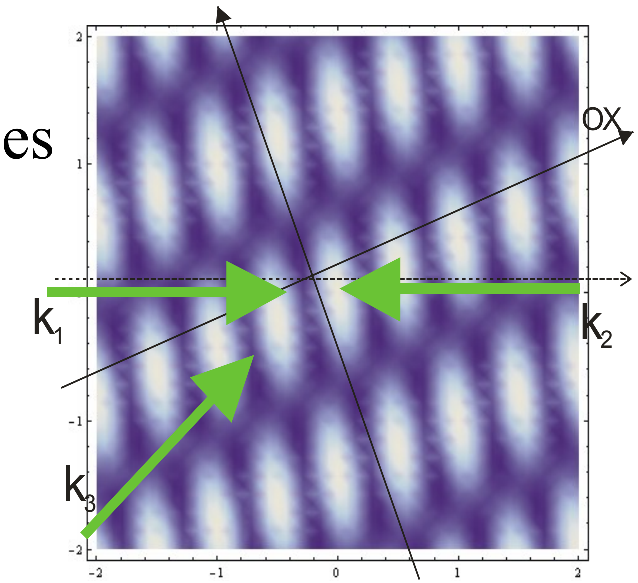


**… well … Part of it !!…**

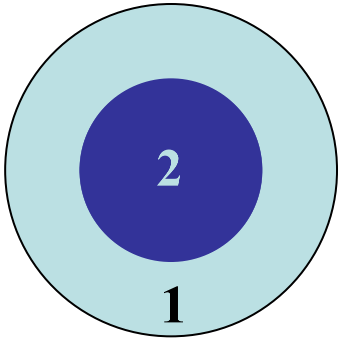
# Magnetism in a 3D optical lattice
## - *Coherent and incoherent spin dynamics*

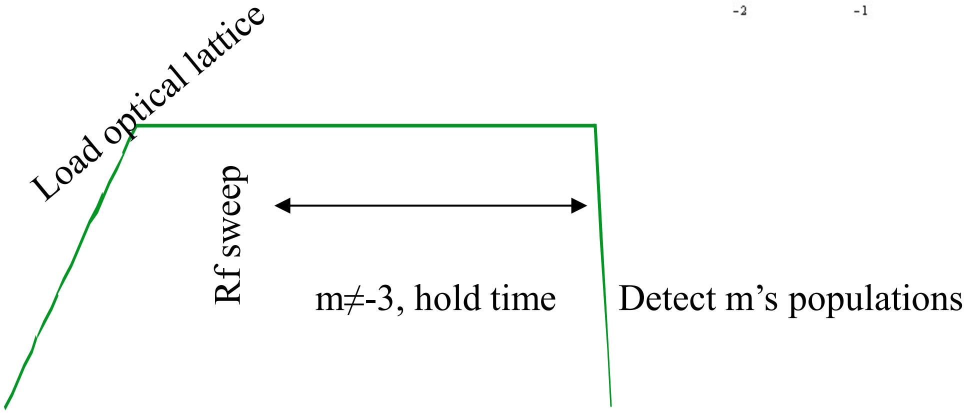
Tight confinement in
an anisotropic 3D lattices
**Green 532nm light**

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

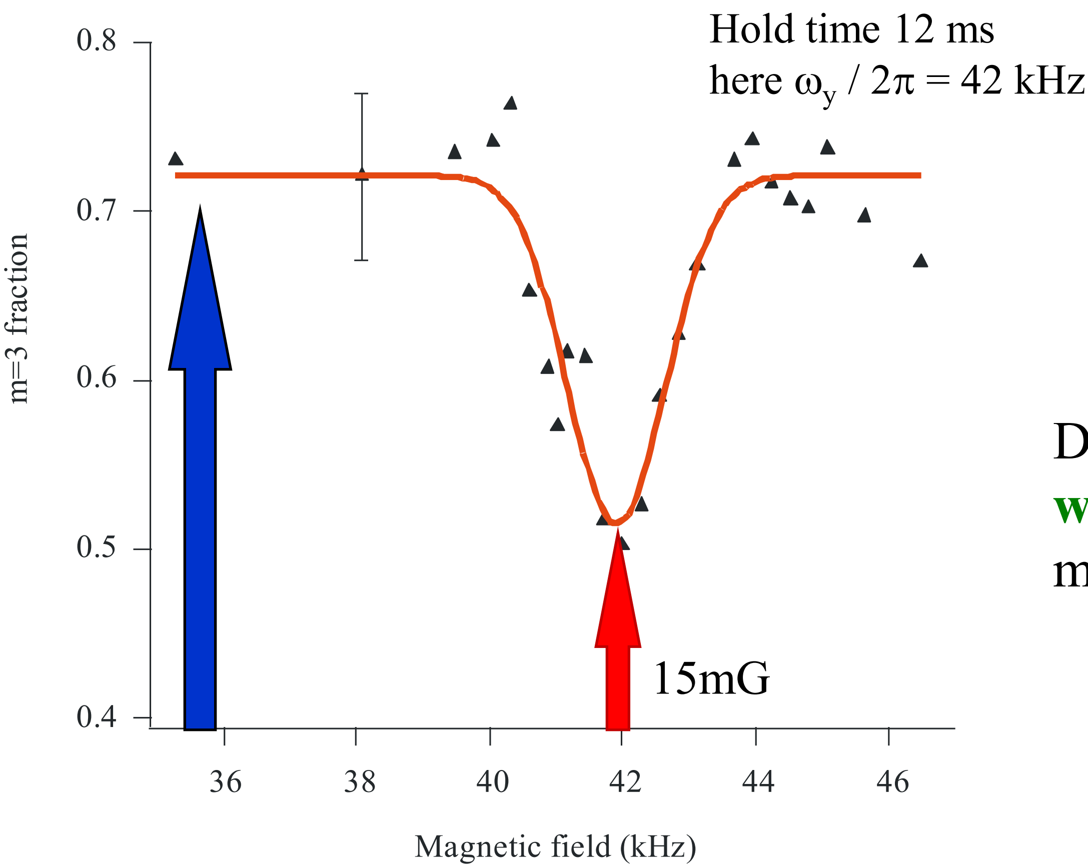


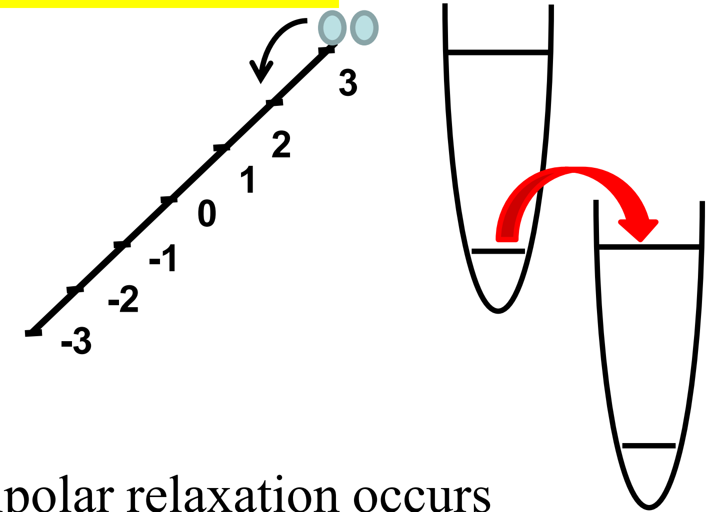

up to 20 000 atoms
Mott state :
a core of doublons
+ a shell of singlons



# Dipolar relaxation resonance with 2 atoms per site

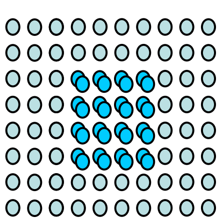


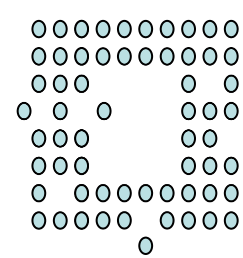




Dipolar relaxation occurs **when** the released energy matches the band excitation

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

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





# S = 3 Spinor physics

**From now on, we forbid dipolar relaxation**

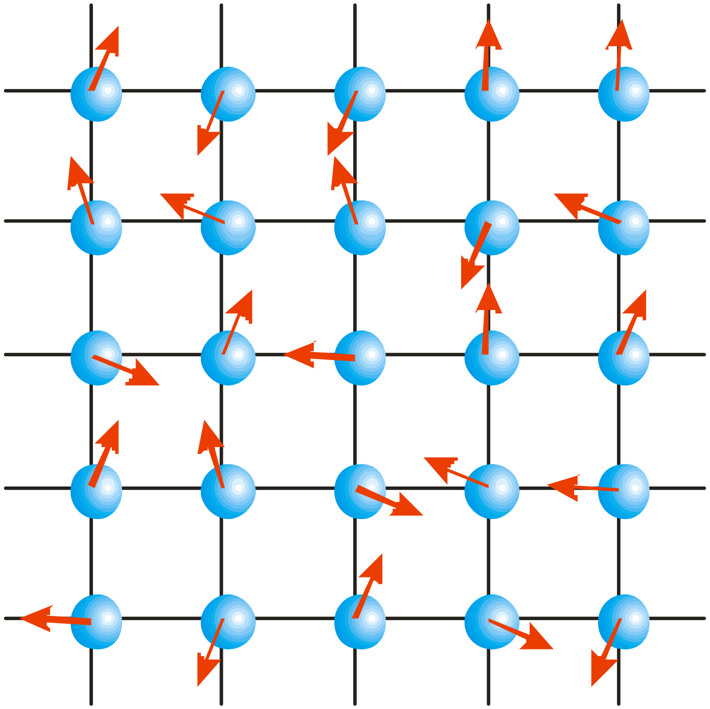
**By setting B below 15 mG (lowest resonance in the lattice)**

**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

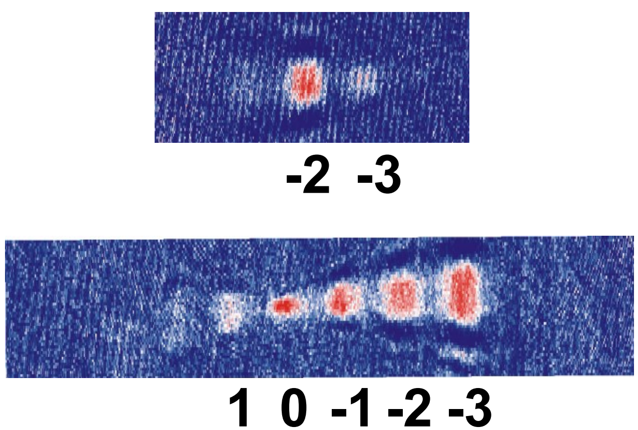
Typically 40 x 40 x 40 sites

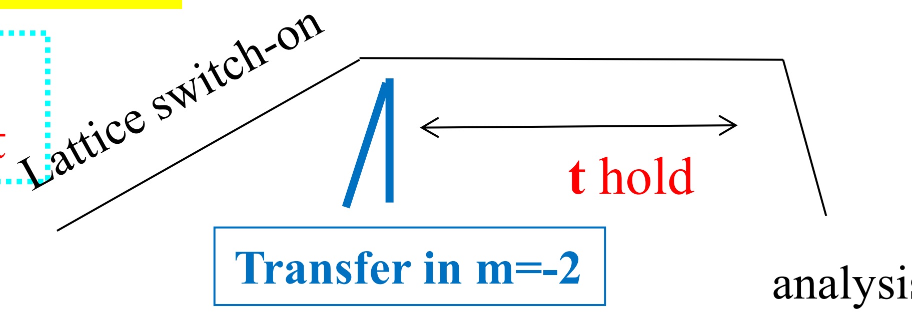
## Adiabatic preparation of a condensate in m = -2

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

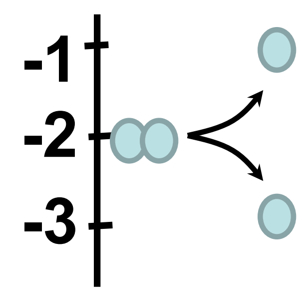

## Out of equilibrium - Spin dynamics

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



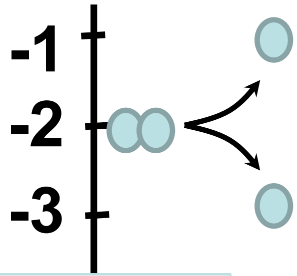

**Interactions redistribute populations**

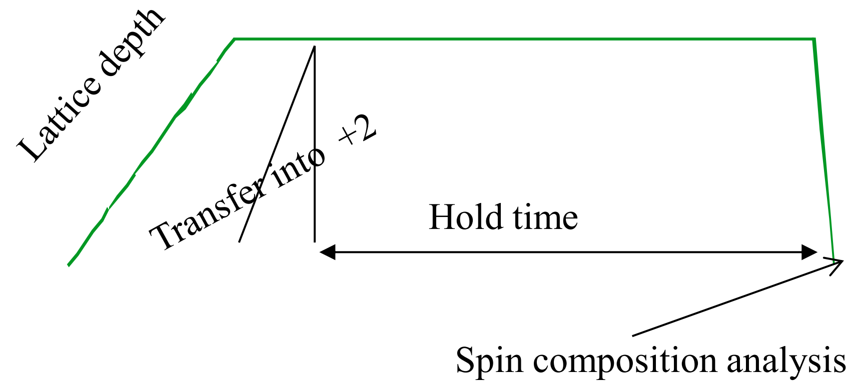



Final stages - after release : Stern Gerlach separation + TOF + absorption imaging

# S= 3 spin exchange within doubly occupied sites

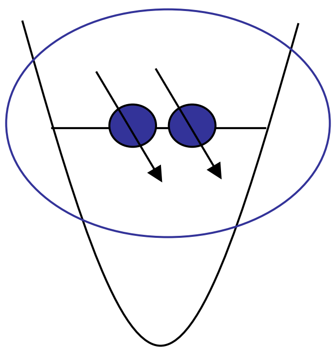
**Fast dynamics**
due to contact interactions

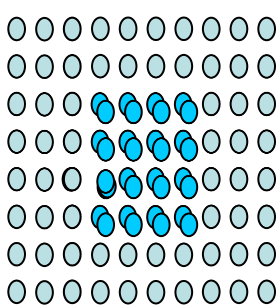


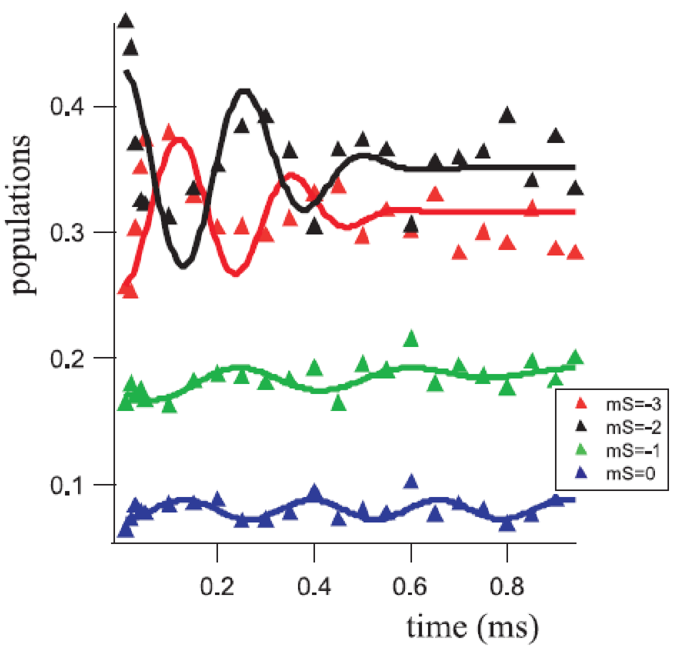




**Preparation : 2 atoms in M = -2 per site**

**| -2 ; -2>$_{atom}$ = α |6, -4>$_{mol}$ + β | 4, -4>$_{mol}$**








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

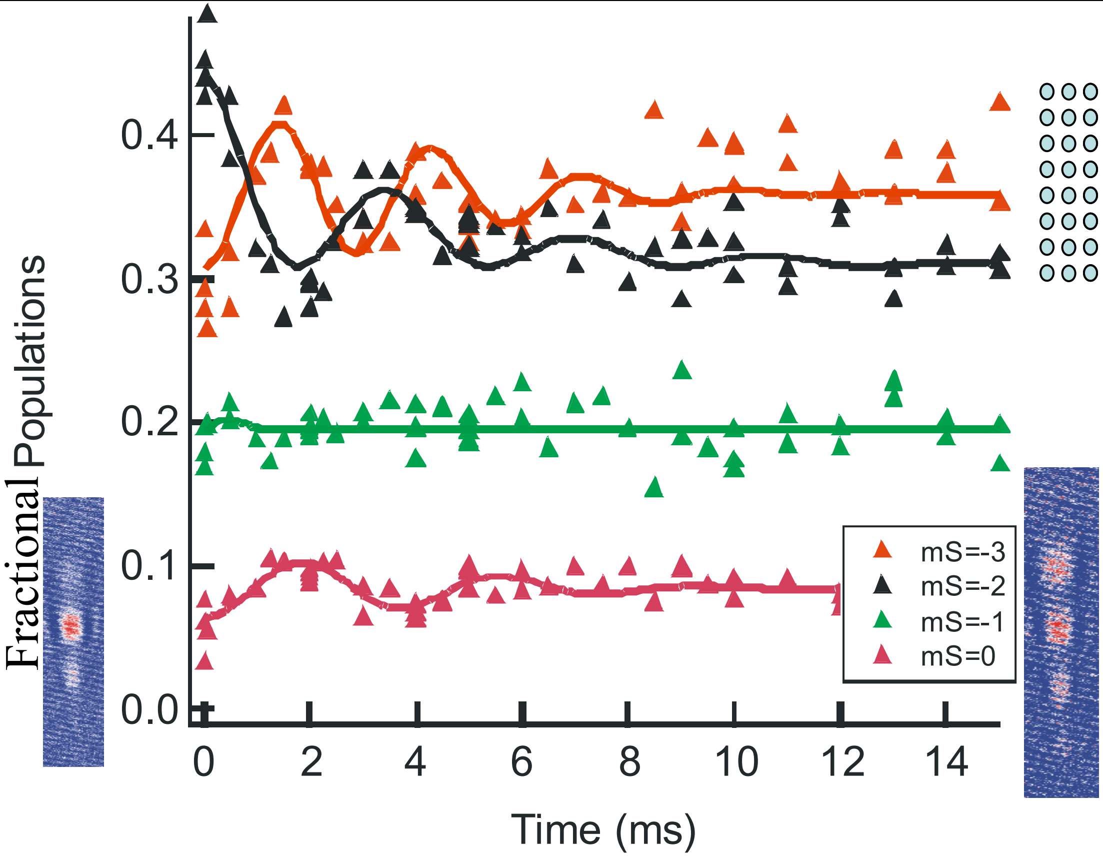
$a_6 = 102\ a_0$
differs greatly from
$a_4 = 58\ a_0$

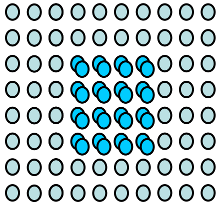
(**exp period ↔ 320 µs**) (theory 1/ Γ = 280 µs)

**Tunneling causes damping + imperfect starting conditions**

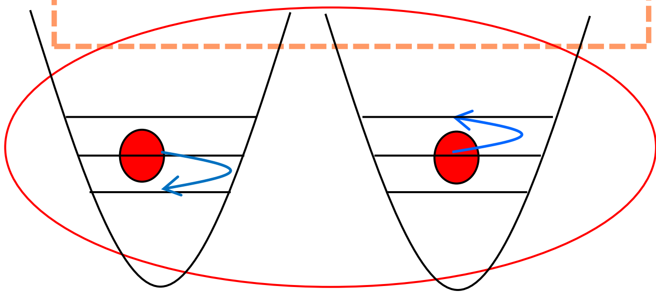
# Long time-scale spin dynamics in lattice : intersite dipolar exchange with doublons

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



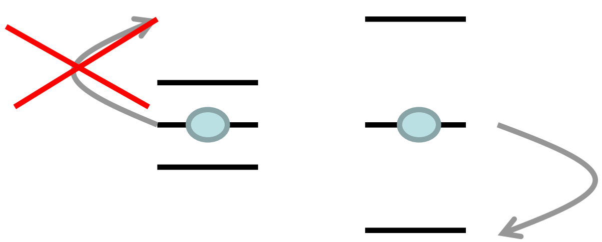



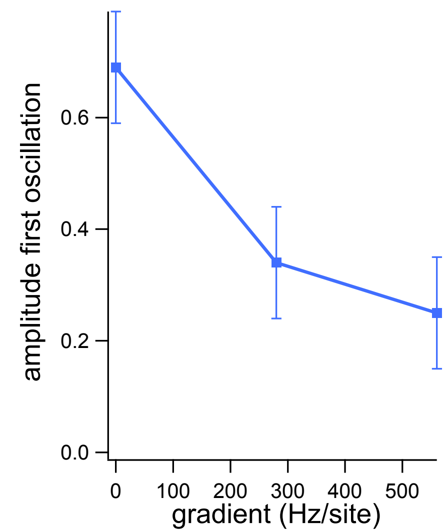
**Intersite dipolar interaction induces 4 ms period oscillations** (much slower than on-site oscillations with period 0.3ms)



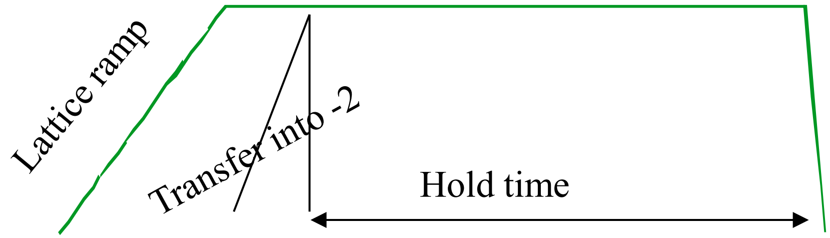
**Magnetization is constant**

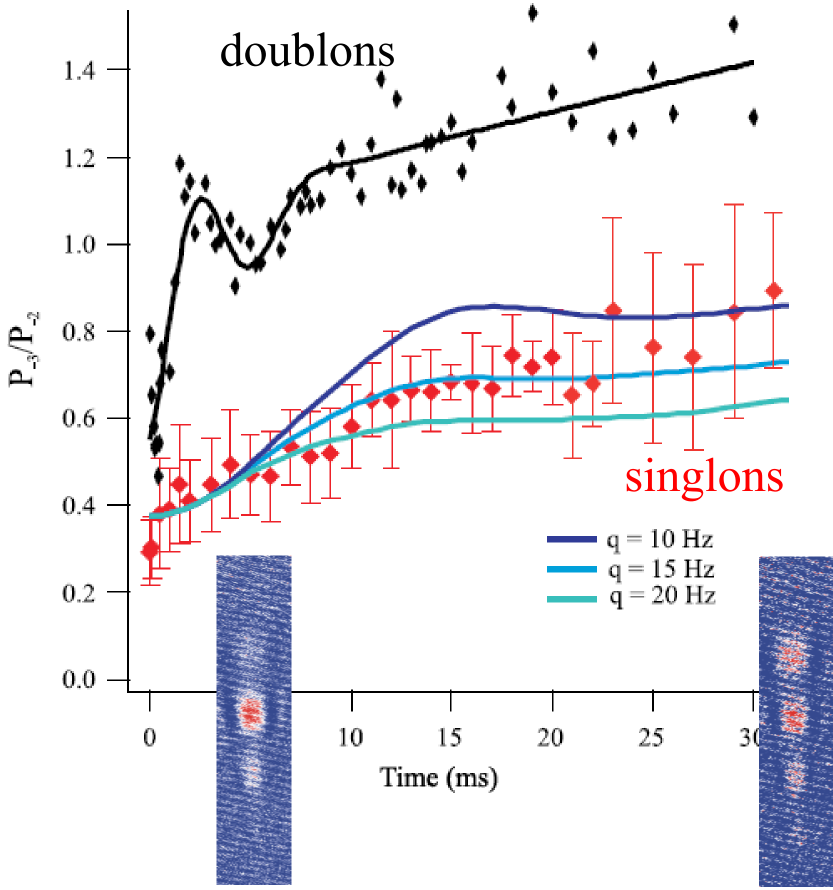
Intersite dynamics disappears in presence of a gradient

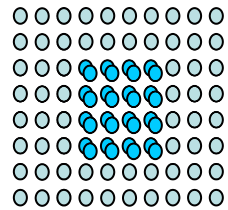


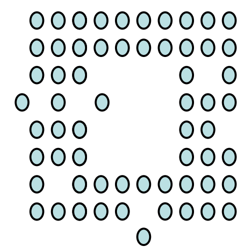


# Spin dynamics in a 3D lattice with 1 or 2 atoms per site (or less)



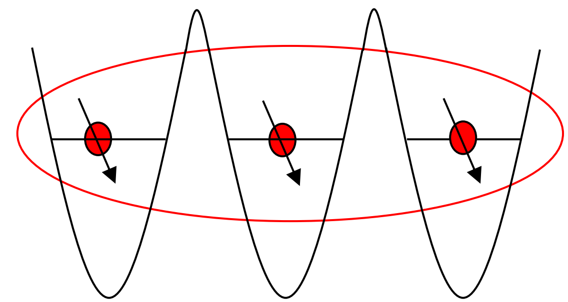





**Intersite spin exchange**

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



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**

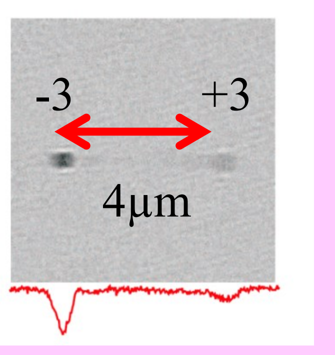
**Other past results**

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

-**Phase transition**;

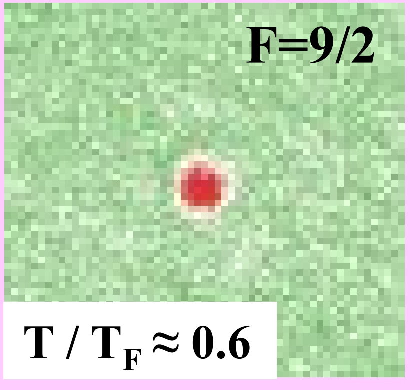
-Thermodynamics of a spin 3 gas with **free magnetization**

# 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

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)