Some experimental aspects of quantum simulation using ultra-cold atoms

Bruno Laburthe-Tolra
Paris 13 University

Focus on quantum magnetism

Practical implementations
State of the art, some challenges
Some possible extensions

1 Quantum simulation with cold atoms ?

Quantum Gases

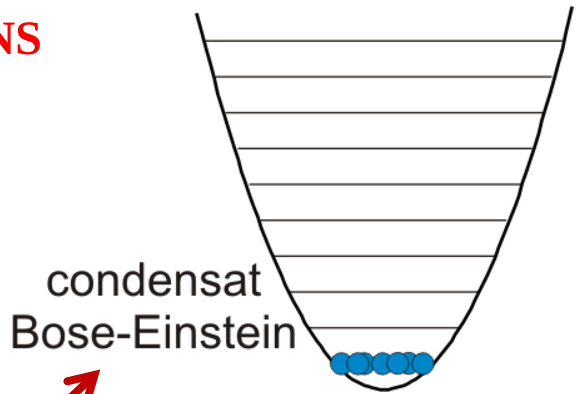
Density : 10^{12} to 10^{15} at/cm^3 ($\leftrightarrow 10^{22}$ at/cm^3 for liquid He)

Temperature : 1 nK to 1µK

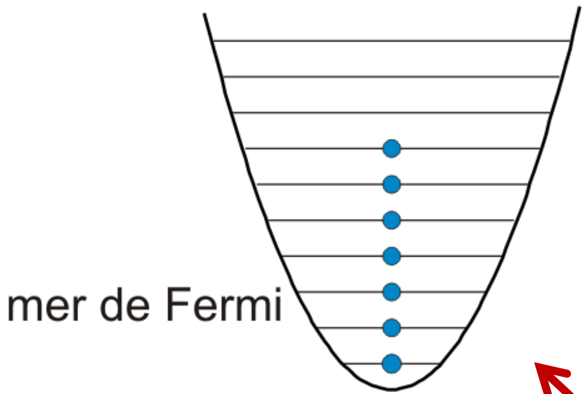
De Broglie wavelength > 100 nm $\Delta x . \Delta p > \hbar/2$

Distance between atoms > 100 nm

BOSONS



FERMIONS



Lasers

(Bose-stimulation)

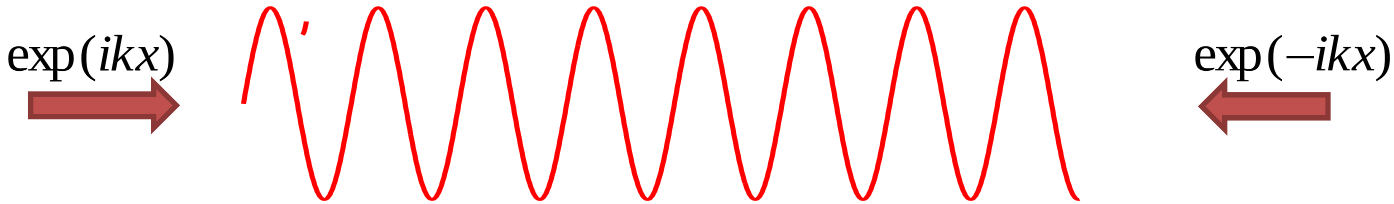
Electrons in solids

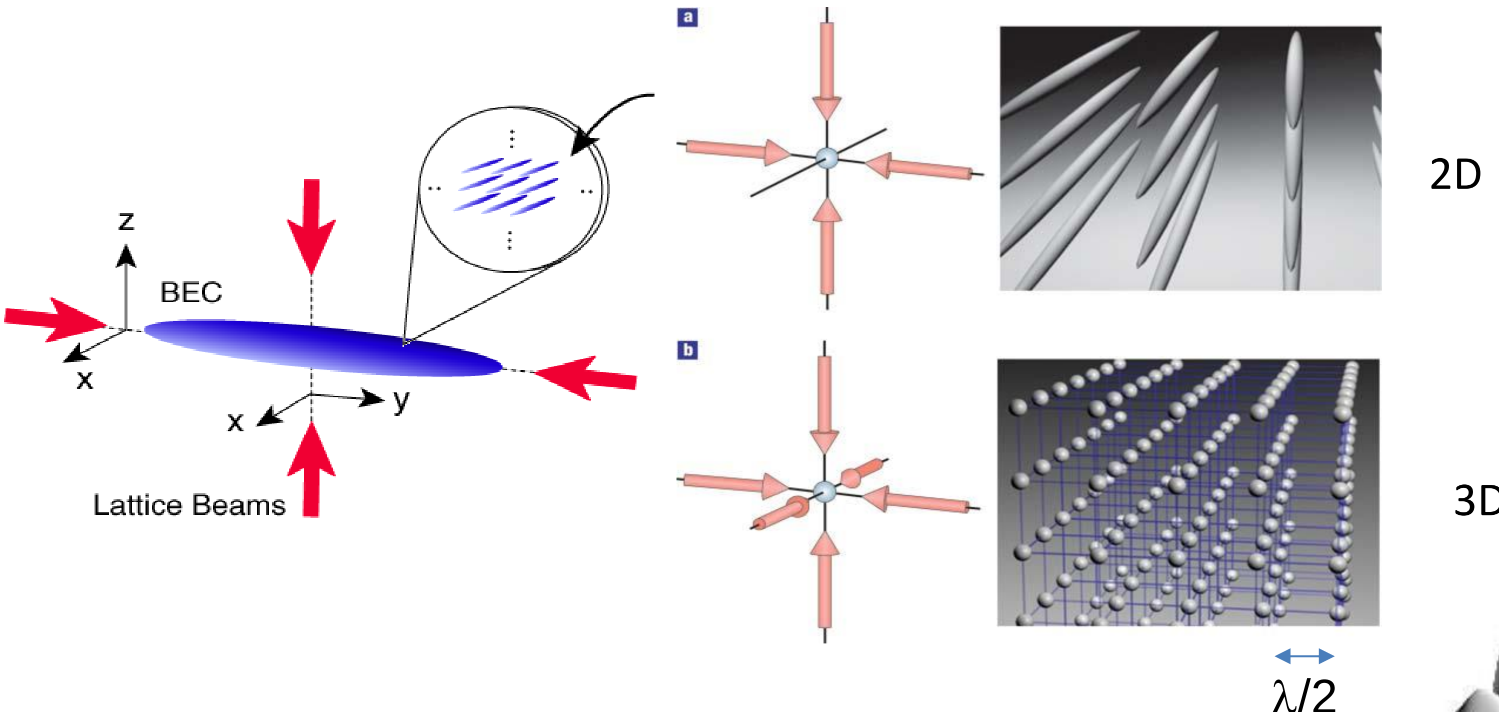
(Pauli-exclusion principle)

Collective behaviour even without interactions

Optical lattices

Perriodic potential introduced by stationnary wave (spin-independent)



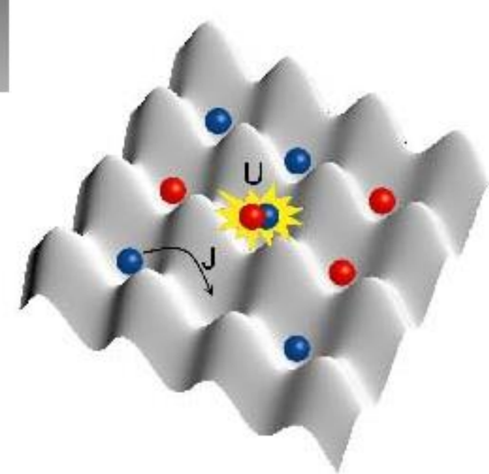


Picture from
I. Bloch

1D lattices → 2D Gases (BKT transition)

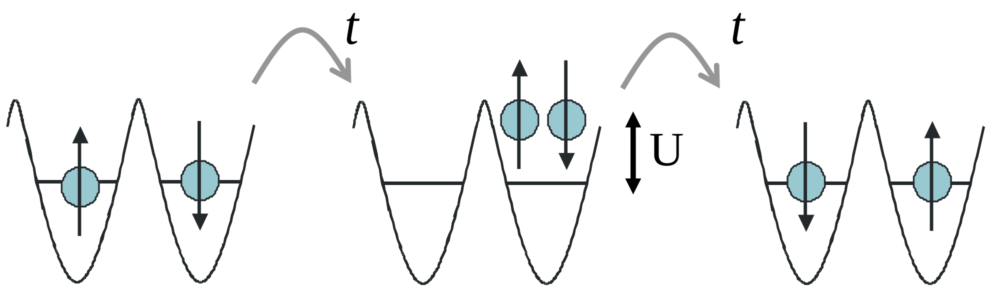
2D lattices → 1D Gases (fluctuations, correlations)

3D lattices → Strongly correlated systems



Magnetism driven by super-exchange interactions

Condensed-matter: effective spin-spin interactions arise due to exchange interactions **(Coulomb)**



$$\Gamma = -\frac{t^2}{U}$$

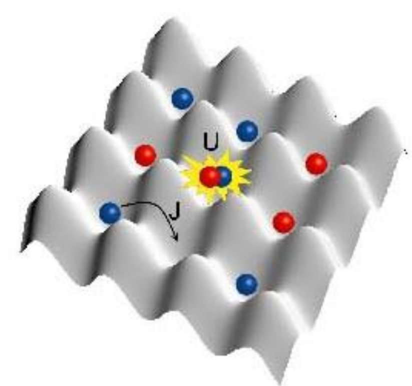
Heisenberg model of magnetism
(real spins, effective spin-spin interaction)
(↔Hubbard model at half-filling)

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

Ising Exchange

Cold atoms: effective spin-spin interactions arise due to exchange interactions **(Van-der-Waals)**

$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi h^2}{m} a(B)\delta(R)$$



Two types of interactions

Van-der-Waals (contact) interactions

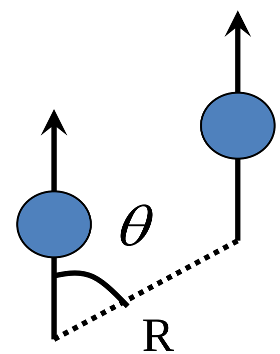
$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi\hbar^2}{m} a_S \delta(R)$$

Short range

Isotropic

Dipole-dipole interactions

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



Long range

Anisotropic

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

Cold atoms offer to revisit paradigms from solid-state physics experimentally.

!!! The Hubbard model is only an approximate Hamiltonian !!!

(dipolar interactions, density-assisted tunneling…)

$$\hat{H} = -t \sum_{\langle i,j \rangle,\sigma} \hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma} + U_{\mathrm{c}} \sum_{i} \hat{n}_{i\uparrow}\hat{n}_{i\downarrow} + \frac{V_{\mathrm{c}}}{2} \sum_{\langle i,j \rangle} \hat{n}_i \hat{n}_j$$

$$- T \sum_{\langle i,j \rangle,\sigma} \hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma}(\hat{n}_{i,-\sigma} + \hat{n}_{j,-\sigma}) + \frac{P}{2} \sum_{\langle i,j \rangle} \hat{c}^{\dagger 2}_{i}\hat{c}^{2}_{j},$$

See Lewenstein Rep. Prog. Phys. 78, 066001 (2015)

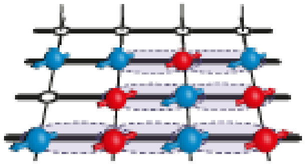
2- Platforms, possibilities, and challenges

Cold atoms revisit (quantum) magnetism

Atoms in periodic potentials

Interacting spin-less bosons
(effective spin encoded in orbital degrees of freedom)
Greiner: **Anti-ferromagnetic (pseudo-)spin chains**
I. Bloch, Sengstock,…

Spin ½ interacting Fermions or Bosons
Super-exchange interaction
Esslinger, Hulet, Bloch, Greiner, Zwierlein, Kohl,…:
(short range) anti-correlations
T. Porto, W. Ketterle,…



Trapped ions

spin lattice models with effective long-range interactions
(couple spins to mode) **(few tens of ions)** C. Monroe, R. Blatt

Dipolar particles

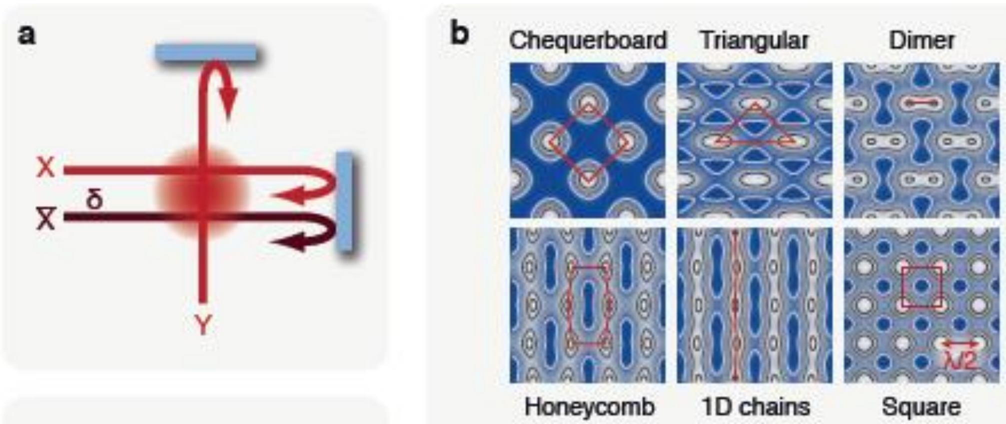
long range spin-spin interactions

Molecules with electric dipole moment (Jin/Ye)

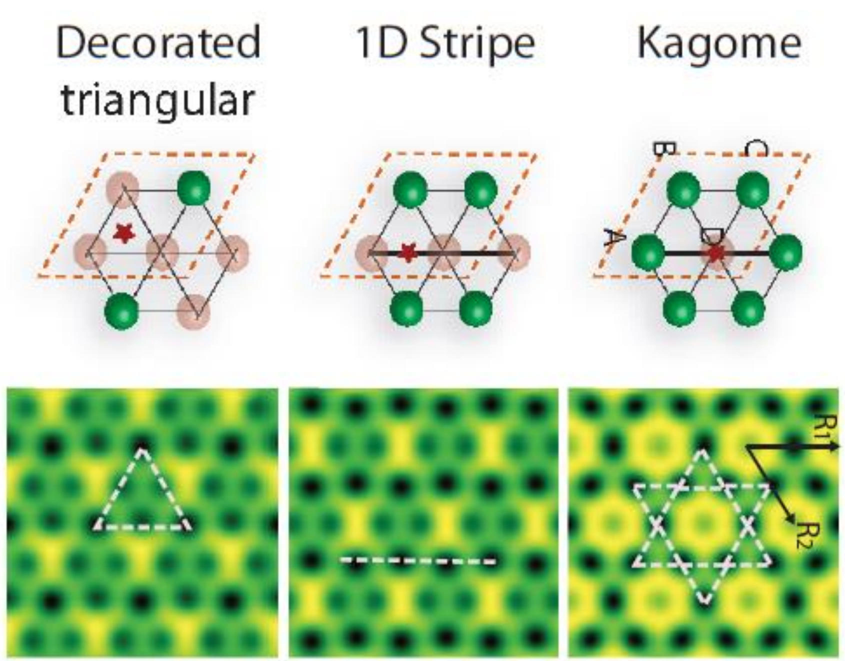
Rydberg atoms with electric dipole moment (Browaeys…) **(few tens of atoms)**

Magnetic atoms with magnetic dipole moment (Villetaneuse, Innsbruck)

One can use lattice with tunable topology, using « simple » beam arrangements



Esslinger

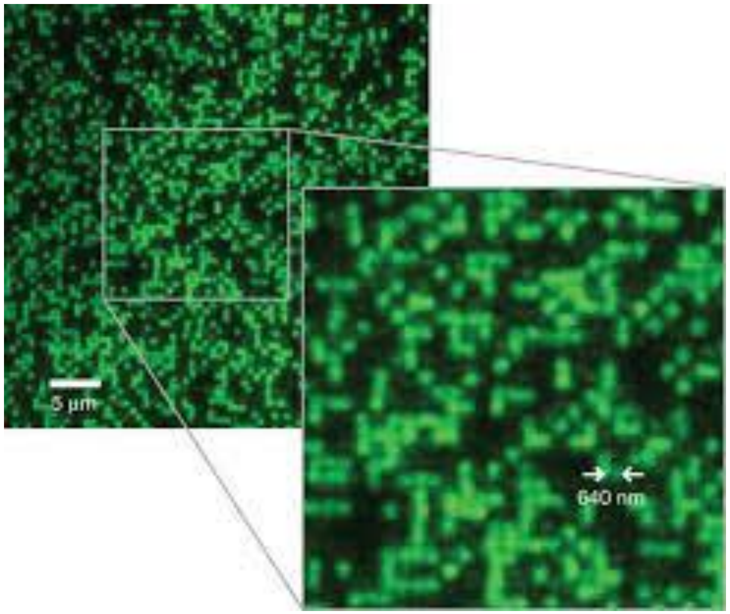


Stamper-Kurn – Kagomé

Sengstock - Triangular

Bloch, Porto – double wells

Site-resolved imaging, and many-body physics



Measure each site independently
(Bloch, Greiner, Zwierlein, Köhl,…)

Procedure : raise lattice depth and illuminate

Not easy to get spin sensitivity

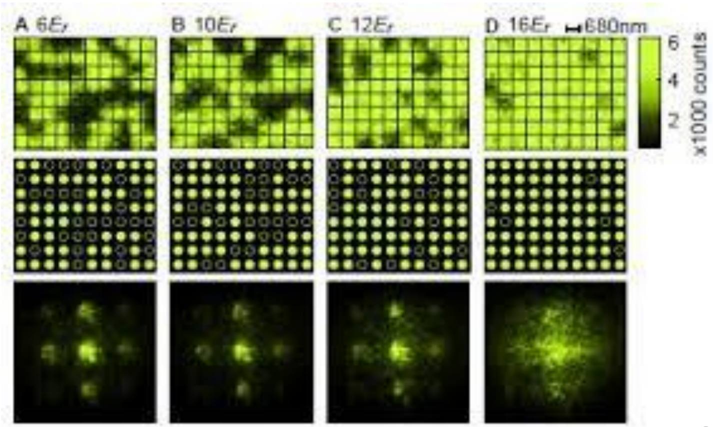
Not easy to get very high super-exchange interactions (λ)

$$\Gamma = -\frac{t^2}{U}$$

Bosons and Fermions !

Site-resolved imaging, and many-body physics

Example: the SF-Mott transition seen atom by atom...



Greiner

Other examples include : Many-body localization (Bloch), artificial gauge fields (Bloch, Ketterle, Sengstock), transport, …

Huge theoretical tasks ahead !

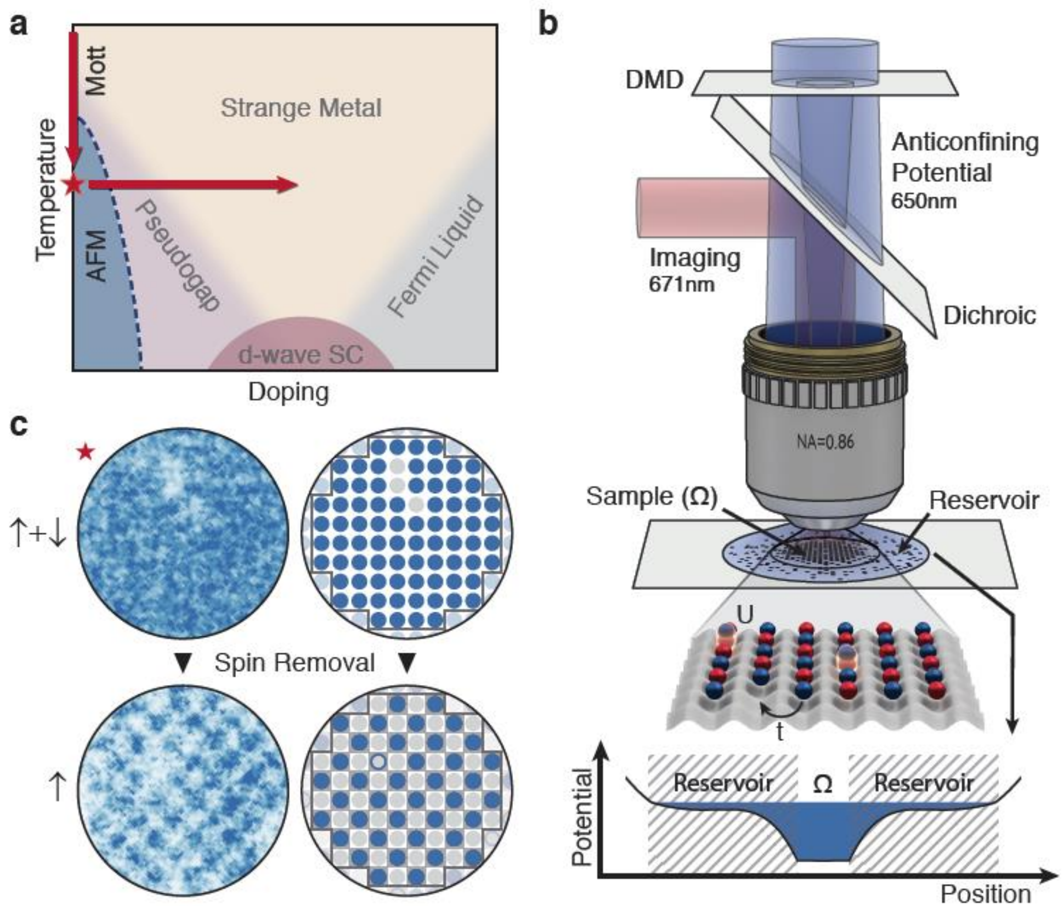
- How to characterize a many-body system ? (limits of quantum tomography)

Observation of anti-ferromagnetic correlations of s=1/2 fermions

Theoretically difficult

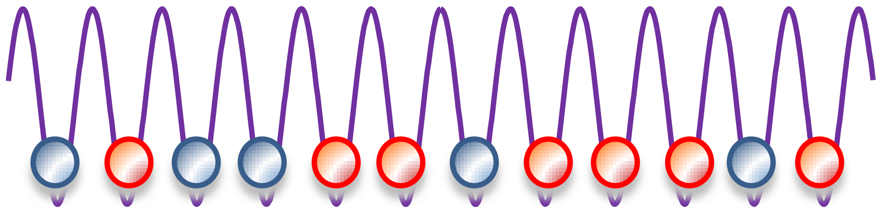
M. Greiner's experiment

Experimentally difficult



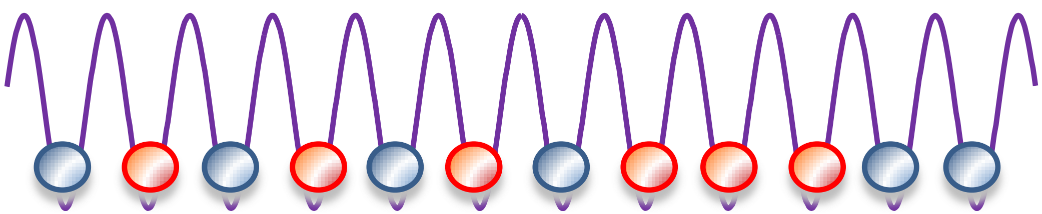
!! Ground state at half filling is the lowest energy singlet state ≠ Néel state !!

Quantum magnetism with cold atoms: the challenge of entropy



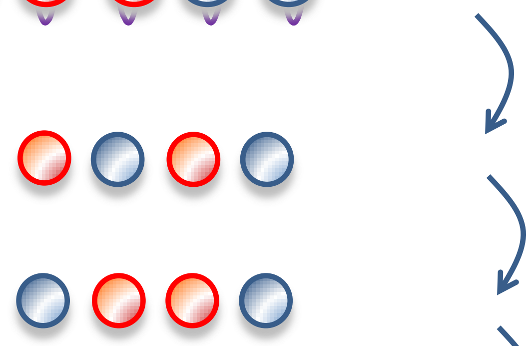
State of the art:

- it is relatively easy to have a Mott insulator with one atom per site.
- spin entropy is still close to Log(2). No direct way to cool the spin!



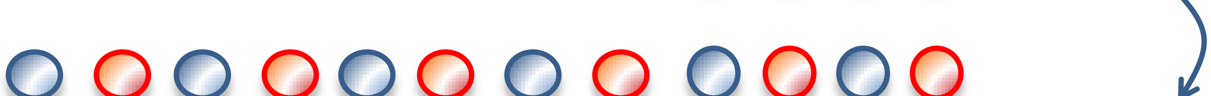
$$\Gamma \propto \frac{t^2}{U}$$

Usual strategy relies on super-exchange



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

(VERY long)



Quantum magnetism with cold atoms: the challenge of total spin

Most (optical) traps and lattices are spin-independent

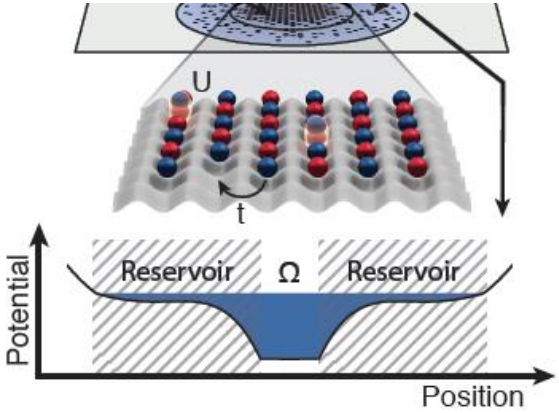
Conservation Laws !

Initially, total spin of a mixture of $N_\uparrow + N_\downarrow = N$ atoms

Total spin is $\propto \sqrt{N}$

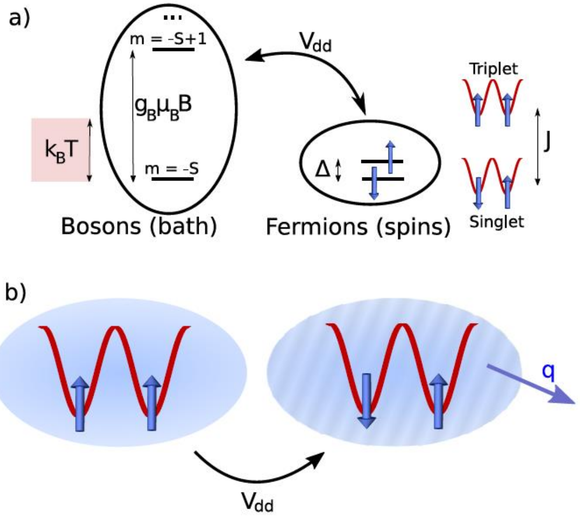
How can you reach the singlet many-body state ????

Evacuate entropy ?



(plays with local density of states)

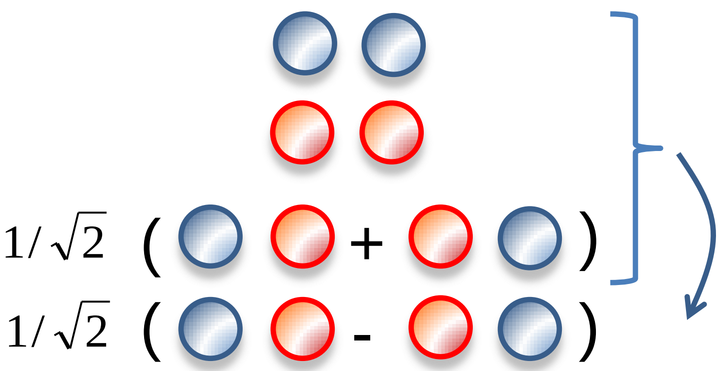
Spin-orbit-coupling ?



How to cool in the lattice ?

Proposal:
interaction of spin 1/2 fermions with a dipolar BEC used as a coolant.

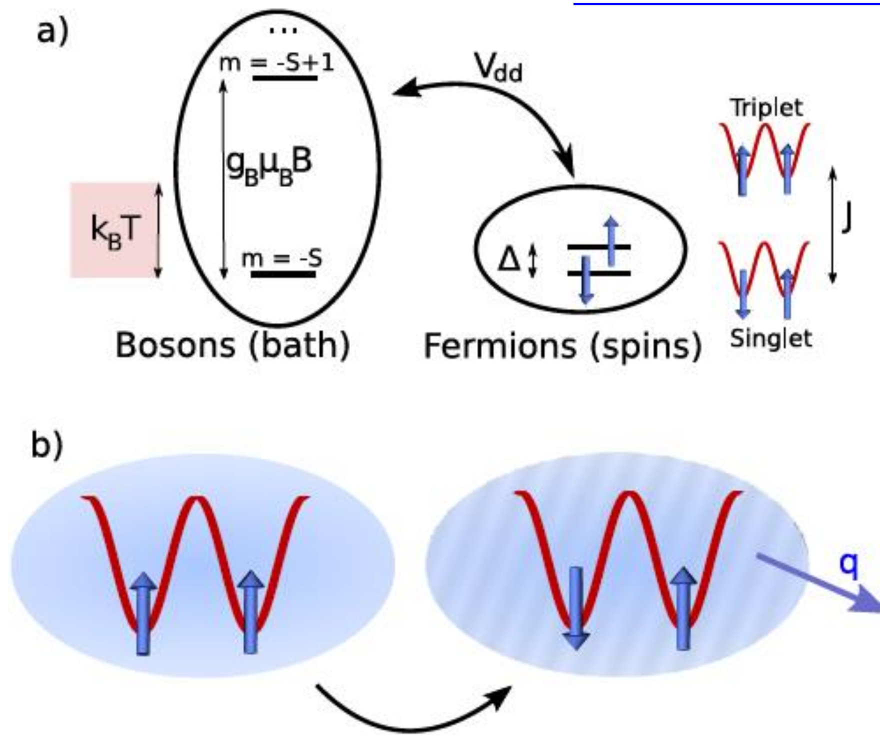
See other dissipative cooling proposals by P. Zoller



$$(S_{Bz}S_{F-}+cc)$$

Use dipolar relaxation to minimize energy?

arXiv:1803.10663



$$V_{col}(\vec{k}_1) = \sum_j e^{-i\vec{k}_1\cdot\vec{R}_j} V_{dd}^j(\vec{k}_1)$$

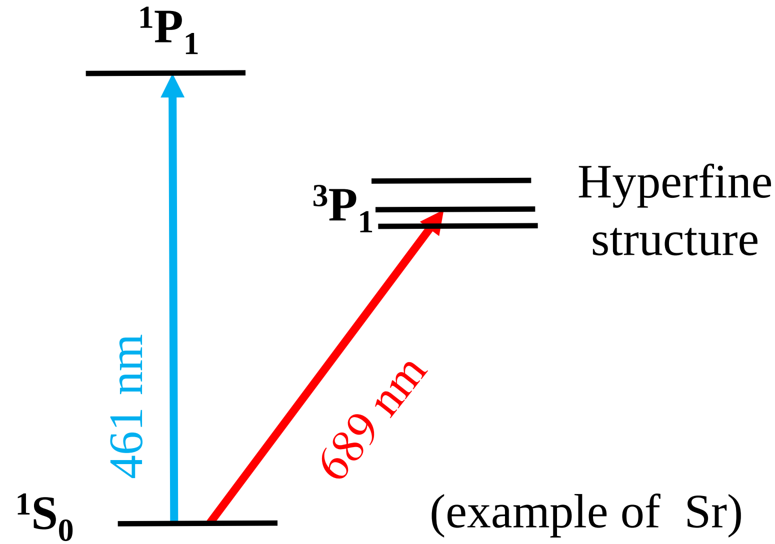
Requires spin-orbit coupling ! Spin-orbit can arise from atom-atom interactions (anisotropy is needed : dipole-dipole interactions are good !)

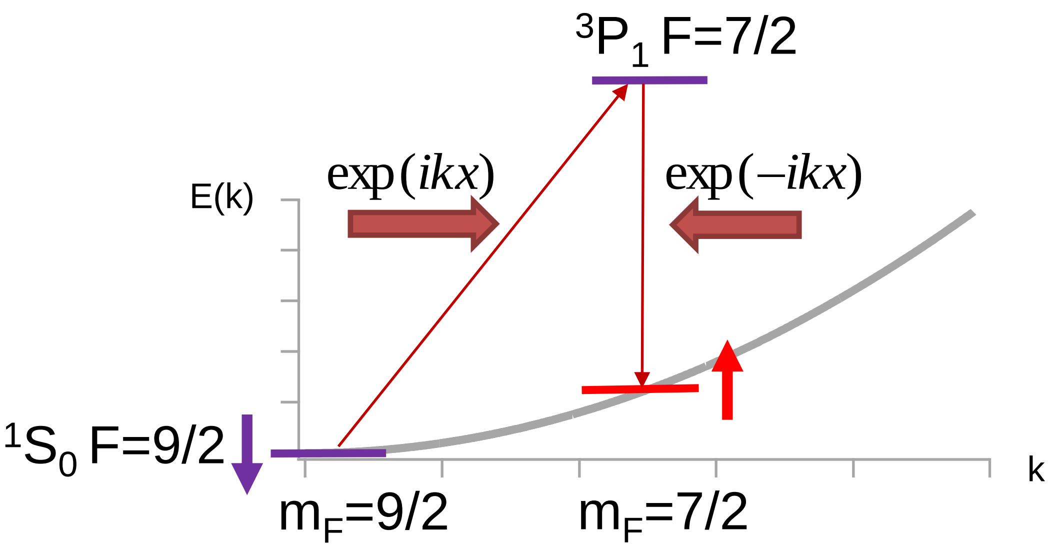
Spin orbit coupling

→ Can be arbitrarily engineered
« Usually » no anisotropy in ground state

→ Use spin-orbit coupling in excited states, and optically dress

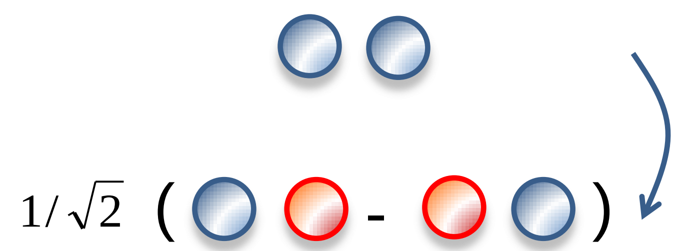
→ Narrow transitions allow to do this without too much heating





$$\hat{H} = \exp(2ikx)\hat{S}^{-}$$

Couples singlet and triplet !



Spin-orbit coupling opens possibilities to adiabatically engineer the ground state

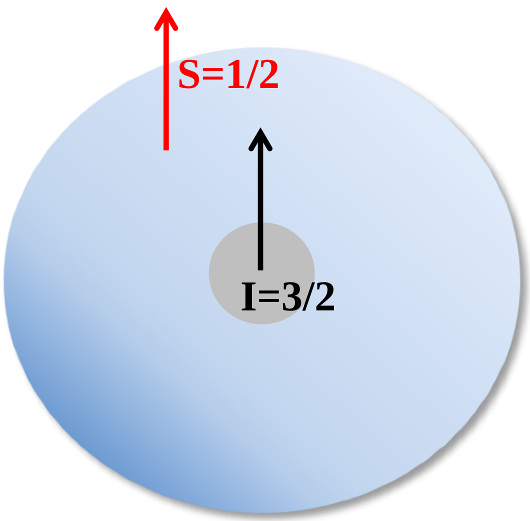
see PRL 107, 165301 (2011)

3- Beyond s=1/2

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

$$F = S + I$$

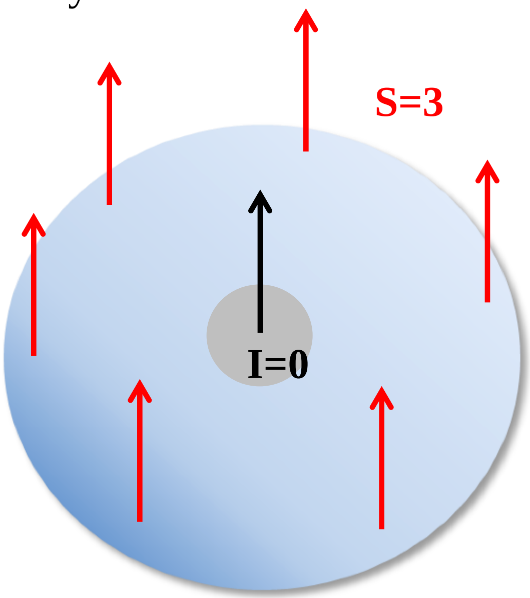
Alkali: spin arrises both from nuclear and electronic spins



e.g. Na, Rb

Spin-dependent
contact interactions

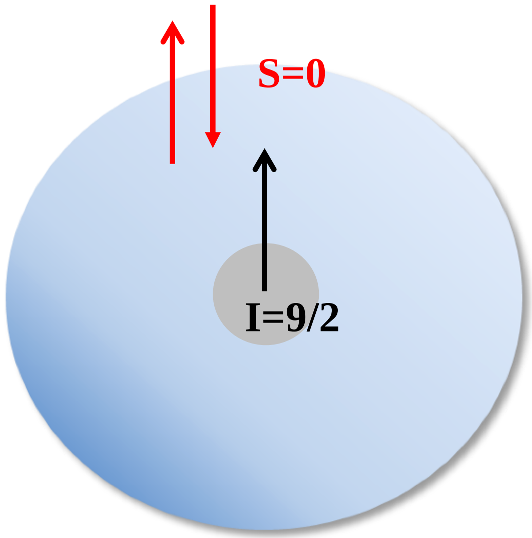
« magnetic atoms »: spin is purely electronic



e.g. Cr, Er, Dy

Strong dipole-dipole
long-range interaction

Alkaline-earth: spin is purely nuclear

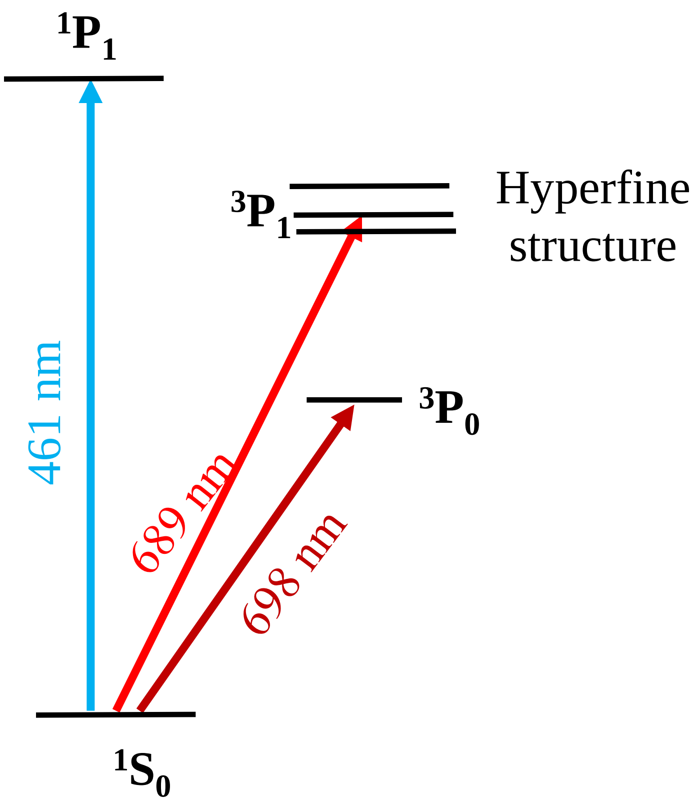


e.g. Sr, Yb

Spin-independent
contact interactions

New opportunities thanks to the atomic structure

Already mentionned: spin-orbit coupling



Articificial gauge fields

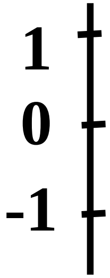
↔

Huge effective magnetic fields
(Spielman, Ketterle, Bloch, Esslinger, Sengstock…)

New opportunities thanks to the atomic structure

Example: spin 1 atoms

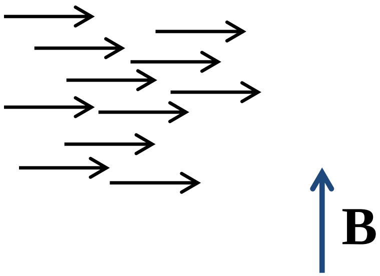
f=1. Three Zeeman states

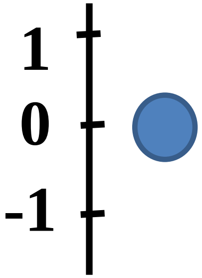


Two molecular potentials F=0,2 ;
two scattering lengths: a_0, and a_2.

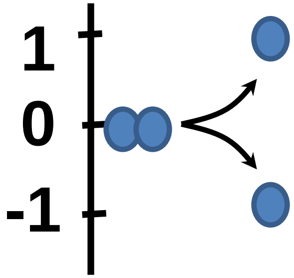
If $a_2 < a_0$: spins align : ferromagnetic

If $a_2 > a_0$: polar phase





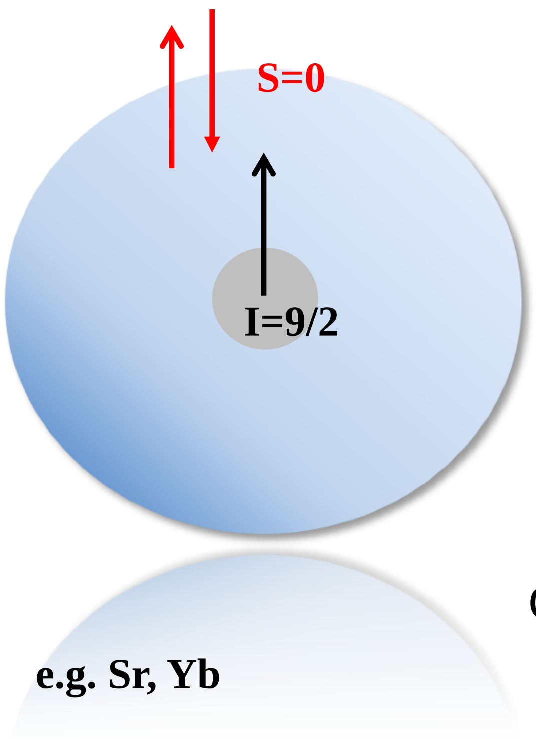
Ho 1998 ; Machida 1998



$$|0,0\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(|1,-1\rangle + |-1,1\rangle\right)$$

Spinor gases: lots of physics being studied beyond mean-field !
(Chapman, Klempt)

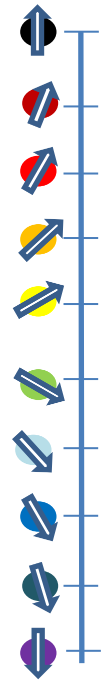
Fermionic Sr or Yb isotope in the ground state: SU(N) symmetry



e.g. Sr, Yb

^{87}Sr

F=9/2



Spin entirely due to nucleus

Spin-independent interactions

One obvious consequence : non spin-exchange dynamics

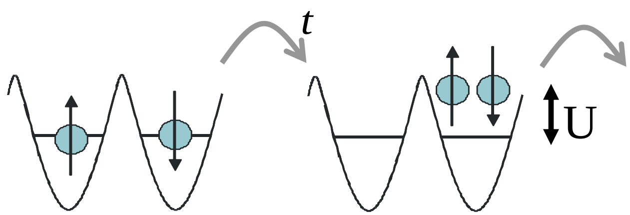
- Can prepare arbitrary number of « colours » in the system.

(see Bloch, Fallani, Takahashi, Schreck)

(New project at LPL !)

Proposal : interplay between SU(N) magnetism and lattice topology

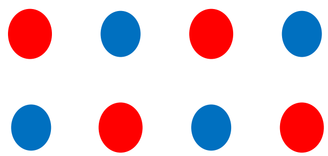
Reminder: SU(2) case. Two atoms in different states can reduce their energy by tunneling

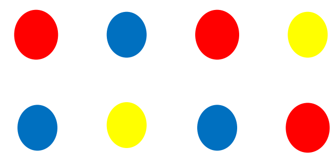


$$\Gamma = -\frac{t^2}{U}$$

Examples:

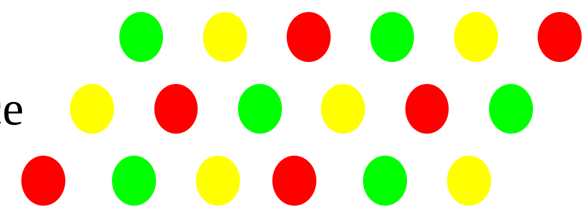
2 colors
Square
Ordered





3 colors
Square
Dis-ordered

3 colors
Triangular lattice
Ordered



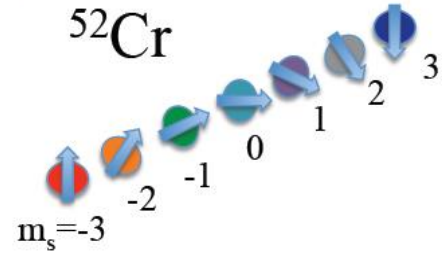
Frederic Mila

For a square lattice:
SU(2) ordered
SU(3 and 4) disordered
SU(5) ordered (very low T's)
SU(6) disordered...
Honeycomb and Kagomé lattice very interesting for SU(N=3,4).

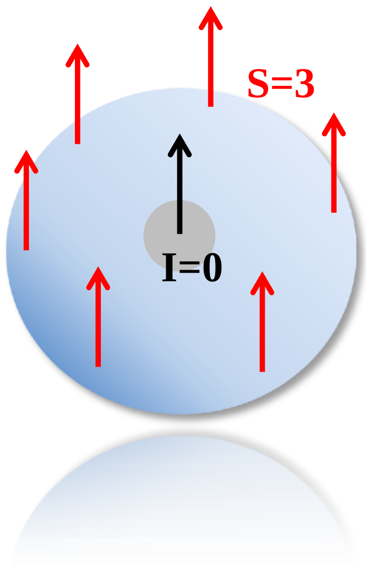
SU(N) symmetry introduces large degeneracies in gound state;
Possibilities of spin liquids;
one singlet takes N atoms !

4- Example of dipolar magnetism

“Our” Magnetism

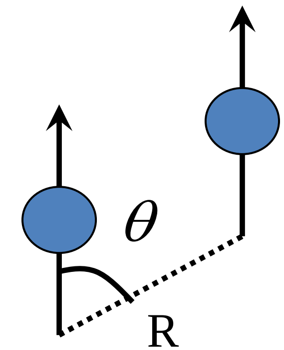


Chromium atoms



Dipole-dipole interactions

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



Long range

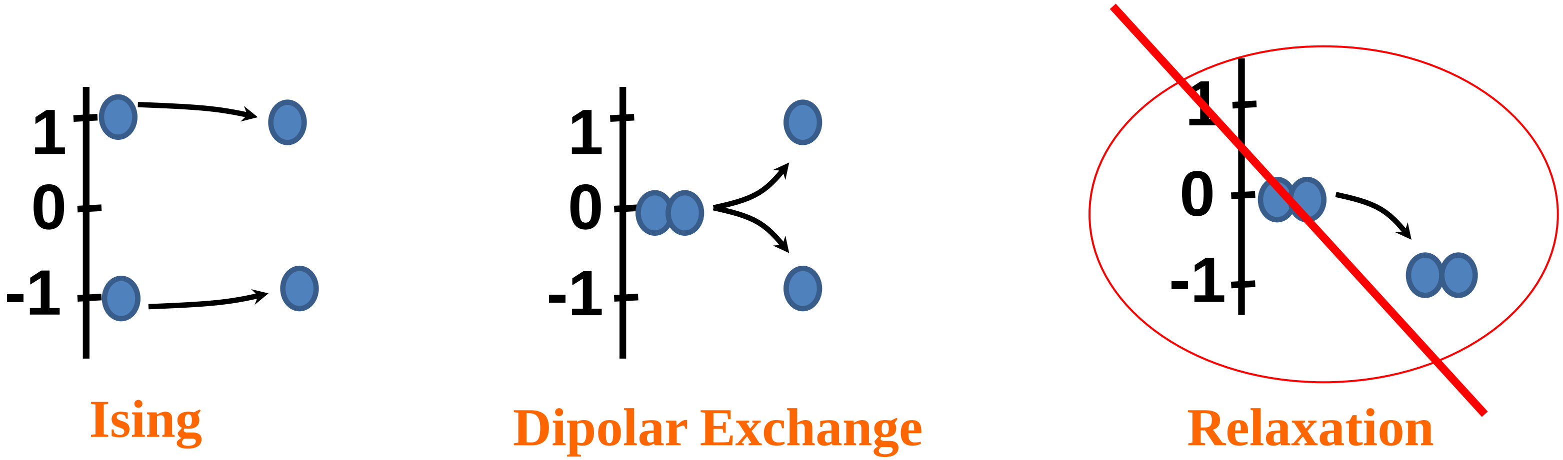
Anisotropic

Unusually large dipolar interactions due to large electronic spin

Main player:

Dipole-dipole interactions

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



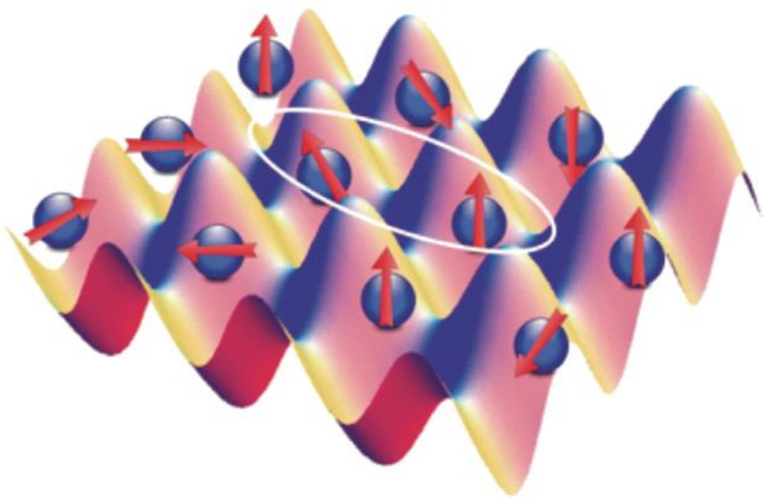
↔ **Nuclear Magnetic Resonance**

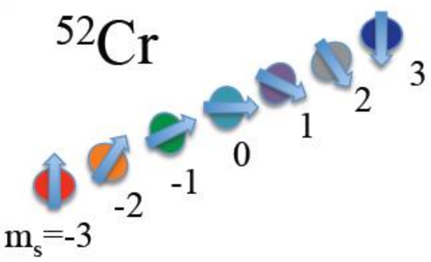
$$S_{1z} S_{2z} - \frac{1}{4}\left(S_{1+} S_{2-} + S_{1-} S_{2+}\right)$$

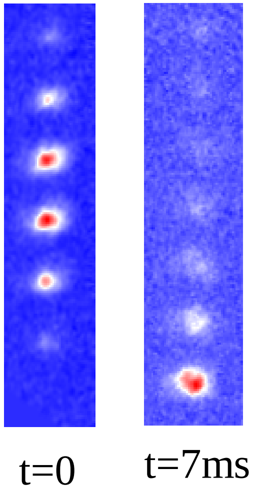
Ising Exchange

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

This Experiment





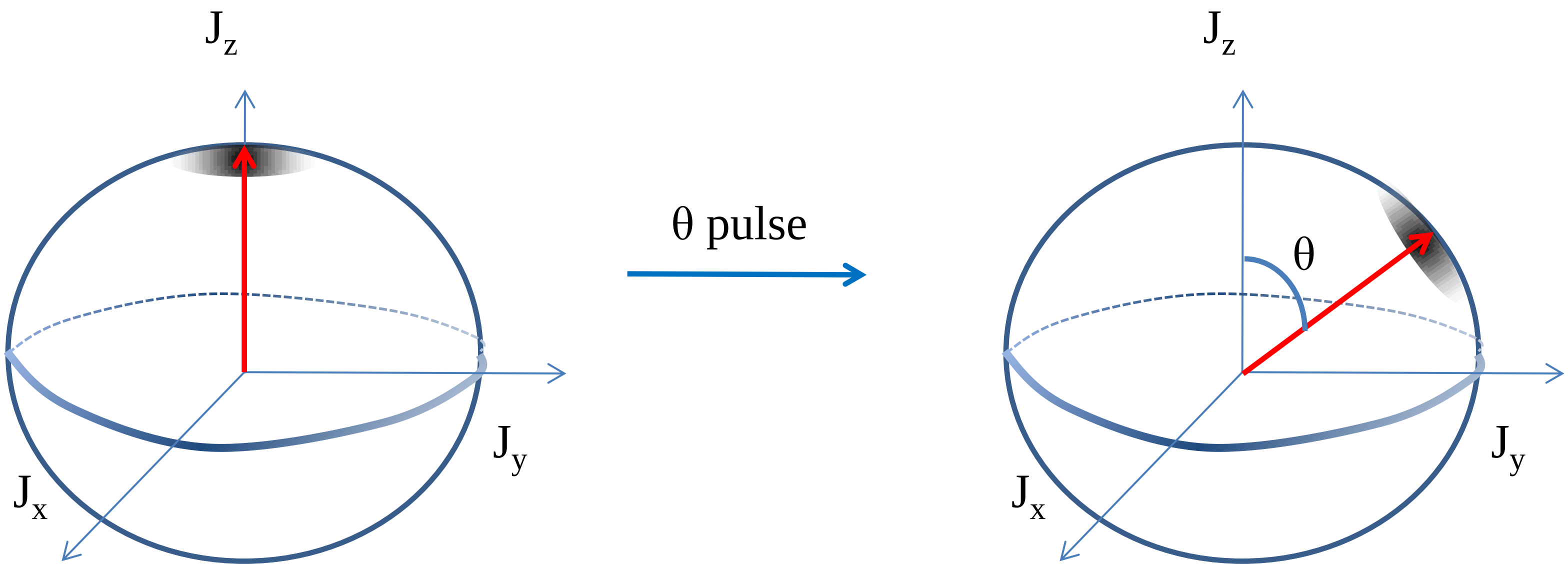


I – Excite the spins

II – Free evolution under the effect of interactions

Question: Under which conditions do correlations develop?

After tilting the spin: from classical to quantum



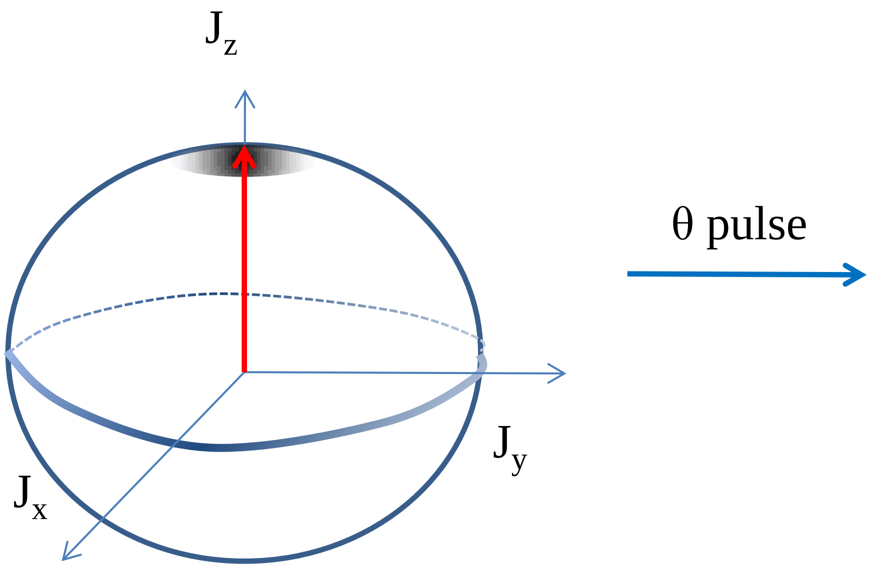
$$S_{1z}S_{2z} - \frac{1}{4}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

Prediction (Ana Maria Rey):

θ small → classical precession
θ large → entanglement grows

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

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

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

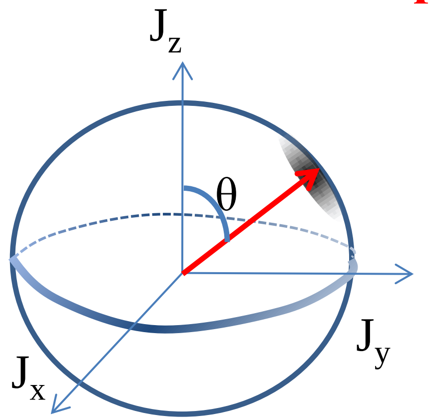
SU(2) symmetric Heisenberg Hamiltonian would introduce no spin dynamics after rf pulse

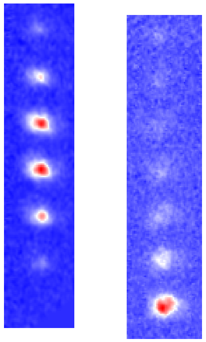
Dynamics associated to:

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

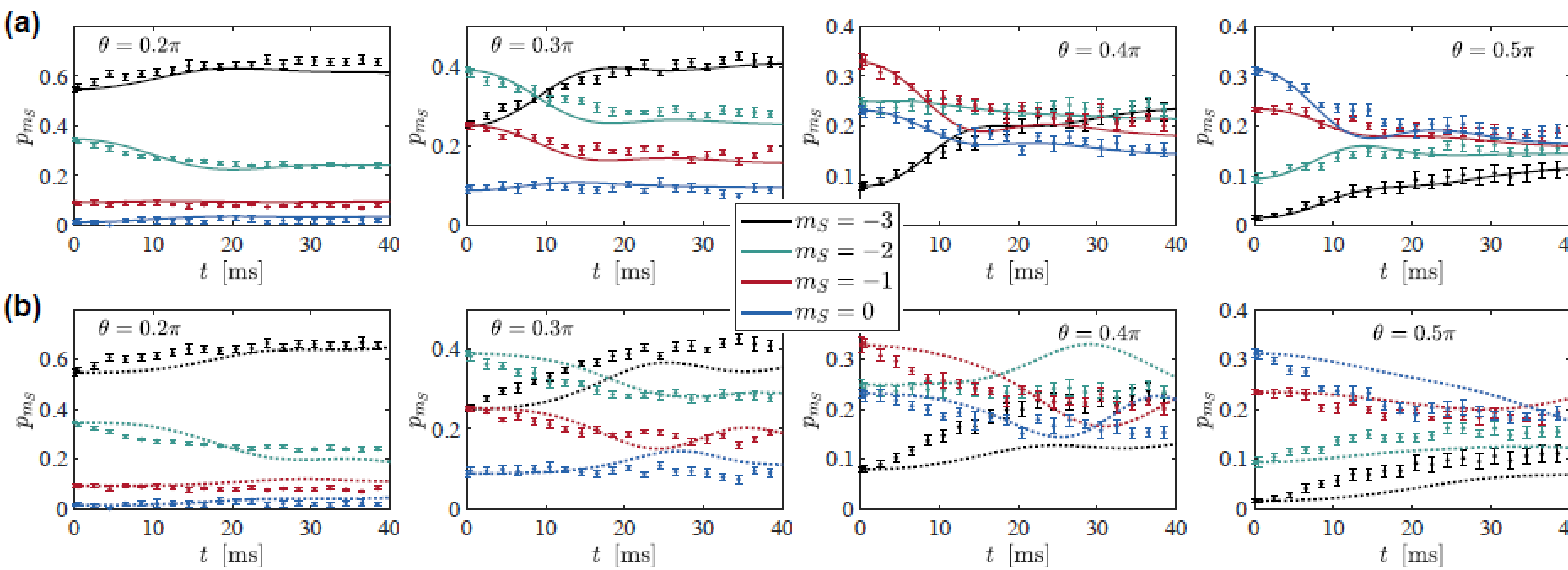
Squeezing ↔ Variance (S_z)

Experimental results…





Quantum theory
GDTWA
Schachenmayer/Rey



arXiv:1803.02628

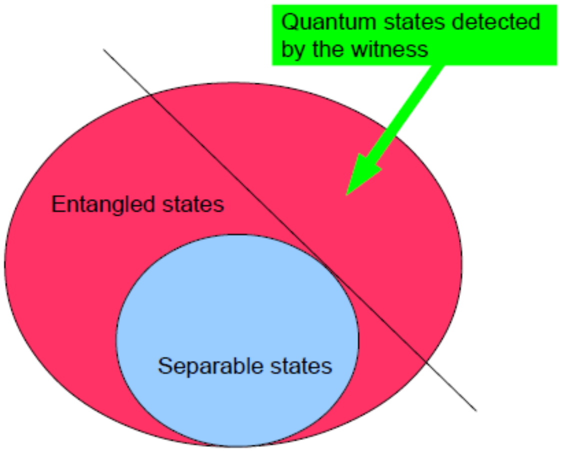
Classical theory

Increasing quantum-ness is seen

How to *experimentally* characterize the growth of entanglement ?

1- Entanglement witness based on measurements of global spin variables.

(e.g. $(\Delta S_x)^2 + (\Delta S_y)^2 + (\Delta S_z)^2 \geq N/2$ for any mixture of separable states)



!!! Beware of large spin systems !!!
(i.e. squeezing is not an EW) – See G. Toth -

1-bis – Measure length of collective spin (on going)

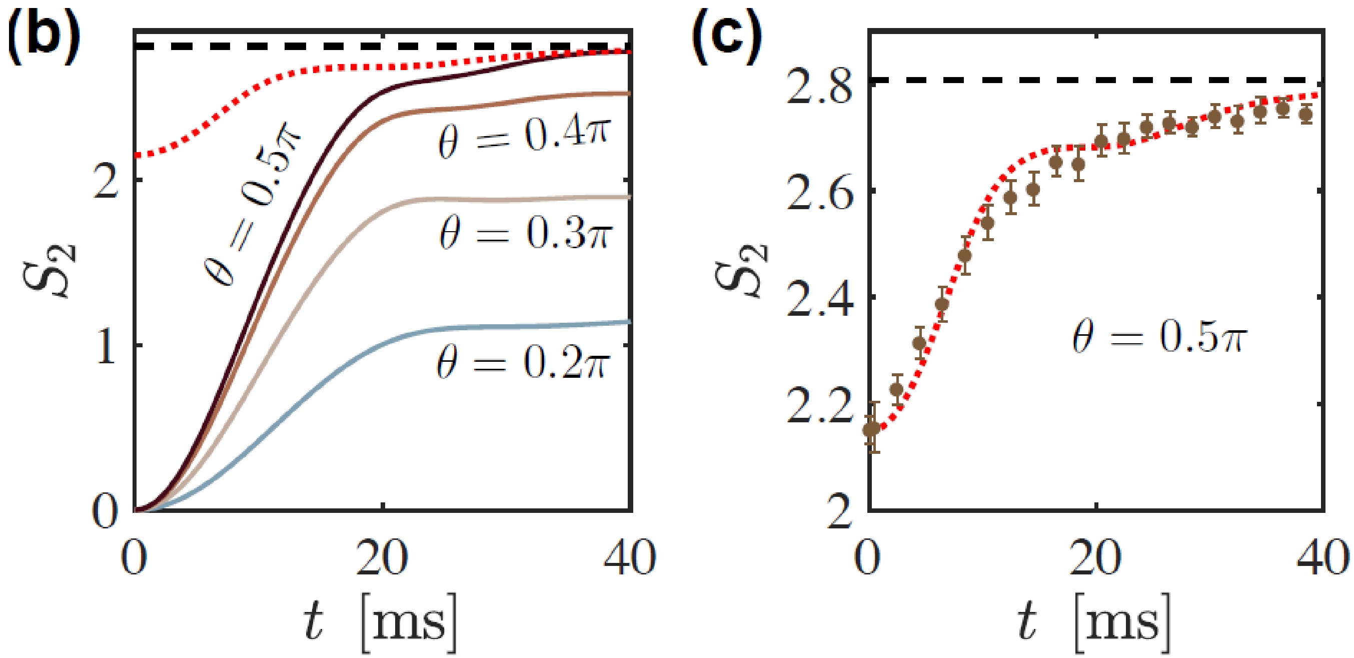
2- Measure the **entropy associated to entanglement**

Basic idea $$\frac{1}{\sqrt{2}}\left(\left|m_s=1, m_s=-1\right\rangle + \left|m_s=-1, m_s=1\right\rangle\right)$$ **= PURE STATE**

But measurement performed in just one lattice site will show random fluctuations ($\left|m_s=\pm 1\right\rangle$) → associated entropy

!!! Difficulty to warrant purity for large systems !!! (Loschmidt echo ?)

Calculated growth of entanglement



Renyi entanglement entropy (NOT measured here)

« Measured » diagonal entropy (NOT a proof of entanglement !)

??? How to characterize purity in a large system ???

(assumes homogeneity)

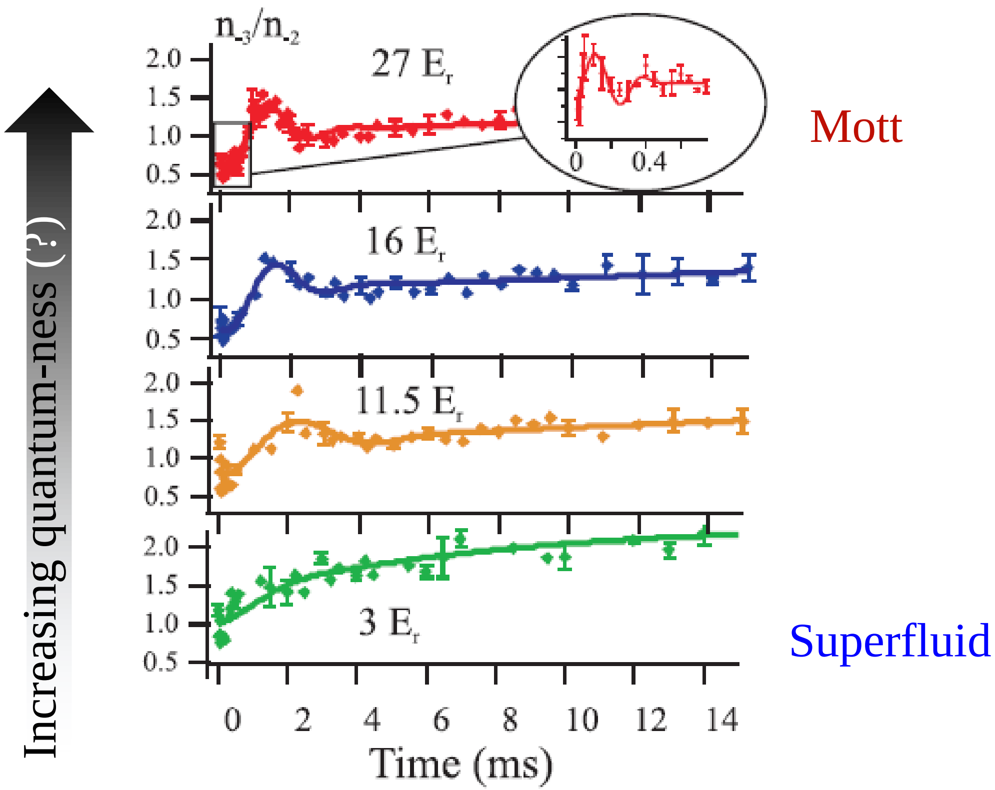
arXiv:1803.02628

Direct access to many-body physics ! Interest of out-of-equilibrium approaches

(no issue with entropy – **However limited timescale !!**)

- **In lattices, beyond mean-field physics is seen at large tilting angles**

…in the regime where theories still keep up with experiments…



PRA 93, 021603(R) (2016)

No theoretical model available at intermediate lattice depths, where transport and magnetism compete

- **On going collaboration with A. M. Rey, B. Zhu, B. Blakie**

-Main messages:

- **Many experimental platforms**
(long-range interactions, short range interactions, geometry)

- **Ground state properties remain difficult from the experimental standpoint**
(need spin-orbit coupling / other cooling schemes)

- **Out of equilibrium dynamics provides a new way to probe strongly correlated systems** (a novelty allowed by long timescales in cold atom physics)

- **Huge tasks ahead for the full characterization of many-body systems**
(entanglement, purity…)

- **There is more in atoms than s=1/2**
(large spin magnetism, spin-orbit coupling) → beyond quantum simulation

arXiv:1803.10663 (2018) (dissipative cooling)

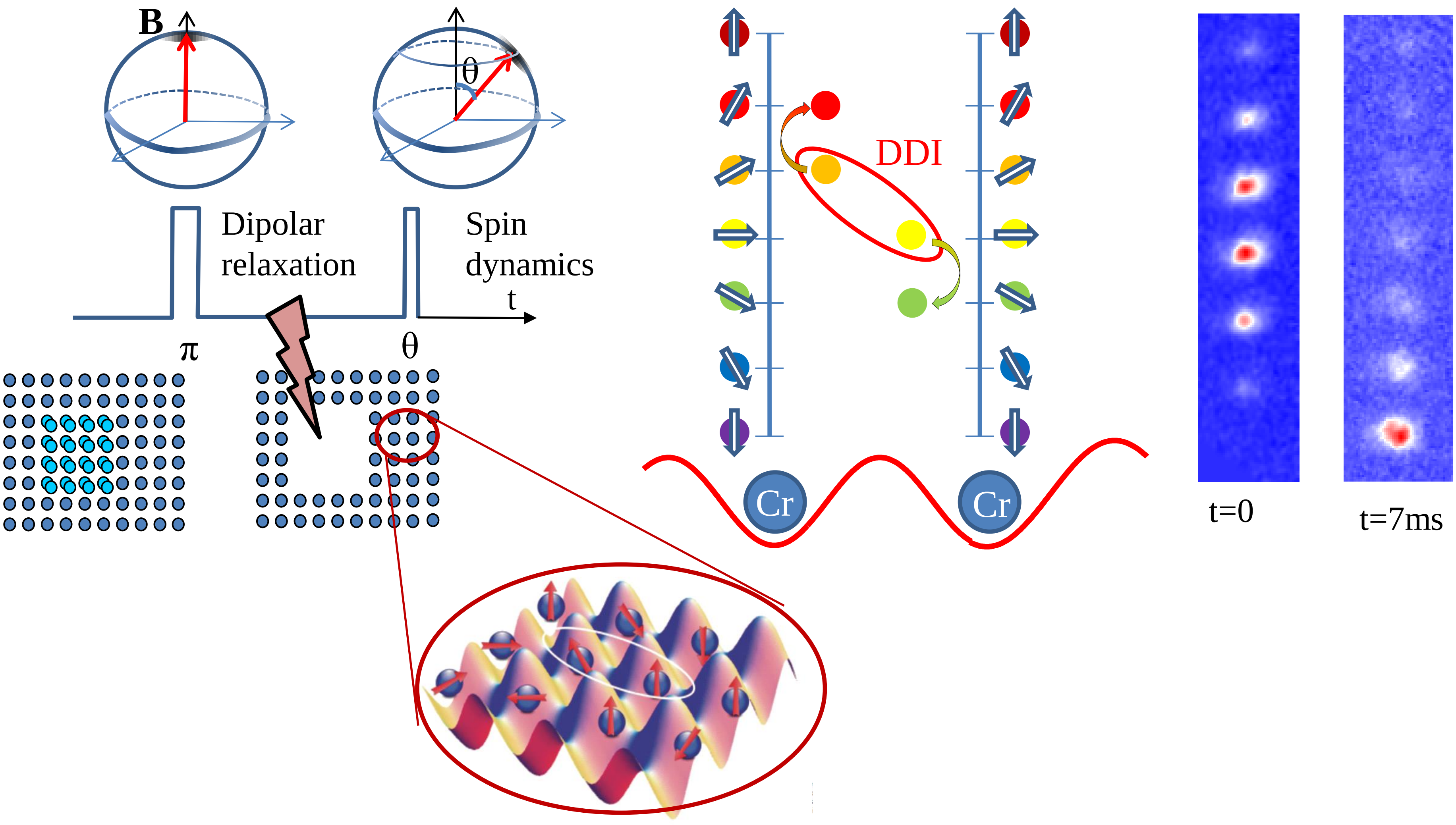
arXiv:1803.02628 (2018) (lattice models)

S. Lepoutre, L. Gabardos (PhD), B. Naylor (PhD)
B. Laburthe-Tolra, O. Gorceix, E. Maréchal, **L. Vernac**,
M. Robert-de-St-Vincent,
K. Kechadi (PhD), P. Pedri

A. M. Rey, J. Schachenmayer, B. Zhu,

Large Spin physics with Chromium… and Strontium coming up.

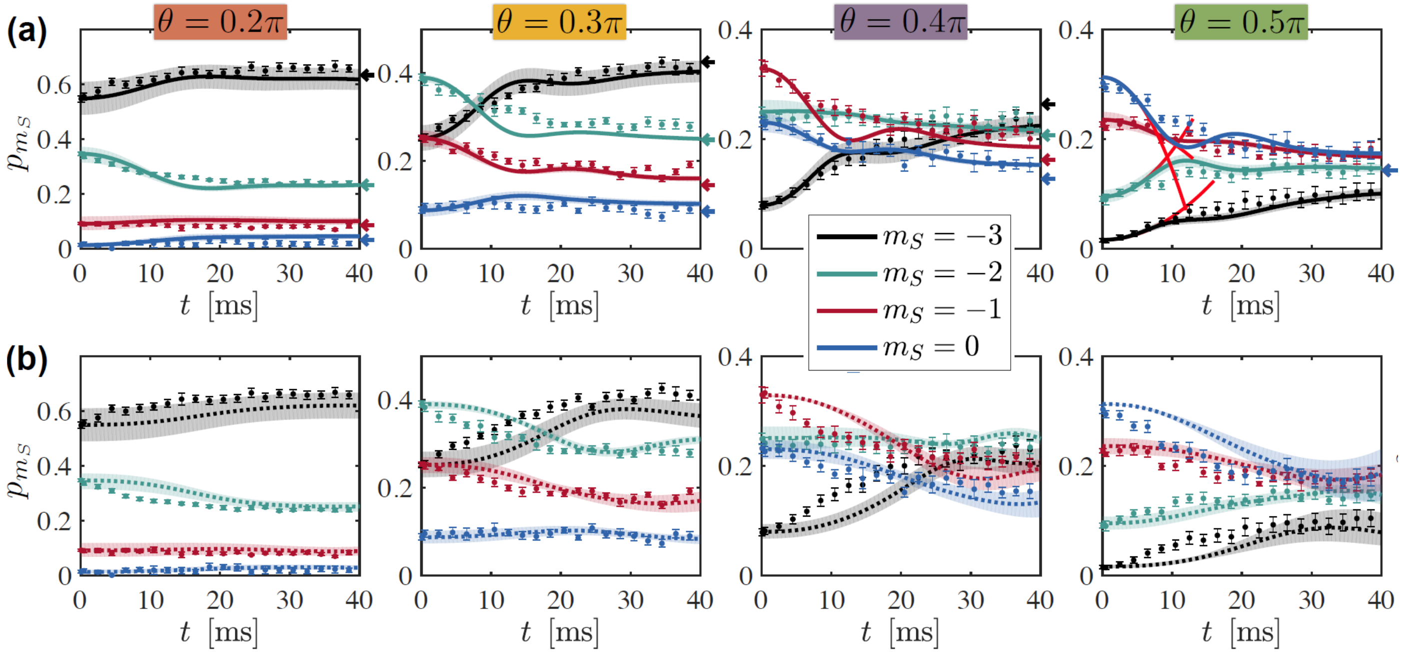
Experimental protocol



Thermalization of an isolated quantum system

How to measure purity ? → Loschmidt echo ? (H→-H)

Eigenstate thermalization hypothesis ?



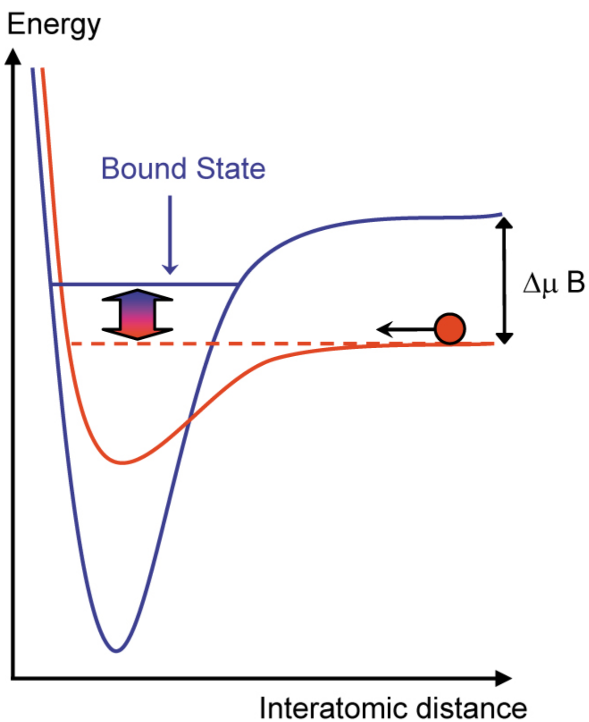
Direct access to many-body physics ! Interest of out-of-equilibrium approaches

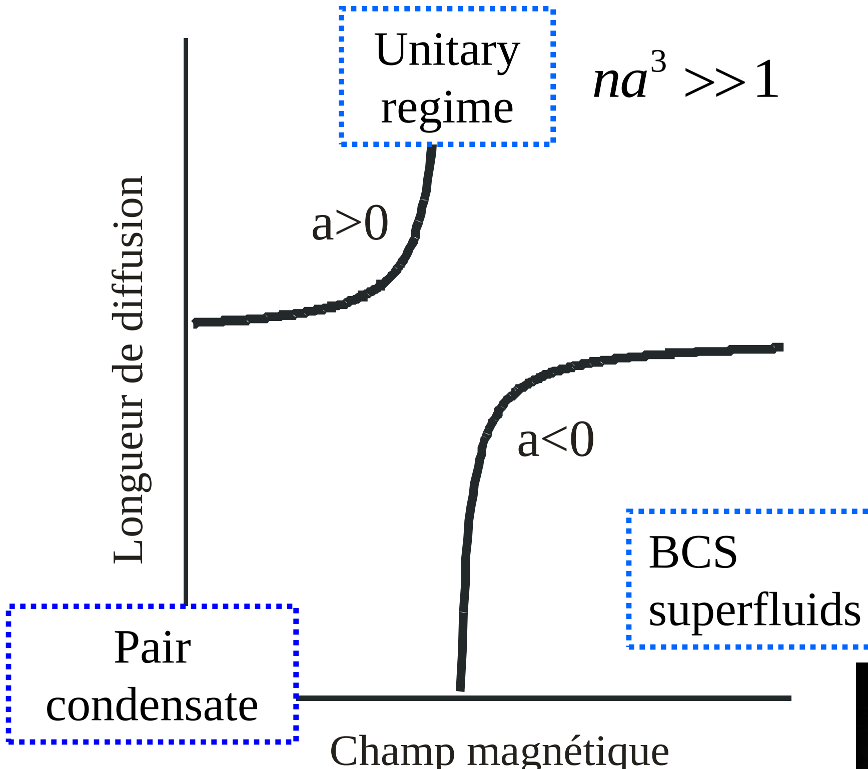
(no issue with entropy – **However limited timescale !!**)

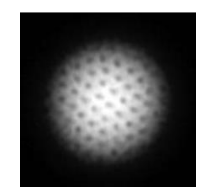
Control of interactions : Feshbach resonances

$$V(R) = -\frac{C_6}{R^6} \longrightarrow V(R) = \frac{4\pi h^2}{m} a(B)\delta(R) \qquad a \approx \Delta x$$

Control of a(B) (scattering length) (-∞,+∞)







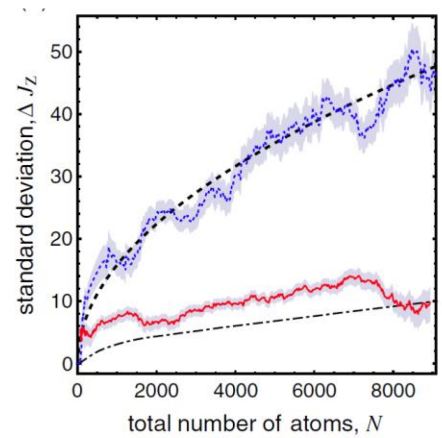
Example : BEC-BCS cross-over with Fermi gases

Spin dynamics and beyond mean-field effects

Spin dynamics generates entanglement.
squeezing (atom interferometry, EPR…)

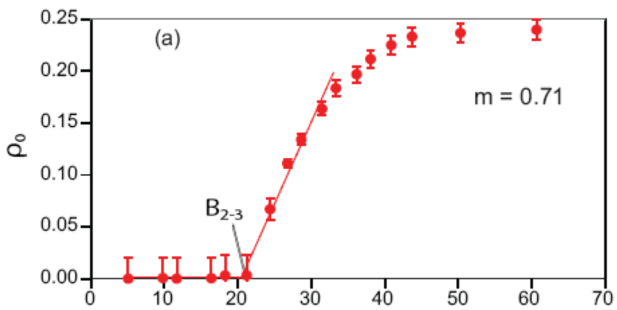
$$|0,0\rangle \leftrightarrow \frac{1}{\sqrt{2}}\left(|1,-1\rangle + |-1,1\rangle\right)$$

Karsten Klemt, M. Chapman



Quantum phase transitions

(interplay between spin-dependent contact interactions and Quadratic Zeeman effect)



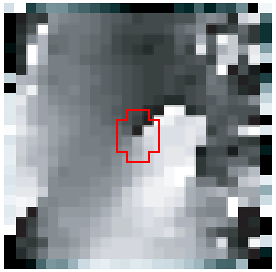
Stamper-Kurn, Lett, Gerbier

New Nematic phases (the spin does not point a well-defined position)

Quench through phase transitions

Here, generation of topological defects

Domains, spin textures, spin waves, topological states



Stamper-Kurn

Towards « non-classical » spinor phases ? What is the true nature of the ground state

$$|SC\rangle = \frac{1}{\sqrt{N!}}\left(\sqrt{\frac{N_1}{N}}a_1^\dagger + e^{i\chi}\sqrt{\frac{N_{-1}}{N}}a_{-1}^\dagger\right)^N |\mathrm{vac}\rangle$$

a2>a0: Possibility of singlet condensates

$$\Theta^+ = -2a_1^+ a_{-1}^+ + a_0^{+\,2}$$

Creates a pair

$$|PC\rangle = \left(\Theta^+\right)^{N/2}|vac\rangle$$

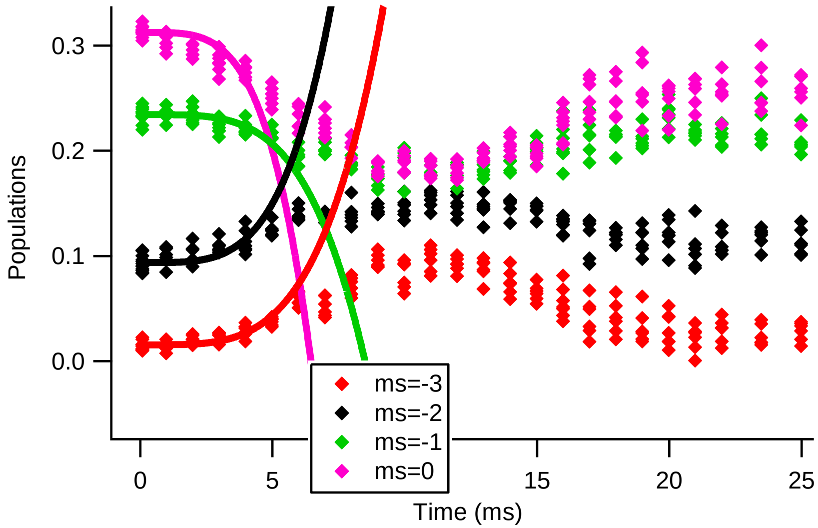
Pair condensate is the real ground state !

a2<a0: Ferromagnetic; Spontaneous symmetry breaking

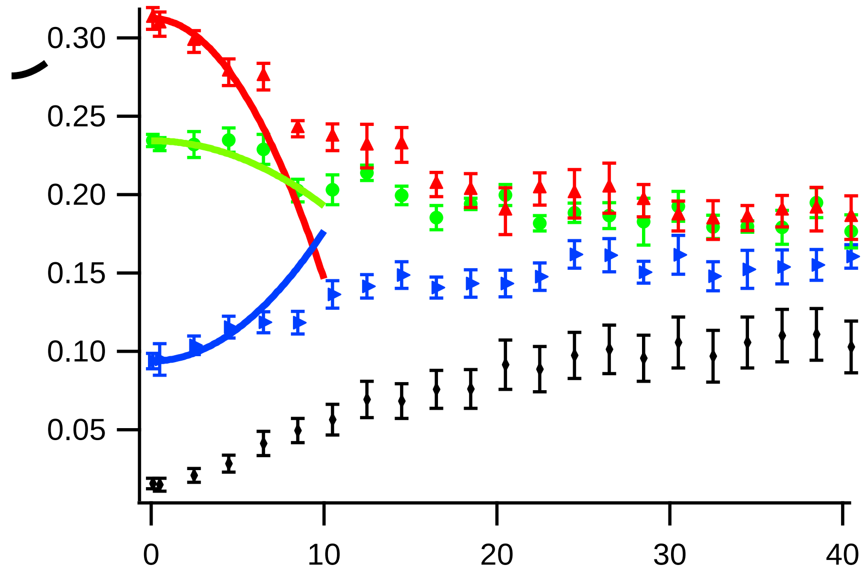
See Bigelow 1998 ; Ho 2000

A side-slide, on the beauty of perturbative equations

BEC, ferrofluid



Lattice, correlated



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

$$p_{m_s}(t) = p_{m_s}(0) + \alpha_m \sum_i V_{dd}^2(\vec{r}_i) t^2$$

$$\alpha_m = 135/512(1,2,-1,-4,-1,2,1)$$

The entropy for quantum degeneracy

Entropy of a thermal (classical) gas

$$S / N \approx -k_B \mathrm{Log}\left(n\Lambda^3\right)$$

(Phase space density measures number of available states, hence entropy.)

Major consequence:

BEC occurs for a fixed entropy per particle (independent of temperature)

$$T_c \approx N^{1/3}\eta\overline{\omega} \quad \longleftrightarrow \quad S_c / N \approx k_B$$

Entropy of a saturated Bose cloud (3D):

$$S / N \approx 3.6 k_B \left(\frac{T}{T_c}\right)^3 = 3.6 k_B f_{th}$$

For a fully saturated gas, the entropy is given by the condensate fraction.

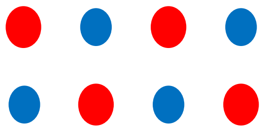
Entropy of a degenerate Fermi gas:

$$S / N \approx \pi^2 k_B \left(\frac{T}{T_F}\right)$$

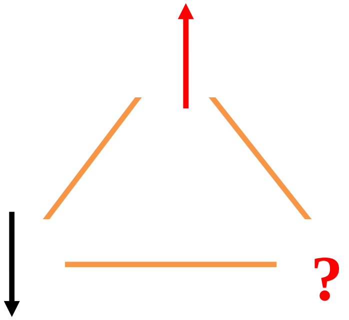
Quantum magnetism, some paradigms from solid-state physics
Strongly correlated (s=1/2) electrons

Condensed matter physics ↔ many-body quantum physics

High-Tc superconductivity ⟷ Antiferromagnetism Hubbard model



Frustrated magnetism

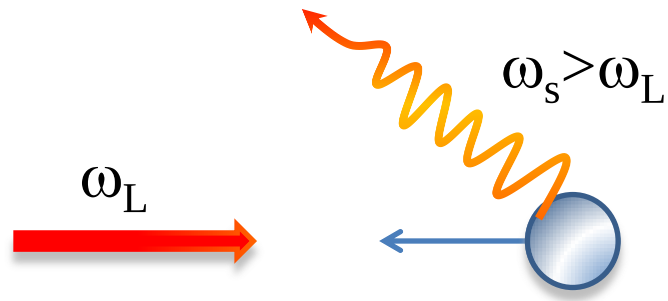


Spin liquids

Heavy fermions (Kondo physics), anomalous superconductivity

Cooling schemes and limitations

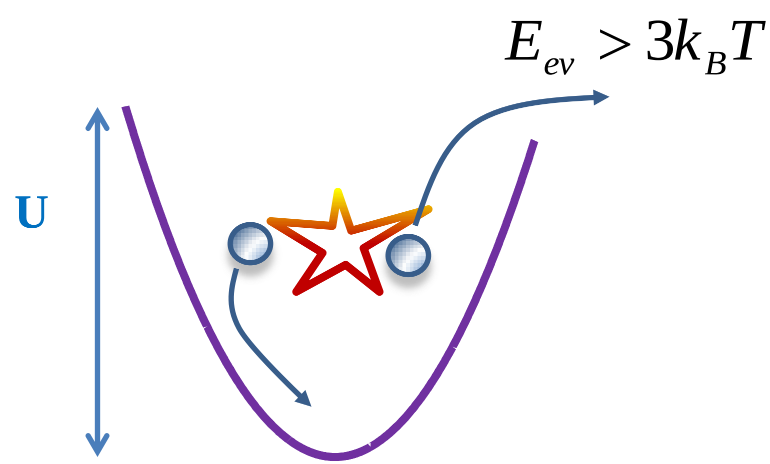
Laser cooling



Temperature limit:

Doppler,
Recoil,
…

Evaporative cooling
In spin-independent potentials



Temperature limit:

$T \sim U/10$

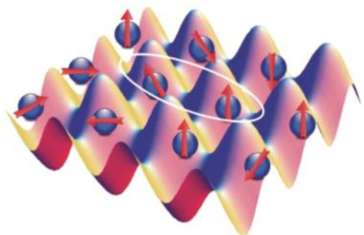
In a quantum degenerate gas, need $U > \mu$ → **$T > \mu/10$**

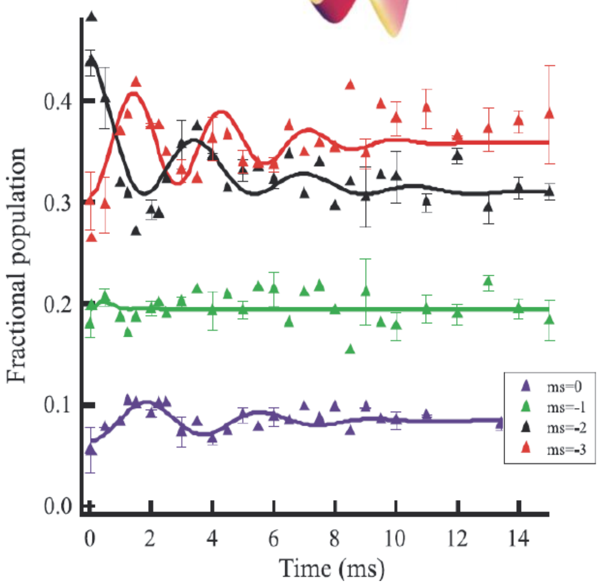
One big limitation: cooling is usually spin-insensitive

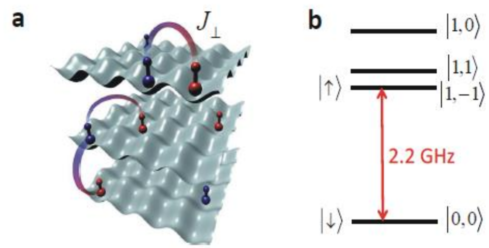
Dipolar systems and magnetism

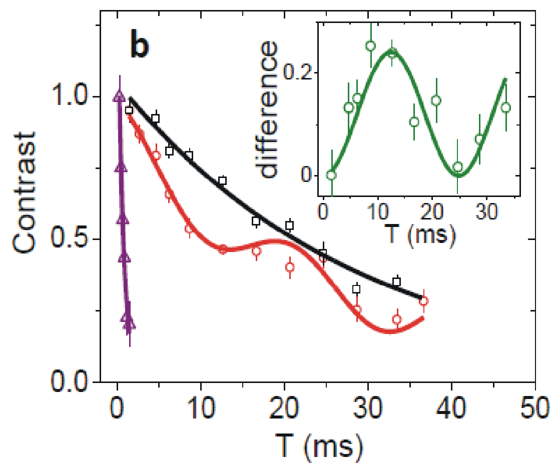
Magnetic atoms vs dipolar molecules vs Rydberg Atoms

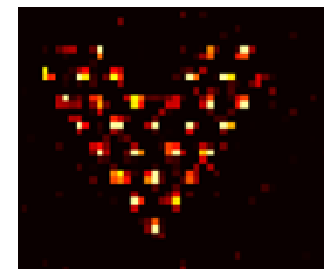
$$\alpha S_{1z}S_{2z} + \beta \frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$

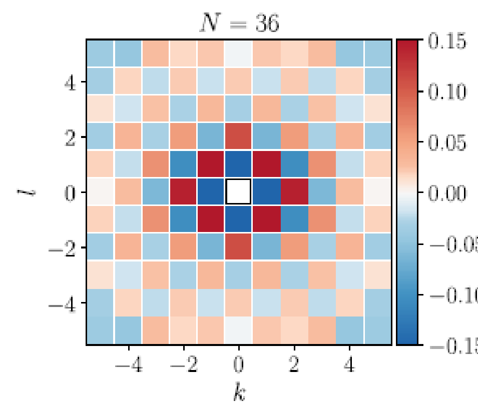












LPL - Paris

transport possible;
truly macroscopic
Large spin

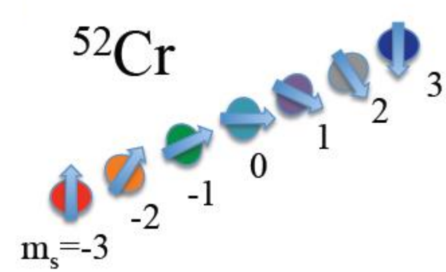
Boulder

Control of Hamiltonian

Orsay

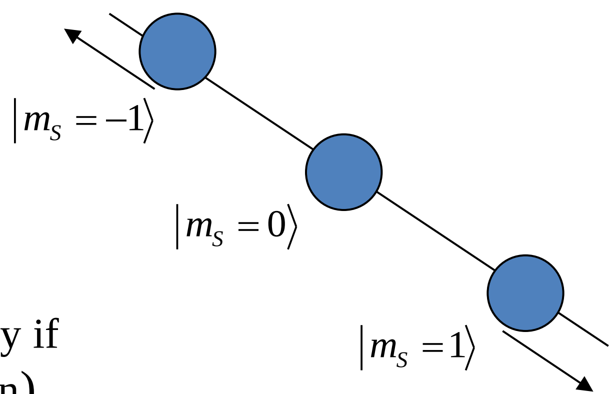
Control of Hamiltonian
And geometry
individual adressing

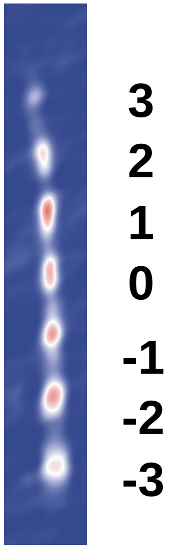
Optical dipole traps equally trap all Zeeman state of a same atom (AC Stark shift)



How to measure?

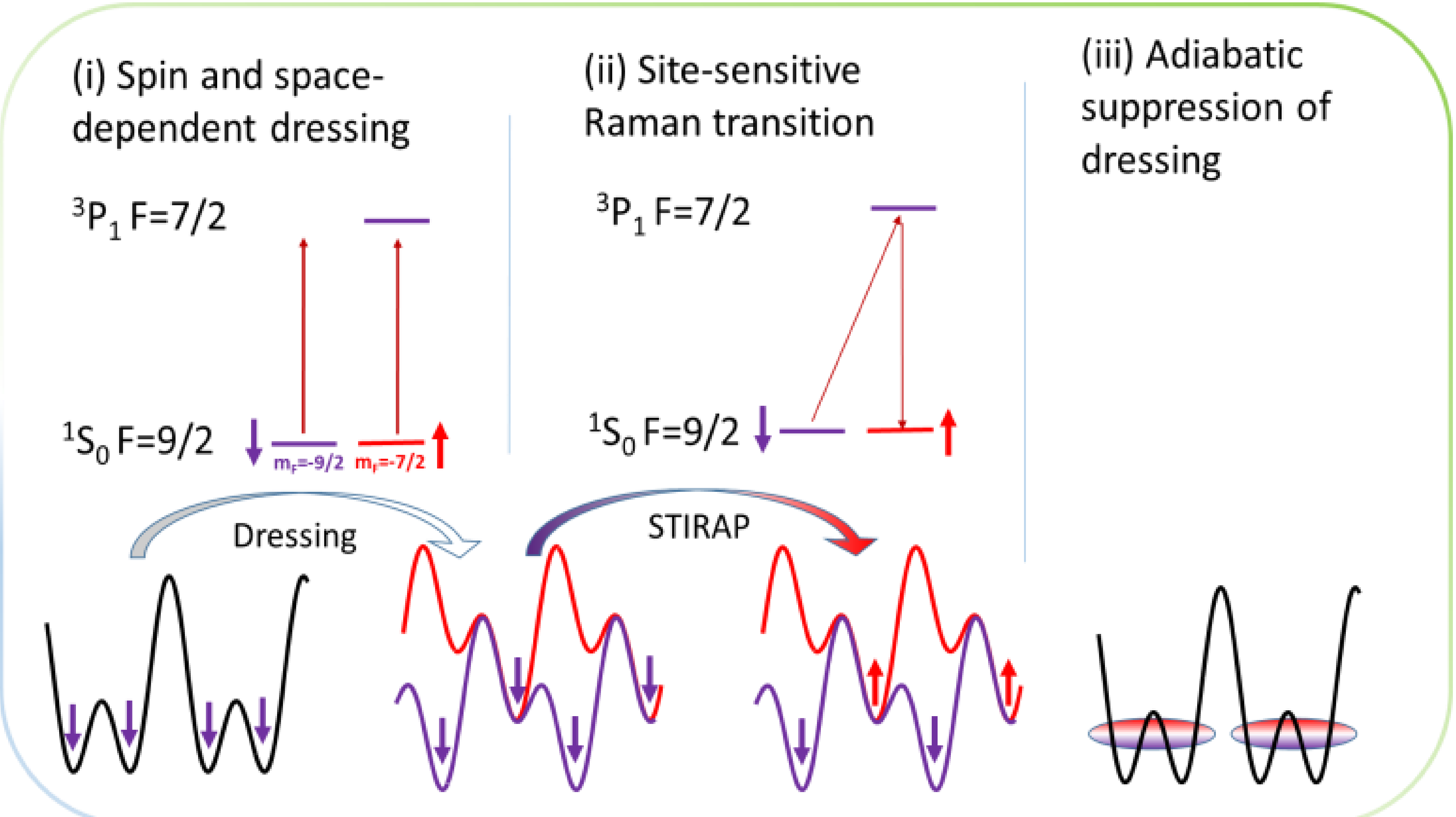
Stern-Gerlach separation:
(magnetic field gradient)





(can be (rather poorly) resolved spatially if separation is fast compared to expansion)
(destructive)

One proposal: use tensor light shift at adiabatically engineer singlet ground state.



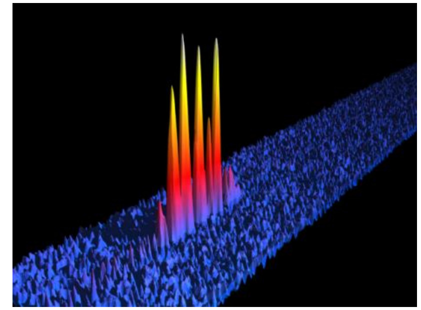
Similar to PRL 107, 165301 (2011)

Effect of interactions on condensates, cold atoms *vs* condensed matter

Attractive interactions

Implosion of BEC for large atom number

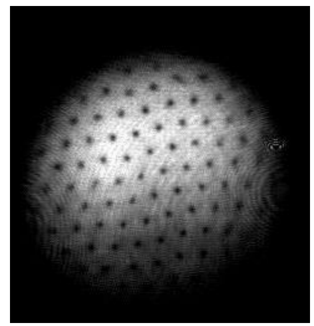
Small solitons



ENS, Rice…

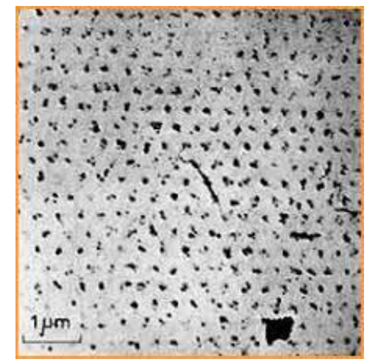
Repulsive interactions

Stable condensate
Phonon spectrum



Superfluidity

ENS, JILA, MIT…



Abrikosov lattice in type II superconductors

Spin dependent interactions

Magnetism

ENS, Berkeley…