Quantum magnetism with cold atoms

1) dissipative cooling of spin chains (theory)
2) birth of the strontium experiment at LPL

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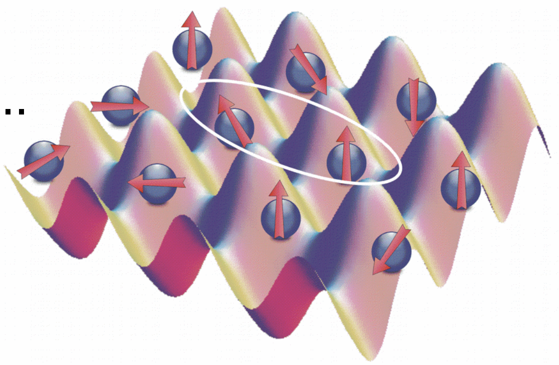
Laboratoire Charles Fabry – 25 February 2019

Magnetism with cold atoms

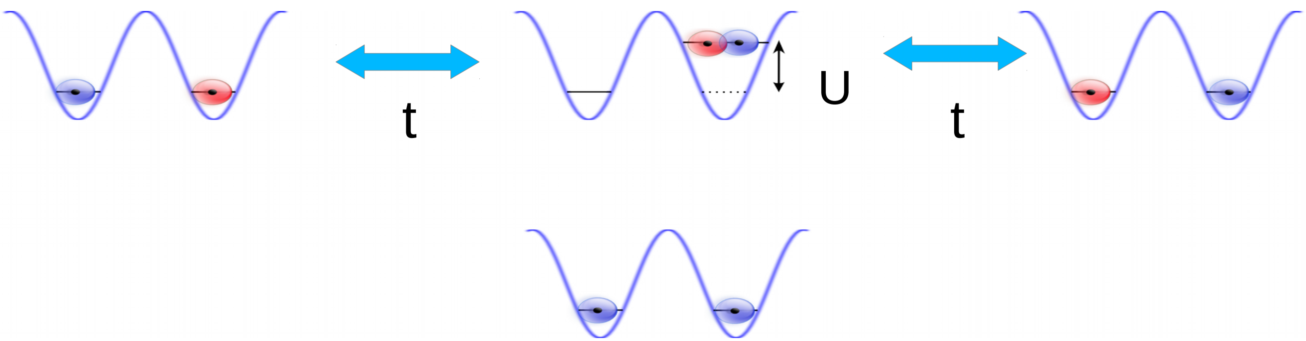
Various magnetic models implemented in cold atoms

Variety of magnetic interactions
using ground state atoms, Rydberg state atoms, molecules, mappings...
(spin-dependence, short- or long-range, anisotropy)

→ Heisenberg, Ising, XXZ, and others...



Much studied : antiferromagnetic Heisenberg model from super-exchange in the Mott regime



$$H = -J \sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j$$

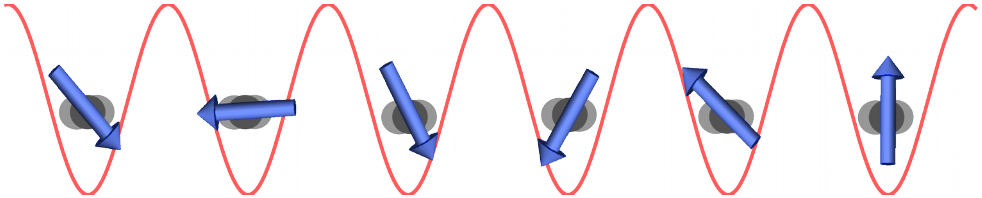
with $J \approx -4t^2/U$

Hulet, Greiner, Bloch, Zwierlein, Kohl, Esslinger, ...

Broad panel of physical questions : frustation (tunable geometries), large spin systems, interplay with transport (t-J model), …

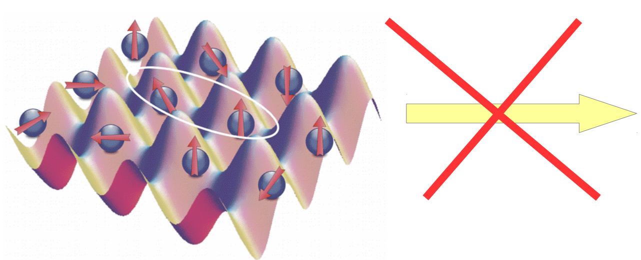
Cold atoms are isolated spin systems

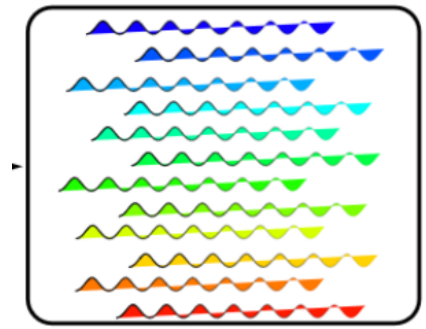
The low entropy challenge (Mc Kay and DeMarco, 2011)



High quality Mott state generation
Very few groups manage spin ordering

Ground state lattice magnetism usually in isolated systems



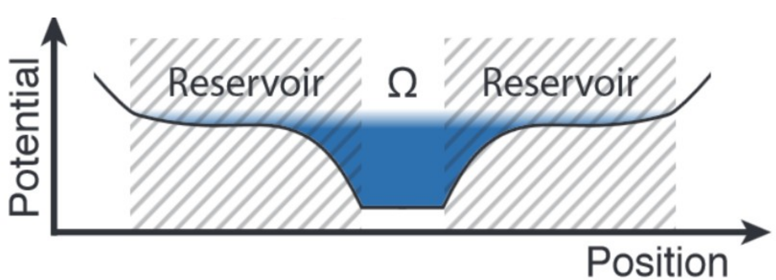


Ground state lattice gas   Cold bath continuum

so far tackled by **inhomogeneous systems**

Ho 2009, Bernier 2009, Mathy 2012,
Hart 2015, Mazurenko 2017, Kantian 2018 ...

A problem tied with spin entropy transport

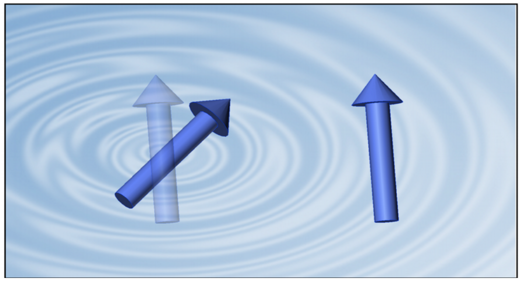


Cold atoms are isolated spin systems

Approach 1 (theoretical work): <u>**Engineer a bath**</u>

Many spin dissipation proposals discuss light as bath: Diehl 2010, Kaczmarczyk 2016, …
Zoller, Weimer, ...

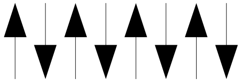
Here
thermalize the spins with the phonons of an atomic bath
(atomic mixtures)



Approach 2 (on a new strontium experiment)

<u>**Dynamics from deterministically prepared "spin patterns"**</u>

Prepare



Evolve

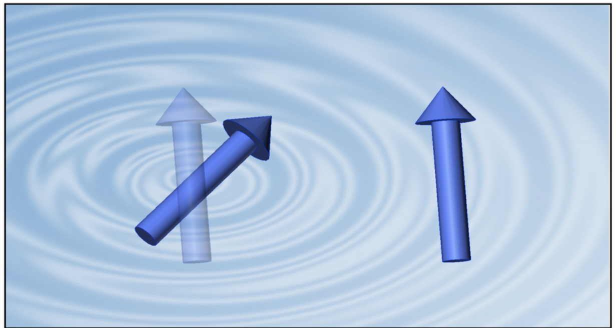
(?)

Heisenberg magnetism from super-exchange in lattices, with 10 spin states.

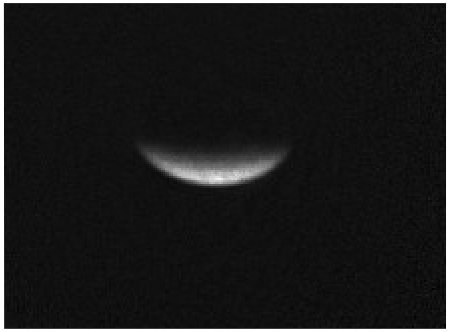
Introduction to the experiment in the second part : general goals
narrow-line cooling

Outline

1) Dissipative cooling of spin chains by a bath of dipolar particles (theoretical proposal)

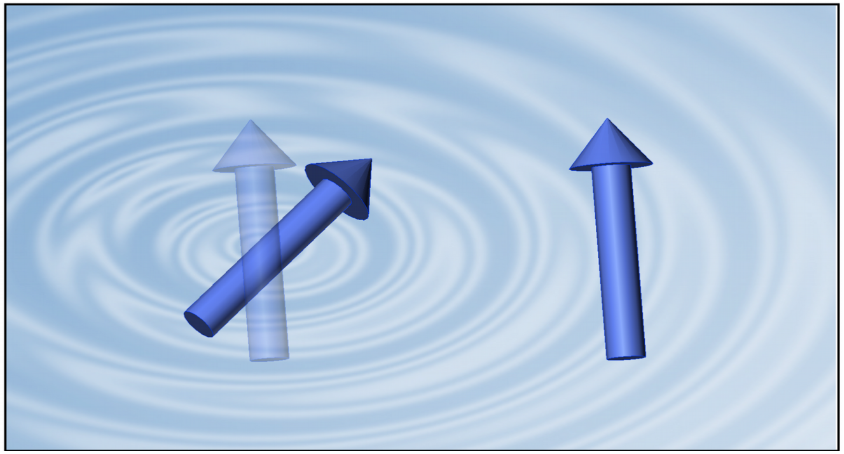


2) Birth of the Strontium experiment



Dissipative cooling

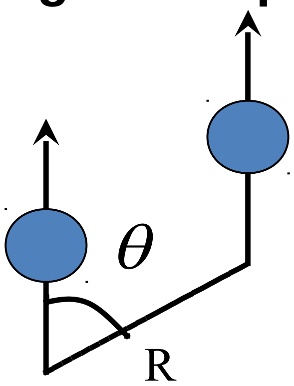
thermalize the spins with the phonons of an atomic bath
(atomic mixtures)



The tool: dipolar interactions

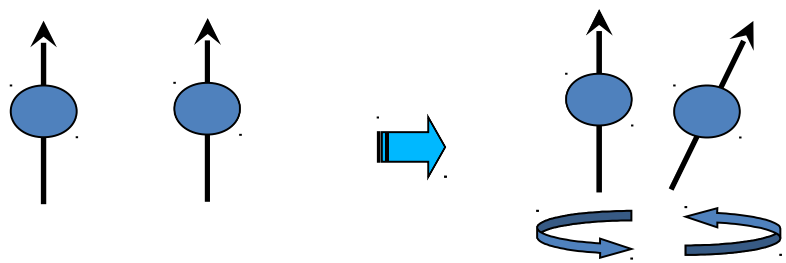
The bath must be able to flip spins

Magnetic dipolar interactions – anisotropic – non spin conserving



$$V_{dd} = \frac{\mu_0}{4\pi}(g_J \mu_B)^2 \frac{S_1.S_2 - 3(S_1.u_R)(S_2.u_R)}{R^3}$$

Dipolar quantum gases:
Pfau, Laburthe-Tolra,
Lev, Ferlaino, Grimm,
Modugno...



Spin-orbit coupling

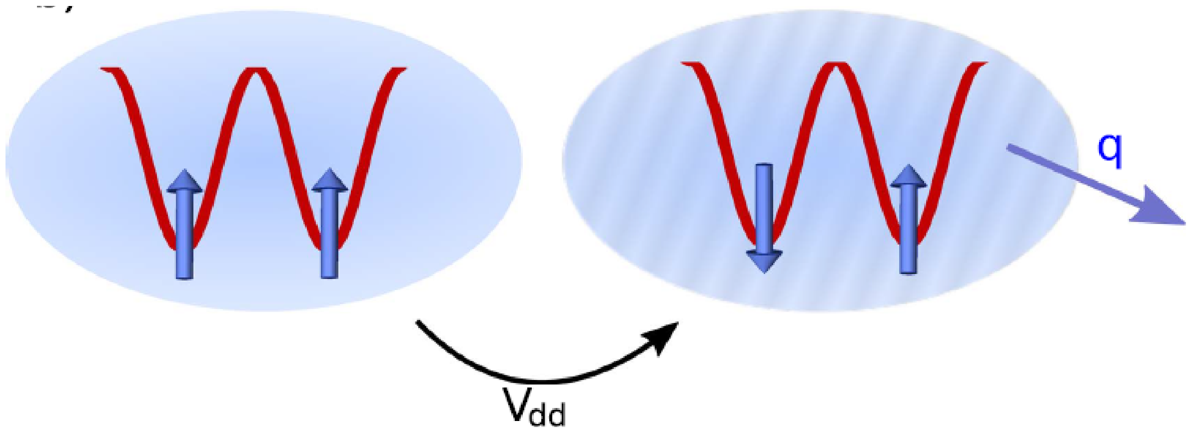
Ising *Exchange*

$$S_{1z}S_{2z} + \frac{1}{2}\left(S_{1+}S_{2-} + S_{1-}S_{2+}\right)$$
$$-\frac{3}{4}\left(2zS_{1z} + r_- S_{1+} + r_+ S_{1-}\right).$$
$$\left(2zS_{2z} + r_- S_{2+} + r_+ S_{2-}\right)$$

Spin-orbit coupling;
includes non-spin conserving terms

The spin degree of freedom can directly thermalize with the motion degree of freedom

Outline



Dipolar interactions between a spinfull Mott insulator and a dipolar BEC
offer true thermalization of the spin degree of freedom of the Mott insulator

- ***spin degree of freedom* fully free:** magnetization, collective spin length
- dissipative preparation / protection of highly correlated states

Timescales : compatible with alkali spin chains

I) Overview of the physics

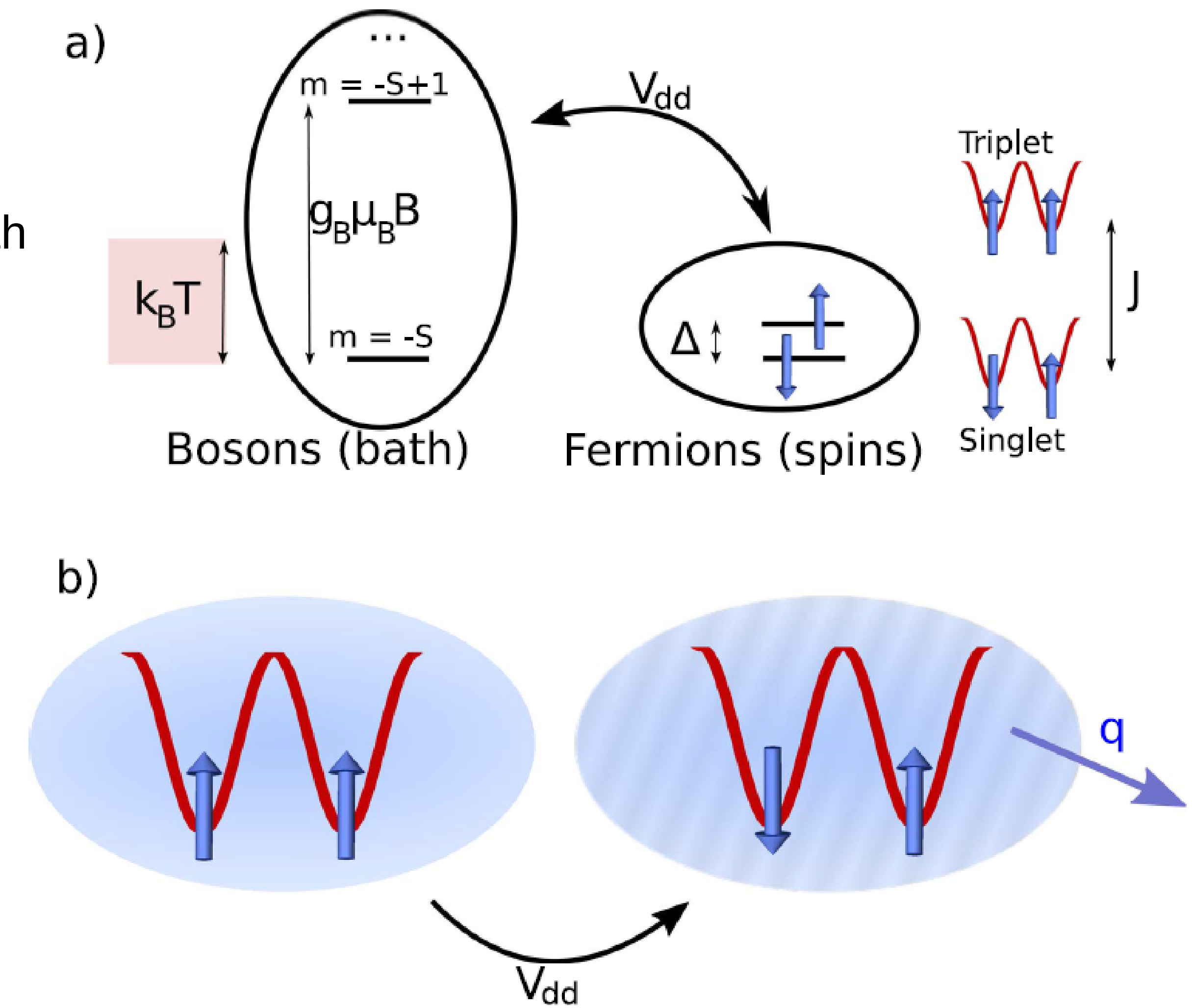
System overview
A Fermi Golden rule treatment
Anisotropic coupling to the bath

II) Realistic system – numerical calculation

Lattice potential effect on the bath
Convergence to a thermal state
Collective spin dynamics

System overview and simplifying assumptions

Polarised bath for simplicity (B > 1mG)



AF Heisenberg model;

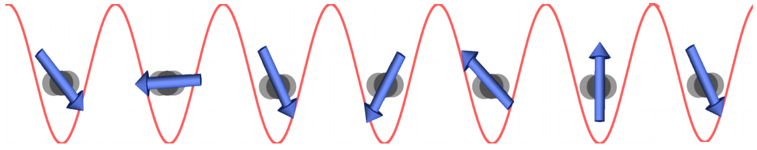
Restricted to two Zeeman states for simplicity

Degenerate

(see NJP appendix, and Gerbier 2006, PRA **73**, 041602)

Bath: Bogoliubov description in the latttice; finite temperature.

Spin chains : finite size 1D chain (up to 7), exactly diagonalized, neglecting any hole/doublon

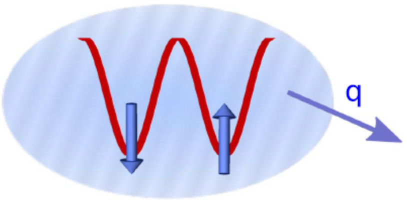


A Fermi Golden rule treatment

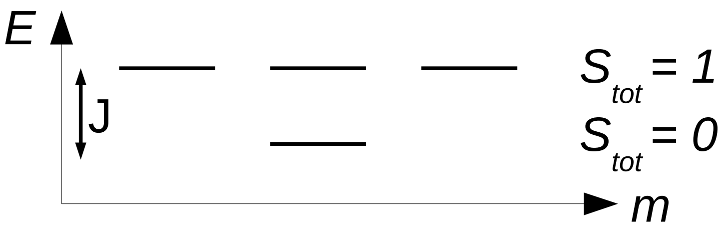
Dissipative evolution evaluated from the Fermi golden rule between collective spin chain eigenstates

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar} \sum_{|f_{\rm bath}\rangle} |\langle f_{\rm spin}; f_{\rm bath}|\, H_{\rm int} | i_{\rm spin}; i_{\rm bath}\rangle|^2 \,\delta(E_{if} + E_{if}^{\rm bath})$$

$$\frac{\mathrm{d}p_i}{\mathrm{d}t} = \sum_f (-\Gamma_{i\to f}\, p_i + \Gamma_{f\to i}\, p_f)$$



Example : 2-atom spin chain, four collective states



Our work: compute explicitly all these matrix elements, in realistic settings

Detailed calculation in NJP 20, 073037 (2018)

Species: alkali + dipolar. Here, **^{40}K as spin chain, ^{164}Dy as highly dipolar species (10 μ_B)***

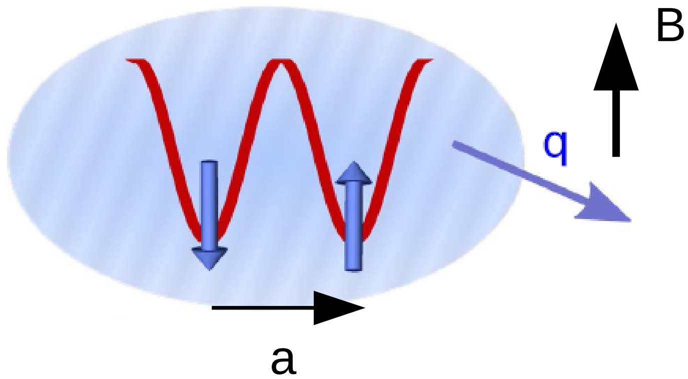
** Ravensburger et. al., Phys. Rev. Lett.* ***120****, 223001 (2018)*

Anisotropic coupling to the bath

Radiation diagrams from two spins (double well)

(here without lattice potential for the bath)

Severe anisotropy and collective spin dependence



Example : rate from $S_{tot} = 1, m = 0$ to $S_{tot} = 0, m = 0$

$$|f_{\text{bath}}(\vec{q})\rangle = b^{\dagger}(\vec{q})|\text{BEC}\rangle \quad \text{with} \quad \epsilon(\vec{q}) = J$$

Radiation diagram calculation, as e.g.
done for spontaneous emission of light,
with cooperative effects at play

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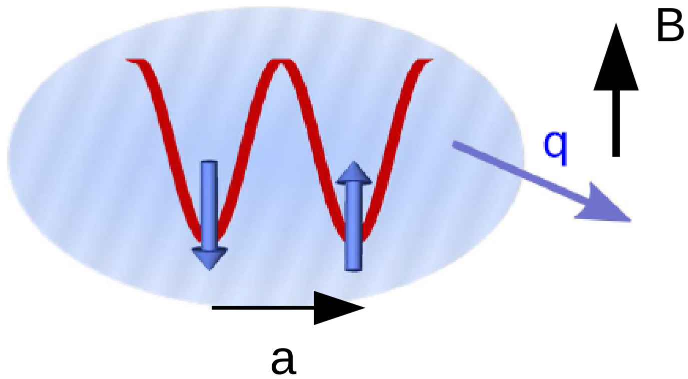

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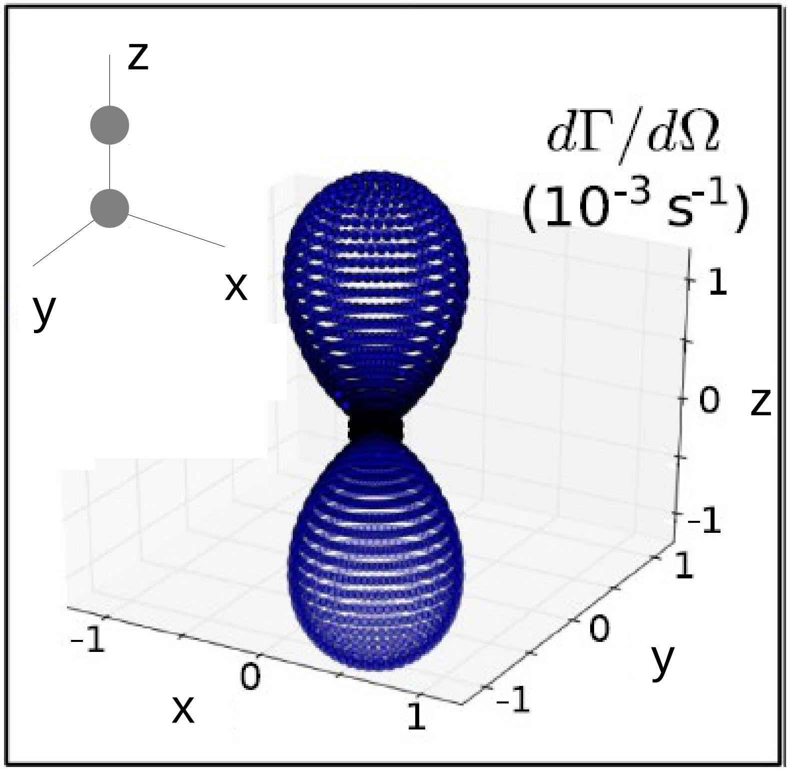
Radiation diagram calculation, as e.g. done for spontaneous emission of light, **with cooperative effects at play**

Radiation diagram for Δm = 0



$\vec{q}\cdot\vec{a} = 0$: global energy shift, no effect

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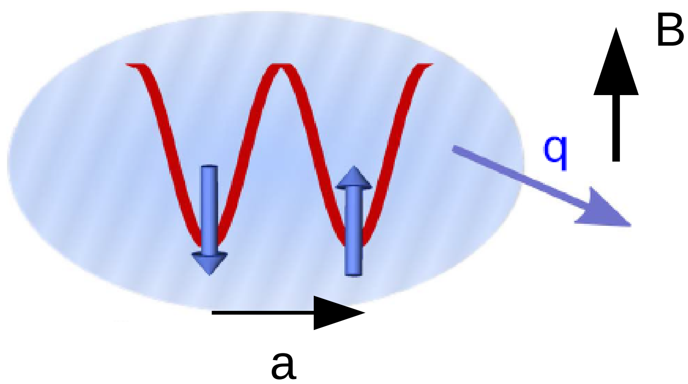

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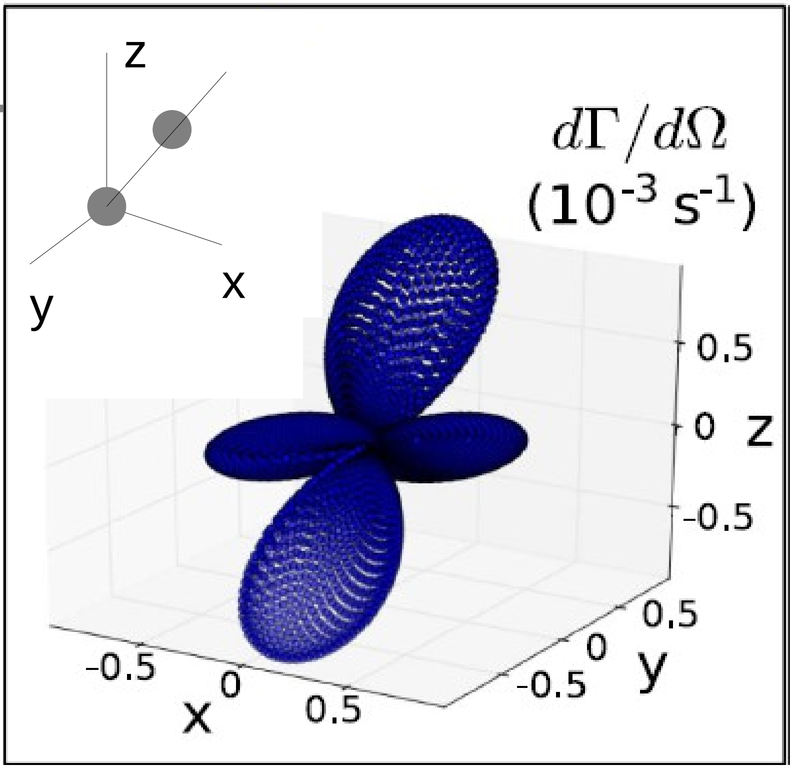

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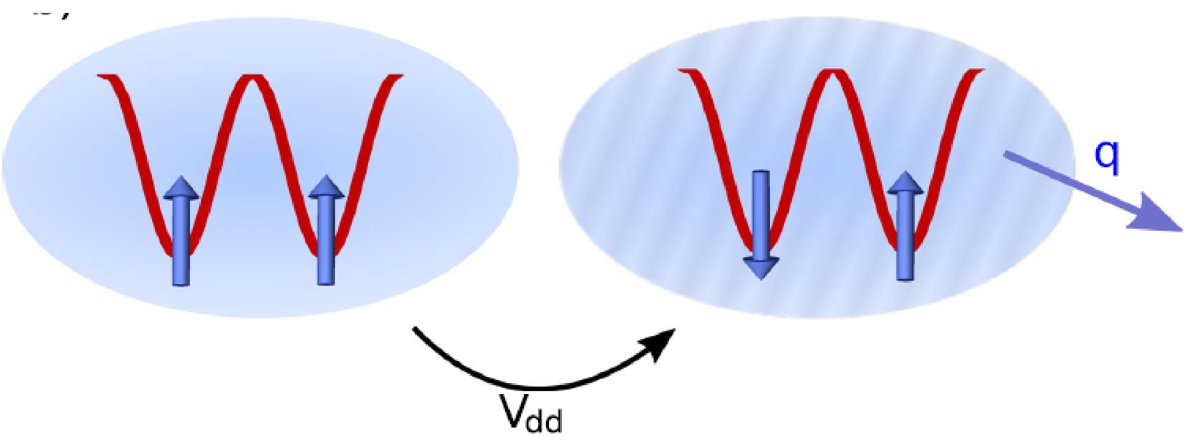
Outline



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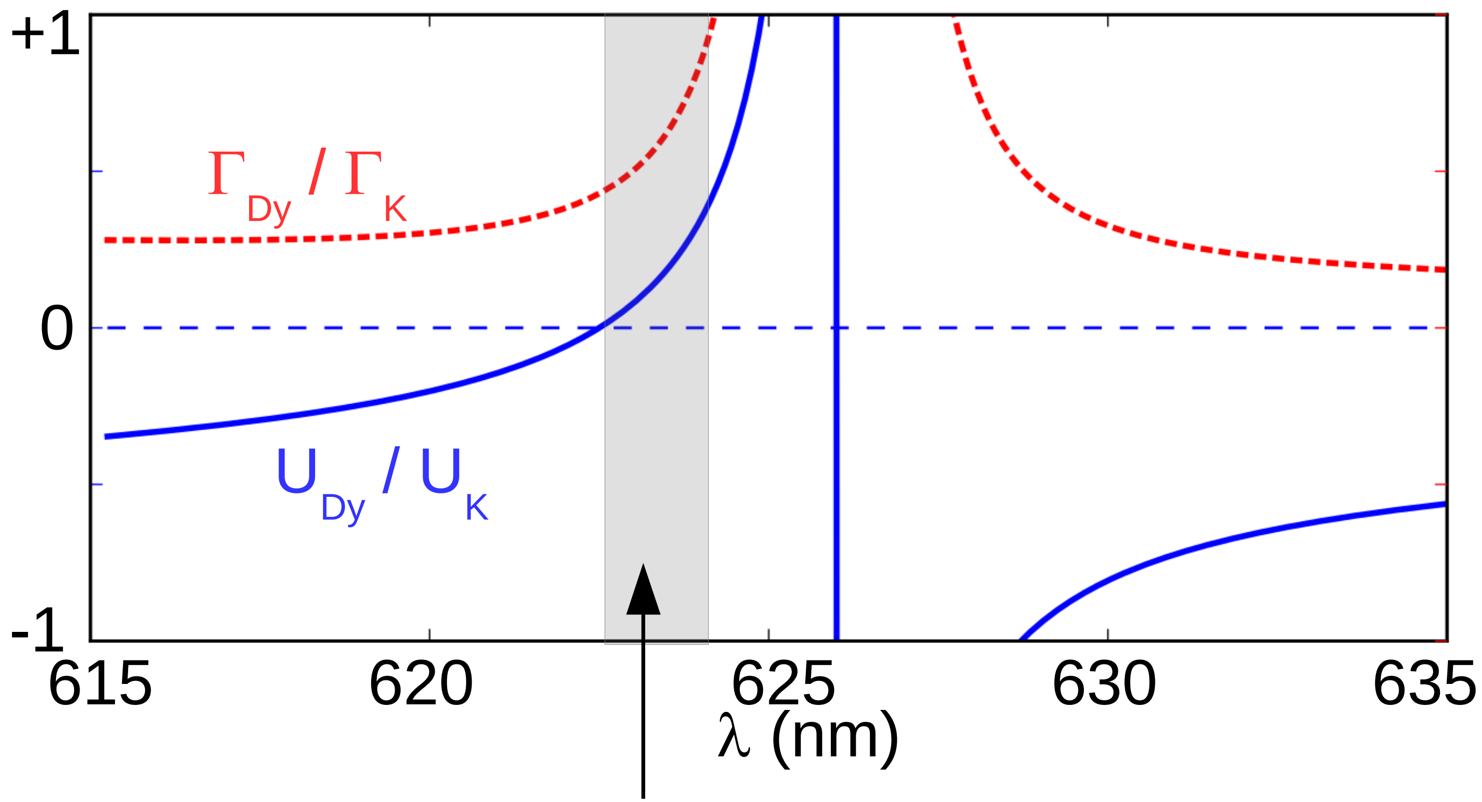
Lattice potential: strong effect on the bath

^{40}K - ^{164}Dy

Given a lattice depth for the spin chain,
In the vicinity of 624 nm (Dy) **the lattice depth for the bath can be independently tuned**



- Mott regime for spin chain
- **3D coherence for bosonic bath**
- Light scattering sufficiently low

Anisotropy effects
- **Dipolar bath stabilized from dynamical instabilities**
- **Enhanced interactions**

Same opportunity for Erbium in the vicinity of 580 nm

Convergence to a thermal state of the collective spin

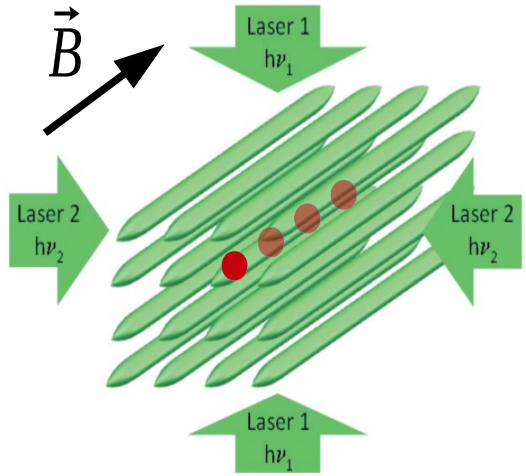
^{40}K - ^{164}Dy

Spin

^{40}K, F = 9/2, restricted to m =-9/2 and -7/2, made degenerate [1]

U_K = (25x25x3.5) E_r^K – **effective decoupled 1D chains**

Weak axis : U_{int}/t = 7.5, J = h x 630 Hz = k_B x 30 nK



Bath

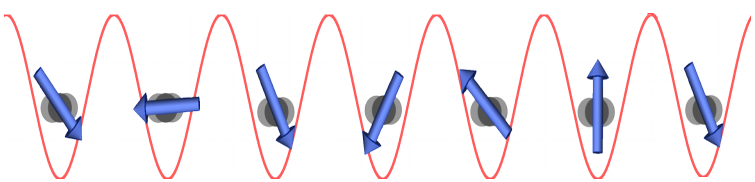
U_{Dy} = (12x12x3.5) E_r^{Dy}

$\langle n_{bec} \rangle = 3.10^{13}$ / cm^3

T_{BEC} = 0,3 J / k_B = 9 nK [Trotzky 2010, Nat. Phys. **6**,998]

3D coherent BEC - Quantum depletion : 5 % [Xu 2006, PRL **96**, 180405]

Chain Length : 7



[1]appendix ; and Gerbier 2006

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^{40}K - ^{164}Dy

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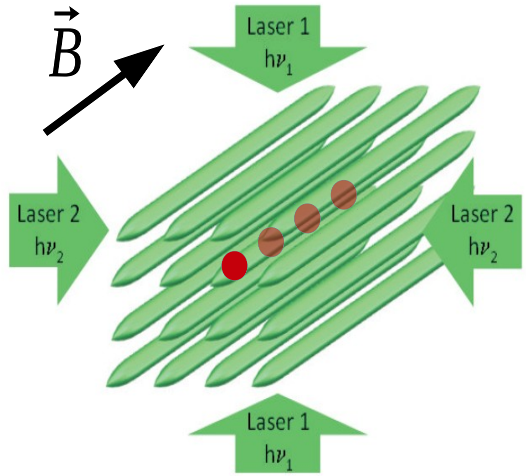

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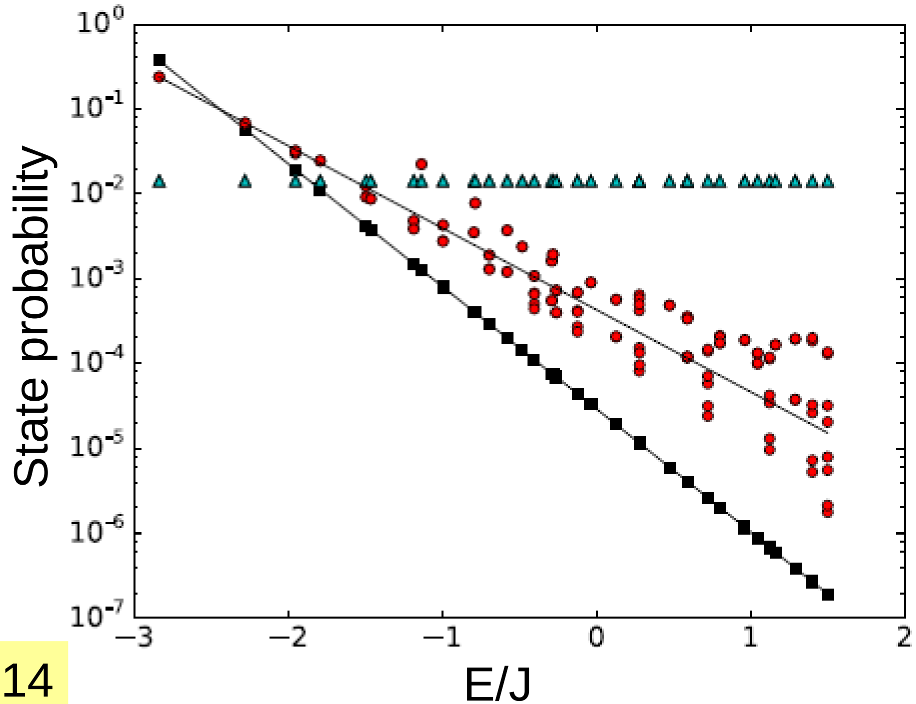
Occupation of the 2^7 = 128 spin chain eigenstates

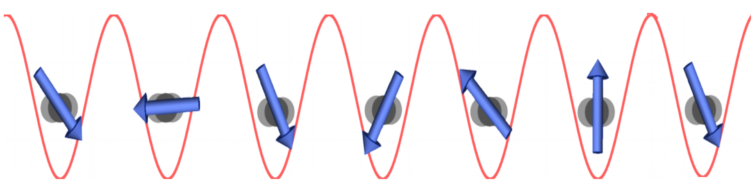


Initial[2]

2 s; k_B T = 0.45 J
highly correlated state

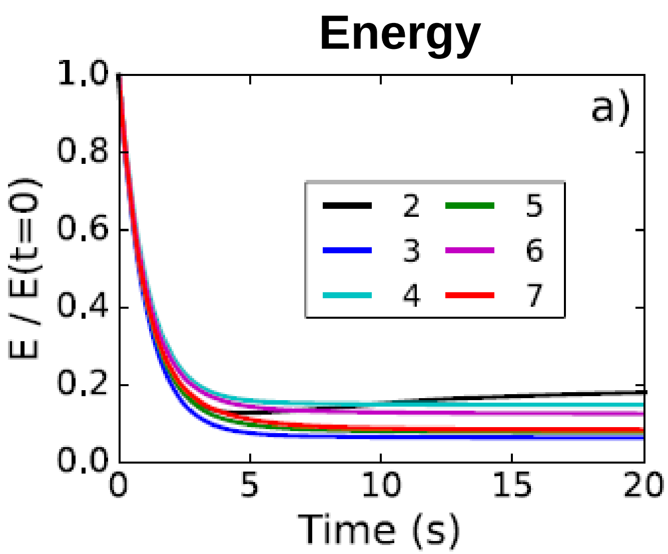
"Infinite time"; k_B T = 0.3 J

Chain Length : 7

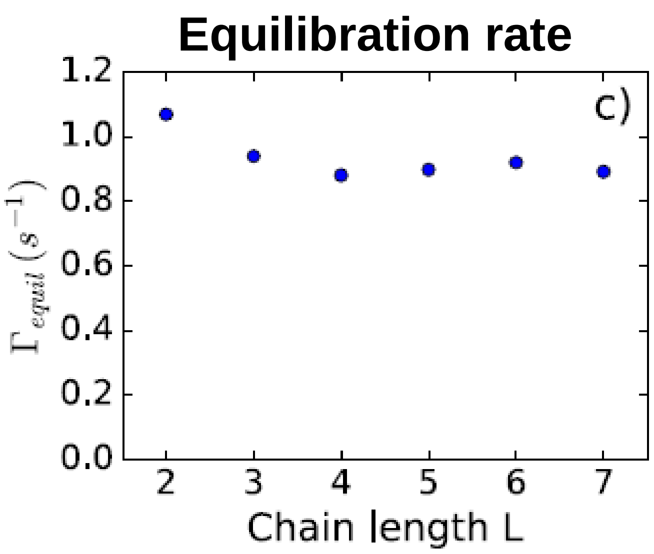


[1]appendix ; and Gerbier 2006
[2]Here: initial magnetization 0

Collective spin dynamics



(Initially balanced spin mixture)



Equilibration rate tends to a value roughly independent on chain length and on preparation condition

Timescale of order ~ 1 s – experimentally relevant, though not fast

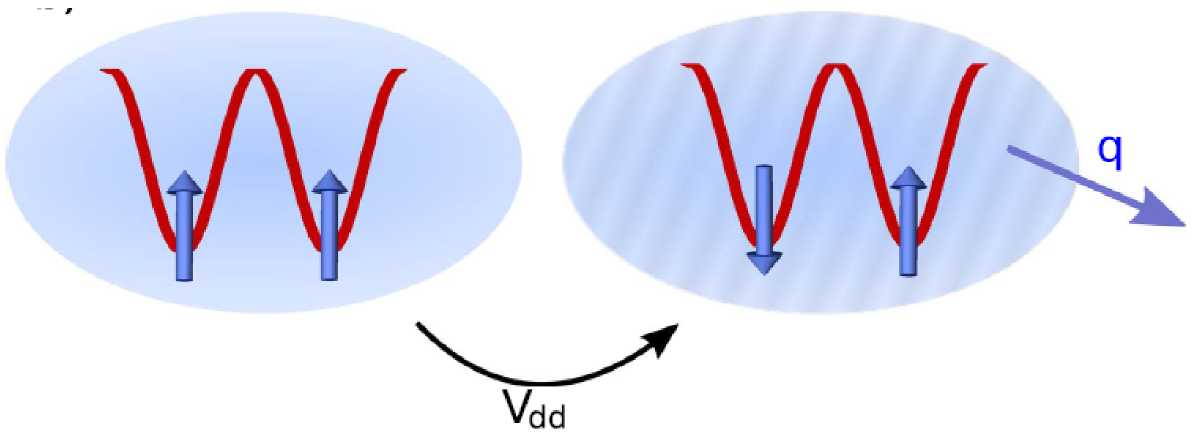
Limited by restraining ourselves to very low quantum depletion (5%)
Faster dynamics plausible in deeper bath lattices,
but this leaves the validity range of the Bogoliubov description

Dysprosium vs Erbium : about similar ($7\mu_B$, but also 583 nm lattice)

Alkali: ^{40}K has low Lande factor, but scientific interest of fermions for the t-J model

Conclusion and outlook

Dissipative preparation of strongly correlated spin states



Use of an atomic bath

Spin chain thermalization
with **free magnetization**
and **free spin length**

The scheme relies on spin-orbit coupling in dipolar interactions

→ **perspective**: cooling with a non-dipolar atomic bath using artificial SOC?

Spielman, Zwierlein, Zhang, Pan ...

Fermionic baths could be favourable

Large density of states at low energy (excitations at the Fermi momentum)

A formalism describing dipole-coupled Mott spin chain and superfluid BEC in lattice

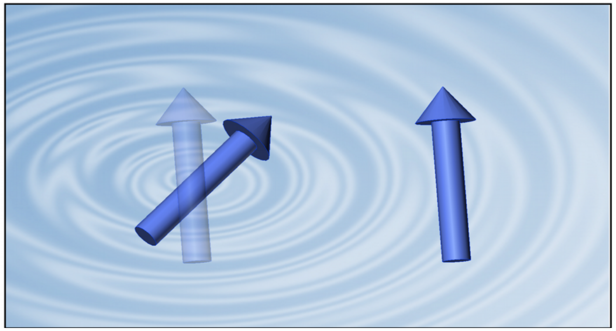
→ useful beyond Heisenberg chains (e.g., mixtures of dipolar isotopes in lattices)

Ferlaino, Lev, Pfau, Laburthe-Tolra, ...

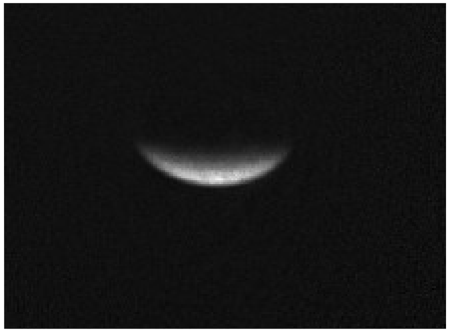
→ other spinor species of interest (bosonic alkalis with higher Lande factor than ^{40}K)

Outline

1) Dissipative cooling of spin chains by a bath of dipolar particles (theoretical proposal)



2) Birth of the Strontium experiment



THE STRONTIUM PROJECT

Which strontium?

Bosons:
84: least abundant (0,6%)
Best collision properties → first degenerate
86
88: most abundant (83%), but unfavourable collisions

All of them:

No spin in the ground state : L=0, S=0

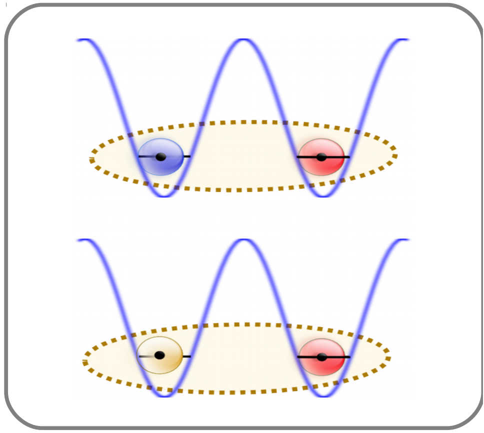
Fermions:
87: abundance 7%
Favourable collisions

Nuclear spin I = 9/2
10 spin states

Contact interactions independent of the spin state:

⇒

- no spin exchange : $N(m_F)$ = constant
- only the Pauli principle matters for the magnetic interaction

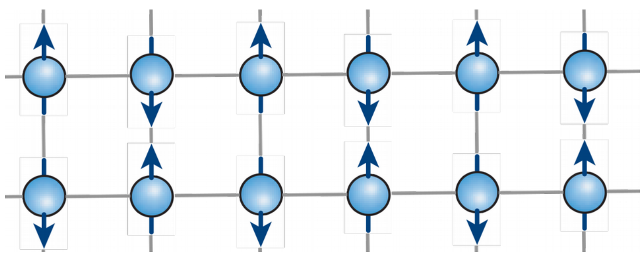


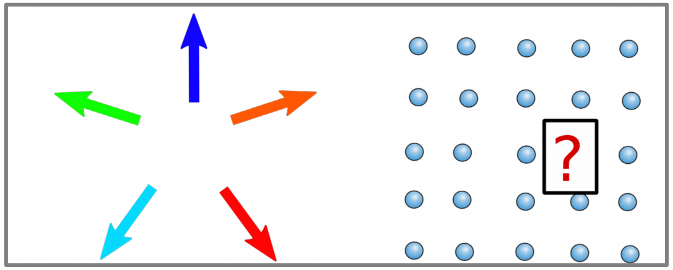
THE STRONTIUM PROJECT

Ultracold fermionic Strontium 87 in optical lattices:
Quantum magnetism beyond spin 1/2 (electron) particles

Exploring magnetism with tunable spin degree of freedom

2 spin states: analogy to spin 1/2 electrons
3 spin states: analogy to quarks with three colours
Up to 10 spin states: ***no equivalent***



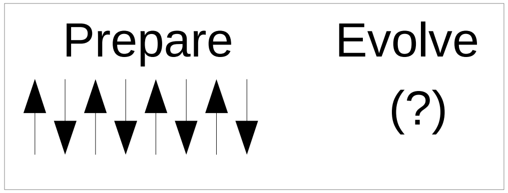


Large spin + spin-independent interactions → underconstrained magnetism (frustration)

Hermele 2009, PRL **103**, 135301

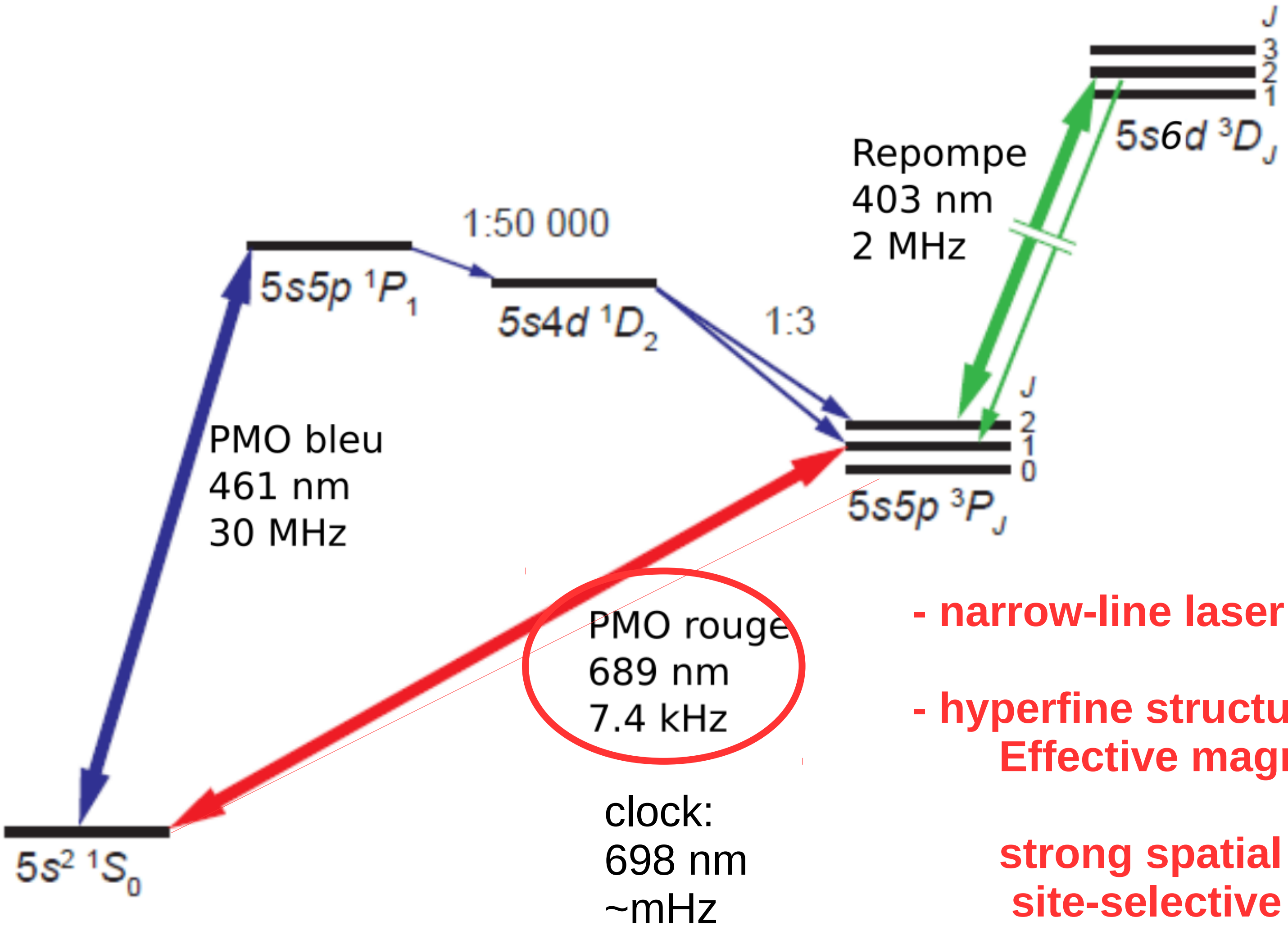
Narrow atomic transitions: metrology tools (atomic clocks)

Cooling
New probes
New preparation protocols
specifically suited for isolated systems



The narrow lines

2 valence electrons
→ singlet and triplet electronic spin states



- narrow-line laser cooling (~µK)

- hyperfine structure:
Effective magnetic fields

strong spatial variations :
site-selective spin control

Collaboration with **Marc, Florence, Anaïs, Clémence, Romaric**
Spectroscopy – a 1 kHz/Sqrt(Hz) reference

The narrow lines

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Temperature

Doppler limit : $k_B T \sim \frac{\hbar \Gamma}{2} \sim k_B \times 350\, nK$

Recoil limit: $k_B T \sim \frac{h^2}{2 m \lambda^2} \sim k_B \times 460\, nK$

Density / Phase space density

Reduced radiation trapping

$$n_0 = \frac{\kappa}{\Gamma s_0 \sigma \hbar k_L} = \frac{4}{3\pi} \frac{|\delta|}{\Gamma} \frac{\gamma_J b'}{\Gamma} k_L^2 .$$

Katori et al (1999) :
free space MOT, 10^{12} / cm^3
10^{-2} phase space density

In principle ideal for loading a 3D optical trap
Ido et al (2000), Stellmer et al (2013) :

Laser cooling in dipole traps to PSD's of up to 1

The narrow lines

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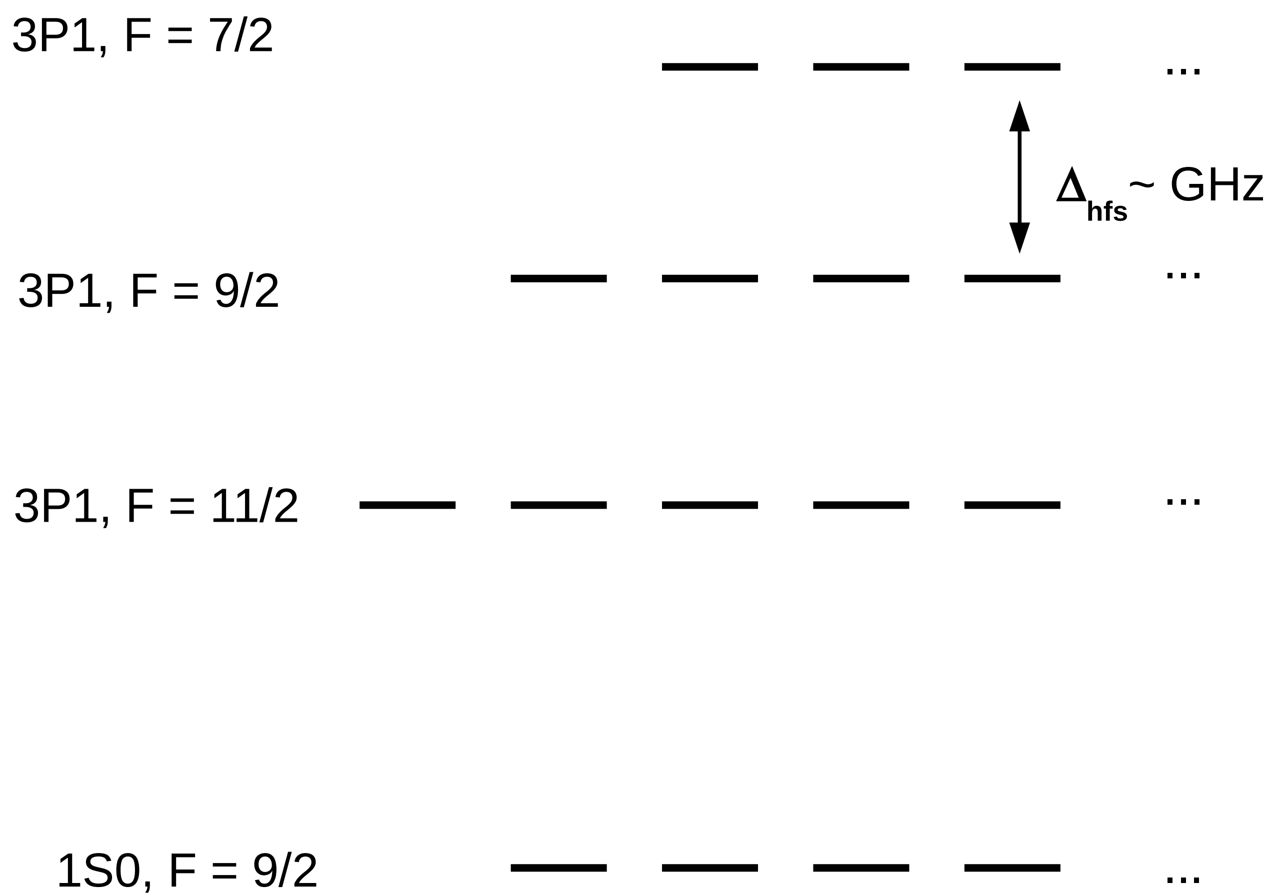
Hyperfine structure Δ_{hfs} ~ GHz >> Γ = 7 kHz



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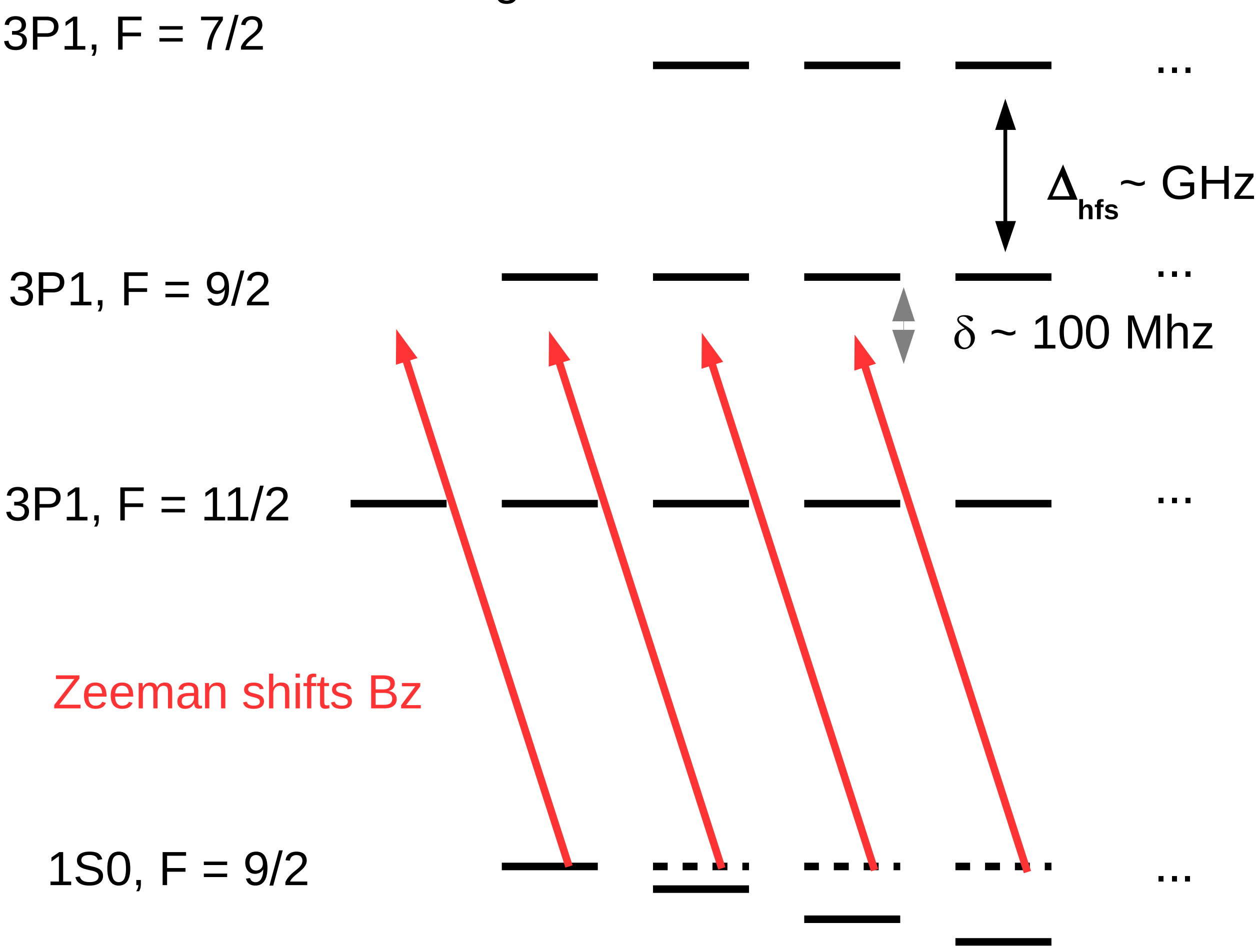
Within the structure:

$$\frac{\text{spontaneous emission}}{\text{light shifts}} \sim \Gamma/\delta \sim 10^{-4} << 1$$



The narrow lines

- **narrow-line laser cooling (~µK)**

- **hyperfine structure:**
  Effective magnetic fields

strong spatial variations :
site-selective spin control

Hyperfine structure Δ_{hfs} ~ GHz >> Γ = 7 kHz

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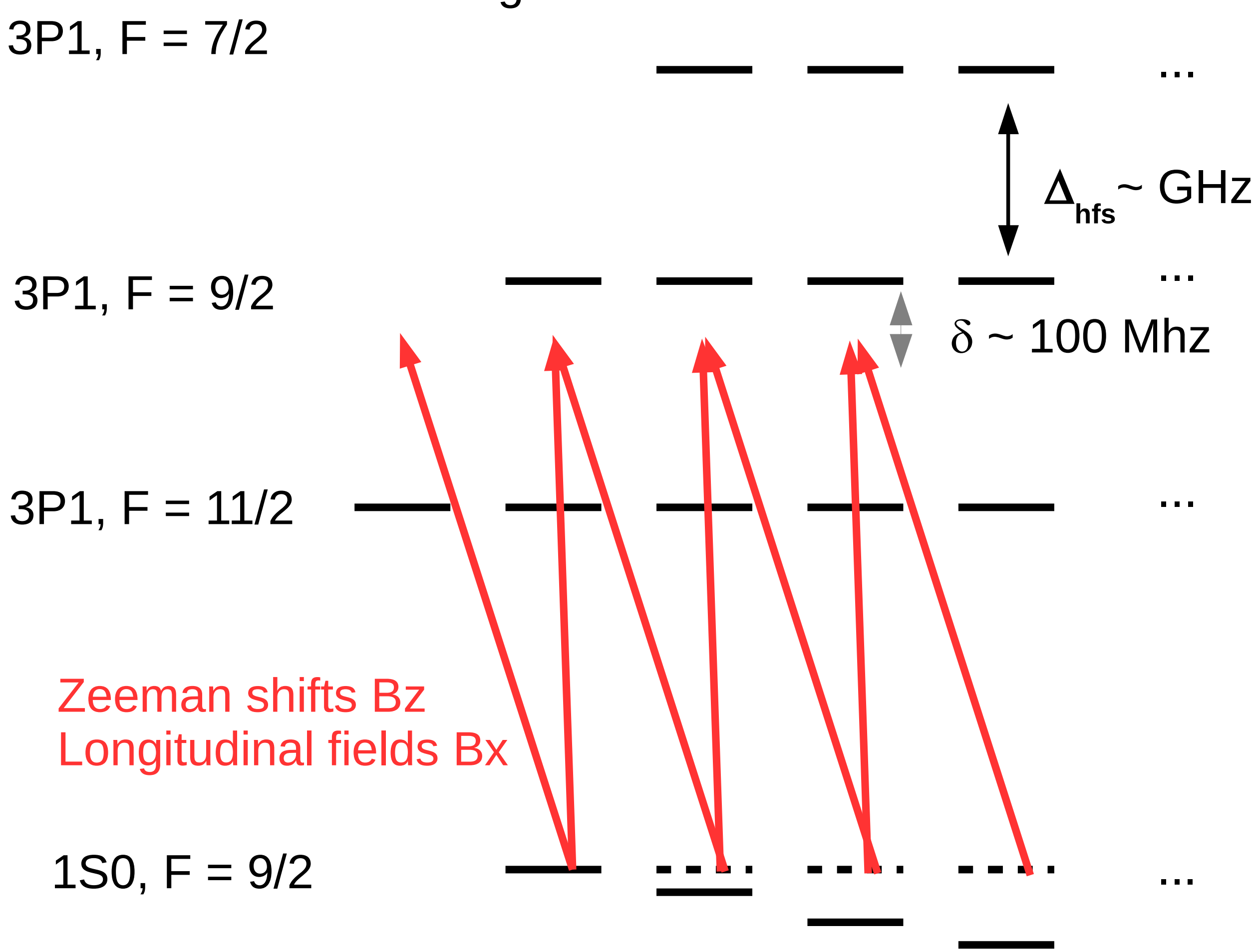
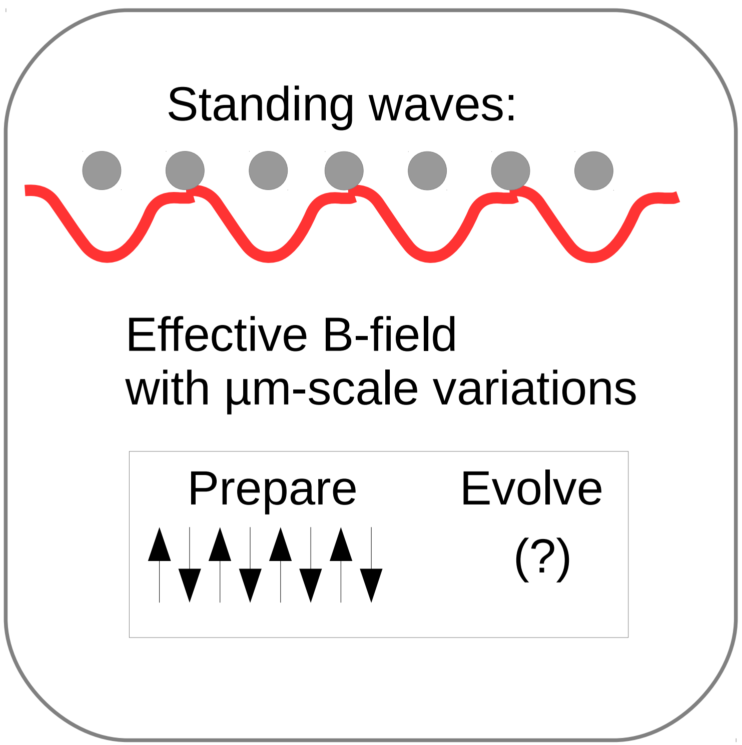


The narrow lines

- narrow-line laser cooling (~µK)

- hyperfine structure:
  Effective magnetic fields

strong spatial variations : site-selective spin control



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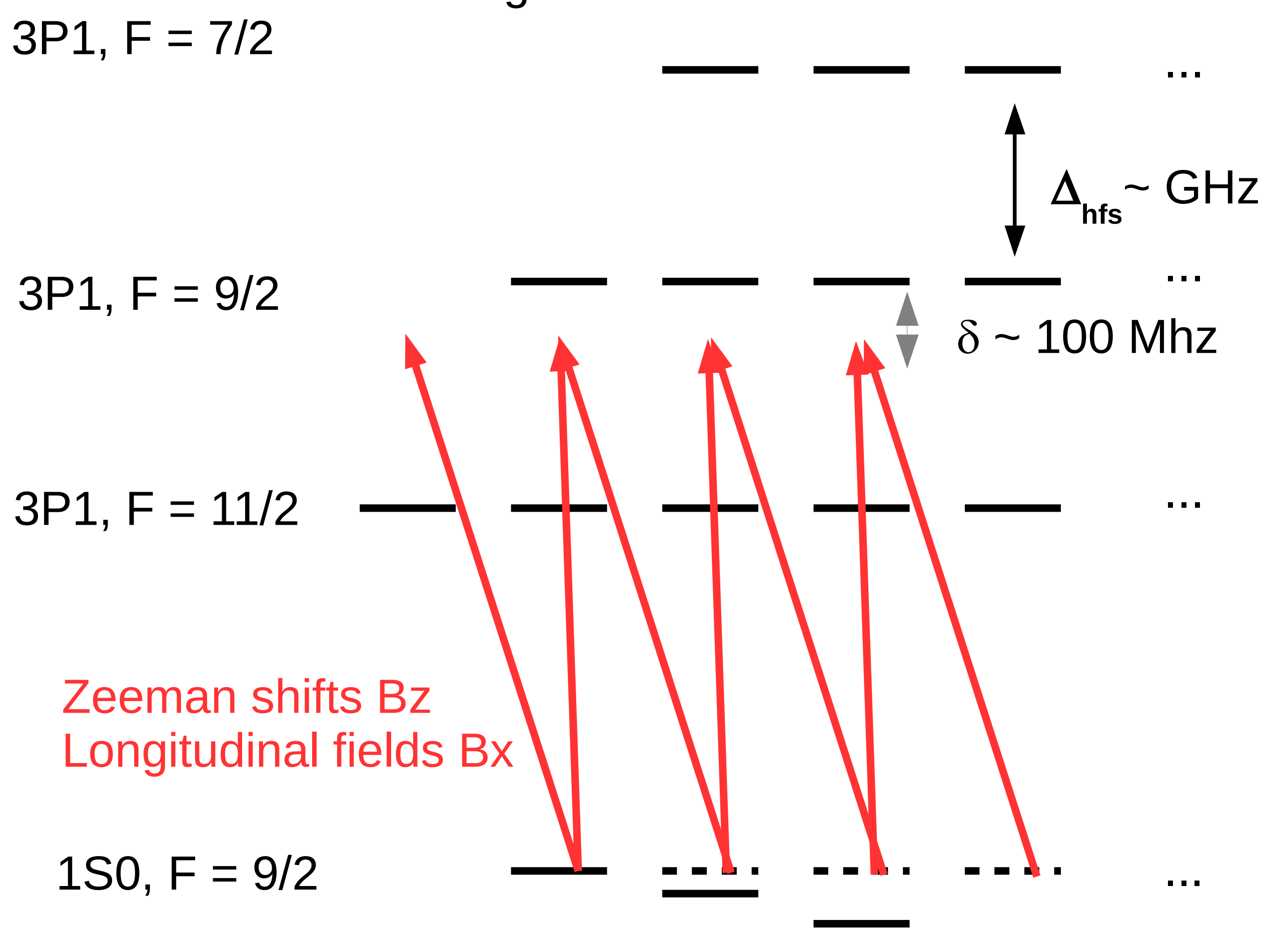
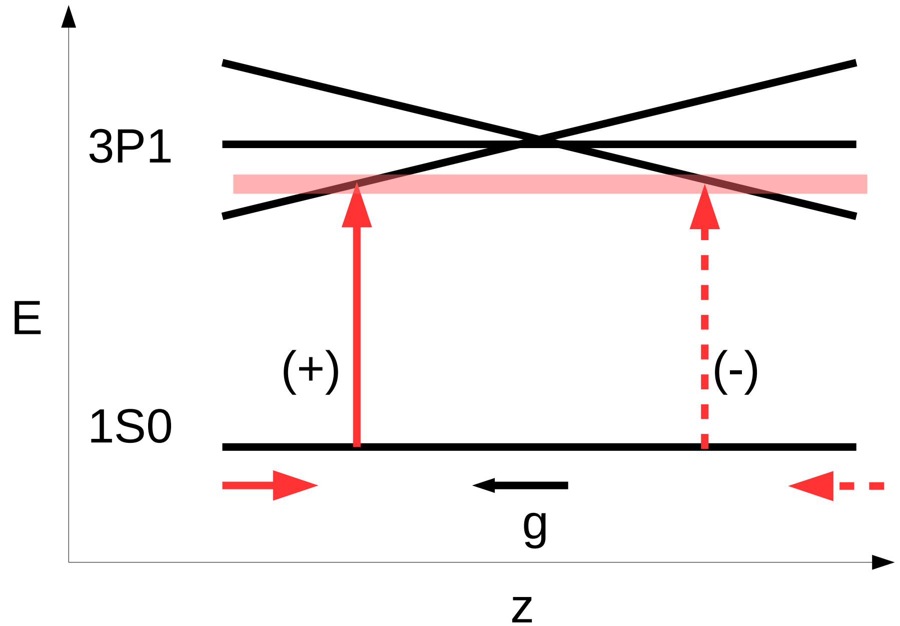


Narrow-line cooling of 88 Sr

Illustrations of specificities in narrow-line MOTs

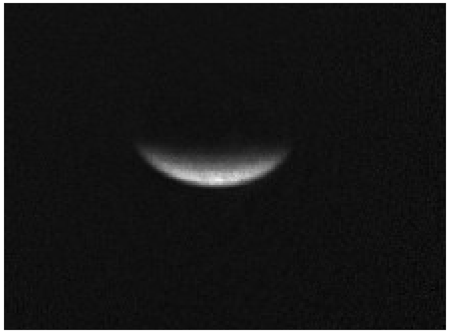
Narrow-line cooling of 88 Sr

Illustrations of specificities in narrow-line MOTs



Laser cooling
on a resonant shell

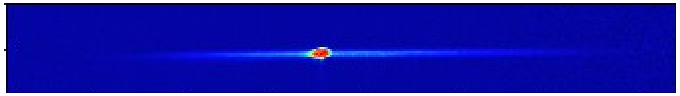
→ capture stage
requires
artificial line
broadening



Tool: strong MOT compression by a frequency ramp

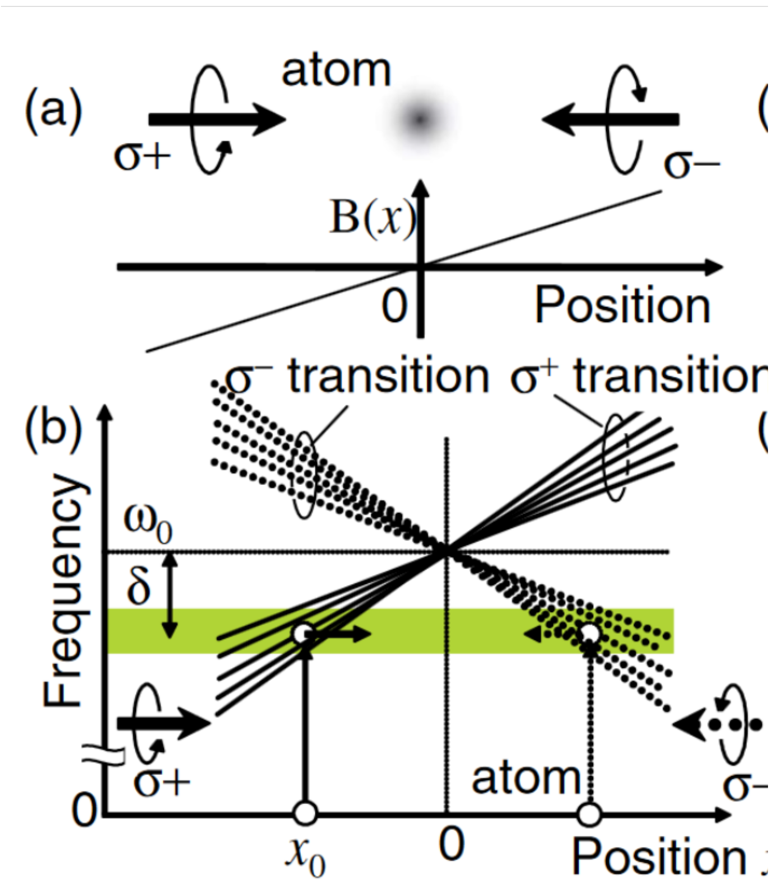
$F = 99\,\mathrm{MHz}$ $F = 99.2\,\mathrm{MHz}$ $F = 99.4\,\mathrm{MHz}$

July 2018: 88 Sr in a dipole trap

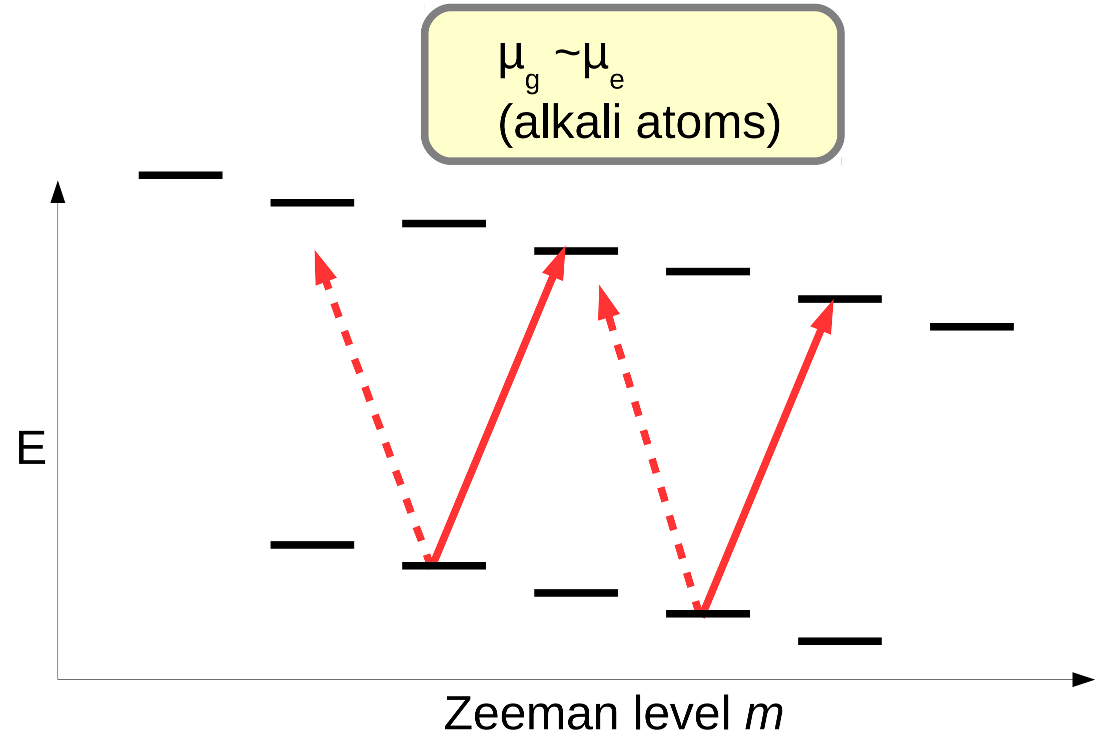


Narrow-line cooling of 87 Sr

Mukayami et al, PRL 90, 113002 (2003): complications from the hyperfine structure



Restoring force from the
polarisation-dependent detuning

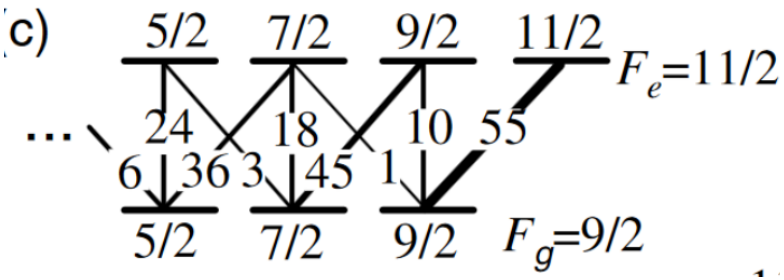


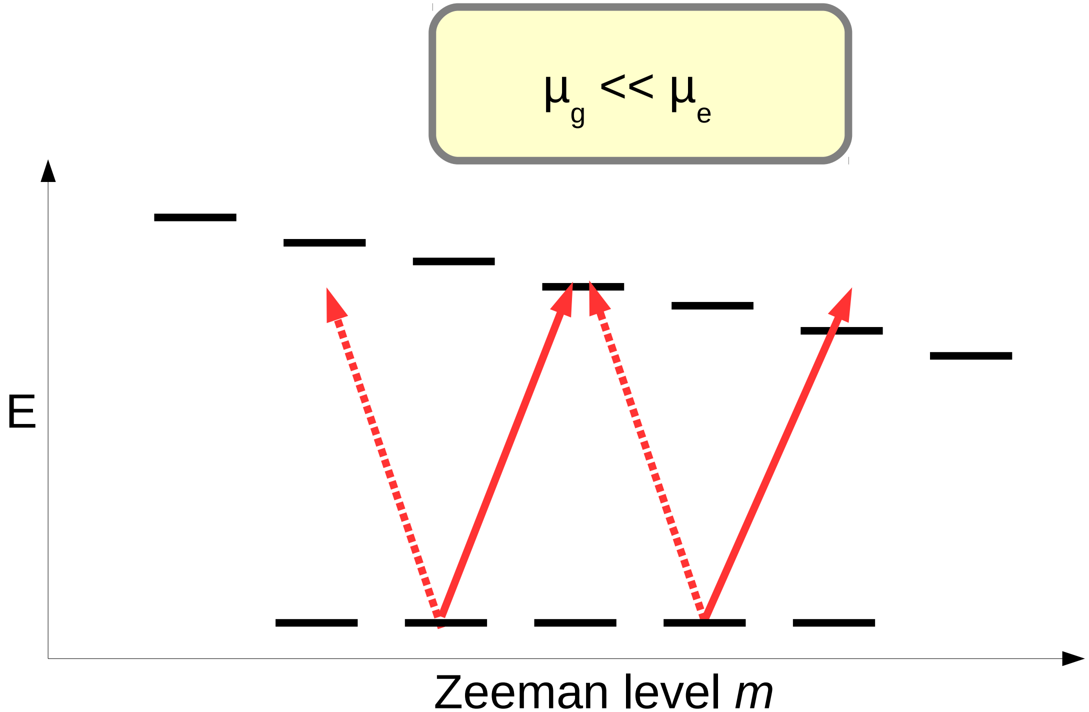
Condition for a F → F+1 transition :

$$F/(F+1) < \mu_e/\mu_g < F/(F-1)$$

Narrow-line cooling of 87 Sr

Mukayami et al, PRL 90, 113002 (2003): complications from the hyperfine structure





Relying on polarisation-dependent detunings,
a restoring force for *m* could be ejecting for another

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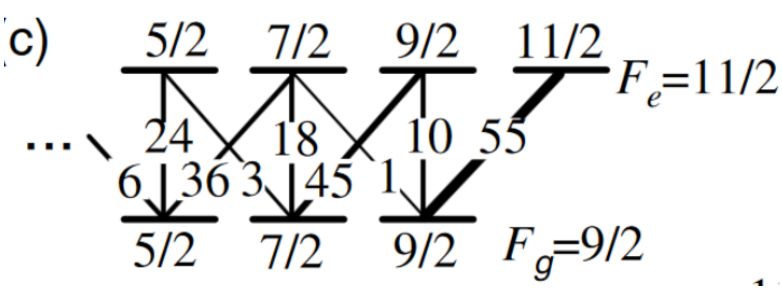
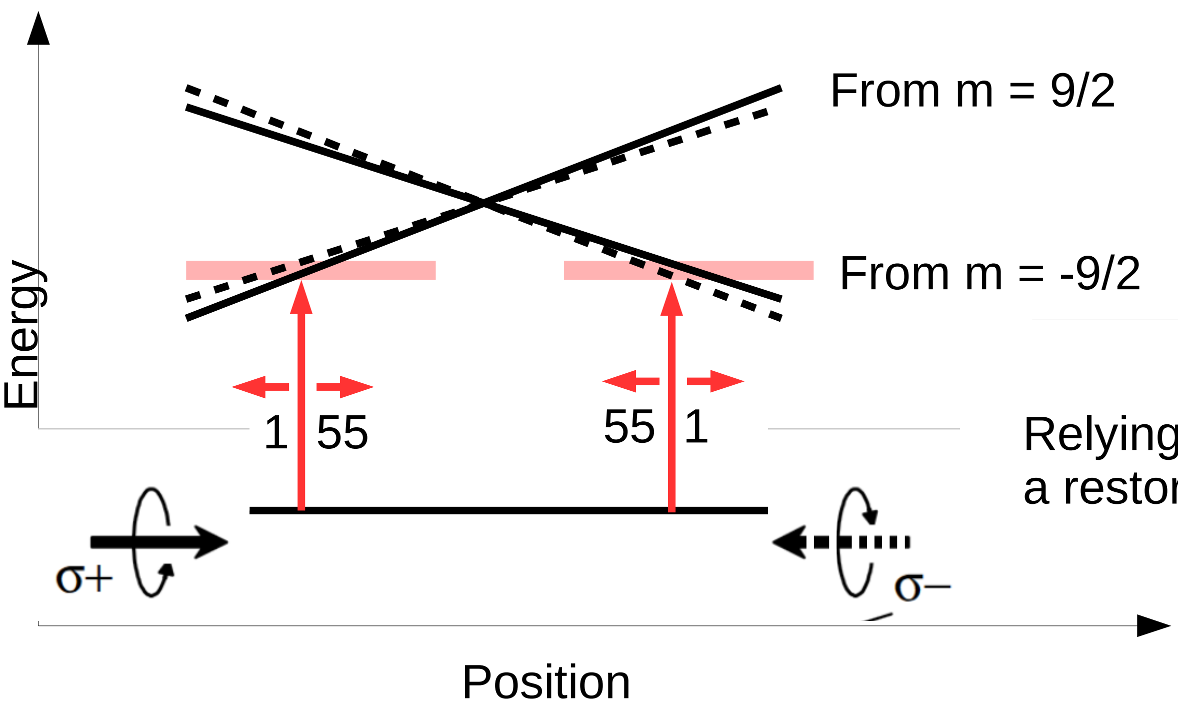
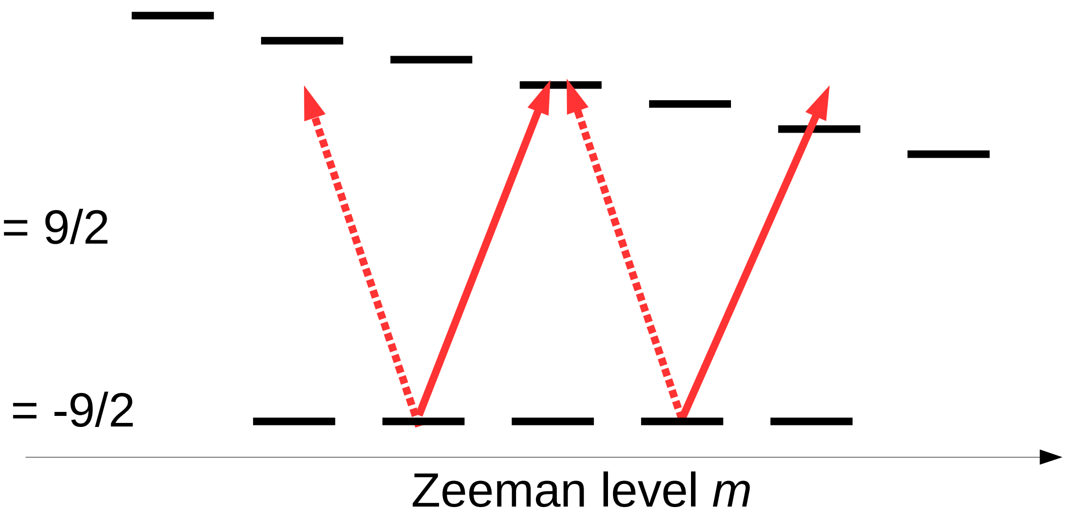




$\mu_g << \mu_e$

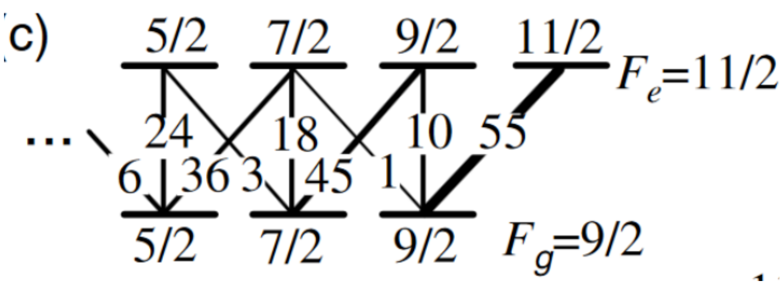


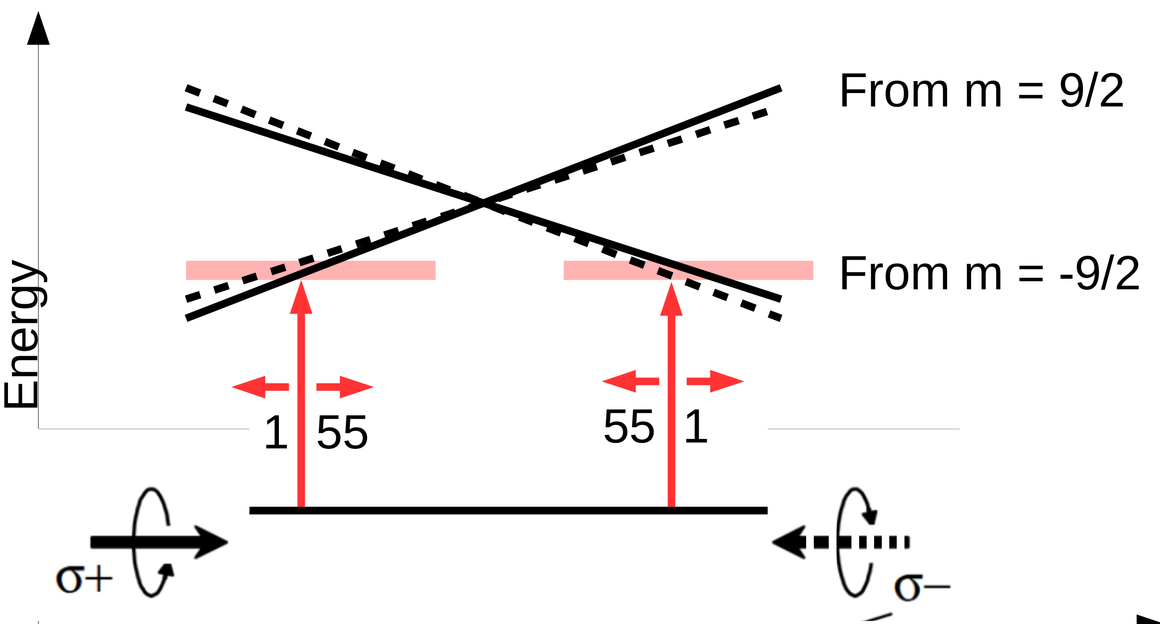
Relying on polarisation-dependent detunings,
a restoring force for *m* could be ejecting for another

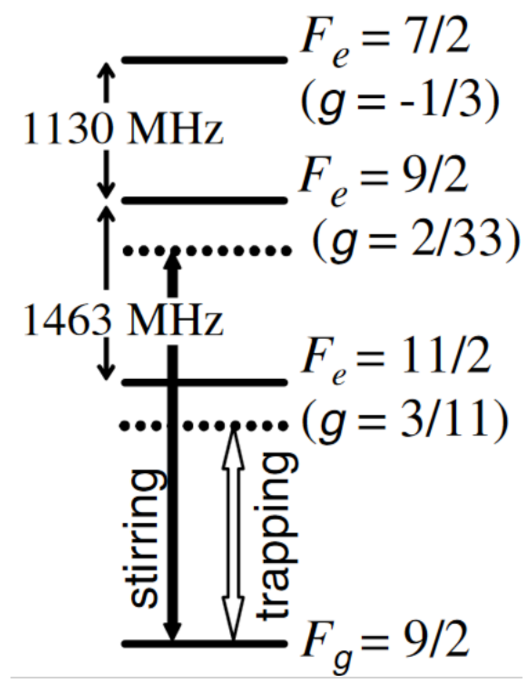
- restoring force from Clebsh Gordan
- Only one side of the trap...

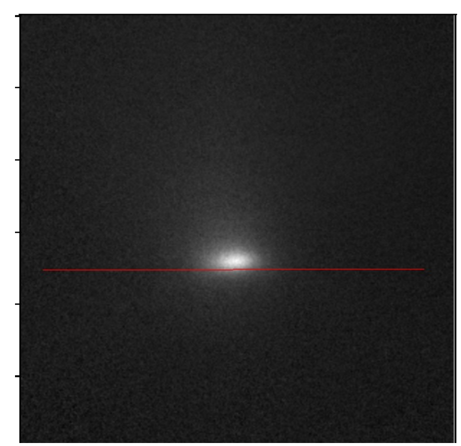
Narrow-line cooling of 87 Sr

Mukayami et al, PRL 90, 113002 (2003): complications from the hyperfine structure





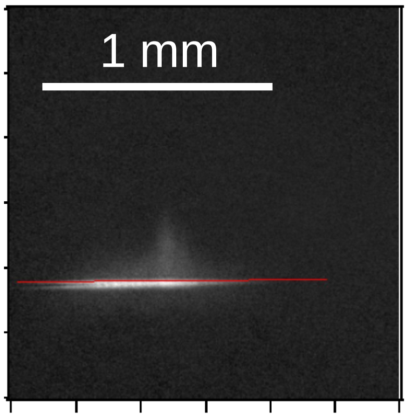


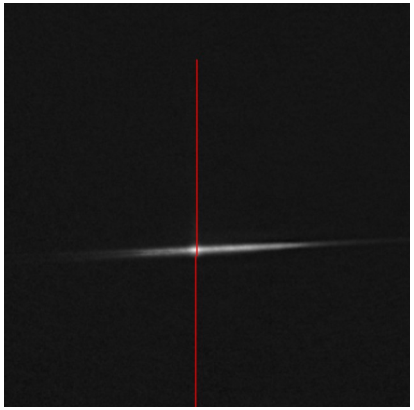


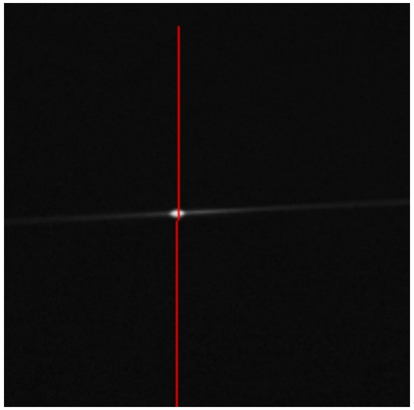
- Restoring force from Clebsh Gordan coefficients
- Spin admixing from a second transition with smaller μ
- *recent alternative: sawtooth adiabatic passage [Norcia et al, Thomson group, NJP 20, 023021 (2018)]*

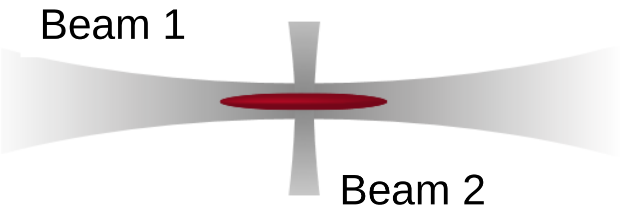
Ultracold 87 Sr

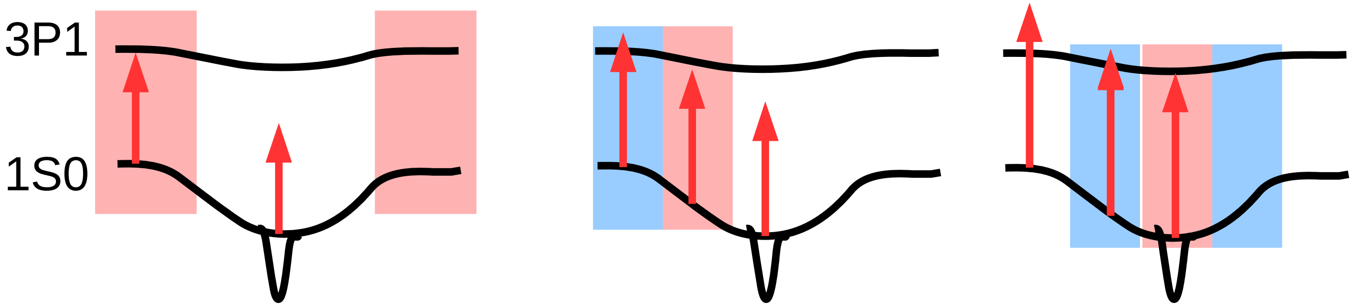
Laser cooling in light shifts from the dipole trap O(100 kHz)
2 μK











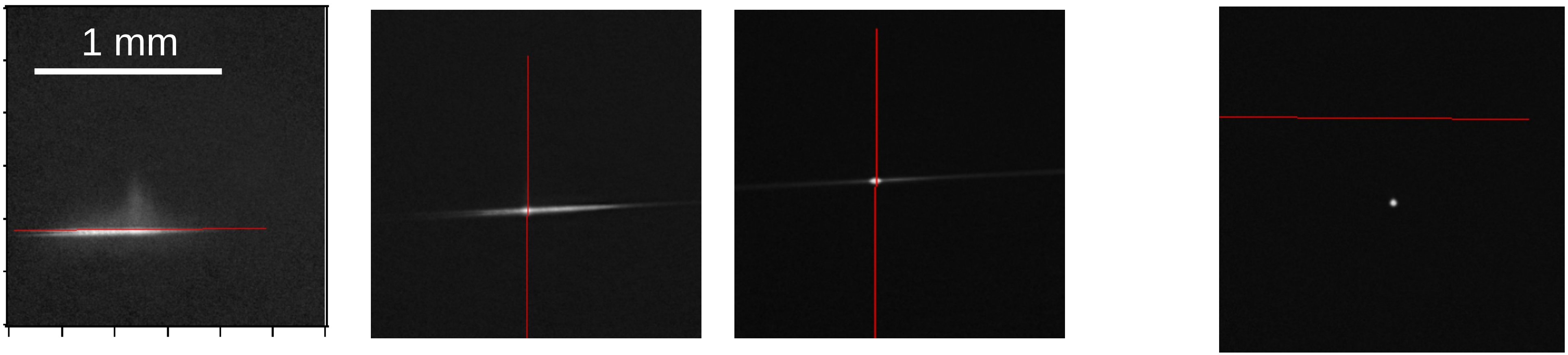
Loading performance still behind Killian and Schreck groups

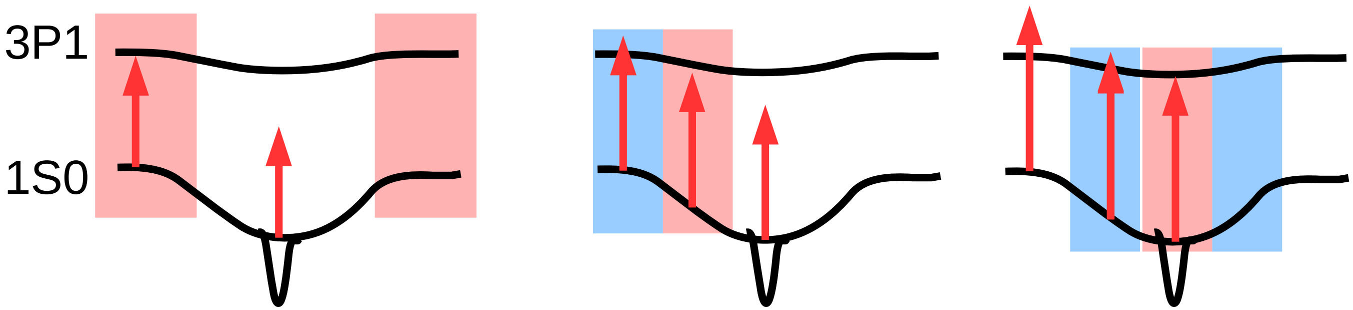
Loading stage sensitive to frequency drifts by O(10 kHz): stable referencing essential (collaborations with Marc's team)

Ultracold 87 Sr

Laser cooling in light shifts from the dipole trap O(100 kHz)
2 µK

Evaporation





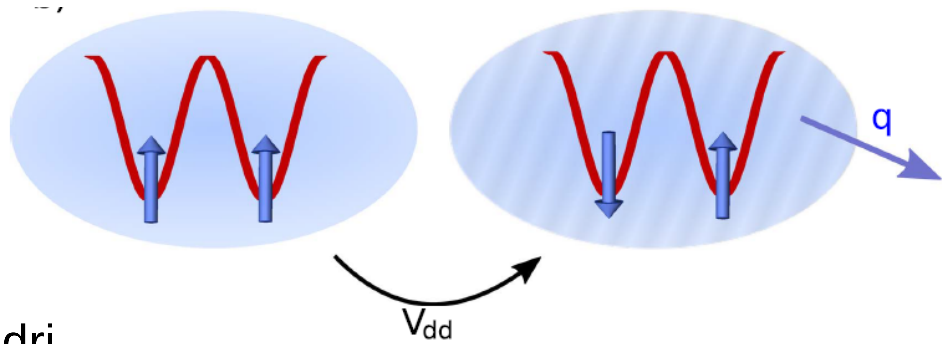
Loading performance still behind Killian and Schreck groups

Loading stage sensitive to frequency drifts by O(10 kHz): stable referencing essential (collaborations with Marc's team)

20th of January 2019 : T/Tf ~ 1 with 10 spin states

This year's ambitions: Optical pumping procedures; spin measurements; Optical lattices

Thank you for your attention



Dissipative cooling of spin chains by a bath of dipolar particles

New Journal of Physics 20, 073037 (2018)

M. Robert-de-Saint-Vincent, B. Laburthe-Tolra, P. Pedri

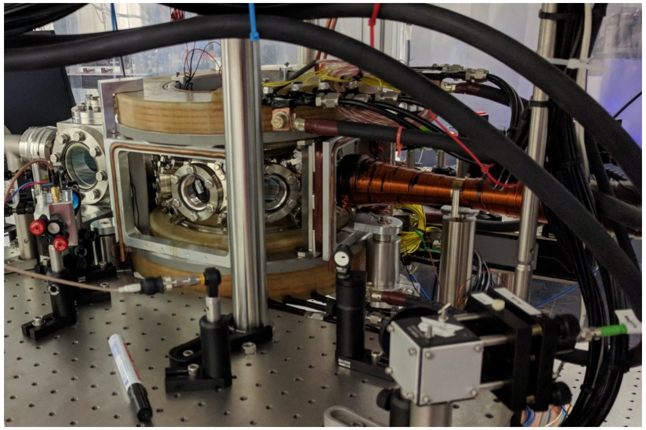
Spin-orbit coupling in collisions enables the use of an atomic bath to thermalize a spin chain, with **free magnetization and free spin length**

Birth of the strontium 87 experiment

Quantum magnetism with narrow-line manipulation tools

I. Manai, P. Bataille, J. Huckans,
E. Maréchal, O. Gorceix, M. Robert-de-Saint-Vincent,
B. Laburthe-Tolra

And many, many fruitful internship contributions presently in cold atoms: W. Dubosclard, C. Duval

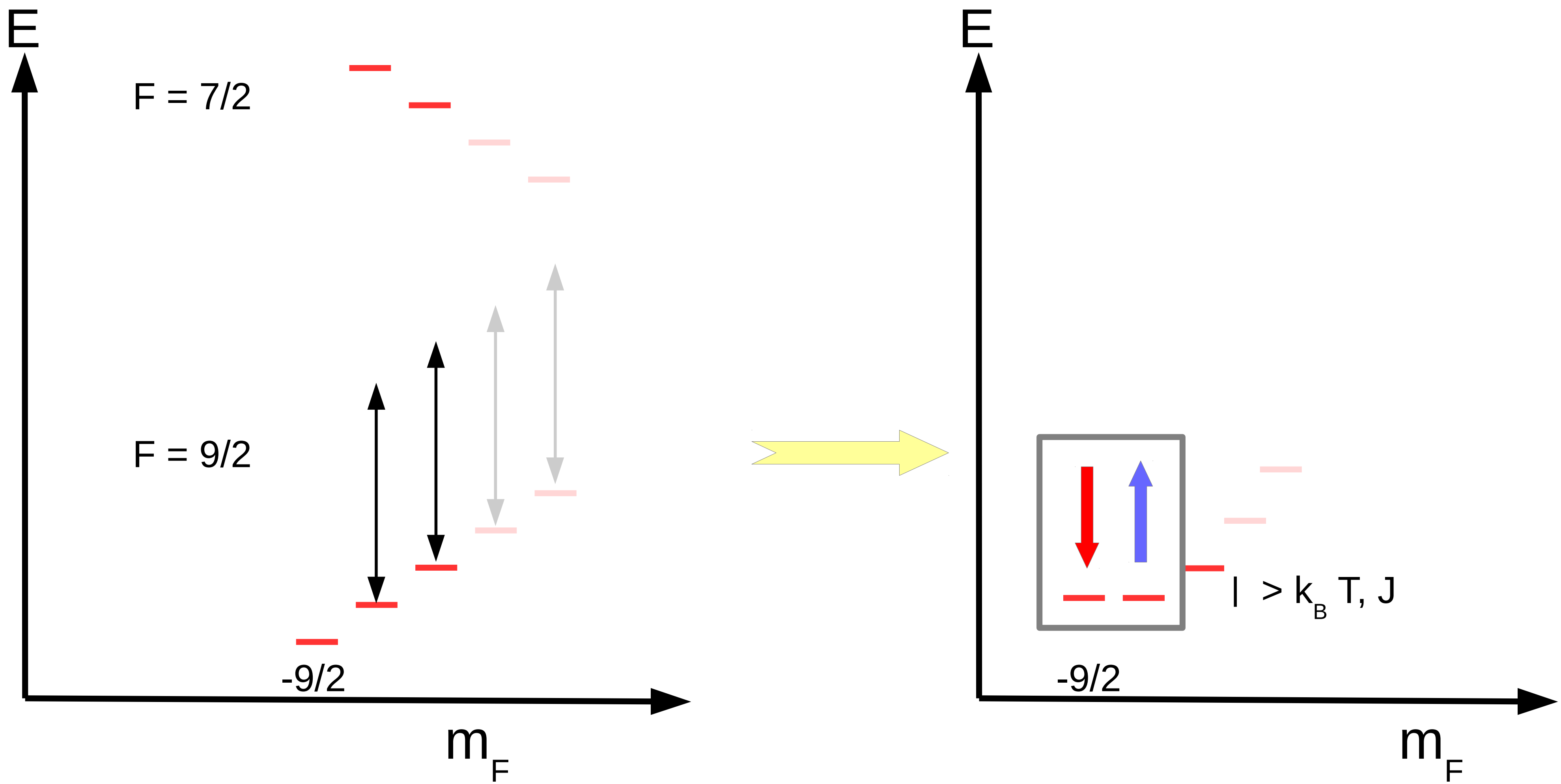


Now at T/Tf ~ 1

Laboratoire de Physique des Lasers
Centre National de la Recherche Scientifique, Université Paris 13

ANR, FIRST-TF, DIM Nano'K, DIM Sirteq, IFRAF, IFCPAR

Microwave dressing



B = 10 mG : linear Zeeman effect with 3 kHz / m_F energy difference

Microwave dressing close to the hyperfine transition at 1,285 GHz, F=9/2 → F = 7/2

Rabi frequency 100 kHz

Detuning 830 kHz

Hyperfine state mixing 0,004

F. Gerbier et. al., Phys. Rev. A. **73**, 041602 (2006)

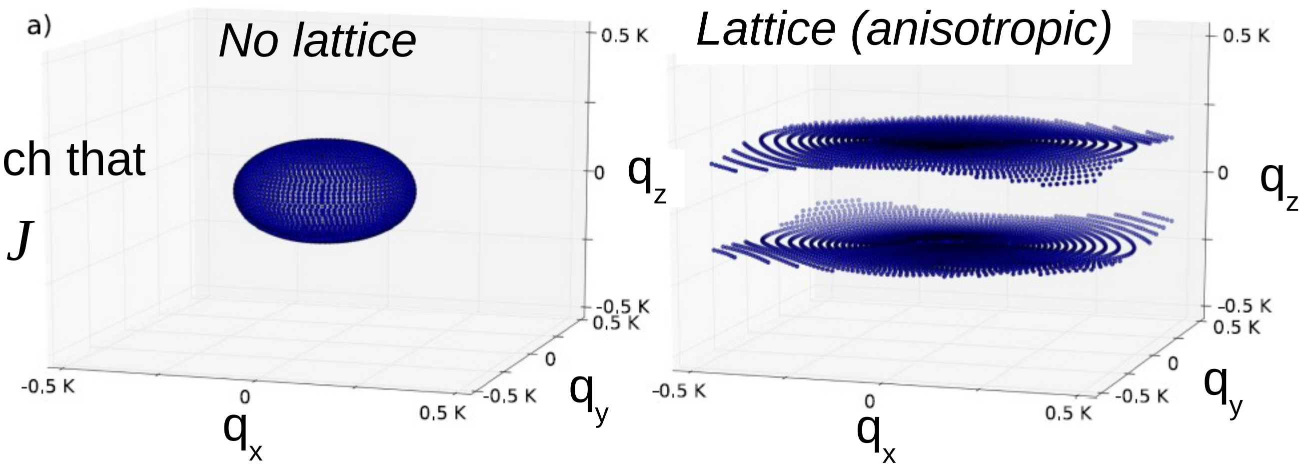
Lattice potential: strong effect on the bath

Enhanced interactions : very sensitive to anisotropies

Dispersion relation : wavevectors and density of states

Wavevectors such that

$$\epsilon(\vec{q}) = J$$

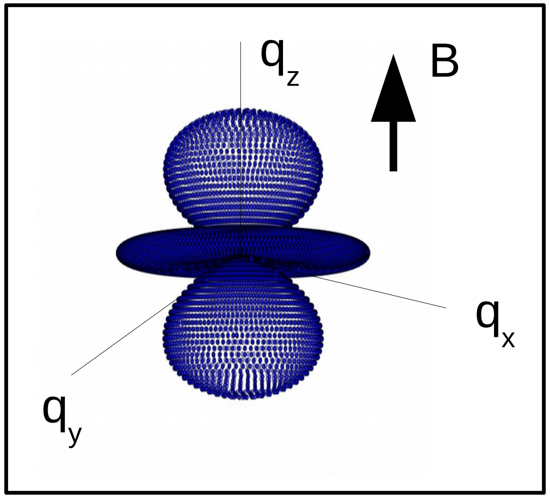


Coupling strength for a given mode q

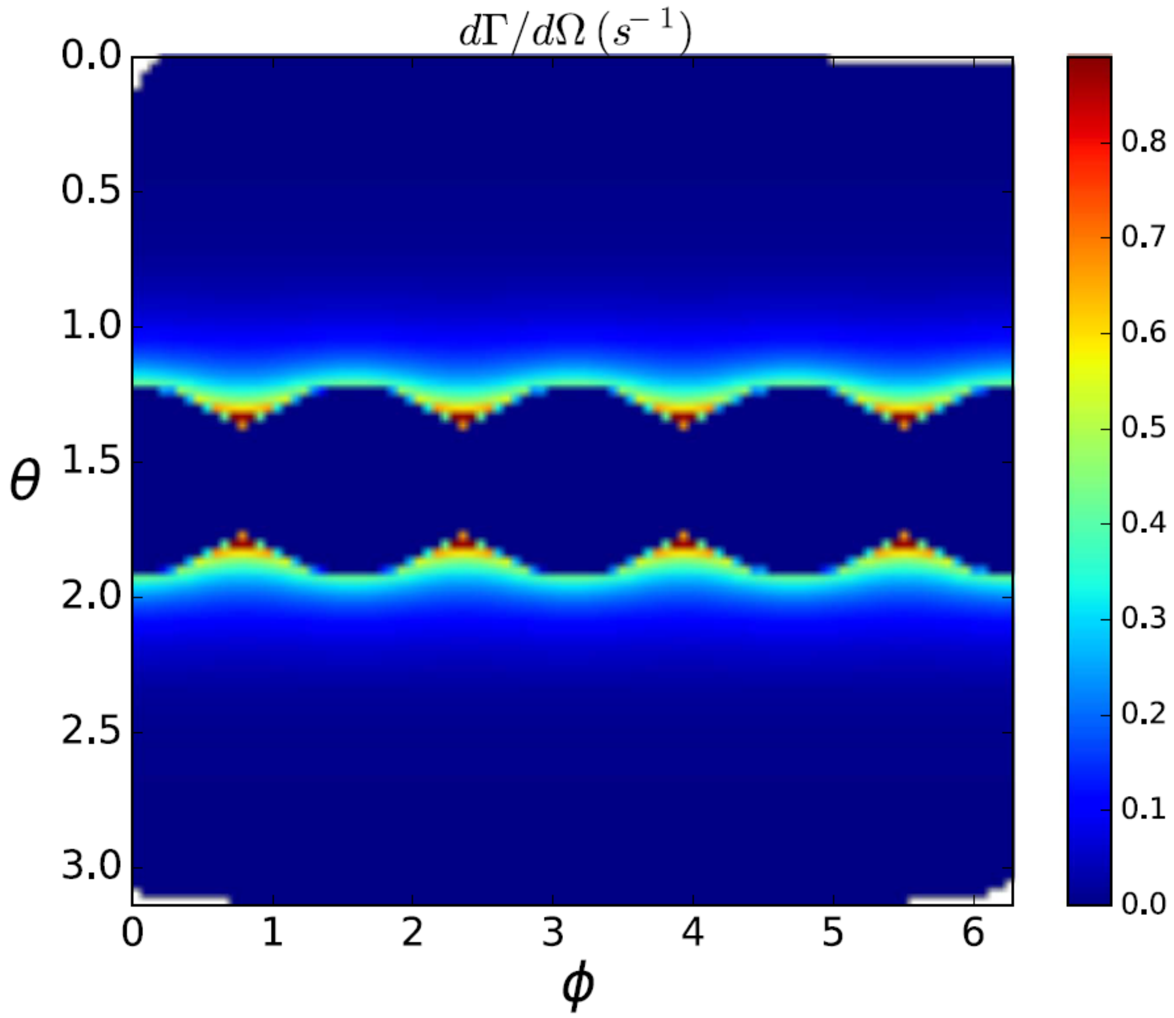
Mode decomposition onto plane waves vs Vdd anisotropy

Vdd(q) :

Lobes of opposite sign



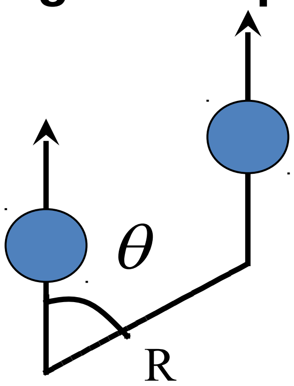
Radiation diagram in lattice



The tool: dipolar interactions

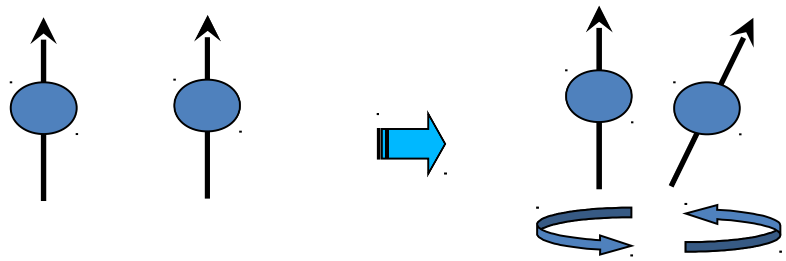
The bath must be able to flip spins

Magnetic dipolar interactions – anisotropic – non spin conserving



$$V_{dd} = \frac{\mu_0}{4\pi}(g_J \mu_B)^2 \frac{S_1.S_2 - 3(S_1.u_R)(S_2.u_R)}{R^3}$$

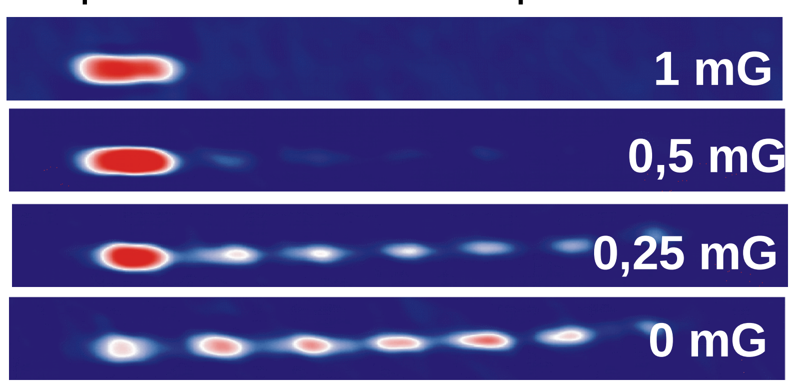
Dipolar quantum gases: Pfau, Laburthe-Tolra, Lev, Ferlaino, Grimm, Modugno...



Spin-orbit coupling

Dipolar relaxation enables true thermalization with free spin degree of freedom

Single-species Chromium experiment at LPL

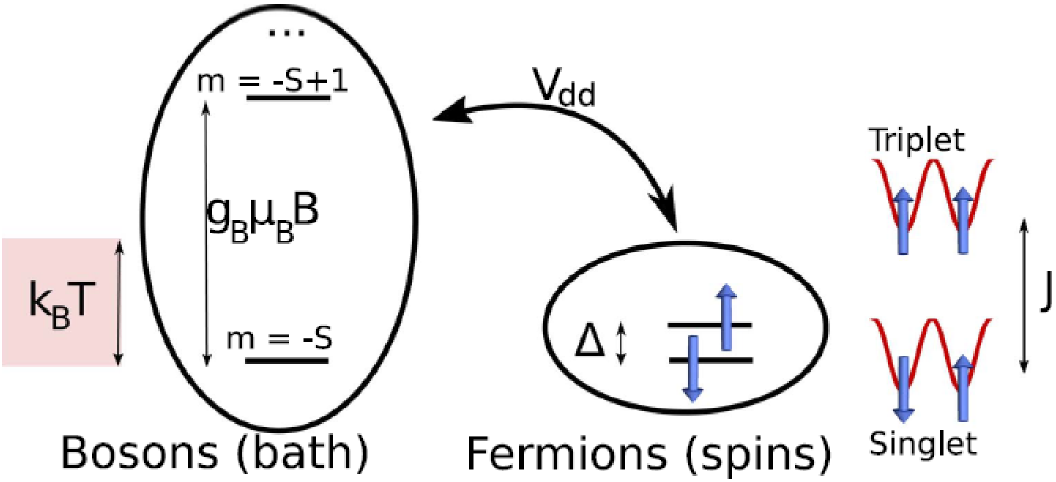


m_s = -3 -2 -1 0 1 2 3

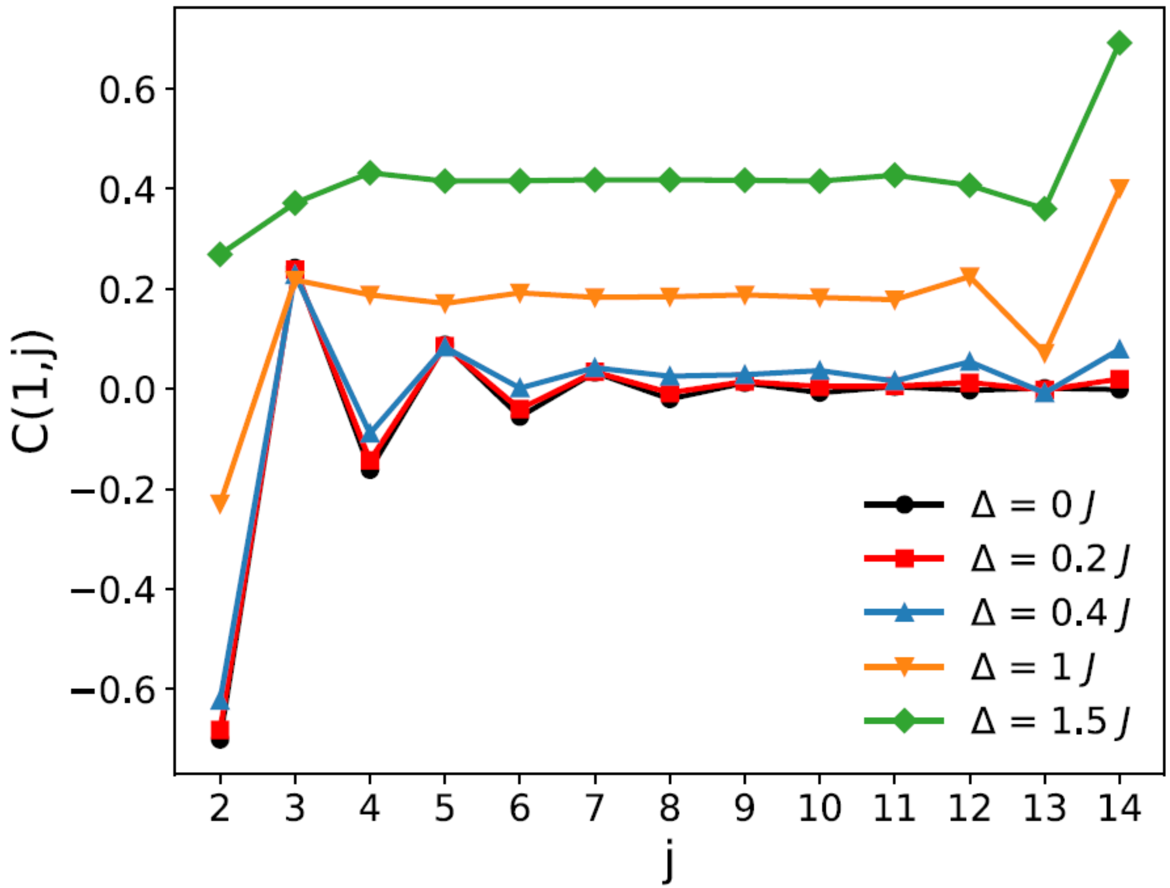
Pasquiou et al, PRL **106**, 255303 (2011)

The gaz always reaches the energetically-favourable spin distribution

Robustness of the AF state to a bias Δ

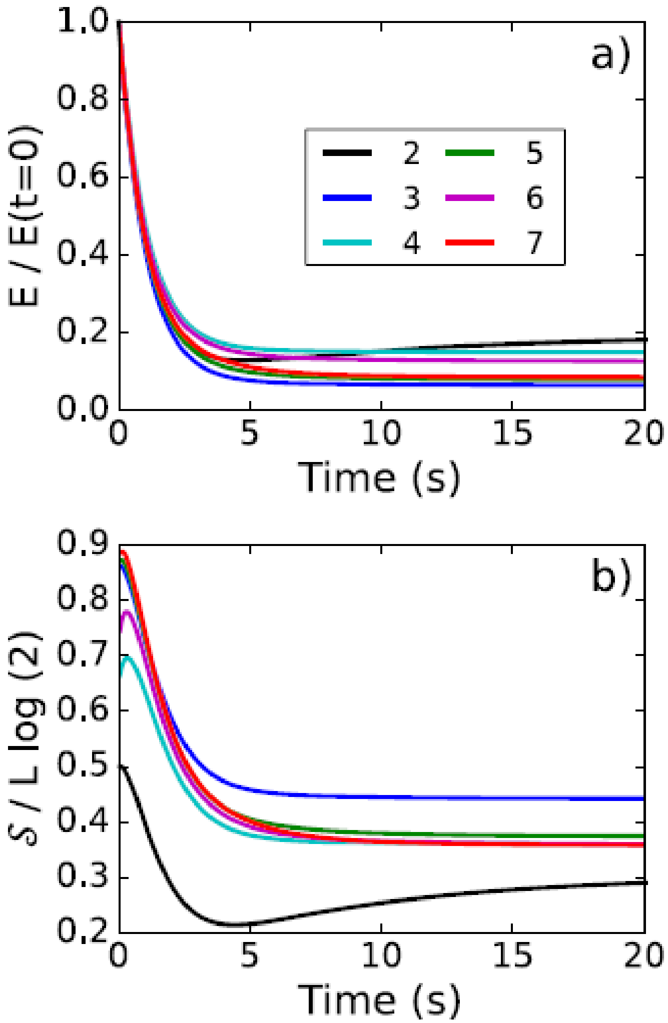


0.2 J ~ 0.4 mG



Collective spin dynamics

Initially balanced spin mixture



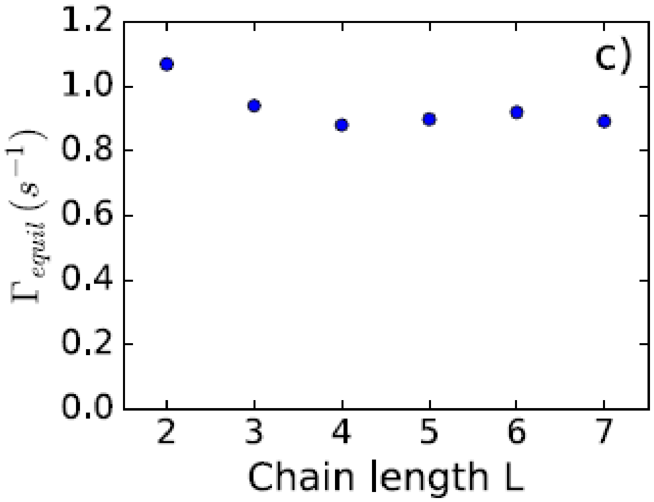
Energy

Von Neumann spin entropy

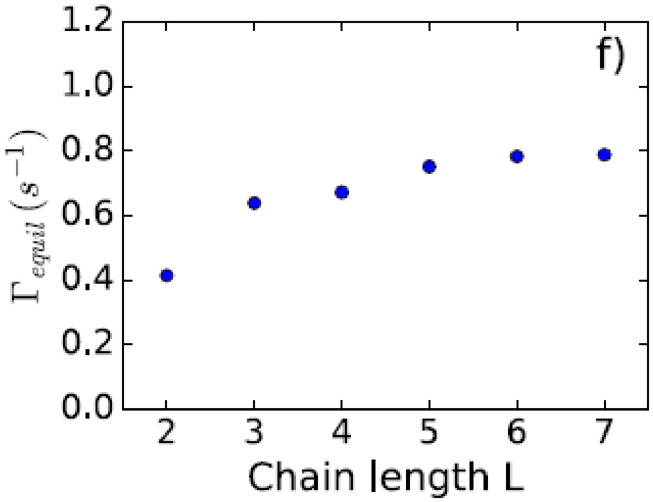
$$\mathcal{S} = -\sum_i p_i \log(p_i)$$

Collective spin dynamics

Initially balanced spin mixture



Initially free spin mixture



Equilibration rate tends to a value roughly independent on chain length and on preparation condition

Timescale of order ~ 1 s – experimentally relevant, though not fast

Limited by restraining ourselves to very low quantum depletion (5%)
Faster dynamics plausible in deeper bath lattices,
but this leaves the validity range of the Bogoliubov description

Dysprosium vs Erbium : about similar (7μ_B, but also 583 nm lattice)

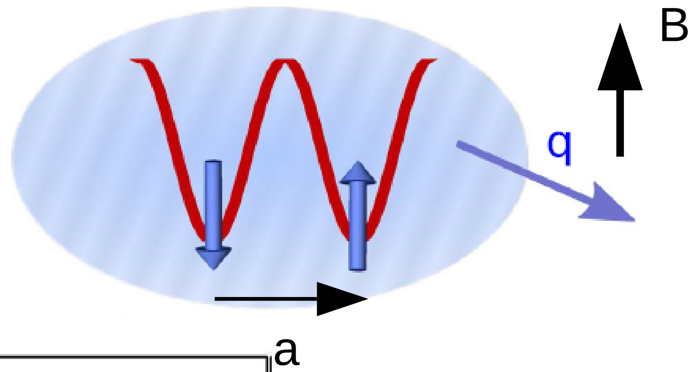
Alkali: ^{40}K has low Lande factor, but scientific interest of fermions for the t-J model

Anisotropic coupling to the bath

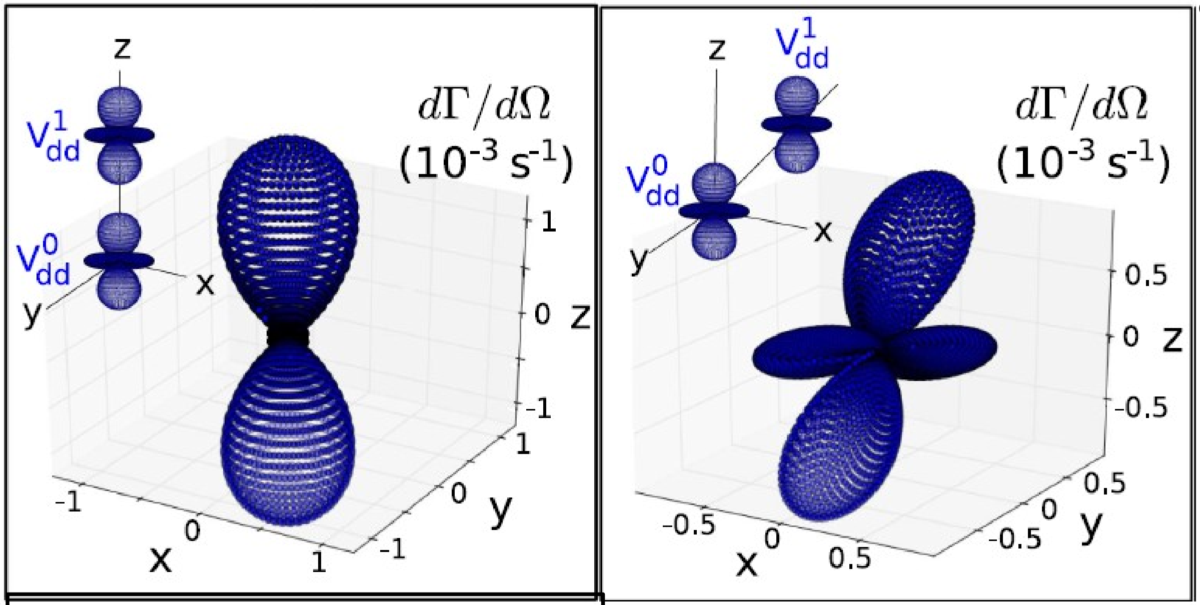
Radiation diagrams from two spins (double well)

(here without lattice potential for the bath)

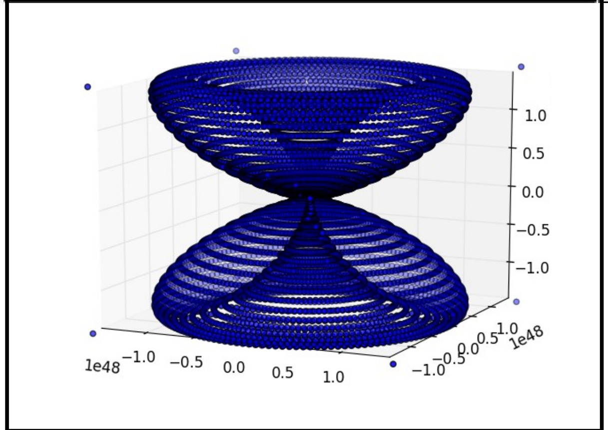
Severe anisotropy and collective spin dependence



from $S_{tot} = 1$, m = 0
to $S_{tot} = 0$, m = 0



from $S_{tot} = 1$, m = ± 1
to $S_{tot} = 0$, m = 0



References

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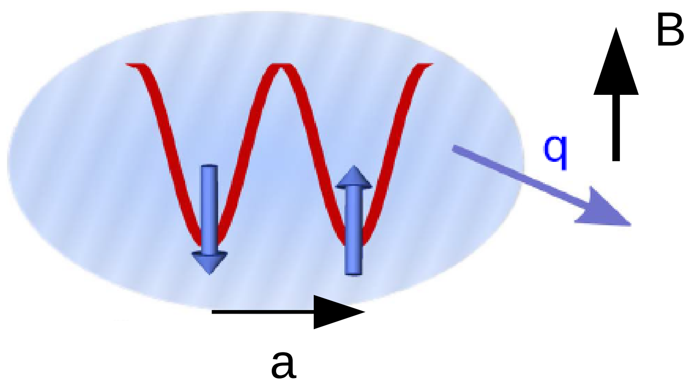
Anisotropic coupling to the bath

Radiation diagrams from two spins (double well)

(here without lattice potential for the bath)



Severe anisotropy and collective spin dependence

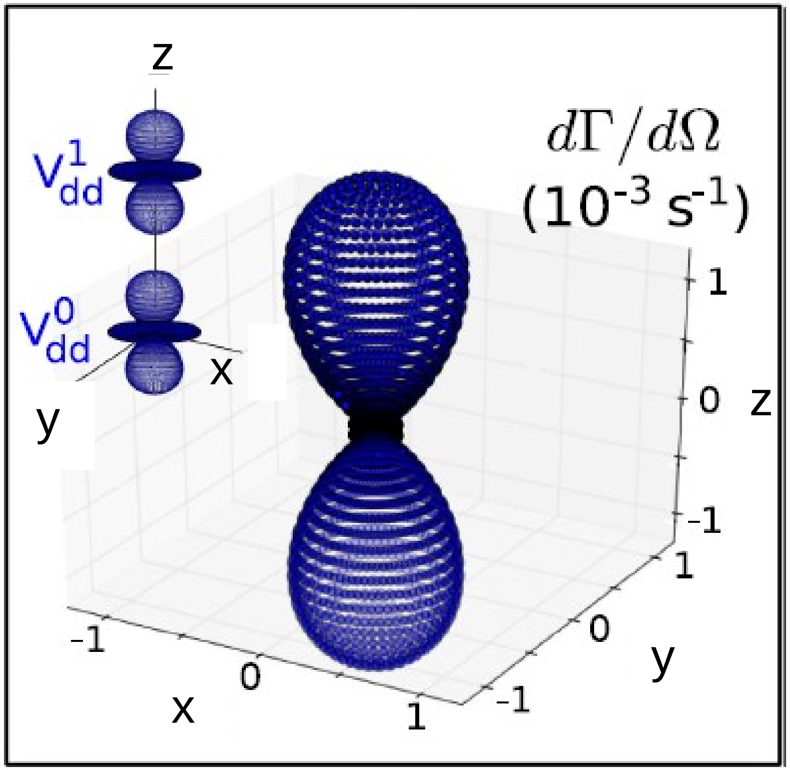
Example : rate from $S_{tot} = 1, m = 0$ to $S_{tot} = 0, m = 0$

Sz component of (m conserving) $|\langle f_{\text{spin}}; f_{\text{bath}} | H_{\text{int}} | i_{\text{spin}}; i_{\text{bath}} \rangle|^2$

$$|f_{\text{bath}}(\vec{q})\rangle = b^{\dagger}(\vec{q})|\text{BEC}\rangle \quad \text{with} \quad \epsilon(\vec{q}) = J$$

Analogous to spontaneous emission of light;
Cooperative effects at play

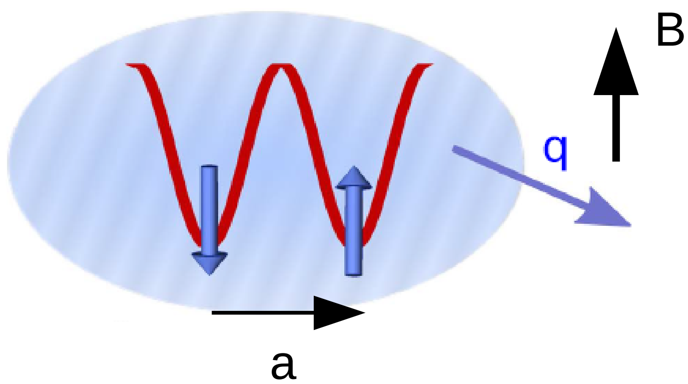
Radiation diagram for $\Delta m = 0$



$\vec{q} \cdot \vec{a} = 0$: global energy shift, no effect

Anisotropic coupling to the bath

Radiation diagrams from two spins (double well)



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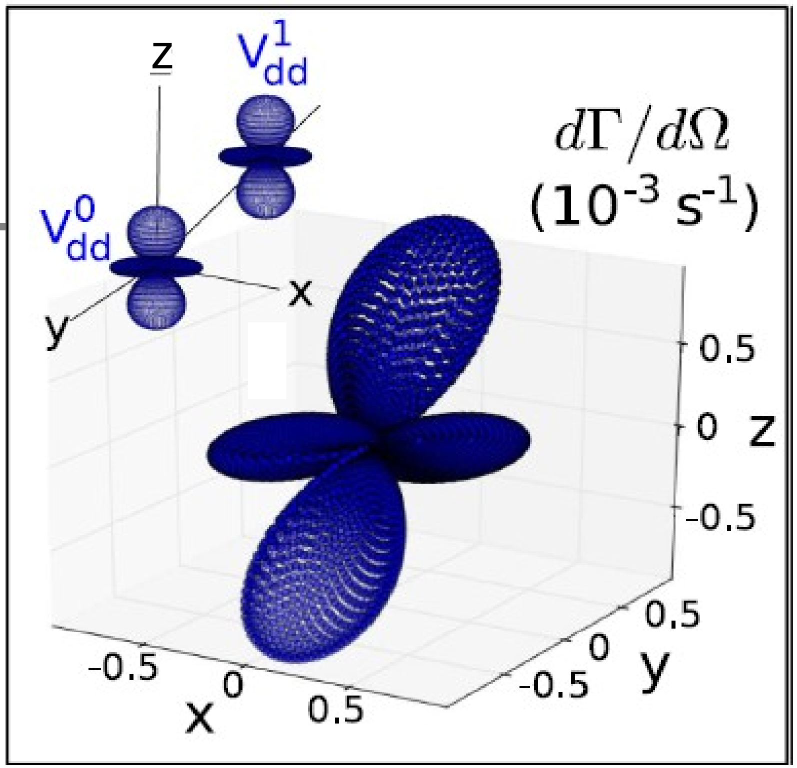
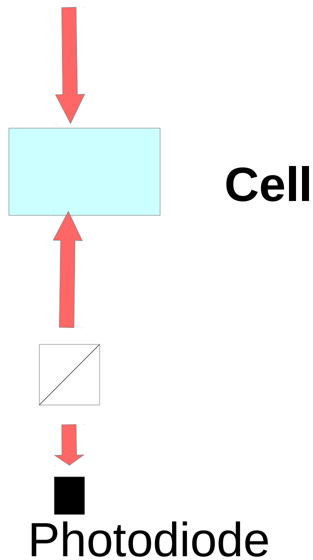
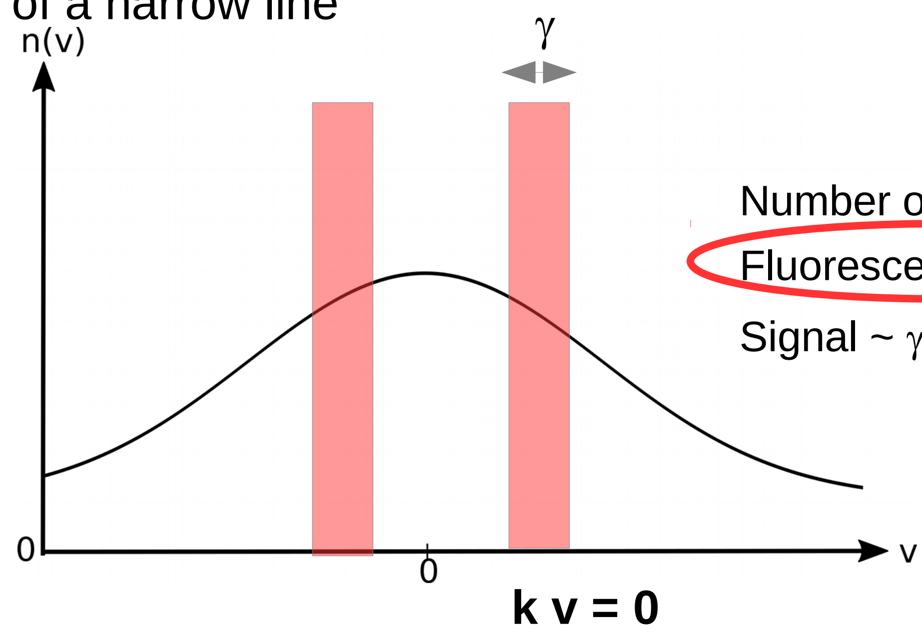


$\vec{q}\cdot\vec{a} = 0$: global energy shift, no effect

Shelving spectroscopy

Saturated absorption spectroscopy of a narrow line



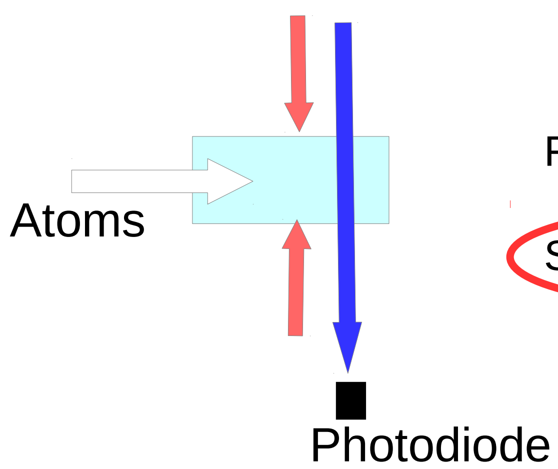


Number of atoms ~ γ or Ω

Fluorescence rate ~ γ

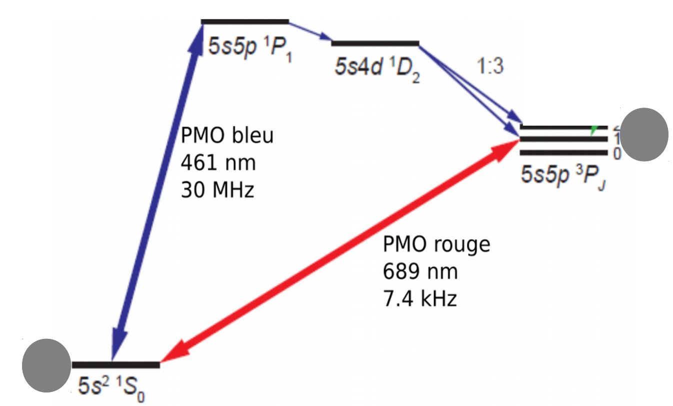
Signal ~ γ^2

Shelving spectroscopy of a narrow line



Fluorescence rate ~ Γ

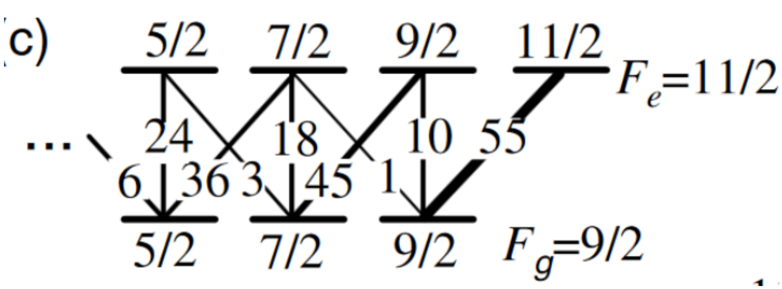
Strontium: Γ/γ = 4000

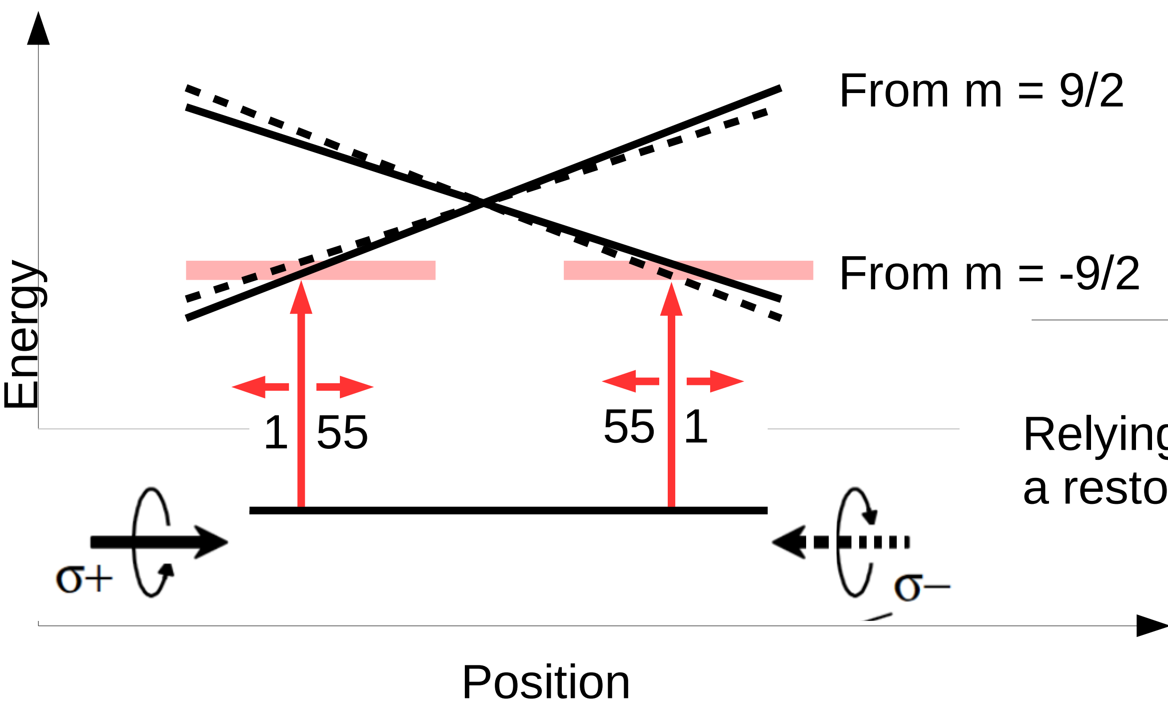


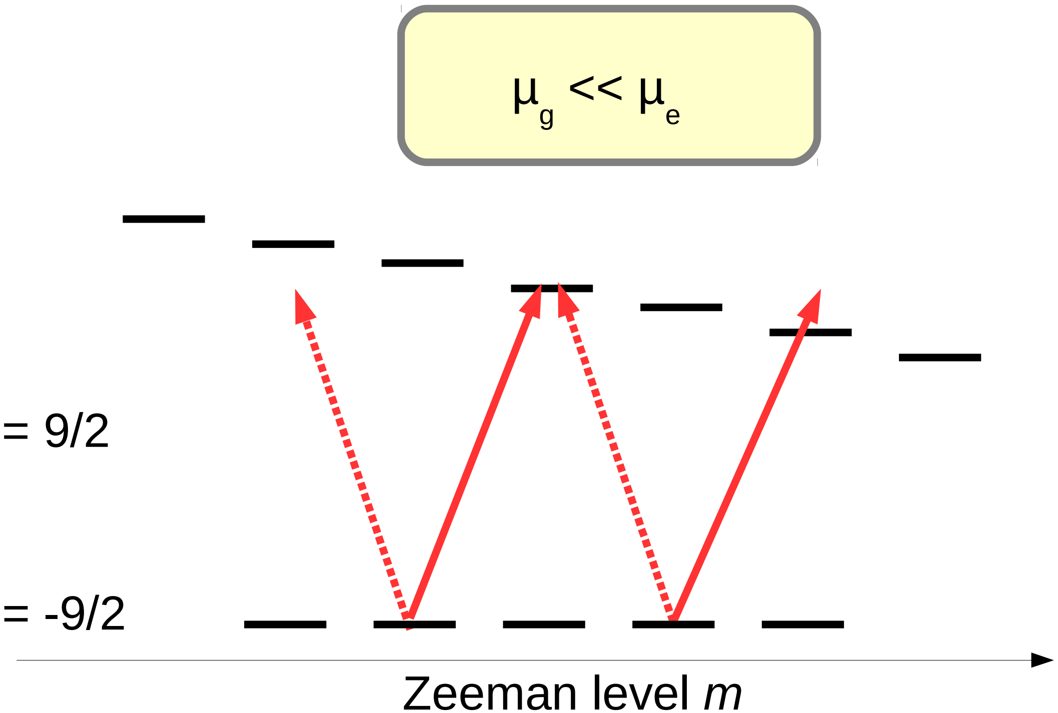
Used in neutral Calcium clocks:
Huang2006 McFerran 2009 Shang2017

Narrow-line cooling of 87 Sr

Mukayami et al, PRL 90, 113002 (2003): complications from the hyperfine structure







Relying on polarisation-dependent detunings,
a restoring force for *m* could be ejecting for another

- restoring force from Clebsh Gordan
- Only one side of the trap...

Enable spin state randomisation
Laser cooling on a second transition
with much lower Lande factor