Dissipative cooling of spin chains by a bath of dipolar particles

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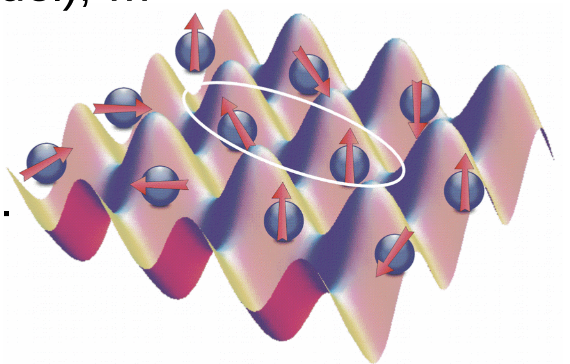
Quantum Technologies Conference IX, 12th September 2018

Magnetism with cold atoms

Various magnetic models implemented in cold atoms

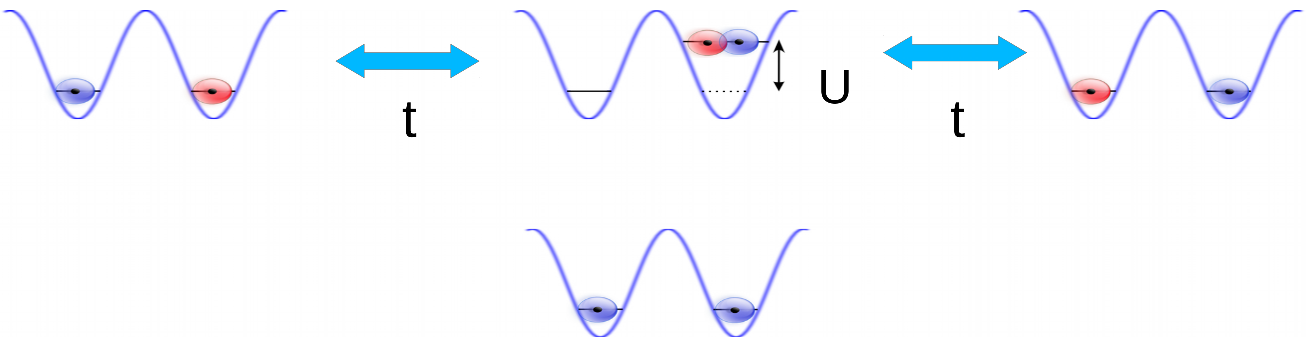
Broad panel of physical questions : frustation (tunable geometries),
large spin systems,
interplay with transport (t-J model), …



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, ...

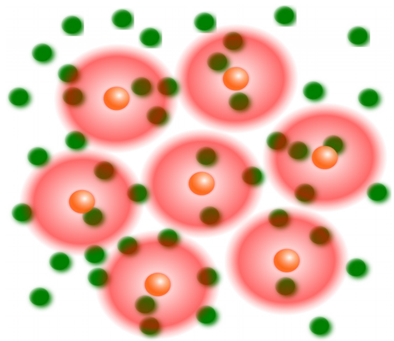
An opportunity for open quantum systems

Many-body quantum systems = resources for quantum simulation and quantum computation

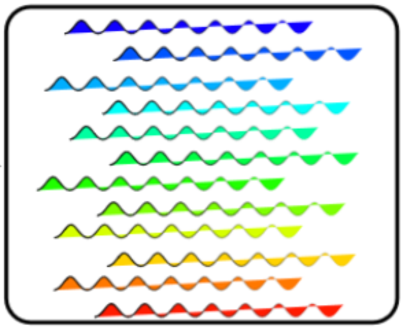
Dissipation ?

Modern research field :
robust entanglement / correlations from engineered dissipation

Benatti et al, PRL 91, 070402 (2003) - Piani, Zoller, Cirac, …
Rydbergs, ions



Many-body system, e.g. Rydberg gas



Bath continuum (e.g., light)

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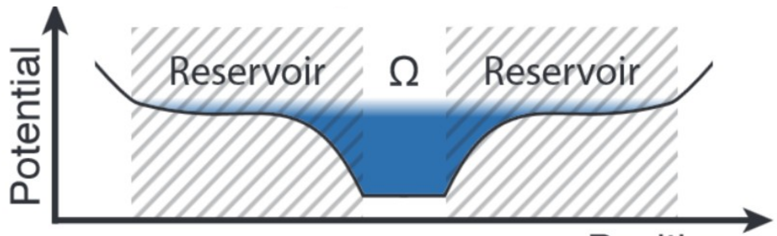
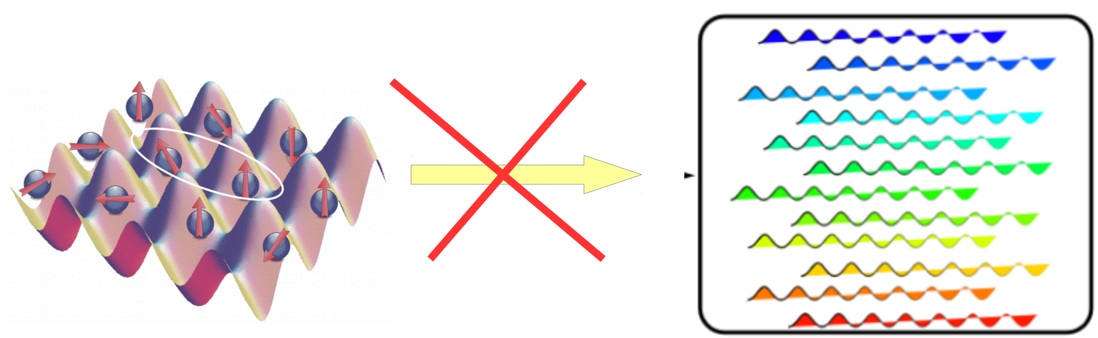
Ground state lattice magnetism usually in isolated systems

Strong motivation: the low entropy challenge (Mc Kay and DeMarco, 2011)

so far tackled by **inhomogeneous systems**
Ho 2009, Bernier 2009, Mathy 2012,
Hart 2015, Mazurenko 2017, Kantian 2018 ...





Ground state lattice gas   Bath continuum (e.g., light)

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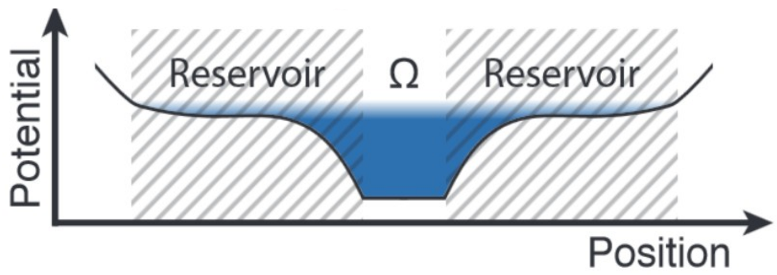
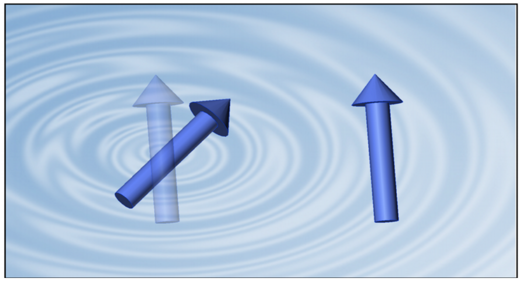


Engineered spin dissipation proposals : growing literature proposing light as bath

Diehl 2010, Kaczmarczyk 2016, …
Zoller, Weimer, ...

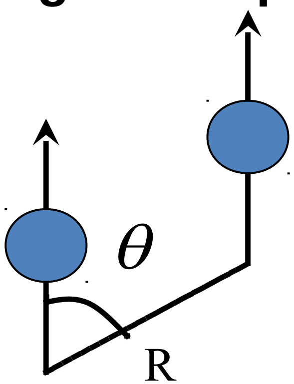
Our discussion:
thermalize the spins with the phonons of an atomic bath
(atomic mixtures)



The tool: dipolar interactions

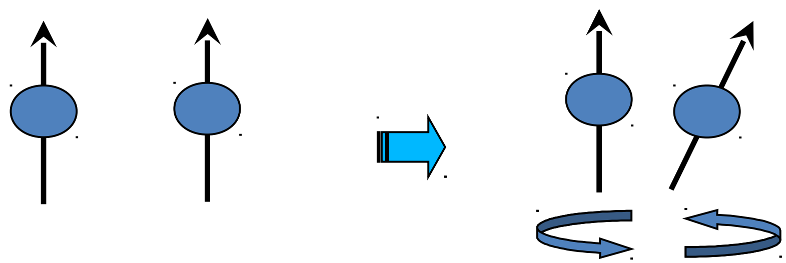
The bath must be able to flip spins

Magnetic dipolar interactions – anisotropic – non spin conserving



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

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



Spin-orbit coupling

Ising *Exchange*

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

Includes non-spin conserving terms

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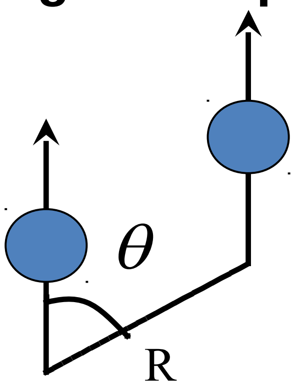

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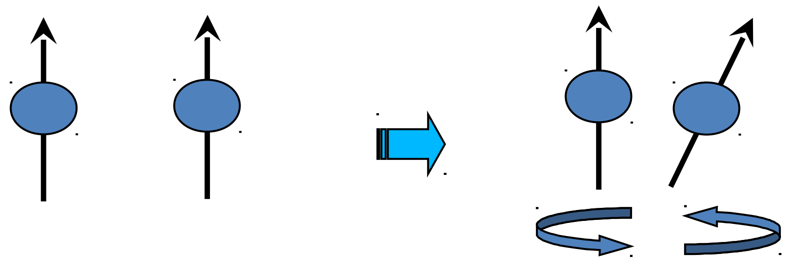
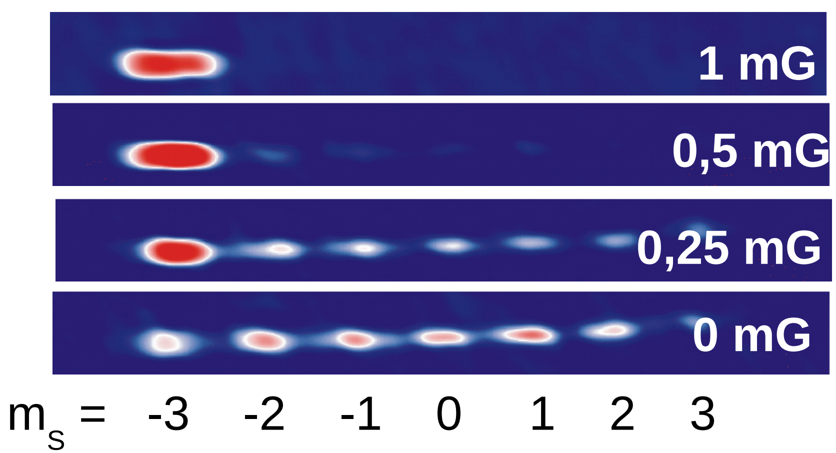


Spin-orbit coupling

Dipolar relaxation enables true thermalization at free magnetization

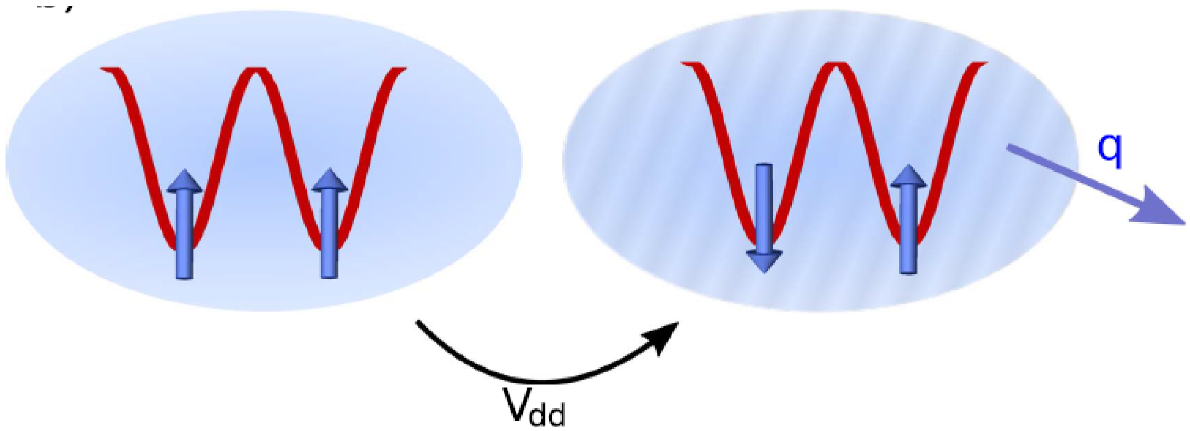
Single-species Chromium experiment at LPL (Laburthe-Tolra)



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

The gaz always reaches the energetically-favourable spin distribution

Outline



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

- ***free magnetization*** from a spin-orbit coupling mechanism
- 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
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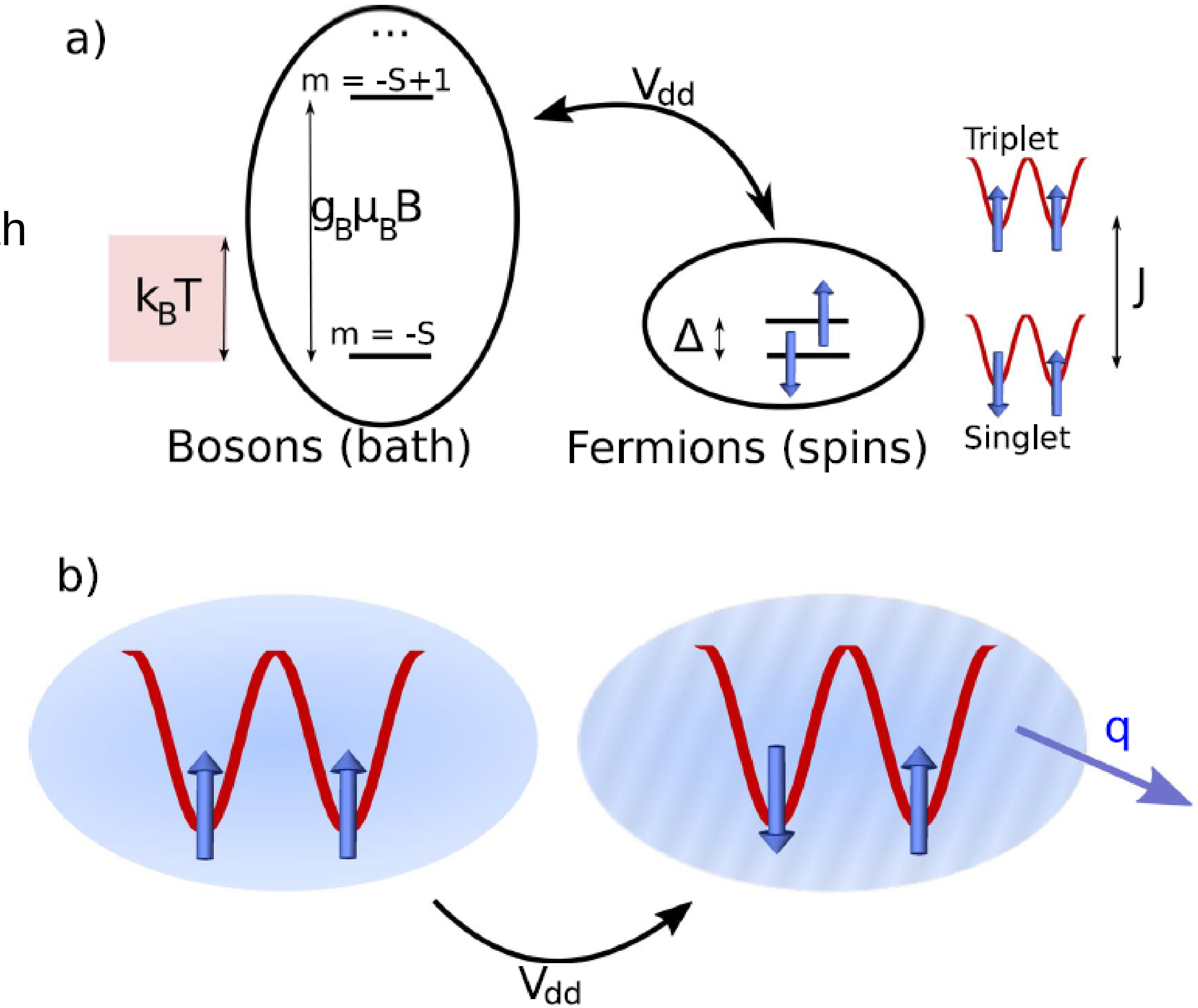
System overview and simplifying assumptions

Polarised bath for simplicity ($B > 1mG$)



AF Heisenberg model;

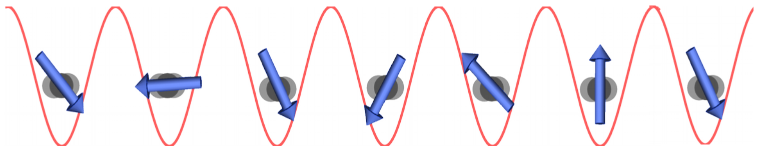
Restricted to two Zeeman states for simplicity

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

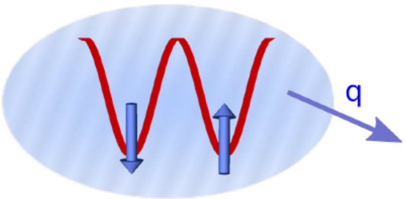


A Fermi Golden rule treatment

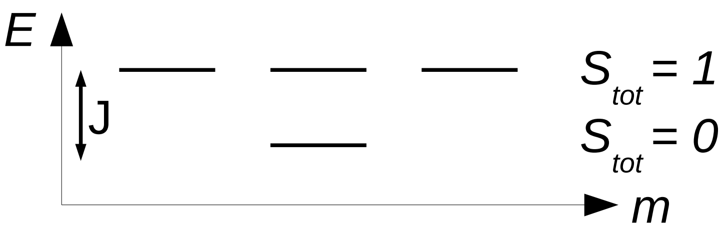
Dissipative evolution evaluated from the Fermi golden rule between collective spin chain eigenstates

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

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



Example : 2-atom spin chain, four collective states



Our work: Compute explicitly all these matrix elements, in realistic setting

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)***

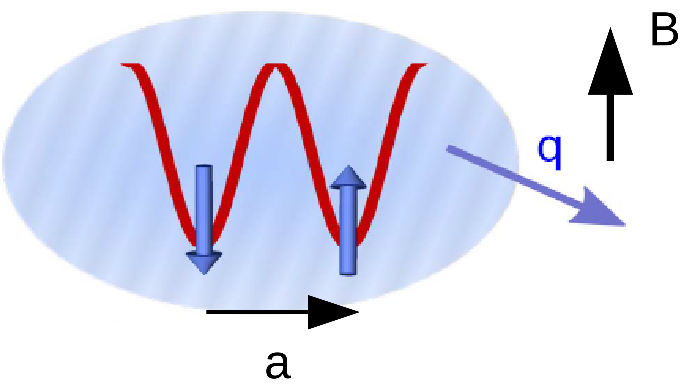
* *Ravensburger et. al., Phys. Rev. Lett.* ***120****, 223001 (2018)*

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 $S_{tot} = 0, m = 0$

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

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

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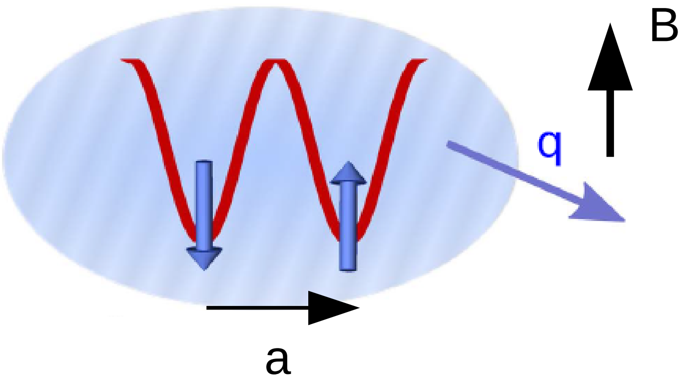

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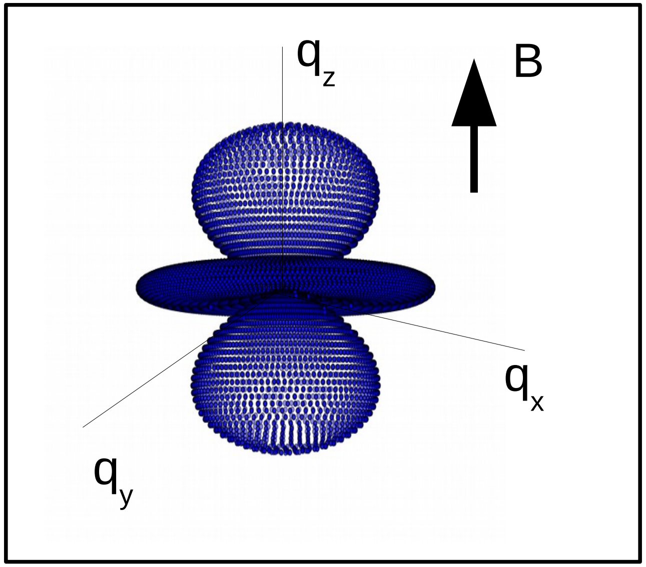
Single spin : Vdd(q)



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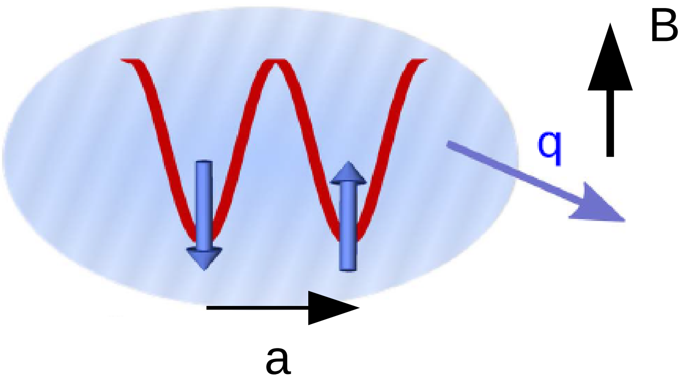

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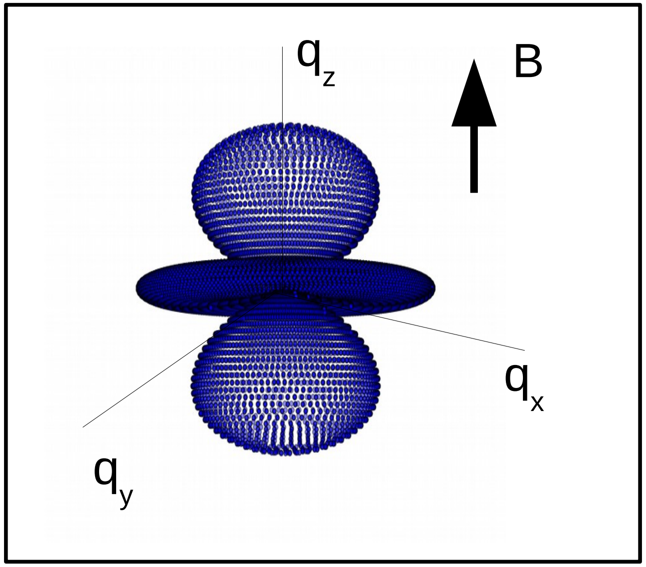
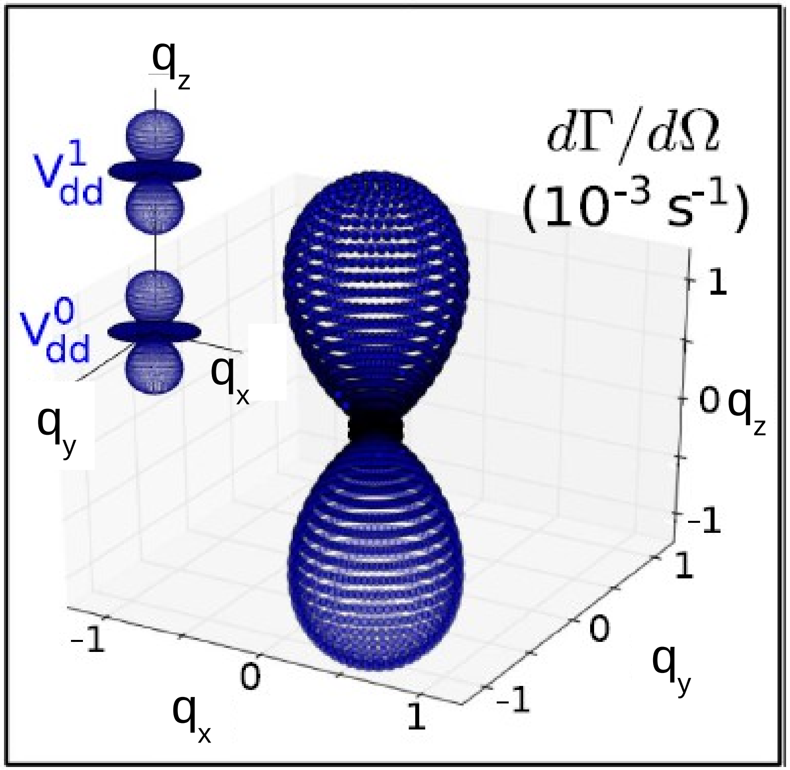


Two spins $|\langle f\,|\,H_{int}\,|\,i\rangle|^2$



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

Anisotropic coupling to the bath

Radiation diagrams from two spins (double well)

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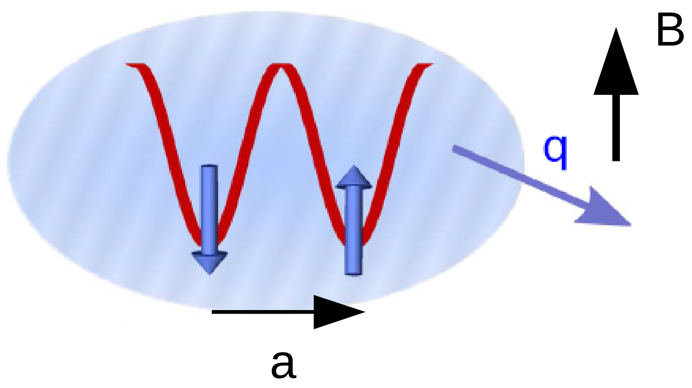
Severe anisotropy and collective spin dependence



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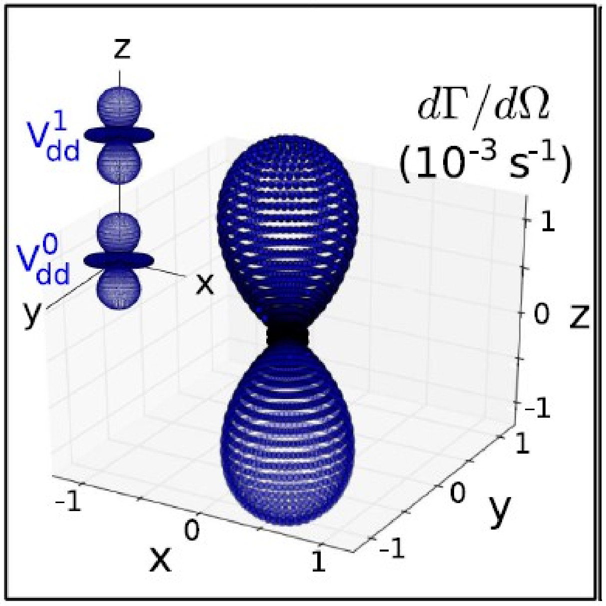

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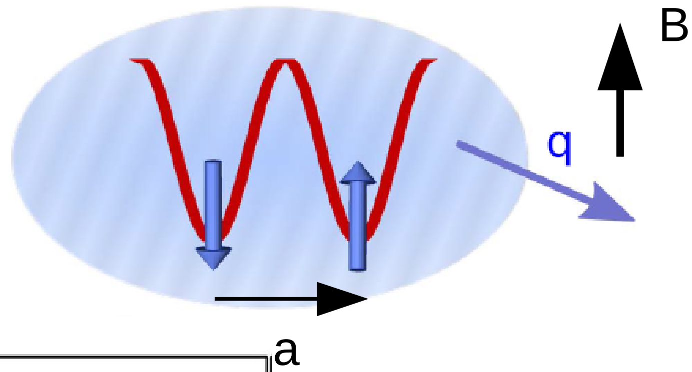

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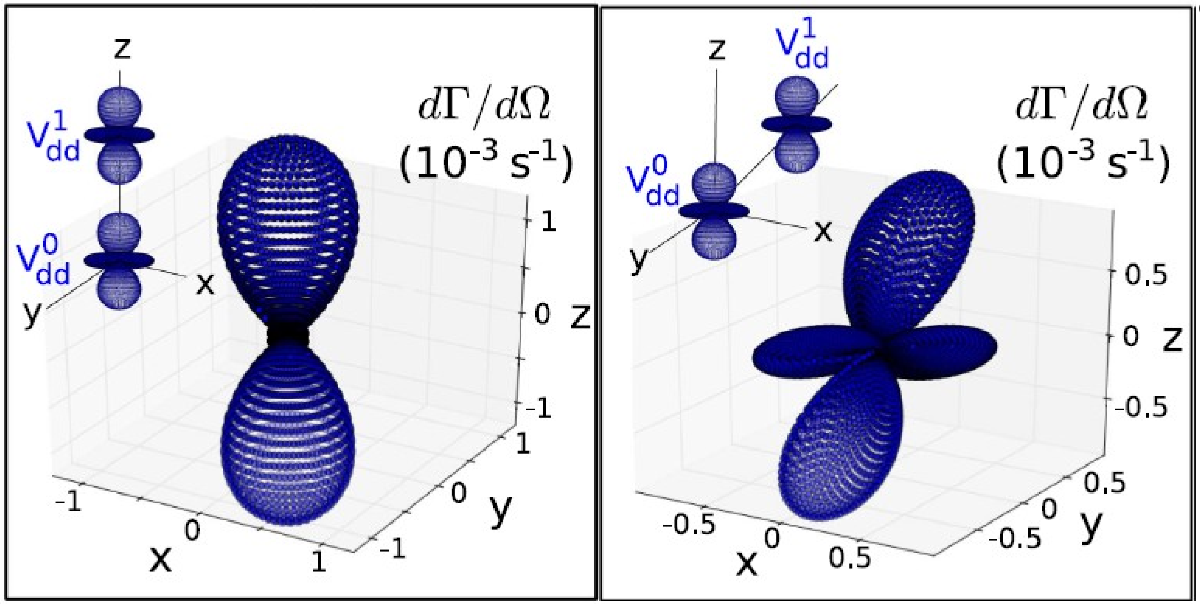

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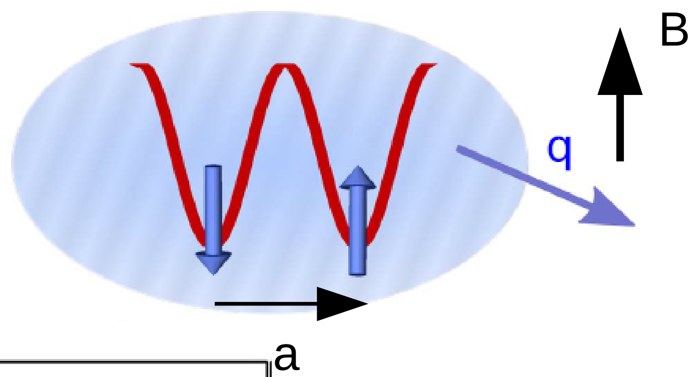

from S_{tot} = 1, m = 0
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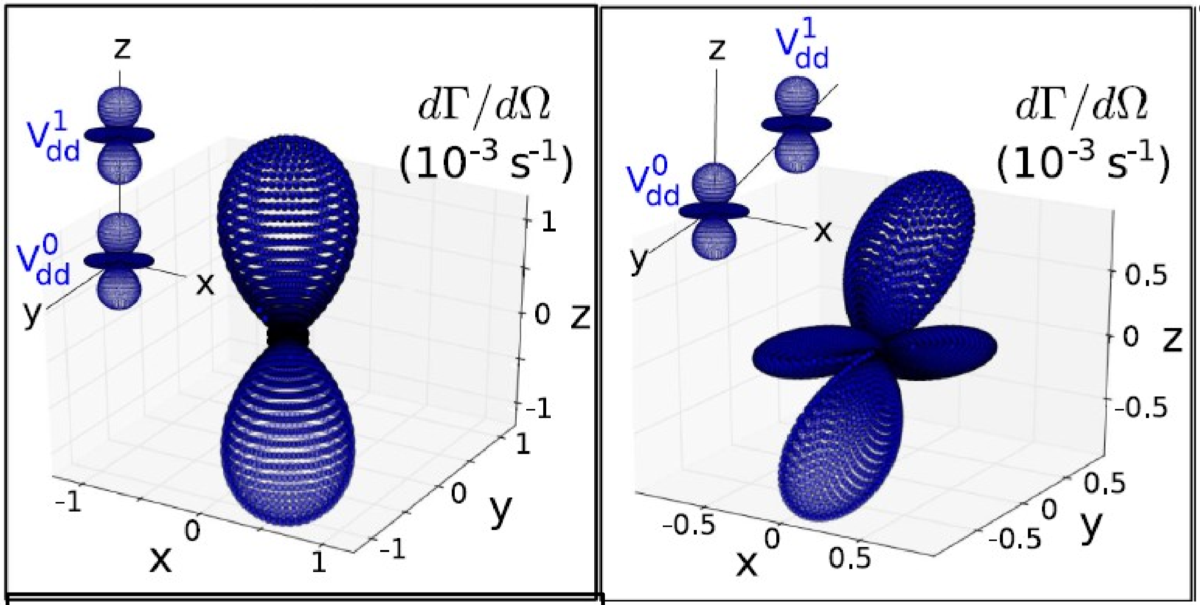
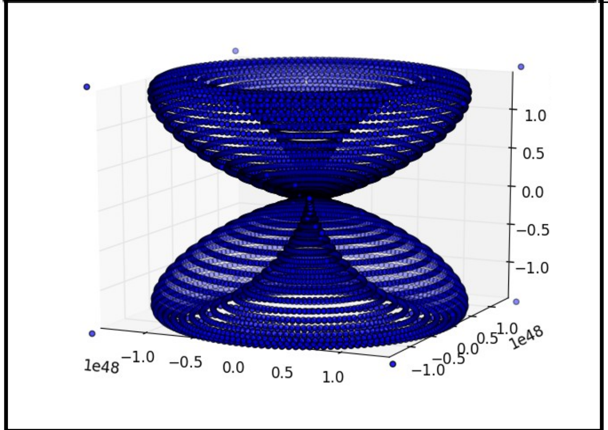


from S_{tot} = 1, m = ± 1
to S_{tot} = 0, m = 0



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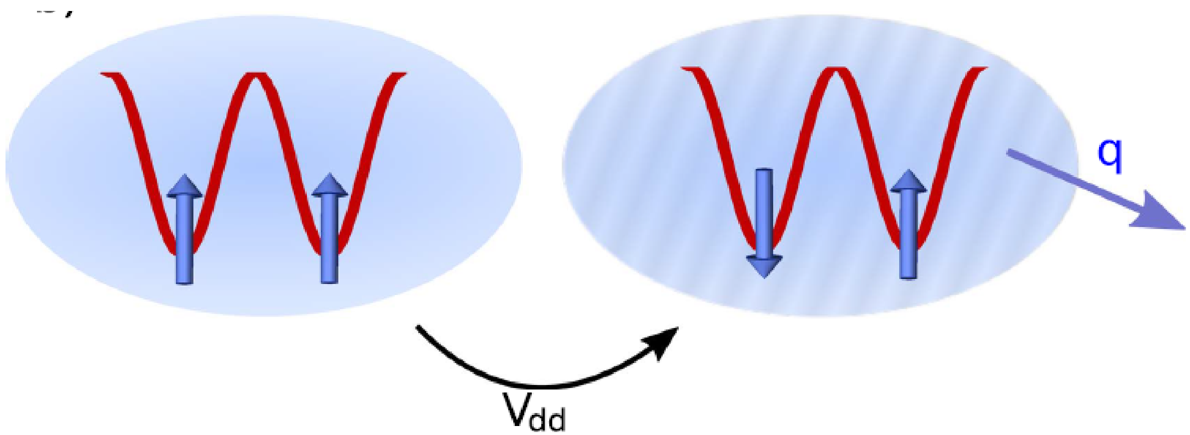

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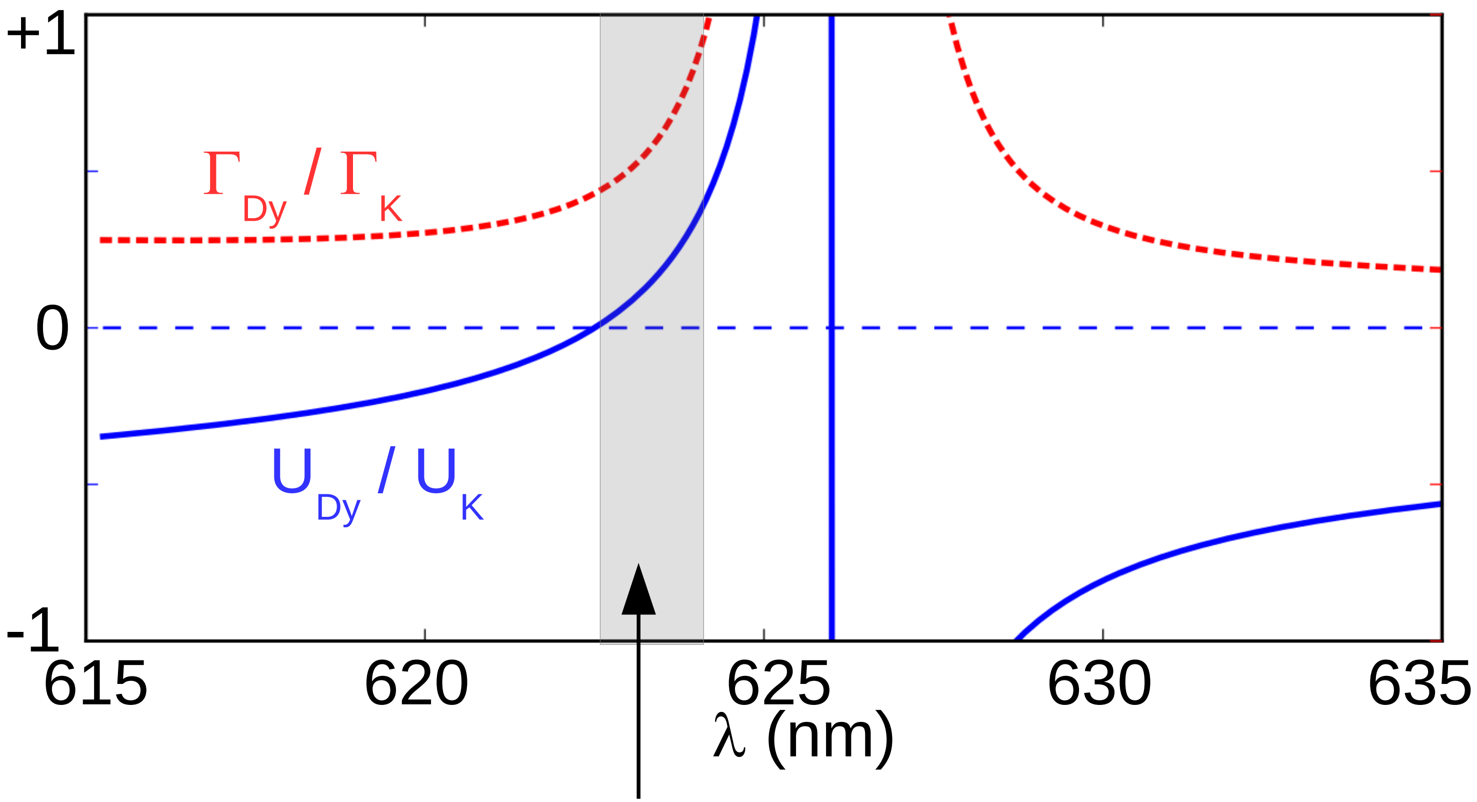
Lattice potential: strong effect on the bath

^{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**



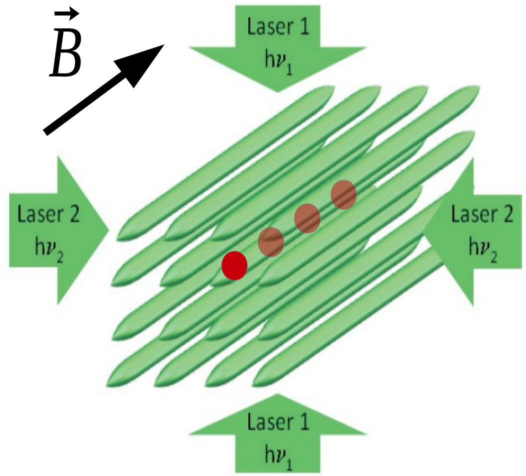
- Mott regime for spin chain
- **3D coherence for bosonic bath**
- Light scattering sufficiently low

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



^{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

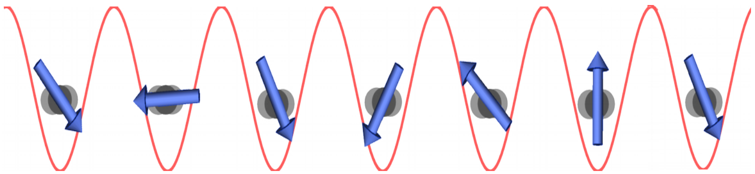
U_{Dy} = (12x12x3.5) E_r^{Dy}

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

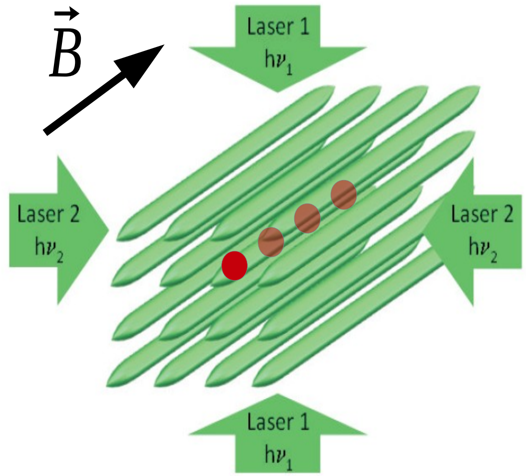
Chain Length : 7



[1]appendix ; and Gerbier 2006

Convergence to a thermal state of the collective spin

^{40}K - ^{164}Dy



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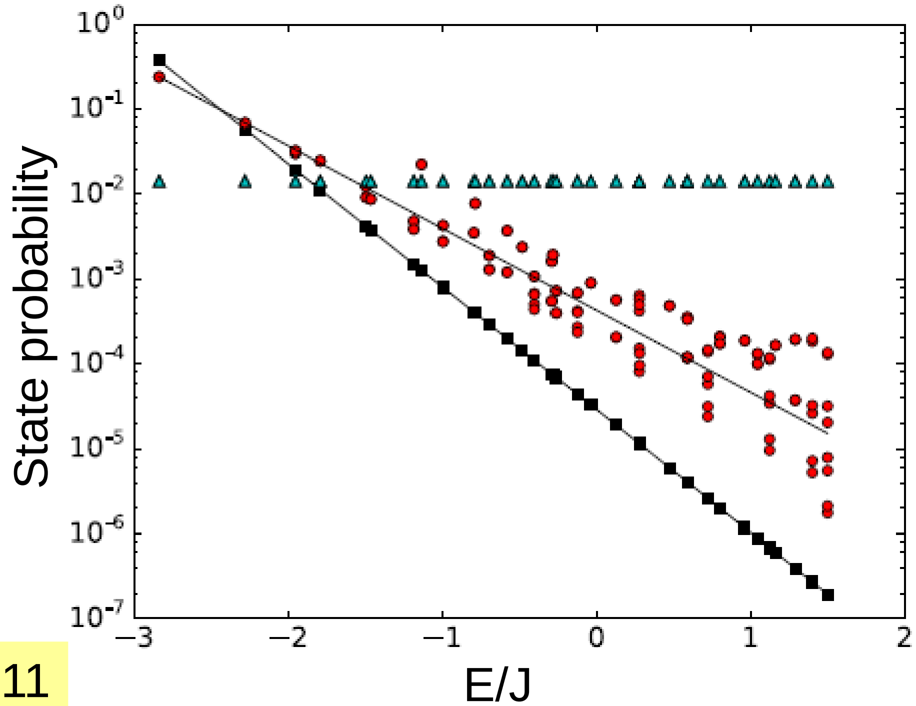
Occupation of the 2^7 = 128 spin chain eigenstates



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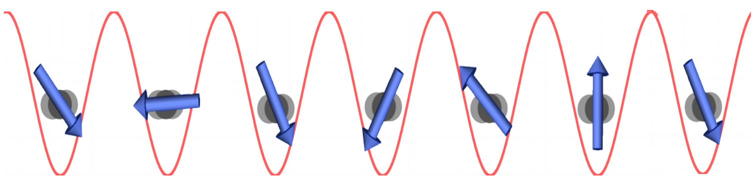
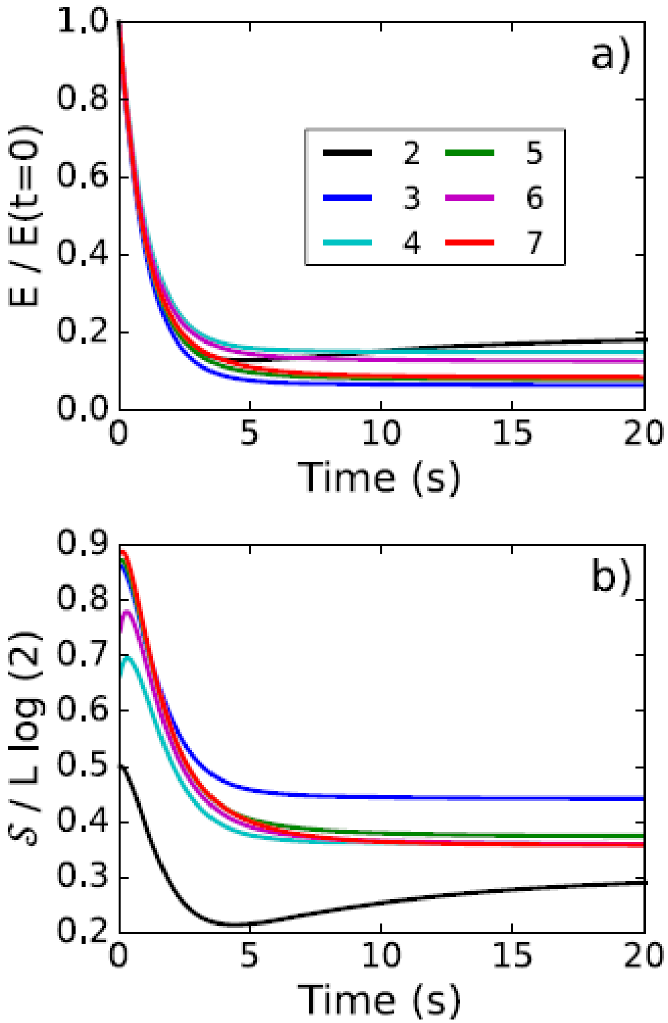


[1]appendix ; and Gerbier 2006
[2]Here: initial magnetization 0

Collective spin dynamics

Initially balanced spin mixture



Energy

Von Neumann spin entropy

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

Collective spin dynamics

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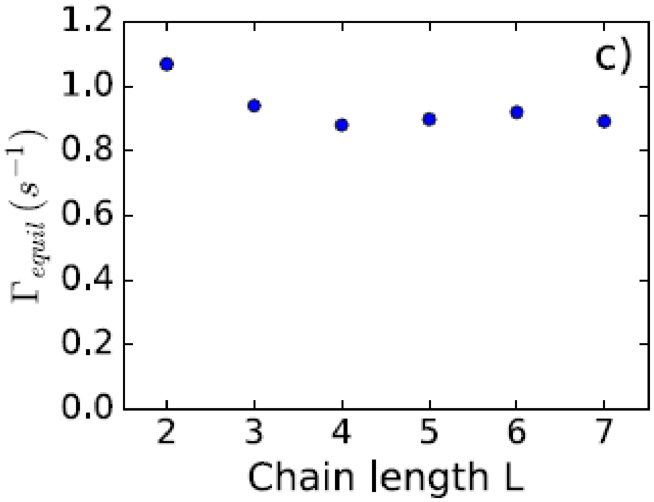

Equilibration rate tends to a value roughly independent on chain length
and on preparation condition

Collective spin dynamics

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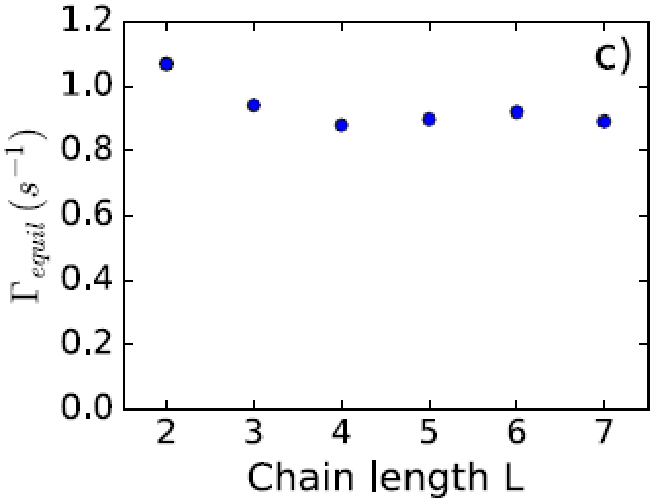
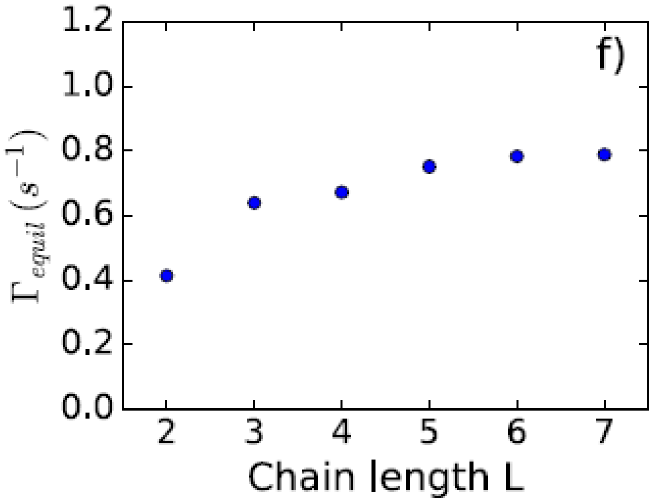


Initially free spin mixture



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

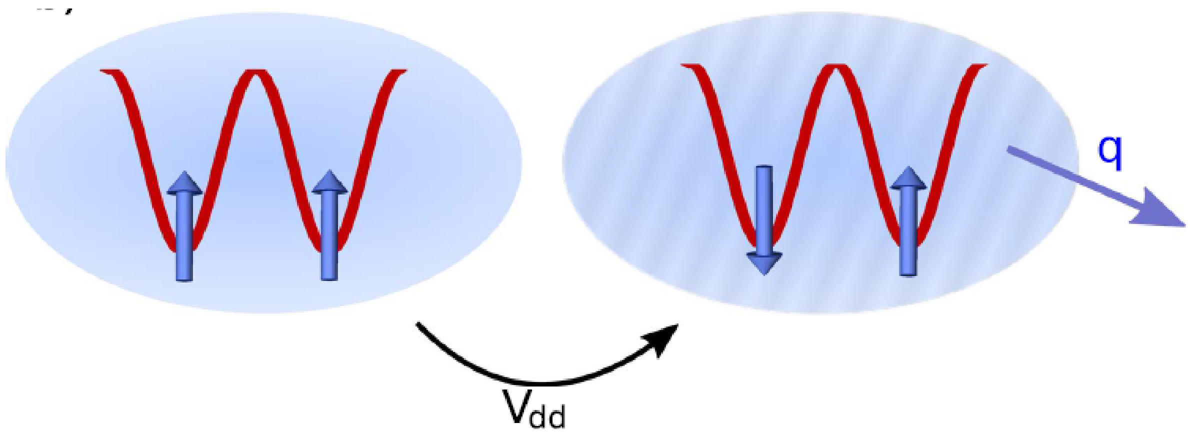
Limited by restraining ourselves to very low quantum depletion (5%)
Faster dynamics plausible in deeper bath lattices,
but this leaves the validity range of the Bogoliubov description

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

Conclusion and outlook

Dissipative preparation of strongly correlated spin states



Use of an atomic bath

Spin chain thermalization with free magnetization

The scheme relies on spin-orbit coupling in Vdd

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

Spielman, Zwierlein, Zhang, Pan ...

A formalism describing dipole-coupled Mott spin chain and SF 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)

→ **perspective**: set the formalism for a conducting **fermionic bath** (large density of states at the Fermi energy, with large excitation wavevector)

Thank you for your attention

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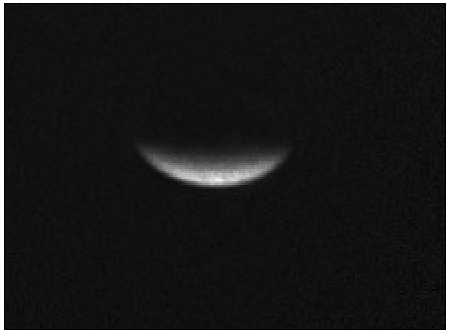
ANR, DIM Nano'K, DIM Sirteq, IFRAF, IFCPAR

Magnetic Quantum gases group at LPL (Laburthe-Tolra's group):

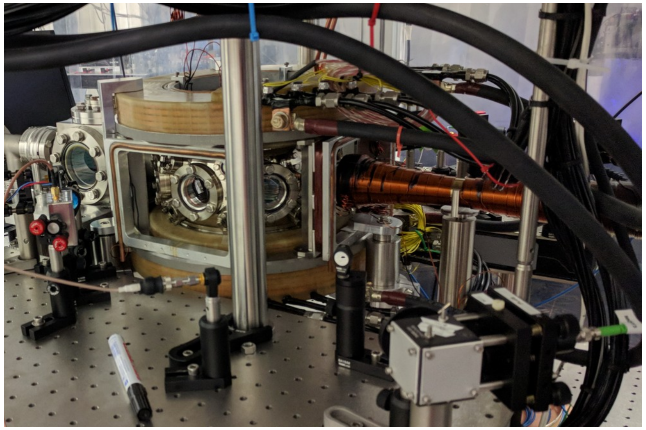
Two experiments : Strongly dipolar Chromium gases
SU(N ≤ 10) symmetric Strontium gases – new machine
One theory team on large spin quantum gases

WE LOOK FOR A POST-DOC ON THE STRONTIUM MACHINE
A PHD ON THE CHROMIUM MACHINE

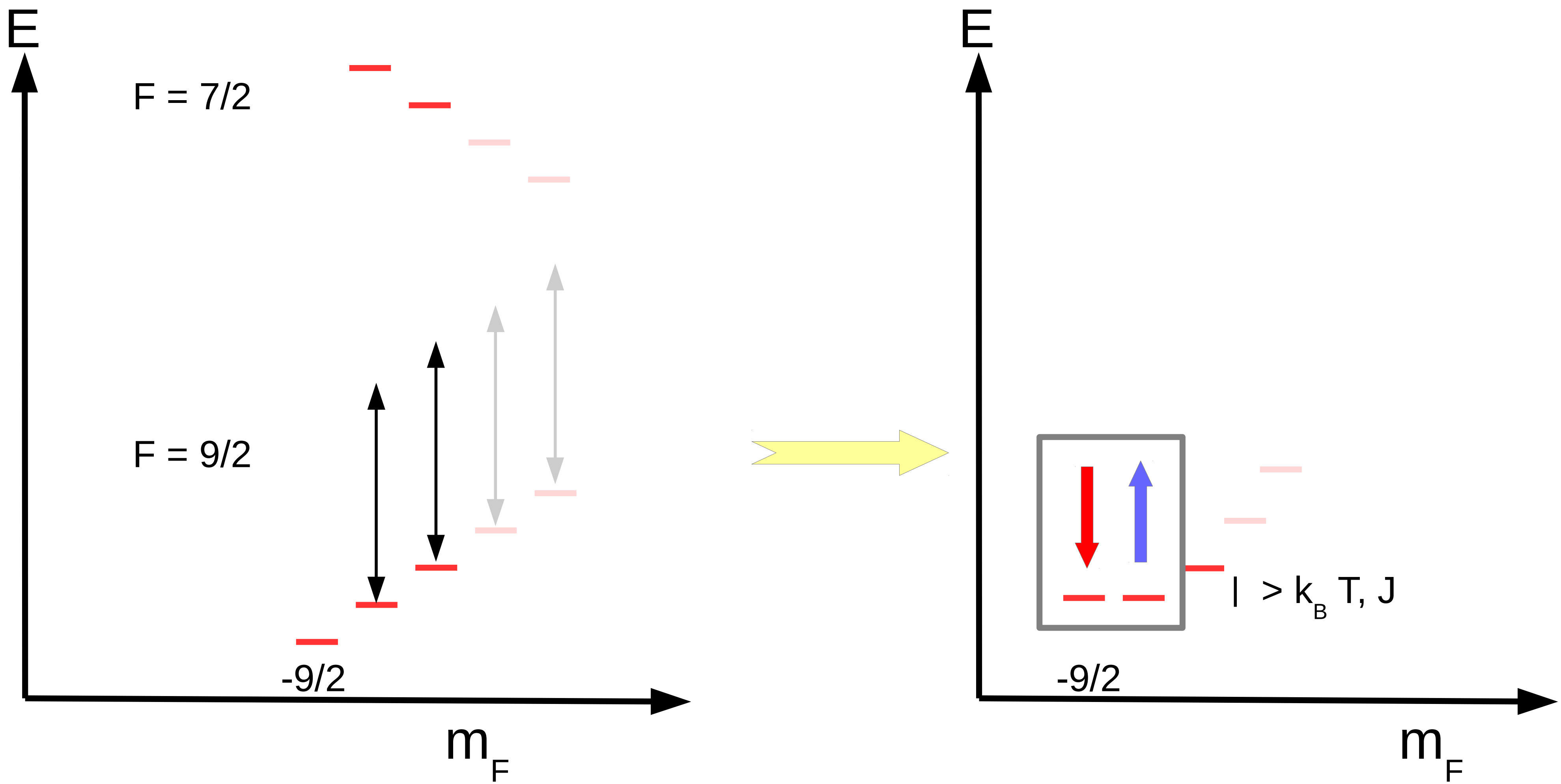


Narrow-line Sr MOT and
dipole trap: spring 2018

Objectives: SU(N) Quantum magnetism
Narrow-line manipulation tools



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

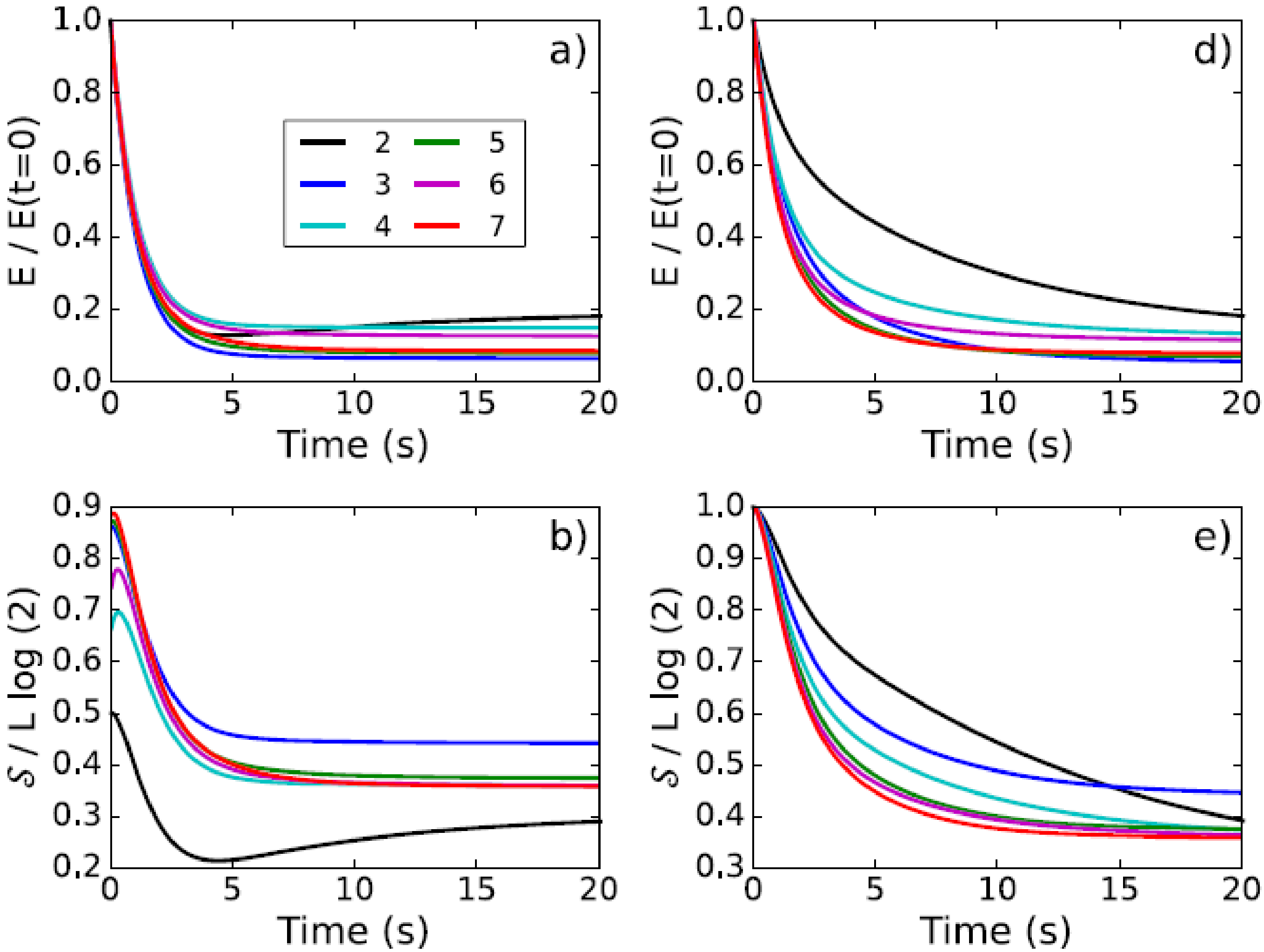
Hyperfine state mixing 0,004

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

Collective spin dynamics

Initially balanced spin mixture

Initially free spin mixture



Energy

Von Neumann spin entropy

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

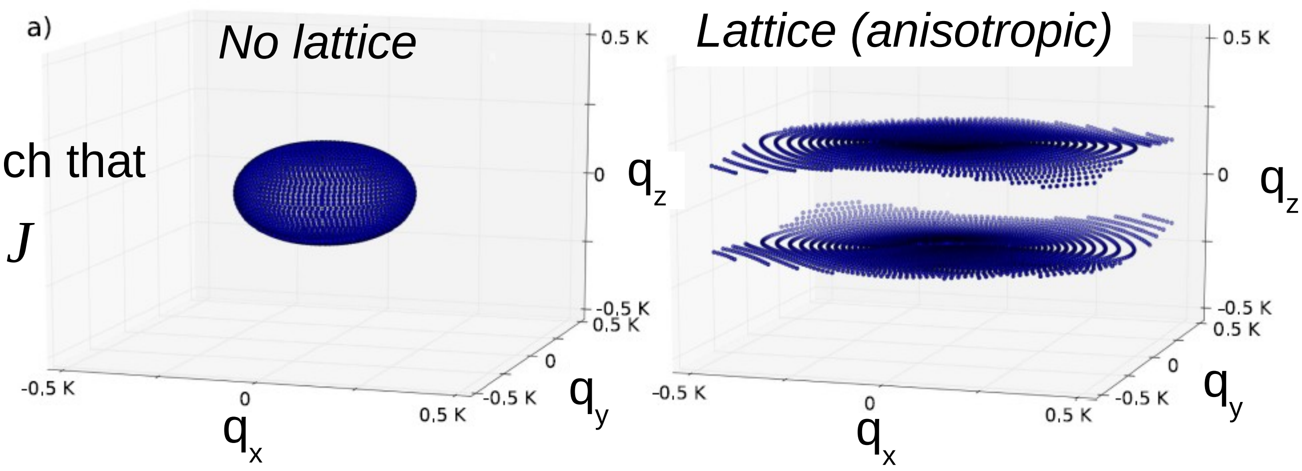
Lattice potential: strong effect on the bath

Enhanced interactions : very sensitive to anisotropies

Dispersion relation : wavevectors and density of states

Wavevectors such that

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

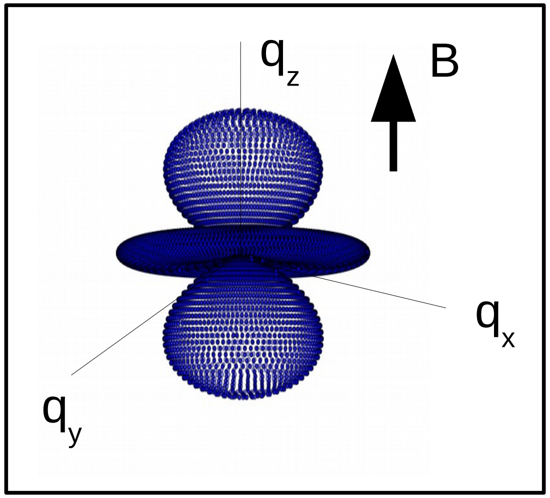


Coupling strength for a given mode q

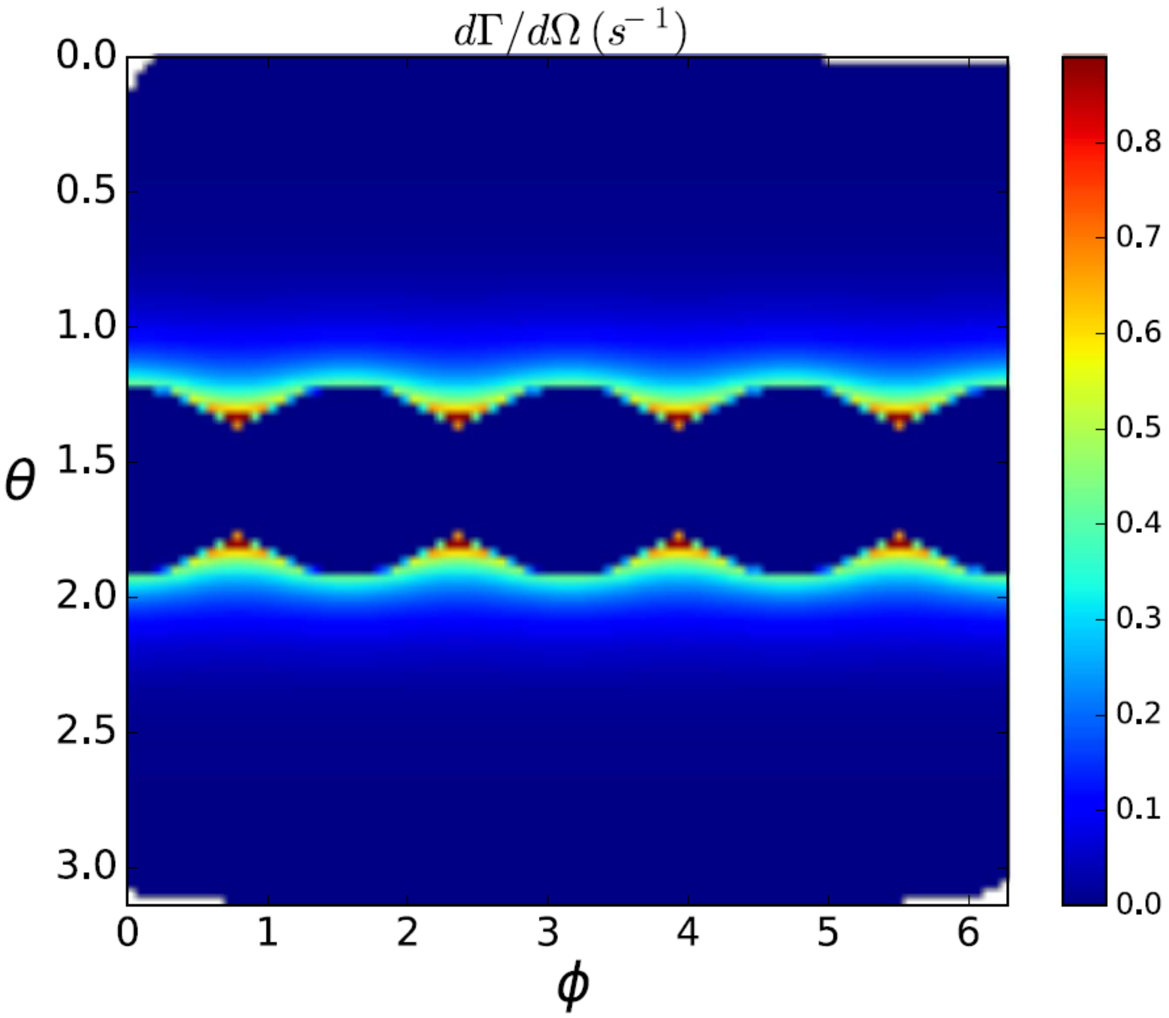
Mode decomposition onto plane waves vs Vdd anisotropy

Vdd(q) :

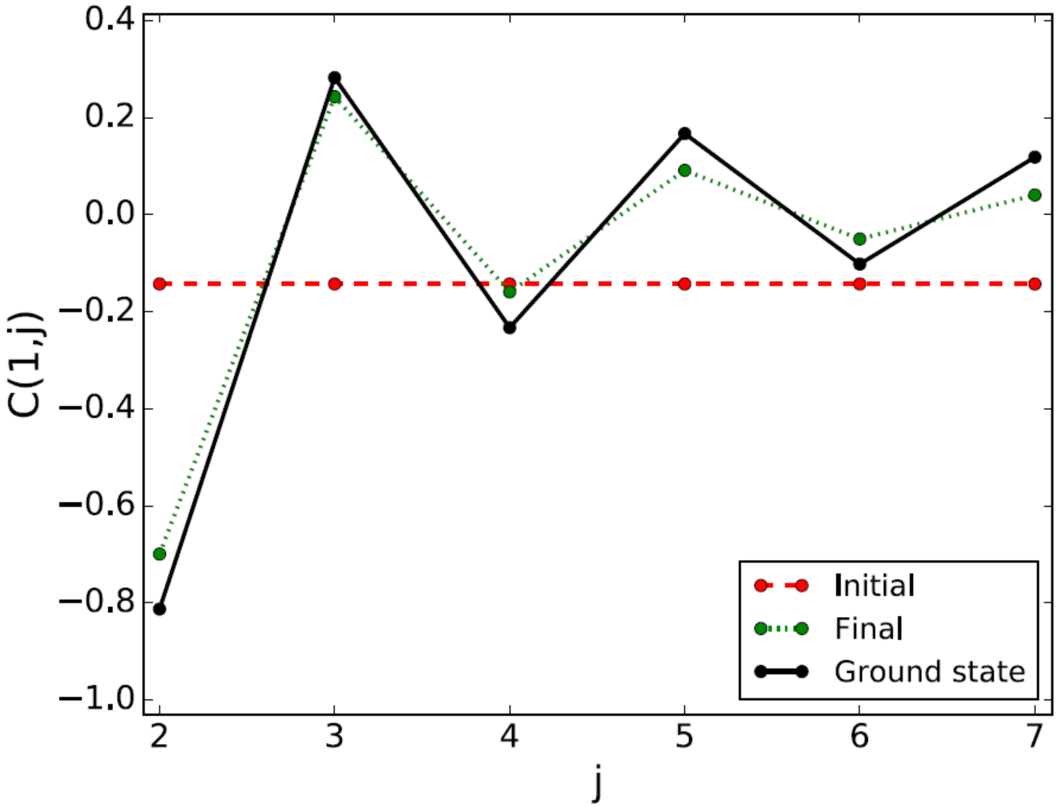
Lobes of opposite sign



Radiation diagram in lattice

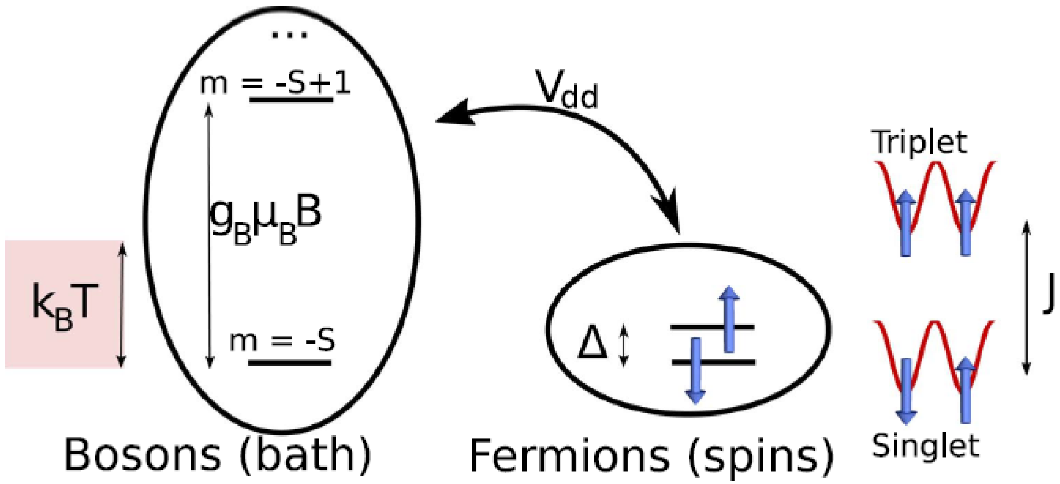


Correlations

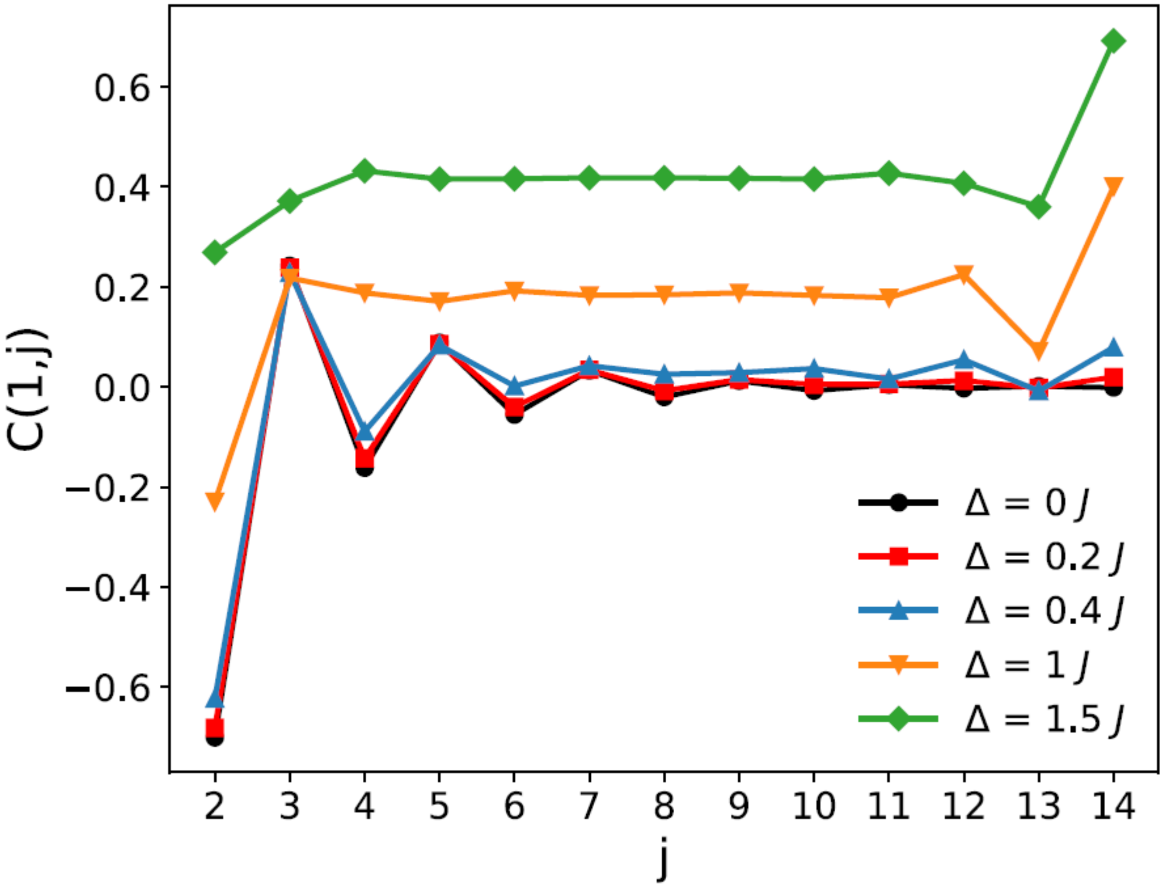


$$C(i,j) = 4\langle \Sigma^z_{\mathrm{eff},i} \Sigma^z_{\mathrm{eff},j} \rangle$$

Robustness of the AF state to a bias Δ



0.2 J ~ 0.4 mG



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