Quantum simulations for dipolar spin systems in optical lattices

Lucas Gabardos (PhD), Steven Lepoutre (post doc – now MCF Orsay),
Bruno Laburthe-Tolra , Laurent Vernac
(Laboratoire de Physique des Lasers, Villetaneuse)

Bihui Zhu (ITAMP, Harvard-Smithsonian Center for Astrophysics)
Johannes Schachenmayer (CNRS Strasbourg), Ana Maria Rey (JILA, Colorado)

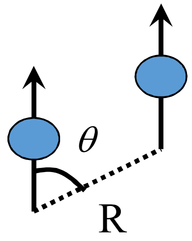
Petra Fersterer, P. Blair Blakie (University of Otago)
Arghavan Safavi-Naini, A.M. Rey (JILA, Colorado)

Tommaso Roscilde (ENS Lyon)

Chromium atom: a dipolar species

Dipole-dipole interactions

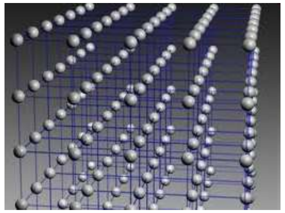
$$V_{dd} = \frac{\mu_0}{4\pi} S^2 \left(g_J \mu_B\right)^2 \left(1 - 3\cos^2(\theta)\right) \frac{1}{R^3}$$



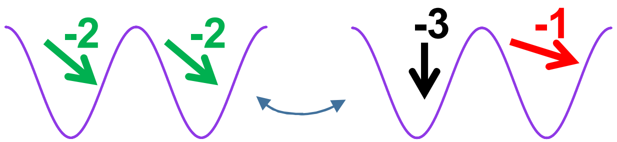
Long range Anisotropic

$$\hat{H}_{dd} \propto S_{1z} S_{2z} - \frac{1}{4}\left(S_{1+} S_{2-} + S_{1-} S_{2+}\right)$$

Ising Exchange



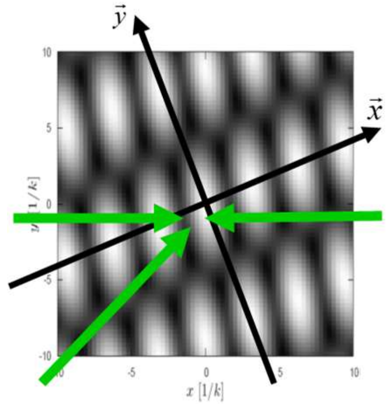
In lattice with one atom per site spin dynamics is purely dipolar



dipolar atomic systems: Stuttgart (Dy), Innsbruck (Er), Stanford (Dy), Paris (Dy), Harvard (Er),…

Quantum Magnetism in 3D lattices: preparation

Rectangular lattice of anisotropic sites



deep 3D lattice → strong correlations, Mott transition

One atom per site ensures pure dipolar interactions at high lattice depth

Shallow 3D lattice → superfluid state

Competition between dipolar interactions, tunneling and tunneling assisted superexchange

Outline

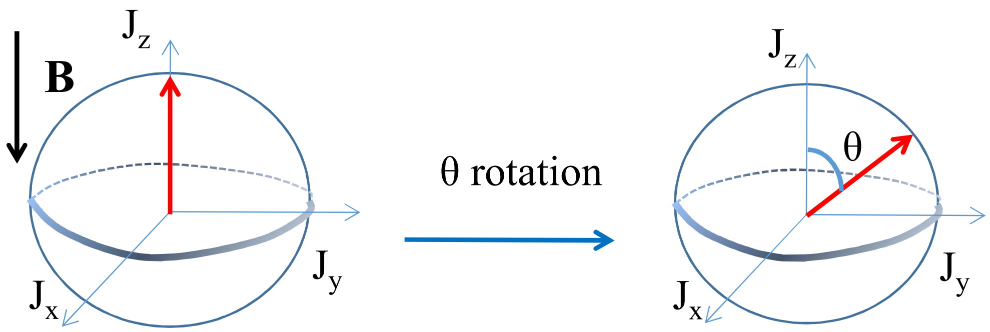
Out of equilibrium spin dynamics

Towards (?) adiabatic production of the ground state of a transverse Hamiltonian

Out of equilibrium dynamics: Principle of the experiments

Spin =3 for chromium

1- Excite the spins



$$\Psi_{initial} = \left| -3_z, -3_z, \ldots., -3_z, -3_z \right\rangle$$

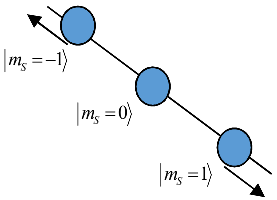
$$\Psi_{(t=0)} = \left| -3_\theta, -3_\theta, \ldots., -3_\theta, -3_\theta \right\rangle$$

2- Free evolution under the effect of interactions

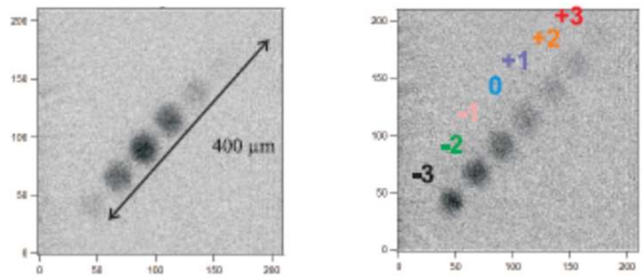
$$\Psi_{(t=0)} \rightarrow \Psi(t)$$

3- Measurement of Spin populations

Stern-Gerlach separation:
(magnetic field gradient)

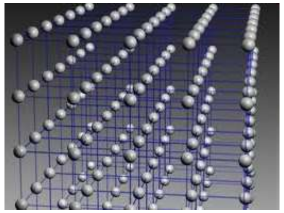


an evolution of spin populations prove the effect of interactions



Out of equilibrium dynamics characterized by the change of the populations of the Zeeman components

Spin dynamics in lattice: comparison with simulations



10000 atoms!

NO exact simulation available beyond 15 atoms: problem with border effects!

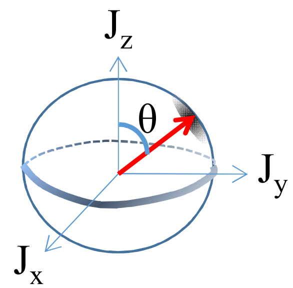
Mean field simulations

Quantum simulations (Generalized Dichotomized Truncated Wigner Approximation)
developed by J. Schachenmayer

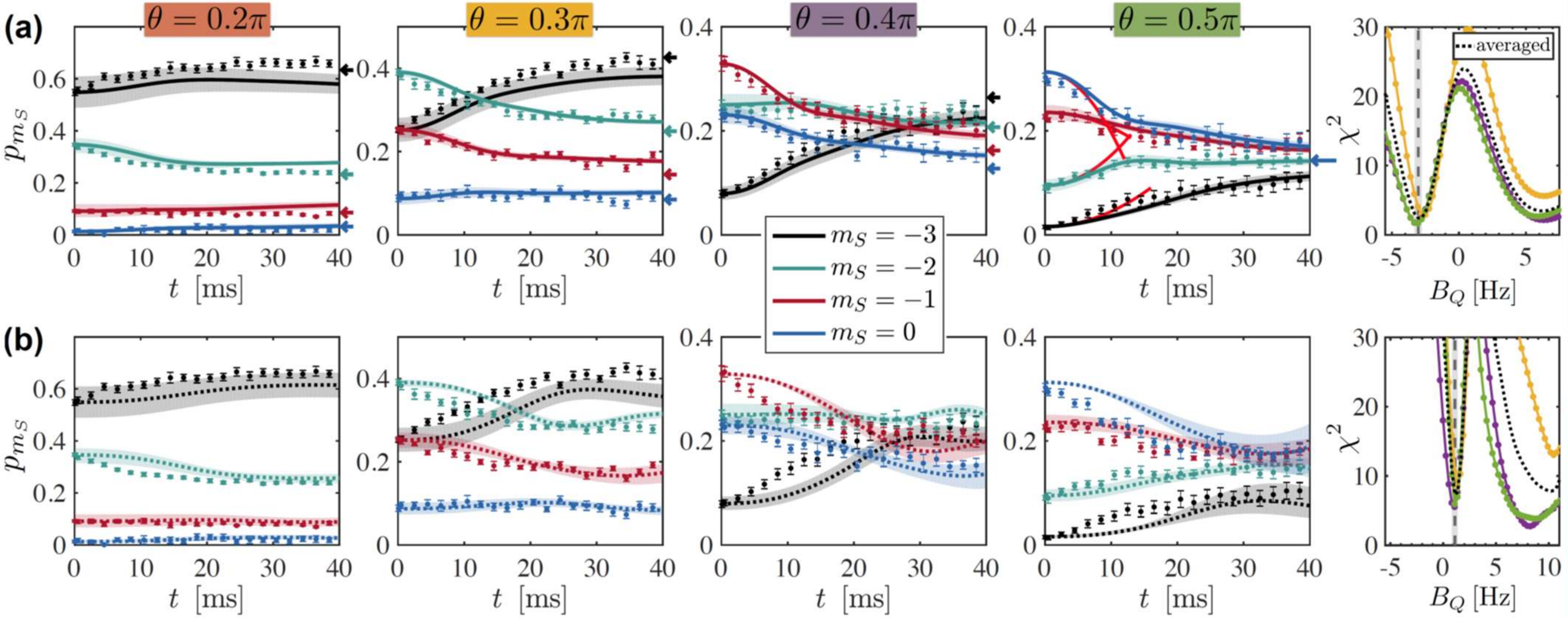
Short time exact results: $\hat{H} = \sum_{i>j}^{N} V_{ij} \left[\hat{S}_i^z \hat{S}_j^z - \frac{1}{2} \left(\hat{S}_i^x \hat{S}_j^x + \hat{S}_i^y \hat{S}_j^y \right) \right]$

$p_{m_S}(t) = p_{m_S}(0) + \sin[\theta]^4 \alpha_{m_S}(\theta) t^2 V_{\text{eff}}^2 \qquad V_{\text{eff}} \equiv \sqrt{\sum_{i,j\neq i}^{N} V_{ij}^2 / N}$

Spin dynamics in lattice: comparison with simulations



Quantum simulations (GDTWA)



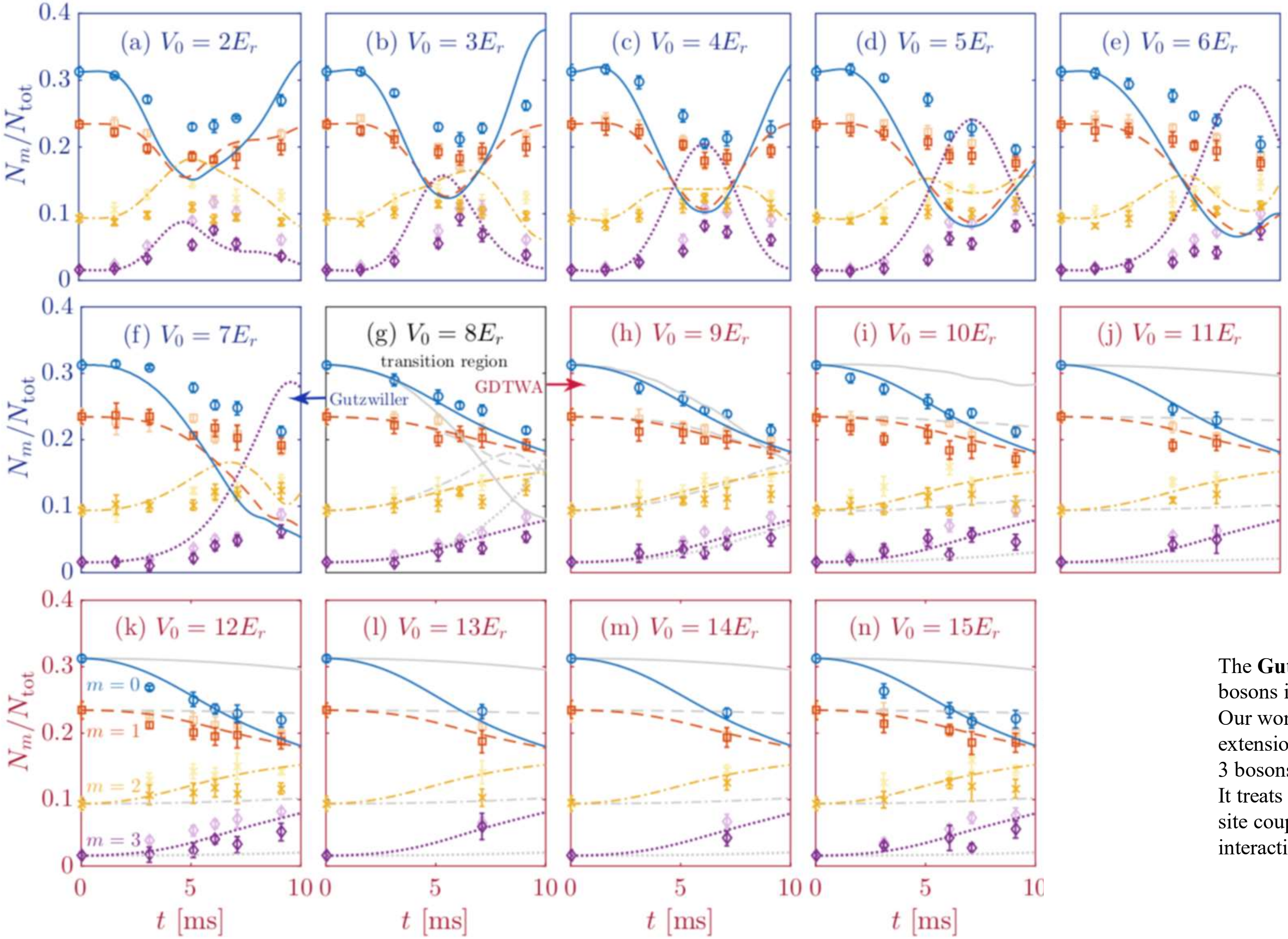
Mean field simulations

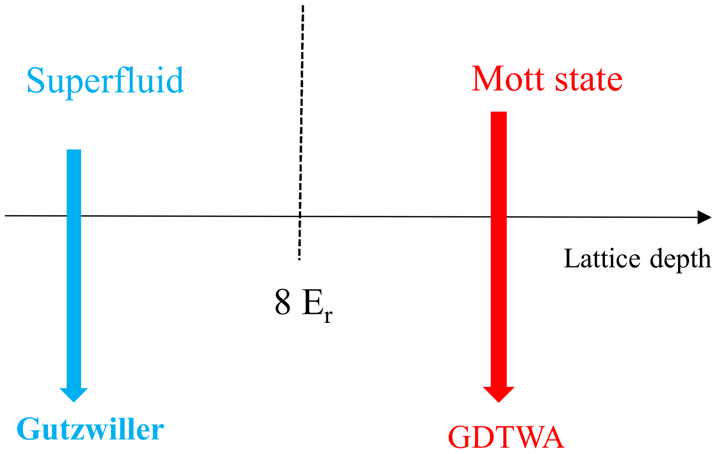
The quantum simulations agree well with data: a very good test for GDTWA for large atom numbers

Lepoutre et al, Nature Com (2019)

Spin dynamics in lattice as a function of lattice depth

Competition between dipolar interactions, tunneling and tunneling assisted superexchange





The **Gutzwiller** method aim to describe bosons in an optical lattice. Our work is the first to consider the extension of this method to describe spin-3 bosons with dipole-dipole interactions. It treats onsite terms exactly and inter-site couplings (due to tunneling and interactions) at the meanfield level.

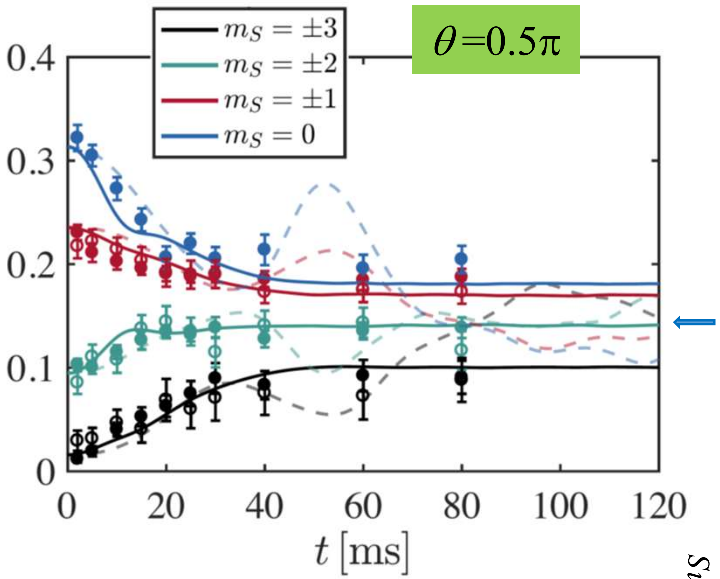
Petra Fersterer et al, arXiv:1905.06123 (2019)

Spin dynamics in lattice: Quantum Thermalization

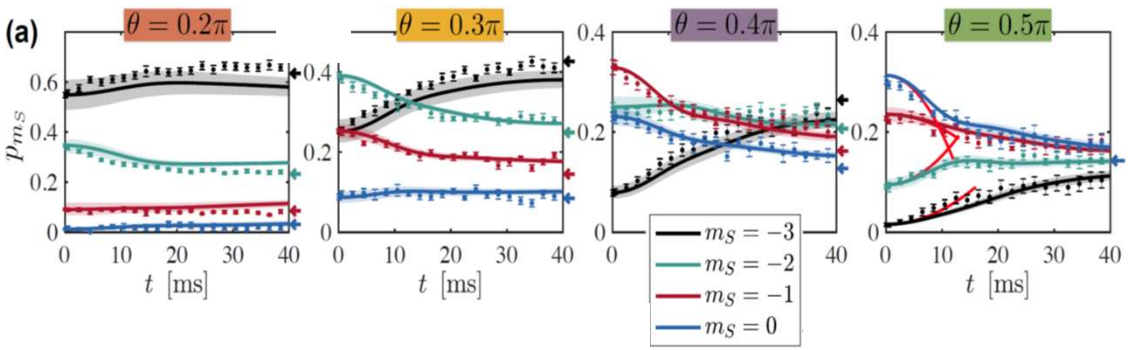
1- Our data show that spin dynamics stops in about 60-80 ms

in agreement with quantum simulations (solid lines)

while mean field simulations show revivals at this time scale (dashed lines)



2- Asymptotic experimental populations are close to population distributions maximizing entropy at fixed magnetization

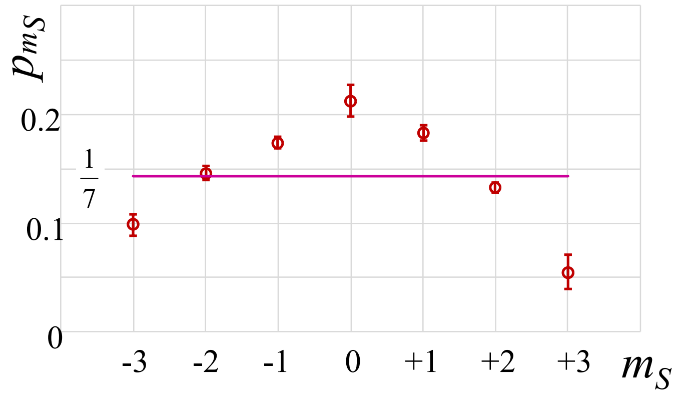


3- A more elaborated model includes the one body physics quadratic energy term

$$E(m_s) = B_Q m_s^{\;2}$$

$$\hat{\rho} = \exp[-\beta\hat{H}] \approx Id - \beta\hat{H}$$

$$\boxed{P_{m_s} = \frac{1}{7}\left(1 + \beta B_Q(4 - m_s^{\;2})\right)}$$



Quantum Thermalization at a few nK

Lepoutre et al, Nature Com (2019)

A long-range interacting many particle isolated system which internally thermalizes through entanglement build-up, and develops an effective thermal-like behavior through a mechanism which is purely quantum and conservative

Other experiments: Greiner: few ½ spins, superexchange processes
B. Lev: Dy atoms, thermalization through collisions

Adiabatic production of the ground state of an Hamiltonian: principle

$$\hat{H}_{\mathrm{XXZ}} = \sum_{i>j}^{N} J_{i,j}\left(\Delta \hat{s}_i^z \hat{s}_j^z + \left(\hat{s}_i^x \hat{s}_j^x + \hat{s}_i^y \hat{s}_j^y\right)\right) + \mu\, B_z \sum_{i=1}^{N} \hat{s}_i^z + \mu\, B_x \sum_{i=1}^{N} \hat{s}_i^x$$

Theoretical model

longitudinal transverse

$$\hat{H}_{\mathrm{tot\ \ rotating\ \ frame}} = \sum_{i>j}^{N} V_{i,j}\left(\hat{s}_i^z \hat{s}_j^z - \frac{1}{2}\left(\hat{s}_i^x \hat{s}_j^x + \hat{s}_i^y \hat{s}_j^y\right)\right) + \hbar\delta \sum_{i=1}^{N} \hat{s}_i^z + \hbar\Omega_{RF} \sum_{i=1}^{N} \hat{s}_i^x$$

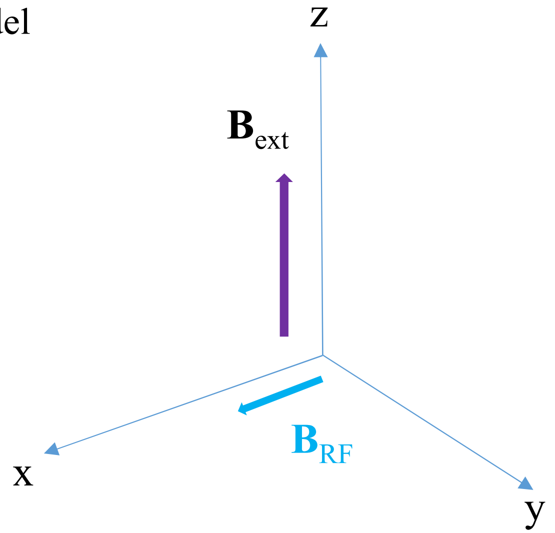
Experimental realization

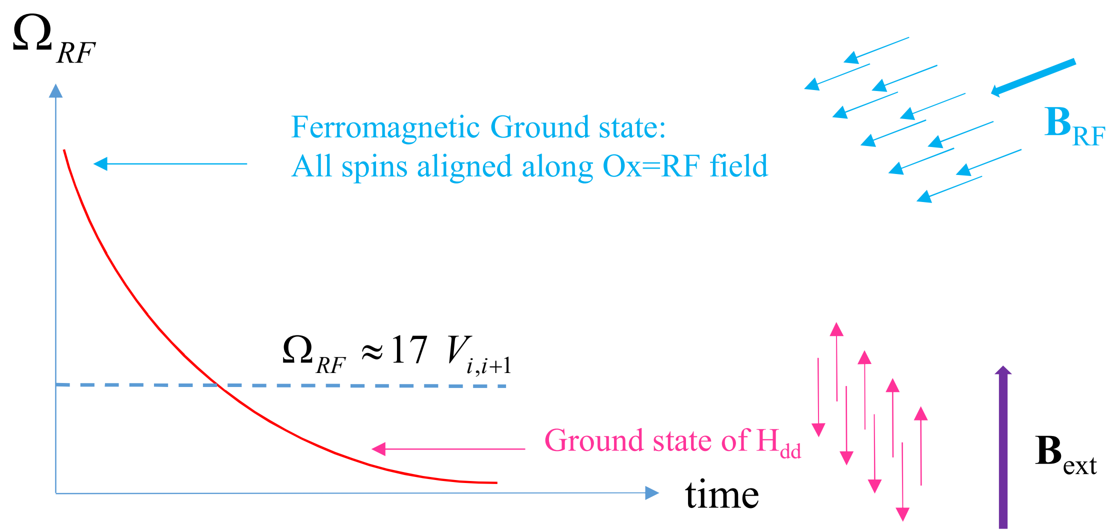
$$V_{i,j} = \frac{\mu_0}{4\pi}(g\mu_B)^2 \frac{1-3\cos^2\theta_{ij}}{r_{ij}^{\ 3}}$$

H_{dd} = Dipolar Hamiltonian

$$\delta = \omega_{\mathrm{Larmor}} - \omega_{RF}$$

Ω_{RF} : RF Rabi frequency

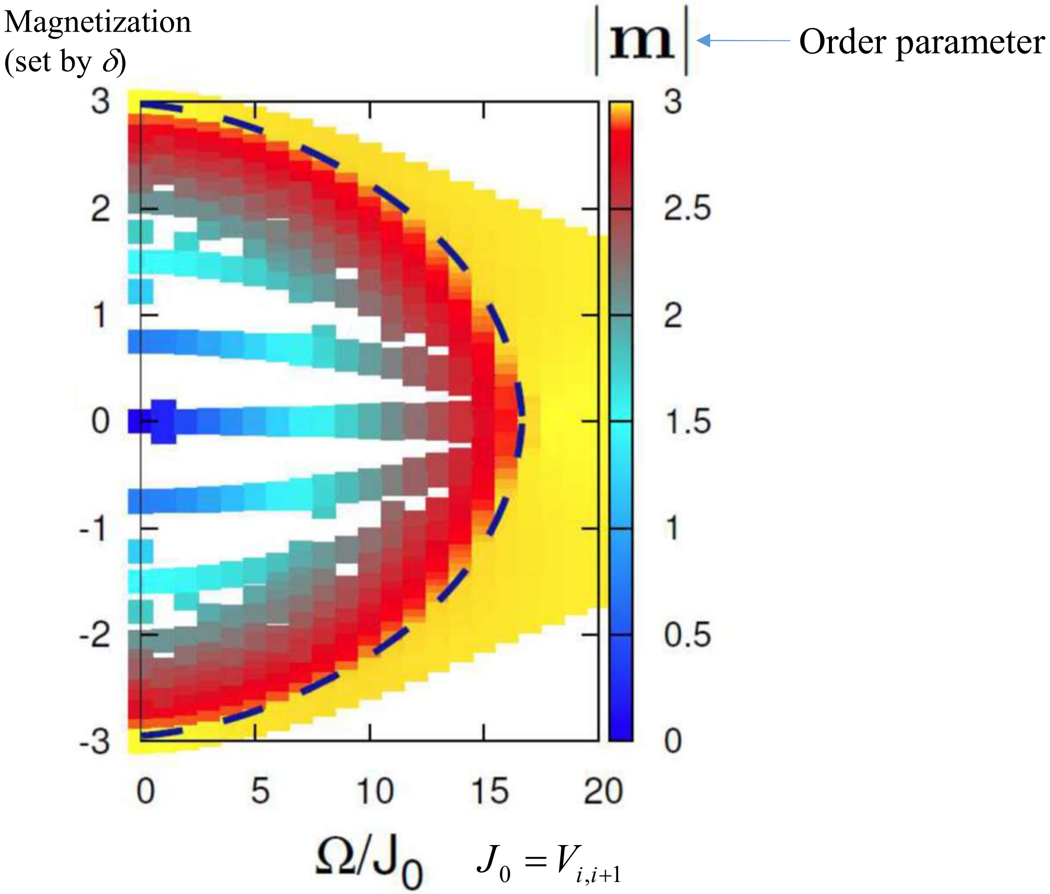




Principle of the experiment:
Perform an adiabatic passage
with an easy knob (RF amplitude)
from a polarized state to a non trivial
ground state of the dipolar Hamiltonian

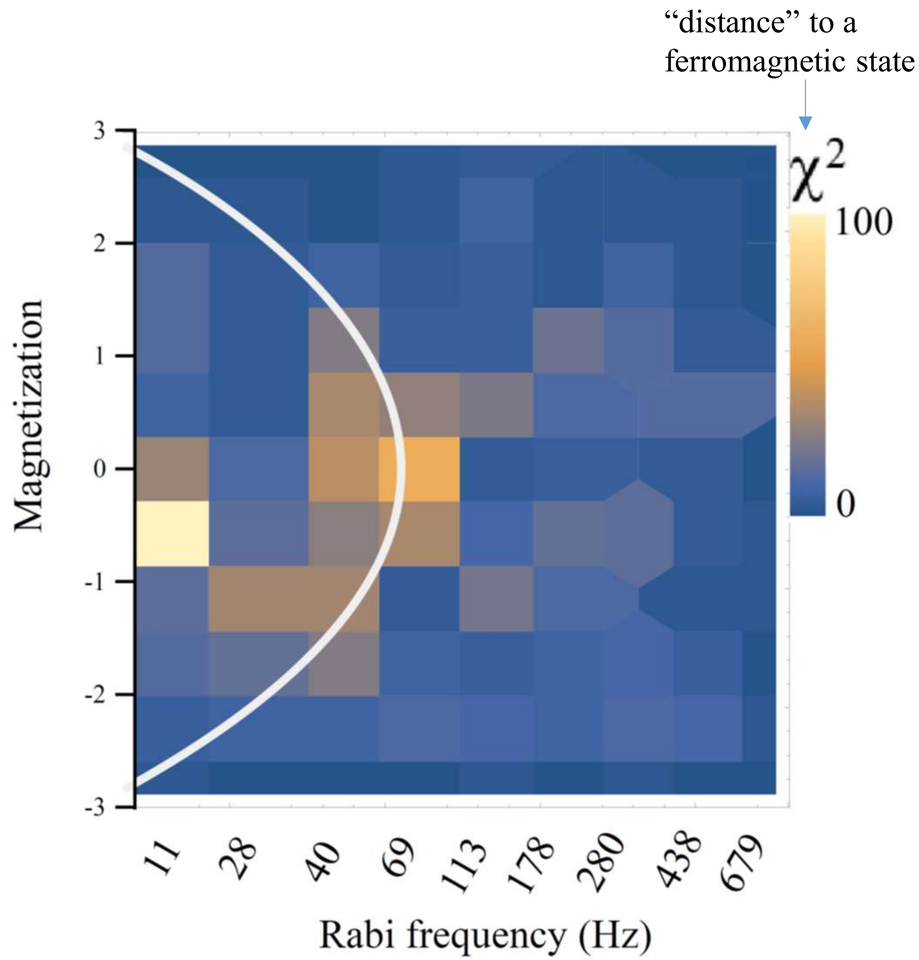
Adiabatic production of the ground state of an Hamiltonian: results (preliminary!)

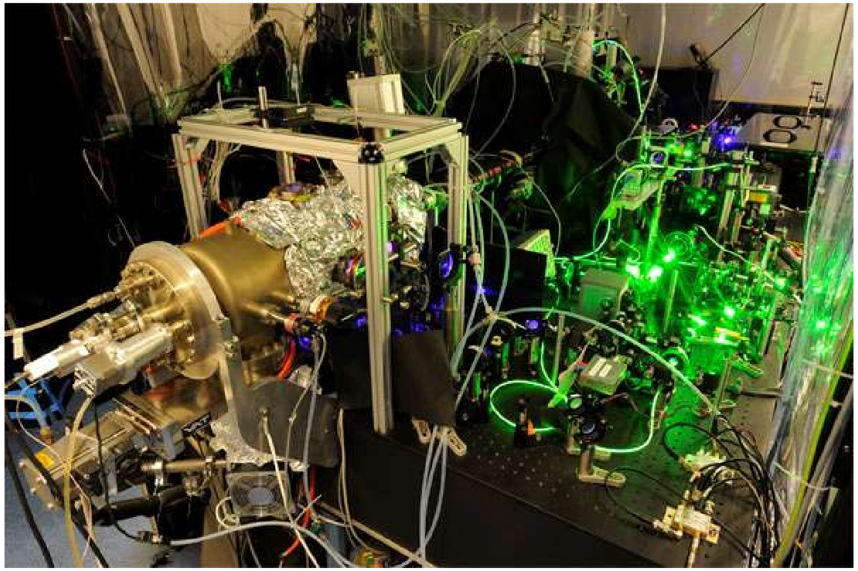
Theoretical prediction (Tommaso Roscilde)
mean field calculations

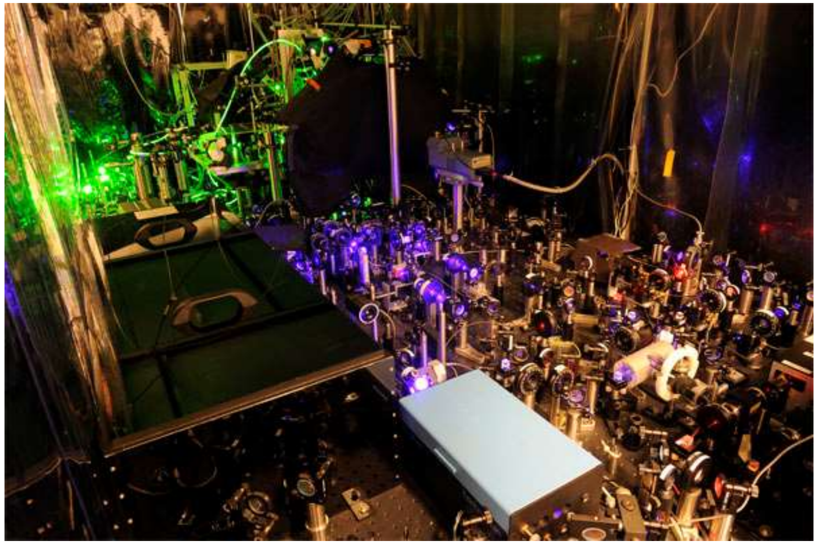


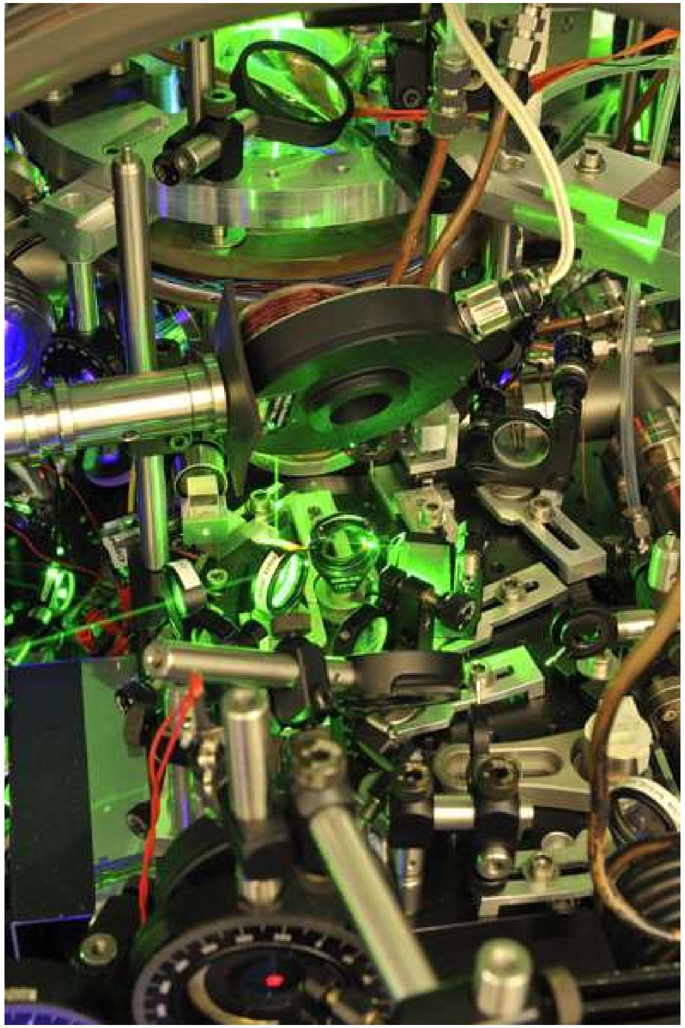
Ω_{RF} : RF Rabi frequency

Experimental measurements









thank you for your attention!

We are looking for a post doc!