

Taming Atomic Giants

How Rydberg atoms became veritable quantum simulators



Matthias Weidemüller

<http://physi.uni-heidelberg.de/Forschung/QD>



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PHYSIKALISCHES
INSTITUT



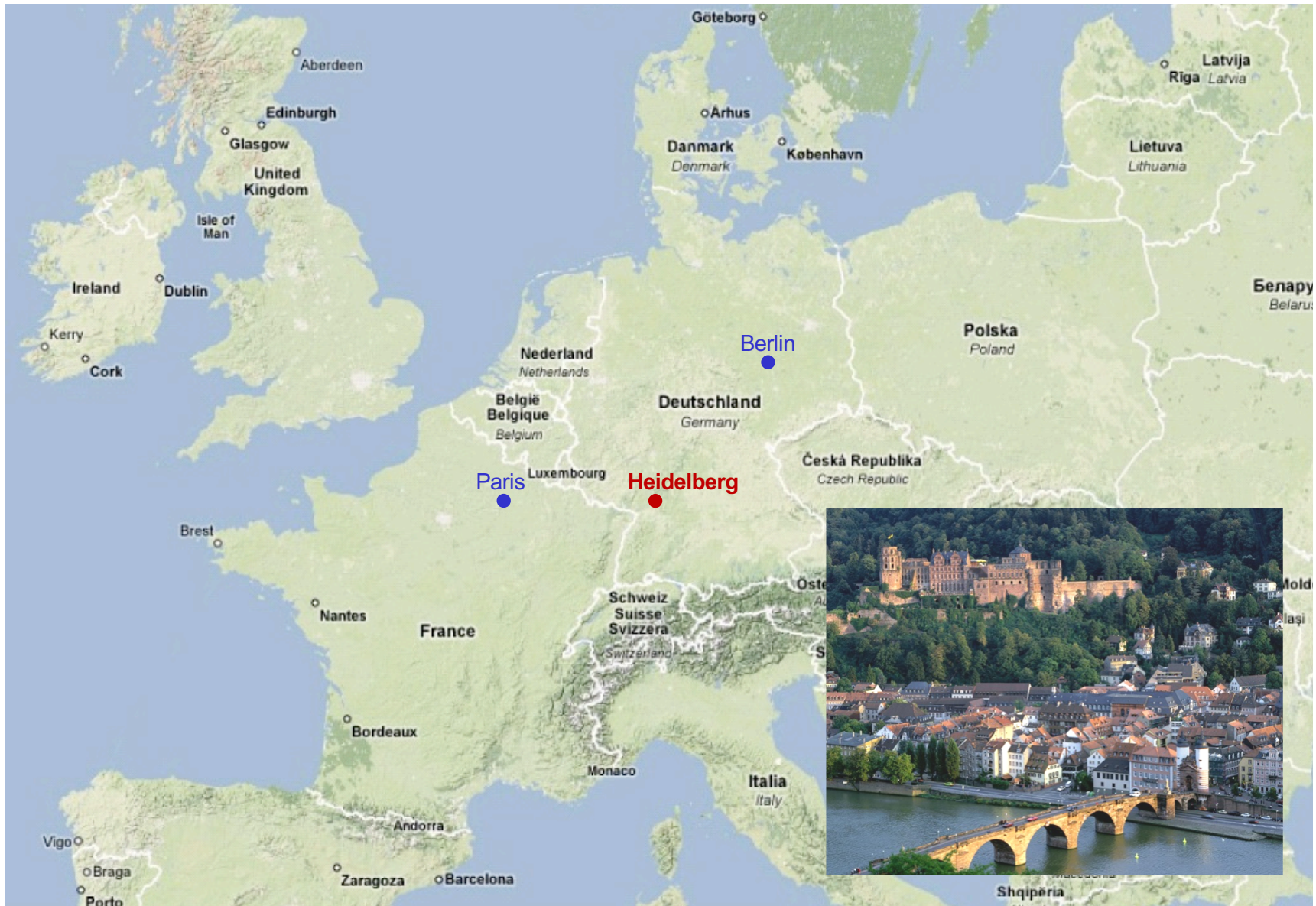
Center for
Quantum Dynamics



中国科学技术大学
University of Science and Technology of China



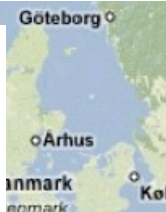
HEFEI NATIONAL LABORATORY
FOR PHYSICAL SCIENCES
AT THE MICROSCALE



RUPRECHT-KARLS- UNIVERSITÄT HEIDELBERG

University of Excellence

Semper apertus. Since 1386.



Natural Sciences, Mathematics, and Computer Sciences



Heidelberg University's traditionally outstanding natural sciences are predominantly located at the Neuenheimer Feld campus. This spatial and academic closeness is highly attractive to researchers worldwide.

Biosciences
Chemistry and Earth Sciences
Mathematics and Computer Sciences
Physics and Astronomy

Liberal Arts and Theology



Pictures and language, religion and philosophy, history and the present - the magnitude of the subjects and the interdisciplinary questions with which they are considered mutually furthers and supports scientific inquiry in the liberal arts.

Philosophy
Modern Languages
Theology

Law, Economics, and Social Sciences



The Faculty of Law is one of the founding faculties of the University. The closeness of economics and the social sciences is underscored by their shared location on the Bergheim Campus.

Law
Economics and Social Sciences
Behavioural and Cultural Studies

Medicine



There are two medical faculties at Heidelberg University. The high standard of research and training combines with a highly performative patient care based on the newest scientific advances.

Medical Faculty of Heidelberg
Medical Faculty of Mannheim



11 Nobel Prize winners taught or conducted their research as professors at Heidelberg University :

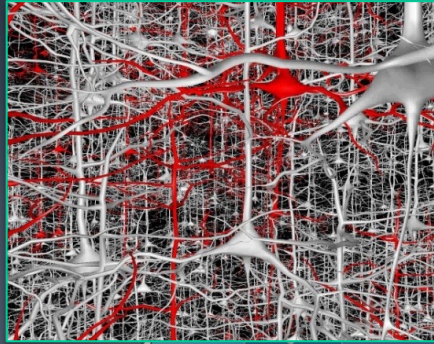
2014: Stefan Hell, chemistry
2008: Harald zur Hausen, medicine
1991: Bert Sakmann, medicine
1979: Georg Wittig, chemistry
1963: Hans Jensen, physics
1963: Karl Ziegler, chemistry
1954: Walter Bothe, physics
1938: Richard Kuhn, chemistry
1922: Otto Meyerhof, medicine
1910: Albrecht Kossel, medicine
1905: Philipp Lenard, physics

45 other Nobel laureates' names are associated with either Heidelberg University or the city of Heidelberg (among them: Ted Hänsch and Wolfgang Ketterle)



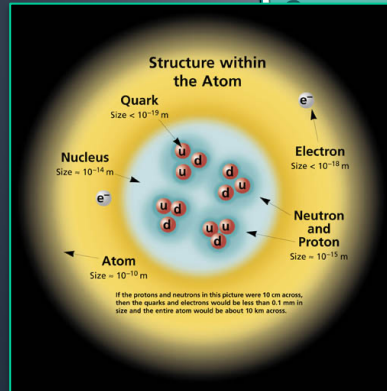


- **QS World University Ranking 2015**
No. 2 in Germany
No. 20 in Europe
No. 66 worldwide
- **Times Higher Education Ranking 2015**
No. 2 in Germany
No. 13 in Europe
No. 37 worldwide
- **Shanghai Ranking of World Universities 2016**
No. 1 in Germany
No. 10 in Europe
No. 46 worldwide



100.000.000.000.000 synapsis

THE
COMPLEX



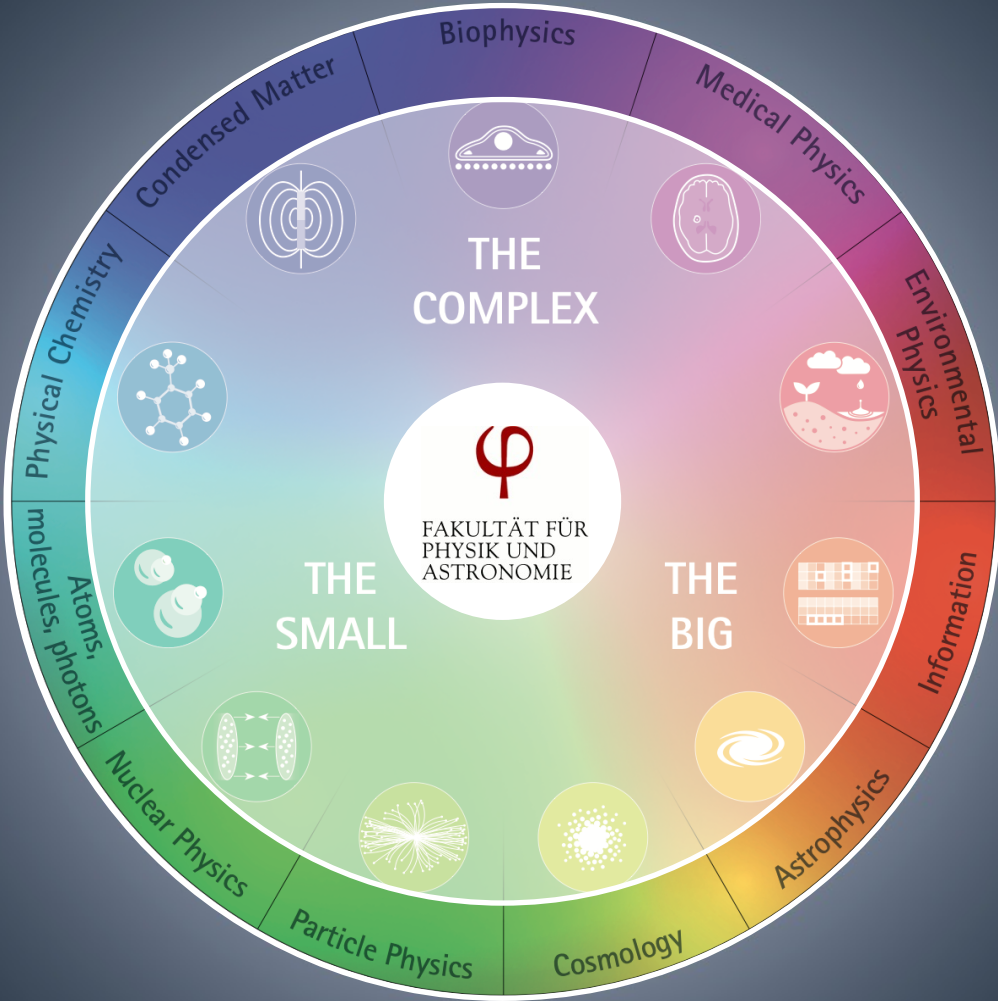
0.00000000000000000001 meter

THE
SMALL

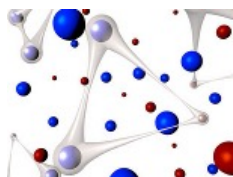
THE
BIG



100.000.000.000.000.000.000.000 stars



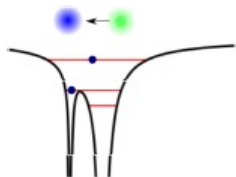
Bose-Fermi (Cs-Li) Mixture



Bing Zhu, Binh Tran, Manuel Gerken,
Eleonora Lippi, *Lauritz Klaus*,
Michael Rautenberg

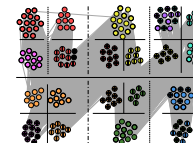


Ultracold Ion-Atom Interactions (OH⁻ + Rb)



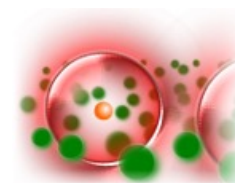
Eric Endres, Jonas Tauch, Saba Zia Hassan, *Henry Lopez*
(University of Innsbruck: Roland Wester, Markus Nötzold)

Network Science / HQA



Marcel Neugebauer, Alexander Jäger,
Laurin Fischer, Julius Vernie, Selim Jochim,
David Wellnitz, Julian Heiss, Armin Kekiç,
Benjamin Claßen, Kathinka Gerlinger
UHeidelberg Computer Science:
Andreas Spitz, Sebastian Lackner,
Michael Gertz

Quantum Simulation with Rydberg Atoms

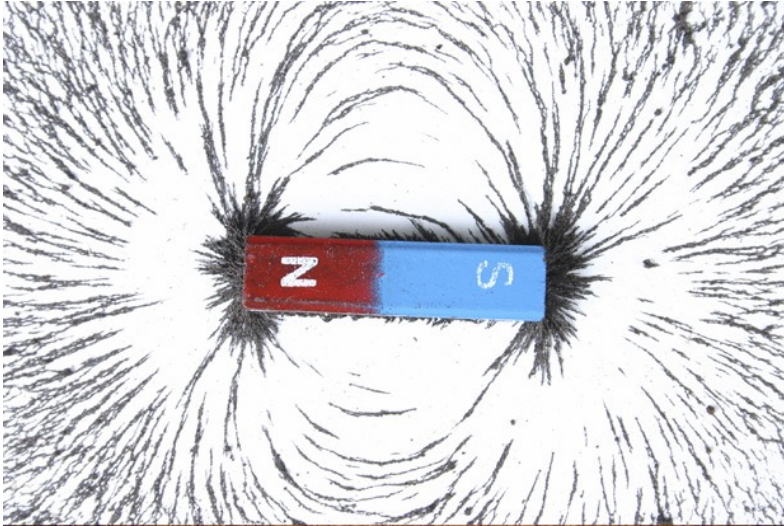


U Heidelberg Team:

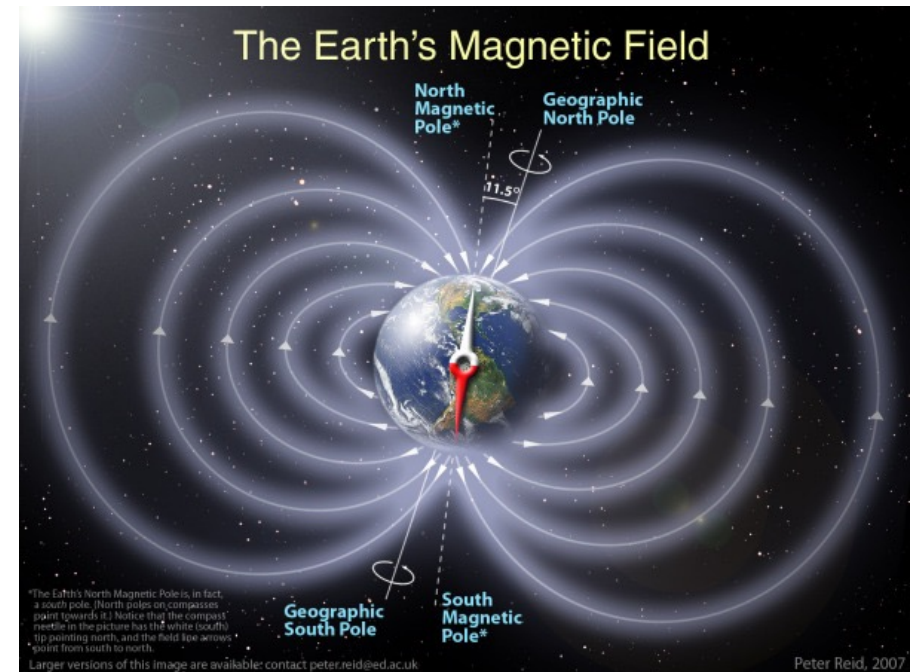
Gerhard Zürn, Clément Hainaut, *Nithiwadee Thaicharoen,*
Titus Franz, Andre Salzinger, Annika Tebben, Sebastian Geier,
David Grimshandl, *Shannon Whitlock, Adrien Signoles,*
Miguel Ferrera Cao, Renato Ferracini Alves, Henrik Zahn

USTC Team:

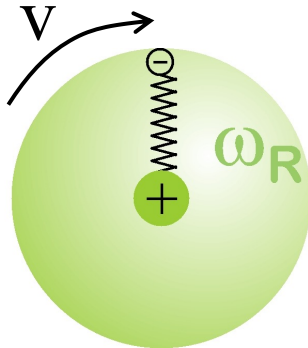
Zhu Bing, Jiang Yuhai, *Chen Peng, Luc Couturier,* Qiao Chang,
Ingo Nosske, Hu Fachao, Tan Canzhu, Julia Siegl



<https://www.tes.com/lessons/JIQpxS49feNIOQ/2-5-2015-magnetism>



Lorentz atom



- magnetic dipole moment through ring current
- no electric dipole moment through symmetry

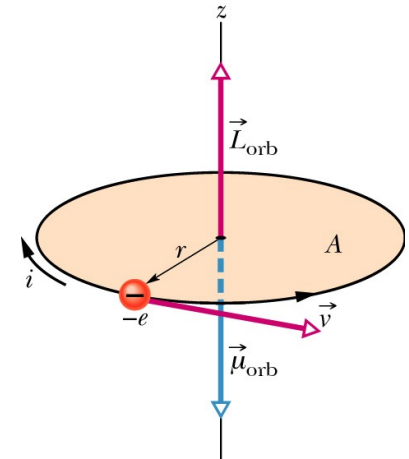
Interaction with magnetic fields

magnetic moment
through orbital momentum

$$\vec{\mu} = -\frac{e}{2m_e} \vec{L}_{\text{orbit}}$$

interaction energy

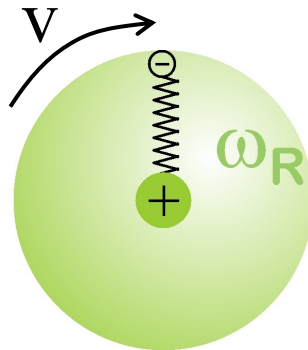
$$E_{\text{mag}} = -\vec{\mu} \cdot \vec{B}$$



Bohr–van Leeuwen theorem

In a classical system there is no magnetization in thermal equilibrium

Lorentz atom



- magnetic dipole moment through ring current
- no electric dipole moment through symmetry

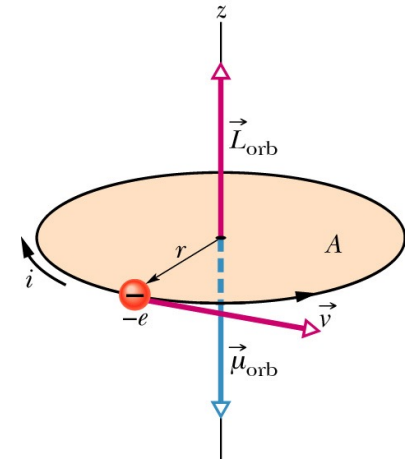
Interaction with magnetic fields

magnetic moment
through orbital momentum

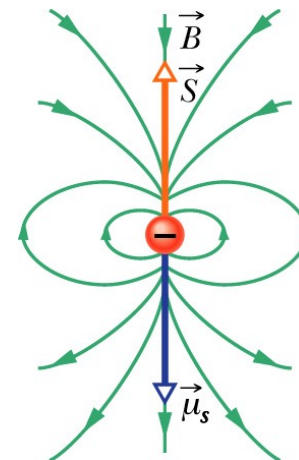
$$\vec{\mu} = -\frac{e}{2m_e} \vec{L}_{\text{orbit}}$$

interaction energy

$$E_{\text{mag}} = -\vec{\mu} \cdot \vec{B}$$



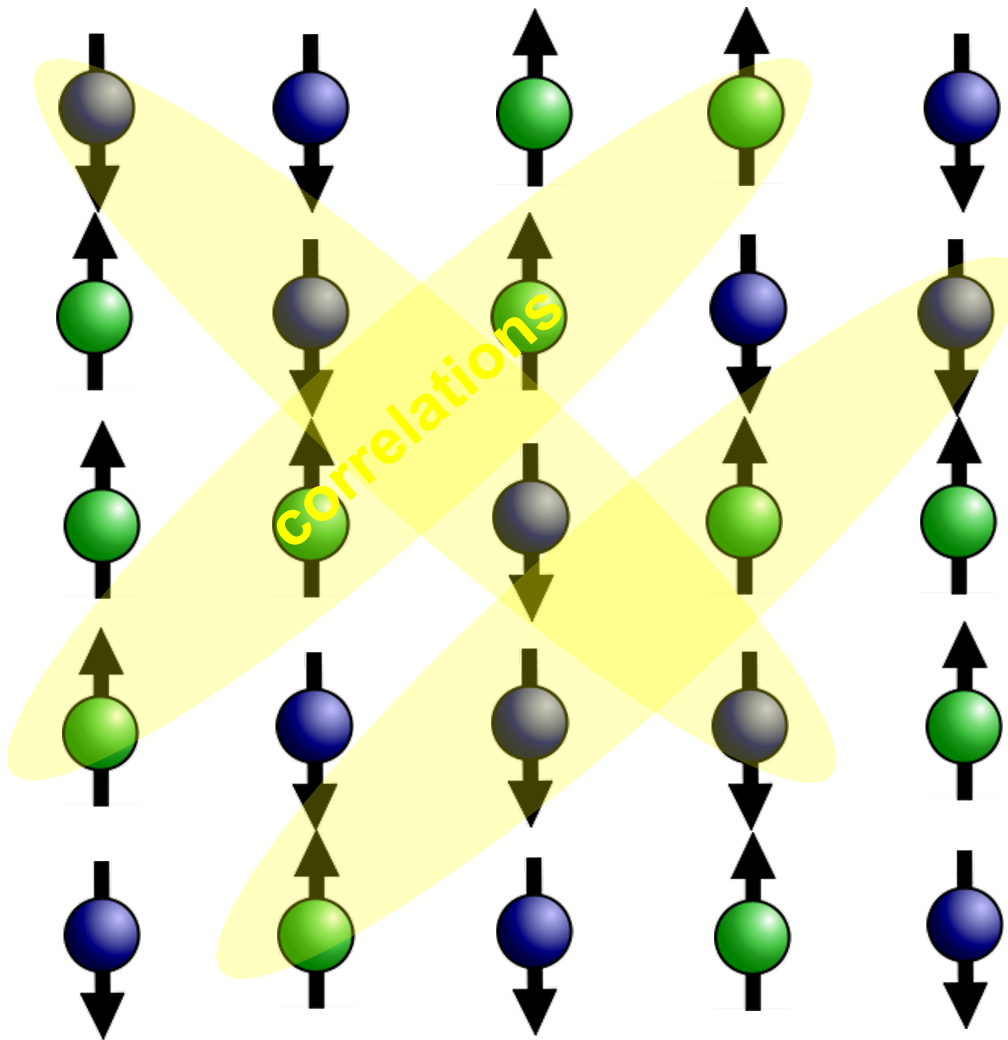
electron spin



$$\vec{\mu}_S = -\frac{e}{m_e} \vec{S}$$

$$|\vec{\mu}_S| = \pm \frac{1}{2} \hbar \frac{e}{m_e} \equiv \pm \mu_{\text{Bohr}}$$

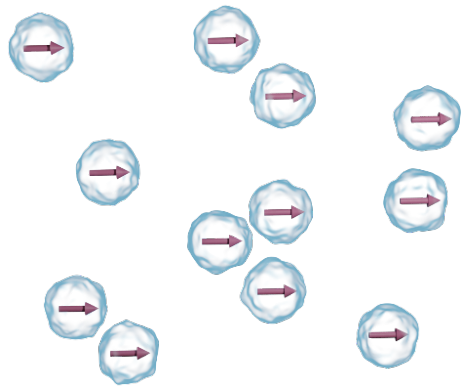
$$\mu_{\text{Bohr}} = 9.72 \times 10^{-24} \text{ J/T}$$



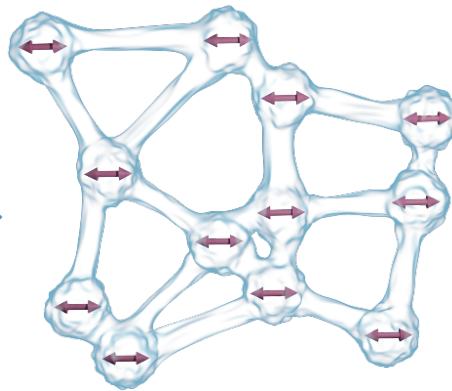
interaction Hamiltonian

$$\mathcal{H} = - \sum_{i,j} J_{ij} \mathbf{S}_i \mathbf{S}_j$$

disordered system



e^{-iHt}

A large blue arrow pointing from the disordered system to the interacting system.

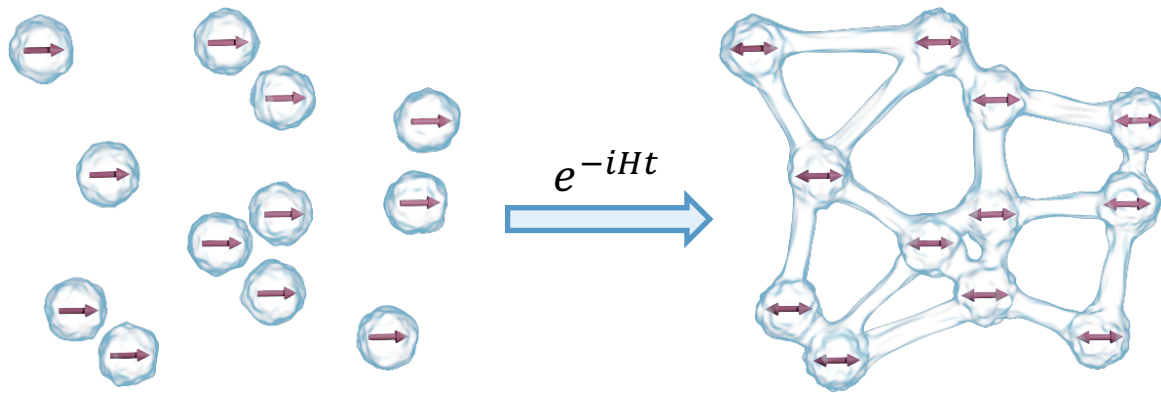
interaction Hamiltonian

$$\mathcal{H} = - \sum_{i,j} J_{ij} \mathbf{S}_i \mathbf{S}_j$$

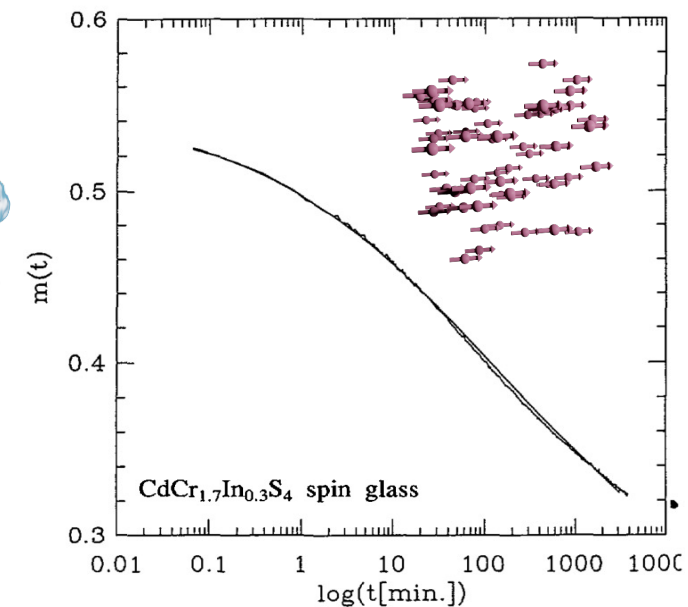
Heisenberg model

competition between ferromagnetic and
antiferromagnetic interaction (frustration)

disordered system



spin glass



J. Bouchaud, Journal de Physique I 2, 1705-1713 (1992)
A. Hamman et al., J. Appl. Phys. 61 (1987) 3683

disordered system

spin glass

How does an isolated system
reach equilibrium?

How do correlations (classical/quantum)
influence the dynamics of the system?

How does the dynamics depend on the degree of
disorder, nature of interactions, symmetries ...?

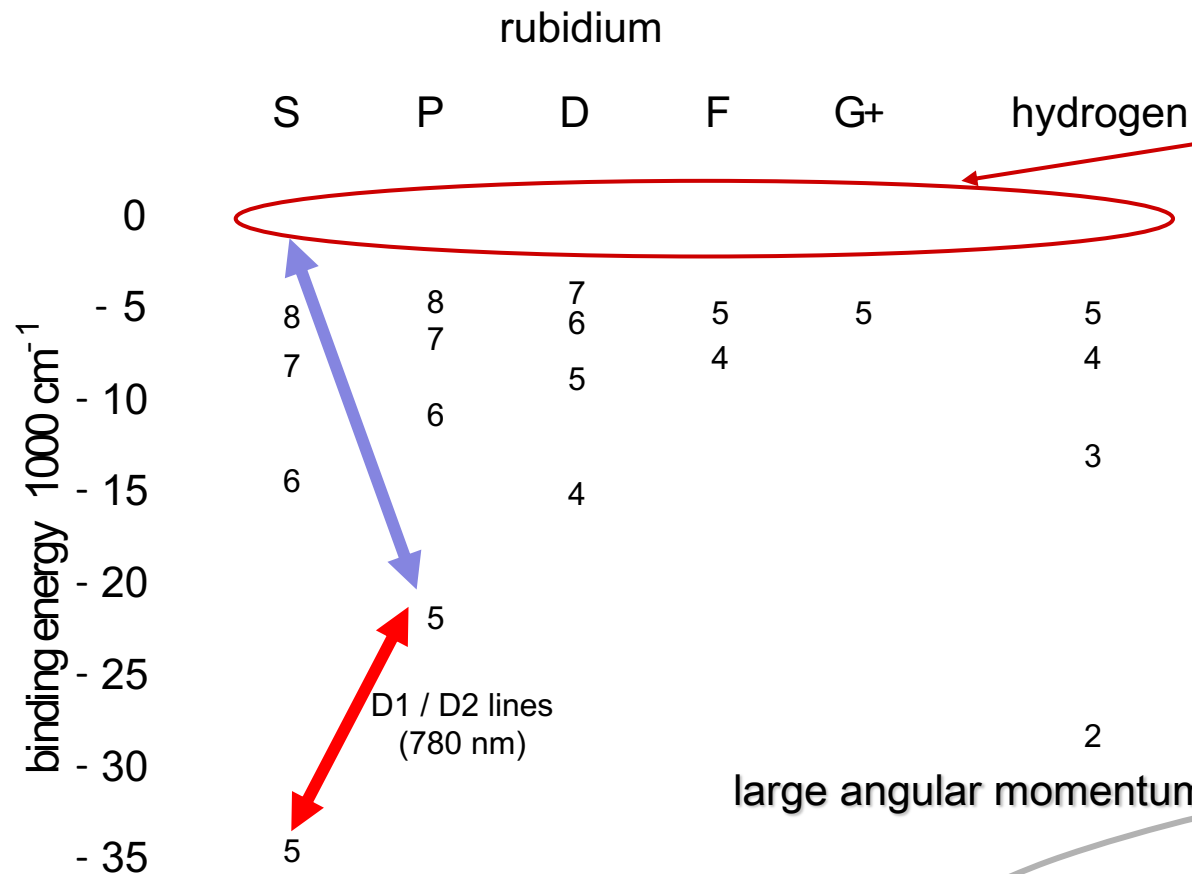
J. Bouchaud, Journal de Physique I 2, 1705-1713 (1992)
A. Hamman et al., J. Appl. Phys. 61 (1987) 3683

“To describe what a **quantum simulator** is, I will first have to disclose a fact that is particularly painful for us theoretical physicists: we can rarely predict the behavior of quantum systems when more than a few particles are interacting. This is not a consequence of limited mathematical prowess or computing power but of the fundamental difficulty of solving quantum mechanics with classical machines.

The aim of a quantum simulator is to bypass the need for theoretical calculations — **if you want to know the underlying properties of a certain quantum system, then build another *more controllable quantum system* that is described by the same model and *measure* its properties.**”

Hazzard, K. R. A. Watching a Quantum Magnet Grow in Ultracold Atoms. *Physics* **11**, 63 (2018)

- Introduction
- Rydberg atoms and spin models
- Universal glassy dynamics in a frozen Rydberg gas
- Floquet Spin Hamiltonian Engineering



Rydberg states:

Highly excited ($n > 10$)
hydrogen-like electronic states

$$E_{n\ell} = -\frac{Ry}{(n - \delta_\ell)^2}$$

$$\delta_0 = 1.348$$

$$\delta_1 = 0.855$$

$$\delta_2 = 0.015$$

$$\delta_3 = 0.011$$

discovery of the Rydberg formula



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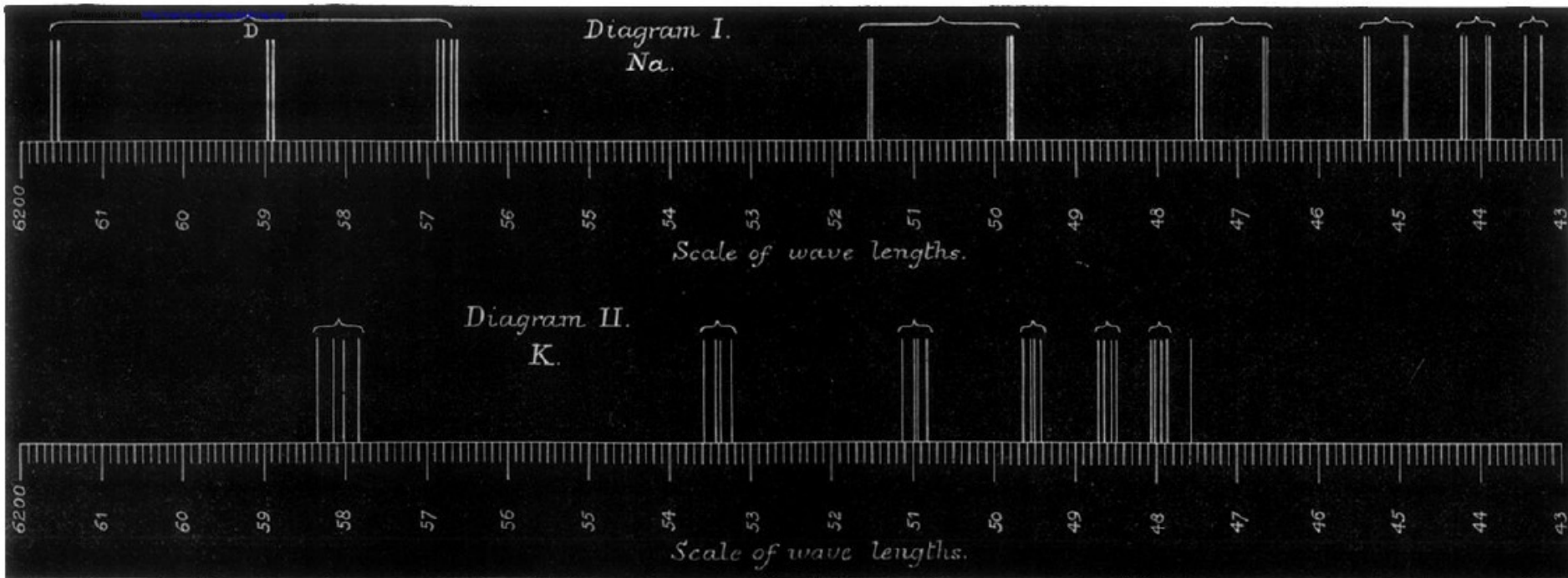


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spectra of alkali metals

Living, G. D. & Dewar, J. On the Spectra of Sodium and Potassium. Proc. R. Soc. London 29, 398–402 (1879).

Spectrum of Sodium in the arc in a lime crucible.



Spectrum of Potassium in the arc in a lime crucible, exclusive of red and violet lines.

Rydberg's discovery

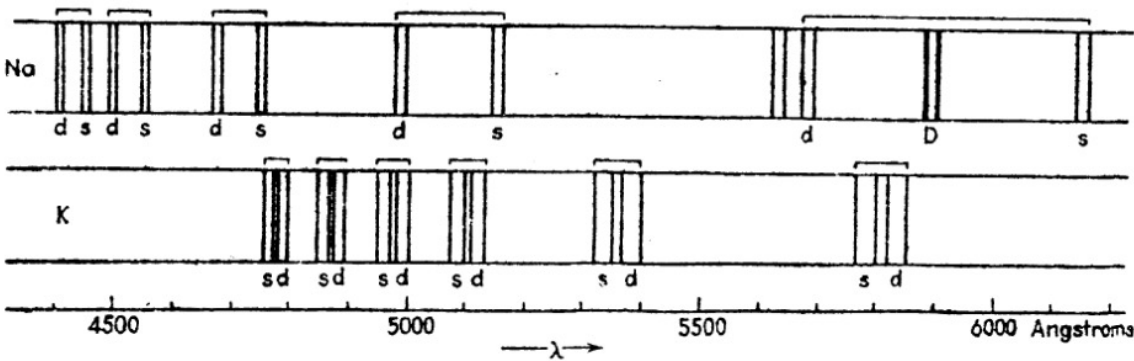
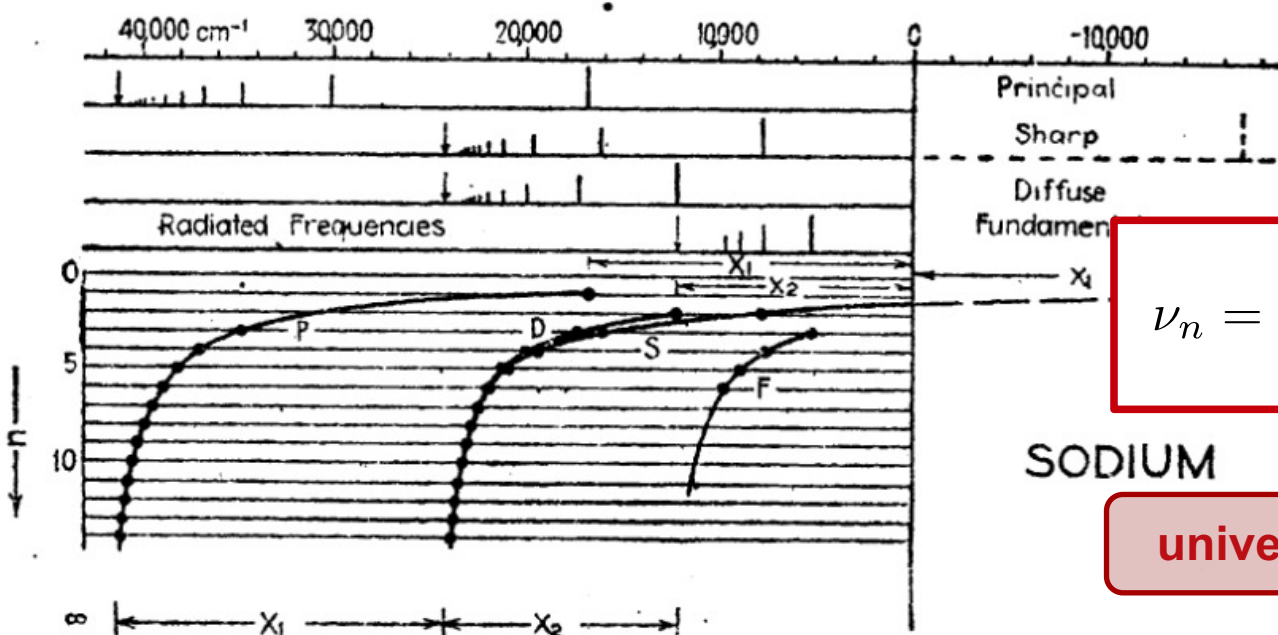


FIG. 1.4.—Schematic representation of the sodium and potassium series. (After *Living and Dewar.*)



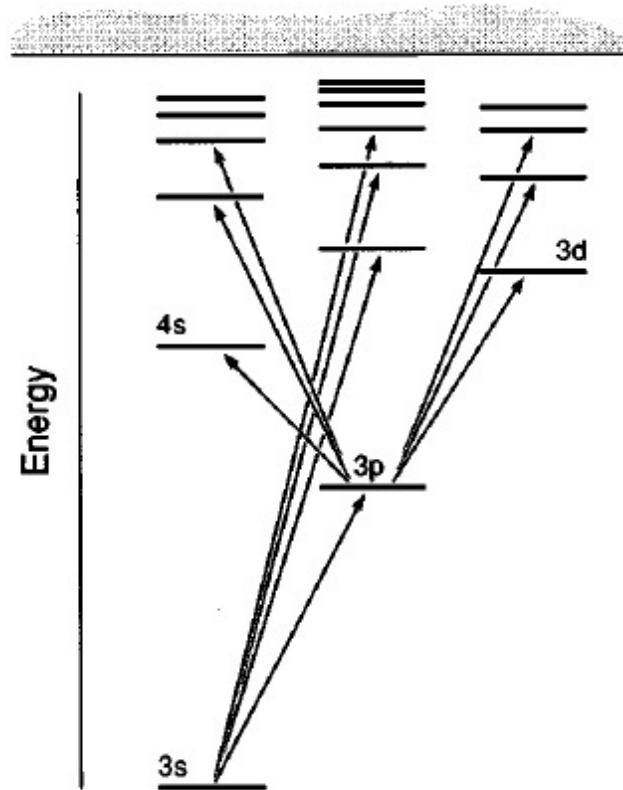
$$\nu_n = \nu_\infty - \frac{R}{(n + \delta_\ell)^2}$$

universal constant R

Rydberg 1890

FIG. 1.7.—Schematic plot of the four chief series of sodium doublets showing the Rydberg-Schuster and Runge laws.

H.E Whiter: *Introduction to Atomic Spectra* (McGraw-Hill, New York, 1934)



$$R = \frac{k^2 Z^2 e^4 m}{2\hbar^2}$$

$k = 1/4\pi\epsilon_0$

Bohr 1913

Fig. 1.1 Energy level diagram for Na showing the sharp 3p–ns, principal 3s–np, and diffuse 3p–nd series.

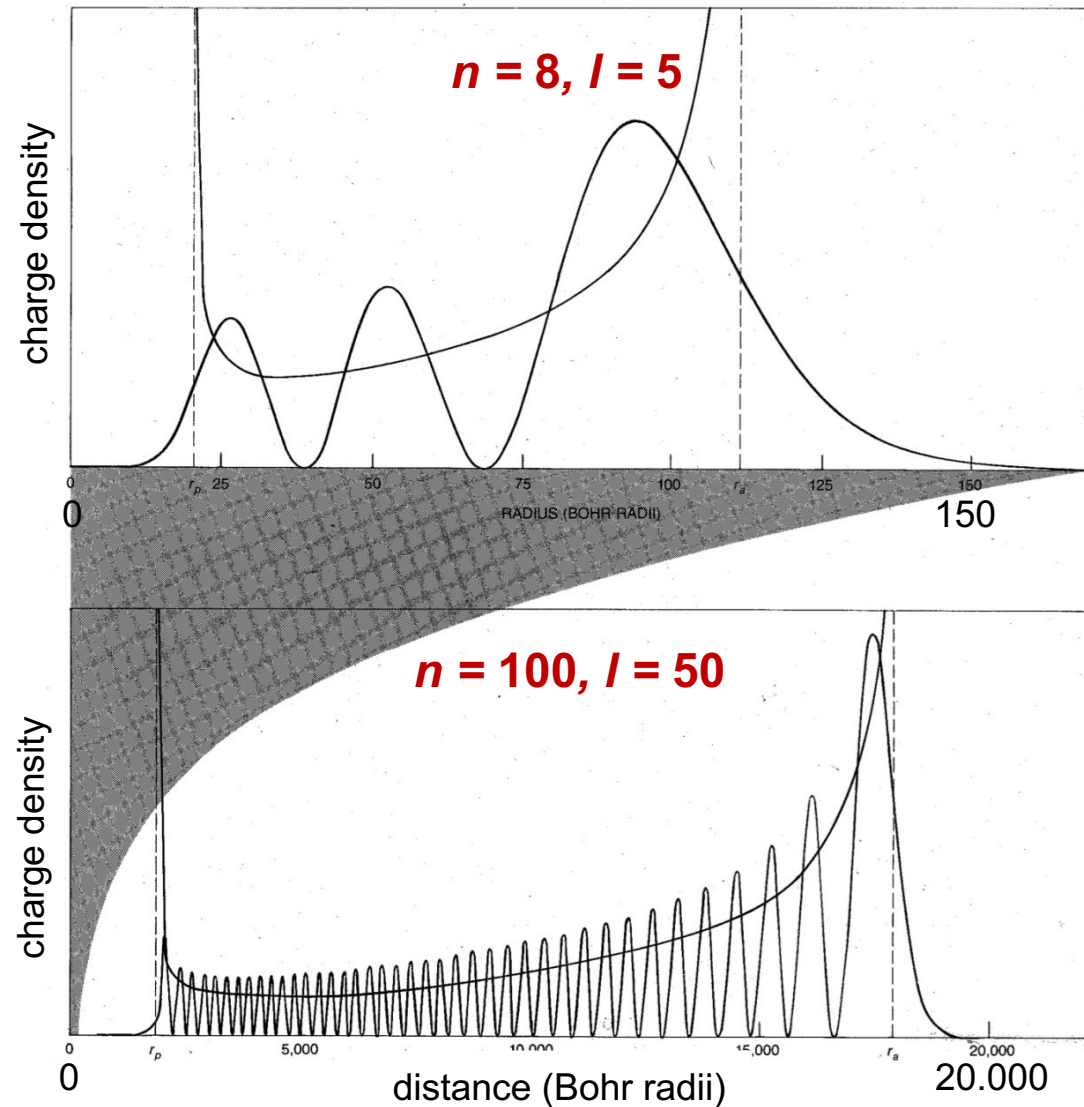
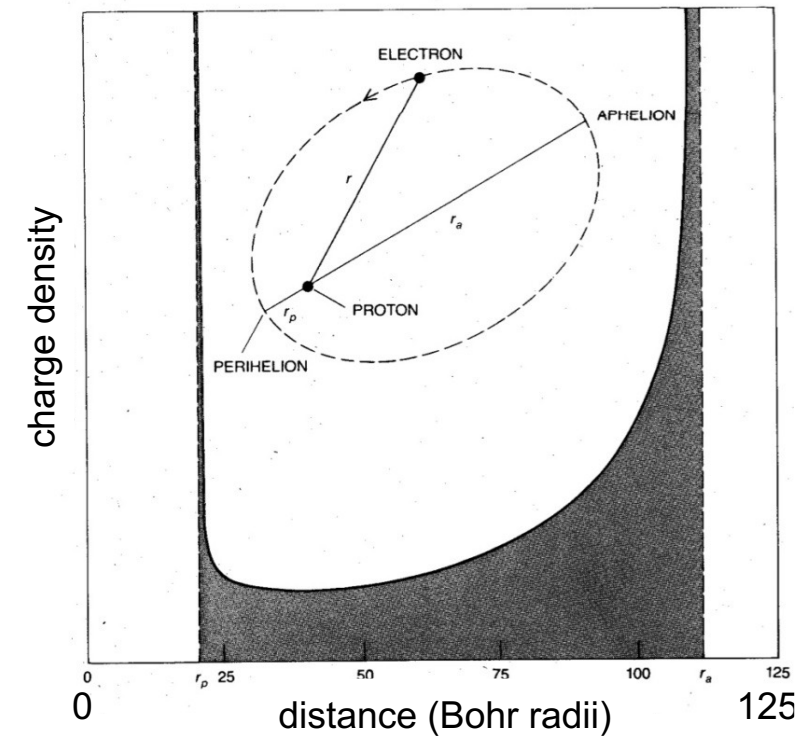
classical vs. quantum world



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Kleppner, D., Littman, M. G., & Zimmerman, M. L. (1981).
Highly Excited Atoms. Scientific American, 244, 108–122.

Rydberg wavefunction

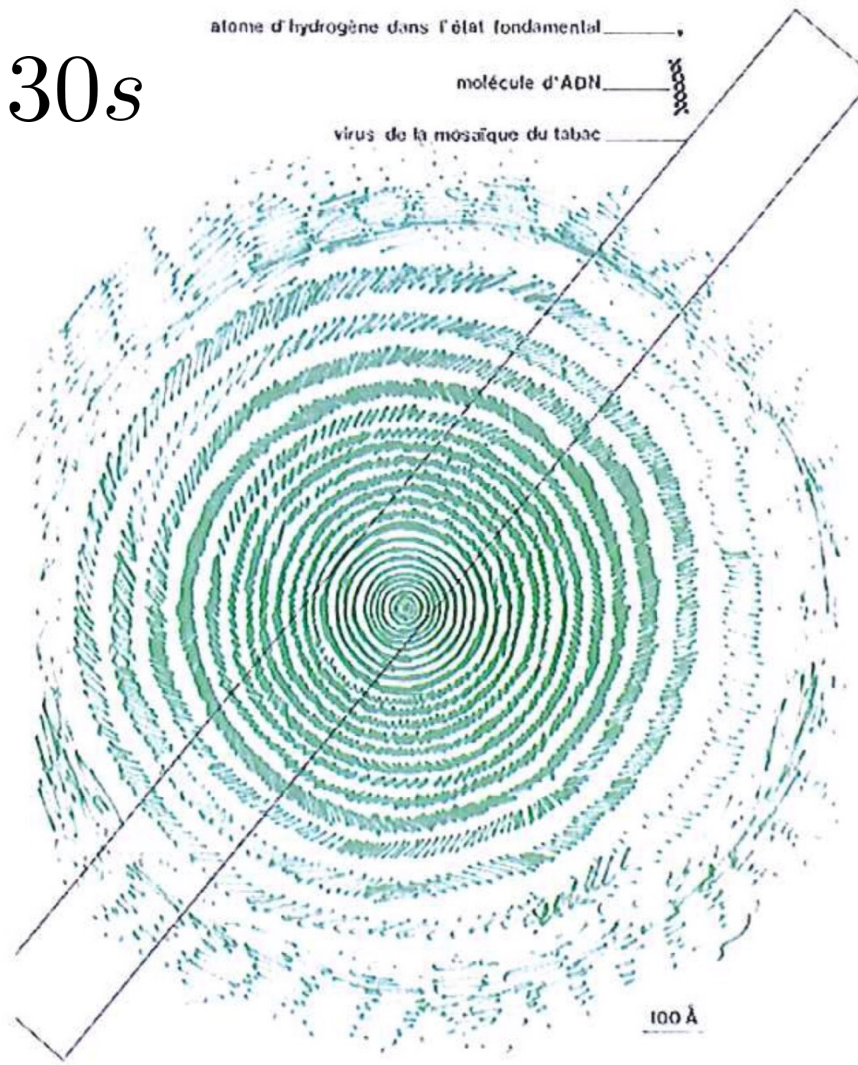


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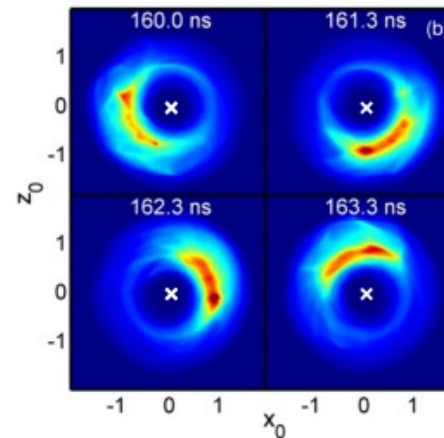


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$30s$



Simulated electron
probability distribution functions



“World” record

Wyker et al, PRL 2012

$n \sim 600$

Orbital radius $\sim 20 \mu\text{m}$

Orbital period $\sim 30 \text{ ns}$



Planetary atoms

Taken from: S. Haroche, “Cours Physique Quantique Collège de France 2013/14”

➤ Hydrogen-like wavefunction

➤ Small binding energy $\propto n^{-2}$ (10 cm⁻¹@ n=100)

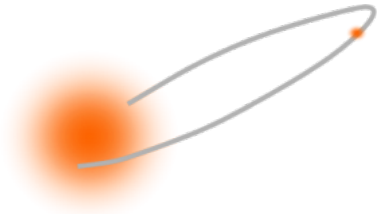
➤ Long radiative lifetimes $\propto n^3$ (1 ms@ n=100)
 n^5 (circular states)

➤ Orbital radius $\propto n^2$ (0.5 μm@ n=100)

➤ Transition dipole moment $\propto n^2$ (10⁴ ea₀@ n=100)

➤ Frequency $n \rightarrow n+1$ $\propto n^{-3}$ (10 GHz@ n=100)

➤ **Polarizability** $\propto n^7$ (10³...10⁴ ea₀ @ n=100)



Rydberg atoms



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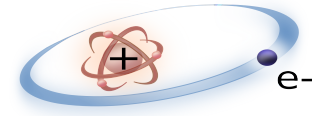
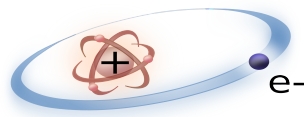


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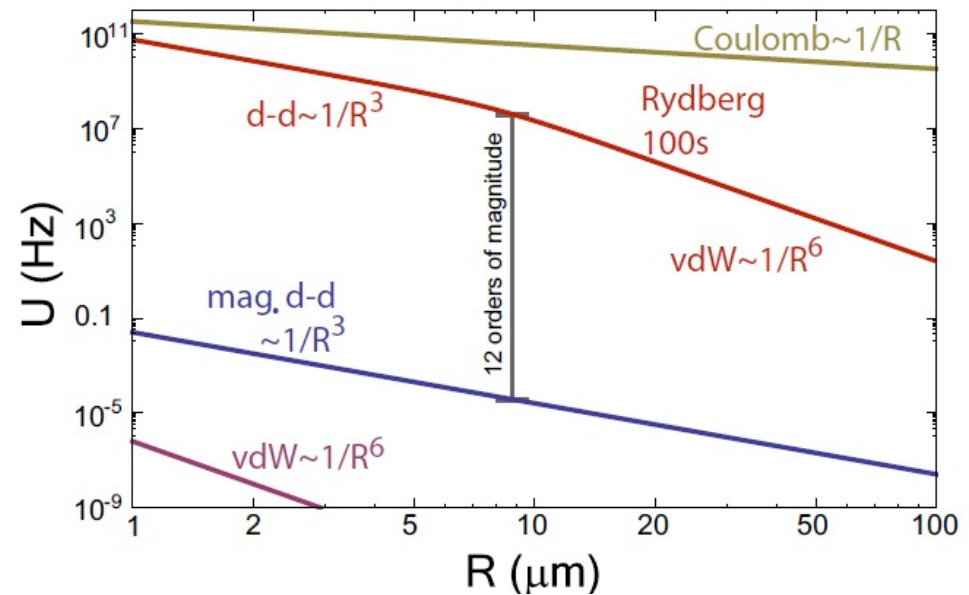
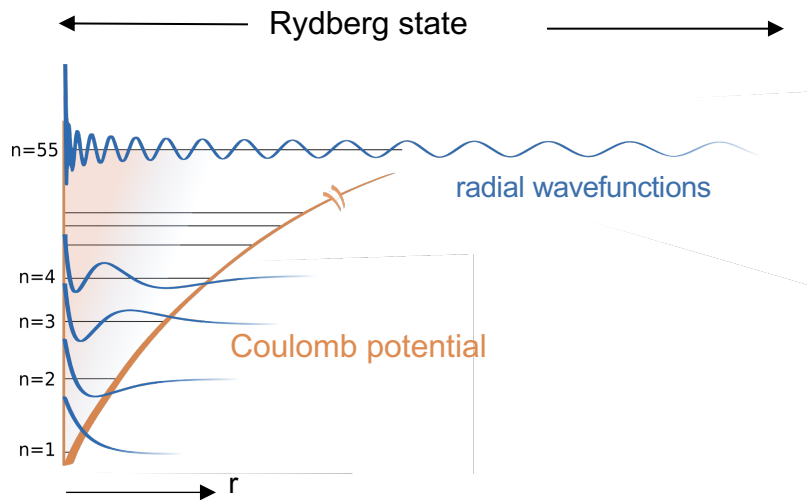
large polarizability

van der Waals (dipolar)
interactions

$$C_6/R^6 \propto n^{11}$$

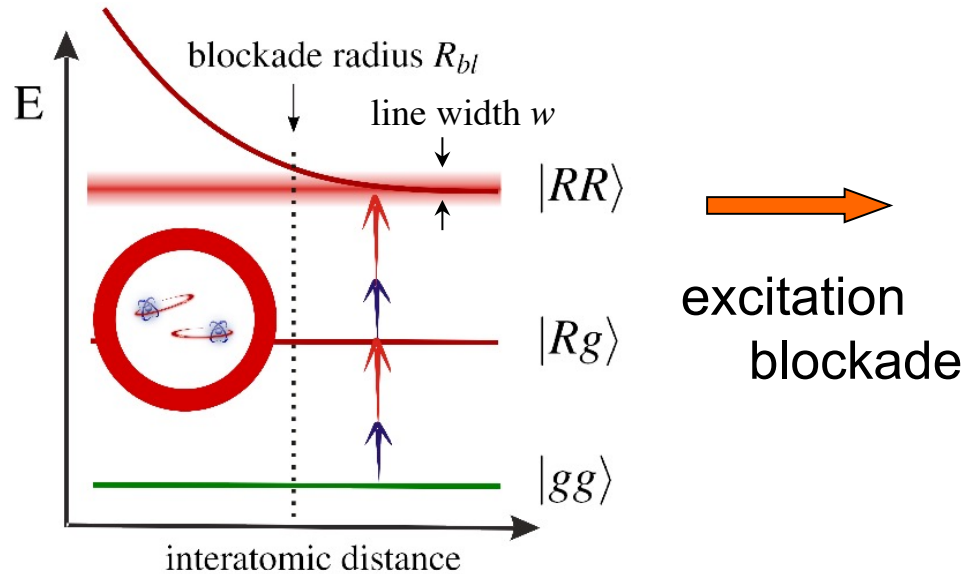


interatomic distance R

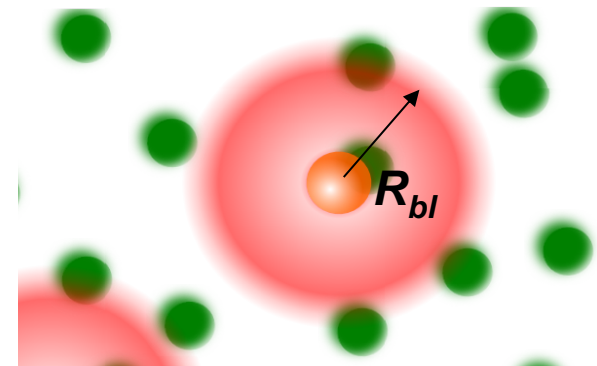
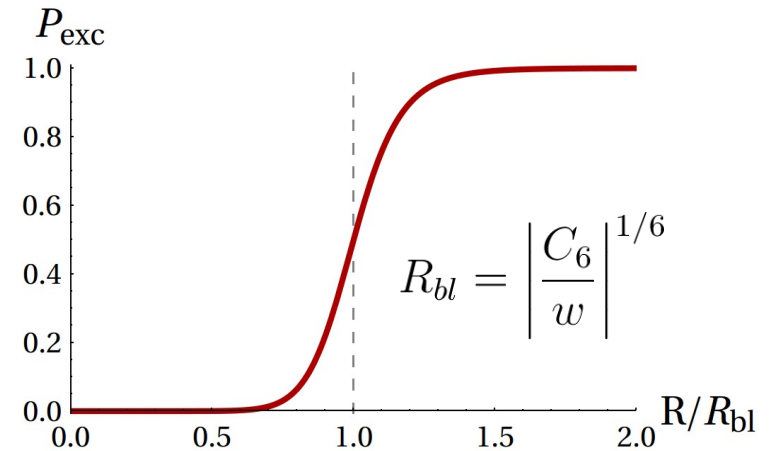


Saffman/Walker/Mølmer, Rev. Mod. Phys. **82**, 2313–2363 (2010)

Lukin, Fleischhauer, Côté, Duan, Jaksch, Cirac, Zoller, PRL 2001

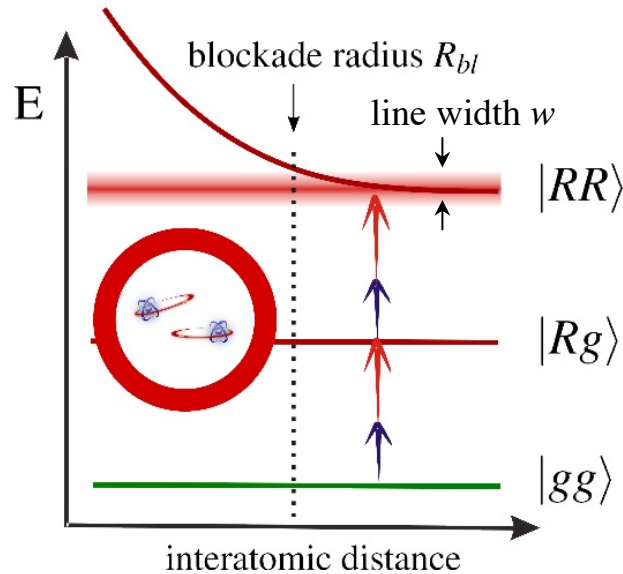


Pair excitation probability

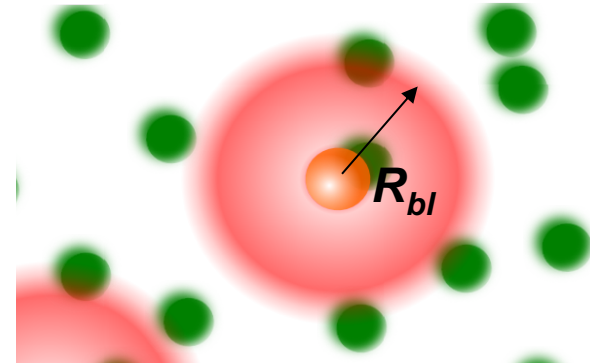


Tong *et al.*, PRL 2004, Singer *et al.*, PRL 2004
For a review see: Comparat & Pillet, JOSA B (2010)

Lukin, Fleischhauer, Côté, Duan, Jaksch, Cirac, Zoller, PRL 2001



excitation
blockade



Tong *et al.*, PRL 2004, Singer *et al.*, PRL 2004
For a review see: Comparat & Pillet, JOSA B (2010)

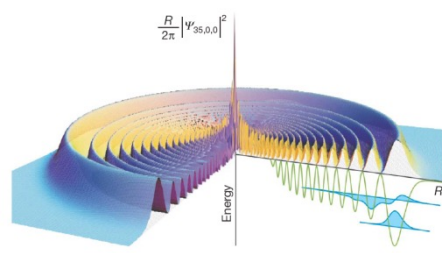
excitation spreads coherently over many atoms:

$$|R\rangle = \frac{1}{\sqrt{N}} \sum_i |g_1\rangle \cdots |R_i\rangle \cdots |g_N\rangle$$

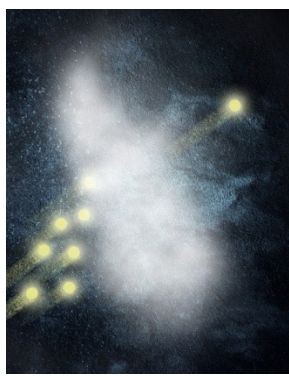
excitation with many-body Rabi frequency:

$$\Omega_N = \sqrt{N} \Omega_{\text{atom}}$$

few-body physics

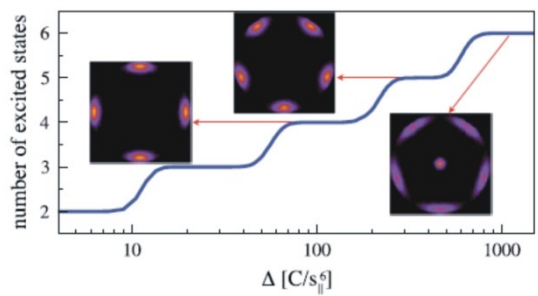


V. Bendkowsky *et al.*,
Nature **458**, 1005 (2009)



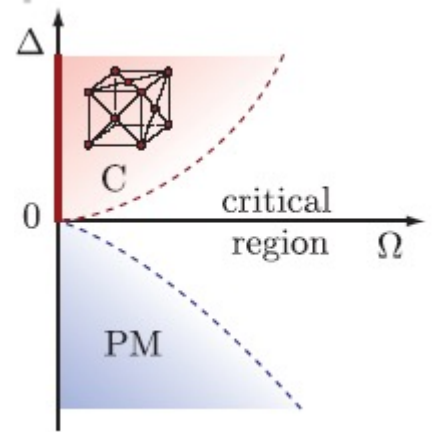
T. Peyronel *et al.*, Nature **488**, 57 (2012)

structure formation



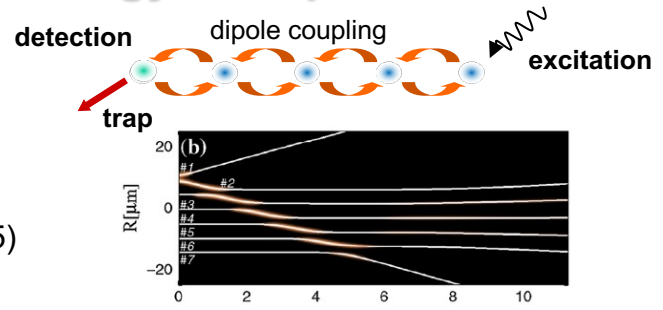
T. Pohl *et al.*, PRL **104**, 043002 (2010)
P. Schauß *et al.*, Science **347**, 1455 (2015)

quantum simulation



H. Weimer *et al.*, PRL **101**, 250601 (2008)
H. Labuhn *et al.*, Nature **534**, 7609 (2016)
H. Bernien *et al.*, Nature **551**, 7682 (2017)

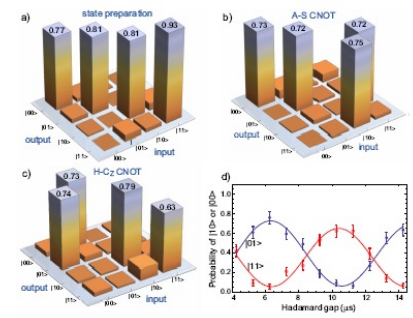
energy transport



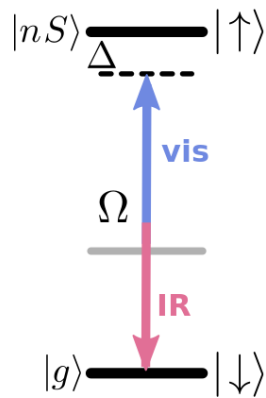
S. Wüster *et al.* PRL **105**, 053005 (2010)
G. Günter *et al.*, Science **342**, 954 (2013)

Rydberg quantum optics

quantum information processing

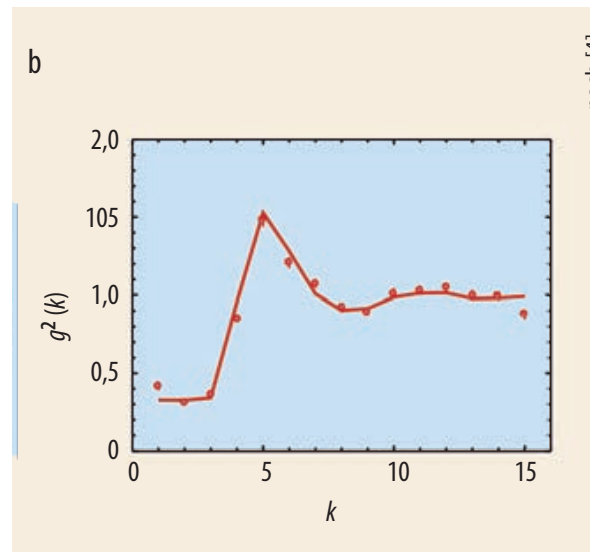
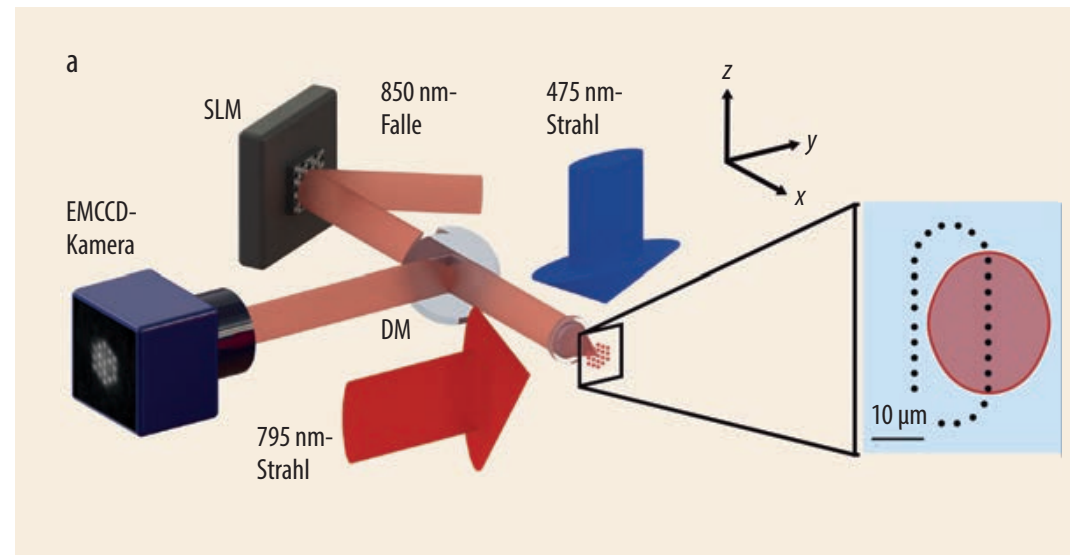


L. Isenhower *et al.*, PRL **104**, 010503 (2010)



**Quantum
Ising**

$$\frac{C_6}{r_{ij}^6} \hat{n}_i \hat{n}_j$$



Labuhn *et al.*, (Browaeys groups),
Nature 2016

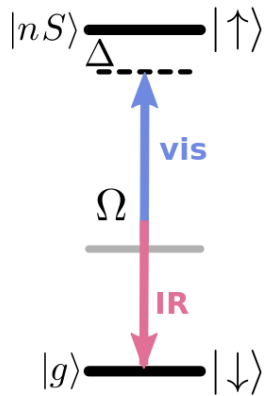
see also recent work by
Lukin/Greiner/Vuletic collaboration
and Bloch/Gross group

ARTICLE

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DOI: 10.1038/ncomms13449

OPEN

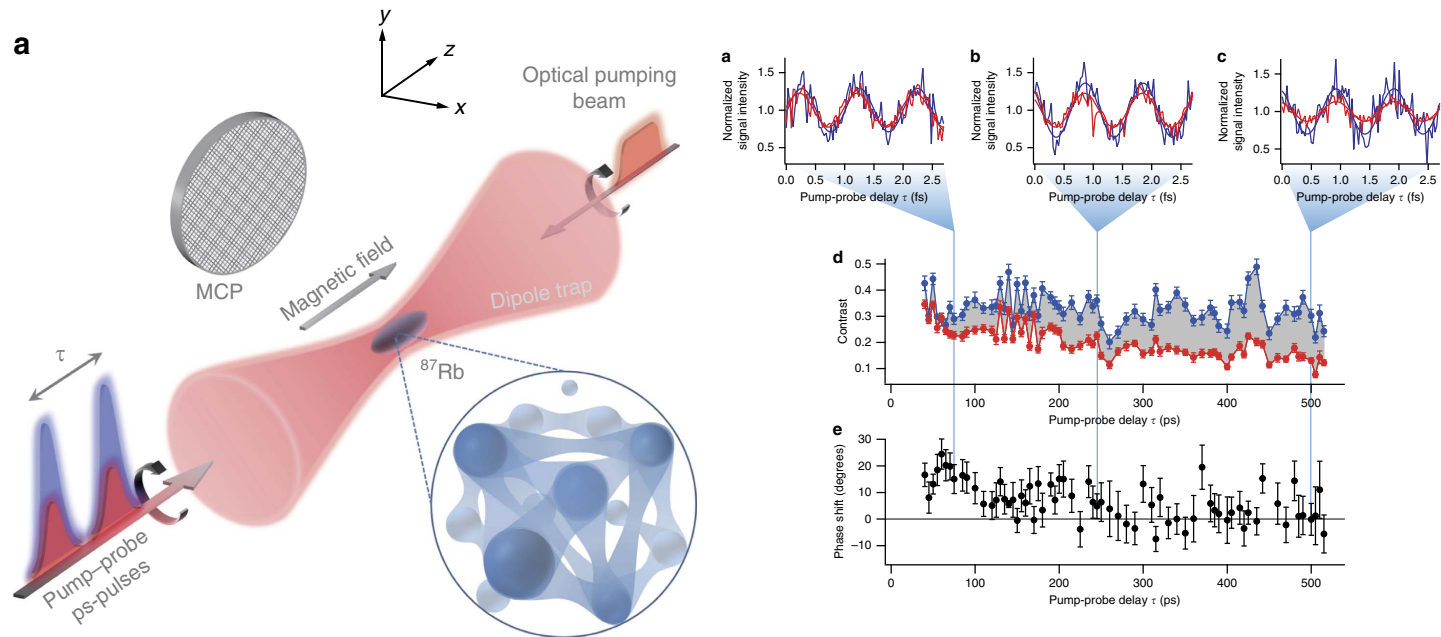


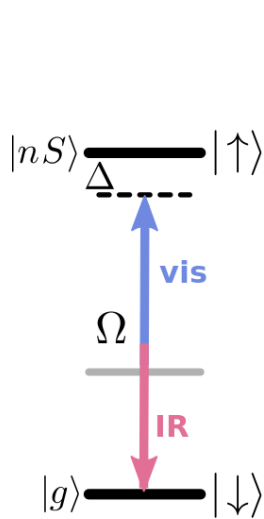
**Quantum
Ising**

$$\frac{C_6}{r_{ij}^6} \hat{n}_i \hat{n}_j$$

Direct observation of ultrafast many-body electron dynamics in an ultracold Rydberg gas

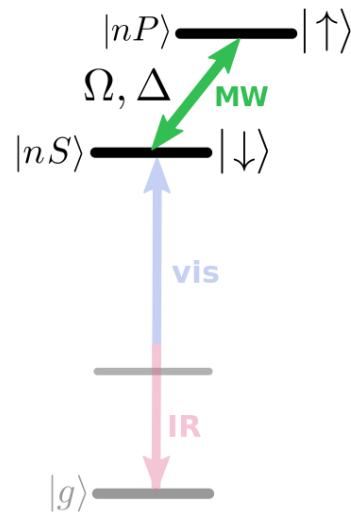
Nobuyuki Takei^{1,2,*}, Christian Sommer^{1,2,*}, Claudiu Genes³, Guido Pupillo⁴, Haruka Goto¹, Kuniaki Koyasu^{1,2}, Hisashi Chiba^{1,5}, Matthias Weidemüller^{6,7,8} & Kenji Ohmori^{1,2}





Quantum Ising

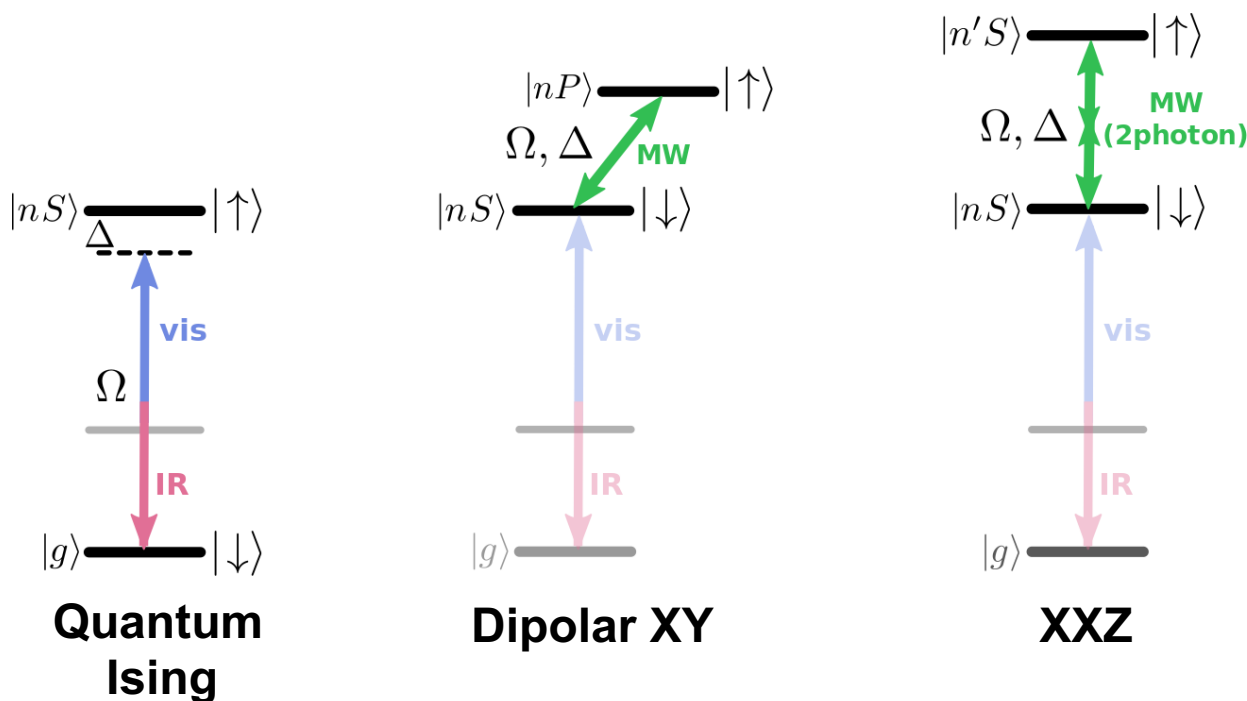
$$\frac{C_6}{r_{ij}^6} \hat{n}_i \hat{n}_j$$



Dipolar XY

$$V_{dd}(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+)$$


 $\frac{1 - 3 \cos^2 \theta_{ij}}{r_{ij}^3}$



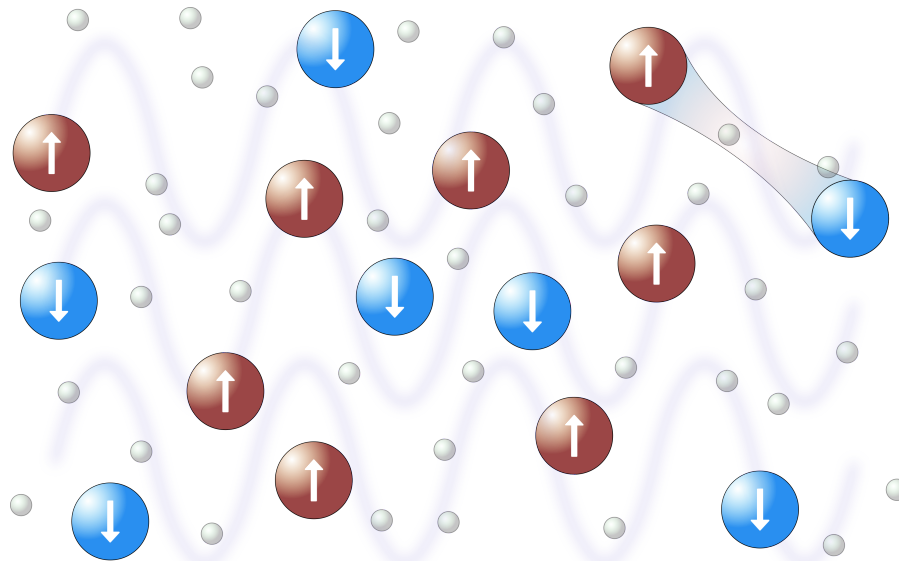
$$\frac{C_6}{r_{ij}^6} \hat{n}_i \hat{n}_j$$

$$V_{dd}(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+) \quad J_{\perp}(\hat{S}_i^x \hat{S}_j^x + \hat{S}_i^y \hat{S}_j^y) + J_z \hat{S}_i^z \hat{S}_j^z$$

$$\uparrow \frac{1 - 3 \cos^2 \theta_{ij}}{r_{ij}^3}$$

+ driving field: $\Omega \sum_i \hat{S}_i^x + \Delta \sum_i \hat{S}_i^z$

disordered system



competition between ferromagnetic and
antiferromagnetic interaction (frustration)

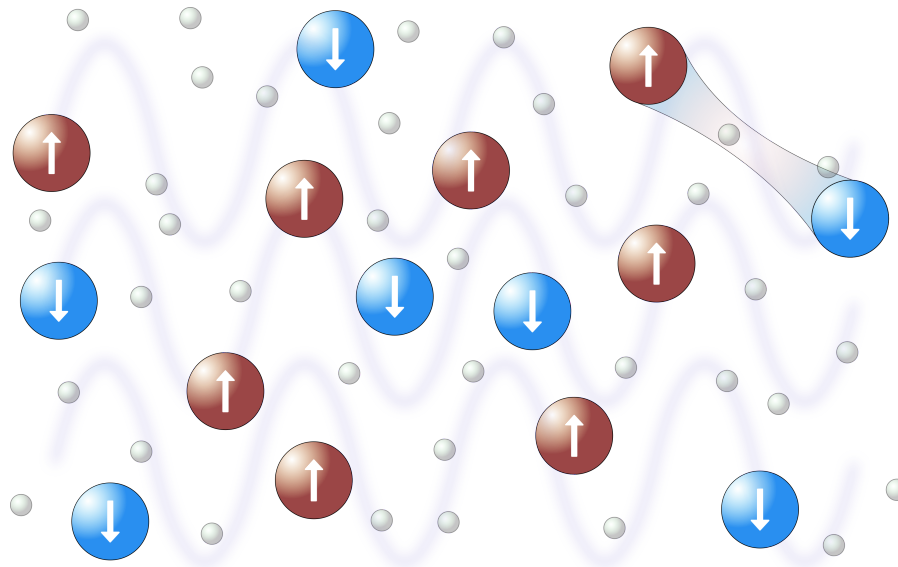
interaction Hamiltonian

$$\mathcal{H} = - \sum_{i,j} J_{ij} \mathbf{S}_i \mathbf{S}_j$$

$$+ \Omega \sum_i \mathbf{S}_i \mathbf{B}$$

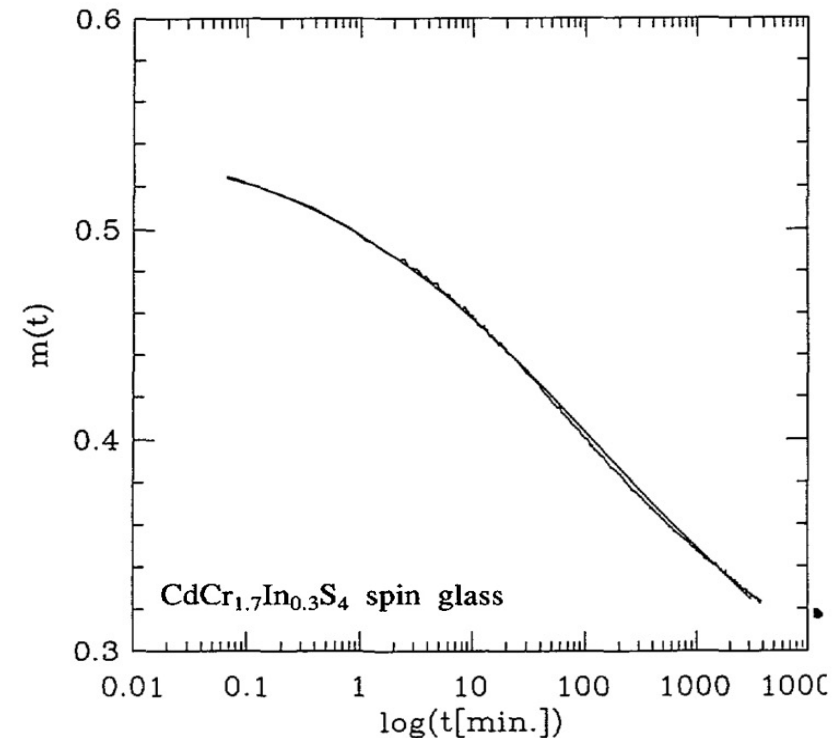
Heisenberg model

disordered system



competition between ferromagnetic and antiferromagnetic interaction (frustration)

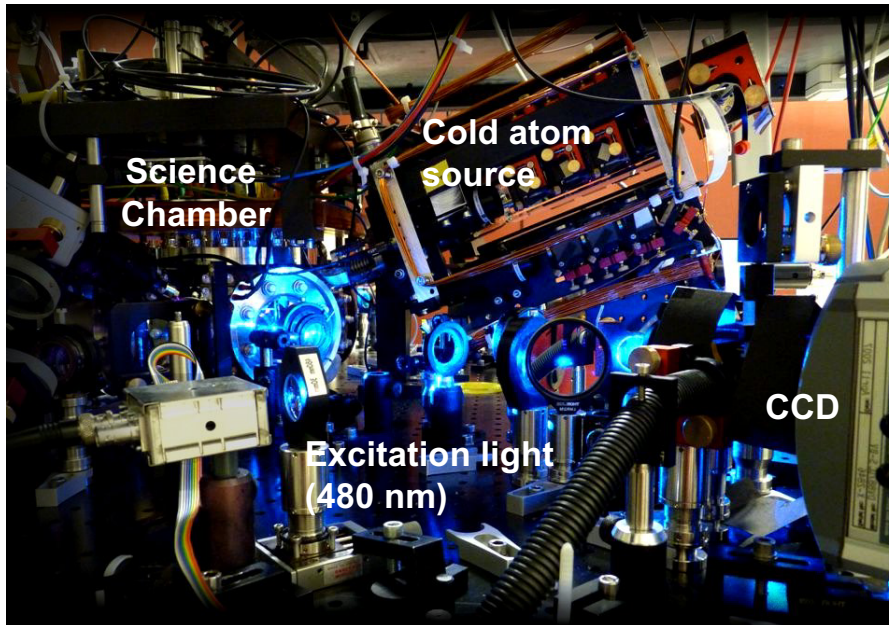
spin glass



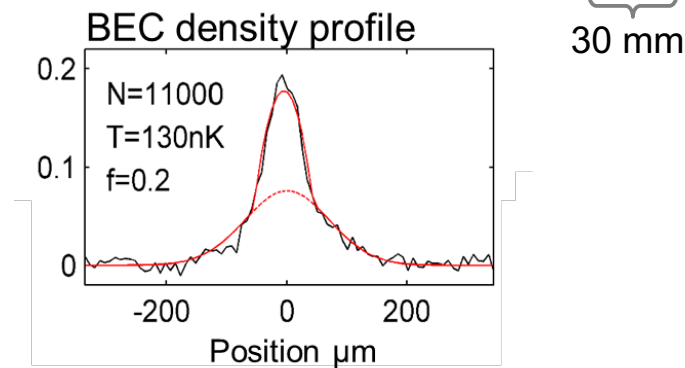
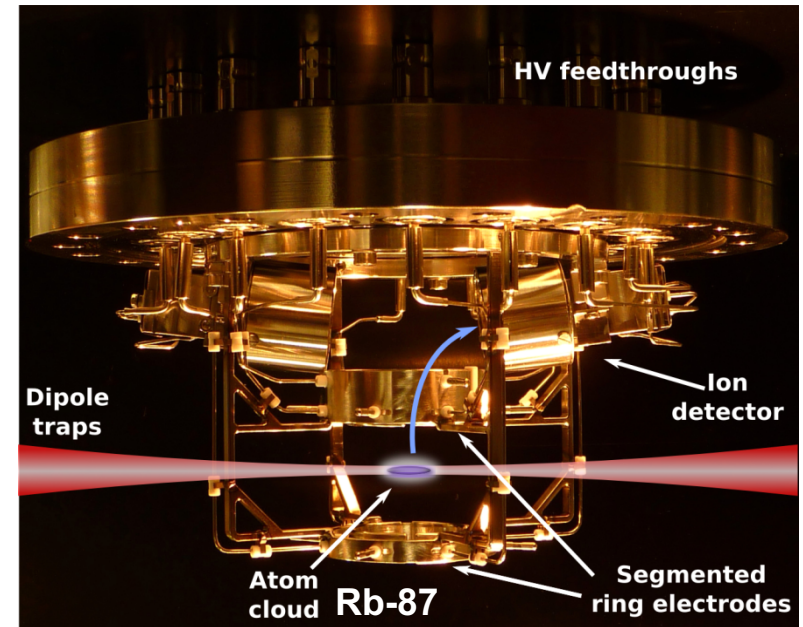
J. Bouchaud, Journal de Physique I 2, 1705-1713 (1992)
A. Hamman et al., J. Appl. Phys. 61 (1987) 3683

Heidelberg Rydberg experiment

Heidelberg Rydberg lab



Rydberg detector



- Introduction
- Rydberg atoms and spin models
- **Universal glassy dynamics in a frozen Rydberg gas**
- Floquet Spin Hamiltonian Engineering

experiment on spin relaxation

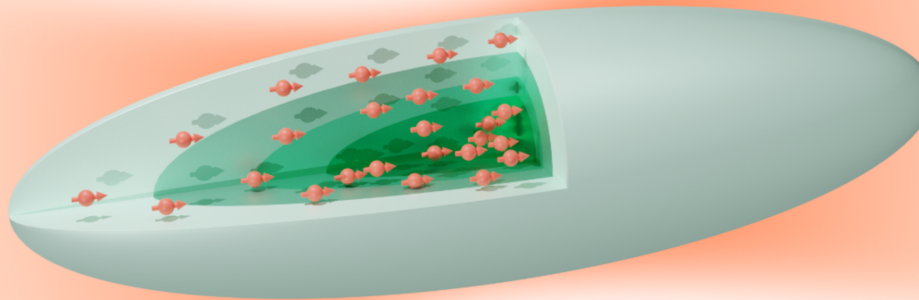
Ultracold atomic gas:

10^4 rubidium atoms in an optical dipole at $T \sim 50 \mu\text{K}$

Laser excitation:

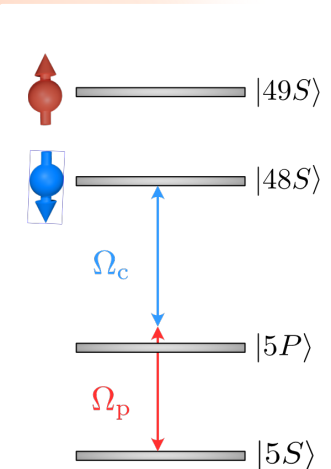
Preparation of 50 ... 1500 spins

Initial state $|\downarrow\downarrow\downarrow\downarrow \dots \downarrow\rangle$ (no entropy)



Excitation

$|48S\rangle$



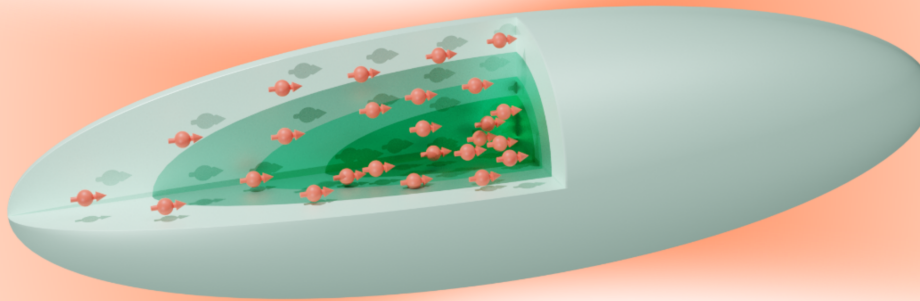
experiment on spin relaxation



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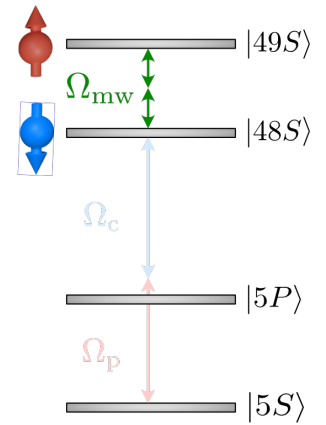
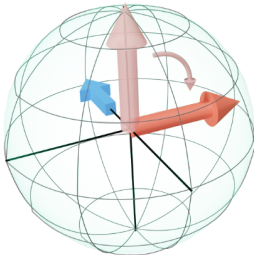


Excitation

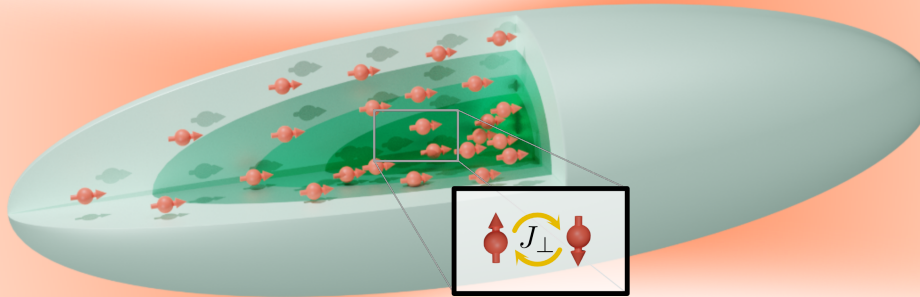
$|48S\rangle$

Preparation

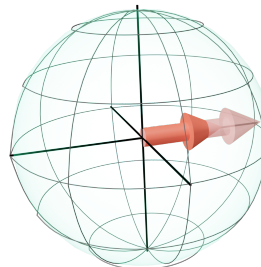
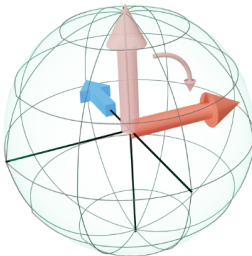
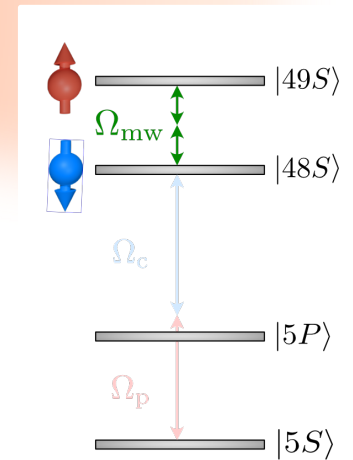
$$\Omega\Delta t = \frac{\pi}{2}$$
$$\Phi = 0$$



$$H_{\text{XXZ}} = \frac{1}{2} \sum_{i,j} J_{ij} (S_x^{(i)} S_x^{(j)} + S_y^{(i)} S_y^{(j)} + \delta S_z^{(i)} S_z^{(j)})$$



Excitation	Preparation	Evolution
$ 48S\rangle$	$\Omega \Delta t = \frac{\pi}{2}$ $\Phi = 0$	$\hat{H}_{\text{XXZ}}$



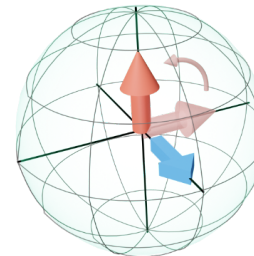
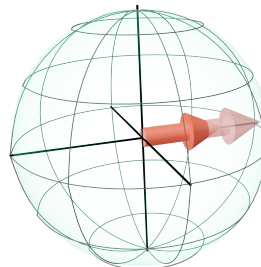
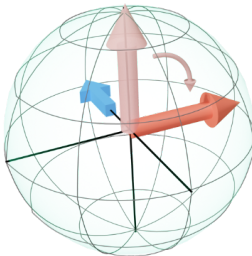
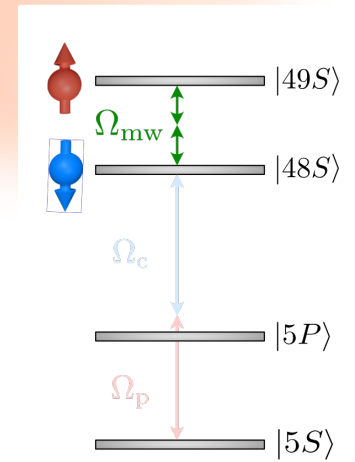
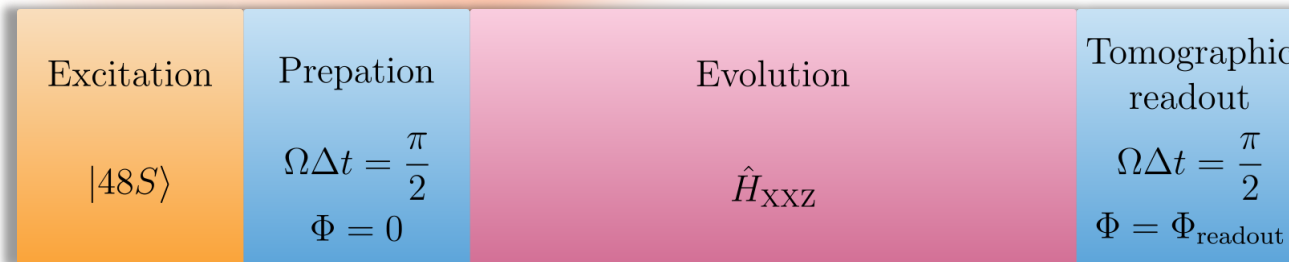
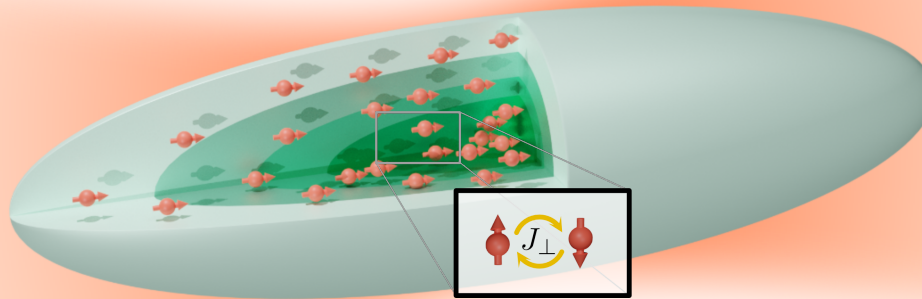
experiment on spin relaxation



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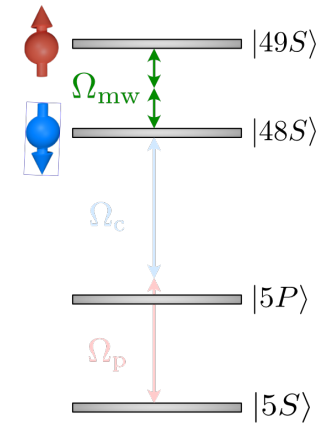
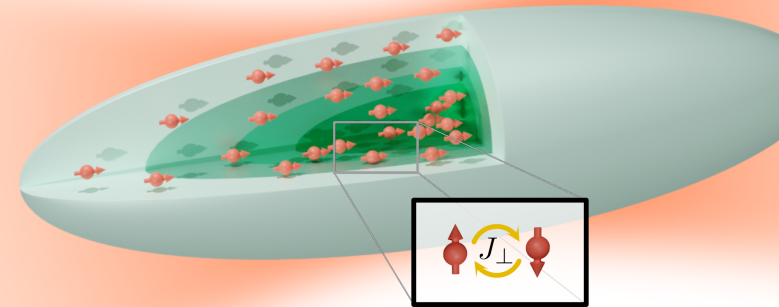
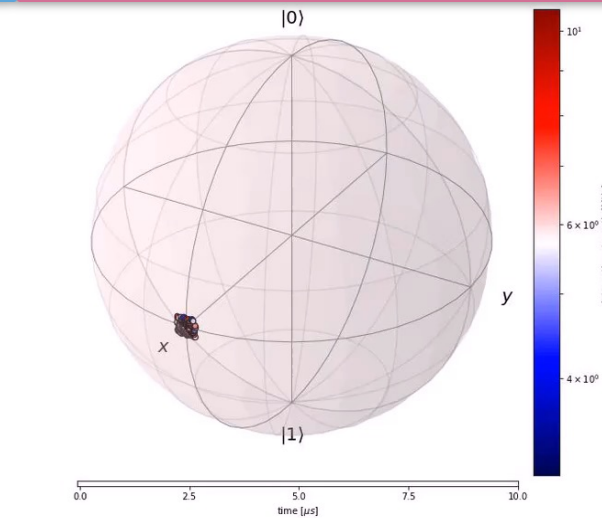
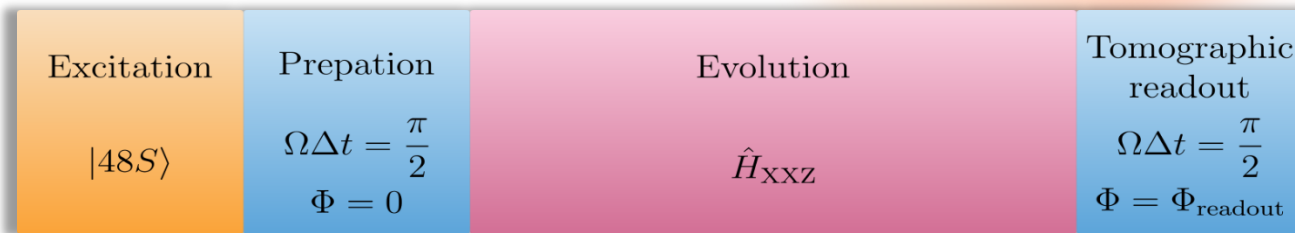
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$$H_{\text{XXZ}} = \frac{1}{2} \sum_{i,j} J_{ij} (S_x^{(i)} S_x^{(j)} + \cancel{S_y^{(i)} S_y^{(j)}} + \cancel{\delta S_z^{(i)} S_z^{(j)}})$$

$\downarrow$

Precession around x



mean-field prediction



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Excitation

$|48S\rangle$

Preparation

$$\Omega\Delta t = \frac{\pi}{2}$$

$$\Phi = 0$$

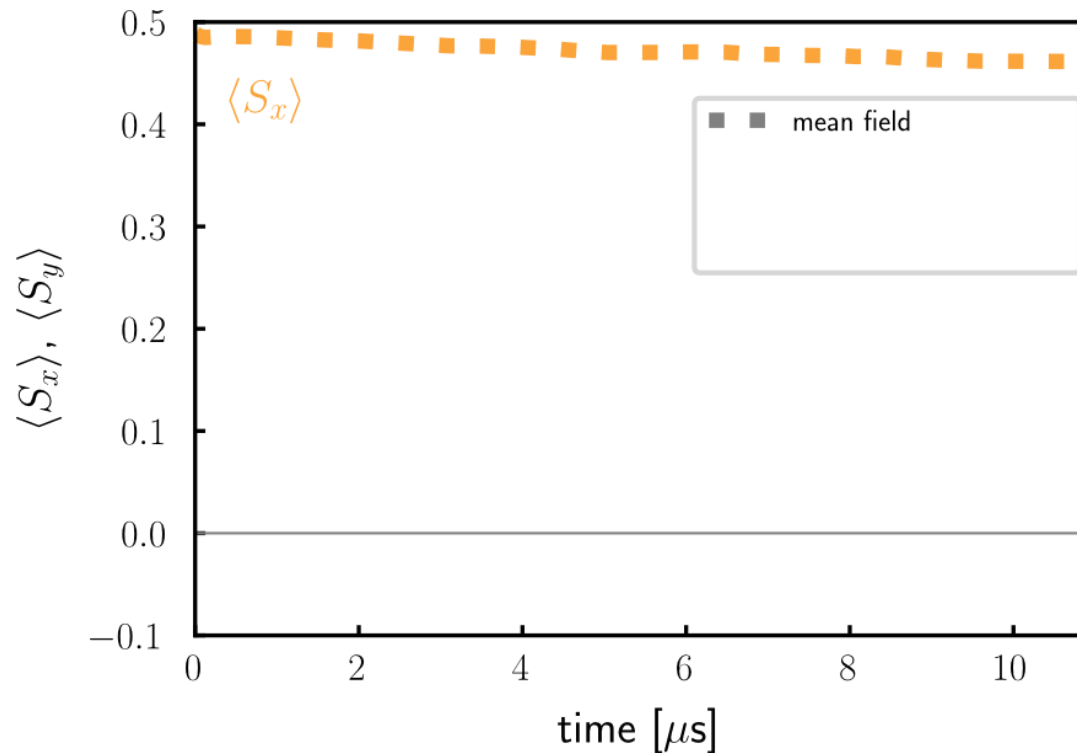
Evolution

$$\hat{H}_{\text{XXZ}}$$

Tomographic
readout

$$\Omega\Delta t = \frac{\pi}{2}$$

$$\Phi = \Phi_{\text{readout}}$$



Excitation

$|48S\rangle$

Preparation

$$\Omega\Delta t = \frac{\pi}{2}$$

$$\Phi = 0$$

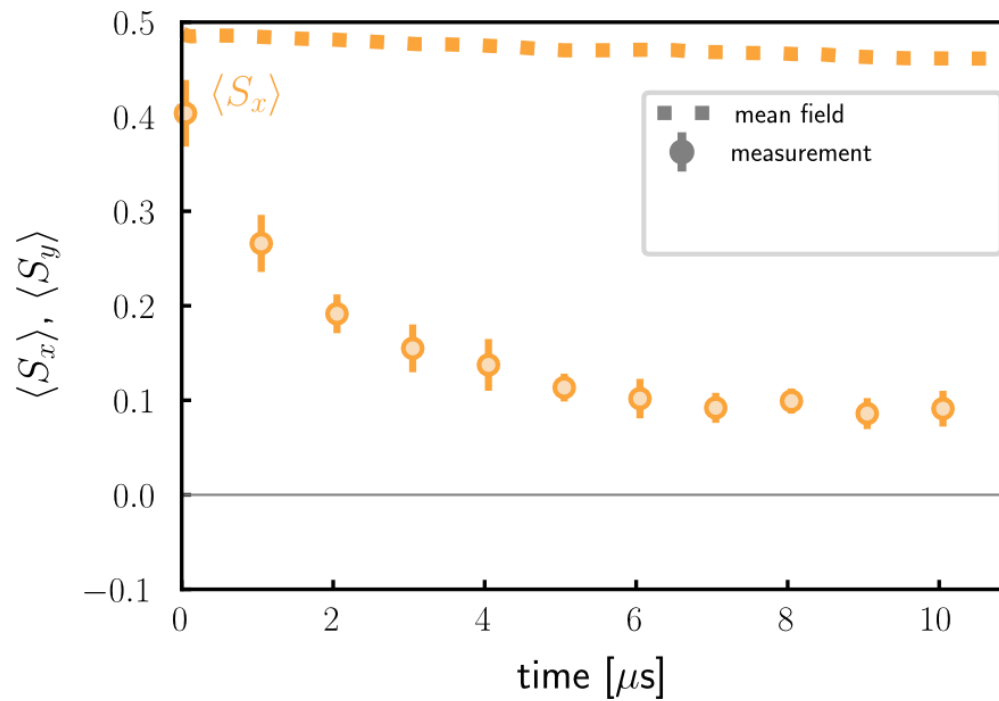
Evolution

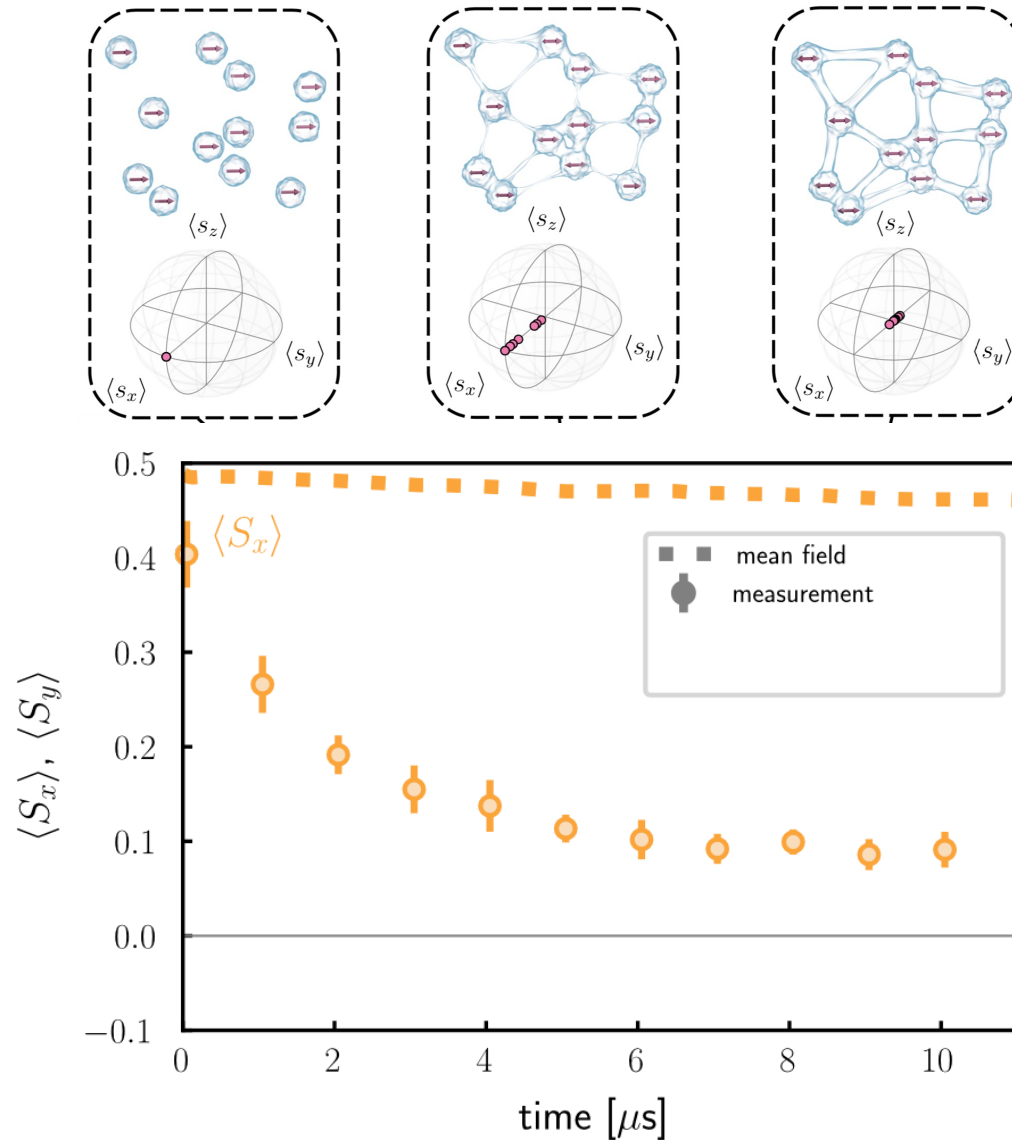
$$\hat{H}_{\text{XXZ}}$$

Tomographic
readout

$$\Omega\Delta t = \frac{\pi}{2}$$

$$\Phi = \Phi_{\text{readout}}$$





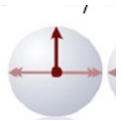
Discrete Truncated Wigner Approximation



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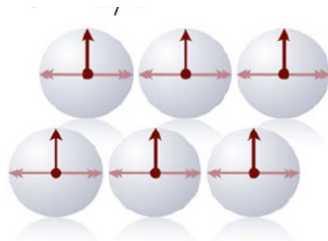
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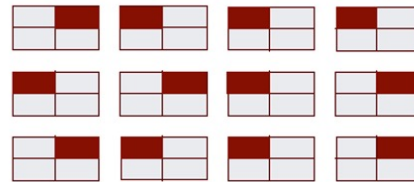
0.5	0.5
0	0



Random configuration

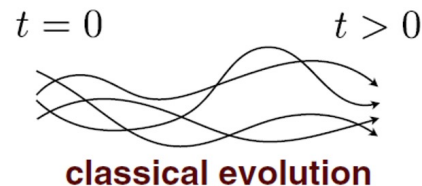


$n_t \times$



initial state

time evolution



Map density matrix of spin-1/2 system on Wigner distribution (quasiprobability distribution in phase-space)

Sample phase points of each spin according to the Wigner distribution

Compute classical time evolution
Average over the different samples

J. Schachenmayer, A. Pikovski, A. M. Rey, PRX **5**, 11022 (2015)

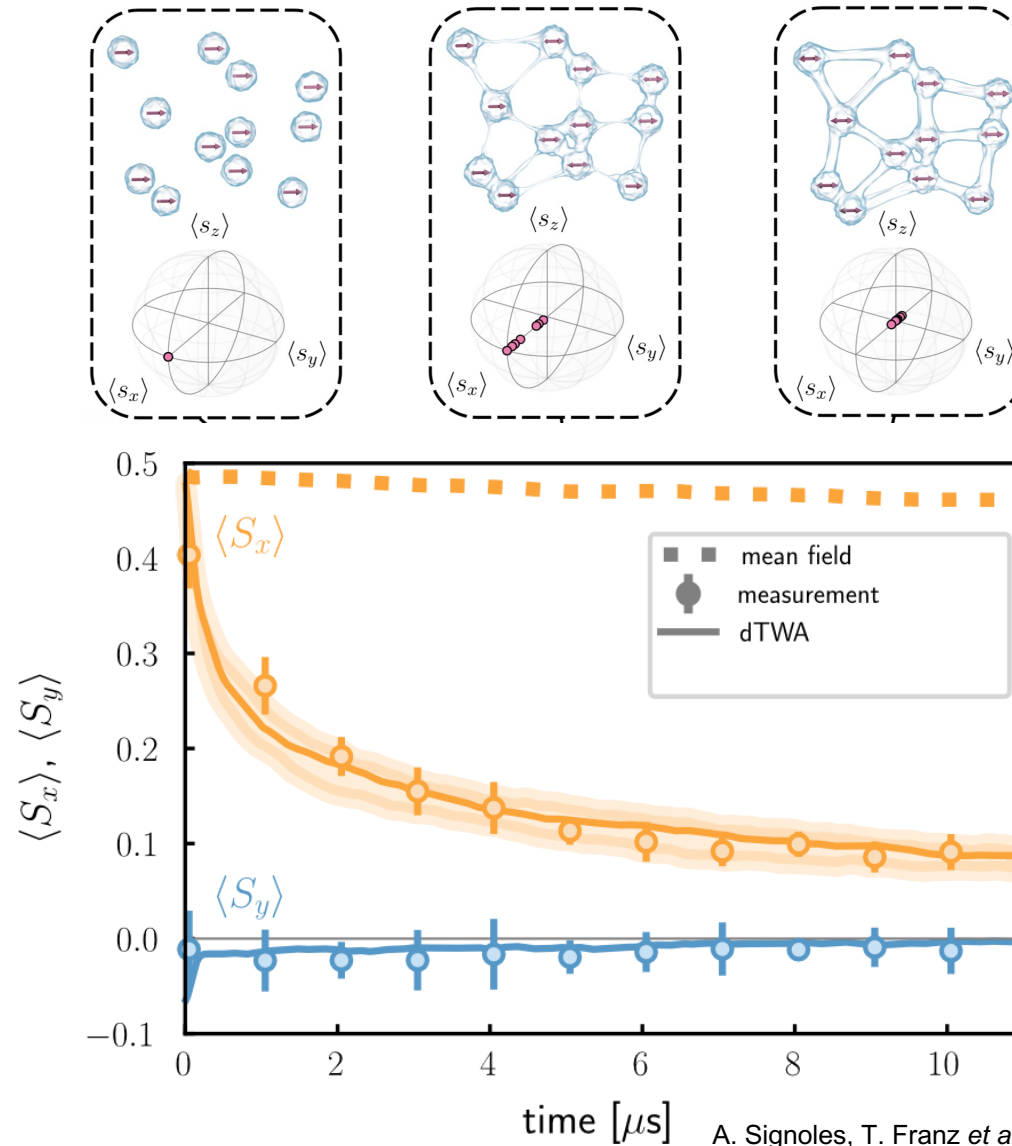
comparison to dTWA



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A. Signoles, T. Franz *et al.*, Phys. Rev. X, in press; arXiv:1909.11959

Stretched exponential function

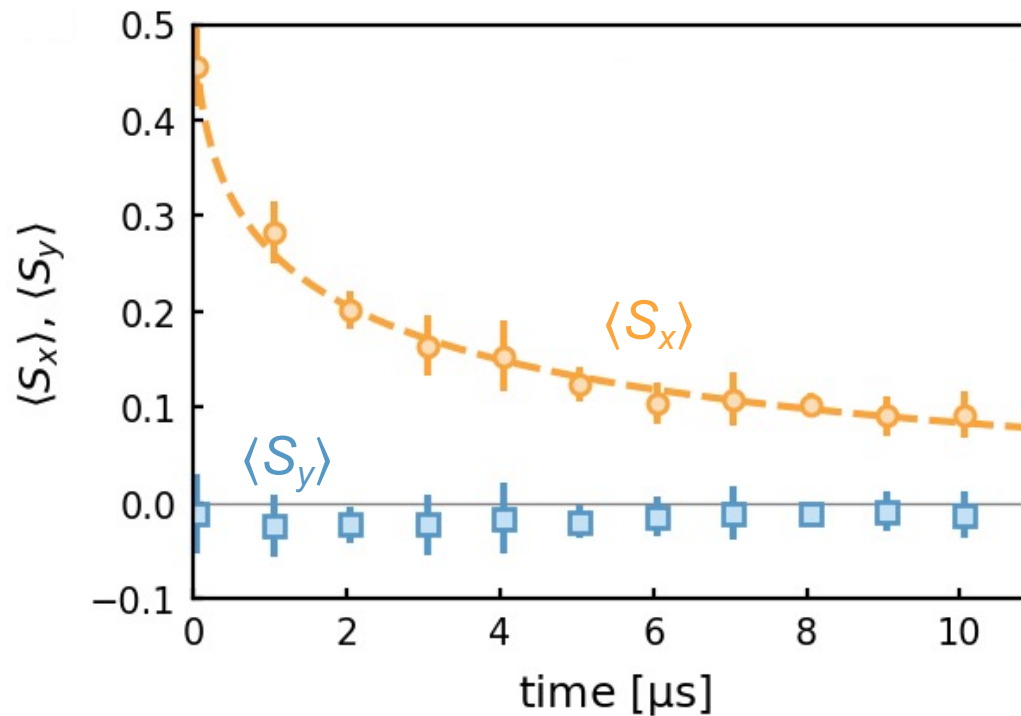
(from spin glass physics)

$$M_{\beta}(t) \propto \exp(-(t/\tau)^{\beta})$$

$$\beta \rightarrow 0$$

$$\exp(-(t/\tau)^{\beta}) = \frac{1}{e} - \frac{\beta \log(\frac{t}{\tau})}{e} + \mathcal{O}(\beta^3)$$

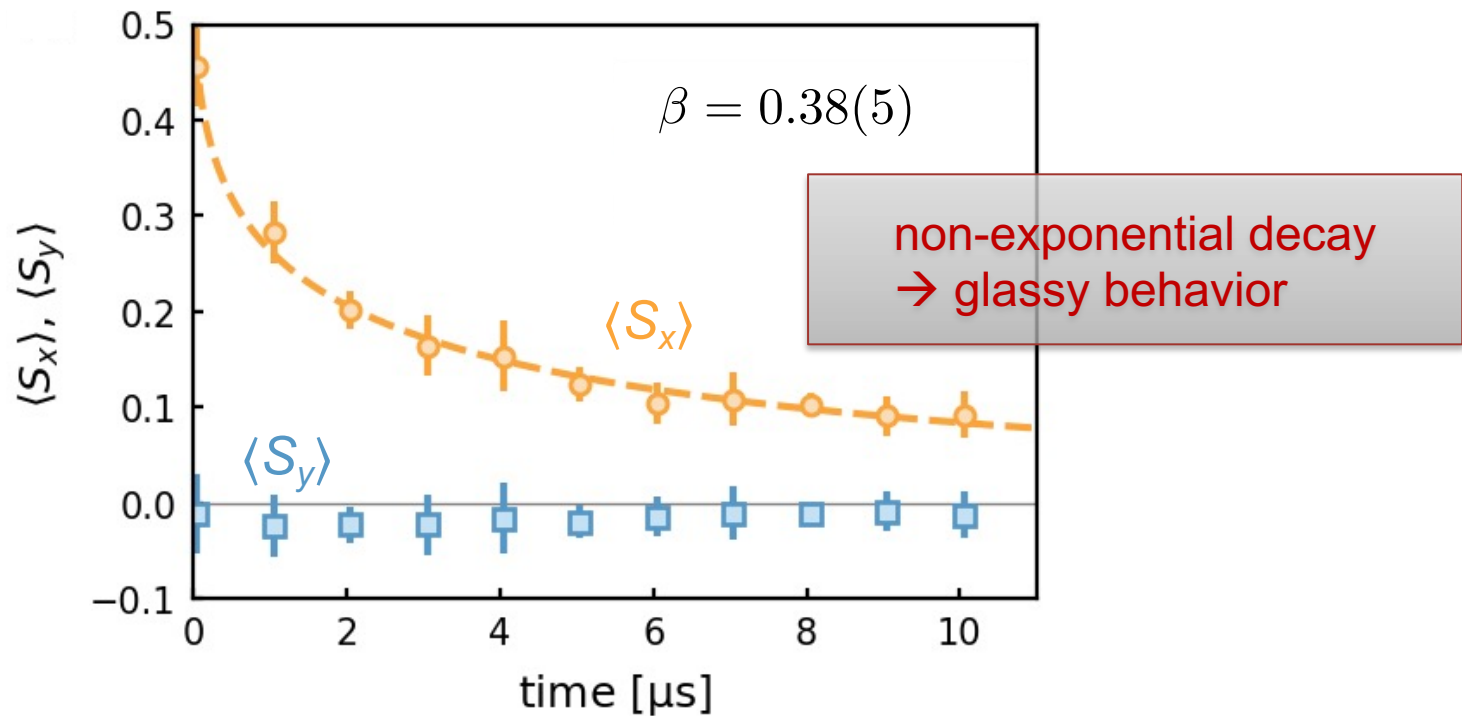
logarithmic decay



Stretched exponential function

(from spin glass physics)

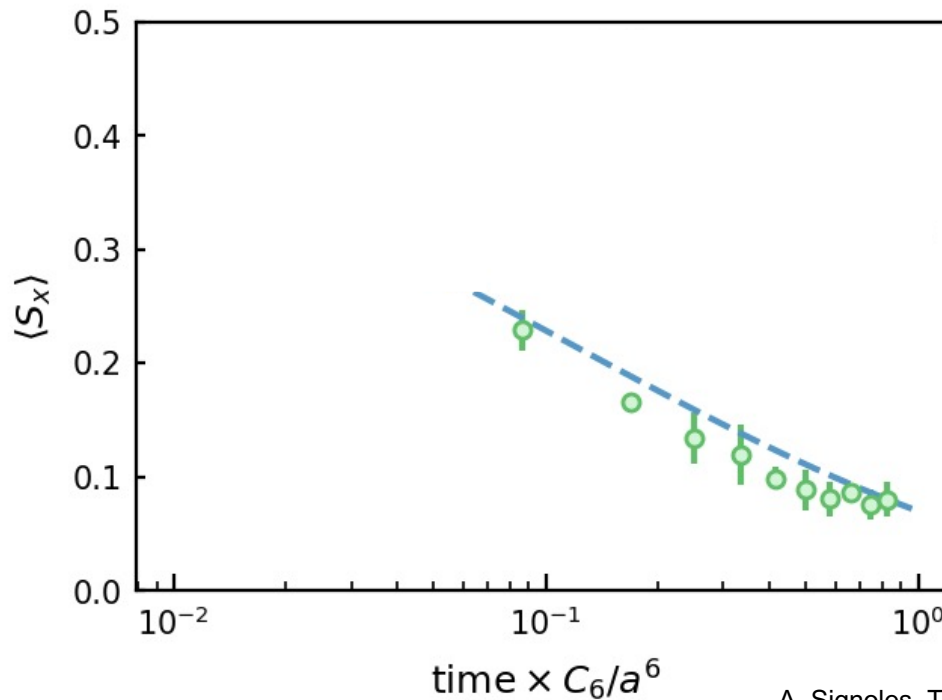
$$M_{\beta}(t) \propto \exp(-(t/\tau)^{\beta})$$



$$H_{\text{XXZ}} = \frac{1}{2} \sum_{i,j} J_{ij} (S_x^{(i)} S_x^{(j)} + S_y^{(i)} S_y^{(j)} + \delta S_z^{(i)} S_z^{(j)})$$

$$J(R) = \frac{C_6}{R^6}$$

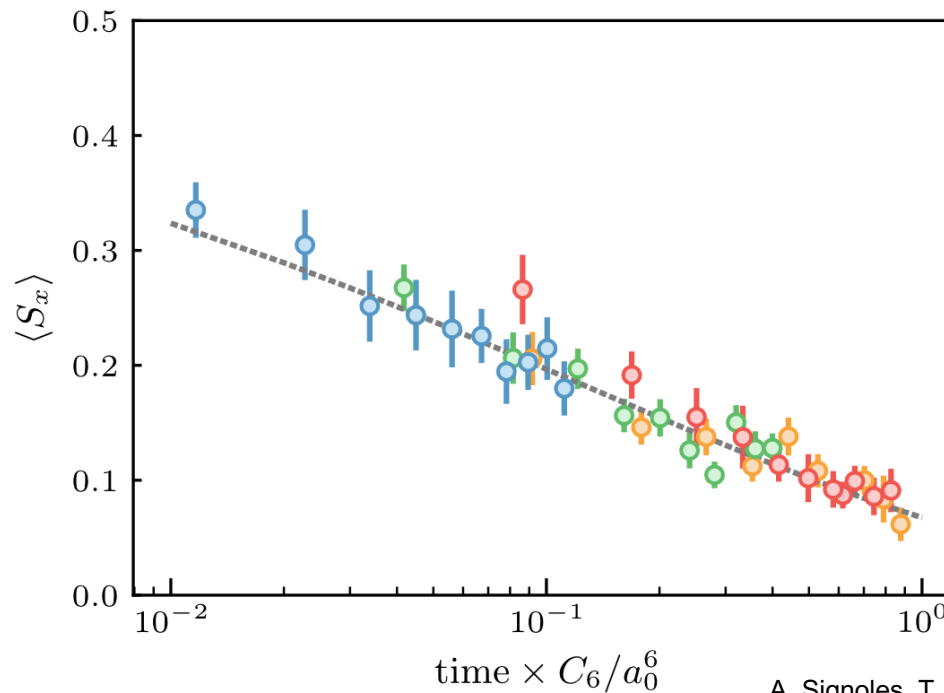
Change density $\Rightarrow$ rescale time: $t' = \frac{t}{C_6/a^6}$ with $a = \sqrt[3]{3/4\pi n}$



$$H_{\text{XXZ}} = \frac{1}{2} \sum_{i,j} J_{ij} (S_x^{(i)} S_x^{(j)} + S_y^{(i)} S_y^{(j)} + S_z^{(i)} S_z^{(j)})$$

$$J(R) = \frac{C_6}{R^6}$$

Change density $\Rightarrow$ rescale time: $t' = \frac{t}{C_6/a^6}$ with $a = \sqrt[3]{3/4\pi n}$



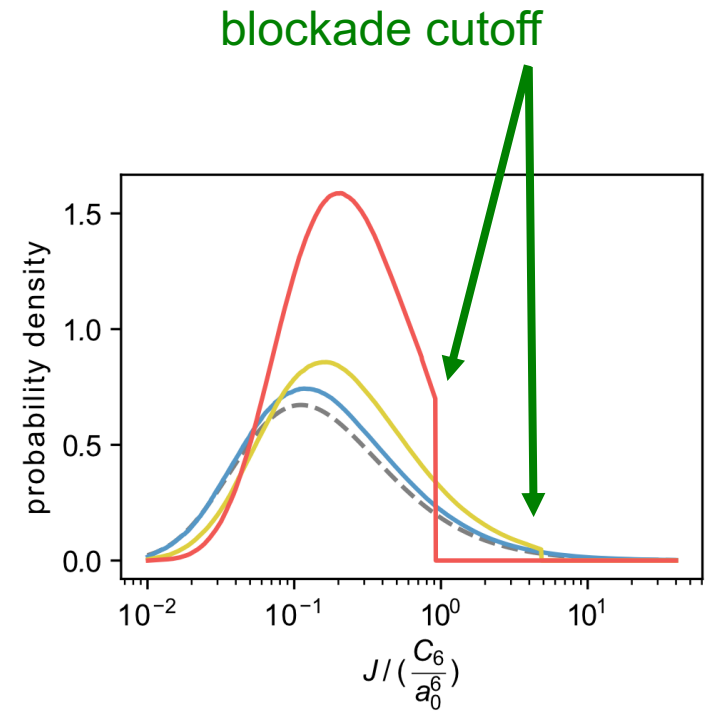
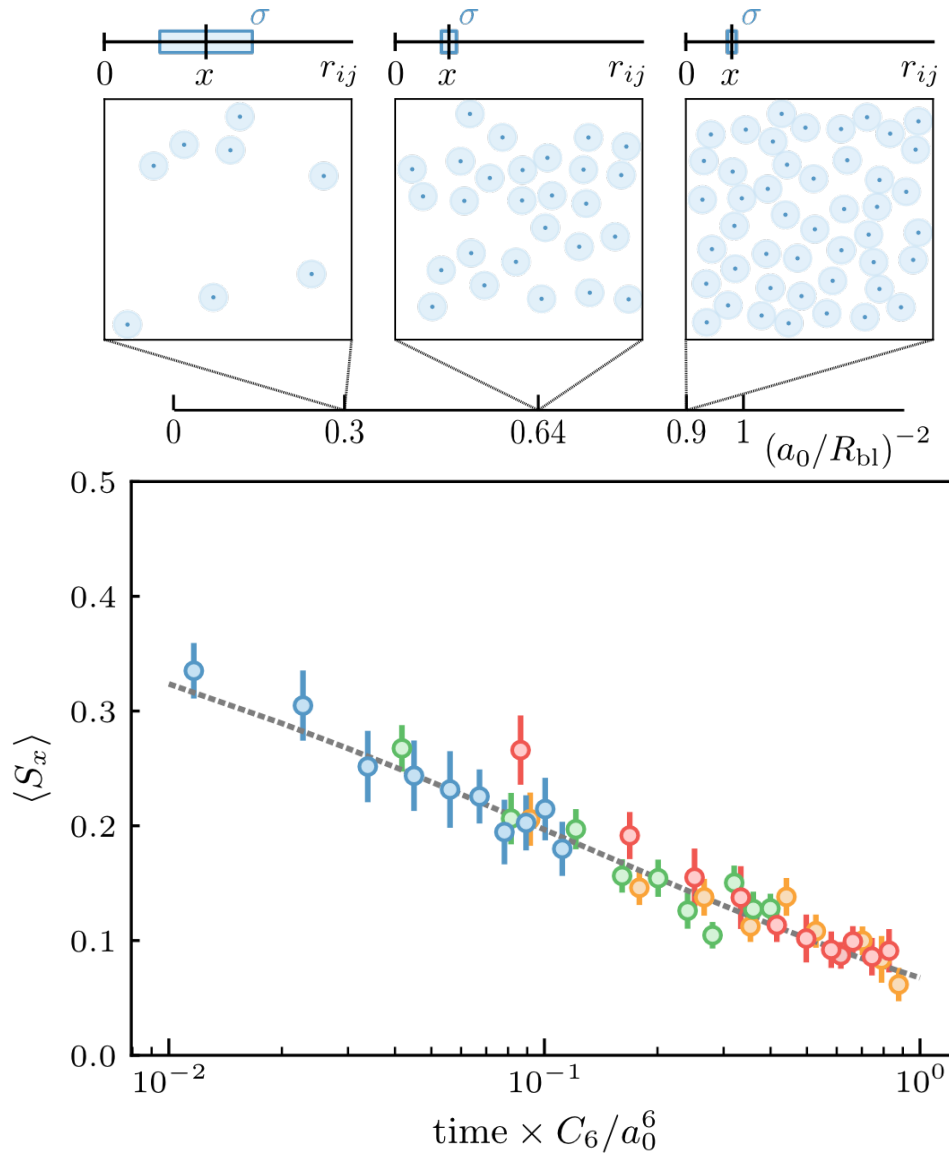
density rescaling

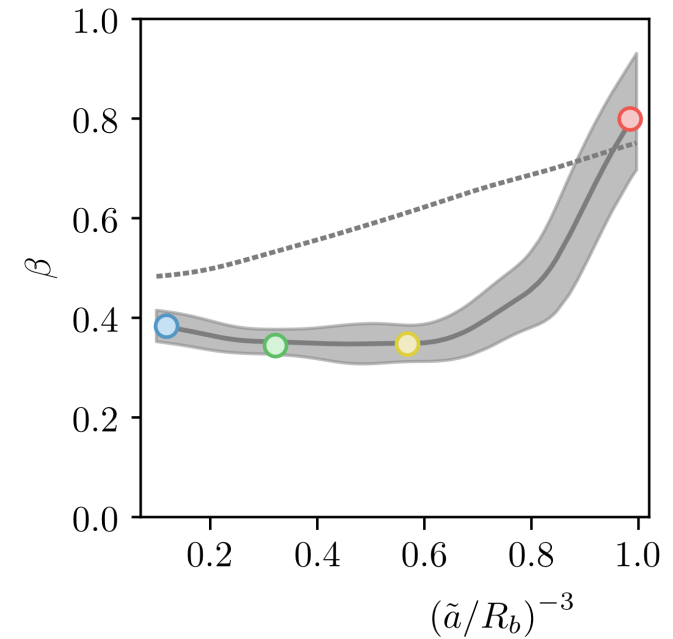
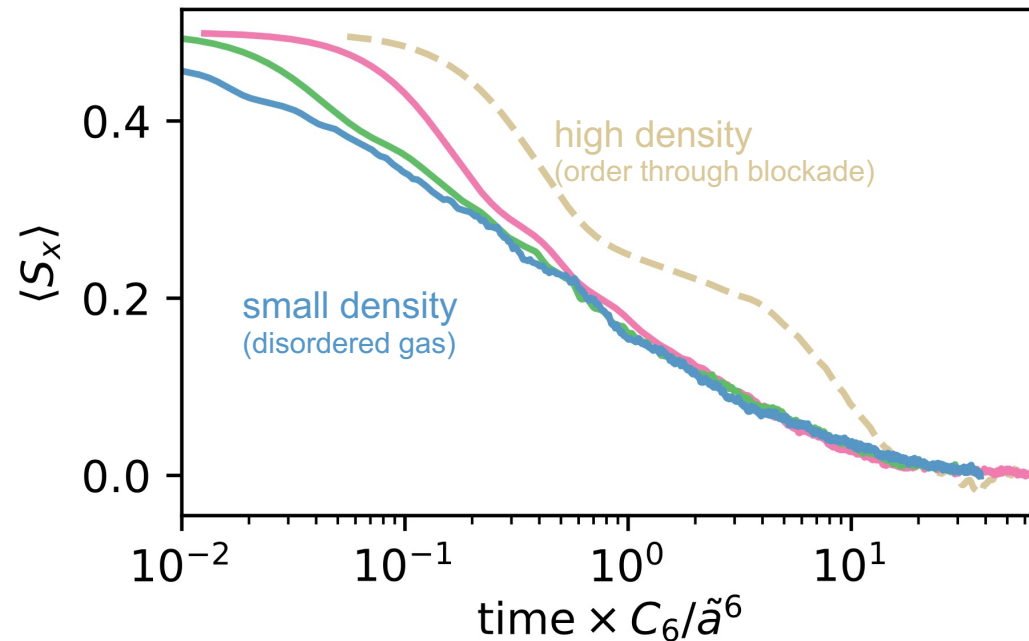


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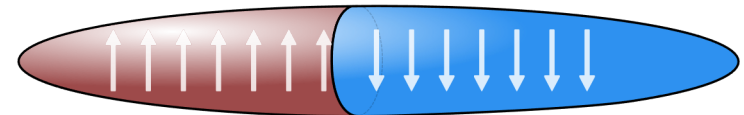
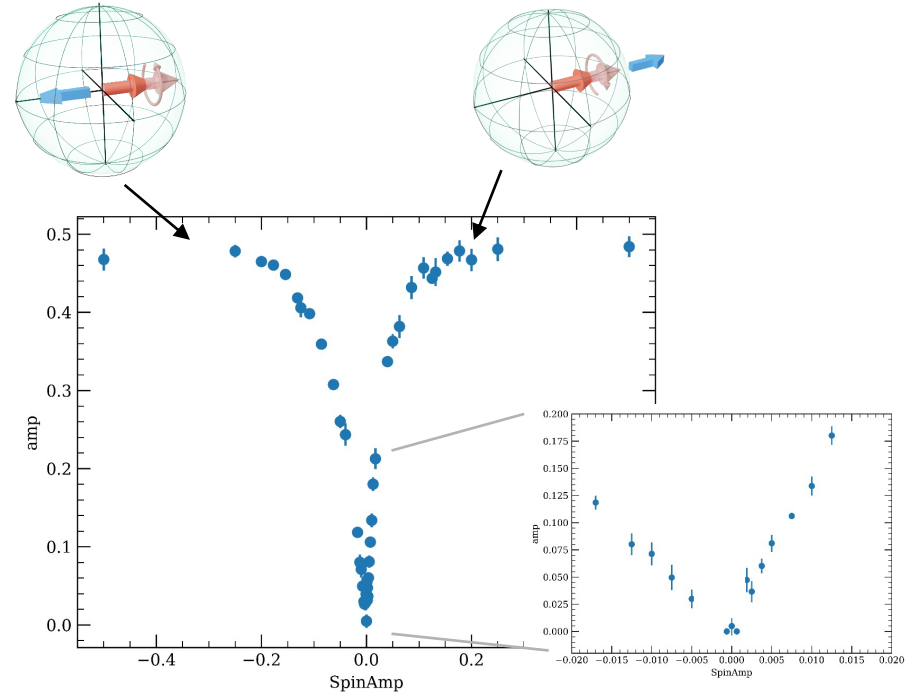
Strongly disordered

- Universal $\beta = 0.36$
- Relaxation rate $\gamma_J = \frac{C_6}{\tilde{a}^6}$
- Amplitude $A = 0.5$

Weakly disordered

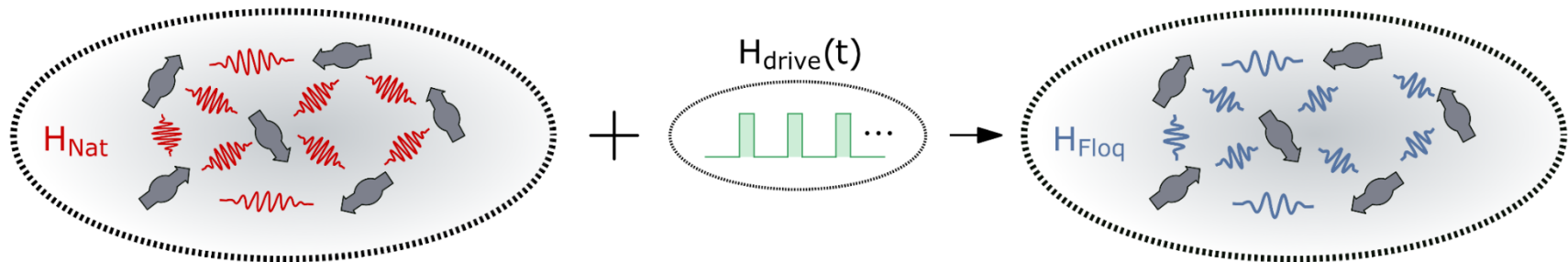
- β, γ_J and A depend on microscopic parameters

- Non-equilibrium dynamics with external field
- Dynamics of the susceptibility (“Aging”)
- Transport across spin boundary (domain wall)



- Introduction
- Rydberg atoms and spin models
- Universal glassy dynamics in a frozen Rydberg gas
- Floquet Spin Hamiltonian Engineering

Control the dynamics of a many-body spin system by periodic driving



Time-periodic Hamiltonian

$$H(t) = H(t + T)$$

→ Effective Hamiltonian description

Evolution over one cycle T

$$U(T, 0) = e^{-\frac{i}{\hbar} T H_{\text{Floq}}}$$



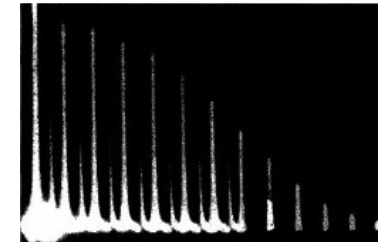
Engineer target Hamiltonian with programmable interactions
that are naturally not accessible

- NMR (decoupling of spins, ...)

E. L. Hahn, Spin Echoes, Phys. Rev. 80, 580 (1950).

J. S. Waugh et al., Approach to High-Resolution NMR in Solids, PRL 20, 180 (1968).

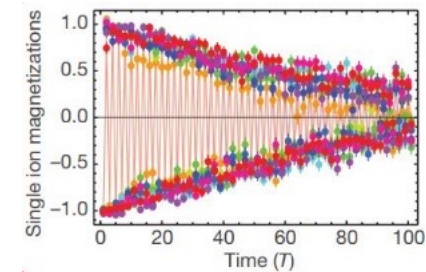
K. X. Wei et al., Exploring Localization in Nuclear Spin Chains, PRL 120, 070501 (2018).



- Trapped ions (non-equilibrium physics, ...)

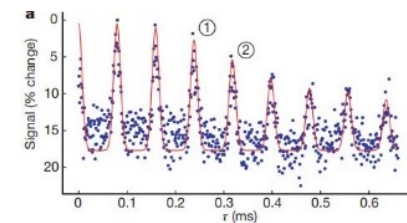
J. Zhang et al., Observation of a discrete time crystal, Nature 543, 217 (2017).

P. Jurcevic et al., Direct Observation of Dynamical Quantum Phase Transitions in an Interacting Many-Body System, Phys. Rev. Lett. 119, 080501 (2017).



- NV centers (quantum sensing, ...)

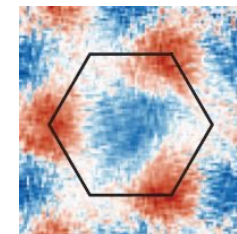
J. R. Maze et al., Nanoscale magnetic sensing with an individual electronic spin in diamond, Nature 455, 644–647(2008)



- Atoms in optical lattices (band-structure engineering, ...)

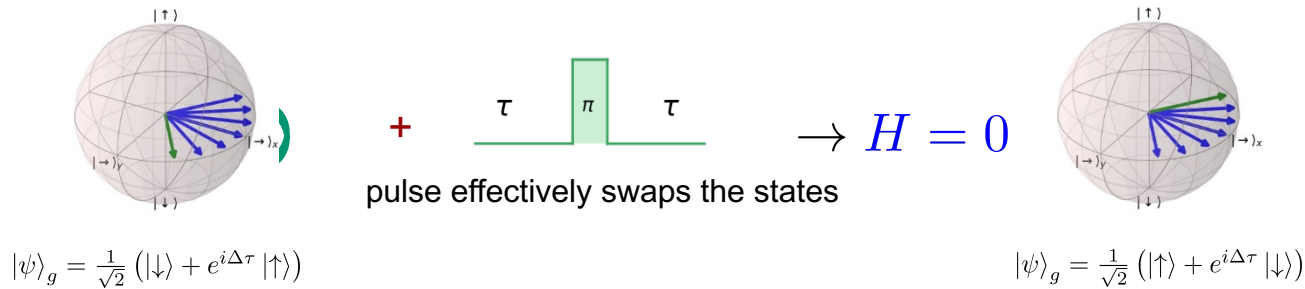
N. Fläschner et al., Experimental reconstruction of the Berry curvature in a Floquet Bloch band, Science 352, 1091 (2016)

C. Schweizer et al., Floquet approach to Z2 lattice gauge theories with ultracold atoms in optical lattices, Nature Physics 15, 1168–1173 (2019)



Basic principle : Spin-echo like sequence to reverse single-spin dephasing

Lab frame:



Effective Hamiltonian over the cycle :

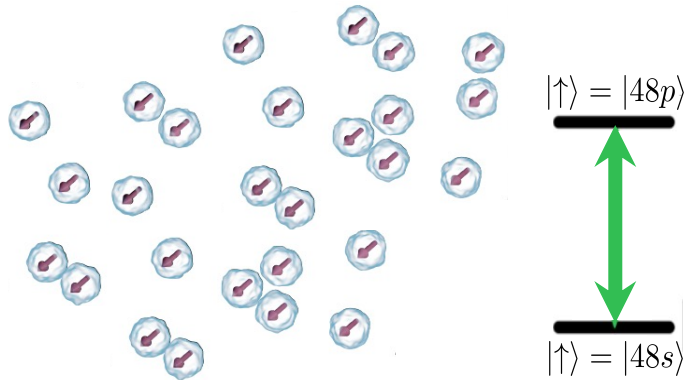
$$U(T, 0) = e^{\frac{i}{\hbar} H_{\text{Floq}} T} = e^{\frac{i}{\hbar} H_0 \tau} e^{\frac{i}{\hbar} H_1 \tau} \approx e^{\frac{i}{\hbar} (H_0 + H_1) T}$$

Average Hamiltonian Theory (Interaction frame)

$$H_{\text{Floq}} = H_0 + H_1 = \Delta \sigma_z \tau + \Delta (-\sigma_z) \tau = 0$$

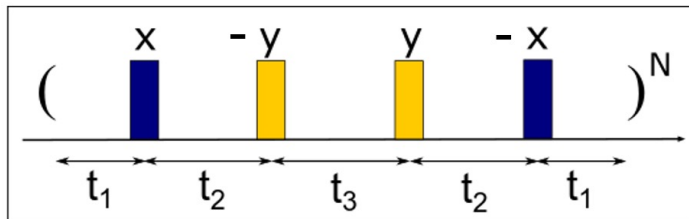
U. Haeberlen, J. S. Waugh, Coherent Averaging Effects
in Magnetic Resonance, Phys. Rev. 175, 453 (1968).

→ Periodic sequences to engineer spin-spin interactions!



- Rydberg system offers a few different Hamiltonians depending on the choice of states.

$$H_{XX} = \sum_{i \neq j} J_{i,j} (\hat{S}_x^i \hat{S}_x^j + \hat{S}_y^i \hat{S}_y^j)$$

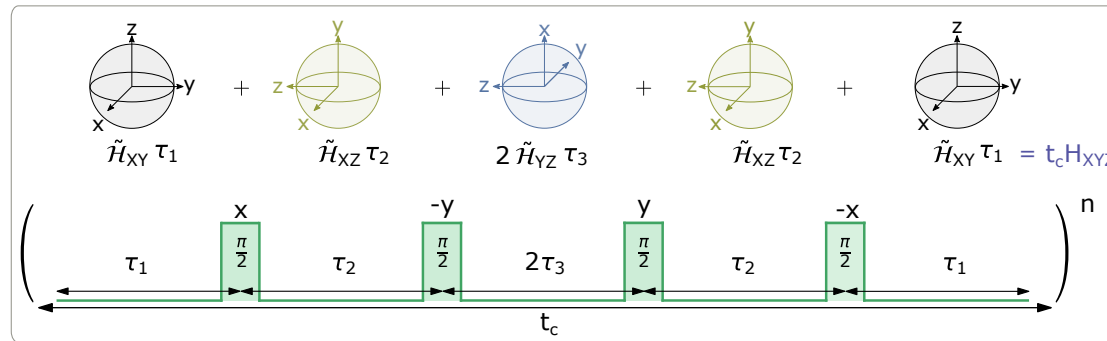


- By applying Hamiltonian Engineering (Floquet driving) we want to tune the system Hamiltonian into an arbitrary XYZ Heisenberg Hamiltonian

$$H_{XYZ}$$

Changing the pulse sequence allows for tuning of the Heisenberg Hamiltonian

- System Hamiltonian H_s
- Drive Floquet cycle: sequence of $\frac{\pi}{2}$ - pulses. $\rightarrow$ rotations P_k around x and y



- Average Hamiltonian (leading order)

$$H_{\text{avg}} = \frac{1}{T} \sum_{k=1}^n \tau_k \tilde{H}_k$$

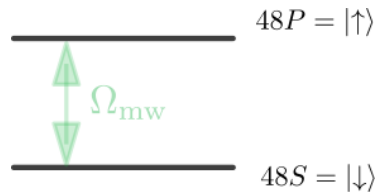
$$\tilde{H}_k = (P_k \dots P_1)^\dagger H_s (P_k \dots P_1)$$

Hamiltonian in the rotated frame: „toggling frame“

- **Conditions:** $T \ll \frac{1}{J_s}$, pulselength $\ll \tau_k$

- **Stroboscopic observation of the system at multiples of T**

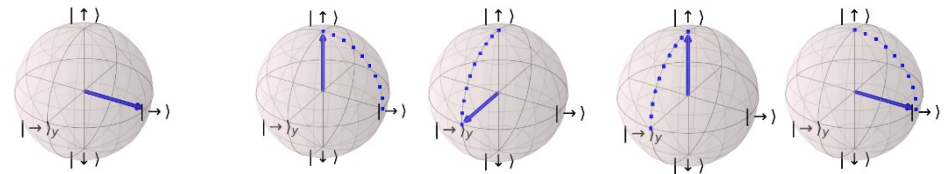
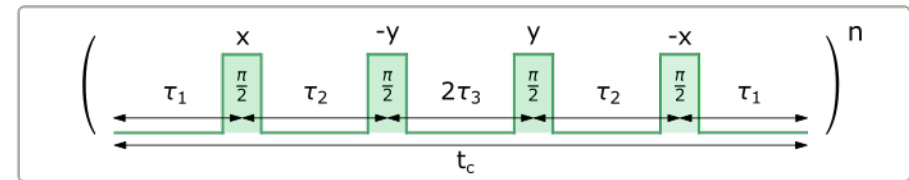
Spin-system:



$$H_{XX} = \frac{1}{2} \sum_{i \neq j} J_{ij} (S_x^i S_x^j + S_y^i S_y^j)$$

Microwave drive: $\tau_1 = \tau(1 - 2v + 2w)$
 $\tau_2 = \tau(1 + 2u - 2w)$
 $\tau_3 = \tau(1 - 2u + 2v)$

+



$$J_{ij} t_c \ll 1$$

$$U(t_c, 0) = e^{\frac{i}{\hbar} H_{\text{Floq}} t_c} = e^{\frac{i}{\hbar} H_0 \tau_1} e^{\frac{i}{\hbar} H_1 \tau_2} e^{\frac{i}{\hbar} H_2 2\tau_3} e^{\frac{i}{\hbar} H_1 \tau_2} e^{\frac{i}{\hbar} H_0 \tau_1} \approx e^{\frac{i}{\hbar} H_{XYZ} t_c}$$

→ Averaging can be chosen by the delay!

$$H_{XYZ} = \frac{1}{3} \sum_{i \neq j} J_{ij} ((1 - v + u) S_x^i S_x^j + (1 + w - u) S_y^i S_y^j + (1 - w + v) S_z^i S_z^j)$$

Naturally given XX-model → Floquet XYZ-model

$$J_m/2\pi = 0.2\text{MHz}, \Omega/2\pi = 20\text{MHz}, t_c \sim 1\mu\text{s}$$

Floquet cycles for Rydberg system

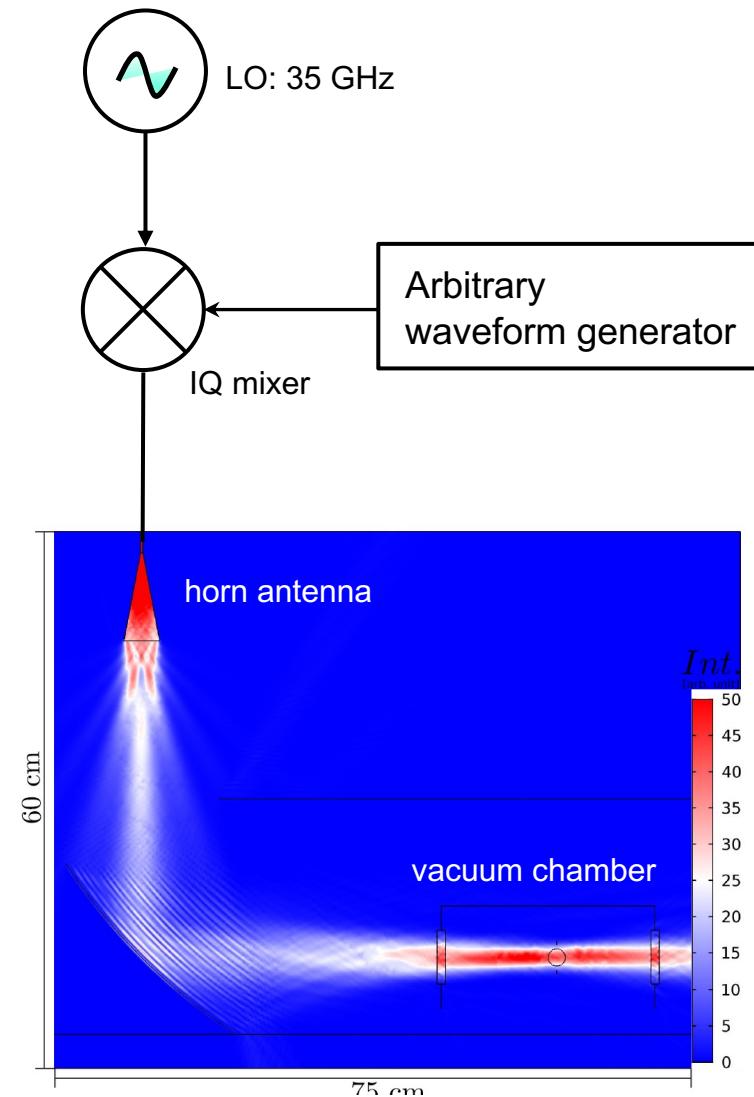


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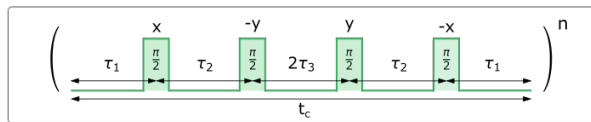
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- ✓ High Rabi frequencies (up to 100 MHz)
- ✓ ns-pulse and phase control – AWG (5 GSPS)
- ✓ Polarization control and Power stability (minimize rotation angle error)



How to verify that many-body dynamics are driven by the effective Hamiltonian?

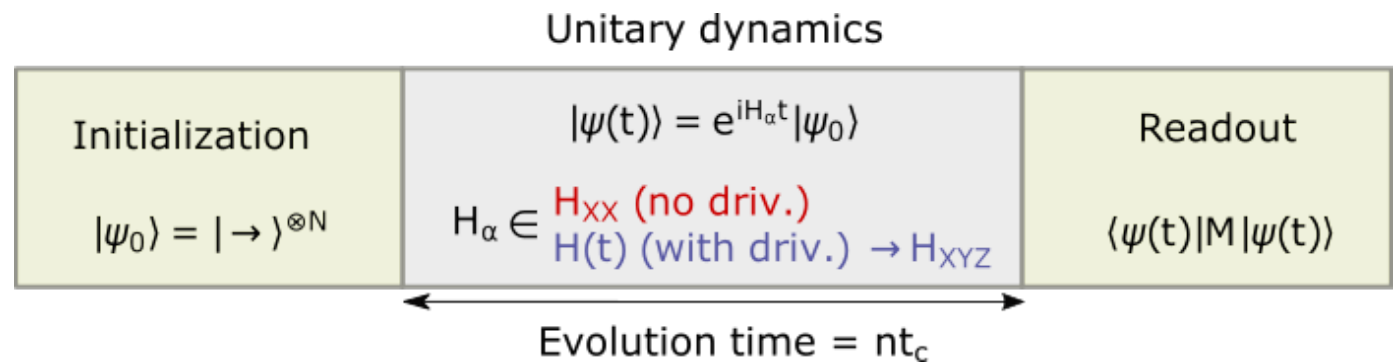
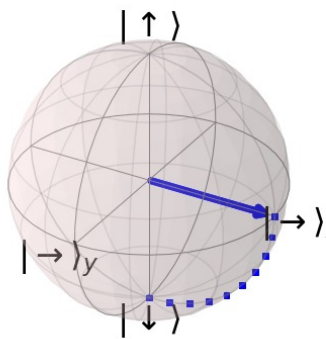
→ Freeze far-from equilibrium dynamics



$$u = v = w \rightarrow H_{XXX} = \frac{1}{3} \sum_{i \neq j} J_{ij} (S_x^i S_x^j + S_y^i S_y^j + S_z^i S_z^j)$$

→ conservation of the total magnetization

Experimental protocol:



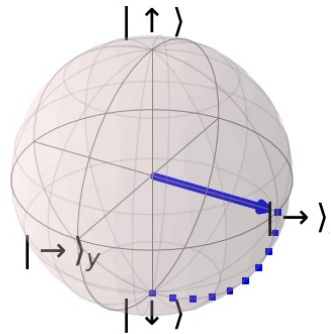
stalling demagnetization



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Unitary dynamics

Initialization

$$|\psi_0\rangle = |\rightarrow\rangle^{\otimes N}$$

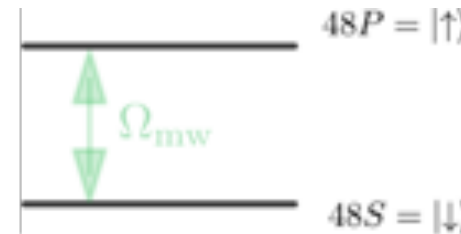
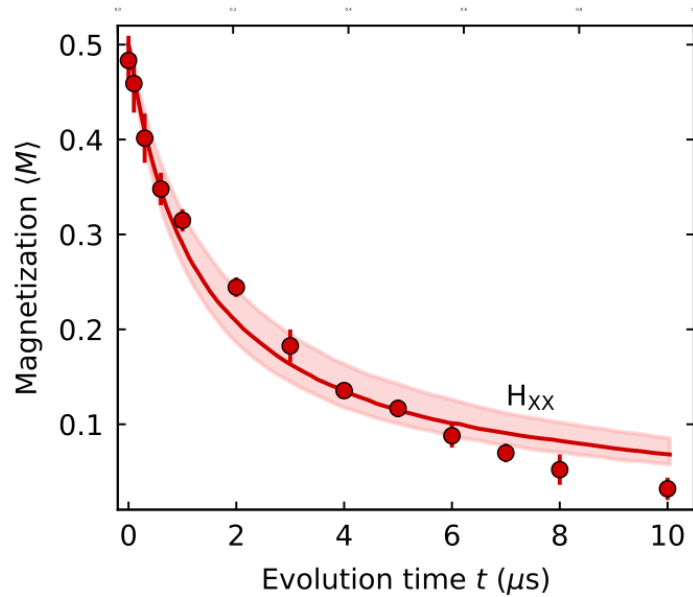
$$|\psi(t)\rangle = e^{iH_\alpha t} |\psi_0\rangle$$

$$H_\alpha \in \begin{matrix} H_{XX} \text{ (no driv.)} \\ H(t) \text{ (with driv.)} \rightarrow H_{XYZ} \end{matrix}$$

Readout

$$\langle \psi(t) | M | \psi(t) \rangle$$

Evolution time = nt_c



$$H_{XX} = \frac{1}{2} \sum_{i \neq j} J_{ij} (S_x^i S_x^j + S_y^i S_y^j)$$

stalling demagnetization

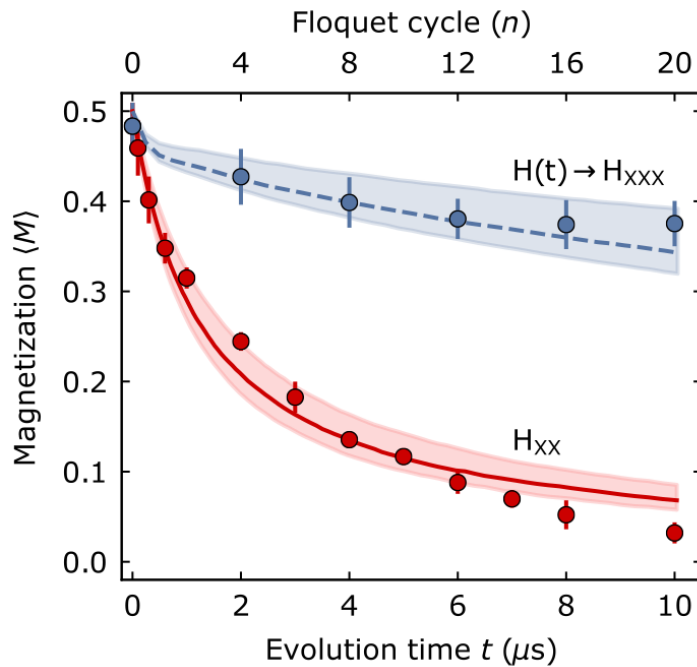
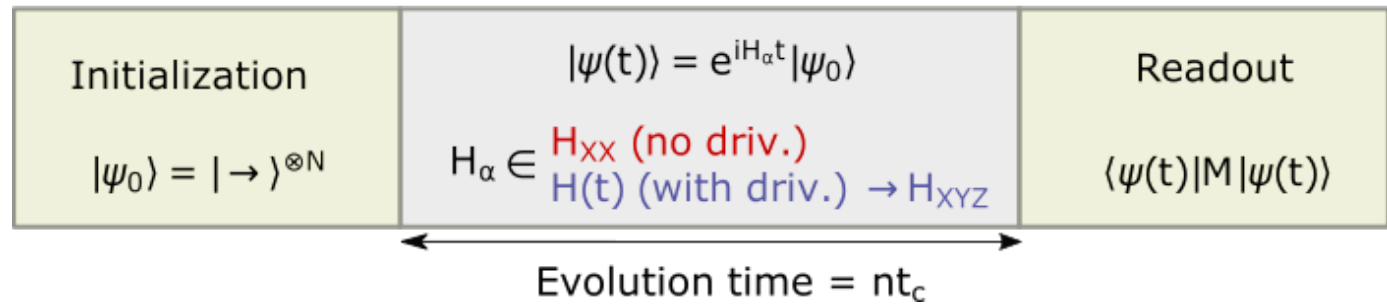


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Unitary dynamics



$$H_{XXX} = \frac{1}{3} \sum_{i \neq j} J_{ij} (S_x^i S_x^j + S_y^i S_y^j + S_z^i S_z^j)$$

stalling demagnetization

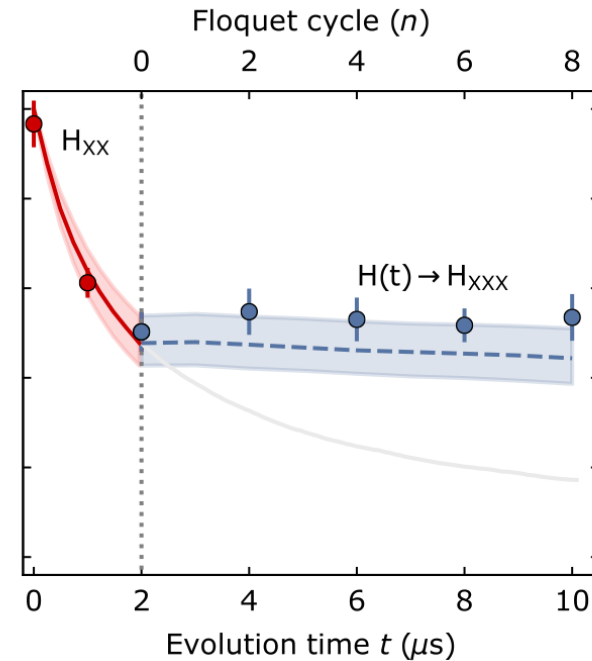
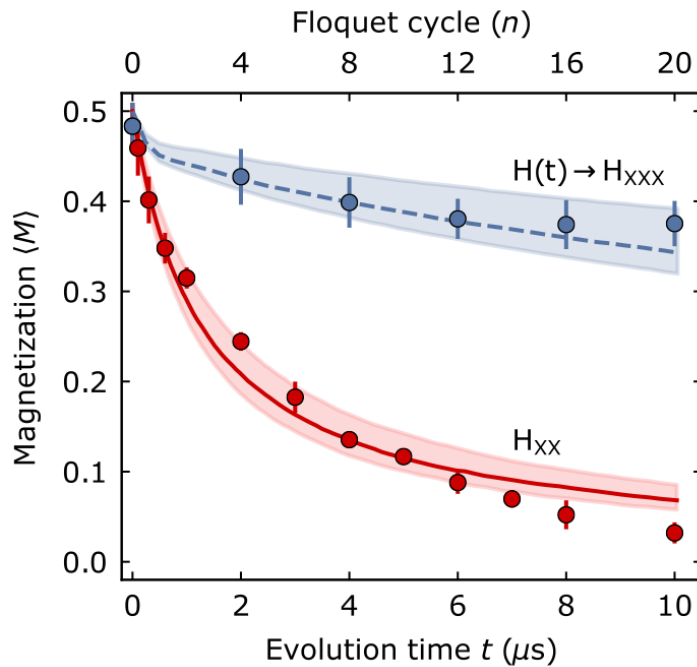
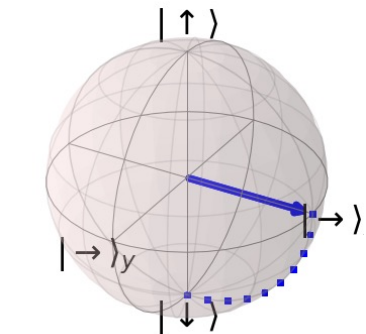
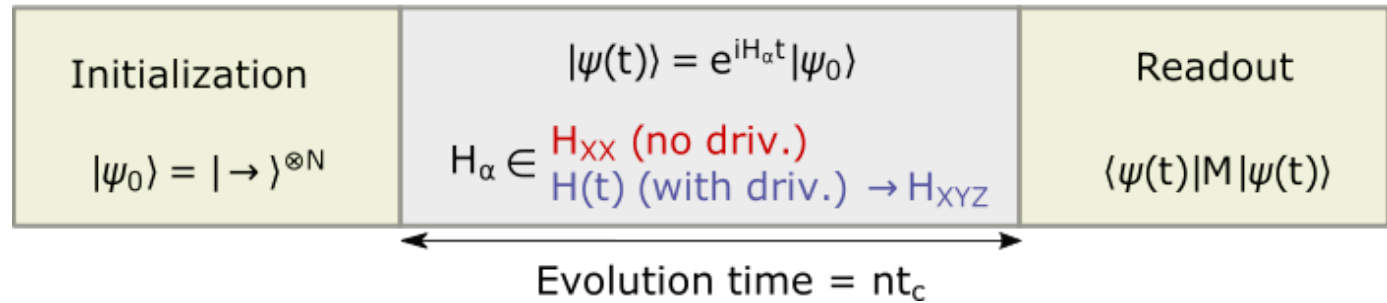


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Unitary dynamics

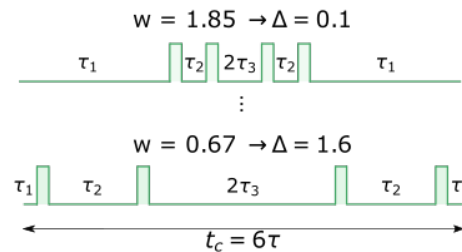


→ Magnetization dynamics slow drastically down

Application to Quantum Simulation:

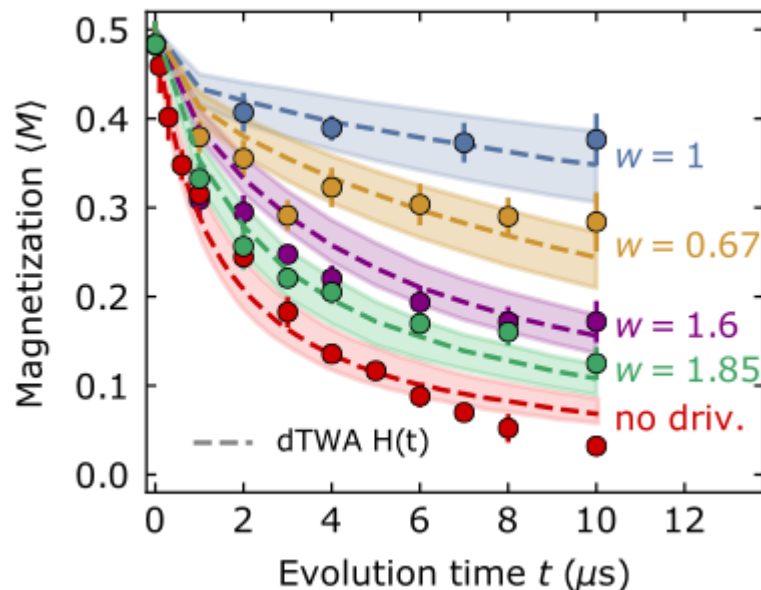
How does the relaxation dynamic depend on the anisotropy of the Hamiltonian?

→ Change relative delay times between pulses ($\triangleq$ averaging in the field frame)



$$\rightarrow H_{\text{XXZ}} = \frac{1+w}{3} \sum_{i \neq j} (J_{ij}/r_{ij}^3) (S_x^i S_x^j + S_y^i S_y^j + \Delta S_z^i S_z^j)$$

SU(2) symmetry for $\Delta = 1$
U(1) symmetry for $\Delta \neq 1$



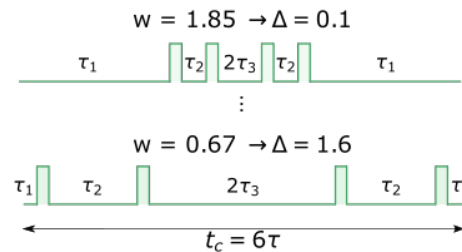
➤ Drastic change in the dynamics!

➤ Non-monotonic in the tuning parameter w !

Application to Quantum Simulation:

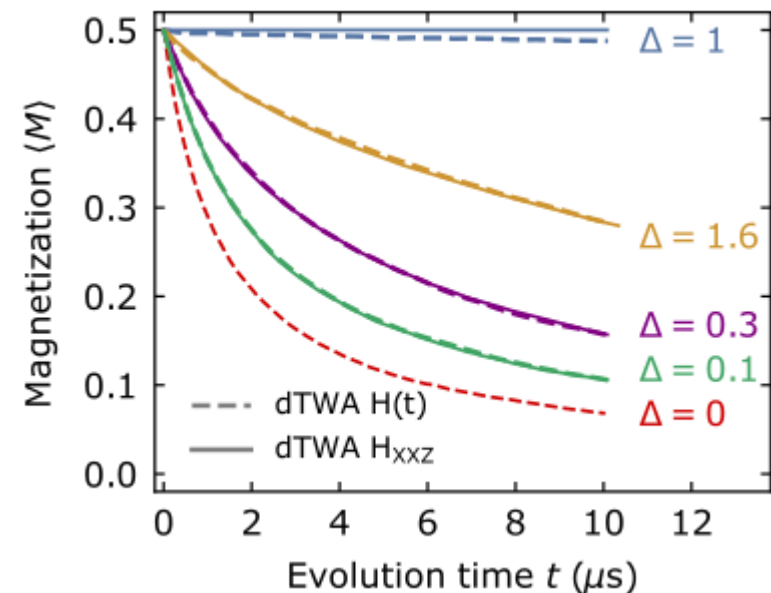
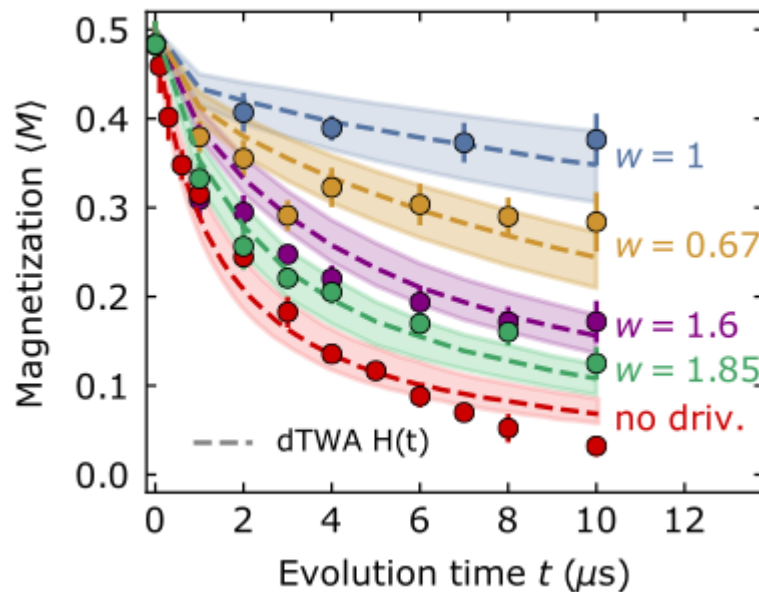
How does the relaxation dynamic depend on the anisotropy of the Hamiltonian?

→ Change relative delay times between pulses ($\triangleq$ averaging in the field frame)



$$\rightarrow H_{\text{XXZ}} = \frac{1+w}{3} \sum_{i \neq j} (J_{ij}/r_{ij}^3) (S_x^i S_x^j + S_y^i S_y^j + \Delta S_z^i S_z^j)$$

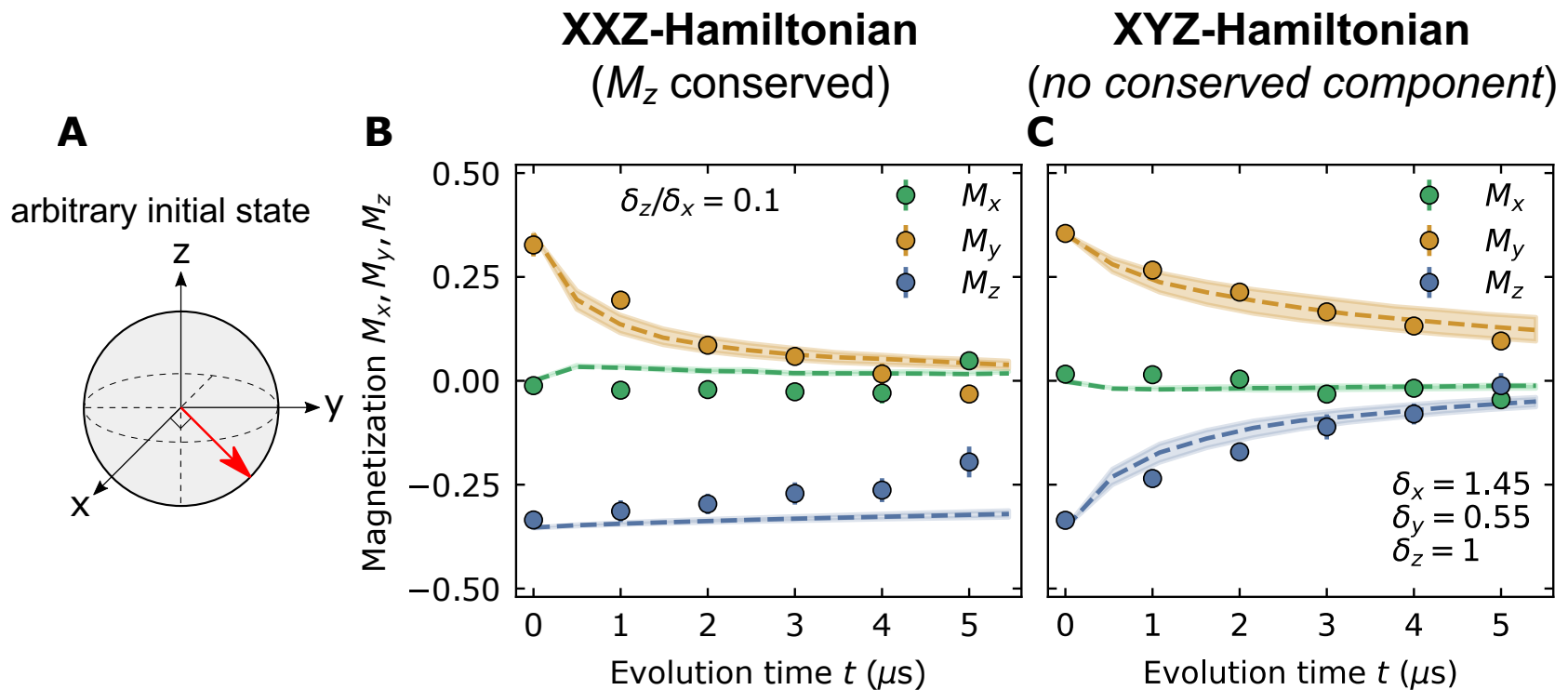
SU(2) symmetry for $\Delta = 1$
U(1) symmetry for $\Delta \neq 1$



Application to Quantum Simulation:

How does the relaxation dynamic depend on the anisotropy of the Hamiltonian?

→ Subsequently break the symmetry of the Hamiltonian



- Engineer time-reversed Hamiltonians (giving access to Out-of-Time Order Correlators)
(collaboration with Antoine Browaeys & Co. @ Institut d'Optique)
- Fluctuation-dissipation theorem beyond equilibrium
- Prethermalization dynamics
- Phase-diagram of Heisenberg Hamiltonians for ordered systems

- Rydberg atoms provide an excellent platform for implementing Ising and Heisenberg Hamiltonians

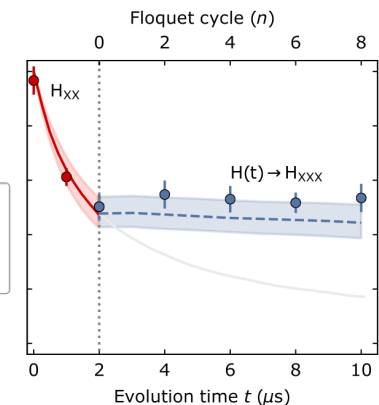
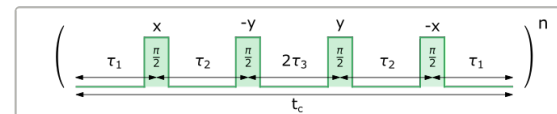
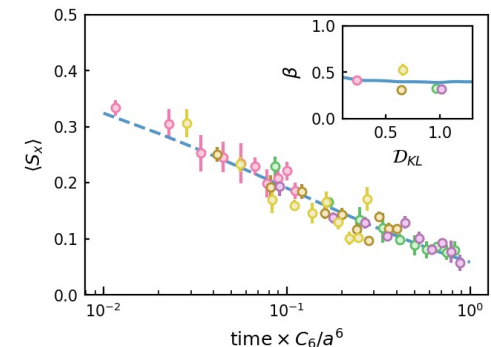
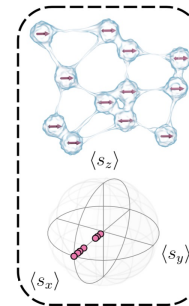
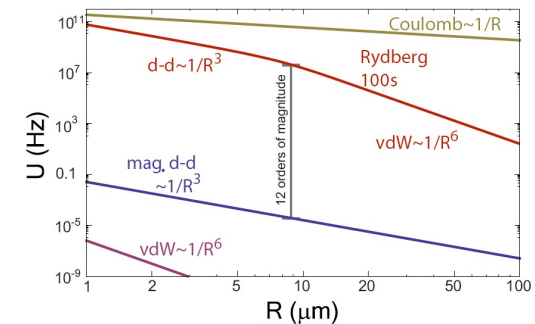
N. Takei *et al.*, Nat. Comm. **7**, 13449 (2016)
see also: M. Mizoguchi *et al.*, PRL **124**, 253201 (2020)

- Discovery of universal dynamics driven by quantum fluctuations beyond mean-field description

A. Orioli *et al.*, PRL **120**, 63601 (2018)
A. Signoles, T. Franz *et al.*, PRX (2021)

- Hamiltonian Engineering using Floquet driving

S. Geier, N. Thaicharoen *et al.*, arXiv:2105.01597



Heidelberg Rydberg team



back:

Renato Ferracini Alves, Annika Tebben, Nithiwadee Thaicharoen, Gerhard Zürn

front:

Alexander Müller, Clément Hainaut, Titus Franz, Henrik Zahn, André Salzinger, Charles Möhl, MW

not on picture: Sebastian Geier, David Grimshandl

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**Shannon
Whitlock**
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**Adrien
Signoles**
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Berges



Asier
Piñeiro Orioli



Martin
Gärtner

Theory (ITP/KIP Heidelberg)

Theory (Aarhus)



Thomas
Pohl

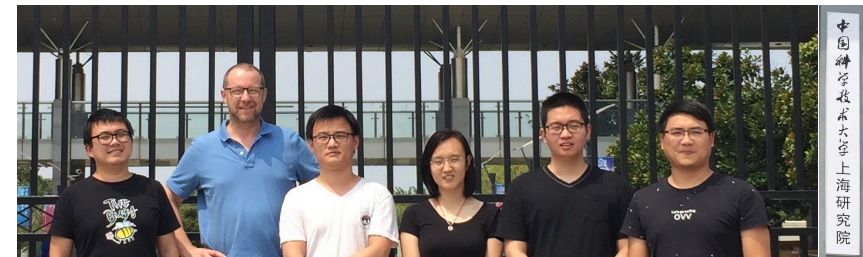


Valentin
Walther



Yongchang
Zhang

USTC Team



Zhu Bing, MW, Hu Fachao, Feng Xiaoshen, Zou Zhihan, Tan Canzhu (*not on picture: Jiang Yuhai, Julia Siegl*)

Former members: Chen Peng, Luc Couturier, Qiao Chang, Ingo Nosske



中国科学技术大学
University of Science and Technology of China



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AT THE MICROSCALE**

Thank you for your attention



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