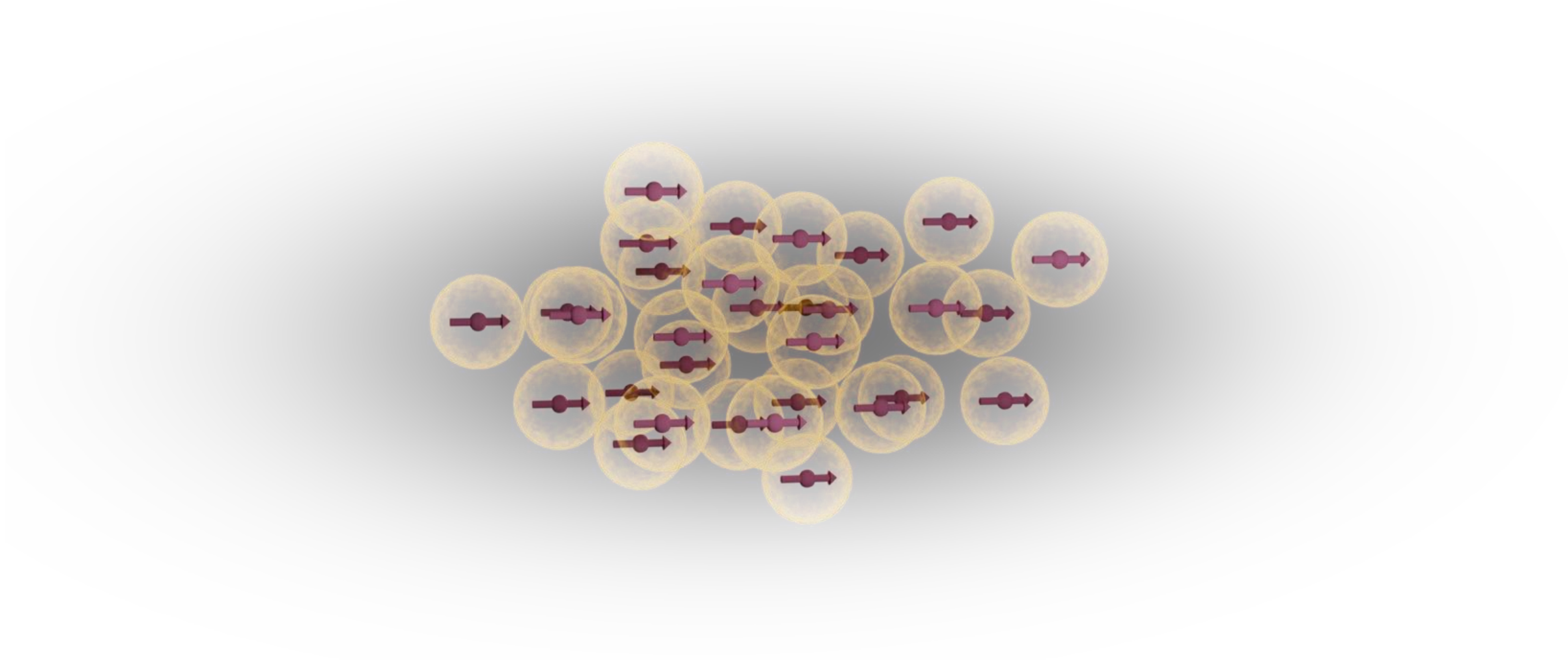
Observation of glassy dynamics in a disordered quantum spin system



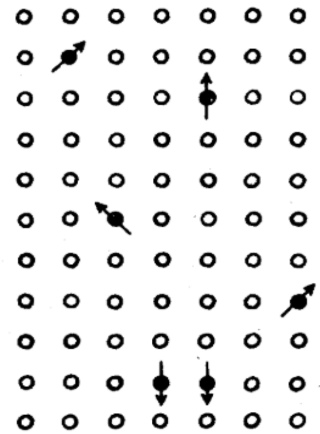
Gerhard Zürn

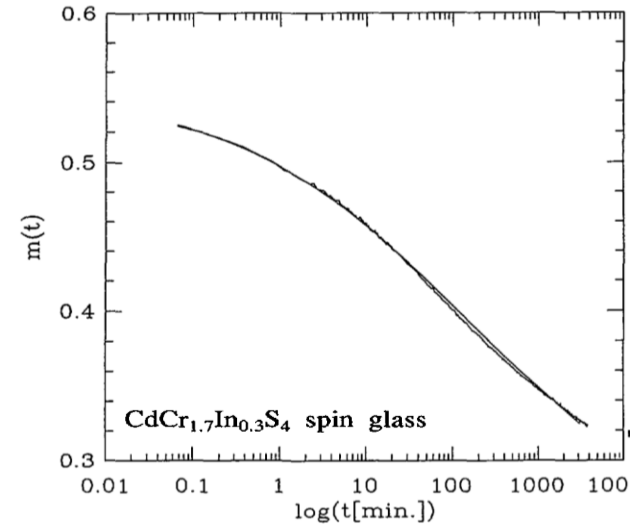
A05: Weidemueller / Whitlock / Gärttner

How do disorderd system relax

Slow dynamics:

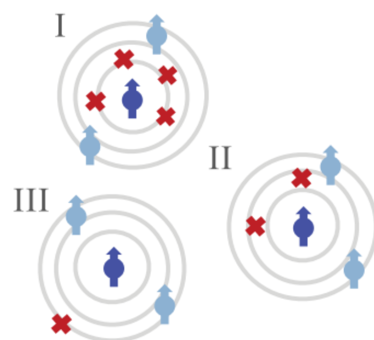
- systems coupled to a bath:
  e.g. spin glasses

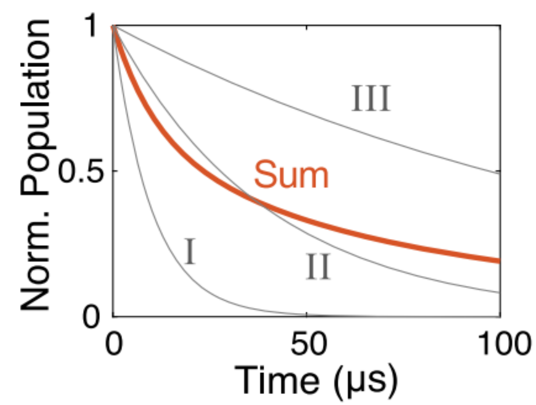




- open quantum systems:
  e.g. NV centers

  coupling to environment
  averaged depolarization



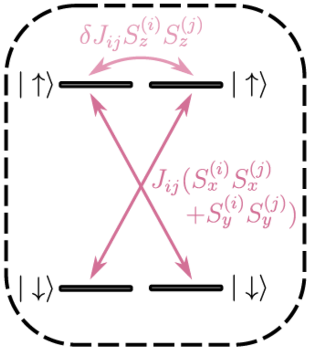


Does such glassy dynamics also exist for <u>isolated quantum systems ?</u>

J. Bouchaud, Journal de Physique I 2, 1705-1713 (1992)
A. Hamman et al., J. Appl. Phys. 61 (1987) 3683
J. Choi et al., *PRL*, *118*, 93601 (2017)

Quantum spin system

Spin ½ -system



Heisenberg XXZ Hamiltonian

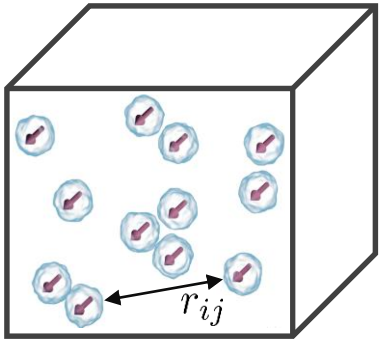
$$H = \sum_{i,j} J_{ij} \left(S_x^{(i)} S_x^{(j)} + S_y^{(i)} S_y^{(j)} + \delta S_z^{(i)} S_z^{(j)} \right)$$

$\delta = -0.7$

Disorder in the coupling constants

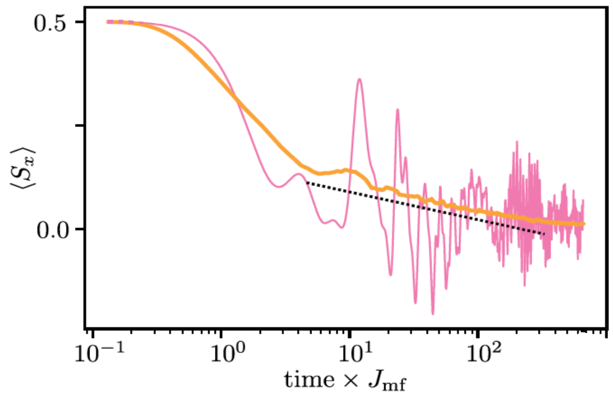
$$J_{ij} \propto \frac{1}{|r_i - r_j|^\alpha}$$

$\alpha = 6$



Few particle prediction

$$|\Psi_0\rangle = |\rightarrow\rangle_x^{\otimes N}$$



- Initial state: Spin aligned in x-direction:

- Calculate magnetization $\langle S_x \rangle$

  pink: single realization
  orange: ensamble average

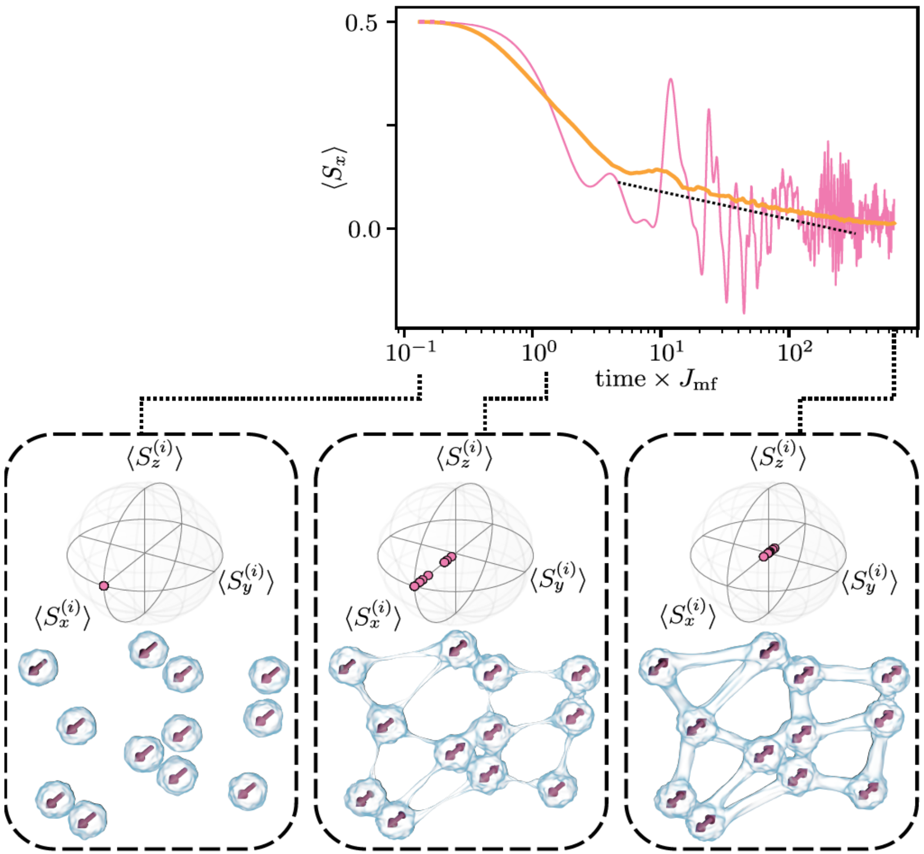
- Short time: quadratic Hamiltonian evolution

- Long time: slowdown of relaxation

  dashed line: logarithm

Few particle prediction

$$|\Psi_0\rangle = |\rightarrow\rangle_x^{\otimes N}$$



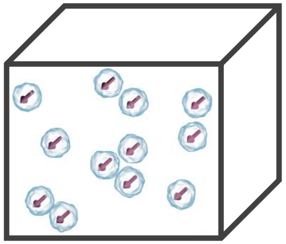
- Initial state: Spin aligned in x-direction:
- Calculate magnetization $\langle S_x \rangle$

  pink: single realization
  orange: ensamble average
- Short time: quadratic Hamiltonian evolution
- Long time: slowdown of relaxation

  dashed line: logarithm
- Built up of entanglement

Limitation of exact diagonalization

12 particles in 3D:
dominated by finite size effects

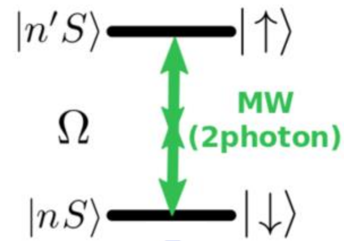


→ **Use Rydberg atom platform to study many-body dynamics**

Rydberg spin system

Implementation:

- **Spin states:** 2 different Rydberg levels:

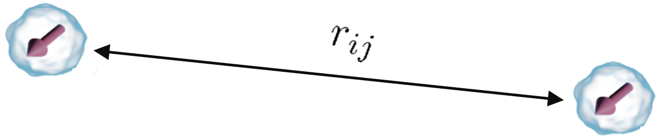


- **Motional degree of freedom frozen**

$$T = 40\,\mu K$$

$$t_{\rm exp} = 10\,\mu s \qquad \rightarrow \Delta r < \; 1\,\mu m$$

Typical distance: $\sim 10\,\mu m$



$$J_{ij} = \frac{C_6}{r_{ij}^6}$$

van der Waals interaction $C_6 \propto n^{11}$

- **Strong interaction**: timescale of coupling

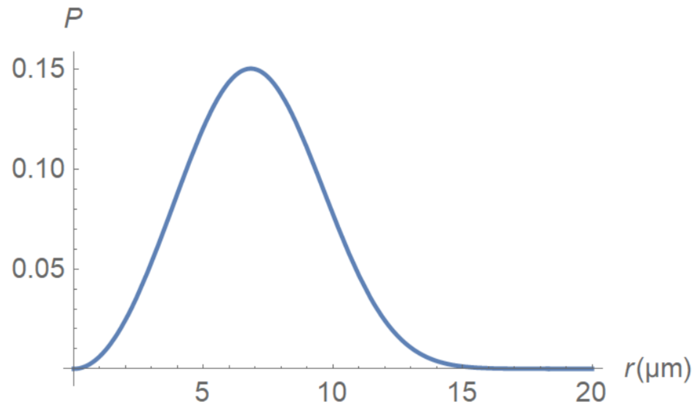
$$\frac{1}{J_{ij}} \ll t_{\rm exp}$$

$$J_{ij} \sim 1\,\mathrm{MHz}$$

Rydberg spin system

- **Disorder**: excite Rydberg atoms from a thermal distribution of ground state atoms

Neirest neighbour distribution

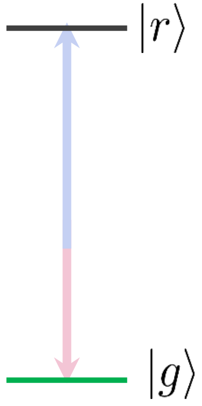


Atoms at short distance with $1/R^6$ interaction would dominate the dynamics

→ Make use of a short distance cut-off

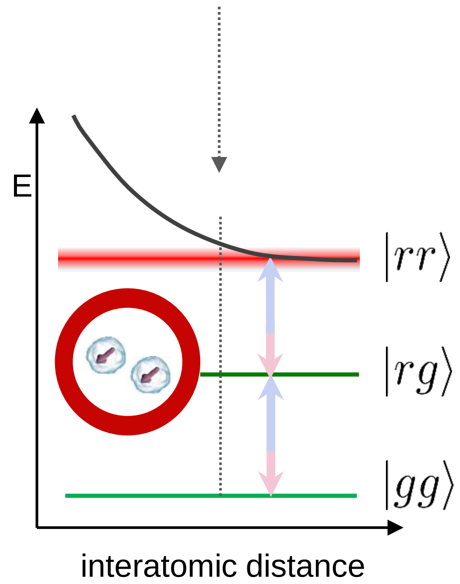
Rydberg spin system

Laser excitation:



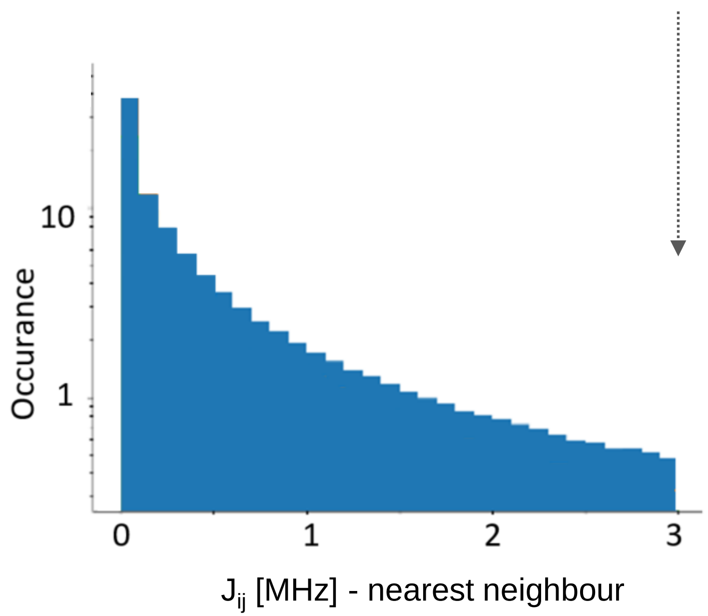
Dipole Blockade:

blockade radius R_{bl} ~ 5 µm



Distribution of coupling constants J_{ij}

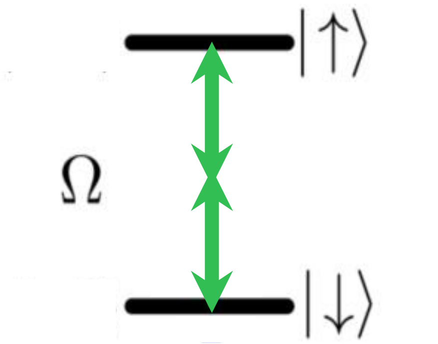
energy cut-off: 3 MHz

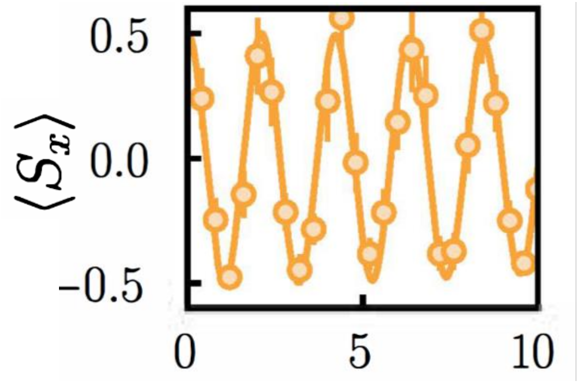


Lukin et al., PRL 87, 037901 (2001)

Rydberg spin system

- **Isolated system:** perform Ramsey measurement





Time[µs]

Ramsey measurement
($\Delta/2\pi$= 0.47 MHz)

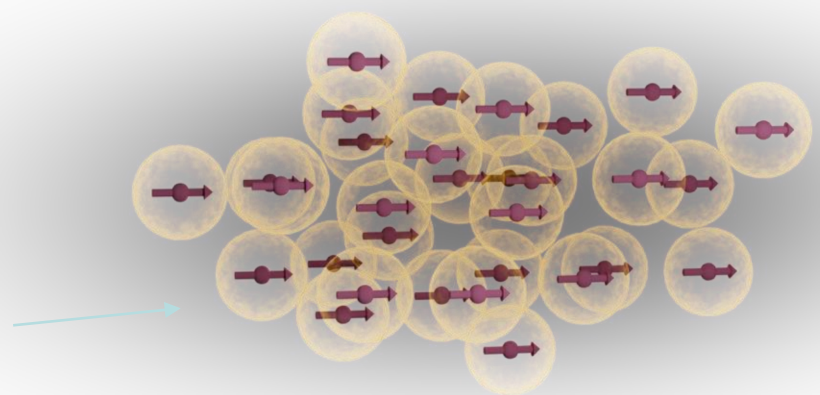
$t_{coherence}$
~ 100 µs > t_{exp}=10 µs

Rydberg spin system

Heisenberg
XXZ Hamiltonian

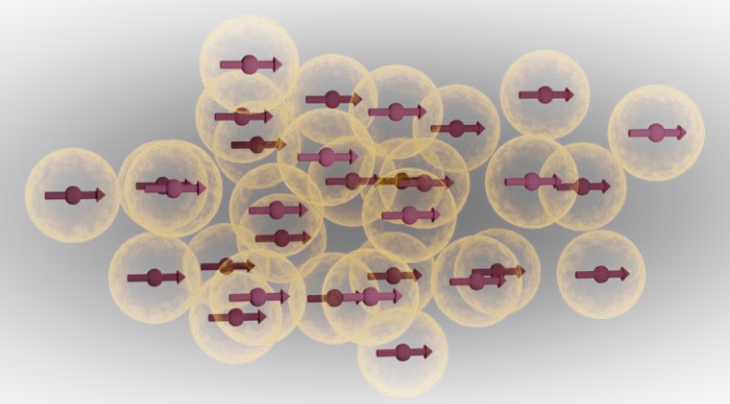
$$H = \sum_{i,j} J_{ij} \left(S_x^{(i)} S_x^{(j)} + S_y^{(i)} S_y^{(j)} + \delta S_z^{(i)} S_z^{(j)} \right)$$

$$\delta = -0.7$$



- Isolated
- Disorderd
- $J_{ij,max}$ = 3 MHz
- Number of spins ~ 1000

Quench – initial state



Perform a quench: $|\Psi_0\rangle = |\rightarrow\rangle_x^{\otimes N}$ $\xrightarrow{H_{XXZ}}$

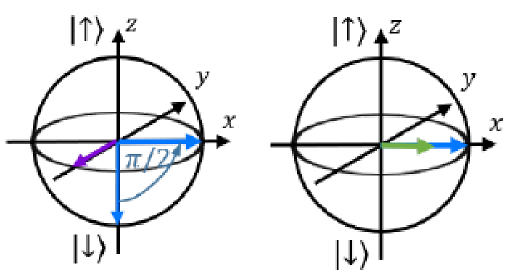
Choice of state: no evolution under the classical equation of motion

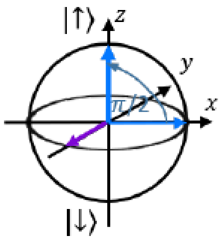
$$\langle S_y^{(j)}\rangle = 0$$
$$\langle S_z^{(j)}\rangle = 0$$

$$H_{\text{mean}} = \sum_i \underbrace{h_x^{(i)}}_{\sum_j J_{ij}\langle S_x^{(j)}\rangle} S_x^{(i)}$$

Quench protocol - readout

Rydberg excitation	Spin rotation	Unitary evolution	Measurement
$\vert\downarrow\rangle^{\otimes N}$	$\vert\Psi_0\rangle = \vert\rightarrow\rangle_x^{\otimes N}$	$\vert\Psi(t)\rangle = \mathrm{e}^{-i\hat{H}_{\mathrm{XXZ}}t}\vert\Psi_0\rangle$	$\langle\Psi(t)\vert S_x\vert\Psi(t)\rangle$

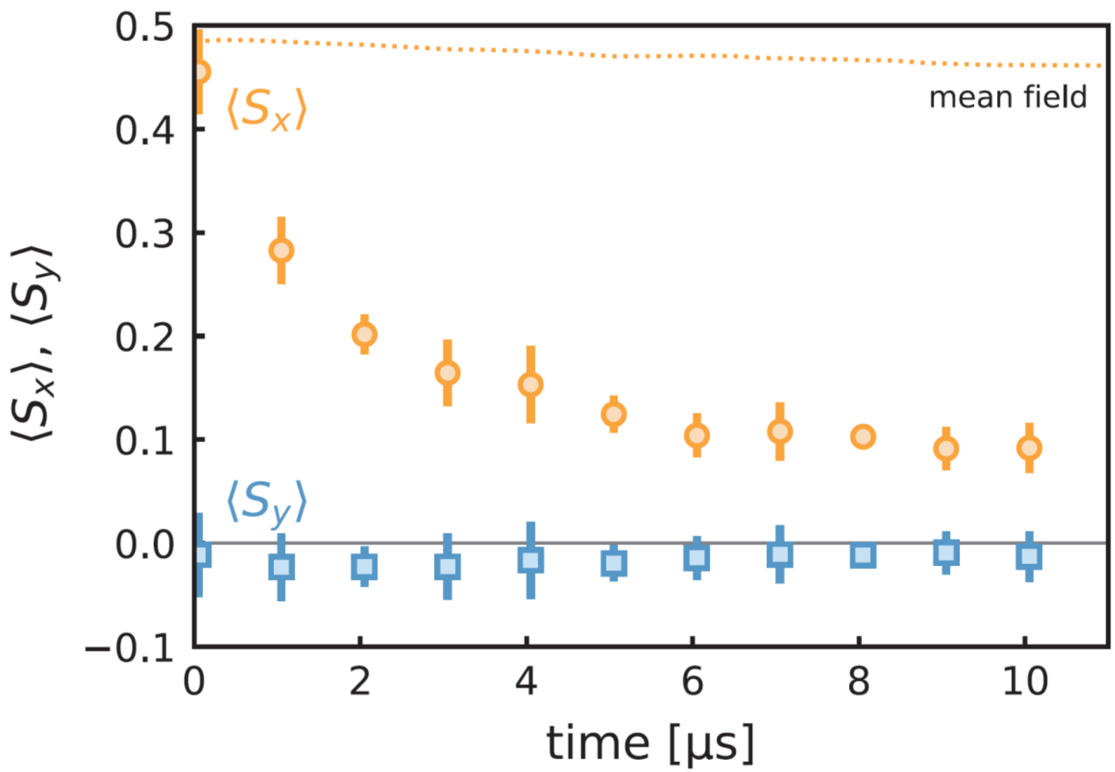




Observed relaxation dynamics

Unitary evolution

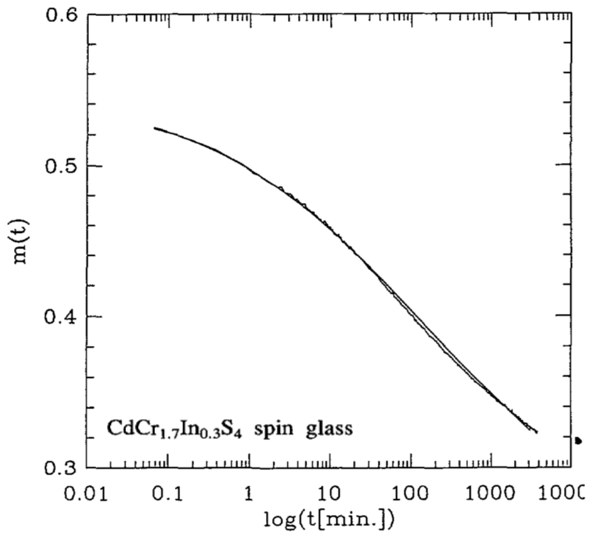
$$|\Psi(t)\rangle = \mathrm{e}^{-i\hat{H}_{\mathrm{xxz}}t}|\Psi_0\rangle$$

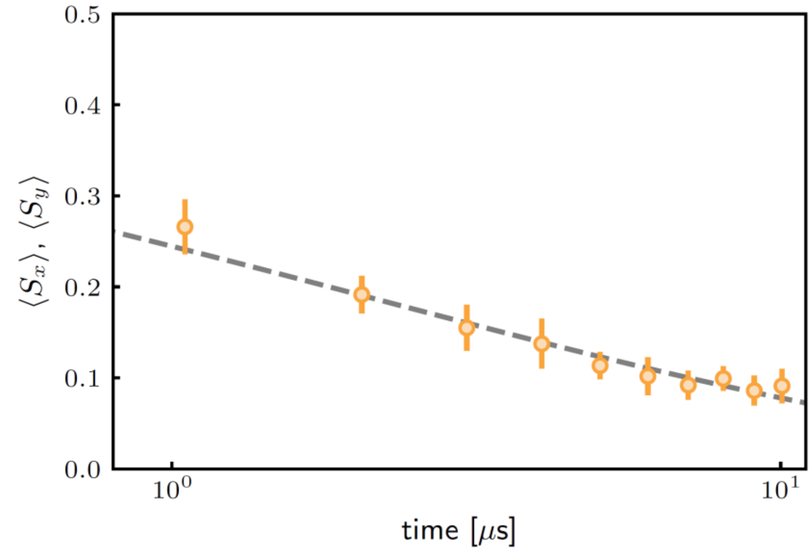


- Relaxation
- Sub-exponential → slow dynamics

→ Quantify slow dynamics

Quantifying slow dynamics





$$M_\beta(t) \propto \exp\left(-(\gamma_J t)^\beta\right)$$

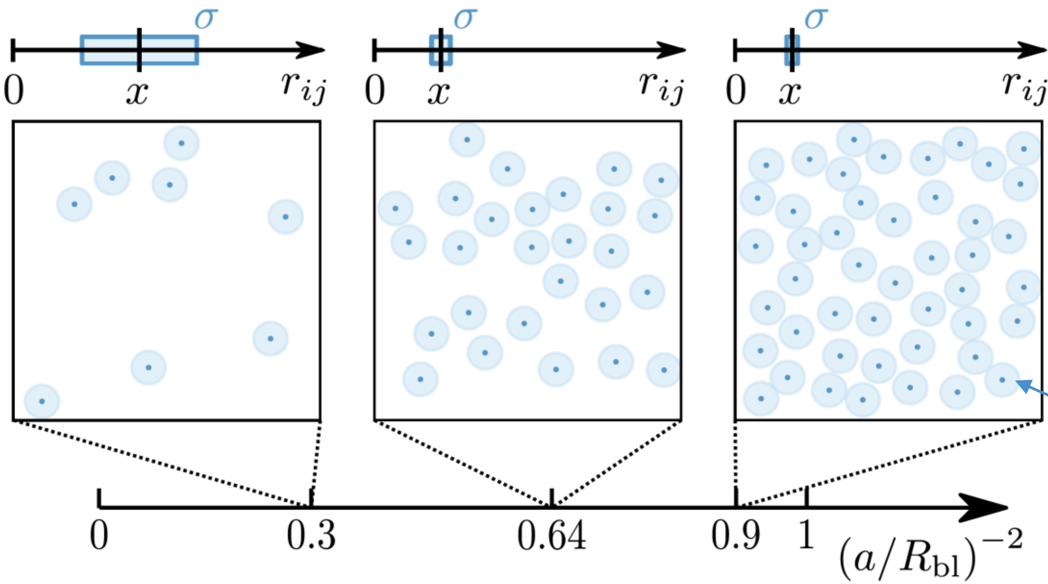
- Phenomenological fit inspired from Spin glasses
- Stretched exponent β characterizes relaxation:
  - $\beta \to 1$: Exponential decay
  - $\beta \to 0$: Logarithmic decay

Experimental fit: $\boldsymbol{\beta = 0.32(2)}$
→ glassy dynamics

How does it depend on the strength of disorder ?

J. Bouchaud, Journal de Physique I 2, 1705-1713 (1992)

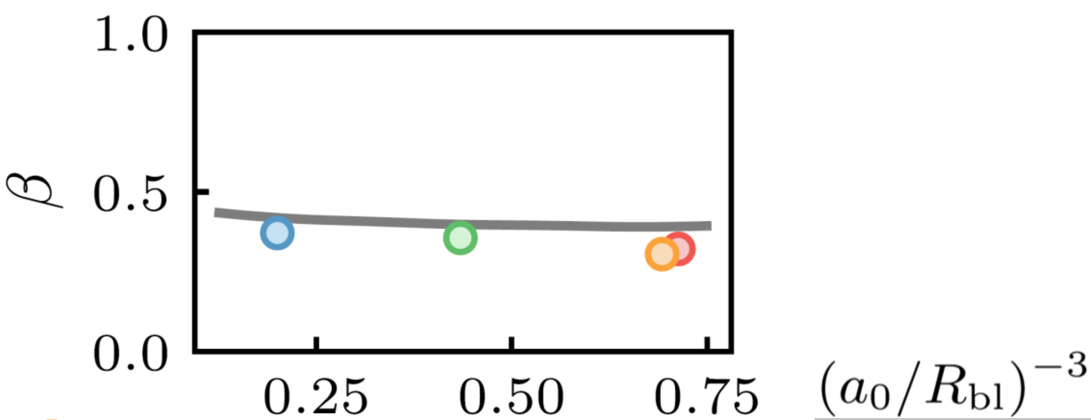
Tuning disorder strength



- Typical distance:
  Wigner-Seitz radius

$$a = \sqrt[3]{\frac{3}{4\pi n}}$$

- Exclusion volume: given by blockade radius

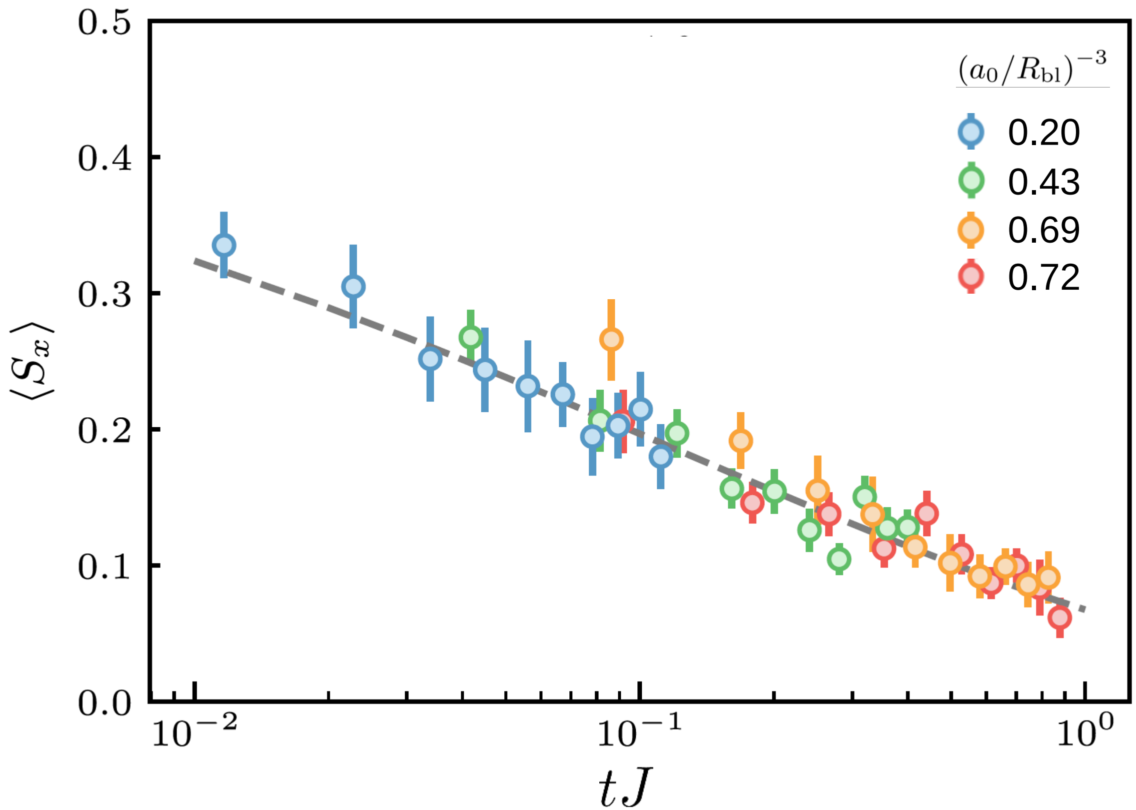


Exponent extracted for different strength of disorder

→ **Constant exponent**

Rescaling

rescale time by characteristic energy $J = C_6/a_0^6$



$$\langle S_x \rangle \propto e^{-(Jt)^{\beta}}$$

$\beta = 0.32\ (2)$

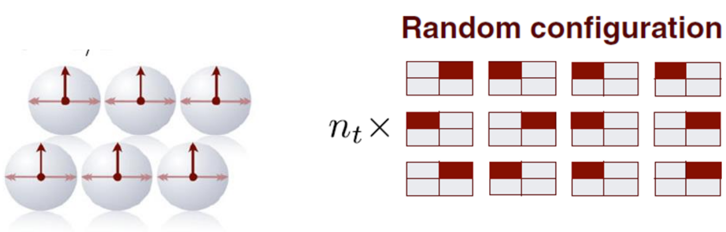
→ **Universal behaviour independent of microscopic details**

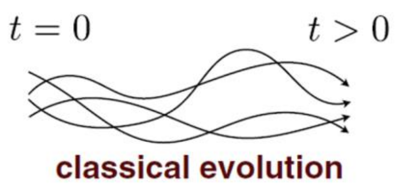
Range of universal behaviour

Further decrease disorder

Experiment: non-blockaded region in the Gaussian wings

→ **Use numerical Method:** discrete truncated Wigner approximation (**dTWA**)



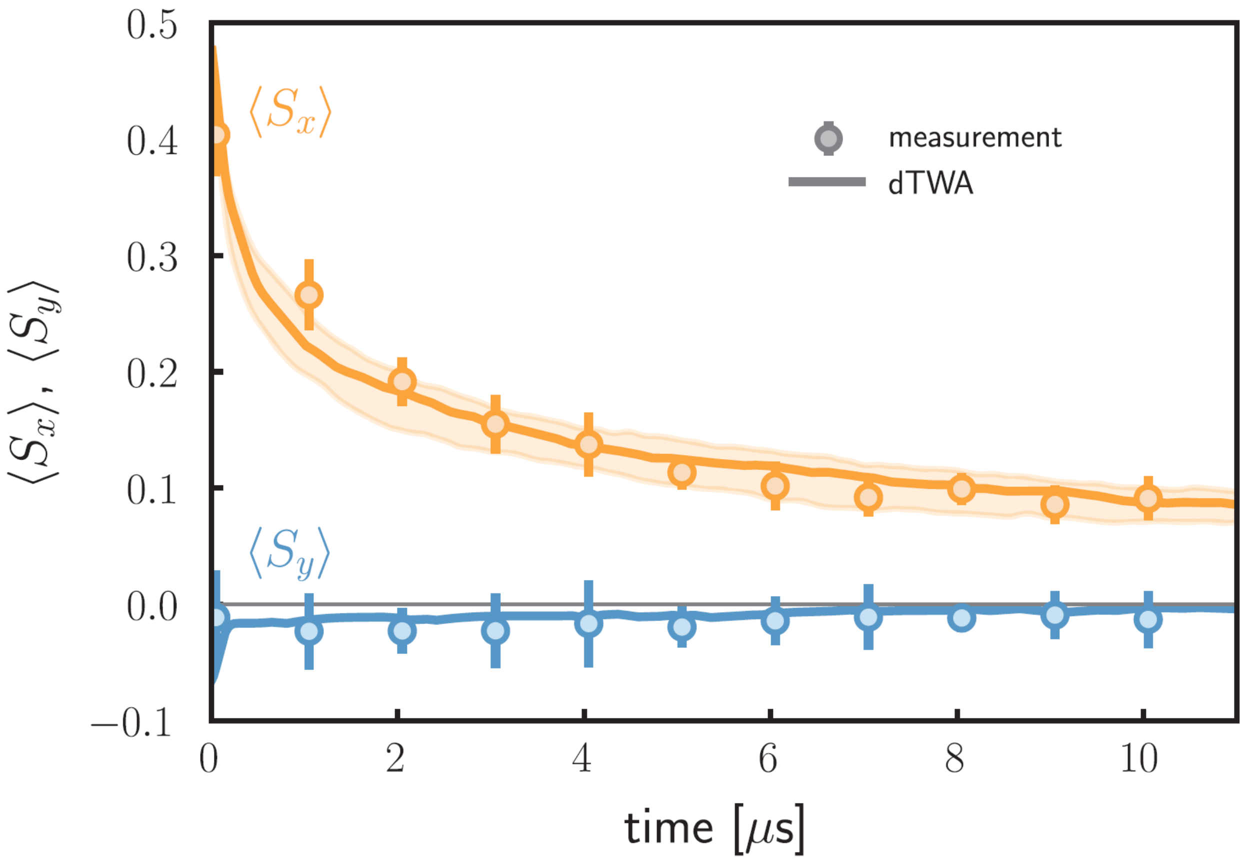


Sample phase points of each spin according to the Wigner distribution

Compute classical time evolution
ensamble average

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

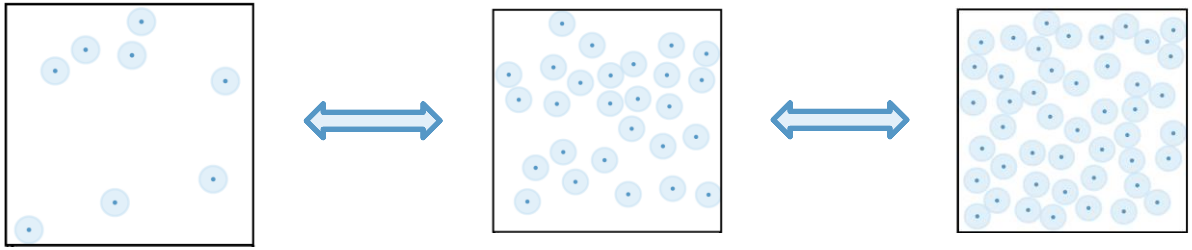
Benchmark of dTWA



- Semiclassical dTWA agrees well with experiment
  → use to study homogeneous spin distribution with disorder

Quantifying disorder

Disordered



Ordered

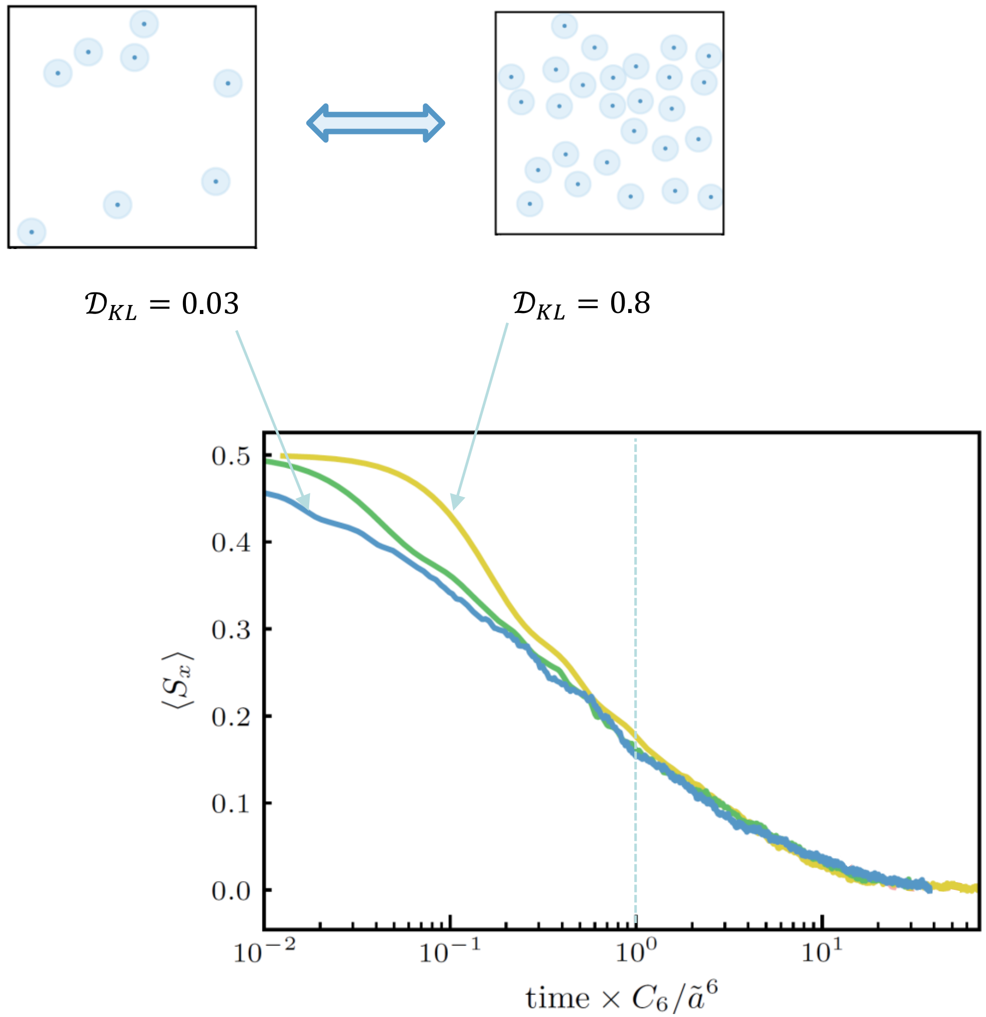
0 ← $$\mathcal{D}_{\mathrm{KL}}(p,q) = \int p(J) \log\left(\frac{p(J)}{q(j)}\right)$$ → ∞

Kullback Leibler divergence

p(J): actual probability distribution function

q(J): probability distribution function for an ideal gas

dTWA: Time evolution



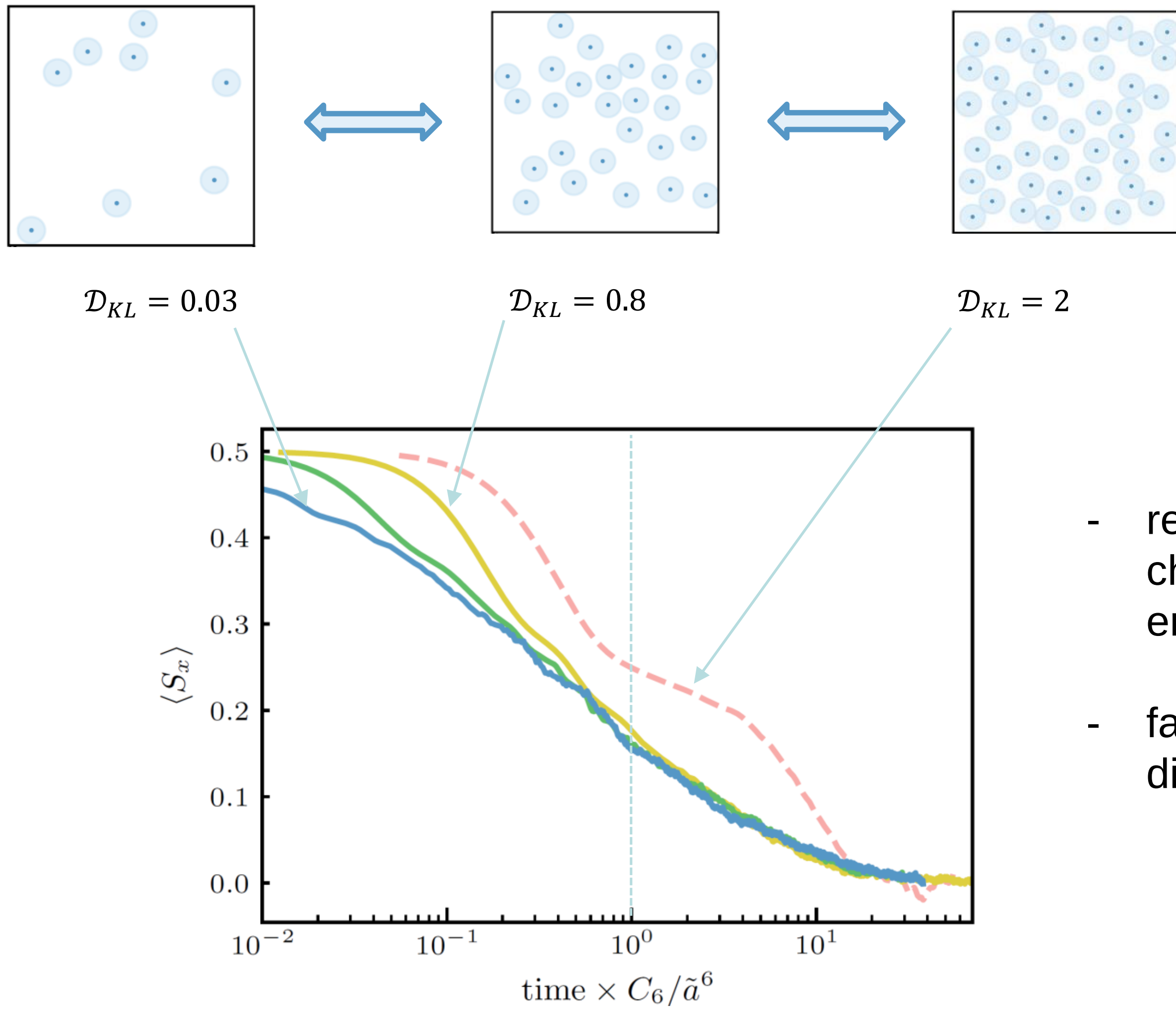
Rescaled time

- rescaling with characteristics energy

Reduced distance:

$$\tilde{a} = \text{median}\left(\sum_i \frac{C_6}{r_{ij}^6}\right)^{-\frac{1}{6}}$$

dTWA: Time evolution



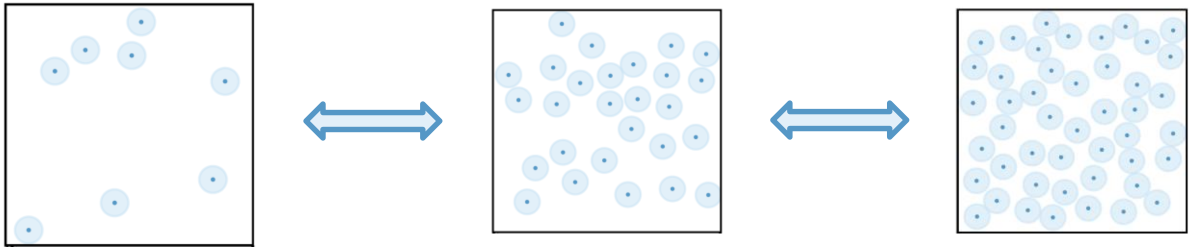
Rescaled time

- rescaling with characteristics energy
- fails for weak disorder

Reduced distance:

$$\tilde{a} = \text{median}\left(\sum_i \frac{C_6}{r_{ij}^6}\right)^{-\frac{1}{6}}$$

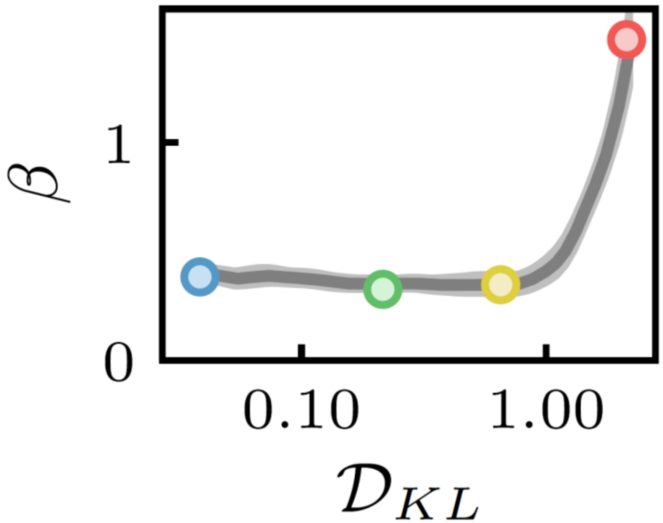
dTWA: range of universal behaviour



Two regimes identified

Strongly disordered
$\mathcal{D}_{KL} \lesssim 1$

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



Weakly disordered
$\mathcal{D}_{KL} \gtrsim 1$

- β, γ_J depend on microscopic parameters

Open questions

What determines the value of β=0.36 ?

- average over exponential decays leads to **β=0.5**
- For Ising Hamiltonian (δ >>1) **β=1/2**

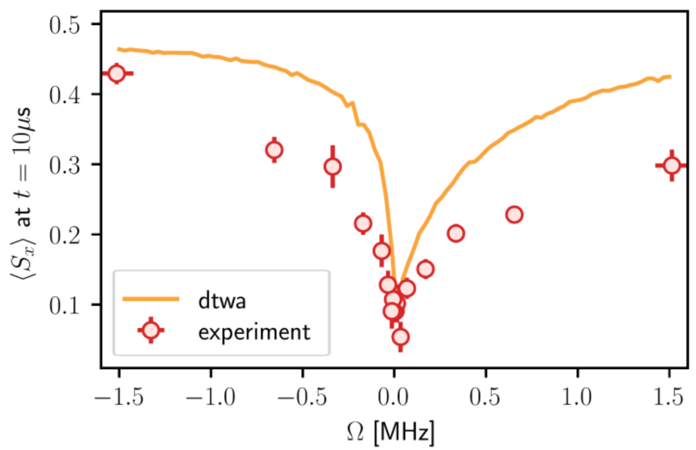
Does the system reach thermal equilbrium ?

Glassy dynamics: can take infinite time to reach zero magnetization

Break the symmetry of the Hamiltonian

$$H = H_{XXZ} - \Omega \sum_i S_x^{(i)}$$

ETH: Diagonal ensamble = thermodynamical ensamble ?

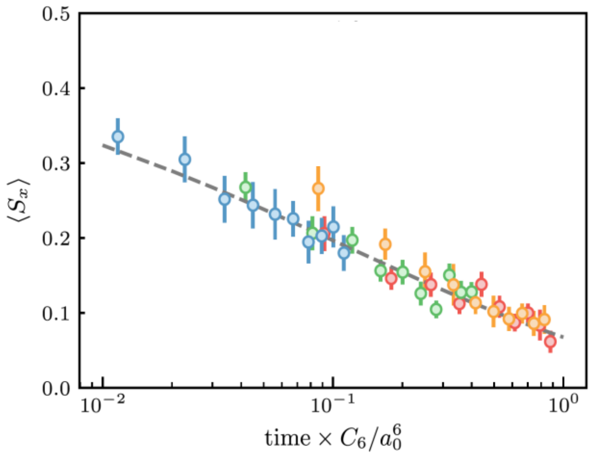


features similar to the diagonal ensamble

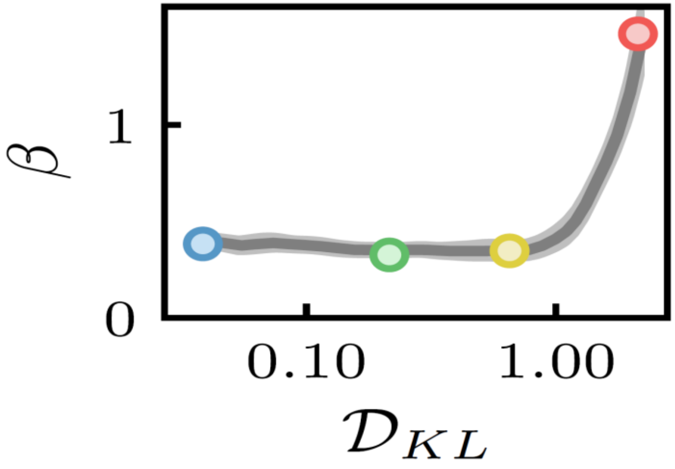
Out of time order correlations → Martin Gärttner

R. Mukherjee, T. C. Killian, K. R. A. Hazzard, PRA 94, 053422 (2016)

Summary



- **Glassy dynamics** independent of microscopic details



- **Range of slow dynamics**

The Team

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Thank you for your attention!