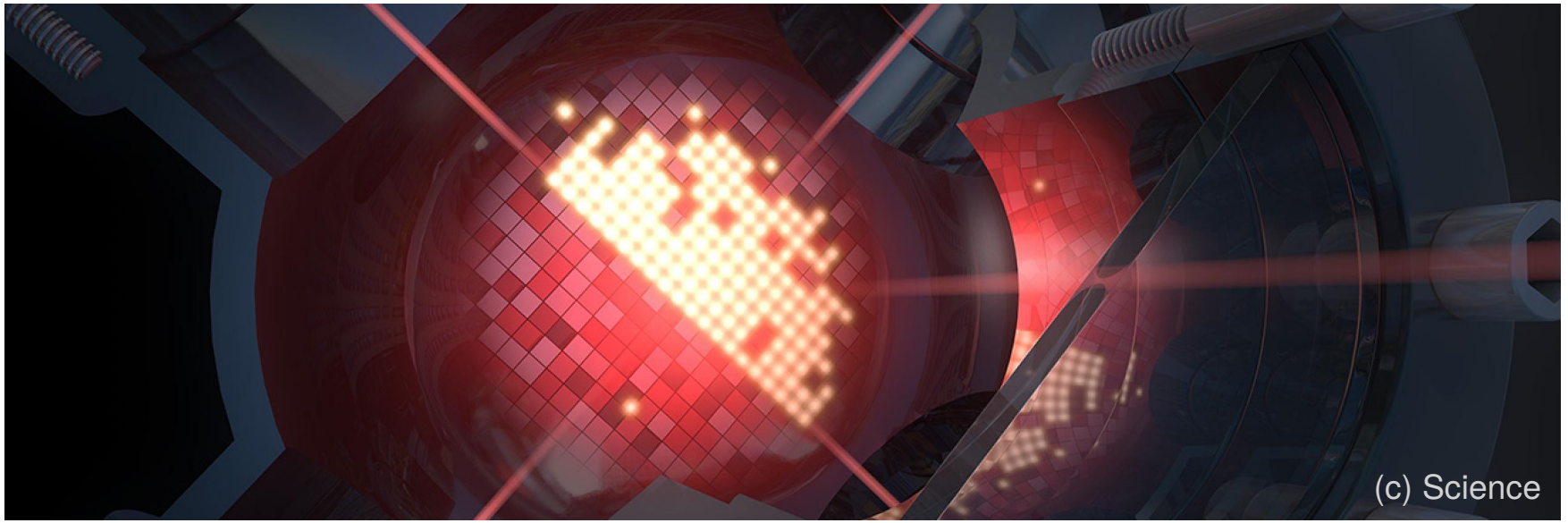
Exploring Non-Equilibrium Many-Body Dynamics at the Single Atom Level



Christian Groß

Max-Planck-Institut für Quantenoptik, Garching

Designer Quantum Systems Out of Equilibrium, KITP, 18.11.2016

LMU

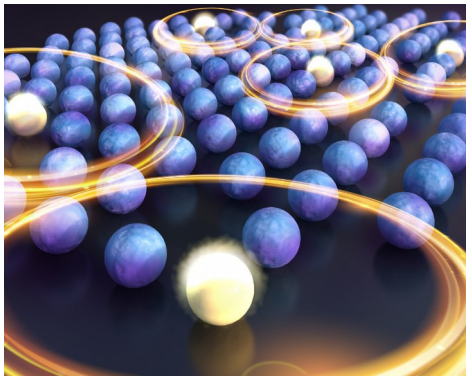
UQUAM ultracold quantum matter

RySQ

MPQ

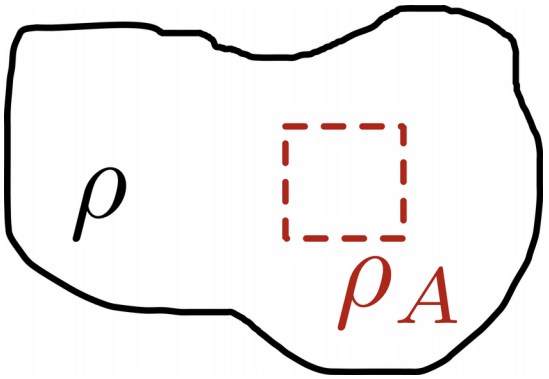
Outline

Many-body localization in
two dimensions



Many-body interferometry of
Rydberg dressed Ising spins

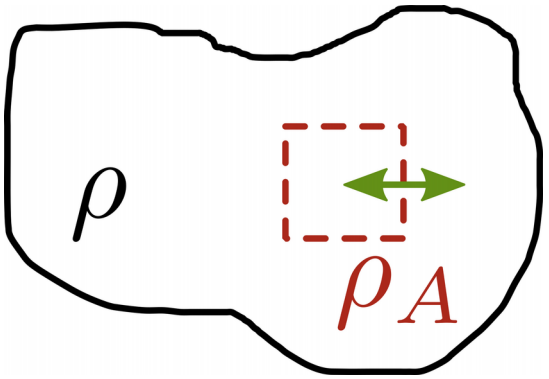
Thermalization of closed quantum systems



Full system S, subsystem A

$$\rho_{\mathrm{A}} = \mathrm{Tr}_{\mathrm{S}\setminus\mathrm{A}}[\rho]$$

Thermalization of closed quantum systems



Full system S, subsystem A

$$\rho_{\mathrm{A}} = \mathrm{Tr}_{\mathrm{S}\setminus\mathrm{A}}[\rho]$$

Unitary evolution

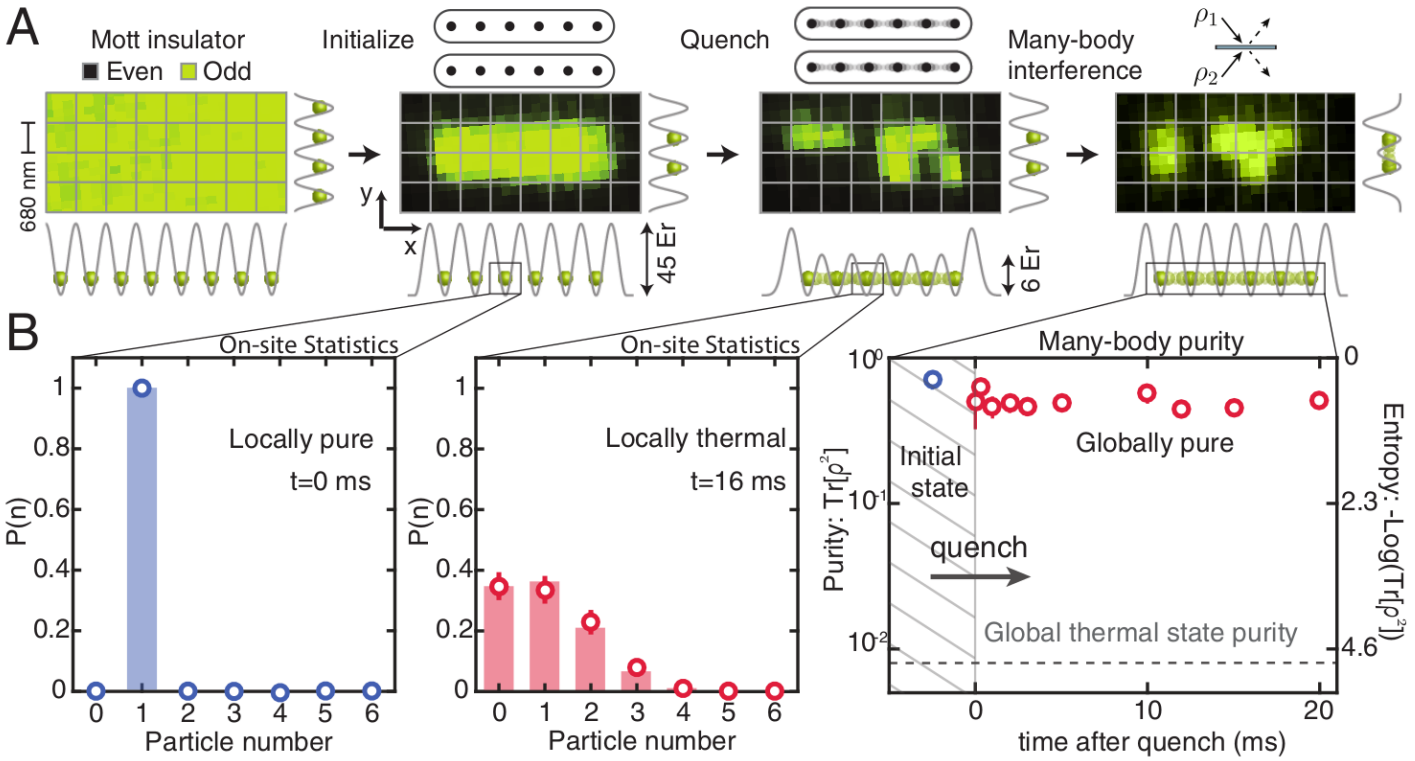
$$\rho(\mathrm{t}) = \mathrm{e}^{-\frac{\mathrm{iHt}}{\hbar}}\,\rho(0)\mathrm{e}^{\frac{\mathrm{iHt}}{\hbar}}$$

Subsystem thermal

$$\rho_{\mathrm{A}}(\infty) = \mathrm{Tr}_{\mathrm{S}\setminus\mathrm{A}}[\rho_{\mathrm{th}}]$$

Rest of system S serves as bath for A

Ultracold atoms – almost ideal closed many-body systems



Classical thermodynamics emerges
locally from a globally pure state

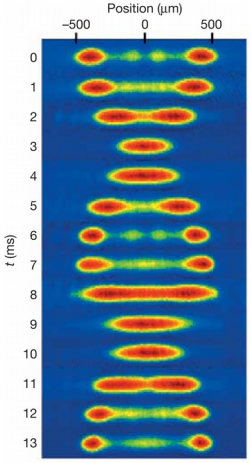
Kaufman, Science 2016

Ions: Clos, PRL (2016) | **SC Qubits**: Neill, arXiv: 1601.00600 (2016)

Non-thermalizing systems

Dynamics constrained by extensive # integrals of motion

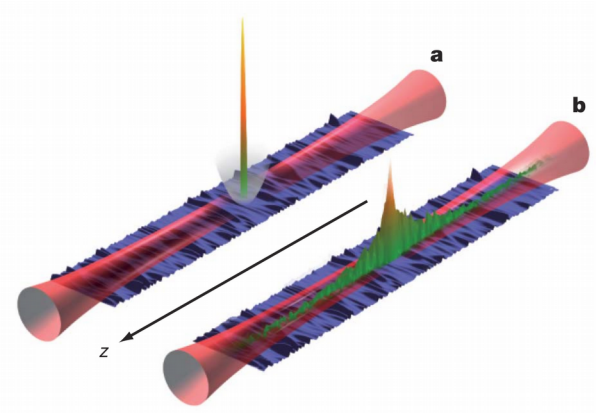
Integrable systems



Absence of thermalization for 1D Bosons

Kinoshita, Nature 2006

Anderson localized systems



Noninteracting systems:

Billy, Nature 2008

Roati, Nature 2008

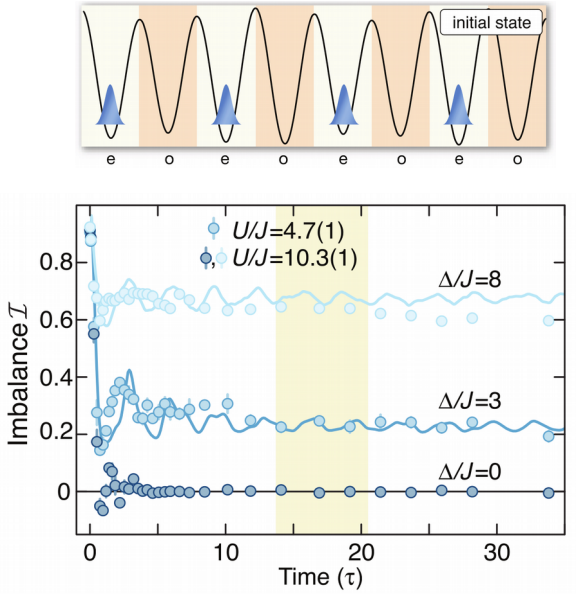
Lahini, PRL 2008

Kondov, Science 2011

Many-body localization – experiments

Non-thermalization despite interactions and starting far-from-equilibrium

Non- thermalization



Schreiber, Science 2015

Bordia, PRL 2016

Ions: Smith, Nat. Phys. 2016

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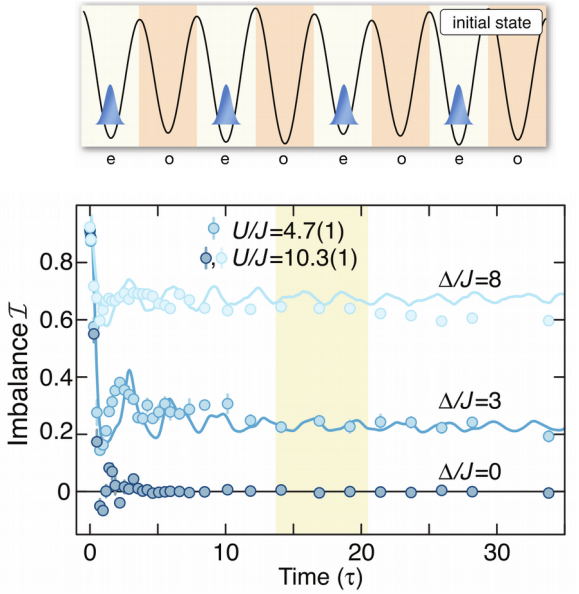
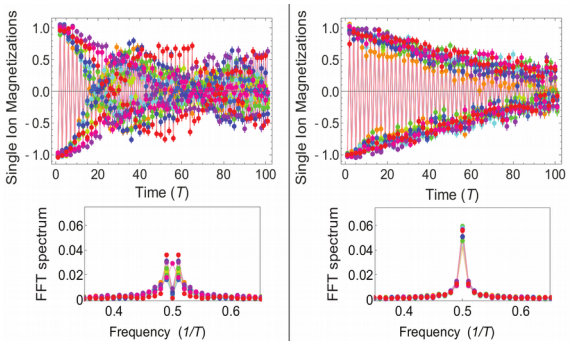


Schreiber, Science 2015

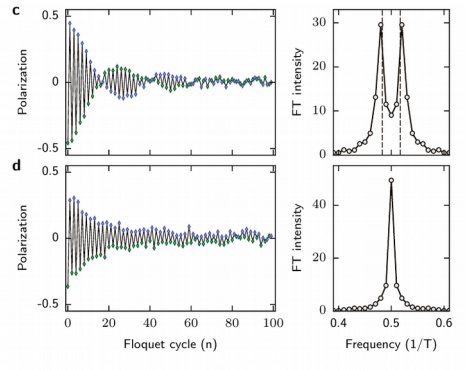
Bordia, PRL 2016

Ions: Smith, Nat. Phys. 2016

Floquet time crystals



Zhang, arXiv: 1609.08684 (2016)



Choi, arXiv:1610.08057 (2016)

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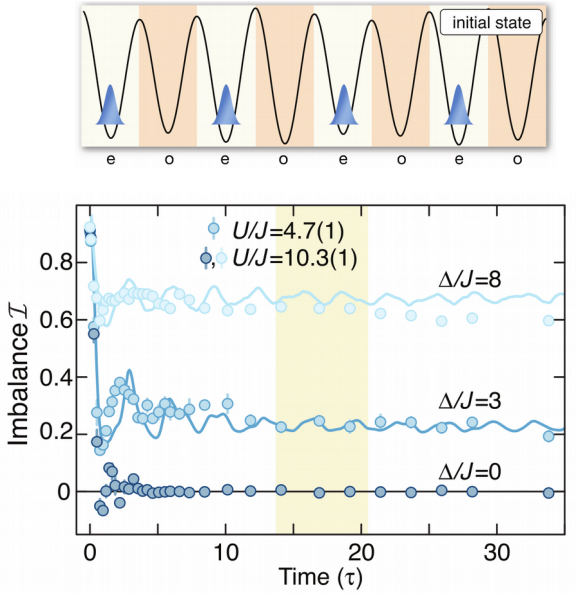
Non- thermalization



Schreiber, Science 2015

Bordia, PRL 2016

Ions: Smith, Nat. Phys. 2016

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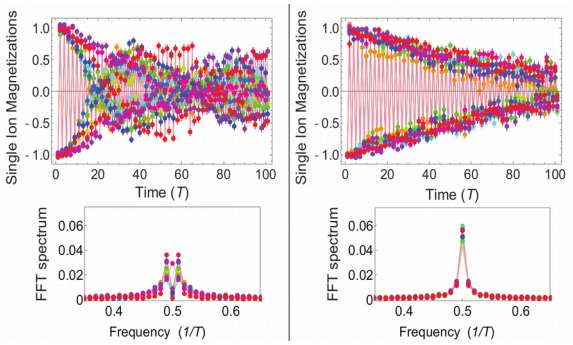
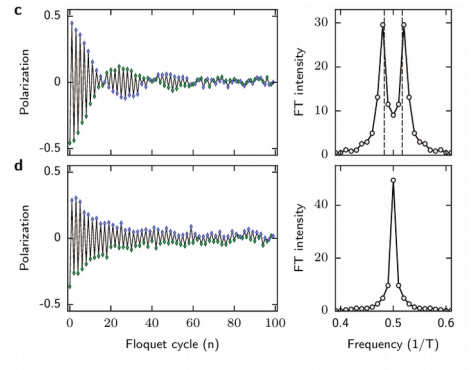


Zhang, arXiv: 1609.08684 (2016)



Choi, arXiv:1610.08057 (2016)

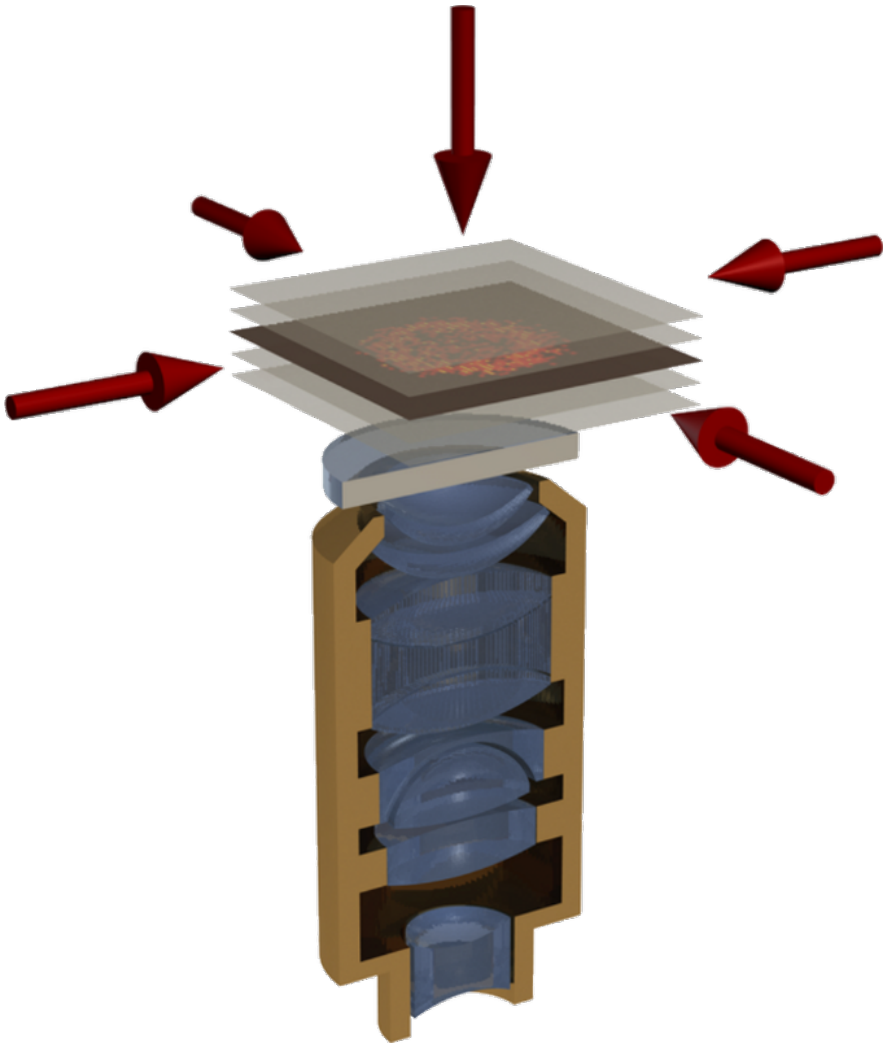
More experiments

AC response: Bordia, arXiv: 1607.07868 (2016)

External bath: Lüschen, arXiv:1610.01613 (2016)

Transport in 3D: Kondov, PRL 2015

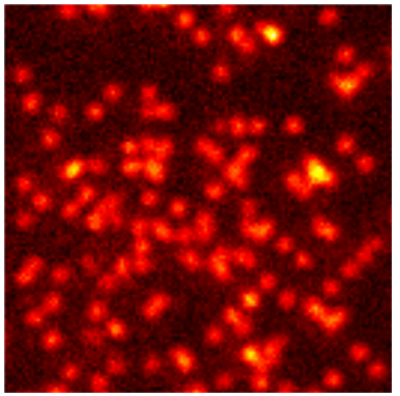
The MPQ bosonic quantum gas microscope

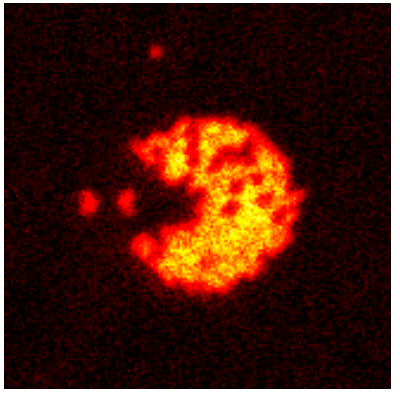


Single atomic plane in 2D lattice

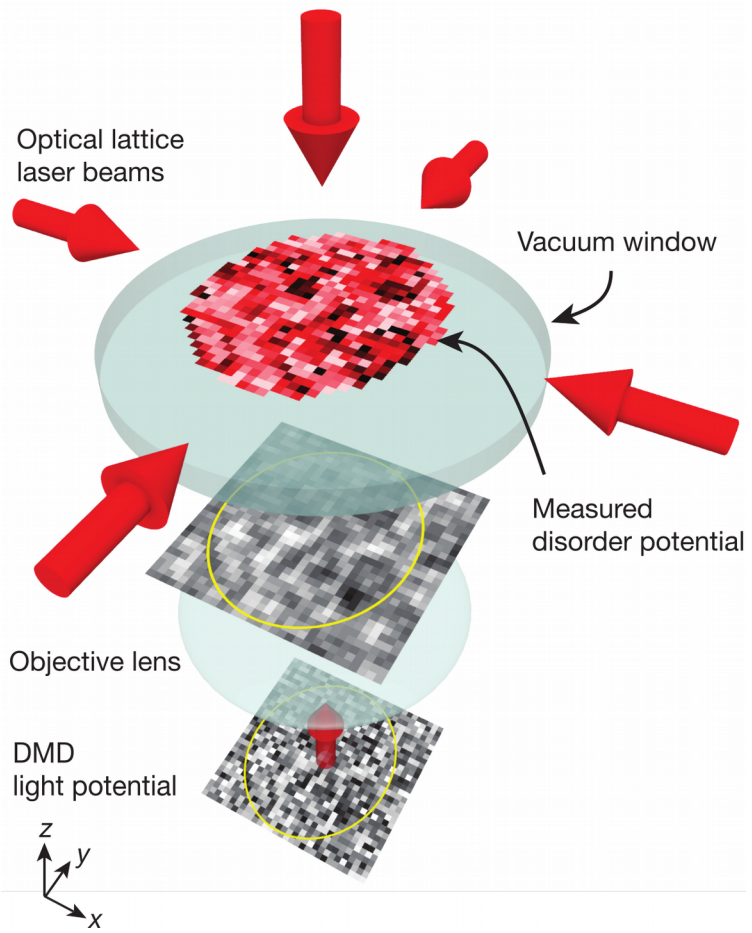
Single site (500nm) effective resolution

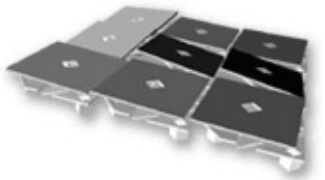
Single atom sensitivity





Generating disorder optically



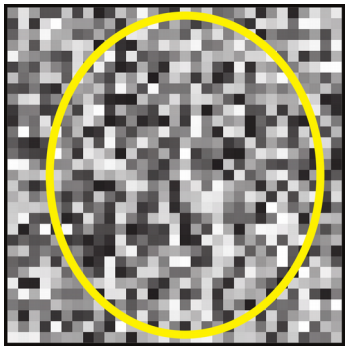


Digital mirror device

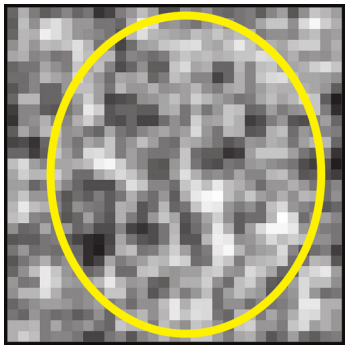
Disorder characterization

Site resolved disorder spectroscopy

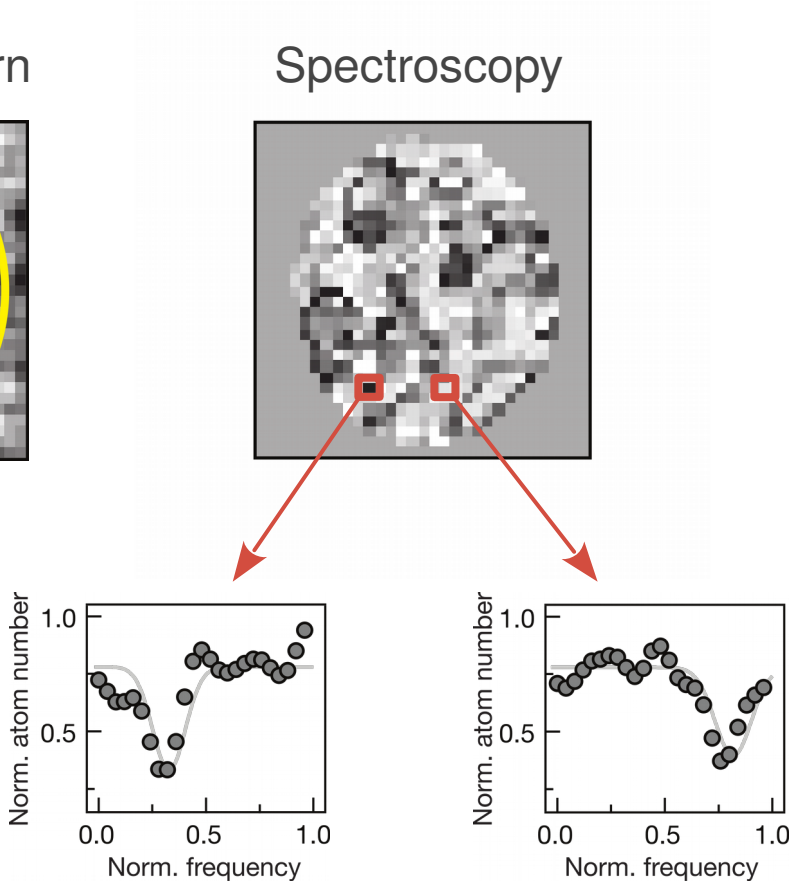
Mirrors



Intensity pattern



Spectroscopy



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Site resolved disorder spectroscopy

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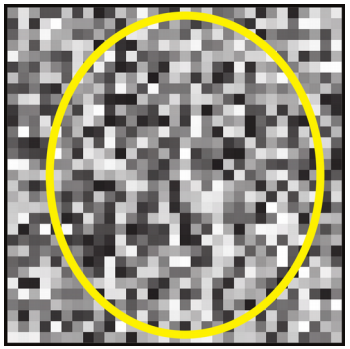

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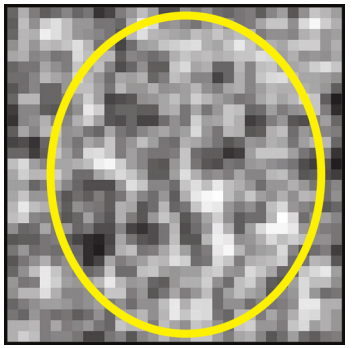

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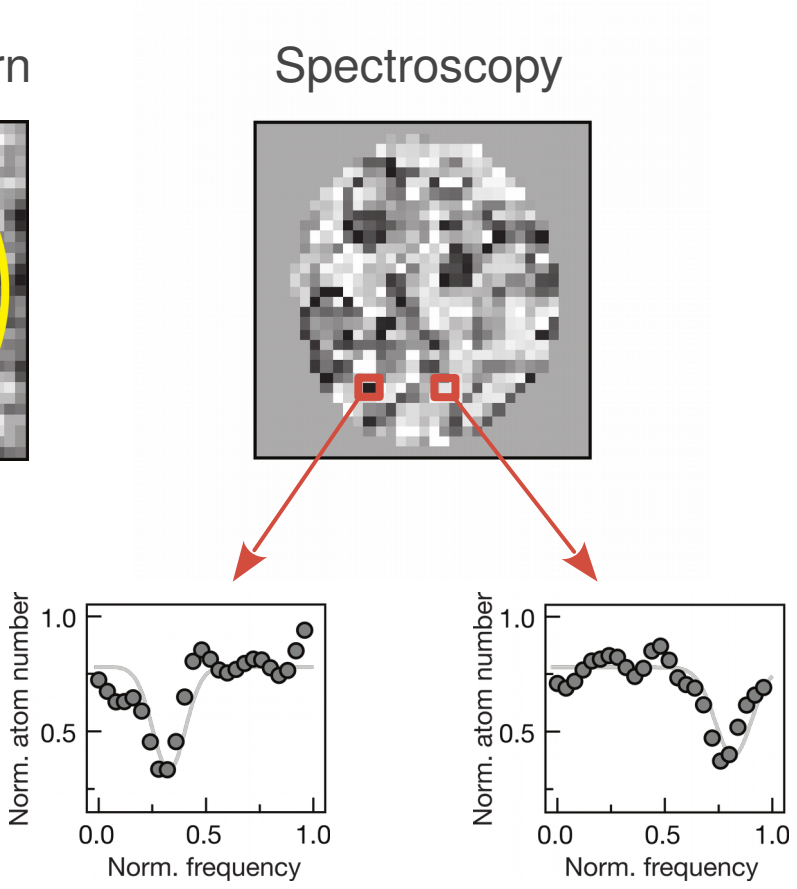
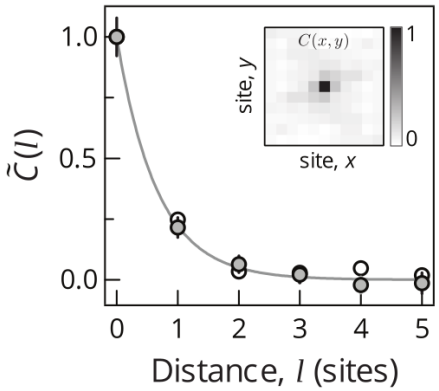
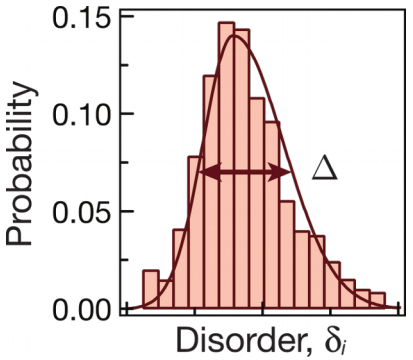


Autocorrelation



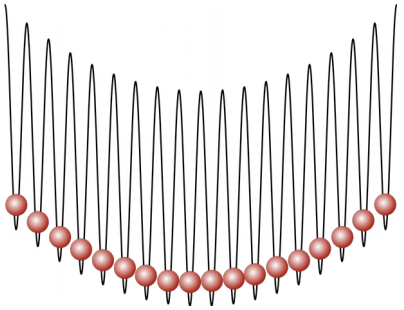
Disorder distribution



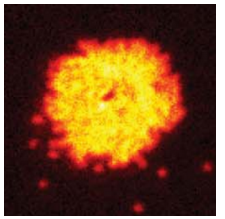
Probing thermalization far from equilibrium

Preparing the system @ high energy and far-from equilibrium

①



Unity filling Mott insulator



Probing thermalization far from equilibrium

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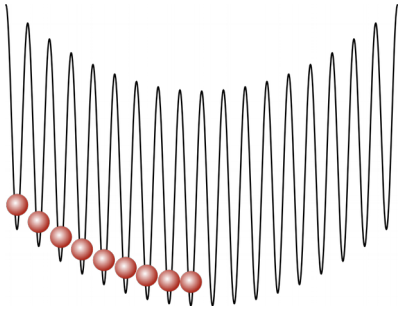
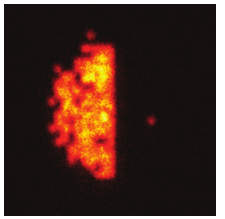


Right half removed



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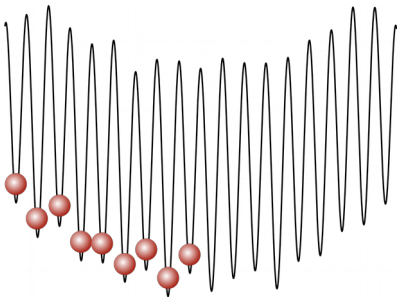
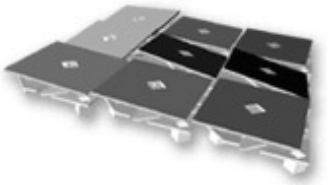
③



Add disorder
(random every shot)



Probing thermalization far from equilibrium

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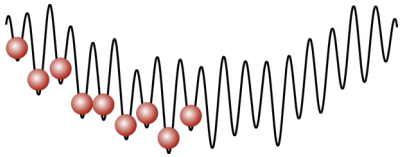
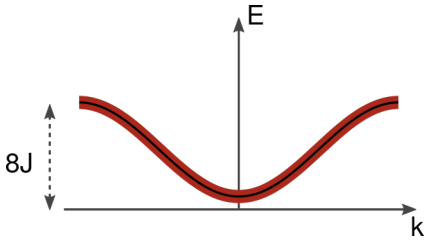
④



Quench lattice
to start dynamics

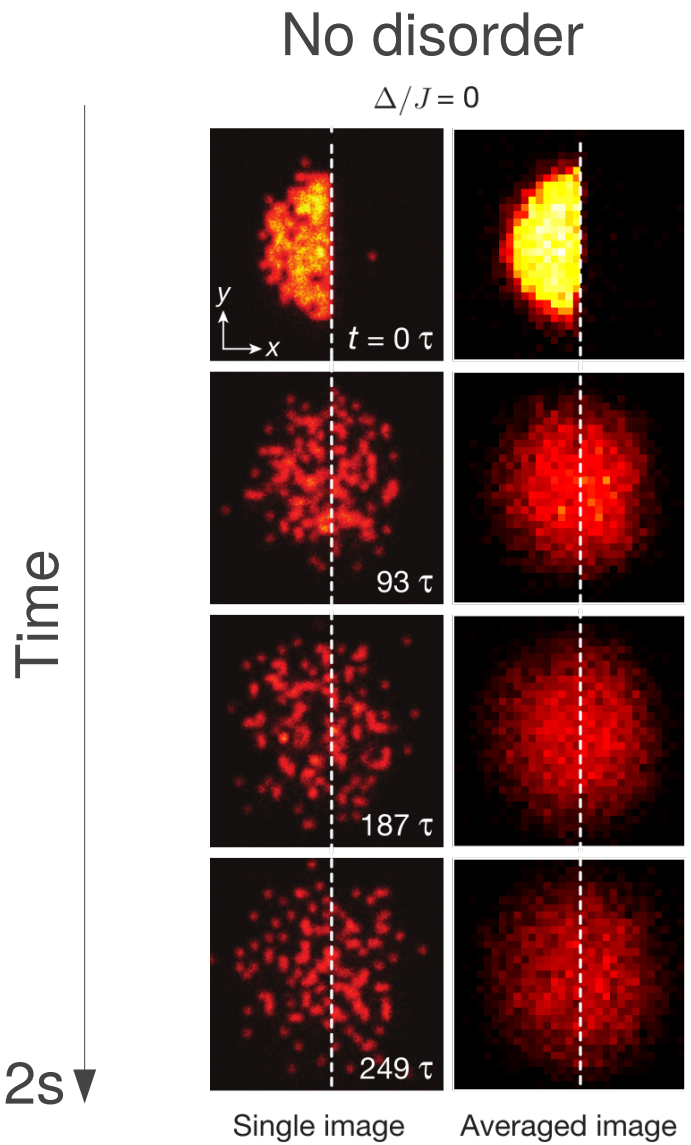


"Infinite T" wrt.
tunneling and disorder

Subsequent evolution:

$$\hat{H} = -J \sum_{<i,j>} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i (\delta_i + V_i)\hat{n}_i$$

Tracking the system's evolution



Choi, Science 2016

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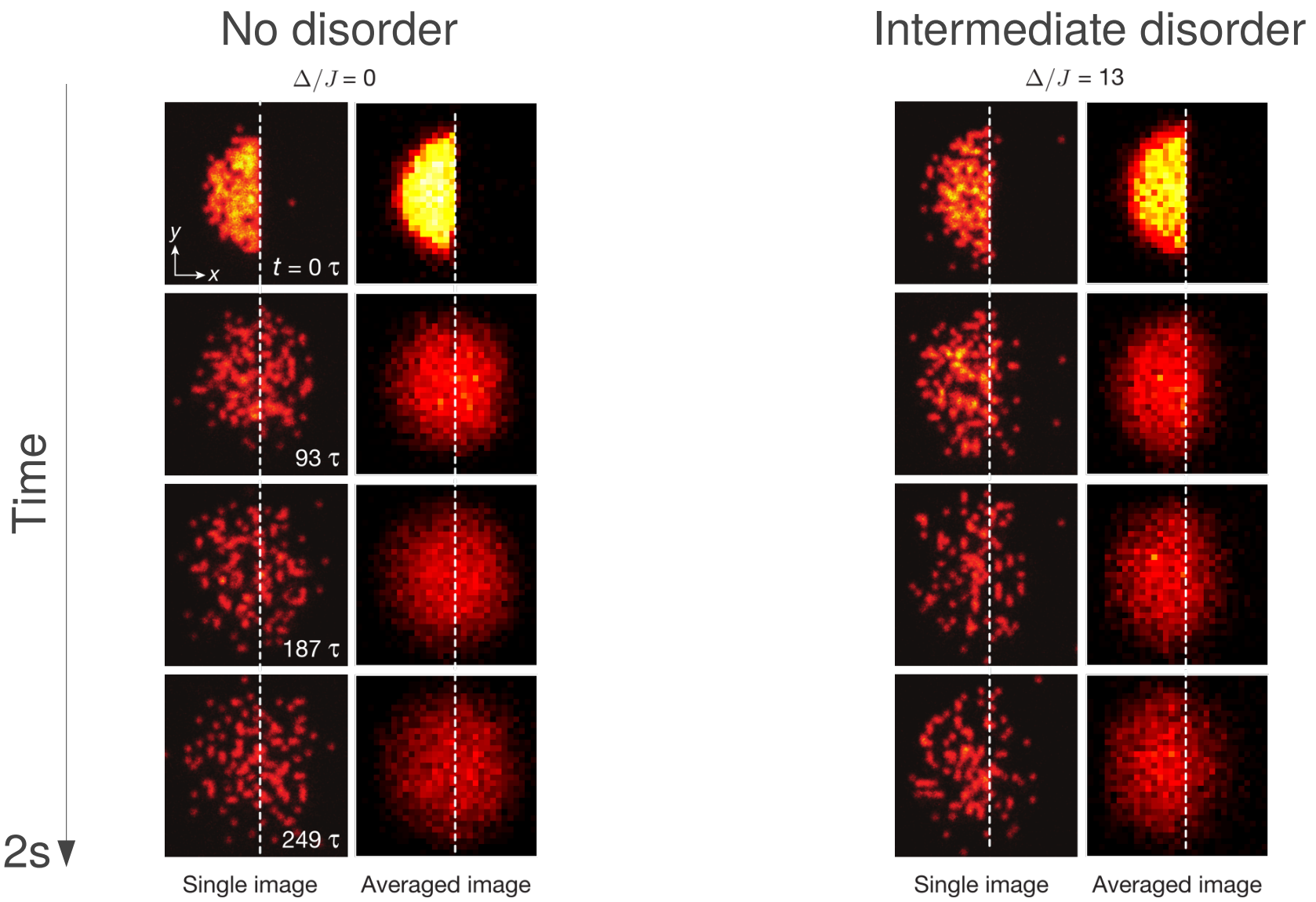
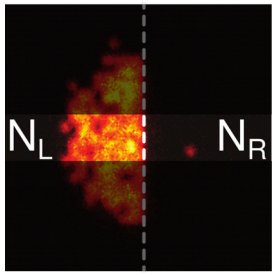


Choi, Science 2016

Quantifying the dynamics



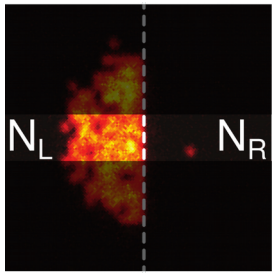
Imbalance $\mathcal{I} = \dfrac{N_L - N_R}{N_L + N_R}$

Model free quantity!

Thermalization $\rightarrow$ $\mathcal{I} = 0$

Choi, Science 2016

Quantifying the dynamics



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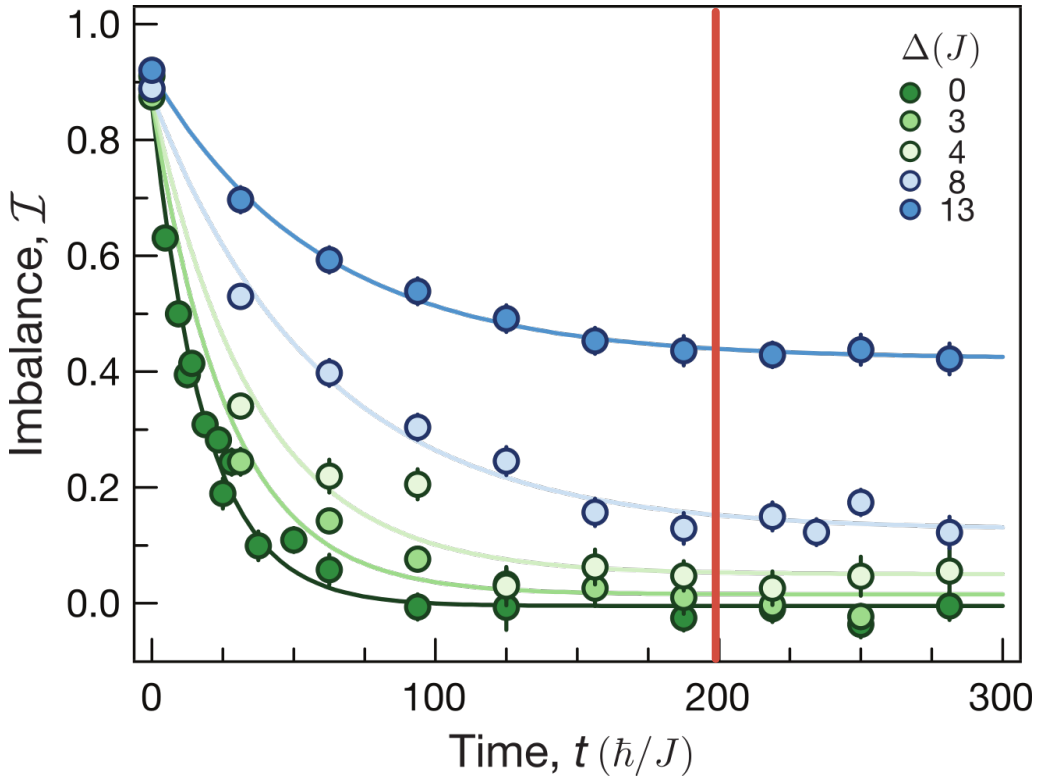
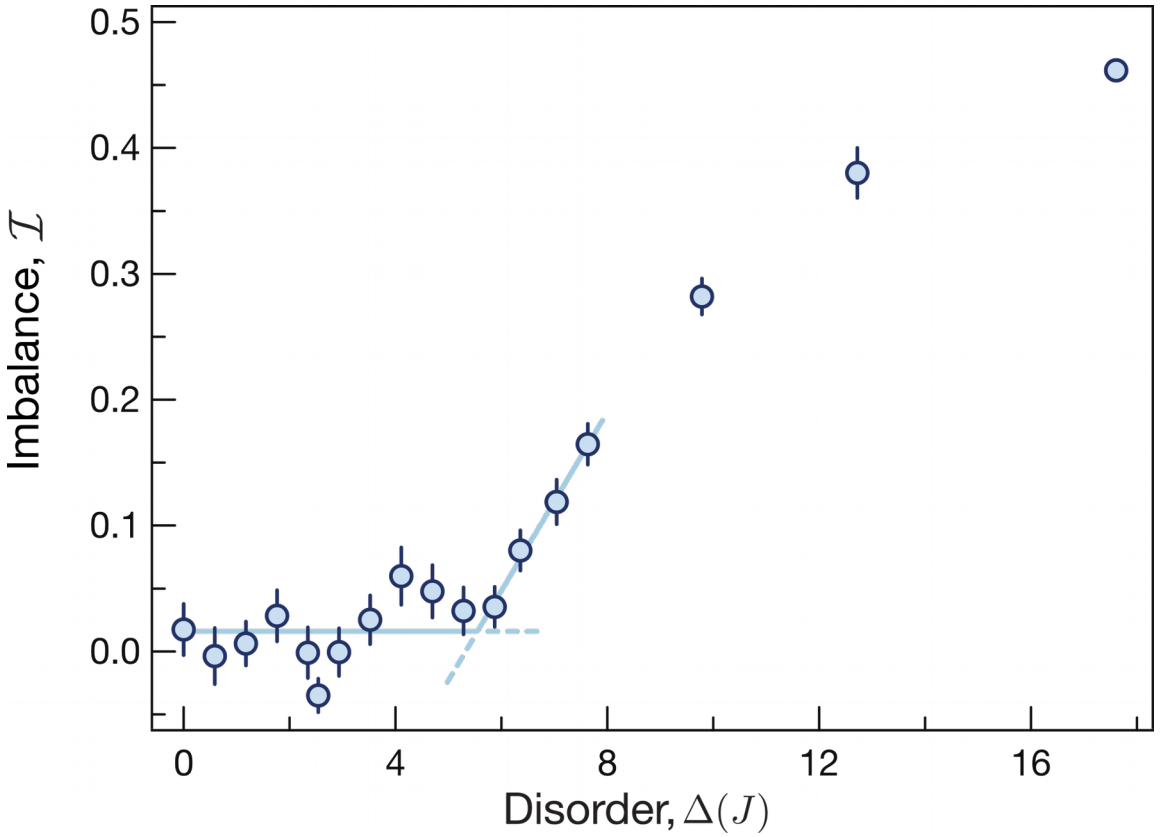


Choi, Science 2016

Locating the localization transition



Choi, Science 2016

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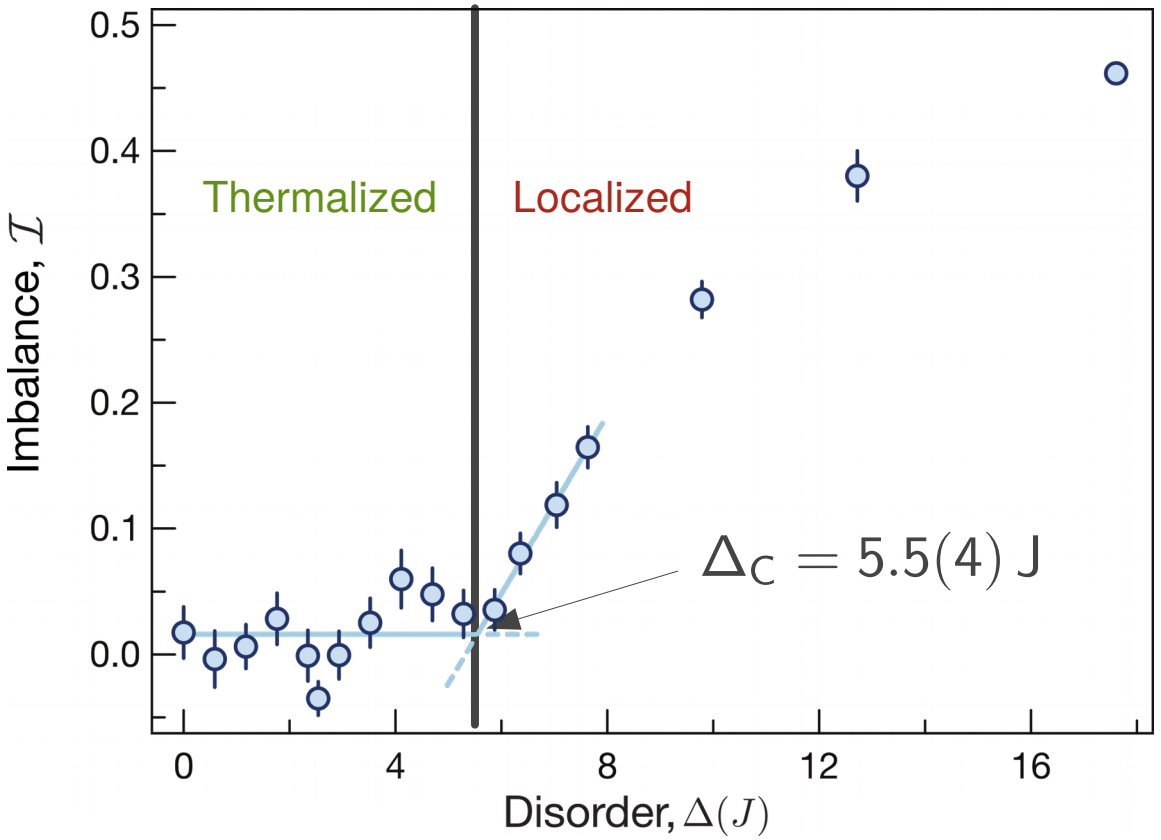
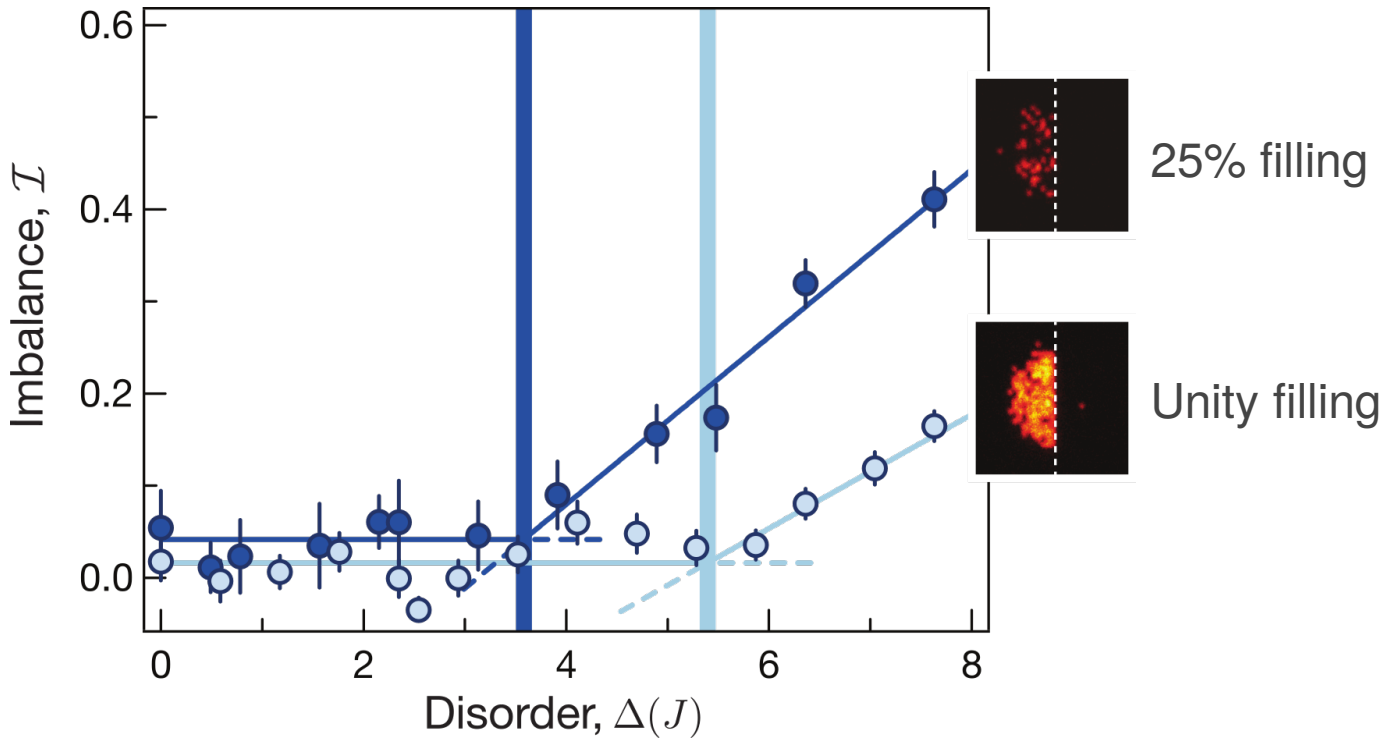


Choi, Science 2016

Transition versus density



Choi, Science 2016

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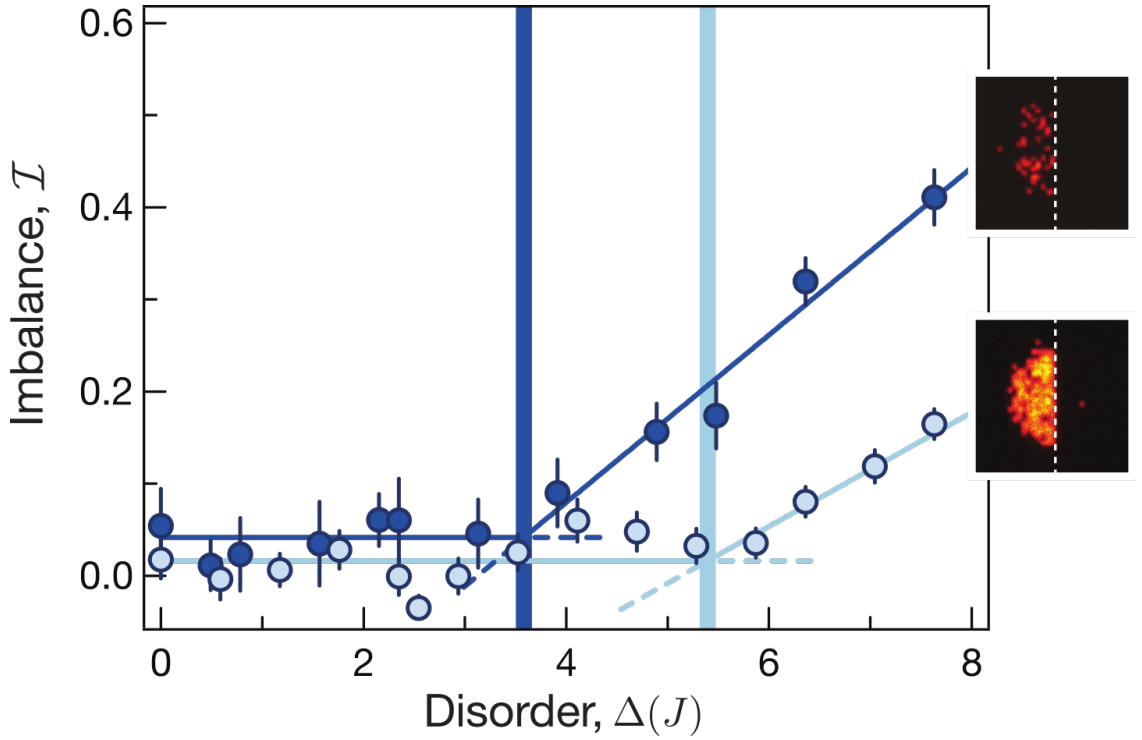


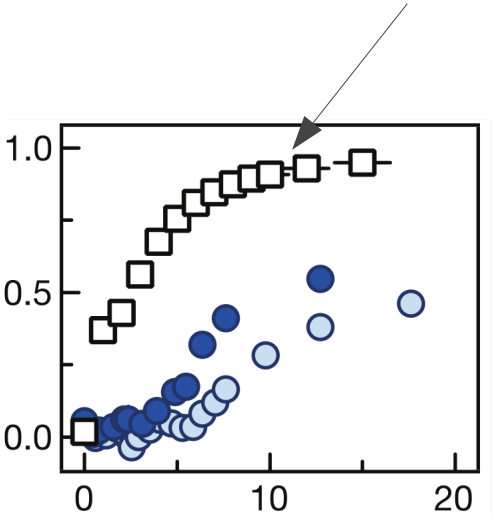
25% filling

Unity filling

U=0 numerics

Vedika Khemani

David Huse



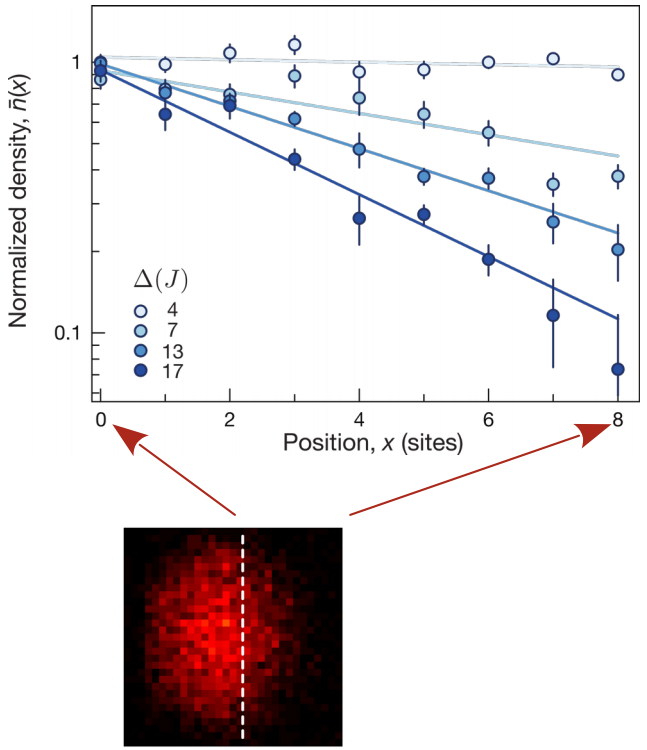
Choi, Science 2016

Diverging density-density correlations @ transition?

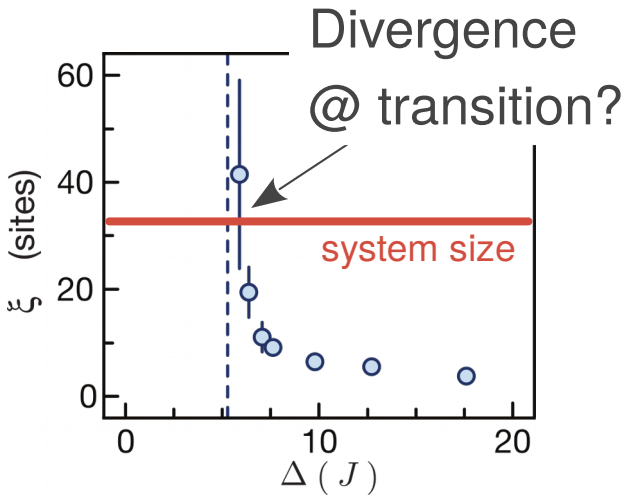
Decay of the normalized density

Localized profile / Thermalized profile

Exponential fits



Decay length ξ vs. disorder



Choi, Science 2016

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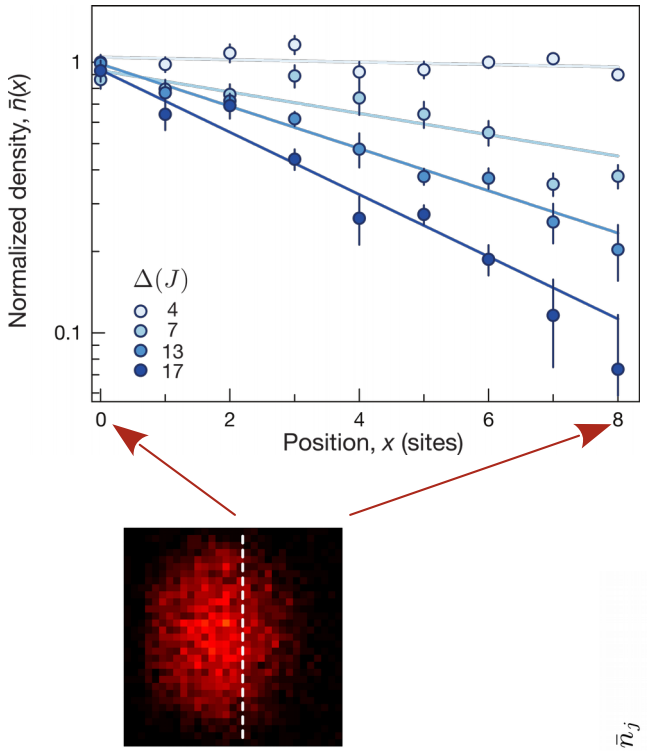

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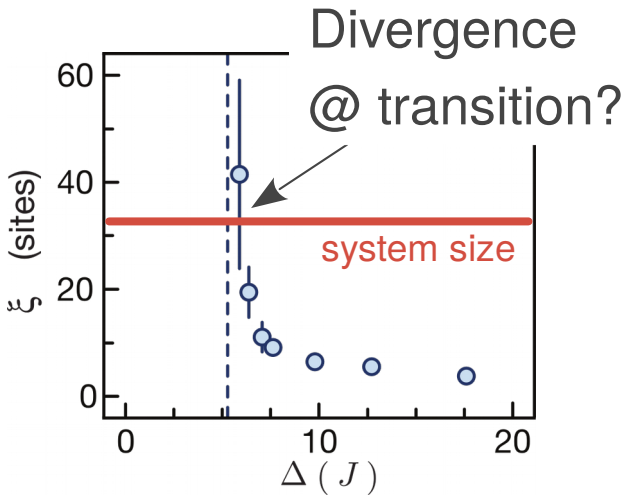
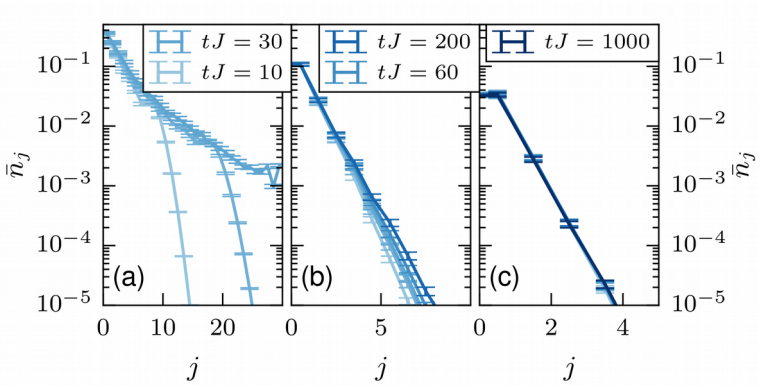


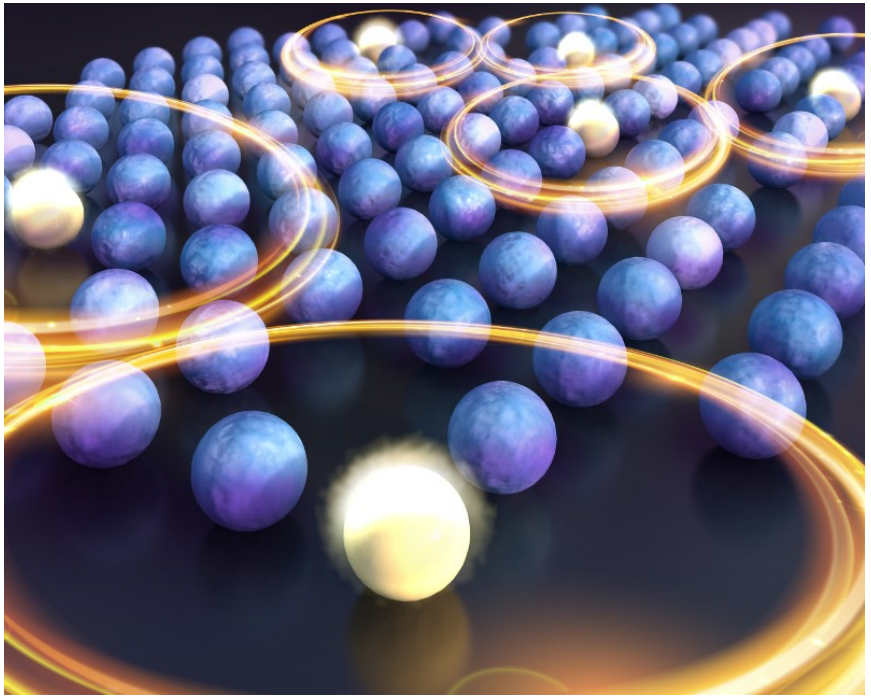
1D XXZ with tDMRG



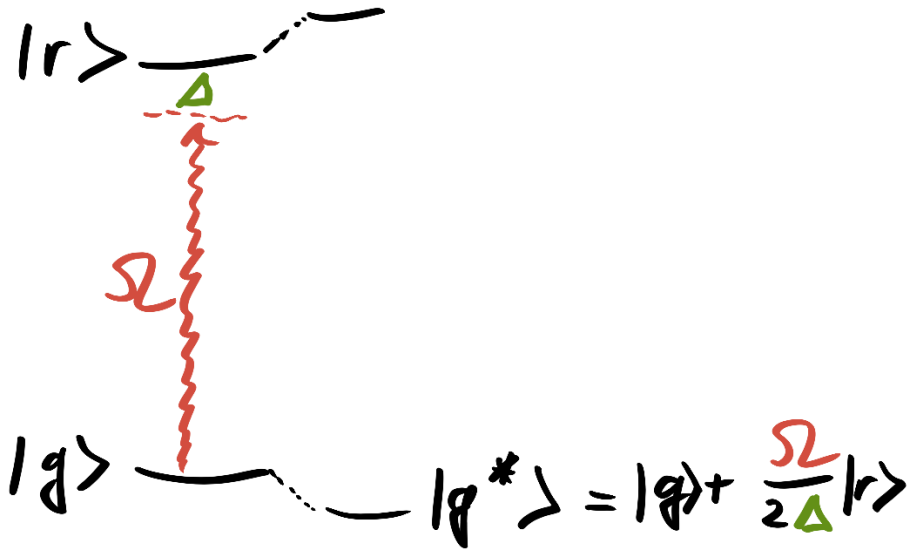
Choi, Science 2016

Hauschild, PRB (2016)

Many-Body Interferometry of Rydberg Dressed Ising Spins



Rydberg dressing



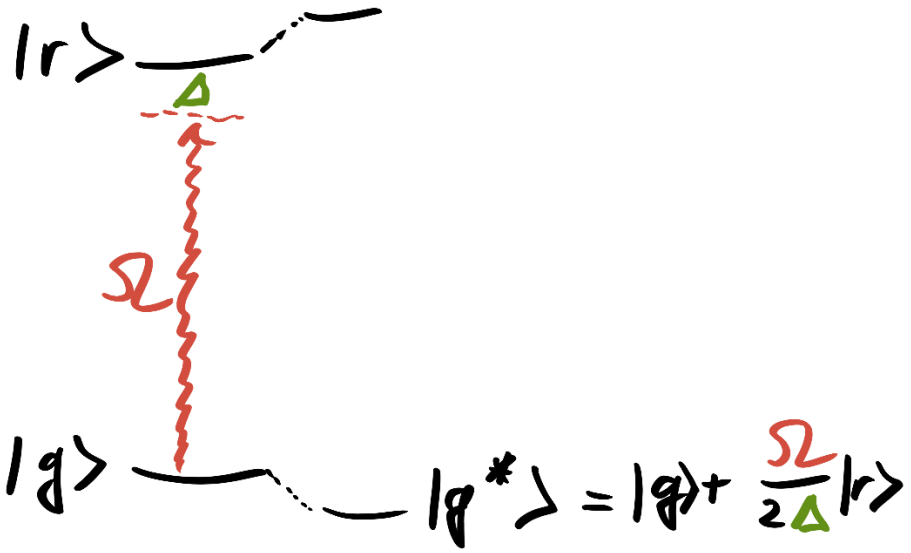
Central idea:

Weakly admix Rydberg state

to the ground state

Santos, PRL (2000) | Bouchoule, PRA (2002) | Johnson, PRA (2010)

Rydberg dressing



Central idea:

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Rydberg properties transferred to ground state

State admixture: $\beta = \Omega/2\Delta$

Lifetime enhancement: $\tau = \tau_R/\beta^2$

Interactions: $U = \beta^4 V_r$

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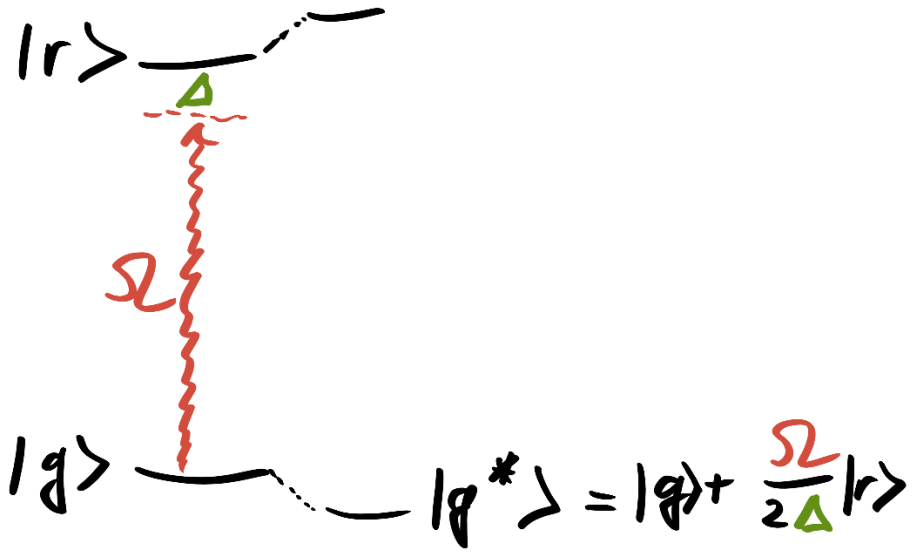

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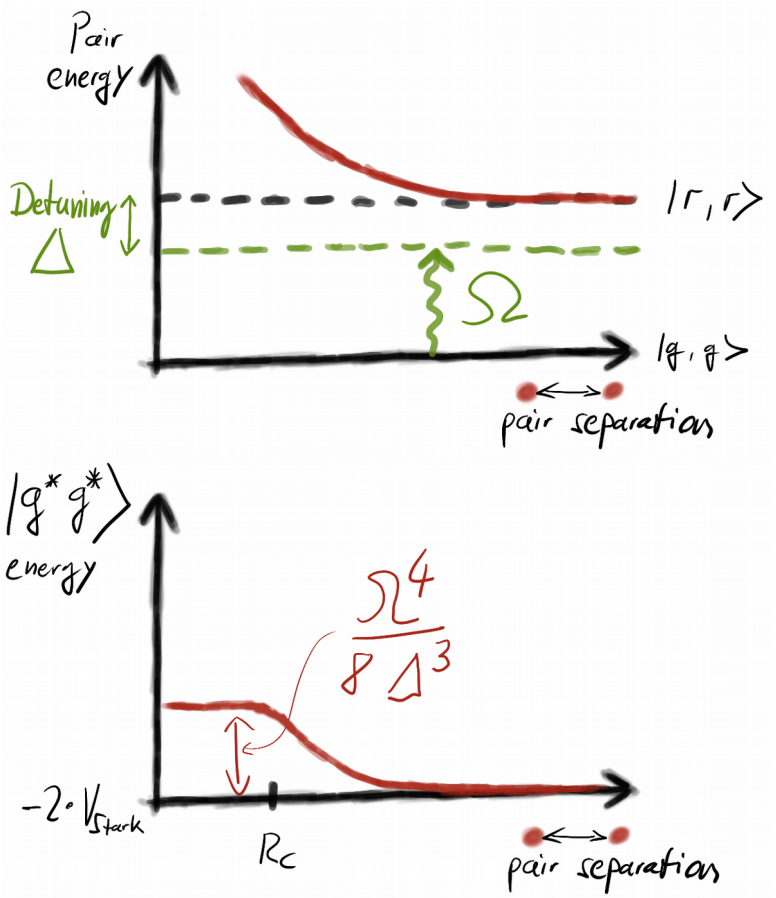
$V_r = C_6/r^6$

$\mathcal{O}(100\,\mathrm{GHz}/\mu\mathrm{m}^6)$

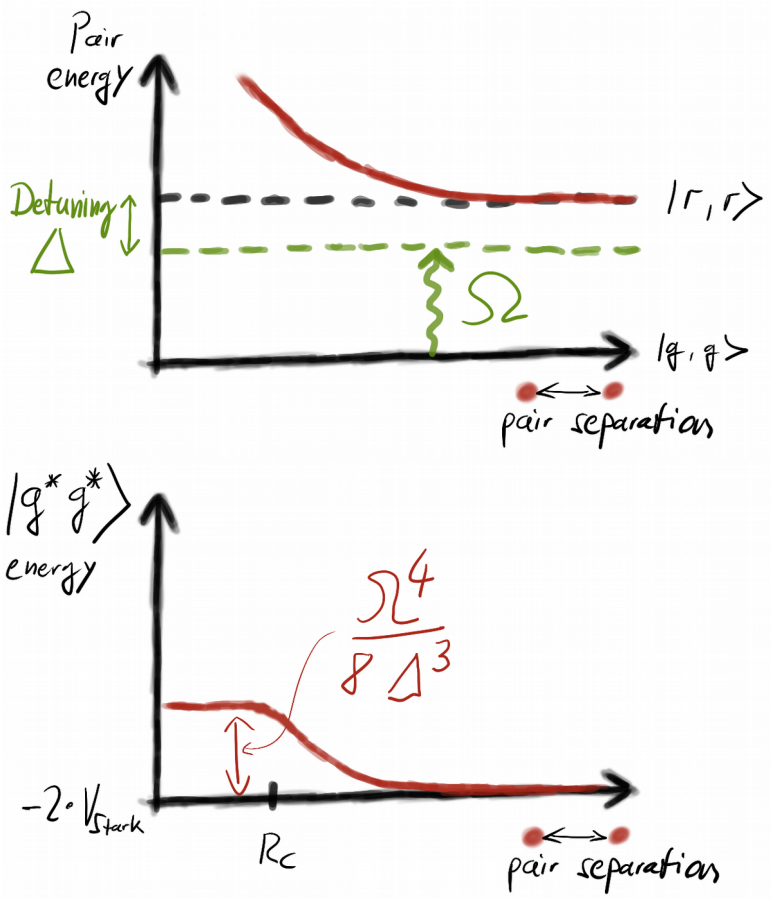
Santos, PRL (2000) | Bouchoule, PRA (2002) | Johnson, PRA (2010)

Dressed interactions



Soft-core potential

Dressed interactions

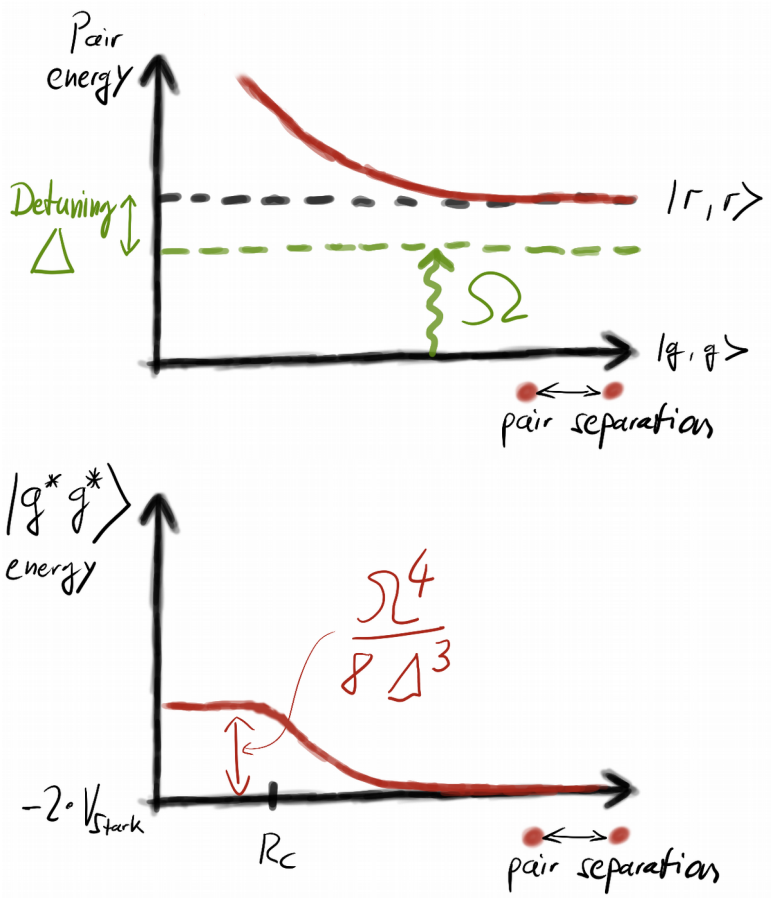


Soft-core potential

$U_0 = \Omega^4/8\Delta^3$ for $\Omega << \Delta$ requires large Rabi frequency

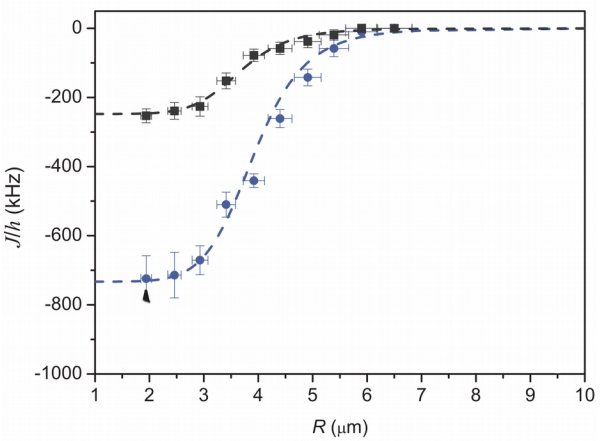
→ Direct coupling to P-states

Dressed interactions



Soft-core potential

Two atoms @ Sandia



Jau, Nat. Phys. 2015

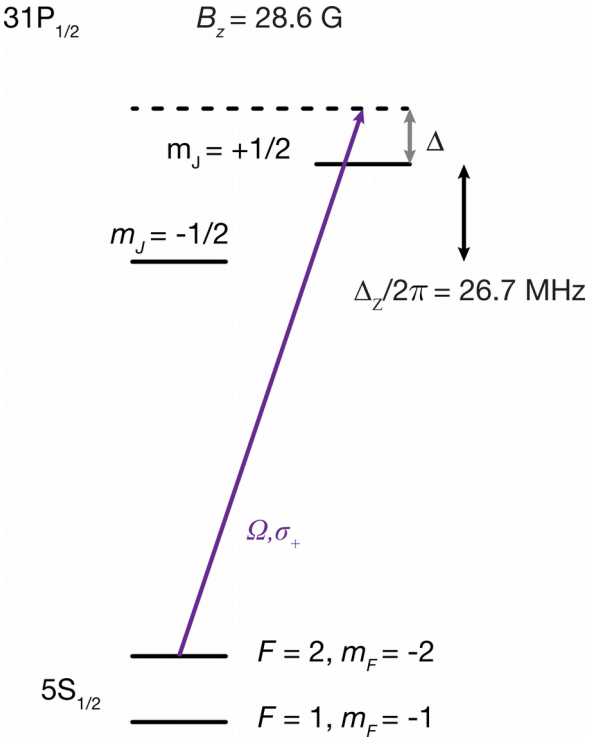
Hard in many-body system due to parasitic losses

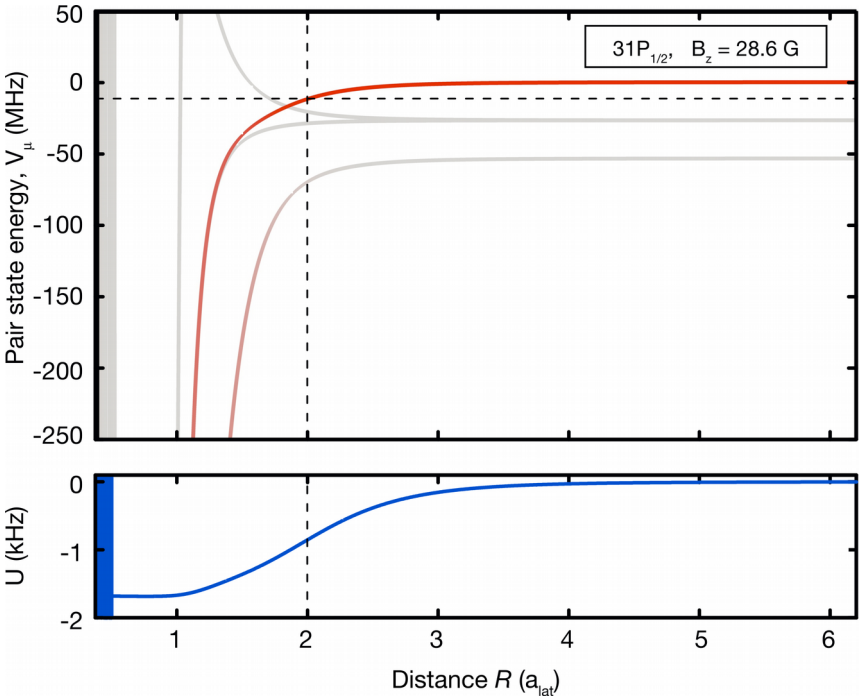
Balewski, NJP 2014
Goldschmidt, PRL 2016
Aman, PRA 2016

$U_0 = \Omega^4/8\Delta^3$ for $\Omega << \Delta$ requires large Rabi frequency

→ Direct coupling to P-states

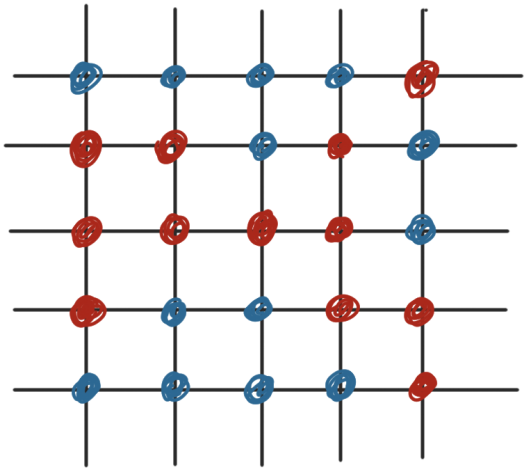
The predicted interaction potential

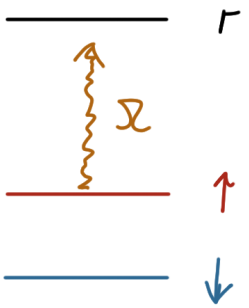




Clean soft-core potential, range ~ 2 sites

Long-range interacting Ising spins

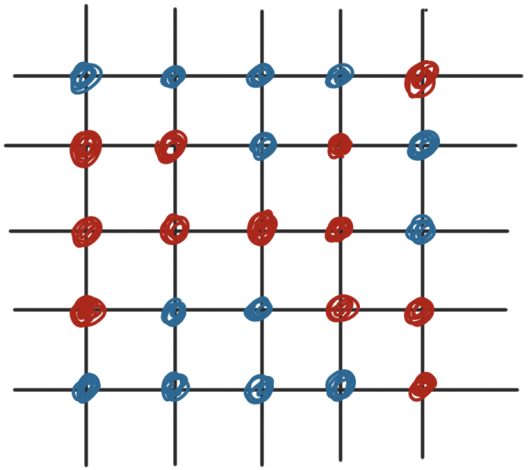


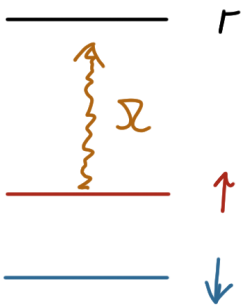


Long-range Ising Hamiltonian

$$\hat{H} = \sum_i (\delta + \delta_{C,i}) \hat{S}_i^z + \sum_{i \neq j} \frac{U_{i,j}}{2} \hat{S}_i^z \hat{S}_j^z$$

Long-range interacting Ising spins





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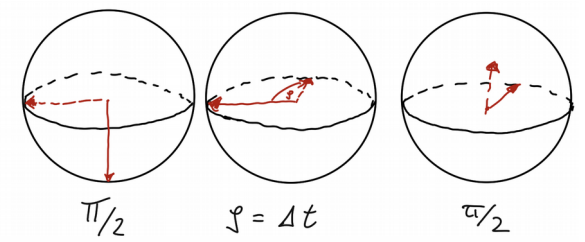
Power dependent

$$\propto \frac{\Omega^2}{\Delta}$$

"Mean field",
Depending in the neighbouring spin distribution

$$\propto \frac{\Omega^4}{\Delta^3}$$

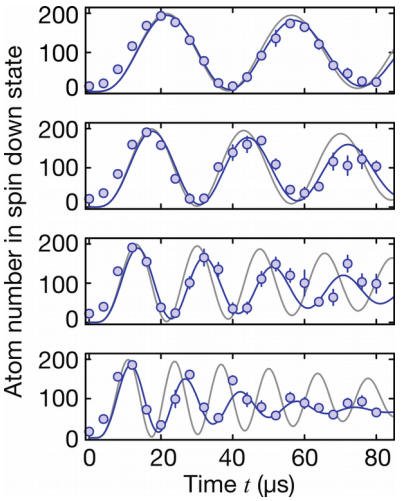
Many-body Ramsey interferometry

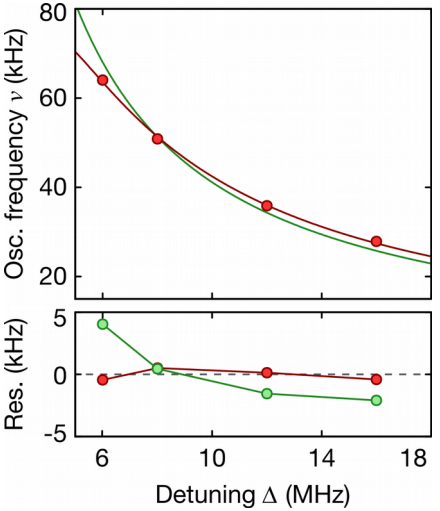


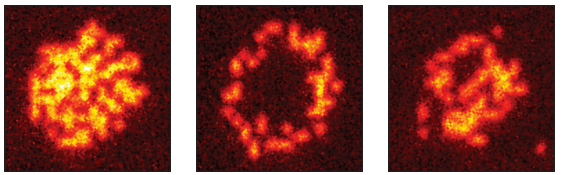
Varying the detuning Δ

$$\hat{H} = \sum_i (\delta + \delta_{C,i}) \hat{S}_i^z + \sum_{i \neq j} \frac{U_{i,j}}{2} \hat{S}_i^z \hat{S}_j^z$$

$$\delta_{C,i} = \sum_j \frac{U_{i,j}}{2} \approx \frac{N_{\text{int}}}{2} \frac{\Omega^4}{8\Delta^3}$$







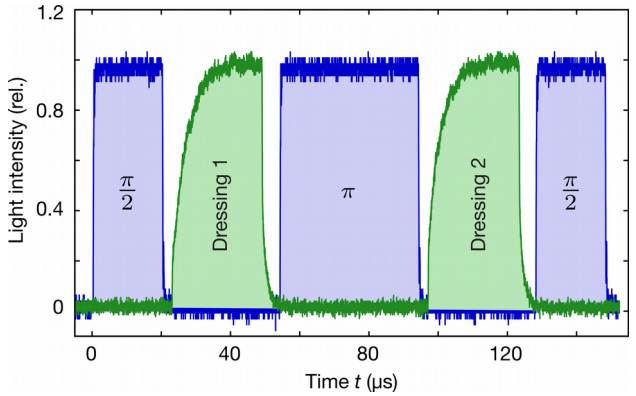
time

Correlation measurements

$$\hat{H} = \sum_i (\delta + \delta_{C,i}) \hat{S}_i^z + \sum_{i \neq j} \frac{U_{i,j}}{2} \hat{S}_i^z \hat{S}_j^z$$

Goal: Measure correlations due to U_{ij}

Problematic: Mean field phase shift → Echo



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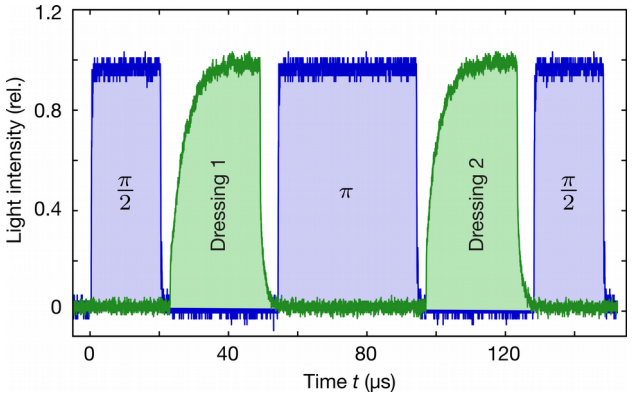
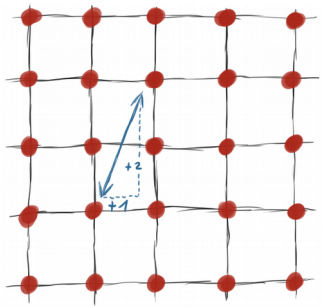
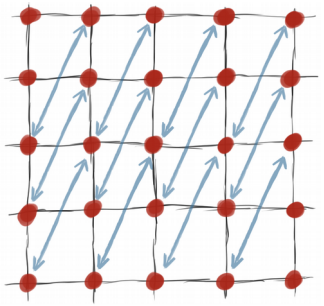
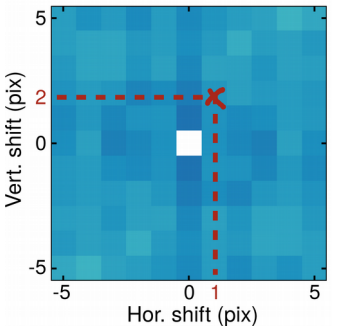


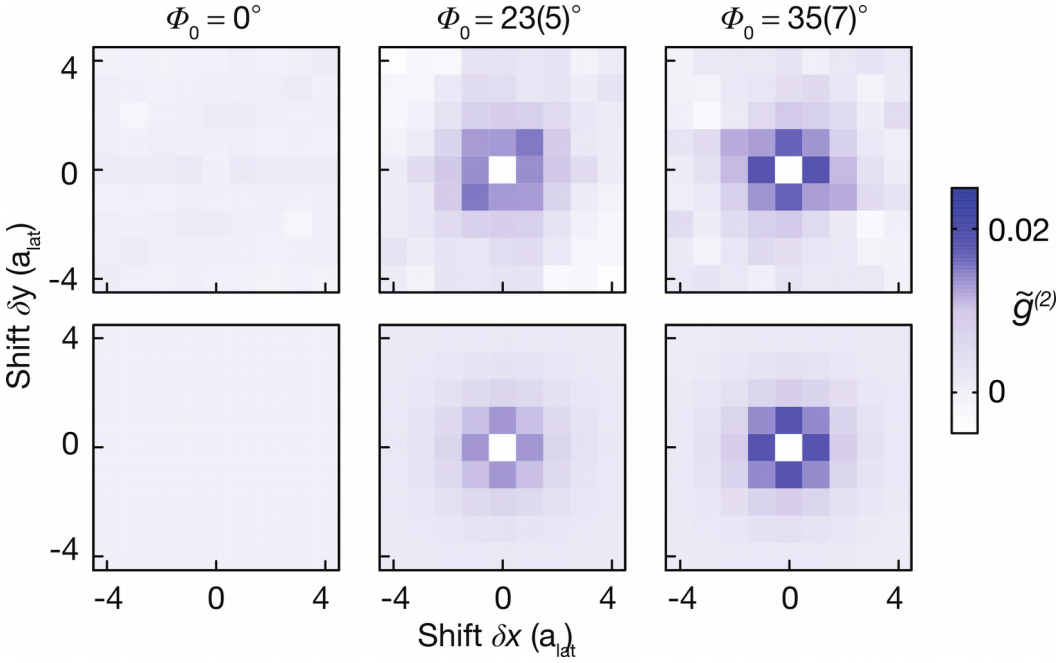
$$g^{(2)}(i,j) = \langle \hat{S}_i^z \hat{S}_j^z \rangle - \langle \hat{S}_i^z \rangle \langle \hat{S}_j^z \rangle$$







Emergence of correlations

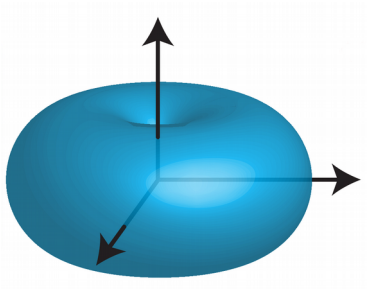


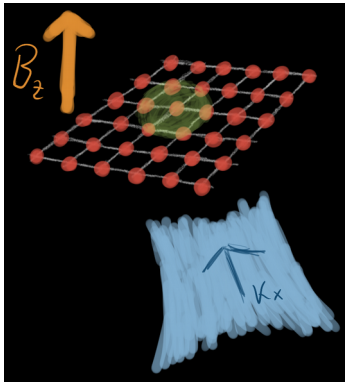
At small t: Direct imaging of the interactions: $g^{(2)}(i,j;t) \propto \varphi(t)^2$

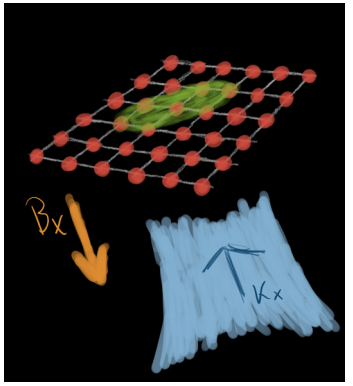
Accumulated phase: $\varphi(t) = U_{i,j}t$ with $U_{i,j} = \dfrac{U_0}{1 + (|r_{i,j}/R_C|)^6}$

Rydberg based potential tuning

$P_{3/2}$: Anisotropic interactions







Rydberg based potential tuning

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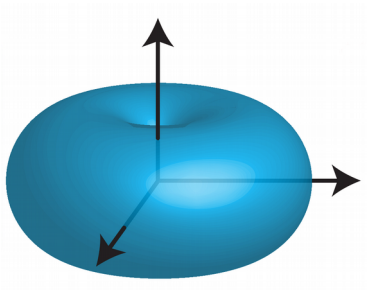
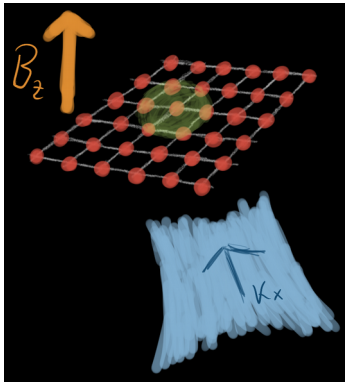
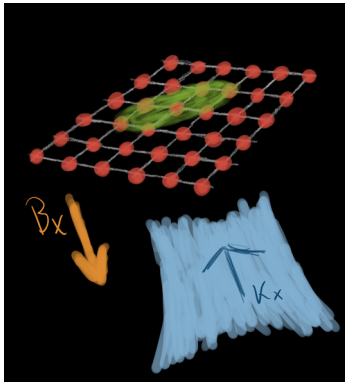
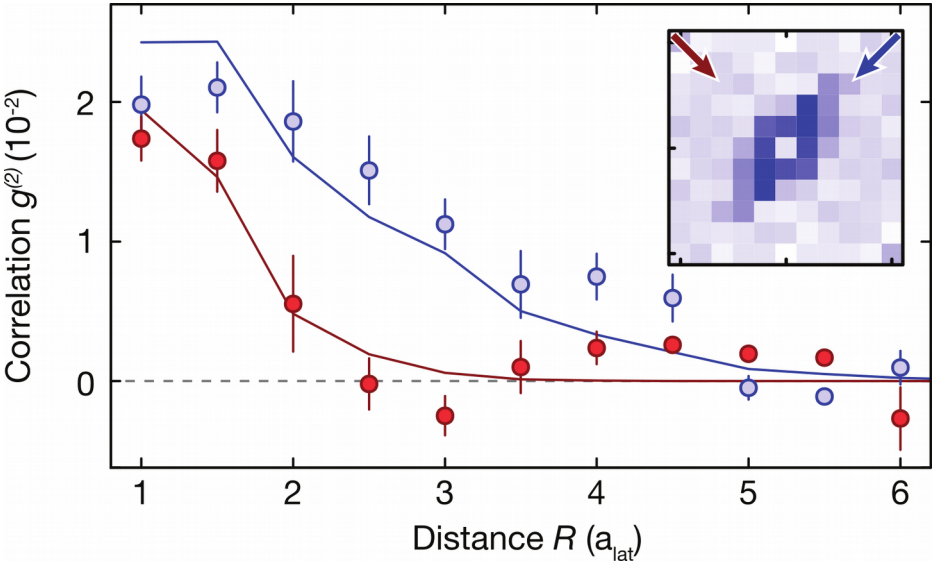


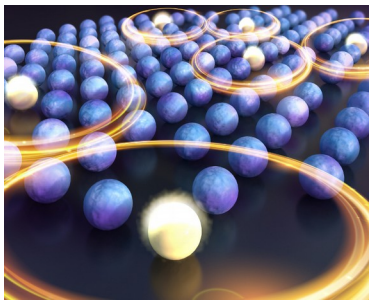






Thank you!!

MBL in 2D



Long-range interacting spins

The team

I.Bloch

J.Choi

S.Hild

J.Zeiher

P.Schauß

T.Yefsah

A.Abadal

S.Hollerith

Collaborators:

V. Khemani & D. Huse

R. van Bijnen & T. Pohl