Dynamics & Entanglement in Synthetic UQM

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Simons Collaboration on
Ultra-Quantum Matter

Synthetic quantum matter

New field in quantum many body physics: arose over the last 20 years

Can be loosely split into:

1. Bottom-up engineering: using elements designed to perform as quantum degrees of freedom to build up a quantum many body systems. Superconducting qubits, cold ions.

2. Hamiltonian engineering: a gas of cold atoms with adjustable interactions, placed in external “trap” or optical lattices, with random potential.

Advantage over more conventional solid state systems:

1. Hamiltonian is known precisely. Can be used as “quantum simulators”.

2. Precise accounting over degrees of freedom. Can be fully isolated from the environment. Can easily be driven out of equilibrium or prepared in an arbitrary state.

3. Detailed probes: measures of momentum distribution, spatial density distribution; harder to measure transport

First quantum-simulated state (2002)

articles

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

Hamiltonian engineering:

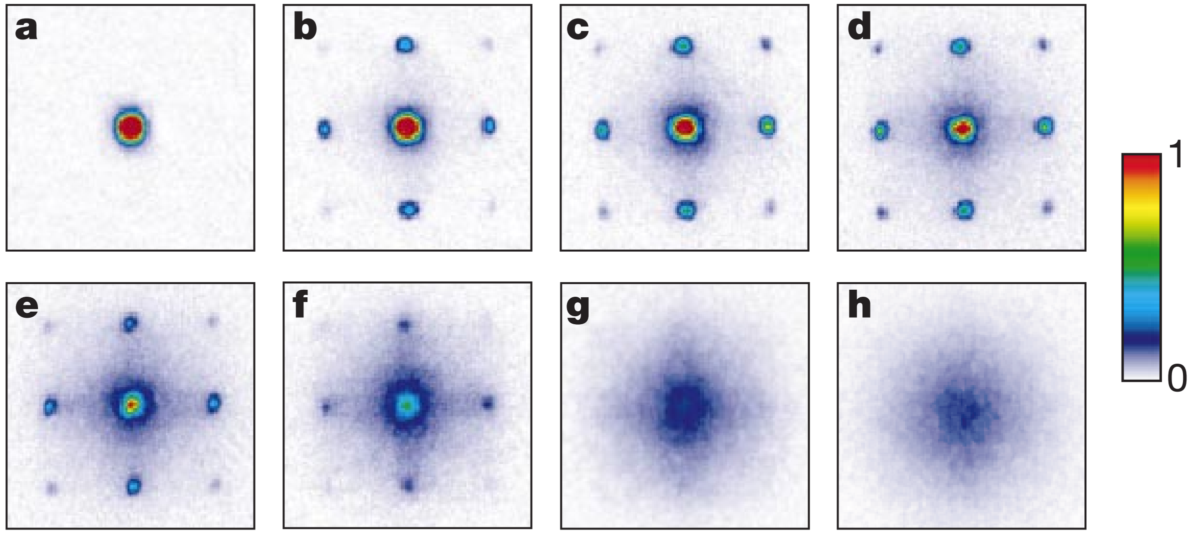
1. Bose-Hubbard model

$$H = -J\sum_{\langle i,j\rangle}\hat{a}_i^{\dagger}\hat{a}_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1) \qquad (1)$$

2. Optical lattice

$$V(x,y,z) = V_0(\sin^2(kx) + \sin^2(ky) + \sin^2(kz)) \qquad (4)$$

3. Probing (quasi)momentum distribution



4. Observing phase transition between synthetic states of matter

17 years later

Progress isn’t as fast as initially anticipated.

Very slow progress on creating equilibrium quantum matter.
Cooling in optical lattice remains a challenge.

Progress comes from just a few key labs.

More progress on quenches (sudden changes of the Hamiltonian) and out of equilibrium evolution.

At the same time, entanglement as a characteristics of quantum many body states received wider recognition.

Synthetic quantum matter provides an access to entanglement inaccessible to other methods.

Experimental platforms

- Quantum gases. Bose, Fermi, Bose-Fermi. Spin-0, 1/2, 1, …

  Spinor condensates
  BCS-BEC Crossover
  Polarons, impurity in gases

- Hubbard model.

  Bose, Fermi, higher spin, SU(N). Disorder: Anderson and MB localization

- Long-range interacting transverse field Ising model.

  Quantum phase transitions.
  Many body localization

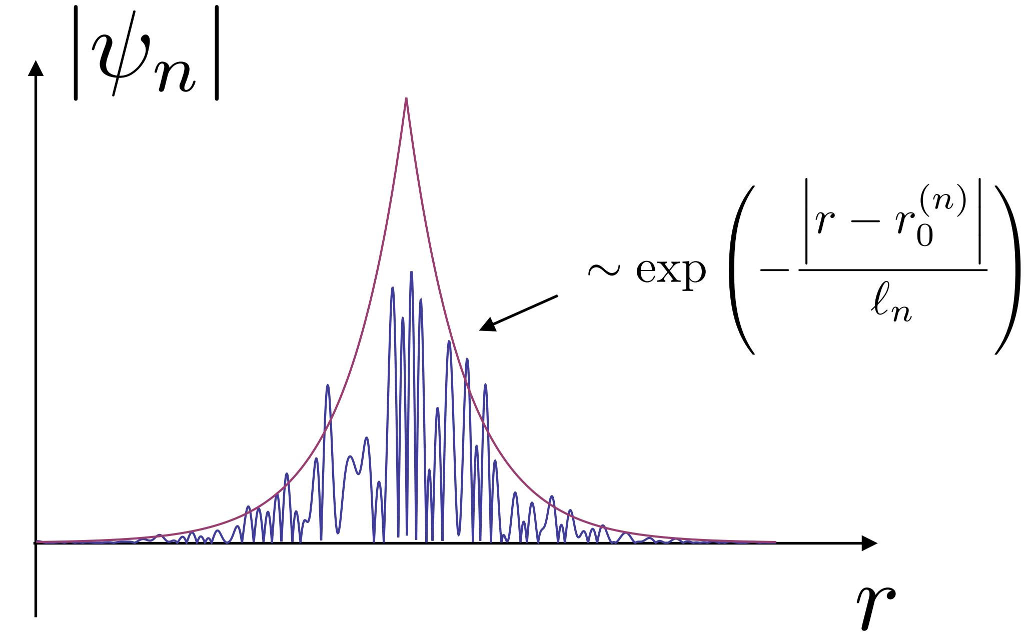
  New observables: $\mathrm{tr}\, e^{-iHt}$
  entanglement entropy

Anderson localization & Many-body localization

AL: Quantum motion in a random potential

$$-\frac{1}{2m}\Delta\psi_n + V(\mathbf{r})\,\psi_n = E_n\psi_n$$

All wave functions below 3D and sufficiently low energy wave functions at 3D and above are localized



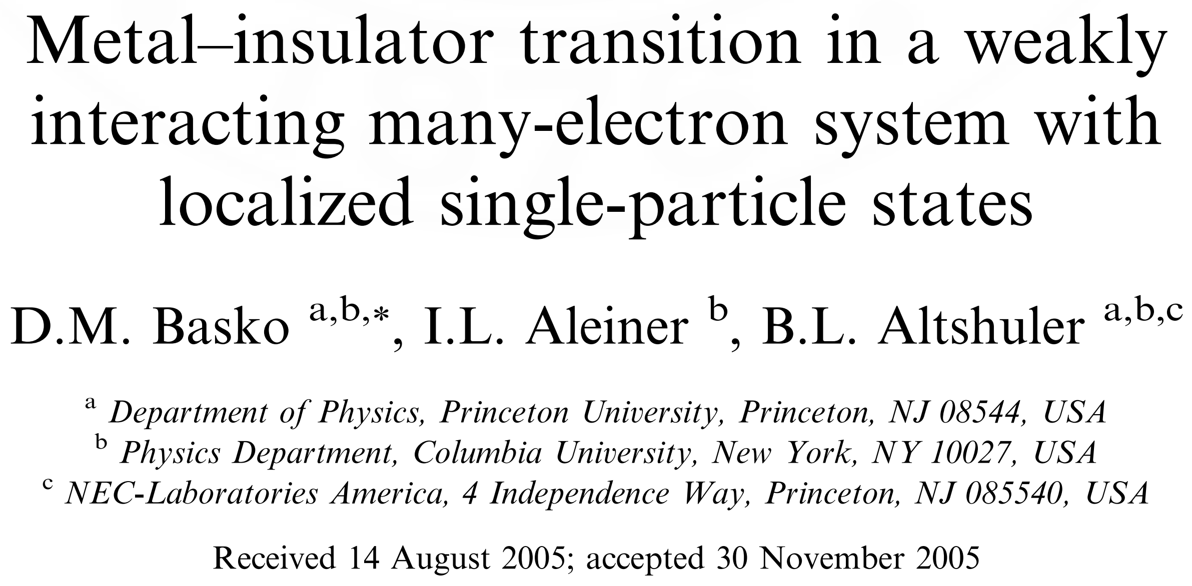
Manifests itself in inhibited transport

Was successfully studied in the 70s-90s using conventional methods of quantum many body theory.

MBL: Originally had to do with adding interactions to the Anderson-localized system and asking if transport is still inhibited.

In this formulation, turned out to be an extremely difficult question because of initial lack of technical tools to access interesting observables.

Basko, Aleiner and Altshuler (2006) were the first to meaningfully address this question using suitably resumed perturbation theory.



Metal–insulator transition in a weakly interacting many-electron system with localized single-particle states

D.M. Basko [a,b,*], I.L. Aleiner [b], B.L. Altshuler [a,b,c]

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MBL & Thermalization

Progress occurred after D. Huse and collaborators recognized that the signature of MBL was lack of thermalization.

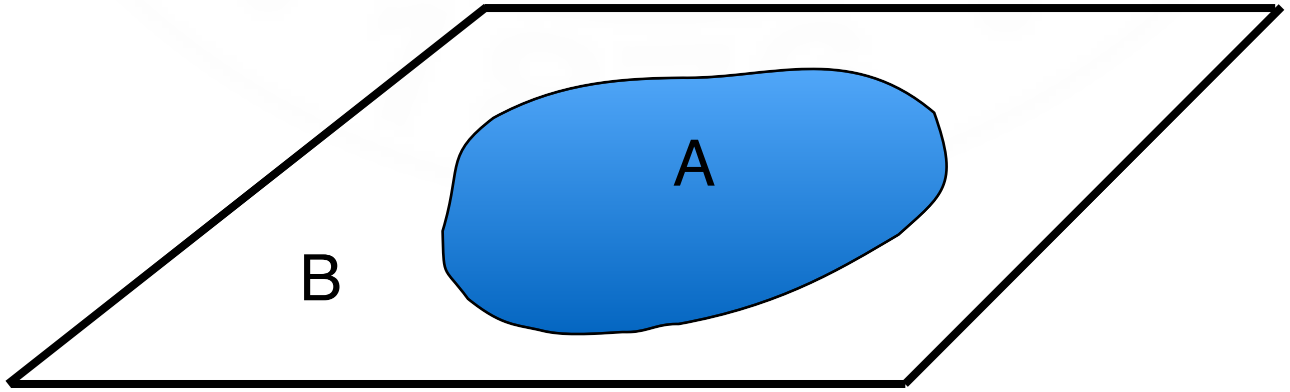
high energy eigenstate $|\psi\rangle$

$$\rho_A = \mathrm{tr}_B \, |\psi\rangle \langle\psi| \qquad S = -\mathrm{tr}_A \left[\rho_A \ln \rho_A\right]$$

ETH (eigenstate thermalization hypothesis):

ρ_A is thermal, *S* obeys volume law

MBL: ρ_A is not thermal, *S* obeys area law



MBL: every eigenstate looks like a ground state for some Hamiltonian

MBL & Thermalization

Occurs in isolated quantum systems.

Manifests itself in the inhibited transport and absence of thermalization.

Hard to see in solid state systems because no solid state system is isolated.

Cold atoms a natural playground to see many body localization.

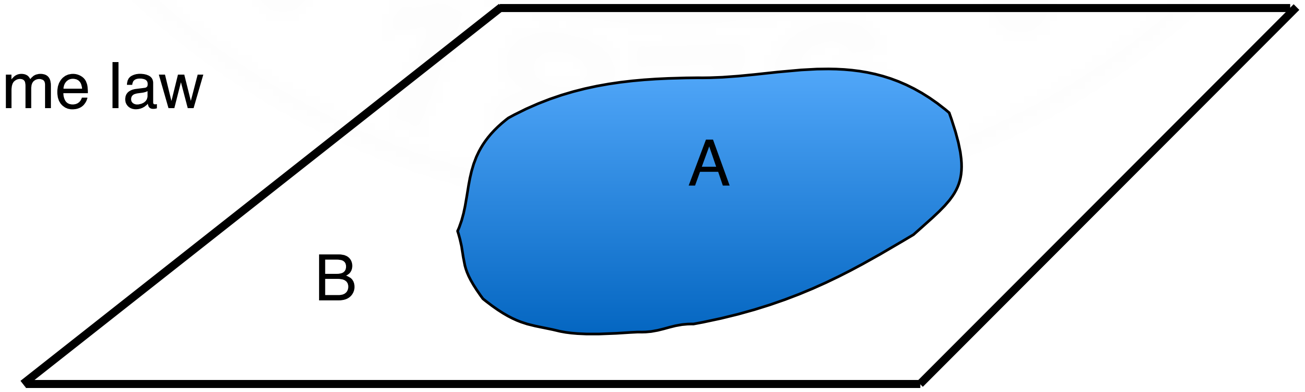
Cold atoms also provide unique tools which allow to measure signatures of MBL unavailable in solid state. In particular, the ability to see entanglement directly.

high energy density state $|\psi\rangle$

$$\rho_A = \mathrm{tr}_B \, |\psi\rangle \langle\psi| \qquad\qquad S = -\mathrm{tr}_A \left[\rho_A \ln \rho_A\right]$$

ETH: ρ_A is thermal, *S* obeys volume law

MBL: ρ_A is not thermal, *S* obeys area law



Observation of MBL in Fermi-Hubbard

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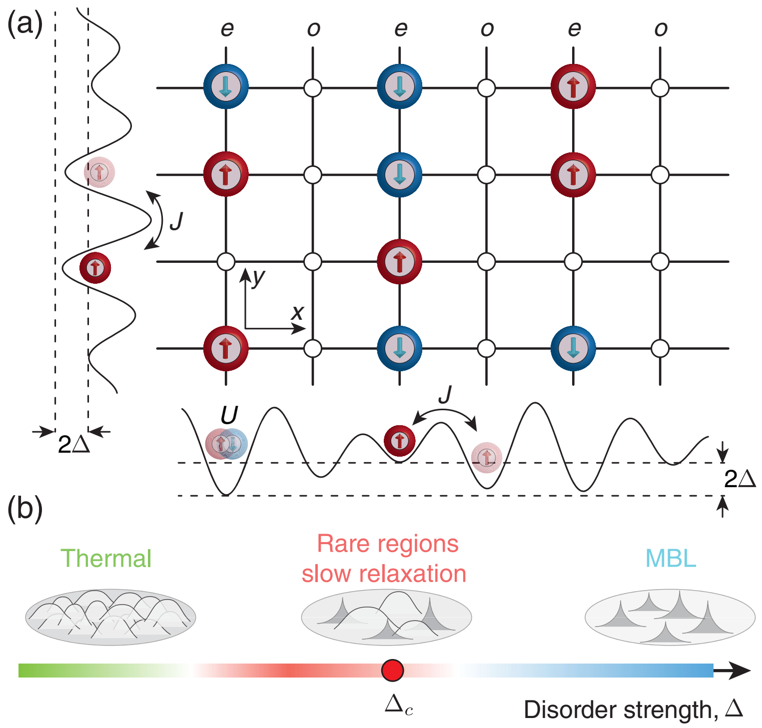
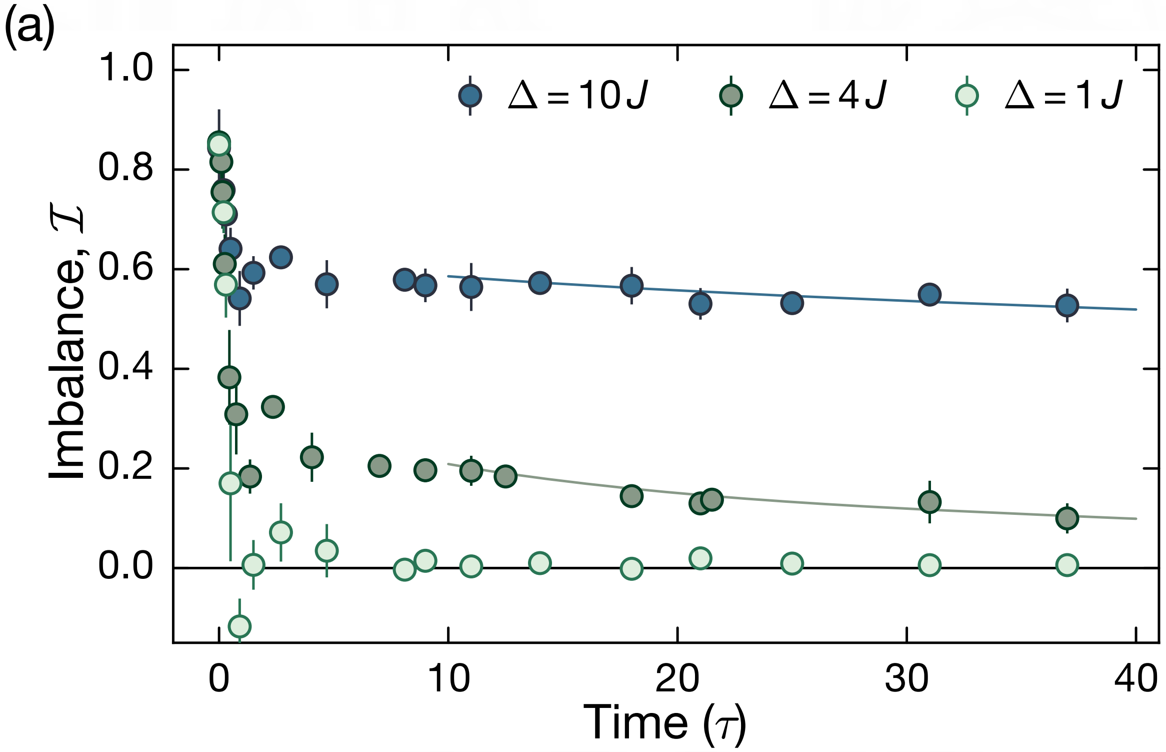
Probing Slow Relaxation and Many-Body Localization in Two-Dimensional Quasiperiodic Systems

Pranjal Bordia,[1,2] Henrik Lüschen,[1,2] Sebastian Scherg,[1,2] Sarang Gopalakrishnan,[3]
Michael Knap,[4] Ulrich Schneider,[1,2,5] and Immanuel Bloch[1,2]



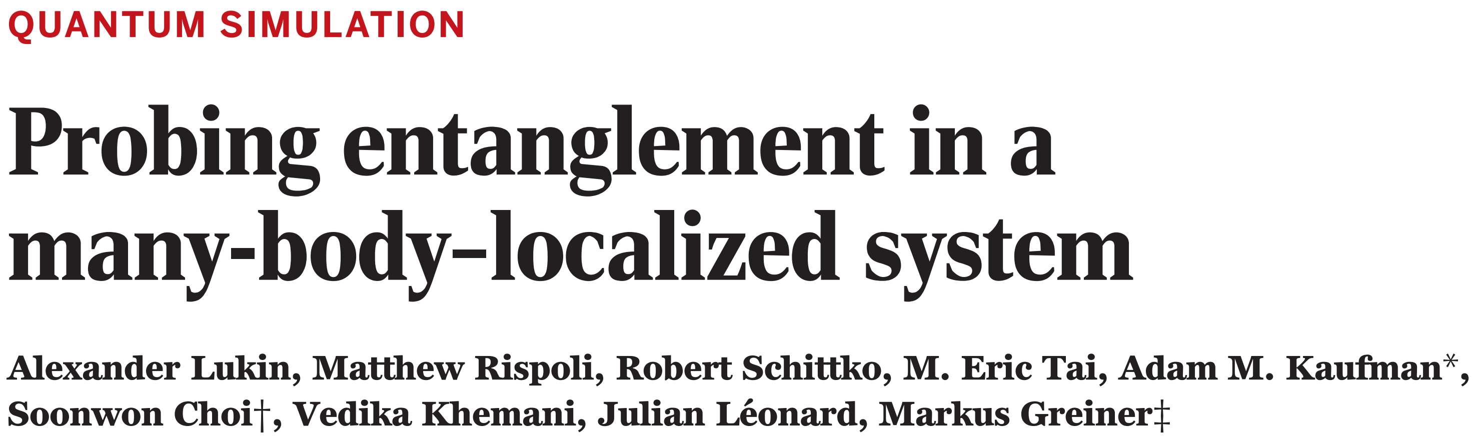


$$\hat{H} = -J \sum_{\langle \mathbf{i},\mathbf{j}\rangle,\sigma} (\hat{c}^{\dagger}_{\mathbf{j},\sigma}\hat{c}_{\mathbf{i},\sigma} + \mathrm{H.c.}) + U \sum_{\mathbf{i}} \hat{n}_{\mathbf{i},\uparrow}\hat{n}_{\mathbf{i},\downarrow} + \Delta \sum_{\mathbf{i},\sigma} [\cos(2\pi\beta_x m) + \cos(2\pi\beta_y n)]\hat{n}_{\mathbf{i},\sigma}. \qquad (1)$$

Fermi-Hubbard model

$$\mathcal{I} = \frac{N_e - N_o}{N_e + N_o}$$

Entanglement & MBL (2019)



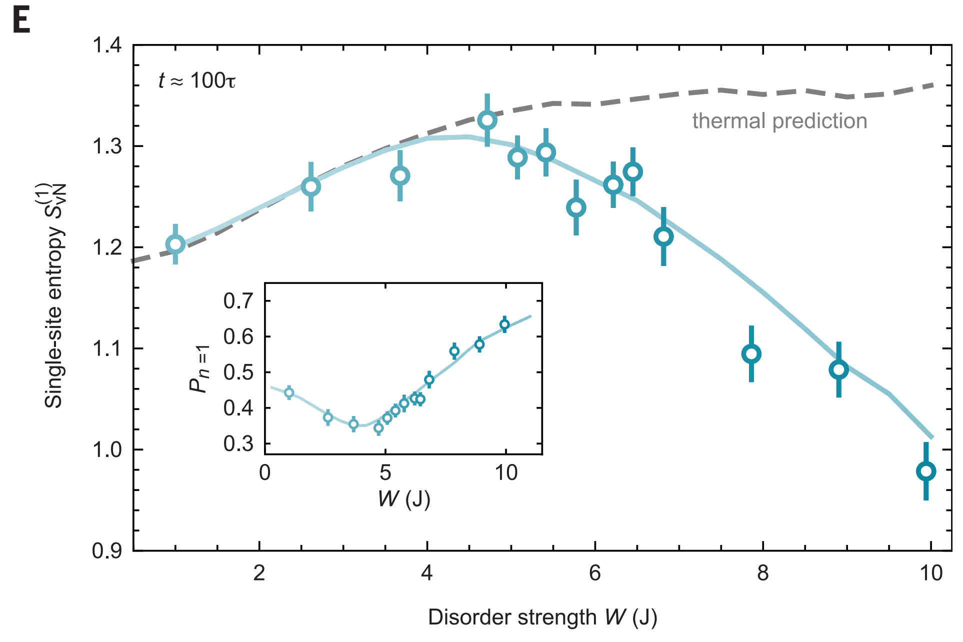
QUANTUM SIMULATION

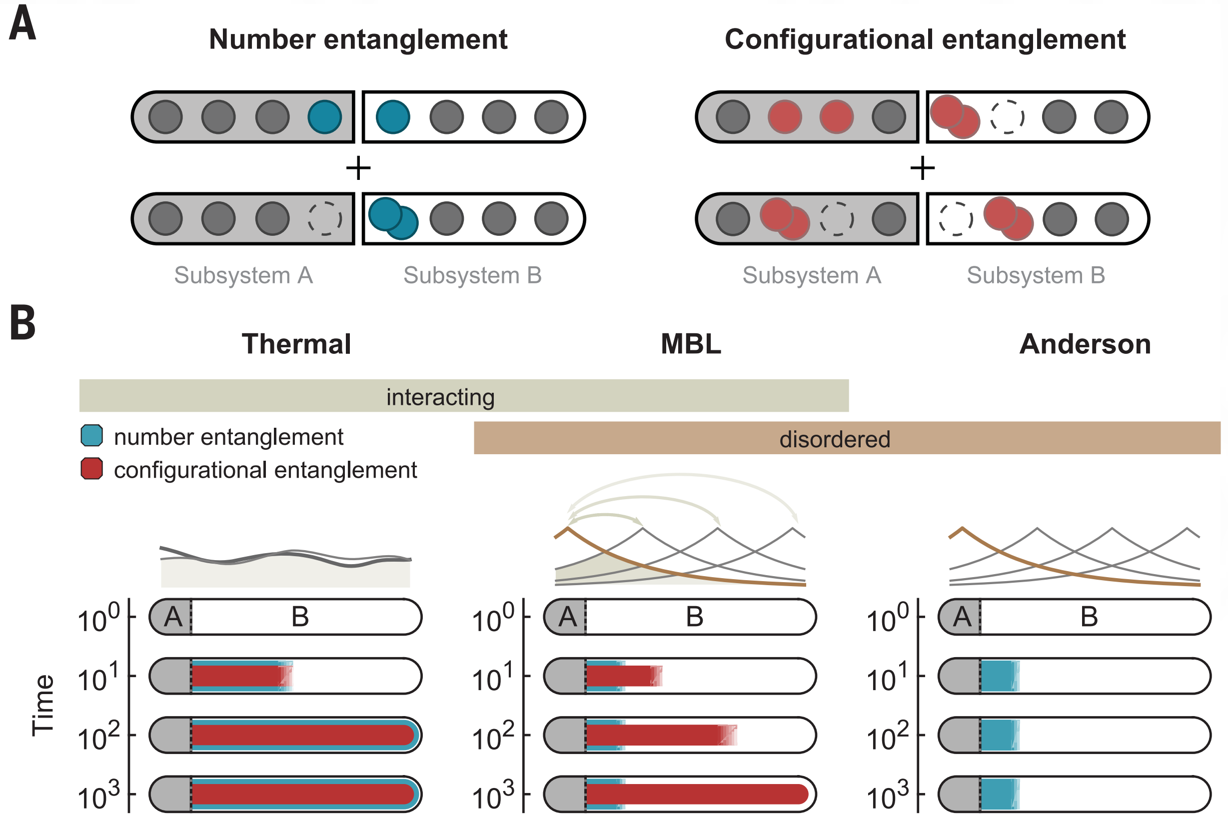
Probing entanglement in a many-body-localized system

Alexander Lukin, Matthew Rispoli, Robert Schittko, M. Eric Tai, Adam M. Kaufman*, Soonwon Choi†, Vedika Khemani, Julian Léonard, Markus Greiner‡

$$\hat{\mathcal{H}} = -J\sum_i(\hat{a}_i^\dagger \hat{a}_{i+1} + h.c.) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + W\sum_i h_i \hat{n}_i \qquad (1)$$

Bose-Hubbard model





Single site entanglement: $S^{(1)} = -\sum_n p_n \ln p_n$

p_n probability of seeing *n* bosons on the leftmost site

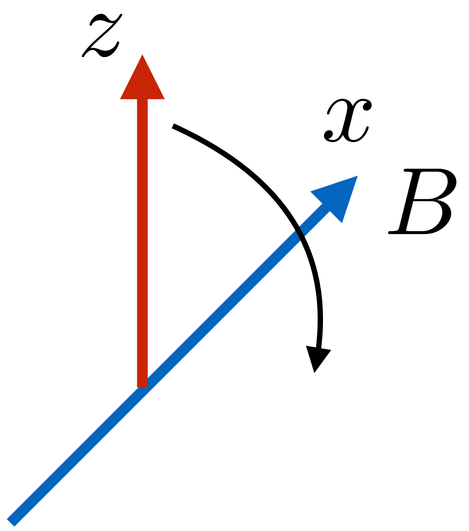
MBL as ultra quantum states

- Every eigenstate looks like a ground state for some Hamiltonian
- Topologically ordered states at finite energy density
- A method to prevent heating in driven systems, such as Floquet quantum matter

Role of measurement: Quantum Zeno effect

Misra, Sudarshan (1977)

Measurements inhibit quantum evolution



Spin rotating in the Zeeman field *B*.

$$H = -JB^x S^x$$

with frequency ω

Suppose we take measurements of the spin's z-component with the rate $\Gamma \gg \omega$

Probability that spin the still points up at the time of the measurement

$$\cos^2\left(\omega/\Gamma\right) \approx 1 - \omega^2/\Gamma^2$$

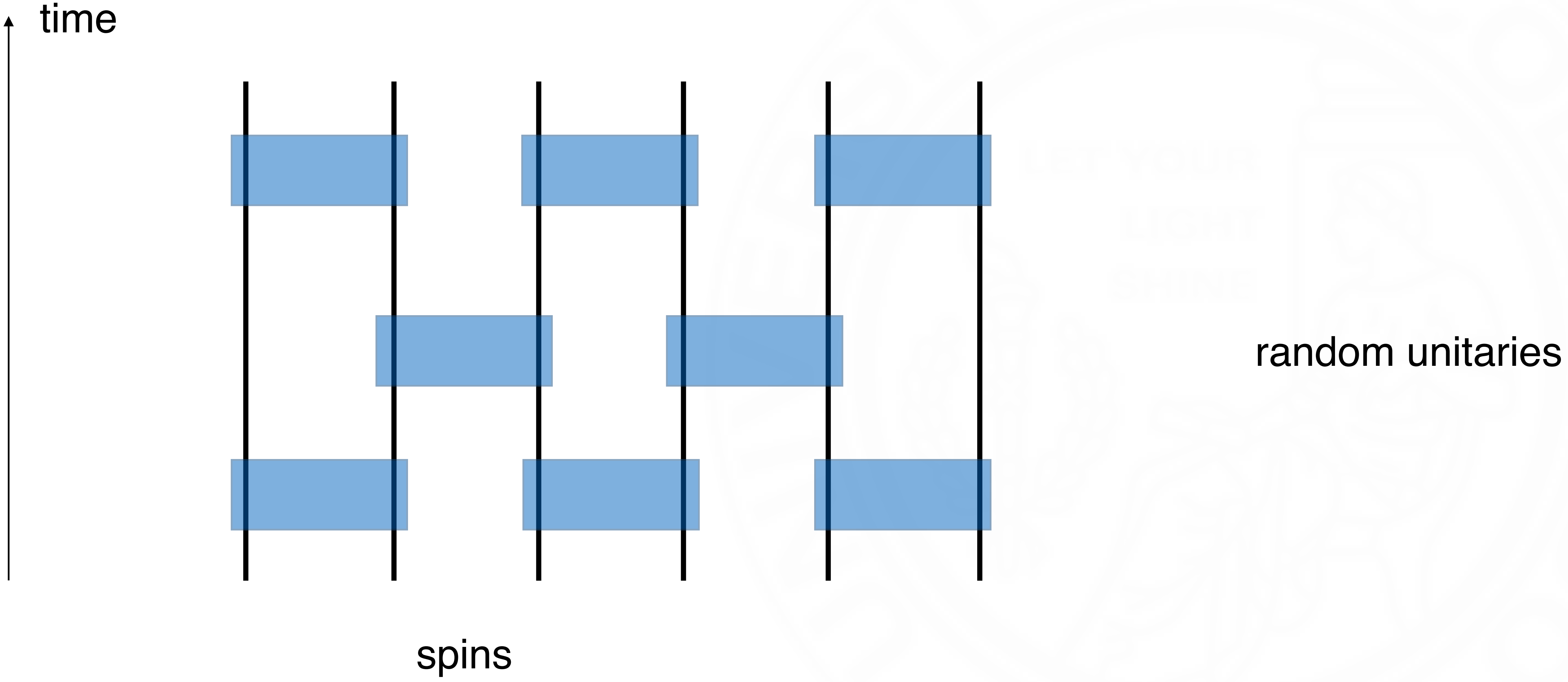
Probability that spin the still points up after time *t* or

$N = t\Gamma$ measurements

$$\cos^{2N}\left(\omega/\Gamma\right) \approx 1 - N\omega^2/\Gamma^2 = 1 - t\omega^2/\Gamma \to 1$$
$$\Gamma \to \infty$$

For frequent measurements the spin stops rotating

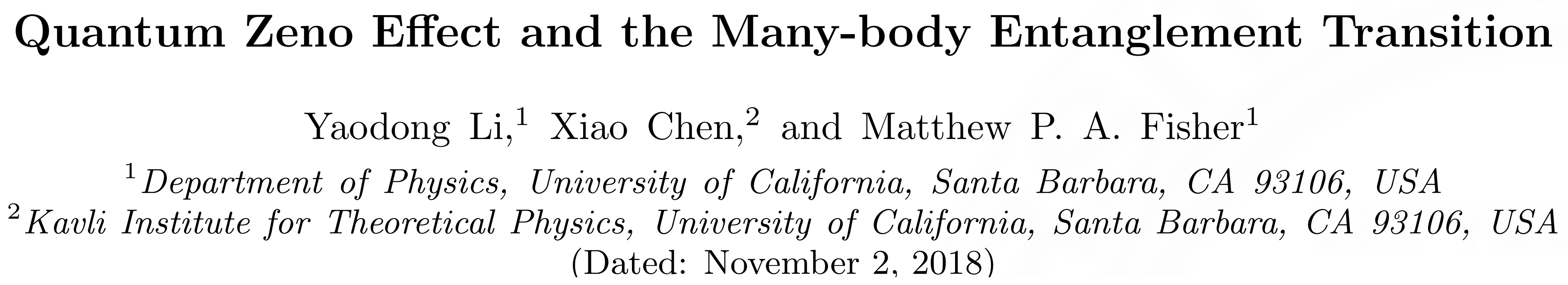
Evolution of entanglement in quantum circuits



A product state evolves into a highly entangled state quickly, saturating in a volume law

$S \sim V_A$ (volume of the smaller of the two subsystems)

Quantum circuits with projective measurements

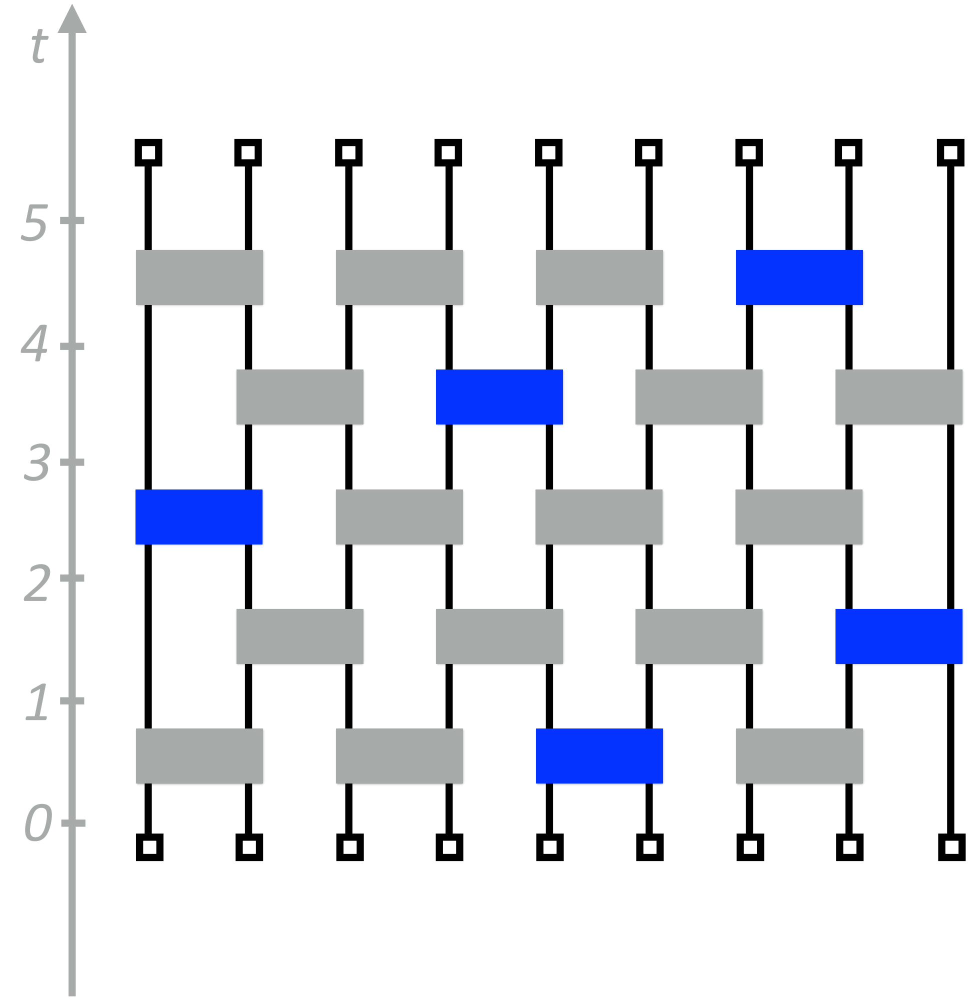


Quantum Zeno Effect and the Many-body Entanglement Transition

Yaodong Li,[1] Xiao Chen,[2] and Matthew P. A. Fisher[1]

[1] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[2] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
(Dated: November 2, 2018)

(also Skinner, Ruhman, Nahum)



U $|\psi\rangle \to U|\psi\rangle$ unitary evolution

UP $|\psi\rangle \to U\frac{P|\psi\rangle}{\|P|\psi\rangle\|}$ unitary plus projective measurement

Novel type of a transition between area law and volume law as a function of the relative number of projective measurements. (Large number of measurements = area law = “Zeno effect”). Perhaps, with new experimental capability, we will see it observed soon?

Synthetic matter

- Synthetic matter = an avenue not only to create new types of quantum matter but also to probe it in new ways.

- Provides access to measure entanglement directly.

- Can create matter in new ways, and also allows us to concentrate on those aspects of quantum matter potentially accessible to synthetic matter experiment.