Title: Many-body localization: a quantum frontier

Date: Feb 27, 2017 10:30 AM

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Abstract: <p>A closed quantum system is ergodic and satisfies equilibrium statistical physics when it completely loses local information of its initial condition under time evolution, by 'hiding' the information in non-local properties like entanglement. In the last decade, a flurry of theoretical work has shown that ergodicity can be broken in an isolated, quantum many-body system even at high energies in the presence of disorder, a phenomena known as many-body localization (MBL). In this novel phase of matter, highly excited states of an interacting system can serve as quantum memory and even protect exotic forms of quantum order. Recent claims of experimental observation of MBL in two dimensions using ultra-cold atoms has further raised a plethora of intriguing questions.</p>

<p> </p>

<p>In one dimension, the strongly localized regime is described in terms of quasi-local integrals of motion, also known as l-bits. Based on this picture I will describe an efficient tensor network method to efficiently represent the entire spectrum of fully many-body localized systems. This ansatz is also successful at capturing features of the MBL to thermal transition. For higher dimensions, I will develop a refined phenomenology of MBL in terms of l*-bits which are only 'approximately' conserved, based on the stability of the localized phase to perturbations on the boundary. I will conclude with a bird's-eye view of some of the open problems in this rapidly growing field.</p>

Arijeet Pal
10:56

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Many-body localization: a quantum frontier

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New College at Oxford University

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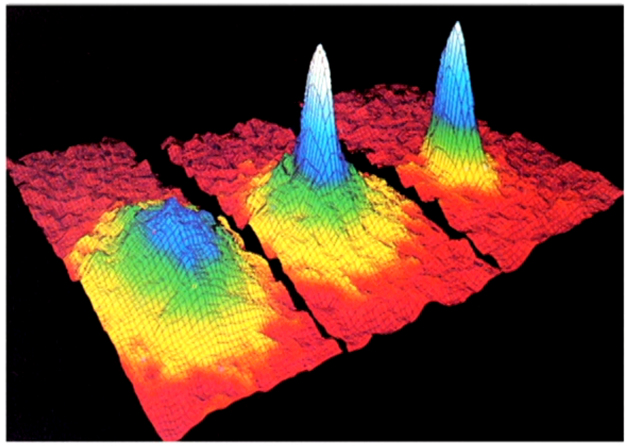
Arijeet Pal

Quantum matter

Bose-Einstein Condensation

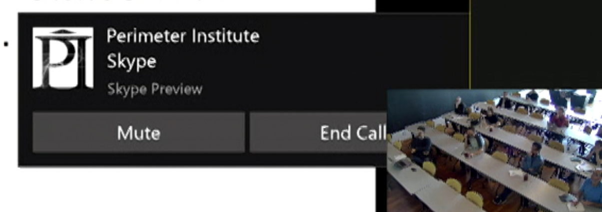


Cornell, Ketterle, and Weimann, Nobelprize (2001)

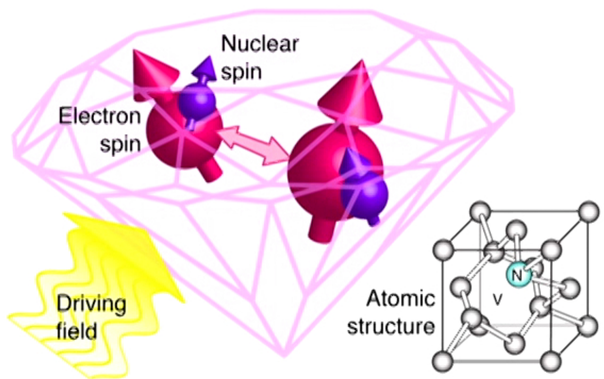
BEC- macroscopic quantum coherence

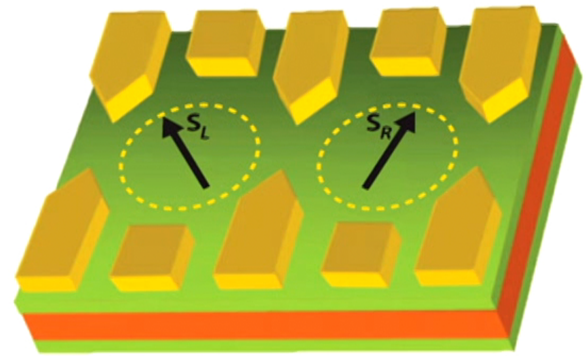
Quantum condensed matter physics: novel equilibrium states with exotic properties.

Major technological applications.



Quantum devices





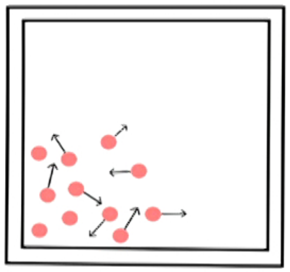
NV centers in diamond,
Awschalom, Lukin, Walmsley,...

Spin qubits in semiconductors,
Loss, DiVincenzo,....

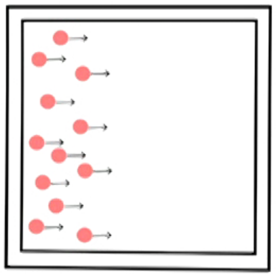
- Manipulation of quantum states in solid state systems- quantum information processing.
- Decoherence due to interactions is a major road-block.

Quantum thermalization

$t=0$

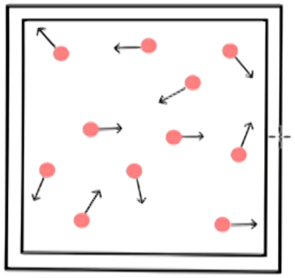


Most interacting quantum systems *decohere* and *thermalize* independent of initial conditions

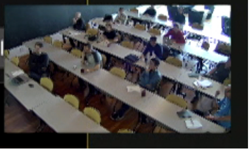


$$i\hbar\frac{d|\Psi\rangle}{dt}=\hat{H}|\Psi\rangle$$

$t=T$



Equilibrium state at finite temperature is classical.



Single-particle localization

Absence of Diffusion in Certain Random Lattices

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)

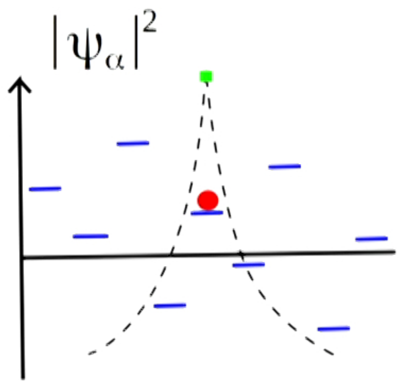
Motivated by experiments raised the question,
can generic, isolated quantum systems fail to equilibrate?

Non-interacting particles

$$H_{AL} = \sum_i \mu_i c_i^\dagger c_i + t \sum_{\langle i,j \rangle} (c_i^\dagger c_j + h.c.)$$

$$\mu_i \in [-W, W]$$

- Eigenstates in the absence of hopping (t) are localized on individual sites.



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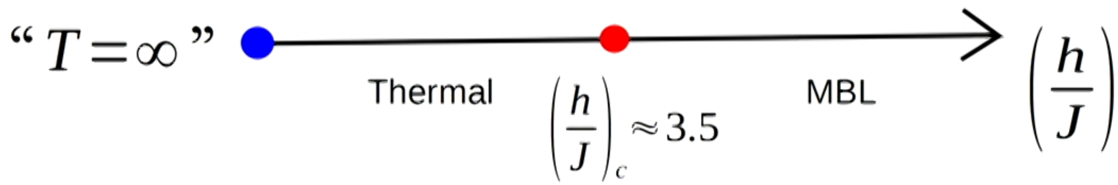
Canonical model of MBL

Pal and Huse, PRB (2010)

$$H = \sum_{i=0}^{N} h_i S_i^z + J \sum_{i=0}^{N-1} \vec{S}_i \cdot \vec{S}_{i+1} \qquad h_i \in [-h, h]$$



Discovered this novel quantum phase transition in this model using conceptually new quantities.

- Entanglement entropy
- Correlation functions
- Local observables
- Matrix elements

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Emergent integrability of MBL in 1D

(L-bit picture)

$$[H, \tau_i^z] = 0 \qquad \Rightarrow \frac{d\tau_i^z}{dt} = 0$$

$$i = 1, \ldots, N$$

Quantum memory

- A complete set quasi-local operators which commute exactly with the Hamiltonian

τ_i^z acts as a two level system with eigenvalues ± 1

$$|\psi_\alpha\rangle = |+--++---\ldots++-\rangle$$

Imbrie (Mathematical Proof), Huse, Abanin...

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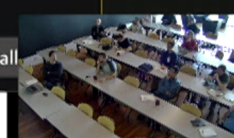
  $$H_{diagonal} = U H U^\dagger \qquad \tau_i^z = U \sigma_i^z U^\dagger$$

- U can be approximated as a *tensor network*- Chandra

Imbrie (Mathematical Proof), Huse, Abanin...



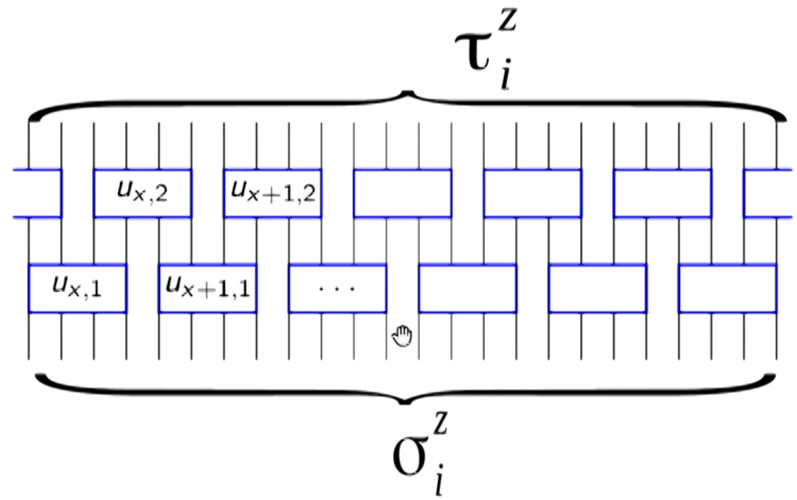
Multi-leg tensor network ansatz

$u_{x,y}$

is a general unitary tensor acting on l spins

l=4

$\widetilde{U} =$



- The multi-leg ansatz captures the structure of short range entanglement efficiently.

$$\widetilde{\tau}_i^z = \widetilde{U} \sigma_i^z \widetilde{U}^\dagger$$

Wahl, Pal, and Simon, arxiv1609:01552

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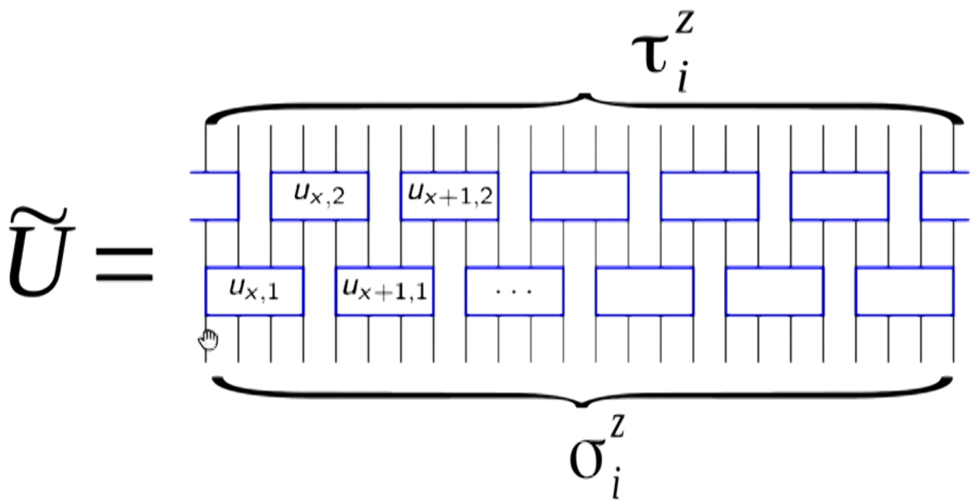


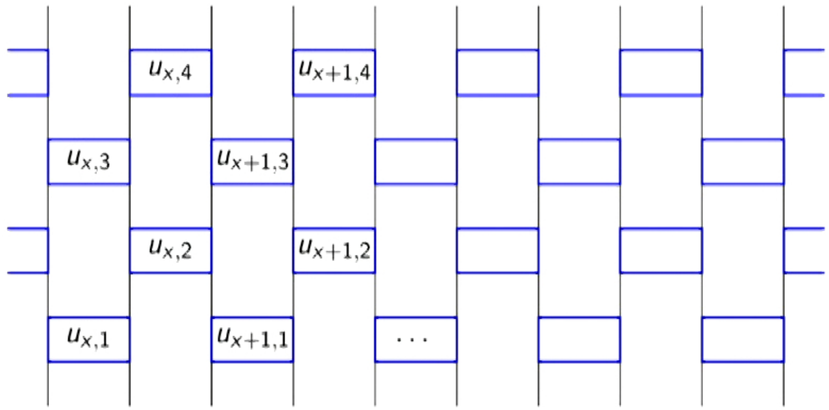
- The multi-leg ansatz captures the structure of short range entanglement efficiently.

$$\widetilde{\tau}_i^z = \widetilde{U}\,\sigma_i^z\,\widetilde{U}^\dagger$$

- Computational resources grow exponentially with l and linearly with N.

Wahl, Pal, and Simon, arxiv1609:01552

Multi-layer tensor network ansatz



- Fixing the the number of legs at 2, but increasing the number of layers (*Deep tensor network*).
- Computational resources grow ***super-exponentially*** with the number of layers for a fixed accuracy. Also, scales linearly in N.

Pollmann et al., PRB (2016)

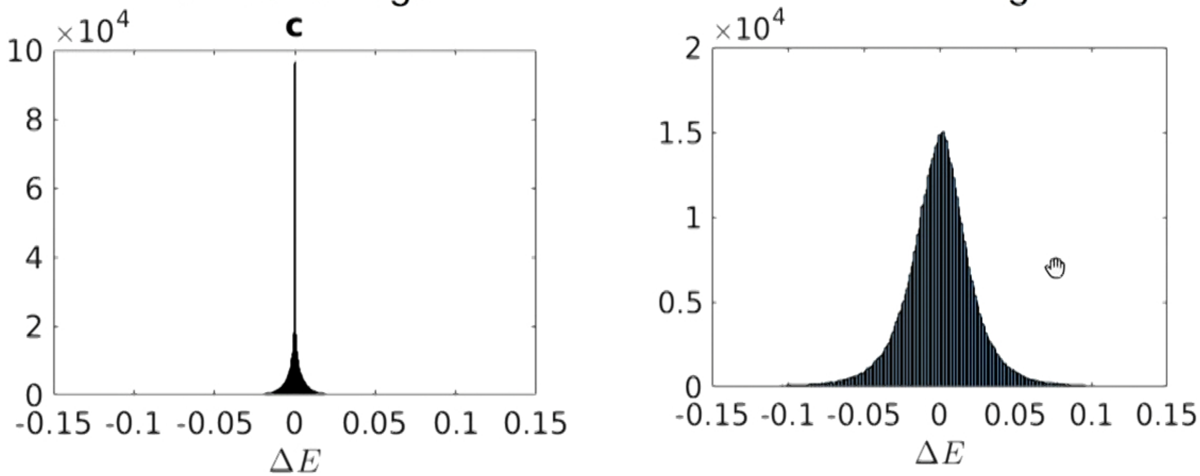
Multi-leg vs Multi-layer

Pal ansatz

Number of layers=2
Number of legs= 4

Pollmann ansatz

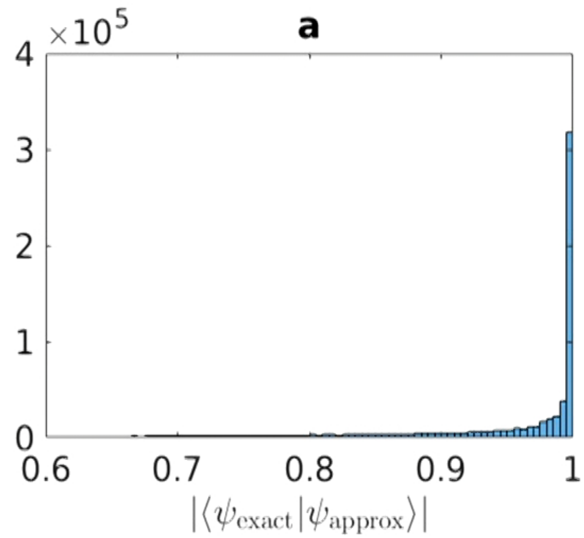
Number of layers=4
Number of legs= 2



Multi-leg ansatz much more accurate than the multi-layer ansatz.

Wahl, Pal, and Simon, arxiv1609:01552

Benchmarking with Exact Diagonalisation



A huge majority of the eigenstates have more than 95% overlap with the exact eigenstates.

Wahl, Pal, and Simon, arxiv1609:01552

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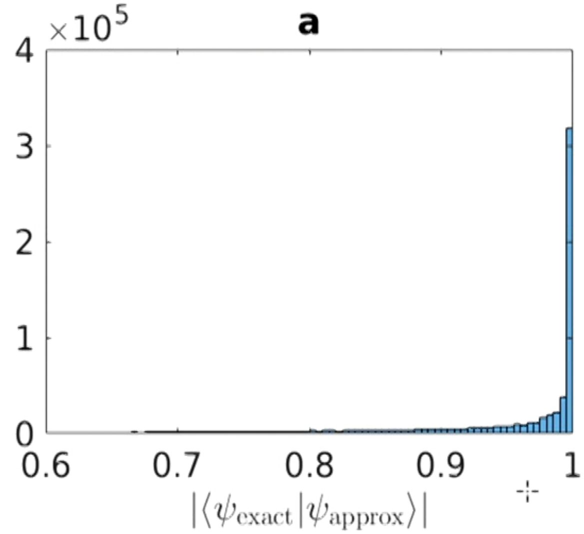

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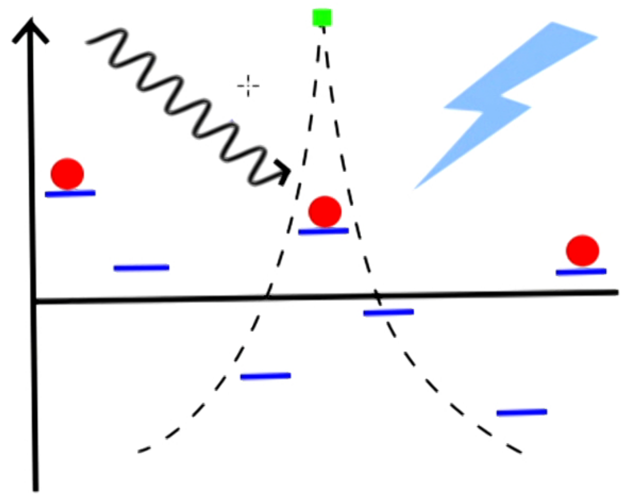
Wahl, Pal, and Simon, arxiv1609:01552

L-bits as quantum memory

- The operators τ^x and τ^z define a qubit in an interacting system.

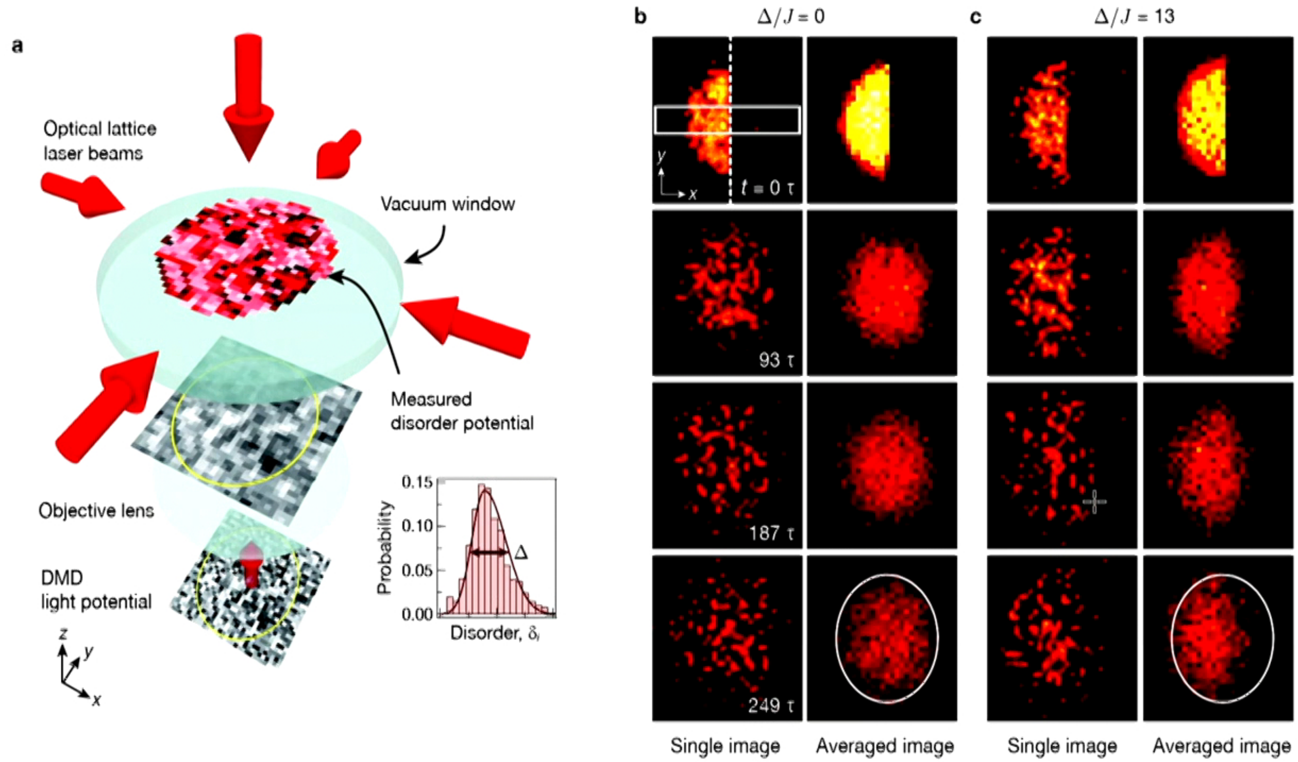
- Not effected by decoherence due to interactions!!



- Effects of noise?

Experiments in 2D

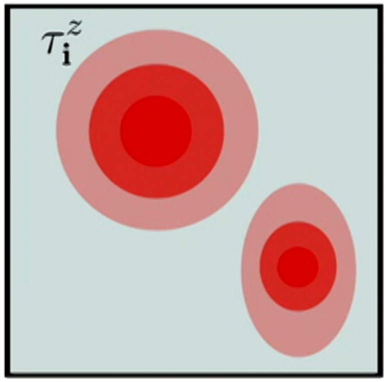
Neutral atoms (Bloch group, Munich)
Jae-yoon Choi et al., Science (2016)



Neutral atoms (Harvard, Cambridge, UIUC, Paris, Florence), Trapped Ions (Maryland), Superconducting qubits (Google), NV centers (Harvard), Superconducting films (Israel)

MBL in d>1: L*-bit

- L-bits are no longer stable $\Rightarrow$ $\|[H, \tau_{\mathbf{i}}^{*z}]\| \sim K \exp(-L/\zeta)$



Chandran, Pal, Laumann, and Scardicchio, PRB (2016)

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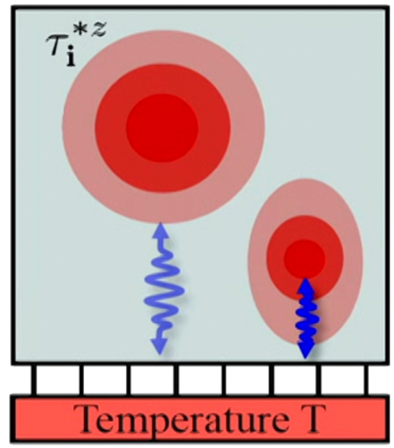
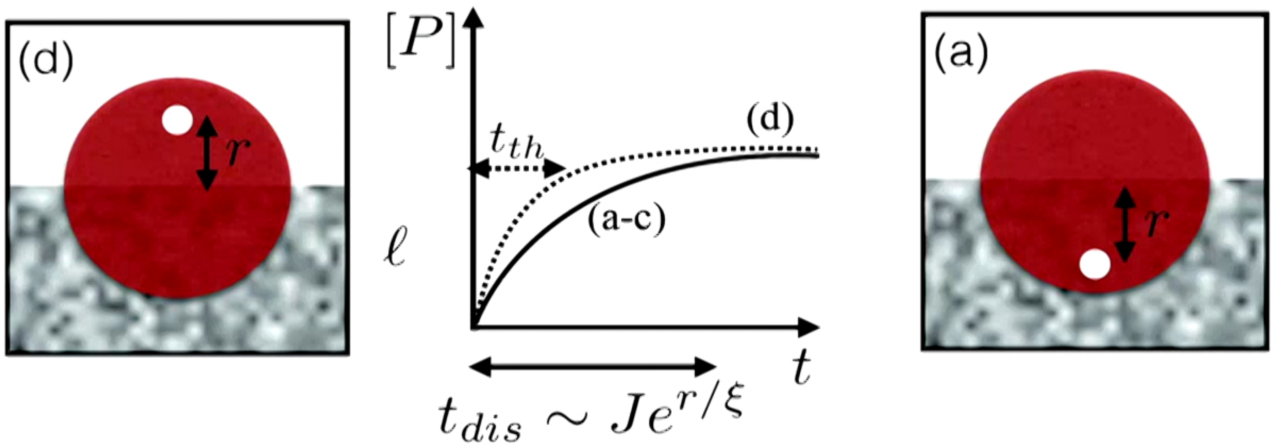


- Gedanken experiment
- Bulk L-bits and boundary thermal.
- Turn on weak coupling.

Chandran, Pal, Laumann, and Scardicchio, PRB (2016)

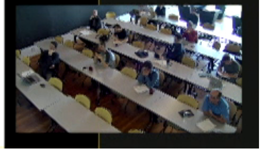
Experimental predictions



- Experiments in the *Bloch* group.
- Local relaxation as a function of position.

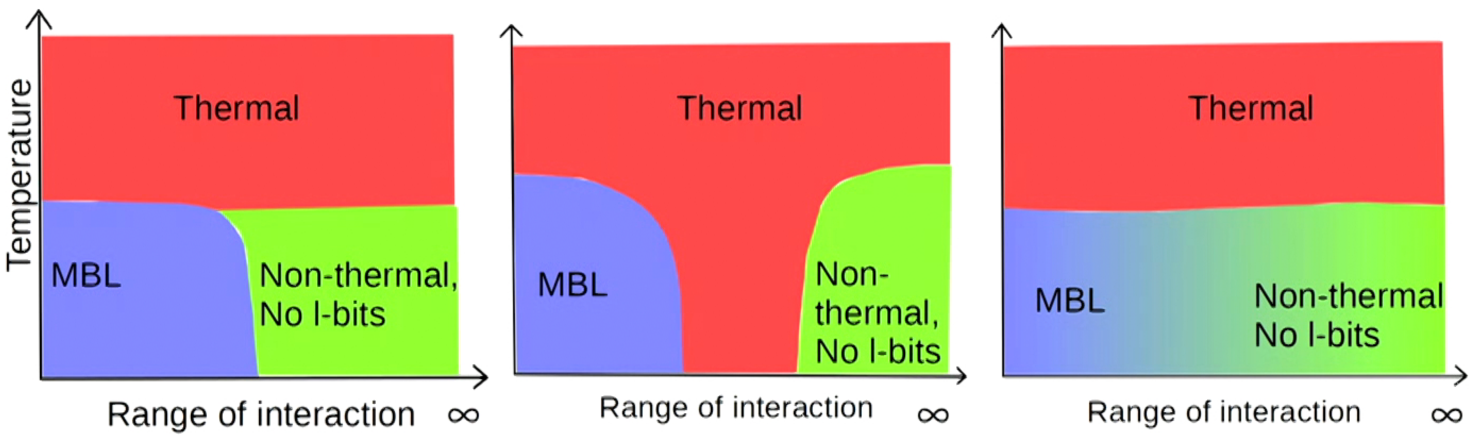
Chandran, Pal, Laumann, and Scardicchio, PRB (2016)

Future Goals

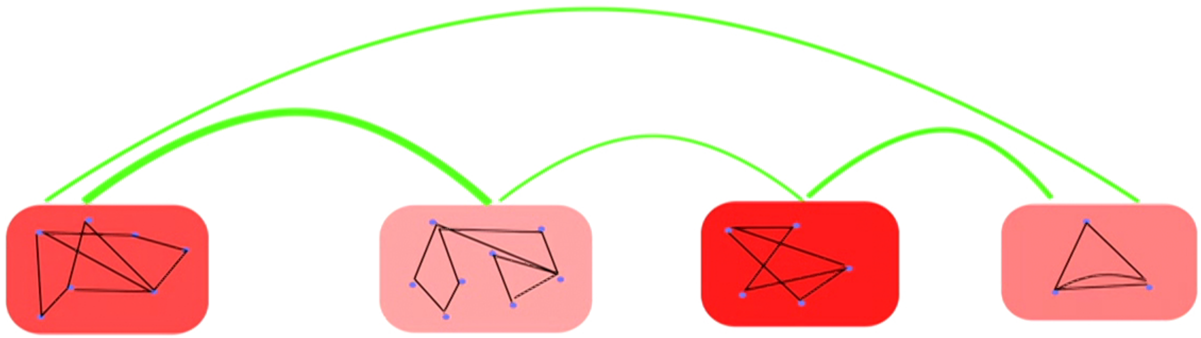


Long range interactions

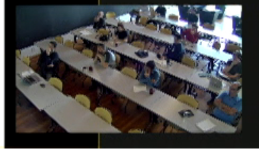
- NV centers, trapped ions, and semiconductors have long-range interactions.
- Infinite-ranged models can avoid thermalization but don't have L-bits.
  Laumann, Pal, Scardicchio PRL (2014),
  Baldwin, Laumann, Pal, Scardicchio PRL (2017)
- Finite temperature MBL in short ranged models.
  Mondragon-Shem, Pal, Hughes, Laumann PRB (2015)



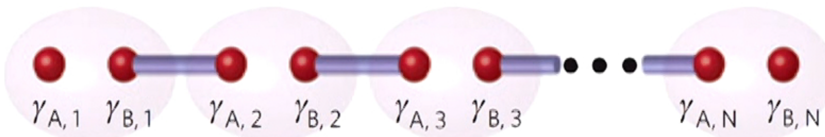
Nature of the phase transition



- No theory for the transition.
- Novel multi-scale concepts to capture the richness of many-body entanglement.
- Measures of quantum information for the transition.



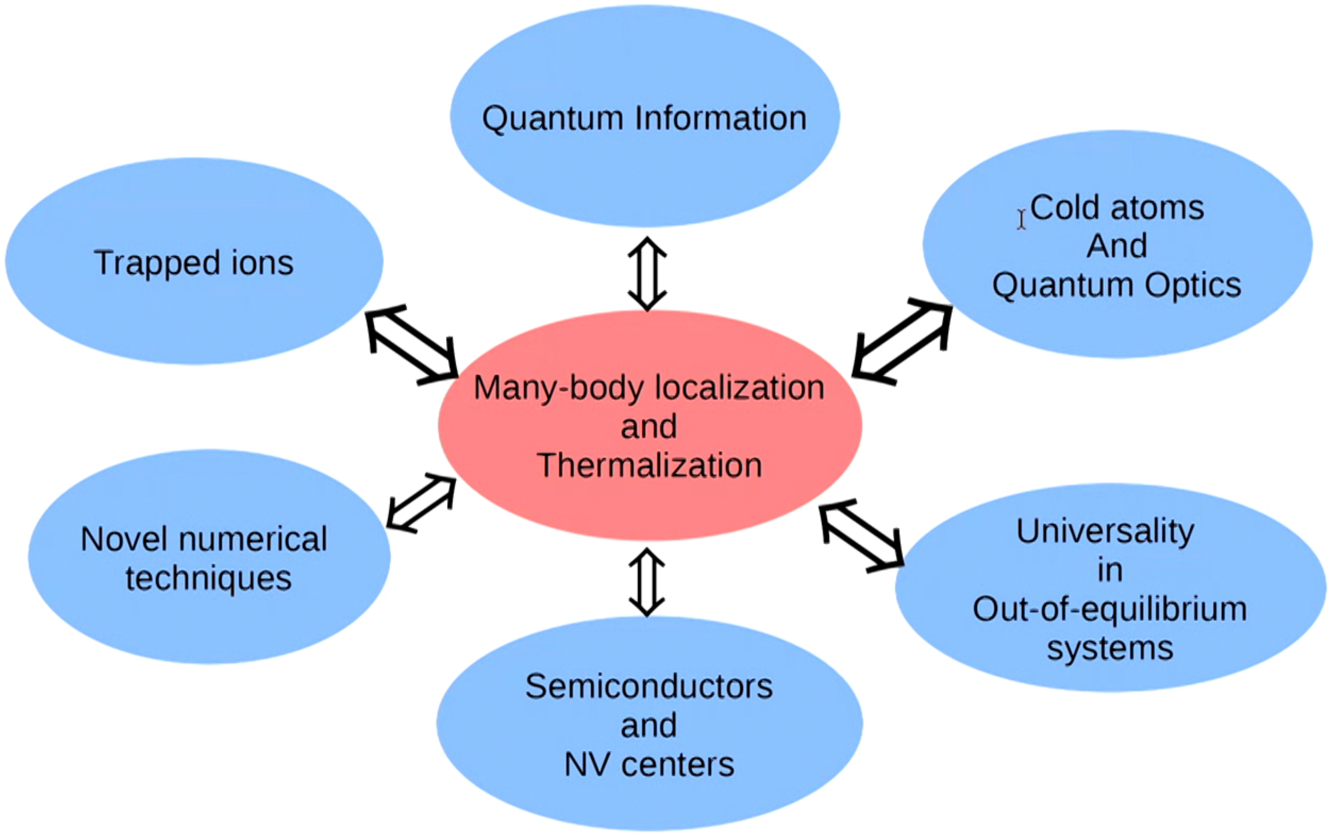
Resource for quantum computation



Microsoft Station Q, Caltech, Delft, Copenhagen

- Topological qubit- Edge modes in ground states of 1D topological superconductors.
- Challenging to realize and manipulate in experiments.
- MBL can protect topological order even in highly excited states. Huse, Nandkishore, Oganesyan, Pal, Sondhi (2013)

Synergies



Prospective collaborations with experimentalists and theorists at
IQC and University of Waterloo

Collaborators

Oxford - Thorsten Wahl, Steven Simon

Boston University – Chris Laumann, Anushya Chandran

ICTP-Trieste – Antonello Scardicchio

Princeton- David Huse

Ph.D. students- Ian Mondragon-Shem (UIUC student → Yale Postdoc)
Chris Baldwin (University of Washington, Seattle)
Abishek Kulshreshtha (Oxford University)

Other work- Amir Yacoby, Bertrand Halperin (Harvard), David Hsieh (Caltech), Zahid Hasan, Shivaji Sondhi (Princeton), Taylor Hughes (UIUC), John Nichol (Rochester), Vadim Oganesyan (CUNY)

Summary

- Efficient representation of MBL systems using tensor networks.
- Construction of L-bits.
- L*-bits in d>1 and experiments.
- Open problems in MBL.