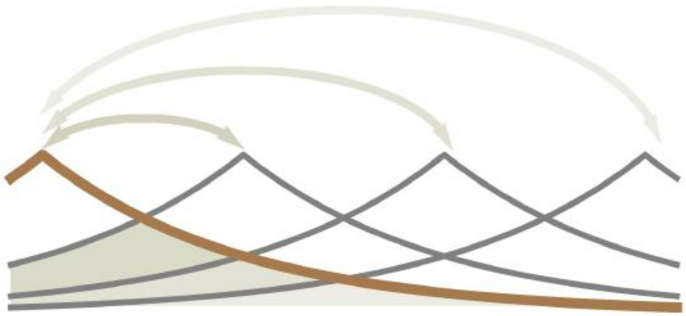
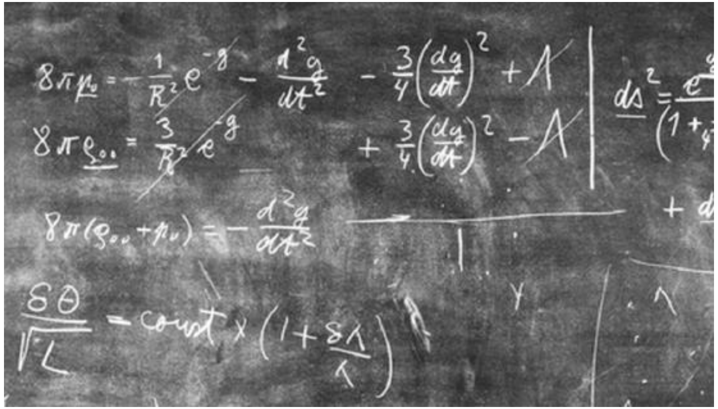
MANY-BODY LOCALIZATION



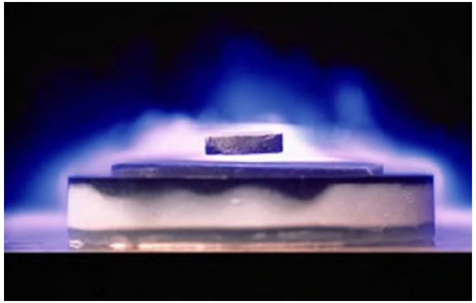
Julian Léonard
TU Wien

Jülich, 16th September 2024



THE CHALLENGE OF MANY-BODY QUANTUM SYSTEMS

Understand and design many-body systems
One of the biggest challenges
of 21st century quantum physics



Technological relevance
- High-Tc superconductivity
- Magnetism
- Novel quantum sensors
- Quantum technologies

Fundamental interest
- Parameter changes
- Benchmark theories
- Many “simple“ models not solvable
- Discern different effects

THE CHALLENGE OF MANY-BODY QUANTUM SYSTEMS

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed view here (after all I'm here and not at home) I'll admit that we don't understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally interconnected*, and therefore sort of think about cellular automata as an example (but I don't want to force it). But I do want something involved with the

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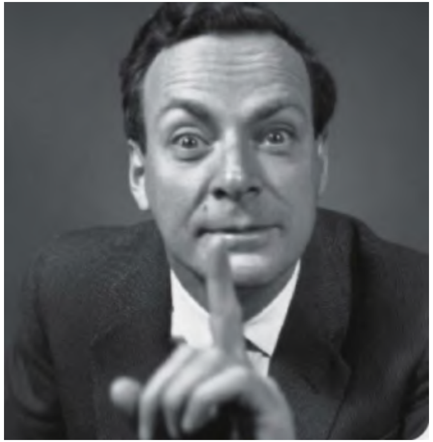


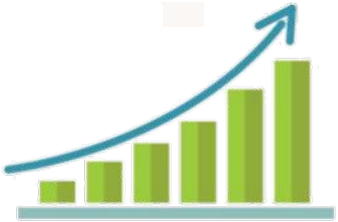
R. P. Feynman's vision

A quantum simulator to study the properties of another quantum system

WHICH PLATFORM?

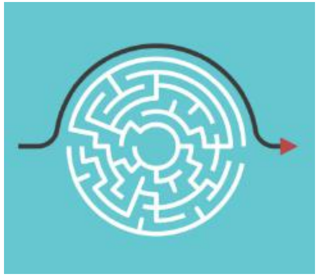
Building blocks

Identical, well understood



Scalable

Ability to connect many building blocks

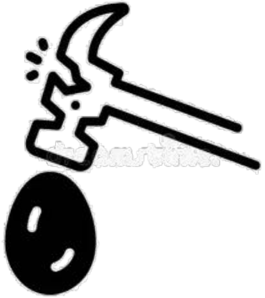


Simple

No behaviour beyond the computation

Controllable

Many control parameters, precise, independent



Robust

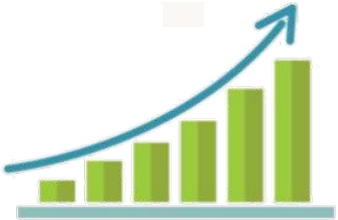
Reproducible results, insensitive to noise

ATOMS ARE IDEAL PLATFORM

Building blocks

Identical, well understood

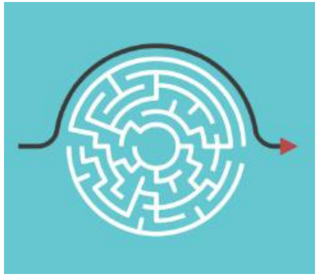
➔ exactly identical, atomic physics highly precise ($\sim 10^{-20}$)



Scalable

Ability to connect many building blocks

➔ possible to trap thousands of atoms



Simple

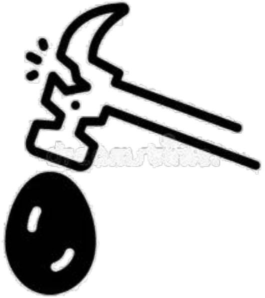
No behaviour beyond the computation

➔ isolated in vacuum

Controllable

Many control parameters, precise, independent

➔ optical control (motion, interactions,...)

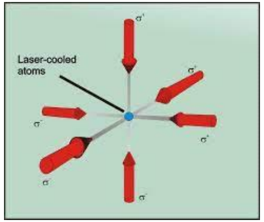


Robust

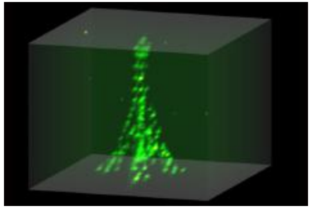
Reproducible results, insensitive to noise

➔ even at microscopic level

QUANTUM SIMULATION TOOLBOX

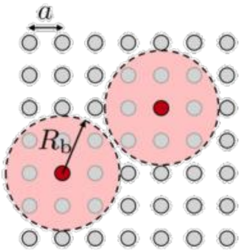


State preparation
Laser cooling
Optical pumping
…

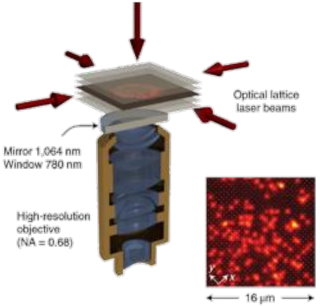


$$U_{dip} \propto -\alpha(\omega) I(\vec{r})$$

Potential control
Holographic beam shaping
Spin-dependent beams
Gauge fields



Interaction control
Feshbach resonance
Photon-mediated interactions
Dipoles, Rydberg,



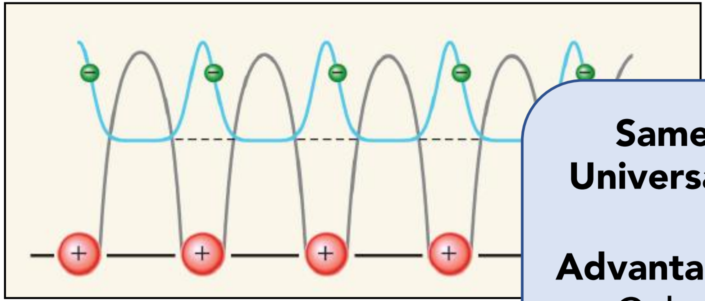
State readout
Microscopy
Fluorescence imaging
Dispersive readout…

Key advantages
- Excellent coherence properties
- Easy to create large numbers of neutral atoms
- Easy to manipulate with light

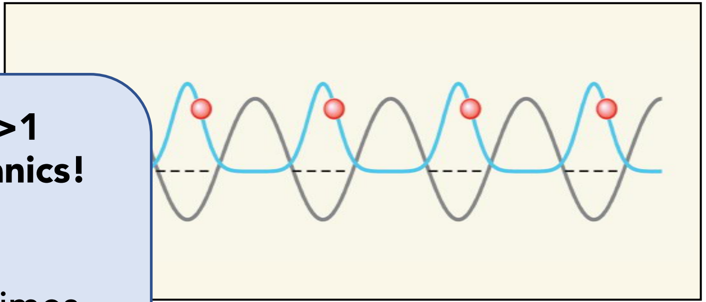
Key challenges
- Bare atoms interact weakly
- Hard to obtain individual control over large numbers of atoms

REALIZING ELECTRONIC SYSTEMS

Electrons in a crystal



Atoms in an optical potential
optical lattice



Same quantum regime: λ/d >1
Universality of quantum mechanics!

Advantages

- Coherent: >1000 tunneling times
- Scalable: >1000 sites
- Fermionic and bosonic statistics
- Tunable interaction, temperature, doping, …
- Microscopic control

Lattice constant: ~Å

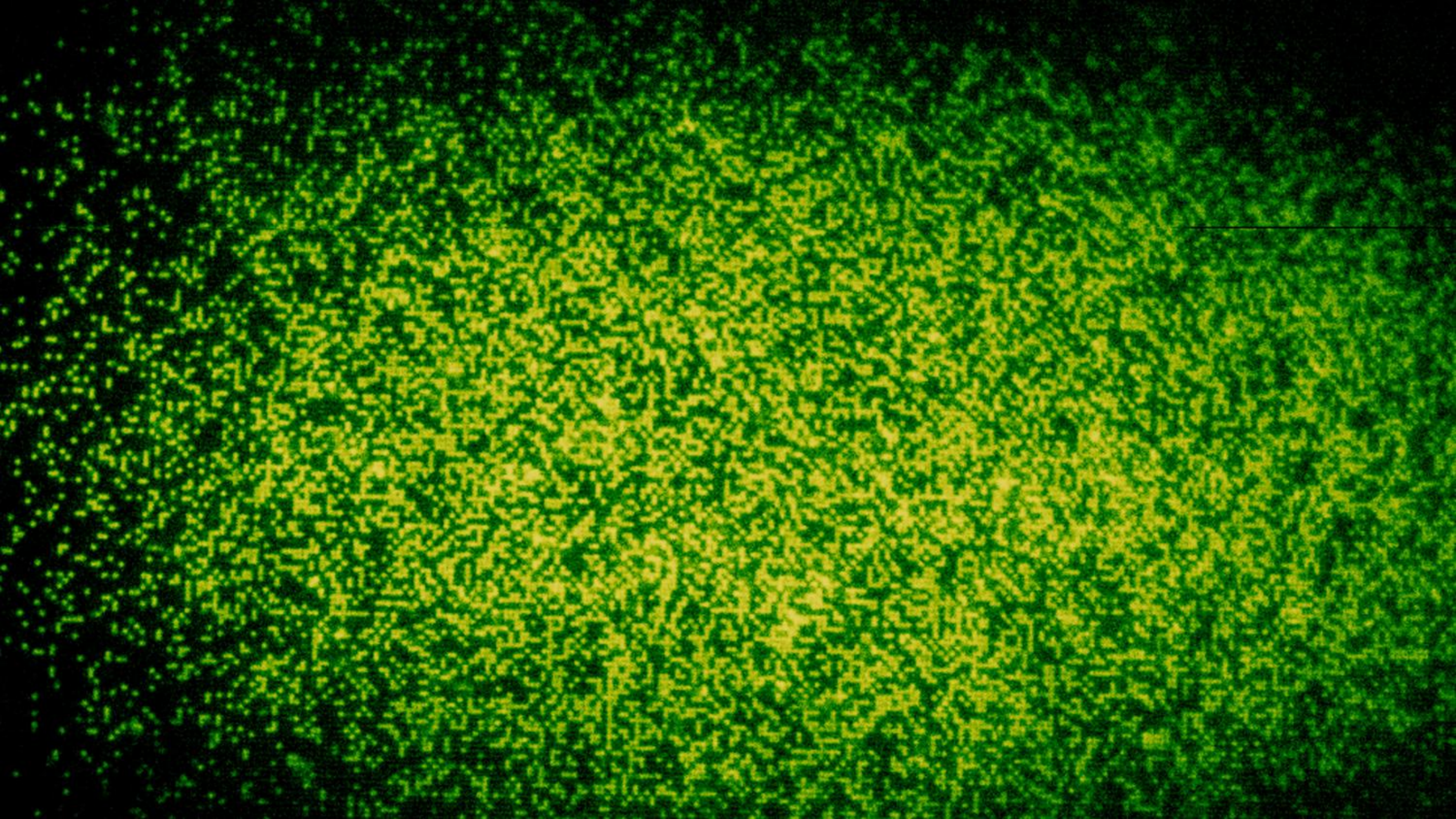
Densities: ~10^{25}/cm^3

Temperatures: ~K

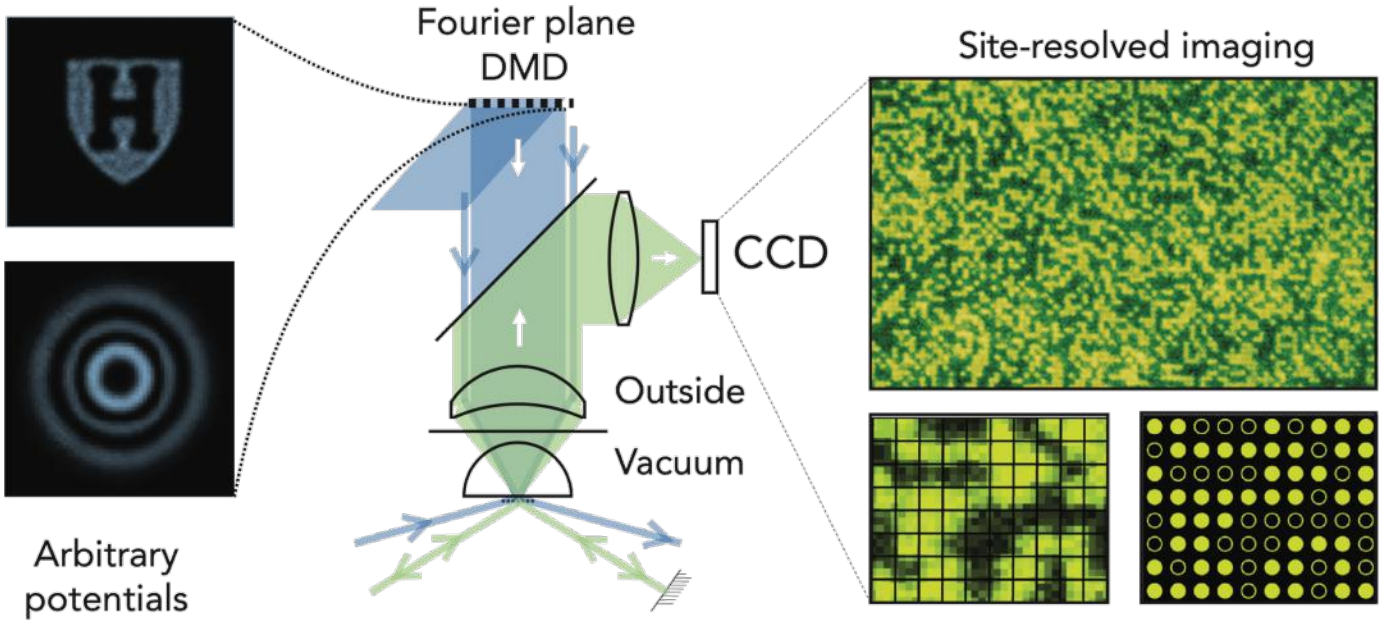
Lattice constant: ~μm

Densities: ~10^{14}/cm^3

Temperatures: ~pK



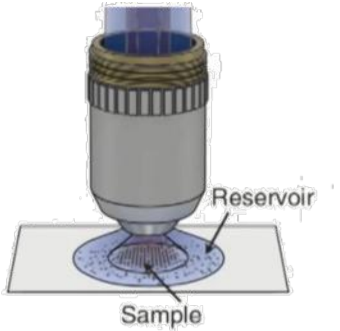
QUANTUM GAS MICROSCOPY

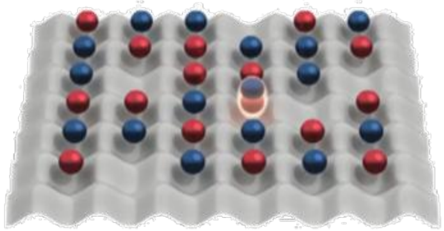


State preparation: Laser cooling, evaporative cooling
Potential: Optical standing waves
Interaction: Collisional on-site interactions
Readout: Fluorescence microscopy

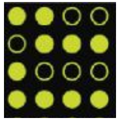
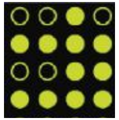
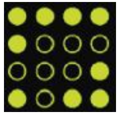
W. Bakr et al., *Science* **329**, 547 (2010)
J. Sherson et al., *Nature* **467**, 68 (2010)

MEASURING THE MANY-BODY STATE





Site-resolved occupation measurement

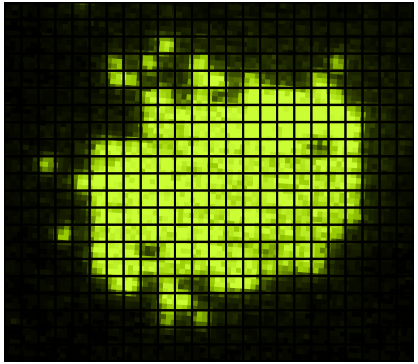
$|\psi\rangle = \Big|$  $\Big\rangle + \Big|$  $\Big\rangle + \Big|$  $\Big\rangle \cdots$

Extendable to other observables

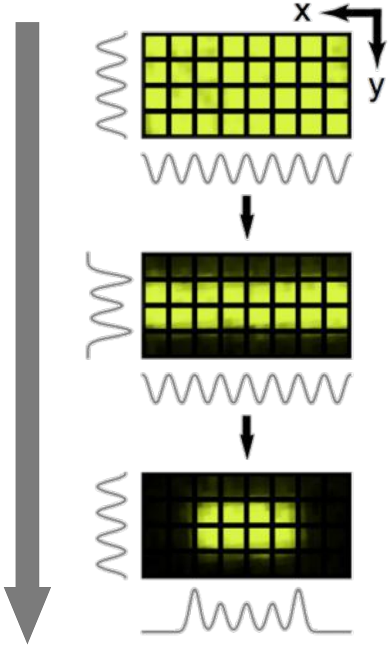
- All density correlations between sites/particles
- Local currents
- Entanglement entropy
- Quantum state purity
- …

PURE QUANTUM STATES

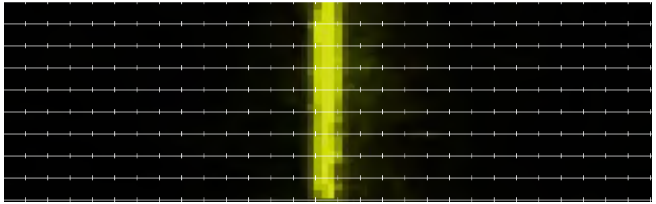
low-entropy
Mott insulator



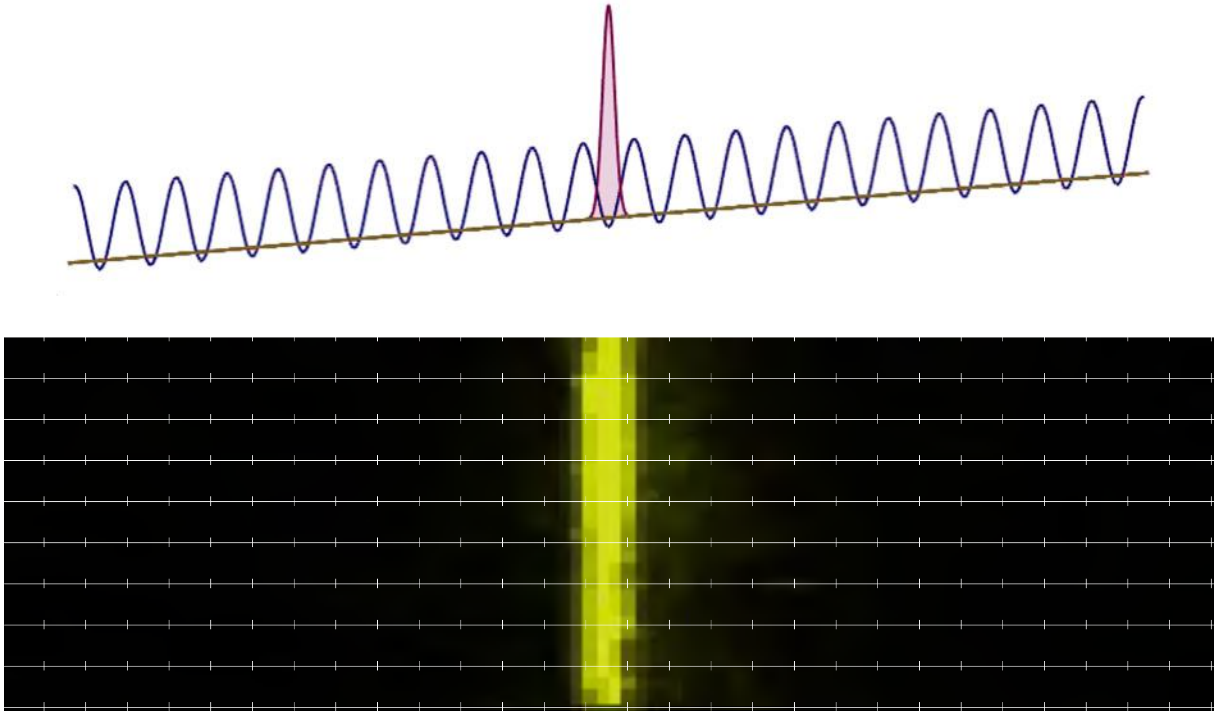
Local potentials

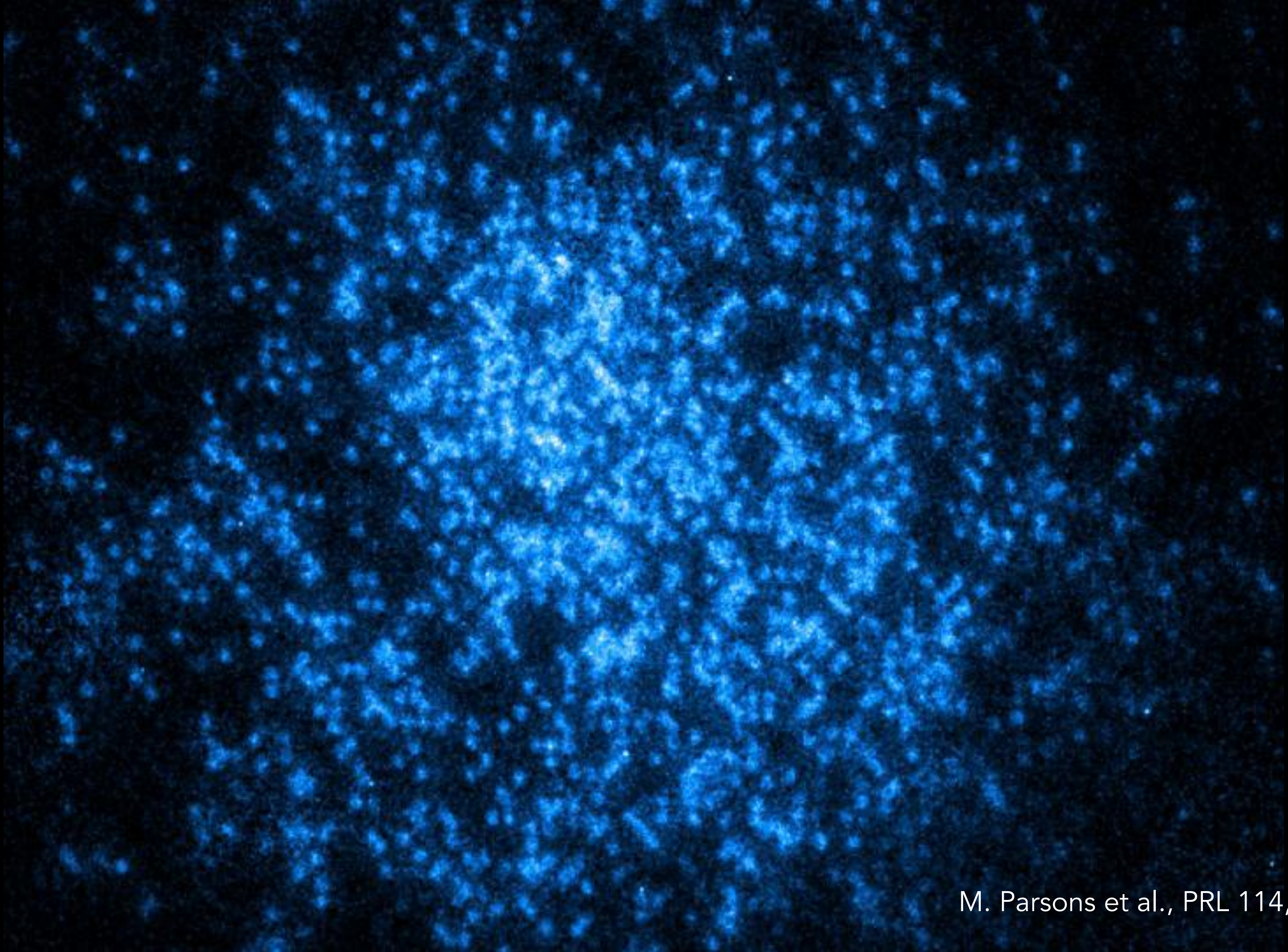


high fidelity
state preparation

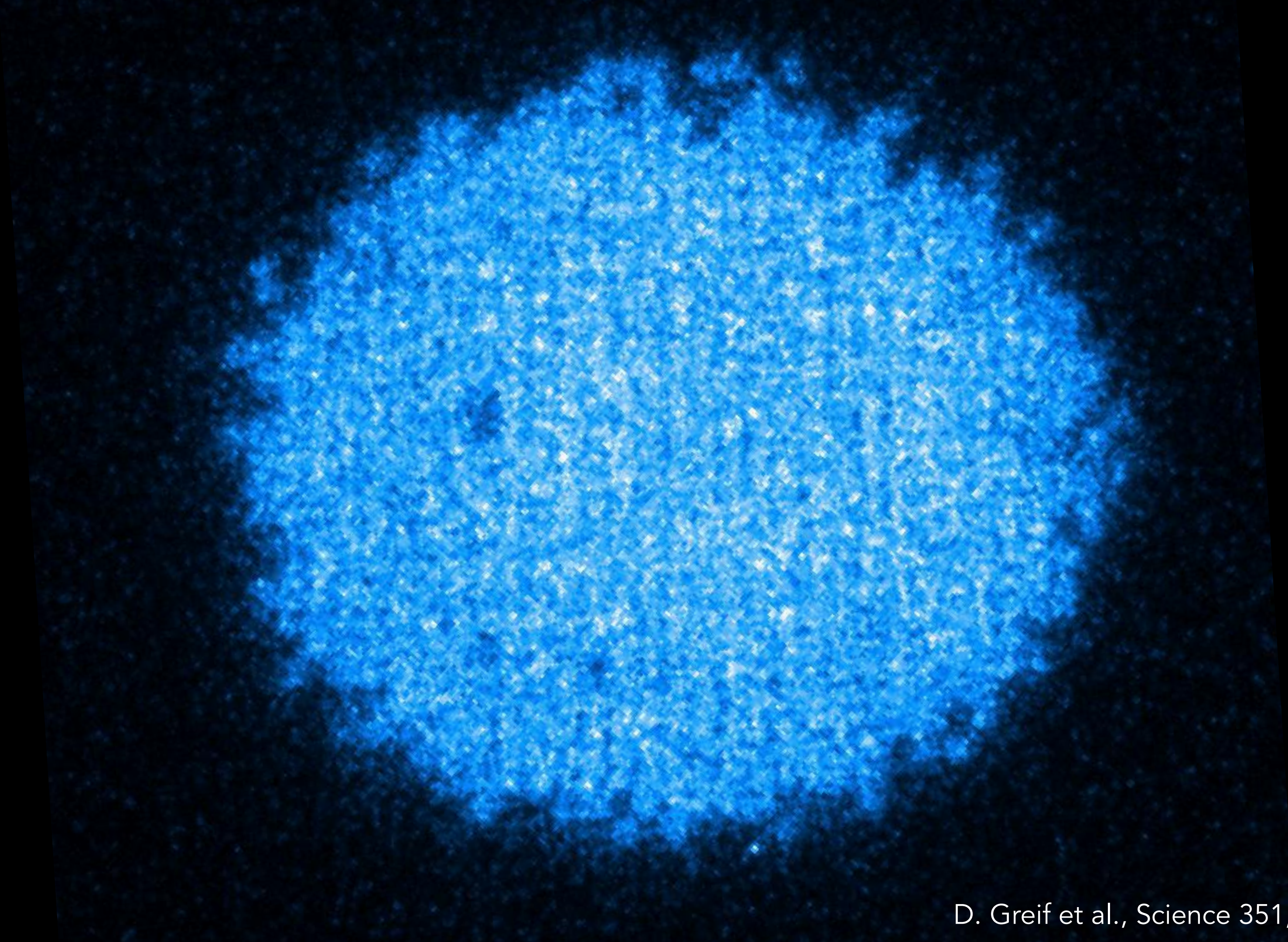


SITE-RESOLVED ADRESSING

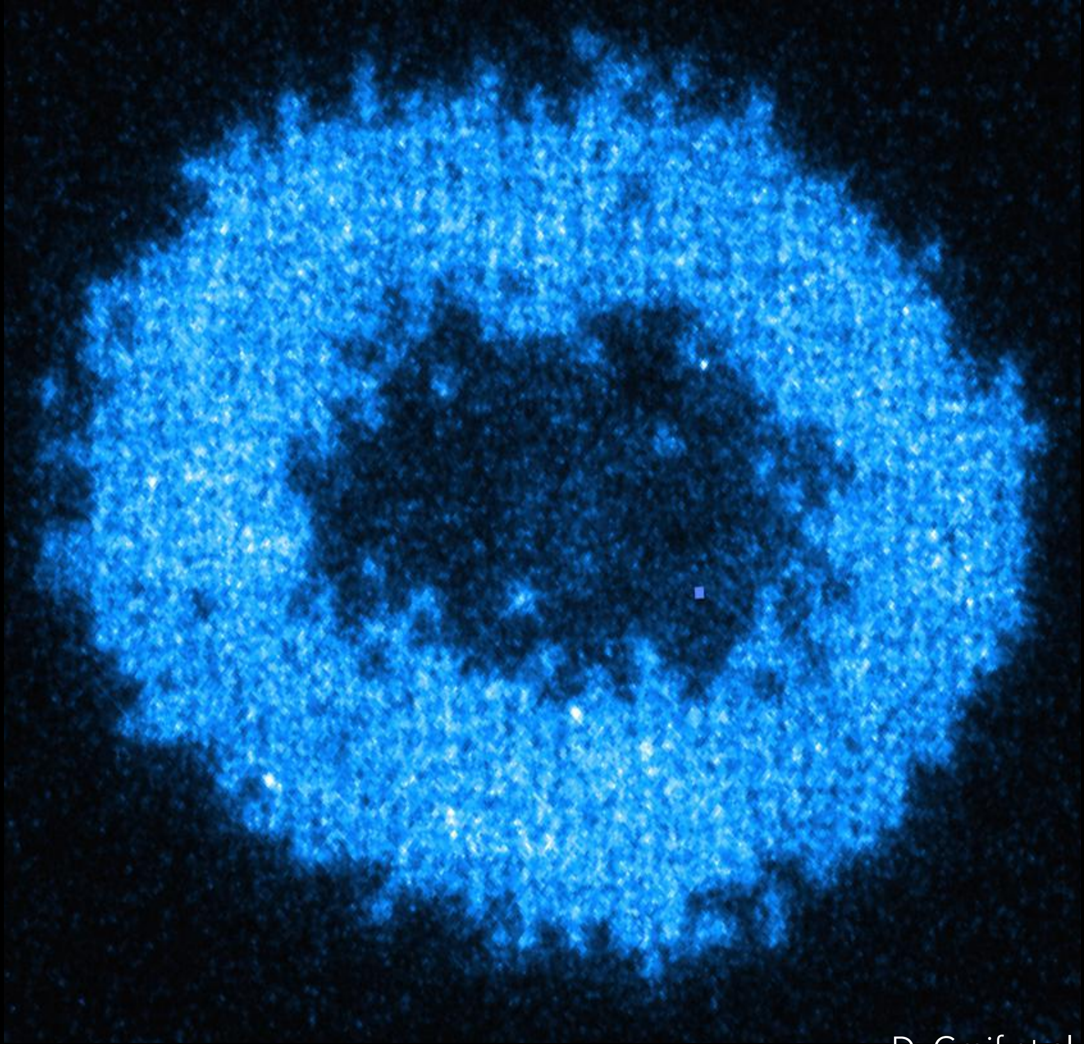




M. Parsons et al., PRL 114, 213002 (2015)

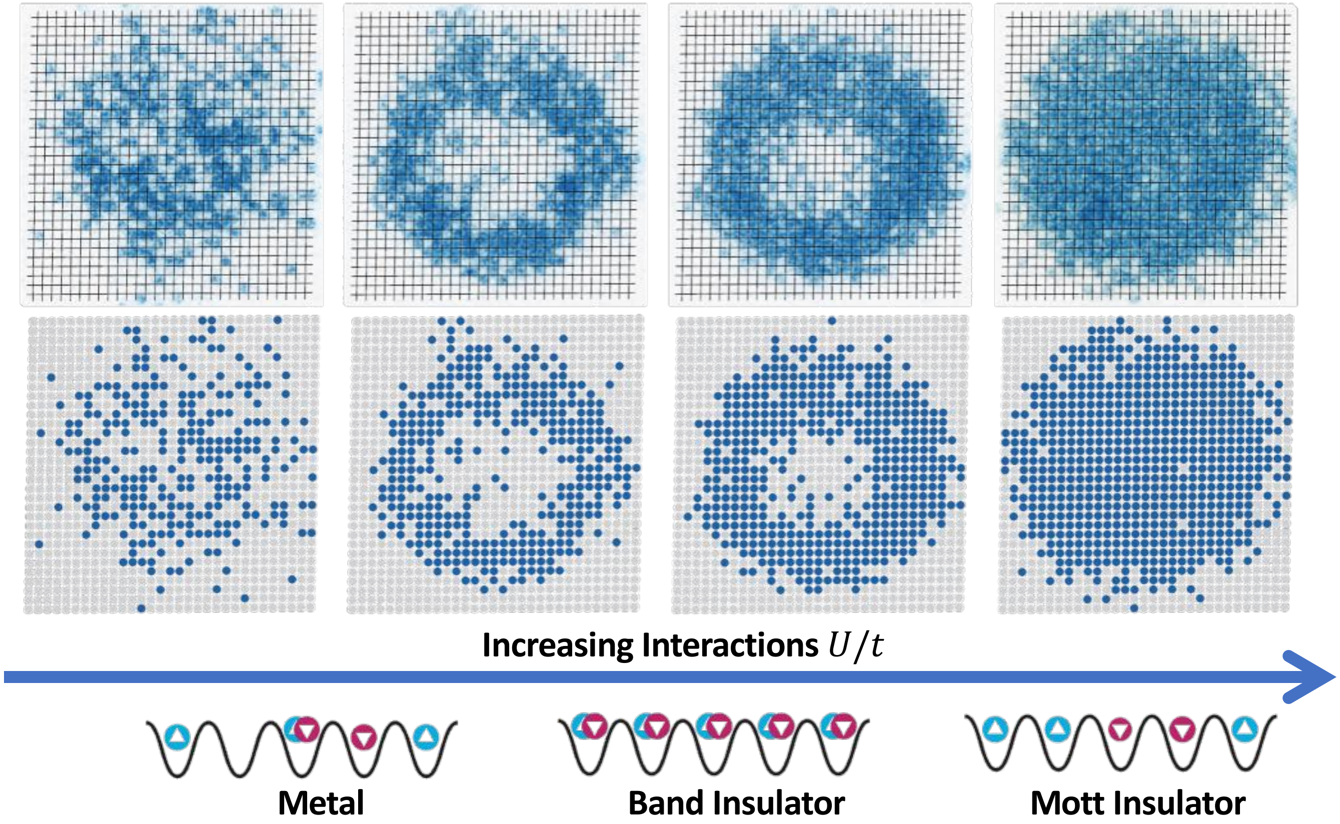


D. Greif et al., Science 351, 953 (2016)



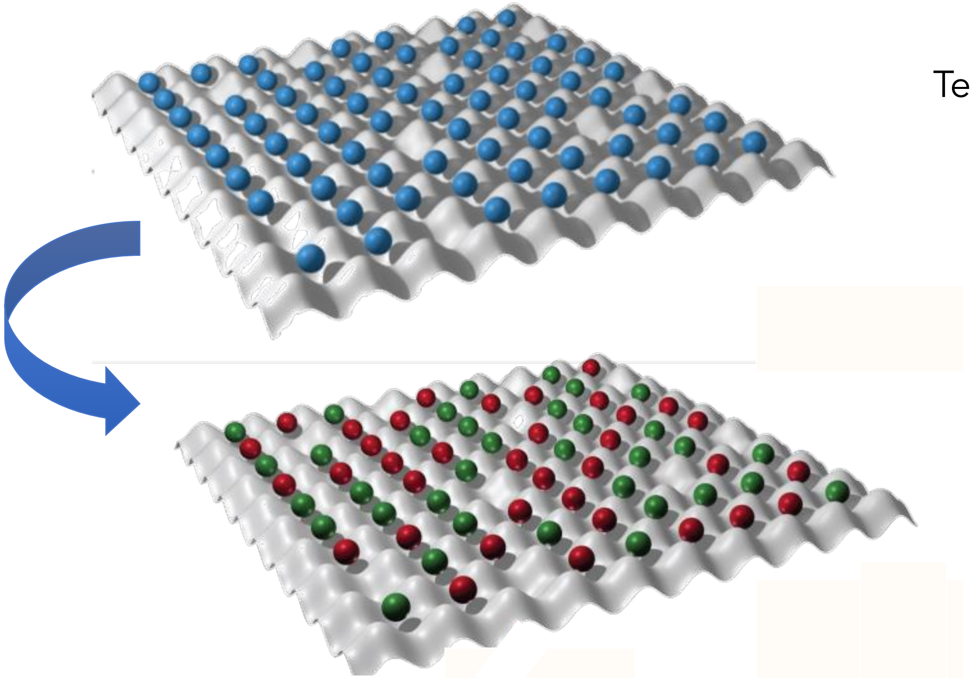
D. Greif et al., Science 351, 953 (2016)

FERMIONIC HUBBARD MODEL

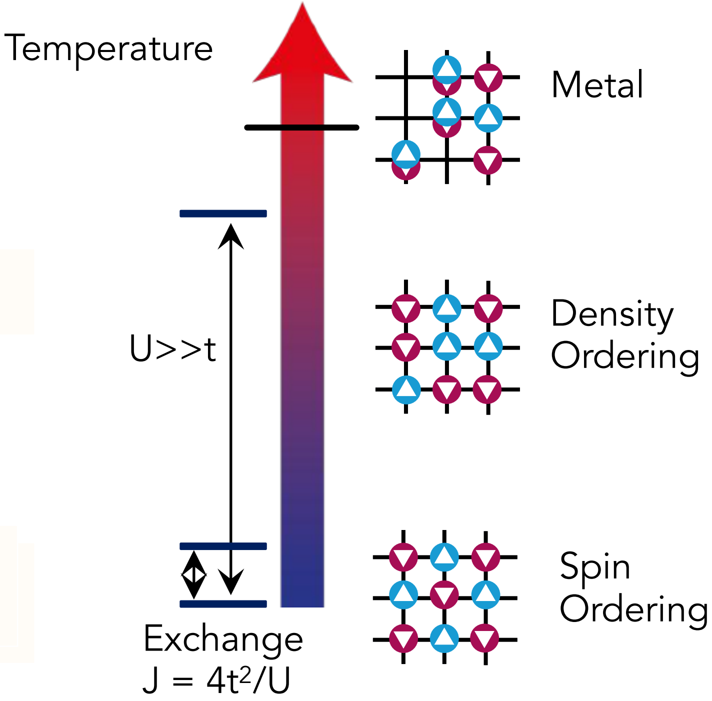


D. Greif et al., Science 351, 953 (2016)

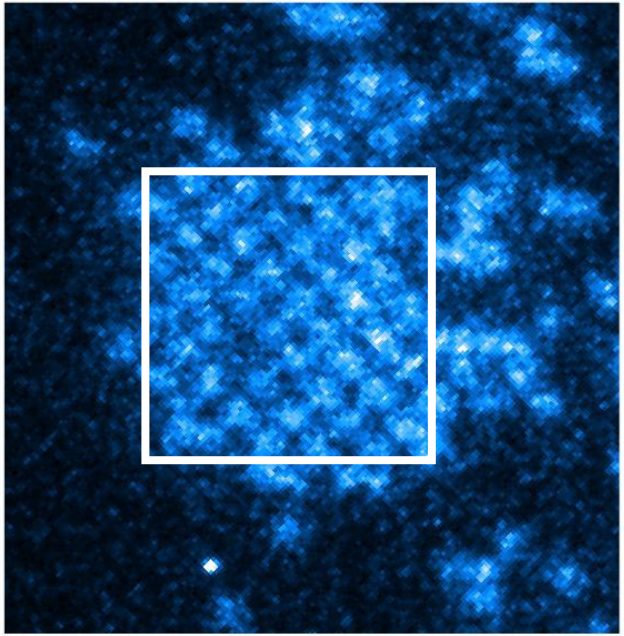
QUANTUM MAGNETISM



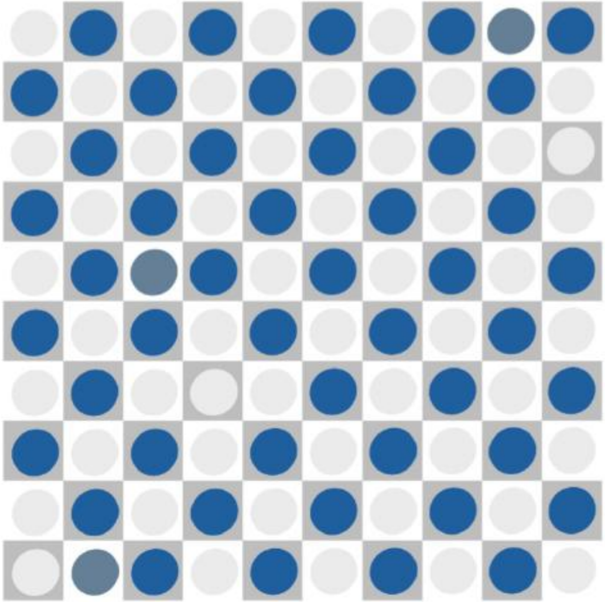
$$\hat{H} = \underbrace{-t \sum_{\langle i,j\rangle,\sigma} \left(c^{\dagger}_{i,\sigma} c_{j,\sigma} + \text{H.c.}\right)}_{\text{tunneling}} + \underbrace{U \sum_{i} \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}}_{\text{On-site interaction}}$$



ANTIFERROMAGNETIC ORDER



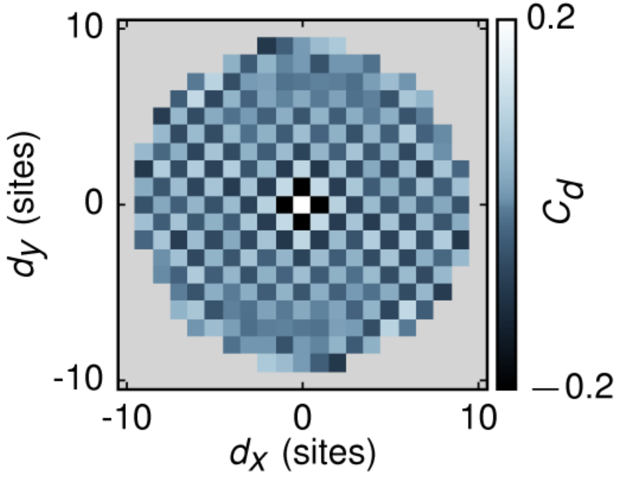
$|\uparrow\rangle$ only



Temperature: T/t = 0.25
T/J = 0.5

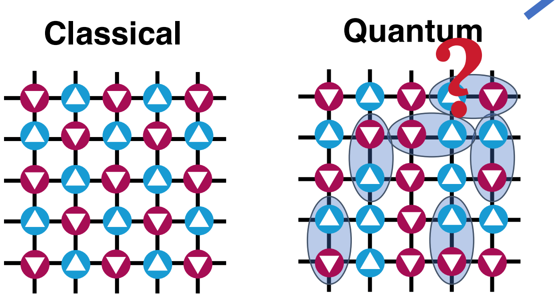
A. Mazurenko et al., Nature 545, 462 (2017)

ANTIFERROMAGNETIC ORDER



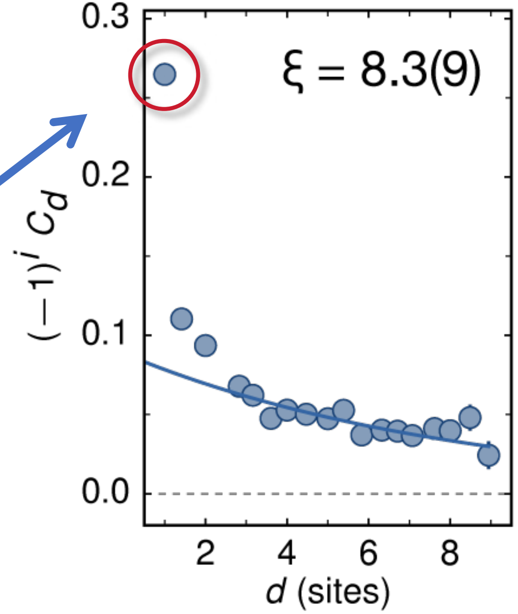
2D: exponential decay of correlations expected

$$\langle S_i^z S_{i+d}^z \rangle \propto \exp\left(-d/\xi\right)$$

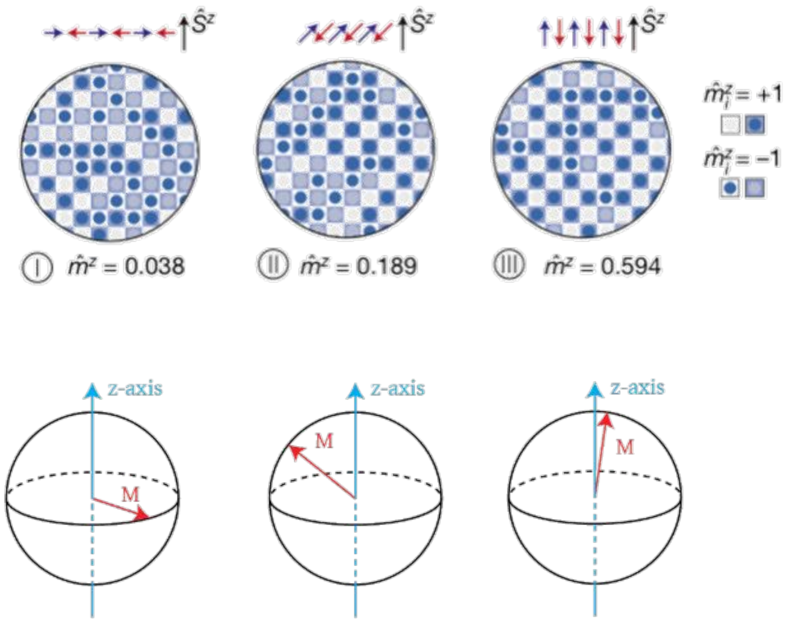


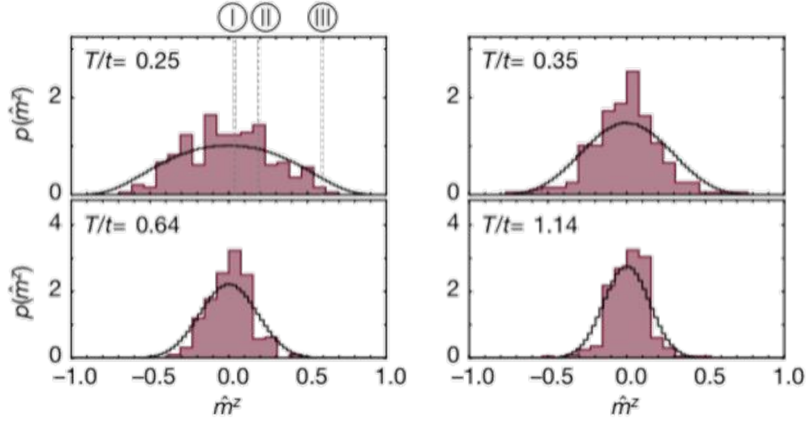
$M_{\mathrm{clas}}(T \to 0) = 1$

$M_{\mathrm{qm}}(T \to 0) = 0.6$



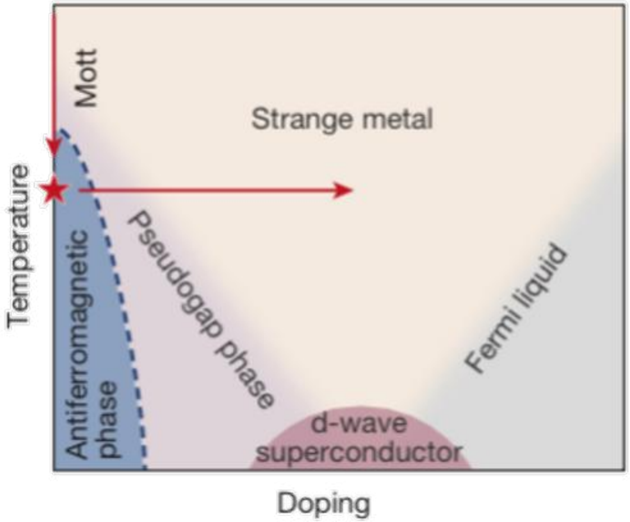
QUANTUM ANTIFERROMAGNET

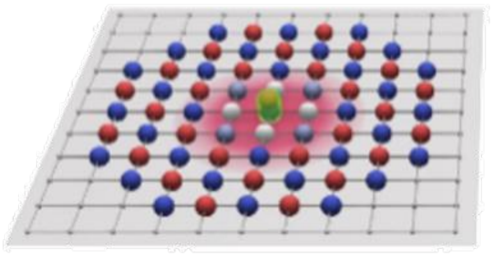


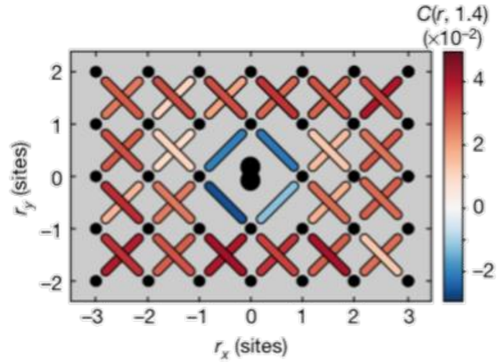


Greiner group (Harvard)
A. Mazurenko et al., Nature 545, 462 (2017)

DOPING AN ANTIFERROMAGNETIC







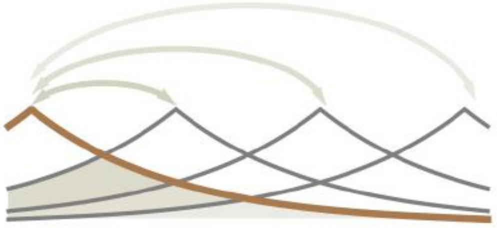
No numerics possible:
Many open questions
about the phase diagram

Controlled doping

➔ Gain microscopic understanding of high-Tc superconductivity

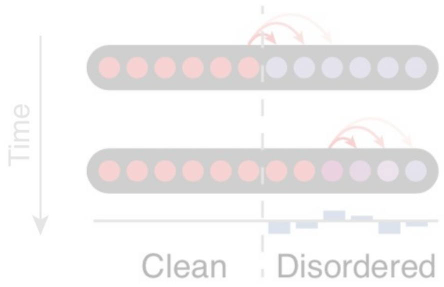
Bloch group (MPQ Munich)
J. Koepsell et al., Nature 572, 358 (2019)

OUTLINE



Localization and entanglement

MBL "transition"



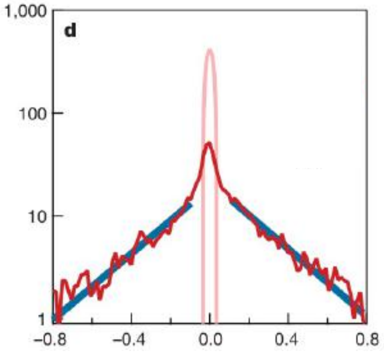
Quantum avalanches

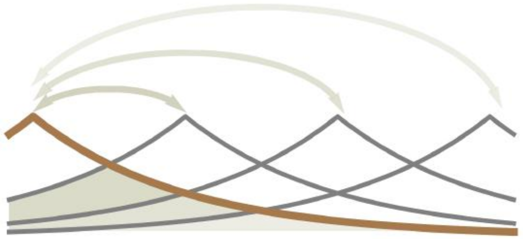
MANY-BODY LOCALIZATION

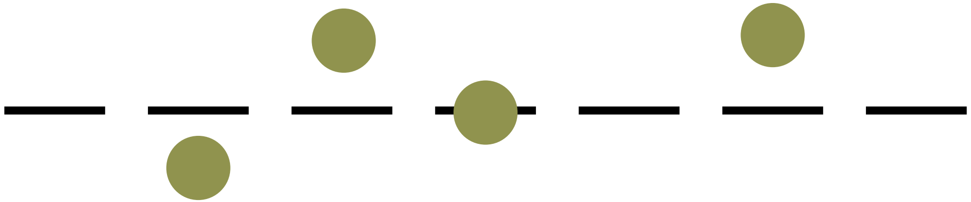
Disorder:
Anderson localization

+

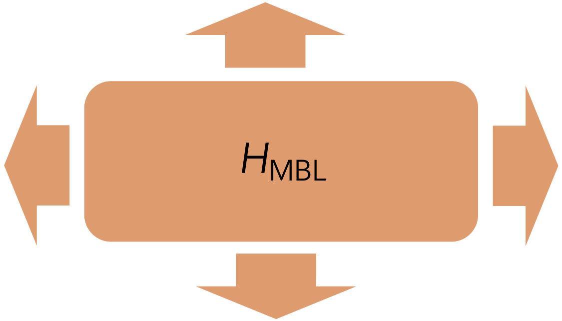
Interactions:
Many-body localization



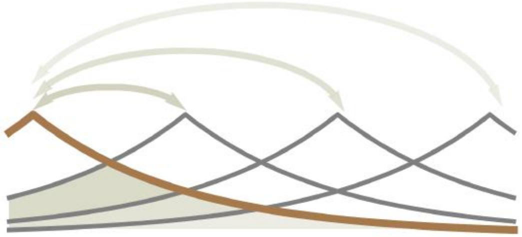




TWO COMPETING EXPONENTIALS



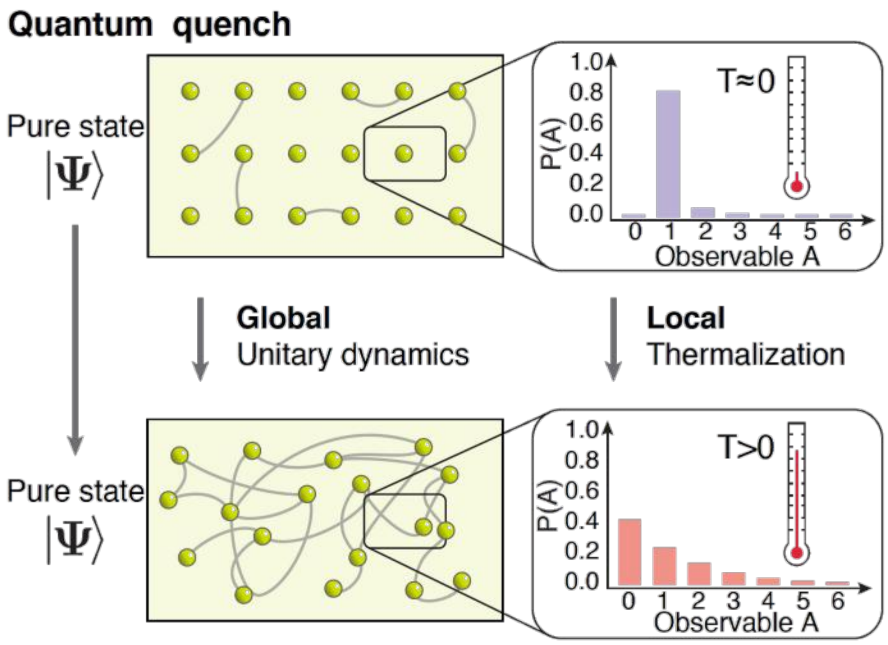
Hilbert space
grows exponentially
➔ thermalization,
ergodicity breaking



Localization
Integrals of motion,
reduces number of
degrees of freedom

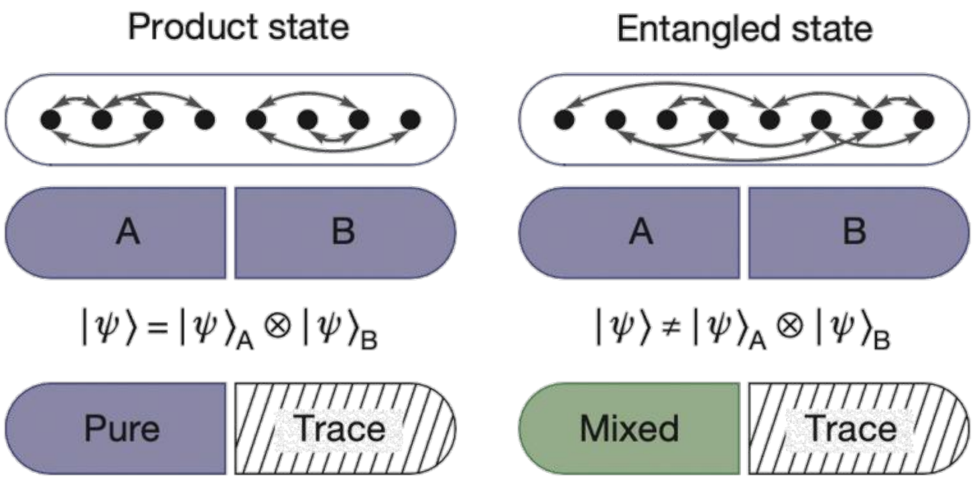
Which one wins?
Basko, Aleiner, Altshuler 2006: localization wins
Also Anderson 1958, Imbrie 2014

QUANTUM THERMALIZATION



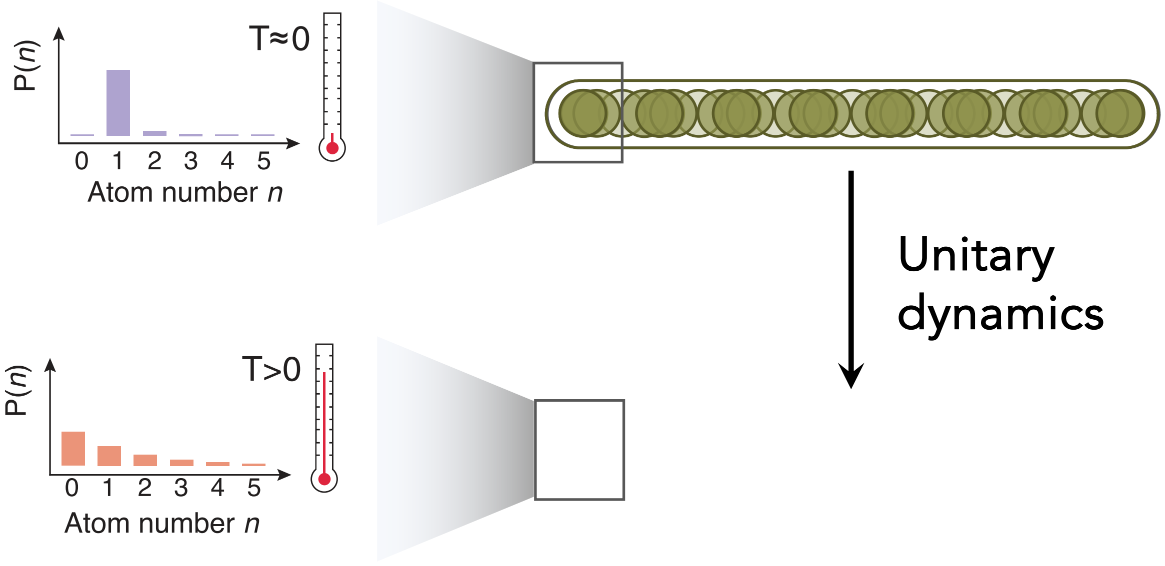
- Local quantum correlations get lost in global d.o.f
- Classical hydrodynamics of remaining slow modes
- Entanglement entropy and classical entropy become indistinguishable

MANY-BODY ENTANGLEMENT



Entanglement:
local **purity** of the quantum state

QUANTUM THERMALIZATION

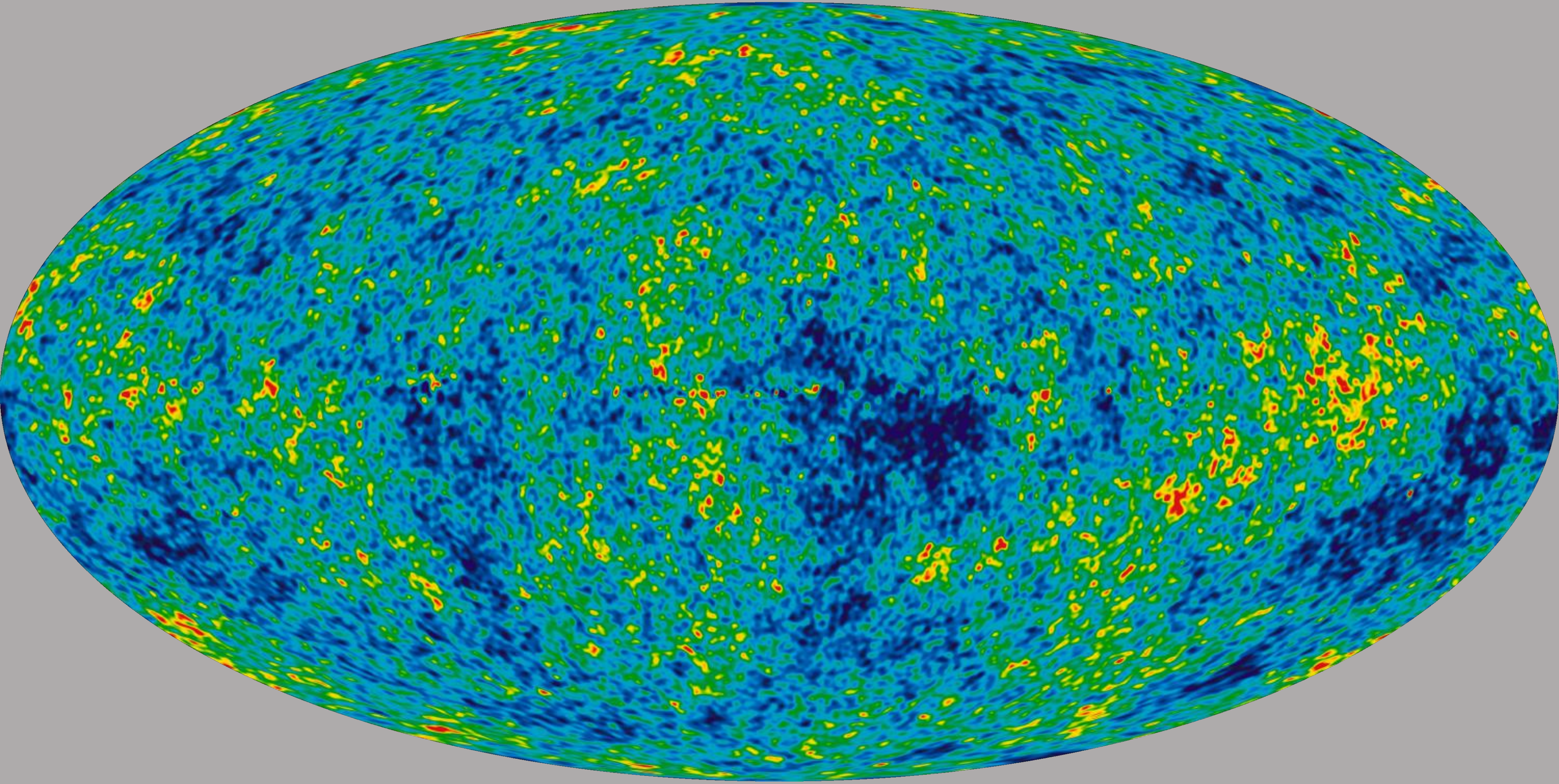


Globally pure
Locally pure

Globally pure
Locally thermal
(ETH)

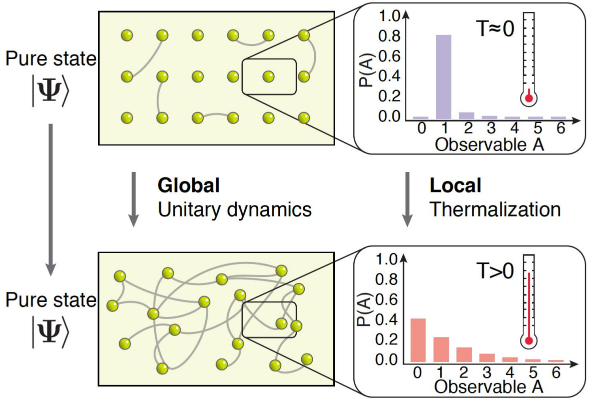
From local observables it is impossible to tell if the global state is pure.

A. Kaufman et al., *Science* 353, 794 (2016)
also: Schmiedmayer, Martinez, Schätz…



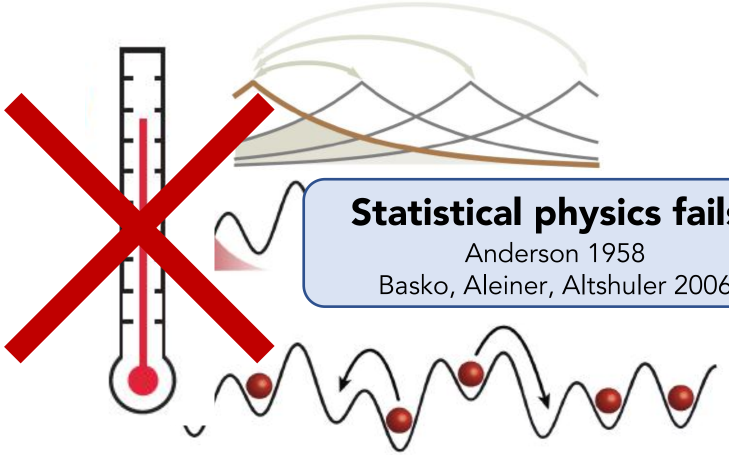
THERMALIZATION VS LOCALIZATION

Thermalization



Local quantum correlations get lost in global d.o.f
➔ Classical hydrodynamics of remaining slow modes

Many-body localization

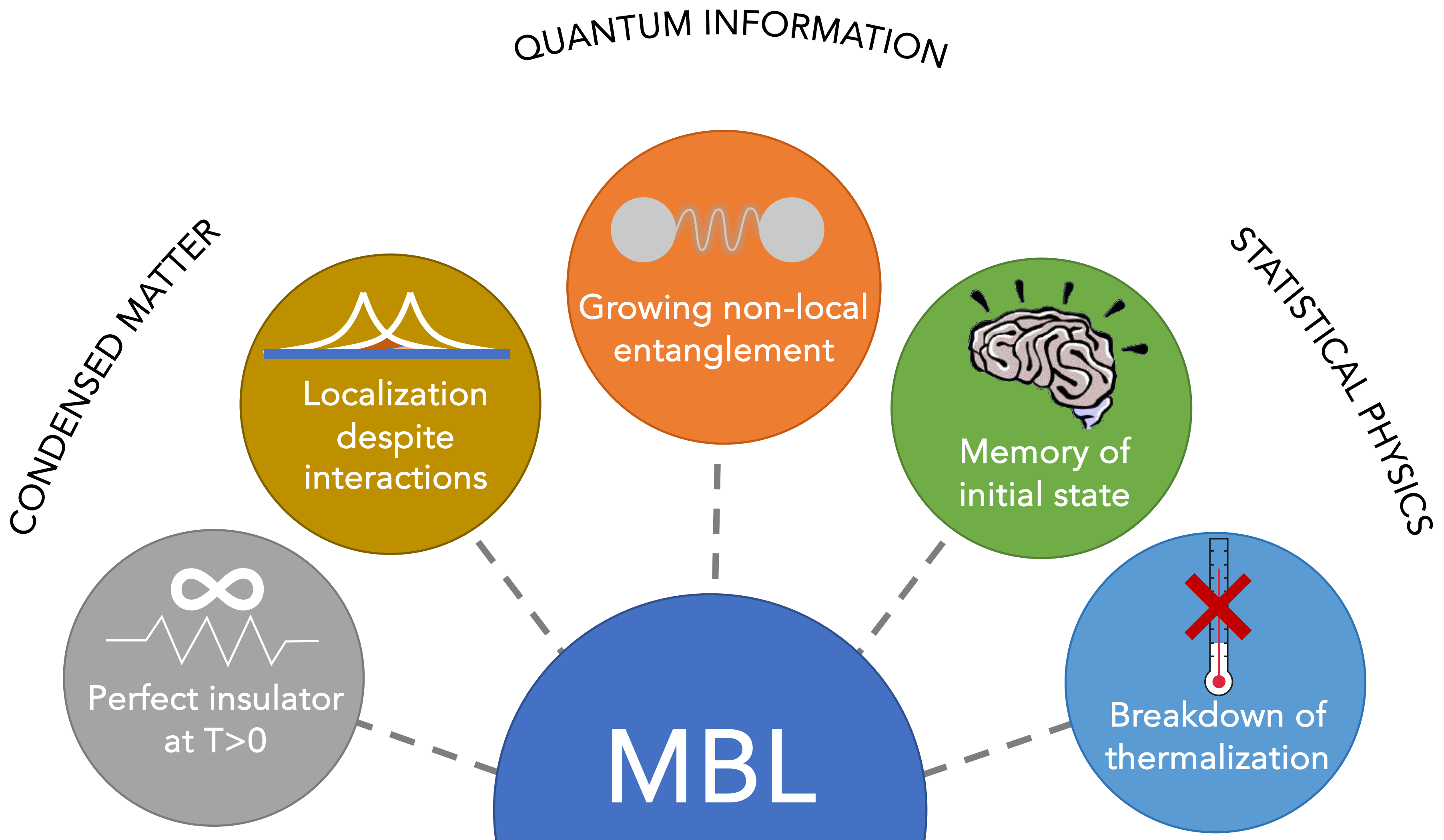


Statistical physics fails!
Anderson 1958
Basko, Aleiner, Altshuler 2006

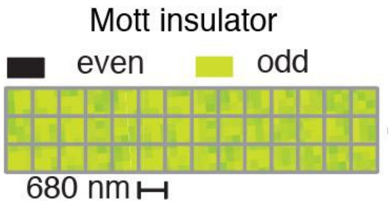
Local quantum information persists
➔ Generally full quantum description required

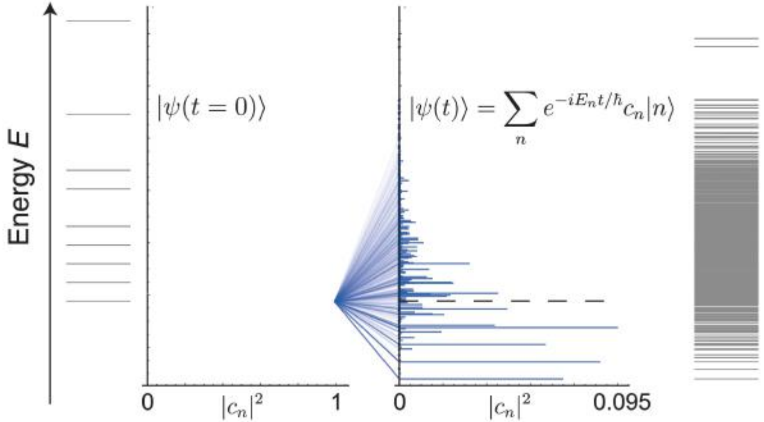
Interface between classical and quantum worlds

Disorder

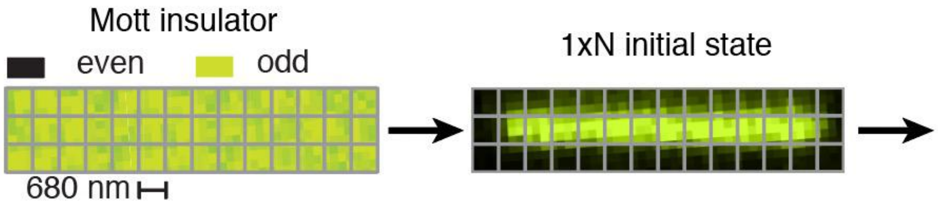

QUANTUM INFORMATION
CONDENSED MATTER
STATISTICAL PHYSICS
Localization despite interactions
Growing non-local entanglement
Memory of initial state
Perfect insulator at T>0
Breakdown of thermalization
MBL

PROTOCOL


Mott insulator
even
odd
680 nm

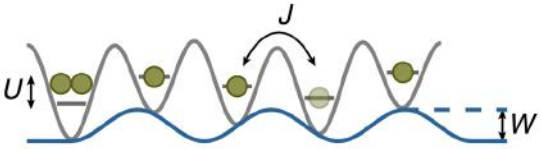

Energy E
$|\psi(t=0)\rangle$
$|\psi(t)\rangle = \sum_n e^{-iE_n t/\hbar} c_n |n\rangle$
0
$|c_n|^2$
1
0
$|c_n|^2$
0.095

PROTOCOL



Unitary evolution

$$|\Psi\rangle = e^{i\hat{\mathcal{H}}t/\hbar}|\Psi_0\rangle$$



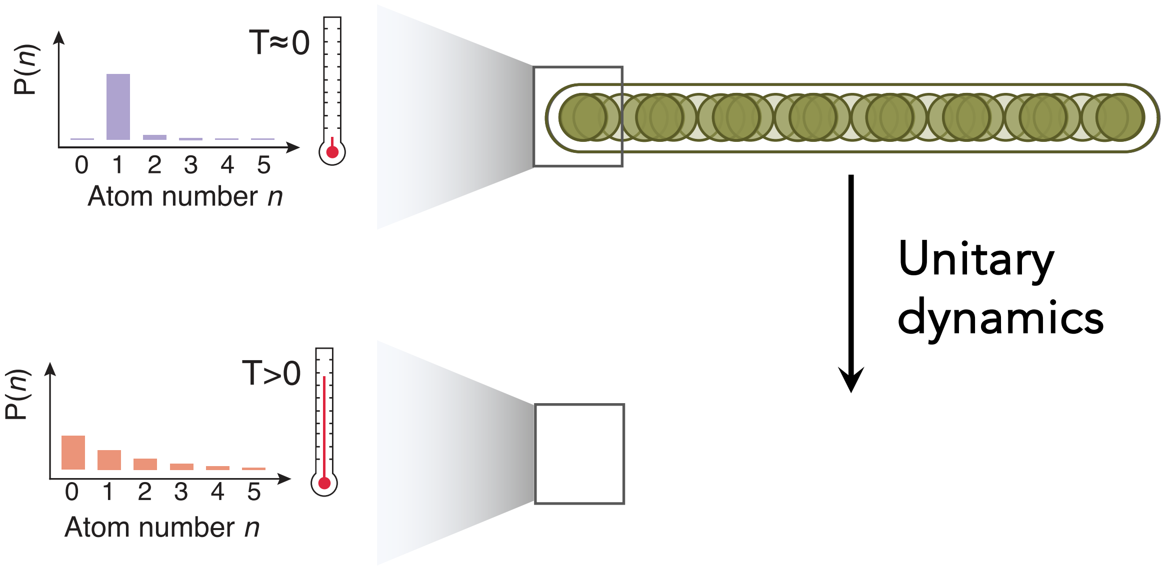
Bose-Hubbard model
programmable site offsets

$$\hat{\mathcal{H}} = -J\sum_i \left(\hat{a}_i^\dagger \hat{a}_{i+1} + h.c.\right) + \frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + W\sum_{i\in L_{\mathrm{dis}}} h_i \hat{n}_i$$

U = 3J

h_i quasi-periodic with golden ratio 1.618

QUANTUM THERMALIZATION



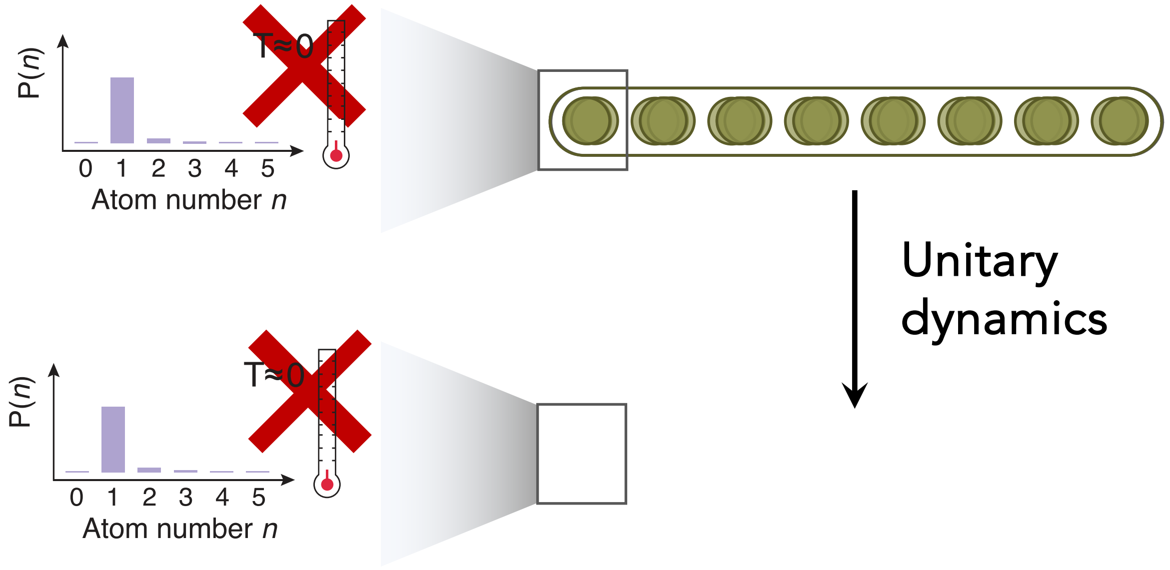
Globally pure
Locally pure

Unitary dynamics

Globally pure
Locally thermal
(ETH)

A. Kaufman et al., *Science* 353, 794 (2016)
also: Schmiedmayer, Martinez, Schätz…

BREAKDOWN OF THERMALIZATION



No thermalization!

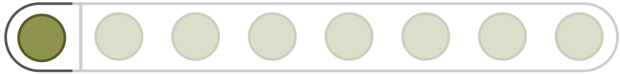
QUANTUM THERMALIZATION

Product state (locally pure)

$$|\Psi\rangle = |\Psi_A\rangle \otimes |\Psi_B\rangle$$

Trace B

Subsystem A



Subsystem B

Diagonal reduced density matrix:

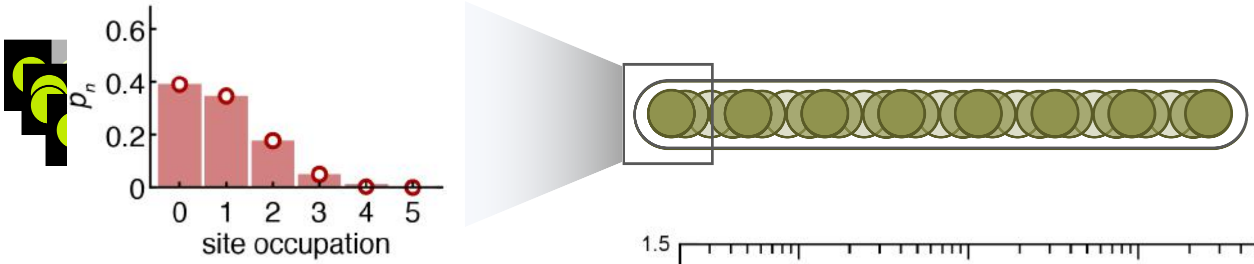
$$\hat{\rho}_A = \sum_n p_n |n\rangle \langle n|$$

Entangled state (locally mixed)

$$|\Psi\rangle \neq |\Psi_A\rangle \otimes |\Psi_B\rangle$$

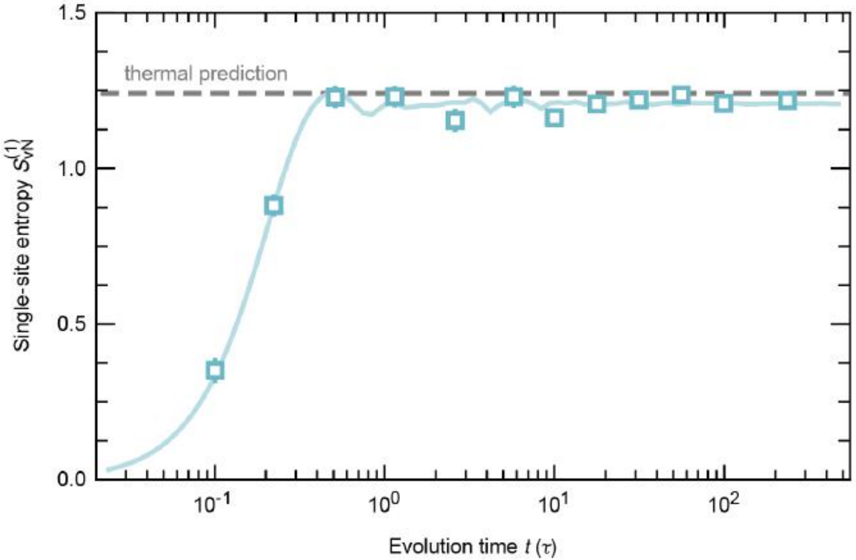
...

QUANTUM THERMALIZATION



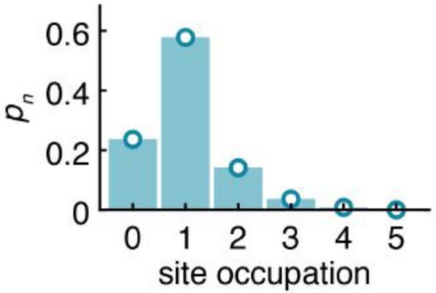
On-site von-Neumann entropy:

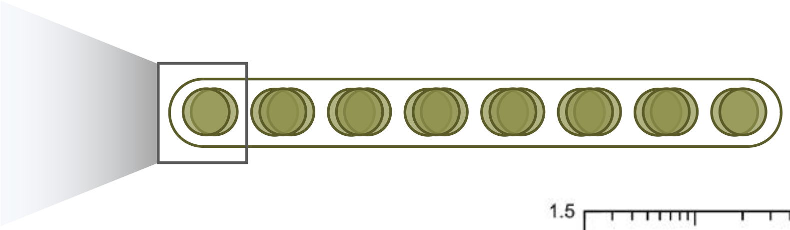
$$S_{\rm vN}^{(1)} = -\sum_n p_n \log p_n$$

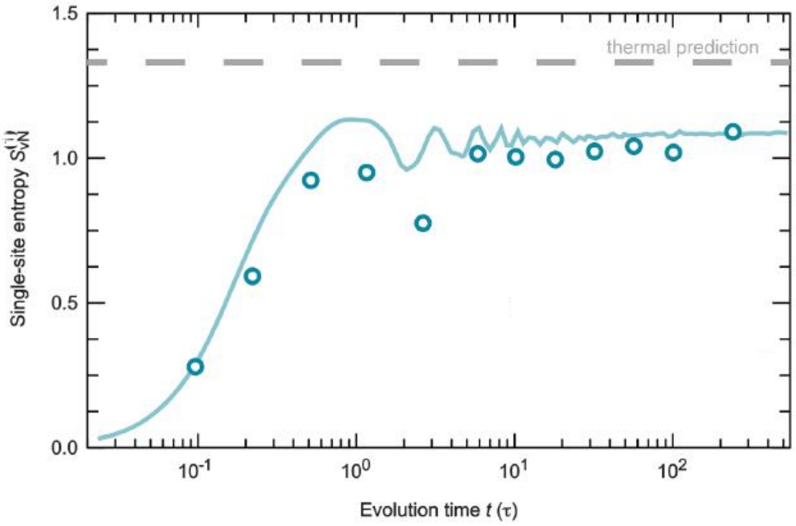


A. Lukin et al., Science 364, 6437 (2019)

BREAKDOWN OF THERMALIZATION





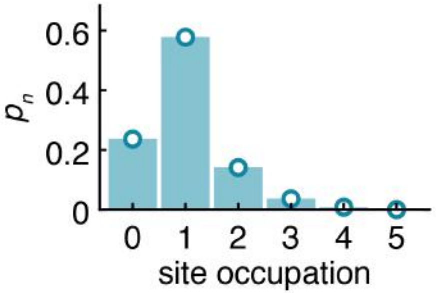


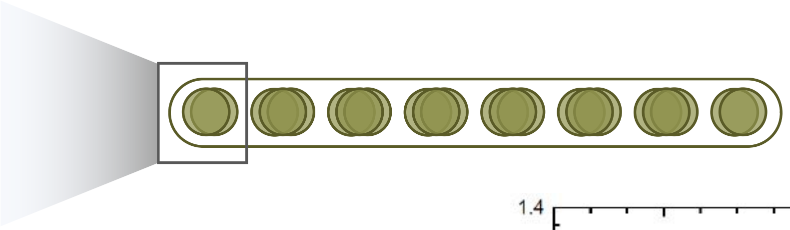
On-site von-Neumann entropy:

$$S_{\mathrm{vN}}^{(1)} = -\sum_n p_n \log p_n$$

A. Lukin et al., Science 364, 6437 (2019)

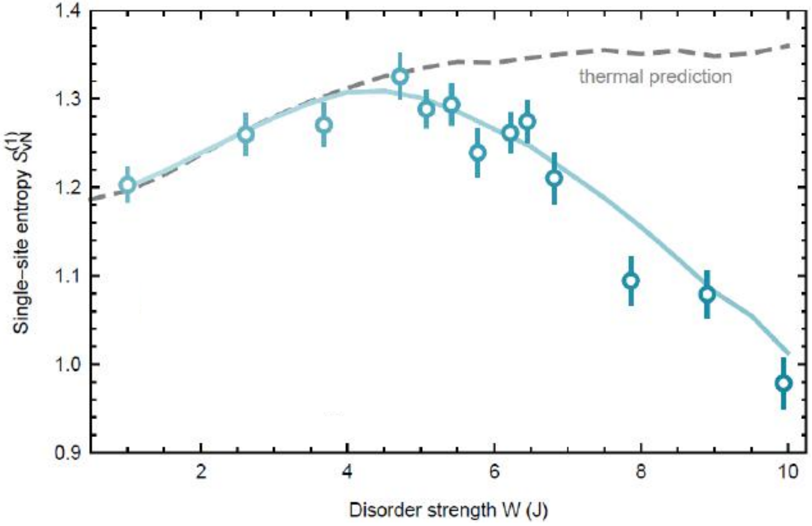
BREAKDOWN OF THERMALIZATION





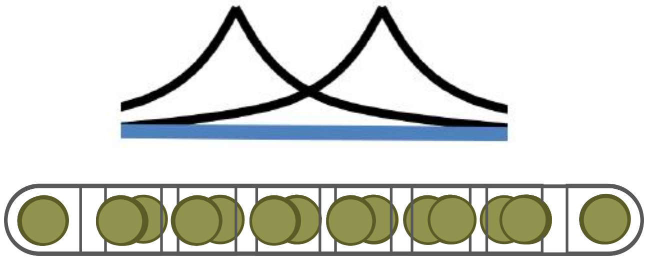
On-site von-Neumann entropy:

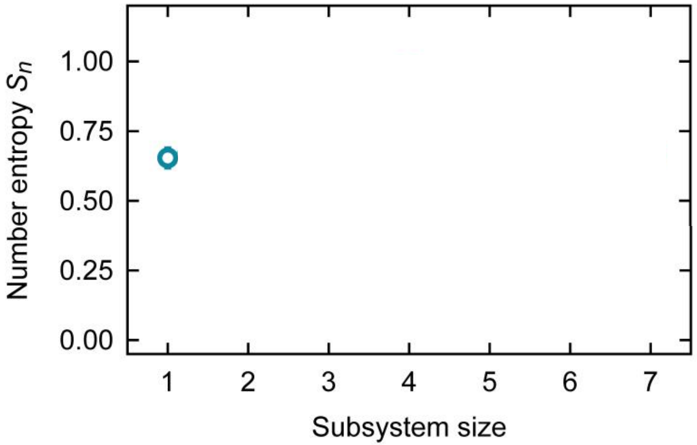
$$S_{\mathrm{vN}}^{(1)} = -\sum_n p_n \log p_n$$



A. Lukin et al., Science 364, 6437 (2019)

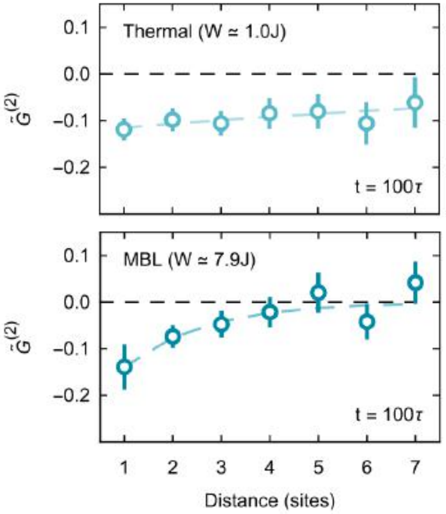
ABSENCE OF TRANSPORT

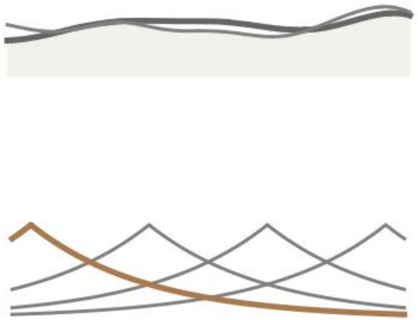


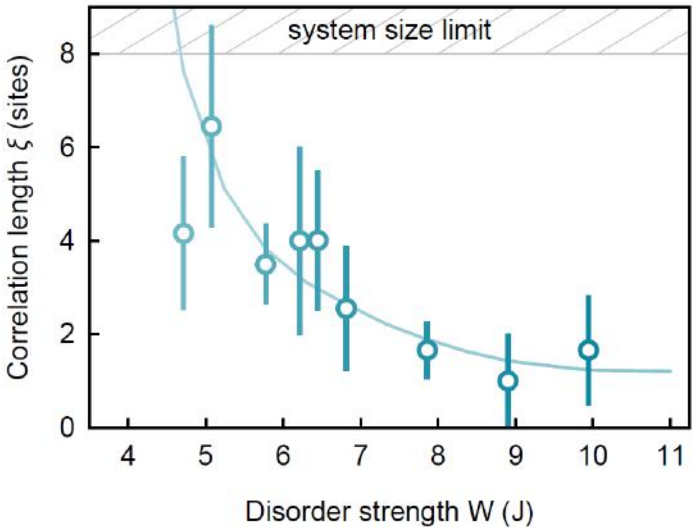


Independent of subsystem size
➔ localized wavefunctions

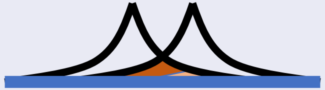
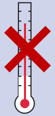
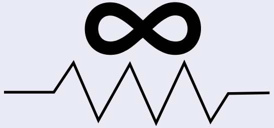
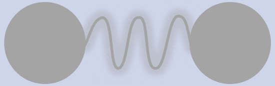
LOCALIZATION



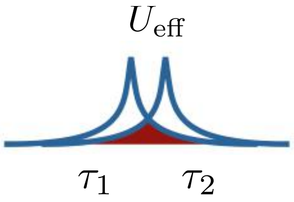




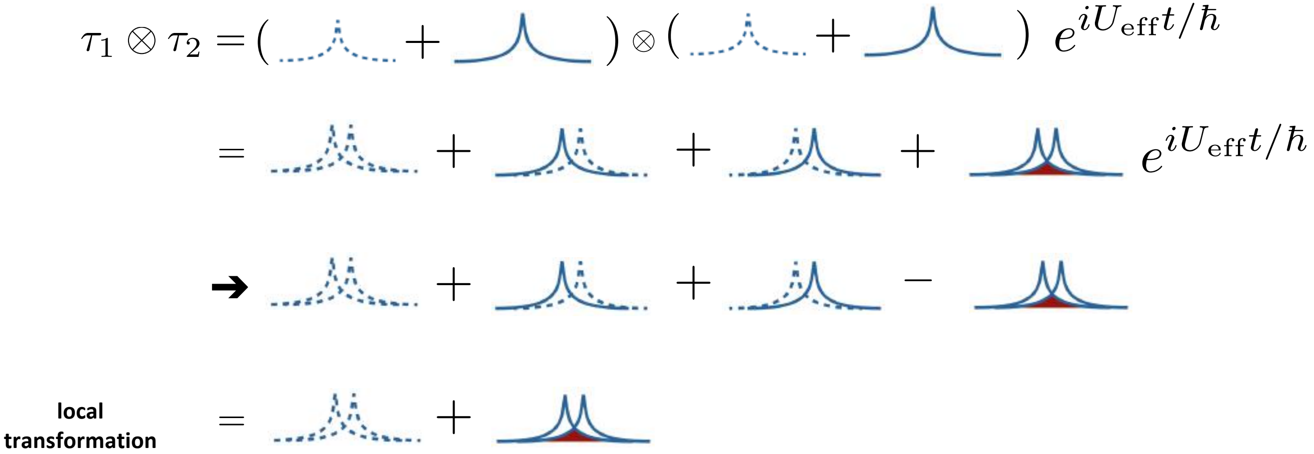
SIGNATURES OF MBL

	Thermal	Anderson (*U=0*)	MBL (*U>0*)
	✗	✓	✓
	✗	✓	✓
	✗	✓	✓
	✗	✓	✓
	✗	✗	✓

LONG-RANGE ENTANGLEMENT



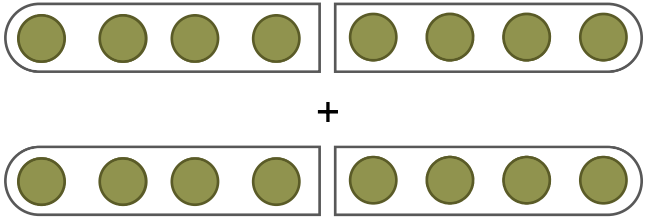
Slow growth of entanglement:



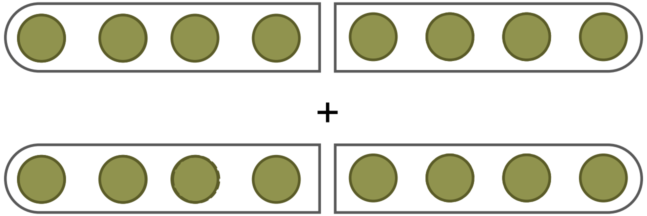
➔ Entanglement from eigenstate superposition!

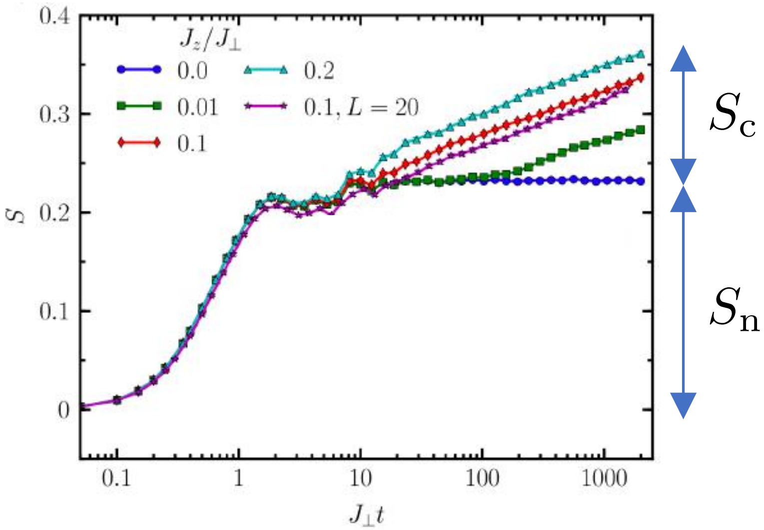
LOGARITHMIC GROWTH OF ENTANGLEMENT

Number entanglement



Configurational entanglement



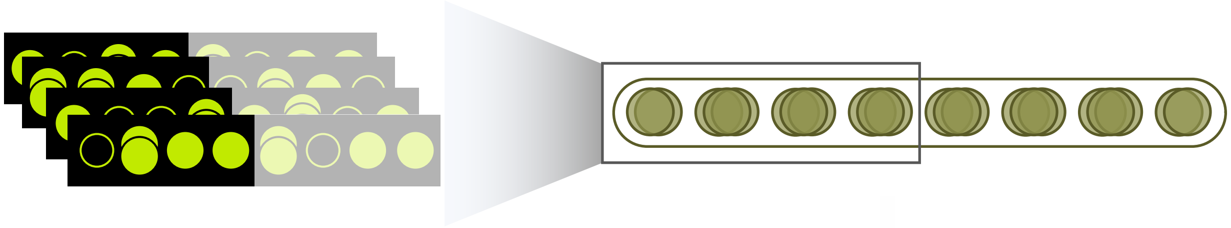


J. H. Bardarson et al., *Phys. Rev. Lett.* 109, 017202 (2012)

Separation of total entanglement entropy

$$S_{\mathrm{vN}} = S_{\mathrm{n}} + S_{\mathrm{c}}$$

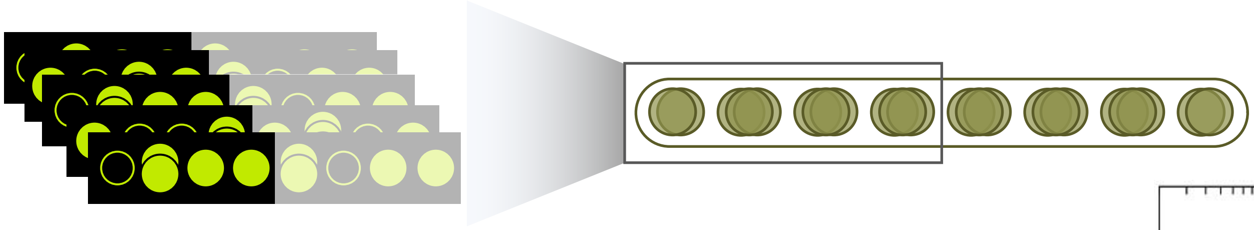
ABSENCE OF TRANSPORT



Number entropy:

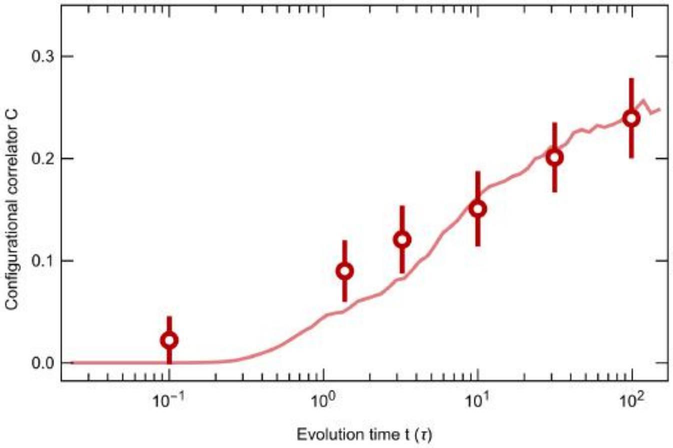
$$S_{\mathrm{n}} = -\sum_n p_n \log p_n$$

LOGARITHMIC GROWTH OF ENTANGLEMENT

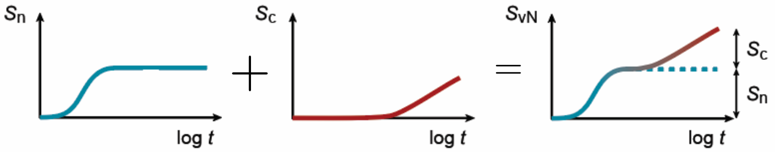


A *B*

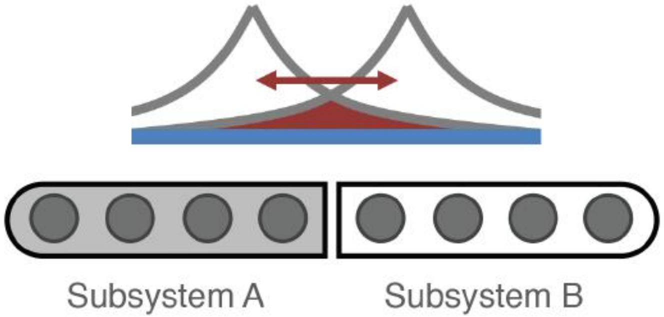
$$C = \sum_{A,B} |p(A \otimes B) - p(A)p(B)|$$



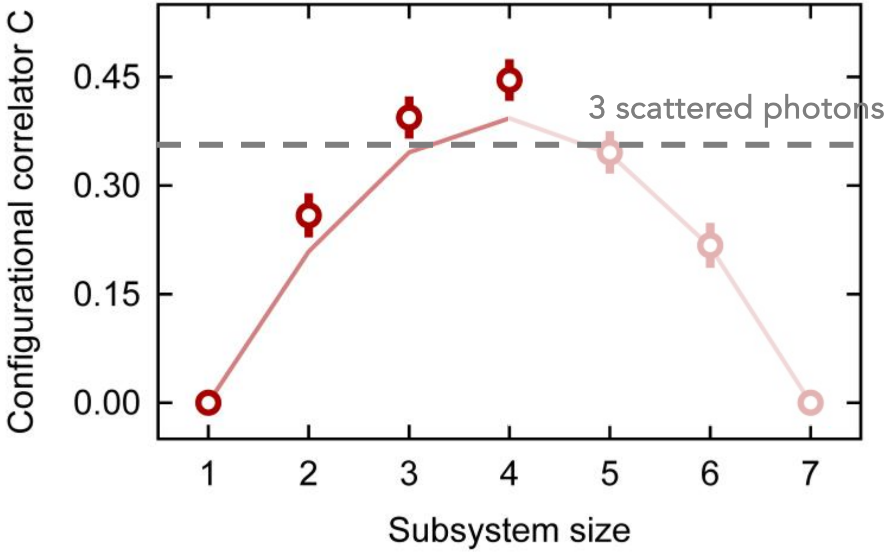
$C \propto S_c$ ➔ probe for many-body entanglement



SUBSYSTEM SIZE



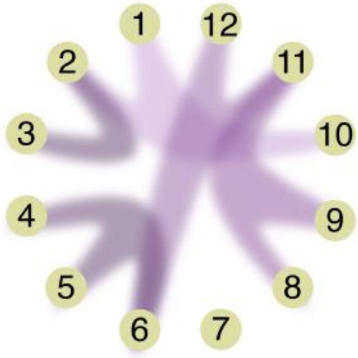
Volume law



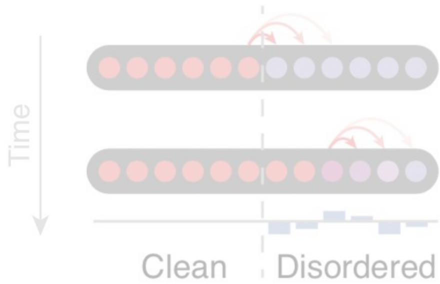
➔ probe for quantum state purity

OUTLINE

Localization and entanglement

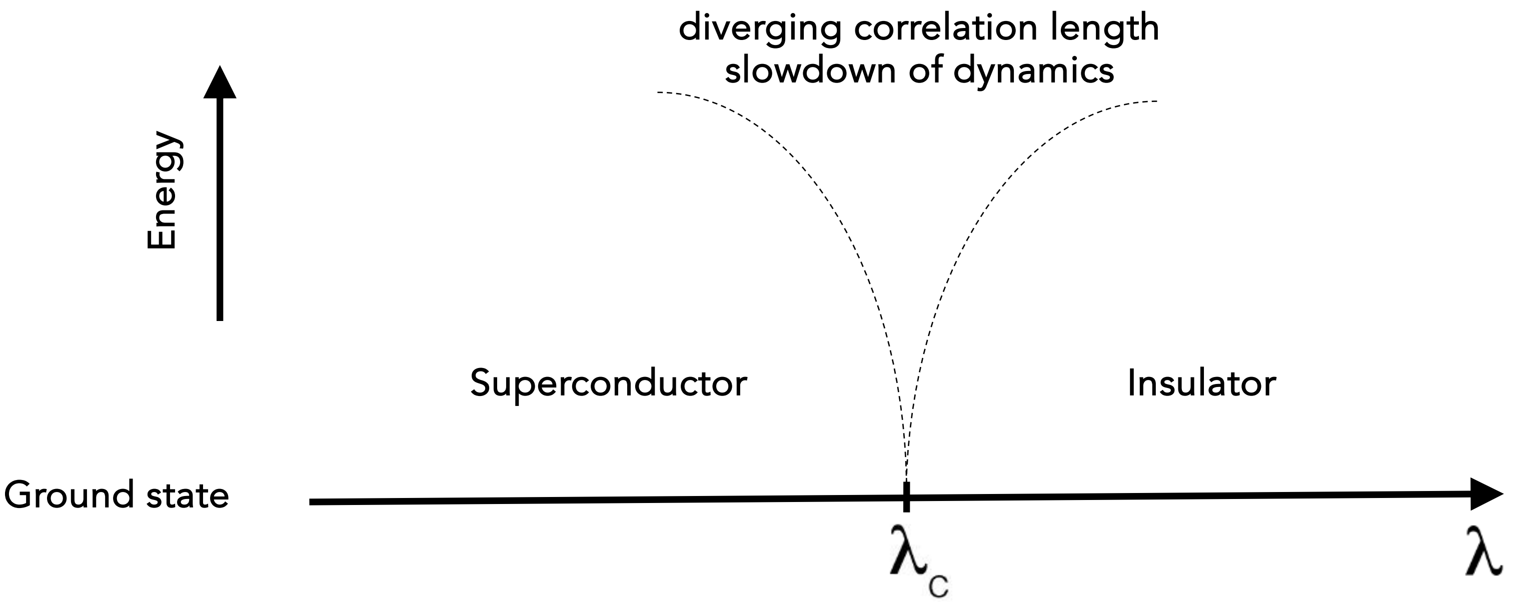


MBL “transition”

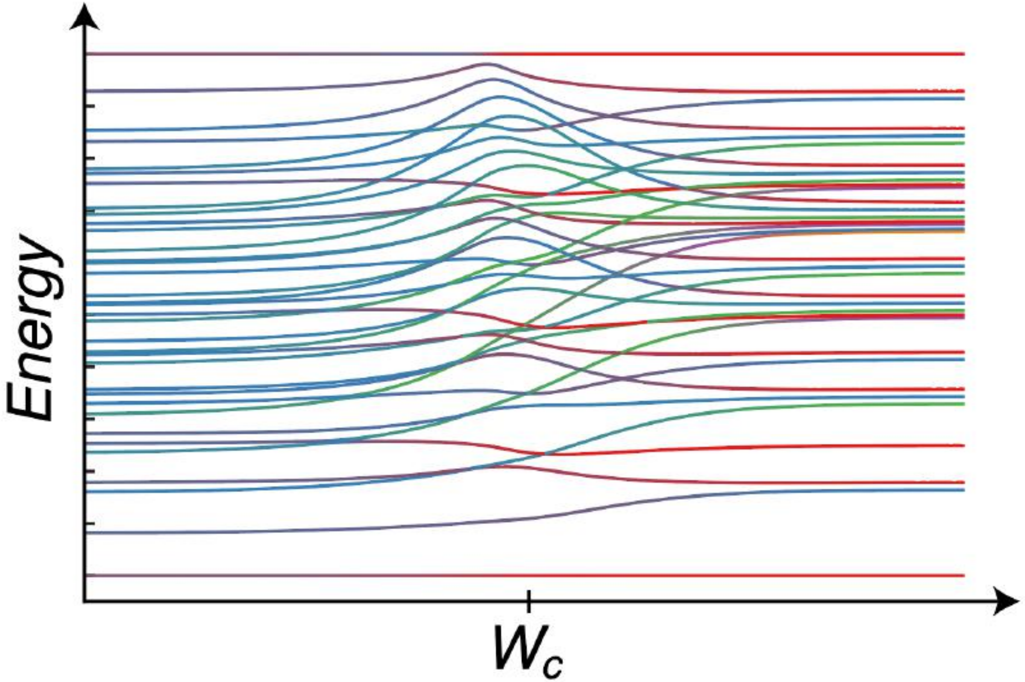


Quantum avalanches

EQUILIBRIUM CRITICAL BEHAVIOUR



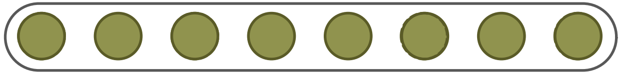
MANY-BODY LOCALIZATION TRANSITION



All eigenstates determine critical behaviour!

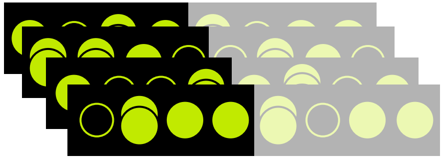
➔ requires new theoretical and experimental concepts to understand

TWO-POINT DENSITY CORRELATIONS



$$G_c^{(2)}(d) = \langle \hat{n}_i \hat{n}_{i+d} \rangle - \langle \hat{n}_i \rangle \langle \hat{n}_{i+d} \rangle$$

Anti-correlations
from particle hopping $G_c^{(2)}(d) < 0$

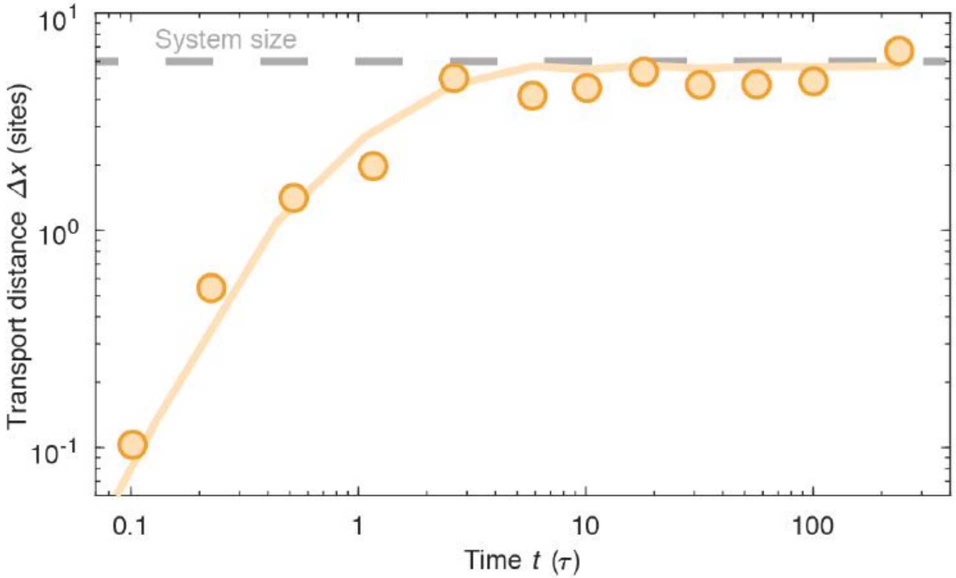


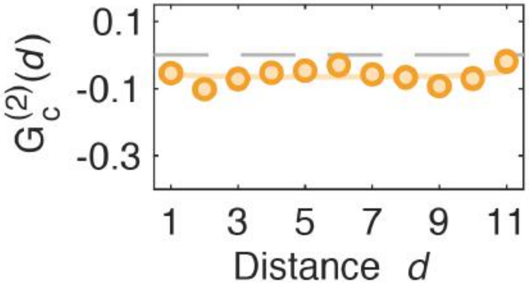
Define transport distance:

$$\Delta x \propto \sum_d d \times G_c^{(2)}(d)$$

(average hopping distance)

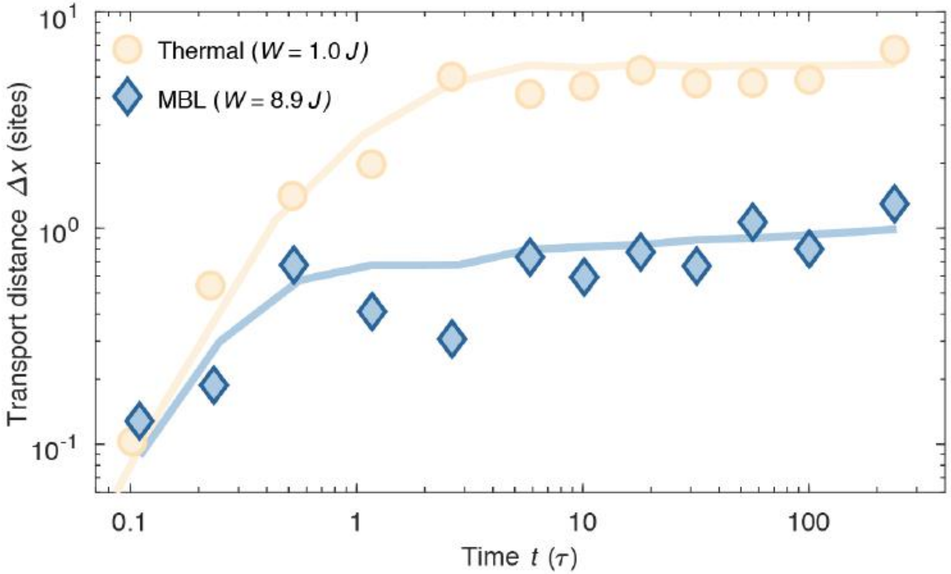
THERMAL REGIME

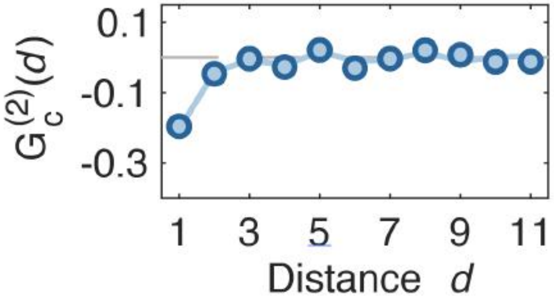




M. Rispoli et al., *Nature* 573, 385 (2019)

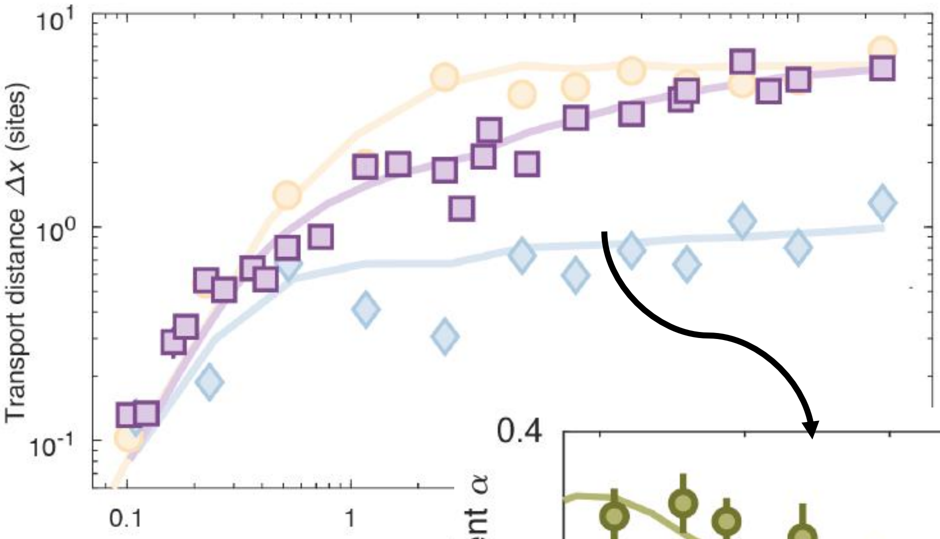
MBL REGIME

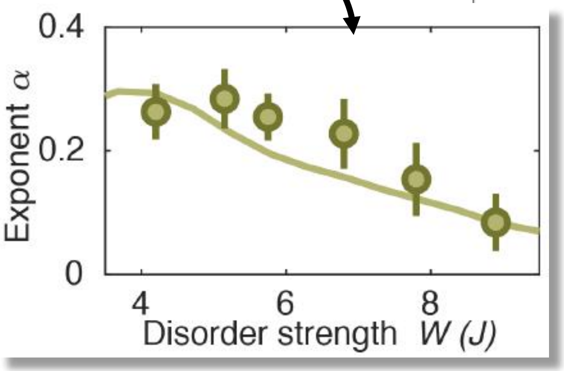




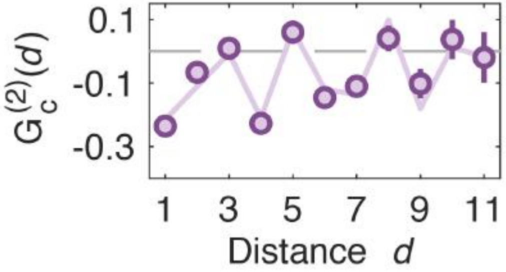
M. Rispoli et al., *Nature* 573, 385 (2019)

QUANTUM CRITICAL REGIME





Experiments on slow dynam
Bloch/Schneider groups

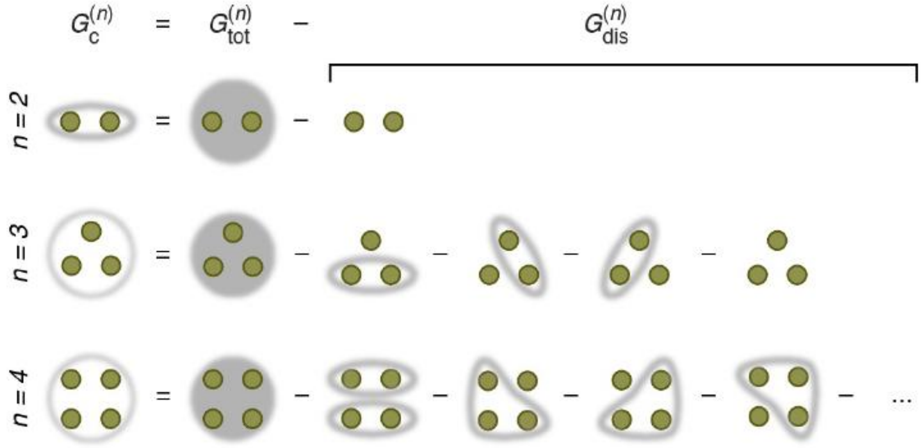


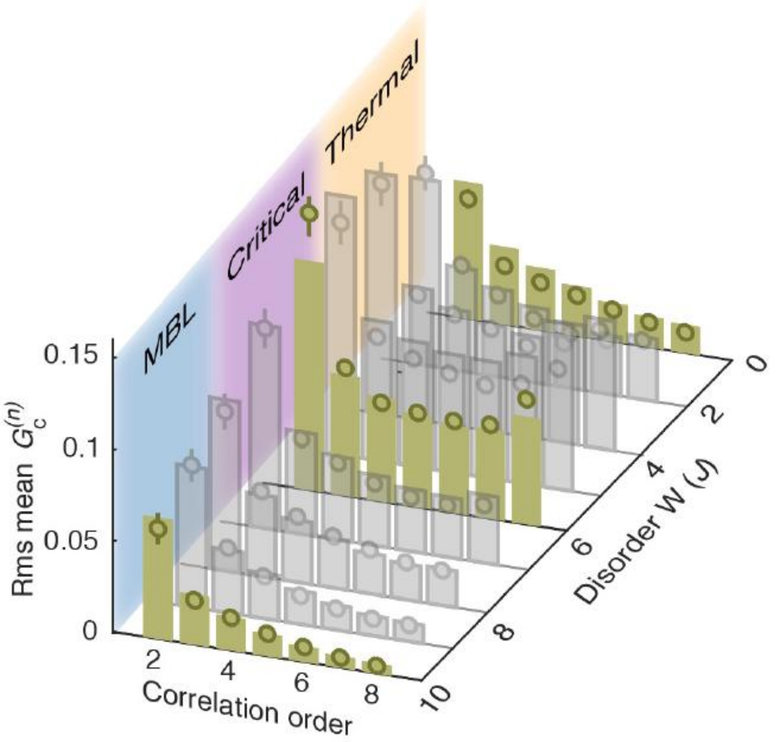
Subdiffusive transport

through complex network

M. Rispoli et al., *Nature* 573, 385 (2019)

MULTI-POINT QUANTUM CORRELATIONS





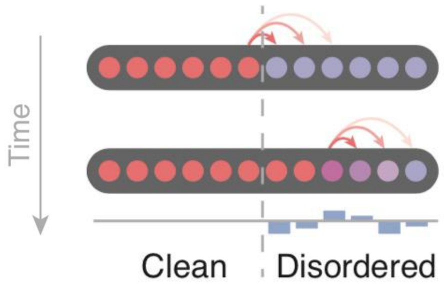
Hierarchy of correlations: non-separable at order n

M. Rispoli et al., *Nature* 573, 385 (2019)

OUTLINE

Localization and entanglement

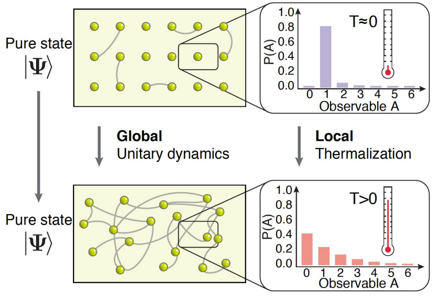
MBL “transition”

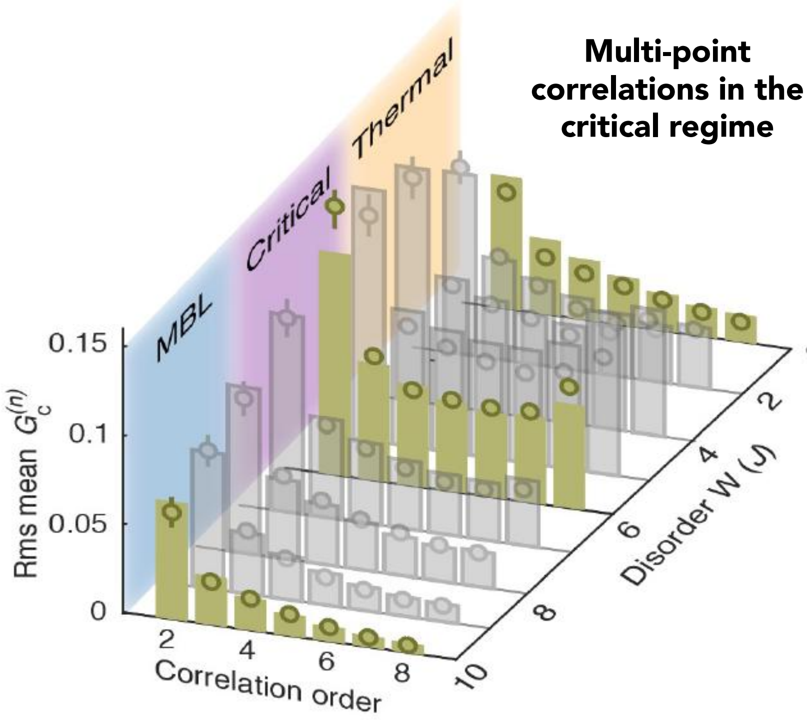


Quantum avalanches

THERMALIZATION VS LOCALIZATION

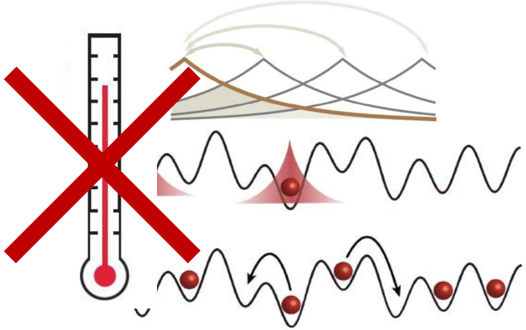
Thermalization





Multi-point correlations in the critical regime

Many-body localization

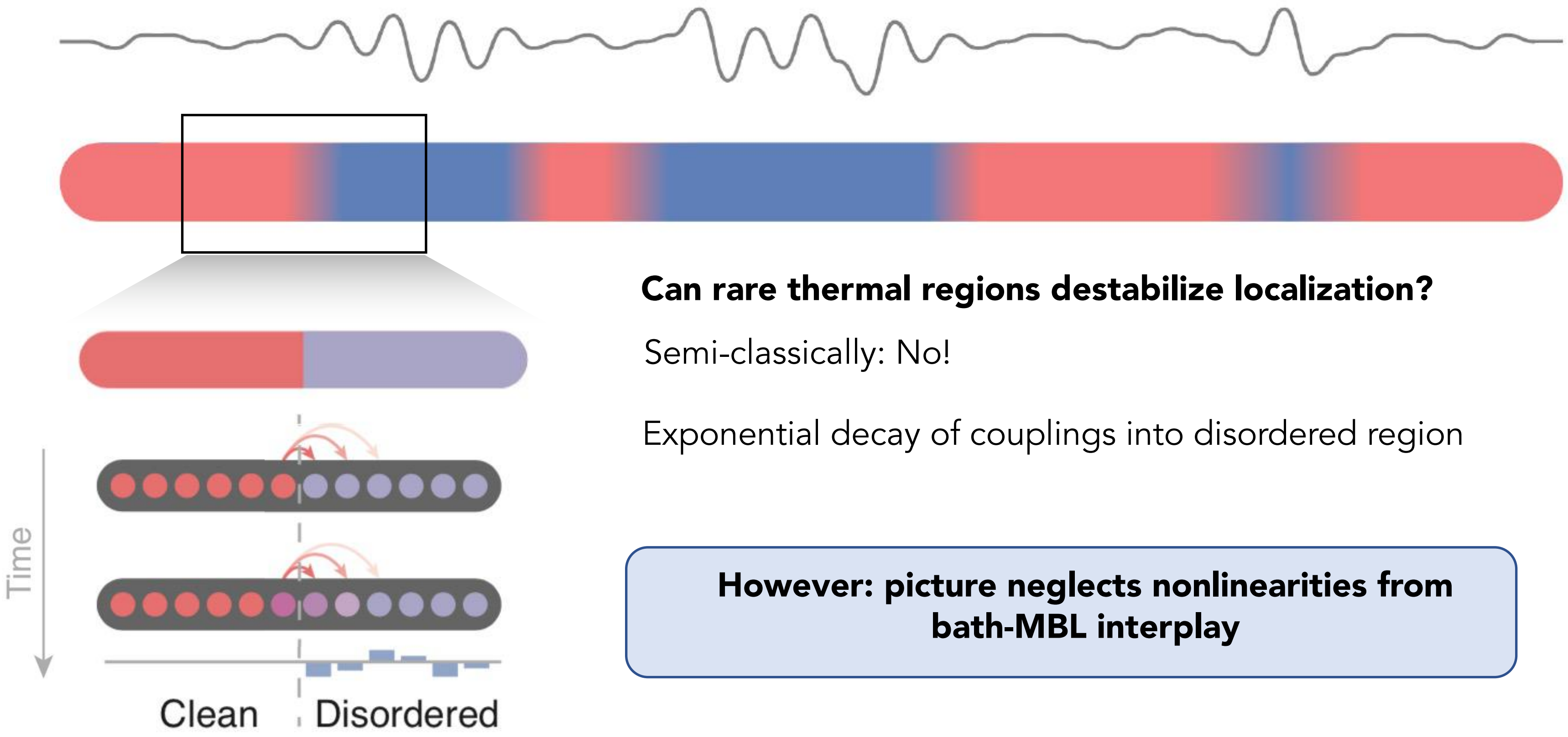


Interface between classical and quantum worlds

Disorder

M. Rispoli et al., Nature 573, 385 (2019)

THERMAL INCLUSIONS



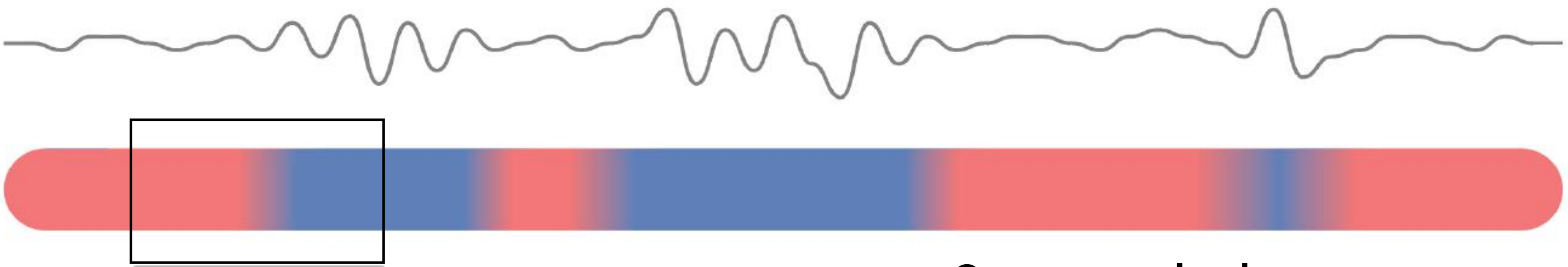
Can rare thermal regions destabilize localization?

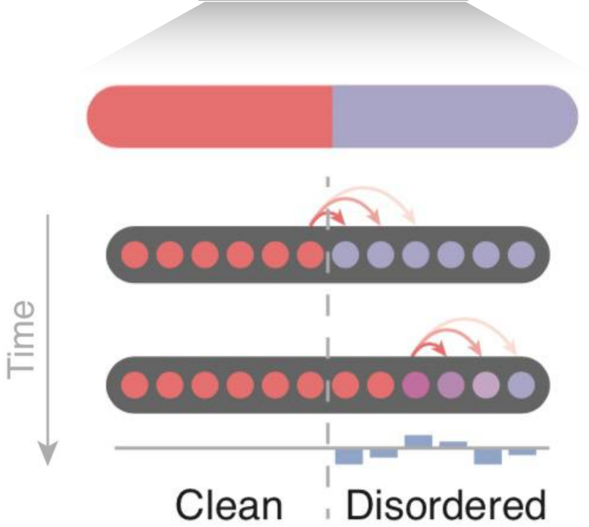
Semi-classically: No!

Exponential decay of couplings into disordered region

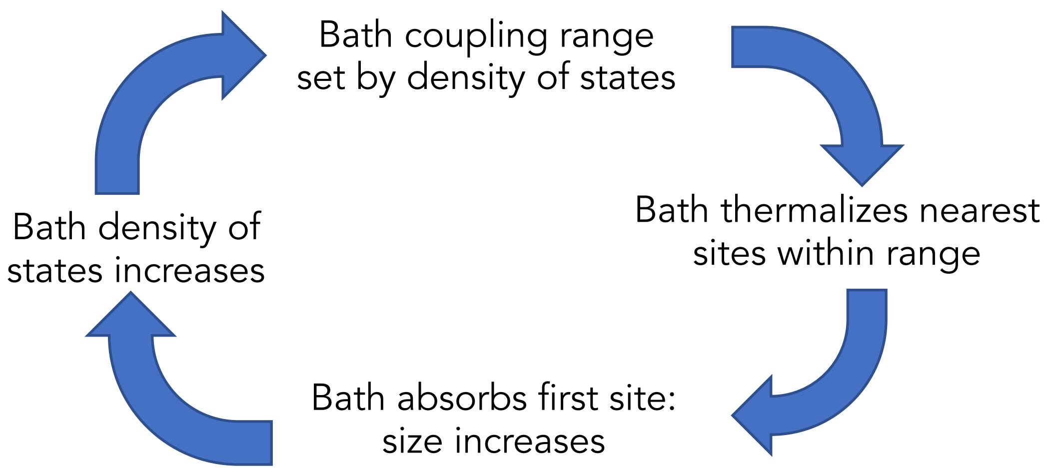
However: picture neglects nonlinearities from bath-MBL interplay

THERMAL INCLUSIONS





Quantum avalanches



MBL unstable after long times due to avalanches!

IS MBL STABLE?

CONTRA

Quantum chaos challenges many-body localization
Jan Šuntajs et al.

Evidence for unbounded growth of the number entropy in many-body localized phases
Maximilian Kiefer-Emmanouilidis et al.

Ergodicity Breaking Transition in finite disordered spin chains Jan Šuntajs et al.

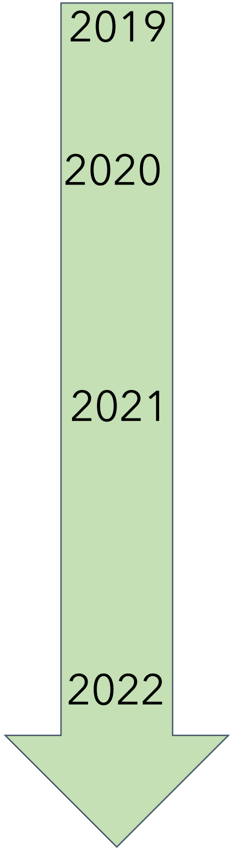
Dynamical obstruction to localization in a disordered spin chain Dries Sels et al.

Slow delocalization of particles in many-body localized phases
Maximilian Kiefer-Emmanouilidis et al.

Unlimited growth of particle fluctuations in many-body localized phases
Maximilian Kiefer-Emmanouilidis et al.

Markovian baths and quantum avalanches
Dries Sels

Particle fluctuations and the failure of simple effective models for many-body localized phases
Maximilian Kiefer-Emmanouilidis et al.



PRO

Distinguishing localization from chaos: Challenges in finite-size systems
Dmitry Abanin et al.

Can we study the many-body localization transition
Rajat K. Panda et al.

Thouless time analysis of Anderson and many-body localization transitions Piotr Sierant et al.

Polynomially filtered exact diagonalization approach to manybody localization Piotr Sierant et al.

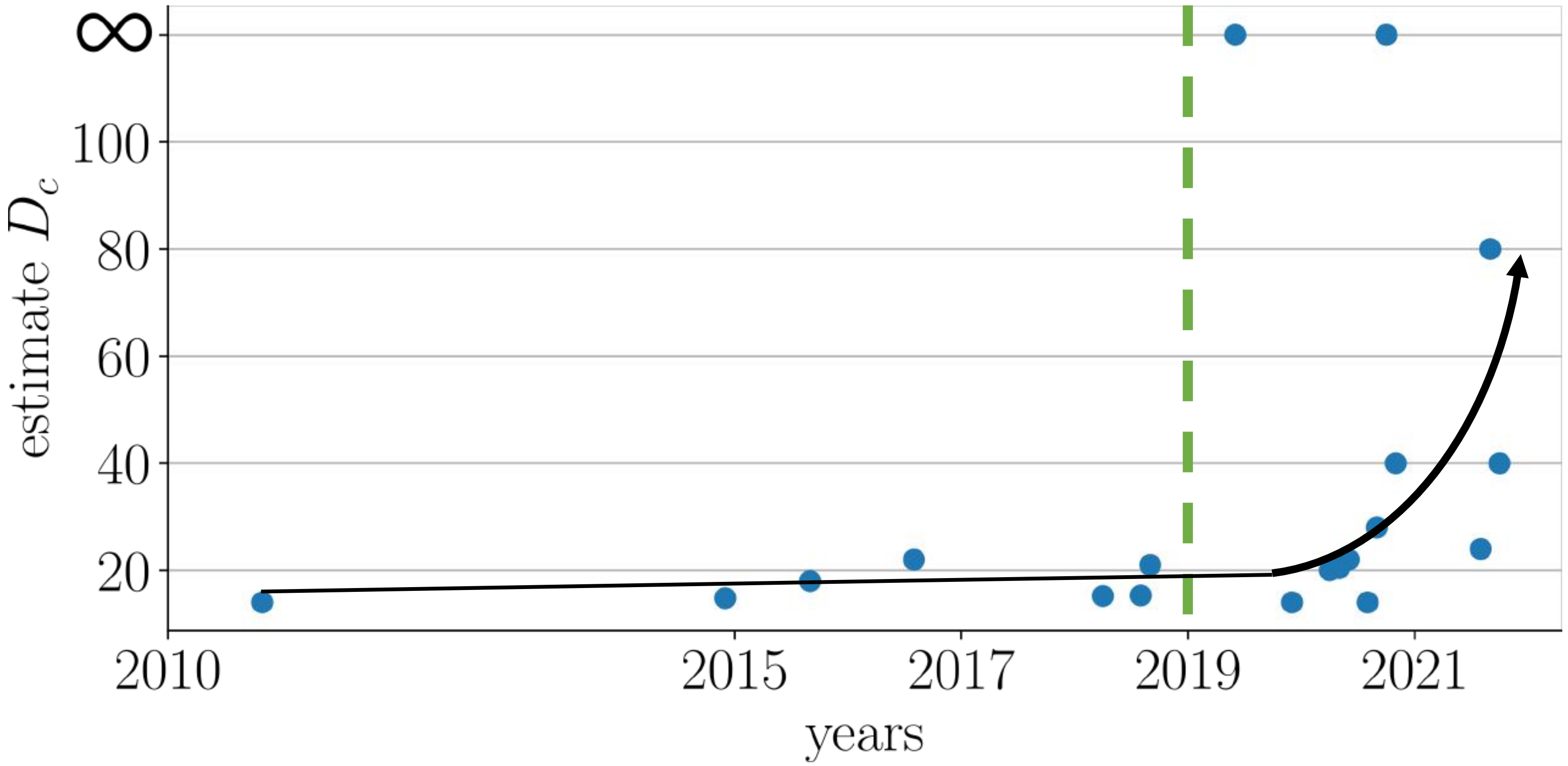
Is there slow particle transport in the MBL phase
David J. Luitz et al.

Avalanches and many-body resonances In many-body localized systems
Alan Morningstar et al.

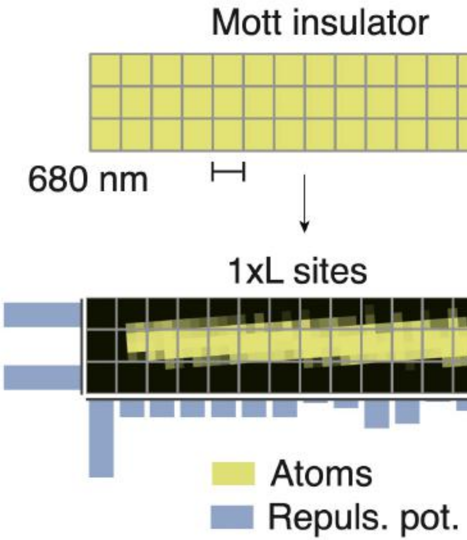
Can we observe the many-body localization
Piotr Sierant et al.

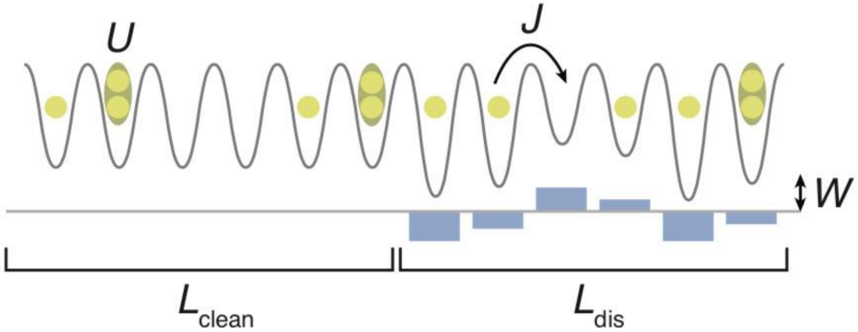
Resonance-induced growth of number entropy in strongly disordered systems
Roopayan Ghosh et al.

IS MBL STABLE?



CLEAN-DISORDER INTERFACE

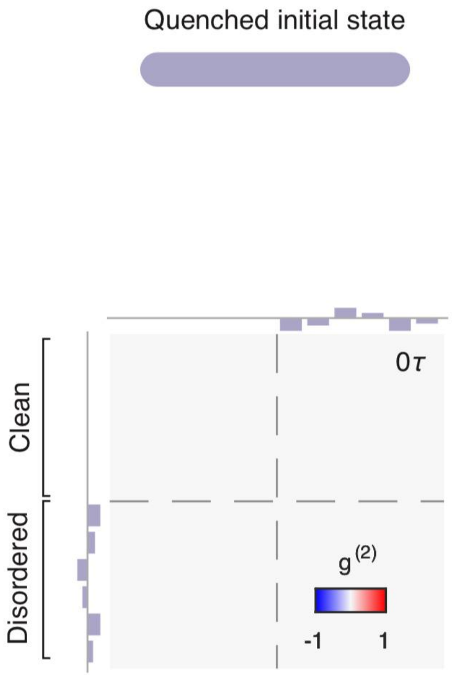




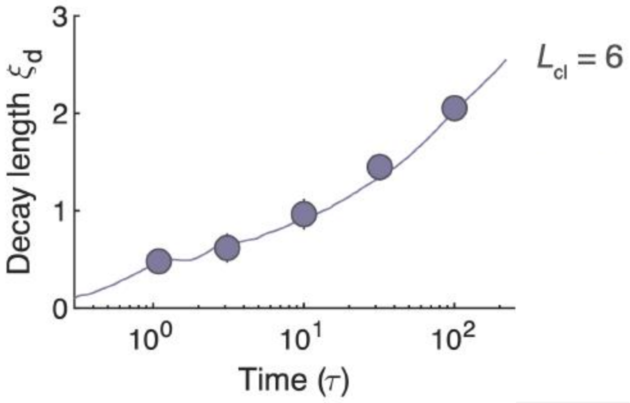
- L_{clean} sites without disorder
- L_{dis} sites with disorder (quasi-periodic)

J. Léonard et al., Nat. Phys. 19, 481 (2023)

AVALANCHE DYNAMICS



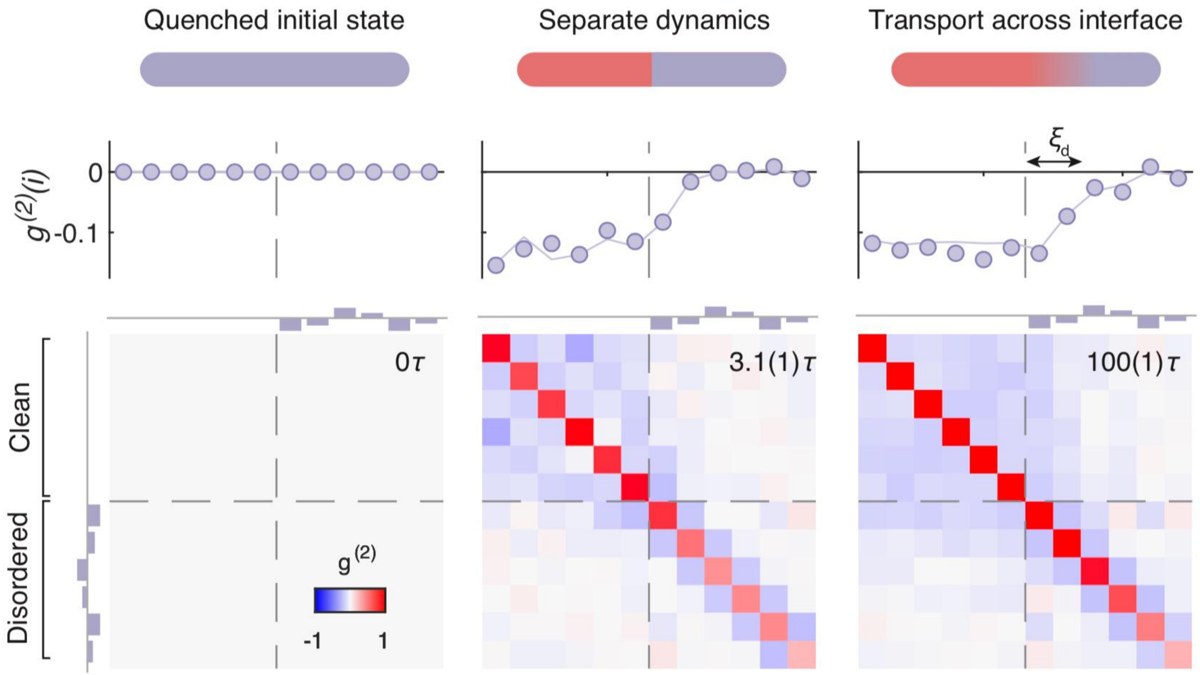
Accelerated thermalization



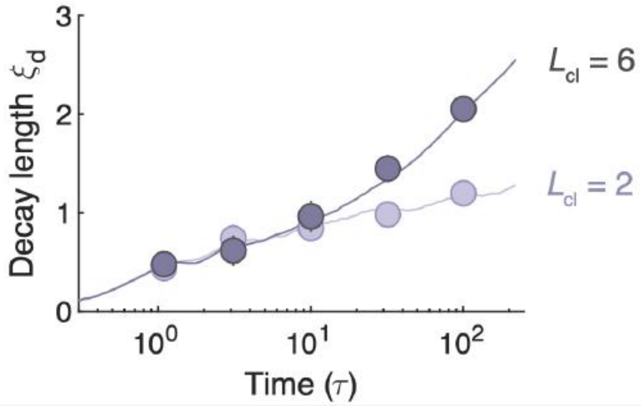
$$g^{(2)}(i,j) = \langle \hat{n}_i n_j \rangle - \langle \hat{n}_i \rangle \langle \hat{n}_j \rangle$$

J. Léonard et al., Nat. Phys. 19, 481 (2023)

AVALANCHE DYNAMICS



Accelerated thermalization



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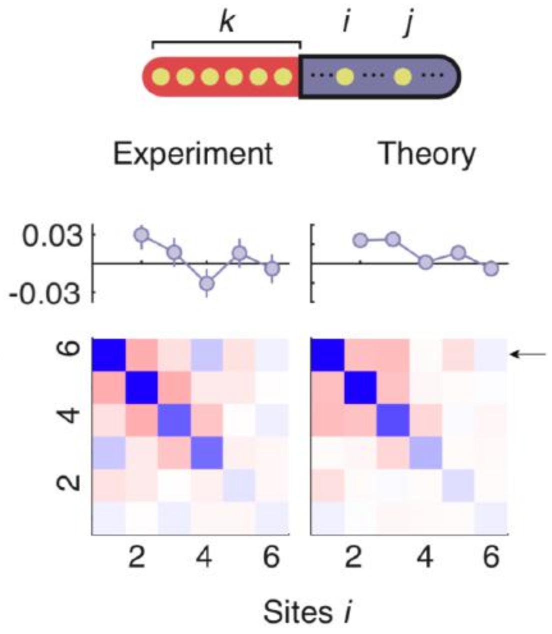
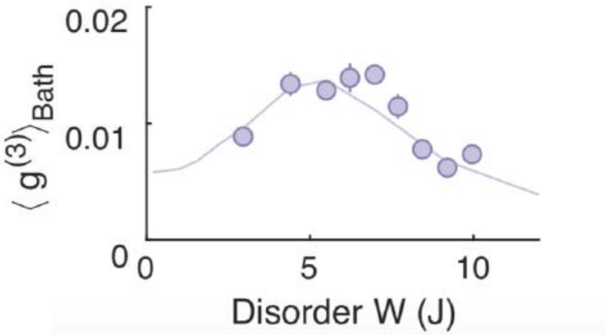
J. Léonard et al., Nat. Phys. 19, 481 (2023)

THREE-BODY CORRELATIONS





➔ driven by many-body processes

J. Léonard et al., Nat. Phys. 19, 481 (2023)

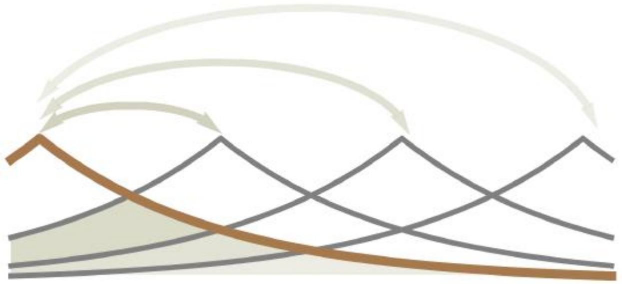
OUTLOOK

What we know

- Localization is possible over accessible time scales
- Long-range entanglement despite localization
- Avalanches destabilize MBL over disorder range
- MBL may be a prethermal phenomenon
  ➔ more research required

What we don't know yet

- Is MBL stable at high disorder?
- If not, are there ways to stabilize MBL?
- Is there any strict exception to statistical physics thermalization?
- What about time crystals, many-body scars?

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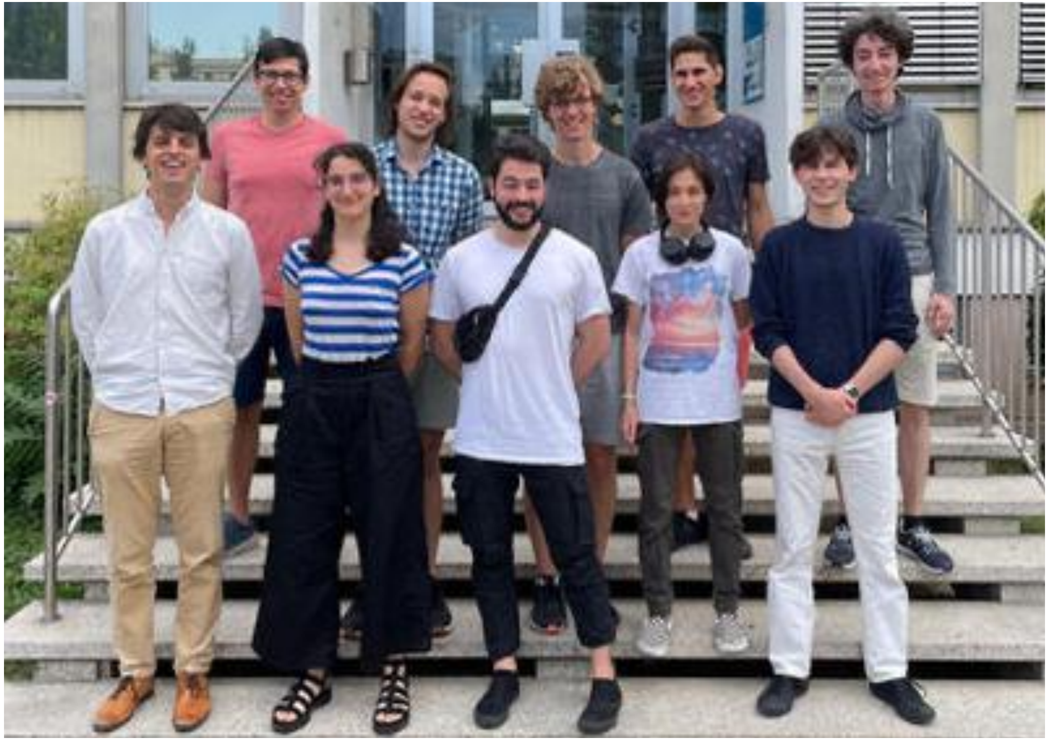


R. Rosa-Medina F. Silva-Tarouca S. Roschinski J. Schabbauer M. Michalek

J. L. I. Safa T. Schubert S. Waddington M. Stümmer

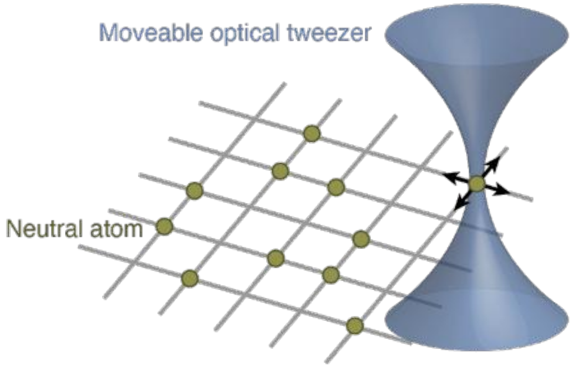
quantA

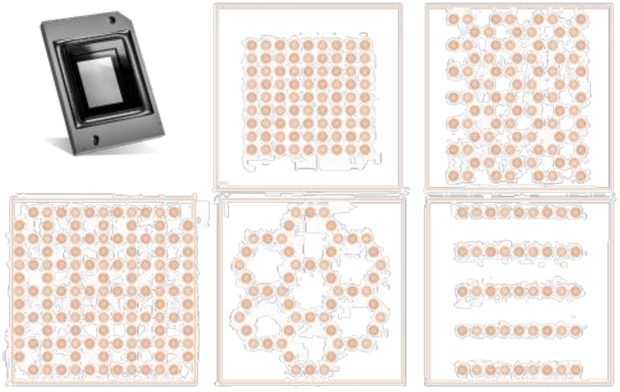
erc European Research Council

FWF Der Wissenschaftsfonds.

FFG Promoting Innovation.

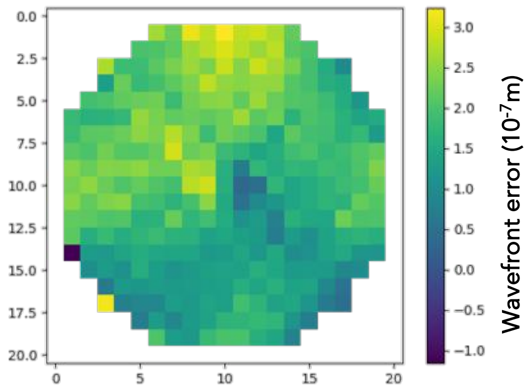
OUTLOOK: ASSEMBLING QUANTUM MATTER



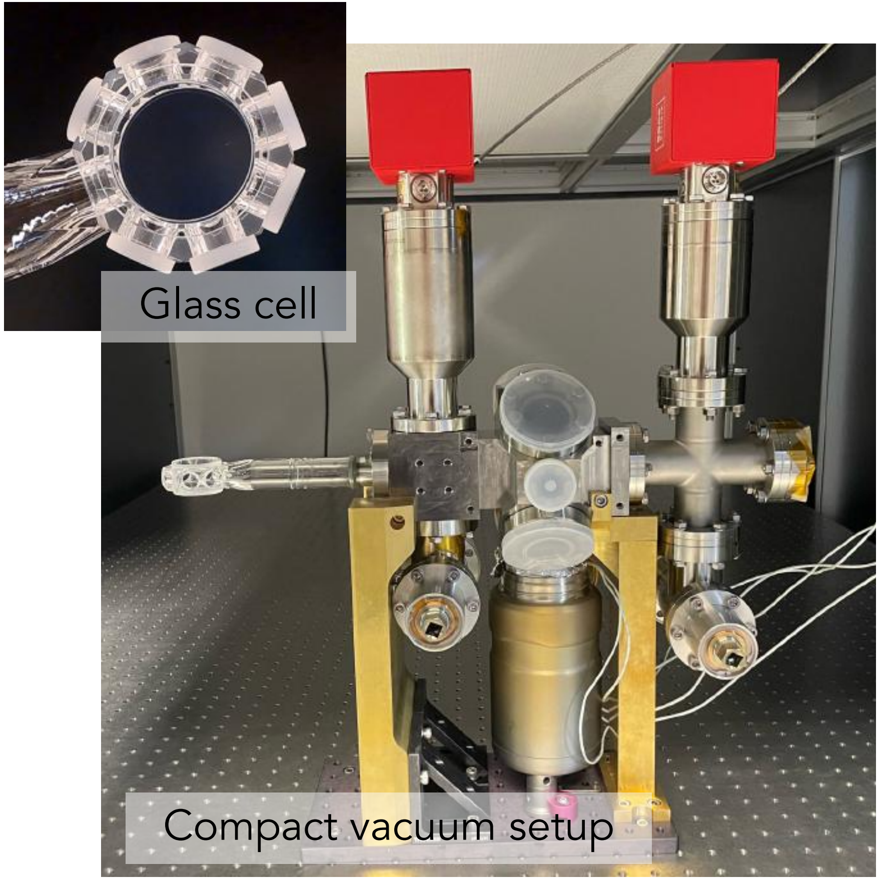


Programmable fermionic systems

- Deterministic initial state by loading from a fermionic tweezer array
- Programmable potentials, beyond square lattices
- Reuse sample (➔ 10-100Hz) to get statistics for quantitative results



ASSEMBLING QUANTUM MATTER

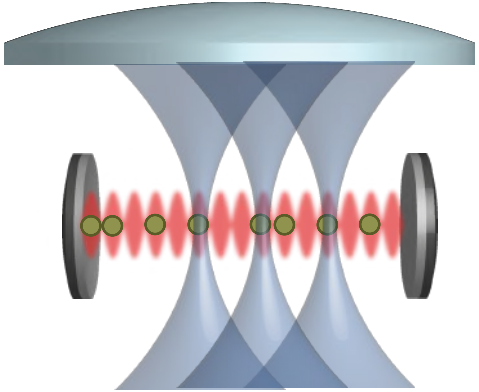


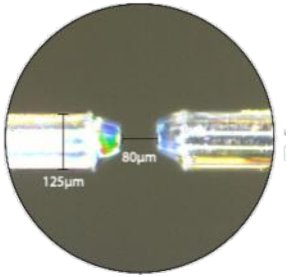
Key features

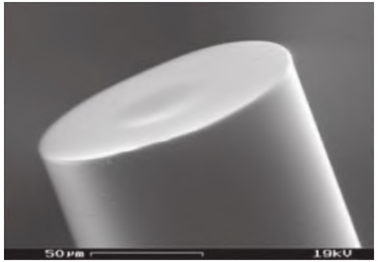
- Lattice constructed and filled site by site
- Fermionic Lithium to reach fast energy scales due to light mass
- Controllable interactions via Feshbach resonance
- Blue-detuned lattices for improved coherence time

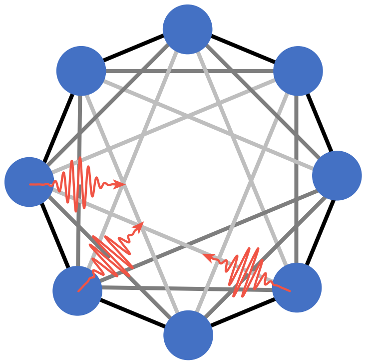
OUTLOOK: PHOTON-COUPLED ATOMIC ARRAYS

New frontier:
Local ***and*** non-local control of interactions



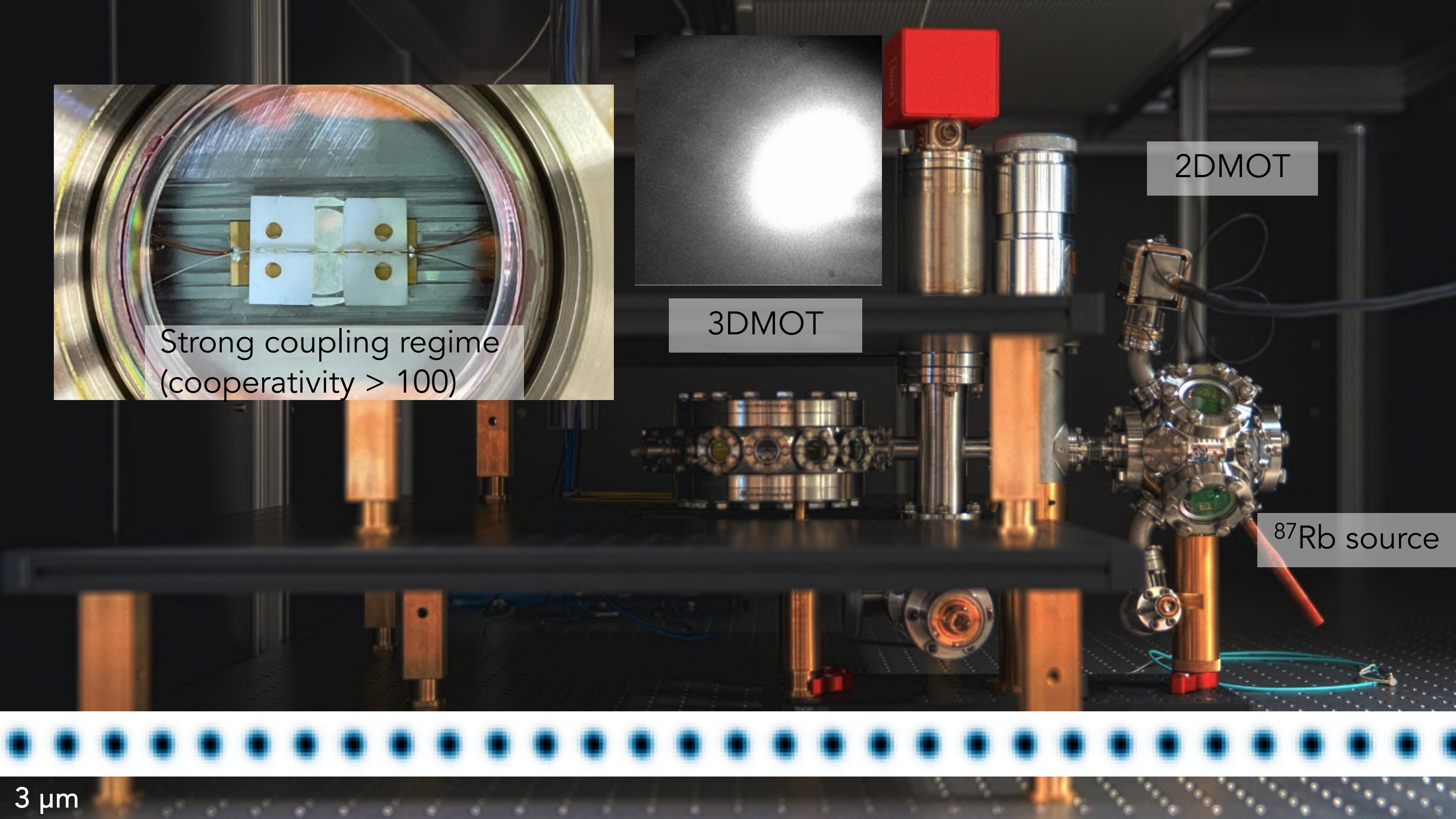






Light-induced coupling
- Spatial control: any distance, any groups of atoms
- Dynamical control
- New readout techniques

Programmable couplings among *all* atoms


Strong coupling regime
(cooperativity > 100)
3DMOT
2DMOT
87Rb source
3 μm

THANK YOU