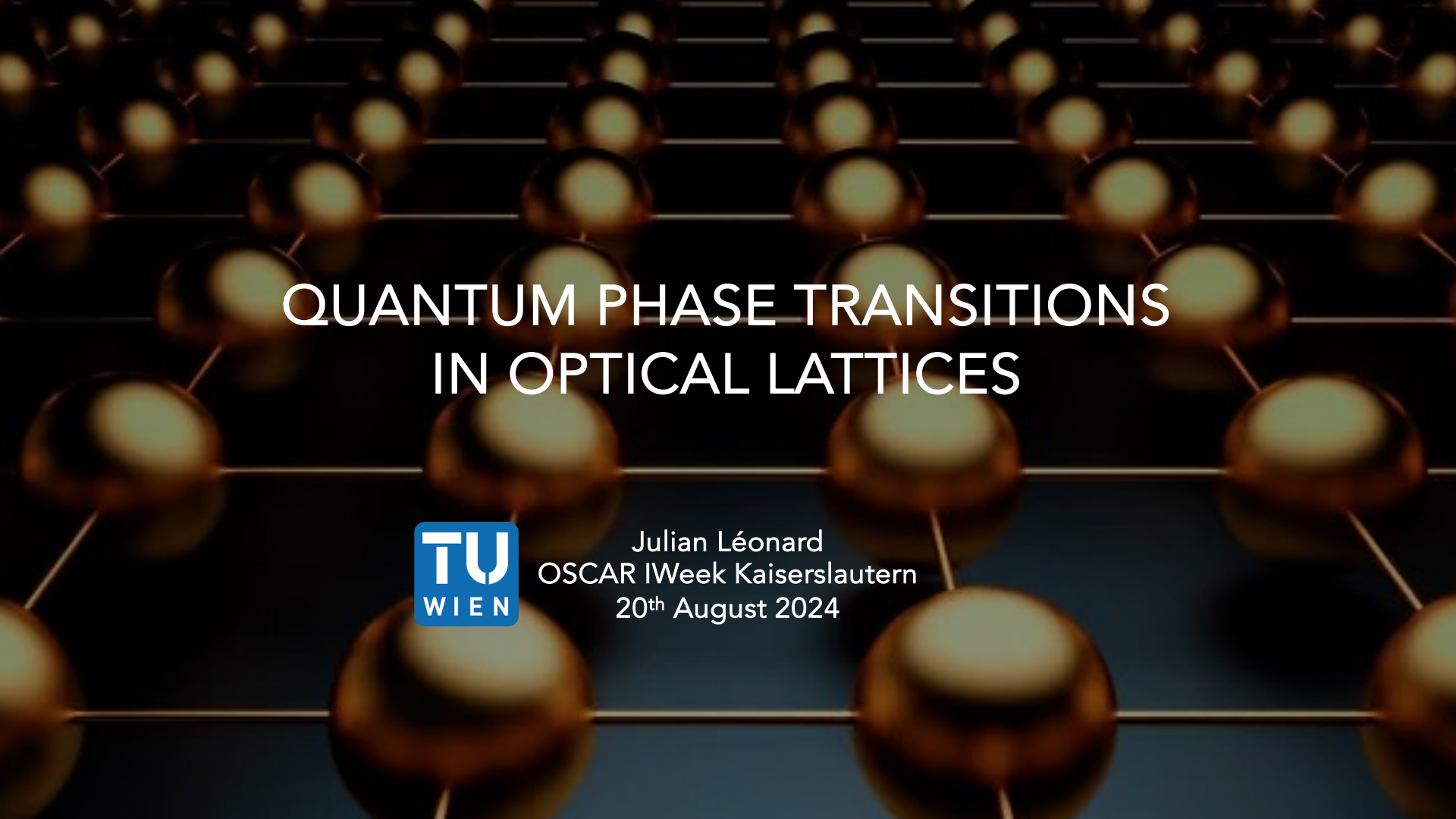


QUANTUM PHASE TRANSITIONS IN OPTICAL LATTICES

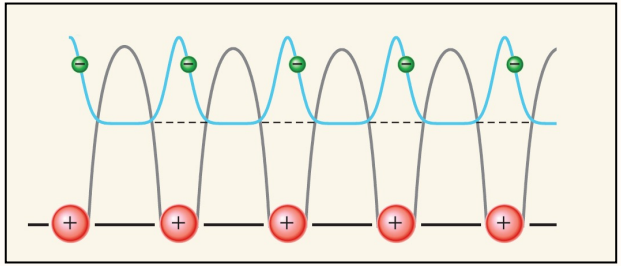
Julian Léonard

OSCAR IWeek Kaiserslautern

20th August 2024

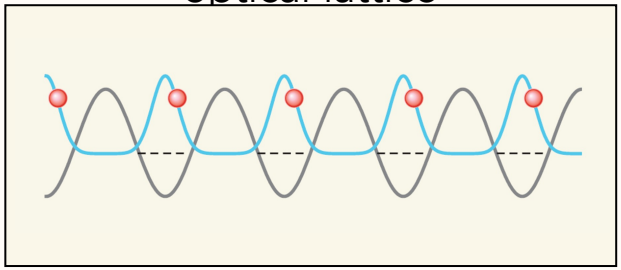
REALIZING ELECTRONIC SYSTEMS

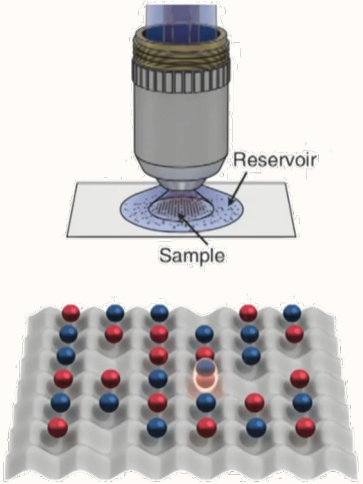
Electrons in a crystal

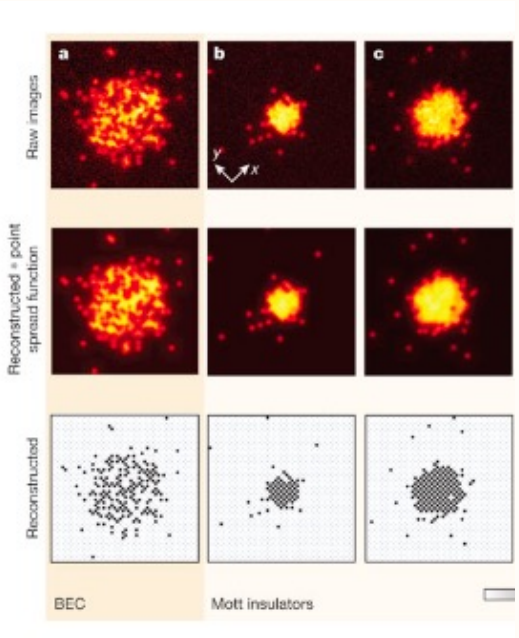


Atoms in an optical potential

optical lattice



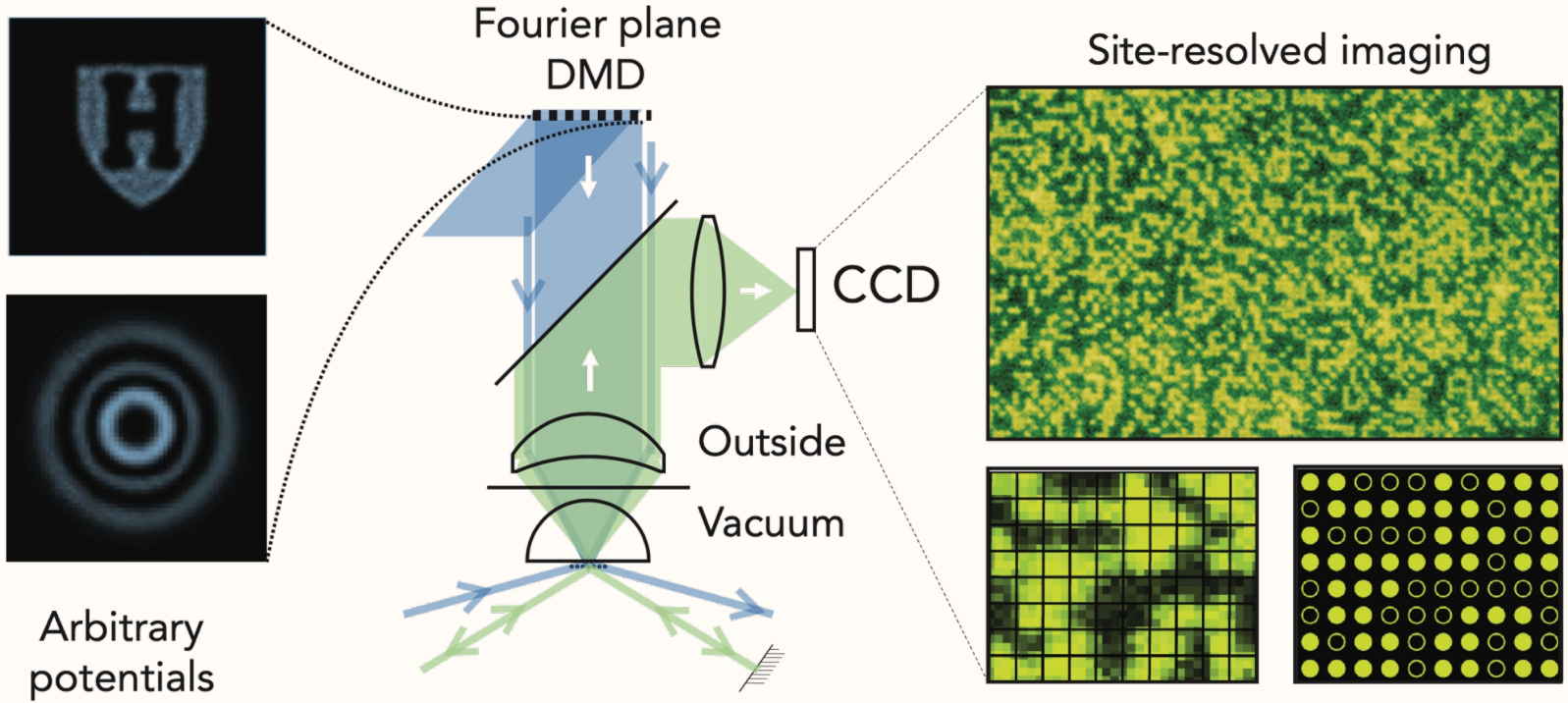




Site-resolved occupation measurement

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

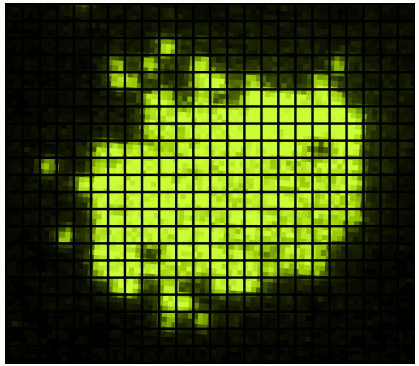
MANIPULATION



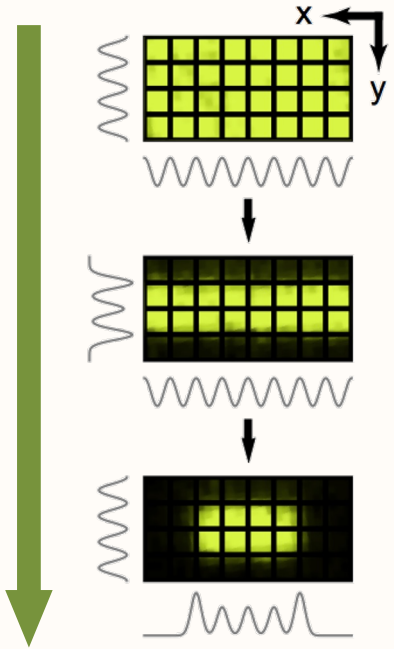
W. Bakr et al., *Science* **329**, 547 (2010)
J. Sherson et al., *Nature* **467**, 68 (2010)

ARBITRARY POTENTIALS

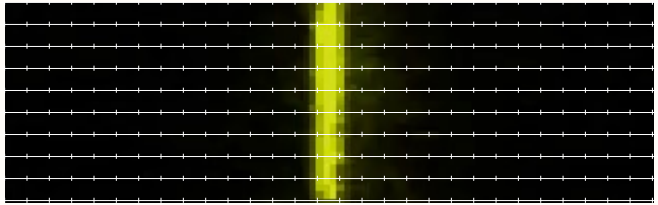
Low-entropy
Mott insulator



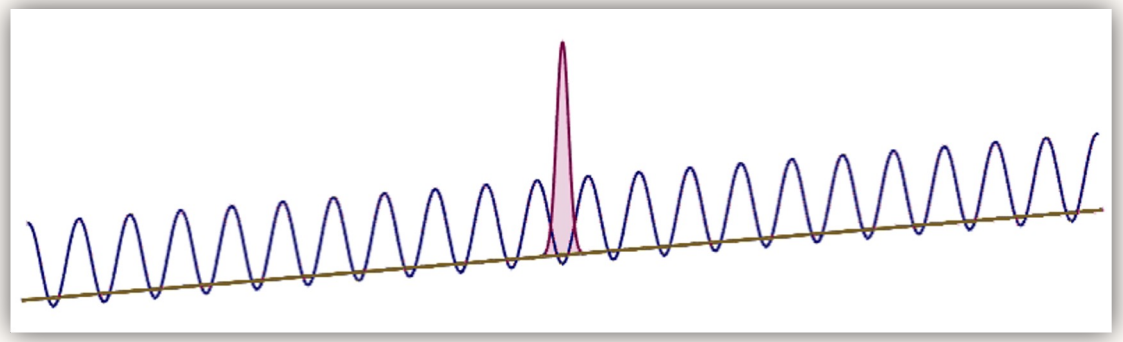
Local potentials

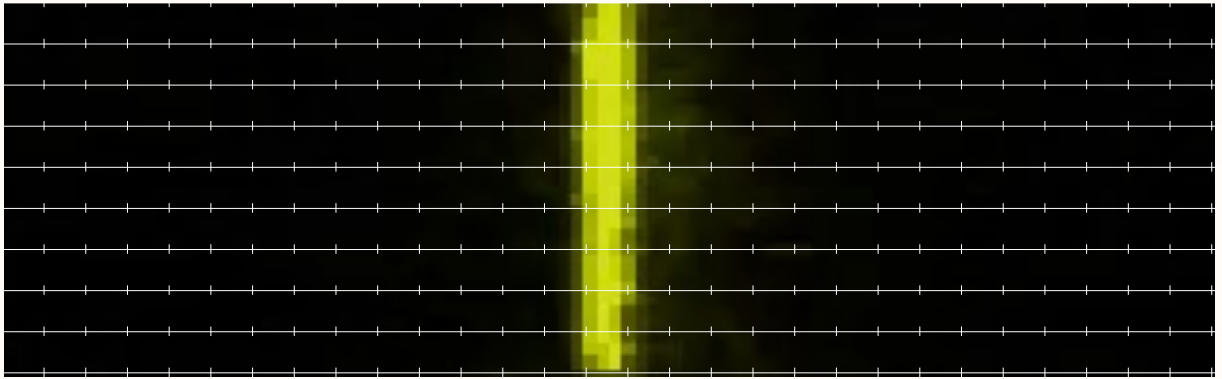


high fidelity
state preparation

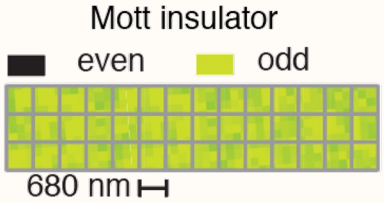


SITE-RESOLVED ADRESSING

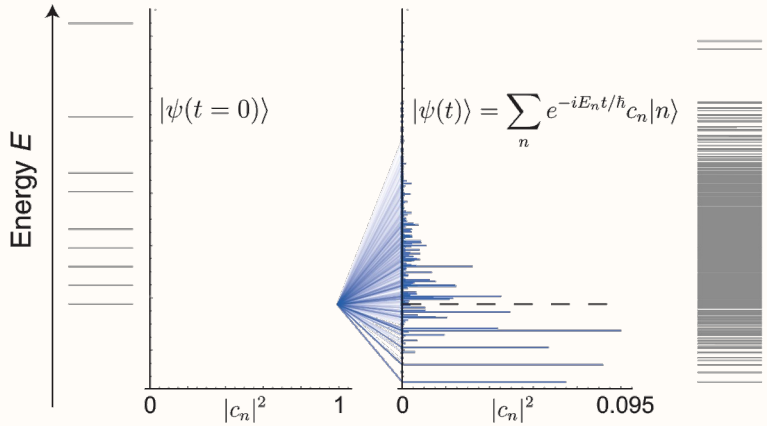




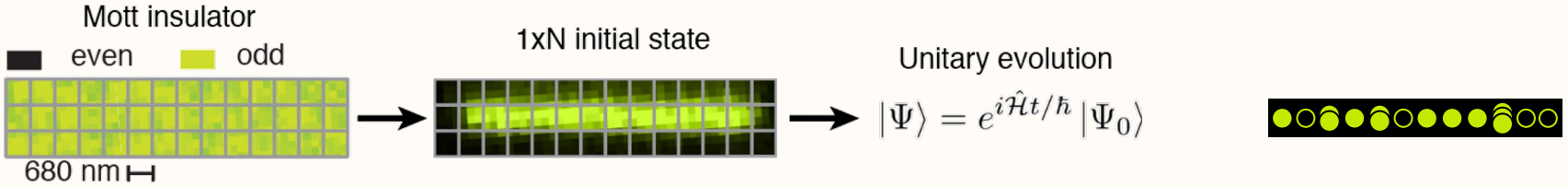
QUANTUM QUENCH

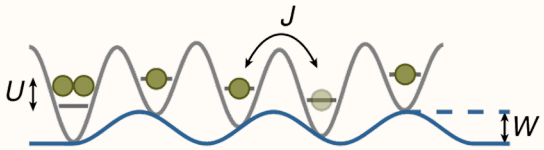






PROTOCOL



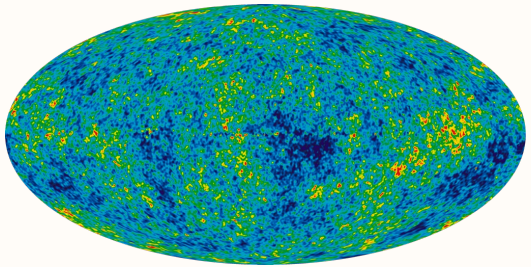


Bose-Hubbard model
programmable site offsets

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

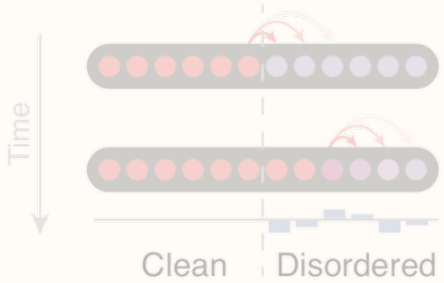
U = 3J
h_i quasi-periodic with golden ratio 1.618

OUTLINE



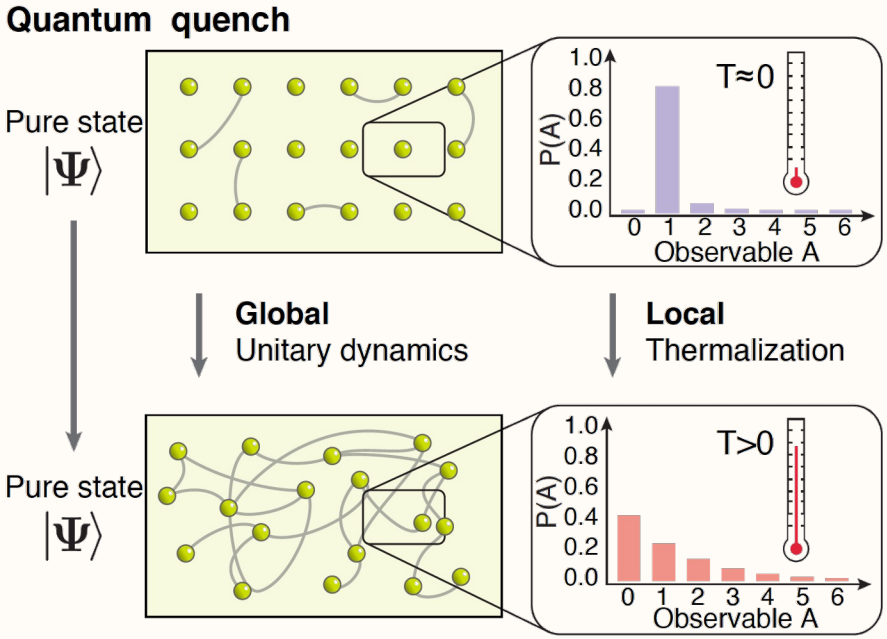
Quantum thermalization

Localization and transition



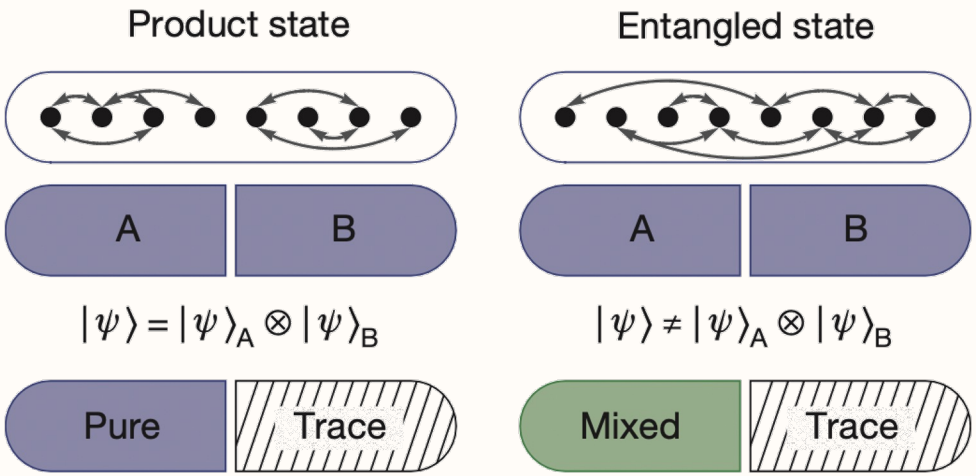
Quantum avalanches

QUANTUM THERMALIZATION



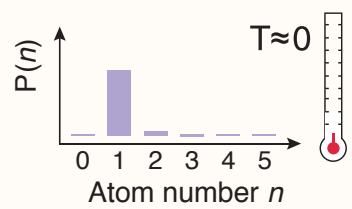
- Local quantum correlations get lost in global d.o.f
- Classical hydrodynamics of remaining slow modes
- Entanglement entropy and classical entropy become indistinguishable

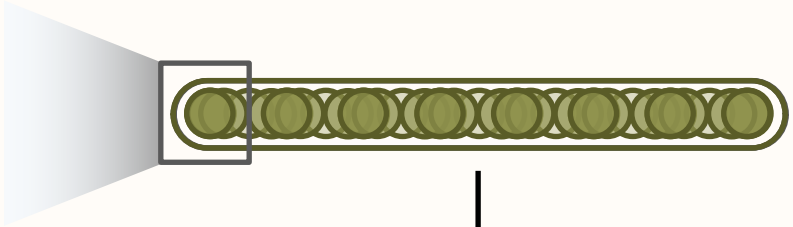
MANY-BODY ENTANGLEMENT



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

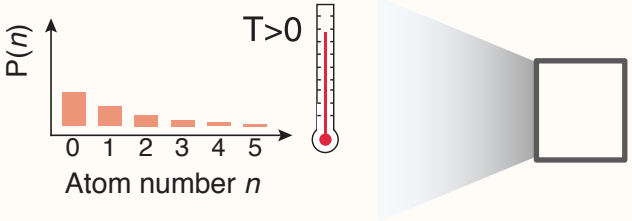
QUANTUM THERMALIZATION





Globally pure
Locally pure

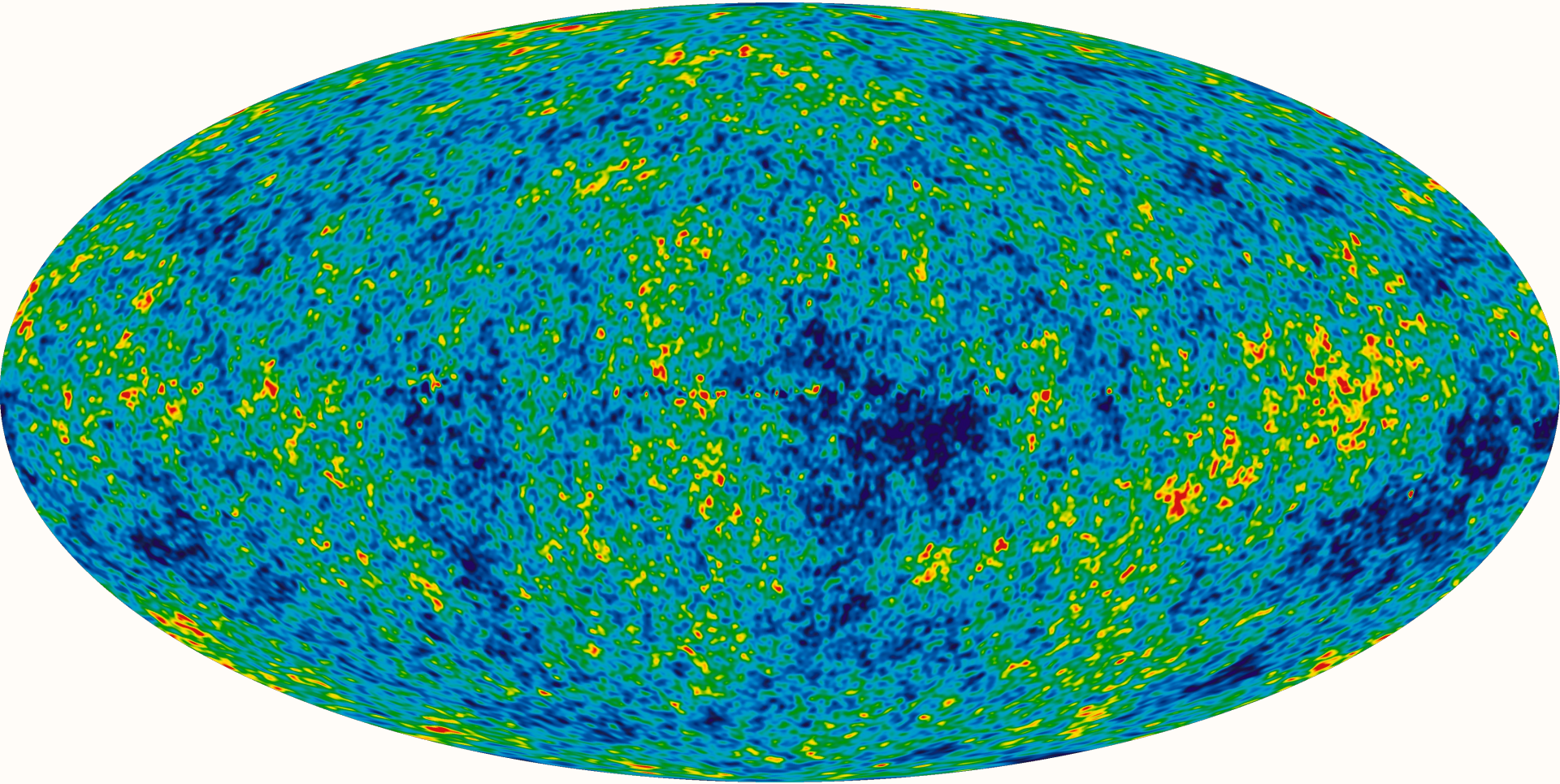
Unitary
dynamics



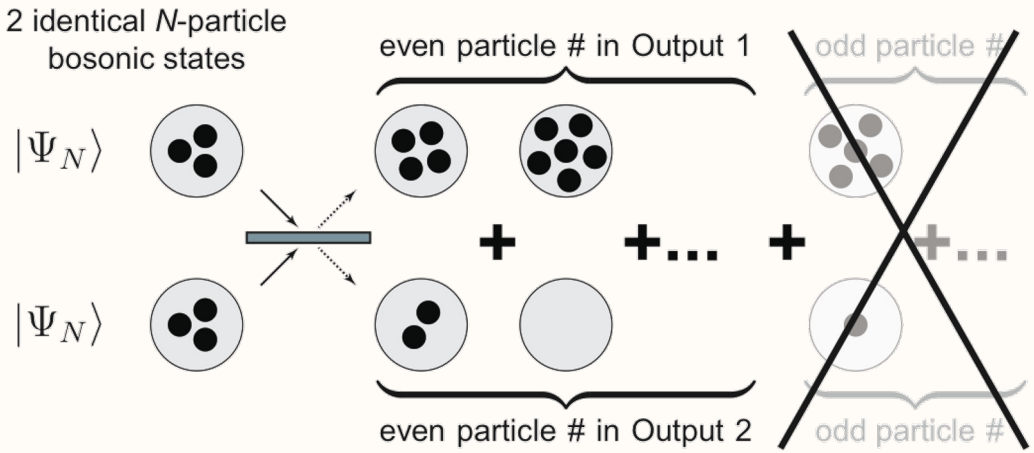
Globally pure
Locally thermal
(ETH)

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

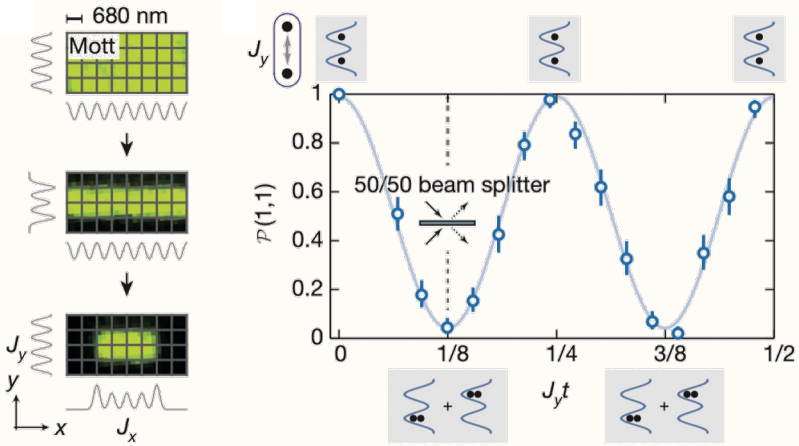
A. Kaufman et al., *Science* 353, 794 (2016)
also: Schmiedmayer, Martinez, Schätz…

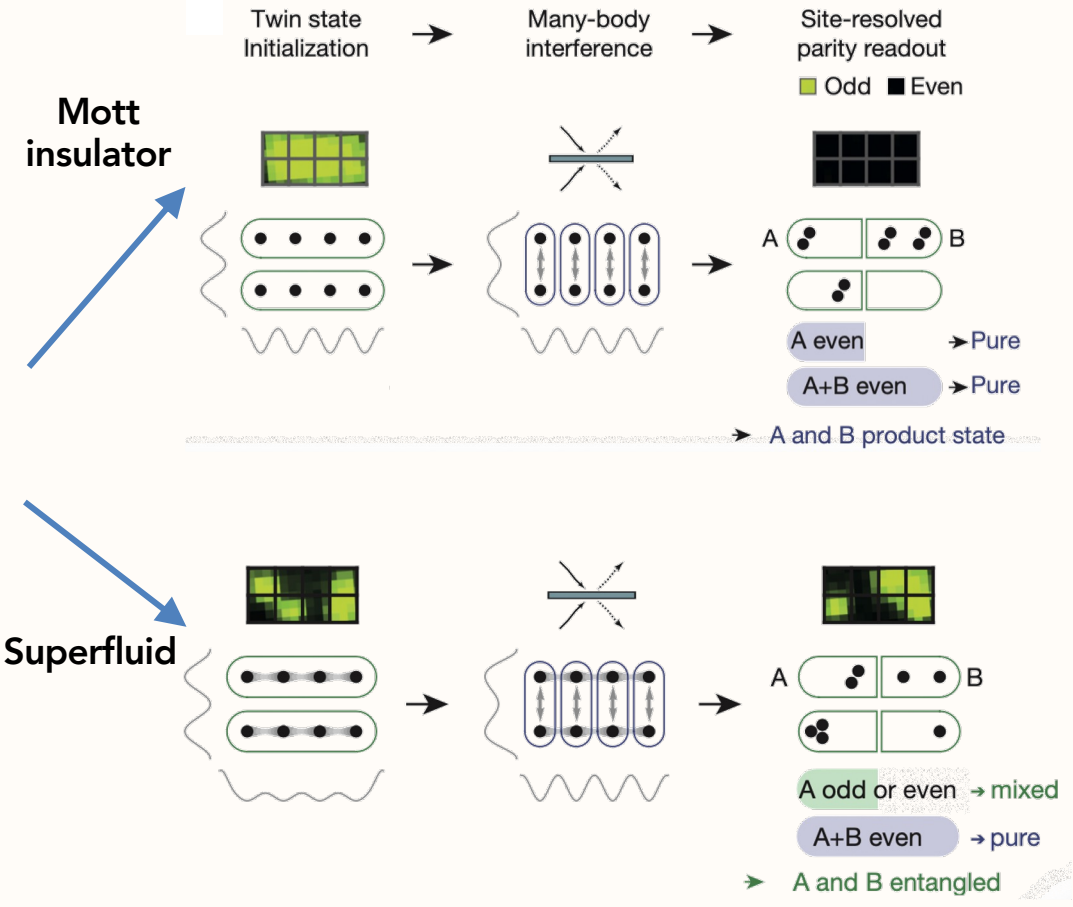


MEASURING MANY-BODY ENTANGLEMENT

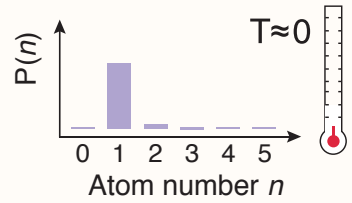


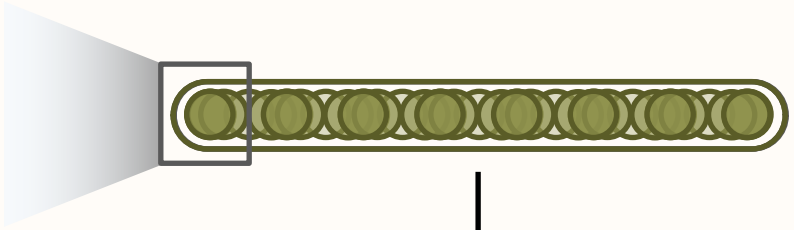
MEASURING MANY-BODY ENTANGLEMENT





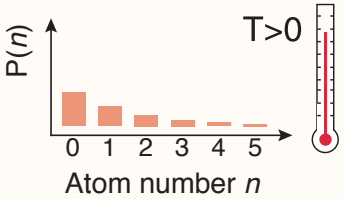
QUANTUM THERMALIZATION

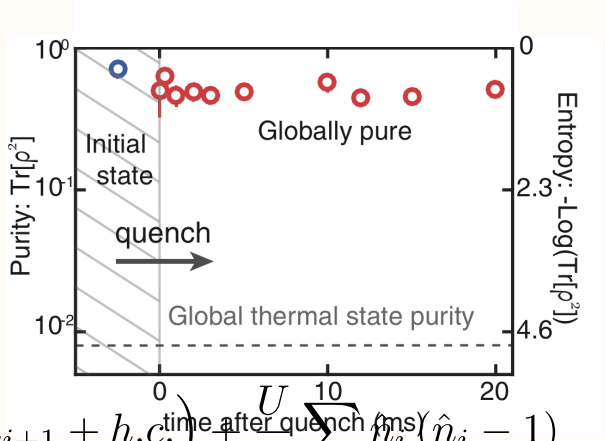


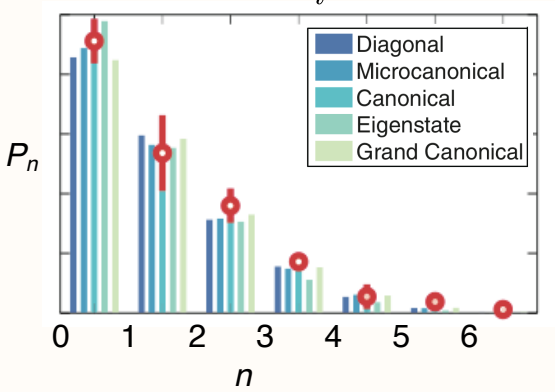


Unitary dynamics

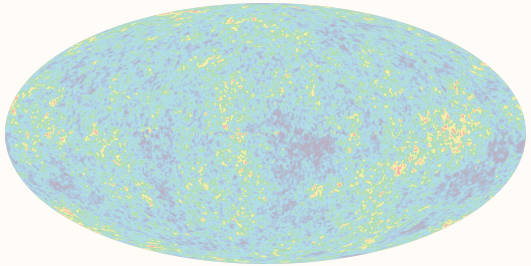
$$\hat{\mathcal{H}} = -J\sum_i \left(\hat{a}_i^\dagger \hat{a}_{i+1} + h.c.\right) + \frac{U}{2}\sum_i \hat{n}_i\left(\hat{n}_i - 1\right)$$



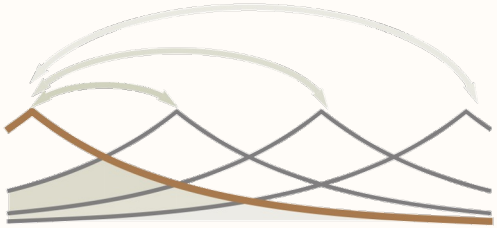




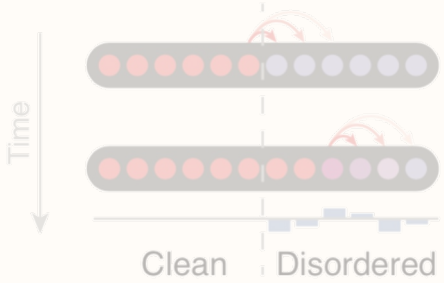
OUTLINE



Quantum thermalization



Localization and transition



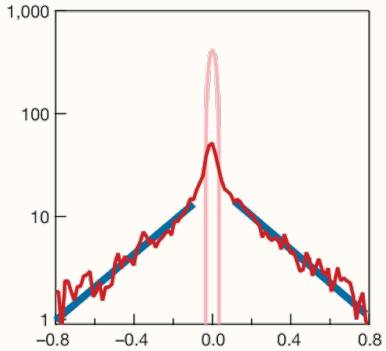
Quantum avalanches

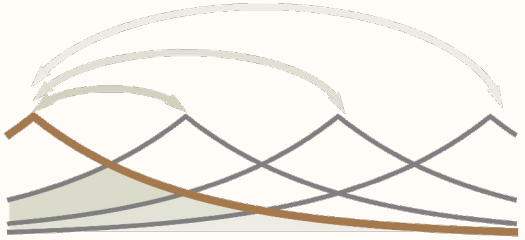
MANY-BODY LOCALIZATION

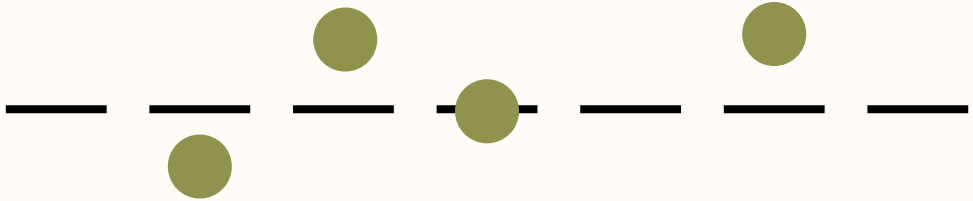
Disorder:
Anderson localization

+

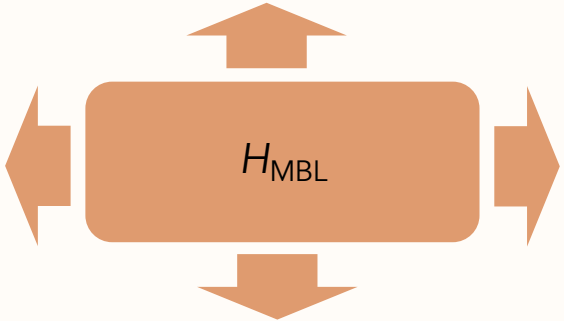
Interactions:
Many-body localization



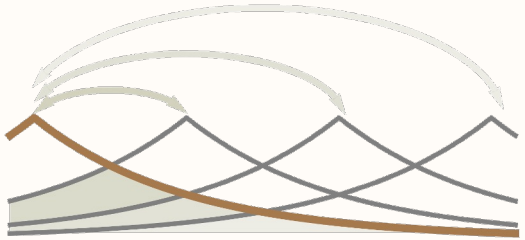




TWO COMPETING EXPONENTIALS



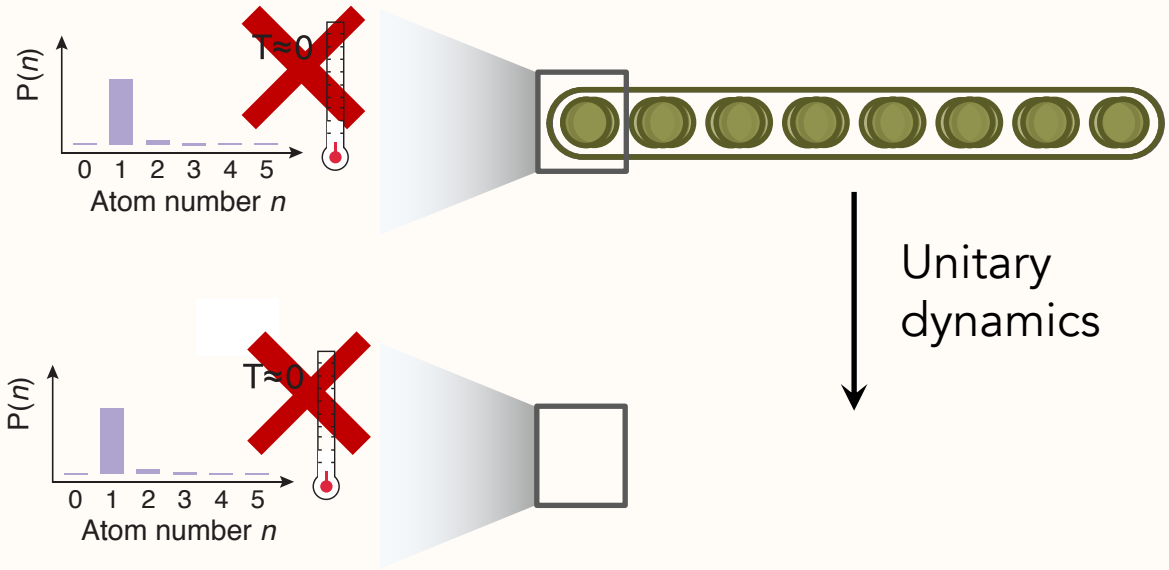
Hilbert space
grows exponentially
➔ thermalization,
ergodicity breaking



Localization
Integrals of motion,
reduces number of
degrees of freedom

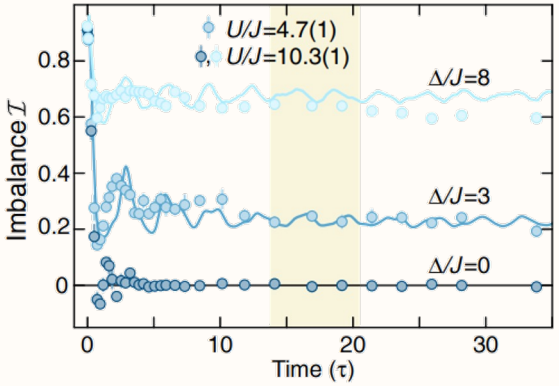
Which one wins?
Basko, Aleiner, Altshuler 2006: localization wins
Also Anderson 1958, Imbrie 2014

BREAKDOWN OF THERMALIZATION

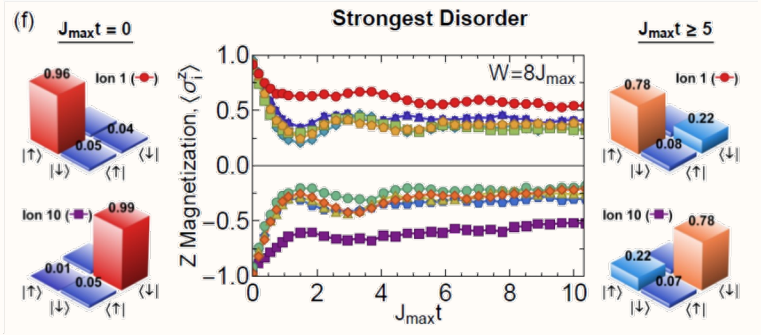


No thermalization!

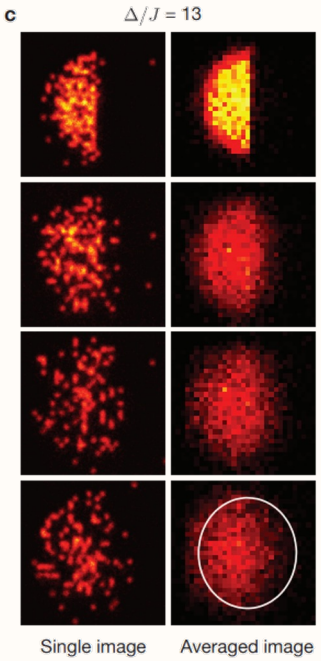
SUPPRESSION OF TRANSPORT



M. Schreiber .et. al., *Science* **349**, 842 (2015)



J. Smith et. al., *Nat. Phys.* **12**, 907 (2016)

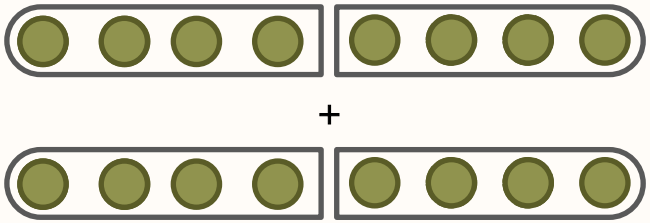


J.-Y. Choi et. al., *Science* **352**, 1547 (2016)

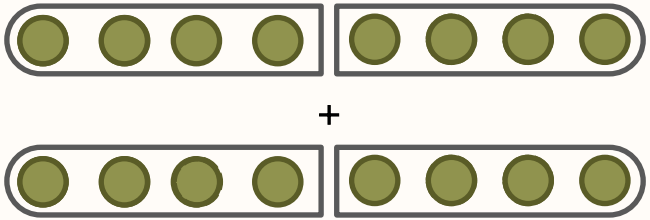
Confirms memory of initial state (global property)
➔ probe microscopically for advanced properties

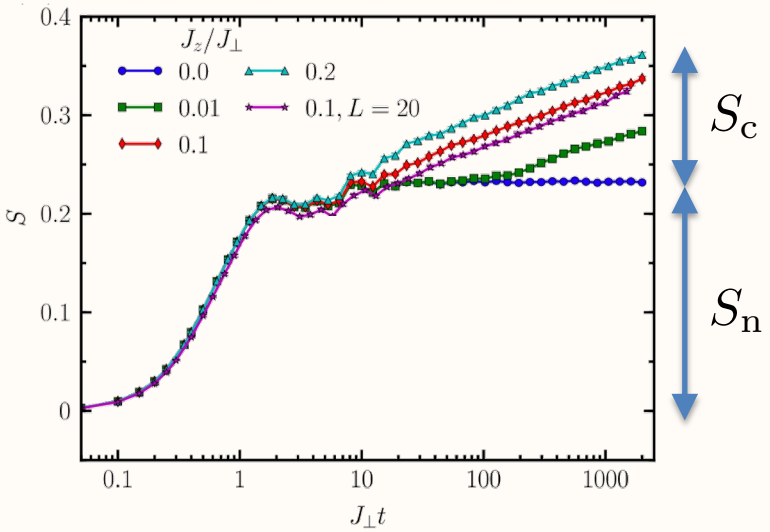
LOGARITHMIC GROWTH OF ENTANGLEMENT

Number entanglement



Configurational entanglement



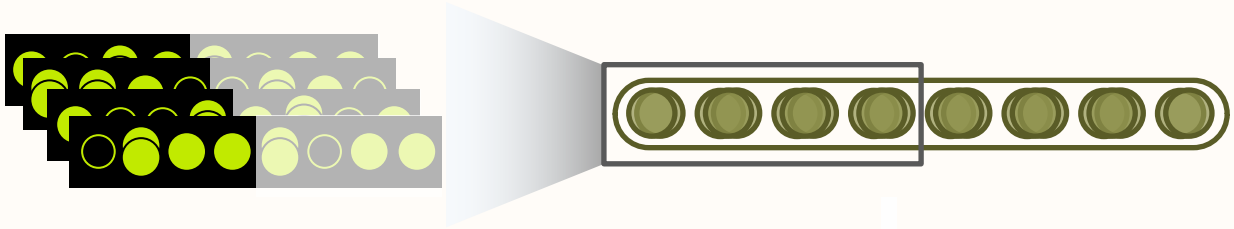


J. H. Bardarson et al., *Phys. Rev. Lett.* **109**, 017202 (2012)

Separation of total entanglement entropy

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

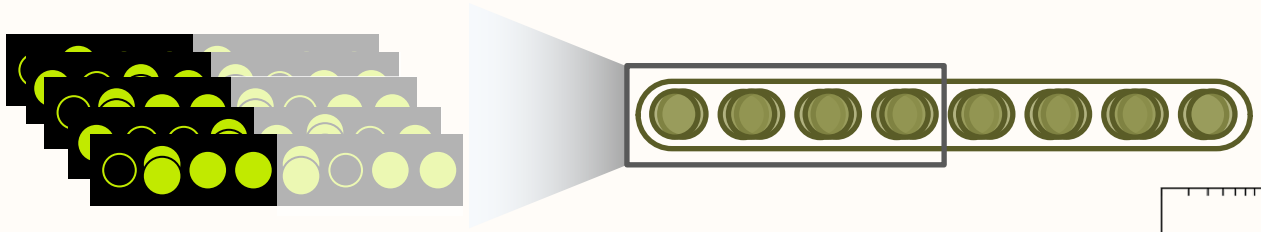
ABSENCE OF TRANSPORT



Number entropy:

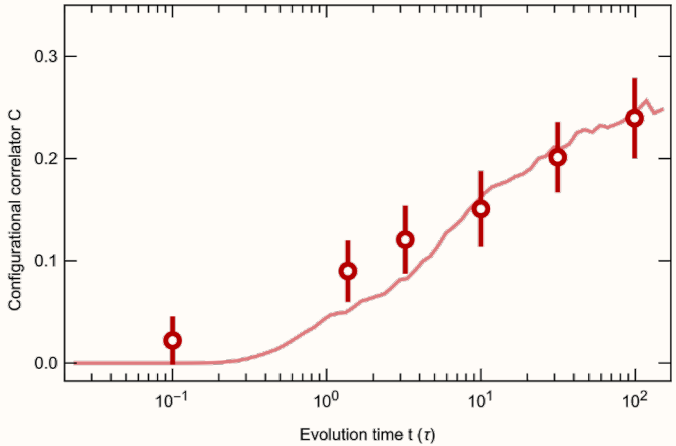
$$S_{\mathrm{n}} = -\sum_{n} p_n \log p_n$$

LOGARITHMIC GROWTH OF ENTANGLEMENT

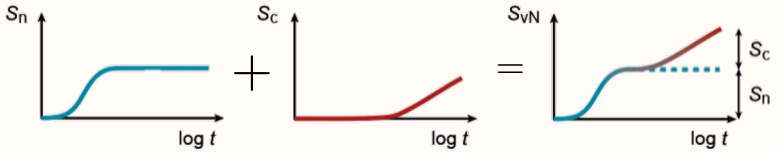


A *B*

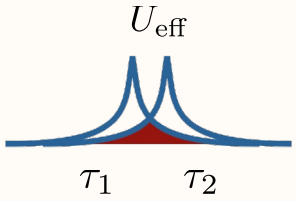
$$C = \sum_{A,B} |p(A \otimes B) - p(A)p(B)|$$



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



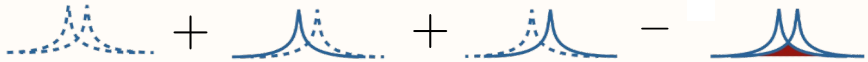
LONG-RANGE ENTANGLEMENT



Slow growth of entanglement:

$\tau_1 \otimes \tau_2 =$  $e^{iU_{\mathrm{eff}}t/\hbar}$

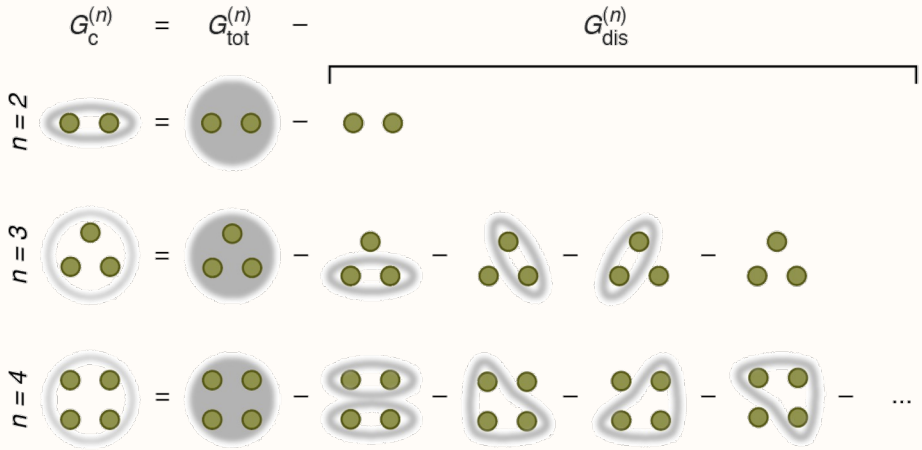
$=$  $e^{iU_{\mathrm{eff}}t/\hbar}$

➔ 

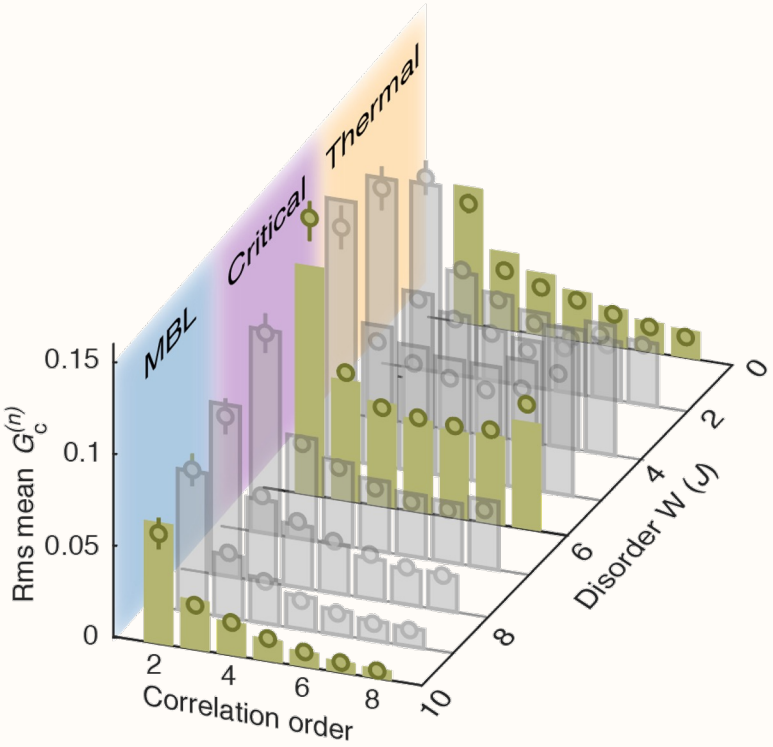
local transformation $=$ 

➔ Entanglement from eigenstate superposition!

MULTI-POINT QUANTUM CORRELATIONS

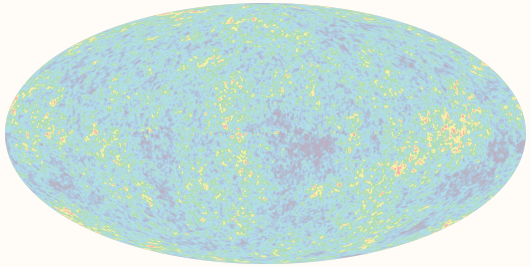


Hierarchy of correlations: non-separable at order n



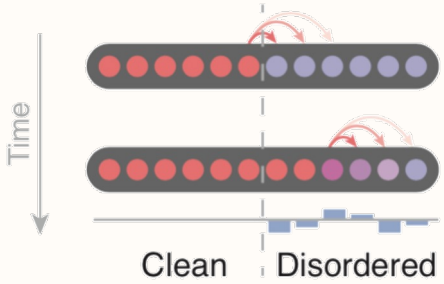
M. Rispoli et al., *Nature* 573, 385 (2019)

OUTLINE



Quantum thermalization

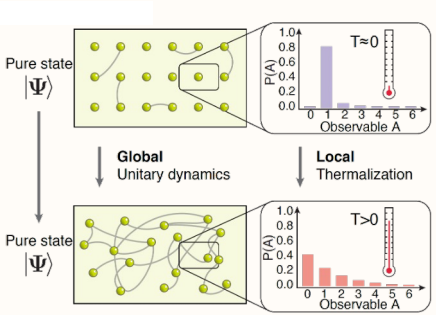
Localization and transition

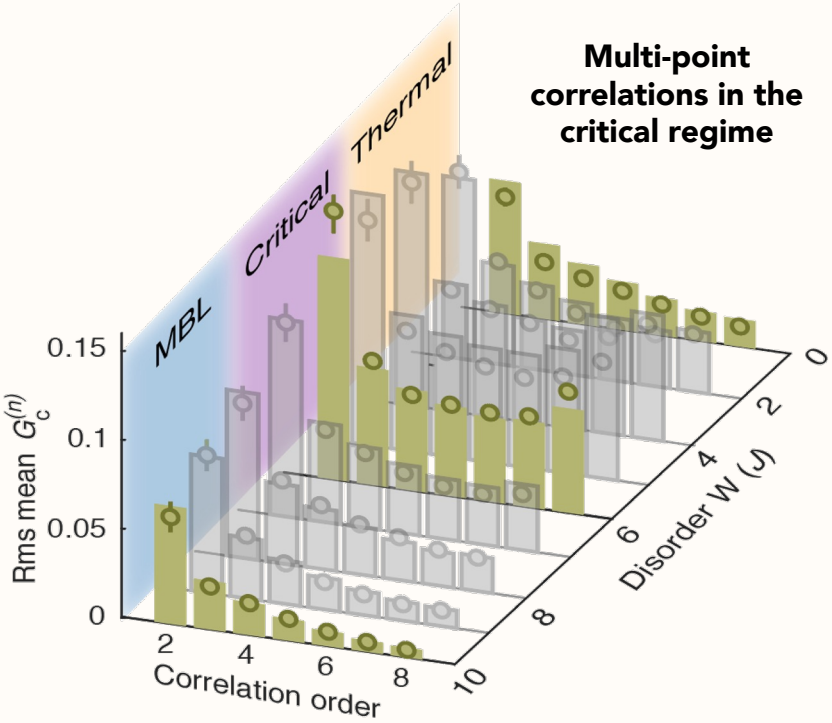


Quantum avalanches

THERMALIZATION VS LOCALIZATION

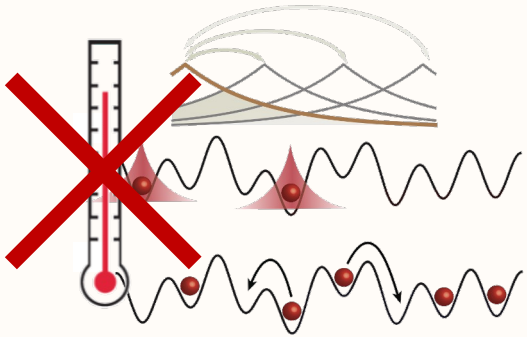
Thermalization





Multi-point correlations in the critical regime

Many-body localization

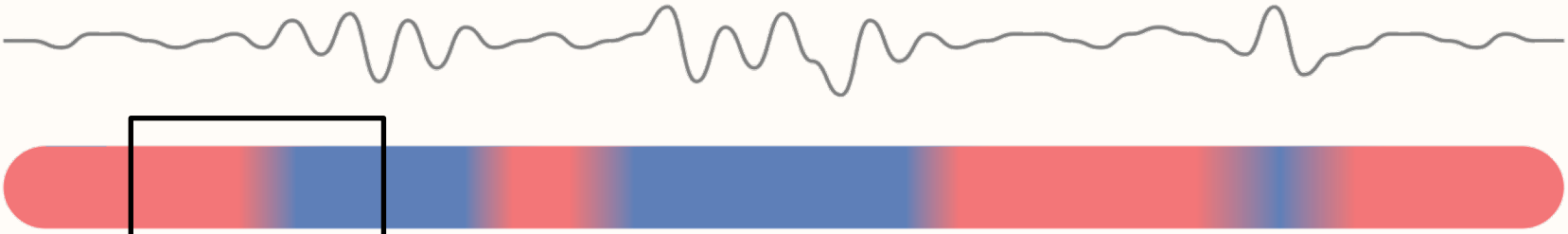


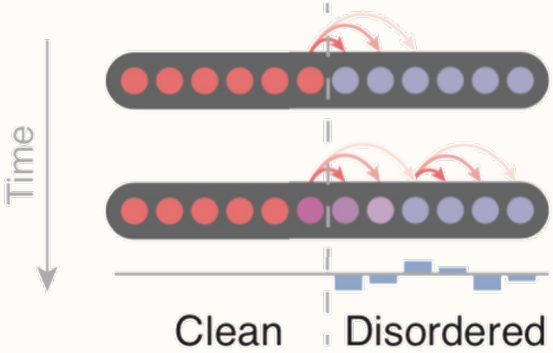
Interface between classical and quantum worlds

Disorder

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

THERMAL INCLUSIONS





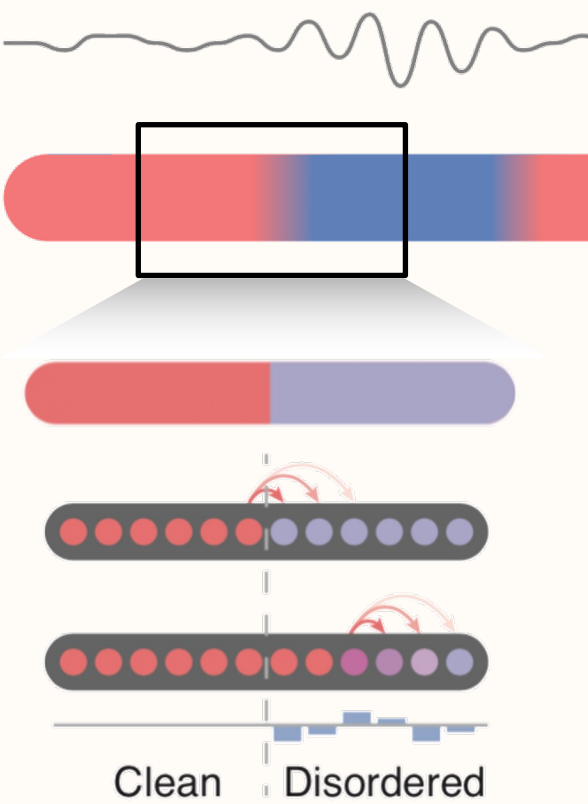
Can rare thermal regions destabilize localization?

Semi-classically: No!

Exponential decay of couplings into disordered region

However: picture neglects nonlinearities from bath-MBL interplay

THERMAL INCLUSIONS



Quantum avalanches

Bath coupling range set by density of states

Bath thermalizes nearest sites within range

Bath absorbs first site: size increases

Bath density of states increases

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.

2019

2020

2021

2022

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.

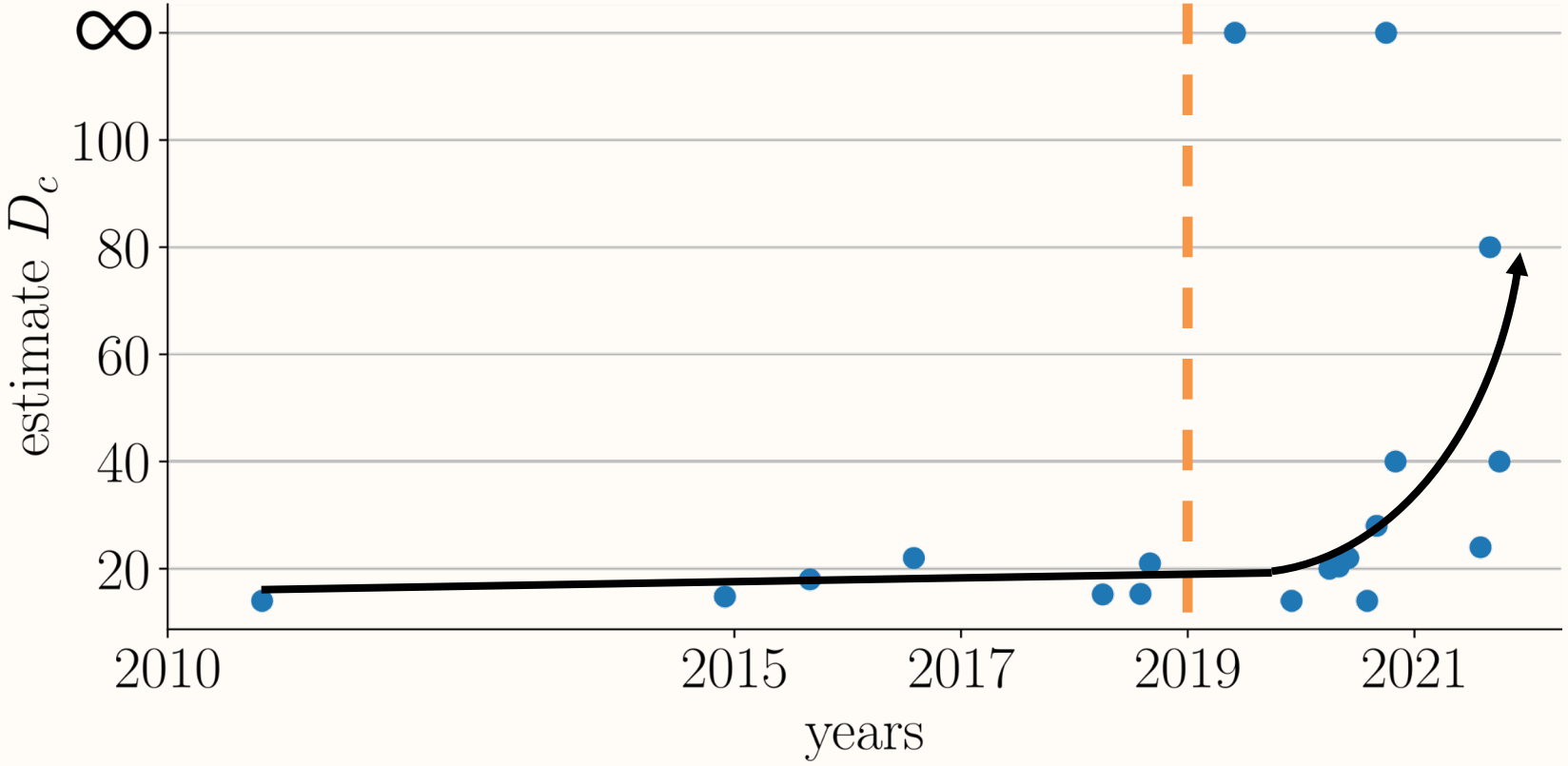
Avalanches and many-body resonances In many-body localized systems
Alan Morningstar et al.

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.

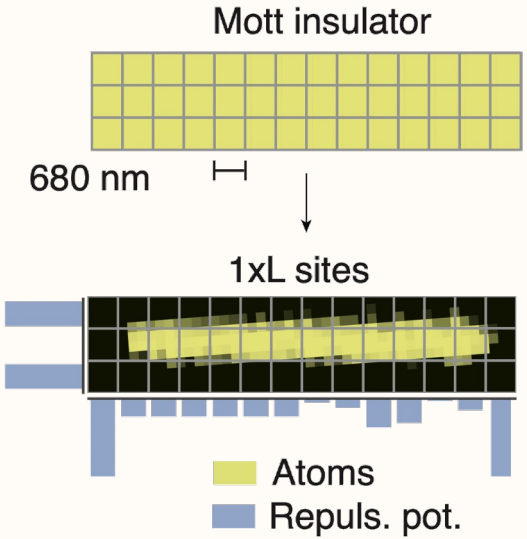
credit: Max Kiefer Emmanouilis

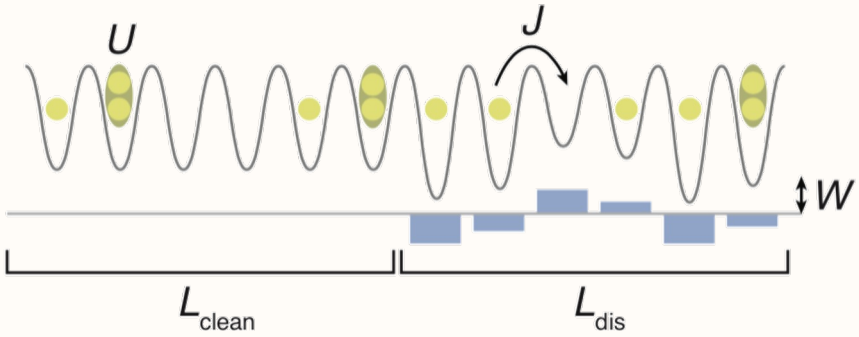
IS MBL STABLE?



credit: Max Kiefer Emmanouilis

CLEAN-DISORDER INTERFACE

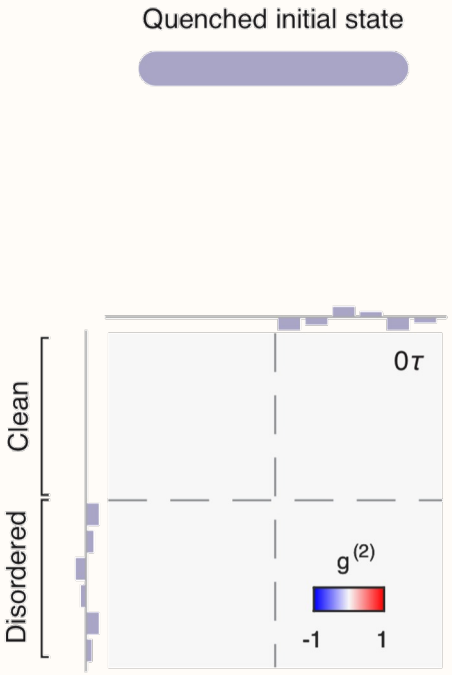




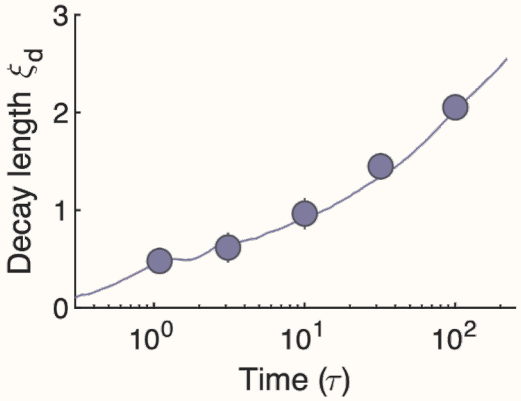
- L_{clean} sites without disorder
- L_{dis} sites with disorder (quasi-periodic)

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

AVALANCHE DYNAMICS



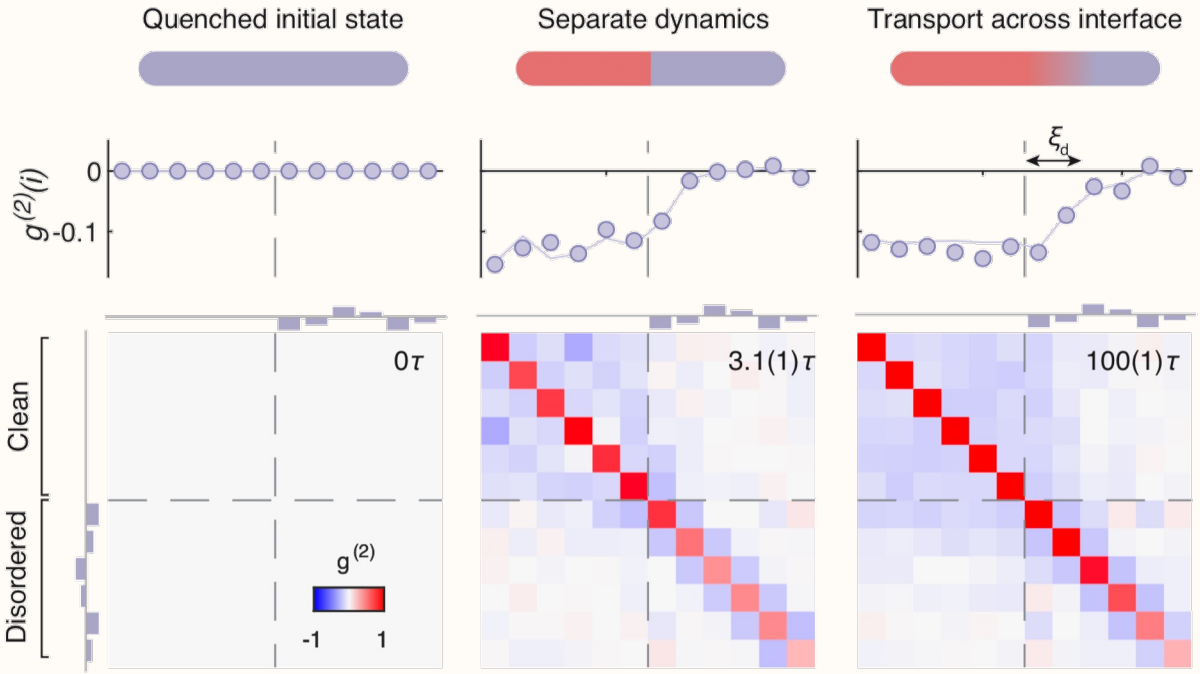
Accelerated thermalization



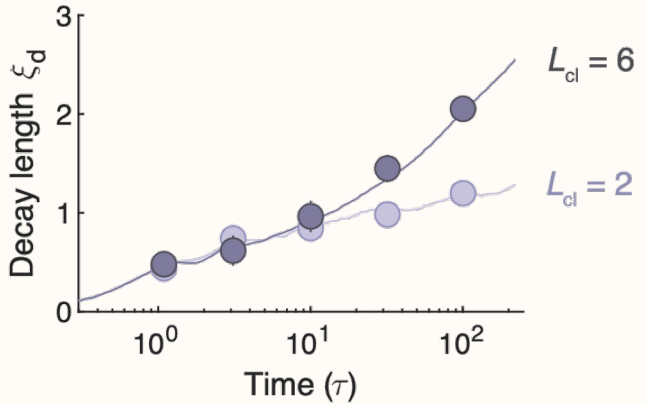
$$g^{(2)}(i,j) = \langle \hat{n}_i n_j \rangle - \langle \hat{n}_i \rangle \langle \hat{n}_j \rangle$$

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

AVALANCHE DYNAMICS



Accelerated thermalization



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

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

OUTLOOK

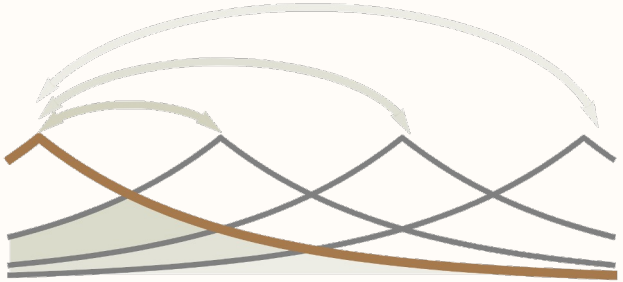
What we know

- 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?



VIENNA LAB





VCQ

FWF
Der Wissenschaftsfonds.

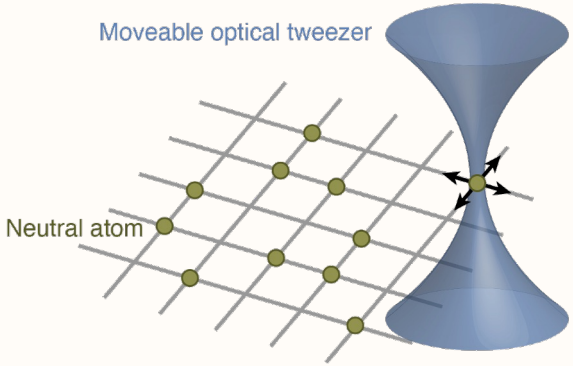
quantA

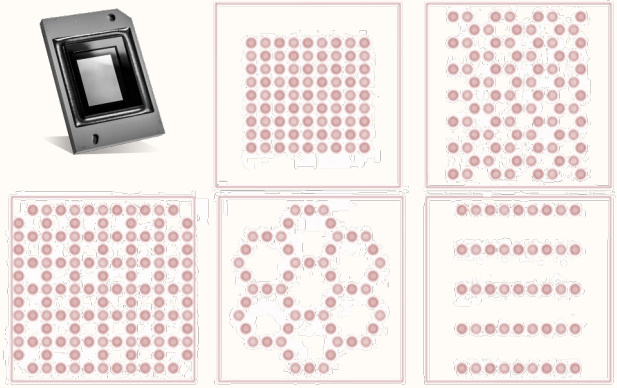
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ASSEMBLING QUANTUM MATTER

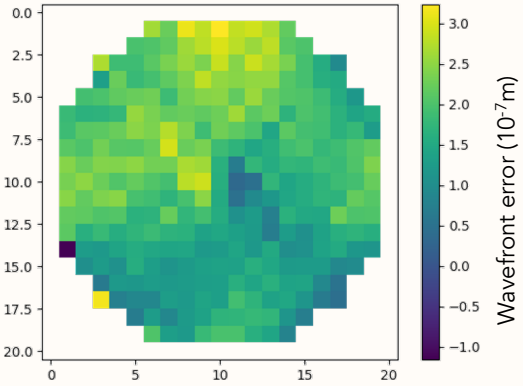




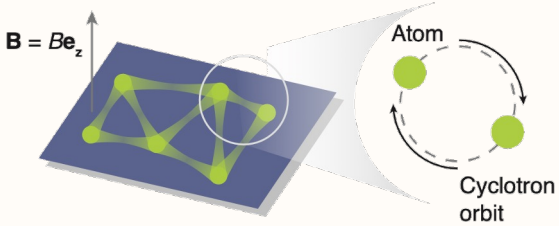
Bluvstein et al., Science 371, 1355 (2021)

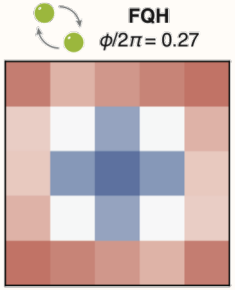
Programmable fermionic systems

- 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



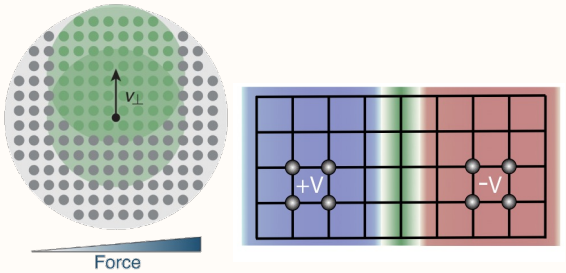
TOPOLOGICAL MATTER WITH COLD ATOMS





J. Léonard et al., *Nature* **619**, 495 (2023)

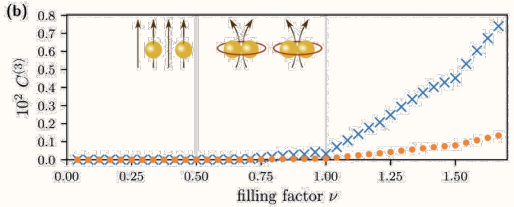
Further topological signatures



Repellin et al., PRA 102, 063317 (2020)

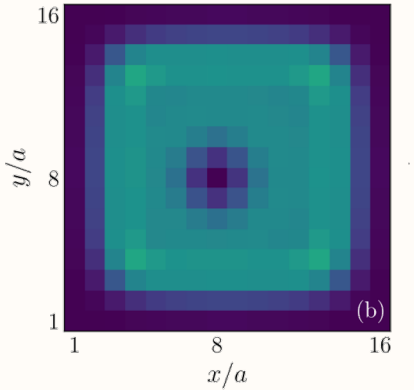
Raciunas et al., PRA 98, 063621 (2018)

Pfaffian states



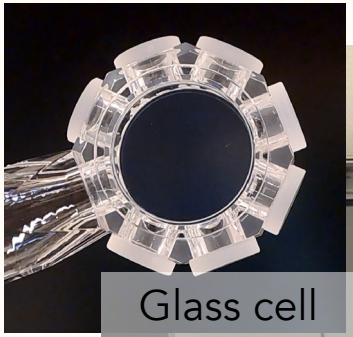
Palm et al., PRB 103, L161101 (2021)

Anyons



Macaluso et al., PRR 2, 013145 (2020)

ASSEMBLING QUANTUM MATTER



Glass cell

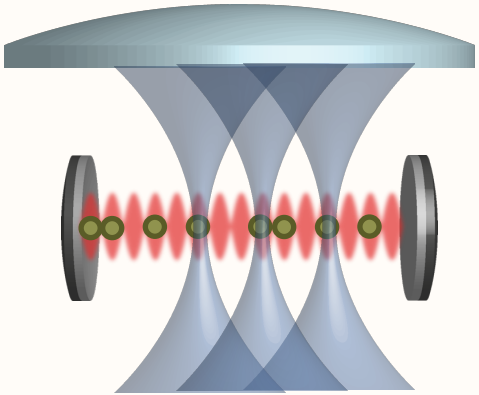
Compact vacuum setup

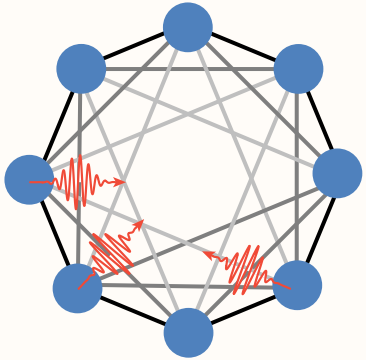
Key features

- Lattice constructed and filled site by site
- Fermionic and bosonic Lithium
- Optimized separation of energy scales for Floquet
- Controllable interactions via Feshbach resonance
- Blue-detuned lattices for improved coherence time

PHOTON-COUPLED ATOMIC ARRAYS

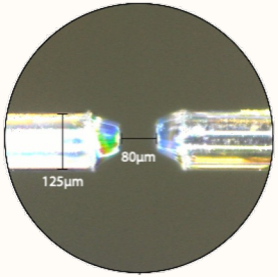
New frontier:
Local ***and*** non-local control of interactions

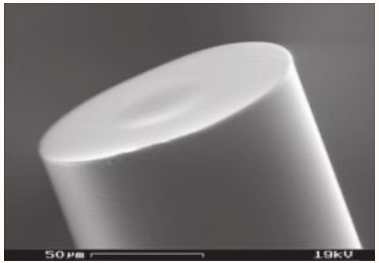




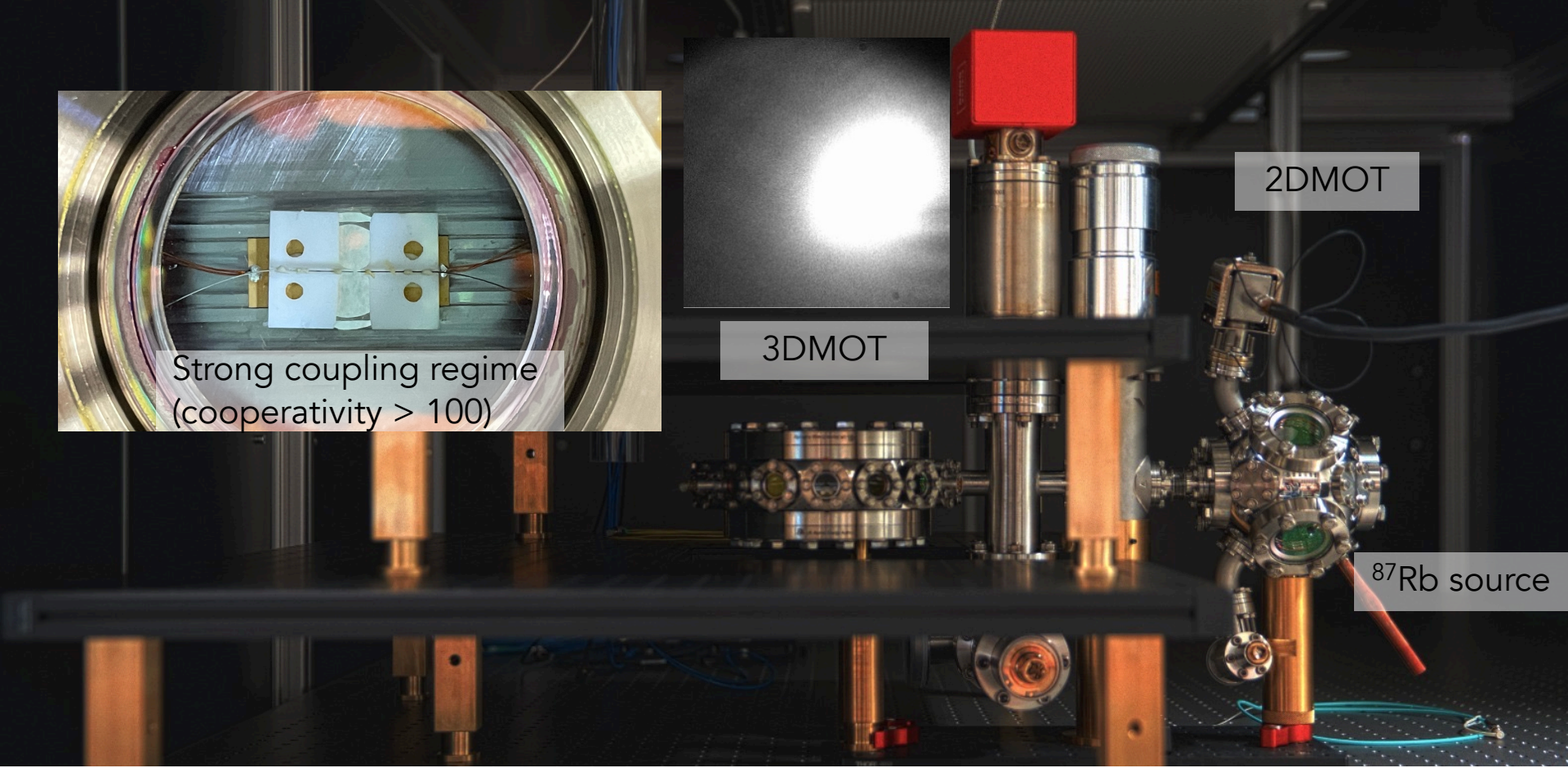


Light-induced coupling
- Spatial control: any distance, any groups of atoms
- Dynamical control
- New readout techniques



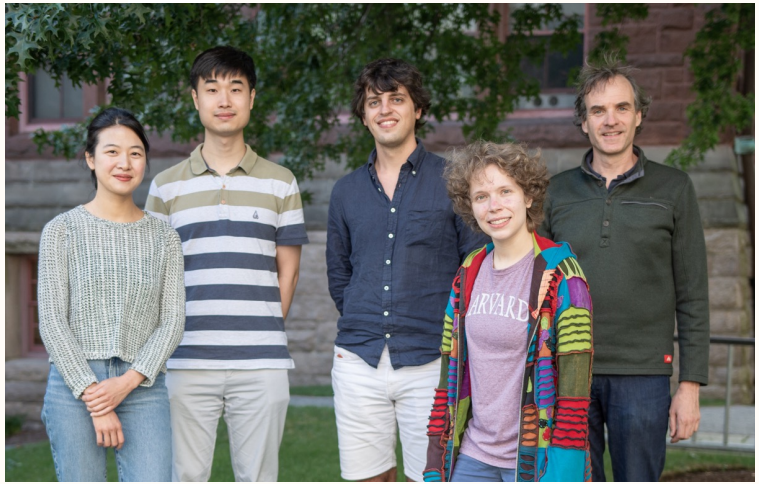


Ideal to prepare topological states, e.g. quantum spin liquids


Strong coupling regime
(cooperativity > 100)
3DMOT
2DMOT
^{87}Rb source

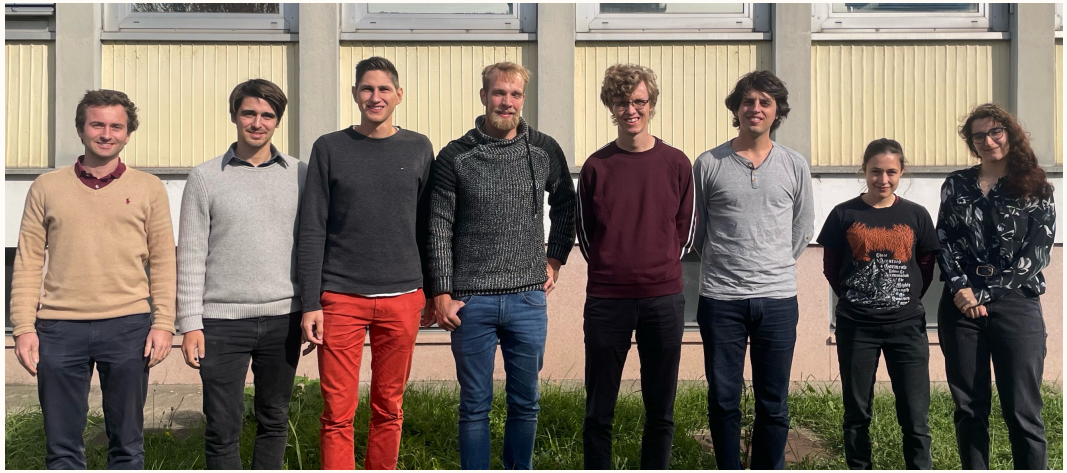

3 µm

HARVARD UNIVERSITY



J. Kwan S. Kim J. L. P. Segura M. Greiner

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C. Grave J. Schabbauer S. Roschinski S. Waddington
F. Leindecker M. Holten J. L. I. Safa



D. Sels,
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C. Repellin,
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THANK YOU