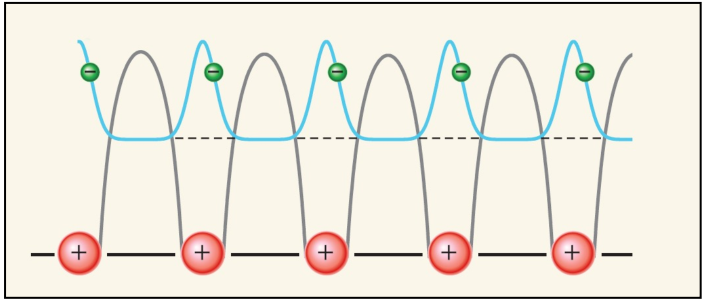
QUANTUM SIMULATION WITH OPTICAL LATTICES

QACTUS workshop Barcelona, 7th September 2023

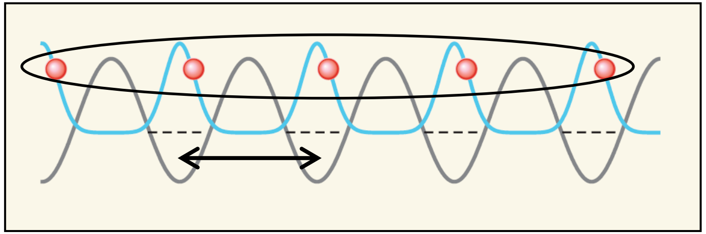
Julian Leonard
TU Wien/Harvard University

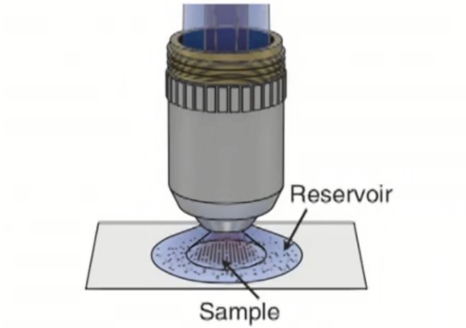
OPTICAL LATTICES

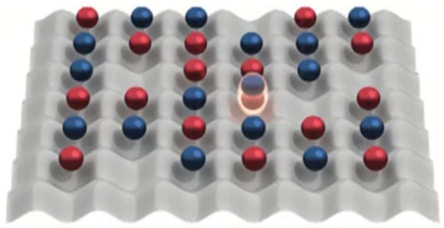
Electrons in a crystal lattice



Atoms in an optical lattice





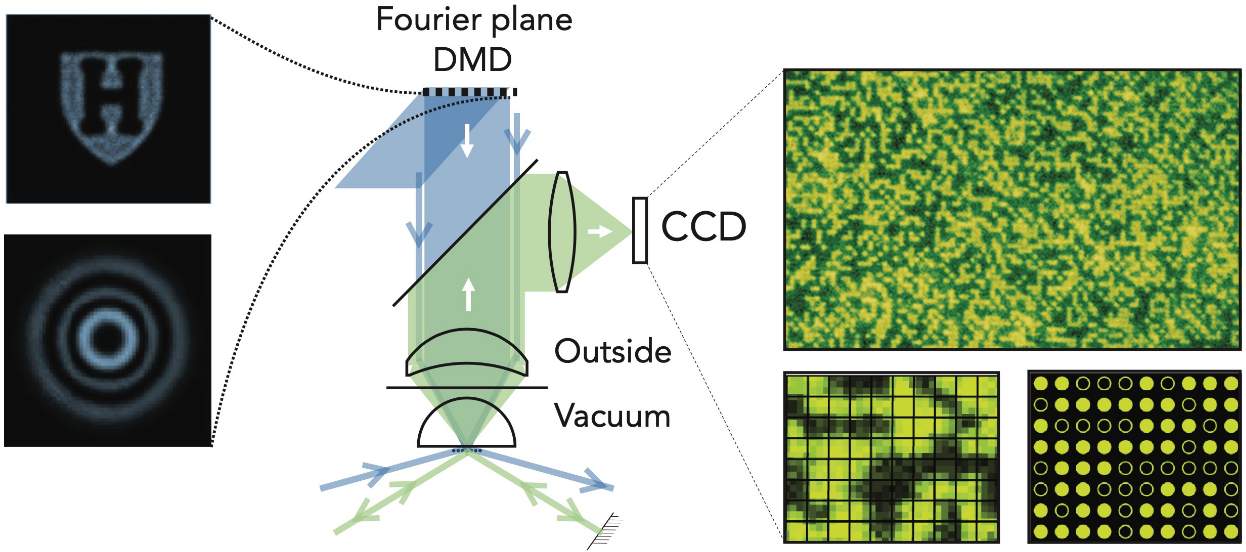


- Excellent coherence
- Scalable
- Site-resolved control
- Single-atom readout

QUANTUM GAS MICROSCOPE

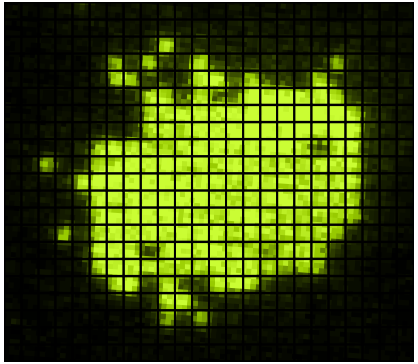
Site-resolved control

Single-atom readout

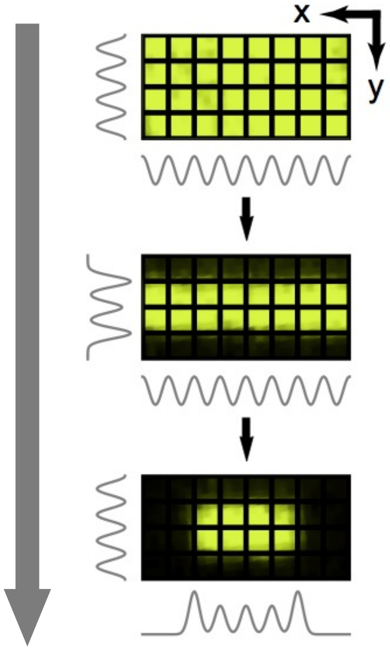


ARBITRARY POTENTIALS

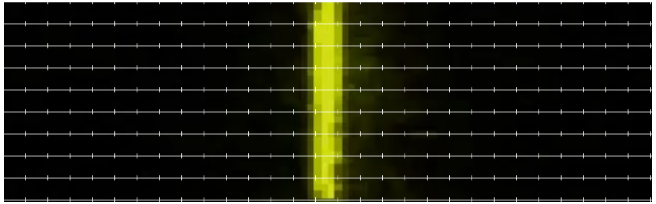
Low-entropy
Mott insulator



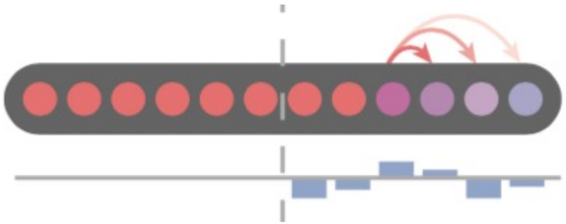
Local potentials



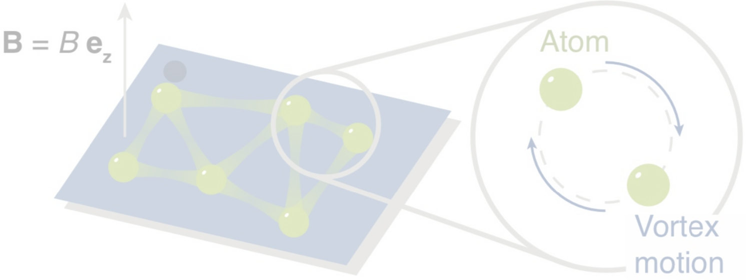
high fidelity
state preparation

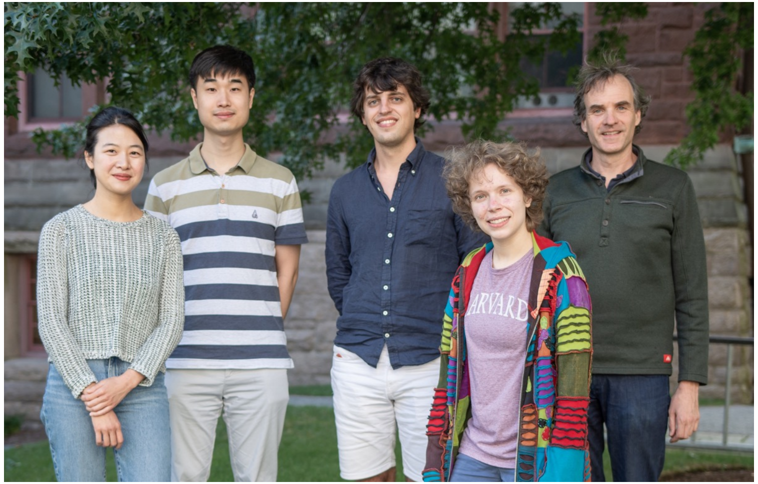


QUANTUM AVALANCHES



FRACTIONAL QUANTUM HALL STATES





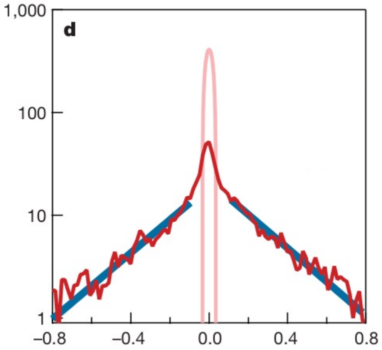
Joyce Kwan | Sooshin Kim | J. L. | Perrin Segura | Markus Greiner

Dries Sels, NYU/Flatiron

Eugene Demler ETH Zürich

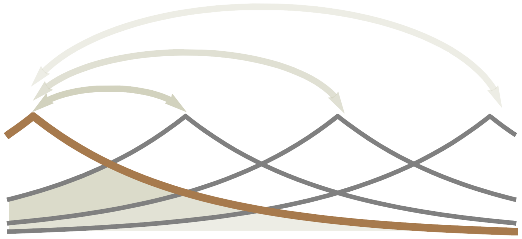
MANY-BODY LOCALIZATION

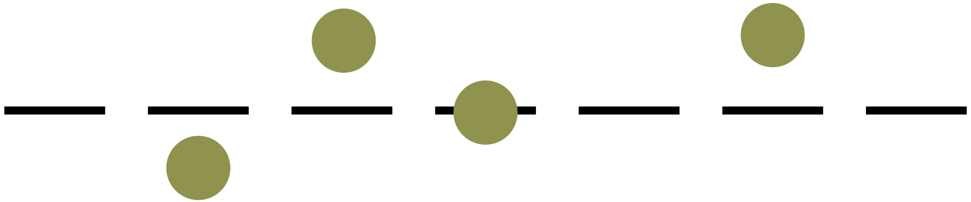
Disorder:
Anderson localization



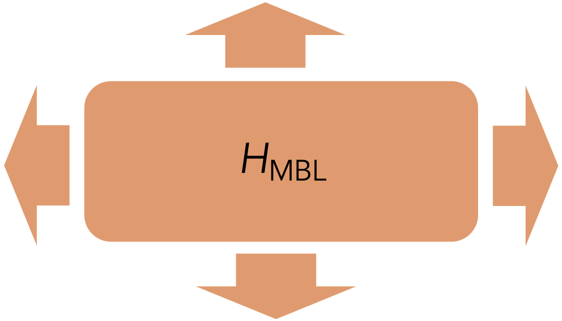
+

Interactions:
Many-body localization

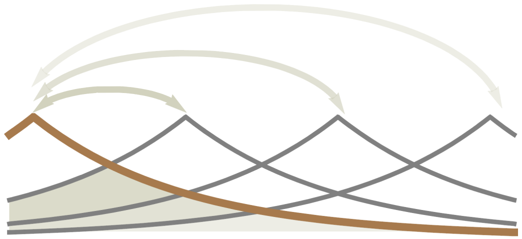




TWO COMPETING EXPONENTIALS



Hilbert space
grows exponentially
➔ thermalization,
ergodicity breaking

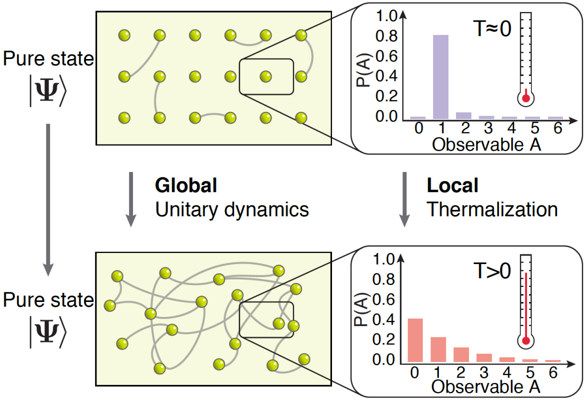


Localization
Integrals of motion,
reduces number of
degrees of freedom

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

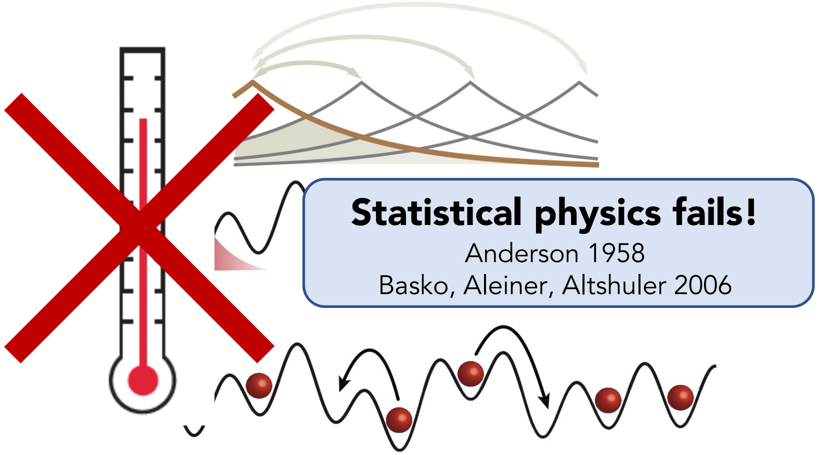
THERMALIZATION VS LOCALIZATION

Thermalization



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

Many-body localization

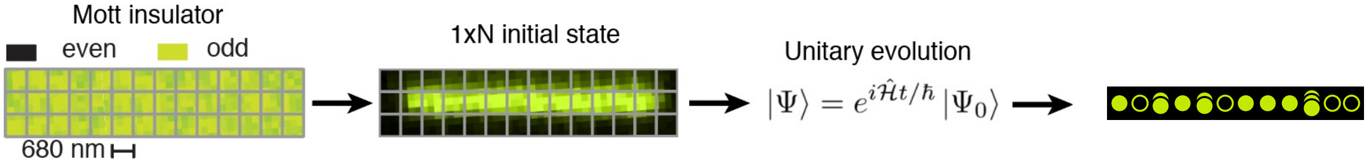


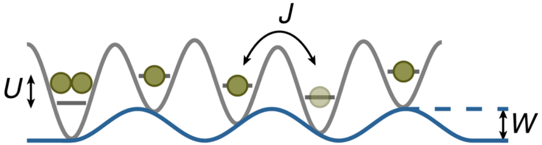
Local quantum information persists
➔ Generally full quantum description required

Interface between classical and quantum worlds

Disorder

NON-EQUILIBRIUM DYNAMICS



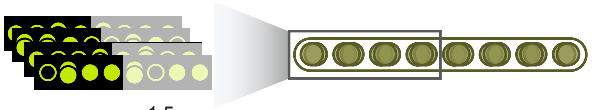


Bose-Hubbard model
programmable site offsets

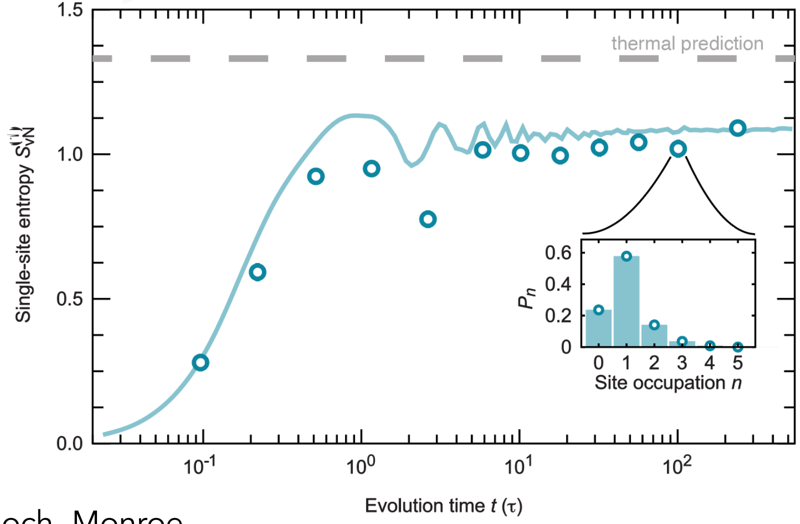
$$\hat{\mathcal{H}} = -J\sum_i \left(\hat{a}_i^\dagger \hat{a}_{i+1} + h.c.\right) + \frac{U}{2}\sum_i \hat{n}_i\left(\hat{n}_i - 1\right) + W\sum_i h_i \hat{n}_i$$

U = 3J

h_i quasi-periodic with golden ratio 1.618



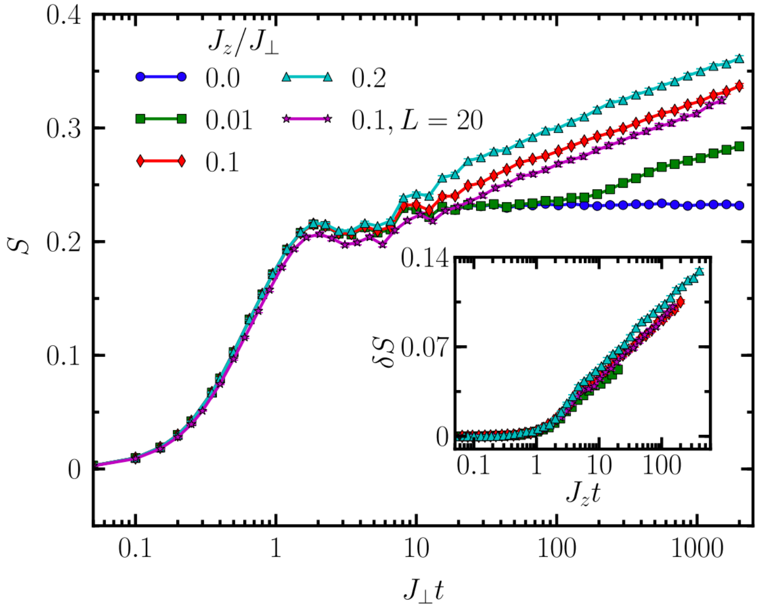
$$S_n = -\sum_n p_n \log p_n$$



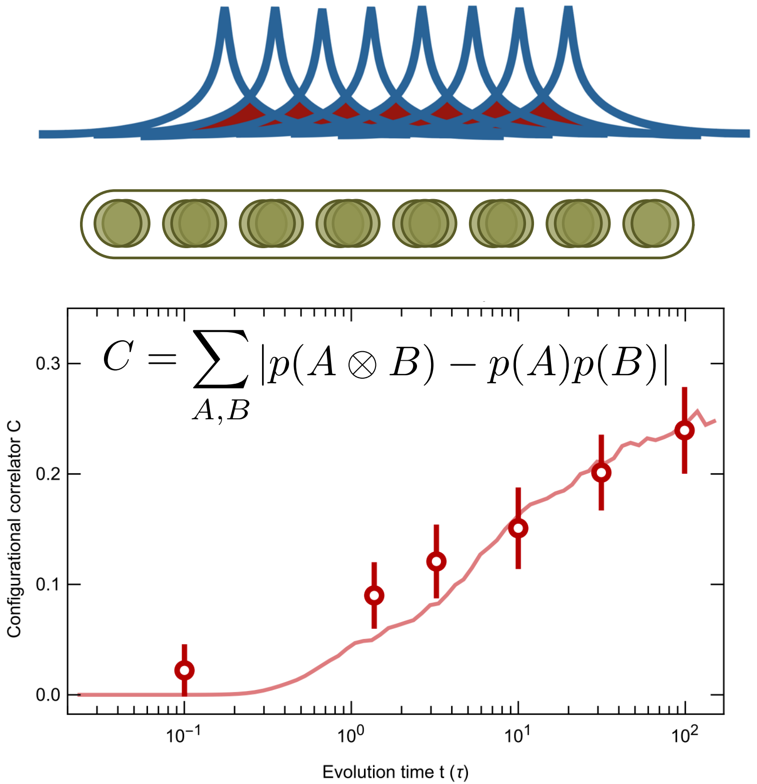
Also: Bloch, Monroe, DeMarco, Inguscio...

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

DEPHASING



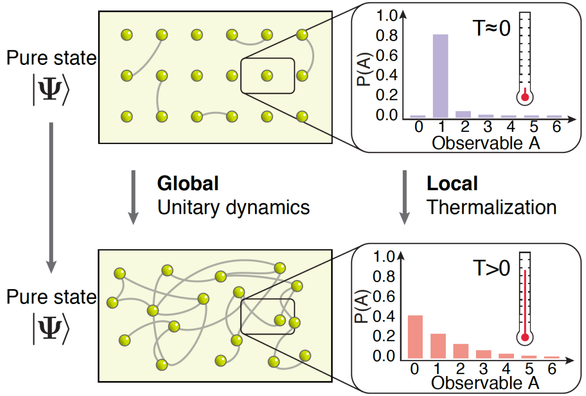
J. H. Bardarson et al., *PRL* **109**, 017202 (2012)



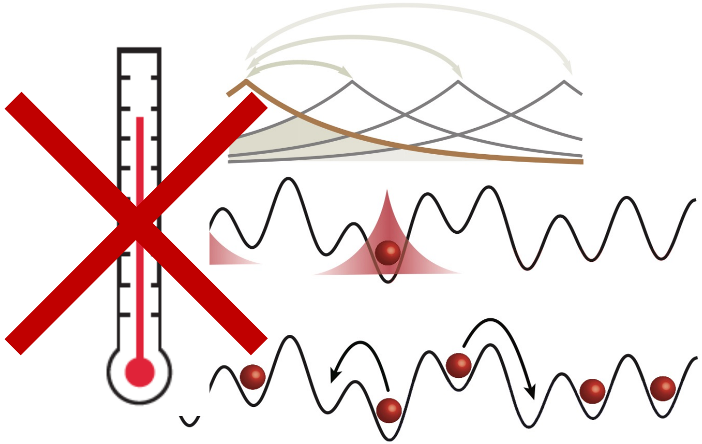
A. Lukin et al., Science 364, 6437 (2019)

THERMALIZATION VS LOCALIZATION

Thermalization



Many-body localization

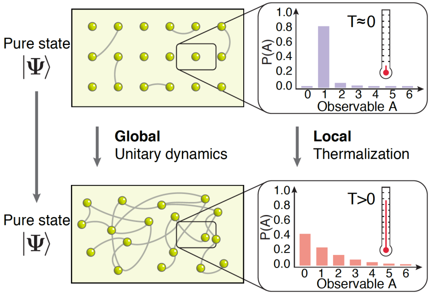


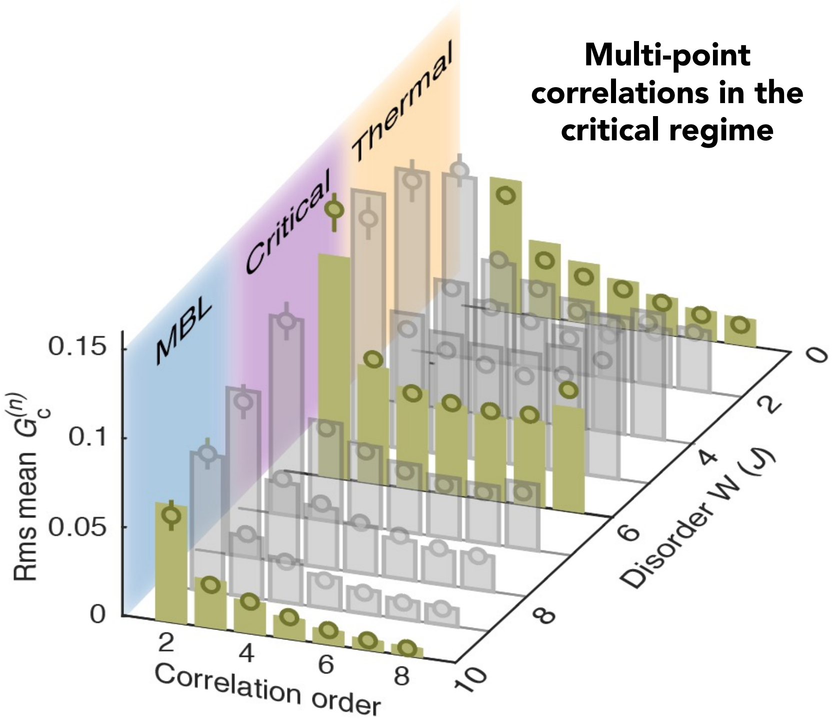
Interface between classical and quantum worlds

Disorder

THERMALIZATION VS LOCALIZATION

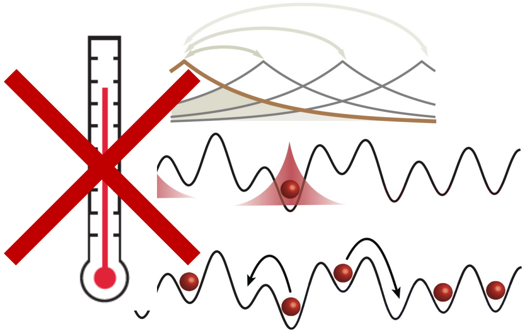
Thermalization





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)

IS MANY-BODY LOCALIZATION STABLE?

CONTRA

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

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

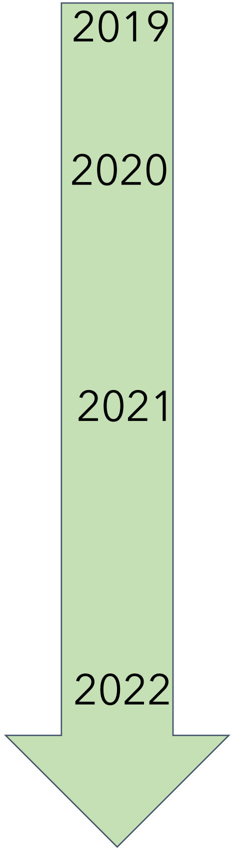
Slow delocalization of particles in many-body localized phases
Maximilian Kiefer-Emmanouilidis et al.

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 the 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 Ander4son and many-body localization transitions
Piotr Sierant et al.

Polynomially filtered exact diagonalization approach to many-body localization
Piotr Sierant et al.

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

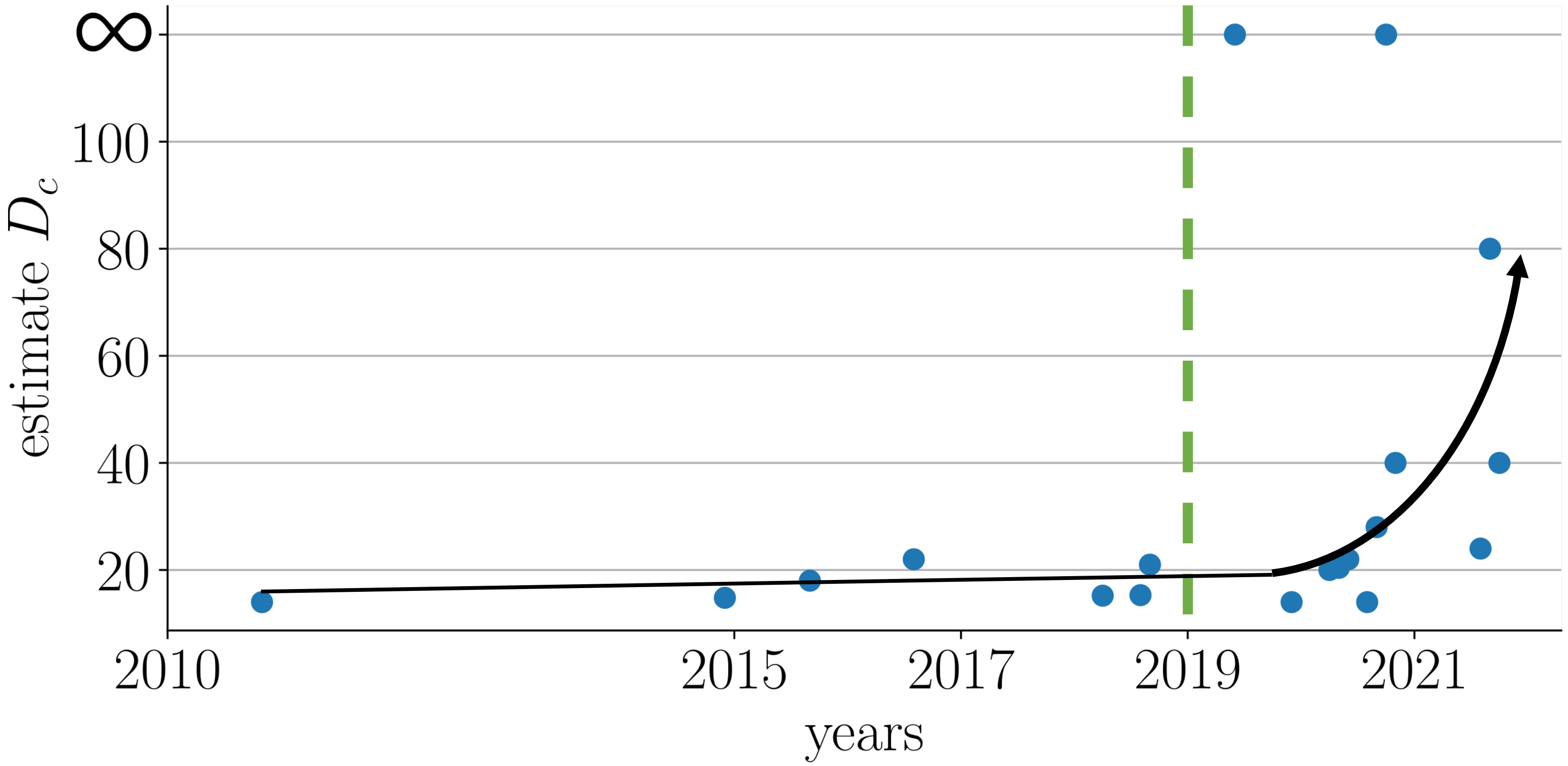
Avalanches and many-body resonances in many-body localized systems
Alan Morningstar et al.

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

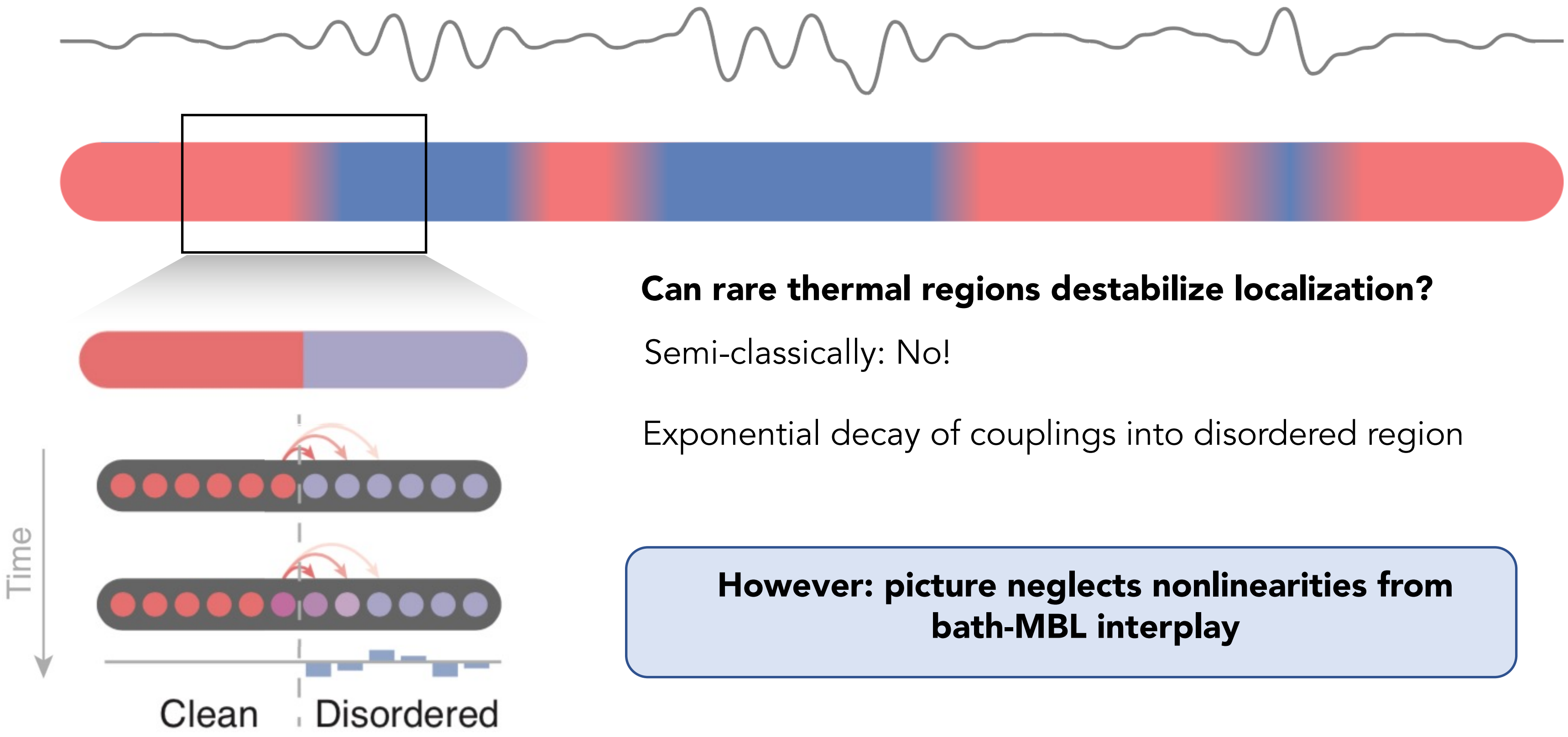
Resonance-induced growth ot eh number entropy in strongly disordered systems
Roopayan Ghosh et al.

…

IS MANY-BODY LOCALIZATION STABLE?



THERMAL INCLUSIONS



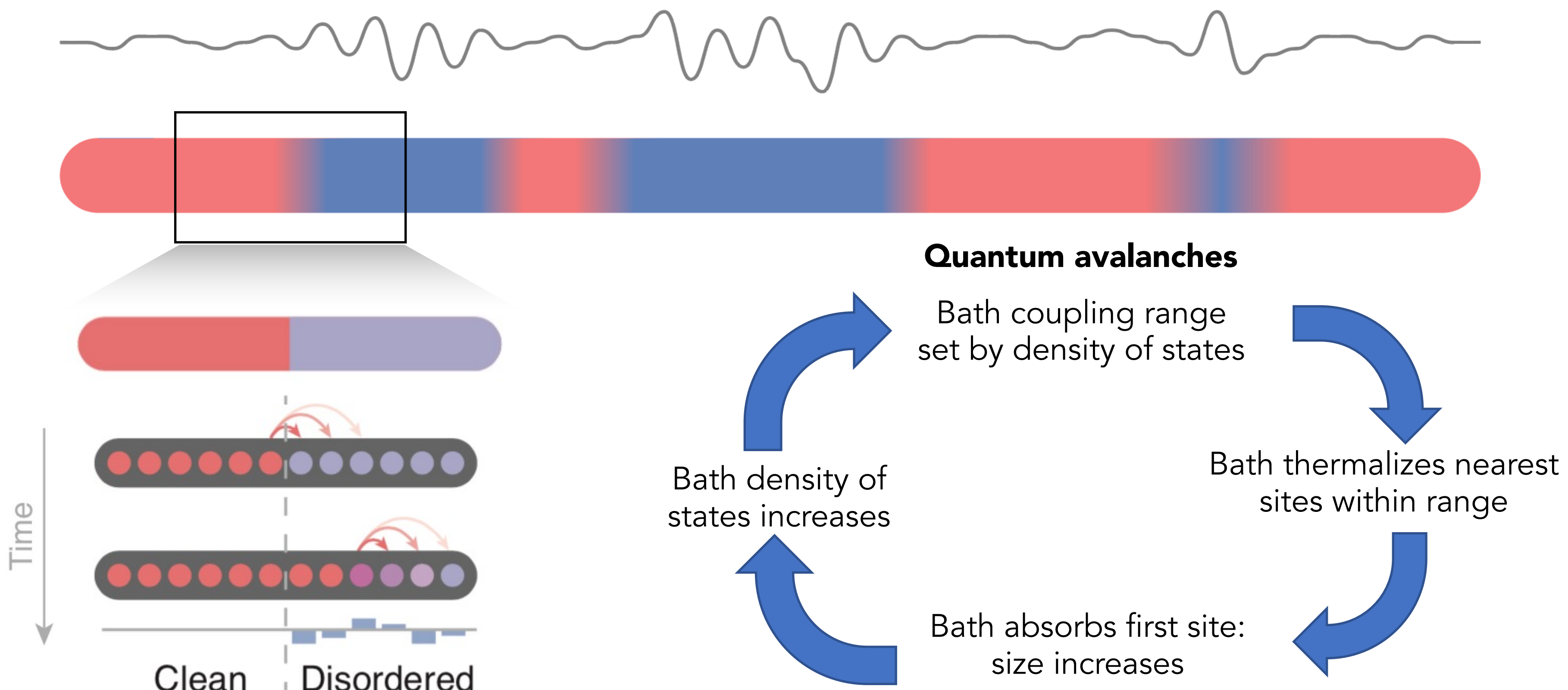
Can rare thermal regions destabilize localization?

Semi-classically: No!

Exponential decay of couplings into disordered region

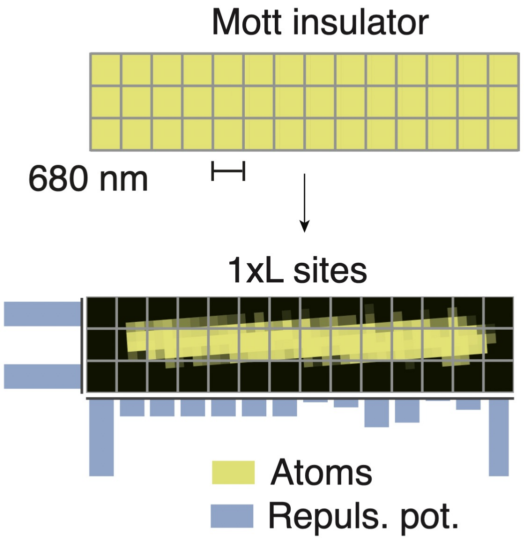
However: picture neglects nonlinearities from bath-MBL interplay

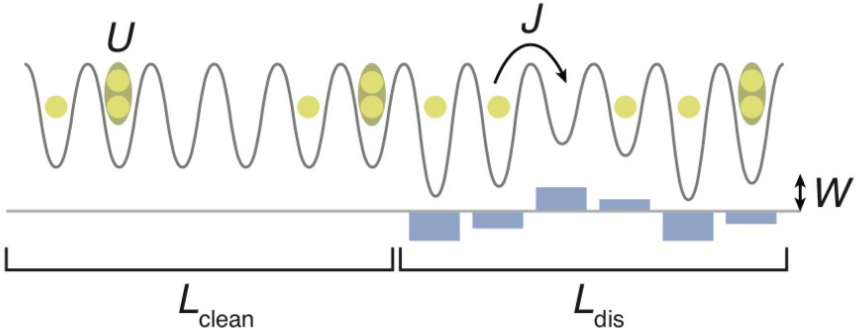
THERMAL INCLUSIONS



Long-term fate of MBL determined by avalanches?

CLEAN-DISORDER INTERFACE

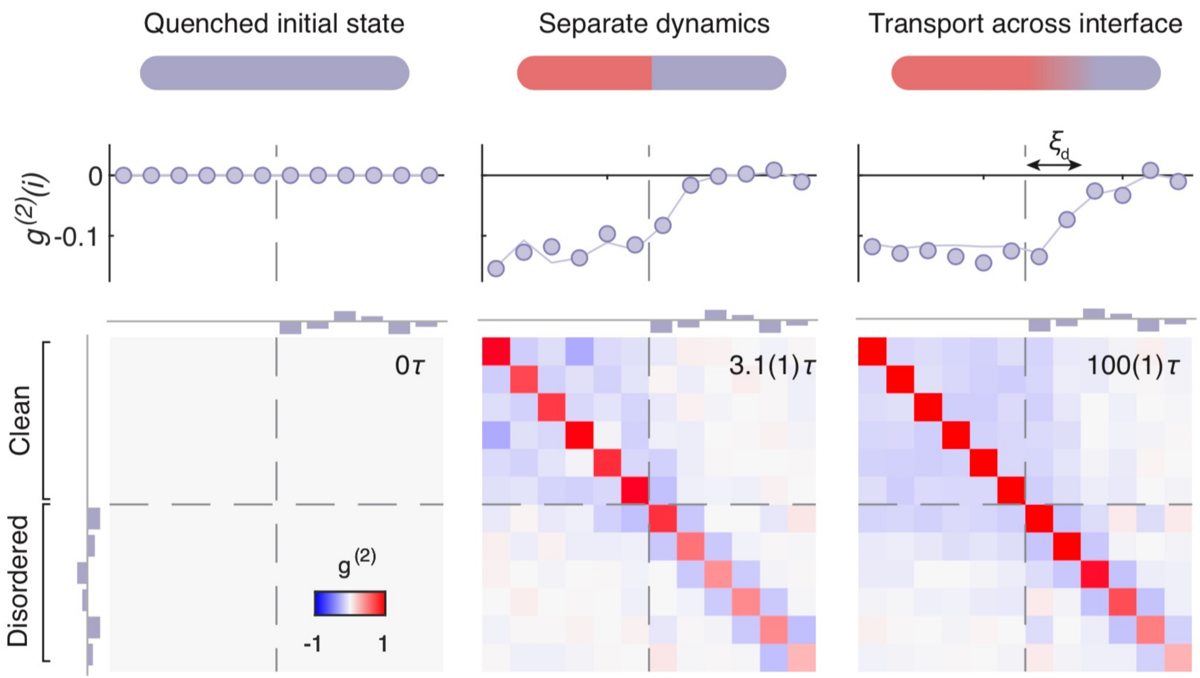




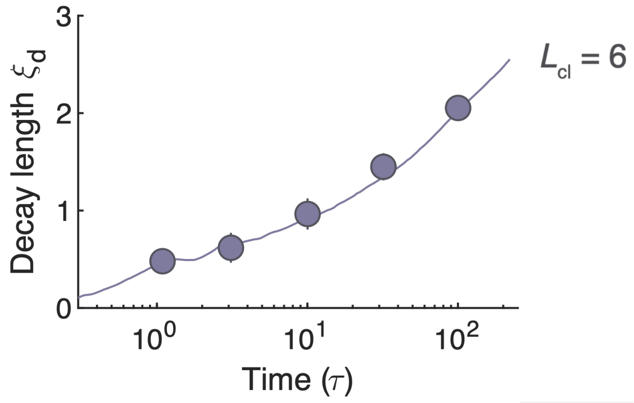
- L_{clean} sites without disorder
- L_{dis} sites with disorder (quasi-periodic)

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

AVALANCHE DYNAMICS



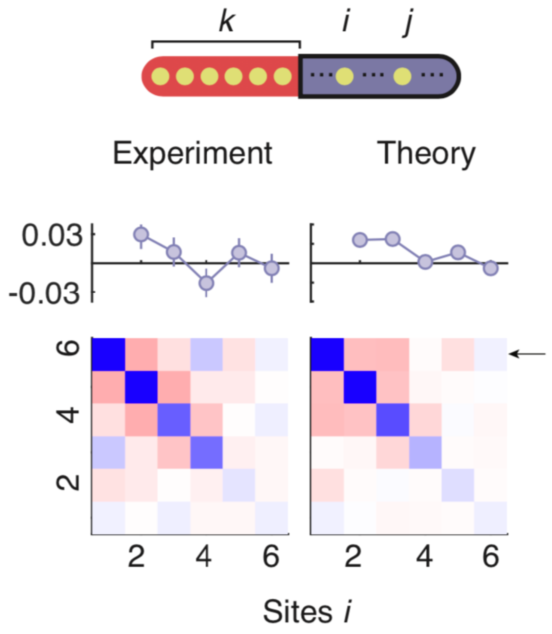
Accelerated thermalization

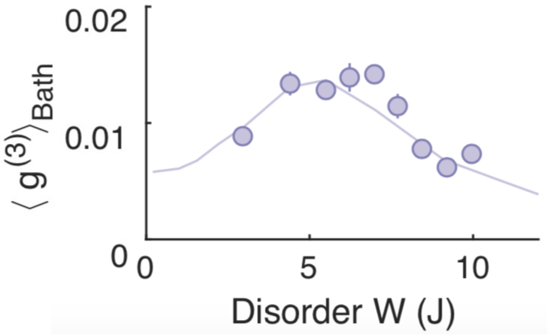


$$g^{(2)}(i,j) = \langle \hat{n}_i n_j \rangle - \langle \hat{n}_i \rangle \langle \hat{n}_j \rangle$$

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

THREE-BODY CORRELATIONS

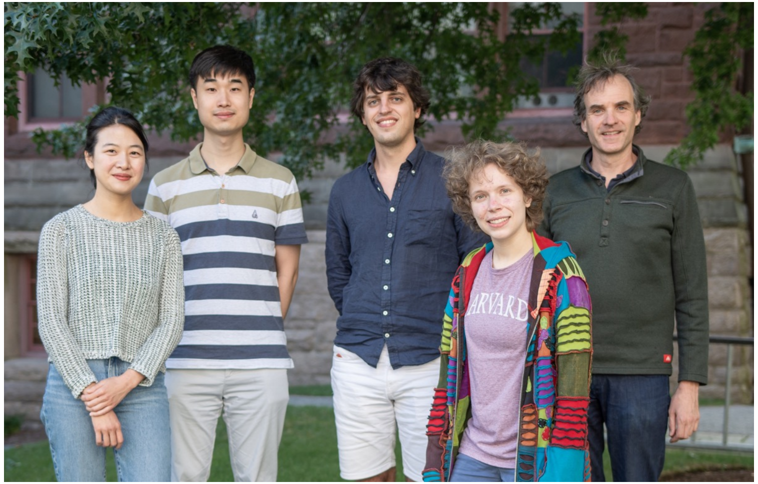




➔ driven by many-body processes

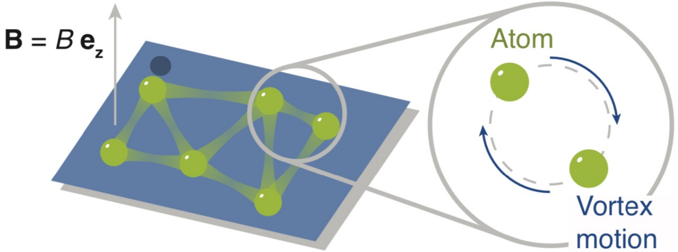
J. Léonard et al., Nat. Phys. 19, 481 (2023)

AVALANCHE THERMALIZATION



Joyce Kwan | Sooshin Kim | J. L. | Perrin Segura | Markus Greiner

FRACTIONAL QUANTUM HALL PHYSICS



Nathan Goldman
ULB

Fabian Grusdt
LMU Munich

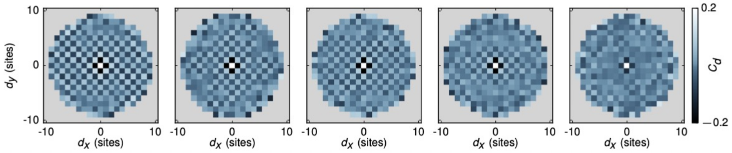
Cécile Repellin,
Univ. Grenoble

NOVEL STATES OF MATTER

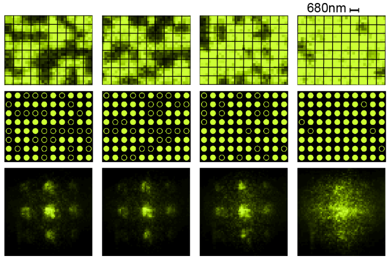
Ginzburg Landau paradigm: order parameter

symmetric — symmetry-broken

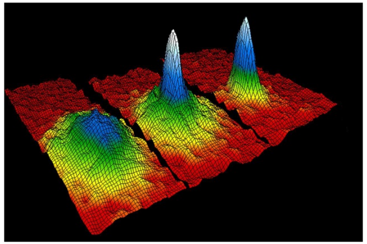
λ_c λ



Mazurenko 2017



Bakr 2010

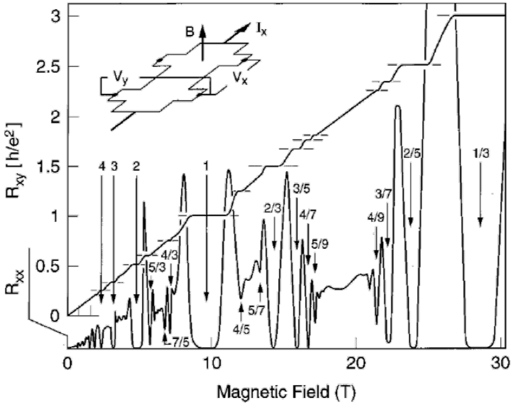


Anderson 1995

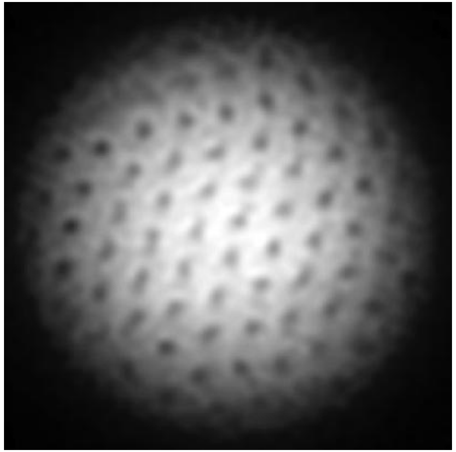
Beyond Ginzburg-Landau: Topological order

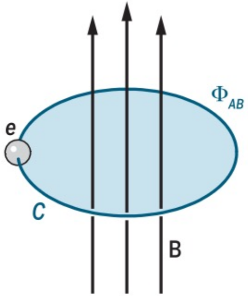
symmetric — symmetric

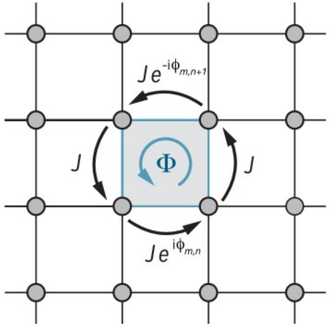
λ_c λ



TWO STRATEGIES FOR COLD-ATOM TOPOLOGY







Rotating systems

Coriolis force emulates Lorenz force

Dalibard, Zwierlein, Spielman, Chu/Gemelke…

Laser-assisted tunneling

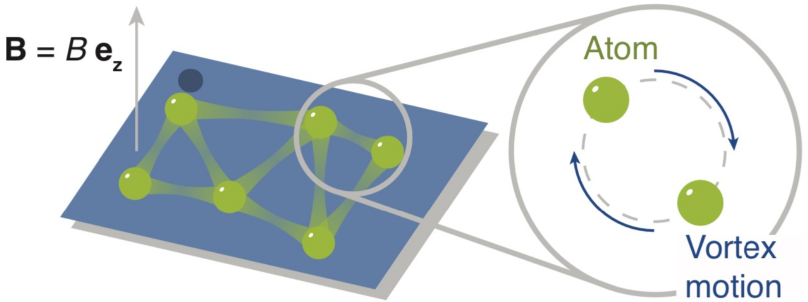
Engineer Peierls phase via lattice modulation

Esslinger, Bloch/Aidelsburger, Sengstock, Ketterle,…

No FQH states yet!

Main challenge: Floquet heating, particularly in interacting systems

KEY PROPERTIES OF FQH STATES



Laughlin states

Paradigmatic class of FQH states

Many-body wavefunction:

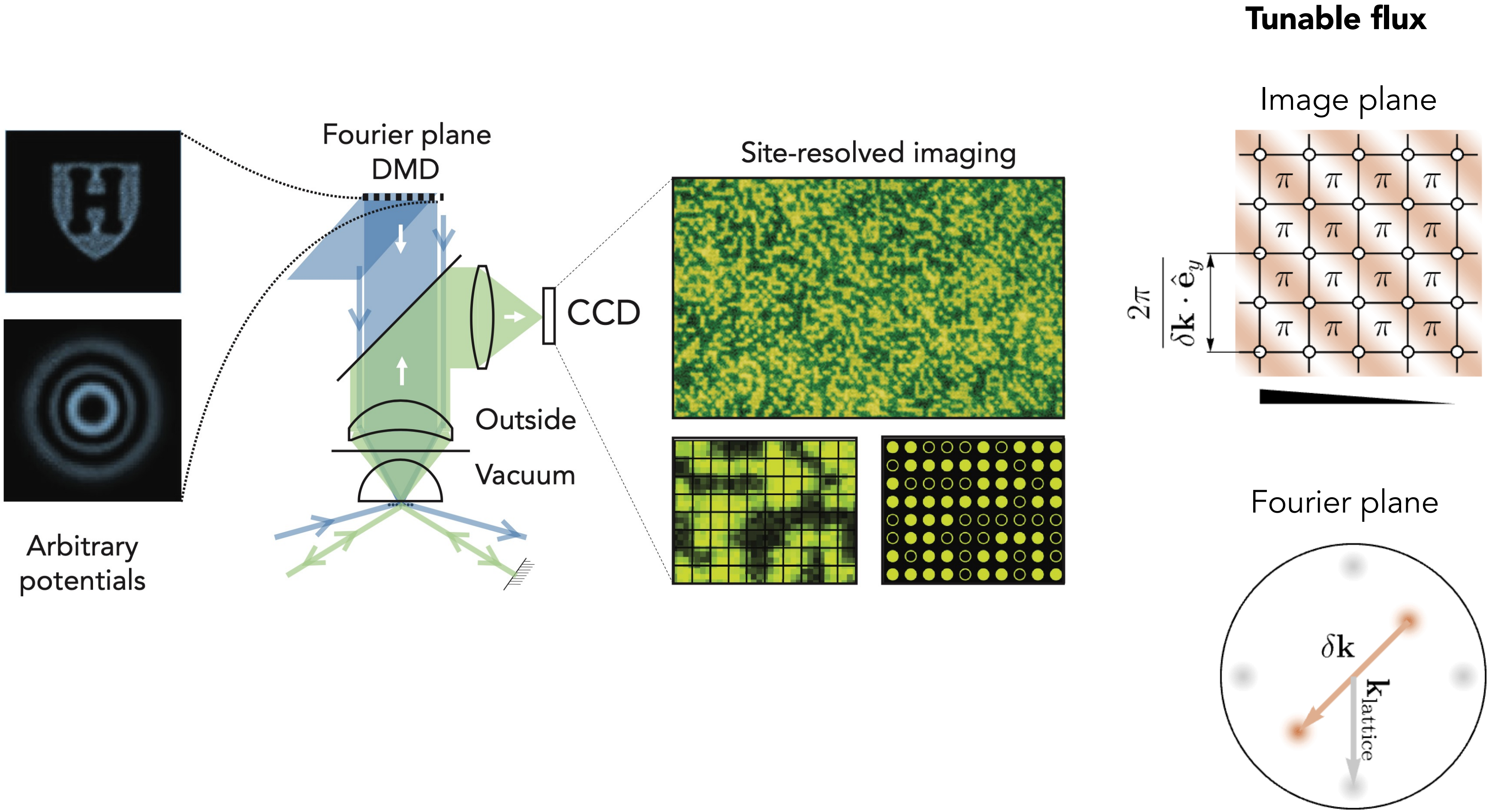
$$\psi \sim \prod_{i<j} \left|z_i - z_j\right|^m e^{-\sum_i |z_i|^2}$$

m even: bosons
m odd: fermions

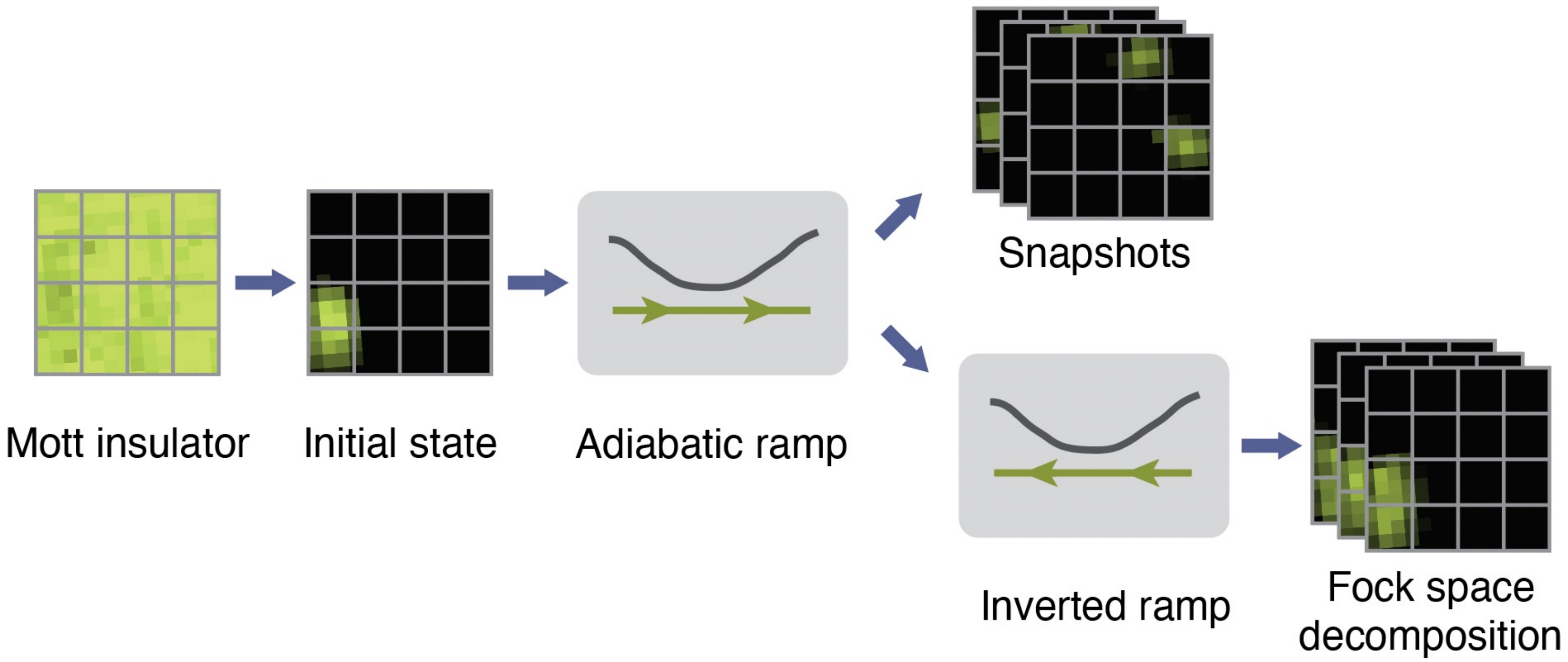
Properties

- Shielded interactions: no two particles at the same position
- Vortex motion protects topology
- Fractional Hall conductivity
- crucial information in $g^{(2)}$ correlations
  ➔ minimal system: $N = 2$

QUANTUM GAS MICROSCOPE

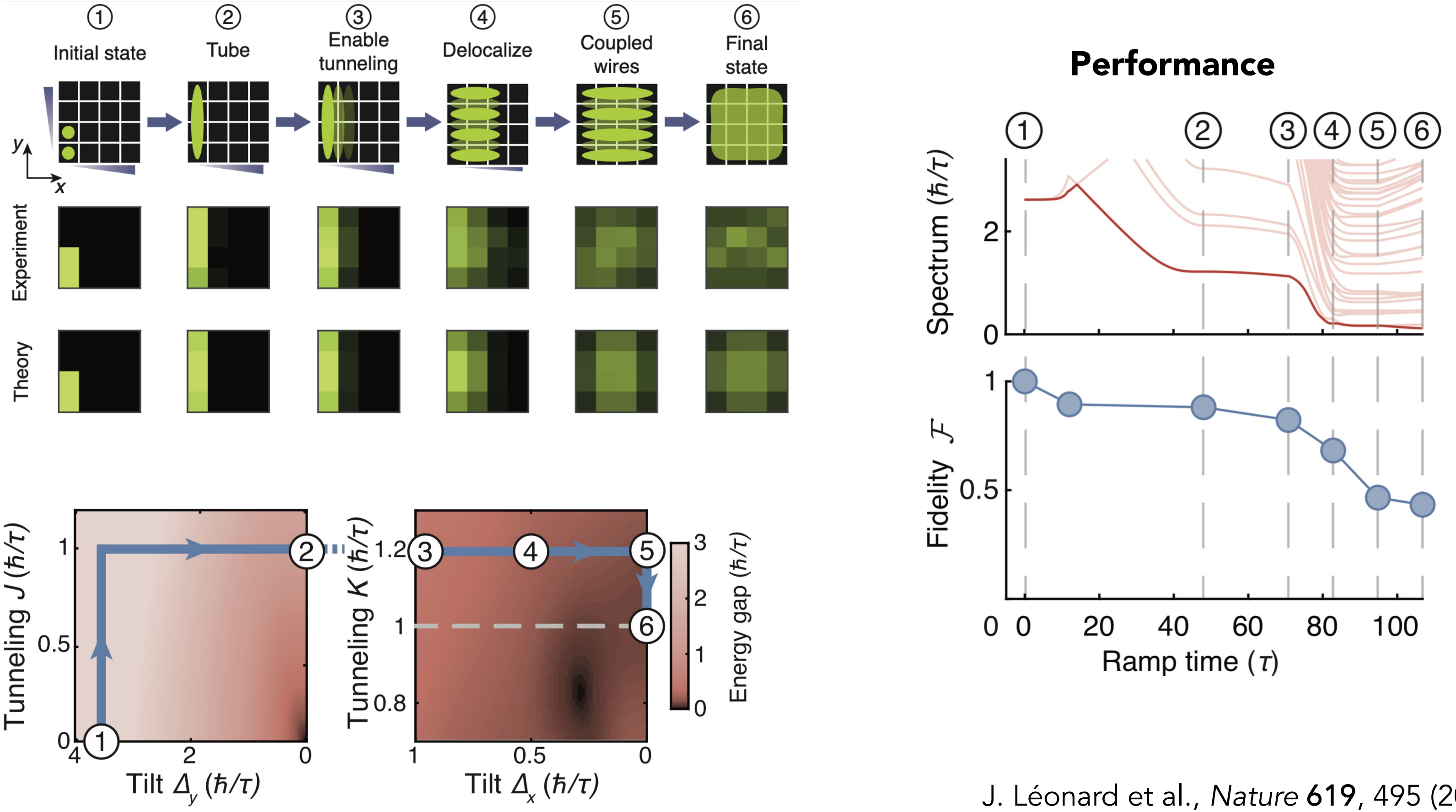


PROTOCOL



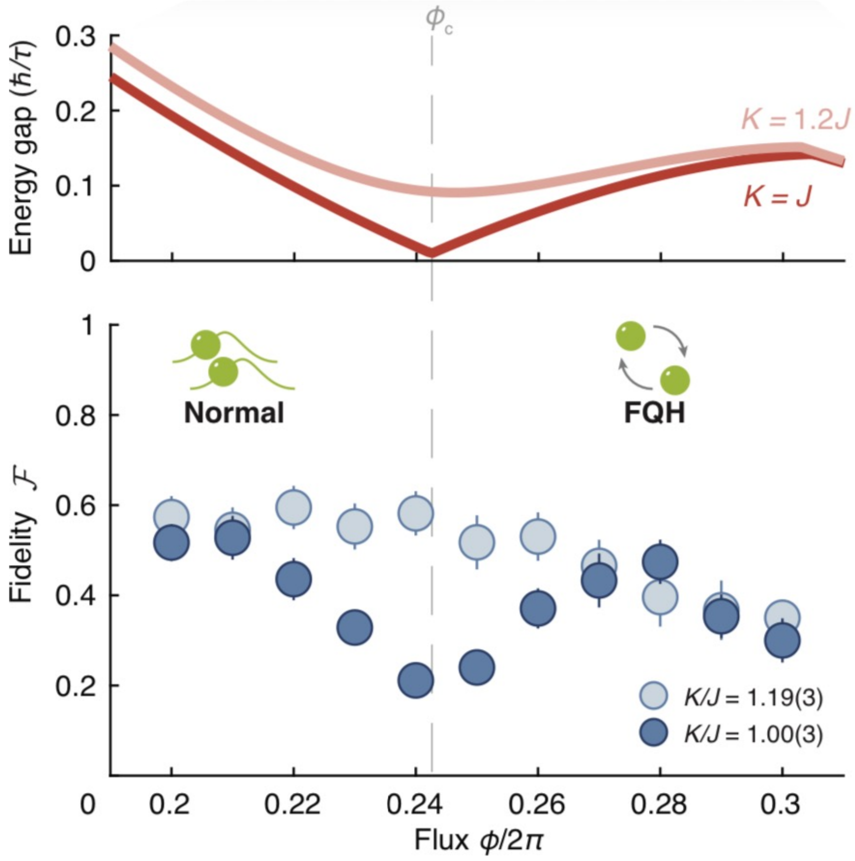
Mott insulator
Initial state
Adiabatic ramp
Snapshots
Inverted ramp
Fock space
decomposition

STATE PREPARATION



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

MAPPING OUT THE PHASE DIAGRAM



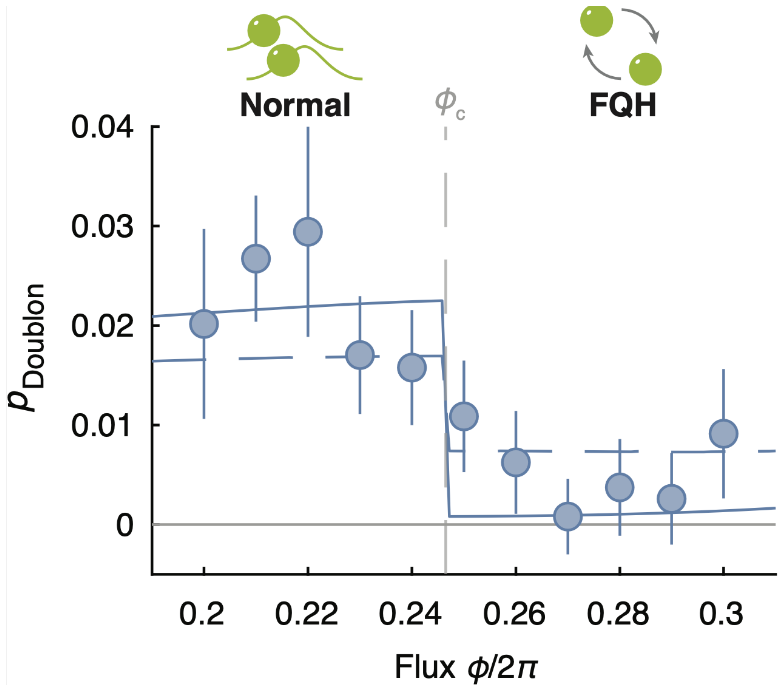
Idea:

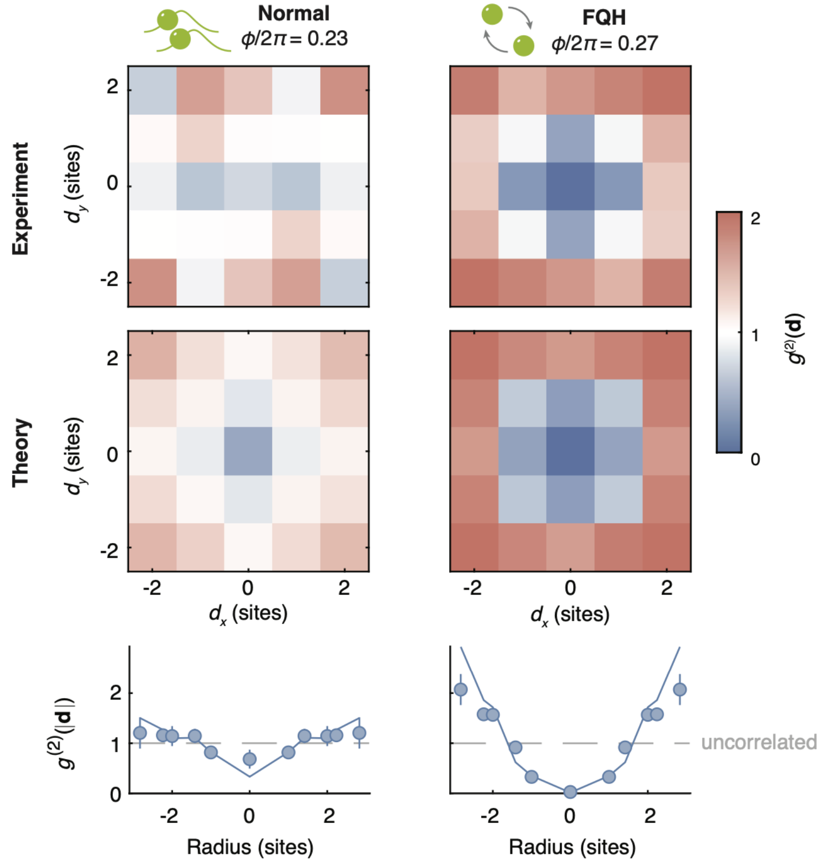
Use fidelity as spectroscopic probe for many-body gap

Many-body gap closing reveals topological transition

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

MICROSCOPIC STRUCTURE

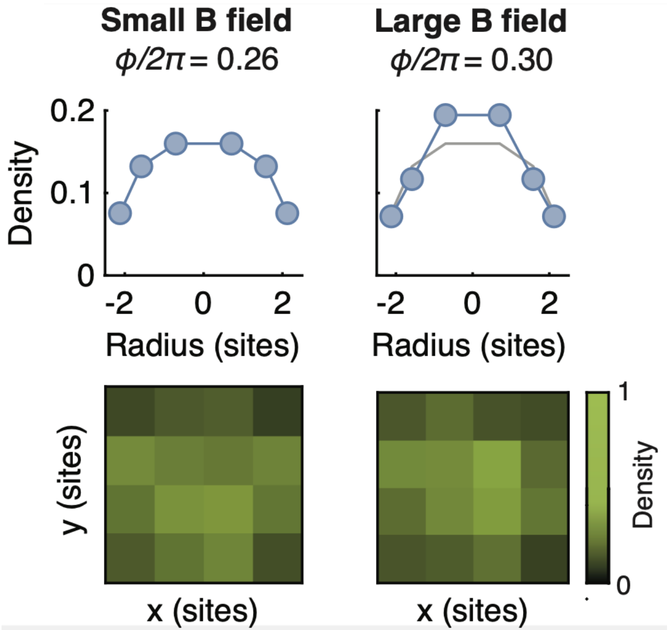


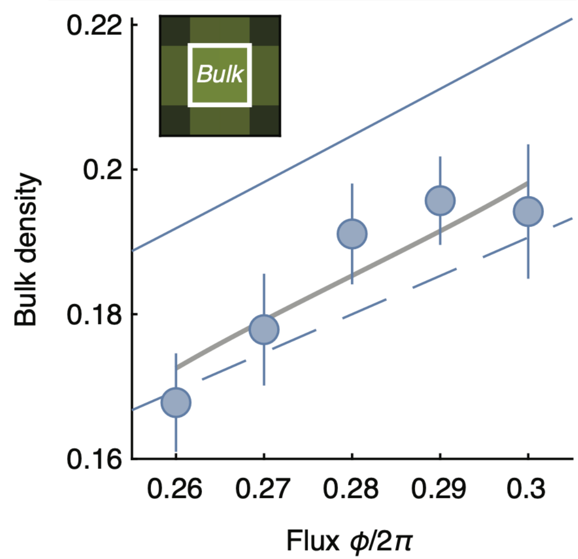


Vortex motion suppresses correlations at short-distance

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

FRACTIONAL HALL CONDUCTIVITY





Streda's formula:

$$\frac{\sigma_{\rm H}}{\sigma_0} = \frac{\partial \rho_{\rm Bulk}}{\partial \alpha}$$

Fractional Hall conductivity:

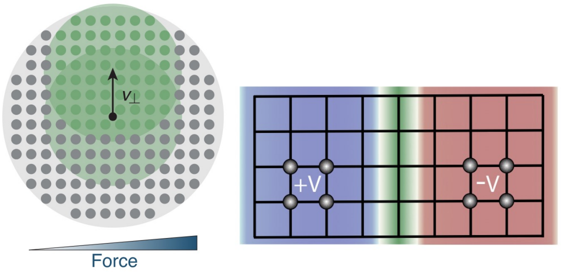
$$\sigma_{\rm H}/\sigma_0 = 0.6(2)$$

Thermodynamic limit: $\nu_{\rm MB}$= 0.5

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

OUTLOOK

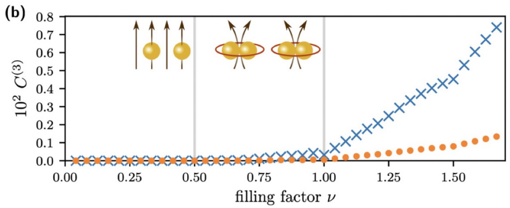
Further topological signatures



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

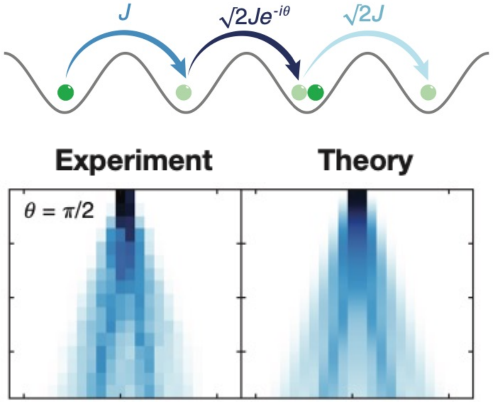
Raciunas et al., PRA 98, 063621 (2018)

Pfaffian states, non-abelian anyons



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

1D anyons



J. Kwan et al., arXiv:2306.01737

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VCQ FWF Der Wissenschaftsfonds. FFG Promoting Innovation. TU WIEN TECHNISCHE UNIVERSITÄT WIEN

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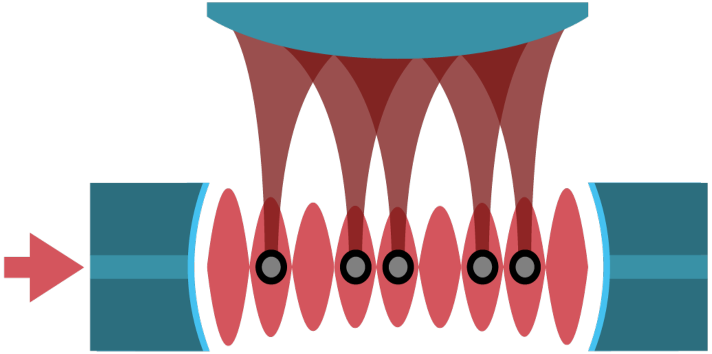
Stephan Roschinski, Isabelle Safa, J. L., Johannes Schabbauer, Marvin Holten

TWEEZER ARRAY IN A CAVITY

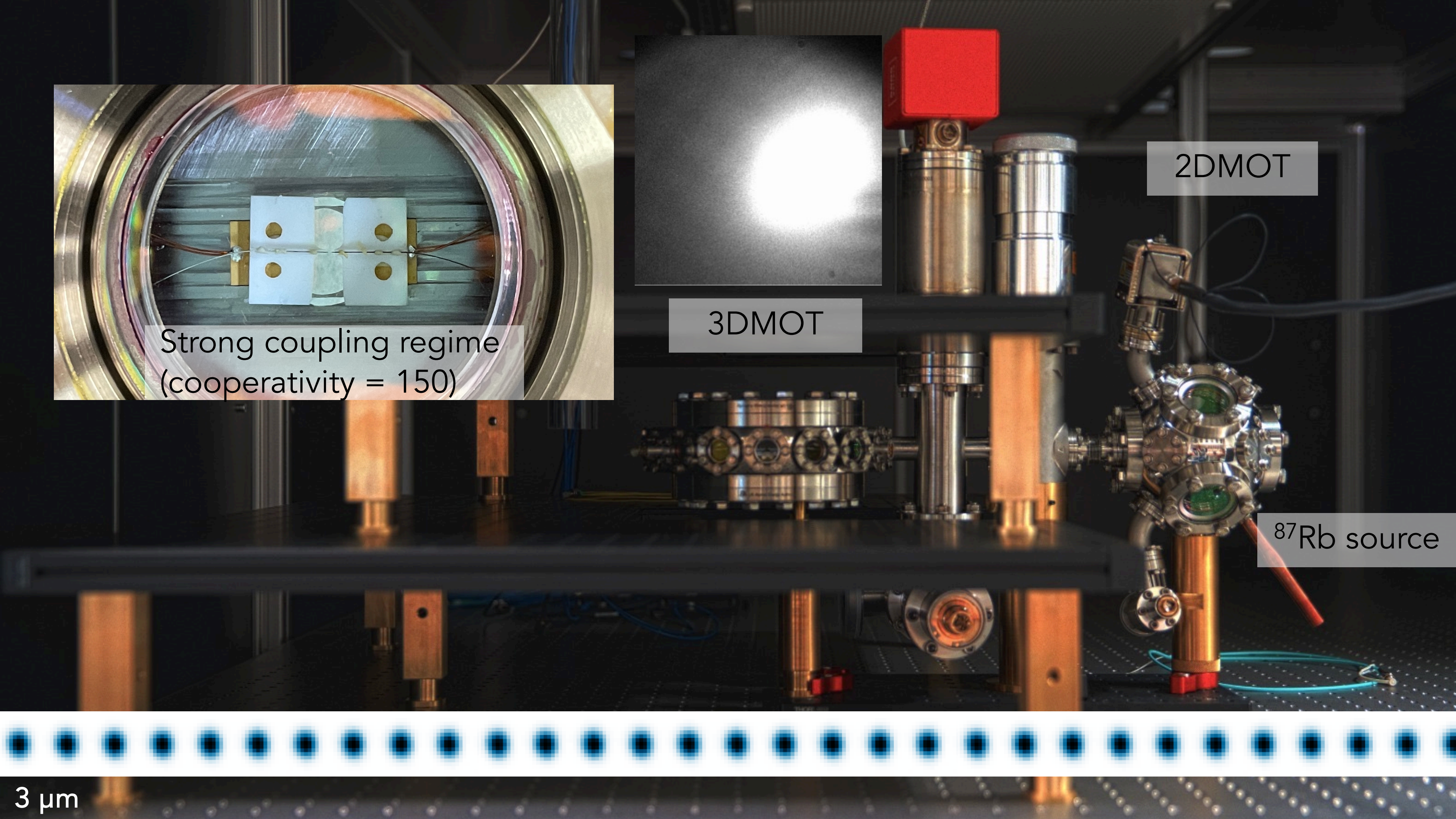


Non-local entanglement

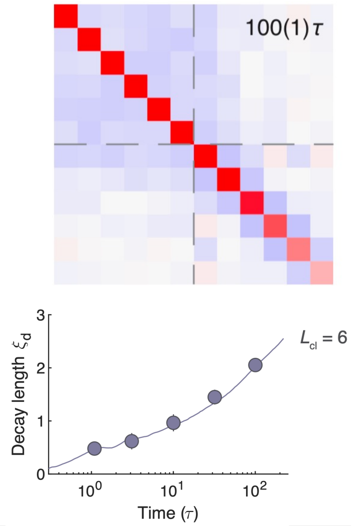
Long-range spin models

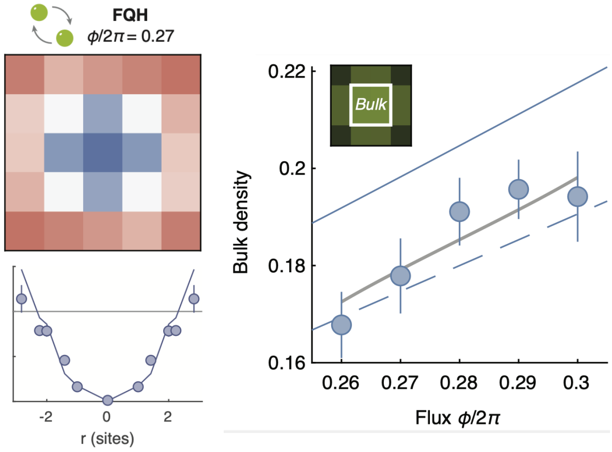
Non-demolition readout

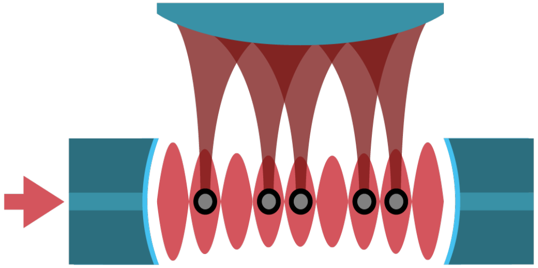
Quantum networks


Strong coupling regime
(cooperativity = 150)
3DMOT
2DMOT
87Rb source
3 μm

SUMMARY







Non-equilibrium quantum systems

Many-body localization
Avalanche instability

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

Topological quantum matter

Fractional quantum Hall state
Microscopy of correlations

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

A photon-coupled neutral atom array

Cavity setup with high aperture
Engineering entanglement

THANK YOU