Disorder-free localization in lattice gauge theories

Markus Heyl
Center for Electronic Correlations and Magnetism
University of Augsburg

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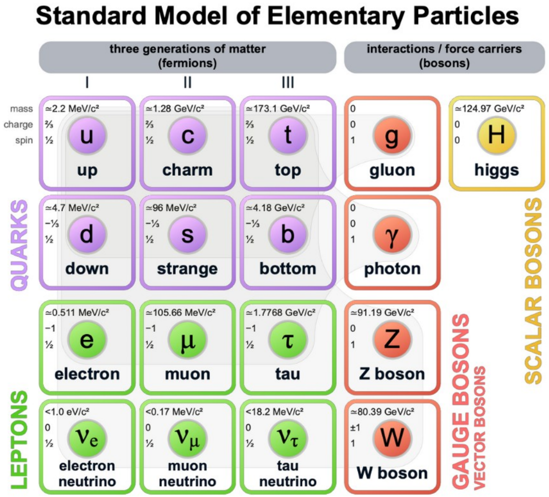
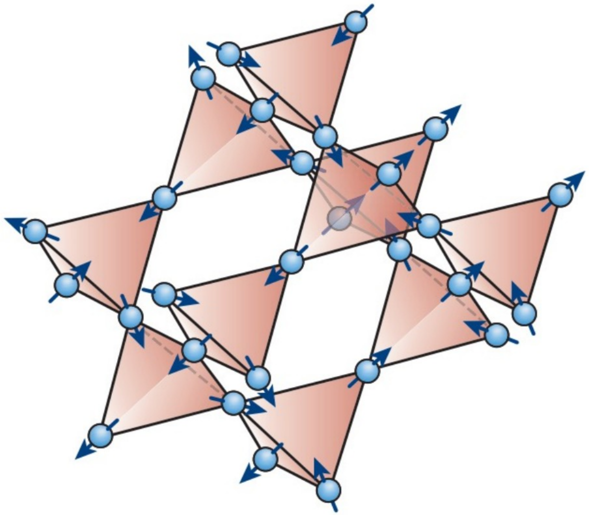
Work together with

ICTP & SISSA: M. Dalmonte, M. Brenes, A. Scardicchio, F. Surace, R. Fazio, S. Notarnicola
MPI-PKS: P. Karpov, R. Moessner, N. Chakraborty, G.-Y. Zhu, R. Verdel, A. Russomanno, Y.-P. Huang
Cologne: M. Schmitt

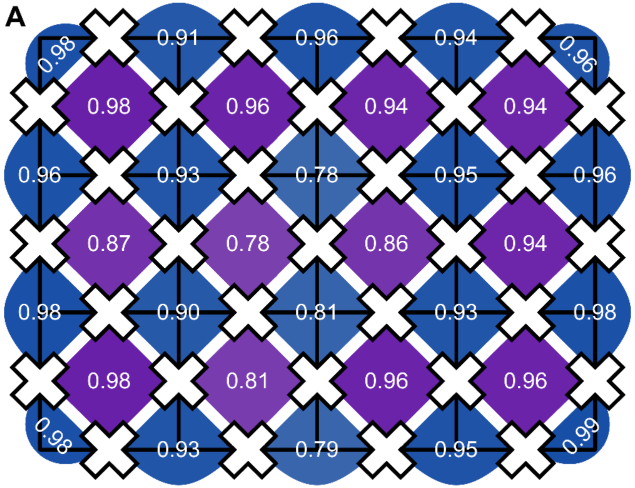
Gauge theories in physics



Wikipedia



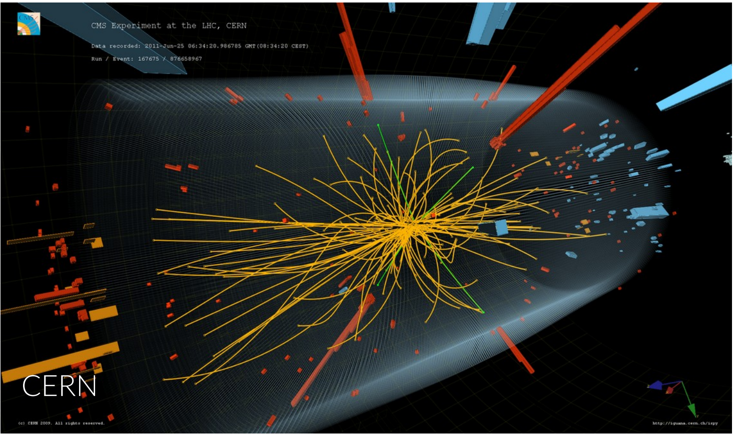
Balents Nature ‘10



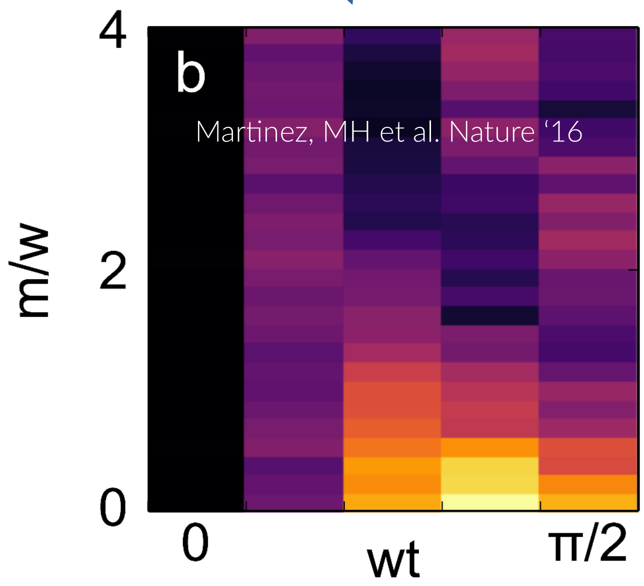
Satzinger et al. Science ‘21

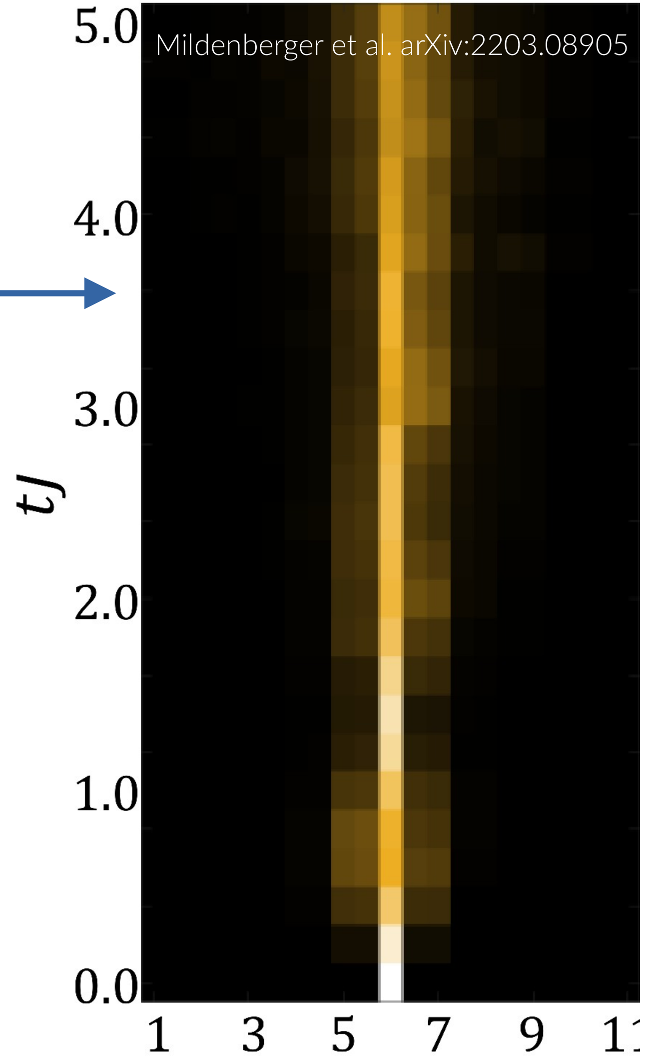
Dynamics in gauge theories

Particle collisions



Quantum simulators



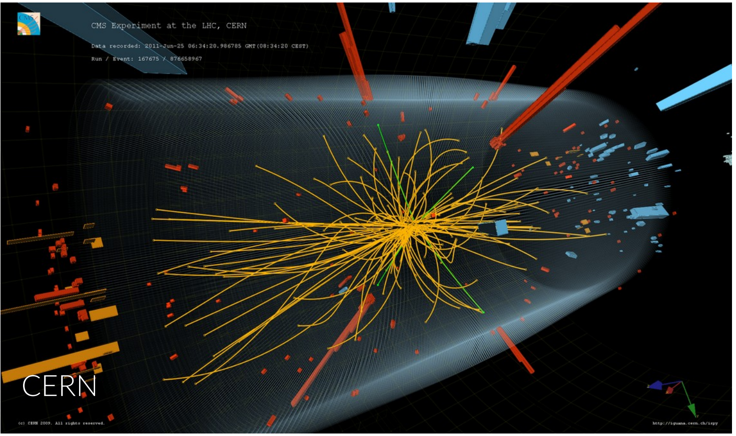


Dynamics in gaug

Goal: explore dynamical principles and dynamical universalities

Challenge: calculate dynamics theoretically

Particle collisions



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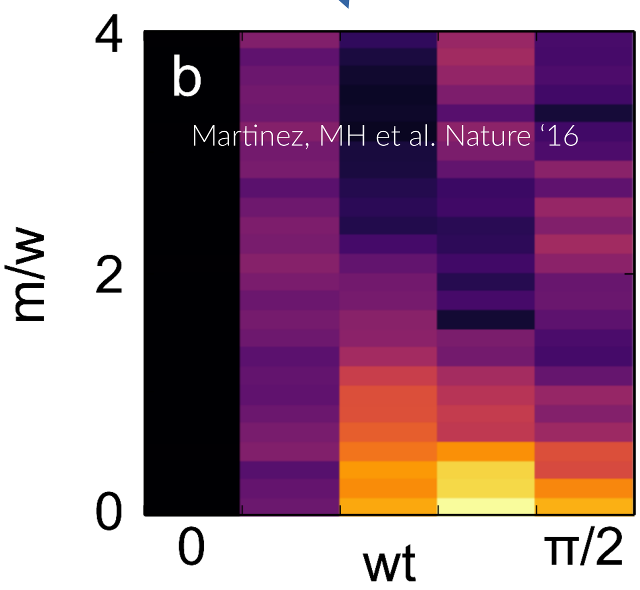
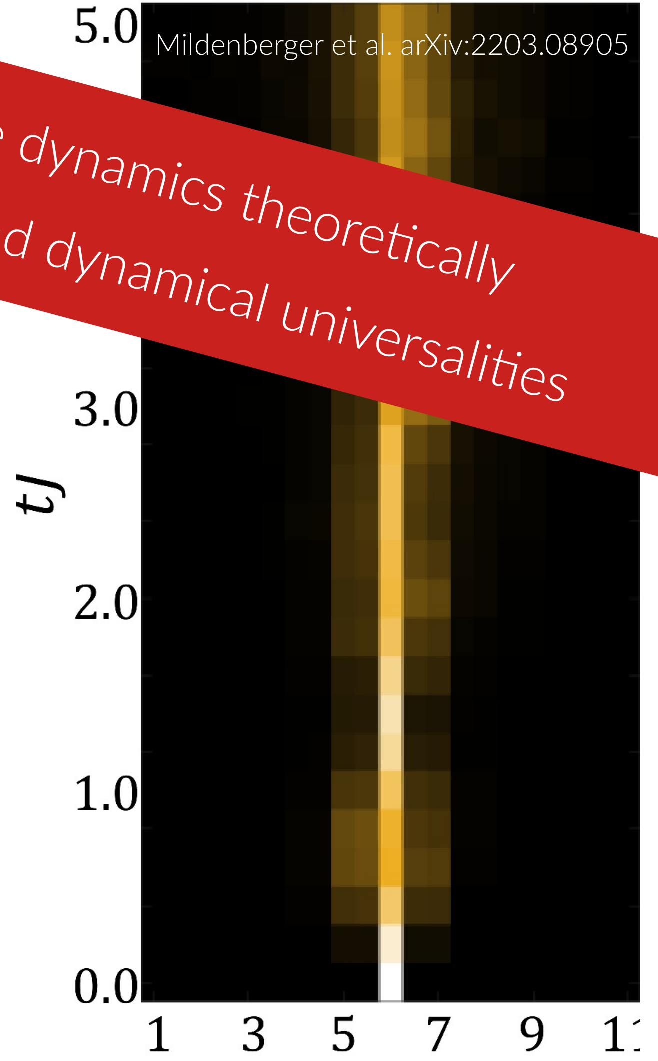
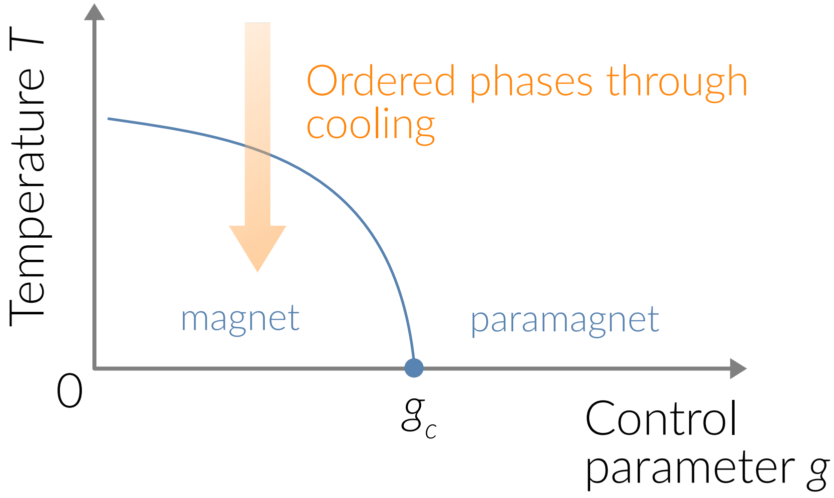




New kinds of order

Conventional matter



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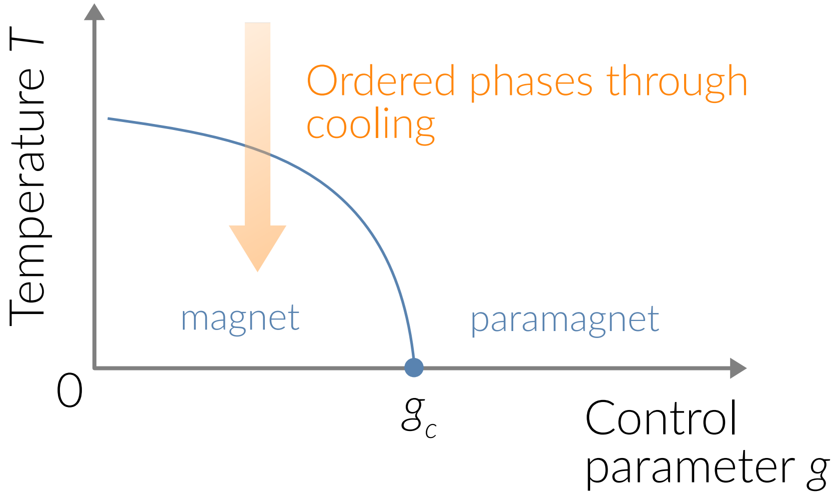
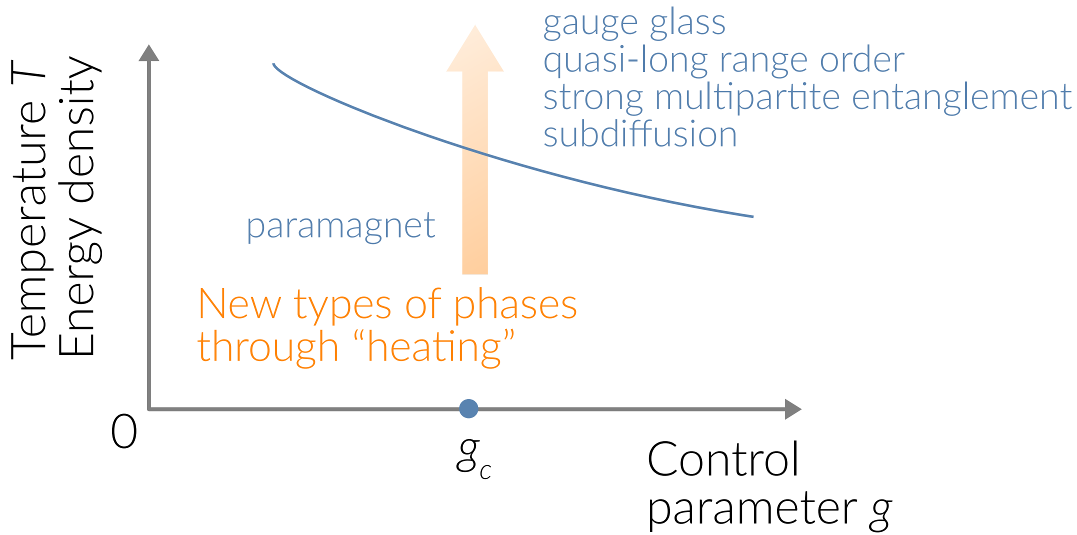


Matter with gauge constraints



Not happening (generically) in thermodynamic systems → requires **new mechanism**

Outline

Quantum thermalization

Disorder-free localization (DFL)

Breaking thermalization through gauge invariance

DFL in 2D lattice gauge theories

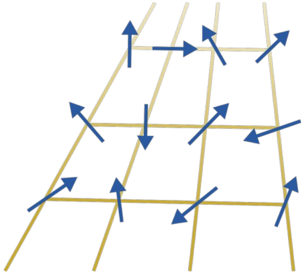
Quantum link model (quantum spin ice, quantum dimer model)

New types of order

Gauge time crystals

Subdiffusion in the Kitaev honeycomb

Quantum thermalization

Isolated quantum magnet  time → ?

Realistic (homogeneous) systems thermalize

Ensemble equivalence: long-time steady state ↔ thermal Gibbs state

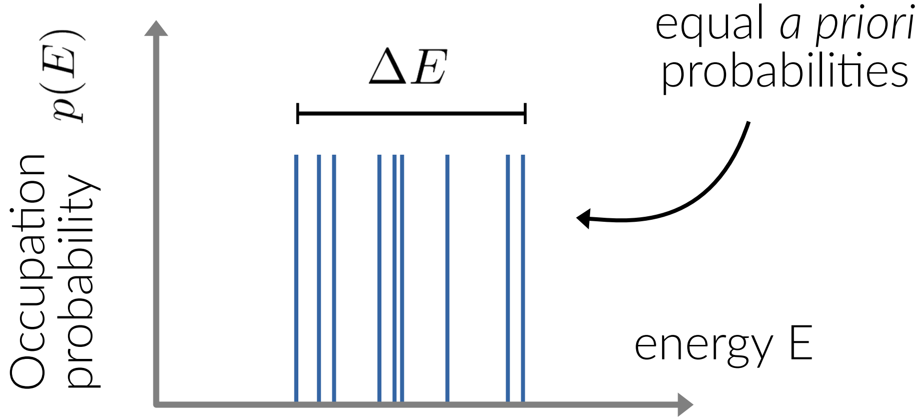
$$\rho_A = \mathrm{tr}_B \rho(t \to \infty) = \mathrm{tr}_B \frac{1}{Z} e^{-\beta H}$$

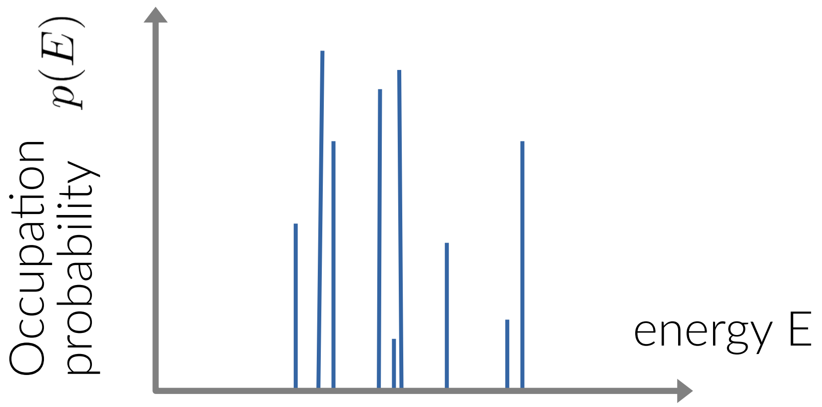
subsystems thermalize

(remainder acting as an effective bath)

Breaking ergodicity

No thermalization: **avoid equipartition**





New quantum states ***beyond thermodynamic constraints***

Breaking ergodicity

Integrability

- Fine-tuning
- *Not robust*
  → no stable nonthermal states

Polkovnikov *et al.* RMP '11

Disorder

- (Many-body) Localization
- Robust in 1D
- But *unstable beyond 1D!*

Vosk & Altman, Nandkishore & Huse, Annu. Rev. '15

Local constraints

- Fractons
- Quantum many-body scars
- *Gauge invariance*
  → *Disorder-free localization*

Smith et al. PRL'17
Brenes, **MH** et al. PRL '18

Breaking ergodicity

Robust ergodicity breaking in any dimension
→ Disorder-free localization

Integrability

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Polkovnikov *et al.* RMP '11

Disorder

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Lo

- Fractons
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  → *Disorder-free localization*

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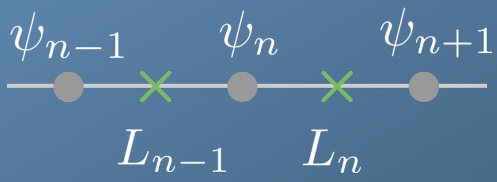
Disorder-free localization

Gauge invariance & conservation laws

Lattice gauge theory (LGT)



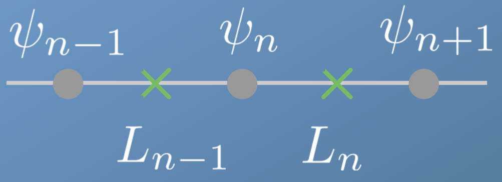
Local gauge symmetry → Generators: $[G_n, H] = 0 \quad \forall n$

Noether theorem: *local symmetry → local conservation law*

Extensive # local conserved operators/quantities
(almost like *integrable* systems, but not equal to the # DOF)

LGTs have *builtin constrained* dynamics

Fragmentation & Superselection sectors



Abelian LGT → Generators:

$$[G_n, H] = 0 \quad \boxed{[G_n, G_{n'}] = 0} \quad \forall n$$

Hamiltonian eigenstates can be labeled by the ***eigenvalues of the generators***

Superselection sector

$$\{q_\alpha\}_{\alpha=1,\dots,N}$$

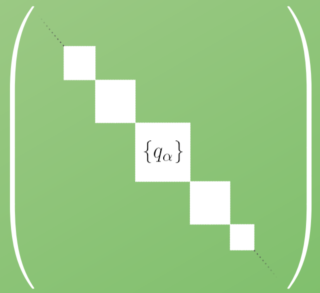
$$G_n|\Psi_{\{q_\alpha\}}\rangle = q_n|\Psi_{\{q_\alpha\}}\rangle$$

$$\Rightarrow [\nabla E_n - \rho_n - q_n]|\Psi_{\{q_\alpha\}}\rangle = 0$$

'static background charge'

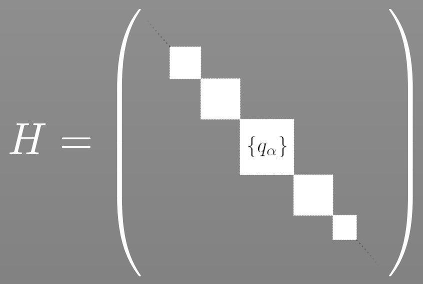
Hamiltonian decomposes into disconnected blocks

(fragmentation builtin automatically)

$H =$ 

Background charges & dynamics

$$e^{-iHt}|\Psi_{\{q_\alpha\}}\rangle = e^{-iH_{\{q_\alpha\}}t}|\Psi_{\{q_\alpha\}}\rangle$$



Dynamics for superposition states:

$$|\Psi\rangle = \sum_{\{q_\alpha\}} C_{\{q_\alpha\}}|\Psi_{\{q_\alpha\}}\rangle$$

Diagonal observable
(gauge invariant)

$$\langle\mathcal{O}(t)\rangle = \sum_{\{q_\alpha\}} |C_{\{q_\alpha\}}|^2 \langle\Psi_{\{q_\alpha\}}|e^{iH_{\{q_\alpha\}}t}\mathcal{O}e^{-iH_{\{q_\alpha\}}t}|\Psi_{\{q_\alpha\}}\rangle$$

"**disorder average**" *even though the state might be* ***homogeneous***

Disorder-free localization from strong ***random background charges***

Smith et al. PRL '17 & Brenes, **MH** et al. PRL '18

DFL Mechanisms

Localization through interference

Disorder landscape generated by the background charges
(disorder often spatially correlated)

→ Anderson or many-body localization

Localization through kinetic constraints

Fragmentation in real & Hilbert space

→ Quantum/classical percolation problem

→ this talk

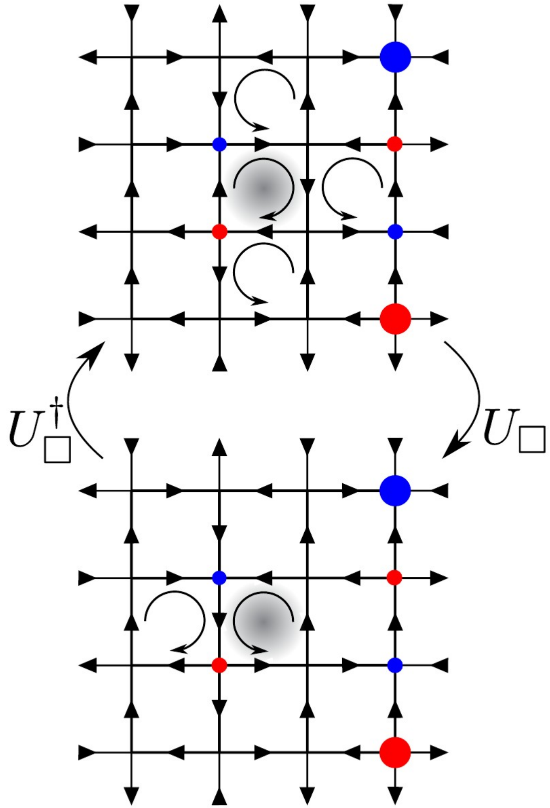
DFL in interacting 2D LGTs

U(1) quantum link model (QLM)

$$H = H_0 + V \equiv \lambda \sum_{\square} (U_\square + U_\square^\dagger)^2 - J \sum_{\square} (U_\square + U_\square^\dagger)$$

Potential energy counting # flippable plaquettes

Correlated spin flip on full plaquette



Local symmetry: $G_n = \frac{1}{2}\left[\#\ \mathrm{out}\ \text{-}\ \#\ \mathrm{in}\right]$

Quantum spin ice (G_n=0) → Emergent strong-coupling QED, quantum dimer model ($G_n=(-1)^n$), …

Nonequilibrium dynamics

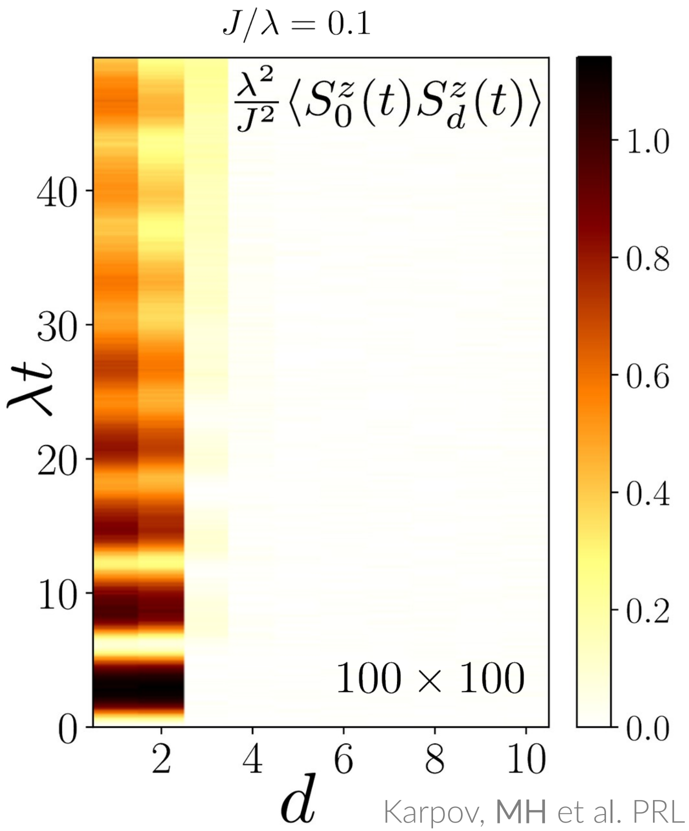
Initial condition:

$$|\psi_0\rangle = |\rightarrow\rangle = \frac{1}{\sqrt{\dim_H}} \sum_s |s\rangle$$

$\rightarrow$ superposition over all superselection sectors

No propagation of quantum correlations

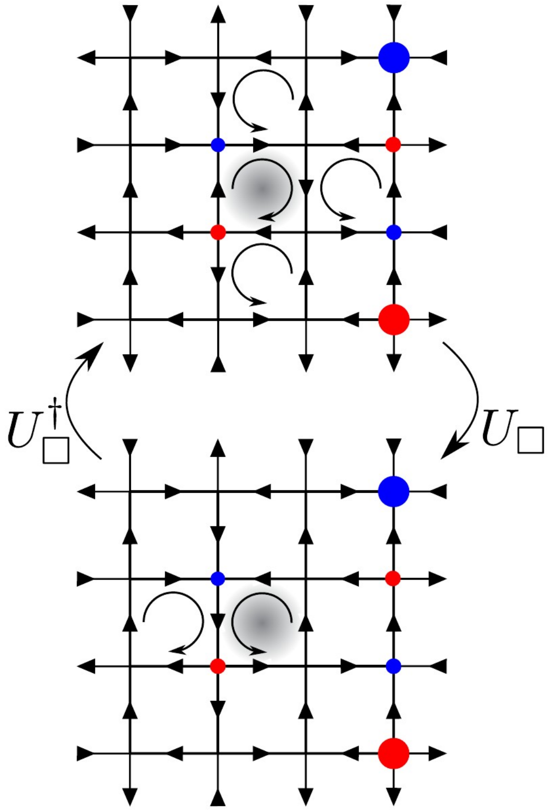
Is this just *slow dynamics* or really *nonergodic* behavior?

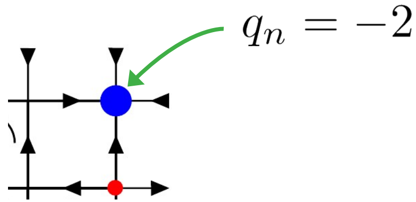


Karpov, MH et al. PRL '21

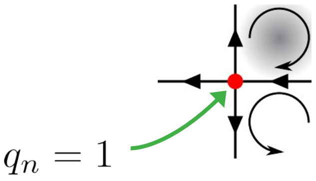
Solution via classical networks
Verdel, MH et al. PRB '21

Background charges & kinetic constraints





All 4 spins will be frozen ***forever***



At least 2 neighboring plaquettes unflippable

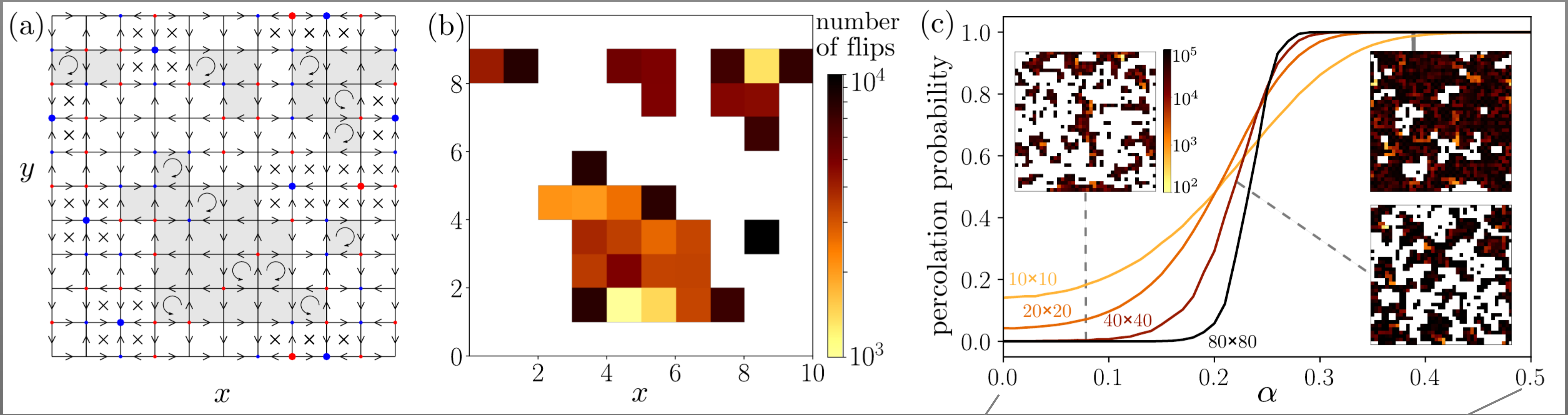
Key question: kinetics local or can excitations still propagate?

Mapping onto percolation problem

Typical superselection sector

Kinetics & clusters

Percolation of clusters



Karpov, **MH** et al. PRL '21

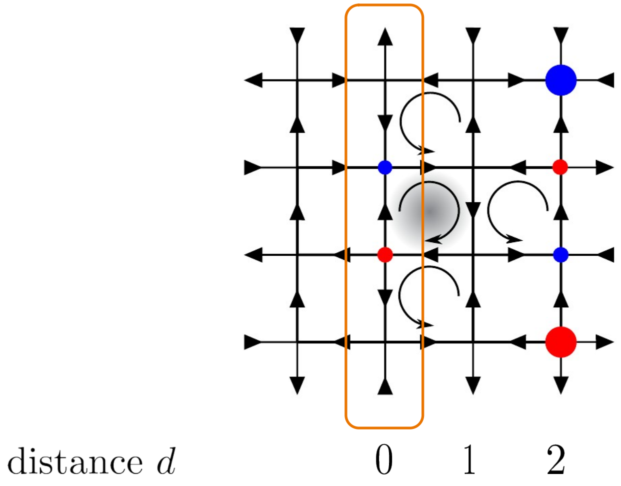
$|\rightarrow\rangle$

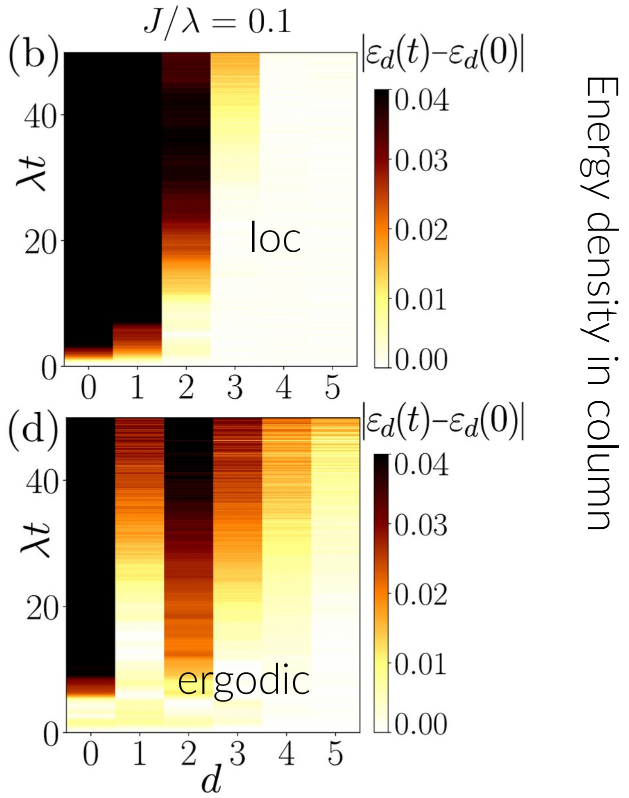
fully-flippable sector
(no background charges)

No percolation → Small clusters → **Ergodicity breaking**

Signatures in quantum dynamics

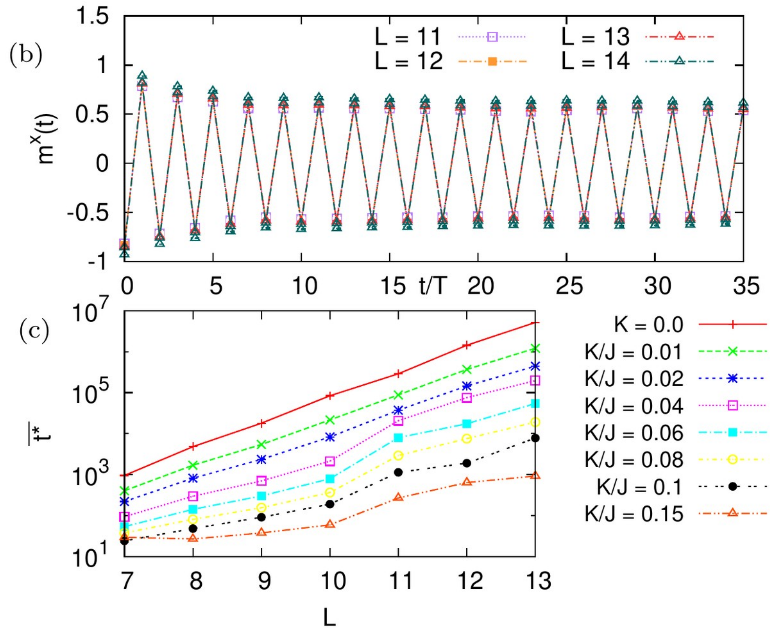
Create an energy inhomogeneity in column





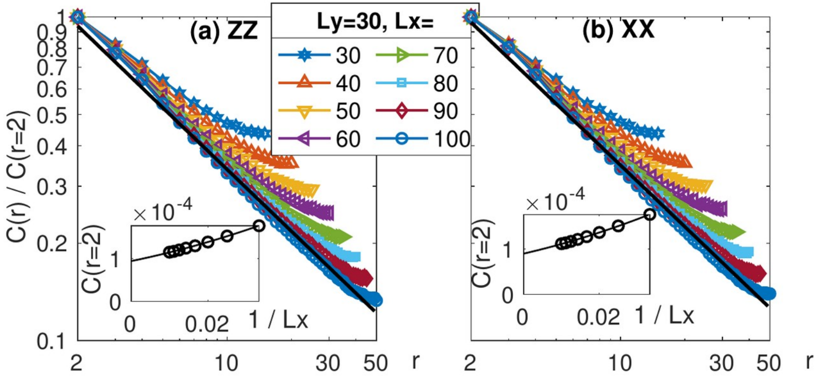
Localization protected quantum order

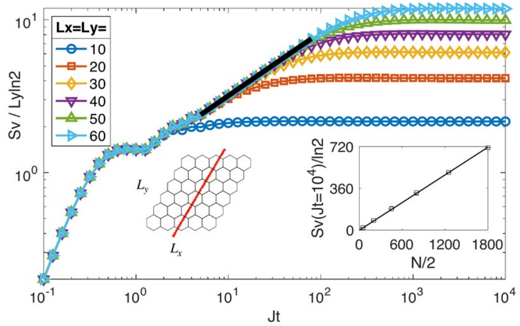
Gauge time crystal



Russomanno, **MH** et al. PRR ‘20

Quasi long-range order





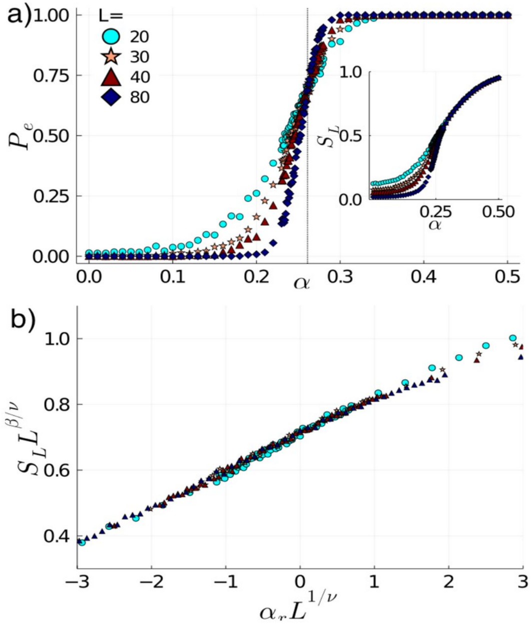
Zhu & **MH** PRR ‘21

Summary & outlook

- Disorder-free localization as a new mechanism for ergodicity breaking
- Robust ergodicity breaking even in 2D (provided gauge invariance is preserved)
- What new types of nonequilibrium phases are possible?
- What about 3D? Can there still be a nonergodic phase?
- What happens in the presence of matter in 2D?
- Implications on high-temperature spectral functions?

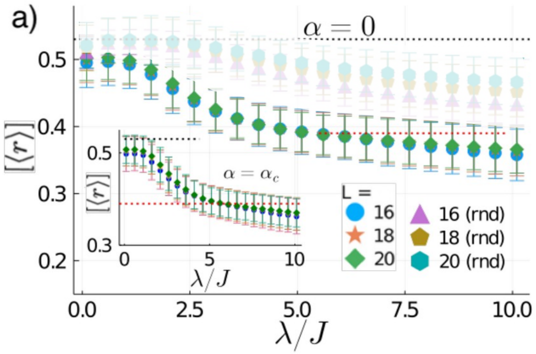
Quantum localization transition

Chakraborty, **MH** et al. '22



Universality class of 2D site percolation

Level-spacing statistics for individual clusters



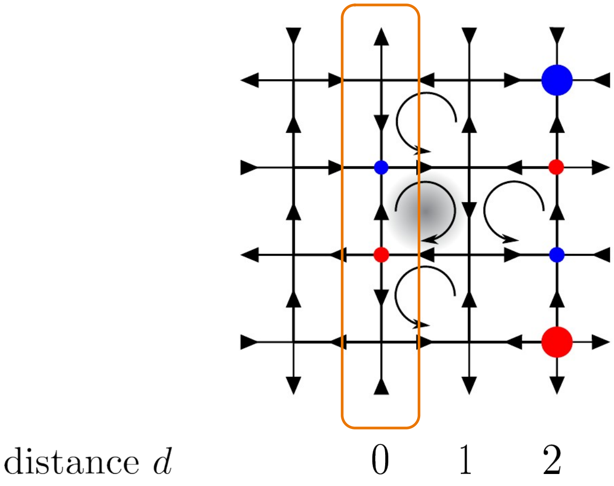
cluster size

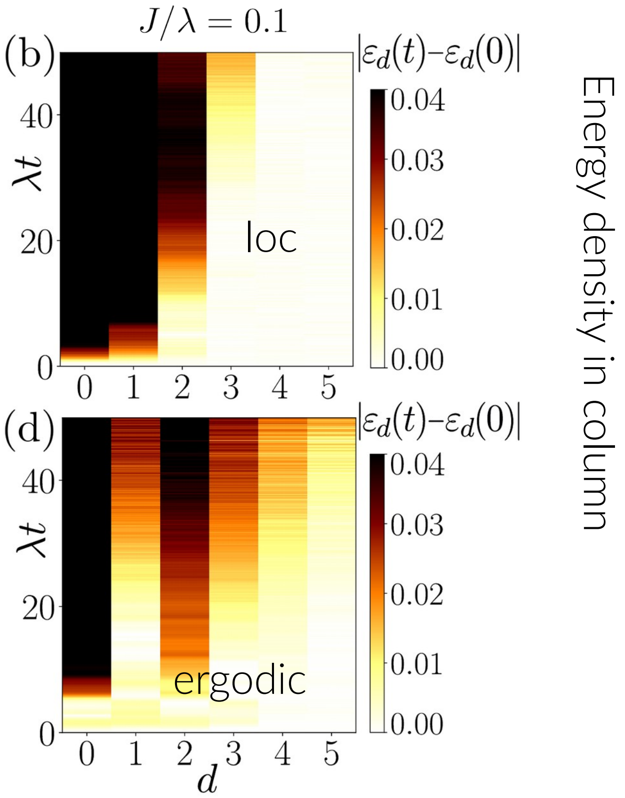
Clusters ergodic

Quantum thermalization transition
= classical percolation transition

Signatures in quantum dynamics

Create an energy
inhomogeneity in column





Method: classical networks

Challenge: no *efficient* compression of quantum states available 2D

$$|\psi\rangle = \sum_s \psi(s)|s\rangle$$

amplitudes exponential in system size

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amplitudes exponential in system size

Classical networks: *“Don’t store. Generate on the fly.”*

$$|s\rangle \longrightarrow \boxed{\text{Machine}} \longrightarrow \tilde{\psi}(s) \approx \psi(s)$$

Sample using MC techniques

Schmitt & MH SciPost ‘18

Method: classical networks

$$|s\rangle \longrightarrow \boxed{\text{Classical network}} \longrightarrow \tilde{\psi}(s,t) = e^{\mathcal{H}_{\text{eff}}(s,t)}$$

Schmitt & MH SciPost '18

Effective classical Hamiltonian

- Structure obtained from cumulant expansion
  (around a classical limit)

$$\mathcal{H}_{\text{eff}}(s,t) = h_0(s,t) + \epsilon h_1(s,t) + \epsilon^2 h_2(s,t) + \ldots$$

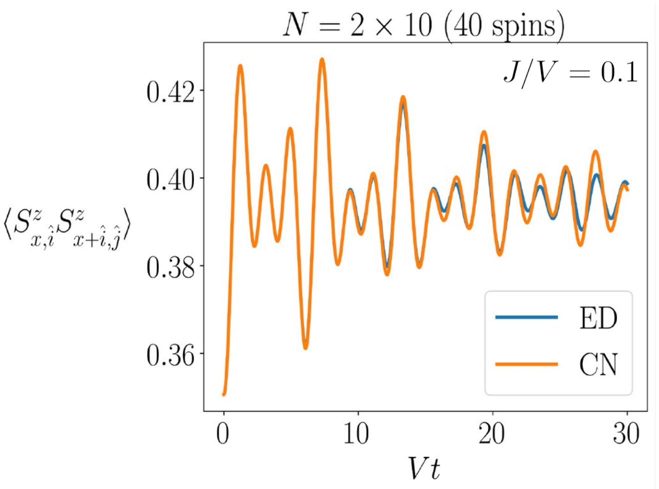
- Further variationally optimized
- "Simple artificial neural network"

Method: classical networks

$|s\rangle \longrightarrow$ Classical network $\longrightarrow \tilde{\psi}(s,t) = e^{\mathcal{H}_{\text{eff}}(s,t)}$

Schmitt & MH SciPost '18

Dynamics in zero charge superselection sector
(worst case for method)



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