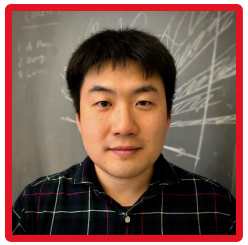
Observation of ballistic plasma and memory in high-energy gauge theory dynamics

Daniel K. Mark (MIT)

with Federica Surace, Tommy Schuster, Adam Shaw, Wenjie Gong,
Soonwon Choi, Manuel Endres

arXiv:2510.xxxxx

QuantHEP 2025, Oct 01 2025


Soonwon Choi


Federica Surace


Wenjie Gong


Tommy Schuster


Manuel Endres


Adam Shaw

Today: a quantum dynamics experiment

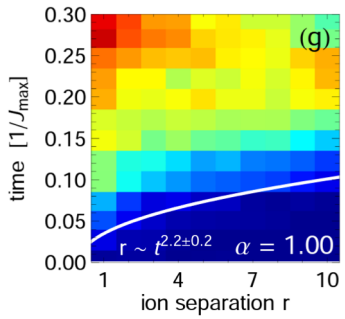
$$|\psi(t)\rangle = \exp(-iHt)|\psi_0\rangle$$

What we know:

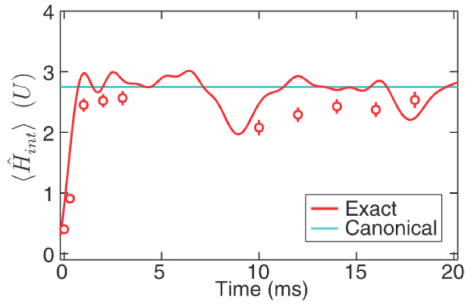
- Light-cone physics
- Local equilibration
- Entanglement growth
- Transport of conserved quantities

Only beginning to do controlled experiments!

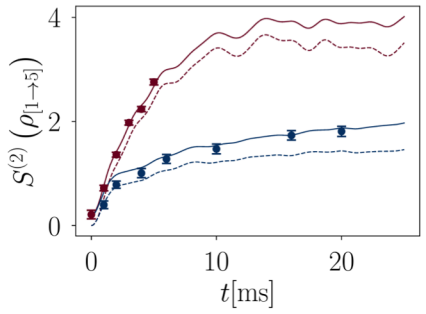
Quantum dynamics in gauge theories?



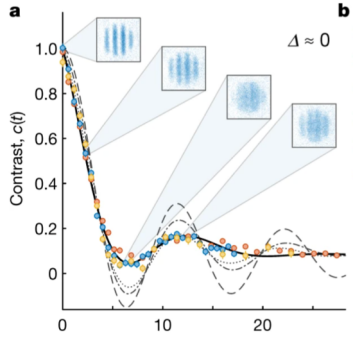
Non-local propagation of correlations in long-range interacting quantum systems
P. Richerme,…, C. Monroe.
Nature 511, 198 (2014)



Quantum thermalization through entanglement in an isolated many-body system
A. Kaufman,…, M. Greiner.
Science 353, 794 (2016)



Probing Rényi entanglement entropy via randomized measurements
T. Brydges, A. Elben, …, C. Roos.
Science 364, 260 (2019)



Spin transport in a tunable Heisenberg model realized with ultracold atoms
P. Jepsen,…, W. Ketterle.
Nature 588, 403 (2020)

The simplest Rydberg quantum dynamics

0 1 0 0 1 0 1 0 0 0 1 0 1 0 1 0 0 0 1 0

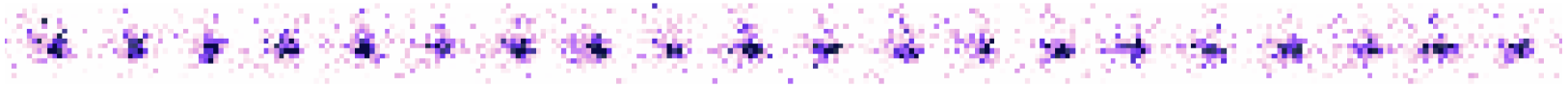
1 0 0 1 0 1 0 0 0 1 0 1 0 1 0 0 0 1 0 1

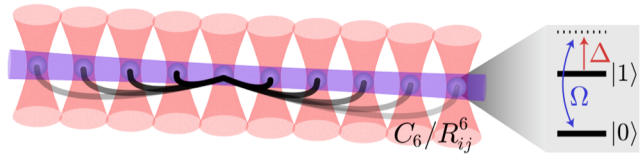
0 0 0 0 1 0 1 0 0 1 0 0 1 0 1 0 1 0 0 0

$|\psi(t)\rangle$

$\exp(-iHt)$

$|0\rangle^{\otimes N}$





$$\hat{H}/h = \Omega \sum_i \hat{S}_i^x - \Delta \sum_i \hat{n}_i + \frac{C_6}{a^6} \sum_{i>j} \frac{\hat{n}_i \hat{n}_j}{|i-j|^6}$$

Parameter	Symbol	Value	Units
Rabi frequency	Ω	6.91(1)	MHz
Detuning	Δ	0.51(2)	MHz
Interaction coefficient	C_6	254(4)	GHz×μm^6
Lattice spacing	a	3.765	μm
Rabi gradient	-	-0.021(3)	kHz/μm
Detuning gradient	-	-0.09(1)	kHz/μm
Beam waist	-	18	μm

Ext. Data Table I | Coherent Hamiltonian parameters

Endres Choi collaboration

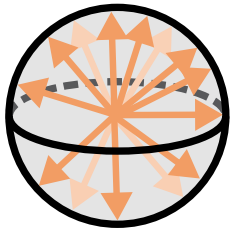
Many-body thermalization

LGT!

Today!

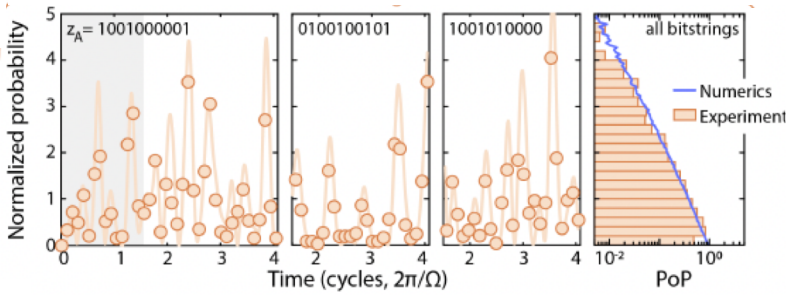
Projected ensembles: local universal randomness

Preparing random states and benchmarking with many-body quantum chaos
Choi*, Shaw*,..., DKM,...,
Choi, Endres,
Nature 613, 468 (2023)



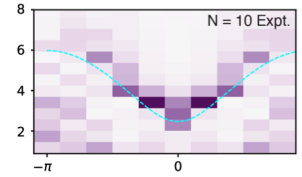
Emergent quantum state designs from individual many-body wavefunctions
Cotler*,DKM*, Huang*, ...,
Endres, Choi
PRX Q 4, 010311 (2023)

Universality in ergodic dynamics



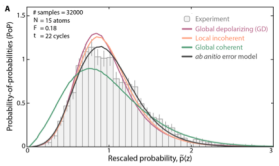
A Maximum Entropy Principle in Deep Thermalization and in Hilbert-Space Ergodicity
DKM, ..., Endres, Choi
PRX 14, 041051 (2024)

Non-equilibrium dynamics



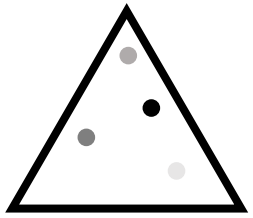
Hot ballistic transport and memory in a 60-atom lattice gauge simulator
DKM,..., Choi, Endres
In prep

Noise learning



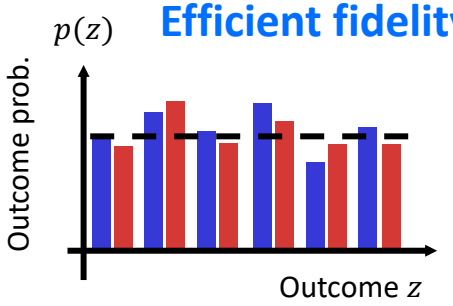
Experimental signatures of Hilbert-space ergodicity: Universal bitstring distributions and applications in noise learning
Shaw*,DKM*,..., Choi, Endres
PRX 15, 031001 (2025)

Multi-parameter estimation



How much can we learn from quantum random circuit sampling?
Manole, DKM,...Choi,
In prep.

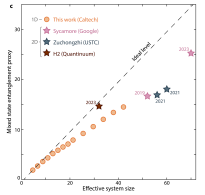
Efficient fidelity estimation



Benchmarking Quantum Simulators using Ergodic Quantum Dynamics
DKM,..., Endres, Choi,
PRL 131, 110601 (2023)

Certifying entanglement and Large-scale benchmarking

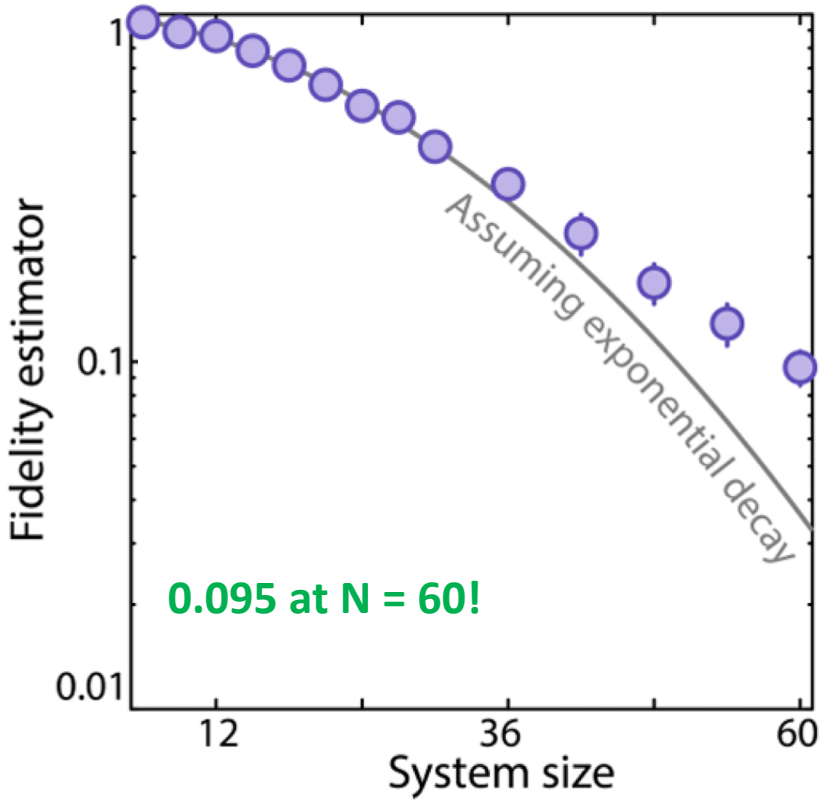
Benchmarking highly entangled states on a 60-atom analog quantum simulator
Shaw*, Chen*, Choi*, DKM*,...,
Choi, Endres,
Nature 628, 71 (2024)

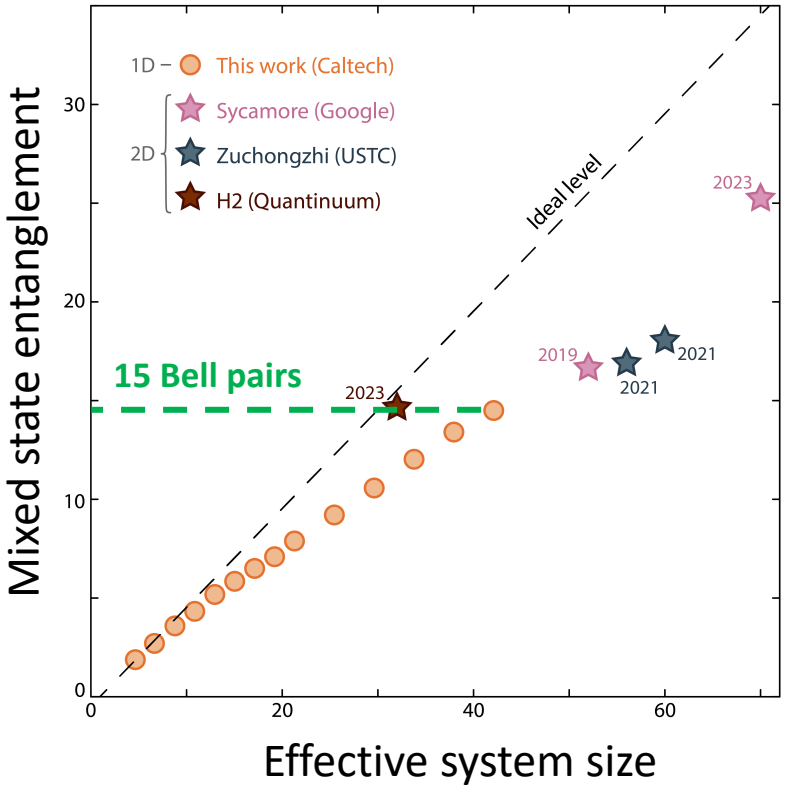


QI Tools

High fidelity quantum simulation!

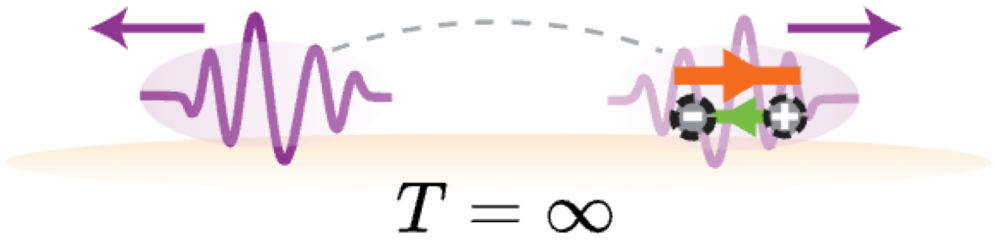
High quality analog simulation:
No error mitigation required!



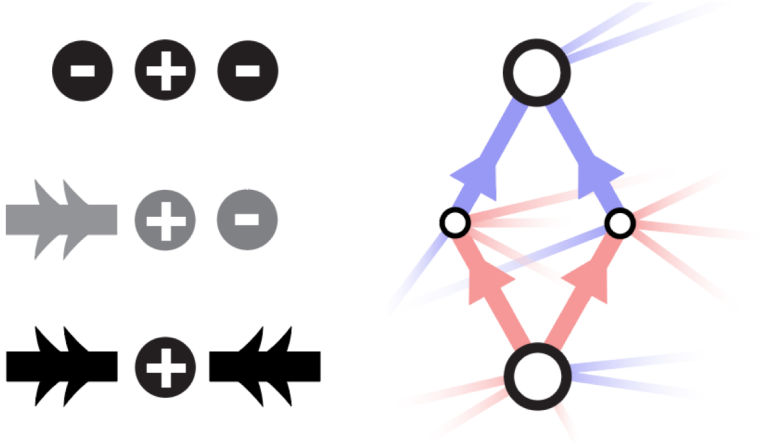


Benchmarking highly entangled states on a 60-atom analog quantum simulator
A. Shaw*, Z. Chen*, J. Choi*, DKM*,…, S.Choi, M. Endres,
Nature 628, 71-77 (2024)

Today: Nonequilibrium dynamics in a gauge theory

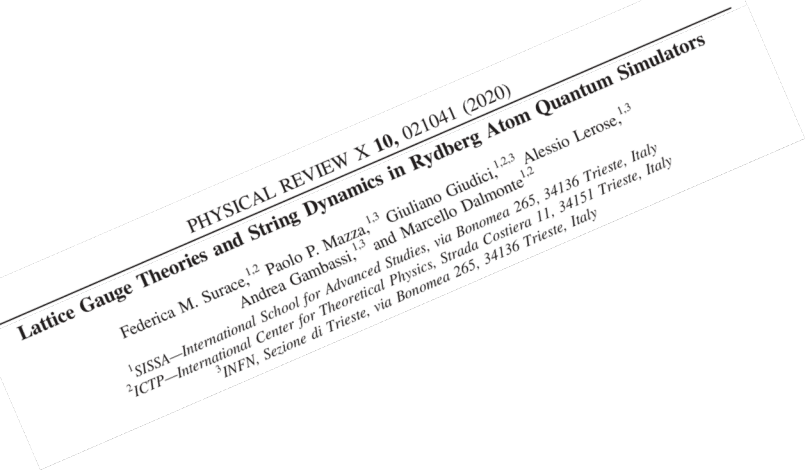


Ballistic plasma mode



Slow thermalization

Experimental observation



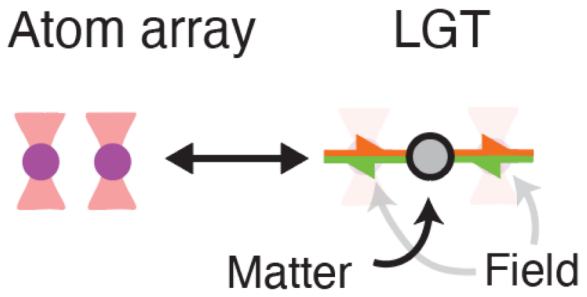
PHYSICAL REVIEW X 10, 021041 (2020)

Lattice Gauge Theories and String Dynamics in Rydberg Atom Quantum Simulators

Federica M. Surace,[1,2] Paolo P. Mazza,[1,3] Giuliano Giudici,[1,2,3] Alessio Lerose,[1,3] Andrea Gambassi,[1,3] and Marcello Dalmonte[1,2]

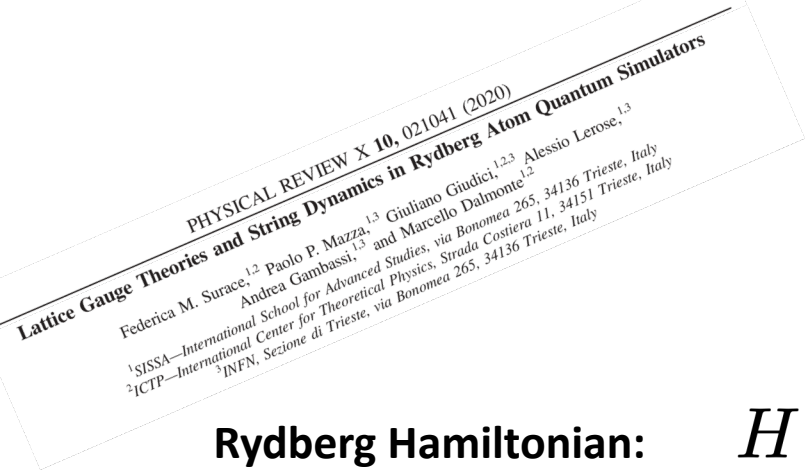
[1]SISSA—International School for Advanced Studies, via Bonomea 265, 34136 Trieste, Italy
[2]ICTP—International Center for Theoretical Physics, Strada Costiera 11, 34151 Trieste, Italy
[3]INFN, Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy

Lattice gauge theory



Electric field Atom spin

$$E_j = (-1)^j Z_j$$



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Lattice gauge theory

PXP model maps onto large-J, massless Schwinger model of (1+1)D QED

Rydberg Hamiltonian:

$$P = |0\rangle\langle 0|$$

$$H = \Omega \sum_i X_i - \Delta \sum_i n_i + P_{j-1} \frac{C_6}{a^6} \sum_{i>j} \frac{n_i n_j}{|i-j|^6} P_{j+1}$$

$$\Omega = -w \qquad m = 0 \qquad J \to \infty \qquad + \text{b. c. } E_0 = 1/2 \text{ (“}\Theta\text{– term”)}$$

Lattice Schwinger model:

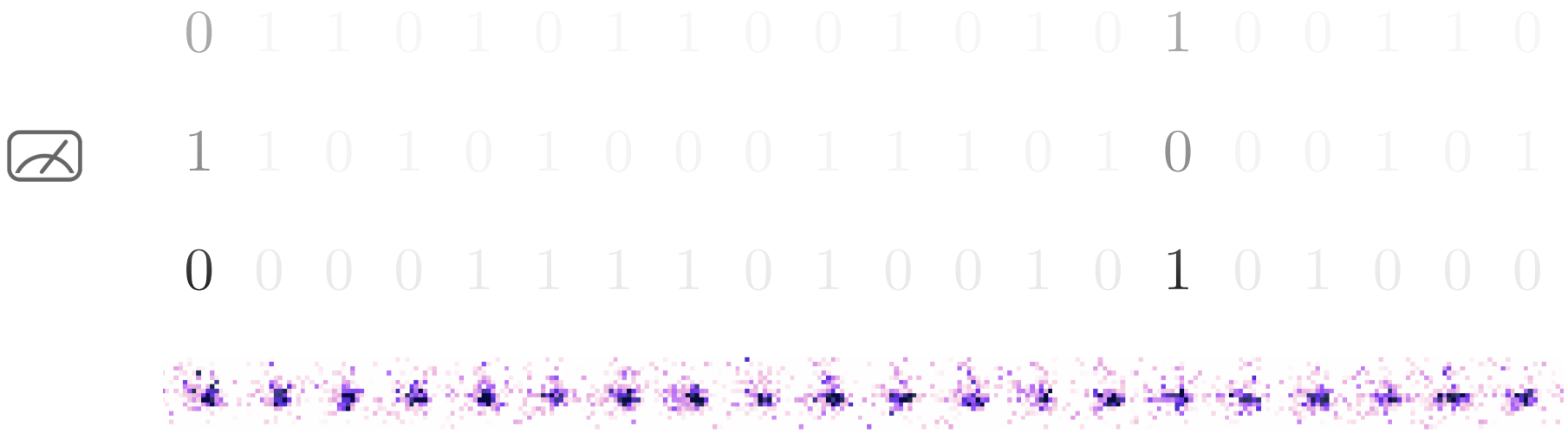
$$H_{\text{Schw.}} = -w \sum_{x=1}^{N-1} \left(c_x^\dagger U_{x,x+1} c_{x+1} + \text{h.c.} \right) + m \sum_{x=1}^{N} (-1)^j c_x^\dagger c_{x+1} + J \sum_{x=1}^{N-1} E_{x,x+1}^2 \ ,$$

Hopping with gauge links *Staggered fermions* *E-field energy*

Gauss’ Law

Spins	Odd/even	Even/odd
0 0	⊕	⊖
1 0	○	○
0 1	○	○

Correlation functions from bitstrings

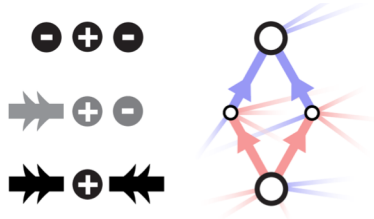


$\langle Z_1 \rangle = 0.1$

$\langle Z_1 Z_{15} \rangle - \langle Z_1 \rangle \langle Z_{15} \rangle = 0.05$

Two-point correlations

Memory of charge clustering

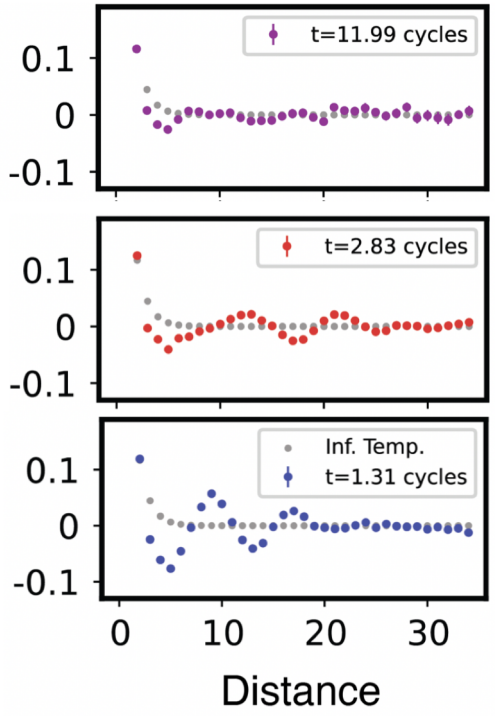


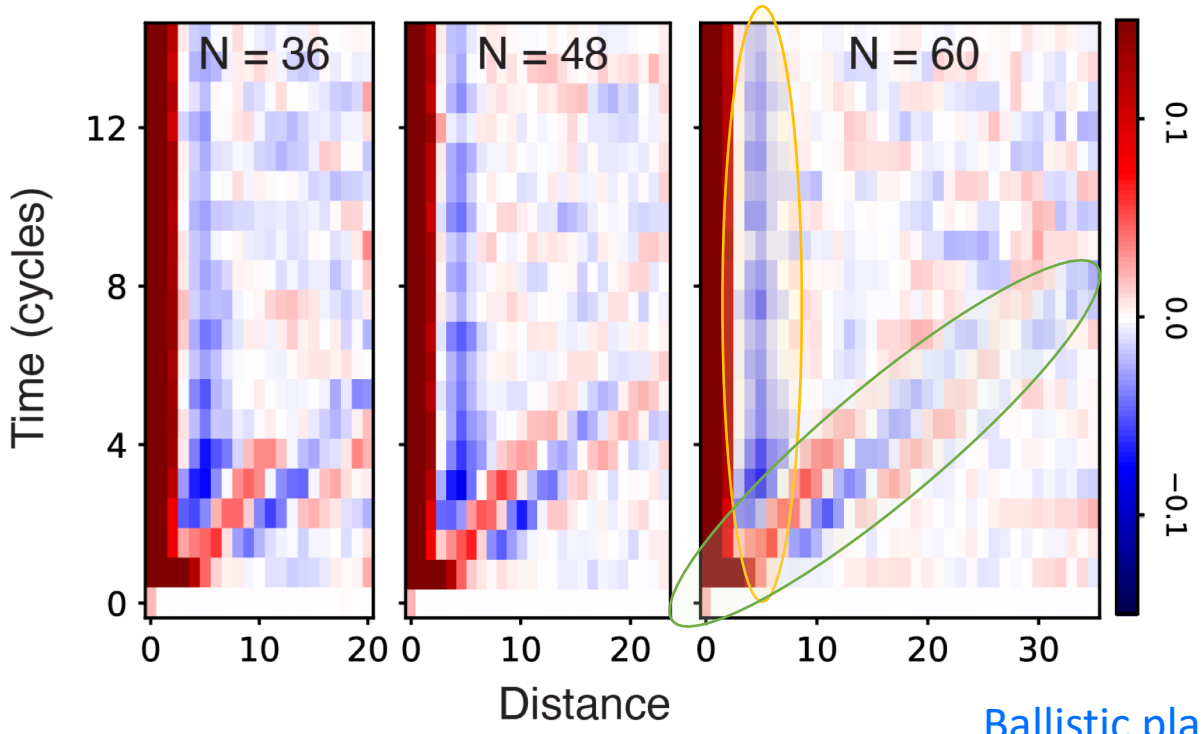
Two-point correlations

$$\mathcal{C}(d)$$

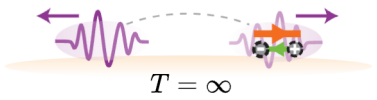
$$= \langle E_j, E_{j+d} \rangle_c (t)$$

$$= (-1)^d \langle Z_j Z_{j+d} \rangle_c$$





Ballistic plasma



I: Plasma modes in a lattice gauge theory

Quantum simulation of LGTs

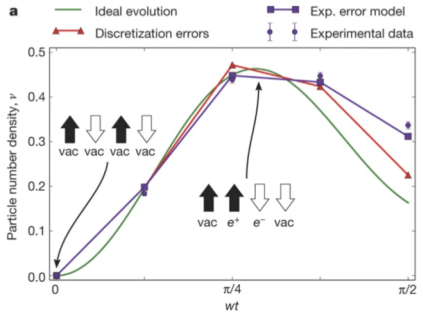
Trapped ions

Letter | Published: 22 June 2016

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez, Christine A. Muschik, Philipp Schindler, Daniel Nigg, Alexander Erhard, Markus Heyl, Philipp Hauke, Marcello Dalmonte, Thomas Monz, Peter Zoller & Rainer Blatt

Nature **534**, 516–519 (2016) | Cite this article



Superconducting circuits

Article | Open access | Published: 04 June 2025

Visualizing dynamics of charges and strings in (2 + 1)D lattice gauge theories

T. A. Cochran, B. Jobst, E. Rosenberg, Y. D. Lensky, G. Gyawali, N. Eassa, M. Will, A. Szasz, D. Abanin, R. Acharya, L. Aghababaie Beni, T. I. Andersen, M. Ansmann, F. Arute, K. Arya, A. Asfaw, J. Atalaya, R. Babbush, B. Ballard, J. C. Bardin, A. Bengtsson, A. Bilmes, A. Bourassa, J. Bovaird, ... P. Roushan

+ Show authors

Nature **642**, 315–320 (2025) | Cite this article

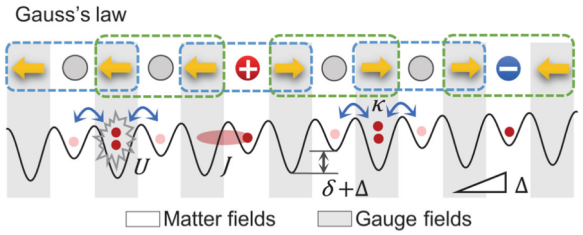
Quantum gas microscopes

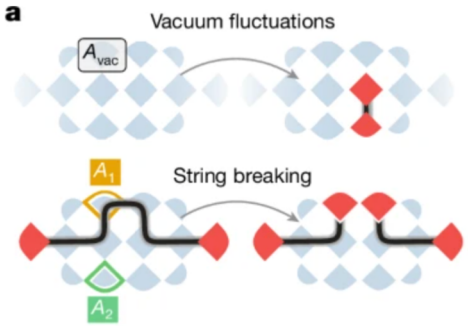
Thermalization dynamics of a gauge theory on a quantum simulator

ZHAO-YU ZHOU, GUO-XIAN SU, JAD C. HALIMEH, ROBERT OTT, HUI SUN, PHILIPP HAUKE, BING YANG, ZHEN-SHENG YUAN, JÜRGEN BERGES, AND JIAN-WEI PAN Authors Info & Affiliations

SCIENCE · 14 Jul 2022 · Vol 377, Issue 6603 · pp. 311-314 · DOI: 10.1126/science.abl6277

Same model as ours (different platform)





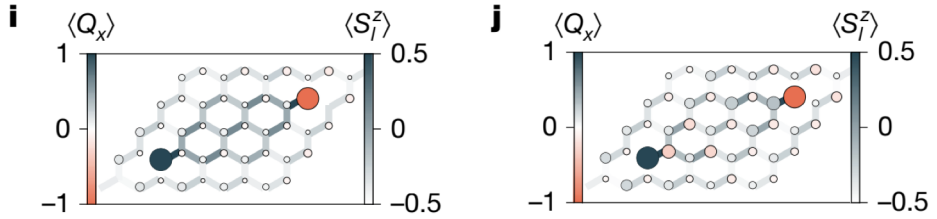
Rydberg atom arrays

Article | Published: 04 June 2025

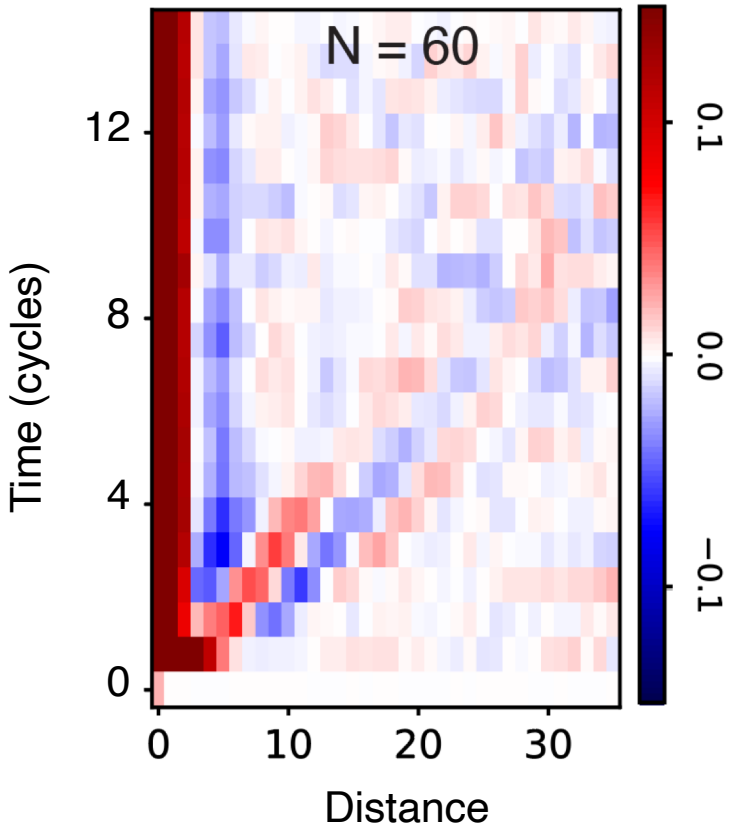
Observation of string breaking on a (2 + 1)D Rydberg quantum simulator

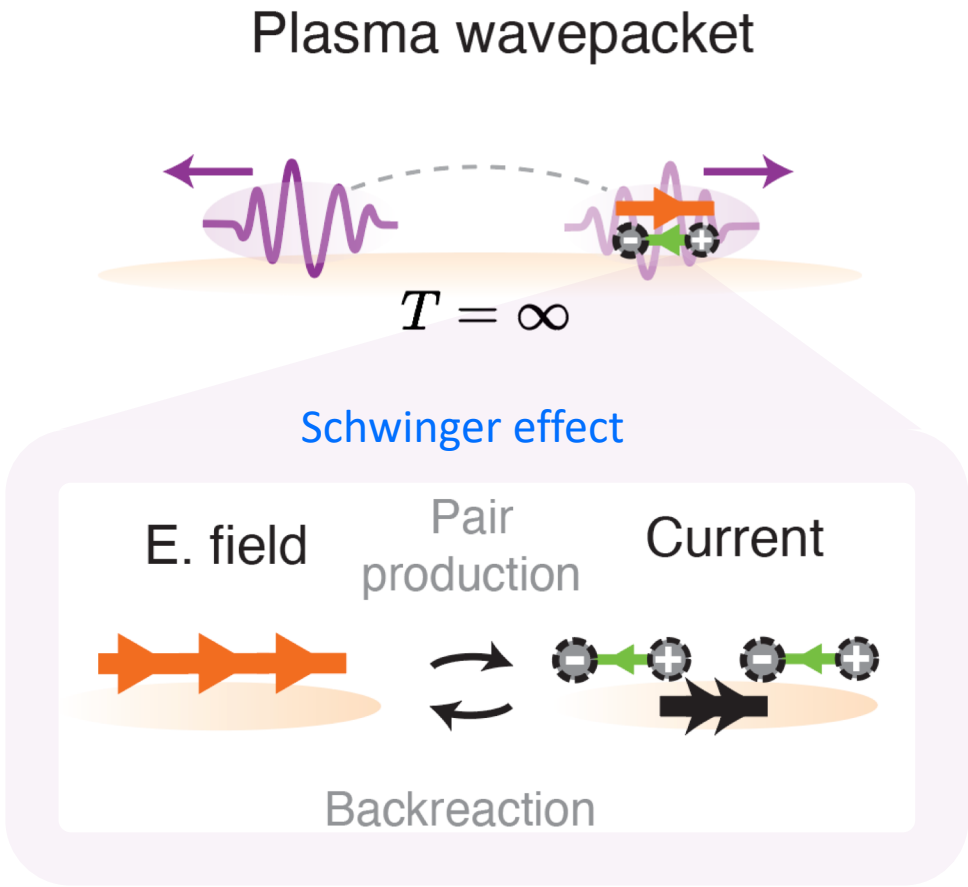
Daniel González-Cuadra, Majd Hamdan, Torsten V. Zache, Boris Braverman, Milan Kornjača, Alexander Lukin, Sergio H. Cantú, Fangli Liu, Sheng-Tao Wang, Alexander Keesling, Mikhail D. Lukin, Peter Zoller & Alexei Bylinskii

Nature **642**, 321–326 (2025) | Cite this article



Plasma oscillations in the LGT



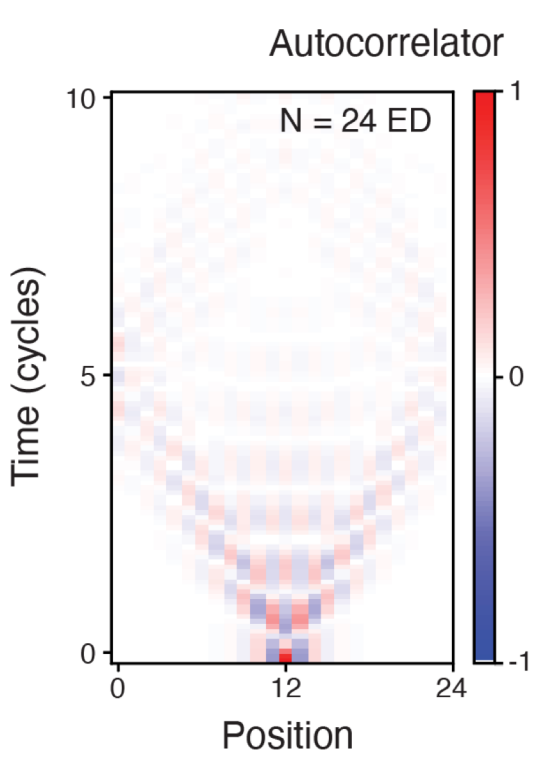


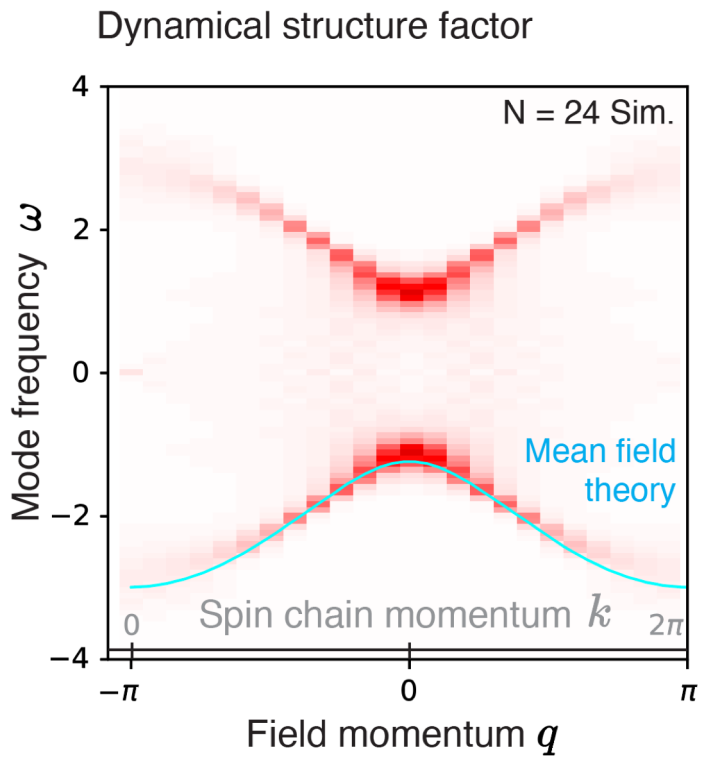
Plasmon band structure

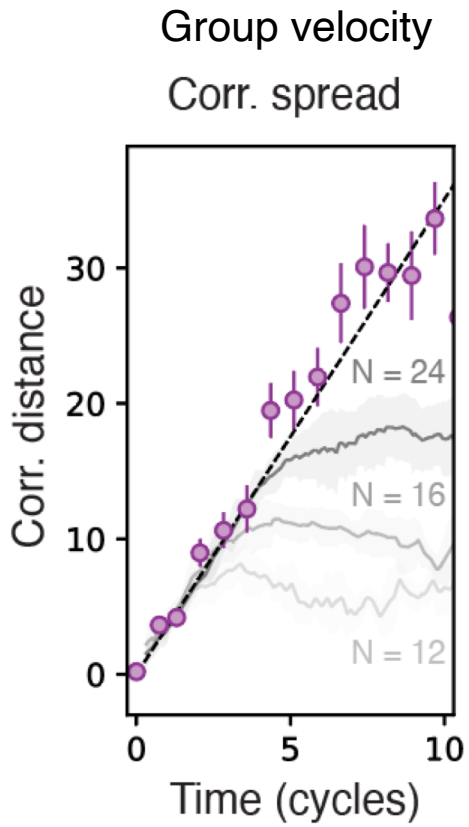
Ballistic propagation suggests quasi-particle structure at infinite temperature…

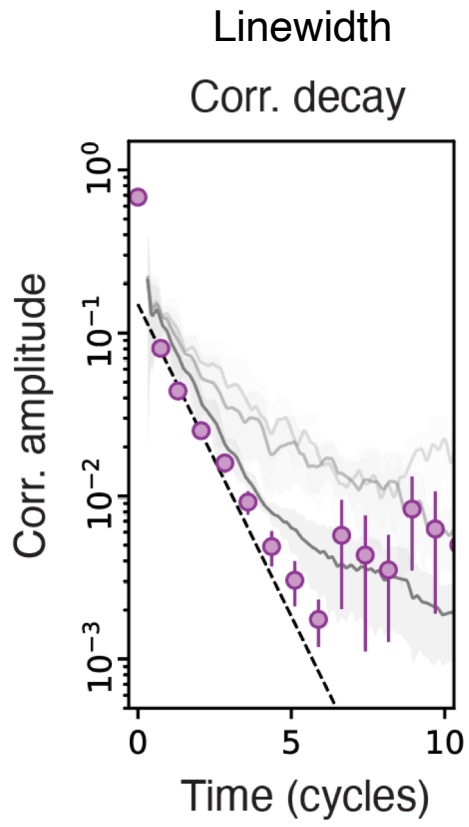
Expt. obs! ✓

DSF = $\left|\mathcal{F}\left[\mathrm{tr}\left(Z_d(t)Z_0(0)\right)\right]\right|^2$

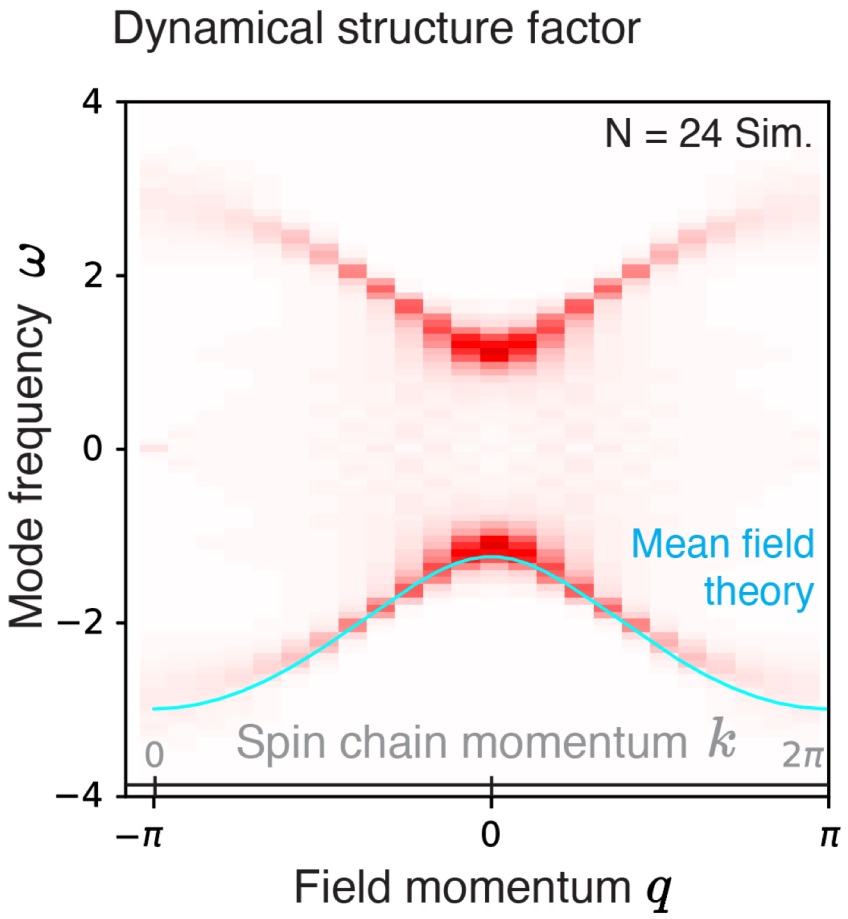








Plasma band structure



1. Connection to Lattice Schwinger model

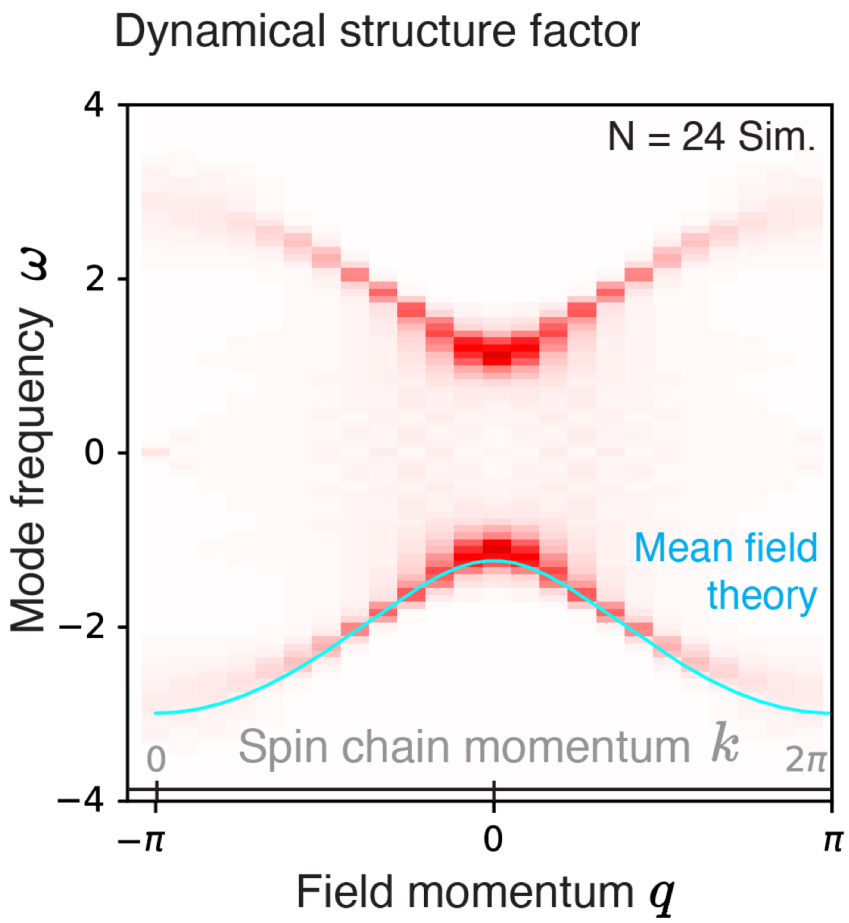
2. Mean field theory

3. Plasma oscillations and scars

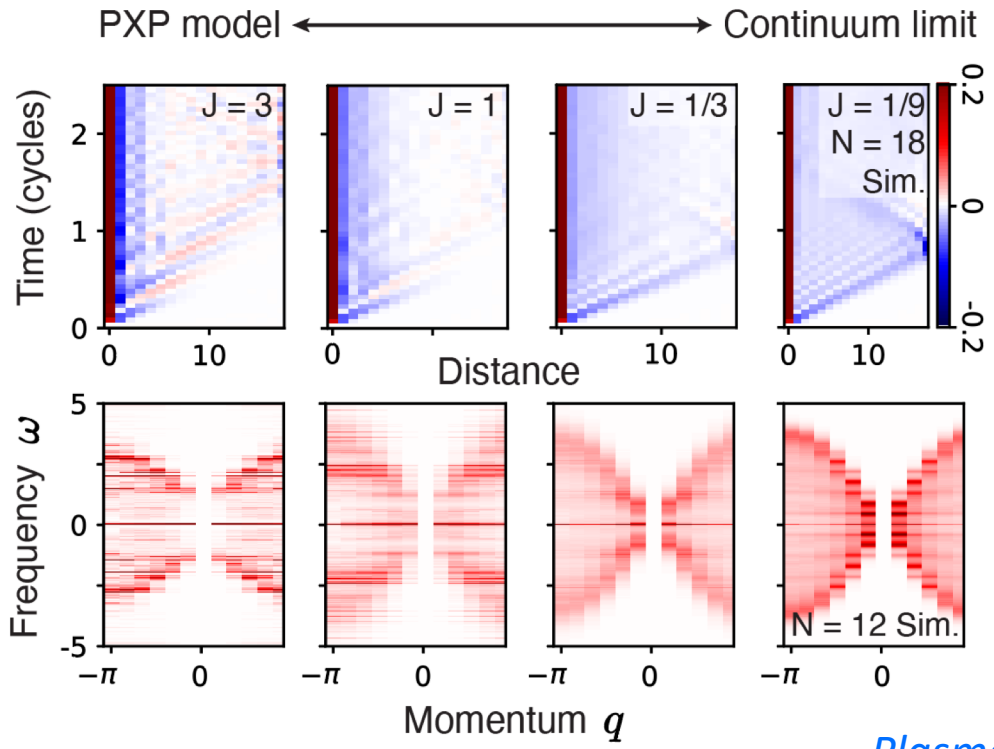
4. Beyond scars: Entanglement transport

5. Experimental observation

Connection to the lattice Schwinger model



$$H_{\text{Schw.}} = -w\sum_{x=1}^{N-1}\left(c_x^\dagger U_{x,x+1}c_{x+1}+\text{h.c.}\right) + m\sum_{x=1}^{N}(-1)^x c_x^\dagger c_{x+1} + J\sum_{x=1}^{N-1}E_{x,x+1}^2 \ ,$$

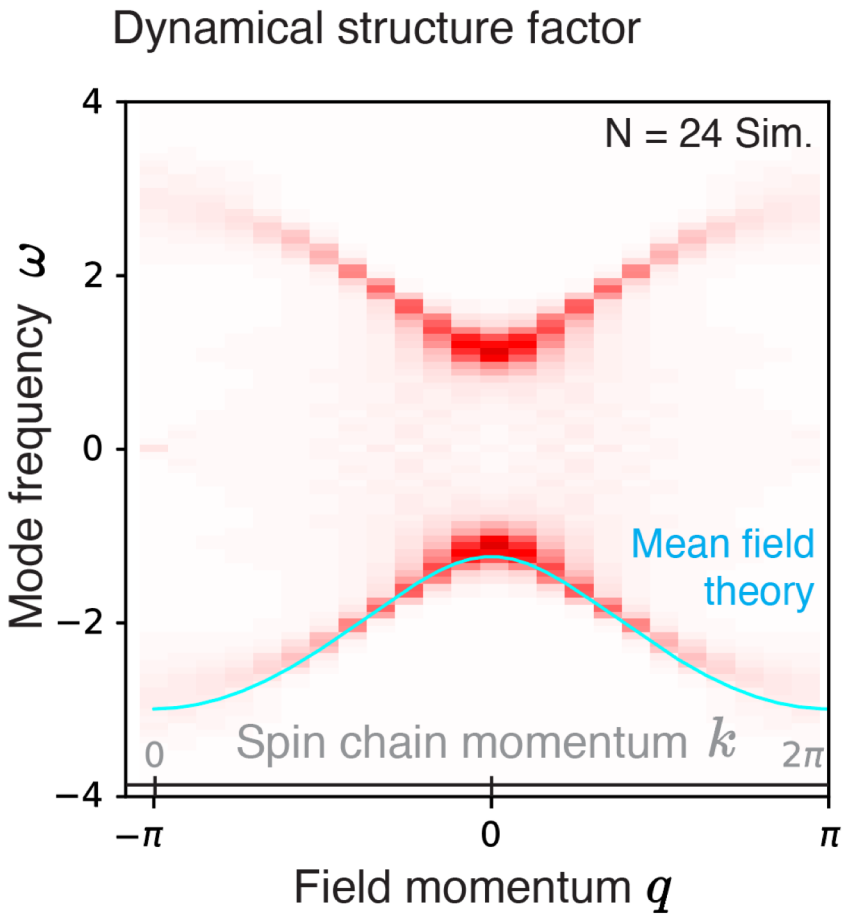


Plasmons persist in continuum limit

Electric field Atom spin

$$E_j = (-1)^j Z_j$$

Mean field theory



Operator equation of motion

Electric field

$$\frac{d}{dt} Z_j = i[H_{\mathrm{PXP}}, Z_j] = 2PY_jP \ ,$$

Coupled oscillations

$$PZP(k) \approx \langle PIP \rangle Z(k)$$

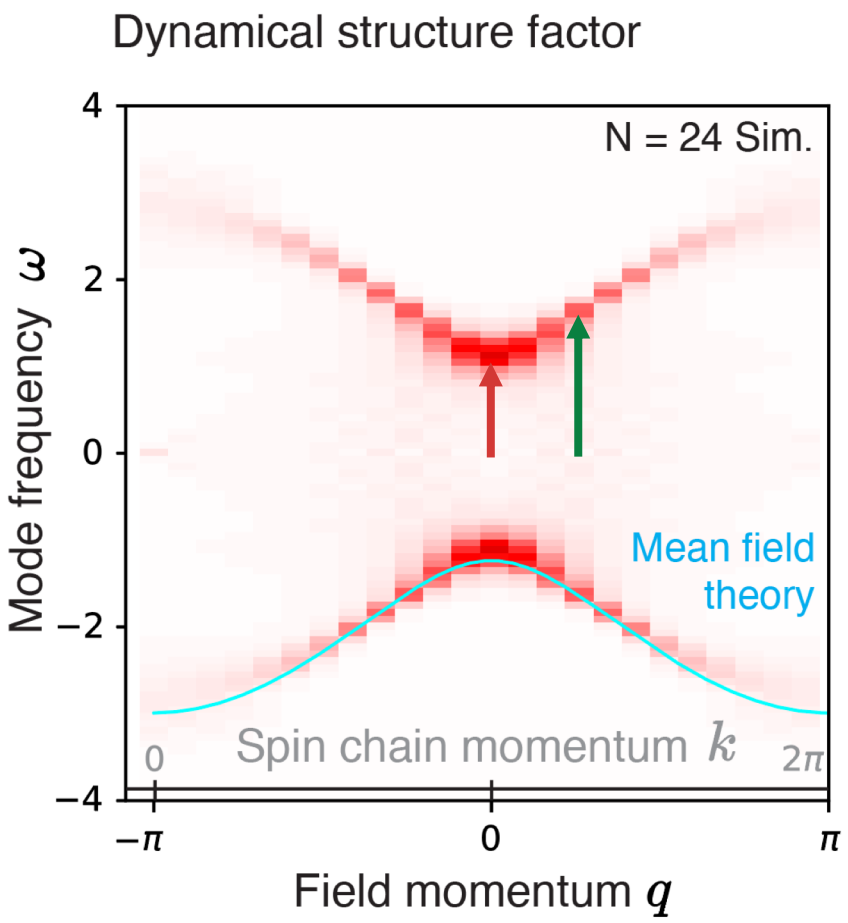
Inf. Temp. Val

Current $ic_j^\dagger c_{j+1} + \mathrm{h.c.}$

$$\frac{d}{dt} PY_jP = -2PZ_jP + P[\sigma_{j-1}^+ \sigma^- + \mathrm{h.c.}]P + P[\sigma_j^+ \sigma^- + \mathrm{h.c.}]P \ .$$

Plasmon band structure

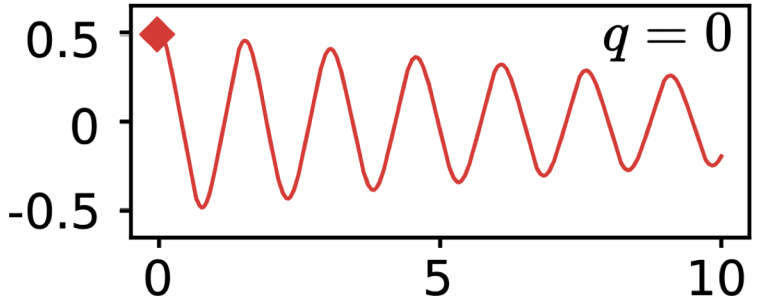
Electric field mode oscillations



Uniform electric field

aka $|\mathbb{Z}_2\rangle$

E field $\sum_j e^{iqj} E_j$



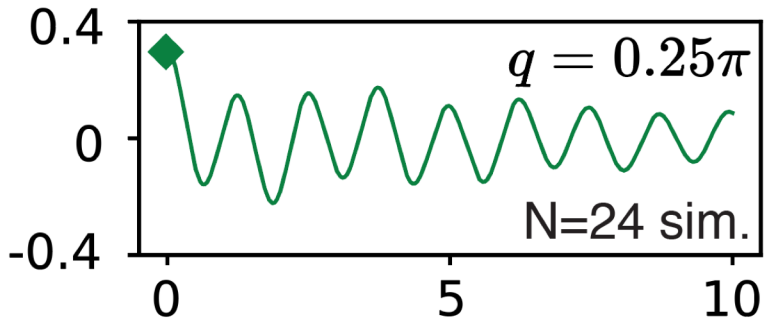
Probing many-body dynamics on a 51-atom quantum simulator
Bernien et. al
Nature 551, 579-584 (2017)

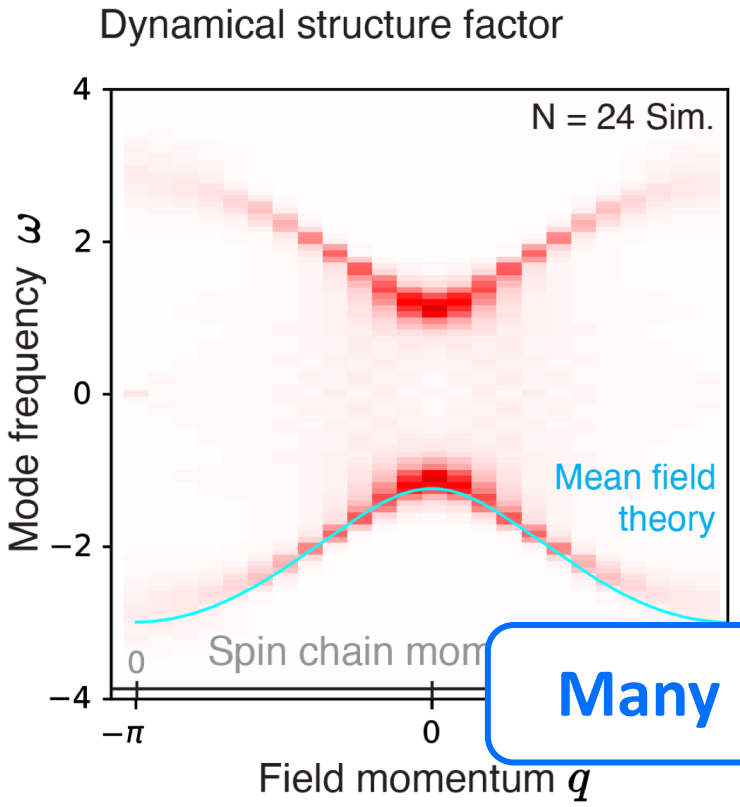
Weak ergodicity breaking from quantum many-body scars
Turner et. al
Nature Physics 14 (2018)

Quantum scarred eigenstates in a Rydberg atom chain
Turner et. al.
PRB (2018)

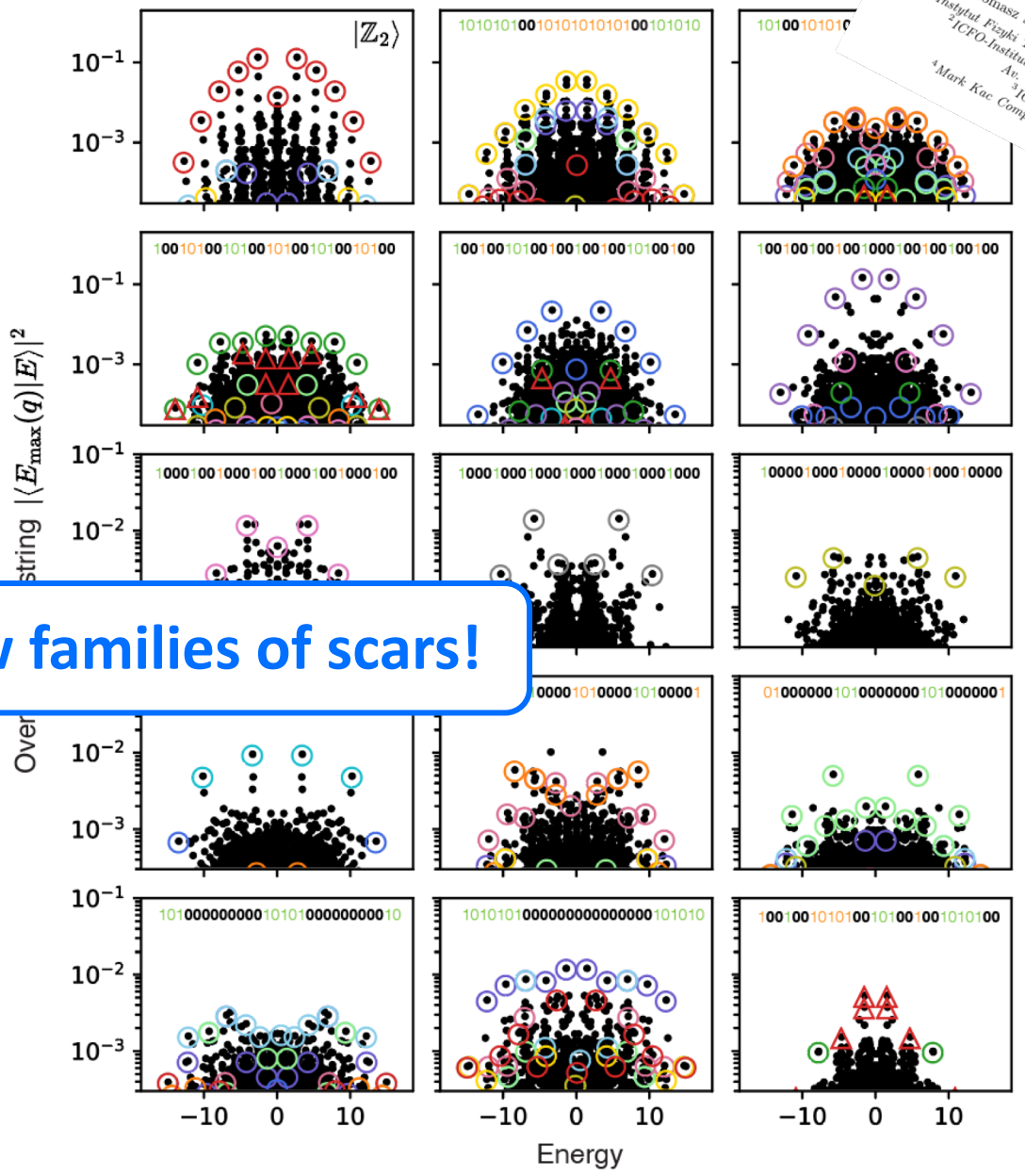
Modulated electric field

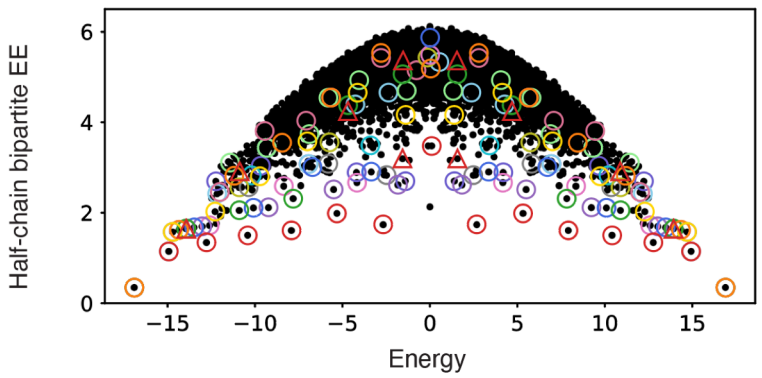
E field $\sum_j e^{iqj} E_j$

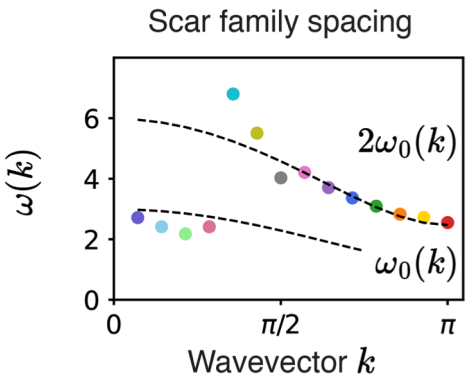




Many new families of scars!







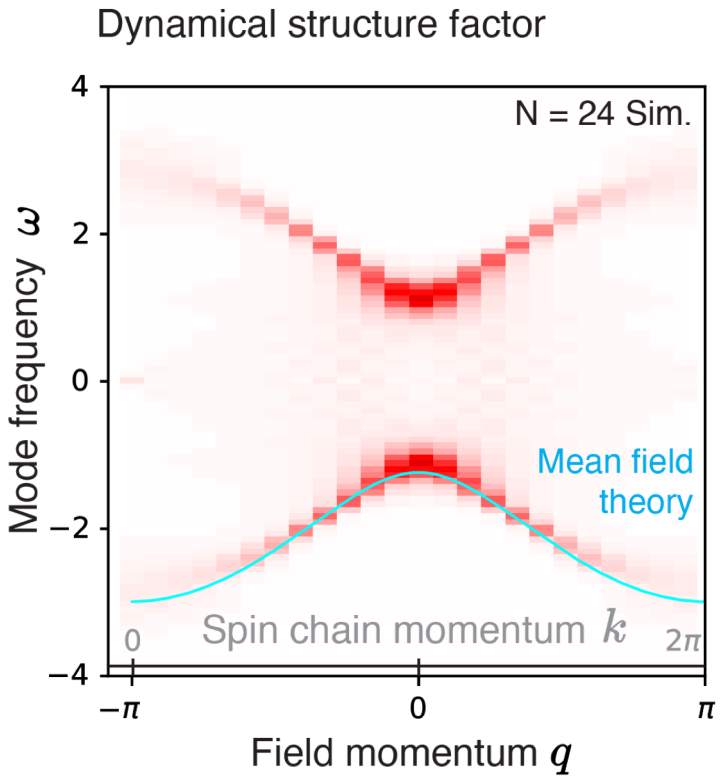
See also:

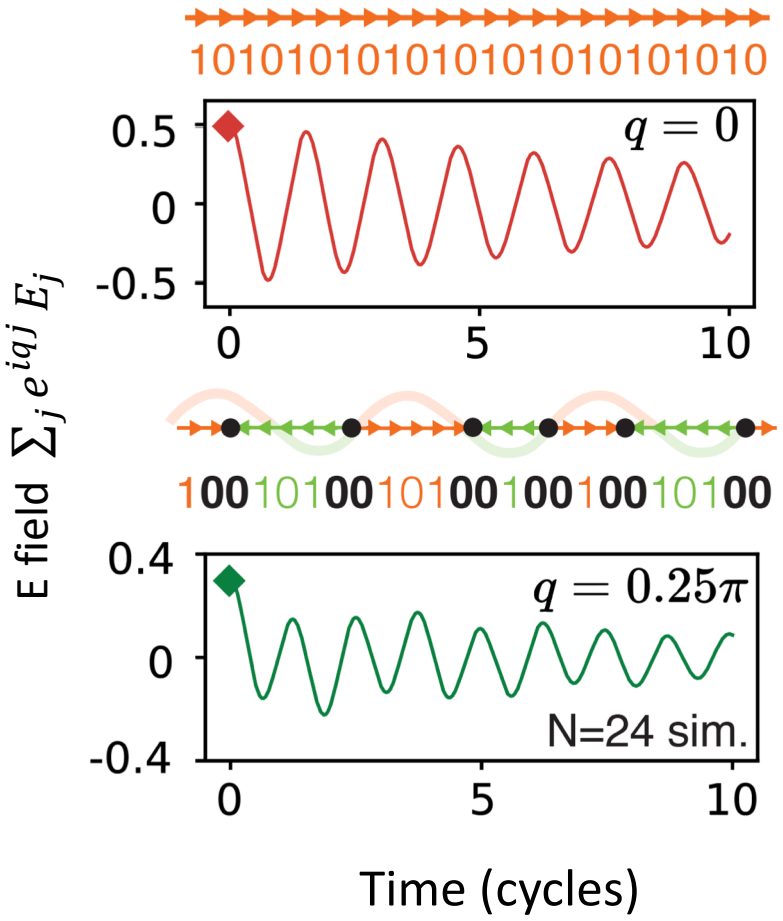
Unsupervised detection of decoupled subspaces: many-body scars and beyond

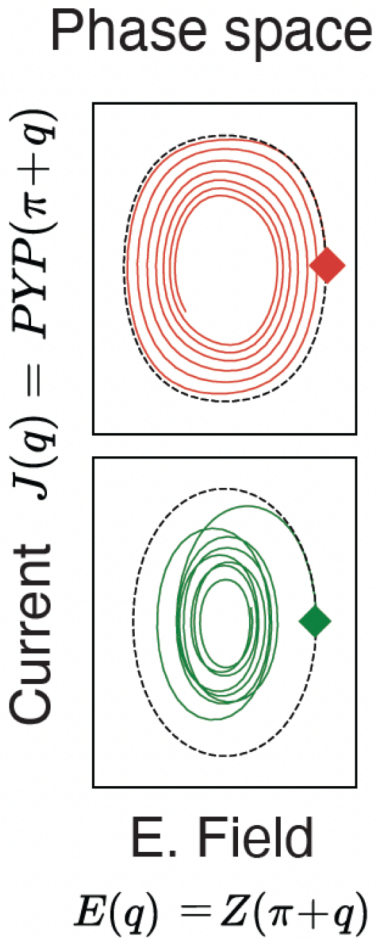
Tomasz Szołdra,[1] Piotr Sierant,[2] Maciej Lewenstein,[2,3] and Jakub Zakrzewski[1,4]
[1]Instytut Fizyki Teoretycznej, Uniwersytet Jagielloński, Łojasiewicza 11, PL-30-348 Kraków, Poland
[2]ICFO-Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain
[3]ICREA, Passeig Lluis Companys 23, 08010 Barcelona, Spain
[4]Mark Kac Complex Systems Research Center, Uniwersytet Jagielloński, Kraków, Poland

(Dated: June 7, 2022)

Higher field modes and phase space





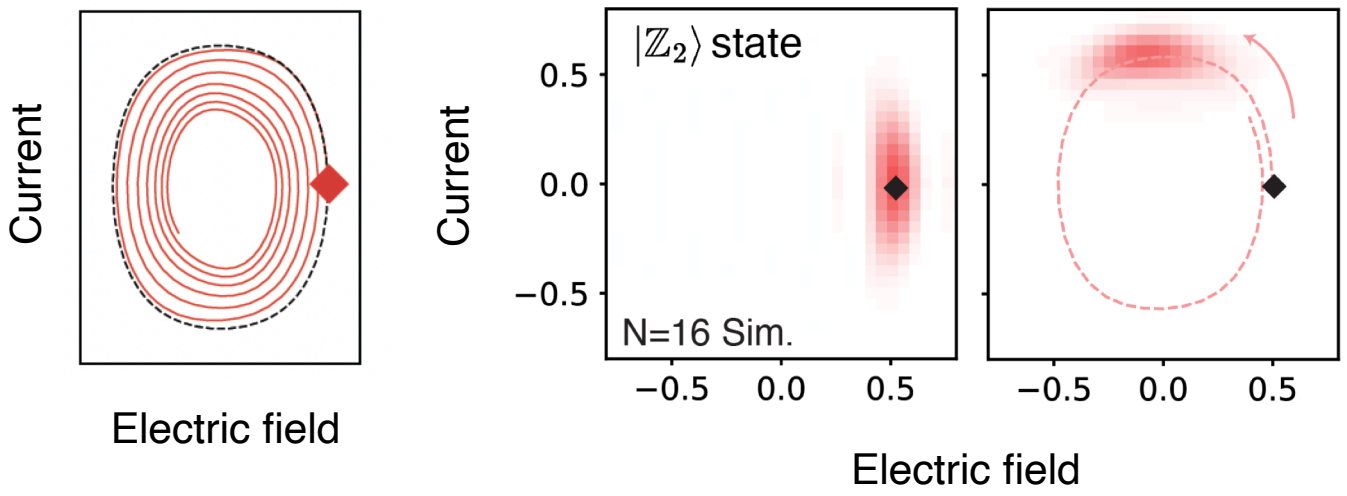


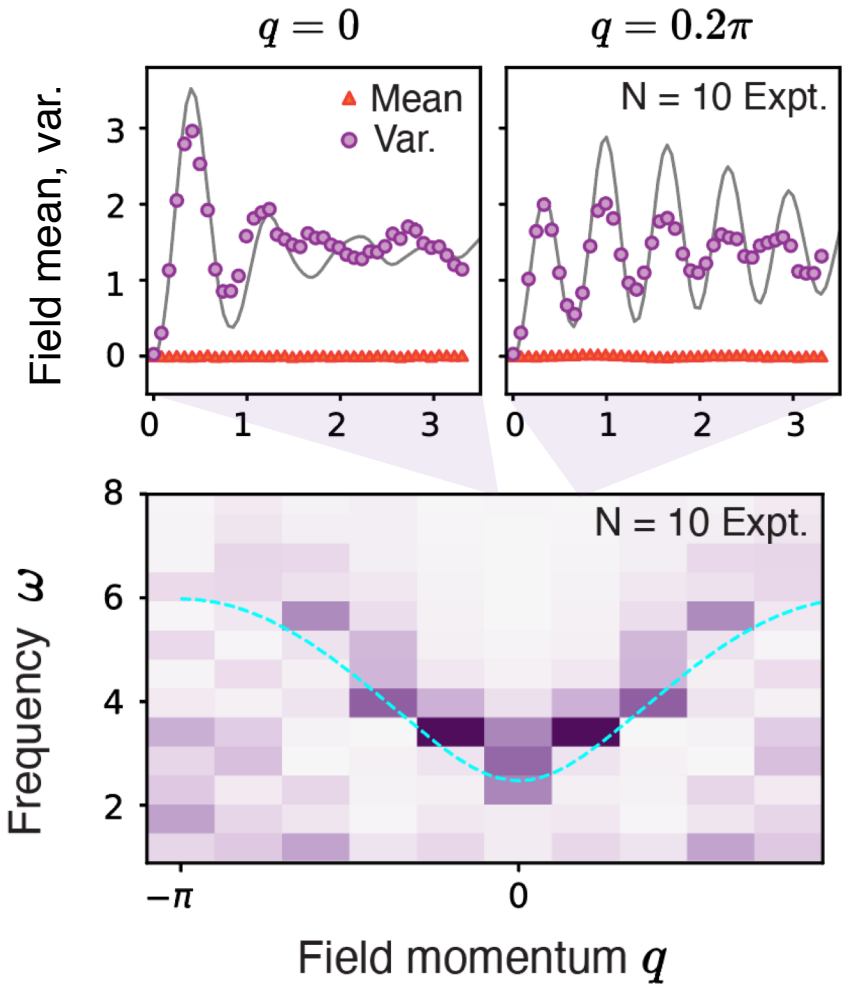
E field/ current behave like simple harmonic oscillator variables!

Wigner functions in phase space

Many-body Wigner distr.

Observables: mean and variance

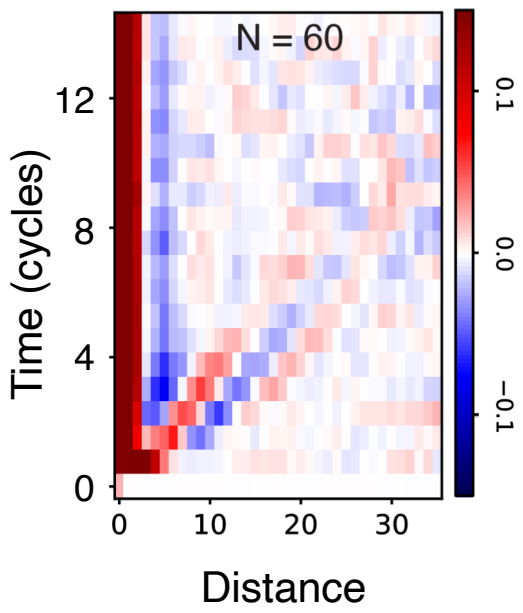




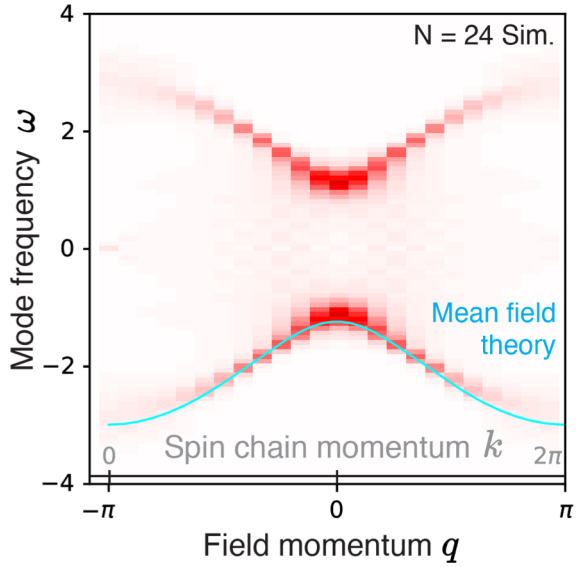
Scars: large coherent states

Summary of part I

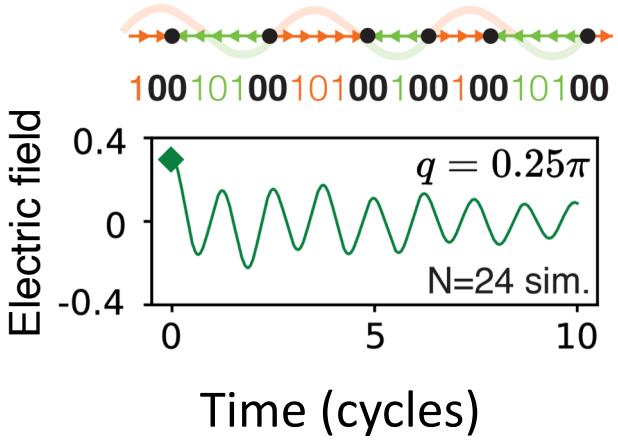
Ballistic correlations…



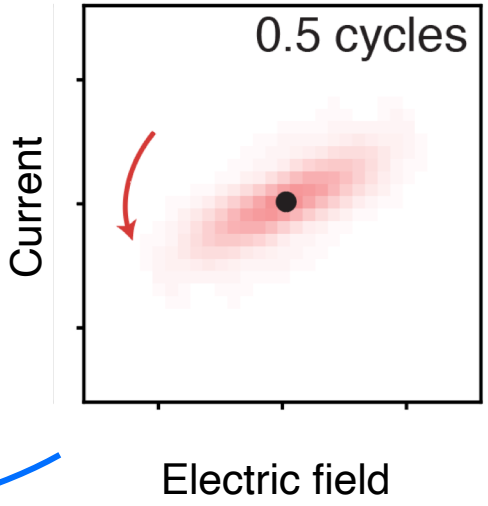
are plasmon wavepackets



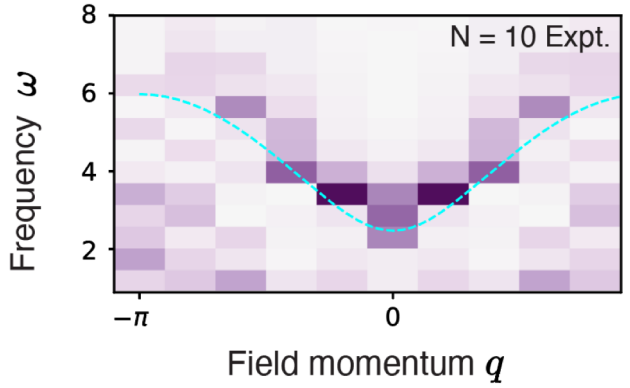
Plasmons are field/current oscillations with momenta



with a phase space representation



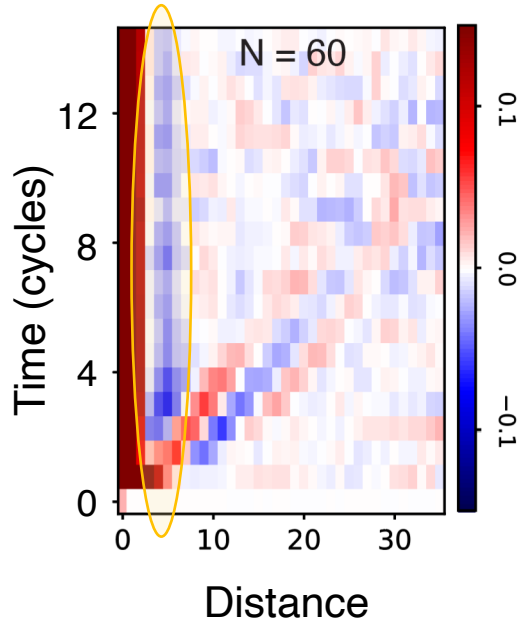
Collective mode in a gauge theory, surviving at inf. temp.

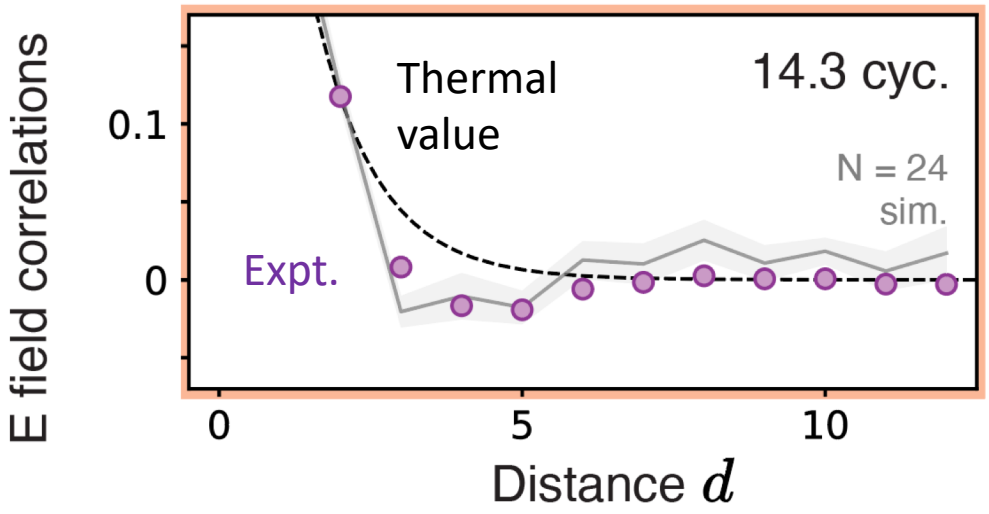


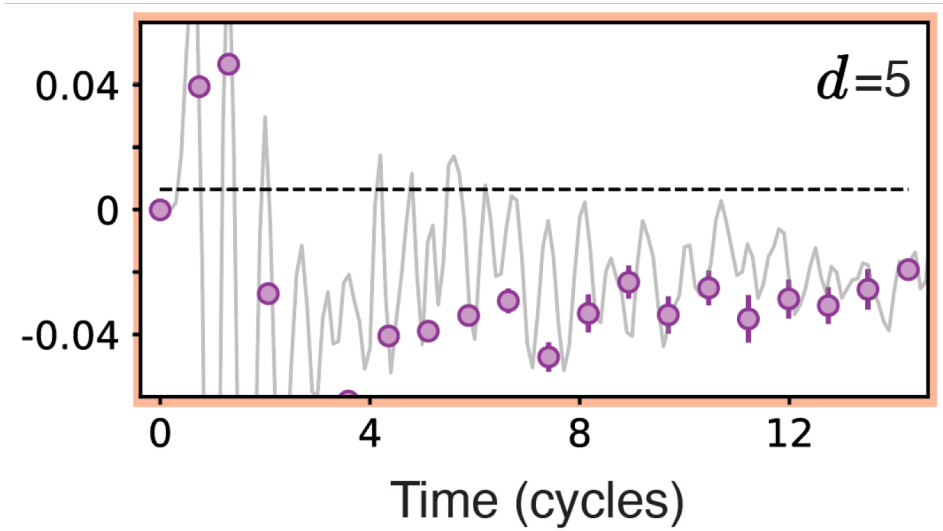
…predicting field variance oscillations

II: Long memory of charge clusters

Long-time correlations



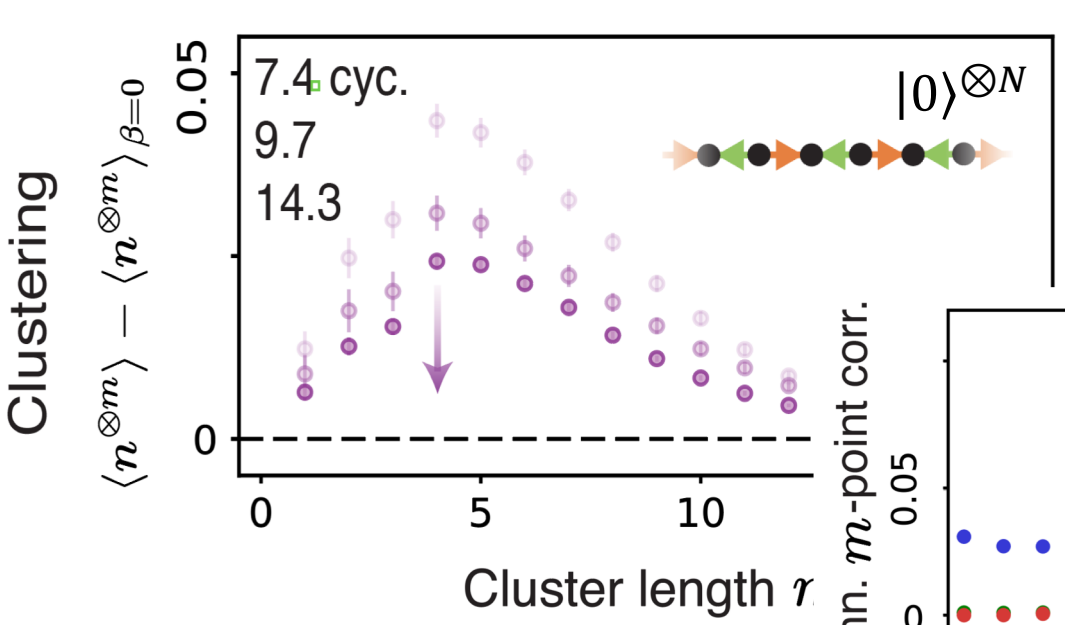


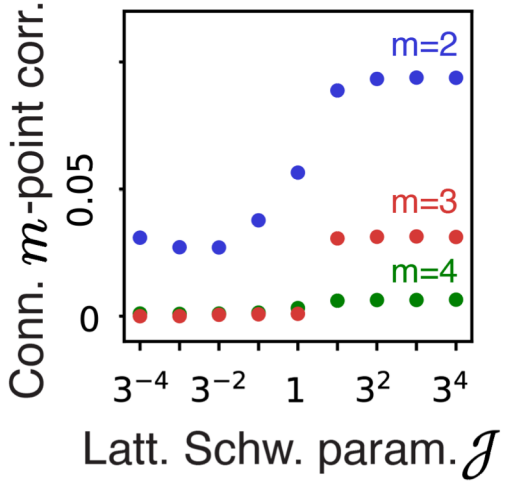


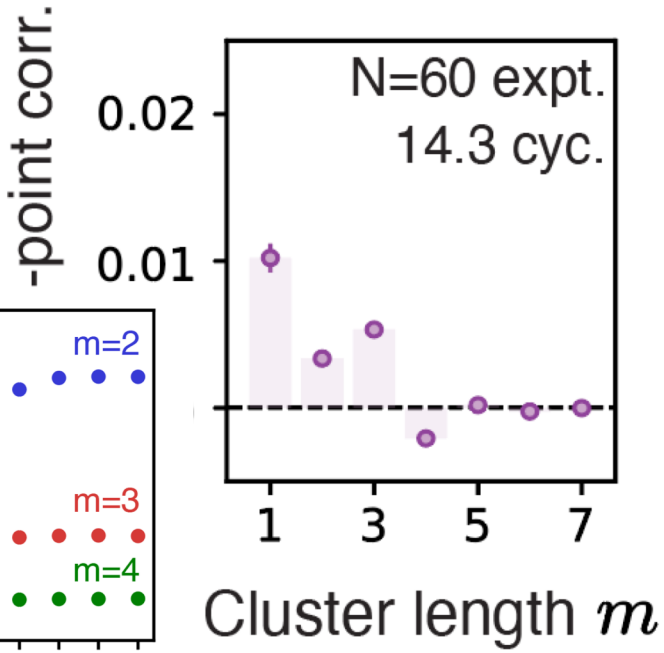
Charge clustering

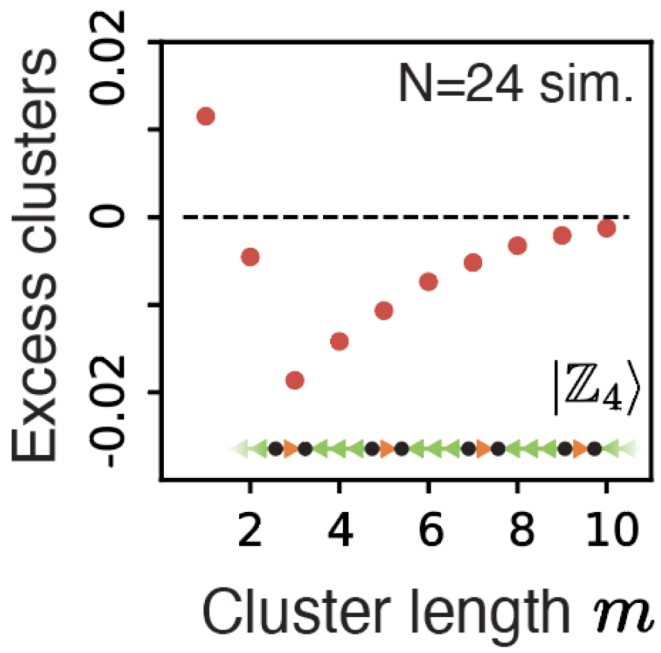
Correlations are largely 3-body!

Memory of initial conditions









Continuum limit ⟷ PXP model

Truncation effect?

Link model: "+,0,+" not allowed, only "+,-,+"

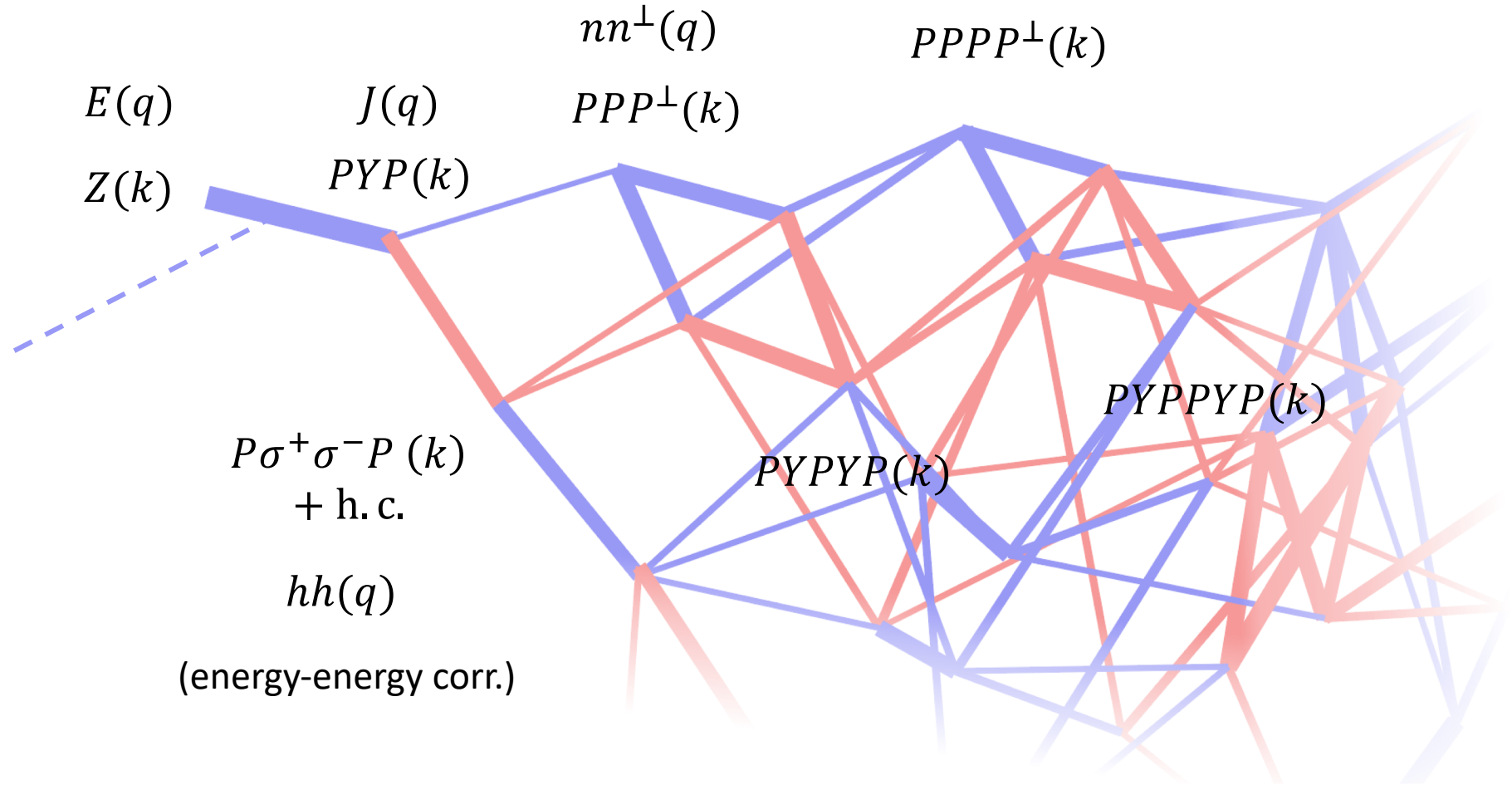
Operator dynamics as a graph hopping problem!

Liouvillian graph

Ehud Altman,
Chris White,
Stuart Yi-Thomas,…

$$\frac{d}{dt}A = i[H, A]$$

$$\frac{d}{dt}Z(k) = i[H, Z(k)]$$
$$= 2iPYP(k)$$



Operator dynamics as a graph hopping problem!

$$\frac{d}{dt}A = i[H, A]$$

$$\frac{d}{dt}Z(k) = i[H, Z(k)]$$
$$= 2iPYP(k)$$

Mean field theory!

Operator equation of motion

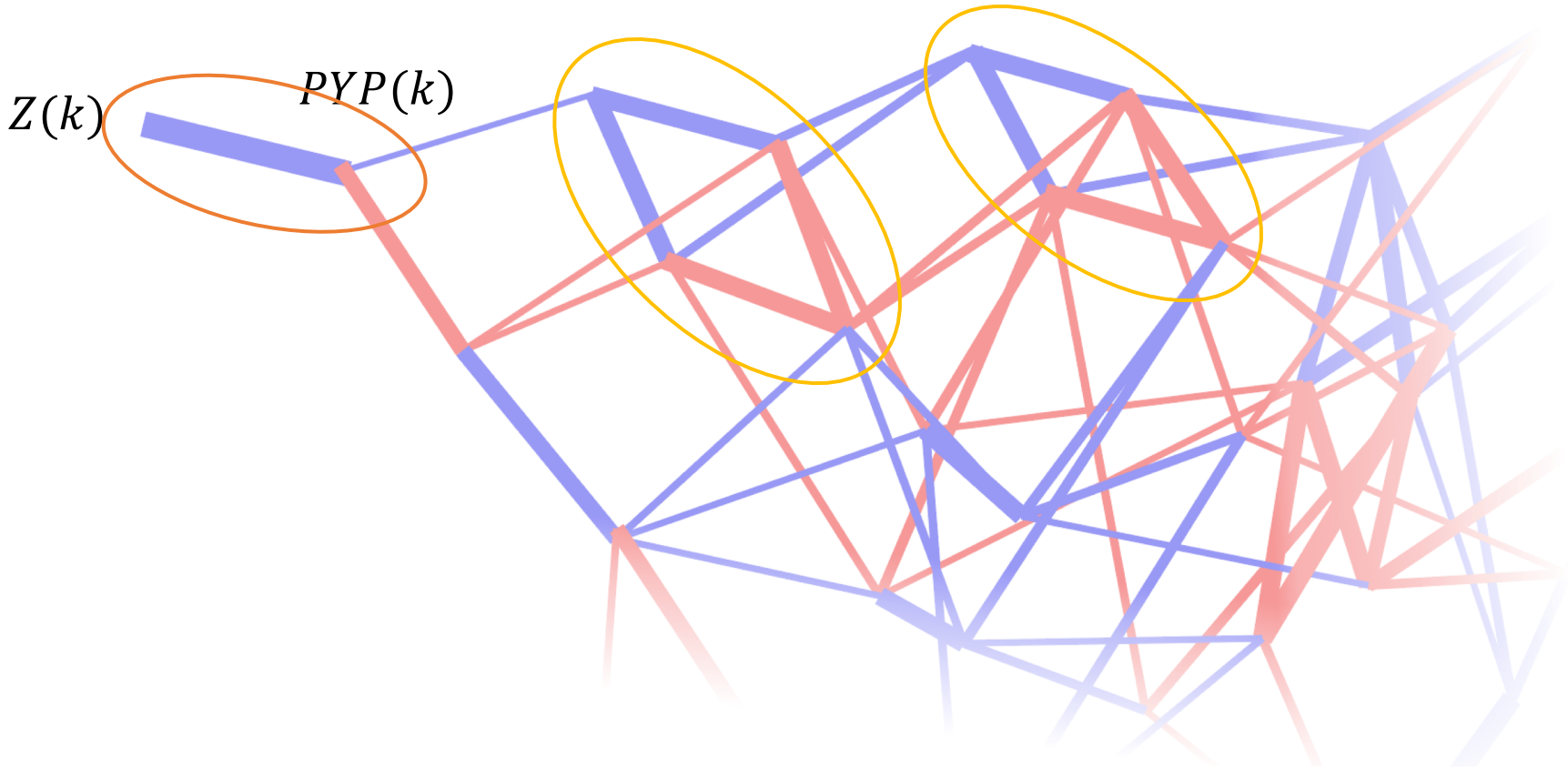
$$\frac{d}{dt}Z_j = i[H_{\mathrm{PXP}}, Z_j] = 2PY_jP \ ,$$

$$\langle PZP(k)\rangle \approx \langle PIP(k)\rangle\langle Z(k)\rangle$$

$$\frac{d}{dt}PY_jP = -2PZ_jP$$
$$+ P[\sigma_{j-1}^{+}\sigma^{-} + \mathrm{h.c.}]P + P[\sigma_j^{+}\sigma^{-} + \mathrm{h.c.}]P \ .$$

Liouvillian graph

Long memory!



State expectation values as hopping on Liouvillian graph!

Operator dynamics as a graph hopping problem!

$$\frac{d}{dt}A = i[H, A]$$

Expanding an operator:

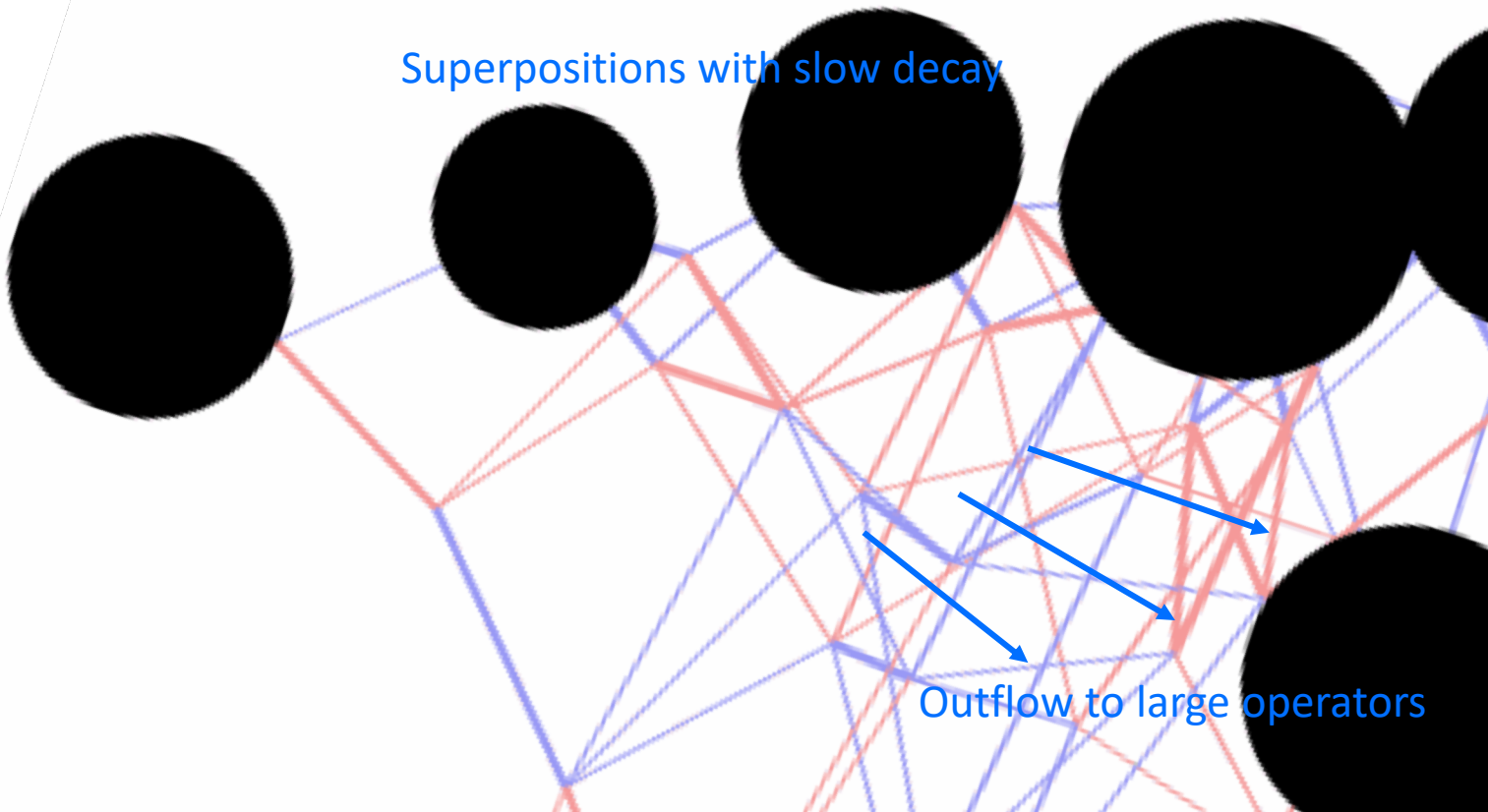
$$|A) = |o_1)(o_1|A) + \cdots$$

Expanding a state:

$$|\rho) = |o_1)(o_1|\rho) + \cdots$$

Operator expectation value

Circles: Expectation values of time-evolved state!



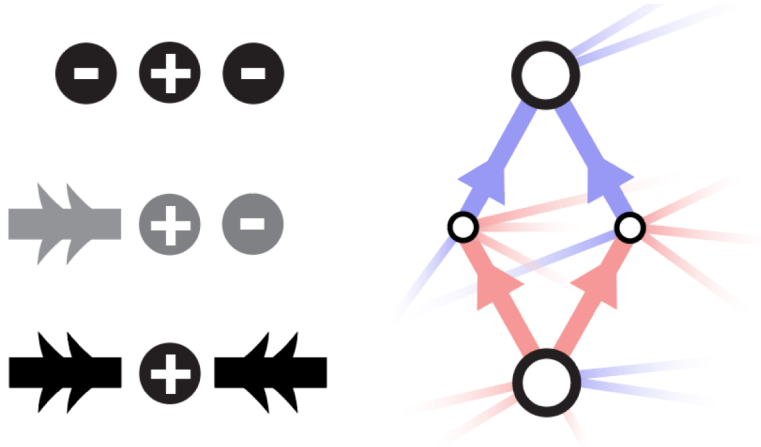
Clustering from “Bound operators”

Charge/charge

$n_{j-1}n_j n_{j+1}$

Current/current

$J_{j-1}n_j J_{j+1}$



Destructive interference

“Dark” operator superpositions

$$A(t) \approx A(0)$$

$$\langle A(t) \rangle = \langle \psi_0 | A(t) | \psi_0 \rangle$$

Memory of initial conditions!

Visualizing states on a Liouvillian graph

Operator dynamics as a graph hopping problem!

$$\frac{d}{dt}A = i[H, A]$$

Expanding an operator:

$$|A) = |o_1)(o_1|A) + \cdots$$

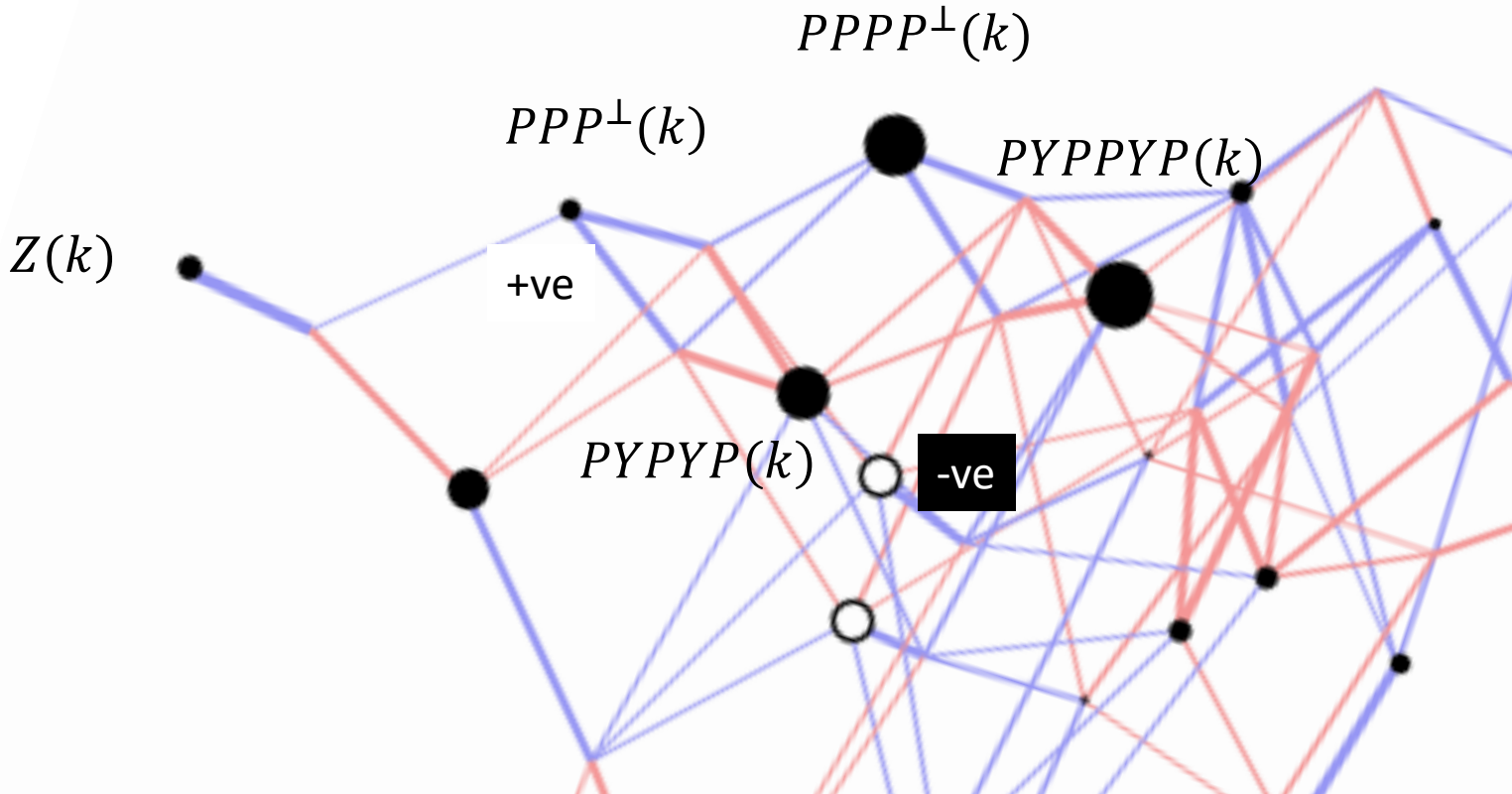
Expanding a state:

$$|\rho) = |o_1)(o_1|\rho) + \cdots$$

Operator expectation value

Stationary state $\rho = \mathbb{E}_t[|\psi(t)\rangle\langle\psi(t)|]$

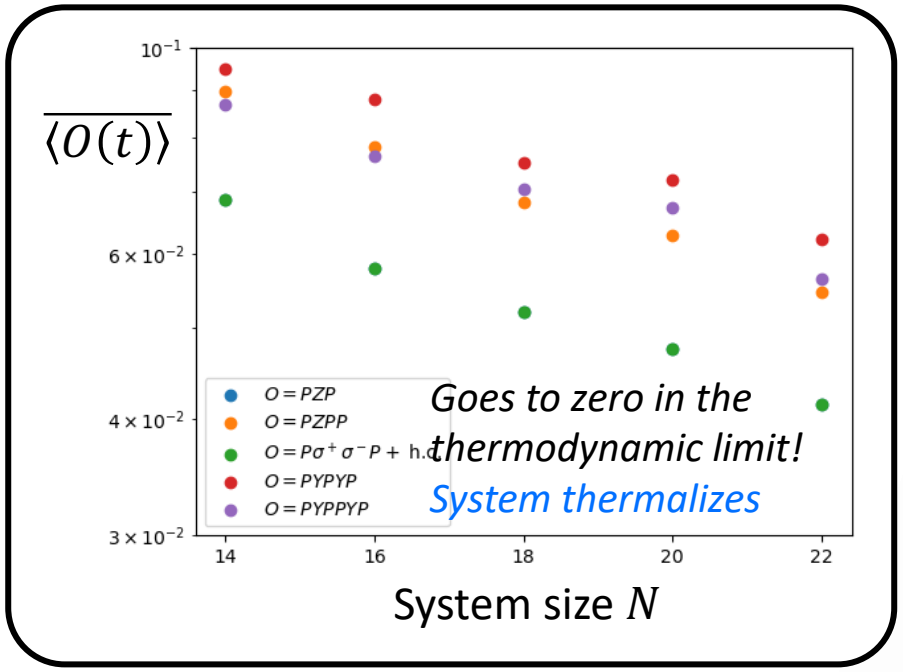
Expectation values of stationary state!

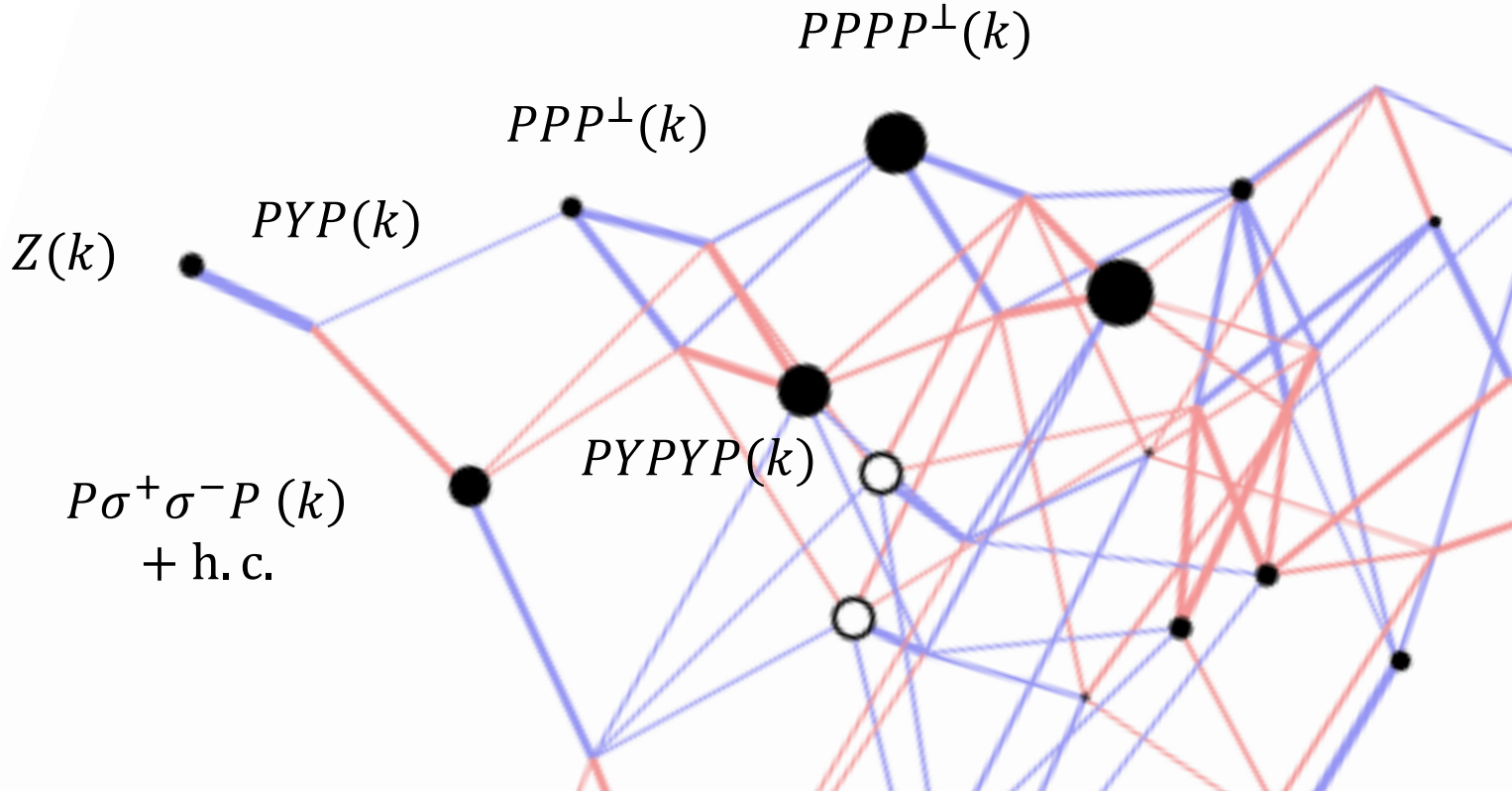


Operator dynamics as a graph hopping problem!

$$\frac{d}{dt}A = i[H, A]$$

Liouvillian graph

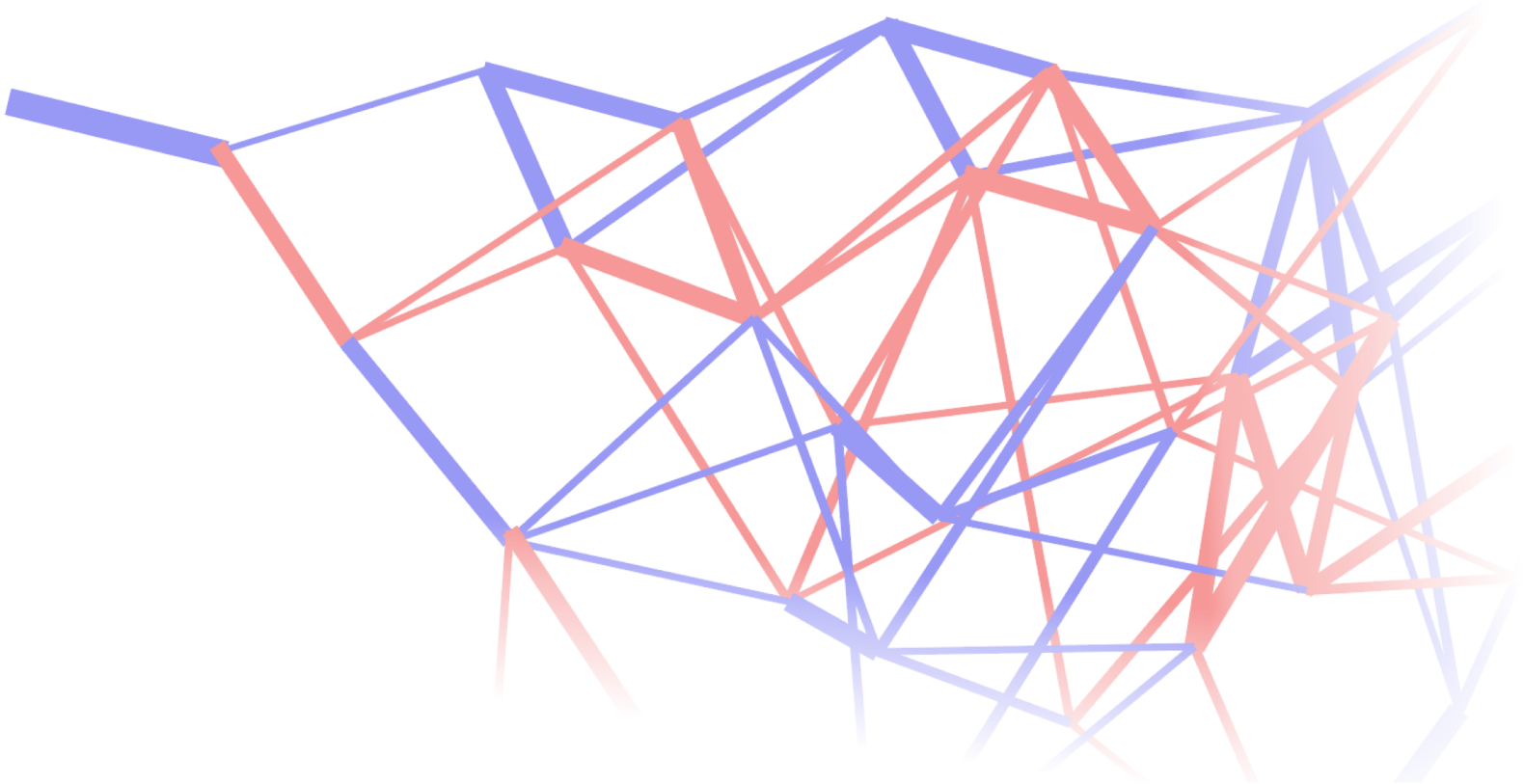




What’s special about our model?

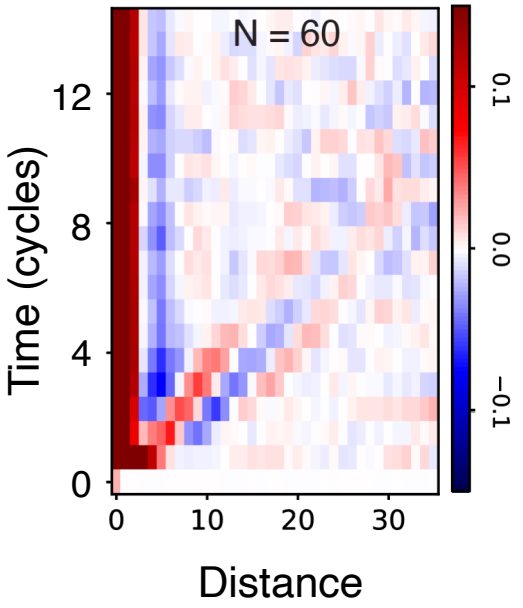
Constrained Hilbert space:
Few number of small operators

Unique graph structures

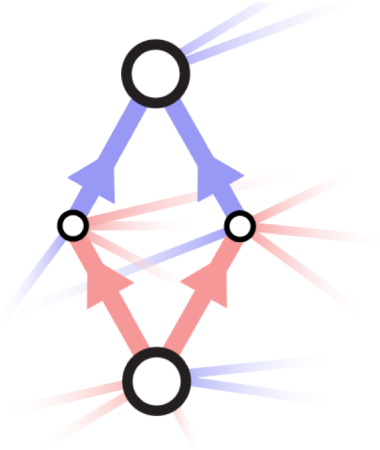


Summary of part II

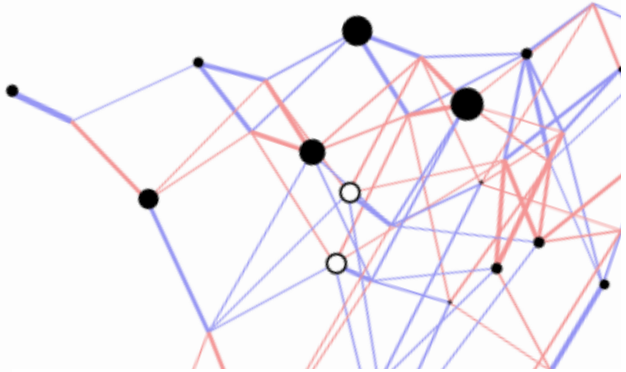
Long-lived correlations…



due to destructive interference of operators



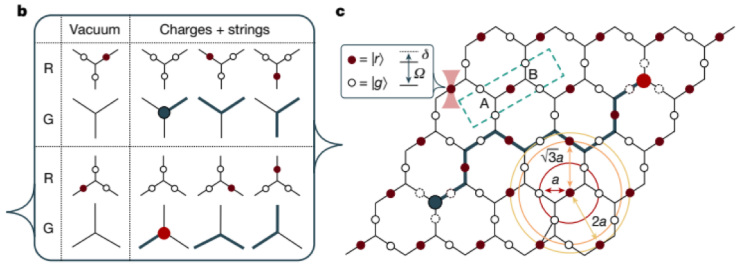
on a Liouvillian graph



Future directions

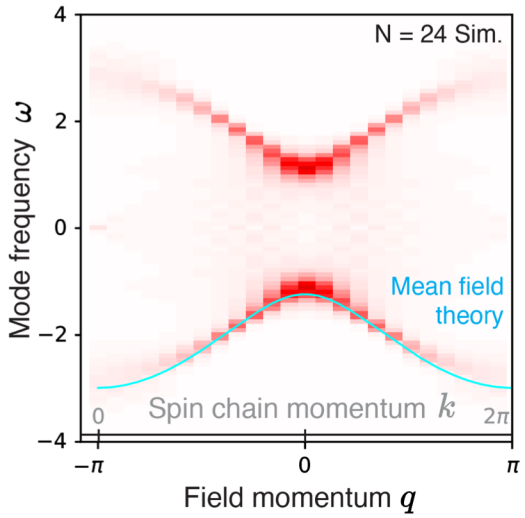
Dynamics in lattice gauge theories?

- 2D
- Constrained models



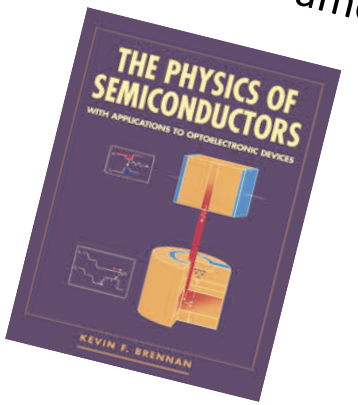
Observation of string breaking on a (2 + 1)D Rydberg quantum simulator
Daniel González-Cuadra, … Alexander Keesling, Mikhail D. Lukin, Peter Zoller & Alexei Bylinskii
Nature **642**, 321–326 (2025)

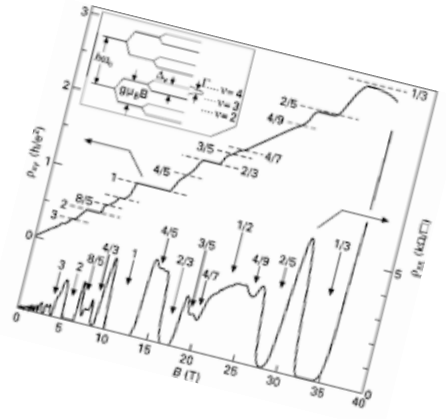
Band structure in operator space



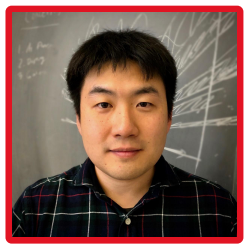
More quantum (dynamics) experiments!

Silicon+ has taught us a tremendous amount of physics!





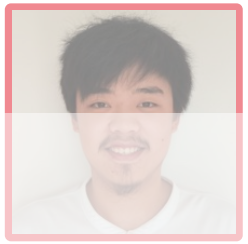
Collaborators


Soonwon Choi


Federica Surace


Tommy Schuster


Wenjie Gong


Zhuo Chen

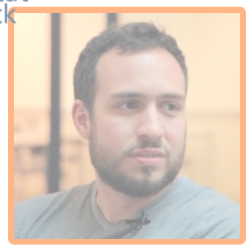

Andreas Eben


Jordan Cotler


Robert Huang

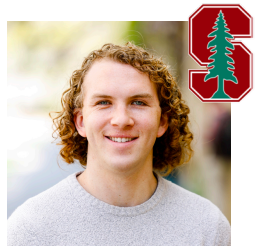

Gil Refael


Hannes Pichler


Fernando Brandão

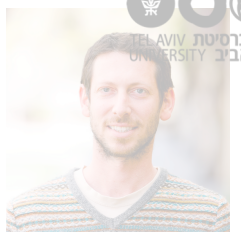
Thank you!


Manuel Endres

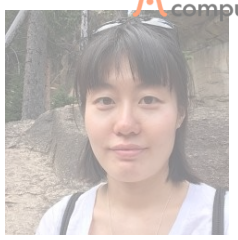

Adam Shaw


Joonhee Choi

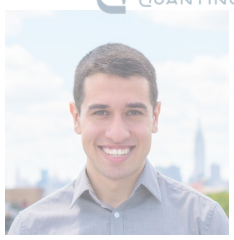

Pascal Scholl


Ran Finkelstein


Anant Kale


Xin Xie


Jacob Covey


Ivaylo Madjarov