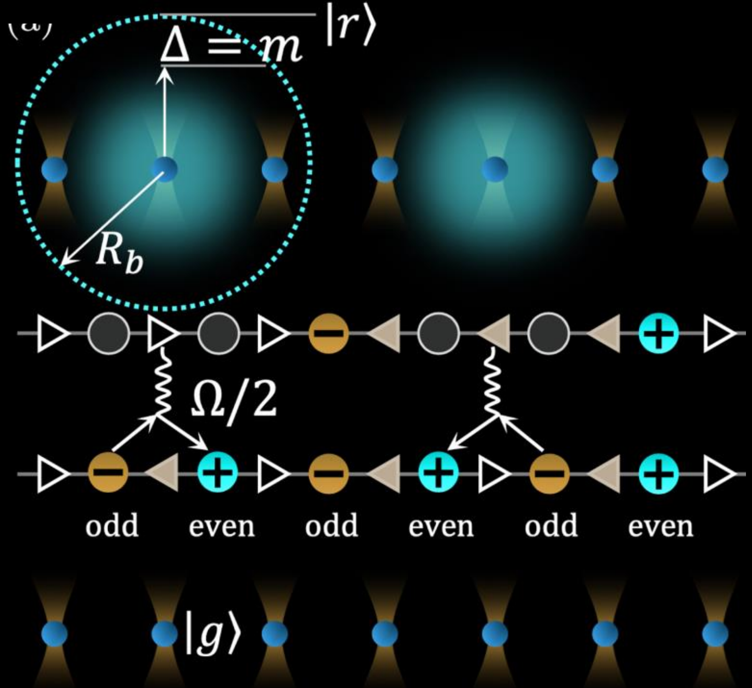
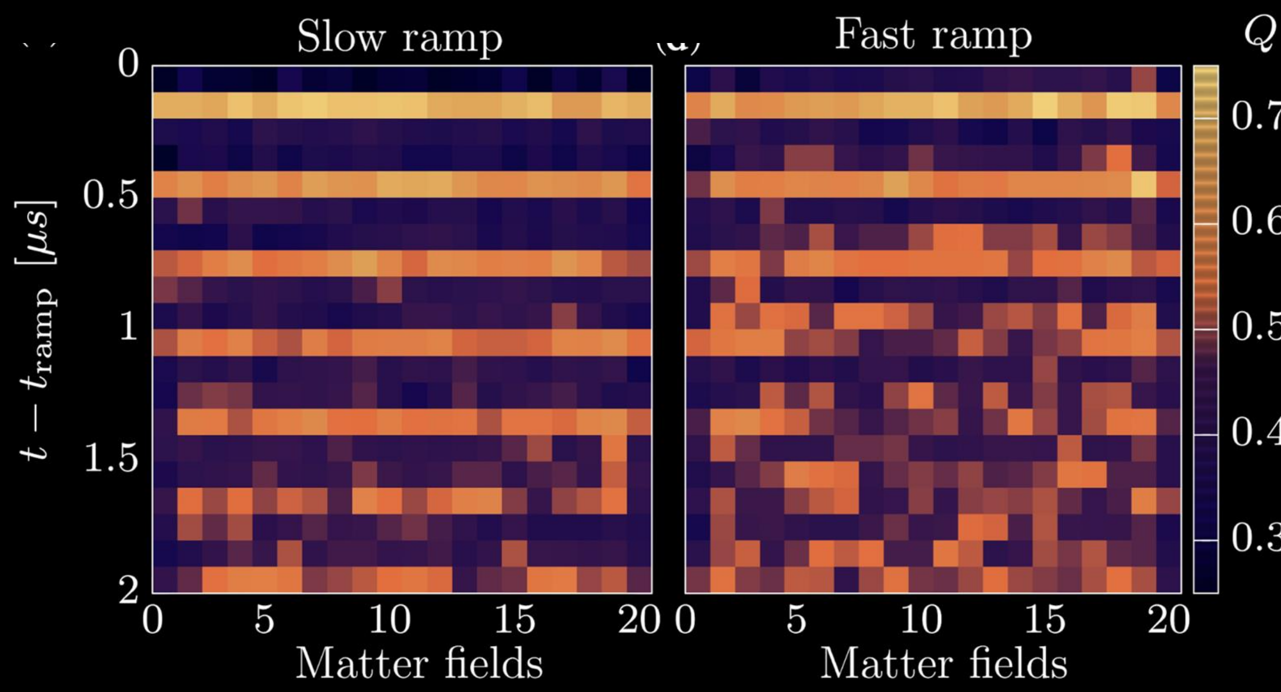
Ergodicity breaking meets criticality in a gauge-theory quantum simulator

Ana Hudomal, Aiden Daniel, Tiago Santiago, Milan Kornjaca, Tommaso Macri, Jad Halimeh, Guoxian Su, Antun Balaz, Zlatko Papic

arXiv:2512.23794





QuantHEP, 13 July 2026

QuEra Putting Quantum to Work
Institute of Physics Belgrade IPB
University of Leeds
Leverhulme Trust
LMU Ludwig-Maximilians-Universität München
MIT
UFRN Universidade Federal do Rio Grande do Norte

How do isolated quantum systems thermalize?

- Ergodic = explores all configurations allowed by conservation laws
- Described by statistical mechanics
- Repulsion of energy levels & quantum chaos
- Subsystems maximally mixed (eigenstates are highly-entangled)

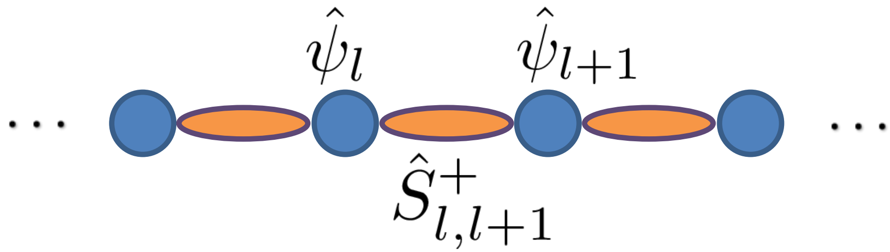
Is this true for gauge theories?

Outline

- Thermalization and its breakdown in gauge theories
- Quantum simulation using QuEra’s Rydberg atom array
- Interplay of criticality & defects with ergodicity breaking
- Conclusions

U(1) gauge theory in (1+1)D: quantum link model

[Kogut & Susskind '75, Wiese '13]



Kinetic | Mass | Electric field

$$\hat{H}^{(S=1/2)}_{\mathrm{QLM}} = J\sum_l \left(\hat{\psi}^\dagger_l \hat{S}^+_{l,l+1}\hat{\psi}_{l+1} + \text{ H.c. }\right) + m\sum_l (-1)^l \hat{\psi}^\dagger_l \hat{\psi}_l + \frac{g^2 a}{2}(\hat{S}^z_{l,l+1})^2$$

trivial constant for S=1/2

$$(\nabla \cdot \vec{E} - \rho)|\Psi\rangle = 0$$

discretized $\longrightarrow$

$$\hat{G}_j = \hat{\psi}^\dagger_j \hat{\psi}_j - \frac{1-(-1)^j}{2} + \hat{S}^z_{j-1,j} - \hat{S}^z_{j,j+1}$$

$$\left[\hat{G}_j, \hat{H}_{\mathrm{QLM}}\right] = 0, \forall j \qquad \hat{G}_j|\Psi\rangle = 0$$

The configurations of matter and gauge field are constrained.

Mapping of S=½ QLM to PXP model

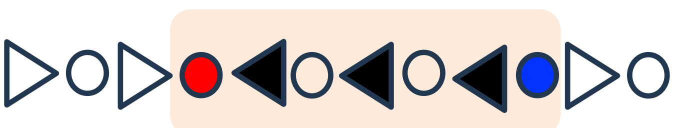
- Gauge theory

Particle on even site = electron

Hole on odd site = positron

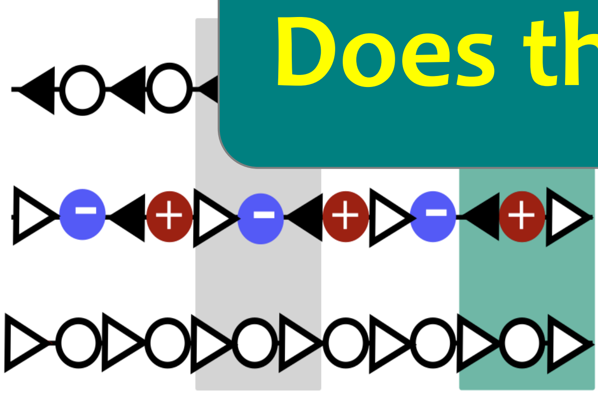
Electric field = ▷ or ◀

QLM kinetic move: a link arrow flips when a particle-hole pair is created or removed



Matter can be integrated out:

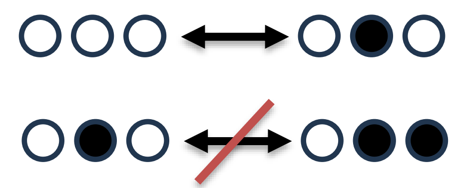
physical st



- PXP spin model: each flux link is a spin ○ ●

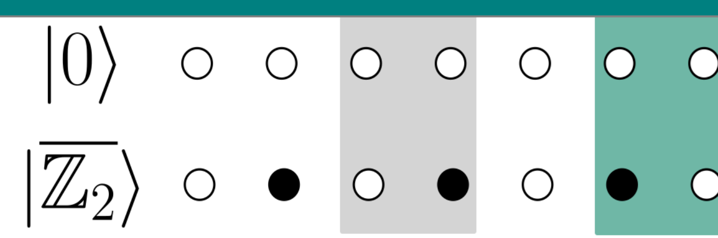
Gauss law = spin constraint $|\ldots \cancel{\bullet\bullet} \ldots\rangle$

Kinetic move:



$$\hat{H}_{\mathrm{PXP}} = J\sum_j \hat{P}_{j-1}\hat{X}_j\hat{P}_{j+1} - 2m\sum_j \hat{n}_j$$

$$\hat{X} = |\circ\rangle\langle\bullet| + |\bullet\rangle\langle\circ| \quad \hat{P} = |\circ\rangle\langle\circ| \quad \hat{n} = |\bullet\rangle\langle\bullet|$$



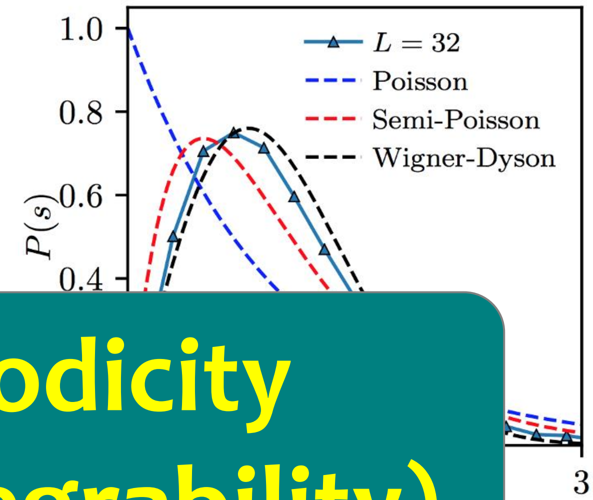
Does the PXP model thermalize?

[Surace *et al.*, PRX **10**, 021041 (2020)]

Quantum many-body scars in the PXP model

$$\hat{H}_{\mathrm{PXP}} = \sum_j \hat{P}_{j-1}\hat{X}_j\hat{P}_{j+1}$$

- **Level statistics** converges to Wigner-Dyson (chaos)



- N
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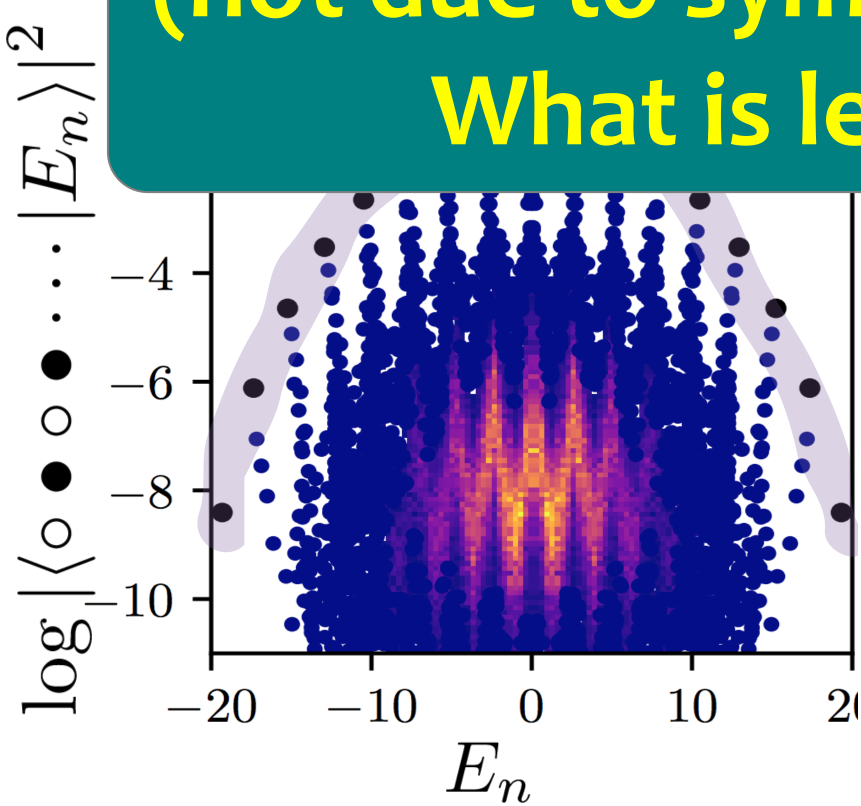
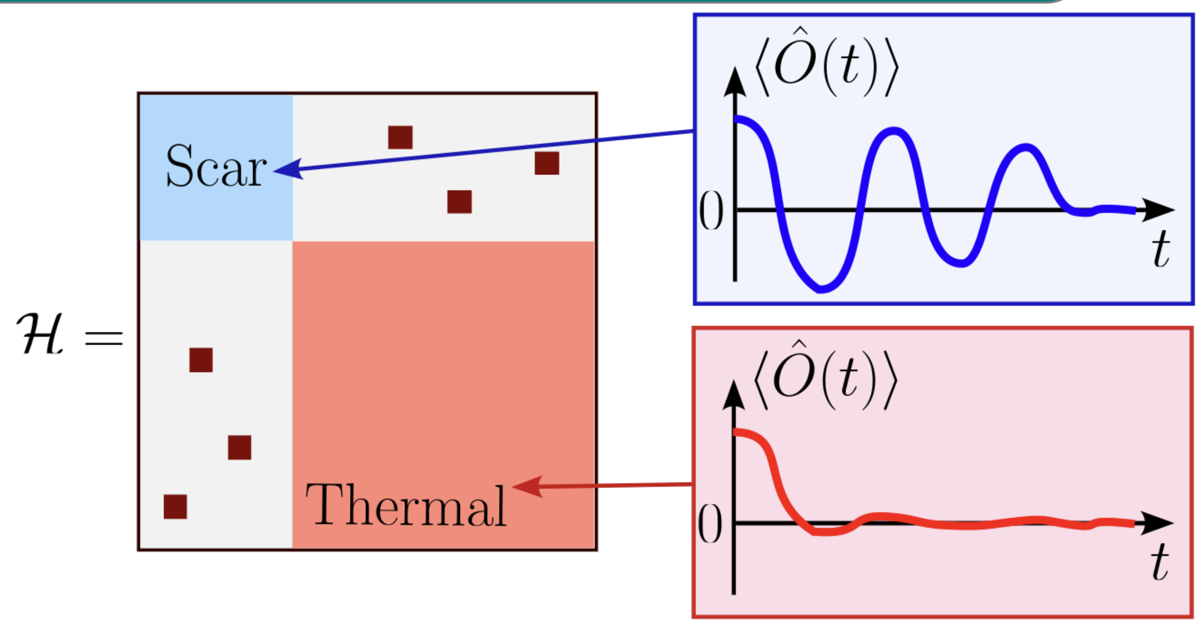
Weak breakdown of ergodicity (not due to symmetry or integrability). What is left to understand?



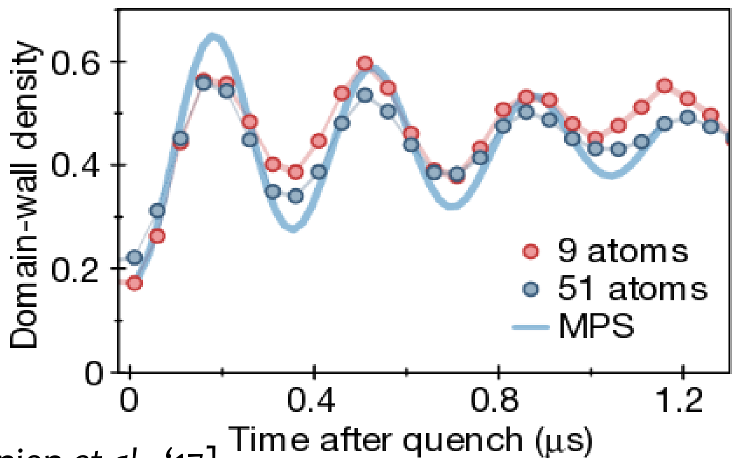


[Turner, Michailidis, Abanin, Serbyn, Papic, Nature Physics **14**, 745 (2018)]

Open questions

- In experiment, scar dynamics was observed in product states like

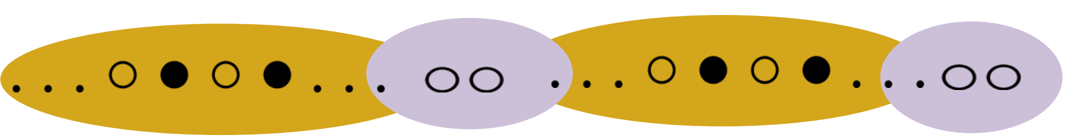
$$|\mathbb{Z}_2\rangle = |\circ\bullet\circ\bullet\ldots\rangle$$



[Bernien *et al.*, ‘17]

Scarring beyond product states?

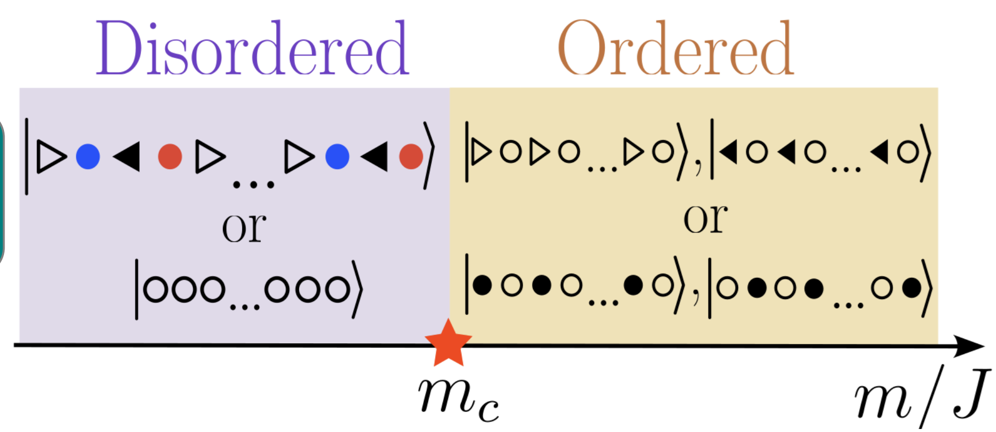
What is the role of defects due to Kibble-Zurek mechanism?



- More general protocol where we ramp to some mass and evolve with a different one:

$$|\psi(t)\rangle = e^{-it\hat{H}_{\mathrm{QLM}}(m_f)}|\psi(m_i)\rangle$$

For what choices of masses is there ergodicity breaking?



Ising critical point

$m_c \approx 0.65J$

[Coleman ‘76; Rico *et al.*, ‘14]

Previous work predicted disappearance of scars at criticality [Zhiyuan Yao *et al.*, PRB **105**, 125123 (2022); Han-Yi Wang *et al.*, PRL **131**, 050401 (2023)]

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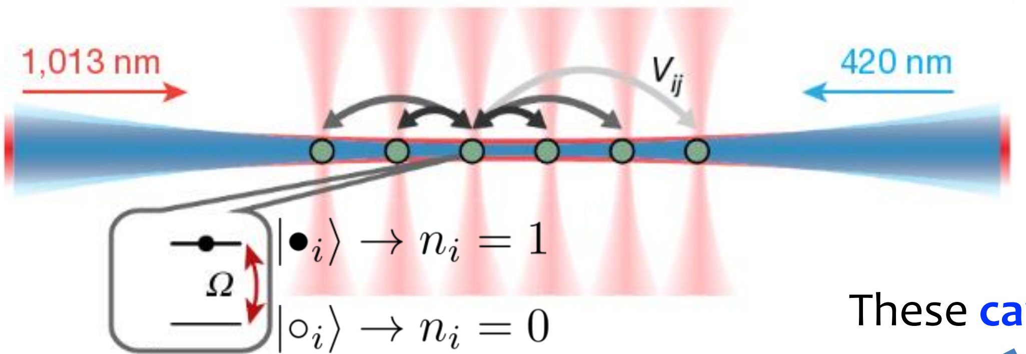
- Conclusions

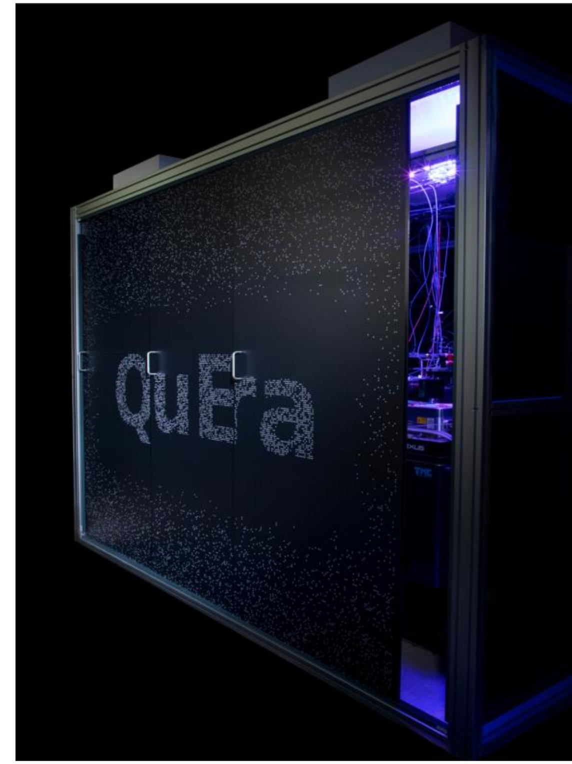
QuEra's programmable Rydberg atom platform

doi:10.1038/nature24622

Probing many-body dynamics on a 51-atom quantum simulator

Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]





These **can be time-dependent**!

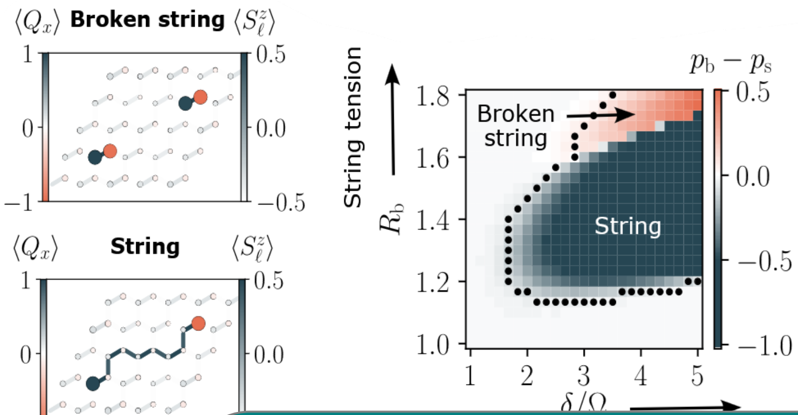
$$\hat{H} = \frac{\Omega}{2}\sum_j \hat{X}_j - \Delta \sum_j \hat{n}_j + \sum_{i<j} V_{i,j}\hat{n}_i\hat{n}_j$$

$\hat{X} = |\circ\rangle\langle\bullet| + |\bullet\rangle\langle\circ|$ Rabi Detuning van der Waals $V_{i,j} = \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6}$

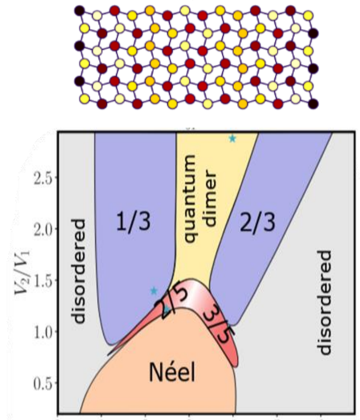
Effective model is PXP when $V \gg \Omega, \Delta$

Analog quantum simulations with QuEra

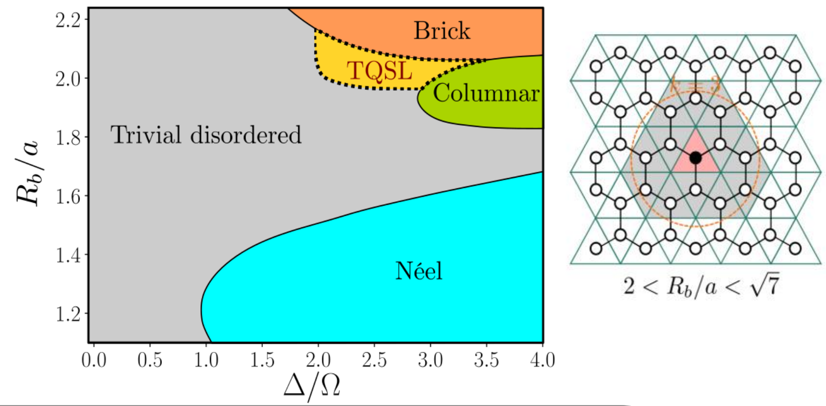
Confinement and string breaking



Frustrated magnetism



Trimer spin liquid

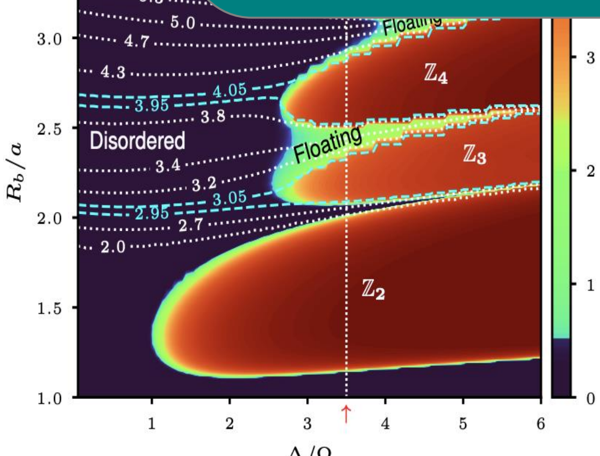


6: 358 (2024)

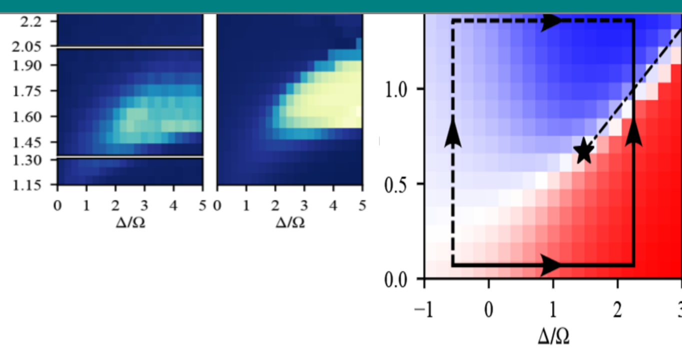
Today: Ergodicity breaking & criticality in a gauge theory

Quant

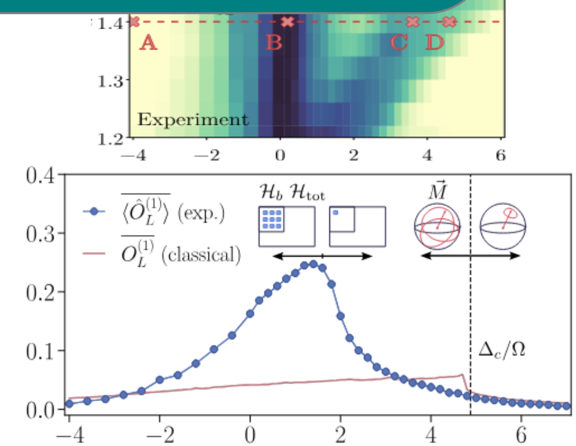
l phases



Zhang *et al.*, Nat. Commun. **16**: 712 (2025)



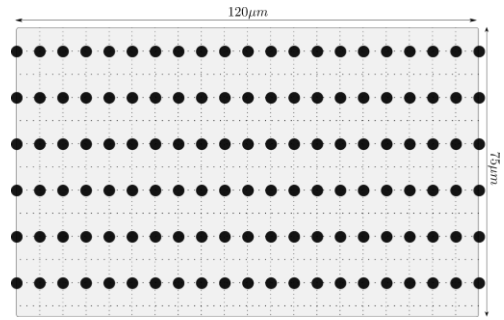
Collab. with NERSC, arXiv:2508.05737

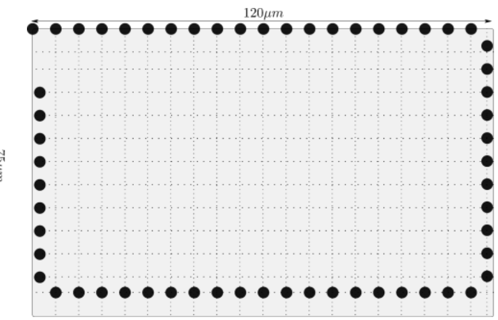


Collab. with NERSC, arXiv:2510.11706

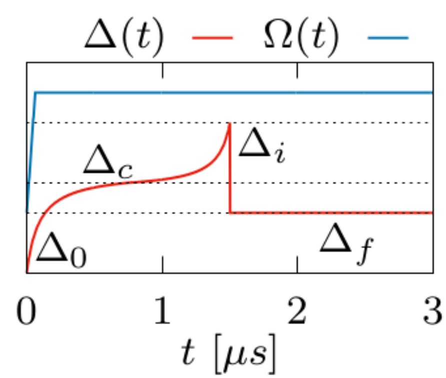
Experimental setup

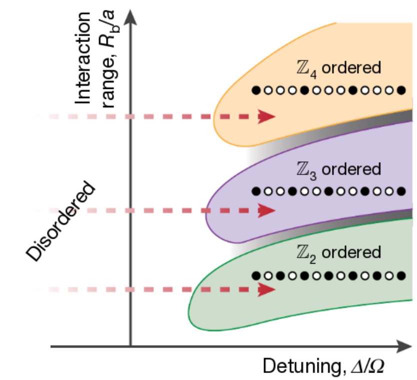
- **Spatial arrangement**
  - six parallel short chains (21 atoms)
  - one long chain (61 atoms)
  - interatomic distance $a = 6\mu m \; \longrightarrow \; R_b \approx 1.4a$





- **State preparation**
  - all atoms initially in the ground state
  - adiabatic sigmoid-type ramp to Δ_i





H. Bernien et al., Nature **551**, 579 (2017).

- **Quench** to Δ_f
  - measurements
  - error-mitigation

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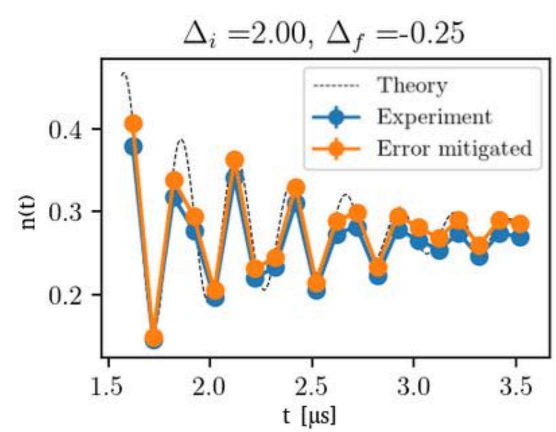

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Dynamical phase diagram

- PXP model with chemical potential

$$\hat{H}_{\mathrm{PXP}} = \frac{\Omega}{2}\sum_j \hat{P}_{j-1}\hat{X}_j\hat{P}_{j+1} - \Delta\sum_j \hat{n}_j$$

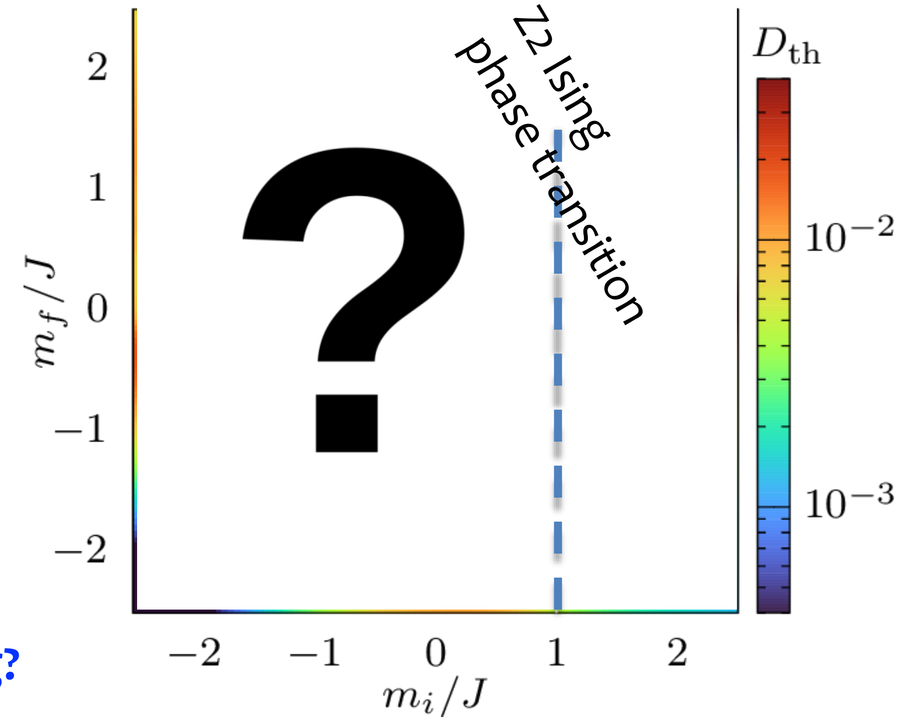
fermionic mass in QLM

$\Delta \leftrightarrow m$

- Ramp to some mass and evolve with a different one:

$$|\psi(t)\rangle = e^{-it\hat{H}_{\mathrm{QLM}}(m_f)}|\psi(m_i)\rangle$$

For what choices of masses is there ergodicity breaking?



- Measure density of matter fields

$$\hat{Q} \propto \sum_j (-1)^j \hat{\psi}_j^{+}\hat{\psi}_j$$

and compute its deviation from thermal value:

$$D_{\mathrm{th}} = \frac{1}{t_1 - t_0}\int_{t_0}^{t_1} |\langle\hat{Q}(t)\rangle - Q_{\mathrm{th}}|^2 dt$$

Dynamical phase diagram

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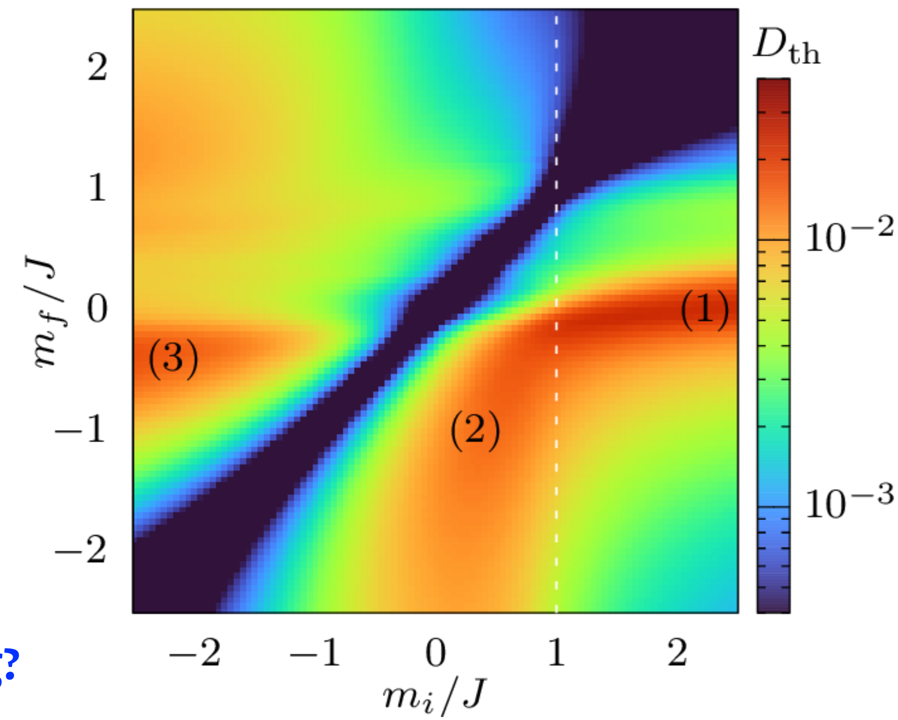

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- Ergodicity breaking regions

(1) Néel/vacuum $|$○● . . . ○●$\rangle$ $|$▷○▷○…▷○$\rangle$

H. Bernien et al., Nature **551**, 579 (2017).

(2) continuous QMBS family

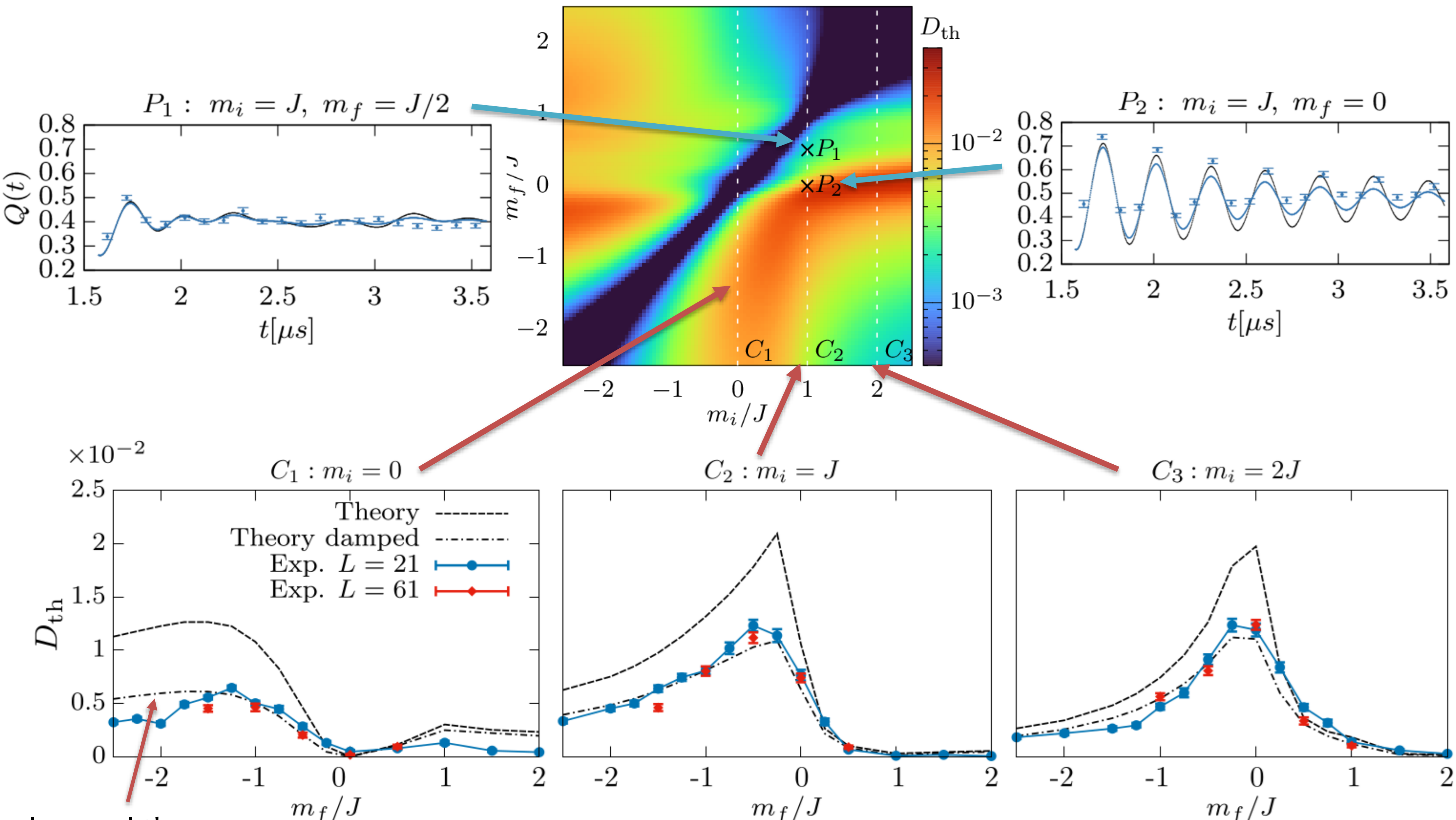
A. Daniel et al., PRB **107**, 235108 (2023).

(3) polarized/charge-proliferated

$|$○○ . . . ○○$\rangle$ $|$▷●◀●▷●…◀●▷●◀●$\rangle$

G.-X. Su et al., PRResearch **5**, 023010 (2023).

Experimental probe of dynamical phase diagram



damped theory

$Q(t)e^{-\alpha t}$

$\alpha = 0.5 \; kHz$

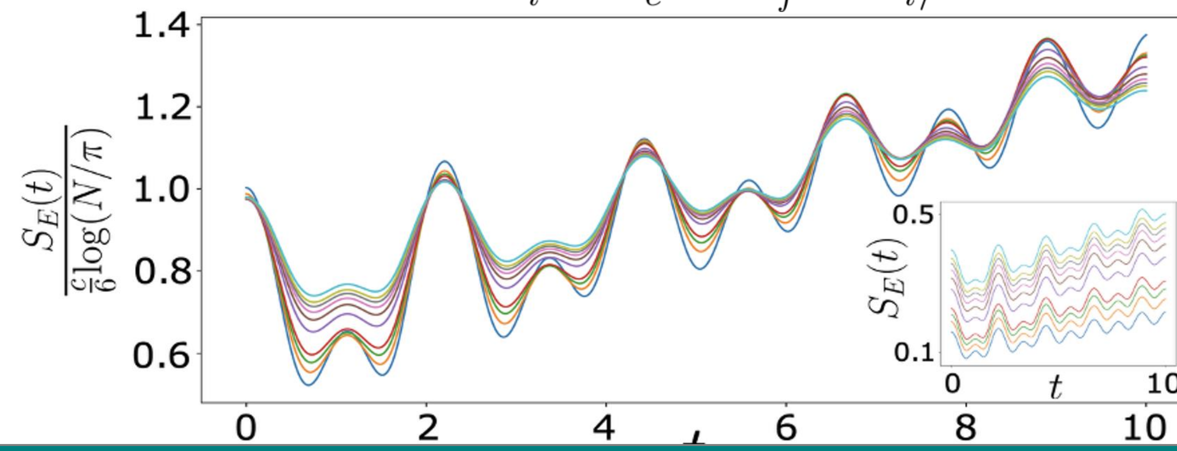
Persistent revivals from a critical (highly entangled) ground state

Why is the critical state so scarred?

- Entanglement growth from the critical initial state is **very slow and oscillating**:

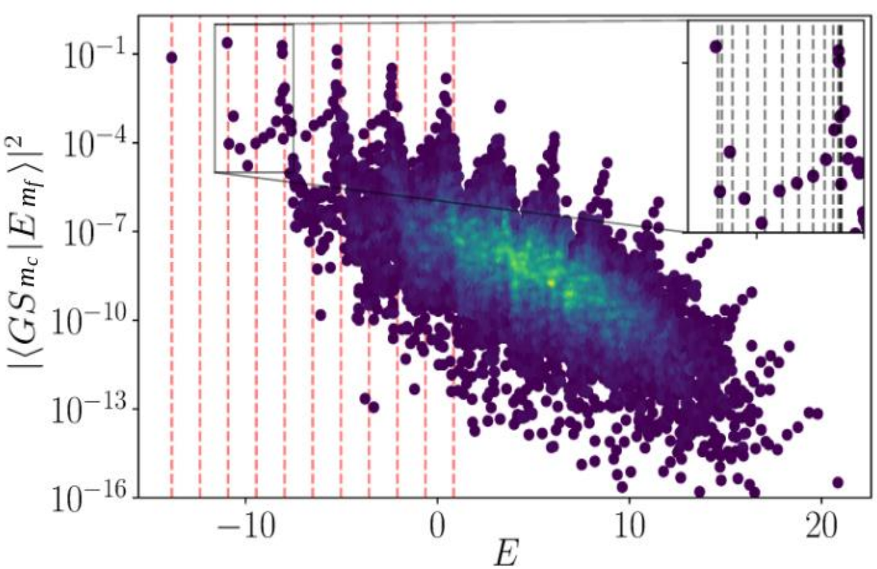
$m_i = m_c \rightarrow m_f \approx m_i/2$

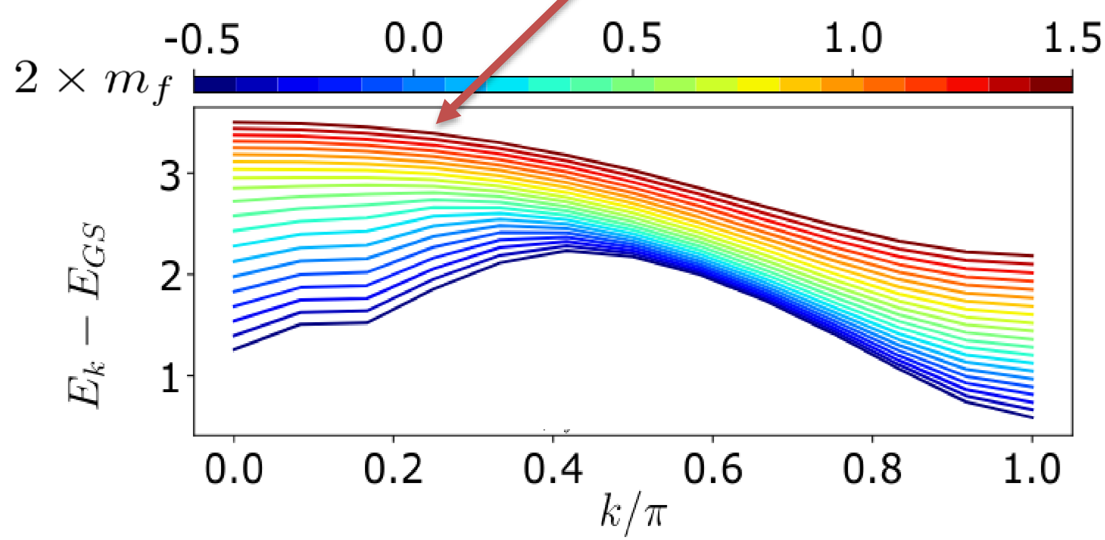
Entanglement in the initial state diverges as $\propto \log(N)$



Mechanism not yet fully understood!

- 2

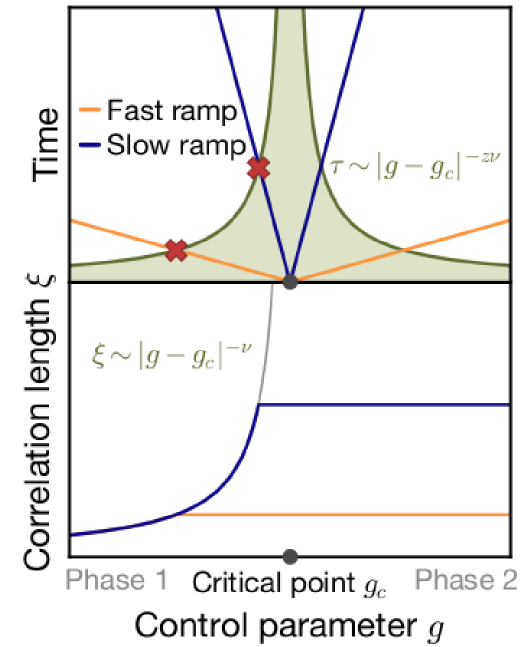




[A. Daniel *et al.*, PRB **107**, 235108 (2023)]

Scar dynamics & Kibble-Zurek mechanism

- Crossing the quantum phase transition
  - relaxation time diverges
  - formation of separate domains
  - domain walls – topological defects

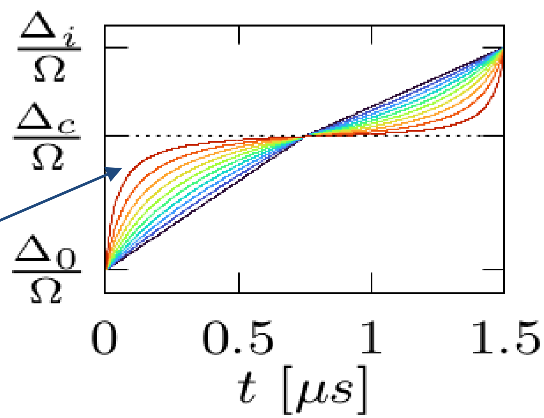


A. Keesling *et al.*, Nature **568**, 207 (2019).

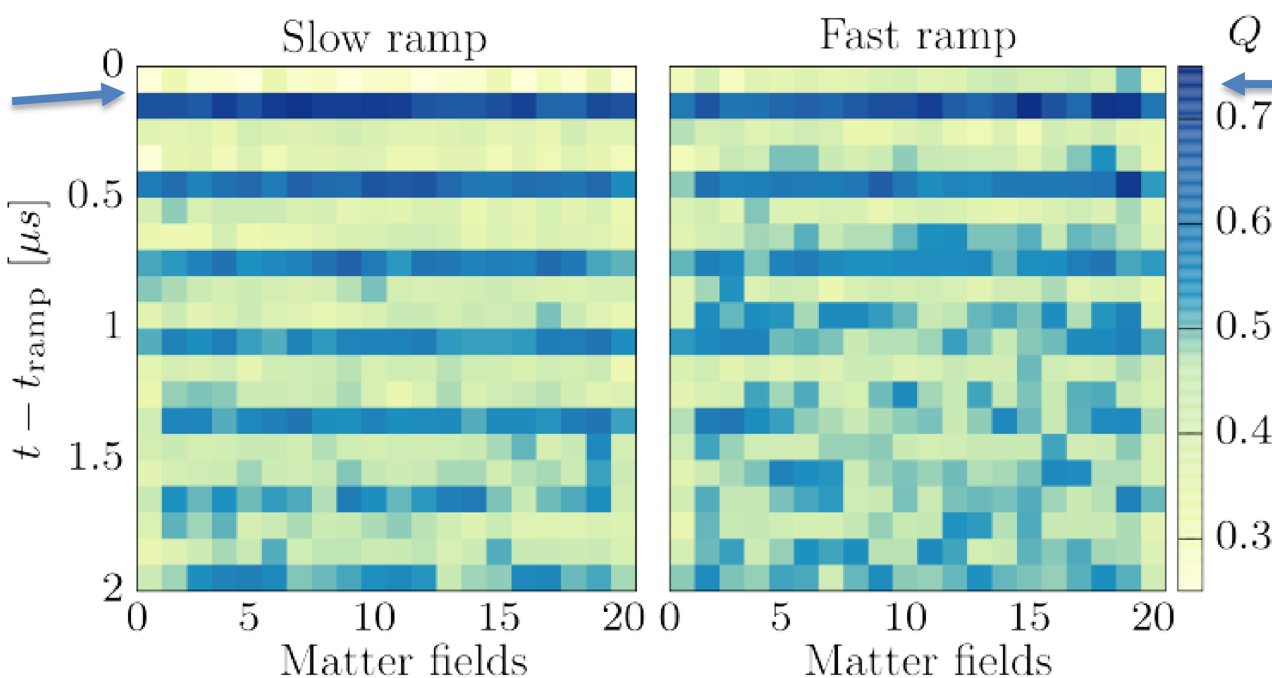
- We use a sigmoid-type ramp

$$f(t) = \frac{t(1-k)}{k(1-2|t|)+1}$$

curvature parameter



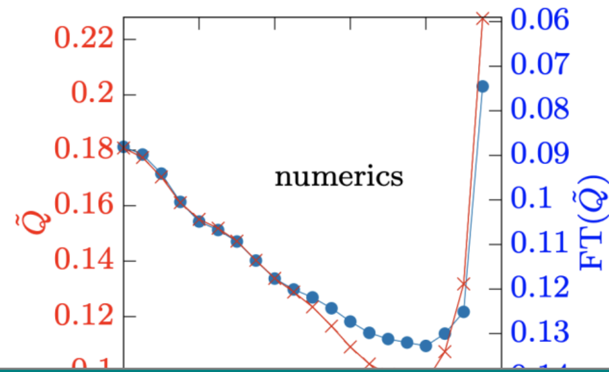
Prepared state is close to one of the flux states (no matter)

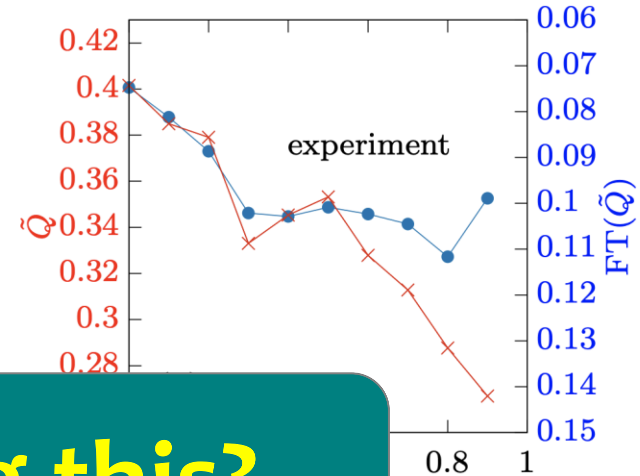


Prepared state contains defects (electron-positron pairs)

Dynamics depends on density *and* type of defects

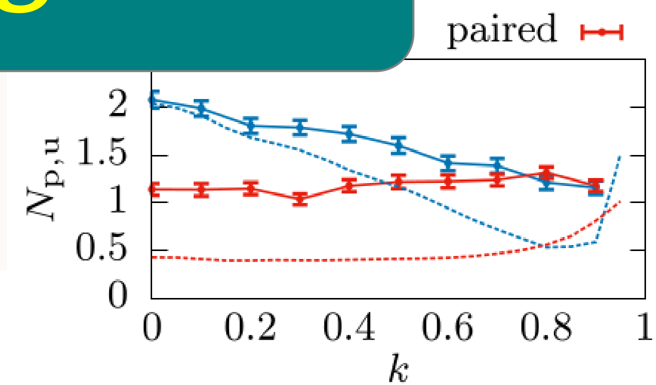
- **Clear correlation** between total matter density and the height of first Fourier peak in the dynamics:

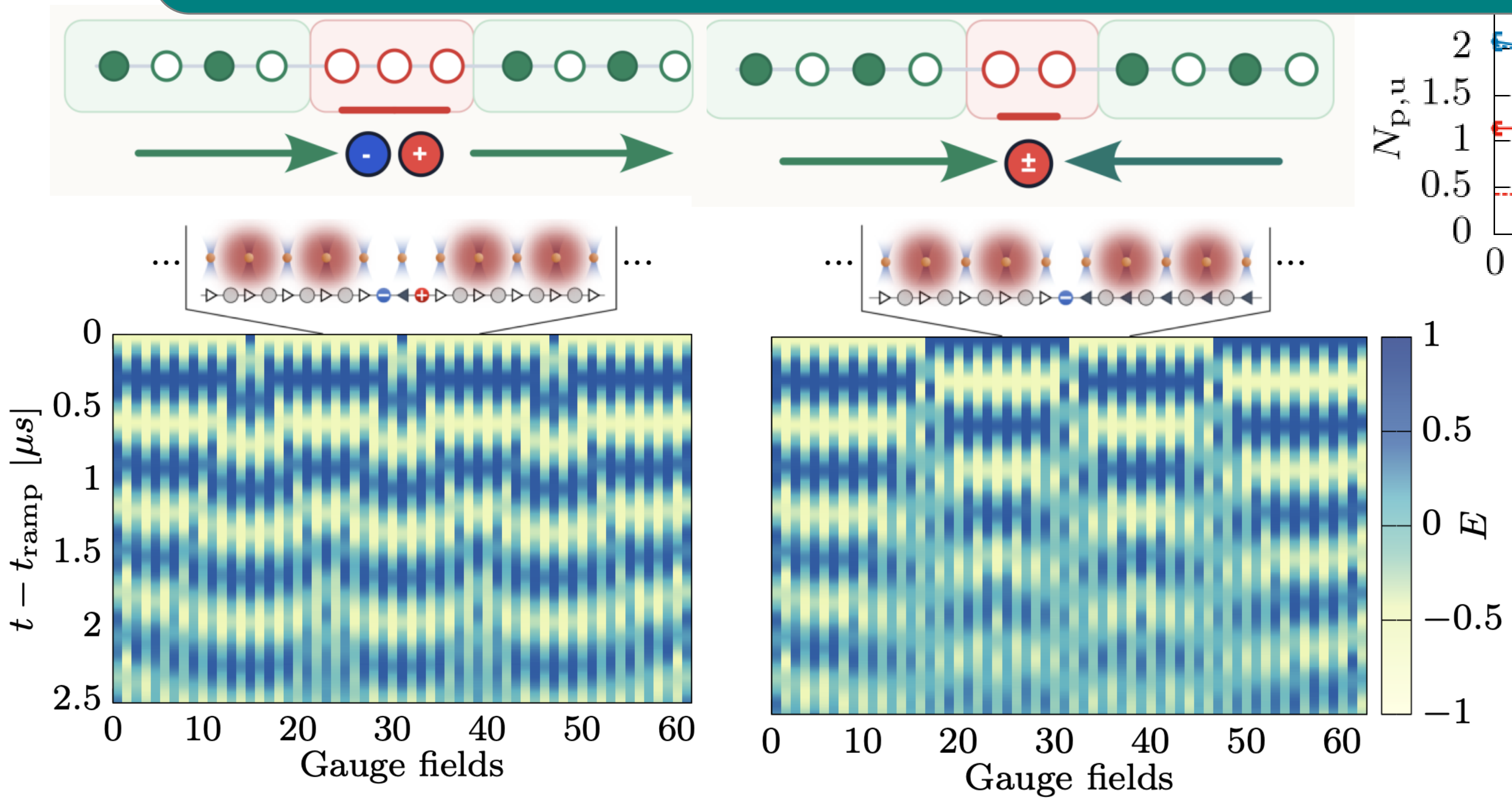




- Typ

KZ-type theory describing this?





- The dynamics of paired and unpaired defects is **very different**!

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Conclusions

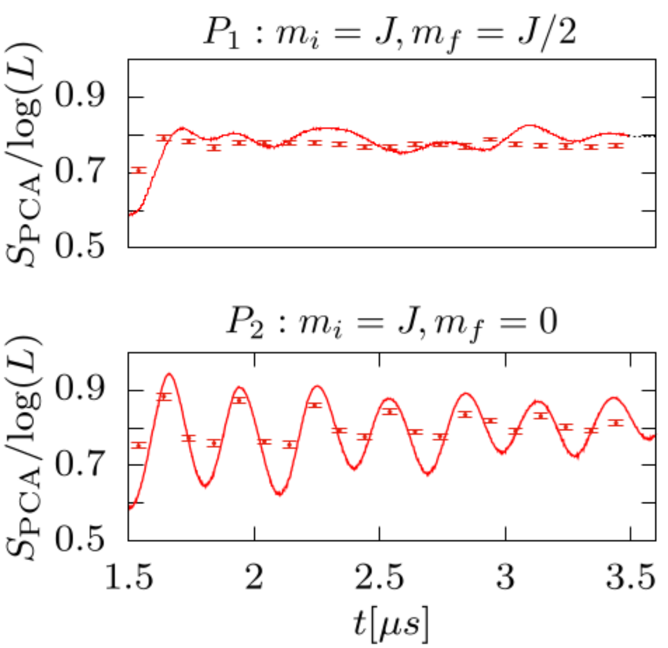
- Rydberg atoms provide a **versatile platform** for probing ergodicity breaking in gauge theories
- Quantum simulation of U(1) quantum link model demonstrated ergodicity breaking from **a continuous family of initial conditions**
- Ergodicity breaking also found from a **critical ground state** with large entanglement, but **mechanism not fully understood**.
- Crucial role of **defects,** **refined Kibble-Zurek theory needed** to explain the observations
- Many **open questions** in 2D Rydberg arrays, other types of gauge theories, interplay with periodic driving, etc.

Thank you for attention!

Questions?

PCA entropy

- What else can we measure?



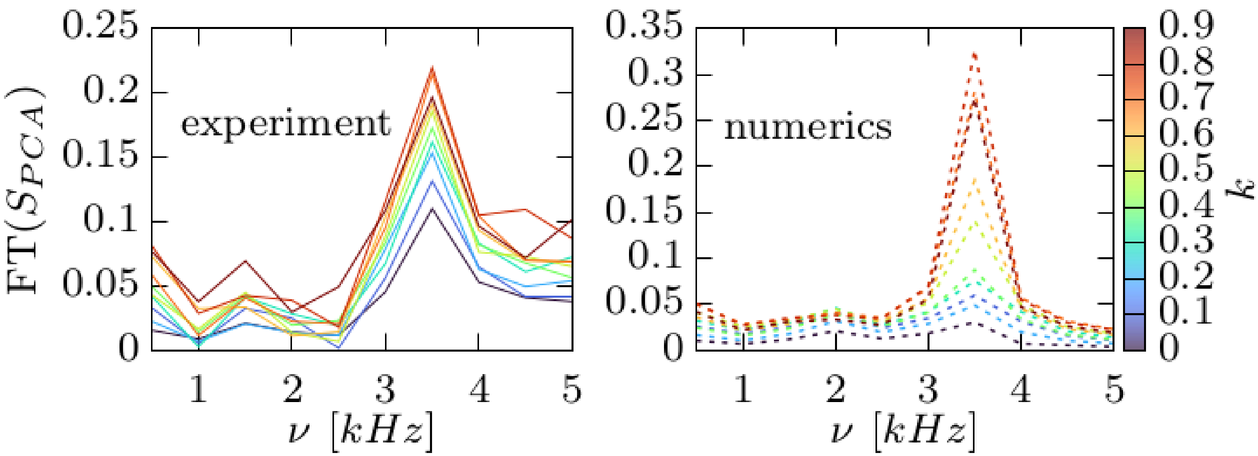
- **Principal Component Analysis (PCA) entropy**
  - proxy for entanglement entropy
  - Shannon entropy defined on a data matrix containing the experimental bitstrings

$$S_{\mathrm{PCA}} = -\sum_k \lambda_k \ln \lambda_k$$

  - normalized singular values of the bitstring matrix

$$\lambda_k \equiv \frac{s_k^2}{\sum_l s_l^2}$$

- Quench dynamics
  - non-QMBS: saturates
  - QMBS: persistent oscillations
  - same frequency as local observables



Phase transition point

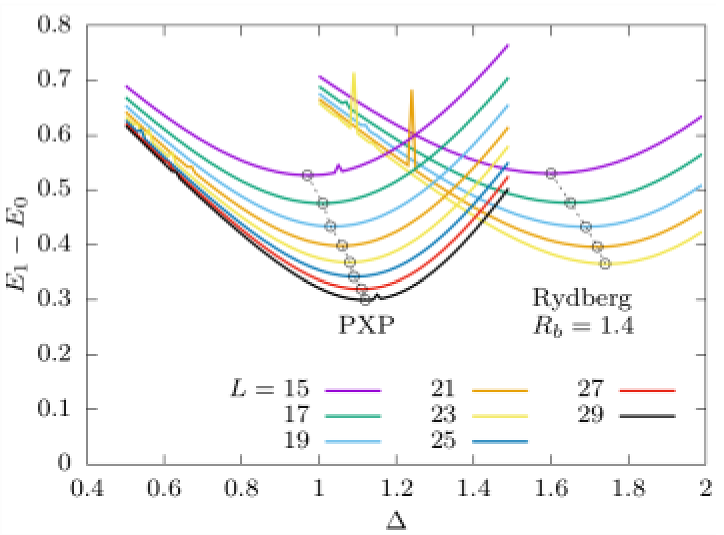
- **Full Rydberg Hamiltonian**

$$\hat{H}_{\mathrm{Ryd}} = \frac{\Omega}{2}\sum_{j=1}^{N}\hat{X}_j - \Delta\sum_{j=1}^{N}\hat{n}_j + \sum_{i,j} V_{ij}\hat{n}_i\hat{n}_j$$

- Long-range VdW interactions

$$V_{ij} = C_6/r_{ij}^6$$

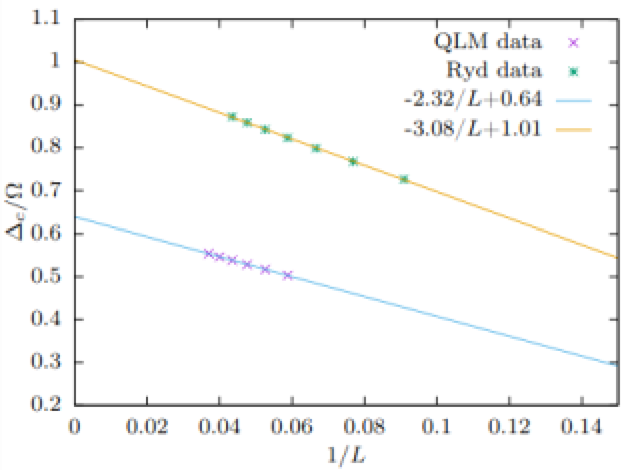
- Blockade radius $R_b \approx 1.4a$

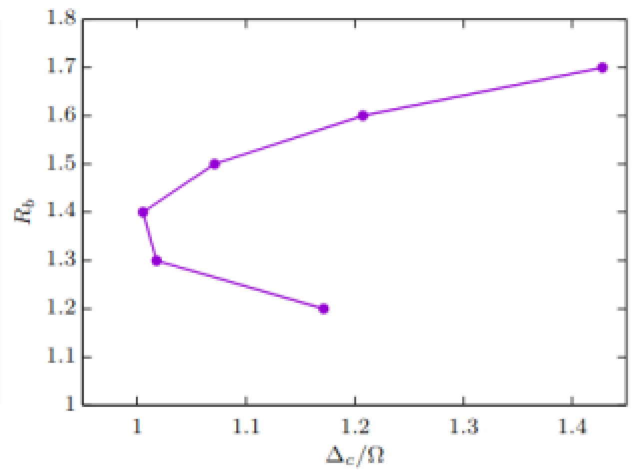


- Different phase transition points

$$\Delta_c^{\mathrm{PXP}} \approx 0.65\Omega$$

$$\Delta_c^{\mathrm{Ryd}} \approx \Omega$$





Scarred states with periodic defects

- Effects of defects on the QMBS dynamics?
- **Numerical results**
- "Odd" defects

  1010100010101

  - removable
  - preserve scarring
- "Even" defects

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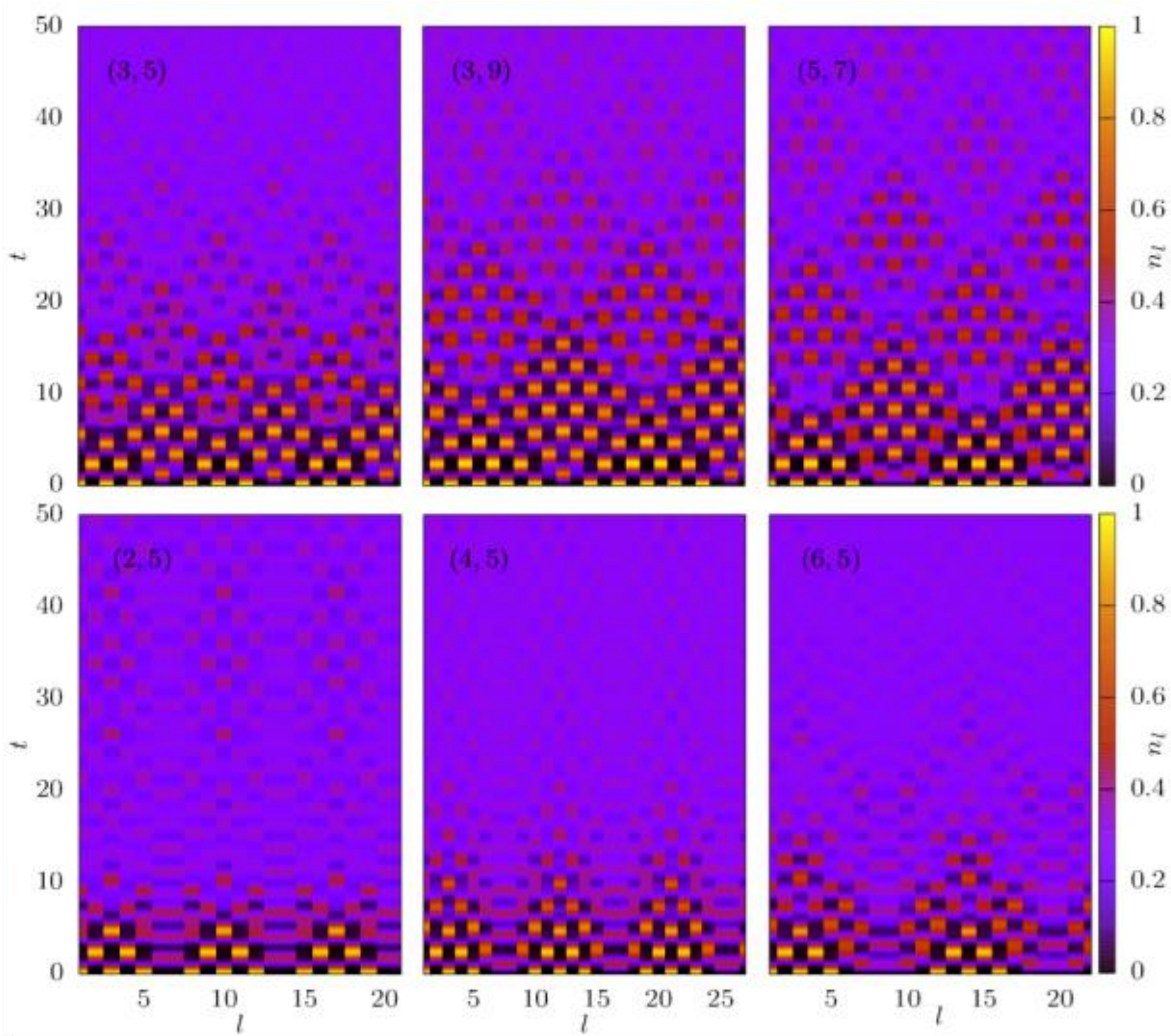
  - frozen
  - split the system into short independent domains



Bitstring statistics

- **Experimental results**

  $\Delta_i/\Omega = 4,\ \Delta_f/\Omega = 0$

- Close to Néel state
  - strong oscillations
- Bitstrings
  - Néel and polarized domains
- Average length of domains
  - Néel: grows with k
  - polarized: almost constant
- Larger k – slower ramp
  - more “even” defects
  - less “odd” defects