Quantum Simulation:
from Quantum Matter to Gauge Theory

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华南师范大学

2022. 11

Quantum Simulation of the PXP Model

- Two Realizations of the PXP Model:

  1. Rydberg Atom Array
  2. Lattice Gauge Simulator

- Physics in the PXP Model

  1. Quantum Thermalization
  2. Confinement-Deconfinement Transition
  3. Quantum Spin Liquid

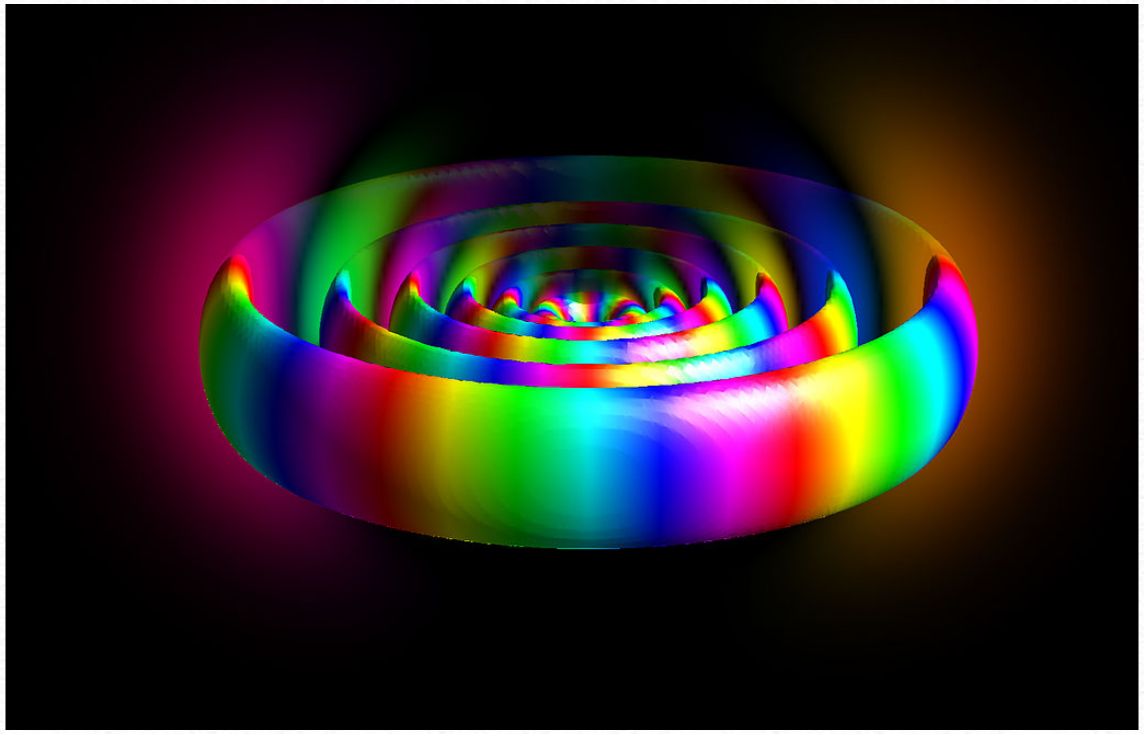
How gauge theory picture helps understand quantum matter ?

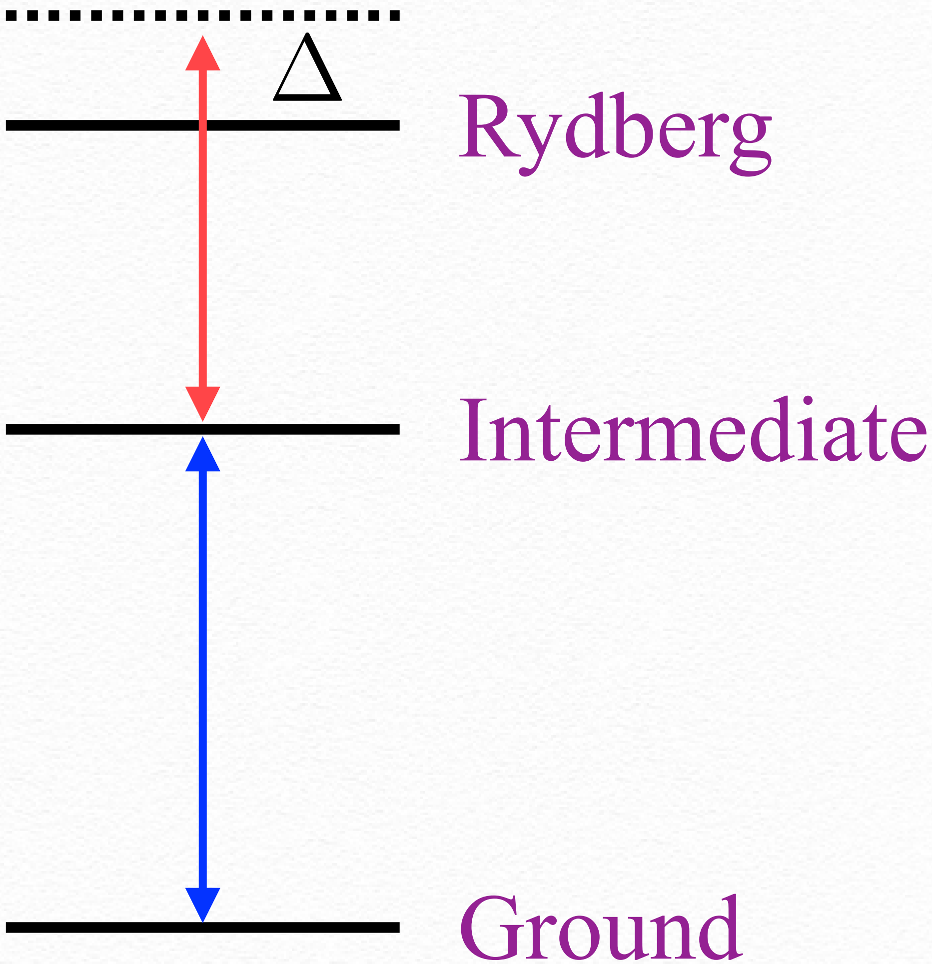
Two Realizations of the PXP Model

$$\hat{H} = \Omega \sum_i P_{i-1} \hat{S}_i^x P_{i+1} - \Delta \hat{n}_i$$

Rydberg Atom

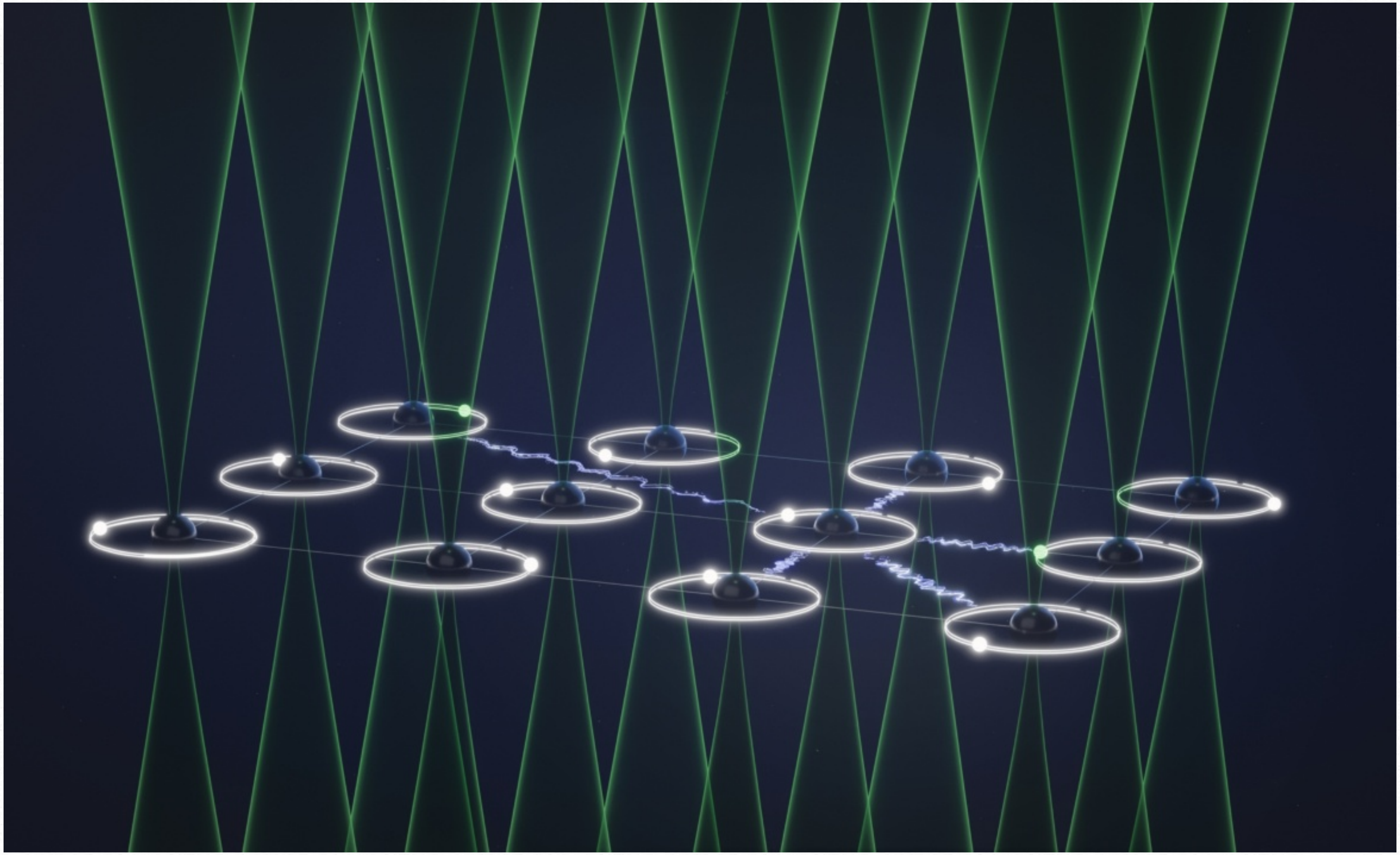
A Rydberg atom is an excited atom with one or more electrons that have a very high principal quantum number





$$\hat{H} = \Omega \hat{S}^x - \Delta \hat{n}$$

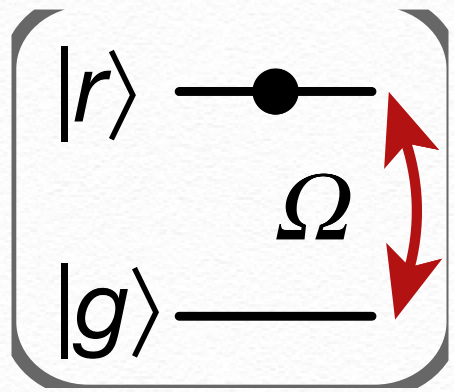
Rydberg Atom Arrays

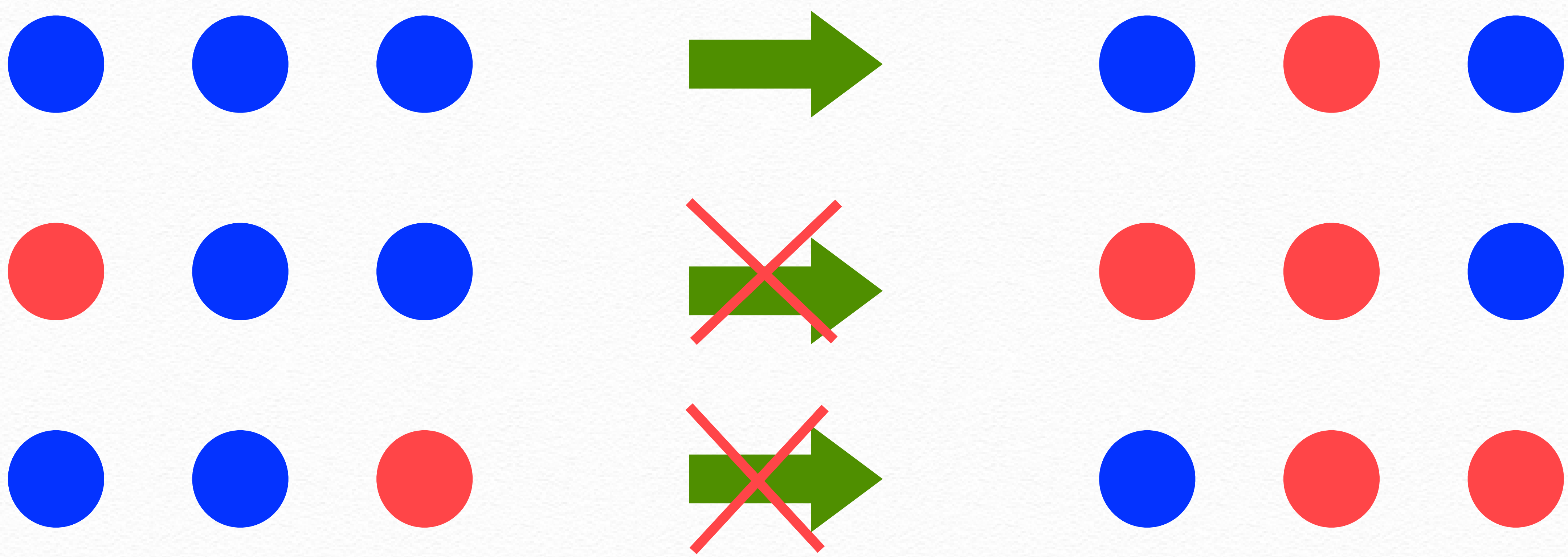


Platform for Quantum Simulation and Quantum Computation

Rydberg Blockade

$$\hat{H} = \sum_i \left(\Omega \hat{S}_i^x - \Delta \hat{n}_i\right) + \sum_{ij} V_{ij}\hat{n}_i\hat{n}_j$$





Rydberg Blockade

$$\hat{H} = \sum_i \left(\Omega \hat{S}_i^x - \Delta \hat{n}_i \right) + \sum_{ij} V_{ij} \hat{n}_i \hat{n}_j$$

$V_{ij} = V$ for $j = i \pm 1$

$V_{ij} = 0$ otherwise

Rydberg Blockade

$$\hat{H} = \sum_i \left(\Omega \hat{S}_i^x - \Delta \hat{n}_i \right) + \sum_{ij} V_{ij} \hat{n}_i \hat{n}_j$$

$V_{ij} = V$ for $j = i \pm 1$

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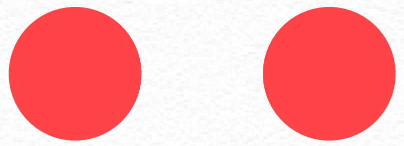
$\mathcal{M} = \prod_i (1 - n_i n_{i+1})$ Prevent 

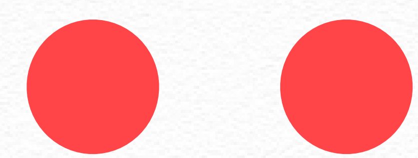
PXP Hamiltonian

$$\hat{H} = \sum_i \left(\Omega \hat{S}_i^x - \Delta \hat{n}_i \right) + \sum_{ij} V_{ij} \hat{n}_i \hat{n}_j$$

$$V_{ij} = V \quad \text{for} \quad j = i \pm 1$$

$$V_{ij} = 0 \quad \text{otherwise}$$

$$\mathcal{M} = \prod_i (1 - n_i n_{i+1})$$

Prevent 

$$\mathcal{M} \hat{H} \mathcal{M} \Rightarrow \hat{H} = \Omega \sum_i P_{i-1} \hat{S}_i^x P_{i+1} - \Delta \hat{n}_i$$

PXP Hamiltonian

$$P_i = 1 - n_i$$

Quantum Simulation with Rydberg Atoms Array

ARTICLE Nature 2017

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]

LETTER Nature 2019

https://doi.org/10.1038/s41586-019-1070-1

Quantum Kibble–Zurek mechanism and critical dynamics on a programmable Rydberg simulator

Alexander Keesling[1], Ahmed Omran[1], Harry Levine[1], Hannes Bernien[1], Hannes Pichler[1,2], Soonwon Choi[1], Rhine Samajdar[1], Sylvain Schwartz[3], Pietro Silvi[4,5], Subir Sachdev[1], Peter Zoller[4,5], Manuel Endres[6], Markus Greiner[1], Vladan Vuletić[7] & Mikhail D. Lukin[1*]

RESEARCH

REPORT

QUANTUM PHYSICS

Science 2019

Generation and manipulation of Schrödinger cat states in Rydberg atom arrays

A. Omran[1*], H. Levine[1*], A. Keesling[1], G. Semeghini[1], T. T. Wang[1,2], S. Ebadi[1], H. Bernien[3], A. S. Zibrov[1], H. Pichler[1,4], S. Choi[5], J. Cui[6], M. Rossignolo[7], S. Montangero[8], T. Calarco[6,9], M. Endres[10], M. Greiner[1], V. Vuletić ...

Article

Quantum phases of matter on a 256-atom programmable quantum simulator

Nature 2021

Sepehr Ebadi[1], Tout T. Wang[1], Harry Levine[1], Alexander Keesling[1,2], Giulia Semeghini[1], Ahmed Omran[1,2], Dolev Bluvstein[1], Rhine Samajdar[1], Hannes Pichler[3,4], Wen Wei Ho[1,5], Soonwon Choi[6], Subir Sachdev[1], Markus Greiner[1], Vladan Vuletić[7] & Mikhail D. Lukin[1]

https://doi.org/10.1038/s41586-021-03582-4
Received: 21 December 2020
Accepted: 26 April 2021

RESEARCH

REPORT

QUANTUM CONTROL

Science 2021

Controlling quantum many-body dynamics in driven Rydberg atom arrays

D. Bluvstein[1], A. Omran[1,2], H. Levine[1], A. Keesling[1], G. Semeghini[1], S. Ebadi[1], T. T. Wang[1], A. A. Michailidis[3], N. Maskara[1], W. W. Ho[1,4], S. Choi[5], M. Serbyn[3], M. Greiner[1], V. Vuletić[6], M. D. Lukin[1*]

Article

Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

Nature 2021

https://doi.org/10.1038/s41586-021-03585-1
Received: 21 December 2020
Accepted: 27 April 2021

Pascal Scholl[1,6], Michael Schuler[2,6], Hannah J. Williams[1,6], Alexander A. Eberharter[3,6], Daniel Barredo[1,4], Kai-Niklas Schymik[1], Vincent Lienhard[1], Louis-Paul Henry[5], Thomas C. Lang[3], Thierry Lahaye[1], Andreas M. Läuchli[3] & Antoine Browaeys[1]

RESEARCH

TOPOLOGICAL MATTER

Probing topological spin liquids on a programmable quantum simulator

Science 2021

G. Semeghini[1], H. Levine[1], A. Keesling[1,2], S. Ebadi[1], T. T. Wang[1], D. Bluvstein[1], R. Verresen[1], H. Pichler[3,4], M. Kalinowski[1], R. Samajdar[1], A. Omran[1,2], S. Sachdev[1,5], A. Vishwanath[1*], M. Greiner[1*], V. Vuletić[6*], M. D. Lukin[1*]

Quantum Simulation of Lattice Gauge Theory

Article

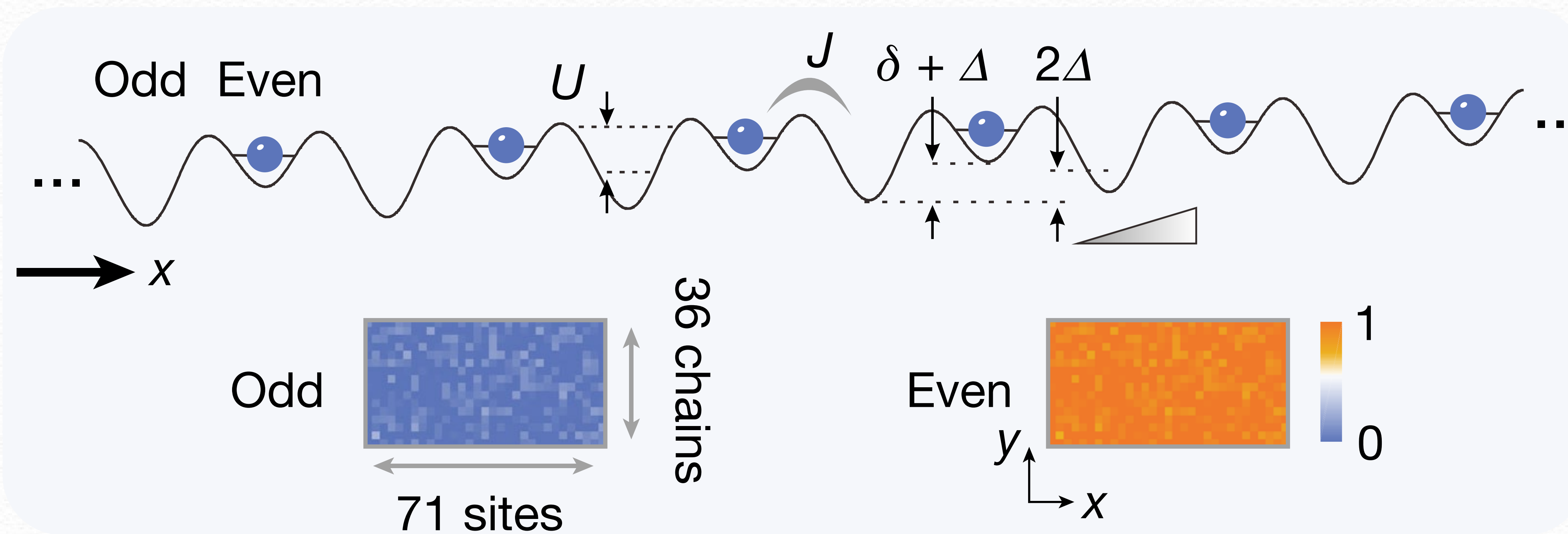
Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator

https://doi.org/10.1038/s41586-020-2910-8

Received: 19 March 2020

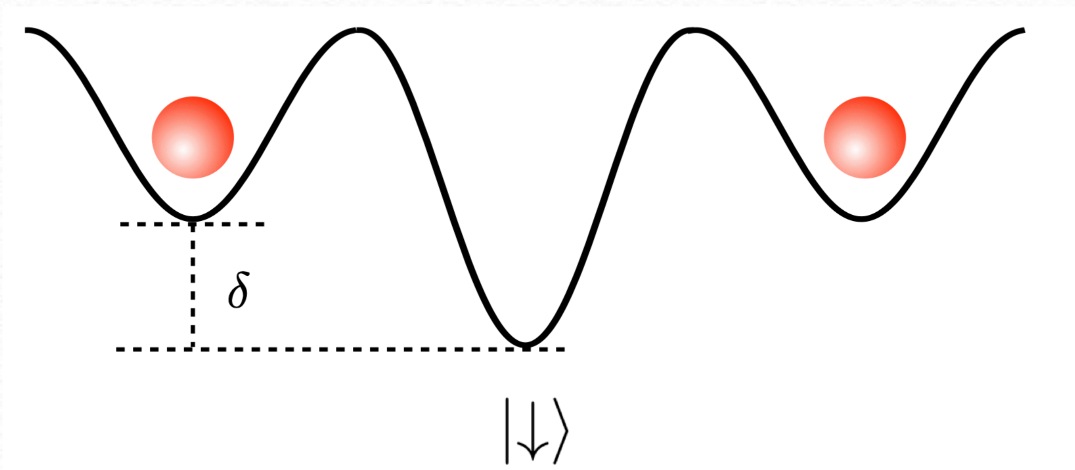
Accepted: 2 September 2020

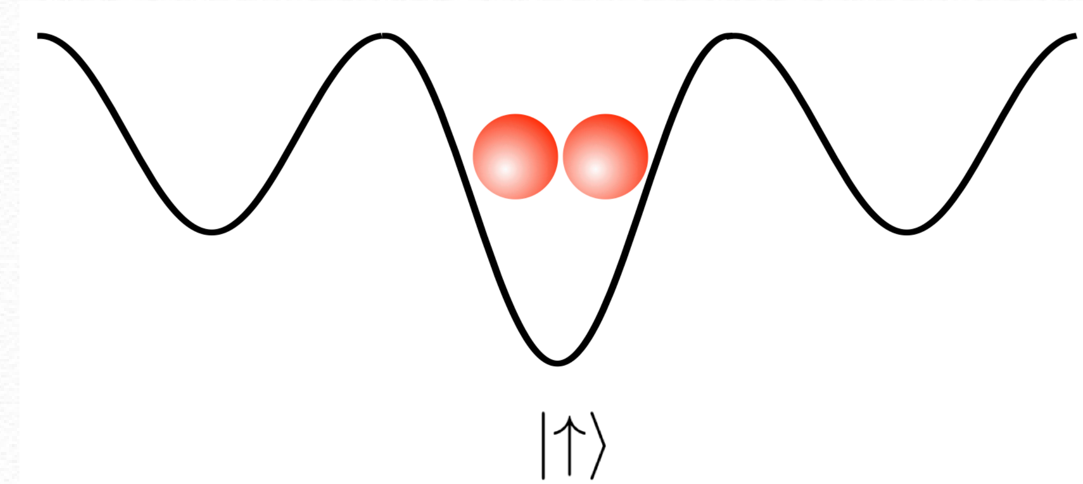
Bing Yang[1,2,3,4,8], Hui Sun[1,2,3,4], Robert Ott[5], Han-Yi Wang[1,2,3,4], Torsten V. Zache[5], Jad C. Halimeh[5,6,7], Zhen-Sheng Yuan[1,2,3,4]✉, Philipp Hauke[5,6,7]✉ & Jian-Wei Pan[1,2,3,4]✉



$$\hat{H}_{\mathrm{BHM}} = \sum_j \left[-J(\hat{b}_j^{\dagger}\hat{b}_{j+1} + \mathrm{h.c.}) + \frac{U}{2}\hat{n}_j(\hat{n}_j - 1) + \varepsilon_j \hat{n}_j \right]$$

Quantum Simulation of Lattice Gauge Theory





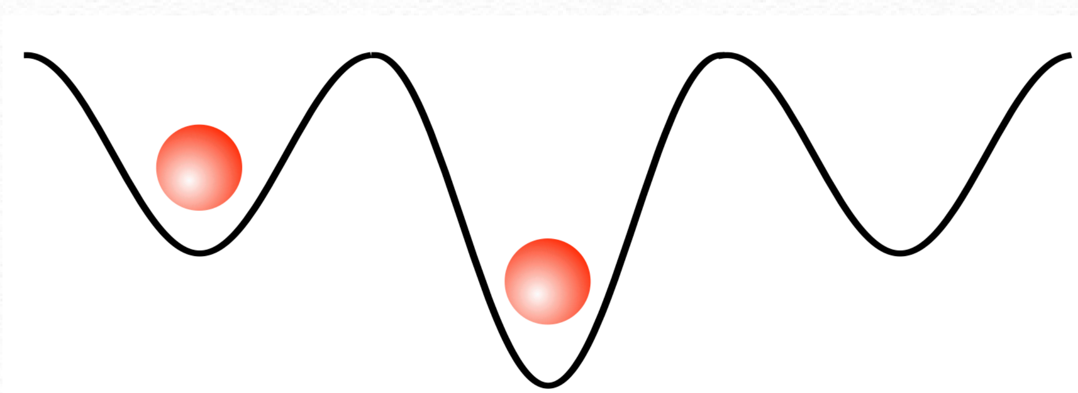
$$E = 2\delta$$

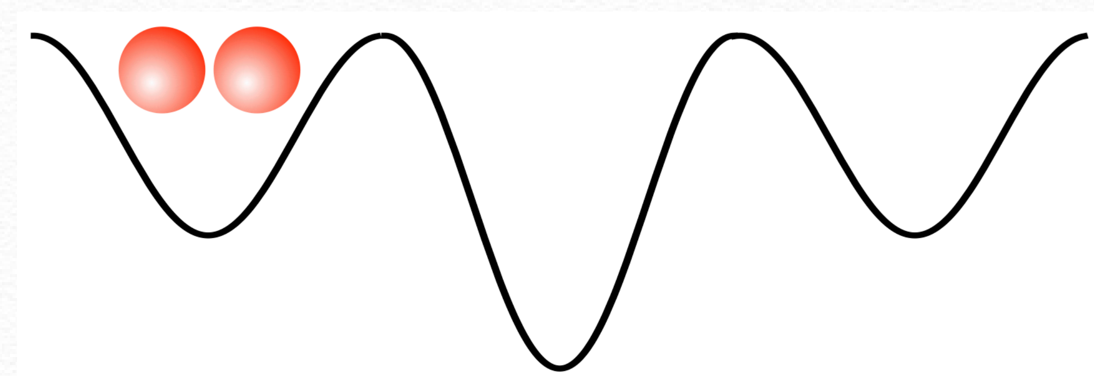
Resonance

$$U \approx 2\delta$$

$$E = U$$

Off-Resonance

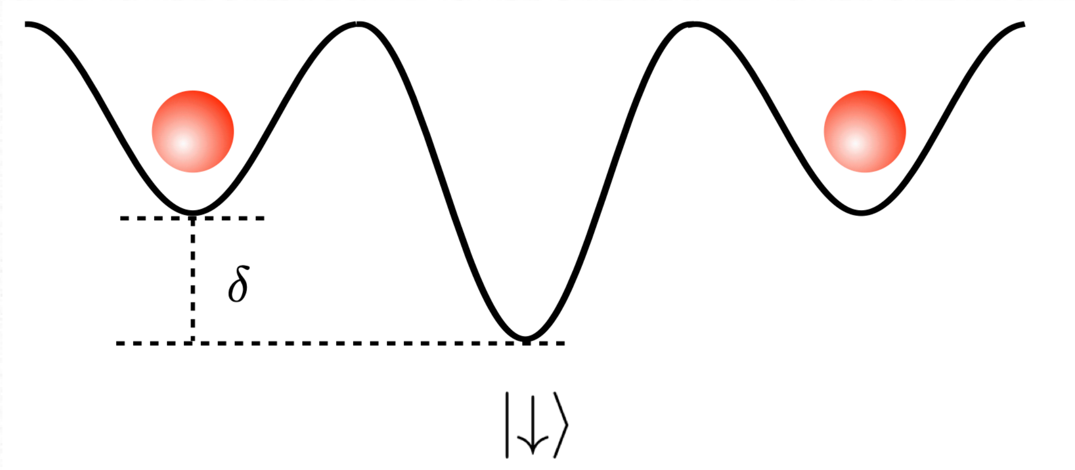


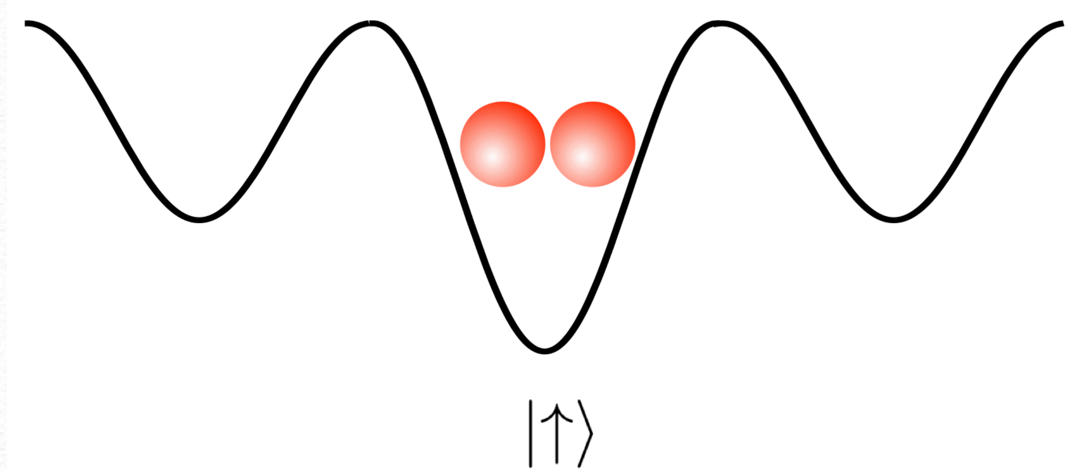


$$E = \delta$$

$$E = \delta + U$$

Quantum Simulation of Lattice Gauge Theory





$$E = 2\delta$$

Resonance

$$U \approx 2\delta$$

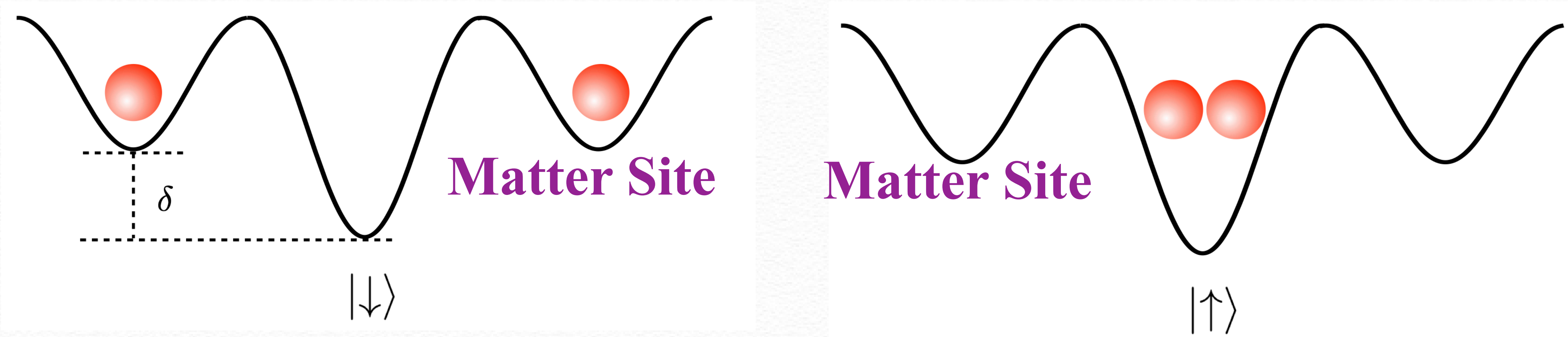
$$E = U$$

$$m = \delta - \frac{U}{2}$$

$$m\hat{\psi}_l^\dagger \hat{\psi}_l$$

Quantum Simulation of Lattice Gauge Theory

Physical charge



Gauge Site

Gauge Site

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2}\hat{S}^{+}_{l,l+1}\hat{b}_l\hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

Lattice Schwinger Model

Local Conserved Quantity

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

Local Gauge Symmetry: $\hat{b}_l \rightarrow e^{i\theta_l} \hat{b}_l$

$$\hat{S}^+_{l,l+1} \rightarrow e^{-i\theta_l} \hat{S}^+_{l,l+1} \qquad \hat{S}^+_{l-1,l} \rightarrow e^{-i\theta_l} \hat{S}^+_{l-1,l}$$

Conservation Quantity:

$$\boxed{G_l = S^z_{l-1,l} + S^z_{l,l+1} + n_l}$$

Local Conserved Quantity

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m \hat{n}_l \right]$$

Conservation Quantity:

$$\boxed{G_l = S^z_{l-1,l} + S^z_{l,l+1} + n_l}$$

Gauss's Law: $\nabla \cdot \mathbf{E} = \rho$

$$E_{l-1,l} = (-1)^l S^z_{l-1,l} \qquad Q_l = (-1)^l n_l$$

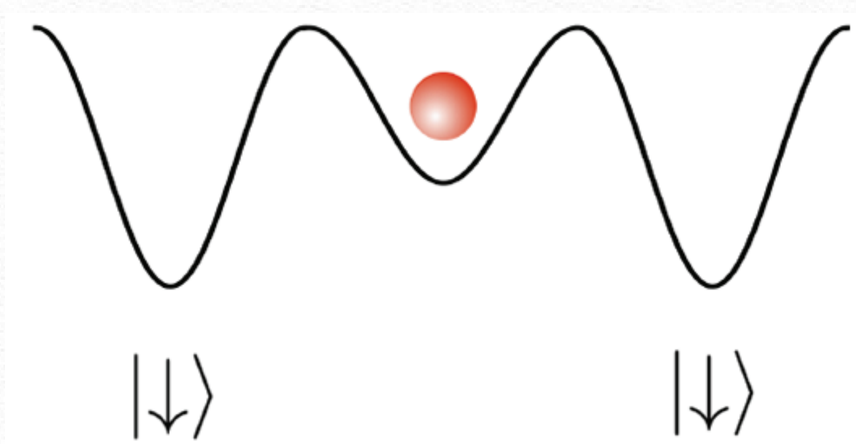
$$\boxed{E_{l,l+1} - E_{l-1,l} = Q_l}$$

Local Conserved Quantity

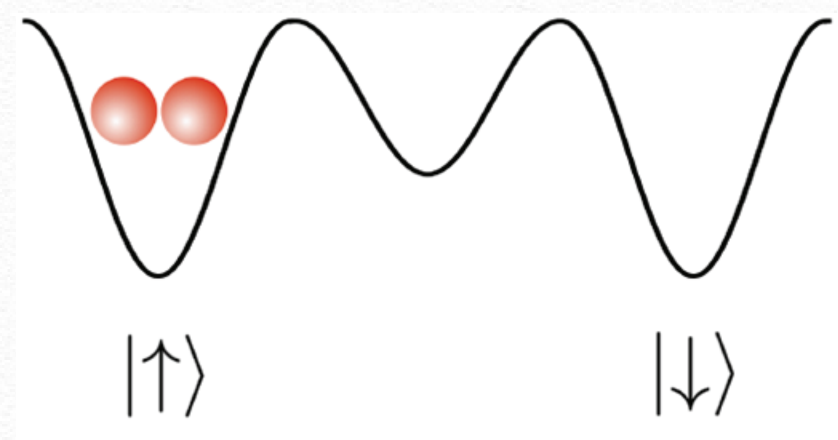
$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^{+}_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

$$\boxed{G_l = S^z_{l-1,l} + S^z_{l,l+1} + n_l}$$

$$\hat{G}_l = 0$$



$$-\frac{1}{2} - \frac{1}{2} + 1$$



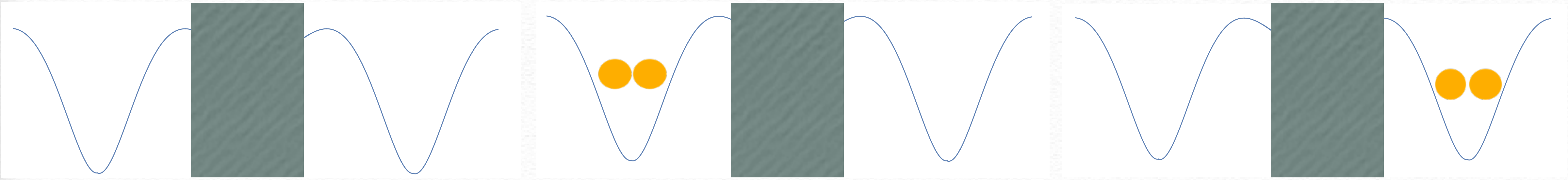
$$\frac{1}{2} - \frac{1}{2} + 0$$

Lattice Gauge Realization of the PXP Model

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^{+}_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m \hat{n}_l \right]$$

$$\hat{G}_l = 0$$ **Gauge charge**

- **No need to read the matter site**



Lattice Gauge Realization of the PXP Model

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^{+}_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

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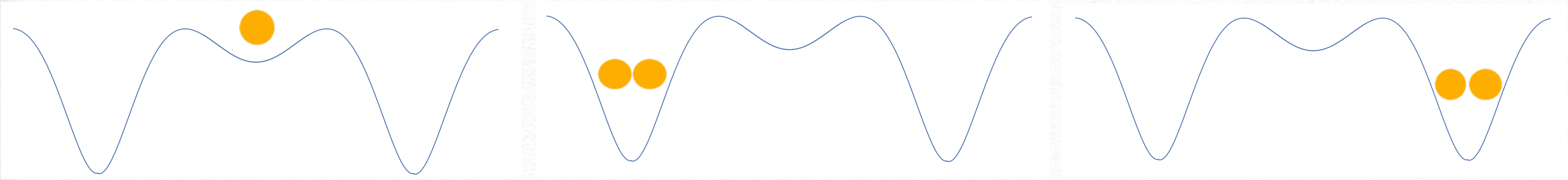

- **Connected by spin flip**

Lattice Gauge Realization of the PXP Model

$$\hat{H}_{\text{eff}} = \sum_{l} \left[-\frac{\tilde{J}}{2} \hat{S}^{+}_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

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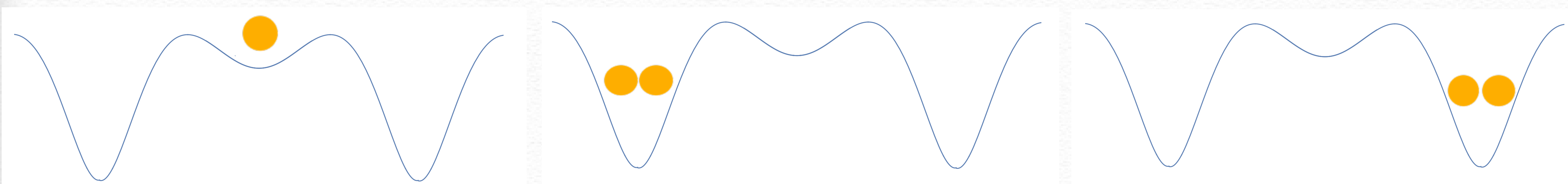

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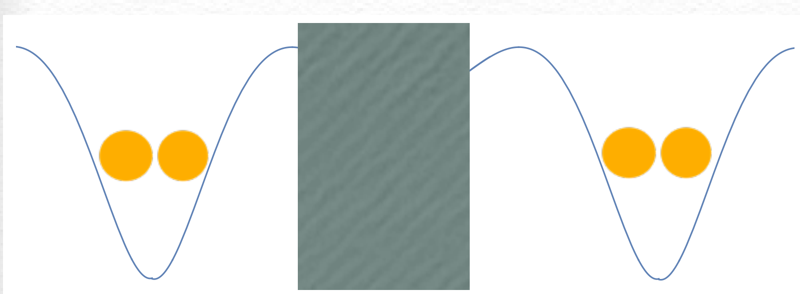
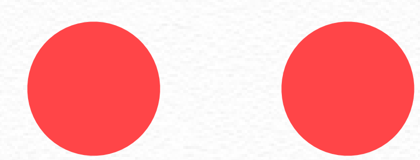




- **Not allowed**

Rydberg Blockade

Lattice Gauge Realization of the PXP Model

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

$$\hat{G}_l = 0$$ **Gauge charge**

$$\Updownarrow$$

$$\hat{H} = \sum_l \left[\hat{P}_{l-1,l} \left(-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} + \text{h.c.} \right) \hat{P}_{l+1,l+2} - m(S^z_{l-1,l} + S^z_{l,l+1}) \right]$$

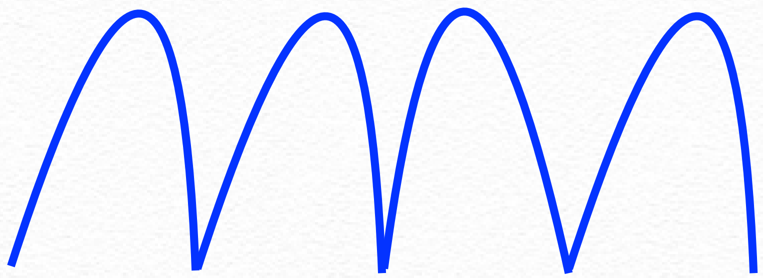
- **Gauge Conservation** $\Longleftrightarrow$ **Rydberg Blockade**
- **Matter Field Mass** $\Longleftrightarrow$ **Excitation Detuning**

Physics in the PXP Model

1. Quantum Thermalization

Quantum Thermalization

- **Loss of initial state memory**



$|\Psi\rangle$

$e^{i\hat{H}t}$

$T, \mu, \ldots$

Quantum wave function

Unitary evolution

Thermal equilibrium

$$\langle \hat{\mathcal{O}} \rangle_\infty = \langle \rho_{eq}(E) \hat{\mathcal{O}} \rangle$$

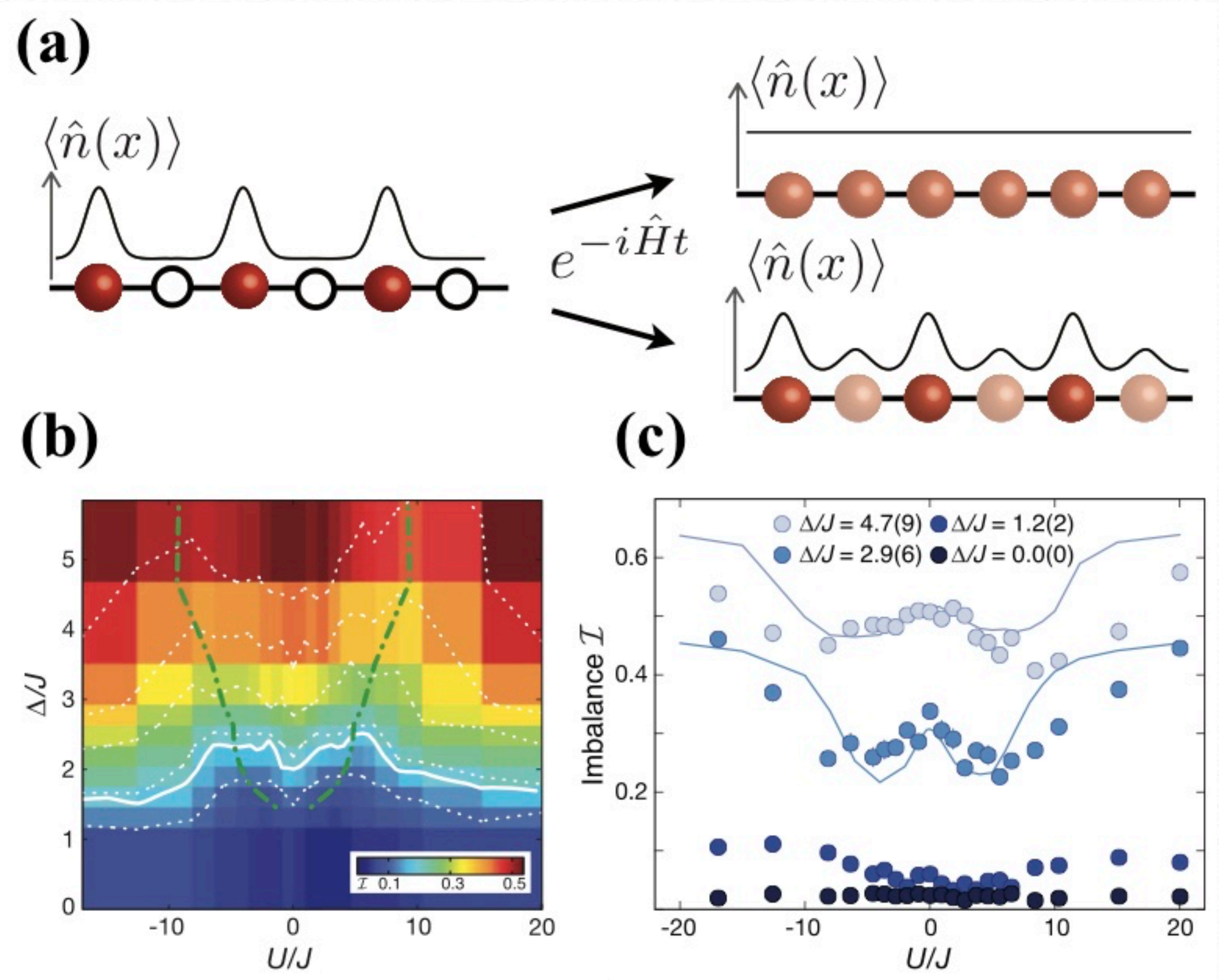
Local observable

Equilibrium Density Matrix of the Whole System

Sufficient Long Time Evolution

Quantum Thermalization

- **Loss of initial state memory**



Munich Group, Science 2015

Quantum Thermalization

- **Eigen-state thermalization**

$$|\Psi(0)\rangle = \sum_\alpha a_\alpha |\alpha\rangle \quad \Rightarrow \quad |\Psi(t)\rangle = \sum_\alpha a_\alpha e^{-iE_\alpha t}|\alpha\rangle$$

$$\langle \hat{\mathcal{O}} \rangle_\infty = \lim_{T\to\infty} \frac{1}{T}\int_0^T \langle \Psi(t)|\hat{\mathcal{O}}|\Psi(t)\rangle dt = \sum_\alpha |a_\alpha|^2 \langle \alpha|\hat{\mathcal{O}}|\alpha\rangle$$

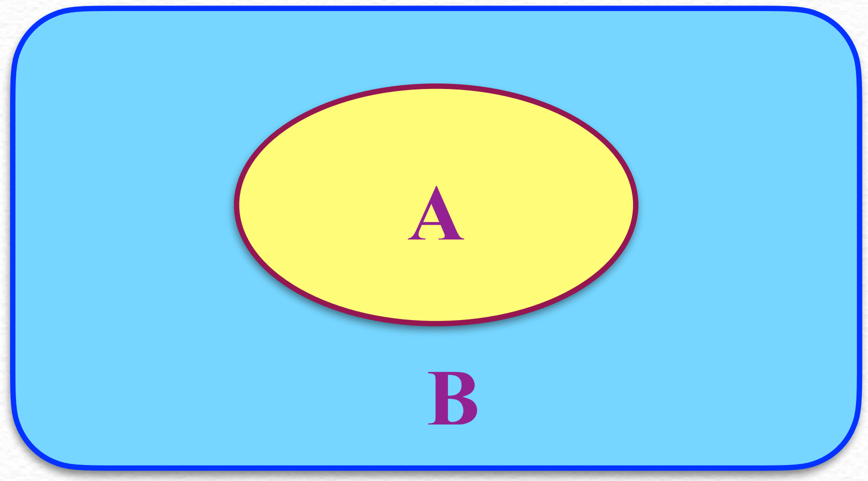
no Eigodicity; all eigenstates are thermal

$$\langle \alpha|\hat{\mathcal{O}}|\alpha\rangle = \underline{\langle \rho_{\mathrm{mc}}(E_\alpha)\hat{\mathcal{O}}\rangle}$$

a function of energy only

Quantum Thermalization

- **Volume-law of entanglement entropy**



$$\rho_{\mathcal{A}}^{\alpha} = \mathrm{Tr}_{\mathcal{B}} |\alpha\rangle\langle\alpha| \quad \Rightarrow \quad \textbf{entanglement entropy}$$

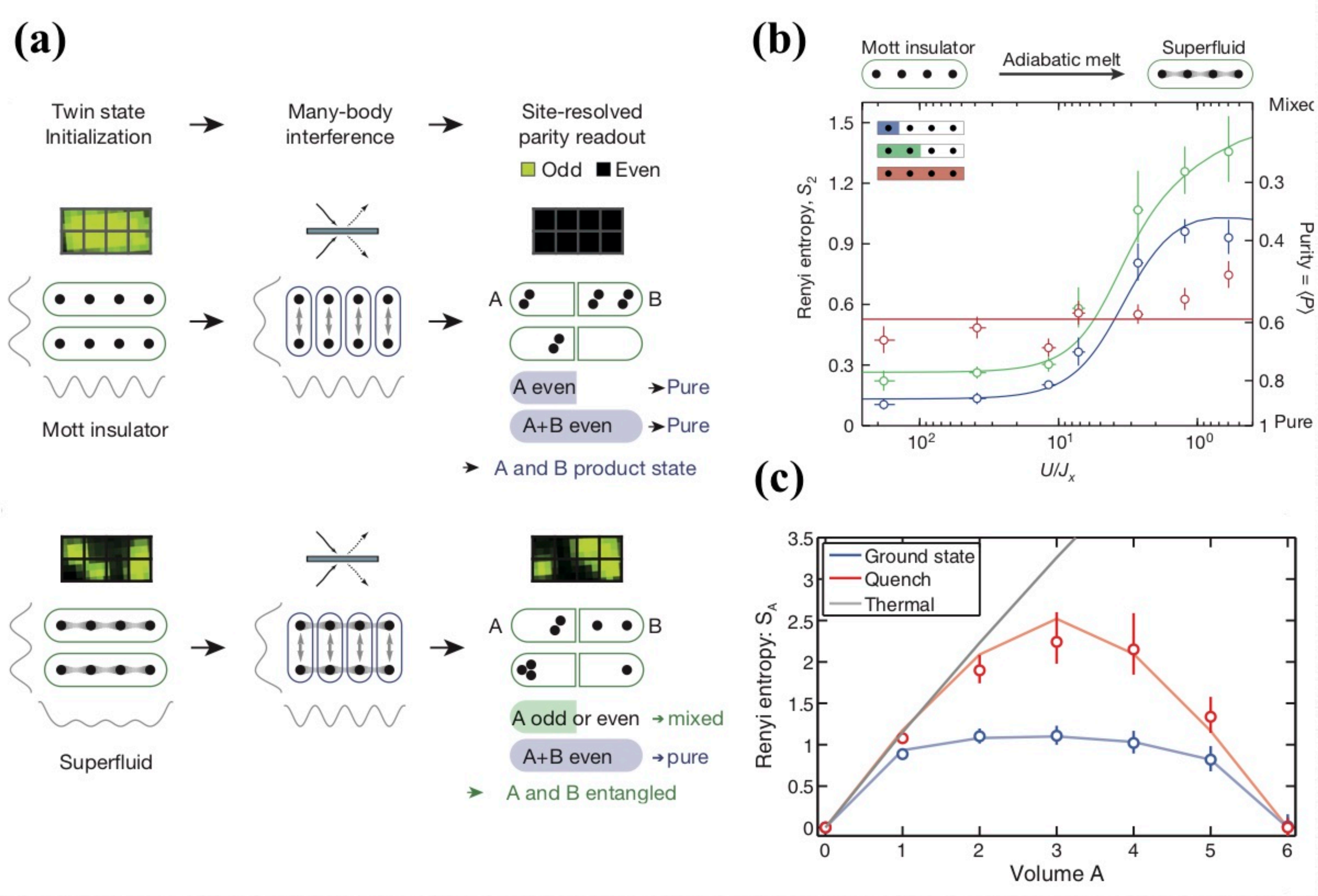
$$\rho_{\mathrm{eq}}(T) = \frac{1}{Z} e^{-\hat{H}/(k_{\mathrm{B}}T)} \quad \Rightarrow \quad \textbf{thermal entropy}$$

volume law

$$\rho_{\mathcal{A}}^{\alpha} = \rho_{\mathcal{A}}^{\mathrm{eq}}$$

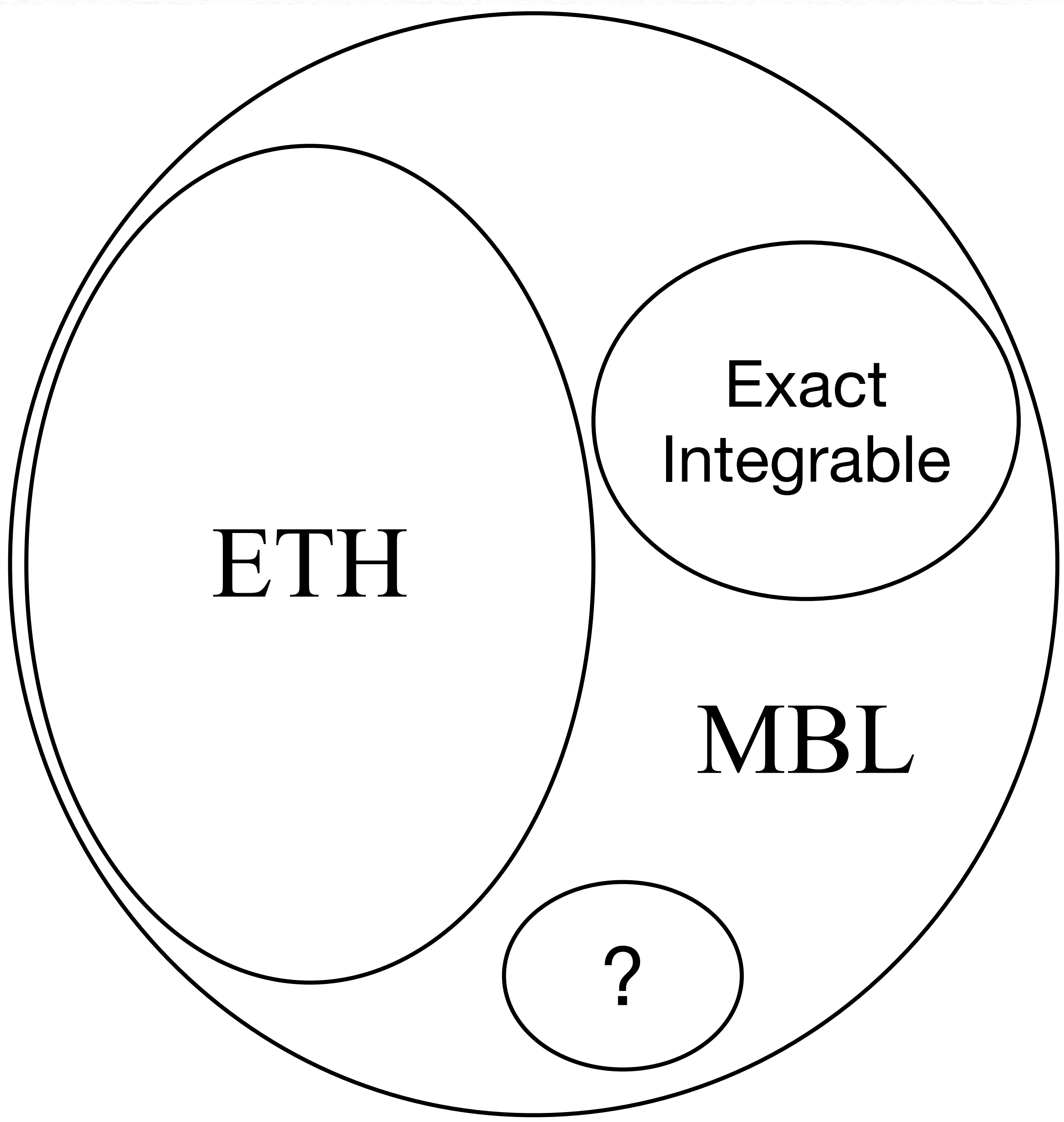
Quantum Thermalization

- **Volume-law of entanglement entropy**



Harvard Group, Science, 2016

Quantum Thermalization



Quantum Many-Body Scars

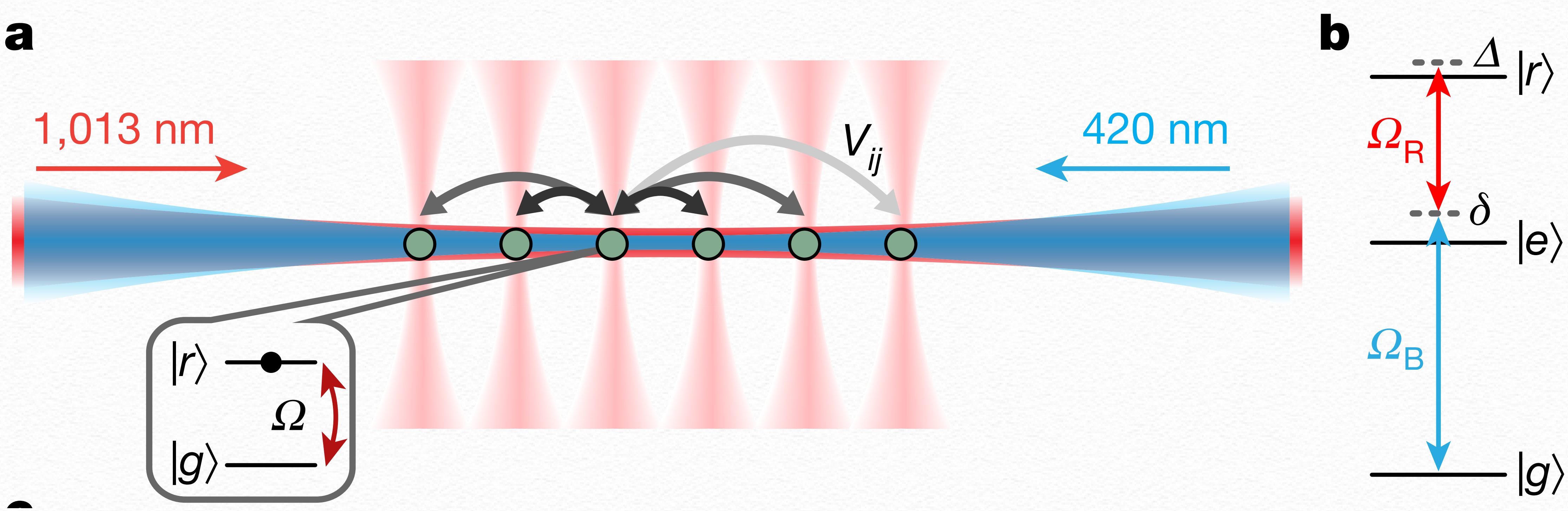
ARTICLE

doi:10.1038/nature24622

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

Nature 2017

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]



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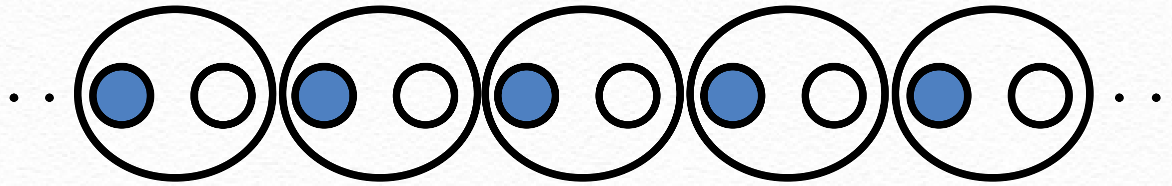

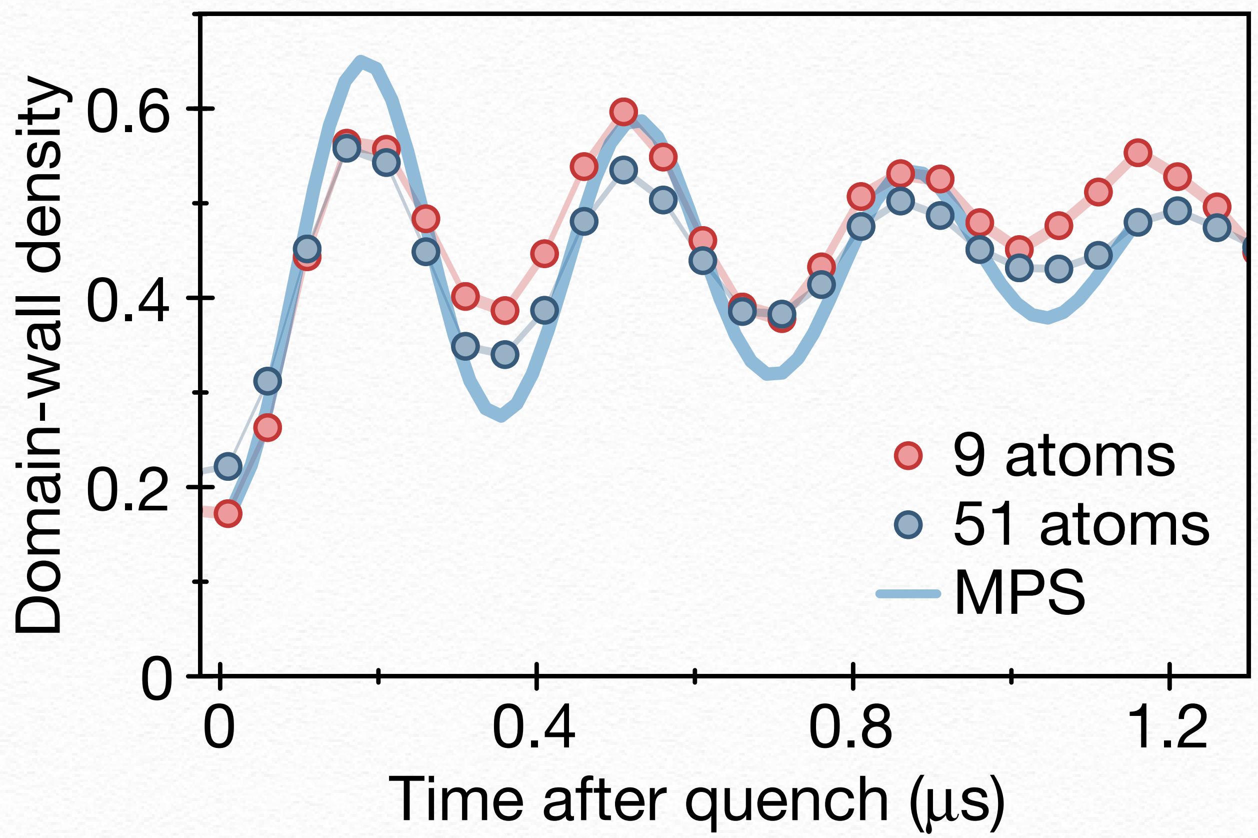

Why This is Unusual ?

ARTICLE

doi:10.1038/nature24622

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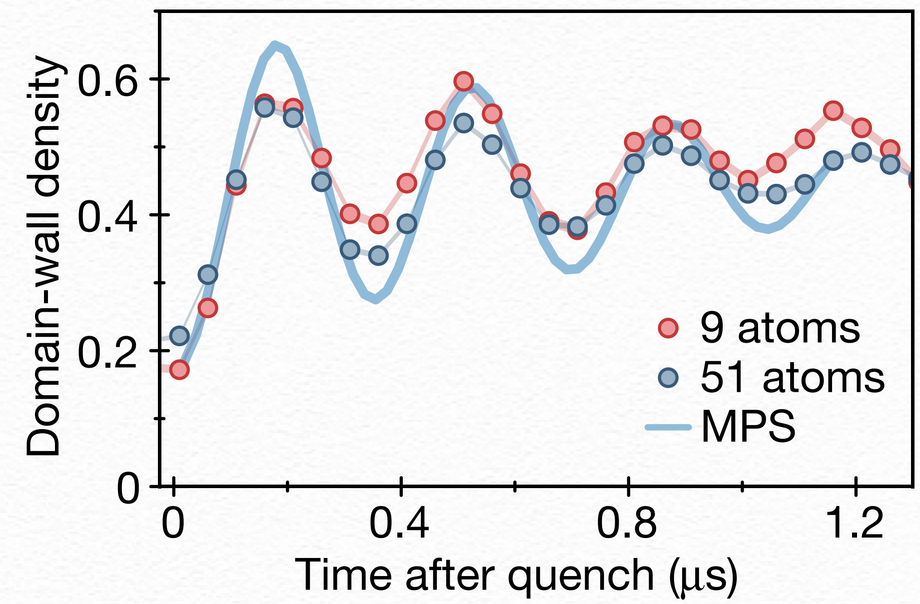
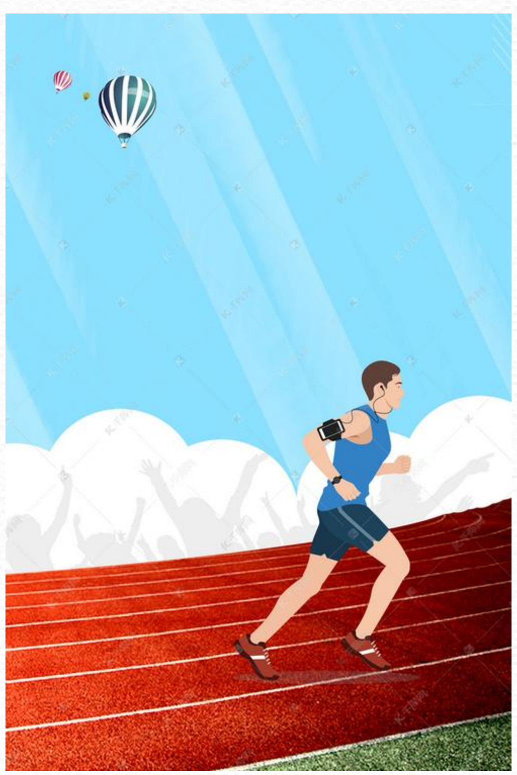
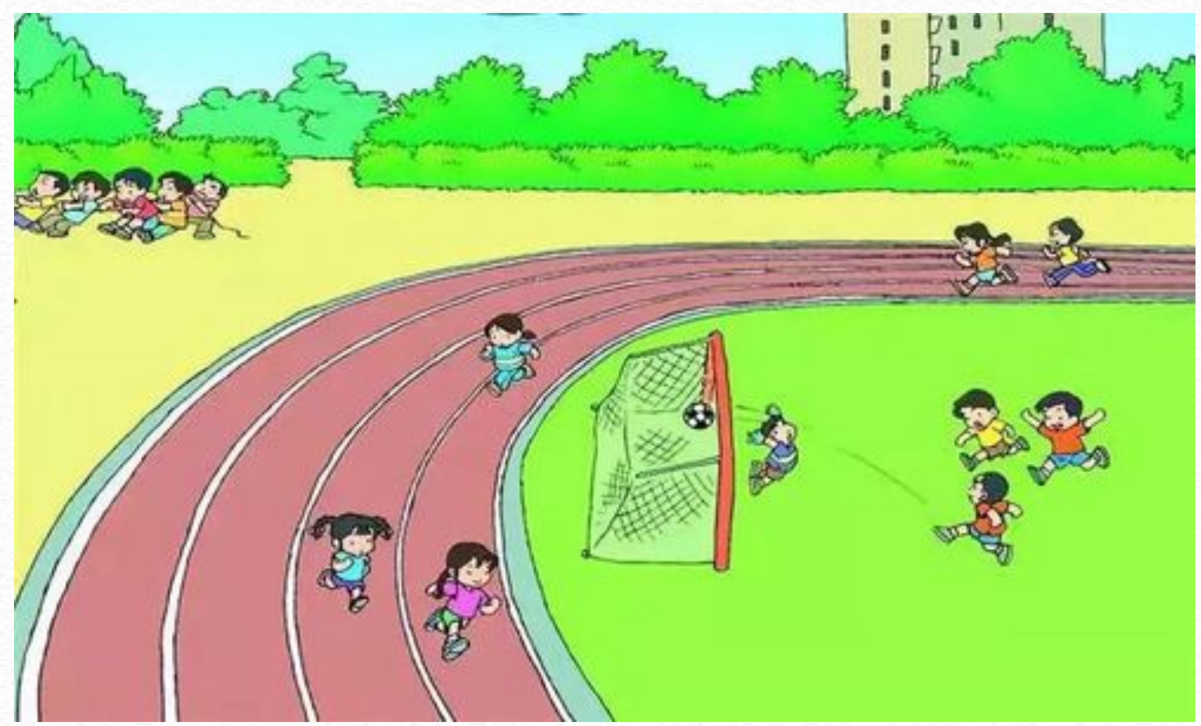




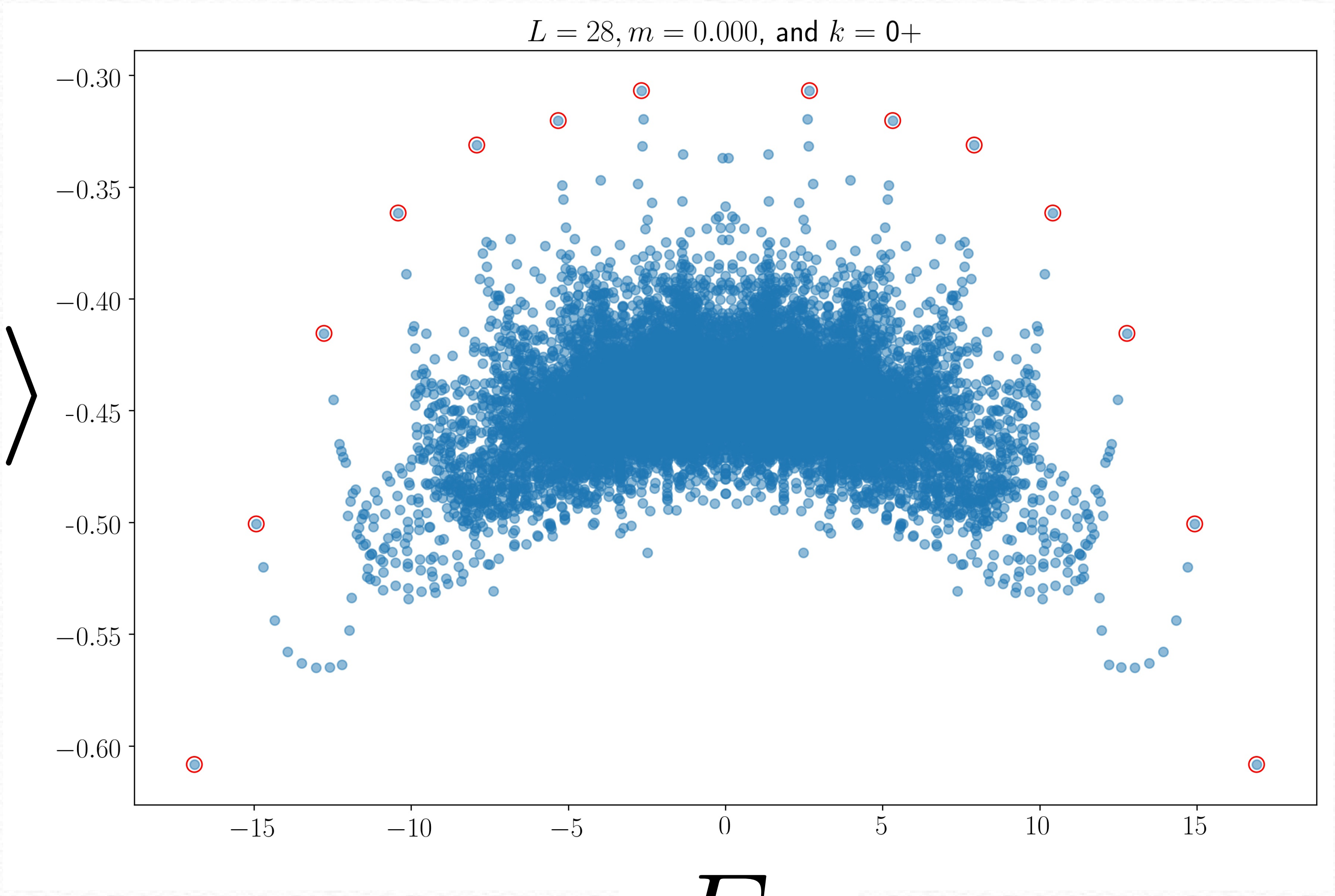


Many-Body Scar in PXP Hamiltonian

Weak ergodicity breaking from quantum many-body scars

Nature Physics 2018

C. J. Turner[1], A. A. Michailidis[1,2], D. A. Abanin[3], M. Serbyn[2] and Z. Papić[1*]



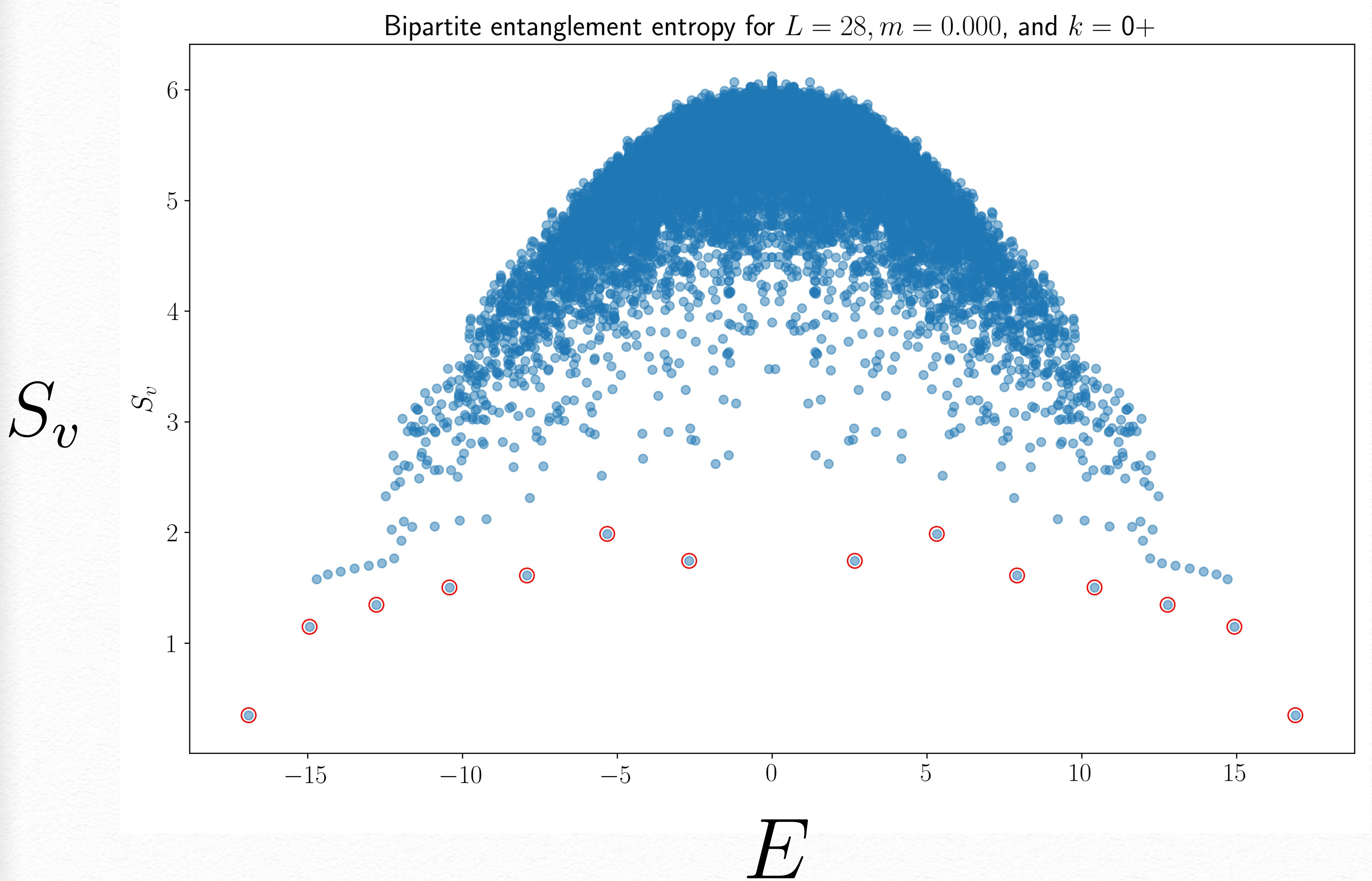
$\langle \sigma^z \rangle$

E

$$\langle \alpha | \hat{\mathcal{O}} | \alpha \rangle = \langle \rho_{\mathrm{mc}}(E_\alpha) \hat{\mathcal{O}} \rangle$$

Many-Body Scar in PXP Hamiltonian

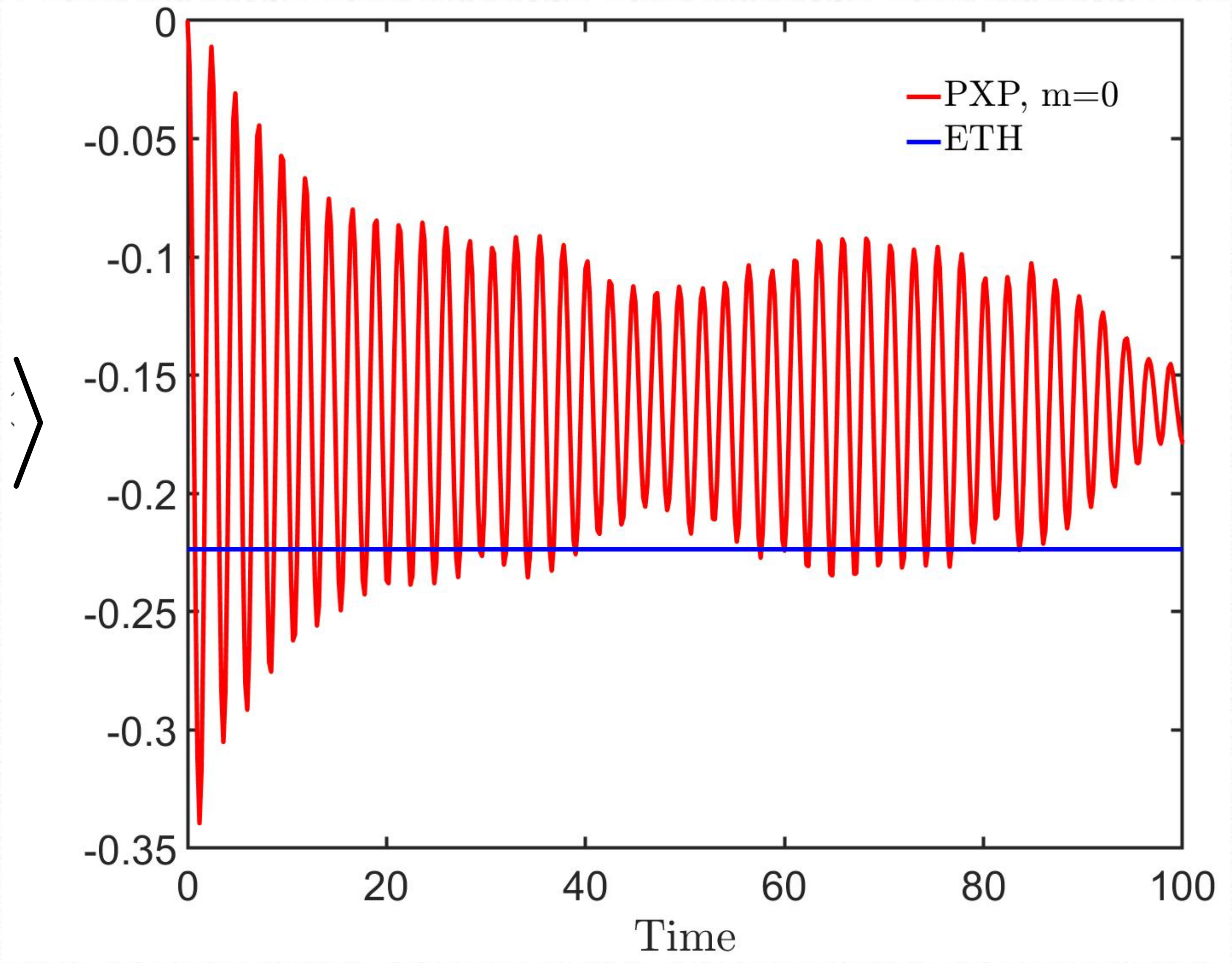
Significantly low entanglement entropy



Many-Body Scar in PXP Hamiltonian

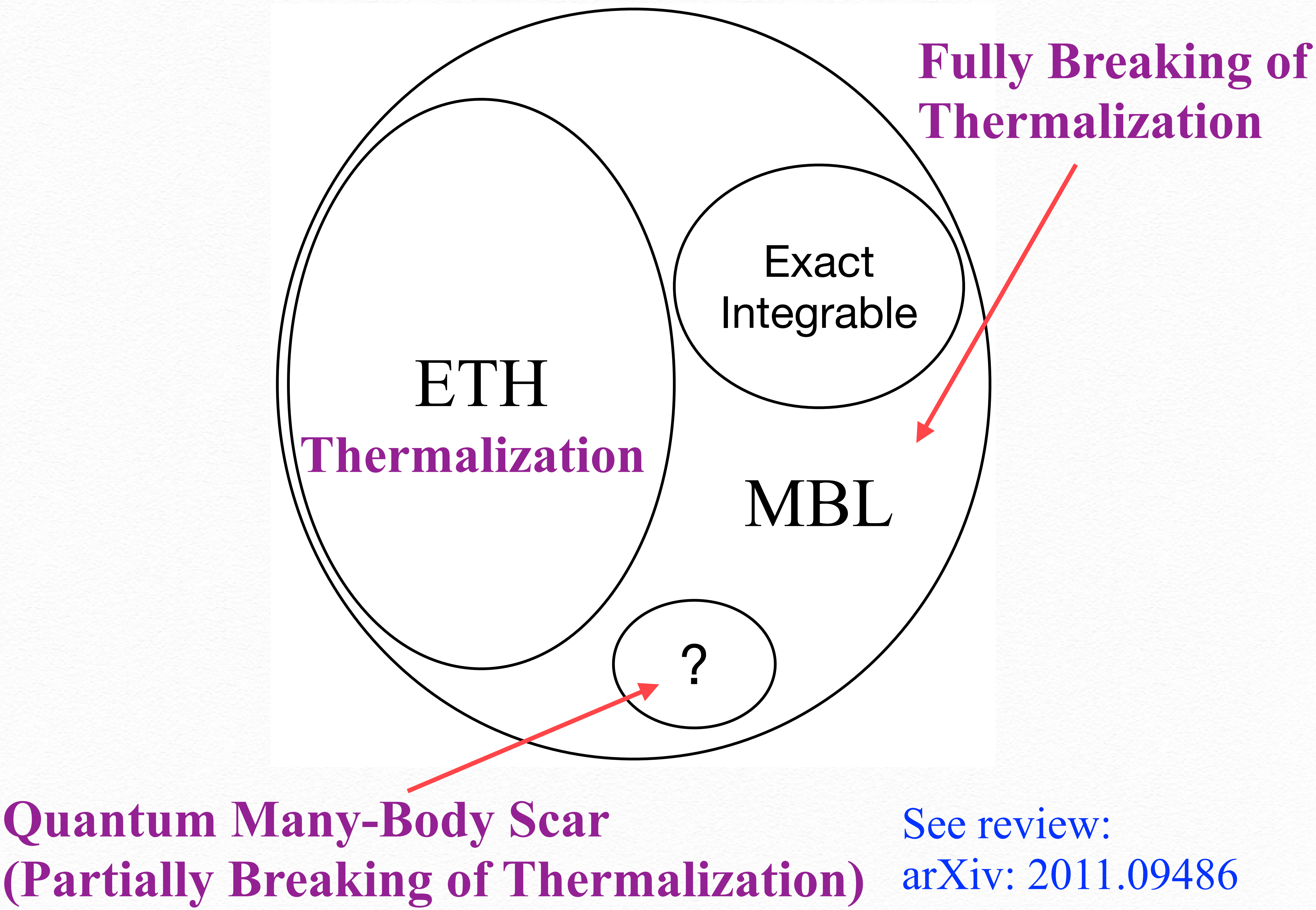
Z2 state cannot thermalize

$$\langle \sigma^z \rangle$$



$$\langle \hat{\mathcal{O}} \rangle_\infty = \langle \rho_{eq}(E) \hat{\mathcal{O}} \rangle$$

Quantum Thermalization



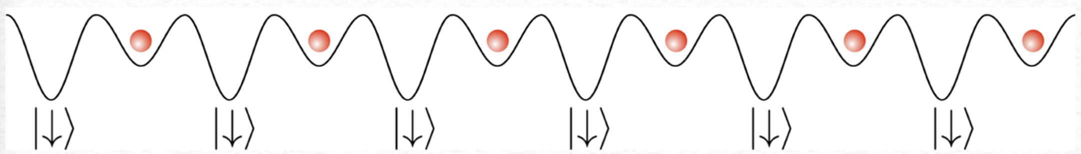
See review:
arXiv: 2011.09486

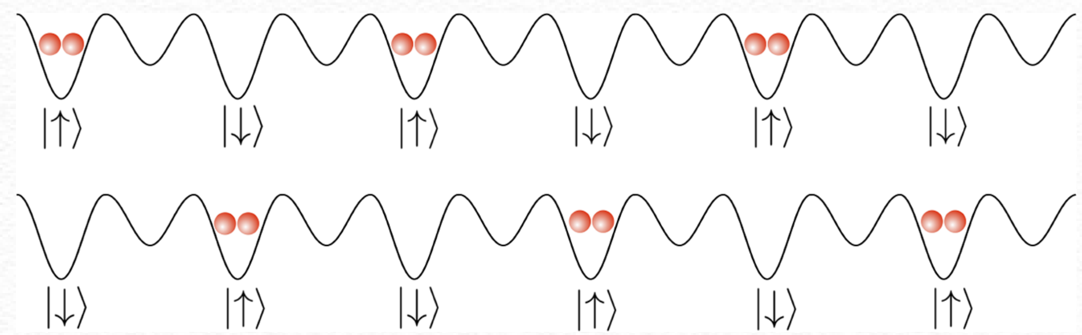
Phase Diagram of Lattice Schwinger Model

$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

$m \to \infty$

$m \to -\infty$





Matter sites occupied

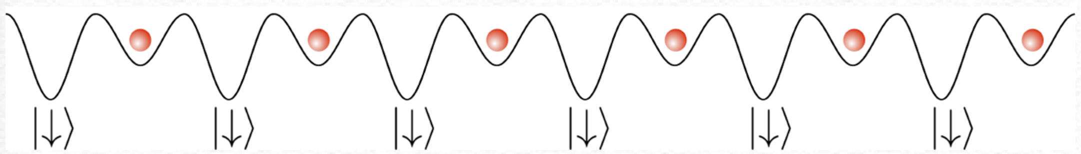
Matter sites vacuum

m

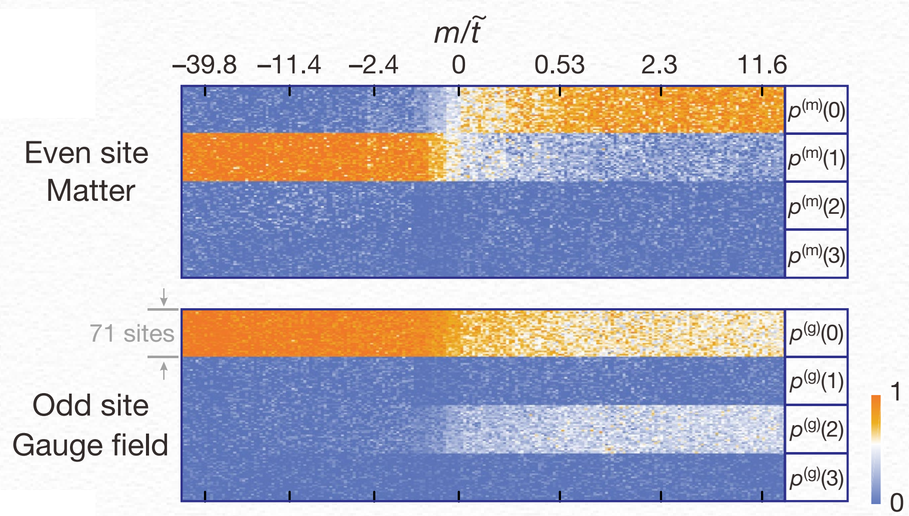
Z2 Symmetry Breaking

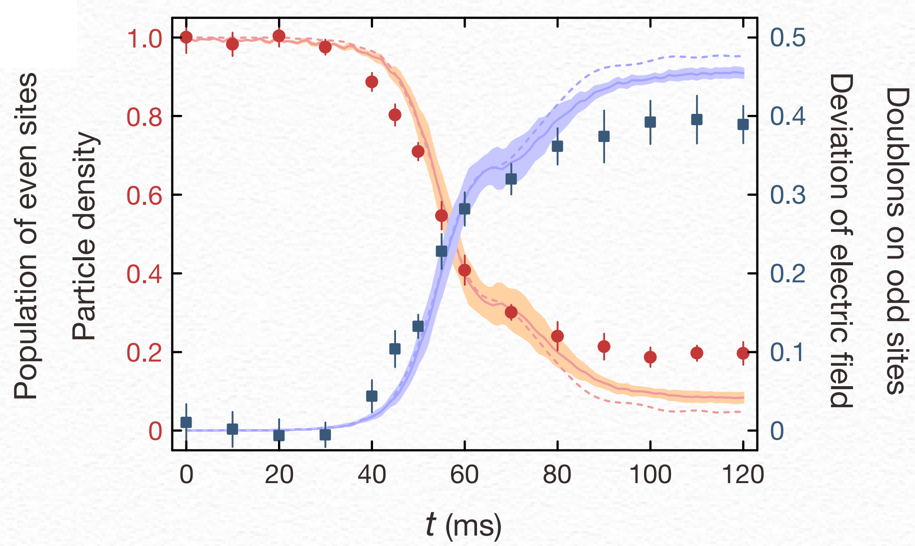
Ising Transition

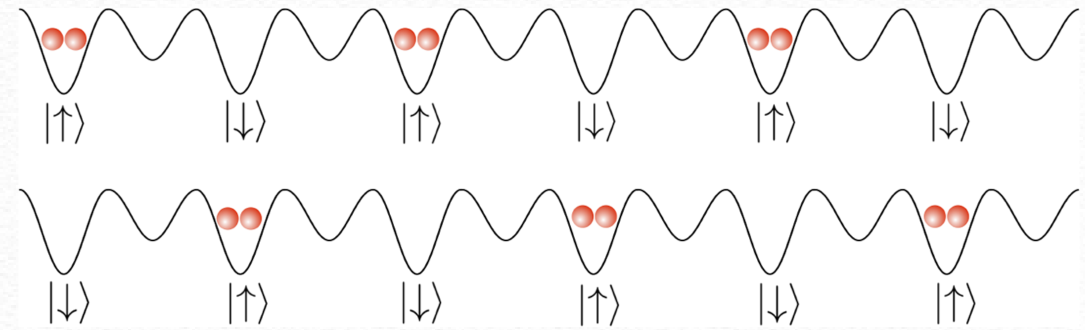
Phase Diagram of Lattice Schwinger Model



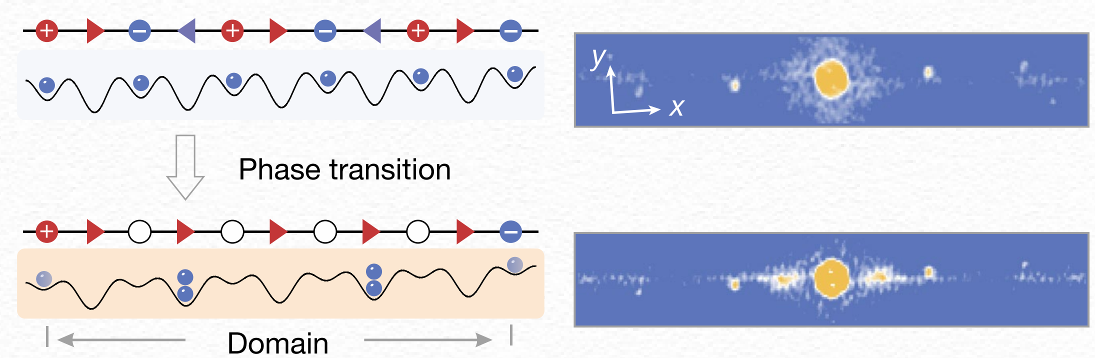
Matter sites occupied

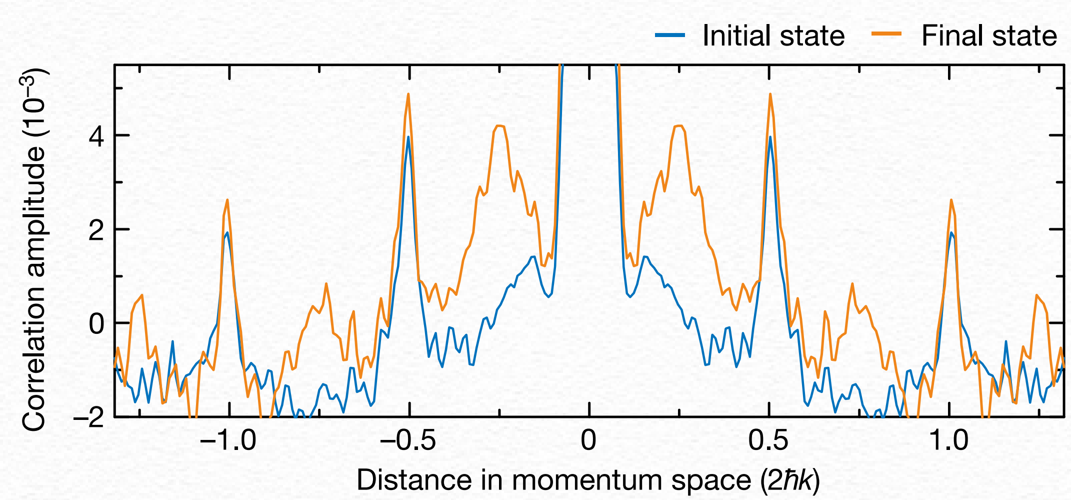






Matter sites vacuum



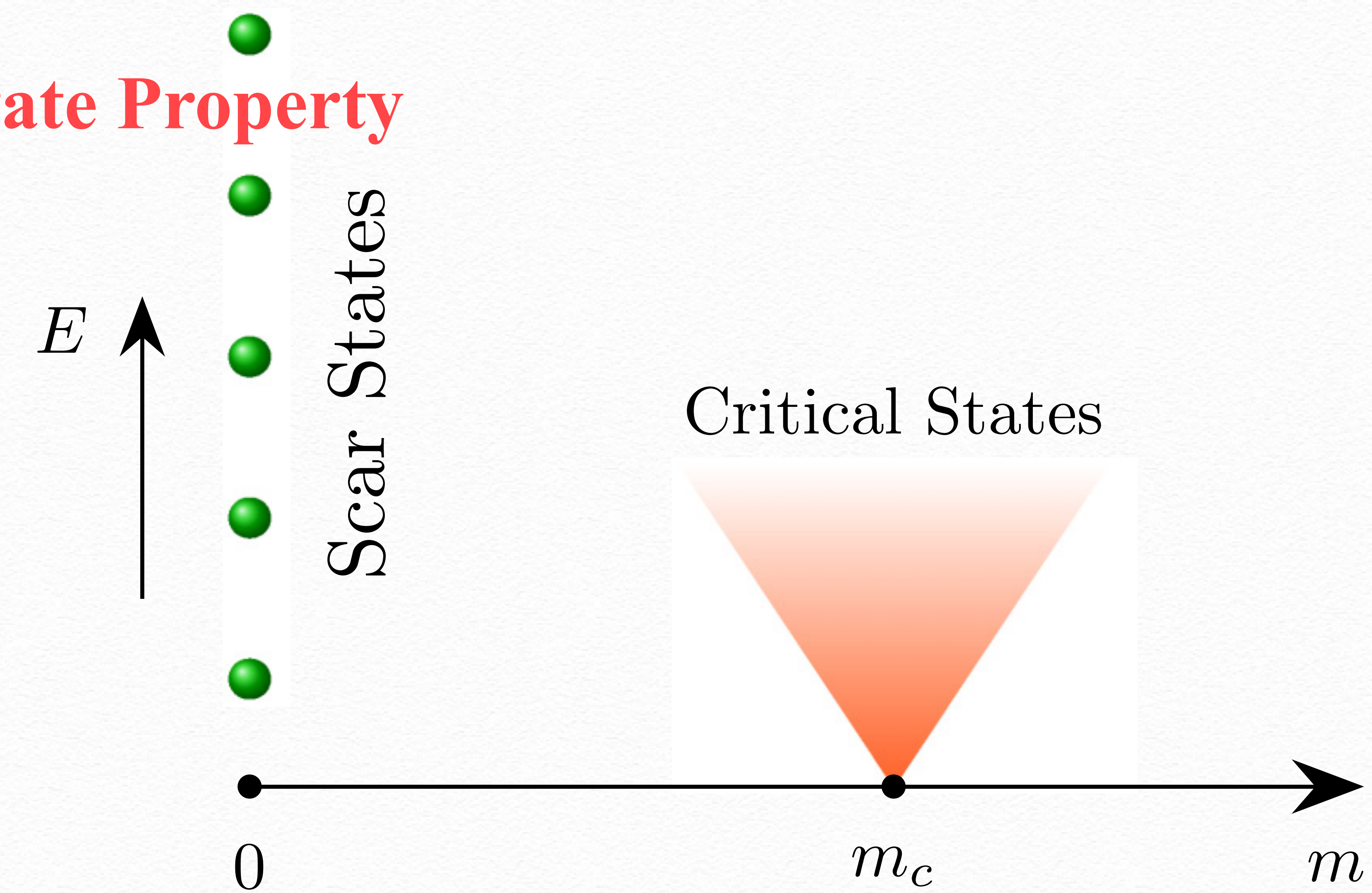


USTC Nature 2020

Insight from Entanglement

Log-volume law of entanglement entropy

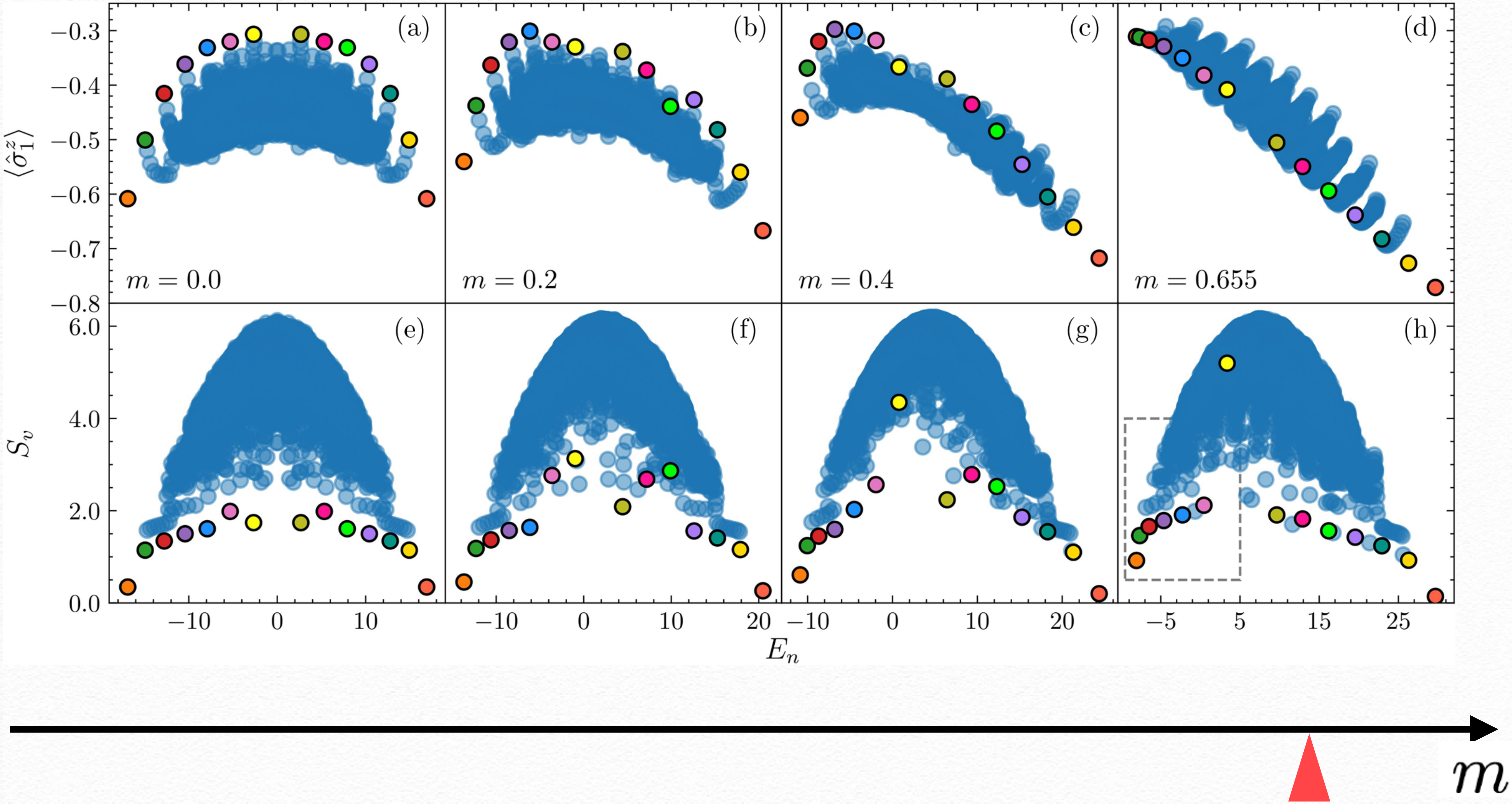
Excited State Property



Ising CFT

Ground State Property

Driving Scars to Critical



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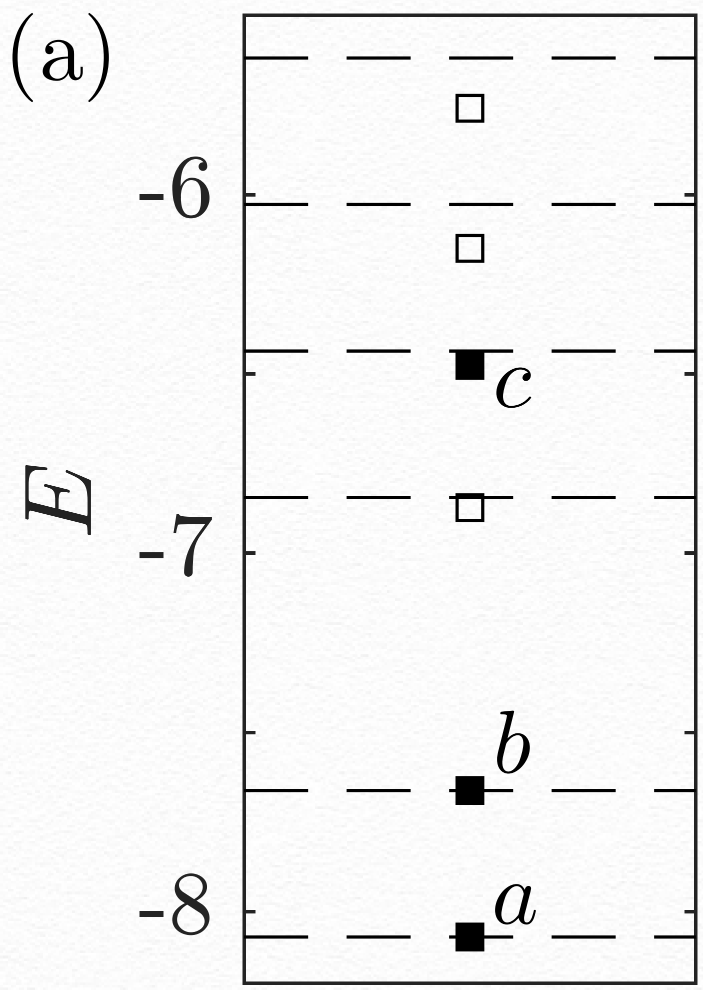
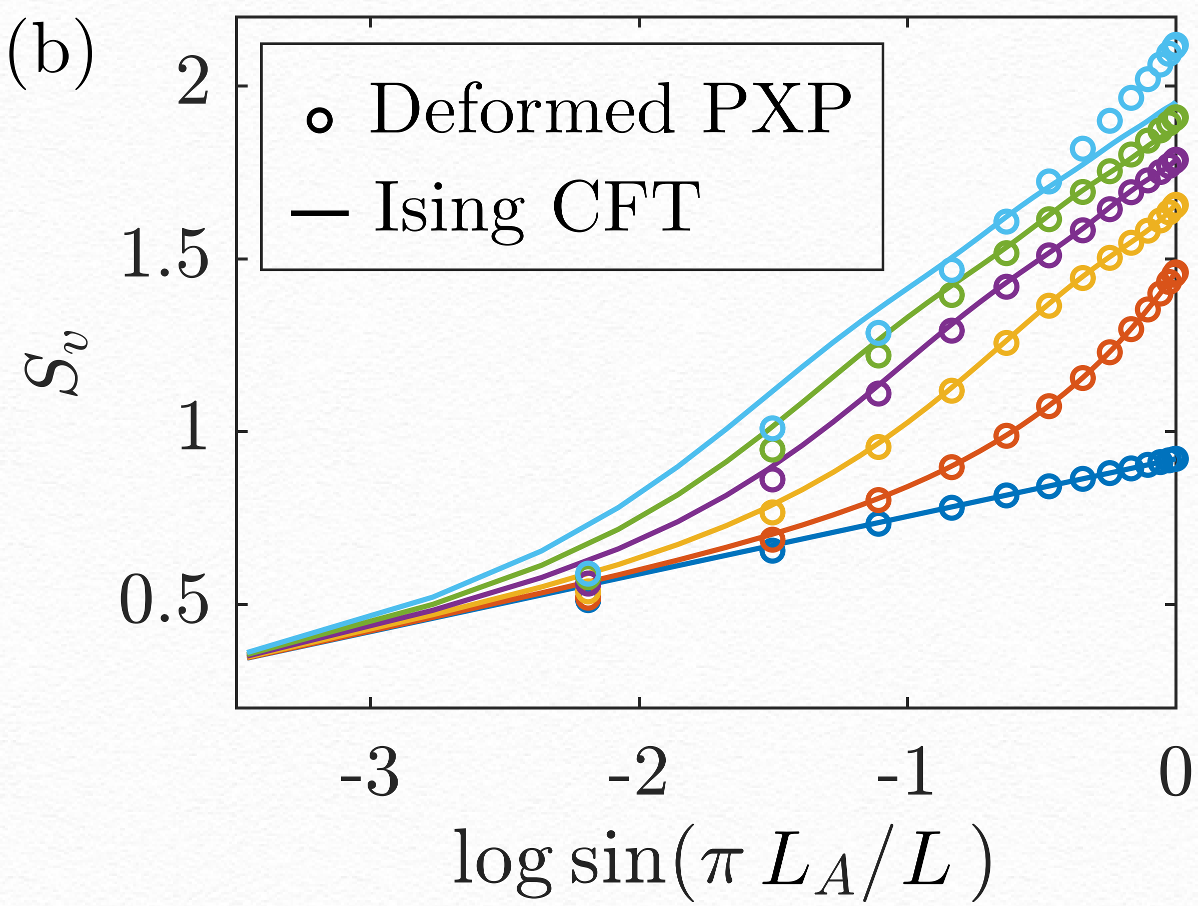
Prediction of Ising CFT

$$\sim \log\left(\sin\frac{\pi L_A}{L}\right)$$





Energy

Entropy

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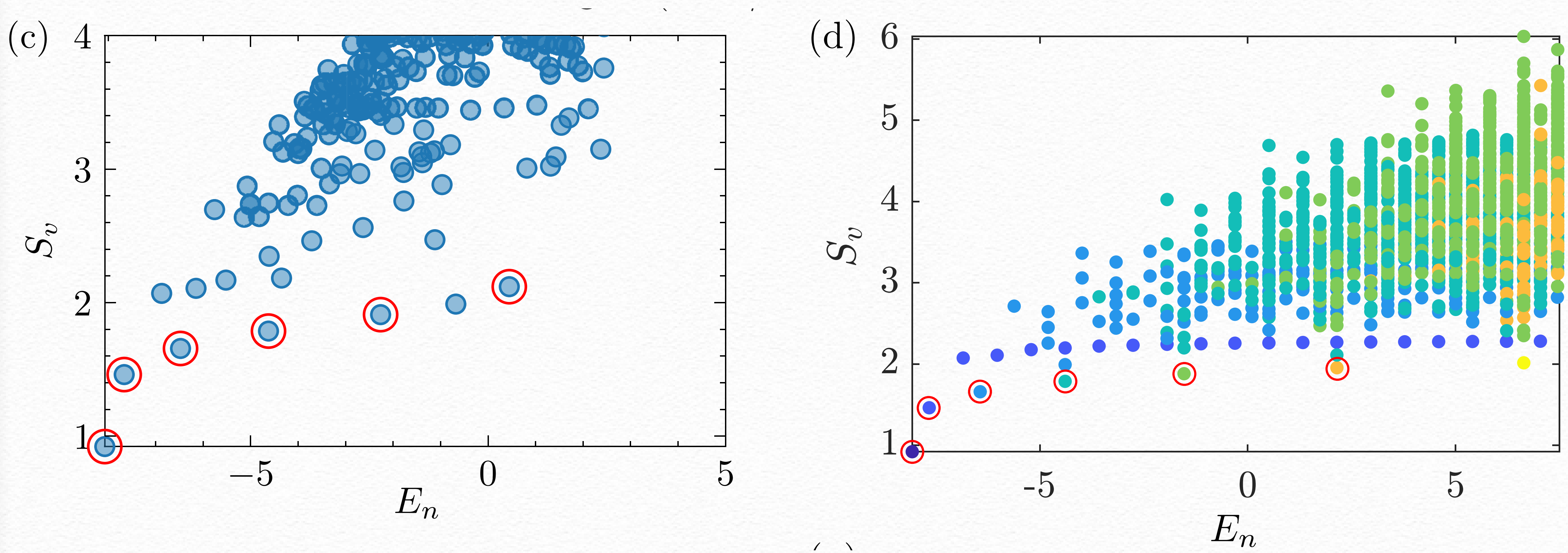
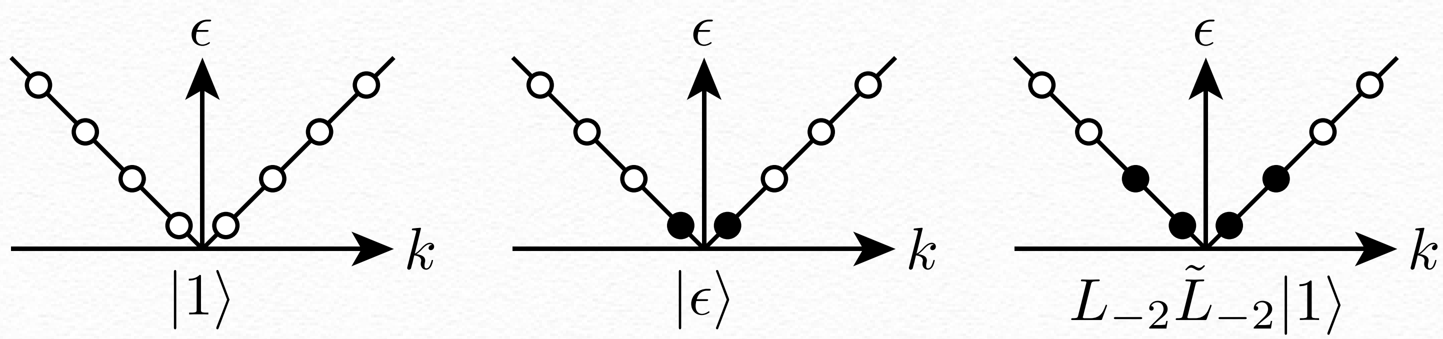
Prediction of Ising CFT



PXP Model **Transverse Field Ising Model**

Free Fermion States



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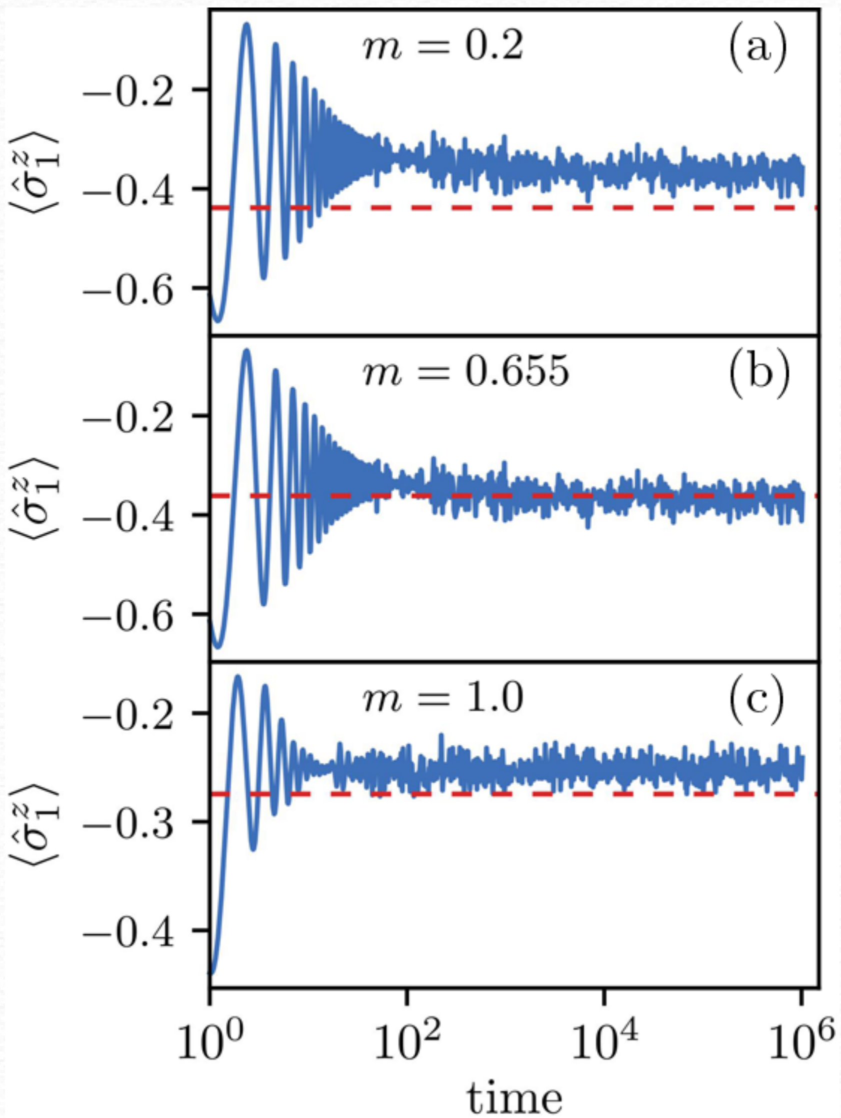
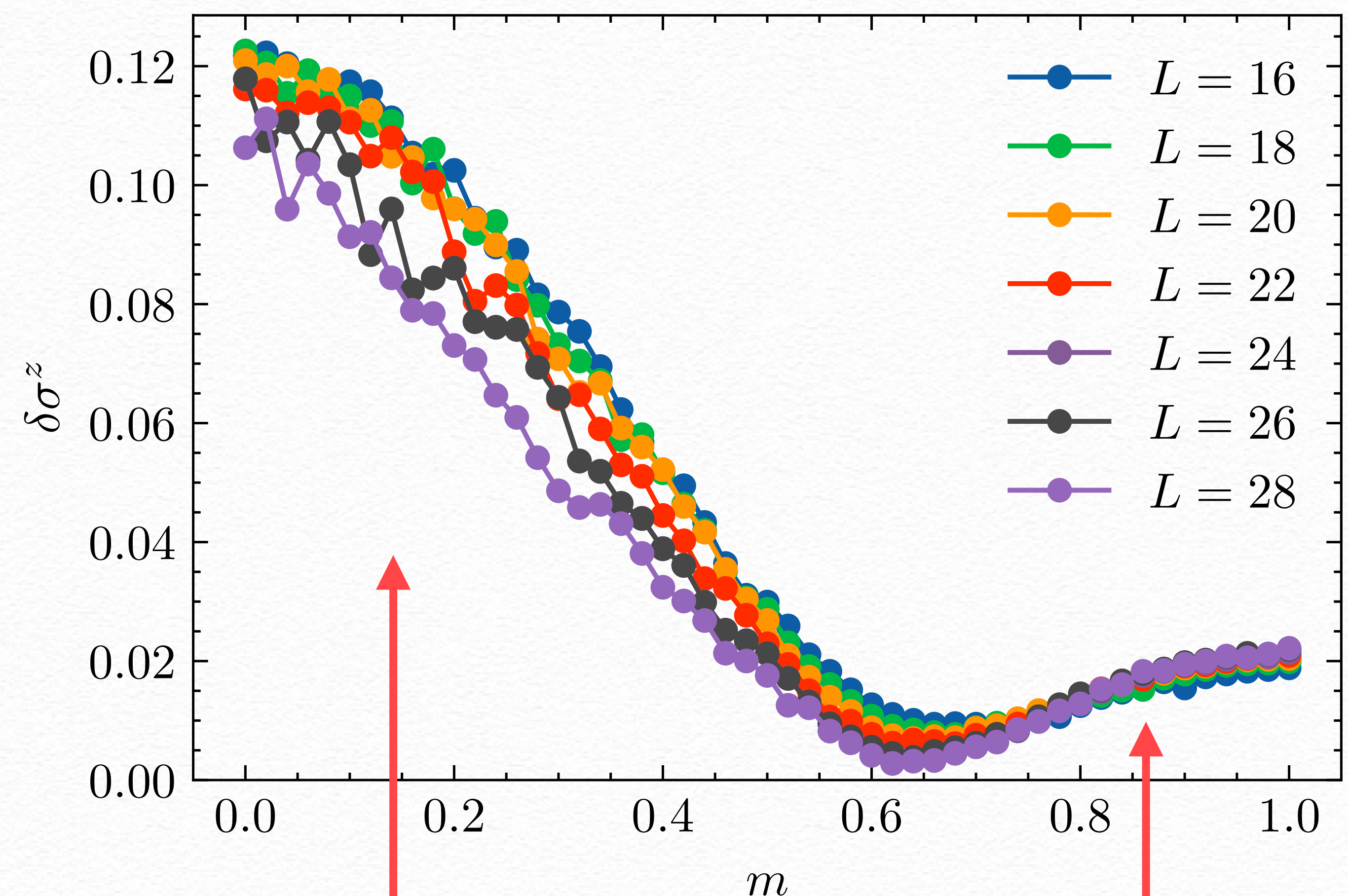
Thermalization and Criticality





Many-body Scars

Symmetry Breaking

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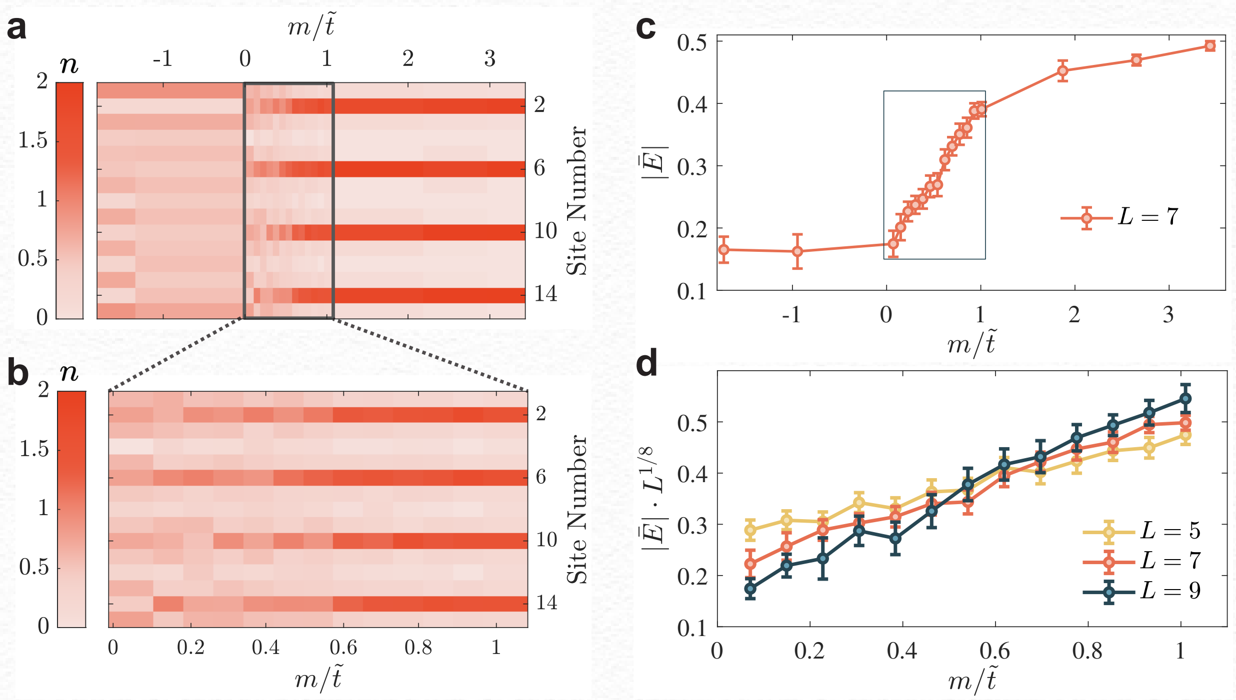
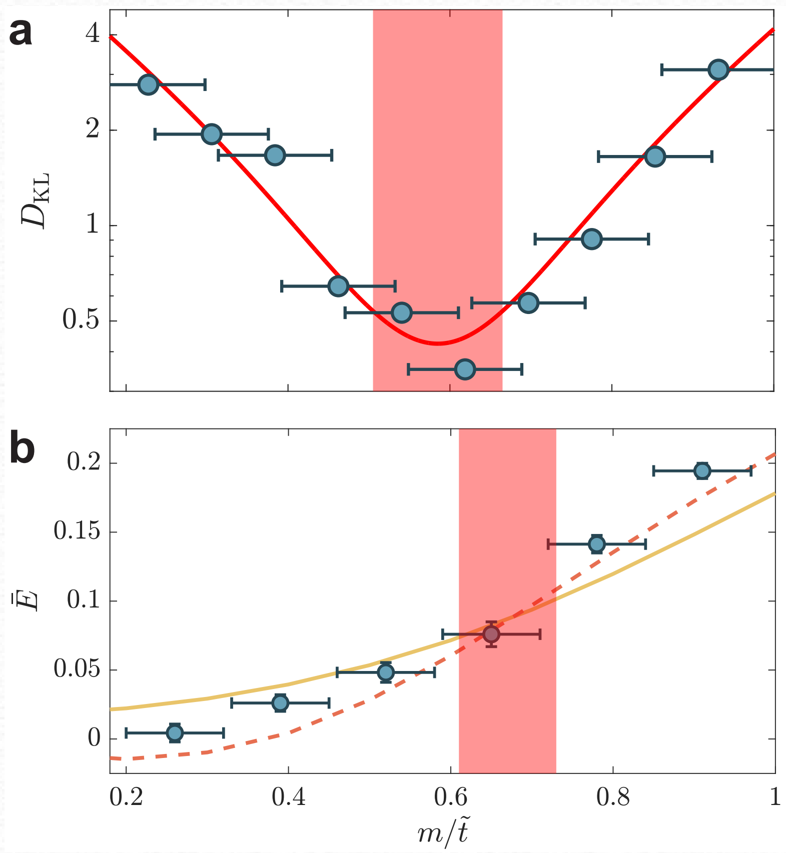
Experimental Observations

Interrelated Thermalization and Quantum Criticality in a Lattice Gauge Simulator

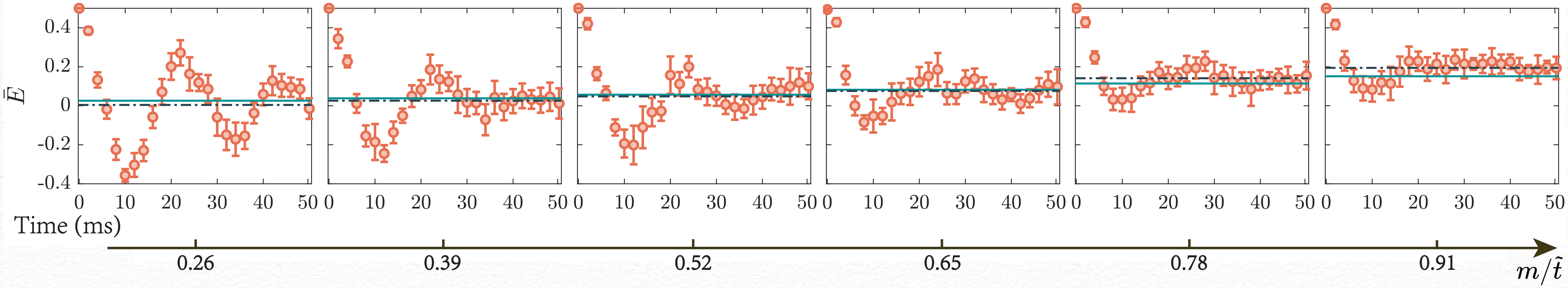
Han-Yi Wang,[1,*] Wei-Yong Zhang,[1,*] Zhi-Yuan Yao,[2,*] Ying Liu,[1] Zi-Hang Zhu,[1] Yong-Guang Zheng,[1] Xuan-Kai Wang,[1] Hui Zhai,[2,3] Zhen-Sheng Yuan,[1,3,4] and Jian-Wei Pan[1,3,4]

arXiv: 2210.17032





Precise Determine the Quantum Critical Point

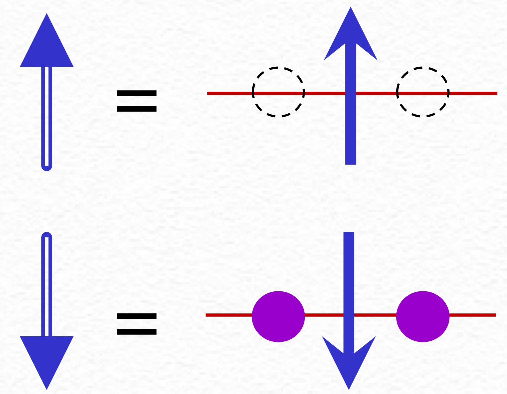


Precise Determine the Thermalization Value

From Ground State to Excitations

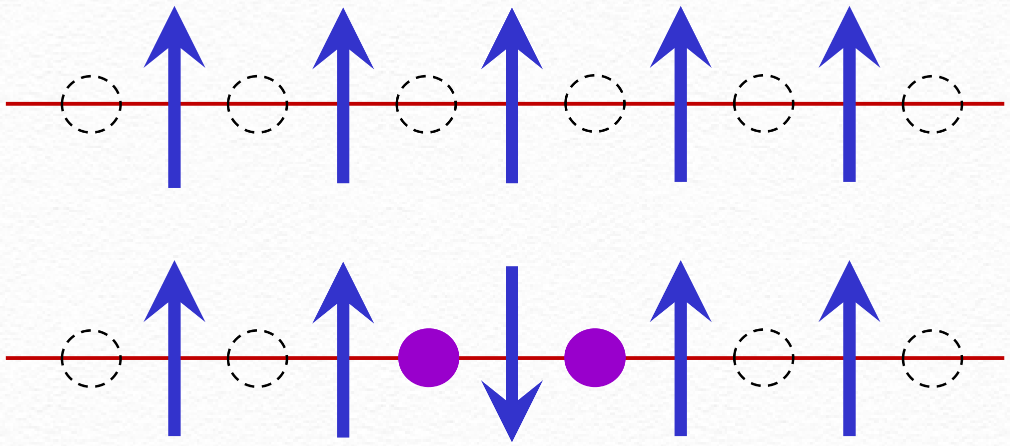
$$\hat{H} = \sum_i \left[\frac{\Omega}{2} (\hat{S}_i^- f^\dagger_{i-1,i} \hat{f}^\dagger_{i,i+1} + \hat{S}_i^+ \hat{f}_{i,i+1} \hat{f}_{i-1,i}) + \Delta \hat{S}_i^z \right]$$

Dressed spins



$$|\Uparrow\rangle = |\uparrow\rangle \otimes |00\rangle$$

$$|\Downarrow\rangle = |\downarrow\rangle \otimes |11\rangle$$



$$\hat{H} = \sum_i \left(\Omega \hat{\tau}_i^x + \Delta \hat{\tau}_i^z \right)$$

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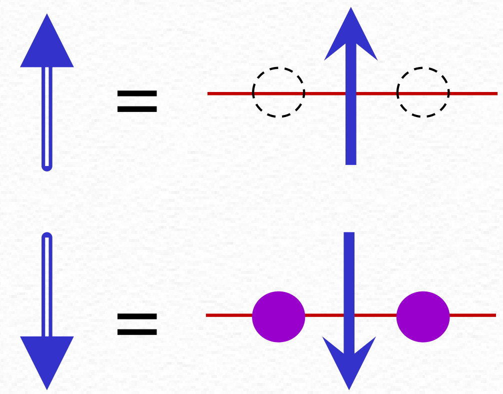
From Ground State to Excitations

$$\hat{H} = \sum_i \left[\frac{\Omega}{2}\left(\hat{S}_i^- f^\dagger_{i-1,i}\hat{f}^\dagger_{i,i+1} + \hat{S}_i^+ \hat{f}_{i,i+1}\hat{f}_{i-1,i}\right) + \Delta \hat{S}_i^z \right]$$

Dressed spins

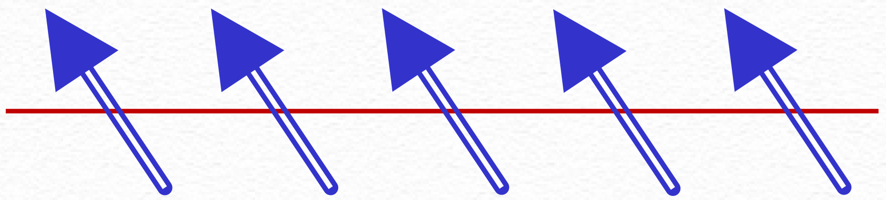


$$|\Uparrow\rangle = |\uparrow\rangle \otimes |00\rangle$$

$$|\Downarrow\rangle = |\downarrow\rangle \otimes |11\rangle$$

$$\hat{H} = \sum_i \left(\Omega \hat{\tau}_i^x + \Delta \hat{\tau}_i^z\right)$$

$$|\mathrm{GS}\rangle = \frac{1}{\mathcal{N}} \prod_i \left(u\,|\Uparrow\rangle_i + v\,|\Downarrow\rangle_i\right)$$



$$u = 1,\ v = -0.63$$

Overlap > 0.99

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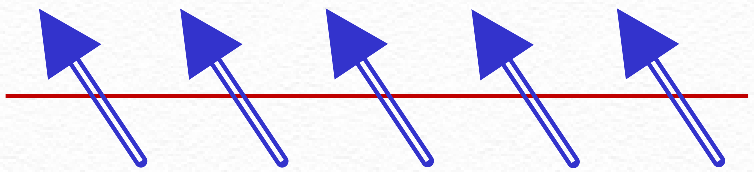
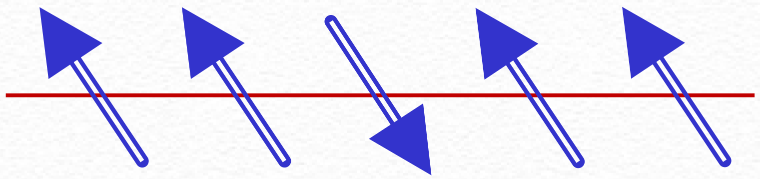
From Ground State to Excitations

Ferromagnetic
state of dressed spins

$|\mathrm{GS}\rangle =$ 

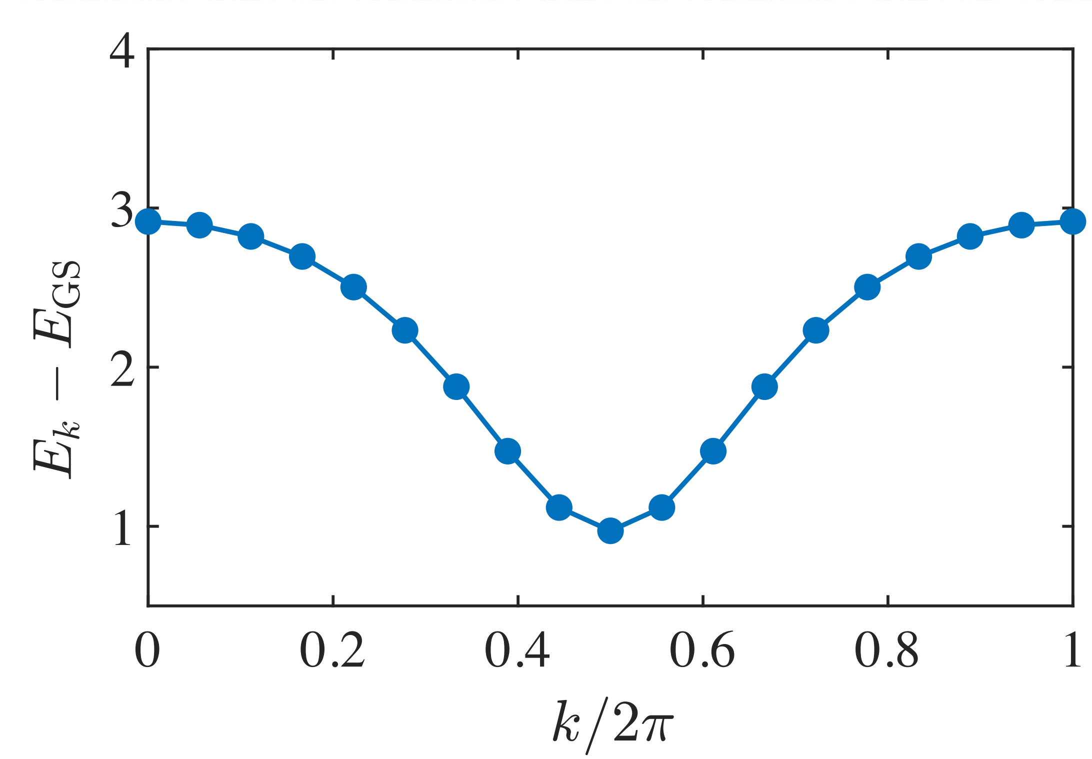
$\hat{\eta}_i^\dagger |\mathrm{GS}\rangle =$ 

$$\hat{\eta}_i^\dagger \left(u|\Uparrow\rangle_i + v|\Downarrow\rangle_i\right) = -v|\Uparrow\rangle_i + u|\Downarrow\rangle_i$$

Spin wave

$$\hat{\eta}_k^\dagger = \sum_i e^{ikR_i}\hat{\eta}_i^\dagger$$

$$\hat{\eta}_k^\dagger |G\rangle$$



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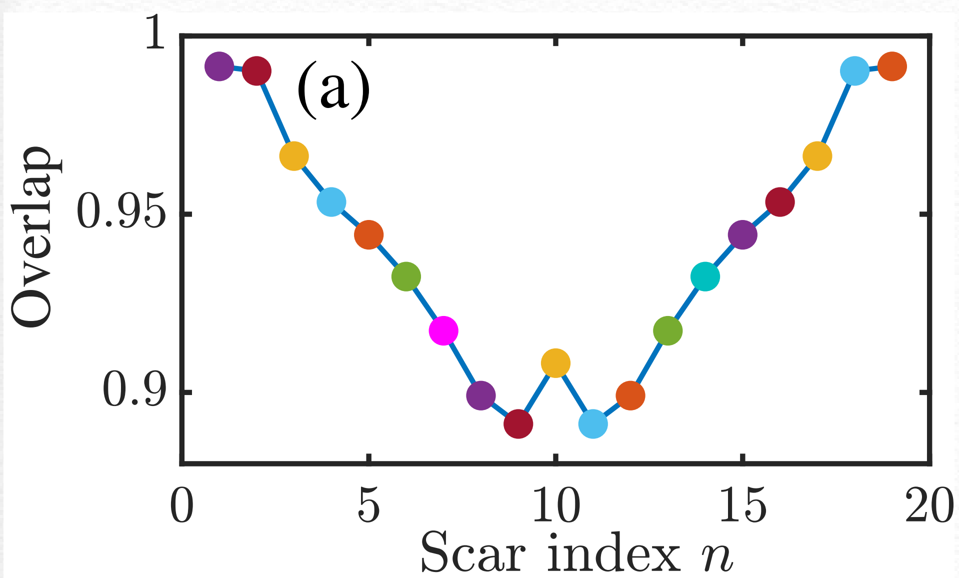
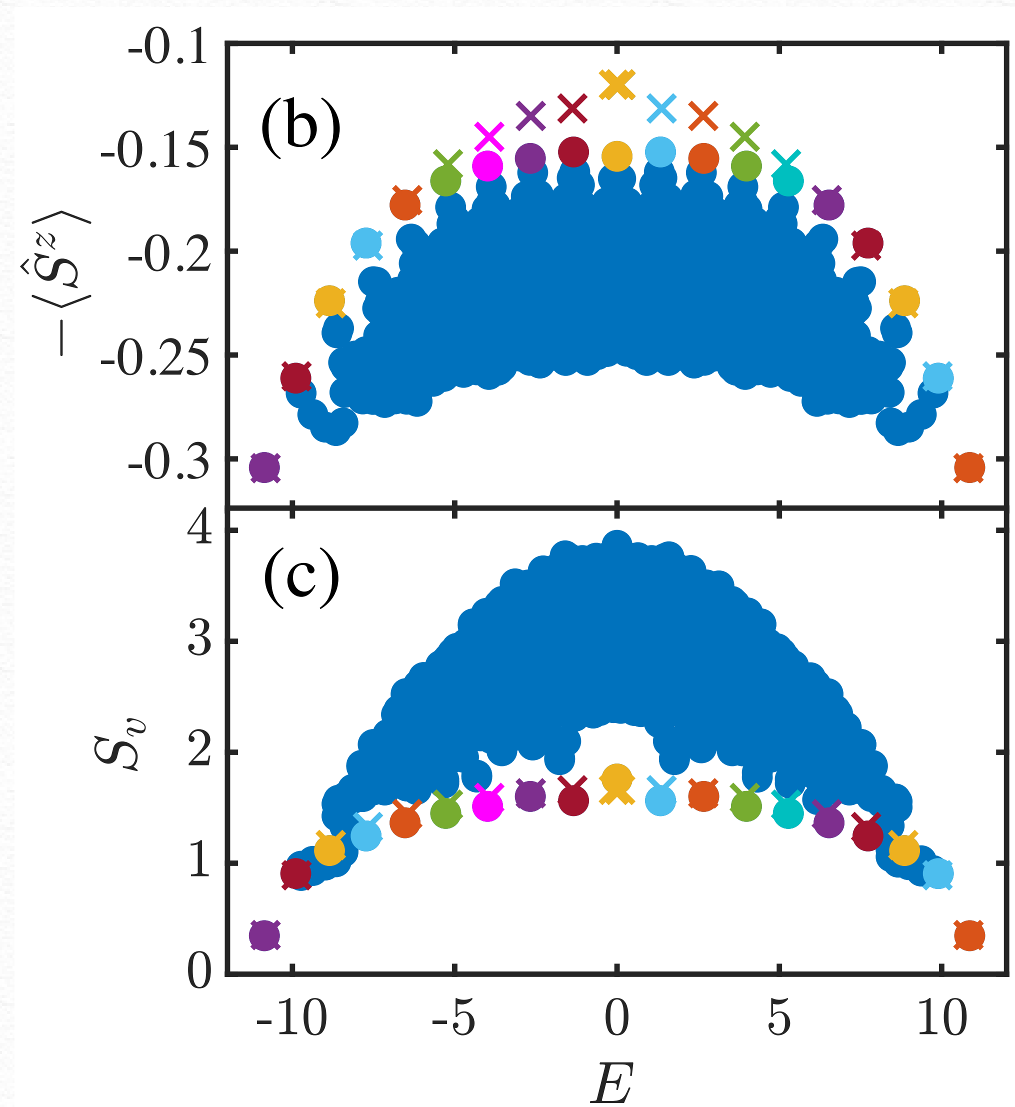
From Ground State to Excitations

$$\{|G\rangle, \quad \hat{\eta}_\pi^\dagger|G\rangle, \quad (\hat{\eta}_\pi^\dagger)^2|G\rangle, \quad (\hat{\eta}_\pi^\dagger)^2|G\rangle, \quad \ldots\}$$





without any fitting parameter

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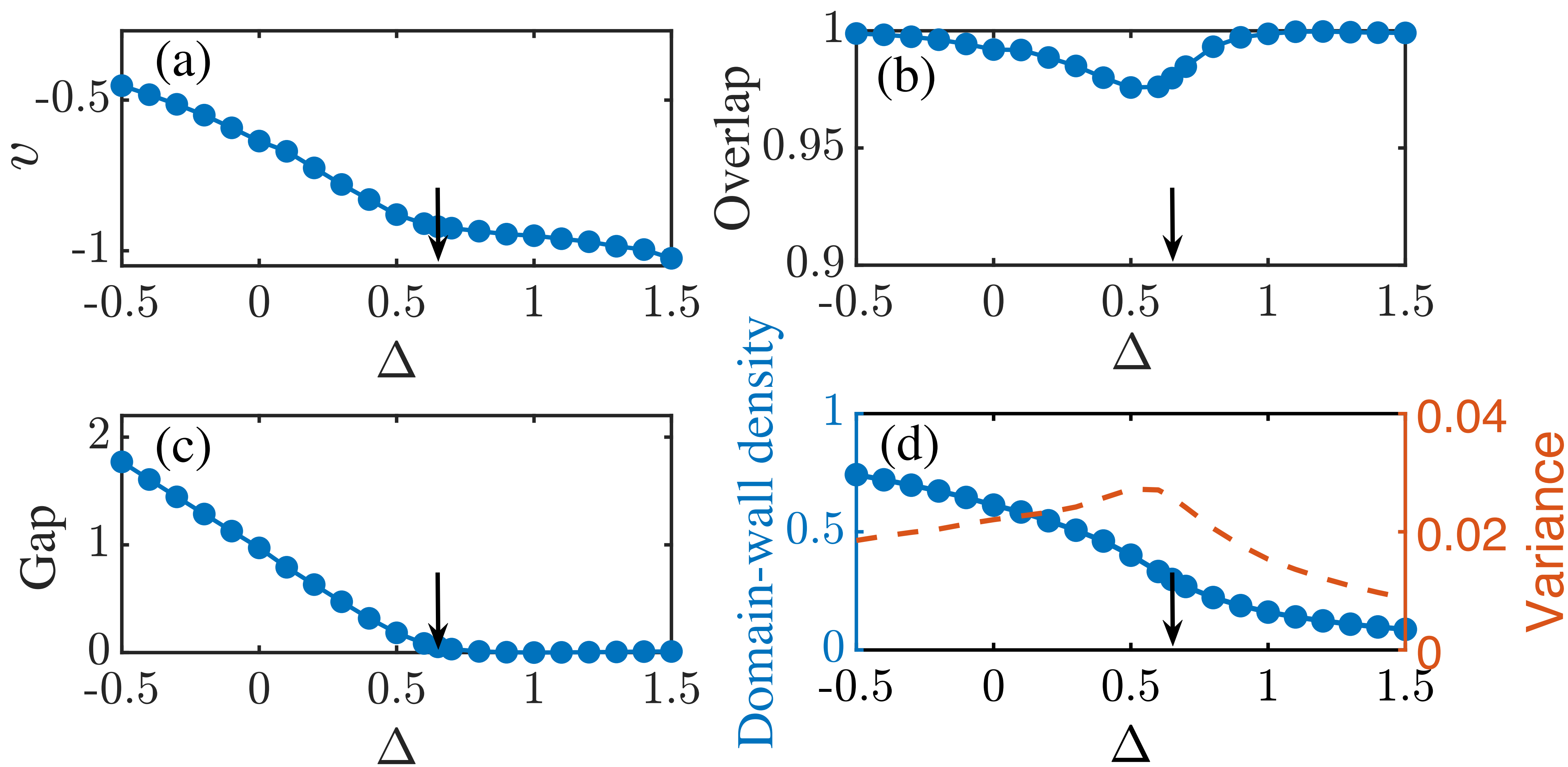
Quantum Phase Transition

$$\hat{H} = \Omega \sum_i P_{i-1} \hat{S}_i^x P_{i+1} - \Delta \hat{n}_i$$



Quantum phase transition

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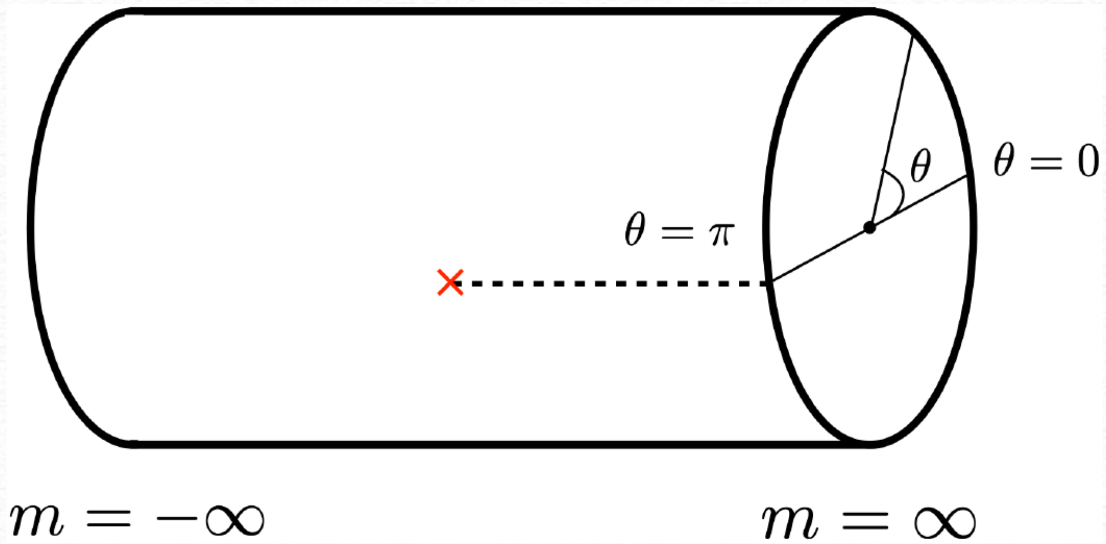
Physics in the PXP Model

1. Quantum Thermalization
2. Confinement-Deconfinement Transition

Topological Angle



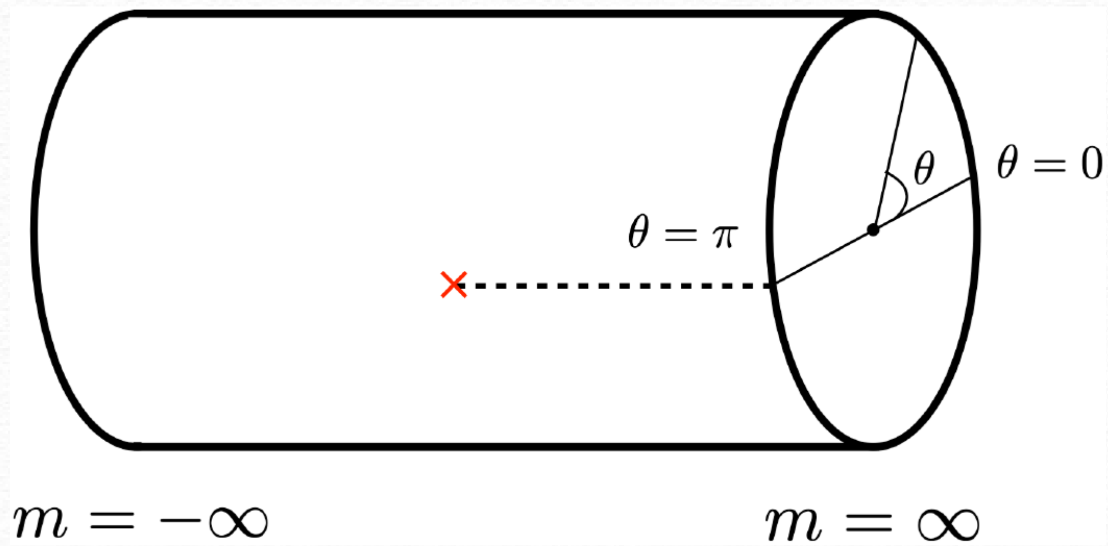
$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right]$$

Gauge-Matter Coupling

Mass of Matter Field

What is Missing ?

Topological Angle



$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right] + \frac{g^2}{2} \sum_l E^2_{l,l+1}$$

Gauge-Matter Coupling

Mass of Matter Field

Energy of Gauge Field

$$\boxed{E = i + \frac{\theta}{2\pi}, \;\; i \in Z}$$

$$E_{l-1,l} = (-1)^l S^z_{l-1,l}$$

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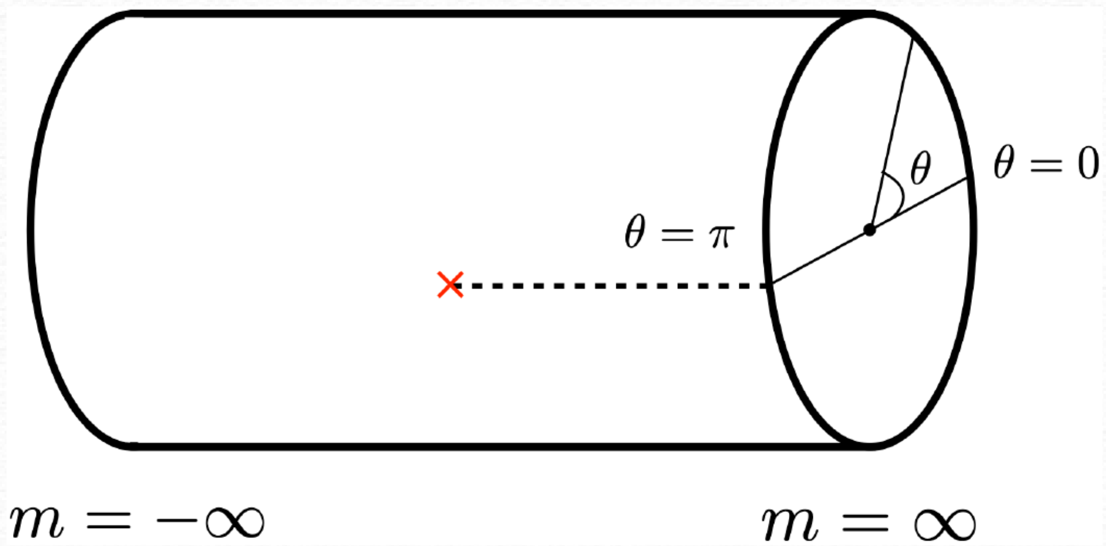
Topological Angle



$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^+_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right] + \frac{g^2}{2} \sum_l E^2_{l,l+1}$$

Gauge-Matter Coupling

Mass of Matter Field

Energy of Gauge Field

$$\boxed{E = i + \frac{\theta}{2\pi}, \ \ i \in Z}$$

$$\theta = \pi$$

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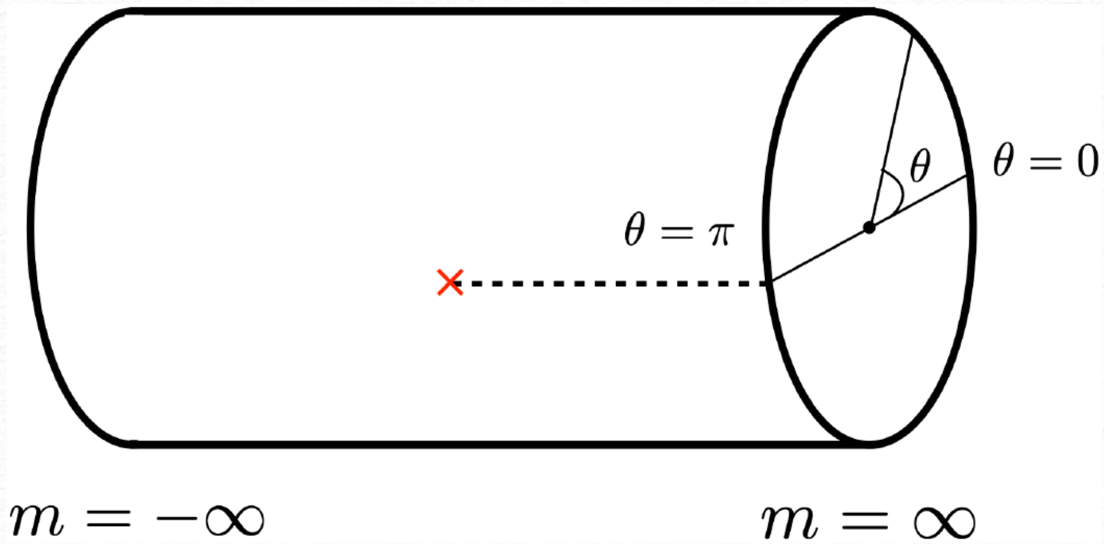
Topological Angle



$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^{+}_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right] + \frac{g^2}{2} \sum_l E^2_{l,l+1}$$

Gauge-Matter Coupling

Mass of Matter Field

Energy of Gauge Field

$$\boxed{E = i + \frac{\theta}{2\pi}, \quad i \in Z}$$

$$E_{l-1,l} = (-1)^l S^z_{l-1,l} + h \qquad \theta \neq \pi$$

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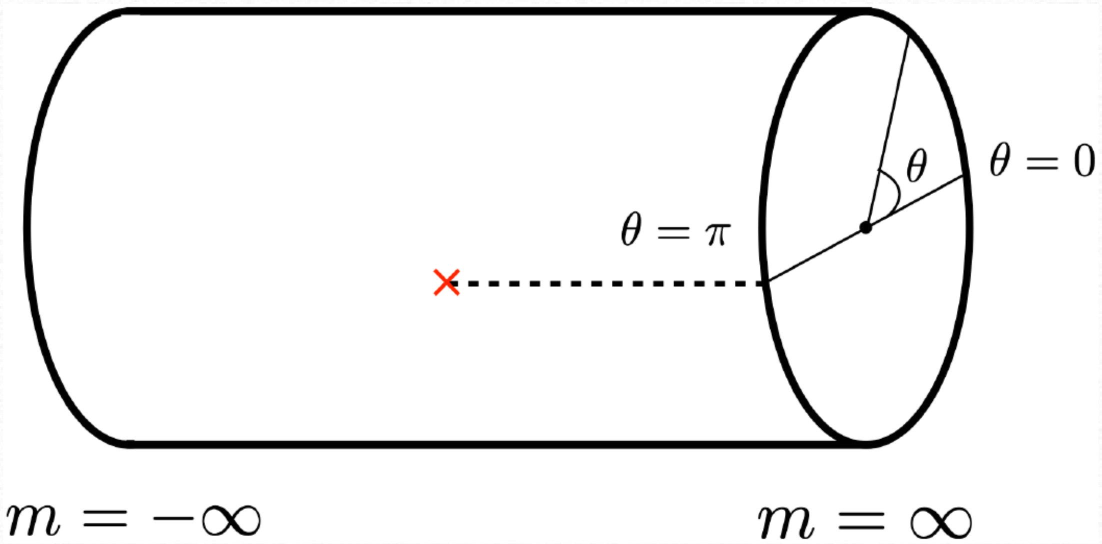
Topological Angle



$$\hat{H}_{\text{eff}} = \sum_l \left[-\frac{\tilde{J}}{2} \hat{S}^{+}_{l,l+1} \hat{b}_l \hat{b}_{l+1} + \text{h.c.} + m\hat{n}_l \right] + \frac{g^2}{2} \sum_l E^2_{l,l+1}$$

Gauge-Matter Coupling

Mass of Matter Field

Energy of Gauge Field

$$g \sum_l E^2_{l-1,l} = g \sum_l ((-1)^l S^z_{l-1,l} + h)^2 \Rightarrow gh \sum_l (-1)^l S^z_{l-1,l}$$

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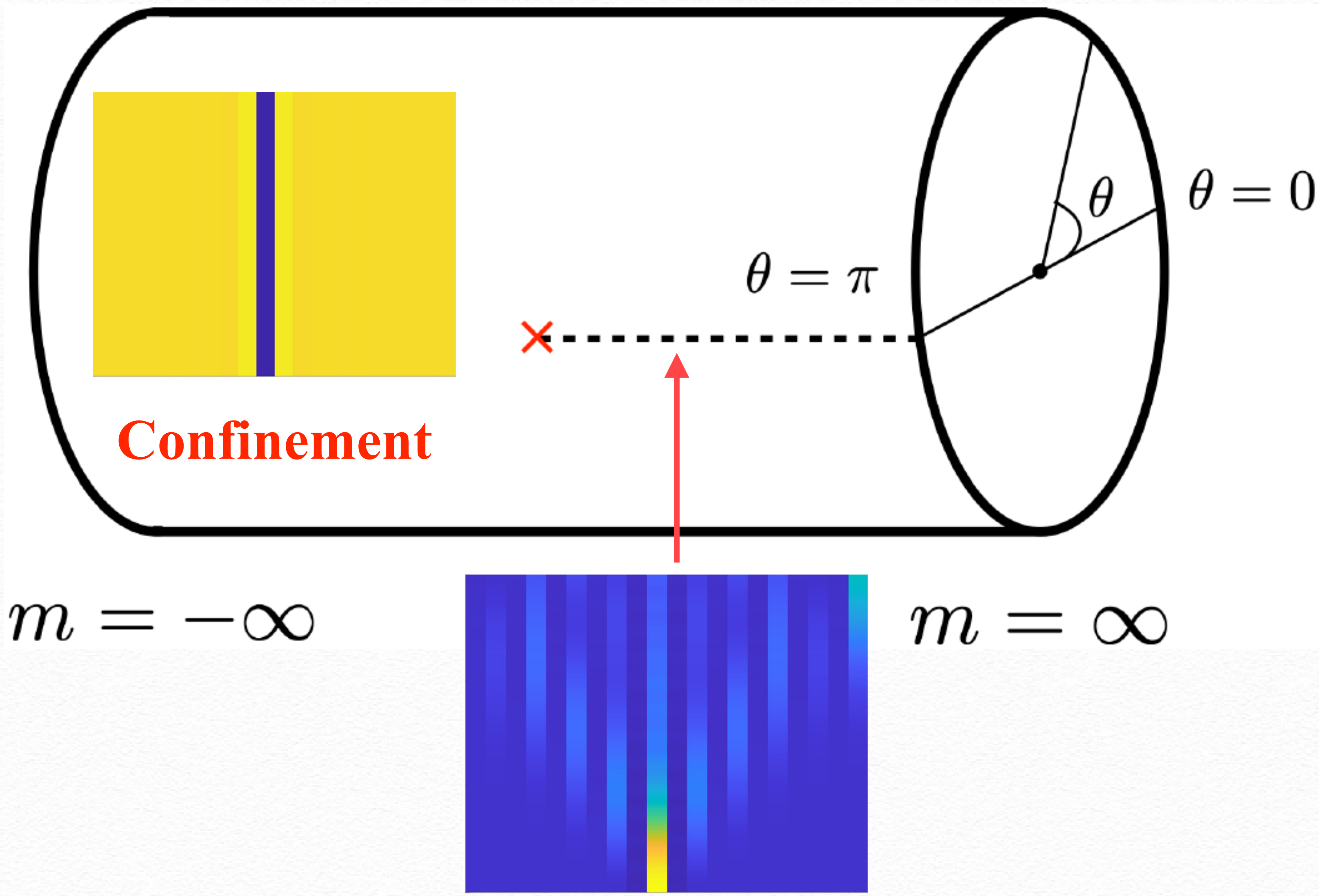
Probe Confinement-Deconfinement



Deconfinement

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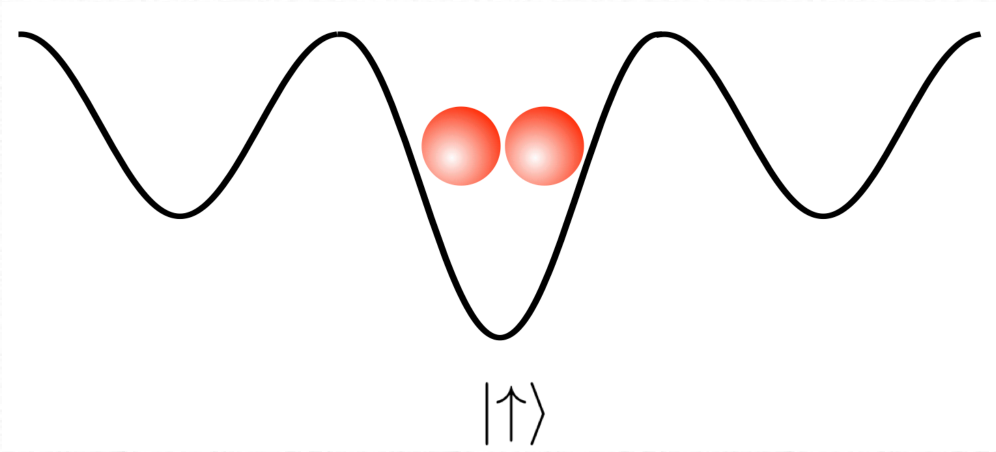
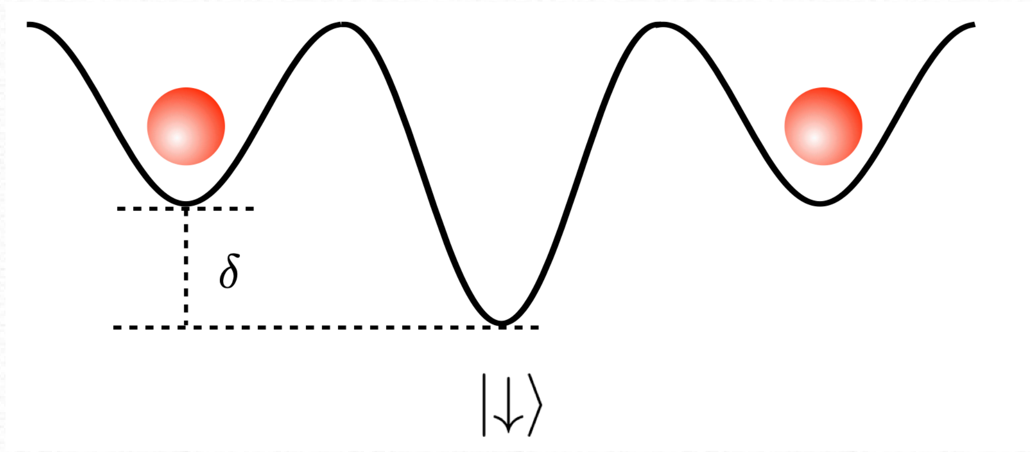
Confinement-Deconfinement Transition





$$Q_l = (-1)^l n_l$$

Produce an electron-positron pair

$$\mathcal{G}(r,t) = \sum_l \langle \Psi(t)|(\hat{n}_l - \bar{n}_l)(\hat{n}_{l+r} - \bar{n}_{l+r})|\Psi(t)\rangle$$

$$\boxed{G_l = S^z_{l-1,l} + S^z_{l,l+1} + n_l}$$

$$\hat{G}_l = 0 \Rightarrow \hat{n}_l - \bar{n}_l = -\hat{S}^z_{l-1,l} - \hat{S}^z_{l,l+1} + \bar{S}^z_{l-1,l} + \bar{S}^z_{l,l+1}$$

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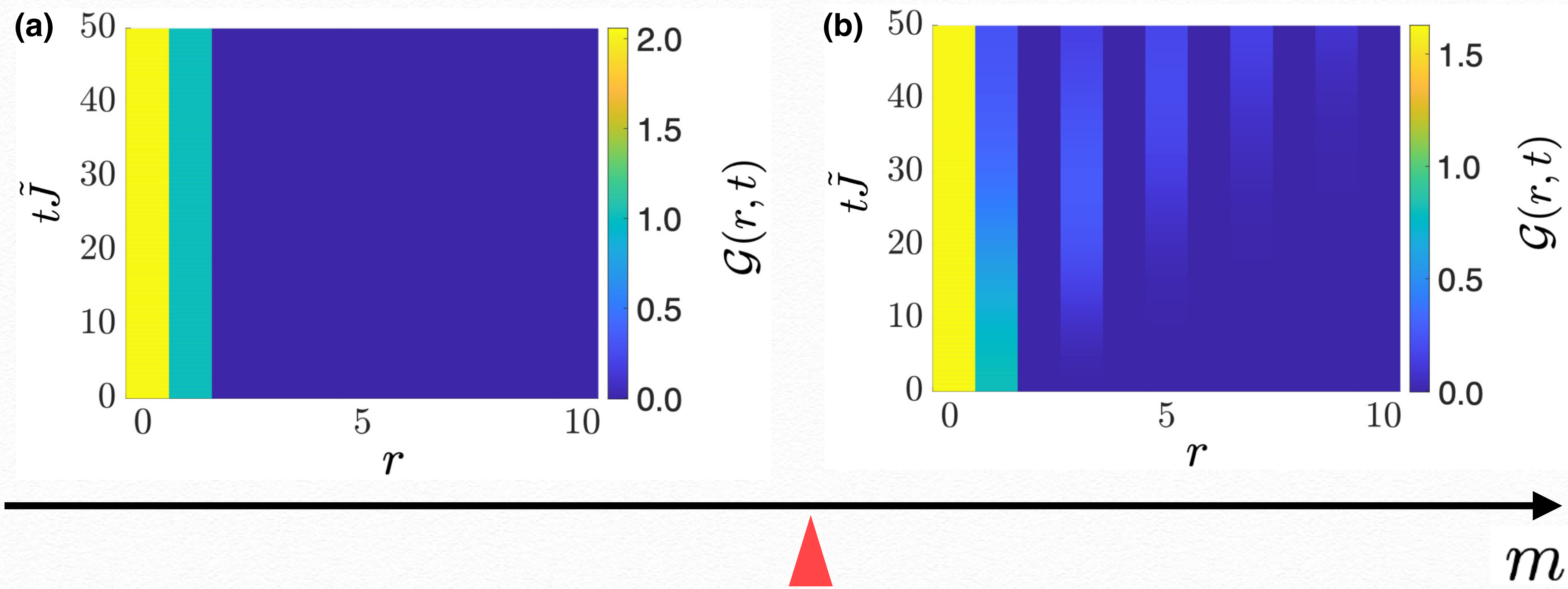
Confinement-Deconfinement in the PXP Model

$$\hat{A}_l = -\hat{S}^z_{l-1,l} - \hat{S}^z_{l,l+1} + \bar{S}^z_{l-1,l} + \bar{S}^z_{l,l+1}$$

$$\mathcal{G}(r,t) = \sum_l \langle \Psi(t) | \hat{A}_l \hat{A}_{l+r} | \Psi(t) \rangle$$



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Physics in the PXP Model

1. Quantum Thermalization
2. Confinement-Deconfinement Transition
3. Quantum Spin Liquid

Quantum Spin Liquid with Rydberg Atom Arrays

RESEARCH

TOPOLOGICAL MATTER

Probing topological spin liquids on a programmable quantum simulator

G. Semeghini[1], H. Levine[1], A. Keesling[1,2], S. Ebadi[1], T. T. Wang[1], D. Bluvstein[1], R. Verresen[1], H. Pichler[3,4], M. Kalinowski[1], R. Samajdar[1], A. Omran[1,2], S. Sachdev[1,5], A. Vishwanath[1]*, M. Greiner[1]*, V. Vuletić[6]*, M. D. Lukin[1]*

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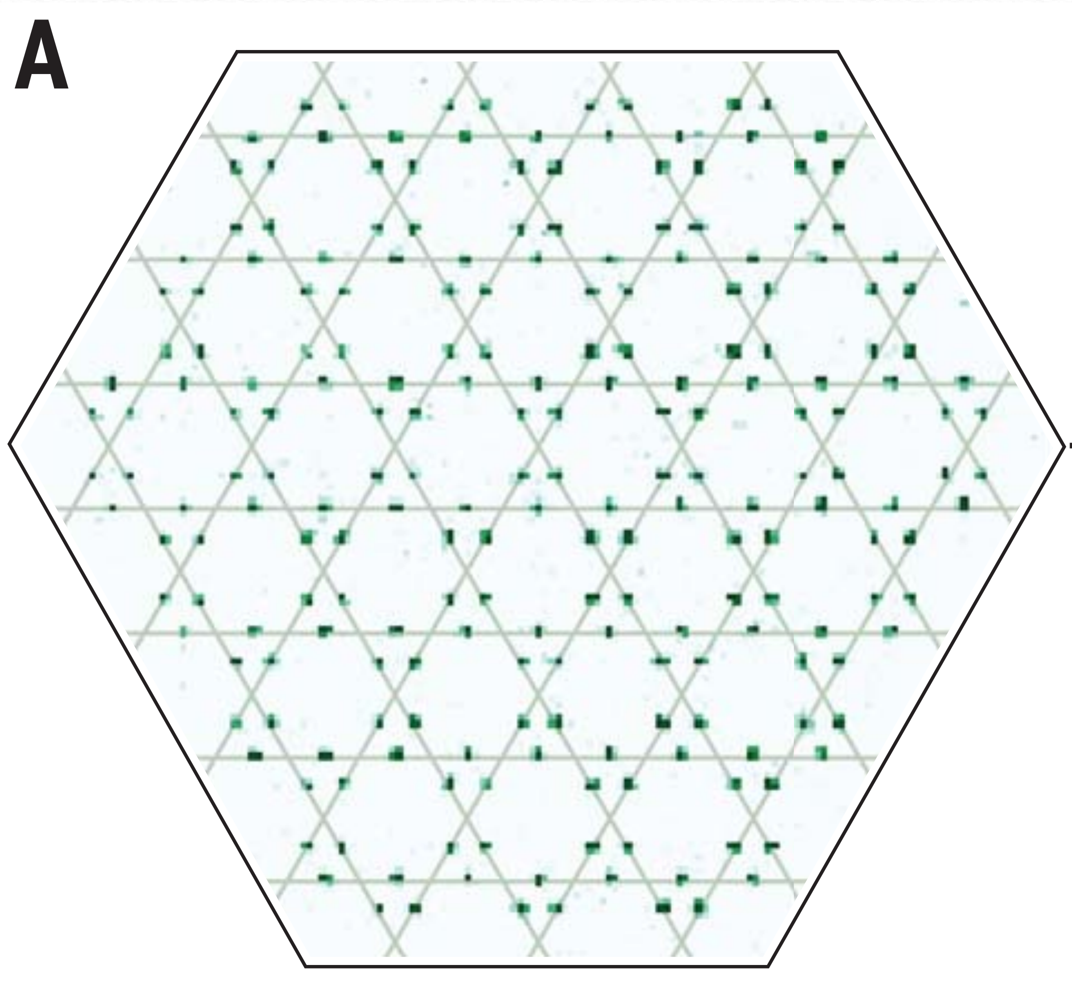
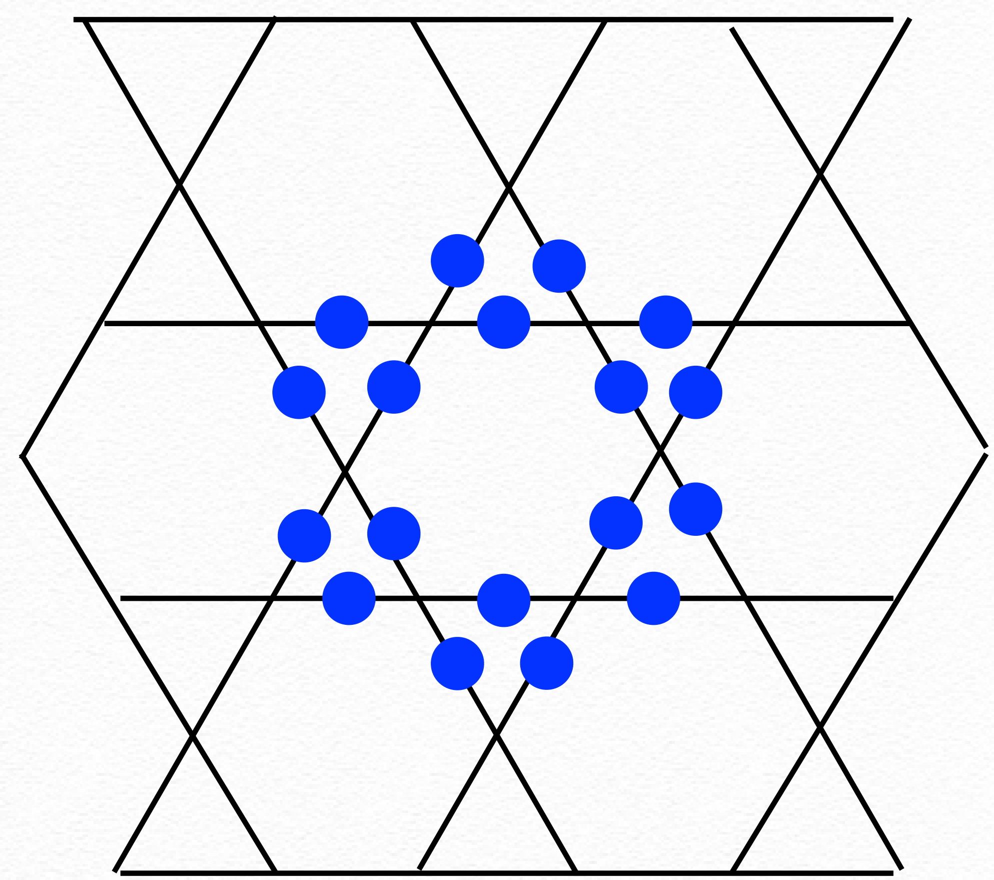
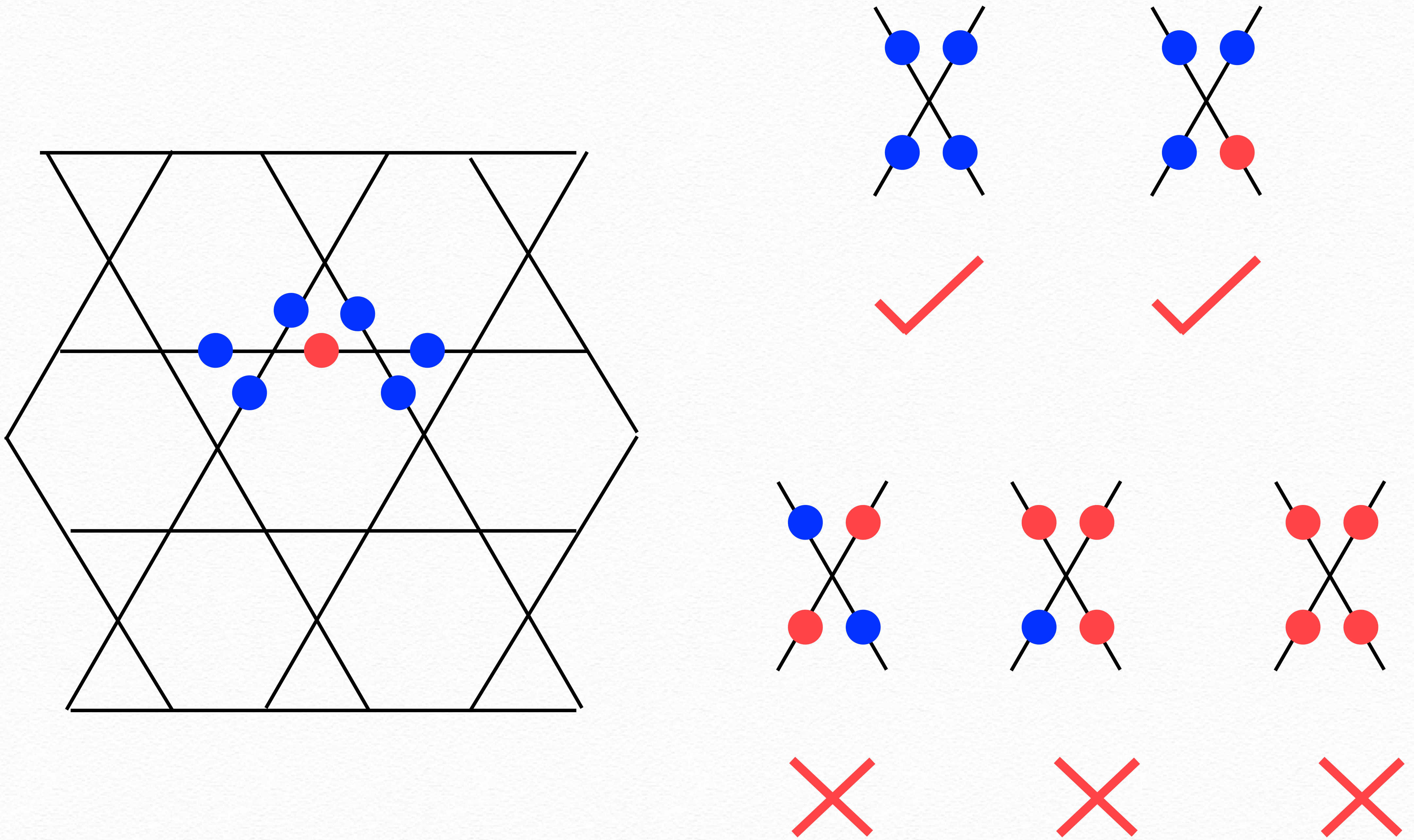
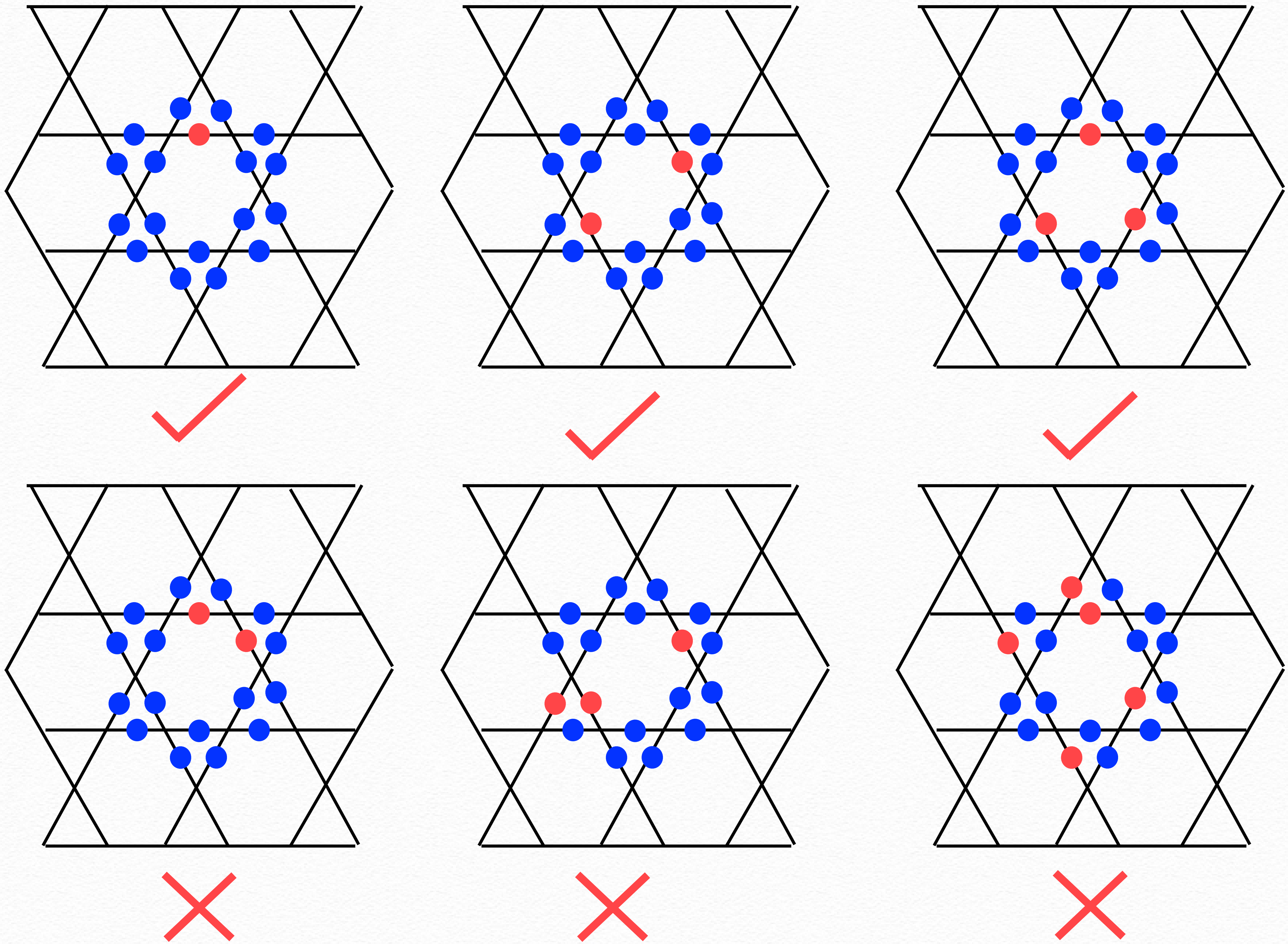




Rydberg Blockade



Rydberg Blockade



Quantum Spin Liquid in Rydberg Atom Arrays

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G. Semeghini[1], H. Levine[1], A. Keesling[1,2], S. Ebadi[1], T. T. Wang[1], D. Bluvstein[1], R. Verresen[1], H. Pichler[3,4], M. Kalinowski[1], R. Samajdar[1], A. Omran[1,2], S. Sachdev[1,5], A. Vishwanath[1]*, M. Greiner[1]*, V. Vuletić[6]*, M. D. Lukin[1]*

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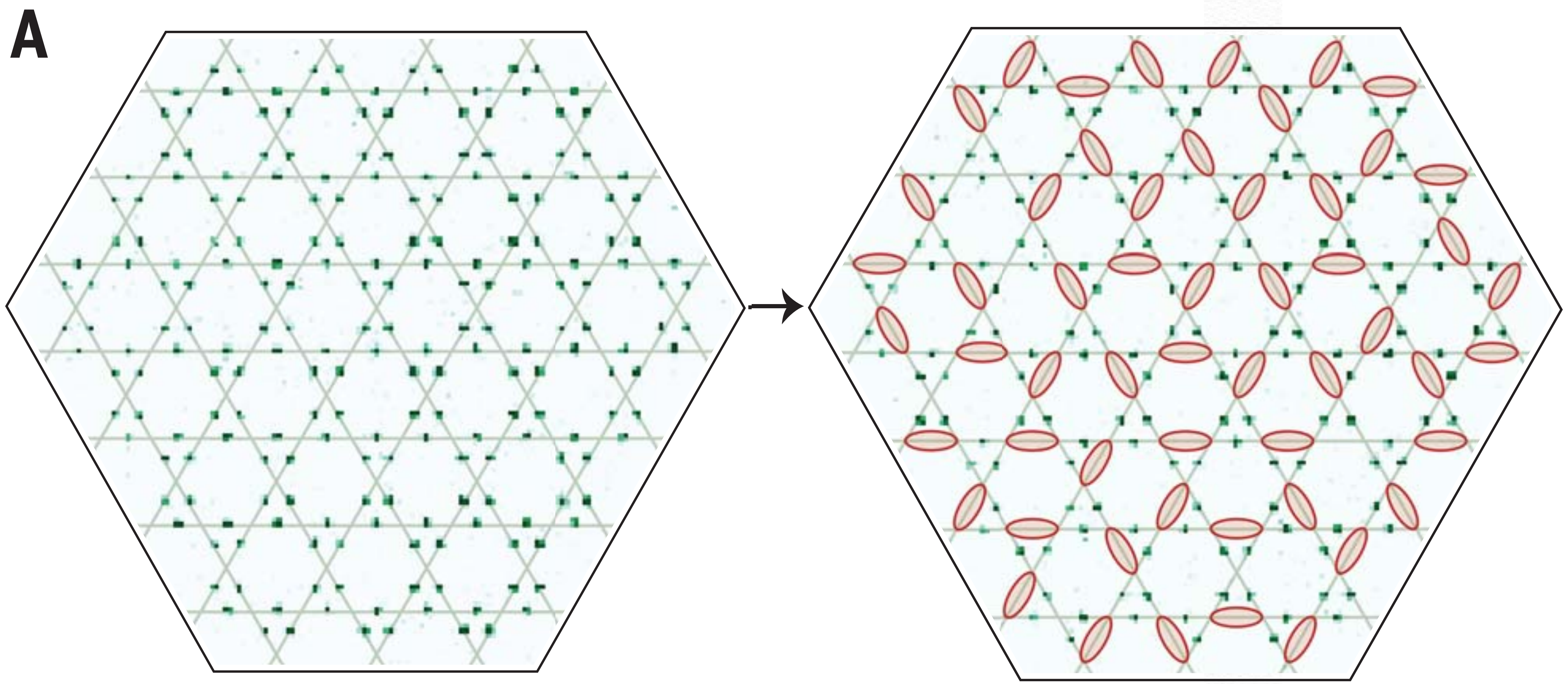
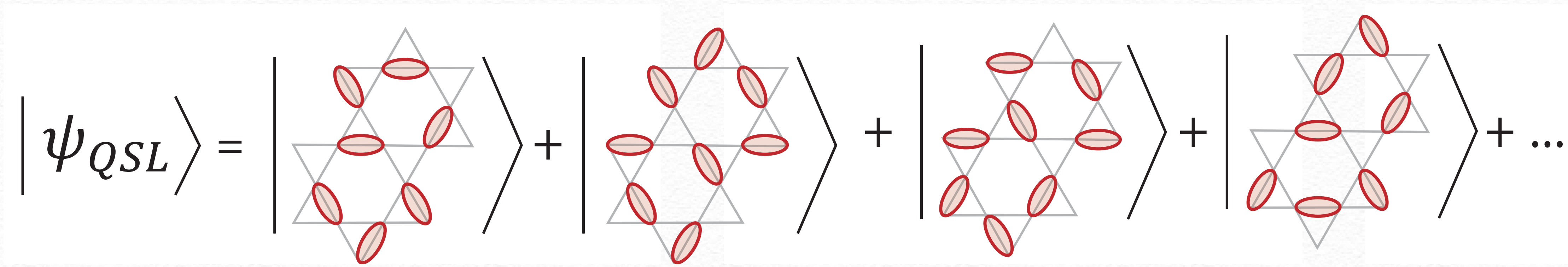
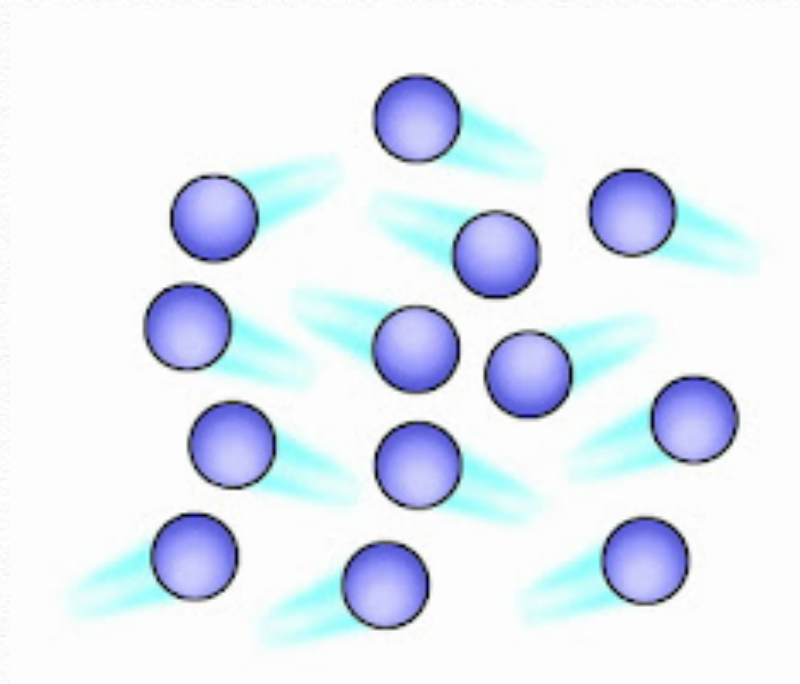


Quantum Spin Liquid

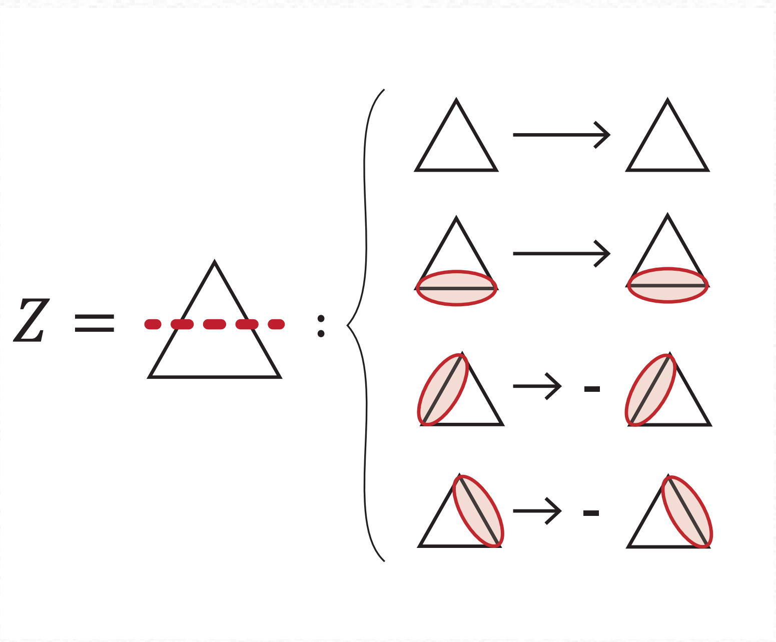


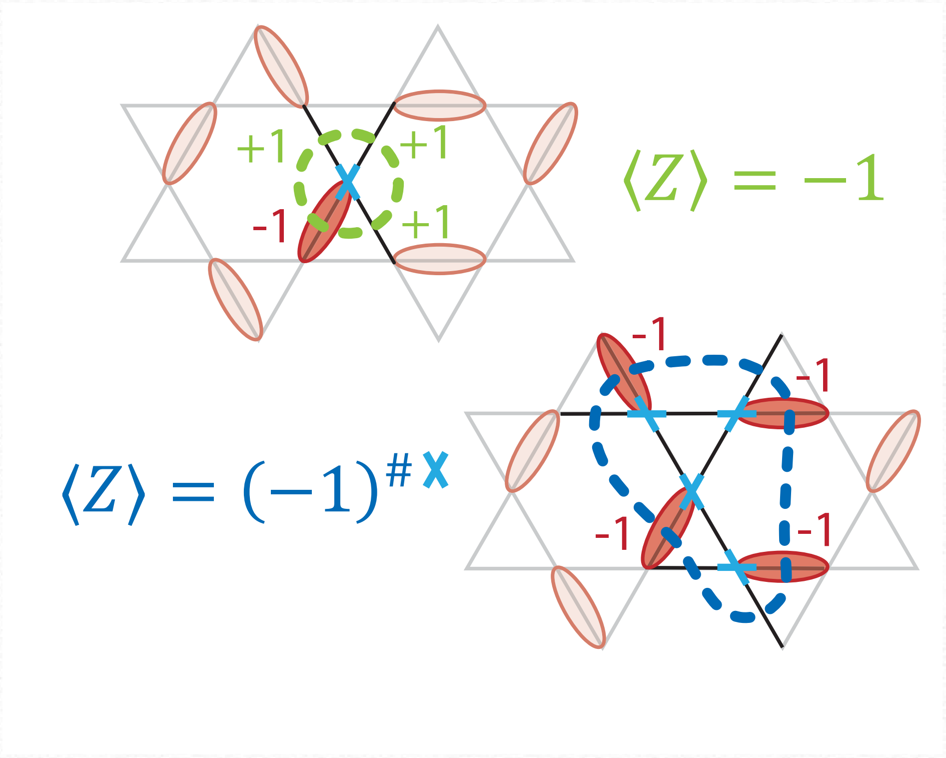
Spin Liquid: A quantum superposition of exponentially many spin configurations.



Quantum Spin Liquid

Advantage of Quantum Simulator:
Direct Probe Topological Order (= Long Rang Coherence)

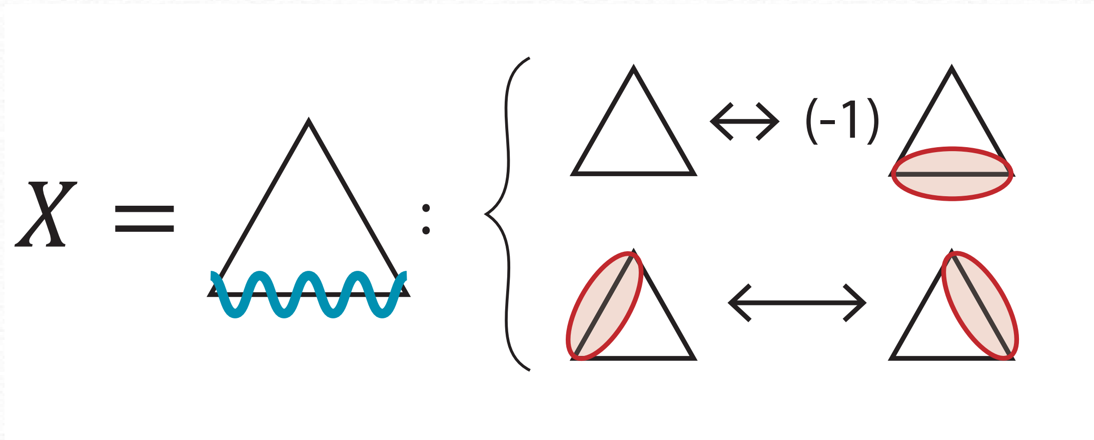


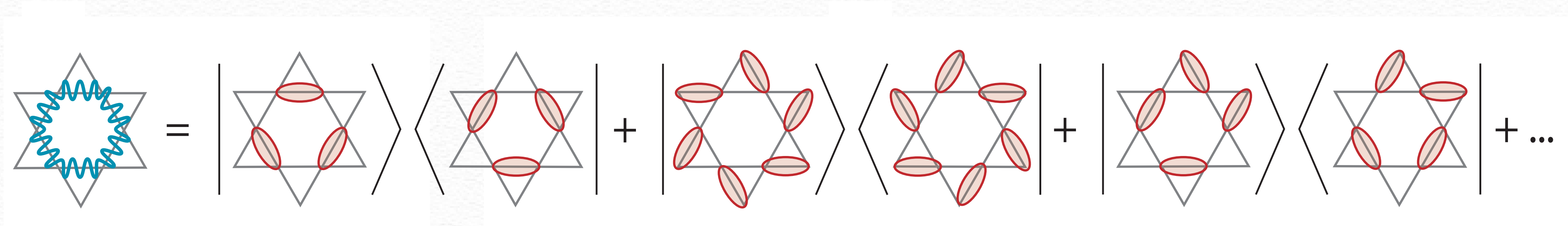


Number Parity of Rydberg Atoms along the Loop

Quantum Spin Liquid

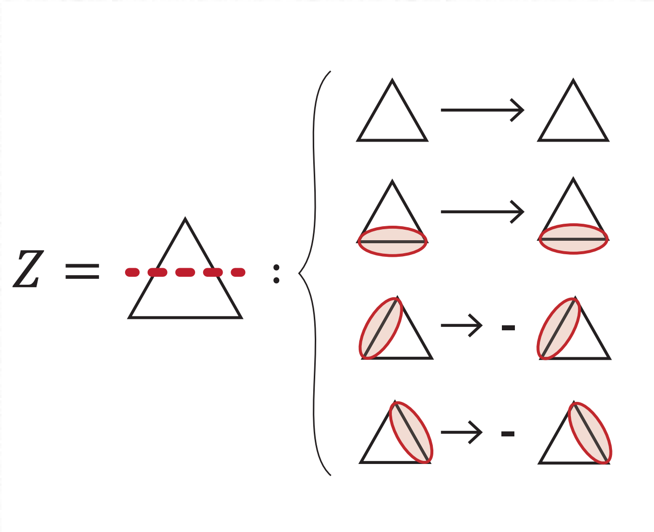
Advantage of Quantum Simulator:
Direct Probe Topological Order (= Long Rang Coherence)

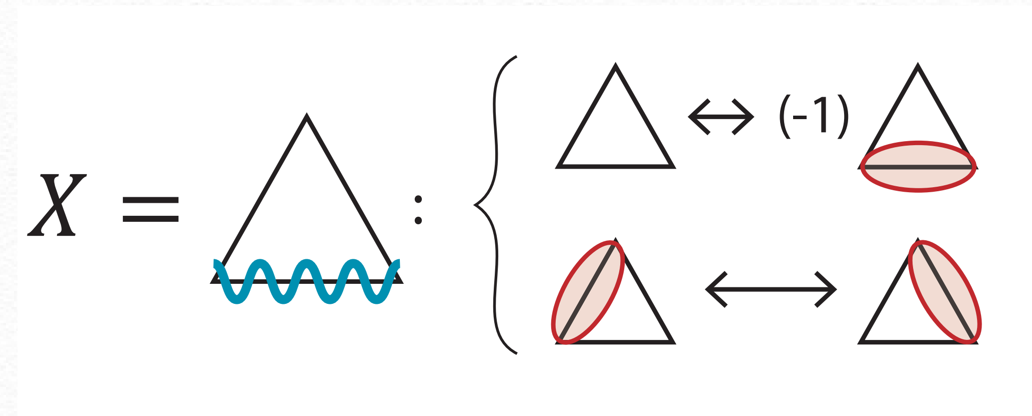


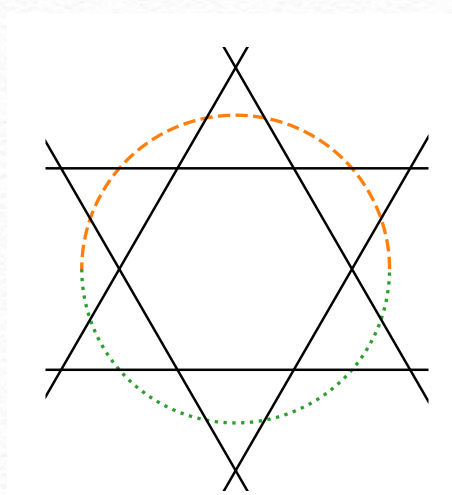


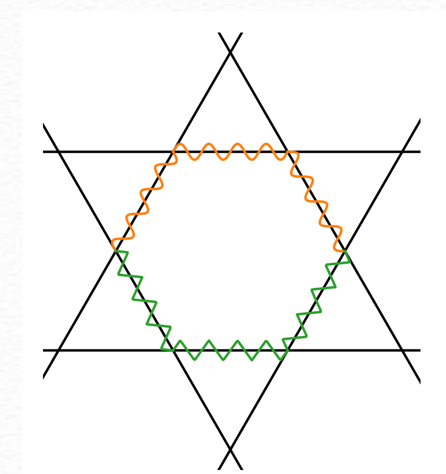
Coherence between Different Configurations

Quantum Spin Liquid









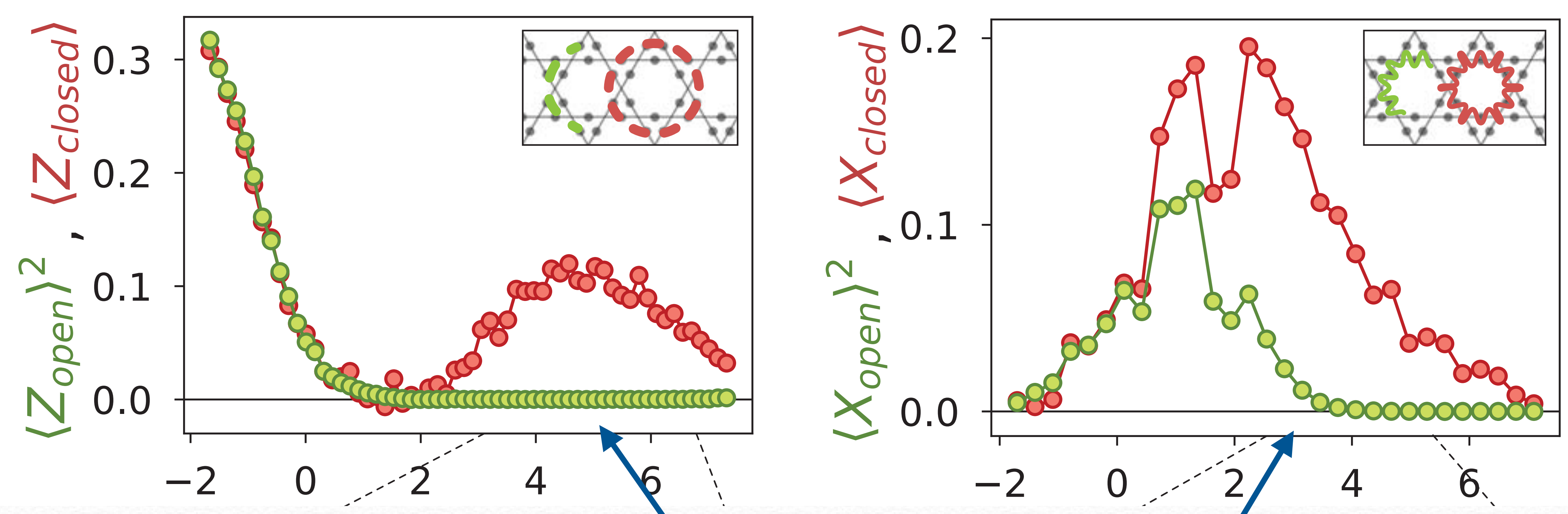
$$\hat{Z}_{\text{close}} = \hat{Z}_{\text{open1}}\hat{Z}_{\text{open2}}$$

$$\langle \hat{Z}_{\text{close}} \rangle \overset{?}{=} \langle \hat{Z}_{\text{open}} \rangle^2$$

$$\hat{X}_{\text{close}} = \hat{X}_{\text{open1}}\hat{X}_{\text{open2}}$$

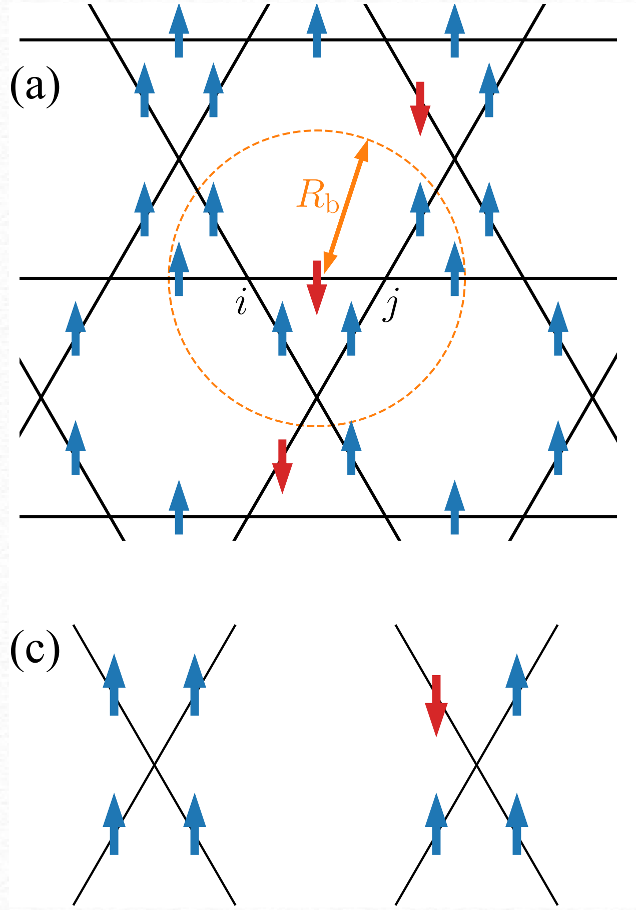
$$\langle \hat{X}_{\text{close}} \rangle \overset{?}{=} \langle \hat{X}_{\text{open}} \rangle^2$$

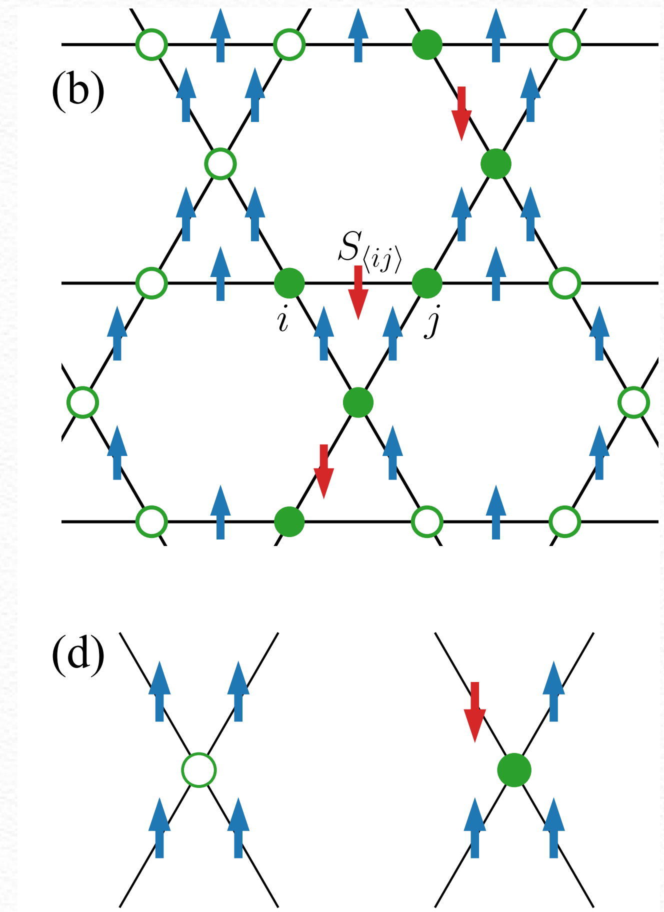
Quantum Spin Liquid



Evidence of Quantum Spin Liquid

PXP = Gauge Theory





$$\hat{H}_{\mathrm{RB}} = \sum_{\langle ij \rangle} -\Omega \hat{S}^{x}_{\langle ij \rangle} - \Delta \hat{n}_{\langle ij \rangle}$$

$$\sum_{j \in X_i} S^{z}_{\langle ij \rangle} \geqslant 1$$

Constraint (inequality)

$$\hat{H}_{\mathrm{LGT}} = \sum_{\langle ij \rangle} -\Omega \left(\hat{S}^{-}_{\langle ij \rangle} \hat{f}^{\dagger}_{i} \hat{f}^{\dagger}_{j} + \mathrm{h.c.} \right) - \Delta \hat{n}_{\langle ij \rangle}$$

$$Q_i = \sum_{j \in X_i} S^{z}_{\langle ij \rangle} + n^{f}_{i} = 2$$

Constraint (equality)

Quantum Many-Body State of Spin Liquid

$$\hat{H}_{\mathrm{LGT}} = \sum_{\langle ij \rangle} -\Omega \left(\hat{S}^{-}_{\langle ij \rangle} \hat{f}^{\dagger}_i \hat{f}^{\dagger}_j + \mathrm{h.c.} \right) - \Delta \hat{n}_{\langle ij \rangle}$$

$$|\mathrm{QSL}\rangle = \frac{1}{\mathcal{N}} \prod_{\langle ij \rangle} \left(u + v \hat{f}^{\dagger}_i \hat{f}^{\dagger}_j \hat{S}^{-}_{\langle ij \rangle} \right) |\mathrm{vac}\rangle$$

$$|\mathrm{vac}\rangle = |0\rangle \otimes |\uparrow\rangle^{\otimes N}$$

- Very efficient way to represent superposition
- Recover two limits of positive and negative detuning
- Automatically satisfy the constraint
- BCS wave function possesses Z2 topological order

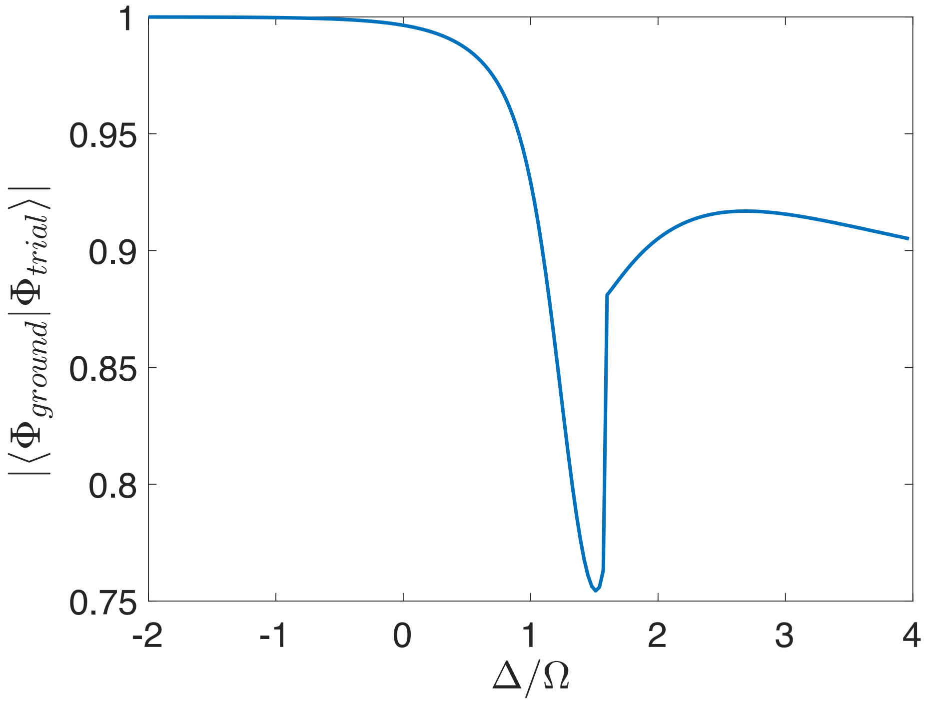
Yanting Cheng, Chengshu Li and HZ, arXiv 2021

Quantum Many-Body State of Spin Liquid

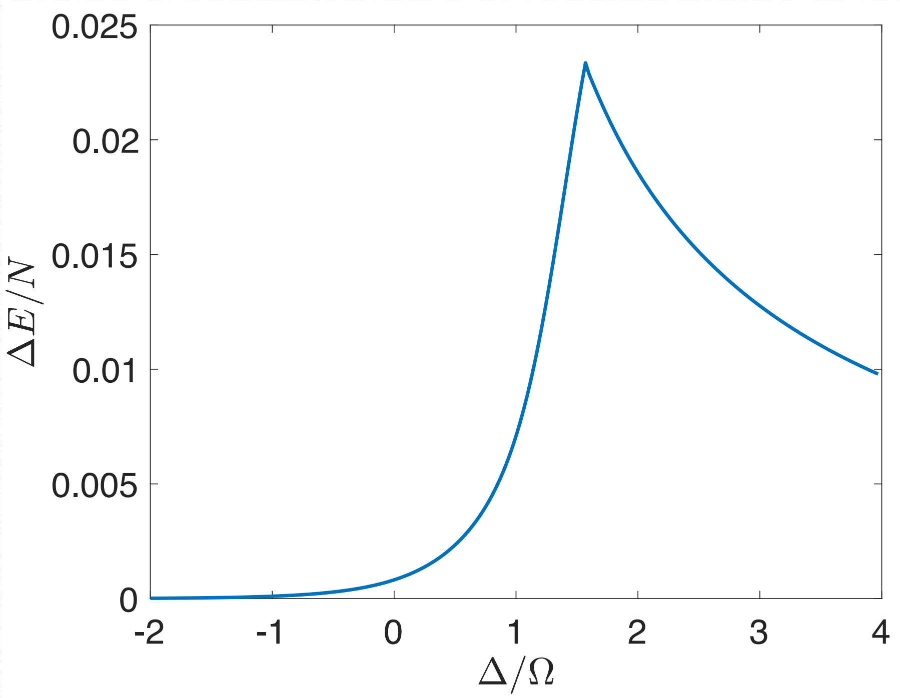
$$|\mathrm{QSL}\rangle = \frac{1}{\mathcal{N}} \prod_{\langle ij \rangle} \left(u + v \hat{f}_i^\dagger \hat{f}_j^\dagger \hat{S}^-_{\langle ij \rangle} \right) |\mathrm{vac}\rangle$$

$$|\mathrm{vac}\rangle = |0\rangle \otimes |\uparrow\rangle^{\otimes N}$$

Comparing with exact diagonalization



Wave function overlap



Energy difference

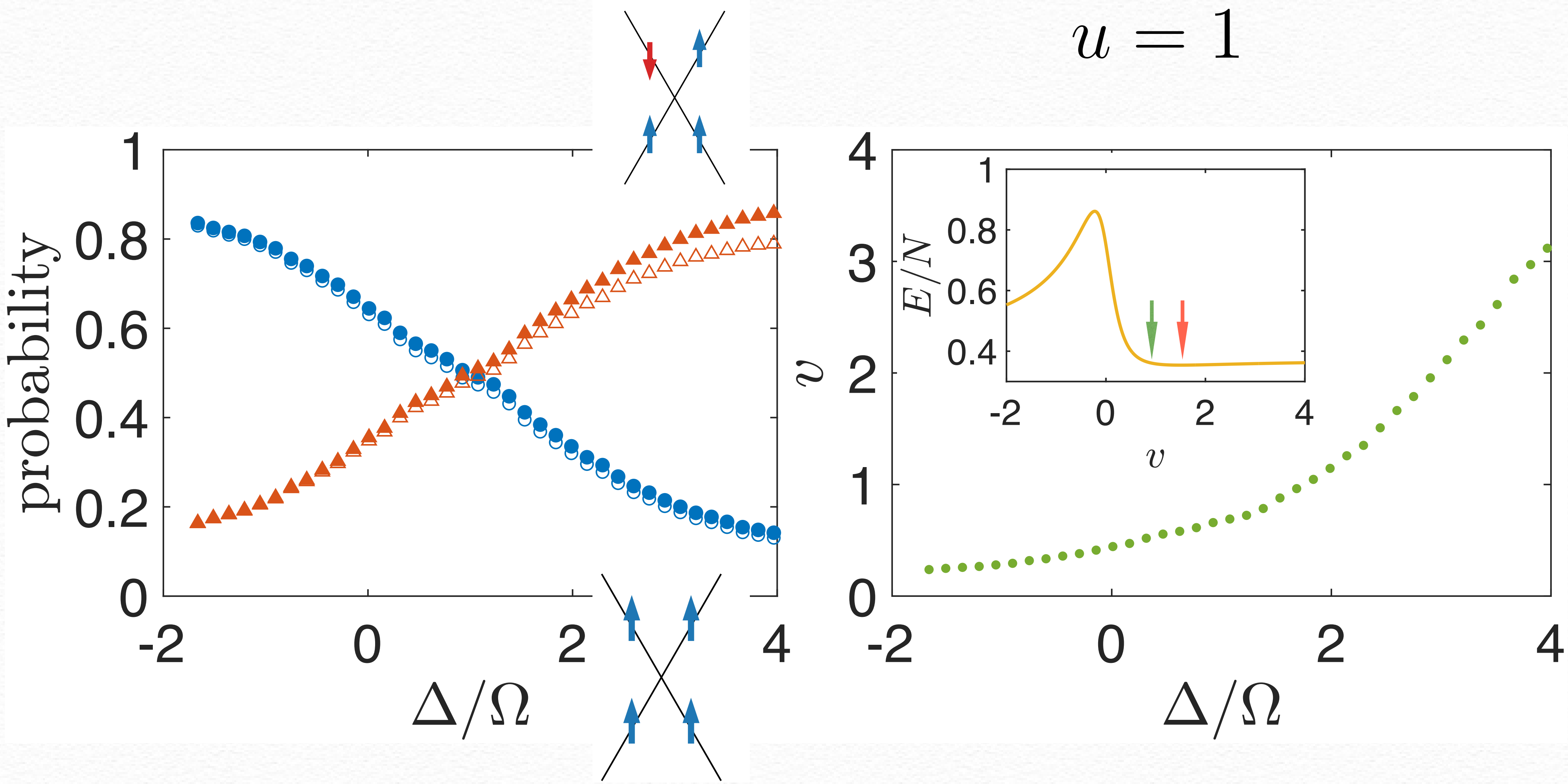
Yanting Cheng, Chengshu Li and HZ, arXiv 2021

Quantum Many-Body State of Spin Liquid

$$|\mathrm{QSL}\rangle = \frac{1}{\mathcal{N}} \prod_{\langle ij \rangle} \left(u + v \hat{f}_i^\dagger \hat{f}_j^\dagger \hat{S}^-_{\langle ij \rangle} \right) |\mathrm{vac}\rangle$$

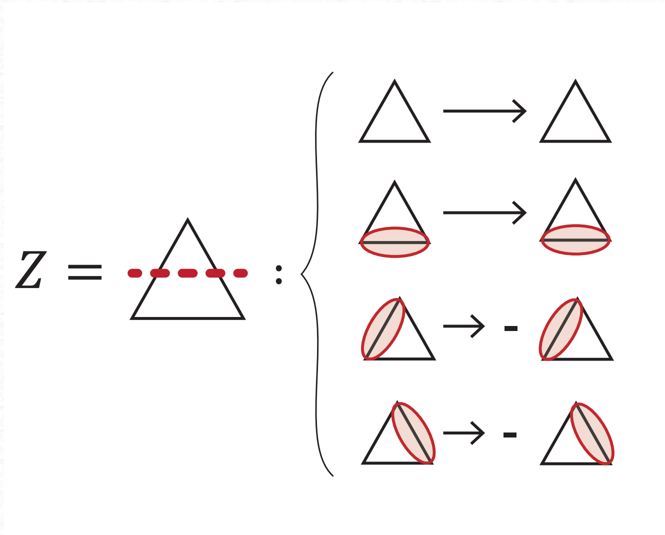
$$|\mathrm{vac}\rangle = |0\rangle \otimes |\uparrow\rangle^{\otimes N}$$

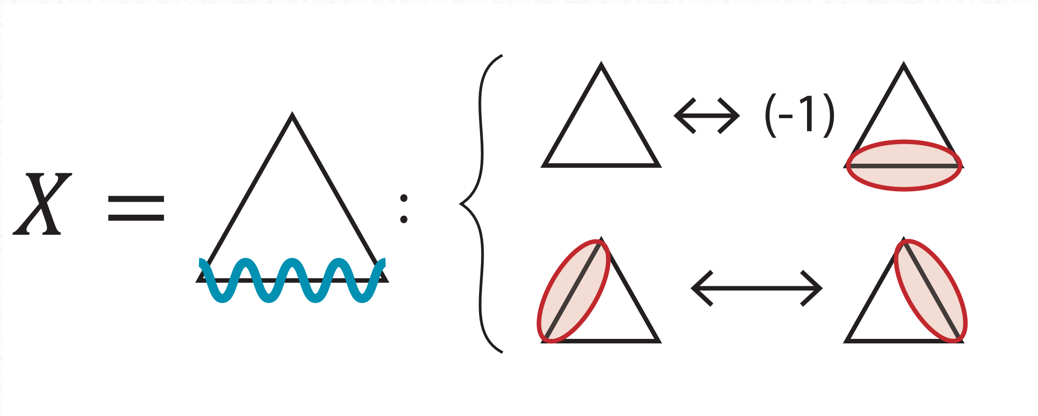
$$u = 1$$

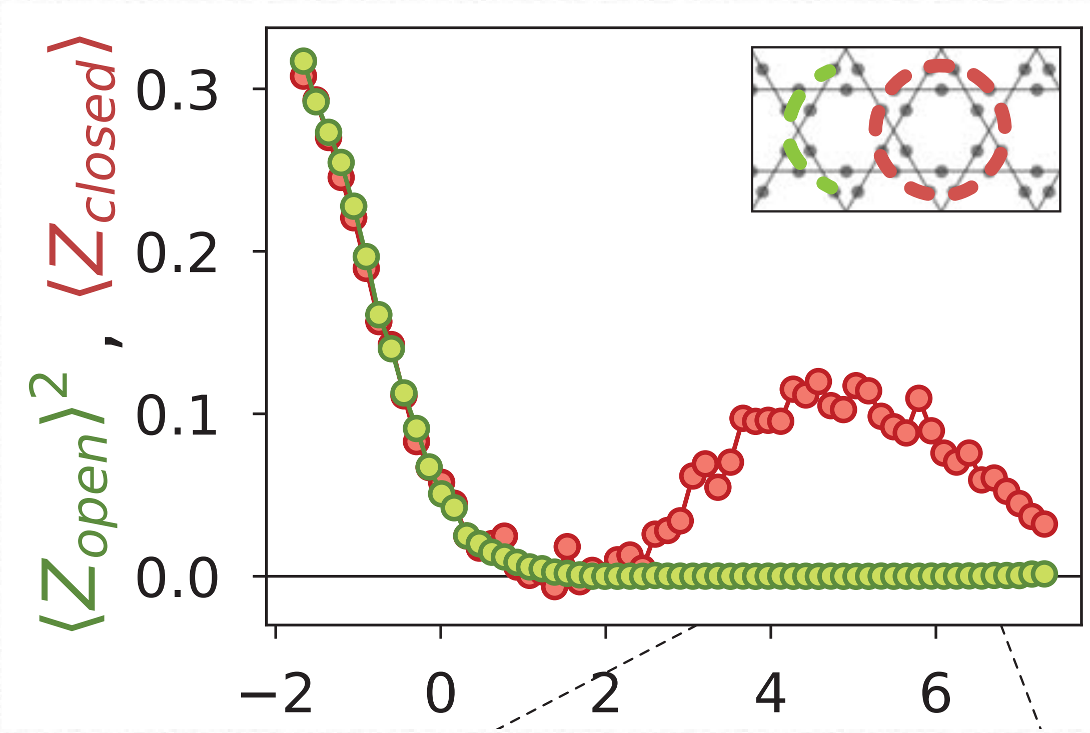


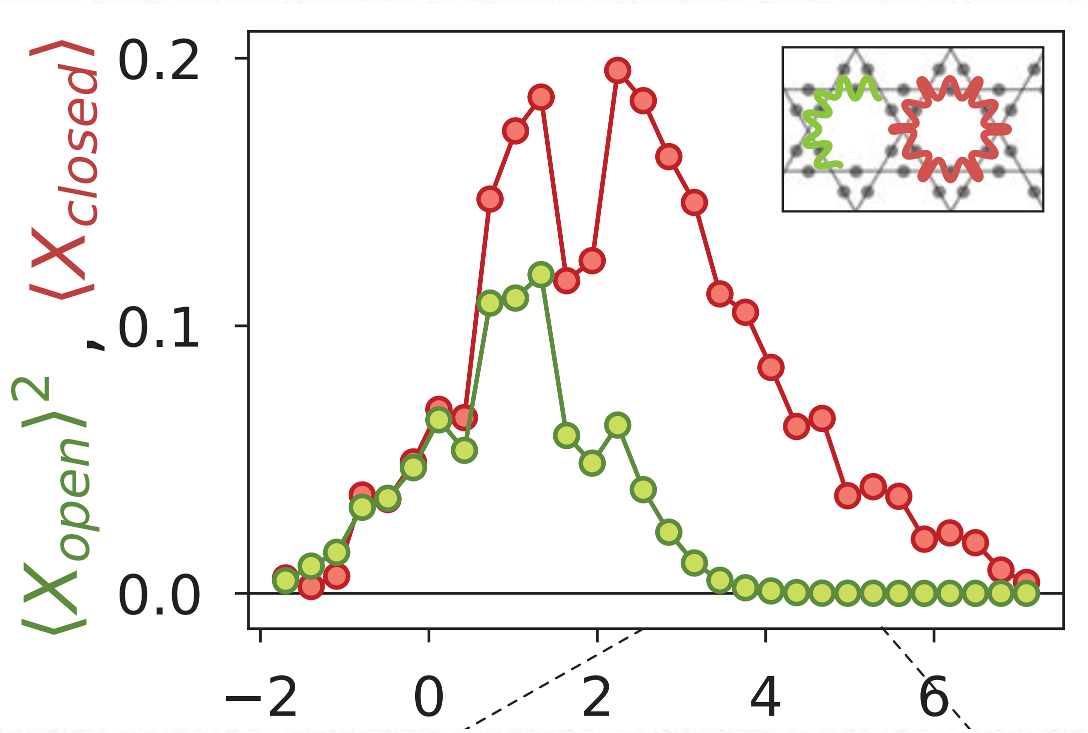
Yanting Cheng, Chengshu Li and HZ, arXiv 2021

Evidence of Quantum Spin Liquid



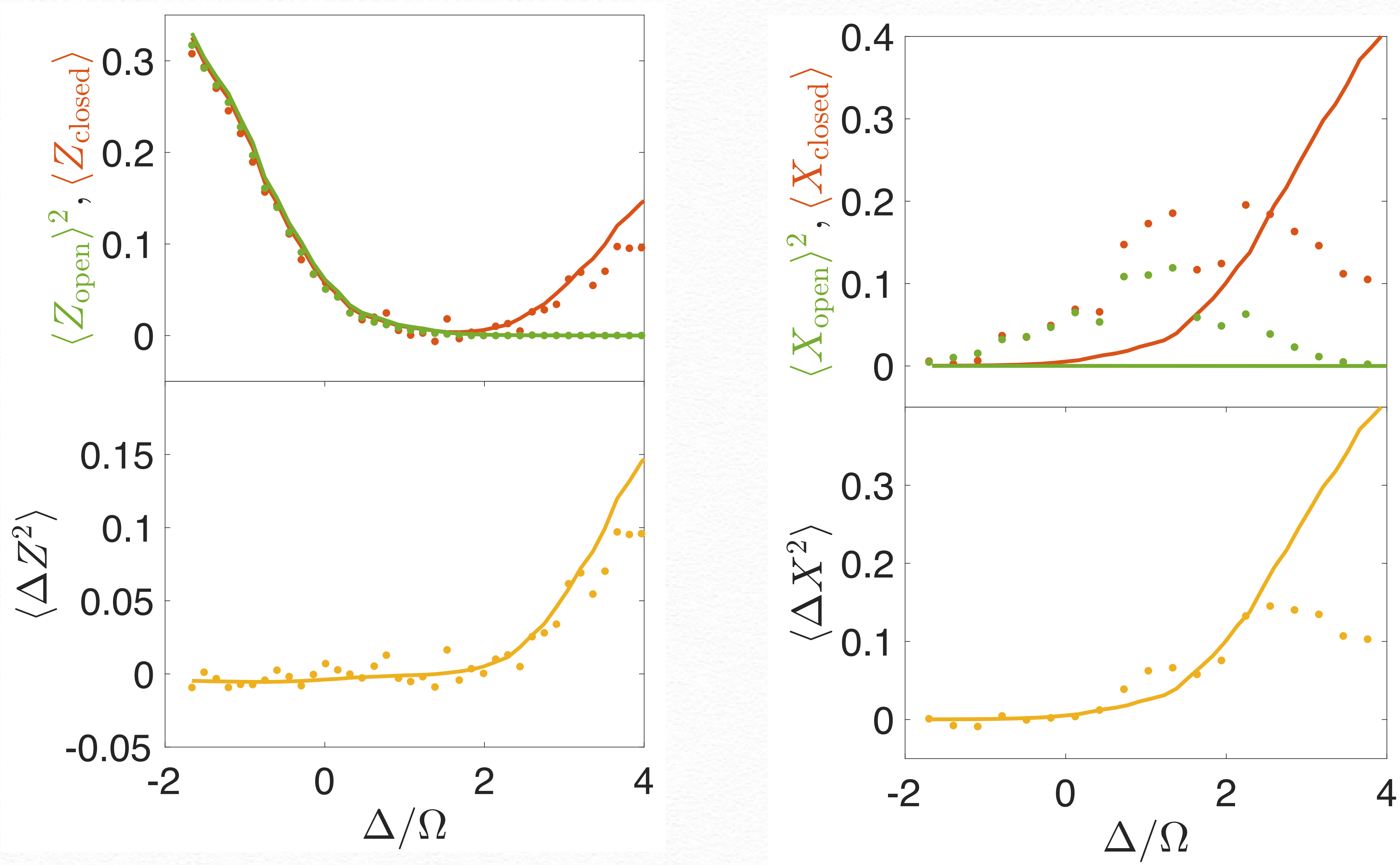






Yanting Cheng, Chengshu Li and HZ, arXiv 2021

Quantum Many-Body State of Spin Liquid



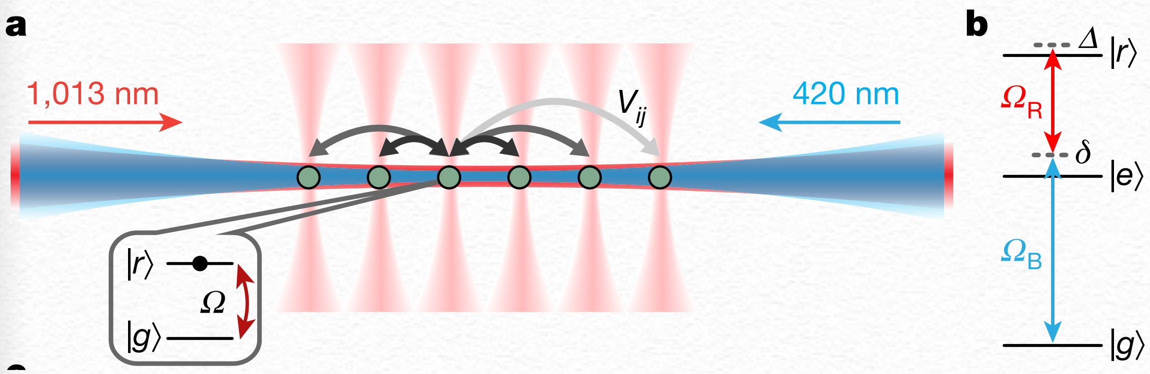
without any fitting parameter

$$\langle \Delta Z^2\rangle \equiv \langle \hat{Z}_{\rm close}\rangle - \langle \hat{Z}_{\rm open}\rangle^2 \quad \langle \Delta X^2\rangle \equiv \langle \hat{X}_{\rm close}\rangle - \langle \hat{X}_{\rm open}\rangle^2$$

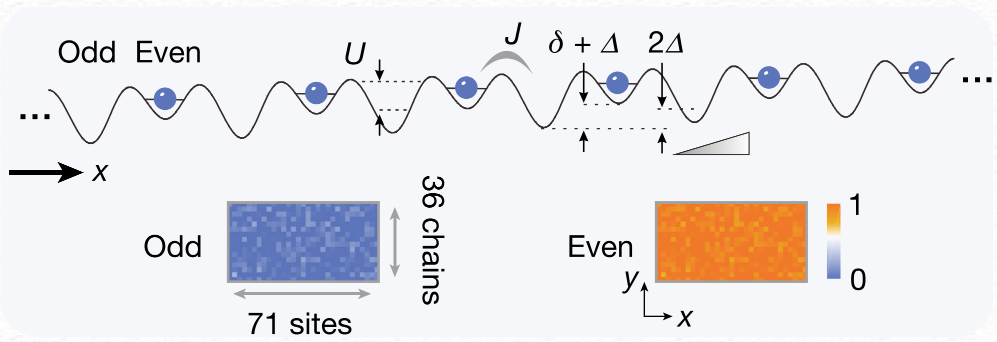
Yanting Cheng, Chengshu Li and HZ, arXiv 2021

Summary

- Two Realizations of the PXP Model:

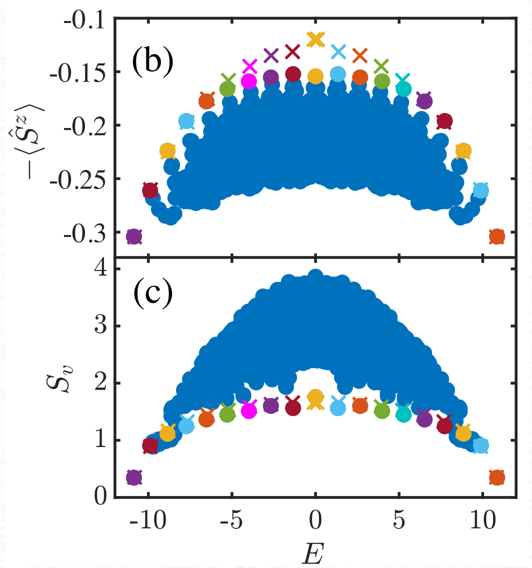


Rydberg Atoms

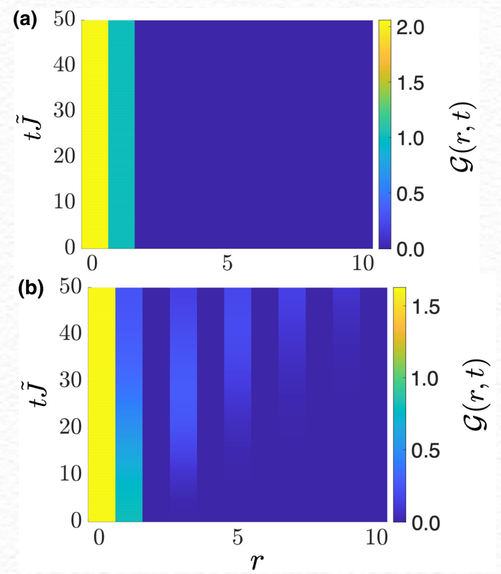


Lattice Schwinger Model

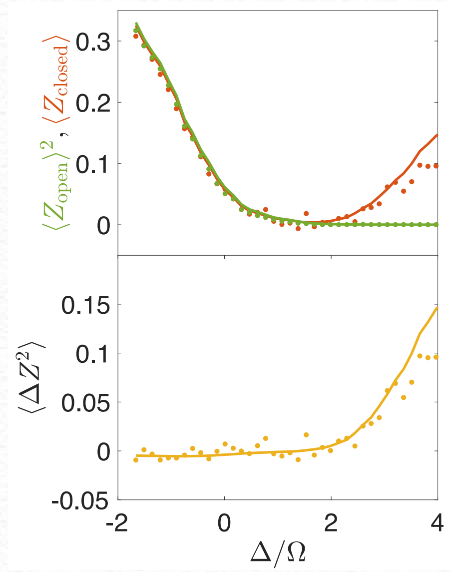
- Physics in the PXP Model



Understand Quantum Many-body Scars



Predict Confinement-Deconfinement Transition



Analyze Quantum Spin Liquid

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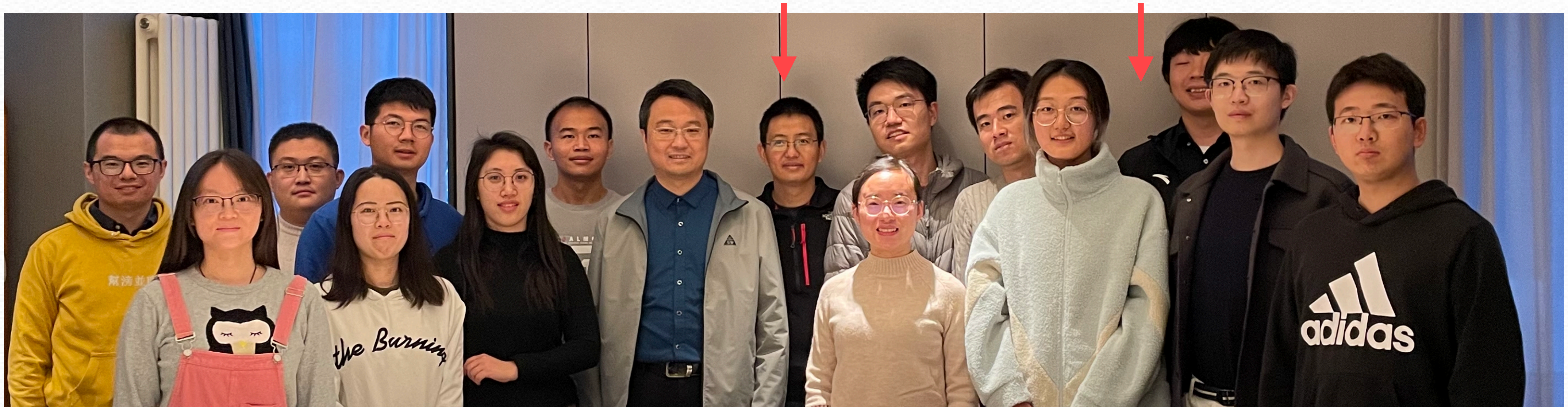

程艳婷

+ 刘尚、郑炜、张鹏飞

Thank you very much for your attention !