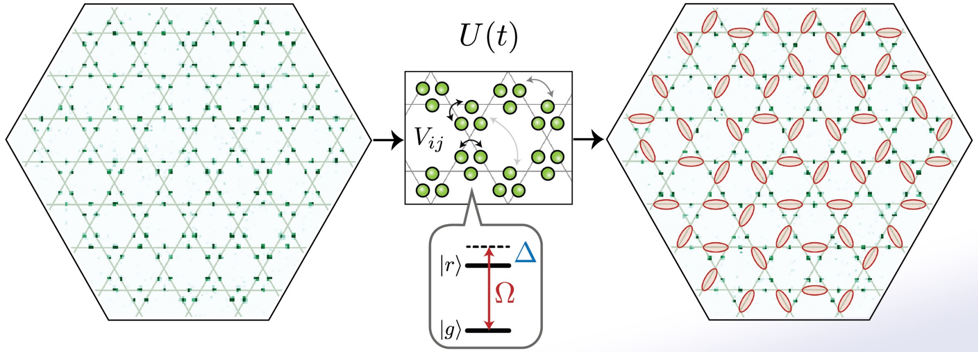
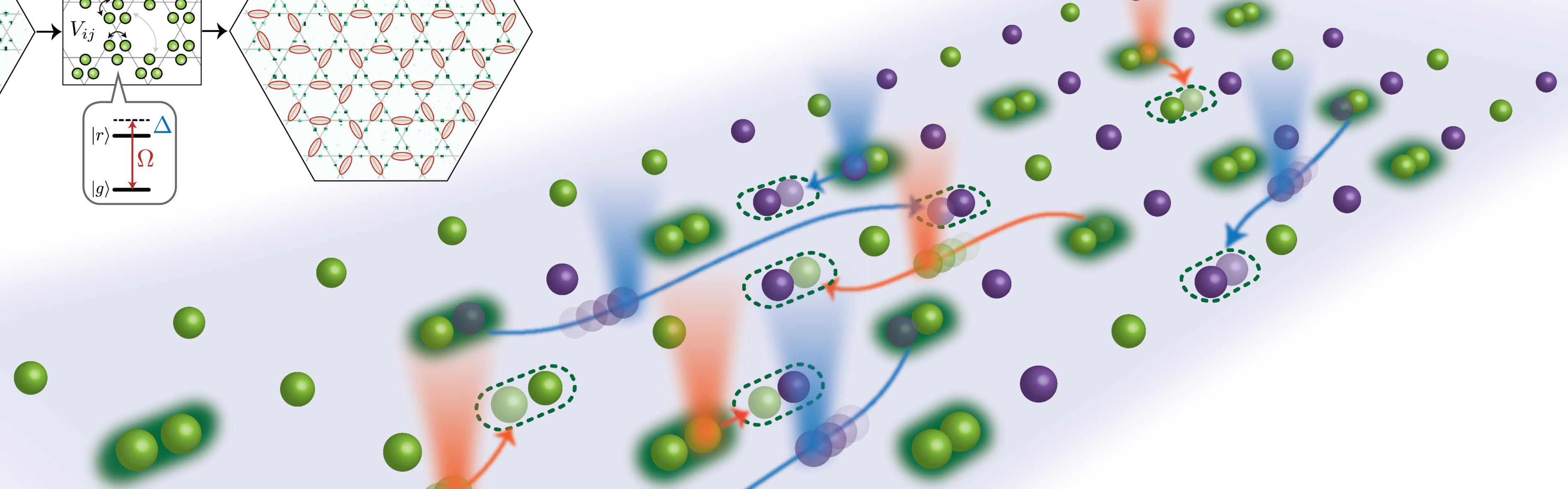
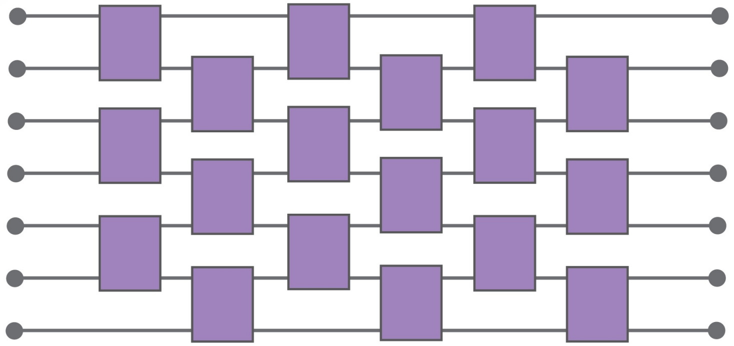
Quantum simulation (and information processing) with Rydberg atoms







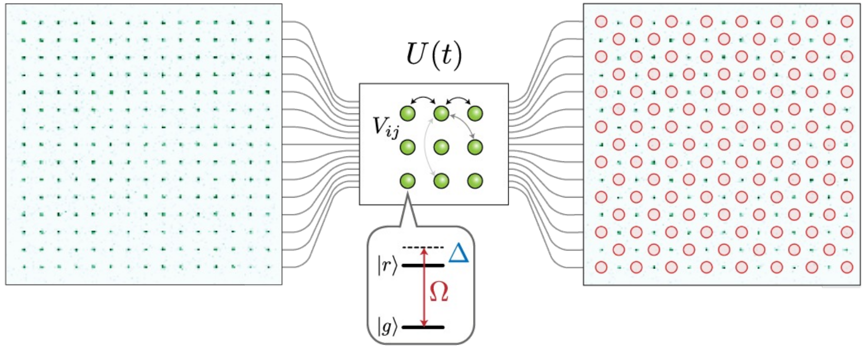
Giulia Semeghini
Harvard University

Boulder Summer School, July 2023

Outline

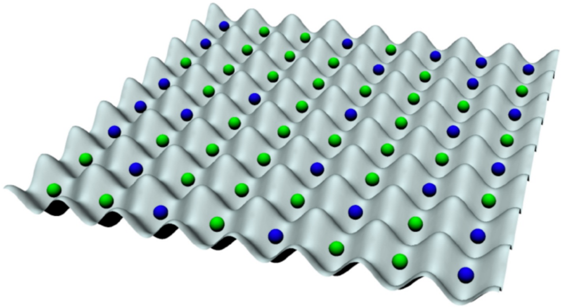
- Lecture 1: Programmable Rydberg arrays – introduction to the platform
- Lecture 2: Quantum simulation experiments with programmable Rydberg arrays
- Lecture 3: Quantum information processing with programmable Rydberg arrays

Programmable quantum platform: modes of operation



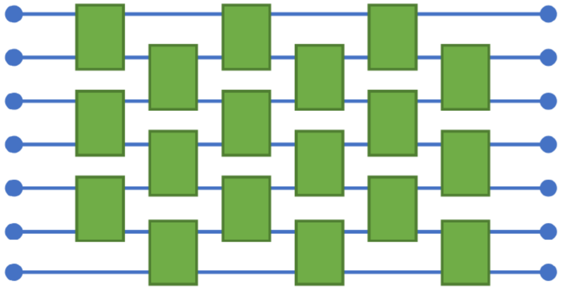
Analog

Engineer the system Hamiltonian such that the desired phase is the ground state in accessible range of parameters



Digital

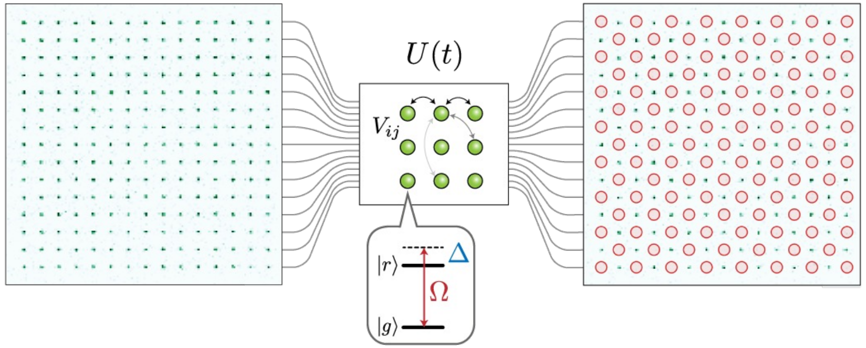
Implement quantum circuit to generate the desired entangled state



Hybrid

analog + digital

Programmable quantum platform: modes of operation



Quantum simulation

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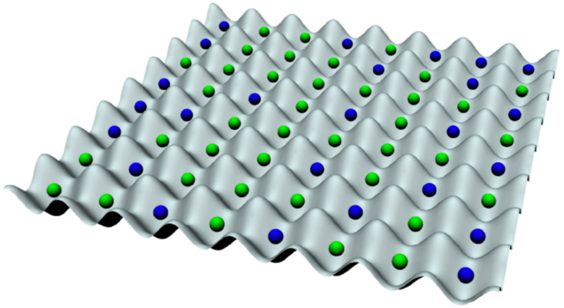
Engineer the system Hamiltonian such that the desired phase is the ground state in accessible range of parameters



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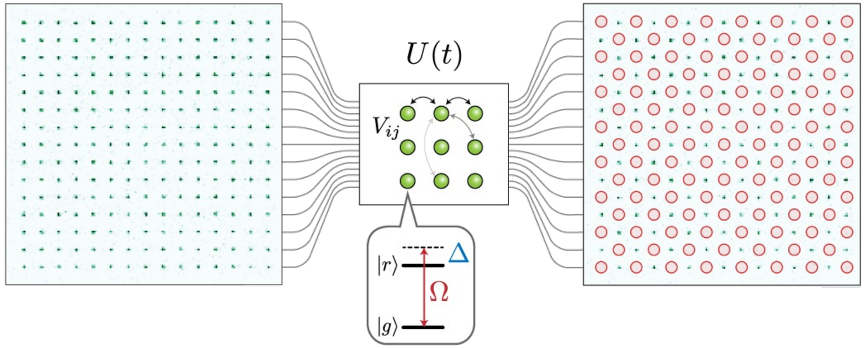
Programmable quantum platform: modes of operation



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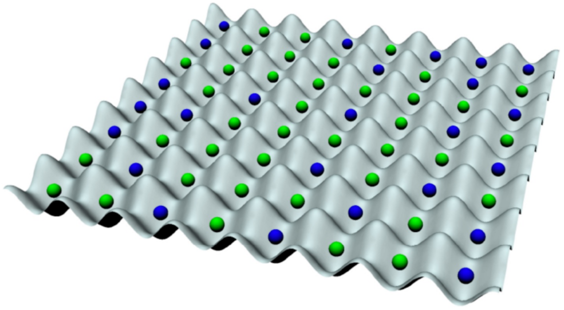


Digital

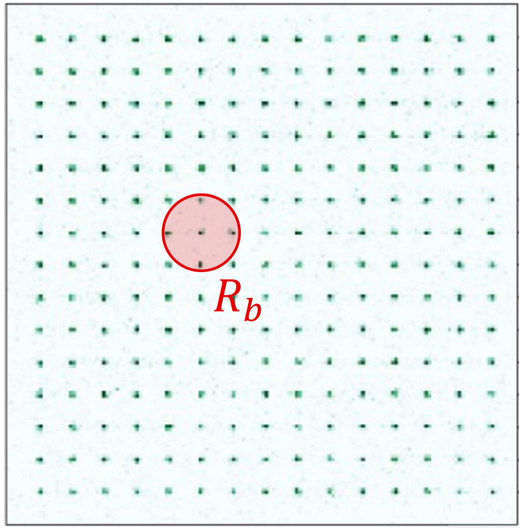
Implement quantum circuit to generate the desired entangled state

Hybrid

analog + digital

Analog quantum dynamics: an example

S. Ebadi et al., Nature 595, 227–232 (2021)

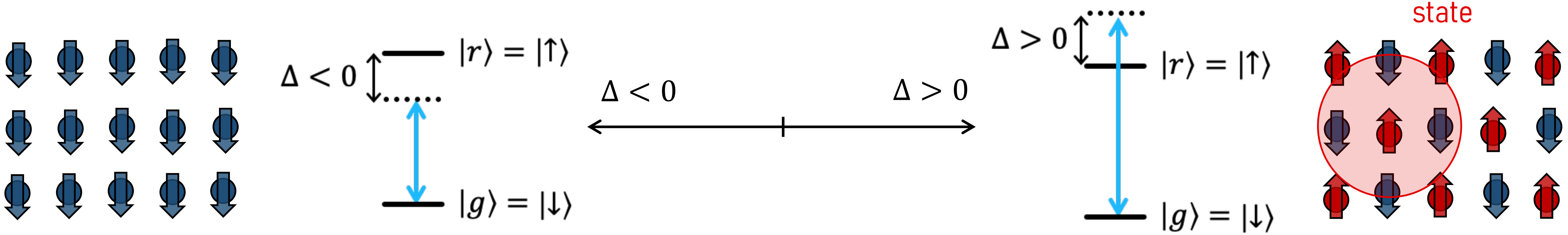


Rydberg Hamiltonian (Ising-type)

$$\mathcal{H} = \frac{1}{2}\Omega(t)\sum_i \sigma_x^{(i)} - \sum_i \Delta(t)\, n_i + \sum_{i<j} V_{ij} n_i n_j \qquad n_i = |r_i\rangle\langle r_i|$$

drive term — detuning — interaction

antiferromagnetic state



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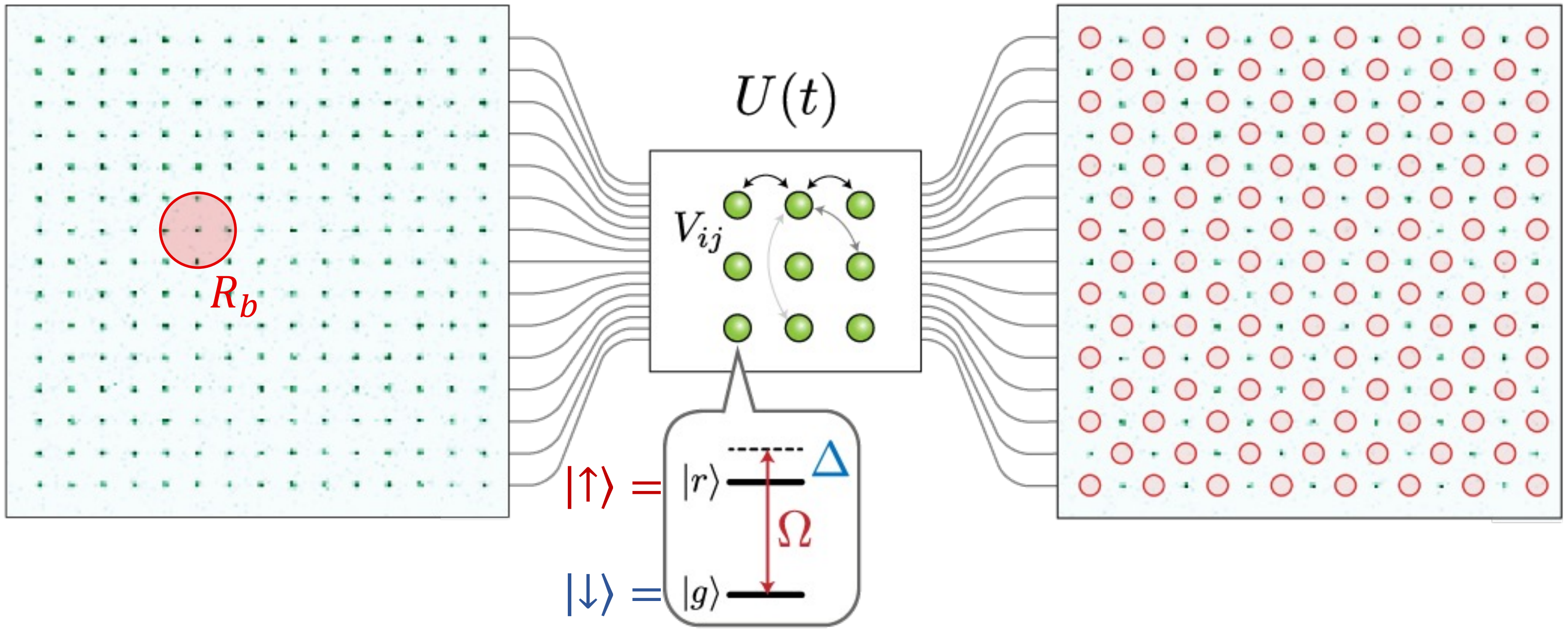

Readout:

Fluorescence imaging

Rydberg atoms are anti-trapped in the tweezers

→ detected as losses

(detection scheme for alkali atoms with spin ½ encoded in g-r basis; other detection schemes mentioned later on in these lectures)

Rydberg Hamiltonian (Ising-type)

$$\mathcal{H} = \frac{1}{2}\Omega(t)\sum_i \sigma_x^{(i)} - \sum_i \Delta(t) n_i + \sum_{i<j} V_{ij} n_i n_j$$

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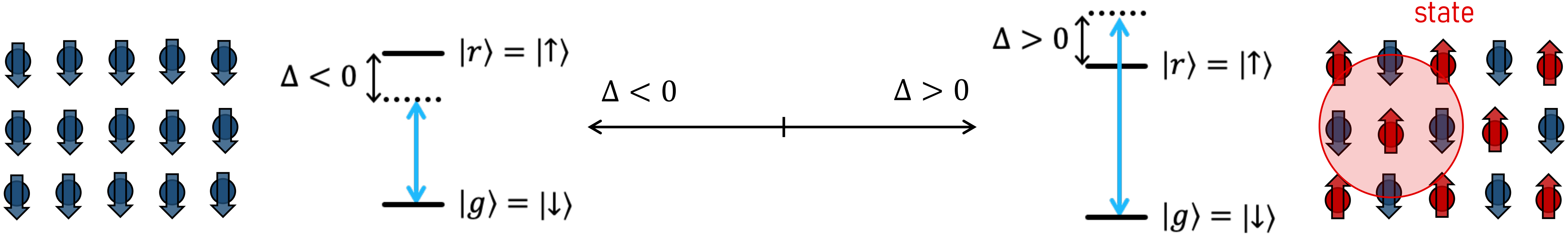

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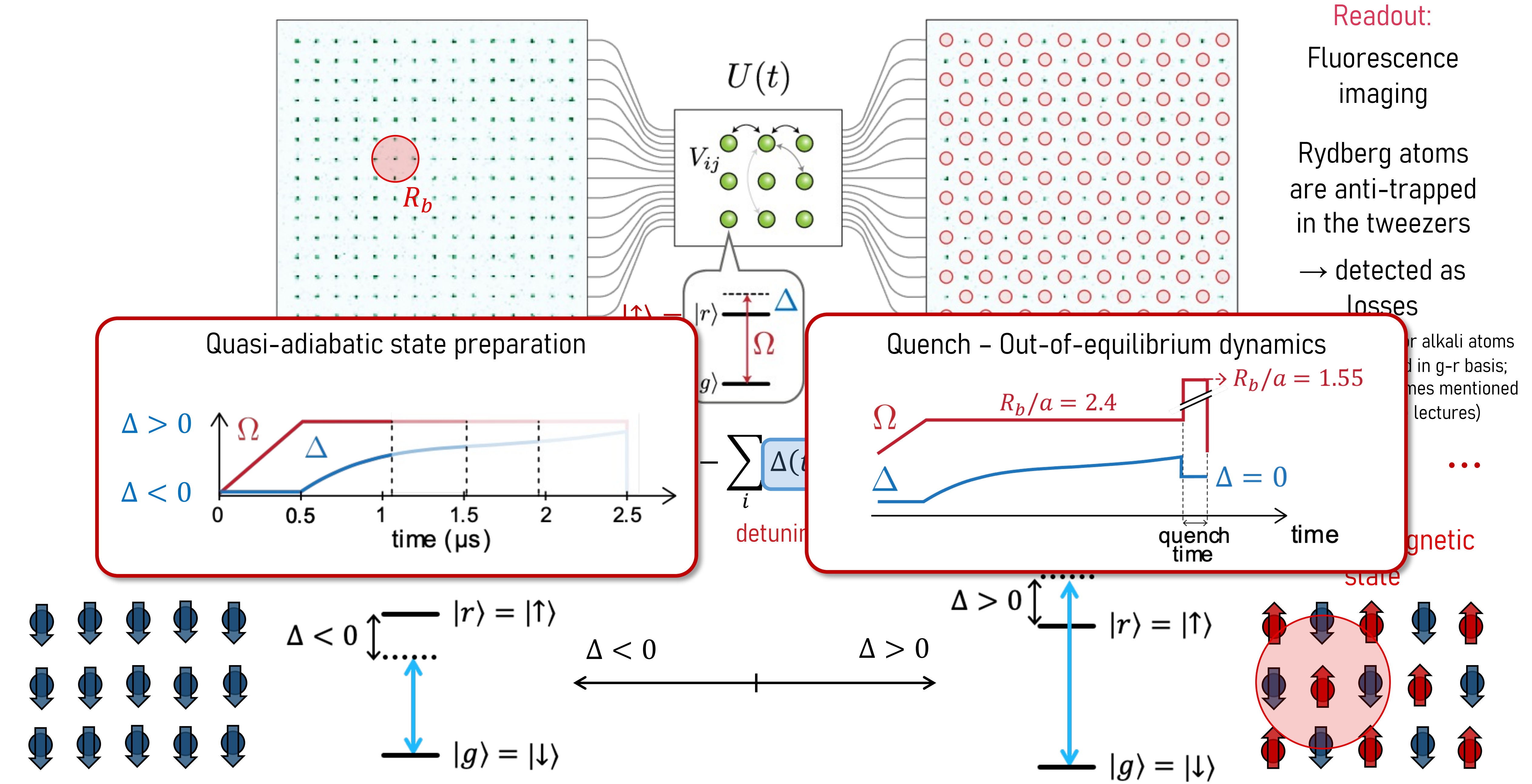
S. Ebadi et al., Nature 595, 227–232 (2021)



Quantum simulation with Rydberg atom arrays

Many-body phases

"Conventional" phases
(symmetry breaking)

Topological phases

Quantum phase transitions and criticality

(2+1)D Ising QPT

Quantum dynamics

Quantum many-body scars

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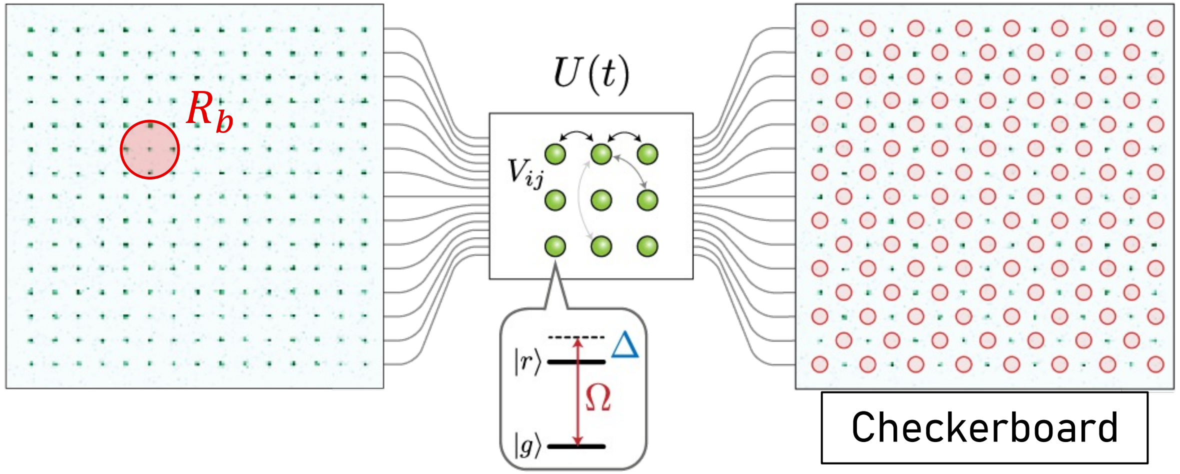
Ordered phases: Square lattice



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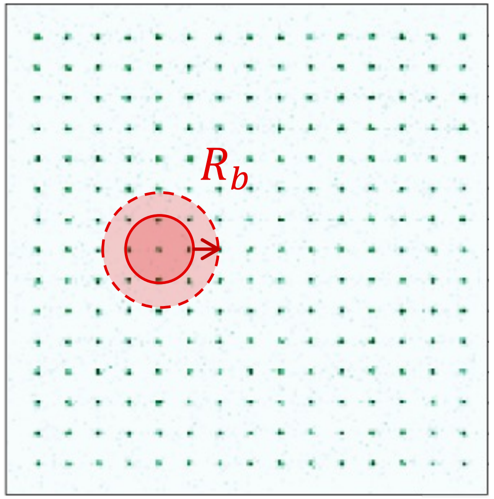
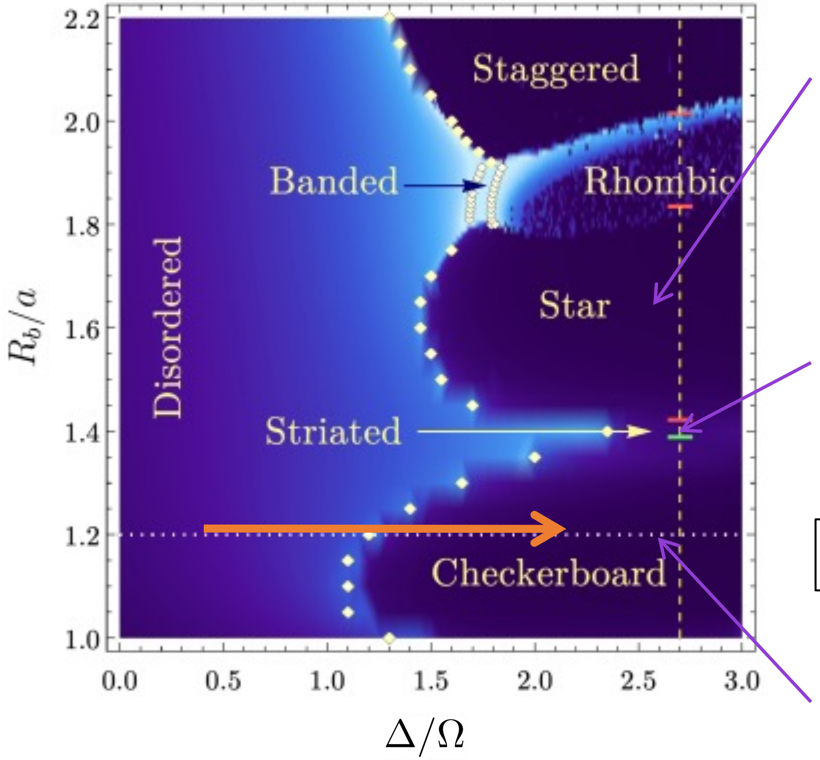
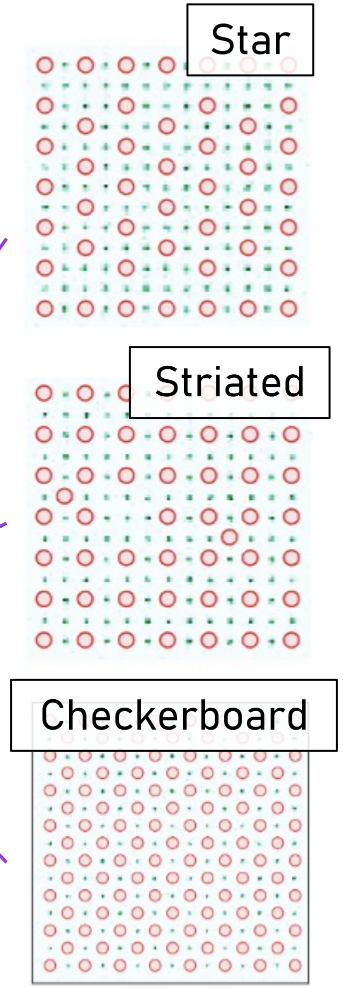


what is the ground state of the Rydberg Hamiltonian when we increase R_b beyond nearest neighbors?

Phase diagram

Numerics from: R. Samajdar et al, PRL (2020)





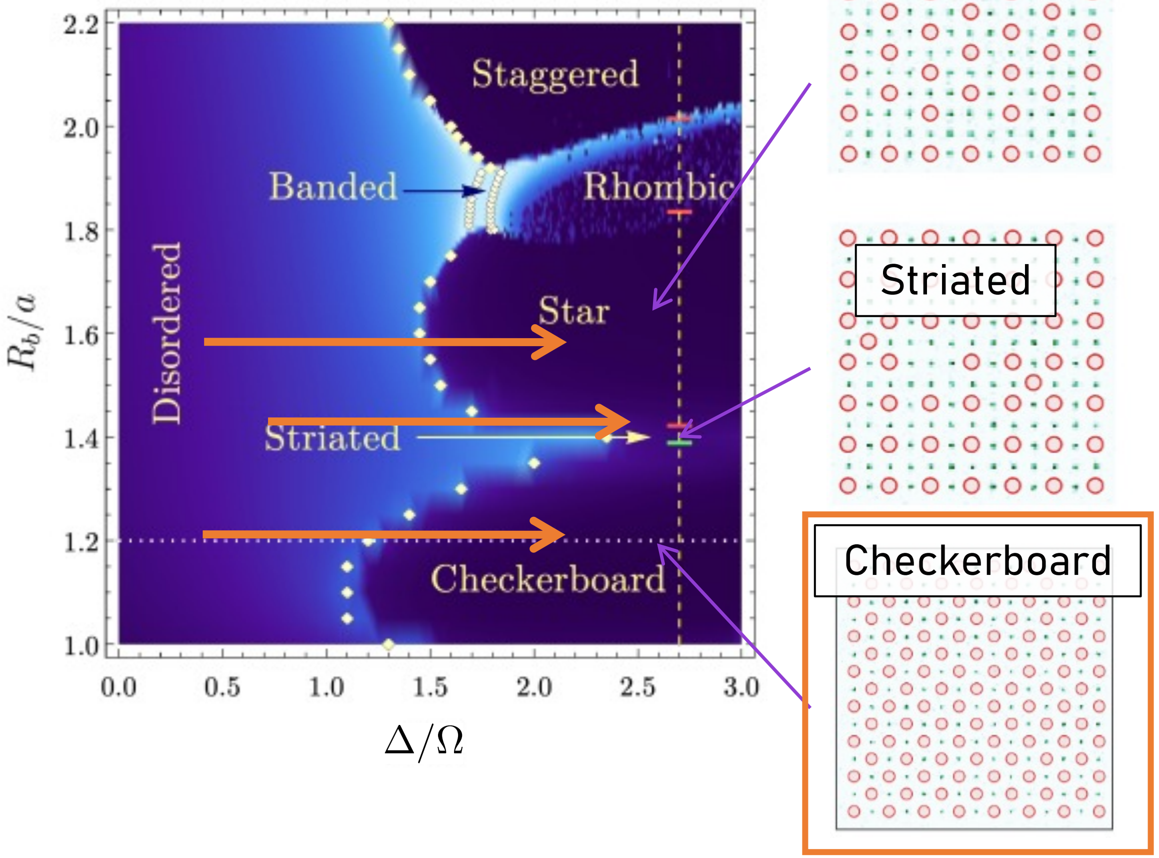
S. Ebadi et al., Nature 595, 227–232 (2021)

Ordered phases: Square lattice

quasi-adiabatic preparation in different points of the phase diagram → how do we characterize the state we prepare?

Numerical phase diagram

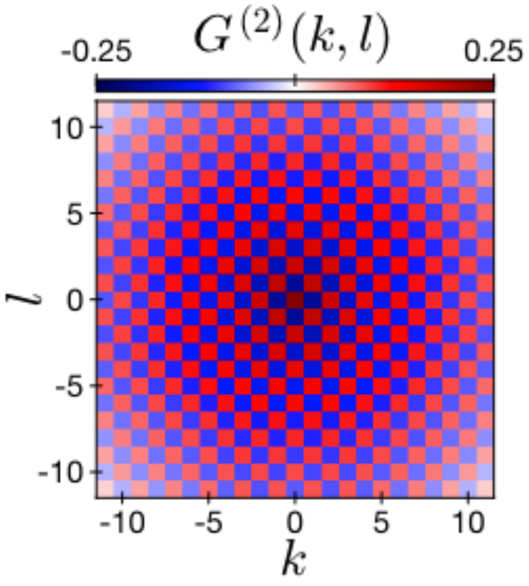
Numerics from: R. Samajdar et al, PRL (2020)



1 Correlation function

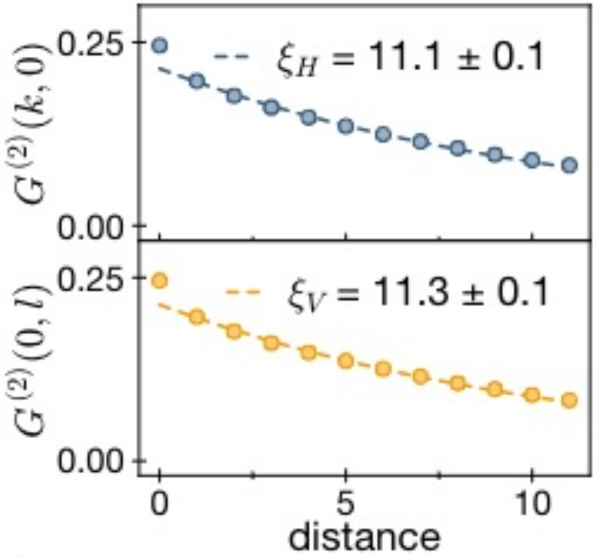
$$G^{(2)}(k,l) = \langle n_k n_l \rangle - \langle n_k \rangle \langle n_l \rangle$$

averaged over all pairs separated by (k, l)



(alternates between +0.25 and -0.25 for perfect checkerboard)

measure correlation lengths



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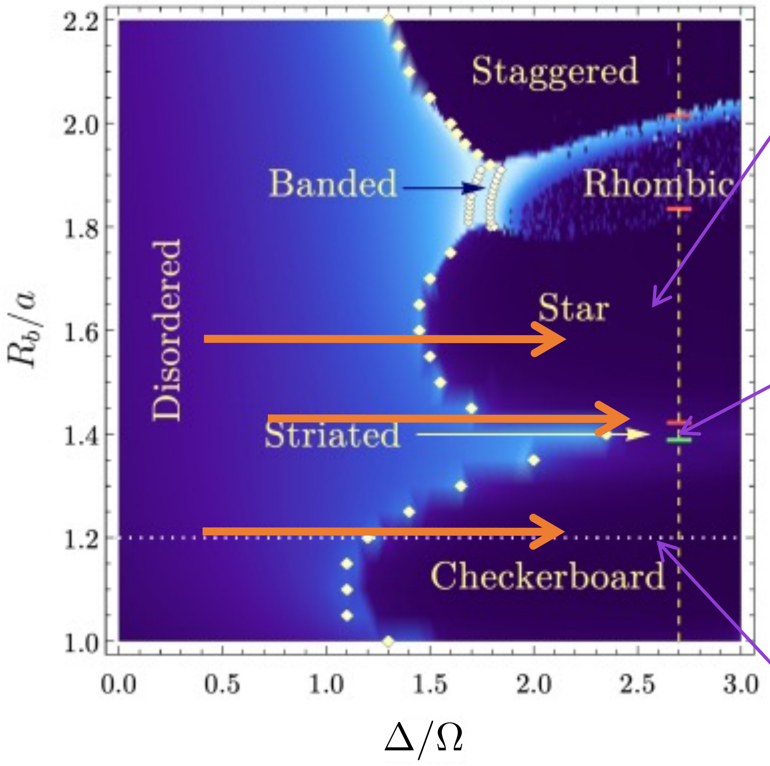

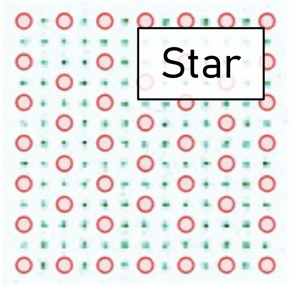

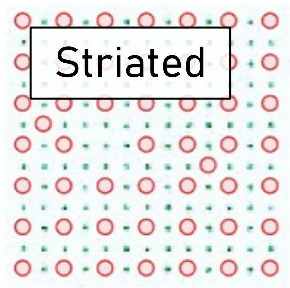

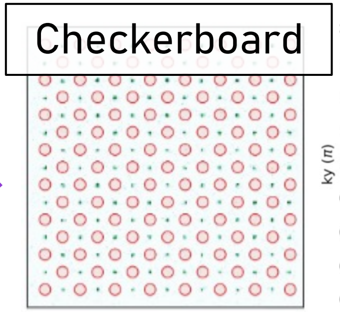

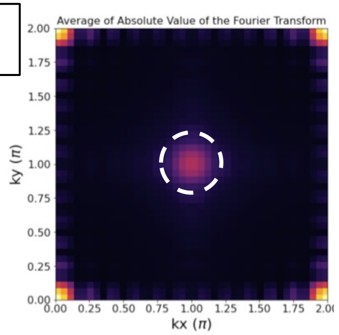

2 Fourier transform

of single-shot measurement outcomes

$$\mathcal{F}(\mathbf{k}) = |\sum_i \exp(i\mathbf{k}\cdot\mathbf{x}_i/a)n_i/N|$$

we construct order parameters for all observed phases using $\mathcal{F}(\boldsymbol{k})$ averaged over all exp repetitions

Peak at (π, π) → canonical AF order parameter: staggered magnetization

S. Ebadi et al., Nature 595, 227–232 (2021)

Ordered phases: Square lattice

quasi-adiabatic preparation in different points of the phase diagram → how do we characterize the state we prepare?

Numerical phase diagram

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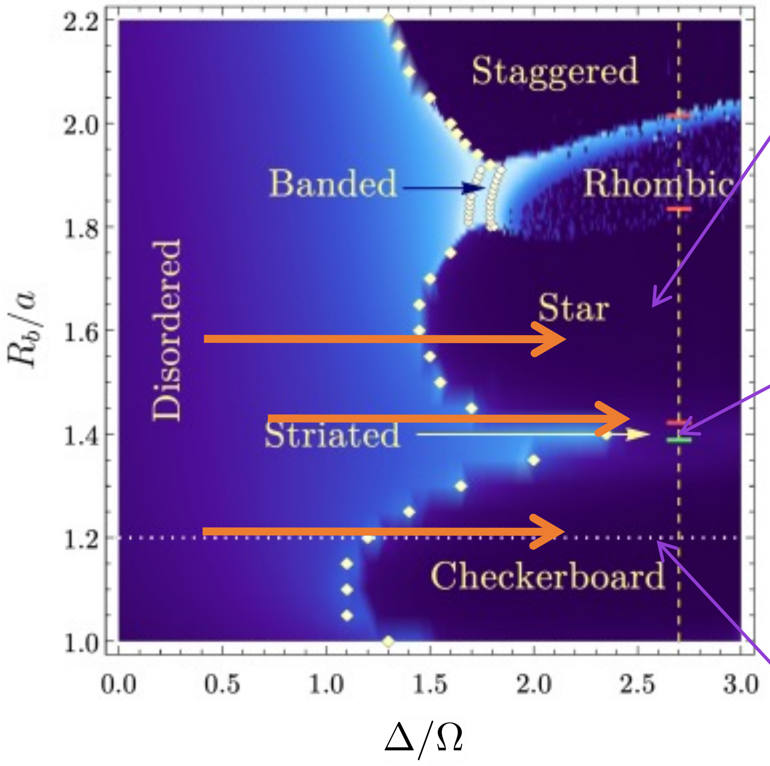
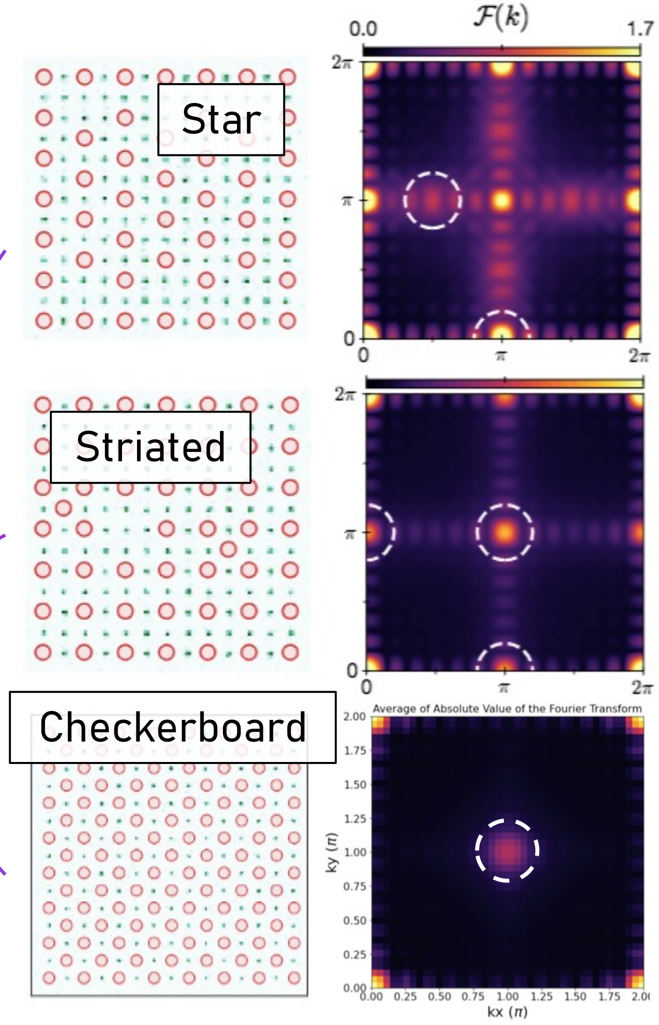
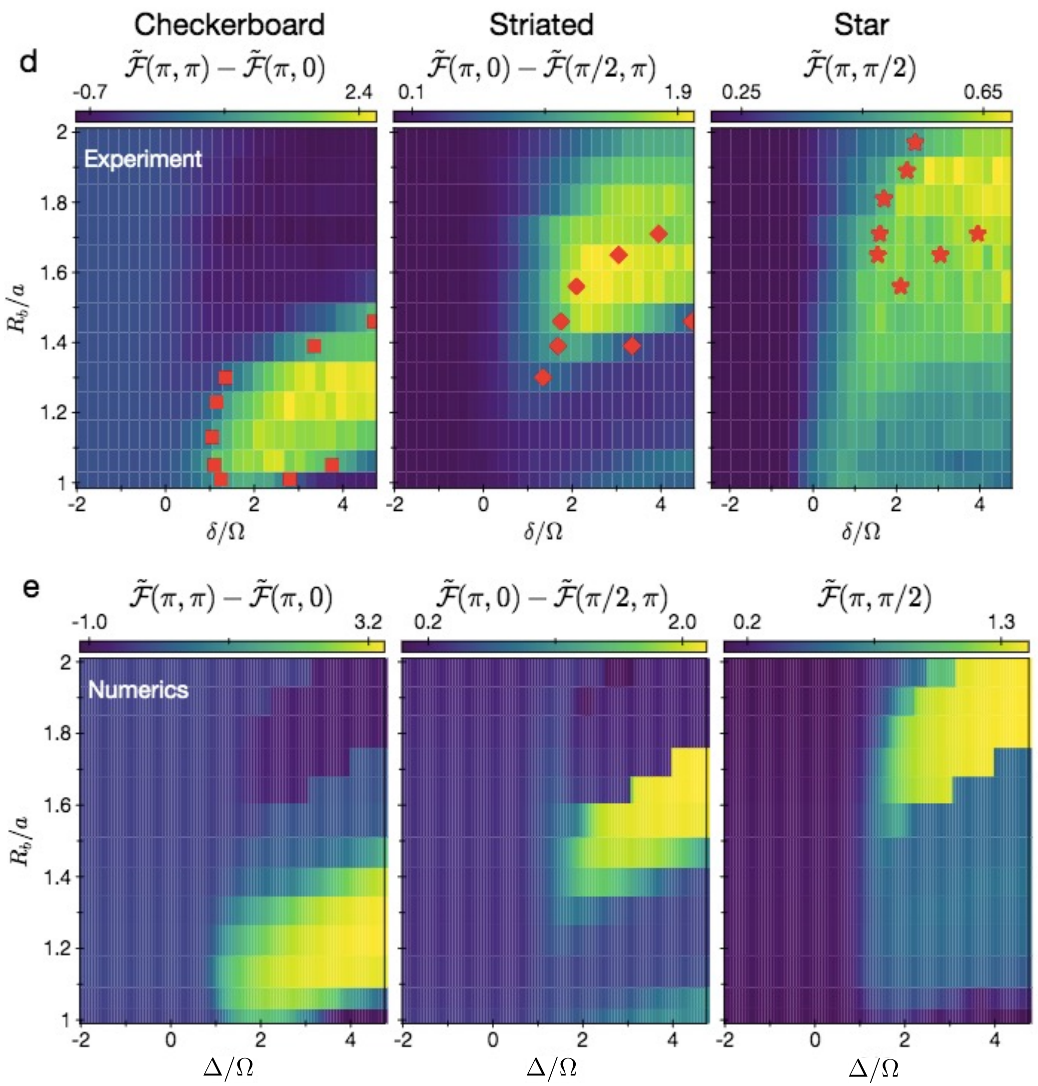




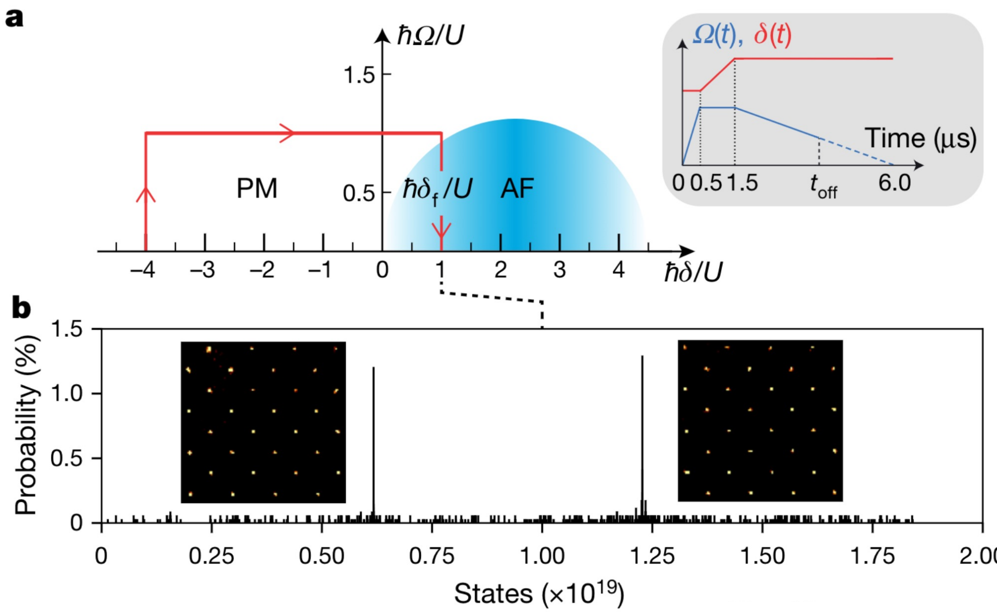
Mapping full phase diagram



S. Ebadi et al., Nature 595, 227–232 (2021)

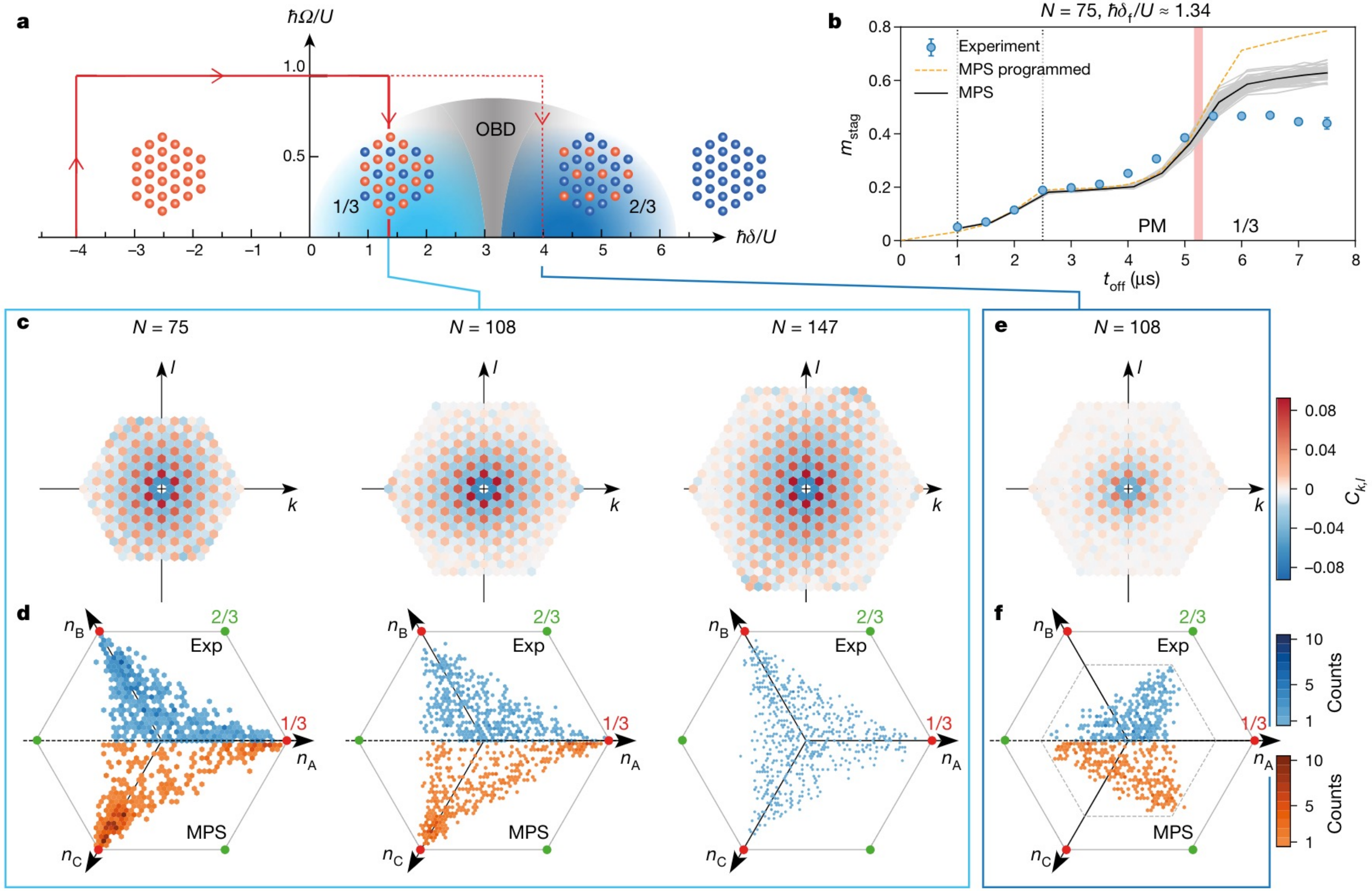
Ordered phases: Square and triangular lattice

Related experiment from Antoine Browaeys' group



Detailed characterization of the AF phase

Extension to triangular lattice:



P. Scholl et al., Nature 595, 233–238 (2021)

Quantum simulation with Rydberg atom arrays

Many-body phases

"Conventional" phases
(symmetry breaking)

Topological phases

Quantum phase transitions and criticality

(2+1)D Ising QPT

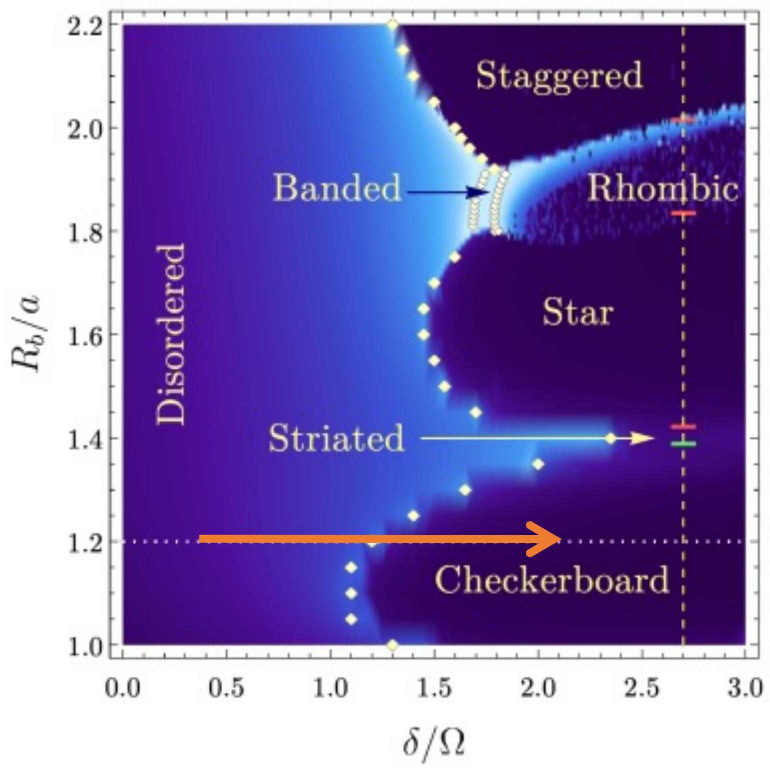
Quantum dynamics

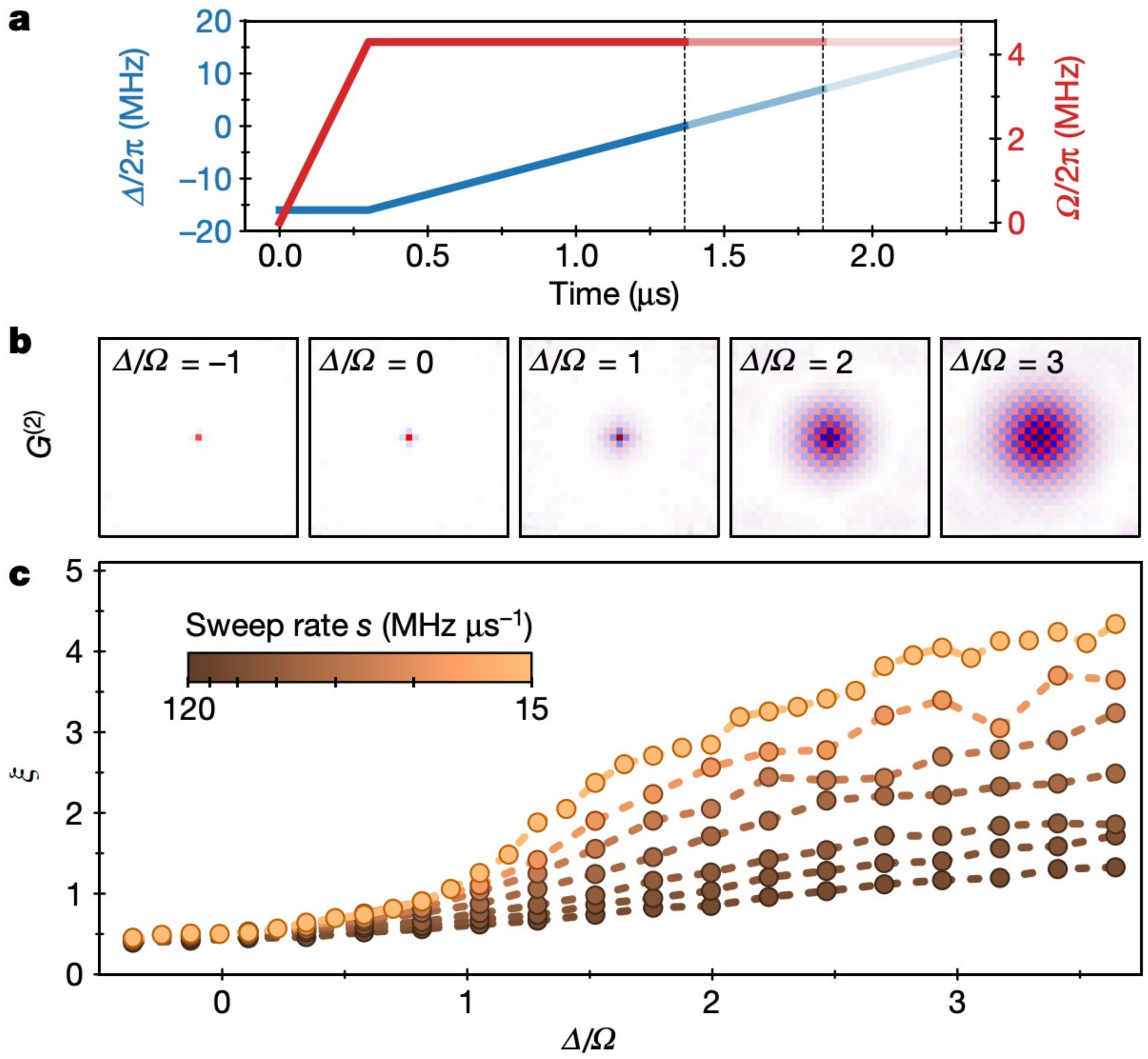
Quantum many-body scars

Quantum phase transition: (2+1)D Ising

Quantum phase transition into the checkerboard phase

Numerics from: R. Samajdar et al, PRL (2020)





Slower sweep rate s

= more adiabatic

= larger correlation length ξ

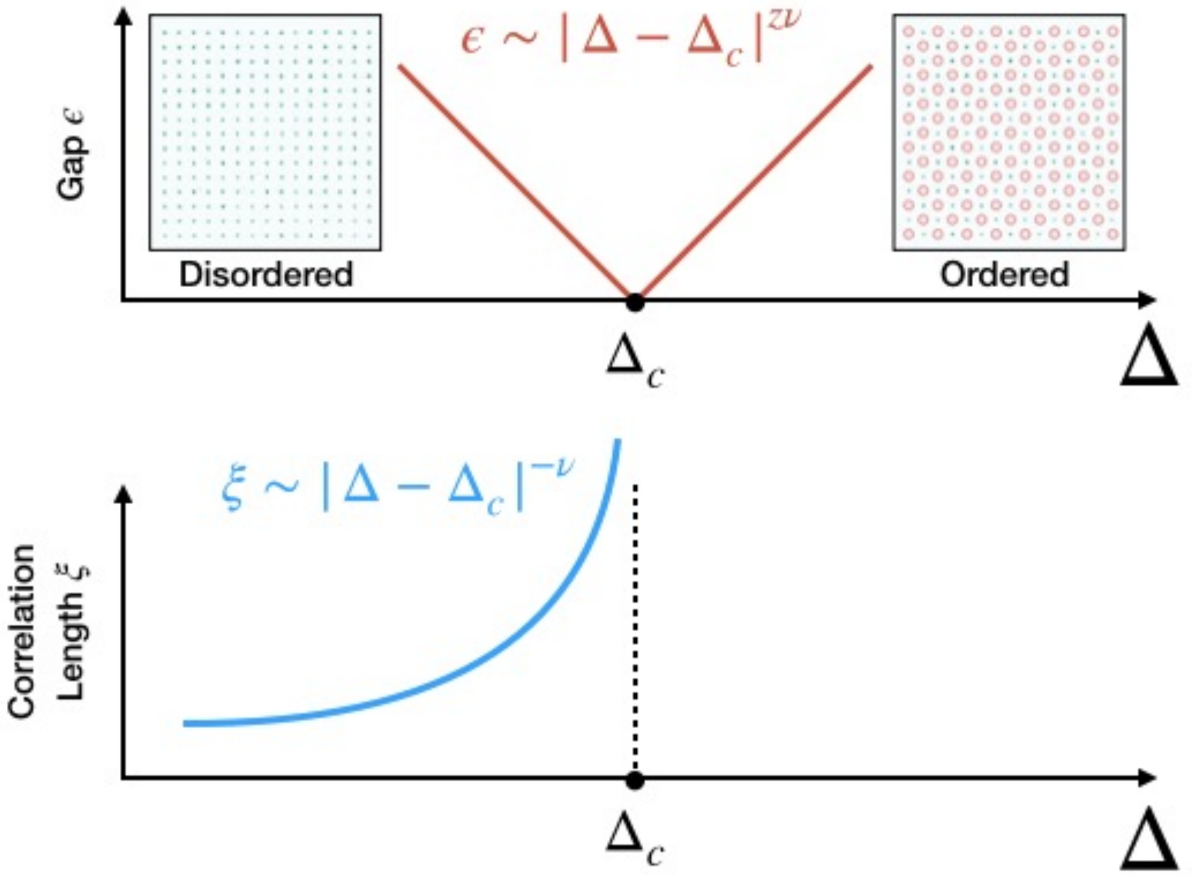
S. Ebadi et al., Nature 595, 227–232 (2021)

Quantum phase transition: (2+1)D Ising

Universality

Quantum phase transitions fall into universality classes characterized by critical exponents that determine universal behaviour of the system near the quantum critical point

Transition into checkerboard phase predicted to be in the (2+1)D quantum Ising universality class



<u>Critical exponents:</u>

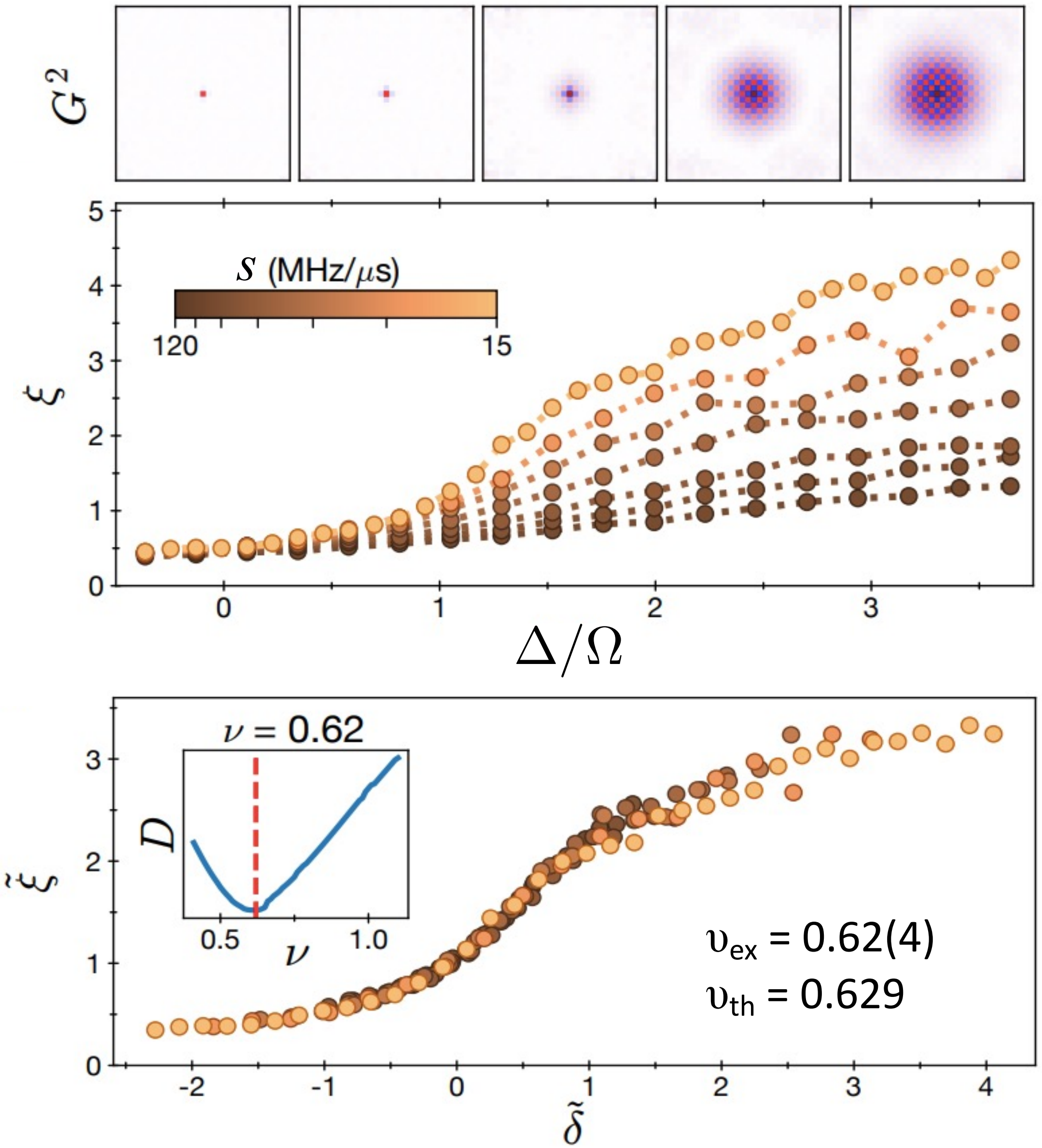
z = 1 (dynamical)

υ = 0.629 (correlation length)

S. Ebadi et al., Nature 595, 227–232 (2021)

Quantum phase transition: (2+1)D Ising

Universal scaling



Study the dynamical build-up of correlations associated with the quantum Kibble–Zurek mechanism

→ predicts a universal scaling between the control parameter Δ and the correlation length ξ (both rescaled with the sweep rate s):

$$\tilde{\xi} = \xi(s/s_0)^{\mu}$$
$$\tilde{\delta} = (\Delta - \Delta_c)(s/s_0)^{\kappa}$$

$$\mu = \nu/(1+z\nu)$$
$$\kappa = -1/(1+z\nu)$$

Hold z = 1 constant and find experimental value of υ that gives universal collapse

First observation of (2+1)D Ising quantum phase transition

S. Ebadi et al., Nature 595, 227–232 (2021)

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Quantum dynamics

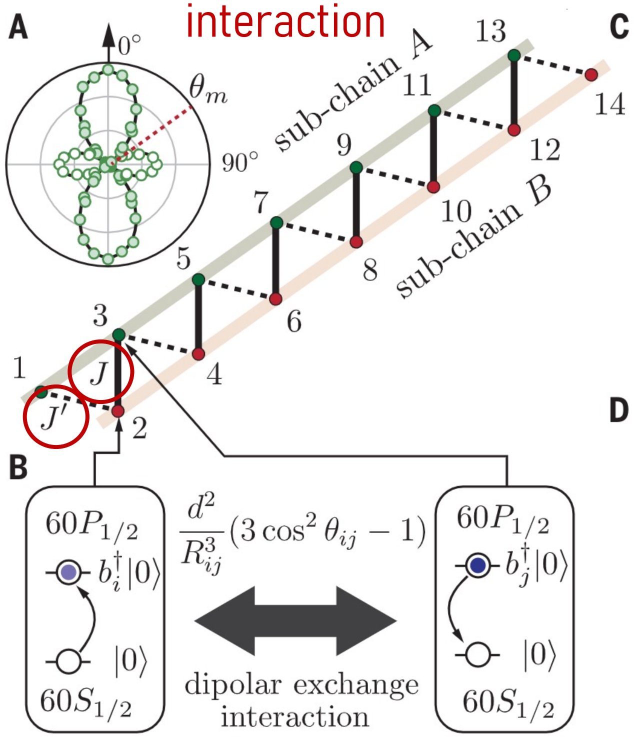
Quantum many-body scars

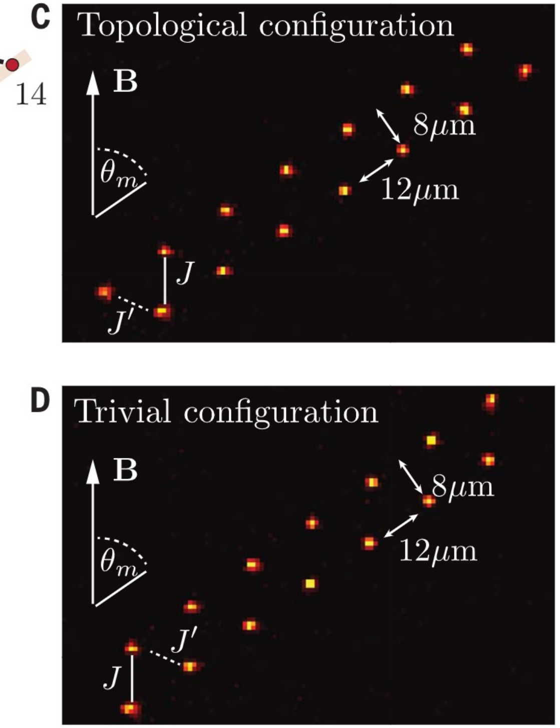
Topological phases: SSH model for hard-core bosons

More recent works with XY Hamiltonian:
G. Bornet et al, arXiv (2023)
V. Liu et al, Nature (2023)

Many-body symmetry-protected topological phase in quasi-1D atom array

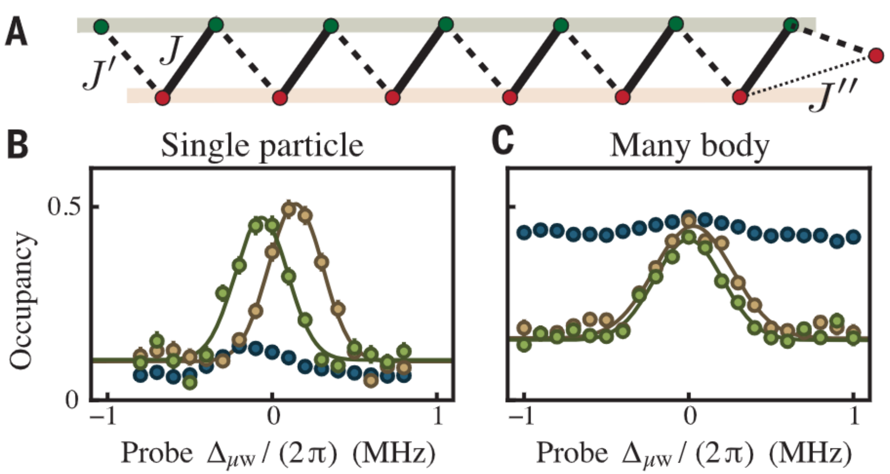
asymmetric interaction





→ four-fold ground state degeneracy due to edge states

Test robustness of SPT phase:



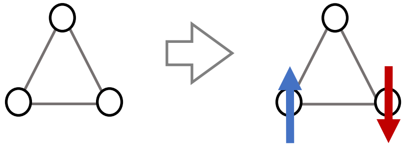
Dipolar flip-flop interaction between 2 Rydberg states coupled by MW → hard-core bosons hopping along the chain → bosonic Su-Schrieffer-Heeger (SSH) model

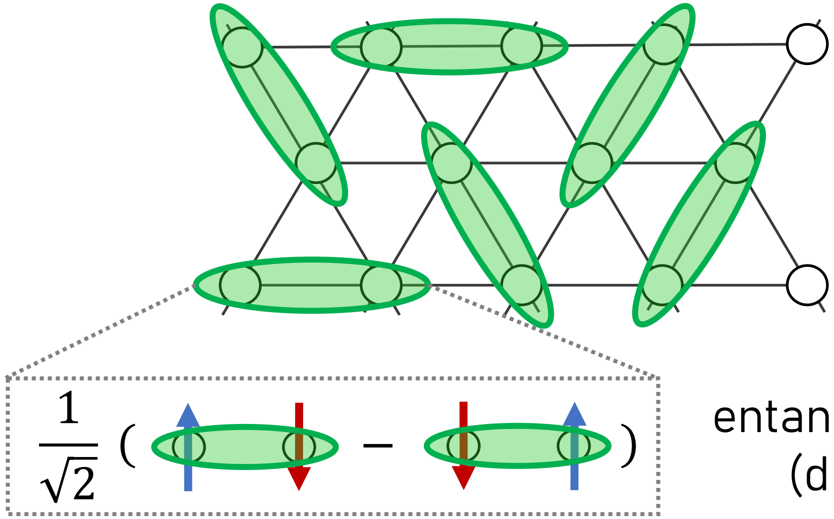
De Léséleuc et al., Science 365, 775–780 (2019)

Topological phases: Quantum spin liquid

P. Anderson, Materials Research Bulletin 8 (1973)

spin 1/2 particles with
AF interactions
on a frustrated lattice

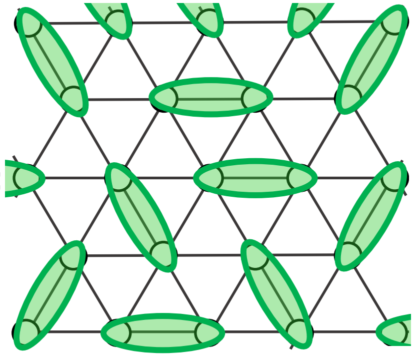




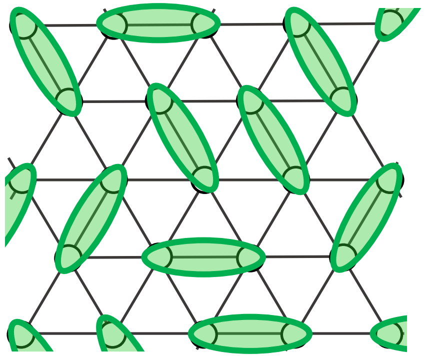
$\frac{1}{\sqrt{2}}$ (−)

entangled pair
(dimer)

$|\psi\rangle =$



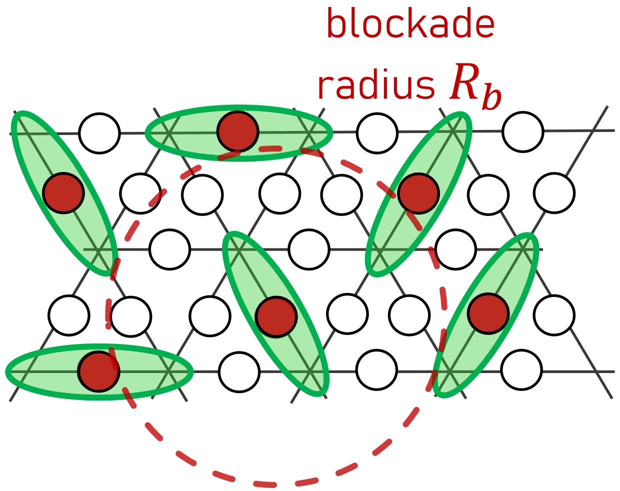
+

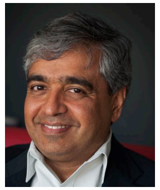


+ ...

resonating valence bond (RVB) state

Analogue dimer models
in Rydberg atom arrays:

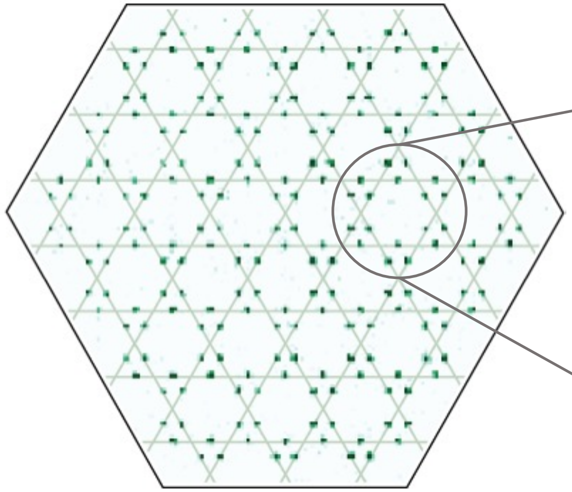




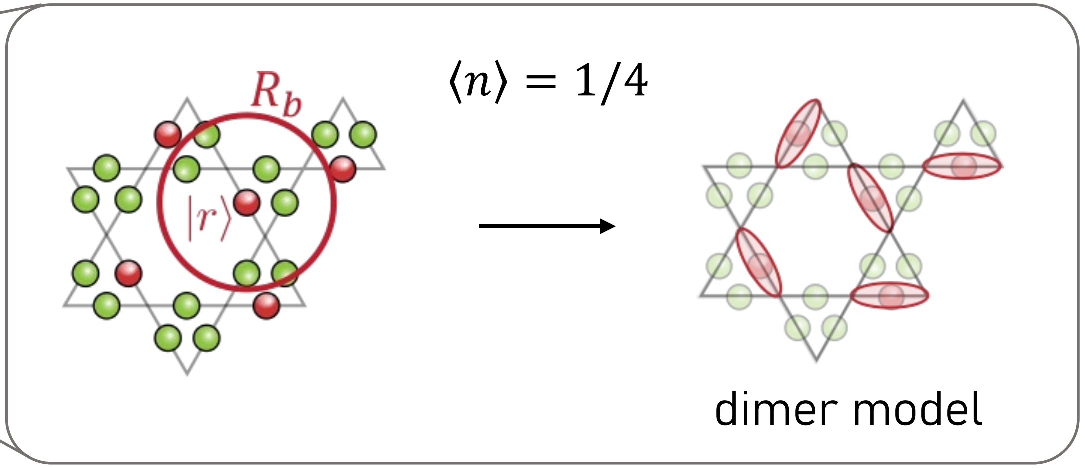
R. Samajdar, W. W. Ho, H. Pichler, M. Lukin, S. Sachdev,
“Quantum phases of Rydberg atoms on a kagome lattice”,
PNAS (2021)

R. Verresen, M. Lukin and A. Vishwanath,
“Prediction of Toric Code Topological Order from Rydberg Blockade”,
PRX (2021)

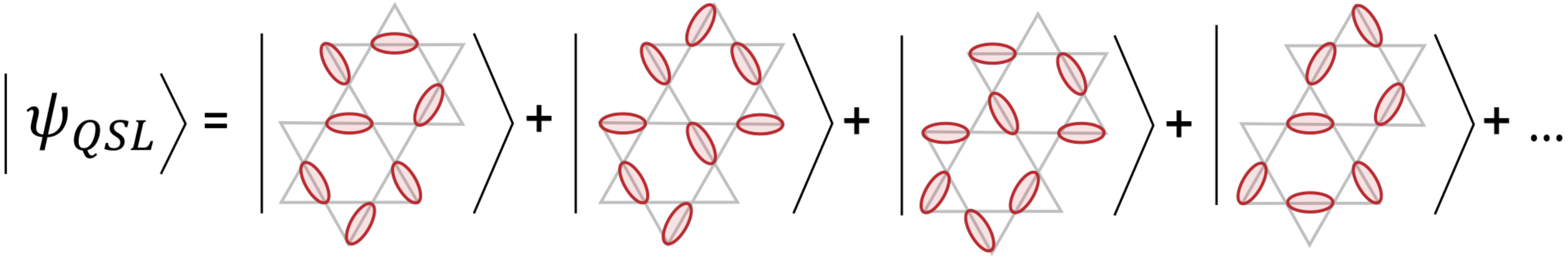
Topological phases: Quantum spin liquid



219 atoms



quantum spin liquid state: superposition of all dimer coverings



R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)
G. Semeghini et al., Science 374, 1242 (2021)
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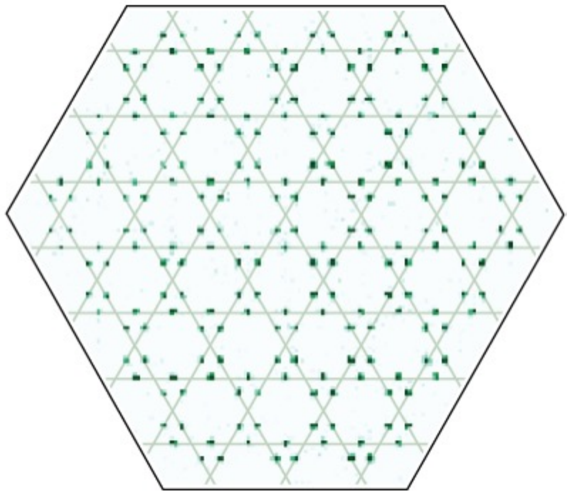
Topological phases: Quantum spin liquid



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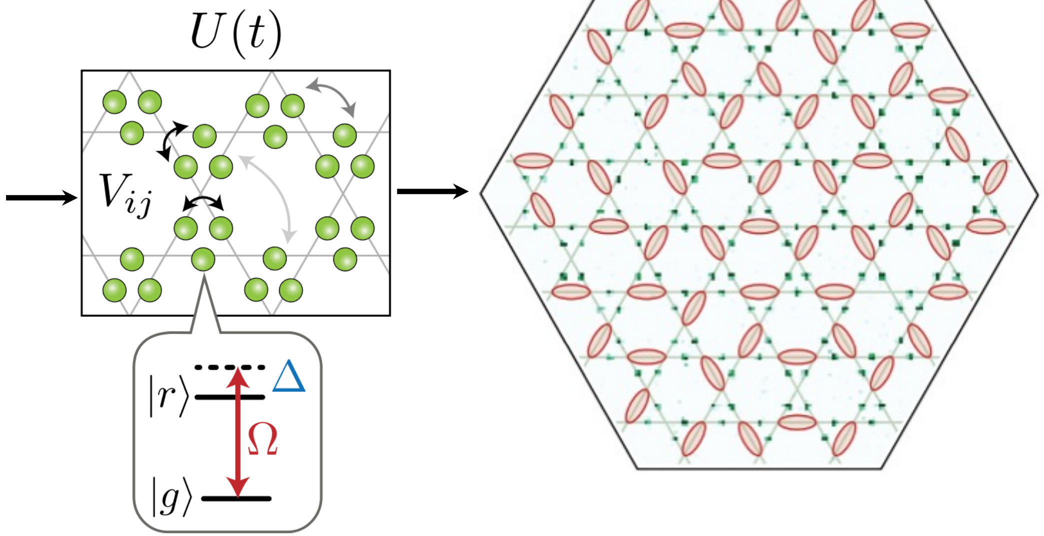
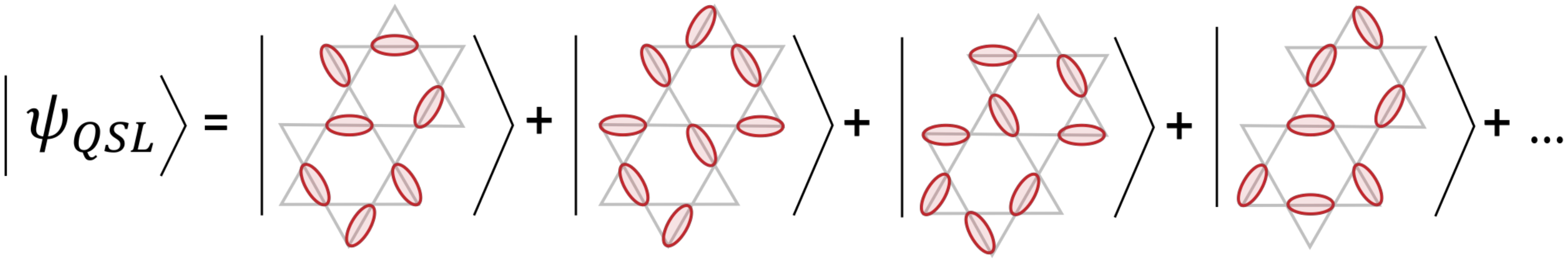


quantum spin liquid state: superposition of all dimer coverings



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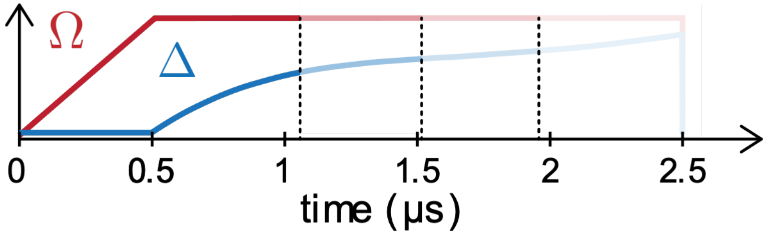
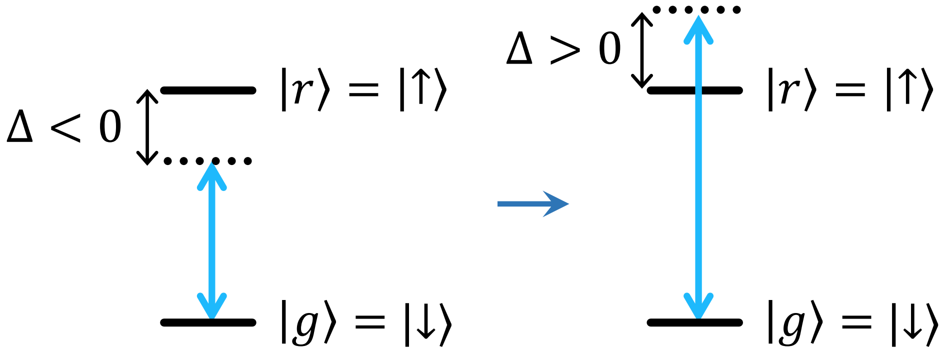
Topological phases: Quantum spin liquid

quasi-adiabatic state preparation





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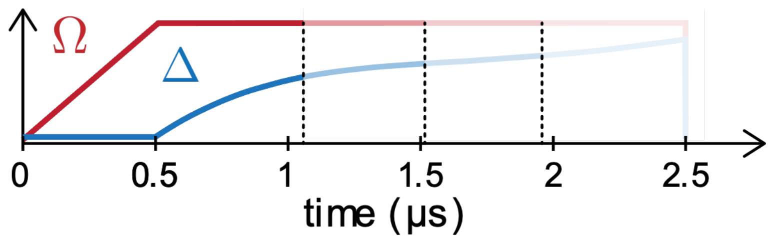
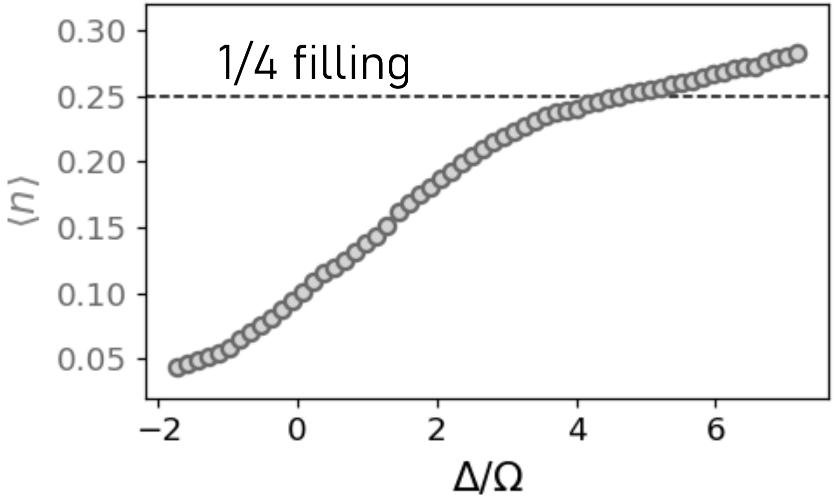
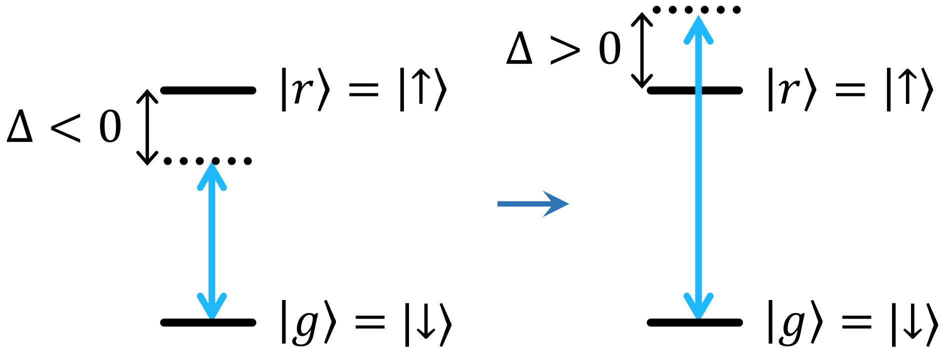
Topological phases: Quantum spin liquid

G. Semeghini et al., Science 374, 1242 (2021)

quasi-adiabatic state preparation



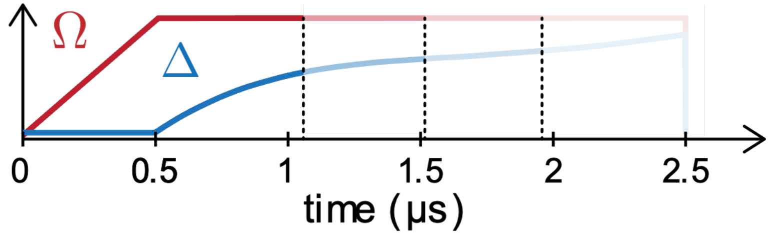


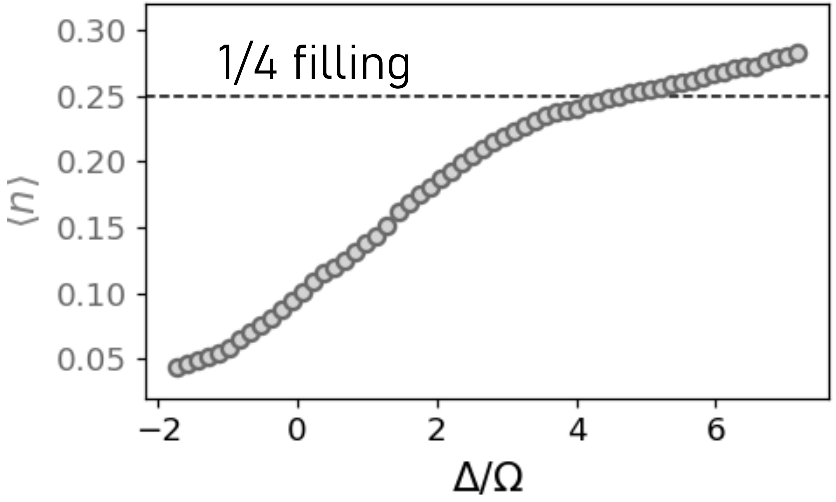


$$\mathcal{H} = \frac{1}{2}\Omega(t)\sum_i \sigma_x^{(i)} - \sum_i \Delta(t)\, n_i + \sum_{i<j} V_{ij} n_i n_j$$

G. Semeghini et al., Science 374, 1242 (2021)

Topological phases: Quantum spin liquid

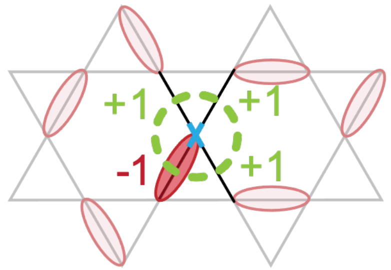


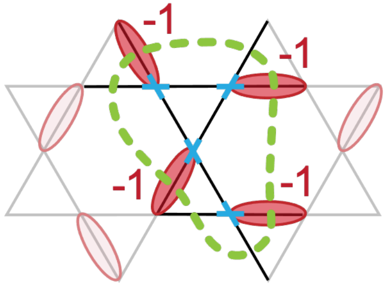


diagonal string operator Z:

$\langle Z \rangle = (-1)^{\#\text{ enclosed vertices}}$

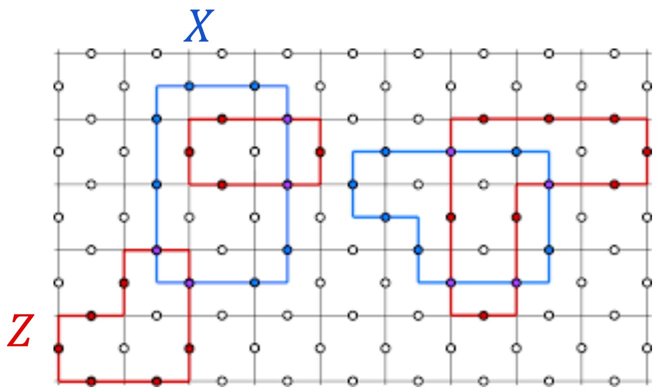
$\langle Z \rangle = -1$





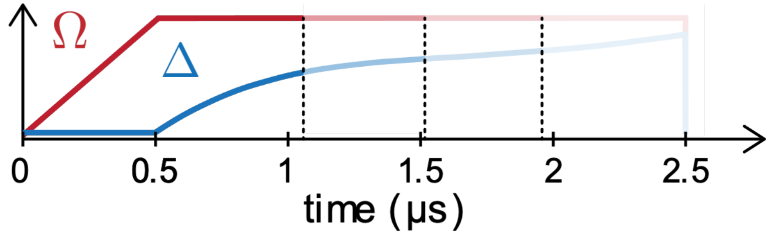
parity of dimers along a string

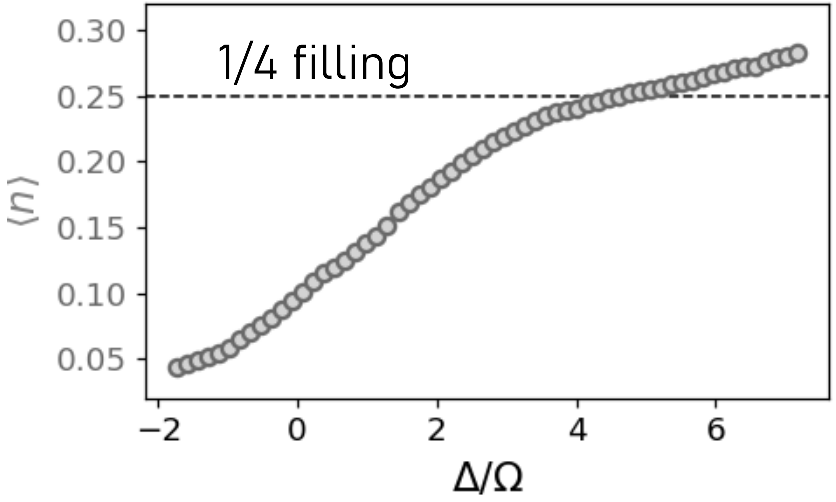
topological string operators associated with a $\mathbb{Z}_2$ quantum spin liquid (toric code)



G. Semeghini et al., Science 374, 1242 (2021)

Topological phases: Quantum spin liquid





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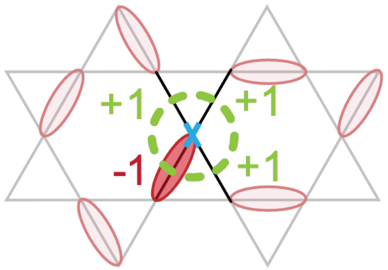
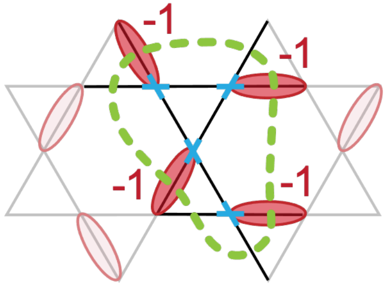
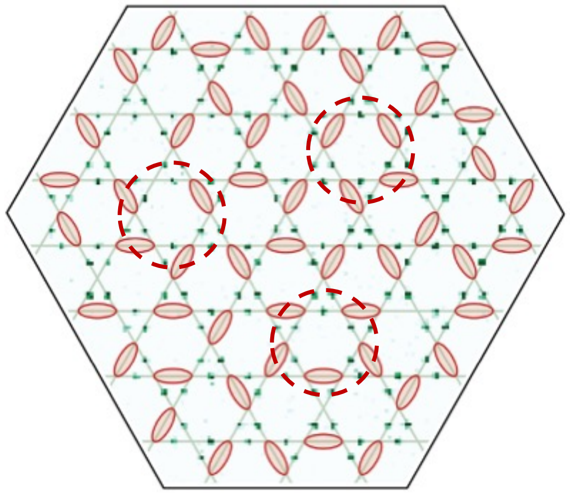




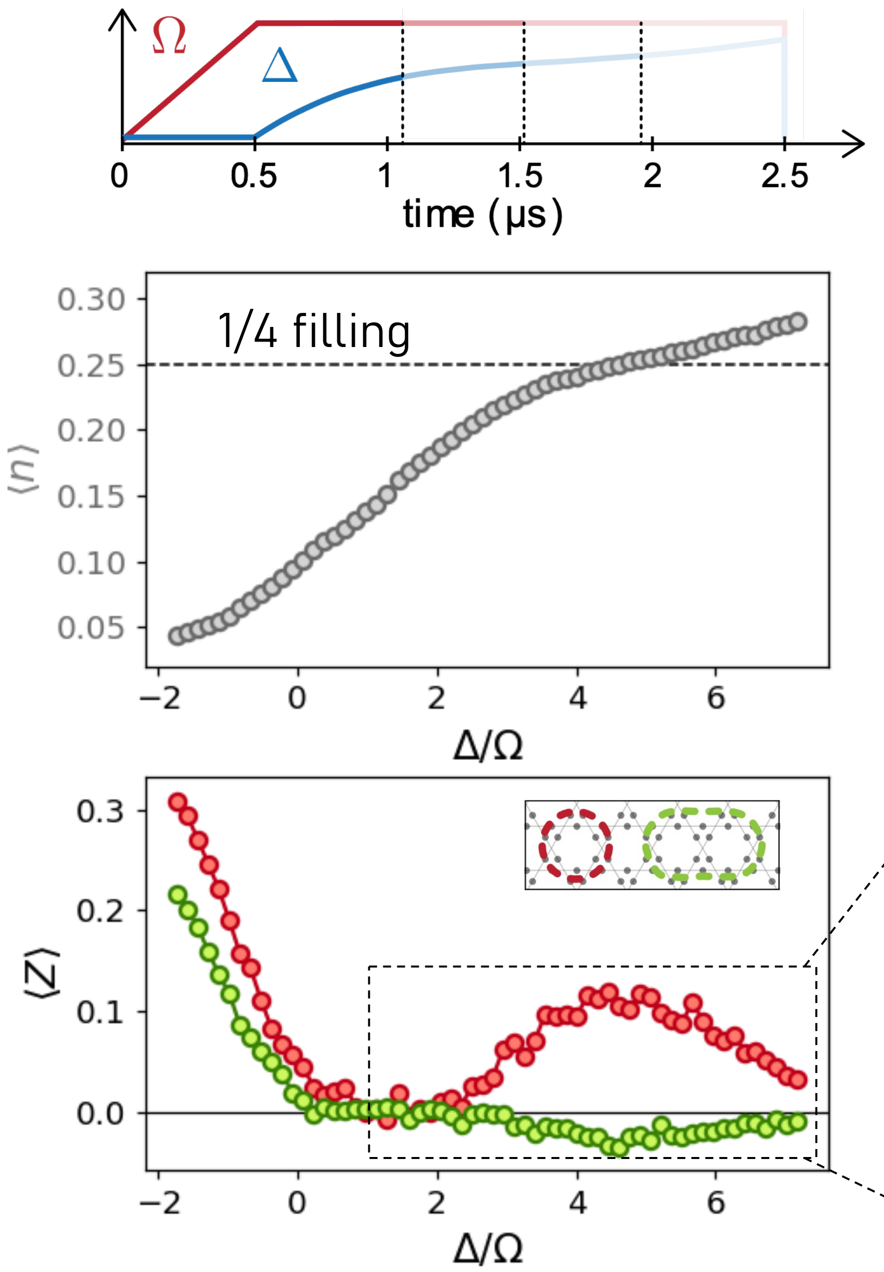
parity of dimers along a string



fluorescence imaging:
atoms in $|r\rangle$ are identified as losses
→ marked as dimers

G. Semeghini et al., Science 374, 1242 (2021)

Topological phases: Quantum spin liquid



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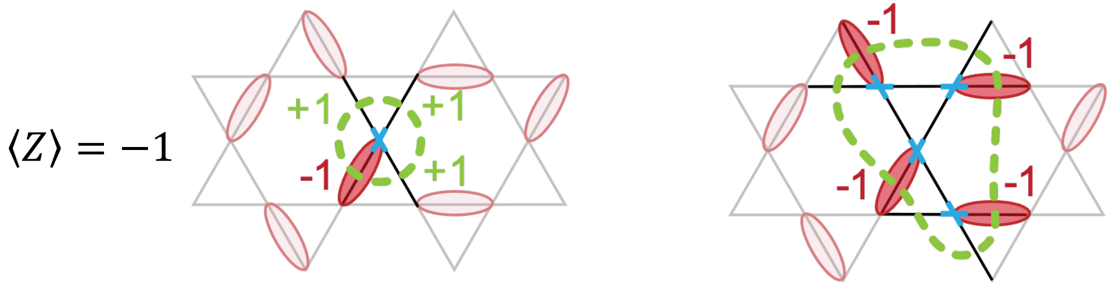
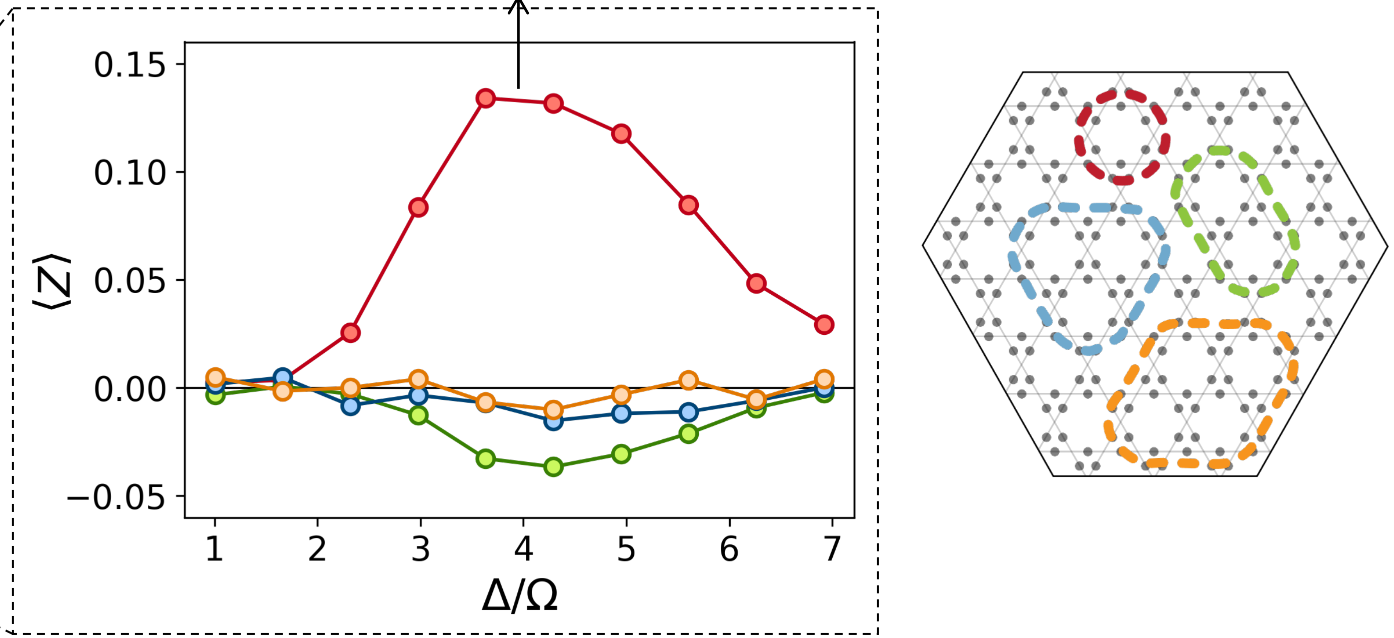
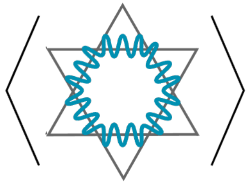


parity of dimers along a string

transition into an approximate dimer phase

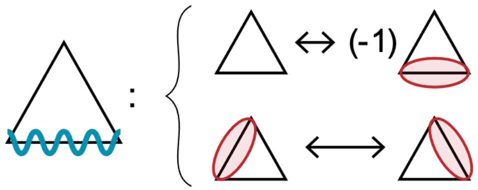


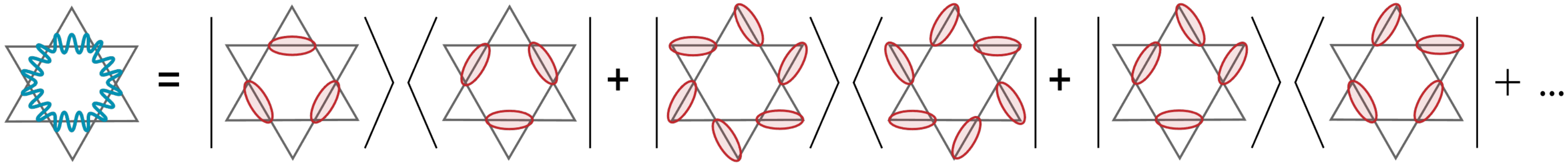
Topological phases: Quantum spin liquid



> 0 ⟶ coherence between dimer coverings

off-diagonal string operator X:

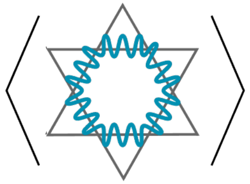




R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)

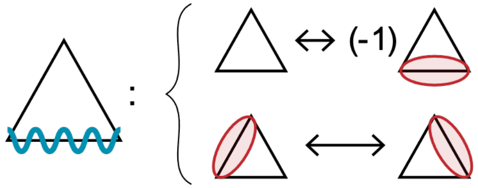
G. Semeghini et al., Science 374, 1242 (2021)

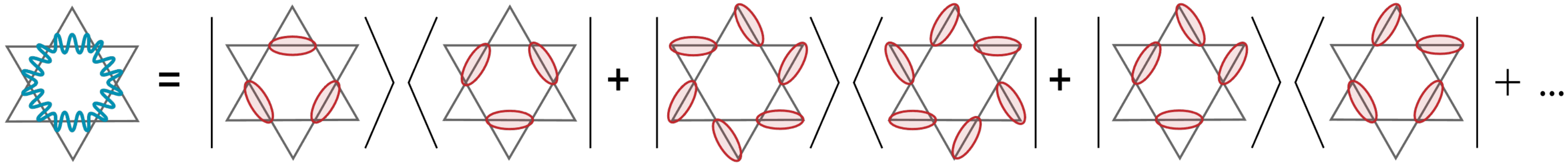
Topological phases: Quantum spin liquid



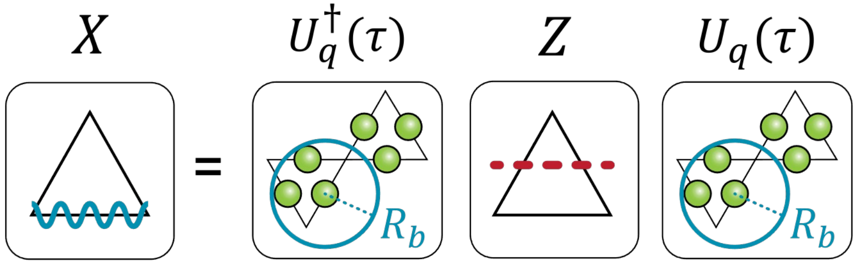
$> 0 \longrightarrow$ coherence between dimer coverings

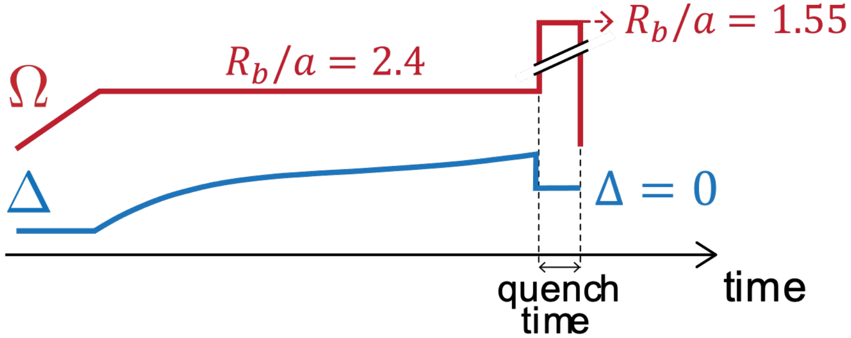
off-diagonal string operator X:





basis rotation to measure X:





R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)

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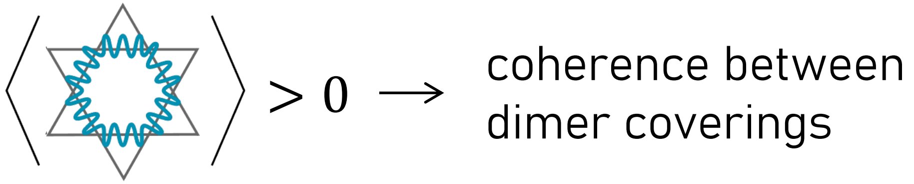
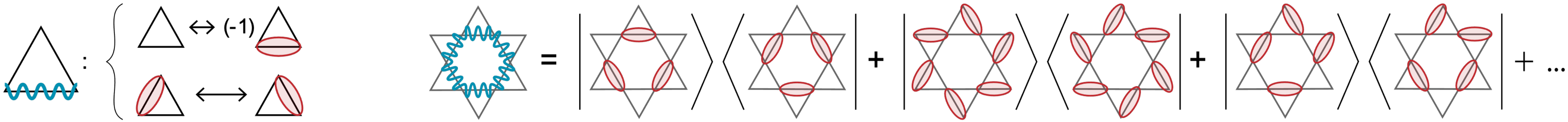
Topological phases: Quantum spin liquid



off-diagonal string operator X:



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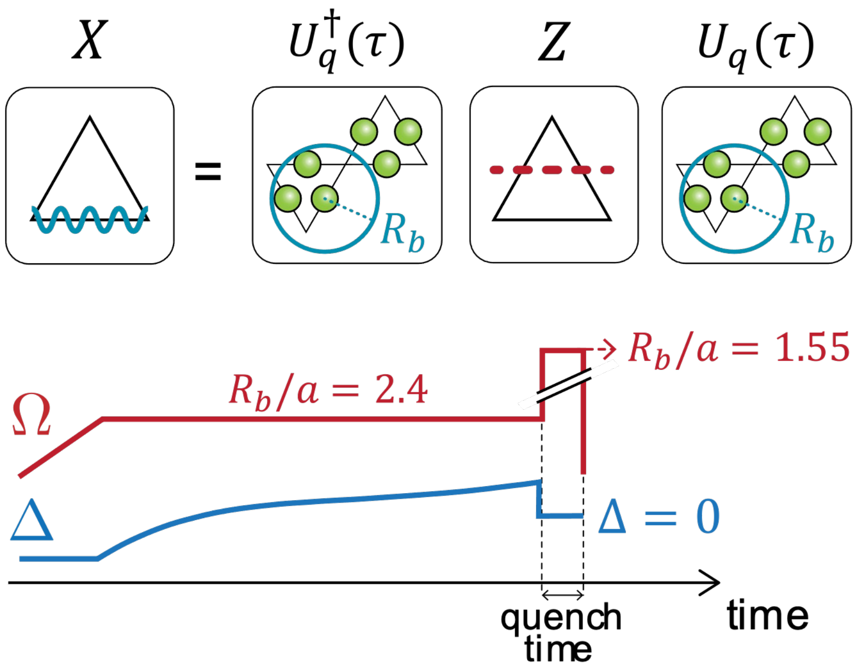
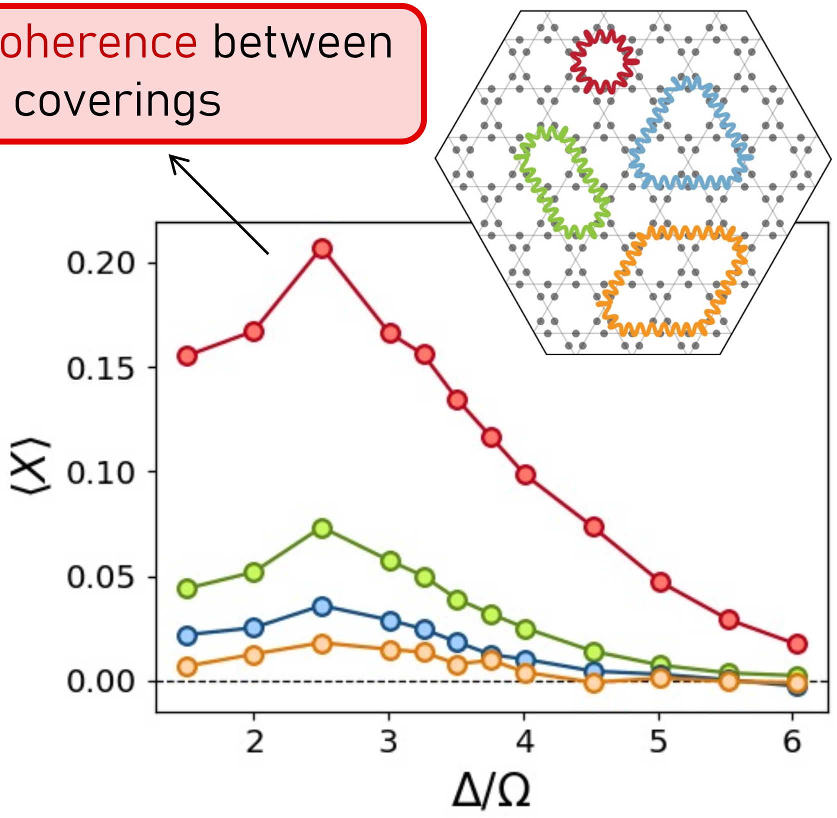


signature of coherence between dimer coverings



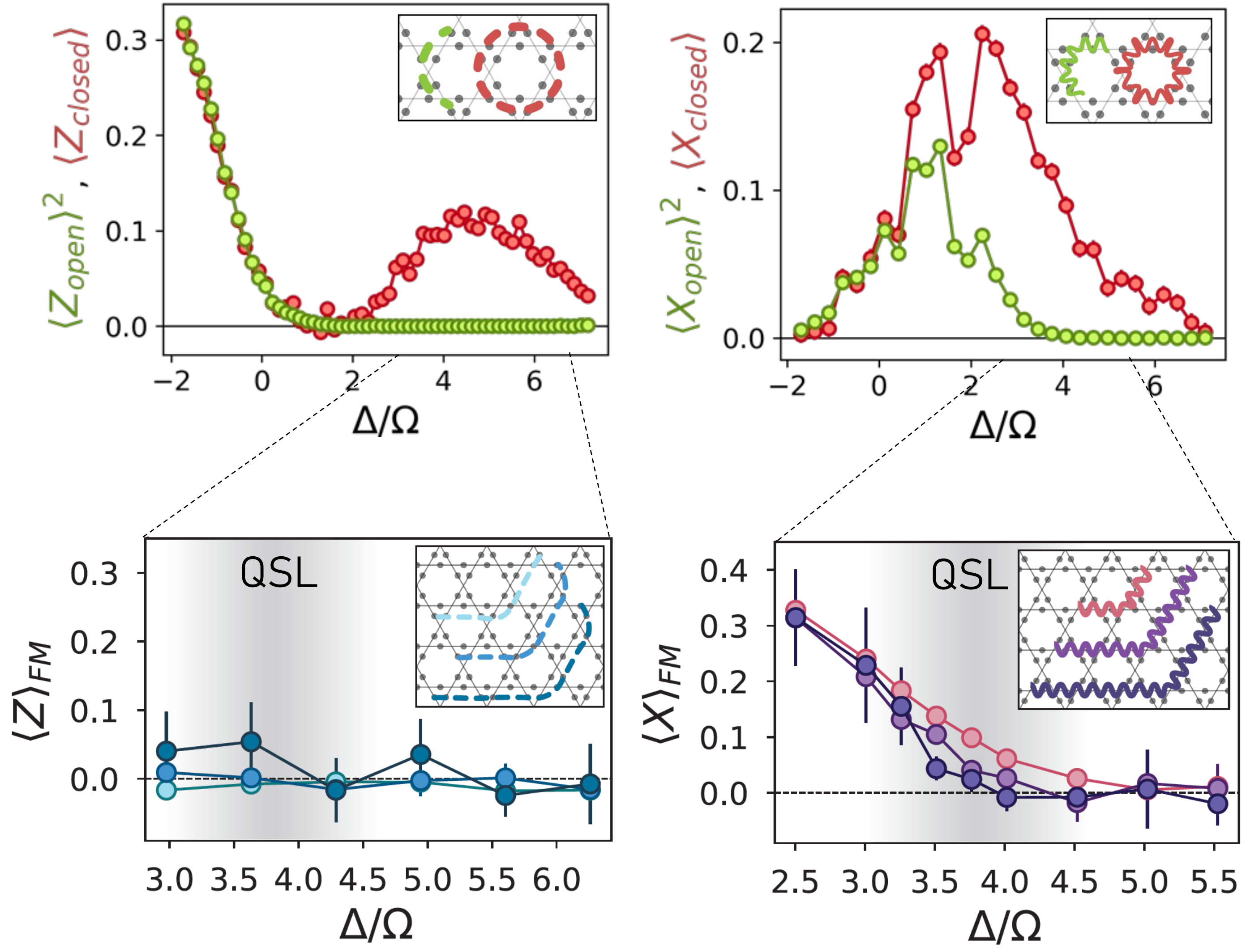
R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)

G. Semeghini et al., Science 374, 1242 (2021)

Topological phases: Quantum spin liquid

Order parameters?

closed loops vs open strings



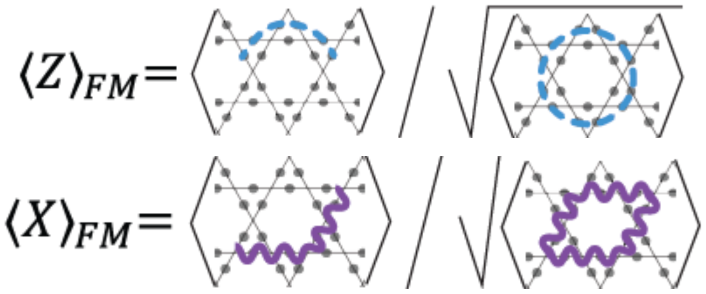
R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)
G. Semeghini et al., Science 374, 1242 (2021)

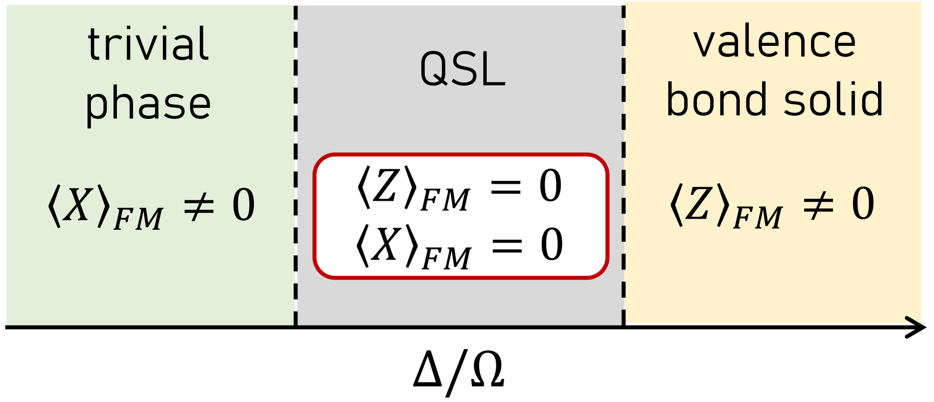
closed loops: detect non-trivial topological correlations

open strings: distinguish QSL from nearby phases

↓

FM string order parameters:





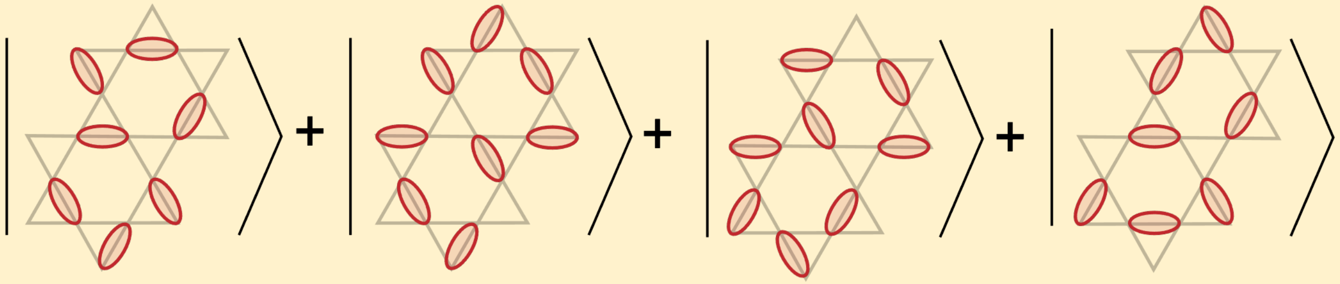
K. Fredenhagen and M. Marcu, Comm. Math. Phys. 92 (1983)

Topol… …rivial

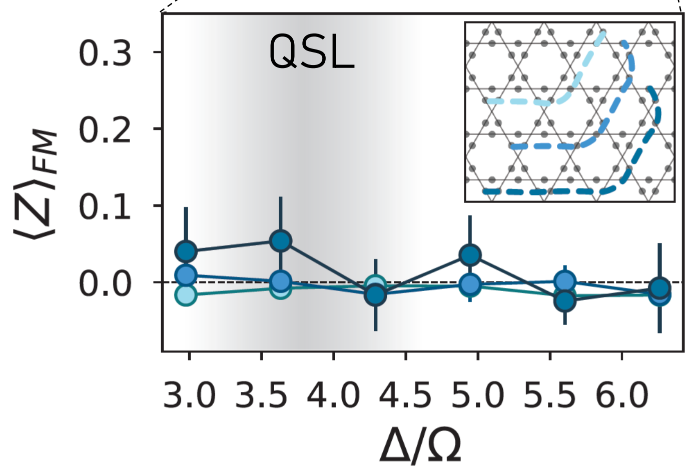
- $|\langle Z_{loop}\rangle| > 0 \longrightarrow$ dimer phase
- $\langle X_{loop}\rangle > 0 \longrightarrow$ coherent superposition
- $\langle Z\rangle_{FM} = 0,\ \langle X\rangle_{FM} = 0 \longrightarrow$ exclude trivial phases

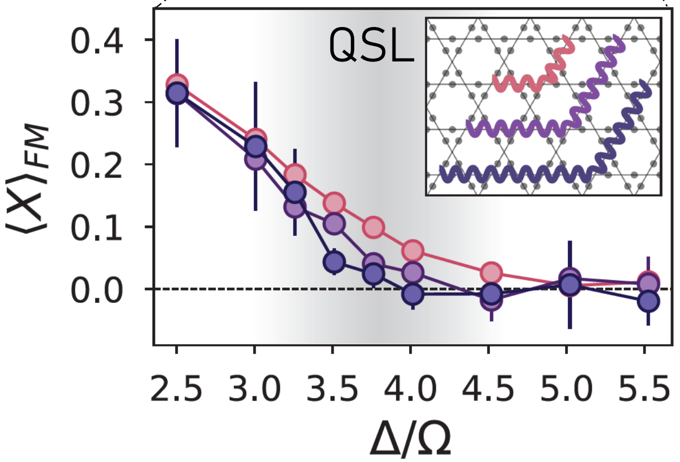
onset of a quantum spin liquid phase!

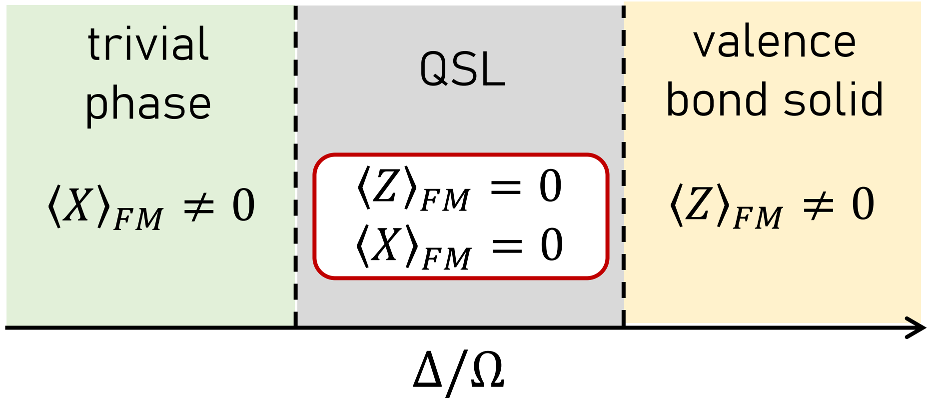
$|\psi_{QSL}\rangle$ = | … ⟩ + | … ⟩ + | … ⟩ + | … ⟩ + …



$\langle Z_{open}\rangle^2$, $\langle Z_{closed}\rangle$







R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)
G. Semeghini et al., Science 374, 1242 (2021)
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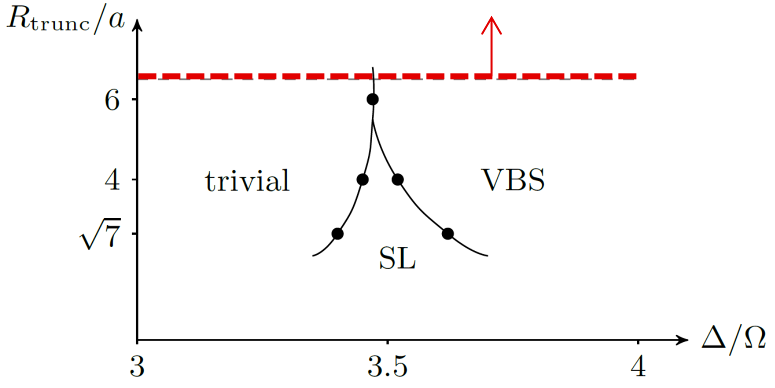
R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)
G. Semeghini et al., Science 374, 1242 (2021)

Understanding experimental observations

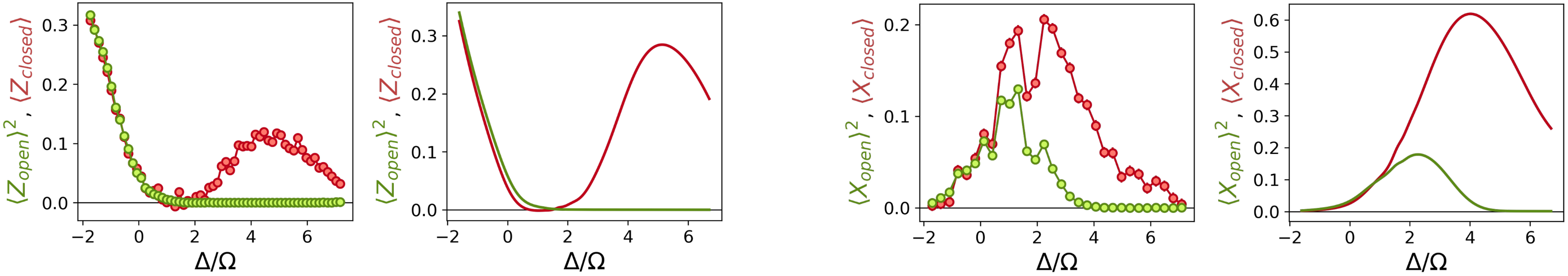
- quantum dynamics of a 219-atom system:
  not possible to simulate classically

long-range interactions result in Valence Bond Solid as the ground state (for the current lattice geometry)



- ground state properties:
  DMRG on a cylinder with periodic boundary conditions
  show that long-range interactions destabilize spin liquids!

- quasi-adiabatic state preparation: time-dependent DMRG simulations on a small system
  state with SL properties; qualitative agreement with experiment



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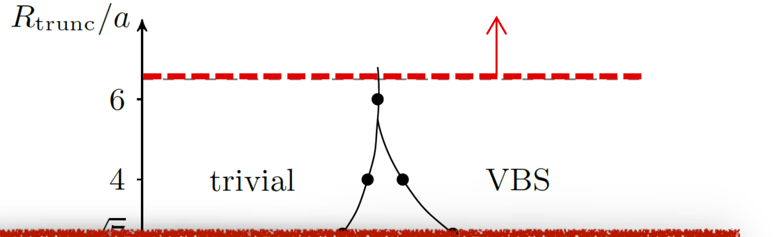
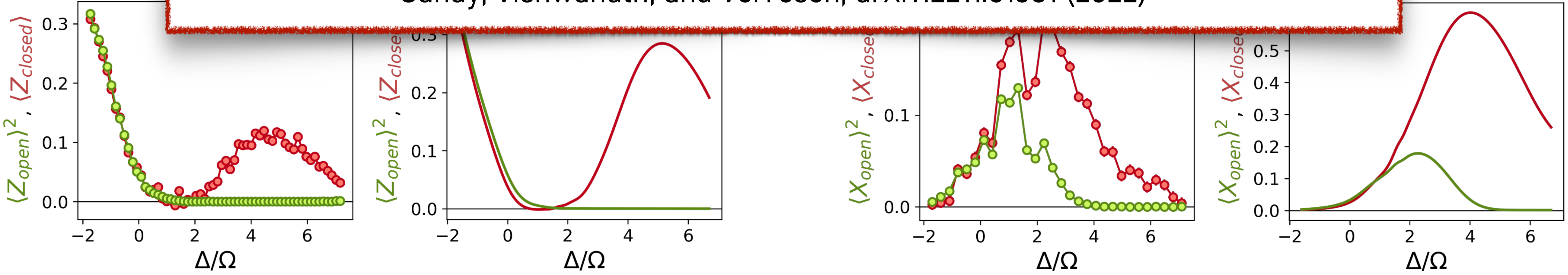


- ground state properties:
  DMRG on a cylinder with periodic boundary conditions
  show th

- quasi-ad

metastable spin liquid state ?
(similar to atomic BEC – ground state is a solid!)

more recent theoretical understanding from:
Giudici, Lukin, and Pichler, PRL 129, 090401 (2022)
Sahay, Vishwanath, and Verresen, arXiv:2211.01381 (2022)

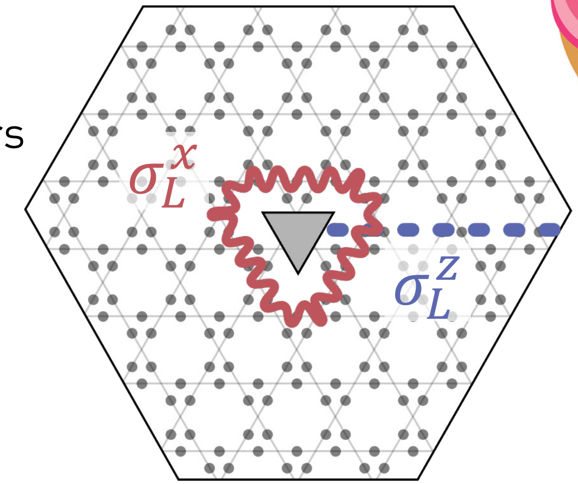


Topological phases: Quantum spin liquid

Topological qubit?

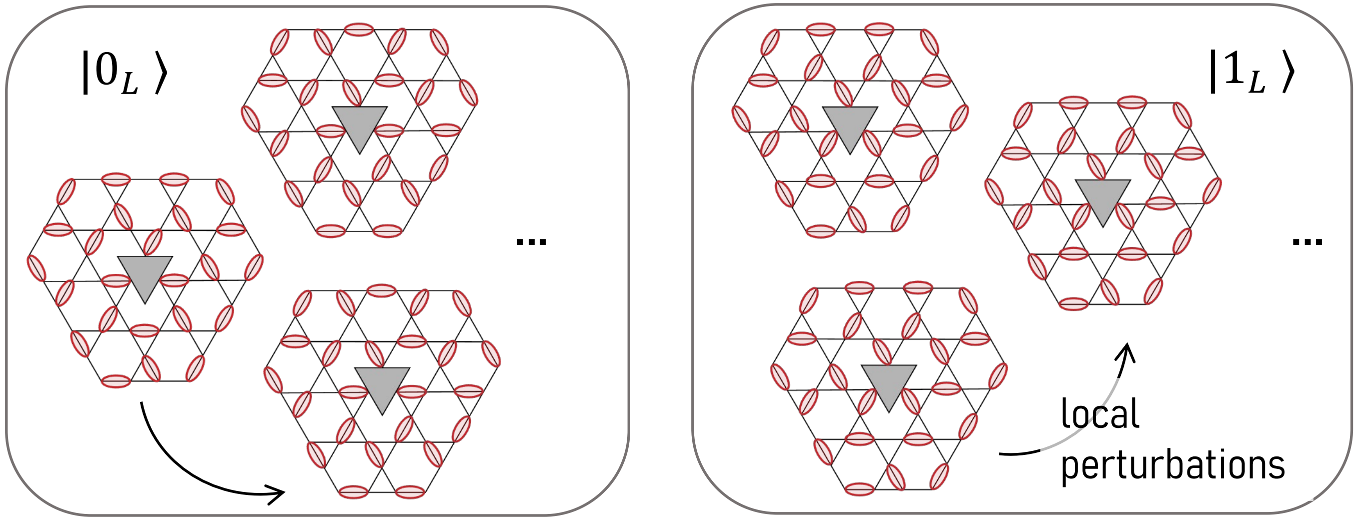
non-trivial topology: array with a **hole**

logical operators



→ topological protection

dimer states separate into two distinct topological sectors:

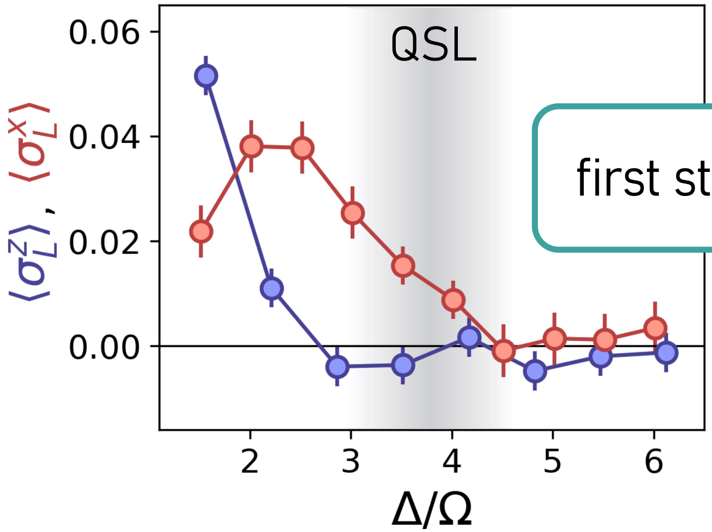


$|0_L\rangle \longrightarrow \langle\sigma_L^z\rangle = -1$

$|1_L\rangle \longrightarrow \langle\sigma_L^z\rangle = +1$

$$|+\rangle \sim \frac{|0_L\rangle + |1_L\rangle}{\sqrt{2}} \longrightarrow \langle\sigma_L^x\rangle = +1$$

$$|-\rangle \sim \frac{|0_L\rangle - |1_L\rangle}{\sqrt{2}} \longrightarrow \langle\sigma_L^x\rangle = -1$$



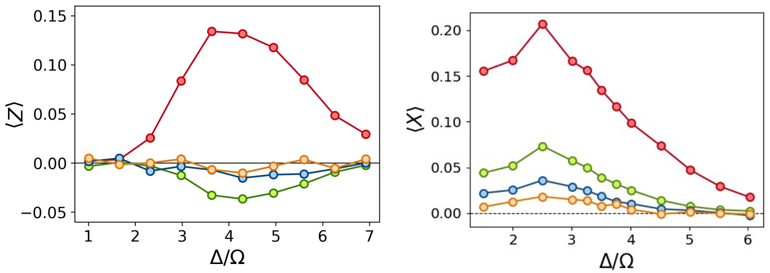
first steps towards a topological qubit!

G. Semeghini et al., Science 374, 1242 (2021)

See related work form Google group: Science 374 (2021) and arXiv:2210.10255

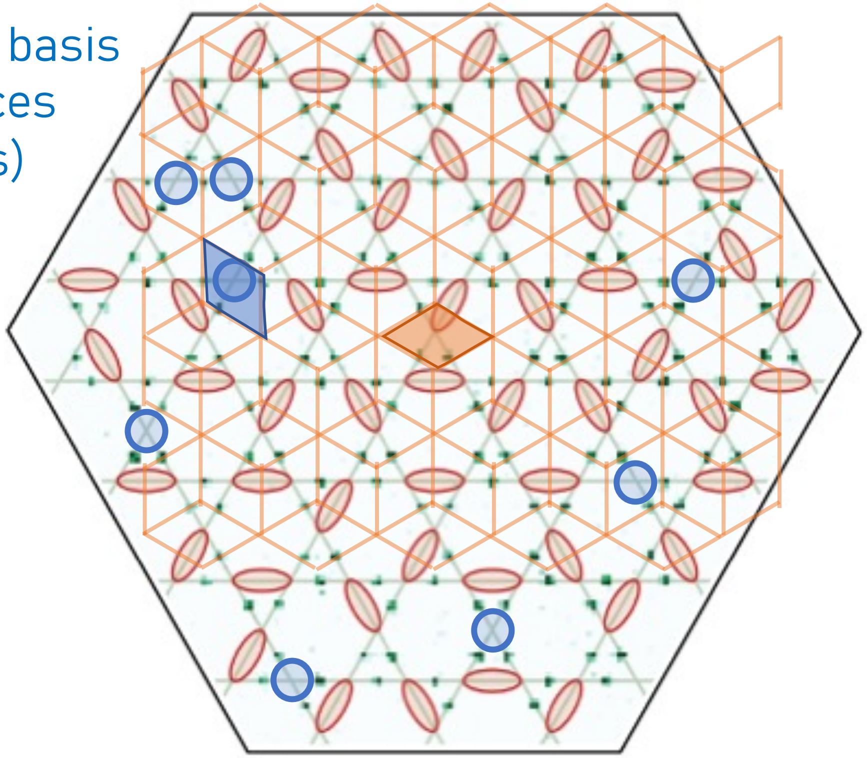
Topological phases: Quantum spin liquid

Enhancing detection of topological order

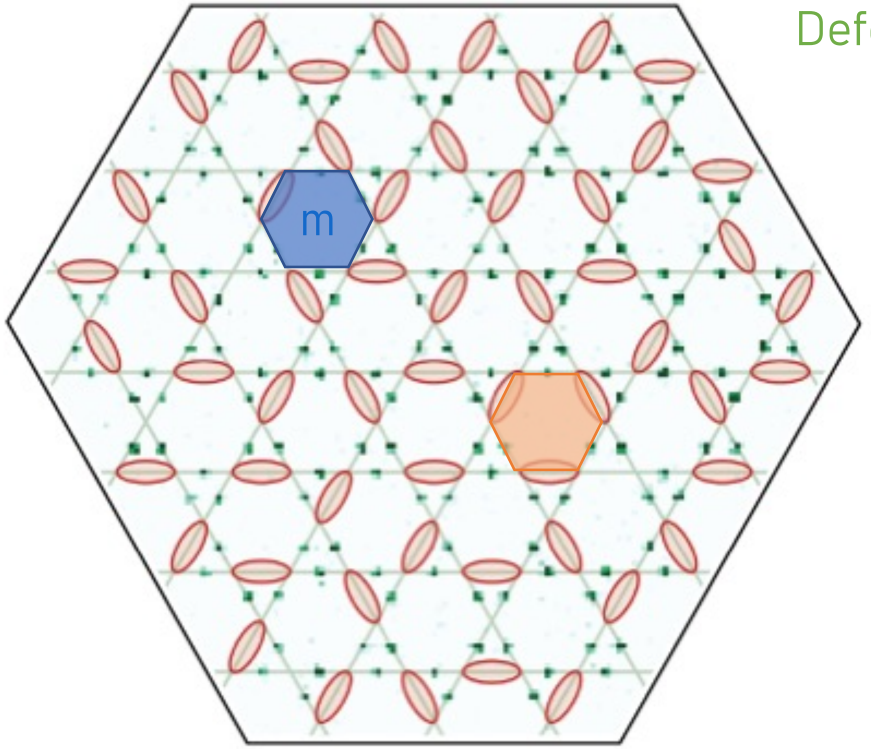


$|\langle Z\rangle|, |\langle X\rangle| < 1$,
decreasing with loop size → prepared state ≠ fixed-point of the dimer model, due to coherent perturbations and incoherent errors

Defects in the Z basis
(empty vertices
→ e-anyons)



detect measuring syndromes
on Z plaquettes



detect measuring syndromes
on X plaquettes

Defects in the X basis
(phase errors
→ m-anyons)

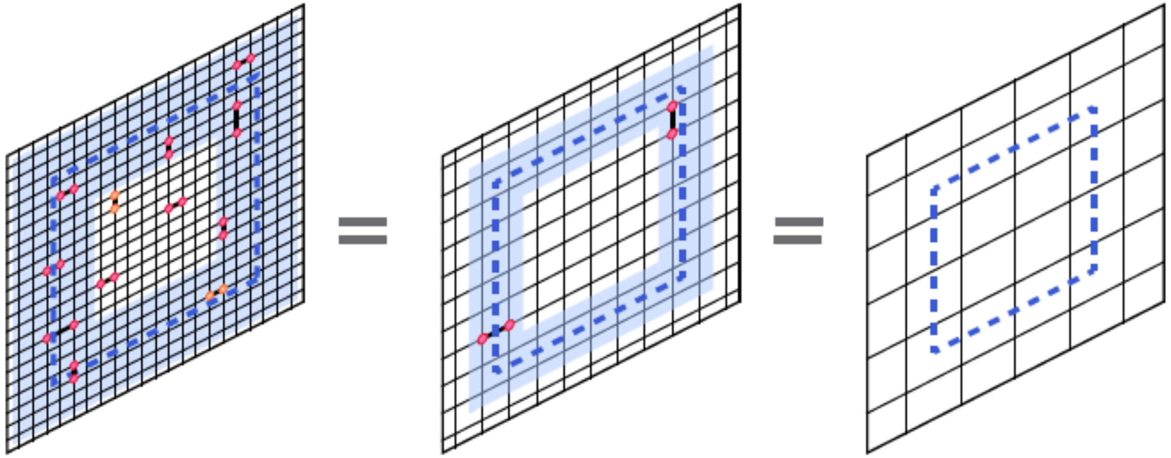
Topological phases: Quantum spin liquid

I. Cong et al, arXiv:2209.12428 (2022)

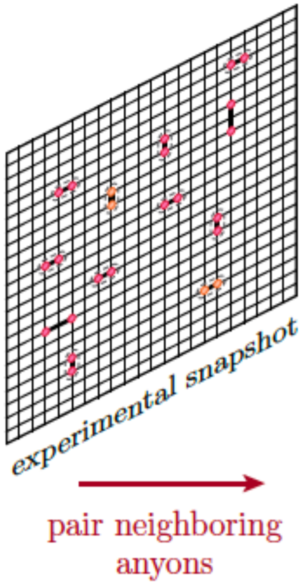
Enhancing detection of topological order

Idea: local error correction
+ coarse graining (RG flow)

decorated ('fattened')
loop operators



Error correction =
anyon pairing



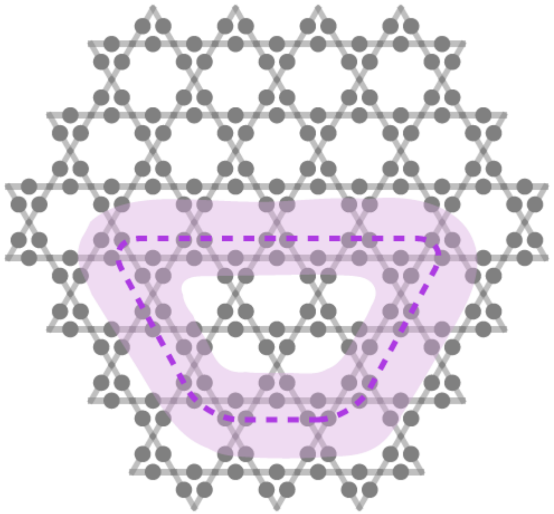
Hastings, Levin, Wen (2005)

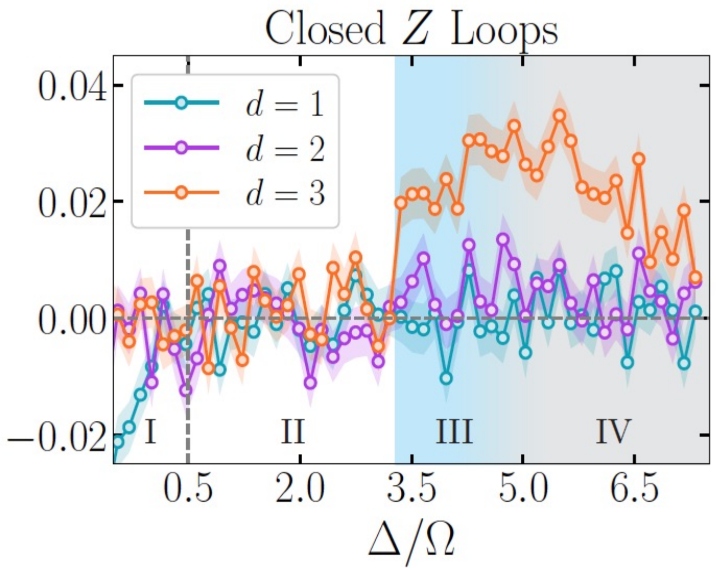
Topological phases: Quantum spin liquid

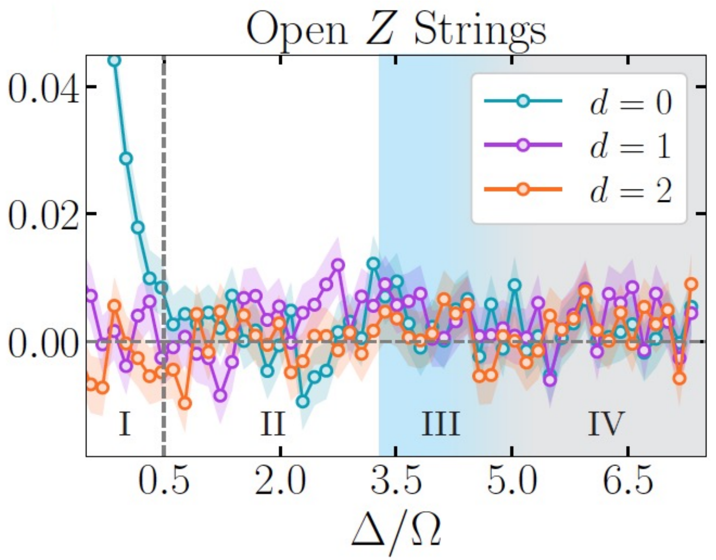
Enhancing detection of topological order

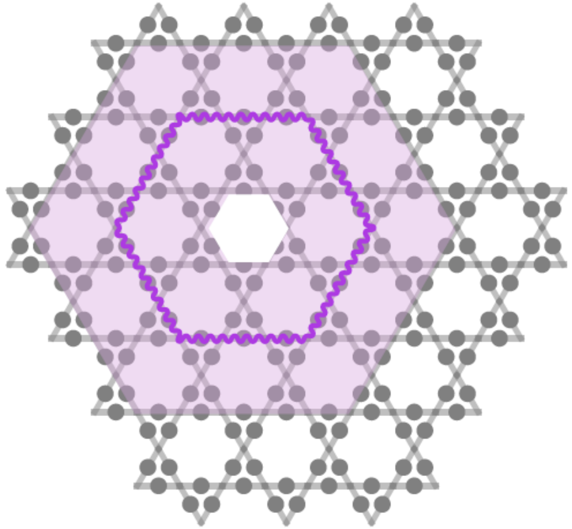
Post-processing of experimental data

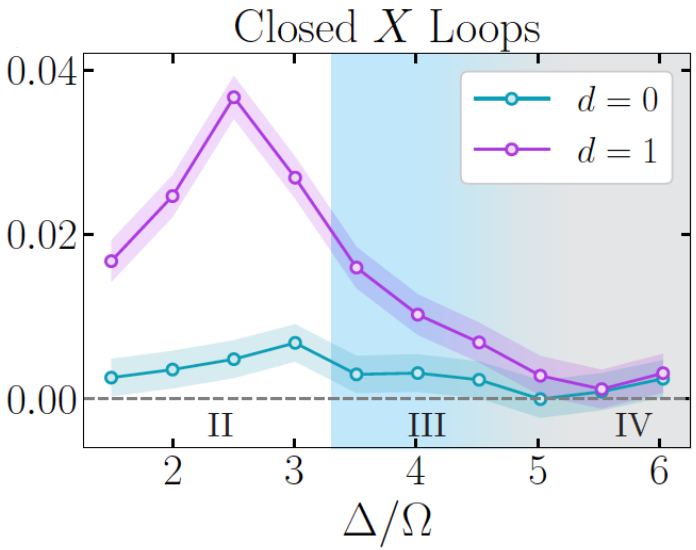
d = correction distance

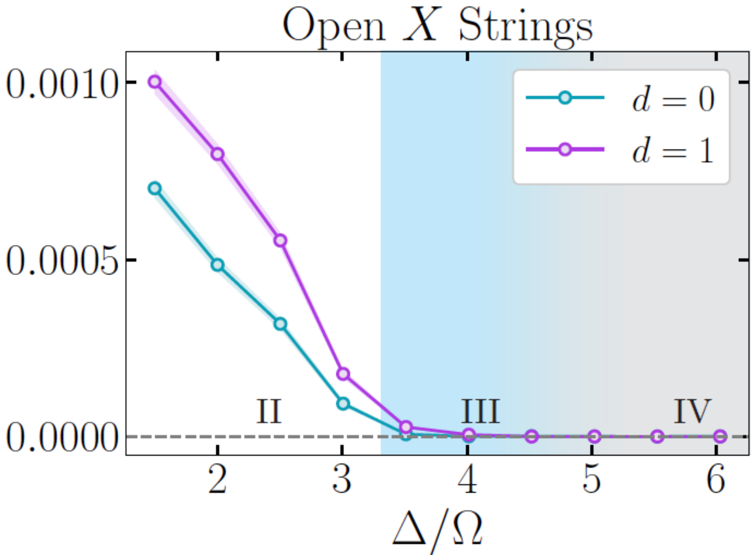










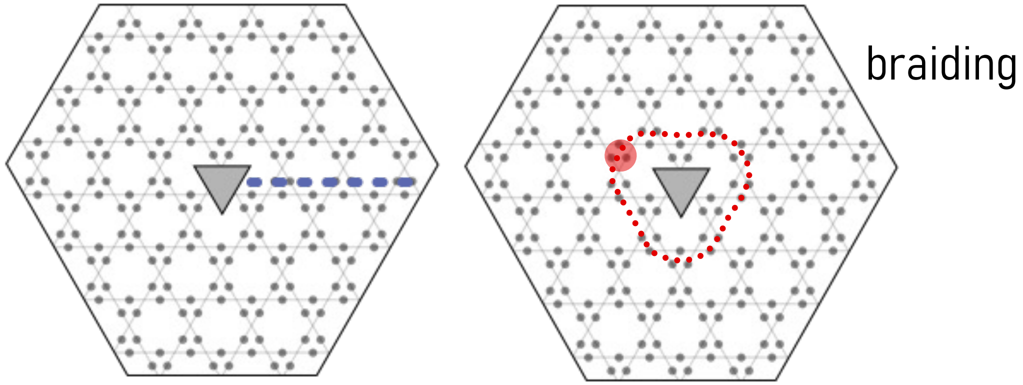


Topological phases: Quantum spin liquid

What's next?

- Topological qubit encoding and manipulation

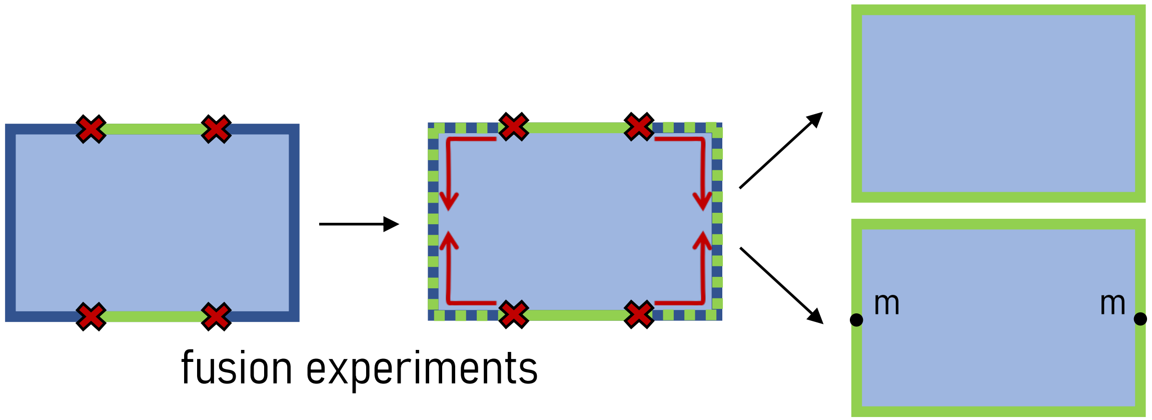
⟶ study of Abelian anyons



- Engineering alternating m- and e- boundaries

⟶ non-Abelian anyons at the intersections

collaboration with S. Choi and B. Kang at MIT,
H. Pichler in Innsbruck

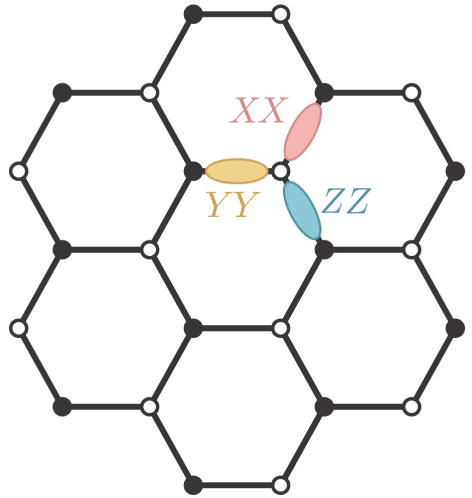


More topological phases with Rydberg atom arrays

A. Kitaev, Ann Phys-New York 321, 2 (2006)
M. Kalinowski, N. Maskara, M. Lukin, arXiv:2211.00017 (2022)

Non-Abelian topological phases?

Kitaev honeycomb model



Anisotropic interactions

$$H_0 = -J_X \sum_{\langle i,j \rangle_X} X_i X_j - J_Y \sum_{\langle i,j \rangle_Y} Y_i Y_j - J_Z \sum_{\langle i,j \rangle_Z} Z_i Z_j$$

H_X $\quad$ H_Y $\quad$ H_Z

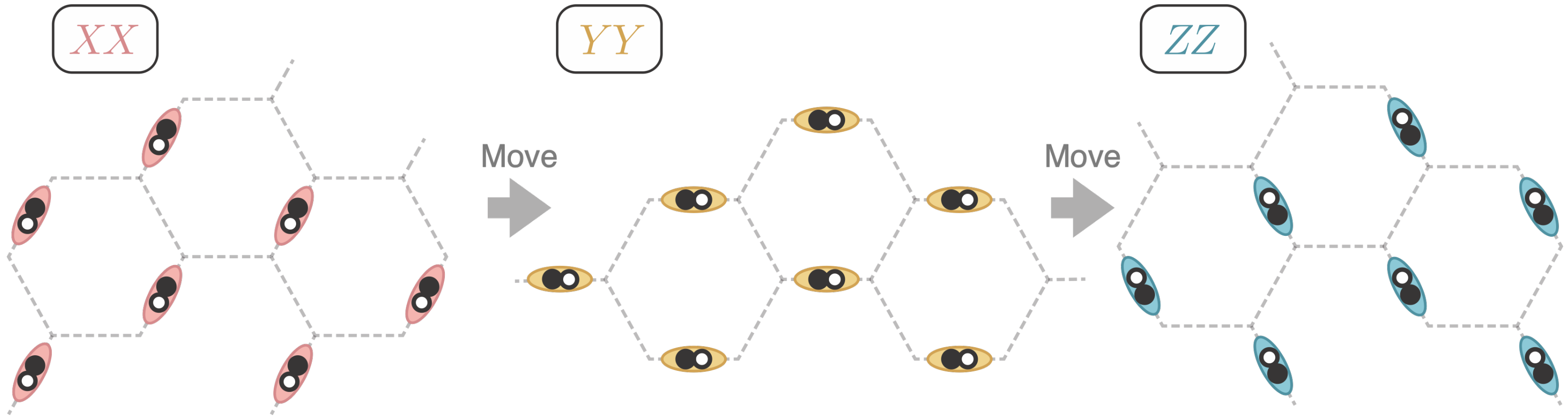
Floquet engineering

periodic drive
→ effective static Hamiltonian

+

Atom transport

to change connectivity between layers of quantum operations



Time-reversal symmetry breaking terms

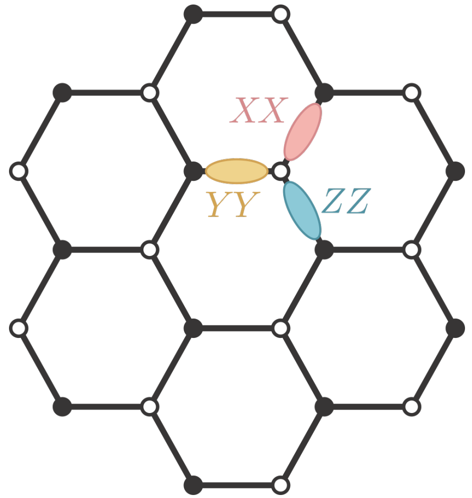
$$U(\tau) = e^{-iH_X\tau} e^{-iH_Y\tau} e^{-iH_Z\tau} = e^{-iH_F[\tau]\tau} \longrightarrow H_F[\tau] = H_0 + \frac{1}{2}\tau[H_X, H_Y] + \frac{1}{2}\tau[H_X, H_Z + \frac{1}{2}\tau[H_Y, H_Z]) + O(\tau^2)$$

More topological phases with Rydberg atom arrays

A. Kitaev, Ann Phys-New York 321, 2 (2006)
M. Kalinowski, N. Maskara, M. Lukin, arXiv:2211.00017 (2022)

Non-Abelian topological phases?

Kitaev honeycomb model



Anisotropic interactions

$$H_0 = -\underbrace{J_X \sum_{\langle i,j \rangle_X} X_i X_j}_{H_X} - \underbrace{J_Y \sum_{\langle i,j \rangle_Y} Y_i Y_j}_{H_Y} - \underbrace{J_Z \sum_{\langle i,j \rangle_Z} Z_i Z_j}_{H_Z}$$

More spin liquid proposals:

Trimer QSL:
- Lee, Oh, Han, and Katsura, PRB 95 (2017)
- Dong, Chen, and Tu, PRB 98 (2018)
- Jandura, Iqbal, and Schuch, PRR 2 (2020)
- Giudice, Surace, Pichler, and Giudici., PRB 106 (2022)

U(1)xU(1) QSL:
- Kornjača*, RS*, … Liu, arXiv:2211.00653 (2022)

Chiral SL:
- Ohler, Kiefer-Emmanouilidis,, and Fleischhauer, PRR 5, 013157 (2023)
- Weber et al., PRX Quantum 3, 030302 (2022)

Time-reversal symmetry breaking terms

$$U(\tau) = e^{-iH_X\tau} e^{-iH_Y\tau} e^{-iH_Z\tau} = e^{-iH_F[\tau]\tau} \longrightarrow H_F[\tau] = H_0 + \boxed{\frac{1}{2}\tau[H_X, H_Y] + \frac{1}{2}\tau[H_X, H_Z + \frac{1}{2}\tau[H_Y, H_Z])} + O(\tau^2)$$

Quantum simulation with Rydberg atom arrays

Many-body phases

"Conventional" phases
(symmetry breaking)

Topological phases

Quantum phase transitions and criticality

(2+1)D Ising QPT

Quantum dynamics

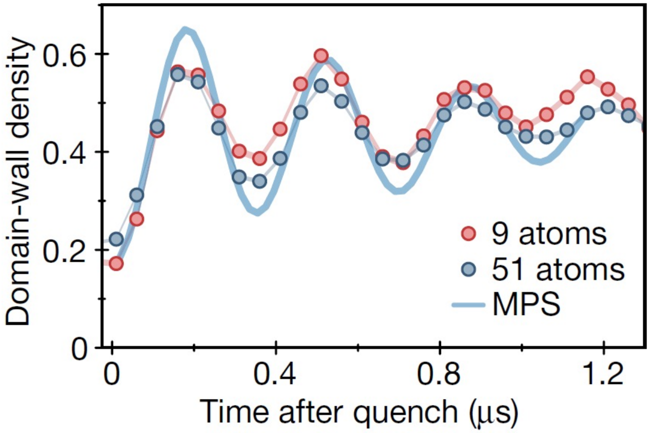
Quantum many-body scars

Quantum dynamics: Quantum many-body scars

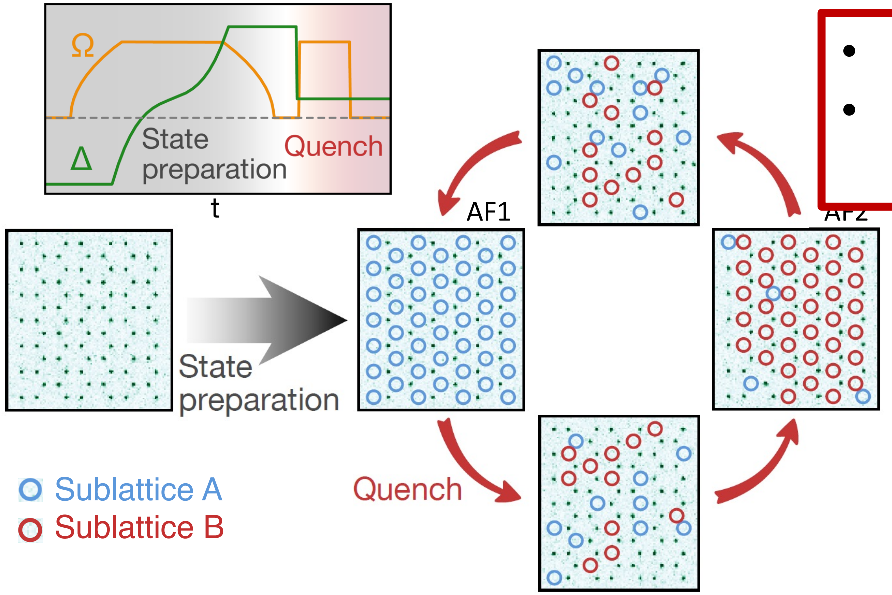
Strongly interacting many-body systems ⟶ Can entangled dynamics be controlled?

Further studies in 2D geometries (Bluvstein et al, Science 2021):

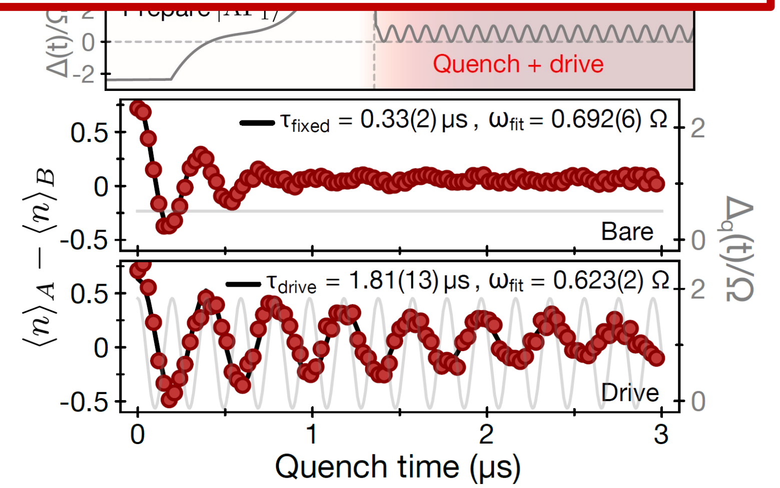
Experiment: 1D arrays of Rydberg atoms
- Persistent oscillations, not relaxing to thermal values after quench



Bernien, et. al. Nature (2017)



- Scars are stabilized by drive!
- Scar frequency changes, to half the drive frequency

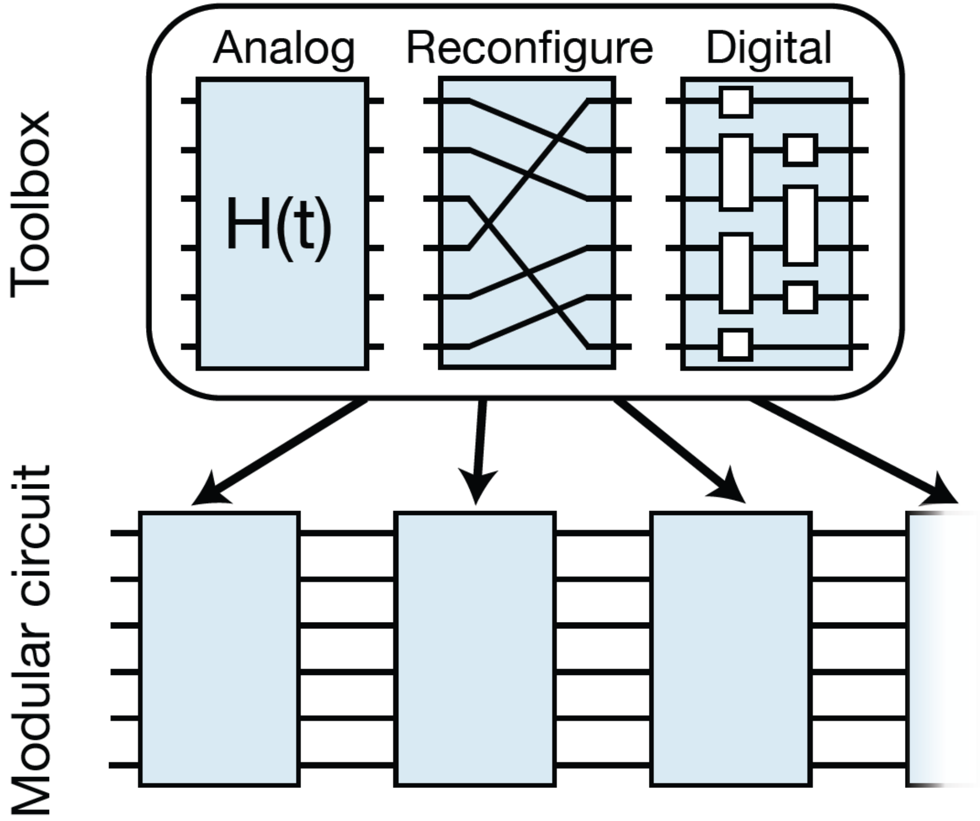


Extensive theoretical efforts to understand this nonthermalizing behavior ⟶ Connection to quantum many-body scars

Heller PRL (1984), Fendley PRB (2004), Lesanovsky PRA (2012), Turner Nat Phys (2018), Lin PRL (2019), Iadecola PRB (2019), Khemani PRB (2019), Sala PRX (2020), Surace PRX (2020), Mukherjee PRB (2020), Michailidis PRX (2020), …

Quantum dynamics: Quantum many-body scars

New tools to probe many-body systems ⟶ Modular and hybrid analog-digital quantum circuits

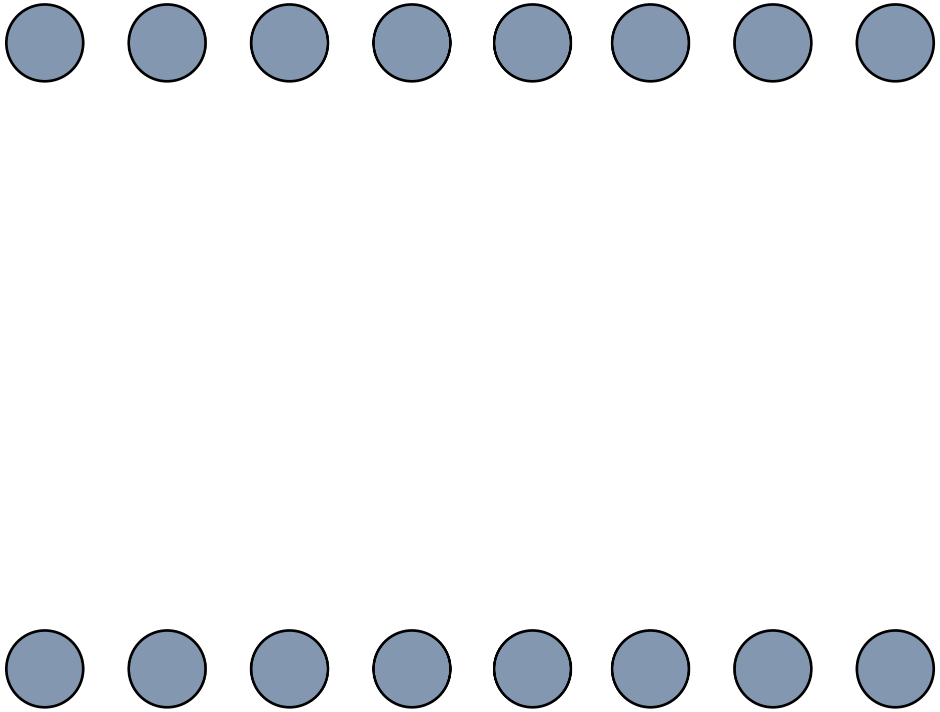


D. Bluvstein, et al, Nature 604, 451-456 (2022)

Quantum dynamics: Quantum many-body scars

Modular and hybrid analog-digital quantum circuits

Measure Renyi entanglement entropy by effectively interfering two copies of a many-body system



Purity $\mathrm{Tr}\left[\rho_A^2\right] = \mathrm{Tr}[S_A \, \rho \otimes \rho]$

Renyi Entropy $S_2 = -\ln\left(\mathrm{Tr}\left[\rho_A^2\right]\right)$

Key idea:
To measure expectation value of SWAP operator, measure occurrences of singlet:
Can be done with a Bell measurement!

$$\frac{|01\rangle - |10\rangle}{\sqrt{2}} = |\Psi^-\rangle$$

Inspired by Islam, Kaufman, … Greiner experiments

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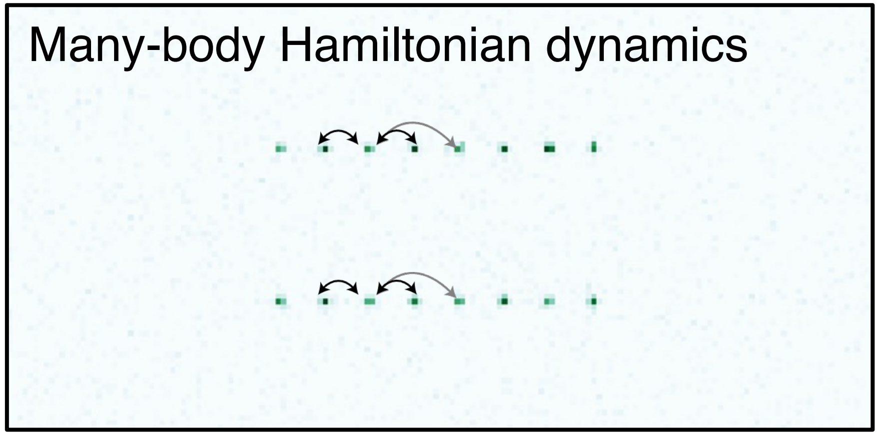

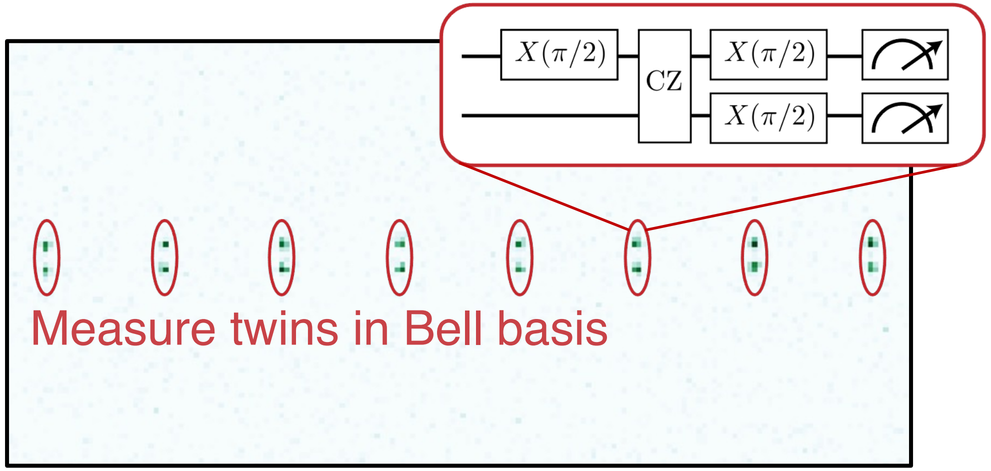

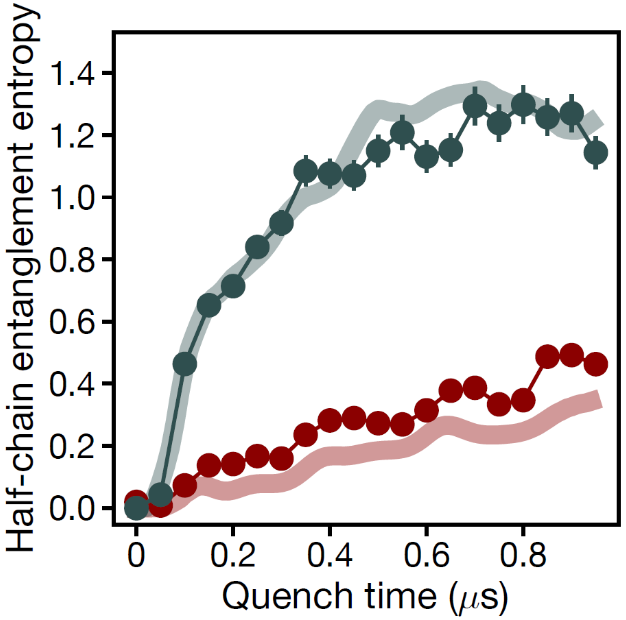

Thermalizing state vs
Non-thermalizing scar state

D. Bluvstein, et al, Nature 604, 451-456 (2022)

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