Title: Exploring new scientific frontiers with programmable atom arrays

Speakers: Mikhail Lukin

Series: Colloquium

Date: April 07, 2021 - 2:00 PM

URL: http://pirsa.org/21040000

Abstract: We will discuss the recent advances involving programmable, coherent manipulation of quantum many-body systems using atom arrays excited into Rydberg states. Specifically, we will describe our recent technical upgrades that now allow the control over 200 atoms in two-dimensional arrays. Recent results involving the realization of exotic phases of matter, study of quantum phase transitions and exploration of their non-equilibrium dynamics will be presented. In particular, we will report on realization and probing of quantum spin liquid states - the exotic states of matter have thus far evaded direct experimental detection. Finally, realization and testing of quantum optimization algorithms using such systems will be discussed.

Exploring new frontiers with programmable quantum systems

Mikhail Lukin
Physics Department, Harvard University

Quantum Science and Engineering: quest for controlling quantum world

✓Isolating & controlling "simple" quantum objects

✓Building complex quantum systems from them

✓New physics with "engineered" many-body systems:
creating and probing new entangled states of matter

✓New applications:
e.g. quantum processing, communication, metrology

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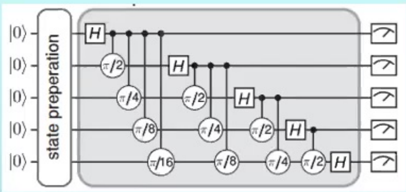
How to build large-scale quantum systems?
How to apply them to achieve useful quantum advantage??

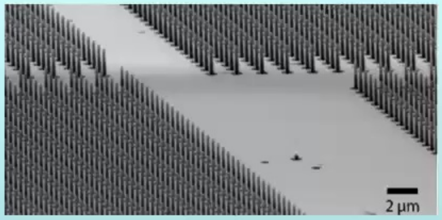
The Ultimate Quantum Rivalry

Two challenges in Quantum Science

Controllability:



Scalability:



Current frontiers:

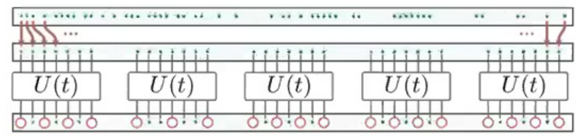
- Tasks beyond modern classical computers with controlled >100 qubit systems
- Building bigger (and better) quantum machines
- Useful algorithms and scientific applications

The age of quantum discovery

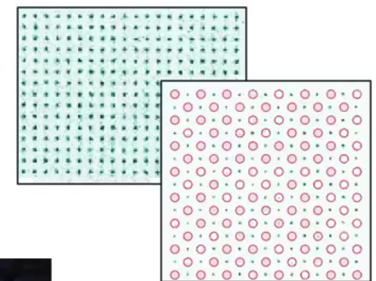
Today's talk

✓ Building scalable quantum systems using Rydberg atom arrays

- Atom-by-atom assembly of strongly interacting quantum matter
- Exploring quantum phase transitions
- Quantum control of large 2D atom arrays

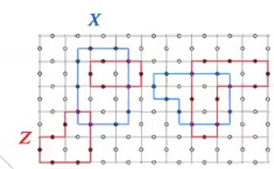


✓ Probing quantum dynamics of many-body systems

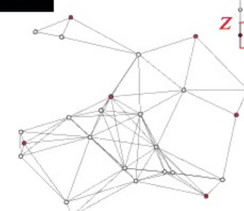


- Quantum phases & phase transitions in 2D spin models
- Non-equilibrium dynamics and many-body scars
- Steering entanglement dynamics

✓ Current efforts and outlook



- From topological spin liquids to quantum optimization



Quantum processors based on cold neutral atoms

Key advantages:

- Excellent coherence properties (think optical clocks)
- Easy to create large number of neutral atoms
- Strongly couple to light

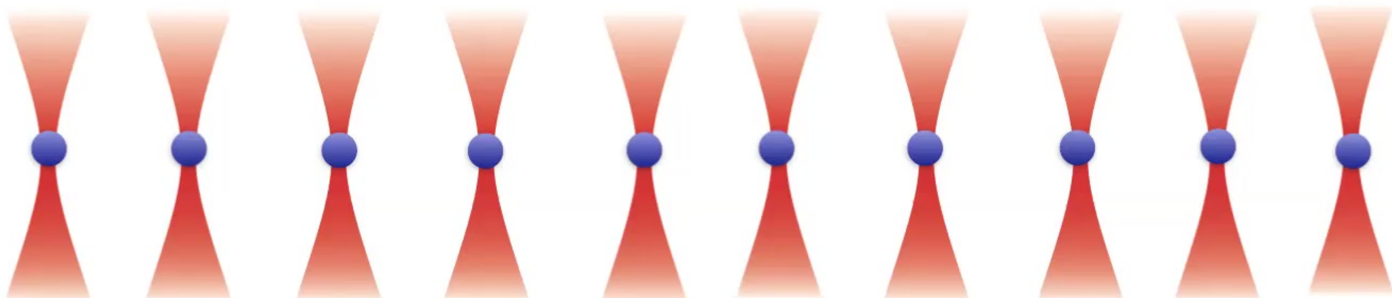
Key challenges:

- Atoms interact weakly
- Neutral atoms are hard to control individually (in large numbers)

Atom-by-atom approach for building scalable quantum systems

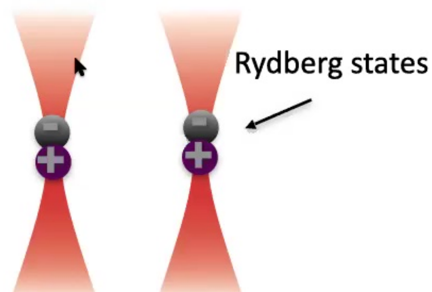
Laser cooled neutral atoms: removing entropy by observation

1. Tightly focused laser trap loads ultra cold atoms from Magneto-Optical Trap
2. Image and remove empty traps
3. Rearrange remaining traps->regular atom array



4. Engineer $\hat{H} = \ldots$

Dipole-dipole

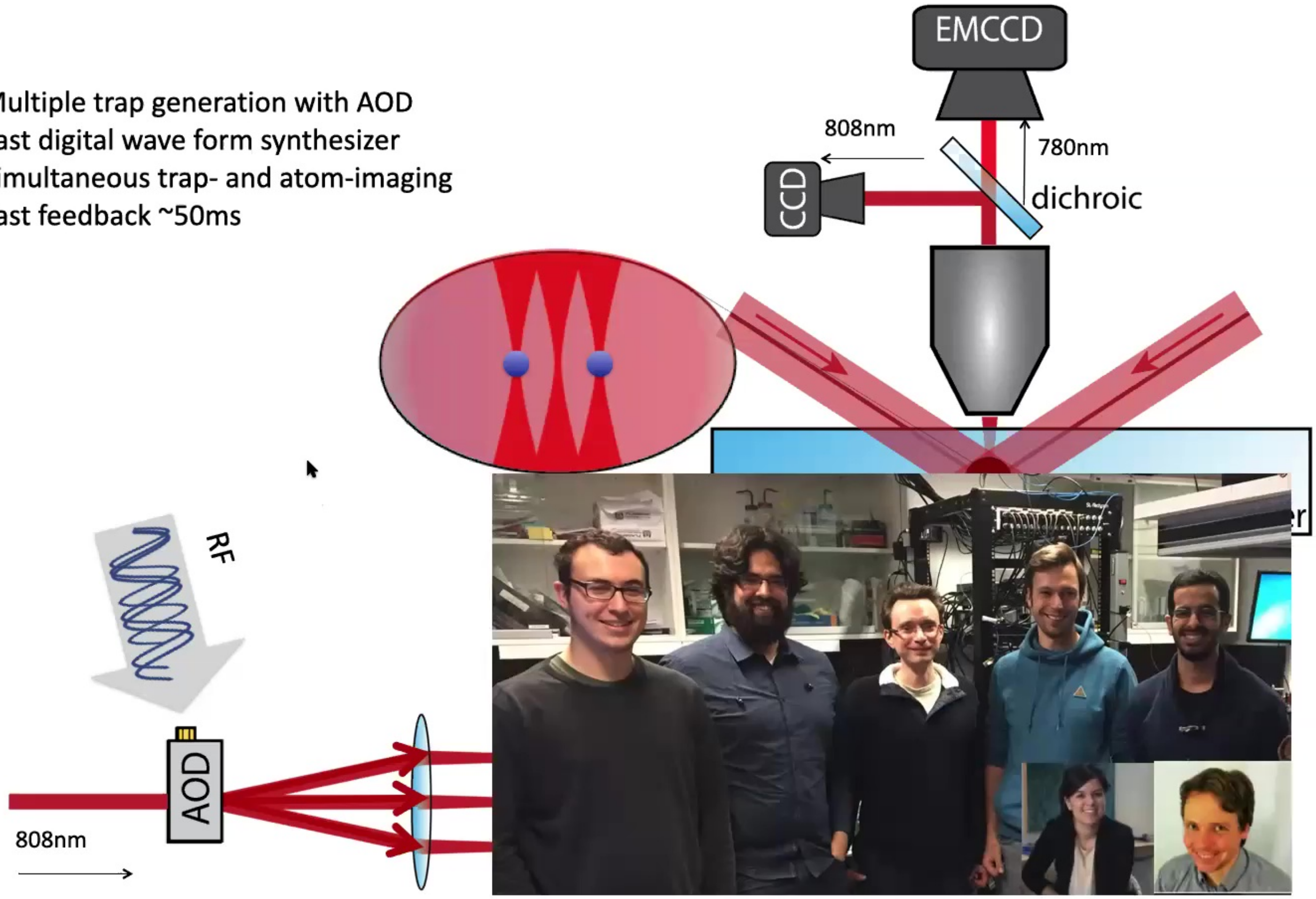


Prior work: Regal, Browaeys groups
A.M. Kaufman, et al., Science **345**, 306 (2014)
H. Labuhn et al., arXiv:1509.04543 (2015)

Hannes Bernien, Sylavin Schwatrz, Alexander Keesling, Harry Levine, Ahmed Omran, Giulia Semeghini
CUA collaboration of Lukin, Greiner & Vuletic groups, Manuel Endres group at Caltech

Experimental setup: first generation

- Multiple trap generation with AOD
- Fast digital wave form synthesizer
- Simultaneous trap- and atom-imaging
- Fast feedback ~50ms



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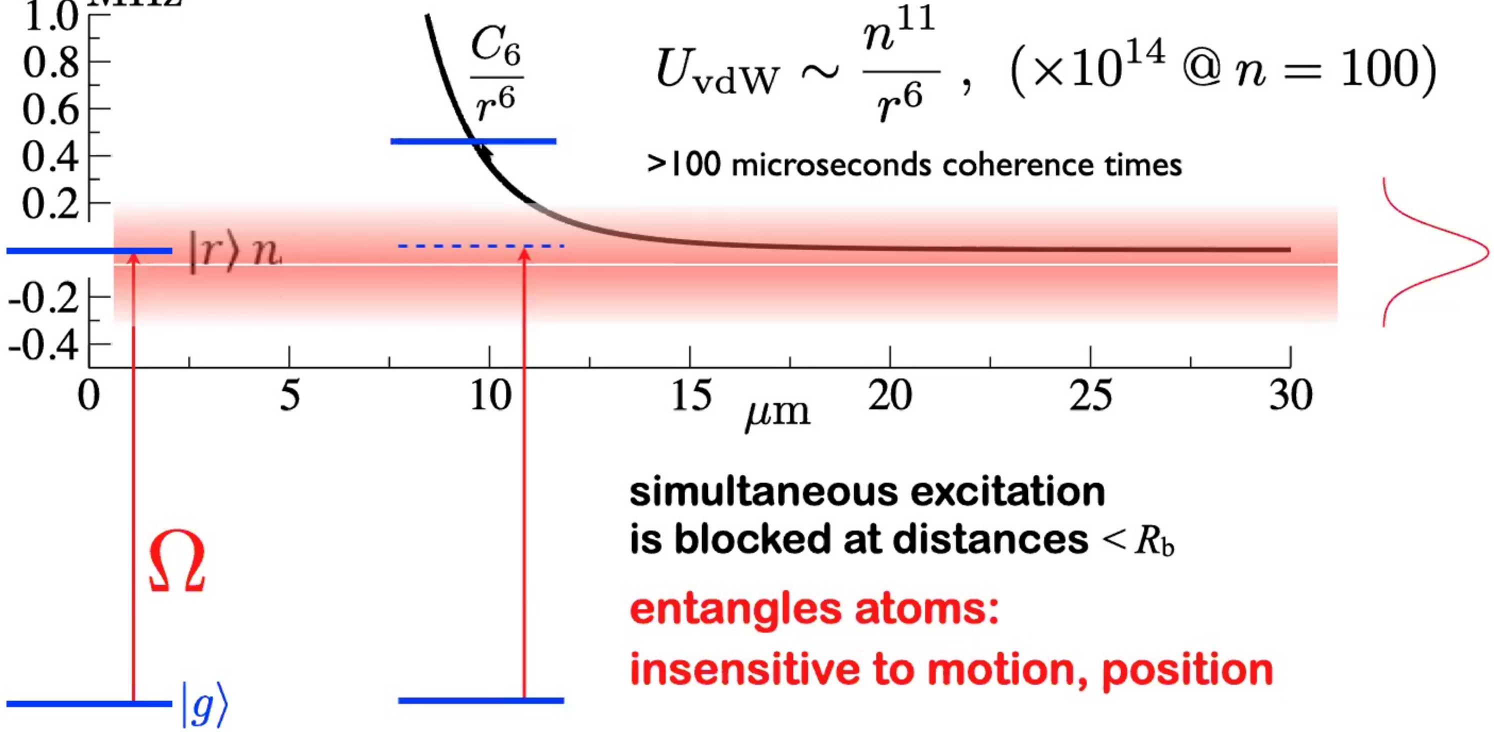
Interactions: Rydberg atoms with larger n

⇒ **long lifetime and strong interaction:**

$$U_{\mathrm{vdW}} \sim \frac{n^{11}}{r^6}\,, \quad (\times 10^{14}\ @\ n = 100)$$

>100 microseconds coherence times



simultaneous excitation
is blocked at distances $< R_b$

entangles atoms:
insensitive to motion, position

$R_b \approx 10\mu m$ **for typical values:** n= 70-100

idea: collaboration with I. Cirac, P. Zoller (2001), first expts Paris, Wisconsin

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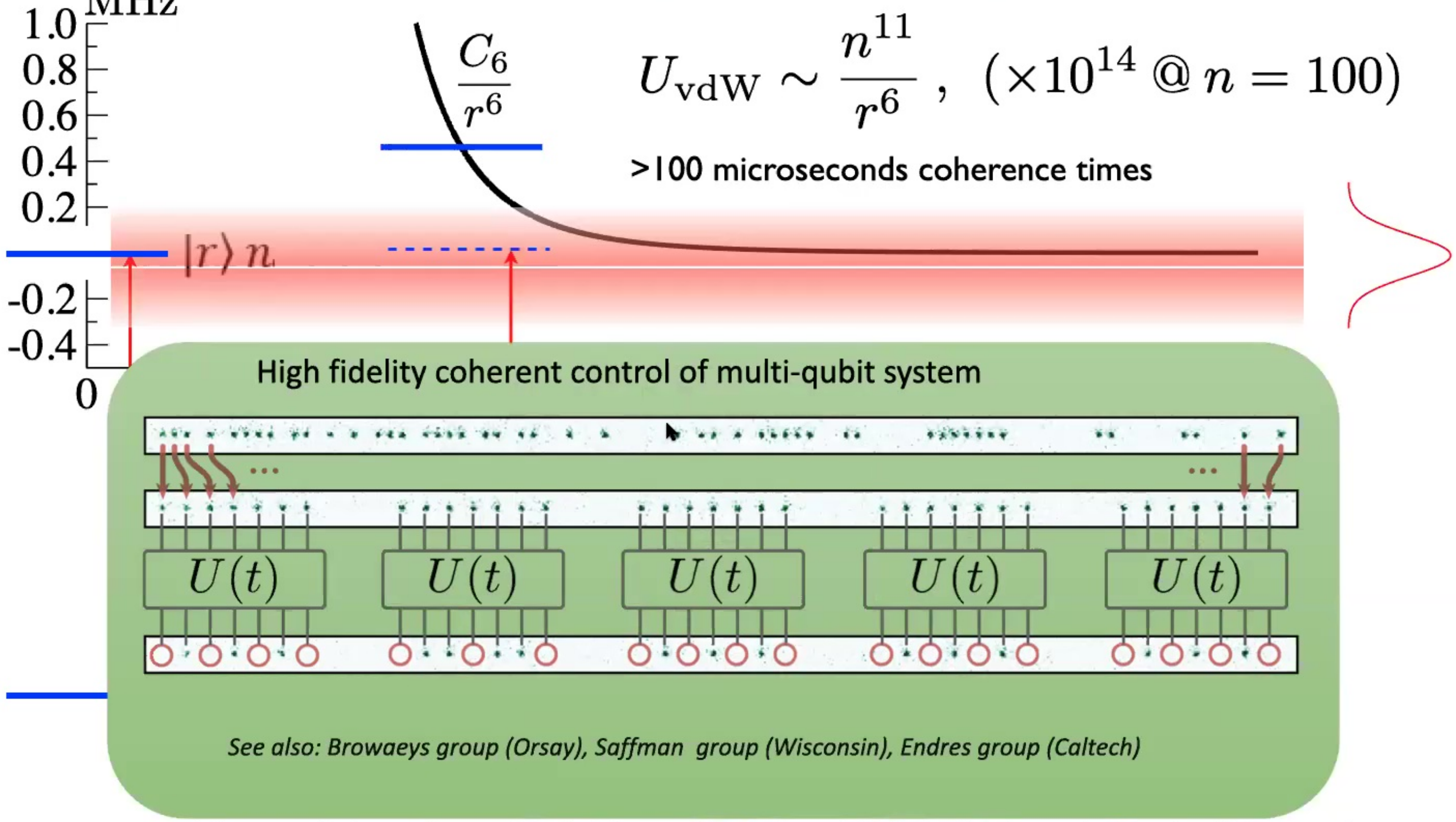

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Programmable Quantum Simulators

Simulating Physics with Computers

Richard P. Feynman

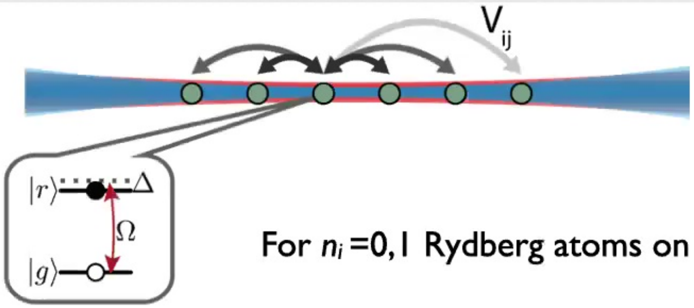
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

Quantum modeling is hard: *N* quantum systems require solution to 2^N coupled eqns

Alternative approach: Implement model of interacting system on a ***quantum simulator***, or "standard" set of qubits with programmable interactions

Quantum simulations using atom arrays



For n_i =0,1 Rydberg atoms on each cite *i*

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

Ising-type model: smilar to "hard" boson model

*Fendley, Sengupta, Sachdev PRB **69**, 075106 (2004)*

Hannes Bernien, et al, arXiv 1707.04344, Nature (2017)

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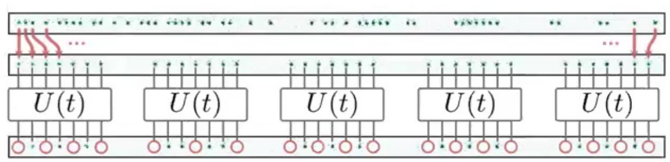

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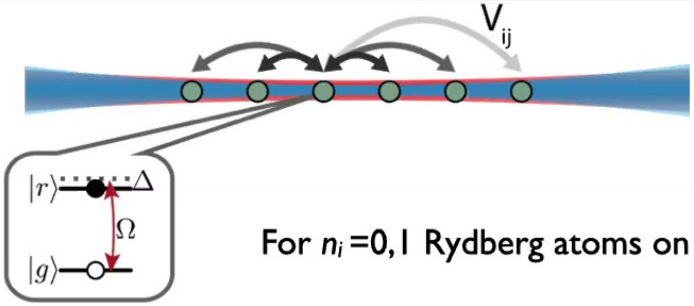

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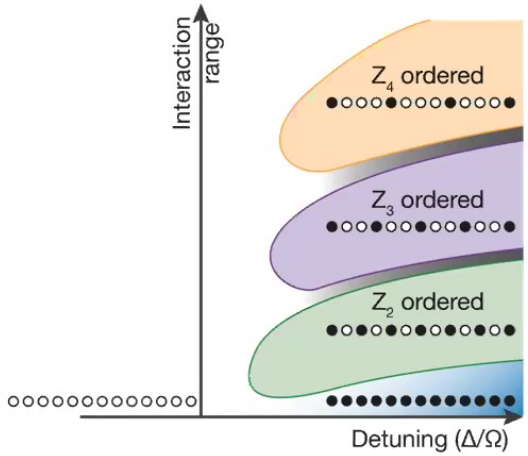

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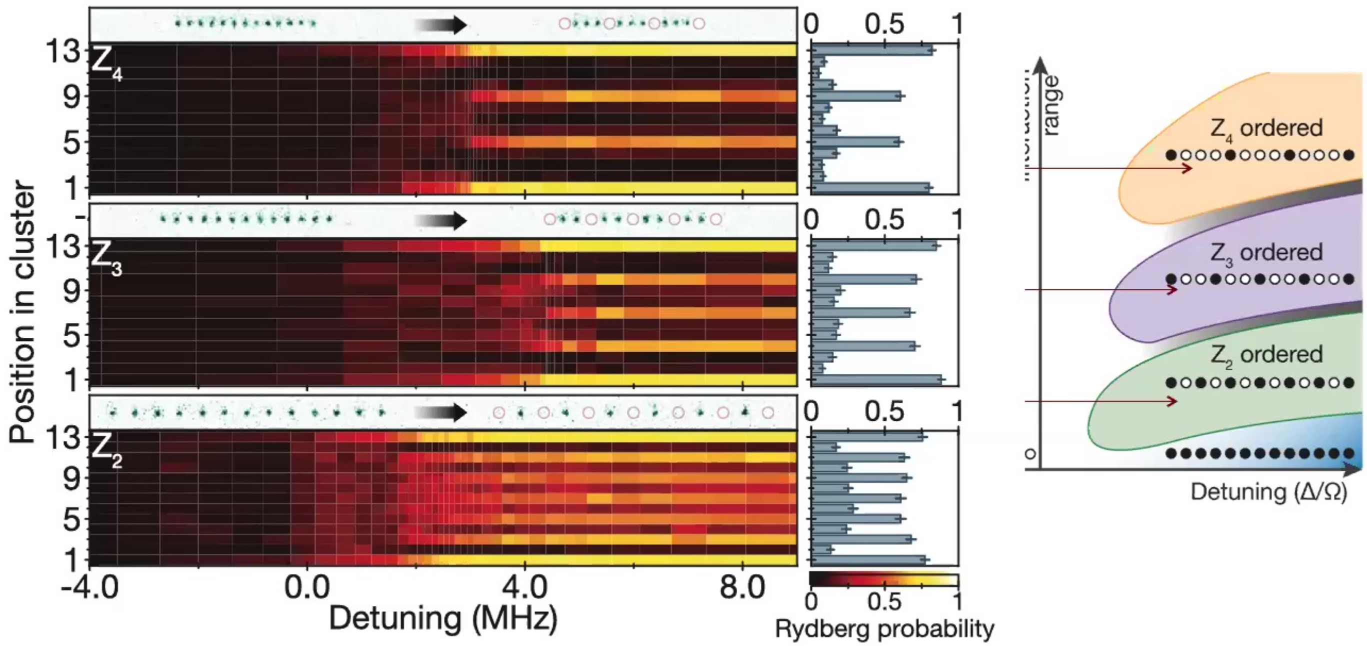


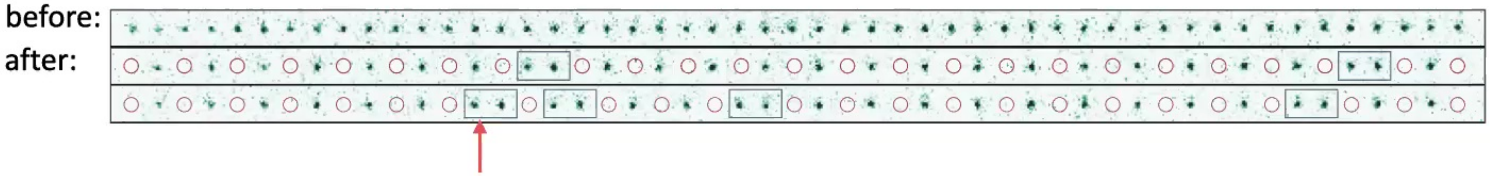
Approach: adiabatic following across phase transition

Programmable interactions result in desired symmetry breaking!

Hannes Bernien, et al, arXiv 1707.04344, Nature (2017)

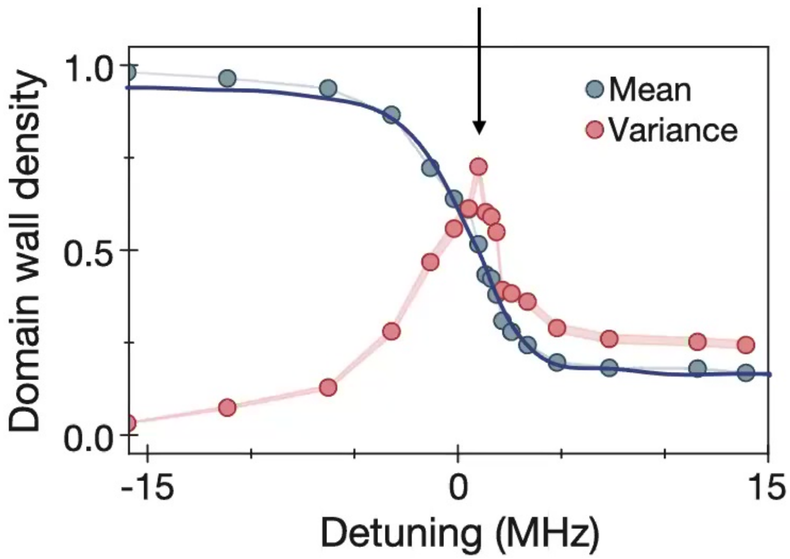
Phase transition in a 51 atoms array

Single shot images:



Domain walls

phase transition



- Smooth changes in order parameter, sharply enhanced fluctuations near Ising-type transition
- Good agreement with theory based on finite size scaling (Sachdev et al)

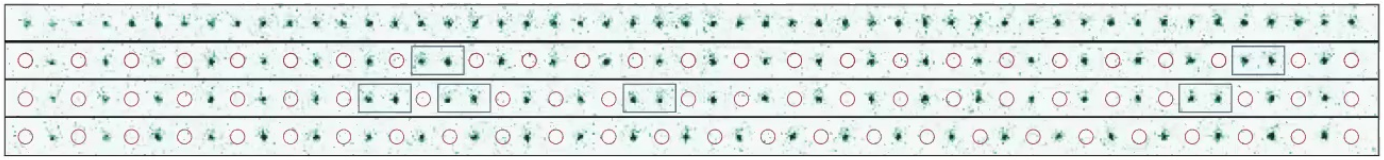
Hannes Bernien, et al, arXiv 1707.04344, Nature (2017)

Phase transition in a 51 atoms array

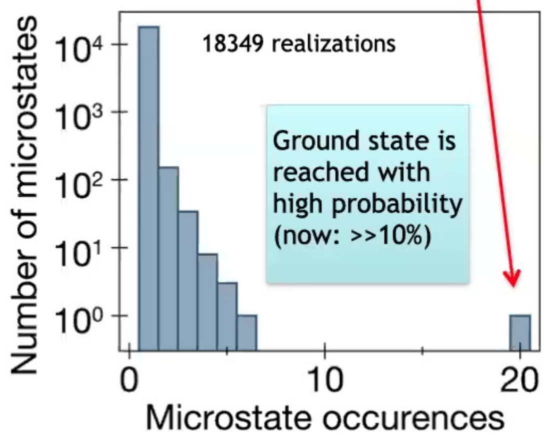
Single shot images:

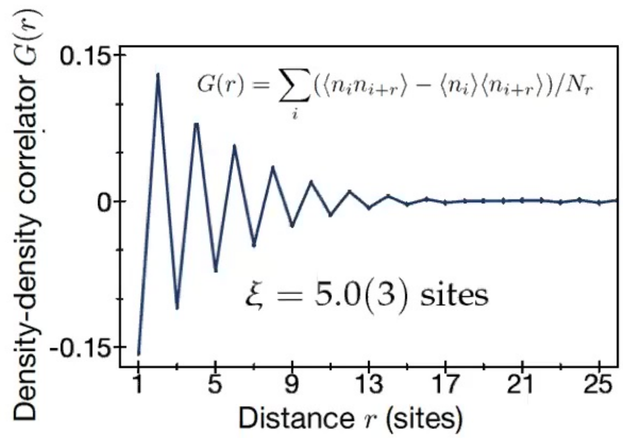
before:

after:



sometimes... >> $1/2^{51}$





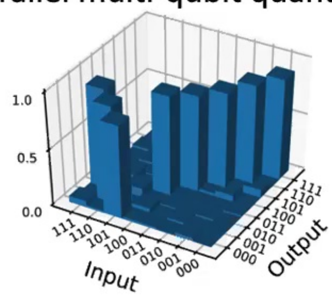
Unique insights into phase transitions, especially quantum dynamics!

H. Bernien, et al, arXiv 1707.04344, Nature (2017); related work by C. Monroe's group, Nature (2017), Google's quantum supremacy, Nature (2019)
also Quantum Gas Microscope experiments

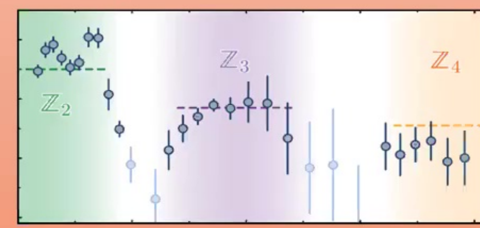
Quantum science & technology with neutral atom arrays

Coherent control of mutli-atom system with ground-Rydberg and hyperfine qubit encoding

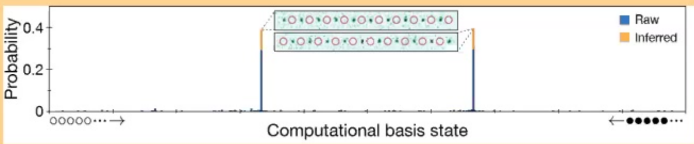
High-fidelity entanglement & parallel multi-qubit quantum gates

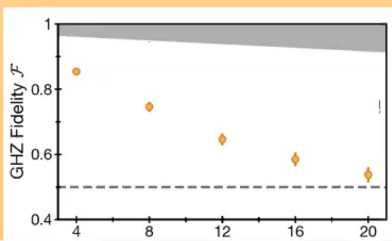


Novel quantum phase transitions



Large-scale entanglement engineering



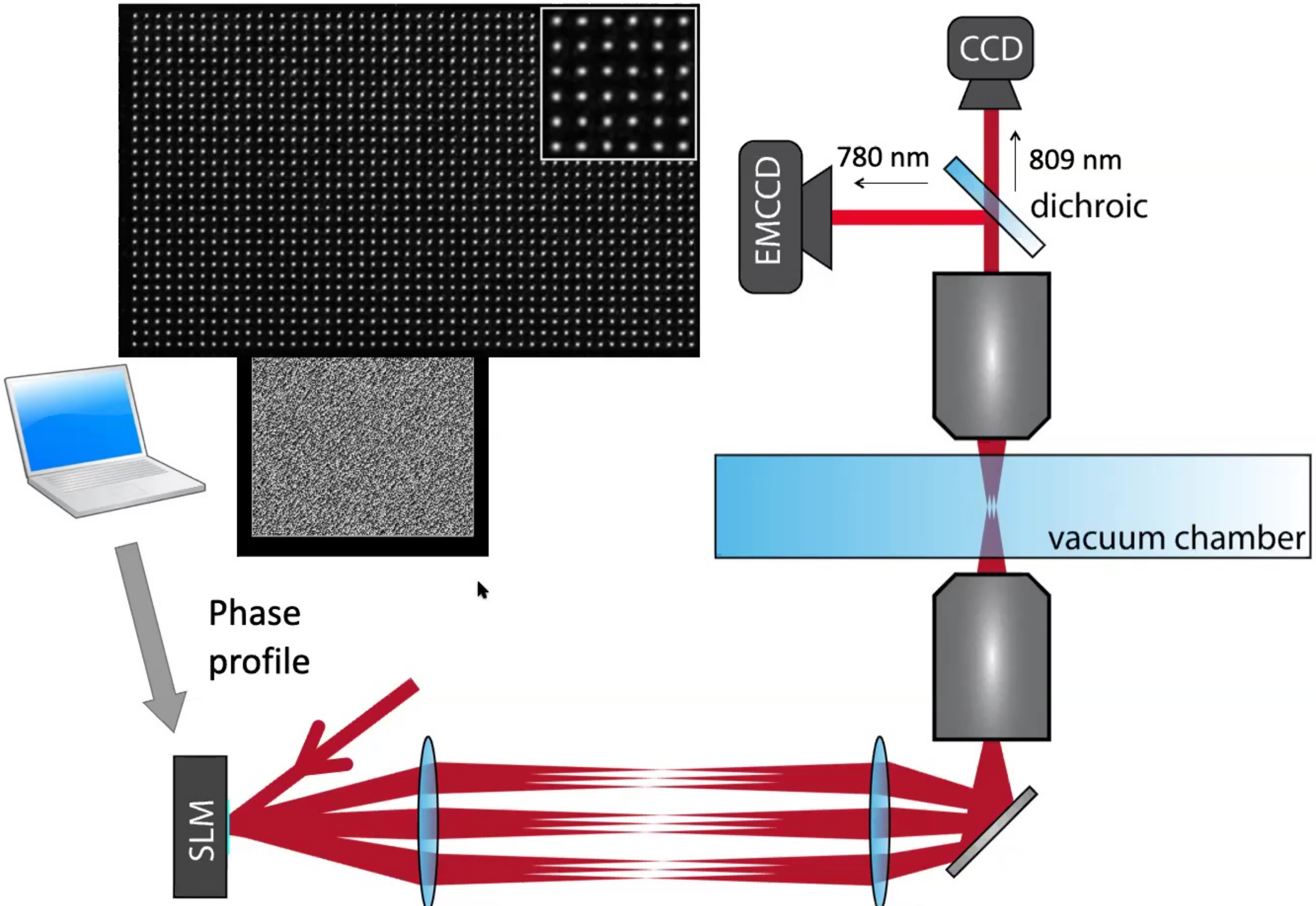


Non-equilibrium dynamics: quantum many-body scars

M. Endres, et. al. *Science (2016)* H. Levine, et. al. *PRL (2018)*
H. Bernien, et. al. *Nature (2017)* A. Keesling, et. al. *Nature* (2019)
A. Omran, et al, Science (2019) H. Levine, et al, *PRL* (2019)
I. Madjarov, et al (Endres lab @ Caltech), *Nature Physics* (2020)

These directions are closely connected: coherent, high-fidelity analog and digital evolution!

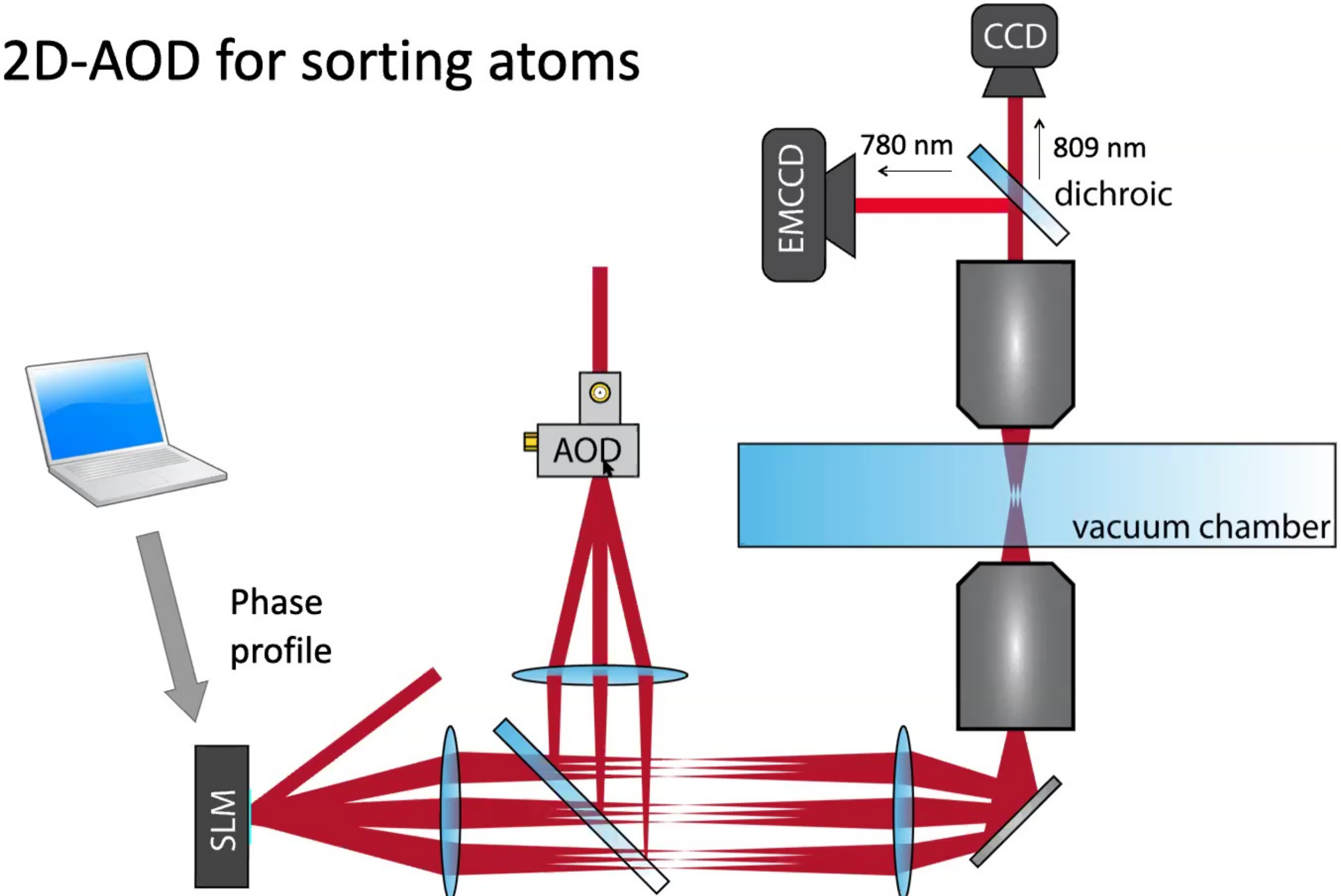
Tweezer Array Gen 2: powered by an SLM



Sepehr Ebadi, Tout Wang, Alexander Keesling, Harry Levine, Ahmed Omran, Giulia Semeghini, Dolev Bluvstein (2020)
CUA collaboration of Lukin, Greiner & Vuletic groups

Tweezer Array Gen 2: powered by an SLM

2D-AOD for sorting atoms



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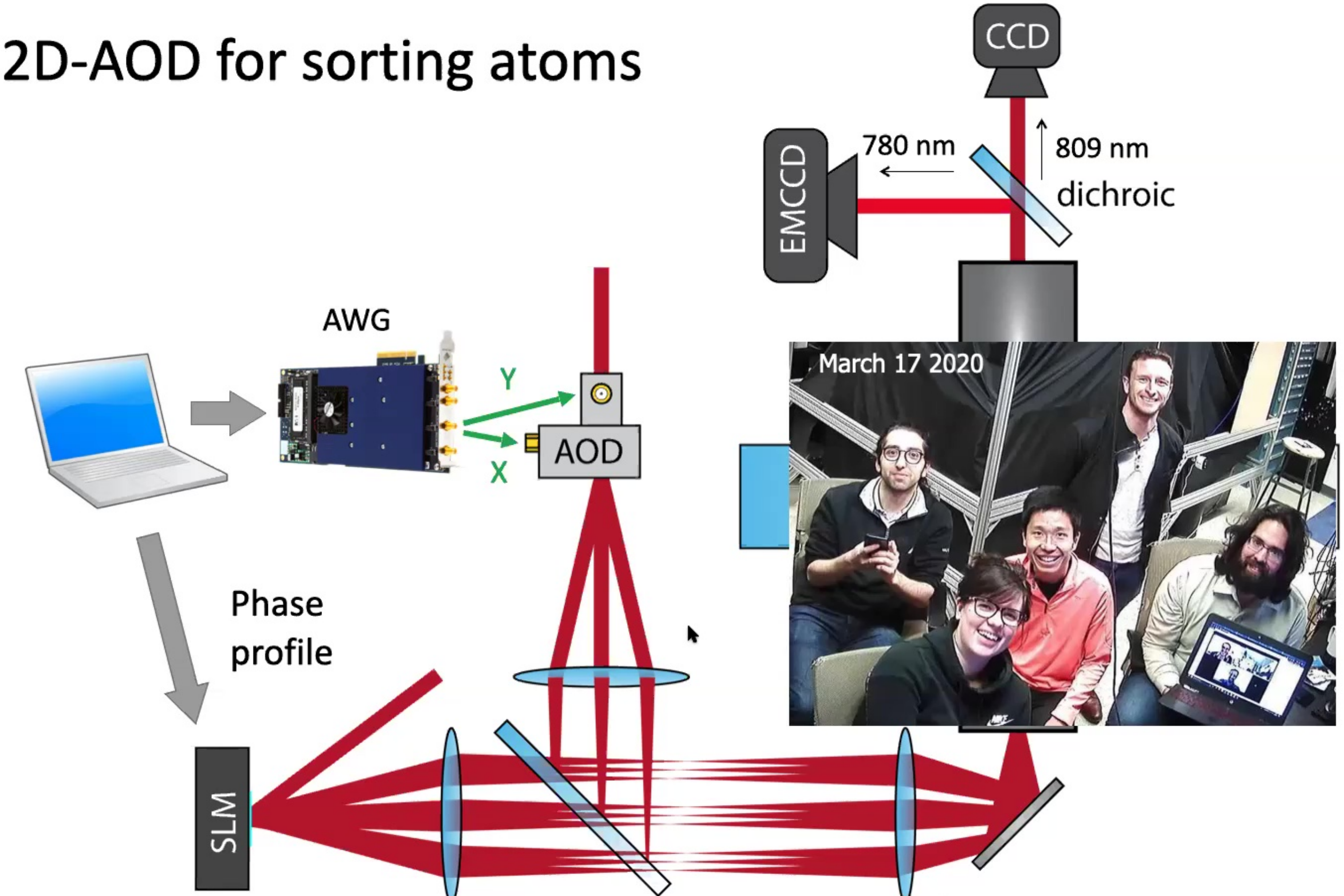

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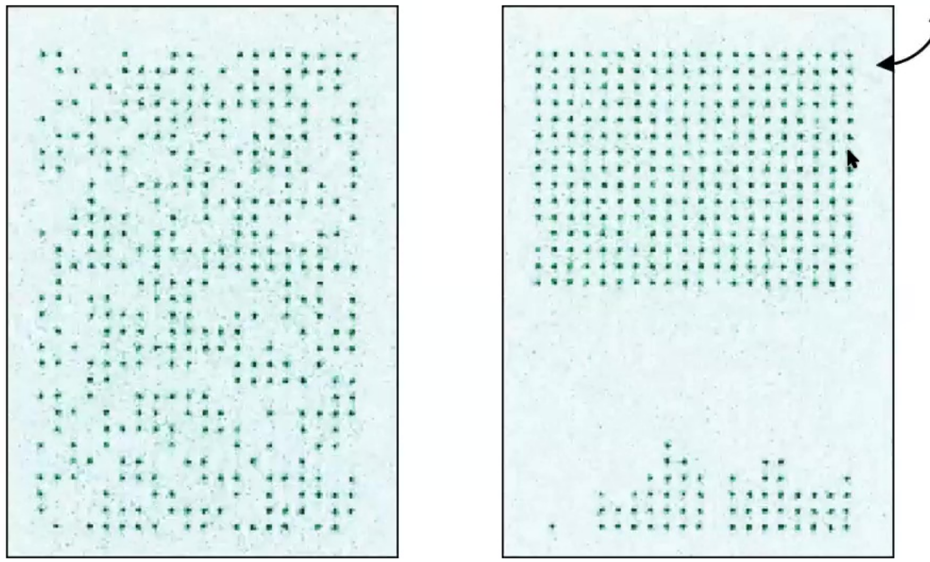
CUA collaboration of Lukin, Greiner & Vuletic groups

Atom Array Gen 2: large scale 2D atom arrays

Initial loading: 20x30 trap array

After sorting

> 99% filling



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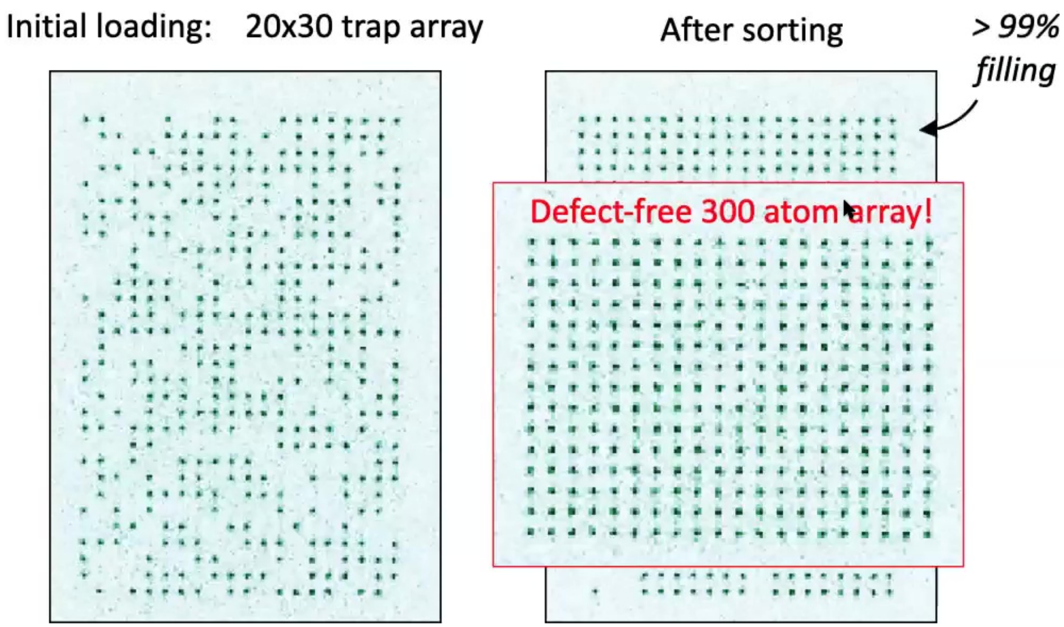
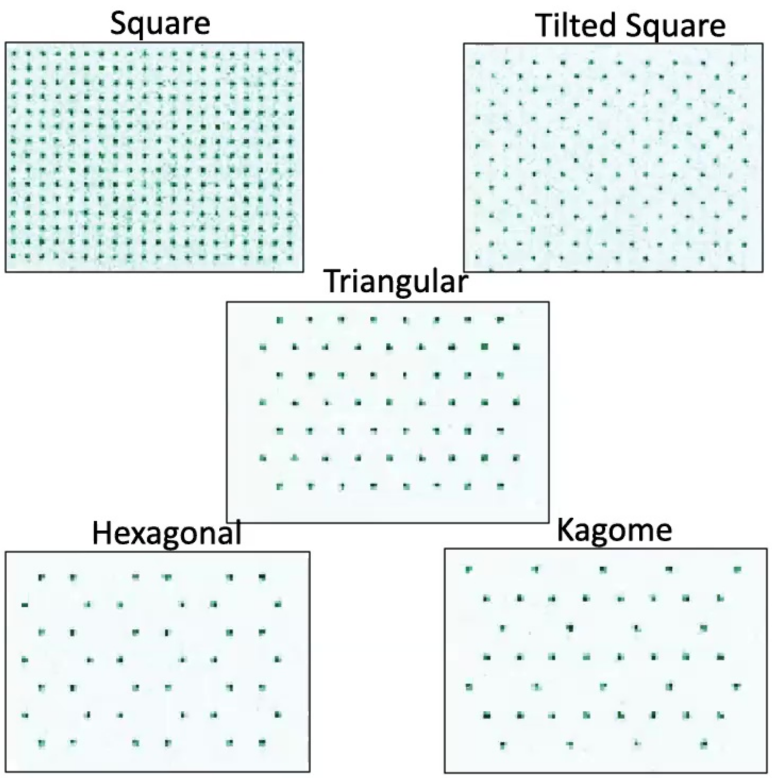
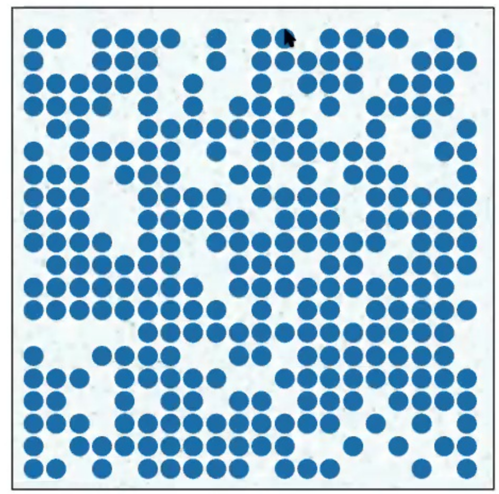


Atom Array Generation 2: large scale 2D atom arrays



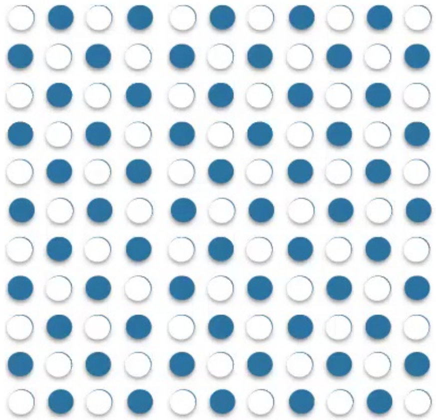
Arbitrary patterns:
randomly generated 75%
filling in 20x20



S. Ebadi et al arxiv 2012.12281

see also work on 2d and 3d atom arrays at Orsay, Penn State

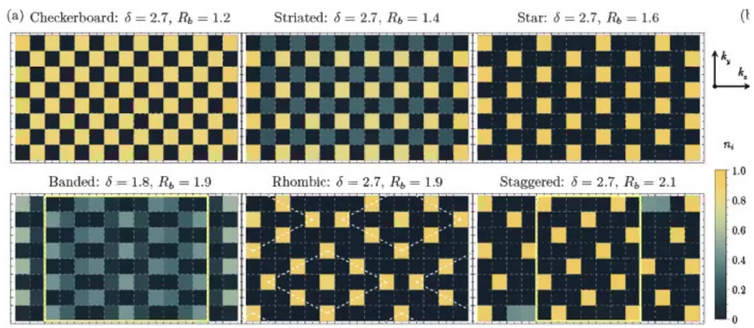
Quantum phases in 2D: square lattice

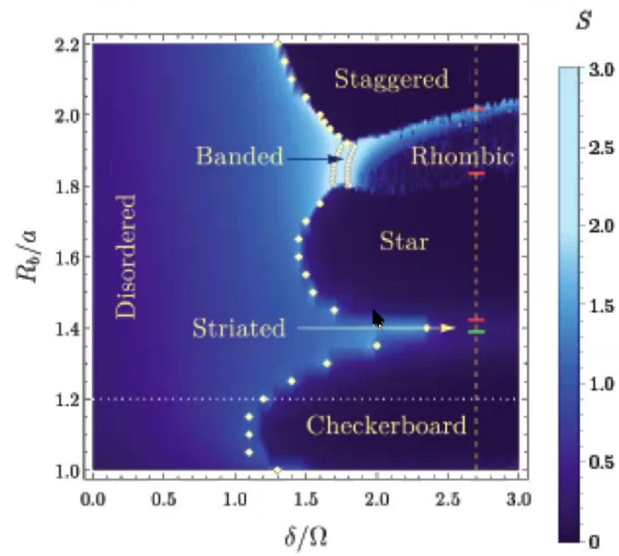


$$\mathcal{H} = \sum_i \frac{\hbar\Omega_i}{2}\sigma_x^i - \sum_i \hbar\Delta_i n_i + \boxed{\sum_{i<j} V_{i,j} n_i n_j}$$

Short range blockade: 2D Ising phase transition, checkerboard phase

Change atom separation = interaction range

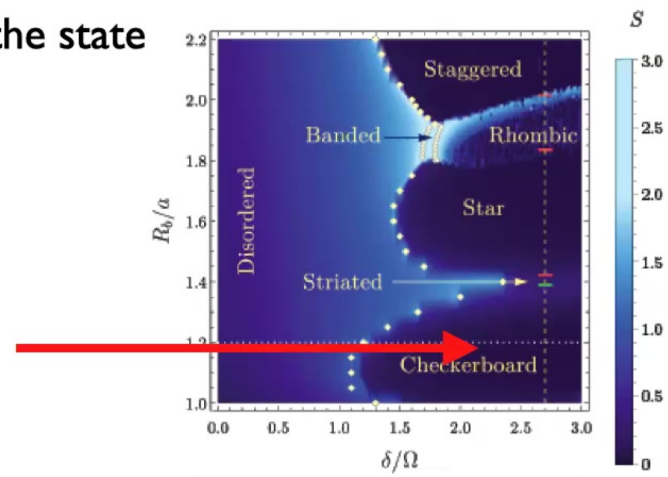


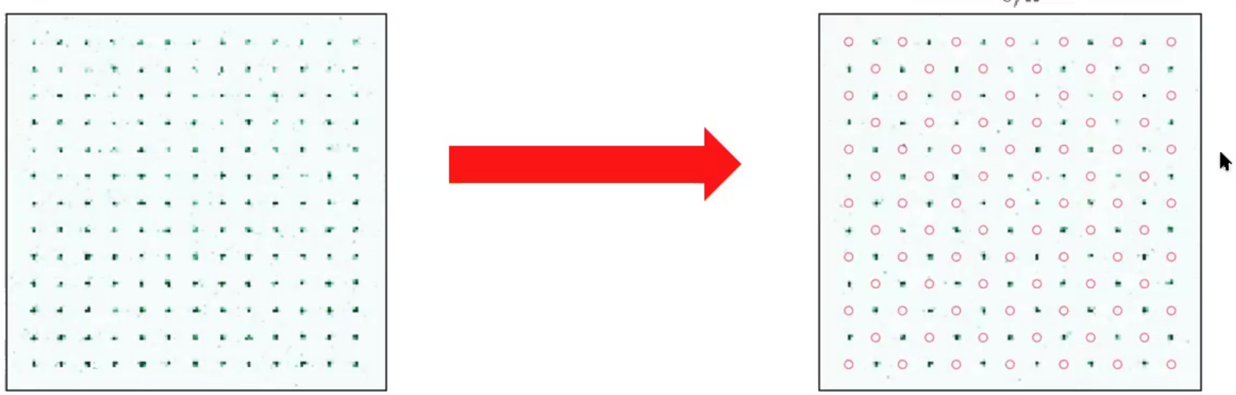


Theory: R. Samajdar, W.W.Ho, H. Pichler, collaboration with S. Sachdev arXiv 1910.09548, Phys. Rev.Lett (2020)

Ising QPT on 2D square lattice

- trap spacing for nearest atom blockade but no blockade on diagonal
- adiabatic detuning sweep to reach the state

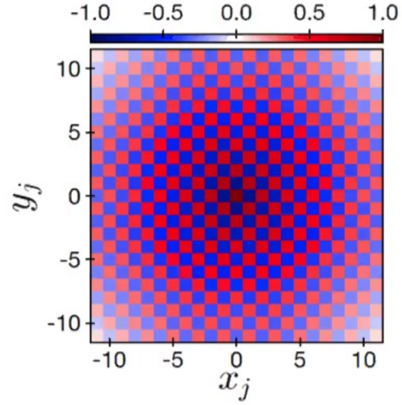




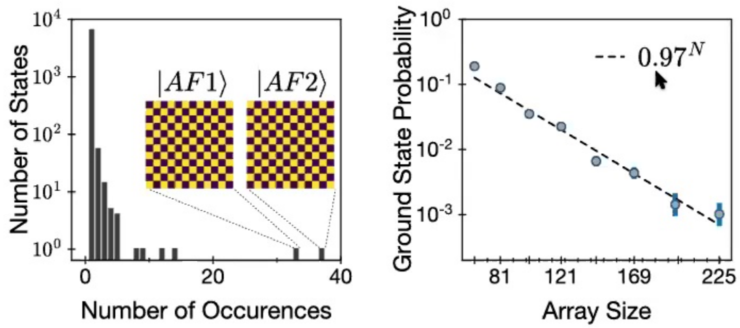
S. Ebadi et al arxiv 2012.12281

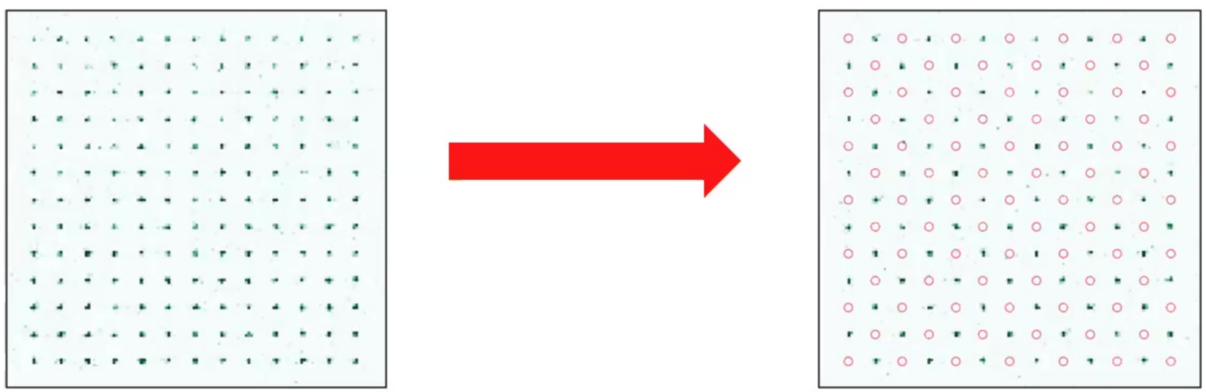
Ising QPT on 2D square lattice

Correlations $g^2(i,j) = \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle$



Distribution of microscopic states





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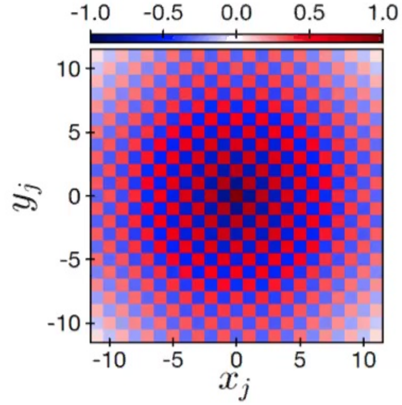

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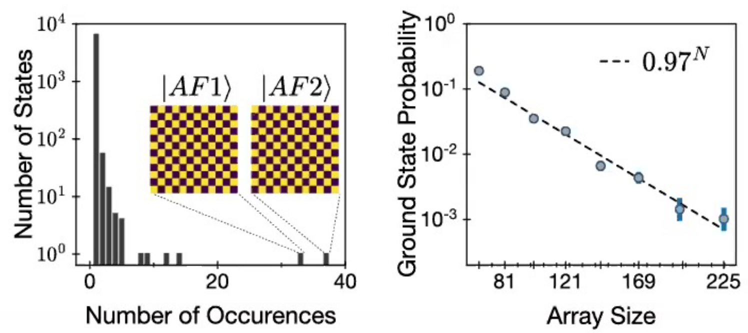
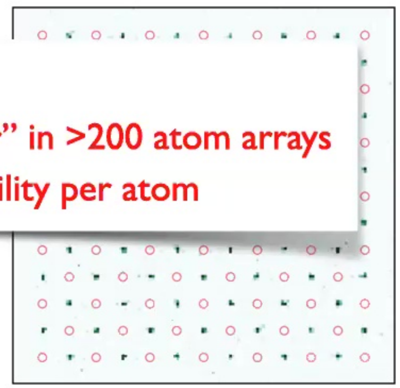




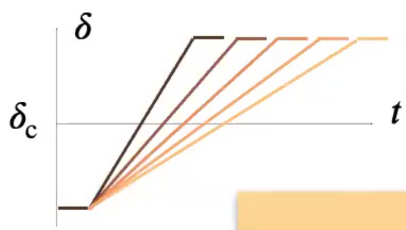
- Correlations extend across the array
- Substantial probability of "perfect order" in >200 atom arrays
- Benchmarking: total ~3% error probability per atom

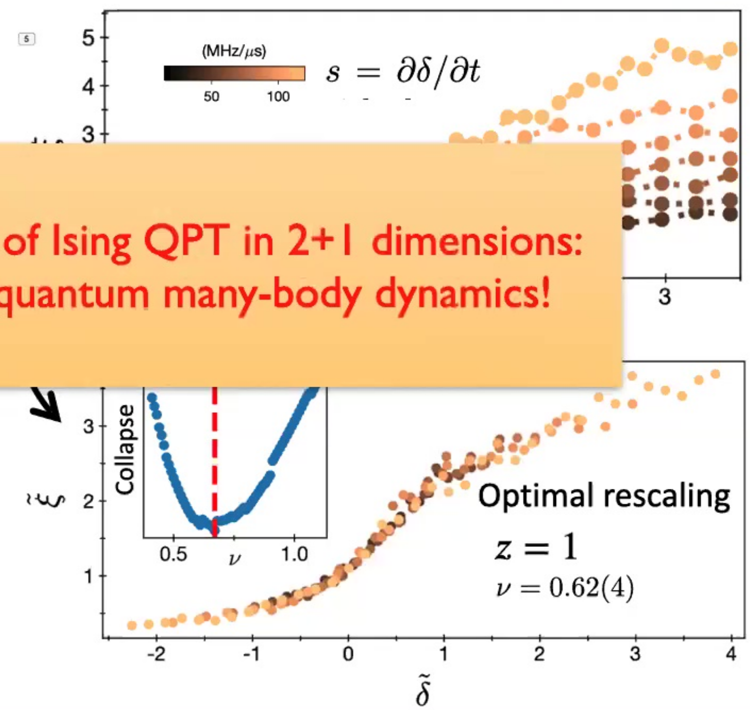
S. Ebadi et al arxiv 2012.12281

Ising QPT on 2D square lattice

Paradigmatic QPT in 2D, characterized by critical exponents: $z = 1 \quad \nu \approx 0.63$

Quantum Kibble-Zurek mechanism (QKZM): connects dynamics across transition to universal scaling exponents





Universality: curves
with proper critical

$\tilde{\xi} = \xi(s/$

$\tilde{\delta} = (\delta - \delta_c)(s/s_0)^{\kappa}$

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

First observation of Ising QPT in 2+1 dimensions: benchmark for quantum many-body dynamics!

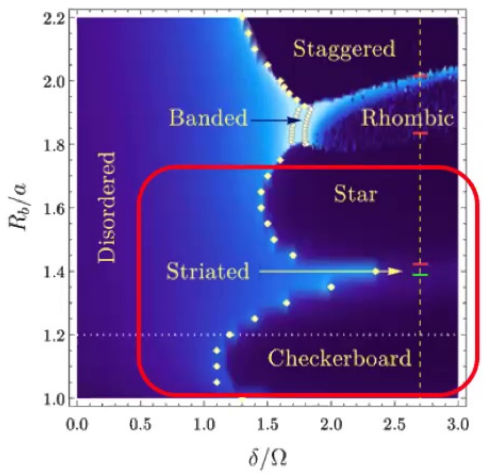
Theory: R. Samajdar et. al, *PRL* (2020)

1D Ising: A. Keesling, et. al. *Nature* (2019)

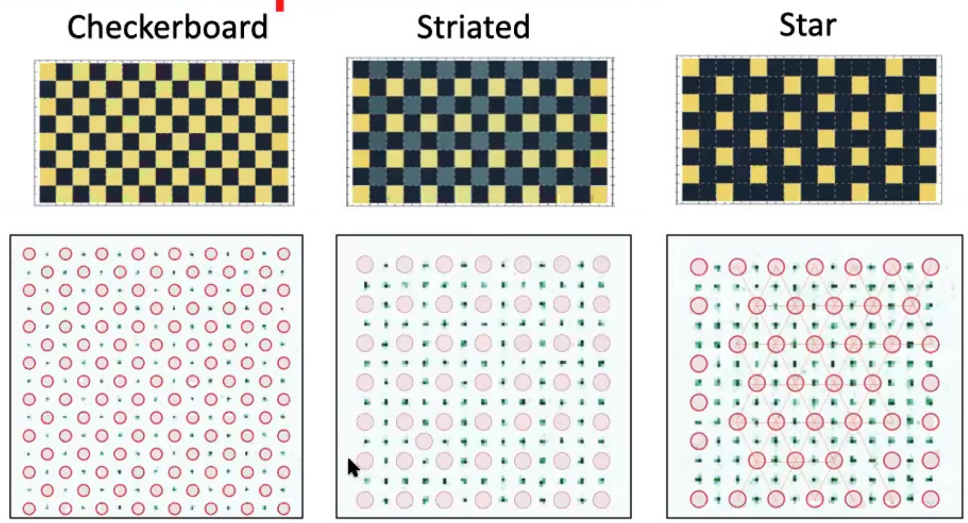
S. Ebadi et al arxiv 2012.12281

Novel phases on 2D square lattice

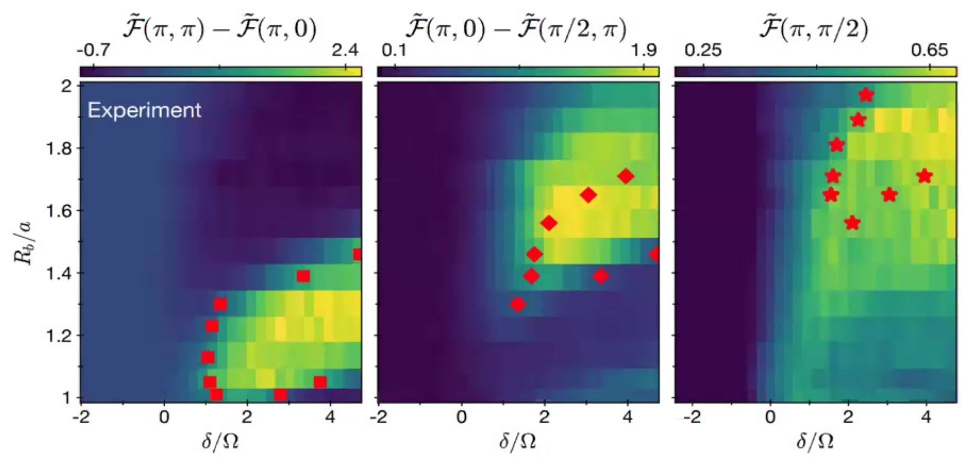
Rich 2D square lattice phase diagram:



R. Samajdar et. al, *PRL* **124**, 103601 (2020)



Experimentally mapping out phase diagram with order parameters:



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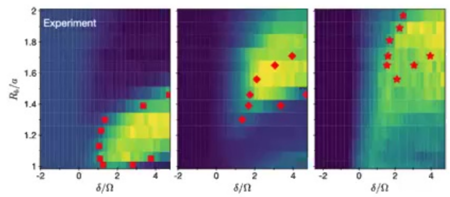
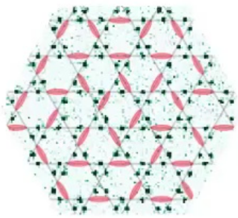
Programmable quantum simulators based on Rydberg arrays: current efforts

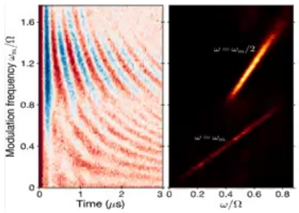
Exploring 2D phase diagrams



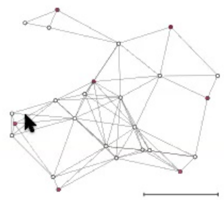
Probing topological phases



Non-equilibrium dynamics



Testing combinatorial optimization

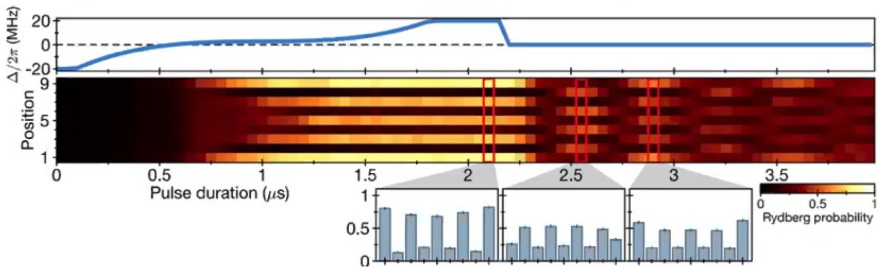


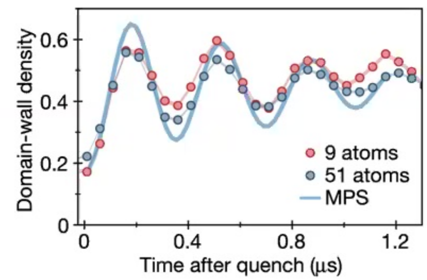
Exciting frontier: from many-body physics to computing and metrology

Non-equilibrium dynamics: "many-body scars"

Initial discovery in 1D:

Prepare ordered state → quench the system to resonance





Experimental:
H. Bernien, et. al. *Nature* (2017)

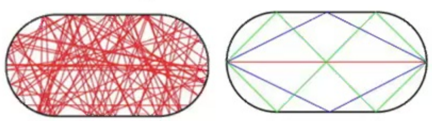
Explanation in terms of many-body scars:
Turner, et. al. *Nature Physics* (2018)

Recent theoretical work
Moudgalya, et. al. *PRB* (2018)
Ho, et. al. *PRL* (2019)
Turner, et. al. *PRB* (2019)
Choi, et. al. *PRL* (2019)
Khemani, et. al. *PRB* (2019)
Lin, Motrunich. *PRL* (2019)
Michailidis, et. al. *Phys Rev Research* (2020)
Lin, et. al. *PRB* (2020)
Surace, et. al. *PRX* (2020)
....

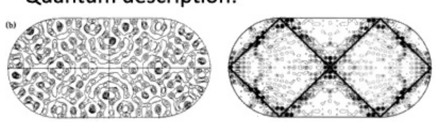
Inspired new theoretical concept: quantum many-body scars

Quantum scars: eigenstates resembling classical periodic orbits in chaotic systems

Classical trajectories in a stadium:

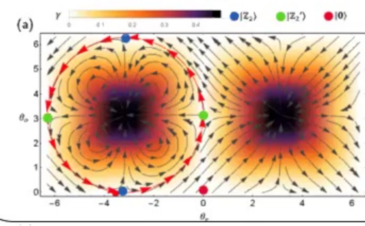


Quantum description:

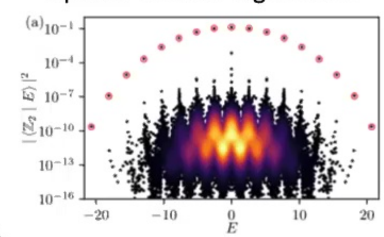


E. Heller, *PRL* **53**, 1515 (1984)

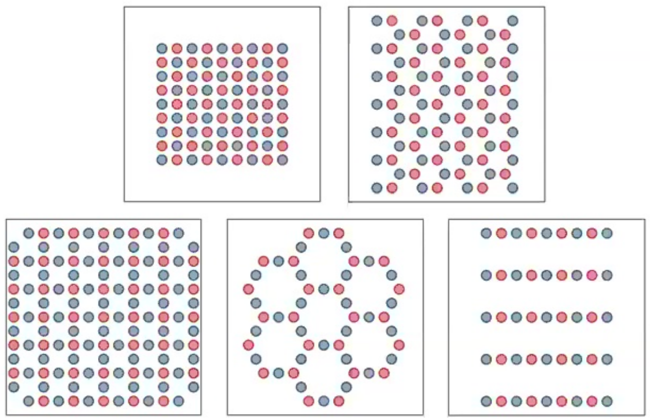
Locally entangled MPS

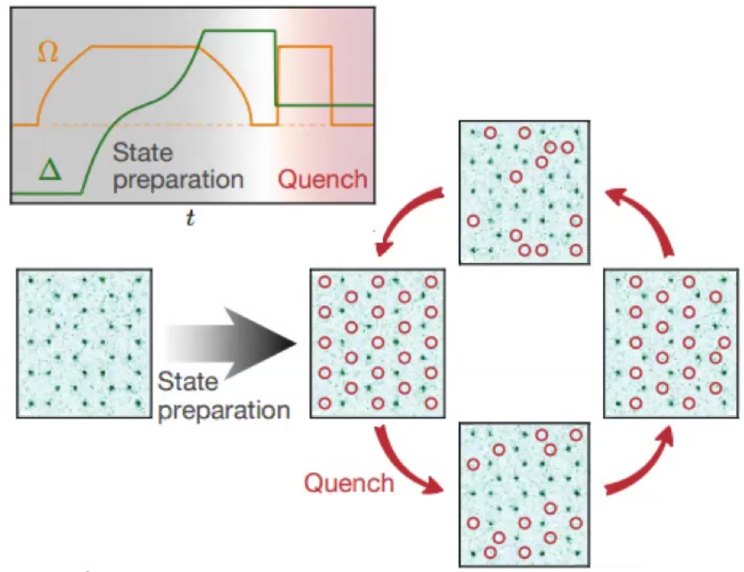


Special 'scarred' eigenstates

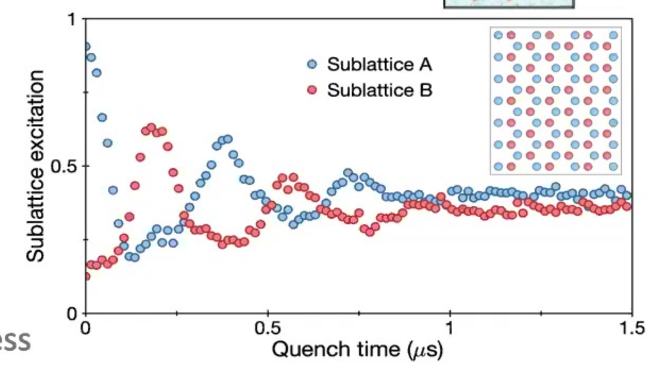


Quantum many-body scars in 2D lattices





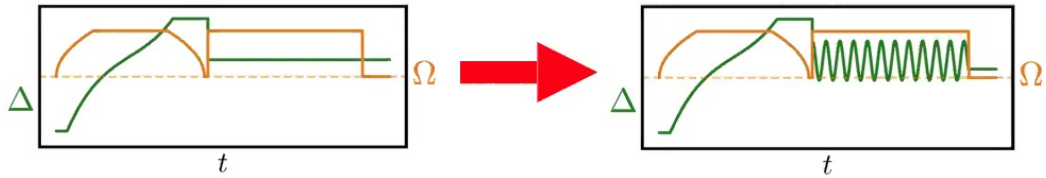
Wide variety of 2D bipartite lattices support many-body scars!



D. Bluvstein, et al, arxiv 2012.12276, Science in press

Stabilizing quantum scars with periodic drive ?

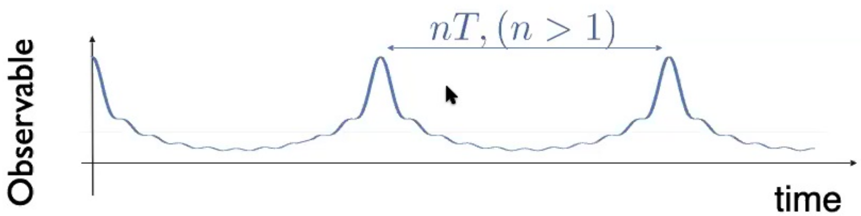
How does a system with *weak* ergodicity breaking respond to a periodic drive?



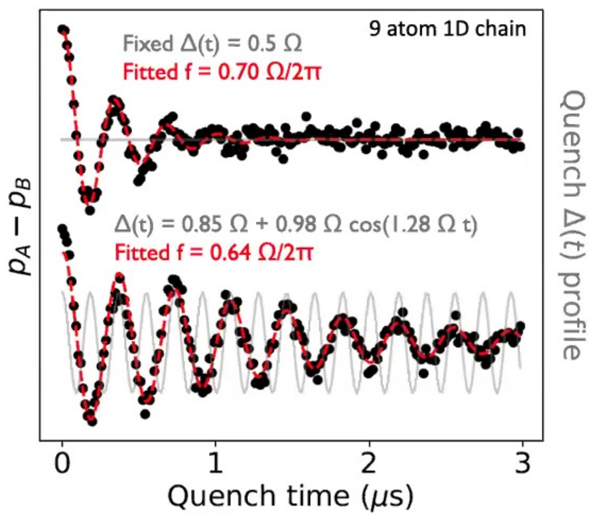
Interacting quantum many-body systems generally expected to heat under drive

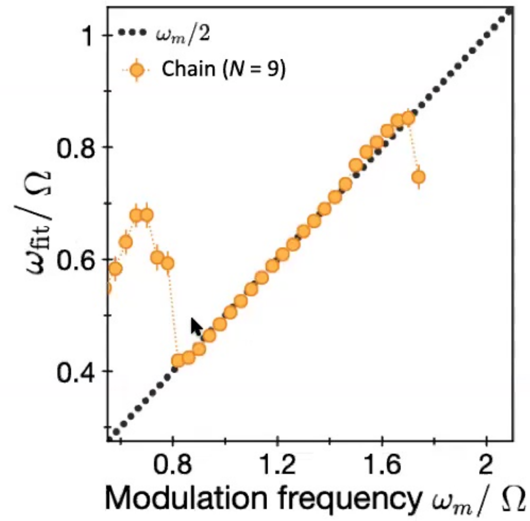
- Effects such as localization suppress heating and allow for non-equilibrium phases
- Example: discrete time crystals
- Can one use similar approach to stabilize quantum many body scars?

Theory: V. Khemani, et al (2016) D. Else, et al (2016).
Experiments: J. Zhang et al, Nature 543, 217 (2017),
S.Choi et al, Nature 543, 221 (2017)



Example: periodic driving of quenched Hamiltonian





Many-body scars are stabilized by drive!

- > 4x extension of lifetime
- Frequency "locks" to half the drive frequency

Experiment: D. Bluvstein, et al, arxiv 2012.12276, Science, in press

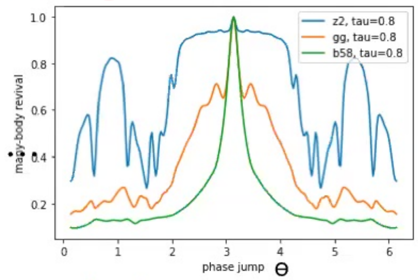
Theory: N. Maskara, W.W. Ho, A. Michailidis, S. Choi, collaboration with M. Serbyn's group

Origin of robust of sub-harmonic response?

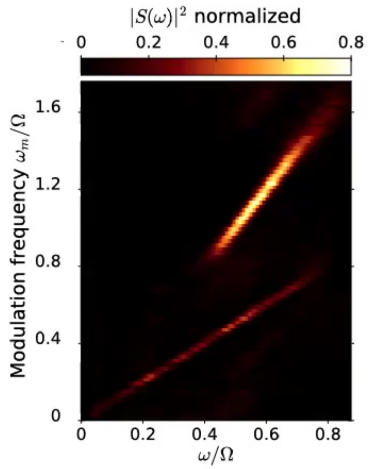
- **Toy model/intuition:** Floquet unitary $U_F = e^{-i\theta \sum_i n_i} e^{-i\tau\pi \sum_i PXP}$

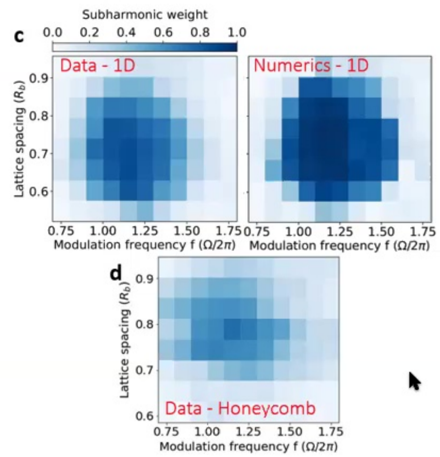
$\Theta = \pi$: perfect "spin echo" for all states due to particle-hole symmetry ...

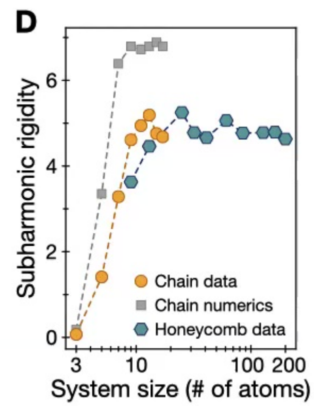
but robustness only for "scarring" states!



- **Experiment:** robust revival of order across a range of parameters for many-body system







For scarring states only!

Robust stabilization akin to (pre-thermal) time-crystalline response

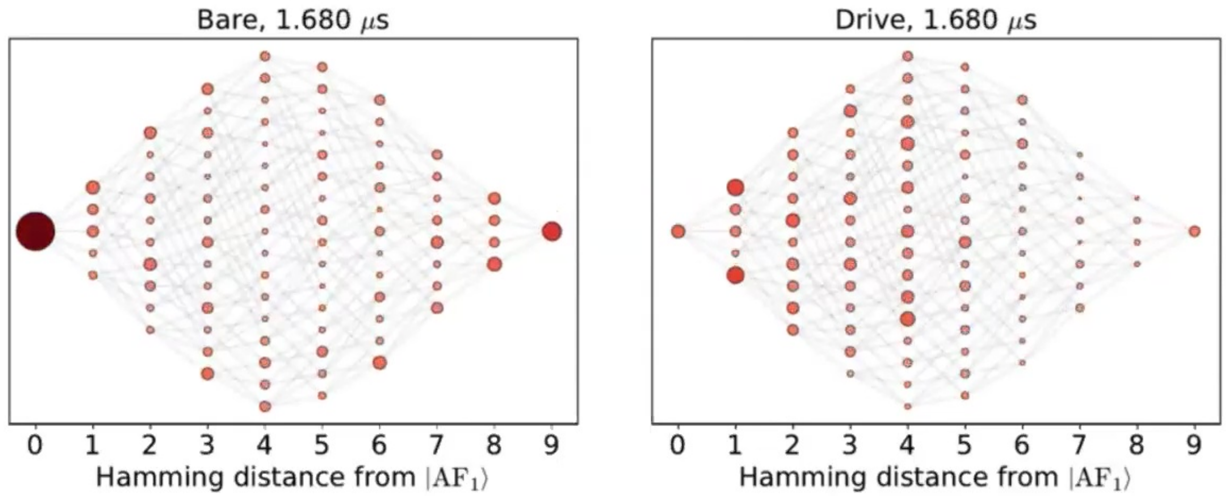
Dolev Bluvstein, et al , Science (2021), theory Nishad Maskara, et al , collaboration with M. Serbin's group

Microscopic view of many-body scars

Track all possible microstates for 9 atom chain:
(*Experimental data!*)

Bare quench

Driven quench



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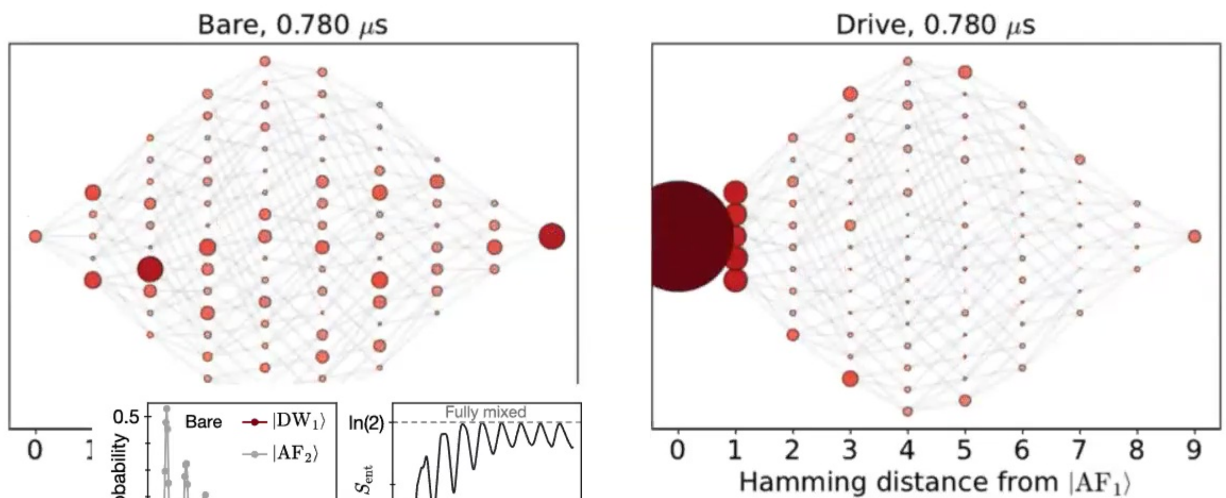

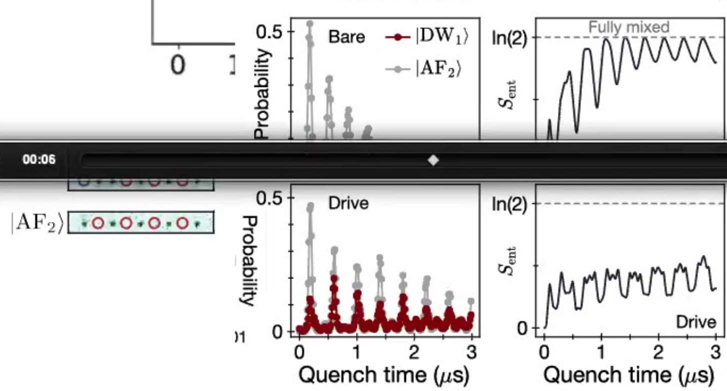

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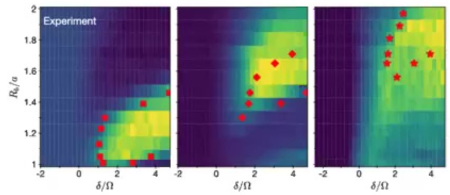

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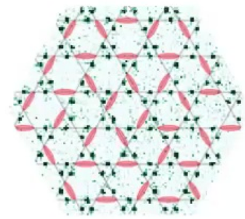
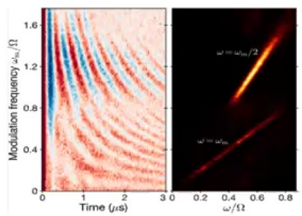


Non-equilibrium dynamics



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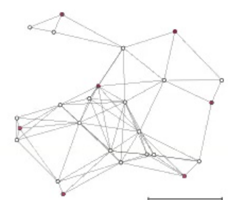
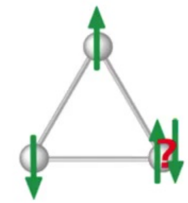


Topological phases in frustrated lattices



Topological spin liquids: emergent phenomenon in frustrated systems
… five decades long quest in condensed matter physics (Anderson 1973, …)

Related to topological order such as Laughlin states in QHE

Resonating valence bonds in frustrated magnets (Sachdev, Read, Wen, …)

Basis for toric code and topological quantum computing (Kitaev 1997, …)

No conclusive experimental evidence in any system to date …

P. W. Anderson, *Science* **235** (1987)

The Resonating Valence Bond State in La_2CuO_4 and Superconductivity 9000+ citations

P. W. ANDERSON

The oxide superconductors, particularly those recently discovered that are based on La_2CuO_4, have a set of peculiarities that suggest a common, unique mechanism: they tend in every case to occur near a metal-insulator transition into an odd-electron insulator with peculiar magnetic properties. This insulating phase is proposed to be the long-sought "resonating-valence-bond" state or "quantum spin liquid" hypothesized in 1973. This insulating magnetic phase is favored by low spin, low dimensionality, and magnetic frustration. The preexisting magnetic singlet pairs of the insulating state become charged superconducting pairs when the insulator is doped sufficiently strongly. The mechanism for superconductivity is hence predominantly electronic and magnetic, although weak phonon interactions may favor the state. Many unusual properties are predicted, especially of the insulating state.

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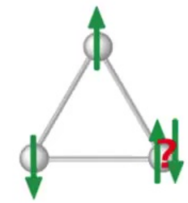

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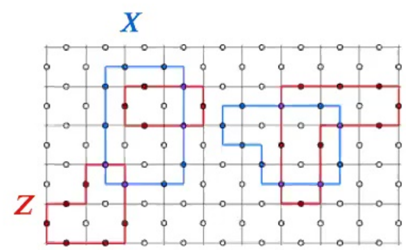


Fault-tolerant quantum computation by anyons

A.Yu. Kitaev*
5200+ citations

L.D. Landau Institute for Theoretical Physics, 117940, Kosygina St. 2, Germany

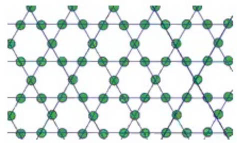
Received 20 May 2002

Toric code ~ coherent "loop gas"

Dimer models & spin liquids in Rydberg arrays

Key idea: geometric frustration + long-range interactions

kagome lattice



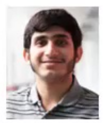
arXiv:2011.12295, PNAS (2020)

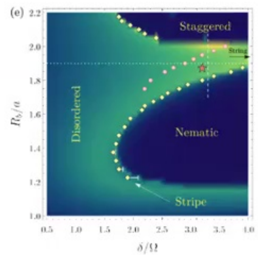
Quantum phases of Rydberg atoms on a kagome lattice

Rhine Samajdar[a,1], Wen Wei Ho[a,b], Hannes Pichler[c,d], Mikhail D. Lukin[a], and Subir Sachdev[a]

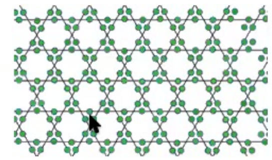
Subir Sachdev

Rhine Samajdar





ruby lattice



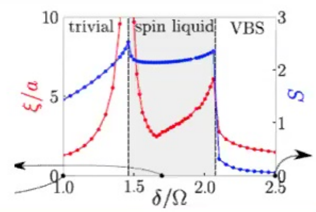
arXiv:2011.12310

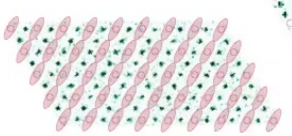
Prediction of Toric Code Topological Order from Rydberg Blockade

Ruben Verresen, Mikhail D. Lukin, and Ashvin Vishwanath
Department of Physics, Harvard University, Cambridge, MA 02138, USA
(Dated: November 26, 2020)

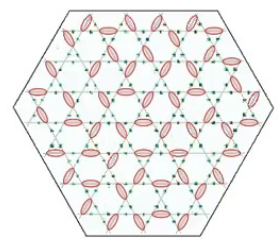
Ashvin Vishwanath

Ruben Verresen





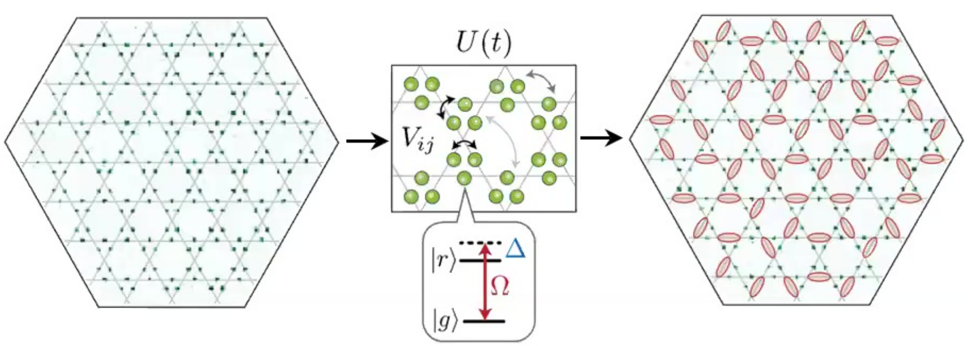
Emergent solid and liquid 'dimer' phases in frustrated lattices

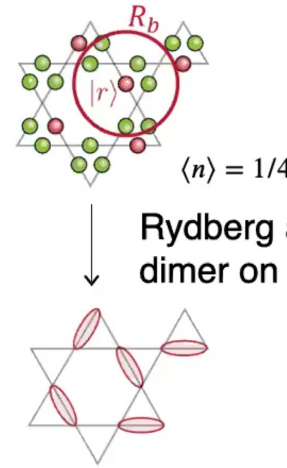


Early work on dimer models: Sachdev, Read, Wen, Moessner, Sondi …

Dimer model with Rydberg atoms on a ruby lattice

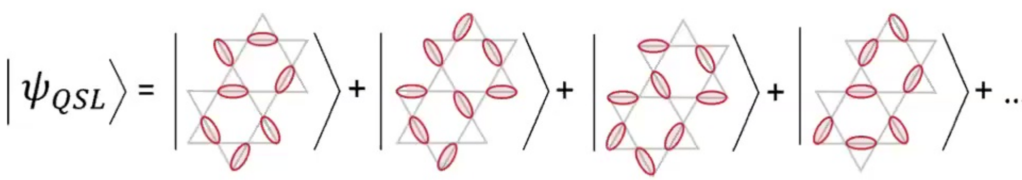
Key idea: properly tuned Rydberg blockade constraint results in highly degenerate states





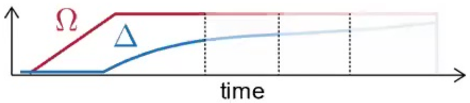
Rydberg atom = dimer on a link

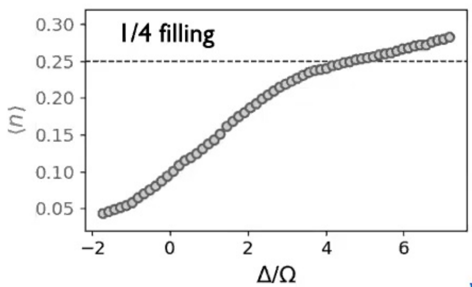
quantum spin liquid state: superposition of all dimer coverings



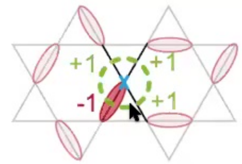
Such states can not be revealed using any local observables …
How to detect, study topological order?

Quasi-adiabatic preparation of dimer states



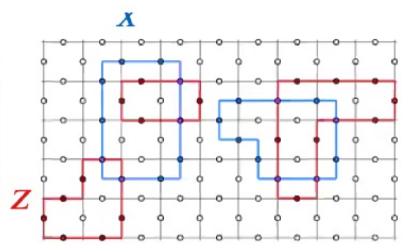


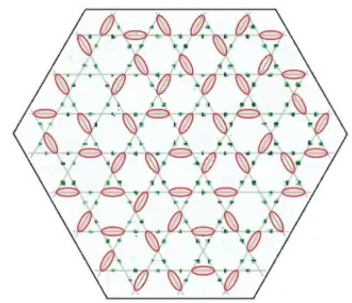
diagonal string operator Z:



parity of dimers along a string

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

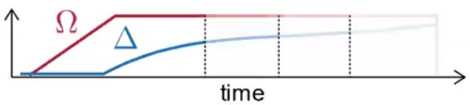


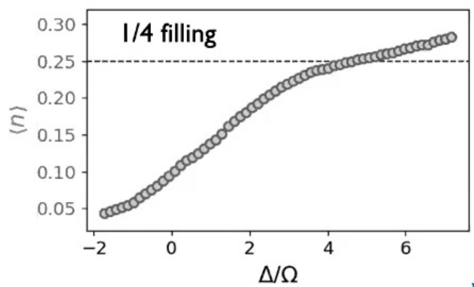


Transition into a state without obvious local order …

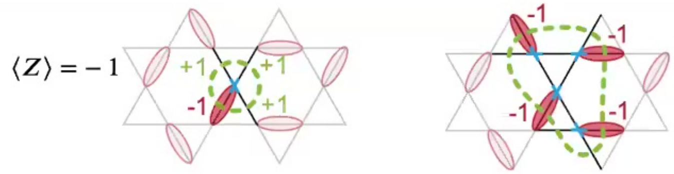
G. Semeghini et al (2021)

Quasi-adiabatic preparation of dimer states



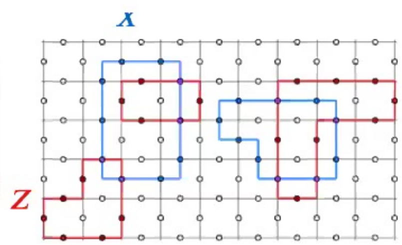


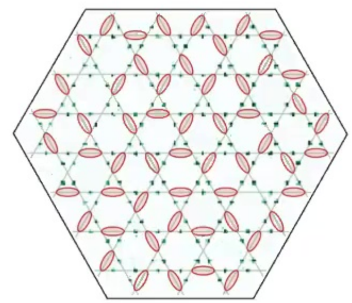
diagonal string operator Z: $\langle Z \rangle = (-1)^{\#\text{ enclosed vertices}}$



parity of dimers along a string

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





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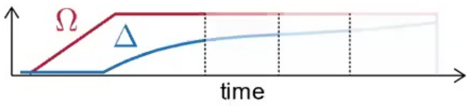

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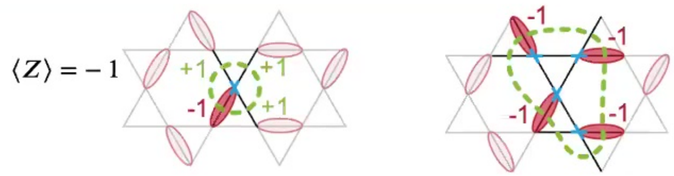

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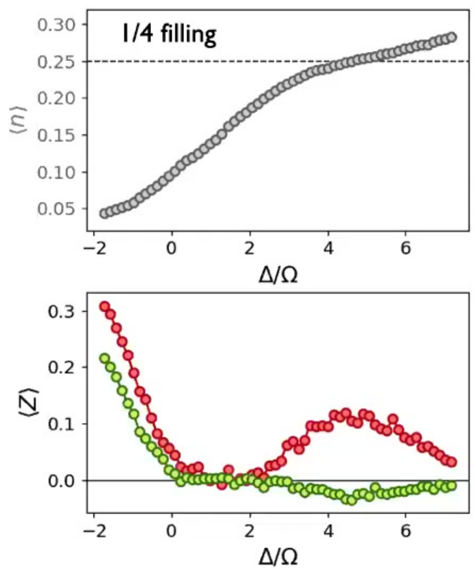
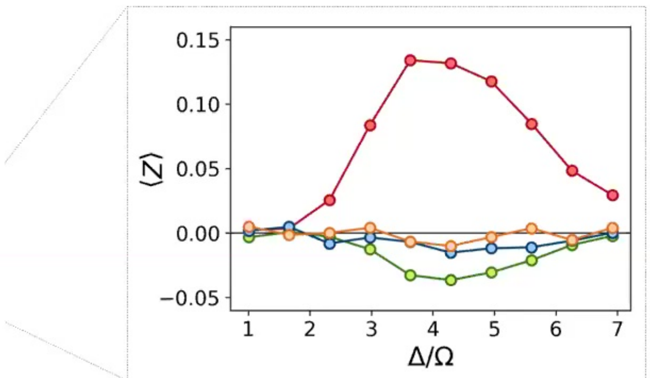
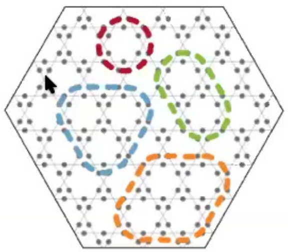






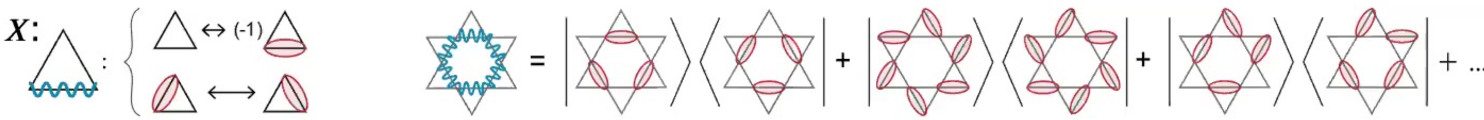
Transition into a state without obvious local order …

String operators reveal transition into the dimer phase!

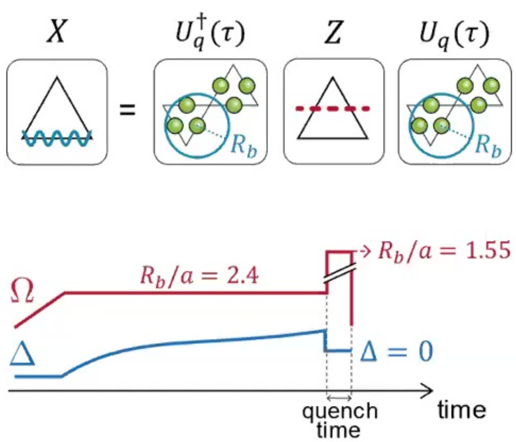
G. Semeghini et al (2021)

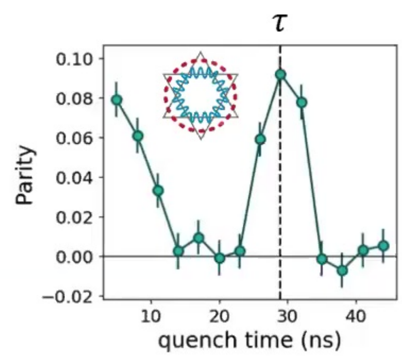
Probing coherence: off-diagonal string operator

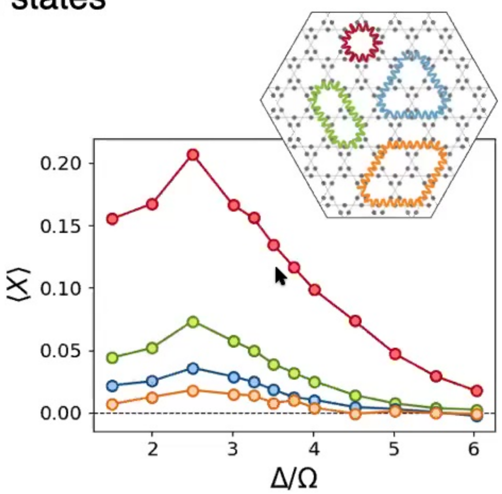
off-diagonal string operator



basis rotation to measure X: collective operation on 3-atom states



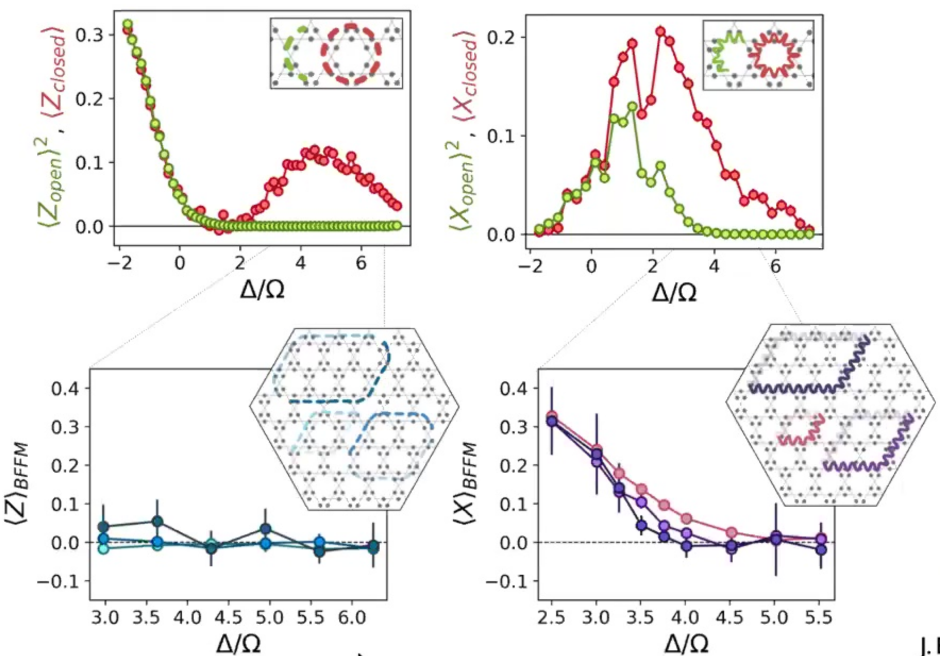




Theory R. Verresen, et al arXiv:2011.12310 (2020)
Experiment G. Semeghini et al (2021)

Order parameters for QSL phase

closed loops vs open strings

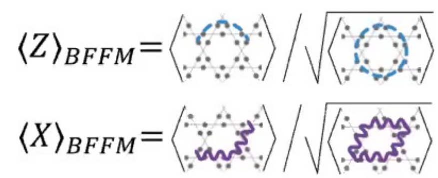


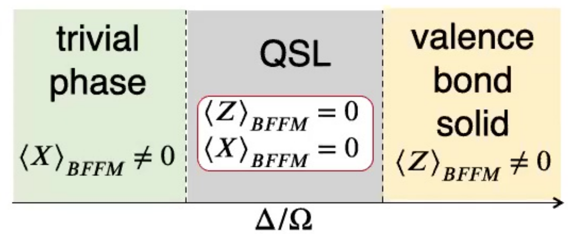
closed loops: detect non-trivial topological correlations

open strings: distinguish QSL from nearby phases

↓

BFFM string order parameters:





J. Bricmont and J. Frölich, Physics Letters B 122 (1983)

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

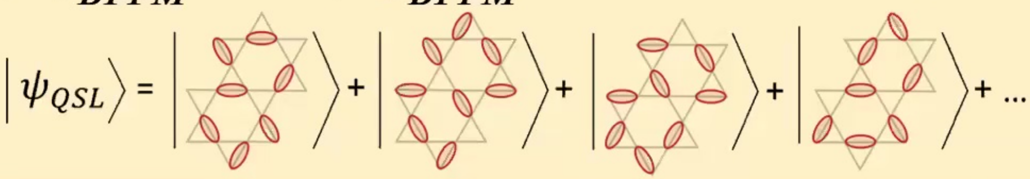
Order parameters for QSL phase

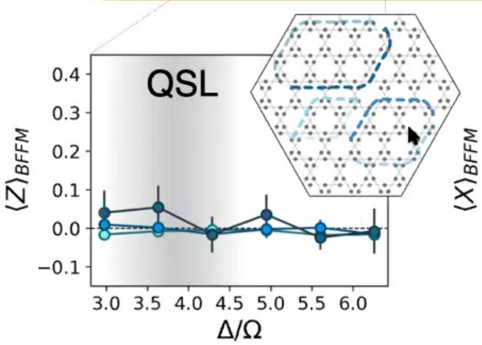
closed loops: detect non-trivial topological

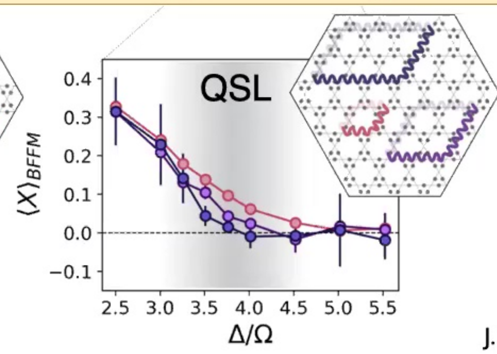
sh
ses

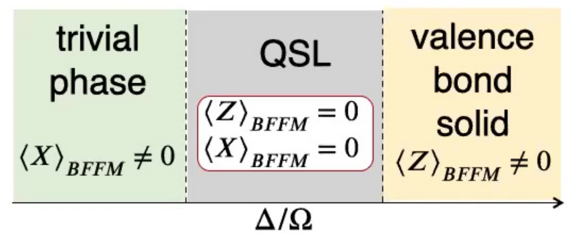
eters:

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









J. Bricmont and J. Frölich, Physics Letters B 122 (1983)
K. Fredenhagen and M. Marcu, Comm. Math. Phys. 92 (1983)

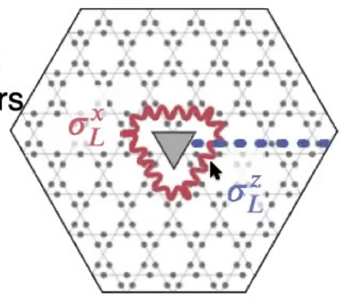
onset of a quantum spin liquid phase!

Probing topological properties of quantum spin liquids

non-trivial topology:

array with a hole

logical operators

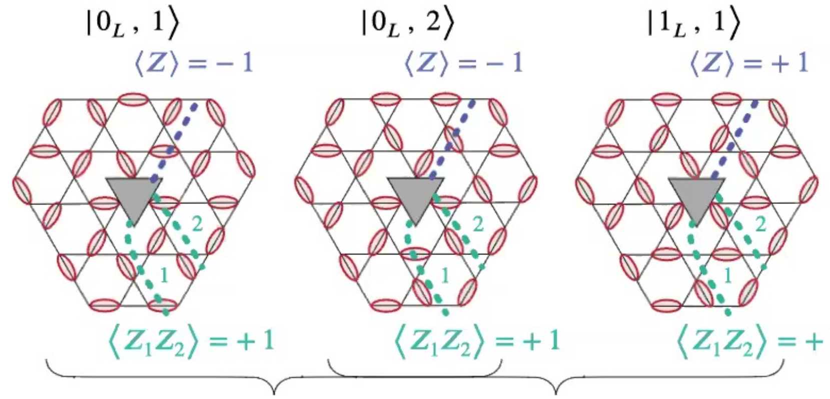


two-fold degenerate ground state:

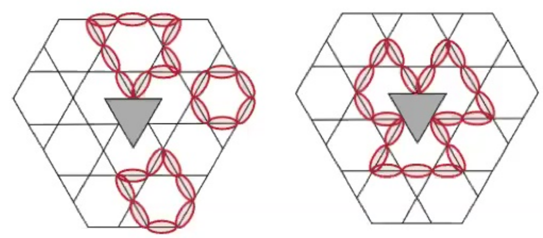
$|\psi_+\rangle \sim |0_L\rangle + |1_L\rangle$ — $\langle \sigma_L^x \rangle = +1$

$|\psi_-\rangle \sim |0_L\rangle - |1_L\rangle$ — $\langle \sigma_L^x \rangle = -1$

two distinct topological sectors



transition graph:
$|A\rangle \cup |B\rangle$



same topological sector

opposite topological sectors

Probing topological properties of quantum spin liquids

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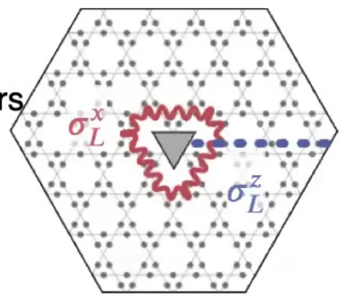
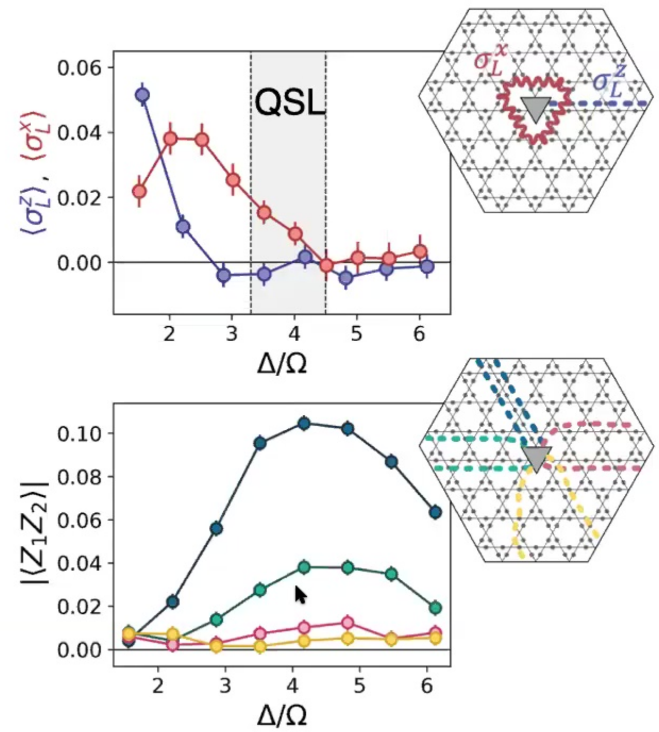
array with a hole

logical operators





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Probing topological properties of quantum spin liquids

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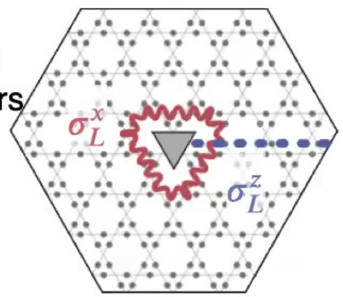

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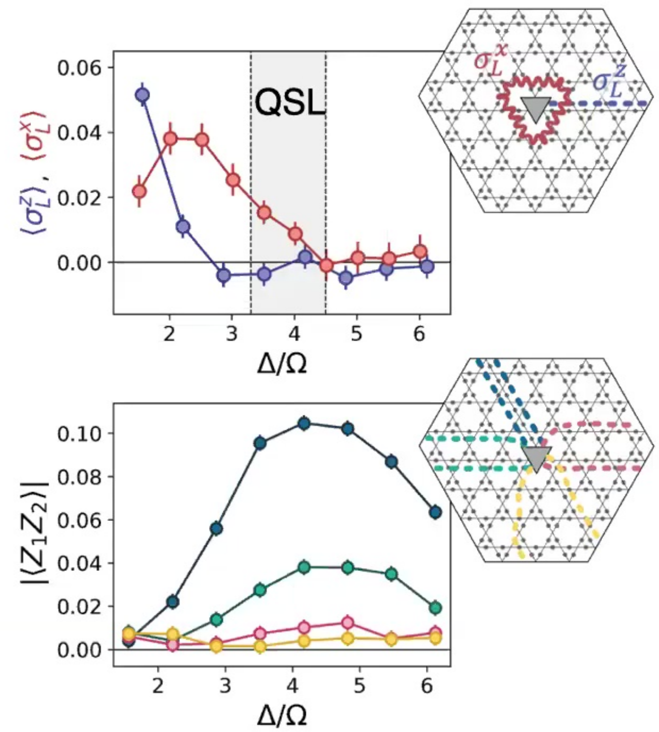


First steps towards topological qubits!

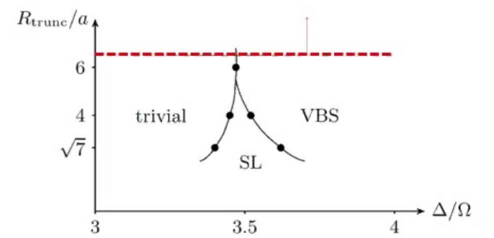
Understanding experimental observations

Theory: R. Verresen, H. Pichler, A. Vishwanath

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

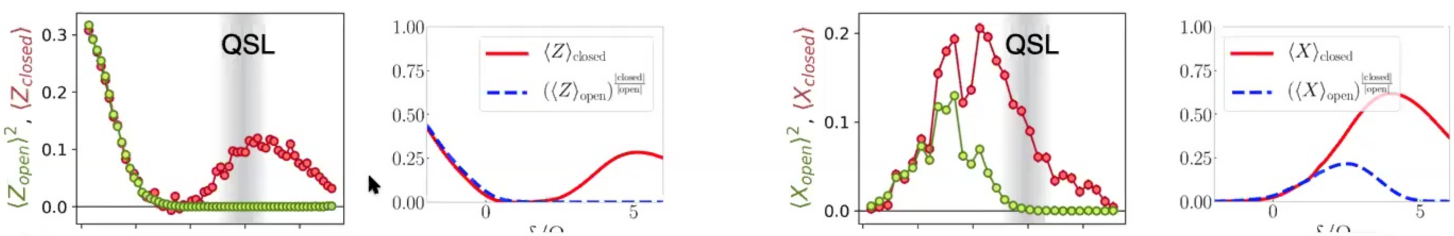
- ground state properties:
  DMRG on a cylinder with periodic boundary conditions show that long-range interactions destabilize spin liquids!

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



- quasi-adiabatic state preparation: time-dependent DMRG simulations on a small system

state with SL properties: good qualitative agreement with experiment



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

Outlook

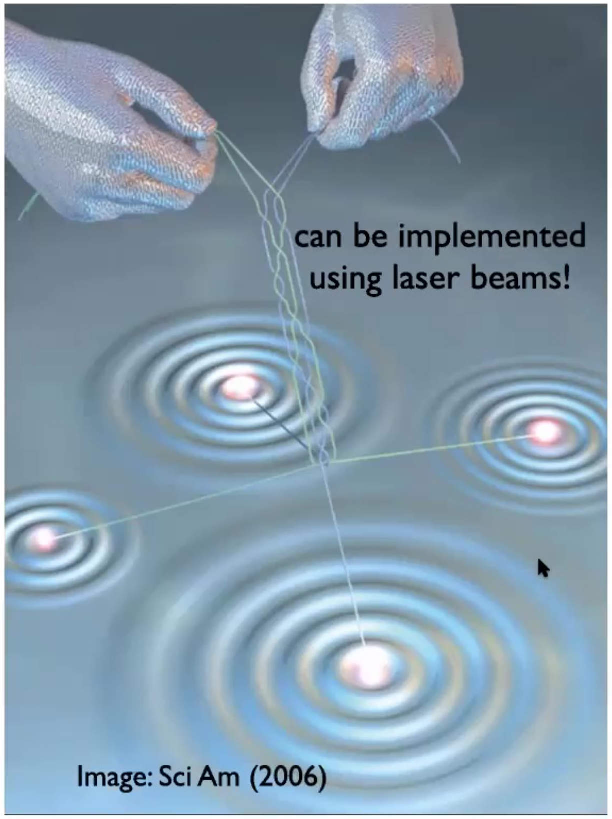


Image: Sci Am (2006)

Unprecedented insights into topological matter

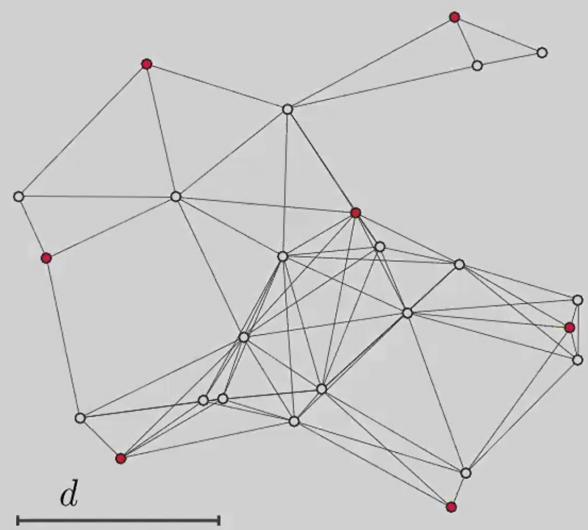
Many open questions:
- nature of the state (ground, metastable, …)
- topological qubit control
- quantum information protection

Exciting new opportunities:
- exploring topological states
- testing ideas for fault tolerant quantum information processing
- simulating Lattice Gauge Theories
- insights for engineering other systems (TMDCs)

Giulia Semeghini et al, (2021)
Greiner, Vuletic, Lukin collaboration with Sachdev & Vishwanath groups

Application for quantum optimization:
Maximum Independent Set

- We are given a undirected graph *G=(V,E)* with vertices *V* and edges *E*
- Independent set *S* is a subset of *V* such that no elements of *S* are neighboring on *G*
- The MIS problem consists in finding the largest independent set
- Example: MIS on unit disk graph - vertices connected if they are within a given distance



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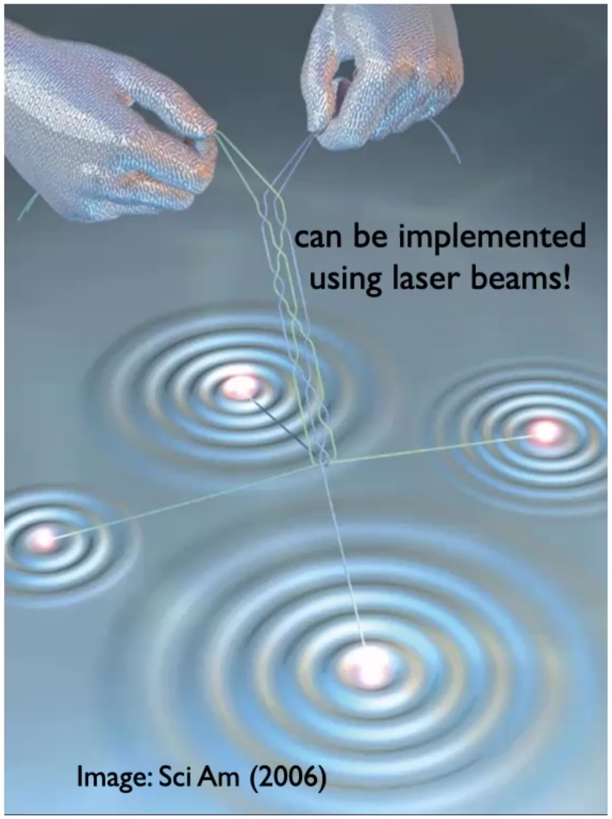
Outlook



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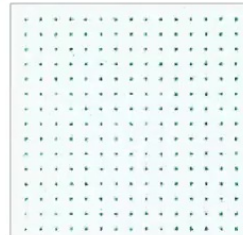
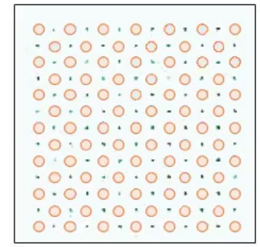
Summary

✓ Atom by atom approach to building quantum matter

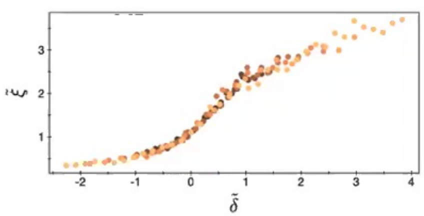
New platform for exploring synthetic quantum matter
Experiments with strongly interacting atom arrays
New generation >200 atom systems in 2D

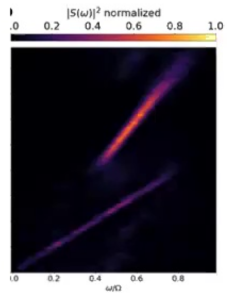


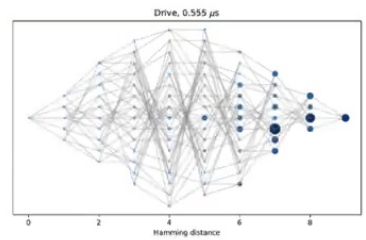


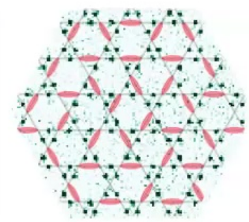
✓ Many-body dynamics on programmable simulator

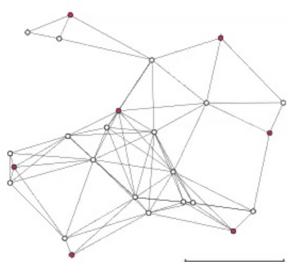
Engineering & exploring phase transitions
Non-equilibrium dynamics and quantum many-body scars
Steering quantum many-body dynamics using parametric driving
Realization and probing quantum spin liquid states





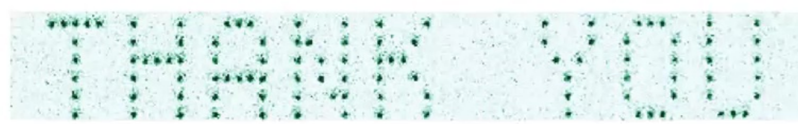






✓Outlook: exciting scientific frontier
era of "quantum discovery"

from quantum many-body physics to new applications



Acknowledgements

Harry Levine | Tout Wang | Sepehr Ebadi | Giulia Semeghini | Alex Keesling | Dolev Bluvstein | Ahmed Omran

CUA collaboration of
Lukin, Vuletic, Greiner, Englund groups
QuEra Computing, Inc.

Funding: NSF, CUA, Vannevar Bush, AFOSR MURI, DARPA, DOE, NDSEG

H. Pichler | S. Choi | N. Maskara | L. Zhou | R. Samajdar | W. W. Ho | R. Verresen

Collaborations with Sachdev group, Vishwanath group, Maksym Serbyn group