Title: Programmable quantum systems based on Rydberg atom arrays

Speakers: Mikhail Lukin

Collection: Cold Atom Molecule Interactions (CATMIN)

Date: July 15, 2022 - 9:00 AM

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Abstract: We will discuss the recent advances involving programmable, coherent manipulation of quantum many-body systems using neutral atom arrays excited into Rydberg states, allowing the control over 200 qubits in two dimensions. These systems can be used for realization and probing of exotic quantum phases of matter and exploration of their non-equilibrium dynamics. Recent advances involving the realization and probing of quantum spin liquid states - the exotic topological states of matter have thus far evaded direct experimental detection and the observation of quantum speedup for solving optimization problems will be described. In addition, the realization of novel quantum processing architecture based on dynamically reconfigurable entanglement and the steps towards quantum error correction will be discussed. Finally, we will discuss prospects for using these techniques for realization of large-scale quantum processors.

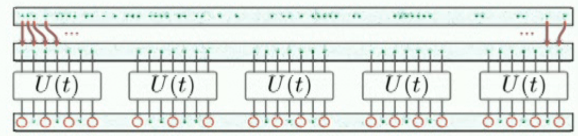
Exploring New Scientific Frontiers using Programmable Rydberg Arrays

Mikhail Lukin
Physics Department, Harvard University

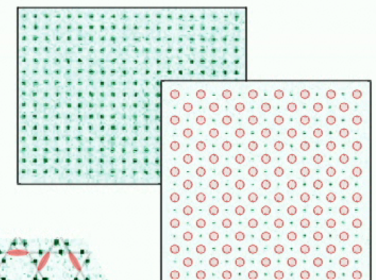
This talk

✓ Building scalable quantum systems using Rydberg atom arrays

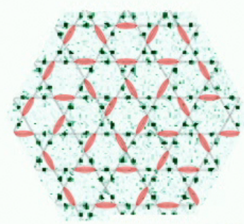
- Atom-by-atom assembly of strongly interacting quantum matter
- Exploring quantum phase transitions
- Quantum control of large 2D atom arrays

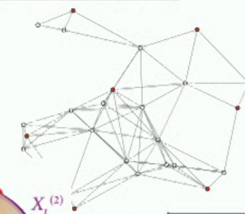


✓ Probing quantum dynamics of many-body systems



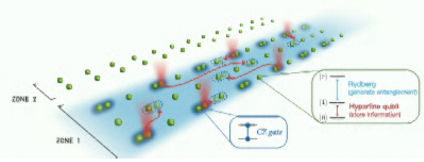
- Quantum phases & phase transitions in 2D spin models
- Probing topological spin liquids
- Applications to quantum optimization

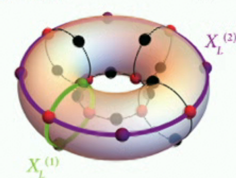




✓ Current efforts and outlook

- Reconfigurable quantum processing architecture





Atom-by-atom approach for building scalable quantum systems

Laser cooled neutral atoms: removing entropy by observation

Prioneering work: Regal, Browaeys groups

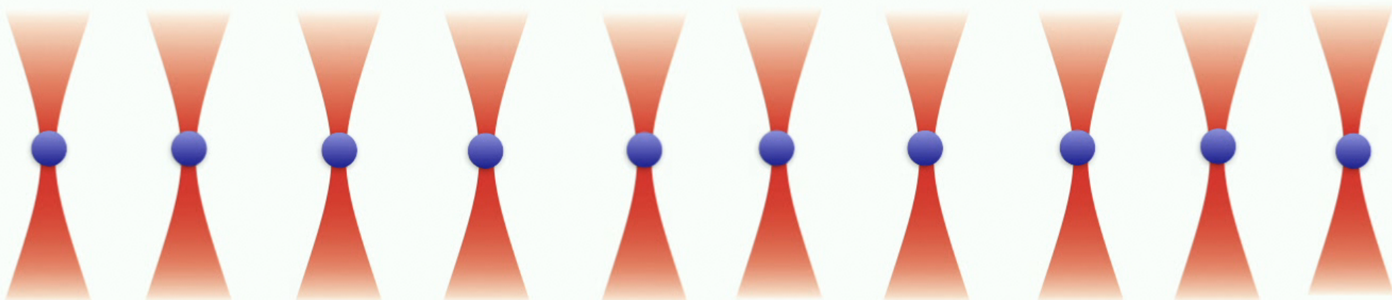
A.M. Kaufman, et al., Science **345**, 306 (2014)
H. Labuhn et al., arXiv:1509.04543 (2015)

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

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



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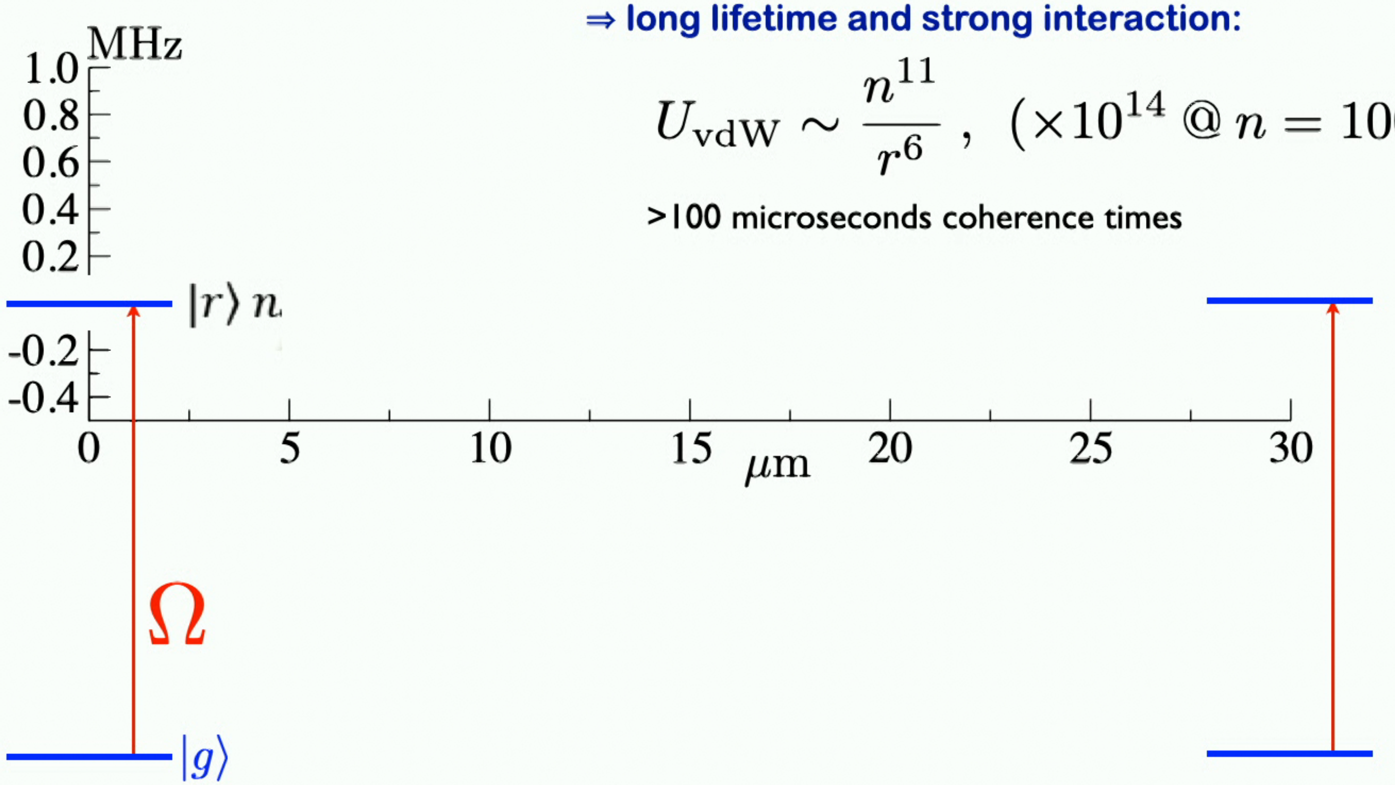
Rydberg blockade for atoms with larger n

⇒ **long lifetime and strong interaction:**

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

>100 microseconds coherence times



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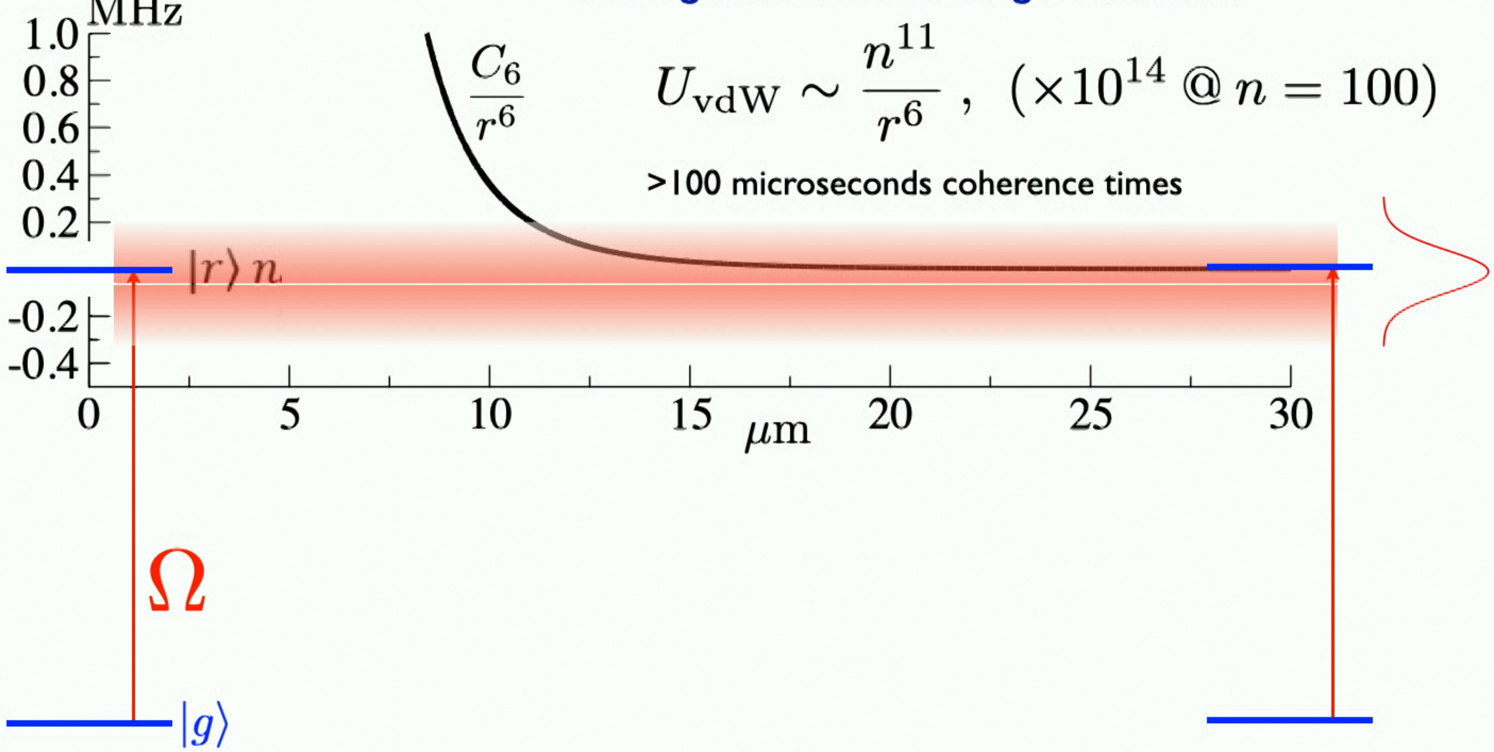

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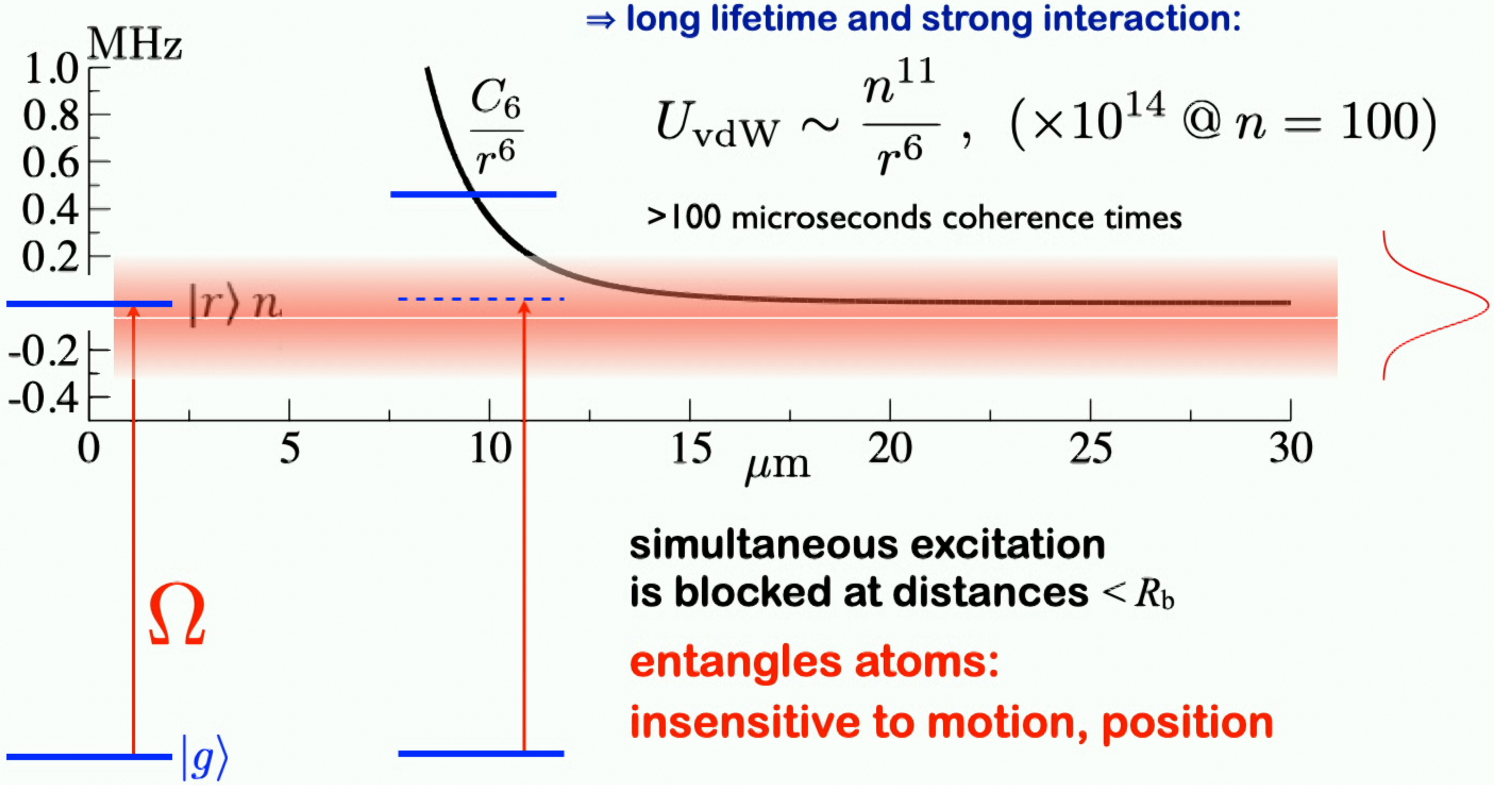

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simultaneous excitation
is blocked at distances $< R_\mathrm{b}$

entangles atoms:
insensitive to motion, position

$R_\mathrm{b} \approx 10\mu\mathrm{m}$ **for typical values:** n= 70-100

idea: collaboration with M. Fleischhauer, R. Cote, I. Cirac, P. Zoller (2001), early expts Paris, Wisconsin

Rydberg blockade for atoms with larger n

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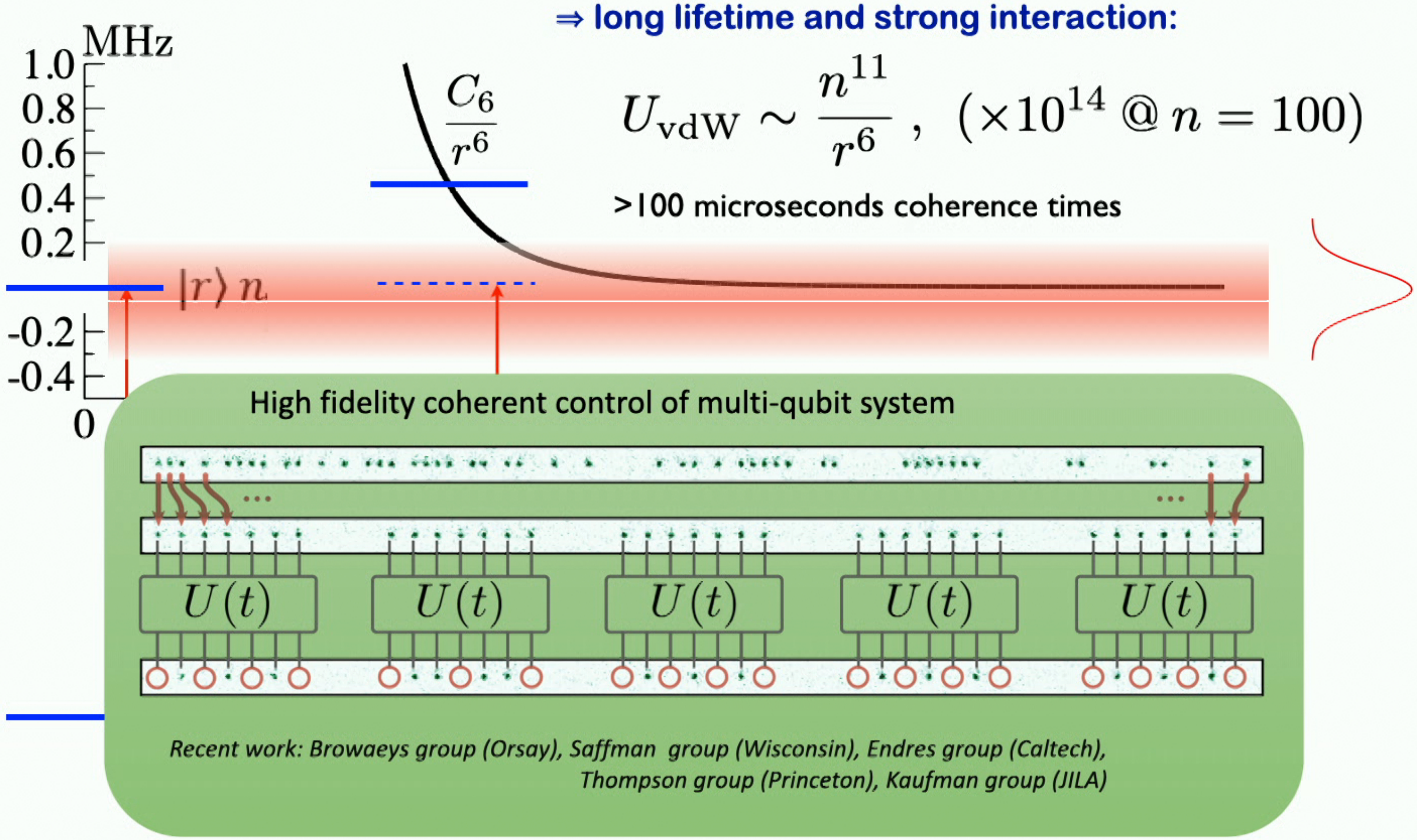

Recent work: Browaeys group (Orsay), Saffman group (Wisconsin), Endres group (Caltech), Thompson group (Princeton), Kaufman group (JILA)

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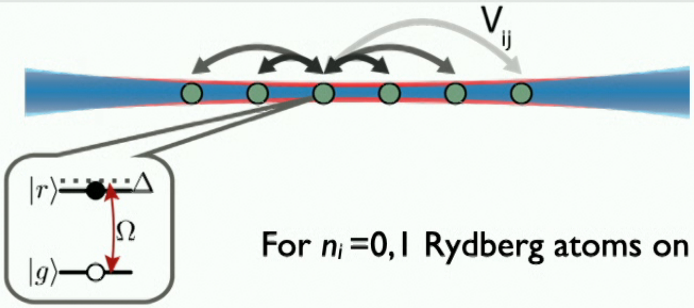
Programmable quantum simulator using atom arrays



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:

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

Original PQS idea: R. Feynman (1981)

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

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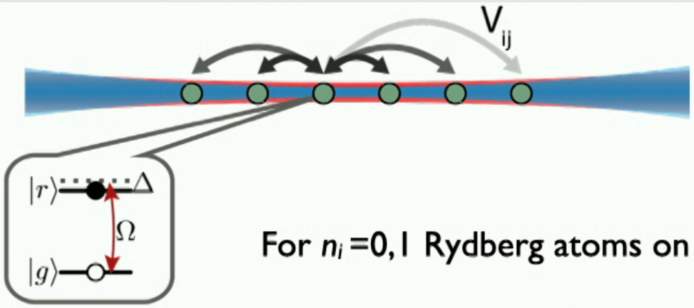

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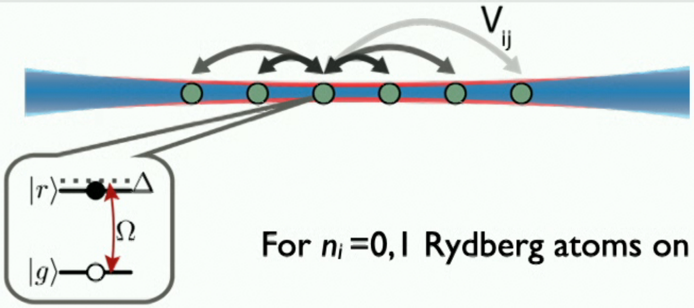

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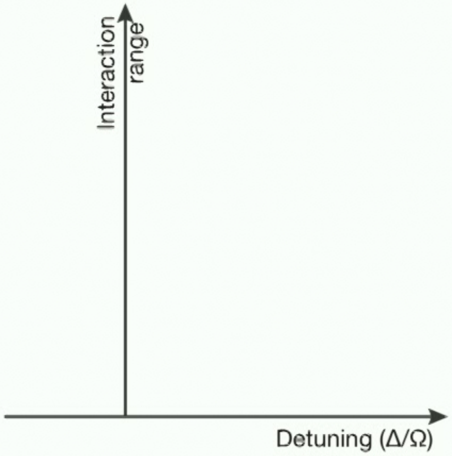

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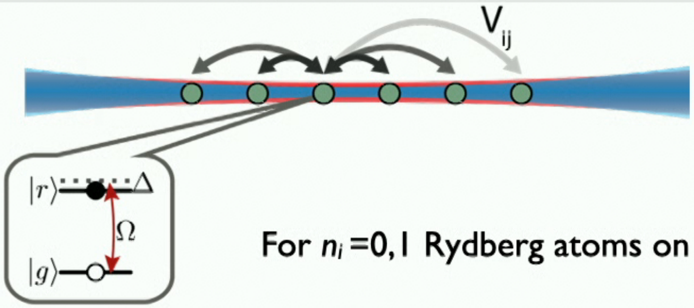

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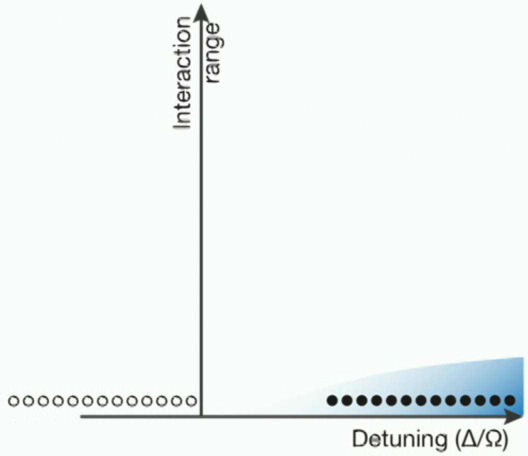

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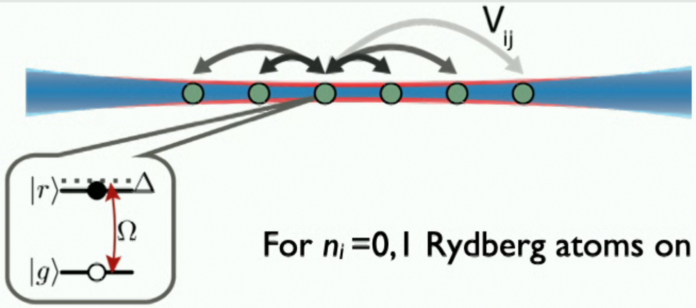

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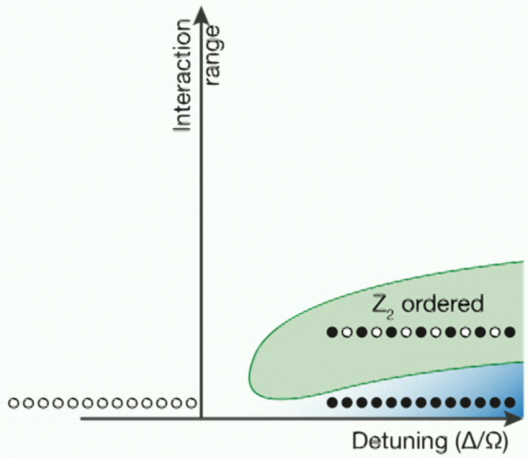

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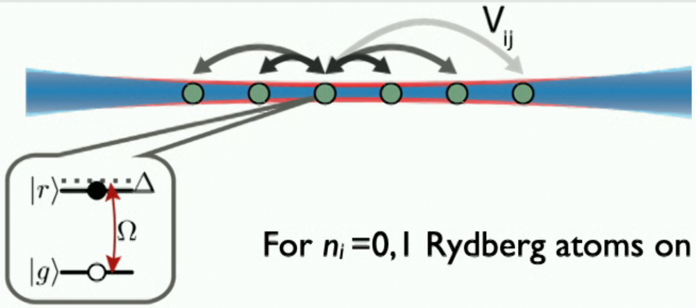

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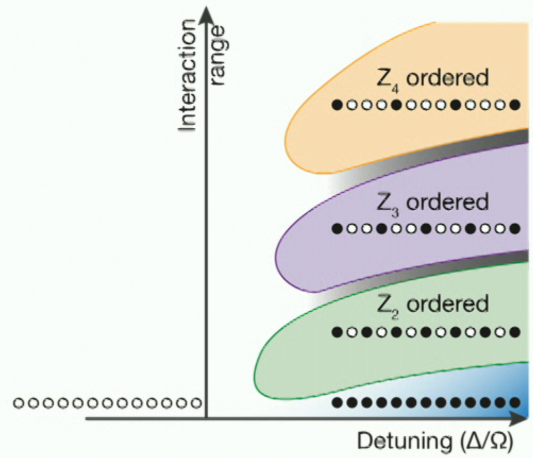

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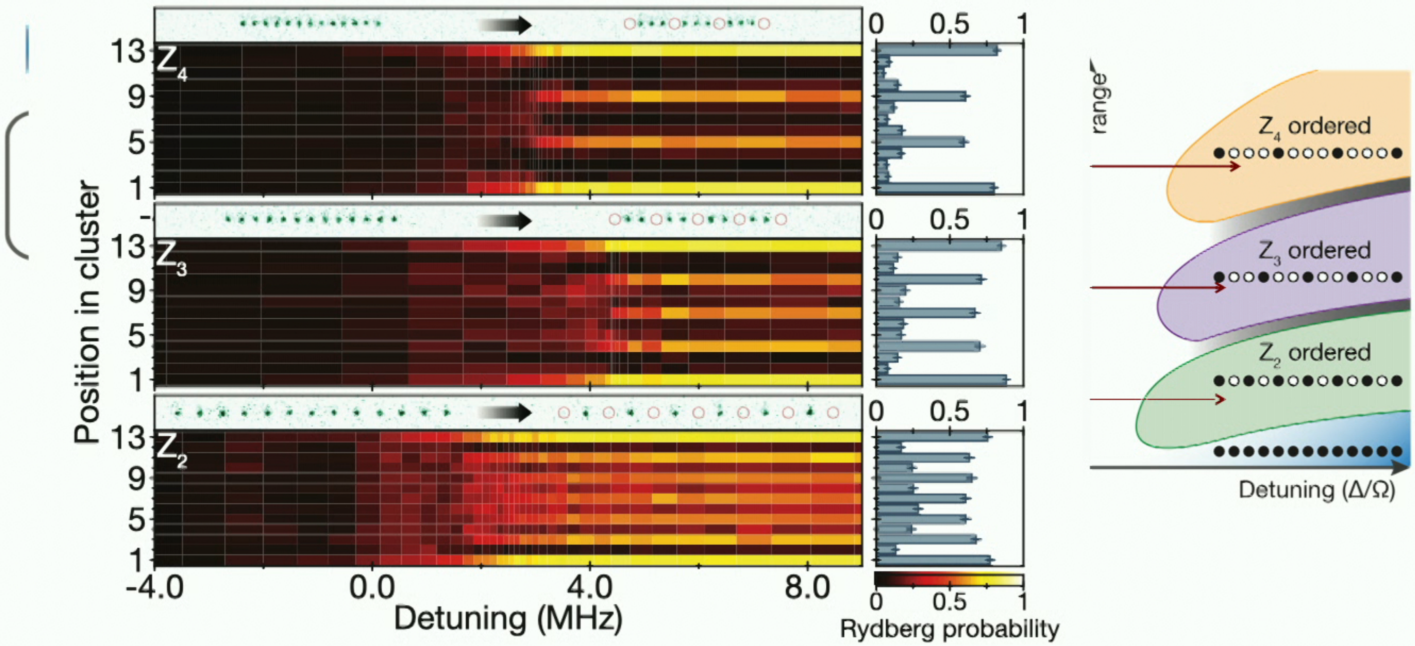

Approach: adiabatic following across phase transition

Original PQS idea: R. Feynman (1981)

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

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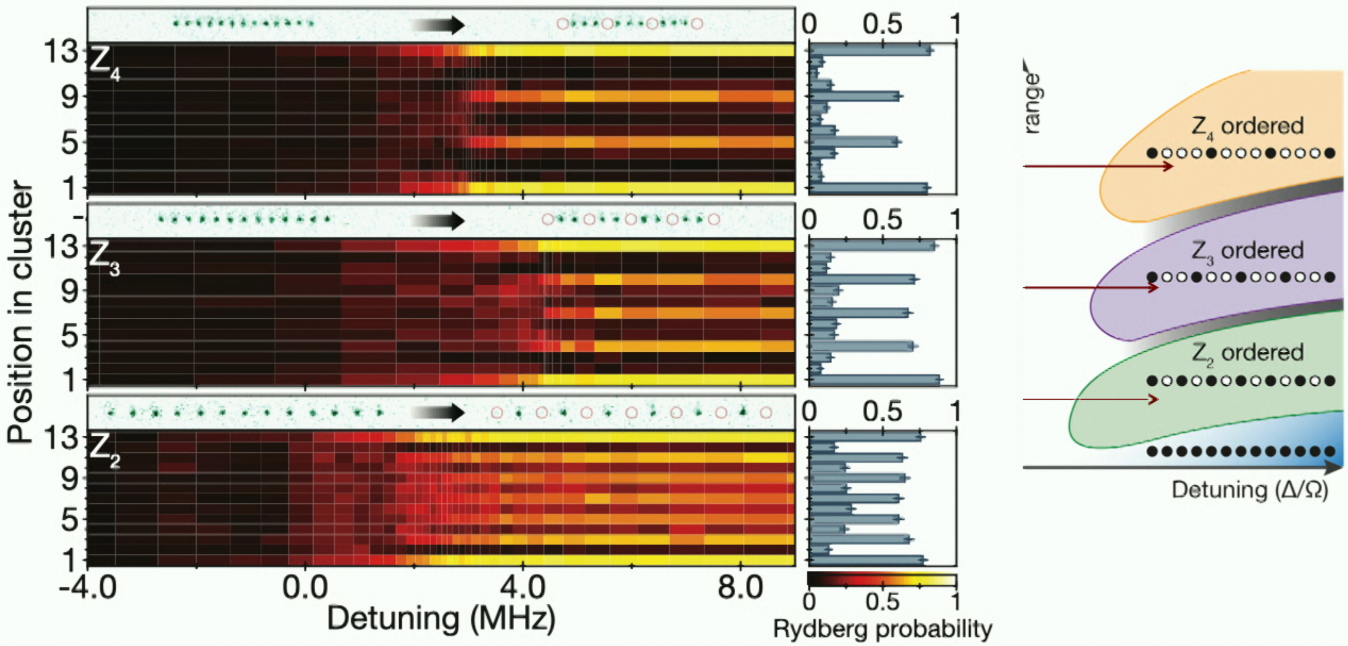

Approach: adiabatic following across phase transition

Programmable interactions result in desired symmetry breaking!

Original PQS idea: R. Feynman (1981)

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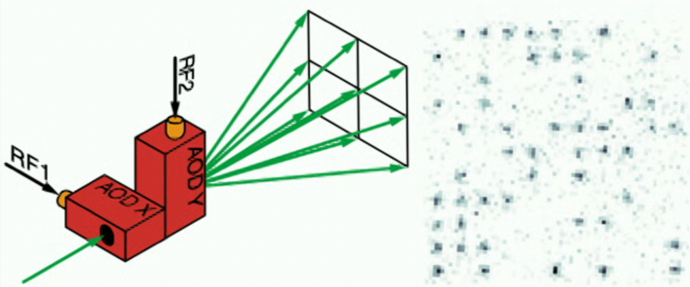
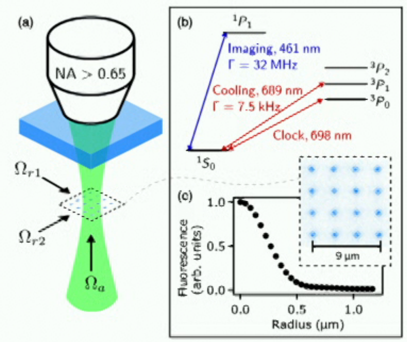
Tweezer arrays for different atoms and molecules

Strontium array, EndresLab@Caltech



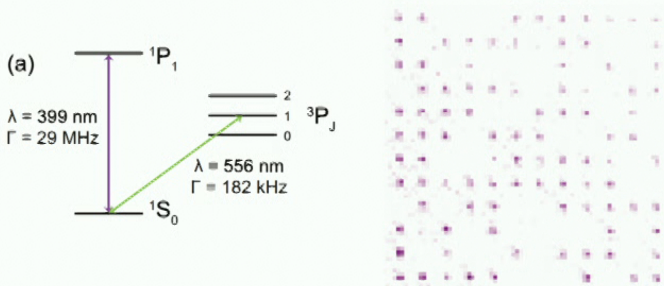
A. Cooper et al. PRX 8, 041055 (2018)

Strontium array, KaufmanLab@JILA



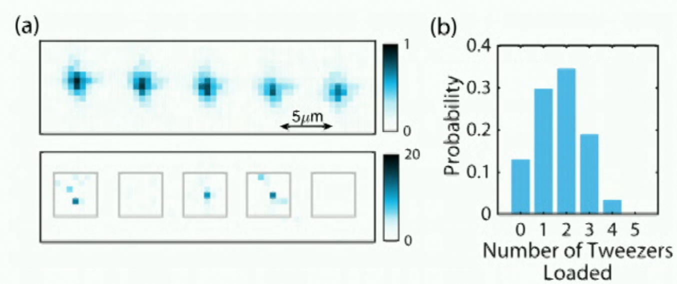
M. A. Norcia et al. PRX 8, 041054 (2018)

Ytterbium array, ThompsonLab@Princeton



S. Saskin et al. arXiv:1810.10517 (2018)

CaF molecules array, DoyleLab@Harvard



L. Anderegg et al. arXiv:1902.00497 (2019)

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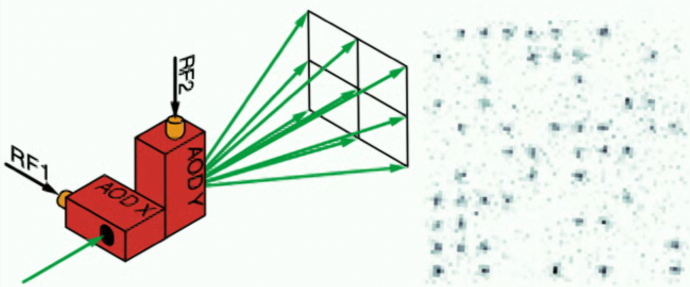

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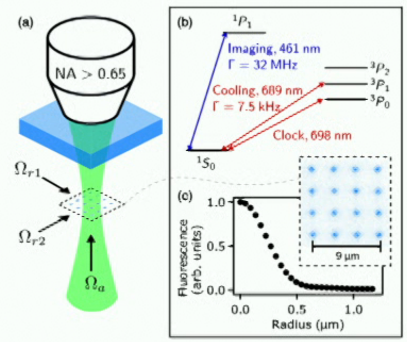

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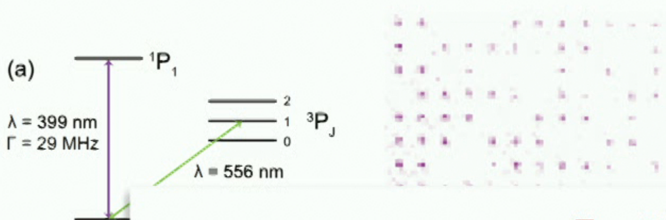

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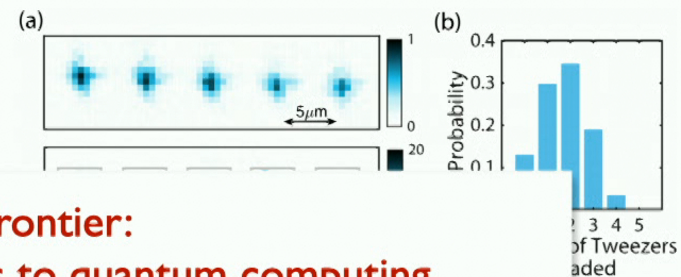
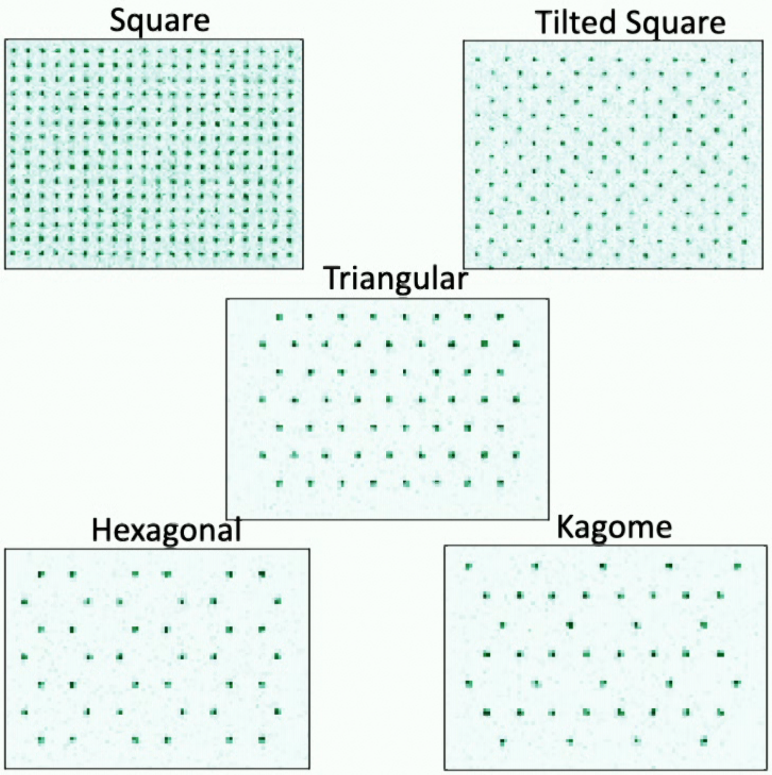


(2019)

Exciting frontier:
from many-body dynamics to quantum computing
and quantum metrology, complimentary to optical lattices

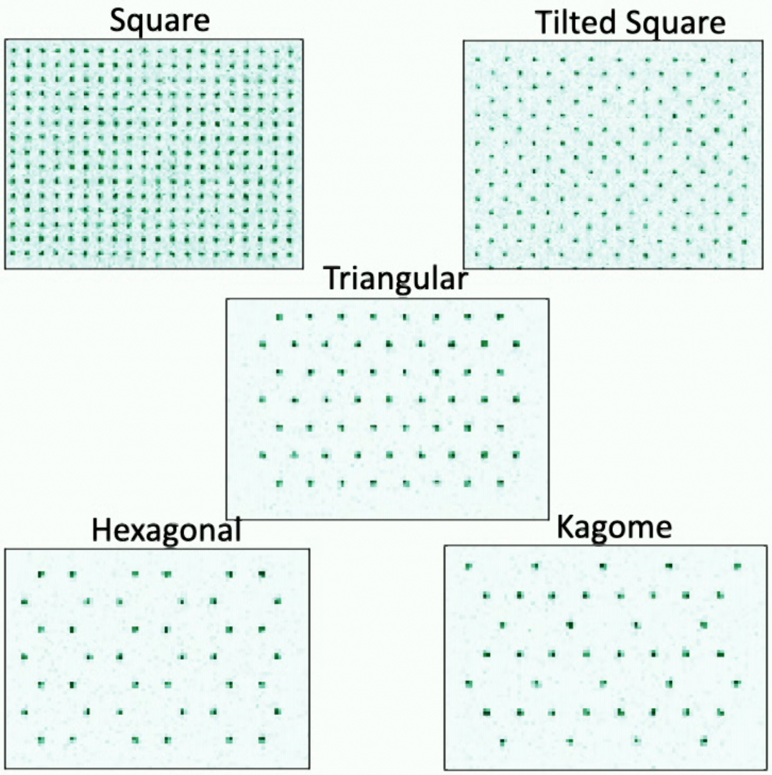
Atom Array Generation 2: large scale 2D atom arrays



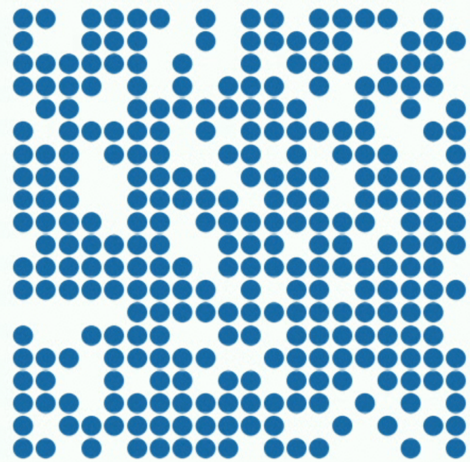
S. Ebadi et al arxiv 2012.12281, Nature (2021)

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

Atom Array Generation 2: large scale 2D atom arrays



Arbitrary patterns:
randomly generated 75%
filling in 20x20



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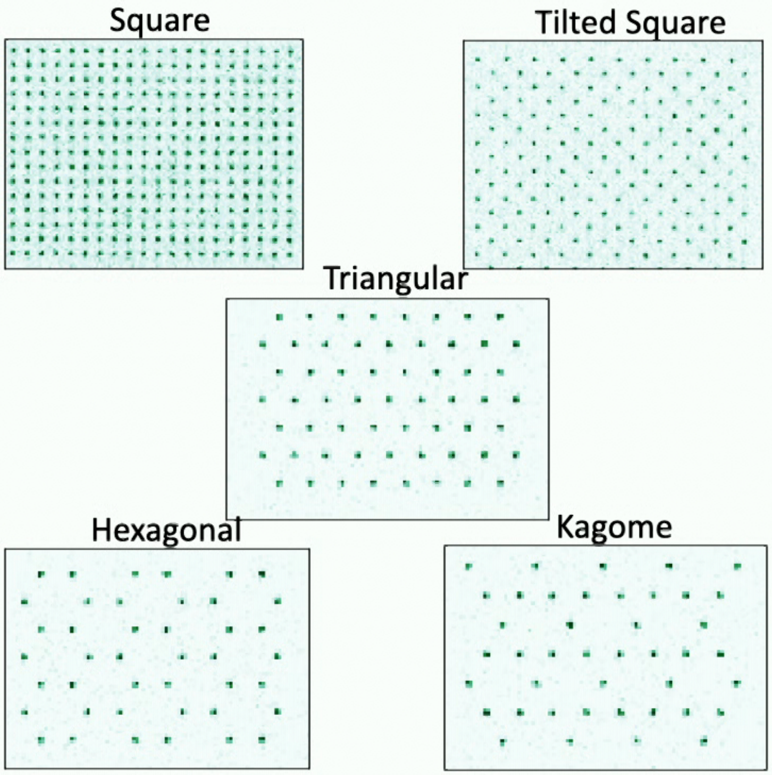

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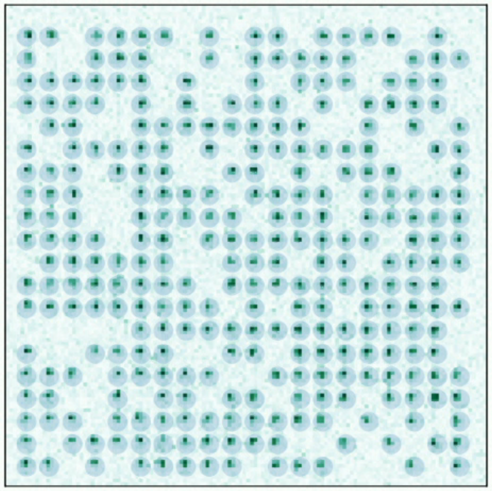

55-60% filling fraction for 600 traps => 300 sorted atoms, each filled trap >99% probability

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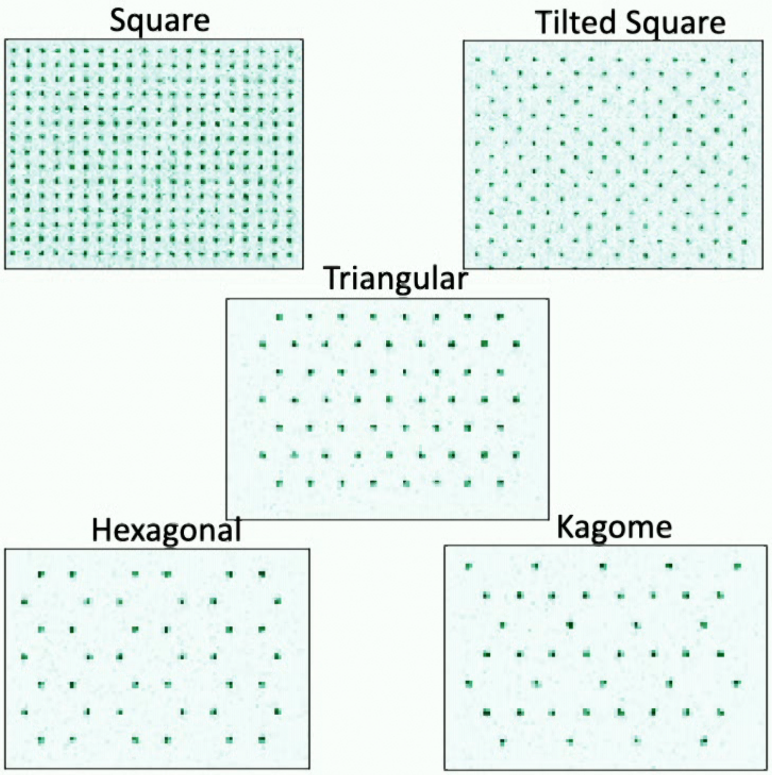

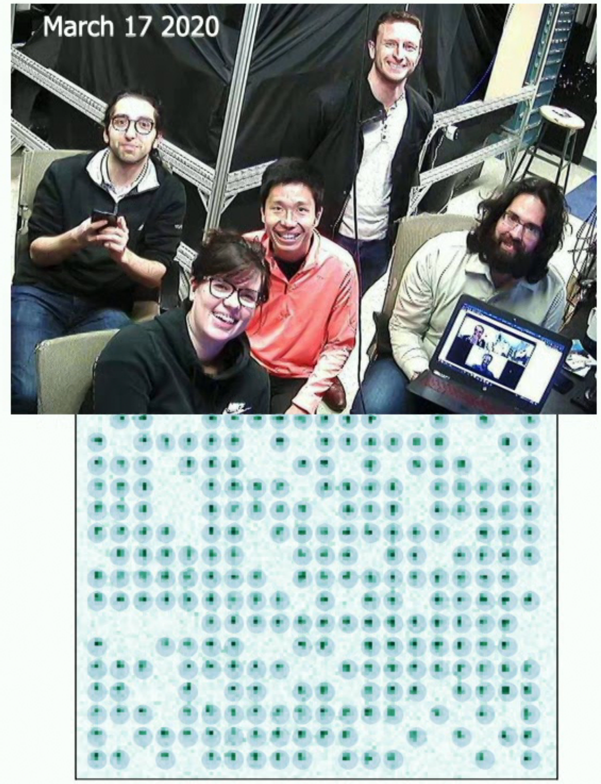

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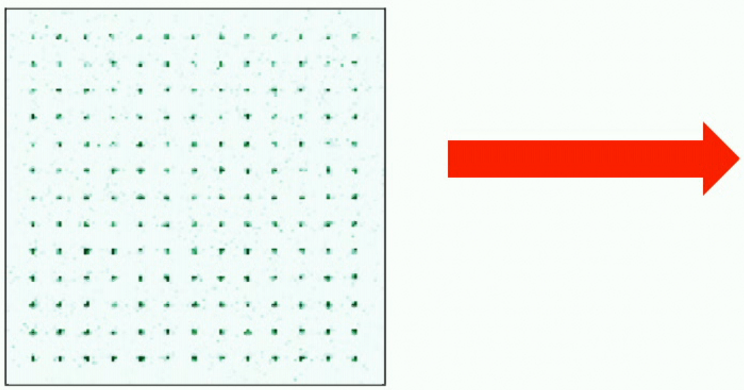
Quantum phase transitions in 2D arrays

- adjust Rydberg blockade to control interaction range
- adiabatic detuning sweep to reach the state



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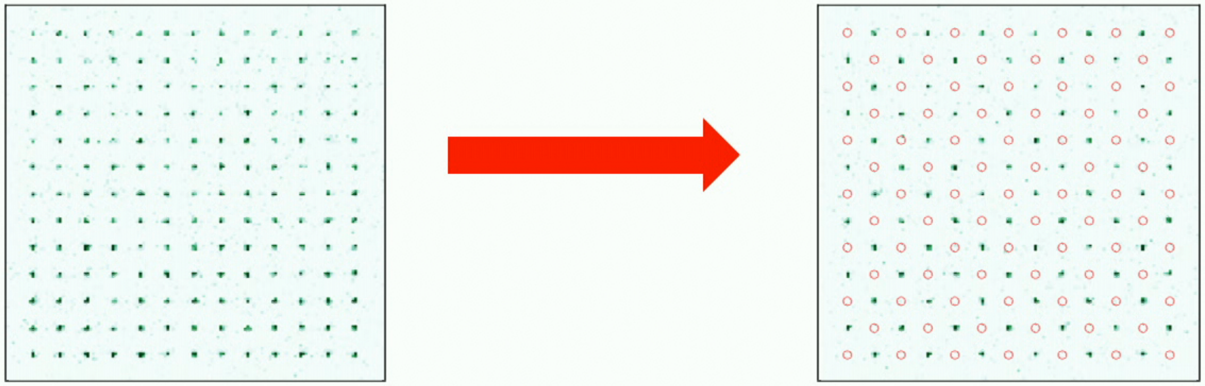

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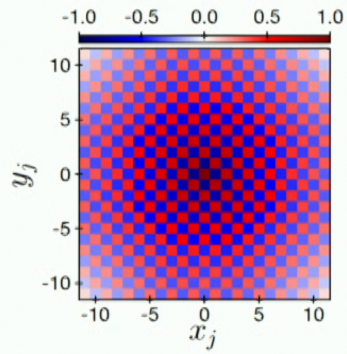
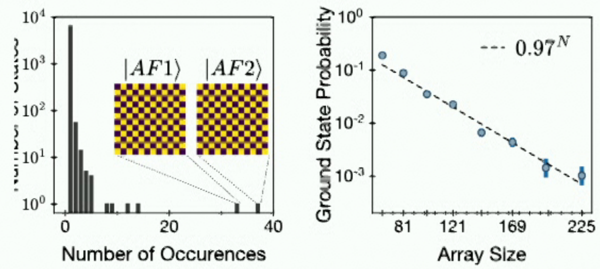
Quantum phase transitions in 2D arrays

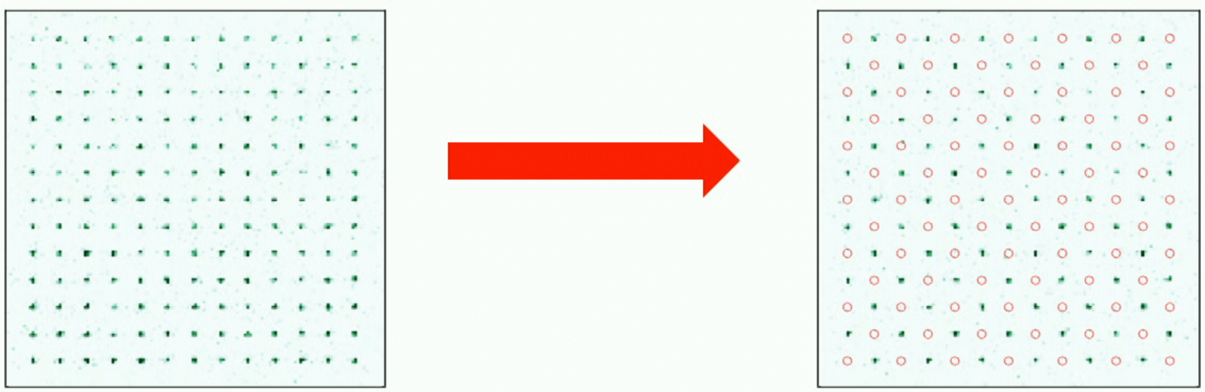
Correlations

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



Distribution of microscopic states





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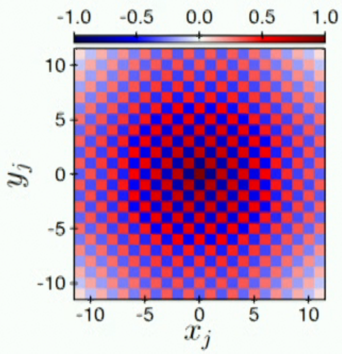

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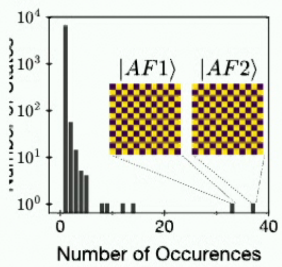
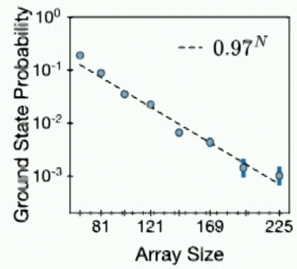
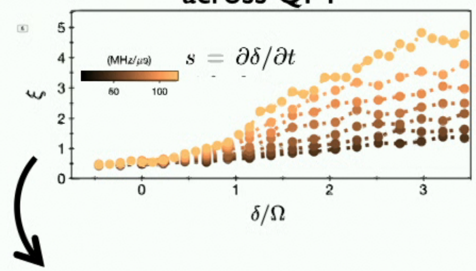
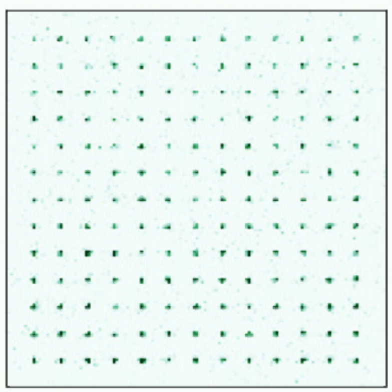
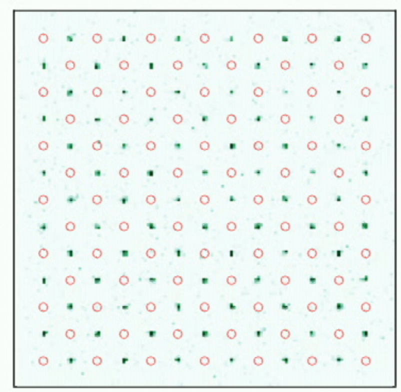




Universal scaling of correlations across QPT







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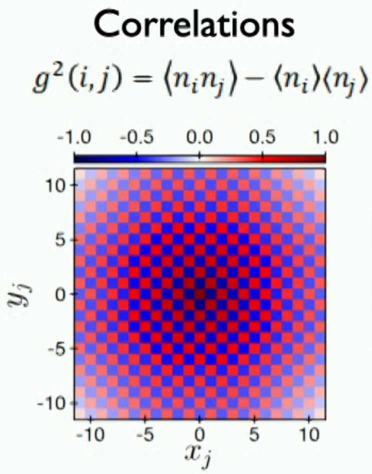
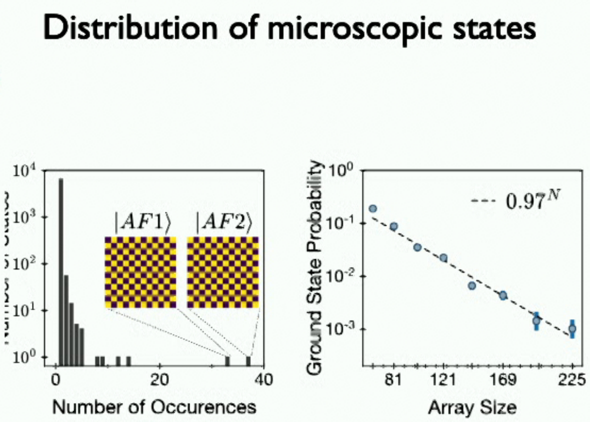
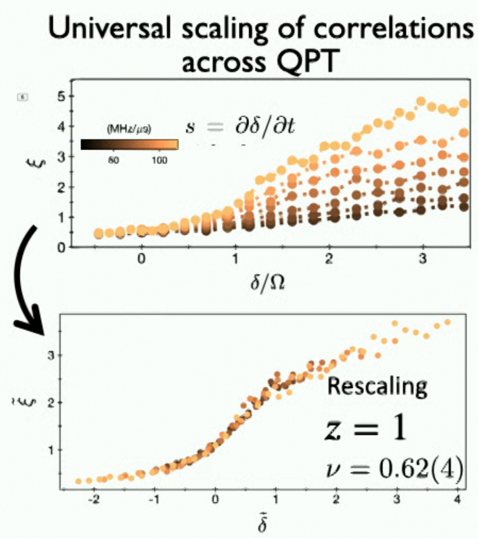
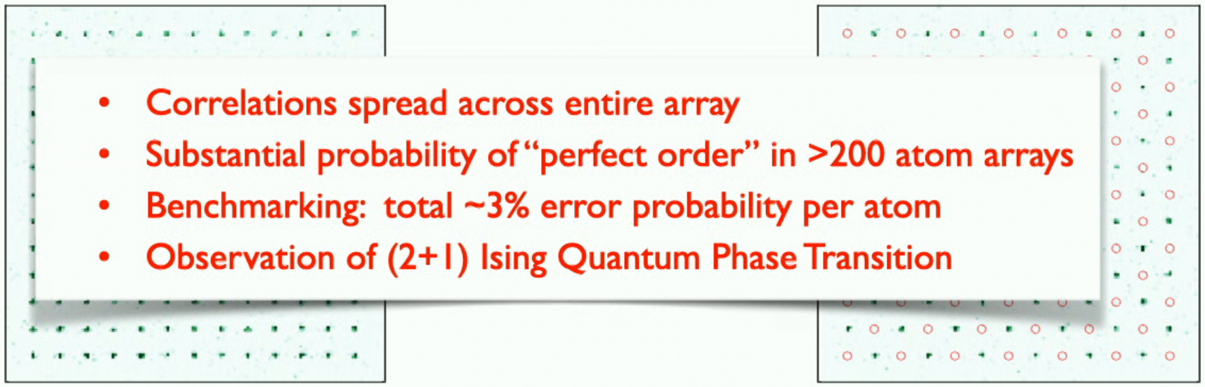
Quantum phase transitions in 2D arrays







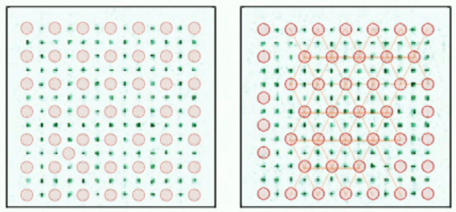


- Correlations spread across entire array
- Substantial probability of "perfect order" in >200 atom arrays
- Benchmarking: total ~3% error probability per atom
- Observation of (2+1) Ising Quantum Phase Transition

S. Ebadi et al arxiv 2012.12281, Nature (2021)

Programmable quantum simulators based on Rydberg arrays: recent progress

Exploring 2D phase diagrams



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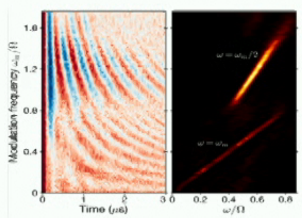
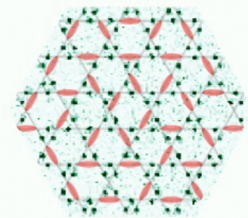
Non-equilibrium dynamics: many-body scars



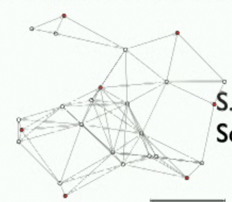
D. Bluvstein, et al, arxiv 2012.12276, Science (2021)

Probing topological spin liquids



G. Semeghini et al, arXiv:2104.04119, Science (2021)

Accelerating combinatorial optimization



S. Ebadi et al, arXiv 2202.09372 Science (2022)

Entanglement transport & universal programmability

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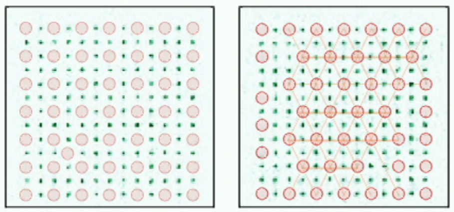

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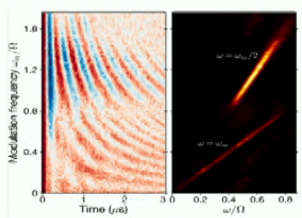
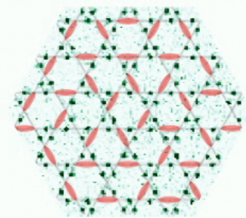


D. Bluvstein, et al, arxiv 2012.12276, Science (2021)

|QuEra>

Available on AWS cloud this year!

Probing topological spin liquids



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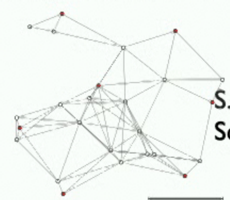

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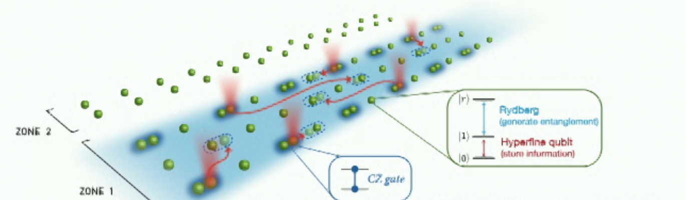

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Tackling a Long-Elusive Goal: Topological Spin Liquids

Special form of matter in "frustrated" systems, postulated by P.W. Anderson
Materials Research Bulletin 8 (1973), *Science* **235** (1987)

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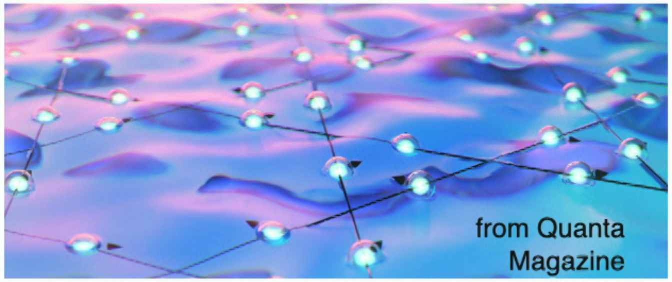
Phase of matter with exotic properties:



topological order robust against perturbations, long-range quantum entanglement, emergent lattice gauge theories, anyonic excitations…

→ major effort in condensed matter physics for the past several decades

Early work: Sachdev, Read, Wen, Kivelson, Moessner, Sondi …

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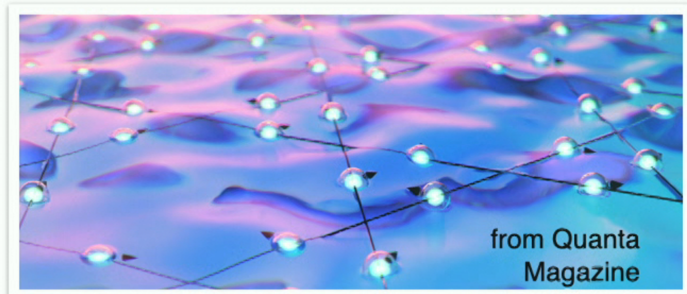

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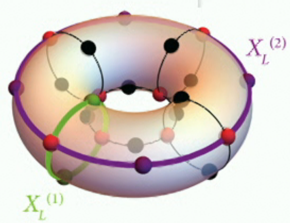
Fault-tolerant quantum computation by anyons

A.Yu. Kitaev*

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

Received 20 May 2002



Application to quantum information processing:

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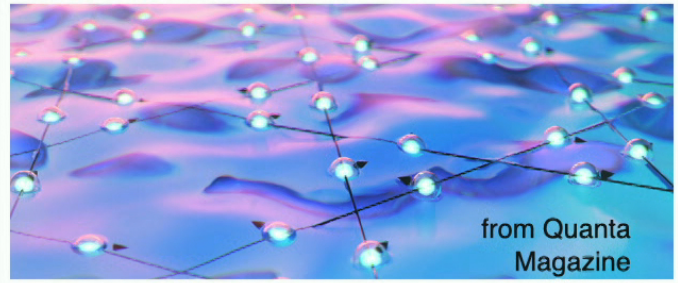

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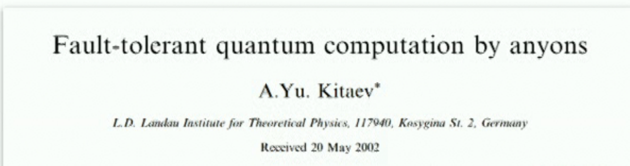
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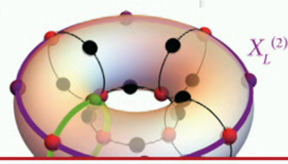

Application to quantum information processing:

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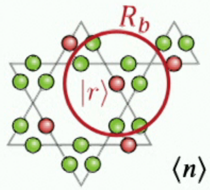
No conclusive experimental evidence in any system

…velson, Moessner, Sondi …

Dimer model with Rydberg atoms on links of kagome lattice

Key idea: Rydberg blockade on frustrated lattice results in highly degenerate states



$\langle n \rangle = 1/4$

Theory: R. Samajdar, et al S. Sachdev's group arXiv:2011.12295, PNAS (2020)
R. Verresen, et al A. Vishwanath's group arXiv:2011.12310, PRX (2021)

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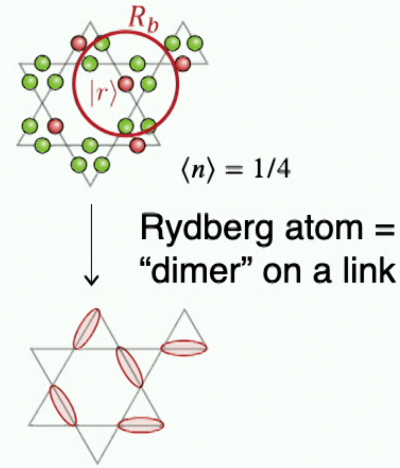

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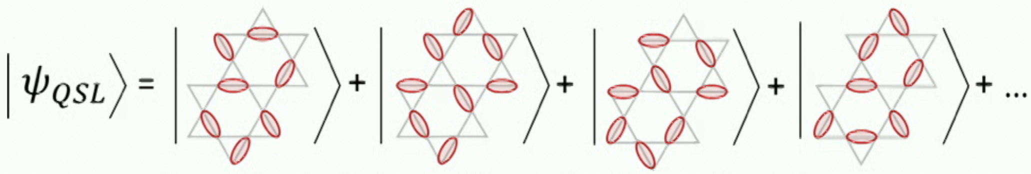
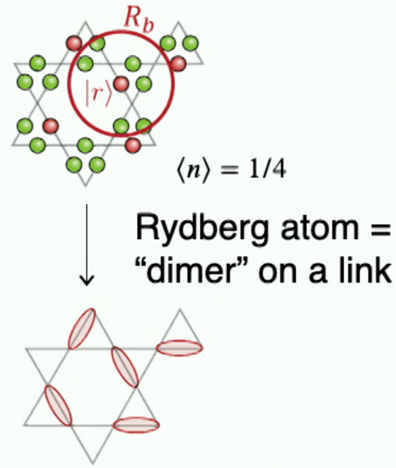


$\rightarrow$ $\mathbb{Z}_2$ topological order (Resonating Valence Bonds)



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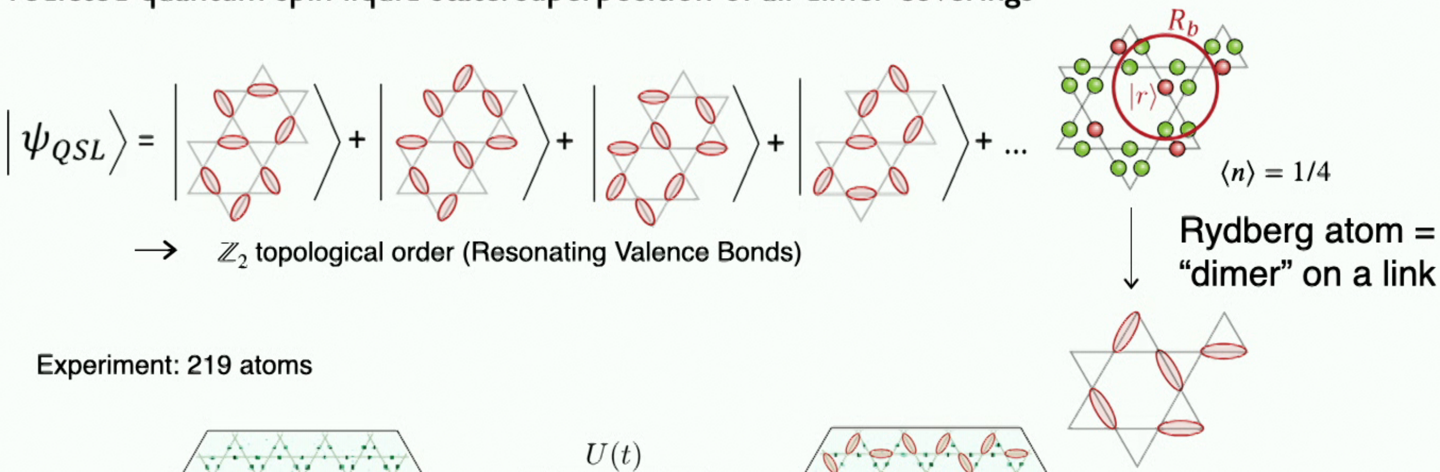
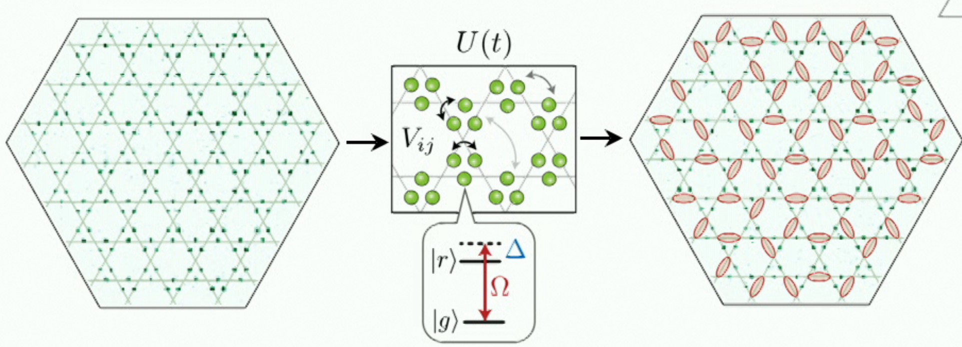


→ $\mathbb{Z}_2$ topological order (Resonating Valence Bonds)

Experiment: 219 atoms



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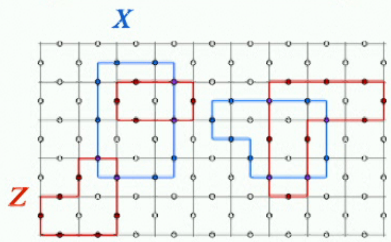
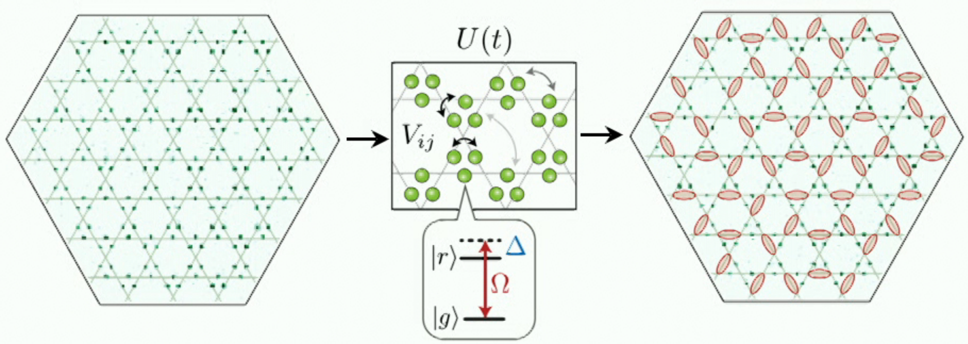
Topological string operators

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





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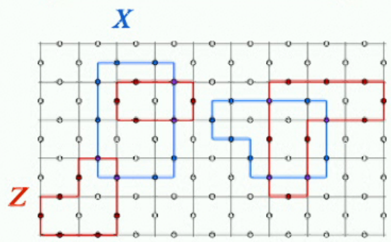
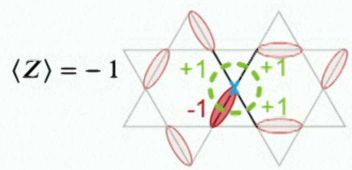
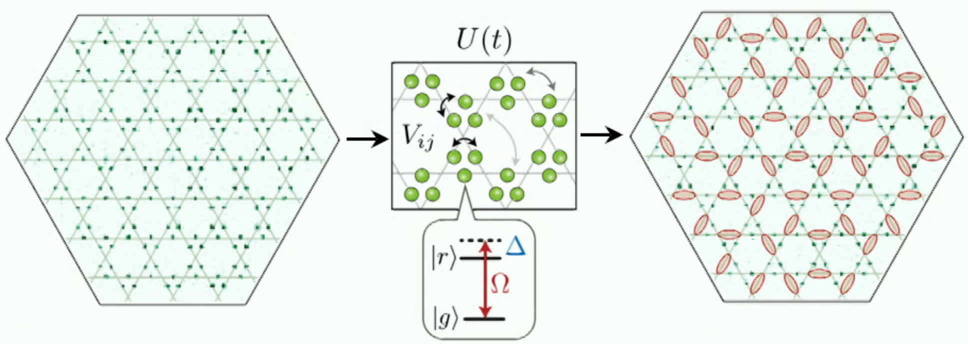


diagonal string operator Z:



parity of dimers along a string
("Gauss law")



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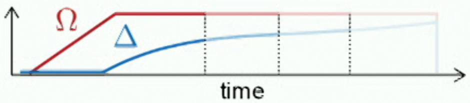
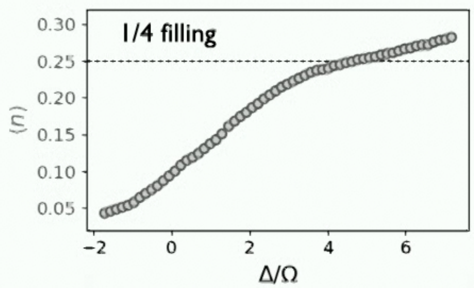
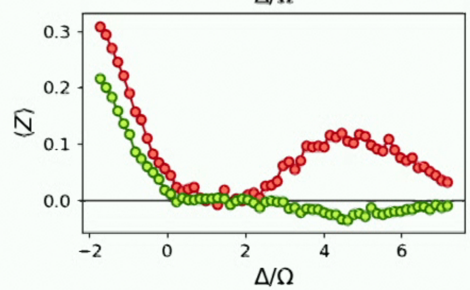
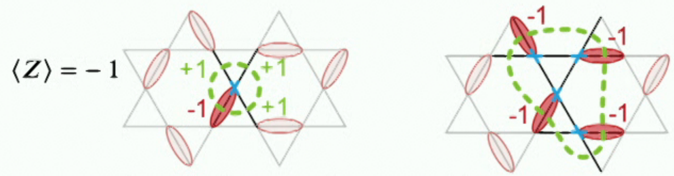






diagonal string operator Z: $\langle Z \rangle = (-1)^{\#\text{ enclosed vertices}}$



parity of dimers along a string
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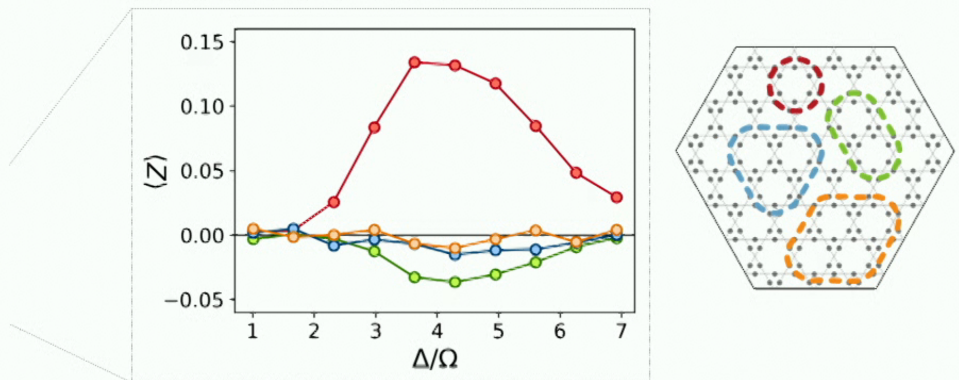

Theory R. Verresen, et al arXiv:2011.12310 (2020)

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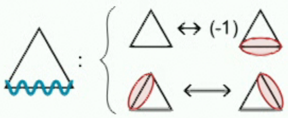
Science (2021)

Probing coherence: off-diagonal string operator

off-diagonal string operator X:



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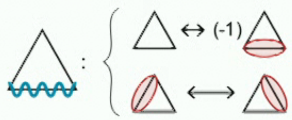

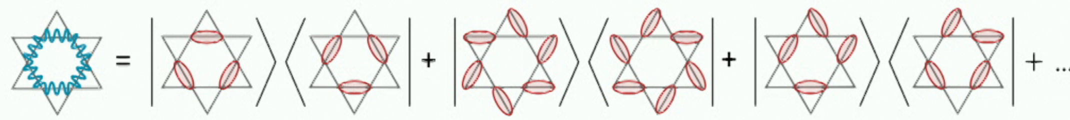

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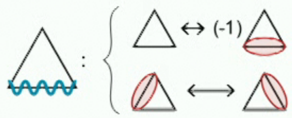

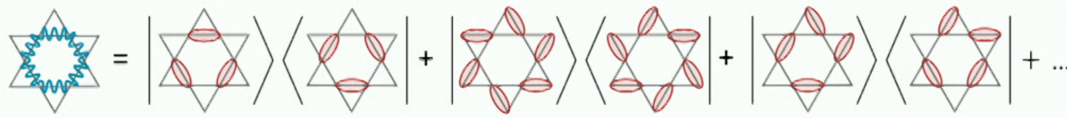

Qubit analogy: measure $\sigma_x = |0\rangle\langle 1| + |1\rangle\langle 0|$

$\langle \psi | \sigma_x | \psi \rangle = \langle \psi | 0 \rangle \langle 1 | \psi \rangle + h.c$ measures coherence between $|0\rangle$ and $|1\rangle$

Probing coherence: off-diagonal string operator

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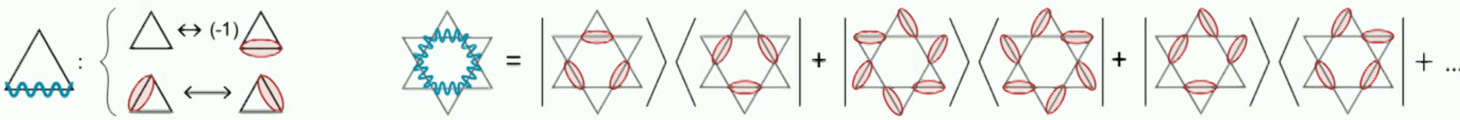
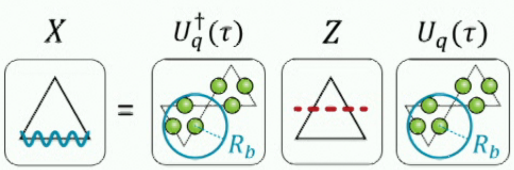


rotation to measure X: operation on 3-atom states transforms X string into “dual” Z string



Theory R. Verresen, et al arXiv:2011.12310 (2020)
Experiment G. Semeghini et al, arXiv:2104.04119, Science (2021)

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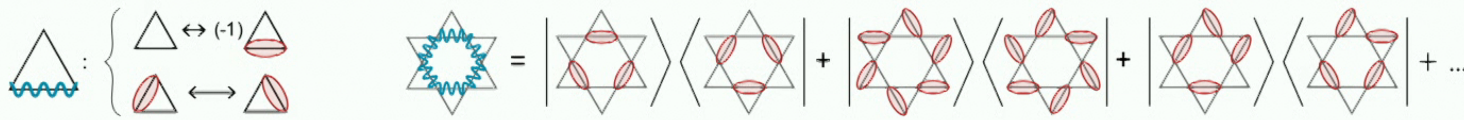

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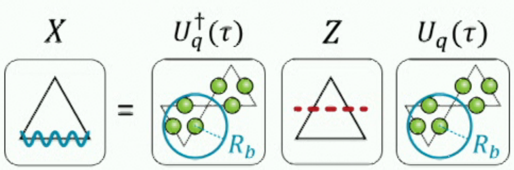

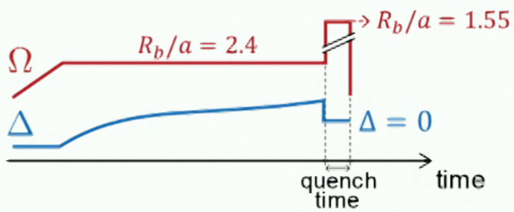

Theory R. Verresen, et al arXiv:2011.12310 (2020)
Experiment G. Semeghini et al, arXiv:2104.04119, Science (2021)

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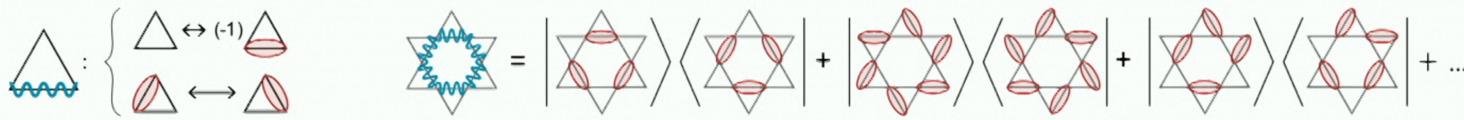

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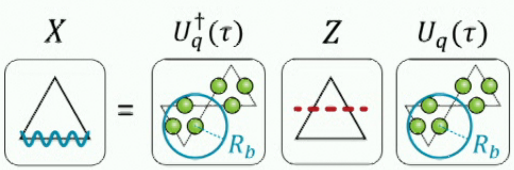

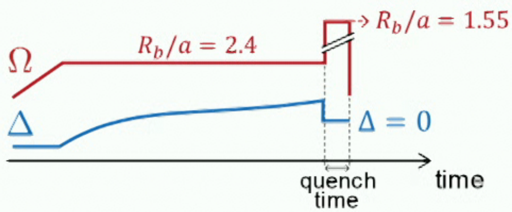

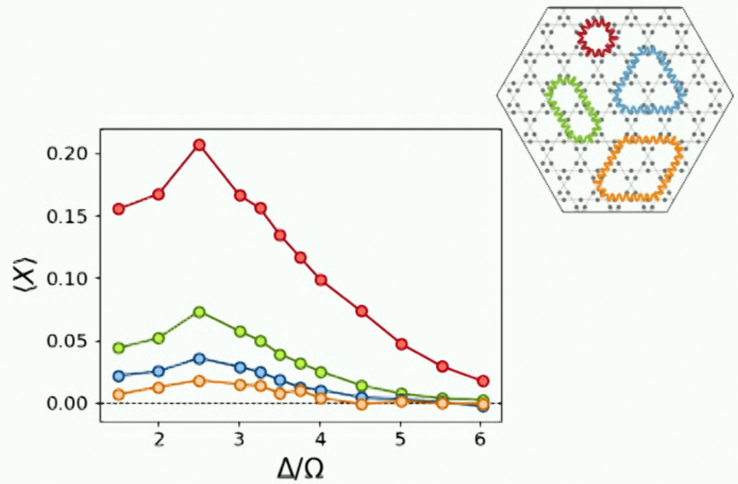

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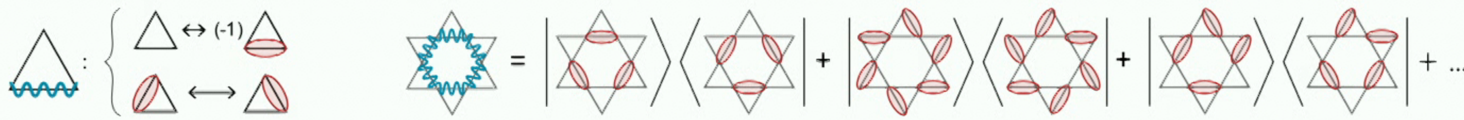

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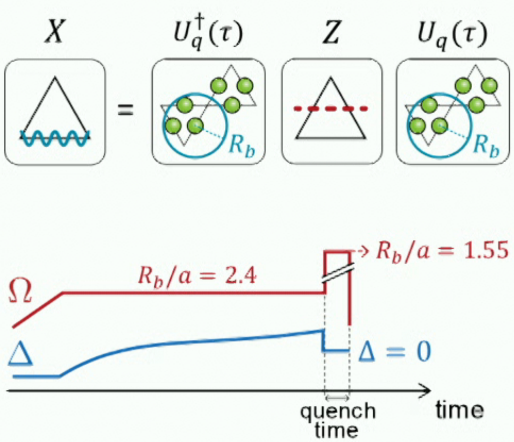
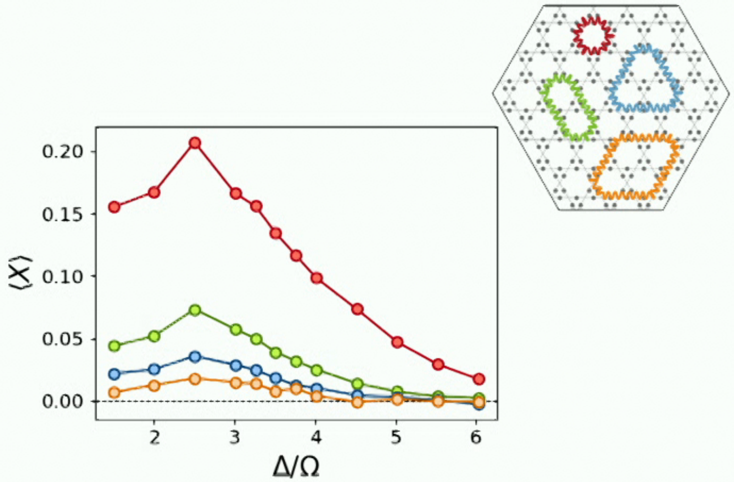


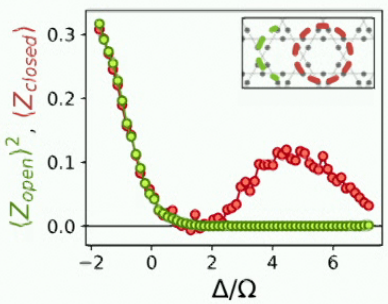


Theory R.Verresen, et al arXiv:2011.12310 (2020)
Experiment G. Semeghini et al, arXiv:2104.04119, Science (2021)

Signature of coherence between dimer coverings!

Topological properties of QSL phase

closed loops vs open strings



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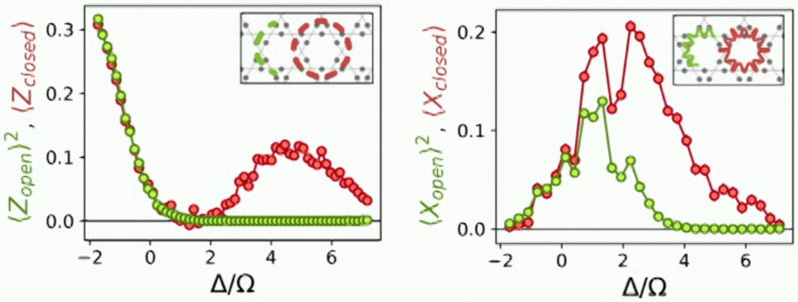

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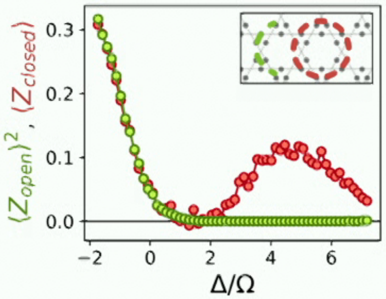
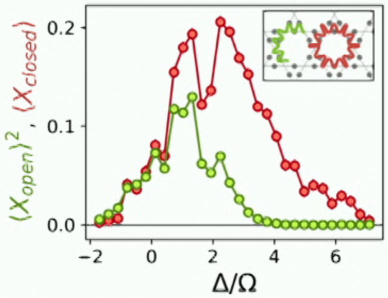




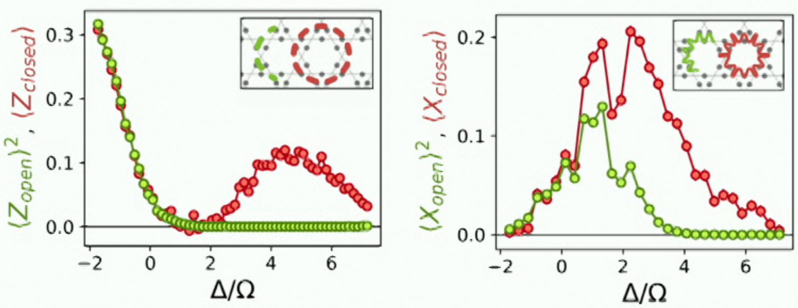
closed loops: detect non-trivial topological correlations

open strings: distinguish QSL from nearby phases

G. Semeghini et al, arXiv:2104.04119, Science (2021)

Topological properties of QSL phase

closed loops vs open strings



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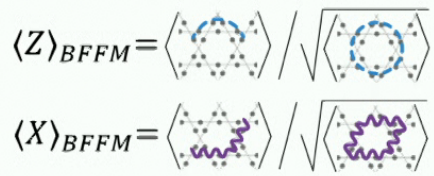
BFFM string order parameters:



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

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

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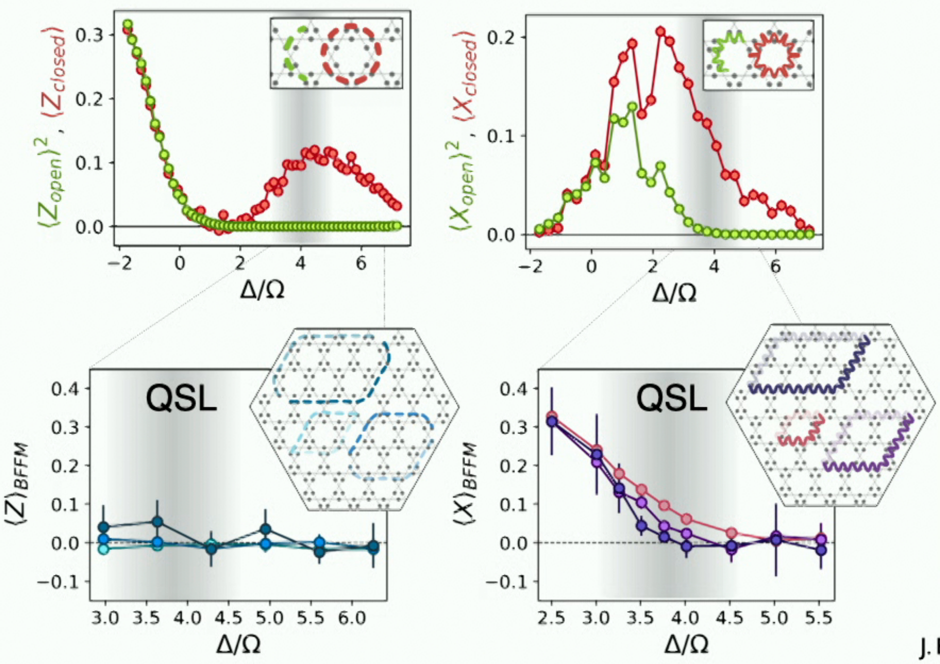

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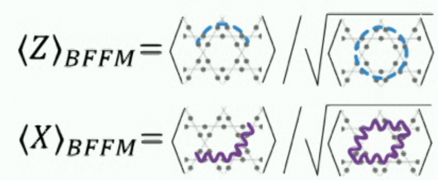

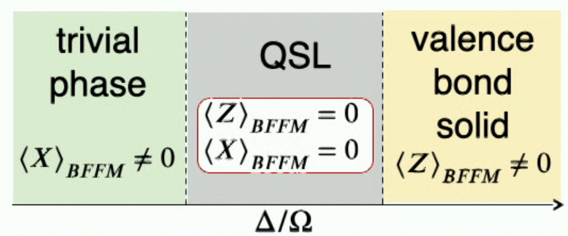

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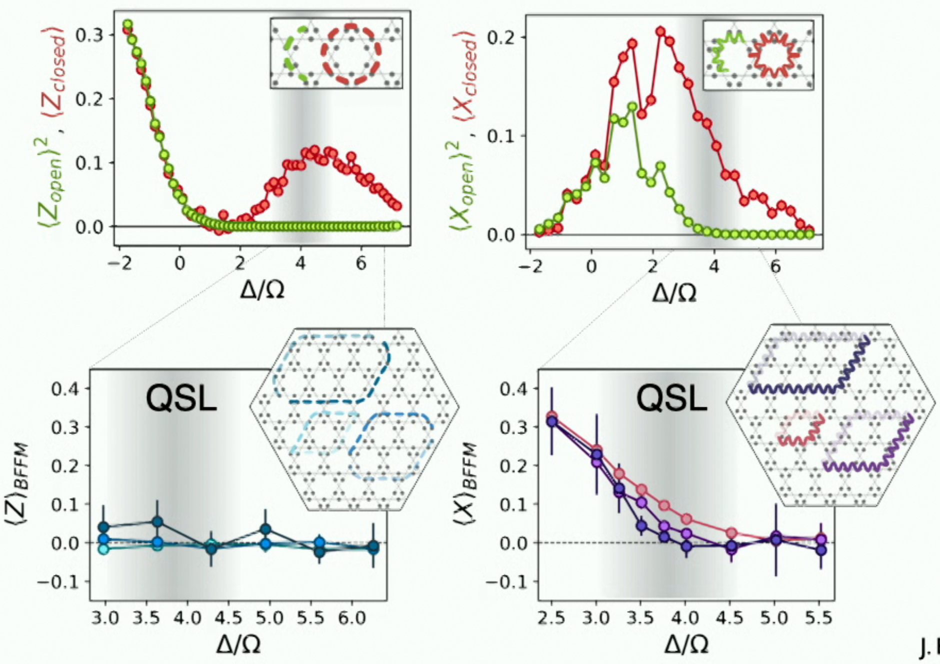

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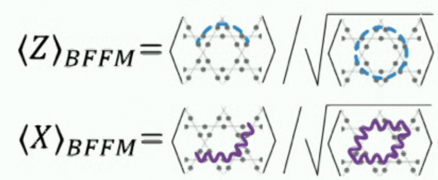

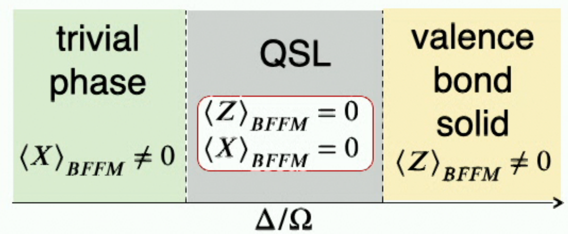

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K. Fredenhagen and M. Marcu, Comm. Math. Phys. 92 (1983)

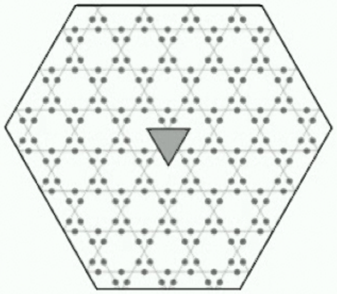
Onset of a quantum spin liquid phase!

G. Semeghini et al, arXiv:2104.04119, Science (2021)

Towards a topological qubit

non-trivial topology:

array with a hole



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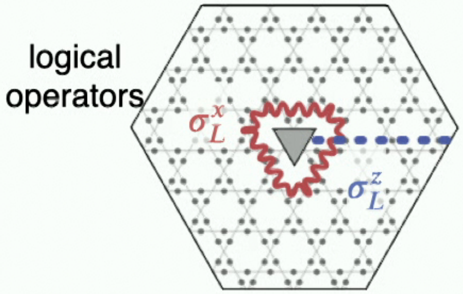

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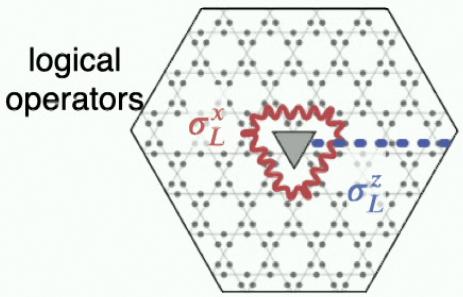


Two-fold degenerate ground state:

$$|\psi_+\rangle \sim |0_L\rangle + |1_L\rangle$$

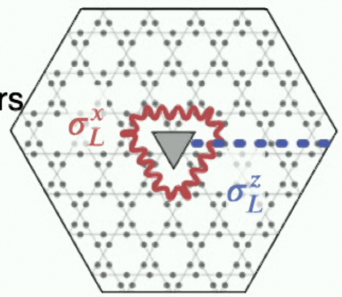
$$|\psi_-\rangle \sim |0_L\rangle - |1_L\rangle$$

Towards a topological qubit

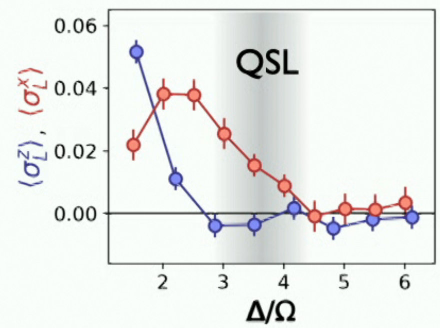
non-trivial topology:

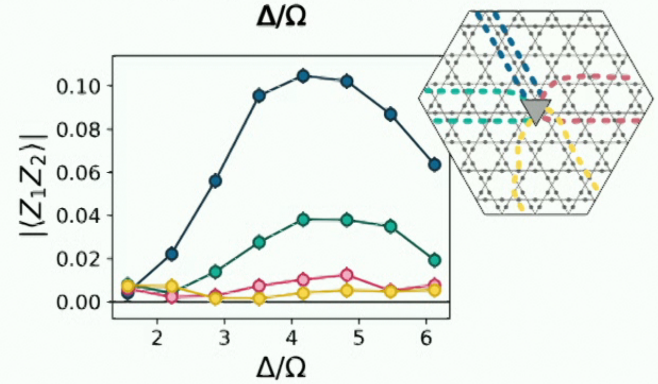
array with a hole

logical operators



Experimental results





Two-fold degenerate ground state:

$|\psi_+\rangle \sim |0_L\rangle + |1_L\rangle$ — $\langle\sigma_L^x\rangle = +1$ Expected in adiabatic state preparation

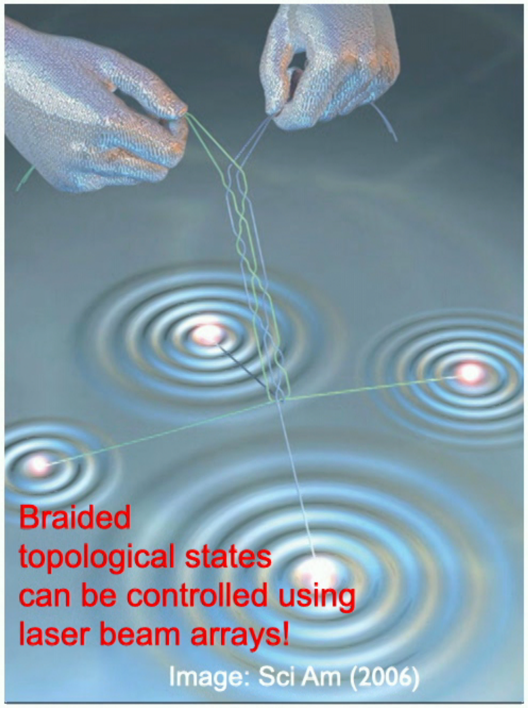
$|\psi_-\rangle \sim |0_L\rangle - |1_L\rangle$ — $\langle\sigma_L^x\rangle = -1$

$\langle\sigma_L^z\rangle = 0$ $\langle\sigma_{L_1}^z \sigma_{L_2}^z\rangle = 1$

First steps towards topological qubits!

G. Semeghini et al, arXiv:2104.04119, Science (2021), related work by Google Quantum AI: K. J. Satzinger et al., arXiv:2104.01180 (2021)

Probing topological matter: new opportunities

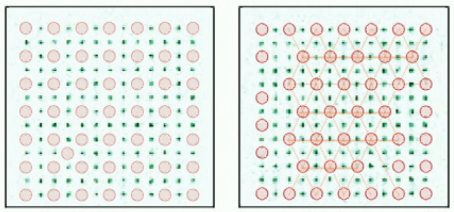


- Unprecedented insights into topological matter
- New tools complementary to analytical theories & numerical simulations
- New methods to analyze, inspired by QEC
- Simulating Lattice Gauge Theories
- Insights for engineering topological 2D materials
- Platforms for exploring fault tolerant quantum information processing

Giulia Semeghini et al, arXiv:2104.04119, Science (2021)
see also work by Google group arXiv:2104.01180

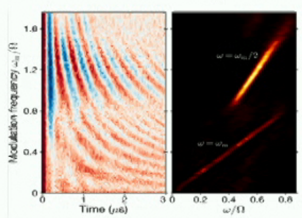
Programmable quantum simulators based on Rydberg arrays: recent progress

Exploring 2D phase diagrams



S. Ebadi et al arxiv 2012.12281, Nature (2021)

Non-equilibrium dynamics



D. Bluvstein, et al, arxiv 2012.12276, Science (2021)

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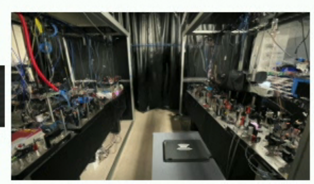
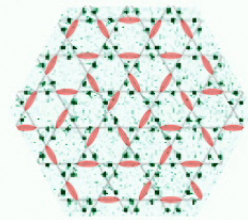
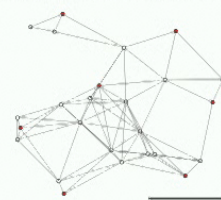


Probing topological spin liquids



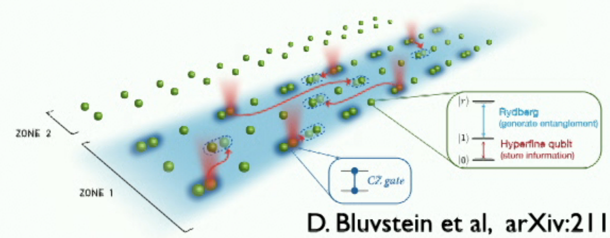
G. Semeghini et al, arXiv:2104.04119, Science (2021)

Accelerating combinatorial optimization



S. Ebadi et al, arXiv 2202.09372 Science (2022)

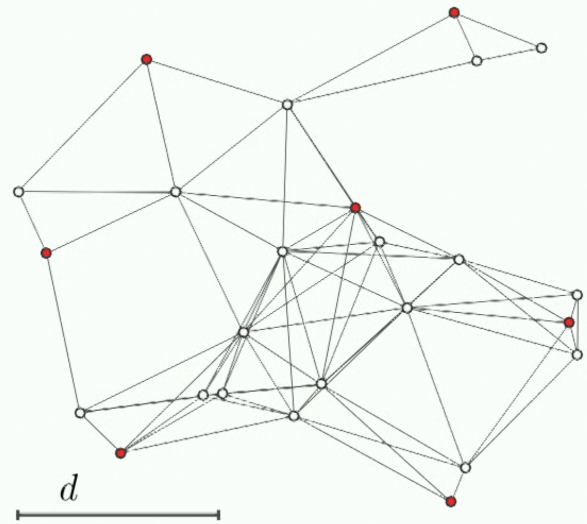
Entanglement transport & universal programmability



D. Bluvstein et al, arXiv:2112.03923

Quantum Optimization of 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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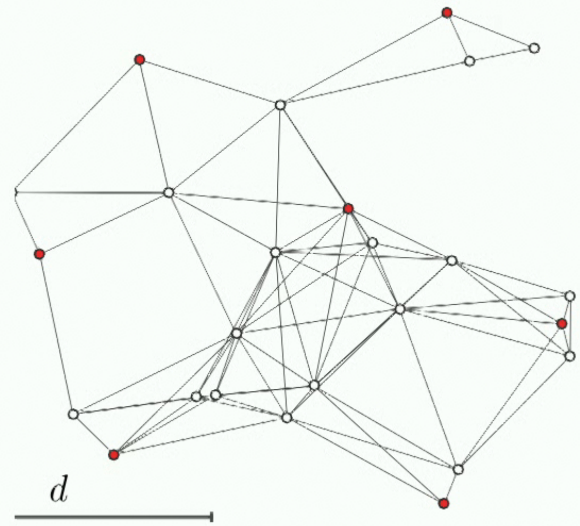
- Example of NP-complete problem
- Cost function => Rydberg blockade Hamiltonian



H. Pichler, S. Wang, L. Zhou et al, arXiv:1808.10816,PRX (2020); D. Wild et al arXiv:2005.14059

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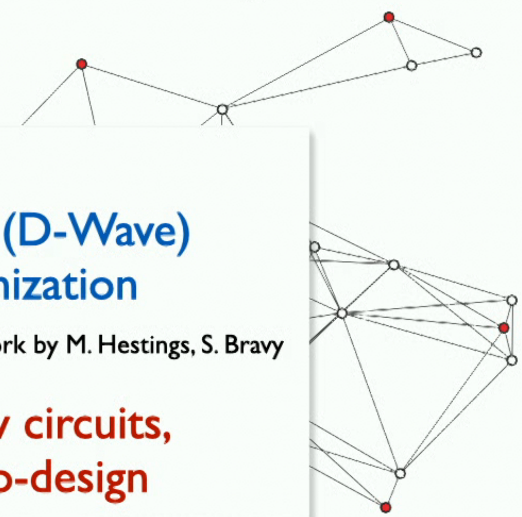


$$H = \sum_{v \in V} -\Delta\, n$$

$$U_{u,w} > \Delta >$$

Prior work/ideas:
Adiabatic evolution, annealing (D-Wave)
Approximate Quantum Optimization

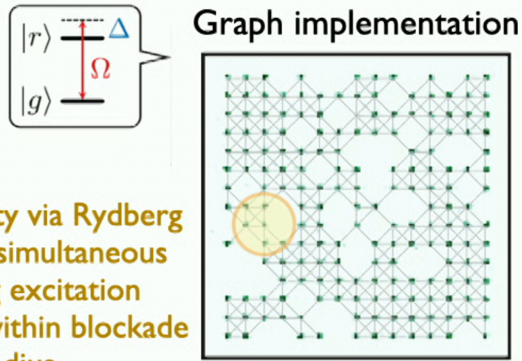
E. Farhi, A. Harrow et al, C. Laumann et al, recent work by M. Hestings, S. Bravy focused on "shallow circuits", several experiments

Our approach: beyond shallow circuits, efficient implementation via co-design

H. Pichler, S. Wang, L. Zhou et al, arXiv:1808.10816,PRX (2020); D. Wild et al arXiv:2005.14059

25

Hardware-efficient encoding MIS on unit disk graphs via Rydberg blockade



Connectivity via Rydberg blockade: simultaneous Rydberg excitation forbidden within blockade radius

Idea H. Pichler, S. Wang, L. Zhou et al, arXiv:1808.10816,PRX (2020)

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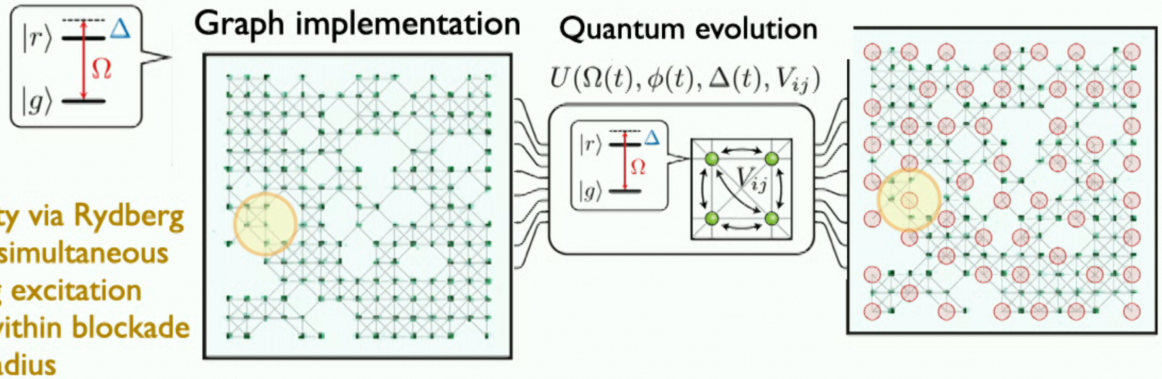

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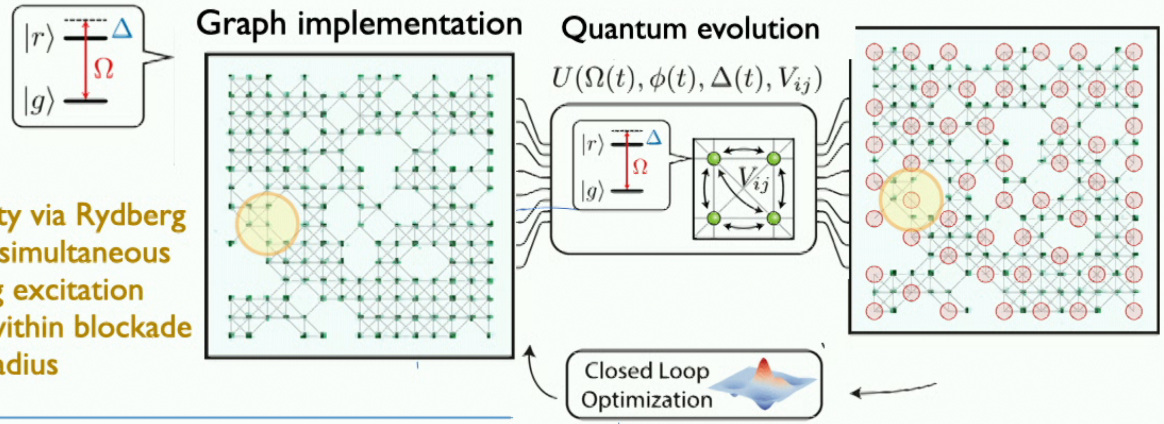

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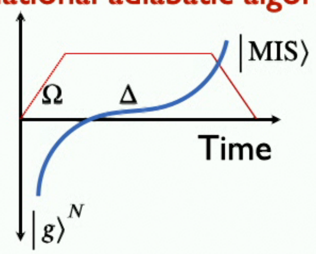
Variational adiabatic algorithm



Maximizes Rydberg atom # subject to blockade = size of independent set

Blockade radius

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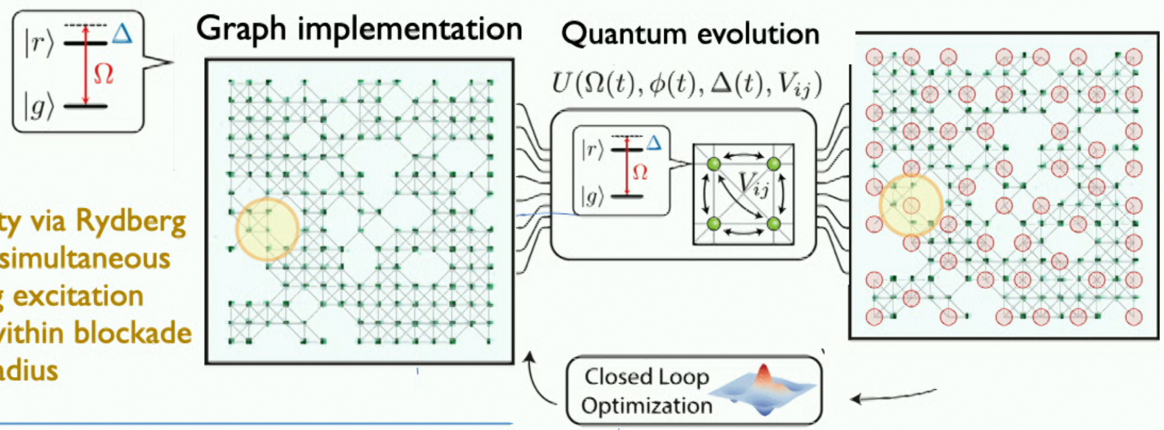

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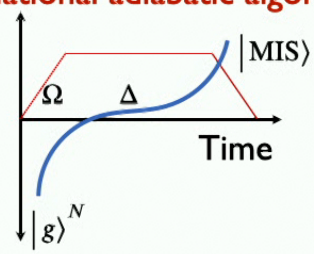

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Figures of merit:

- Approximation ratio

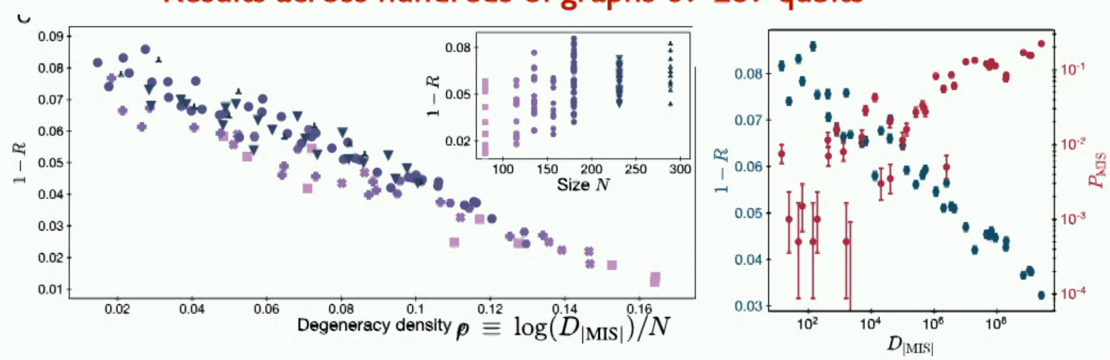
$$R = \frac{\text{mean of independent set sizes}}{\text{size of MIS}}$$

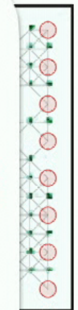
- MIS probability

Idea H. Pichler, S. Wang, L. Zhou et al, arXiv:1808.10816,PRX (2020)

Hardware-efficient encoding MIS on unit disk graphs via Rydberg blockade

Results across hundreds of graphs 69-289 qubits





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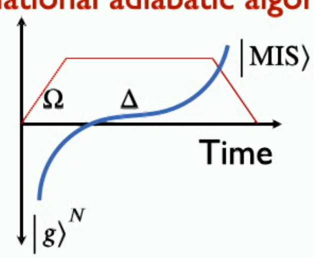

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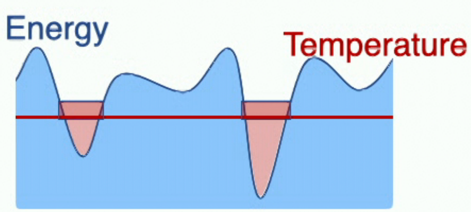
Benchmarking against simulated annealing

Simulated annealing (SA): classically cool to Hamiltonian ground state by stochastically flipping spins



S. Ebadi, A. Keesling, M. Cain et al, arXiv 2202.09372
Science (2022), collaboration with B. Barak, E. Farhi

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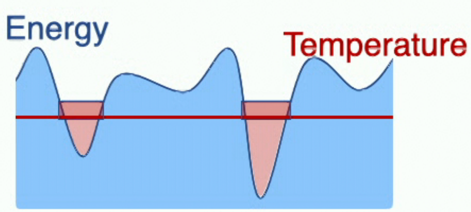

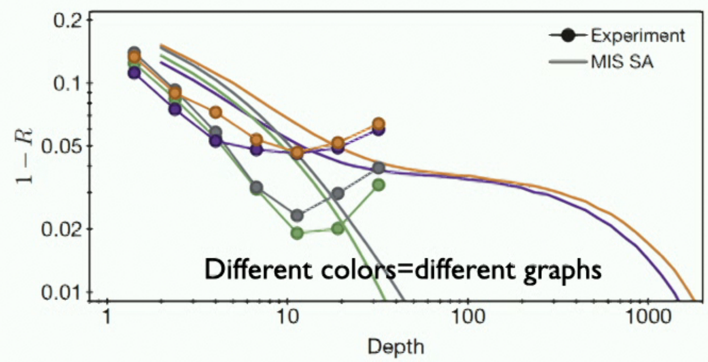

This work: optimized SA with collective updates

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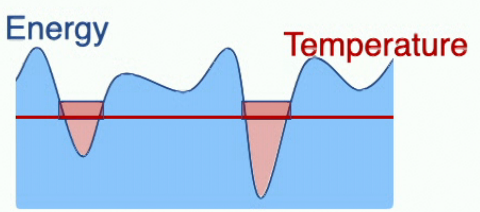
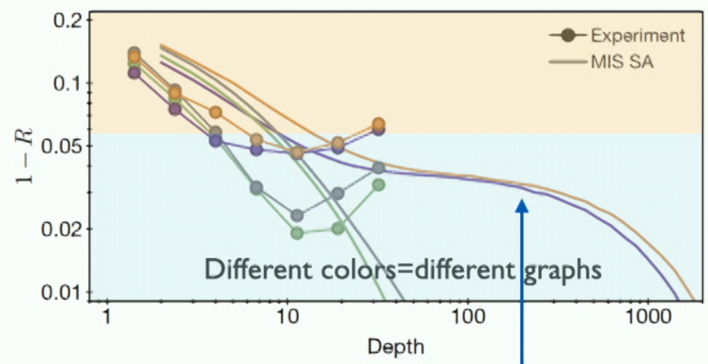


This work: optimized SA with collective updates

Two regimes emerge

High energies:
comparable depth to fixed approximation ratio

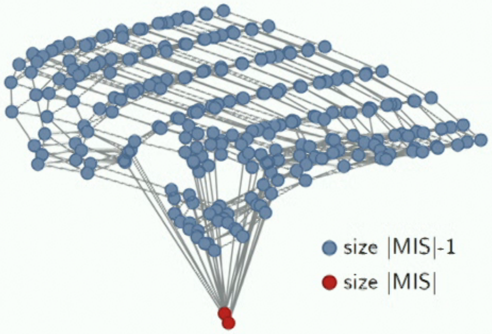


Low energies:
SA trapped in local minima on some instances

S. Ebadi, A. Keesling, M. Cain et al, arXiv 2202.09372
Science (2022), collaboration with B. Barak, E. Farhi

Simulated annealing trapped in local minima

SA randomly walks **(edges)** between solution configurations **(nodes)** until it finds an MIS



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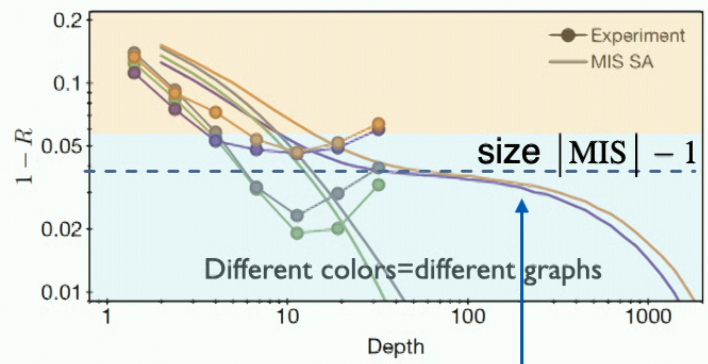

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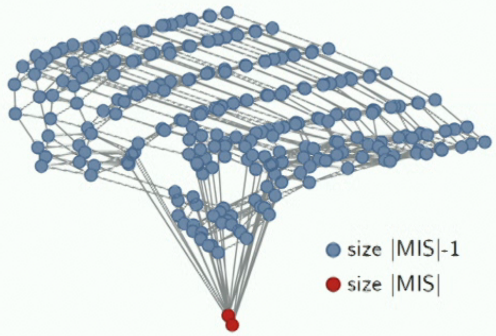

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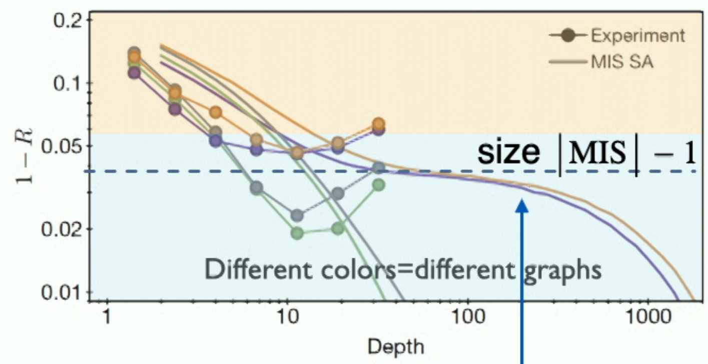

Low energies:
SA trapped in local minima on some instances

Fundamental limit to SA (provable)

Hardness parameter $\mathscr{HP} = \dfrac{\text{Number of |MIS|-1}}{\text{Number of edges leading into MIS}}$

S. Ebadi, A. Keesling, M. Cain et al, arXiv 2202.09372
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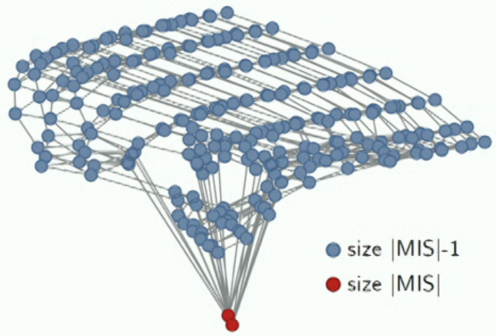

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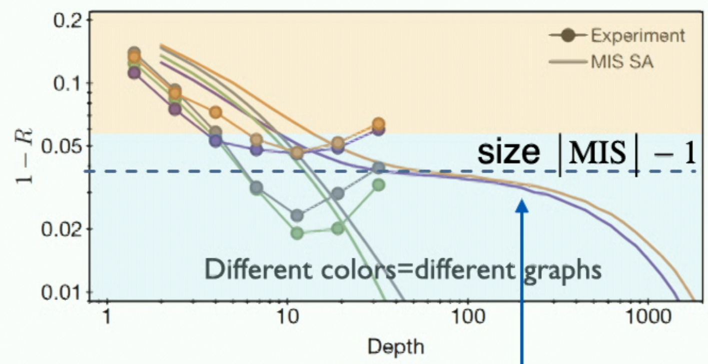

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Exponential runtime in (system size)$^{1/2}$
(numerical evidence, worst case)

Low energies:
SA trapped in local minima on some instances

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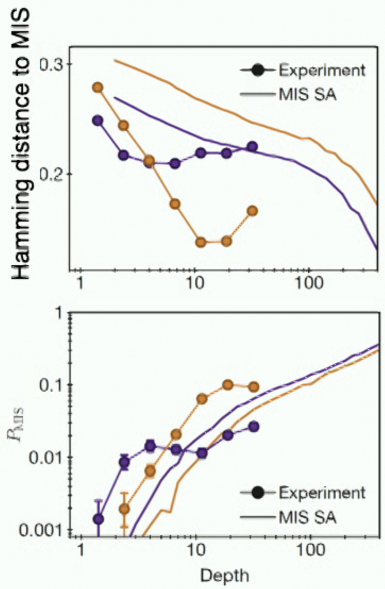
Performance comparison on hardest instances

How does performance scale with $\mathscr{H}\mathscr{P}$?

Example: top 2% hardest graphs

Instances with similar classical hardness



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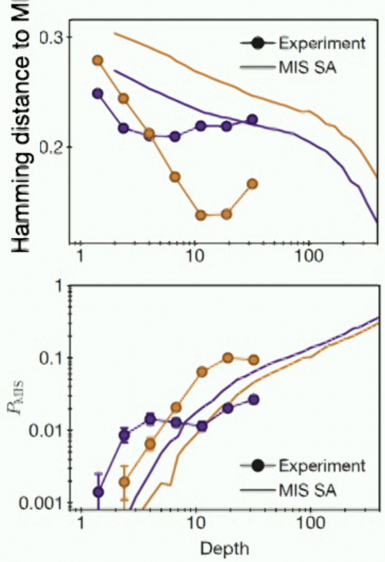
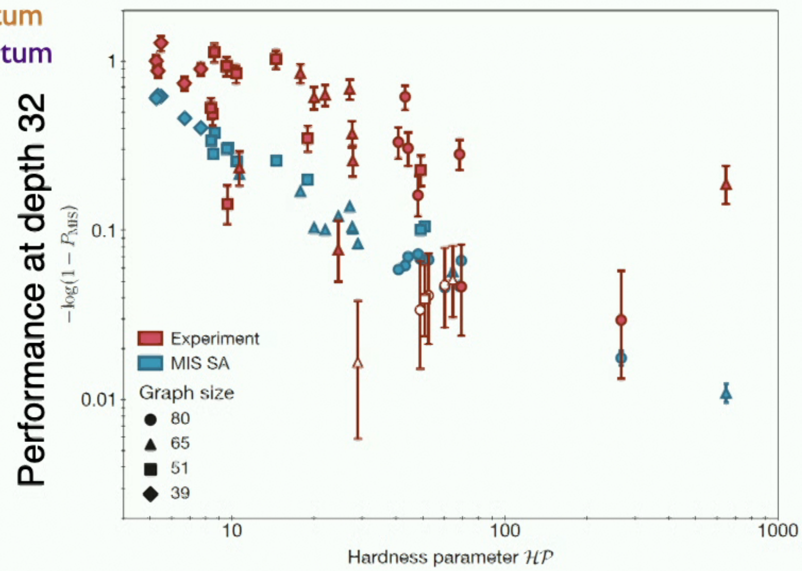
Easy graph for quantum
Hard graph for quantum





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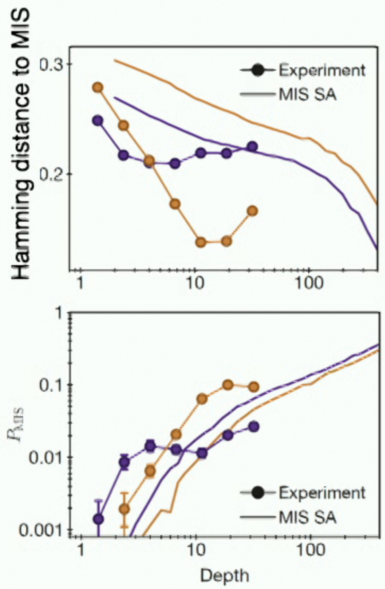
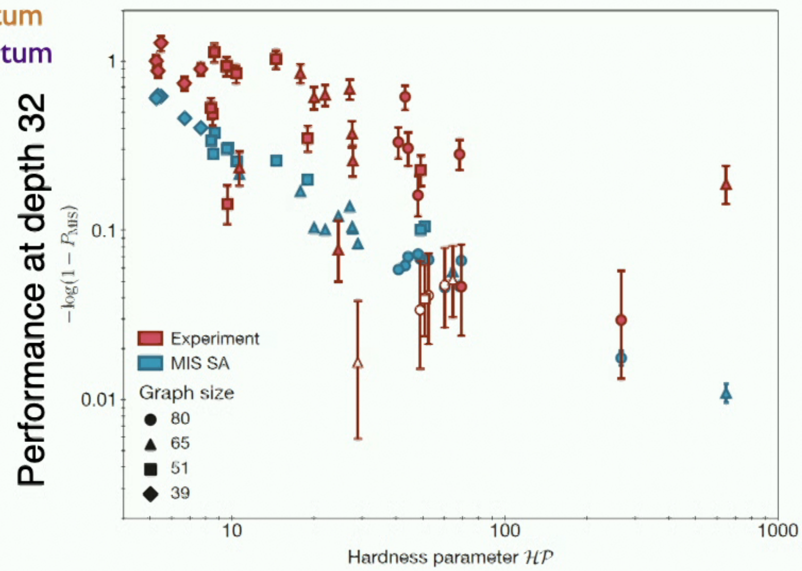


Easy graph for quantum
Hard graph for quantum



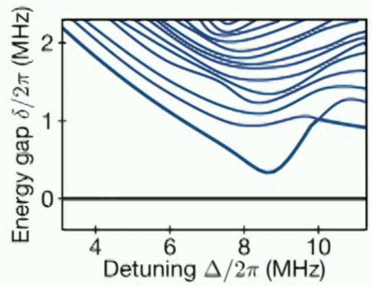
Quantum algorithm is faster on many (but not all) instances:
what controls quantum hardness?

S. Ebadi, A. Keesling, M. Cain et al, arXiv 2202.09372
Science (2022), collaboration with B. Barak, E. Farhi

Quantum hardness controlled by minimum energy gap

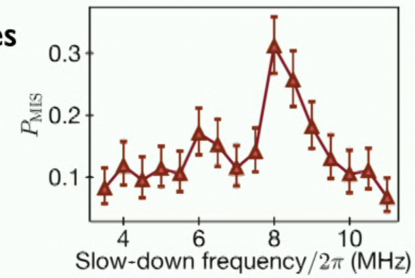
Adiabaticity is limited by the minimum energy gap

Example : 65 node graph



Experiment is sensitive to many-body gap

MIS probability increases when detuning sweep slowed at gap minimum



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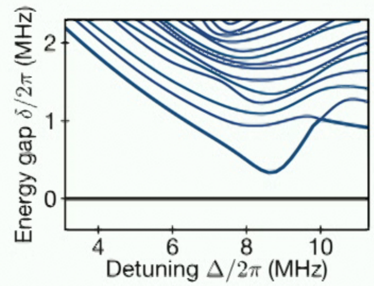

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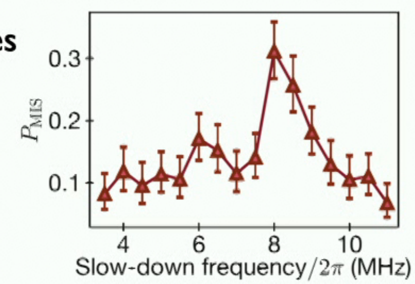
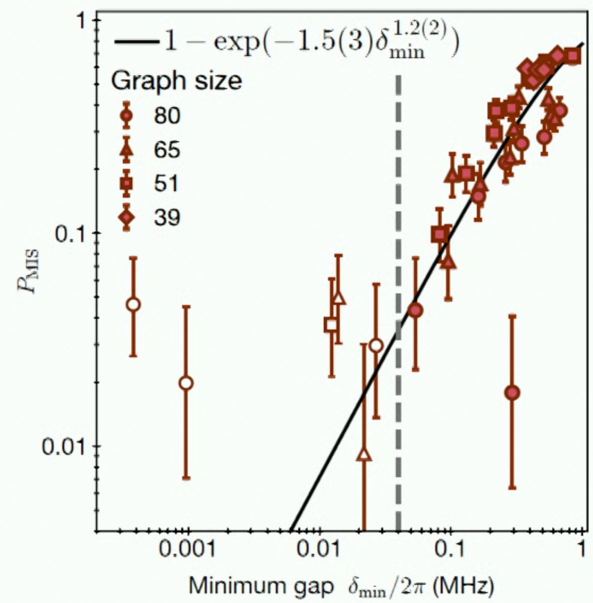


Probability to find solution for fixed evolution time



S. Ebadi, A.Keesling, M. Cain et al, arXiv 2202.09372 Science (2022)

Quantum speedup in deep circuit regime

Hardness controlled by adiabatic gap: Landau-Zener scaling

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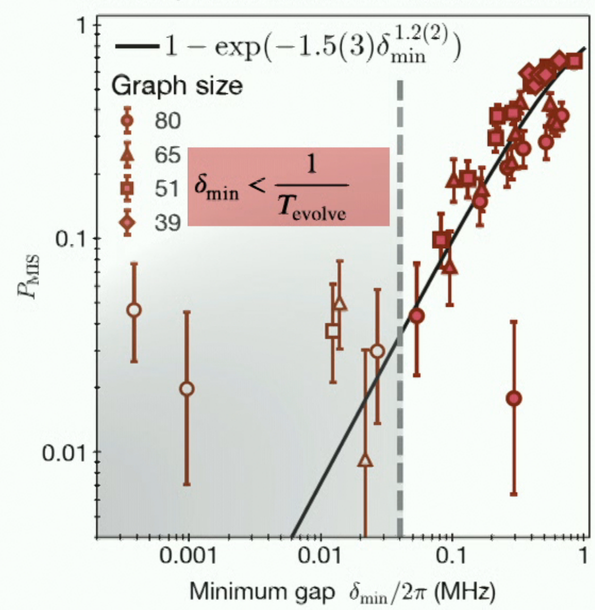

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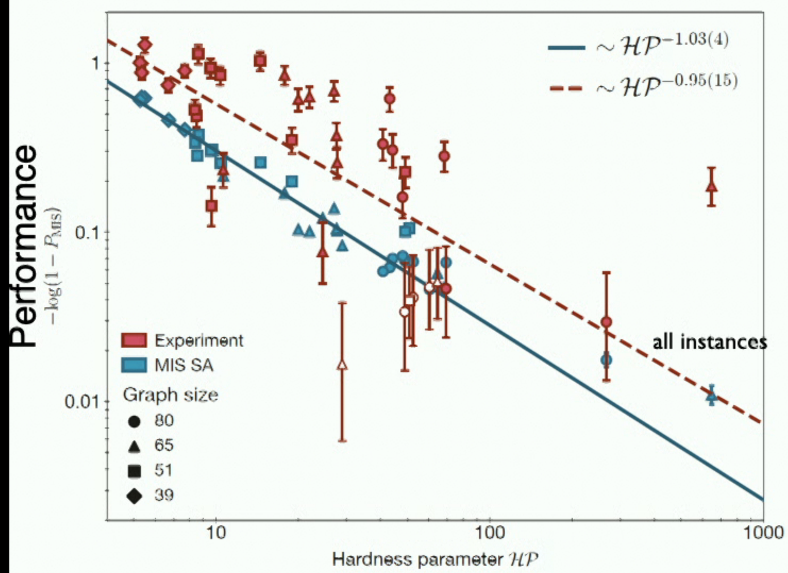

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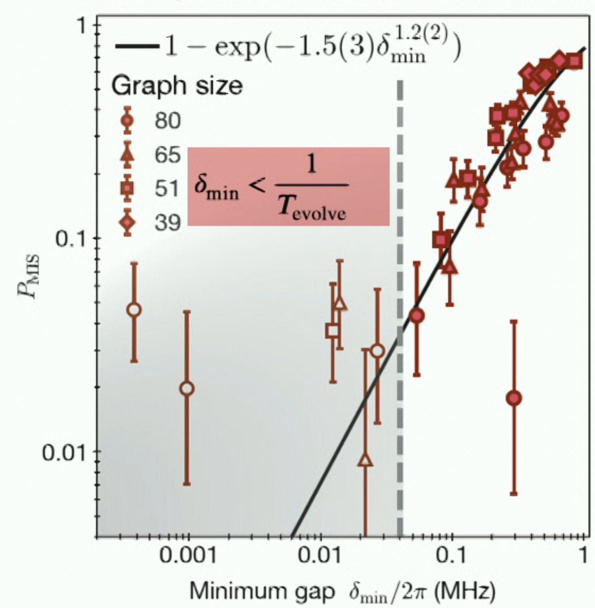

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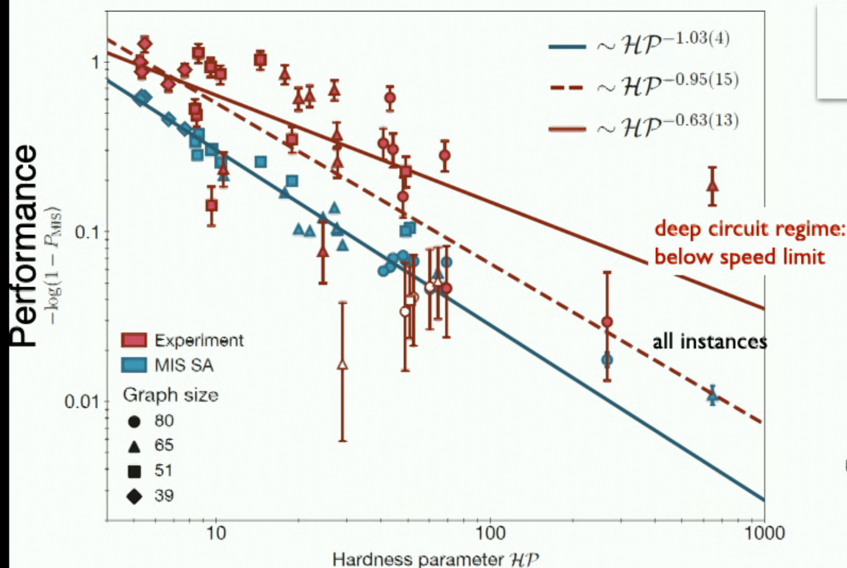

Superlinear (nearly quadratic) speedup in deep circuit regime!

Hardness controlled by adiabatic gap: Landau-Zener scaling

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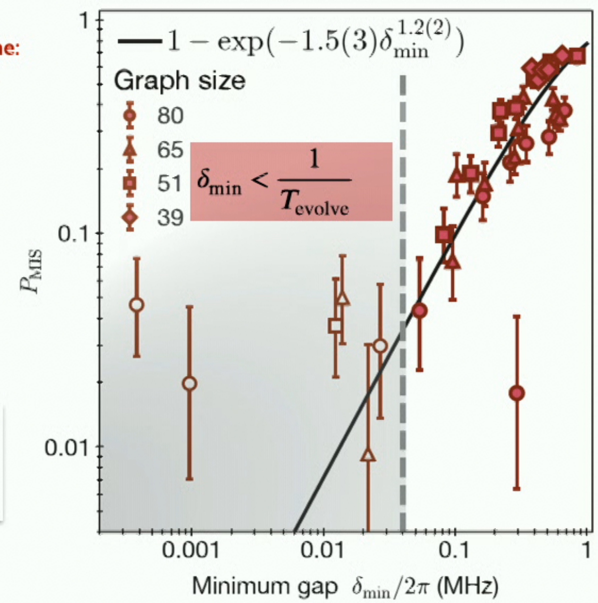
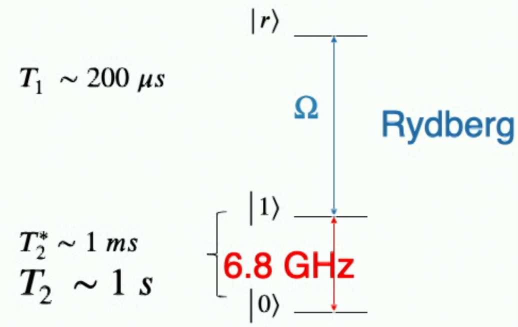


S. Ebadi, A. Keesling, M. Cain et al, arXiv 2202.09372
Science (2022)

Outlook: reconfigurable quantum architecture

Idea: Rydberg interactions to **entangle** atoms, then store in **long-lived states**



Entanglement via CZ gate: Levine, Pichler *et al*, PRL 2019

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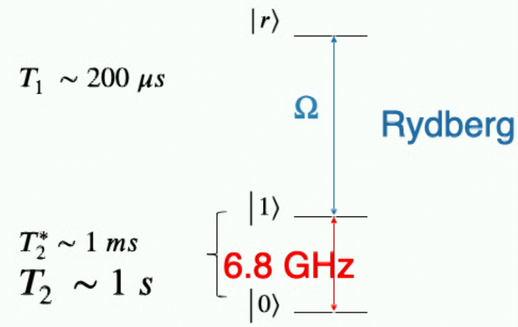

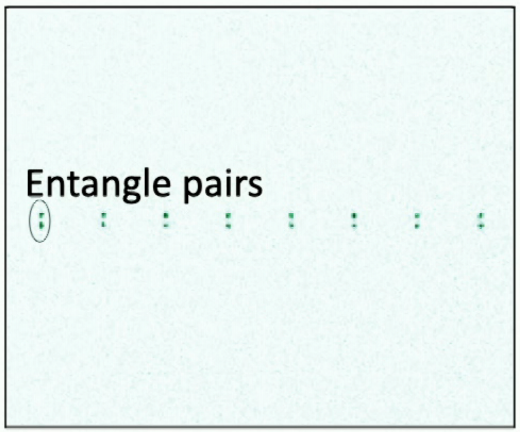

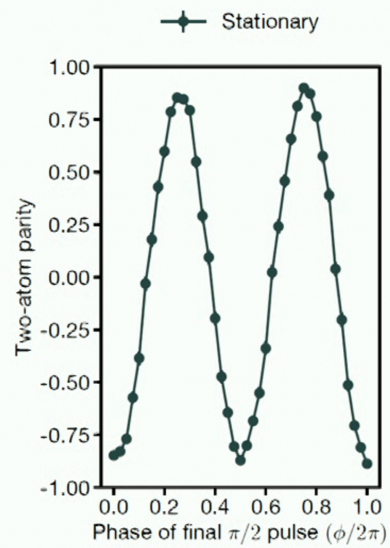

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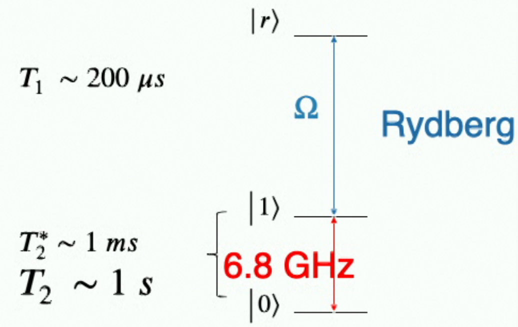
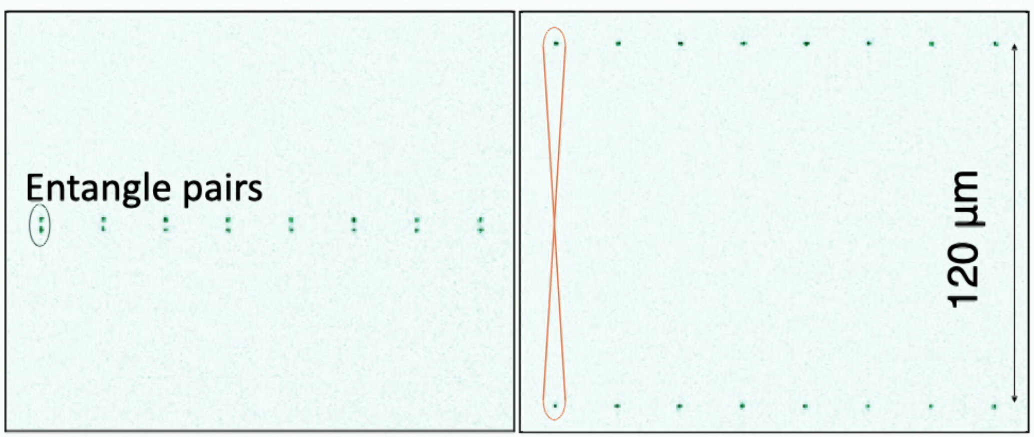
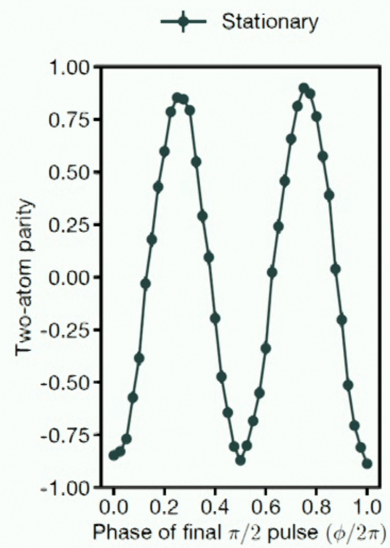


in ~500 microseconds …





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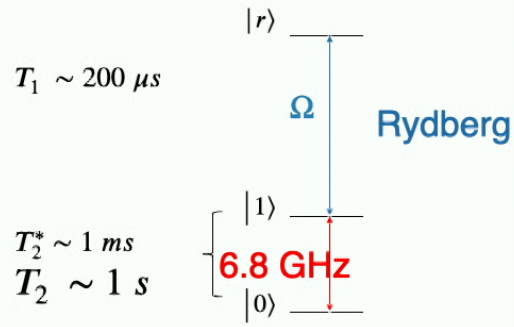

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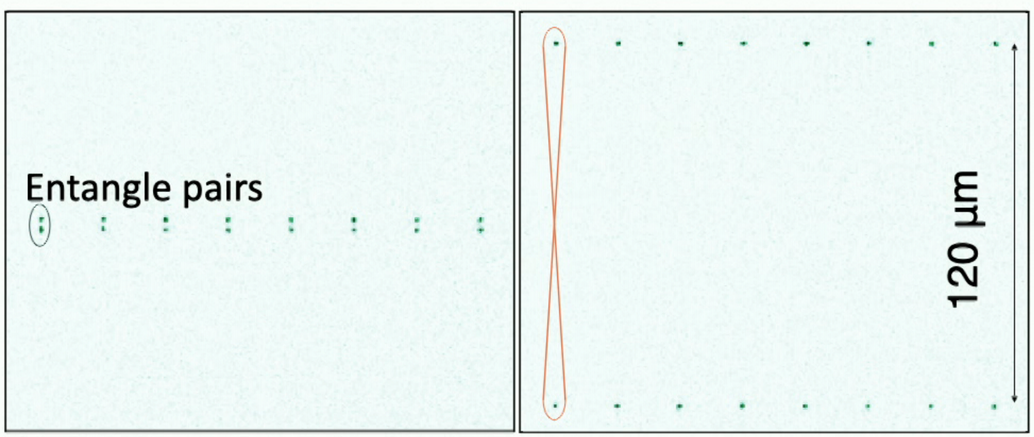

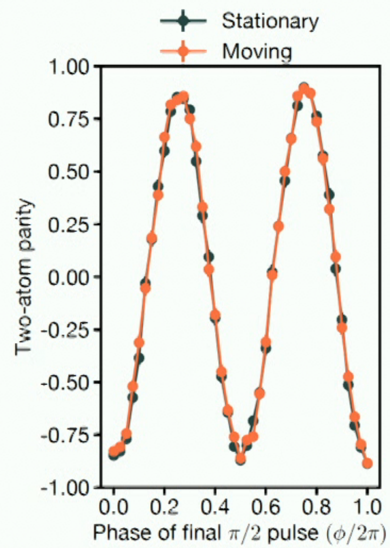

Entanglement and coherence **preserved** while moving!

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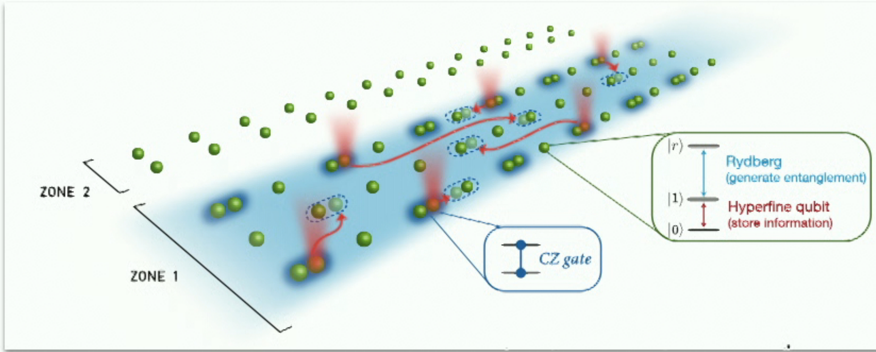
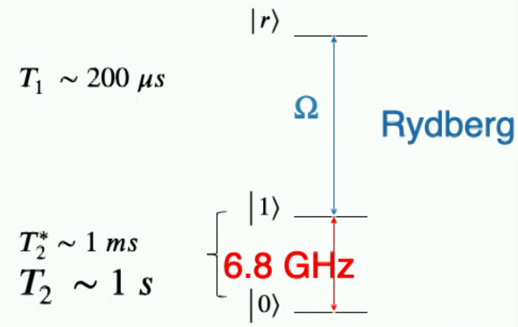
Outlook: reconfigurable quantum architecture





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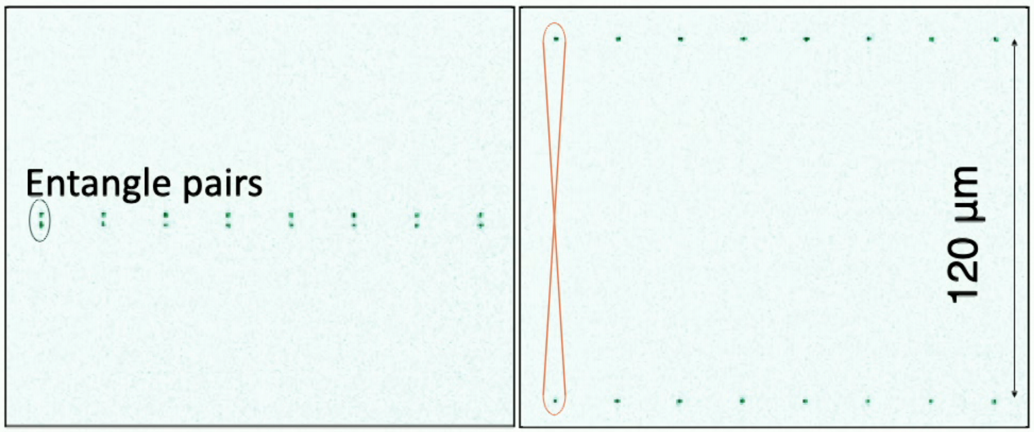

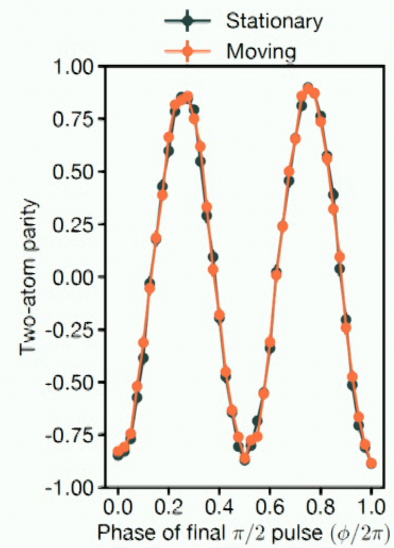

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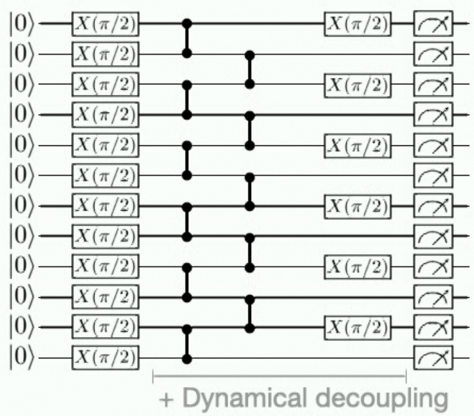
Gate-based quantum evolution: graph states

Example: two copies of cluster states - parallel preparation



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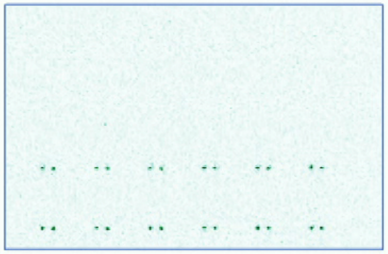
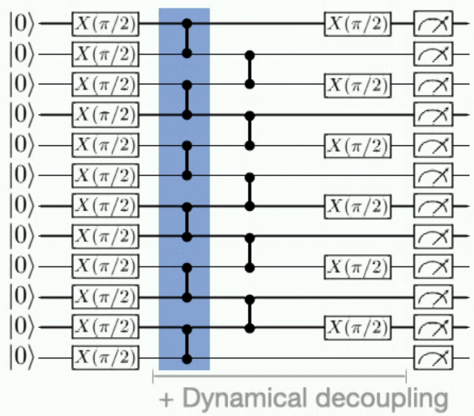
1st CZ gate





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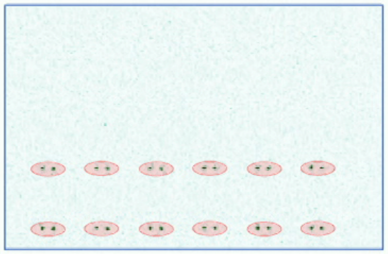

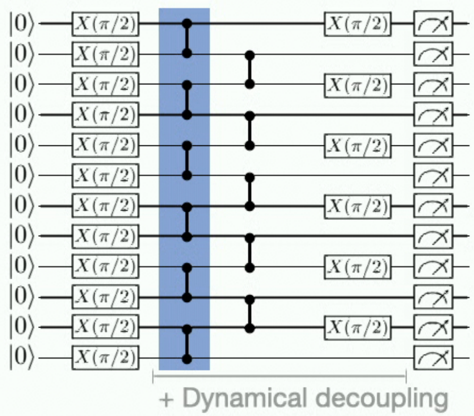

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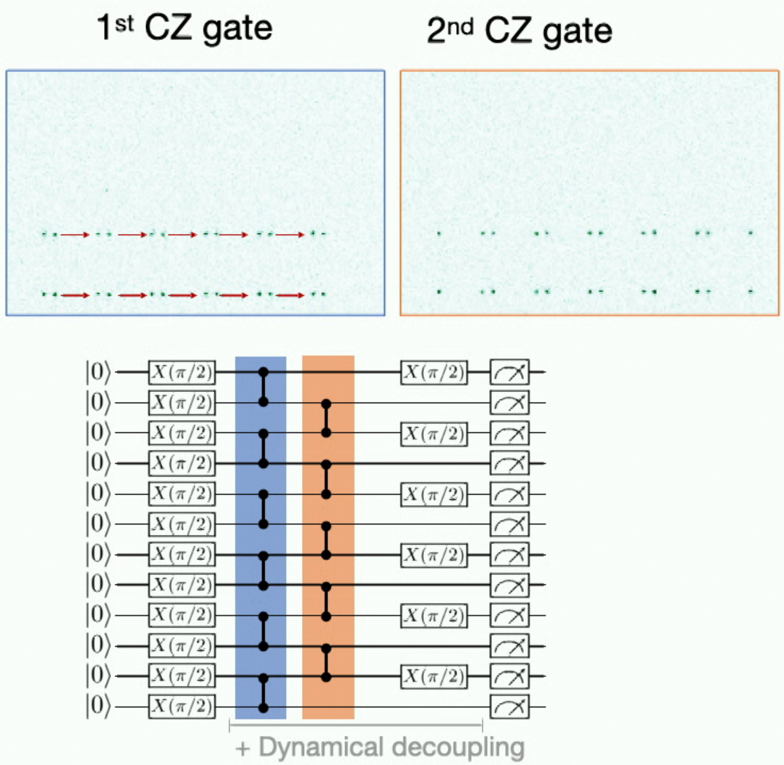

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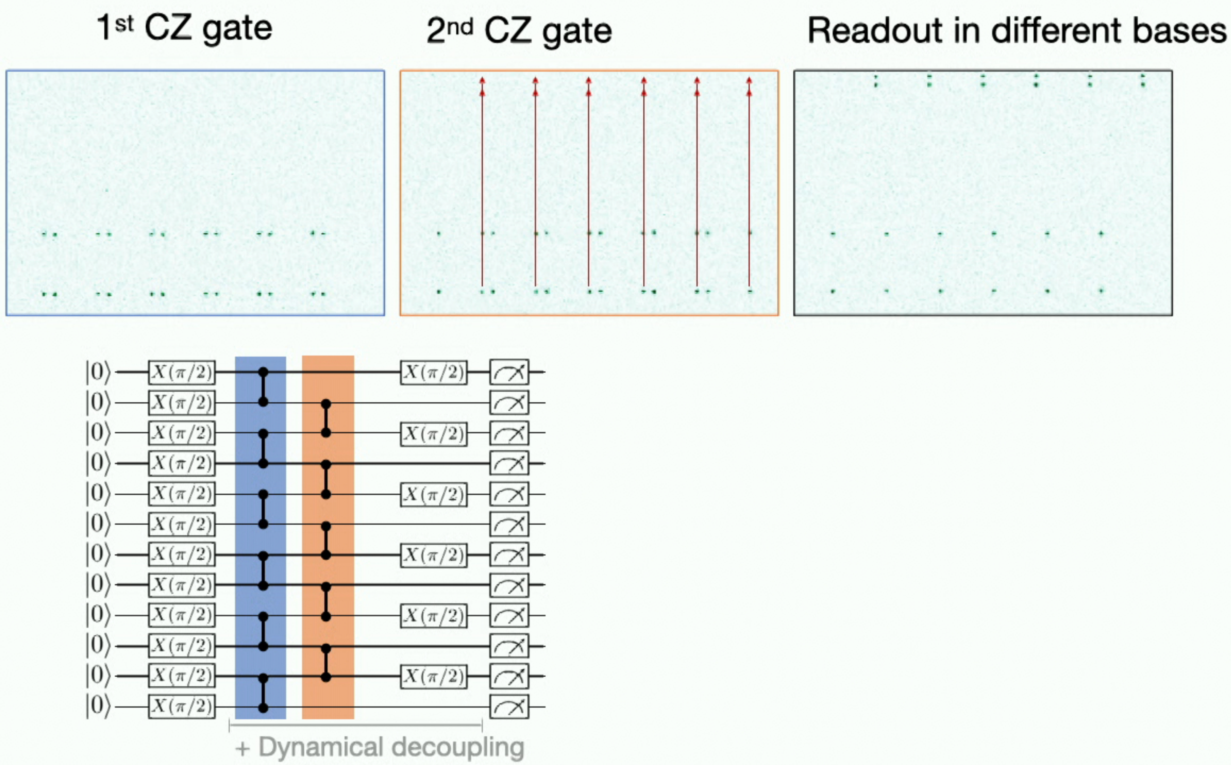

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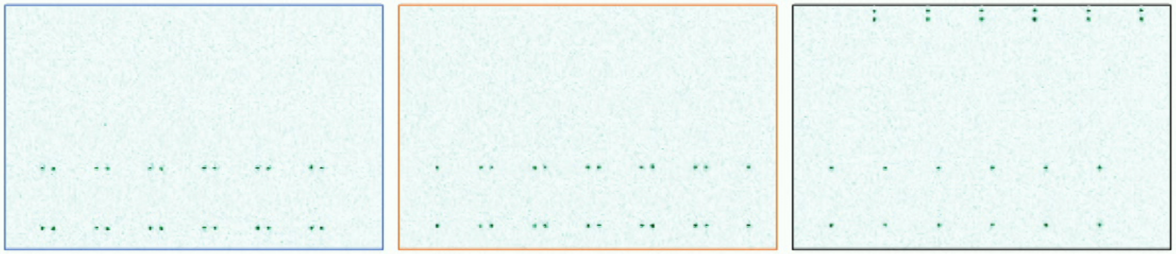
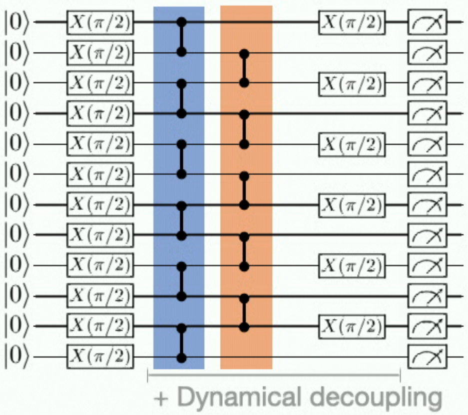
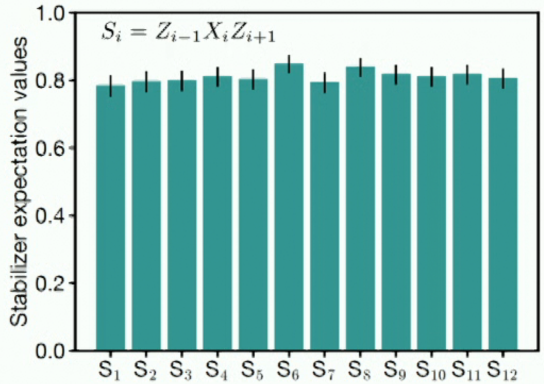
Gate-based quantum evolution: graph states

Example: two copies of cluster states - parallel preparation

1st CZ gate | 2nd CZ gate | Readout in different bases







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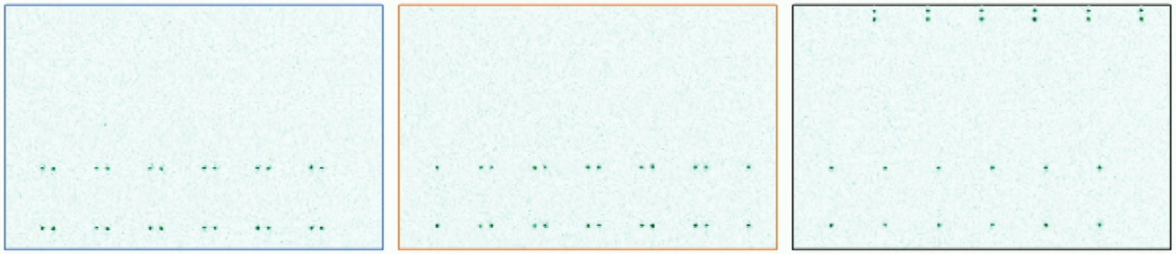
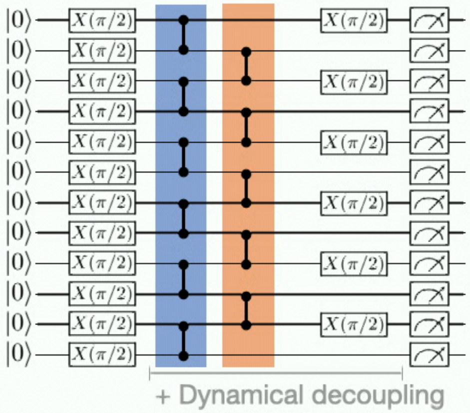
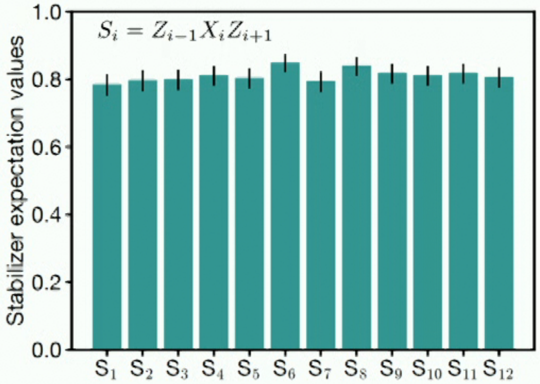


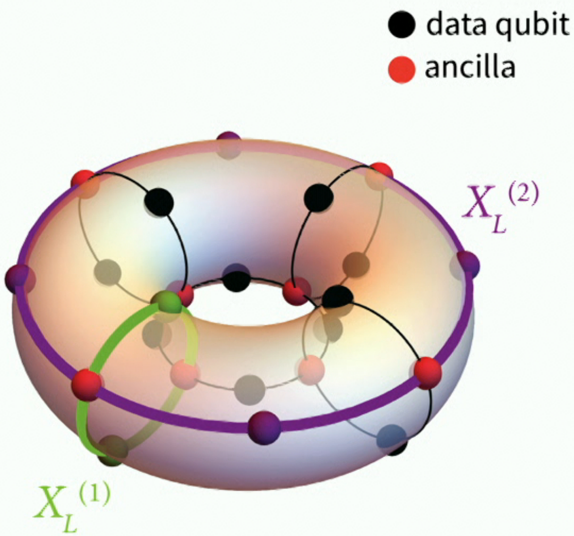




Can one prepare more complex states?

Entanglement via CZ gate: Levine, Pichler *et al*, PRL 2019 D. Bluvstein et al, arXiv:2112.03923, Nature (2022)

Towards quantum error correction: toric code … on the torus???



Quantum Error Correction primer

Toric code:

- Grid of physical qubits encodes logical qubit(s)
- Logical qubit: building block of fault-tolerant QC
- Stabilizer measurements detect local errors

D. Bluvstein et al, arXiv:2112.03923, Nature (2022)

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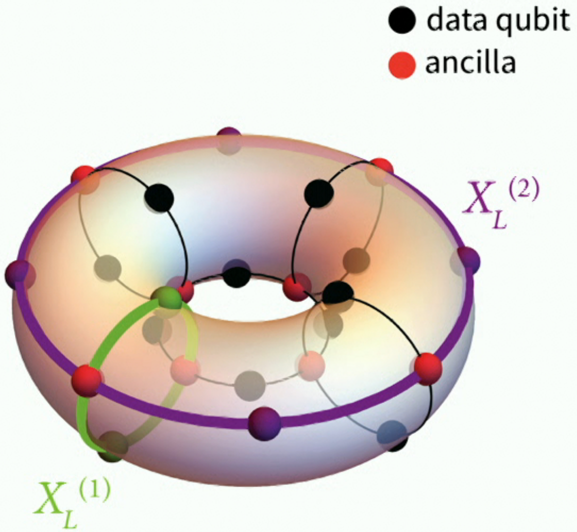

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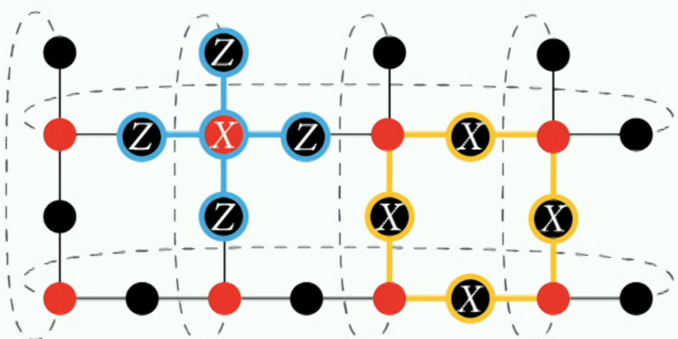
Equivalent to graph state with non-local connectivity



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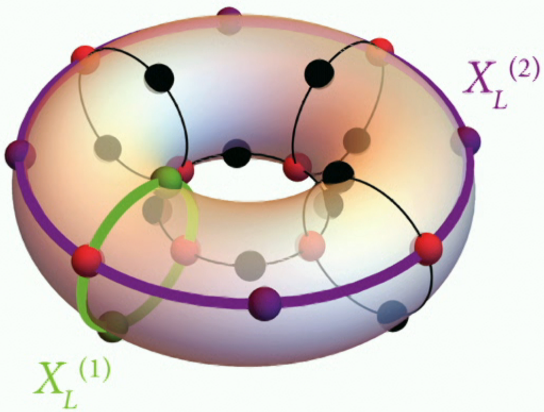
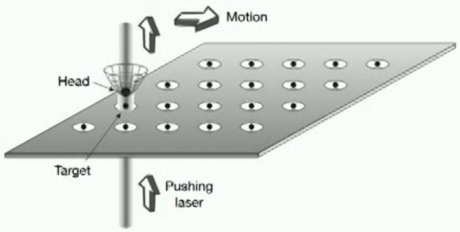


Realization via parallel ancilla transport

(idea Cirac, Zoller, Nature 2001)



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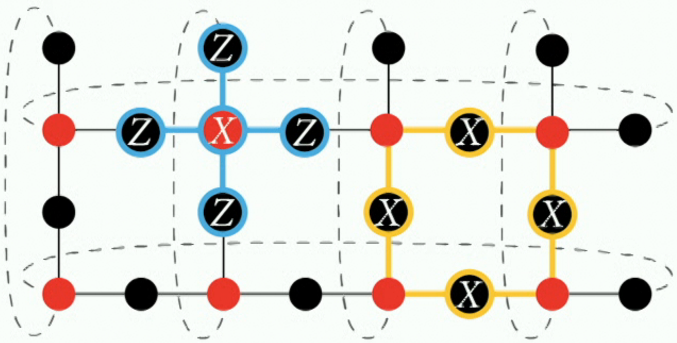

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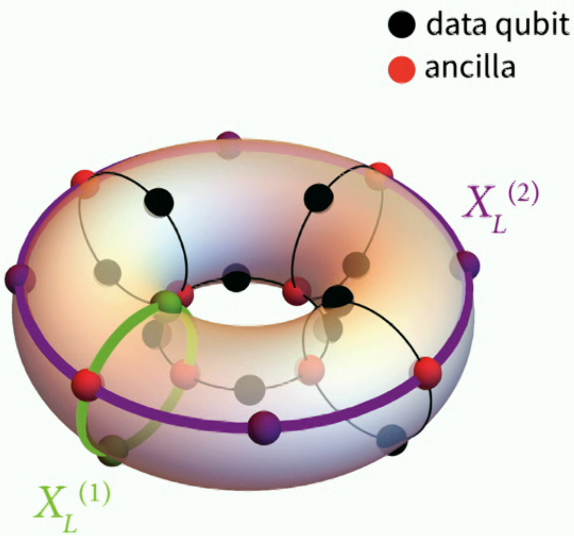

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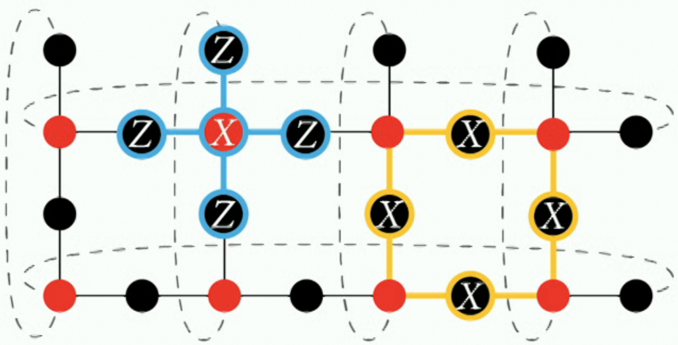

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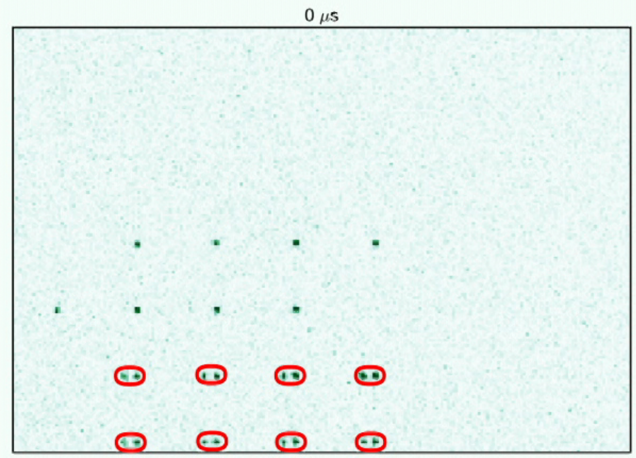

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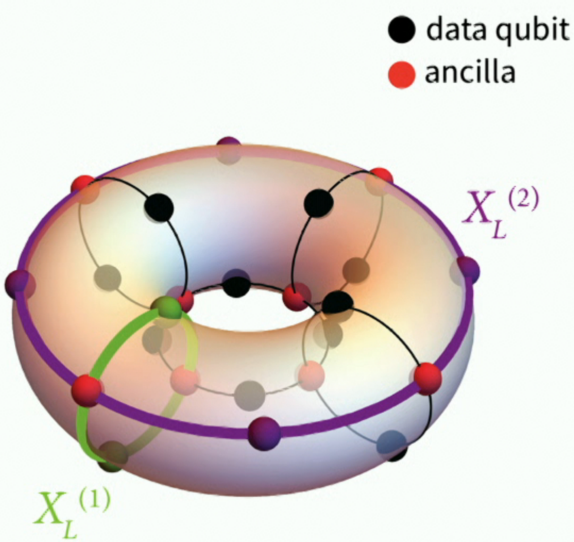

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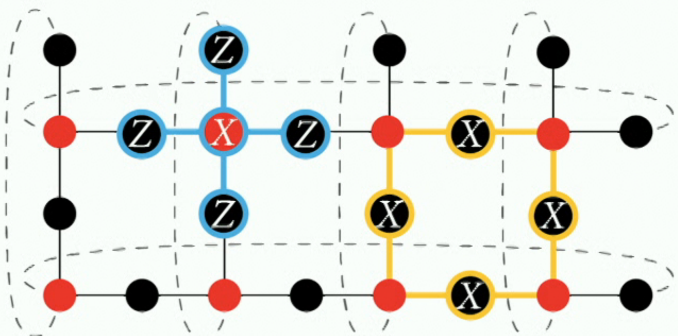

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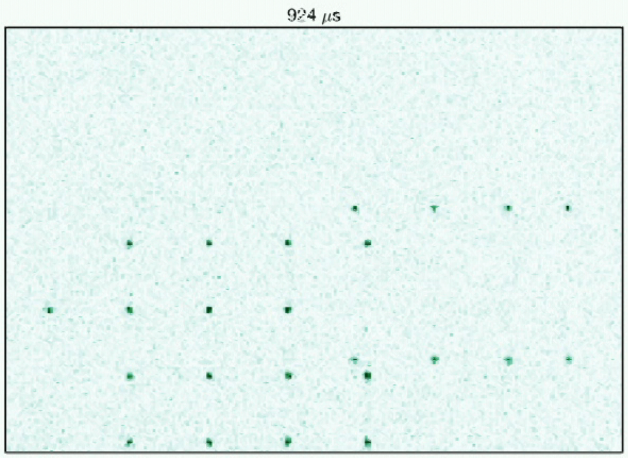

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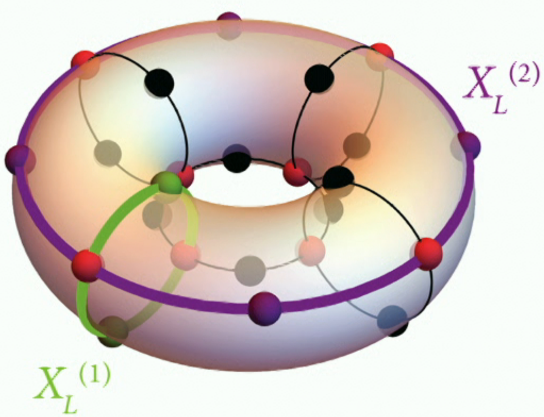
Towards quantum error correction: toric code … on the torus???

● data qubit
● ancilla



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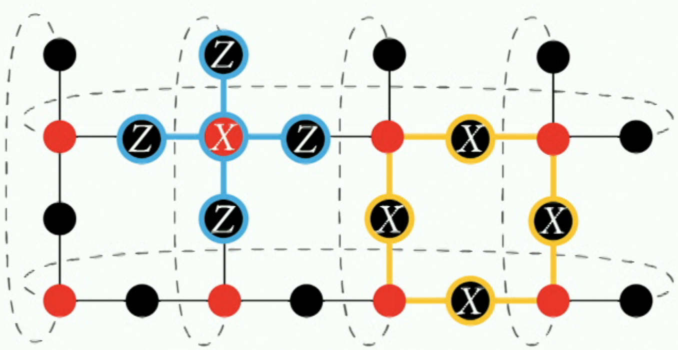

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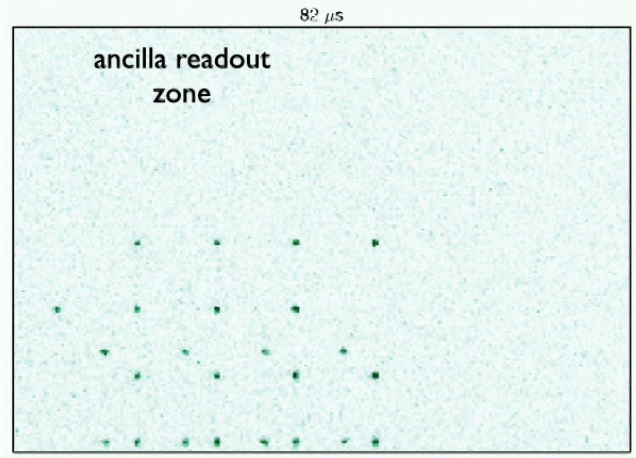

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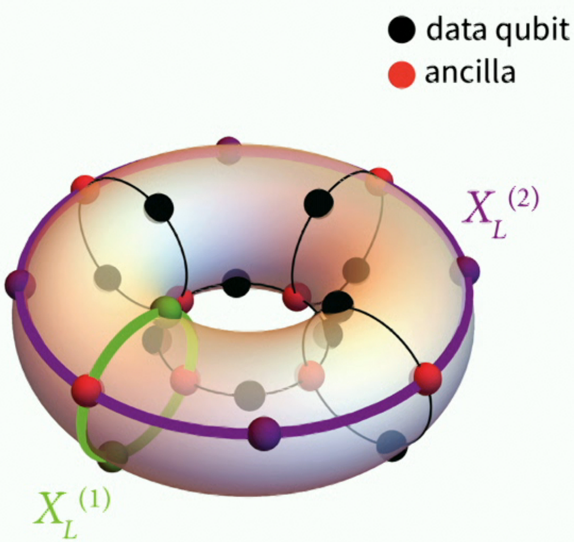

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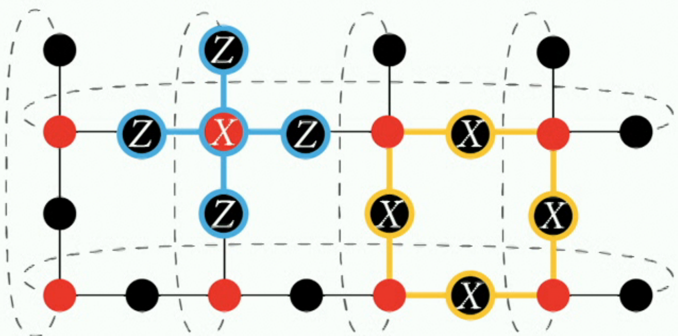

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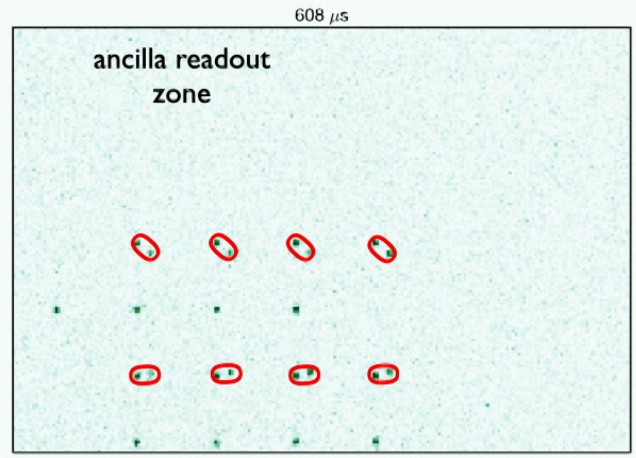

Encodes two (!) logical qubits

D. Bluvstein et al, arXiv:2112.03923, Nature (2022)

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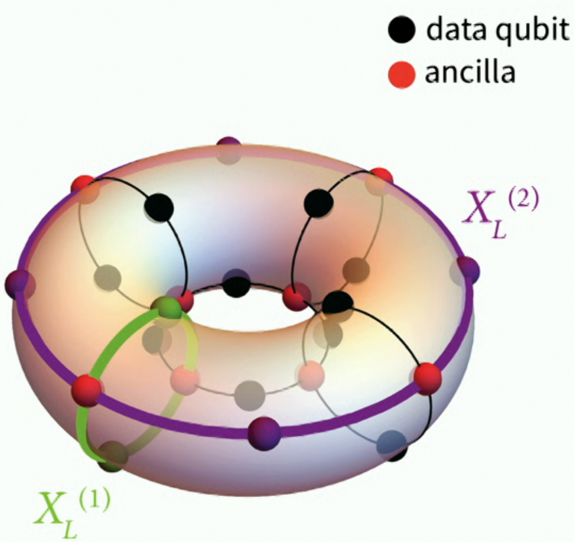

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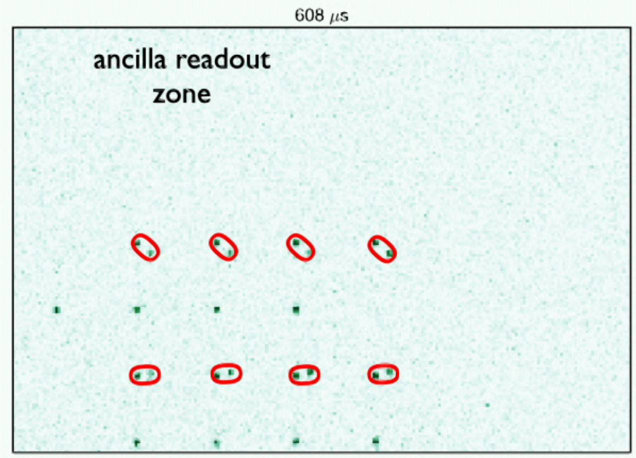
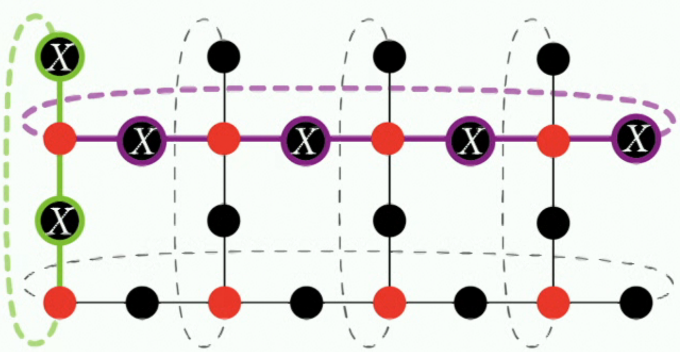
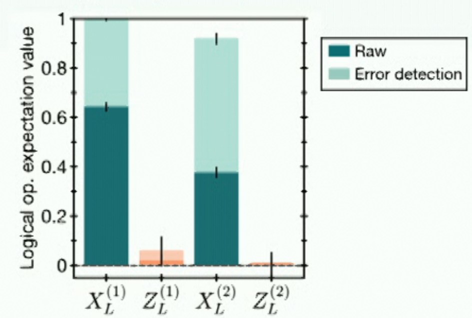


Equivalent to graph state with non-local connectivity

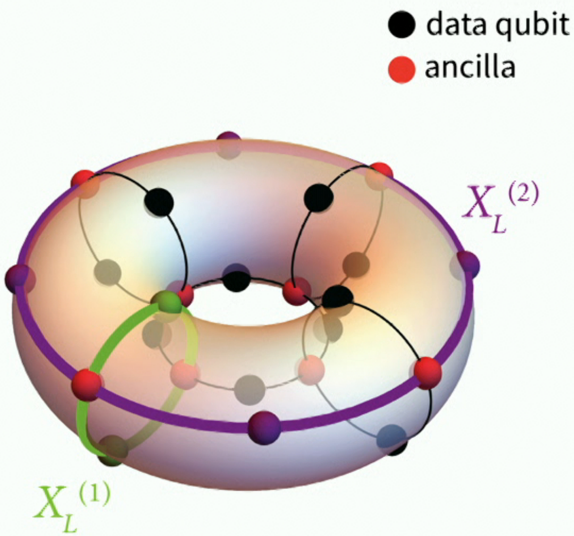


Encodes two (!) logical qubits



D. Bluvstein et al, arXiv:2112.03923, Nature (2022)

Towards quantum error correction: toric code … on the torus???



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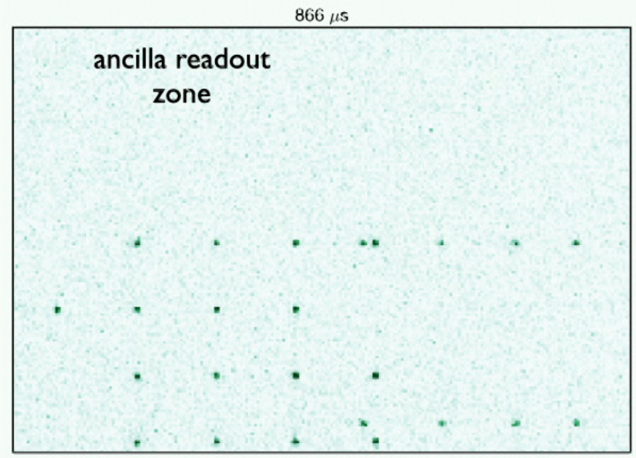

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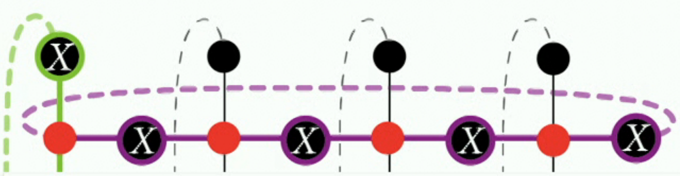

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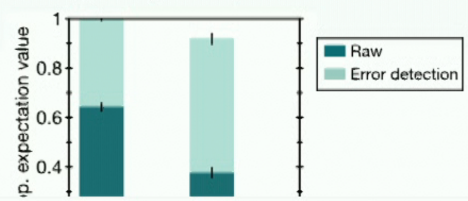
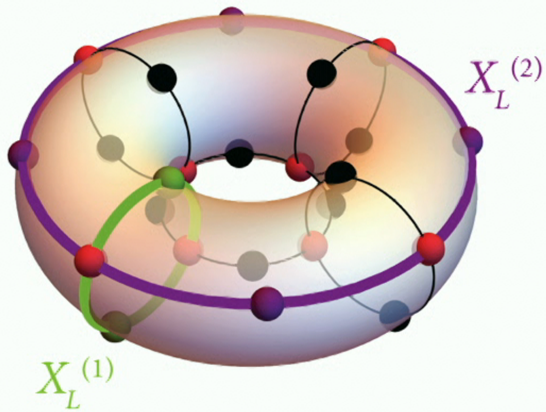


New opportunities for fault-tolerant quantum processing (e.g hypergraph, LDPC codes)
Hardware-efficient methods for quantum error correction I. Cong et al, PRX (2022)
Hybrid approaches combining analog and digital quantum dynamics

Towards quantum error correction: toric code … on the torus???

● data qubit
● ancilla



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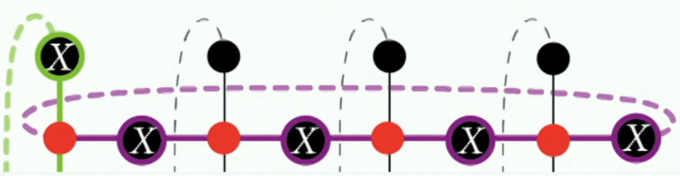

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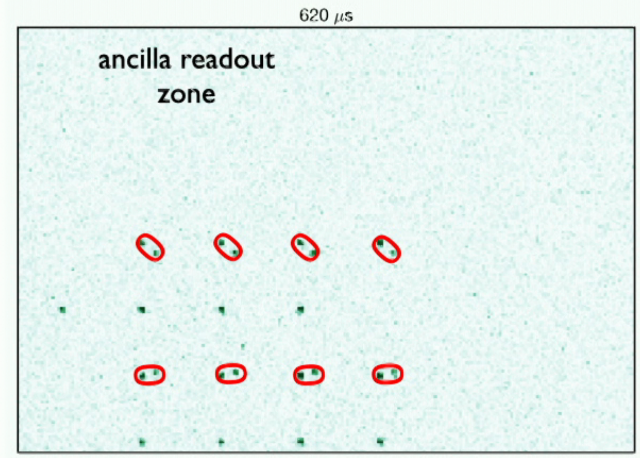

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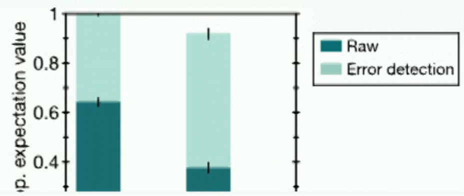

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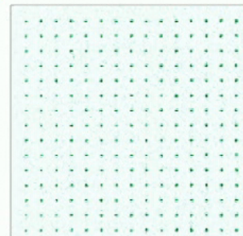
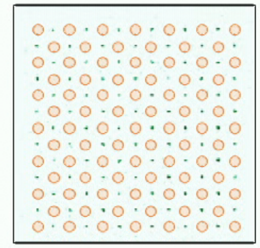
Summary

✓ **Atom by atom approach to building quantum matter**

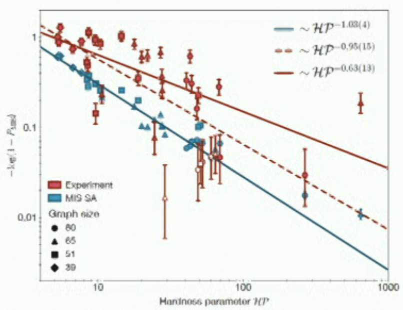
New platform for exploring synthetic quantum matter
Experiments with strongly interacting atom arrays
New generation >200 atom systems in 2D

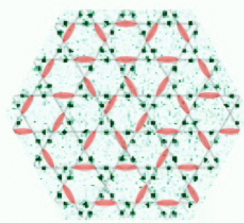


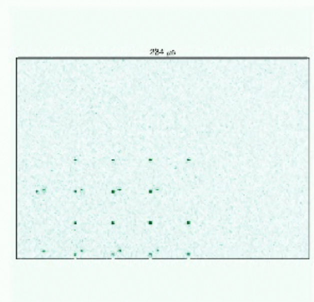


✓ **Many-body dynamics on programmable simulator**

Engineering & exploring phase transitions
Realization and probing quantum spin liquid states
Exploring quantum optimization algorithm
New architecture based on entanglement transport: towards QEC

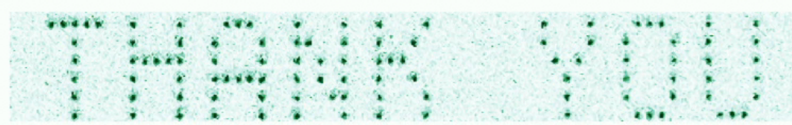




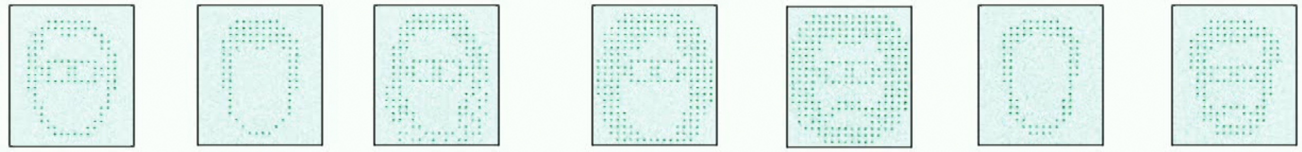


✓ **Outlook: exciting scientific frontier**
era of "quantum discovery"

from quantum many-body physics to new applications



Acknowledgements



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|QuEra>

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