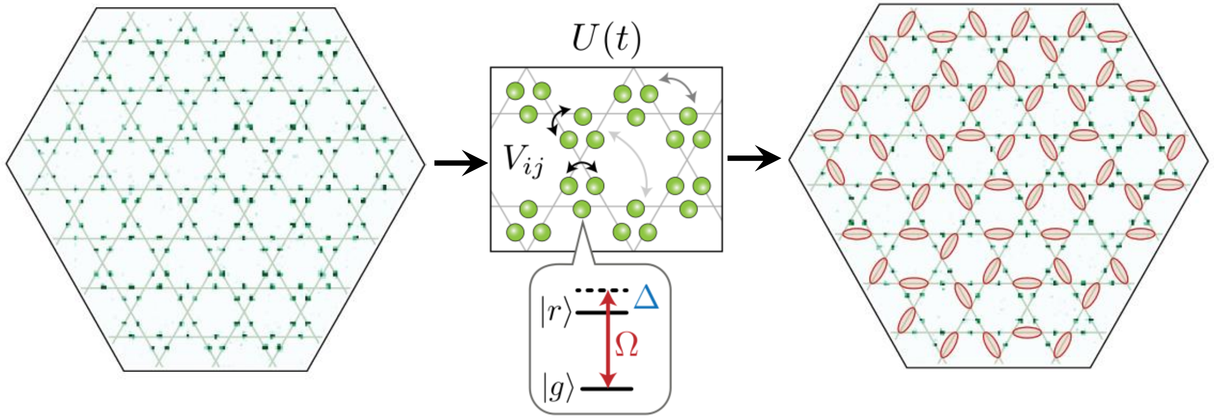
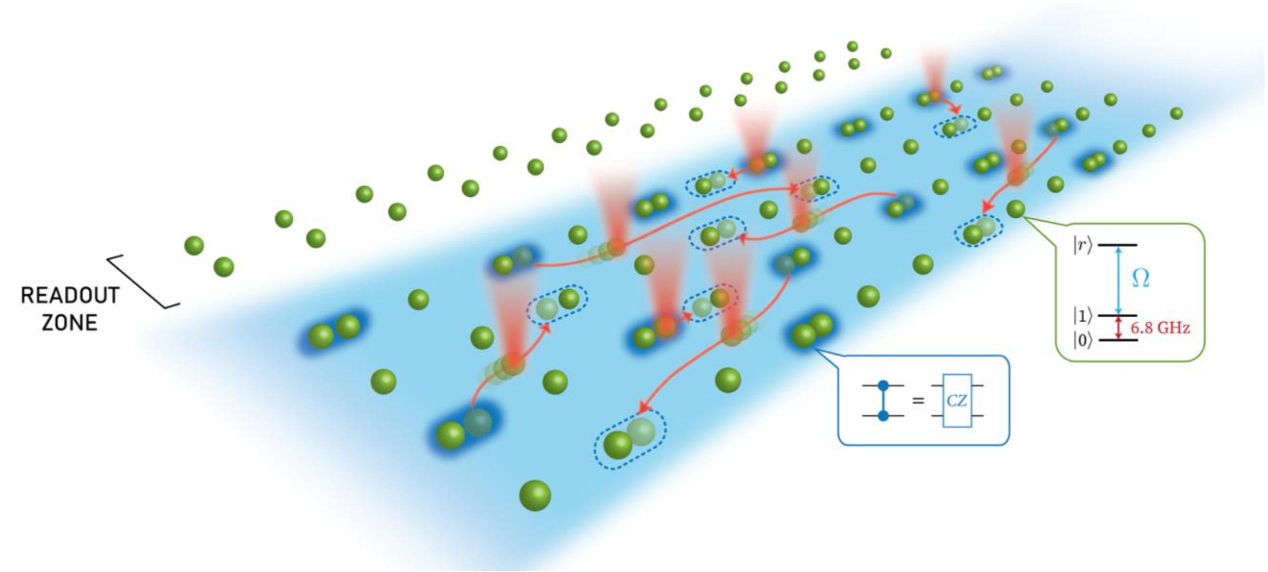
New frontiers in quantum simulation and computation with neutral atom arrays





Giulia Semeghini

Harvard University - Lukin Group

SPICE Workshop – Non-Equilibrium Emergence in Quantum Design

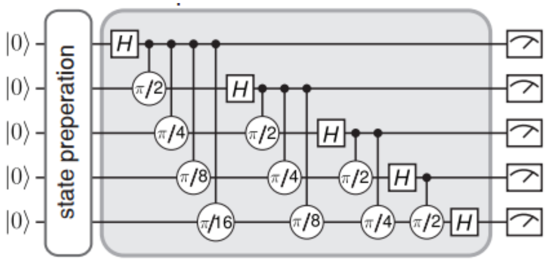
June 23rd, 2022

New frontiers in quantum science

Two key challenges:

1) building large scale quantum machines

Controllability:



Scalability:

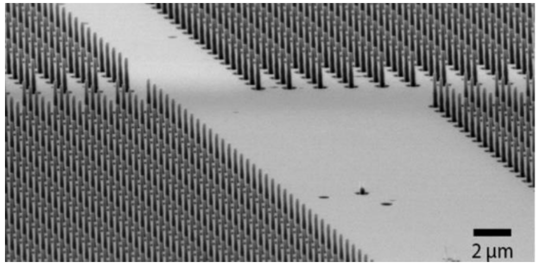
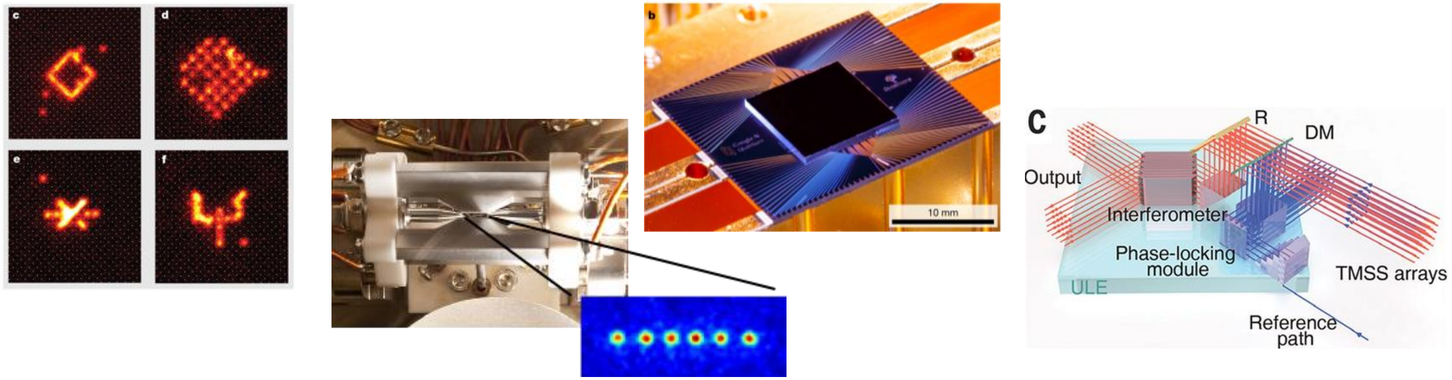


Image from Loncar's group

2) developing new algorithms and science applications

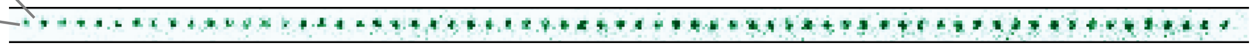
Several platforms: ions, atoms, superconductors, photons, defects…



Images from: Blatt, Bloch, Google, Jian-Wei Pan groups

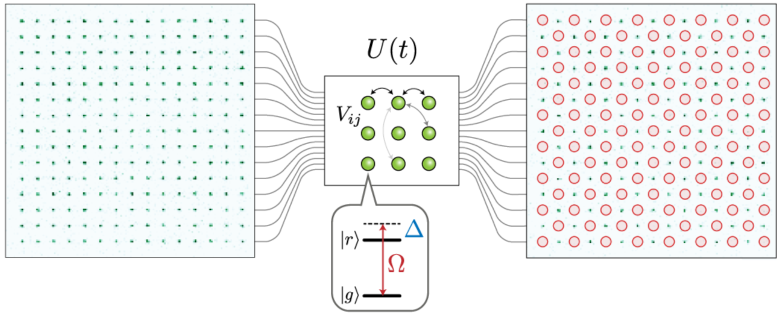
Our approach:

individual neutral atoms in optical tweezers



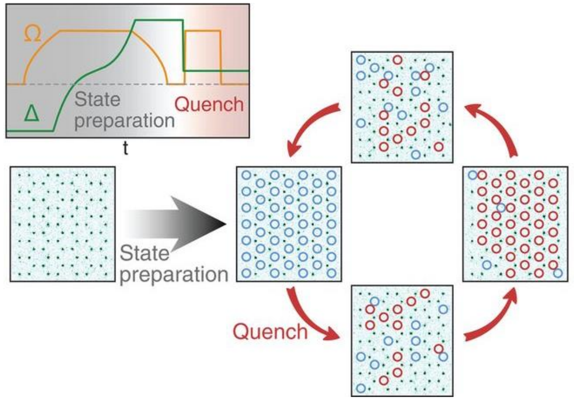
- Excellent isolation from the environment
- Highly scalable defect-free arrays (100s of identical atoms)
- Well-developed toolbox:
  - Initialization, readout
  - Strong, switchable Rydberg interactions
- Scalability → large-scale parallel photonic control

Exploring quantum phases with 256 qubits



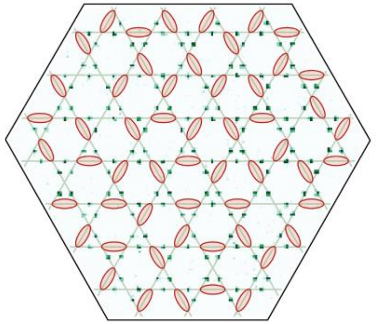
S. Ebadi et al, Nature (2021)

Non-equilibrium dynamics: many-body scars



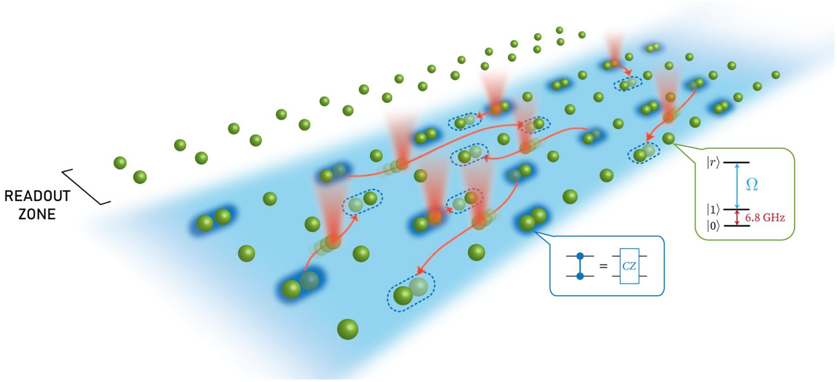
D. Bluvstein et al, Science (2021)

Topological spin liquids



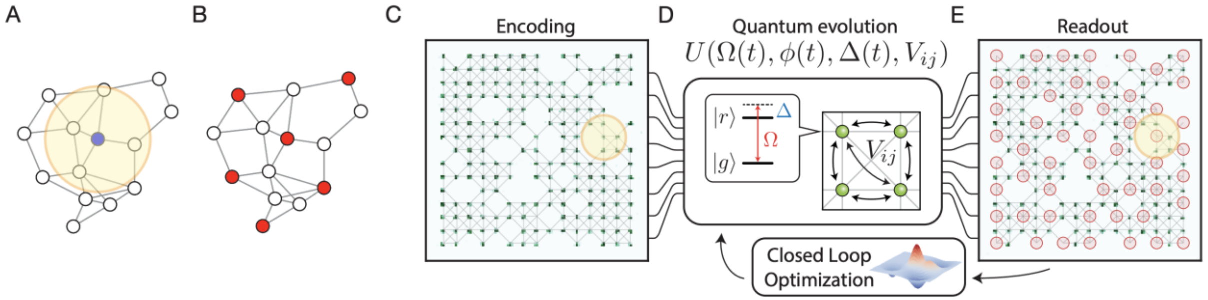
GS et al, Science 374, 1242 (2021)

Entanglement transport & universal programmability



D. Bluvstein et al, Nature (2022)

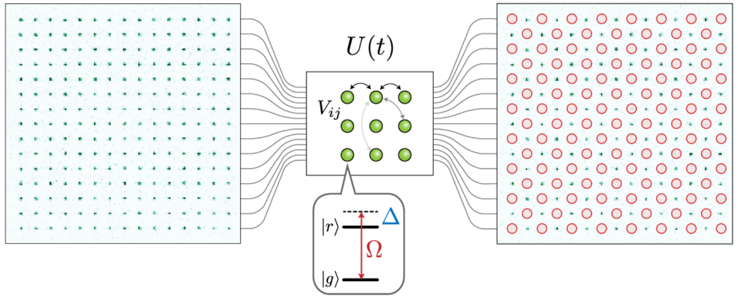
Accelerating combinatorial optimization



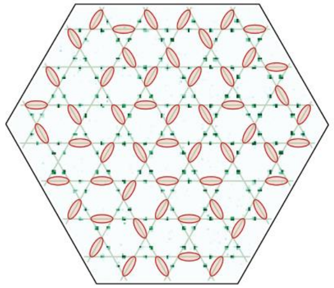
S. Ebadi et al, arXiv:2202.09372, Science (2022)

Outline

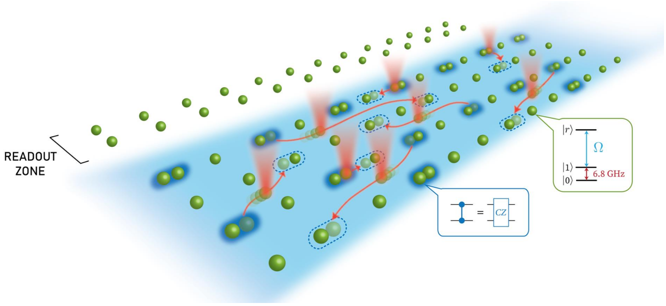
Programmable arrays of Rydberg atoms



Experimental evidence of a quantum spin liquid phase



Dynamically reconfigurable architecture for quantum information processing



Outline

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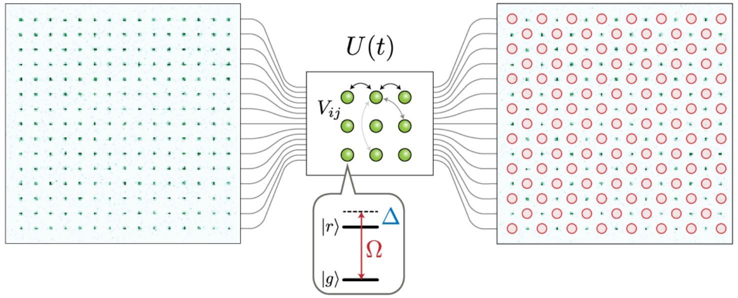

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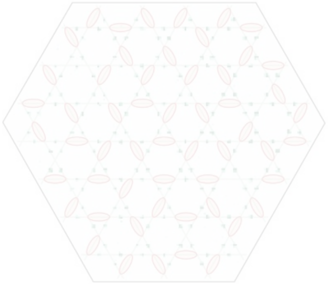
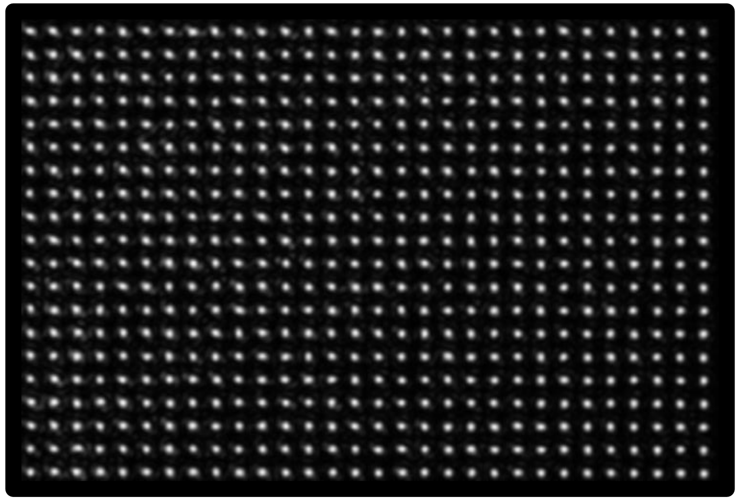


Dynamically reconfigurable architecture for quantum information processing

2D array of optical tweezers

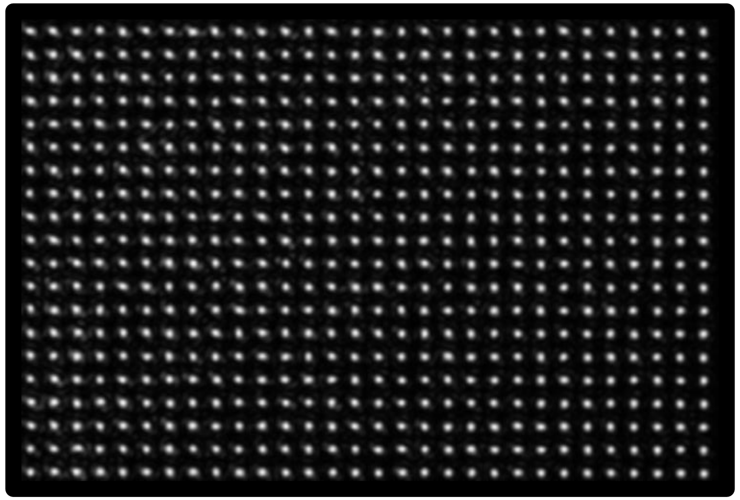


D. Kim, et al, Opt. Lett. 44, 3178 (2019)

Ebadi et al Nature 2021

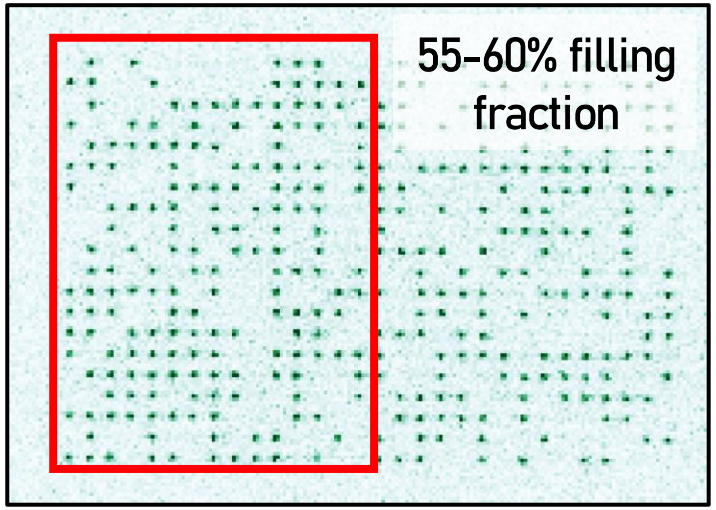
Related work: Browaeys' group;
Ahn, Regal, Endres, Kaufman, Saffman,
Thompson, Ni, Bakr, Bloch, Bernien, …

2D array of optical tweezers



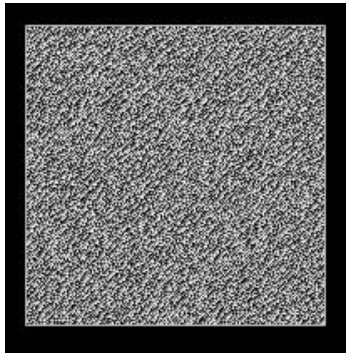
D. Kim, et al, Opt. Lett. 44, 3178 (2019)

Atoms:



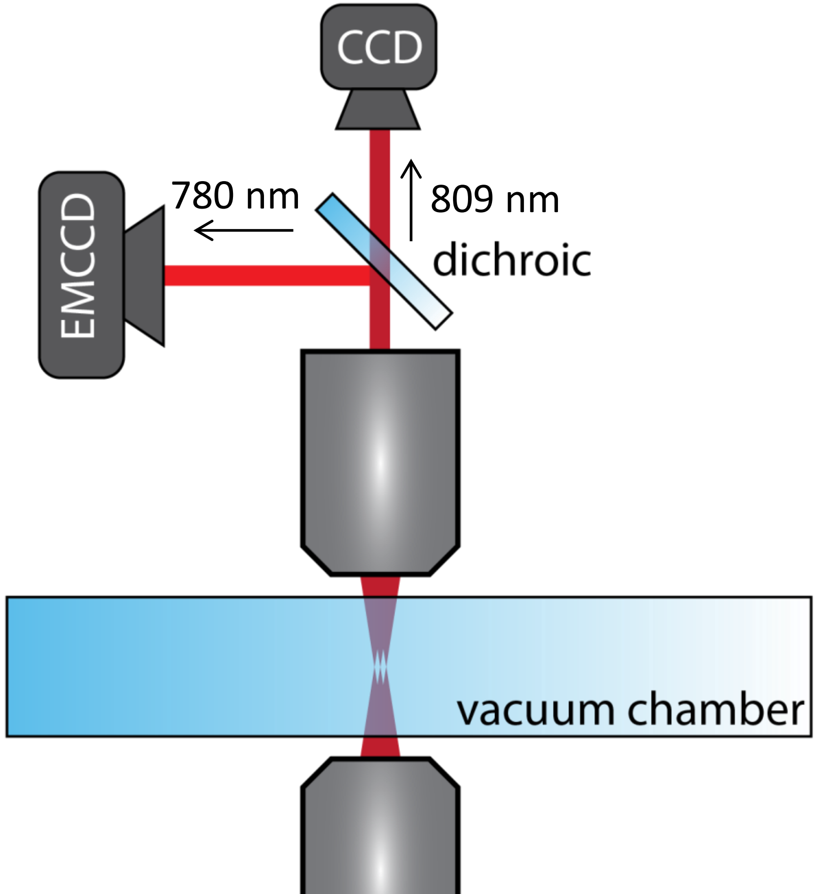
55-60% filling fraction

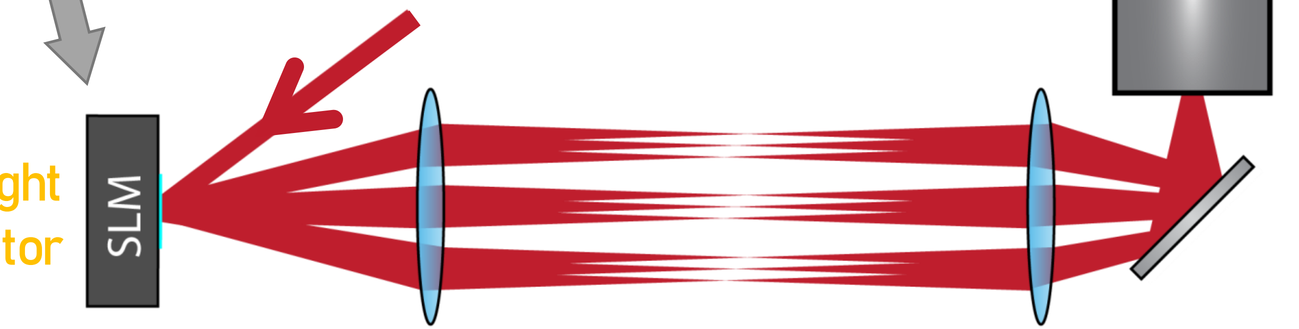
Deterministically fill subset of traps?



phase profile

Spatial Light Modulator





Ebadi et al Nature 2021

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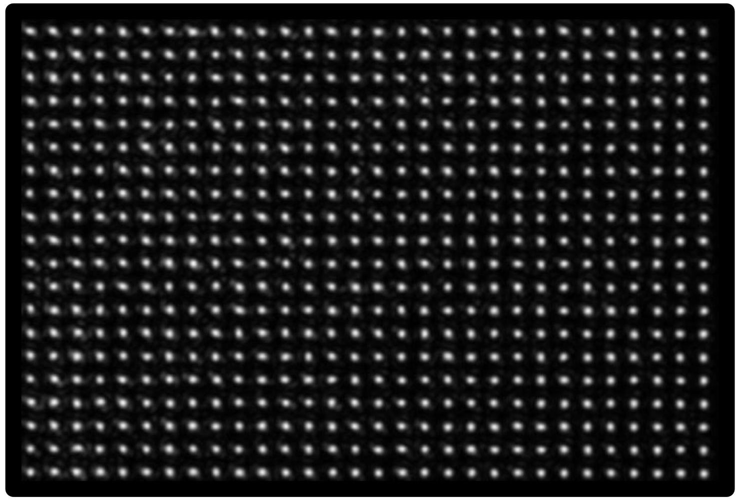

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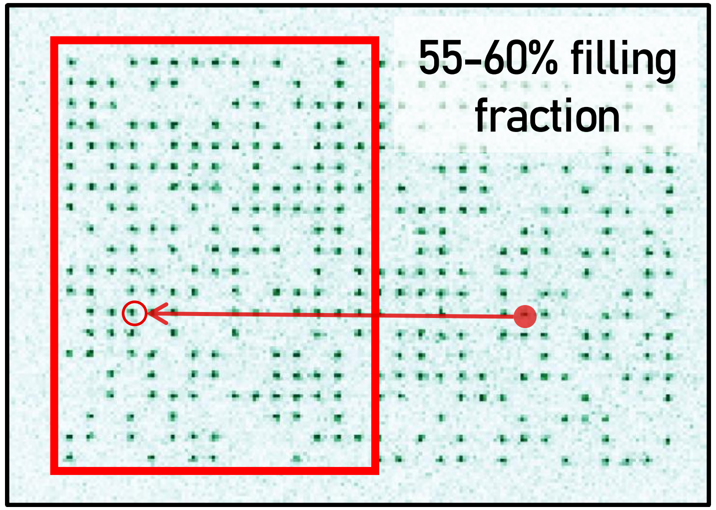
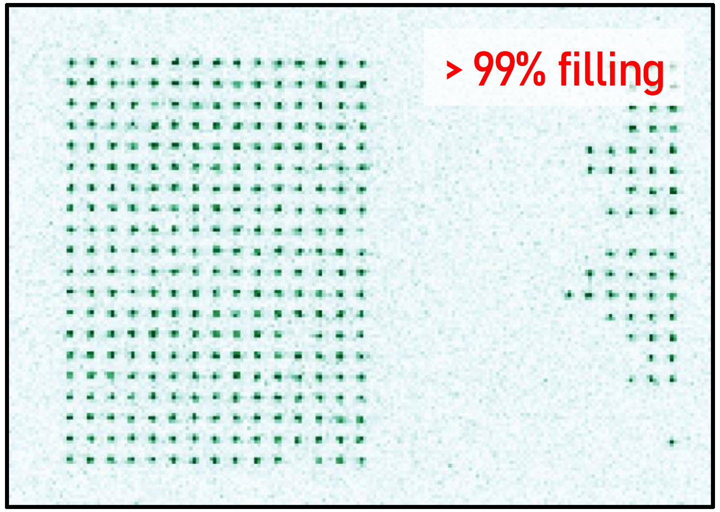


After sorting:



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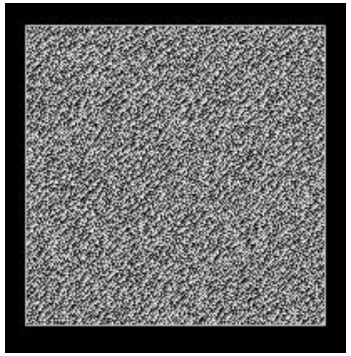

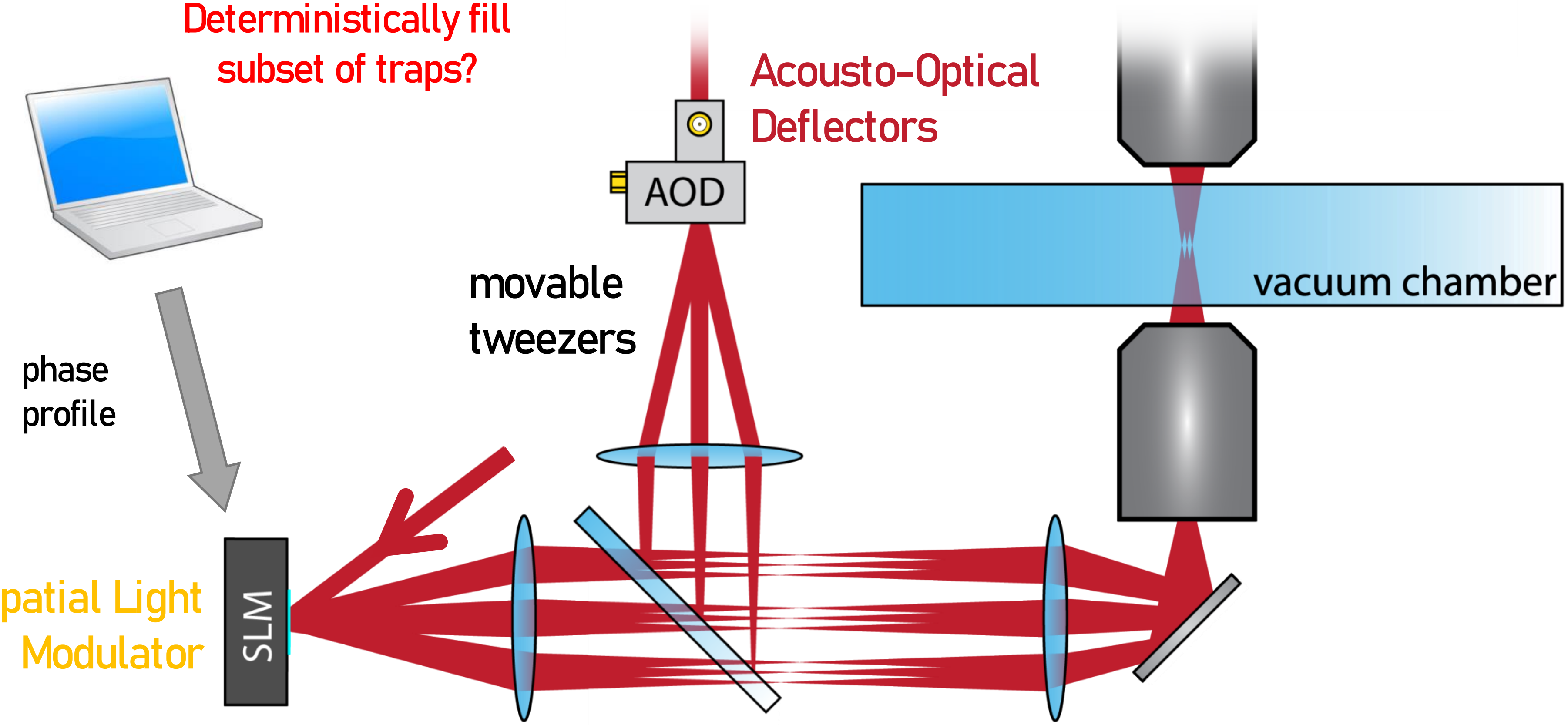

phase profile

Spatial Light Modulator

movable tweezers

Acousto-Optical Deflectors

vacuum chamber

Ebadi et al Nature 2021

Related work: Browaeys' group;
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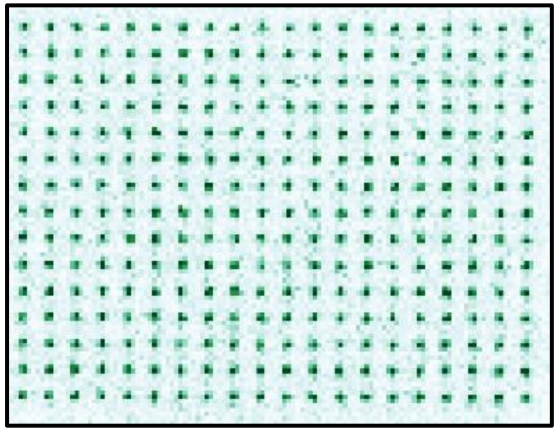
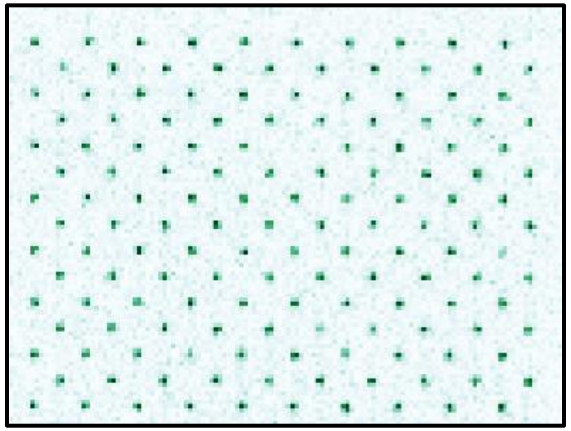
Thompson, Ni, Bakr, Bloch, Bernien, …

Programmable 2D arrays

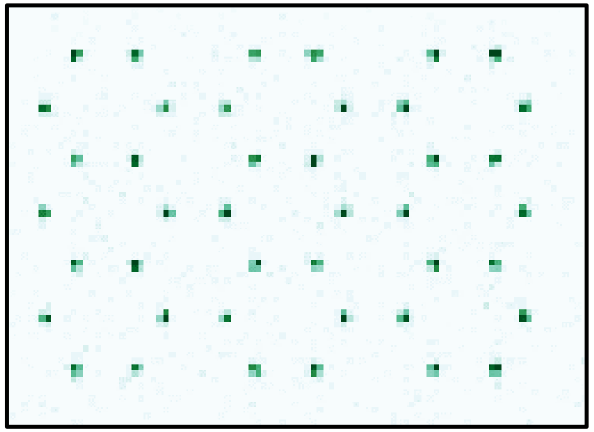
Square



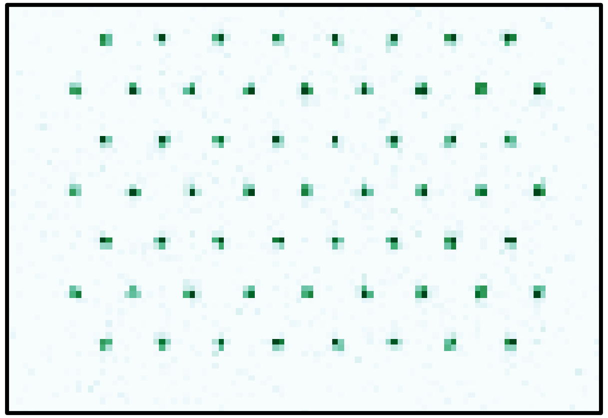
Tilted Square



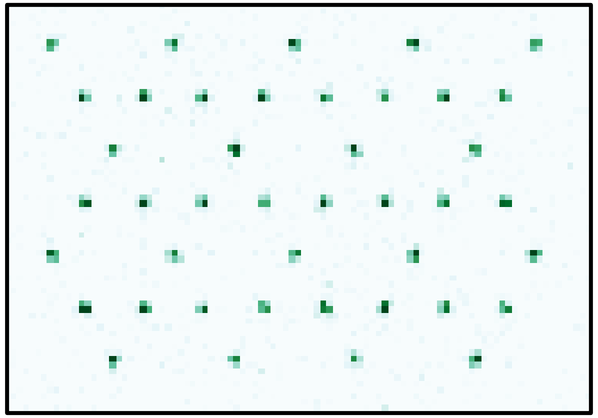
Honeycomb



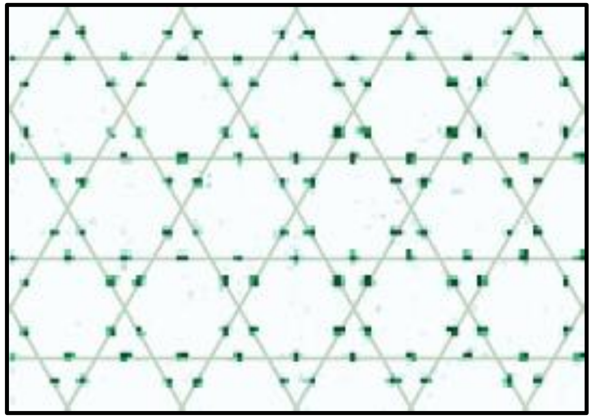
Triangular



Kagome



Link-kagome



Programmable 2D arrays

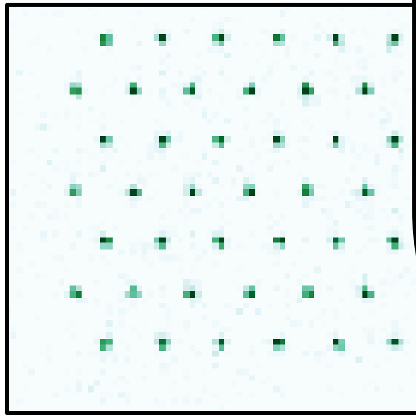
Square

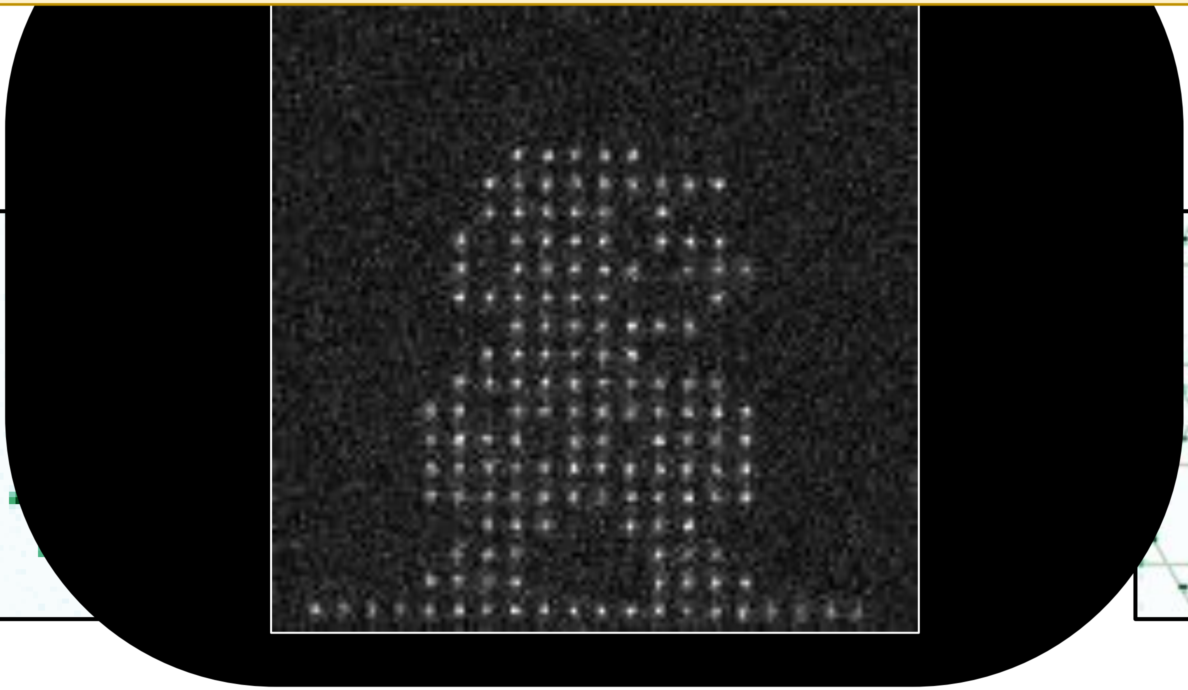
Tilted Square

Honeycomb

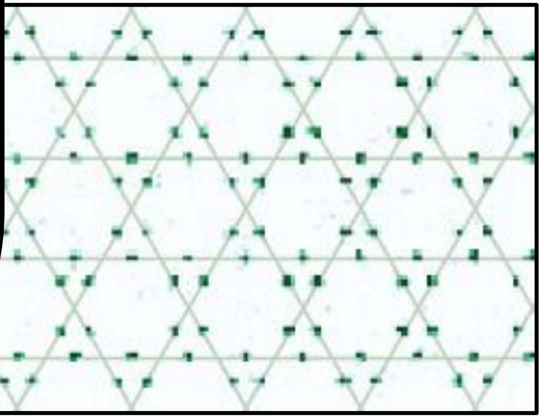
1) Programmable 2D arrays of neutral atoms

Triangular



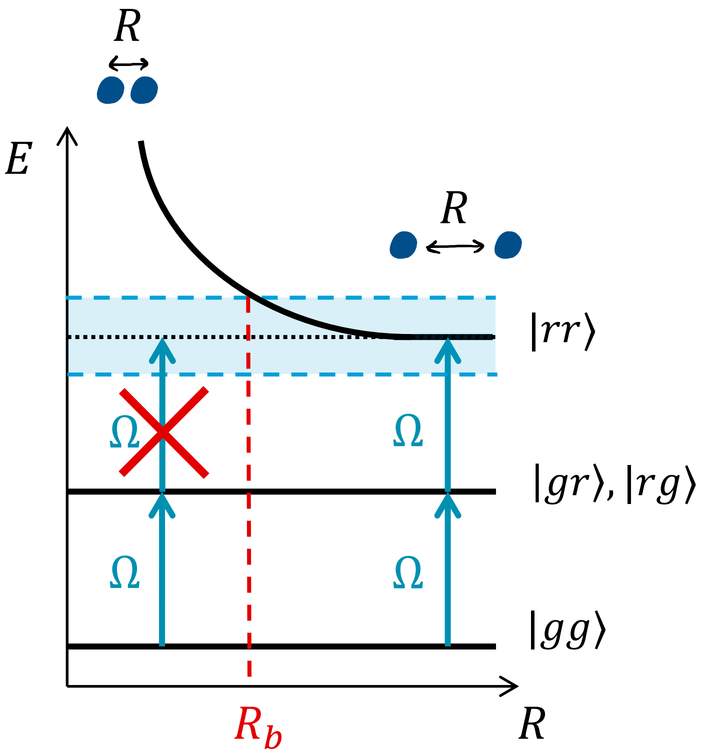


Link-kagome



Rydberg states and long-range interactions

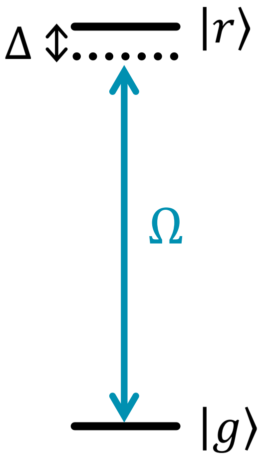
Rydberg blockade



blockade radius R_b :

$$V(R_b) = \Omega$$

excitation to Rydberg state:

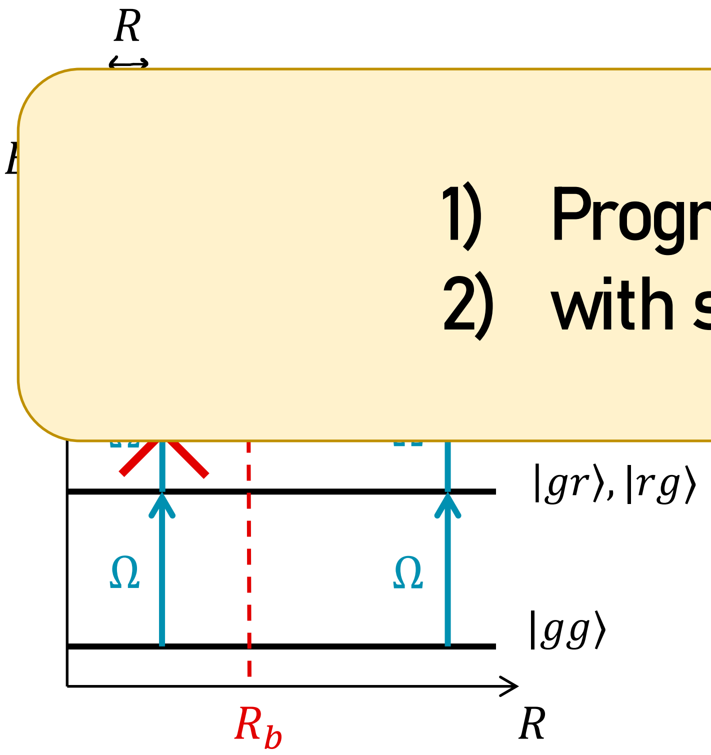


van der Waals interactions $\propto 1/R^6$

Lukin, Zoller 2000
Saffman, RMP 2020
Browaeys, Nat Phys 2020

Rydberg states and long-range interactions

Rydberg blockade



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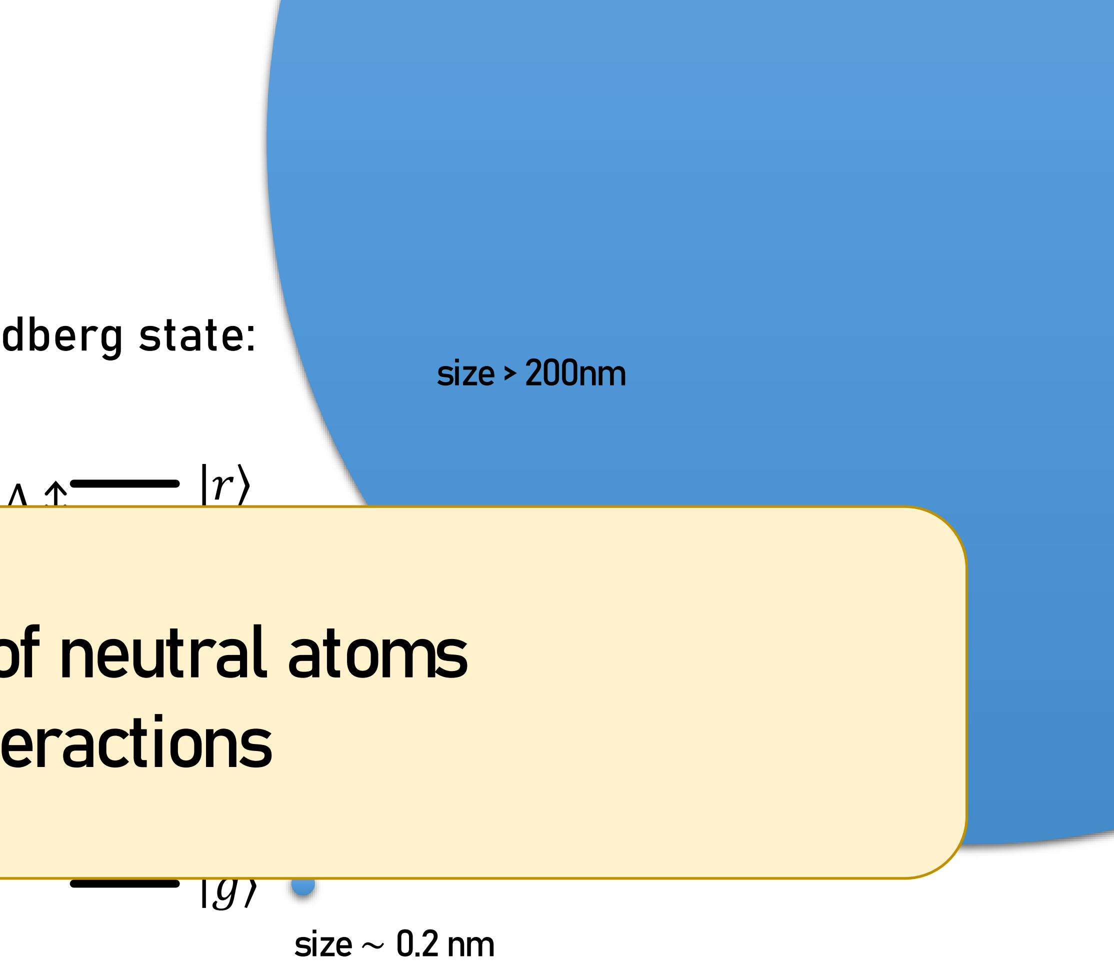


1) Programmable 2D arrays of neutral atoms
2) with strong long-range interactions

van der Waals interactions $\propto 1/R^6$

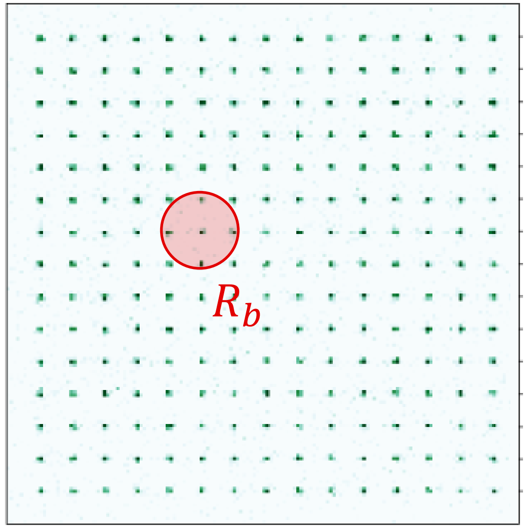
Lukin, Zoller 2000
Saffman, RMP 2020
Browaeys, Nat Phys 2020

Rydberg blockade and quantum many-body phases

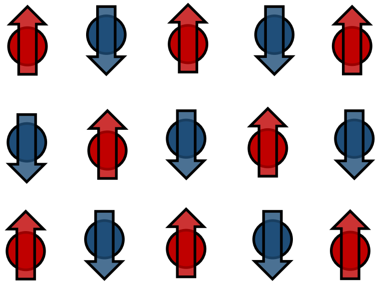
Many-Body ground state

$\Delta > 0$

Maximize number of disconnected Rydberg atoms



antiferromagnetic state



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

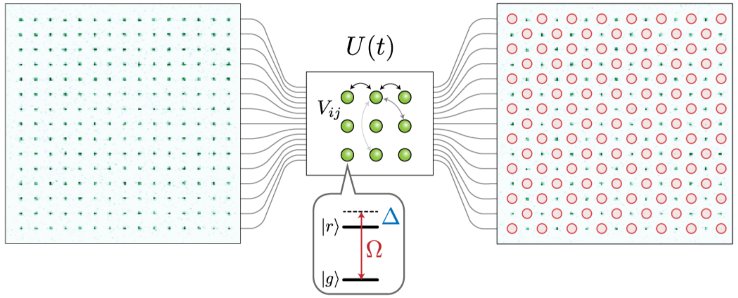
drive term detuning interaction

S. Ebadi et al., Quantum Phases of Matter on a 256-Atom Programmable Quantum Simulator, Nature 595, 227–232 (2021)

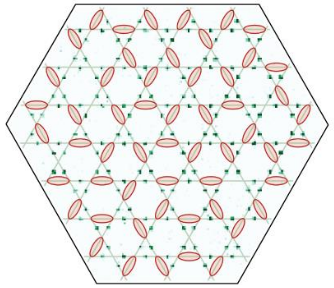
P. Scholl et al., Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms, Nature 595, 233–238 (2021)

Outline

Programmable arrays of Rydberg atoms



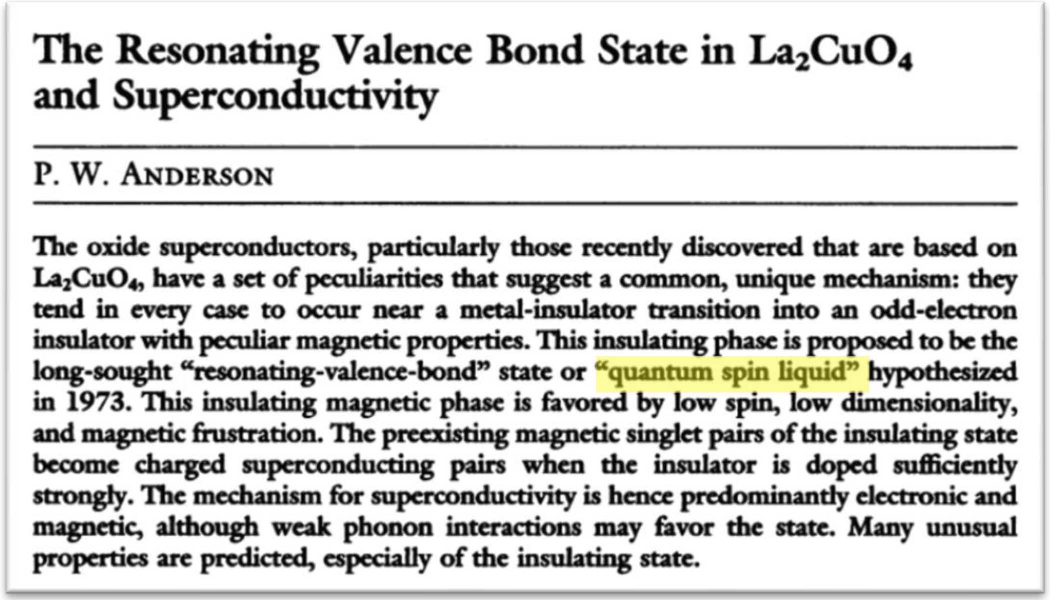
Experimental evidence of a quantum spin liquid phase



Dynamically reconfigurable architecture for quantum information processing

Quantum spin liquids

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

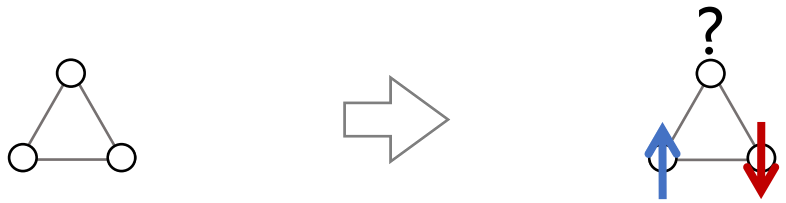


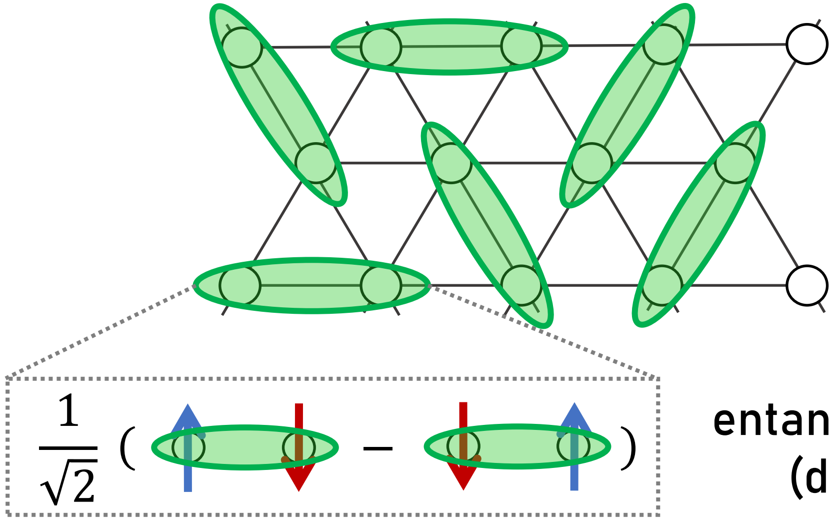
The Resonating Valence Bond State in La_2CuO_4 and Superconductivity

P. W. ANDERSON

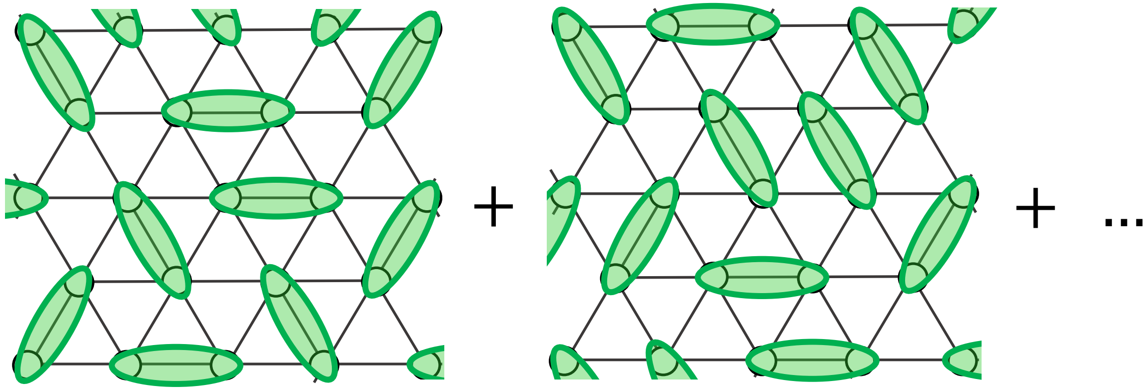
The oxide superconductors, particularly those recently discovered that are based on La_2CuO_4, have a set of peculiarities that suggest a common, unique mechanism: they tend in every case to occur near a metal-insulator transition into an odd-electron insulator with peculiar magnetic properties. This 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.

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





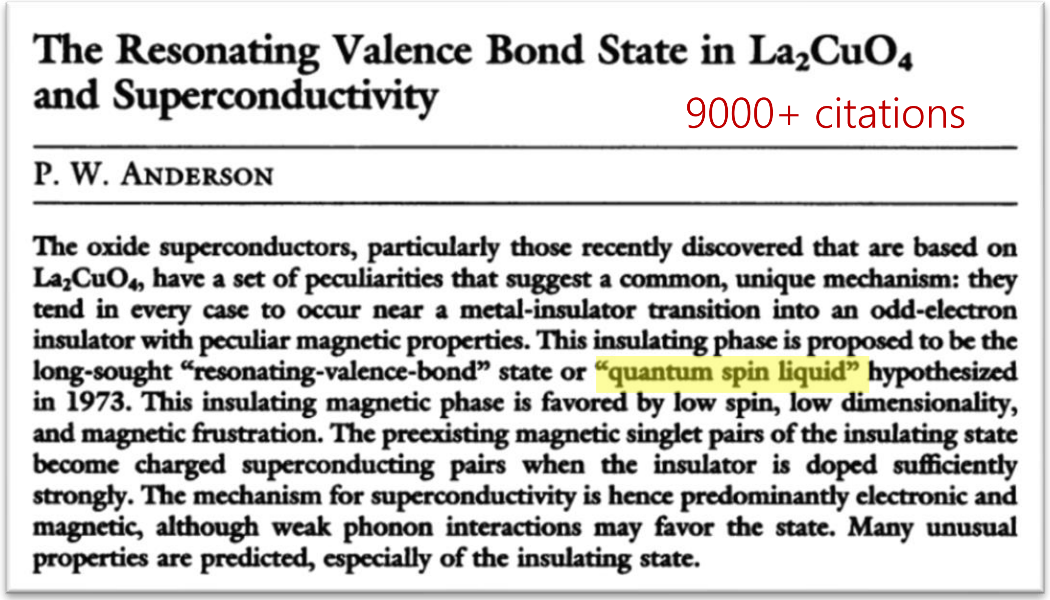
entangled pair
(dimer)



resonating valence bond (RVB) state

Quantum spin liquids

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



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9000+ citations

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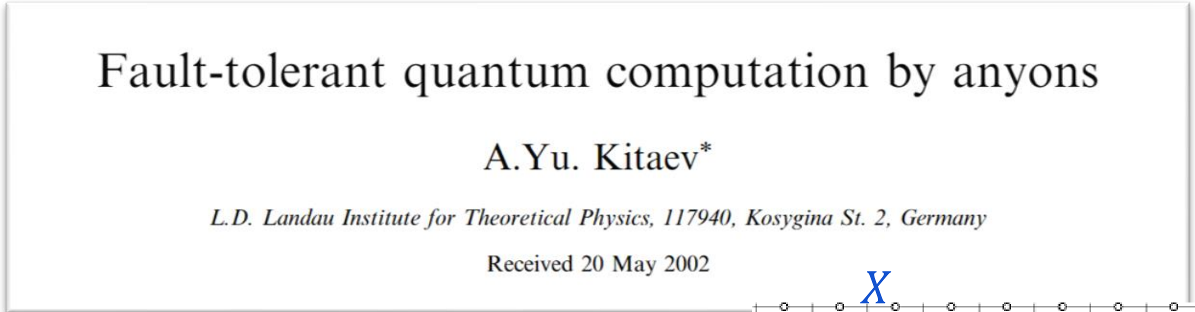
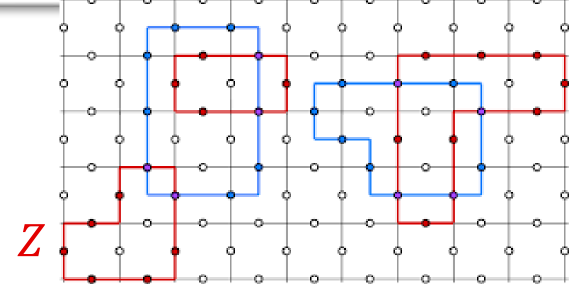


Fault-tolerant quantum computation by anyons

A.Yu. Kitaev*

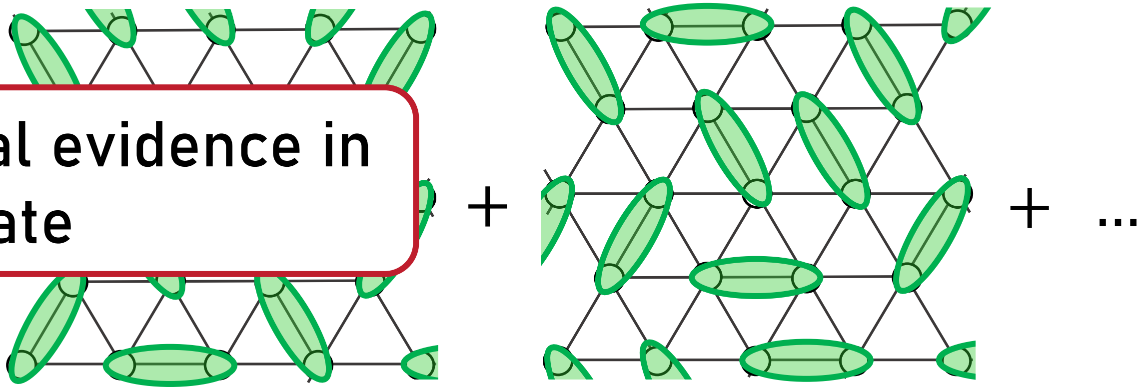
L.D. Landau Institute for Theoretical Physics, 117940, Kosygina St. 2, Germany

Received 20 May 2002



- no spatial order
- topological order
- long-range quantum enta
- anyonic non-local excitat
- emergent gauge fields
- robust ground state degeneracy
- link with high-T$_c$ superconductivity
- application to fault-tolerant quantum computing → toric code

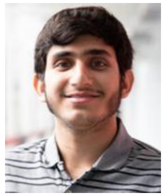
No conclusive experimental evidence in any system to date



resonating valence bond (RVB) state

Quantum spin liquids in Rydberg atom arrays

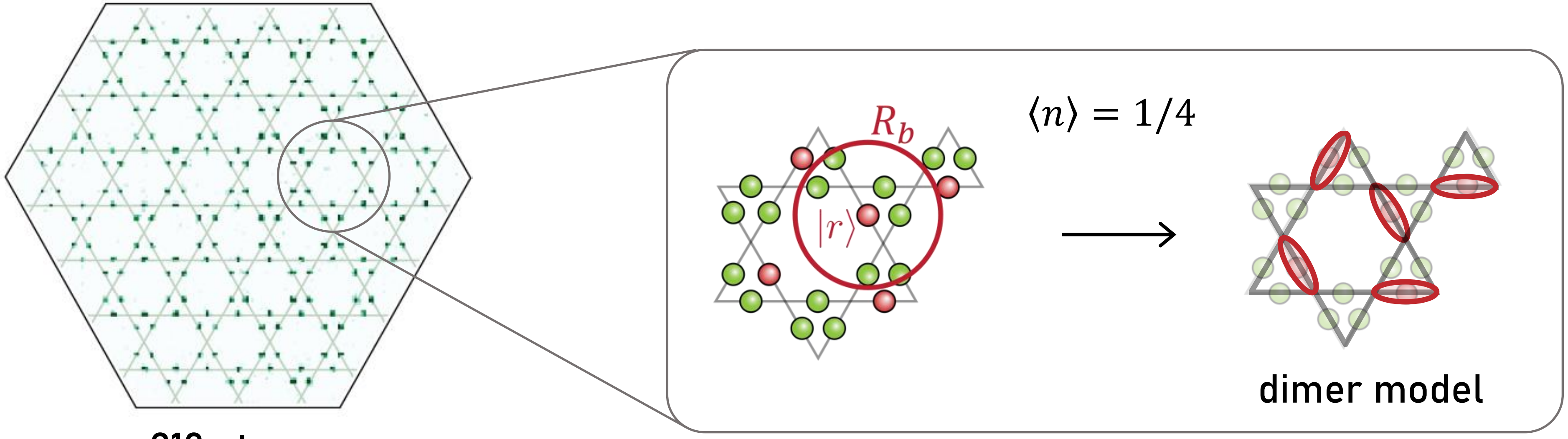
R. Samajdar



S. Sachdev

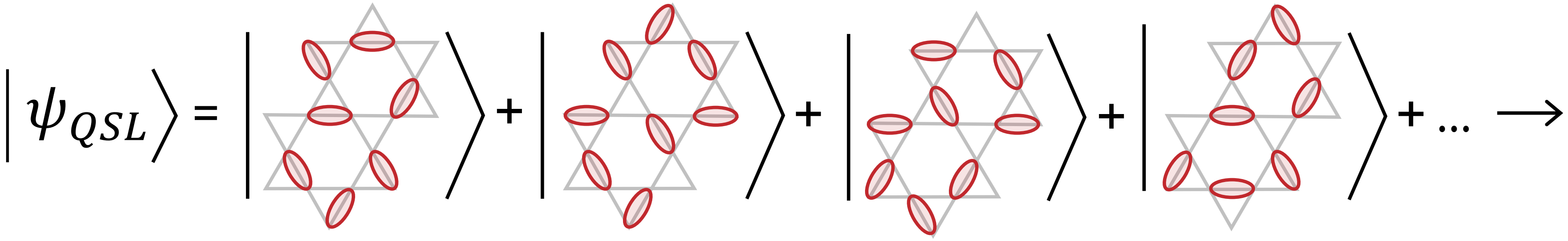
R. Verresen

A. Vishwanath



219 atoms

quantum spin liquid state: superposition of all dimer coverings



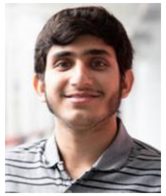
$$|\psi_{QSL}\rangle = |\;\rangle + |\;\rangle + |\;\rangle + |\;\rangle + \ldots \longrightarrow \mathbb{Z}_2 \text{ topological order}$$

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

P. Anderson, Materials Research Bulletin 8 (1973)

Quantum spin liquids in Rydberg atom arrays

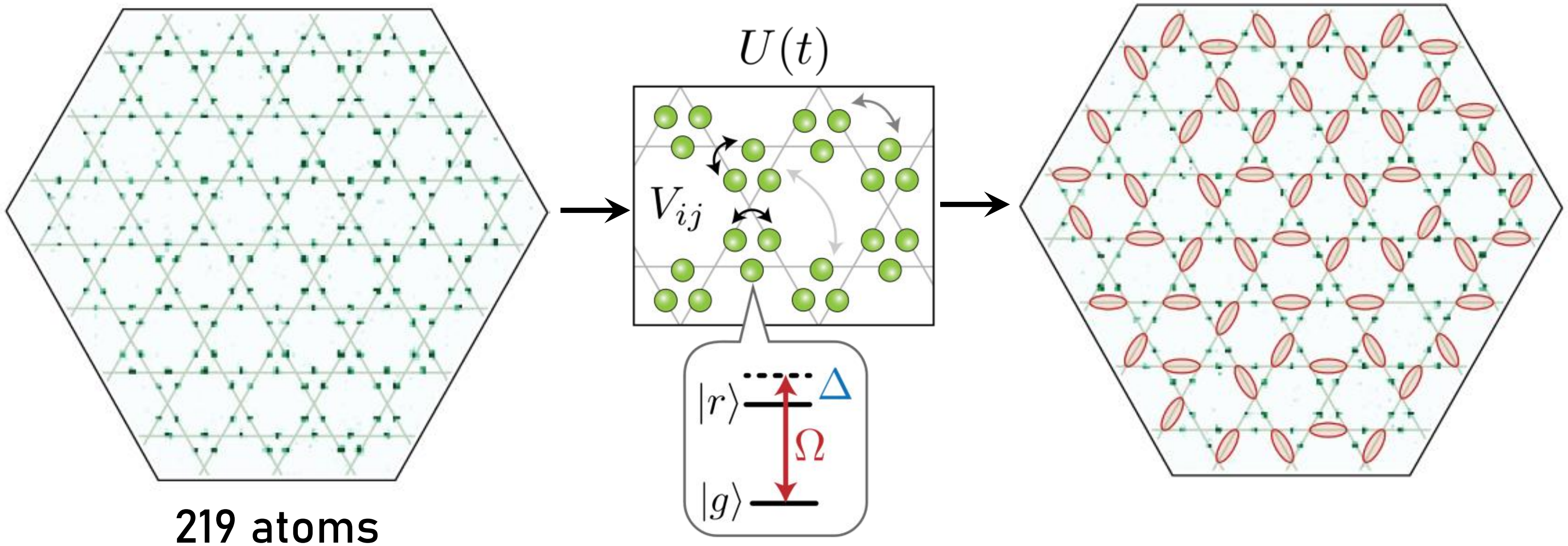
R. Samajdar



S. Sachdev

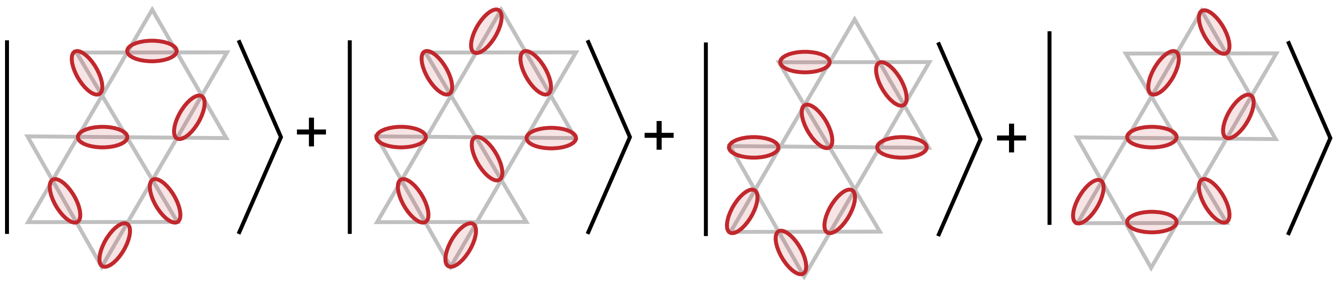
R. Verresen

A. Vishwanath



219 atoms

quantum spin liquid state: superposition of all dimer coverings



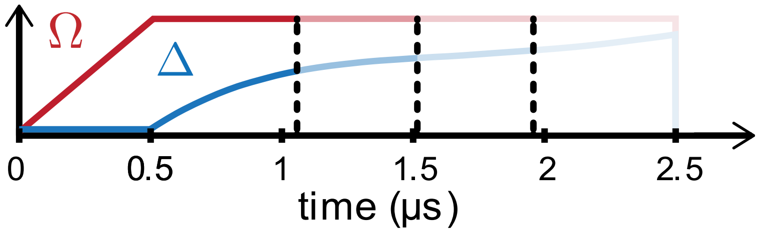
$|\psi_{QSL}\rangle = |\ \rangle + |\ \rangle + |\ \rangle + |\ \rangle + \ldots \longrightarrow$ $\mathbb{Z}_2$ topological order

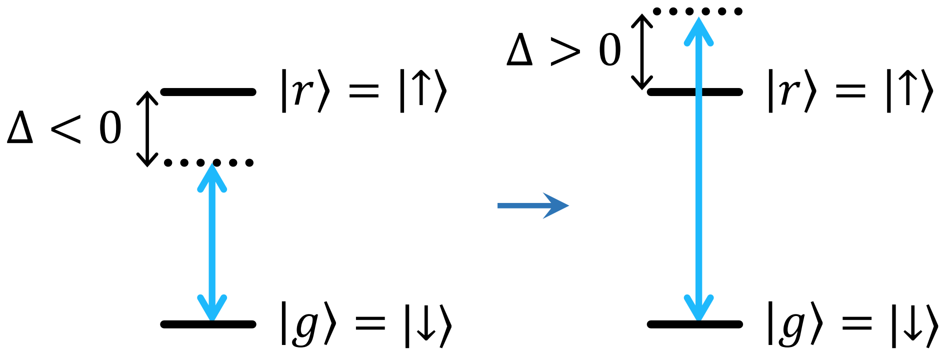
R. Verresen, M. Lukin and A. Vishwanath, Phys Rev. X 11, 031005 (2021)
G. Semeghini et al., Science 374, 1242 (2021)

P. Anderson, Materials Research Bulletin 8 (1973)

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

Quasi-adiabatic preparation of a dimer phase

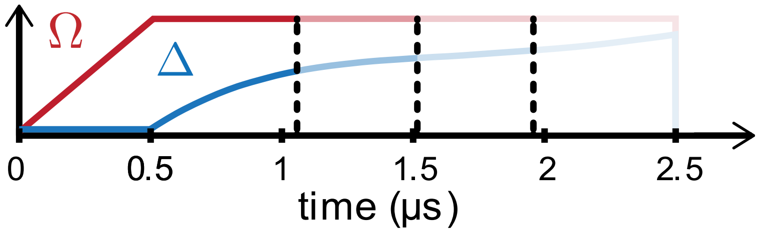


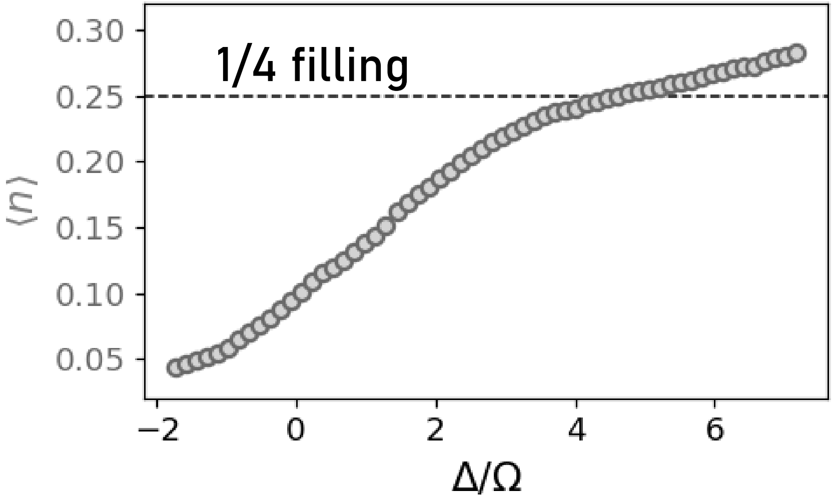


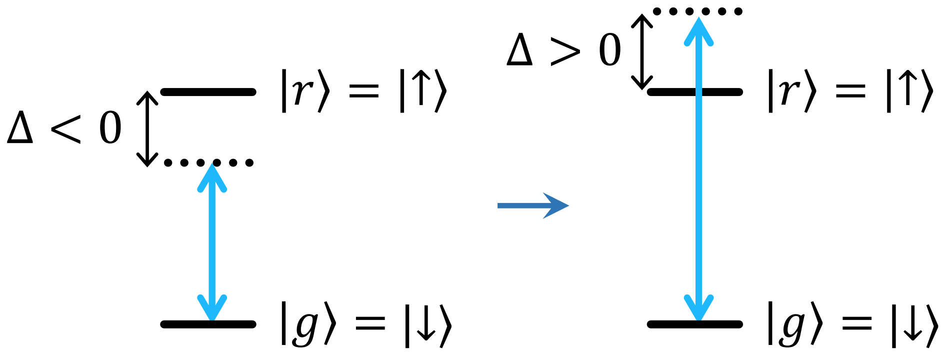
$$\mathcal{H} = \frac{1}{2}\Omega(t)\sum_i \sigma_x^{(i)} - \sum_i \boxed{\Delta(t)}\, n_i + \sum_{i<j} V_{ij} n_i n_j$$

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

Quasi-adiabatic preparation of a dimer phase

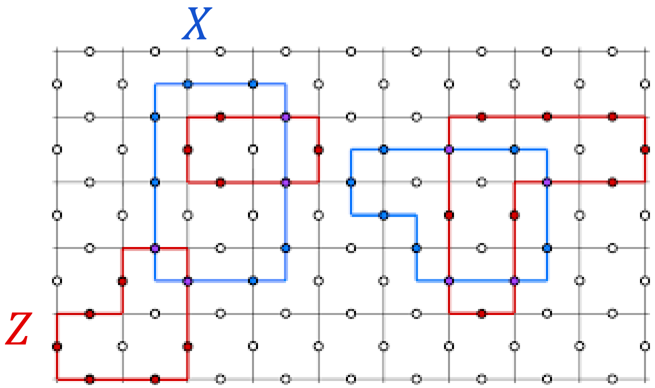




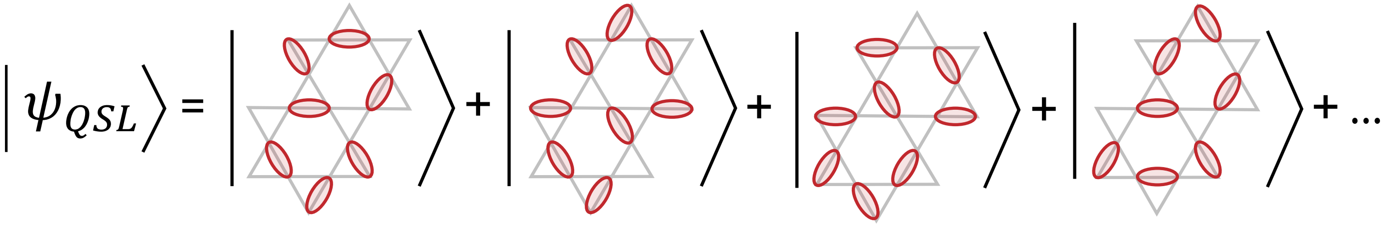


$$\mathcal{H} = \frac{1}{2}\Omega(t)\sum_i \sigma_x^{(i)} - \sum_i \boxed{\Delta(t)}\, n_i + \sum_{i<j} V_{ij} n_i n_j$$

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

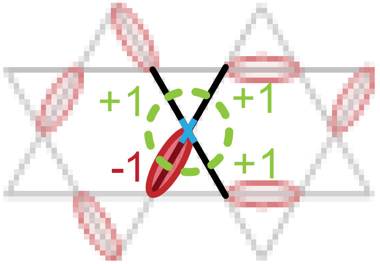


Probing topological correlations

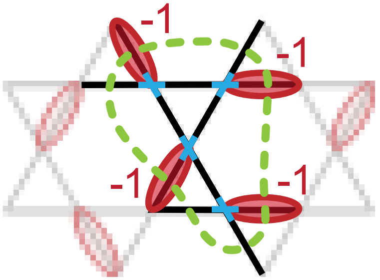


① Identify dimer phase

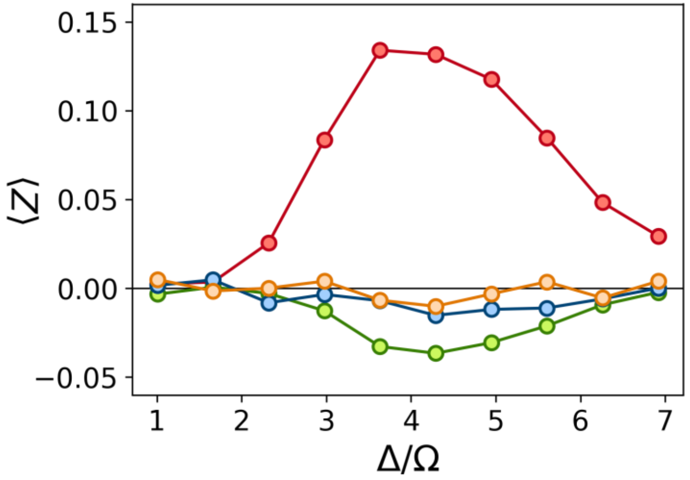
diagonal string operator $\mathbb{Z}$:
parity of dimers along a string

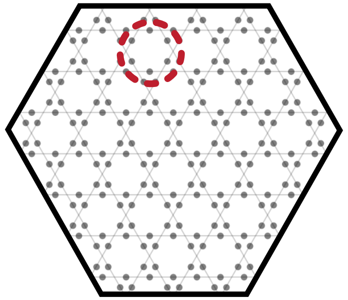


$\langle Z \rangle = -1$



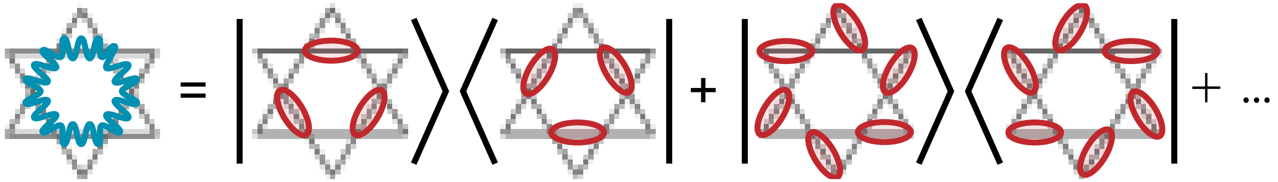
$\langle Z \rangle = (-1)^{\#\text{ enclosed vertices}}$

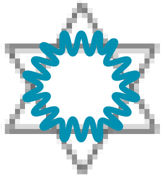




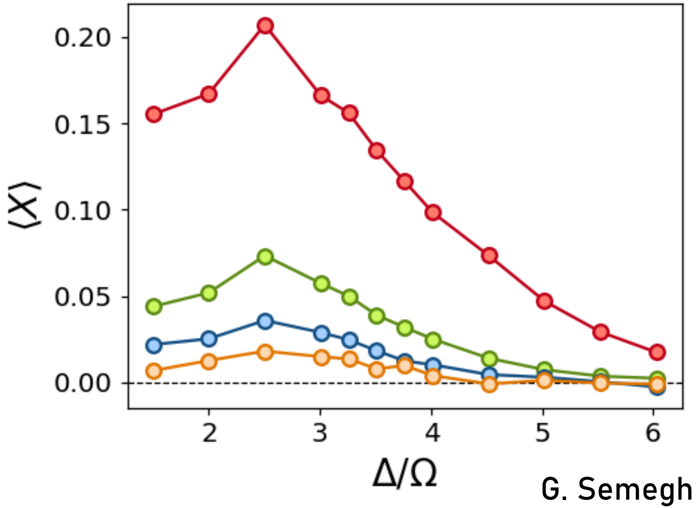
② Probe coherence between dimer states

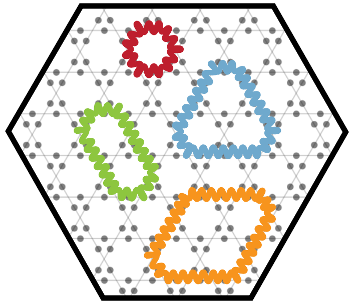
off-diagonal string operator $\mathbb{X}$:





$> 0 \longrightarrow$ coherence between dimer coverings

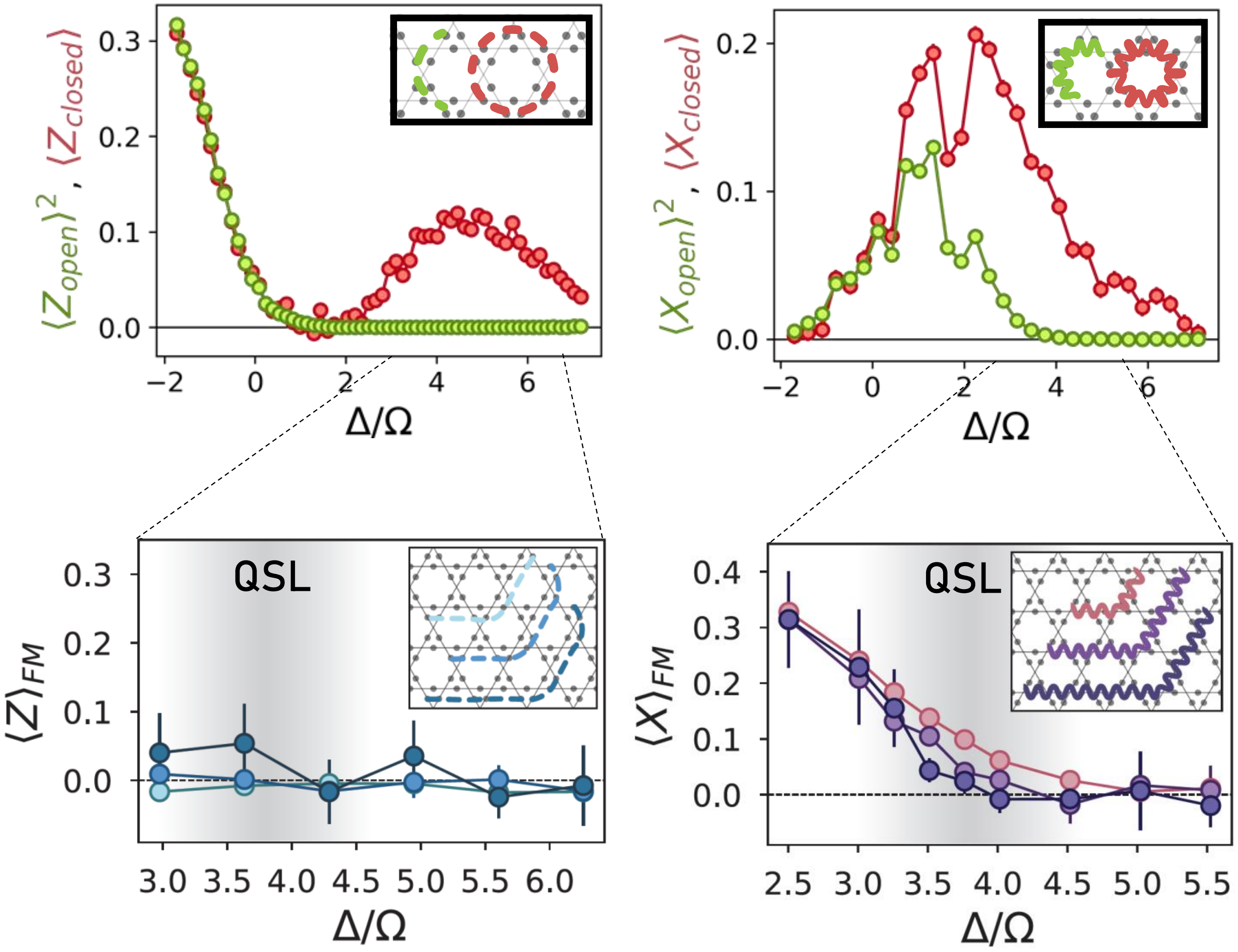




G. Semeghini et al., Science 374, 1242 (2021)

Order parameters for QSL phase

closed loops vs open strings

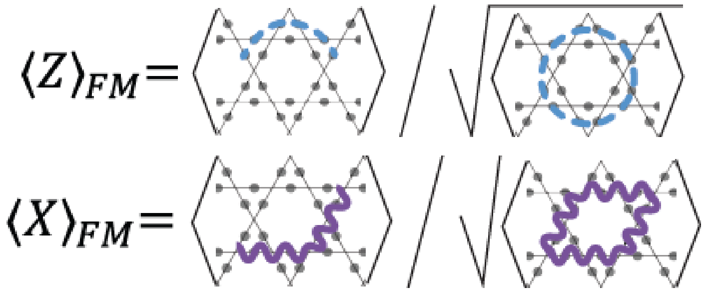


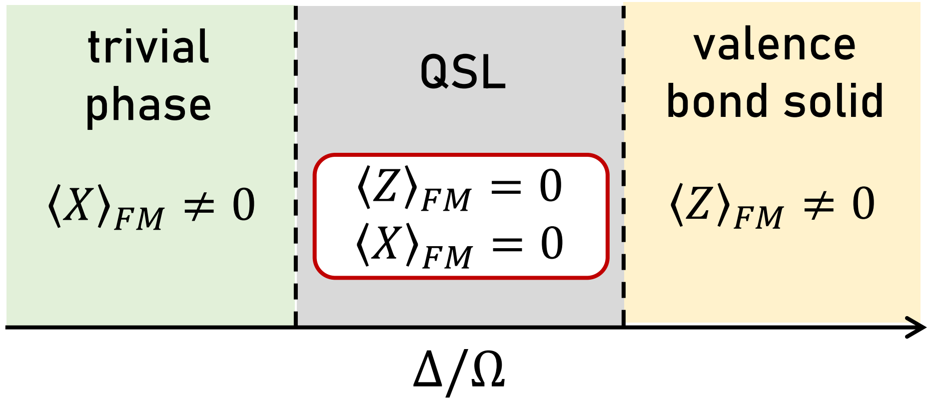
closed loops: detect non-trivial topological correlations

open strings: distinguish QSL from nearby phases

↓

FM string order parameters:





trivial phase	QSL	valence bond solid
$\langle X\rangle_{FM} \neq 0$	$\langle Z\rangle_{FM} = 0$ $\langle X\rangle_{FM} = 0$	$\langle Z\rangle_{FM} \neq 0$

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

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

Order parameters for QSL phase

closed loops vs open strings

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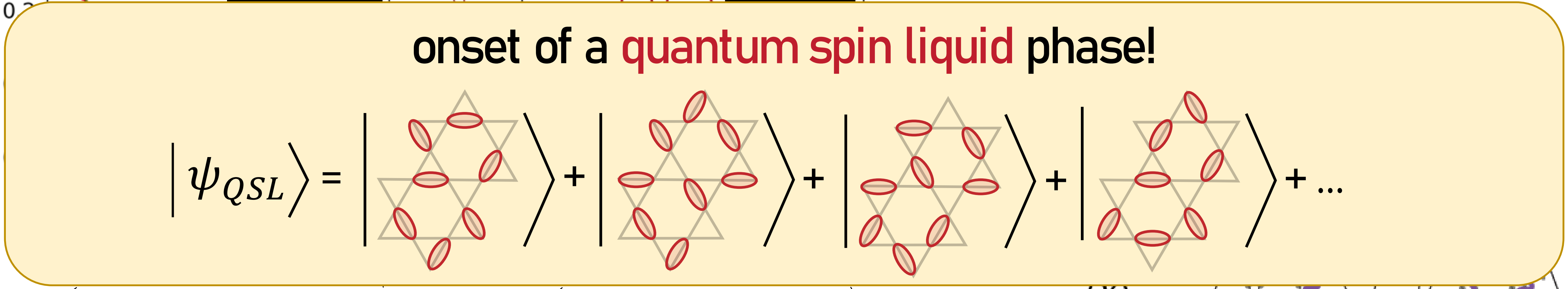
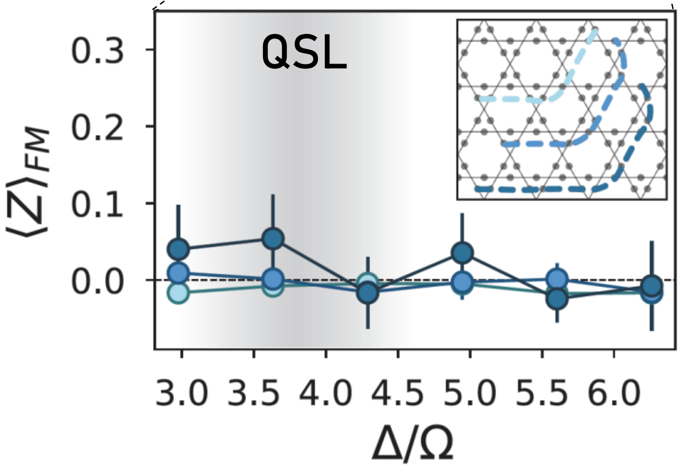
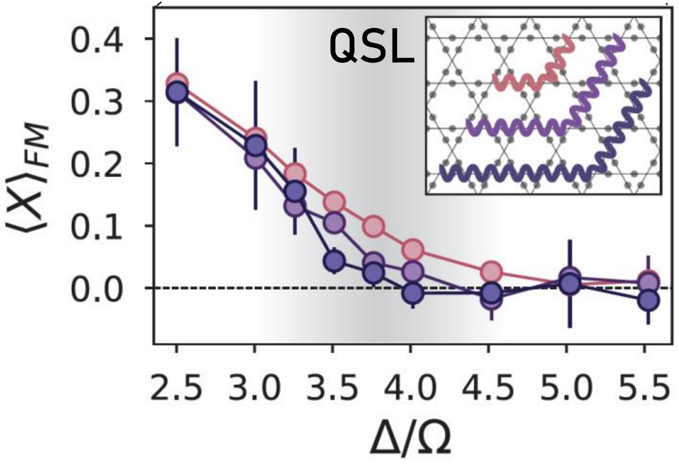
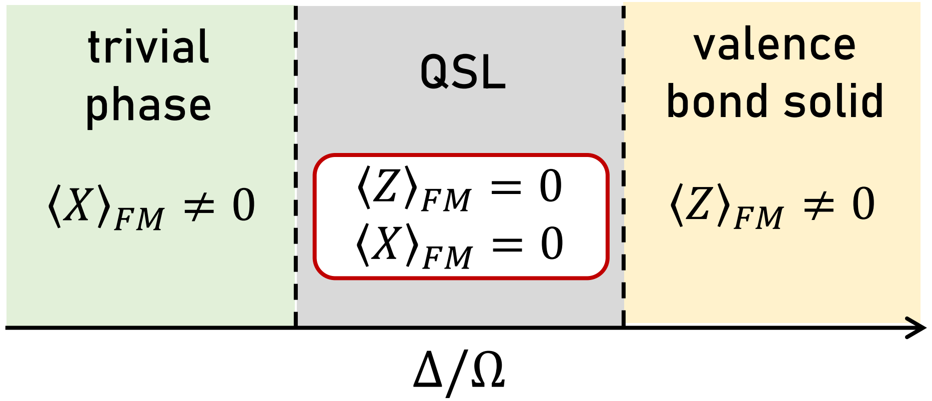
open strings: distinguish QSL from nearby phases


onset of a quantum spin liquid phase!






trivial phase

$\langle X\rangle_{FM} \neq 0$

QSL

$\langle Z\rangle_{FM} = 0$
$\langle X\rangle_{FM} = 0$

valence bond solid

$\langle Z\rangle_{FM} \neq 0$

Δ/Ω

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

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

Towards a topological qubit

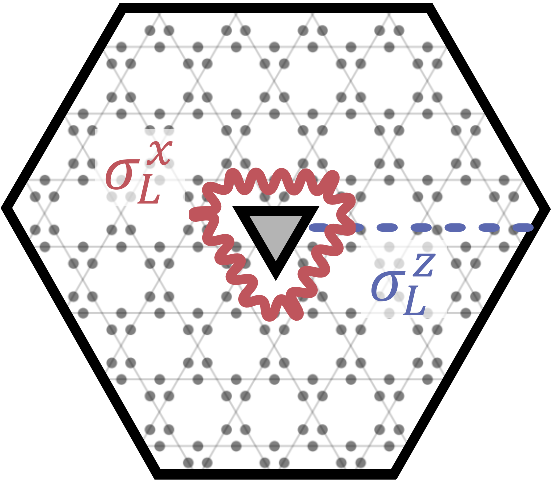
two distinct topological sectors

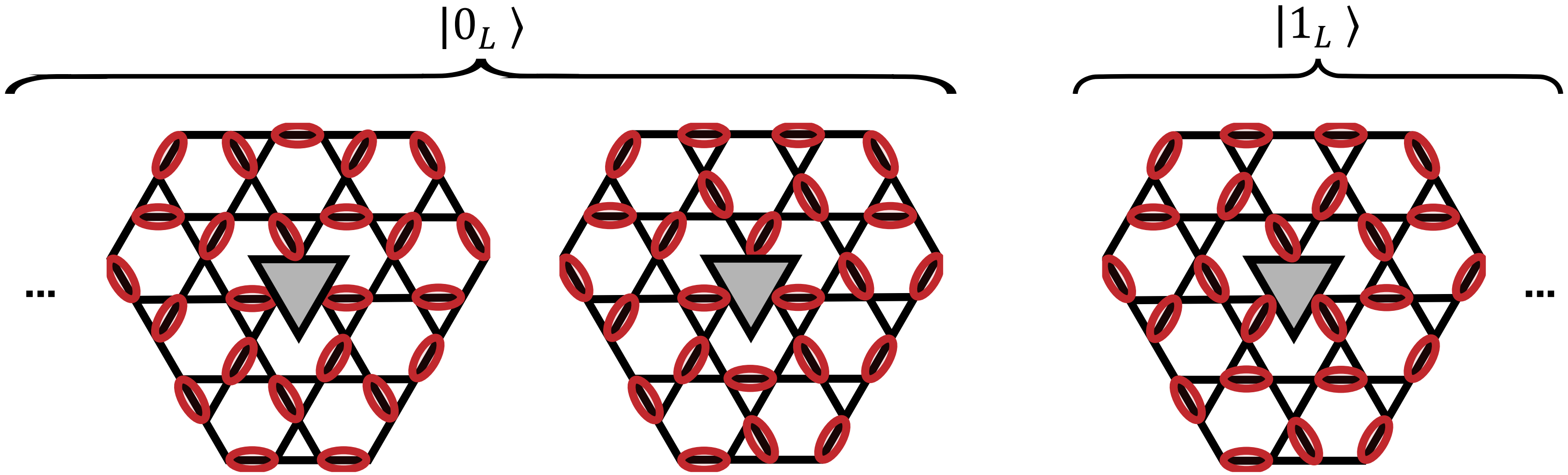
↓

logical states of the topological qubit

non-trivial topology:
array with a hole

logical operators

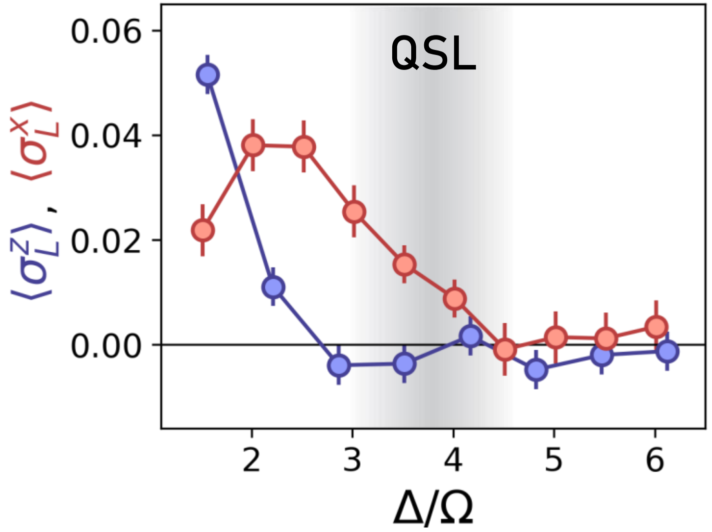




Two-fold degenerate ground state:

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

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

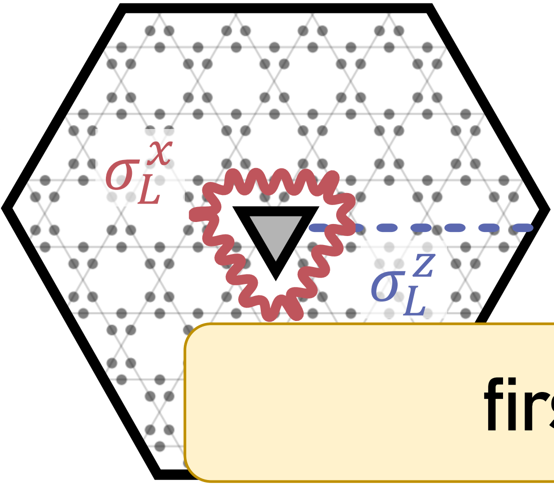


G. Semeghini et al., Science 374, 1242 (2021), related work from Google Quantum AI: K. J. Satzinger et al, Science 374 (2021)

Towards a topological qubit

non-trivial topology:
array with a hole

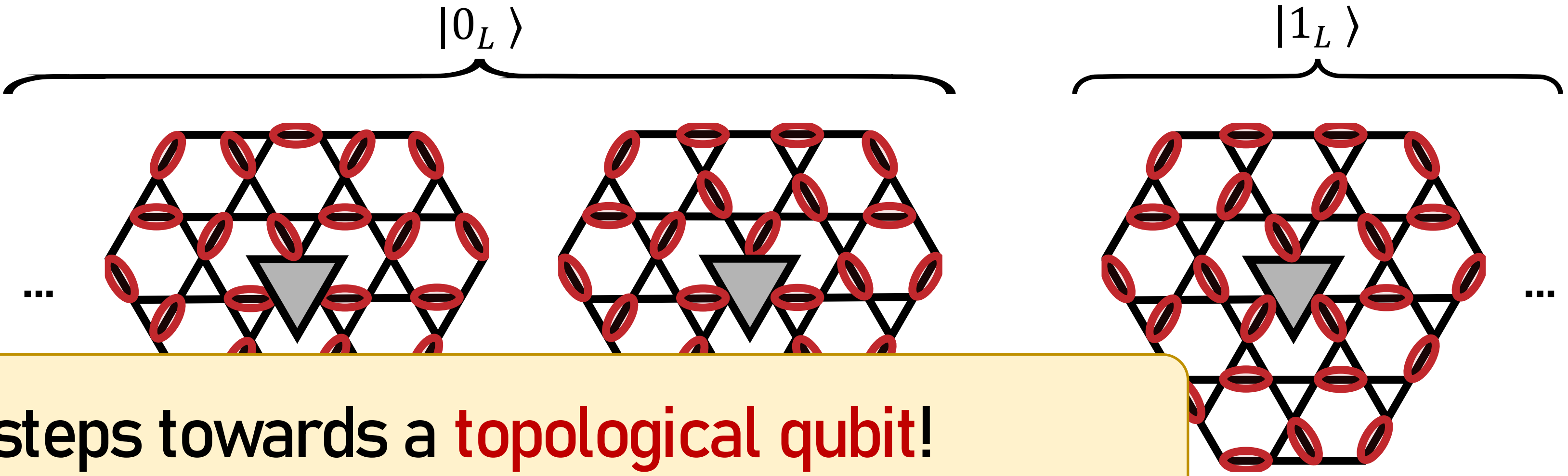
logical operators



two distinct topological sectors

↓

logical states of the topological qubit



first steps towards a topological qubit!

Two-fold degenerate ground state:

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

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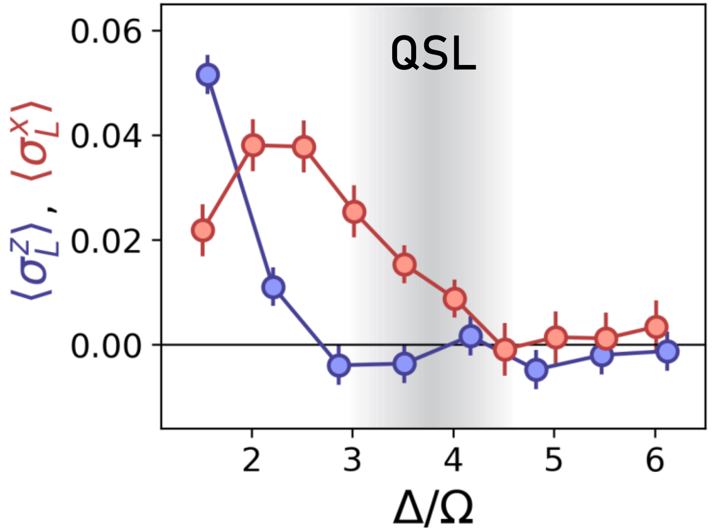
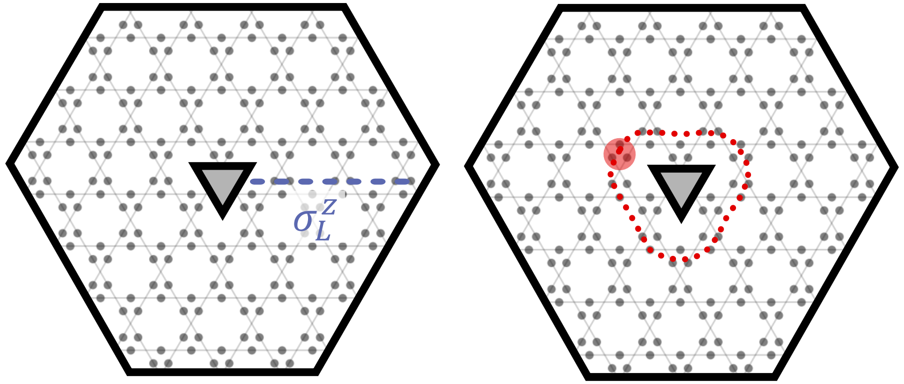


G. Semeghini et al., Science 374, 1242 (2021), related work from Google Quantum AI: K. J. Satzinger et al, Science 374 (2021)

Outlook



braiding!

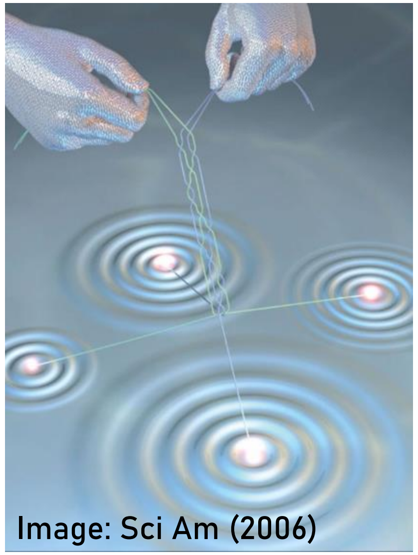
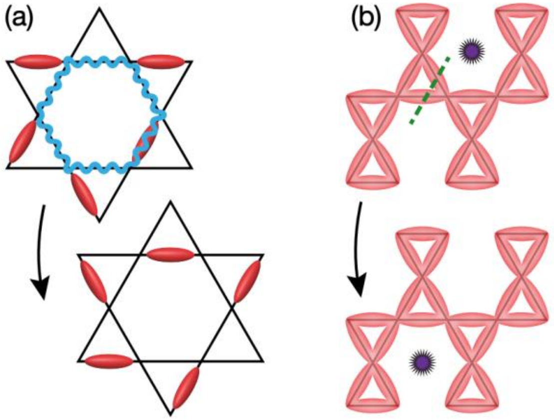


Image: Sci Am (2006)

- topological qubit encoding and manipulation

  requires arrays of local addressing laser beams
  (dynamically tunable on fast time scales)



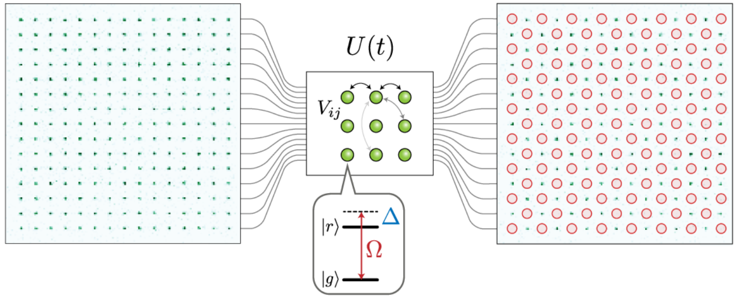
- error correction on the topological phase

  detect and annihilate anyons using ancilla atoms

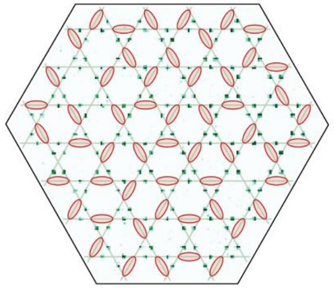
- platform for exploring fault-tolerant quantum information processing

Outline

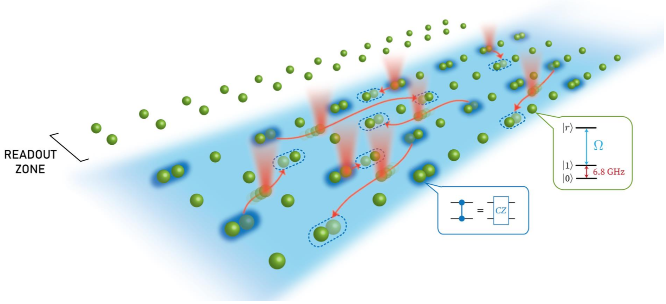
Programmable arrays of Rydberg atoms



Experimental evidence of a quantum spin liquid phase



Dynamically reconfigurable architecture for quantum information processing

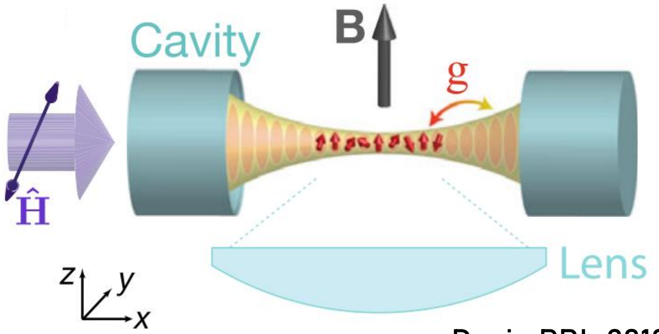


Dynamically reconfigurable architecture

Nonlocal connectivity and entanglement: approaches

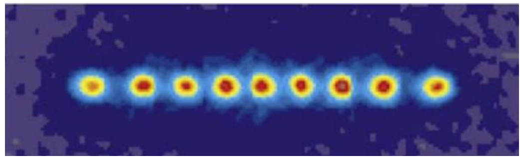
Quantum data bus

Cavity-mediated interactions



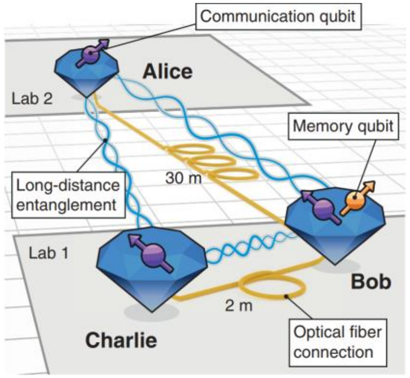
Davis PRL 2019

Shared motional modes

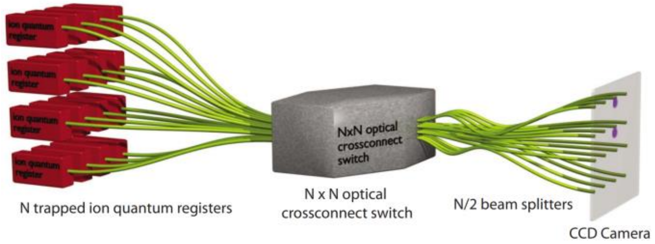


Innsbruck

Quantum networks



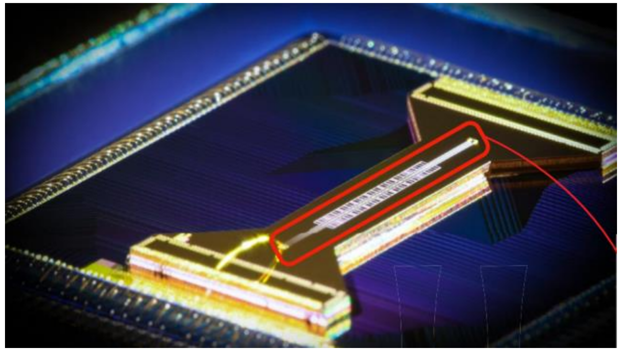
Pompili … Hanson (Science 2021)



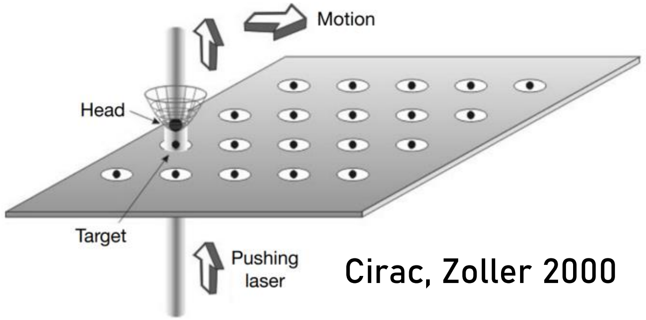
Monroe … Duan, Kim

See also SC qubit transduction to optical photons

Quantum ion "CCD"



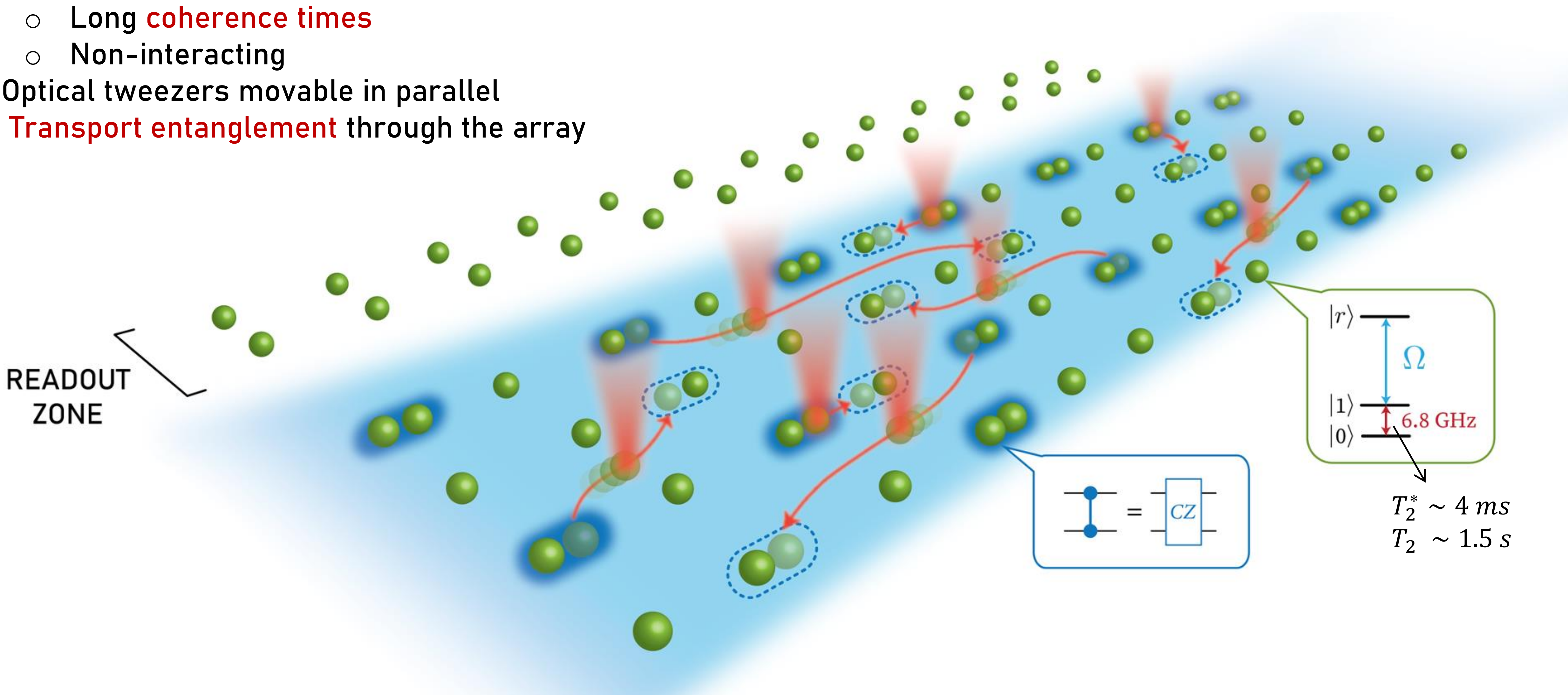
Honeywell 2021



Cirac, Zoller 2000

Dynamically reconfigurable architecture

- Use Rydberg for generating entanglement
- Store information in hyperfine qubit
    - Long coherence times
    - Non-interacting
- Optical tweezers movable in parallel
- Transport entanglement through the array



$T_2^* \sim 4\,ms$
$T_2 \sim 1.5\,s$

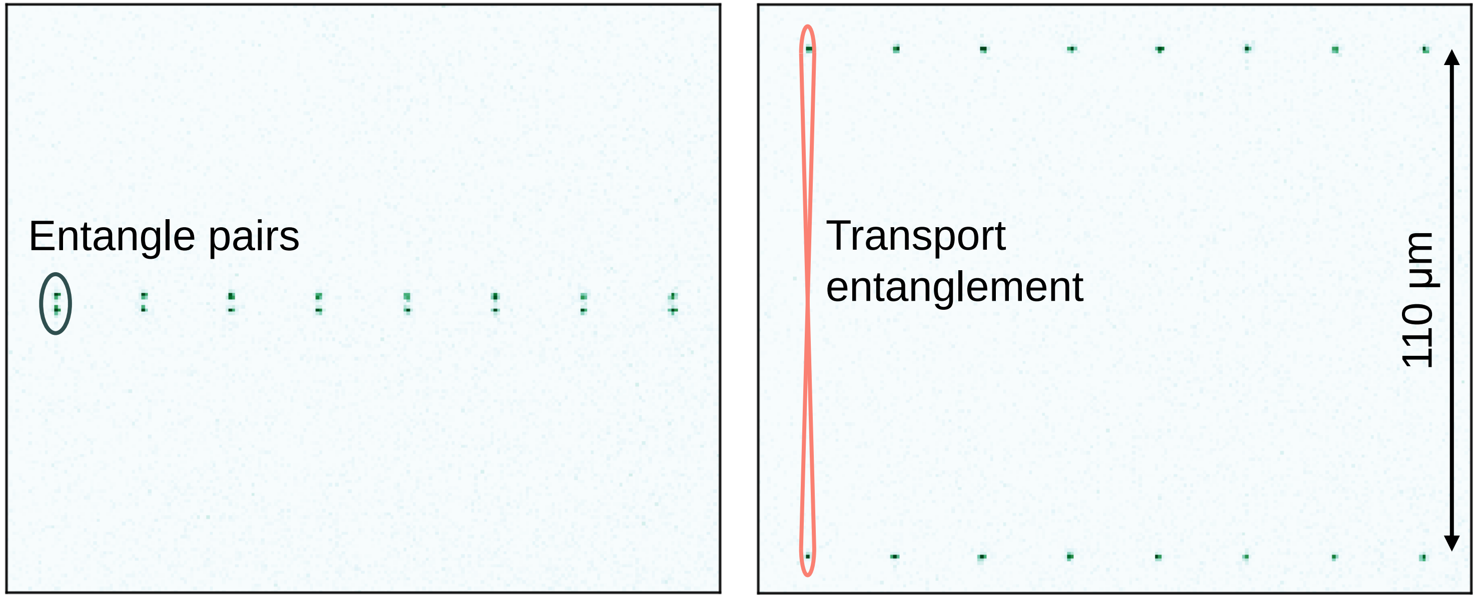
D. Bluvstein, et al, Nature 604, 451-456 (2022)

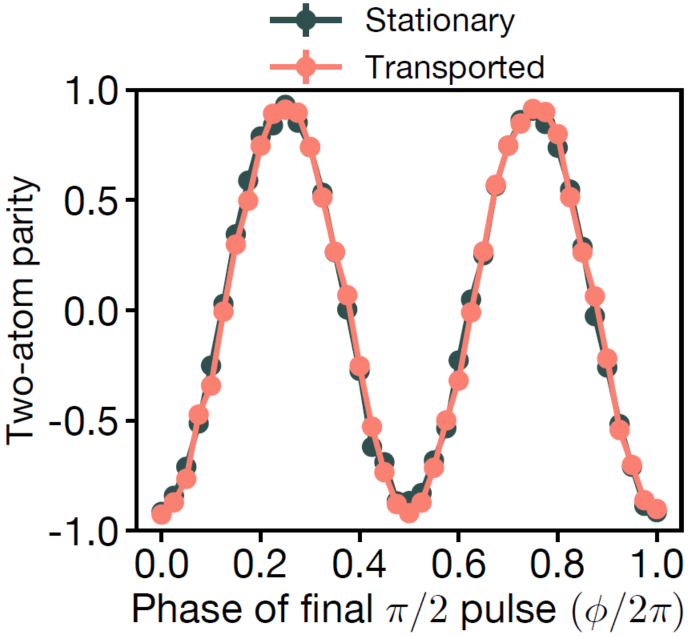
CZ gate: H. Levine et al, PRL 2019

D. Bluvstein, et al, Nature 604, 451-456 (2022)
CZ gate: H. Levine et al, PRL 2019

Dynamically reconfigurable architecture

Transporting entanglement across the array





Many potential applications:
complex quantum computing architectures
& new probes for many-body phases

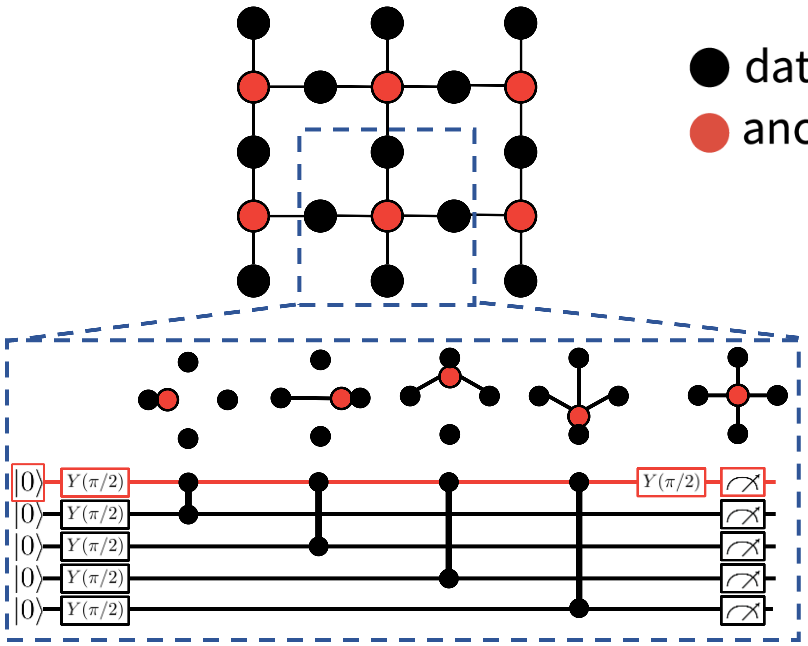
←

Coherence is preserved when transporting the atoms over a hundred μm in a few hundred μs (~10^{-4} T_2)

Related work: T. Đorđević et al Science (2021)

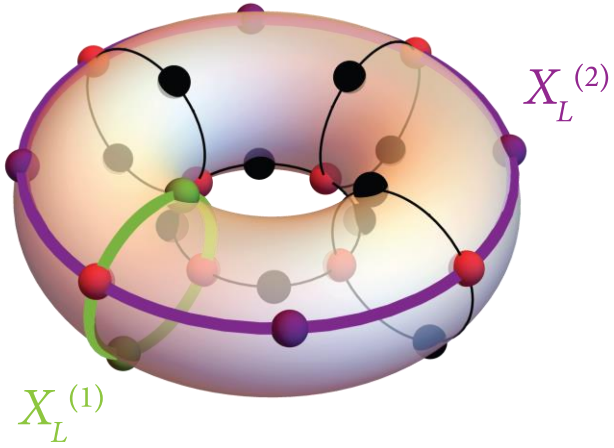
Dynamically reconfigurable architecture

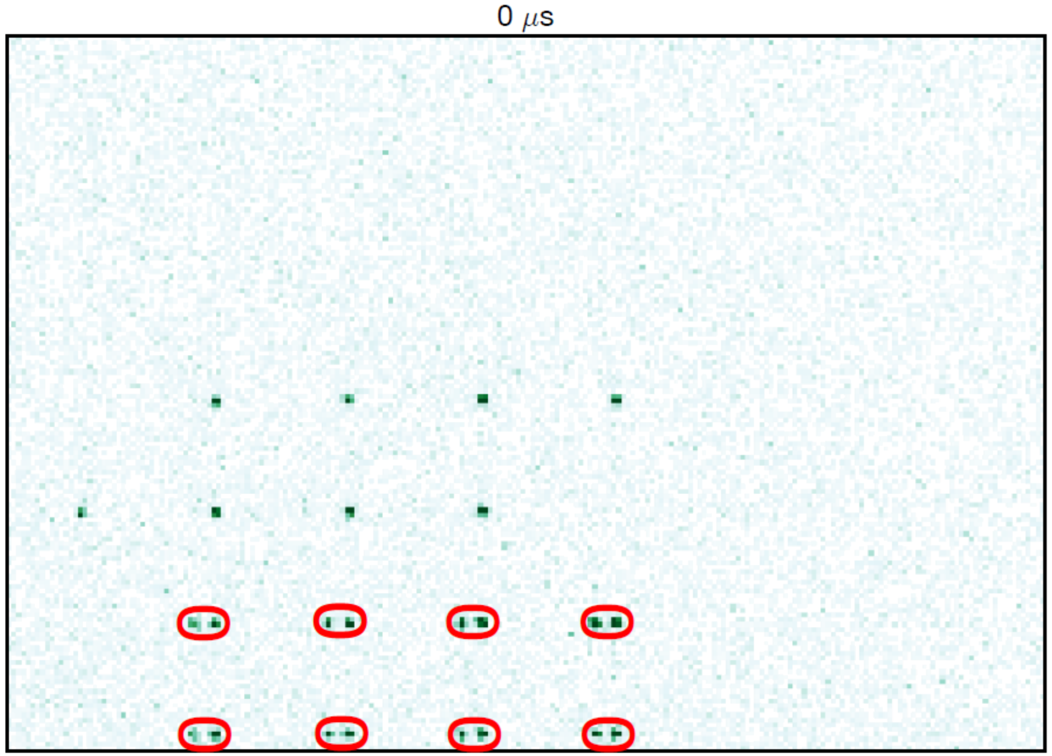
Toric code on a 3D torus



● data qubit

🔴 ancilla

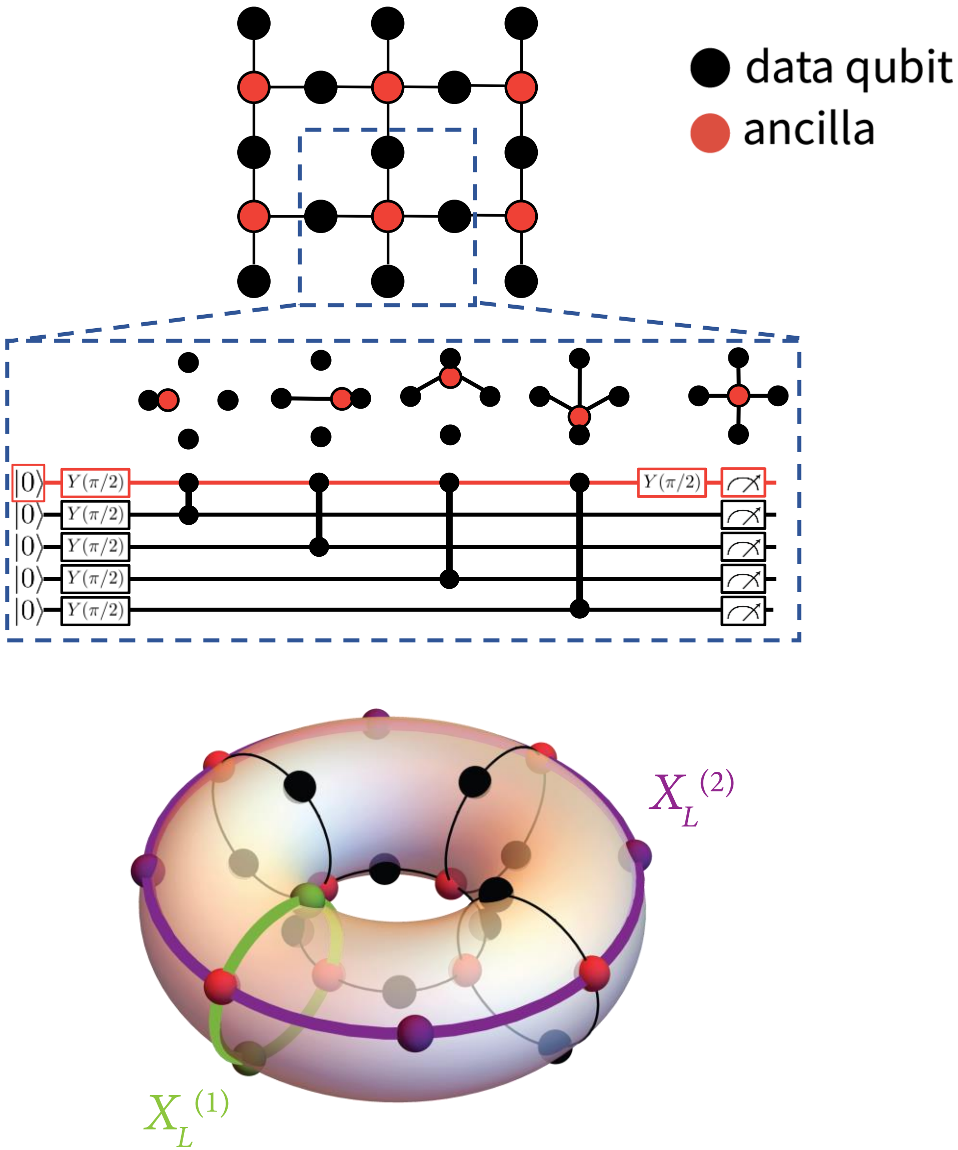


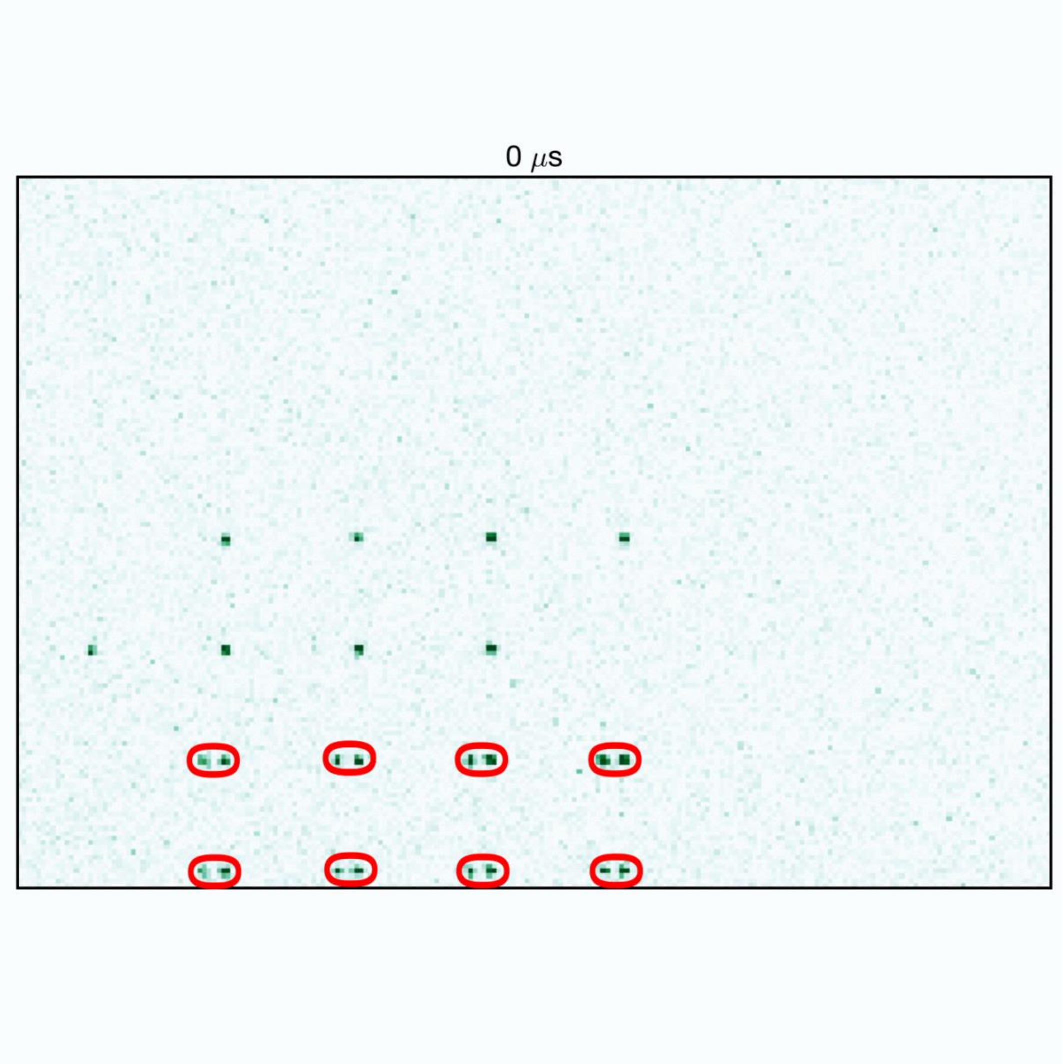


D. Bluvstein, et al, Nature 604, 451-456 (2022)

Dynamically reconfigurable architecture

Toric code on a 3D torus

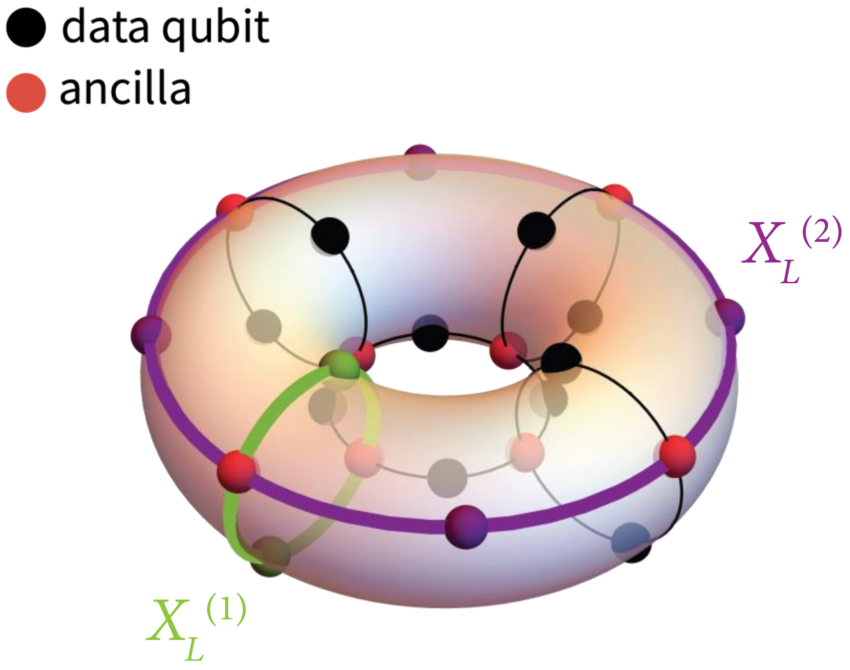




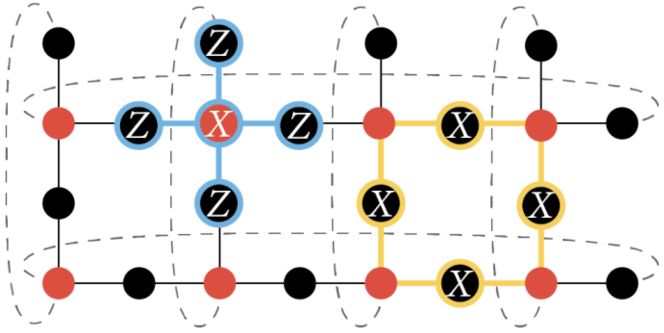
D. Bluvstein, et al, Nature 604, 451-456 (2022)

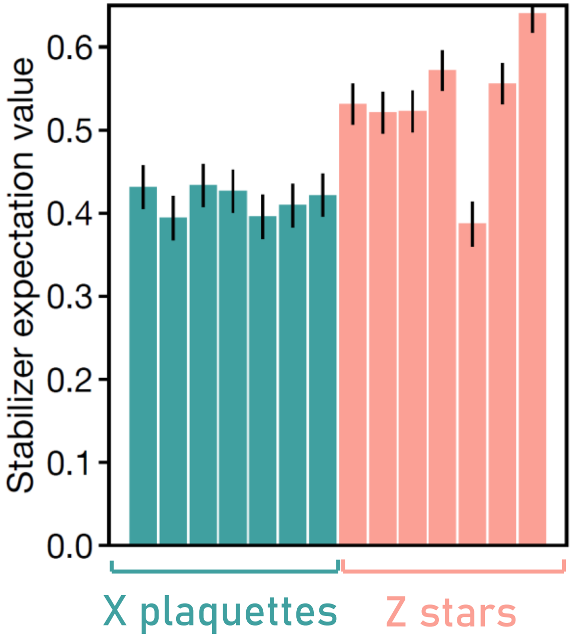
Dynamically reconfigurable architecture

Toric code on a 3D torus

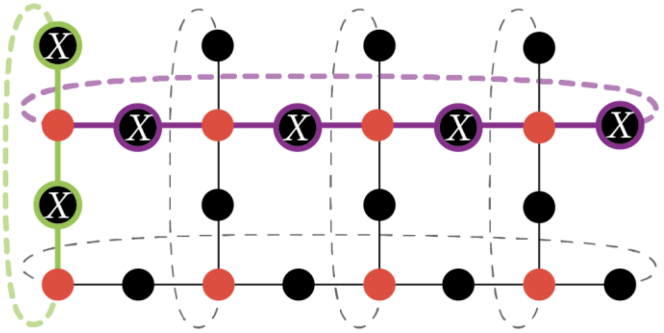


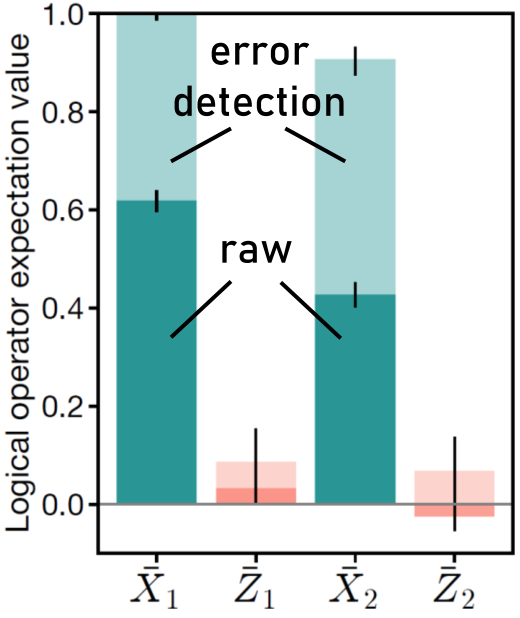
Stabilizers





Two logical qubits!





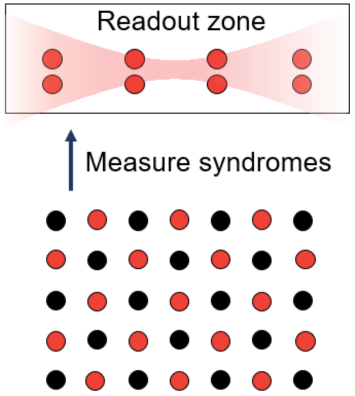
realization of QEC via highly parallel atom control

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

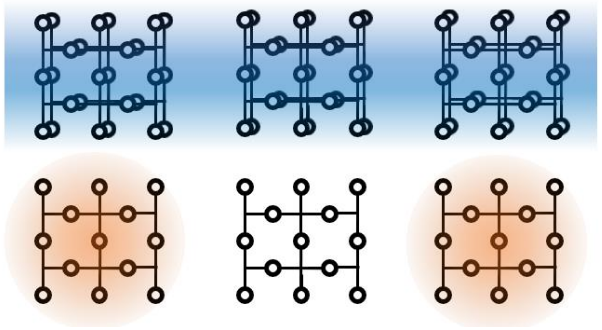
Outlook

- Logical state preservation

  Repetitive, mid-circuit measurement and correction (repetition code, surface code)

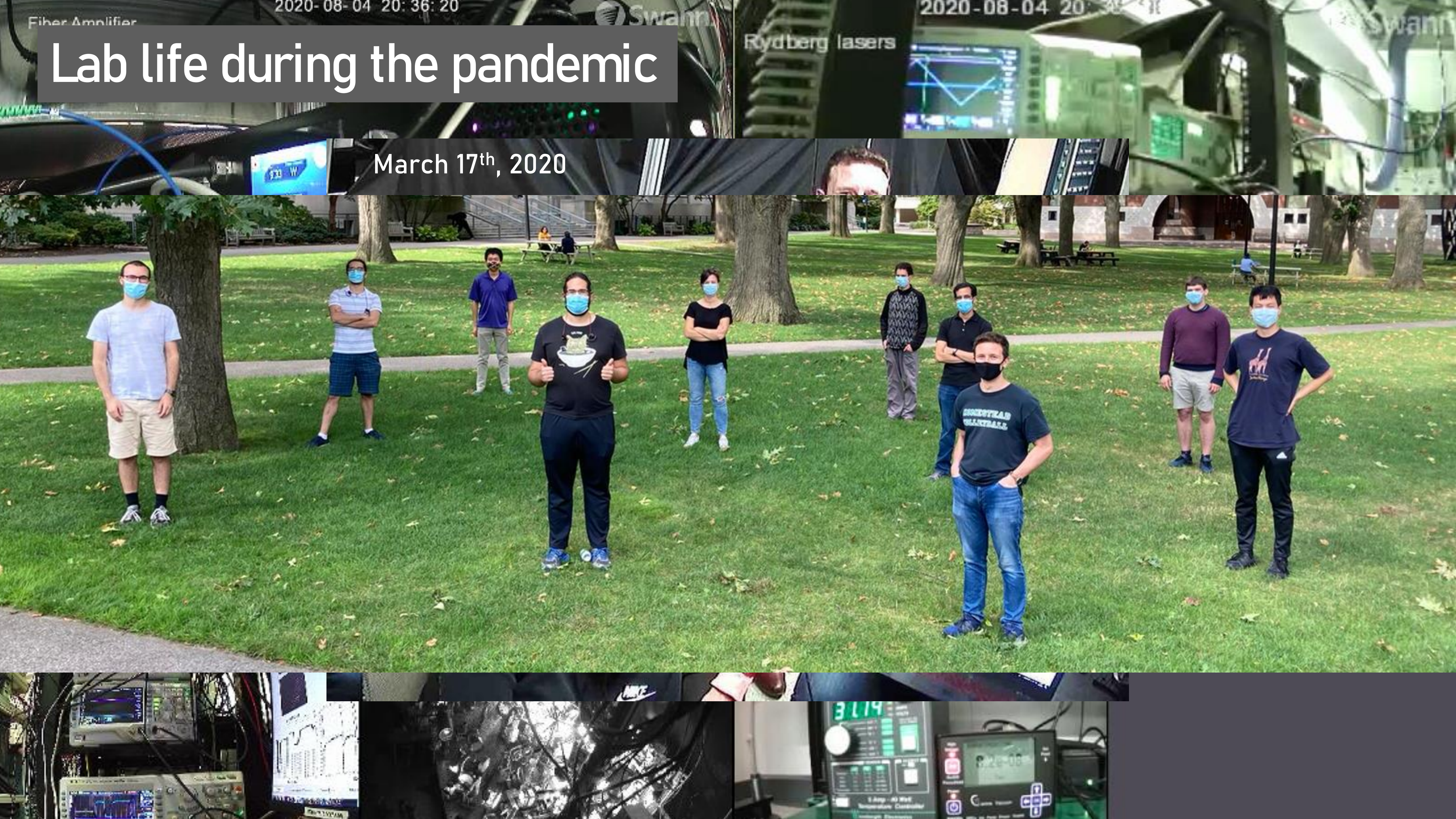


- Logical qubit gates

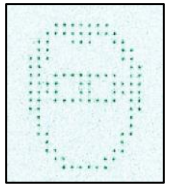


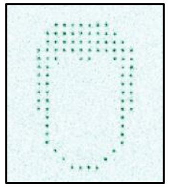
- Fault-tolerant logical algorithms (~10s logical qubit) empowered by highly-parallel optical control

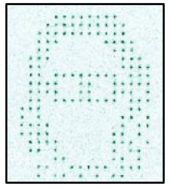
Lab life during the pandemic



March 17^{th}, 2020


Harry Levine


Tout Wang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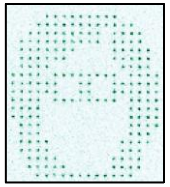
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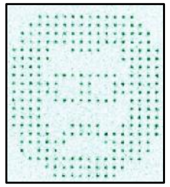
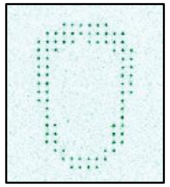
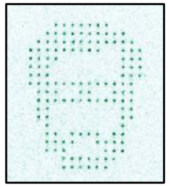

Alex Keesling


Dolev Bluvstein


Ahmed Omran

PIs: M. Lukin

V. Vuletic

M. Greiner

THEORY COLLABORATORS

R. Verresen

R. Samajdar

N. Maskara

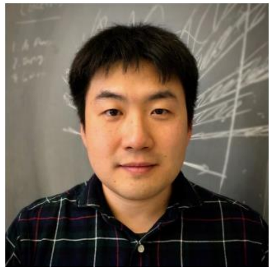
M. Kalinowski

A. Vishwanath

S. Sachdev

H. Pichler

S. Choi



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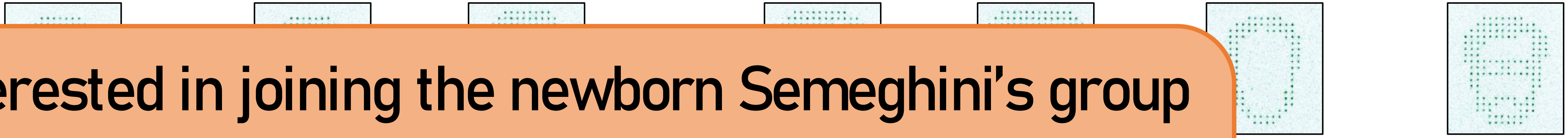
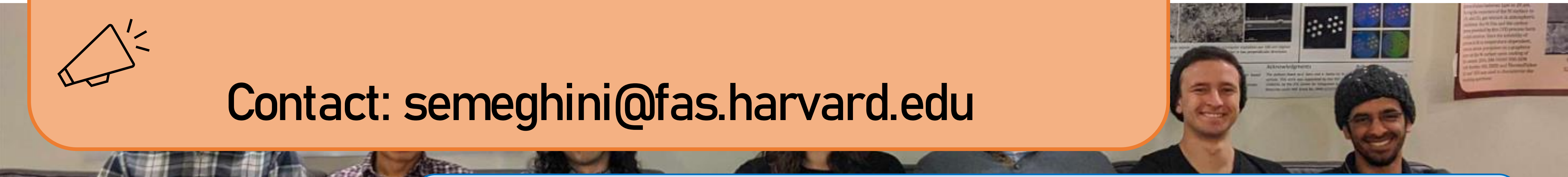


Bluvstein

Ahmed Omran

Interested in joining the newborn Semeghini's group at Harvard as a PhD student or PostDoc?

Contact: semeghini@fas.harvard.edu

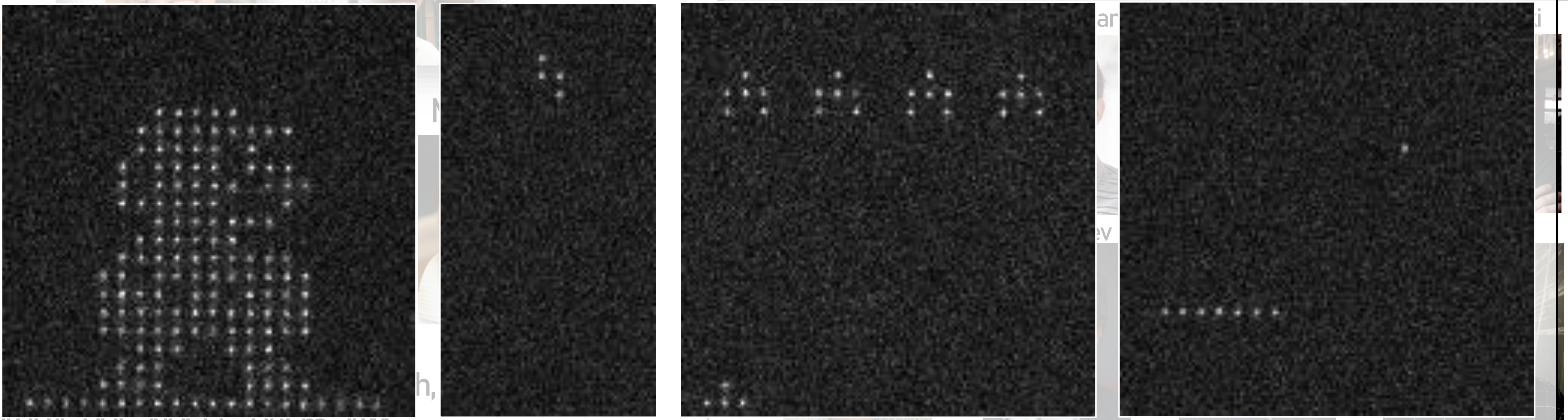


Tom Manovitz

Simon Evered

Ha

Thank you!



ar

ev

PIs:

N

h,

Funding

MURI, DARPA, DOE, NDSEG, QuEra, AWS