Title: New frontiers in quantum simulation and computation with neutral atom arrays

Speakers: Giulia Semeghini

Series: Quantum Matter

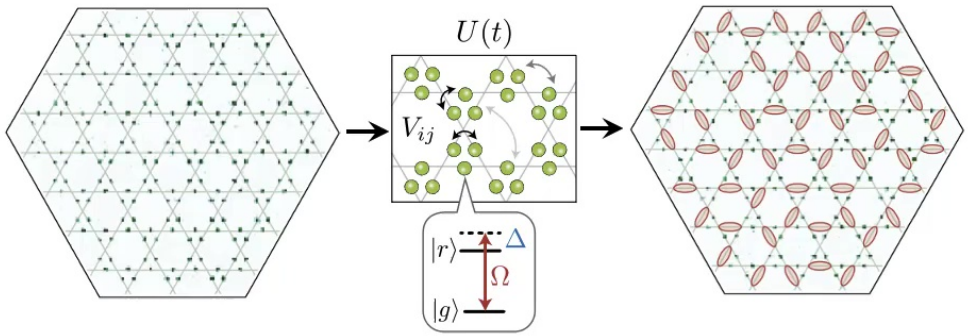
Date: March 07, 2022 - 12:00 PM

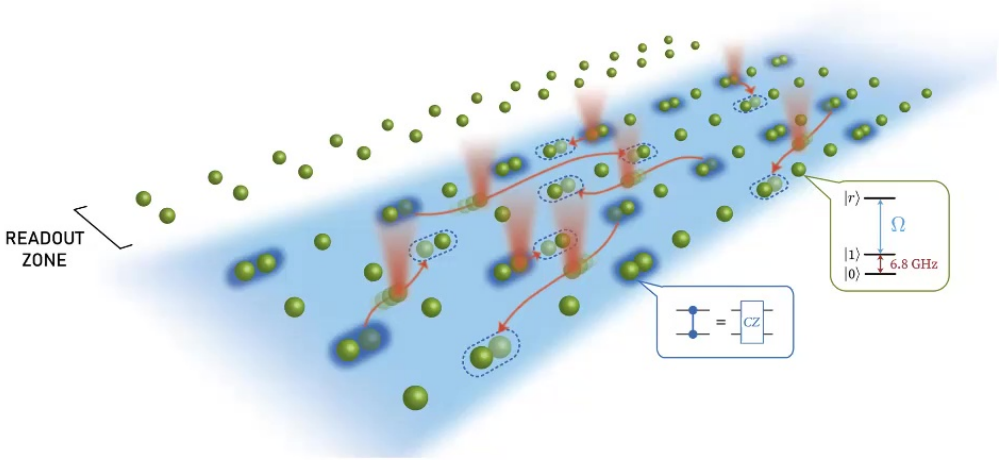
URL: https://pirsa.org/22030101

Abstract: Learning how to create, study, and manipulate highly entangled states of matter is key to understanding exotic phenomena in condensed matter and high energy physics, as well as to the development of useful quantum computers. In this talk, I will discuss recent experiments where we demonstrated the realization of a quantum spin liquid phase using Rydberg atoms on frustrated lattices and a new architecture based on the coherent transport of entangled atoms through a 2D array. Combining these results with novel technical tools on atom array platforms could open a broad range of possibilities for the exploration of entangled matter, with powerful applications in quantum simulation and information.

Zoom link: https://pitp.zoom.us/meeting/register/tJcqc-ihqzMvHdW-YBm7mYd_XP9Amhypv5vO

New frontiers in quantum simulation and computation with neutral atom arrays



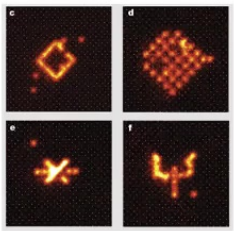


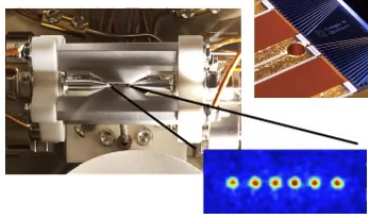
Giulia Semeghini
Harvard University, Lukin Group

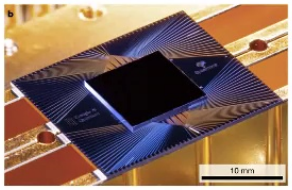
Quantum Matter Frontier Seminar Series - Mar 7, 2022

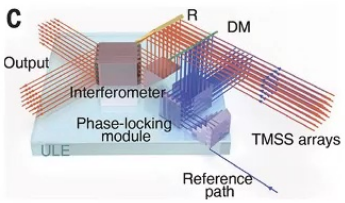
New frontiers in quantum science

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







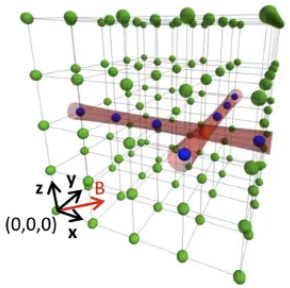


Images from: Blatt, Bloch, Google, Jian-Wei Pan groups

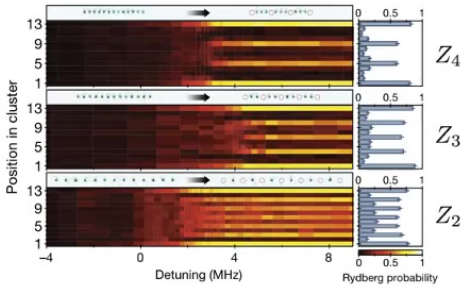
Impressive results over the past couple of decades:

quantum simulations of Fermi-Hubbard model, high-fidelity entangling gates, demonstrations of quantum advantage…

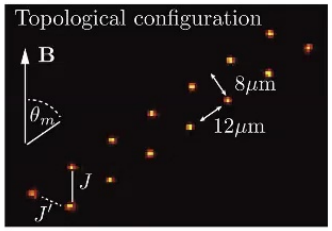
Programmable neutral atom arrays: new, rapidly developing approach, potentially favorable for scalability



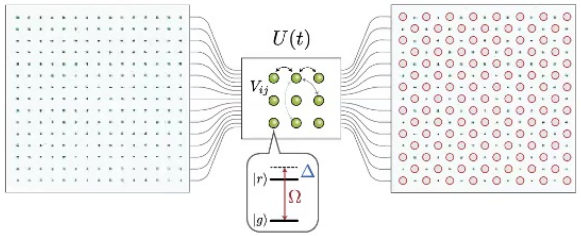
Y. Wang et al,
PRL 115, 043003 (2015)



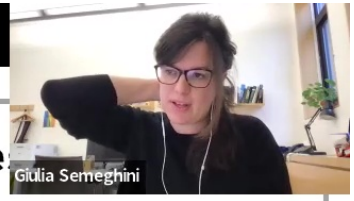
H. Bernien et al,
Nature 551, 579 (2017)



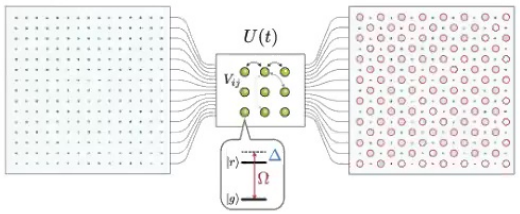
S. de Léséleuc et al,
Science 365, 775–780 (2019)



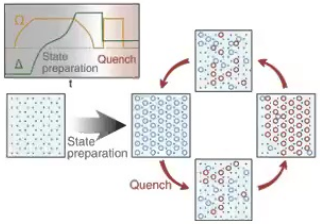
S. Ebadi et al, Nature 595, 227–232 (2021)



Quantum simulation of many-body phases and dynamics

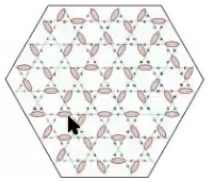


S. Ebadi et al, Nature (2021)



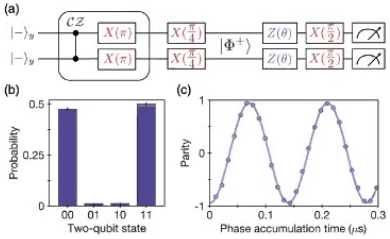
D. Bluvstein et al, Science (2021)

Topological spin liquids

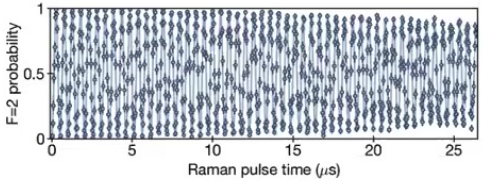


GS et al, Science 374, 1242 (2021)

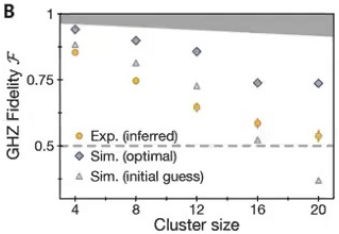
Quantum information proce



H. Levine et al, PRL (2019)

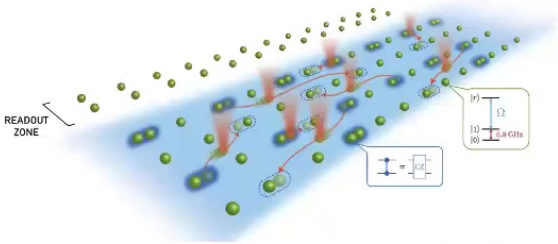


H. Levine et al, arXiv:2110.14645 (2021)



A. Omran et al, Science (2019)

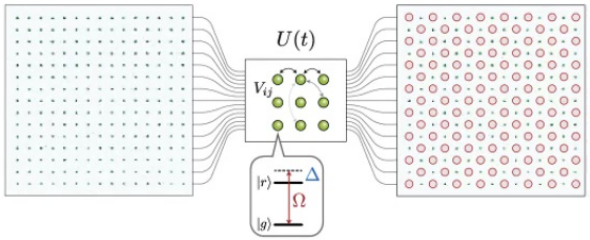
Dynamically reconfigurable architecture



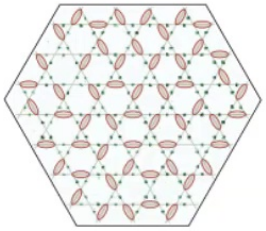
D. Bluvstein et al, arXiv:2112.03923 (2021)

Outline

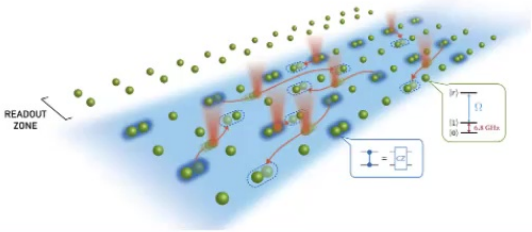
Programmable arrays of Rydberg atoms



Experimental evidence of a quantum spin liquid phase

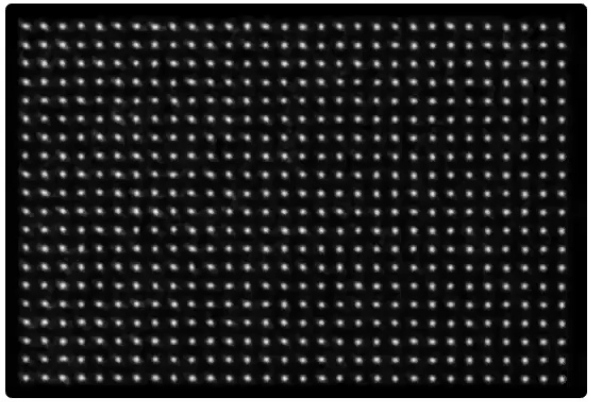


Dynamically reconfigurable architecture

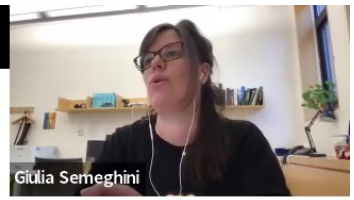


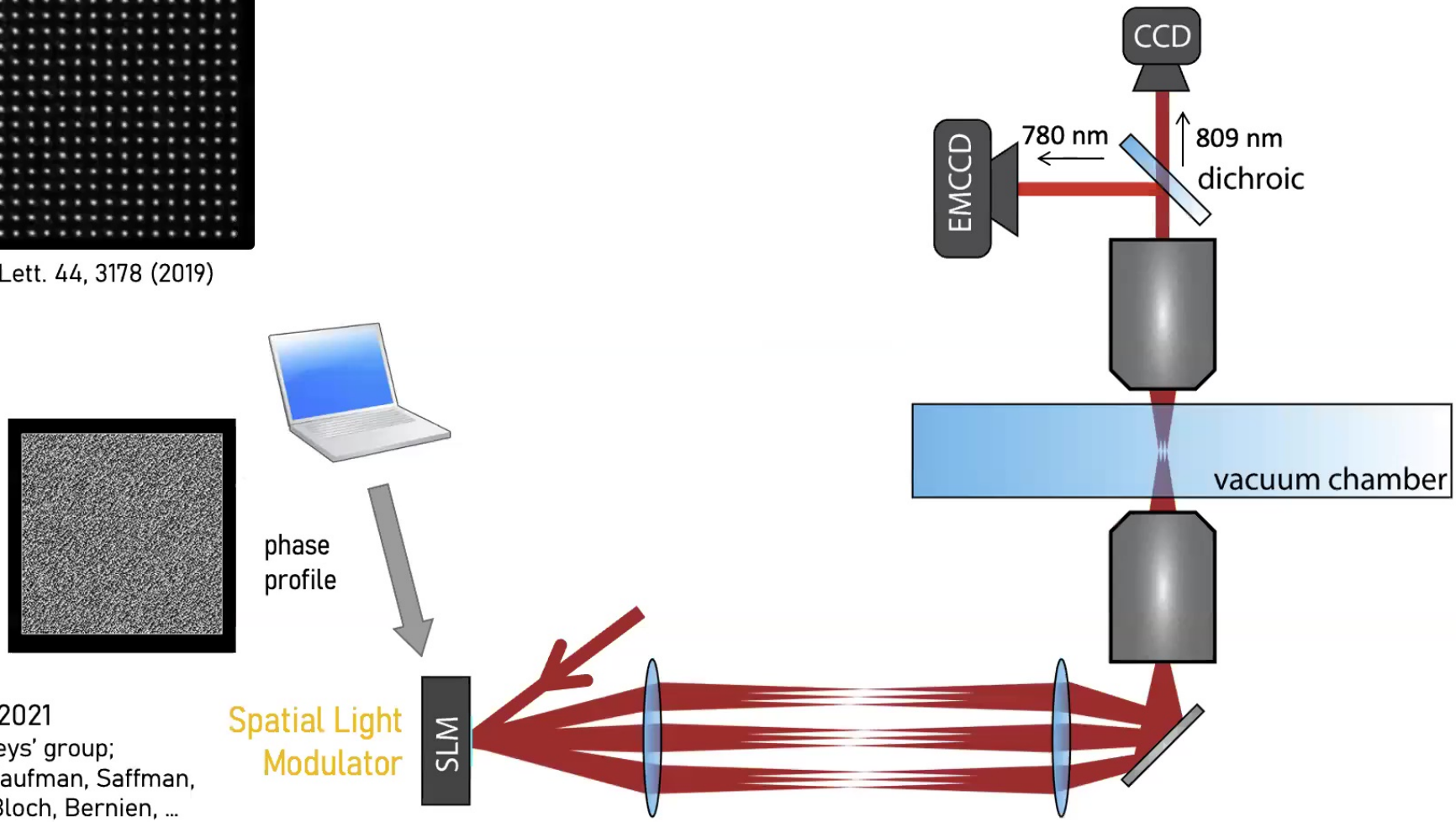
Outlooks

2D array of optical tweezers



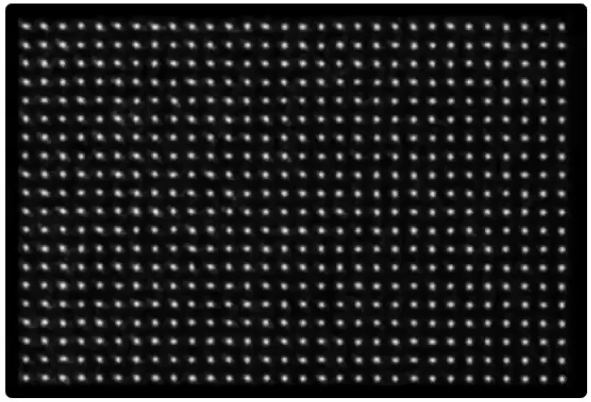
D. Kim, et al, Opt. Lett. 44, 3178 (2019)





Ebadi et al Nature 2021
Related work: Browaeys' group;
Ahn, Regal, Endres, Kaufman, Saffman,
Thompson, Ni, Bakr, Bloch, Bernien, ...

2D array of optical tweezers



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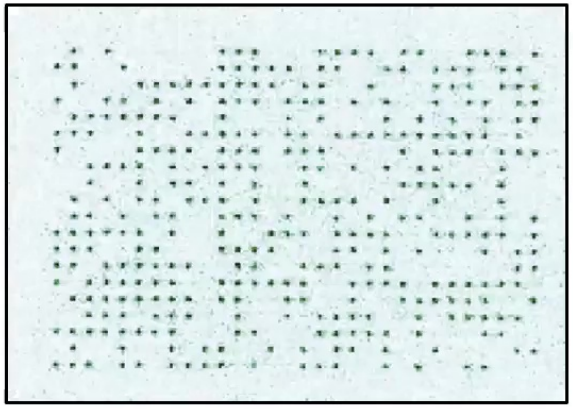
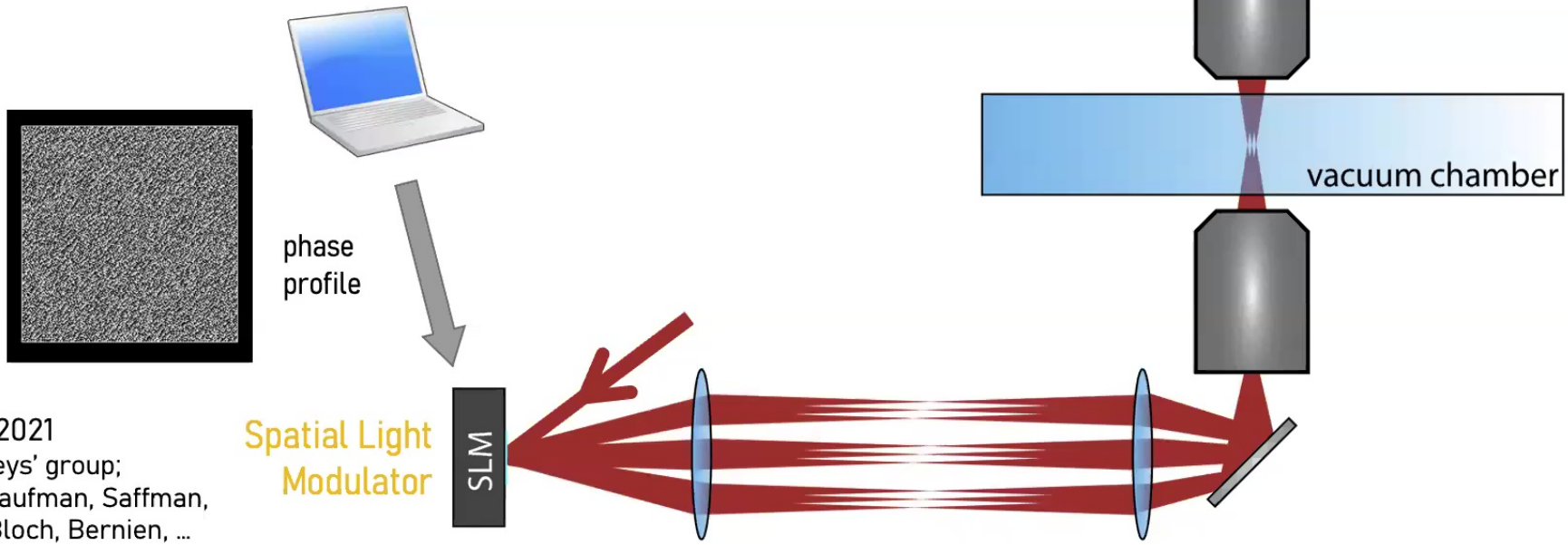
Atoms:





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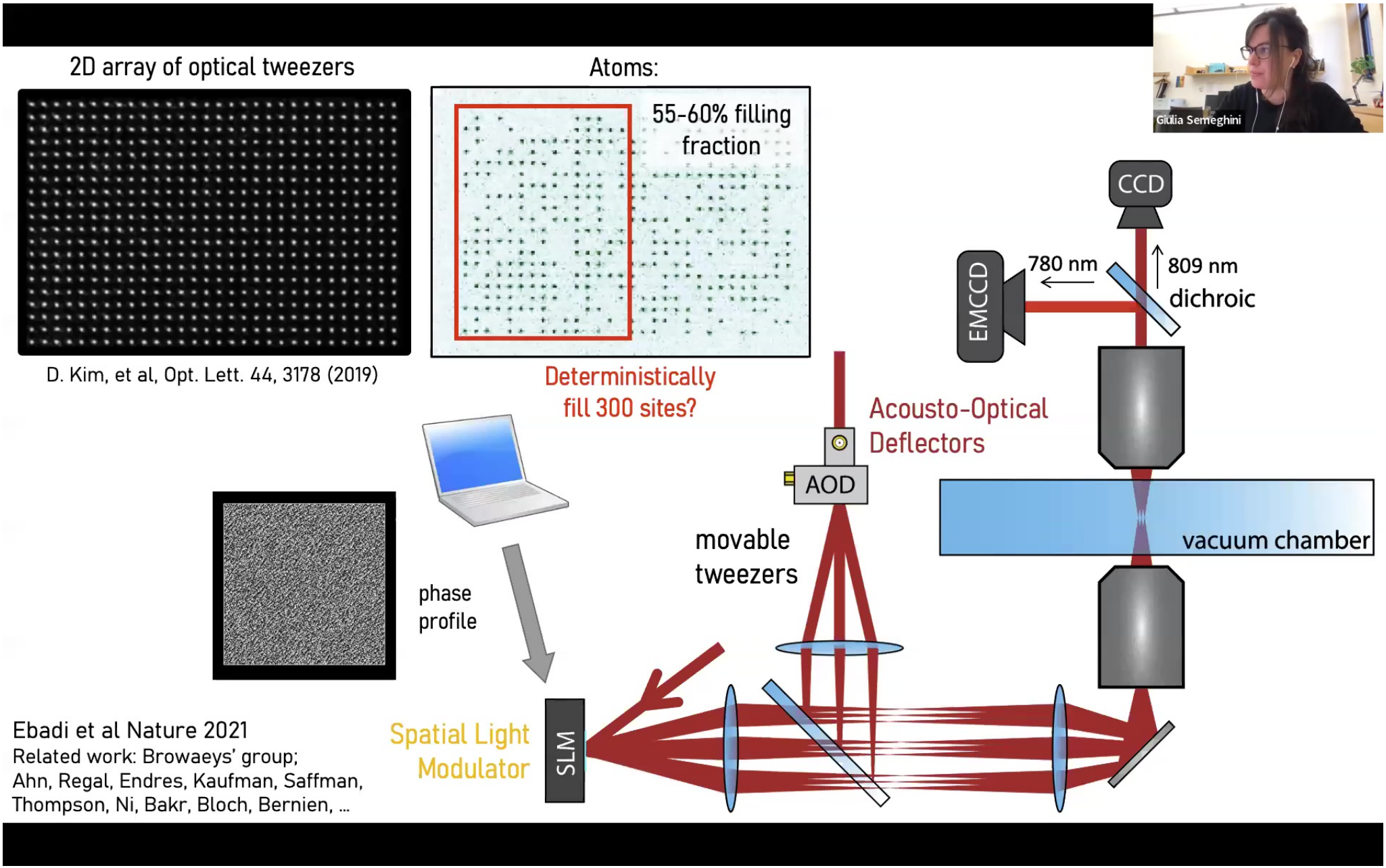
2D array of optical tweezers
D. Kim, et al, Opt. Lett. 44, 3178 (2019)
Atoms:
55-60% filling fraction
Deterministically fill 300 sites?
Giulia Semeghini
CCD
780 nm
809 nm
dichroic
EMCCD
Acousto-Optical Deflectors
AOD
movable tweezers
vacuum chamber
phase profile
Spatial Light Modulator
SLM
Ebadi et al Nature 2021
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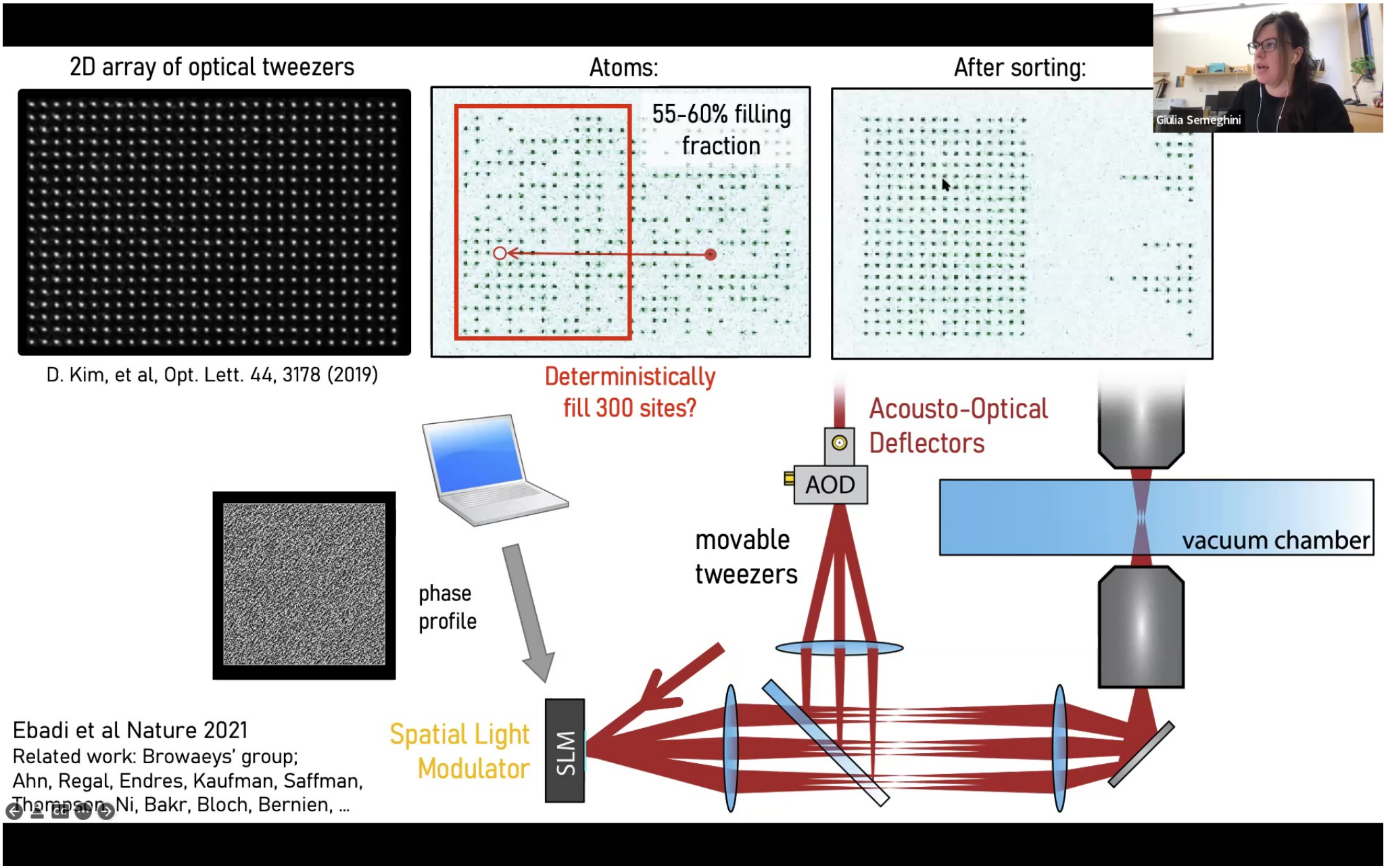
2D array of optical tweezers
Atoms:
After sorting:
55-60% filling fraction
Giulia Semeghini
D. Kim, et al, Opt. Lett. 44, 3178 (2019)
Deterministically fill 300 sites?
Acousto-Optical Deflectors
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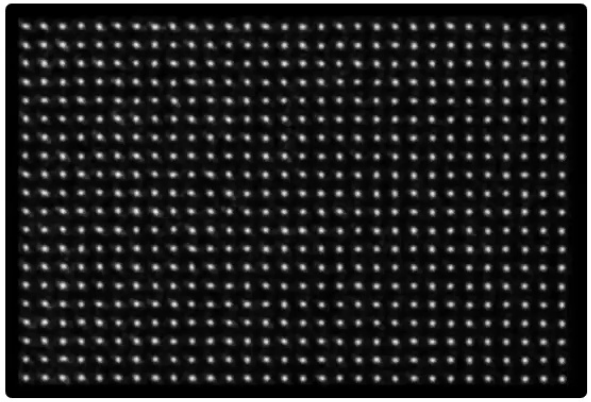
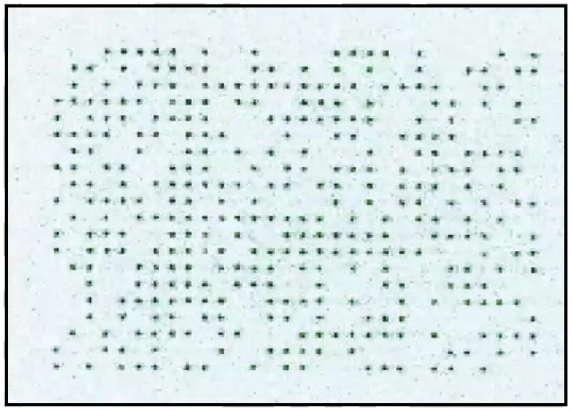
2D array of optical tweezers



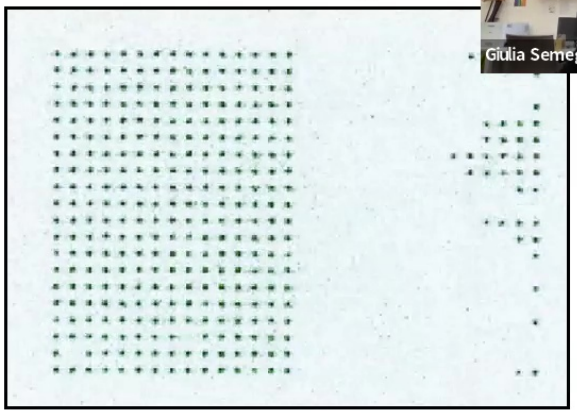
D. Kim, et al, Opt. Lett. 44, 3178 (2019)

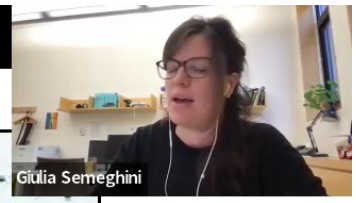
Atoms:

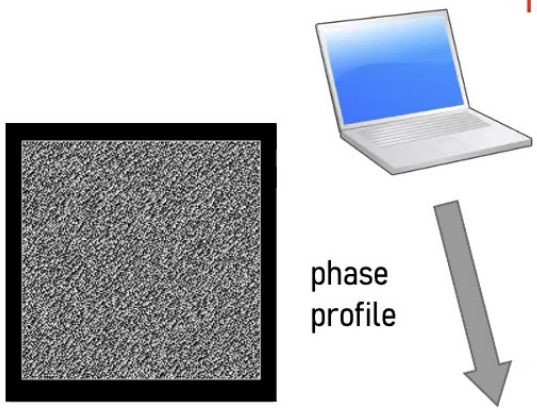


Deterministically fill 300 sites?

After sorting:







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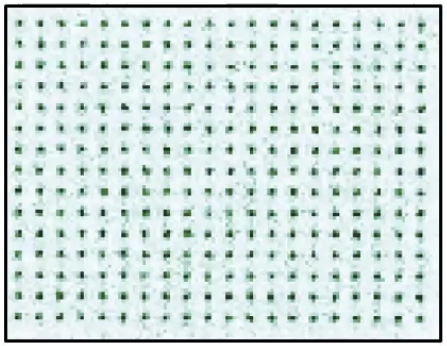
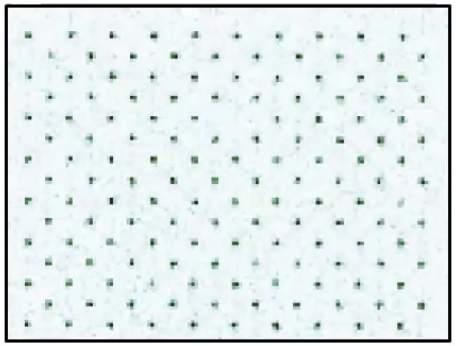
Programmable 2D arrays

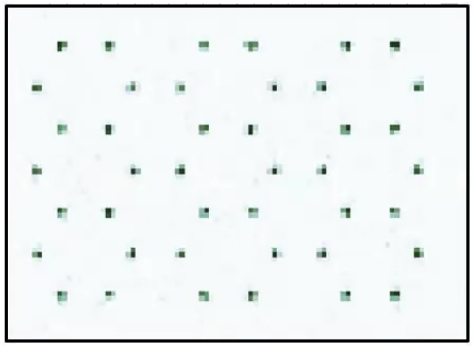
Square



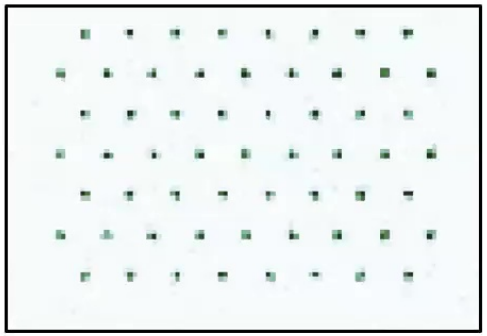
Tilted Square



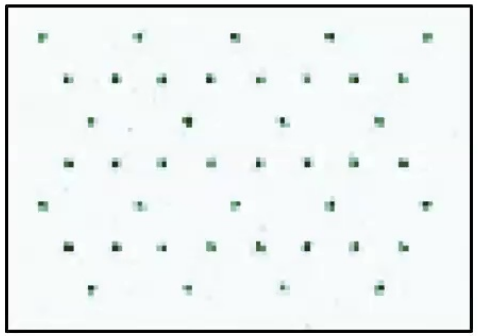
Honeycomb



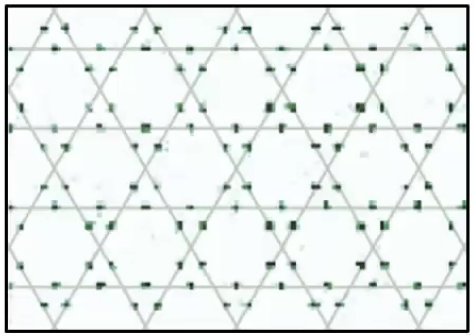
Triangular



Kagome

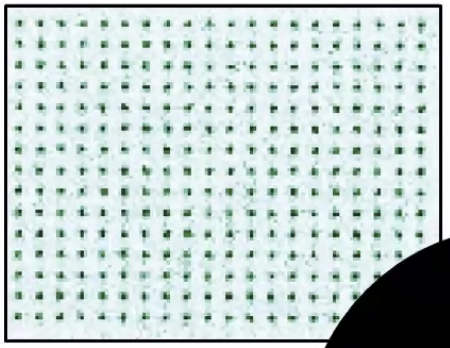


Link-kagome

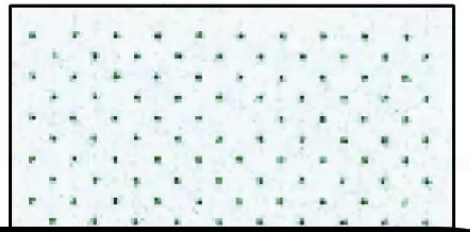


Programmable 2D arrays

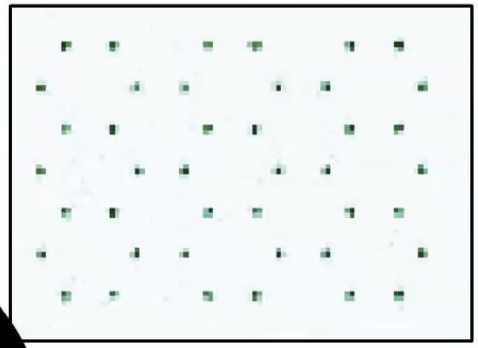
Square



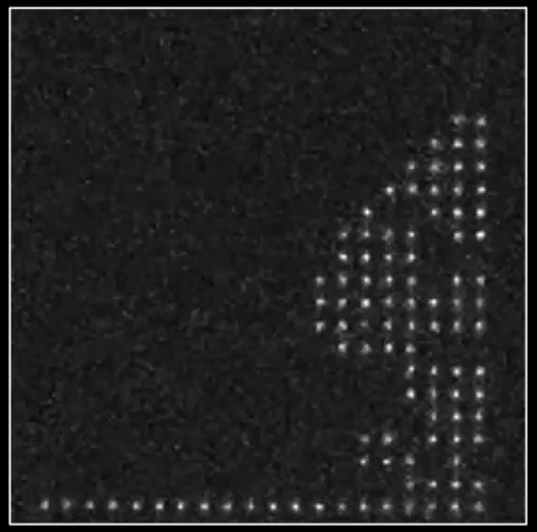
Tilted Square



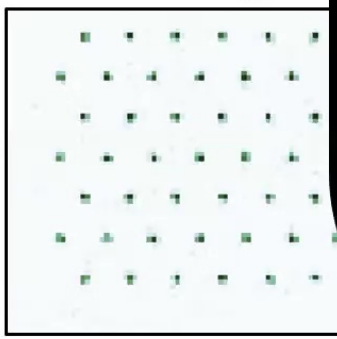
Honeycomb



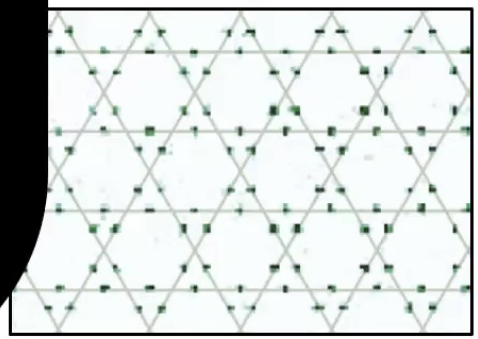
Atomic Mario



Triangular



Link-kagome



Programmable 2D arrays

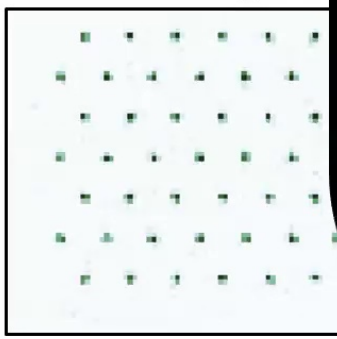
Square

Tilted Square

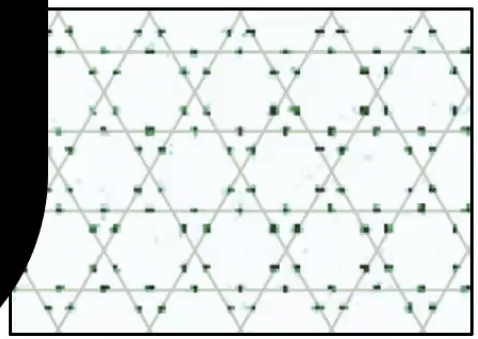
Honeycomb

1) Programmable 2D arrays of neutral atoms

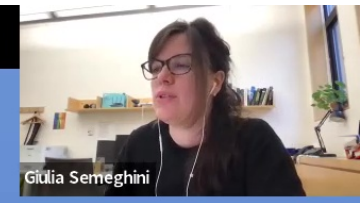
Triangular



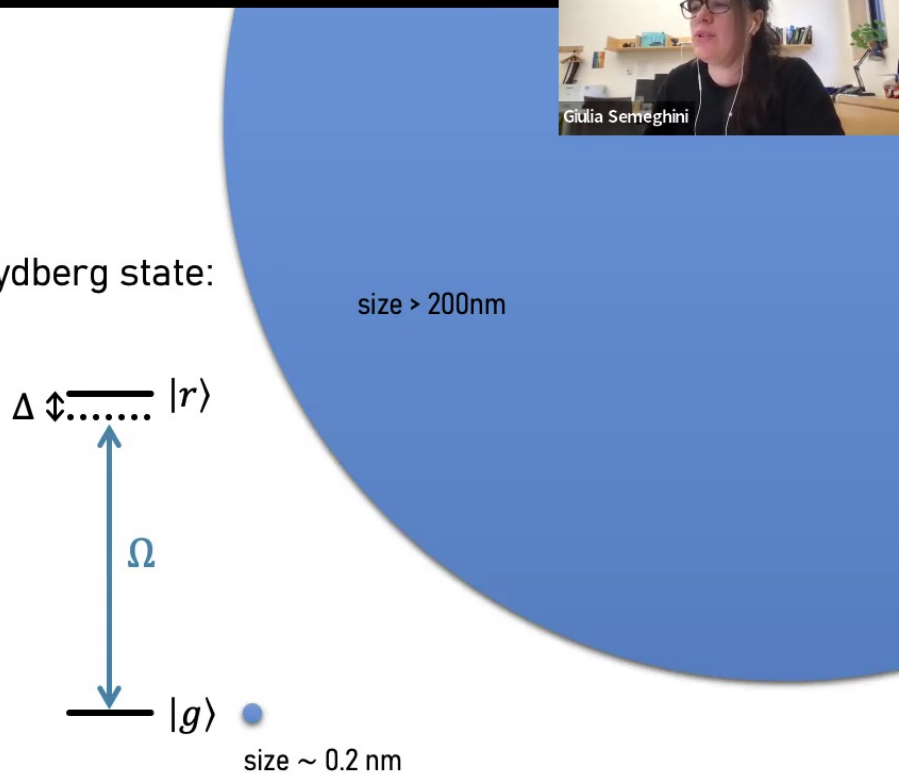
Link-kagome



Rydberg states and long-range interactions

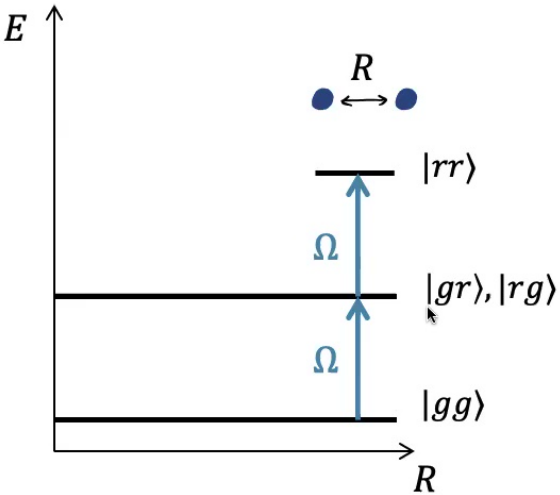


excitation to Rydberg state:



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

Rydberg states and long-range interactions



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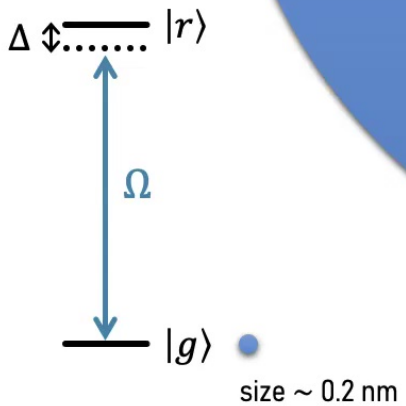

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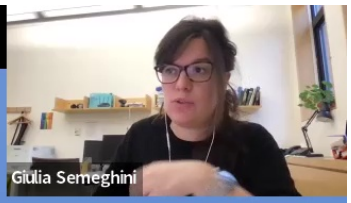
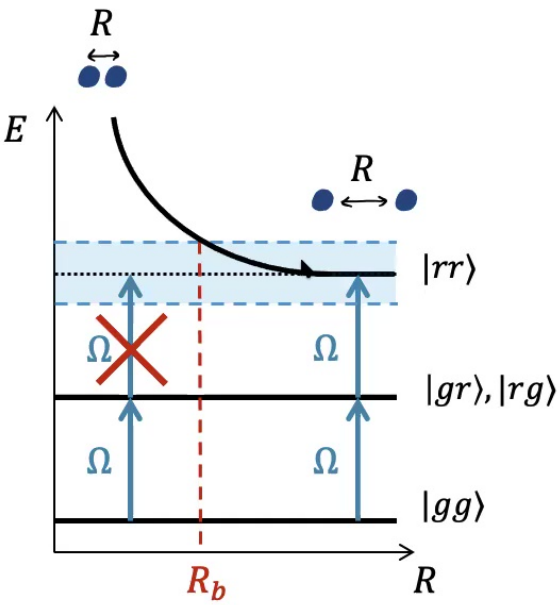
Rydberg states and long-range interactions





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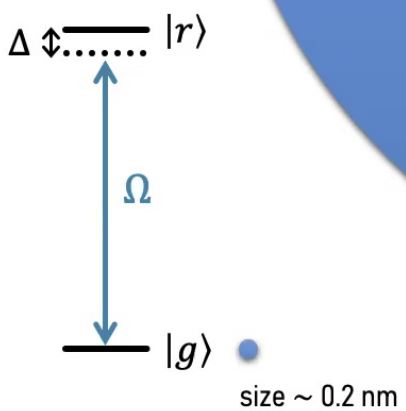

size > 200nm

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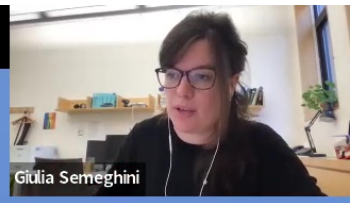
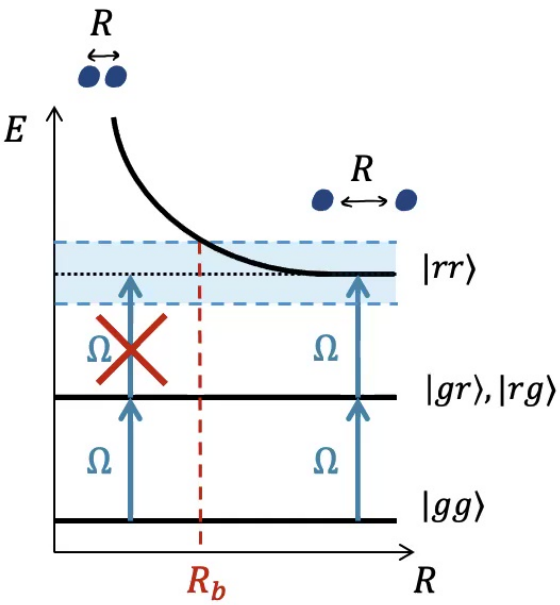


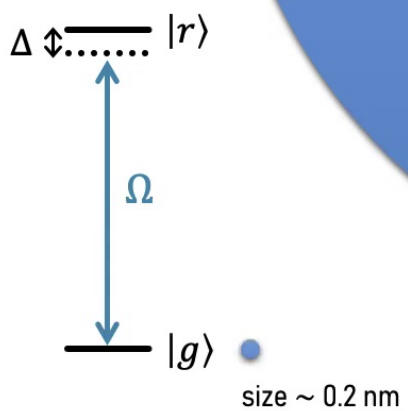
Rydberg blockade



blockade radius R_b :
$V(R_b) = \Omega$

excitation to Rydberg state:

size > 200nm



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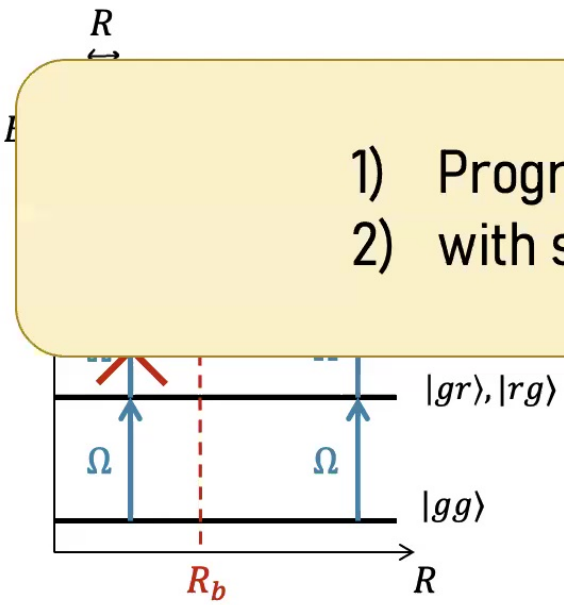
Rydberg states and long-range interactions

Rydberg blockade



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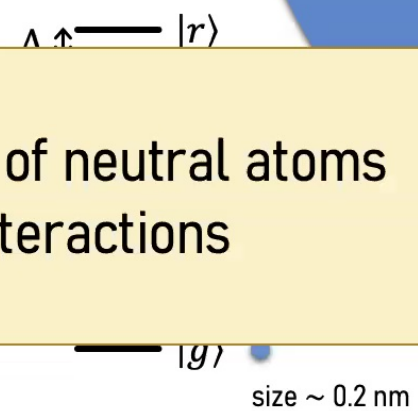


van der Waals interactions $\propto 1/R^6$

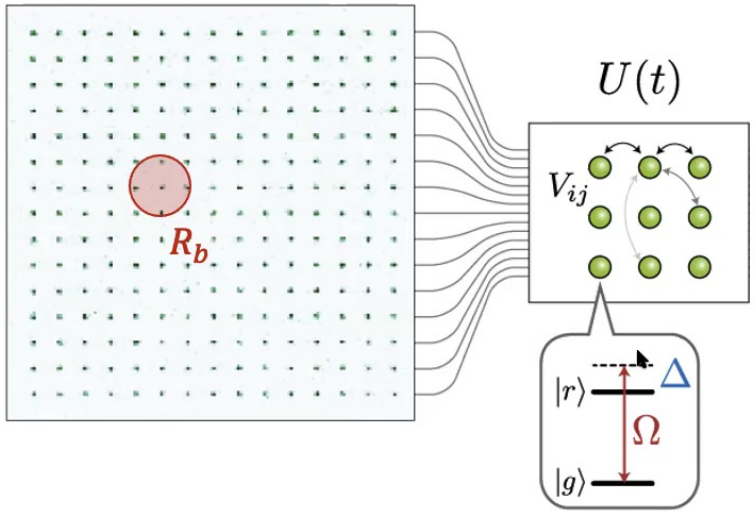
1) Programmable 2D arrays of neutral atoms
2) with strong long-range interactions

Rydberg blockade and quantum many-body phases

Many-Body ground state

$\Delta > 0$

Maximize number of disconnected Rydberg atoms



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

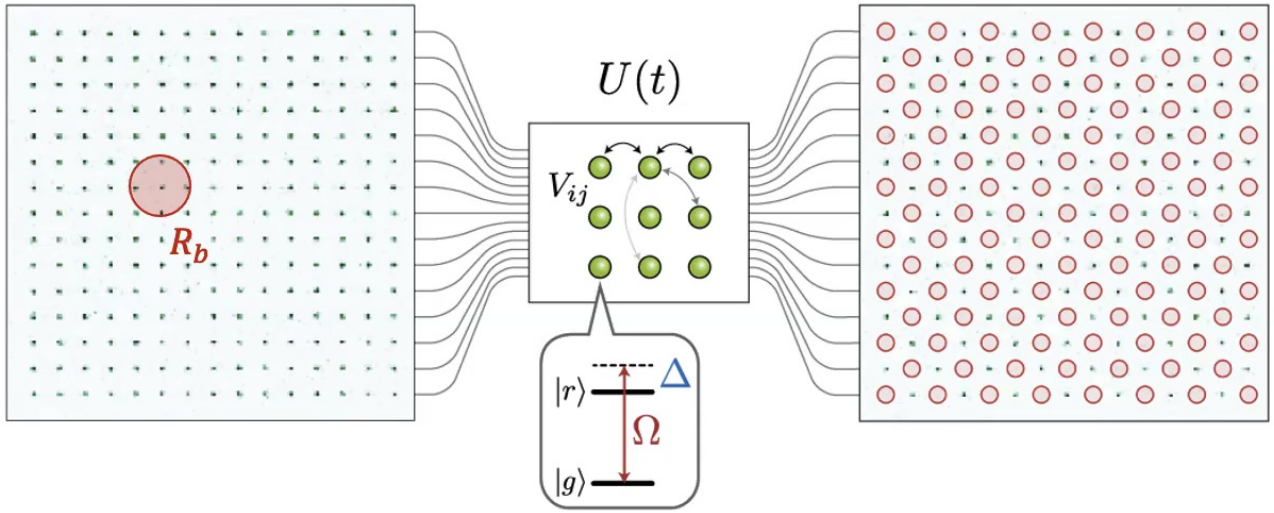
drive term detuning interaction

Rydberg blockade and quantum many-body phases

Many-Body ground state

$\Delta > 0$

Maximize number of disconnected Rydberg atoms



antiferromagnetic state

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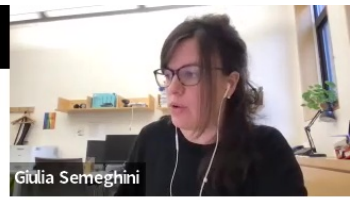

Many-Body ground state

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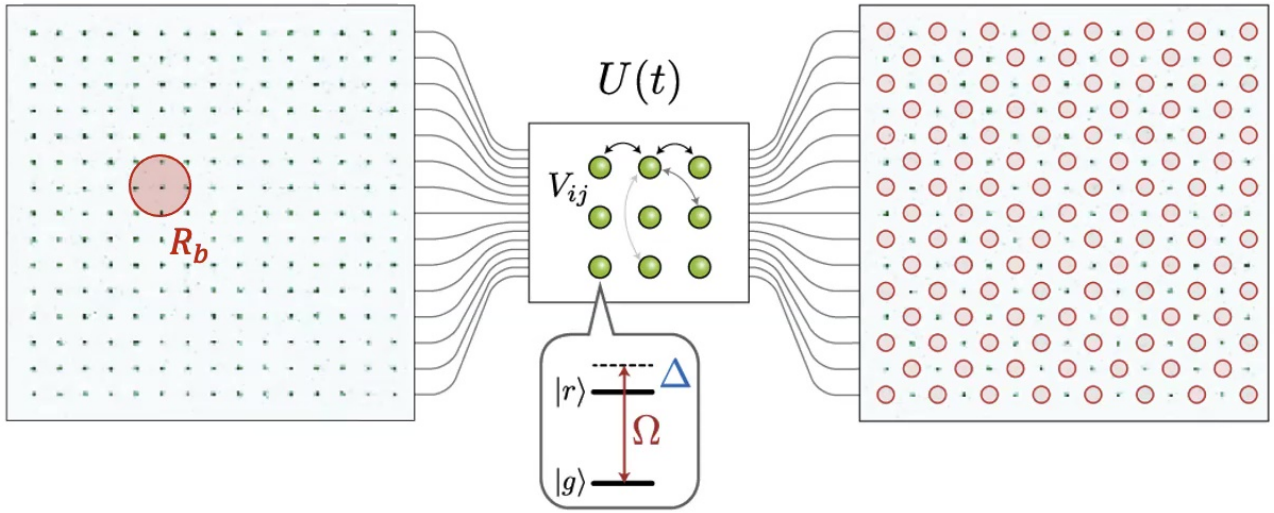

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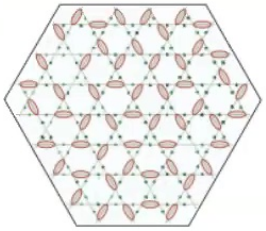
drive term detuning interaction

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

Outlooks

Quantum spin liquids

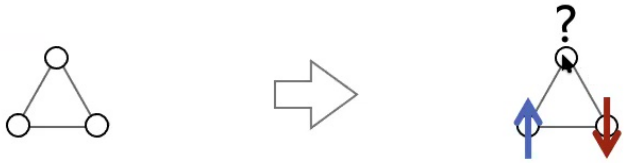
P. W. Anderson, *Science* 235 (1987)

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



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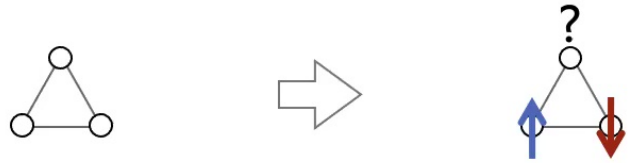
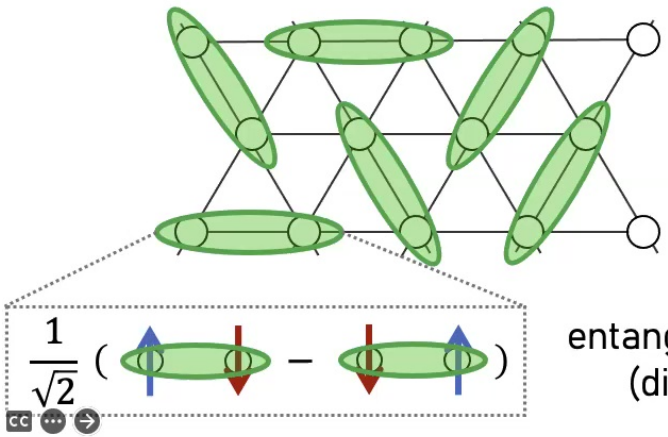
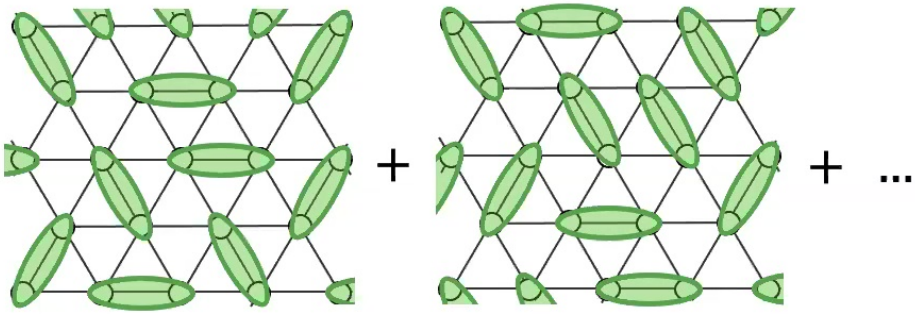




entangled pair (dimer)



resonating valence bond (RVB) state

Quantum spin liquids

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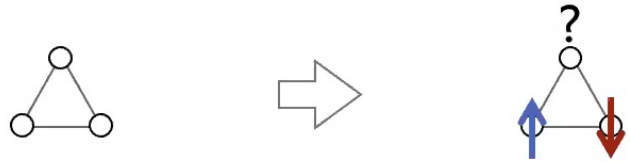
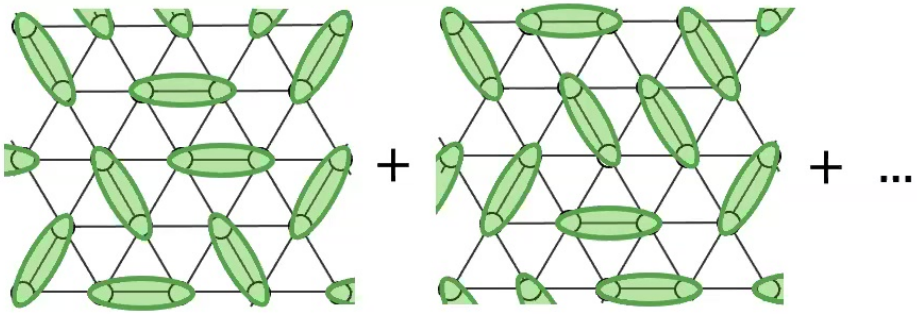


- no spatial order
- topological order
- long-range quantum entanglement
- anyonic non-local excitations with fractional quantum numbers
- emergent gauge fields
- robust ground state degeneracy
- link with high-T_c superconductivity
- application to fault-tolerant quantum computing → toric code



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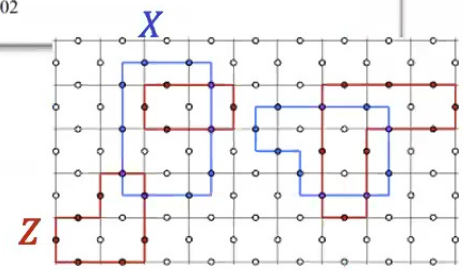
Fault-tolerant quantum computation by anyons

A.Yu. Kitaev*

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

Received 20 May 2002



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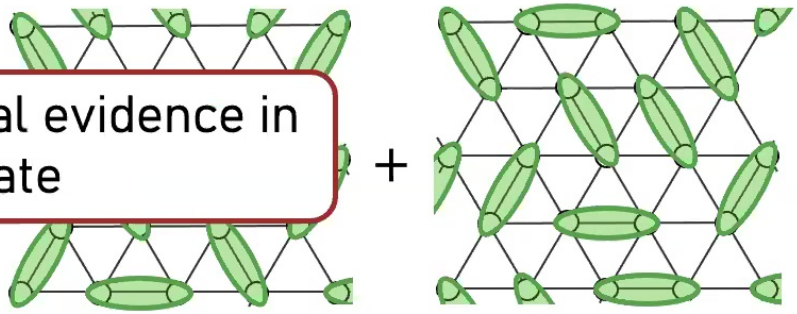
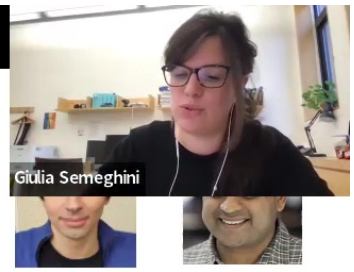
No conclusive experimental evidence in any system to date

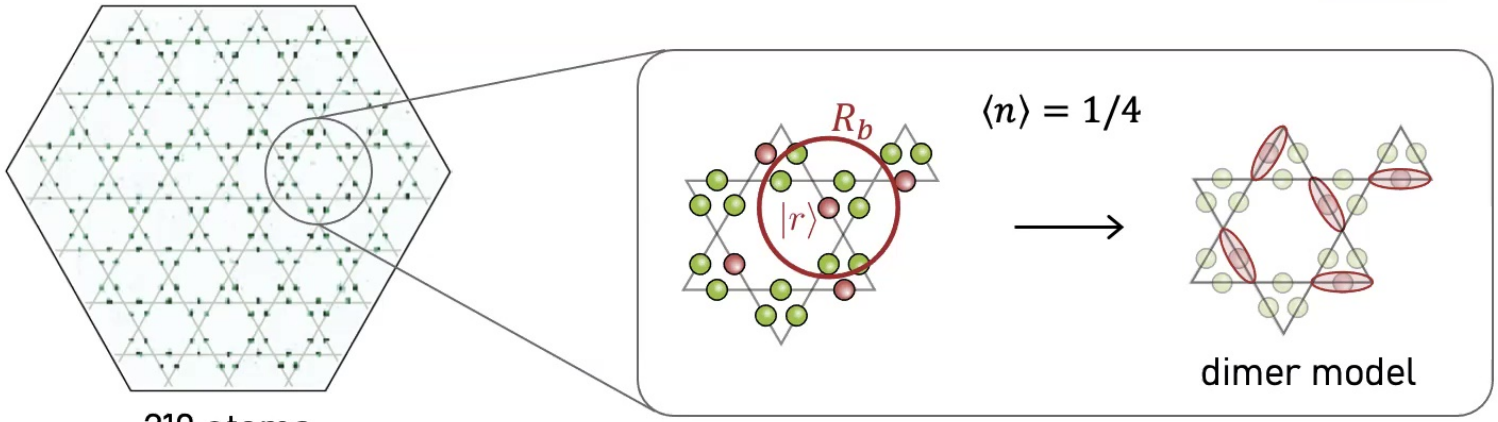


resonating valence bond (RVB) state

Quantum spin liquids in Rydberg atom arrays

R. Samajdar S. Sachdev





219 atoms

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

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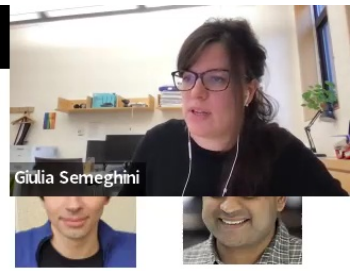
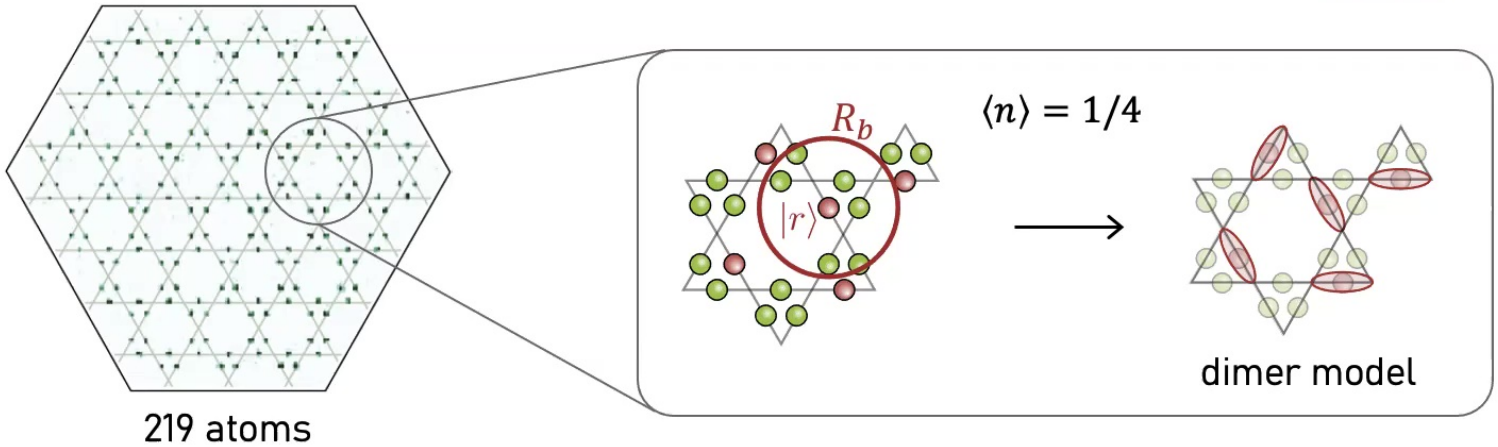
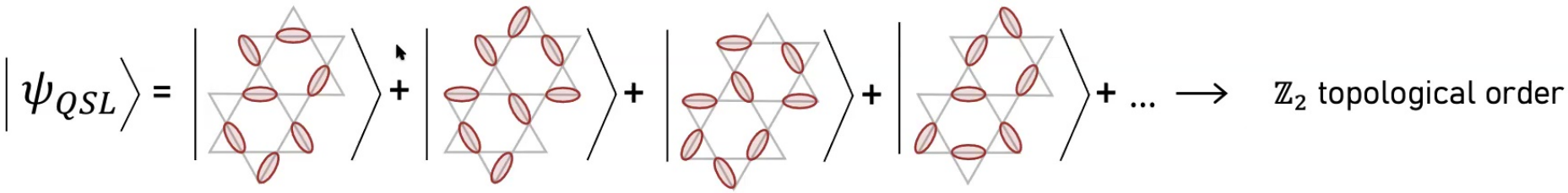




quantum spin liquid state: superposition of all dimer coverings



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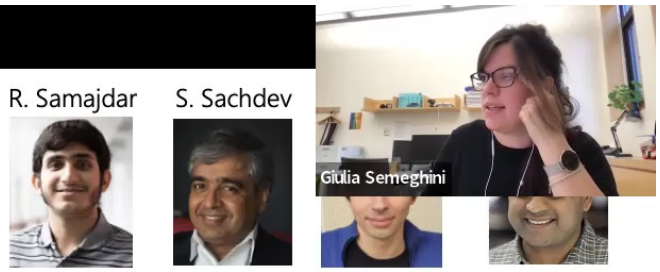

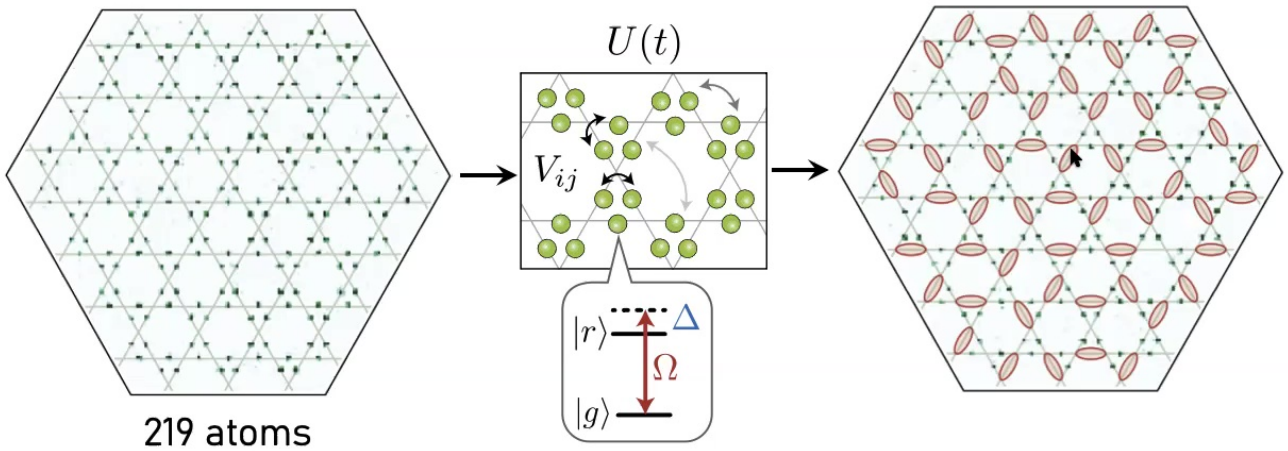

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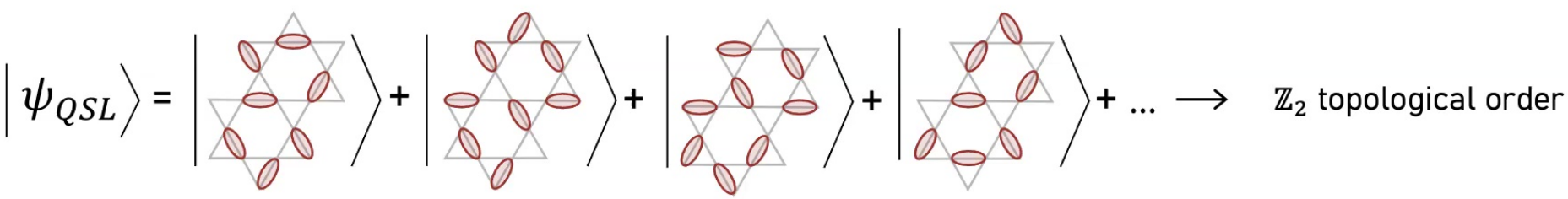

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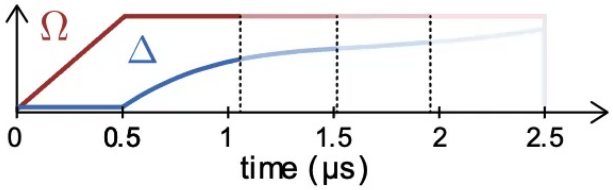
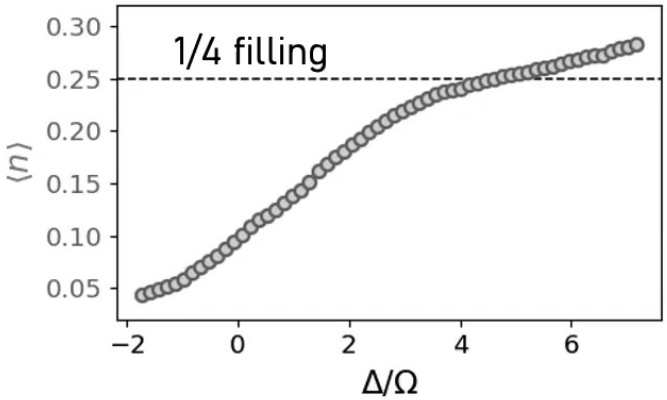
Quasi-adiabatic preparation of a dimer phase

G. Semeghini et

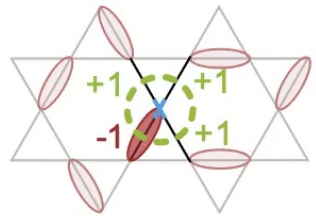


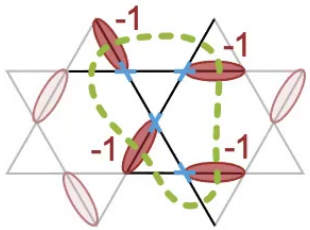


diagonal string operator Z:

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

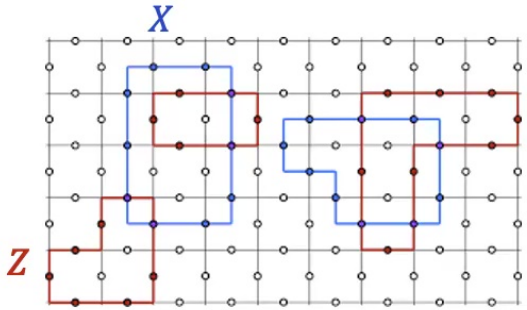
$\langle Z \rangle = -1$





parity of dimers along a string

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



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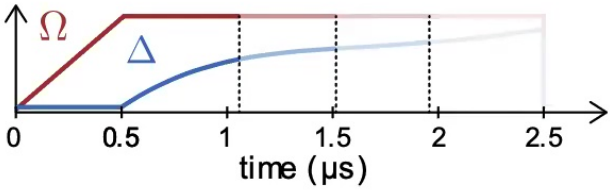
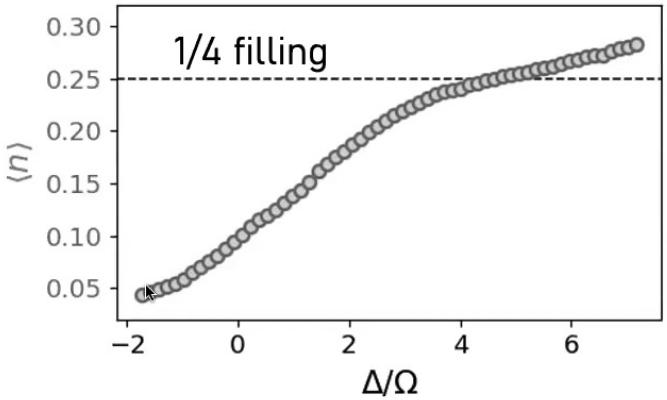
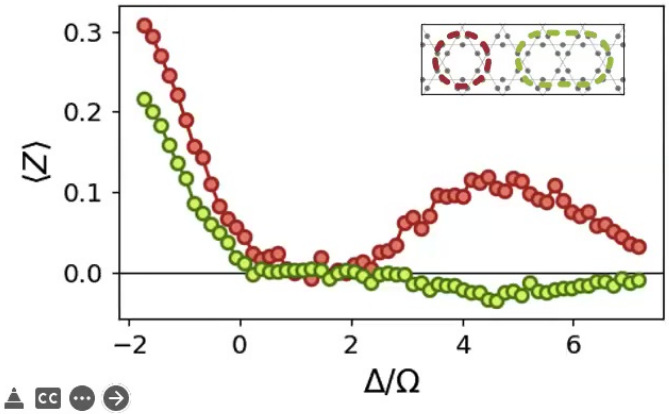
G. Semeghini et



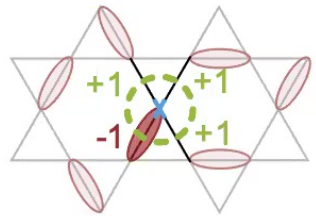


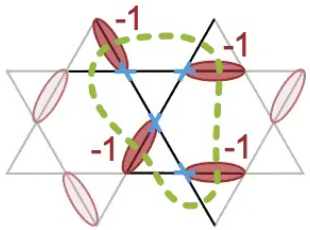


diagonal string operator Z:

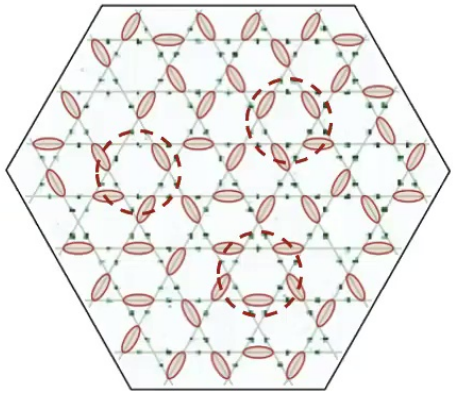
$\langle Z \rangle = (-1)^{\#\text{ enclosed vertices}}$

$\langle Z \rangle = -1$





parity of dimers along a string



Quasi-adiabatic preparation of a dimer phase

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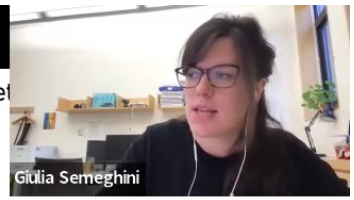

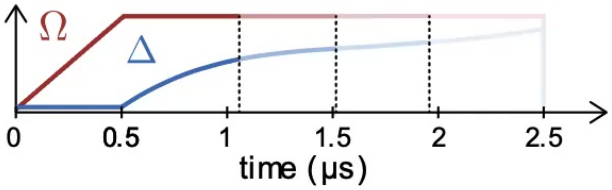

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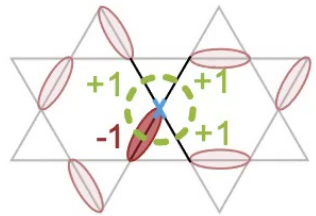
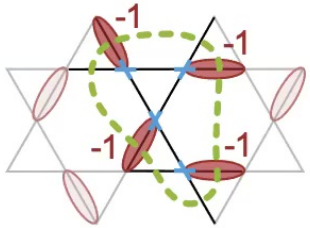
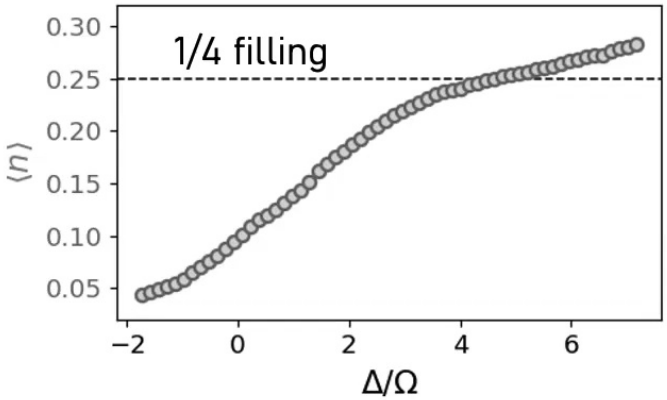
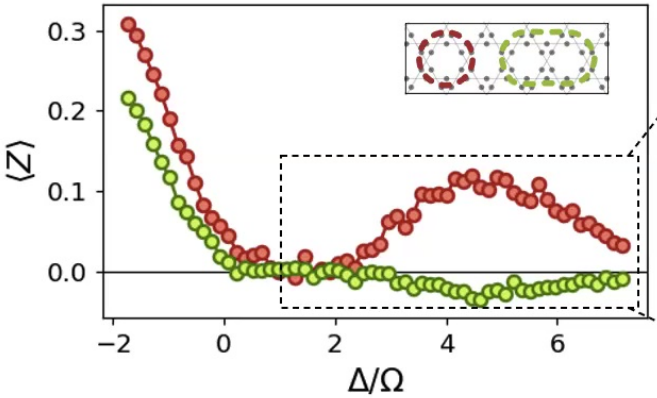


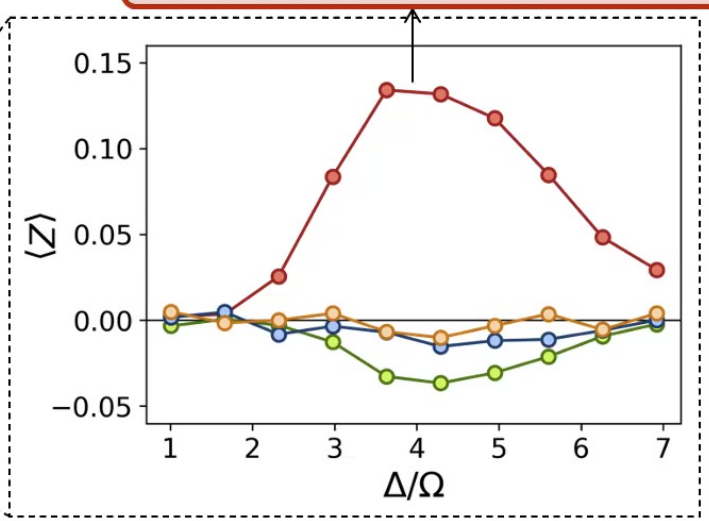


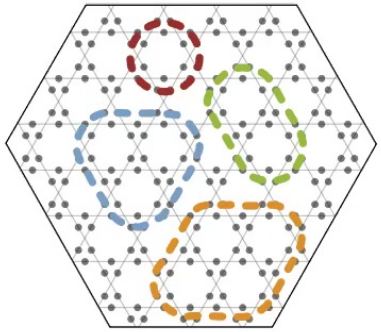
parity of dimers along a string



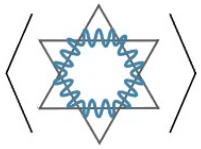


transition into an approximate dimer phase



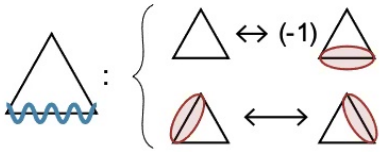


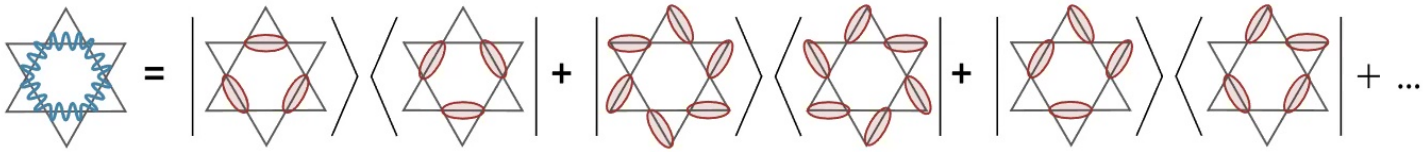
Probing coherence: off-diagonal string operator



dimer coverings

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





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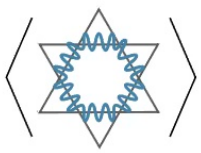
Probing coherence: off-diagonal string operator



dimer coverings

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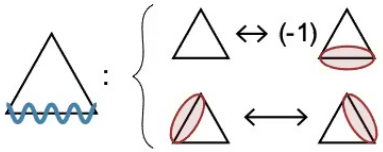
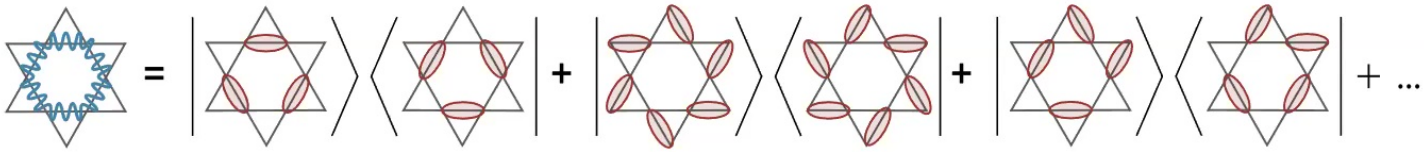
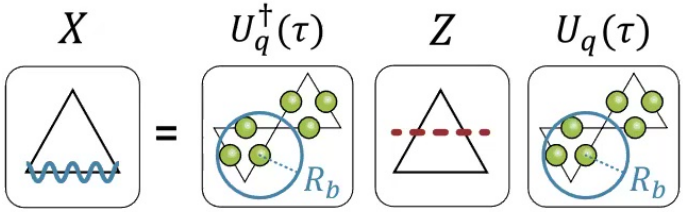
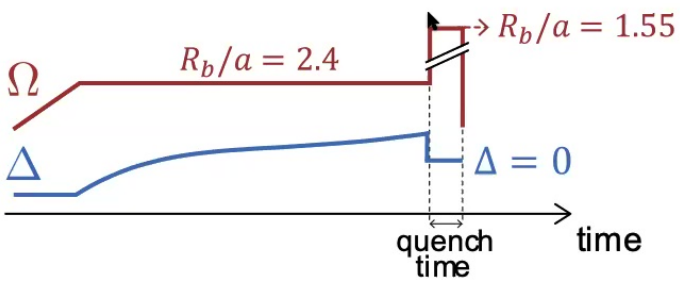




basis rotation to measure X:





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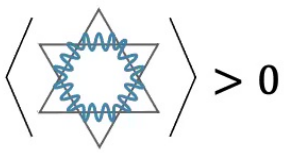
Probing coherence: off-diagonal string operator



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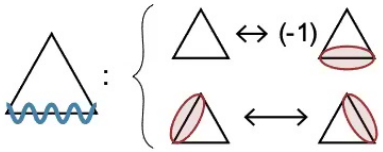

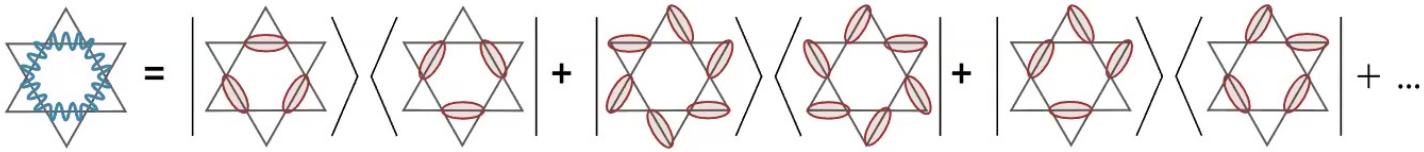

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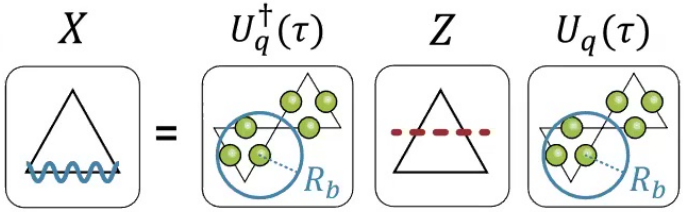
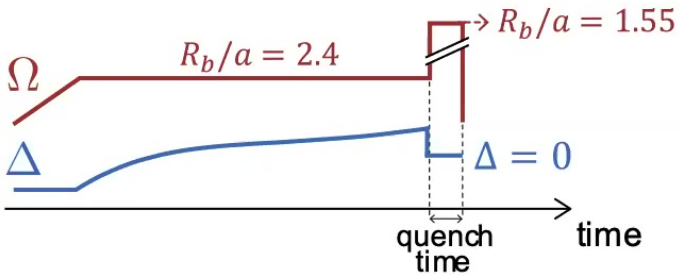
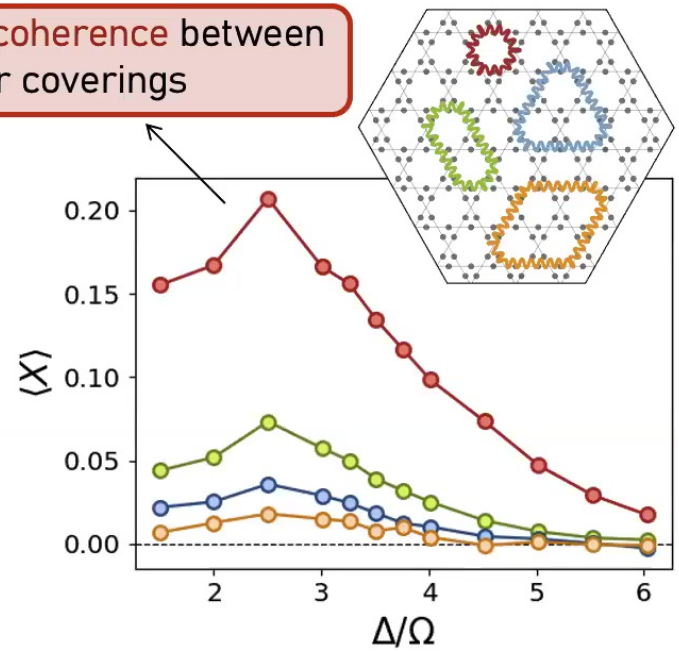




signature of coherence between dimer coverings



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QSL properties

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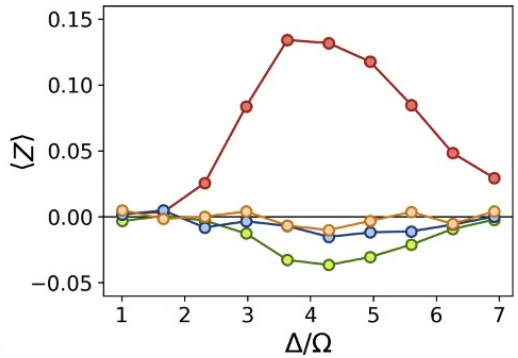
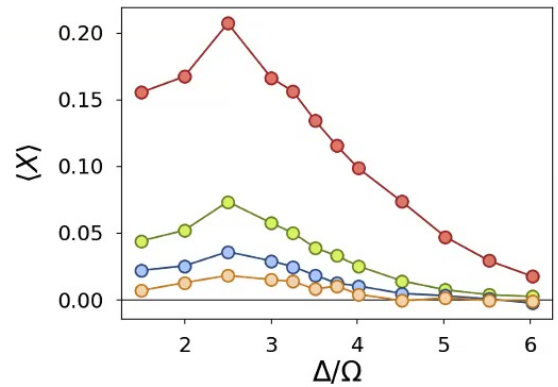
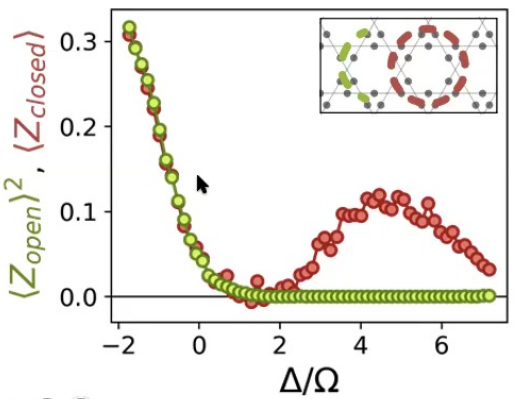
- $|\langle Z_{loop}\rangle| > 0 \longrightarrow$ dimer phase

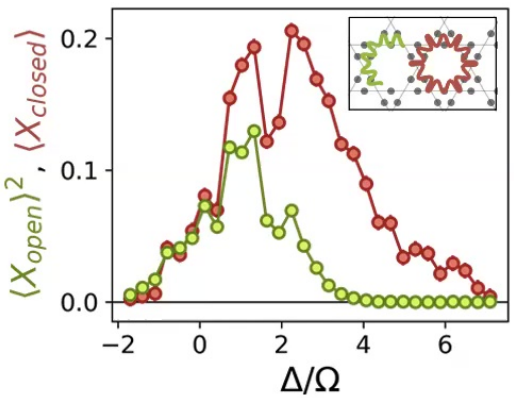


- $\langle X_{loop}\rangle > 0 \longrightarrow$ coherent superposition



- exclude trivial phases: closed loops vs open strings





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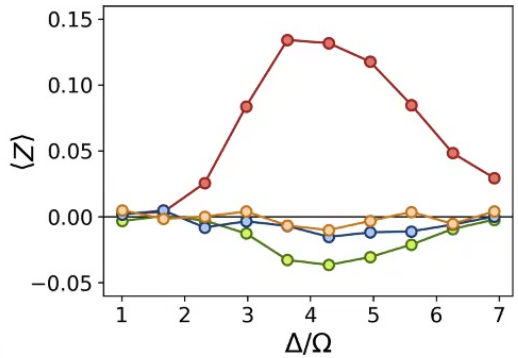

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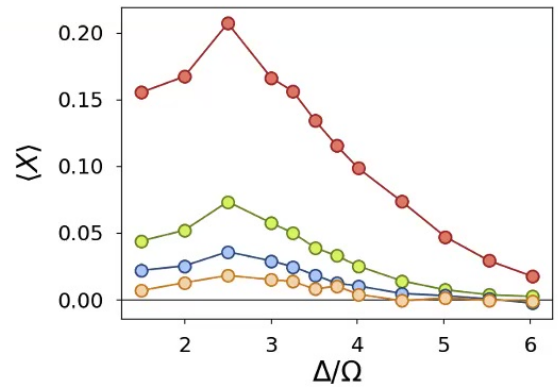

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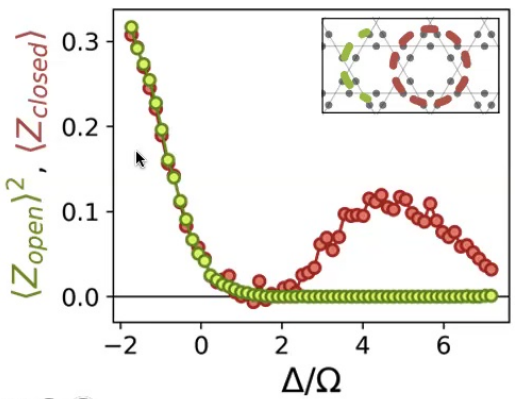

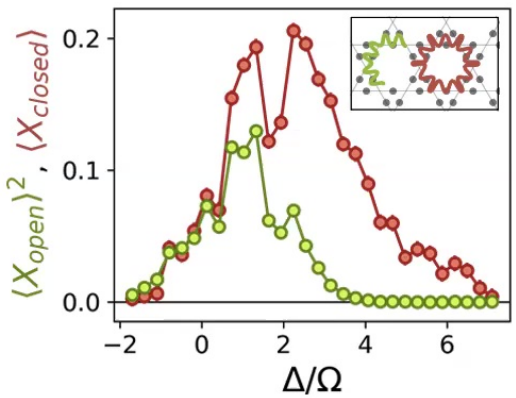

closed loops: detect non-trivial topological correlations

open strings: distinguish QSL from nearby phases

QSL properties

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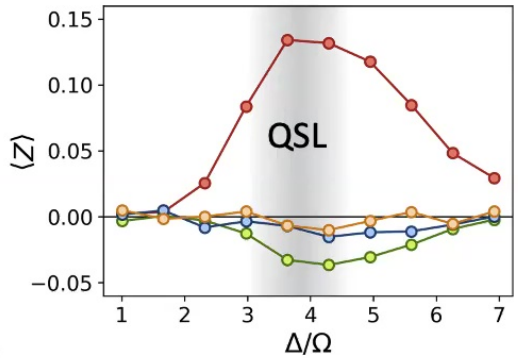

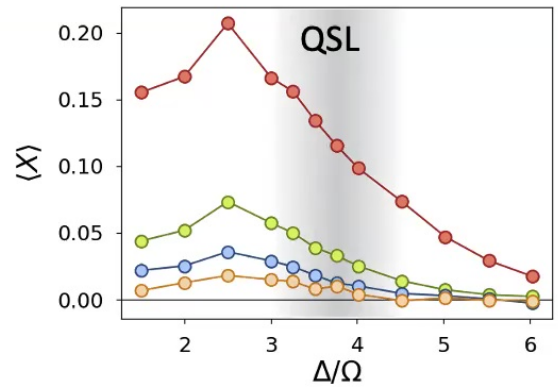

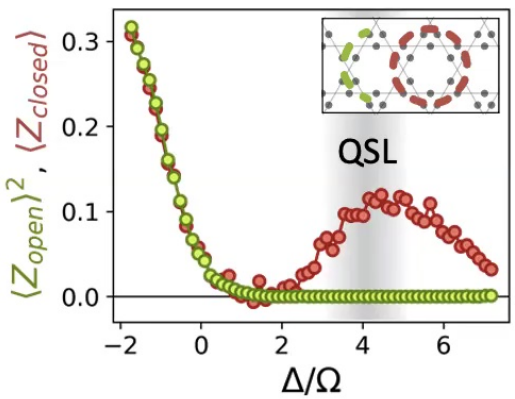

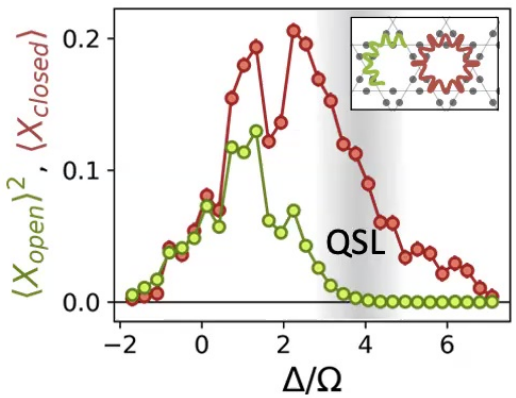

closed loops: detect non-trivial topological correlations

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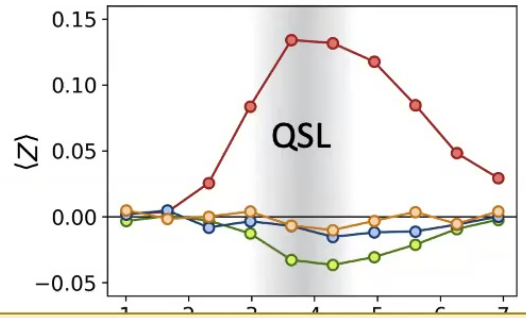
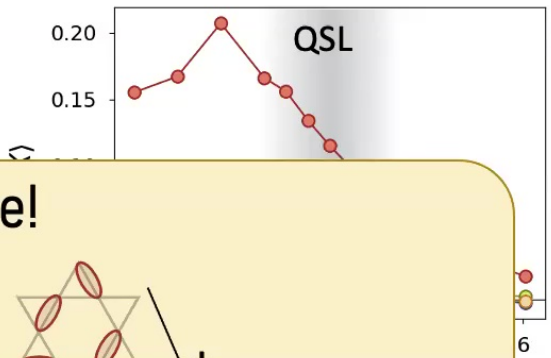
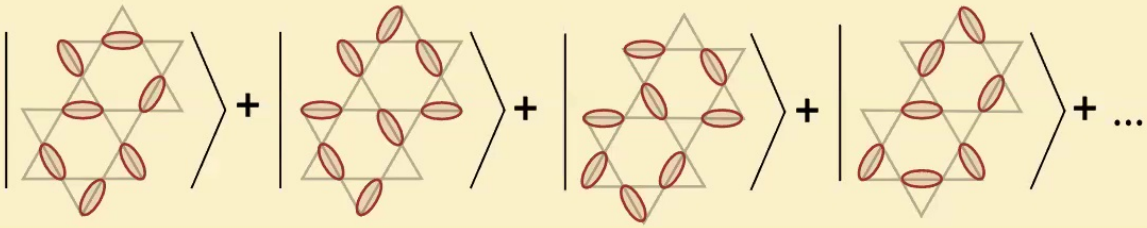
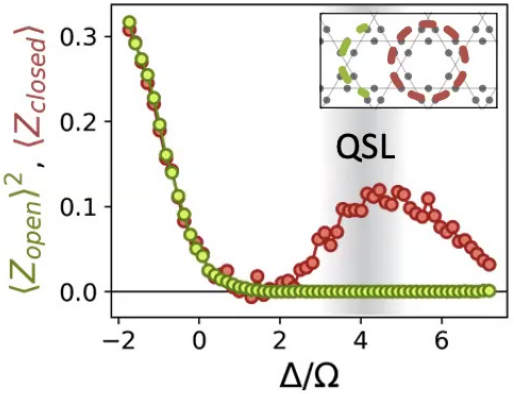
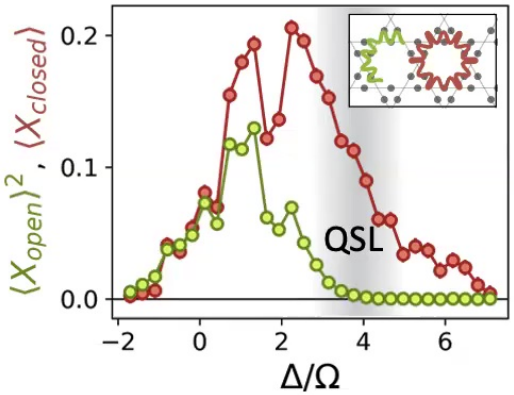




onset of a quantum spin liquid phase!

$|\psi_{QSL}\rangle =$ 





closed loops: detect non-trivial topological correlations

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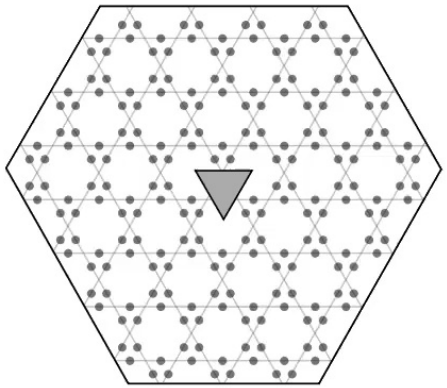
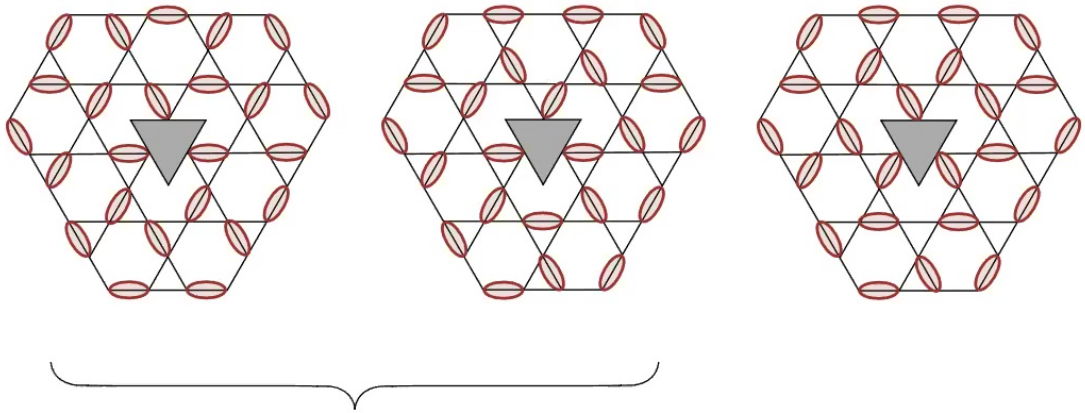
Towards topological states – array with a hole

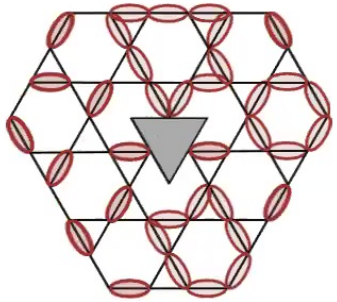
non-trivial topology



two distinct topological sectors



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



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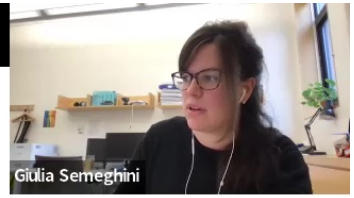
Towards topological states – array with a hole



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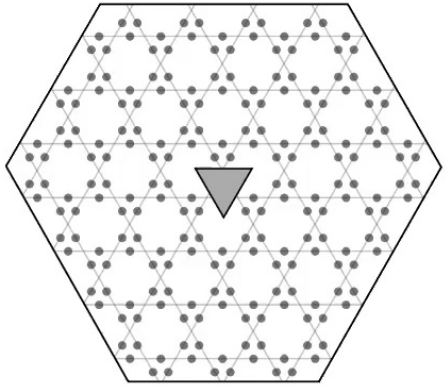

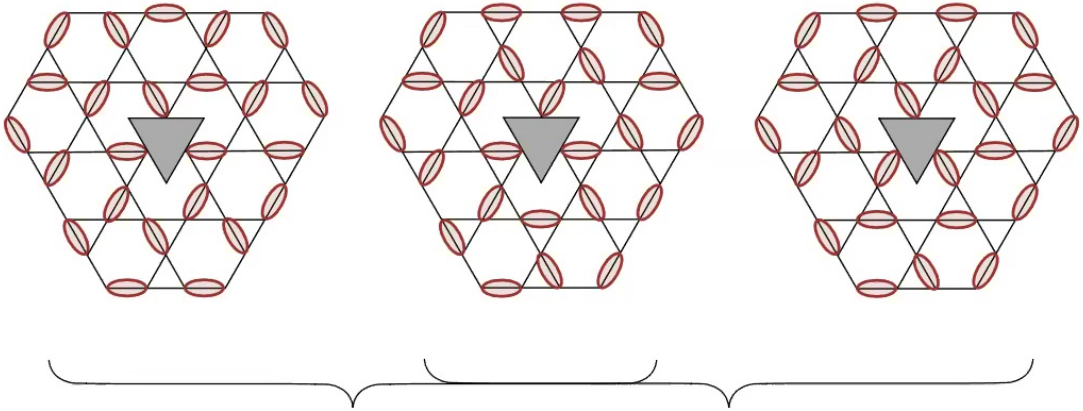

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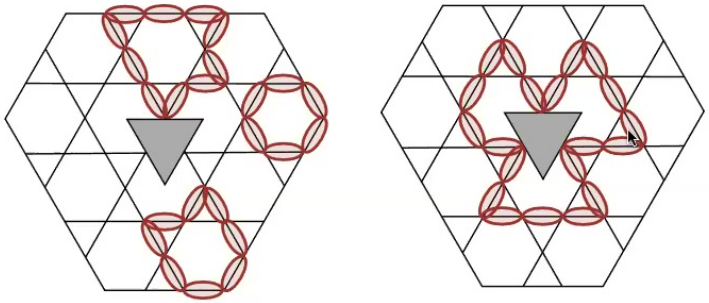
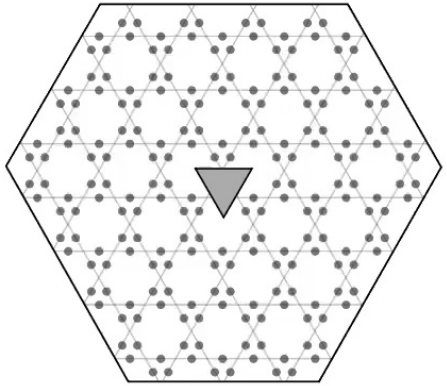


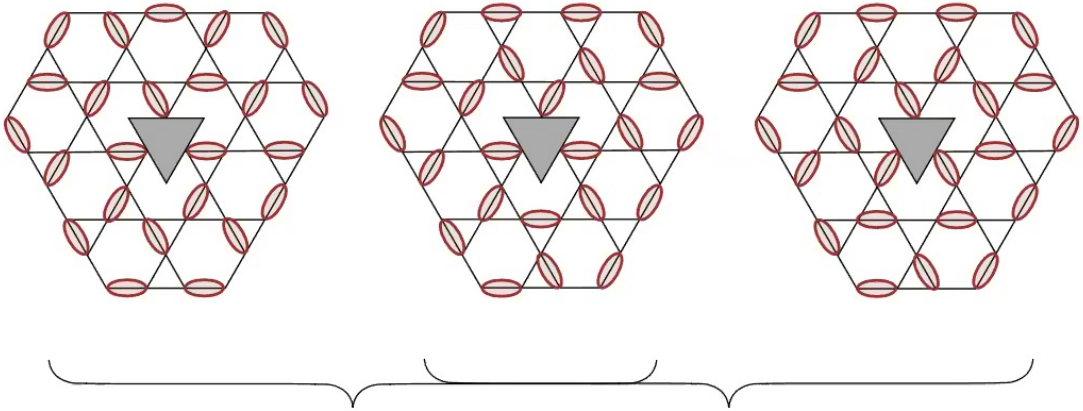
G. Semeghini et al., Science 374, 1242 (2021)

Towards topological states – array with a hole

non-trivial topology



two distinct topological sectors



transition graph:
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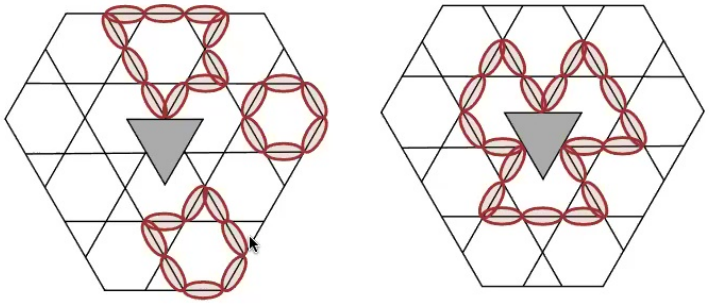


same
topological sector

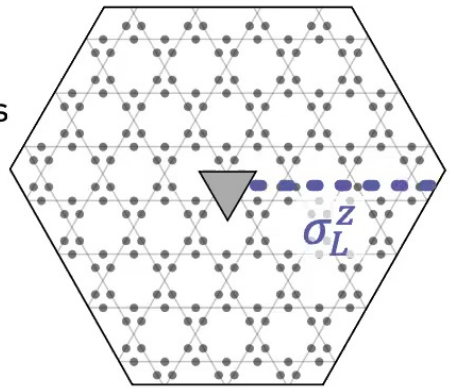
opposite
topological sectors

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

Towards topological states – array with a hole

non-trivial topology

logical operators



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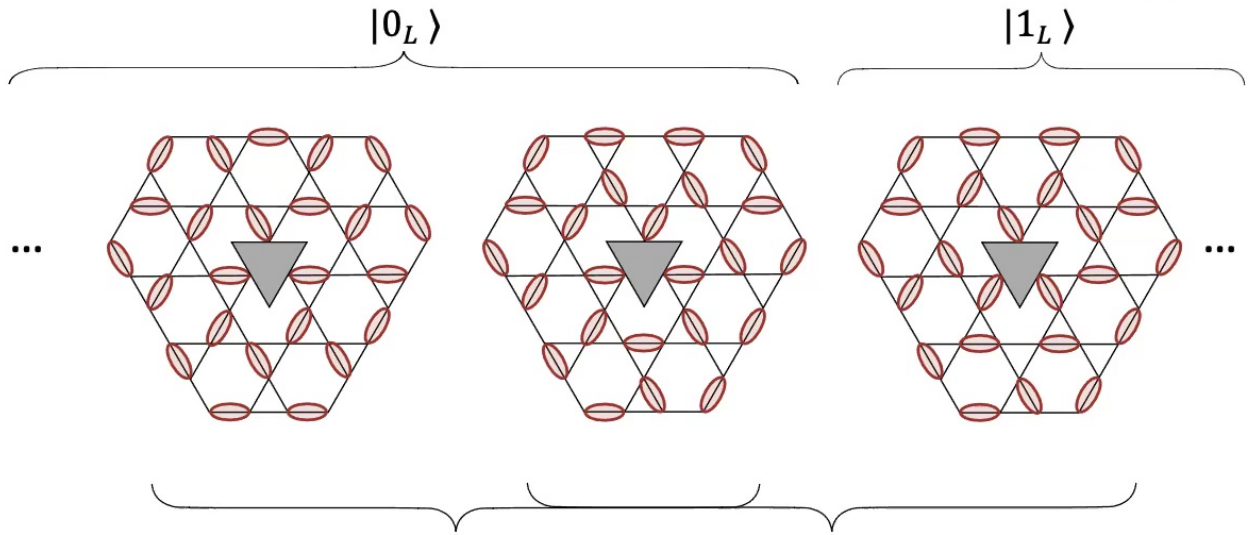

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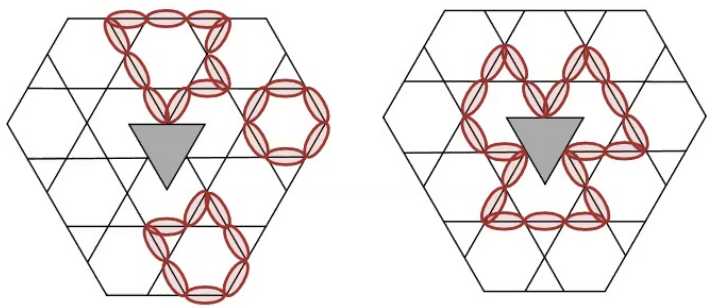

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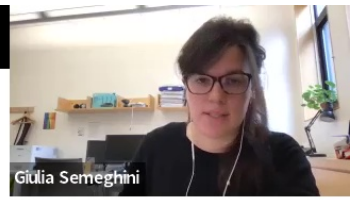

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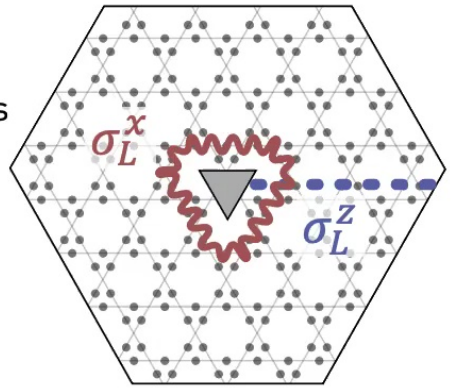

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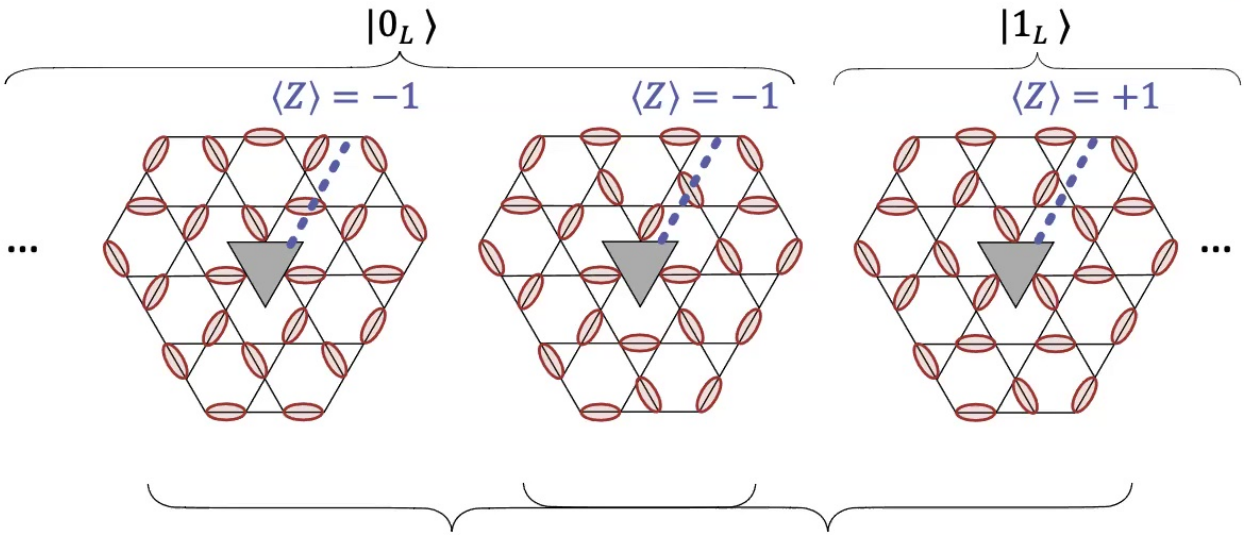

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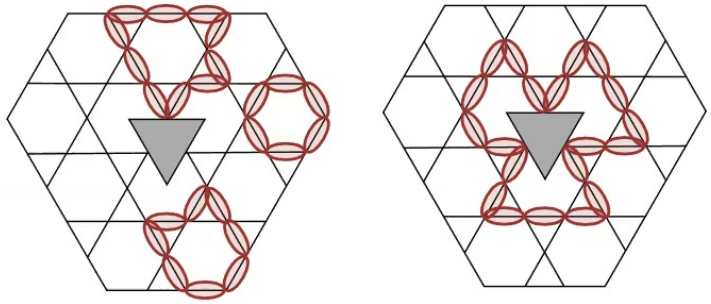

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G. Semeghini et al., Science 374, 1242 (2021)

Towards topological states – array with a hole

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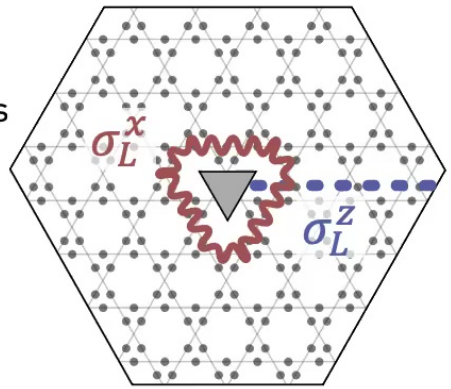

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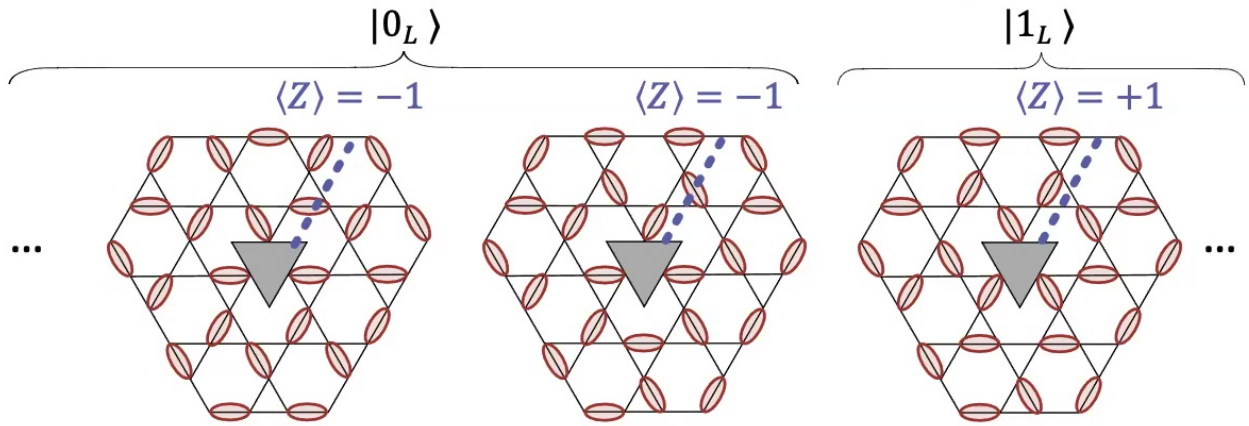

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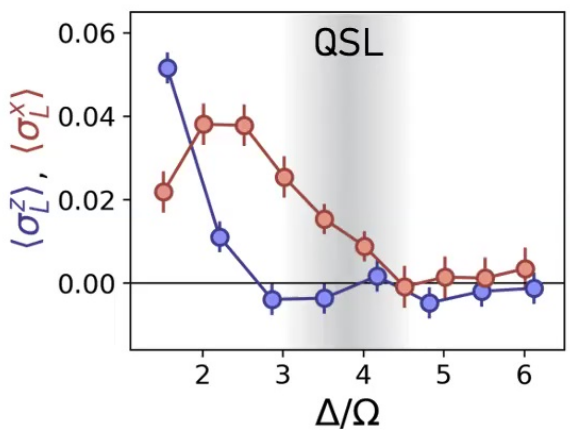
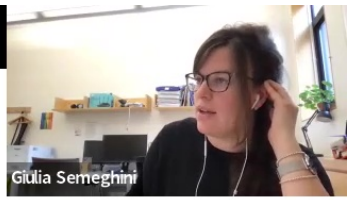


G. Semeghini et al., Science 374, 1242 (2021)

Towards topological states – array with a hole



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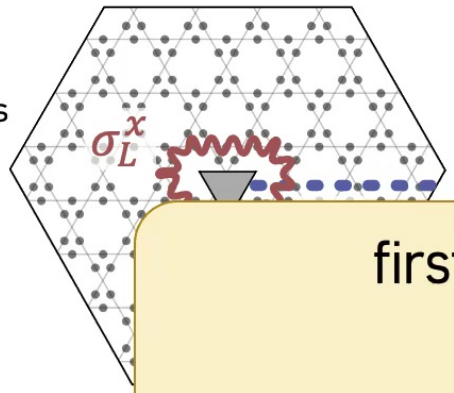

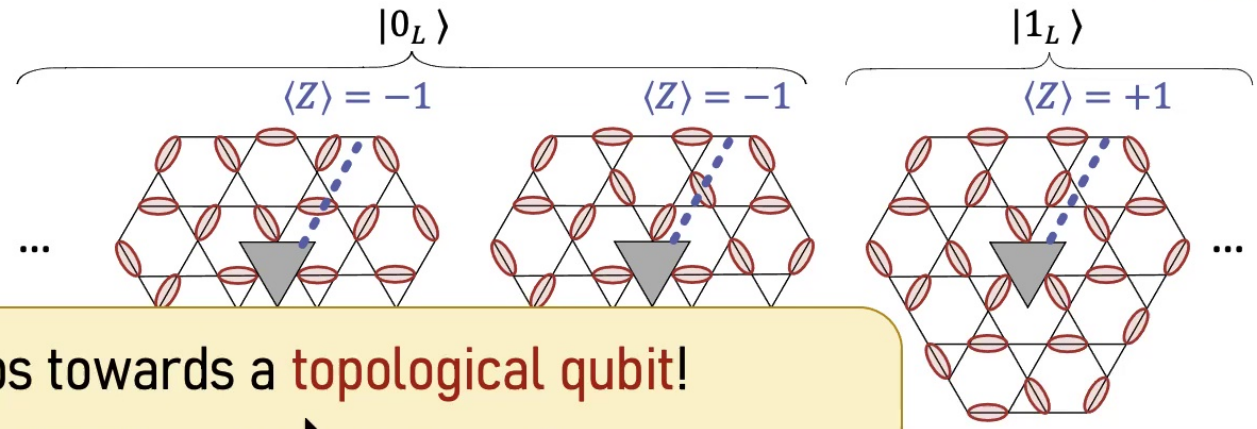

first steps towards a topological qubit!

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

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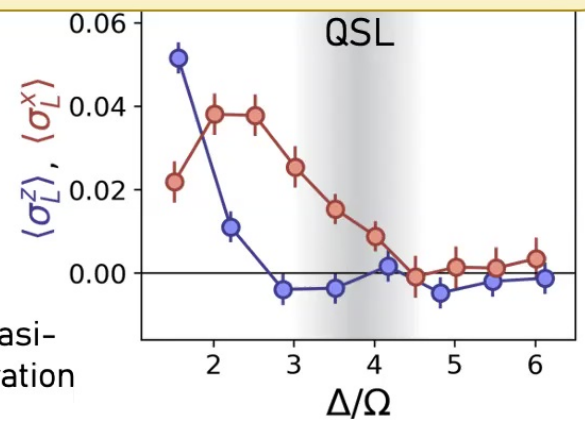
as expected from quasi-adiabatic state preparation



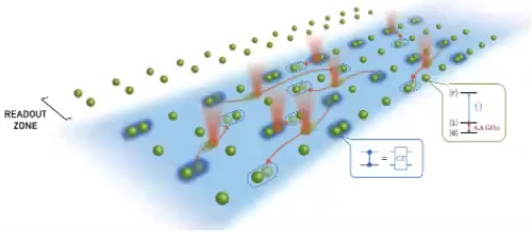
G. Semeghini et al., Science 374, 1242 (2021)

Outline

Programmable arrays of Rydberg atoms

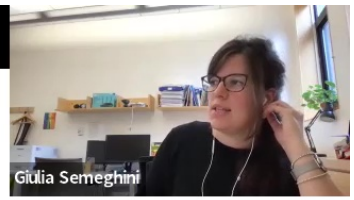
Experimental evidence of a quantum spin liquid phase

Dynamically reconfigurable architecture



Outlooks

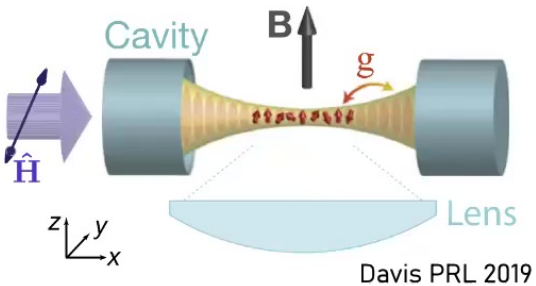
Dynamically reconfigurable architecture



Nonlocal connectivity and entanglement: approaches

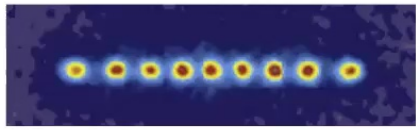
Quantum data bus

Cavity-mediated interactions



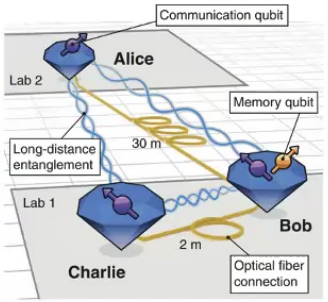
Davis PRL 2019

Shared motional modes

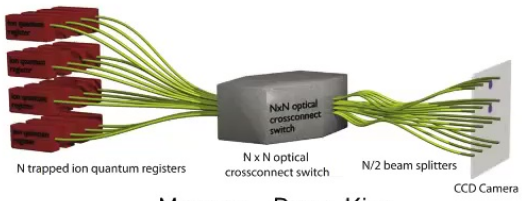


Innsbruck

Quantum networks



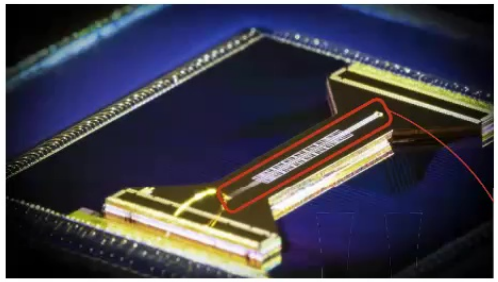
Pompili ... Hanson (Science 2021)



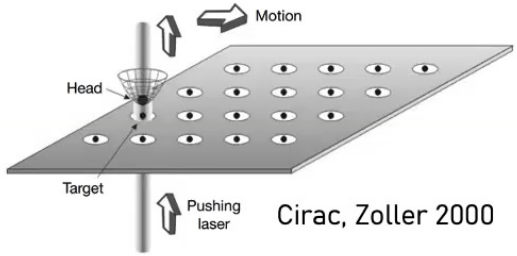
Monroe ... Duan, Kim

See also SC qubit transduction to optical photons

Quantum ion "CCD"

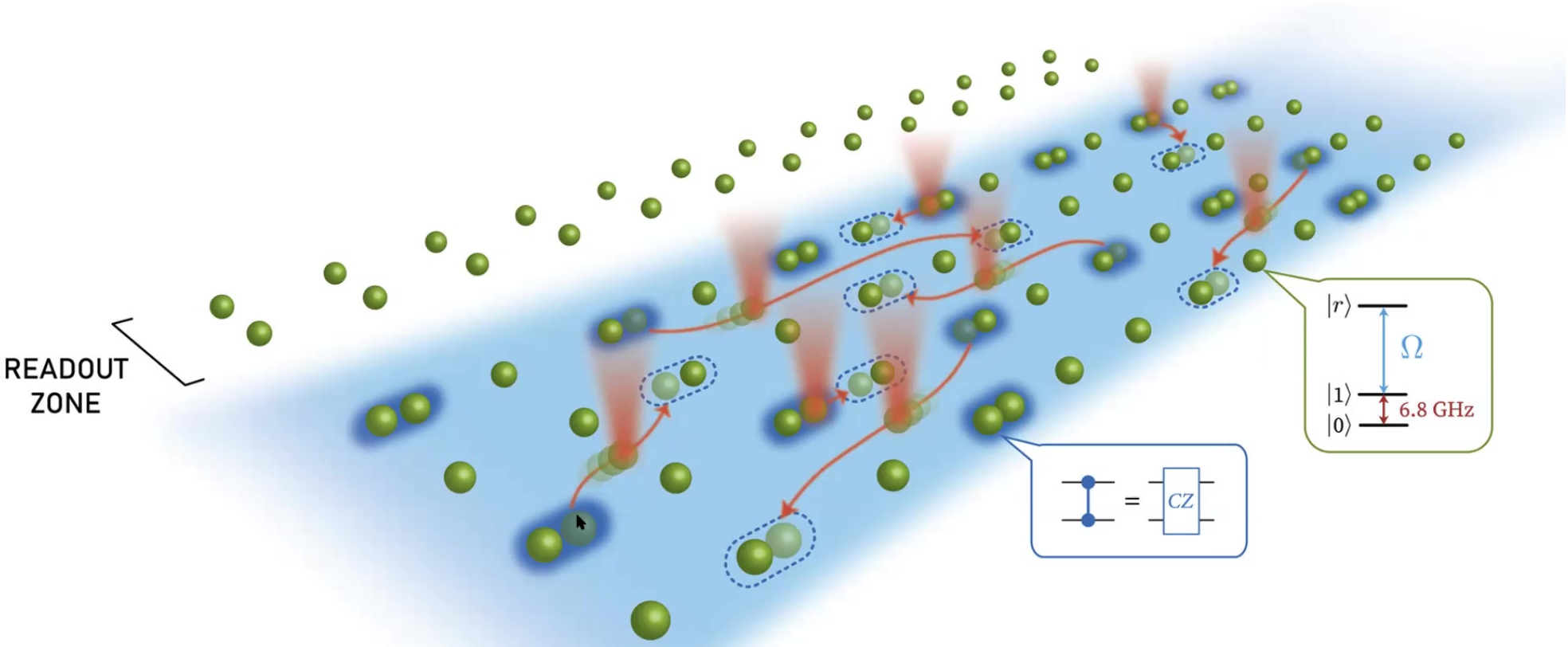


Honeywell 2021



Cirac, Zoller 2000

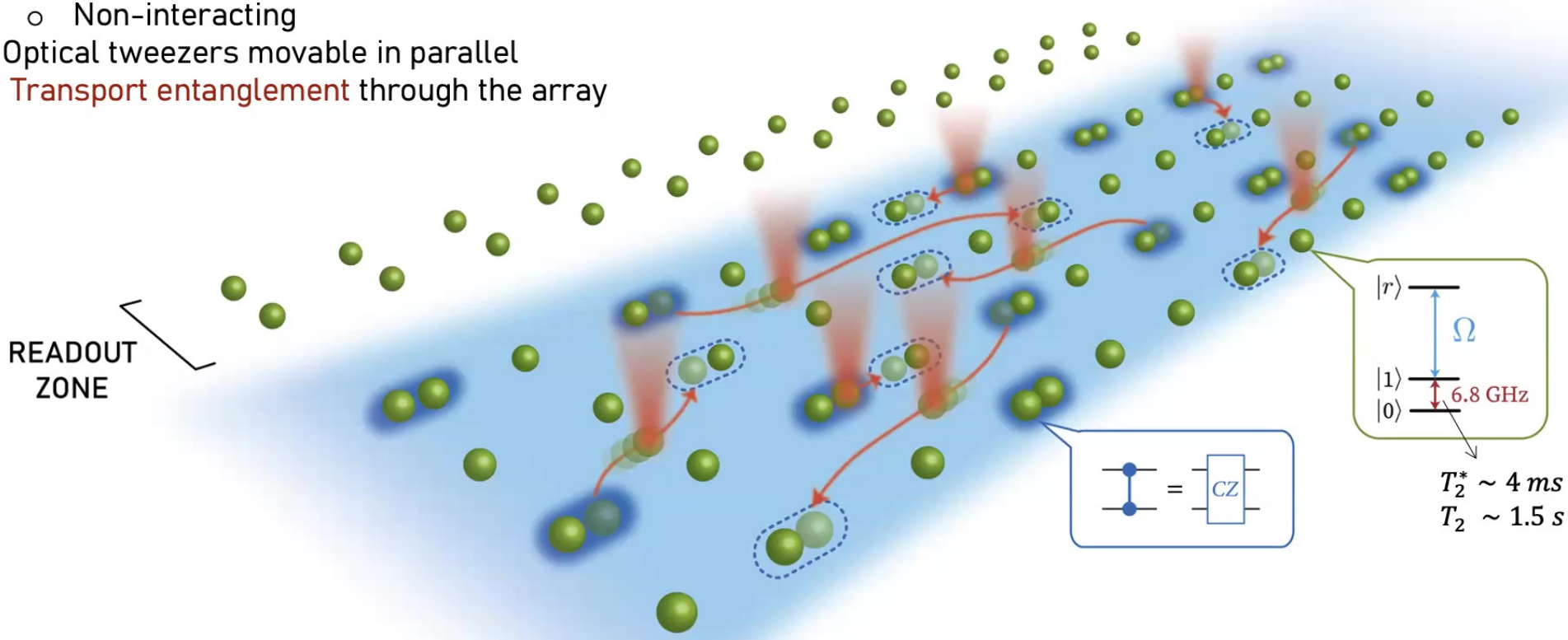
Dynamically reconfigurable architecture



D. Bluvstein, H. Levine, GS et al, arXiv:2112.03923 (2021)

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



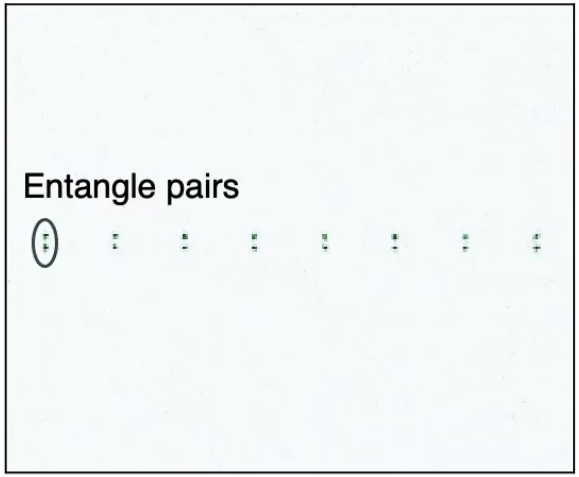
D. Bluvstein, H. Levine, GS et al, arXiv:2112.03923 (2021)

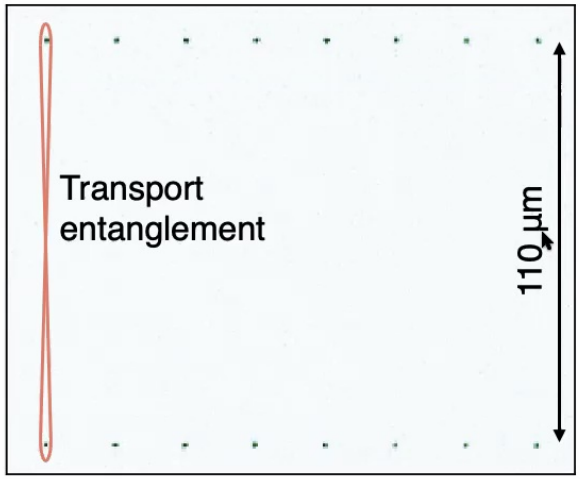
CZ gate: H. Levine et al, PRL 2019

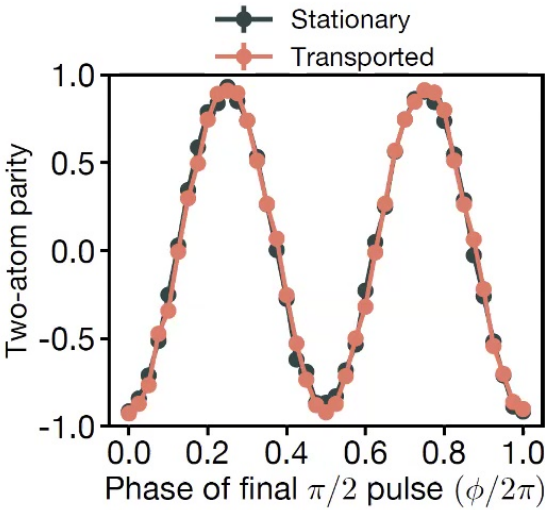
Dynamically reconfigurable architecture

Transporting entanglement across the array

D. Bluvstein, H. Levine, GS et a
CZ gate:







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

Dynamically reconfigurable architecture

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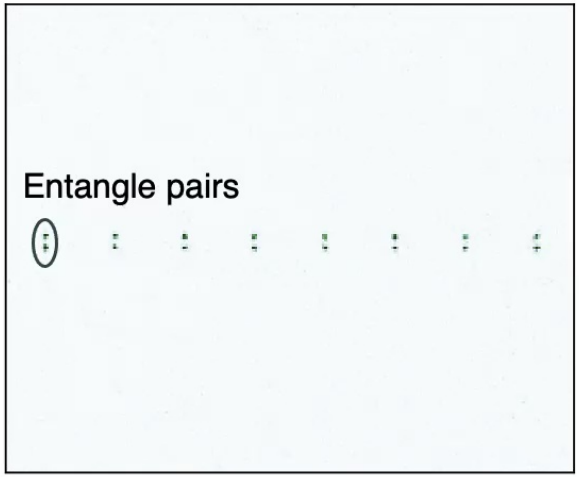
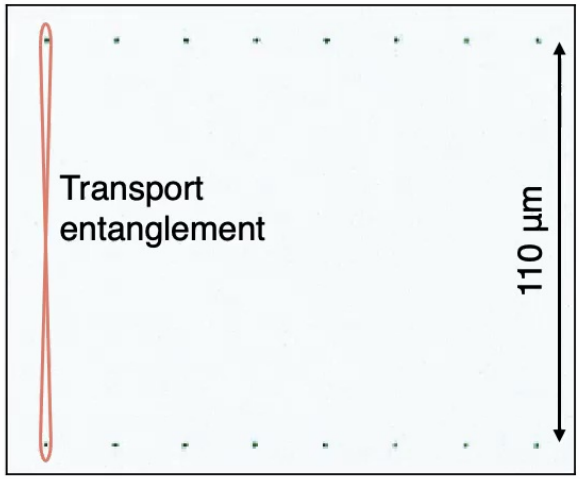
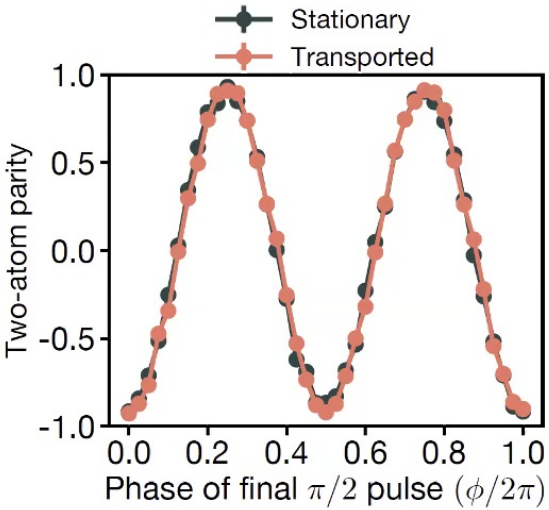






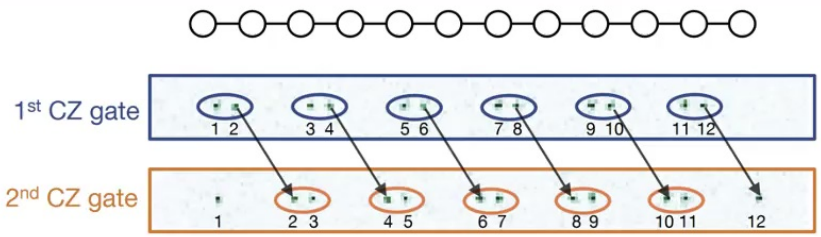
Coherence is preserved when transporting the atoms over a hundred µm in a few hundred µs (~10^{-4} T_2)

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

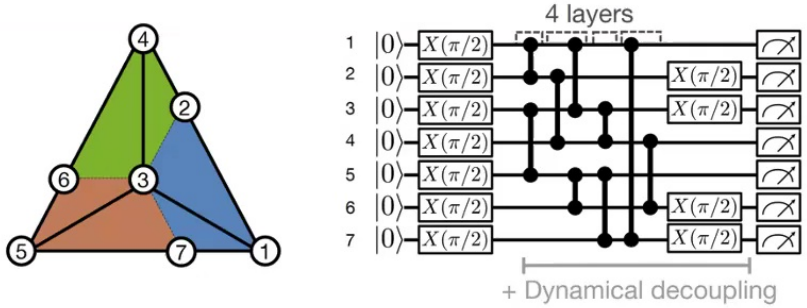
Dynamically reconfigurable architecture

D. Bluvstein, H. Levine, GS et a

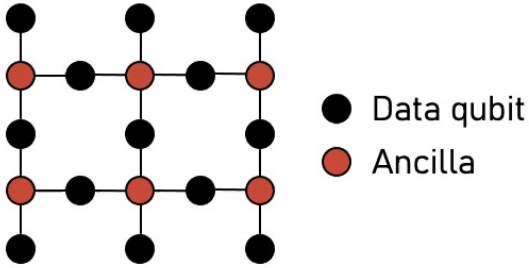
1D cluster states



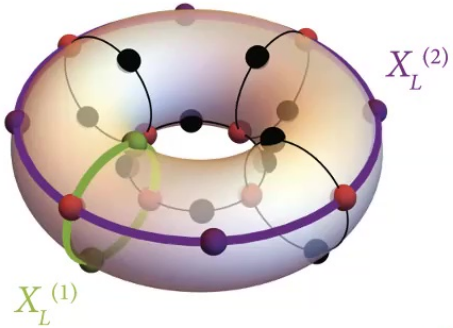
Steane Code



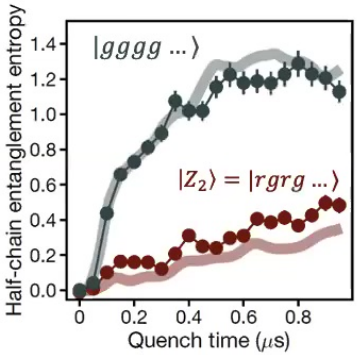
Surface Code (2D)



Toric Code (3D)



Measurement of entanglement entropy



Dynamically reconfigurable architecture

D. Bluvstein, H. Levine, GS et a

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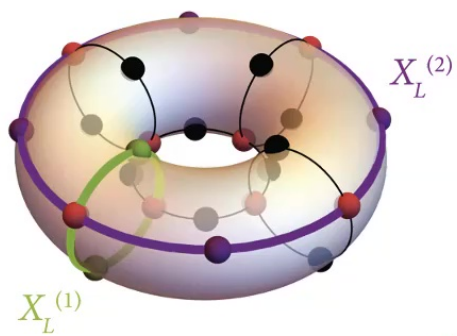
Toric Code (3D)



Measurement of entanglement entropy

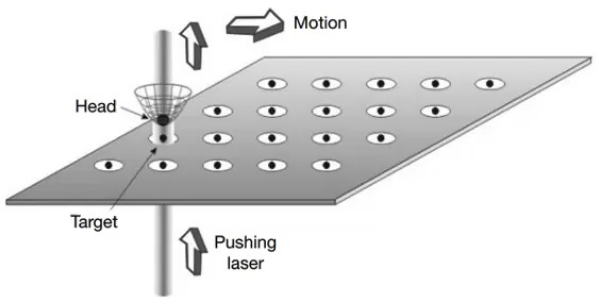
Dynamically reconfigurable architecture

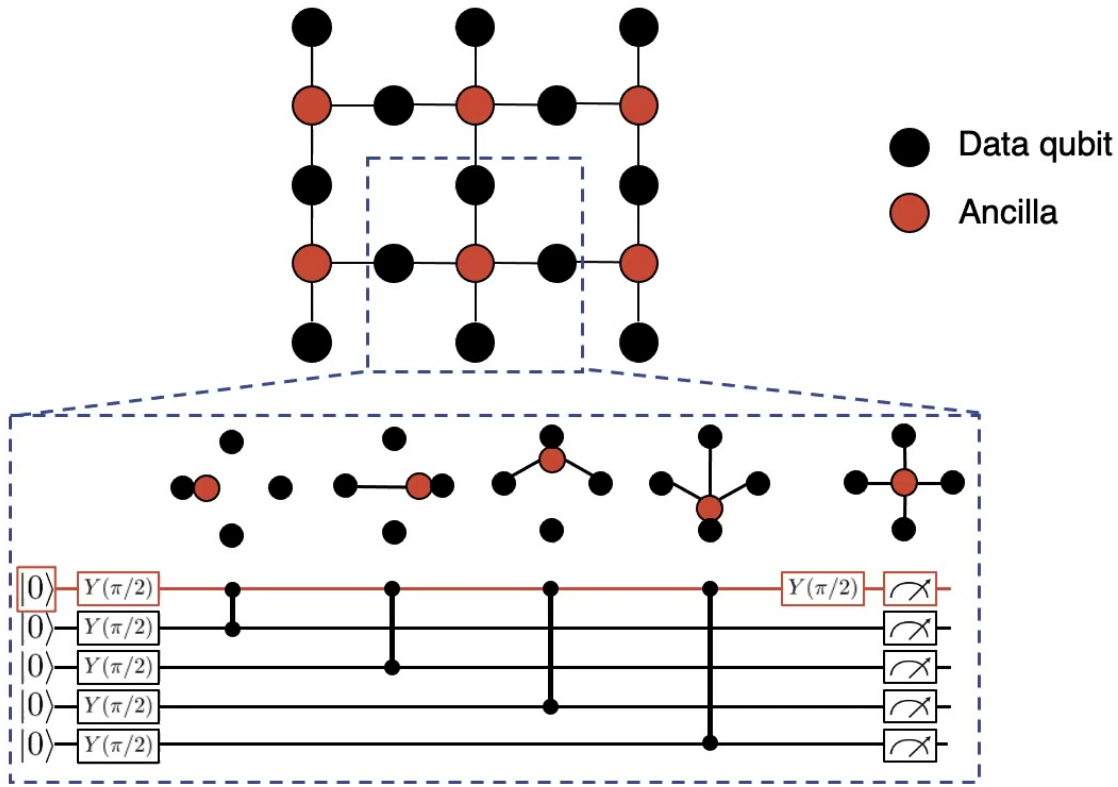
Toric code on a 3D torus

D. Bluvstein, H. Levine, GS et a

Ancillas mediate entanglement between qubits that never directly interact

Realization via parallel ancilla transport
(idea Cirac, Zoller, Nature 2001)



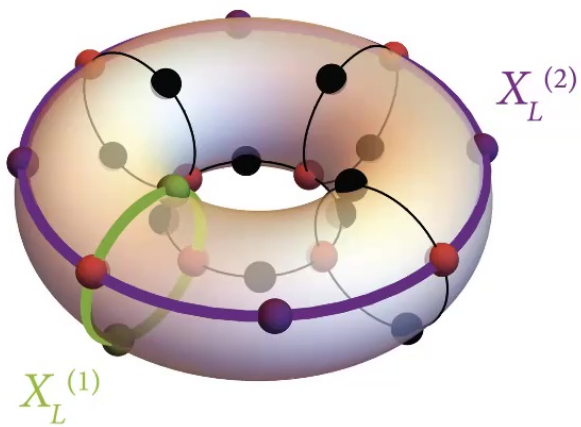


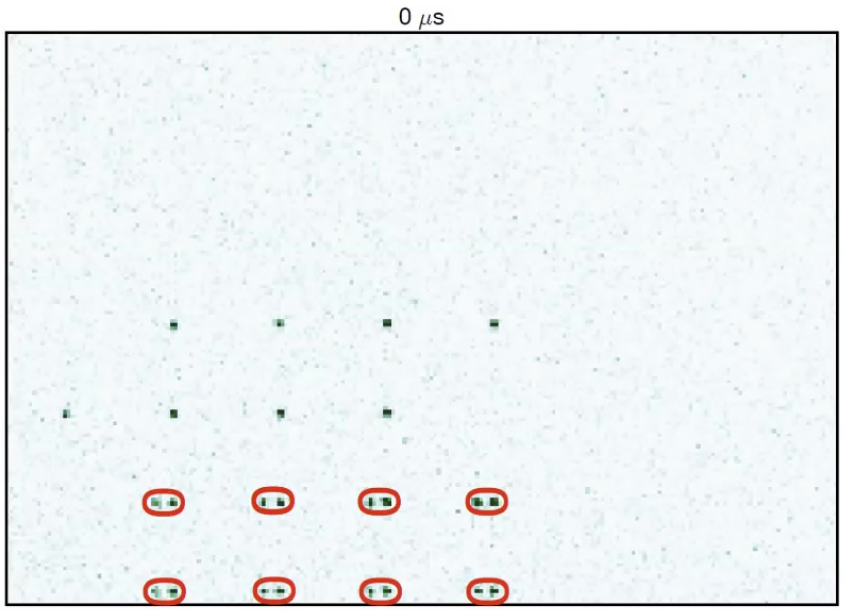
Dynamically reconfigurable architecture

Toric code on a 3D torus

D. Bluvstein, H. Levine, GS et a

● data qubit
● ancilla





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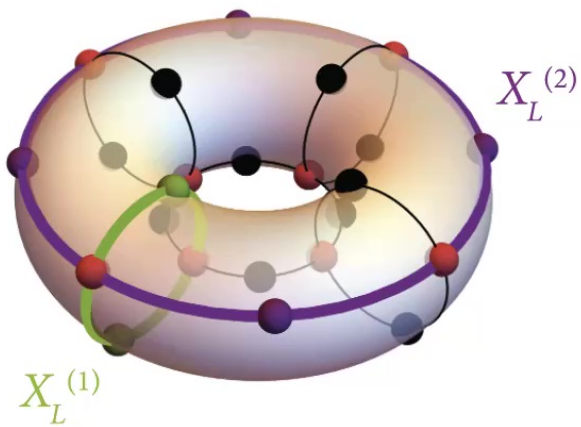

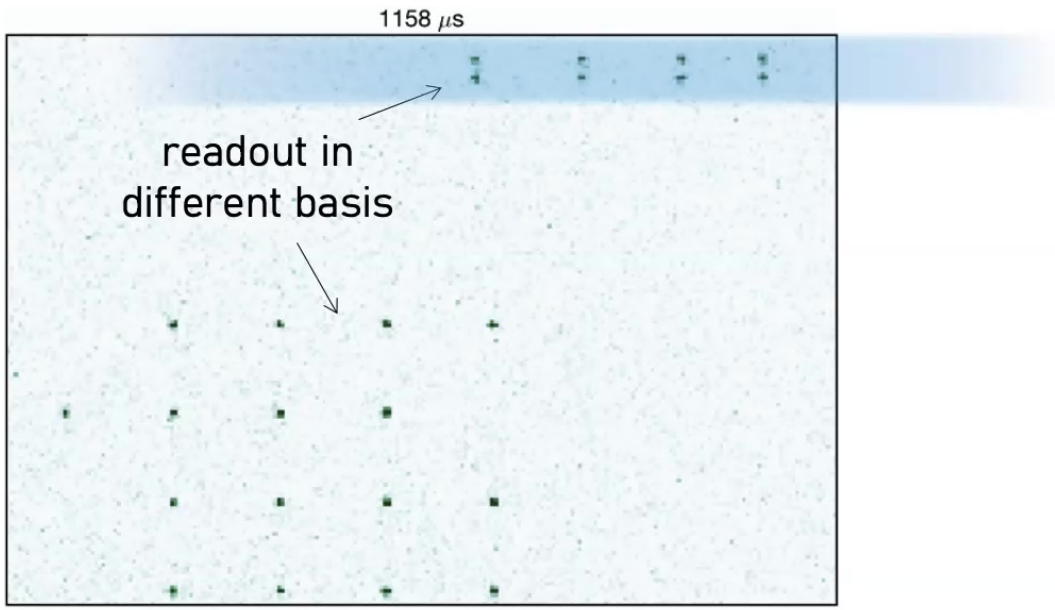

Dynamically reconfigurable architecture

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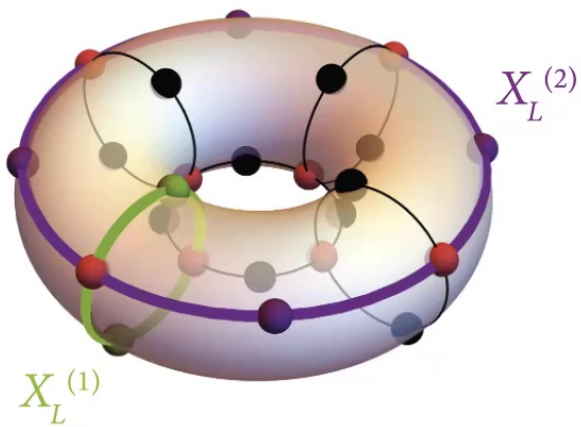
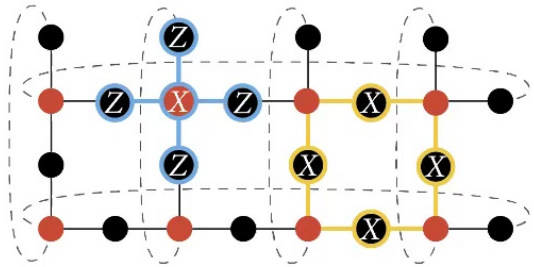
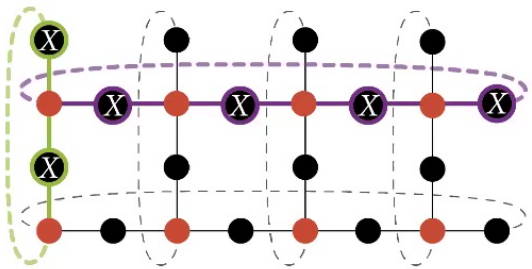
● data qubit
● ancilla

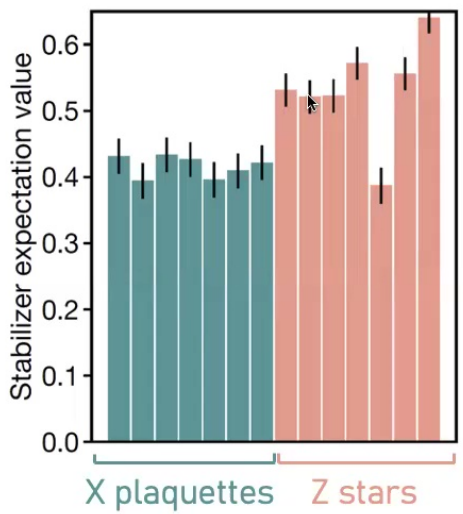


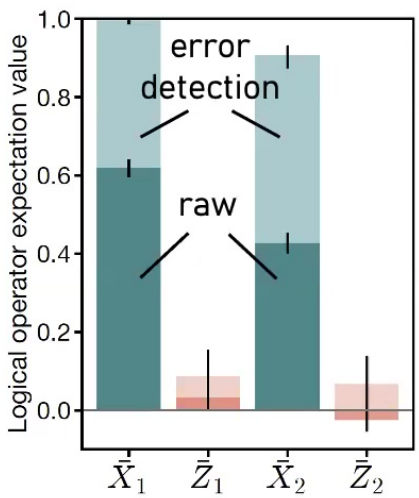
Stabilizers



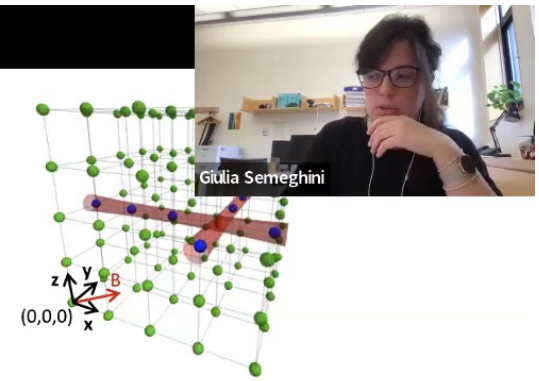
Two logical qubits!





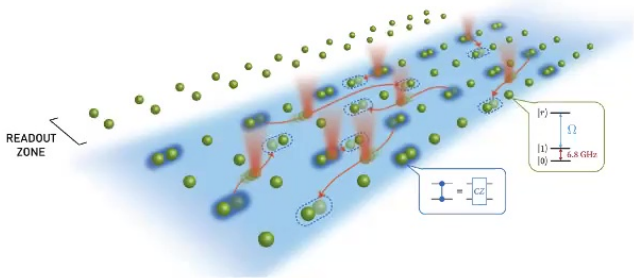


Outlooks



- Local single-site addressing

- Dynamically reconfigurable entanglement



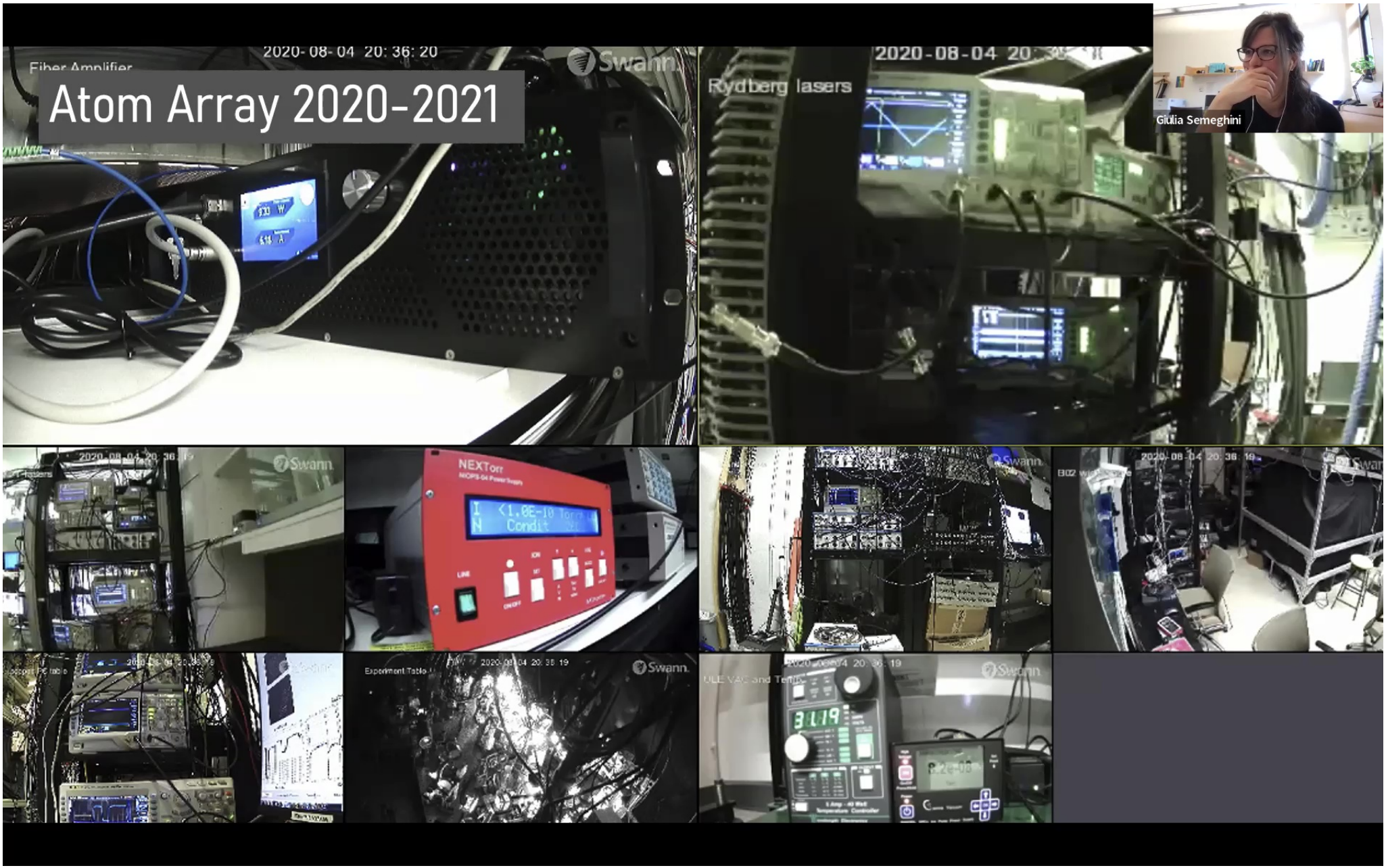
- Fast atom state detection

- Hardware efficient error detection and correction (I. Cong at al., arXiv:2105.13501)

- Hybrid approaches combining analog and digital quantum dynamics

→ new directions in the exploration of many-body phases and robust quantum computation

Atom Array 2020-2021



Atom Array 2020-2021
March 17th, 2020
Rydberg lasers
Giulia Semeghini

Harry Levine

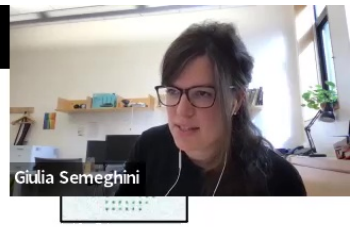
Tout Wang

Sepehr Ebadi

GS

Alex Keesling

Dolev Bluvstein



Ahmed Omran

Pls: M. Lukin

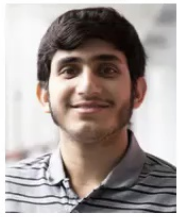
V. Vuletic

M. Greiner

THEORY COLLABORATORS

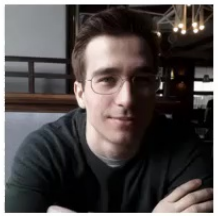
R. Verresen

R. Samajdar



N. Maskara

M. Kalinowski

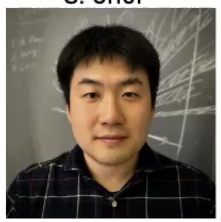


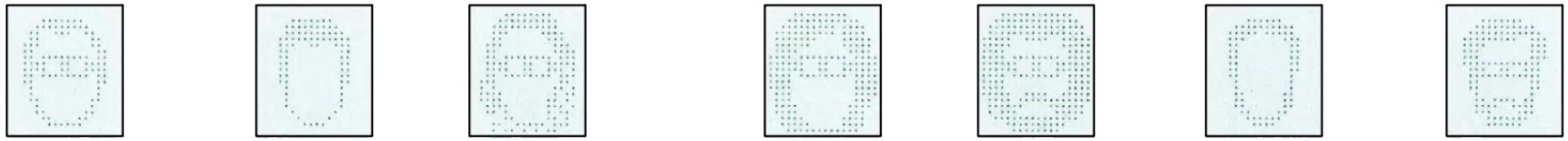
A. Vishwanath

S. Sachdev

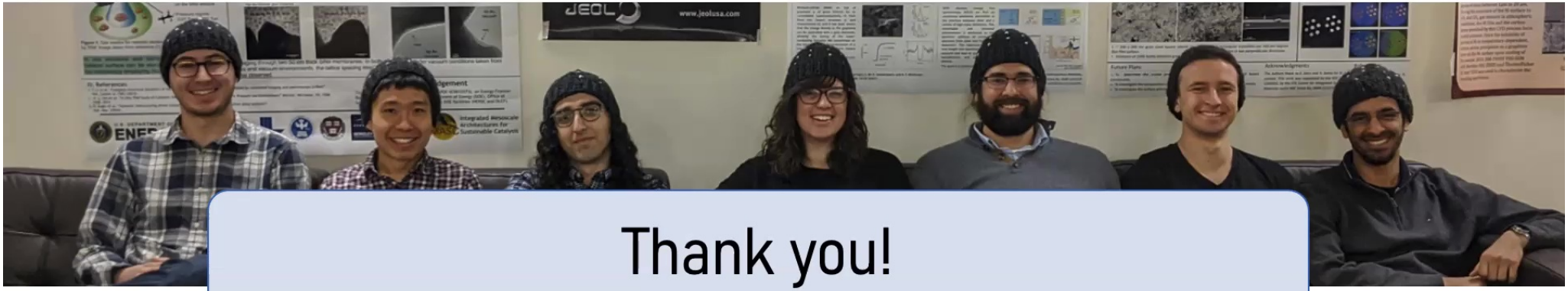
H. Pichler

S. Choi





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



Thank you!

Pls: M. Lukin

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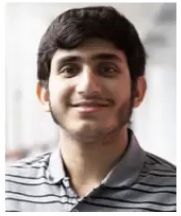

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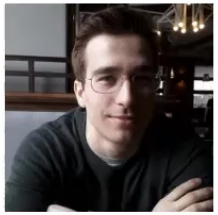

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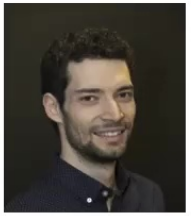
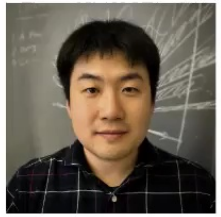
S. Choi