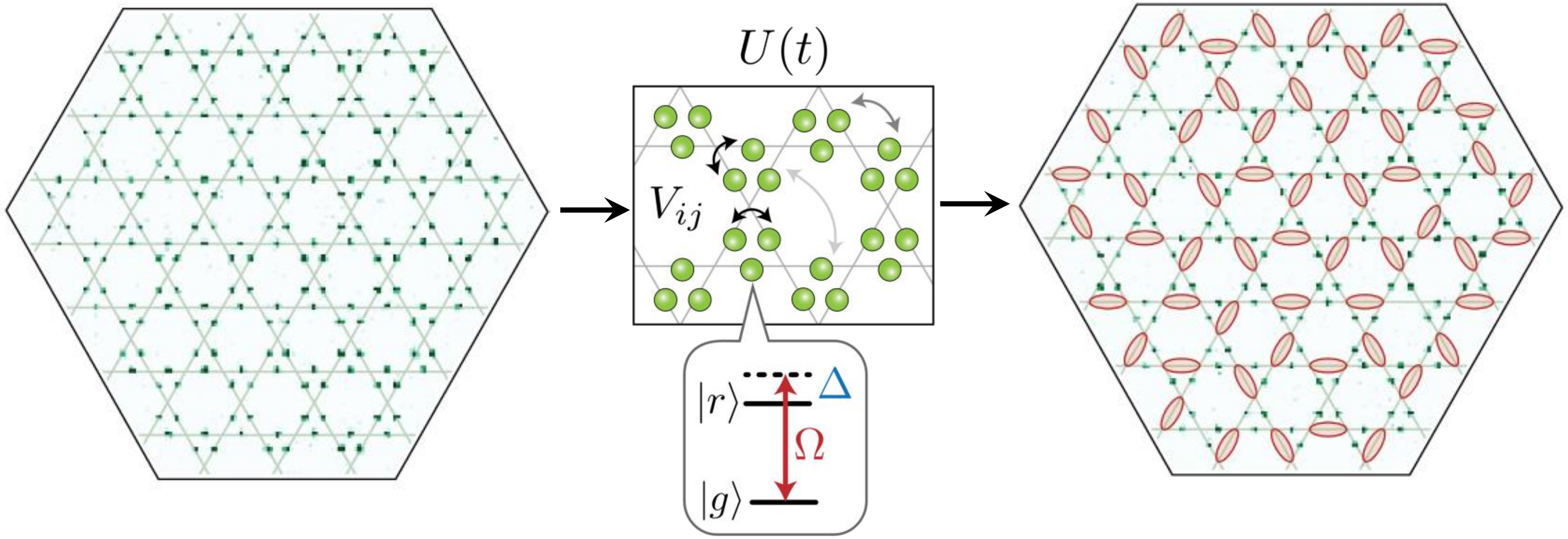
# Exploring new scientific frontiers with programmable atom arrays




May 3rd, 2021

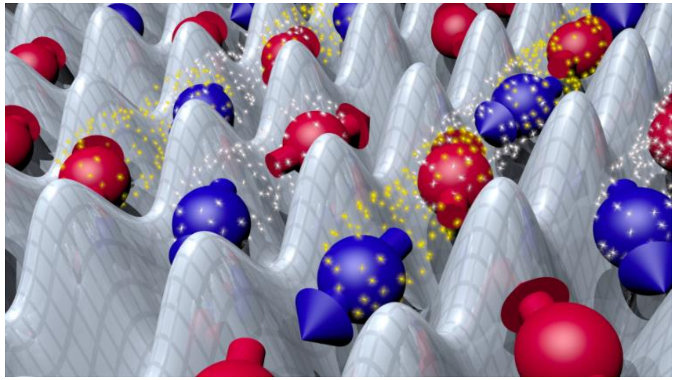
Giulia Semeghini

Lukin group - Harvard University

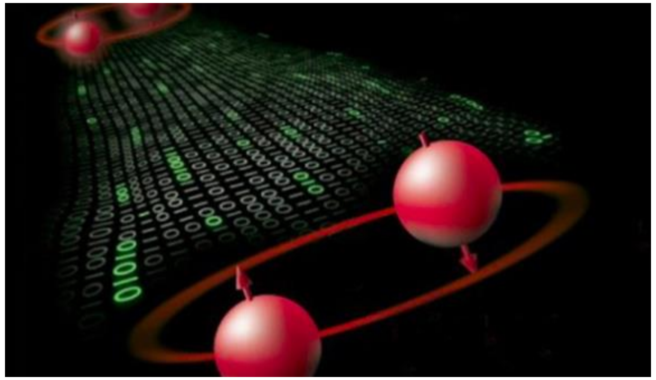
# Frontiers of Quantum Science

Can we harness the power of quantum systems to learn new things about nature and develop new technology?

Quantum simulation



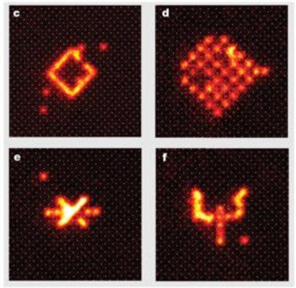
Quantum computing

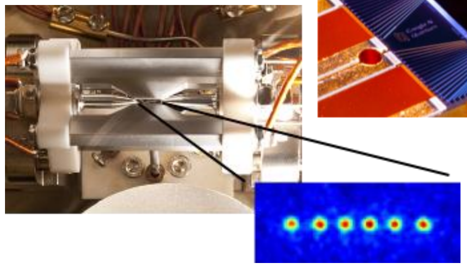


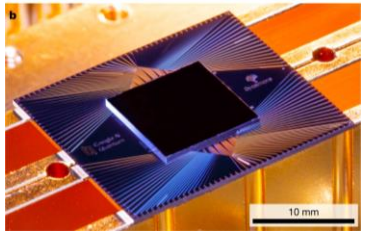
# Frontiers of Quantum Science

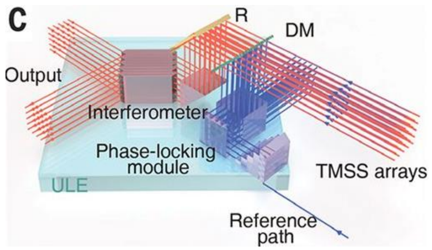
Images from: Blatt, Bloch, Google, Jian-Wei Pan groups

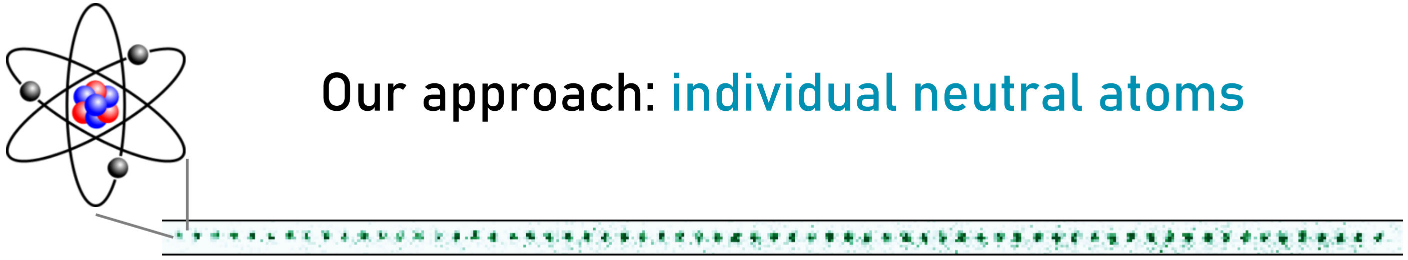
Several platforms: ions, atoms, superconductors, photons, defects…







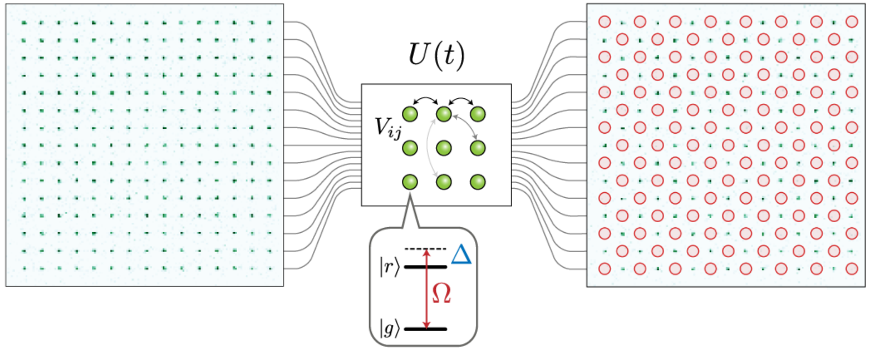



Our approach: individual neutral atoms

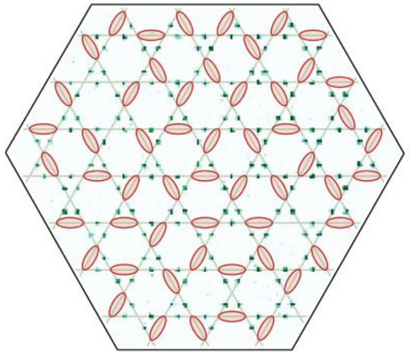
- Excellent isolation from the environment
- Well-developed toolbox:
  - Initialization, readout
  - Strong, switchable Rydberg interactions
- Highly scalable defect-free arrays (hundreds of atoms)
- Tunable system parameters

# Outline

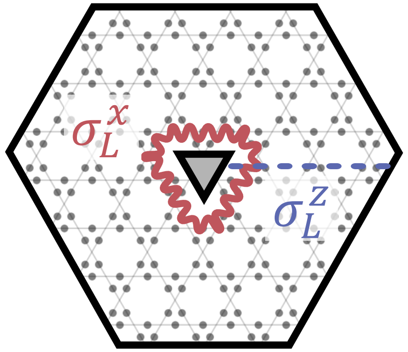
Programmable arrays of Rydberg atoms




Quantum spin liquid phase on a frustrated lattice

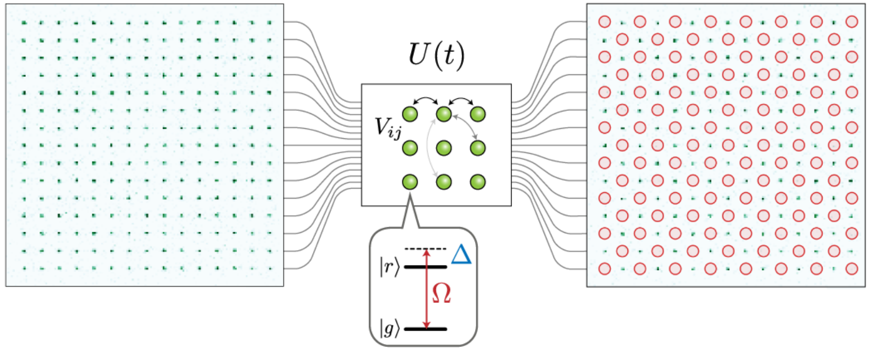


First steps towards a topological qubit



# Outline

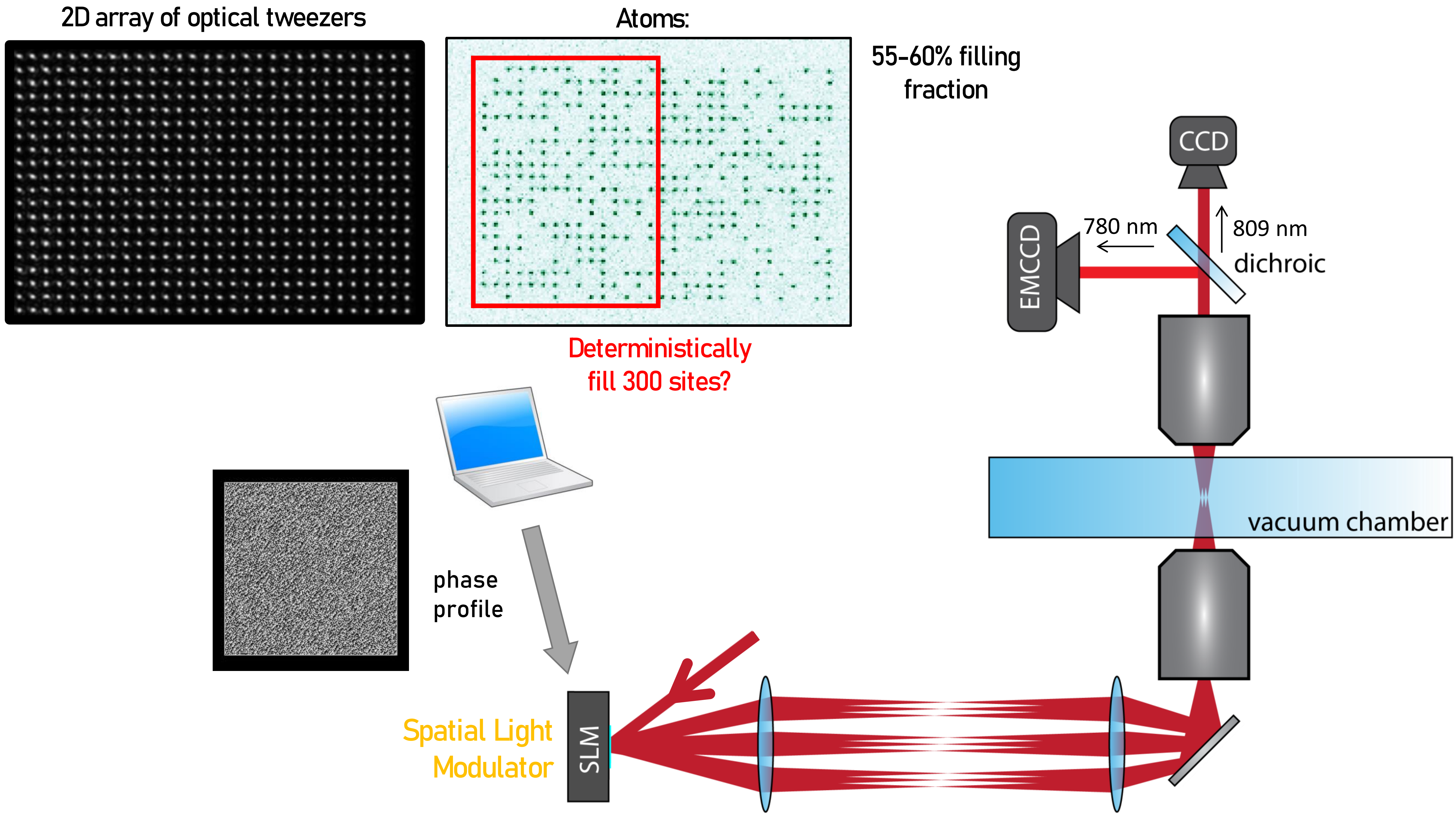
## Programmable arrays of Rydberg atoms

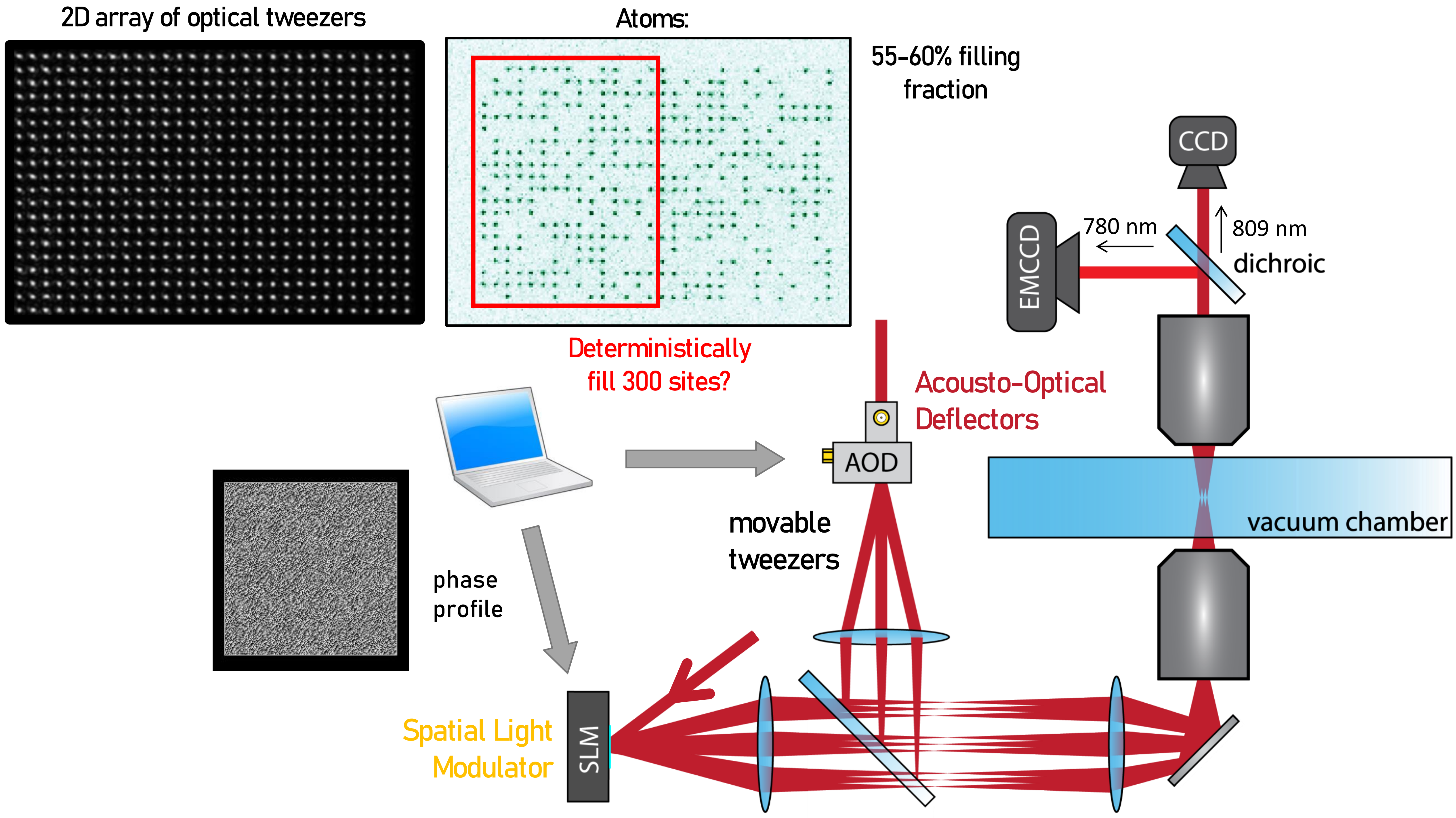



## Quantum spin liquid phase on a frustrated lattice



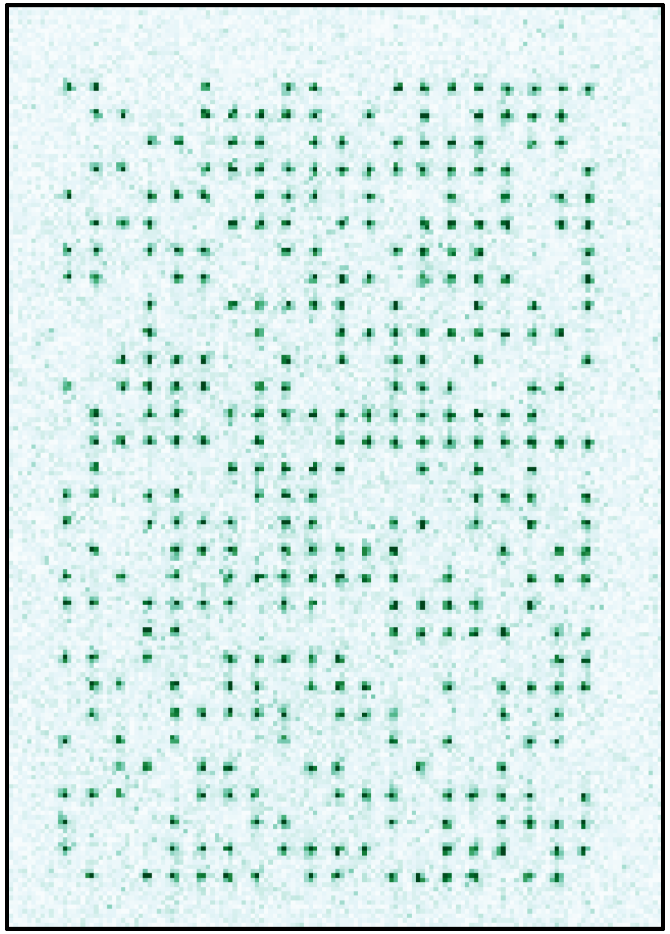
## First steps towards a topological qubit


2D array of optical tweezers
Atoms:
55-60% filling
fraction
Deterministically
fill 300 sites?
CCD
780 nm
809 nm
dichroic
EMCCD
vacuum chamber
phase
profile
Spatial Light
Modulator
SLM

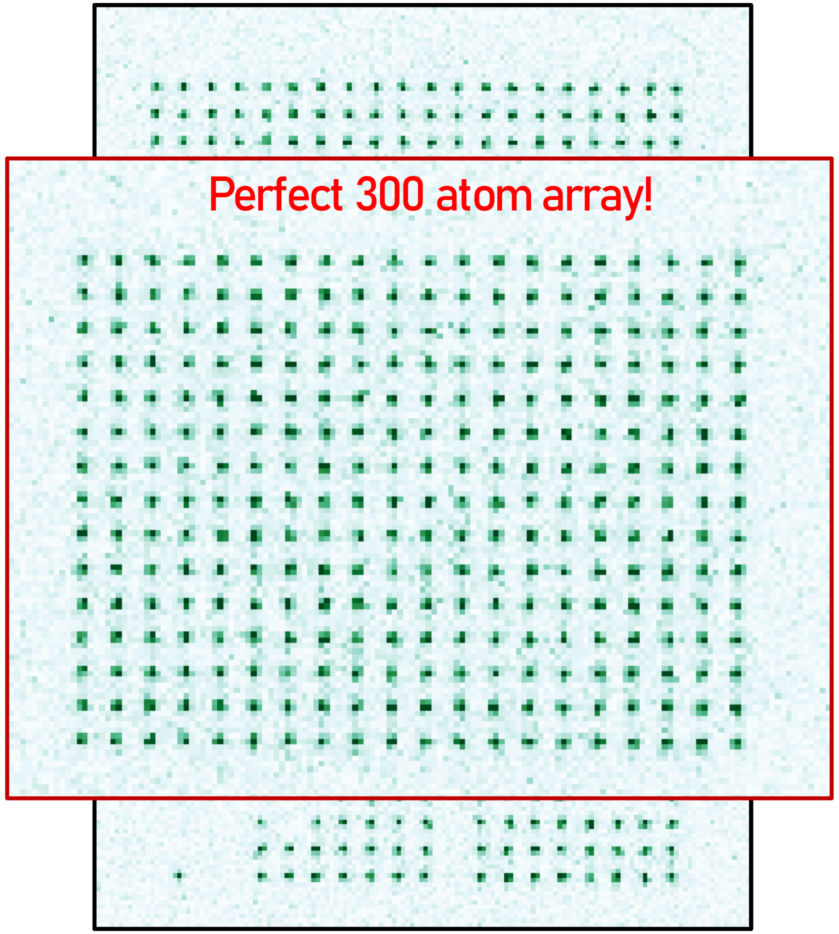


2D array of optical tweezers
Atoms:
55-60% filling fraction
CCD
780 nm
809 nm
EMCCD
dichroic
Deterministically fill 300 sites?
Acousto-Optical Deflectors
AOD
vacuum chamber
movable tweezers
phase profile
Spatial Light Modulator
SLM

Initial loading:



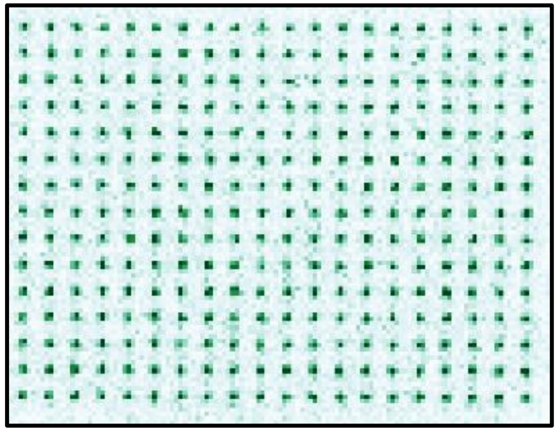
After sorting:



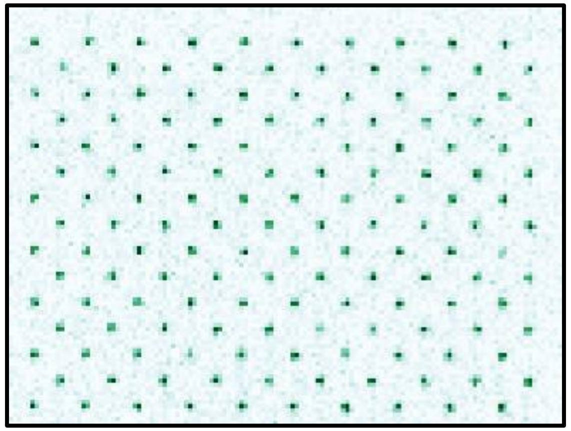

> 99% filling

# Programmable 2D arrays

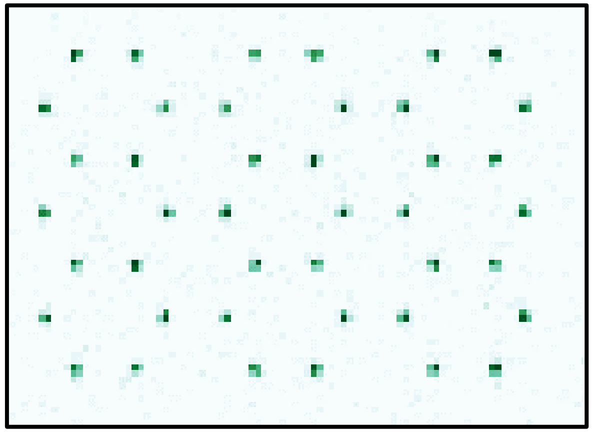
Square



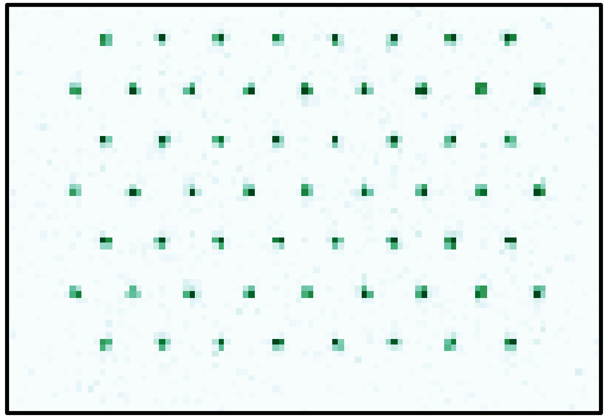
Tilted Square



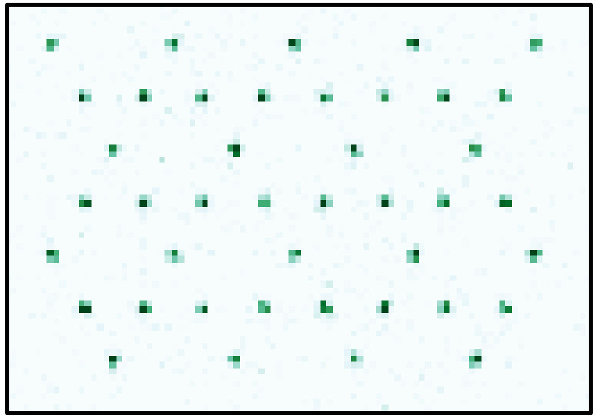
Honeycomb



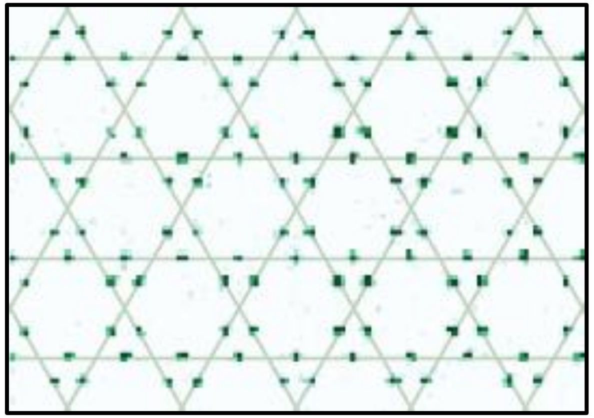
Triangular



Kagome



Link-kagome

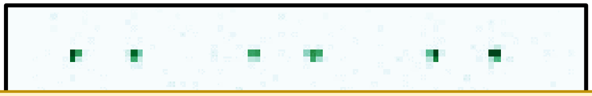


# Programmable 2D arrays

Square

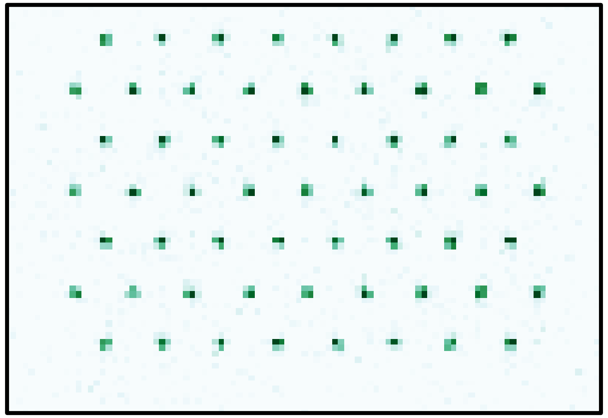
Tilted Square

Honeycomb

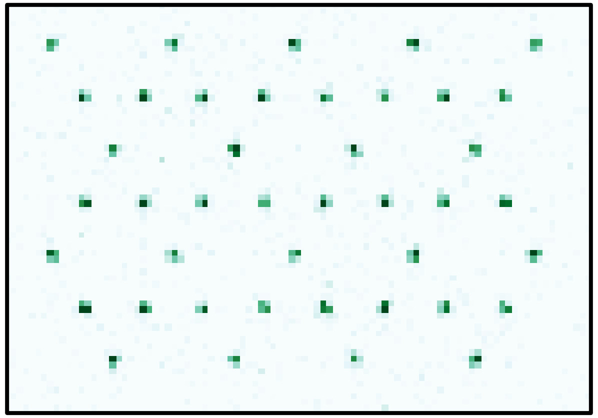


## 1) Programmable 2D arrays of neutral atoms

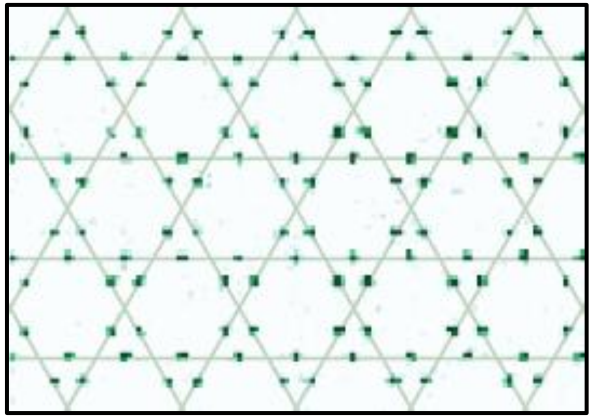
Triangular



Kagome

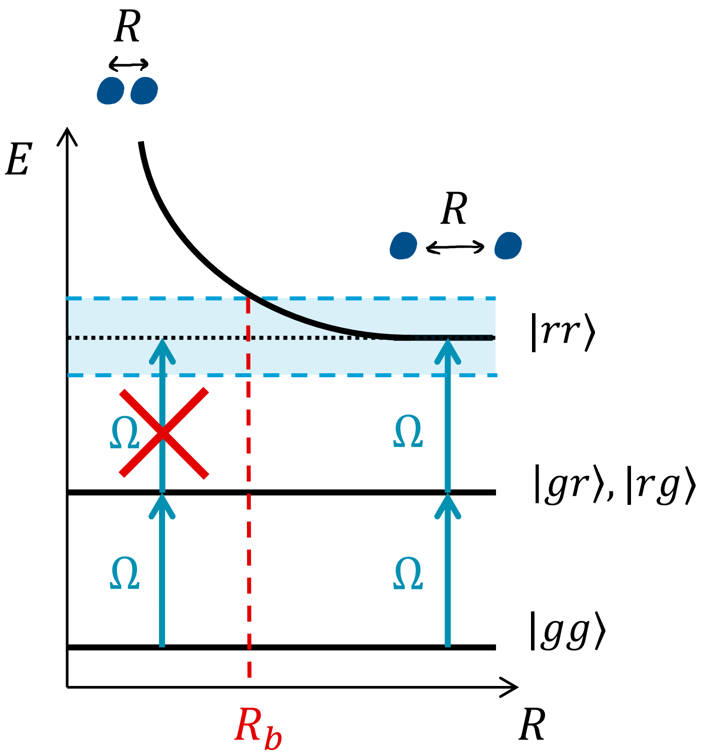


Link-kagome



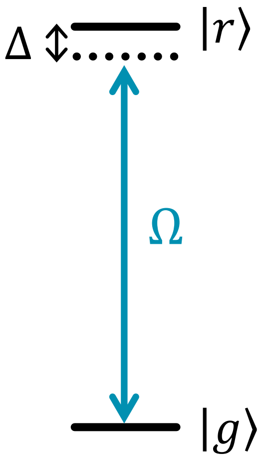
# Rydberg states and long-range interactions

## Rydberg blockade




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

excitation to Rydberg state:

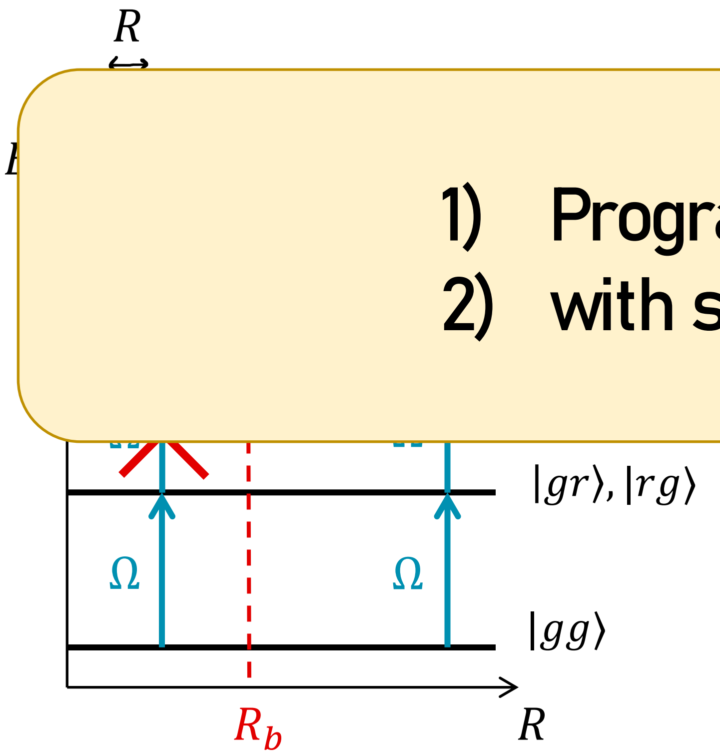




van der Waals interactions $\propto 1/R^6$

# Rydberg states and long-range interactions

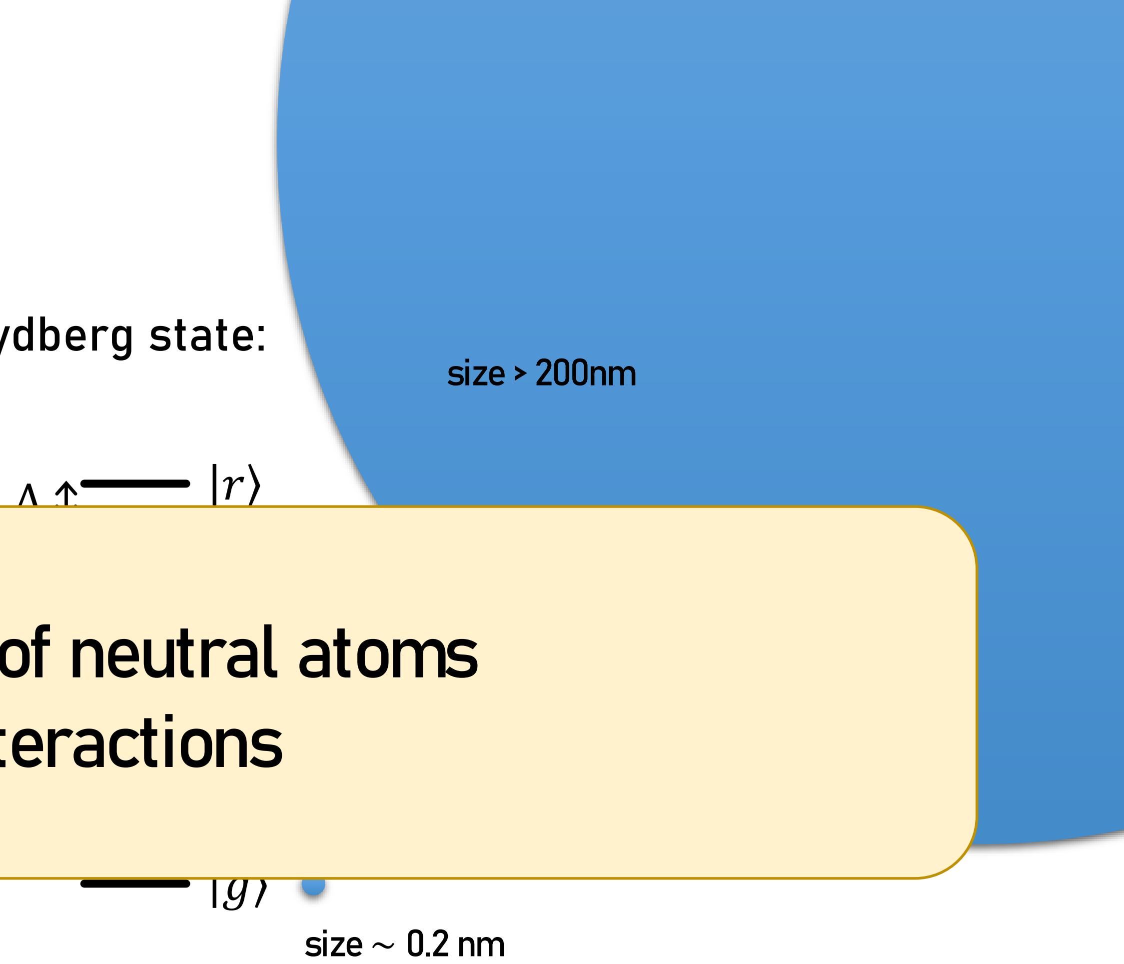
Rydberg blockade




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

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

excitation to Rydberg state:



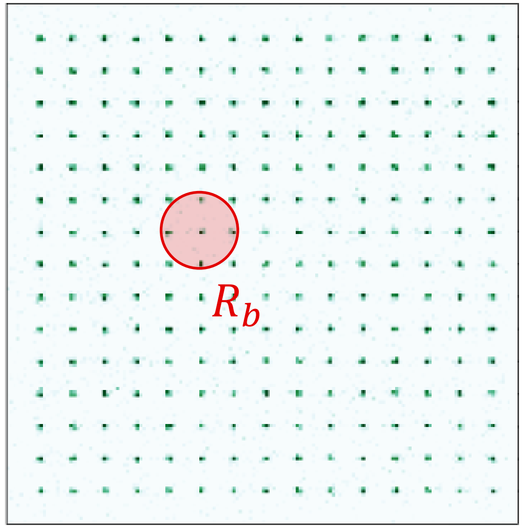

van der Waals interactions $\propto 1/R^6$

# 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, arXiv:2012.12281 (2020)

P. Scholl et al., Programmable quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms, arXiv:2012.12268 (2020)

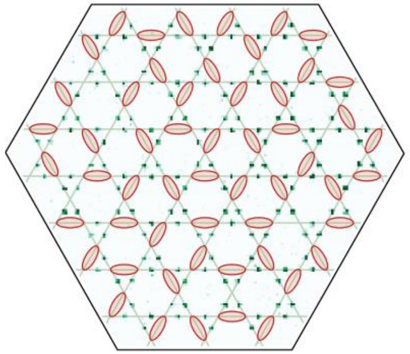
D. Bluvstein et al., Controlling quantum many-body dynamics in driven Rydberg atom arrays, Science 371, 1355 (2021)

# Outline

Programmable arrays of Rydberg atoms




Quantum spin liquid phase on a frustrated lattice



First steps towards a topological qubit

# Quantum spin liquids

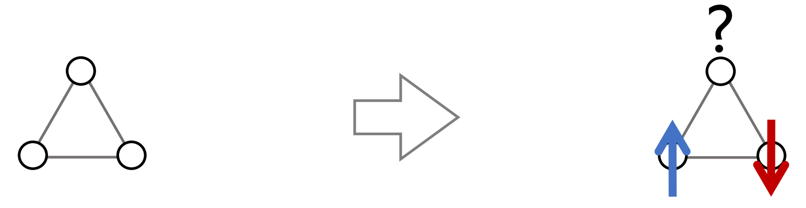
P. W. Anderson, *Science* **235** (1987)

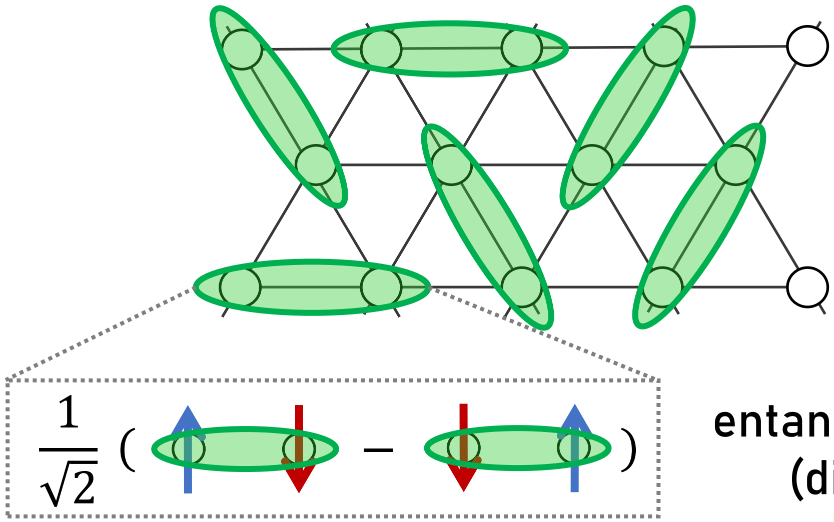
**The Resonating Valence Bond State in $La_2CuO_4$ and Superconductivity**

P. W. Anderson

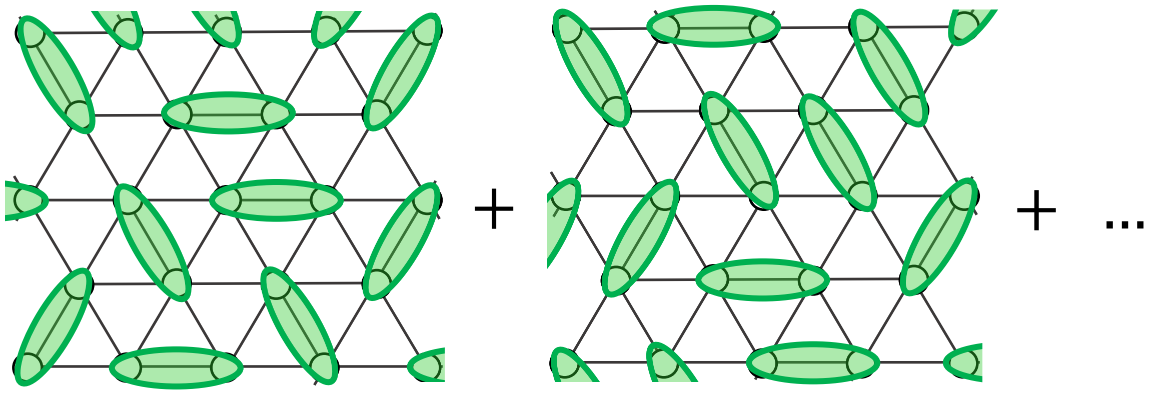
The oxide superconductors, particularly those recently discovered that are based on $La_2CuO_4$, have a set of peculiarities that suggest a common, unique mechanism: they tend in every case to occur near a metal-insulator transition into an odd-electron insulator with peculiar magnetic properties. This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

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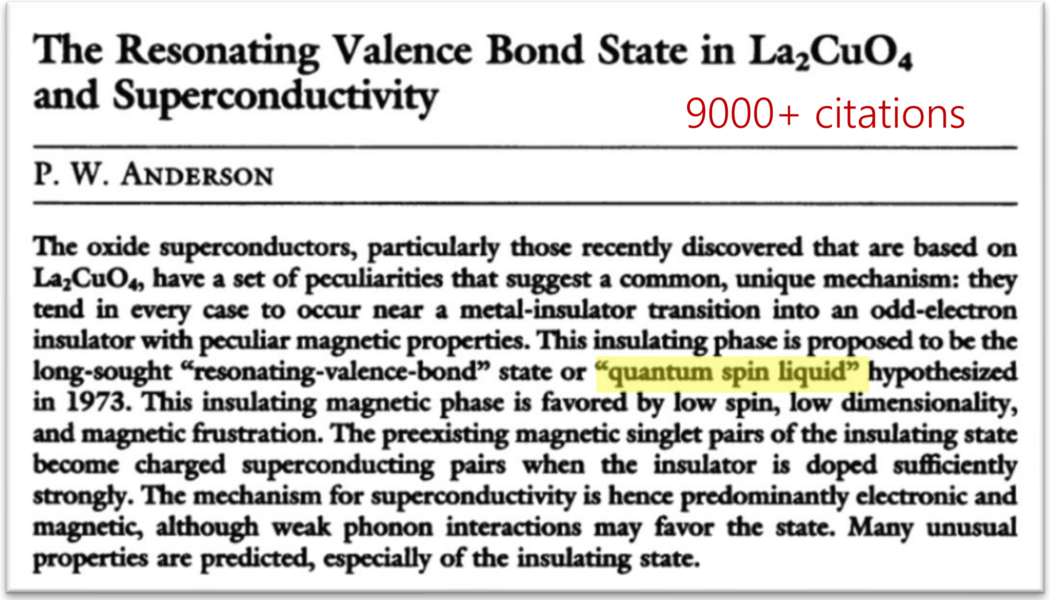

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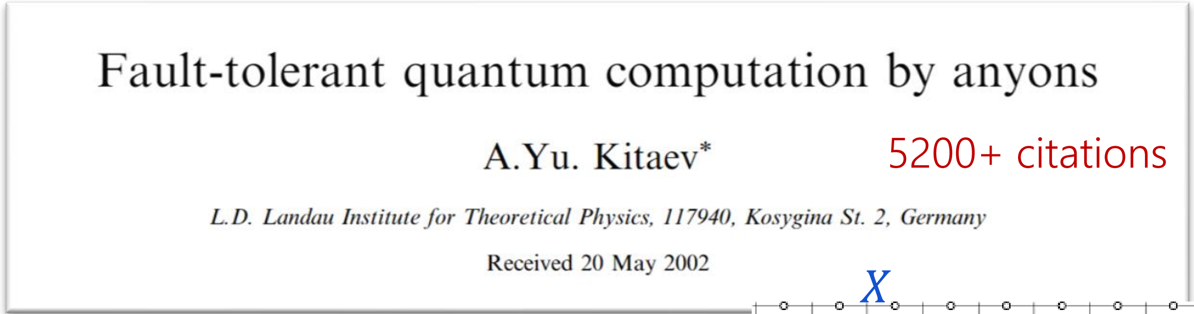
9000+ citations



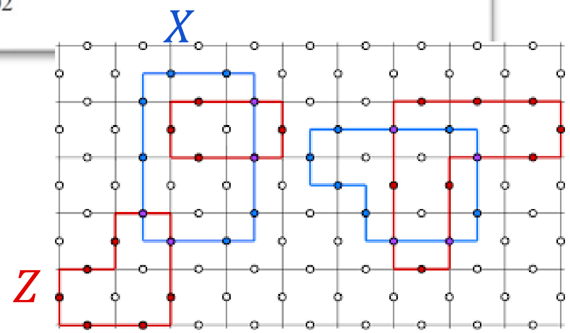
Fault-tolerant quantum computation by anyons

A.Yu. Kitaev*

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

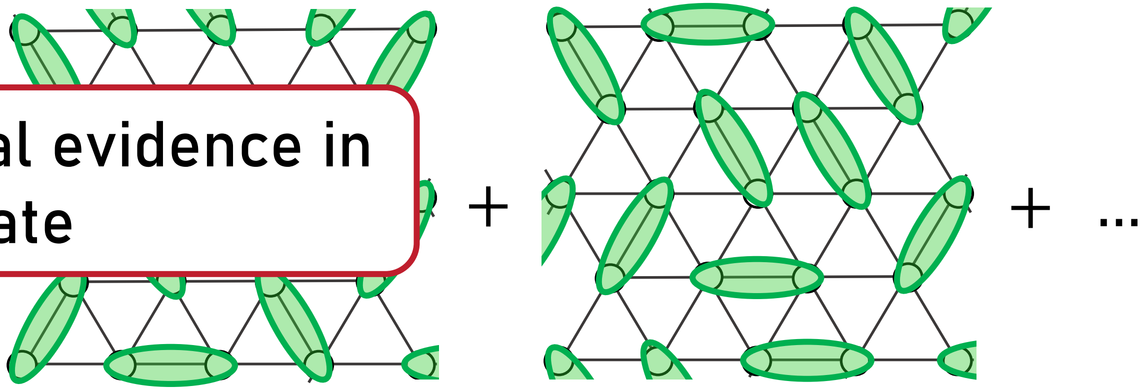
Received 20 May 2002

5200+ citations




- no spatial order
- topological order
- long-range quantum ent
- 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

# Towards topological phases in frustrated lattices of Rydberg atoms

Subir Sachdev

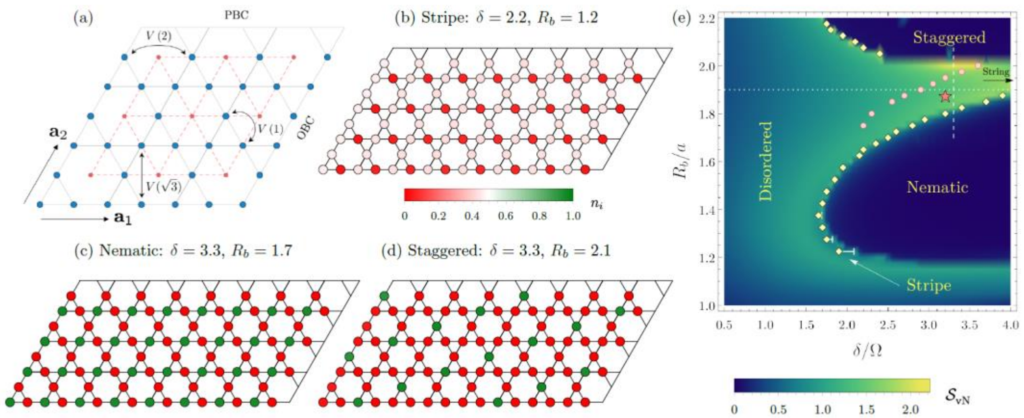
Wen Wei Ho

Rhine Samajdar

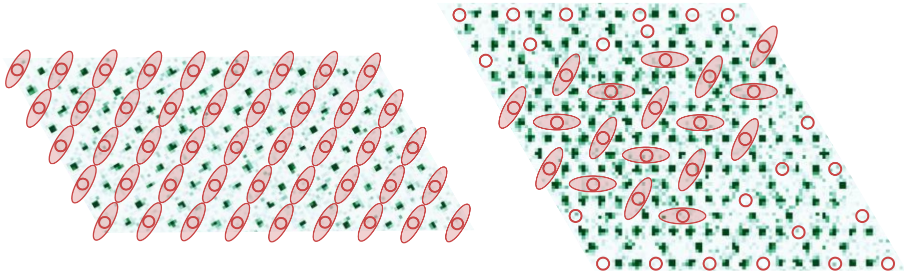
Hannes Pichler

**Quantum phases of Rydberg atoms on a kagome lattice**

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




Emergent solid and liquid 'dimer' phases in frustrated lattices

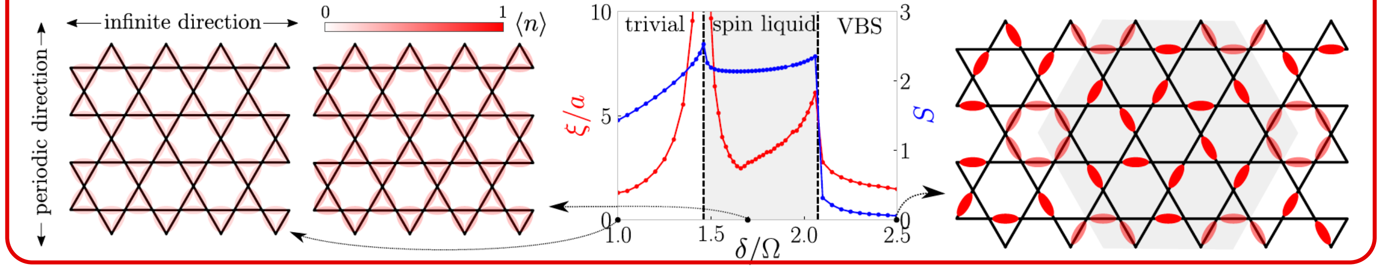


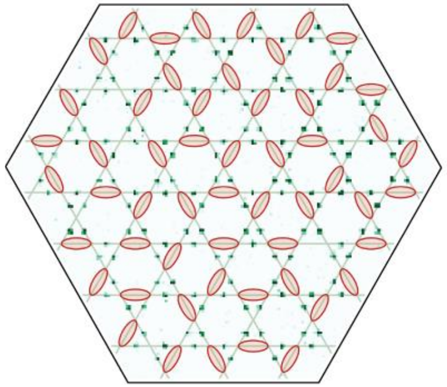
Ashvin Vishwanath

Ruben Verresen

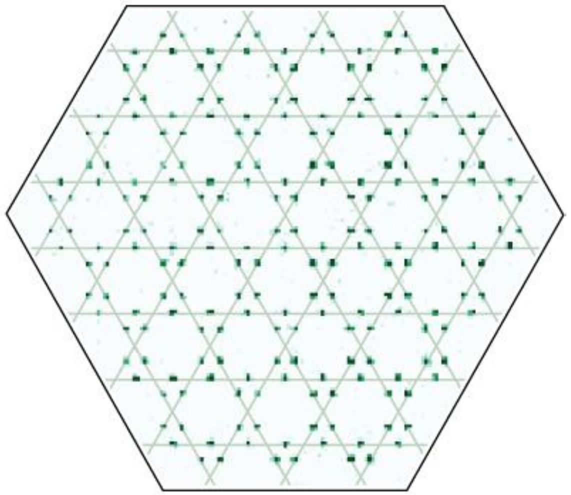
**Prediction of Toric Code Topological Order from Rydberg Blockade**

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

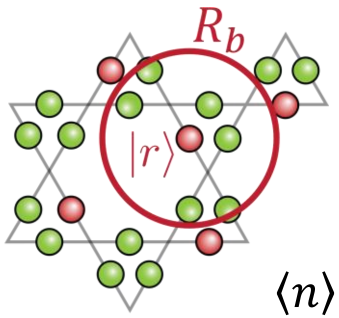


# Rydberg atoms on a ruby lattice – dimer model

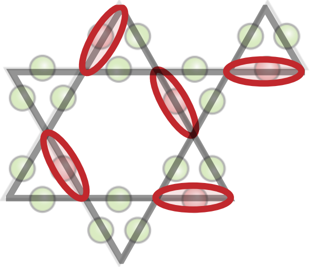


219 atoms

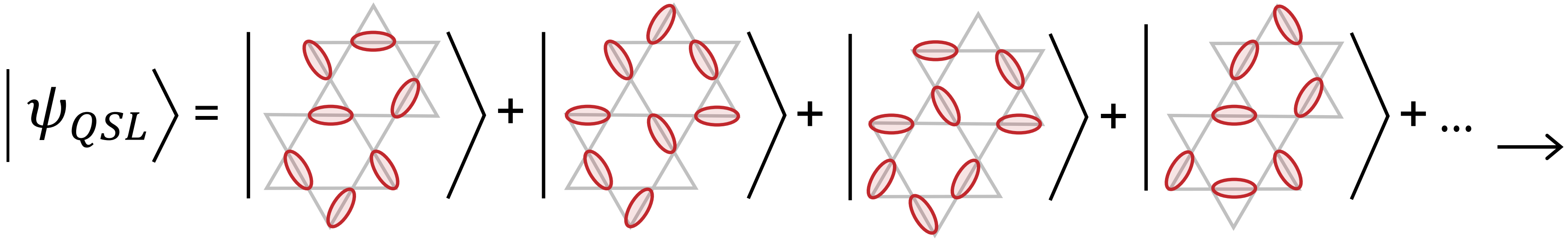


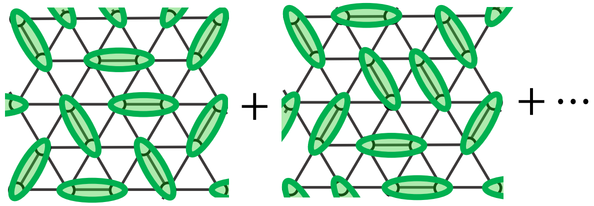

$\langle n \rangle = 1/4$

dimer model



quantum spin liquid state: superposition of all dimer coverings




RVB state

$\mathbb{Z}_2$ topological order

R. Verresen, M. Lukin and A. Vishwanath, arXiv:2011.12310 (2020)
G. Semeghini et al., arXiv:2104.04119 (2021)
P. Anderson, Materials Research Bulletin 8 (1973)

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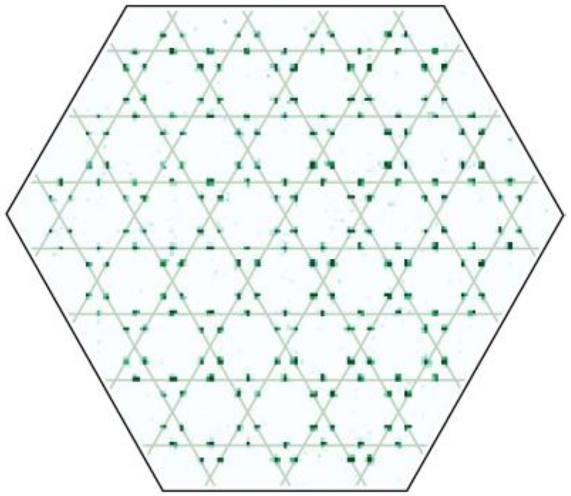

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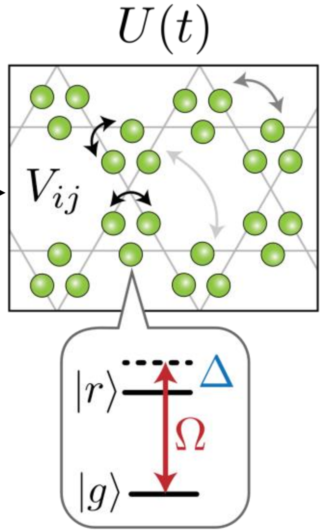


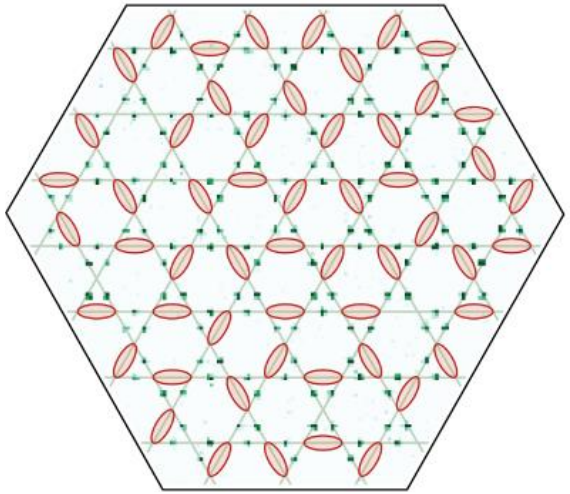

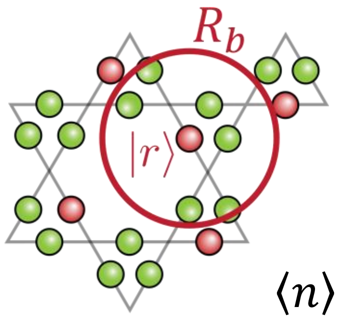


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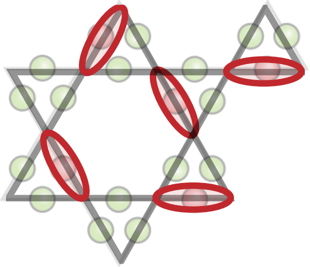
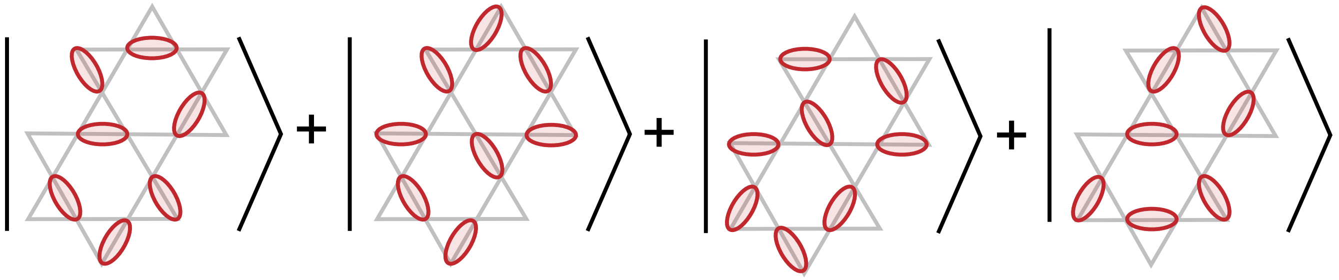
dimer model

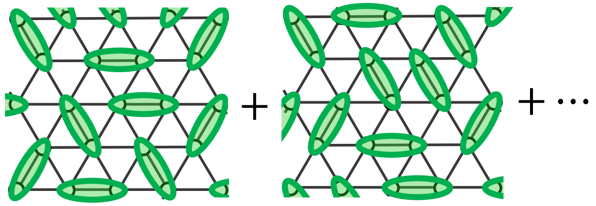


quantum spin liquid state: superposition of all dimer coverings

$|\psi_{QSL}\rangle$ =



+ ... $\longrightarrow$

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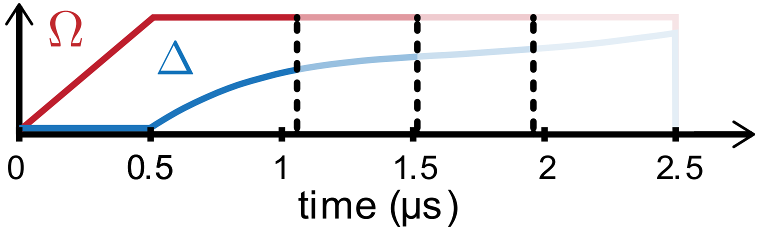
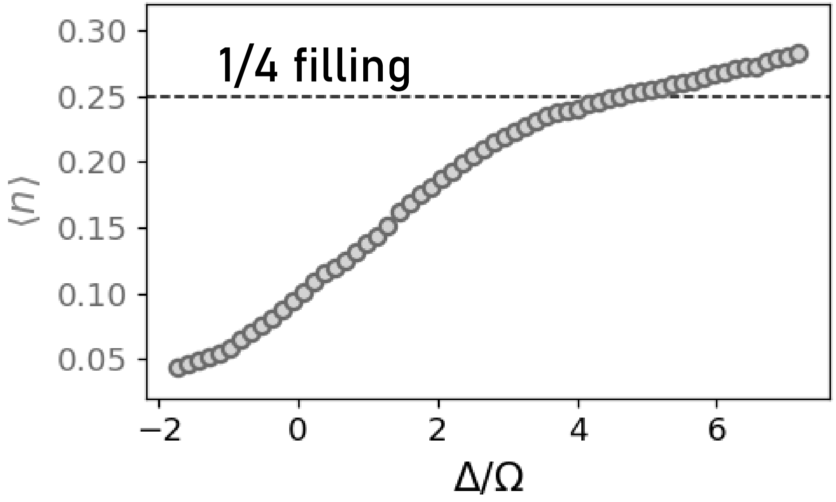
G. Semeghini et al., arXiv:2104.04119 (2021)

P. Anderson, Materials Research Bulletin 8 (1973)

# Quasi-adiabatic preparation of a dimer phase

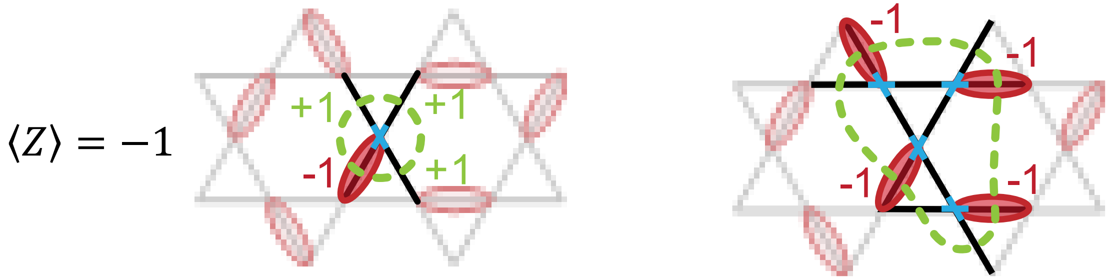
G. Semeghini et al., arXiv:2104.04119 (2021)



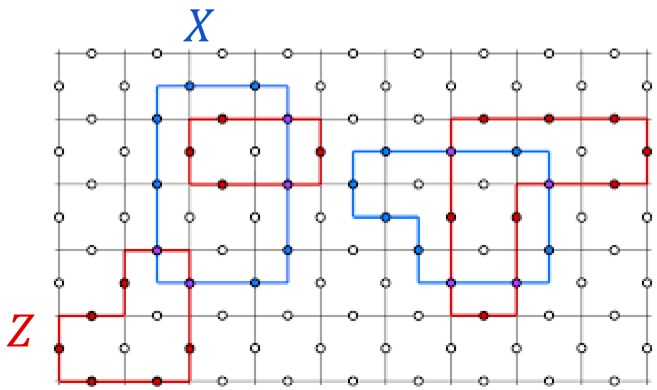

**diagonal string operator $Z$:**

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



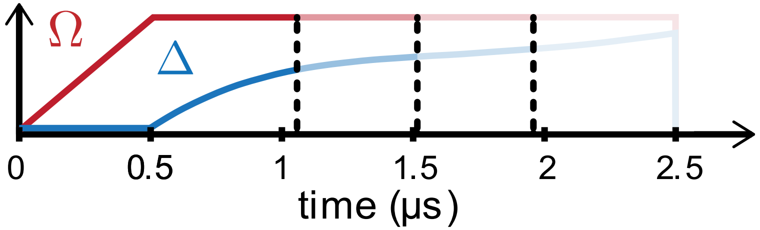

parity of dimers along a string

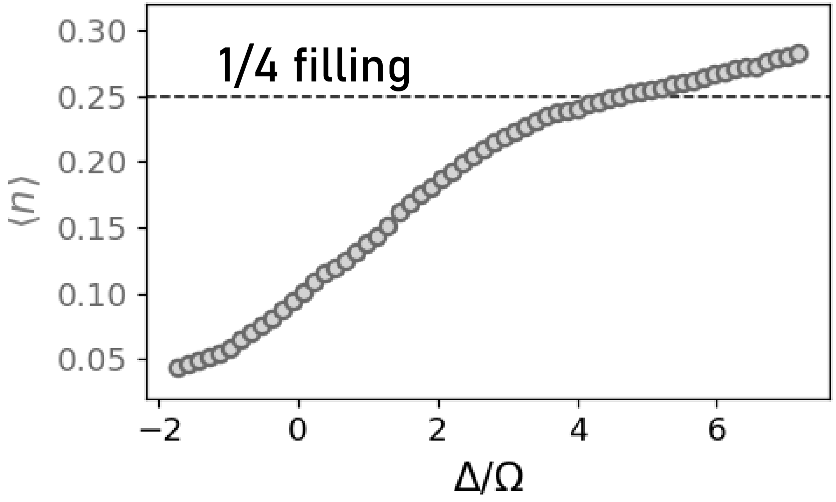
topological string operators associated with a $\mathbb{Z}_2$ quantum spin liquid (toric code)

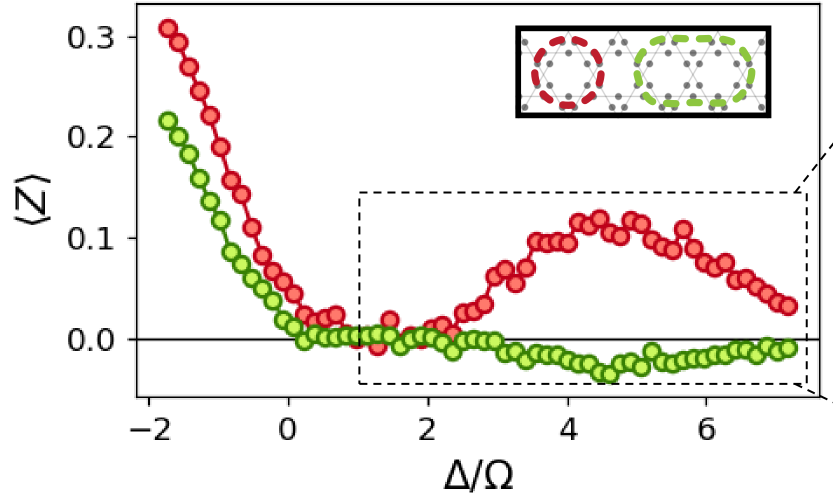


G. Semeghini et al., arXiv:2104.04119 (2021)

# Quasi-adiabatic preparation of a dimer phase

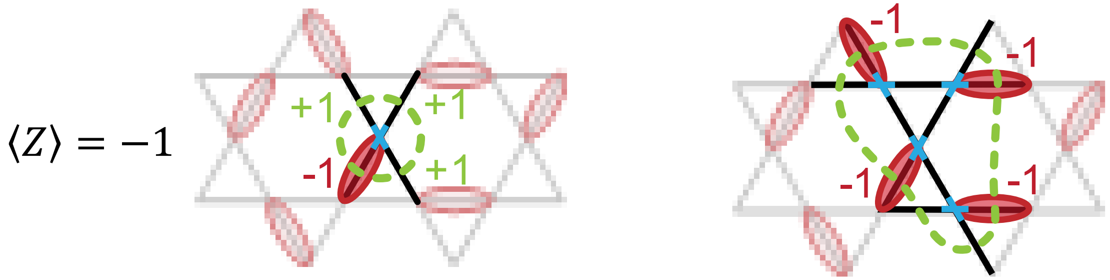


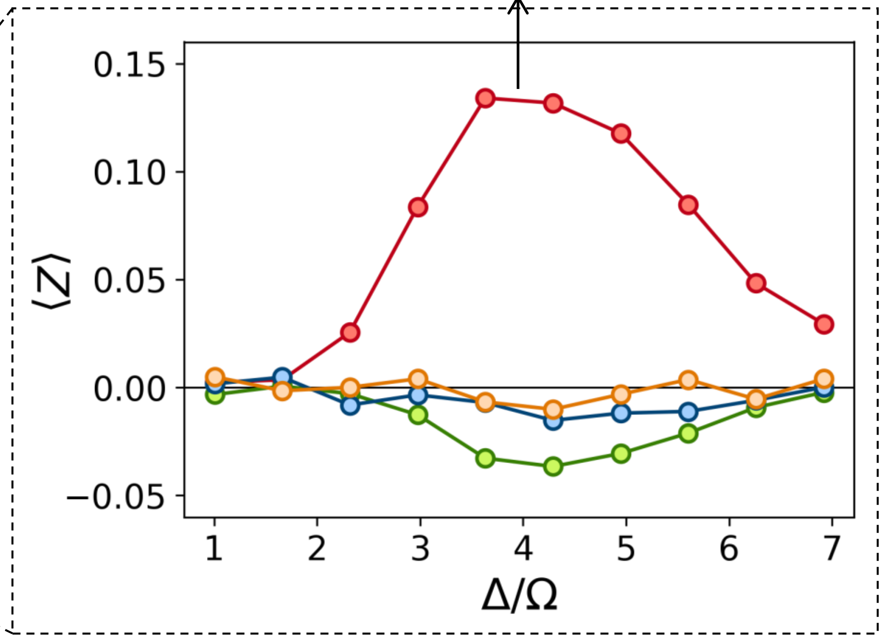

**diagonal string operator $Z$:**

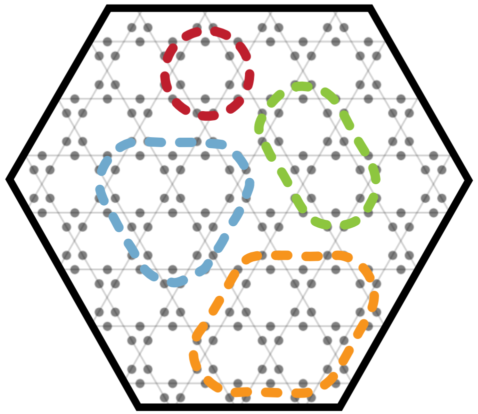
$\langle Z \rangle = (-1)^{\#\text{ enclosed vertices}}$



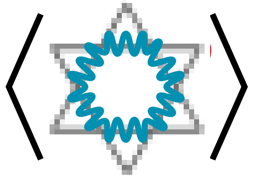

parity of dimers along a string

**transition into an approximate dimer phase**



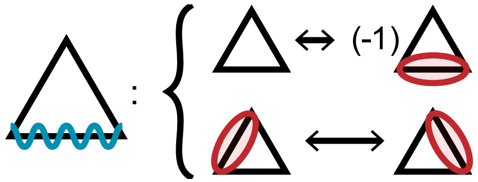



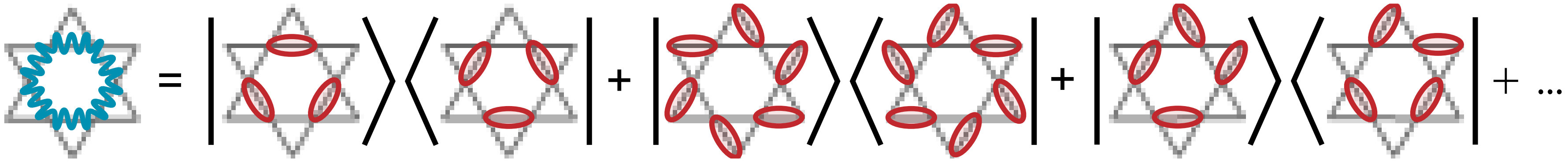
# Probing coherence: off-diagonal string operator



$> 0 \longrightarrow$ coherence between dimer coverings

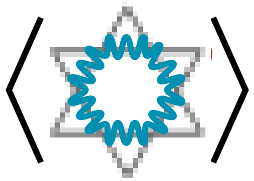
off-diagonal string operator $X$:



R. Verresen, M. Lukin and A. Vishwanath, arXiv:2011.12310 (2020)
G. Semeghini et al., arXiv:2104.04119 (2021)

# Probing coherence: off-diagonal string operator



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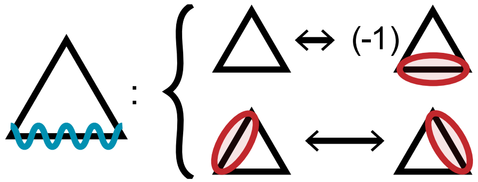
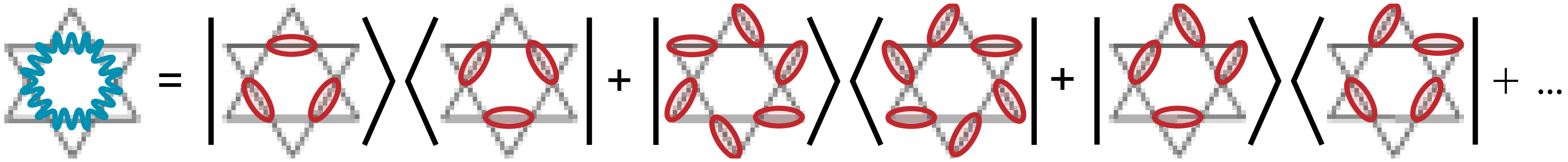
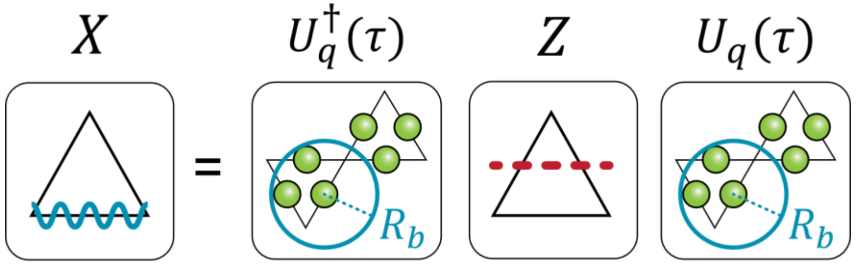
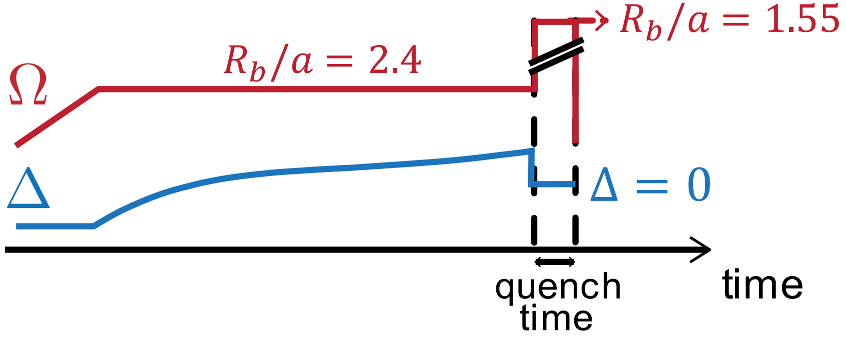



basis rotation to measure $X$:




R. Verresen, M. Lukin and A. Vishwanath, arXiv:2011.12310 (2020)
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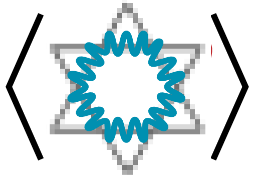
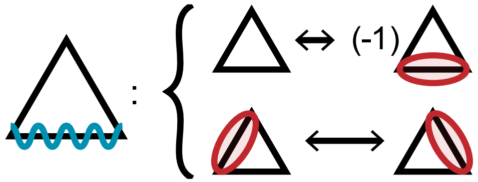
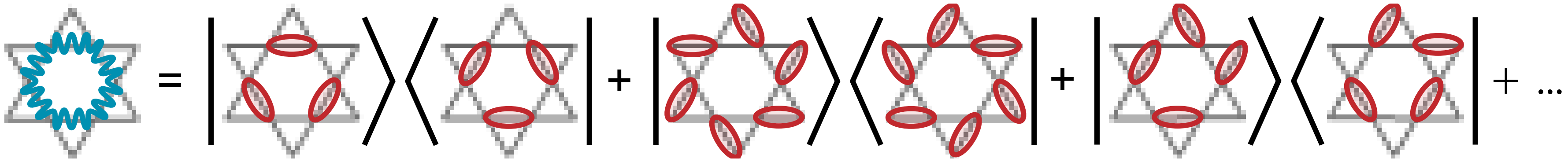
# Probing coherence: off-diagonal string operator




coherence between dimer coverings

off-diagonal string operator $X$:

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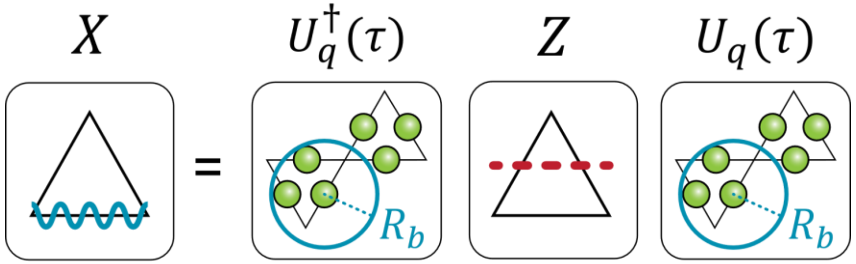
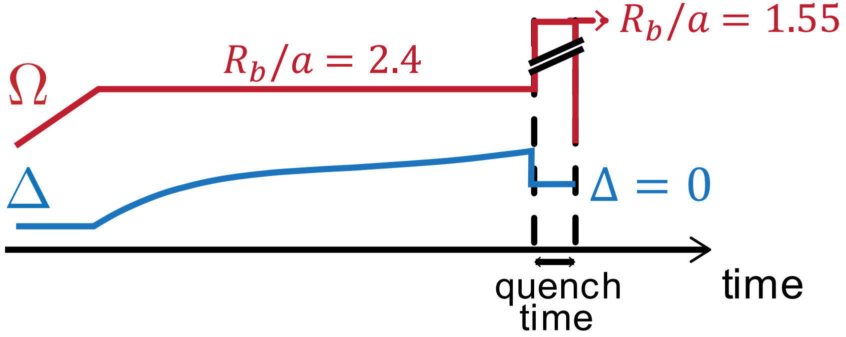
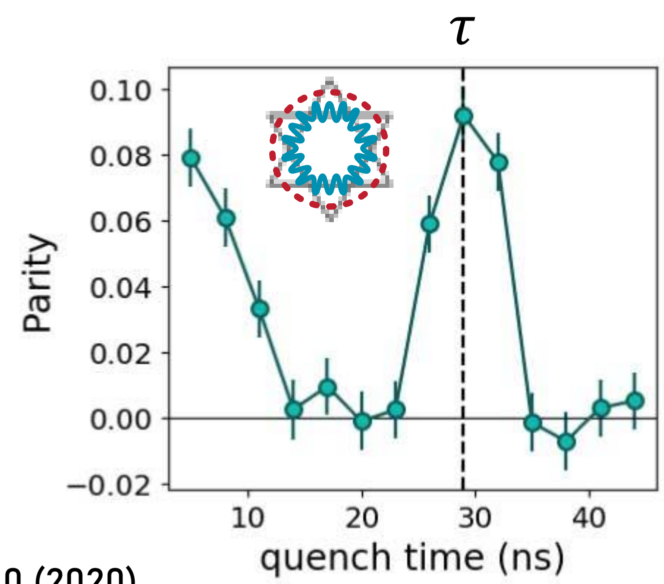
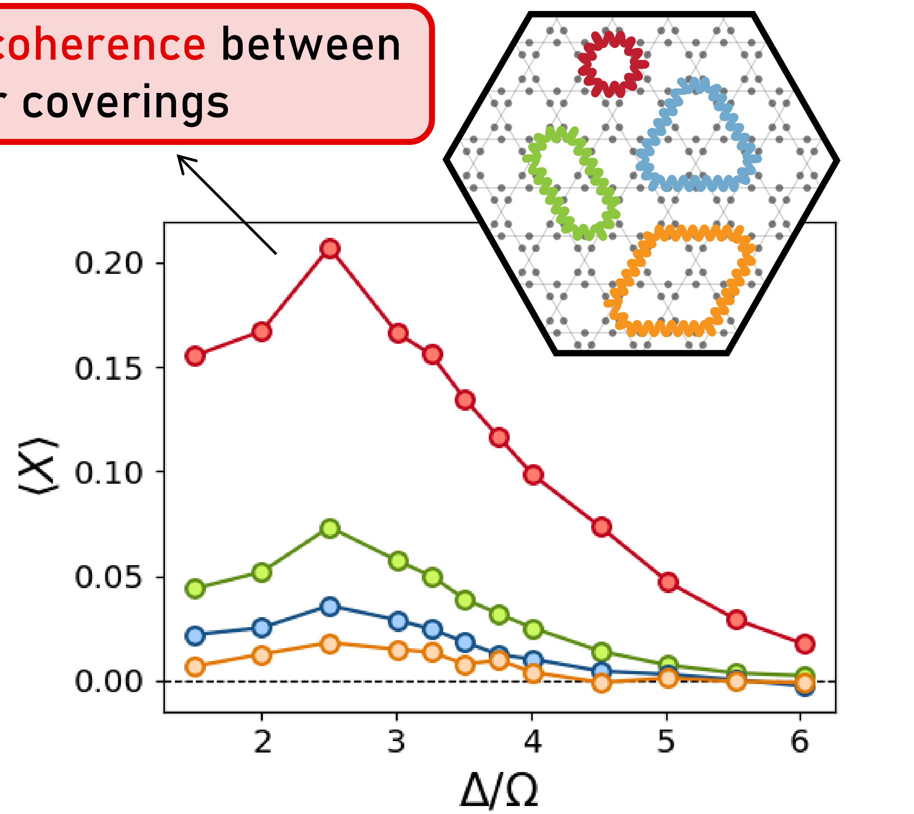



signature of coherence between dimer coverings




R. Verresen, M. Lukin and A. Vishwanath, arXiv:2011.12310 (2020)
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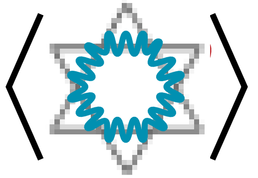
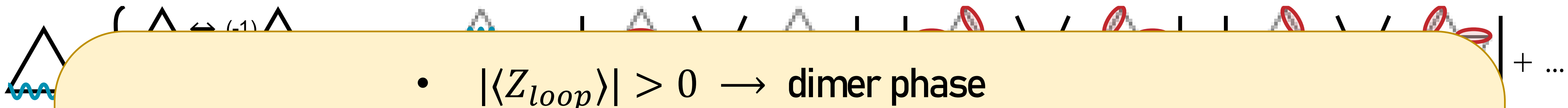
# Probing coherence: off-diagonal string operator

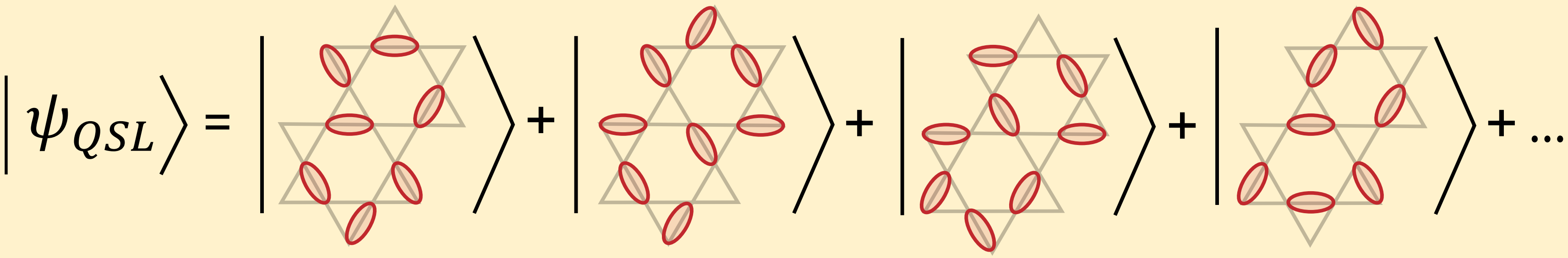



off-diagonal string operator $X$:



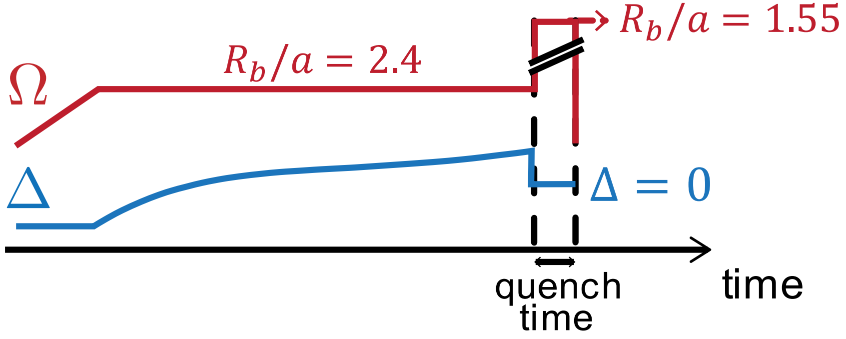

- $|\langle Z_{loop} \rangle| > 0 \longrightarrow$ dimer phase
- $\langle X_{loop} \rangle > 0 \longrightarrow$ coherent superposition

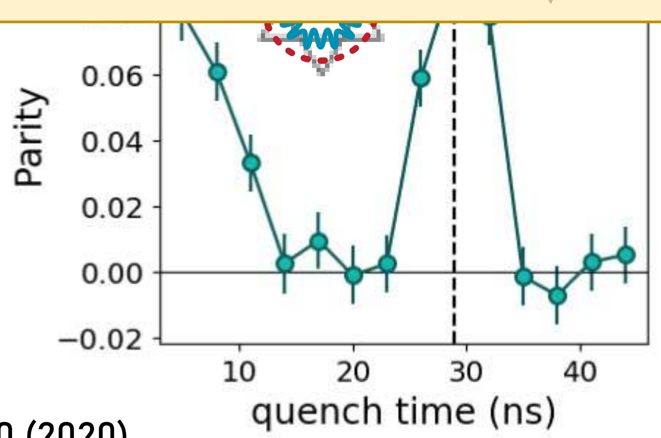
**onset of a quantum spin liquid phase!**

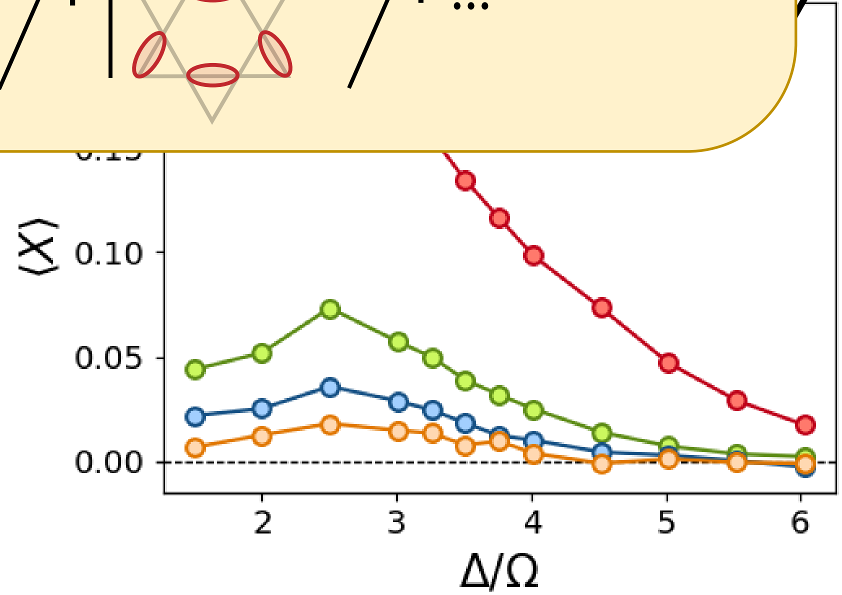



basis

$X$




R. Verresen, M. Lukin and A. Vishwanath, arXiv:2011.12310 (2020)
G. Semeghini et al., arXiv:2104.04119 (2021)

# Outline

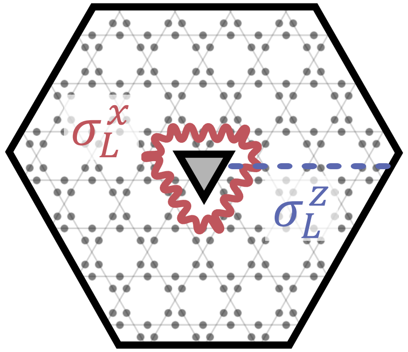
Programmable arrays
of Rydberg atoms




Quantum spin liquid phase
on a frustrated lattice



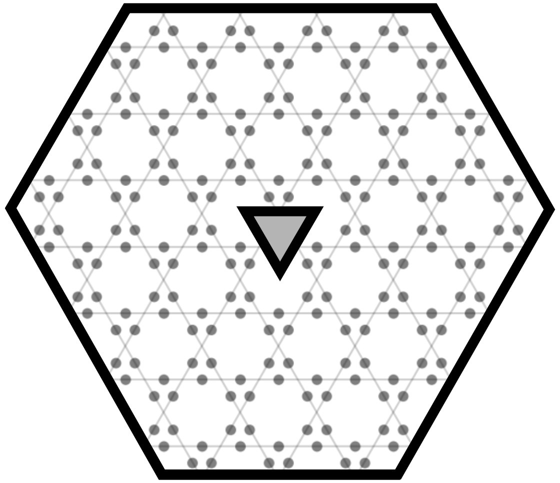
First steps towards a
topological qubit

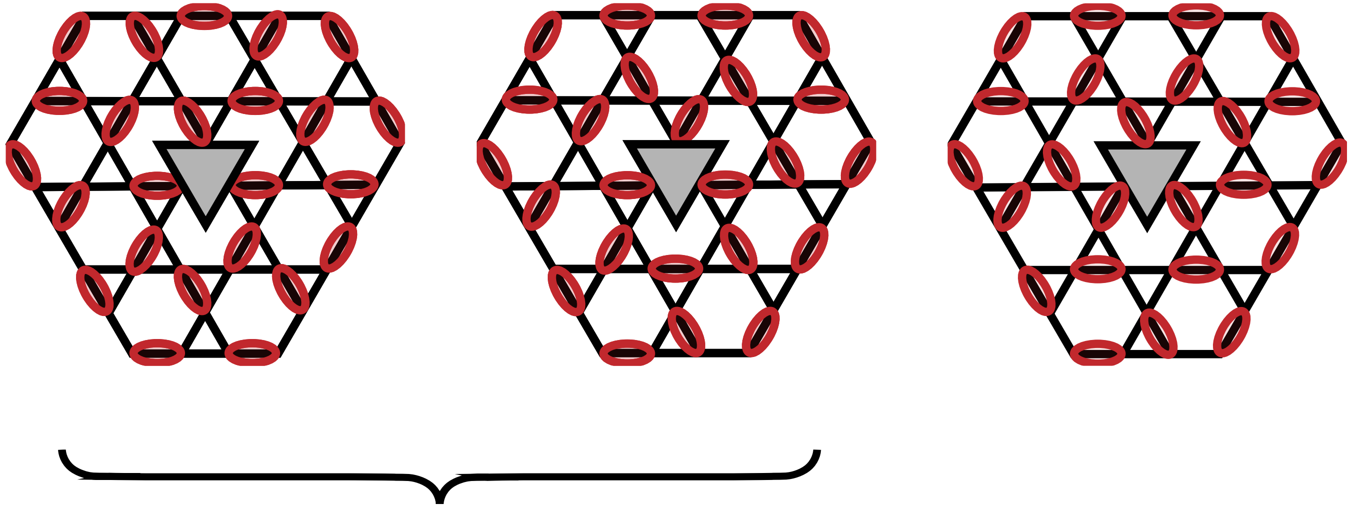


# Towards topological states – array with a hole

two distinct topological sectors

non-trivial topology





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

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

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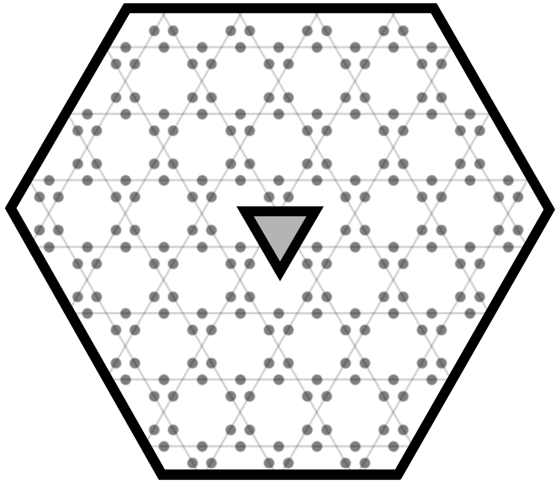

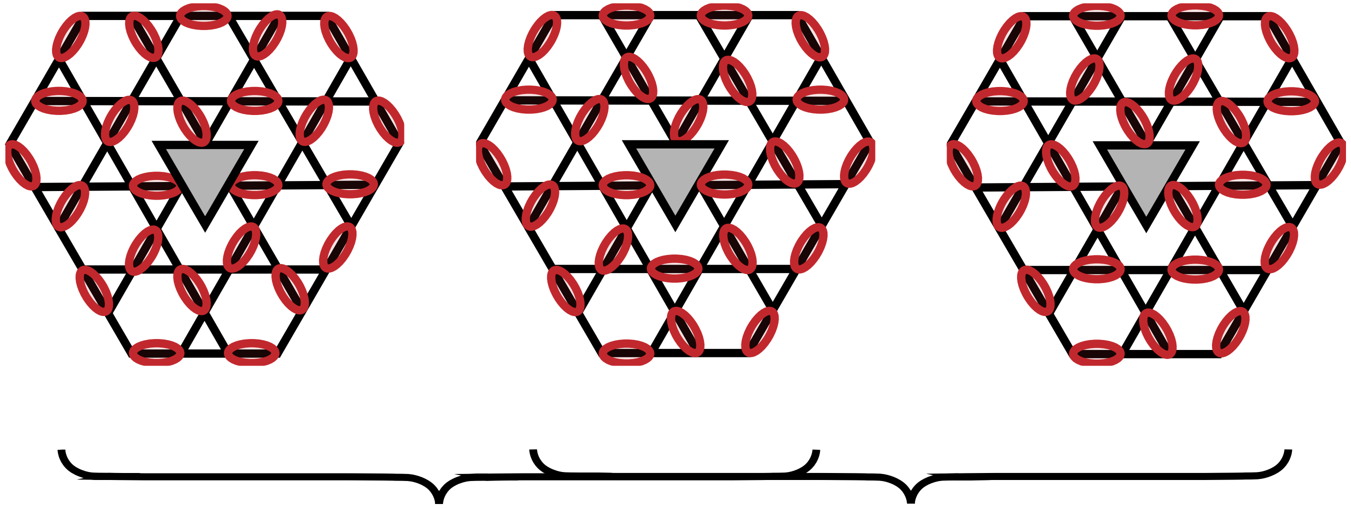

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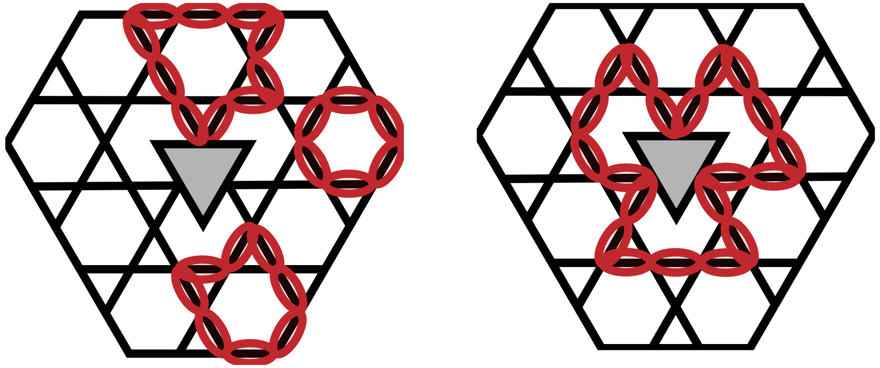


same
topological sector

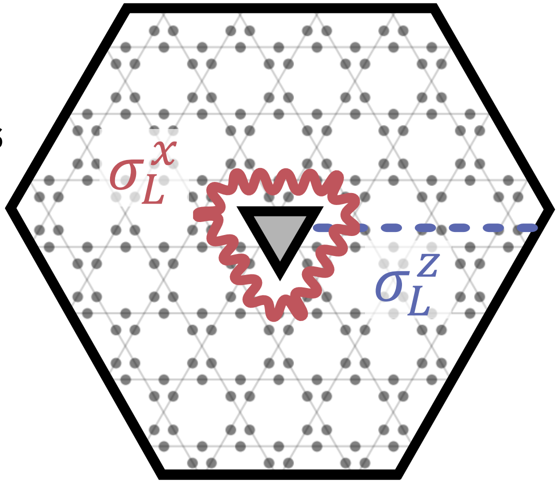
opposite
topological sectors

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

# Towards topological states – array with a hole

non-trivial topology

logical operators




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

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

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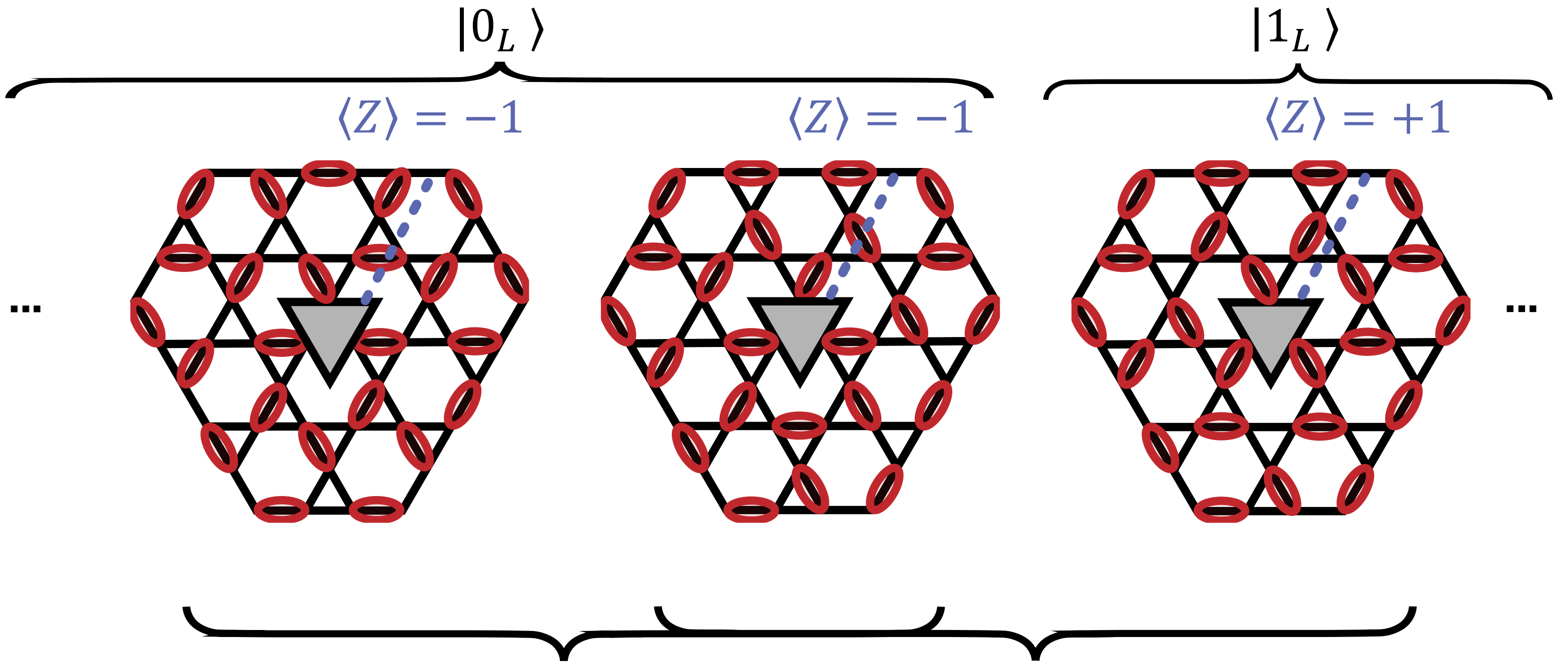
two distinct topological sectors

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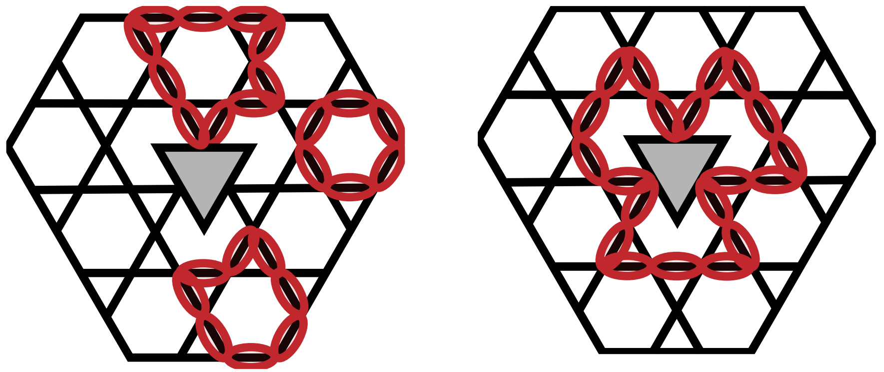

same
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opposite
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G. Semeghini et al., arXiv:2104.04119 (2021)

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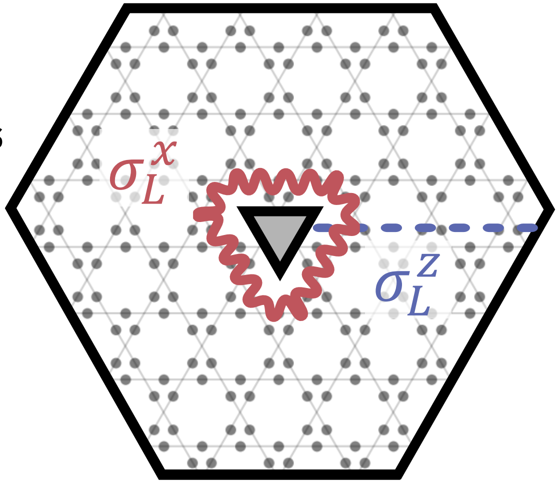
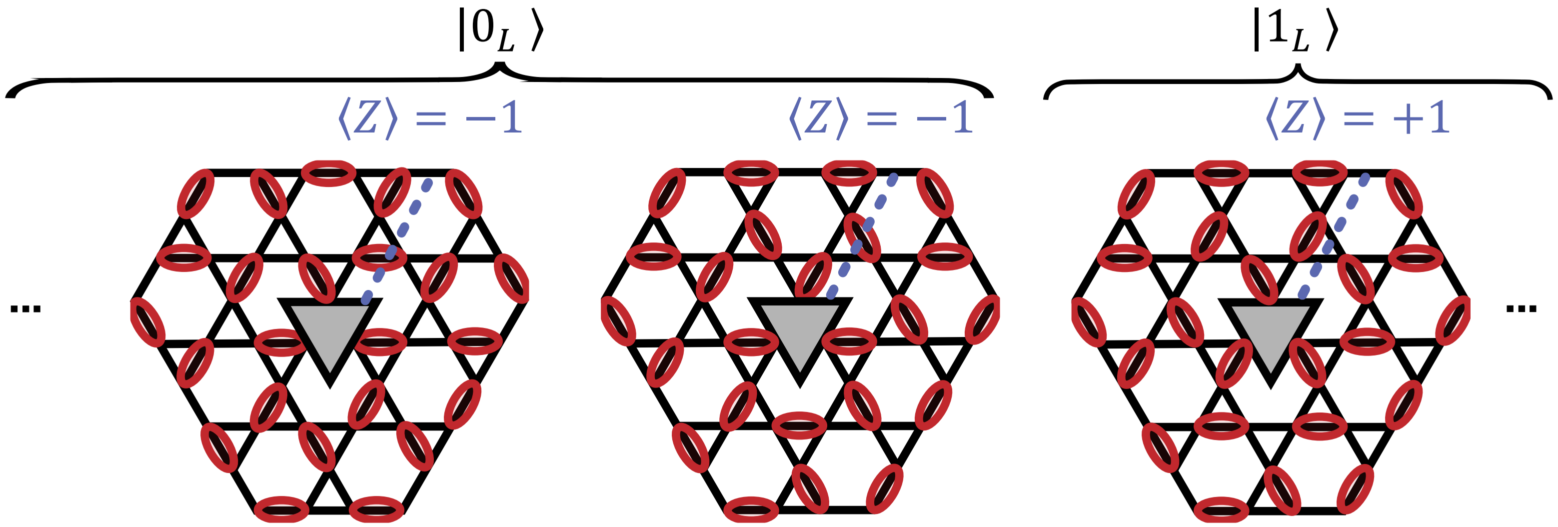
non-trivial topology

logical operators




two distinct topological sectors

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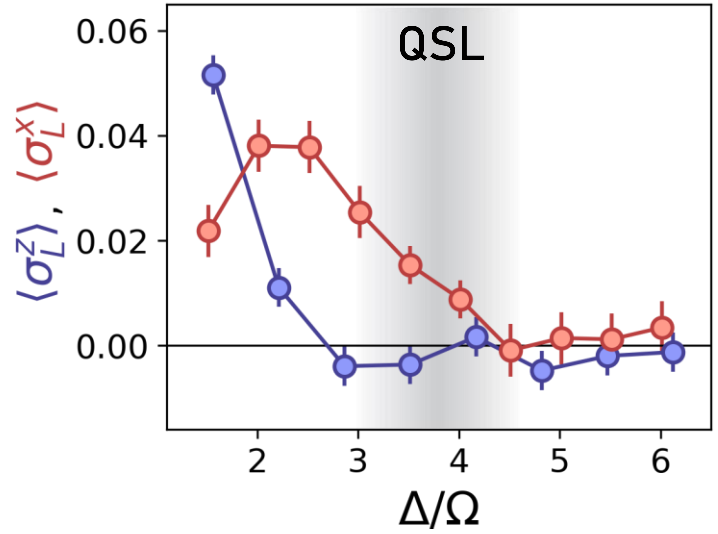


G. Semeghini et al., arXiv:2104.04119 (2021)

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non-trivial topology

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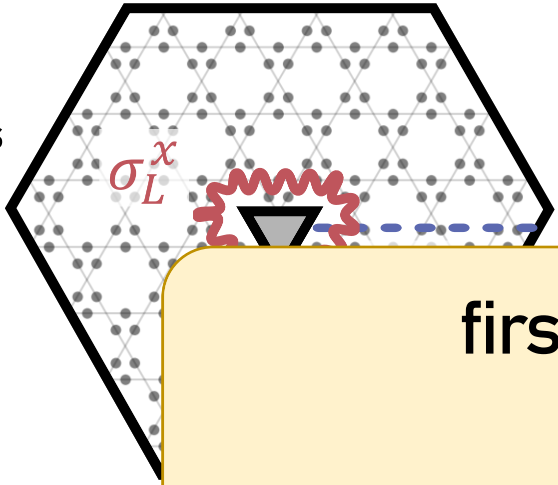
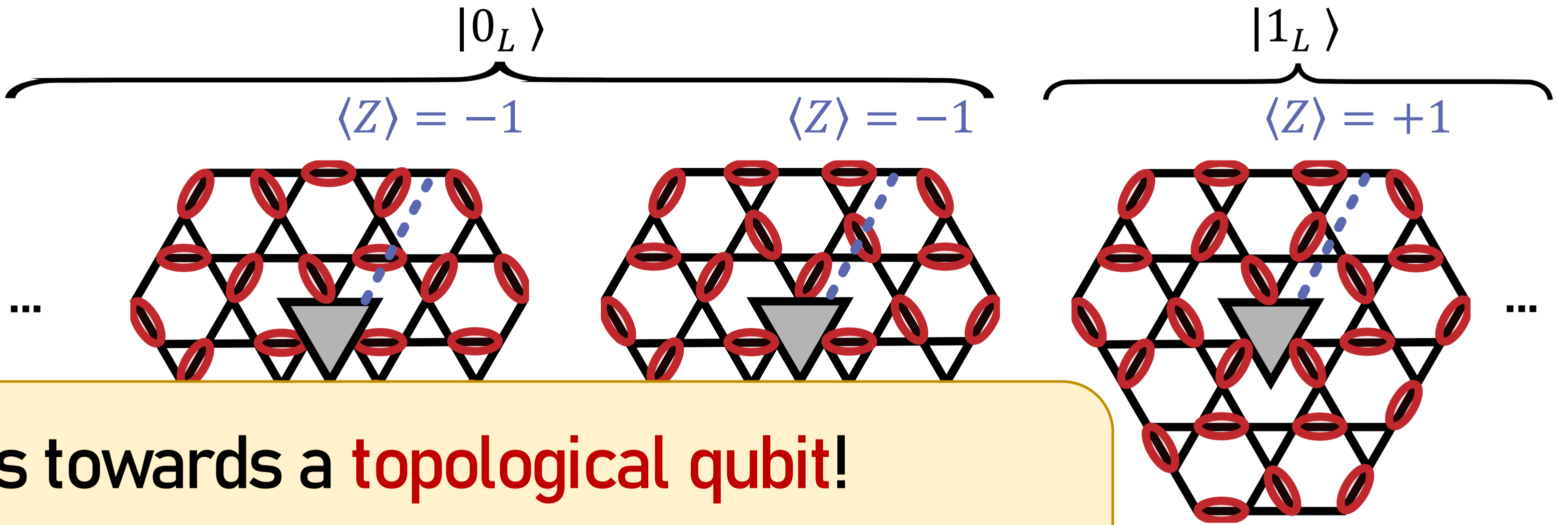



two distinct topological sectors




**first steps towards a topological qubit!**

related work from Google Quantum AI:
K. J. Satzinger et al., arXiv:2104.01180 (2021)

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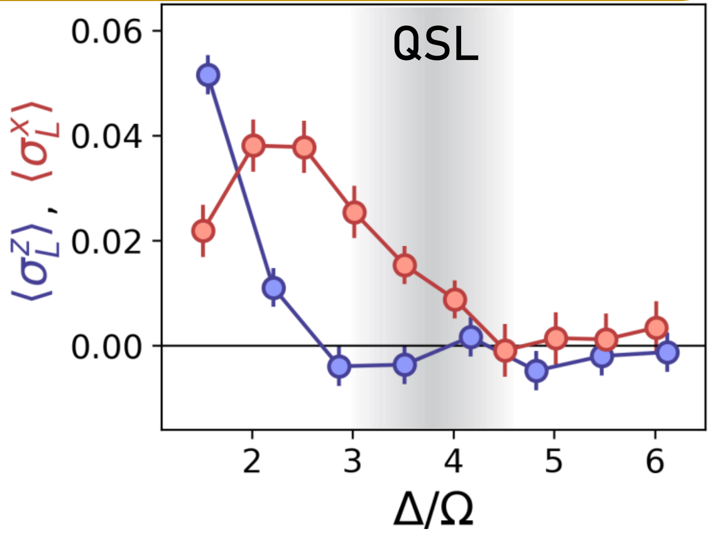
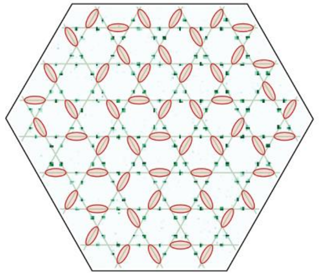
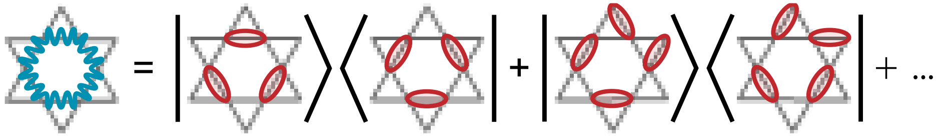



G. Semeghini et al., arXiv:2104.04119 (2021)

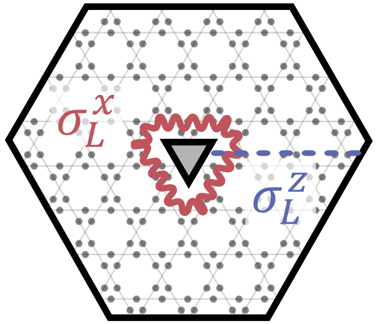
# Summary



1) Transition into a dimer phase with no local order
2) Experimental evidence for coherent superposition of dimer coverings




3) First signatures of non-trivial topological order

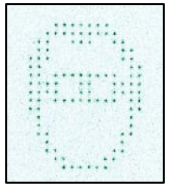



4) Exciting opportunities for experimental exploration of topological states of matter!

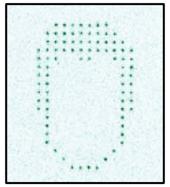
# Open questions

1) Origin of the observed QSL: metastable state?
2) Improving state preparation and measurement of string operators
3) Encoding and manipulating topological qubits
4) Implications for topological matter in other systems, e.g. 2D materials

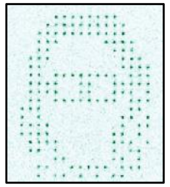
Image: Sci Am (2006)



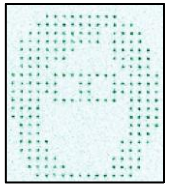
Harry Levine



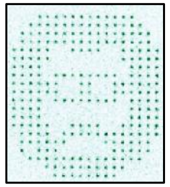
Tout Wang



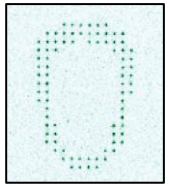
Sepehr Ebadi



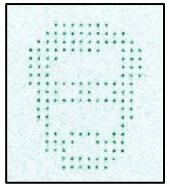
GS



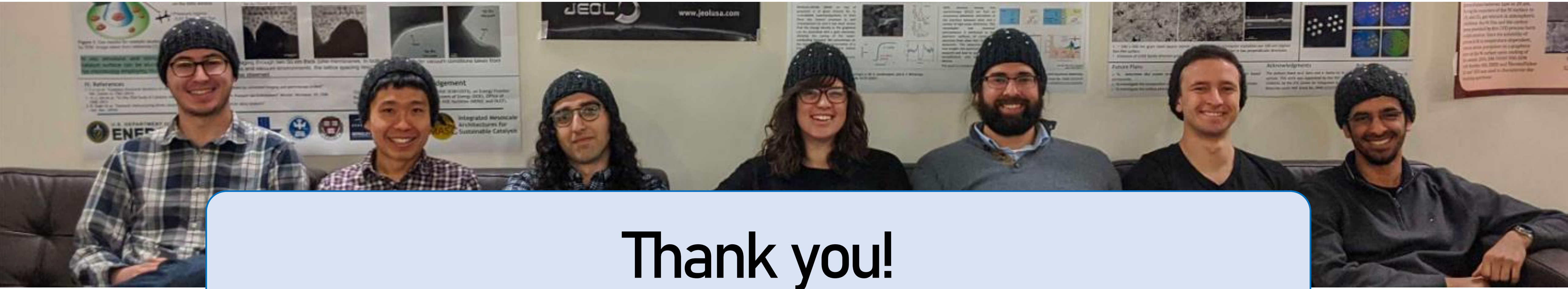
Alex Keesling



Dolev Bluvstein



Ahmed Omran



# Thank you!

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