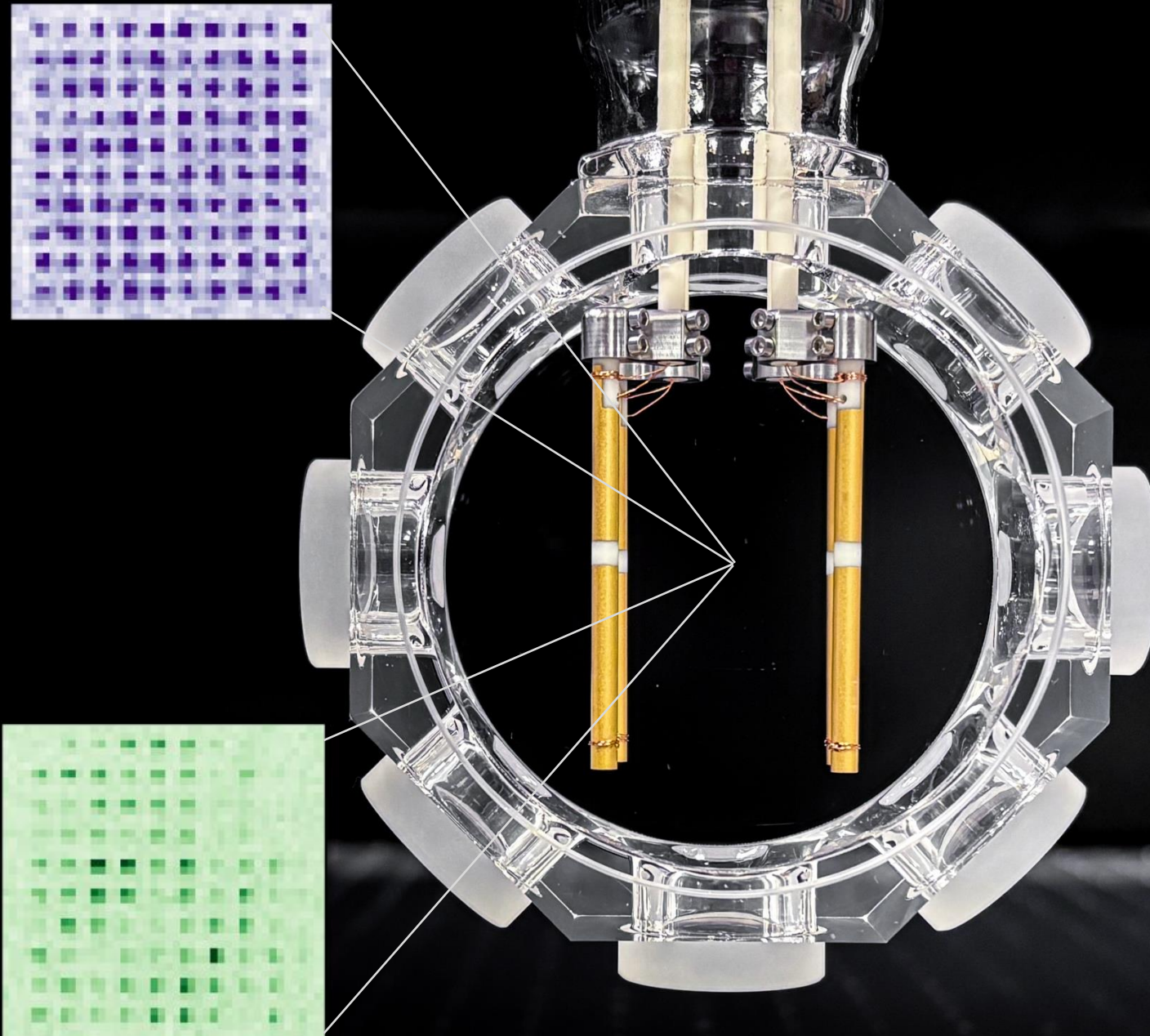


# New avenues for quantum simulation of materials with programmable atom arrays

Giulia Semeghini  
SPICE - May 21, 2026

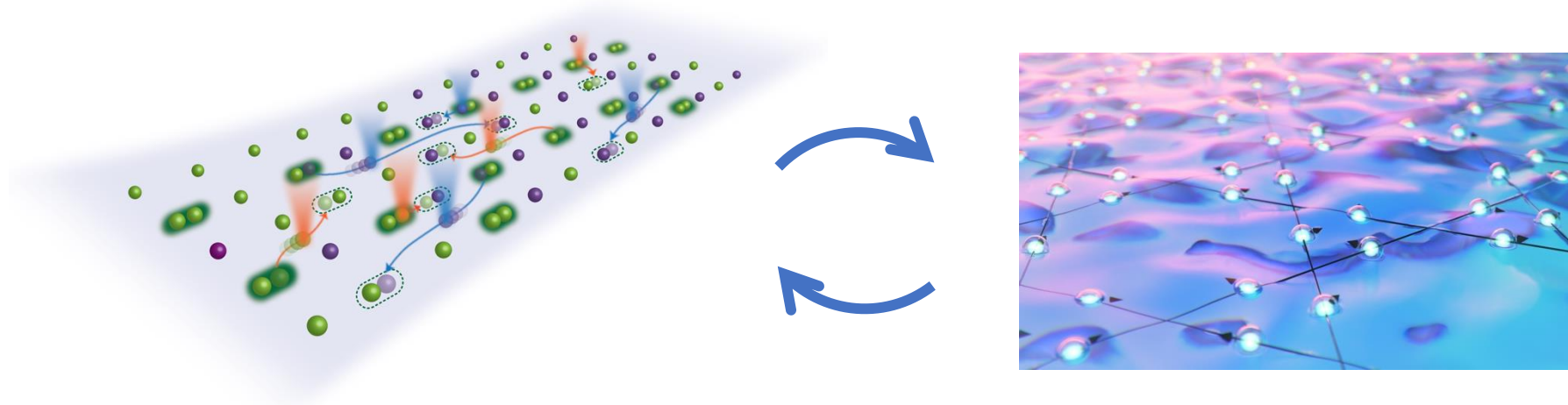


Harvard John A. Paulson  
School of Engineering  
and Applied Sciences

# QUANTUM MATERIALS AND QUANTUM INFORMATION SCIENCE

“opportunities for synergy”

programmable quantum platforms (atom arrays)  
for useful quantum simulation

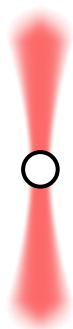


what platform capabilities are needed to close the gap between what we can simulate  
and what is interesting (e.g. in condensed matter or chemistry)?

# Quantum science with atom arrays

combined into \*large\* many-body systems  
with engineered interactions

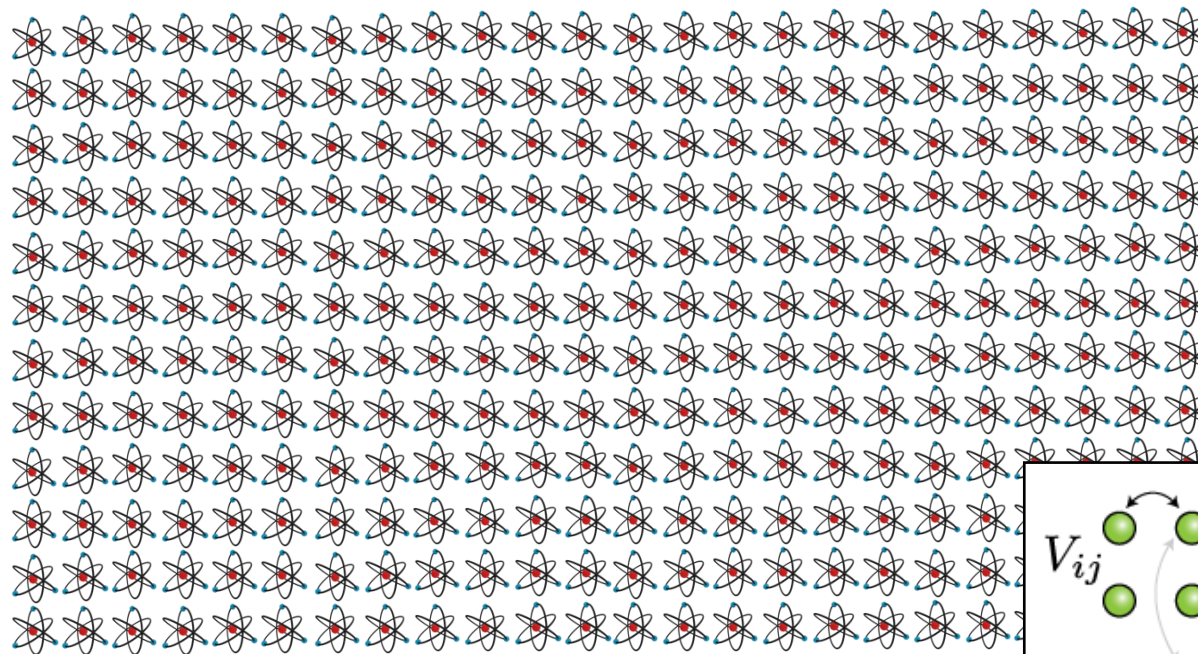
control of single  
neutral atoms



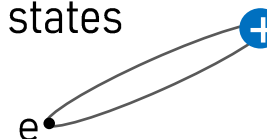
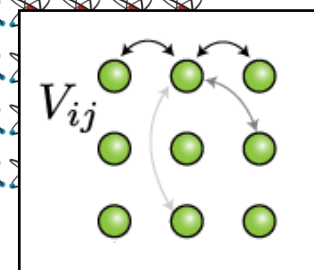
optical tweezer = tightly focused  
laser beam → traps single atoms



+



tunable interactions via excitation  
to Rydberg states

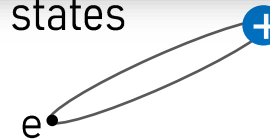


# Quantum science with atom arrays

combined into \*large\* many-body systems  
with engineered interactions

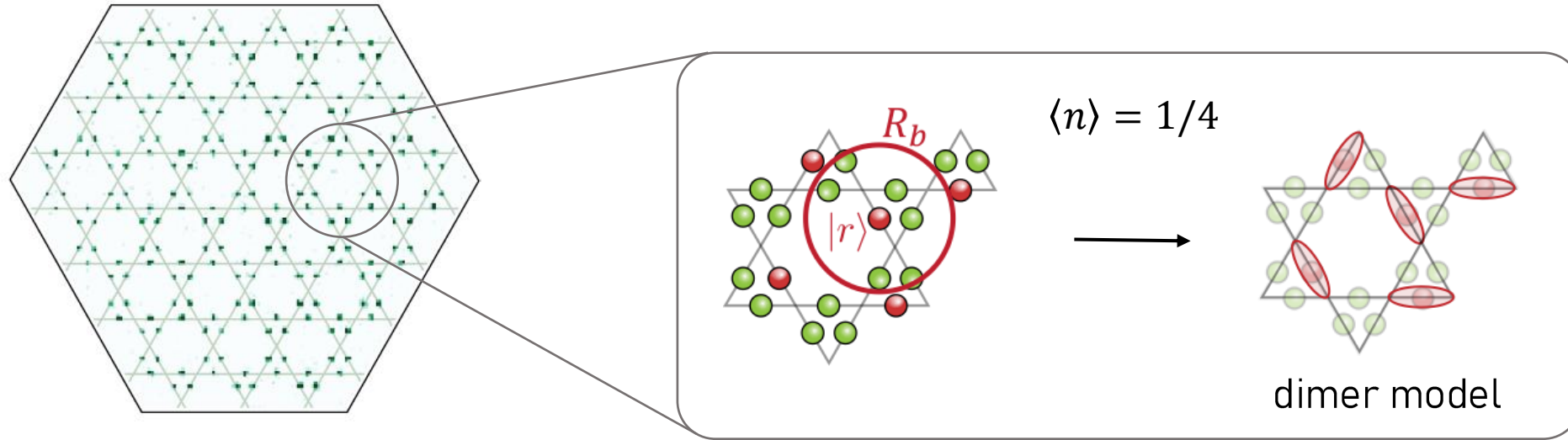


to Rydberg states





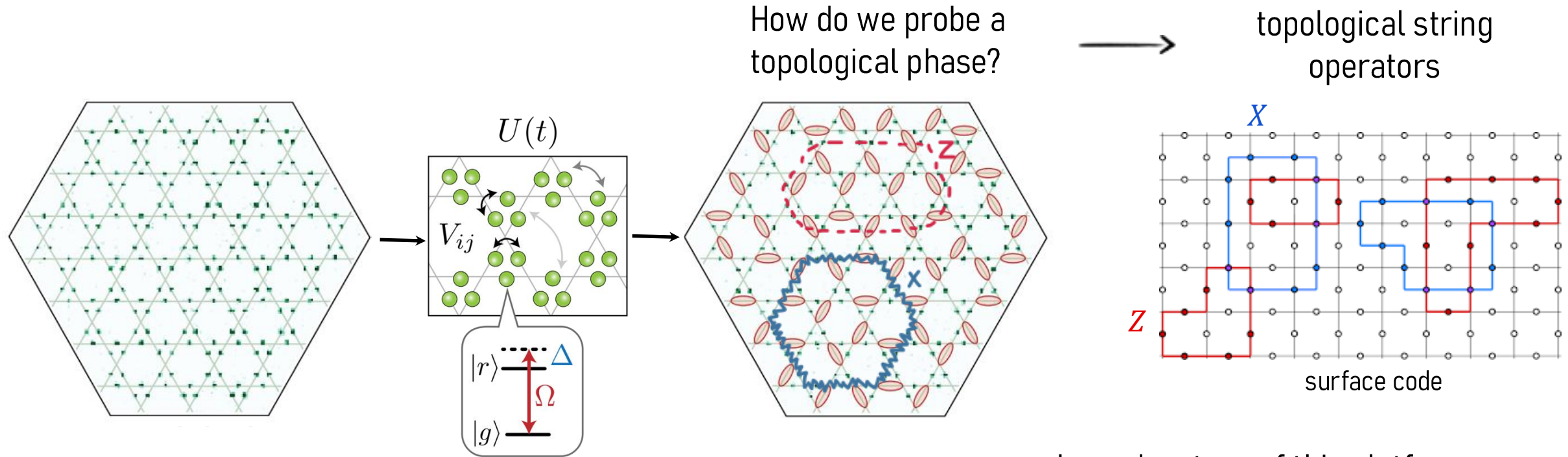
# Experimental realization of $\mathbb{Z}_2$ spin liquid



quantum spin liquid state: superposition of all dimer coverings

$$|\psi_{QSL}\rangle = \left| \begin{array}{c} \text{dimer covering 1} \\ \text{dimer covering 2} \\ \text{dimer covering 3} \\ \text{dimer covering 4} \end{array} \right\rangle + \left| \begin{array}{c} \text{dimer covering 5} \\ \text{dimer covering 6} \\ \text{dimer covering 7} \\ \text{dimer covering 8} \end{array} \right\rangle + \left| \begin{array}{c} \text{dimer covering 9} \\ \text{dimer covering 10} \\ \text{dimer covering 11} \\ \text{dimer covering 12} \end{array} \right\rangle + \left| \begin{array}{c} \text{dimer covering 13} \\ \text{dimer covering 14} \\ \text{dimer covering 15} \\ \text{dimer covering 16} \end{array} \right\rangle + \dots$$

# Experimental realization of $\mathbb{Z}_2$ spin liquid



quantum spin liquid state: superposition of all dimer coverings

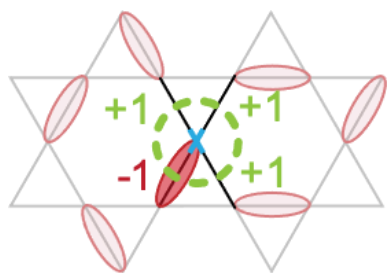
$$|\psi_{QSL}\rangle = \left| \begin{array}{c} \text{dimer covering 1} \\ \text{dimer covering 2} \\ \text{dimer covering 3} \\ \text{dimer covering 4} \end{array} \right\rangle + \left| \begin{array}{c} \text{dimer covering 5} \\ \text{dimer covering 6} \\ \text{dimer covering 7} \\ \text{dimer covering 8} \end{array} \right\rangle + \left| \begin{array}{c} \text{dimer covering 9} \\ \text{dimer covering 10} \\ \text{dimer covering 11} \\ \text{dimer covering 12} \end{array} \right\rangle + \left| \begin{array}{c} \text{dimer covering 13} \\ \text{dimer covering 14} \\ \text{dimer covering 15} \\ \text{dimer covering 16} \end{array} \right\rangle + \dots$$

key advantage of this platform:  
access to single-particle information

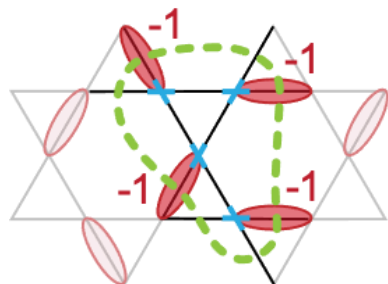
# Probing topological correlations

## ① Identify dimer phase

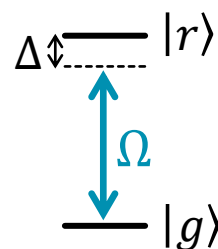
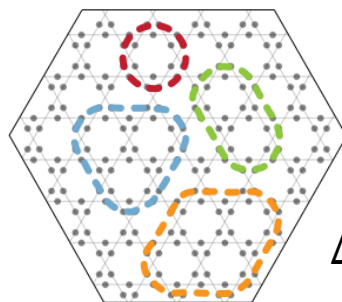
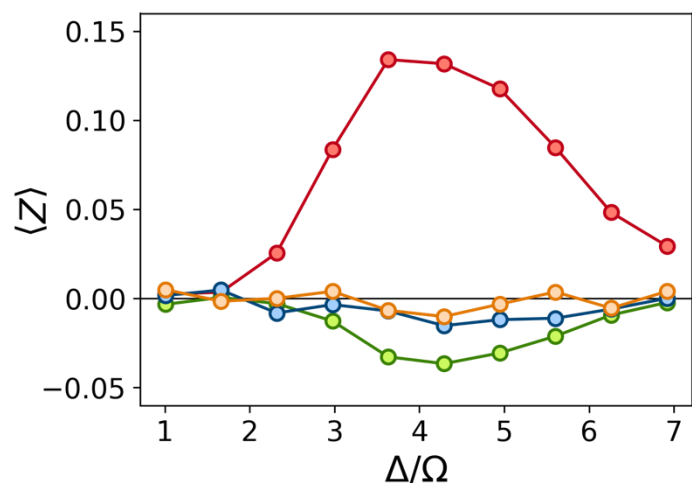
diagonal string operator  $\mathbf{Z}$ :  
parity of dimers along a string



$$\langle Z \rangle = -1$$



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



$$|\psi_{QSL}\rangle = \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \dots$$

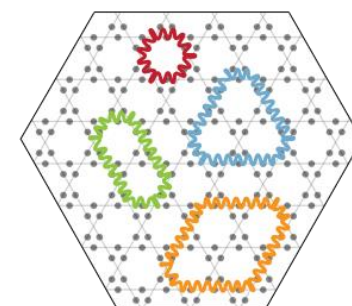
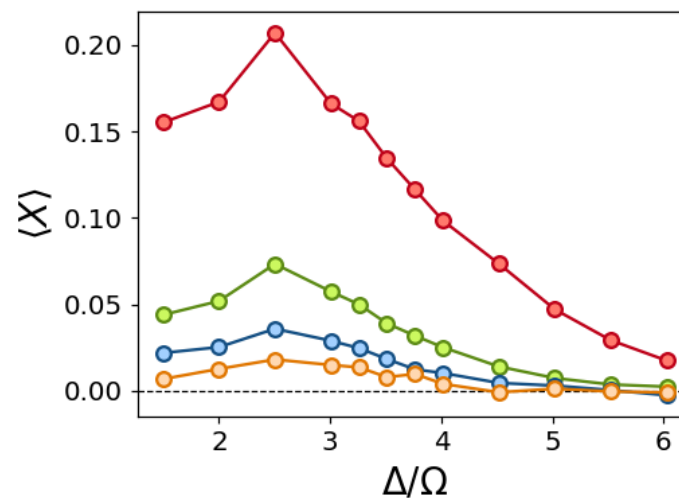
## ② Probe coherence between dimer states

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

$$\left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle = \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle \langle \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} | + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle \langle \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} | + \dots$$

$$\langle \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} | \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \rangle > 0 \rightarrow$$

coherence between  
dimer coverings



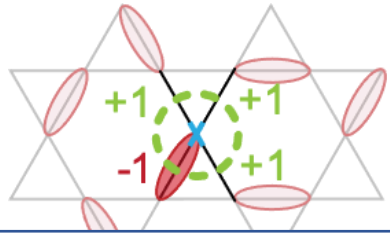
# Probing topological correlations

$$|\psi_{QSL}\rangle = \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \left| \begin{array}{c} \triangle \\ \triangle \\ \triangle \end{array} \right\rangle + \dots$$

① Identify dimer phase

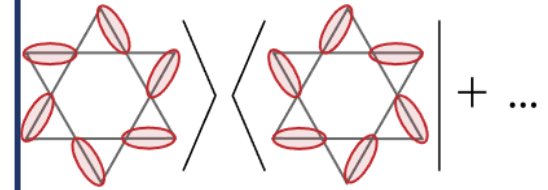
② Probe coherence between dimer states

diagonal string  
parity of dimers



Experimental observation of  
the onset of a quantum spin liquid

operator X:



coherence between

Experiments from the **Lukin group** at Harvard:

PIs: M. Lukin V. Vuletic M. Greiner

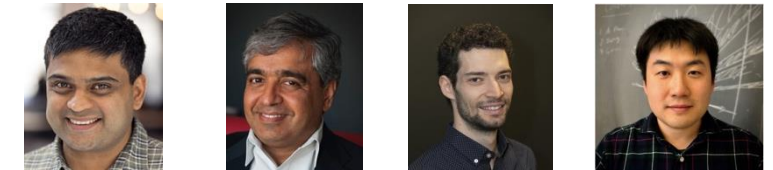


THEORY COLLABORATORS

R. Verresen R. Samajdar N. Maskara M. Kalinowski



A. Vishwanath S. Sachdev H. Pichler S. Choi

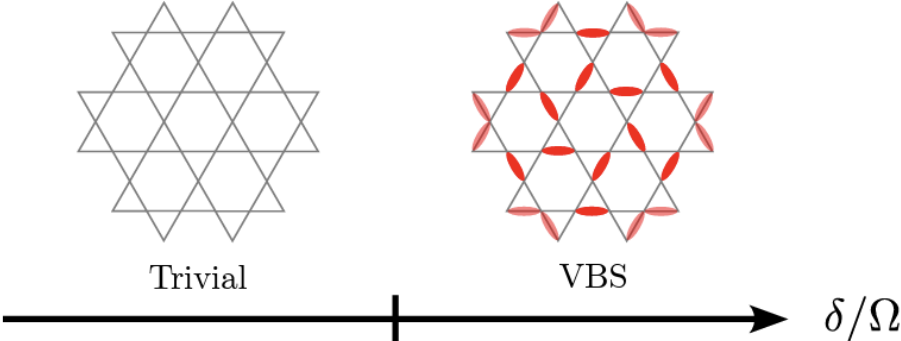


Harry Levine Tout Wang Sepehr Ebadi GS Alex Keesling Dolev Bluvstein Ahmed Omran

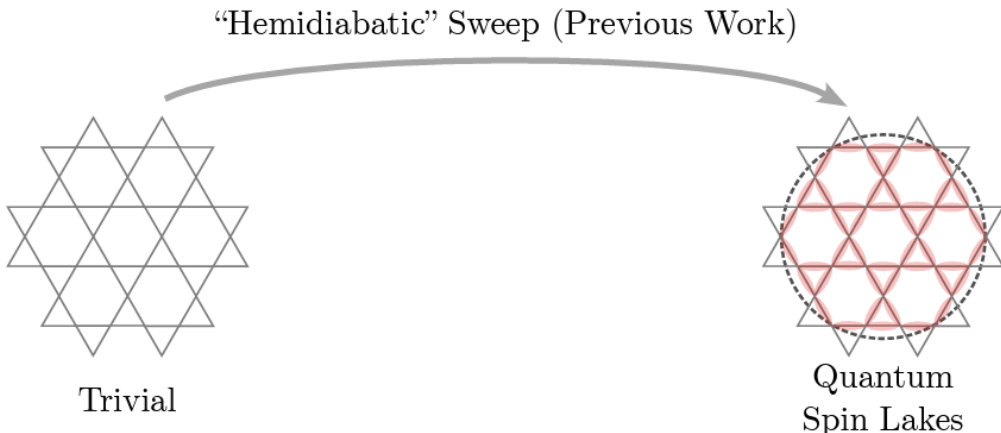
# Metastable SL and effect of dynamical state preparation

$\mathbb{Z}_2$  spin liquid is not the actual ground state (due to long-range tails of vdW interactions)

(a) Equilibrium:



(b) Dynamics:

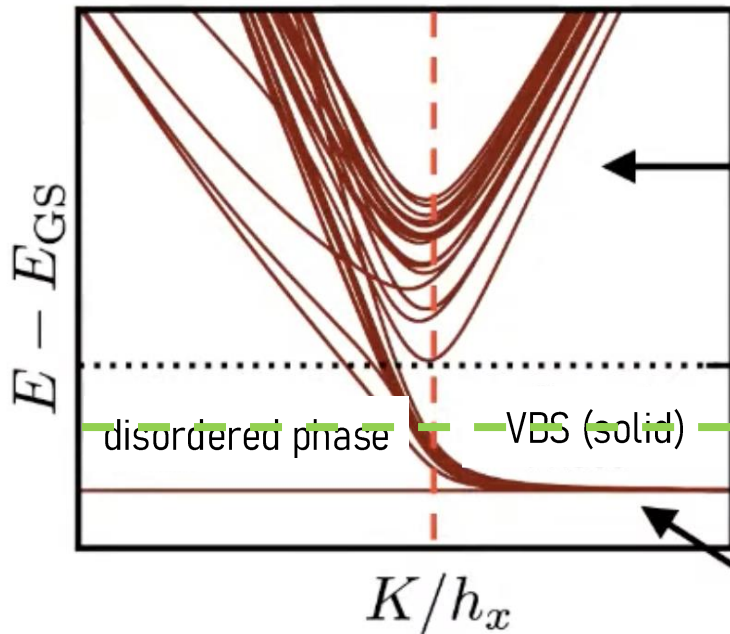


adapted from N. O. Gjonbalaj, R. Sahay and S. F. Yelin, arXiv:2502.03518 (2025)

## Quantum spin lakes

R. Sahay, A. Vishwanath, and R. Verresen, arXiv:2211.01381 (2023)

energy levels across the phase transition:



Two distinct branches of states

"e-anyon" branch: condenses at the transition

Sweep across transition: adiabatic relative to the "e" branch but sudden relative to the "m" branch

Gauss Law satisfying "m-anyon" branch

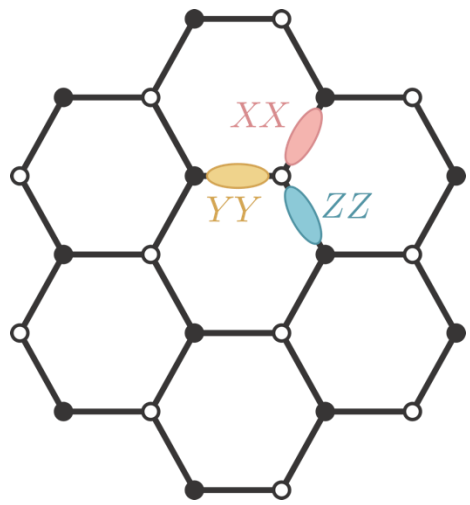
→ Equilibrate out e-anyons, but avoid nucleating m-anyons

See also related work:

G. Giudici, M. Lukin, and H. Pichler, Phys. Rev. Lett. 129, 090401 (2022)

# More topological phases with Rydberg atom arrays: **Kitaev honeycomb model**

## Non-Abelian topological phases



Anisotropic interactions

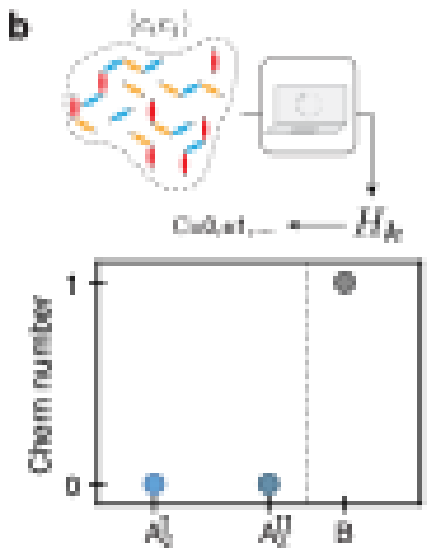
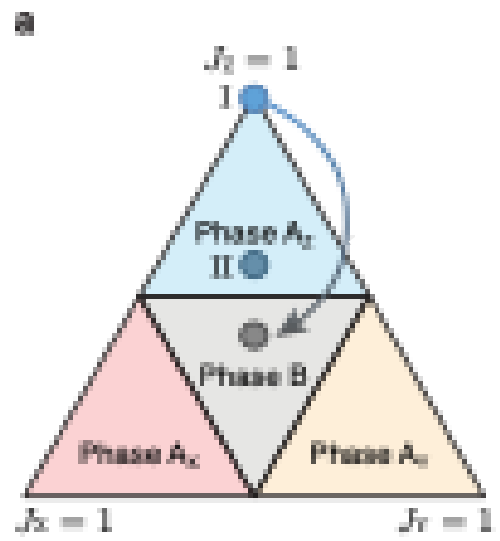
$$H_0 = - \underbrace{J_X \sum_{\langle i,j \rangle_X} X_i X_j}_{H_X} - \underbrace{J_Y \sum_{\langle i,j \rangle_Y} Y_i Y_j}_{H_Y} - \underbrace{J_Z \sum_{\langle i,j \rangle_Z} Z_i Z_j}_{H_Z}$$

Floquet engineering

periodic drive  
→ effective static Hamiltonian

Atom transport

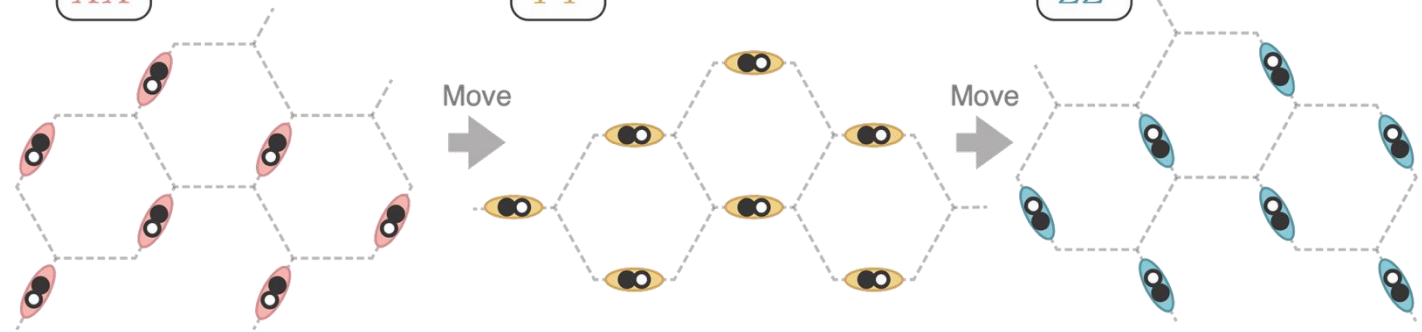
+ to change connectivity between layers of quantum operations



XX

YY

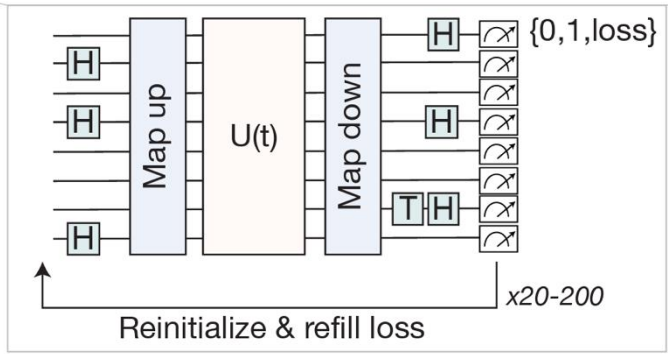
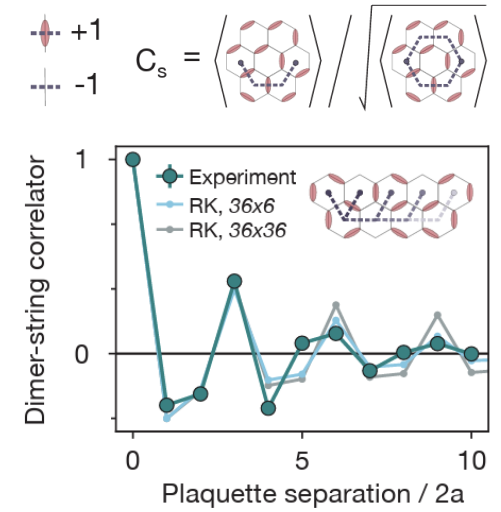
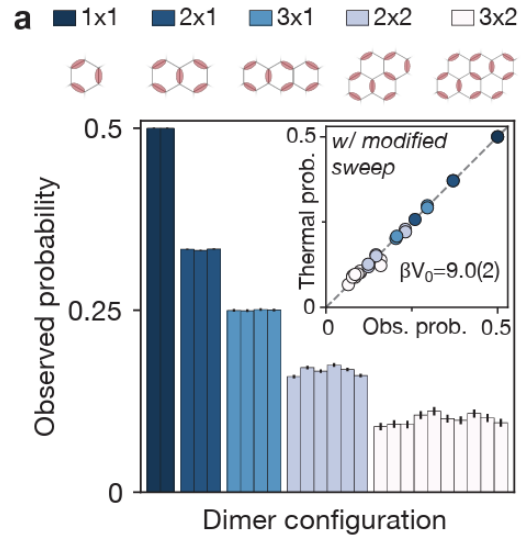
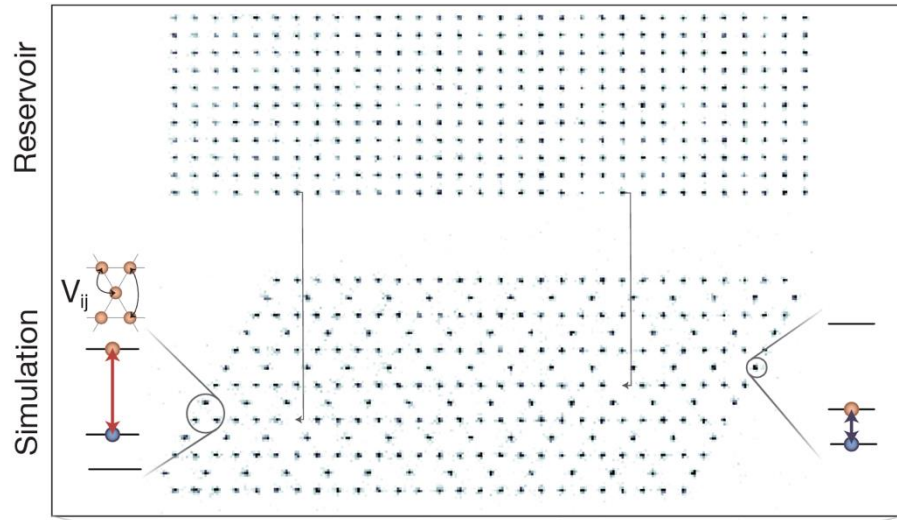
ZZ



A. Kitaev, Ann Phys-New York 321, 2 (2006)  
 M. Kalinowski, N. Maskara, M. Lukin, arXiv:2211.00017 (2022)  
 S. Evered, ... M. Lukin, Nature 645, 341 (2025)

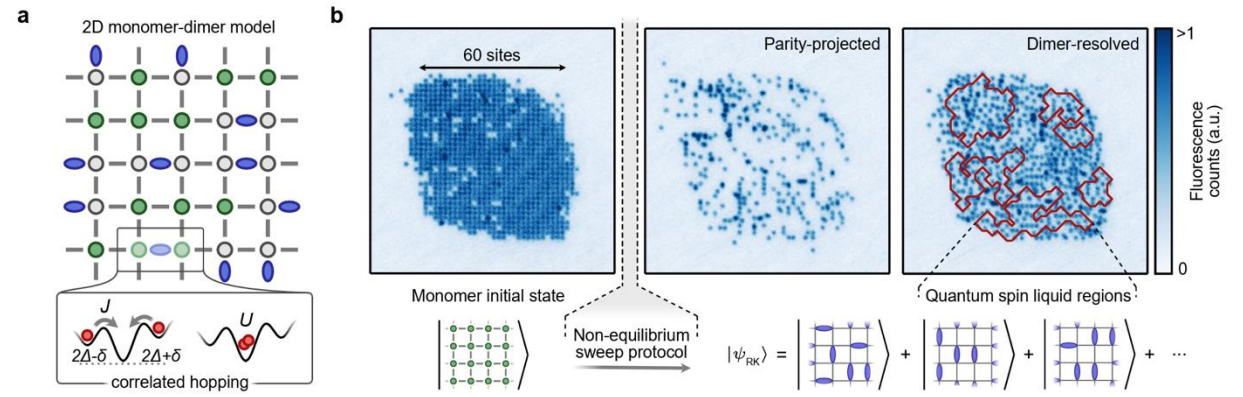
# More topological phases with Rydberg atom arrays: **U(1) spin liquid**

Out-of-equilibrium realization of the honeycomb quantum dimer model near the Rokhsar-Kivelson point  
 → target U(1) quantum spin liquid wavefunction (equal-phase superposition of dimer coverings)



A. Geim, ... M. Lukin, arXiv:2602.18555 (2026)

related result on optical lattices: RK-like U(1) spin-liquid wavefunction on square lattice



S. Karch, ... M. Aidelsburger, arXiv:2604.24744 (2026)

# GOALS OF NEW EXPERIMENTAL SETUP IN MY GROUP:

improve **speed/efficiency,**  
**versatility and robustness**  
of programmable atom arrays  
(co-design approach)

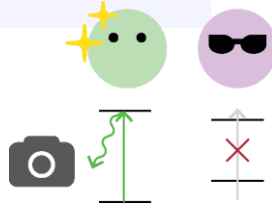
explore **new paradigms**  
for computing and simulation  
(both analog and digital)

# Dual-species Yb-Rb atom array

+

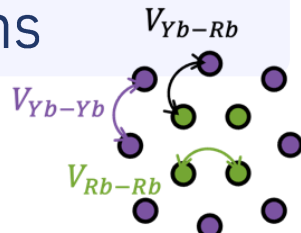
# Fast atom reloading

Spectral separation

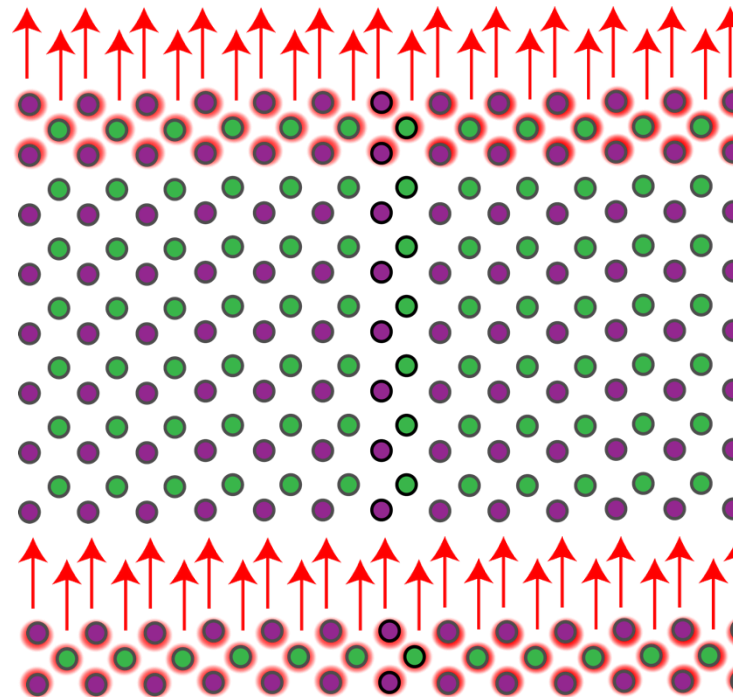
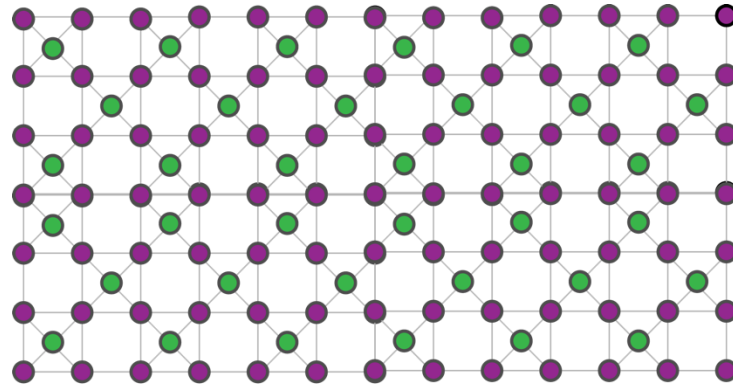


Selective control of qubit subsets  
(e.g. data and ancilla qubits)

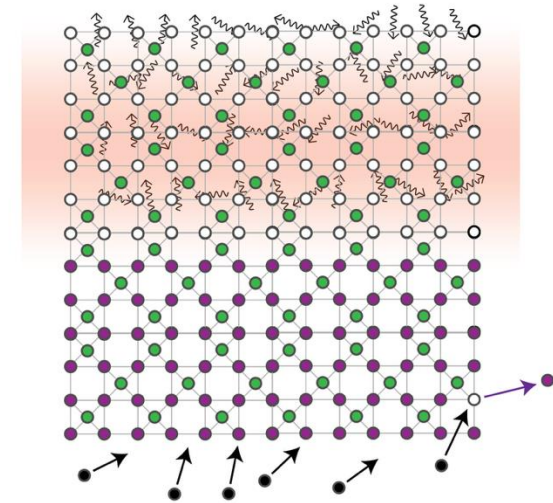
Tunable inter/intra-species interactions



Additional versatility for  
quantum architectures



Compensate for atom losses



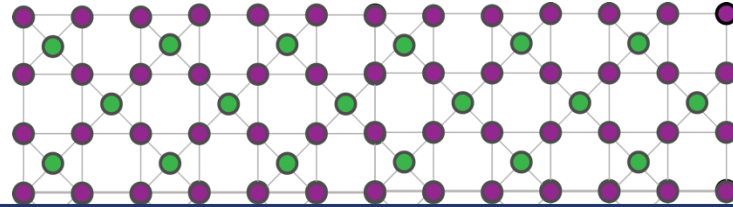
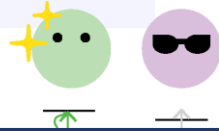
- improved scalability
- faster cycle times
- deep QEC circuits

# Mixed-species Yb-Rb atom array

+

# Fast atom reloading

Spectral separation



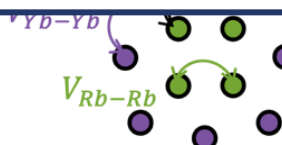
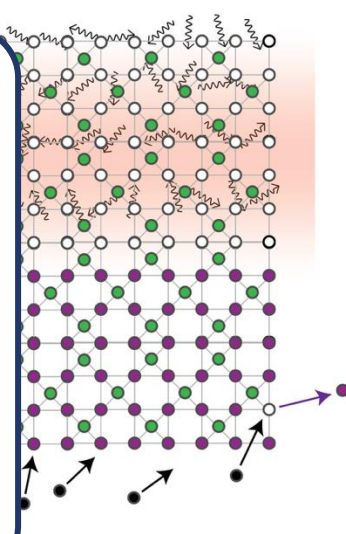
Compensate for atom losses

Selective control  
(e.g. data readout)

Tunable interaction  
in

New possibilities enabled by dual-species array in quantum simulation for:

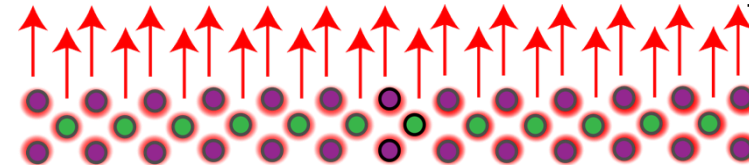
- characterization of many-body phases
- Hamiltonian engineering



voir

- faster cycle times
- deep QEC circuits

Additional versatility for quantum architectures



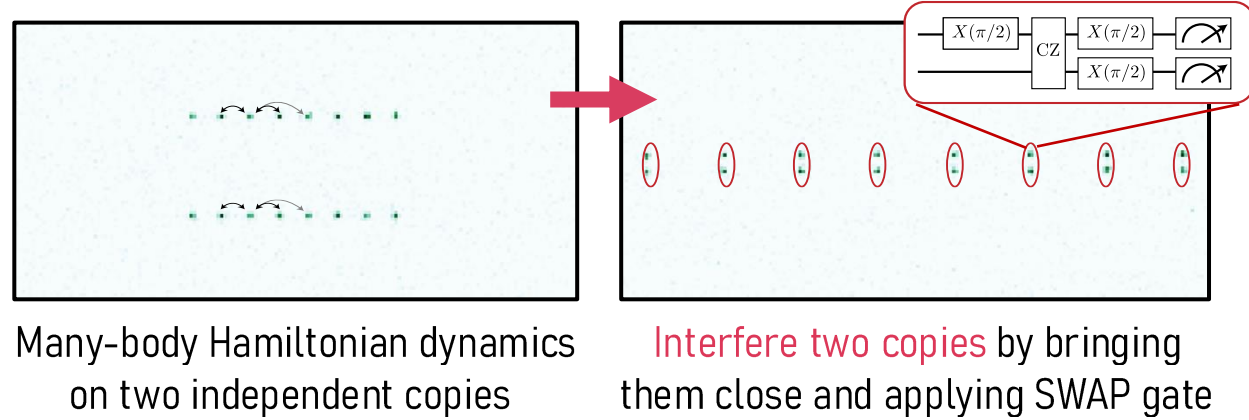
# Characterization of many-body phases

Increasing need for efficient approaches for measurement of observables, e.g. entanglement entropy, or exotic quasiparticles

interesting solution: **hybrid analog-digital** approach

e.g. measurement of Renyi entanglement entropy

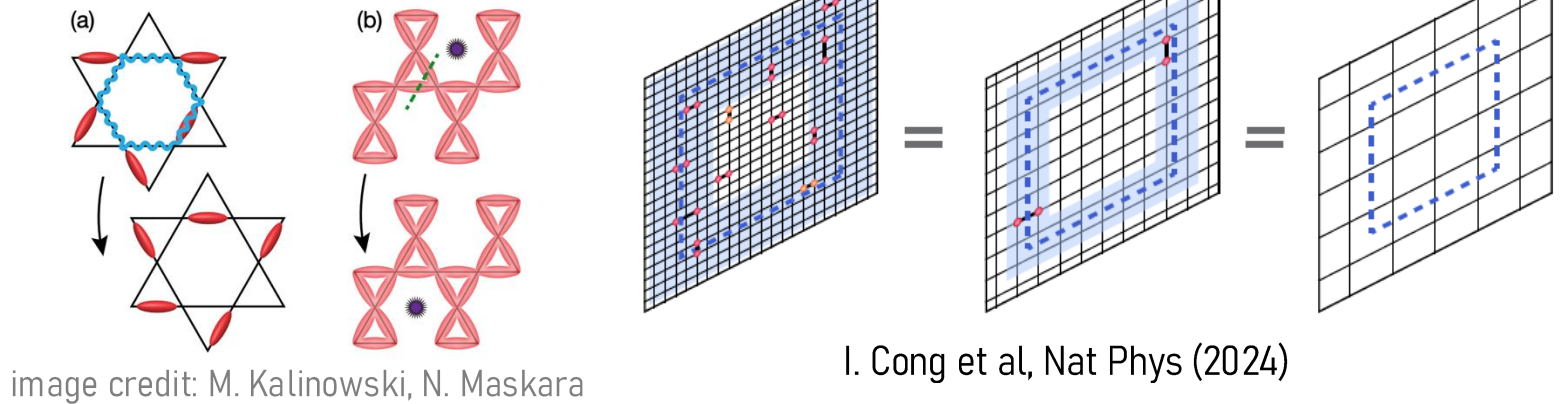
D. Bluvstein ... M. Lukin, Nature (2024)



Approach inspired by QEC: **auxiliary atoms used to measure or provide controlled excitations**

e.g. for detection and manipulation of **anyons in spin liquid state**

→ detect and annihilate anyons using ancilla atoms in different species

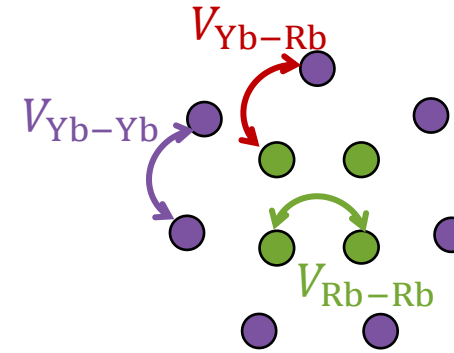
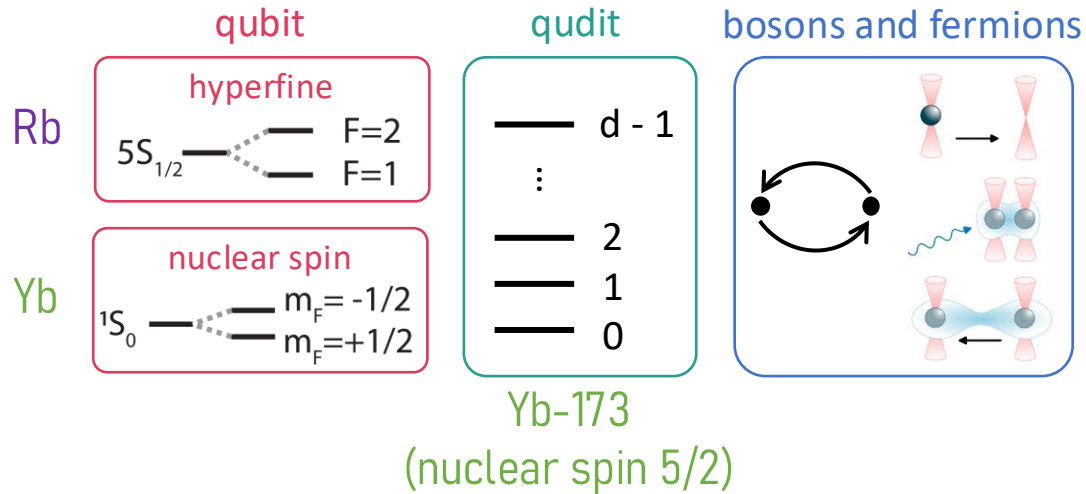


# Versatile Hamiltonian engineering for quantum simulation

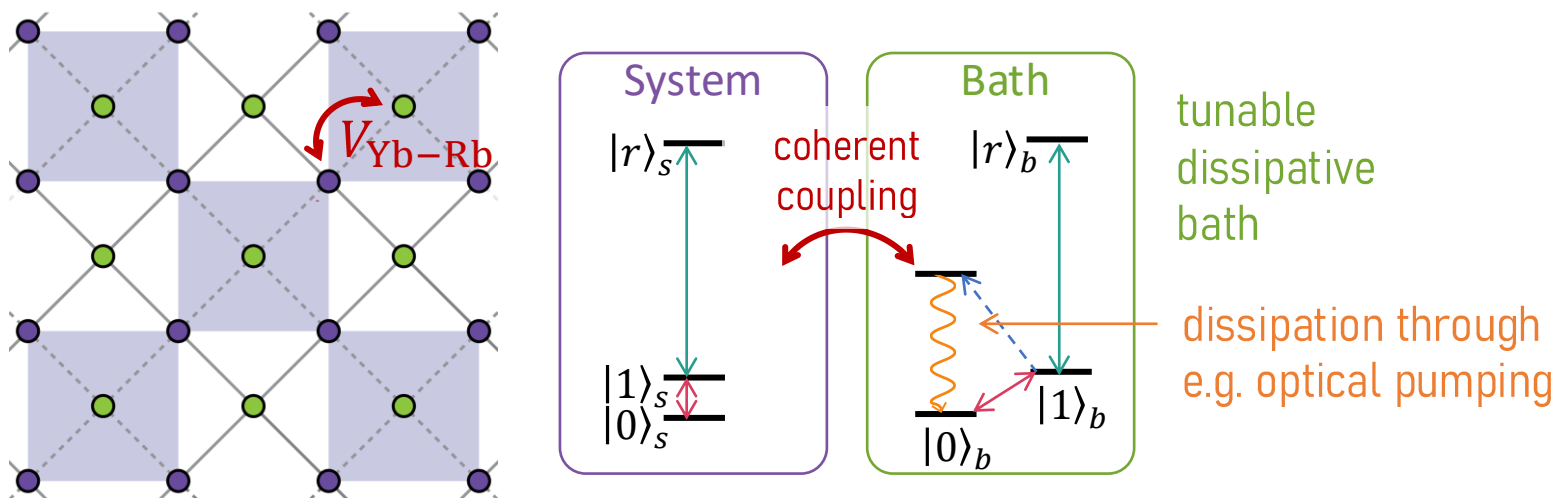
multiple options for encoding of degrees of freedom:

+

3 tunable interaction strengths:

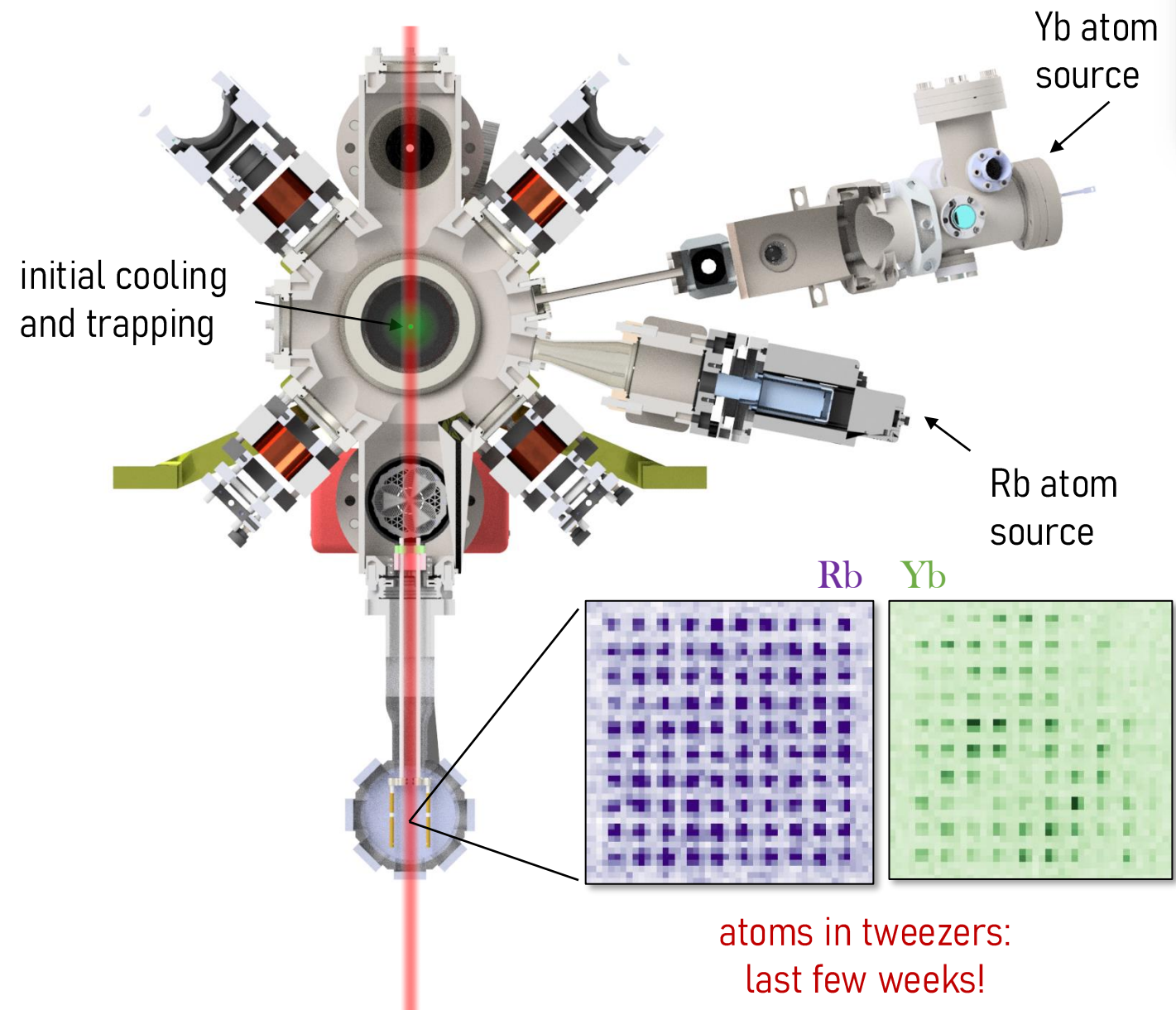


+ engineered dissipations via coupling to a bath

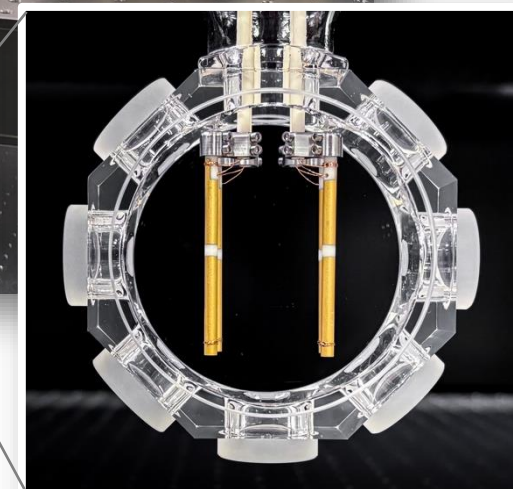
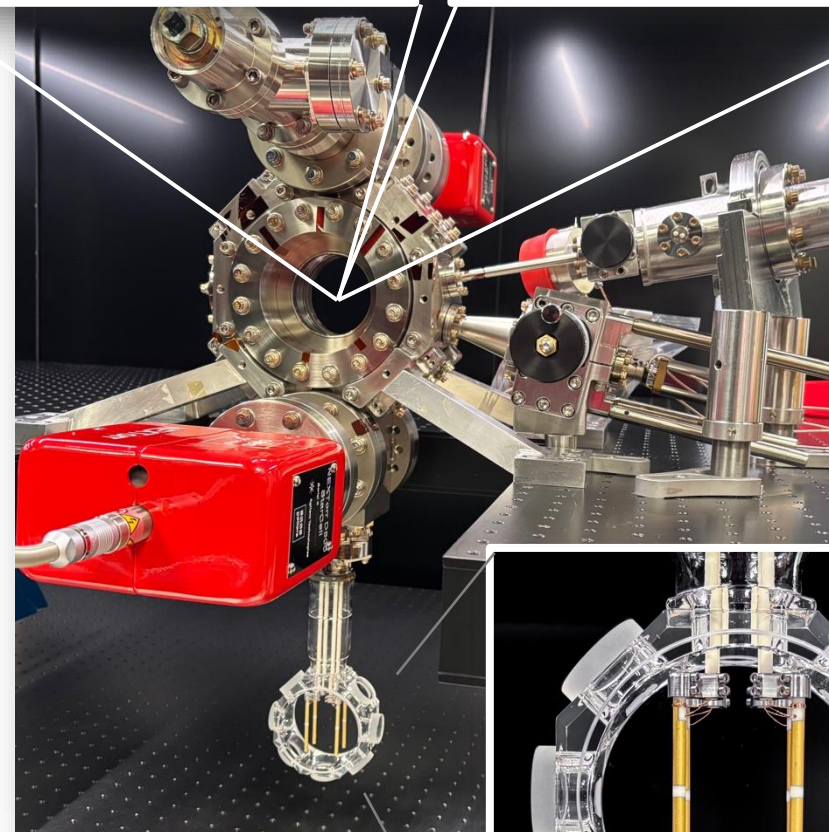
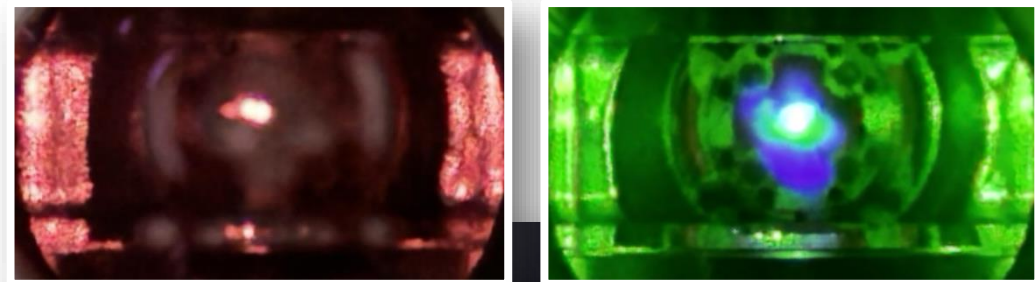


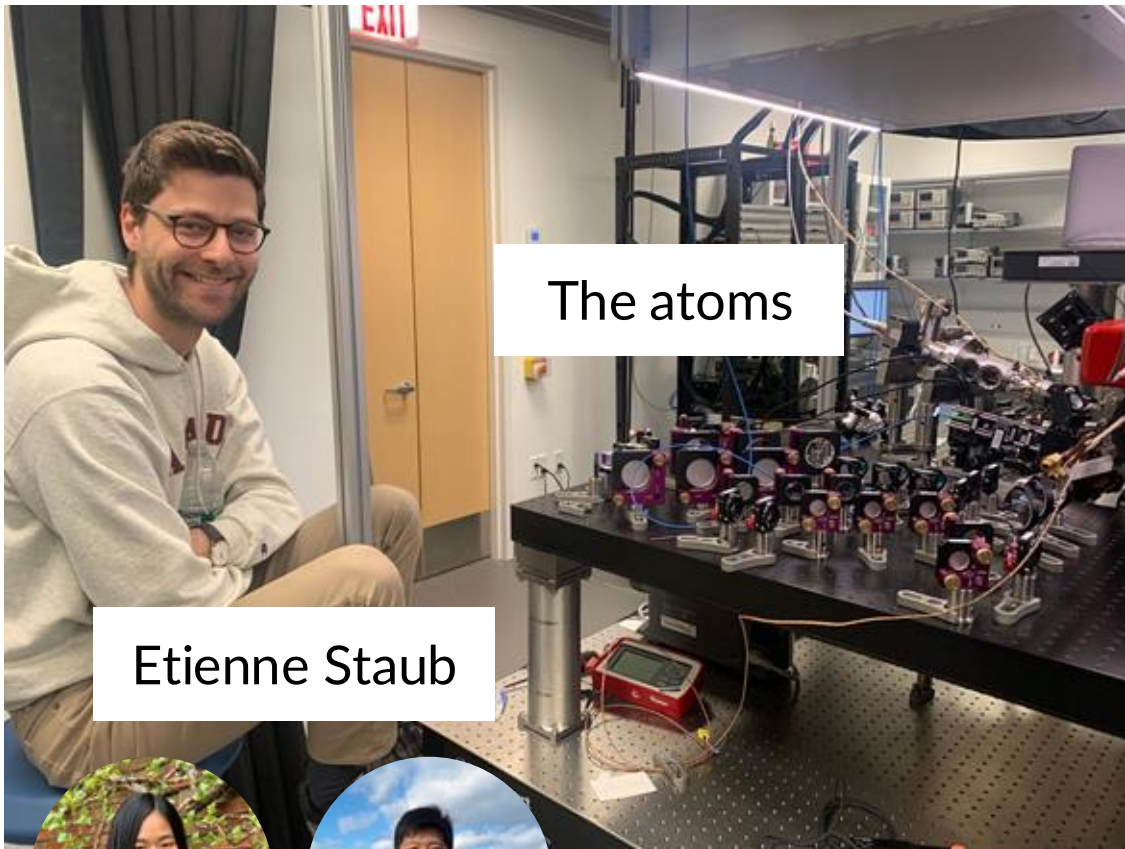
can be used for state preparation, cooling/stabilization + study open quantum systems

# PLATFORM AT A GLANCE



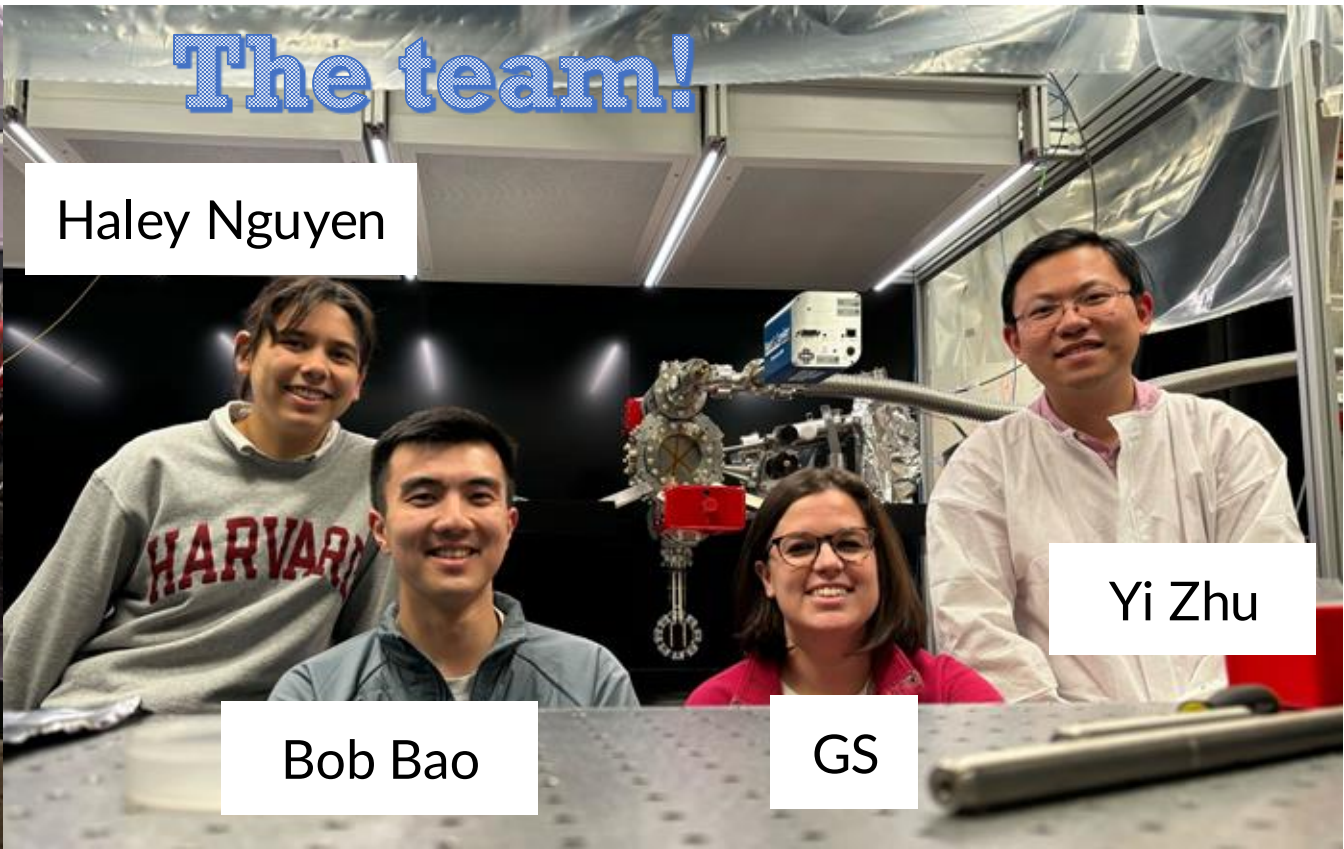
dual-species magneto-optical trap





The atoms

Etienne Staub



Haley Nguyen

Bob Bao

GS

Yi Zhu



Lillian Zhong



William Tang

Alumni:

Ken Shen, Fang Fang, Nicholas Lyu

Funding:



U.S. DEPARTMENT of ENERGY



Aramont Foundation, Star-Friedman Challenge