

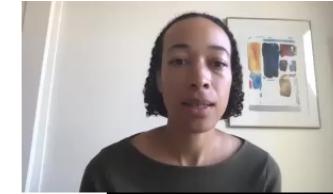
Title: Seminar: Engineering quantum spin models with atoms and light

Speakers: Monika Schleier-Smith

Collection: Online School on Ultra Quantum Matter

Date: August 10, 2020 - 12:45 PM

URL: <http://pirsa.org/20080018>

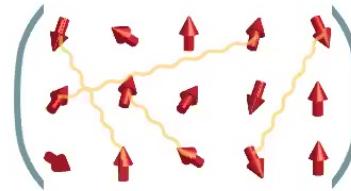


# Engineering Quantum Spin Models with Atoms and Light

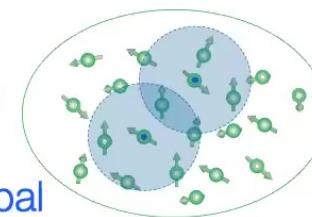
Monika Schleier-Smith

August 9, 2020

Emily Davis  
Avikar Periwal  
Eric Cooper  
Greg Bentsen



Tori Borish  
Ognjen Markovic  
Jacob Hines  
Shankari Rajagopal





## Vision

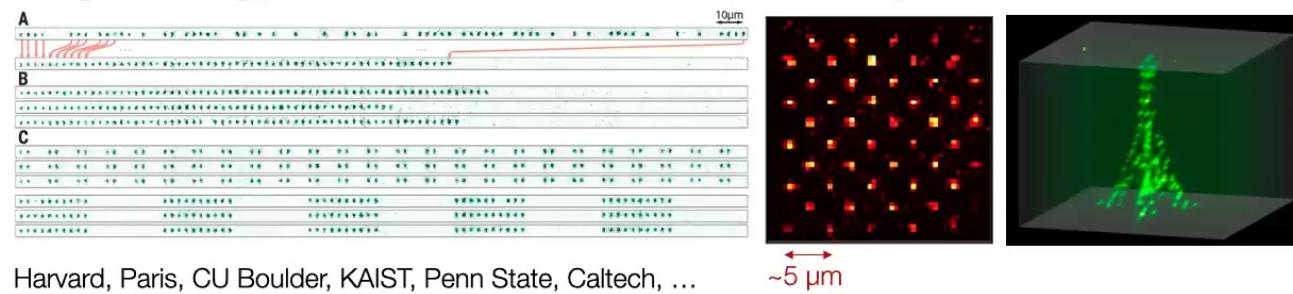
An arbitrary waveform generator for quantum engineers:





# Programmable Quantum Systems

Programming positions of individual atoms with optical tweezers

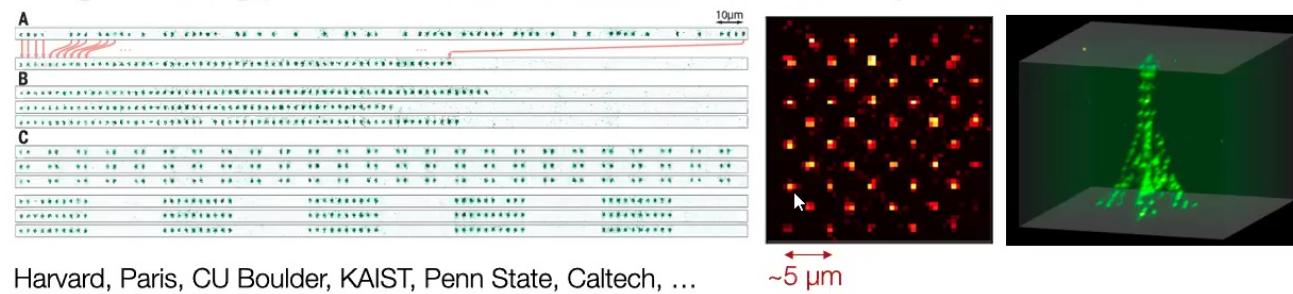


Harvard, Paris, CU Boulder, KAIST, Penn State, Caltech, ...



# Programmable Quantum Systems

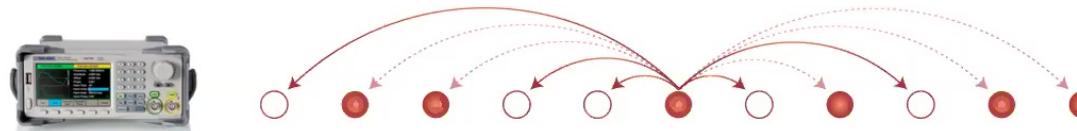
Programming positions of individual atoms with optical tweezers



Harvard, Paris, CU Boulder, KAIST, Penn State, Caltech, ...

~5 μm

**Today:** programming the *interactions* between atoms

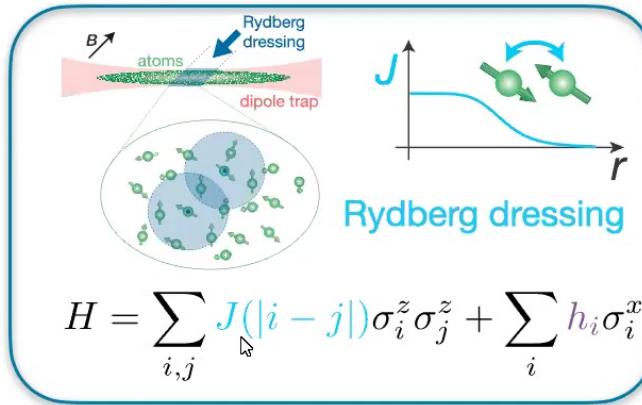




# Optically Controlled Interactions

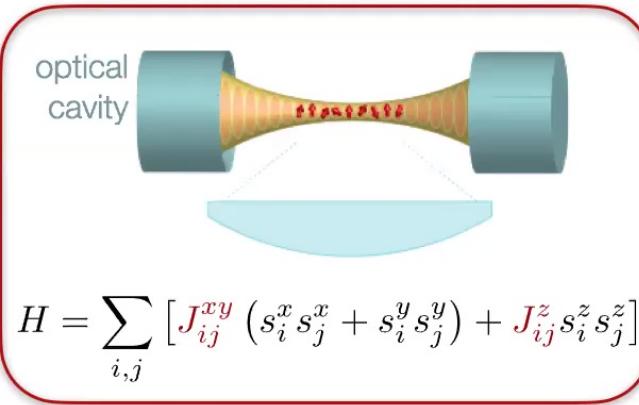
Engineering spin-spin interactions among laser-cooled atoms:

## Rydberg interactions



Long-range but local

## Photon-mediated interactions



Highly non-local



# Motivation

## Quantum Control

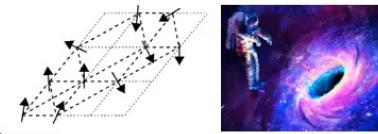
Entangled states for sensing,  
computation, communication

$$|\psi\rangle = \frac{|{\downarrow\downarrow\downarrow}\rangle + |{\uparrow\uparrow\uparrow}\rangle}{\sqrt{2}}$$



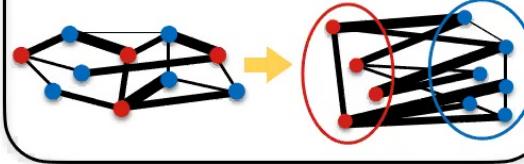
## Quantum Simulation

...from condensed matter  
to quantum gravity



## Combinatorial Optimization

Encode classical cost function  
in energy of quantum system

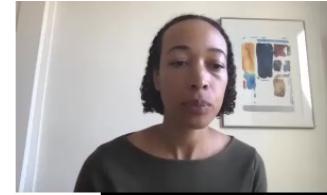




## Optimization Example

Scheduling classes in two possible time slots

- Each student can attend one in **morning** and one in **afternoon**

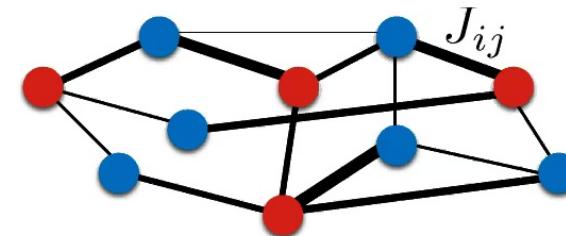


## Optimization Example

Scheduling classes in two possible time slots

- Each student can attend one in **morning** and one in **afternoon**
- *Draw a graph: vertices are classes and edges are weighted by the # of people who want to take both*
- *Optimization: “cut” the most heavily weighted edges (MAX-CUT)*

⇒ minimize energy of Ising model



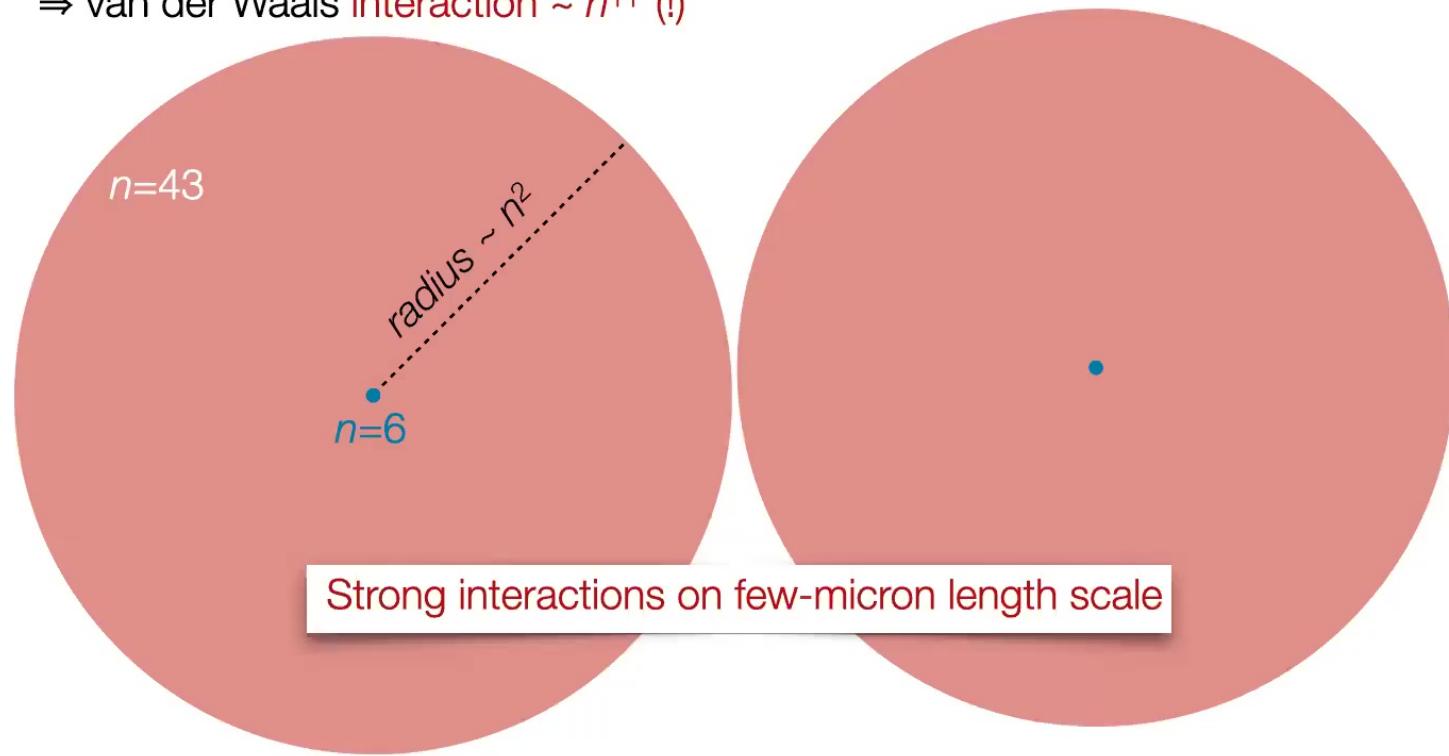
$$H = \sum_{i,j} J_{ij} s_i^z s_j^z + h \sum_i s_i^x$$

- Tools for exploring:  
**Spins + long-range interactions + programmability**



## Rydberg Interactions

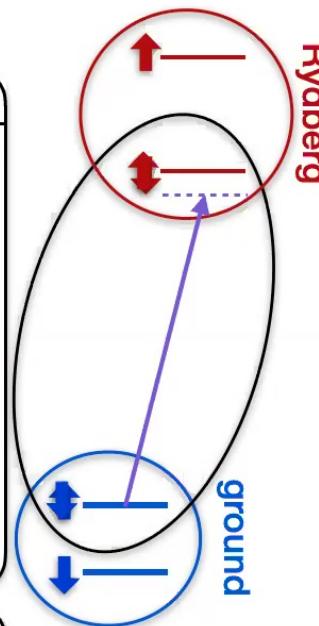
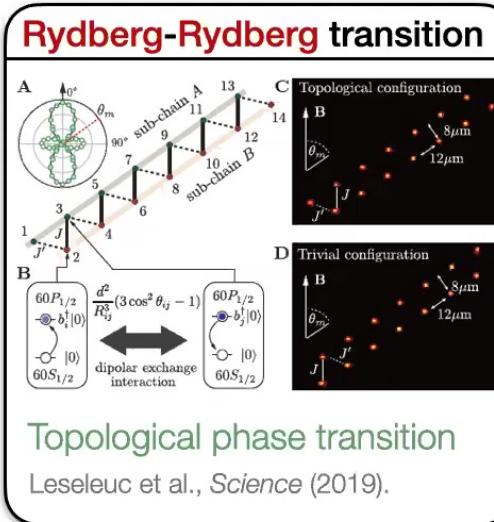
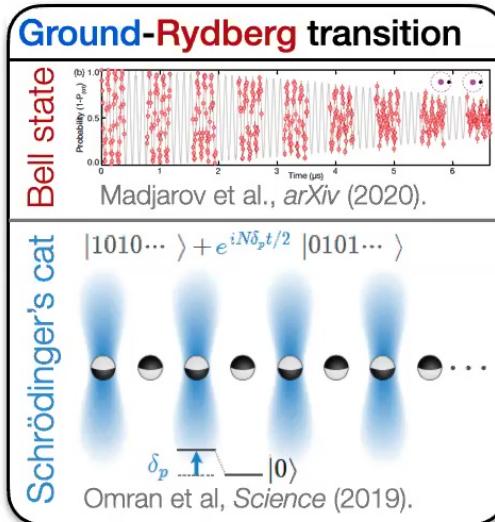
Rydberg atoms (high principal quantum number  $n$ ) are large & polarizable  
⇒ van der Waals interaction  $\sim n^{11}$  (!)





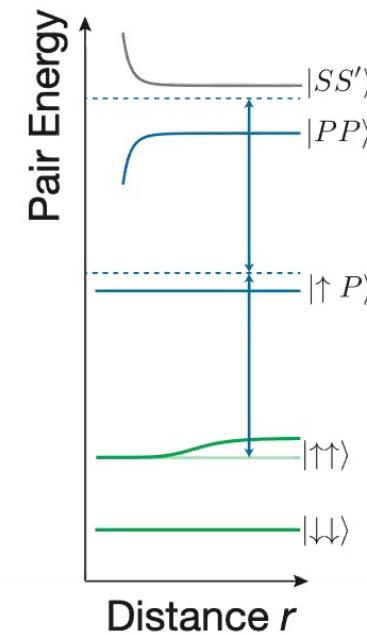
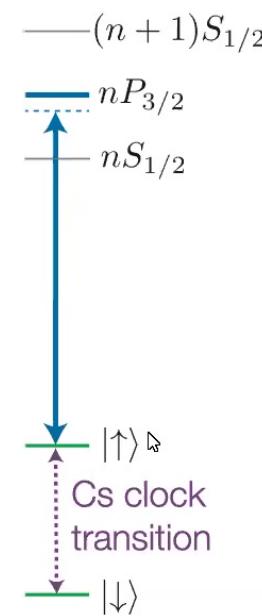
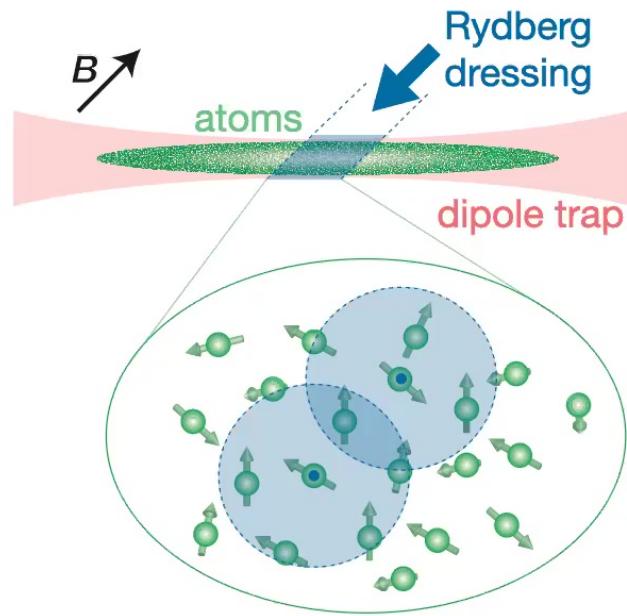
# Rydberg Atoms as Quantum Spins

Spin can be encoded in...

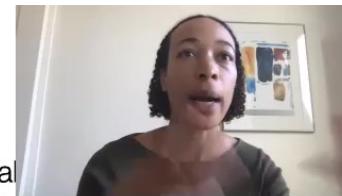




## Rydberg Dressing Setup



**Related experiments:** Sandia, Munich, JQI, Rice, Strasbourg/Heidelberg



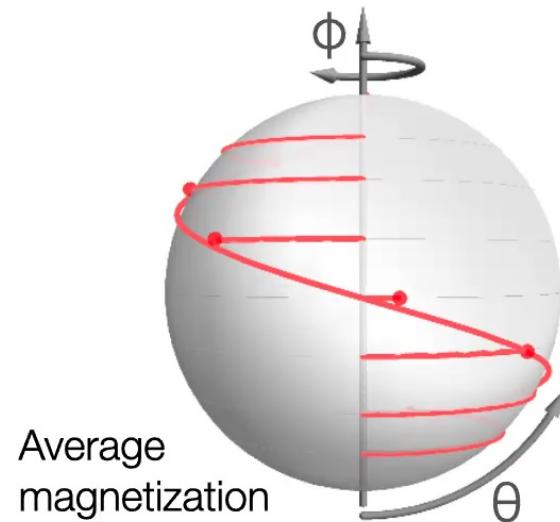
# Ising Dynamics

Borish, Markovic, Hines, Rajagopal  
& MS-S, *PRL* **124**, 063601 (2020).

Each spin precesses at a rate that depends on number of surrounding atoms in state  $|\uparrow\rangle$

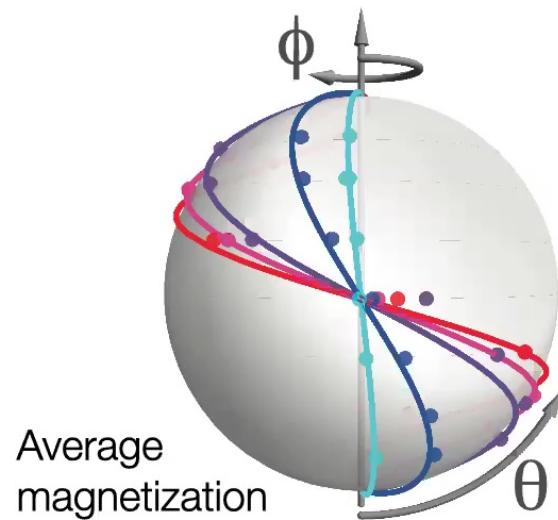
$$H = \sum_{i,j} \mathcal{J}(|i-j|) \sigma_i^z \sigma_j^z$$

↳

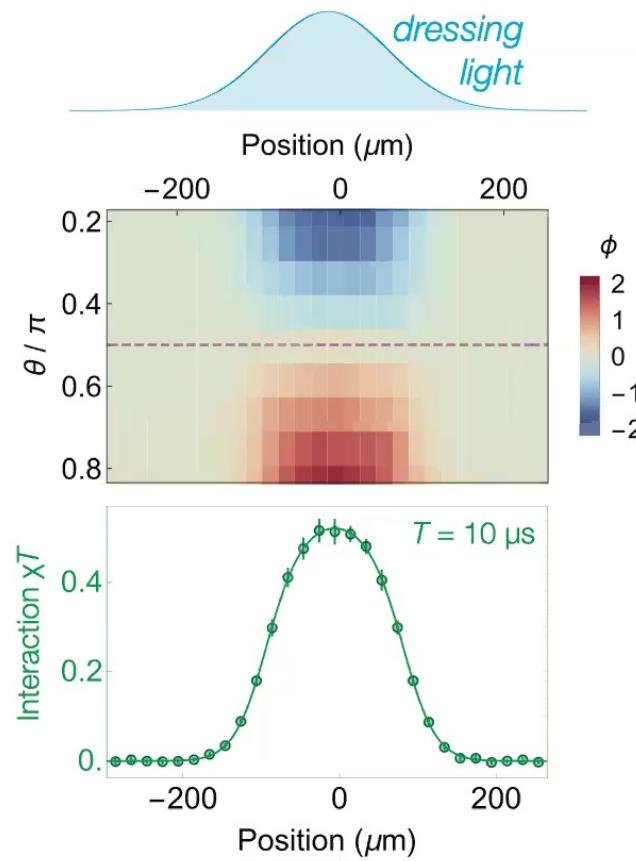


# Ising Dynamics

Interaction strength  $\chi$  set by local intensity of Rydberg dressing light



Borish, Markovic, Hines, Rajagopal  
& MS-S, *PRL* **124**, 063601 (2020).



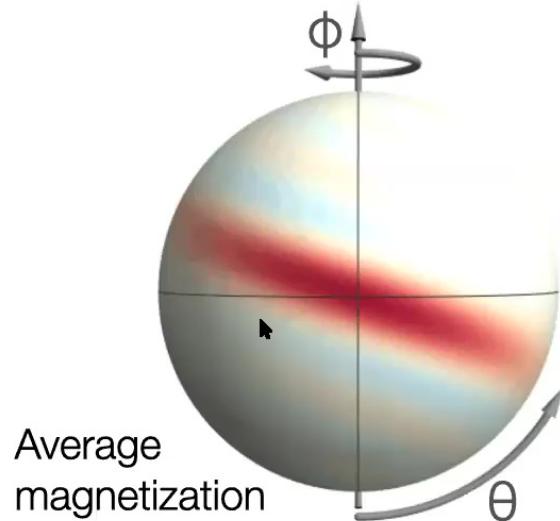


# Rydberg-Dressed Ising Interactions

## Prospect:

new mechanism for spin squeezing

Gil, Mukherjee, Bridge, Jones, & Pohl, *PRL* (2014).



Gil...& Pohl 00:04 & Zoller *PRL* (2019).

## Local control of interactions:

arrays of entangled states for dynamic range, spatial resolution, and/or bandwidth...

**Challenge:** long-range correlations from finite-range interactions?

**Resource:** transverse field enables correlations to spread

Kaubruegger, ... & Zoller, *PRL* (2019).

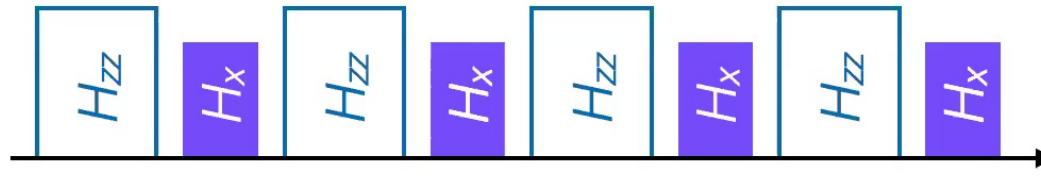


# Transverse-Field Ising Model

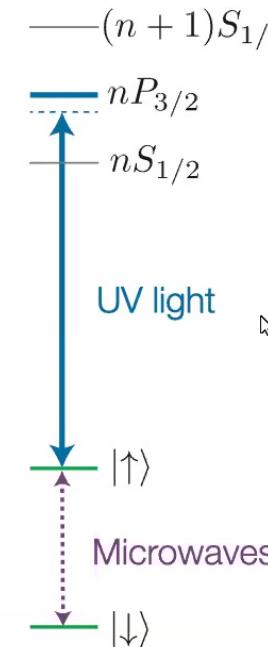
Borish, Markovic, Hines, Rajagopal  
& MS-S, *PRL* **124**, 063601 (2020).

Floquet implementation: alternate  $H_{zz}$  and  $H_x$

$$H_{zz} = \sum_{i,j} J(\mathbf{r}_{ij}) \sigma_i^z \sigma_j^z \quad H_x = \sum_i h_i \sigma_i^x$$



$$\Rightarrow H_{\text{eff}} = \sum_{i,j} J(\mathbf{r}_{ij}) \sigma_i^z \sigma_j^z + h \sum_i \sigma_i^x$$

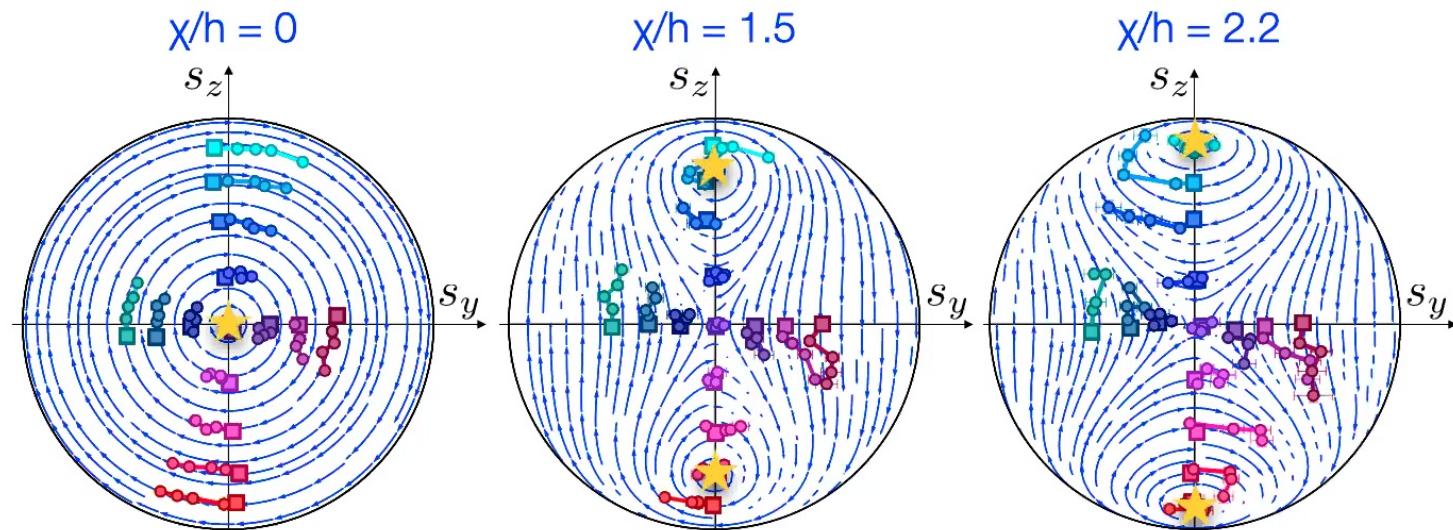




# Transverse-Field Ising Dynamics

Borish, Markovic, Hines, Rajagopal  
& MS-S, *PRL* **124**, 063601 (2020).

Mean-field model:  $H \approx -\chi \langle s_z \rangle^2 - h \langle s_x \rangle$

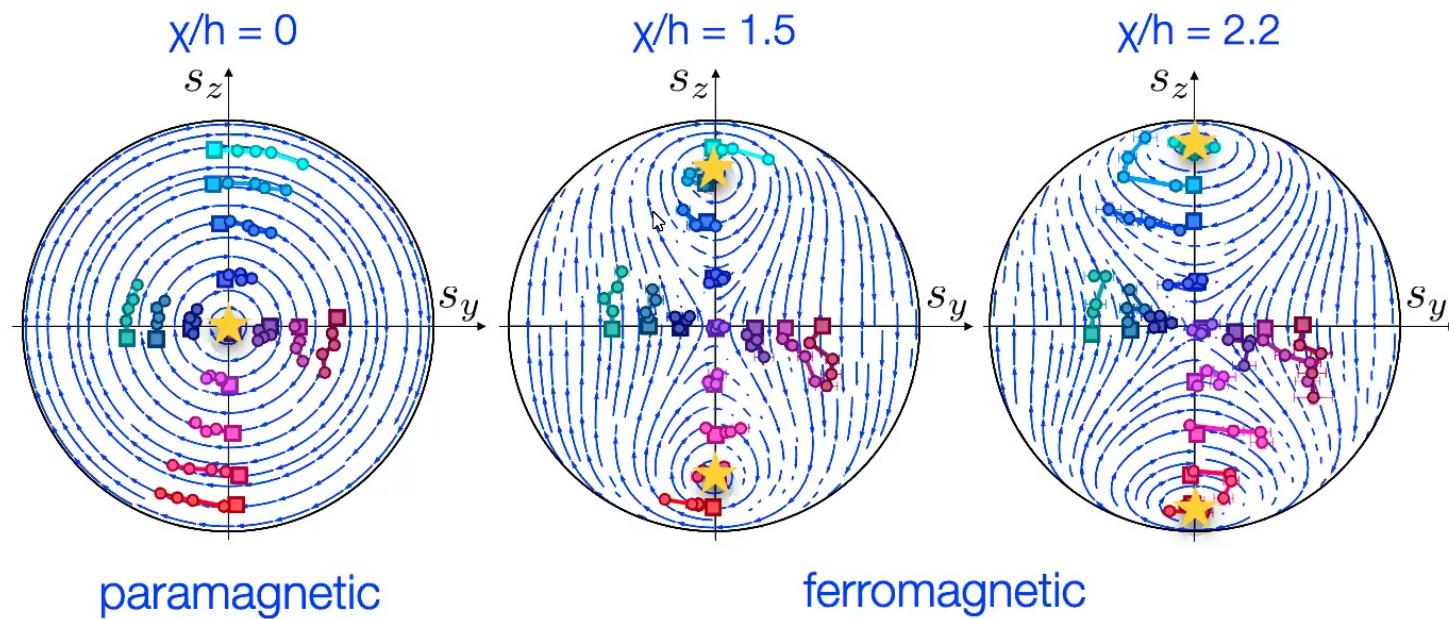




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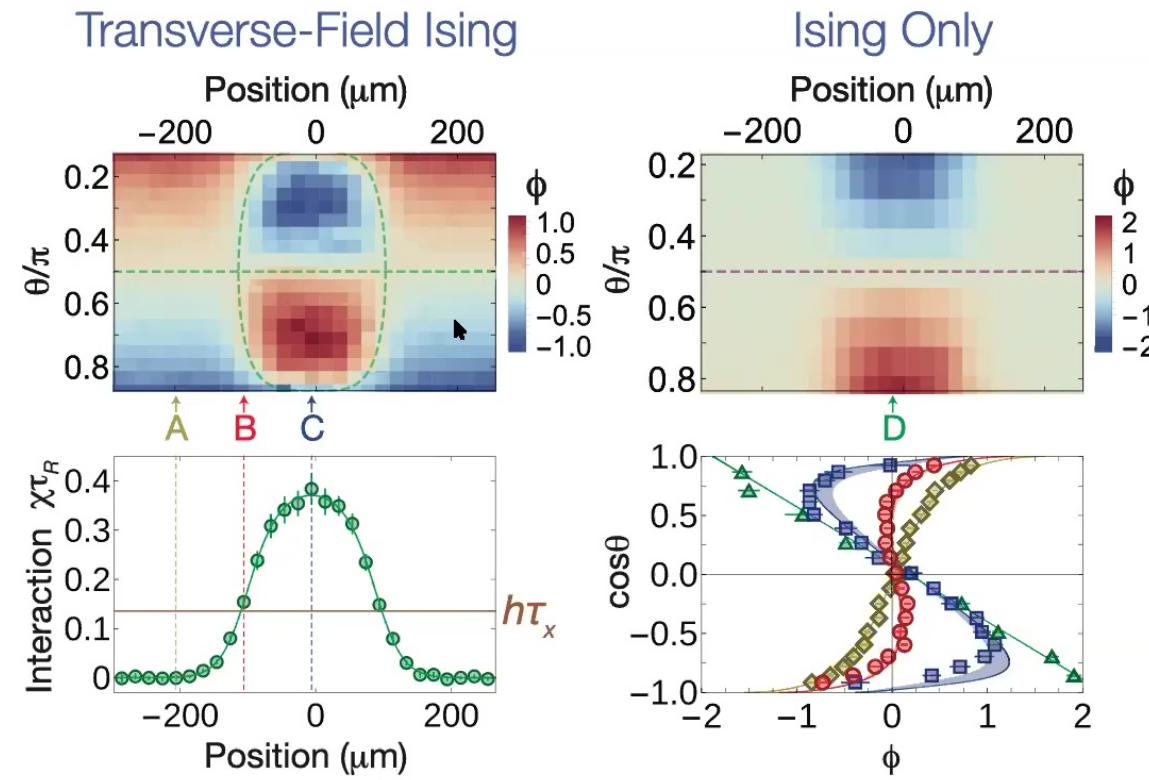
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# Bifurcation of Fixed Points

Borish, Markovic, Hines, Rajagopal  
& MS-S, *PRL* **124**, 063601 (2020).

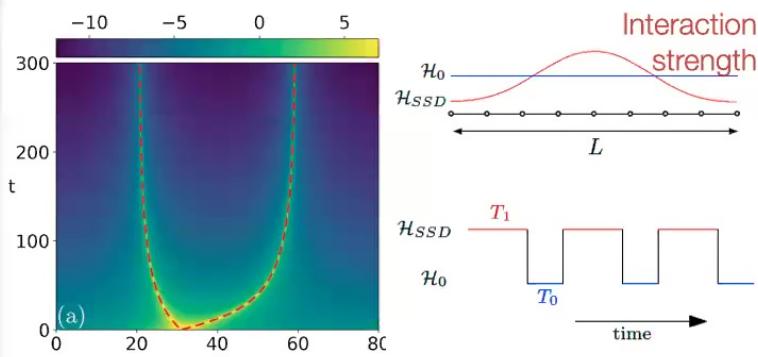




# Prospects in Quantum Simulation

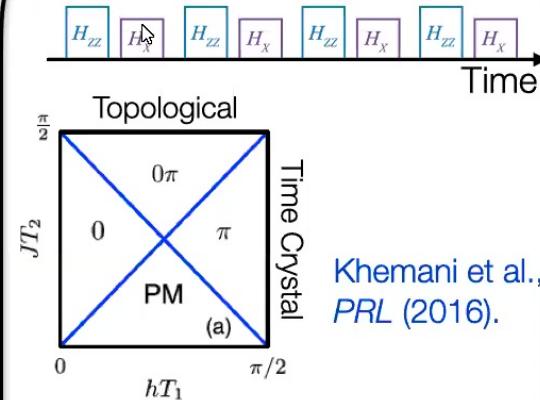
- Optical control allows for varying interactions in **space** and **time**.

## Emergent black-hole dynamics



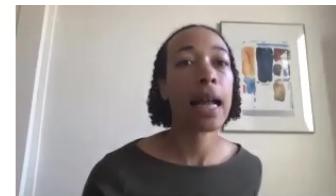
B. Lapierre, ..., & R. Chitra, *arXiv:1909.08618* (2019).  
Fan, Gu, Vishwanath & Wen, *arXiv:1908.05289* (2019).

## Non-equilibrium phases



**Rydberg:** Potirniche, ..., MSS, Vishwanath & Yao, *PRL* (2017).

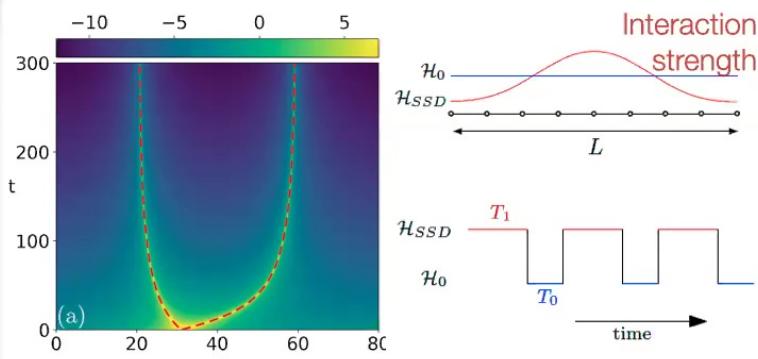
**Kapitza phases:** Leroose, Marino, Gambassi & Silva, *PRB* (2019).



# Prospects in Quantum Simulation

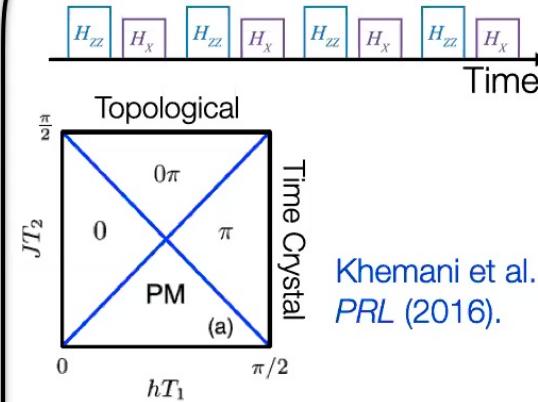
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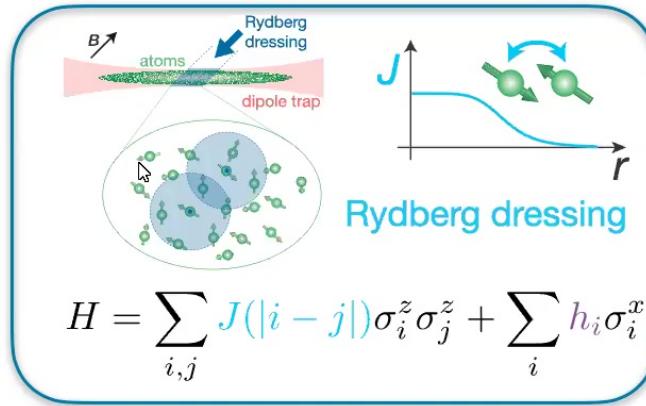
- Frustration in AFM Ising model  $\leftrightarrow$  combinatorial optimization



# Optically Controlled Interactions

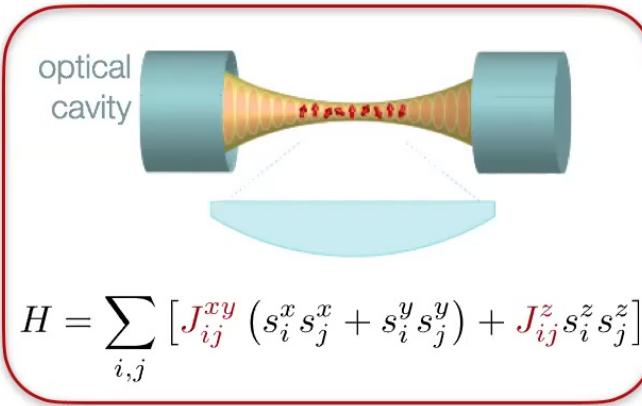
Engineering spin-spin interactions among laser-cooled atoms:

## Rydberg interactions



Long-range but local

## Photon-mediated interactions



Highly non-local



# Motivation

## Quantum Control

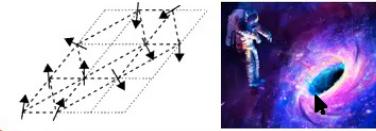
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$$|\psi\rangle = \frac{|{\downarrow\downarrow\downarrow}\rangle + |{\uparrow\uparrow\uparrow}\rangle}{\sqrt{2}}$$



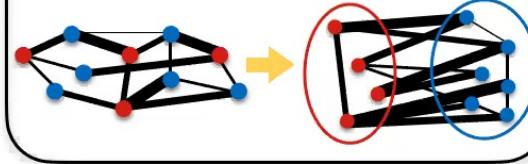
## Quantum Simulation

...from condensed matter  
to quantum gravity



## Combinatorial Optimization

Encode classical cost function  
in energy of quantum system



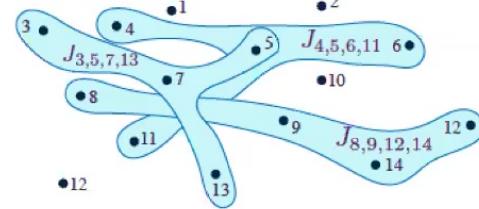


# Information Scrambling in Black Holes

Toy models involve particles that can hop *non-locally*....

## Fermions

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^N J_{ij;kl} c_i^\dagger c_j^\dagger c_k c_\ell$$

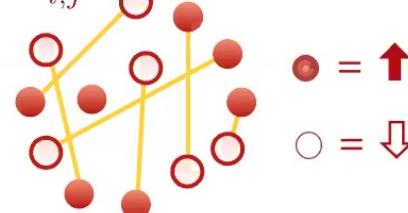


## Black-hole duality:

S. Sachdev, PRX (2015).  
Kitaev, KITP (2015).

## Spin excitations?

$$H \propto \sum_{i,j} J_{ij} \sigma_+^i \sigma_-^j$$

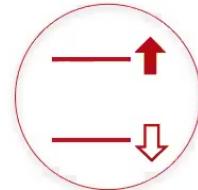


Natural approach:  
particles = spin excitations,  
hopping mediated by light

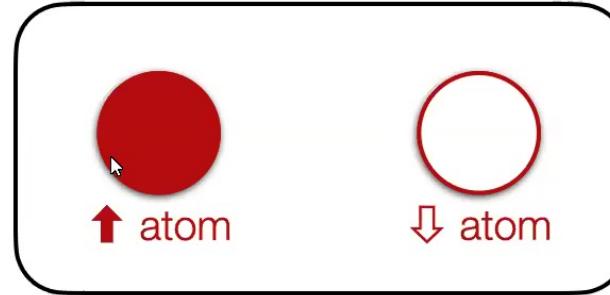


## Photon-Mediated Interactions

Each atom as an “occupied” [ $\bullet = \uparrow$ ] or “empty” [ $\circ = \downarrow$ ] site



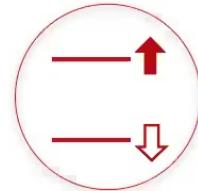
Spin-exchange interaction



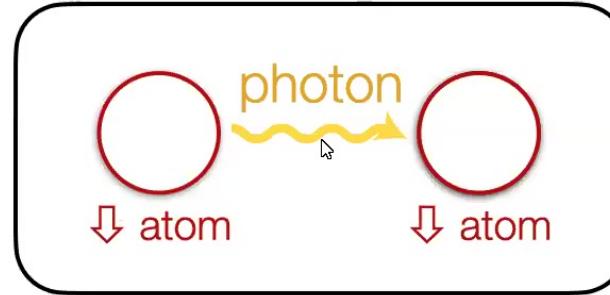


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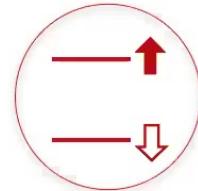
Spin-exchange interaction



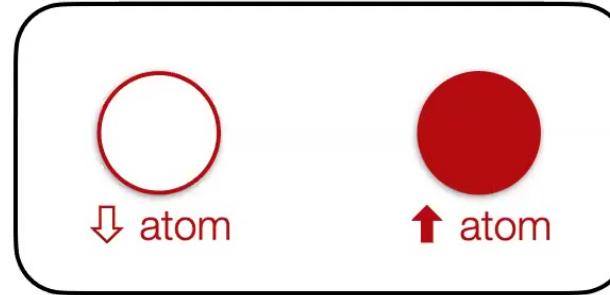


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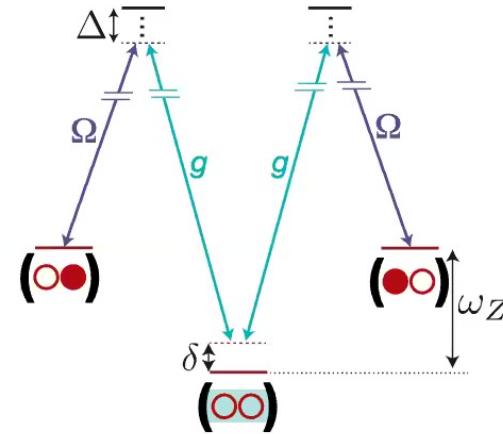
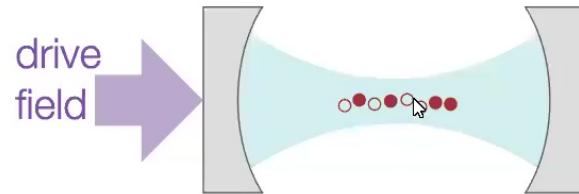
Spin-exchange interaction





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Each atom as an “occupied” [ $\bullet = \uparrow$ ] or “empty” [ $\circ = \downarrow$ ] site



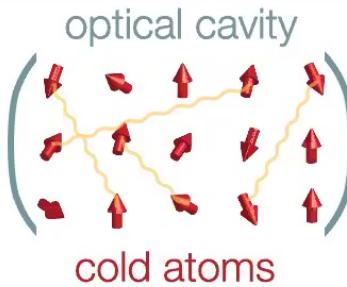
$$\text{Spin-exchange interaction } H = \sum_{i,j} J_{ij} s_i^+ s_j^-$$



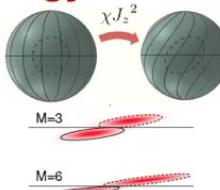
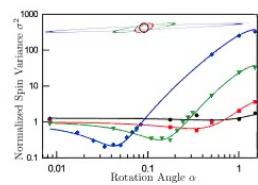
# Photon-Mediated Interactions

## New ingredient:

Real-space observation  
of spin dynamics



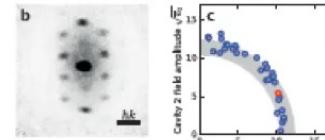
## Quantum metrology



Leroux, MS-S & Vuletic, *PRL* (2010).  
Hosten, ... & Kasevich, *Science* (2016).  
Norcia, ..., Rey & Thompson, *Science* (2018).  
Braverman, ... & Vuletic, *PRL* (2019).

## Quantum simulations

### supersolids



Léonard et al., *Nature* (2017).

### spin glasses?

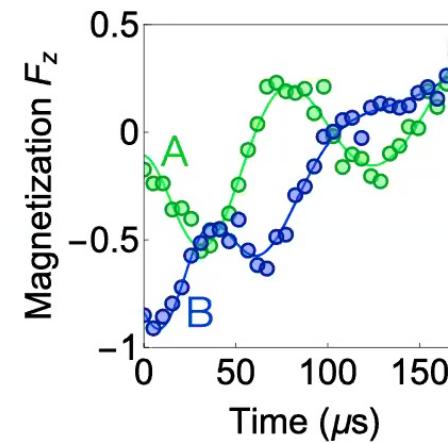
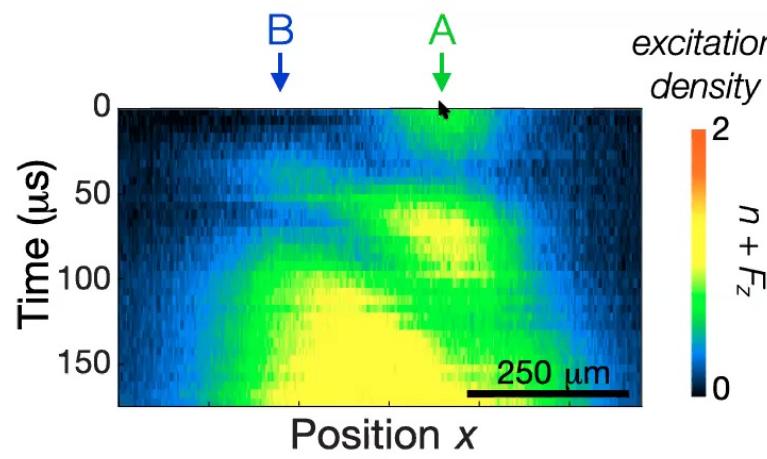
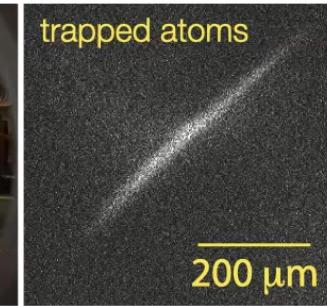
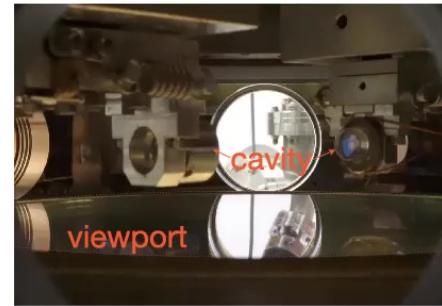
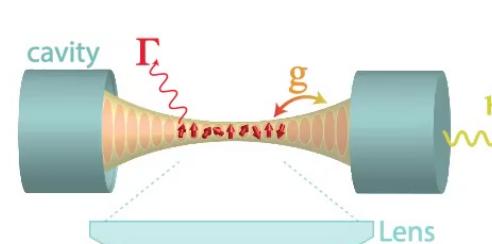


Gopalakrishnan, Lev;  
Strack & Sachdev,  
*PRL* (2011).

+ topological phases,  
dynamical gauge fields, ... ?

# Experimental Setup

E. Davis, G. Bentsen, L. Homeier, T. L  
& M. S-S. *PRL* **122**, 010405 (2019).





# Programmable Interactions?



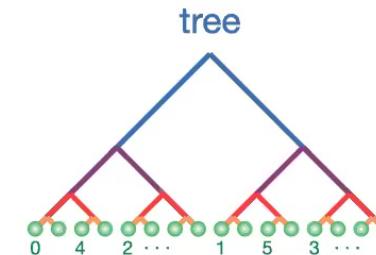
$$H = \sum_{i,j} [J_{ij}^{xy} (s_i^+ s_j^- + s_i^- s_j^+) + J_{ij}^z s_i^z s_j^z]$$

## Knobs we would like:

- Sign of interaction (ferro- vs antiferromagnetic)
- Form of couplings (flip-flop vs Ising)
- Spatial structure



Bentsen, Potirniche,  
Bulchandani, Scaffidi,  
Cao, Qi, MS-S & Altman,  
*PRX* **9**, 041011 (2019).



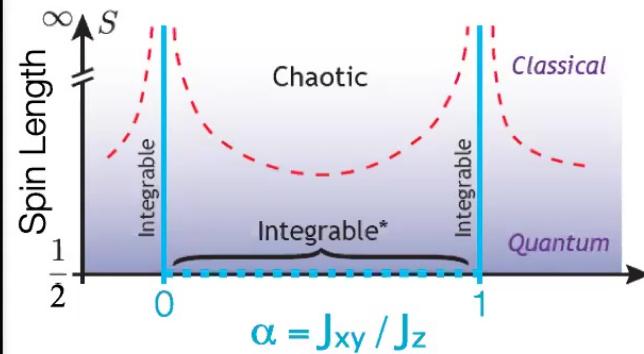
Bentsen, Hashizume, Buyskikh,  
Davis, Daley, Gubser, & MS-S,  
*PRL* **123**, 130601 (2019).



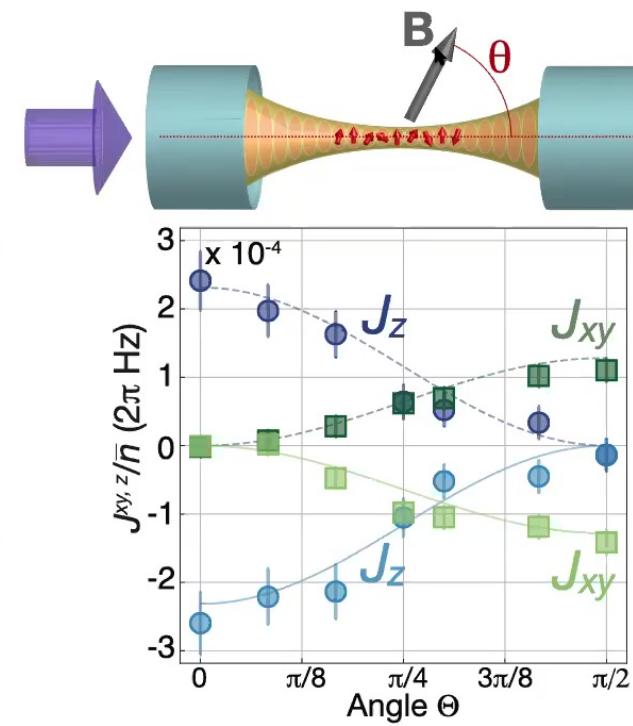
## Tunable Heisenberg Models

$$H = \pm \sum_{i,j} \Omega_i \Omega_j [J_{xy} (S_i^x S_j^x + S_i^y S_j^y) + J_z S_i^z S_j^z]$$

Rich phase diagram for inhomogeneous atom-light couplings  $\Omega_i$

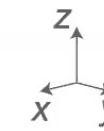
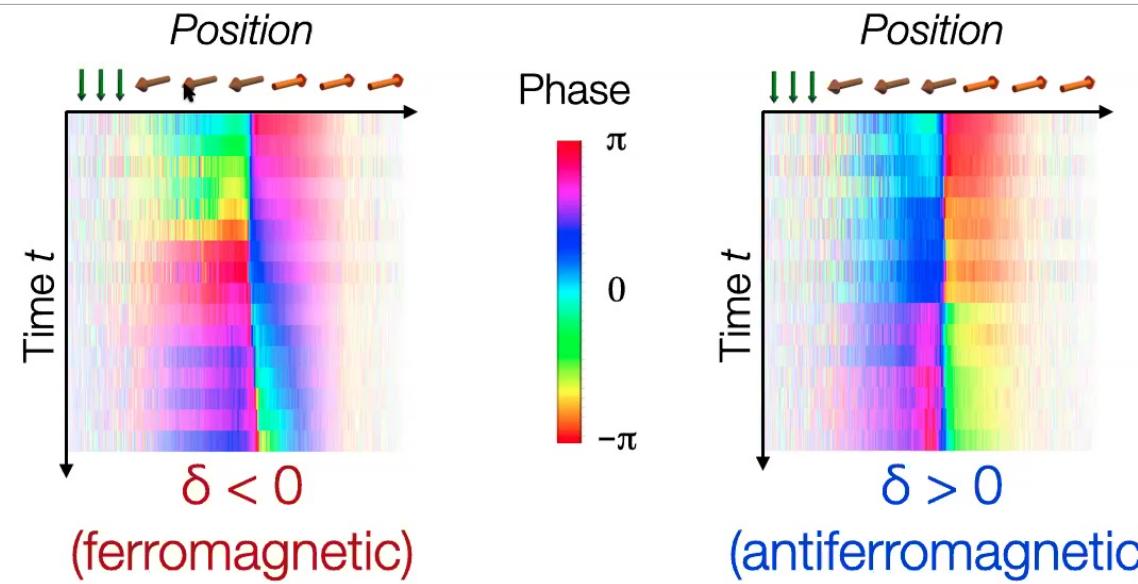


G. Bentsen, I.-D. Potirniche, V. Bulchandani, T. Scaffidi, X. Cao, X. Qi, MS-S & E. Altman, *Phys. Rev. X* **9**, 041011 (2019).



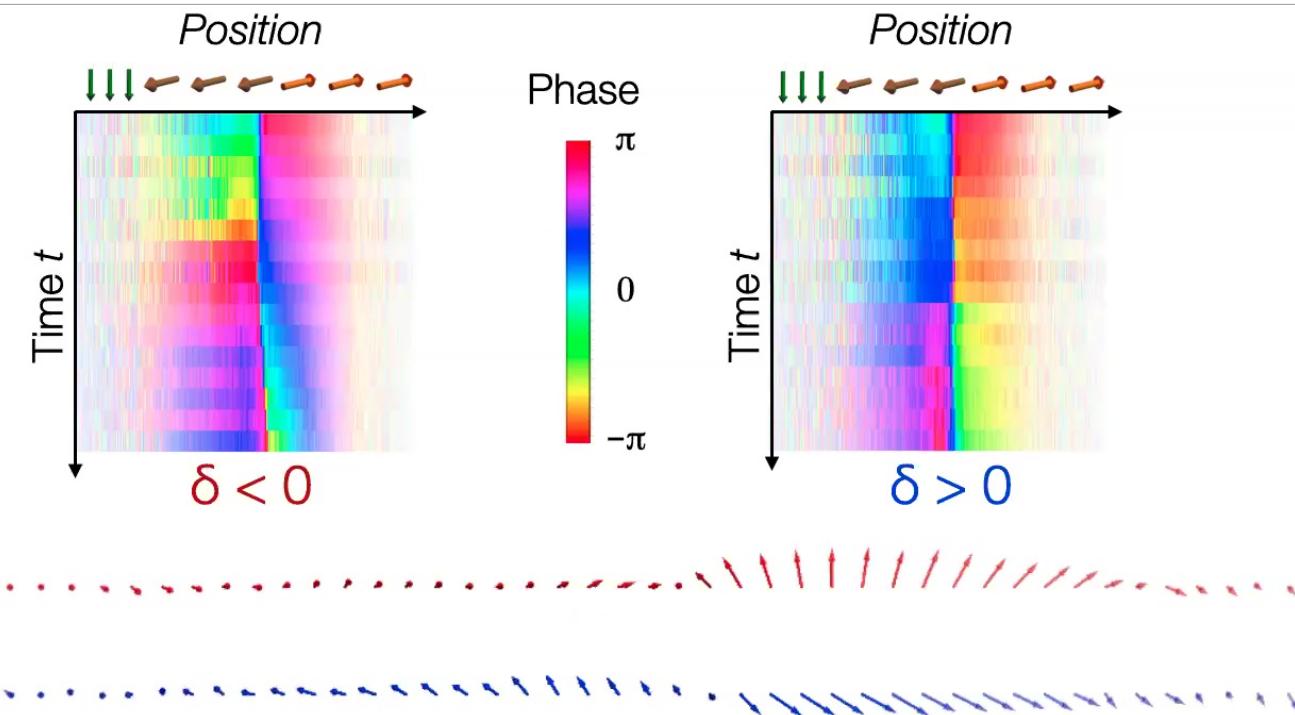


## Measuring Ising Couplings



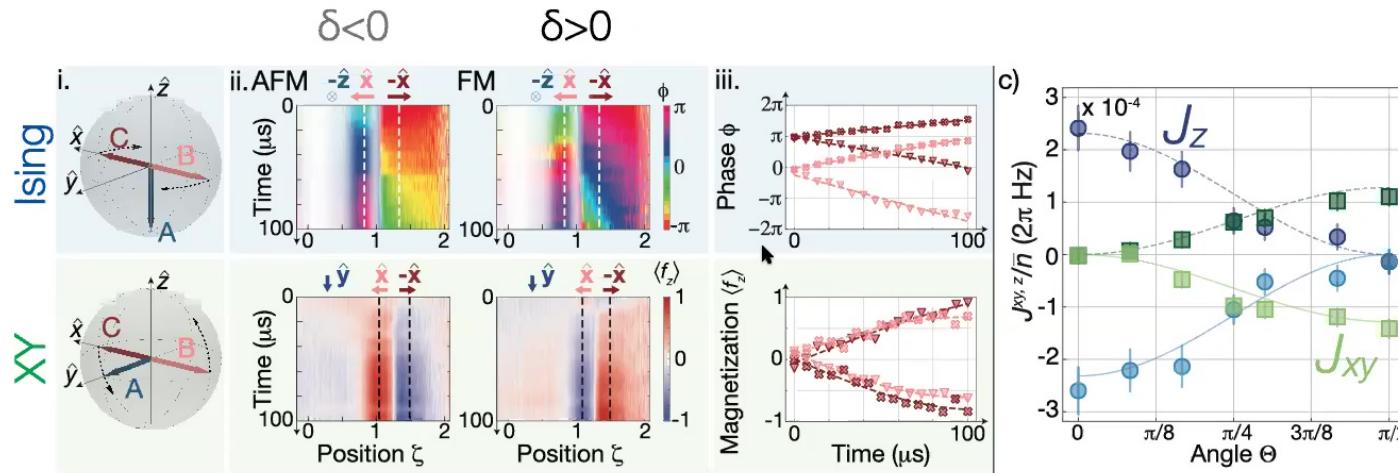


## Measuring Ising Couplings



# Hamiltonian Tomography

E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).



- ✓ Verified interaction Hamiltonian by dynamics after sudden quench
  - **Cross-check:** prepare low-energy states



# Exploring the Phase Diagram

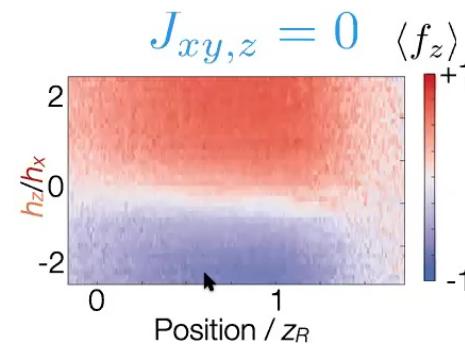
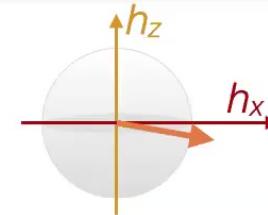
E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).

$$H_I = \textcolor{blue}{J_{xy}} (\mathcal{F}_x^2 + \mathcal{F}_y^2) + \textcolor{blue}{J_z} \mathcal{F}_z^2$$

$$\mathcal{F} = \sum_i \xi_i S_i^z$$

Prepare low-energy state by slow quench

$$H = H_I - \textcolor{red}{h_x} F_x - \textcolor{brown}{h_z} F_z$$





# Exploring the Phase Diagram

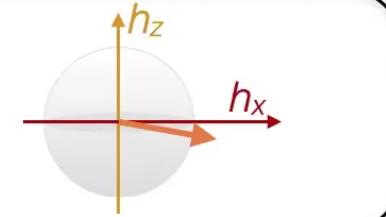
E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).

$$H_I = \textcolor{teal}{J}_{xy} (\mathcal{F}_x^2 + \mathcal{F}_y^2) + \textcolor{teal}{J}_z \mathcal{F}_z^2$$

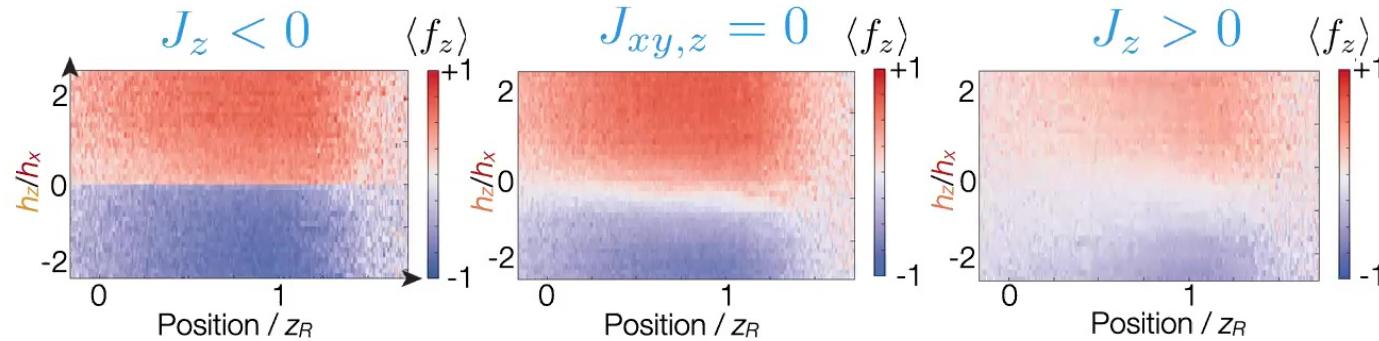
$$\mathcal{F} = \sum_i \xi_i S_i^z$$

Prepare low-energy state by slow quench

$$H = H_I - \textcolor{red}{h}_x F_x - \textcolor{brown}{h}_z F_z$$



E.g., Ising interactions:

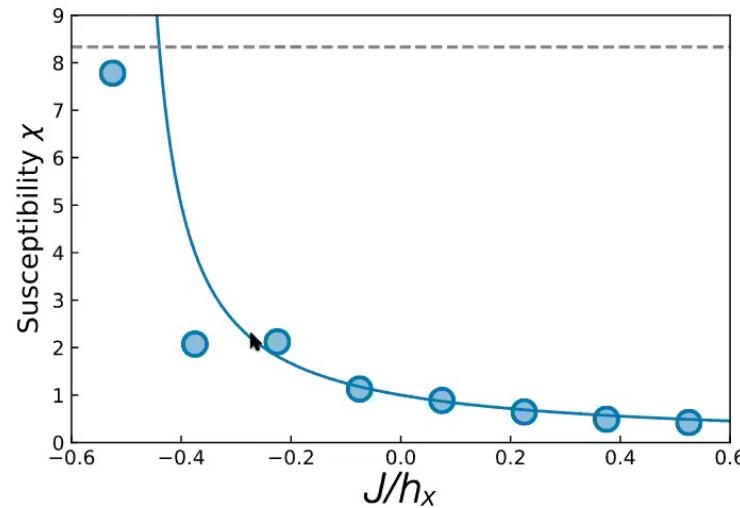




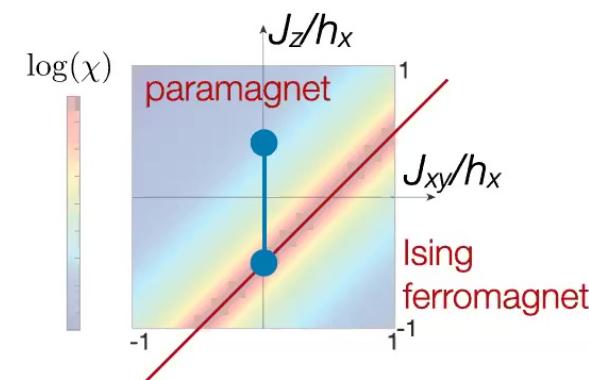
# Magnetic Susceptibility

E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).

$$H_I = \textcolor{teal}{J}_{xy} (\mathcal{F}_x^2 + \mathcal{F}_y^2) + \textcolor{red}{J}_z \mathcal{F}_z^2 + \textcolor{teal}{h}_x F_x$$



$$\mathcal{F} = \sum_i \xi_i S_i^z$$
$$\mathbf{F} = \sum_i S_i^z$$

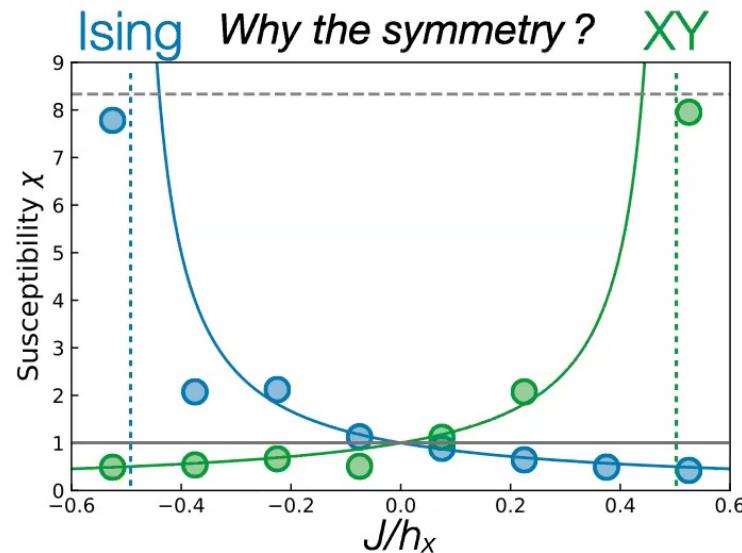




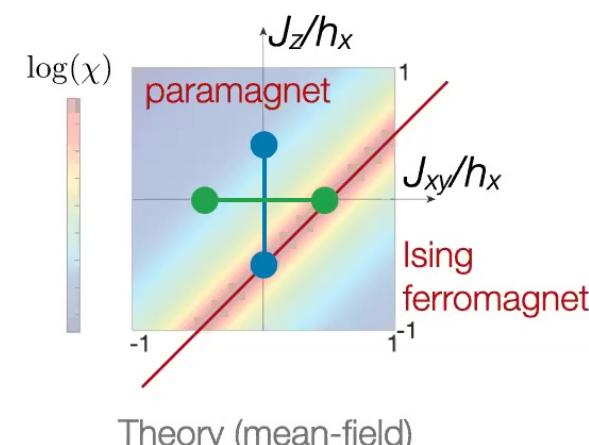
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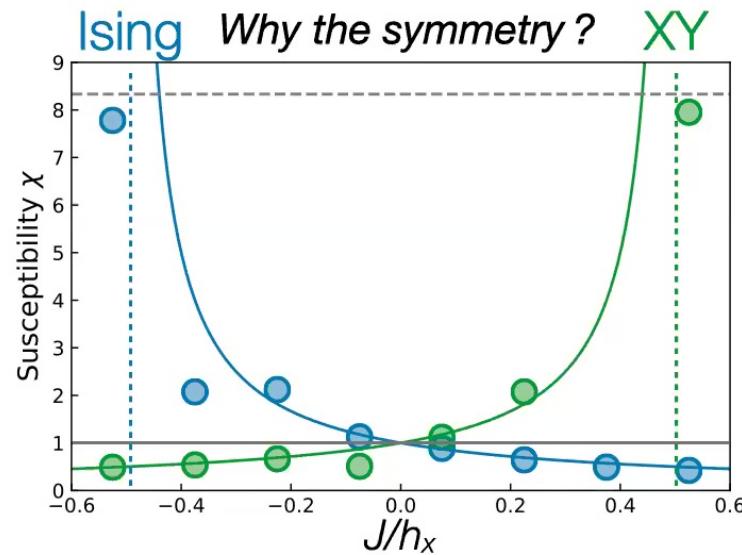




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G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).

$$H_I = \textcolor{teal}{J}_{xy} (\mathcal{F}_x^2 + \mathcal{F}_y^2) + \textcolor{teal}{J}_z \mathcal{F}_z^2 + \textcolor{teal}{h}_x F_x$$



$$\mathcal{F} = \sum_i \xi_i S_i^z$$
$$\mathbf{F} = \sum_i S_i^z$$

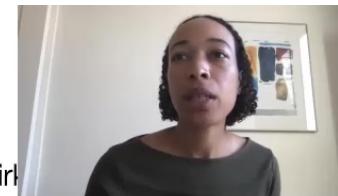
$$F_z^2 = -\textcolor{teal}{F}_x^2 - \textcolor{teal}{F}_y^2 + F(F+1)$$

⇒ approx. symmetry:

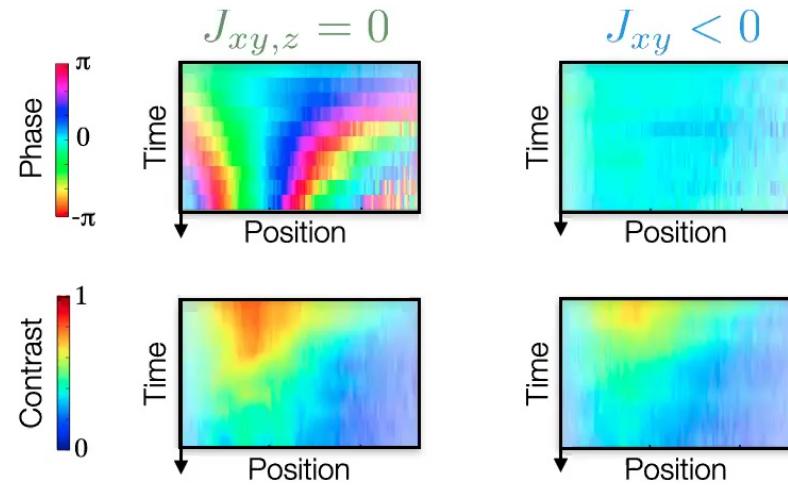
$$J_z \leftrightarrow -J_{xy}$$

# Beyond Single-Mode Dynamics

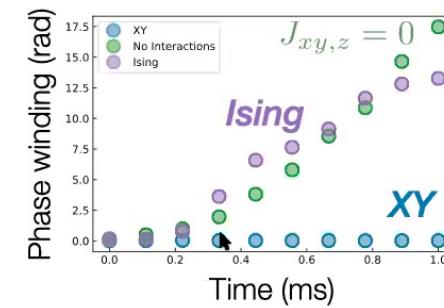
E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).



Dynamical response to inhomogeneous  $z$  field:



Ferromagnetic **XY** interactions  
protect spin coherence!

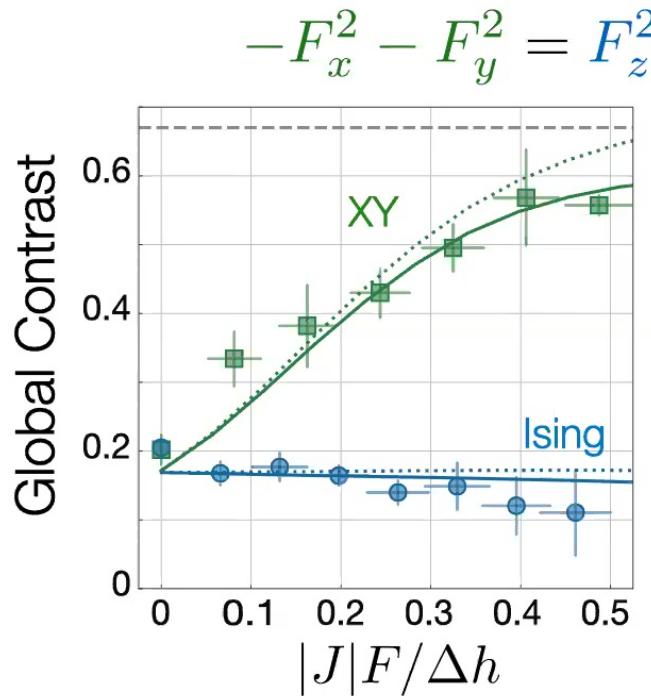


AFM **Ising** interactions don't.



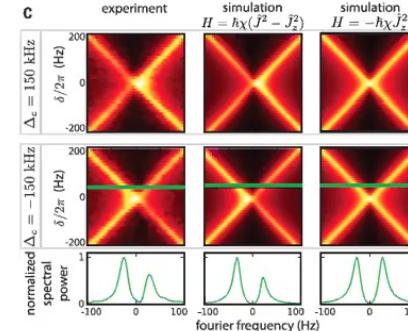
# Protection of Spin Coherence

E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).



Dephasing suppressed by energy cost of reducing total spin  $\mathbf{F}$

Norcia et al, *Science* (2018):  
spectroscopy of energy gap



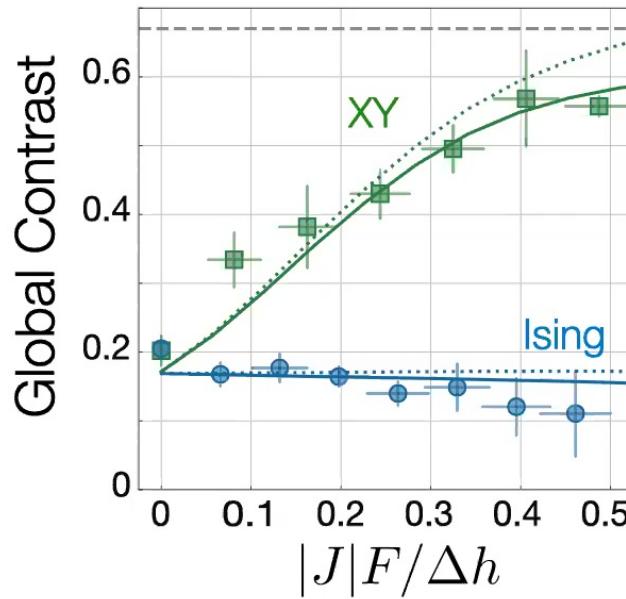
**Prospect:** enhancing robustness of light-induced spin squeezing  
+ extensions to other systems (e.g., local interactions)



# Protection of Spin Coherence

E. Davis, A. Periwal, E. Cooper,  
G. Bentsen, S. Evered, K. Van Kirk  
& MS-S, *PRL* **125** 060402 (2020).

$$-F_x^2 - F_y^2 = F_z^2 - F(F+1)$$

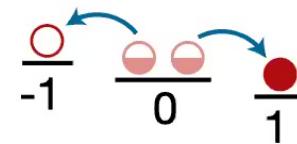


Dephasing suppressed by energy cost of reducing total spin  $\mathbf{F}$



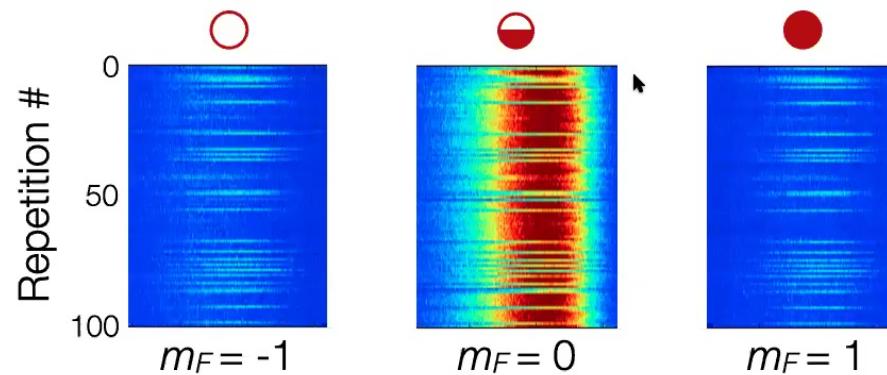
## Evidence of *Quantum* Dynamics?

**Pair creation** in a spin-1 system



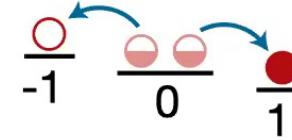
...initialized with all atoms in  $m_F = 0$

$$H = \sum_{i,j} J_{ij} F_i^+ F_j^-$$



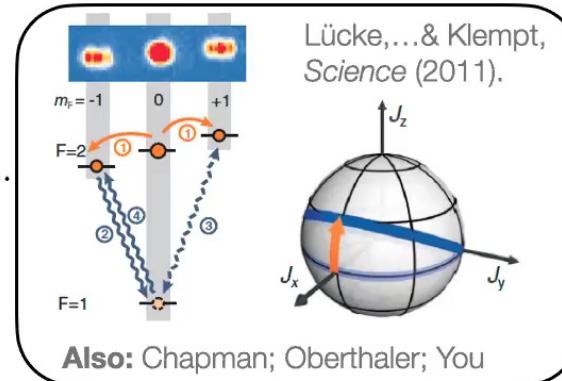


# Photon-Mediated Pair Creation

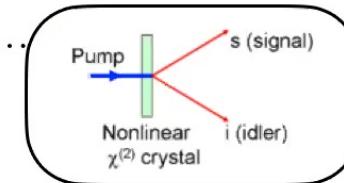


## Analogies:

- Collisional spin mixing in .....  
Bose-Einstein condensates



- Spontaneous parametric down-conversion .....



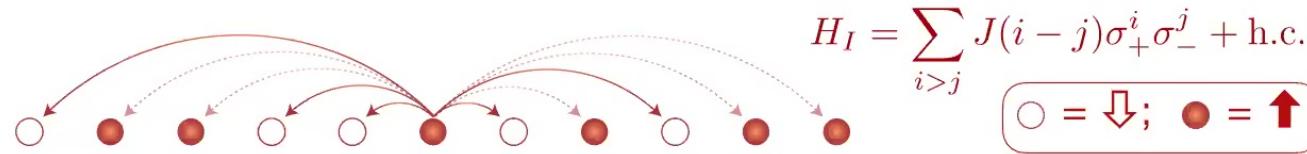
## Prospects:

- Fast generation of **twin Fock states** for sensing near Heisenberg limit
- **Spatially structured entanglement** by **optical control**

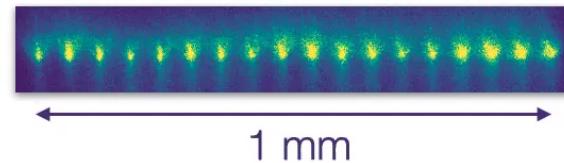


# Towards Programmable Interactions

Photon-mediated interactions for versatile control of spin-spin couplings:



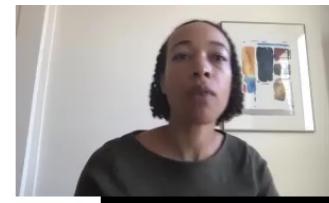
...in an **array of small atomic ensembles**:



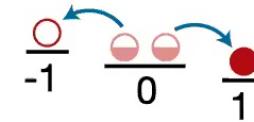
- 18 sites with  $10^3$  atoms/site
- Collective enhancement of interaction strength

**Objective:** arbitrary control of translationally invariant couplings

... and beyond, by controlling the positions of trapping sites



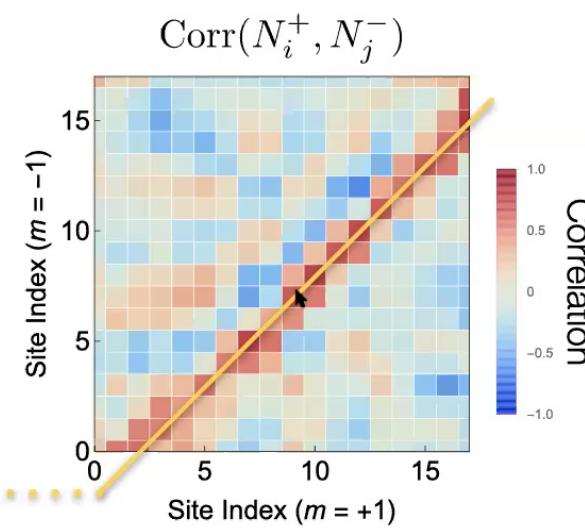
## Spatial Control of Pair Creation

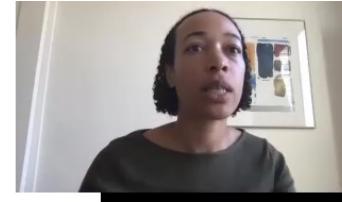


- 1) Turn off long-range interactions by adding a magnetic field gradient

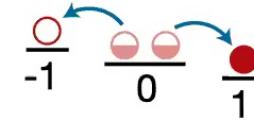


$m = \pm 1$  pairs form only locally,  
or at a single distance set by  
quadratic Zeeman shift  
 $E_{+1} + E_{-1} - 2E_0$

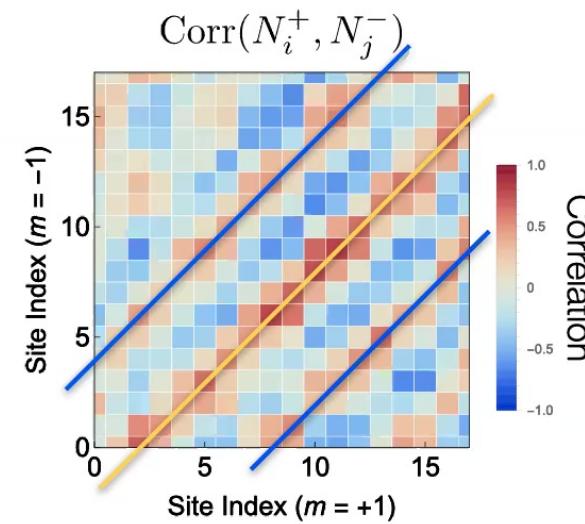
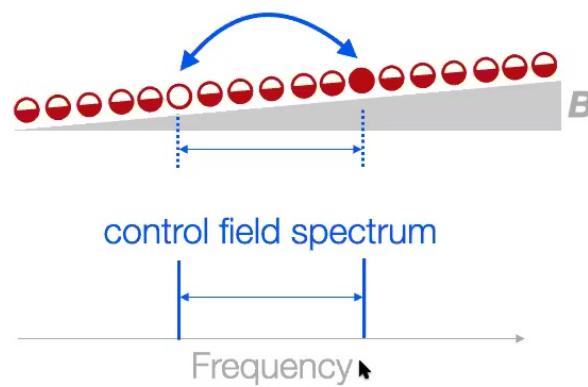




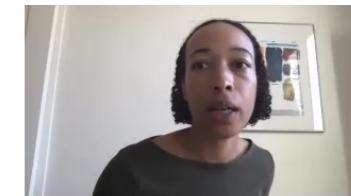
## Spatial Control of Pair Creation



- 1) Turn off long-range interactions by adding a magnetic field gradient
- 2) Reintroduce interactions at distance(s) set by spectrum of drive field

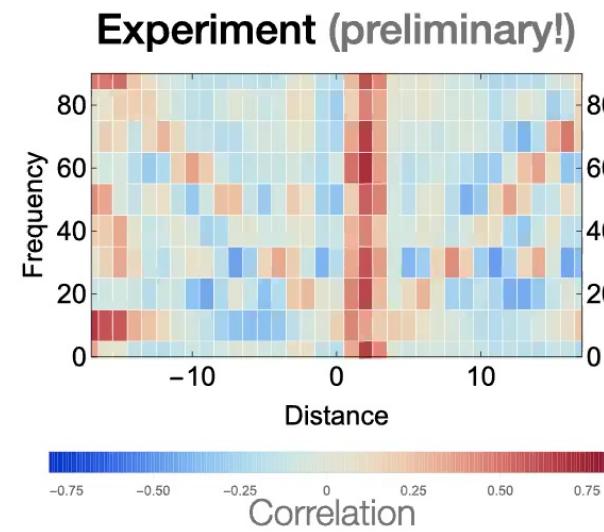
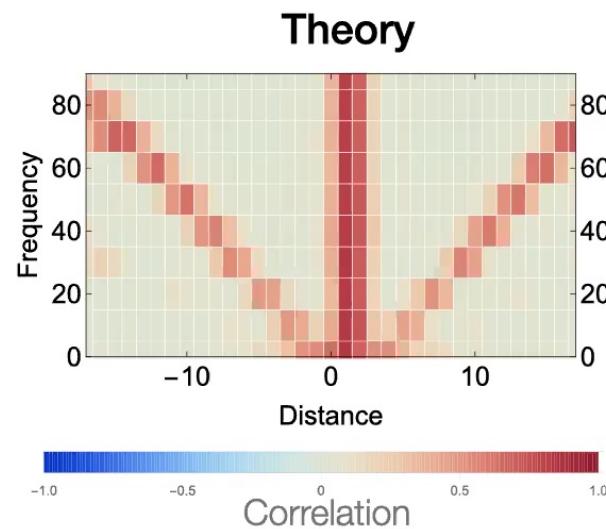


**Proposal:** Hung, Gonzales-Tudela, Cirac & Kimble, *PNAS* (2016).



# Programmable Interactions

Controlling interaction distance by frequency spacing between drive fields



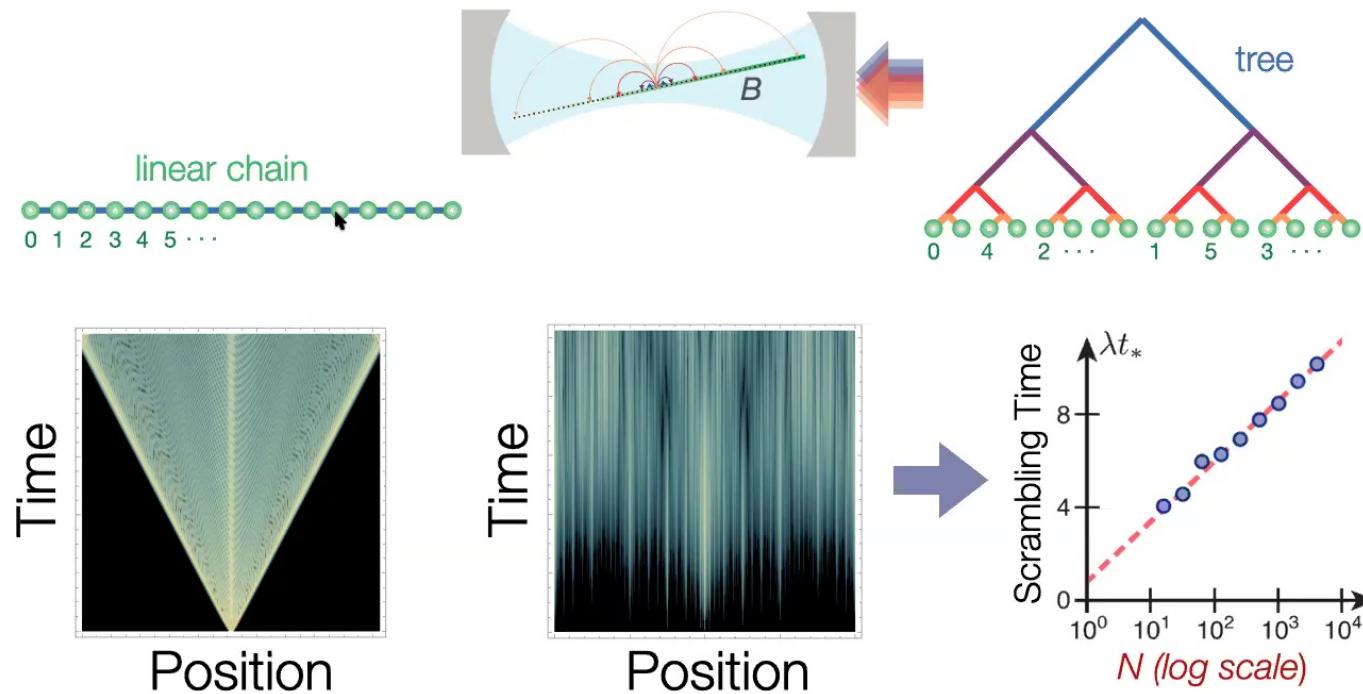
**Generalization:** multifrequency drive enables *arbitrary* couplings  $J(i-j)$

# Prospect: Fast Scrambling

Bentsen, Hashizume, Buyskikh, Davis, Daley, Gubser, & MS-S, *PRL* **123**, 130601 (2019).



Efficiently spread information by coupling  $i^{\text{th}}$  spin to  $i \pm 1, i \pm 2, i \pm 4, i \pm 8, \dots, i \pm 2^l$



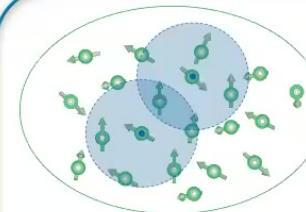


# Summary & Outlook

optical cavity



$$H = \sum_{i,j} [J_{ij}^{xy} (s_i^x s_j^x + s_i^y s_j^y) + J_{ij}^z s_i^z s_j^z]$$

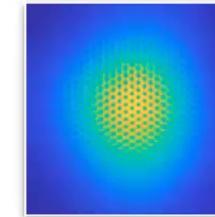


Rydberg dressing

$$H = \sum_{i,j} J(|i - j|) \sigma_i^z \sigma_j^z + \sum_i h_i \sigma_i^x$$

## Optically controlled interactions

- Programmable form, sign, & interaction graph
- Spatiotemporal control
- Interactions can protect spin coherence



## Prospects in quantum simulation:

- Toy models for quantum gravity
- Non-equilibrium phases & frustrated magnetism
- Quantum optimization (number partitioning, max-cut)

