Title: Choreographing Quantum Spin Dynamics with Light

Speakers: Monika Schleier-Smith

Series: Colloquium

Date: May 12, 2021 - 2:00 PM

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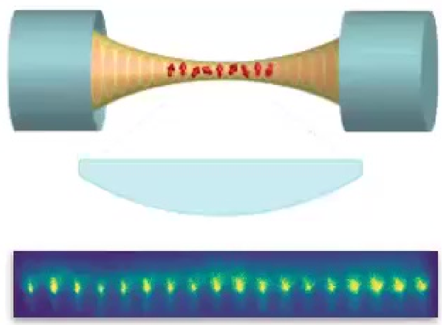
Abstract: The power of quantum information lies in its capacity to be non-local, encoded in correlations among entangled particles. Yet our ability to produce, understand, and exploit such correlations is hampered by the fact that the interactions between particles are ordinarily local. I will report on experiments in which we use light to engineer non-local interactions among cold atoms, with photons acting as messengers conveying information between them. We program the spin-spin couplings in an array of atomic ensembles by tailoring the frequency spectrum of an optical control field. We harness this programmability to access interaction graphs conducive to frustration and to explore quantum spin dynamics in exotic geometries and topologies. More broadly, advances in optical control of interactions open new opportunities in areas ranging from quantum technologies to fundamental physics. I will touch on implications for quantum-enhanced sensing, combinatorial optimization, and simulating quantum gravity.

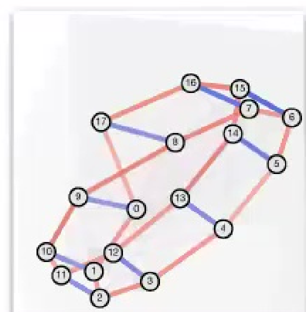
Choreographing Quantum Spin Dynamics with Light

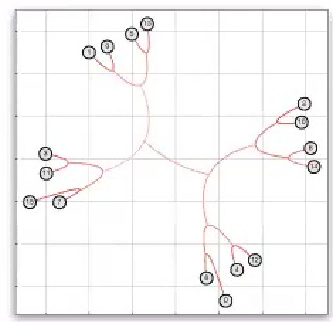
Monika Schleier-Smith

May 12, 2021

Avikar Periwal
Eric Cooper
Philipp Kunkel
Emily Davis
Greg Bentsen



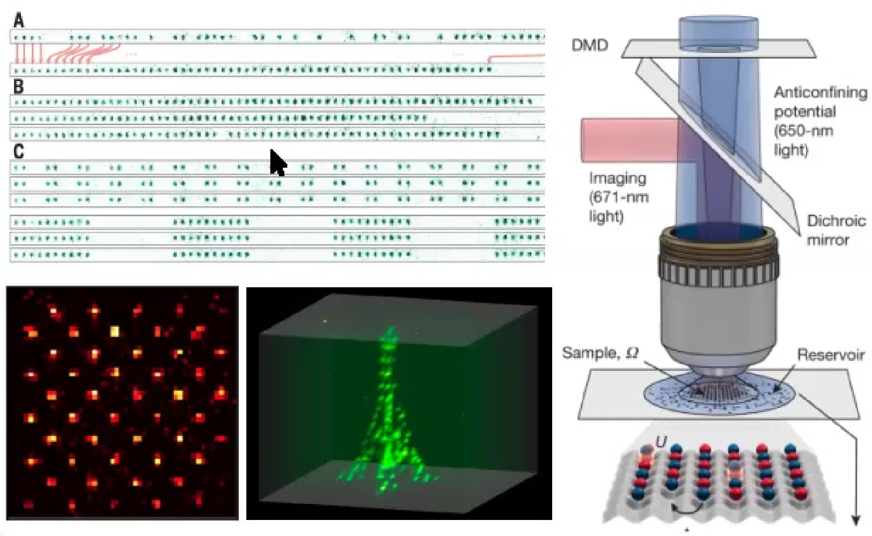




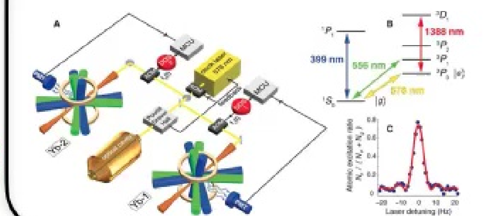
Stanford University

Quantum Engineering with Cold Atoms

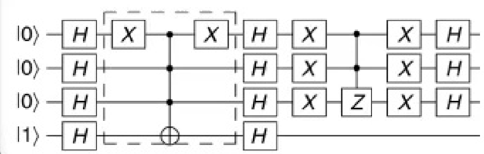
Single-atom control & detection + scalability



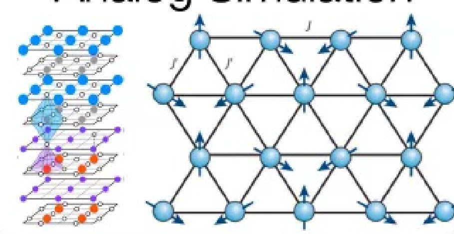
Ultra-stable Clocks



Computation?

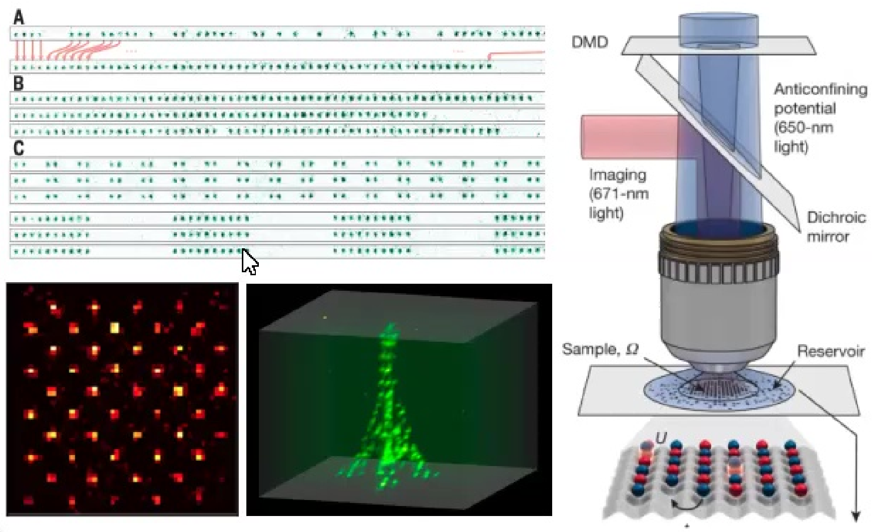


Analog Simulation

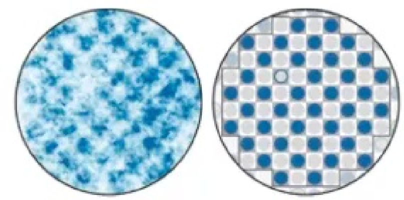


Quantum Engineering with Cold Atoms

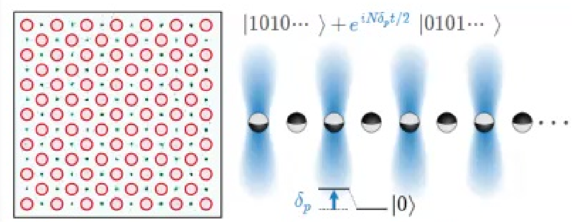
Single-atom control & detection + scalability



Interactions & Entanglement



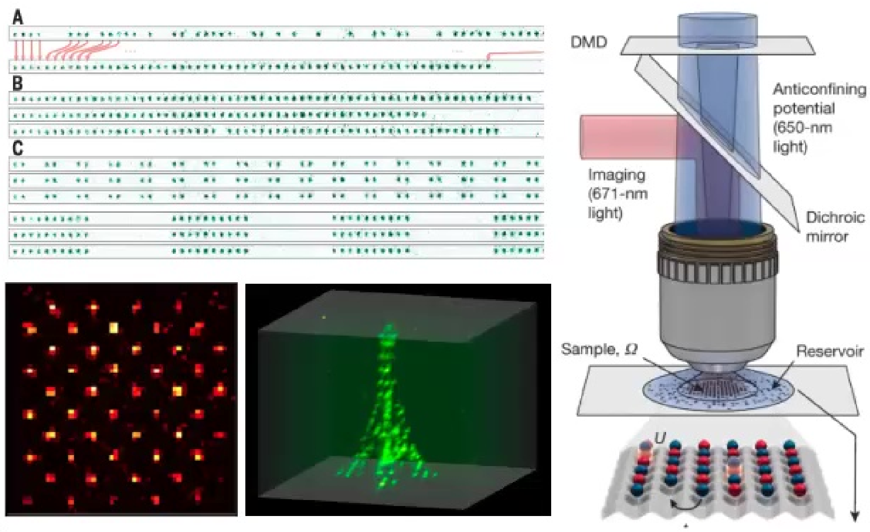
Contact interactions in lattice



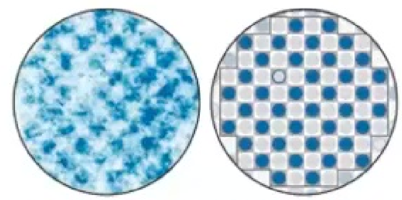
Rydberg atoms in optical tweezers

Quantum Engineering with Cold Atoms

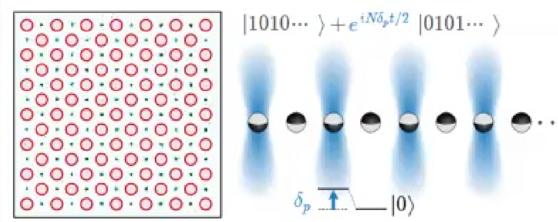
Single-atom control & detection + scalability



Interactions & Entanglement



Contact interactions in lattice



Rydberg atoms in optical tweezers

Limitation: connectivity of interactions — atoms interact only with neighbors

Connectivity Matters

A *classical* example…

The Internet

Connectivity Matters

A *classical* example…

The Internet

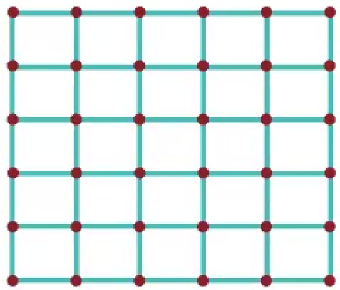
Before,
what mattered was
physical distance.

Now,
what matters is
network distance.

Connectivity governs the flow of information.

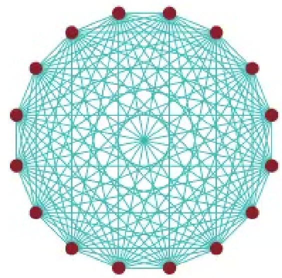
Connectivity in Quantum Systems

Nearest-Neighbor



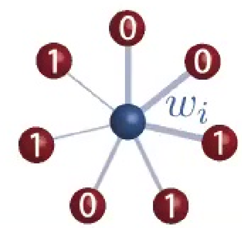
Cluster state:
Resource for universal quantum computation

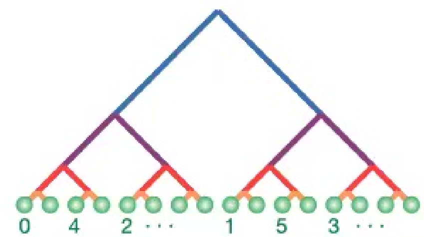
All-to-All



Squeezed state:
Resource for enhanced sensing & metrology

Other graphs?



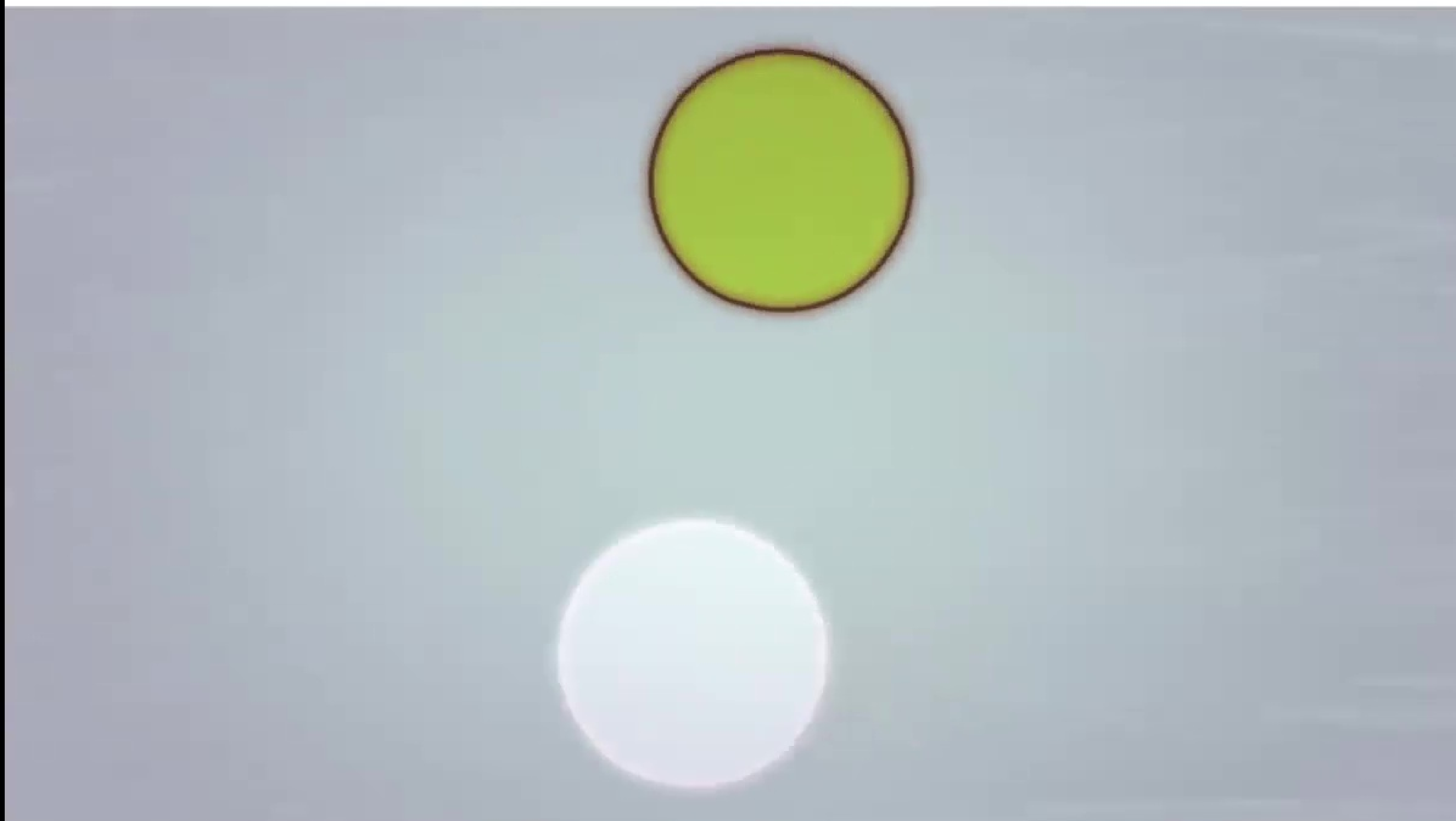


New opportunities?

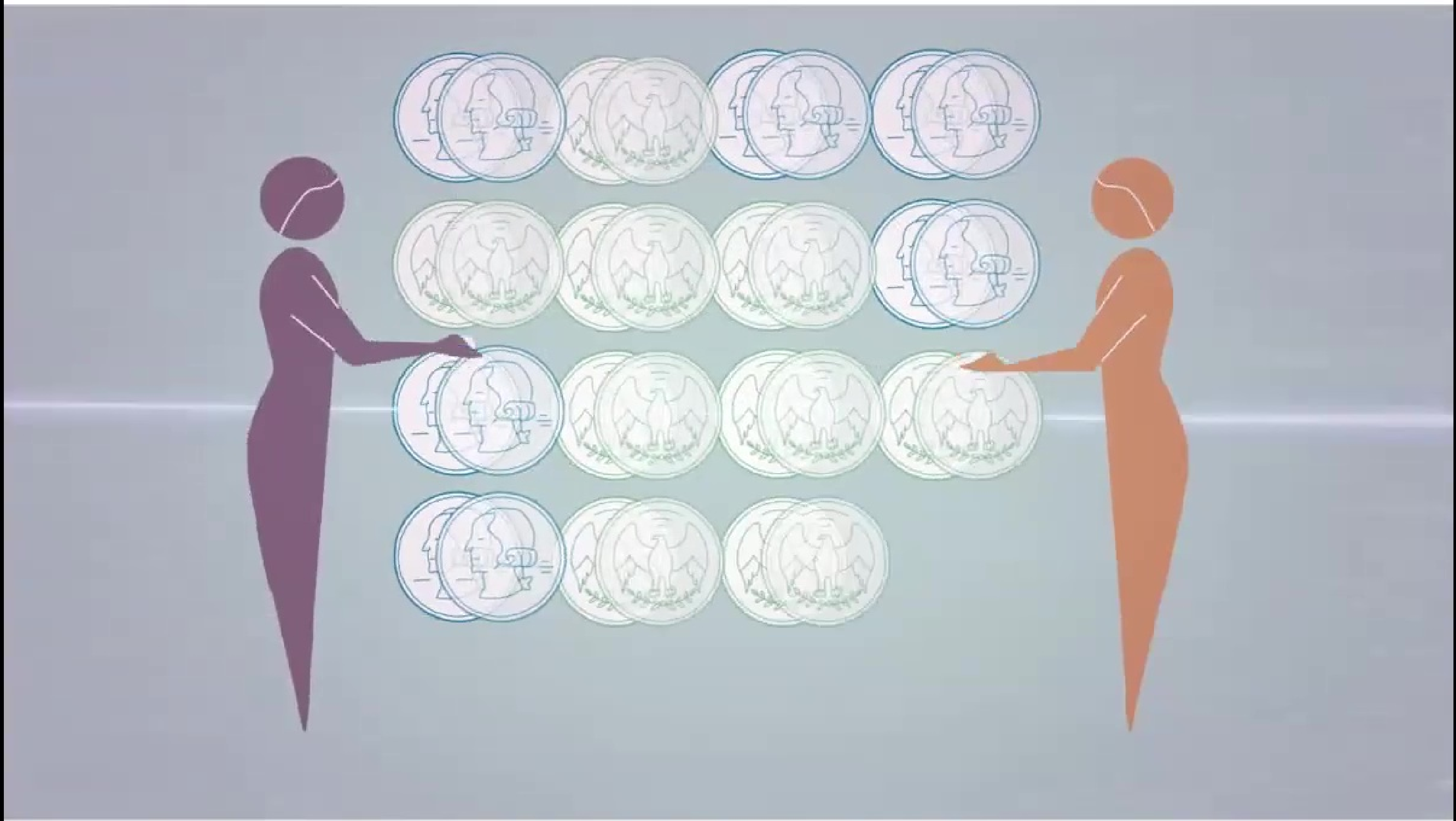
Structure of interactions governs form of entanglement

MacArthur Foundation

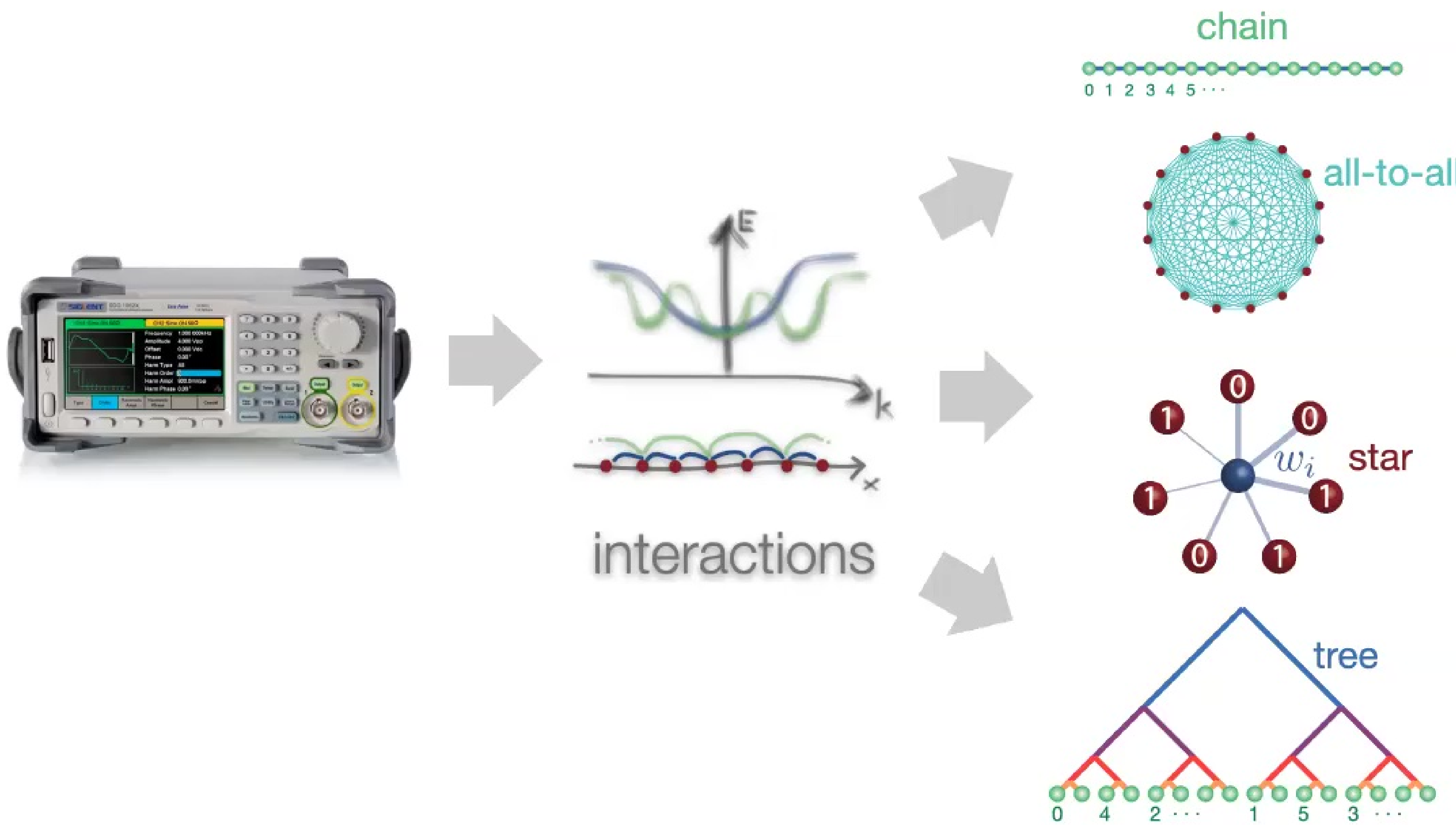
What is Entanglement?



What is Entanglement?

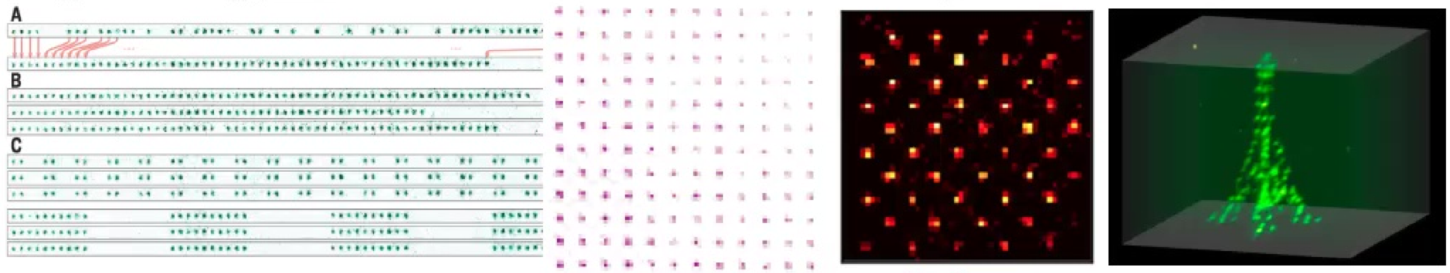


Vision: Programmable Interactions



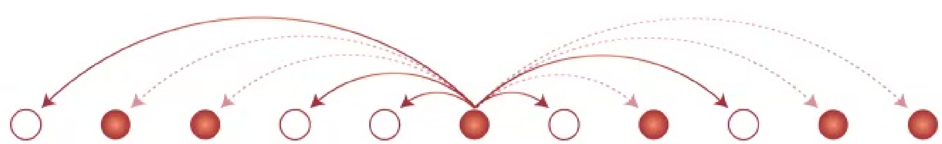
Programmable Quantum Systems

Programming *positions* of individual atoms with optical tweezers



Harvard, Paris, CU Boulder, KAIST, Penn State, Caltech, Princeton… ~5 μm

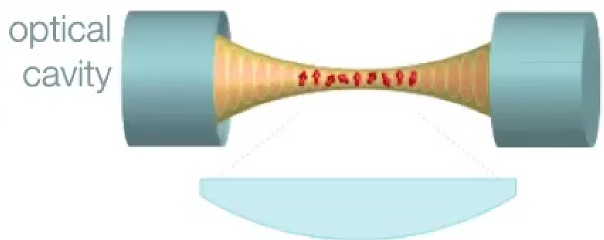
Programming the *interactions* between atoms with light?



Optically Controlled Interactions

Engineering spin-spin interactions among laser-cooled atoms:

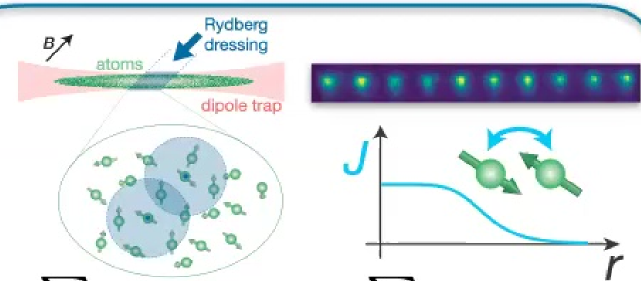
Photon-mediated interactions



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

Highly non-local

Rydberg interactions



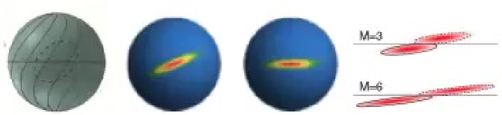
$$H = \sum_{i,j} J(|i-j|)\sigma_i^z \sigma_j^z + \sum_i h_i \sigma_i^x$$

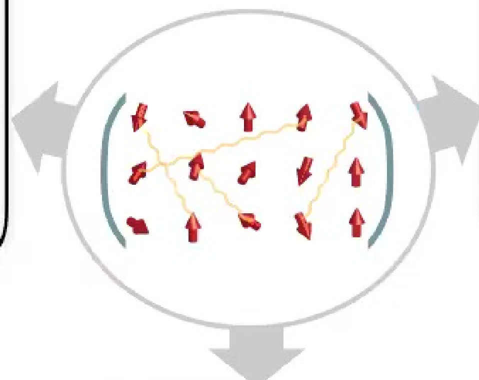
Borish, Markovic, Hines, Rajagopal, & MS-S, *PRL* **124,** 063601 (2020).

Long-range but local

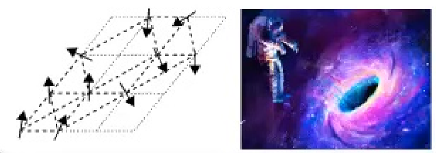
Motivation

Quantum Control
Entangled states for sensing, computation, communication

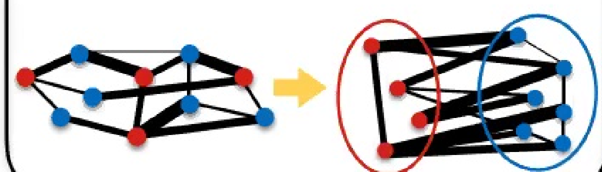




Quantum Simulation
…from condensed matter to quantum gravity



Combinatorial Optimization
Encode classical cost function in energy of quantum system



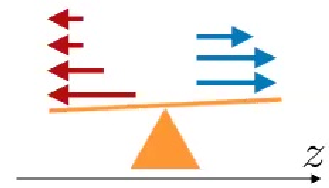
Optimization

- *Is there a quantum speed-up? Role of entanglement?*
- *How to map real-world problem to physical model?*

Optimization Example

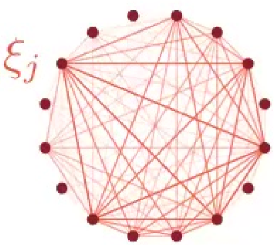
Number partitioning problem (NP complete):
Given n objects with weights ξ_i, does there exist a partition into two equally weighted groups?

Physicist's approach: define imbalance $\mathcal{F}_z = \sum_i \xi_i S_i^z$



…and minimize $\mathcal{F}_z^2 \propto \sum_{i,j} J_{ij} S_i^z S_j^z$

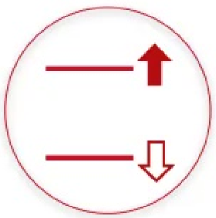
$J_{ij} \propto \xi_i \xi_j$



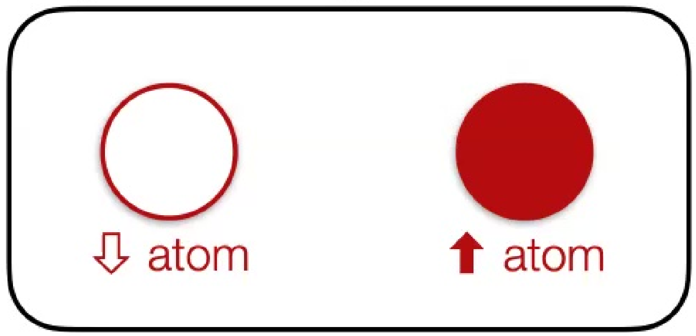
Tools for exploring:
Spins + non-local interactions + programmability

Photon-Mediated Interactions

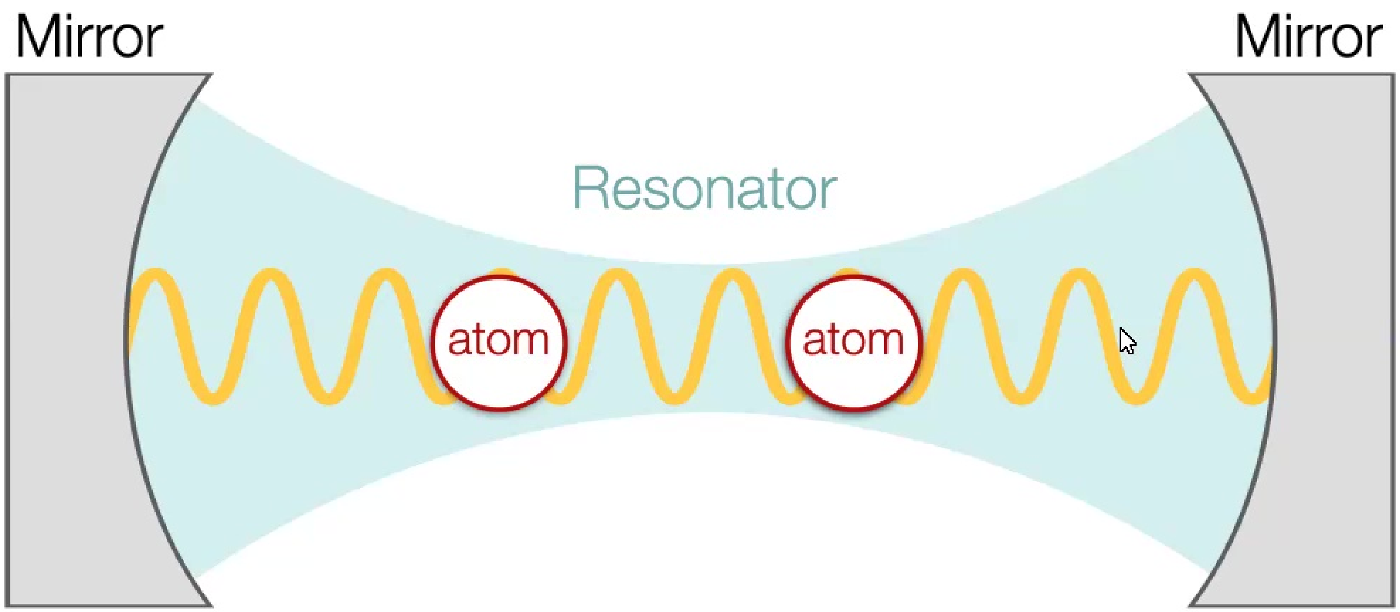
Each atom as a spin with two states: [● = ⬆] or [○ = ⇩]



Spin-exchange interaction



Corralling Photons

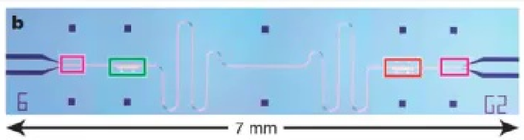


Constructive interference enhances probability of emitted photon interacting with another atom

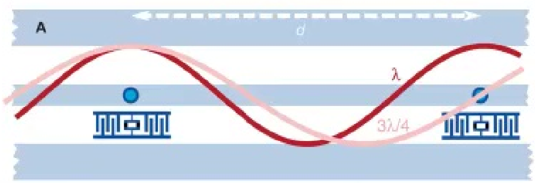
Photon-Mediated Interactions

Microwave Photons

Superconducting Qubits

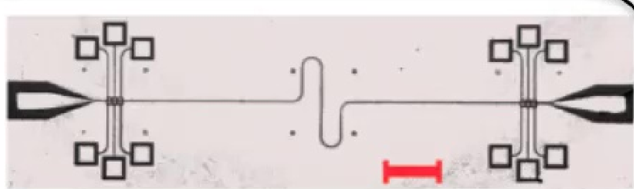


Majer, … & Schoelkopf, *Nature* (2007).



van Loo, …, & Wallraff, *Science* (2013).

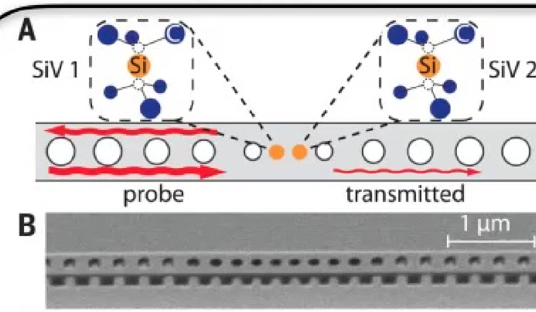
Quantum Dots



Delbecq … & Kontos, *Nat. Comm.* (2013).

Optical Photons

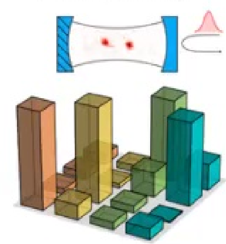
Color Centers

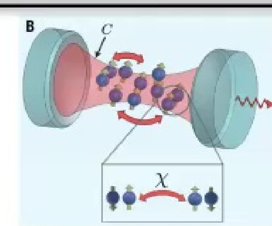


Evans, …, & Lukin, *Science* (2018).

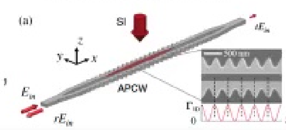
Cold Atoms

Welte et al., *PRX* (2018).



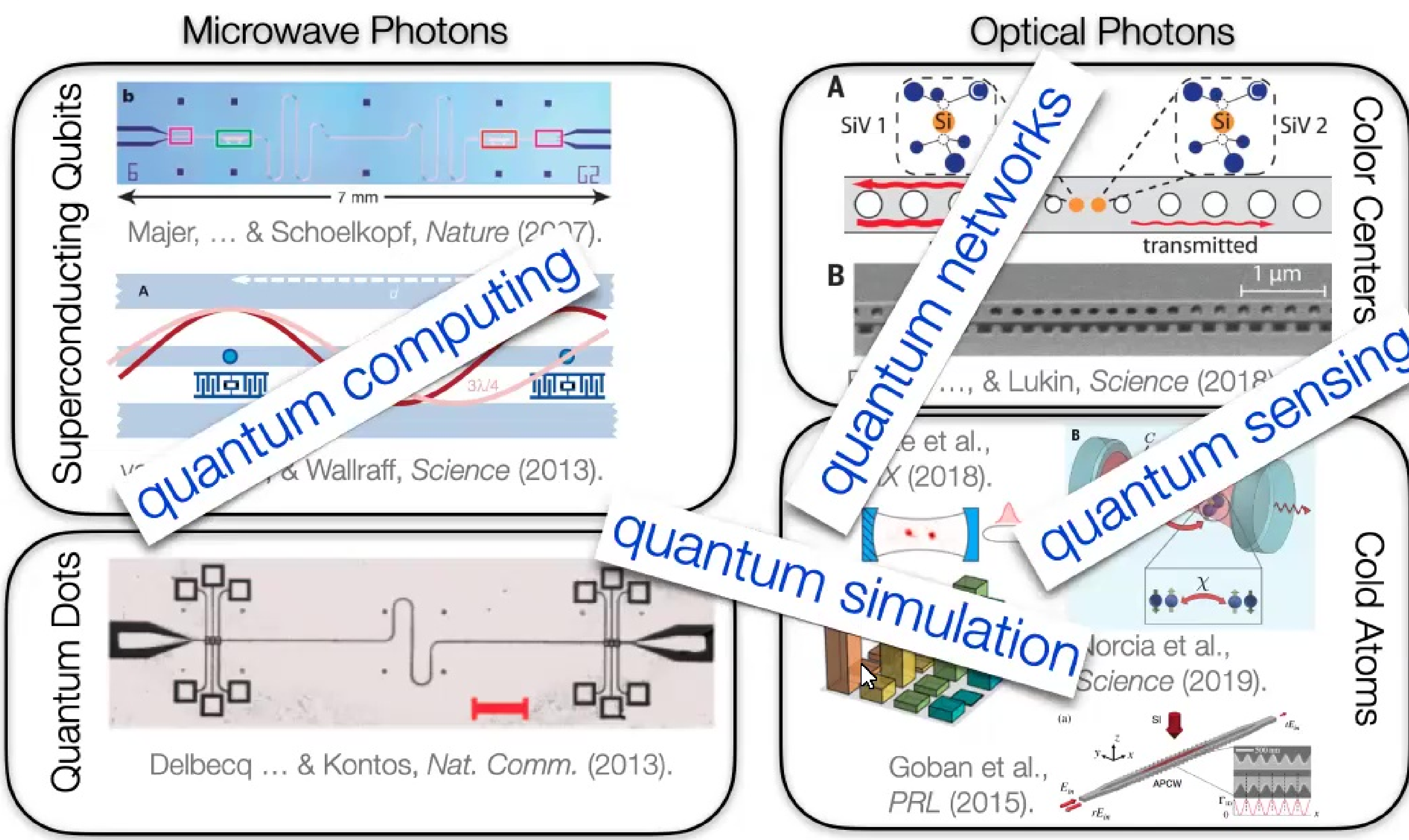


Norcia et al., *Science* (2019).



Goban et al., *PRL* (2015).

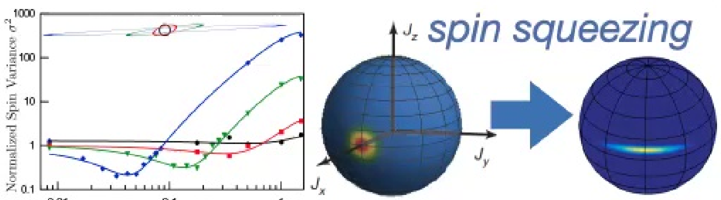
Photon-Mediated Interactions

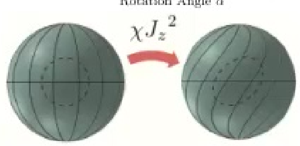


Cavity QED with Cold Atoms

Entanglement for metrology

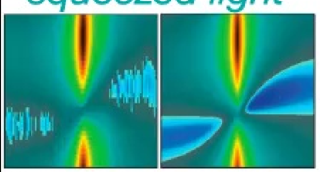
spin squeezing



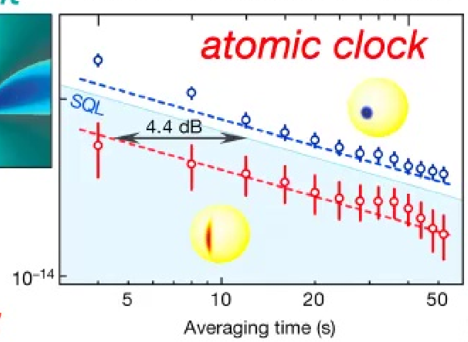


Leroux, et al, *PRL* (2010).
Hosten, et al, *Nature* (2016).
Norcia, et al, *Science* (2018).
Huang, et al, *arXiv* (2020).
Pedrozo-P et al, *Nature* (2020).

squeezed light



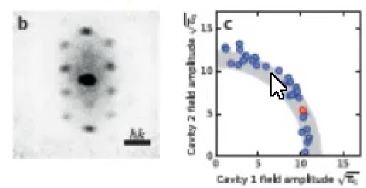
Brooks et al, *Nature* (2012)



Applications:
clocks, gravimeters, accelerometers…

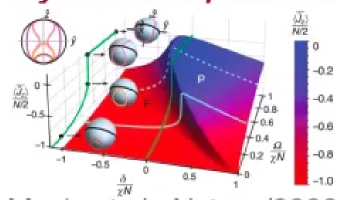
Quantum simulations

supersolids



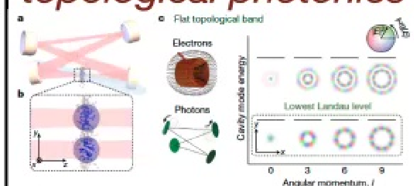
Léonard *et al., Nature* (2017).

dynamical phases



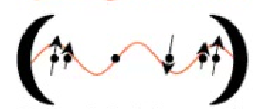
Muniz *et al., Nature* (2020).

topological photonics



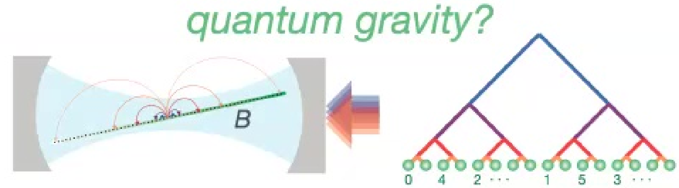
Clark *et al., Nature* (2020).

spin glasses?



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

quantum gravity?

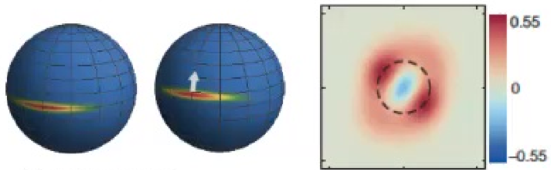


Swingle et al *PRA* (2016); Bentsen et al, *PRL* (2019).

Quantum Control vs Quantum Simulation

Quantum Control

Known resources for sensing, computation, communication



Hosten et al. *Nature* (2016).

McConnell et al. *Nature* (2015).

>1000-atom entanglement!

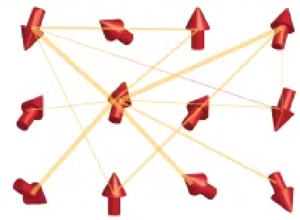
…but conceptually simple states

optical cavity

cold atoms

Quantum Simulation

Generic states of interacting many-body systems

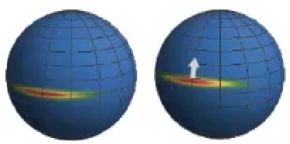


Too complex to calculate!

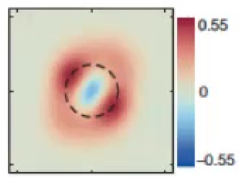
Quantum Control vs Quantum Simulation

Quantum Control

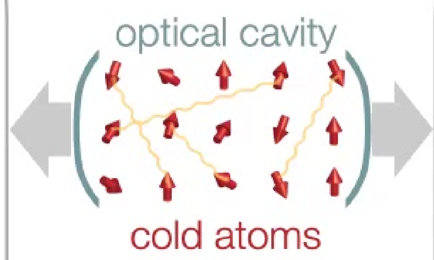
Known resources for sensing, computation, communication



Hosten et al. *Nature* (2016).

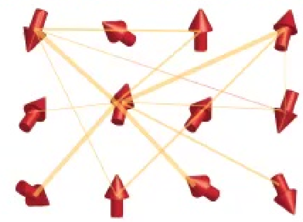


McConnell et al. *Nature* (2015).



Quantum Simulation

Generic states of interacting many-body systems



>1000-atom entanglement!

…but conceptually simple states

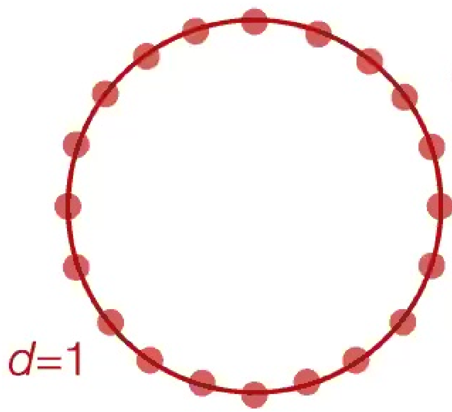
Too complex to calculate!

…hopeless to try to visualize?

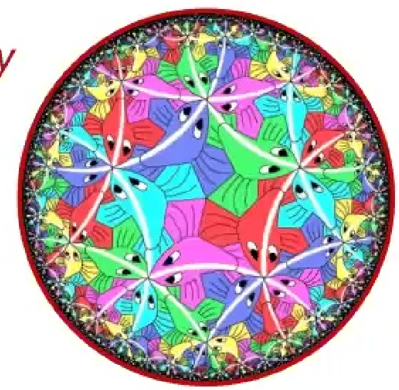
Holographic Duality

Quantum many-body system,
d spatial dimensions

Spacetime geometry (gravity),
d+1 spatial dimensions



Entanglement of boundary
encoded in
geometry of bulk



- Can we probe the emergent geometry experimentally?
  …in simple model systems? …in cases where not *a priori* known?
- Can models with a **simple holographic description** provide a starting point for understanding & visualizing a wider range of quantum many-body systems?

Quantum Information Scrambling

Black hole as a quantum system where information spreads exponentially fast across all degrees of freedom

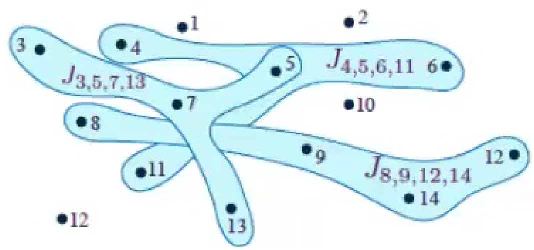
Fast scrambling:
fundamental speed limit in quantum many-body dynamics

Hayden, Preskill, Maldacena, Shenker, Susskind, Stanford …

Models for Fast Scrambling

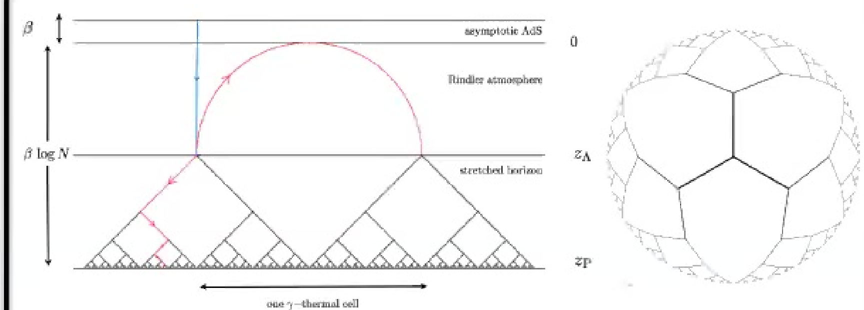
Sachdev-Ye-Kitaev (SYK)

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



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

Billiards on Expander Graph



Barbon & Magan, *JHEP* (2012) [*arXiv*:1204.6435].
Barbon & Magan, *JHEP* (2013) [*arXiv*:1306.3873].

Non-local couplings

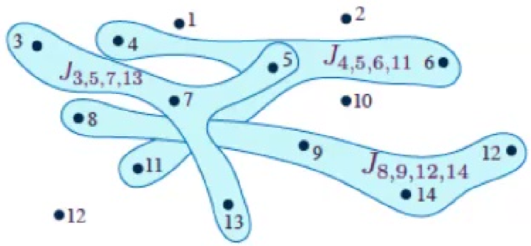
Local, but in *ultrametric* geometry

Non-Local Interactions

Realizing models where particles hop *non-locally*?

Fermions

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



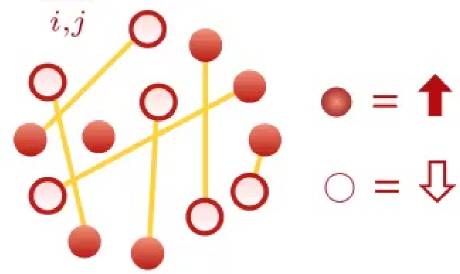
Black-hole duality:

S. Sachdev, *PRX* (2015).

Kitaev, KITP (2015).

Spin excitations?

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



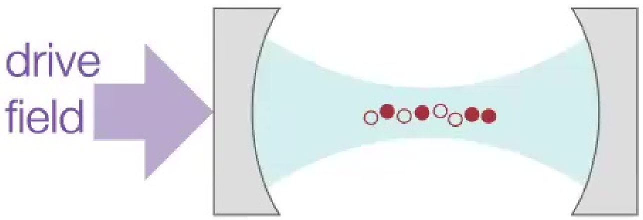
Natural approach:

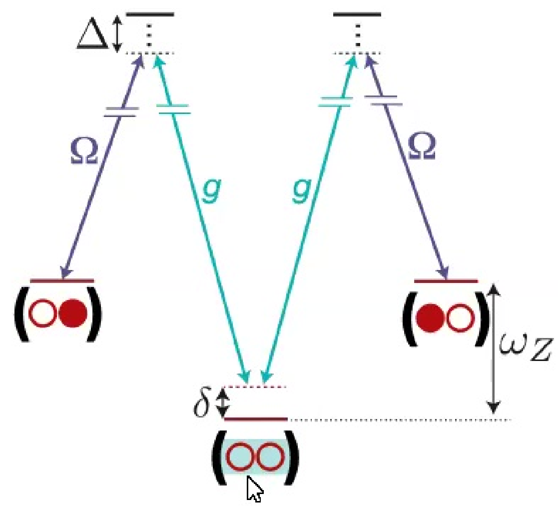
particles = spin excitations,

hopping mediated by light

Photon-Mediated Interactions

Spin-1/2 case: each atom has two ground states, [● = ⬆] and [○ = ⇩]



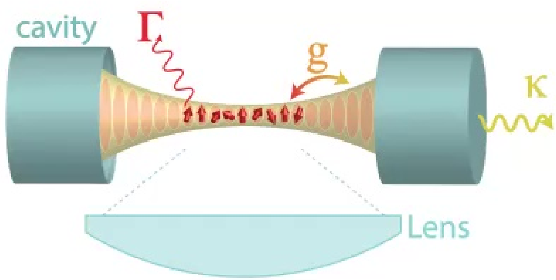


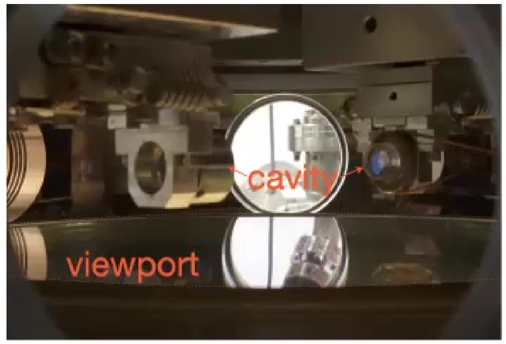
Spin-exchange interaction $H = \sum_{i,j} J_{ij} s_i^+ s_j^-$

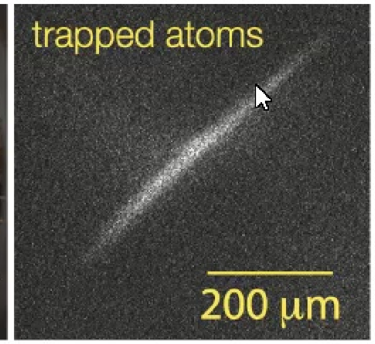
controlled by optical drive field

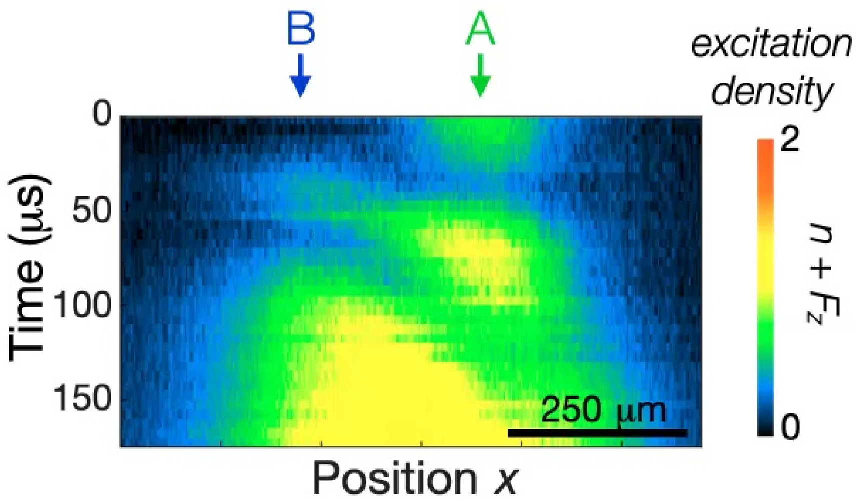
Spin Excitations Hopping

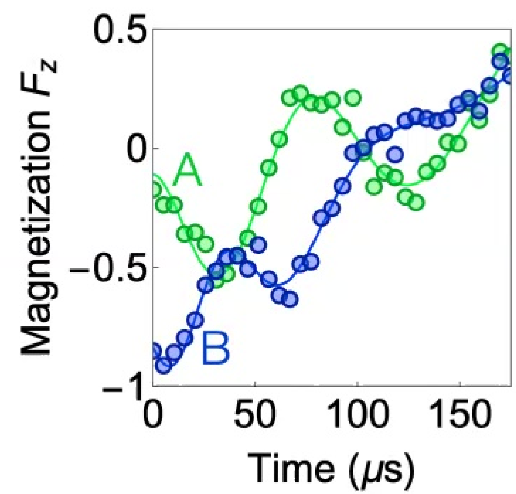
E. Davis, G. Bentsen, L. Homeier, T. Li, & M. S-S. *PRL* **122,** 010405 (2019).











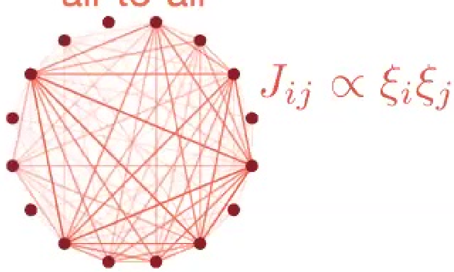
Programmable Interactions?

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

Knobs we would like:

- Spatial structure

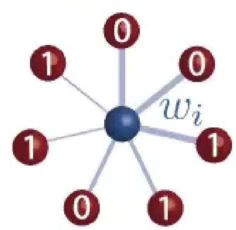
all-to-all



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

slow thermalization

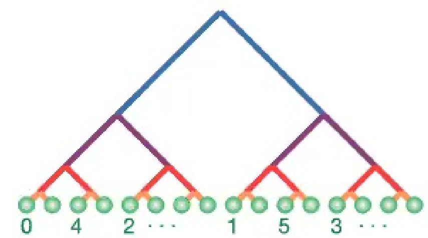
one-to-all



Anikeeva, Markovic, Borish, Hines, Rajagopal, Cooper, Periwal, Safavi-Naeini, Davis & MS-S, *arXiv:2009.05549.*

optimization

tree



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

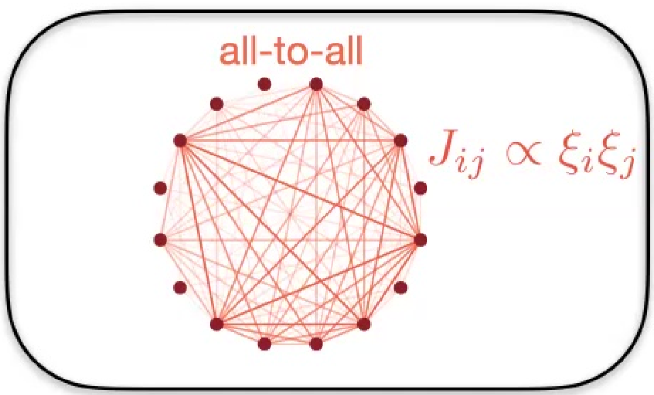
fast scrambling

Programmable Interactions?

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

Knobs we would like:

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



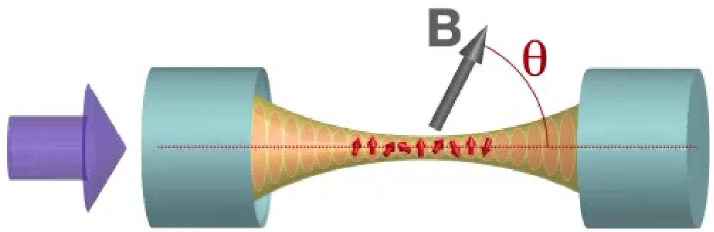
Tunable Heisenberg Interactions

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

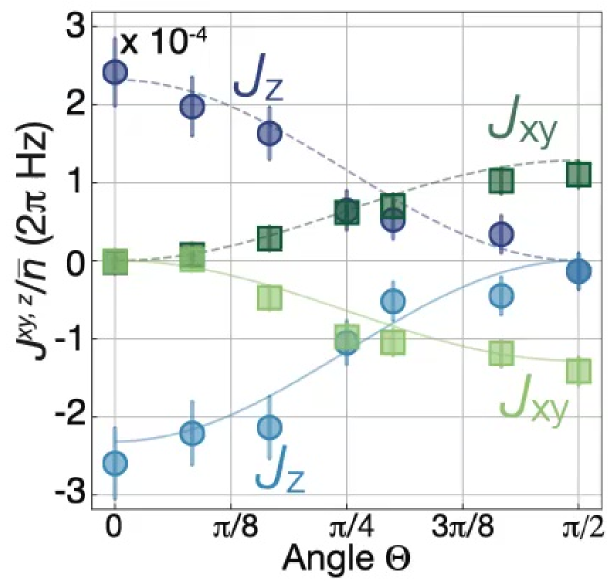
$$H_I = J_{xy}\left(\mathcal{F}_x^2 + \mathcal{F}_y^2\right) + J_z \mathcal{F}_z^2$$

$$\mathcal{F} = \sum_i \xi_i \mathbf{S}_i$$

$$\mathbf{F} = \sum_i \mathbf{S}_i$$



- **Form of spin-spin couplings** continuously tunable via orientation of a magnetic field
- **Sign of interaction** controlled by laser frequency



Exploring the Phase Diagram

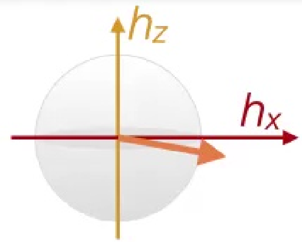
E. Davis, A. Periwal, E. Cooper, G. Bentsen, S. Evered, K. Van Kirk & MS-S, *PRL* **125** 060402 (2020).

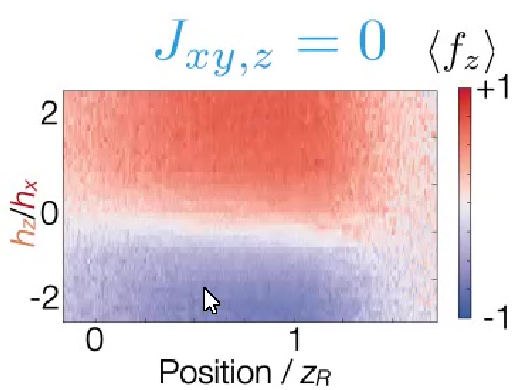
$$H_I = J_{xy}\left(\mathcal{F}_x^2 + \mathcal{F}_y^2\right) + J_z \mathcal{F}_z^2$$

$$\mathcal{F} = \sum_i \xi_i \mathbf{S}_i$$

Prepare low-energy state by slow quench

$$H = H_I - h_x F_x - h_z F_z$$





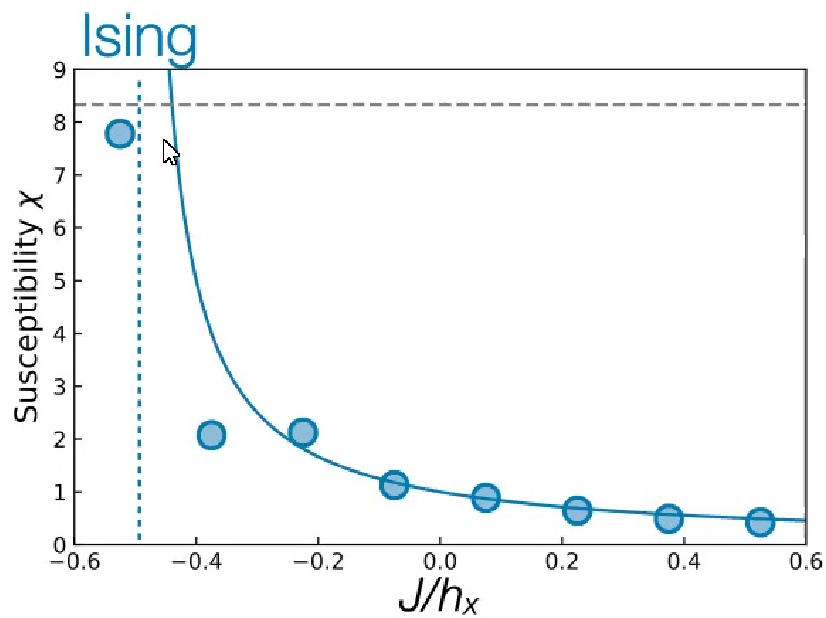
Magnetic Susceptibility

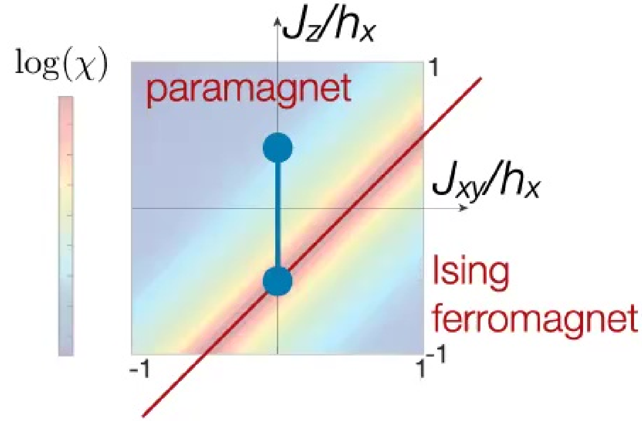
E. Davis, A. Periwal, E. Cooper, G. Bentsen, S. Evered, K. Van Kirk & MS-S, *PRL* **125** 060402 (2020).

$$H_I = J_{xy}\left(\mathcal{F}_x^2 + \mathcal{F}_y^2\right) + J_z \mathcal{F}_z^2 + h_x F_x$$

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

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





Theory (mean-field)

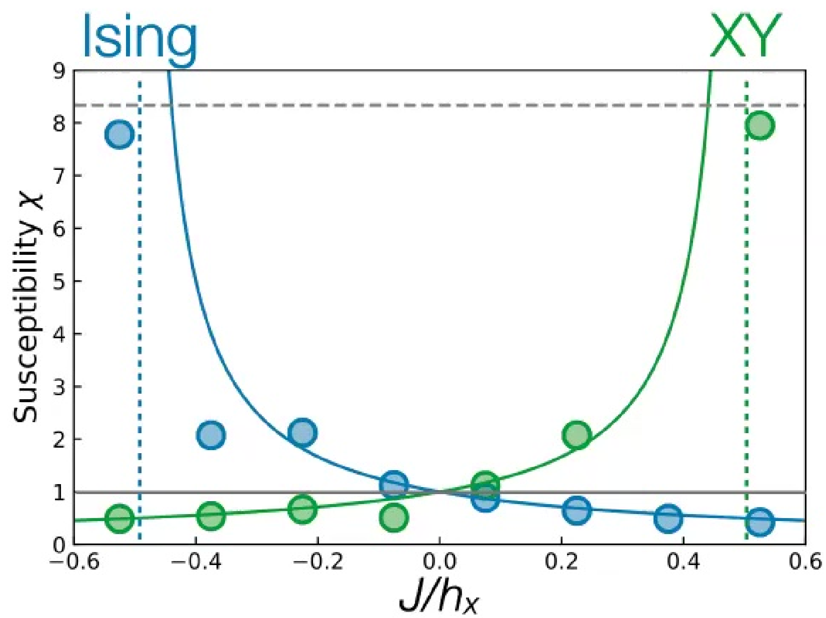
Magnetic Susceptibility

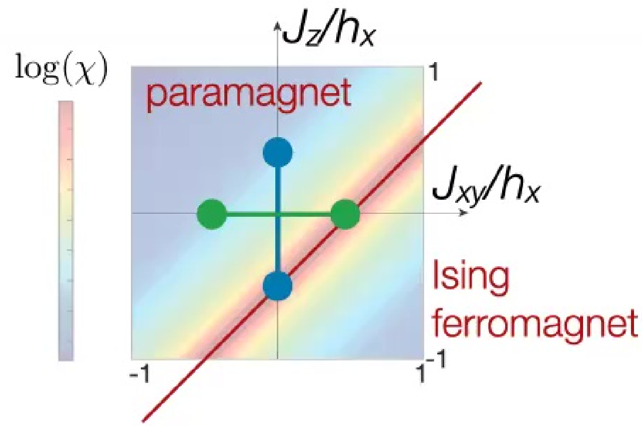
E. Davis, A. Periwal, E. Cooper, G. Bentsen, S. Evered, K. Van Kirk & MS-S, *PRL* **125** 060402 (2020).

$$H_I = J_{xy}\left(\mathcal{F}_x^2 + \mathcal{F}_y^2\right) + J_z\mathcal{F}_z^2 + h_x F_x$$

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

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

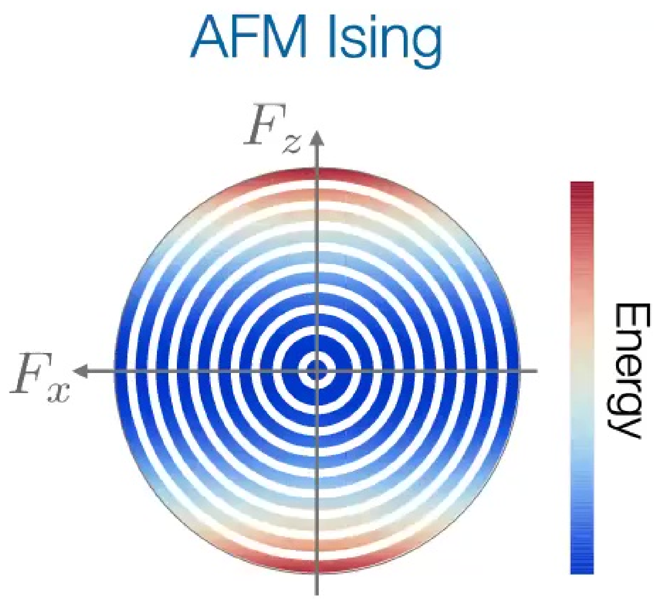


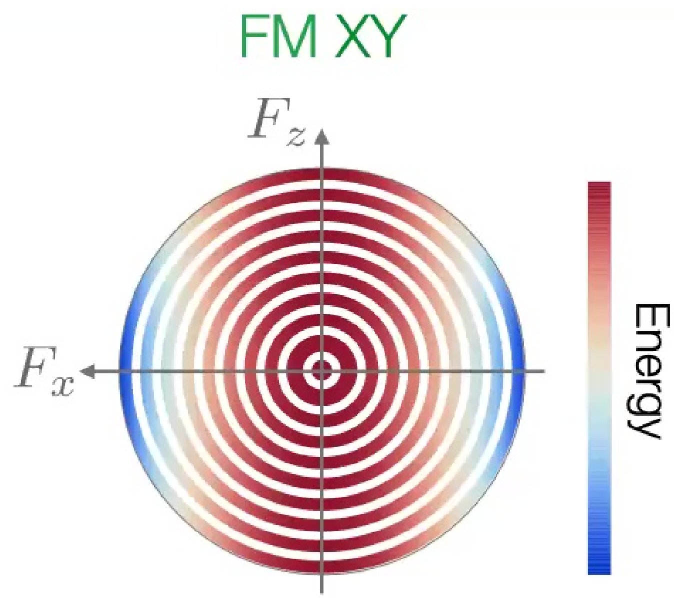


Theory (mean-field)

Why the Symmetry?

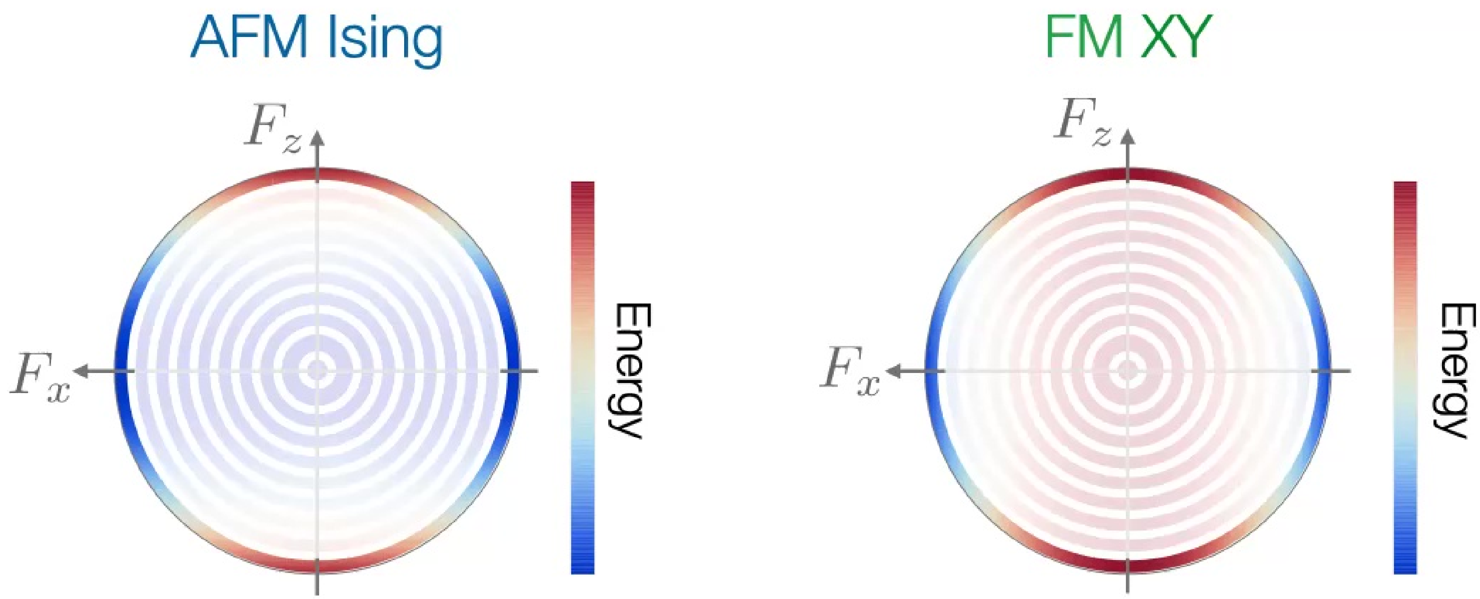
$$F_z^2 = -F_x^2 - F_y^2 + |\mathbf{F}|^2$$





Why the Symmetry?

$$F_z^2 = -F_x^2 - F_y^2 + |\mathbf{F}|^2$$

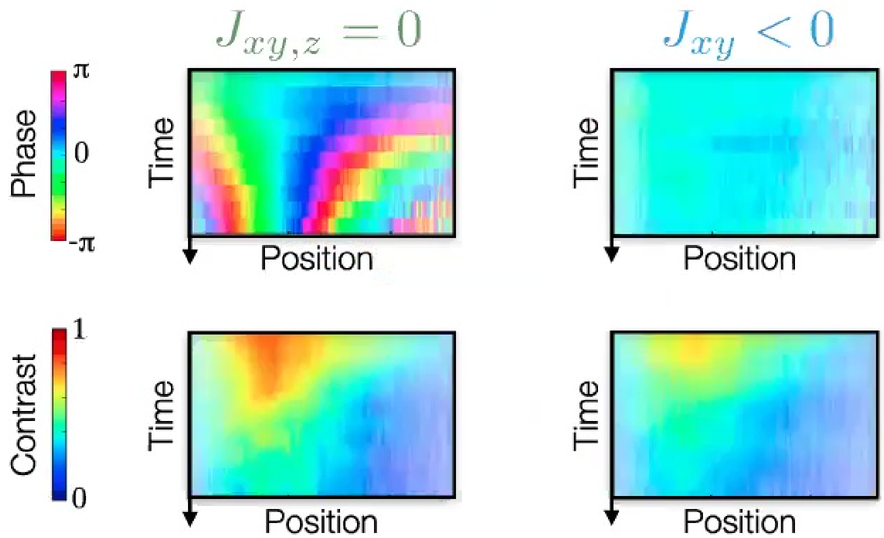


- **Equivalent** if constrained to surface of fixed spin length $|F|$,

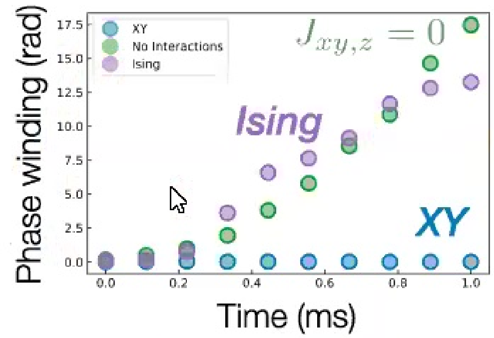
Protection of Spin Coherence

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:**



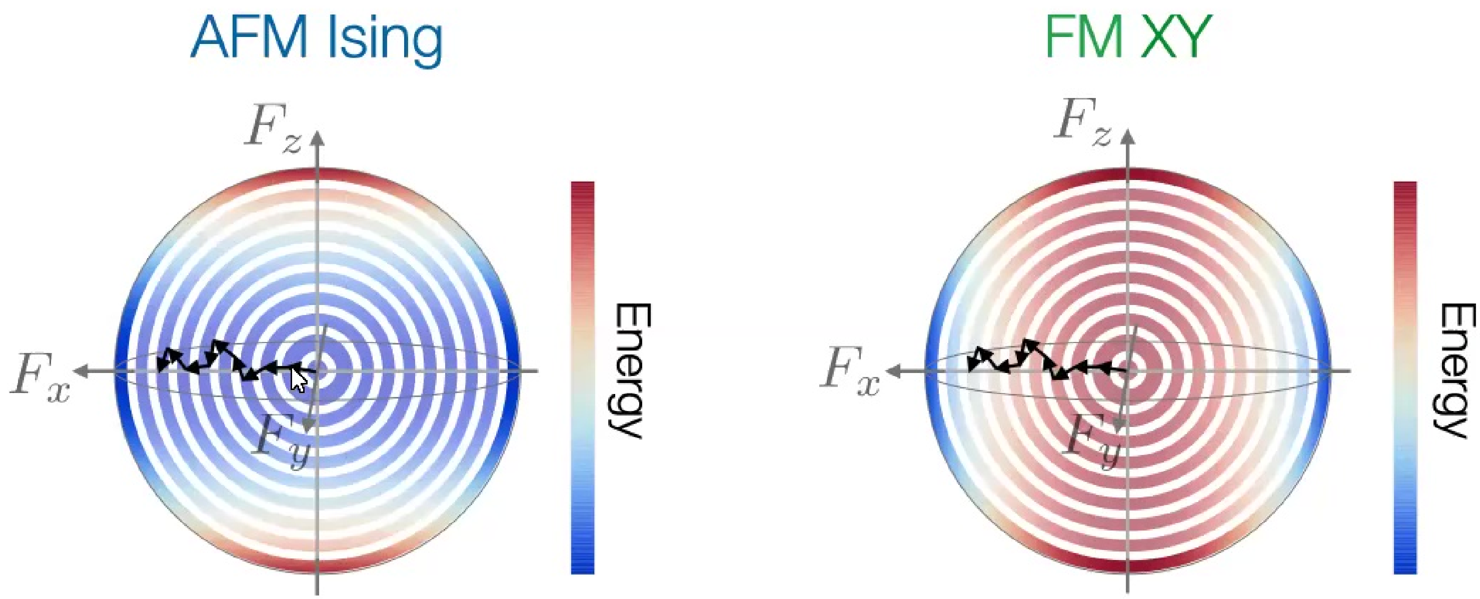
*Ferromagnetic **XY** interactions protect spin coherence!*



*AFM **Ising** interactions don't.*

Why the Symmetry?

$$F_z^2 = -F_x^2 - F_y^2 + |\mathbf{F}|^2$$

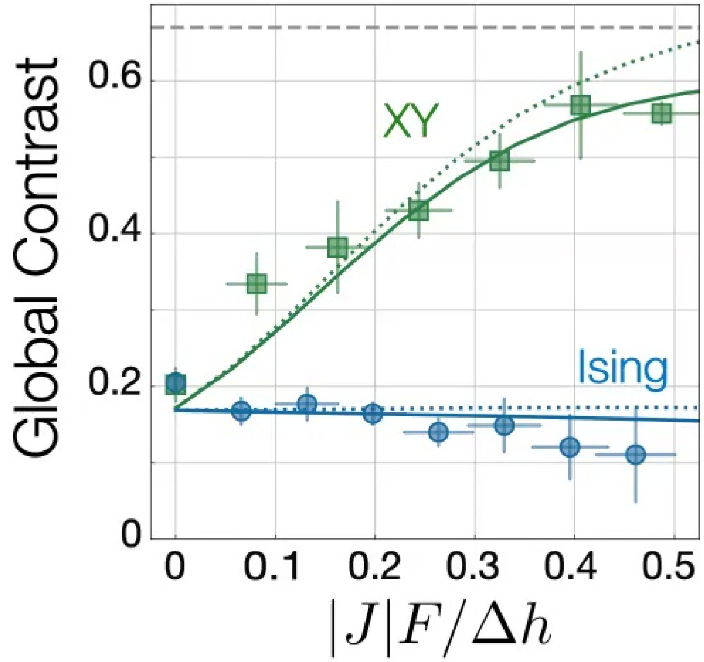


- **Equivalent** if constrained to surface of fixed spin length $|F|$, i.e., if the N-atom system is behaving as a single large spin
- **Difference:** shortening the spin by dephasing costs energy for *XY* model

Protection of Spin Coherence

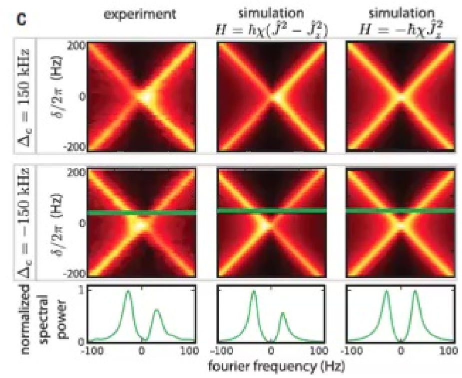
E. Davis, A. Periwal, E. Cooper, G. Bentsen, S. Evered, K. Van Kirk & MS-S, *PRL* **125** 060402 (2020).

$$-F_x^2 - F_y^2 = F_z^2 - \boxed{F(F+1)}$$



Dephasing suppressed by energy cost of reducing total spin *F*

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



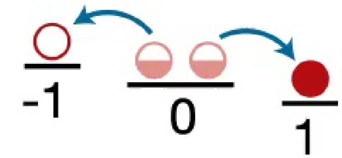
Prospect: enhancing robustness of light-induced entanglement

+ extensions to systems with local (e.g. Rydberg) interactions

Evidence of *Quantum* Dynamics?

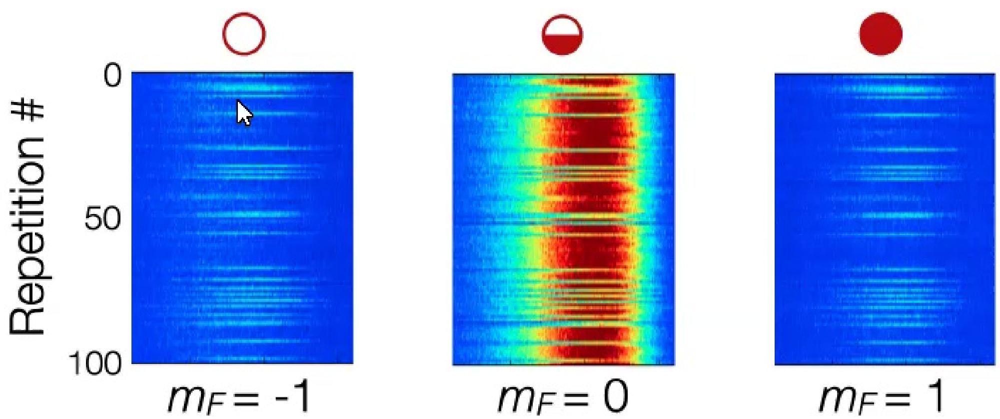
E. Davis, G. Bentsen, L. Homeier, T. Li, & MS-S, *PRL* **122,** 010405 (2019).

Approach: pair creation in a spin-1 system

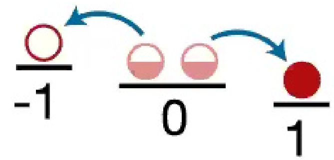


…initialized with all atoms in $m_F = 0$

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

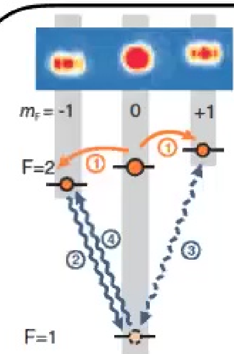


Photon-Mediated Pair Creation

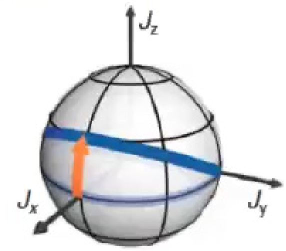


Analogies:

- Collisional spin mixing in Bose-Einstein condensates

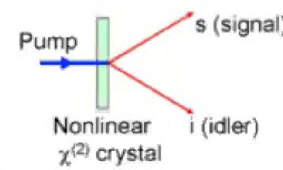


Lücke,…& Klempt, *Science* (2011).



Also: Chapman; Oberthaler; You

- Spontaneous parametric down-conversion



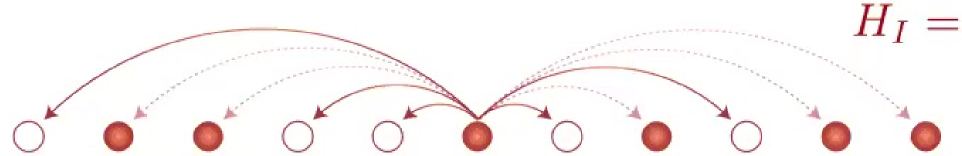
Opportunities:

- Fast generation of correlated atom pairs for enhanced quantum sensing
- Spatially structured entanglement by optical control

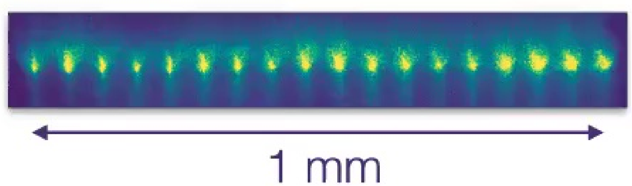
Programmable Interactions?

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

$$H_I = \sum_{i>j} J(i-j) F_i^+ F_j^- + \text{h.c.}$$



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

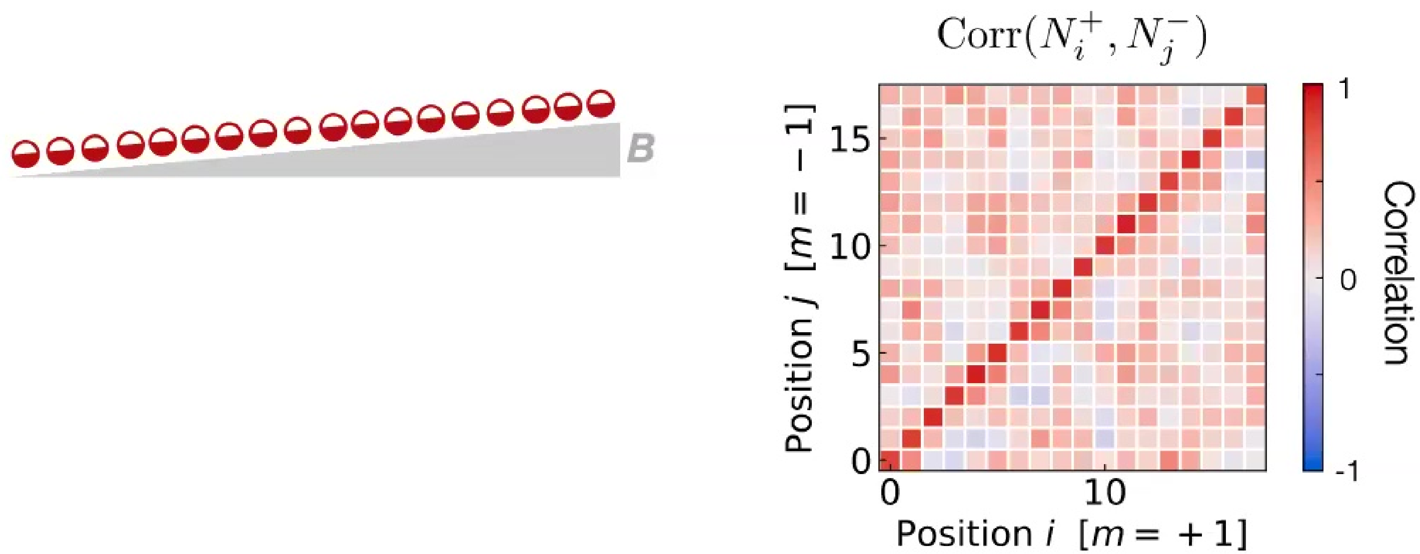


- 18 sites with ~10^4 atoms/site
- Collective enhancement of interaction strength

Objective: arbitrary control of translationally invariant couplings

Spatial Control of Pair Creation

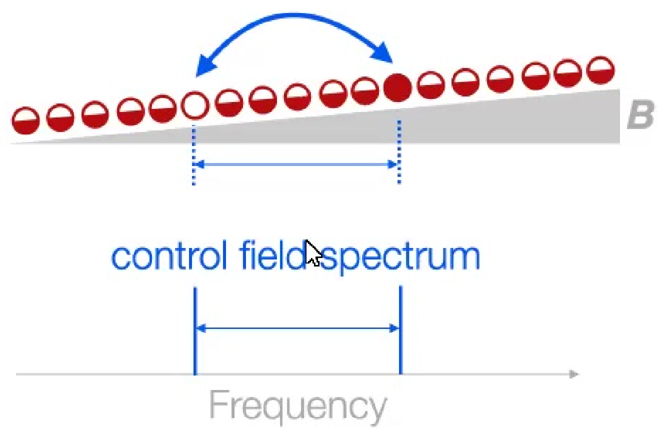
1) Turn off long-range interactions by adding a magnetic field gradient

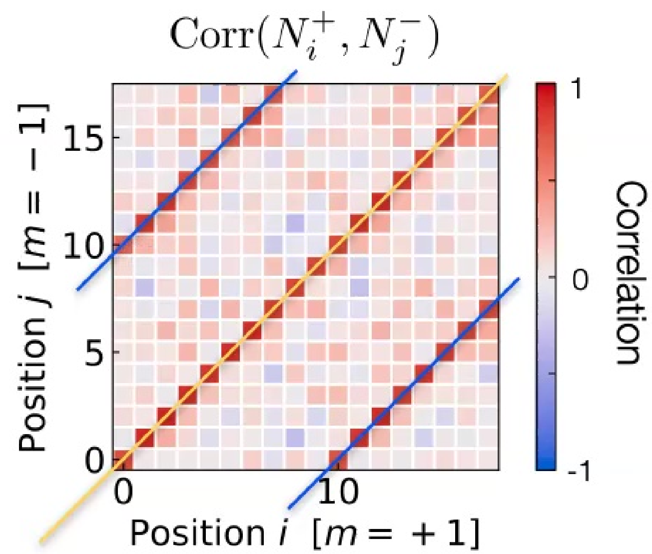


Spatial Control of Pair Creation

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

2) Reintroduce interactions at distance(s) set by spectrum of drive field



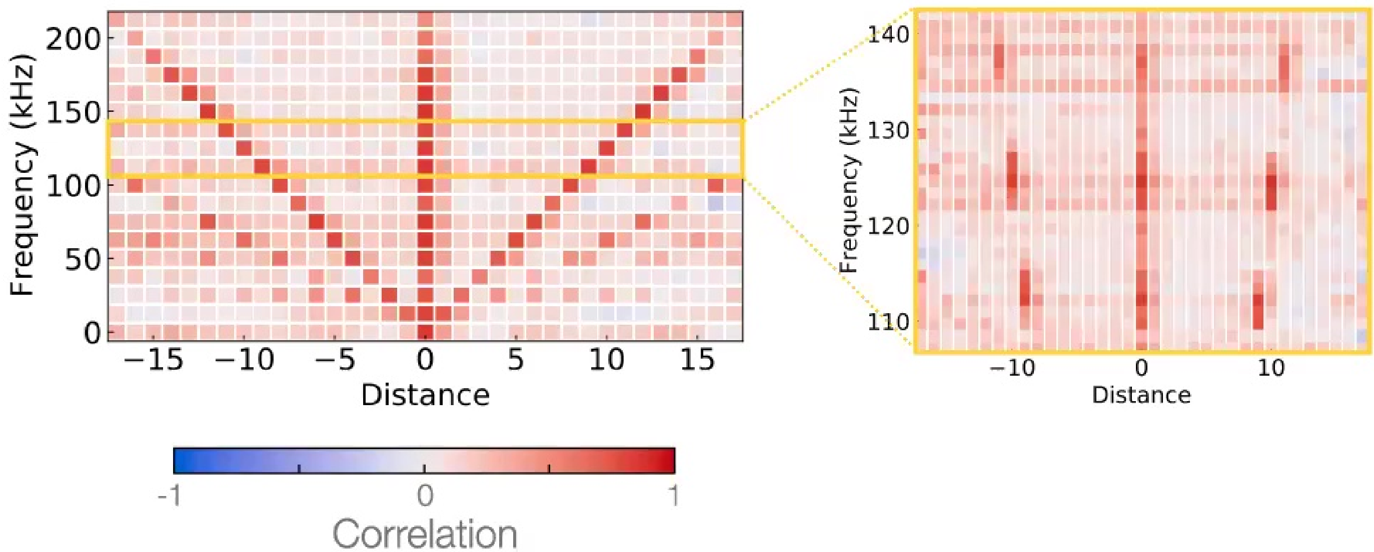


Proposals: Hung, Gonzales-Tudela, Cirac & Kimble, *PNAS* (2016) — nanophotonics.
Manovitz, … & Ozeri *PRX Quantum* (2020) — trapped ions.

Programmable Interactions

A. Periwal, E. Cooper, P. Kunkel,
E. Davis & MS-S, in preparation.

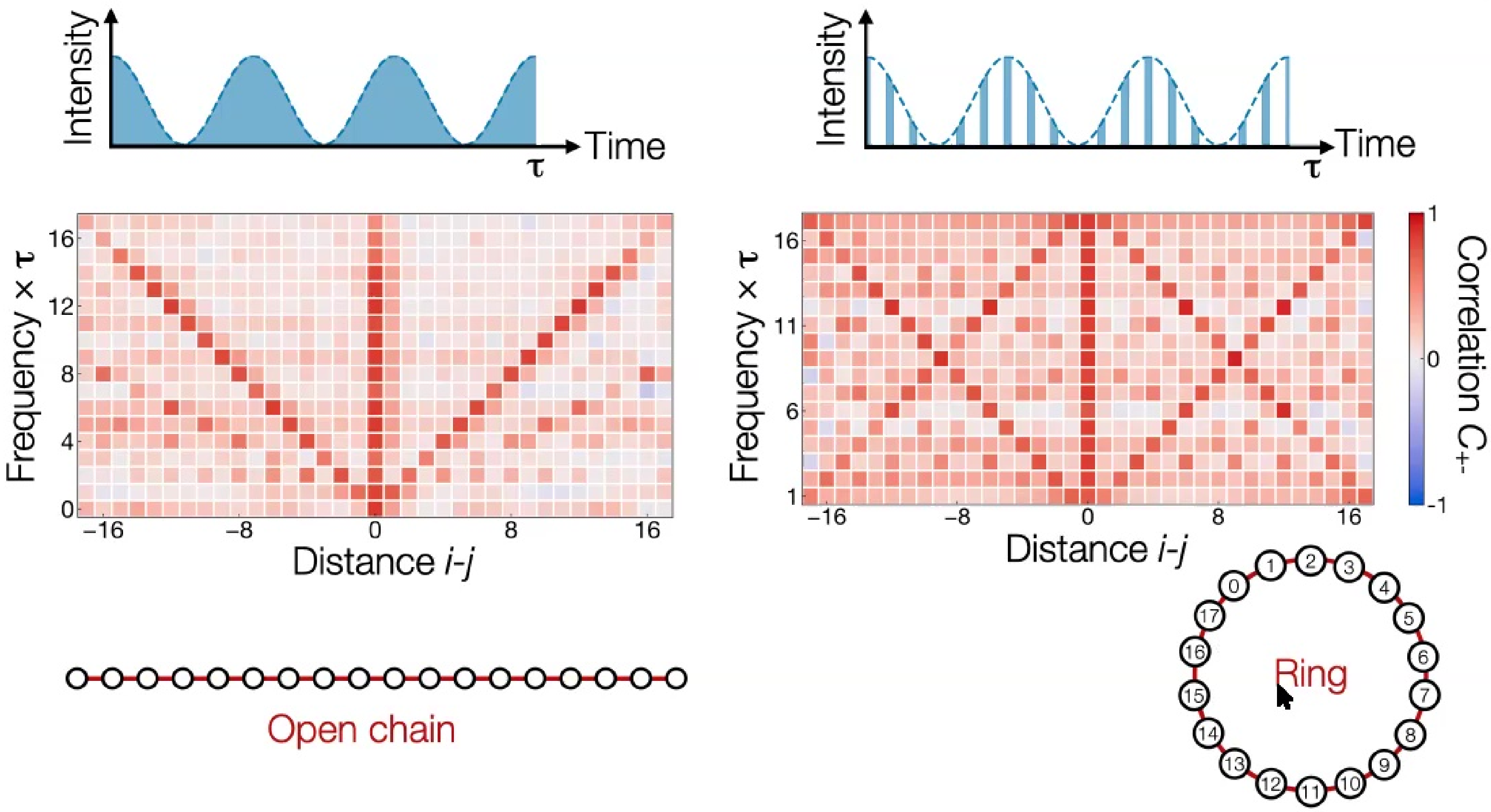
Controlling interaction distance by frequency spacing between drive fields



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

Periodic Boundary Conditions

A. Periwal, E. Cooper, P. Kunkel, E. Davis & MS-S, in preparation.



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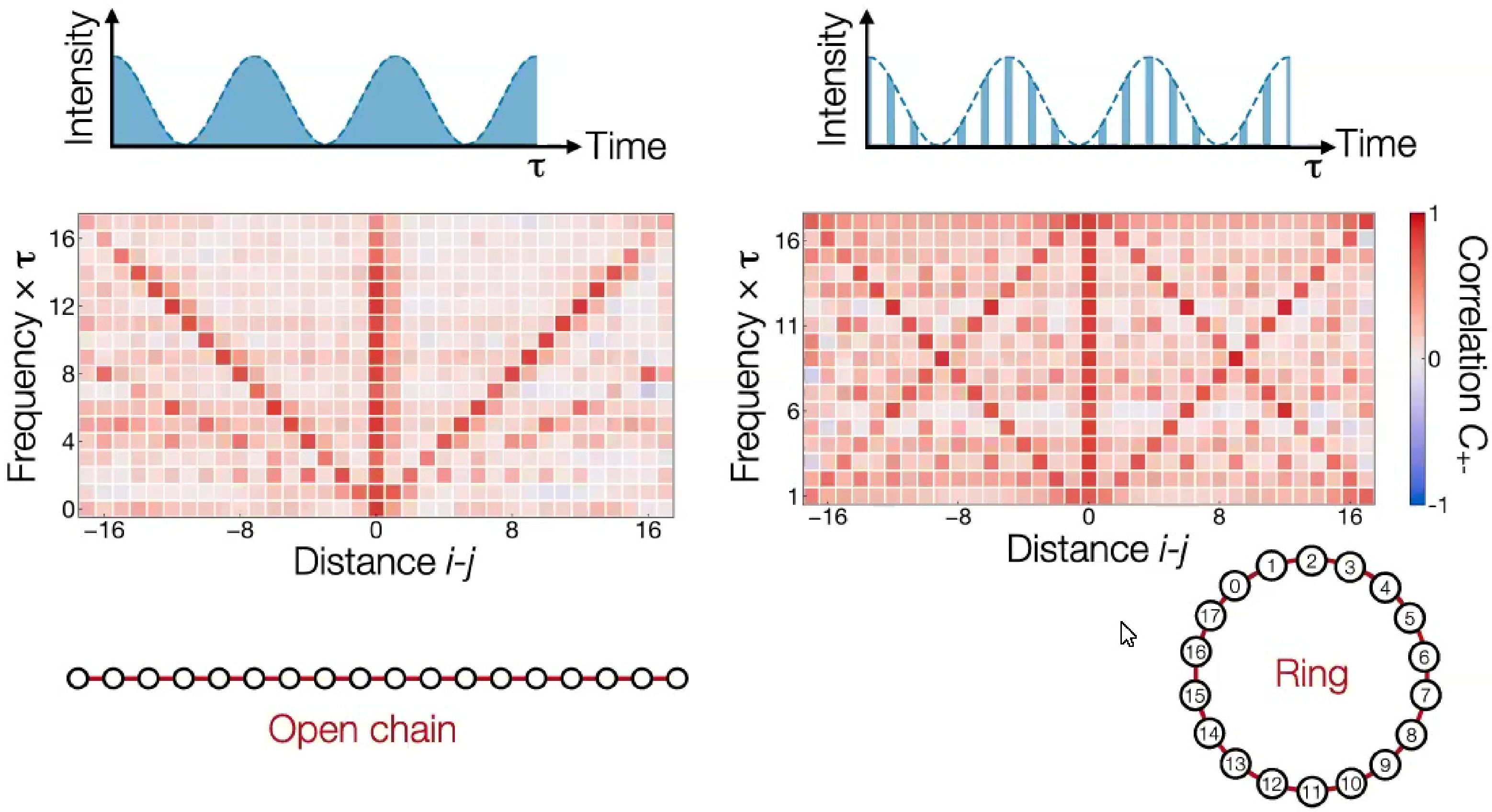
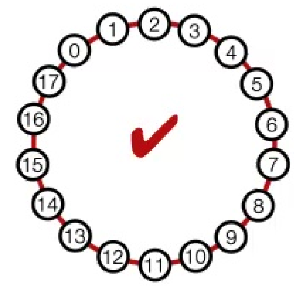


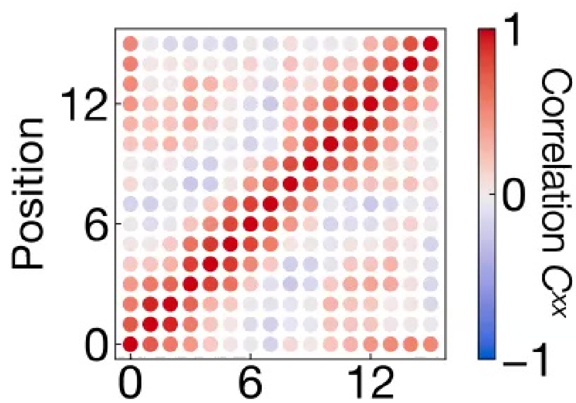
Geometry of the interaction graph need not be same as physical geometry…

Reconstructing Geometry

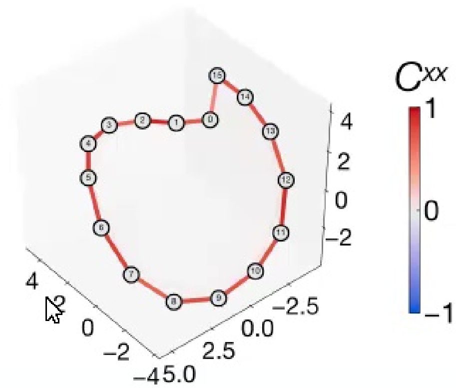
Drive Waveform



Measured Correlations



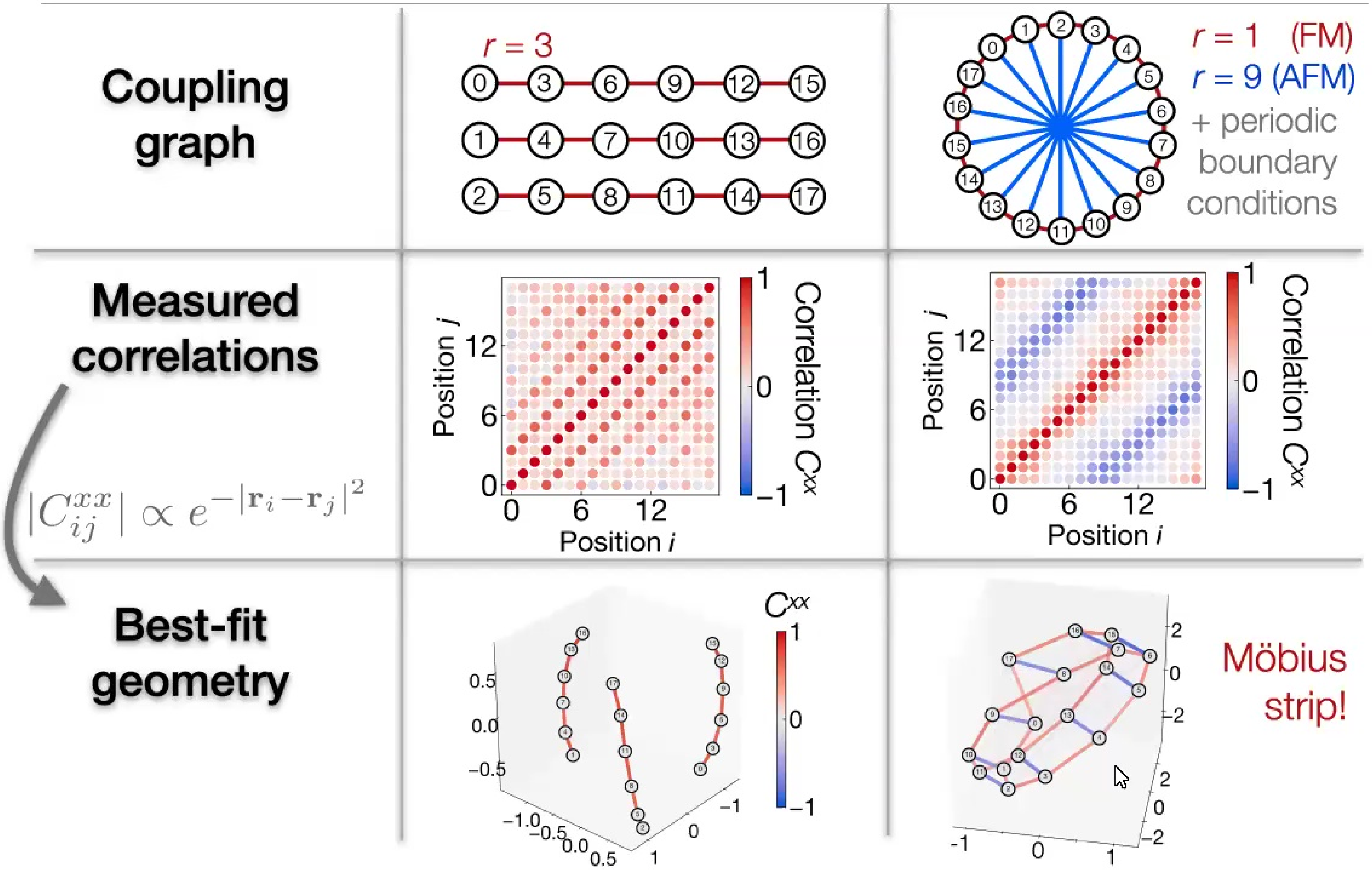
$$|C_{ij}^{xx}| \propto e^{-|\mathbf{r}_i - \mathbf{r}_j|^2}$$



Best-Fit Geometry

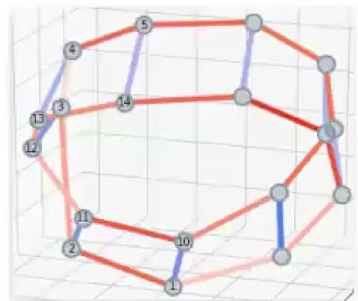
Reconstructing Geometry

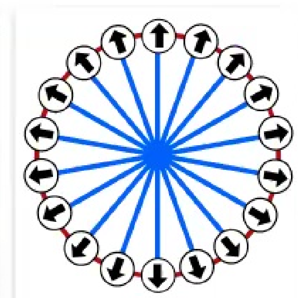
A. Periwal, E. Cooper, P. Kunkel, E. Davis & MS-S, in preparation.



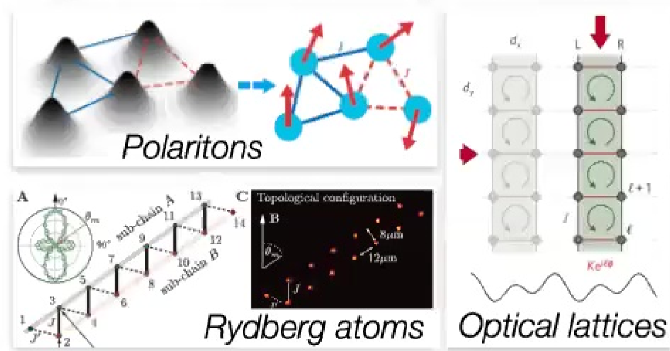
Programmable Couplings Enable…

Opportunities
- Exotic geometries
- Non-trivial topology
- Geometrical frustration
- Sign-changing interactions
- Peierls phases for magnetic flux





Inspiration from other platforms…

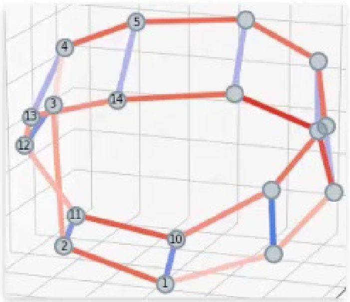


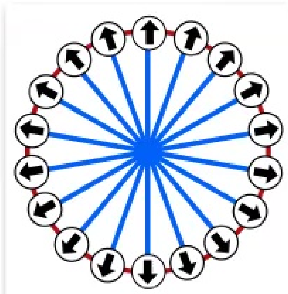
Applications
- Spin glasses
- Combinatorial optimization
- Topological phases
- Fast scrambling
- Toy models for quantum gravity?

Programmable Couplings Enable…

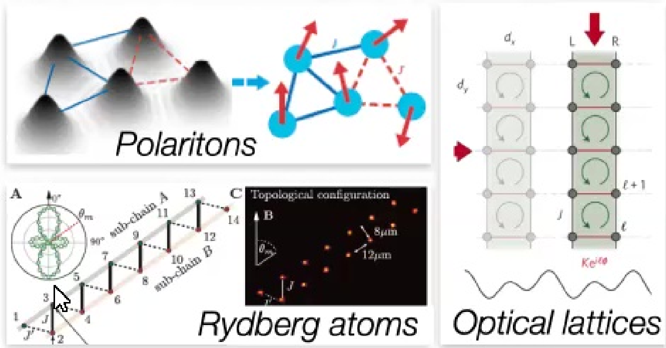
Opportunities

- Exotic geometries
- Non-trivial topology
- Geometrical frustration
- Sign-changing interactions
- Peierls phases for magnetic flux





Inspiration from other platforms…



…but non-local interactions offer unique opportunities!

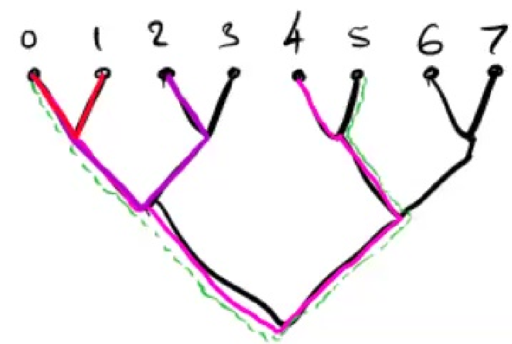
Applications

- Spin glasses
- Combinatorial optimization
- Topological phases
- Fast scrambling
- Toy models for quantum gravity?

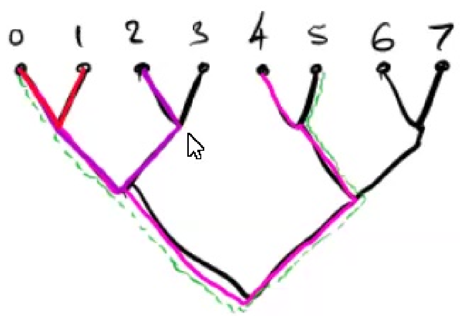
In Memoriam

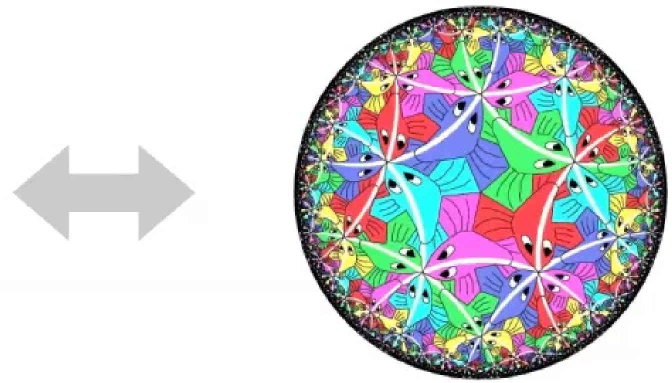
Steve Gubser (1972 - 2019)

What mathematics is behind the reality which we experience as smooth spacetime, but which is in all likelihood discrete at a fundamental level?



Tree-Like Geometry

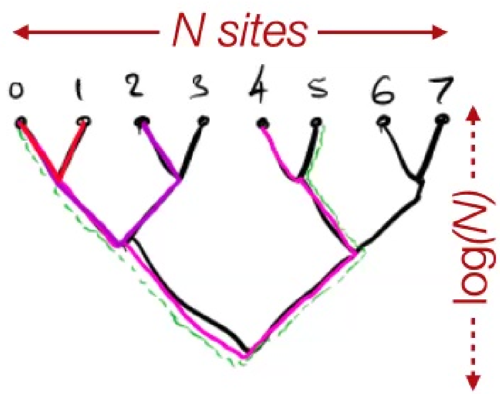


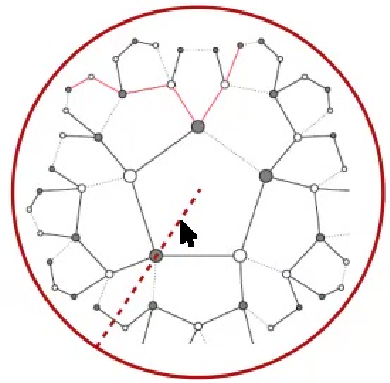


Tree = discretized model of curved space → gravity

Gubser et al., *Comm. Math. Phys.* (2017).

Tree-Like Geometry





Heydeman *et al, arXiv* (2017).

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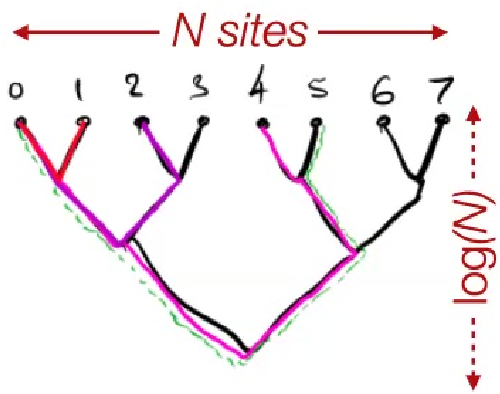
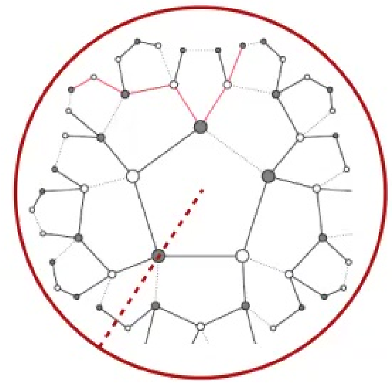




Heydeman *et al, arXiv* (2017).

Tree = discretized model of curved space → gravity

Gubser et al., *Comm. Math. Phys.* (2017).

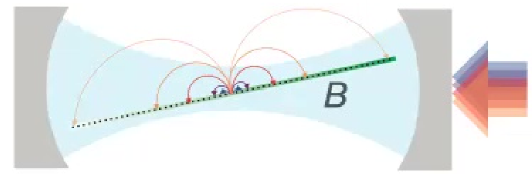
Quantum mechanics on a tree graph → quantum gravity?

Tree-Like Interactions

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

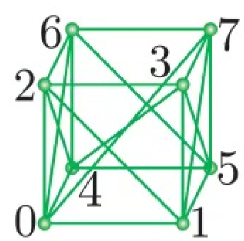
Efficiently spread information by coupling i^{th} spin to $i\pm1$, $i\pm2$, $i\pm4$, $i\pm8,\ldots$, $i\pm2^l$

$$J(i-j) = \begin{cases} |i-j|^{s} & |i-j| = \text{ a power of 2} \\ 0 & \text{otherwise} \end{cases}$$

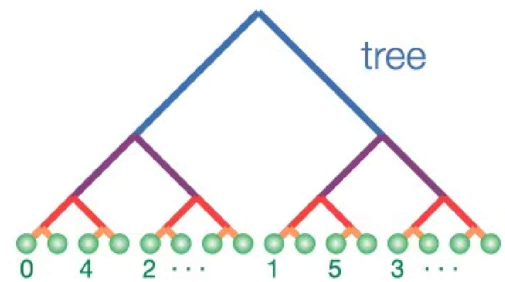


$s < 0$

$s = 0$



$s > 0$



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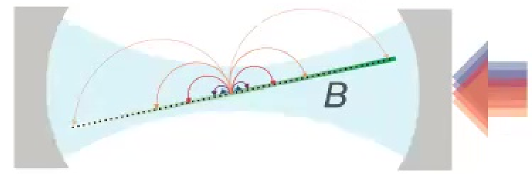
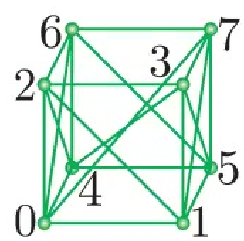


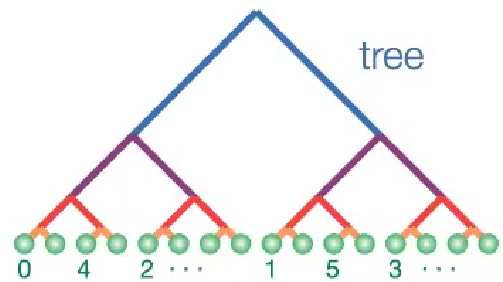
$s < 0$

$s = 0$



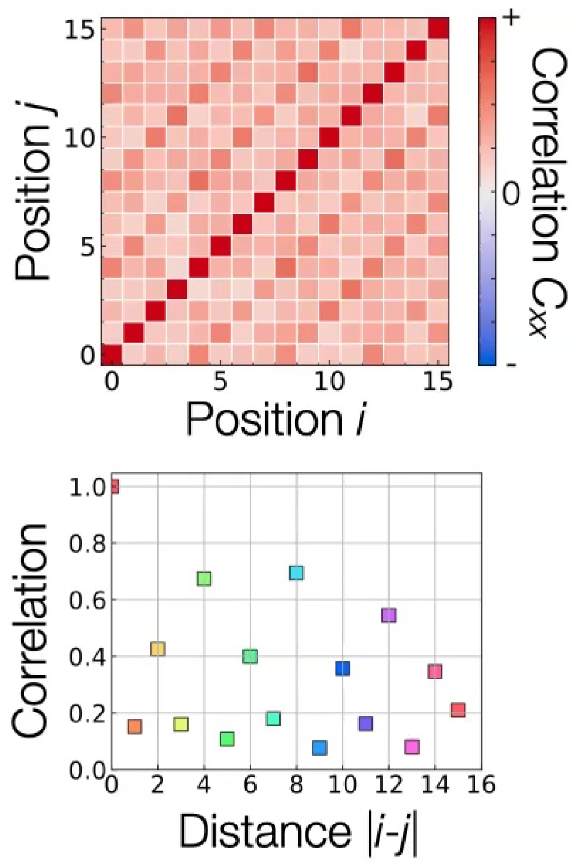
fast scrambling

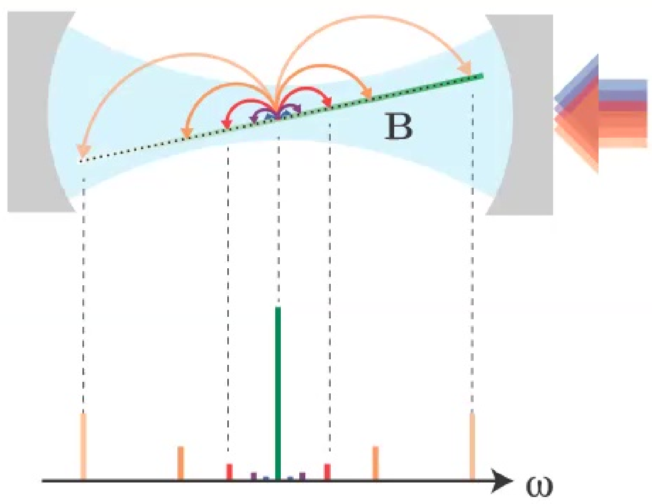
$s > 0$



Treelike Geometry?

$$J(i-j) = \begin{cases} |i-j| & |i-j| = \text{ a power of } 2 \\ 0 & \text{otherwise} \end{cases}$$





Treelike Geometry?

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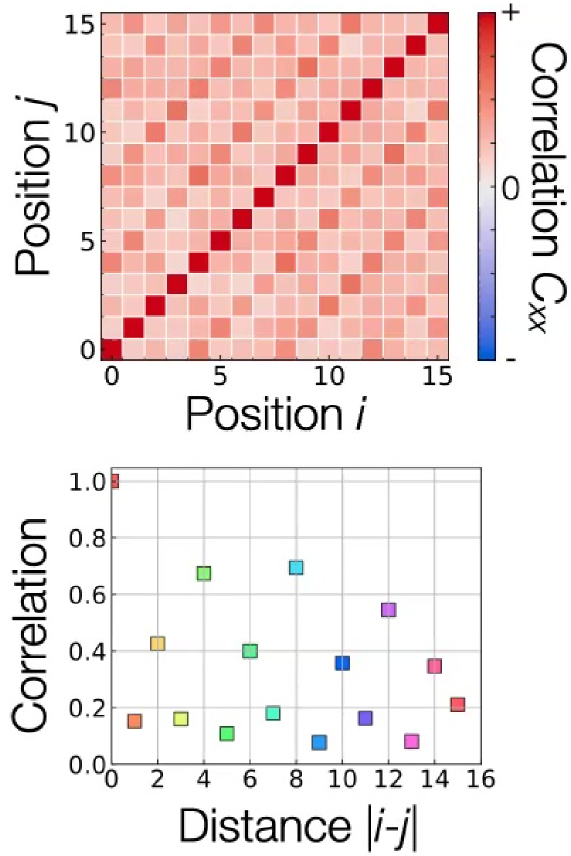
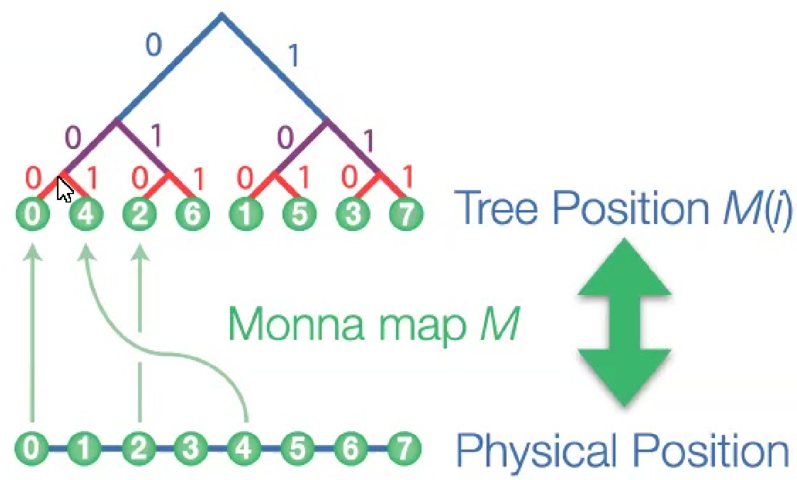


Hypothesis: effective geometry is a tree

Test: rearrange sites via *Monna map*, reversing order of bits



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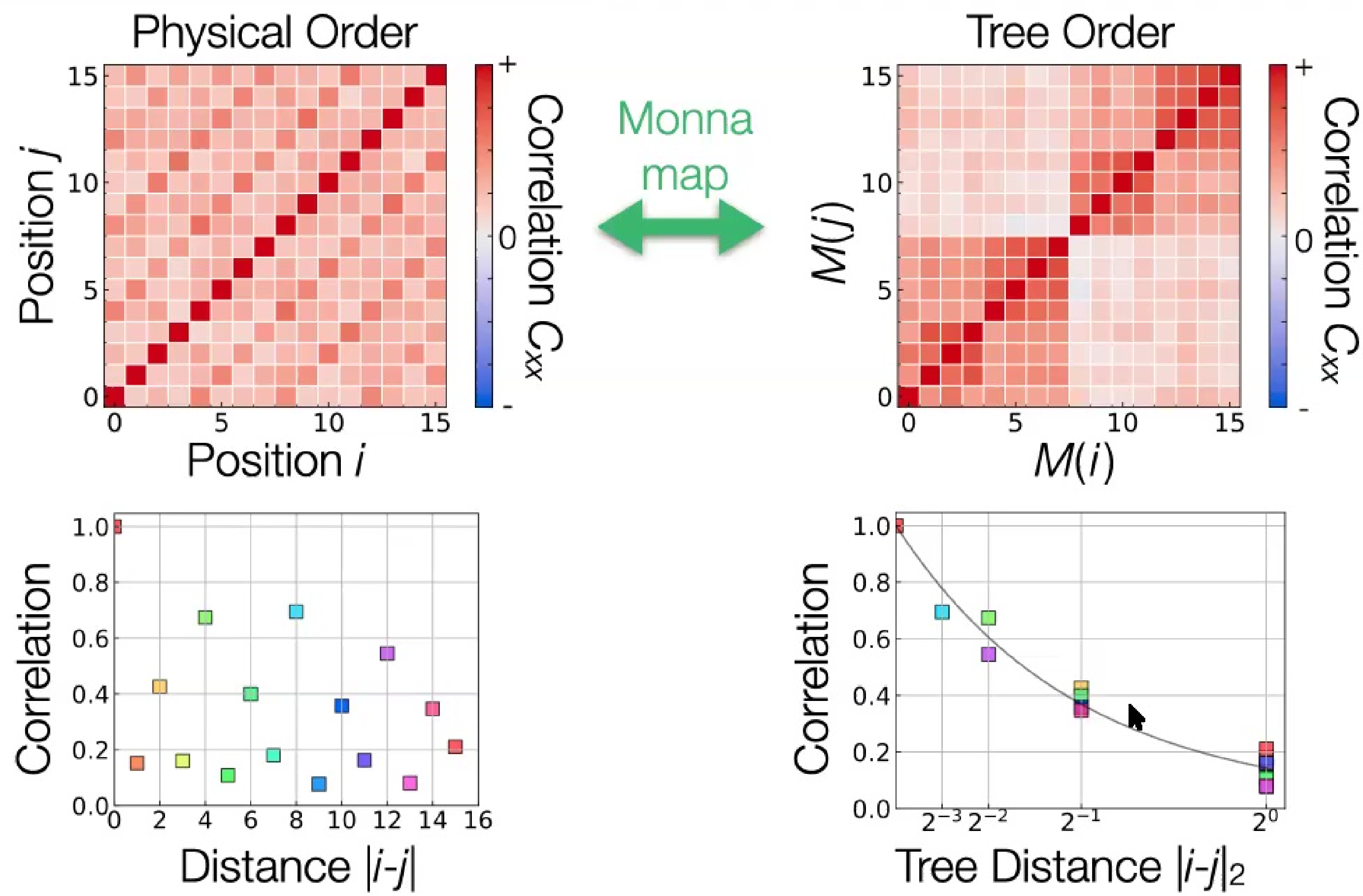
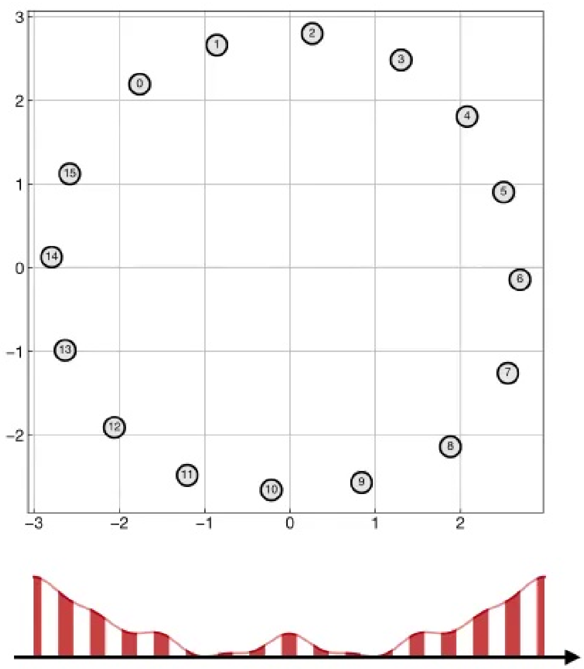


Probing the Holographic Bulk?

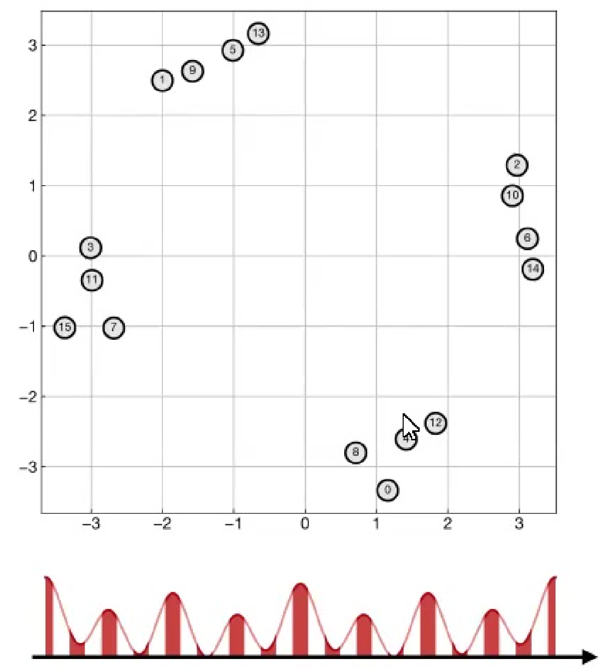
$$J(i-j) = \begin{cases} |i-j|^s & |i-j| = \text{power of } 2 \\ 0 & \text{otherwise} \end{cases}$$

1. Reconstruct boundary geometry from spin correlations

s = -1



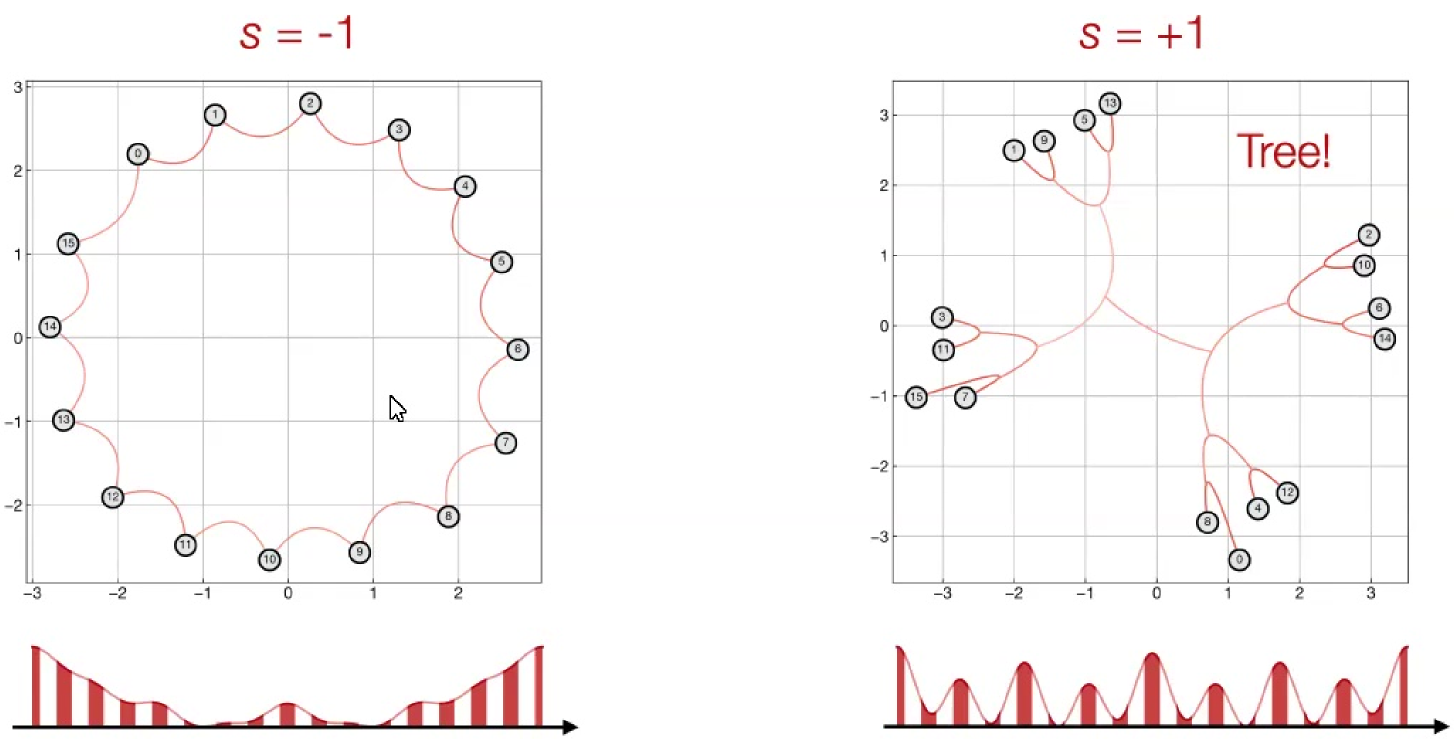
s = +1



Probing the Holographic Bulk?

$$J(i-j) = \begin{cases} |i-j|^s & |i-j| = \text{power of } 2 \\ 0 & \text{otherwise} \end{cases}$$

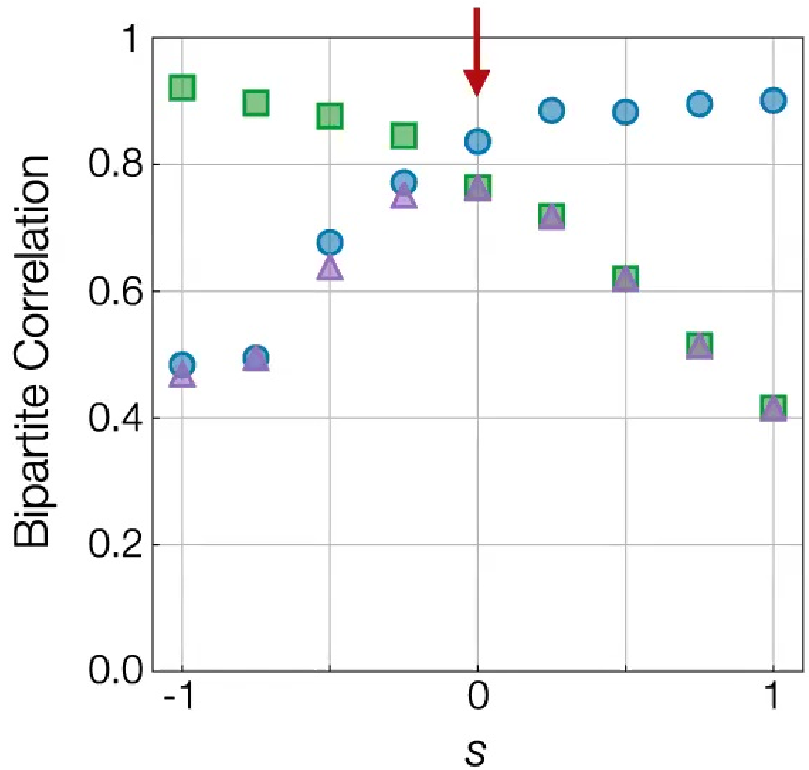
1. Reconstruct boundary geometry from spin correlations
2. Find strongest correlations & coarse-grain to reconstruct holographic bulk

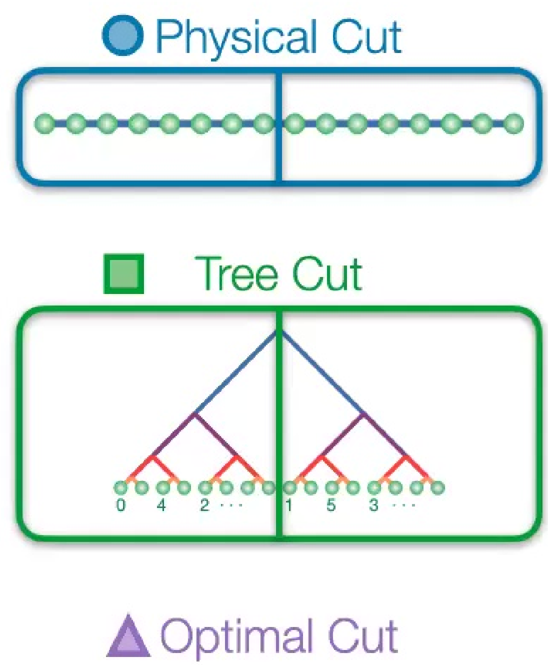


Toward Fast Scrambling?

$$J(i-j) = \begin{cases} |i-j|^s & |i-j| = \text{power of } 2 \\ 0 & \text{otherwise} \end{cases}$$

At $s = 0$: *no way* to cut the system into two weakly correlated halves





Programmable Interactions

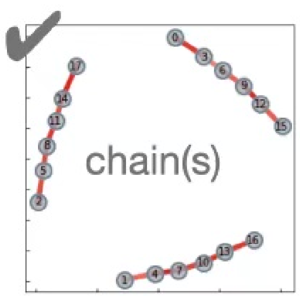
$$H = \sum_{i,j} \left[J_{ij}^{xy} \left(s_i^+ s_j^- + s_i^- s_j^+ \right) + J_{ij}^{z} s_i^z s_j^z \right]$$

Knobs:

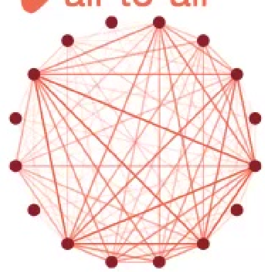
✔ Sign of interaction (ferro- *vs* antiferromagnetic)

✔ Form of couplings (flip-flop *vs* Ising)

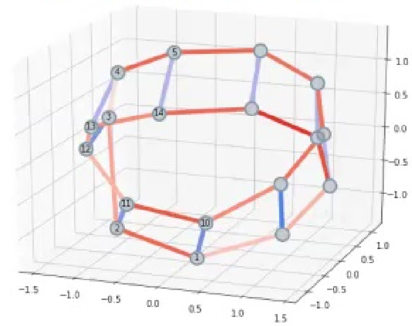
✔ Spatial structure

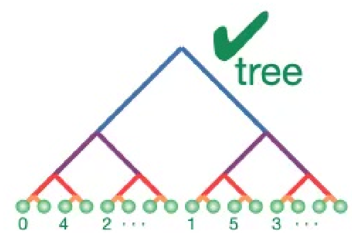


✔all-to-all

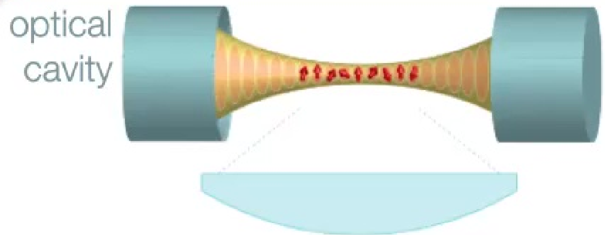


✔Möbius ladder





Summary & Outlook



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

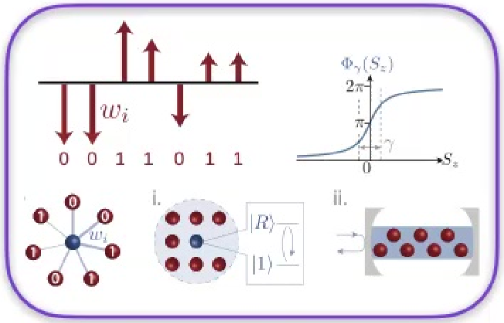
Optically programmable interactions: *form (XY vs Ising), signs, interaction graph*

Interactions can **protect spin coherence**

Exotic geometries: black-box reconstruction from spin correlations

Prospects

- Simulations of quantum gravity
- Topological phases
  …on topologically non-trivial manifolds
- Frustrated magnetism
- Quantum optimization
  …gain-based? …Grover search
- Spatially structured entanglement for metrology



Anikeeva, Markovic, Borish, Hines, Rajagopal, Cooper, Periwal, Safavi-Naeini, Davis & MS-S, *arXiv:2009.05549, (PRX Quantum*, 2021*).*

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