Title: Holographic Quantum Simulation with Atoms and Photons

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Collection: It from Qubit 2023

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Holographic Quantum Simulation with Atoms and Photons

Monika Schleier-Smith

Avikar Periwal
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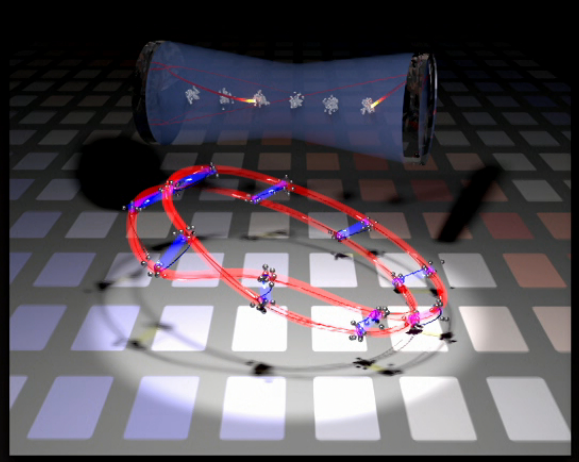
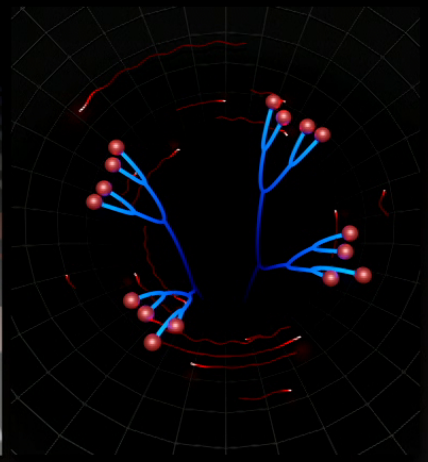
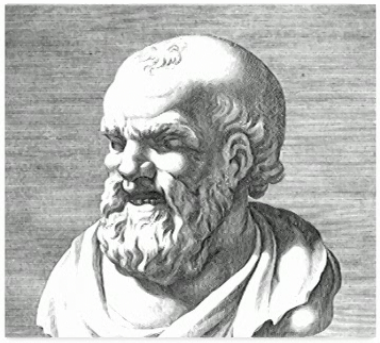
August 1, 2023



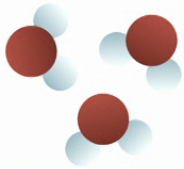


Stanford University

Atoms in Ancient Philosophy



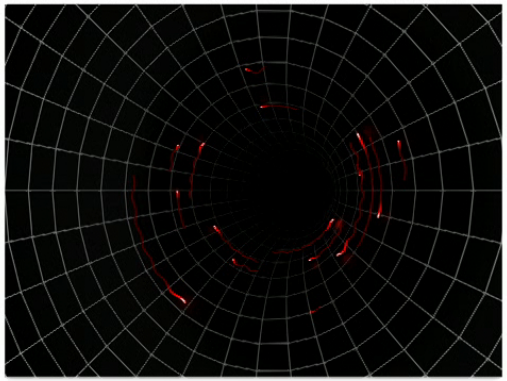
Sweet is by convention and bitter is by convention,
hot by convention, cold by convention,
color by convention;
in truth there are but atoms and the void.
— Democritus (b. 460 BCE)

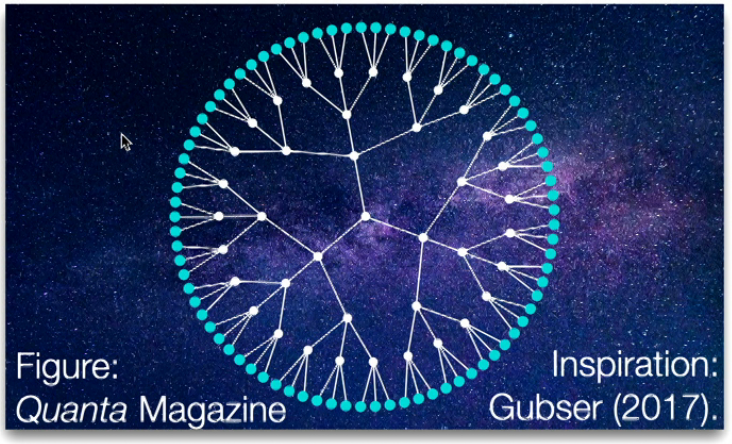


Macroscopic behavior emerges from microscopic configuration of atoms

Modern Frontier: Understanding the Void

Is spacetime *really* smooth?





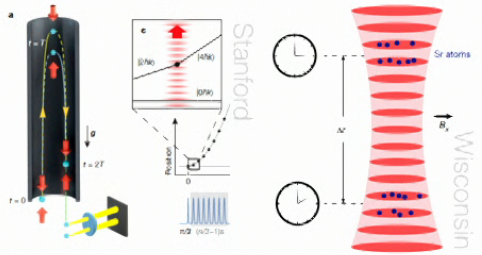
…or do curved space & gravity emerge from discrete constituents?

- Can gravity *emerge* from *entanglement*? (Holographic duality)
- Useful for visualizing & understanding quantum many-body systems?

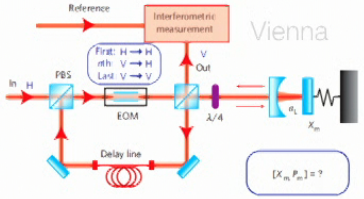
Quantum Gravity in the Lab?

Precision Measurement

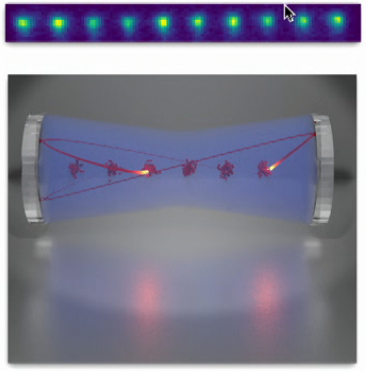
Quantum gravimeters & clocks

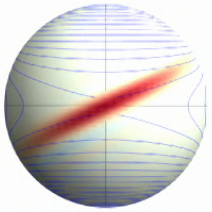


Massive quantum objects

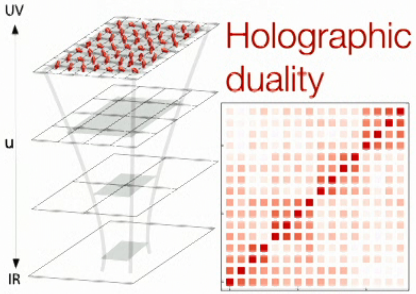


Quantum Engineering

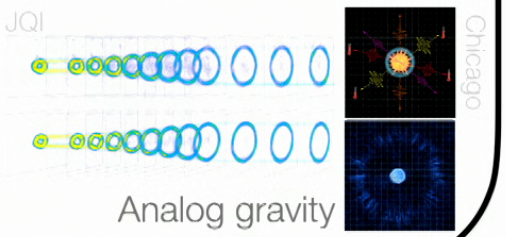




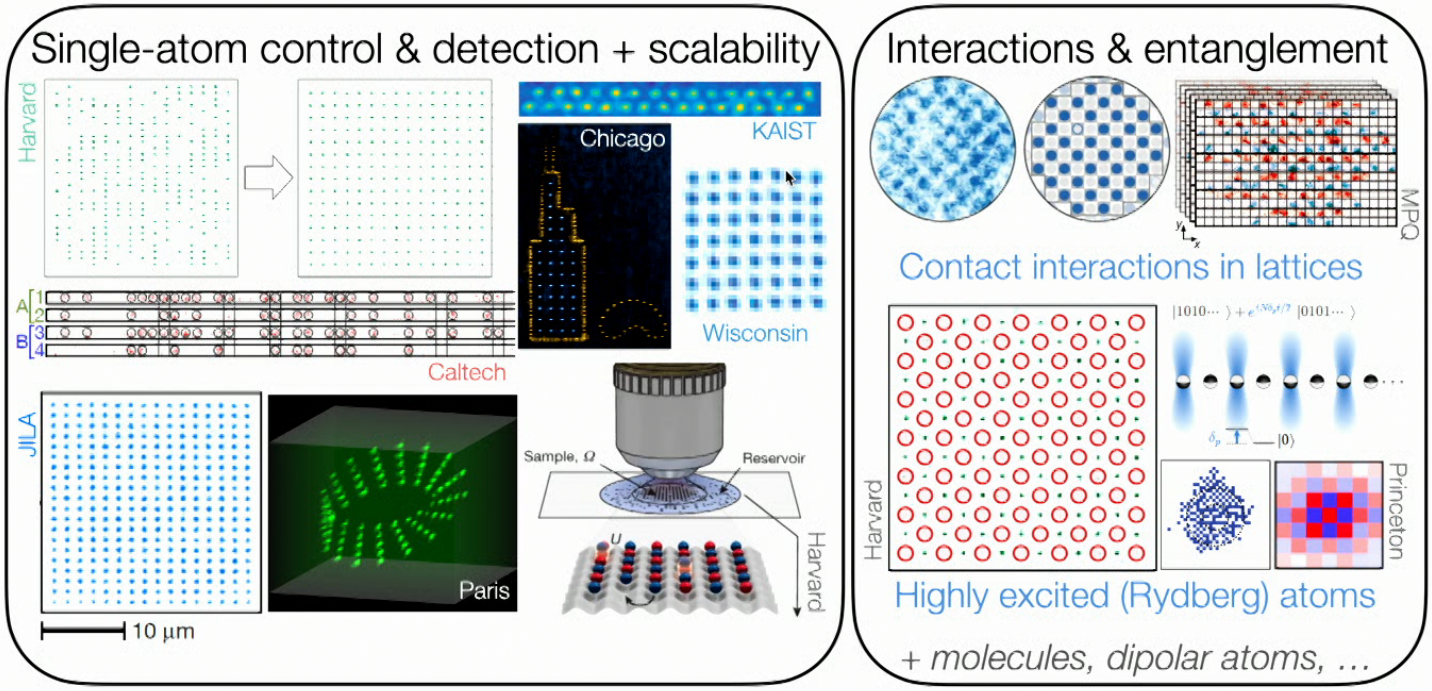
Quantum Simulation



Build interacting system & probe correlations

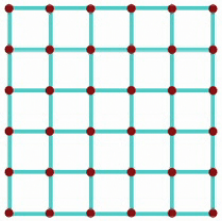
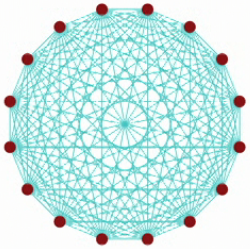
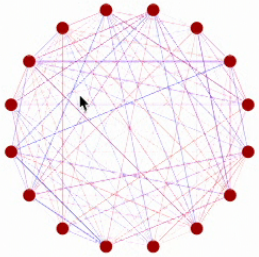
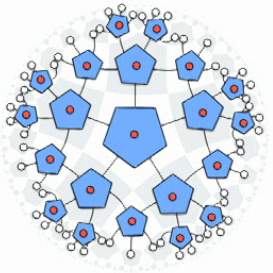


Quantum Engineering with Cold Atoms

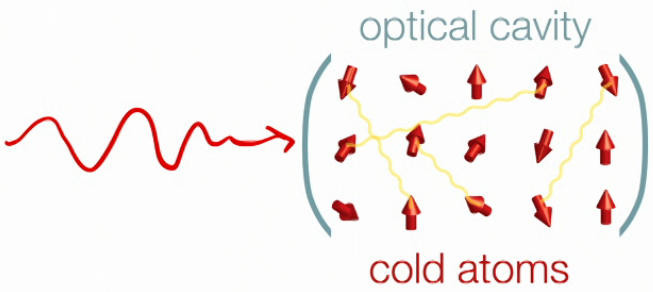


Limitation: connectivity of interactions — atoms interact only with neighbors

Connectivity in Quantum Systems

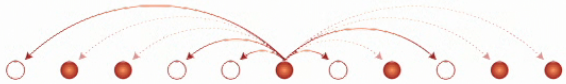
Lattice	All-to-All	Random	Programmable
			
Cluster state: Resource for computation	Squeezed state: Resource for sensors & clocks	Fast scrambler: Simulating black holes	Hyperbolic code: Low-overhead error correction

Photon-Mediated Interactions



Photons carry information between distant atoms, letting any atom “talk” to any other

Approach:

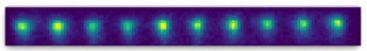


- Programmable non-local interactions by optical control

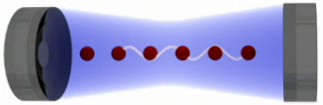
- Local detection for probing spatial correlations and entanglement

Outline

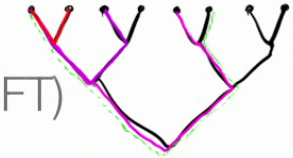
✔ **Motivation & Background**



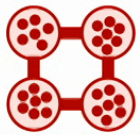
- **Experimental Toolbox**
  Programmable photon-mediated interactions



- **Emergent Geometry**
  Toy model of holographic duality (p-adic AdS/CFT)



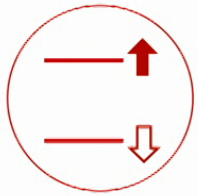
- **Engineering & Probing Entanglement**
  Multimode squeezing & graph states

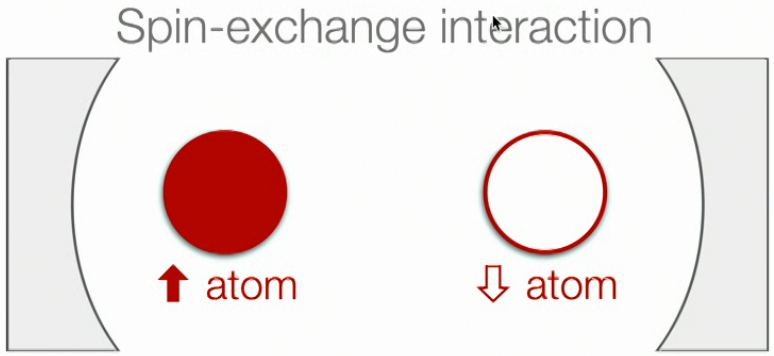


- **Outlook**

Photon-Mediated Interactions

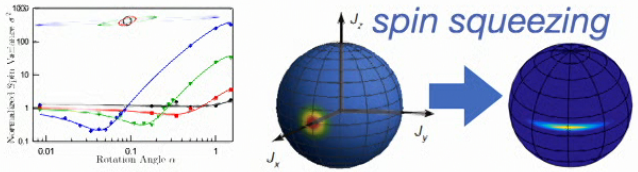
Each atom as a spin with two states: [● = ⬆] or [○ = ⇩]





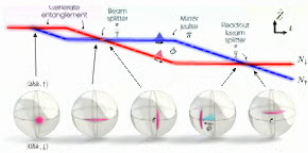
Many Atoms + Photons

Entanglement for metrology

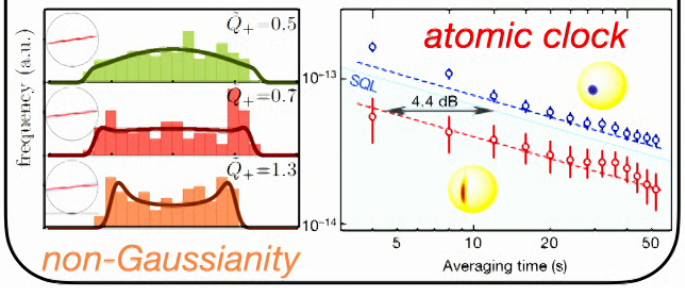


spin squeezing

atom interferometer



Leroux, et al, *PRL* (2010).
Hosten, et al, *Nature* (2016).
Greve, et al, *arXiv* (2021).
Huang, et al, *arXiv* (2020).
Pedrozo et al, *Nature* (2020).

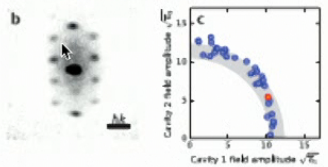


non-Gaussianity

~10^3 atoms provably entangled,
but conceptually simple states…

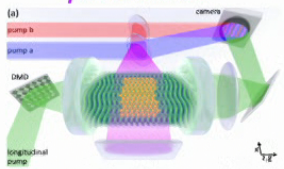
Quantum simulations

supersolids



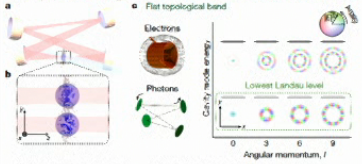
Léonard *et al., Nature* (2017).

phonons

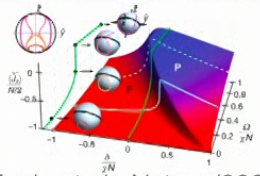


Guo *et al., Nature* (2021).

topological photonics

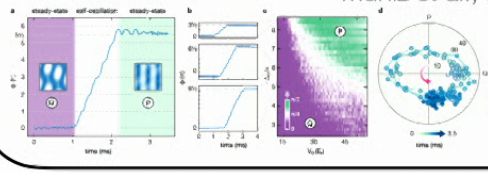


dynamical phases



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

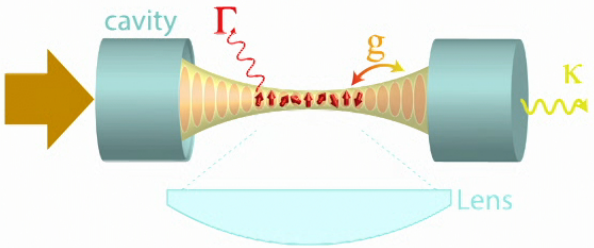
Muniz *et al., Nature* (2020).

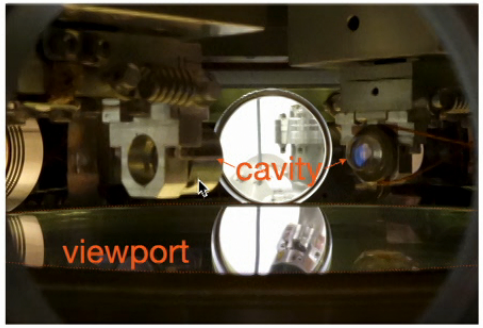


Dreon *et al.*, *arXiv* (2021).

+ Toy models of quantum gravity?

Experimental Setup



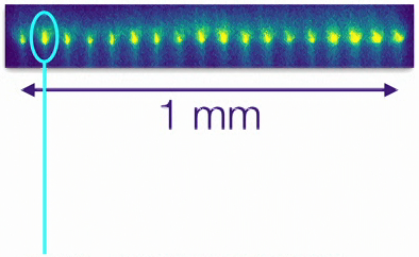


Finesse = 1.2×10^4

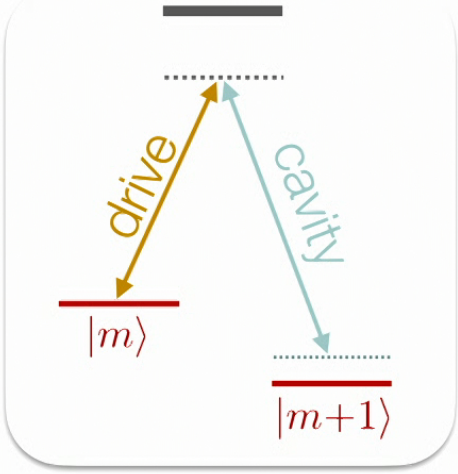
Waist = 18 μm

Cooperativity
$4g^2/(\kappa\Gamma) = 5$

array of atom clouds

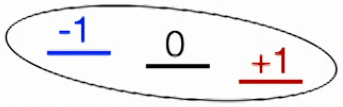


10^3 - 10^4 rubidium atoms per site

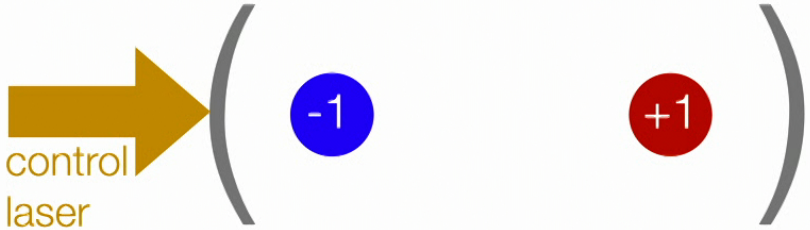


Our Rubidium Atoms

Each atom has *three* magnetic sublevels:



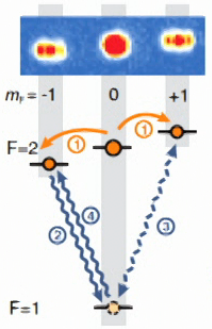
We initialize in $m = 0$ and let photons mediate pair creation:



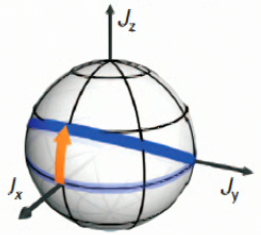
$$|0\,0\rangle \rightarrow |{-1}\,{+1}\rangle + |{+1}\,{-1}\rangle$$

$$H = -\chi\left(a^\dagger b^\dagger cc + \text{h.c.}\right) + q(a^\dagger a + b^\dagger b)$$

Cf. collisional spin mixing
⇒ correlated atom pairs

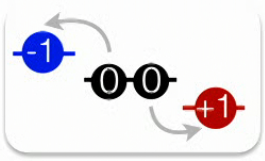


Lücke,…& Klempt, *Science* (2011).

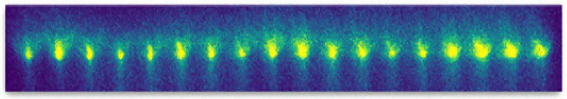


Also: Chapman; Oberthaler; You

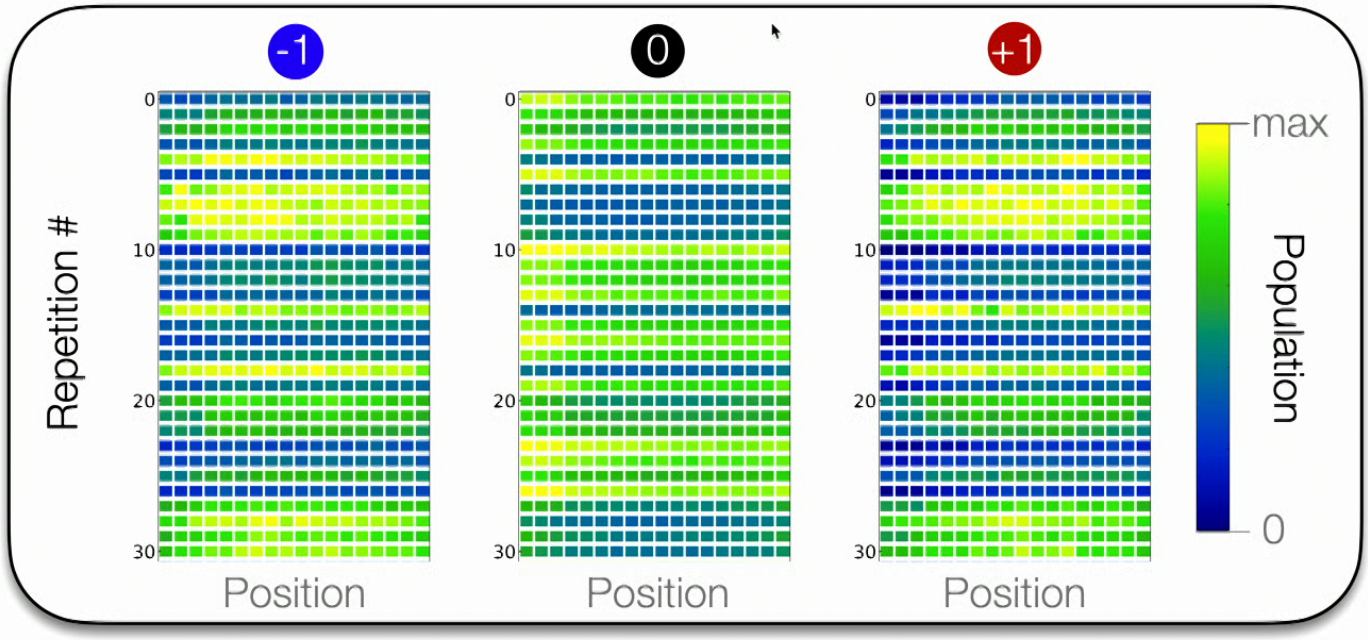
Photon-Mediated Spin Mixing



…in an **array of small atomic clouds,**



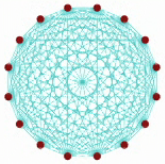
initialized with all atoms in state 0



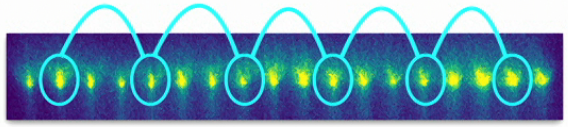
Davis, Bentsen, Li, Homeier & MSS, *PRL* (2019).
Periwal, Cooper, Kunkel, Wienand, Davis & MSS, *Nature* (2021).

Programmable Interactions?

So far every atom talked to every other:



Next step: programming the graph of interactions

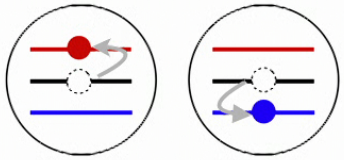


$$H = \sum_{\mu,\nu} J(r_{\mu\nu}) f_\mu^+ f_\nu^- + \text{h.c.}$$

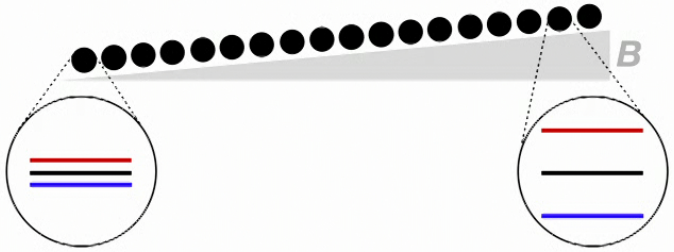
Objective: arbitrary control of translation-invariant couplings

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

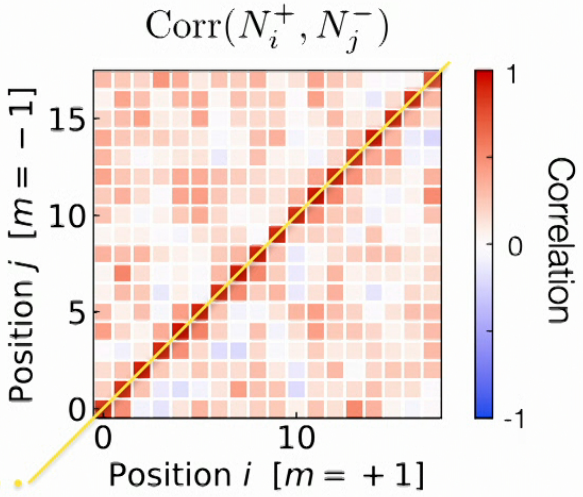
Spatial Control of Pair Creation



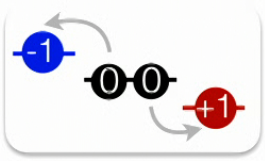
1) Turn off long-range interactions by adding a magnetic field gradient



$m = \pm 1$ pairs form only locally

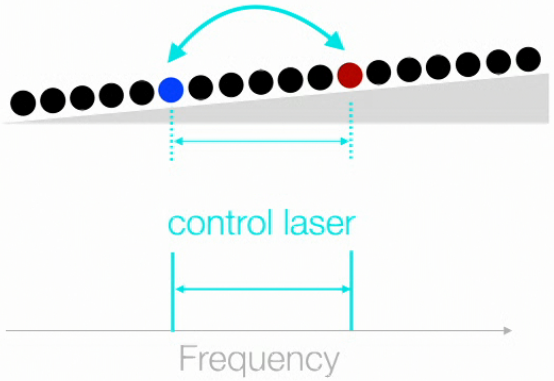


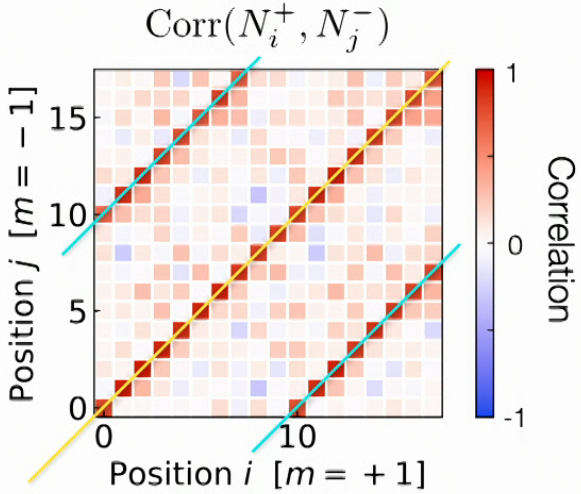
Spatial Control of Pair Creation



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

2) Reintroduce interactions at distance(s) set by laser frequencies



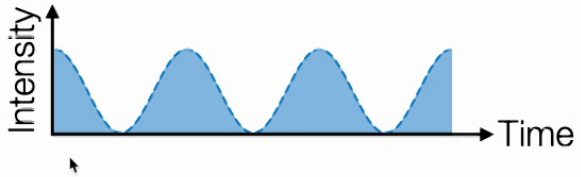


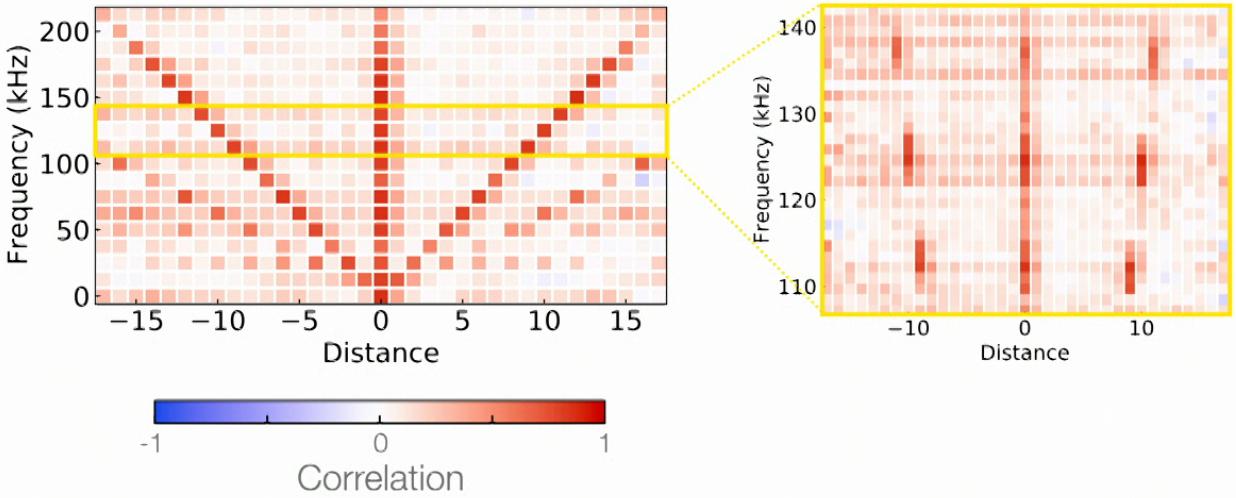
Proposals: Hung, Gonzales-Tudela, Cirac & Kimble, *PNAS* (2016) — nanophotonics.
Manovitz, … & Ozeri *PRX Quantum* (2020) — trapped ions.

Programmable Interactions

Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).

Controlling interaction distance by laser modulation frequency



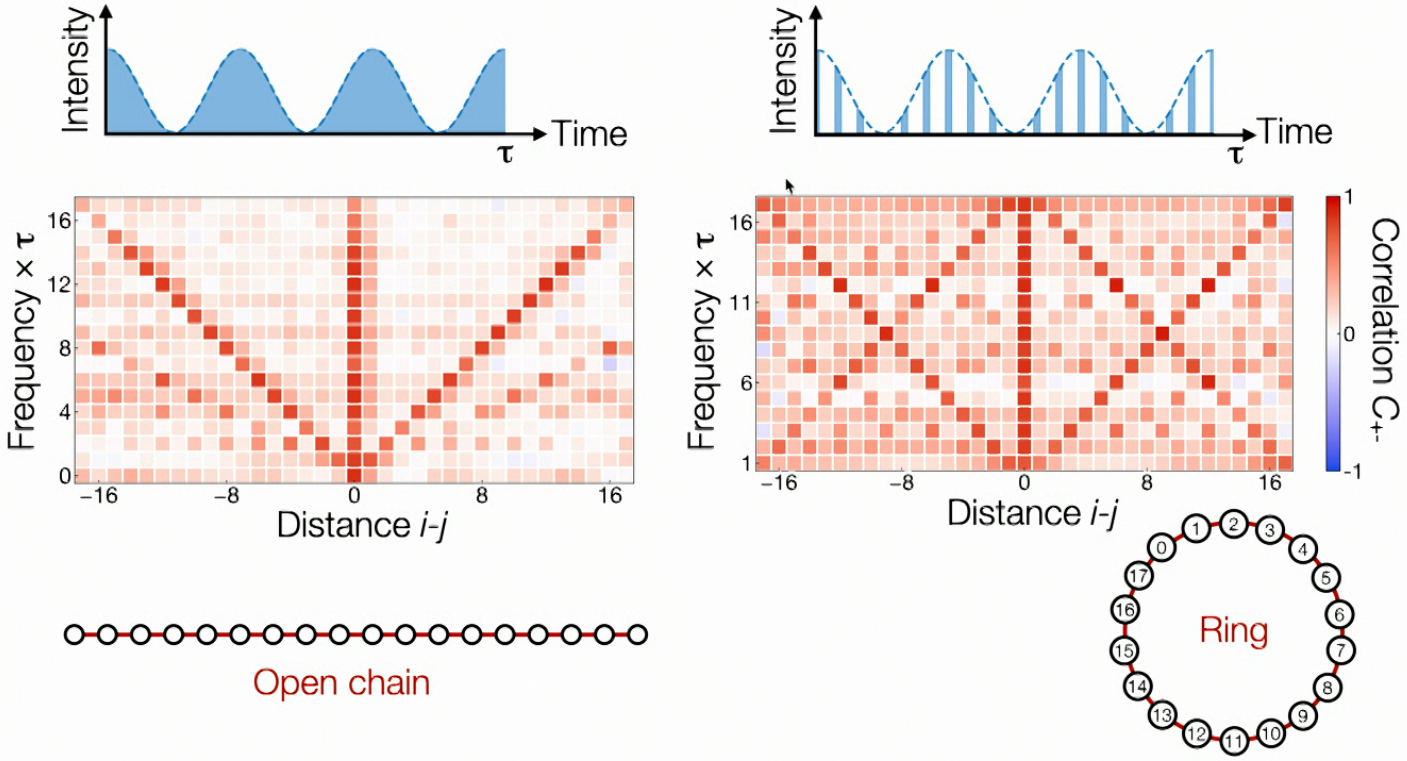


Generalization:

arbitrary control of interactions vs distance via modulation waveform

Periodic Boundary Conditions

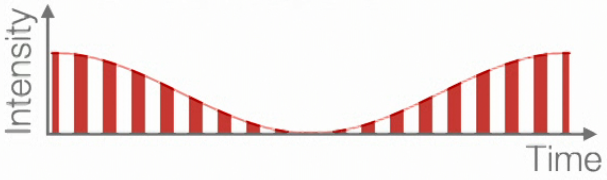
Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).



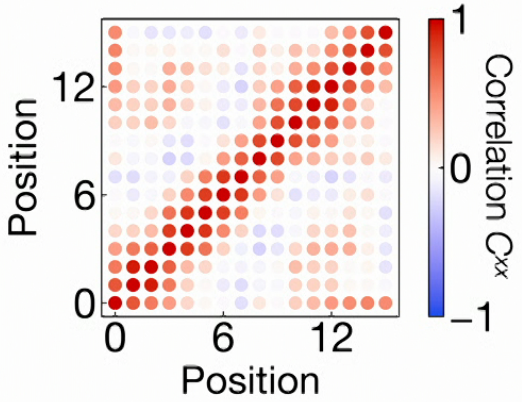
Reconstructing Geometry

Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).

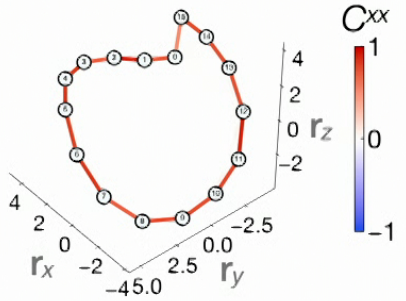
Drive Waveform



Measured Correlations



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



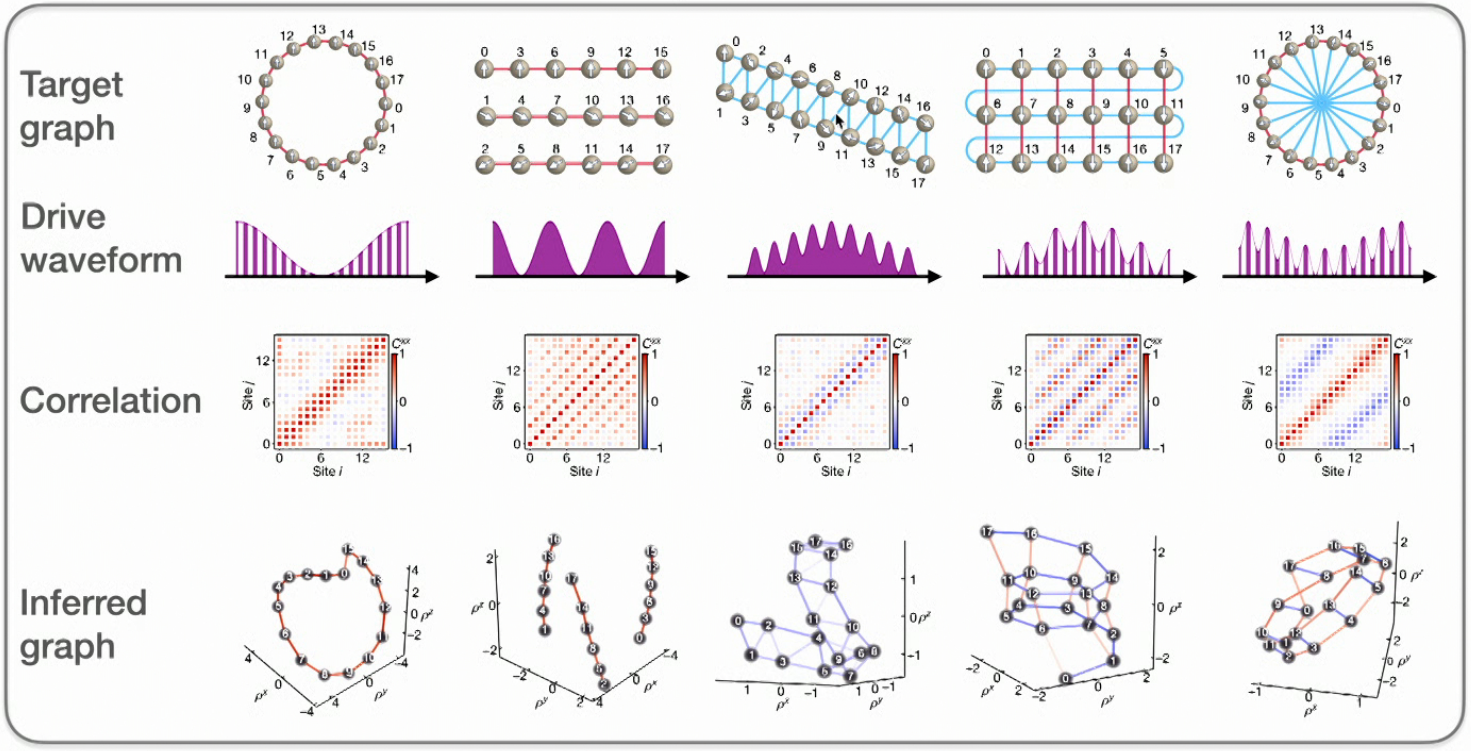
Best-Fit Geometry

All possible bonds drawn: color & opacity from C^{xx}

Gallery of Graphs

Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).

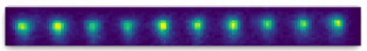
Spin correlations & reconstructed geometries for different drive waveforms



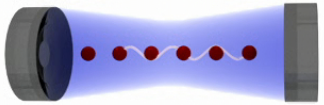
Bond color indicates spins aligned or anti-aligned

Outline

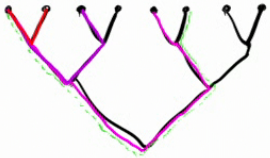
- ✔ **Motivation & Background**



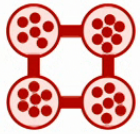
- ✔ **Experimental Toolbox**
  Programmable photon-mediated interactions



- **Emergent Geometry**
  Toy model inspired by *p*-adic AdS/CFT



- **Engineering & Probing Entanglement**
  Multimode squeezing & cluster states

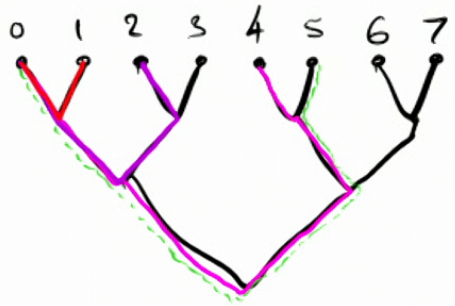


- **Outlook**

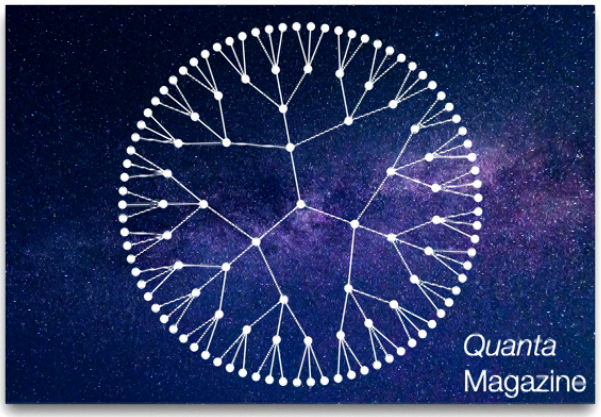
Inspiration

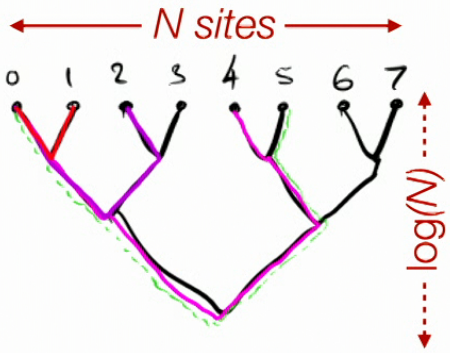
Steve Gubser (1972 - 2019)

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



Treelike Geometry





Tree = discretized model of hyperbolic space → gravity

p-adic AdS/CFT [Gubser et al., *Comm. Math. Phys.* (2017); Heydeman et al, *arXiv* (2016).]

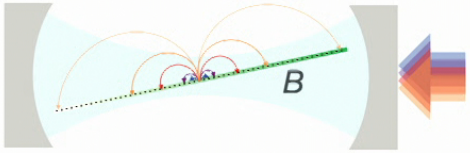
Leaves of tree = physical system
Interior vertices = holographic bulk

Toy Model

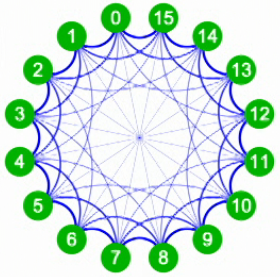
Bentsen, Hashizume, Buyskikh, Davis, Daley, Gubser, & MS-S, *PRL* **123**, 130601 (2019).

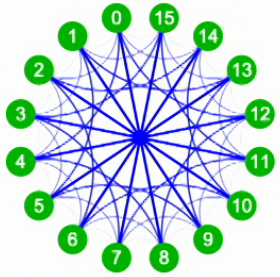
Couple i^{th} spin to $i\pm1$, $i\pm2$, $i\pm4$, $i\pm8$,…, $i\pm2^l$

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



$s < 0$

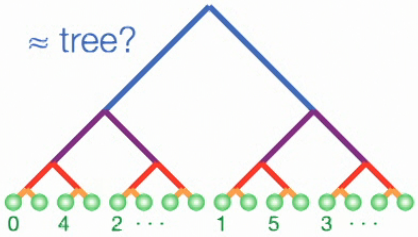




$s > 0$

≈ chain

≈ tree?



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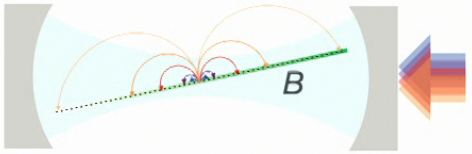
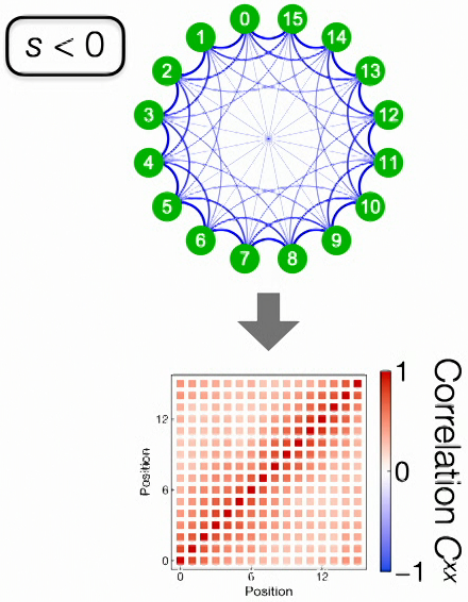
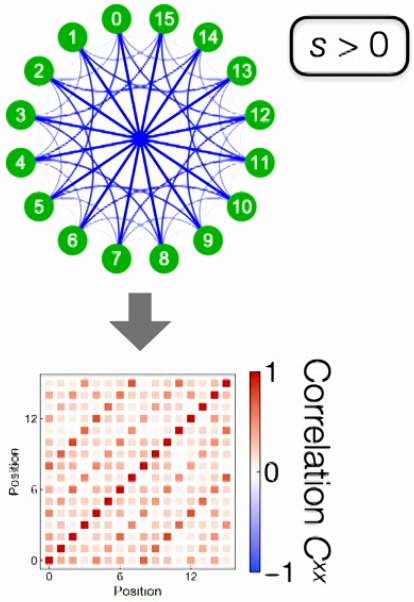
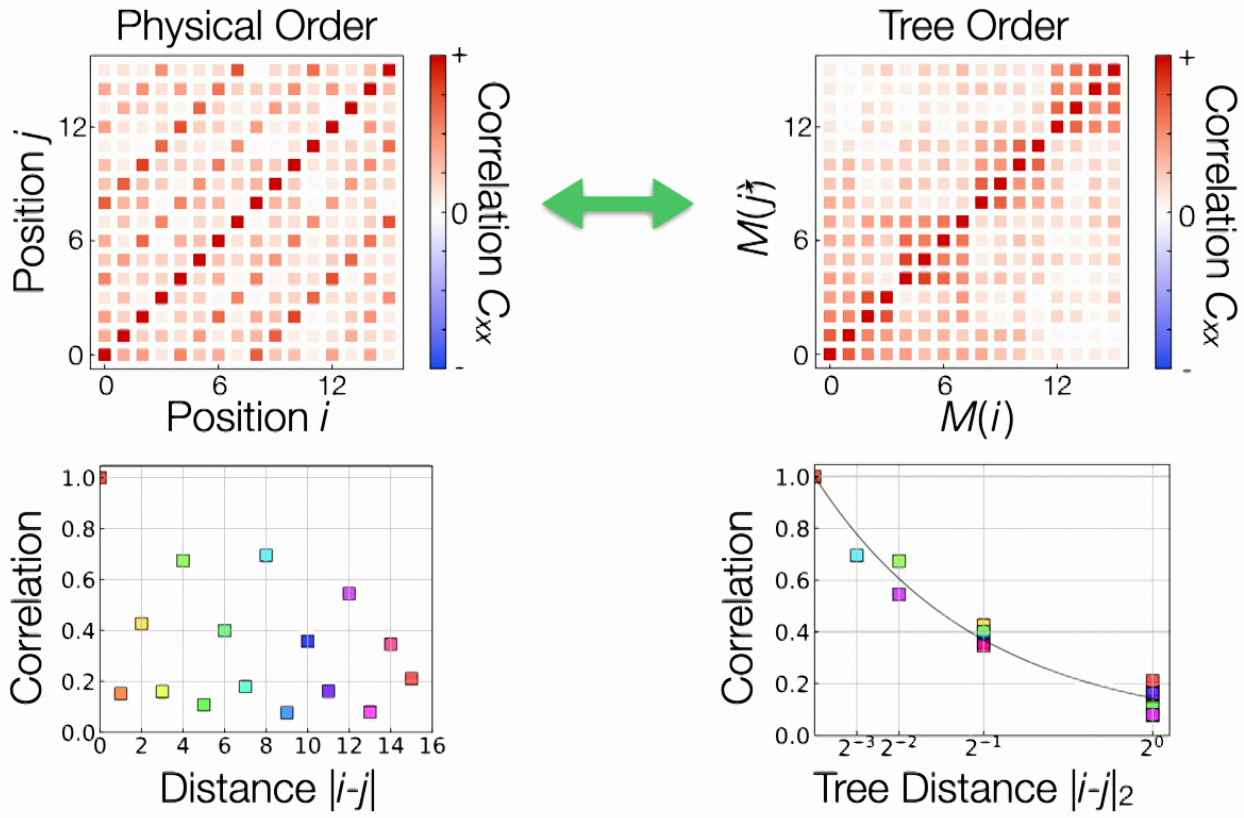






Treelike Geometry

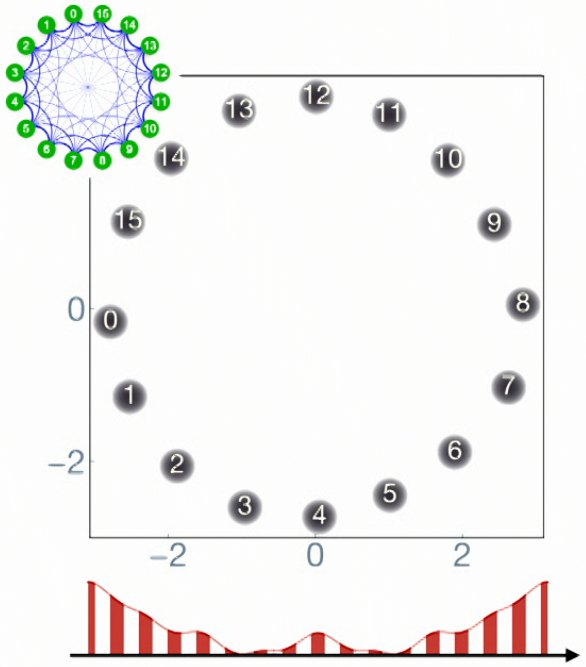
Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).

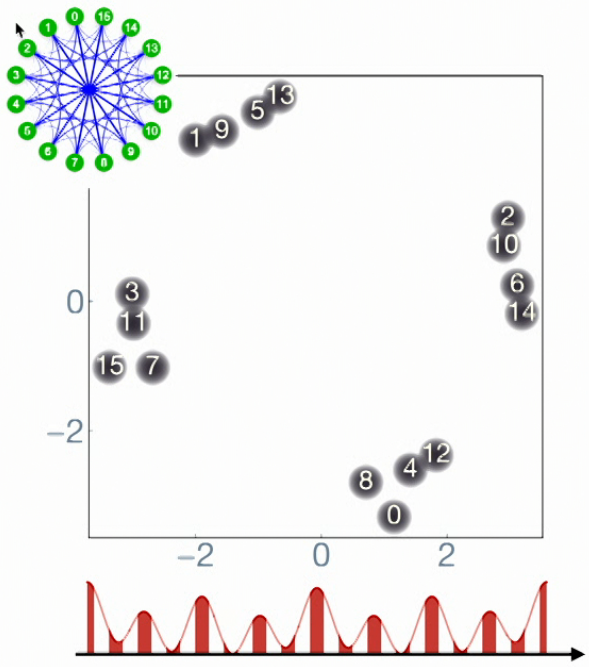


Emergent Geometry

Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).

1. Reconstruct boundary geometry from spin correlations



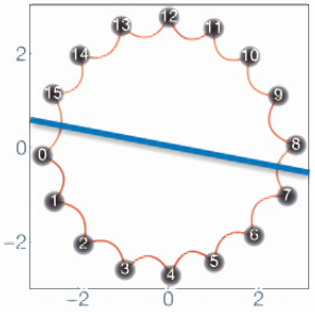


$$J(i-j) = \begin{cases} |i-j|^s & |i-j| = \text{power of 2} \\ 0 & \text{otherwise} \end{cases}$$

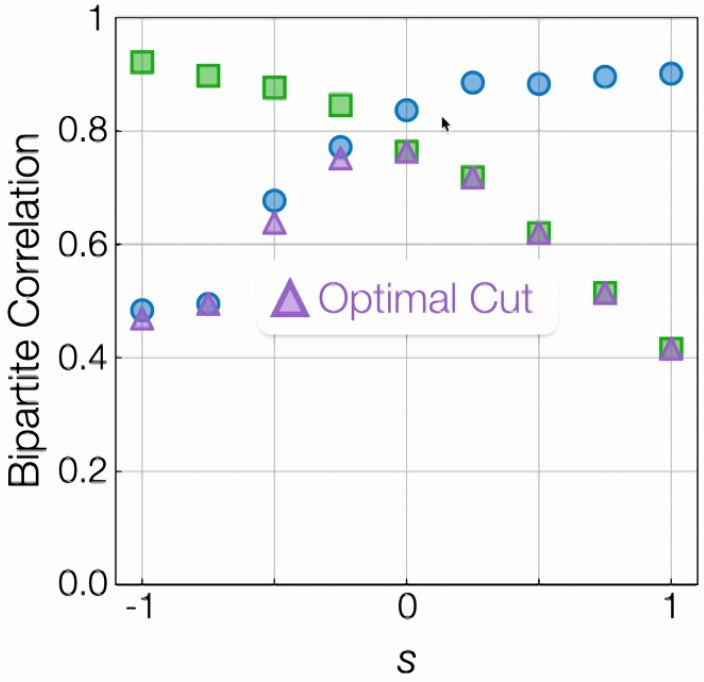
Between Geometries…

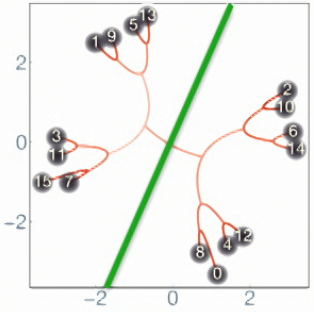
Periwal, Cooper, Kunkel, Wienand, Davis & MS-S, *Nature* **600**, 630-635 (2021).

For *s*=0: *no way* to cut the system into weakly correlated halves



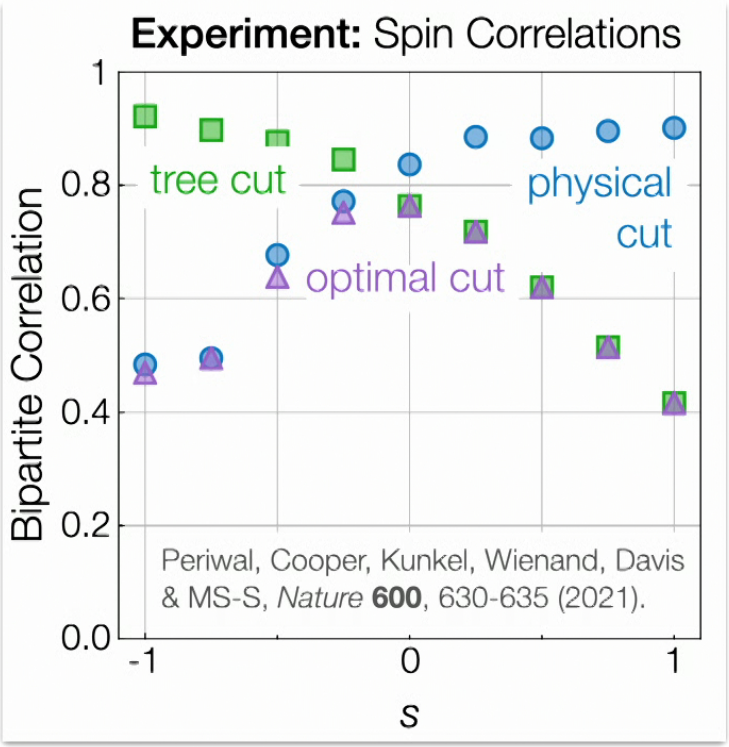
Physical Cut

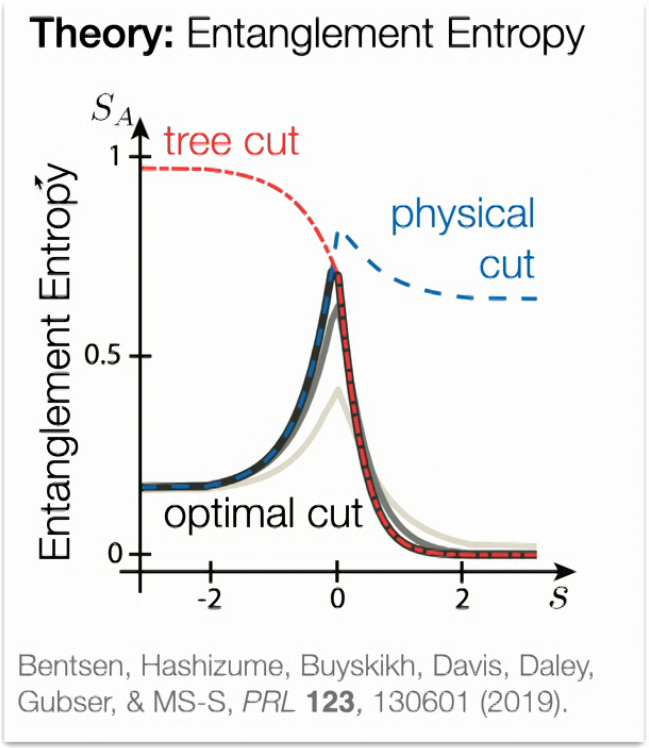




Tree Cut

From Correlations to Entanglement?



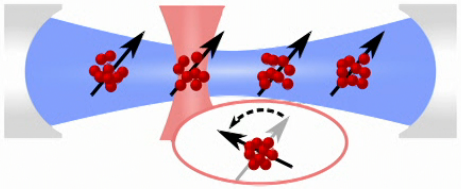


- Observed spin correlations qualitatively similar to predicted entanglement

What Next?

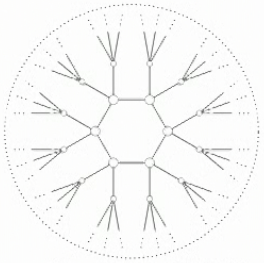
Detecting entanglement?

- Inspiration from quantum metrology
- Experiments so far in 4-site array



Accessing richer bulk geometries?

- Prospect: *p*-adic BTZ black hole
- Inspiration: **Heydeman**, Marcolli, Saberi & Stoica

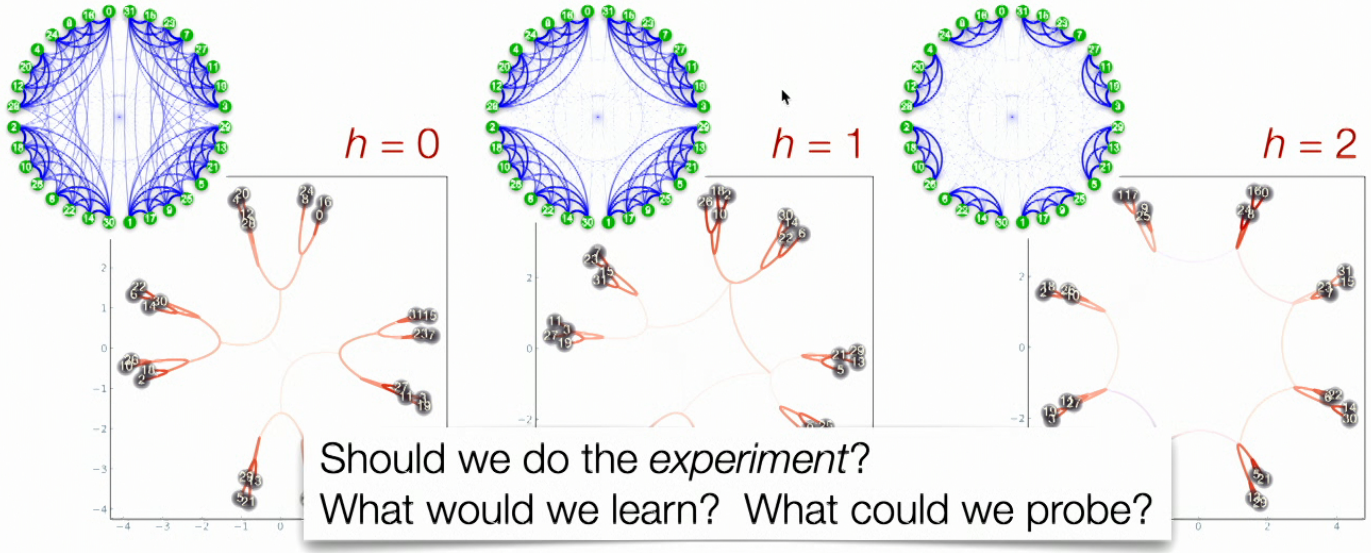


*arXiv:*1605.07639.

Prospect: *p*-adic Black Hole

Inspiration: Matt Heydeman

Modify couplings so geometry is treelike only outside horizon at radius *h*

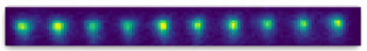


Should we do the *experiment*?
What would we learn? What could we probe?

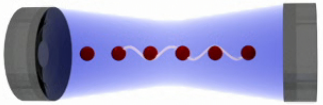
- Coupling graph shown with sites arranged by position on tree
- Bulk geometry reconstructed from numerically simulated spin correlations

Outline

- ✔ **Motivation & Background**



- ✔ **Experimental Toolbox**
  Programmable photon-mediated interactions



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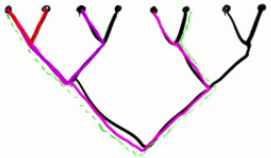
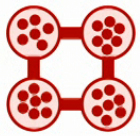
  Toy model inspired by *p*-adic AdS/CFT



- **Engineering & Probing Entanglement**
  Multimode squeezing & graph states

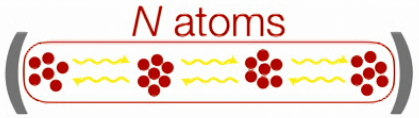


- **Outlook**

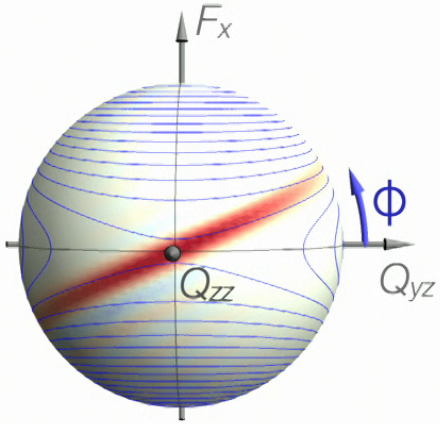
Detecting Entanglement

Cooper, Kunkel, Periwal, & MSS, arXiv:2212.11961.

…via **squeezed** quantum fluctuations

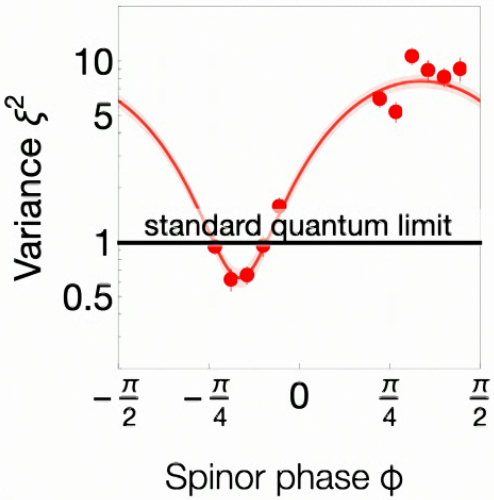


$$H = -\chi\left(F_x^2 + F_y^2\right) + q\,Q_{zz}$$



Ensemble of spin-1 atoms
F_α = collective spin vector
$Q_{\alpha\beta}$ = quadrupole tensor

Spin Nematic Squeezing



- Apply interactions
- Rotate by ϕ about Q_{zz}
- Measure F_x

⇒ Normalized variance:

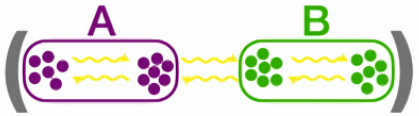
$\xi^2 \propto (\Delta F_x)^2$

Proposal: Masson, Barrett & Parkins, *PRL* (2017).

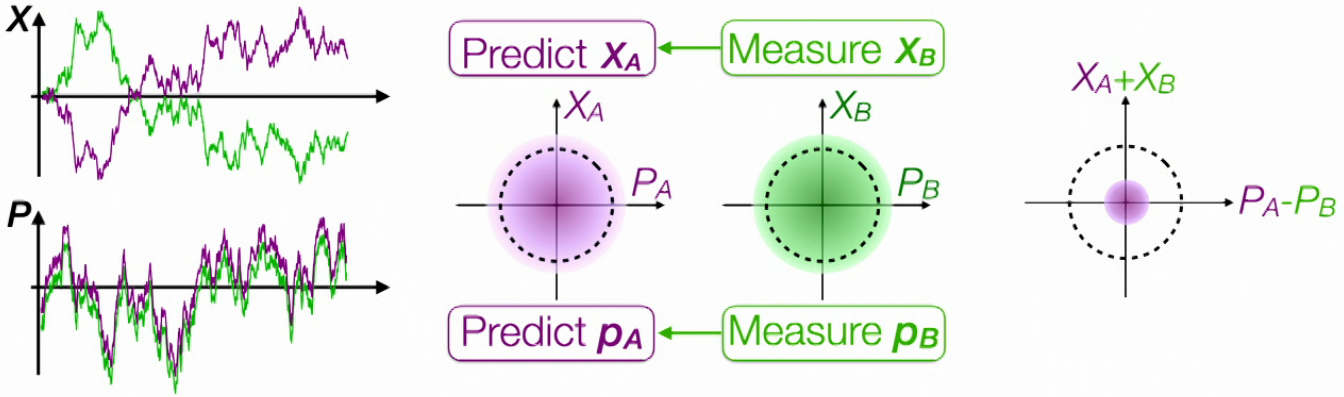
$\xi^2 < 1 \Rightarrow$ entanglement: $\rho \neq \rho_1 \otimes \rho_2 \otimes \cdots \otimes \rho_N$

Entanglement Between Subsystems

Is ***A*** entangled with ***B***?



Signature: correlations between ***A*** & ***B*** in two non-commuting observables.



$\Delta(X_A + X_B)\,\Delta(P_A - P_B) \geq \hbar$ for **separable** states…

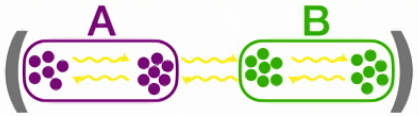
…but can be **violated by entangled states** since $[X_A + X_B, P_A - P_B] = 0$.

Einstein, Podolsky & Rosen, *Phys. Rev.* (1935); Duan, Giedke, Cirac & Zoller, *PRL* (2000).

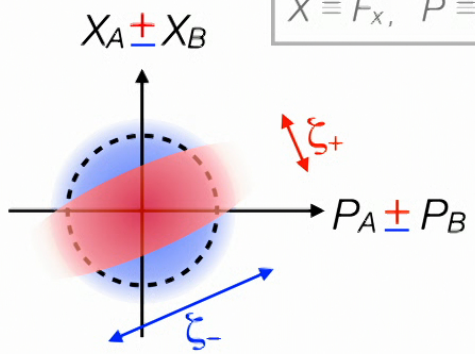
Entanglement Between Subsystems

Cooper, Kunkel, Periwal, & MSS, arXiv:2212.11961.

Is ***A*** entangled with ***B***?

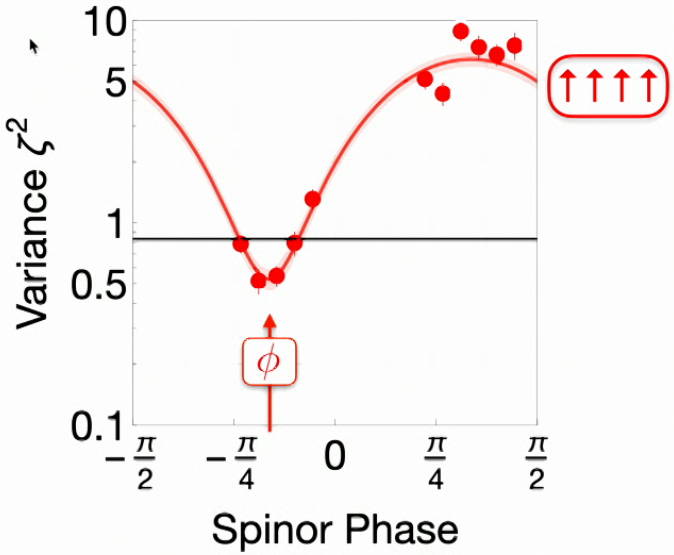


$X \equiv F_x, \quad P \equiv Q_{yz}$



$$W \equiv \zeta_{+,\phi}\zeta_{-,\phi+\pi/2} \overset{?}{<} 1$$

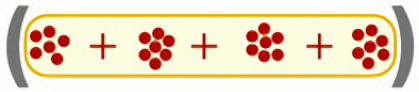
Mancini et al, *PRL* (2002).



Spatially Structured Entanglement?

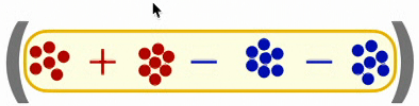
Applications:

- Global entanglement



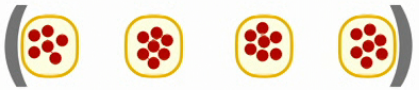
Sensing B

… in chosen delocalized mode



B

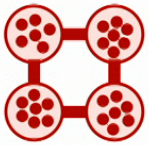
- Array of squeezed states



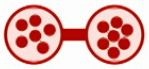
B

- Graph states (*i.e.*, cluster states)

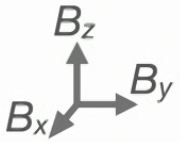
…with programmable graph



…minimal instance: EPR state

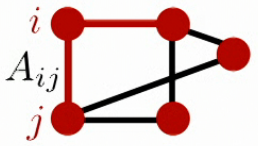


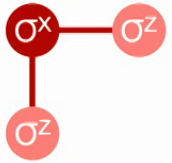
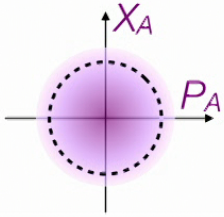
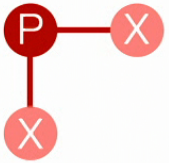
Computation, QM-free sensing, teleportation



Graph (Cluster) States

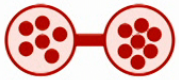
- Resource for universal measurement-based computation
- Graph specifies correlations between modes (or qubits)



Canonical preparation:	**Initialize** each node	**Interact** on each edge	Resulting **correlations**
Qubits		$H = \sum_{i,j} A_{ij} \sigma_i^z \sigma_j^z$	
Ensembles ≈ continuous variables		$H = \sum_{i,j} A_{ij} X_i X_j$	

Generating Graph States

Entanglement structure specified by adjacency matrix A: $\vec{P} - A\vec{X} \to 0$



$$A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

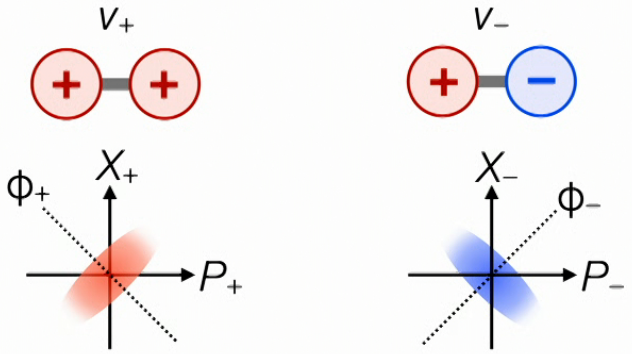
Prescription for state preparation:

Eigenvectors v_i

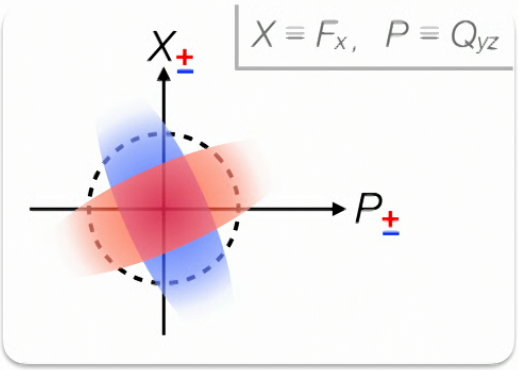
⇒ collective modes to squeeze

Eigenvalues $\tan(\phi_i)$

⇒ orientations ϕ_i of squeezed quadratures

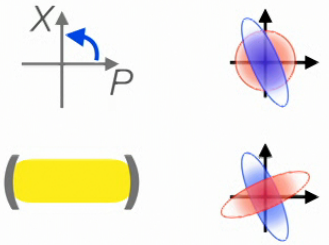


Einstein-Podolsky-Rosen (EPR) State



Prepare by squeezing both the sum and difference modes:

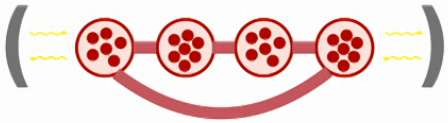
- Squeeze (global)
- Local π spin rotation
- $\frac{\pi}{2}$ phase-space rotation
- Squeeze (global)



Four-Mode Cluster State

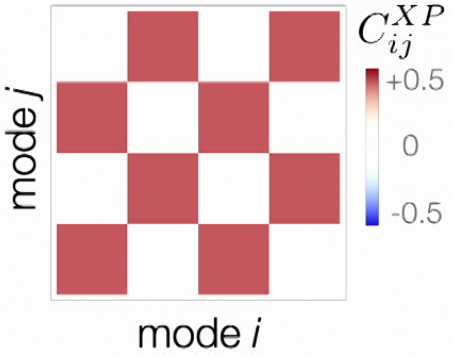
Cooper, Kunkel, Periwal,
& MSS, arXiv:2212.11961.

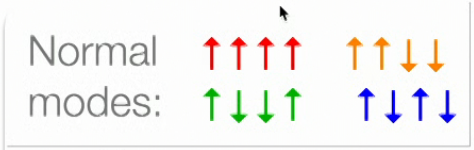
Programming specified graph of entanglement

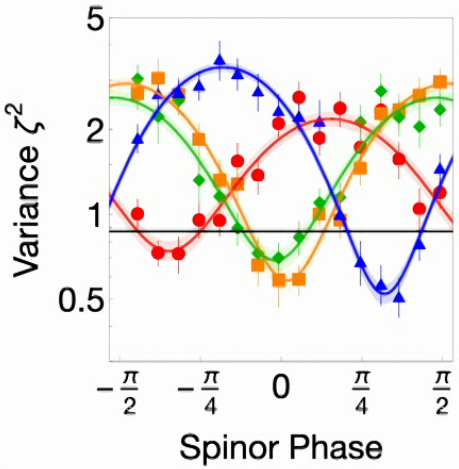


Target State

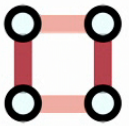
Correlation Matrix



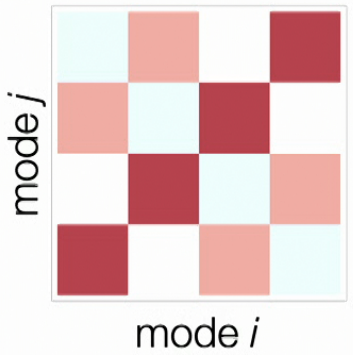




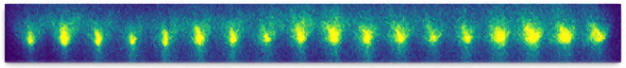
Actual State



Correlation Matrix



Scaling Up

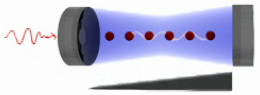


- Efficiently generate arbitrary *M*-node graphs via *M* collective squeezing operations on eigenmodes

- Generic graphs accessible with weighted couplings to cavity

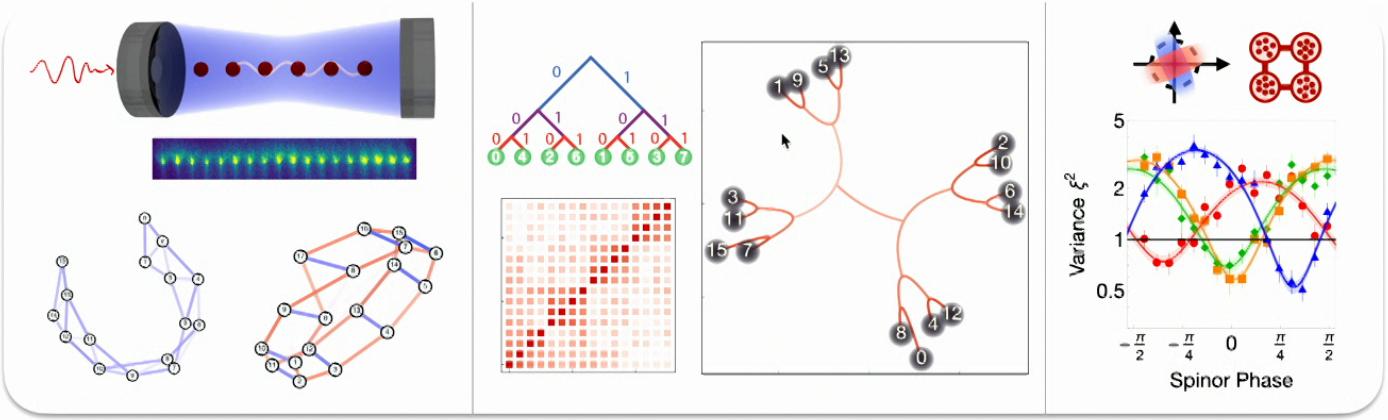
- For translation-invariant graphs, eigenmodes are spin-wave modes:

⇒ Magnetic field gradient transforms between eigenmodes



Seems like a powerful toolbox…thoughts on how to use it?
Graph state + measurements in bulk → holographic state on boundary?

Summary



- Programmable interactions between atom clouds in cavity
- Emergent treelike bulk geometry from measured spin correlations:
  Toy model of *p*-adic AdS/CFT
- Entanglement engineered & detected in graph states:
  Resources for quantum teleportation (+ sensing & computation)

Prospects in Quantum Simulation

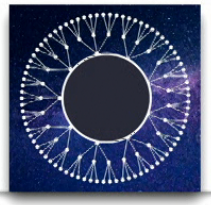
Reconstructing bulk geometry from experimentally accessible entanglement measures?

PRL 115, 261602 (2015) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2015

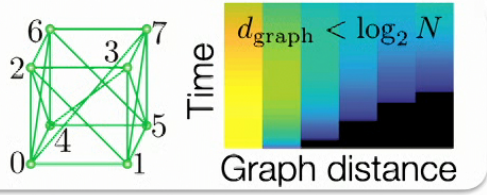
Distance between Quantum States and Gauge-Gravity Duality

Masamichi Miyaji,[1] Tokiro Numasawa,[1] Noburo Shiba,[1] Tadashi Takayanagi,[1,2] and Kento Watanabe[1]
[1]Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan
[2]Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8582, Japan

Exploring richer holographic geometries:
e.g., *p*-adic black hole horizon (with Matt Heydeman)



Observing fast scrambling
& investigating dependence on graph
(power-of-2 model; SYK-like models; …)



Quantum simulations in strongly interacting regime:
increase atom-photon coupling → single spin per site

Acknowledgements

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AFOSR

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