Quantum Spin Dynamics with Non-Local Interactions

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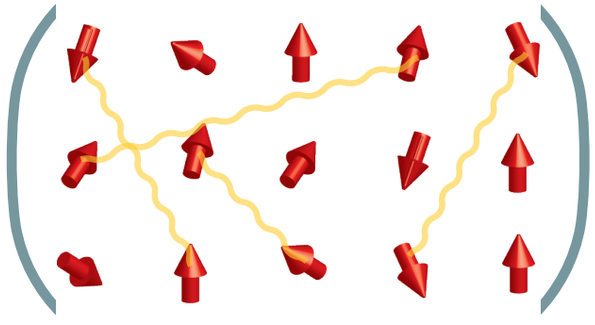
Anton Buyskikh
Andrew Daley

December 22, 2018



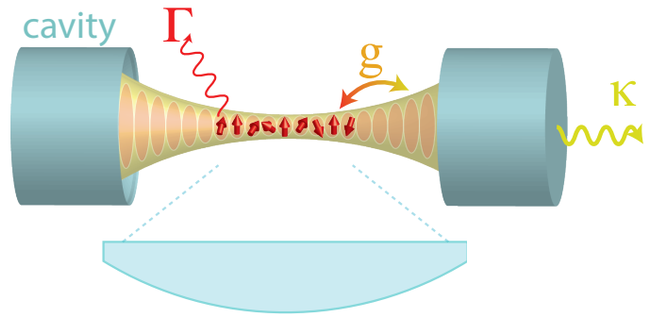
Stanford University

Outline

Motivation

Understanding many-body entanglement

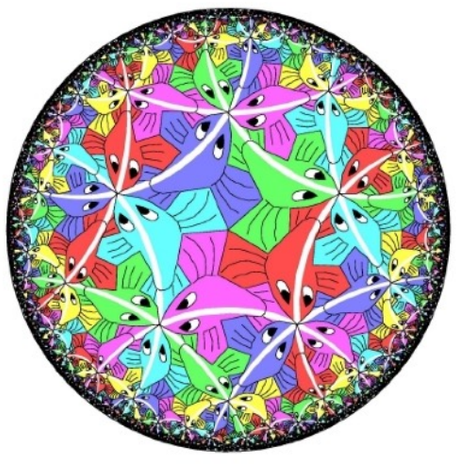
—insights from holographic duality?



Experiments with cold atoms and photons

What kinds of models can we engineer?

What are our experimental observables?



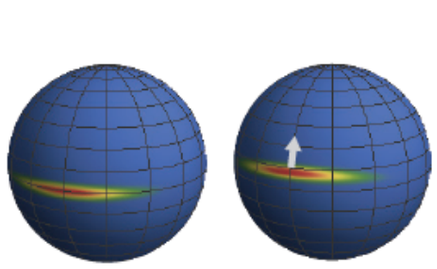
Prospects & Questions

Fast scrambling & toy models for quantum gravity

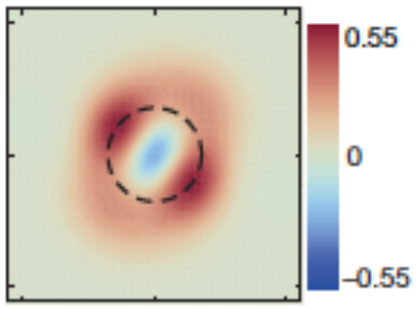
Motivation: Understanding Entanglement

Useful Entanglement

Known resources for metrology, computation or communication



Hosten et al.
Nature (2016).



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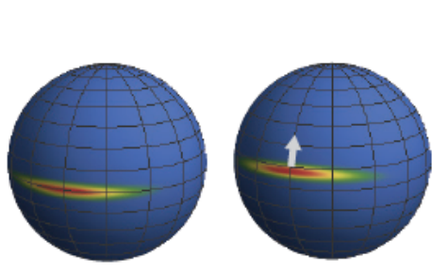

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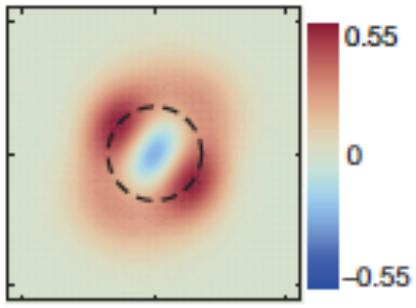

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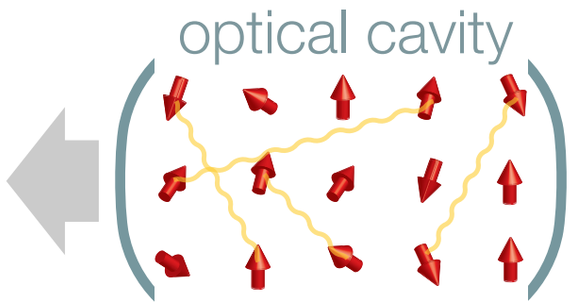
>1000-atom entanglement!



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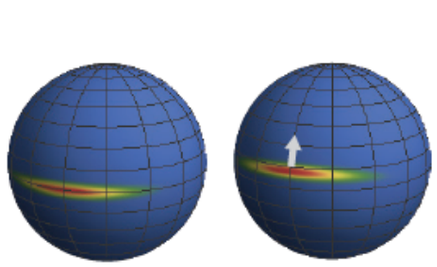

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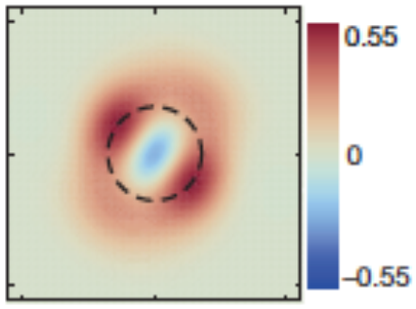

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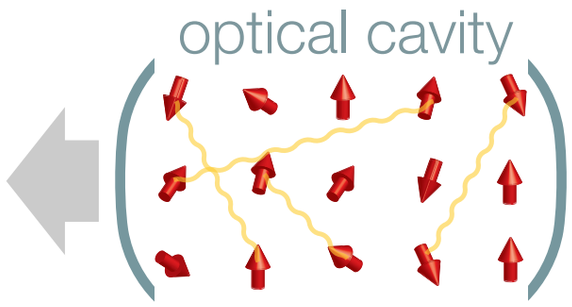
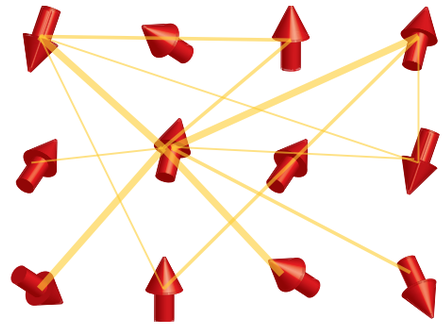


Useless entanglement

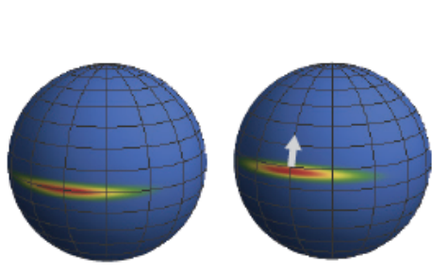
Generic states of interacting many-body systems



Motivation: Understanding Entanglement

Quantum Control

Known resources for metrology, computation or communication



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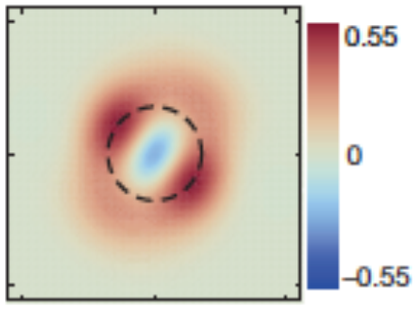

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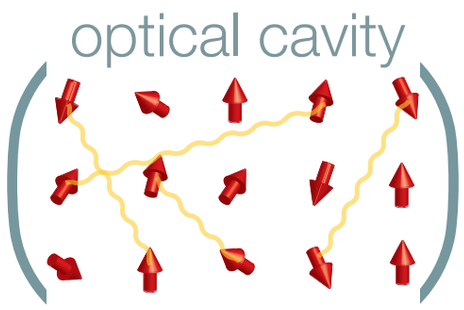

Quantum Simulation

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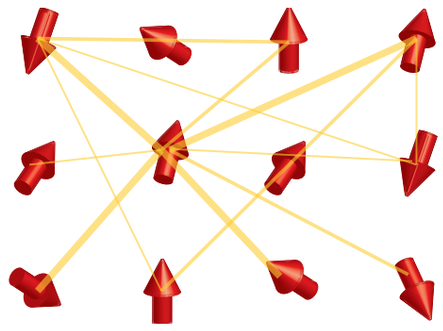

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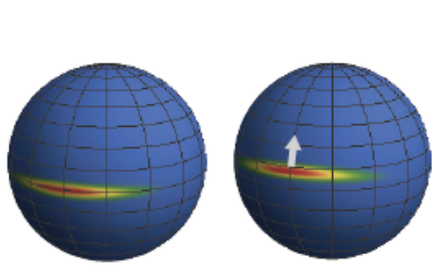

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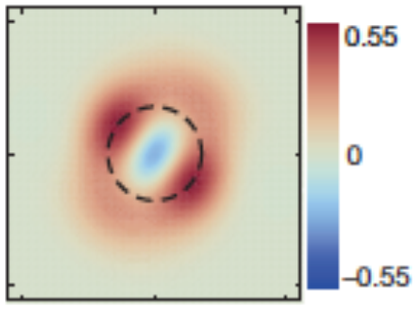

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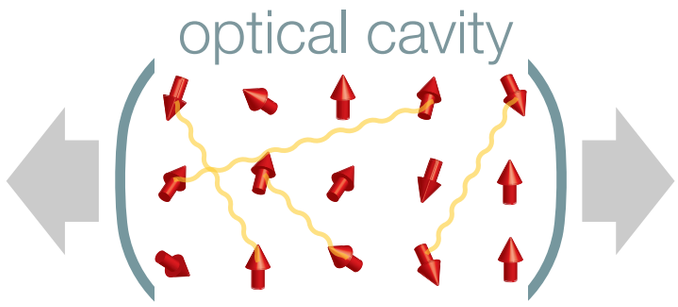

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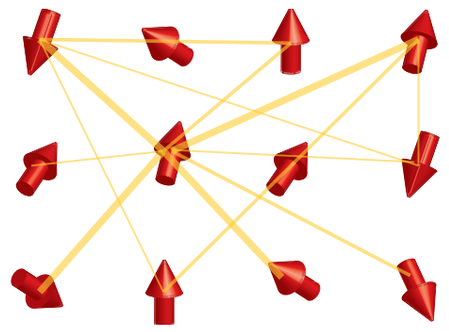
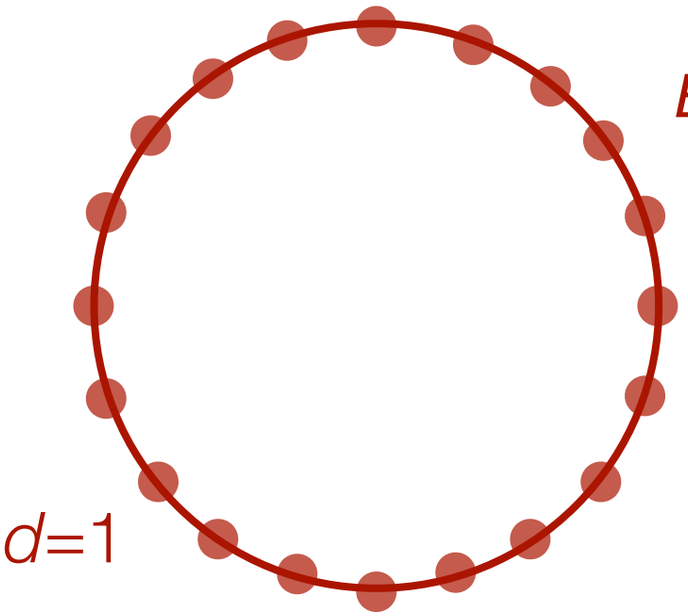


How can we visualize complex quantum states?

Holographic Duality

Quantum many-body system,
d spatial dimensions



Spacetime geometry (gravity),
d+1 spatial dimensions

Entanglement of boundary
encoded in
geometry of bulk

Figure adapted from Ramallo, *arXiv*:1310.4319v3[hep-th].

Holographic Duality

Quantum many-body system,
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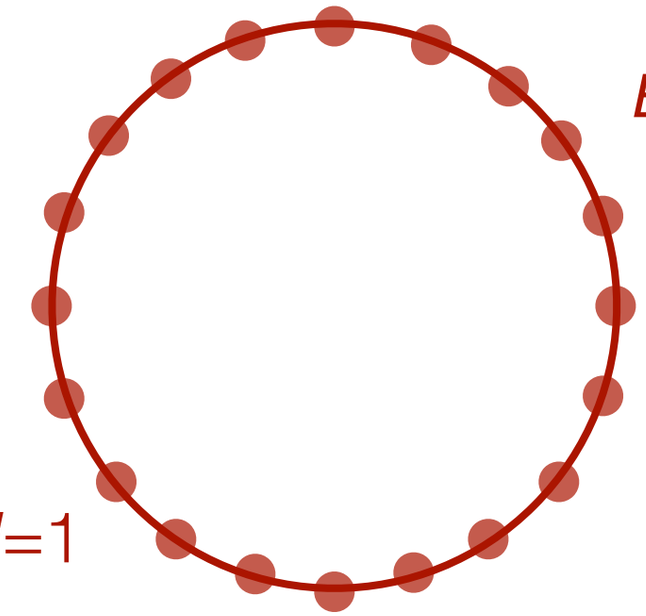

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- Can we probe the emergent geometry experimentally?
  …in simple model systems? …in cases where not *a priori* known?

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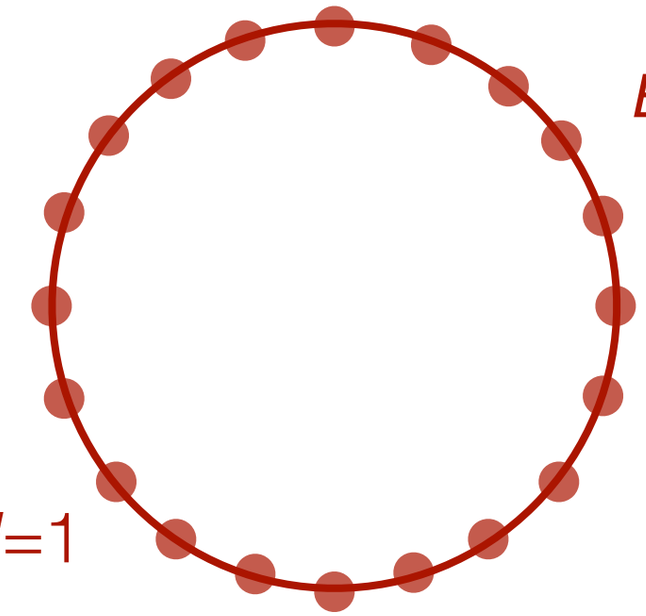

Entanglement of boundary
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Spacetime geometry (gravity),
d+1 spatial dimensions

- 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?

Figure adapted from Ramallo, *arXiv*:1310.4319v3[hep-th].

Quantum Information Scrambling

How fast can an initially localized quantum bit become entangled with all degrees of freedom, i.e., scrambled?

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

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Inspiration: information problem in black holes

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Quantum Information Scrambling

How fast can an initially localized quantum bit become entangled with all degrees of freedom, i.e., scrambled?

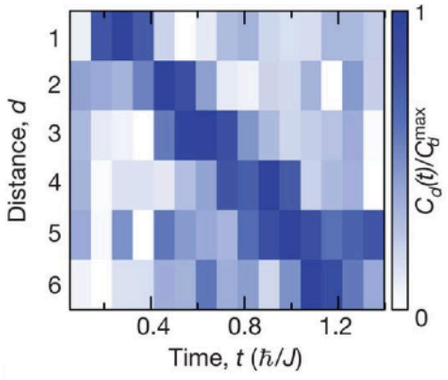
Inspiration: information problem in black holes

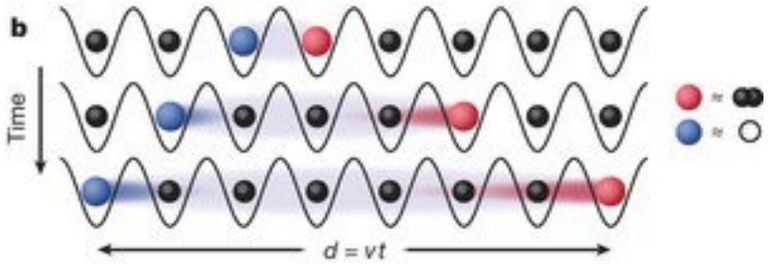
Resolution: black hole as a quantum system where information spreads exponentially fast across all degrees of freedom

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

Challenge: Light Cone

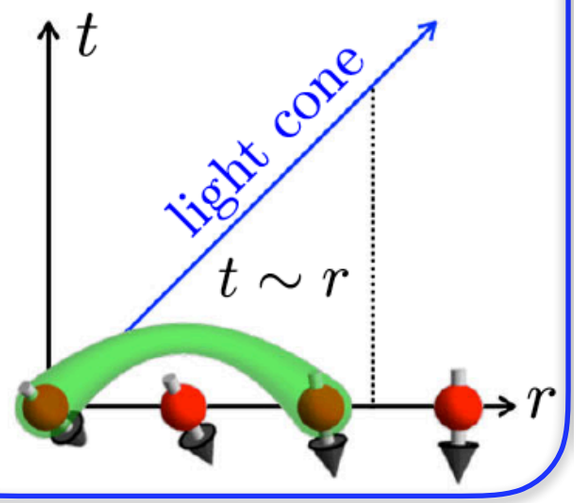
…limits propagation of information





Cheneau, … & Kuhr, *Nature* (2012).

Short-range interaction



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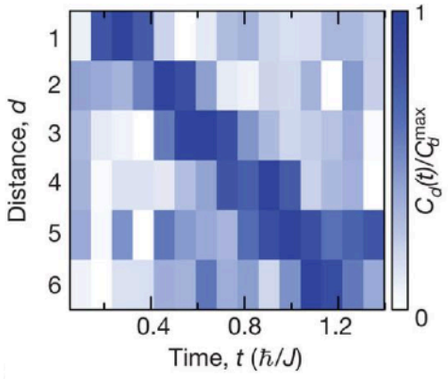

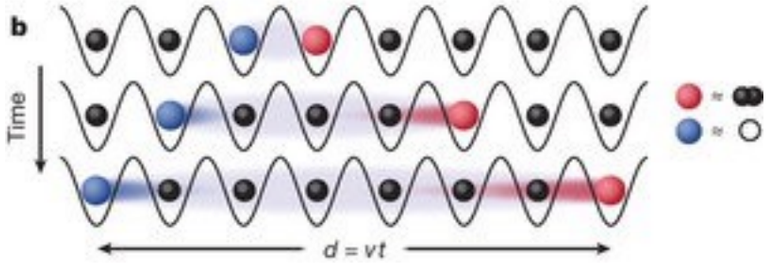

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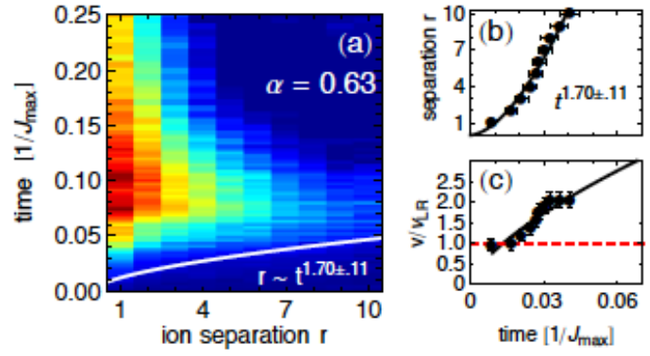

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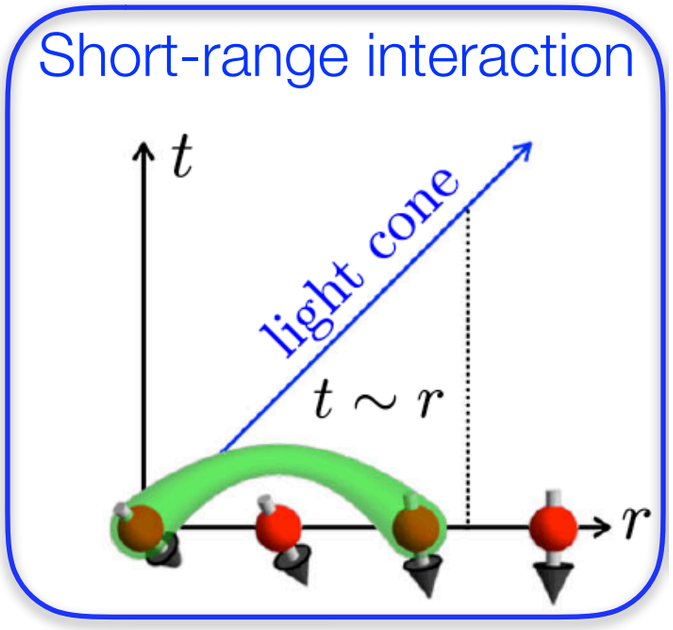

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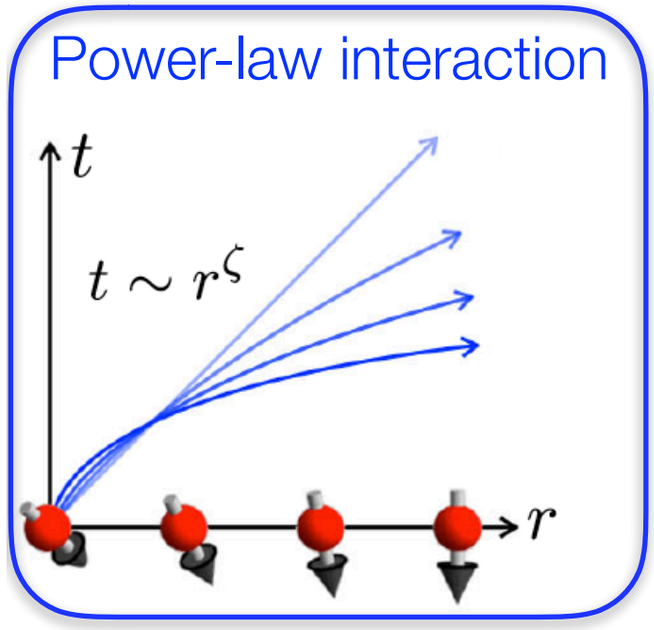

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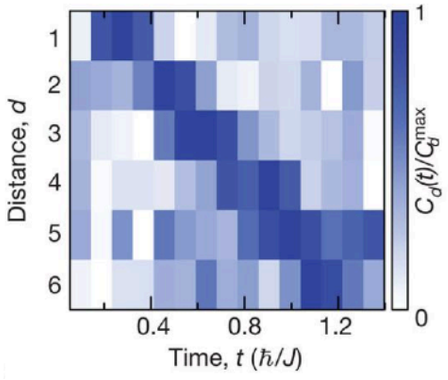

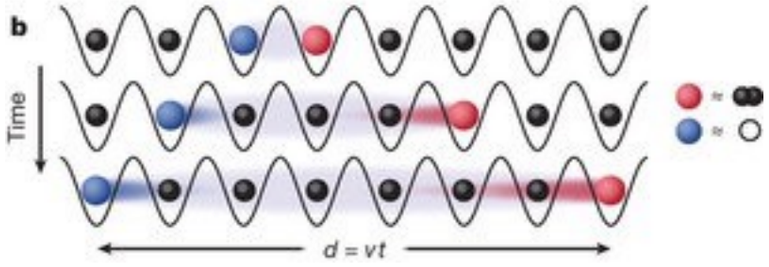

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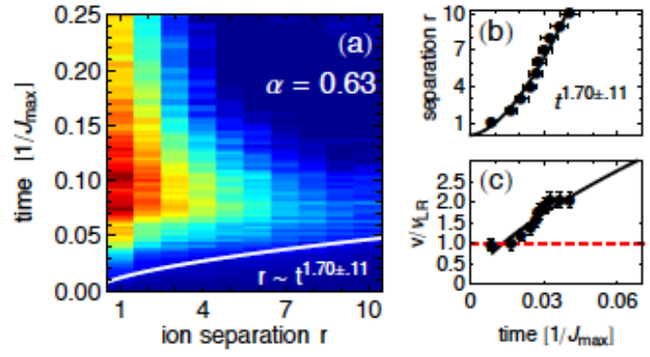

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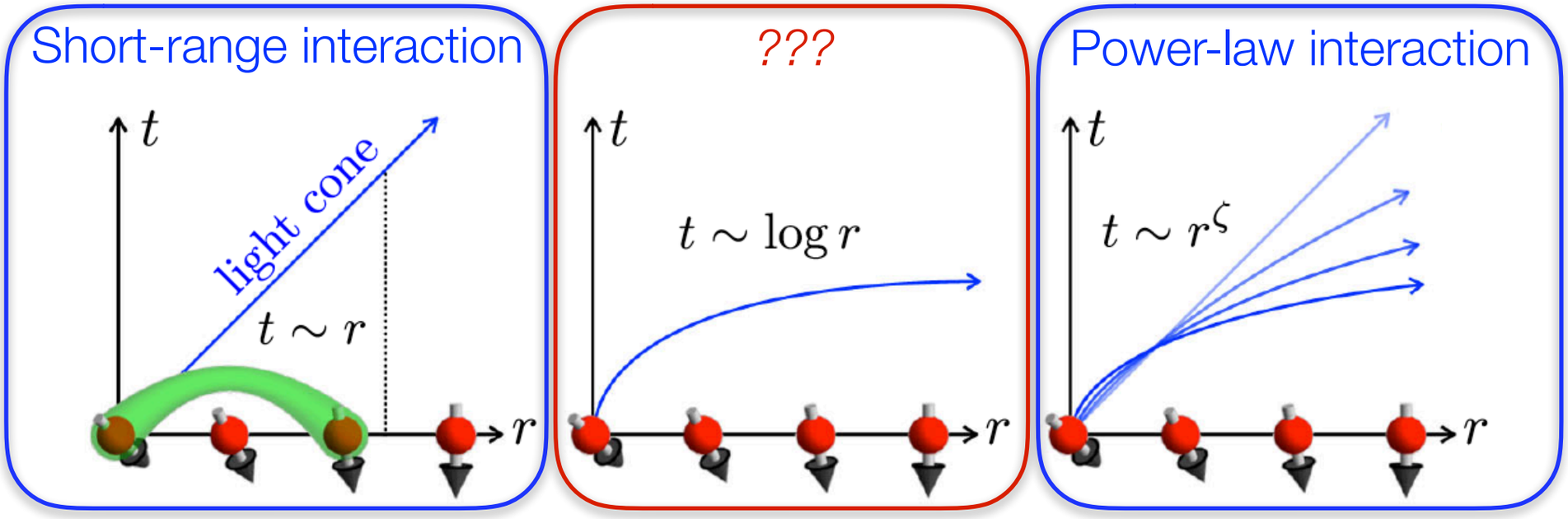

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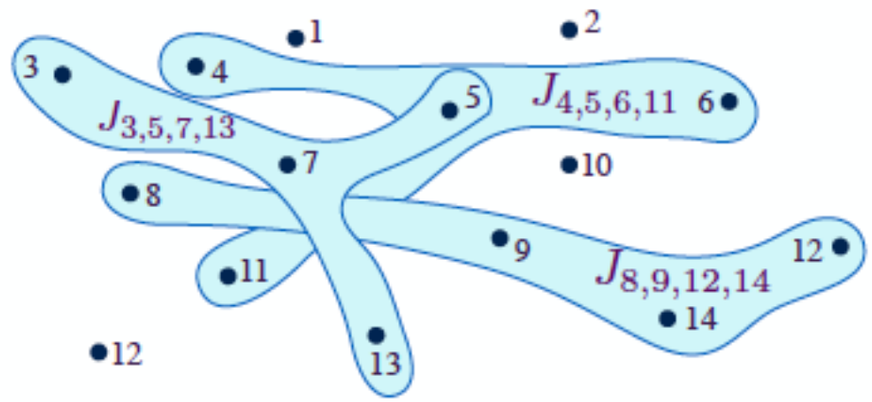
Non-Local Hopping

Fermions

with non-local hopping

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



Black-hole duality:

S. Sachdev, *PRX* (2015).

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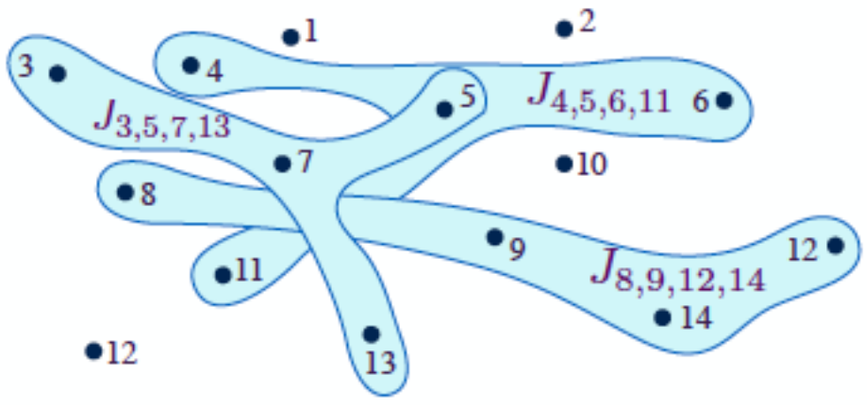

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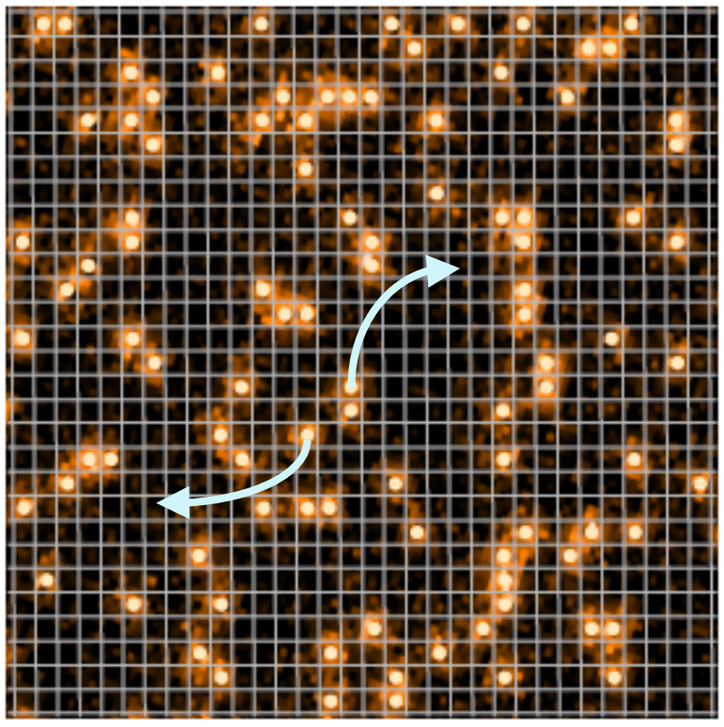
Implementation??



Fermionic atoms in optical lattice?
Image: Cheuk, …, & Zwierlein, *PRL* (2015).

Challenge: atoms only hop to nearest-neighbor sites

But see: Danshita *et al., arXiv*:1606.02454.

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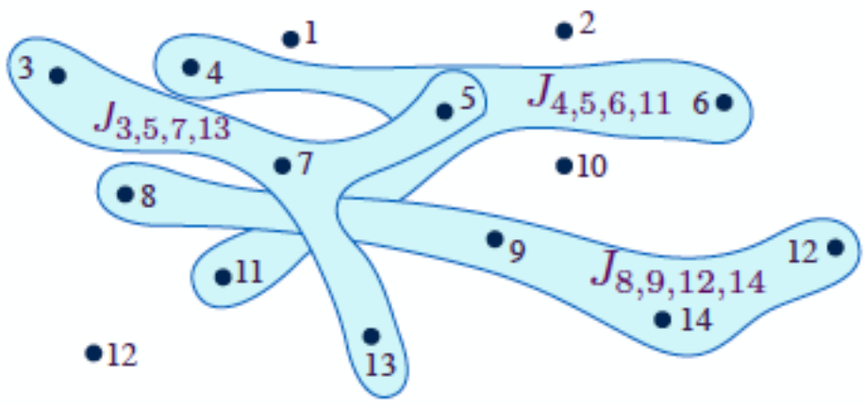

● = ⬆

○ = ⇩

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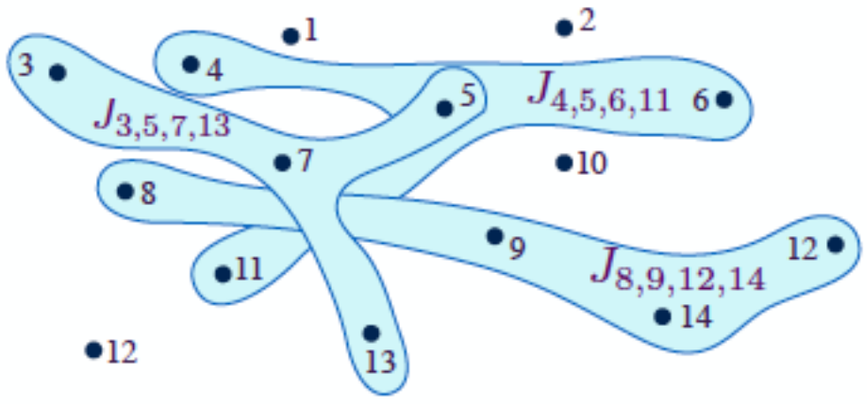

Black-hole duality:

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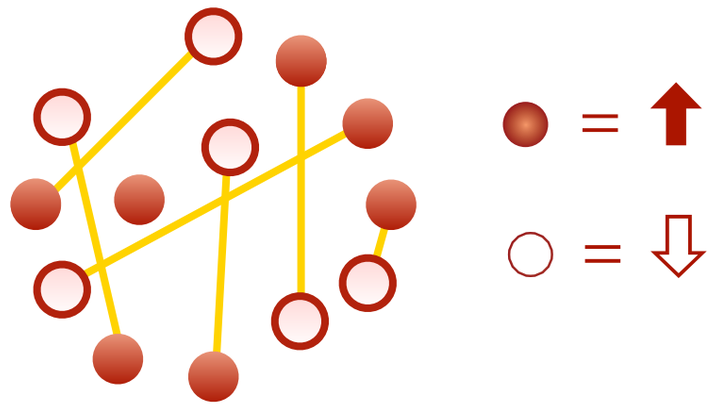
Spin excitations
with non-local hopping

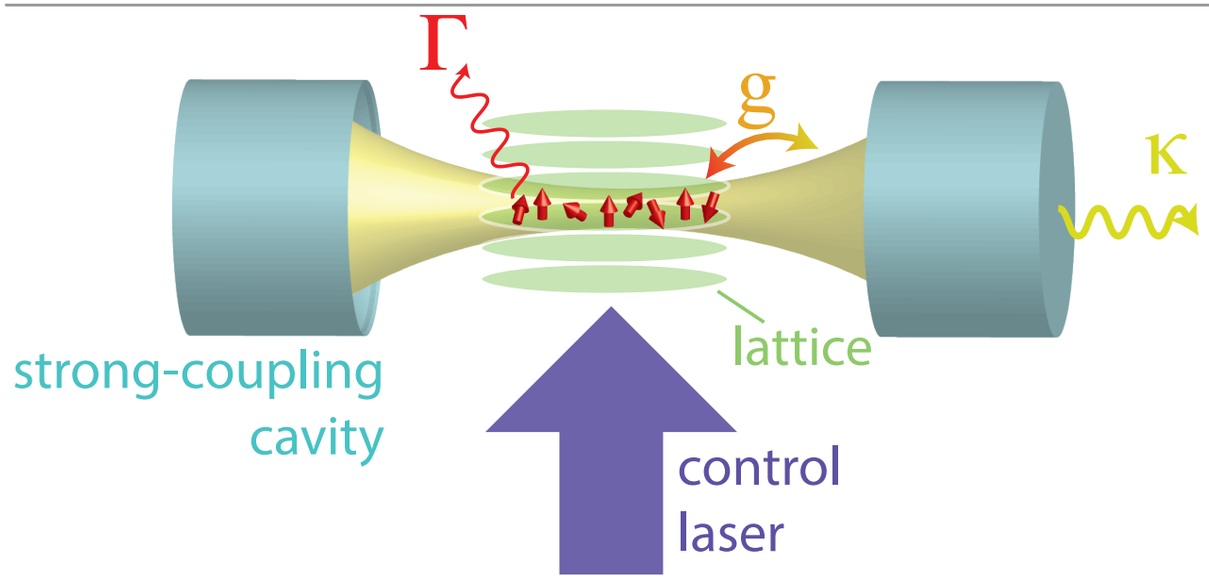
$$H \propto \sum_{i,j} J_{ij} \sigma_+^i \sigma_-^j$$

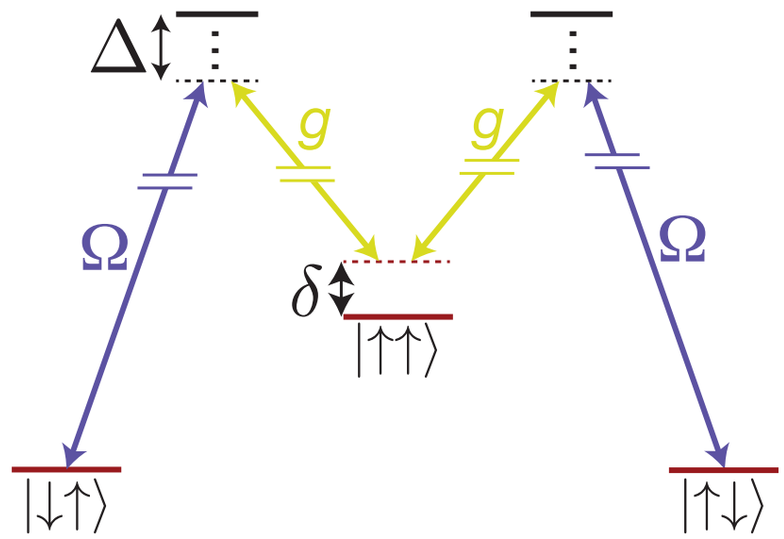


Natural approach:

spin excitations = bosons,
hopping mediated by light

Photon-Mediated “Hopping”





$$H = \sum_{i,j} J_{ij} \sigma_i^+ \sigma_j^-$$

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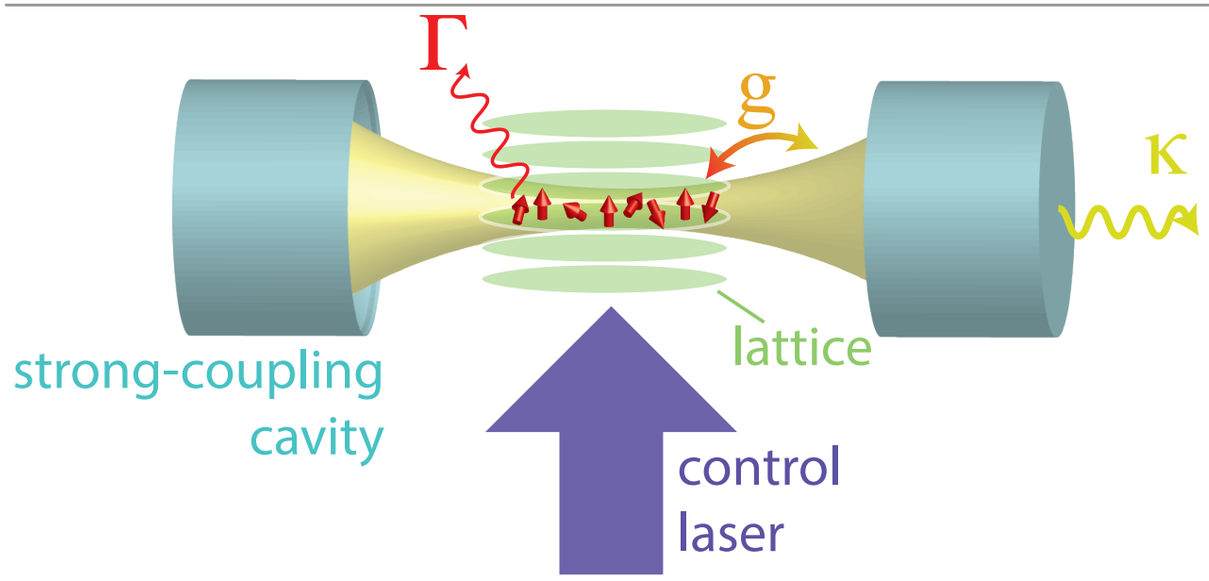

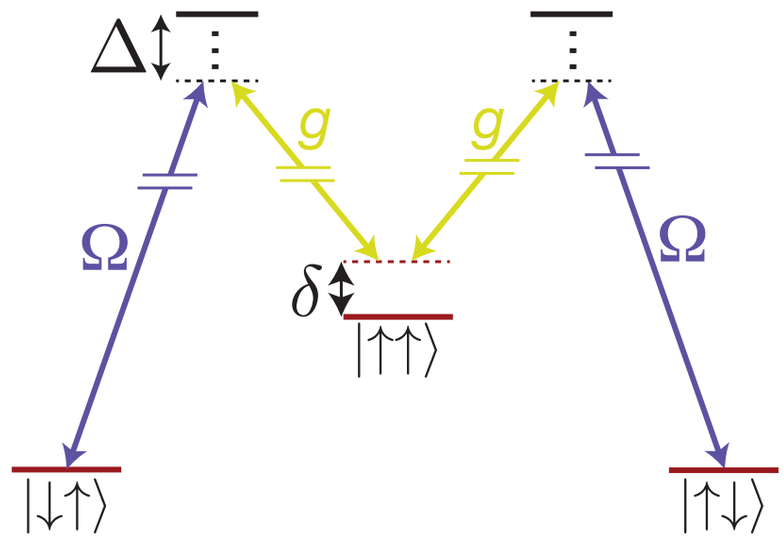

Pairwise correlated spin flips: $H = \sum_{i,j} J_{ij} \sigma_i^+ \sigma_j^-$

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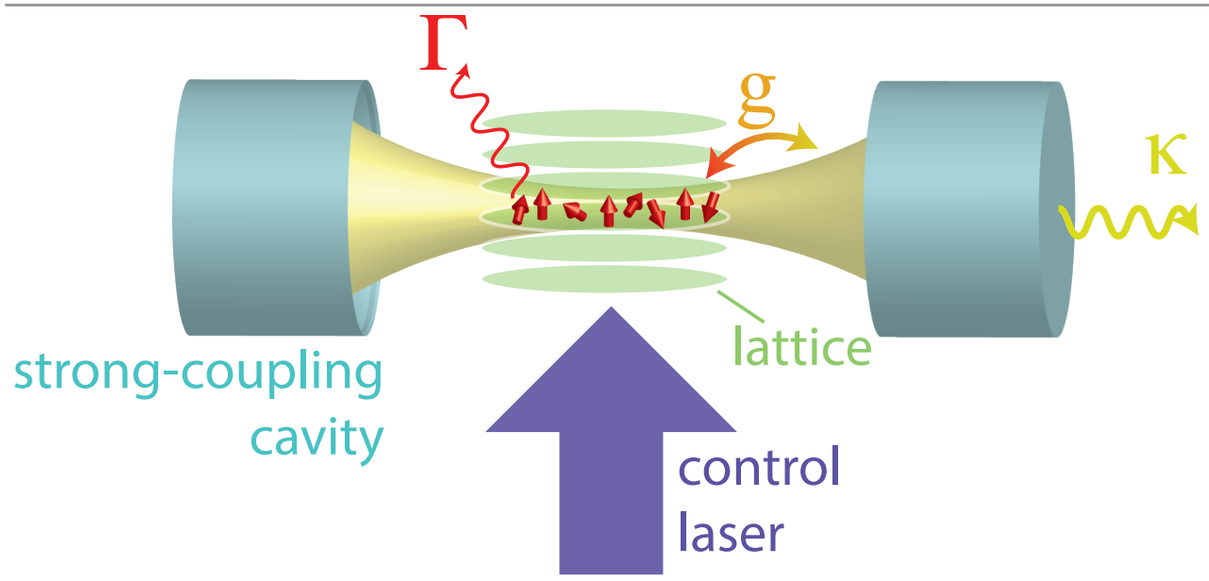

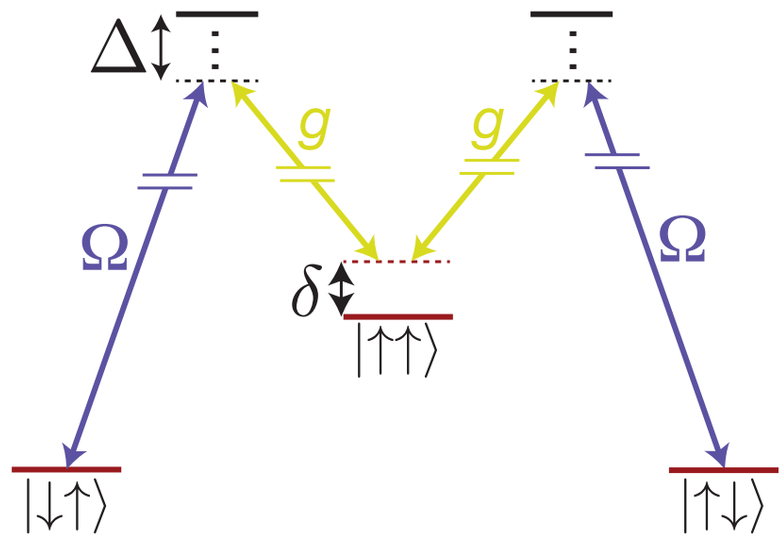

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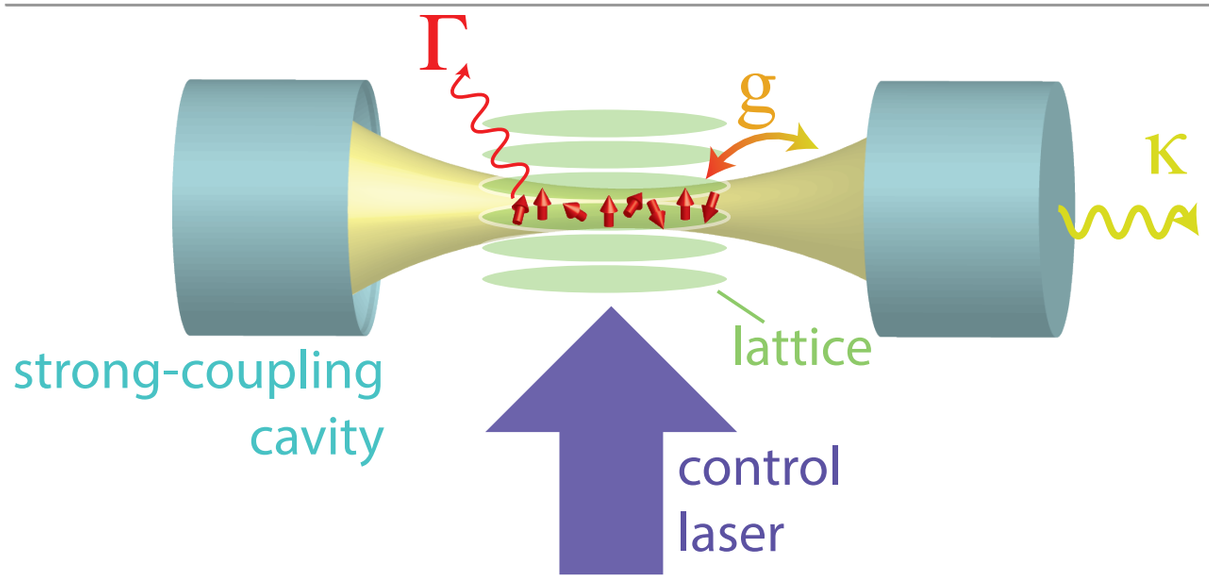
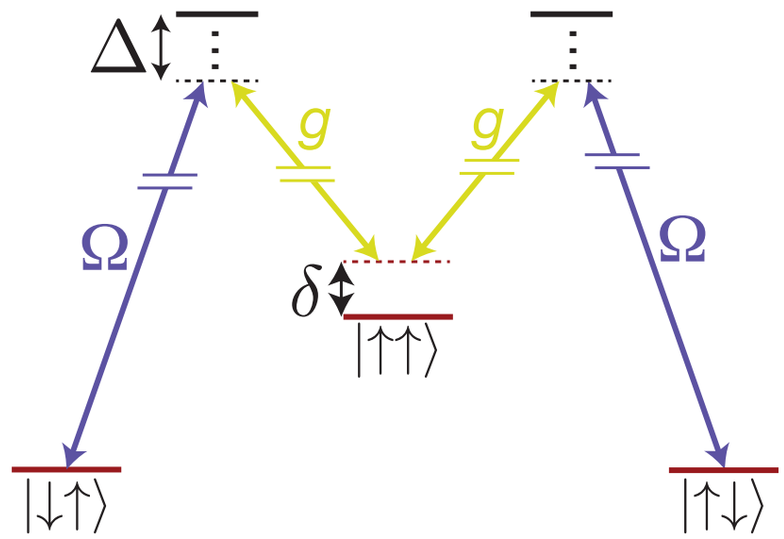
- Sign of interaction (ferro/antiferromagnetic) controlled by detuning **δ**

Photon-Mediated “Hopping”

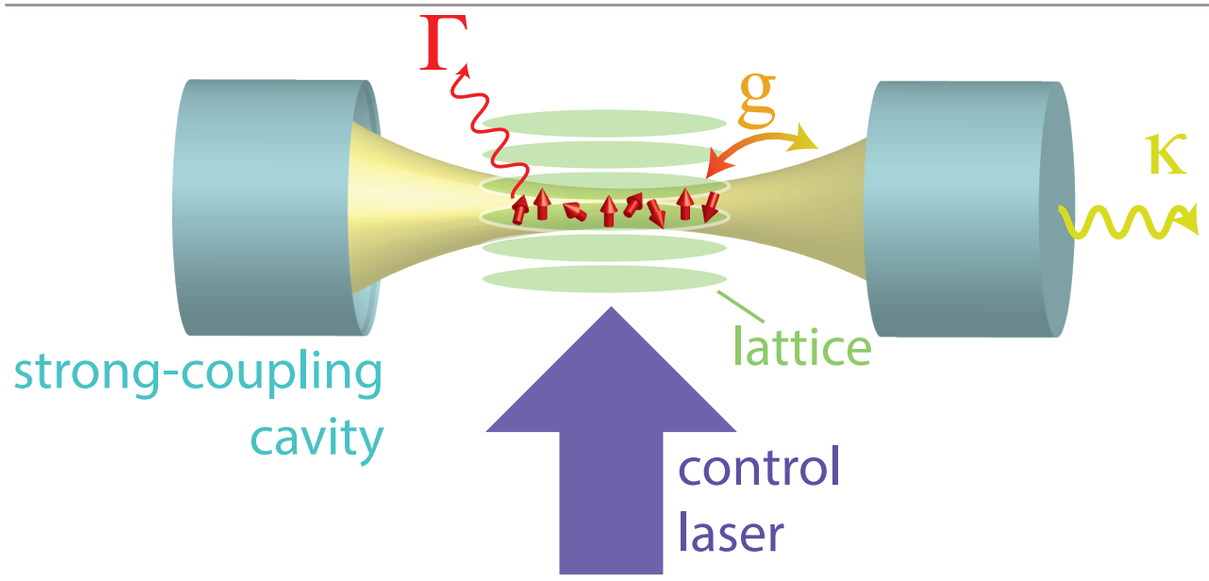


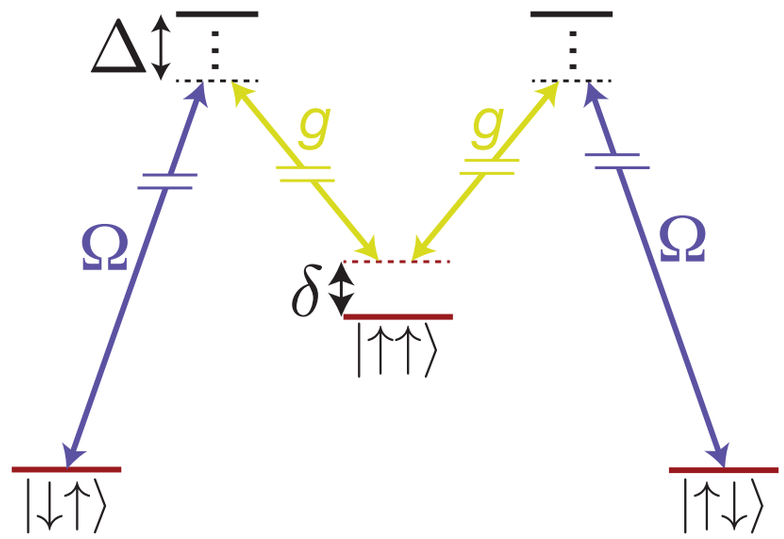


Pairwise correlated spin flips: $H = \sum_{i,j} J_{ij} \sigma_i^+ \sigma_j^-$

- Sign of interaction (ferro/antiferromagnetic) controlled by detuning **δ**
- Optical control of couplings J_{ij}

Photon-Mediated “Hopping”

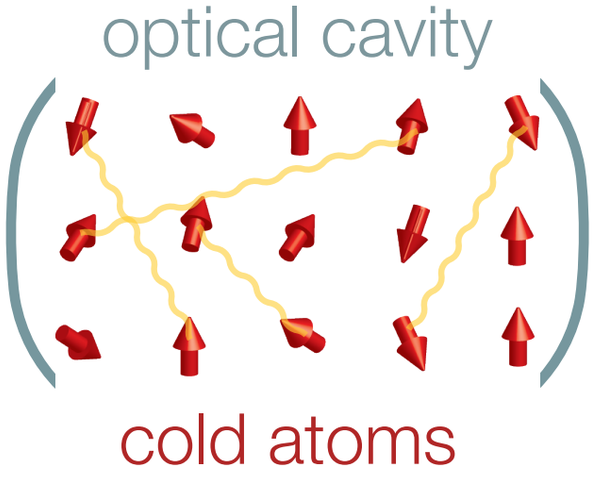




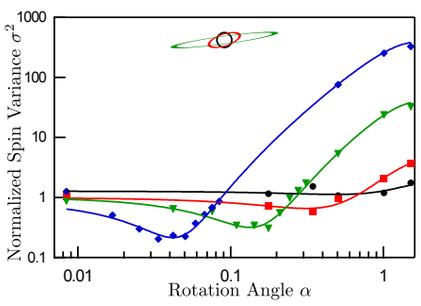
Pairwise correlated spin flips: $H = \sum_{i,j} J_{ij} \sigma_i^+ \sigma_j^-$

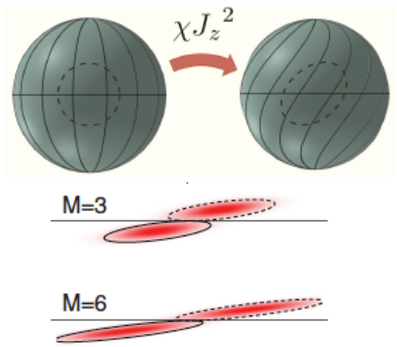
- Sign of interaction (ferro/antiferromagnetic) controlled by detuning **δ**
- Optical control of couplings J_{ij}
- Coherent interactions for **δ≫κ** and strong coupling $\eta \equiv 4g^2/(\kappa\Gamma) \gg 1$

Photon-Mediated Interactions



Entanglement for metrology

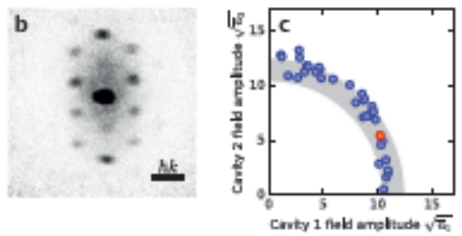




Leroux, MS-S & Vuletic, *PRL* (2010).
Hosten, … & Kasevich, *Science* (2016).
Norcia, …, Rey & Thompson, *Science* (2018).

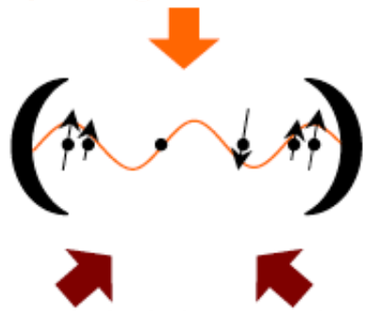
Quantum simulations

supersolids



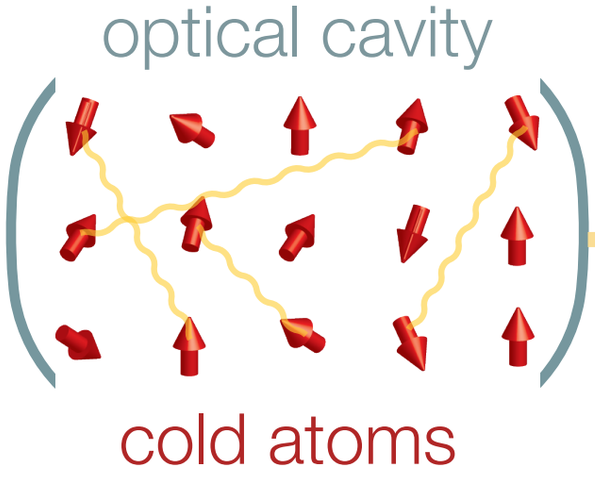
Léonard *et al.*
Nature (2017).

spin glasses?



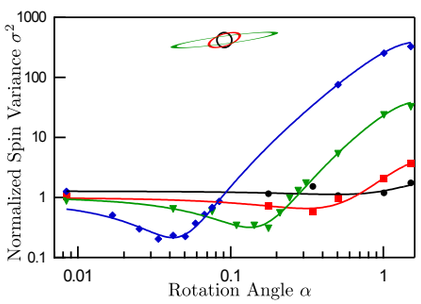
Gopalakrishnan, Lev;
Strack & Sachdev,
PRL (2011).

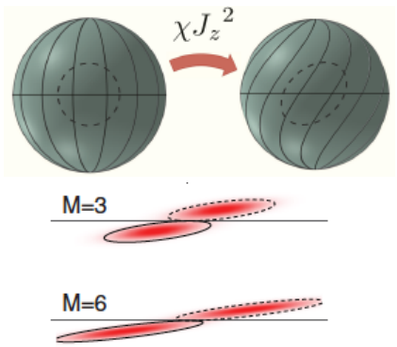
Photon-Mediated Interactions



Standard approach:
Measure collective observables via the outgoing light

Entanglement for metrology





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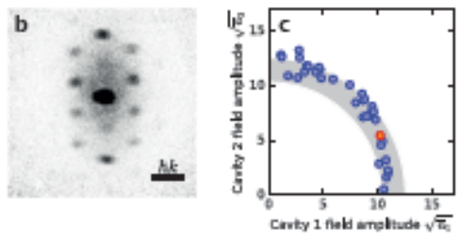
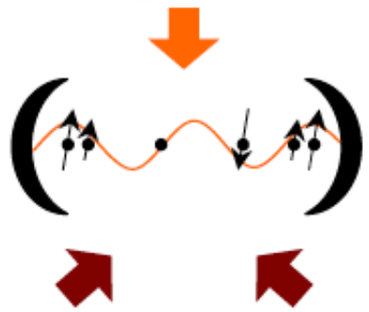


Léonard *et al.* *Nature* (2017).

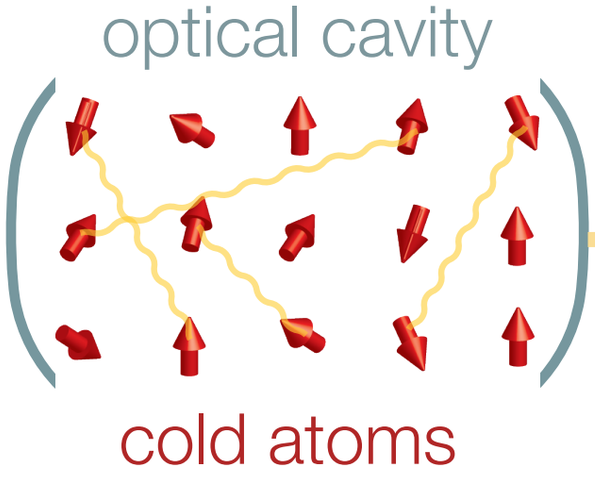
spin glasses?



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

Photon-Mediated Interactions

Our approach:
Real-space observation of spin dynamics



Standard approach:
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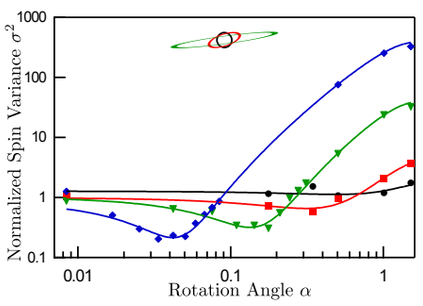
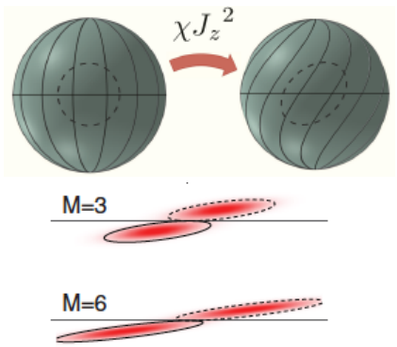
Entanglement for metrology





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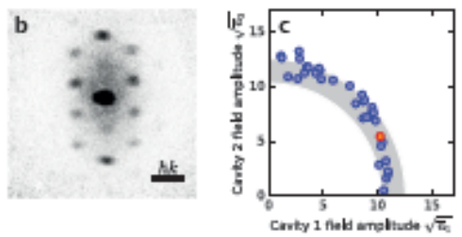
Quantum simulations

supersolids



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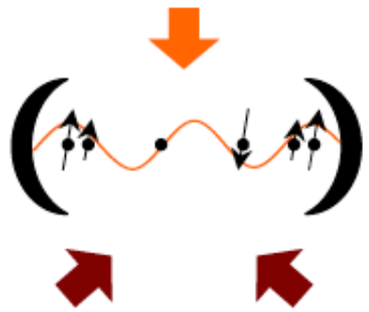

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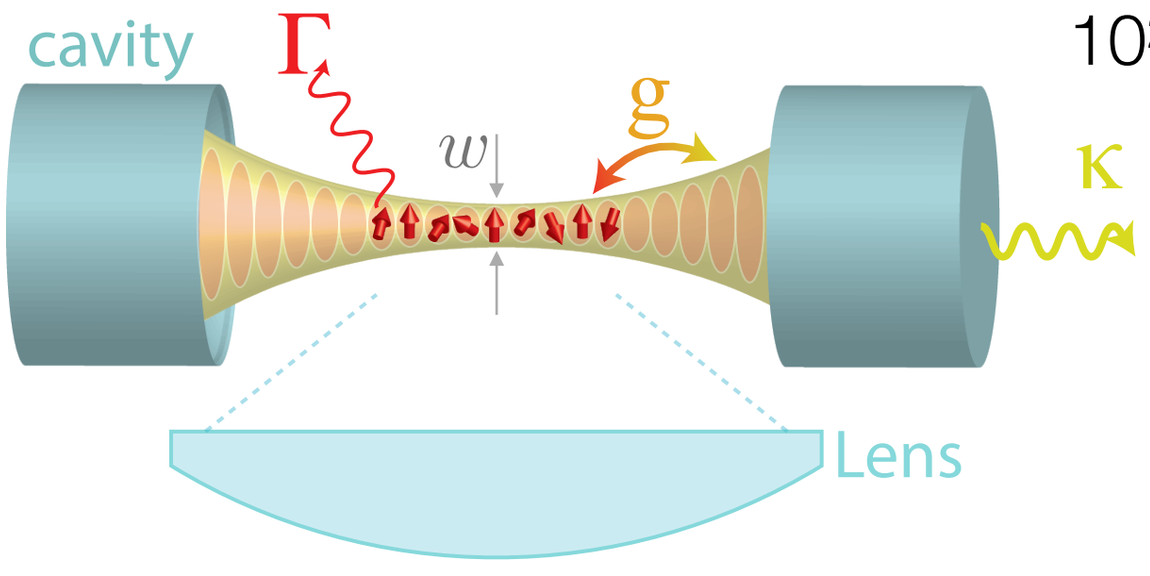
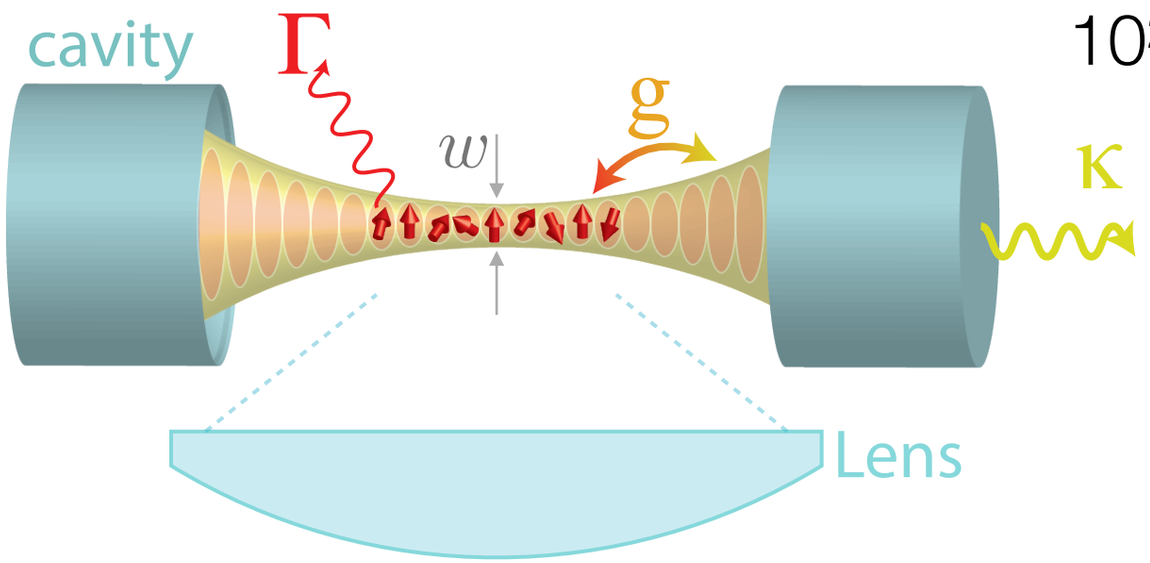
Experimental Setup



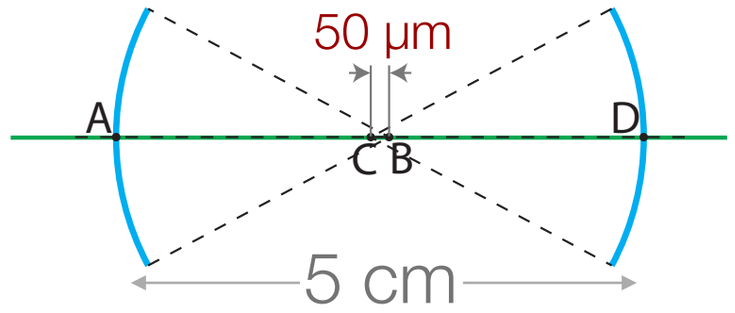
10^2 - 10^5 atoms

- Strong coupling: $\eta \equiv \frac{4g^2}{\kappa\Gamma} \sim \frac{F\lambda^2}{w^2} \gg 1$
- Optical access for imaging & addressing

Experimental Setup



10^2 - 10^5 atoms



- Strong coupling: $\eta \equiv \dfrac{4g^2}{\kappa\Gamma} \sim \dfrac{F\lambda^2}{w^2} \gg 1$
- Optical access for imaging & addressing

$\Rightarrow$ Near-concentric resonator

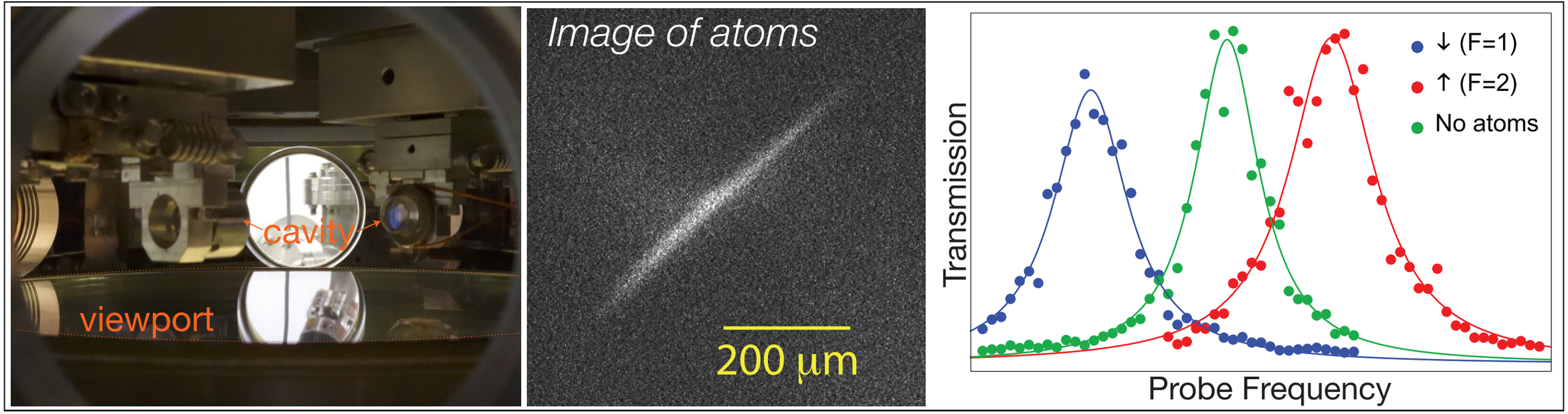
Waist w ~ 12 μm

Finesse F ~ 6 × 10^4

Non-degenerate modes

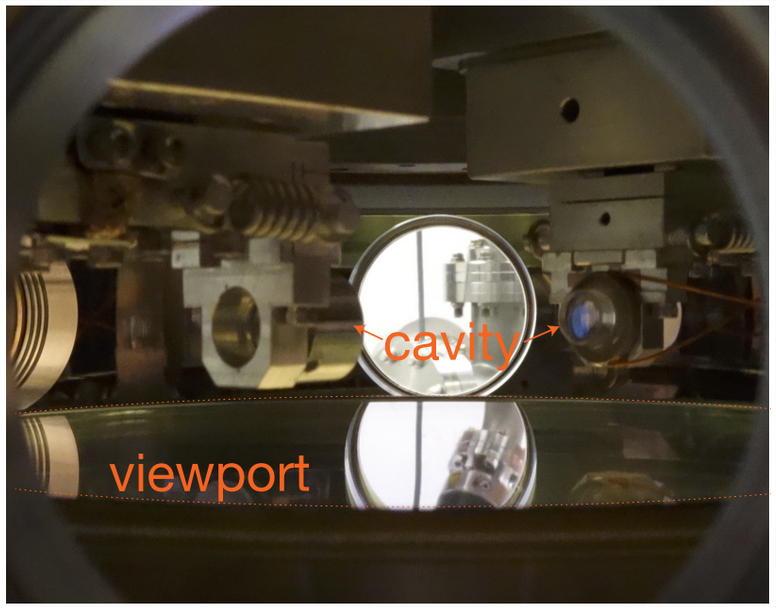
Interaction-to-decay ratio η_{max} ~ 50

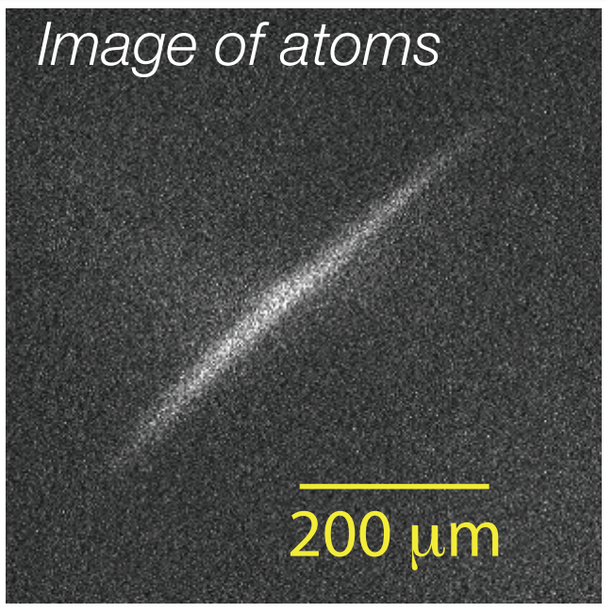
Experimental Toolbox

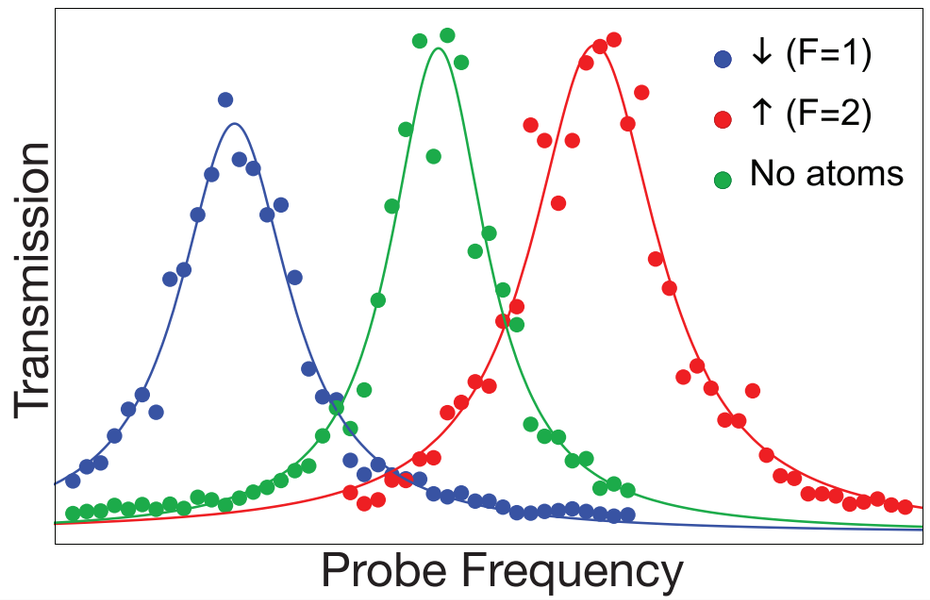


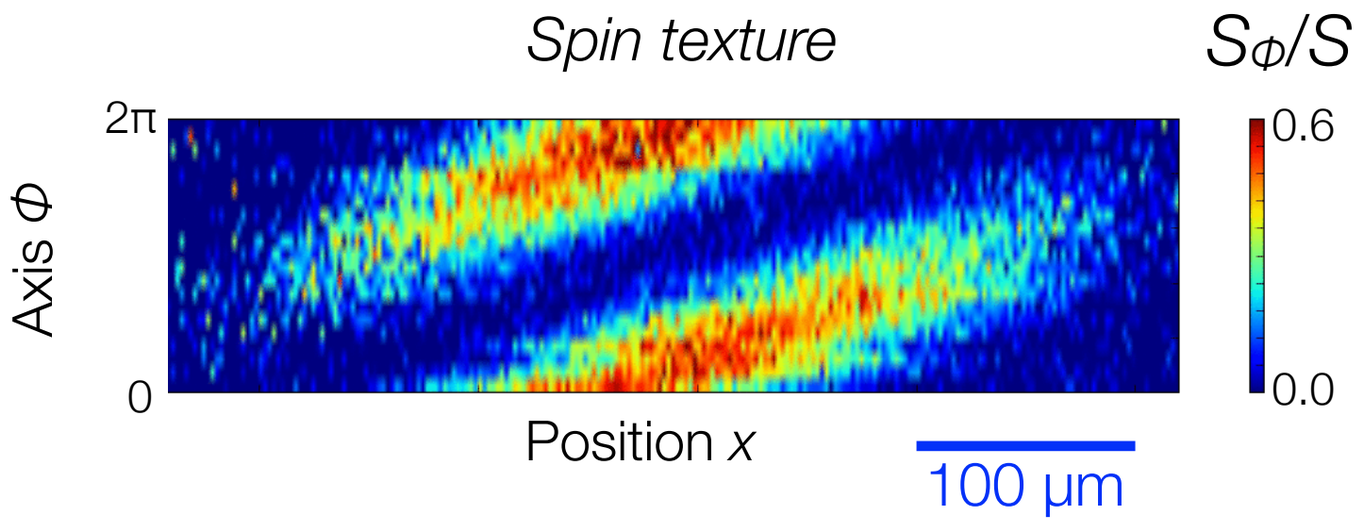
Spin-dependent shift of cavity resonance due to thousands of atoms

Experimental Toolbox



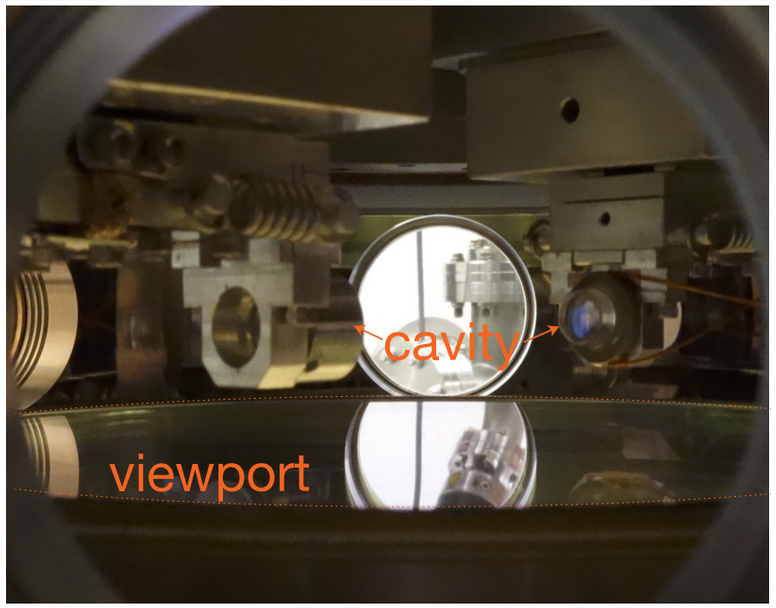


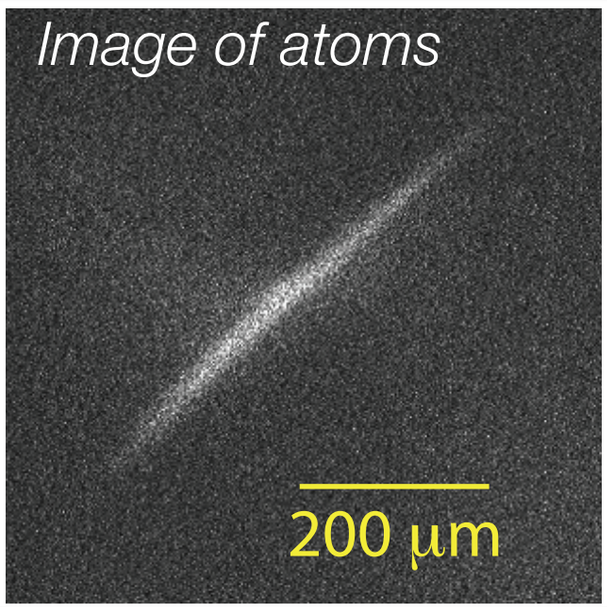


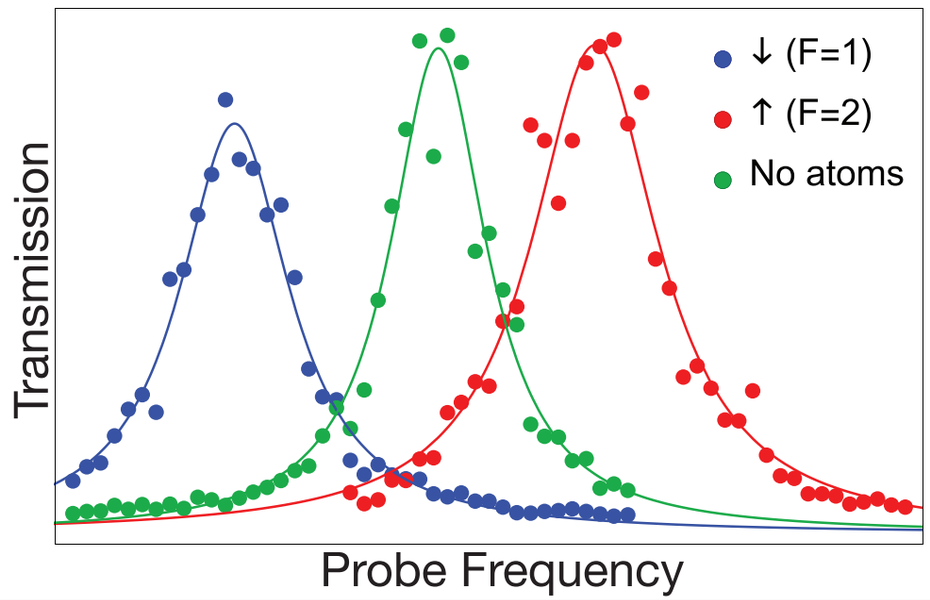


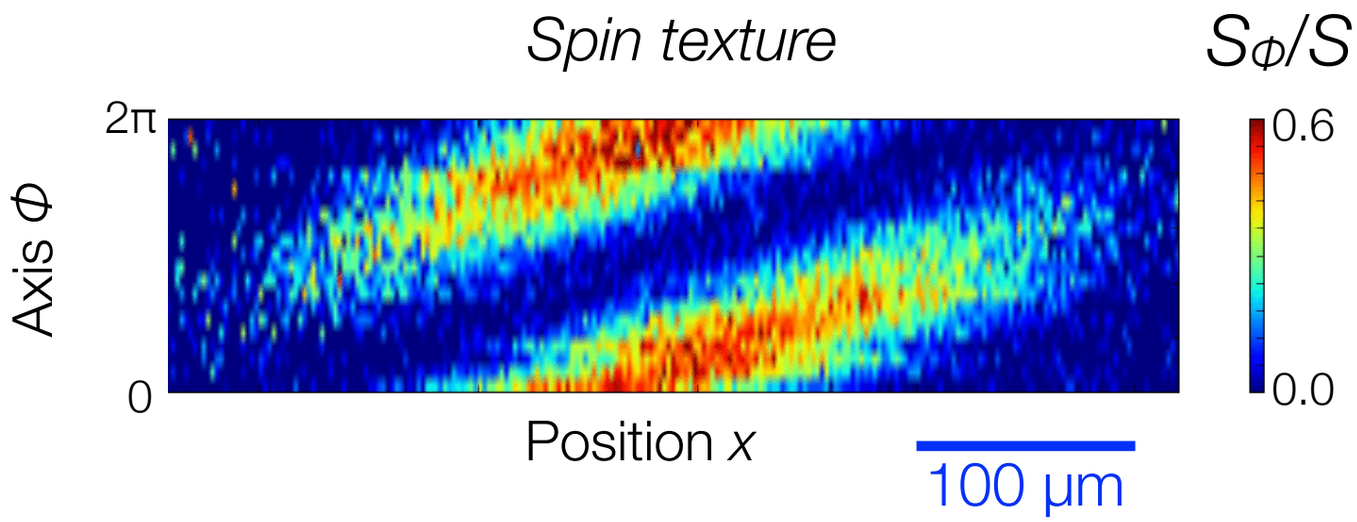
Imaging spin precession in magnetic field gradient

Experimental Toolbox







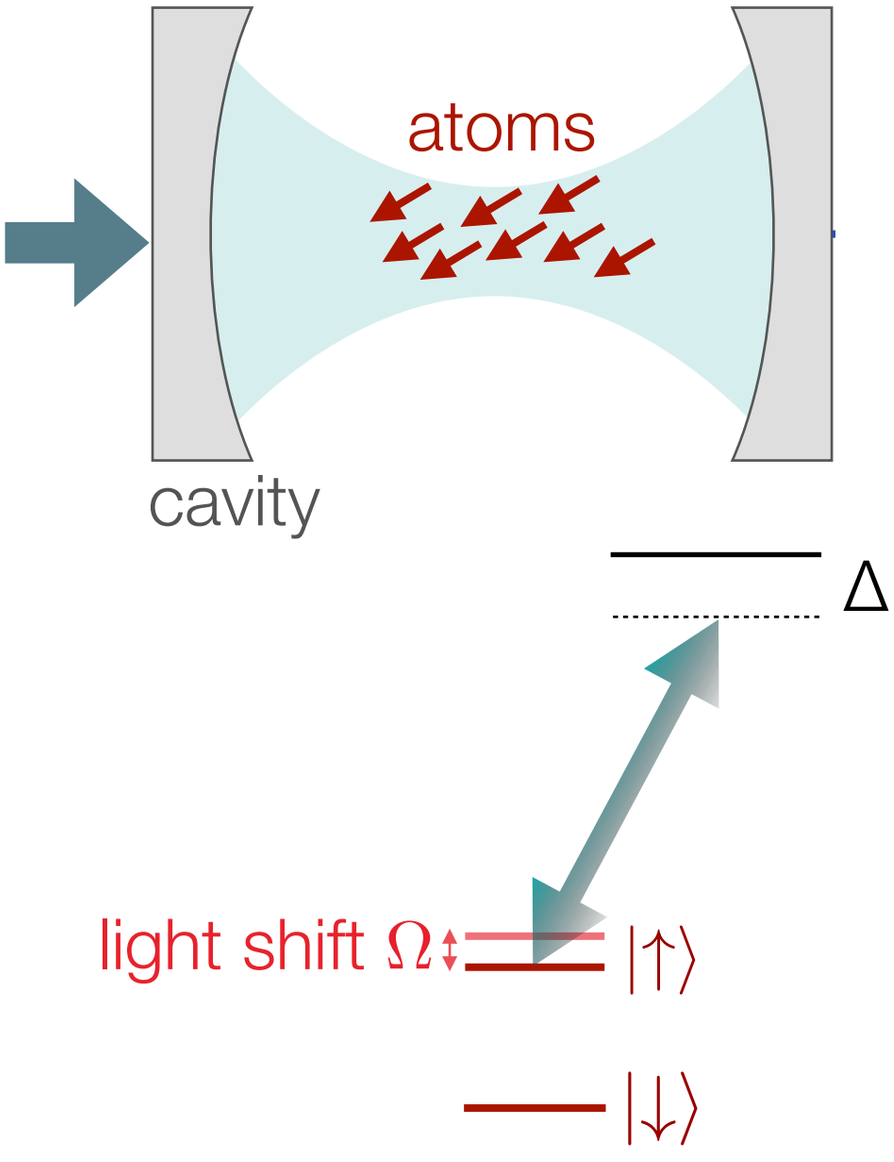


Imaging spin precession in magnetic field gradient

Imaging Atom-Light Interactions

Intracavity light

makes spins precess



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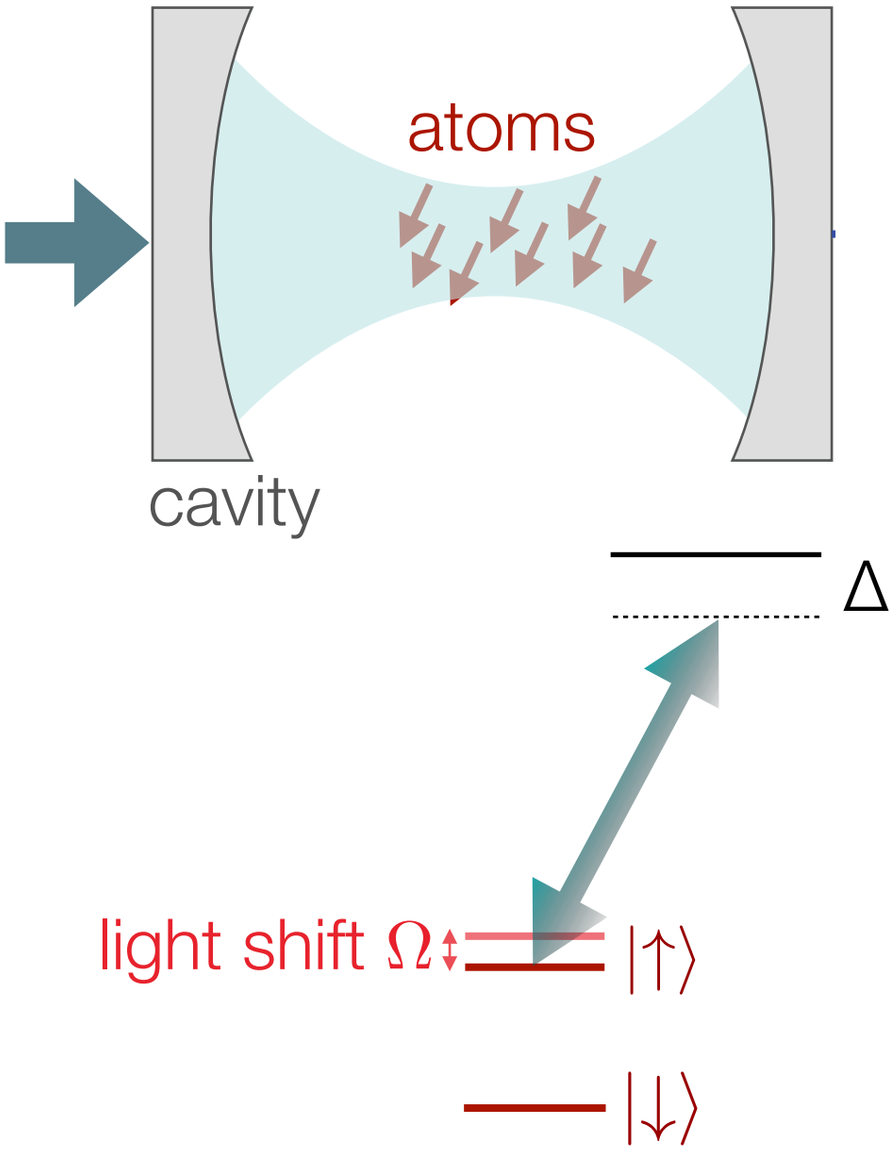
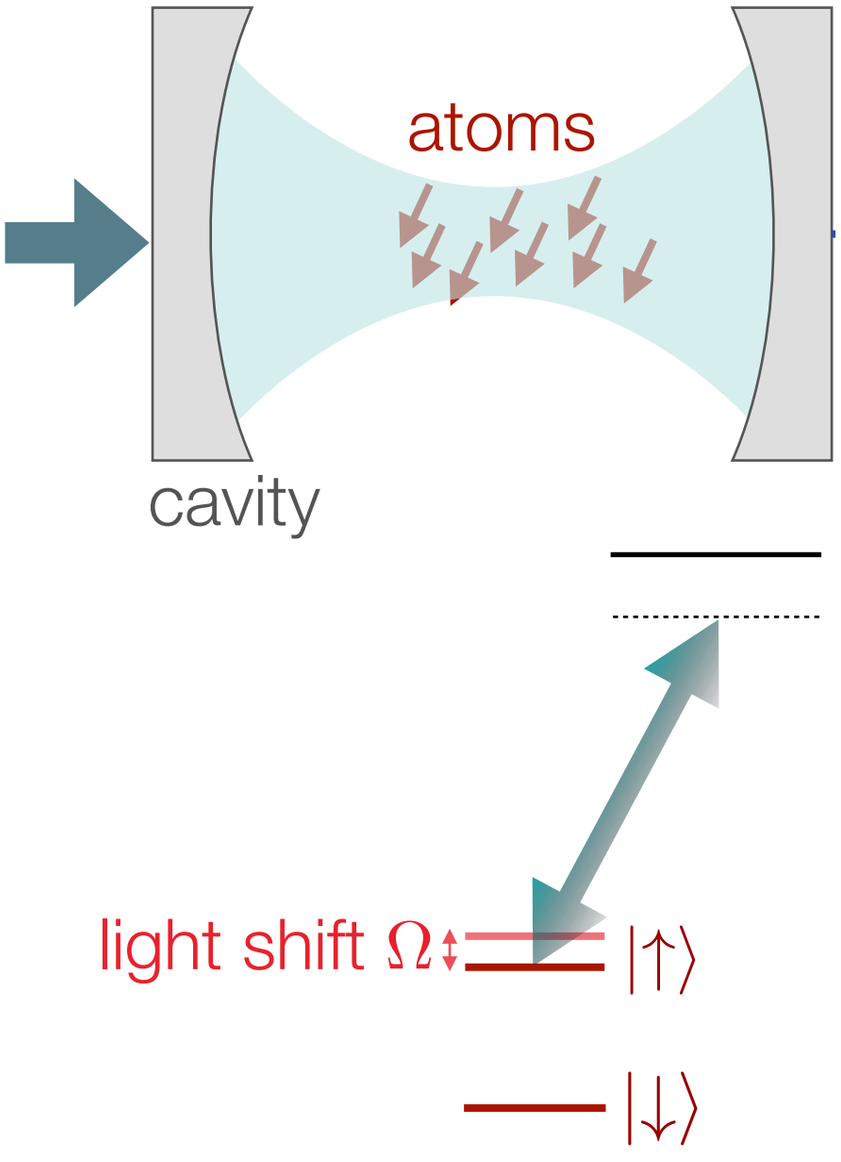


Turn on light for variable time
to measure precession rate

Imaging Atom-Light Interactions

Intracavity light
makes spins precess



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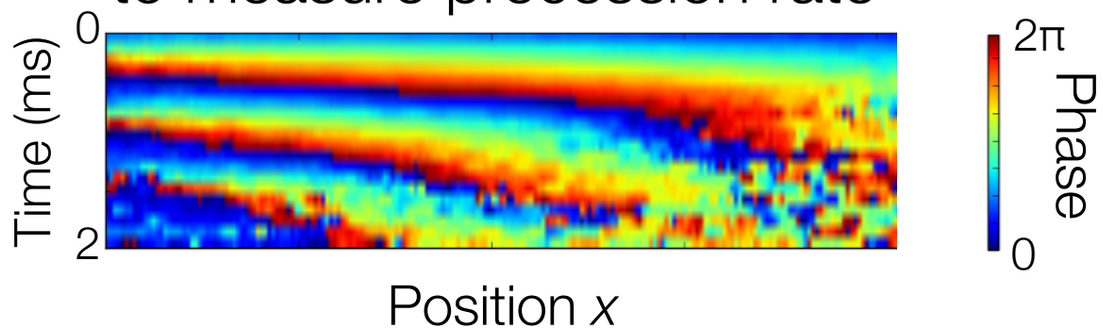

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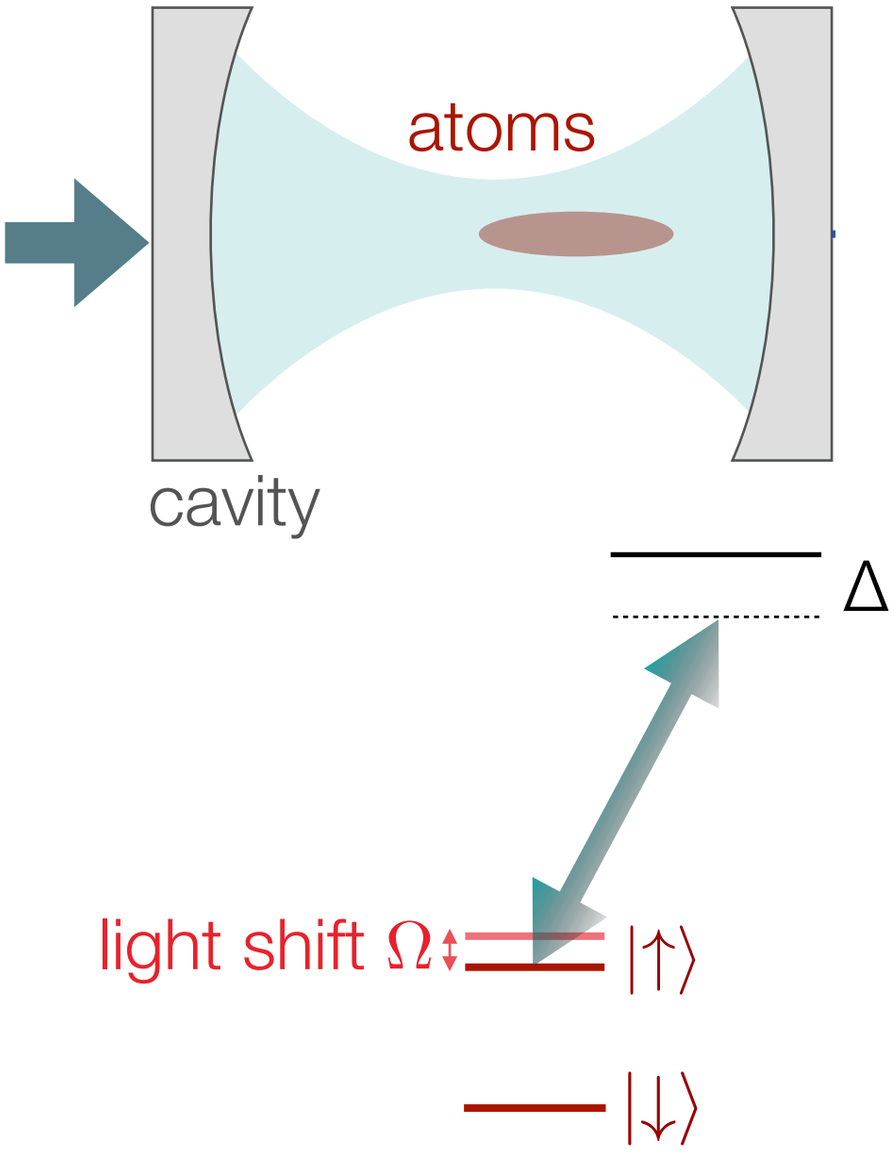

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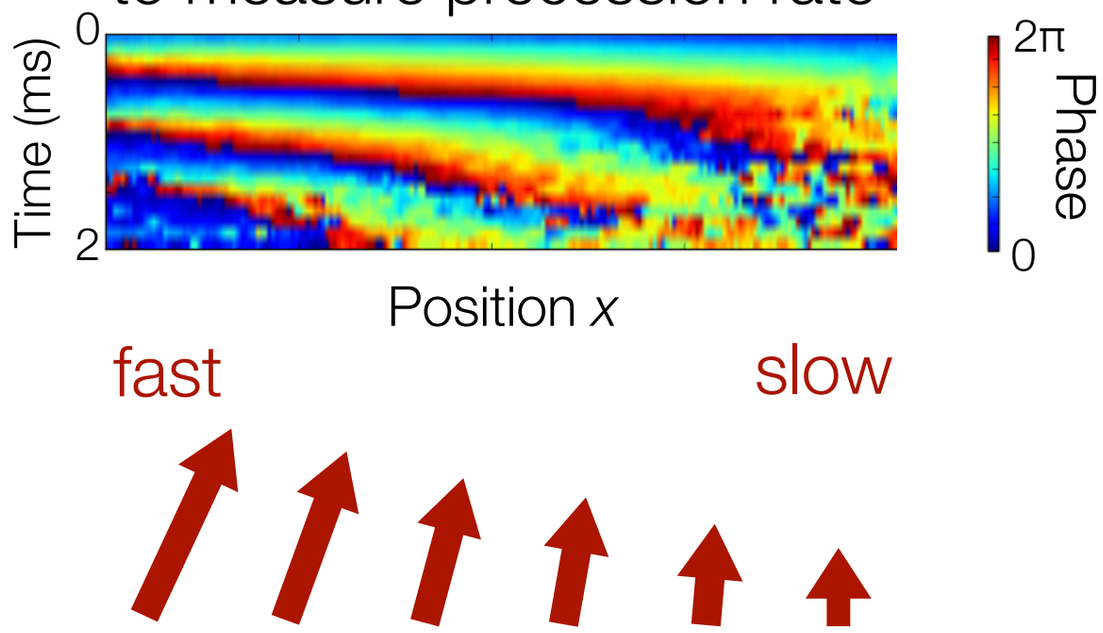
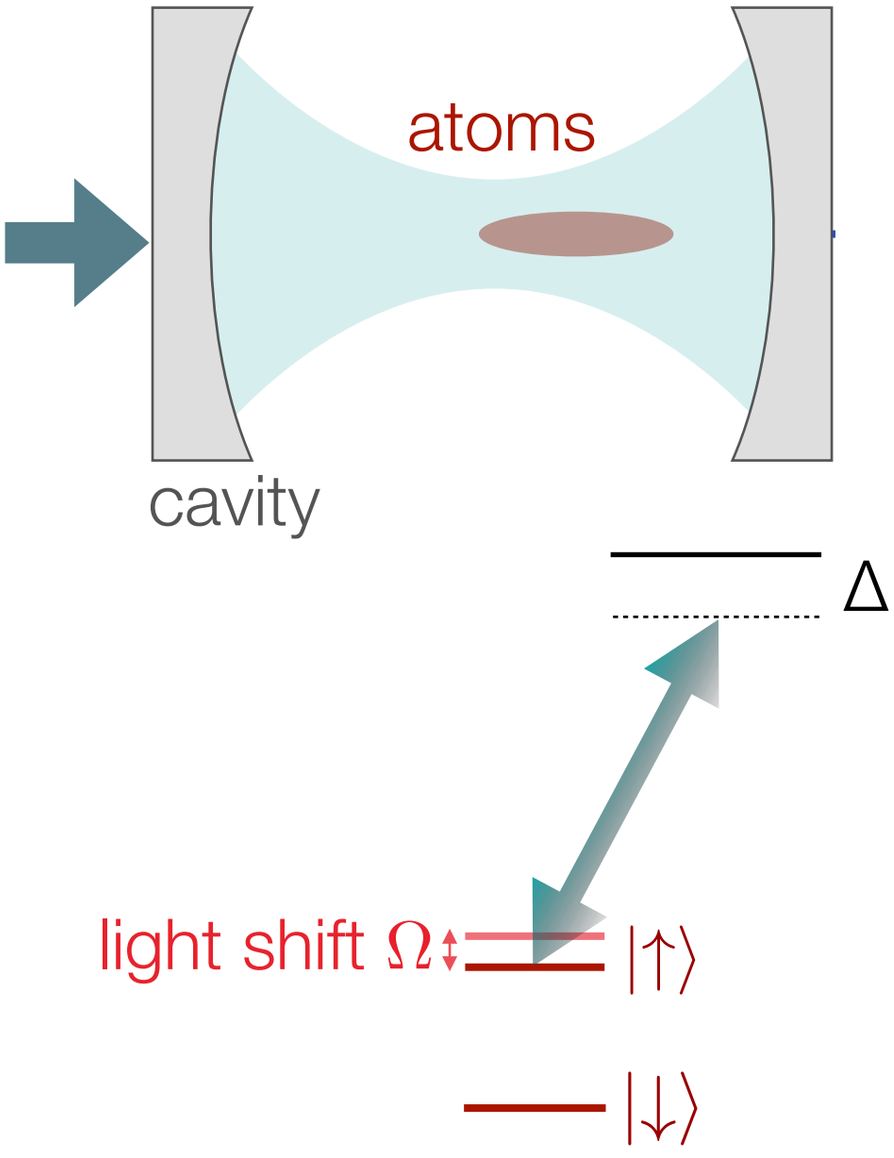


The light generically couples to a **weighted** sum of spins.

Imaging Atom-Light Interactions

Intracavity light
makes spins precess



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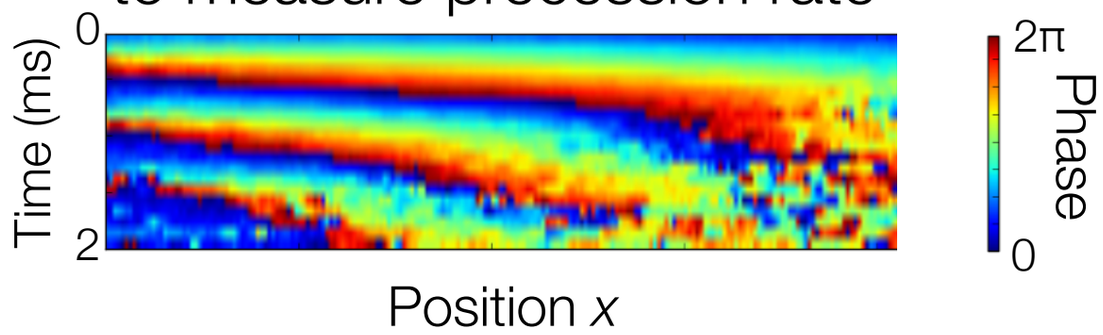
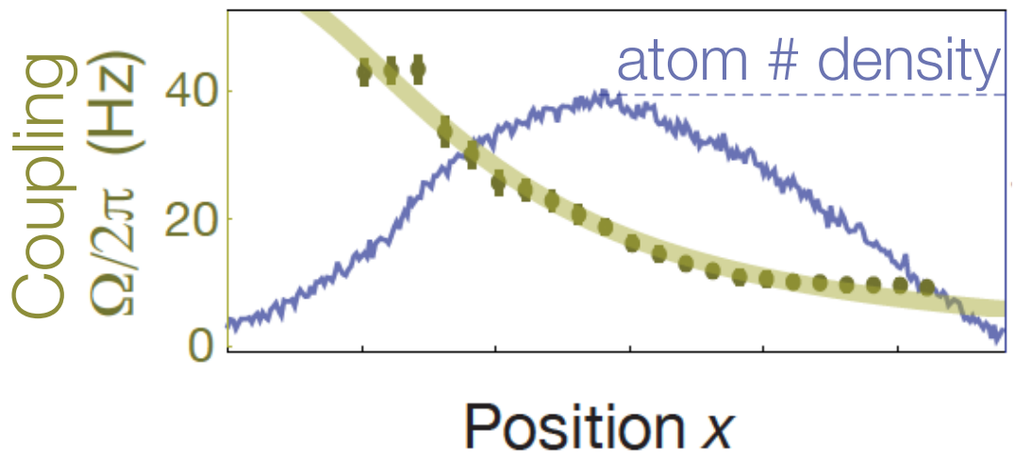
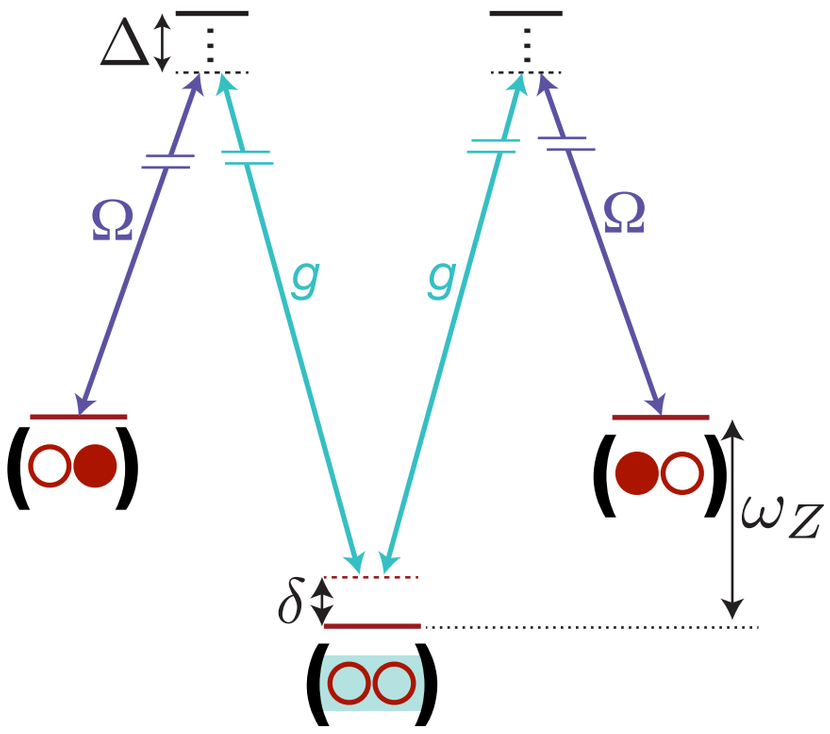
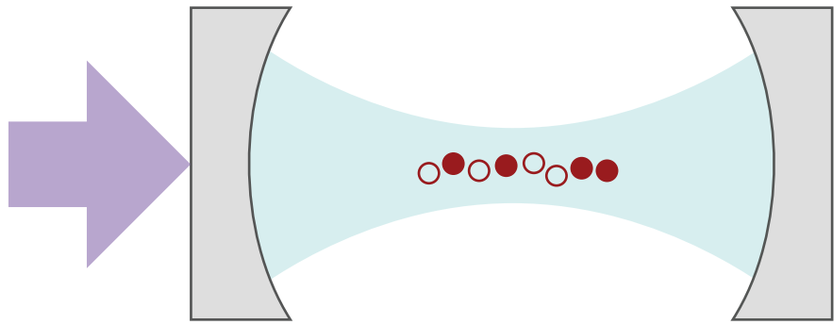




Non-Local Hopping: Implementation

Each atom as an “occupied” [● = ⬆] or “empty” [○ = ⇩] site





“Flip-Flop” interaction

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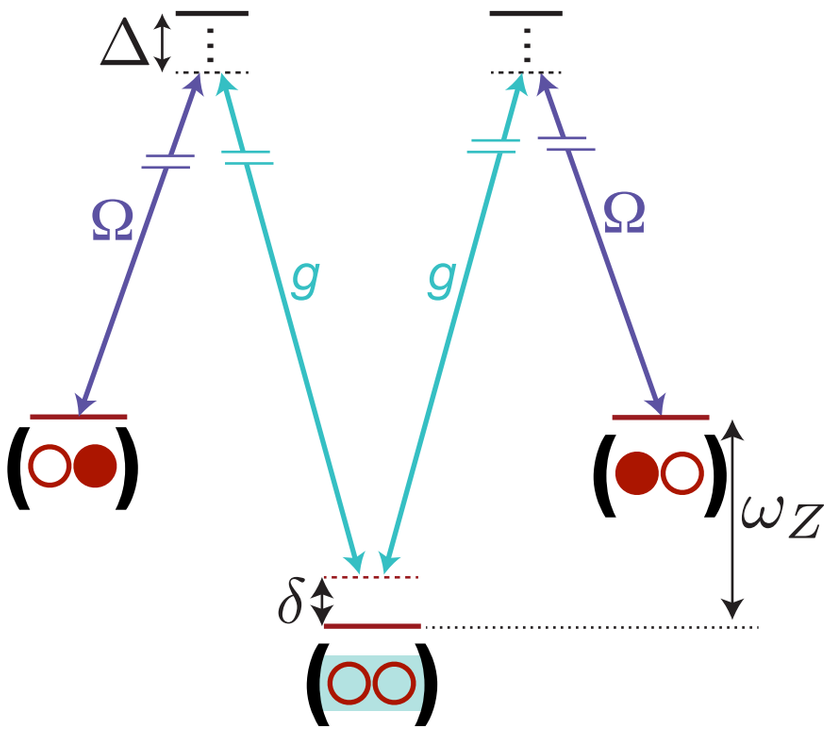

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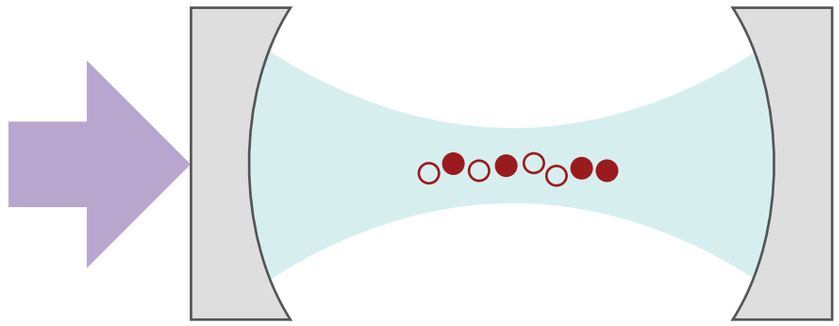

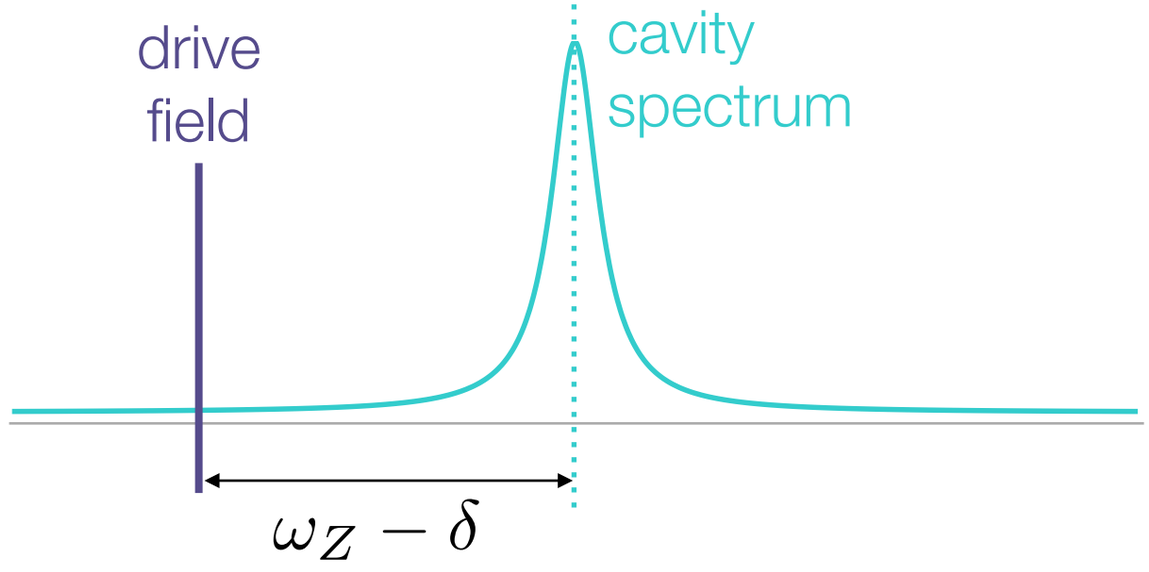

Experiment

Experiment

- Initialize all atoms in ground state

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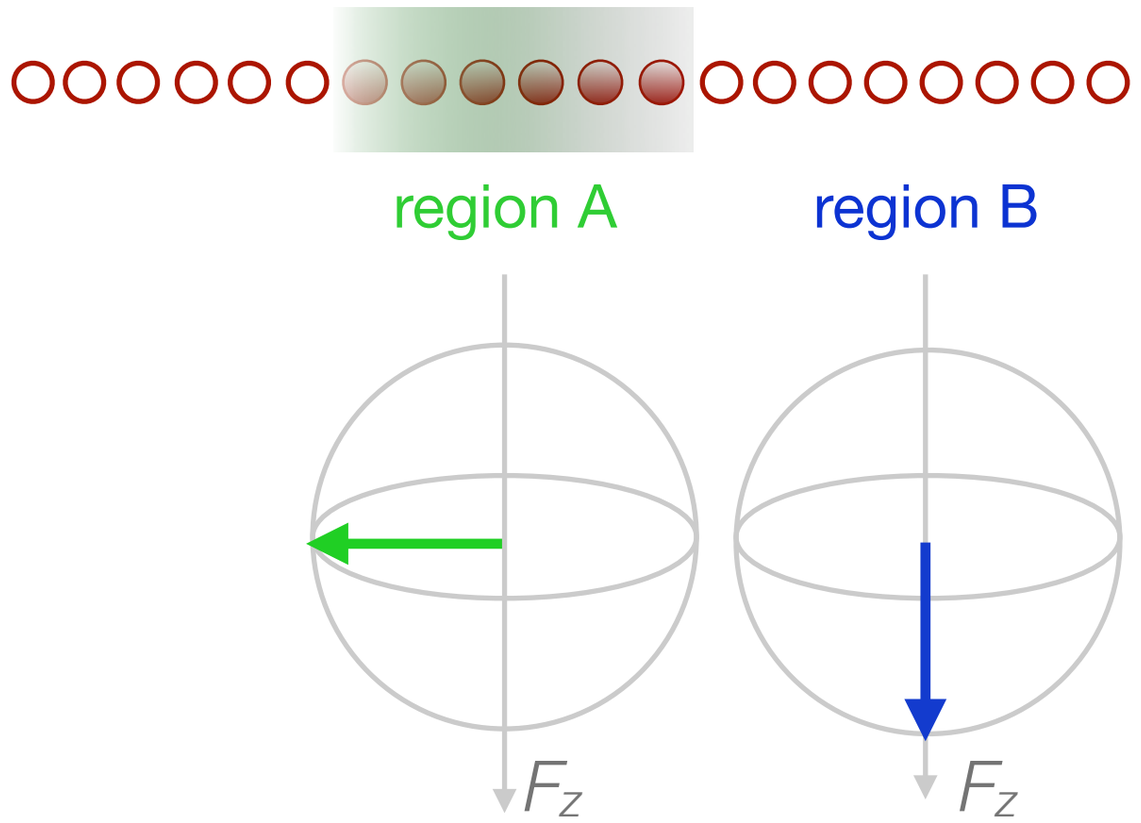
- Apply local spin rotation (~π/2)



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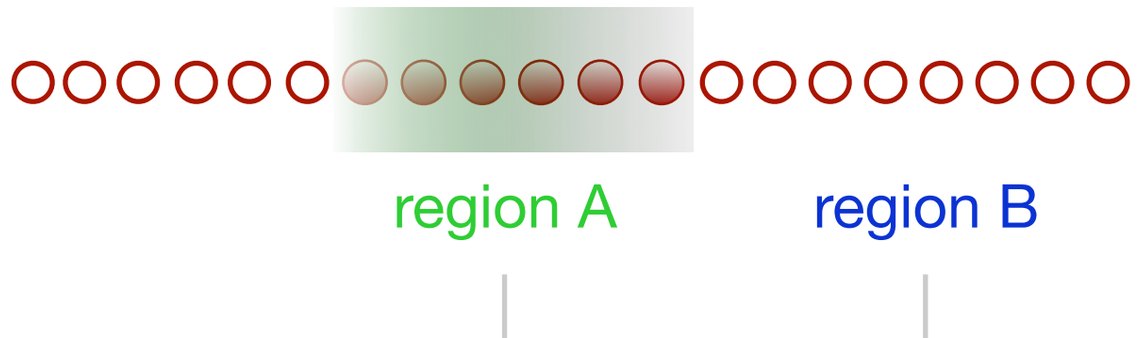
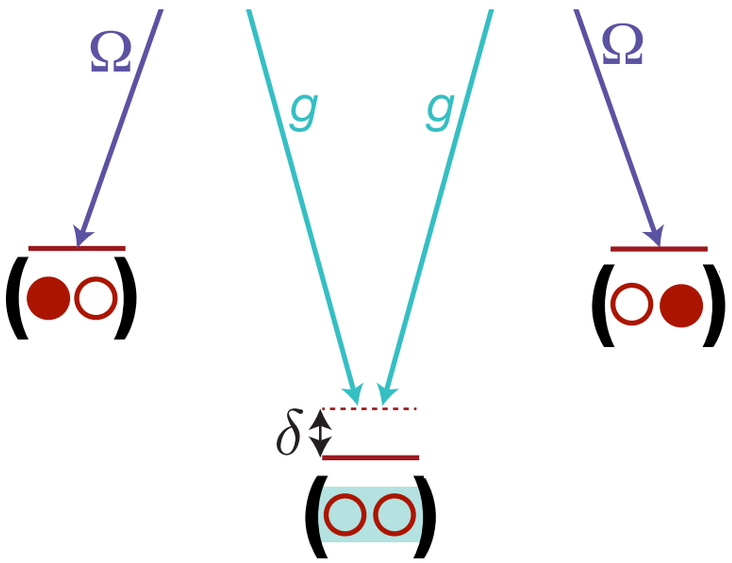
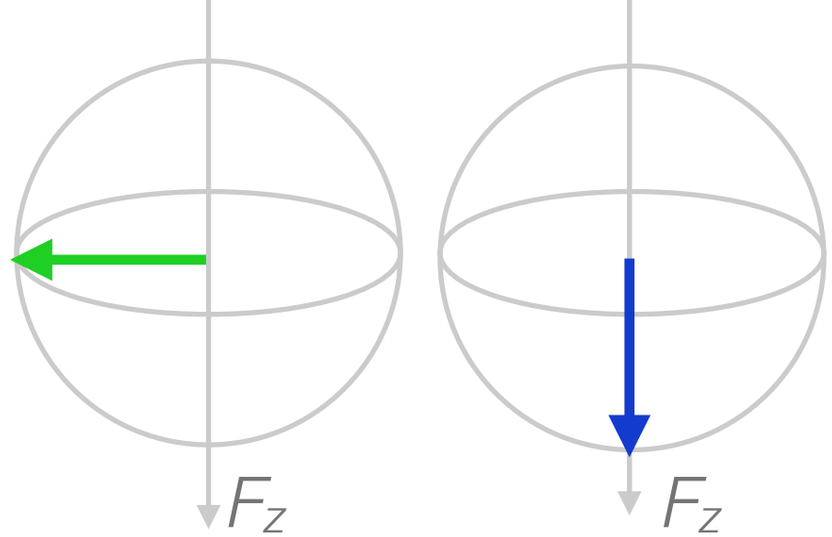


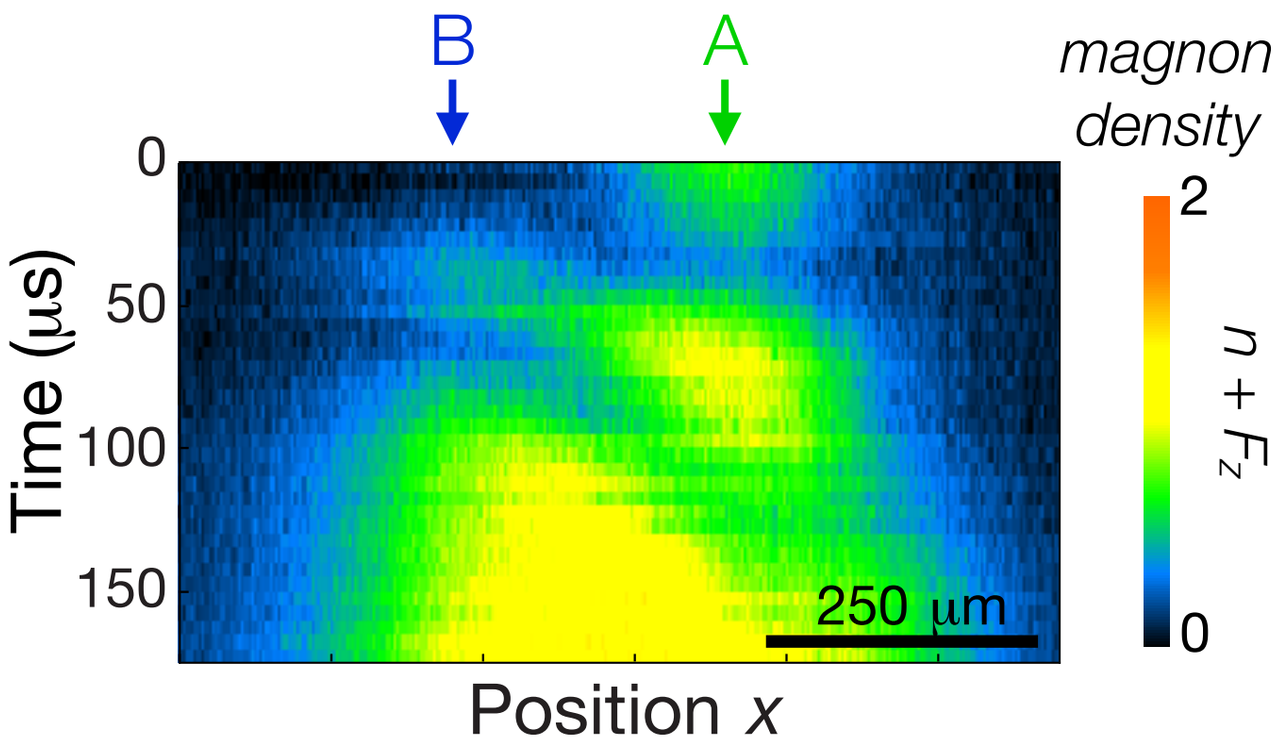
- Turn on control light





Spin Excitations Hopping

E. Davis, G. Bentsen, L. Homeier, T. Li,
& M. S-S., *arXiv*:1809.02114[quant-ph].



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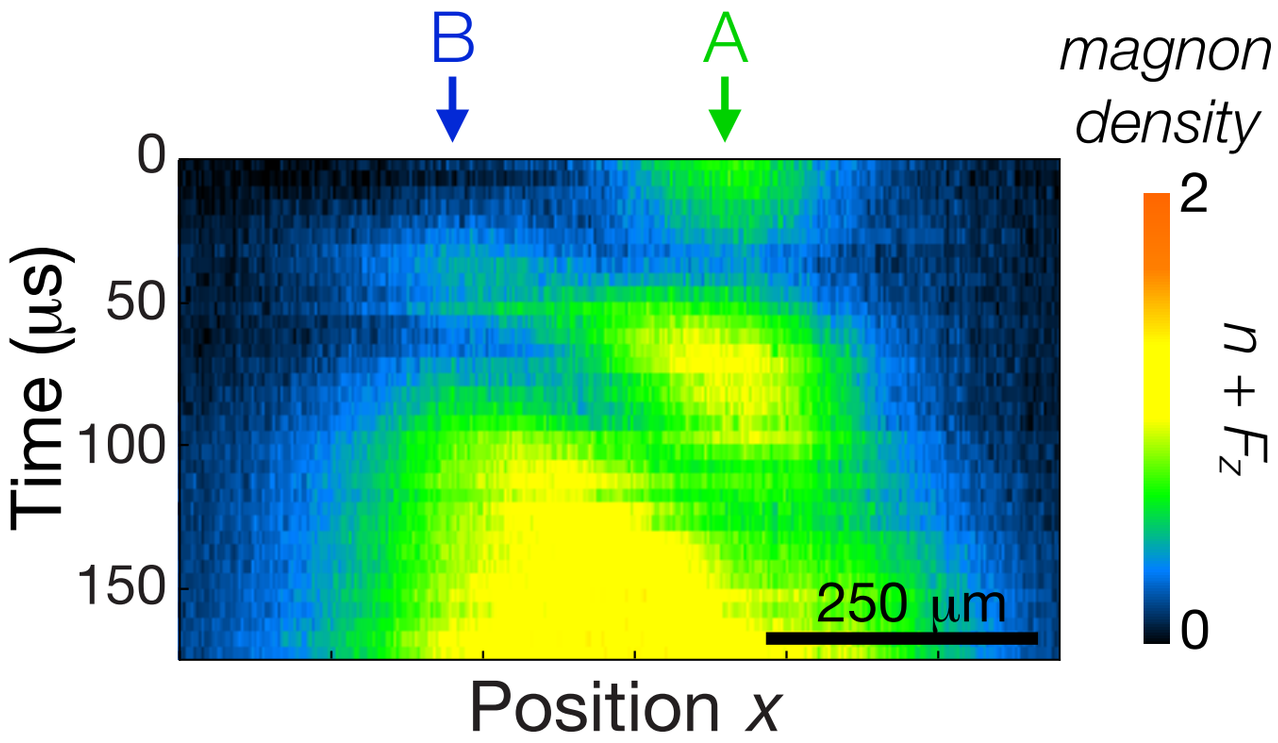

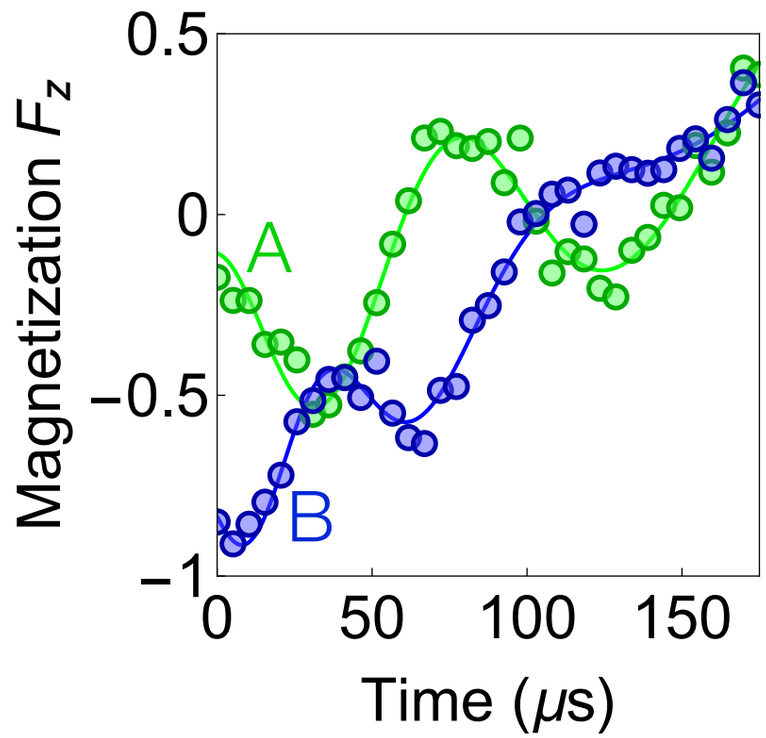

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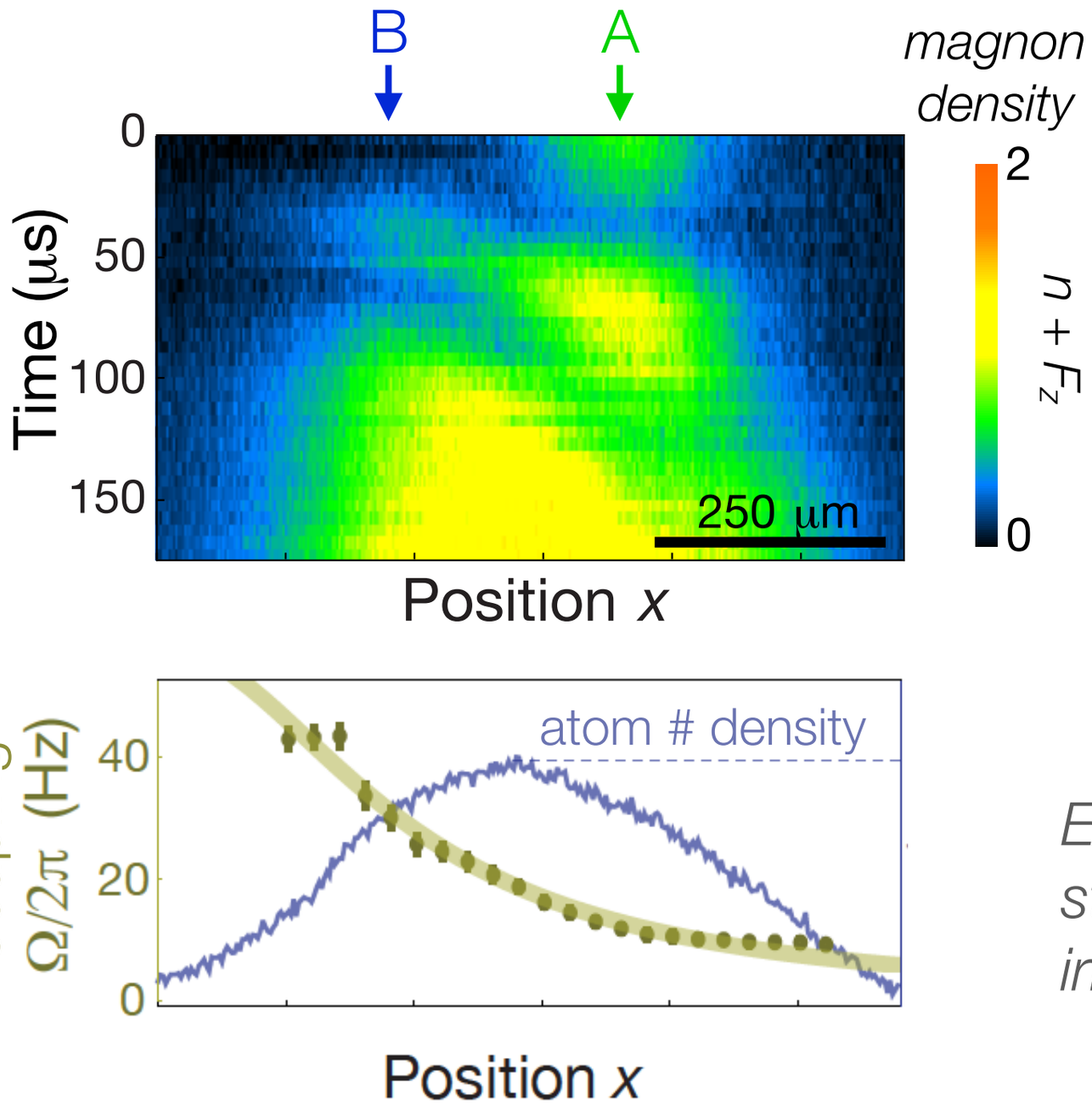

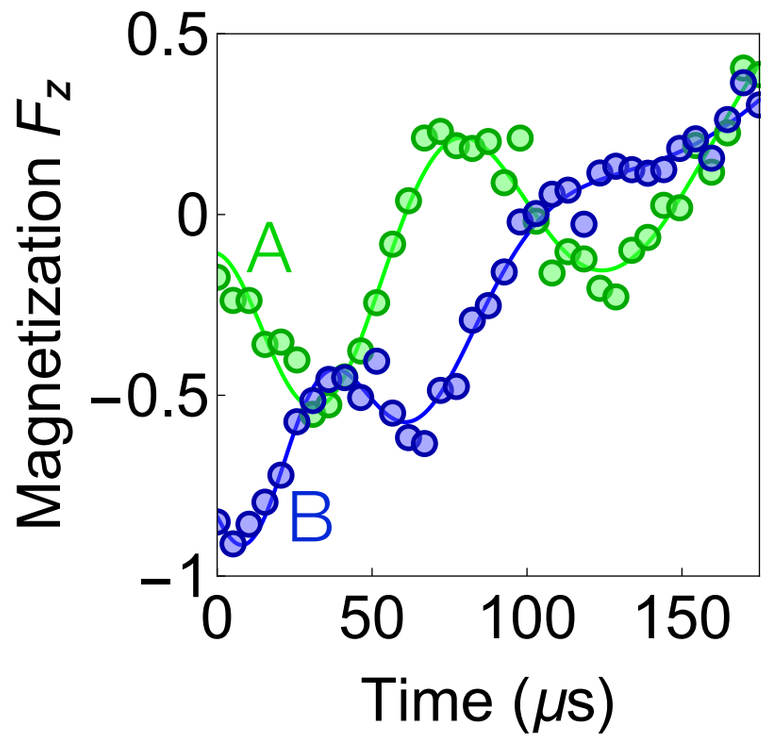

Excitations first hop to most strongly coupled region, irrespective of physical distance

Spin Excitations Hopping

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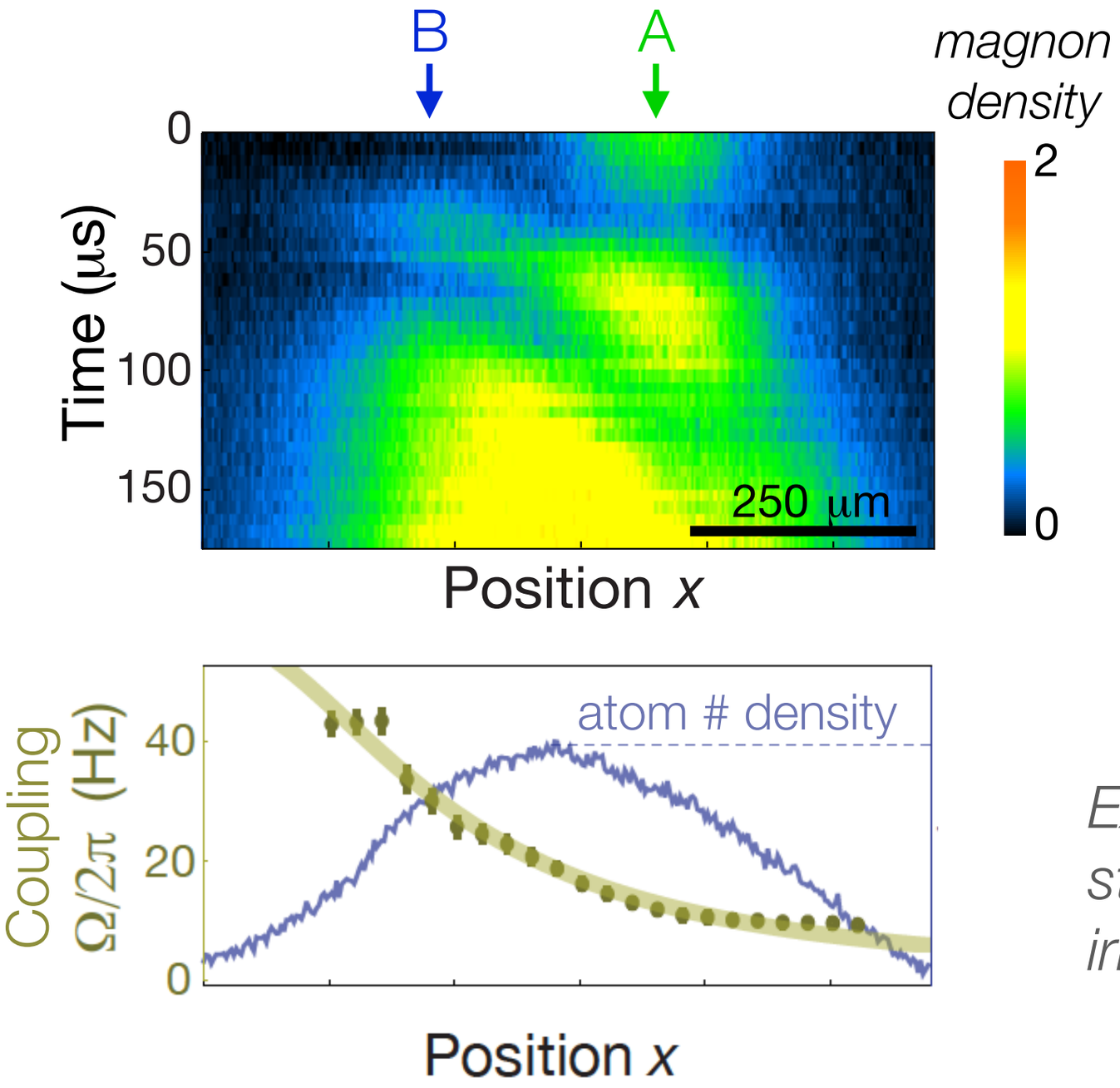
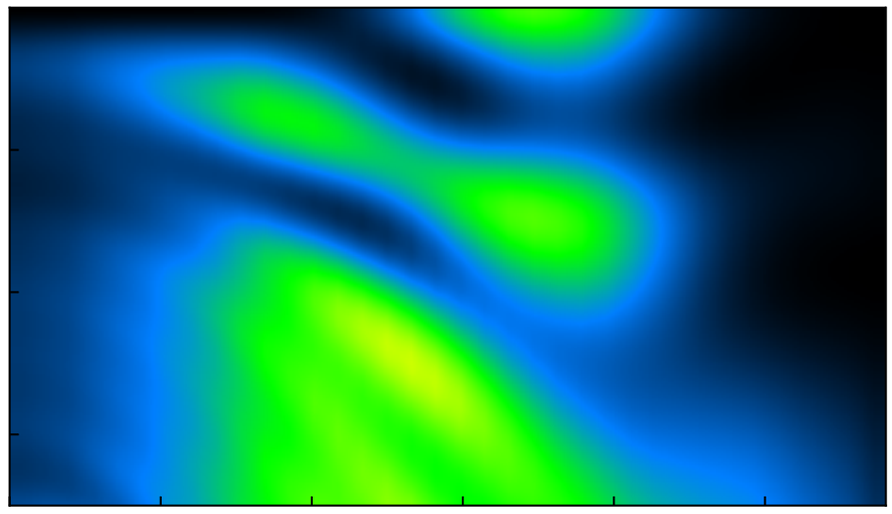


Mean-Field Model



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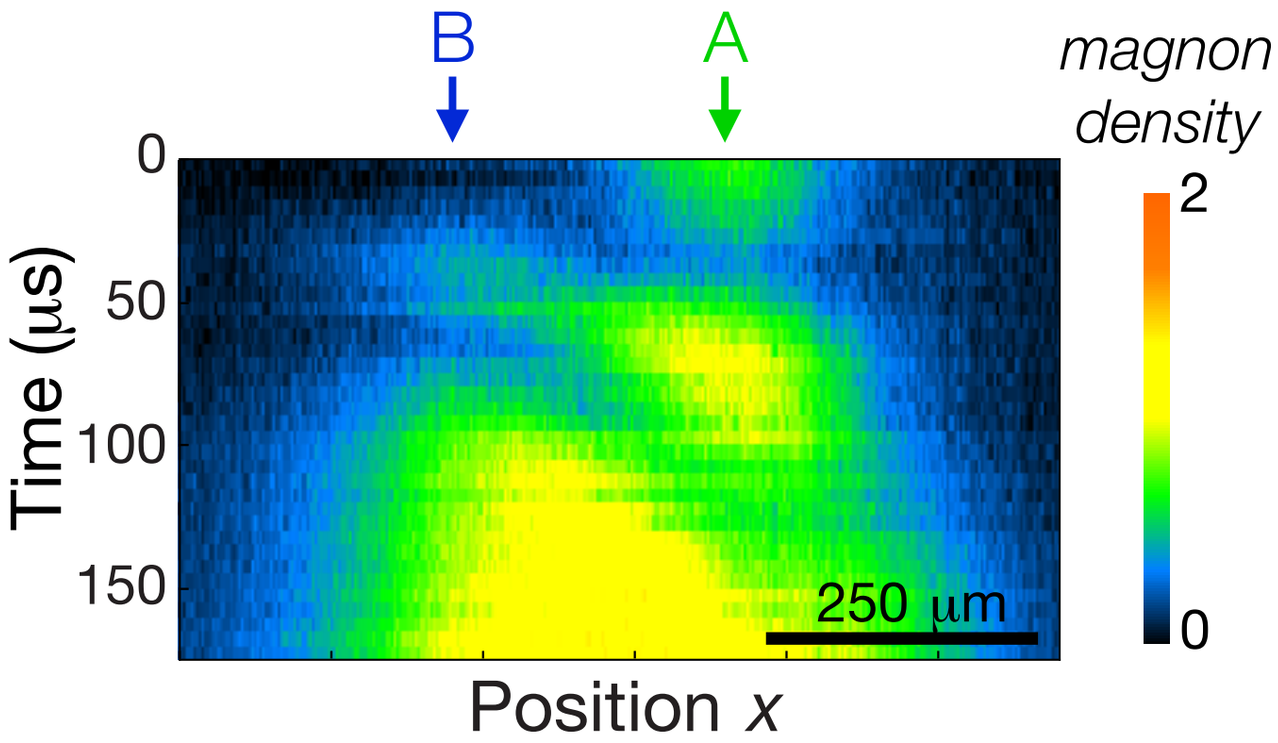
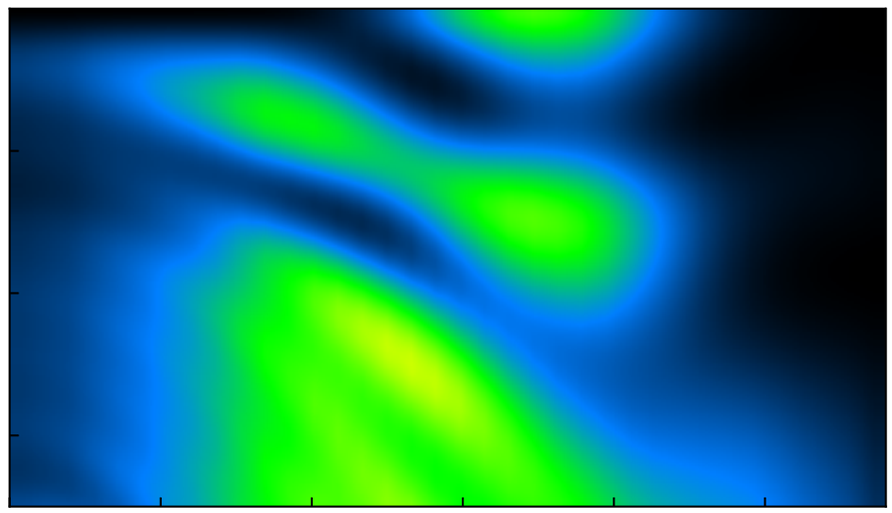
Spin Excitations Hopping

E. Davis, G. Bentsen, L. Homeier, T. Li,
& M. S-S., *arXiv*:1809.02114[quant-ph].



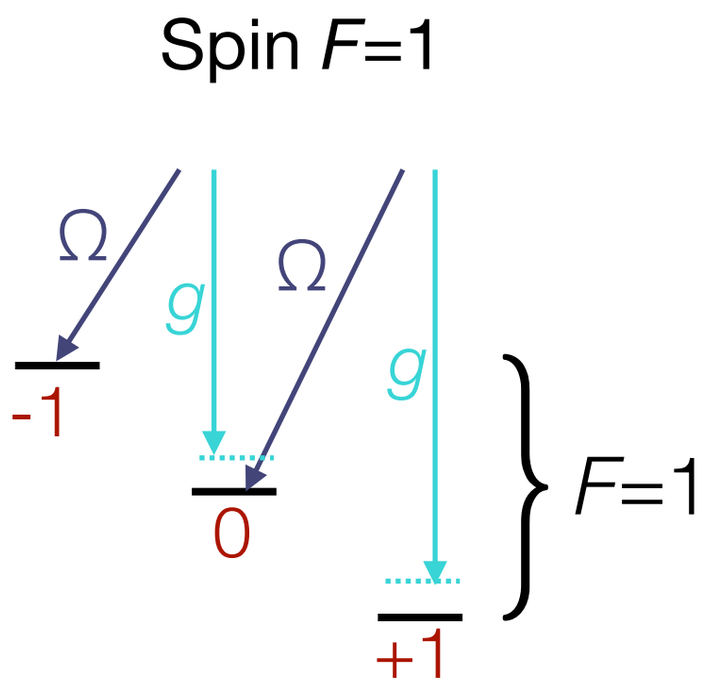
Mean-Field Model



Model: Faraday effect couples magnetization to Stokes vector of light
& light acts back on atoms

c.f. Kohler, Gerber, Dowd, and Stamper-Kurn, *PRL* **120**, 013601 (2018).

Is Anything *Quantum* Happening?



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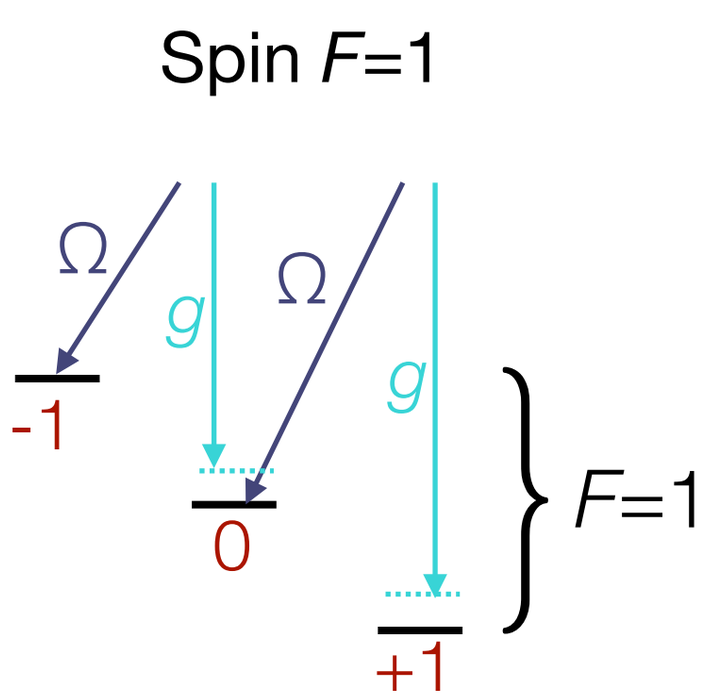


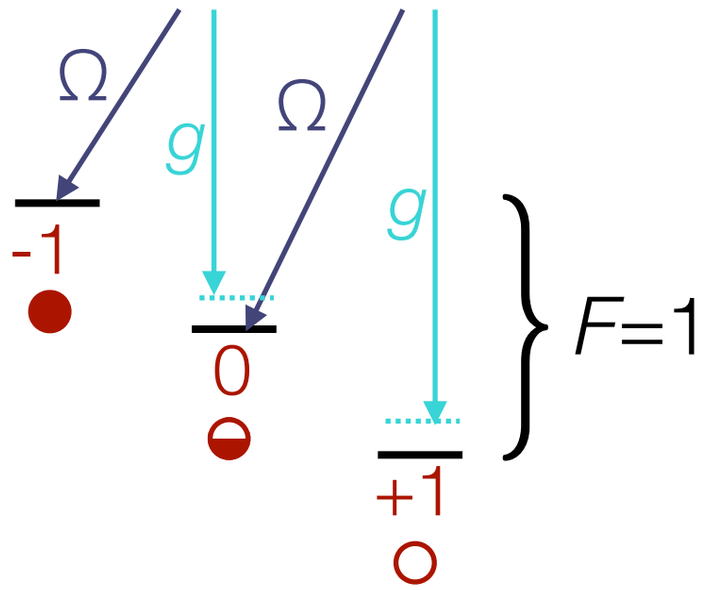
Suppose we initialize with no magnetization, $\langle \boldsymbol{F} \rangle = 0$, by placing atoms in $|m_F = 0\rangle$.

0 0 0 0 0 0 0 0 0 0 0 0 0

Will anything happen?

Flip-Flop Dynamics in Rubidium

Spin *F*=1: each atom as a site with up to 2 spin excitations



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

↔ *spin exchange* ✔

↔ ●○+○● *spin mixing?*

Flip-Flop Dynamics in Rubidium

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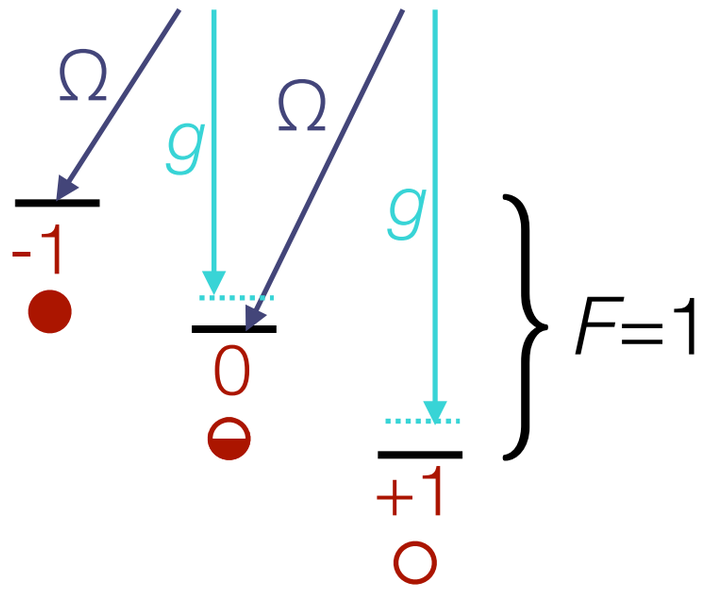

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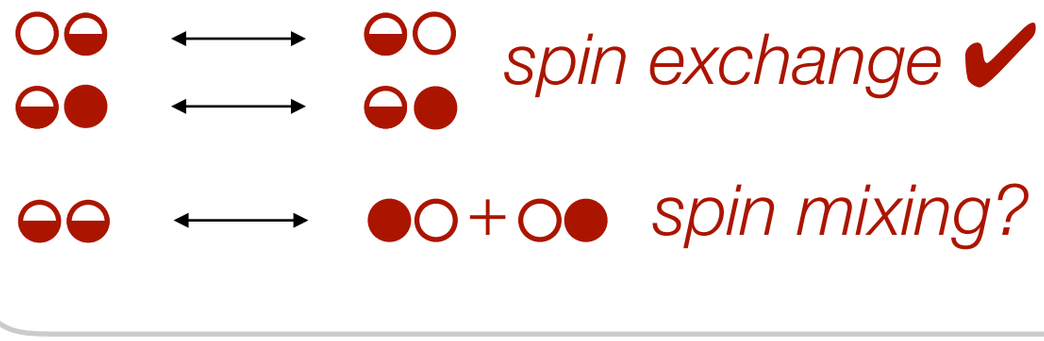
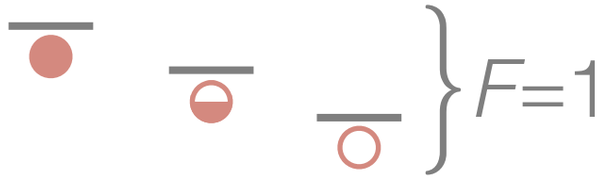


$$H_{\mathrm{mix}} = \sum_{i,j} J_{ij} a_i^\dagger b_j^\dagger c_i c_j + \mathrm{h.c.}$$

Cavity-Mediated Spin Mixing



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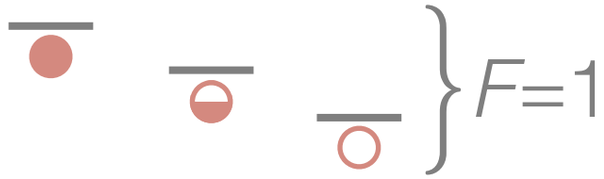

- Initialize all atoms in $|m_F = 0\rangle$

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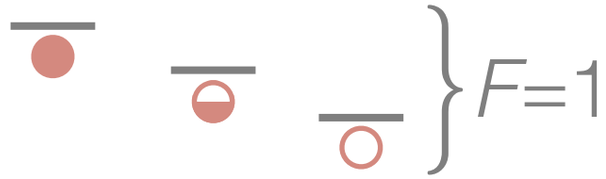

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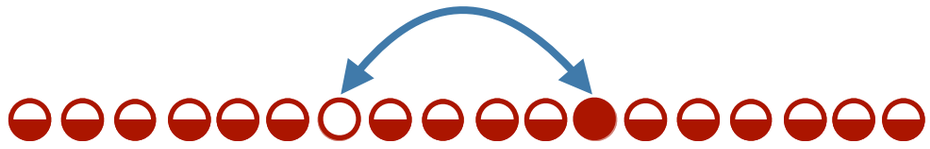
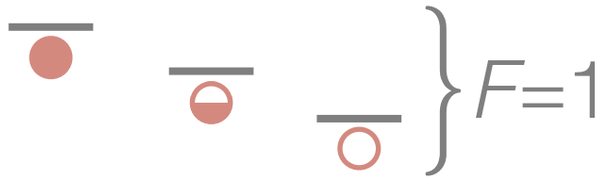


- Turn on control light

Cavity-Mediated Spin Mixing



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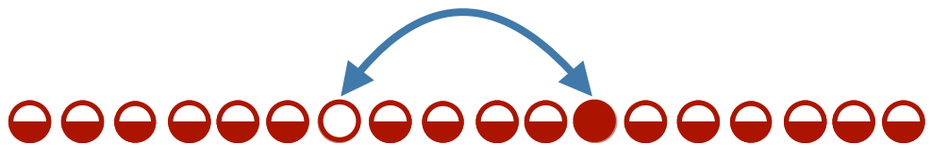
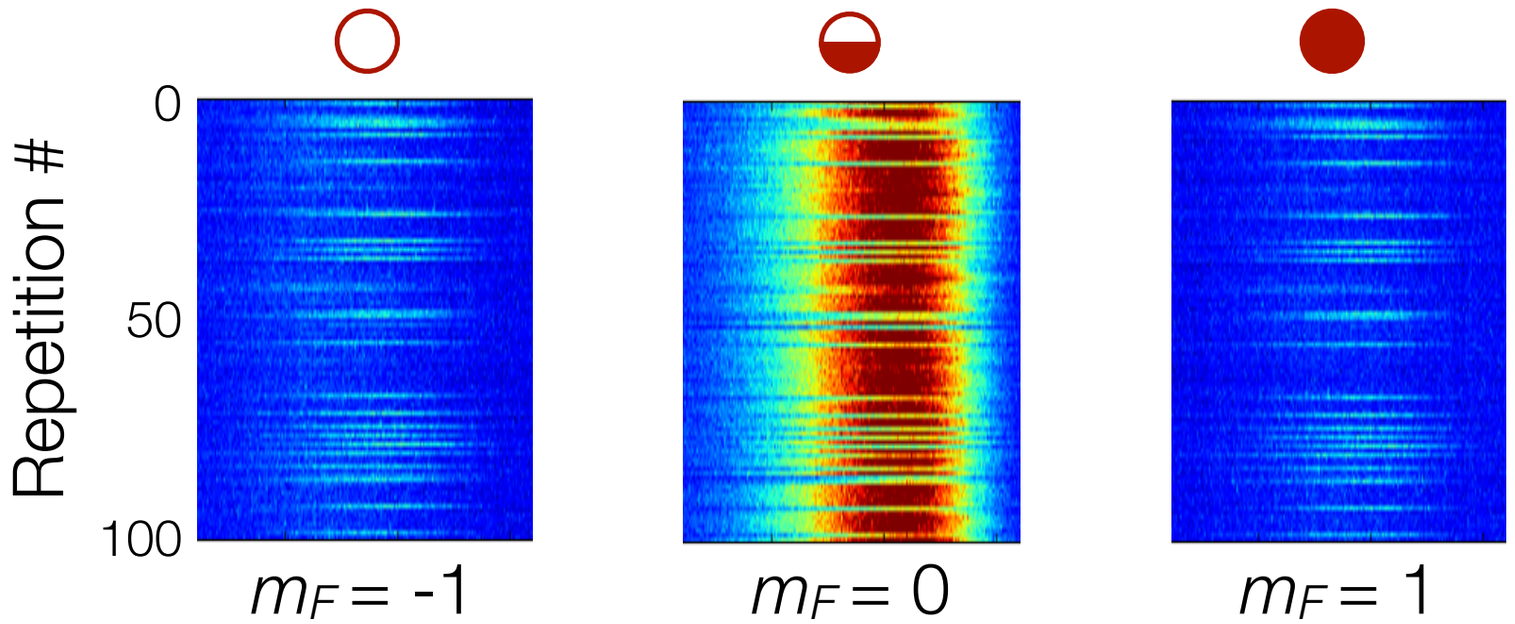
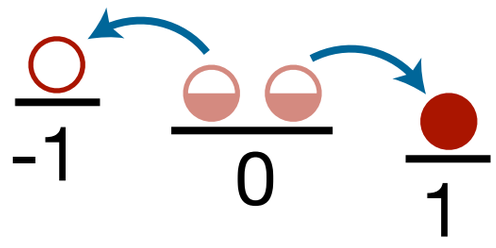


- Turn on control light
- Image populations of all three Zeeman states



Photon-Mediated Pair Creation



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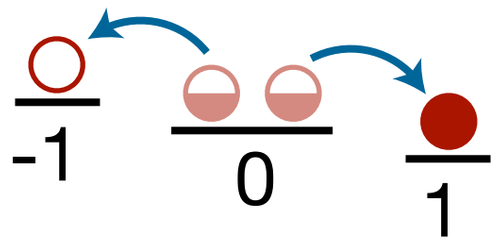

Analogies:

- Formation of doublon-hole pairs

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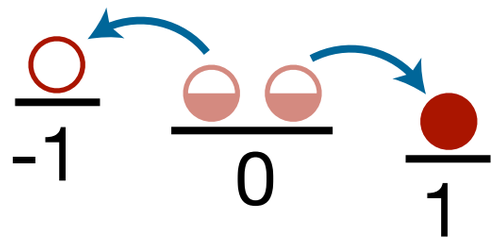

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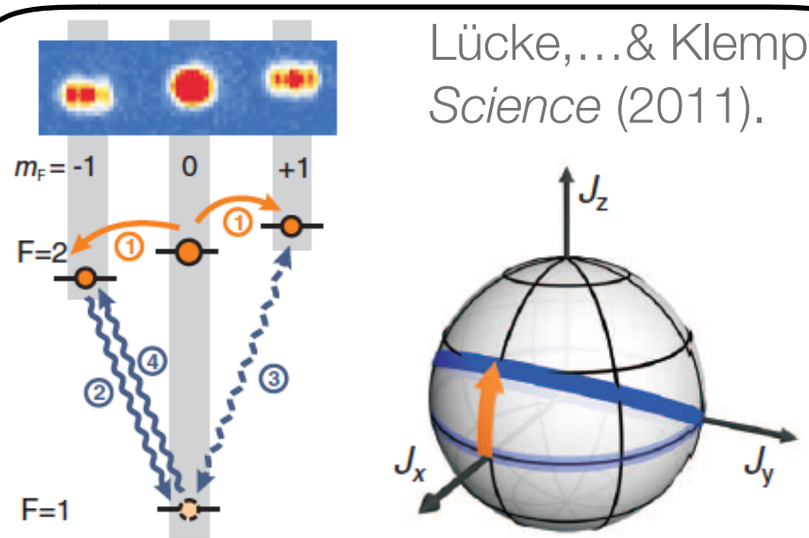

Lücke,…& Klempt, *Science* (2011).

Also: Chapman; Oberthaler; You

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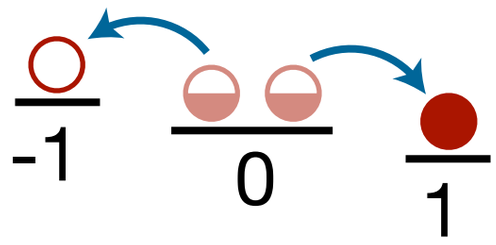

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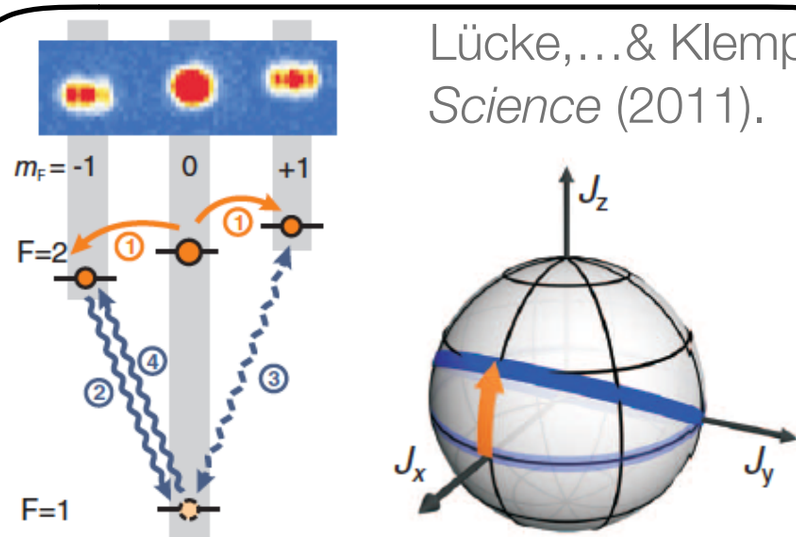

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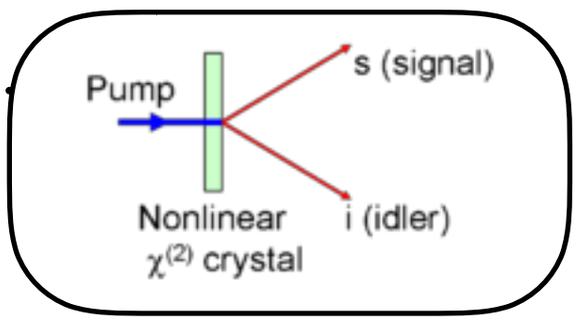
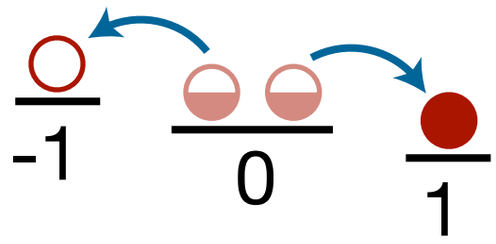
- Spontaneous parametric down-conversion …… “pumped” by $m_F = 0$ atoms

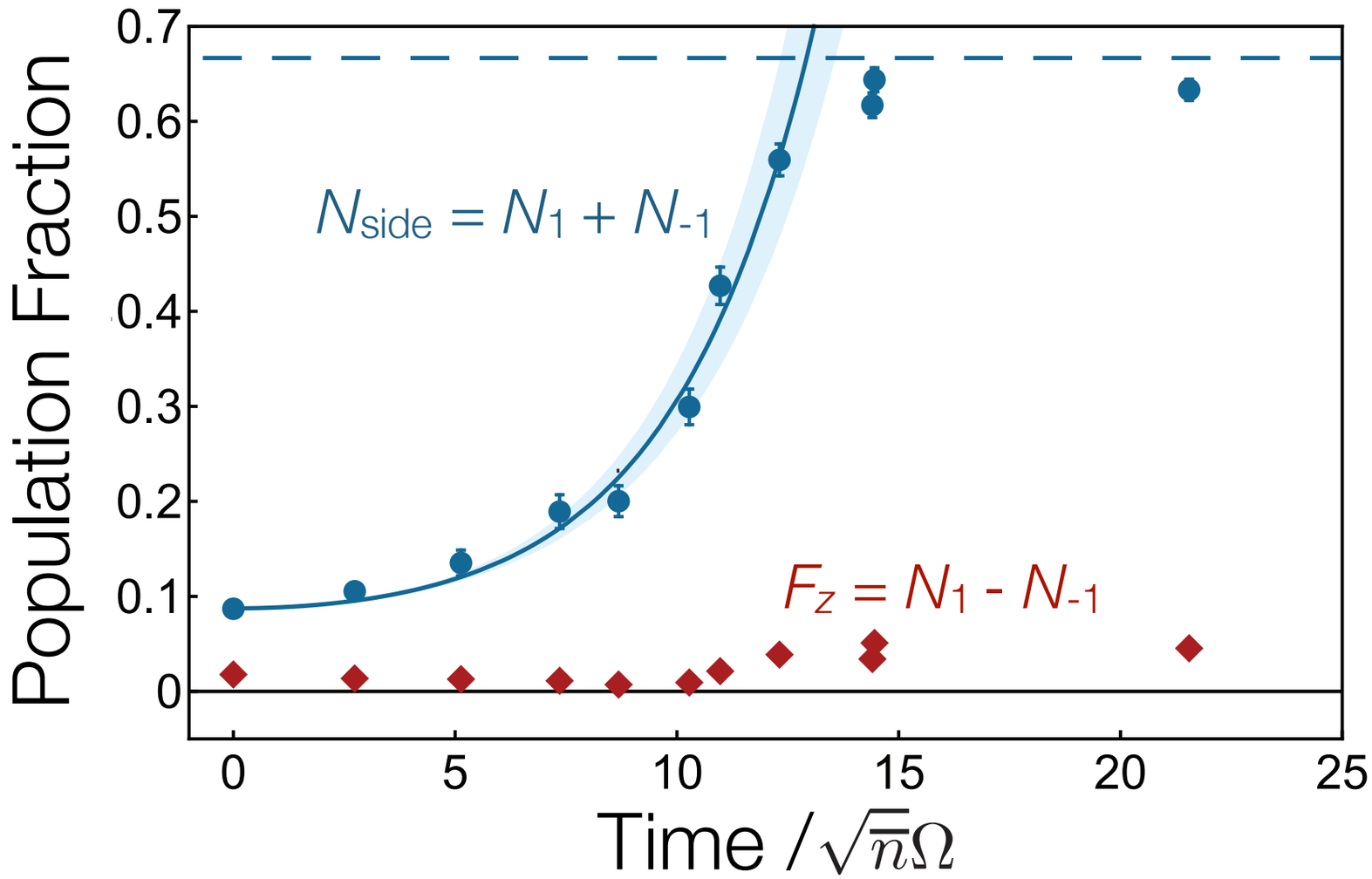


Evidence for Pair Creation

E. Davis, G. Bentsen, L. Homeier, T. Li,
& M. S-S., *arXiv*:1809.02114[quant-ph].

Rapid amplification of side mode population $N_{side} = N_1 + N_{-1}$
while population difference remains fixed





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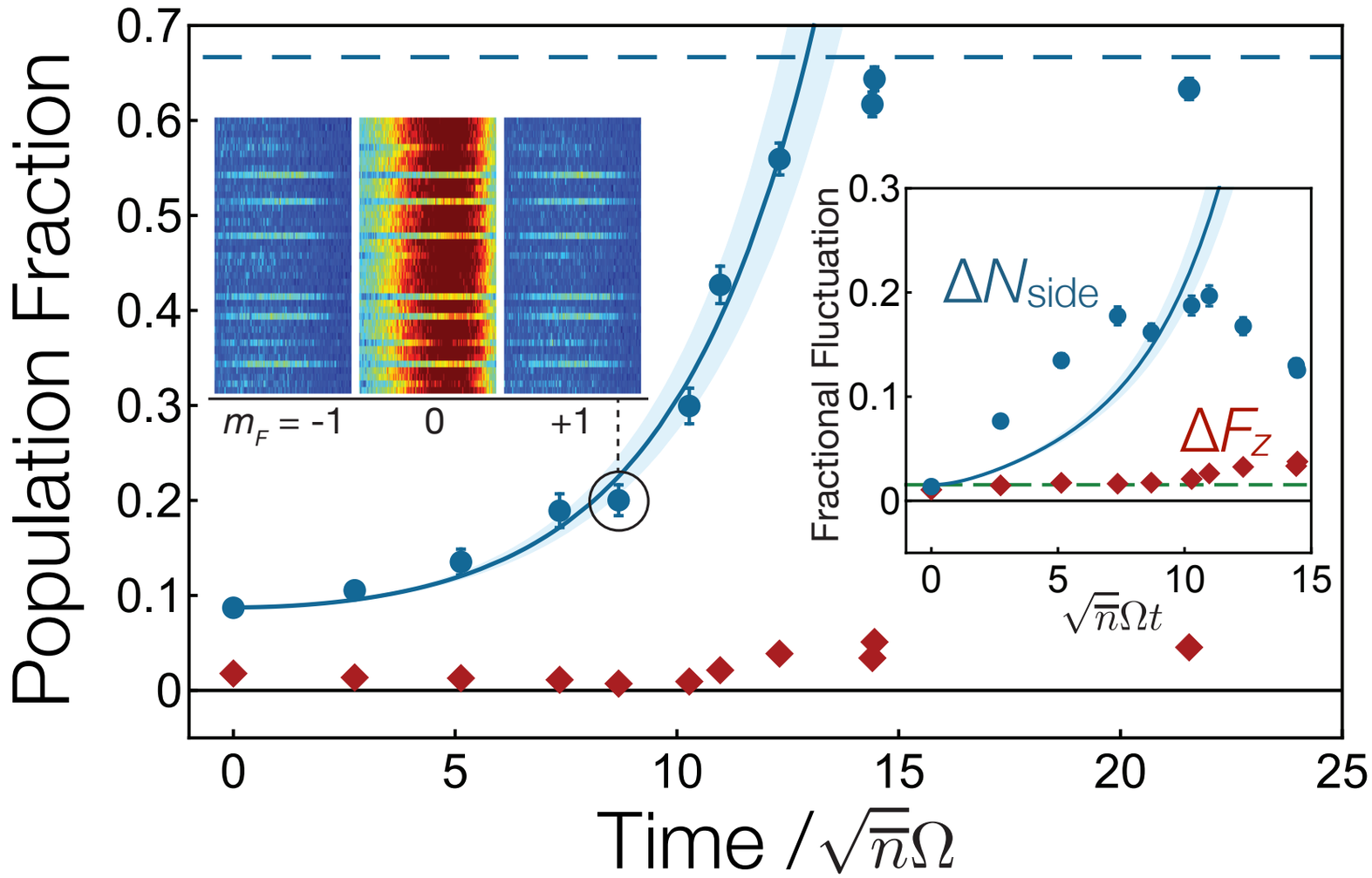

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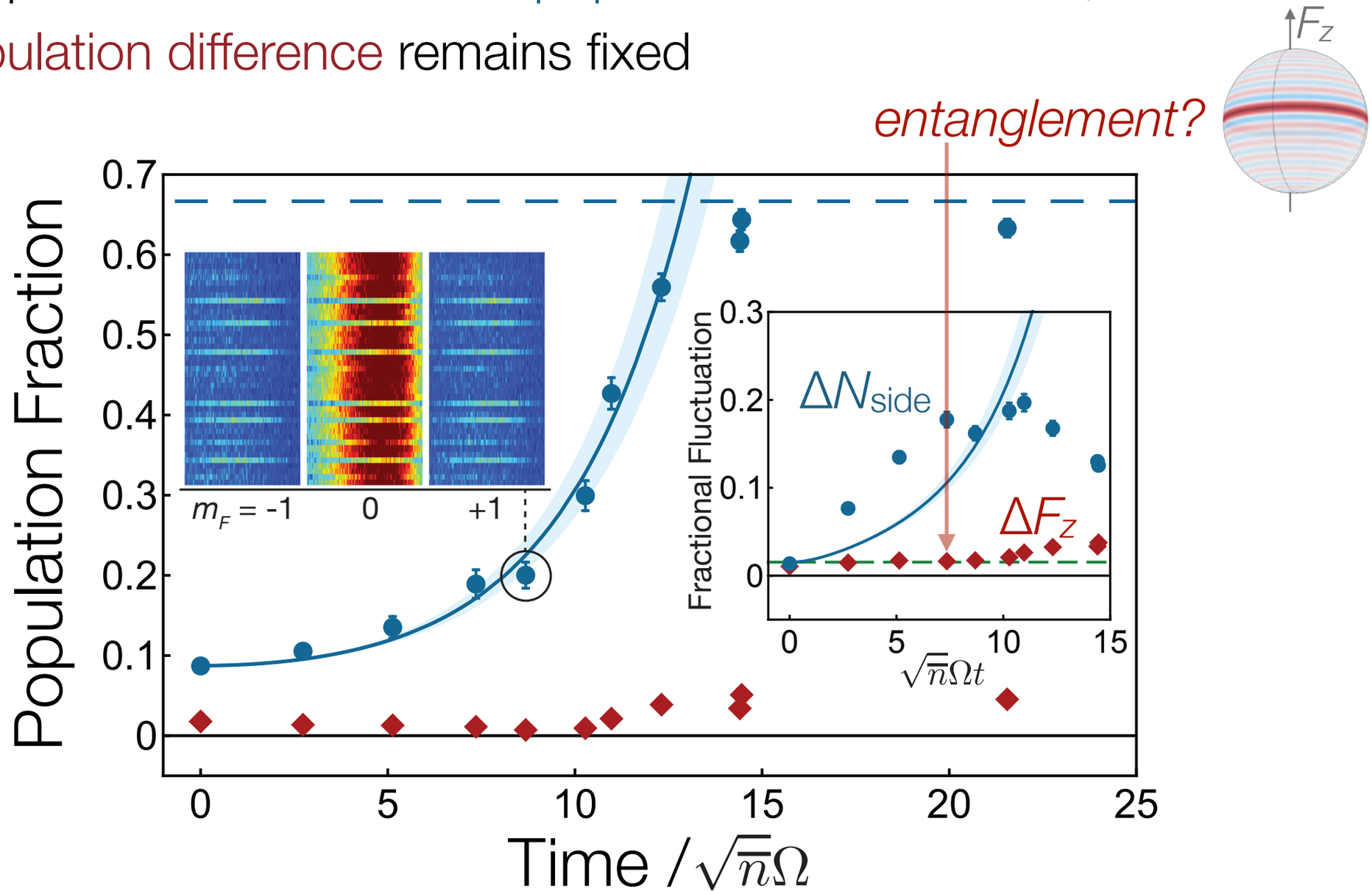
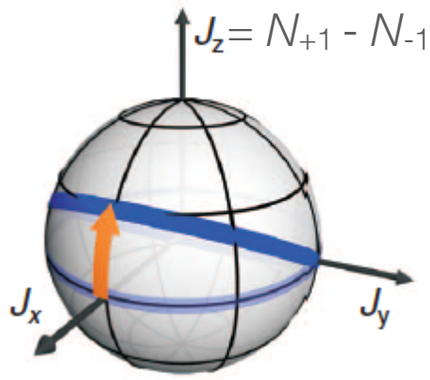


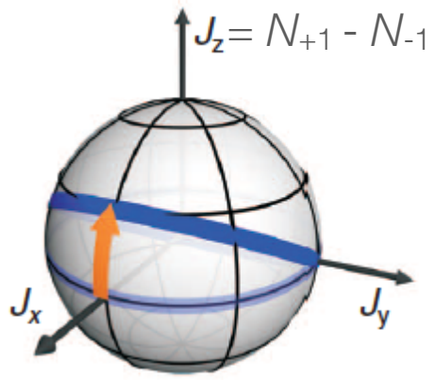
Prospects



Prospects

All-to-all interactions ⇒ twin Fock states for quantum sensing

Enhanced sensitivity to perturbations implies entanglement



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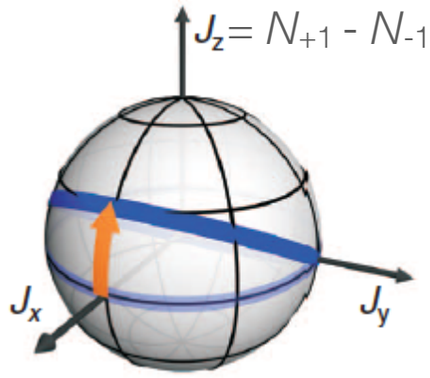
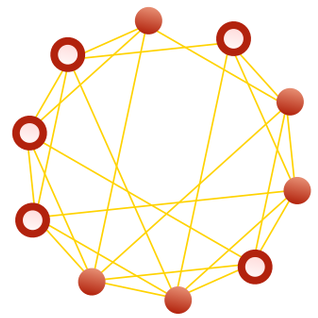


Enhanced sensitivity to perturbations implies entanglement

Richer interaction graphs ⇒ more complex quantum states



Detect entanglement via sensitivity to perturbations

⇒ reconstruct bulk geometry?

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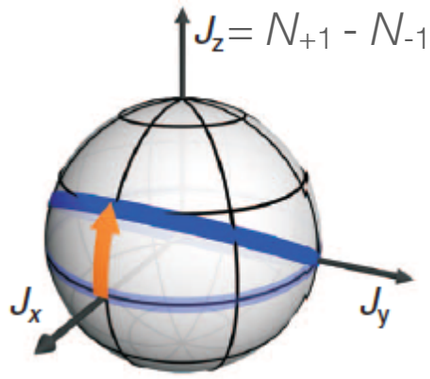

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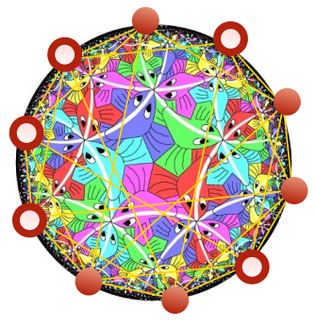
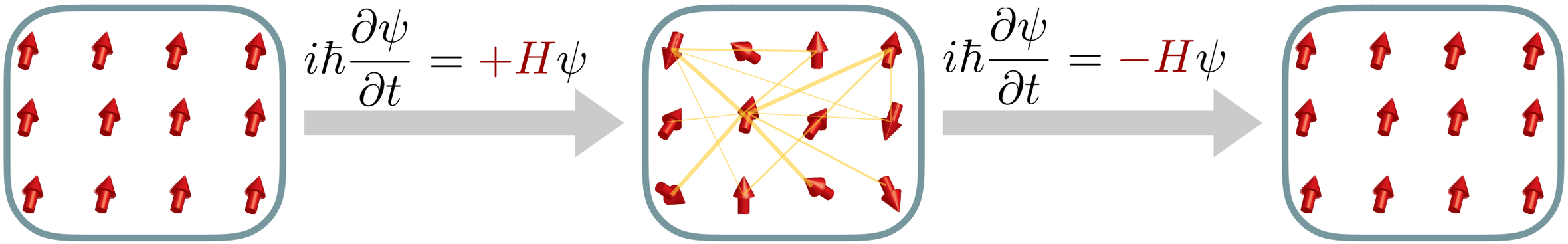


PRL **115,** 261602 (2015) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2015

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*

Sensitivity to Perturbations



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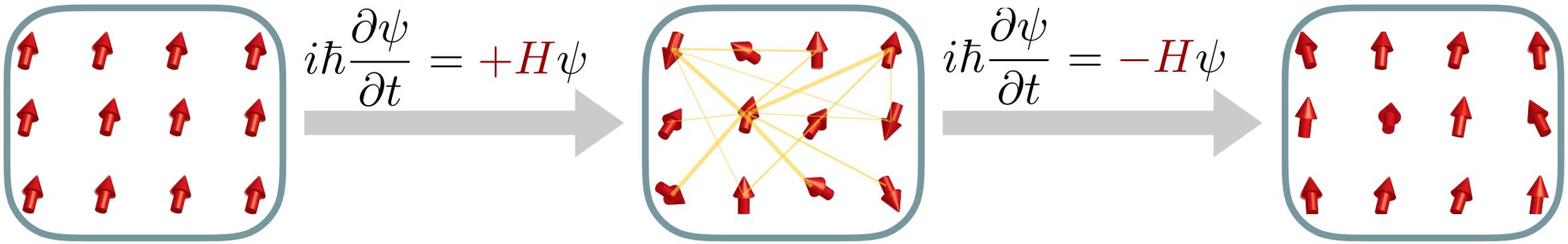

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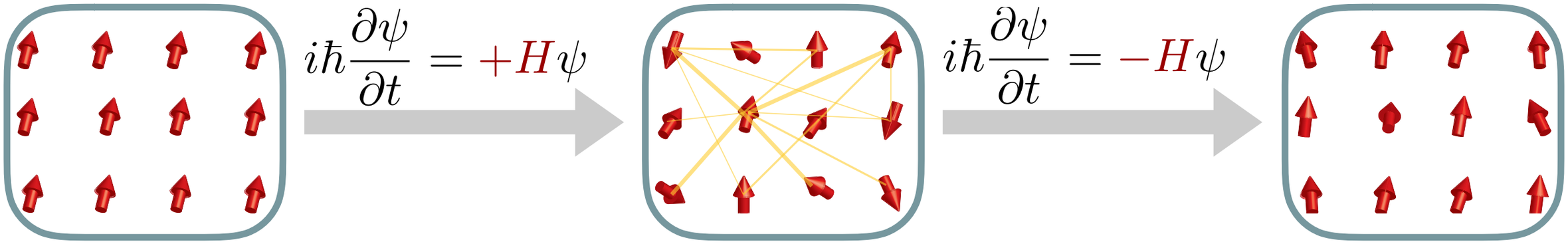
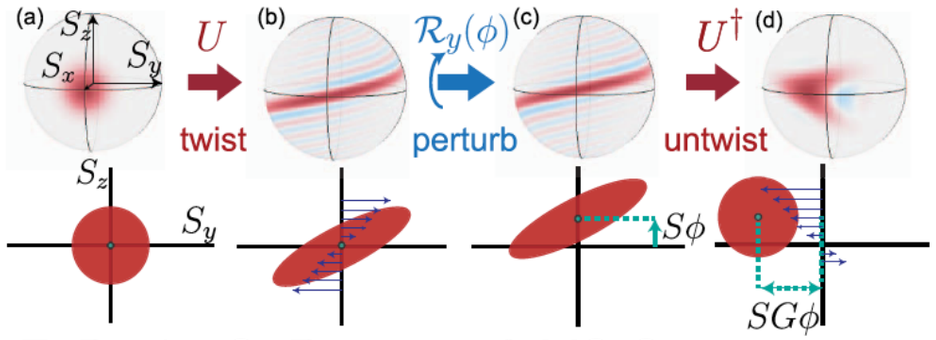
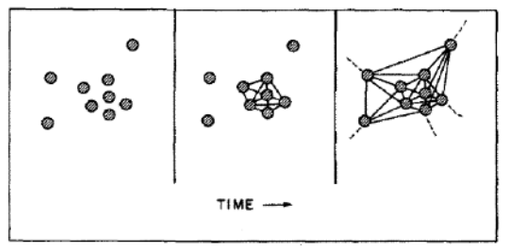


Exploiting sensitivity to perturbations for **precision measurements**



E. Davis, G. Bentsen, & MS-S, *PRL* **116**, 053601 (2016).

Probing chaos via sensitivity to perturbations



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⇒ *Quantifying information scrambling*

B. Swingle, G. Bentsen, MS-S, & P. Hayden, *PRA* **94** 040302(R) 2016.

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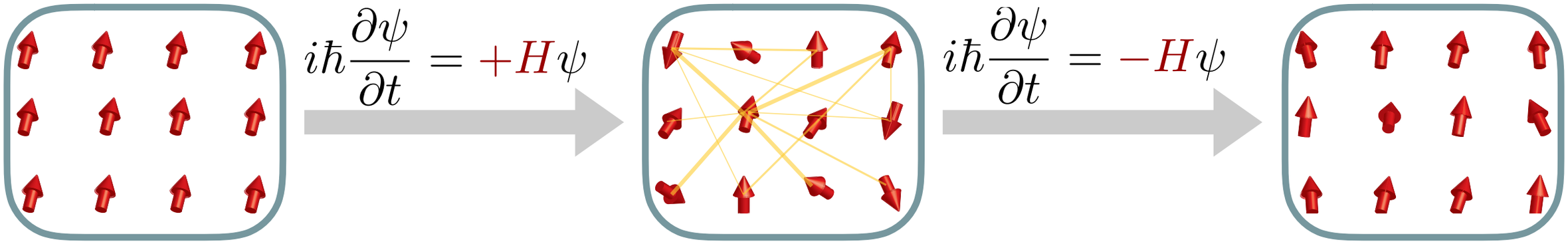

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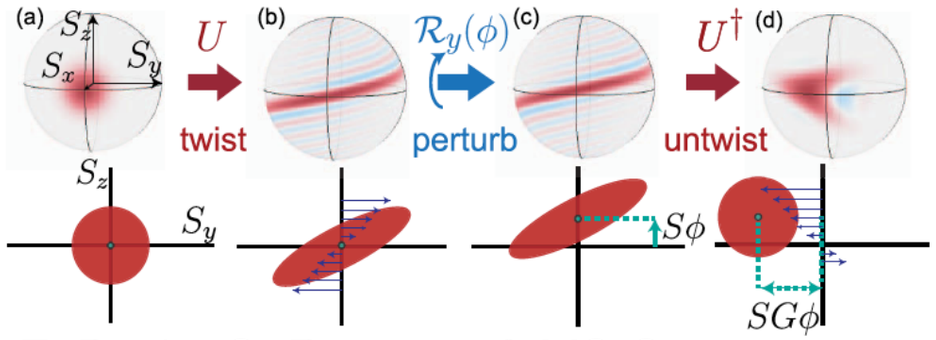

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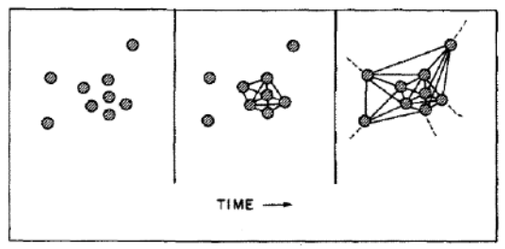

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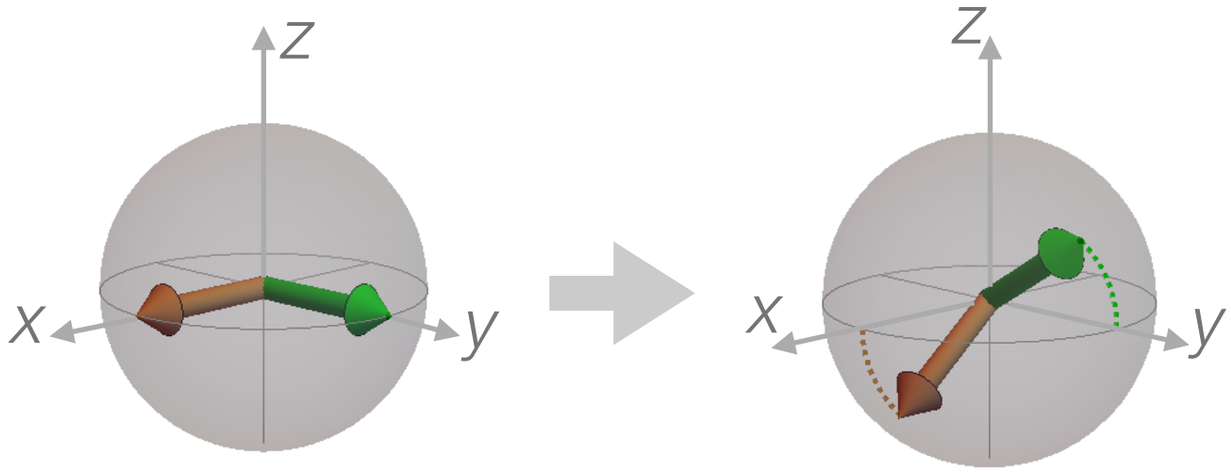
"Time reversal" requires switchable-sign interactions

Measuring the Sign of Interaction

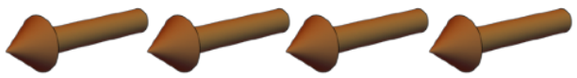
$$H = \sum_{i,j} J_{ij} s_i^+ s_j^- = \sum_{i,j} J_{ij} \left(s_i^x s_j^x + s_i^y s_j^y \right) + \sum_i J_{ii} s_i^z$$

Each spin should precess about the mean field of all other spins.

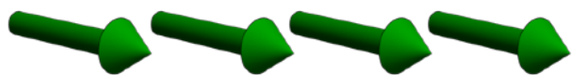


Magnetization Dynamics

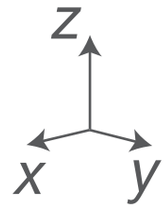
Initialize cloud with
*x- and y-*polarized regions



region A



region B



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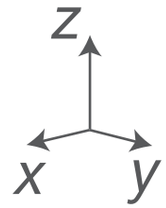
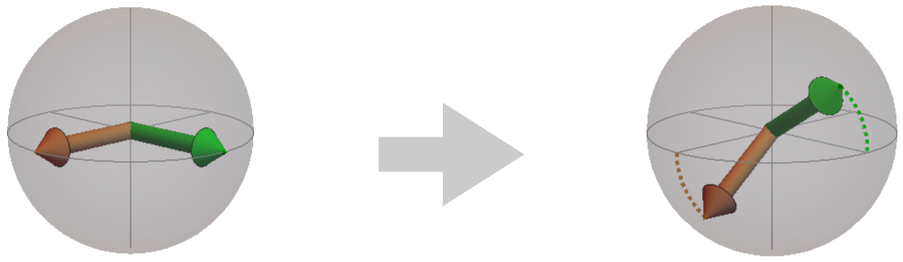


Turn on interactions



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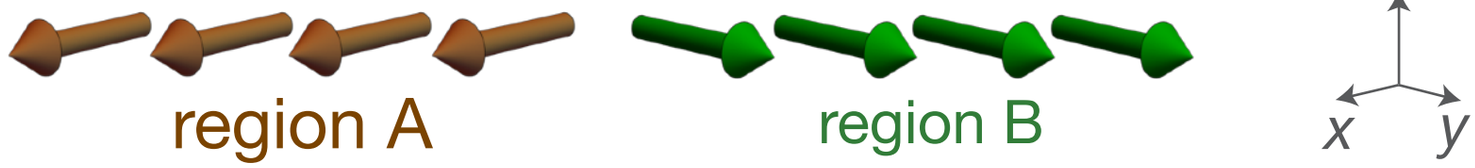

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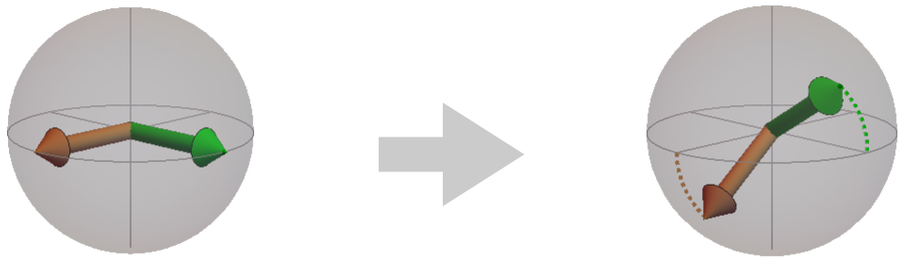
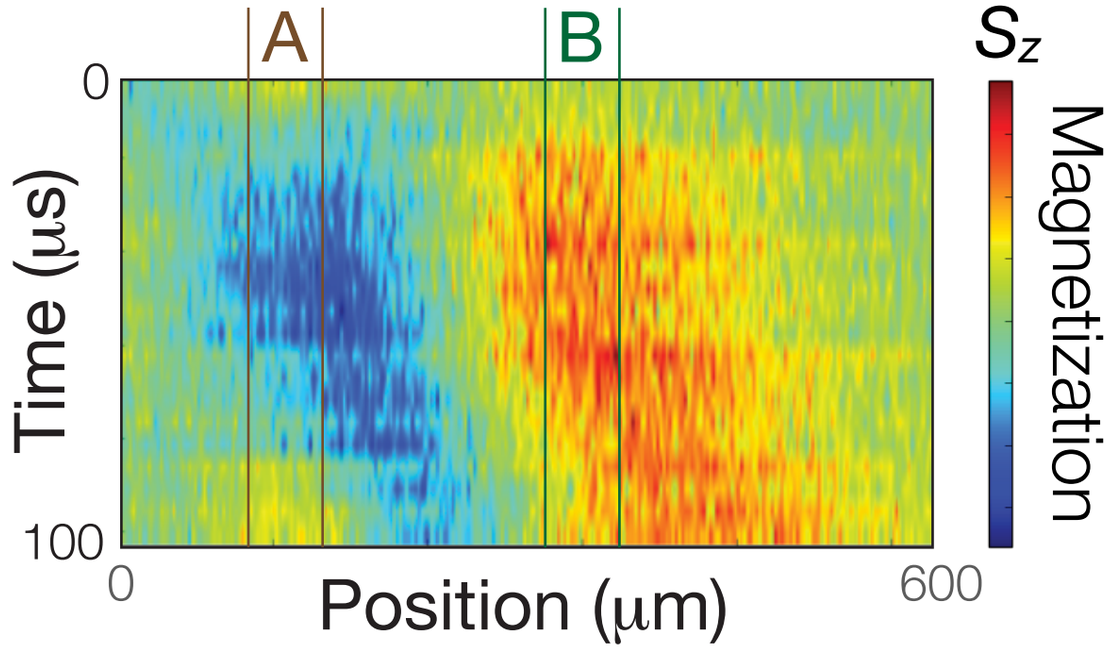


Image ***z***-polarization
vs. time



Strength & Sign of Interactions

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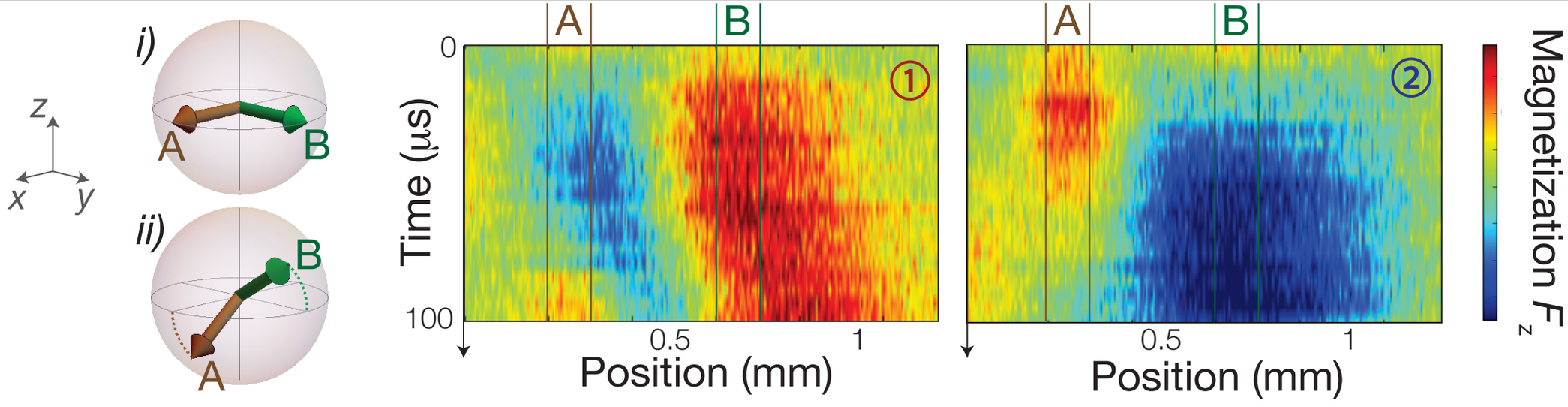

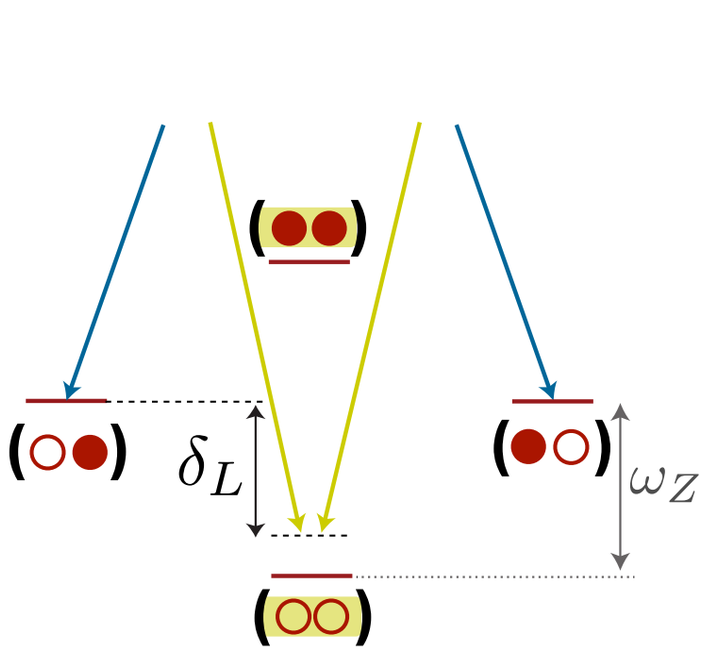

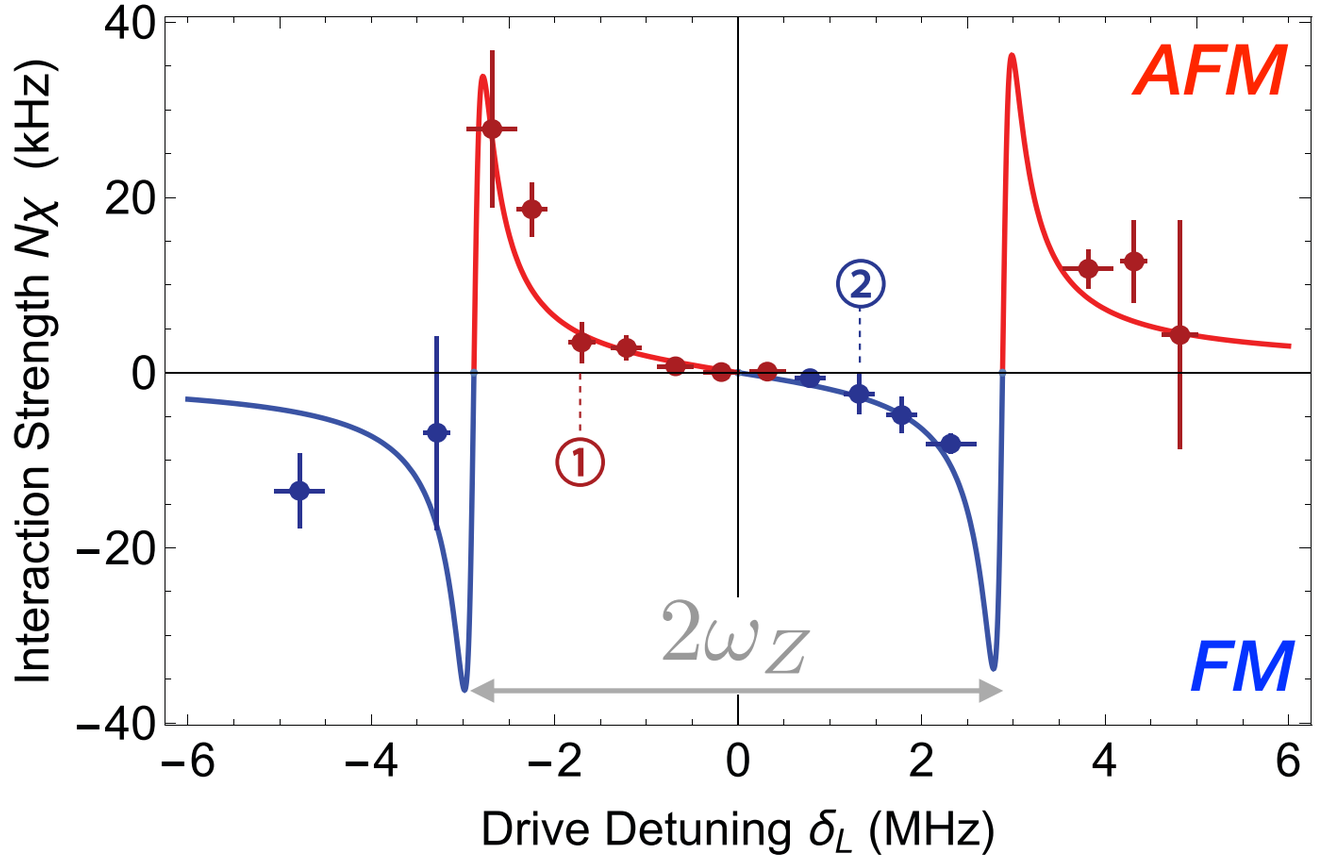

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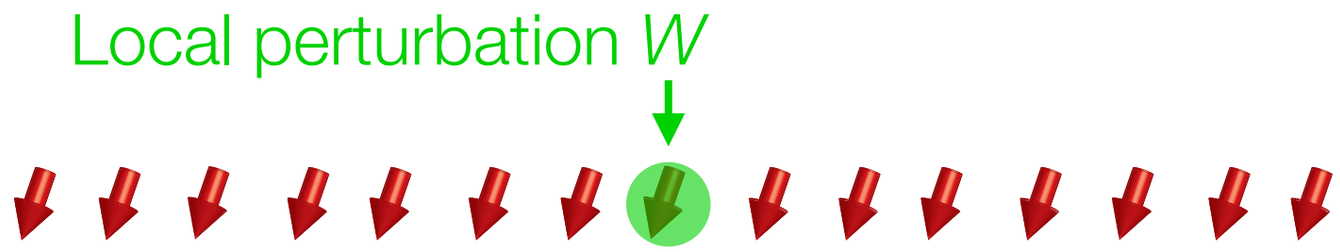

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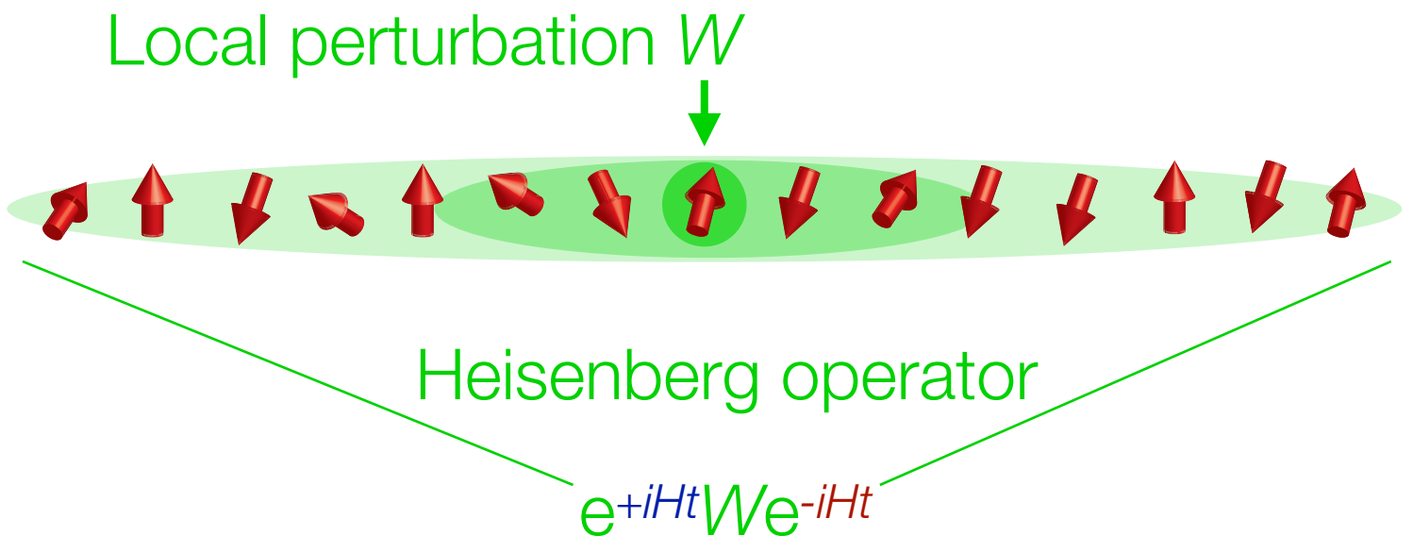
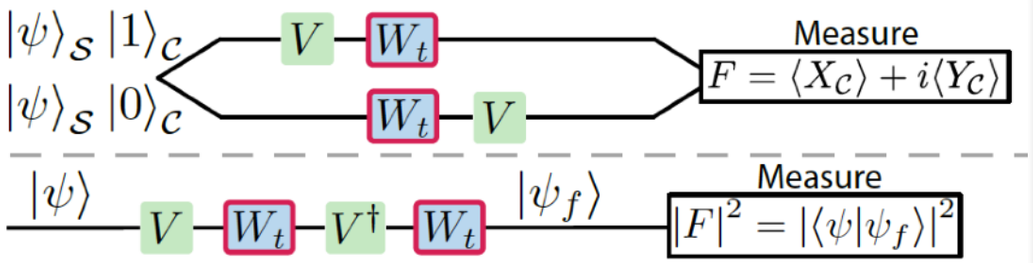


Time Reversal for Probing Scrambling

Theory



B. Swingle, G. Bentsen, MS-S, & P. Hayden, *PRA* 040302(R) 2016.

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Experiments

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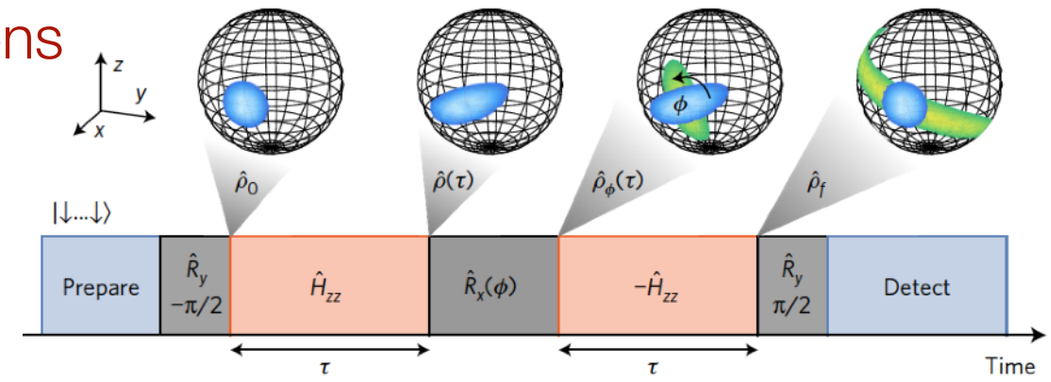

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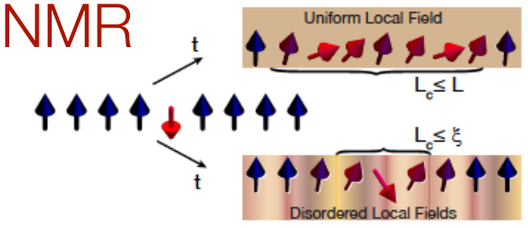
NMR



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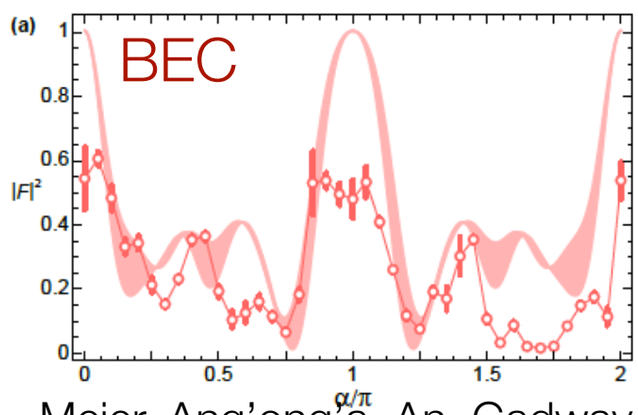

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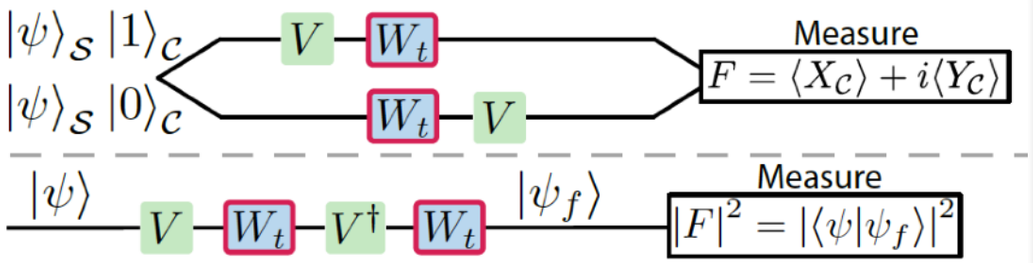

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Routes to fast scrambling?

Role of the structure of interactions?

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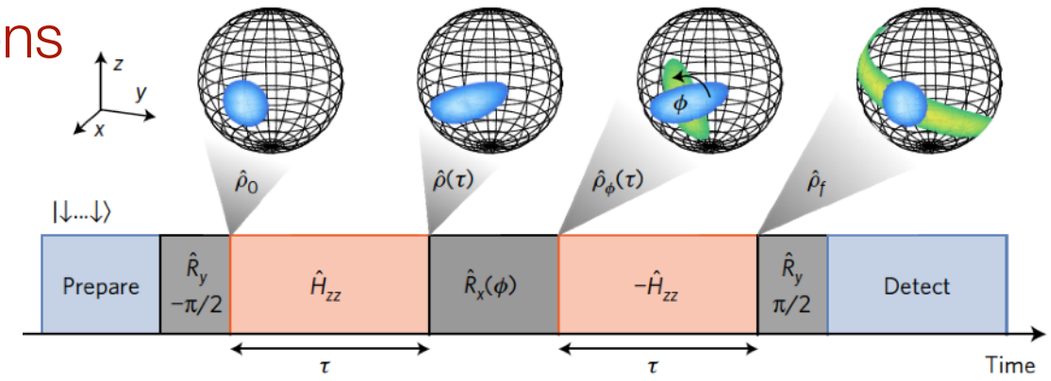

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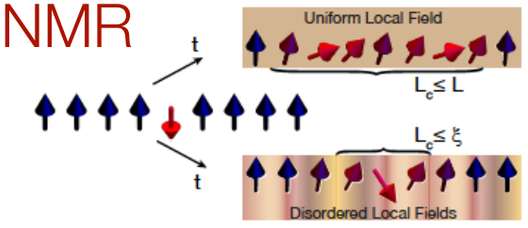

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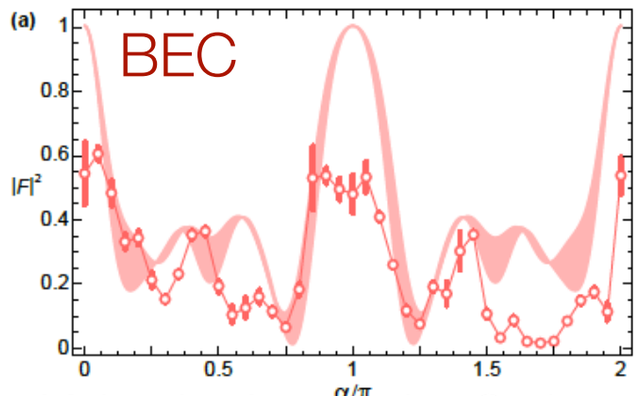

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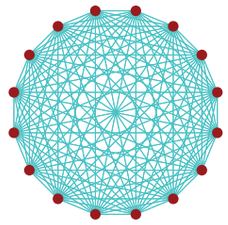
Non-Local Interactions for Fast Scrambling?

Symmetric all-to-all interactions yield “single-particle” physics…



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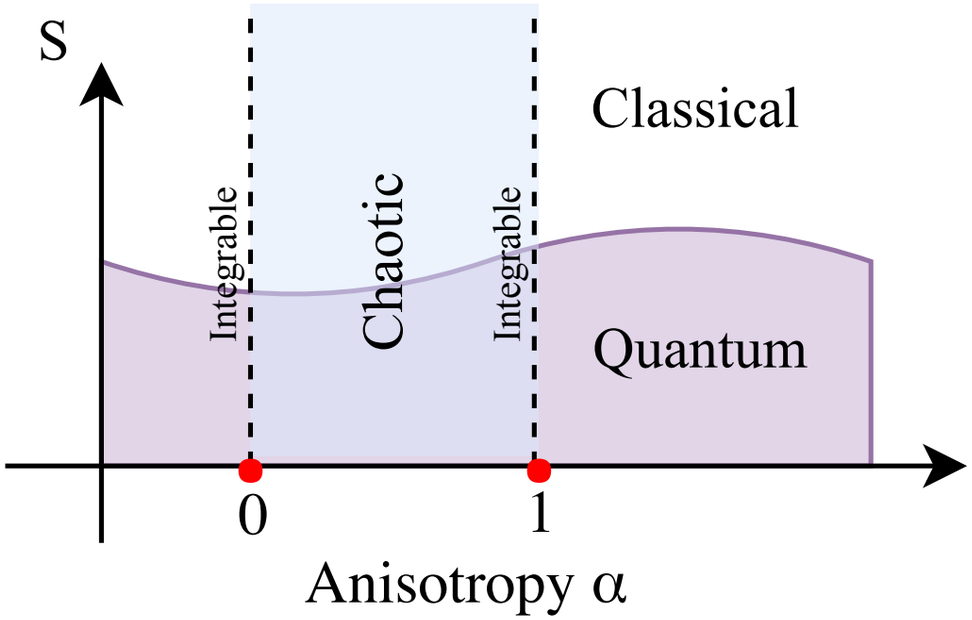

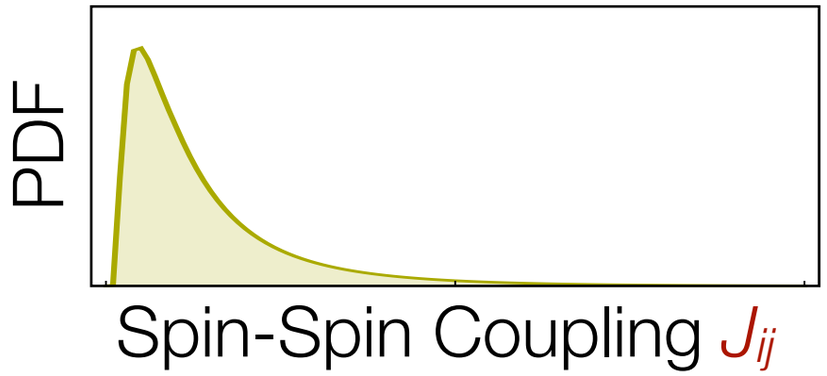

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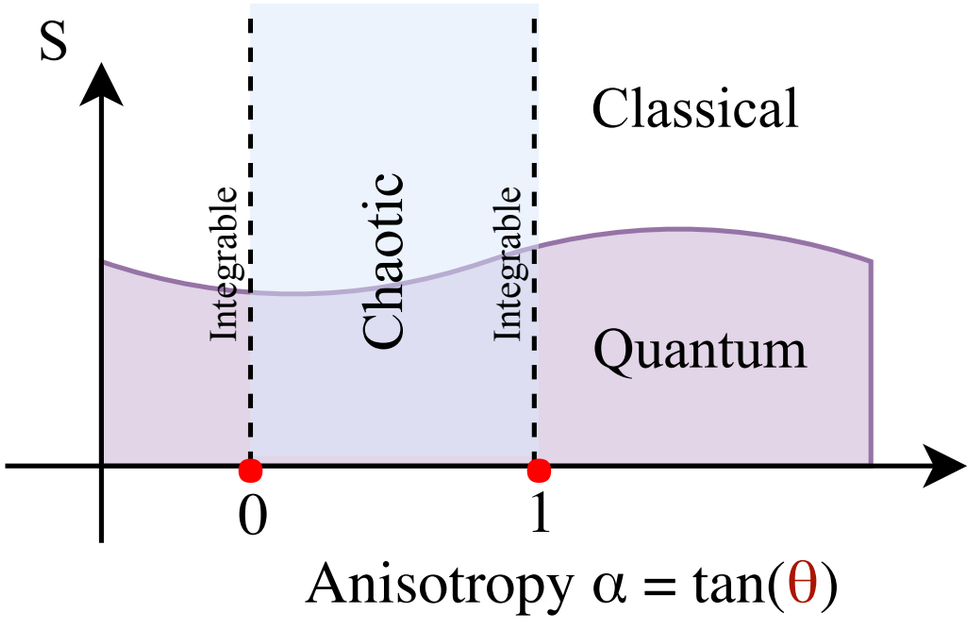

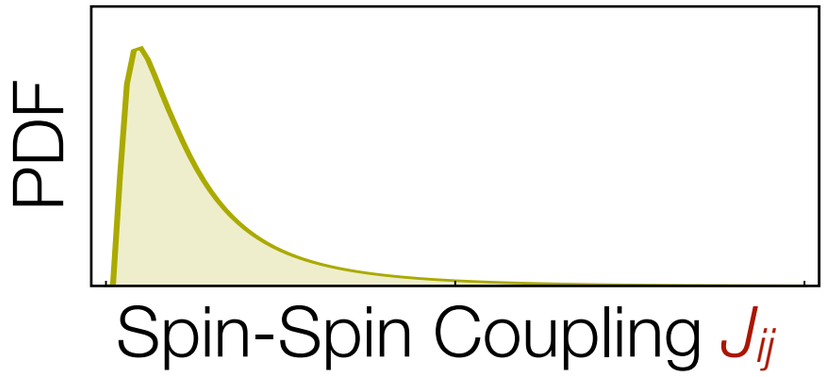

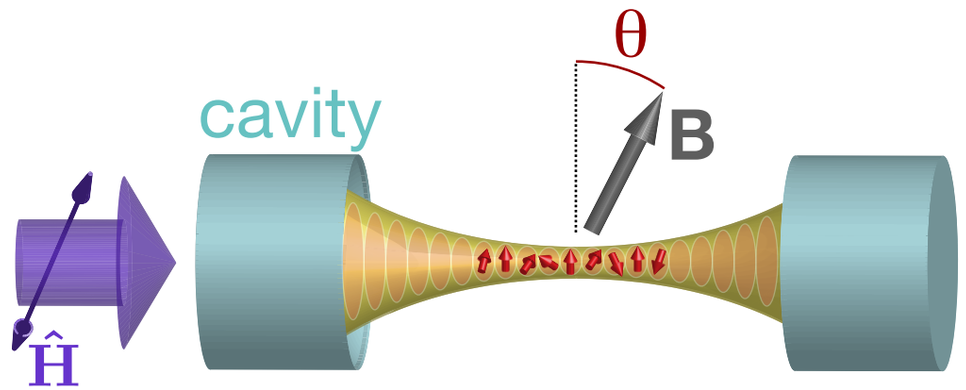

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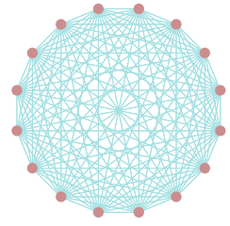

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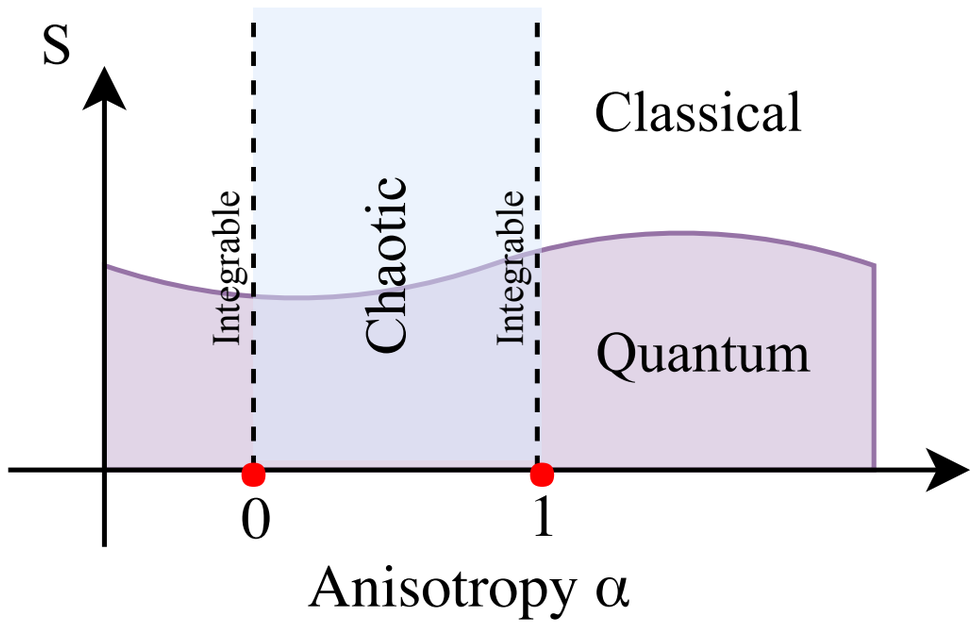

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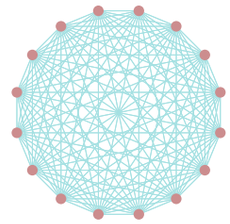

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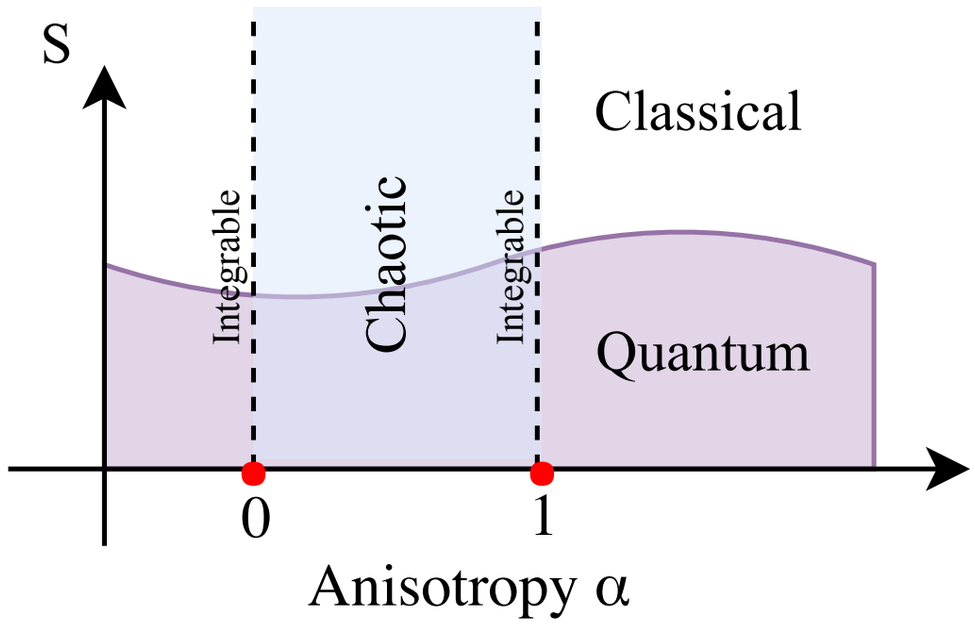

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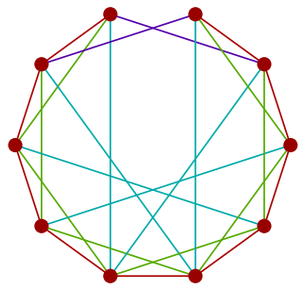
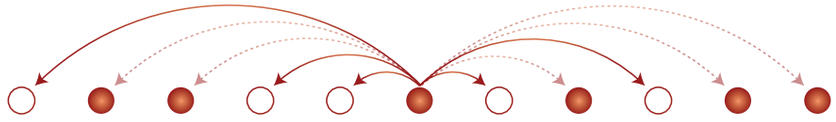
More broadly: how does the structure of interactions…

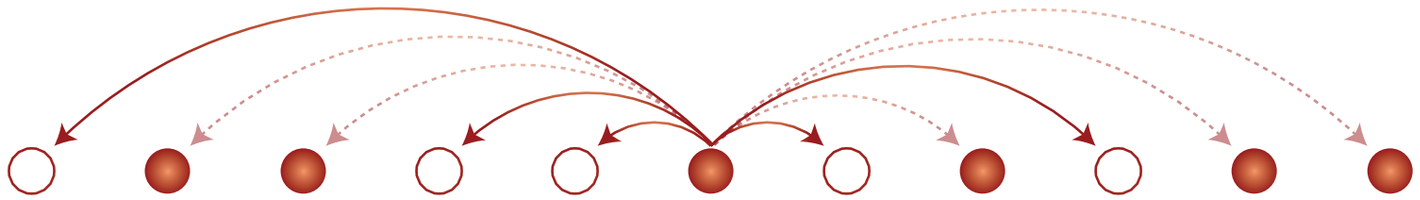


…govern *whether* and *how fast* quantum correlations spread?



Vision: Programmable Interactions

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



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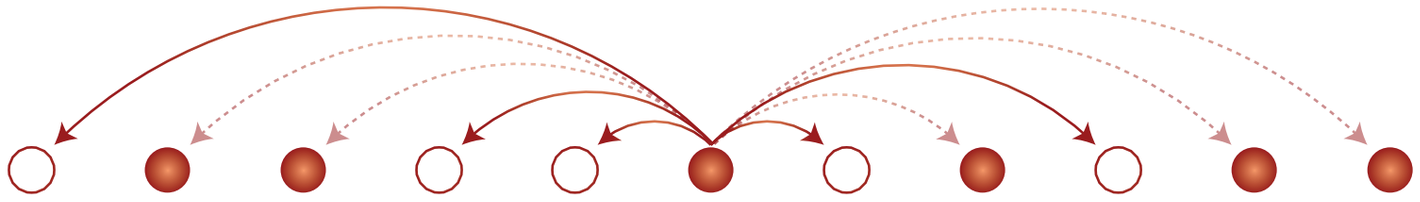

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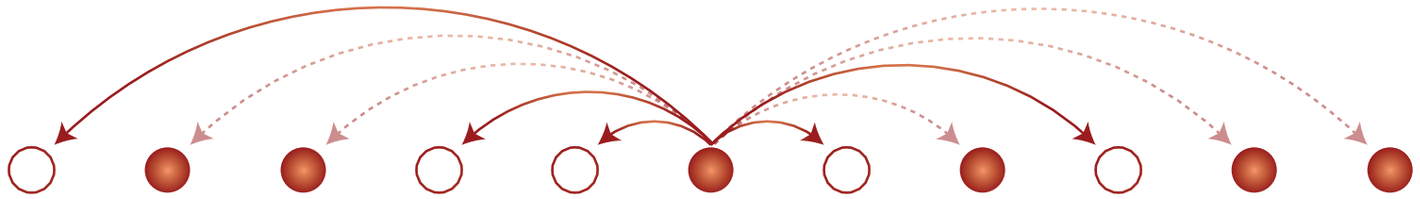

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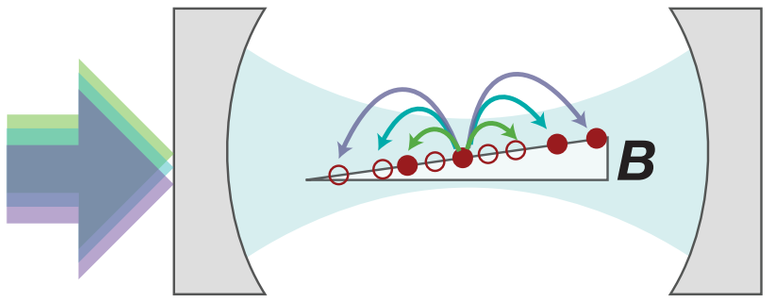
Approach:

- Suppress hopping with magnetic field gradient
- Restore hopping at *arbitrary* distances *i-j* with modulated control field



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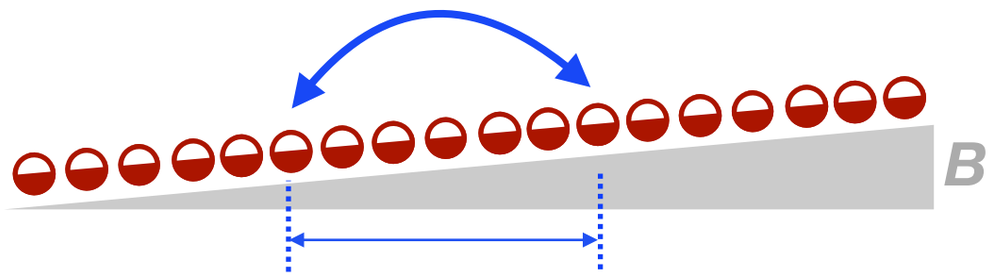
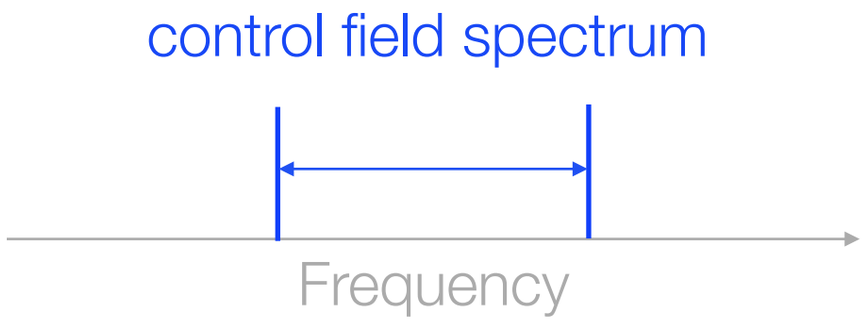
Spatial Control of Spin-Exchange Interactions





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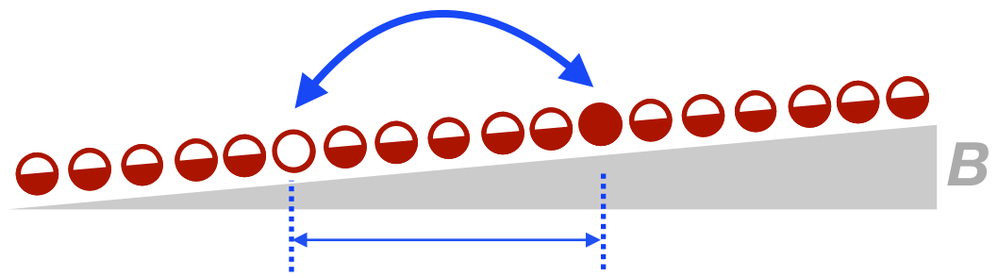

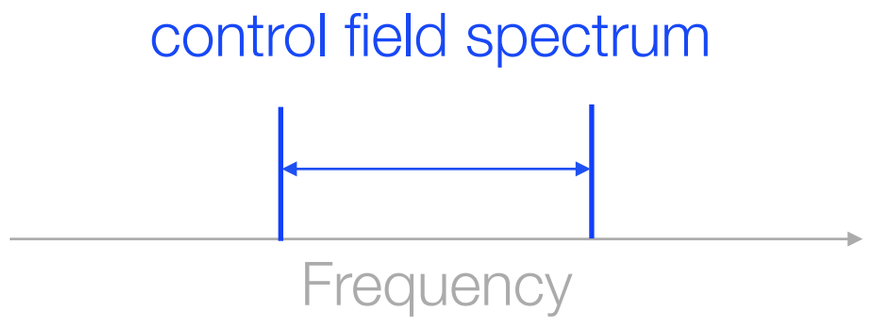

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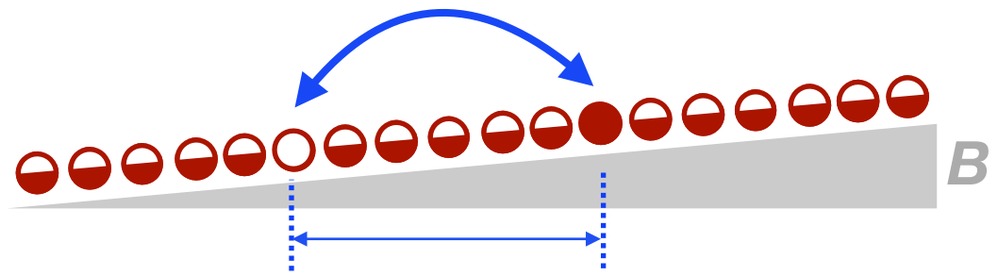
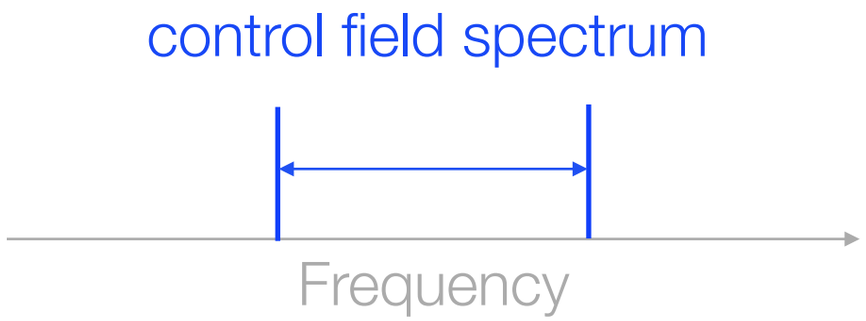
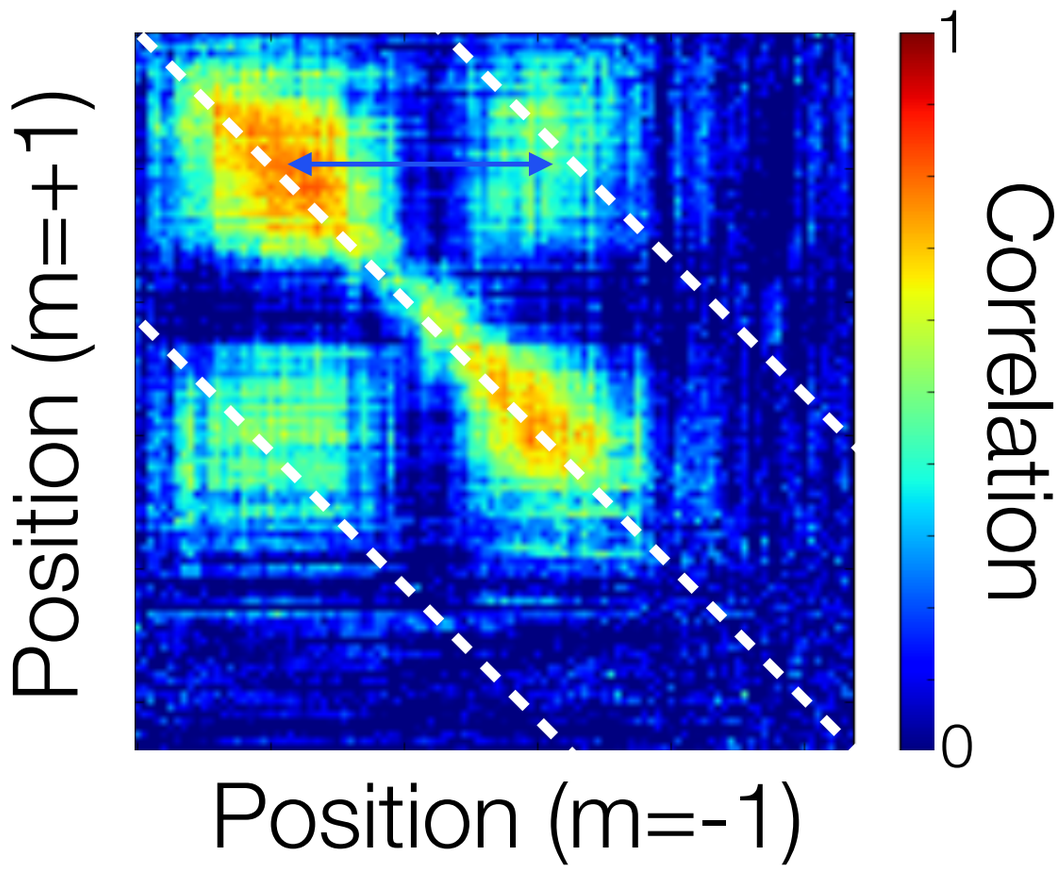


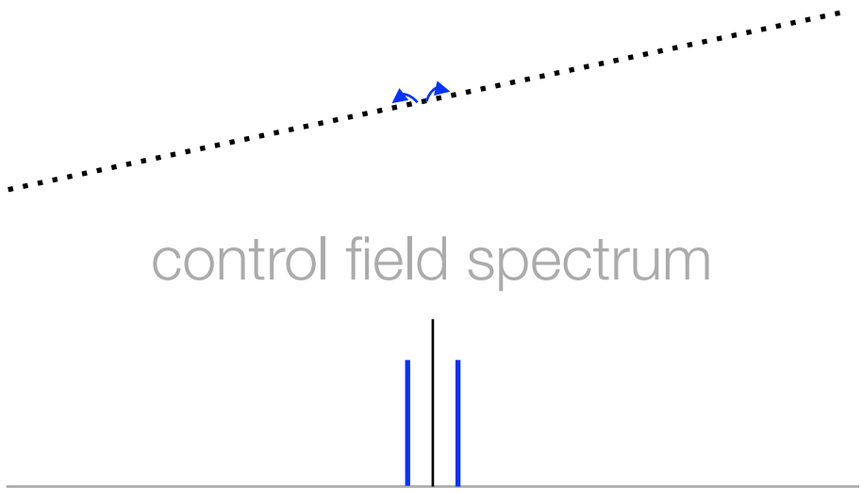




Prospect: Dispersion Engineering

Efficiently spread information over long distances

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



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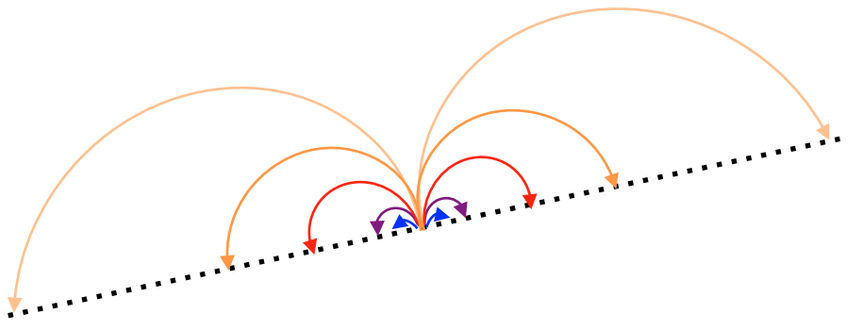
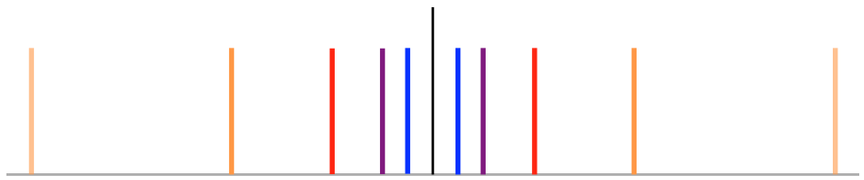


control field spectrum



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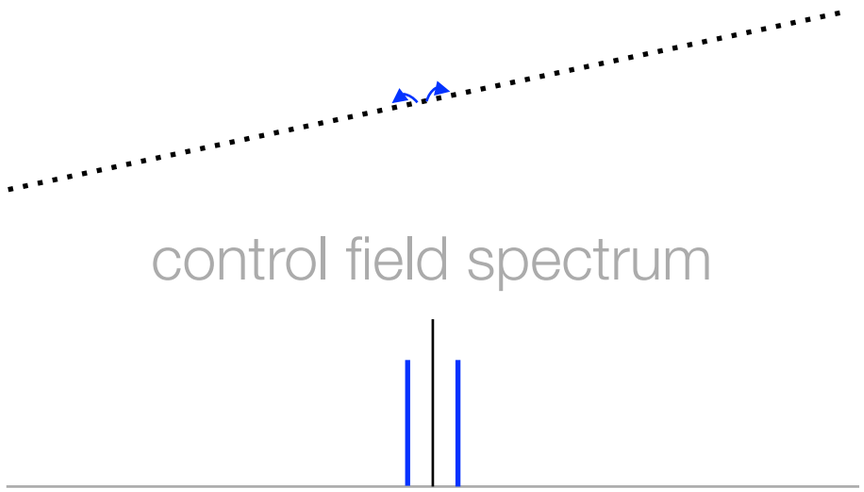

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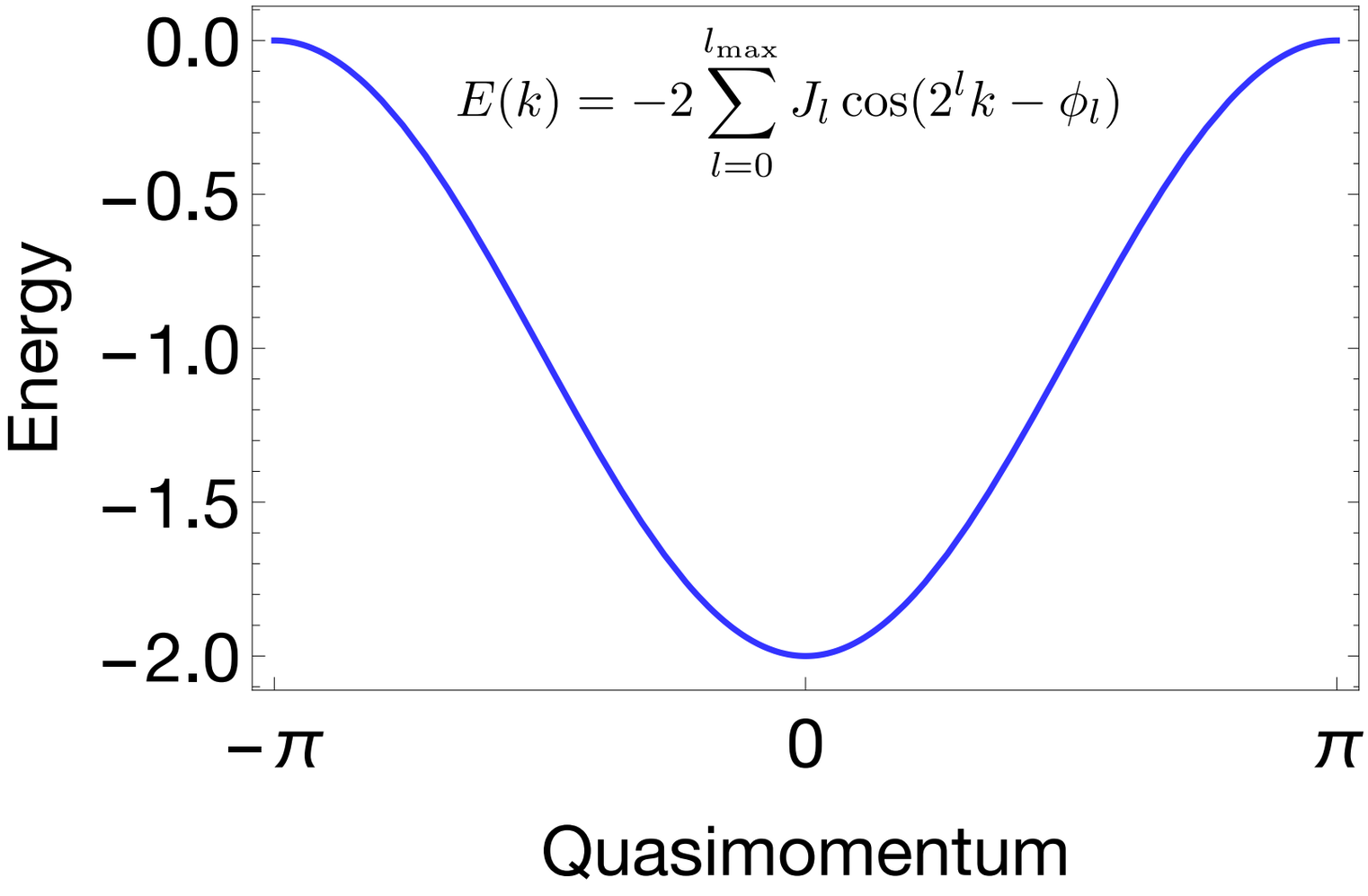

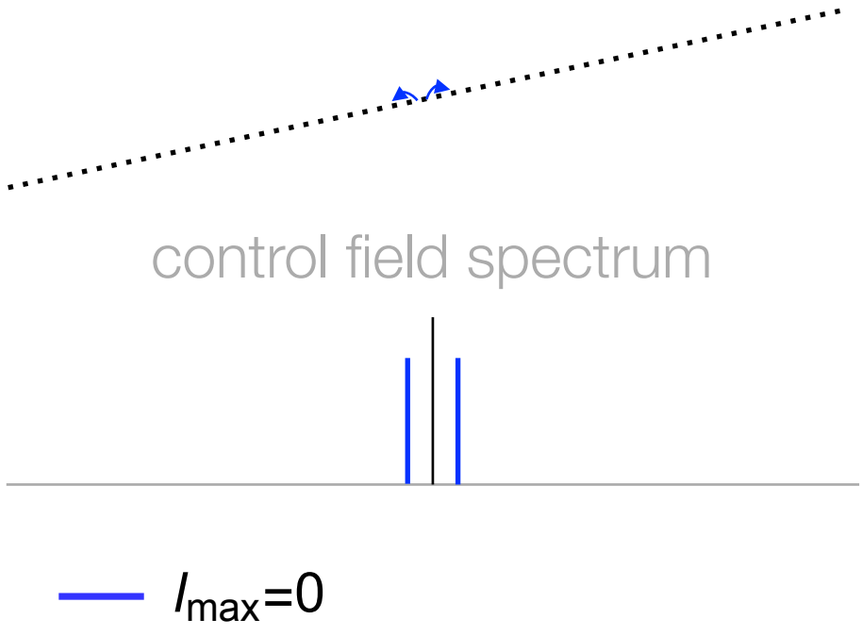

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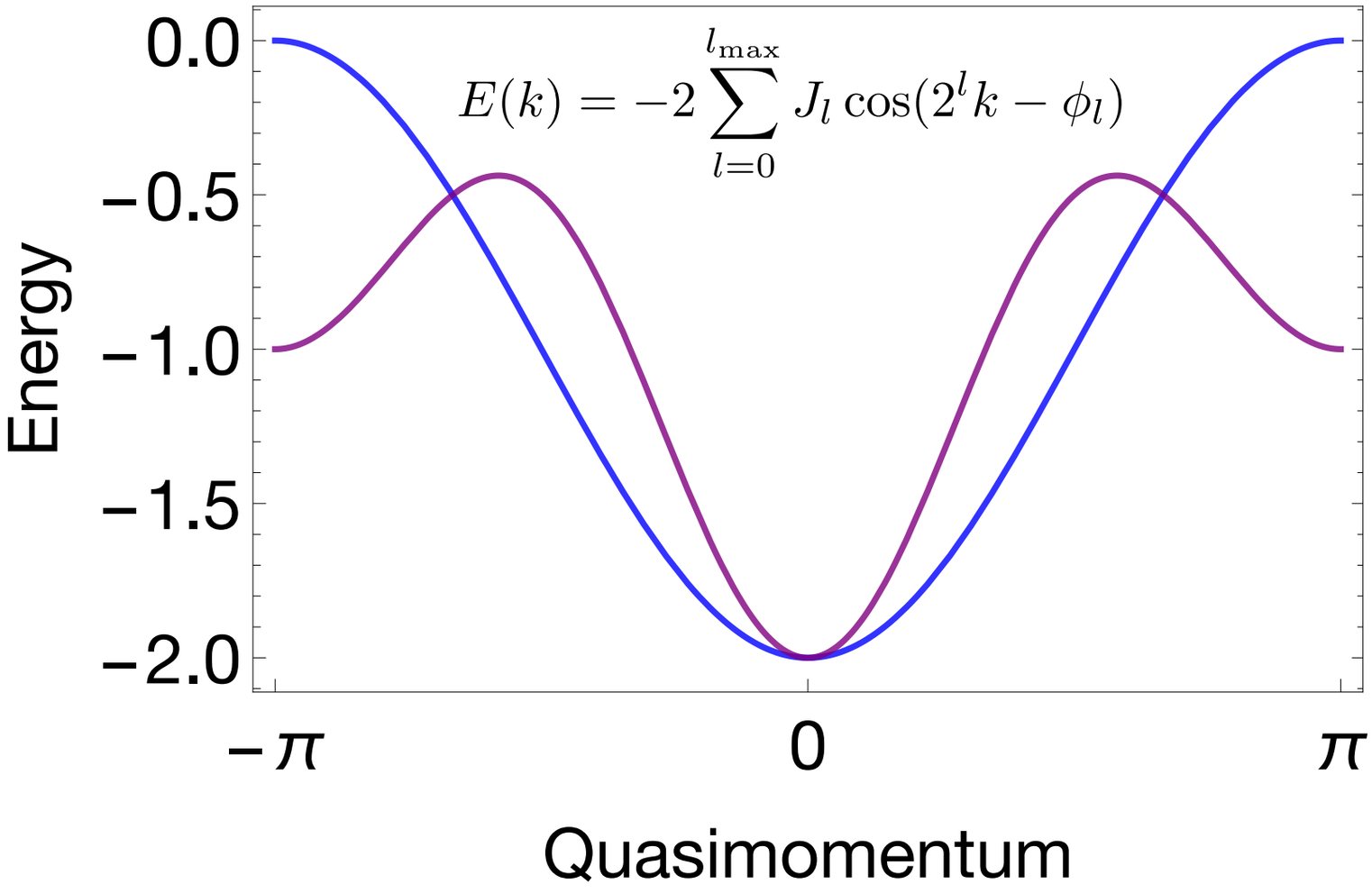

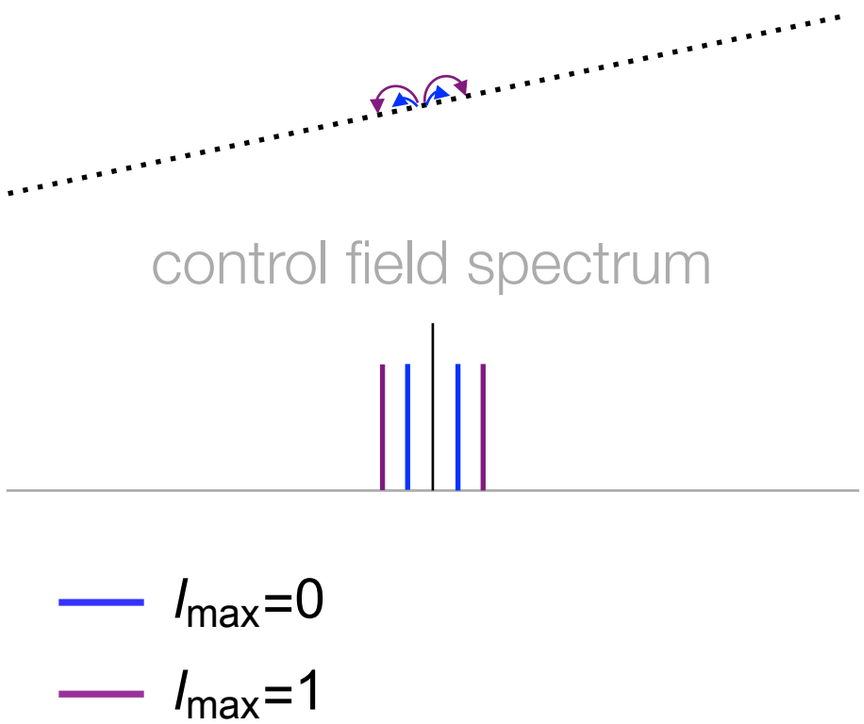

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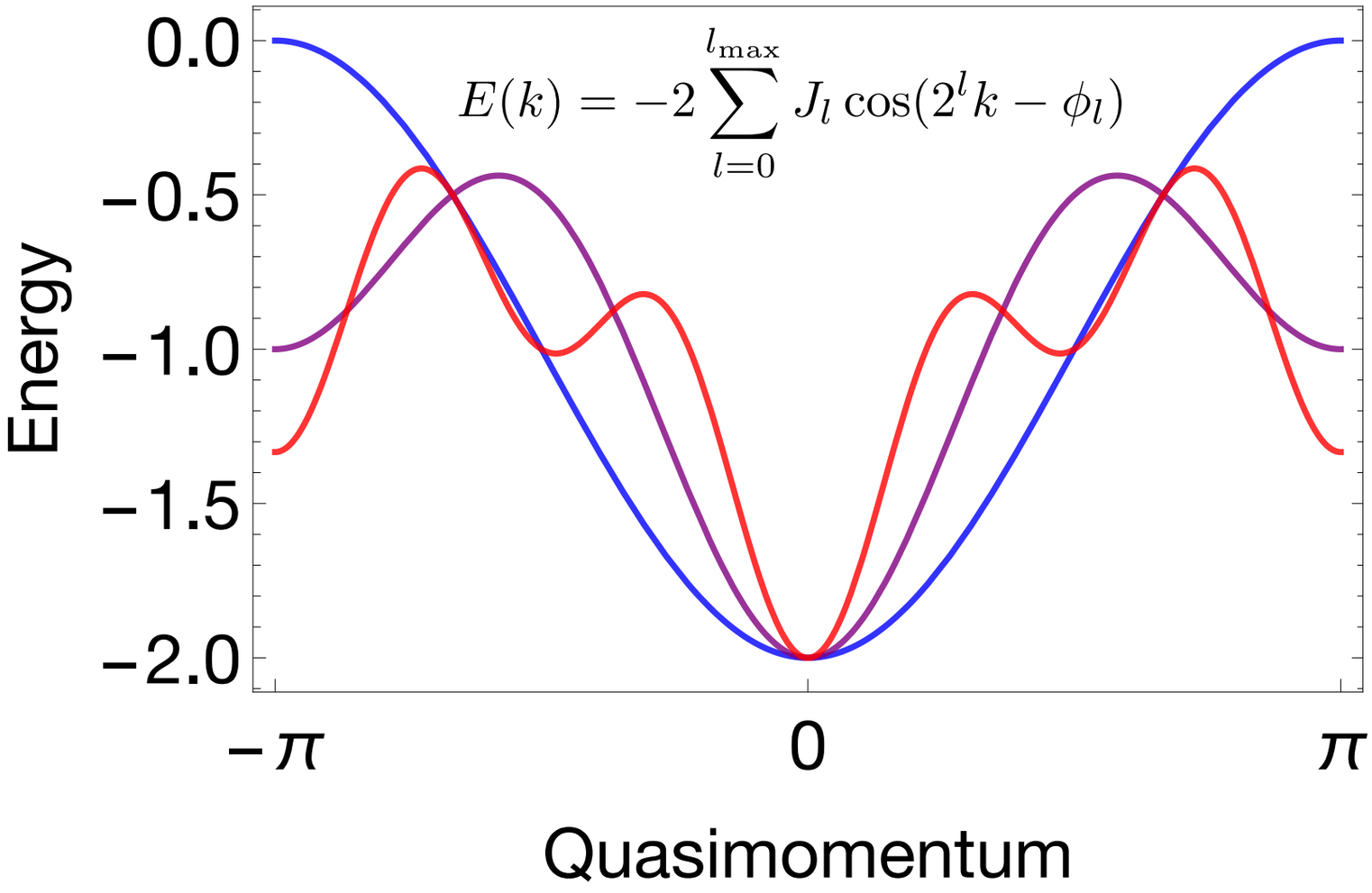

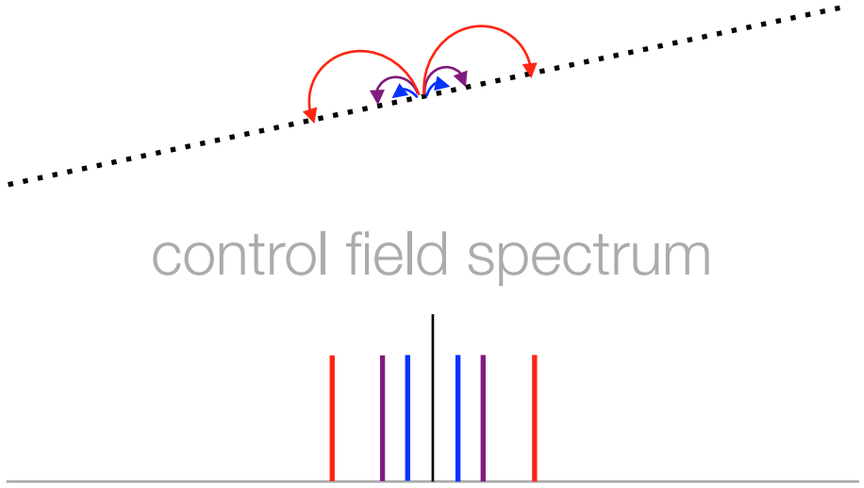

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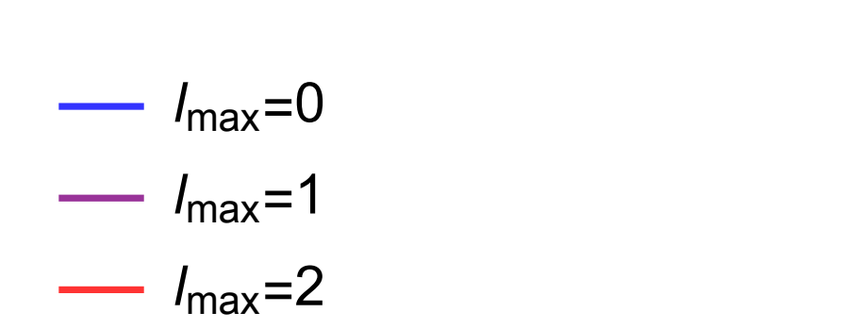

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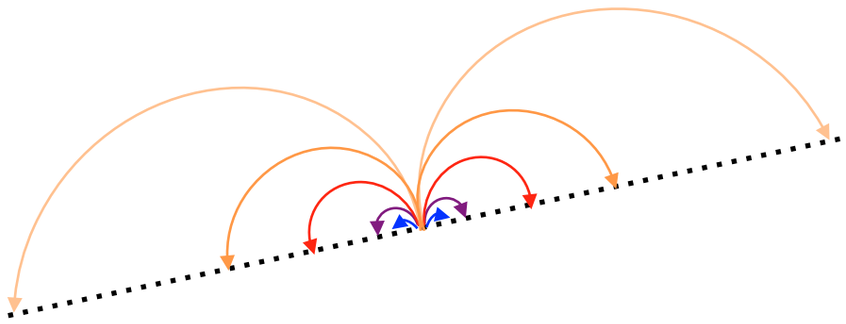
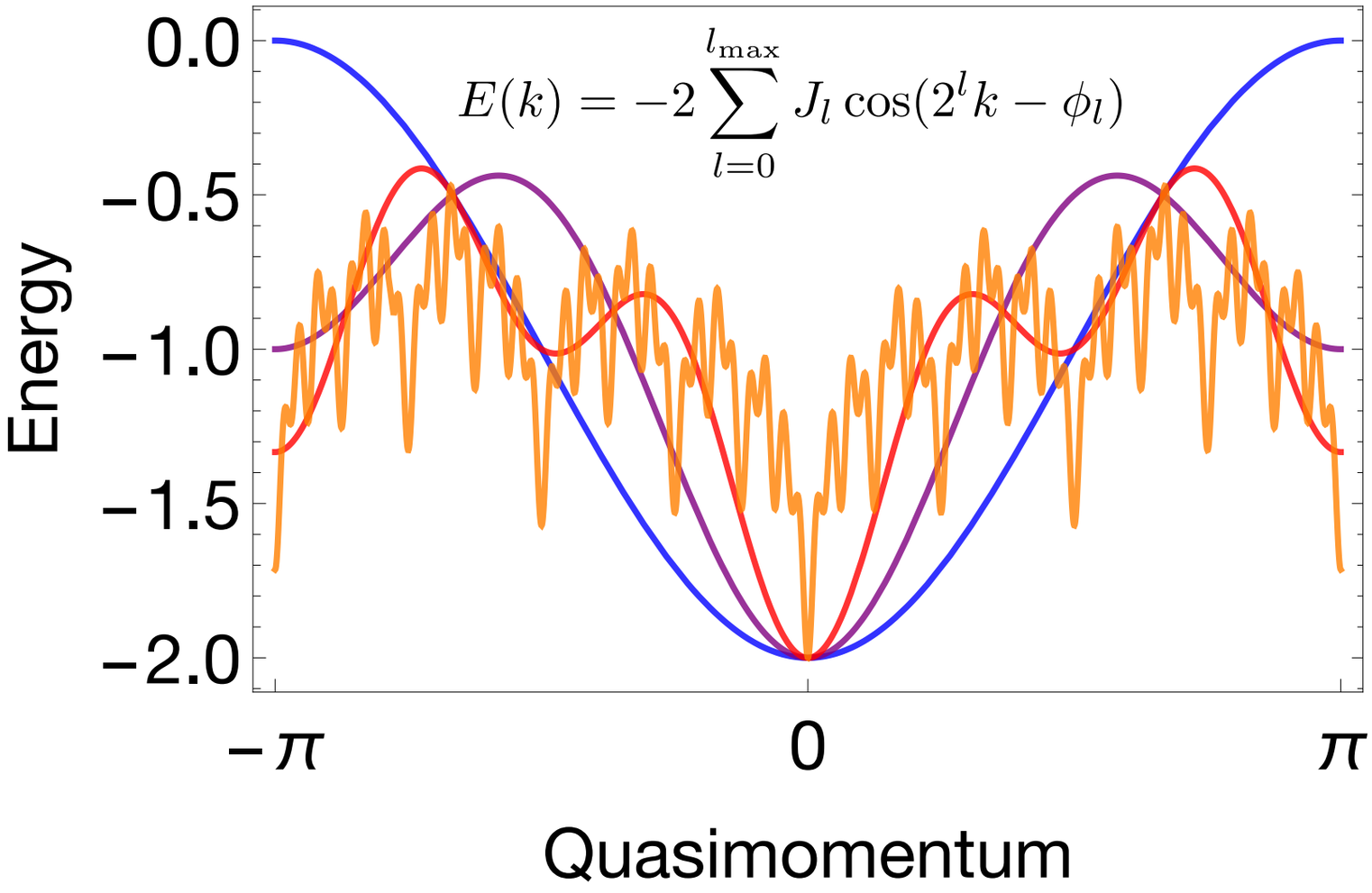
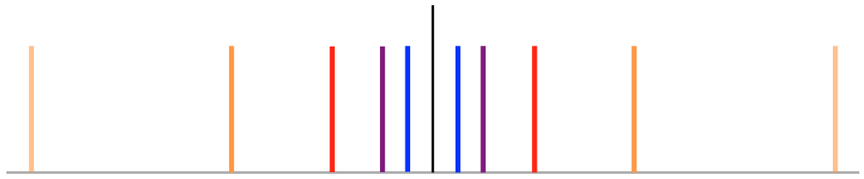
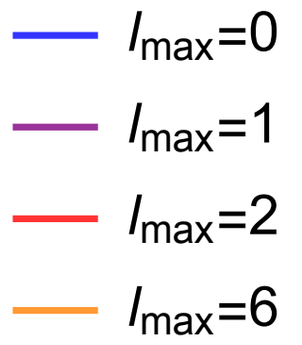




control field spectrum





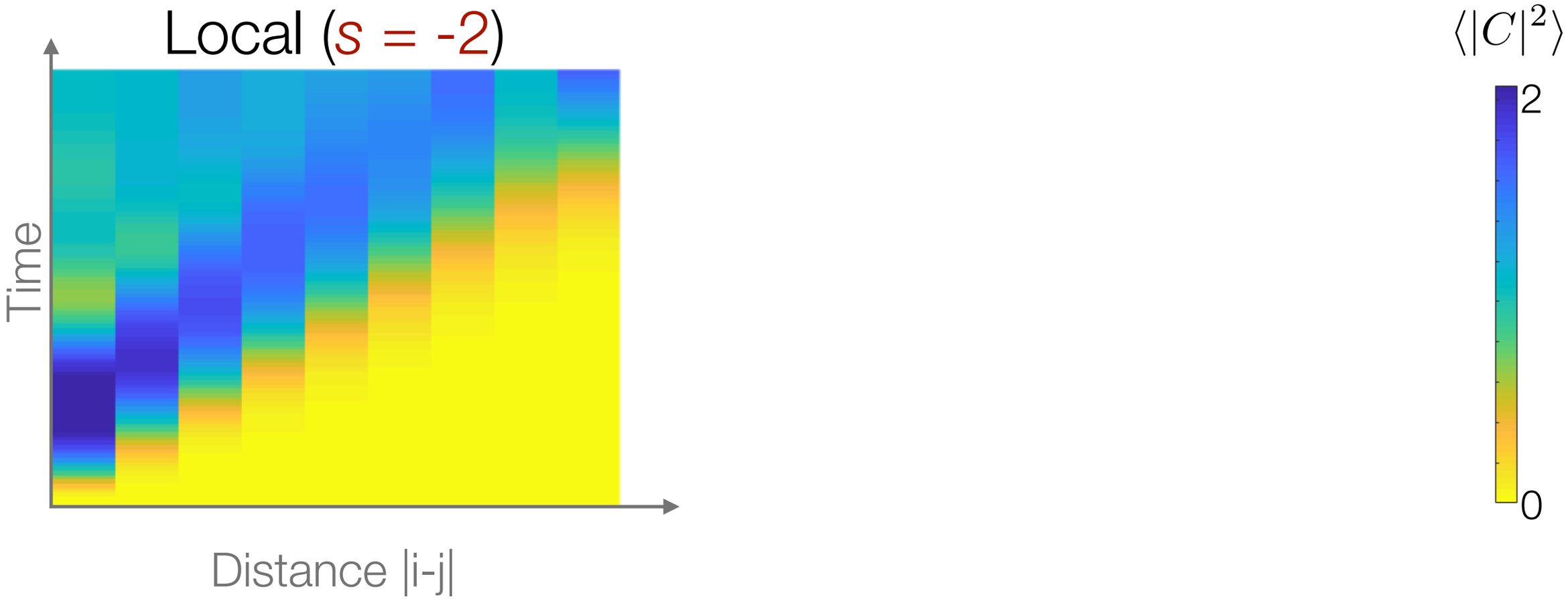
Dispersion relation is a fractal!

Fast Scrambling?

Theory, N = 10 sites

Growth of commutator $C = [V_i, V_j]$ between local operators at sites i, j

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



See Bentsen, Gu & Lucas, *arXiv*:1805.08215, for L-R bound on sparse graph.

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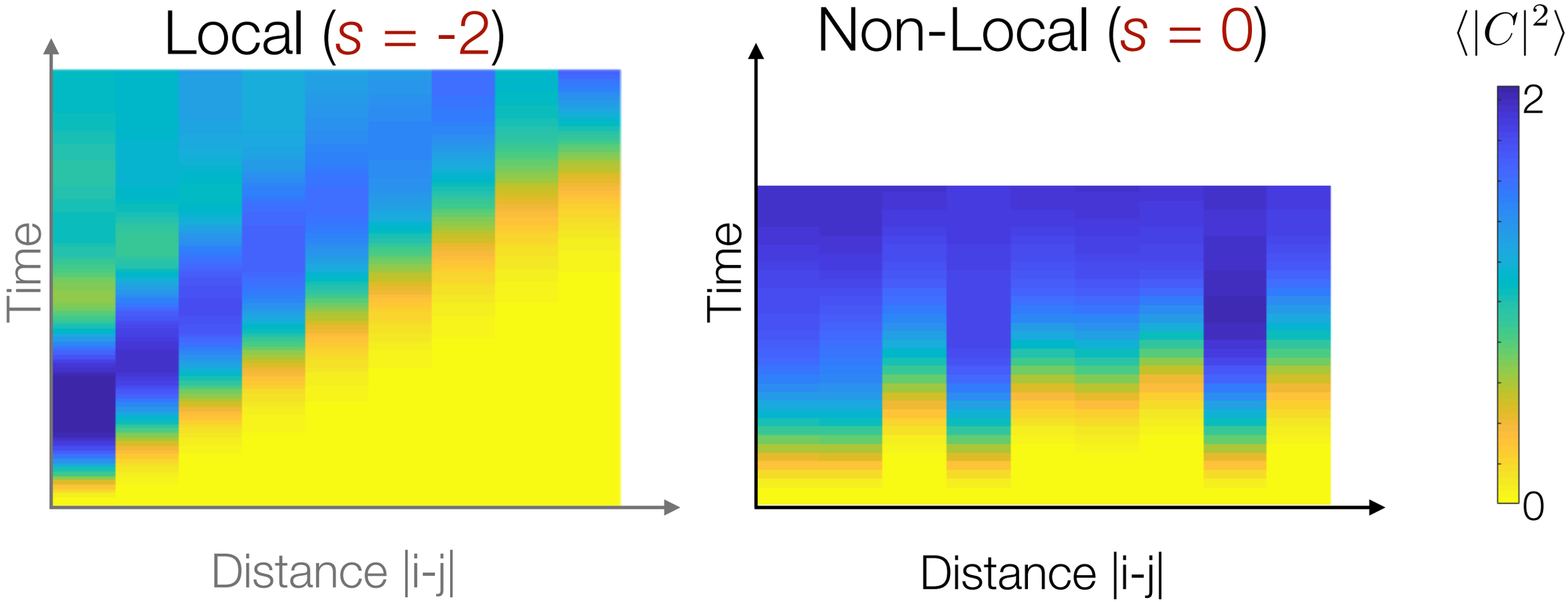

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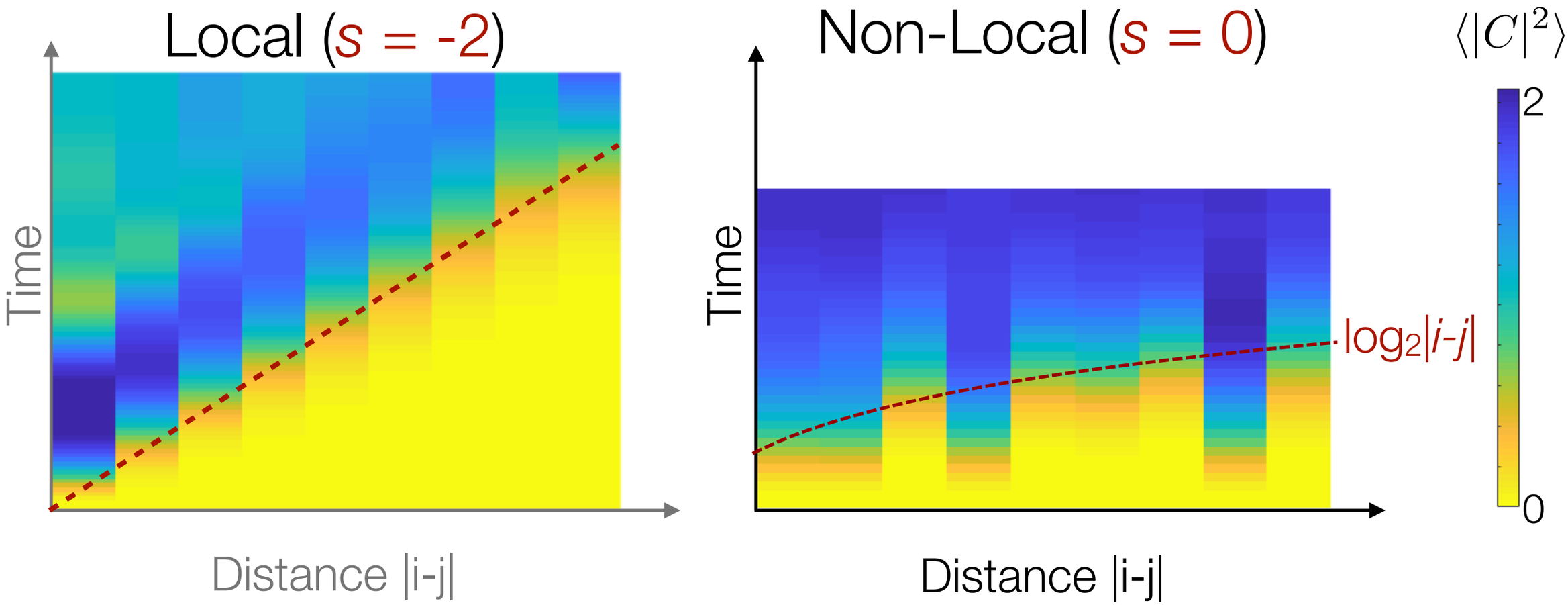

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Geometrical Interpretation

Collaborator: S. Gubser

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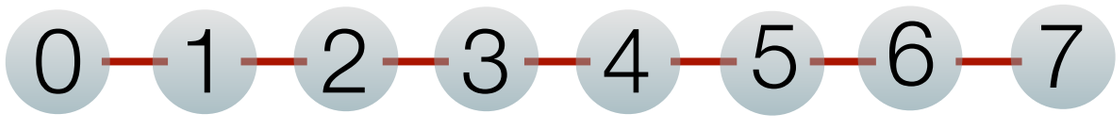

local in real space

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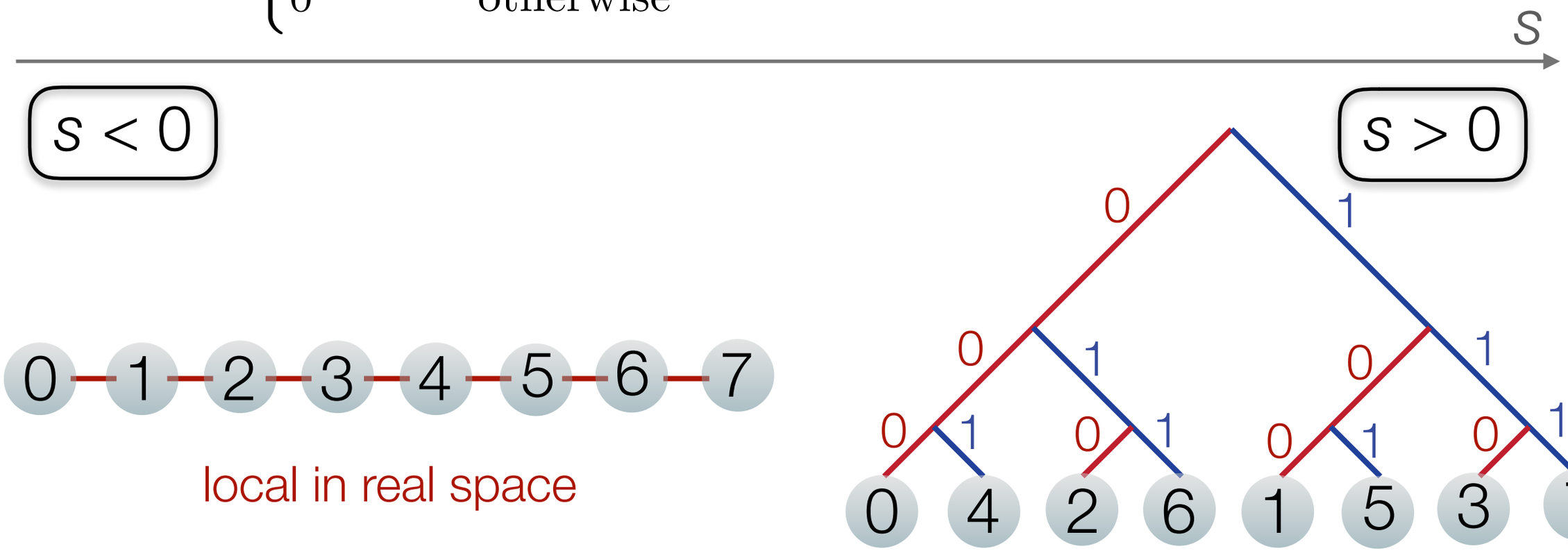

F. J. Dyson, *Commun. Math. Phys.* (1969).
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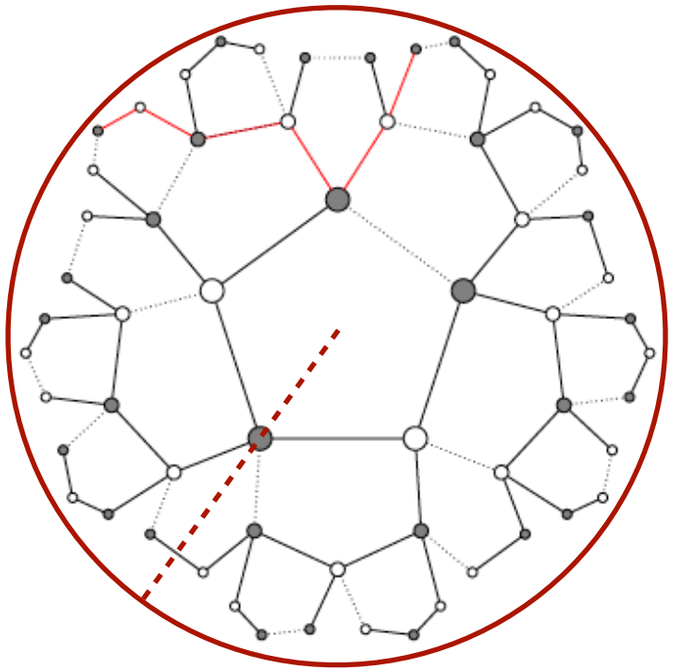
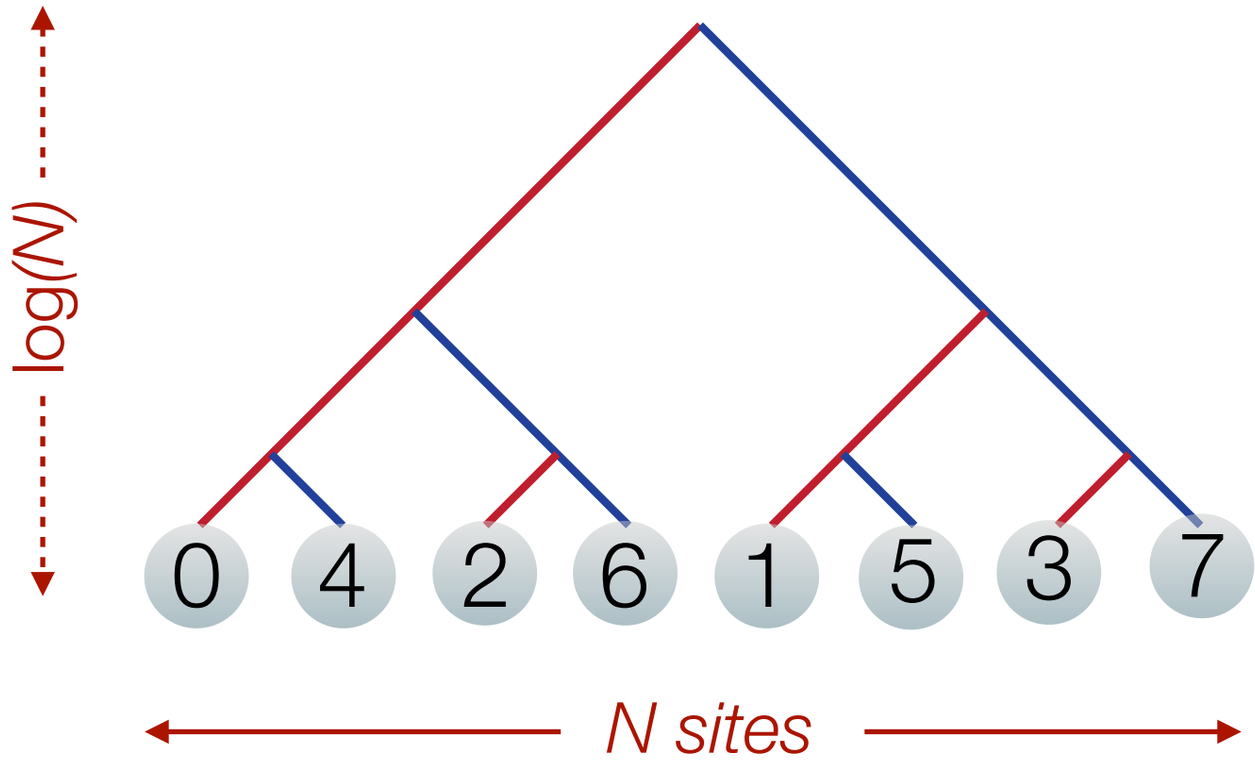
Bruhat-Tits tree = discrete version of anti de Sitter space

⇒ toy model for quantum gravity





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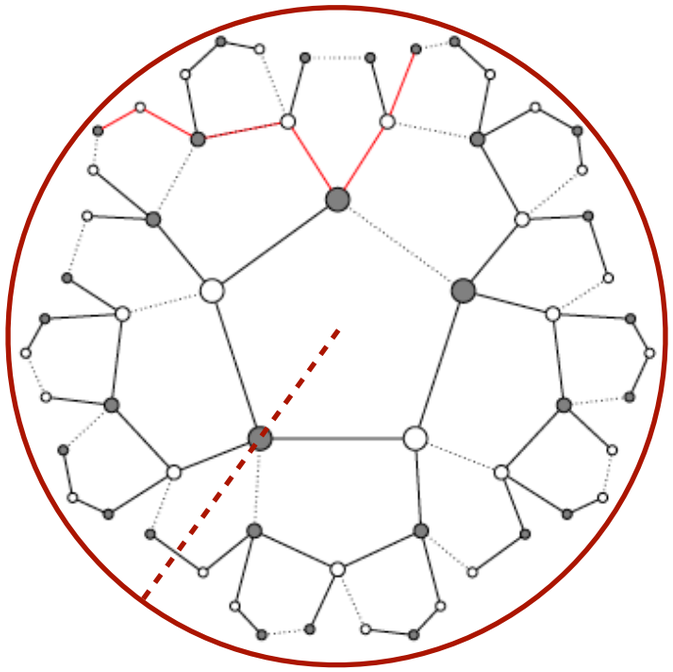
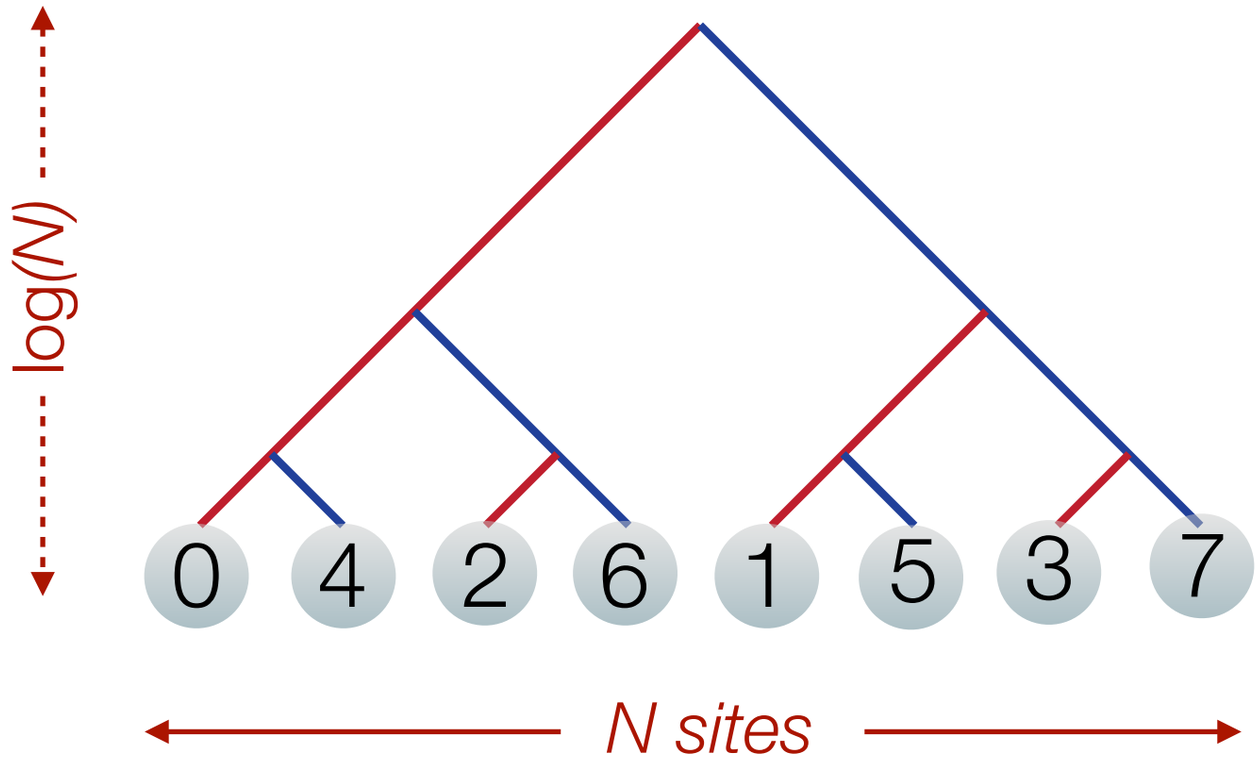


Heydeman *et al, arXiv* (2017).



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Tunable Geometry

G. Bentsen, T. Hashizume, A. Buyskikh,
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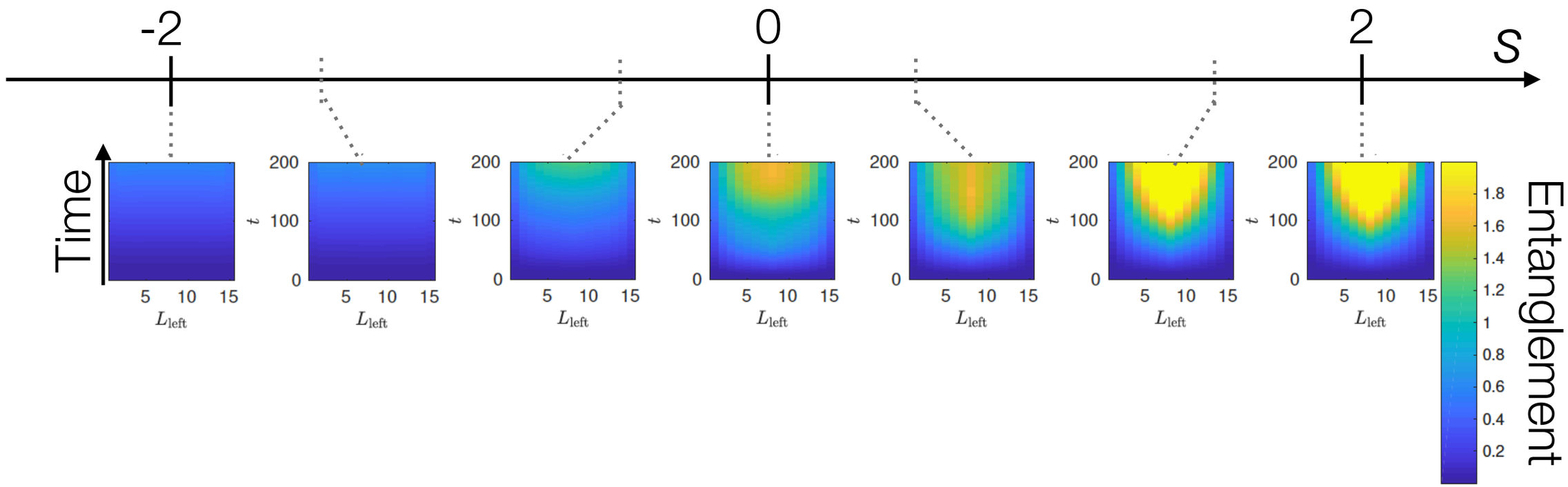

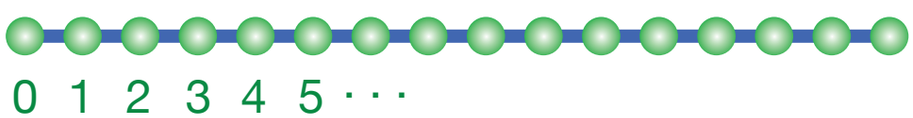

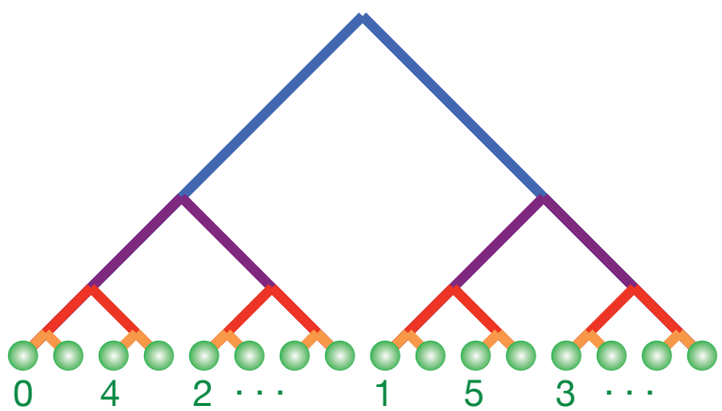

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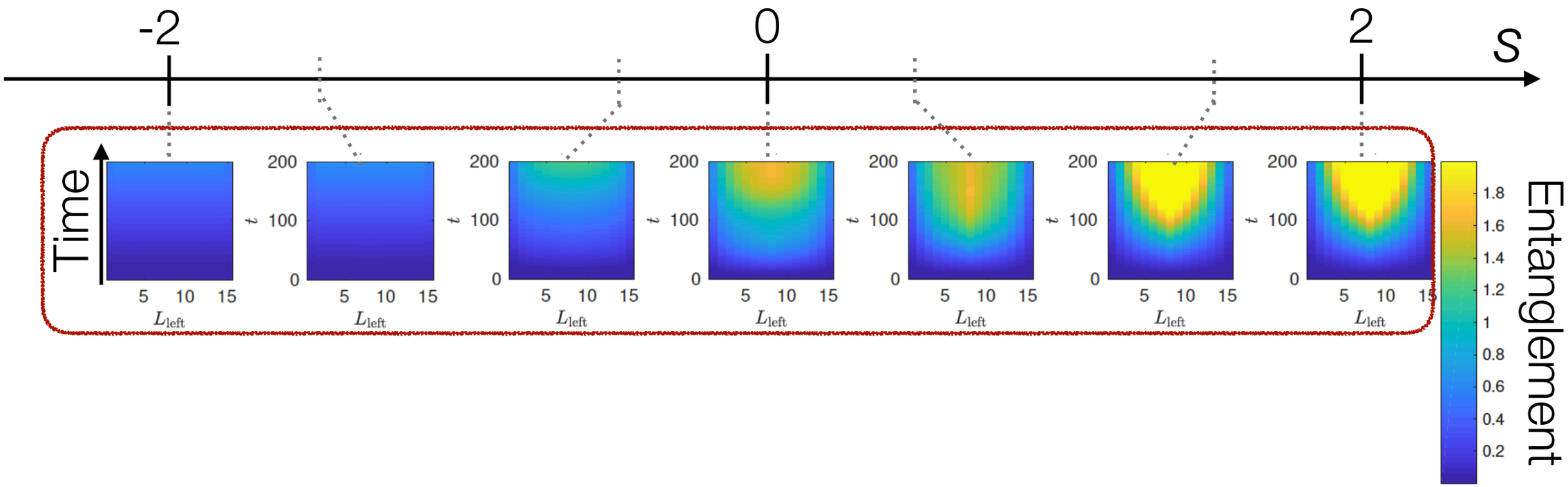

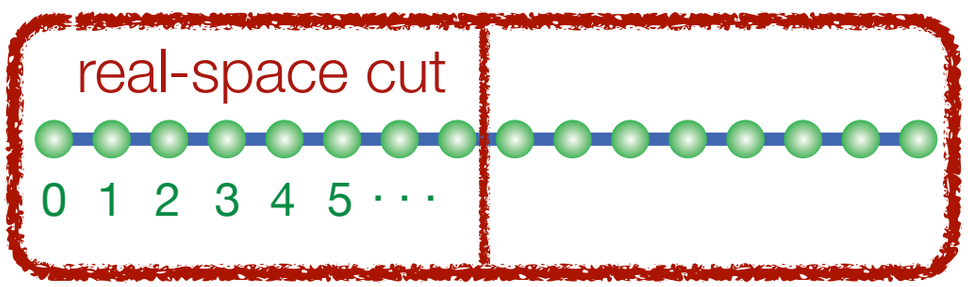

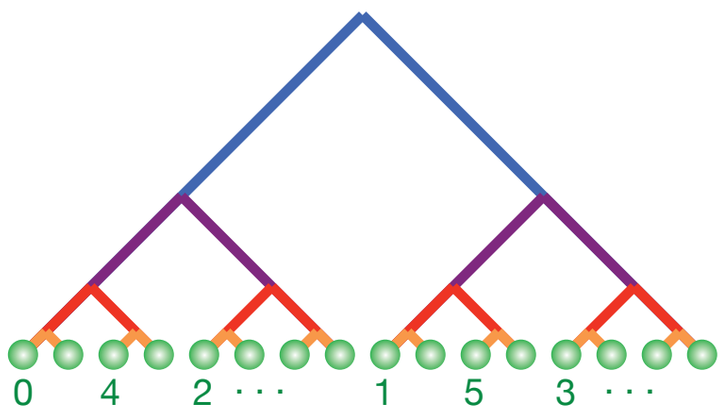

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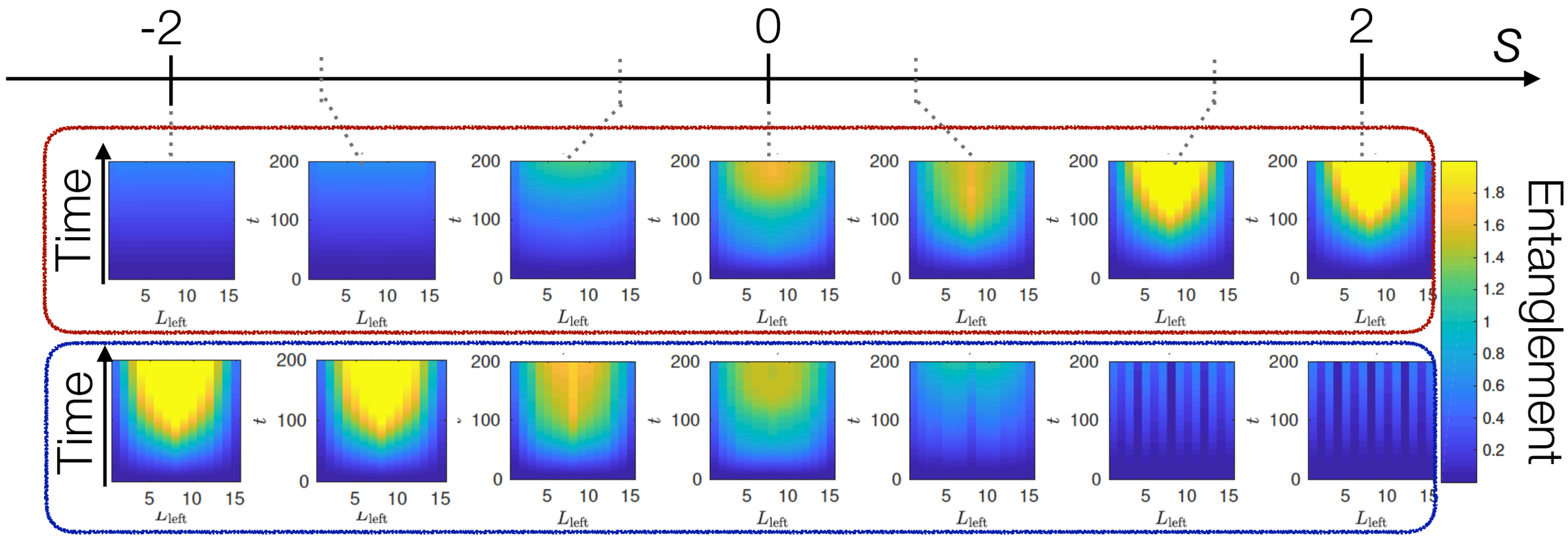

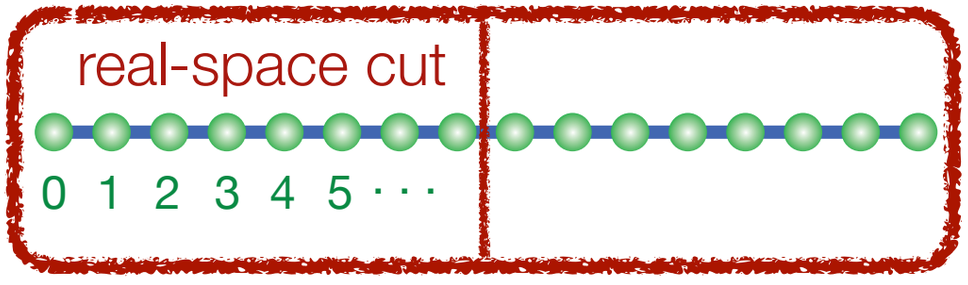

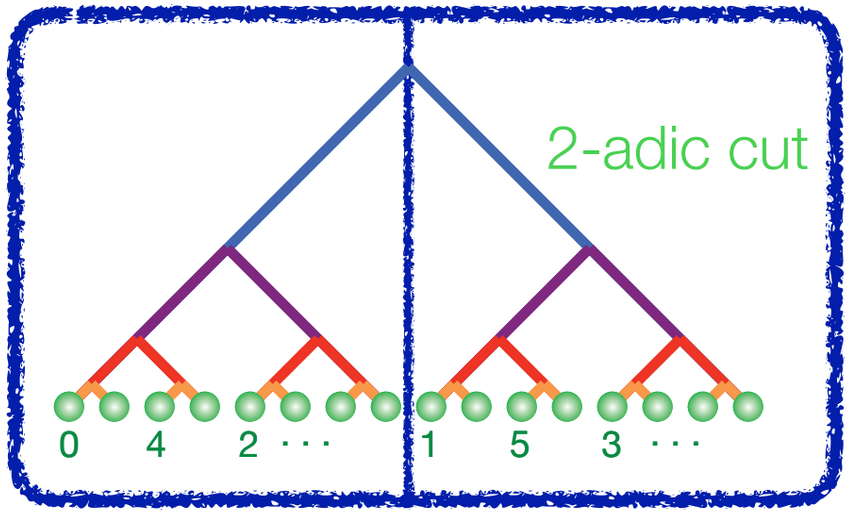

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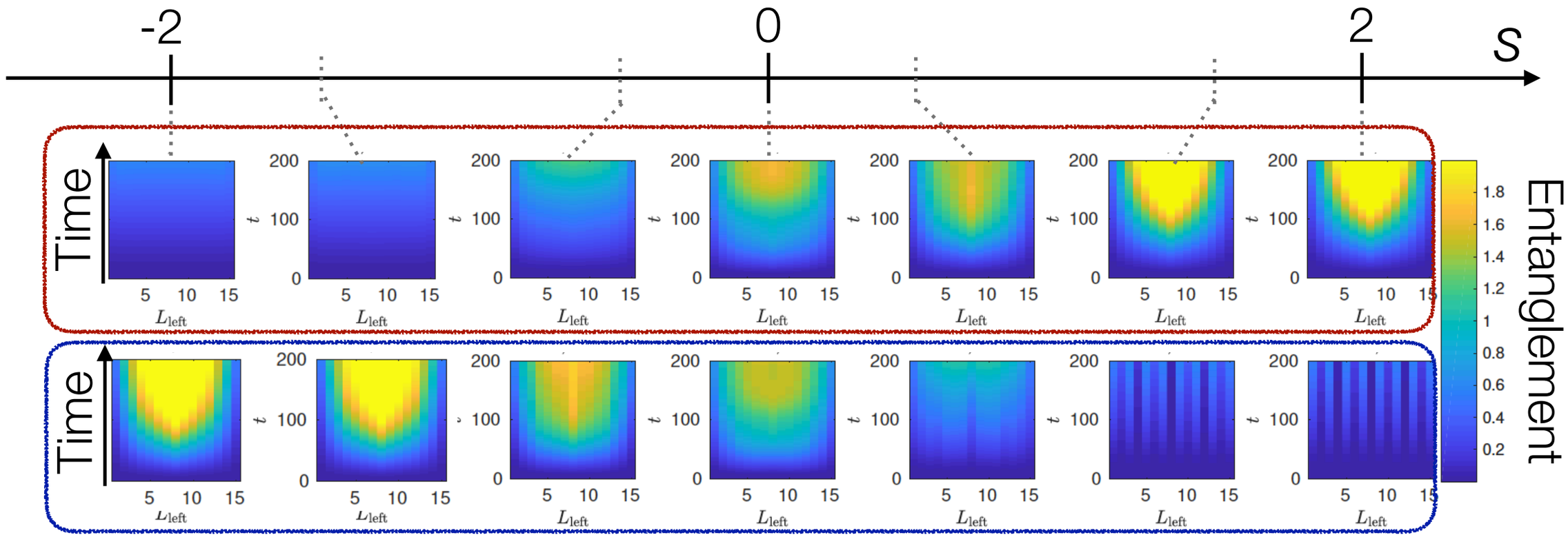
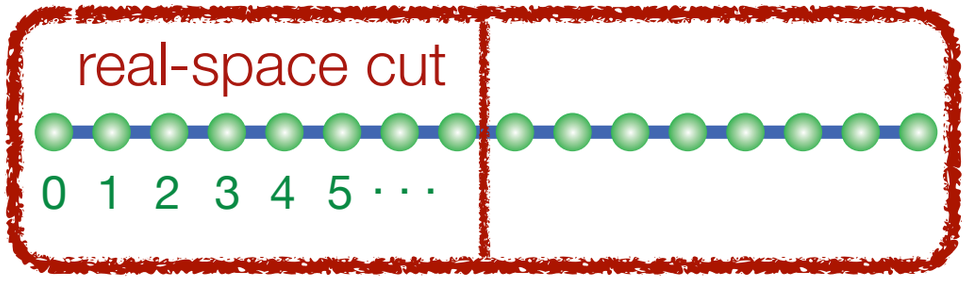
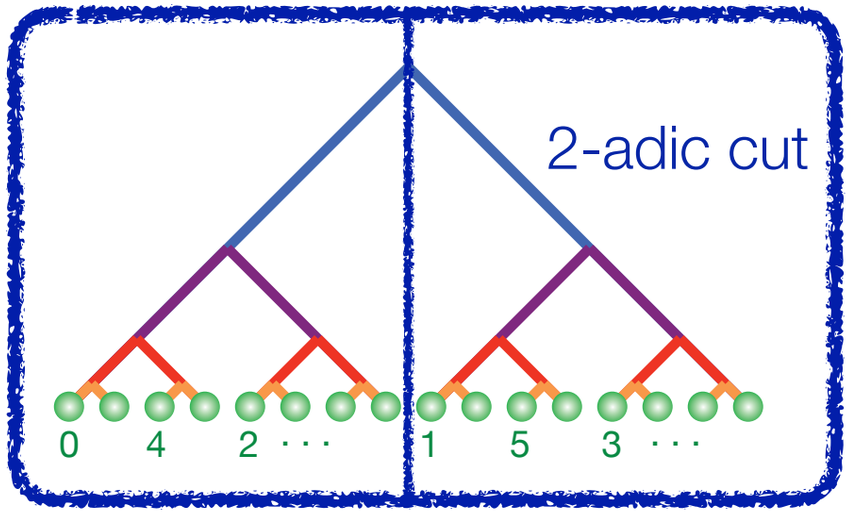






Summary & Outlook

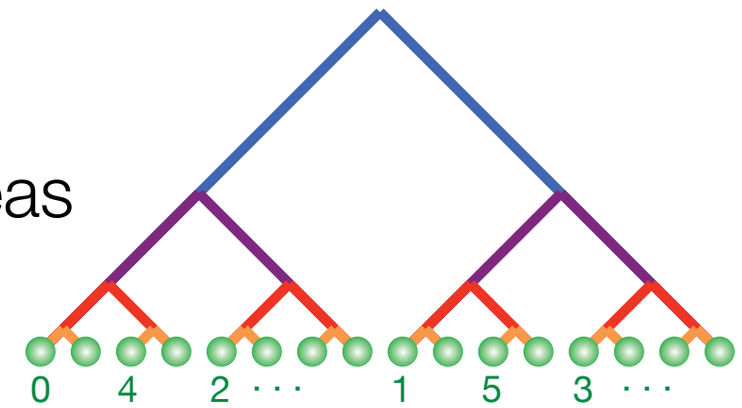
- Can engineer all-to-all spin models with non-trivial couplings

- Switchable sign + local addressing + imaging
  ⇒ watch operators grow?

- Images contain information about (multi-point) spin correlations…
  ⇒ signatures of complexity of quantum states?

  ⇒ reconstruction of bulk geometry?

- Simple toy models will help to explore these ideas



Acknowledgements

Research Group

Emily Davis
Gregory Bentsen
Tori Borish
Ognjen Markovic
Jacob Hines
Avikar Periwal
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Simon Evered
Katherine Van Kirk

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