Simulations of Magnetic Spin Phases with Atoms/Ions/Molecules

D. Stamper-Kurn, A. Vishwanath, J. Moore	U. California, Berkeley
R. Scalettar	U. California, Davis
C. Chin	U. Chicago
A. Rey, J. Ye	U. Colorado/JILA
J. Freericks	Georgetown
R. Slusher	Georgia Tech
C. Monroe, T. Porto, I Spielman, W. Phillips	JQI/U. Maryland/NIST
I. Cirac	Max Planck Inst. for Q. Opt.
J. Bollinger	NIST-Boulder
L.-M. Duan	U. Michigan
J. Ho	Ohio State

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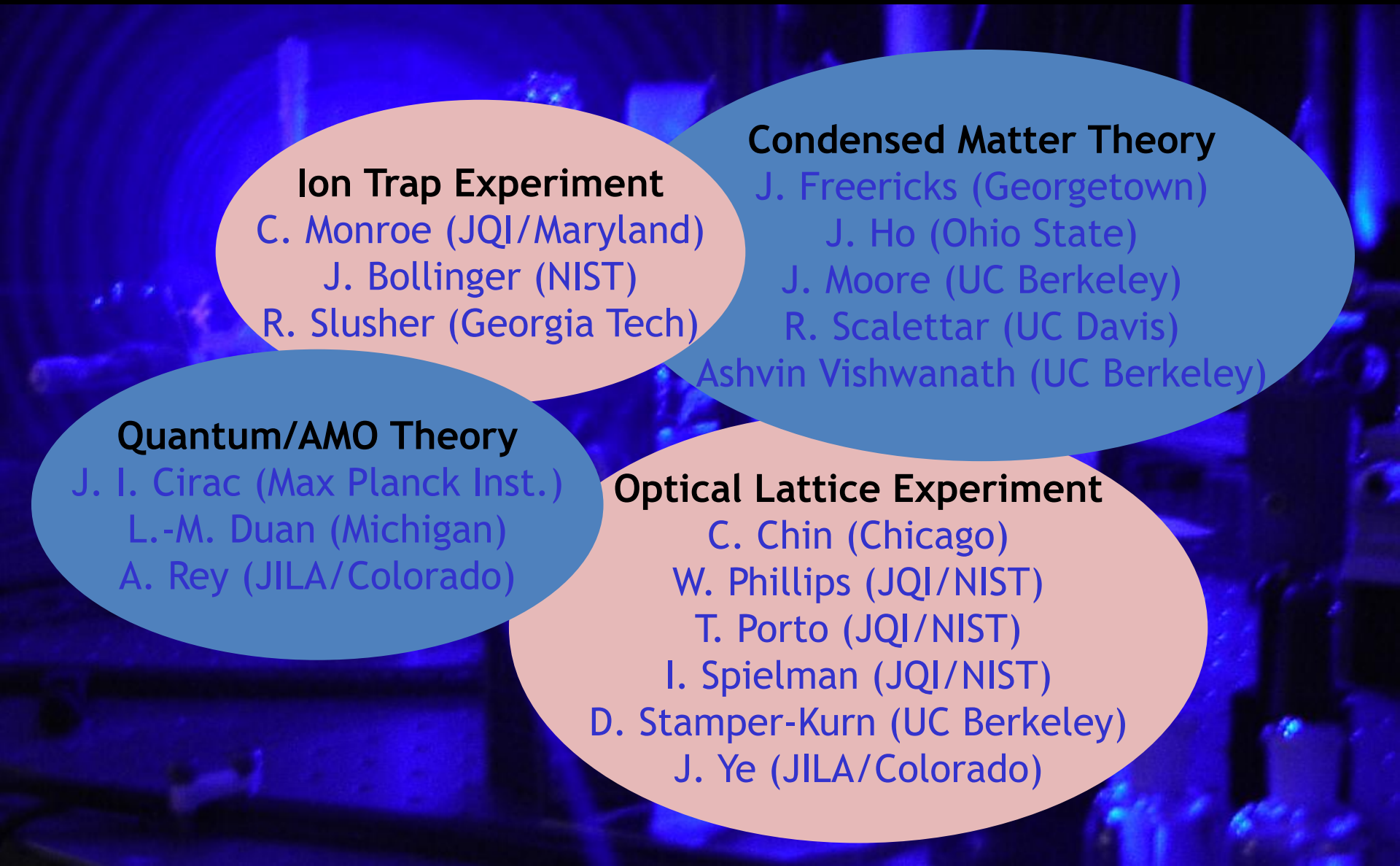
OLE OPTICAL LATTICE EMULATOR

Simulations of Magnetic Spin Phases with Atoms/Ions/Molecules



Ion Trap Experiment
C. Monroe (JQI/Maryland)
J. Bollinger (NIST)
R. Slusher (Georgia Tech)

Condensed Matter Theory
J. Freericks (Georgetown)
J. Ho (Ohio State)
J. Moore (UC Berkeley)
R. Scalettar (UC Davis)
Ashvin Vishwanath (UC Berkeley)

Quantum/AMO Theory
J. I. Cirac (Max Planck Inst.)
L.-M. Duan (Michigan)
A. Rey (JILA/Colorado)

Optical Lattice Experiment
C. Chin (Chicago)
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T. Porto (JQI/NIST)
I. Spielman (JQI/NIST)
D. Stamper-Kurn (UC Berkeley)
J. Ye (JILA/Colorado)

Quantum Magnetism with Atoms/Ions/Molecules

Chris Monroe *JQI and University of Maryland*	*5*	*Introdution*
Crystal Senko *JQI and University of Maryland*	*20*	*Quantum Simulations of Magnetism: Beyond Adiabaticity*
Kaden Hazzard *JILA and University of Colorado*	*20*	*Strongly Correlated Quantum Magnetism with Molecules*
Dan Campbell *JQI and NIST*	*15*	*Gauge Fields in Optical Lattices*
Jason Ho *Ohio State University*	*15*	*Quantum Simulation, synthetic Gauge Fields, and Exotic Quantum Matter in Box Potentials*

BREAK

Trey Porto *JQI and NIST*	*10*	*Engineering Dissipation in Quantum Gas Mixtures*
Cheng Chin *University of Chicago*	*20*	*Stable Z2 Superfluid in Optical Lattices*
Ehsan Khatami *University of Caifornia, Davis*	*15*	*Phase Diagram of the 1/5-Depleted Square Lattice Hubbard Model*
Chris Monroe *JQI and University of Maryland*	*15*	*Summary*

Quantum Simulations of Magnetism: Beyond Adiabaticity

Crystal Senko

DARPA OLE final review, Arlington

Feb. 12, 2014

With P. Richerme, J. Smith, A. Lee, Z.-X. Gong, M. Foss-Feig, A. Gorshkov, and C. Monroe

Joint Quantum Institute and University of Maryland Department of Physics

Quantum simulations of interacting spins with trapped ions

Proof of principle:

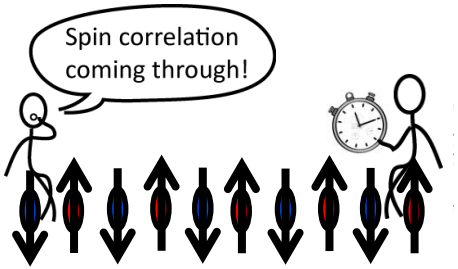
Check!

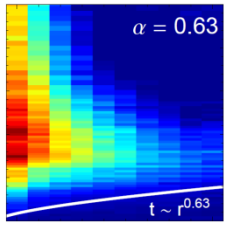
a few particles, a particular Hamiltonian, physics we can predict exactly

Meanwhile, how to further the goal of classically intractable physics?

- Identify physics questions that a small simulator can shed light on

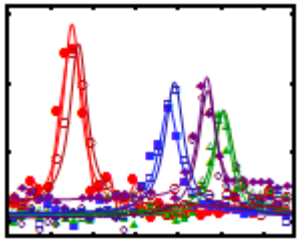
  → Information propagation and Lieb-Robinson bounds

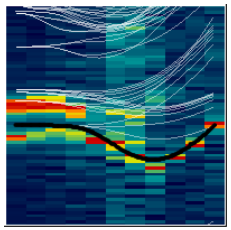




- Develop tools for validation when classical numerics are impossible

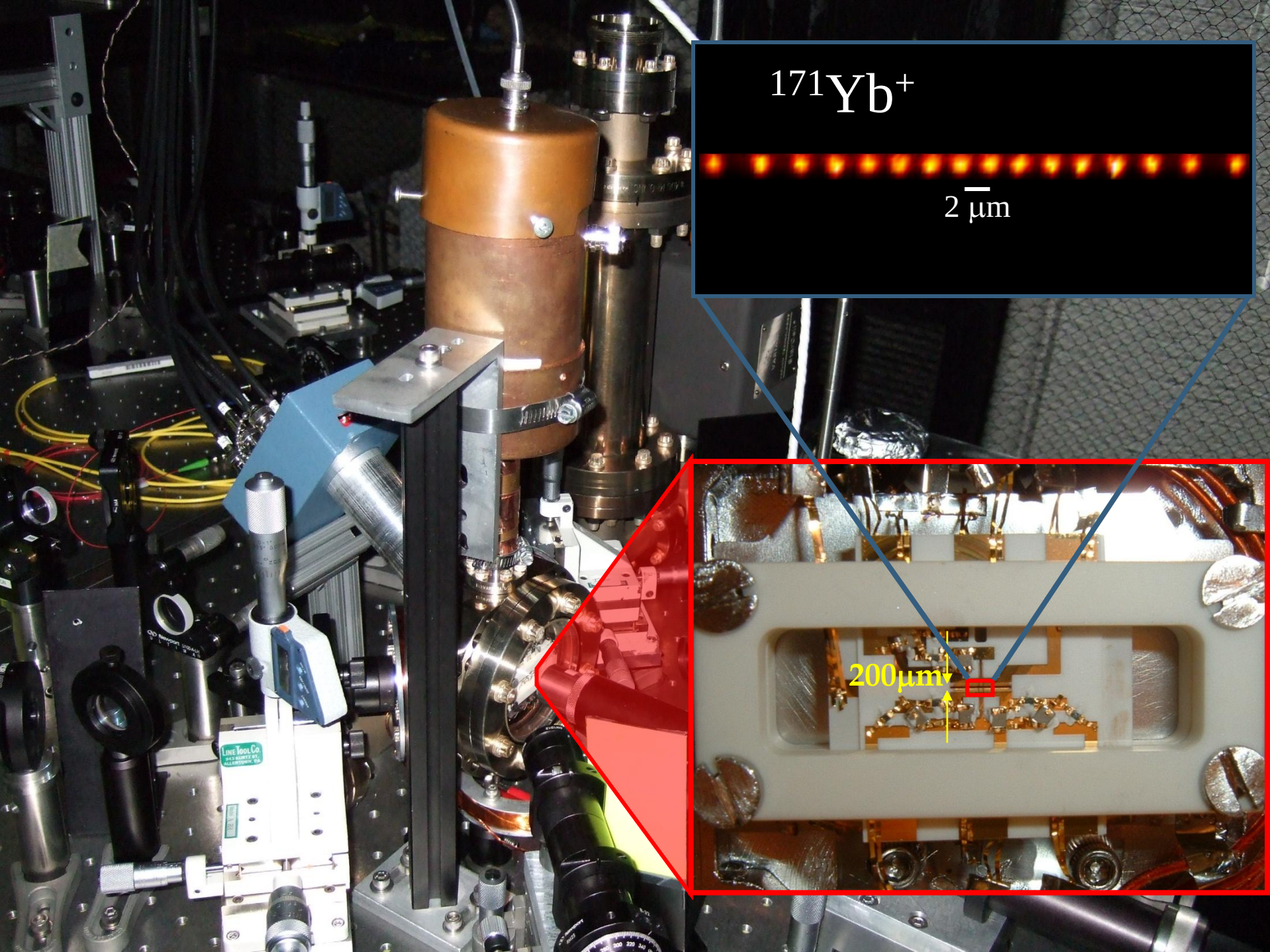
  → Many-body spectroscopy of interacting spins

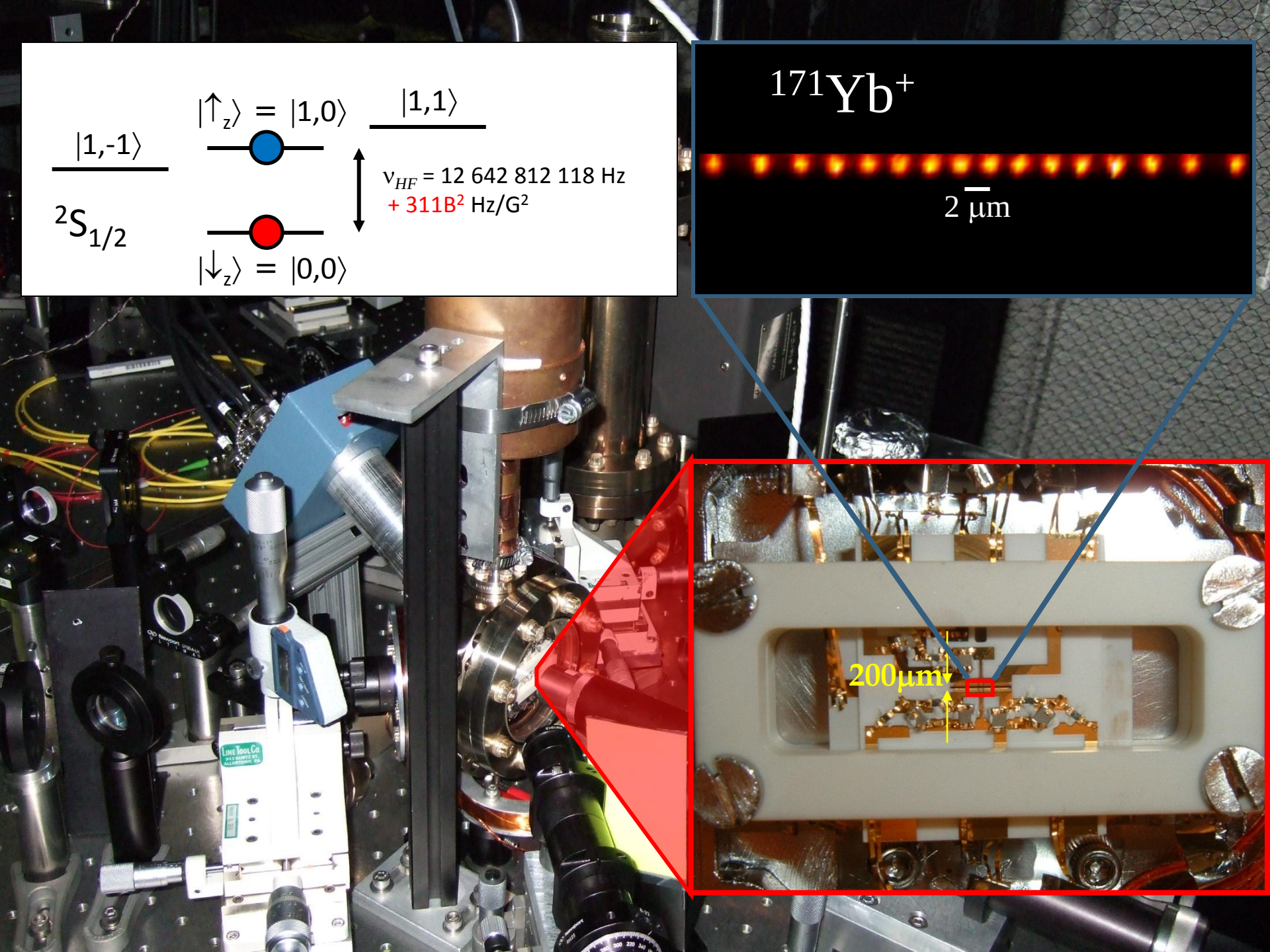




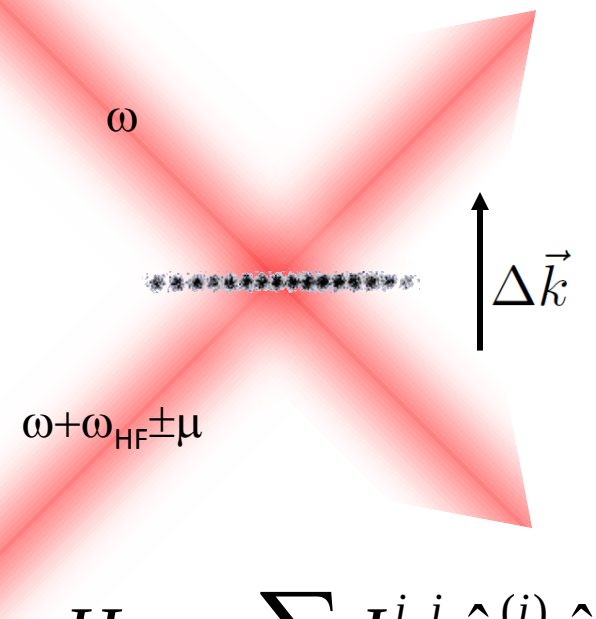
Long-term goal:

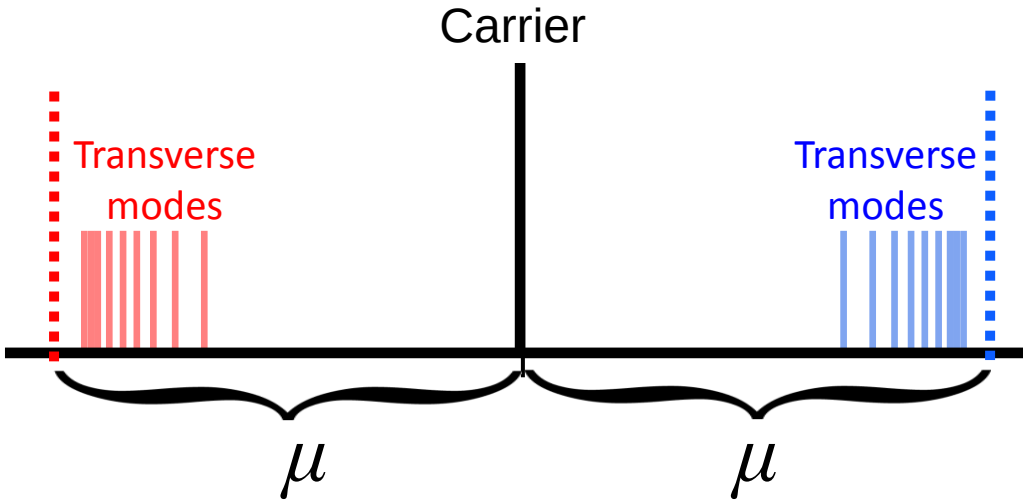
oodles of particles, arbitrary Hamiltonian, classically intractable physics


$^{171}Yb^{+}$
2 μm
200μm


$|\uparrow_z\rangle = |1,0\rangle$
$|1,1\rangle$
$|1,-1\rangle$
$^2S_{1/2}$
$|\downarrow_z\rangle = |0,0\rangle$
ν_{HF} = 12 642 812 118 Hz
+ 311B^2 Hz/G^2
$^{171}Yb^+$
2 μm
200μm

Implementing spin Hamiltonians





$$H_{eff} = \sum_{i \neq j} J^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)}$$

$$J^{i,j} = \Omega_i \Omega_j \Omega_R \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

Recoil freq ~ $\Delta k^2/m$

Spin *i*'s component of *k*th normal mode eigenvector

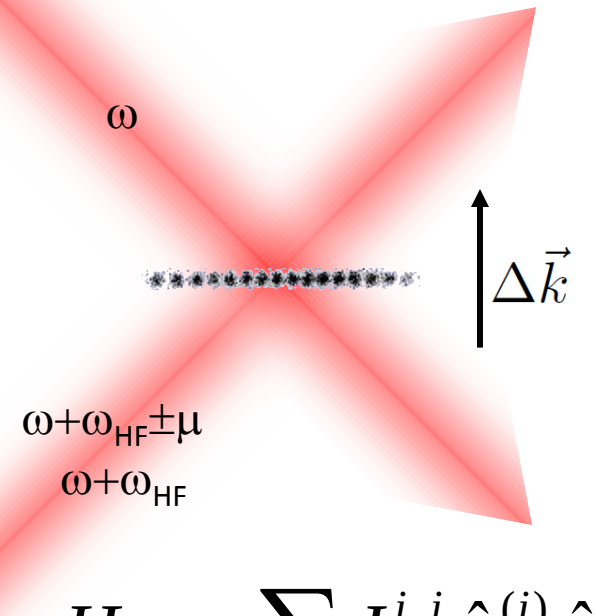
Rabi freqs ~ laser intensities at spin *i*, *j*

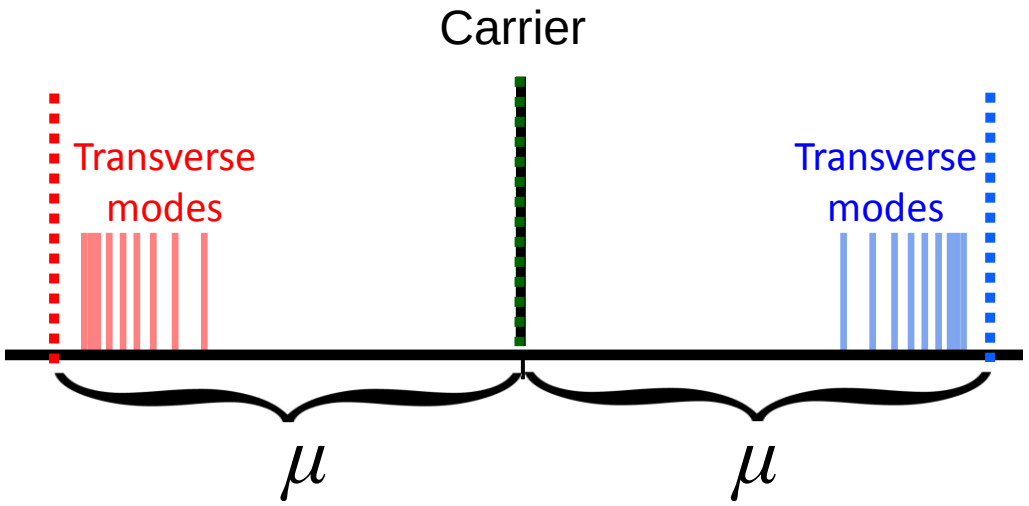
Laser frequency

Frequency of *k*th normal mode

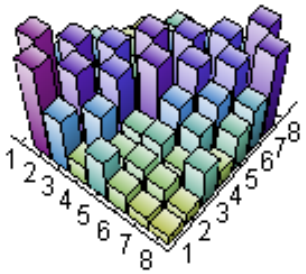
K. Kim *et. al.*, PRL **103**, 120502 (2009)

Implementing spin Hamiltonians





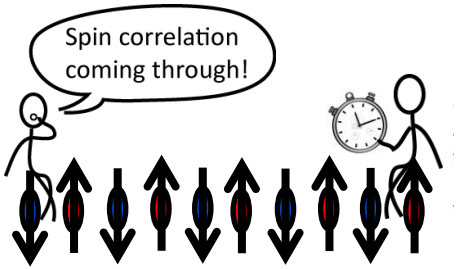
$$H_{eff} = \sum_{i \neq j} J^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B_y(t) \sum_i \hat{\sigma}_y^{(i)}$$

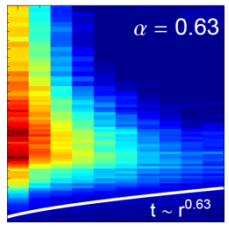


$$J^{i,j} \approx \frac{J_0}{|i-j|^{\alpha}}, \quad 0 < \alpha < 3$$

K. Kim *et. al.*, PRL **103**, 120502 (2009)

- Relevant physics
  - →Information propagation and Lieb-Robinson bounds



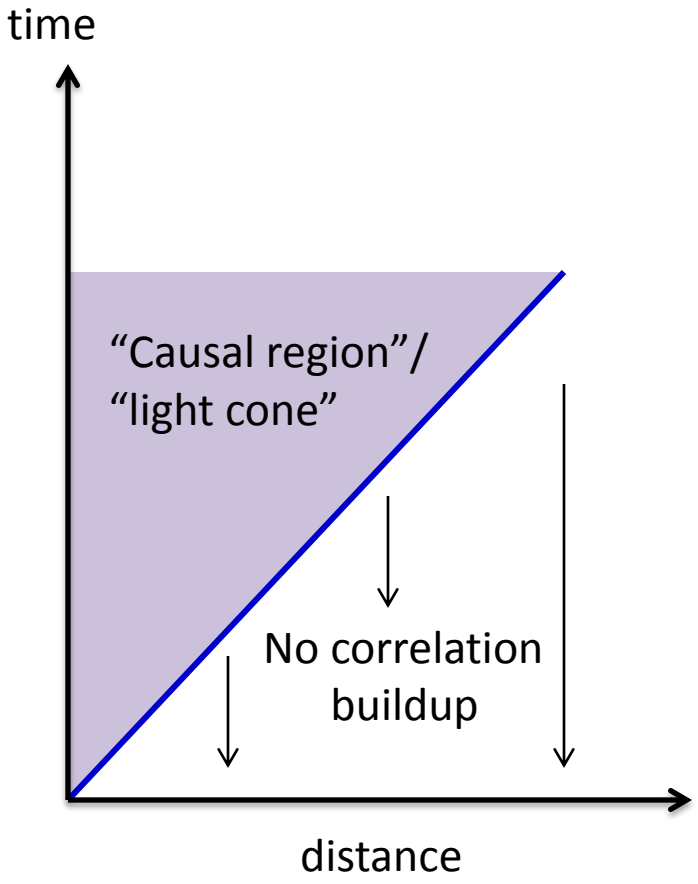


- Tools for validation
  - →Many-body spectroscopy of interacting spins

Critical gap

Correlation Propagation in Quantum Systems

How fast can quantum information spread?



- Short-range systems: Lieb and Robinson find linear light cone [1]
  - Bounds on entanglement growth
  - Difficulty of classical simulation
  - Constrains timescales for thermalization, decay of correlations, etc.,
- Long-range systems: not well understood
  - Lieb-Robinson bound breaks down
  - Rarely analytic solutions
  - Numerics fail for 30+ spins

P. Richerme *et al.*, arXiv 1401.5088 (2014)

[1] E. Lieb and D. Robinson, Comm. Math. Phys. **28**, 251 (1972)

Correlation Propagation in Quantum Systems

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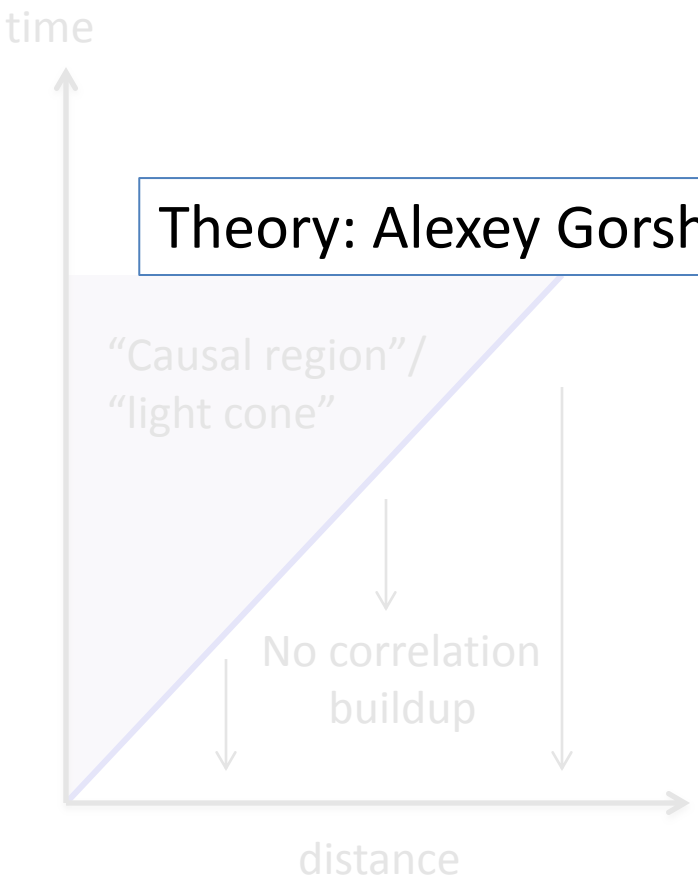

Theory: Alexey Gorshkov, Zhe-Xuan Gong, Michael Foss-Feig

- Short-range systems: Lieb and Robinson find
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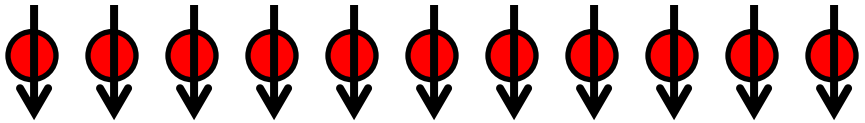
Correlation Propagation with 11 ions

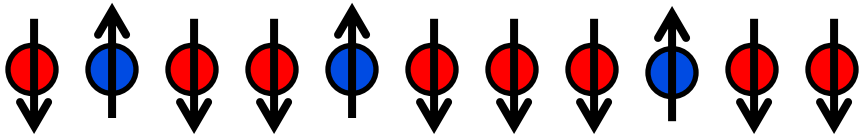
Step 1: Initialize all spins along *z*



Step 2: Quench to XY model at *t = 0* and let system evolve

$$H_{\mathrm{Ising}} = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x \qquad H_{\mathrm{XY}} = \frac{1}{2}\sum_{i<j} J_{ij}(\sigma_i^x\sigma_j^x + \sigma_i^z\sigma_j^z)$$

Step 3: Measure all spins along z



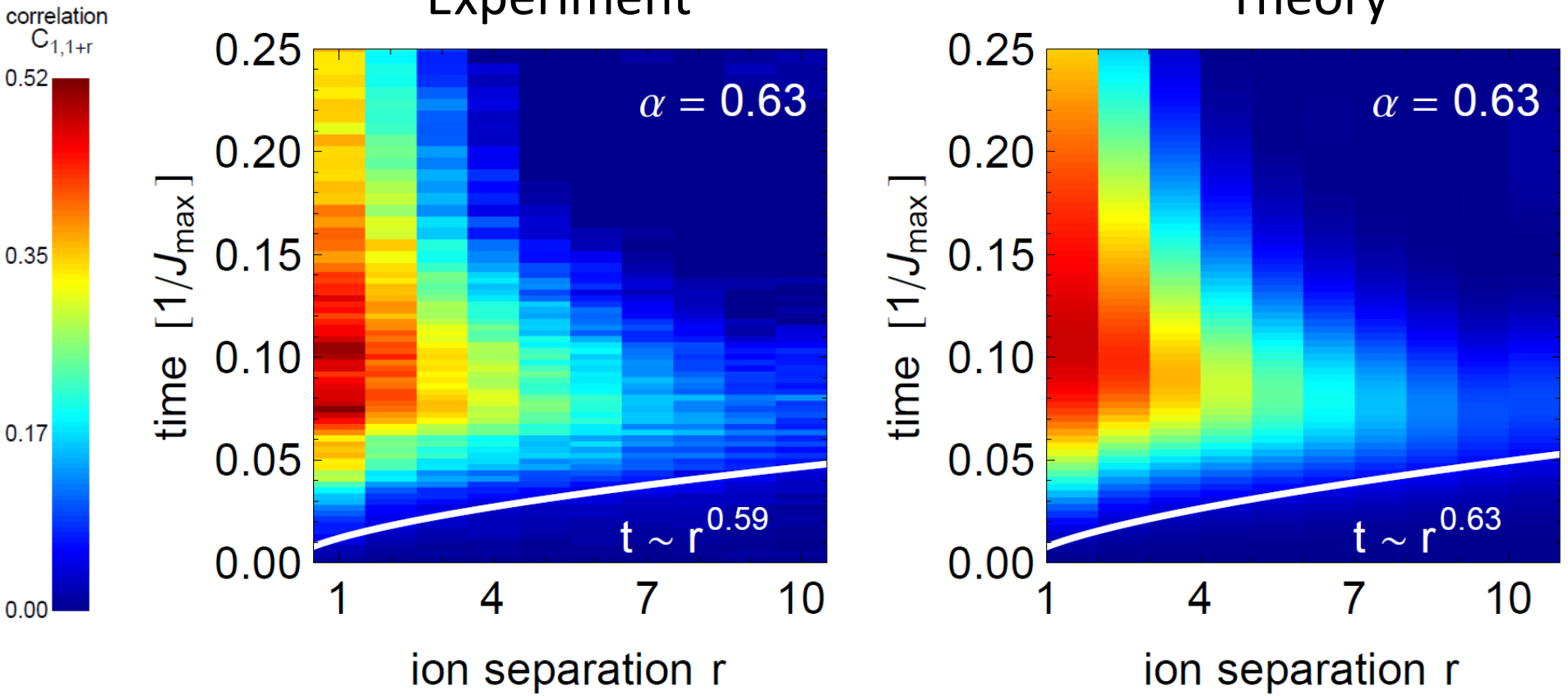
Step 4: Calculate correlation function

$$C_{ij}(t) = \langle\sigma_i^z(t)\sigma_j^z(t)\rangle - \langle\sigma_i^z(t)\rangle\langle\sigma_j^z(t)\rangle$$

P. Richerme , Z.-X. Gong, A. Lee, CS, J. Smith, M. Foss-Feig, S. Michalakis, A. Gorshkov, and C. Monroe, **arXiv:1401.5088**

Global Quench: Ising Model

$$H_{\mathrm{Ising}} = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x \qquad J_{ij} \approx \frac{J_0}{r^\alpha}$$



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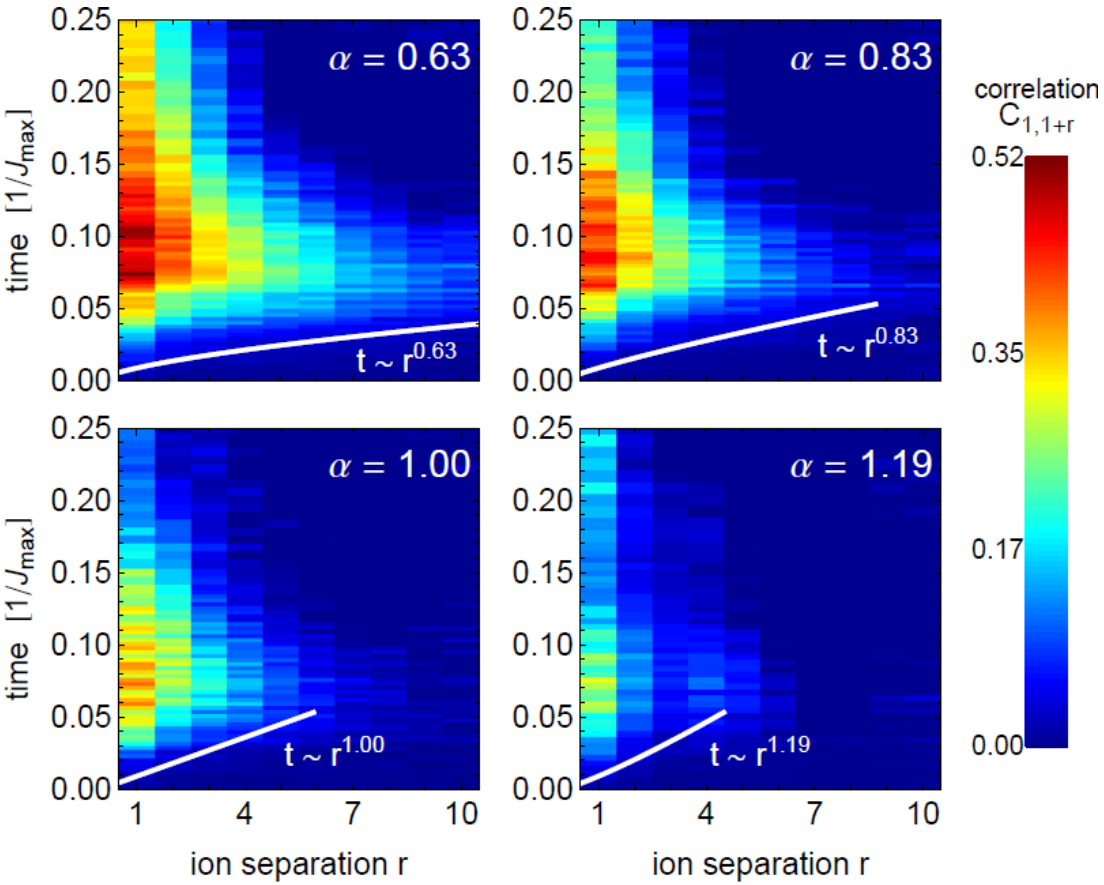

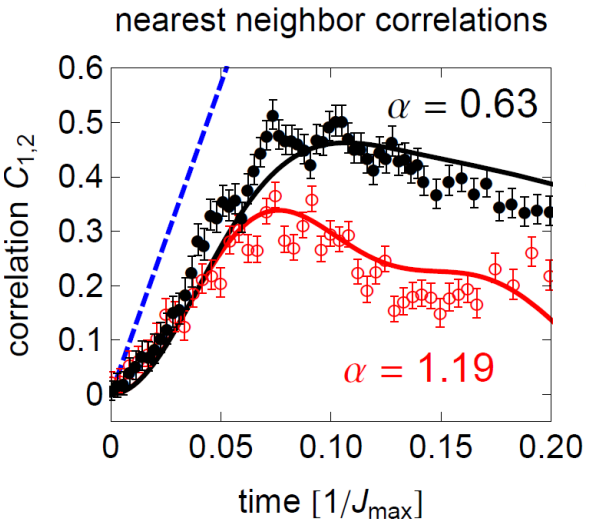

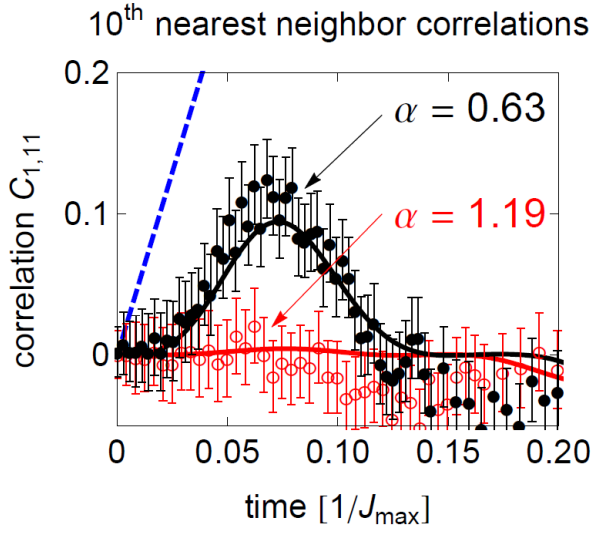

P. Richerme , Z.-X. Gong, A. Lee, CS, J. Smith, M. Foss-Feig, S. Michalakis, A. Gorshkov, and C. Monroe, **arXiv:1401.5088**

Global Quench: XY Model

$$H_{\mathrm{XY}} = \frac{1}{2}\sum_{i<j} J_{ij}(\sigma_i^x\sigma_j^x + \sigma_i^z\sigma_j^z) \qquad J_{ij} \approx \frac{J_0}{r^\alpha}$$

$$H = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + B_y\sum_i \sigma_i^y \qquad B_y \gg J_{ij}$$

$$(\sigma^+ + \sigma^-)(\sigma^+ + \sigma^-)$$

$$= \cancel{\sigma^+\sigma^+} + \sigma^+\sigma^- + \sigma^-\sigma^+ + \cancel{\sigma^-\sigma^-}$$

$$H = \sum_{i<j} J_{ij}(\sigma^+\sigma^- + \sigma^-\sigma^+) + \cancel{B_y\sum_i \sigma_i^y}$$

P. Richerme , Z.-X. Gong, A. Lee, CS, J. Smith, M. Foss-Feig, S. Michalakis, A. Gorshkov, and C. Monroe, **arXiv:1401.5088**

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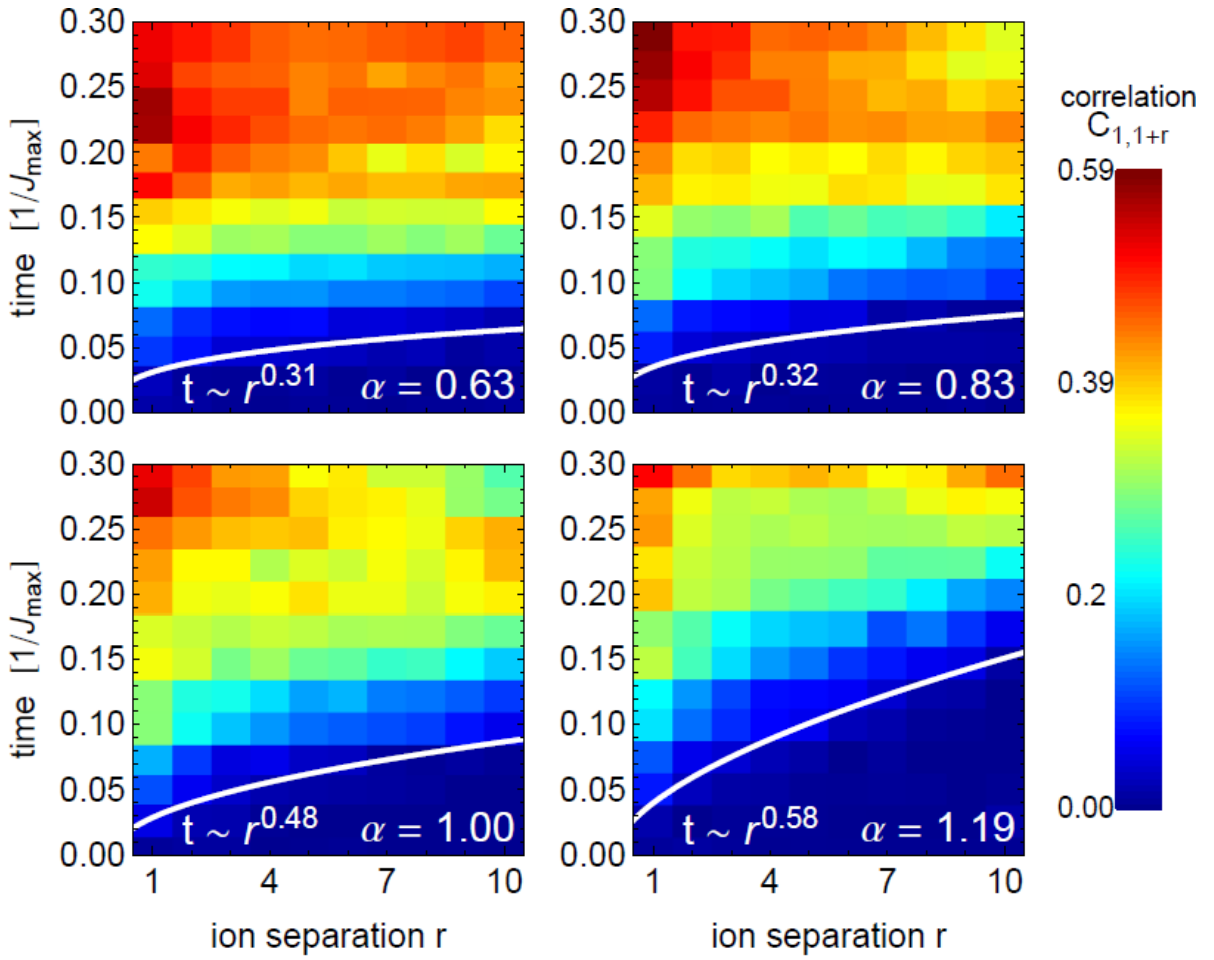
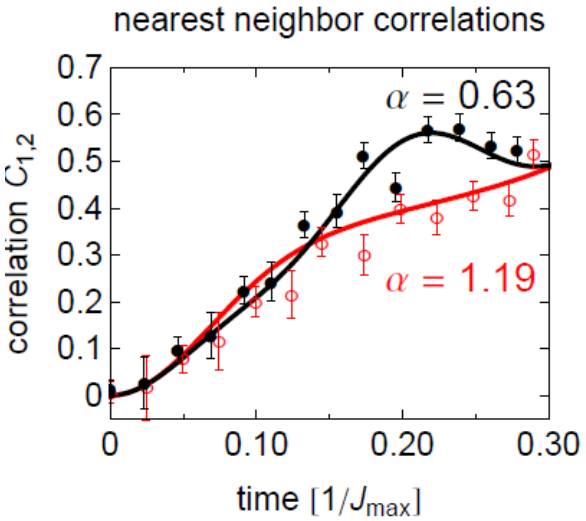
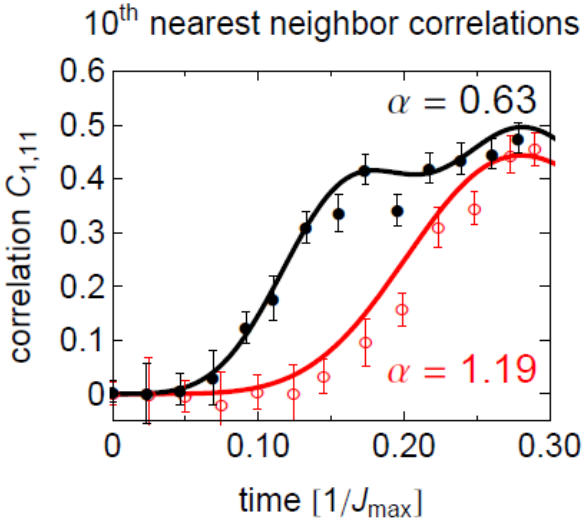
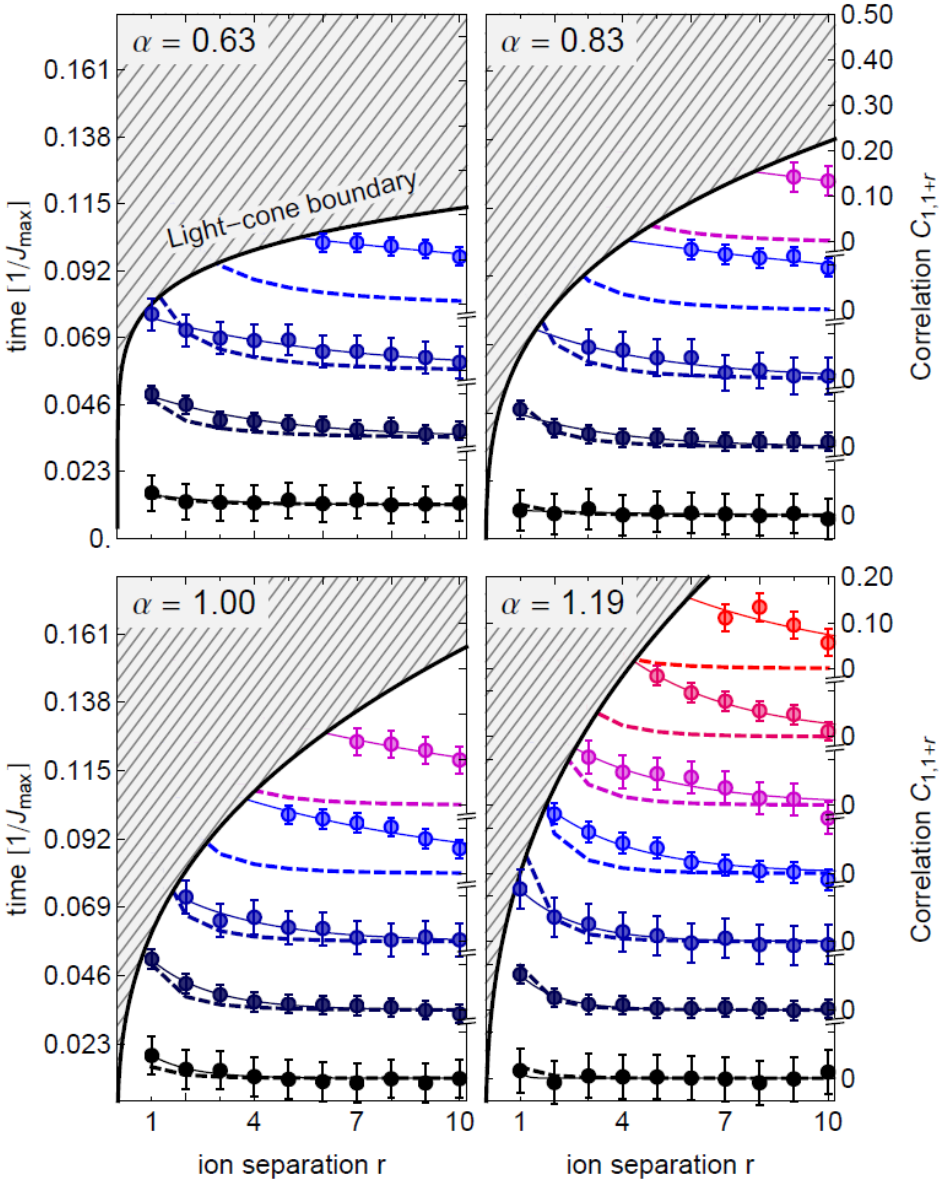






Global Quench: XY Model



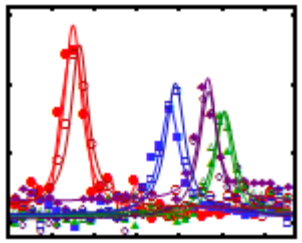
- Perturbation result fails at later evolution times
- Light-cone shape cannot be predicted by any known theory
- Numerics inherently limited to N < 30 spins
- Prime use for quantum simulators

Exponential fit

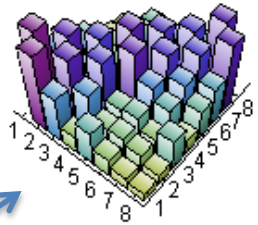
Perturbation result

- Relevant physics
  - →Information propagation and Lieb-Robinson bounds

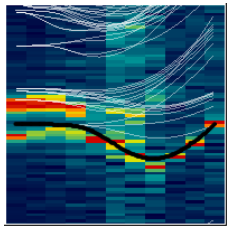
- Tools for validation
  - →Many-body spectroscopy of interacting spins



Spin-spin interactions

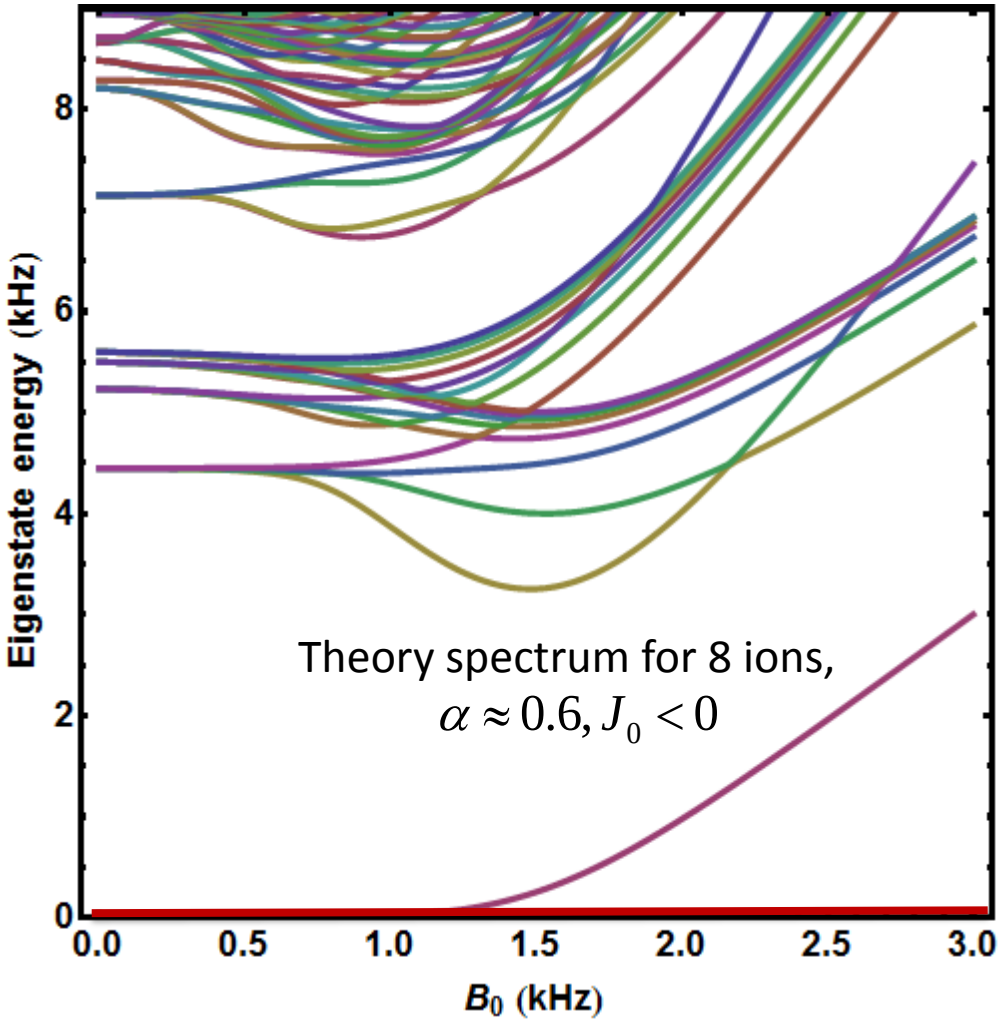


Critical gap



Many-body Rabi spectroscopy

$$H = \sum_{i \neq j} J_x^{\,i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + \left(B_0 + B_{probe} \sin(2\pi f t)\right) \sum_i \hat{\sigma}_y^{(i)}$$



B_{probe} drives transitions if:

- $\left\langle a \left| \sum_i \hat{\sigma}_y^{(i)} \right| b \right\rangle \neq 0$

- Probe freq. matches energy splitting, $f \approx |E_a - E_b|$

C. Senko et al., arXiv:1401.5751

Many-body Rabi spectroscopy

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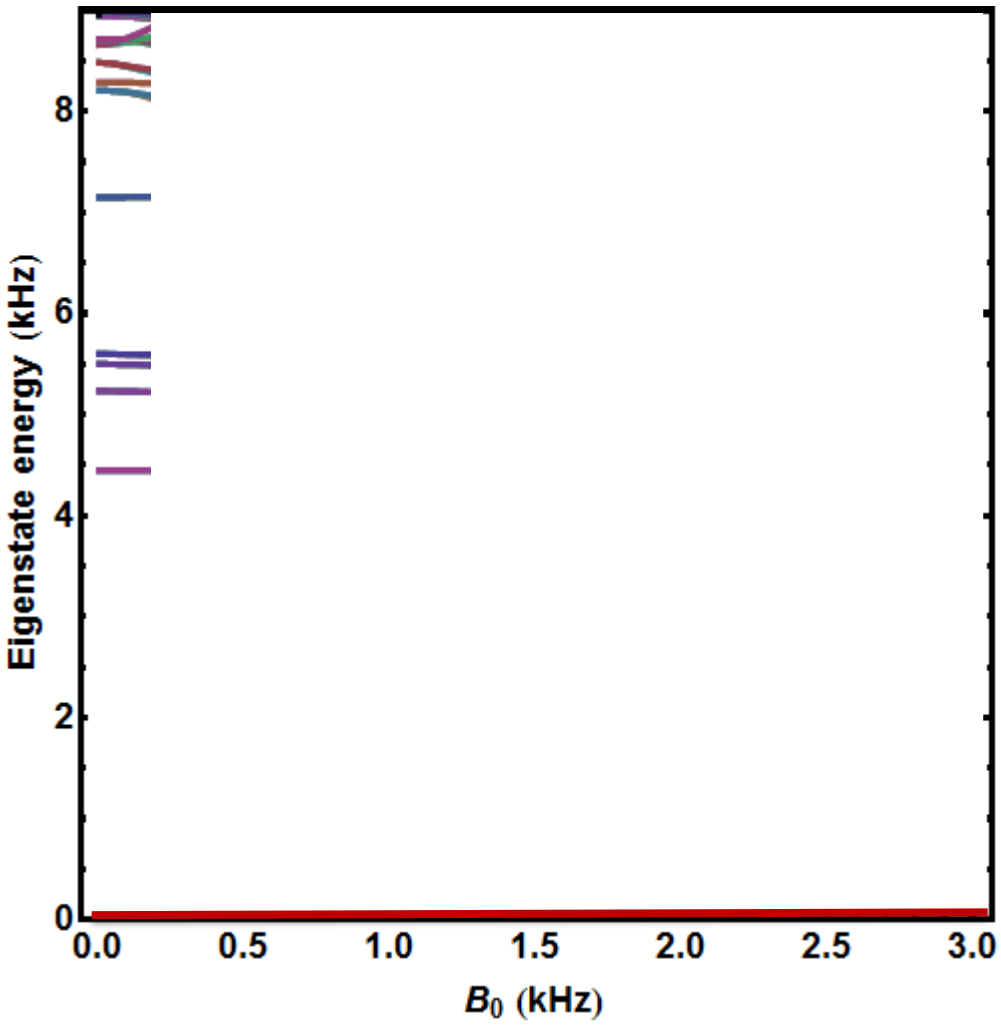

E.g., at low field,
B_{probe} drives transitions if:

- States differ by exactly one spin flip along x

- Probe freq. matches energy splitting, $f \approx |E_a - E_b|$

C. Senko et al., arXiv:1401.5751

Many-body Rabi spectroscopy

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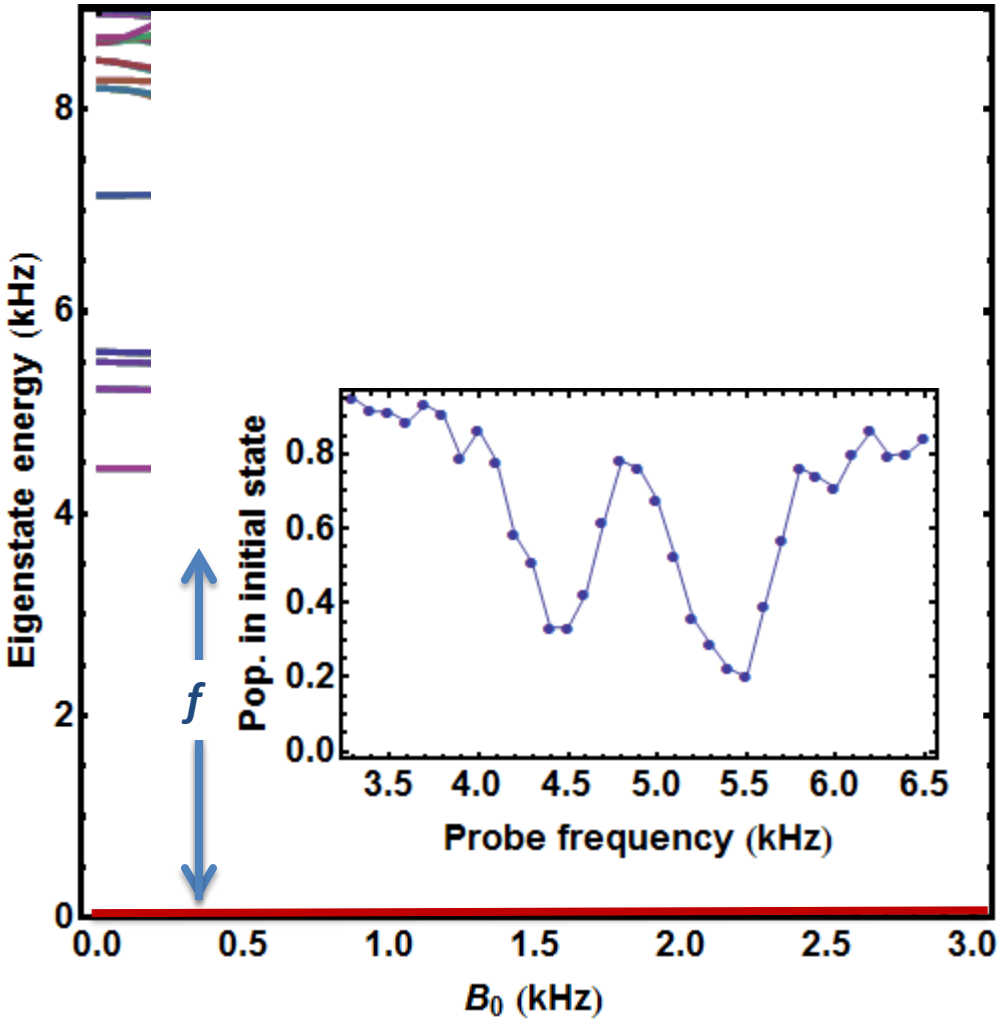

Protocol:

- Prepare eigenstate
  E.g., $|\uparrow\uparrow\uparrow\uparrow\ldots\rangle_x$
- Apply probe field for fixed time (3 ms)
- Scan probe frequency and observe transitions

C. Senko et al., arXiv:1401.5751

Many-body Rabi spectroscopy

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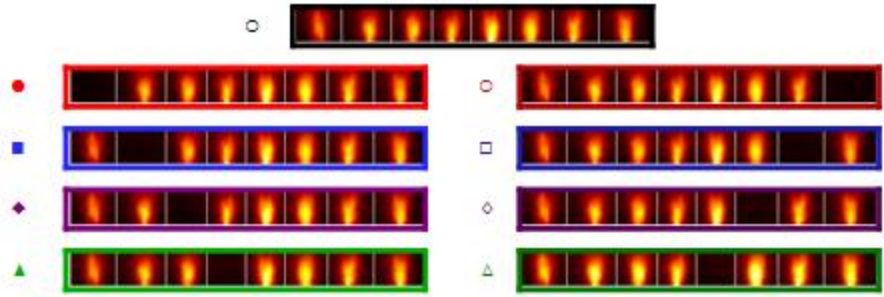
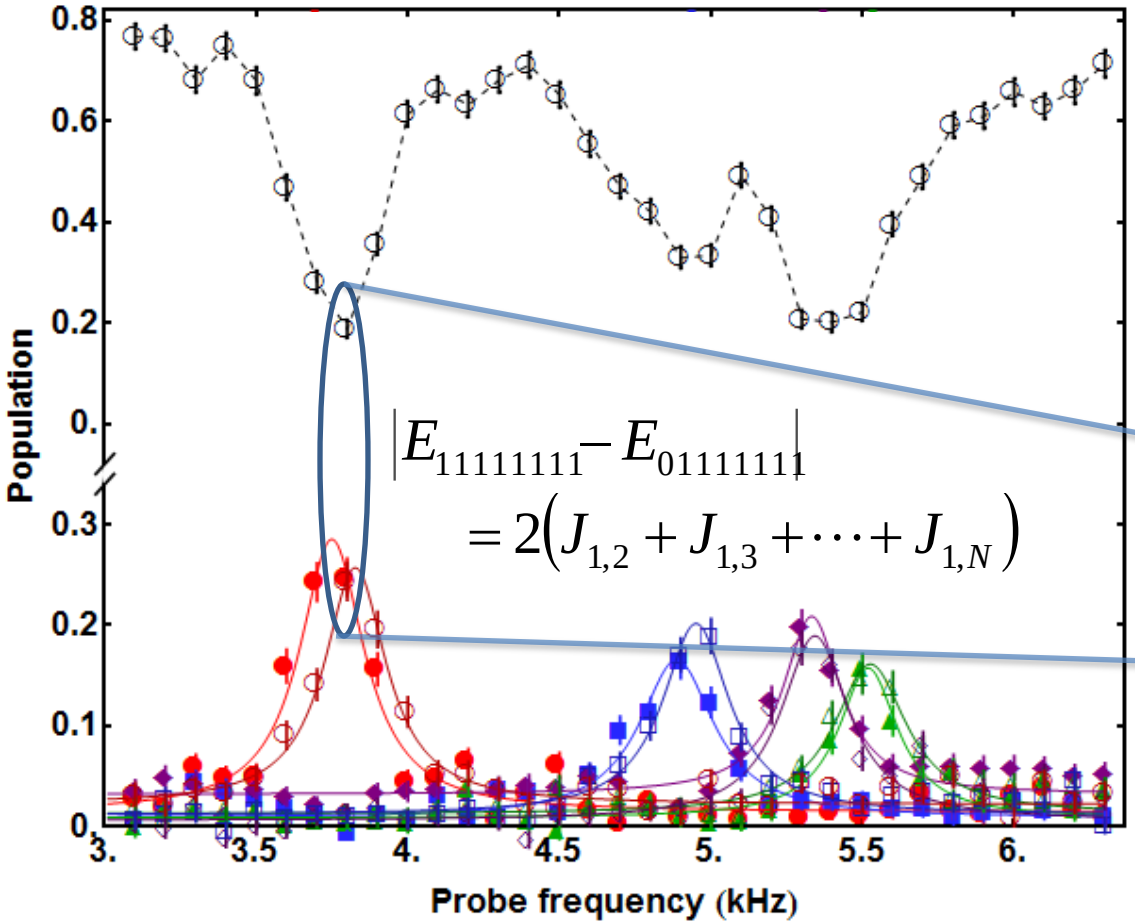
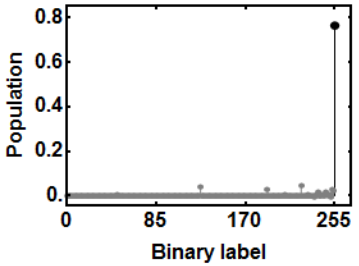


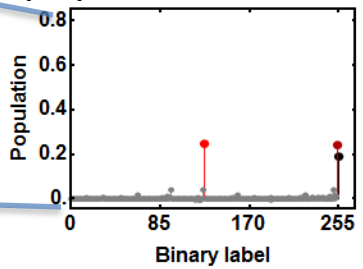
8 spins



Initial population distribution



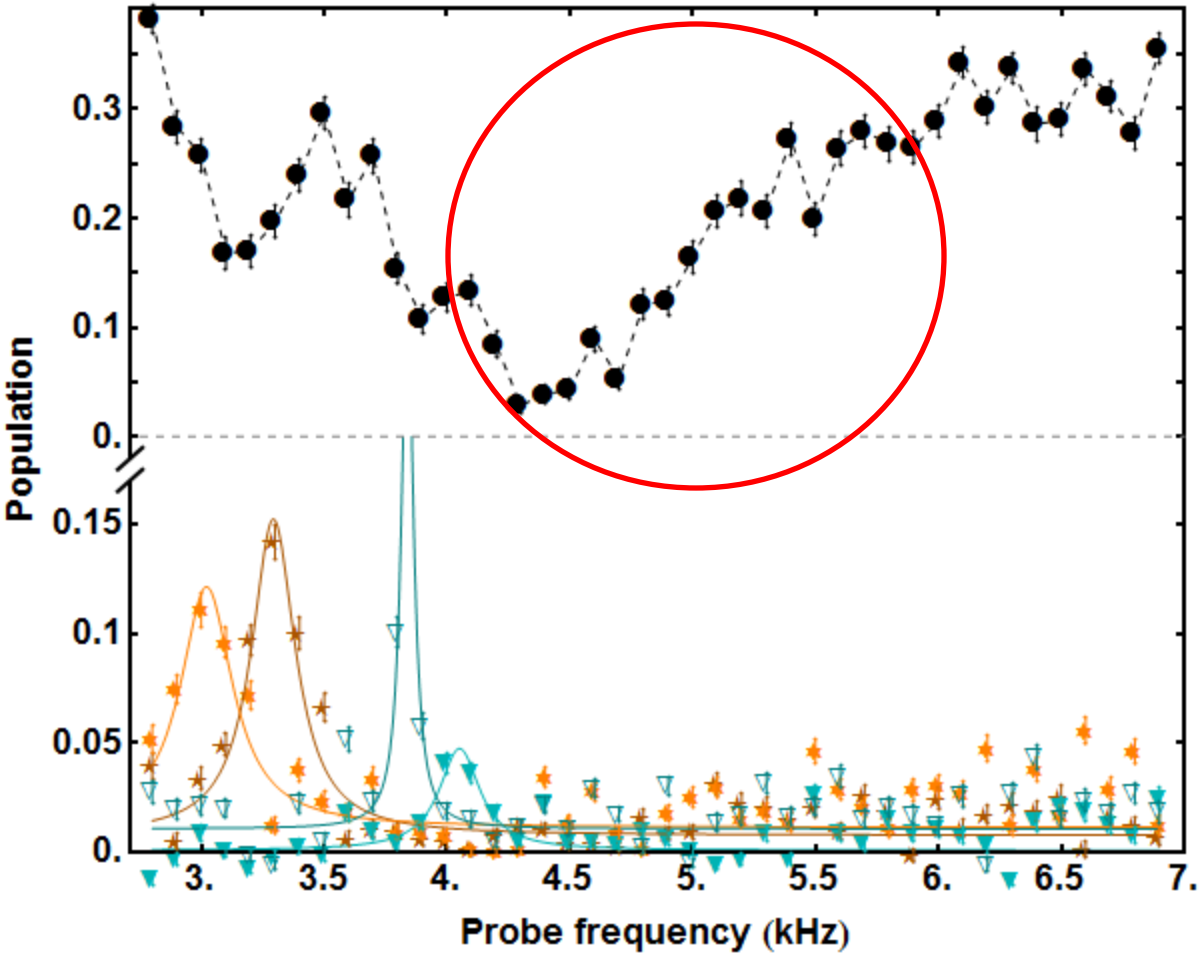
Final population distribution

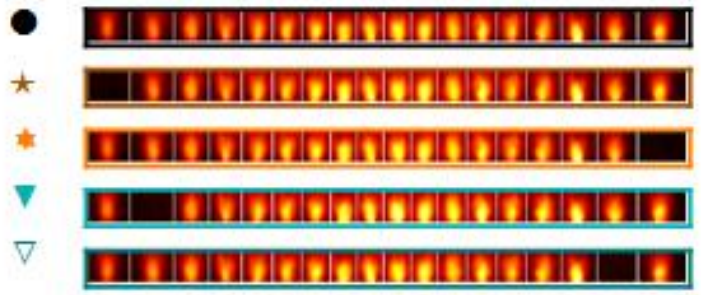


Binary coding:
11111111 (base 2) = 255 (base 10)

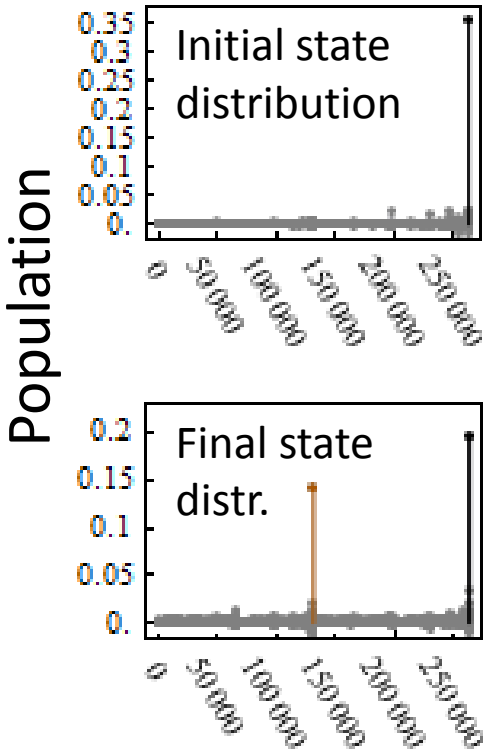
C. Senko et al., arXiv:1401.5751

Many-body Rabi spectroscopy



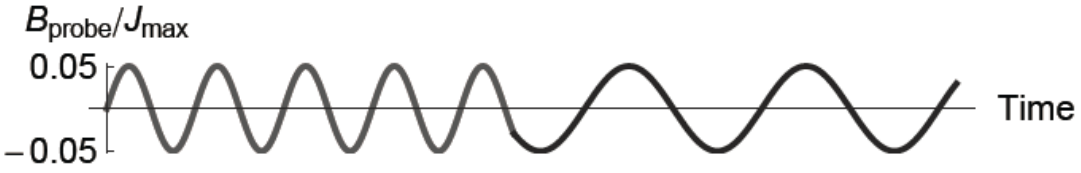


18 spins

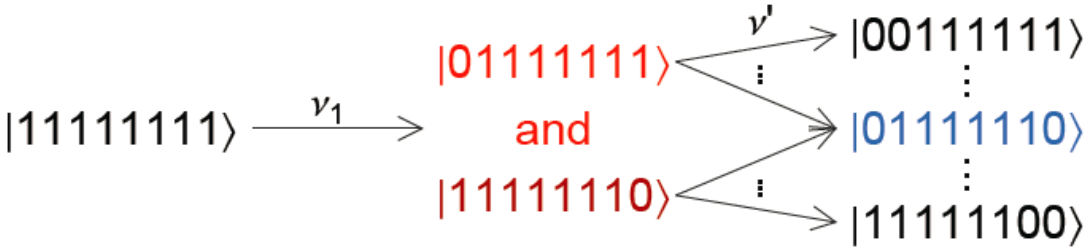


C. Senko et al., arXiv:1401.5751

Many-body Rabi spectroscopy for multiple excitations



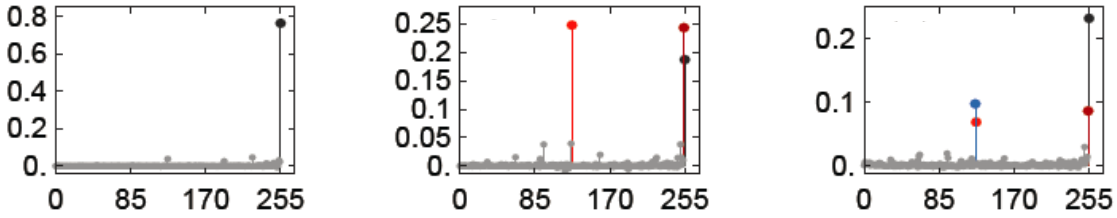
$$H = \sum_{i<j} J_{i,j}\sigma_x^{(i)}\sigma_x^{(j)}$$

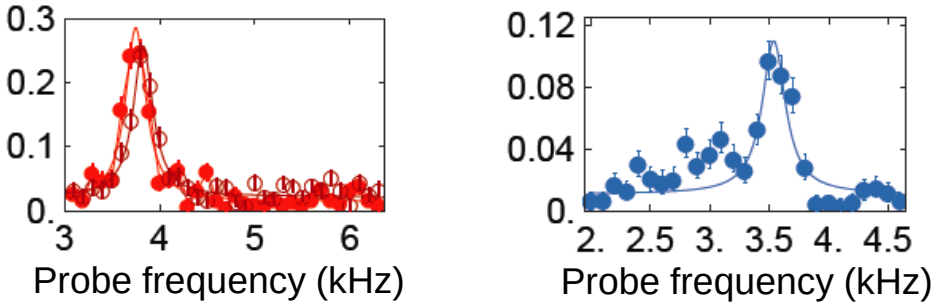


Measuring interaction strengths:

~N^2 terms in J_{ij} matrix, need

~N^2 measurements of ΔE



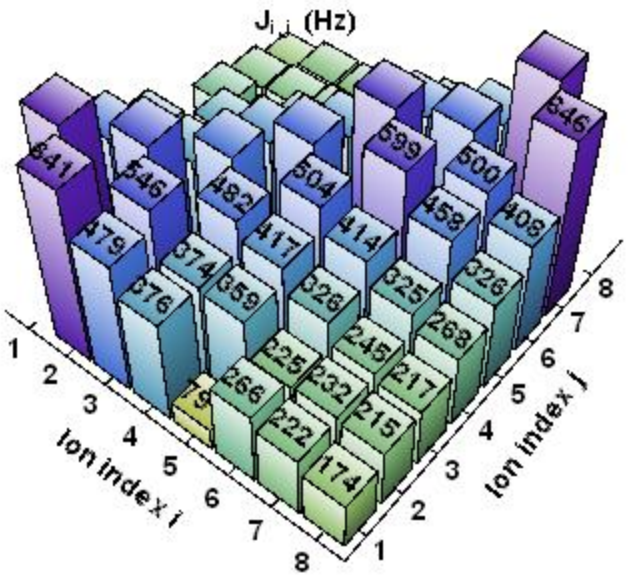


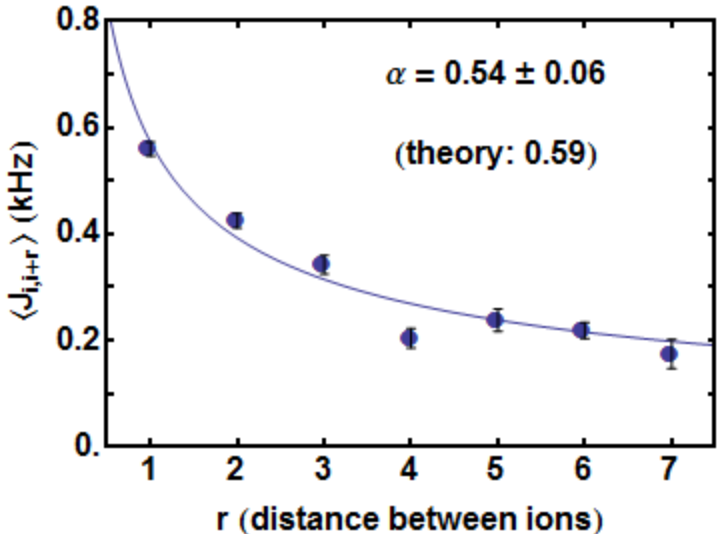
Measuring full spectrum

(need to measure 2^N levels)

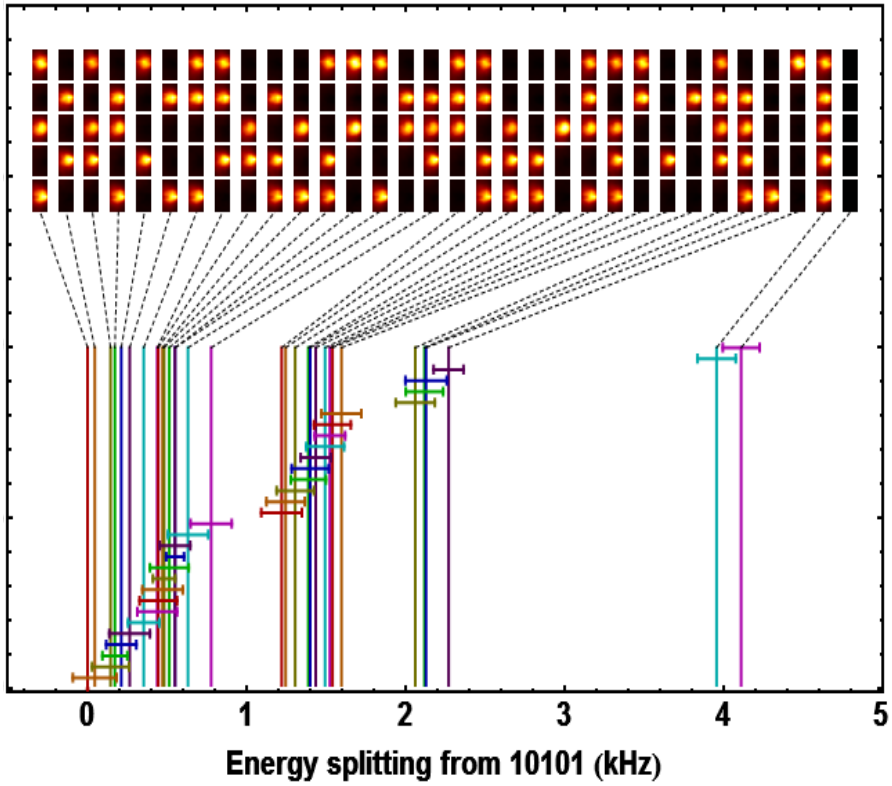
C. Senko et al., arXiv:1401.5751

Spin-spin interactions





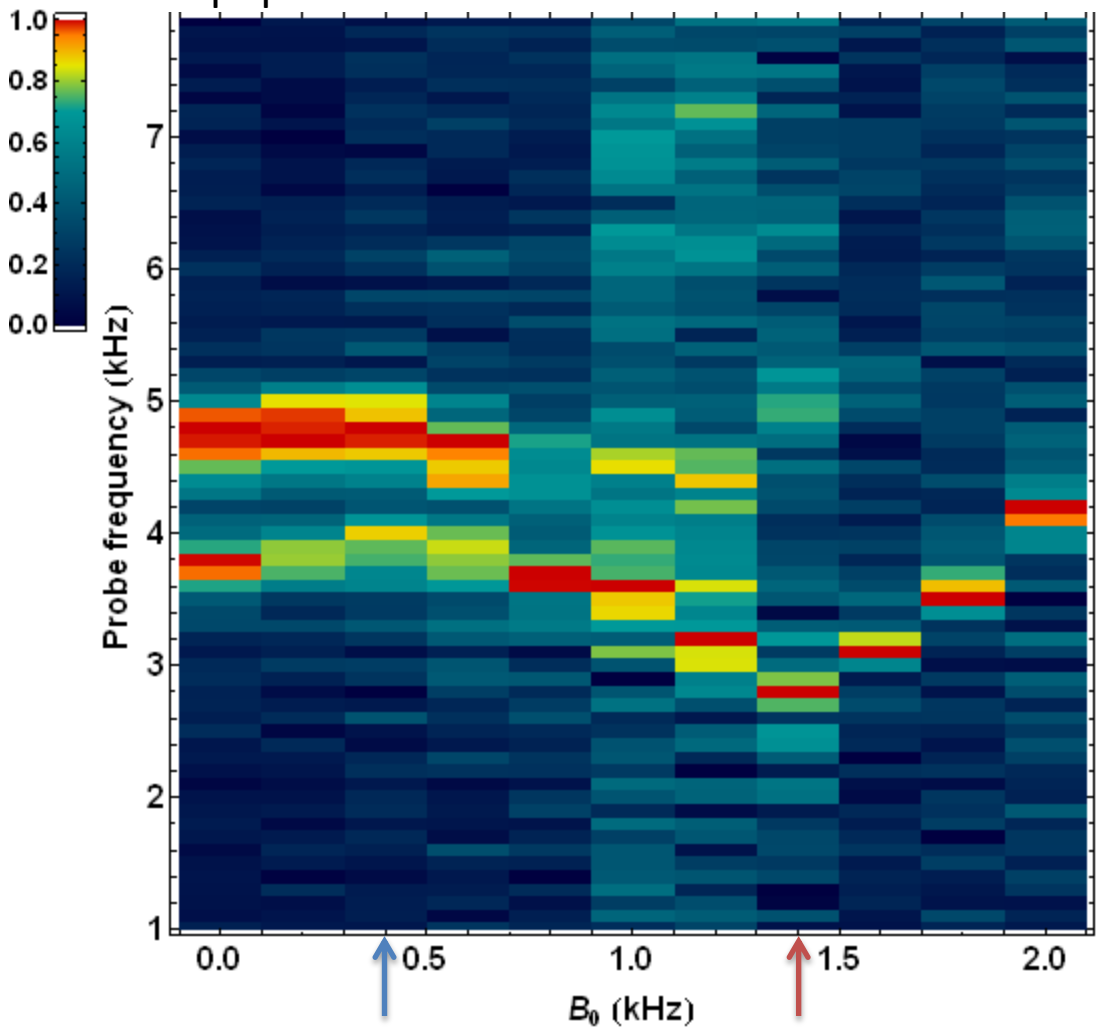
Full spectrum (5 spins)

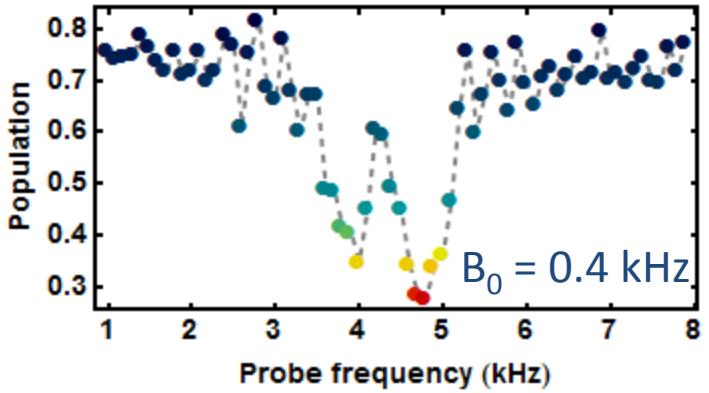


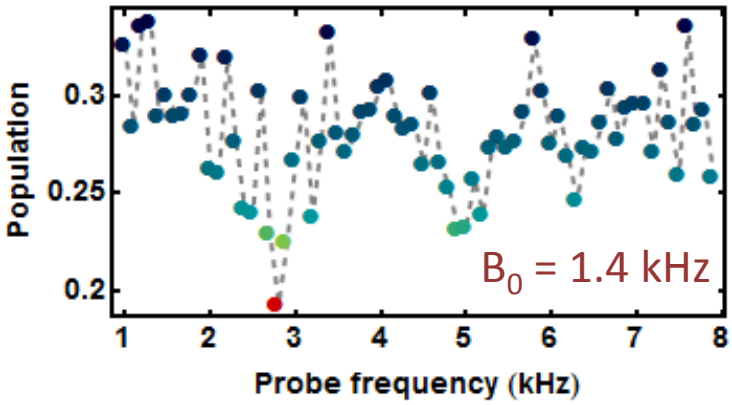
C. Senko et al., arXiv:1401.5751

Measuring a critical gap

$$H = \sum_{i \neq j} J_x^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + \left(B_0 + B_{probe} \sin(2\pi f t)\right) \sum_i \hat{\sigma}_y^{(i)}$$







C. Senko et al., arXiv:1401.5751

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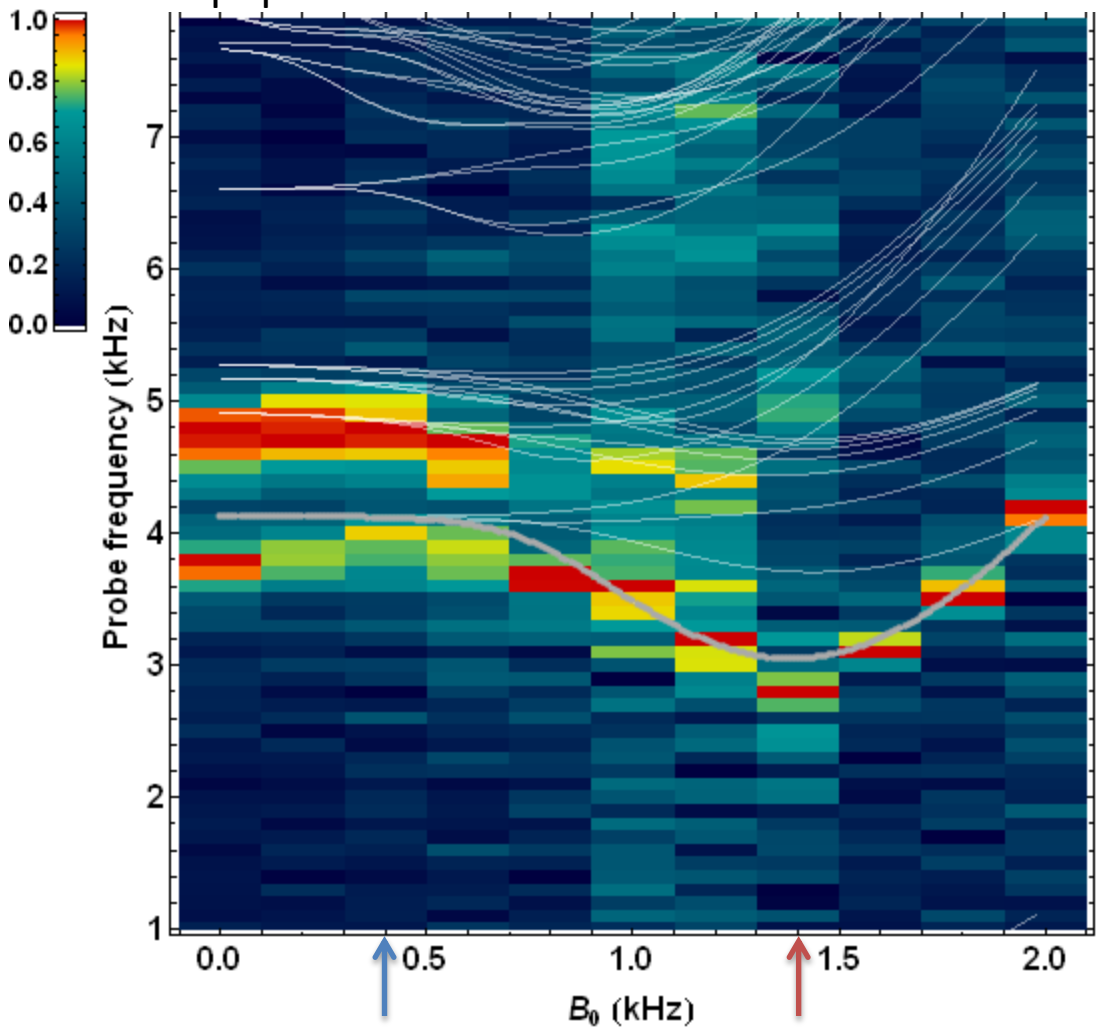
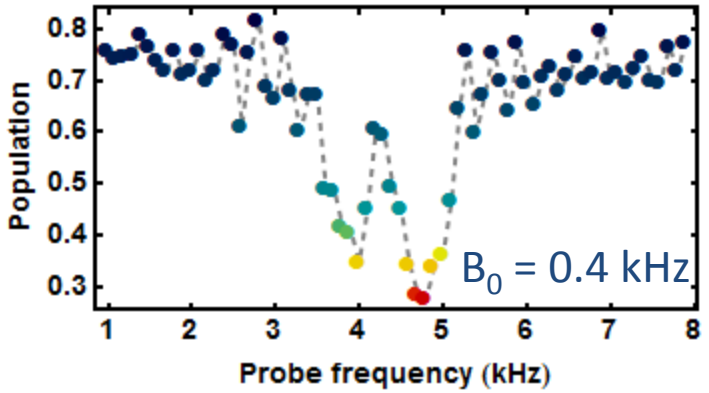
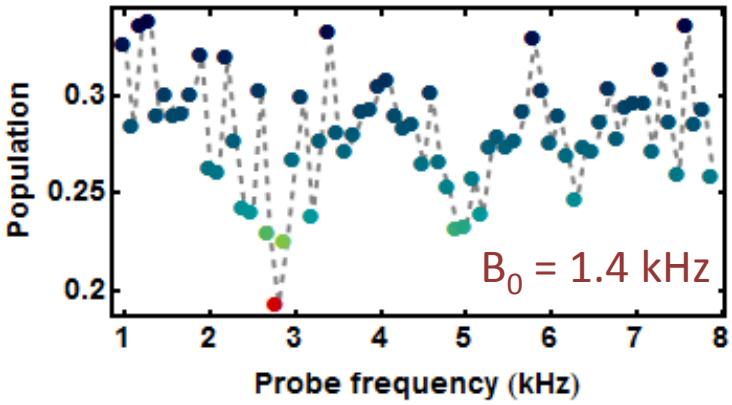
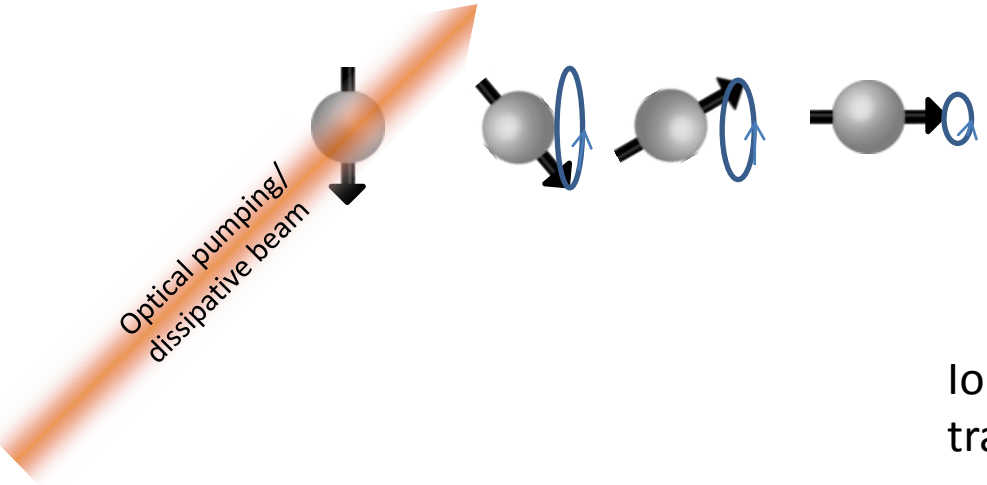






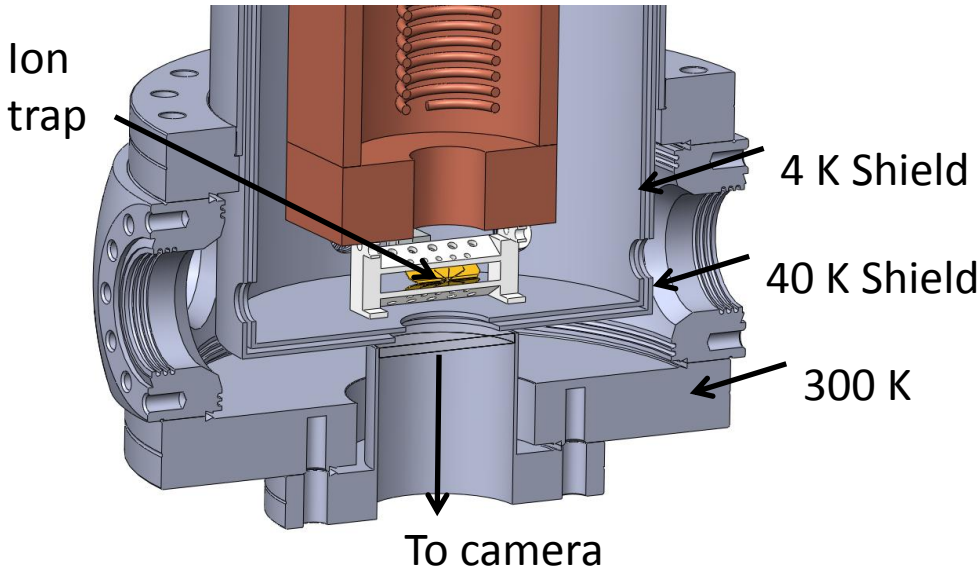
C. Senko et al., arXiv:1401.5751

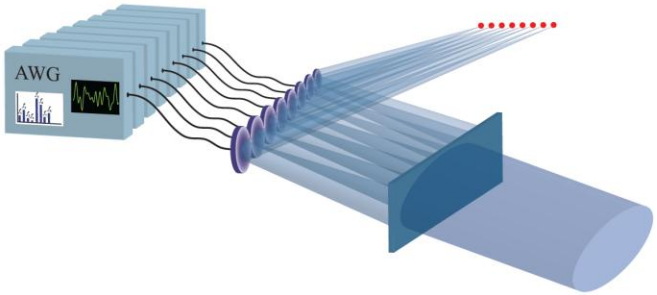
Future directions at JQI



Individually addressed lasers for new initial states, localized dissipation

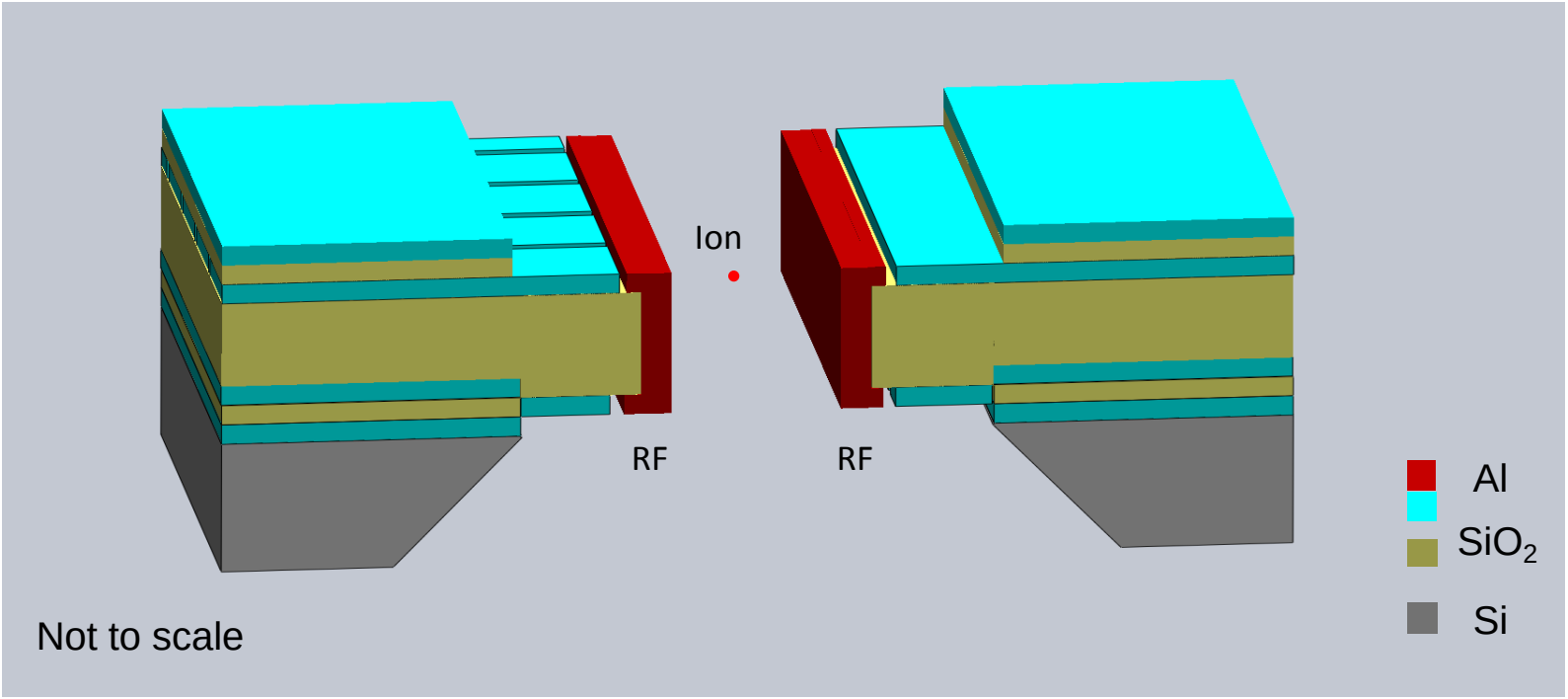
Cryogenic vacuum chamber for lower pressure and more ions





32-channel AOM for full control of spin-spin interactions

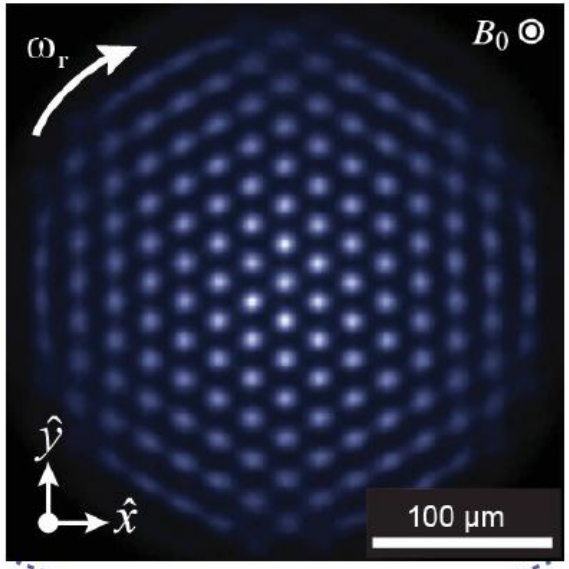
Symmetric trap design

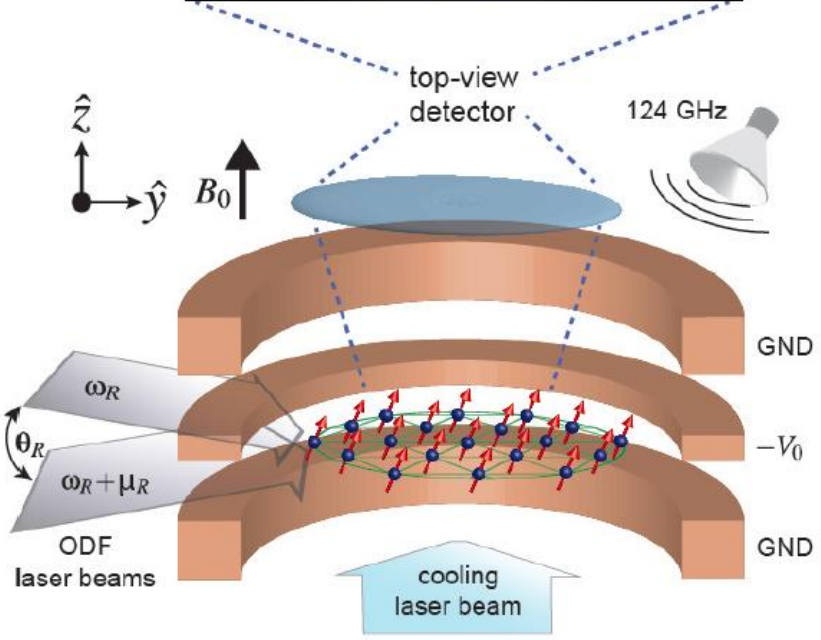


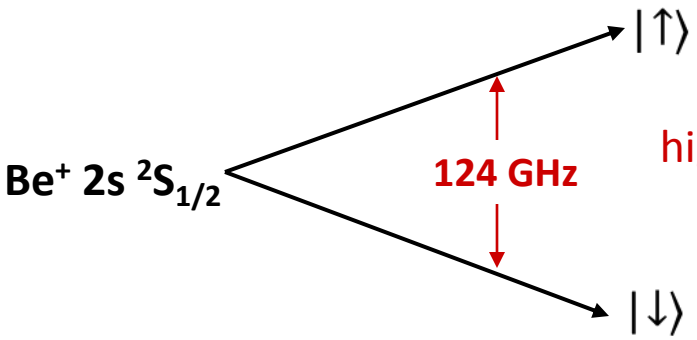
- Ion located between symmetric RF and DC electrodes
- Large radial trapping depth: ~1 eV for $^{171}Yb^{+}$ ion
- Wide angle laser access
- No line of sight to exposed oxide
- Trap 20+ ion chains in anharmonic potentials
- Equal ion spacing for longer chains

Penning trap quantum simulator

Joe Britton, Brian Sawyer, Carson Teale & John Bollinger (NIST Boulder)
Theory: J. Freericks, J. Wang, A. Keith (Georgetown); A. M. Rey, K. Hazzard, M. Foss-Feig (JILA); D. Dubin (UCSD)







high-magnetic field (4.5 T) qubit

$$H = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z + B_x\sum_i \sigma_i^x$$

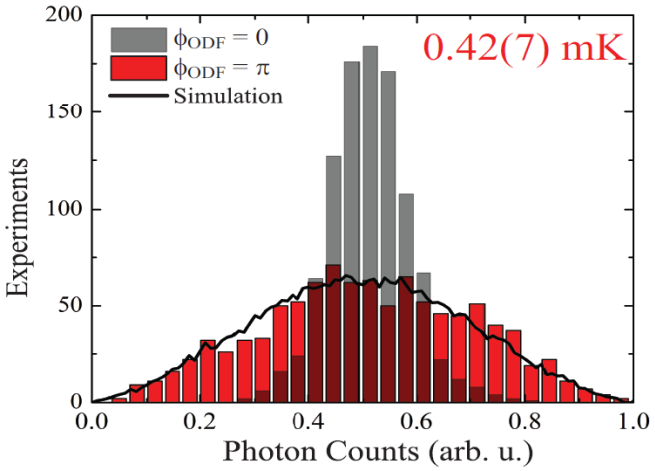
transverse B-field from 124 GHz microwaves → $H_B = B_x\sum_i \sigma_i^x$

engineered Ising interaction from spin-dependent force → $H_I = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$

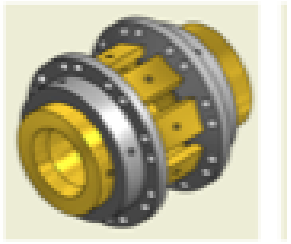
$$J_{i,j} \propto d_{i,j}^{-\alpha}$$

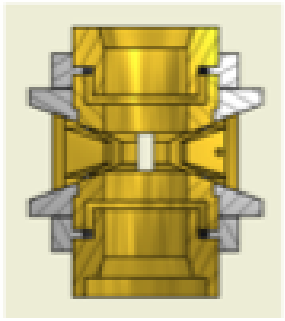
See poster by Brian Sawyer, Joe Britton, Justin Bohnet, John Bollinger, ..

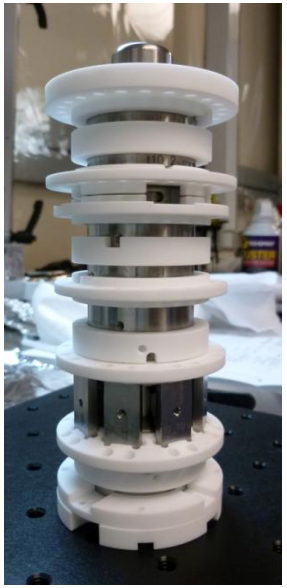
- Use of spin-dependent ODF to characterize ion motional state distributions

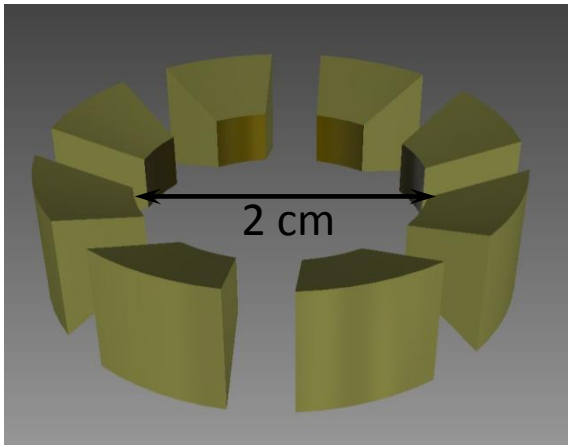


- Features of new Penning ion trap
  - 50-times stronger spin-spin coupling
  - More uniform triangular lattice through m=3 rotating wall

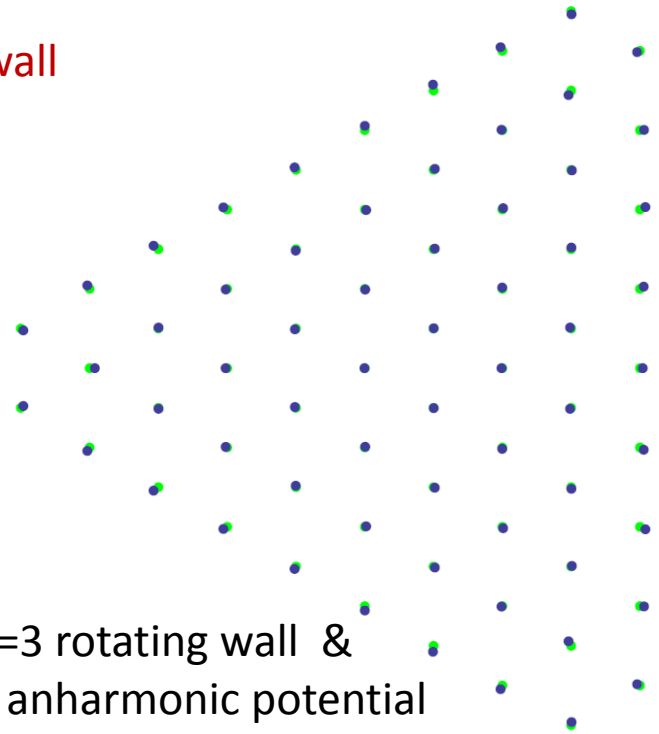








rotating wall electrodes



m=3 rotating wall & C_4 anharmonic potential

Quantum Simulation with Trapped Ions

3 spins in 2009

-- “Entanglement and Tunable Spin-Spin Couplings between Trapped Ions Using Multiple Transverse Modes”, Kim et al, **PRL** 103, 120502 (2009)

-- ”Quantum Simulation of Frustrated Ising Spins with Trapped Ions”, K. Kim et al, **Nature** 465, 590 (2010)

-- “Quantum simulation and phase diagram of the transverse field Ising model with three atomic spins”, E. Edwards et al, **PRB** 82, 060412 (2010)

-- “Onset of a Quantum Phase Transition with a Trapped Ion Quantum Simulator”, R. Islam et al, **Nature Communications** 2, 377 (2011)

JQI

- - “Emergence and Frustration of Magnetism with Variable-Range Interactions in a Quantum Simulator”, R. Islam et al, **Science** 340, 583 (2013)

-- “Experimental Performance of a Quantum Simulator: Optimizing Adiabatic Evolution and Identifying Ground States” P. Richerme et al, **PRA** 88, 012334

-- “Quantum Catalysis of Magnetic Phase Transitions in a Quantum Simulator”, P. Richerme et al, **PRL** 111, 100506 (2013)

-- “Non-local propagation of correlations in long-range interacting quantum systems”, P. Richerme et al, arXiv 1401.5088 (2014)

18 spins in 2014

-- “Coherent Imaging Spectroscopy of a Quantum Many-Body Spin System”, C. Senko et al, arXiv 1401.5751 (2014)

NIST

-- "Engineered two-dimensional Ising interactions in a trapped-ion quantum simulator with hundreds of spins", J. Britton et al, **Nature** 484, 489 (2012).

-- "Spectroscopy and Thermometry of Transverse Modes in a Planar One-Component Plasma,“ B. Sawyer et al, **PRL**. 108, 213003 (2012).

-- “Spin Dephasing as a Probe of Mode Temperature, Motional State Distributions, and Heating Rates in a 2D Ion Crystal”, B. Sawyer et al, arXiv 1401.0672

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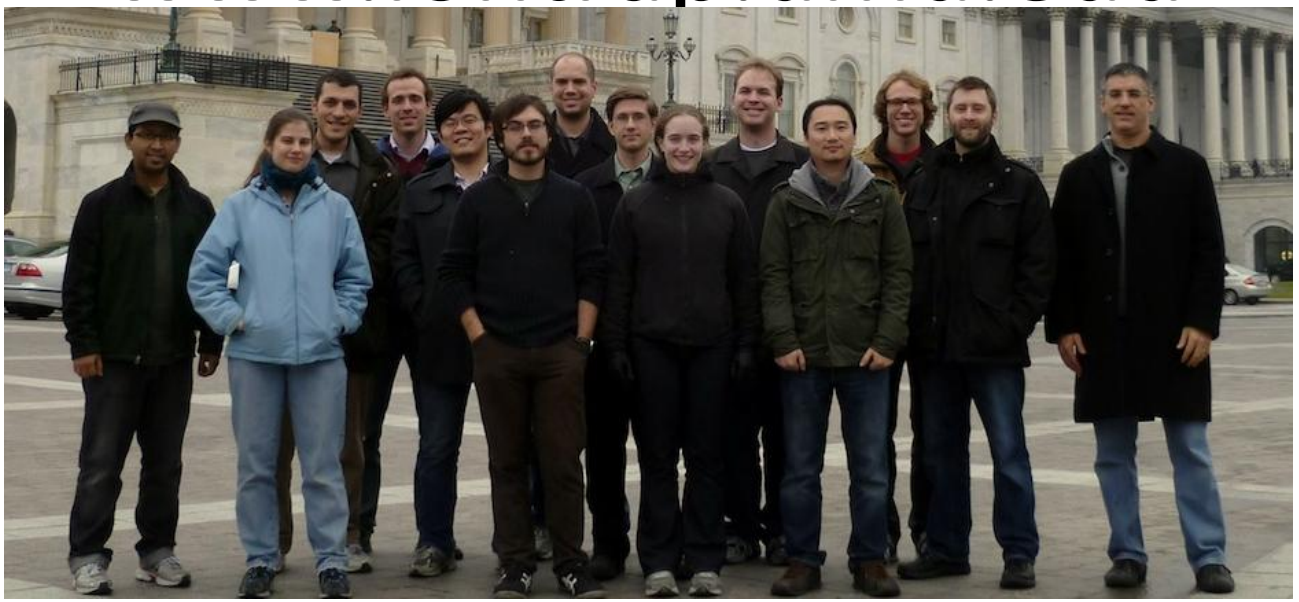

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Prof. Chris Monroe

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Volkan Inlek
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Aaron Lee
Andrew Manning
Crystal Senko
Jacob Smith
David Wong
Ken Wright

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Daniel Brennan
Katie Hergenreder
Geoffrey Ji

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Susan Clark
Charles Conover
Emily Edwards
David Hayes
Rajibul Islam
Kihwan Kim
Simcha Korenblit
Jonathan Mizrahi

Theory Collaborators

Jim Freericks
C.C. Joseph Wang
Bryce Yoshimura

Zhe-Xuan Gong
Michael Foss-Feig
Alexey Gorshkov