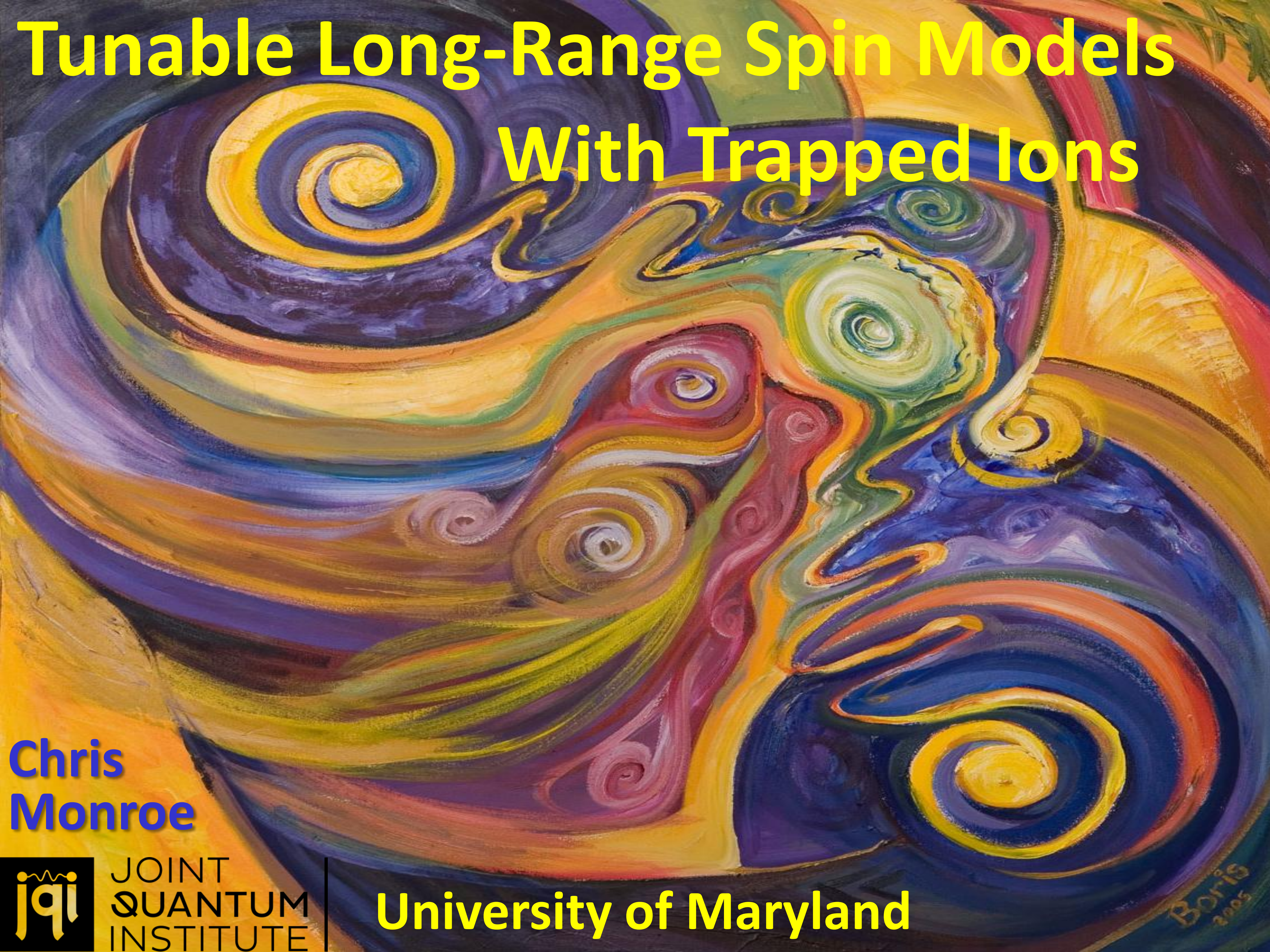
Tunable Long-Range Spin Models With Trapped Ions



Chris Monroe

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University of Maryland

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

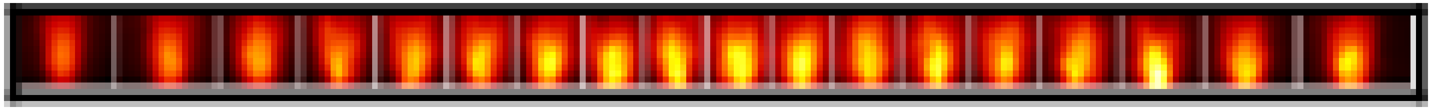
- Direct Many-Body Spectroscopy
- Lieb-Robinson Bounds

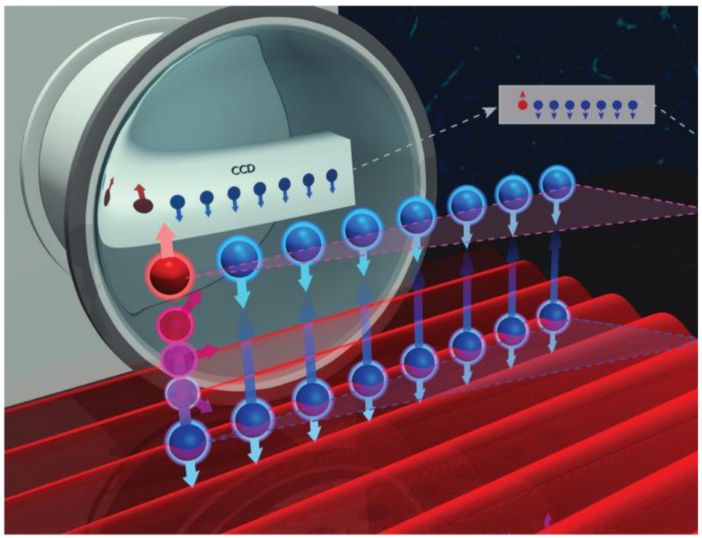
Many-Body Thermalization/Localization?

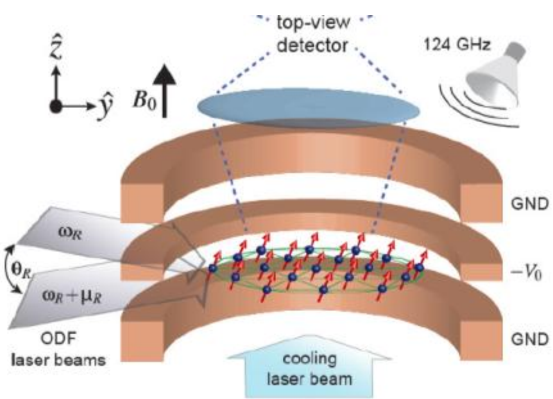
Spin-1

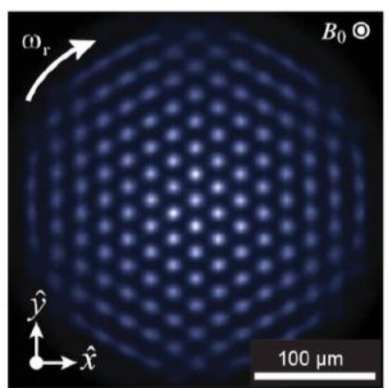
Future

Trapped Atomic Ions: Spin Models





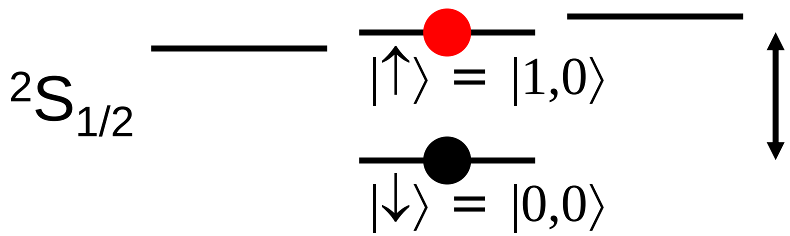




Porras and Cirac, PRL 92, 207901 (2004)
Deng, Porras, Cirac, PRA 72, 063407 (2005)
Taylor and Calarco, PRA 78, 062331 (2008)

A. Friedenauer *et al.*, Nat. Phys. 4, 757 (2008)
K. Kim *et al.*, PRL 102, 250502 (2009)
K. Kim *et al.*, Nature 465, 590 (2010)
E. Edwards *et al.*, PRB 82, 060412 (2010)
J. Barreiro *et al.*, Nature 470 , 486-491 (2011)
R. Islam *et al.*, Nature Comm. 2, 377 (2011)
B. Lanyon *et al.*, Science 334, 57 (2011)
J. Britton *et al.*, Nature 484, 489 (2012)
A. Khromova *et al.*, PRL 108, 220502 (2012)
R. Islam *et al.*, Science 340, 583 (2013)
P. Richerme *et al.*, PRL 111, 100506 (2013)
P. Richerme *et al.*, PRA 88, 012334 (2013)
P. Richerme *et. al.*, Nature 511, 198 (2014)
P. Jurcevic *et al.*, Nature 511, 202 (2014)
C. Senko *et. al.*, Science 345, 430 (2014)

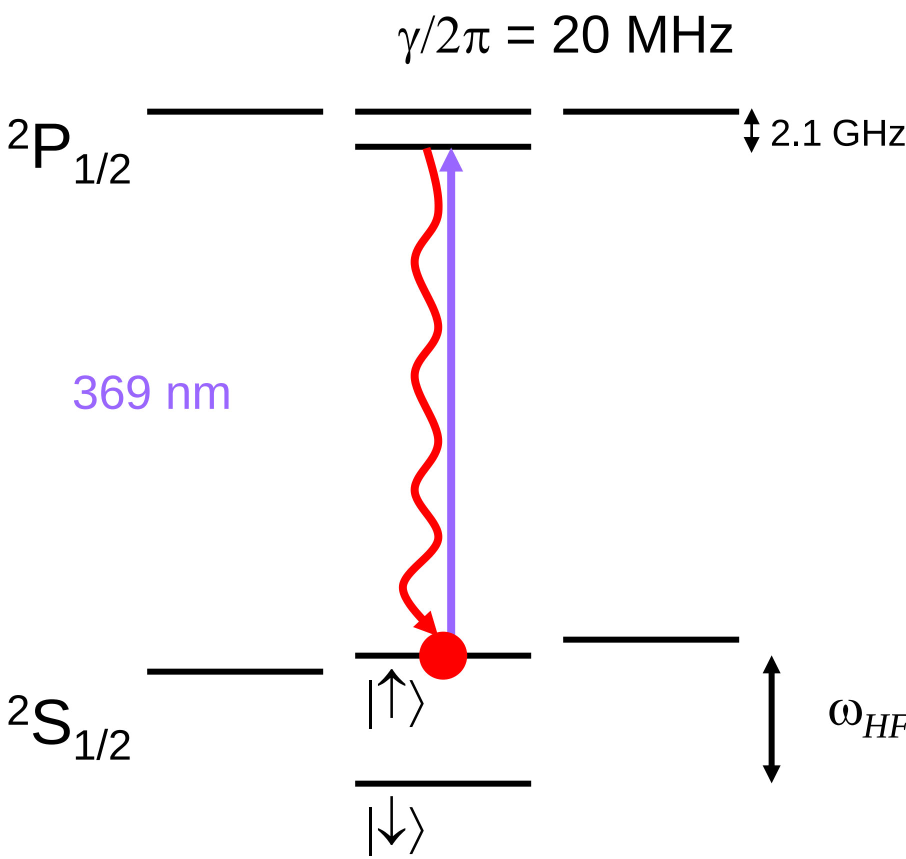
$^{171}Yb^{+}$ hyperfine spin

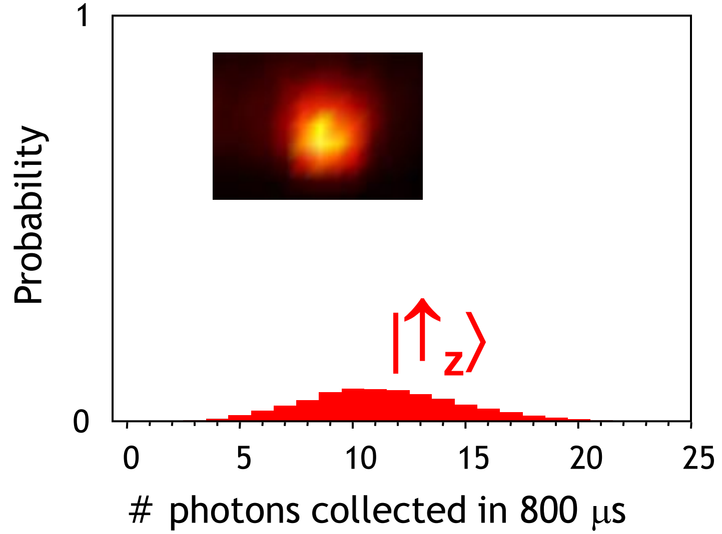


$\omega_{HF}/2\pi = \mathbf{12\ 642\ 812\ 118} + \mathbf{311B^2}$ Hz

(600 Hz/G @ 1 G)

$^{171}Yb^+$ spin detection

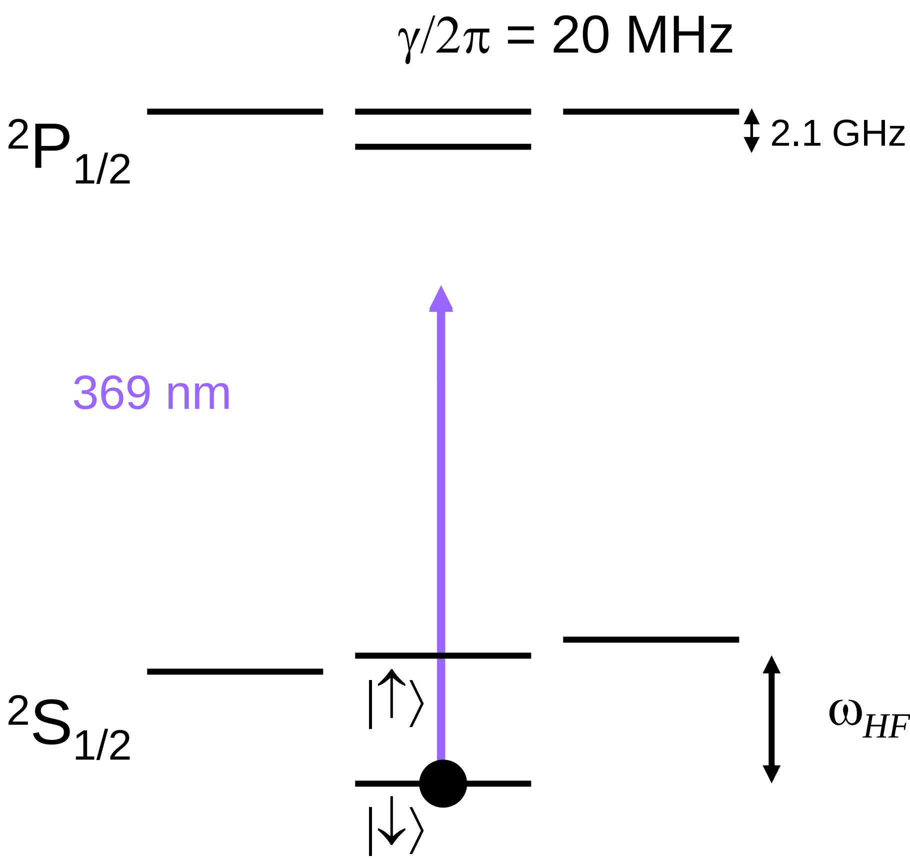




$\omega_{HF}/2\pi$ = **12 642 812 118** **+ 311B²** Hz

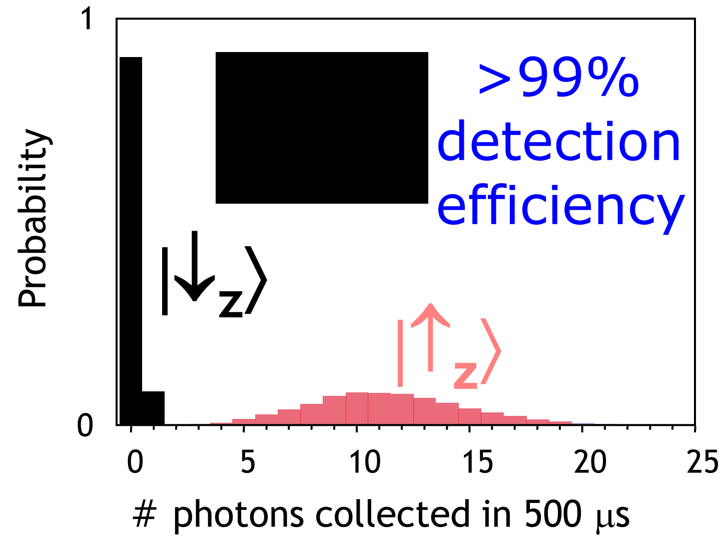
(600 Hz/G @ 1 G)

$^{171}Yb^{+}$ spin detection

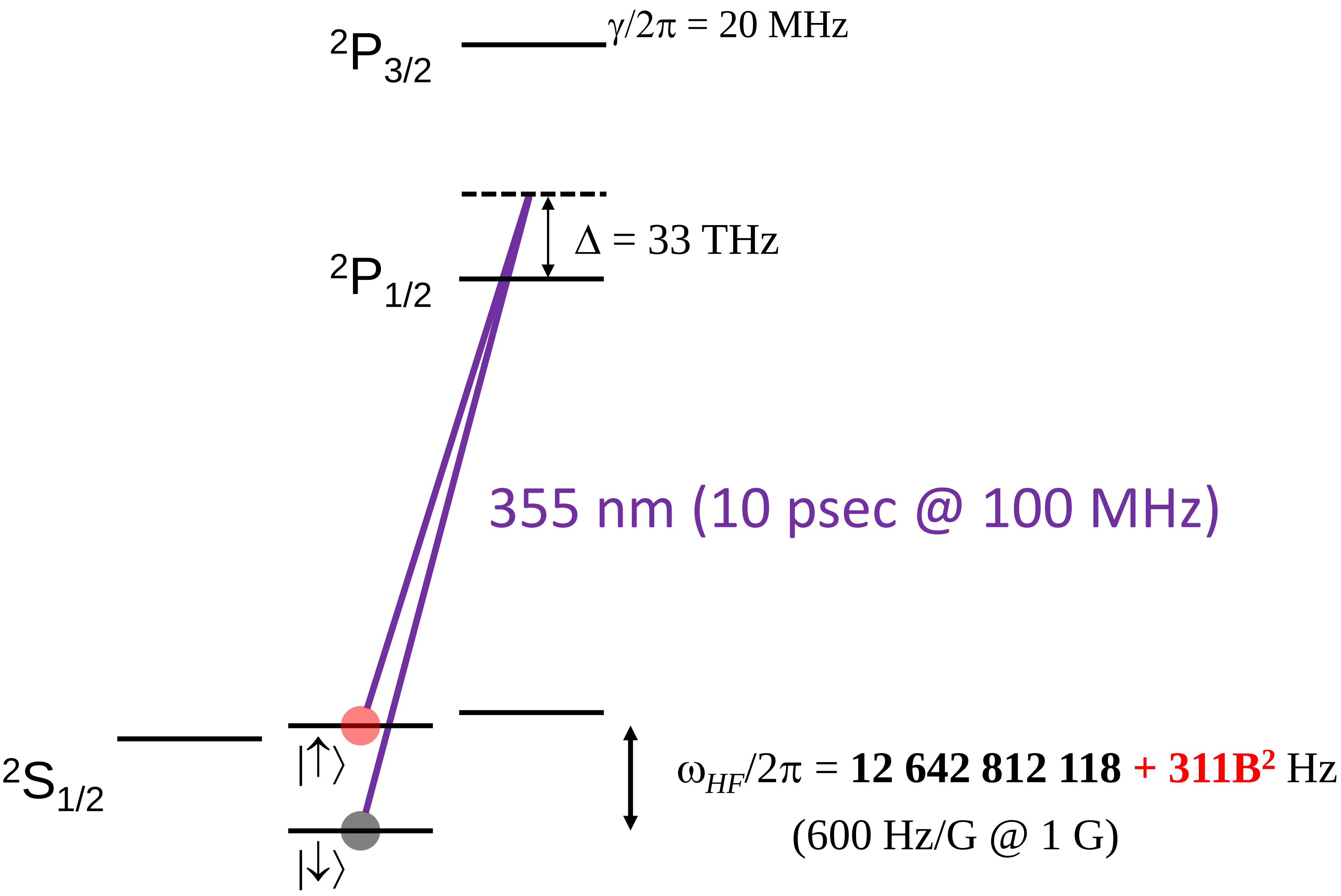


$$\omega_{HF}/2\pi = \mathbf{12\ 642\ 812\ 118} + \mathbf{311B^2}\ \text{Hz}$$

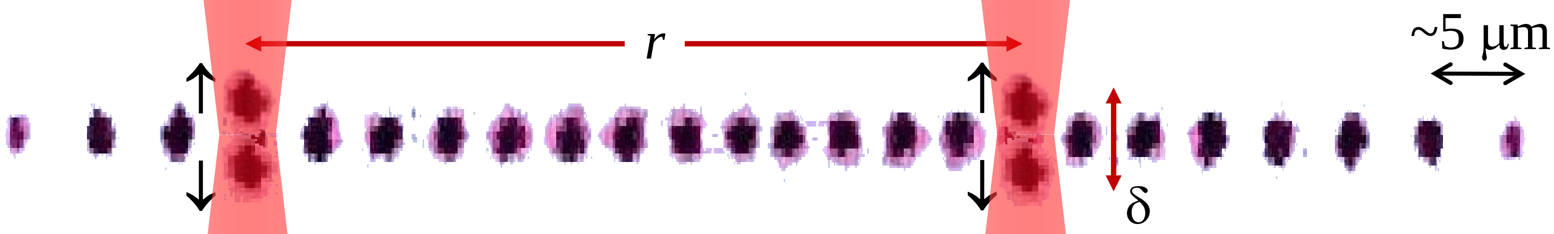
(600 Hz/G @ 1 G)



$^{171}Yb^{+}$ spin manipulation



Entangling Trapped Ion Spins



"dipole-dipole coupling" $$\Delta E = \frac{e^2}{\sqrt{r^2+\delta^2}} - \frac{e^2}{r} \approx -\frac{(e\delta)^2}{2r^3}$$

δ ~ 10 nm
eδ ~ 500 Debye

$$\begin{aligned} |{\downarrow\downarrow}\rangle &\rightarrow \quad\;\; |{\downarrow\downarrow}\rangle \\ |{\downarrow\uparrow}\rangle &\rightarrow e^{-i\varphi}|{\downarrow\uparrow}\rangle \\ |{\uparrow\downarrow}\rangle &\rightarrow e^{-i\varphi}|{\uparrow\downarrow}\rangle \\ |{\uparrow\uparrow}\rangle &\rightarrow \quad\;\; |{\uparrow\uparrow}\rangle \end{aligned} \longrightarrow \varphi = \frac{\Delta E t}{\hbar} = \frac{e^2\delta^2 t}{2\hbar r^3} = \frac{\pi}{2}$$ for full entanglement

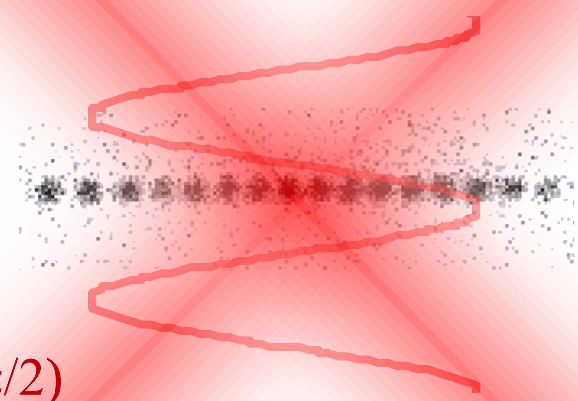
Cirac and Zoller (1995)
Mølmer & Sørensen (1999)
Solano, de Matos Filho, Zagury (1999)
Milburn, Schneider, James (2000)

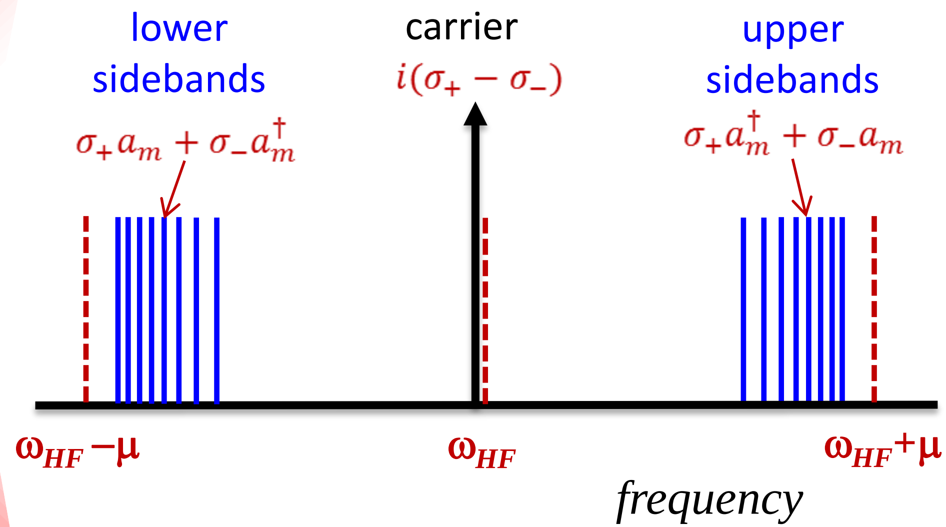
Resonant spin-dependent force

Raman beatnotes:

$\omega_{HF} \pm \mu$

ω_{HF} $(\Delta\phi = \pi/2)$





$$H = \Delta k \Omega \sum_{i,m} \hat{\sigma}_x^{(i)} x_0^m b_i^m [a_m^\dagger e^{i(\mu-\omega_m)t} + a_m e^{-i(\mu-\omega_m)t}]$$

normal mode eigenvectors (ion i mode m)

$$H_{eff} = \sum_{i<j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B \sum_i \hat{\sigma}_y^{(i)}$$

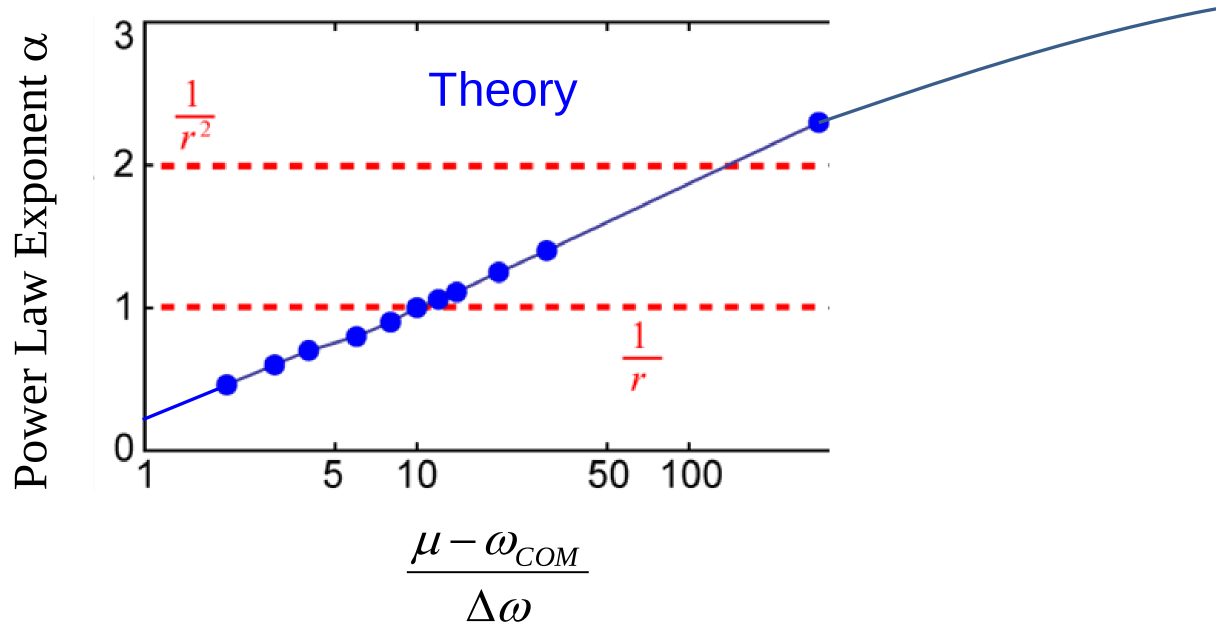
$$J_{i,j} = \Omega^2 \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_m \frac{b_i^m b_j^m}{\mu^2 - \omega_m^2}$$

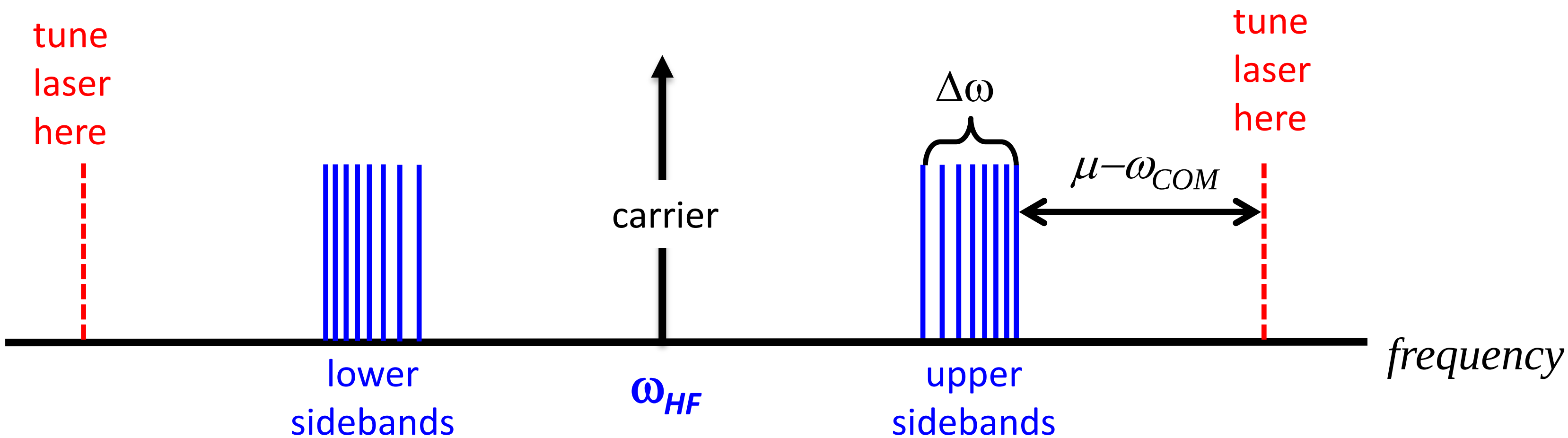
control

Control of interaction range

$$J_{i,j} = \Omega^2 \frac{\hbar(\Delta k)^2}{2m} \sum_k \frac{b_i^k b_j^k}{\mu^2 - \omega_k^2}$$

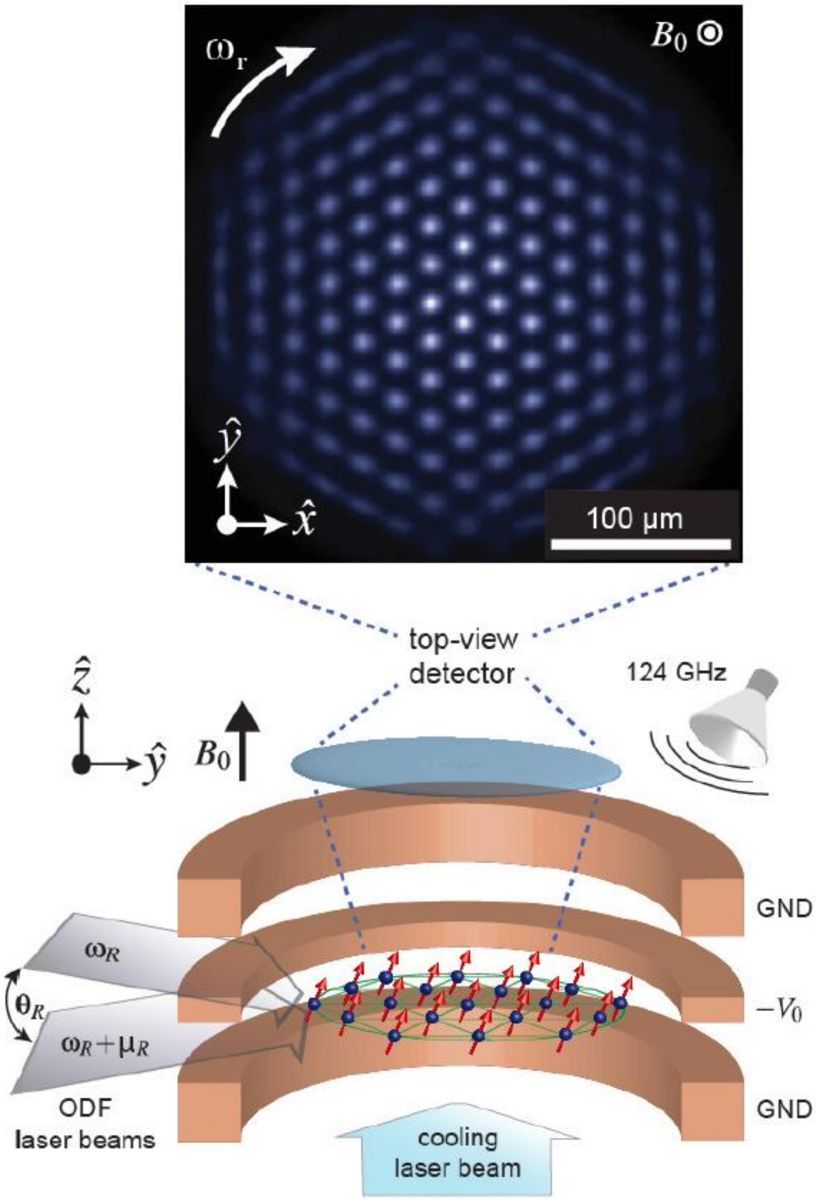
$$\sim \quad + \frac{1}{r^\alpha}$$



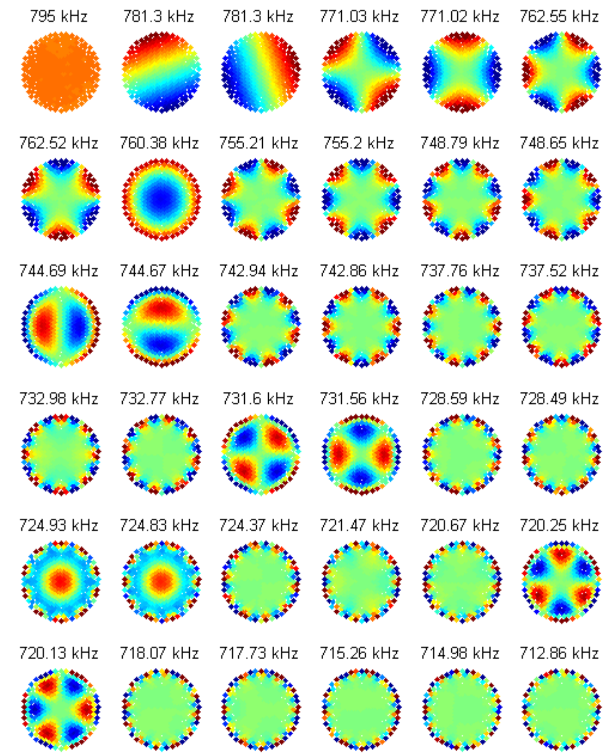


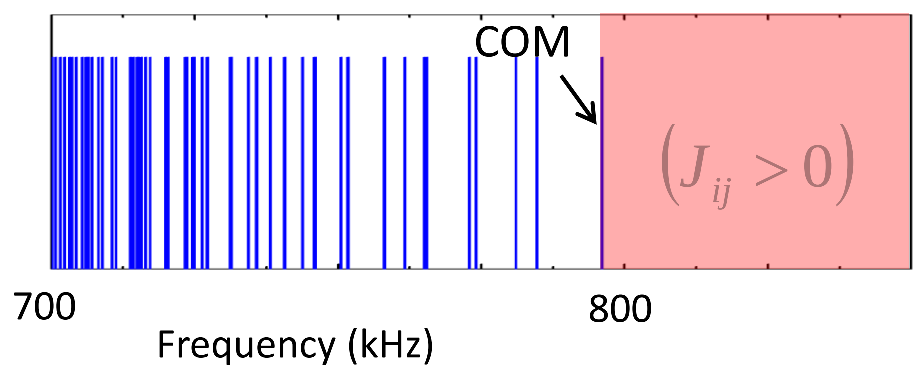
2D Penning trap

John Bollinger (NIST Boulder)



Axial mode spectrum





J. W. Britton et al., Nature **484**, 489 (2012)

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

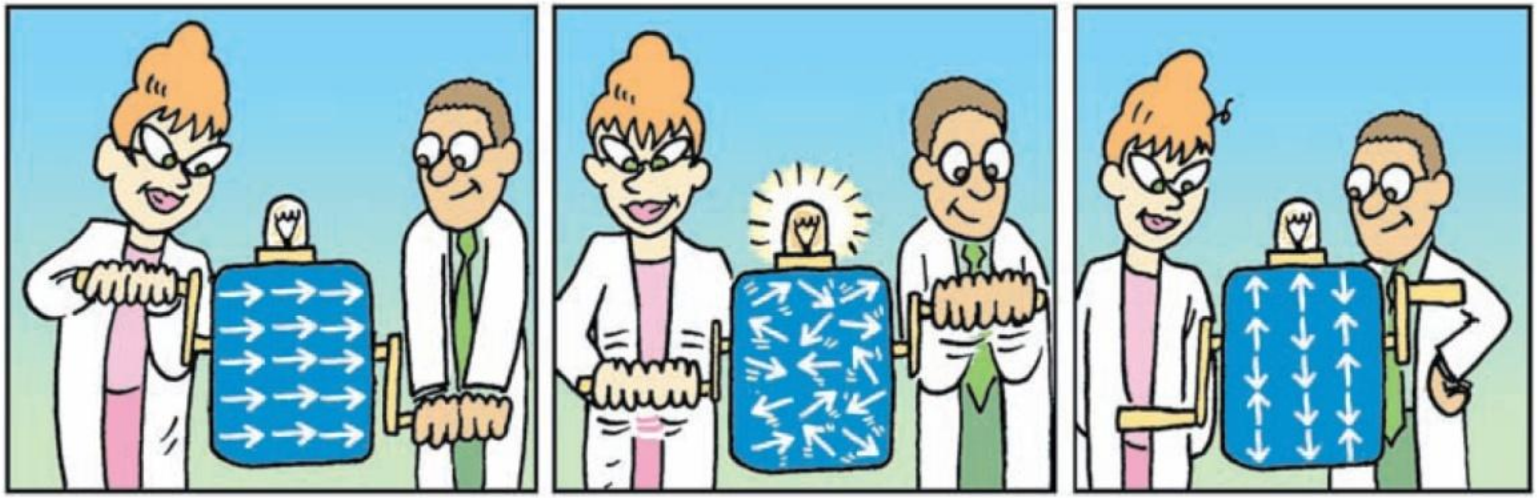
- Direct Many-Body Spectroscopy
- Lieb-Robinson Bounds

Many-Body Thermalization/Localization?

Spin-1

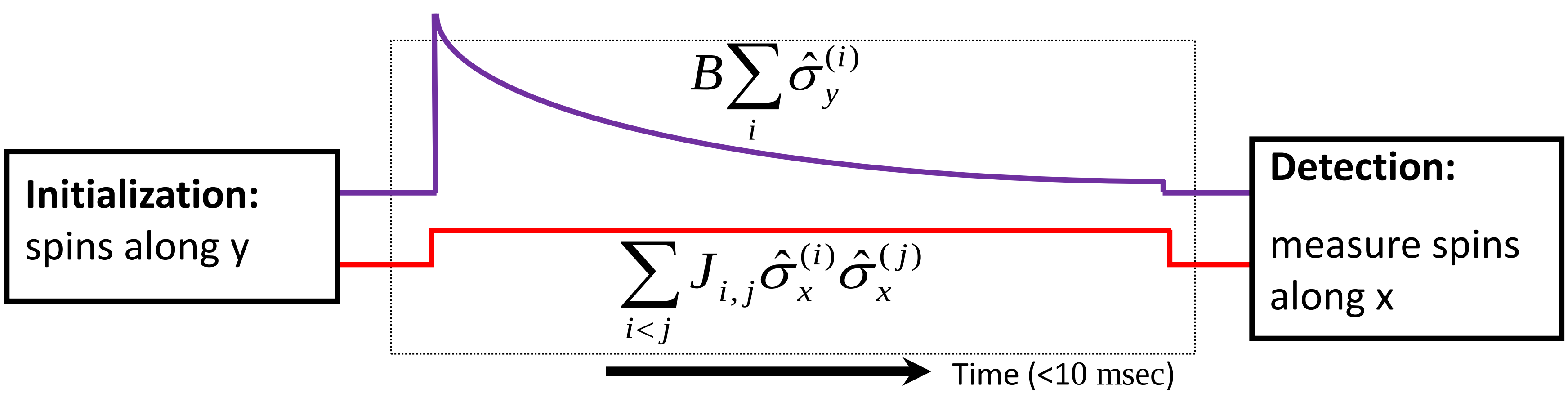
Future

Equilibrium: Adiabatic Quantum Simulation



from S. Lloyd, Science **319**, 1209 (2008)

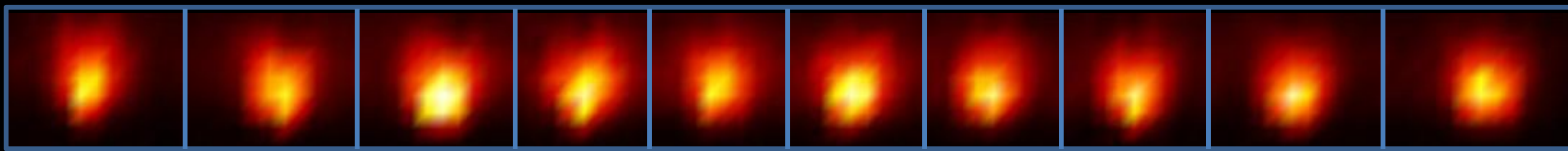
$$H_{eff} = \sum_{i<j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B \sum_i \hat{\sigma}_y^{(i)}$$



Antiferromagnetic Néel order of N=10 spins

2600 runs, α=1.12

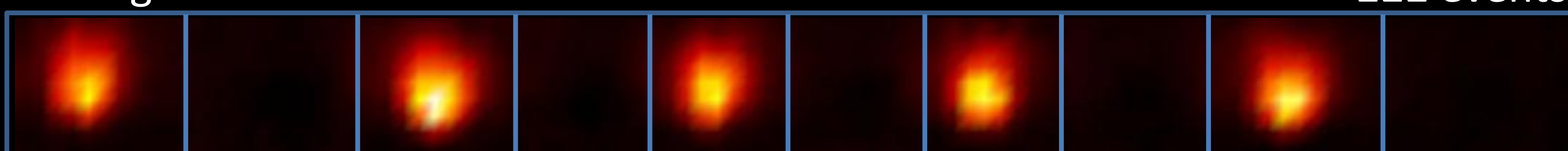
All in state $\uparrow$



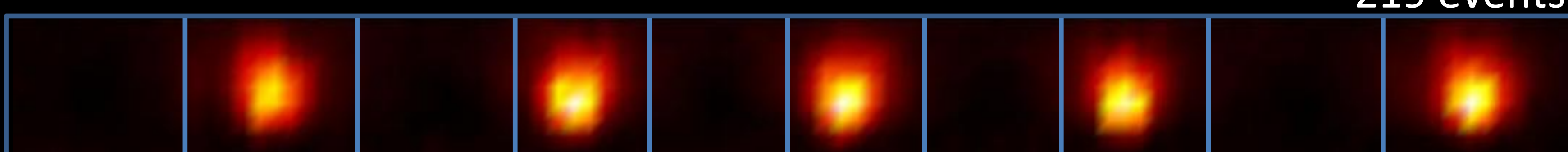
All in state $\downarrow$

AFM ground state order

222 events



219 events



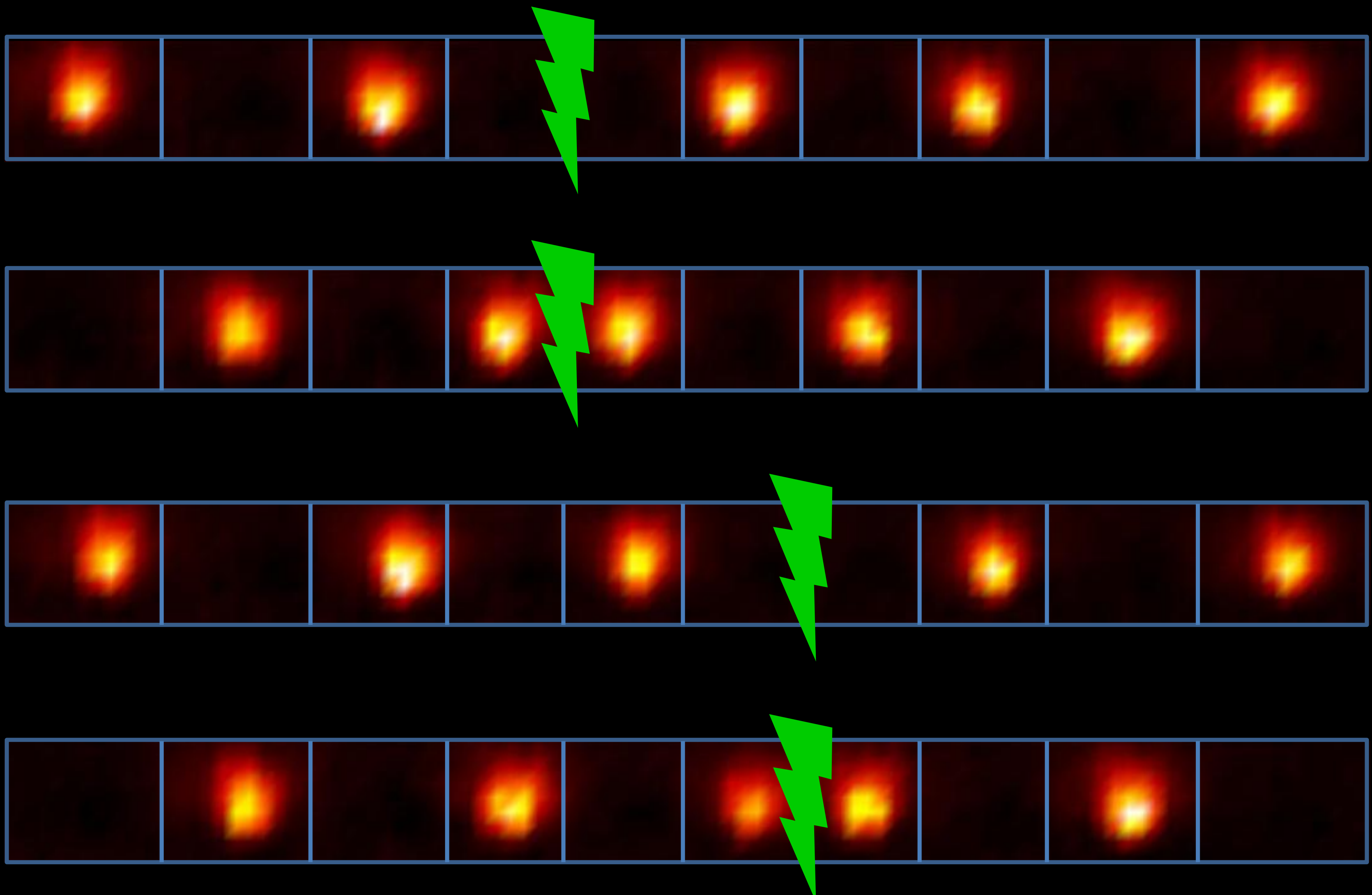
441 events out of 2600 = 17%

Prob of any state at random =2 x $(1/2^{10})$ = 0.2%

R. Islam et al., Science 340, 583 (2013)

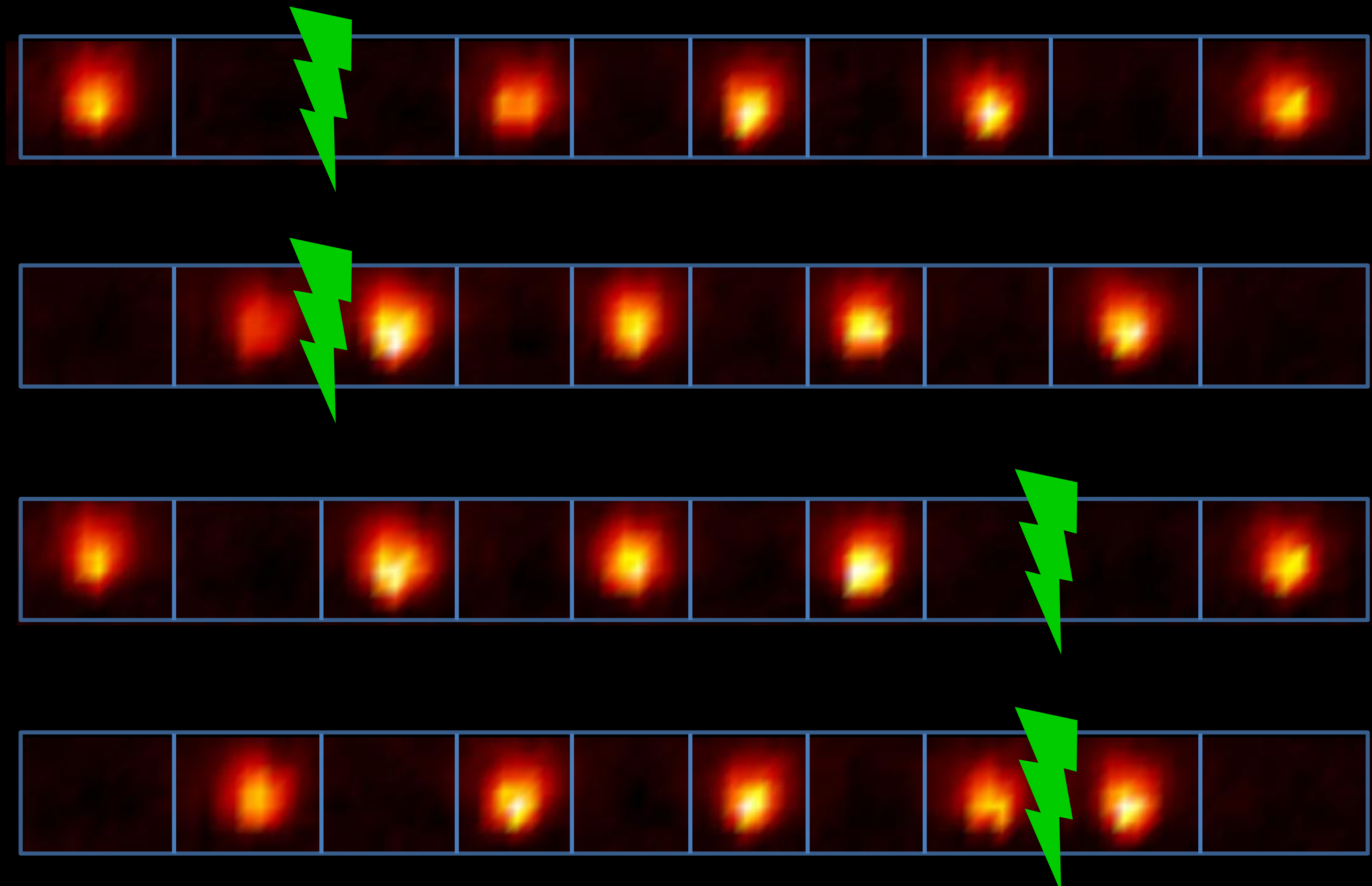
First Excited States

(Pop. ~2% each)

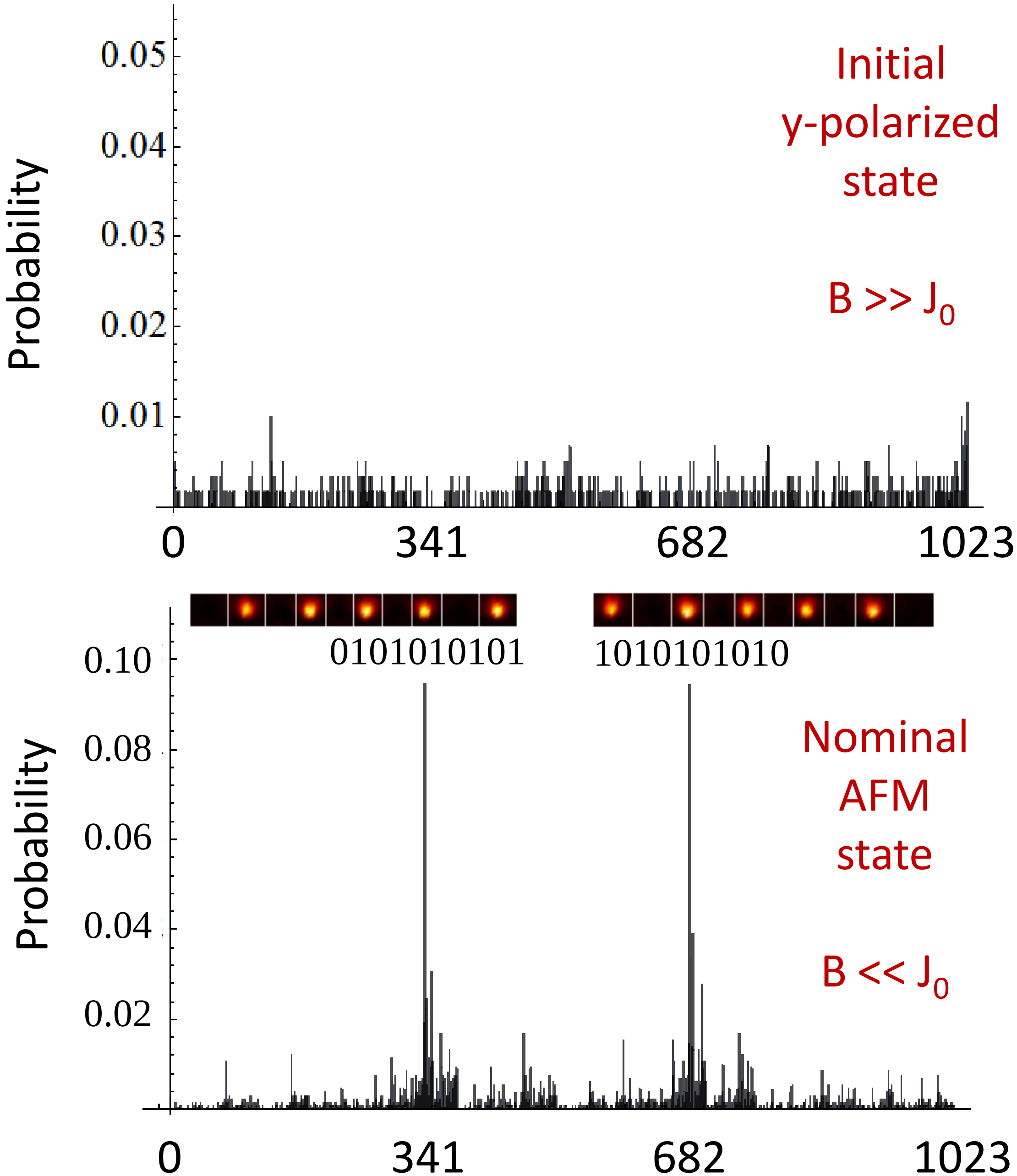


Second Excited States

(Pop. ~1% each)

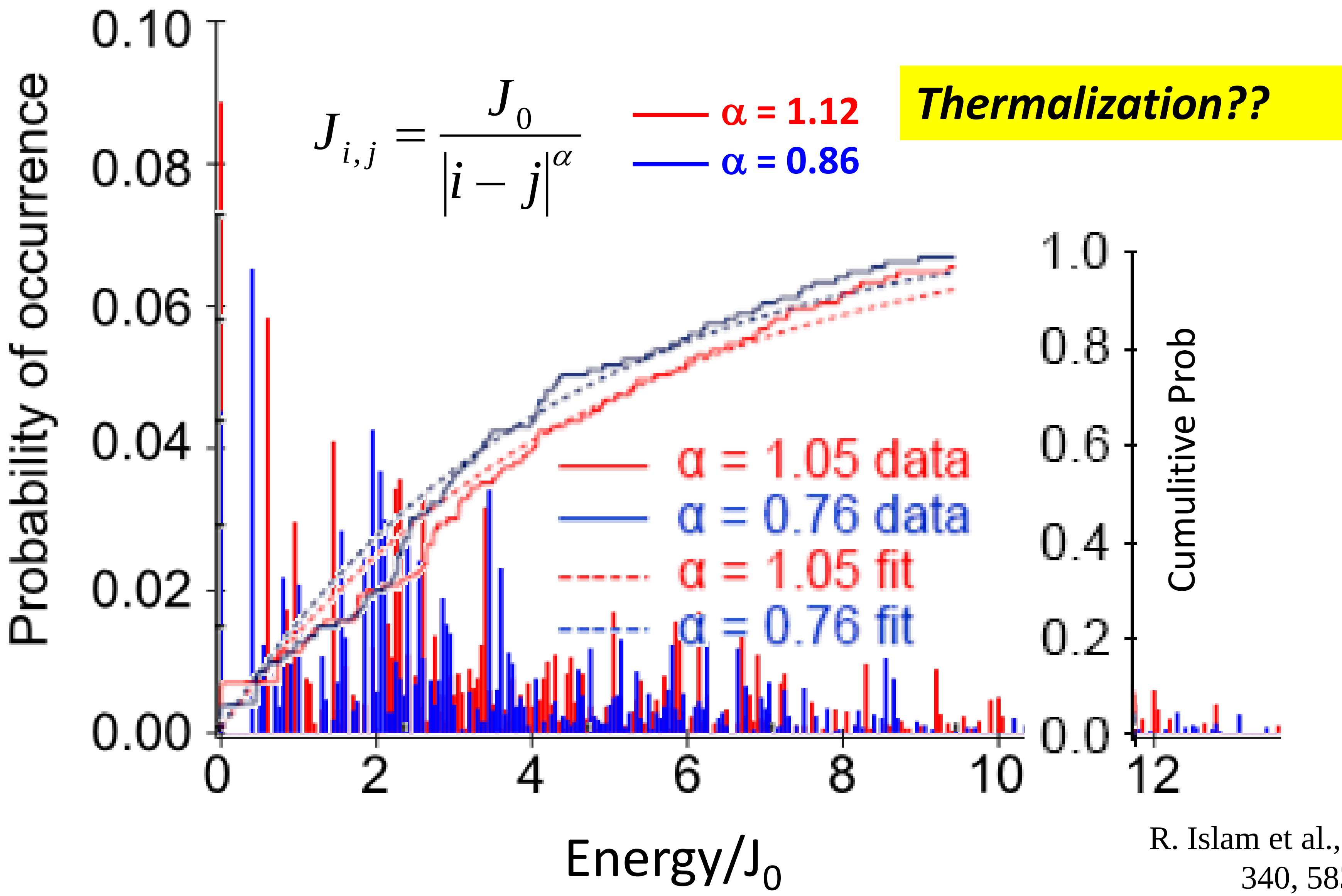


Distribution of all $2^{10} = 1024$ states



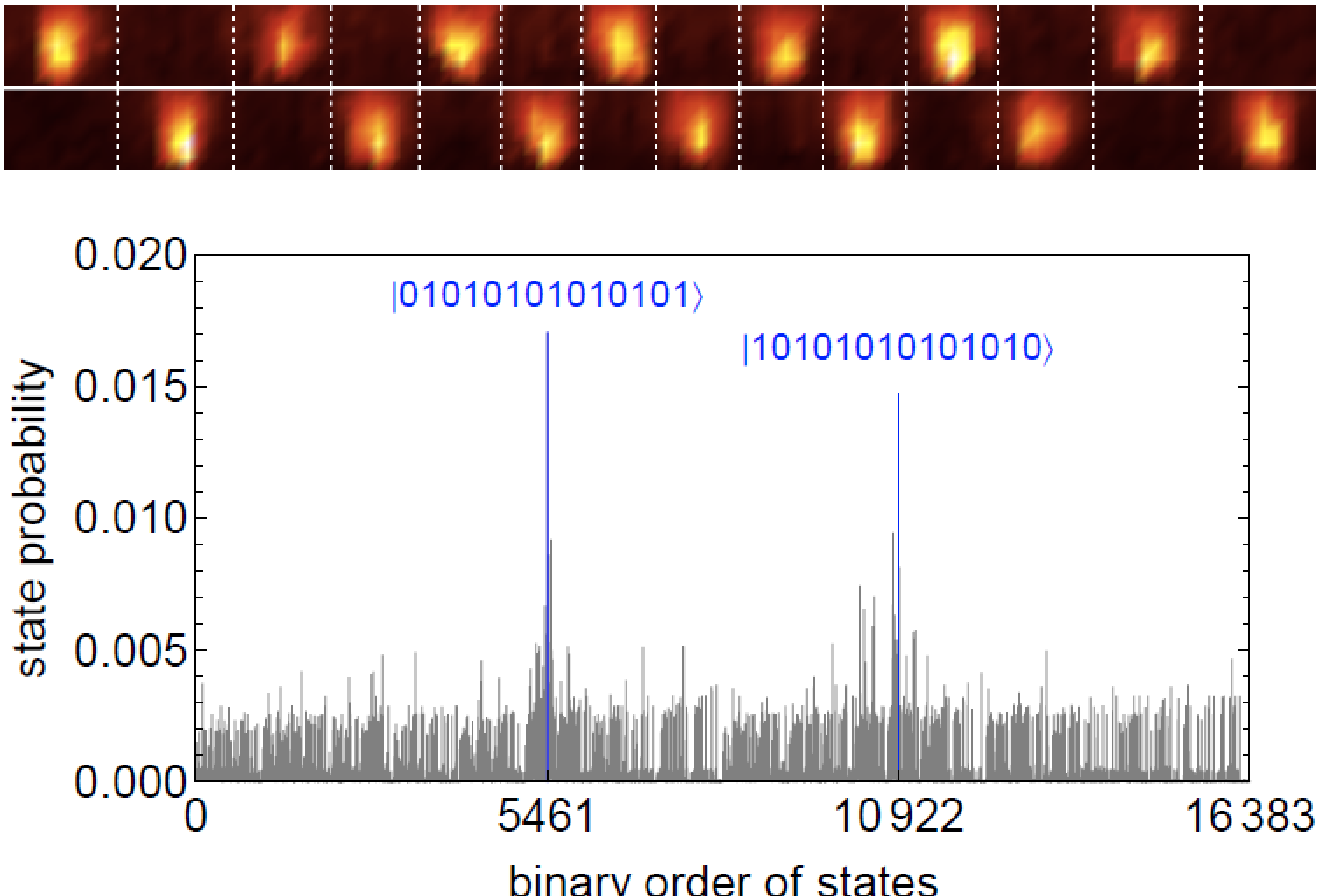
R. Islam et al., Science
340, 583 (2013)

Distribution of states ordered by energy (N=10)

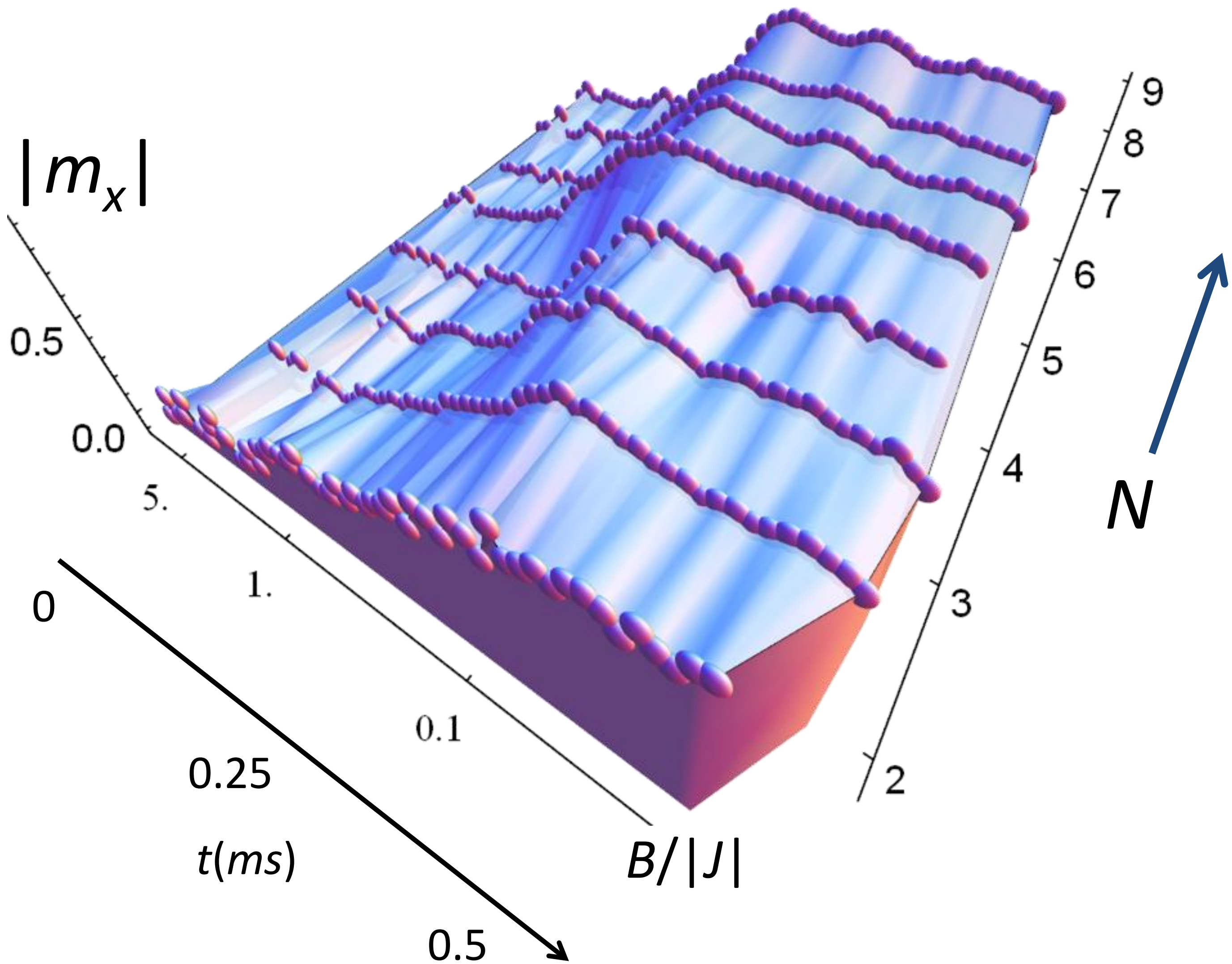


R. Islam et al., Science 340, 583 (2013)

AFM order of N=14 spins (16,384 configurations)

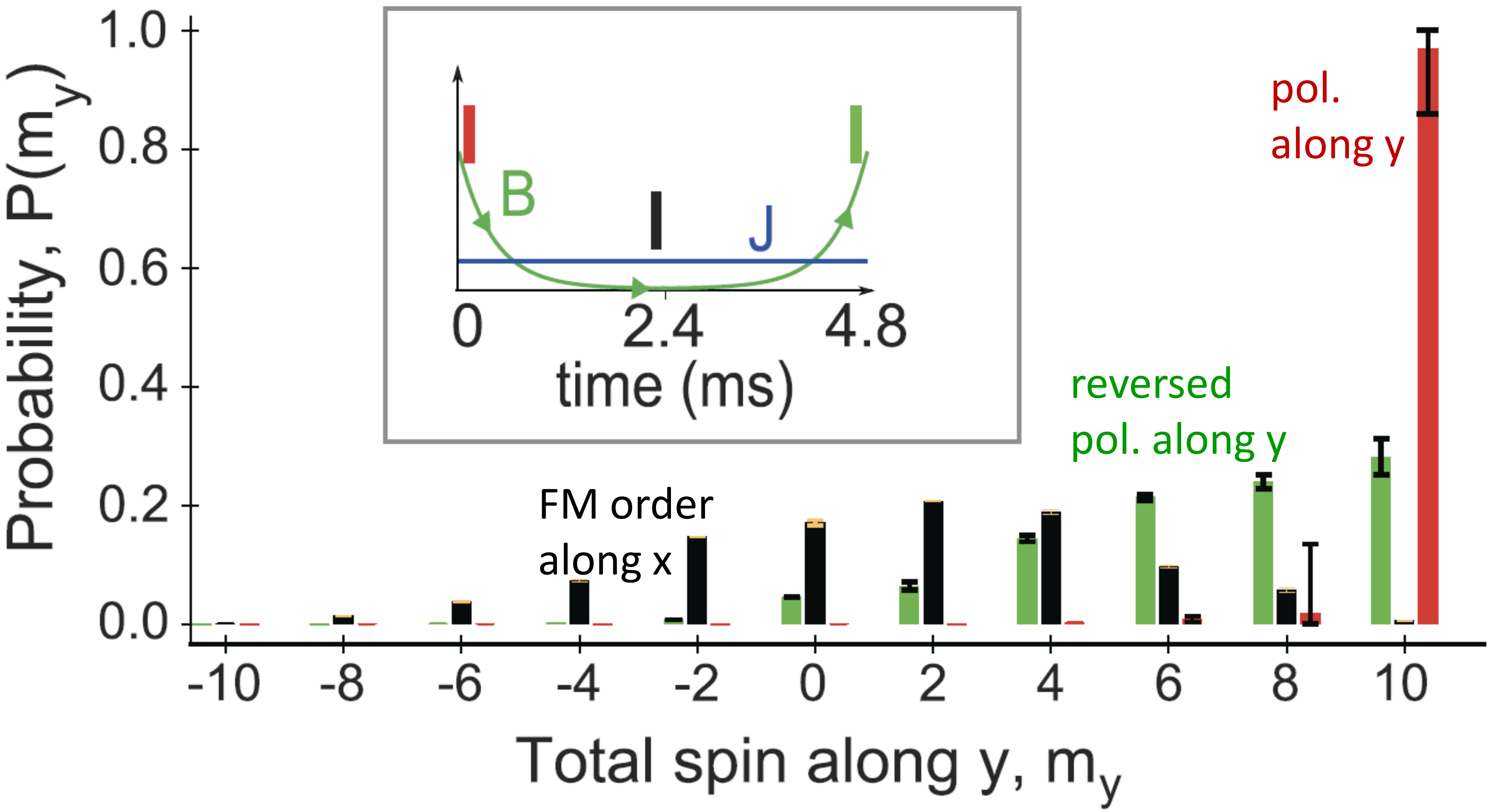


Ferromagnet order vs. # spins N



R. Islam et al., Nature Communications 2, 377 (2011)

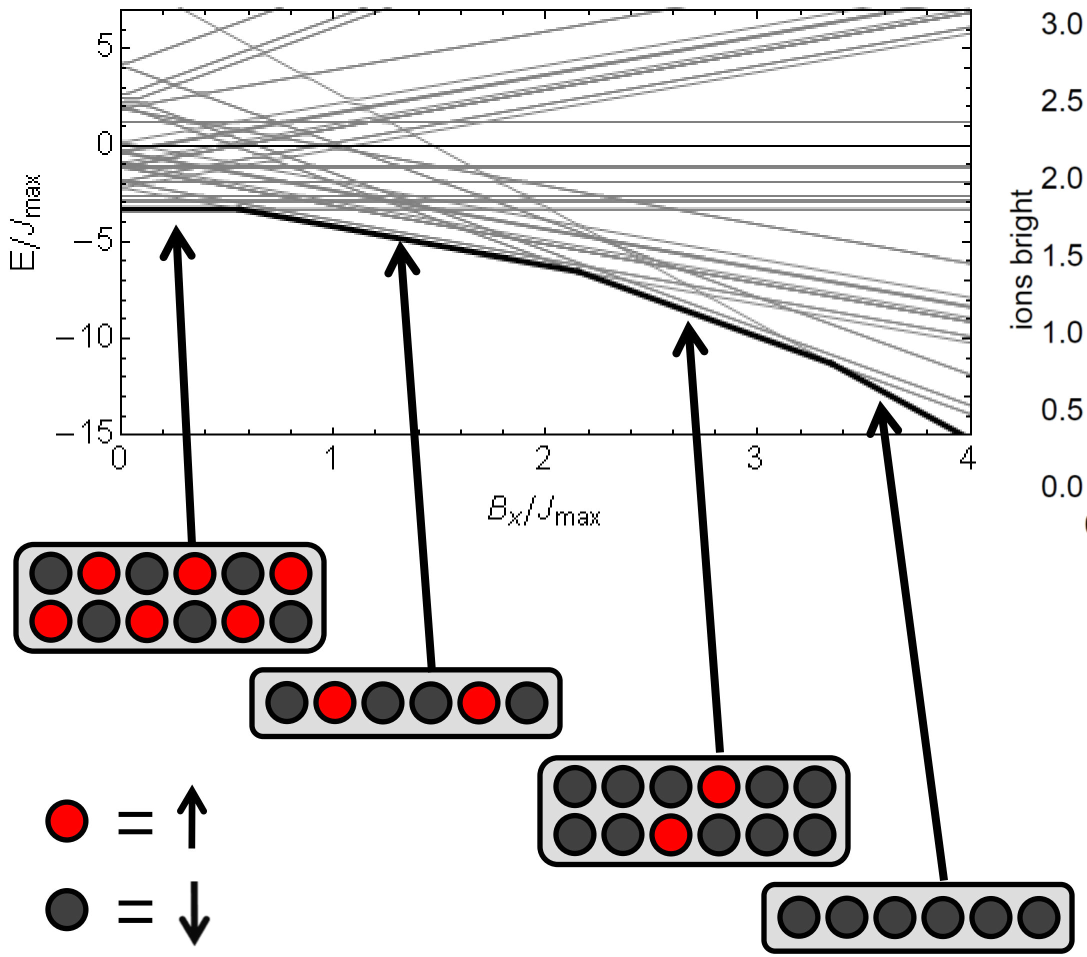
Ferromagnetic reversal of evolution (N=10)

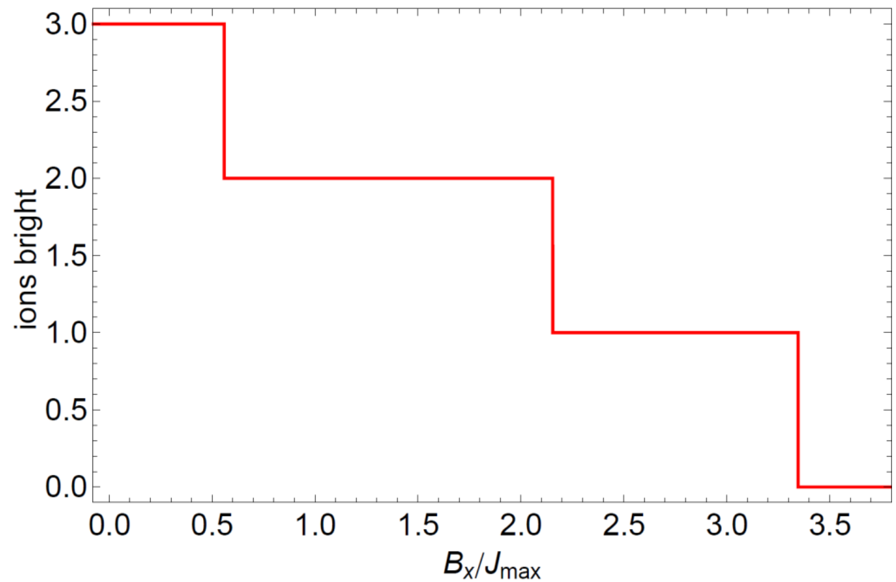


$\langle m_y \rangle$ returns to 70% of its initial value

AFM Ising Model with axial Field

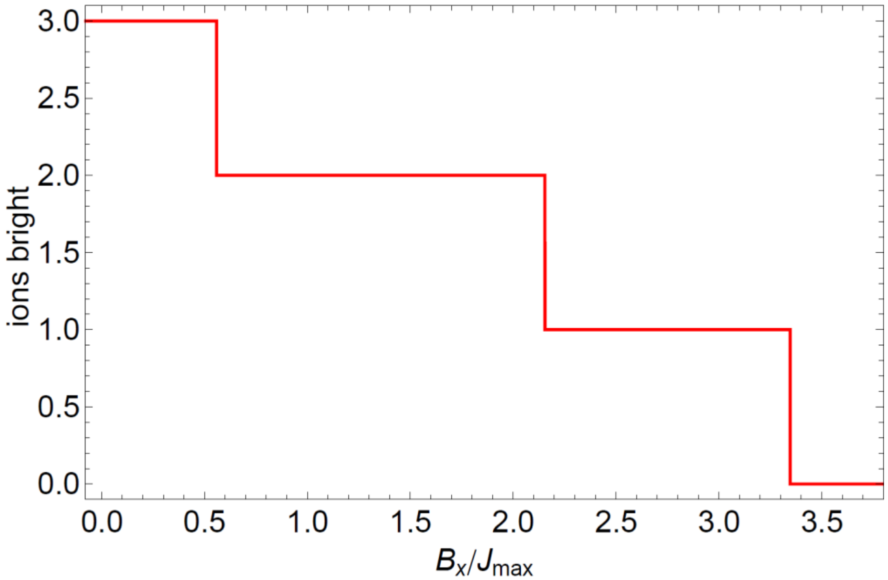
At $B_y = 0$: $$H = \sum_{i \neq j} J_x^{\,i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + \cancel{B_y(t) \sum_i \hat{\sigma}_y^{(i)}} + B_x \sum_i \hat{\sigma}_x^{(i)}$$





P. Richerme *et. al.*, PRL **111**, 100506 (2013)

AFM Ising Model with axial field + tranverse field ramp: 6 ions



P. Richerme *et. al.*, PRL **111**, 100506 (2013)

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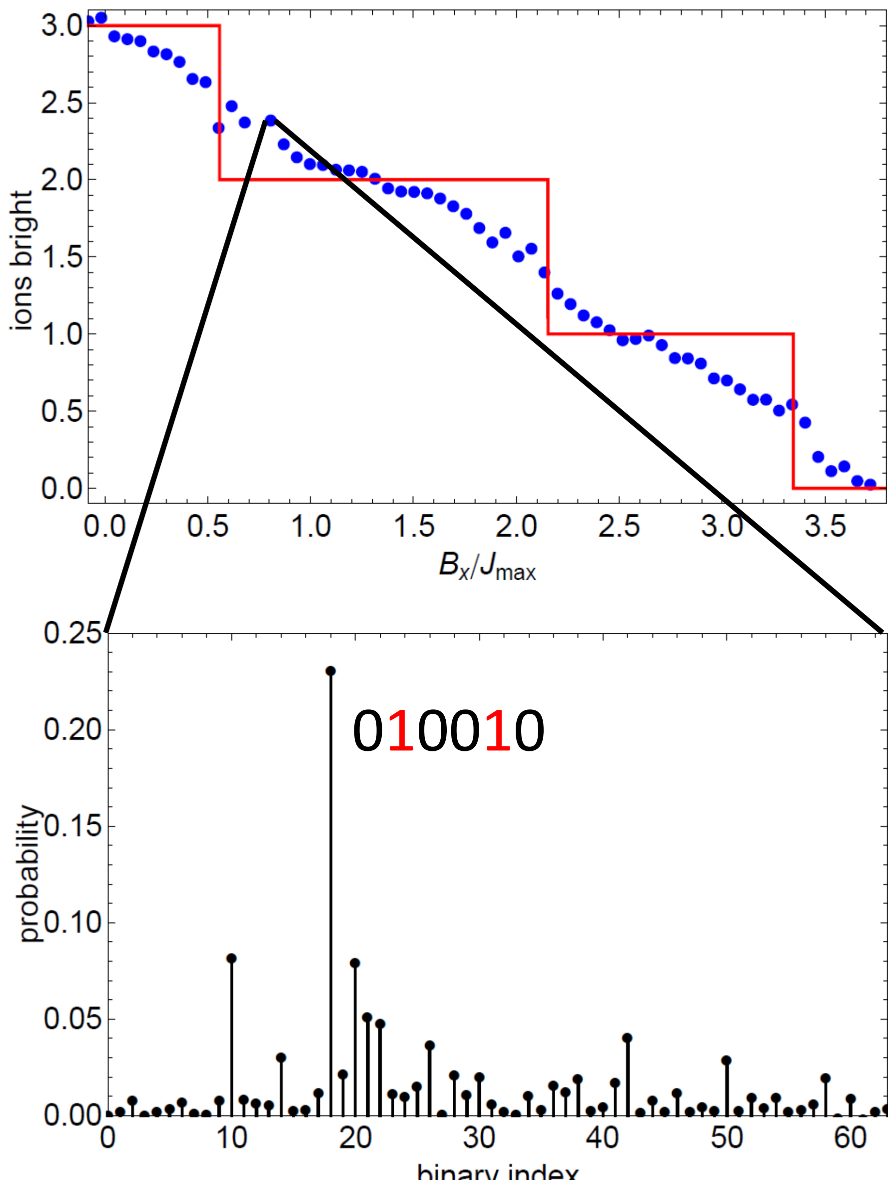
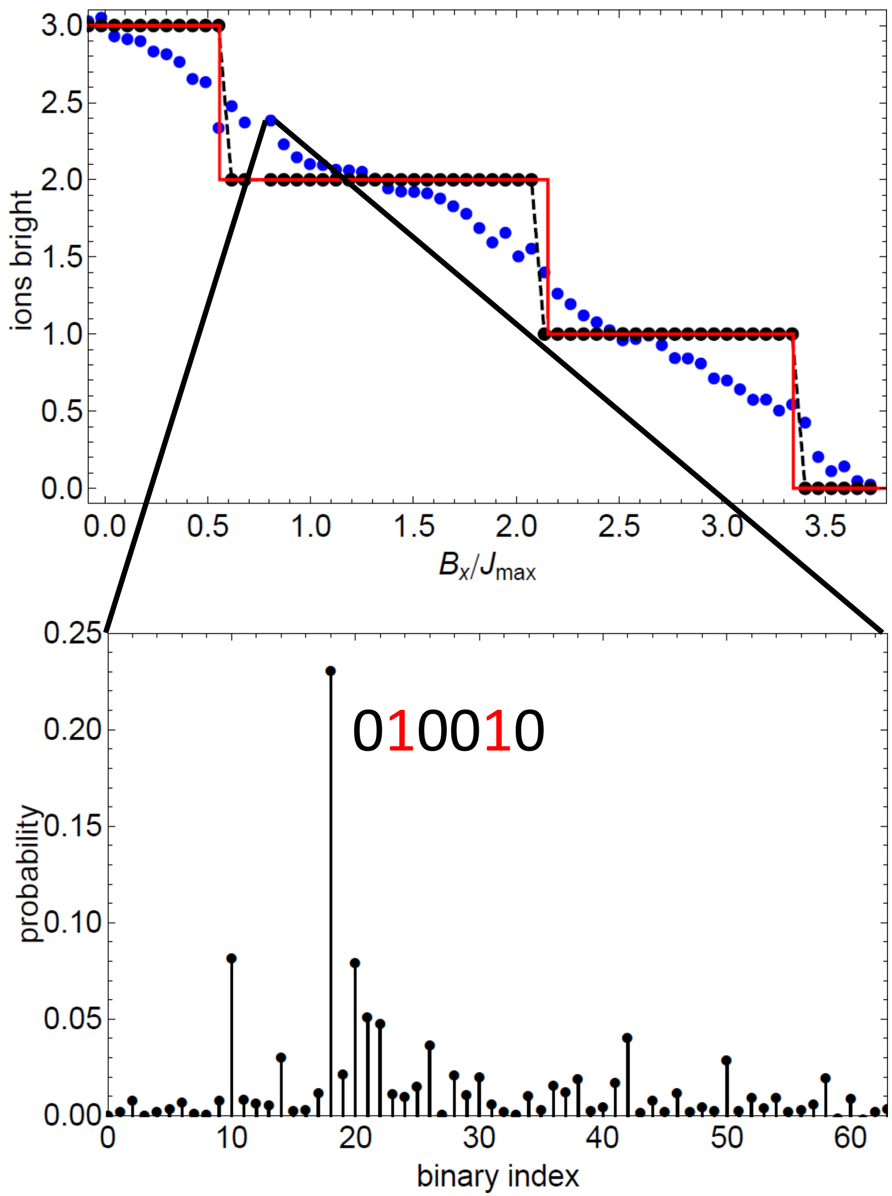
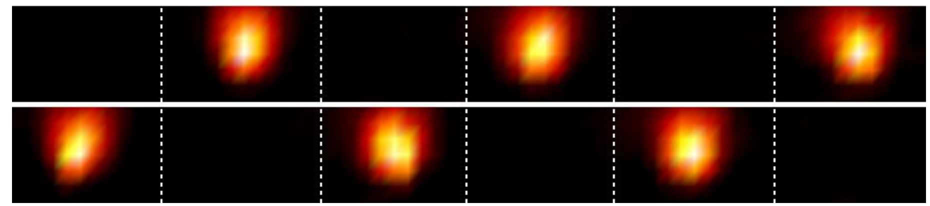


P. Richerme *et. al.*, PRL **111**, 100506 (2013)

AFM Ising Model with axial field + tranverse field ramp: 6 ions

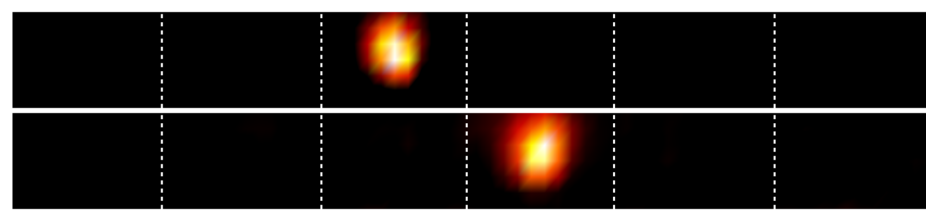


AFM Ground States



2-Bright Ground State

1-Bright Ground States

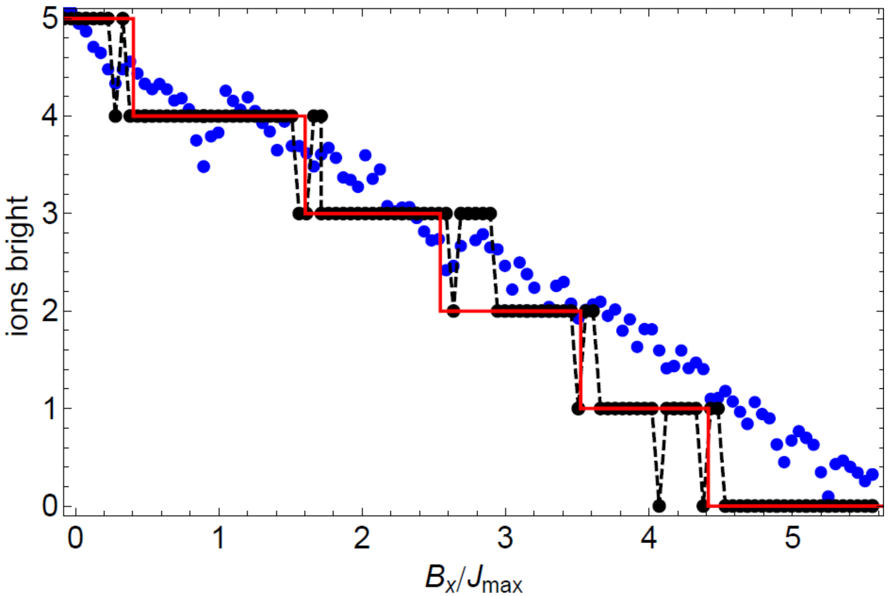


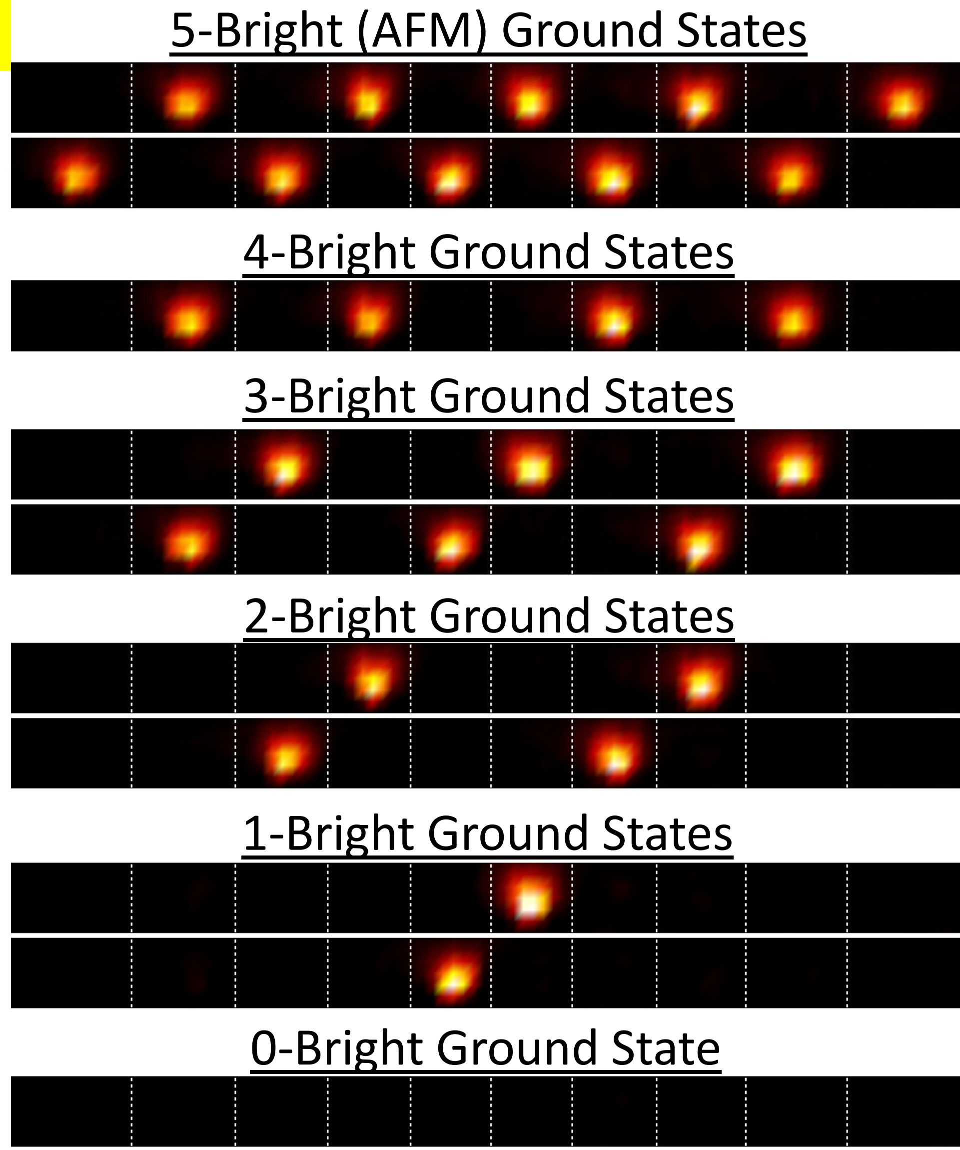
0-Bright Ground State

P. Richerme *et. al.*, PRL **111**, 100506 (2013)

AFM Ising Model with axial field + tranverse field ramp: 10 ions

$$H = \sum_{i \neq j} J_x^{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)} + B_y(t) \sum_i \hat{\sigma}_y^{(i)} + \boxed{B_x \sum_i \hat{\sigma}_x^{(i)}}$$





System exhibits a complete devil's staircase for N ⟶ ∞

P. Bak and R. Bruinsma, PRL **49**, 249 (1982)

P. Richerme *et. al.*, PRL **111**, 100506 (2013)

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

- Direct Many-Body Spectroscopy
- Lieb-Robinson Bounds

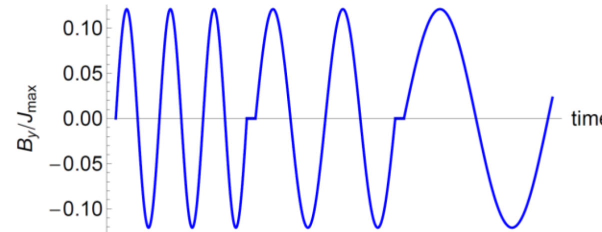
Many-Body Thermalization/Localization?

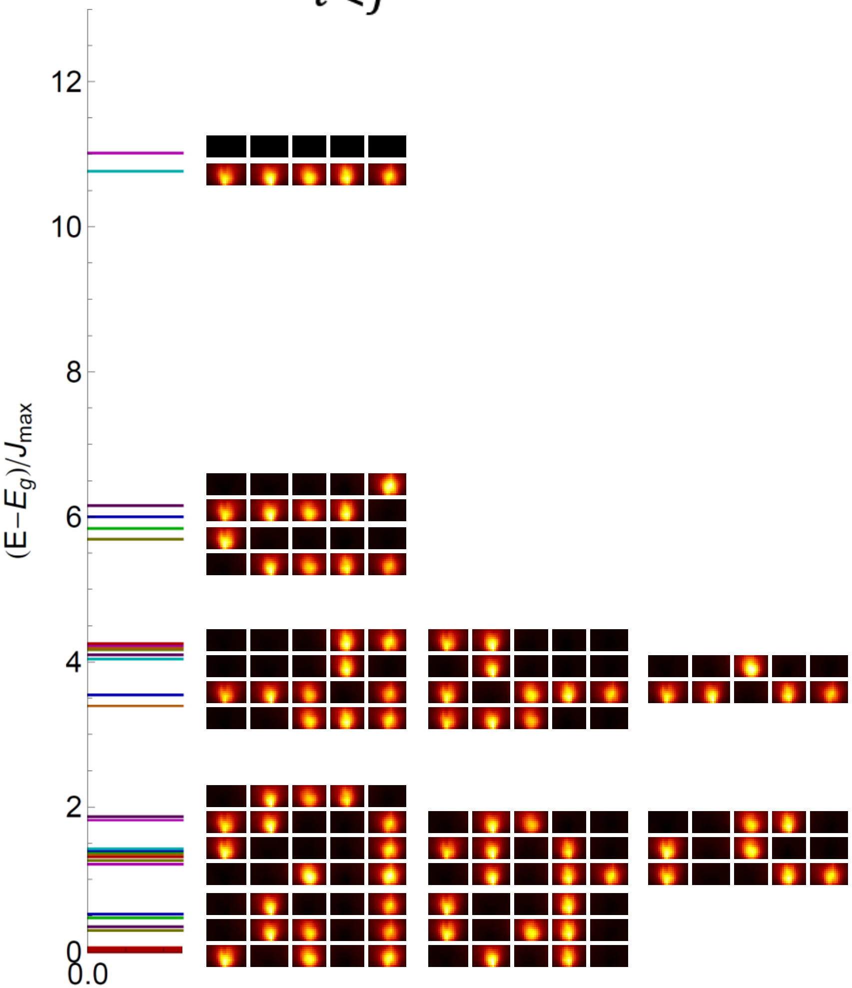
Spin-1

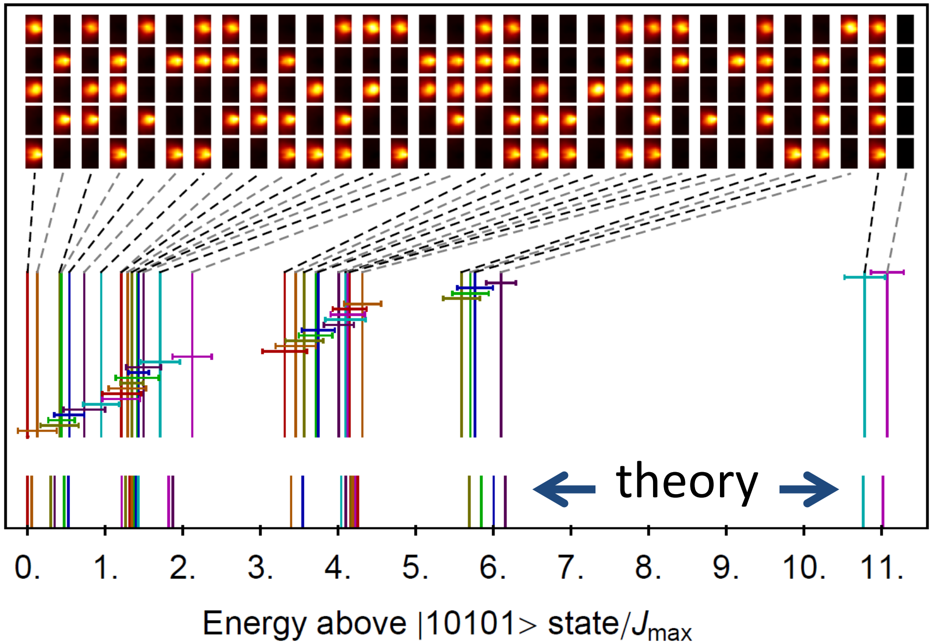
Future

Coherent Imaging Spectroscopy (N=5 spins)

$$H = \sum_{i<j} J_{ij}\sigma_x^i \sigma_x^j$$

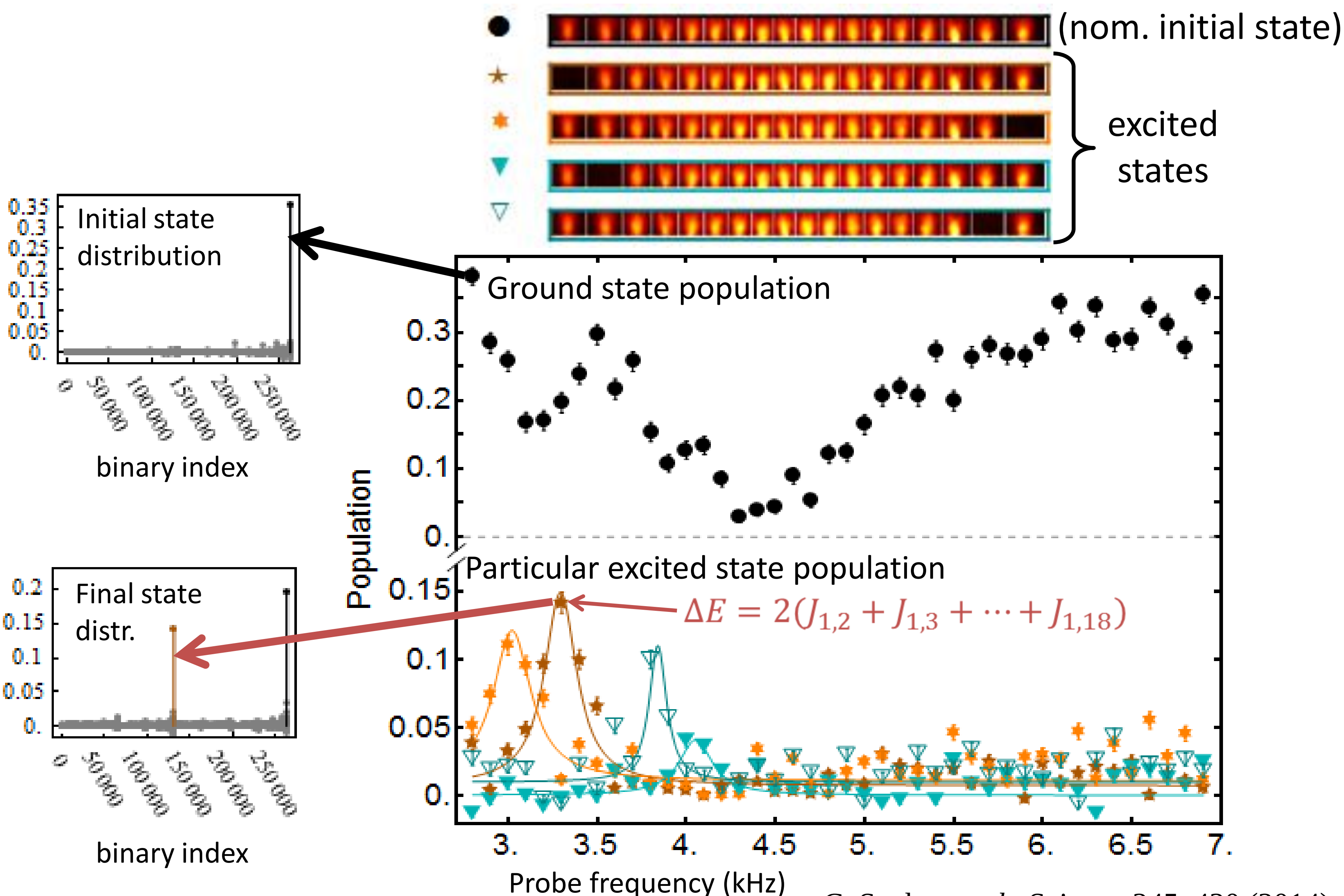






C. Senko *et. al.*, Science 345, 430 (2014)

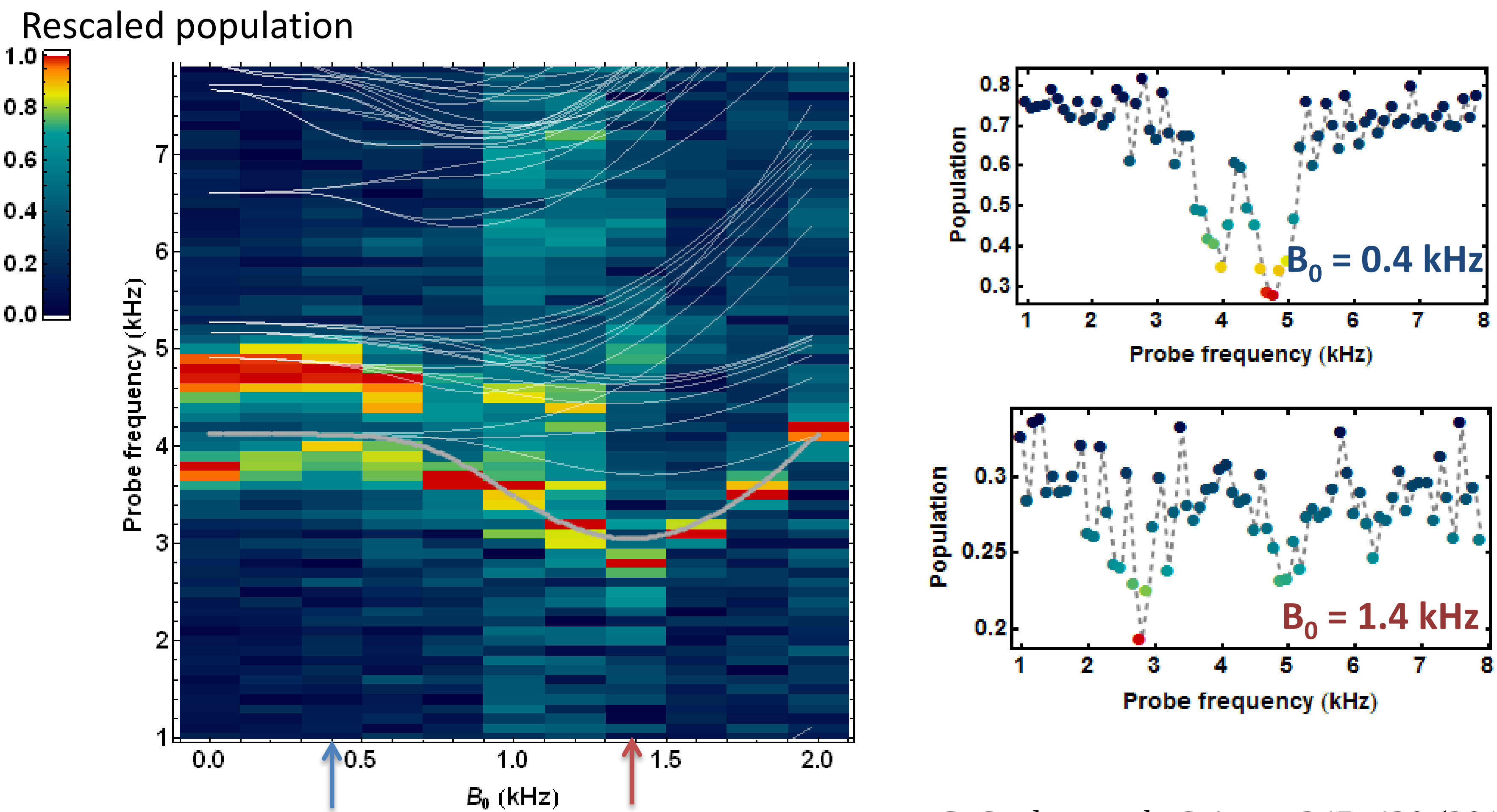
Coherent Imaging Spectroscopy (N=18 spins)



C. Senko *et. al.*, Science 345, 430 (2014)

Coherent Imaging Spectroscopy: Critical Gap (N=8 spins)

$$H = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + \left[\boxed{B_0} + B_y \sin(\omega t)\right]\sum_i \sigma_y^i$$

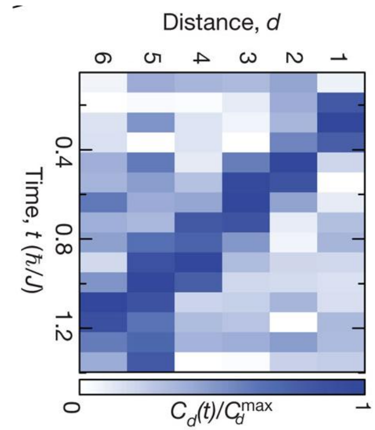


C. Senko *et. al.*, Science 345, 430 (2014)

Dynamics: quantum quench

E.H. Lieb and D.W. Robinson, "*The finite group velocity of quantum spin systems*," Commun. Math. Phys. 28, 251–257 (1972).

M. Cheneau, et al., Nature 481, 484 (2012)
P. Hauke, et al., PRL 111, 207202 (2013)
M. Knap, et al., PRL 111, 147205 (2013)
Z.-X. Gong, et al., PRL 113, 030602 (2014)



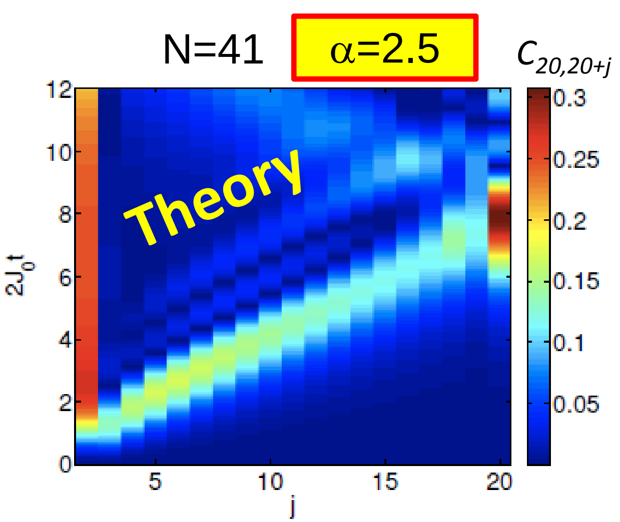
"Global Quench"

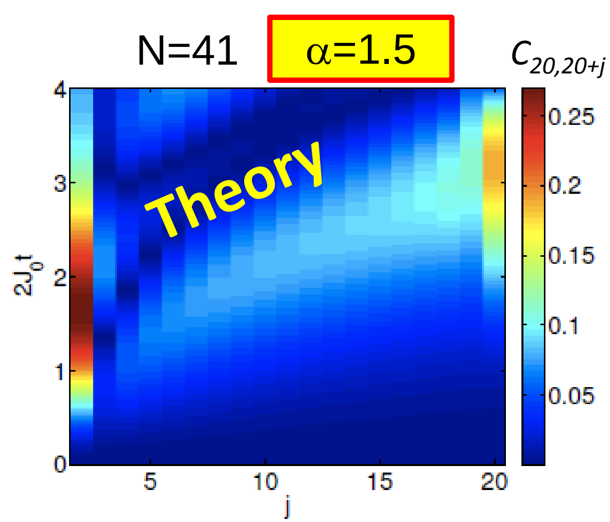
(a) Prepare $(\downarrow_x + \uparrow_x)^{\otimes N}$ "$kT = \infty$"

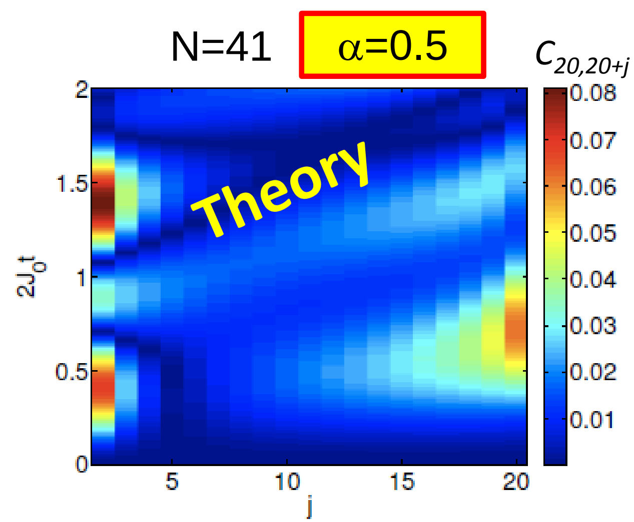
(b) Turn on XX Ising interactions

(c) Meaure correlations $C_{ij}(t) = \langle \sigma_z^{(i)} \sigma_z^{(j)} \rangle - \langle \sigma_z^{(i)} \rangle \langle \sigma_z^{(j)} \rangle$

$$J_{i,j} = \frac{J_0}{|i-j|^{\alpha}}$$

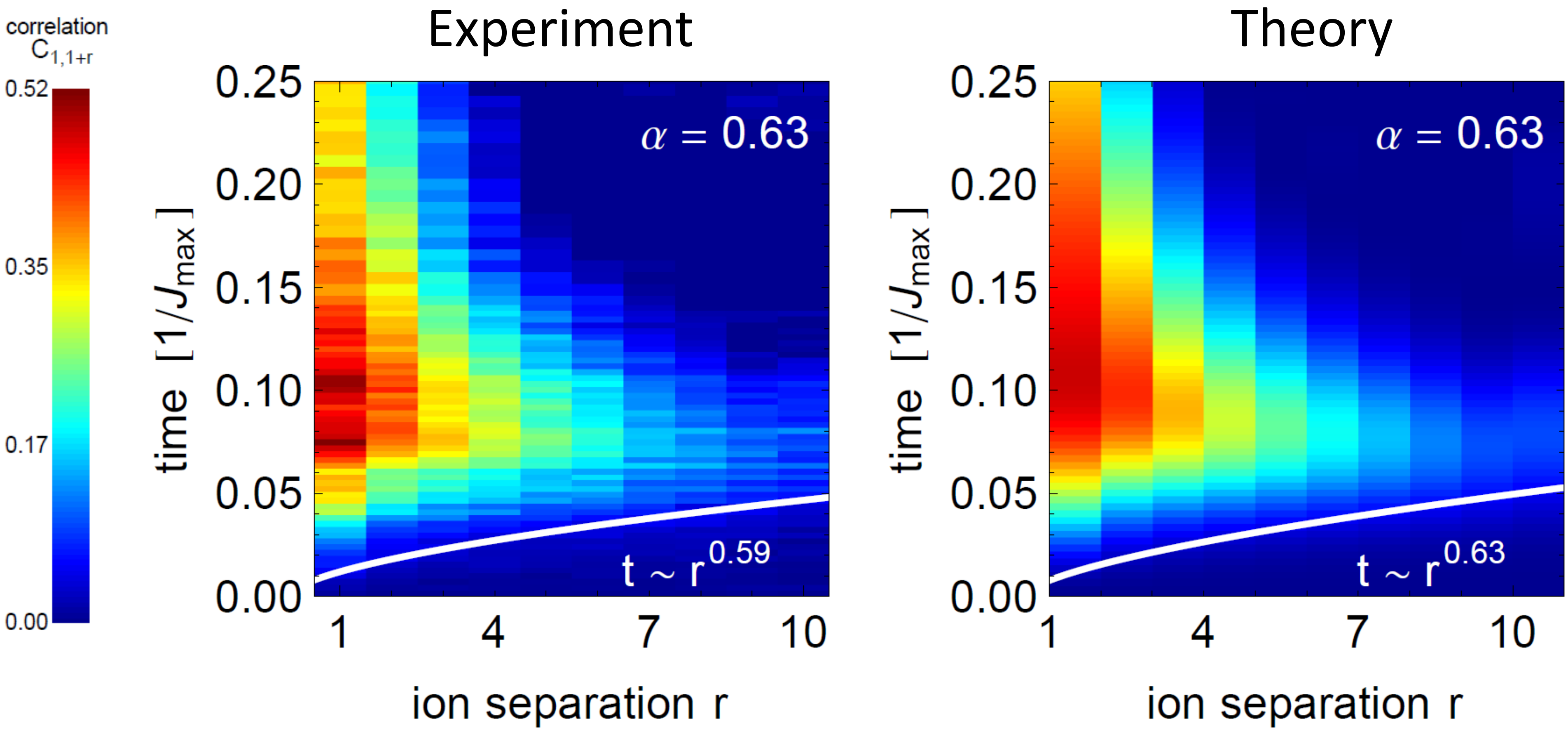






Long range "Light Cones" (Ising: N=11 spins)

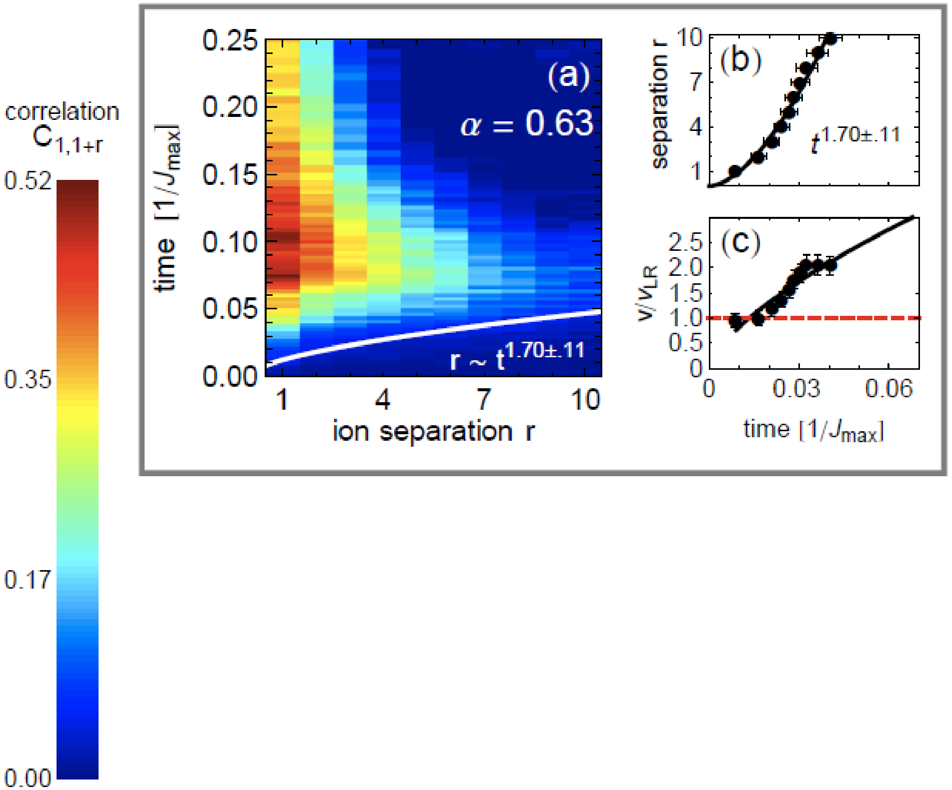
<u>Ising Model</u> $H_{Ising} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j$ $\qquad J_{ij} \approx \frac{J_0}{r^\alpha}$



P. Richerme et. al., *Nature* **511**, 198 (2014)
P. Jurcevic et al., *Nature* **511**, 202 (2014)

Long range “Light Cones” (Ising: N=11 spins)

Ising Model $H_{Ising} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j$ $\qquad J_{ij} \approx \frac{J_0}{r^\alpha}$



P. Richerme et. al., *Nature* **511**, 198 (2014)
P. Jurcevic et al., *Nature* **511**, 202 (2014)

Long range "Light Cones" (XY: N=11 spins)

<u>XY Mode</u> $$H_{XY} = \sum_{i<j} J_{ij}\left(\sigma_x^i \sigma_x^j + \sigma_z^i \sigma_z^j\right) + B_y \sum_i \sigma_y^i \qquad B_y \gg J_{ij}$$

P. Richerme *et. al.*, *Nature* **511**, 198 (2014)
P. Jurcevic et al., *Nature* **511**, 202 (2014)

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

- Direct Many-Body Spectroscopy
- Lieb-Robinson Bounds

Many-Body Thermalization/Localization?

Spin-1

Future

Thermalization/Localization

How can quantum systems thermalize?

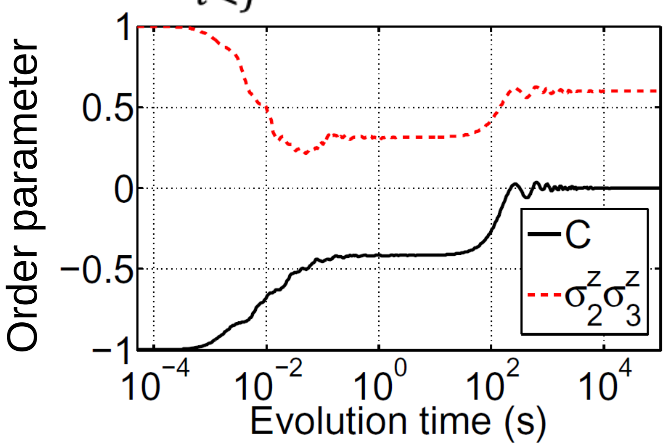
→ Eigenstate Thermalization Hypothesis (Rigol et al., *Nature* 2008)

How can quantum systems fail to thermalize?

Prethermalization

- XY Model with inhomogeneous couplings

$$H_{XY} = \sum_{i<j} J_{ij}\left(\sigma_x^i \sigma_x^j + \sigma_z^i \sigma_z^j\right)$$



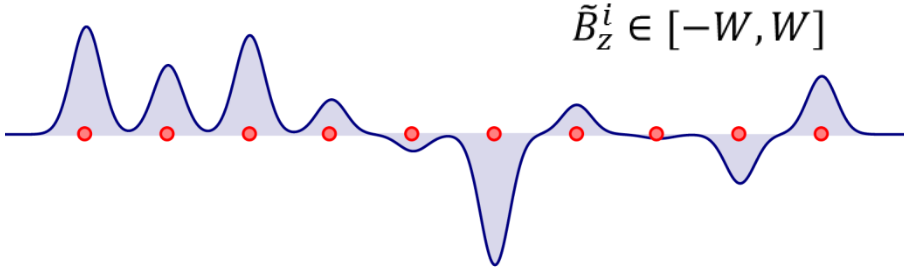
Z. Gong and L.-M. Duan, *NJP* **15,** 113051 (2013)

Many-Body Localization

- Ising Model with random disorder

$$H_{MBL} = \sum_{i<j} J_{ij}\sigma_x^i \sigma_x^j + \sum_i \tilde{B}_z^i \sigma_z^i$$

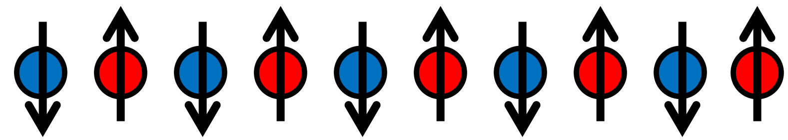
$\tilde{B}_z^i \in [-W, W]$



A. Polkovnikov et al., Rev. Mod. Phys. **83**, 863 (2011)
P. Hauke and M. Heyl, arXiv:1410.1491 (2014)
R. Nandkishore & D. Huse, Annual Review of Condensed Matter Physics 6, 15 (2015)

Thermalization/Localization

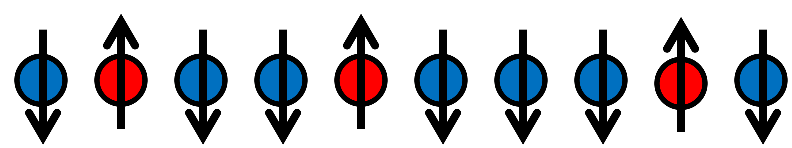
Step 1: Initialize spins AFM Neel ordered along *z* (“kT=∞”)



Step 2: Quench to transverse Ising model with random disorder

$$H_{MBL} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_0\sum_i \sigma_z^i + \sum_i \tilde{B}_z^i\sigma_z^i \qquad \tilde{B}_z^i \in [-W, W]$$

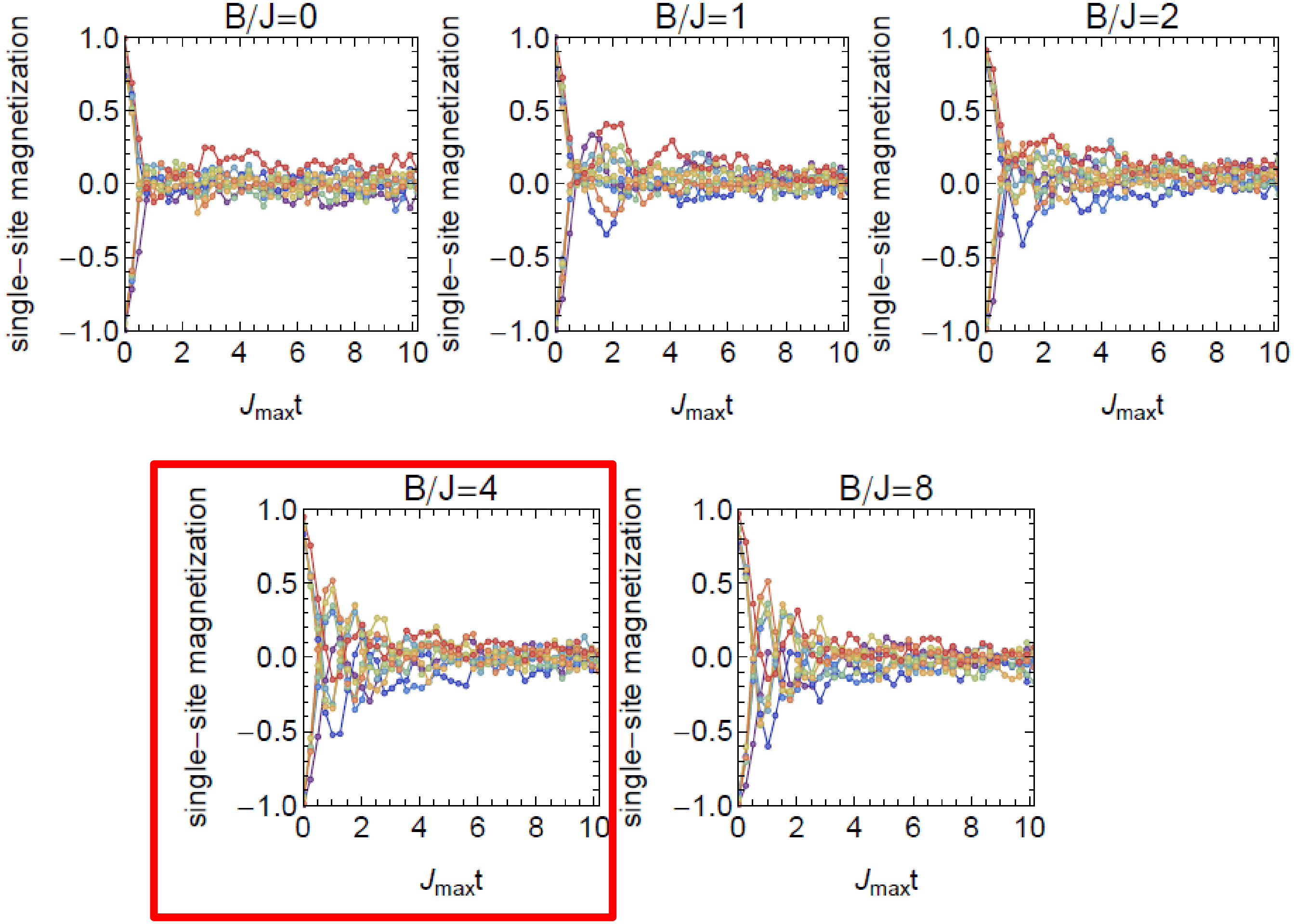
Step 3: Measure each spin along z after time *t*



Step 4: Repeat for many different disorder instances and strengths

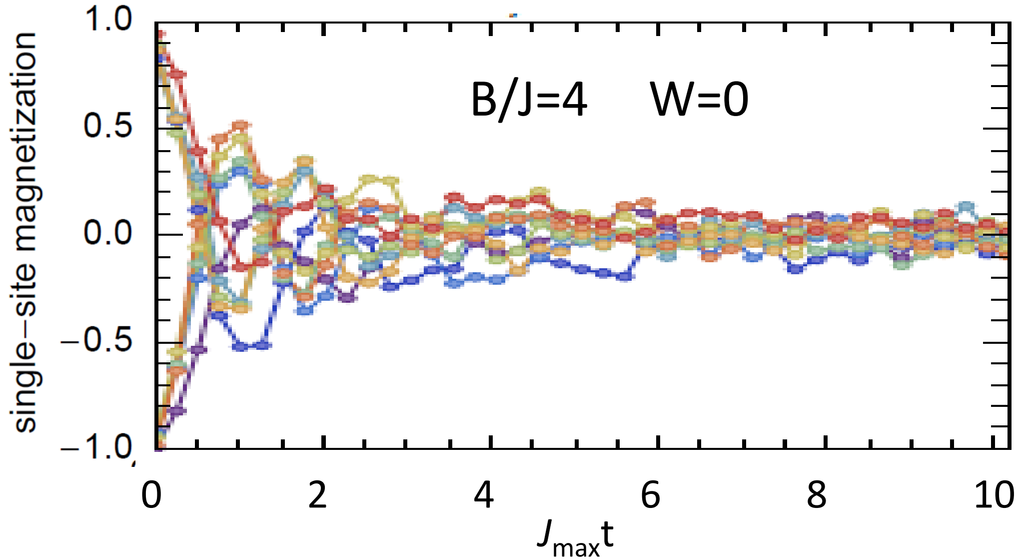
No disorder (thermalization)

$$H = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B\sum_i \sigma_z^i$$

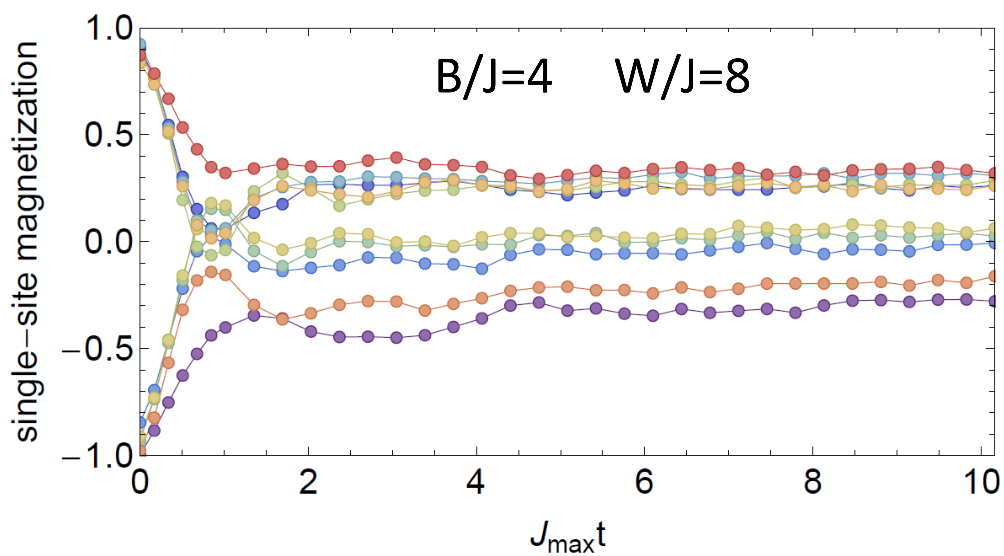


$$H_{MBL} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_0\sum_i \sigma_z^i + \sum_i \tilde{B}_z^i\sigma_z^i \qquad \tilde{B}_z^i \in [-W, W]$$

No disorder



Some disorder



Trapped Ion Spin Hamiltonian Engineering

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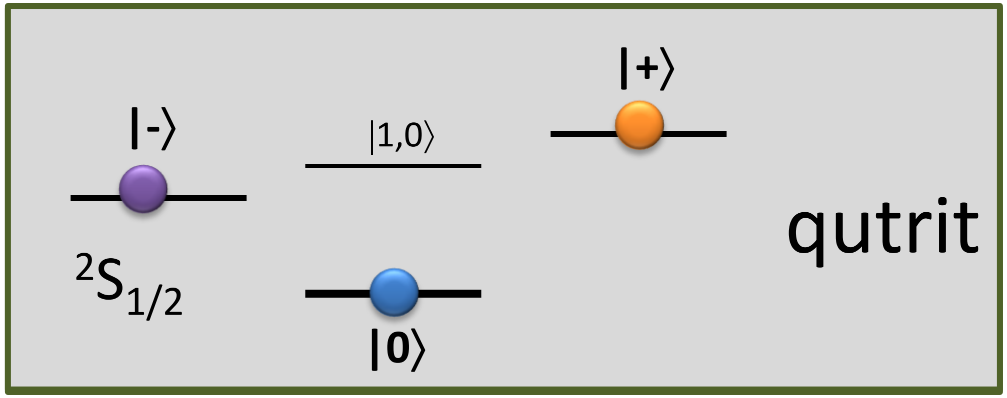
Future

Quantum simulations with Spin-1



rsb+bsb on both transitions $$H = \sum_{i,j} J_{ij} S_x^i S_x^j$$

rsb $|0\rangle \leftrightarrow |+\rangle$
bsb $|0\rangle \leftrightarrow |-\rangle$ $$H = \sum_{i,j} J_{ij}\left(S_+^i S_-^j + S_-^i S_+^j\right) + D\sum_i (S_z^i)^2 + \cancel{\sum_{i,m} V_{im}(2\hat{n}+1)S_z^i}$$

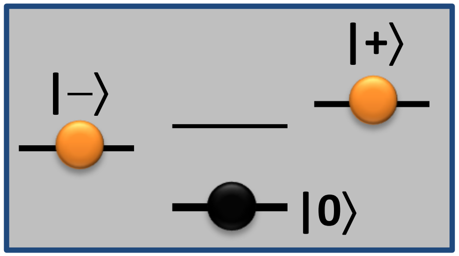
$$J_{ij} \approx \frac{J_0}{r^\alpha}$$

Work in $\langle S_i^z \rangle = 0$ subspace: $\frac{3^N}{2\sqrt{N}}$ states

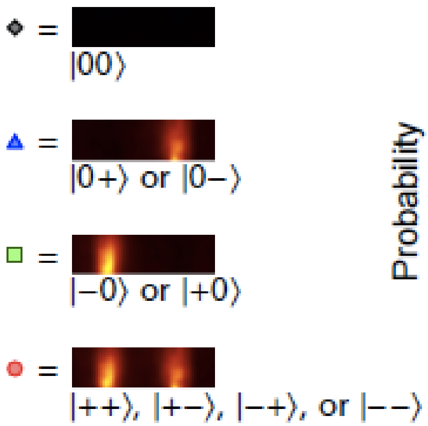
I. Cohen and A. Retzker, PRL **112**, 040503 (2014)
C. Senko, et al., arXiv 1410.0937 (2014)

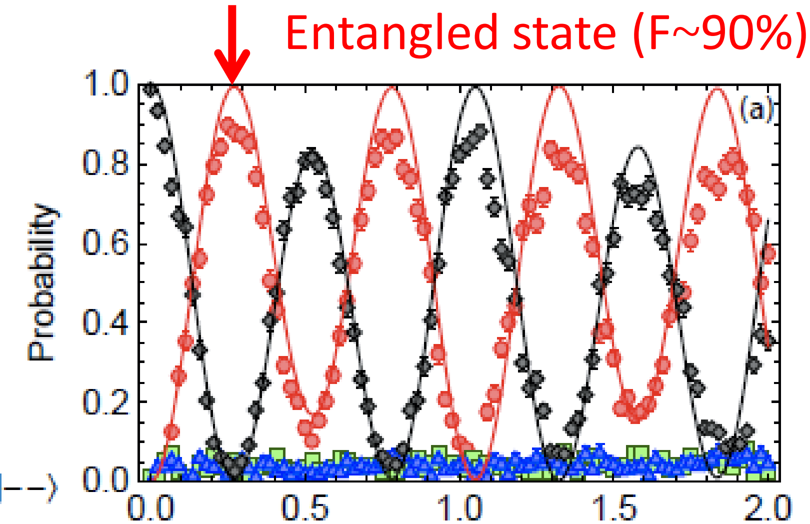
Spin-1 dynamics (N=2)

$$H=\sum_{i,j} J_{i,j}\left(S_i^{+}S_j^{-}+S_i^{-}S_j^{+}\right)$$



Dark = |0>; Bright = not |0>

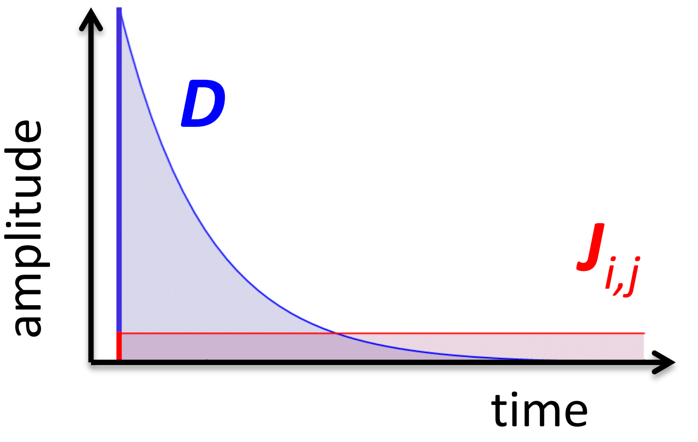




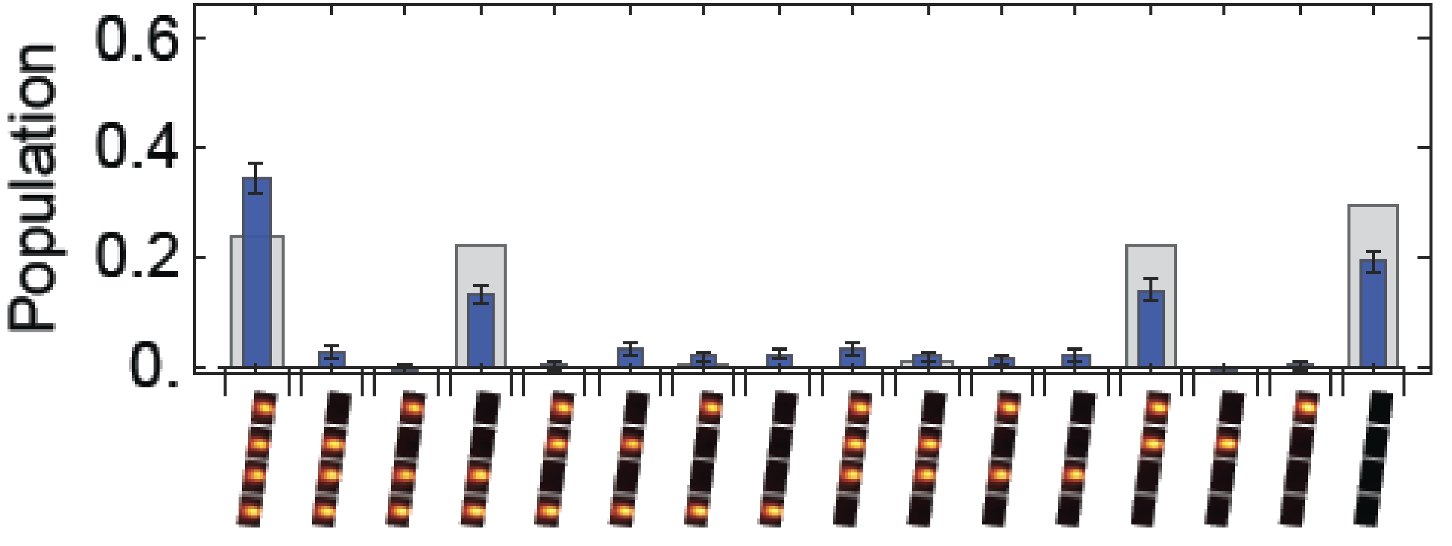
C. Senko, et al., arXiv 1410.0937 (2014)

Spin-1 adiabatic ramp (N=4)

$$H = \sum_{i,j} J_{i,j}\left(S_i^+ S_j^- + S_i^- S_j^+\right) + D(t)\sum_i \left(S_z^i\right)^2$$



Step 1: prepare $|00\ldots0\rangle$
Step 2: ramp from D>>J to D<<J

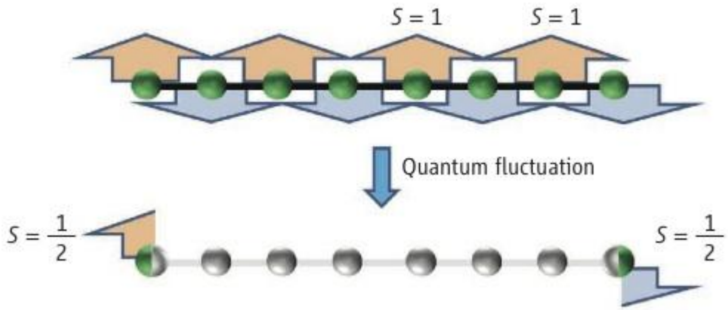


C. Senko, et al., arXiv 1410.0937 (2014)

Quantum simulations with Spin-1

$$H = \underbrace{\sum_{i,j} J_{ij}\left(S_+^i S_-^j + S_-^i S_+^j + \lambda\, S_z^i S_z^j\right)}_{\text{(long-range) Haldane Hamiltonian}} + D\sum_i (S_z^i)^2$$

D. Haldane, PRL 50, 1153 (1983)



Adiabaticaly transform D, $\lambda \to 0$
"Haldane phase" – topological edge states

ground state:
nonlocal string order

$$\lim_{|i-j|\to\infty} \left\langle S_x^i \middle| exp\left[i\pi\left(S_x^{i+1} + S_x^{i+2} + \cdots + S_x^{j-1}\right)\right] \middle| S_x^j \right\rangle$$

I. Cohen and A. Retzker, PRL **112**, 040503 (2014)
C. Senko, et al., arXiv 1410.0937 (2014)

Trapped Ion Spin Hamiltonian Engineering

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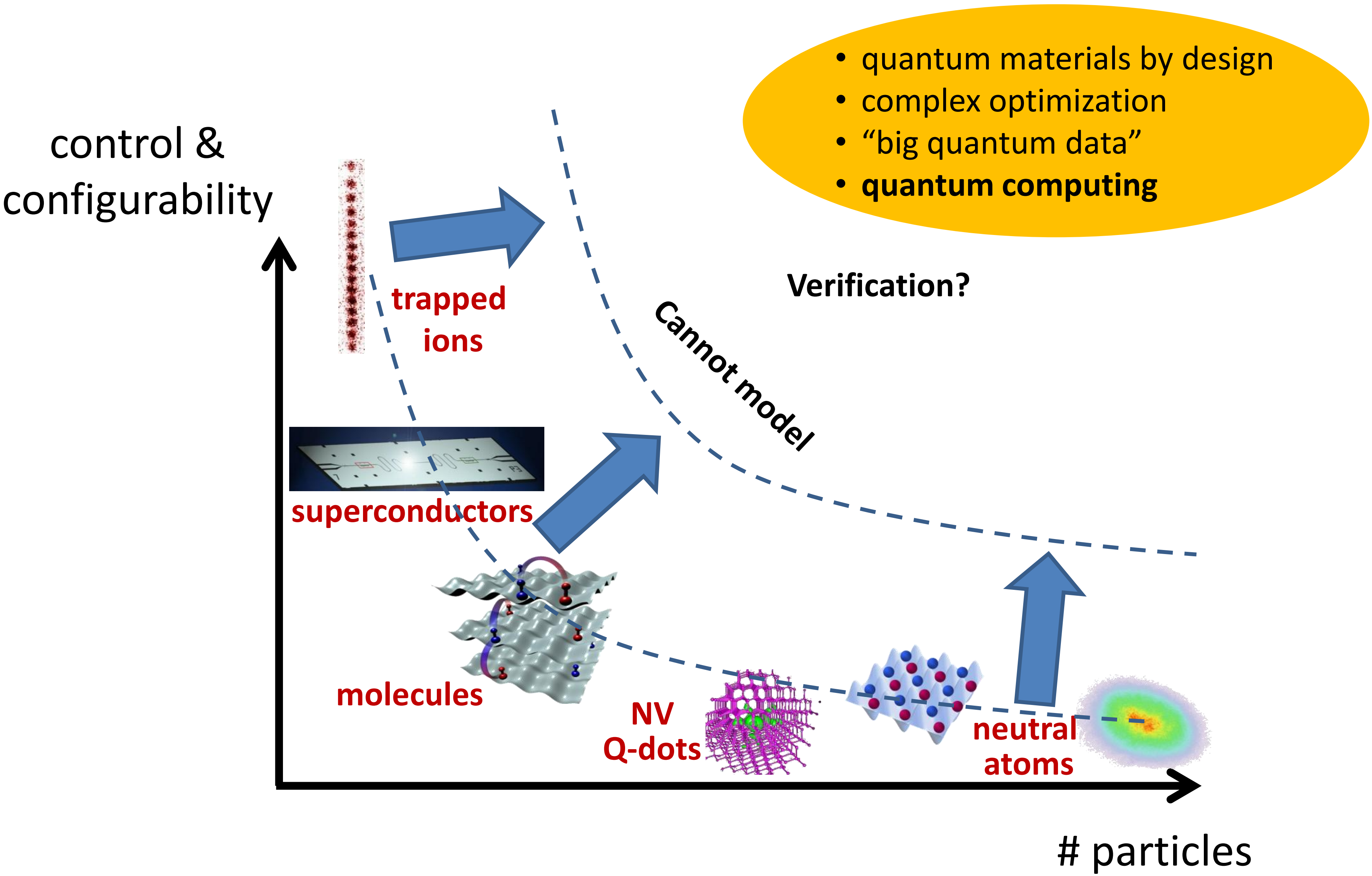
Many-Body Thermalization/Localization?

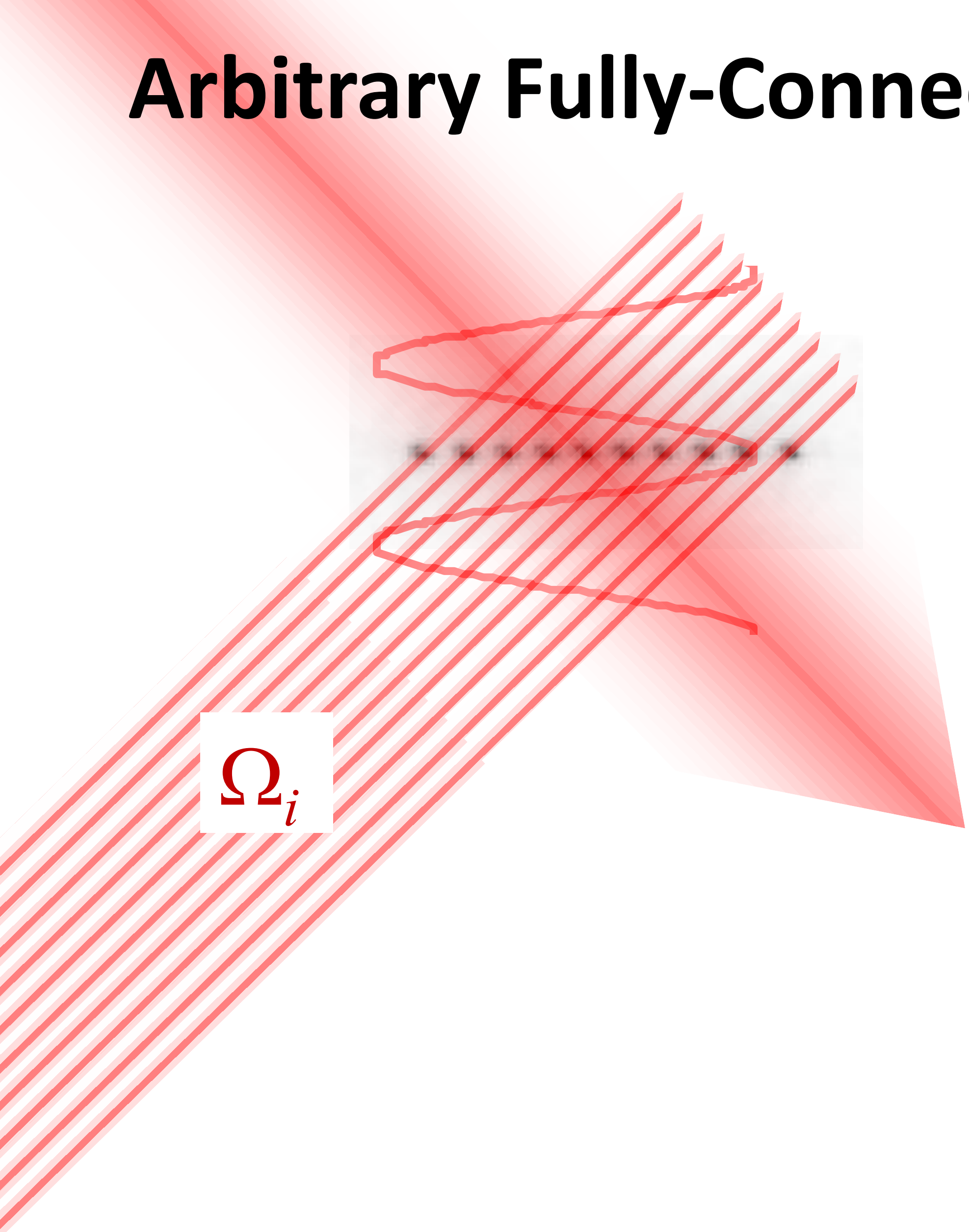
Spin-1

Future

Implementations of Quantum Simulators



Arbitrary Fully-Connected Spin Models



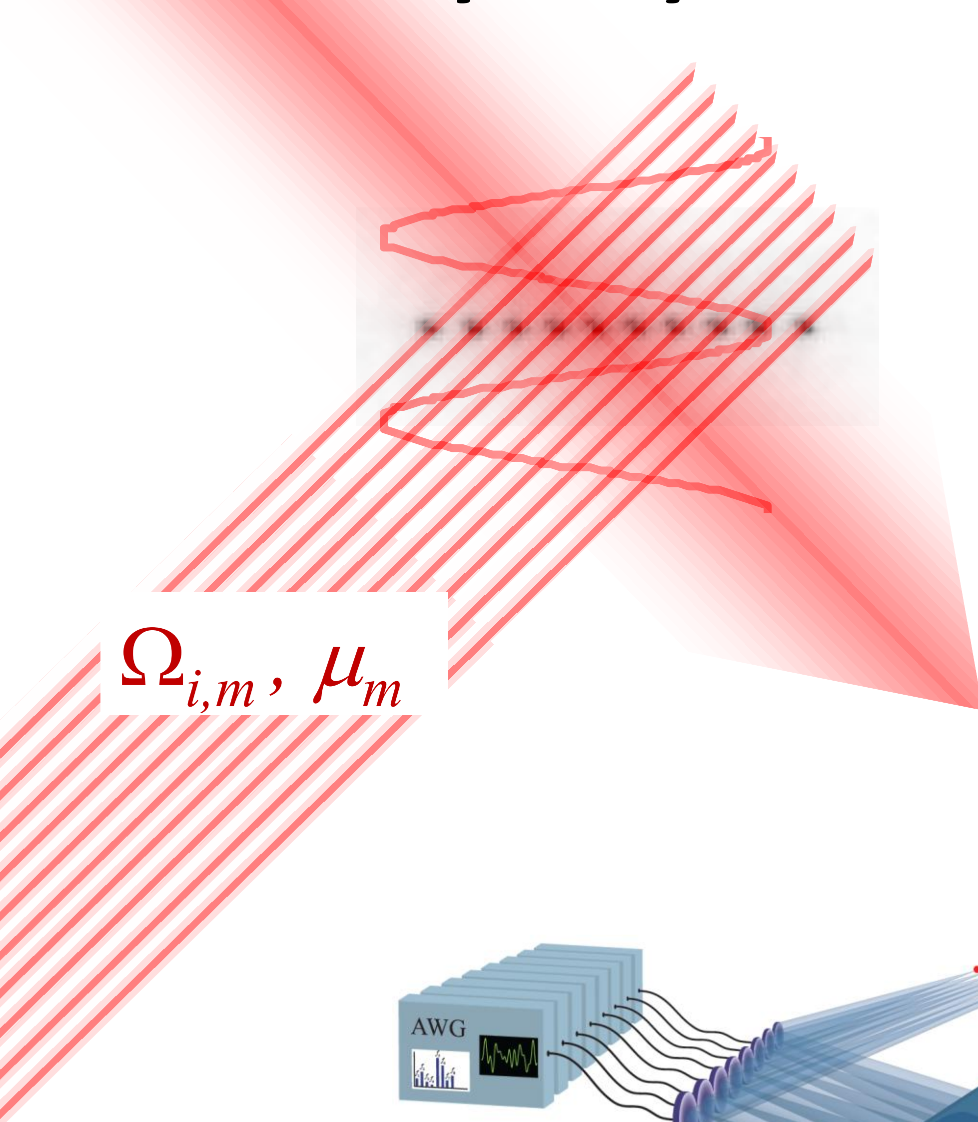
$$H = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)}$$

$\dfrac{N(N-1)}{2}$ couplings $J_{i,j}$

$$J_{i,j} = \left(\frac{\hbar \, \Delta k^2}{2m} \right) \Omega_i \Omega_j \sum_m \frac{b_i^m b_j^m}{\mu^2 - \omega_m^2}$$

***N*+*1* controls**

Arbitrary Fully-Connected Spin Models

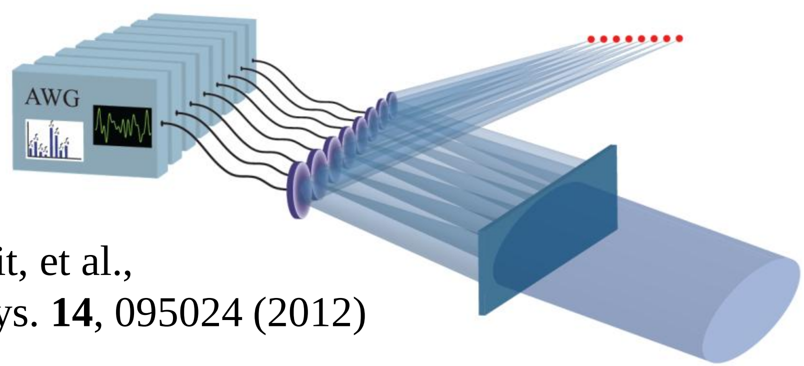


$$H = \sum_{i \neq j} J_{i,j} \hat{\sigma}_x^{(i)} \hat{\sigma}_x^{(j)}$$

$\dfrac{N(N-1)}{2}$ couplings $J_{i,j}$

$$J_{i,j} = \left(\frac{\hbar \Delta k^2}{2m} \right) \sum_m \Omega_{i,m} \Omega_{j,m} \frac{b_i^m b_j^m}{\mu_m^2 - \omega_m^2}$$

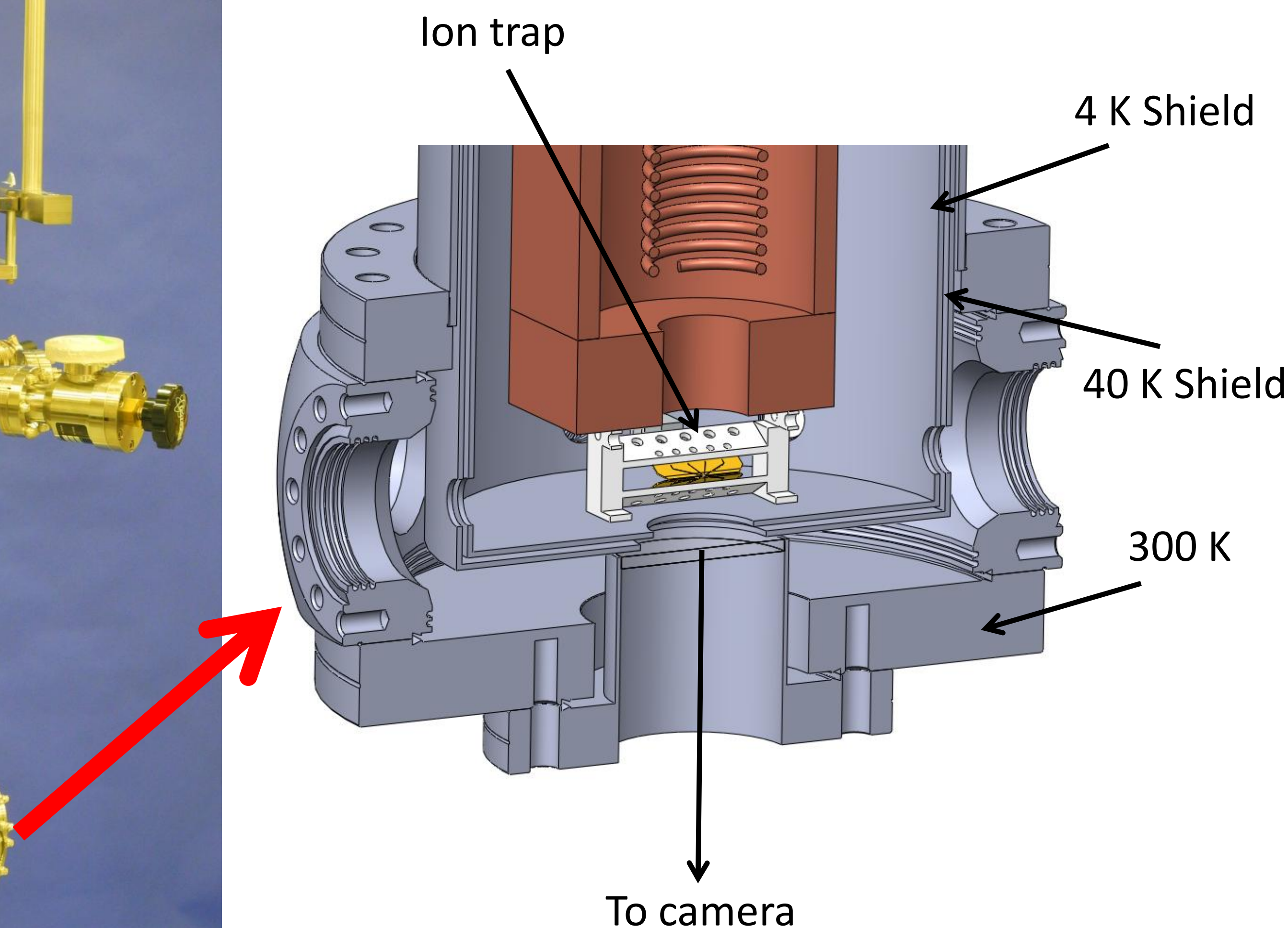
N^2 controls



S. Korenblit, et al.,
New. J. Phys. **14**, 095024 (2012)

32-channel optical modulator

Scaling Up: 4K to get lower pressure



P. Richerme

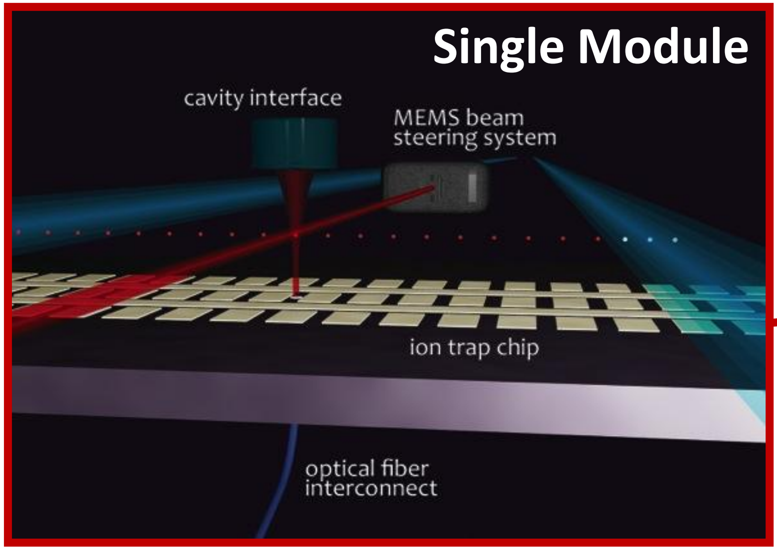
Modular Scaling to 10^6 qubits?

Quantum Computation in Small Quantum Registers

- Linear ion chain with 20-100 ions (Elementary Logic Unit, or ELU)
- Arbitrary quantum logic operation among the qubits in the chain

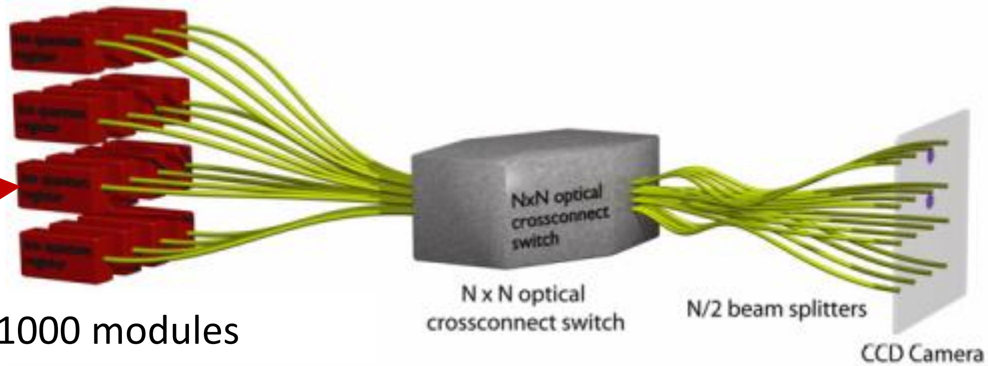
Interconnect of Multiple Such Registers via Photonic Channel

- Reconfigurable interconnect using optical crossconnect switches
- Efficient optical interface for remote entanglement generation

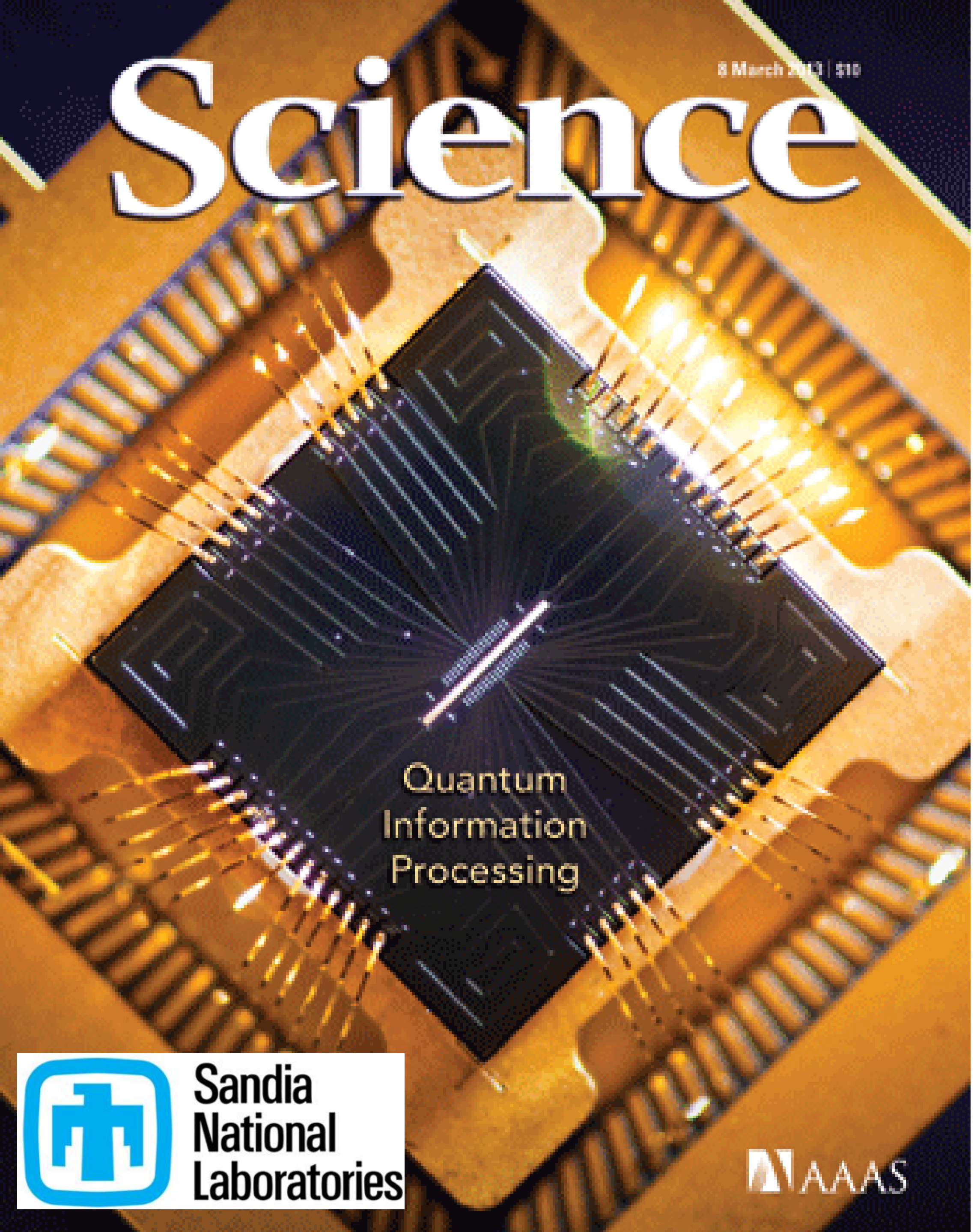


100 qubits / module

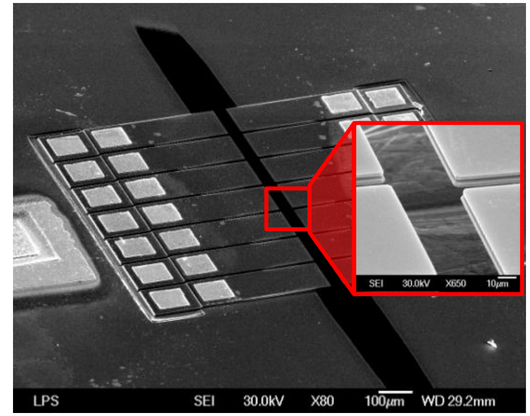
100,000 qubit quantum computer



1000 modules

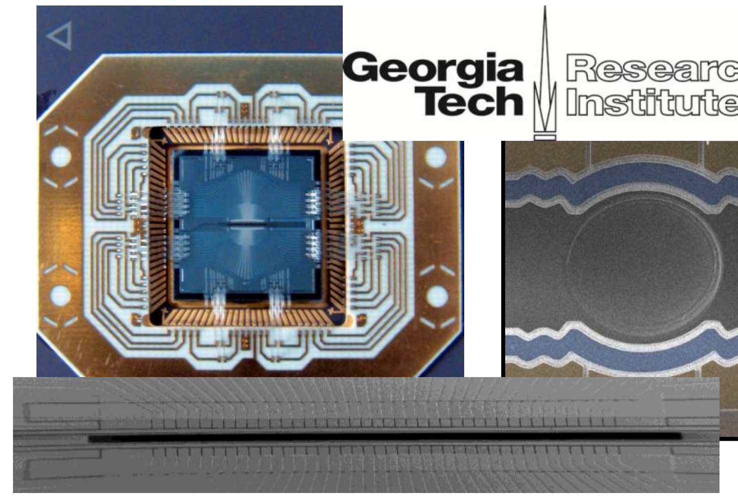


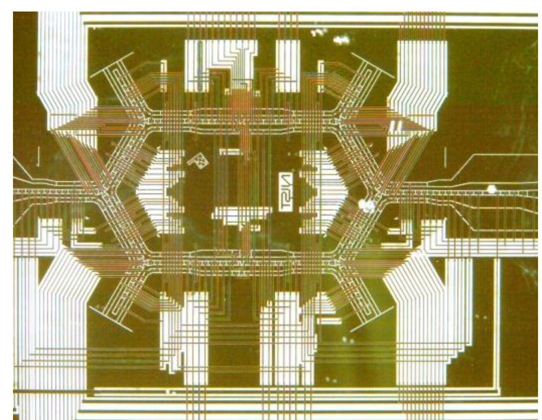
Sandia
National
Laboratories



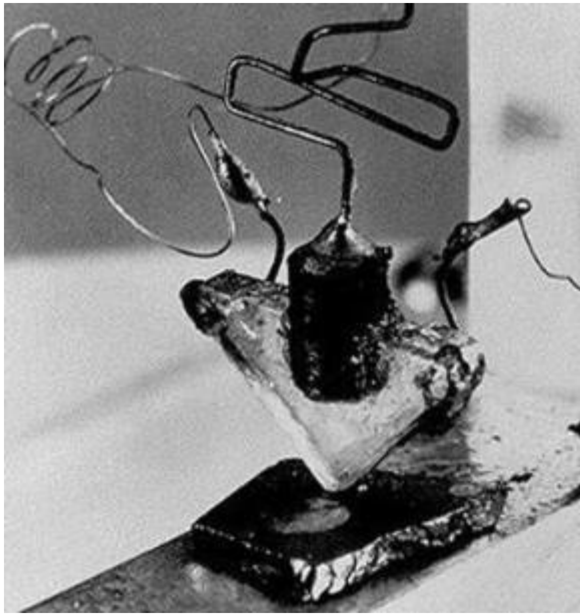
LPS
The Laboratory for Physical Sciences

Georgia Tech
Research Institute



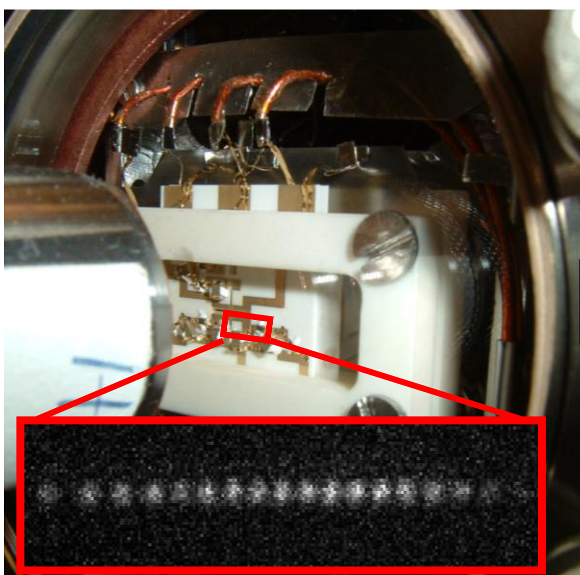


NIST

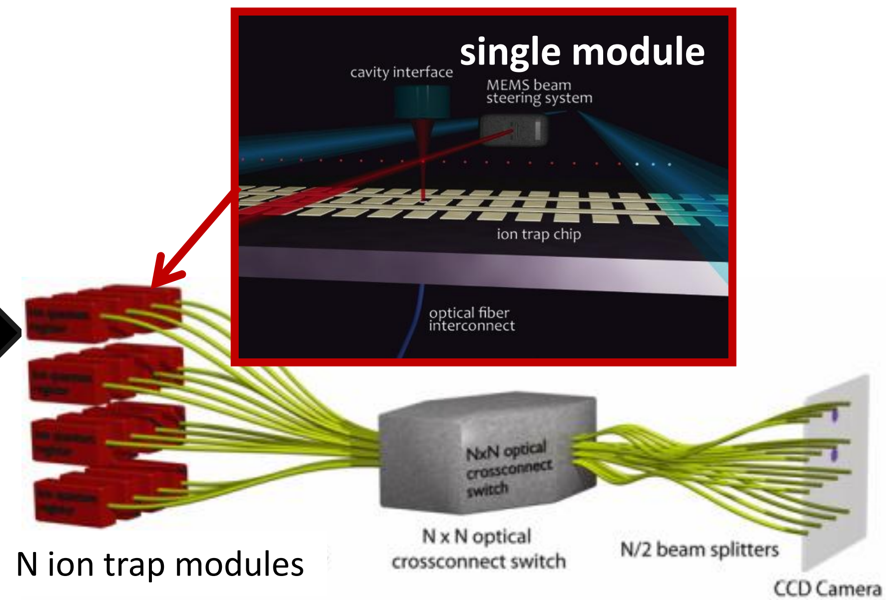


1947: first transistor

2000: integrated circuit



2015: qubit collection



Large scale quantum network?

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Jim Freericks
Alexey Gorshkov
Jungsang Kim (Duke)
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