Trapped Ions: Condensed Matter From The Bottom Up

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SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncrit-

planation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
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.	.
.	.

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

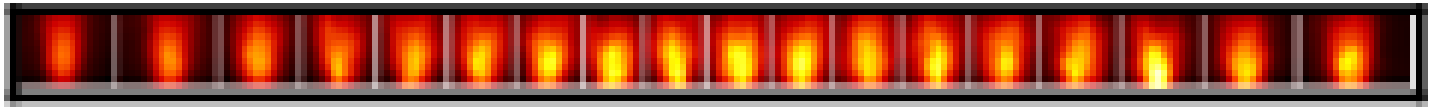
Dynamics

- Many-Body Spectroscopy
- Propagation of Excitations: Lieb-Robinson
- Prethermalization
- Many-Body Localization

Spin-1

Extending to N~100 spins and beyond

Trapped Atomic Ions: Spin Models



Porras and Cirac, PRL 92, 207901 (2004)
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A. Friedenauer *et al.*, Nat. Phys. 4, 757 (2008)
K. Kim *et al.*, PRL 102, 250502 (2009)
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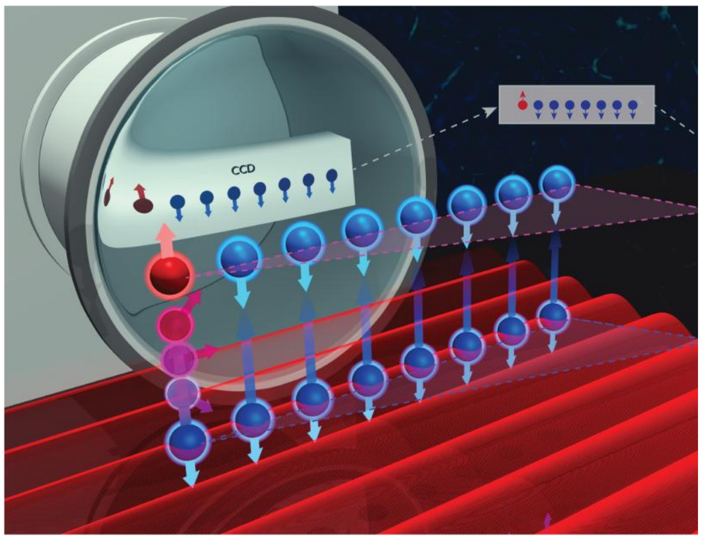
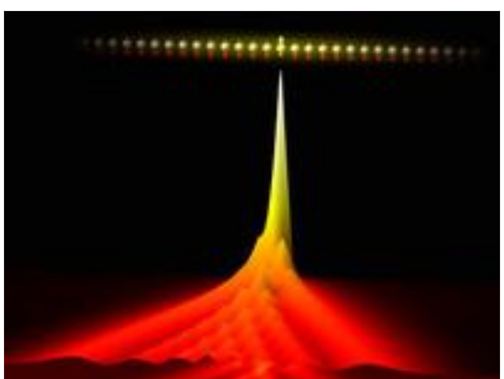
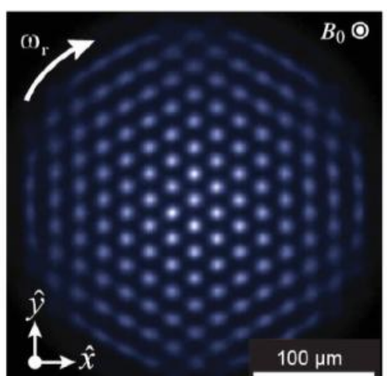
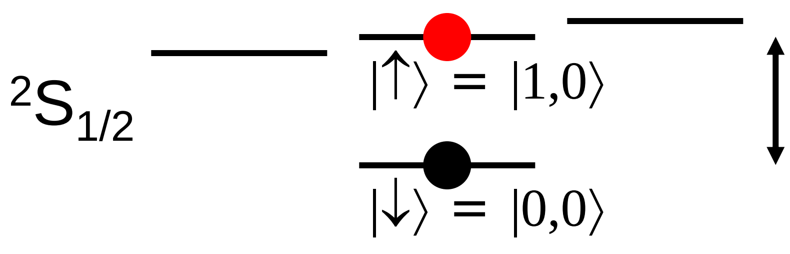






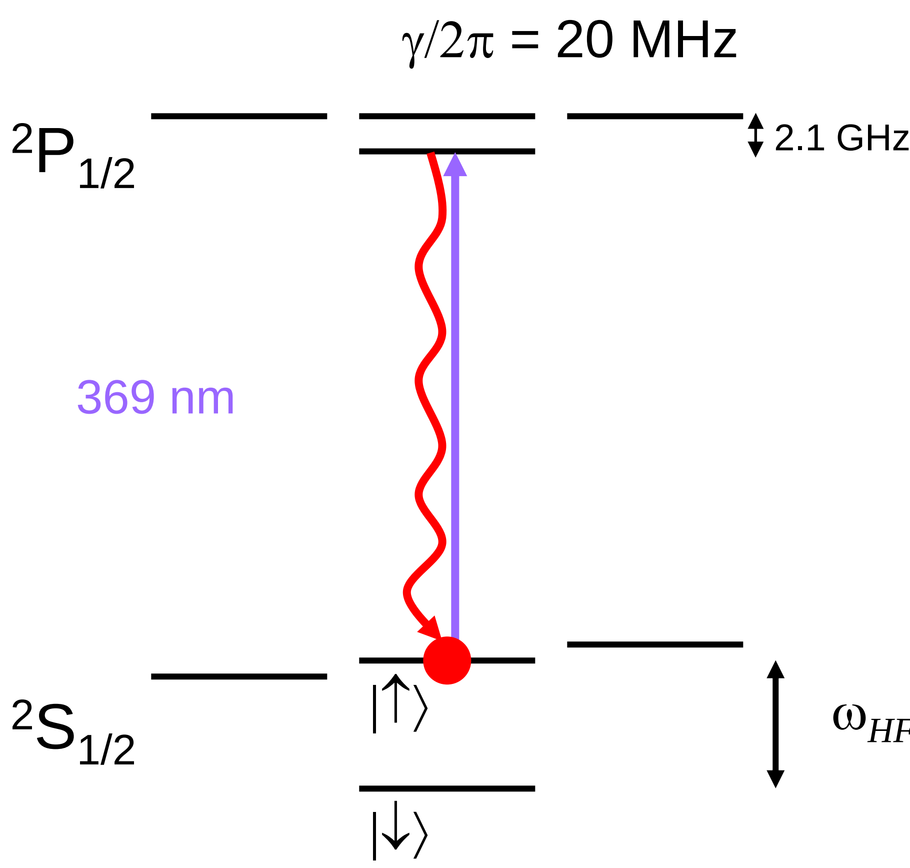
$^{171}Yb^+$ hyperfine spin

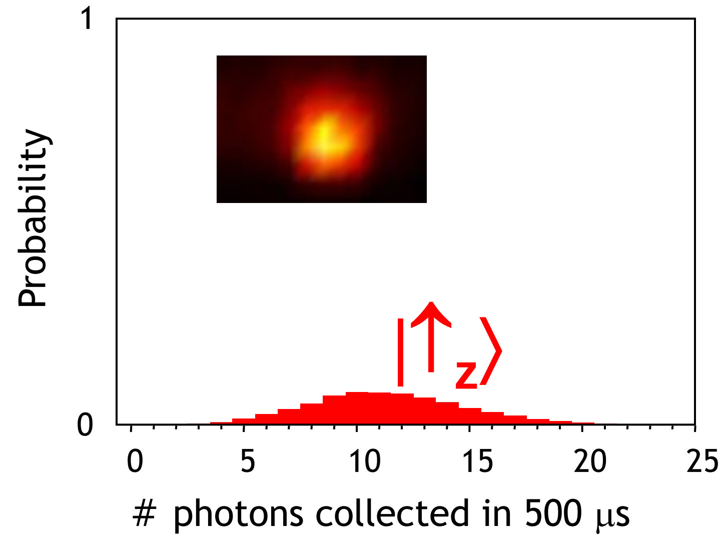


$\omega_{HF}/2\pi = \mathbf{12\ 642\ 812\ 118} + \mathbf{311B^2}$ Hz

(600 Hz/G @ 1 G)

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





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

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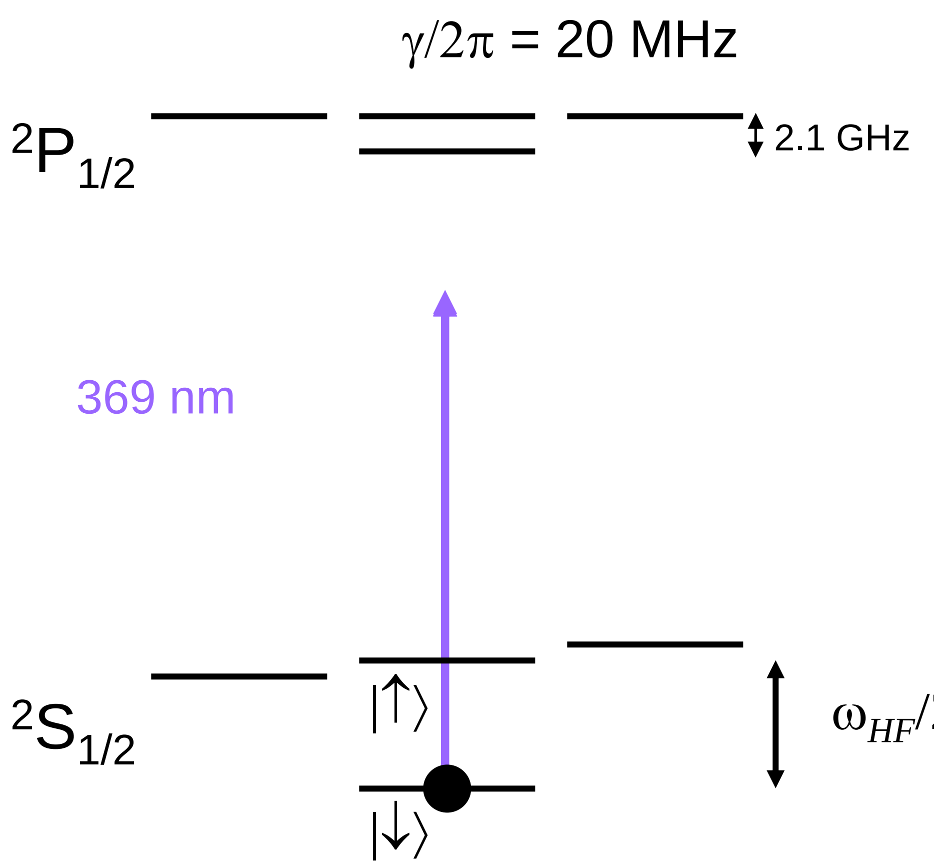
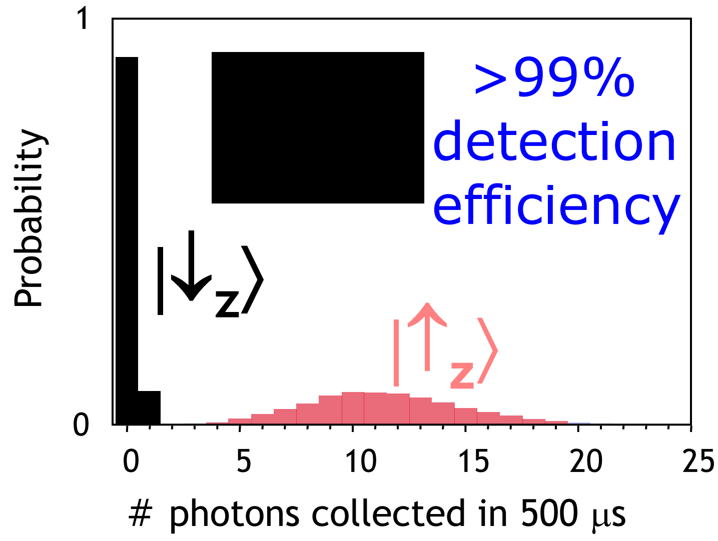
$^{171}Yb^+$ spin detection

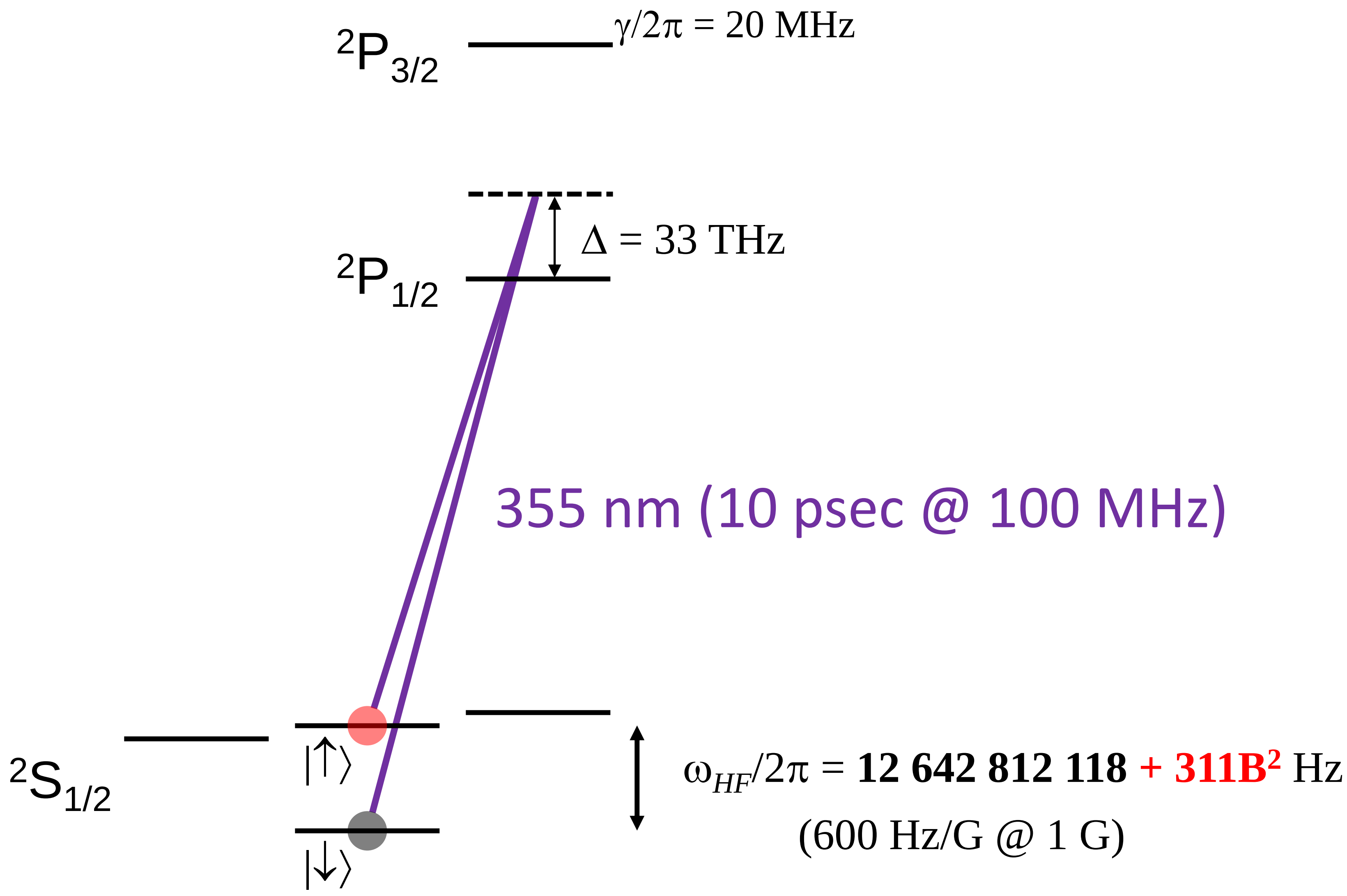


$\omega_{HF}/2\pi$ = **12 642 812 118** **+ 311B²** Hz

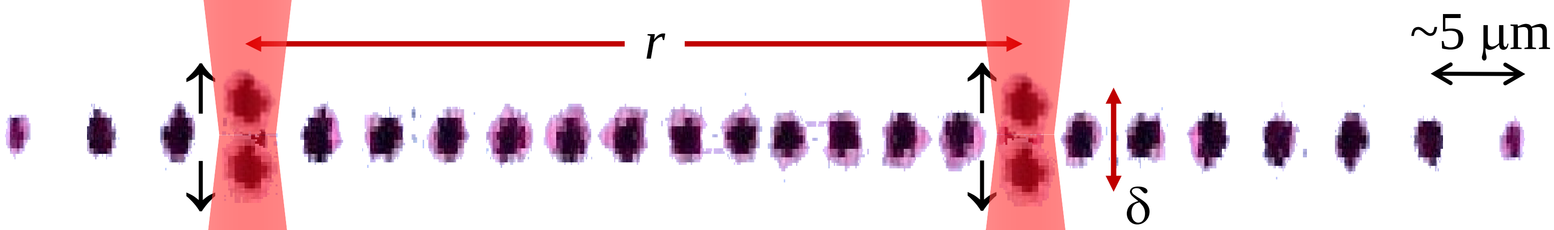
(600 Hz/G @ 1 G)



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



Entangling Trapped Ion Spins



"dipole-dipole coupling"

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

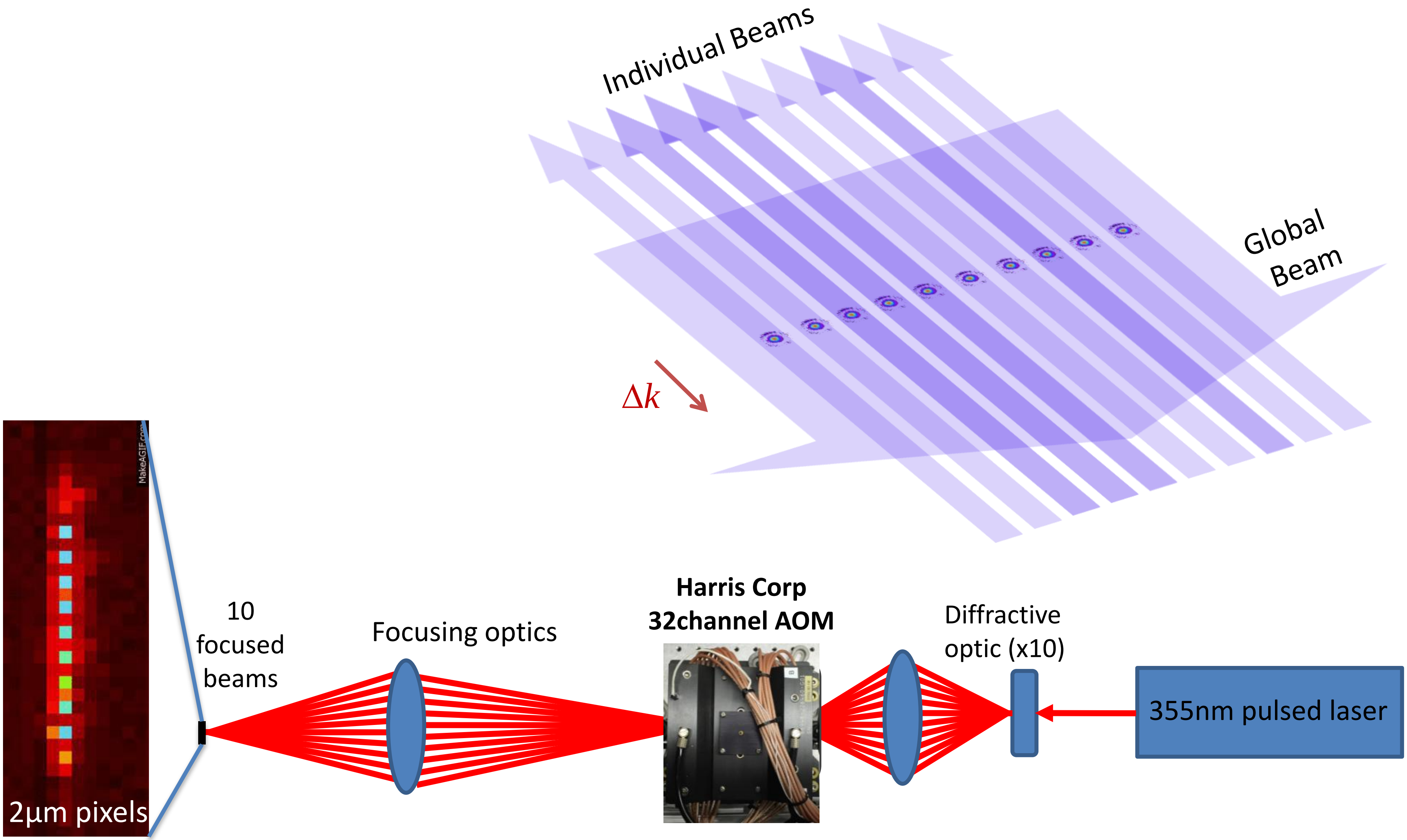
δ ~ 10 nm
$e\delta$ ~ 500 Debye

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

for full entanglement

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

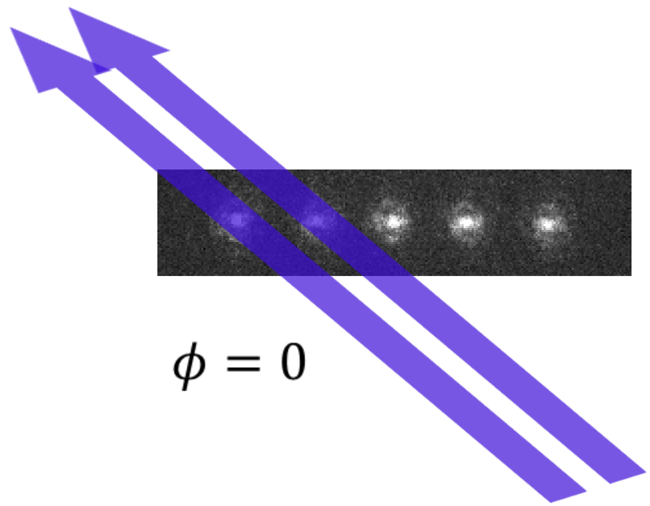
Gates within a single crystal

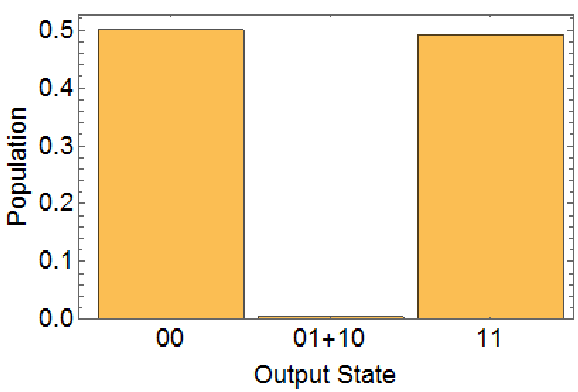


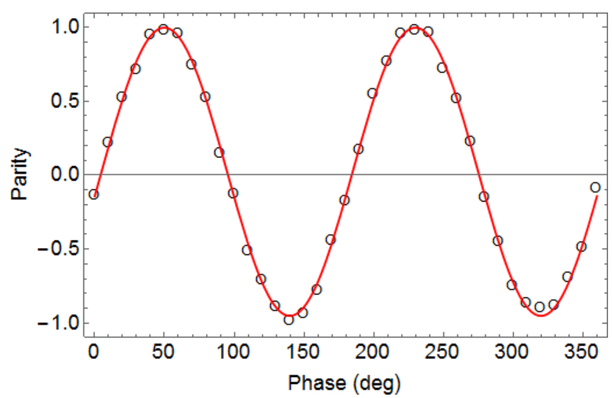
T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

Ising (XX) gate [1,2]

$$
\begin{aligned}
|0_1 0_2\rangle &\rightarrow |0_1 0_2\rangle - i|1_1 1_2\rangle e^{-i\phi} \\
|0_1 1_2\rangle &\rightarrow |0_1 1_2\rangle - i|1_1 0_2\rangle \\
|1_1 0_2\rangle &\rightarrow |1_1 0_2\rangle - i|0_1 1_2\rangle \\
|1_1 1_2\rangle &\rightarrow |1_1 1_2\rangle - i|0_1 0_2\rangle e^{i\phi}
\end{aligned}
$$





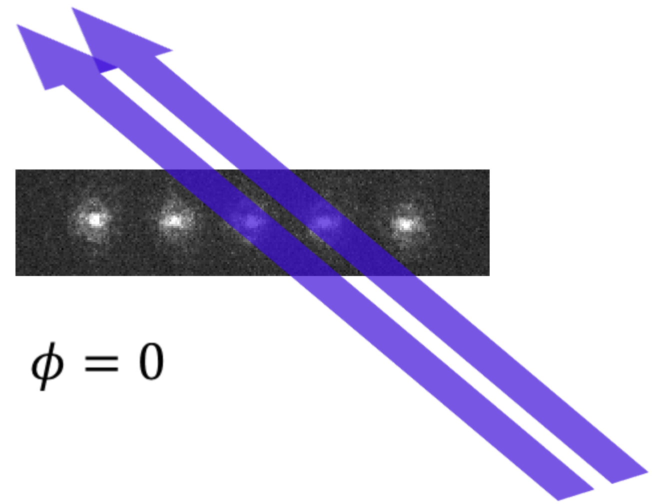


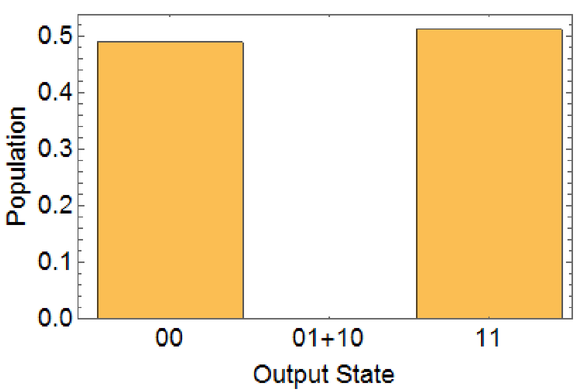
F=0.983(4)
(excluding SPAM errors)

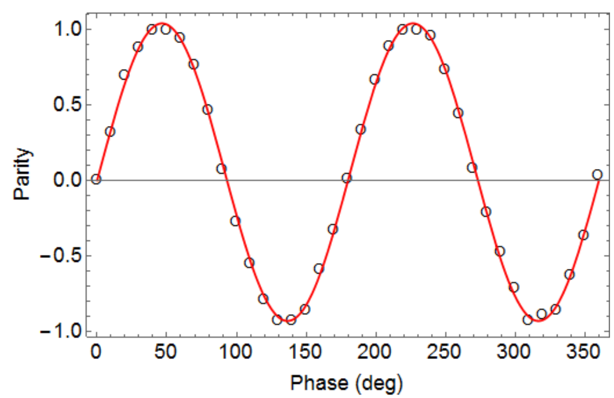
T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

Ising (XX) gate [3,4]

$$
\begin{aligned}
|0_3 0_4\rangle &\rightarrow |0_3 0_4\rangle - i|1_3 1_4\rangle e^{-i\phi} \\
|0_3 1_4\rangle &\rightarrow |0_3 1_4\rangle - i|1_3 0_4\rangle \\
|1_3 0_4\rangle &\rightarrow |1_3 0_4\rangle - i|0_3 1_4\rangle \\
|1_3 1_4\rangle &\rightarrow |1_3 1_4\rangle - i|0_3 0_4\rangle e^{i\phi}
\end{aligned}
$$





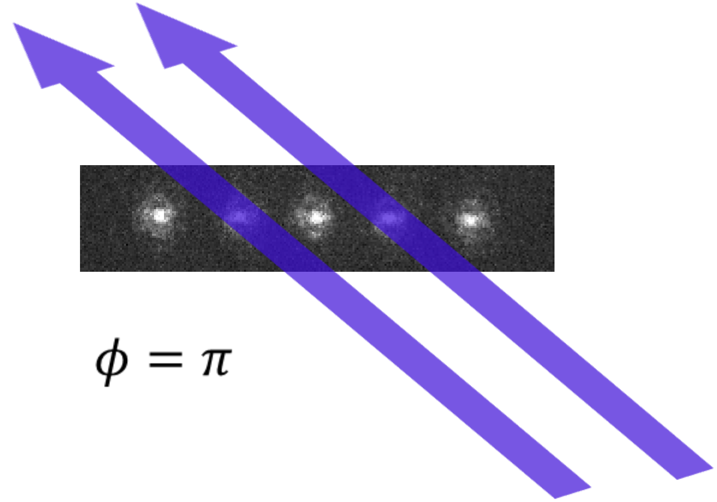


F=0.992(3)
(excluding SPAM errors)

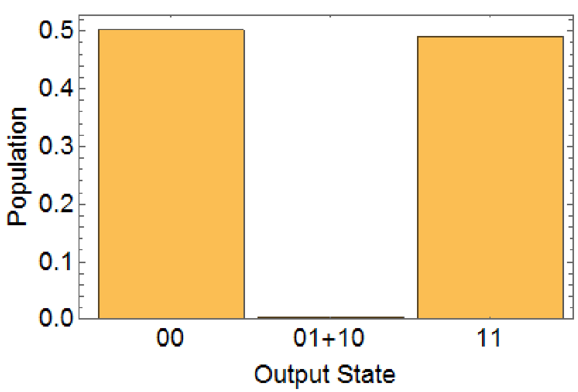
T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

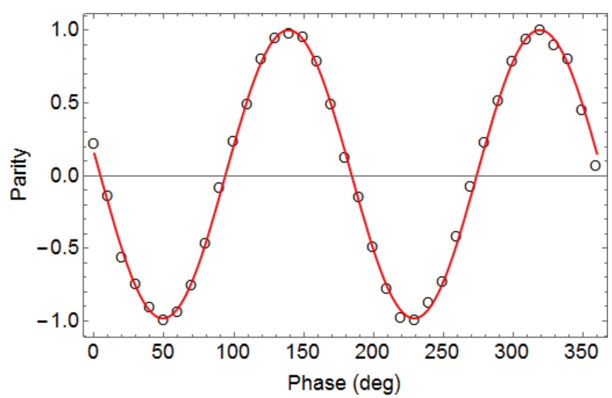
Ising (XX) gate [2,4]

$$|0_2 0_4\rangle \rightarrow |0_2 0_4\rangle - i|1_2 1_4\rangle e^{-i\phi}$$
$$|0_2 1_4\rangle \rightarrow |0_2 1_4\rangle - i|1_2 0_4\rangle$$
$$|1_2 0_4\rangle \rightarrow |1_2 0_4\rangle - i|0_2 1_4\rangle$$
$$|1_2 1_4\rangle \rightarrow |1_2 1_4\rangle - i|0_2 0_4\rangle e^{i\phi}$$



$\phi = \pi$



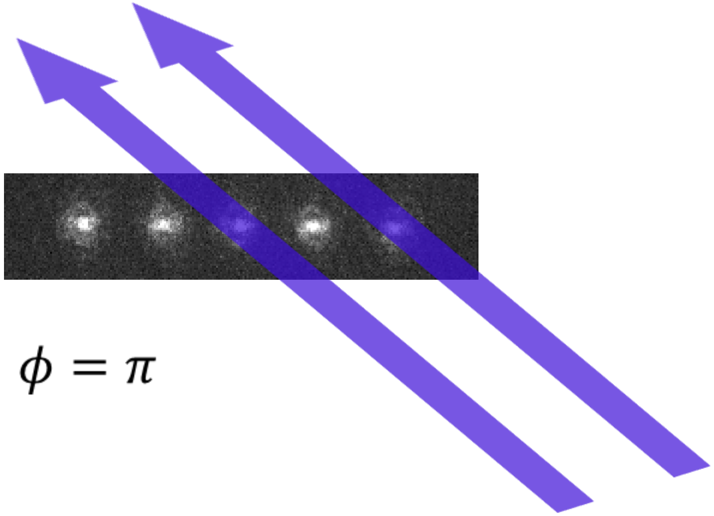


F=0.991(4)
(excluding SPAM errors)

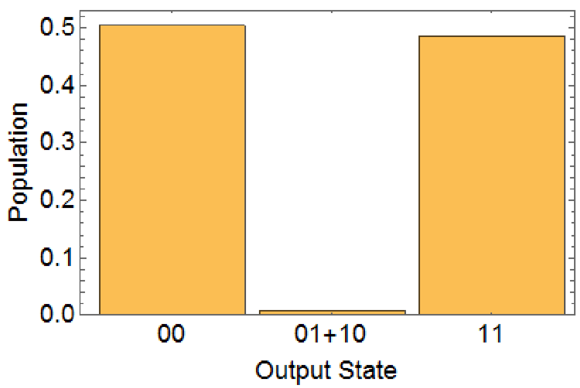
T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

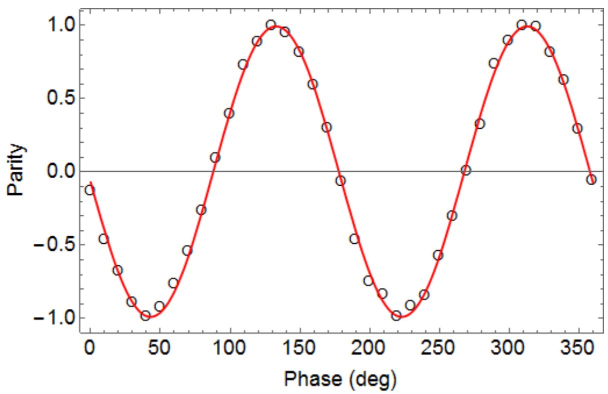
Ising (XX) gate [3,5]

$$|0_3 0_5\rangle \rightarrow |0_3 0_5\rangle - i|1_3 1_5\rangle e^{-i\phi}$$
$$|0_3 1_5\rangle \rightarrow |0_3 1_5\rangle - i|1_3 0_5\rangle$$
$$|1_3 0_5\rangle \rightarrow |1_3 0_5\rangle - i|0_3 1_5\rangle$$
$$|1_3 1_5\rangle \rightarrow |1_3 1_5\rangle - i|0_3 0_5\rangle e^{i\phi}$$



$\phi = \pi$



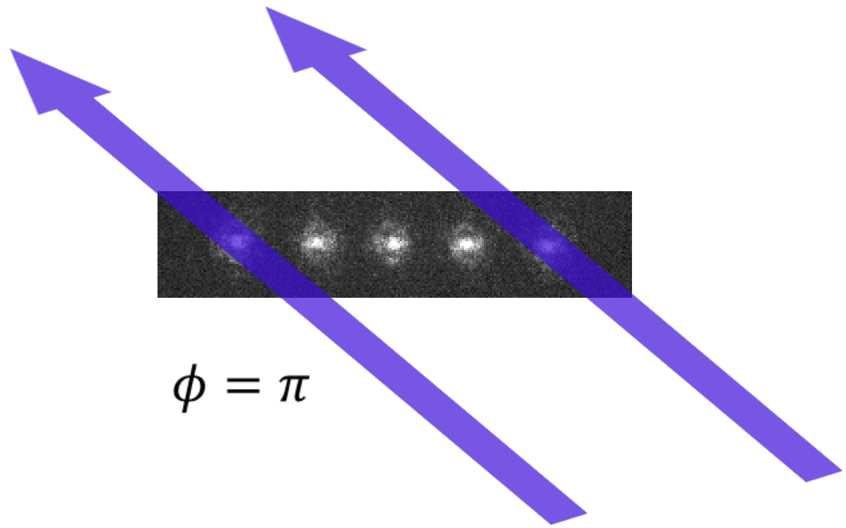


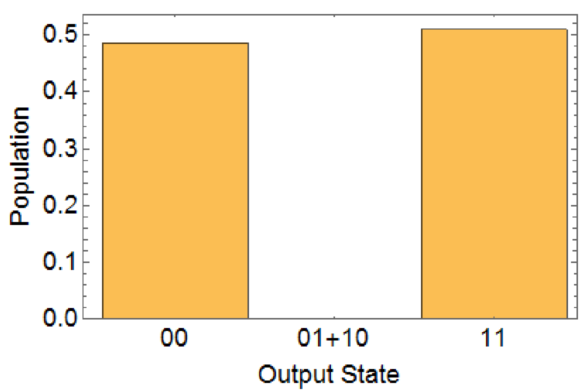
F=0.991(4)
(excluding SPAM errors)

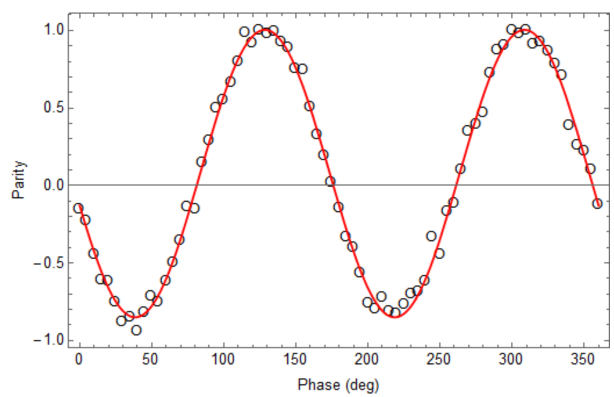
T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

Ising (XX) gate [1,5]

$$|0_1 0_5\rangle \rightarrow |0_1 0_5\rangle - i|1_1 1_5\rangle e^{-i\phi}$$
$$|0_1 1_5\rangle \rightarrow |0_1 1_5\rangle - i|1_1 0_5\rangle$$
$$|1_1 0_5\rangle \rightarrow |1_1 0_5\rangle - i|0_1 1_5\rangle$$
$$|1_1 1_5\rangle \rightarrow |1_1 1_5\rangle - i|0_1 0_5\rangle e^{i\phi}$$







F=0.961(5)
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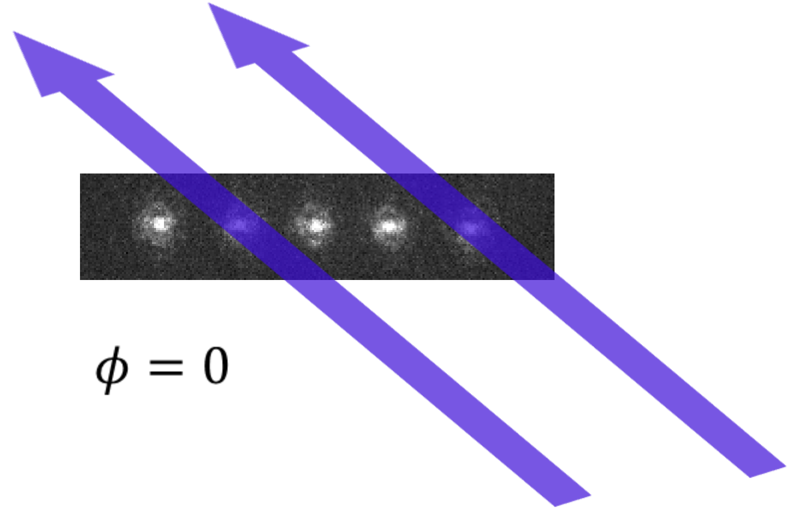
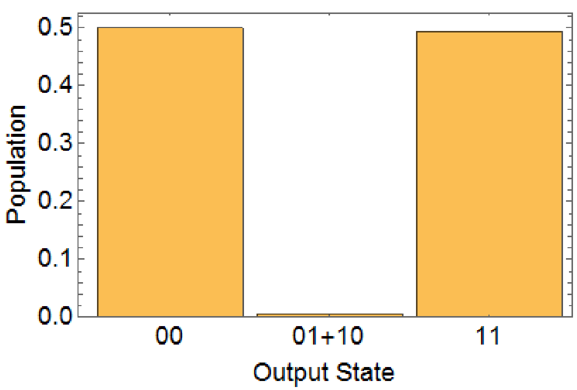
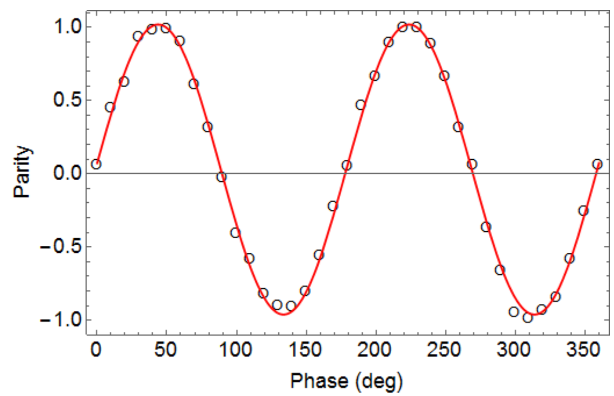
T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

Ising (XX) gate [2,5]

$$|0_2 0_5\rangle \rightarrow |0_2 0_5\rangle - i|1_2 1_5\rangle e^{-i\phi}$$
$$|0_2 1_5\rangle \rightarrow |0_2 1_5\rangle - i|1_2 0_5\rangle$$
$$|1_2 0_5\rangle \rightarrow |1_2 0_5\rangle - i|0_2 1_5\rangle$$
$$|1_2 1_5\rangle \rightarrow |1_2 1_5\rangle - i|0_2 0_5\rangle e^{i\phi}$$





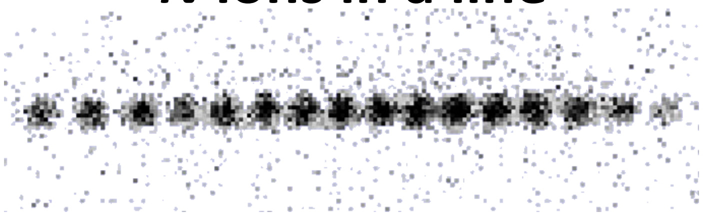


F=0.992(4)
(excluding SPAM errors)

T. Choi, et al., PRL 112, 19502 (2014)
S. Debnath, et al., in preparation (2015)

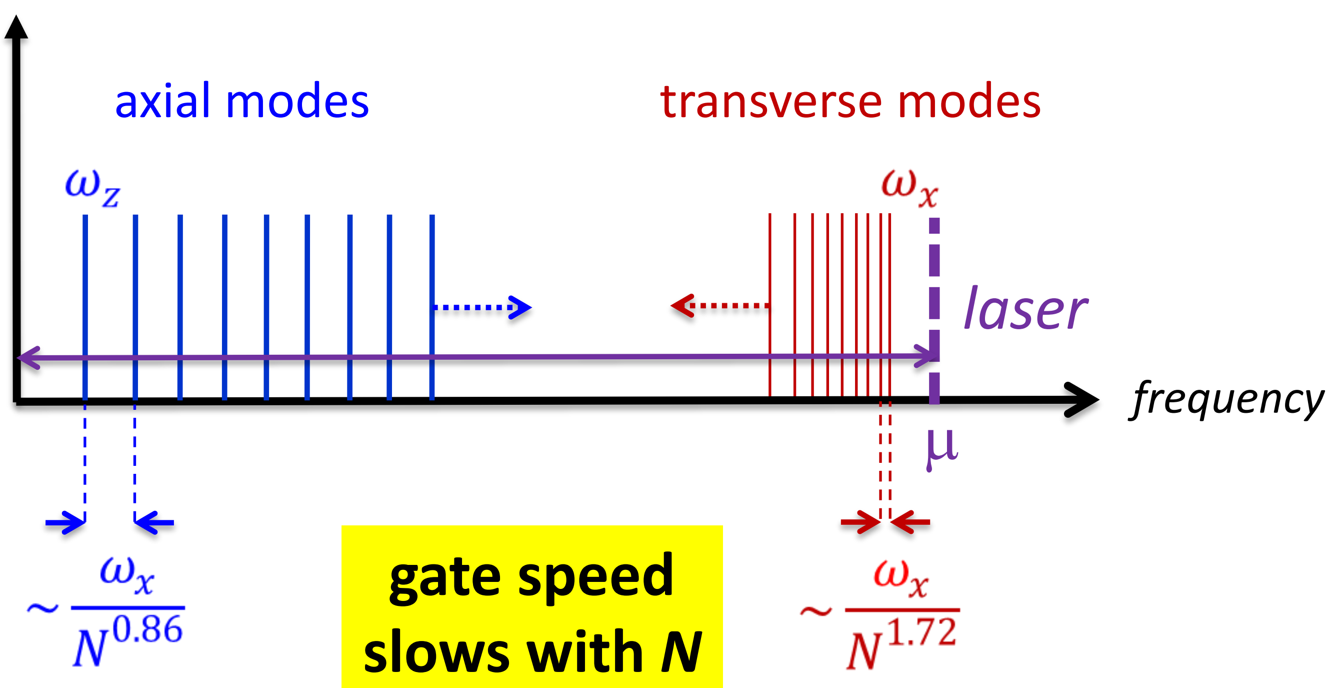
Many ions: phonon modes

***N* ions in a line**



transverse trap frequency ω_x = high as you can go

axial trap frequency $\omega_z < \frac{\omega_x}{N^{0.86}}$

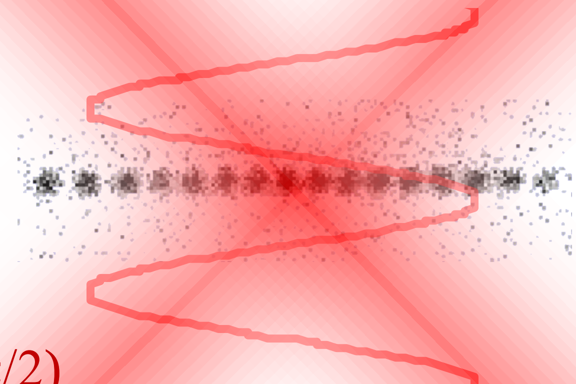


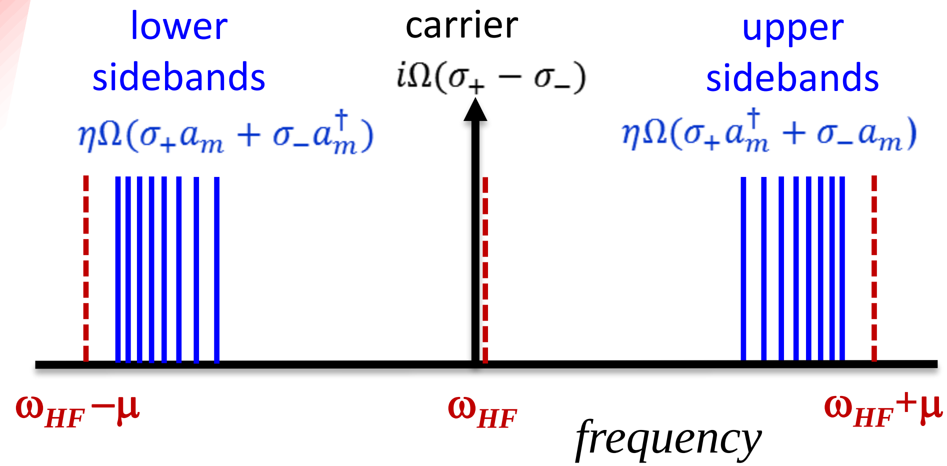
Resonant spin-dependent force

Raman beatnotes:

$\omega_{HF} \pm \mu$

ω_{HF} $(\Delta\phi = \pi/2)$





Lamb-Dicke limit: $\Delta k\langle x\rangle = \eta\langle a + a^\dagger\rangle \ll 1$

RWA: $\omega_{HF} \gg \mu, \omega_m \gg \eta\Omega$

$$H = \sum_{i,m} \eta_{im}\Omega\sigma_x^i \left[a_m e^{-i(\mu-\omega)t} + a_m^\dagger e^{i(\mu-\omega)t}\right]$$

$$\eta_{im} = b_i^m \sqrt{\frac{\omega_{rec}}{\omega_m}}$$

normal mode eigenvectors ion i mode m

Ad. eliminate phonons: $|\mu - \omega_m| \gg \eta\Omega$

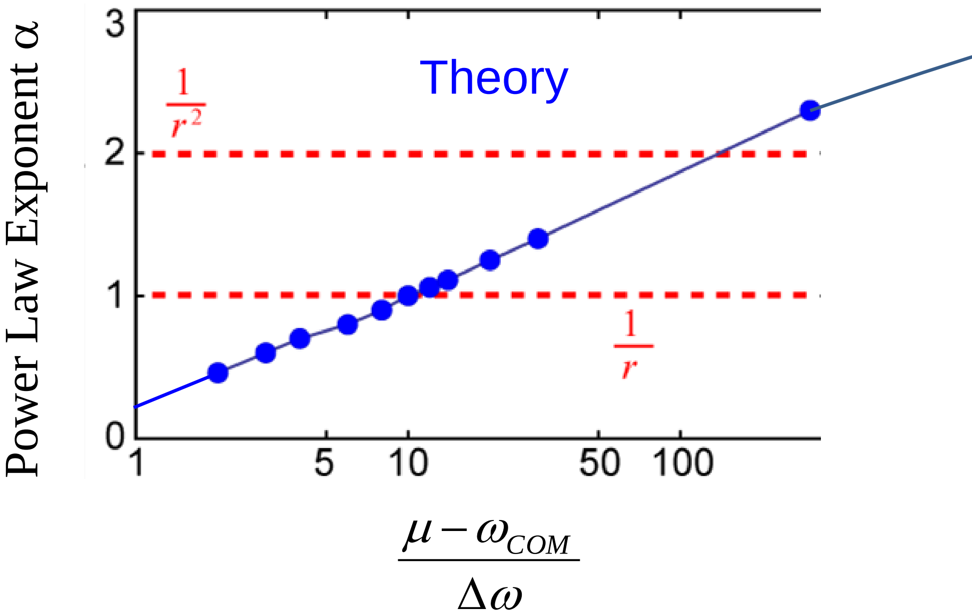
$$H = \sum_{i<j} J_{ij}\sigma_x^i \sigma_x^j + B\sum_i \sigma_y^i$$

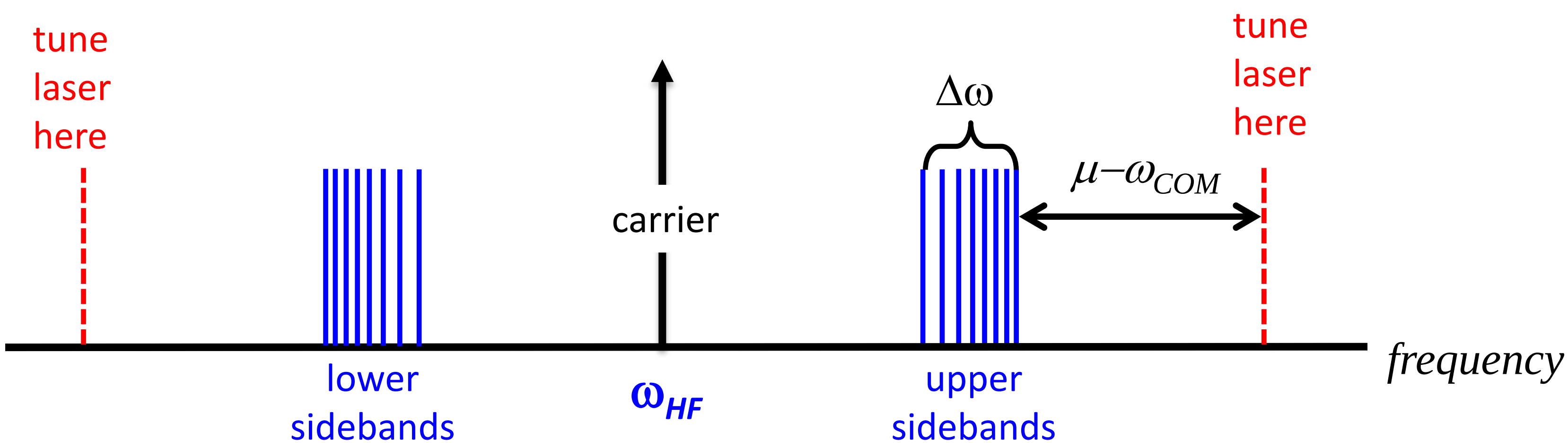
$$J_{ij} = \omega_{rec}\Omega^2 \sum_m \frac{b_i^m b_j^m}{\mu^2 - \omega_m^2}$$

Control of interaction range

$$J_{ij} = \omega_{rec}\Omega^2 \sum_m \frac{b_i^m b_j^m}{\mu^2 - \omega_m^2}$$

$$\sim + \frac{J_0}{|i-j|^\alpha}$$





Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

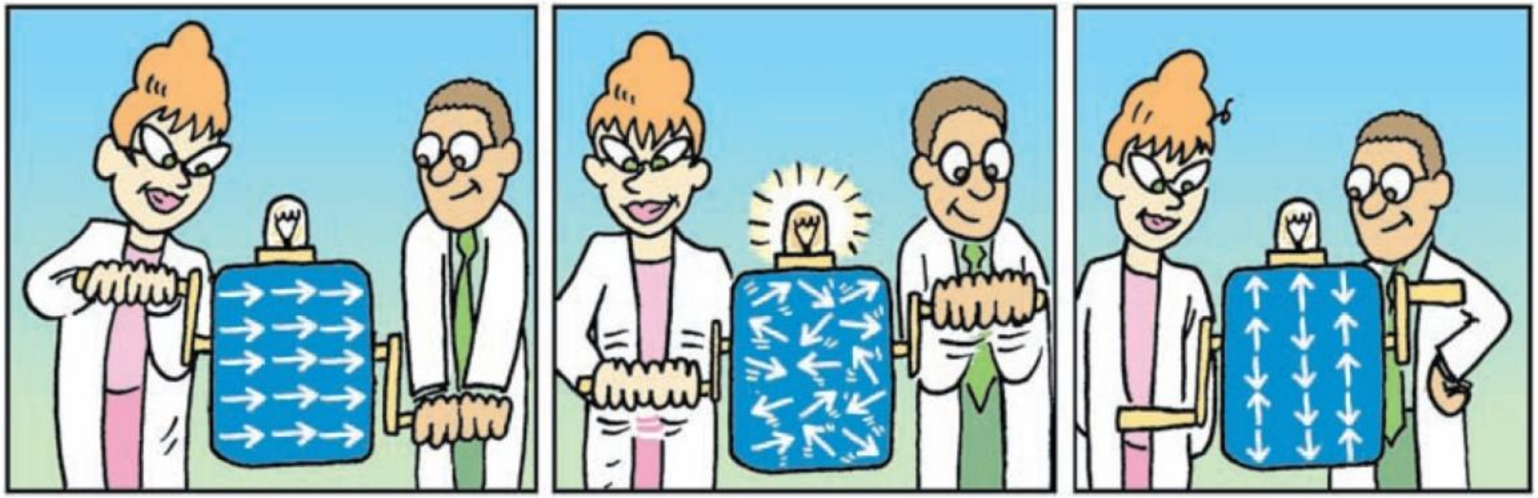
Dynamics

- Many-Body Spectroscopy
- Propagation of Excitations: Lieb-Robinson
- Prethermalization
- Many-Body Localization

Spin-1

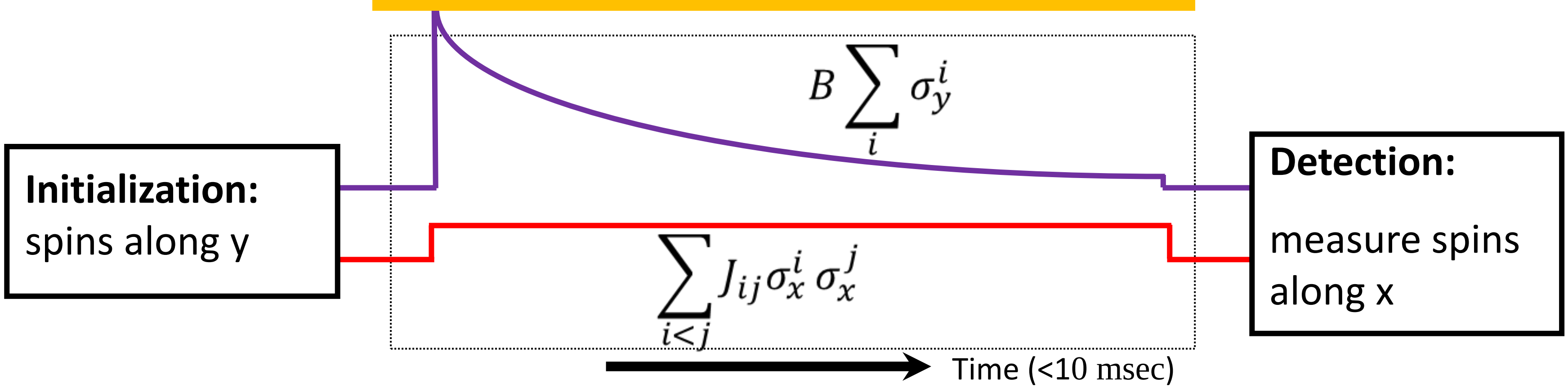
Extending to N~100 spins and beyond

Equilibrium: Adiabatic Quantum Simulation



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

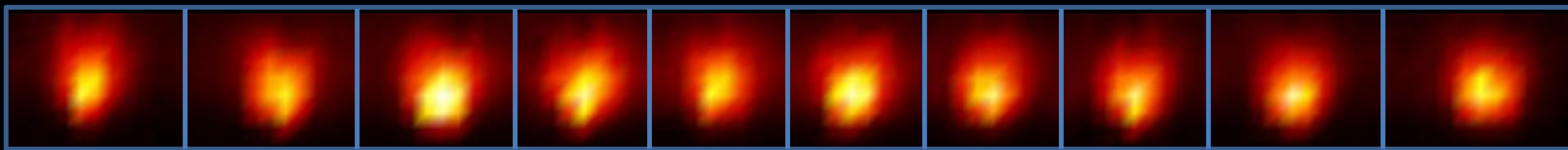
$$H = \sum_{i<j} J_{ij}\sigma_x^i \sigma_x^j + B \sum_i \sigma_y^i$$



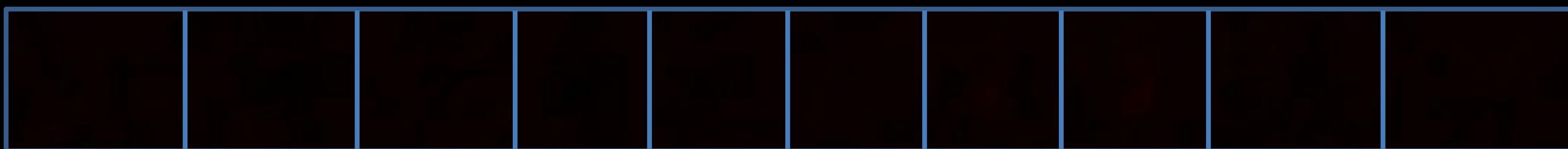
Antiferromagnetic Néel order of N=10 spins

2600 runs, α=1.12

All in state ↑

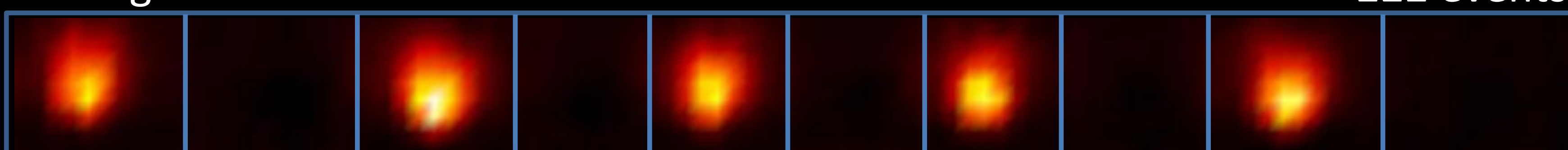


All in state ↓

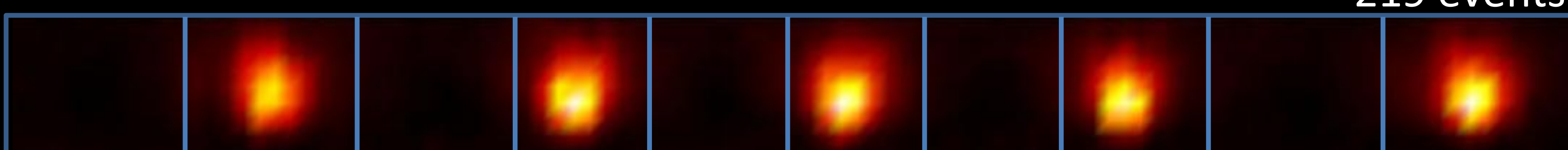


AFM ground state order

222 events



219 events



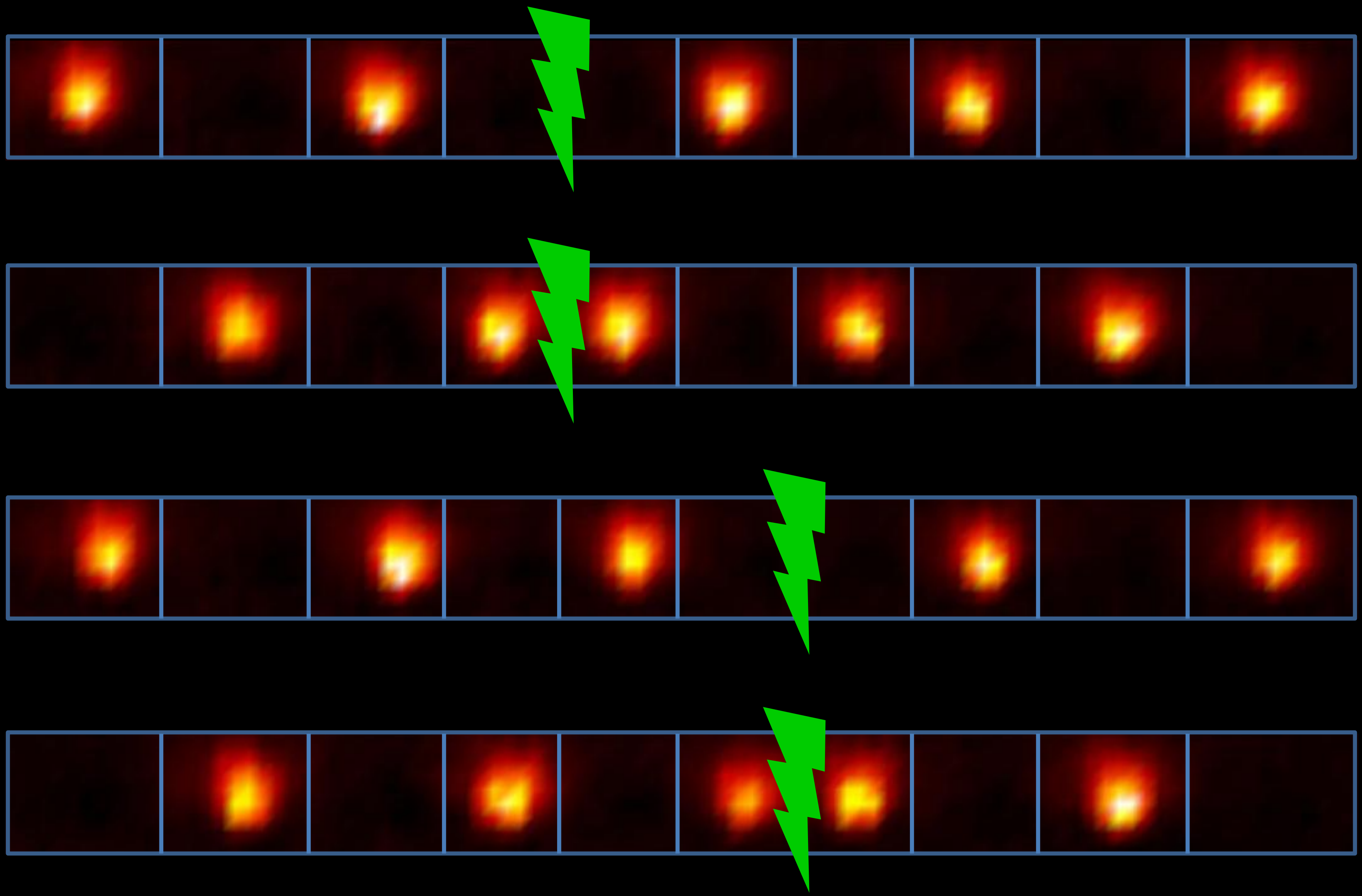
441 events out of 2600 = 17%

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

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

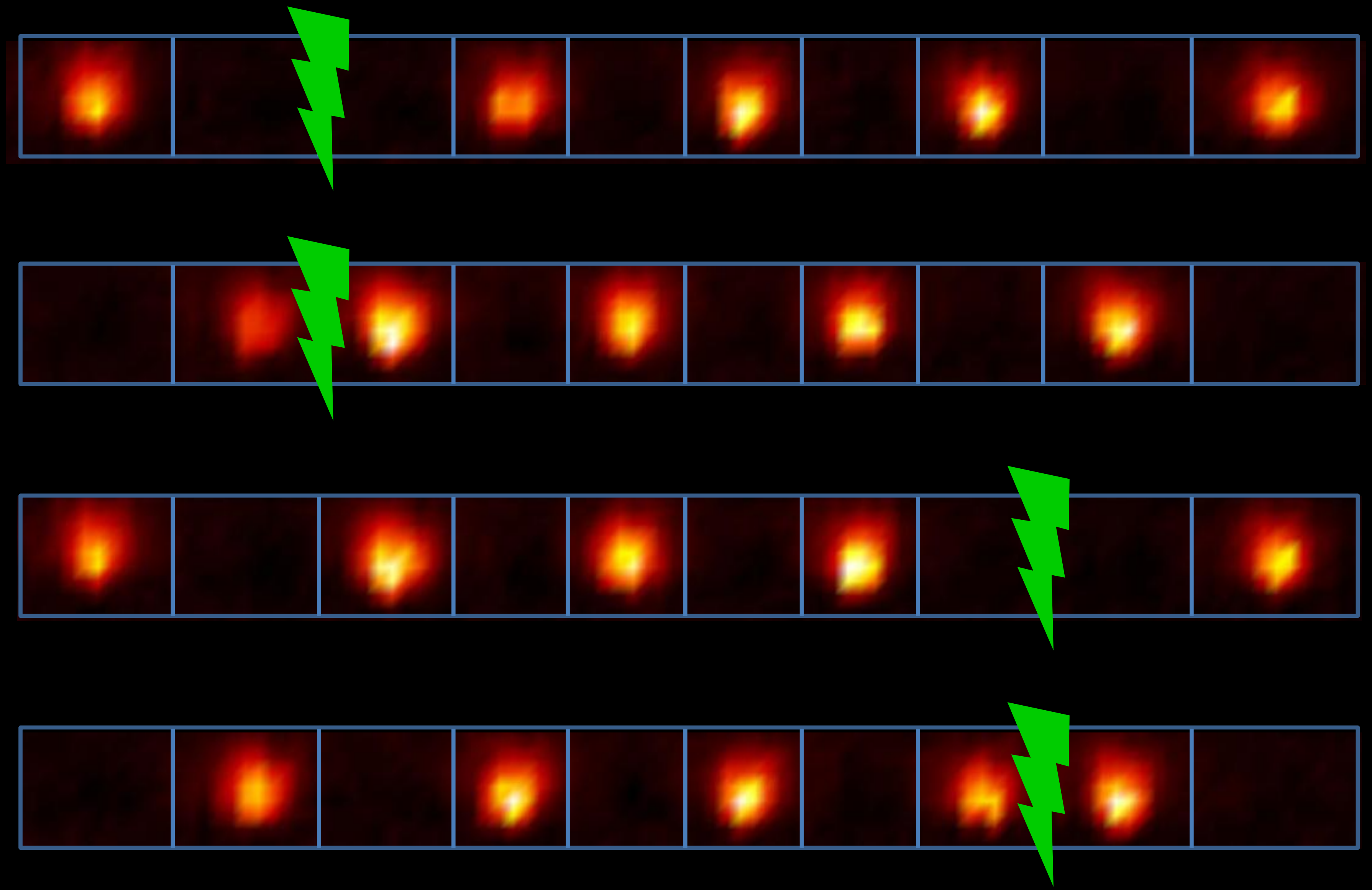
First Excited States

(Pop. ~2% each)

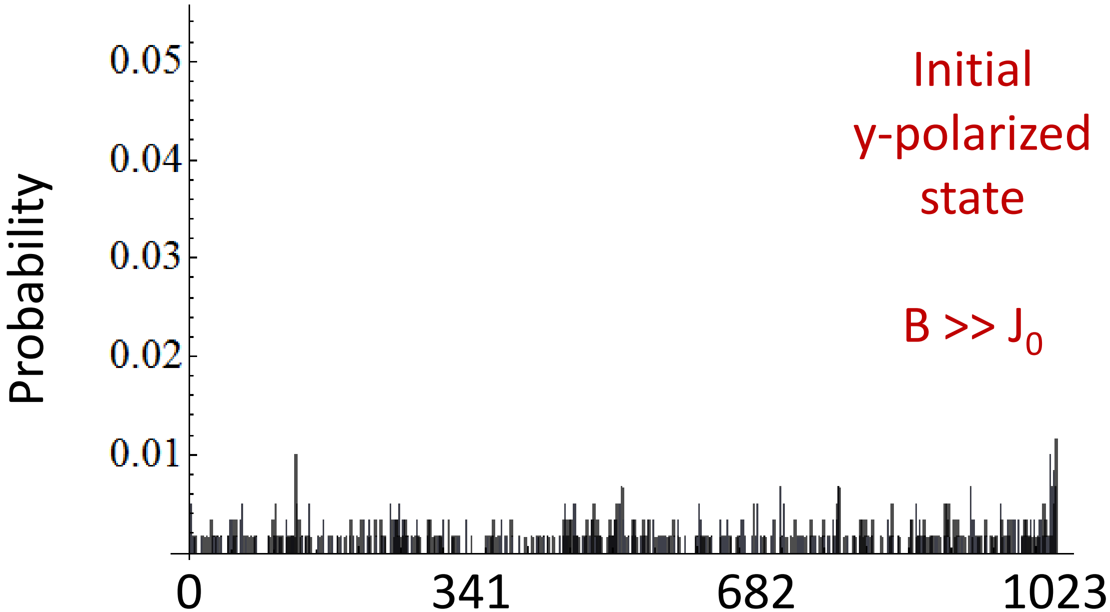


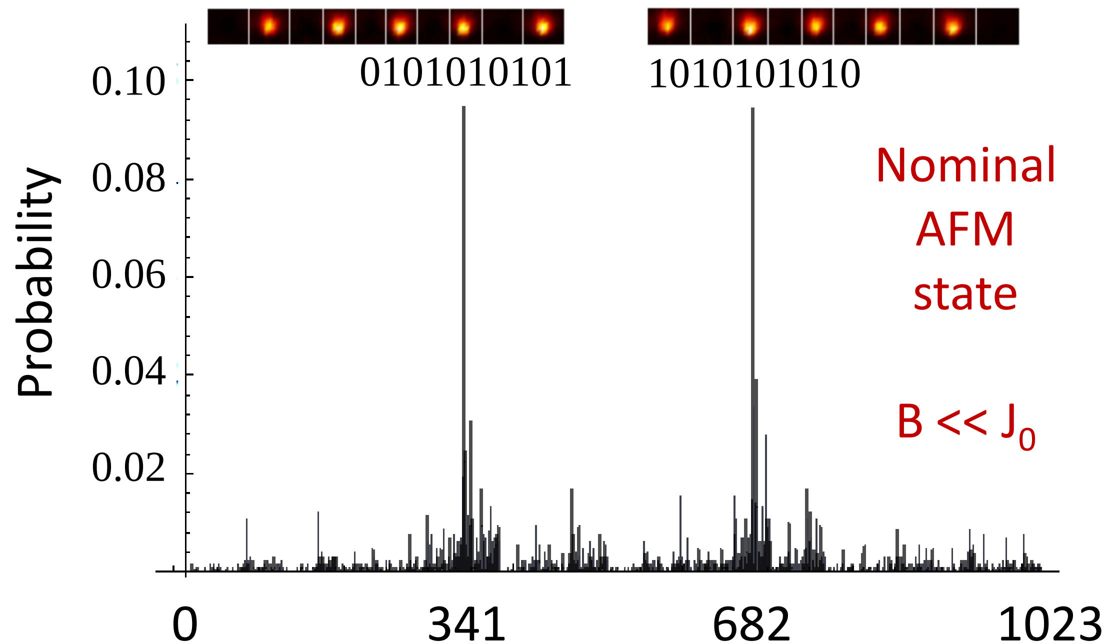
Second Excited States

(Pop. ~1% each)



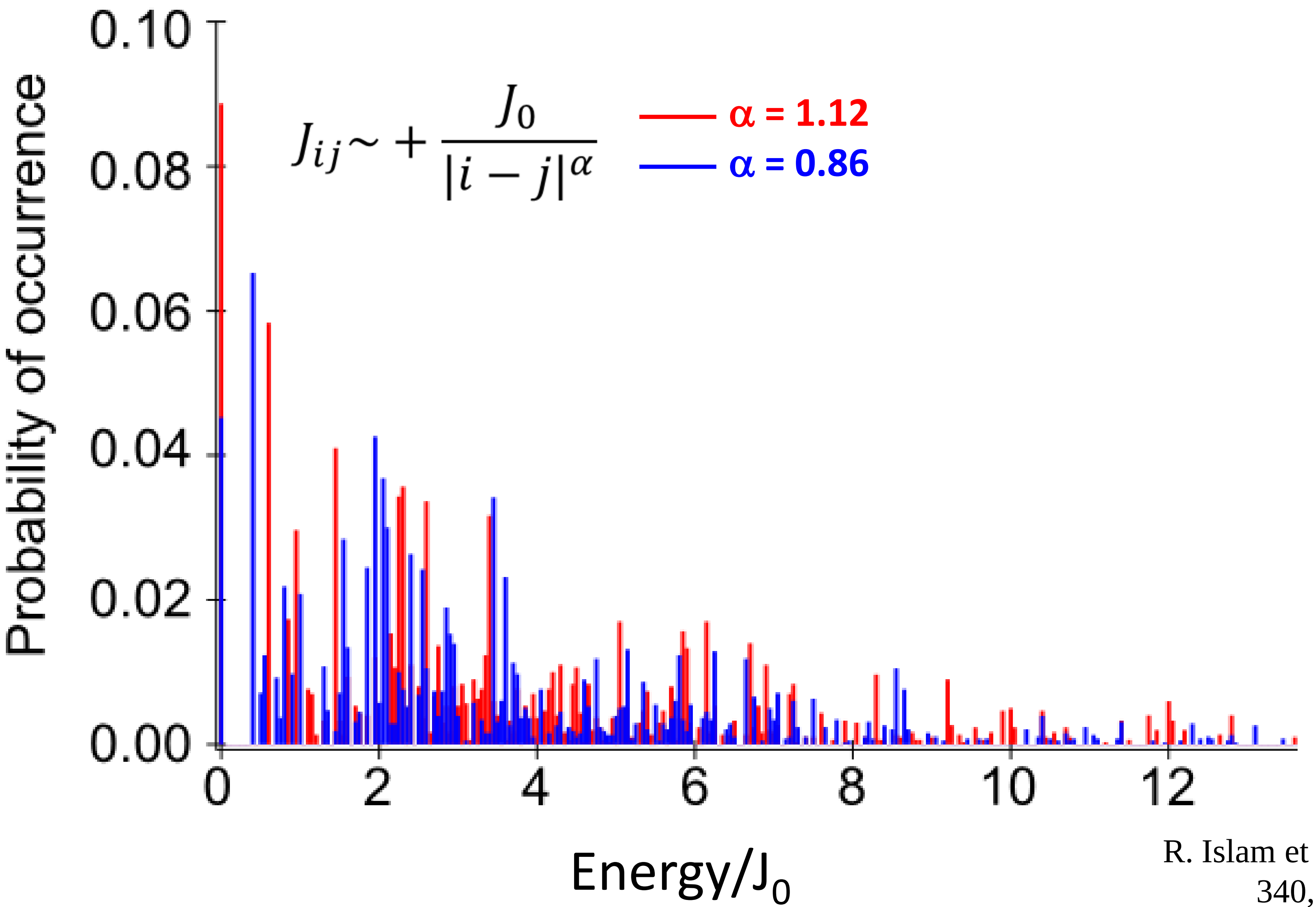
Distribution of all 2^{10} = 1024 states





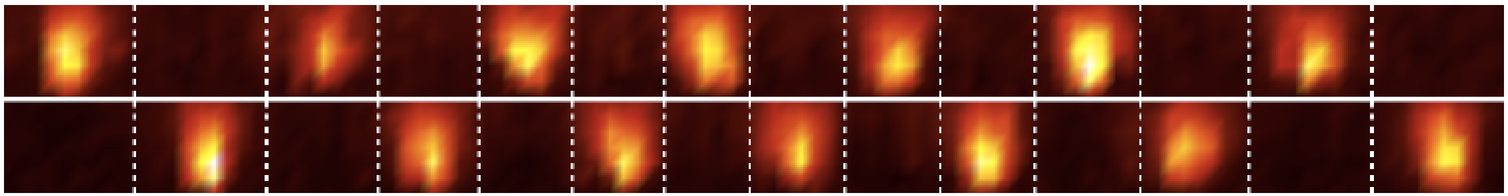
R. Islam et al., Science 340, 583 (2013)

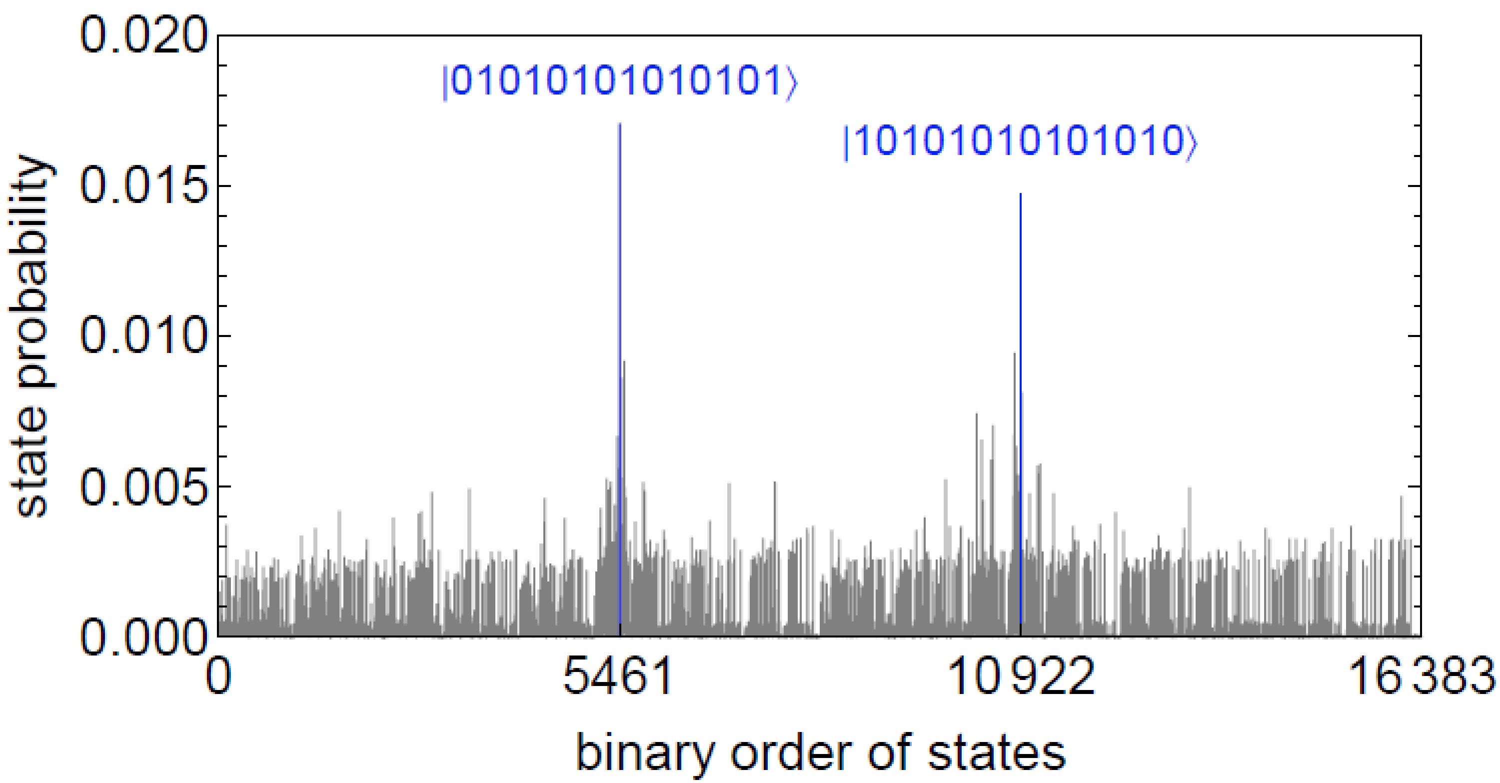
Distribution of states ordered by energy (N=10)



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

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





Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

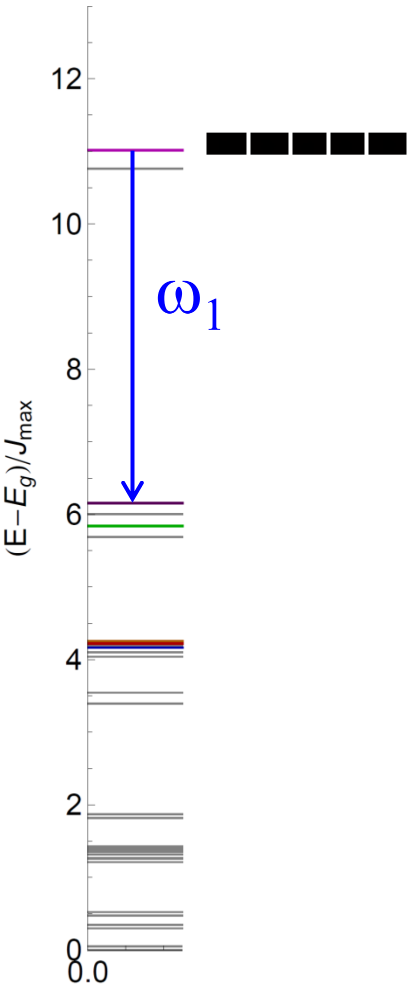
- Many-Body Spectroscopy
- Propagation of Excitations: Lieb-Robinson
- Prethermalization
- Many-Body Localization

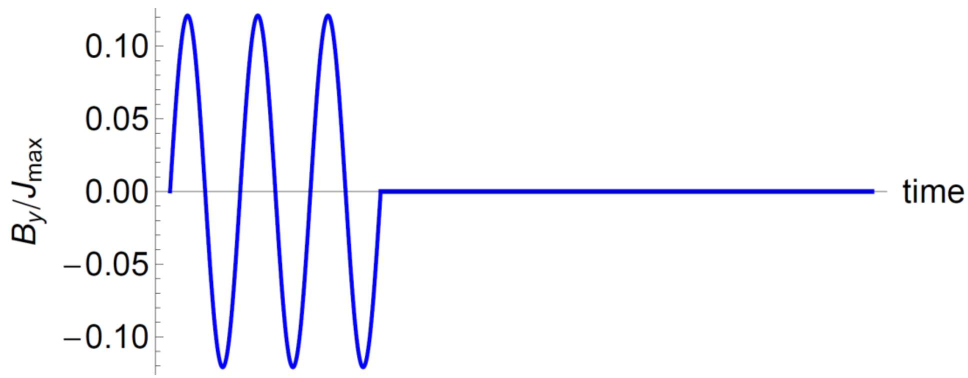
Spin-1

Extending to N~100 spins and beyond

Coherent Imaging Spectroscopy (N=5 spins)

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



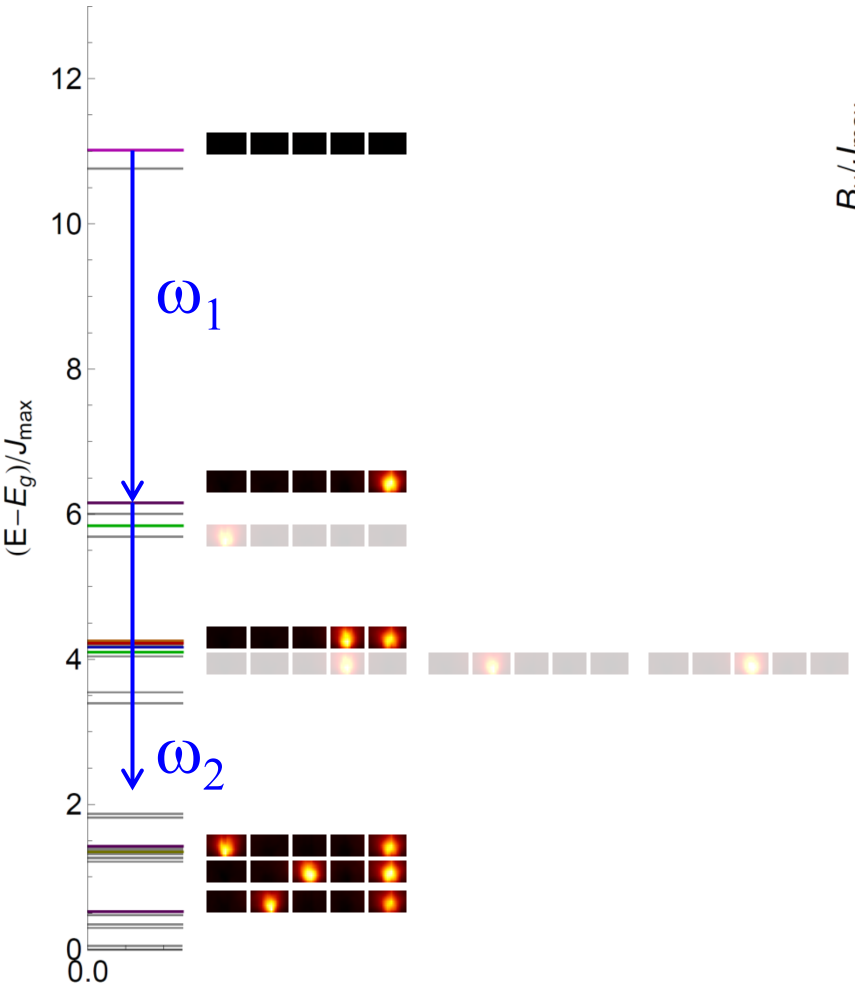


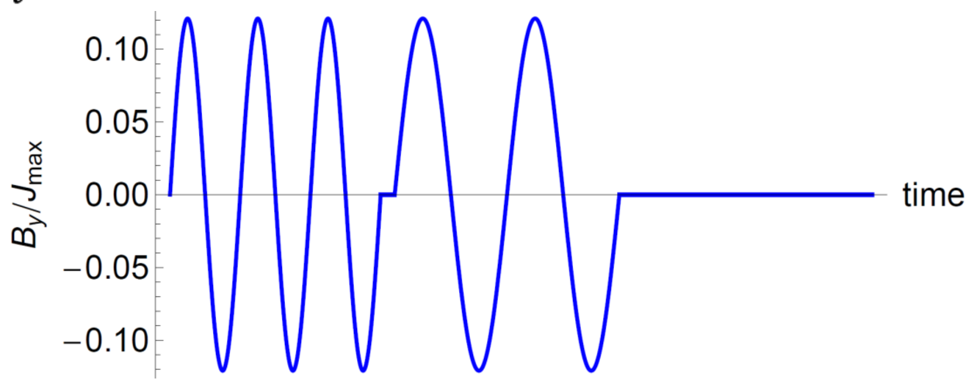
C. Senko *et. al.*, Science 345, 430 (2014)

Coherent Imaging Spectroscopy (N=5 spins)

$$H = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_y \sin(\omega t)\sum_i \sigma_y^i$$

multiple frequencies

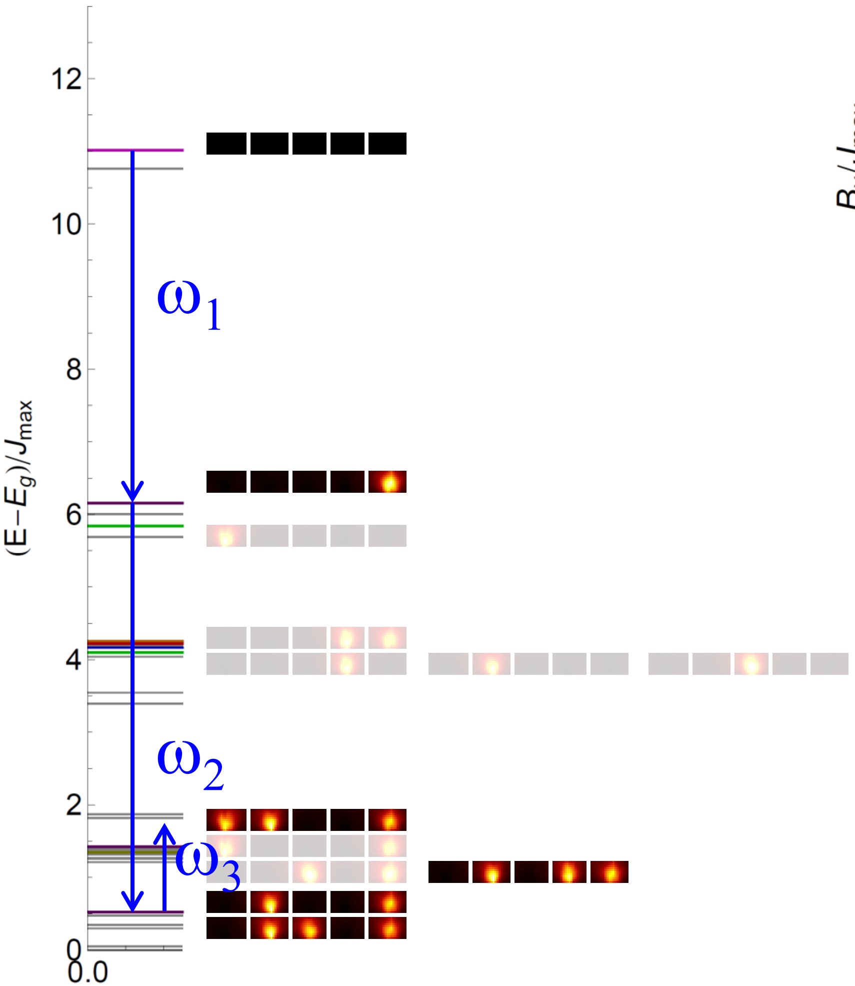




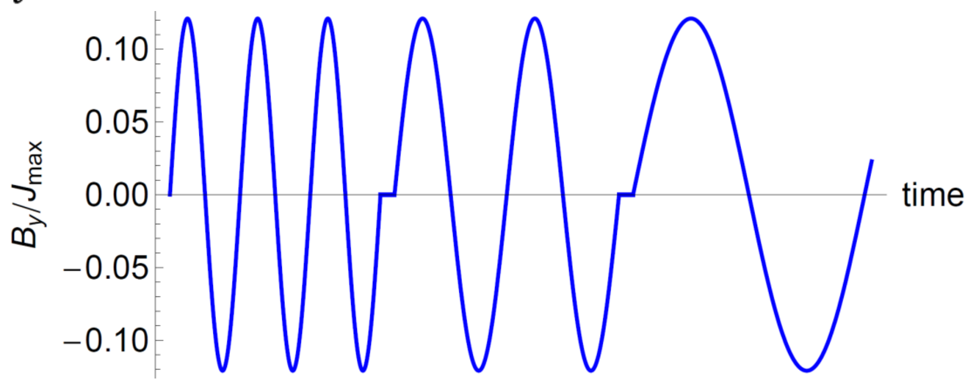
C. Senko *et. al.*, Science 345, 430 (2014)

Coherent Imaging Spectroscopy (N=5 spins)

$$H = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_y \sin(\omega t)\sum_i \sigma_y^i$$



multiple frequencies



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

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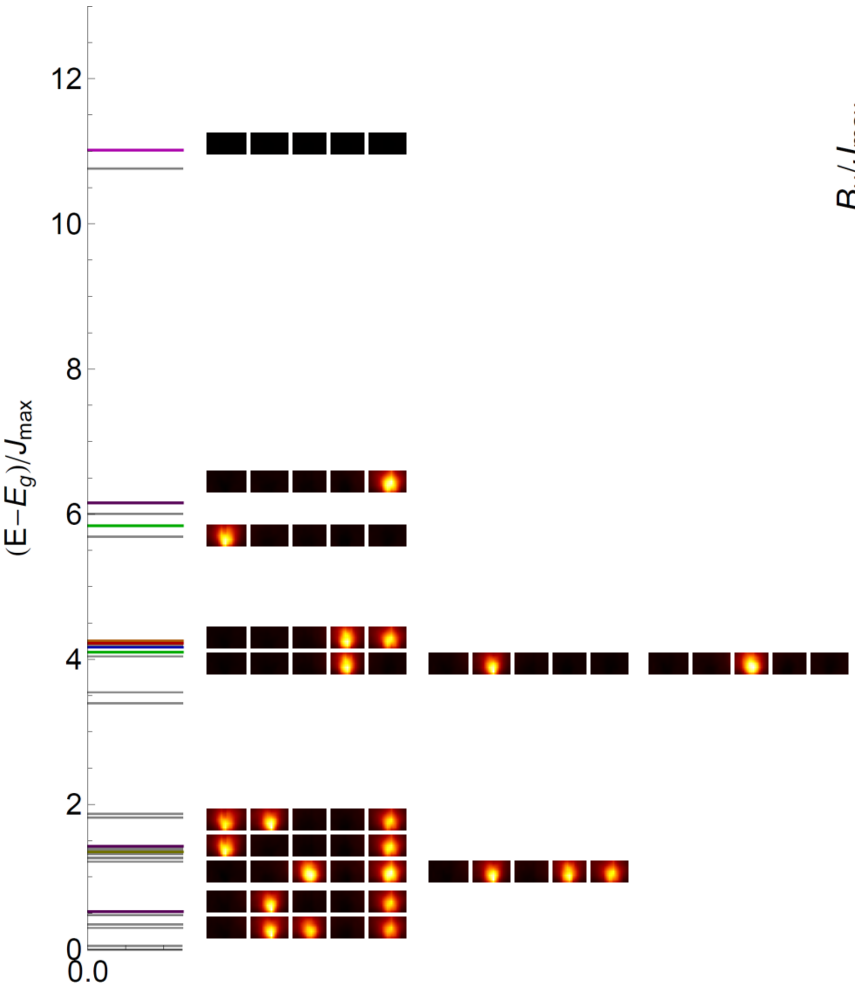
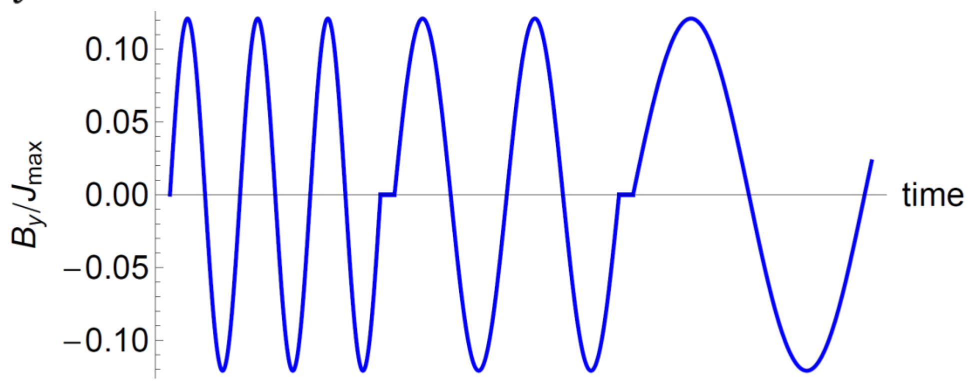
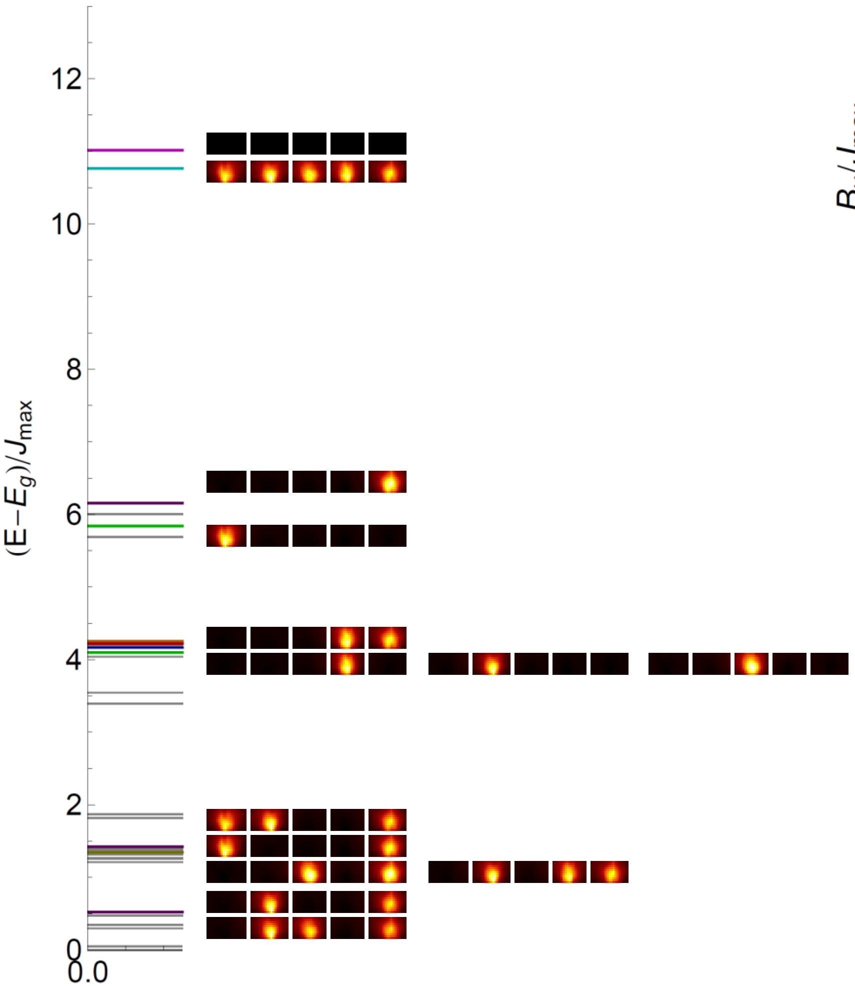


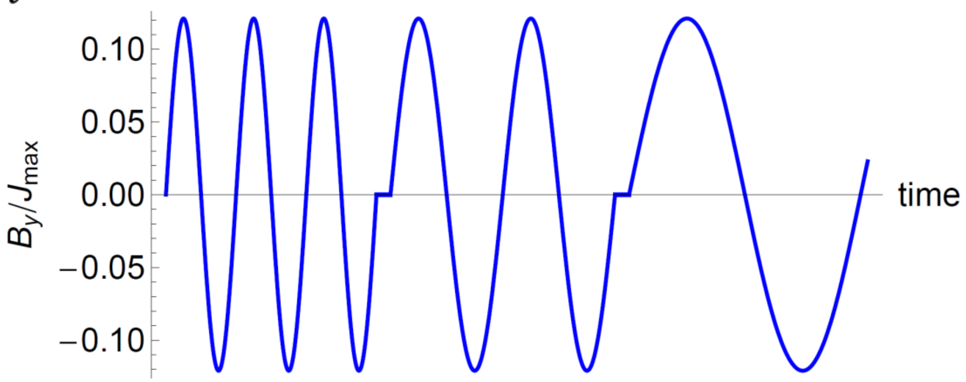


C. Senko *et. al.*, Science 345, 430 (2014)

Coherent Imaging Spectroscopy (N=5 spins)

$$H = \sum_{i<j} J_{ij} \sigma_x^i \sigma_x^j + B_y \sin(\omega t) \sum_i \sigma_y^i$$





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

Coherent Imaging Spectroscopy (N=5 spins)

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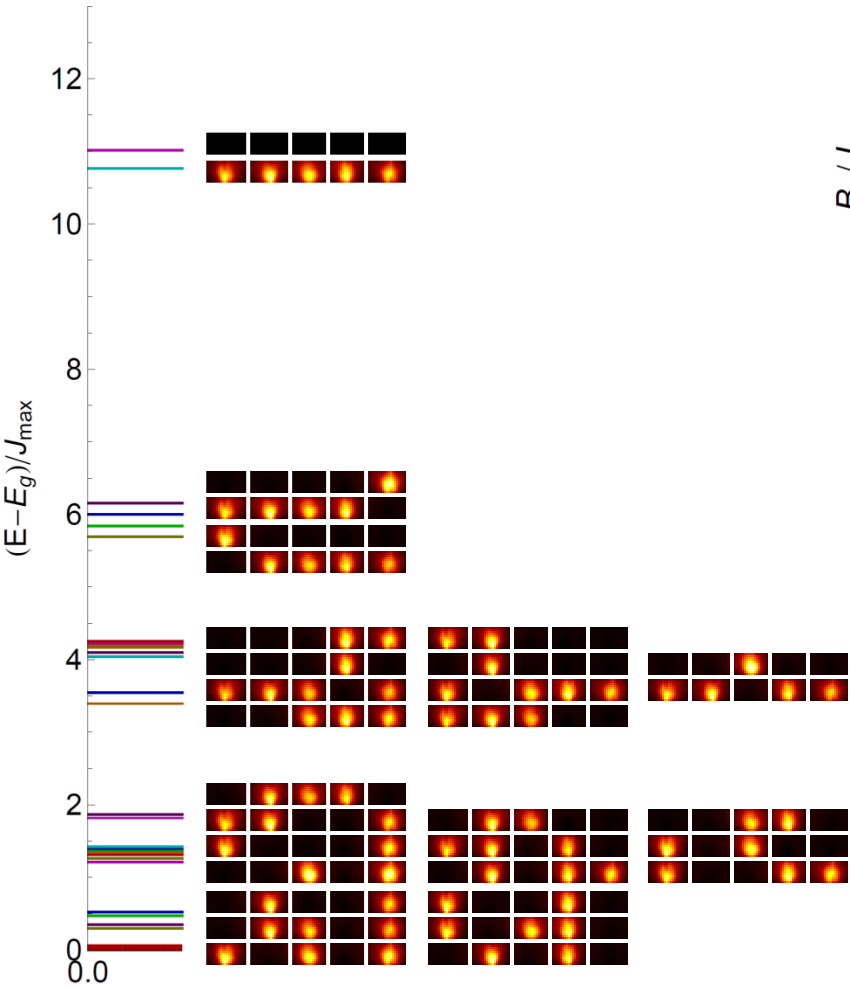
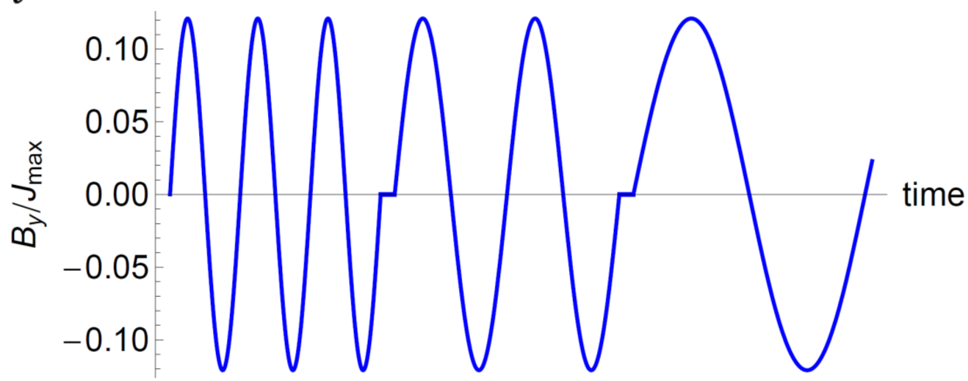
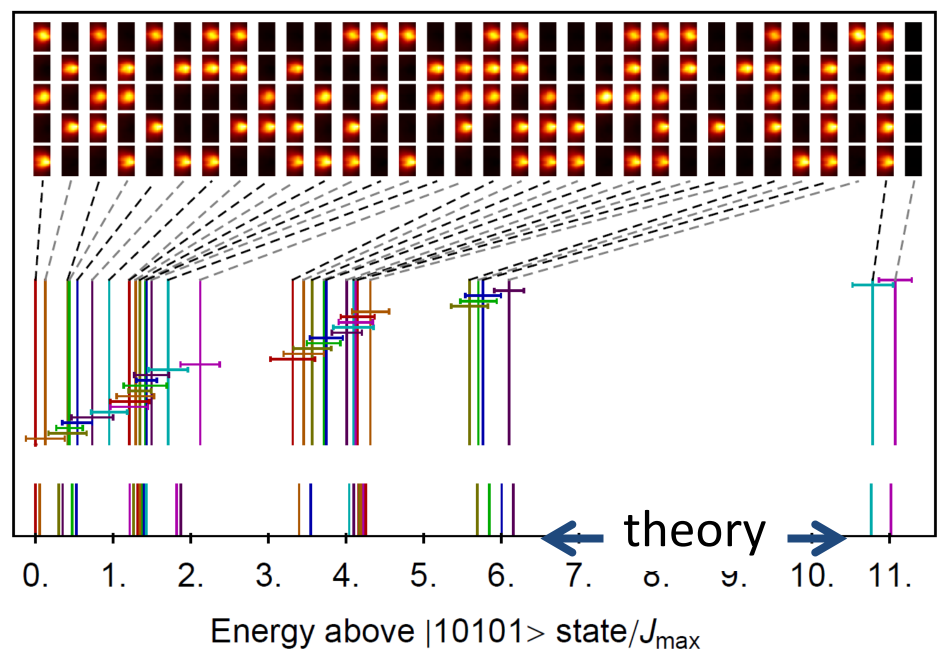
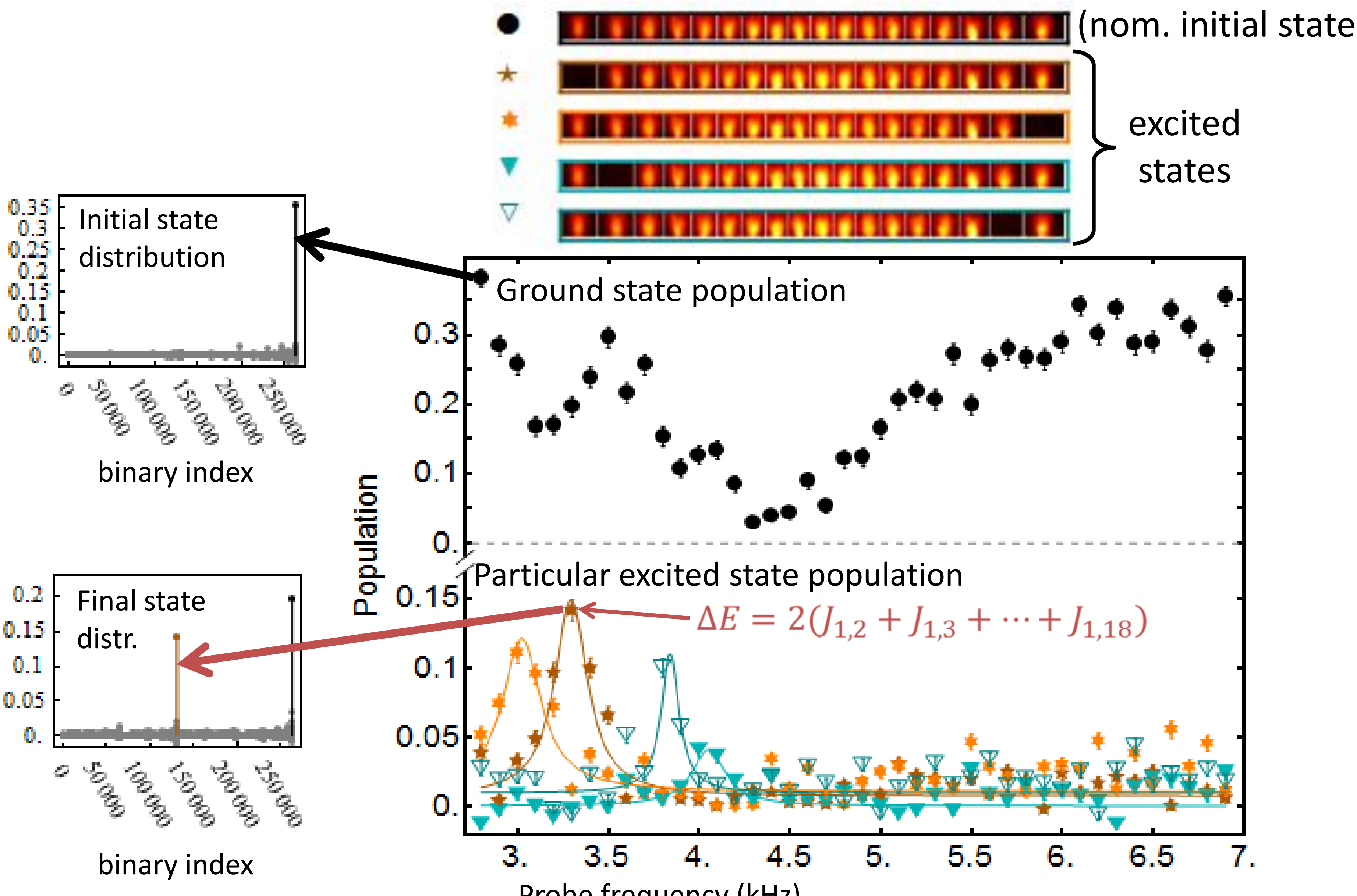






C. Senko *et. al.*, Science 345, 430 (2014)

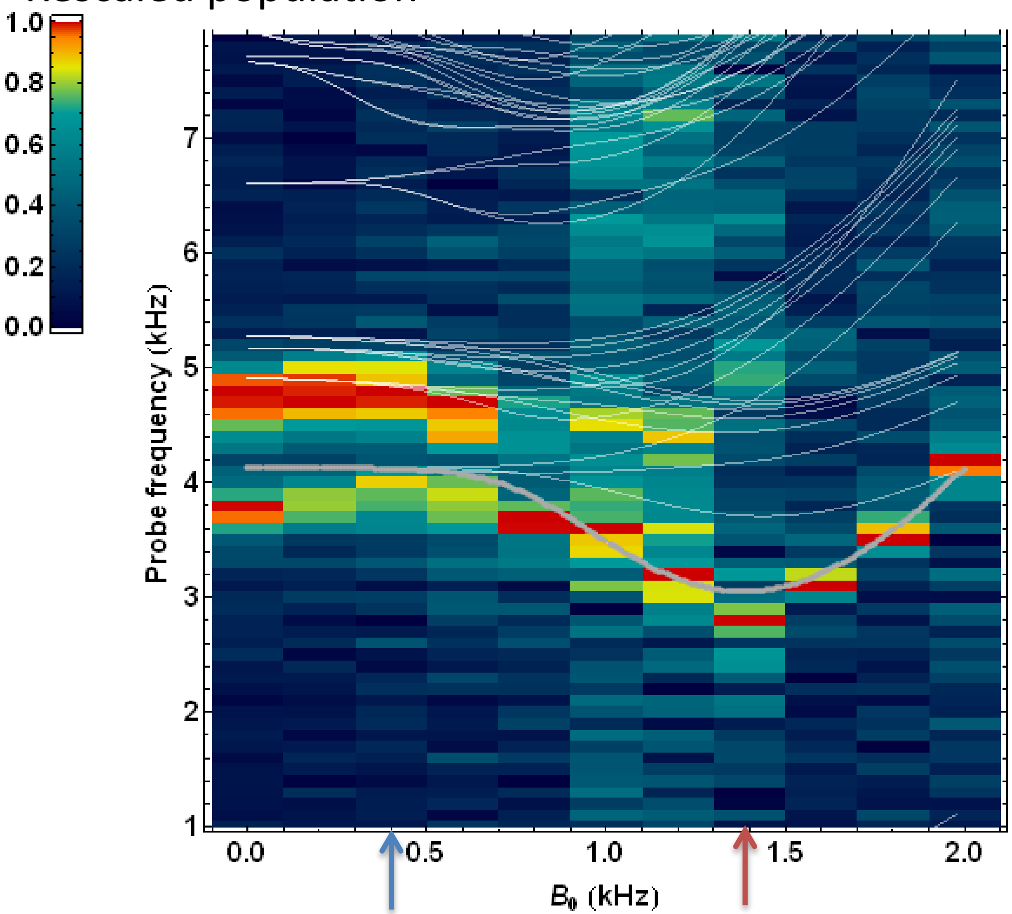
Coherent Imaging Spectroscopy (N=18 spins)

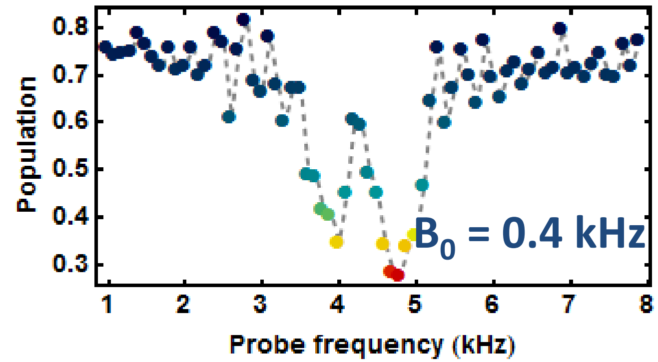


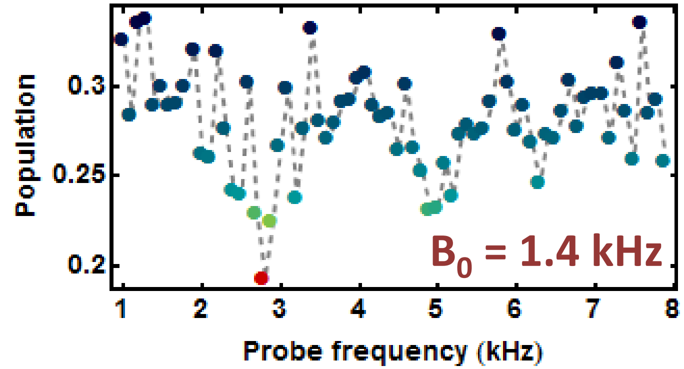
C. Senko *et. al.*, Science 345, 430 (2014)

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

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





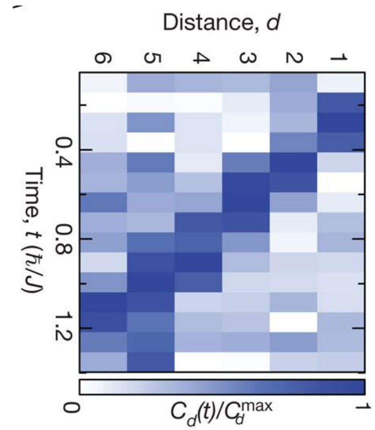


C. Senko *et. al.*, Science 345, 430 (2014)

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)



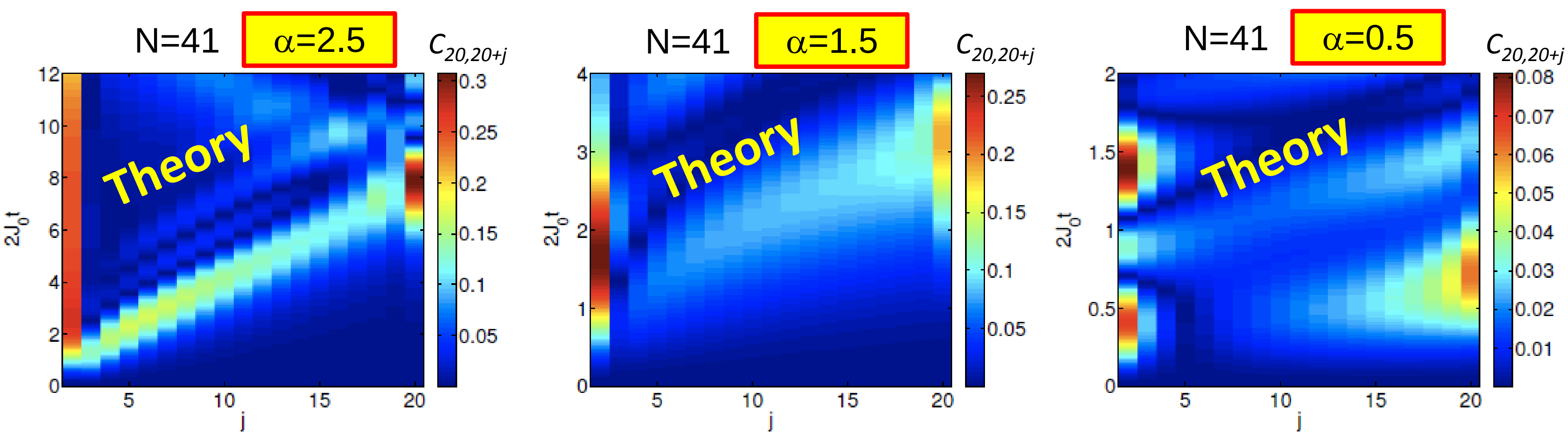
"Global Quench"

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

(b) Turn on interactions

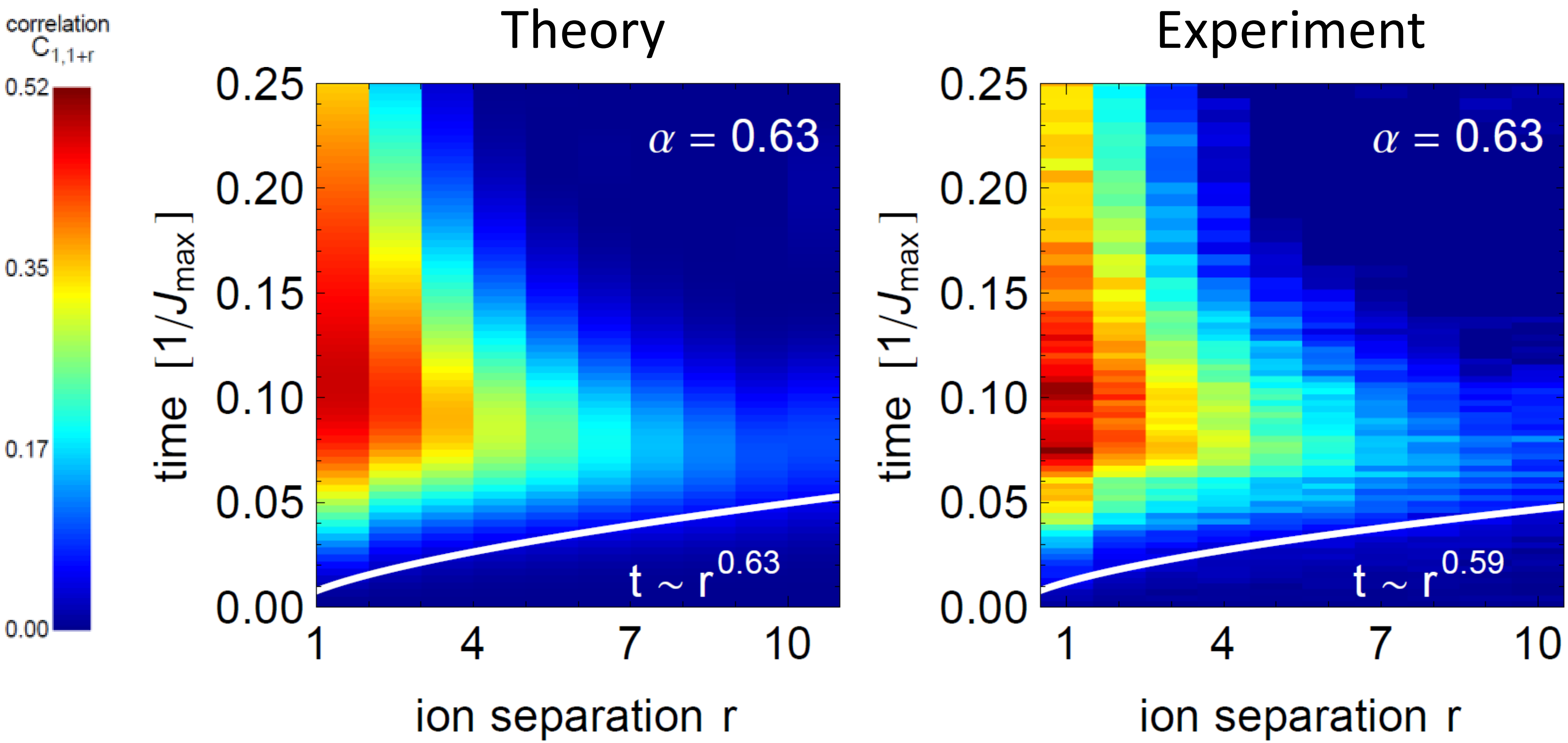
(c) Measure correlations $C^z_{ij} = \sum_{i,j} \left[\langle \sigma_i^z \sigma_j^z \rangle - \langle \sigma_i^z \rangle \langle \sigma_j^z \rangle \right]$

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



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

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



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

Long range "Light Cones" (XY: N=25 spins)

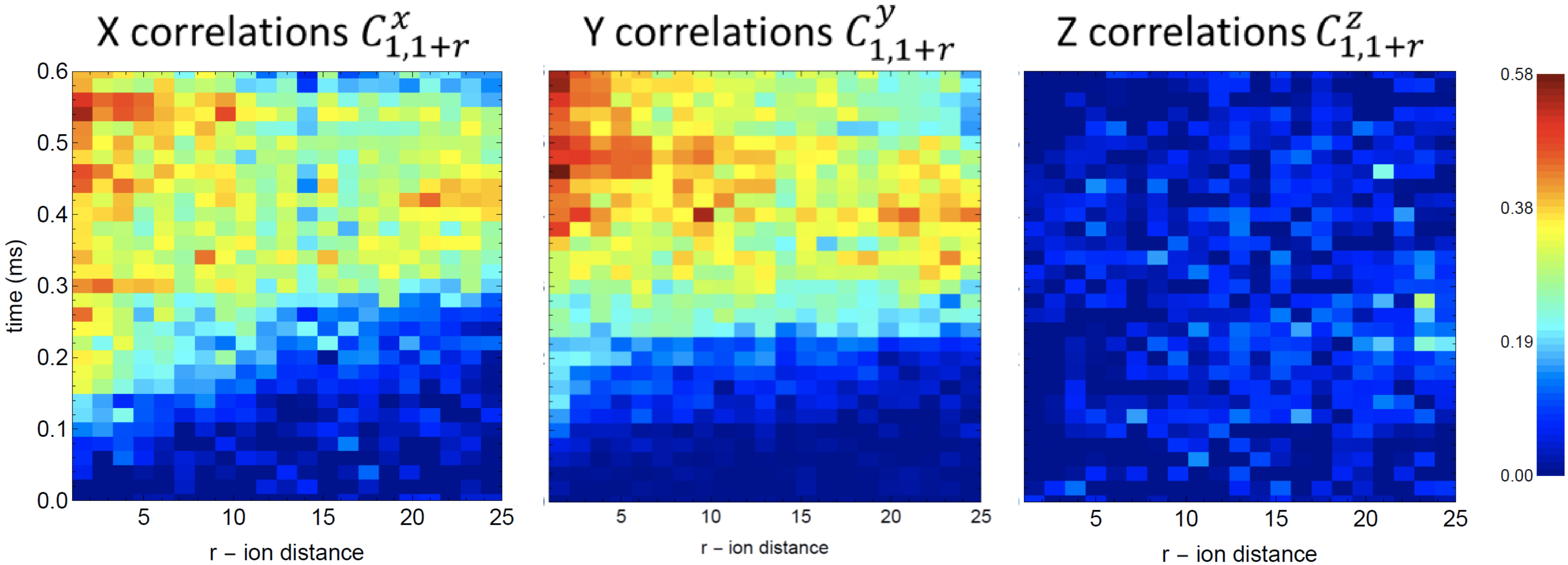
$$H_{XY} = \sum_{i<j} J_{ij}\left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j\right) \qquad J_{ij} \approx \frac{J_0}{r^\alpha} \qquad \alpha = 1.3$$

"Global Quench"

(a) Prepare $(\downarrow_z + \uparrow_z)^{\otimes N}$

(b) Turn on interactions

(c) Measure correlations in spacetime

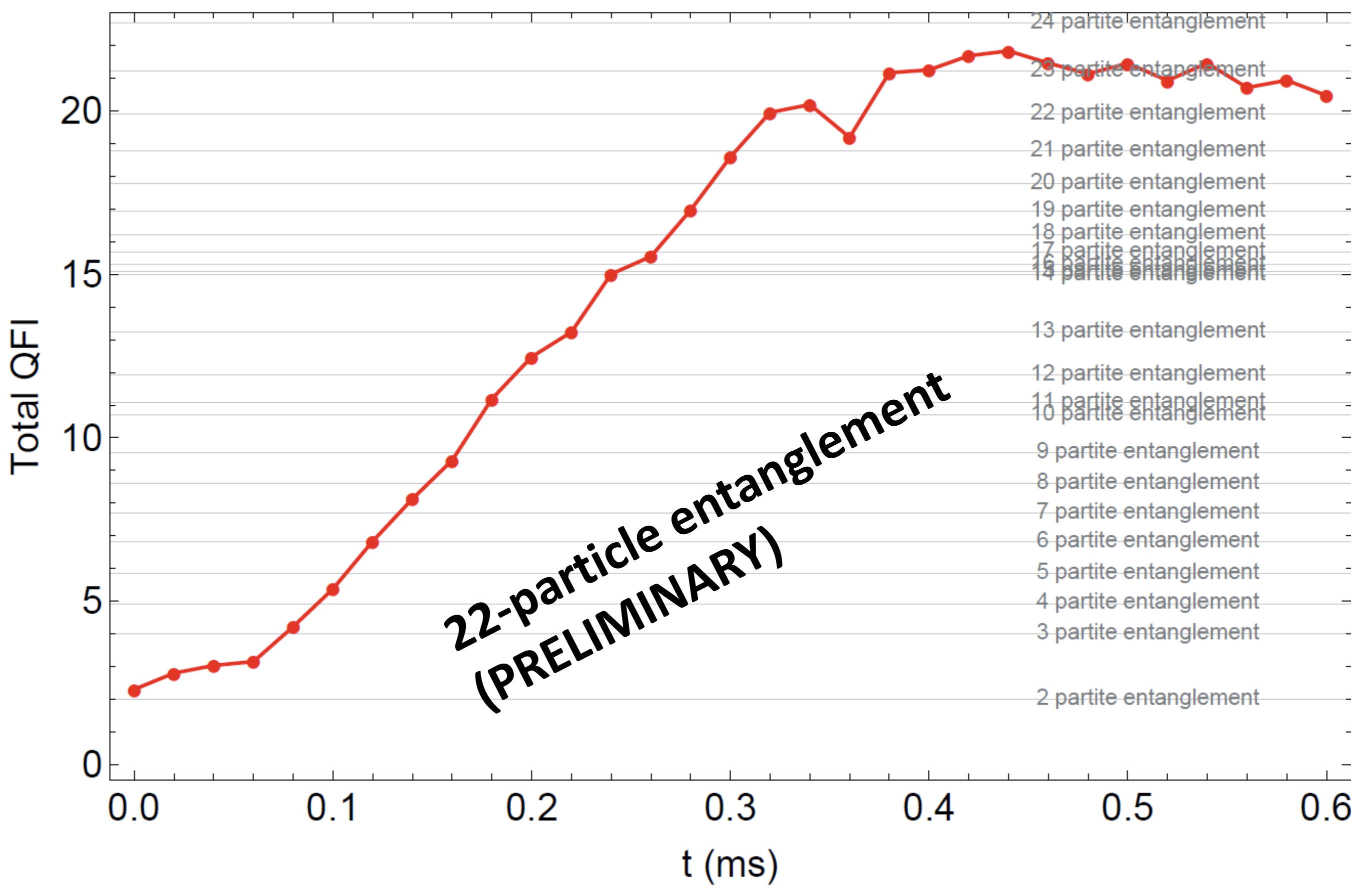


P. Richerme *et. al.*, *Nature* **511**, 198 (2014)
P. Jurcevic et al., *Nature* **511**, 202 (2014)

Quantum Fisher Information: characterizes system entanglement

$$F_Q = \sum_{i,j} C_{ij}^x + C_{ij}^y + C_{ij}^z$$ is an entanglement witness operator

Braunstein and Caves Phys. Rev. Lett. 72, 3439 (1994)
Hauke, Heyl, Tagliacozzo, Zoller, arXiv:1509.01739 (2015)



Thermalization/Localization

How can quantum systems thermalize?

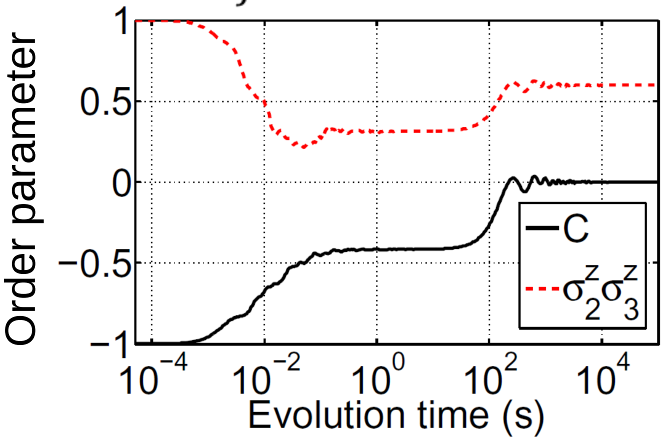
→ Eigenstate Thermalization Hypothesis (Rigol et al., *Nature* 2008)

How can quantum systems fail to thermalize?

<u>Prethermalization</u>

XY Model with inhomogeneous couplings

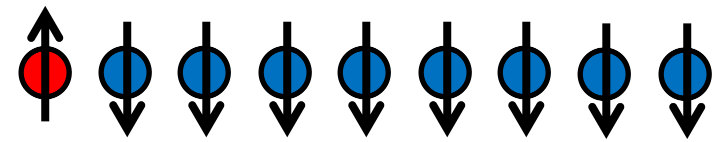
$$H_{XY} = \sum_{i<j} J_{ij}\left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j\right)$$



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

Prethermalization

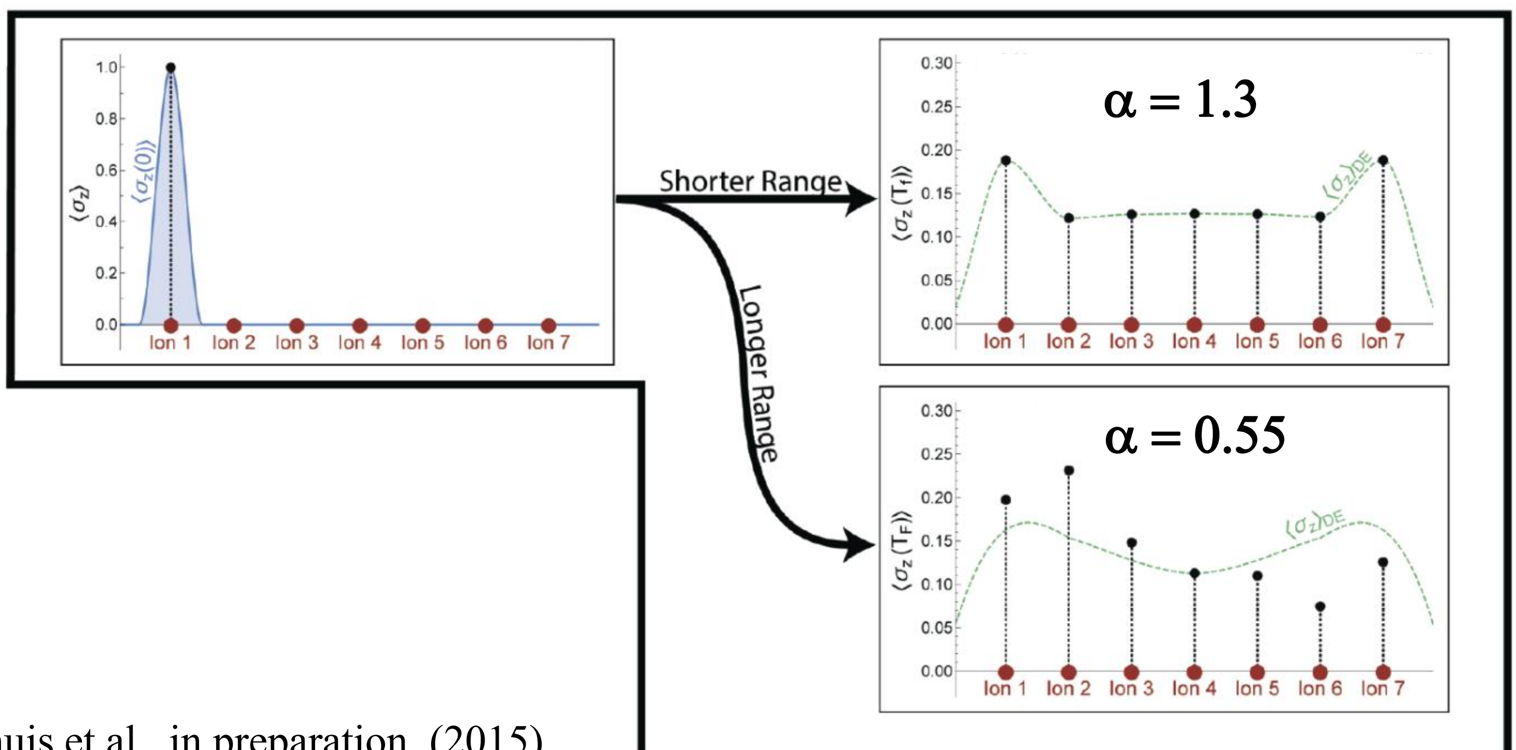
Step 1: Initialize with localized excitation



Step 2: Evolve under variable-range XY model

Step 3: Measure spins after time t

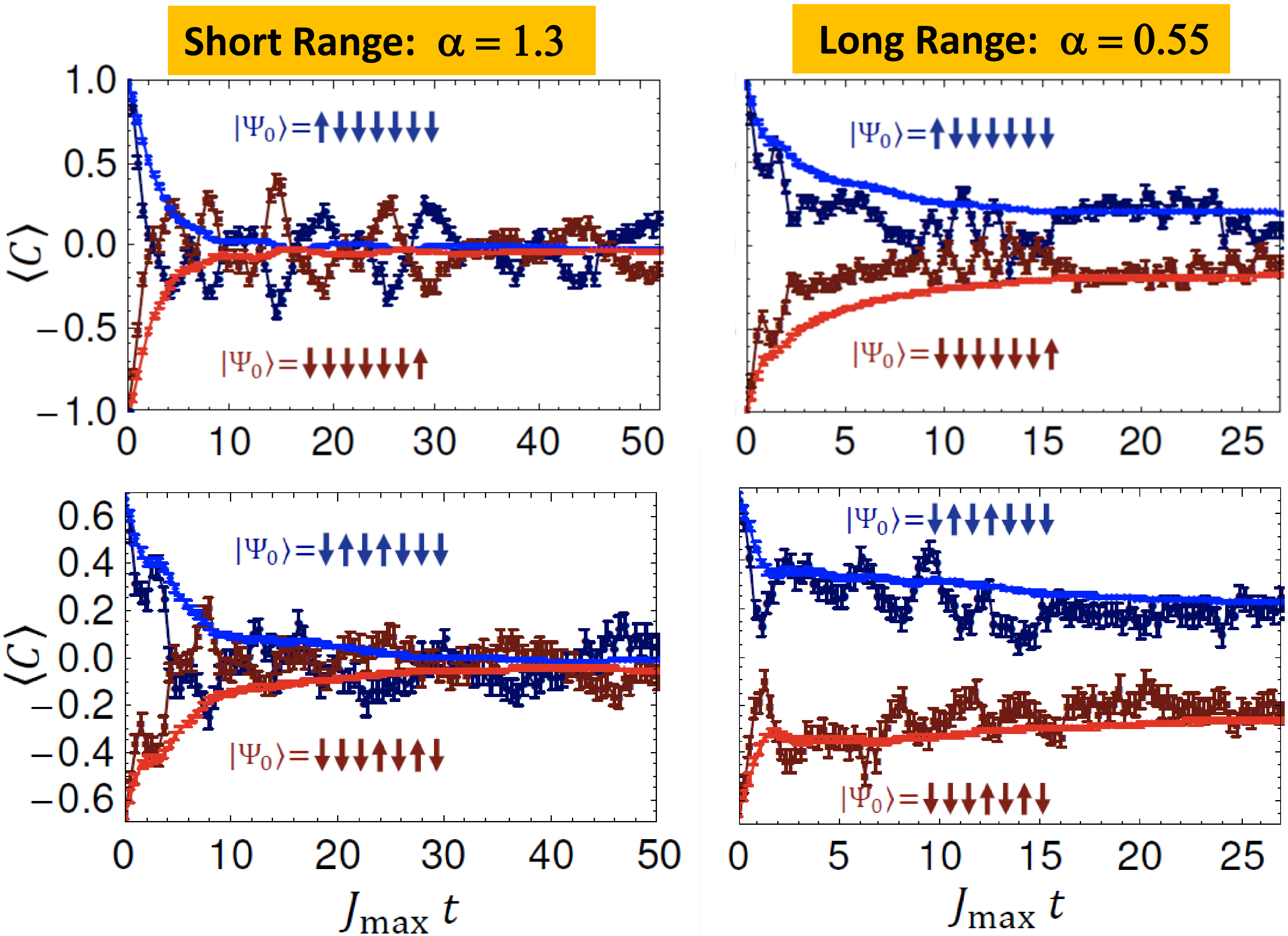
$$H_{XY} = \sum_{i<j} \frac{J_0}{|i-j|^\alpha}\left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j\right)$$



B. Neyenhuis et al., in preparation (2015)

Track “center” of spin excitation

$$C = \sum_{i=1}^{N} \left(\frac{2i - N - 1}{N - 1} \right) \frac{1 + \sigma_z^i}{2}$$



B. Neyenhuis et al., in preparation (2015)

N=22 spins

$$H_{XY} = \sum_{i<j} \frac{J_0}{|i-j|^{\alpha}} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j \right) \qquad \alpha = 0.6$$

state measured at $J_0 t = 36$

B. Neyenhuis et al., in preparation (2015)

Thermalization/Localization

How can quantum systems thermalize?

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

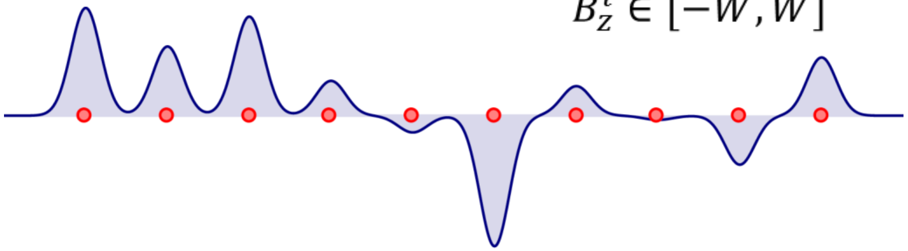
How can quantum systems fail to thermalize?

<u>Many-Body Localization</u>

- Ising Model with random disorder

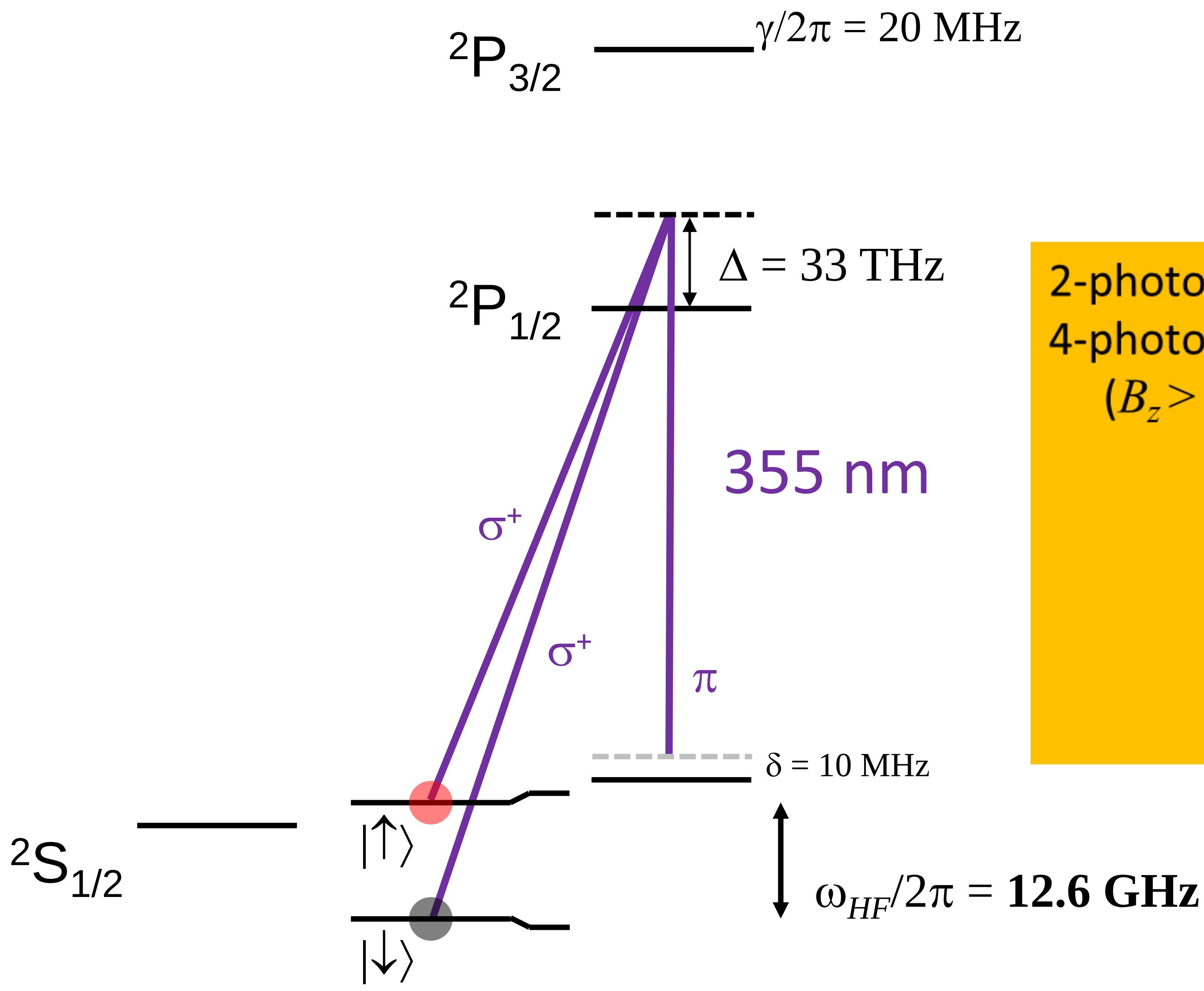
$$H_{MBL} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + \sum_i \tilde{B}_z^i \sigma_z^i$$

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



A. Polkovnikov et al., Rev. Mod. Phys. **83**, 863 (2011)
P. Hauke and M. Heyl, arXiv:1410.1491 (2014)
Exp: W. R. McGehee, et al., PRL 111, 145303 (2014)
Exp: M. Schreiber, et al., Science 349, 842 (2015)

$^{171}Yb^+$ site-resolved field σ_z



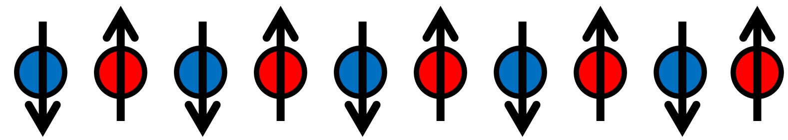
2-photon Stark shift ~100Hz
4-photon Stark shift HUGE
($B_z > 1000\,J$ possible)

$$J \sim \frac{\eta^2 g^4}{\omega_t \Delta^2}$$

$$B_z \sim \frac{g^4}{\delta \Delta^2}$$

Many Body Localization (N=10)

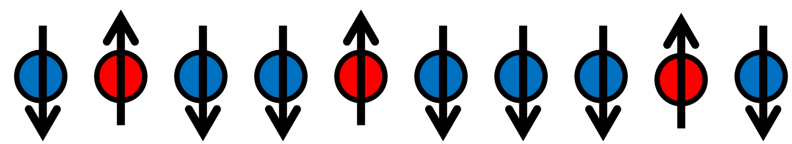
Step 1: Initialize spins staggered along *z* (“$kT=\infty$”)



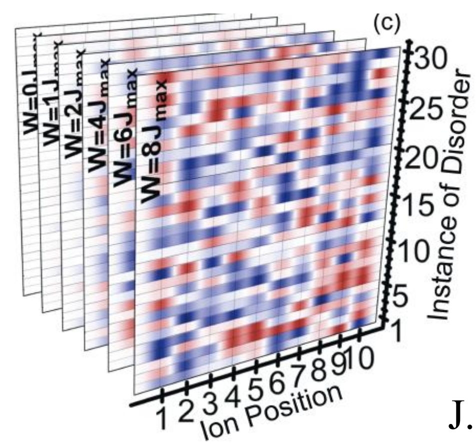
Step 2: Quench to transverse Ising model with random disorder

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

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



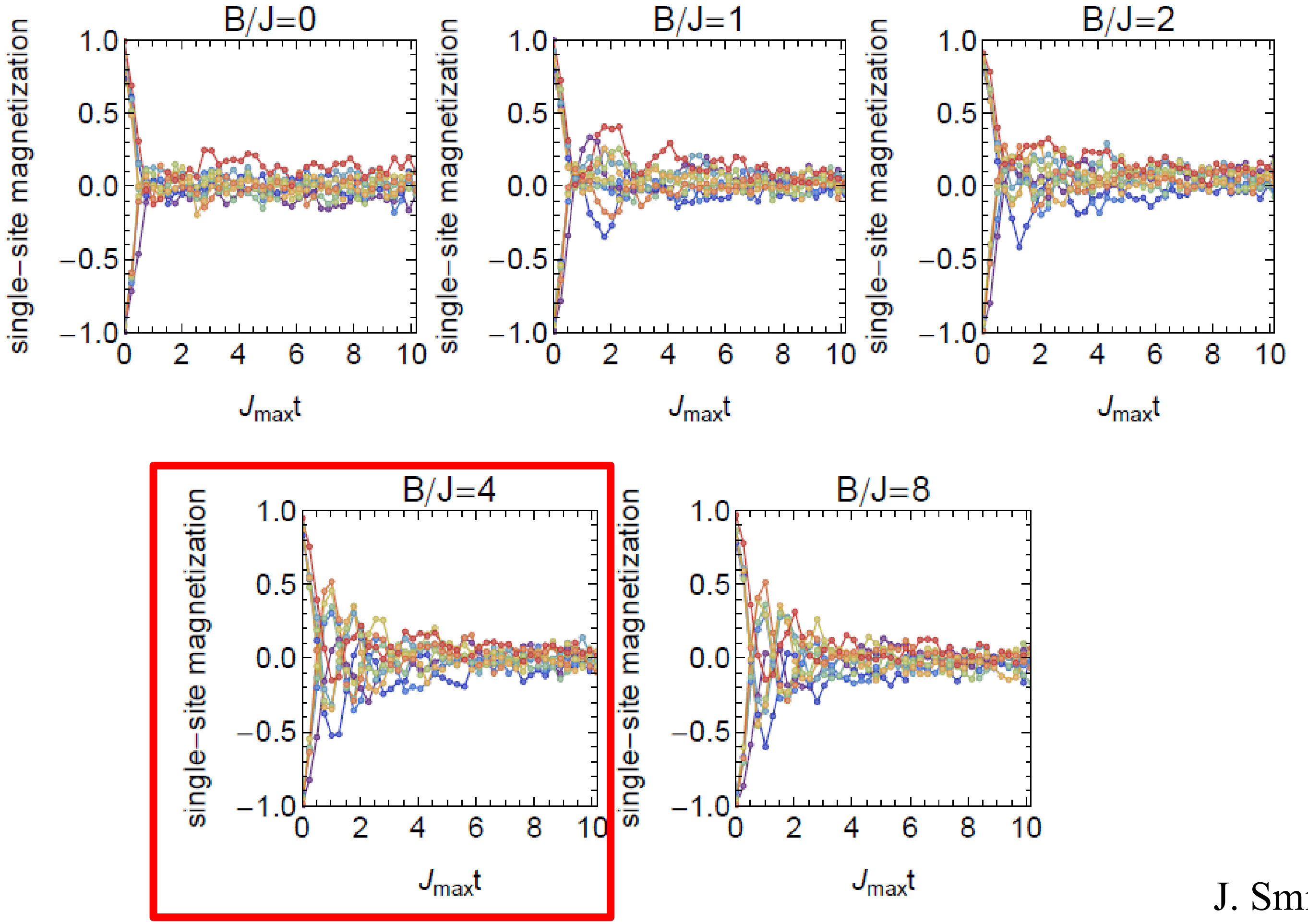
Step 4: Repeat for many different disorder instances and strengths



J. Smith et al., ArXiv 1508.07026 (2015)

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

(no disorder)

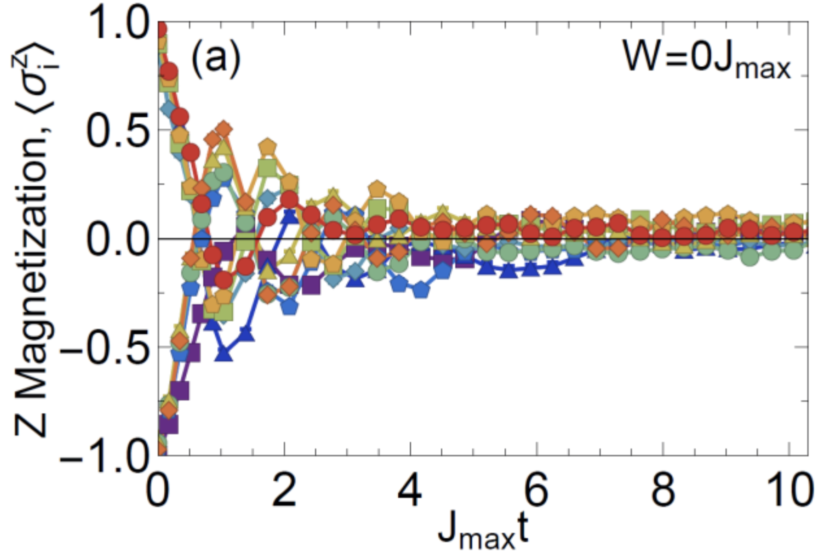


J. Smith et al., ArXiv 1508.07026 (2015)

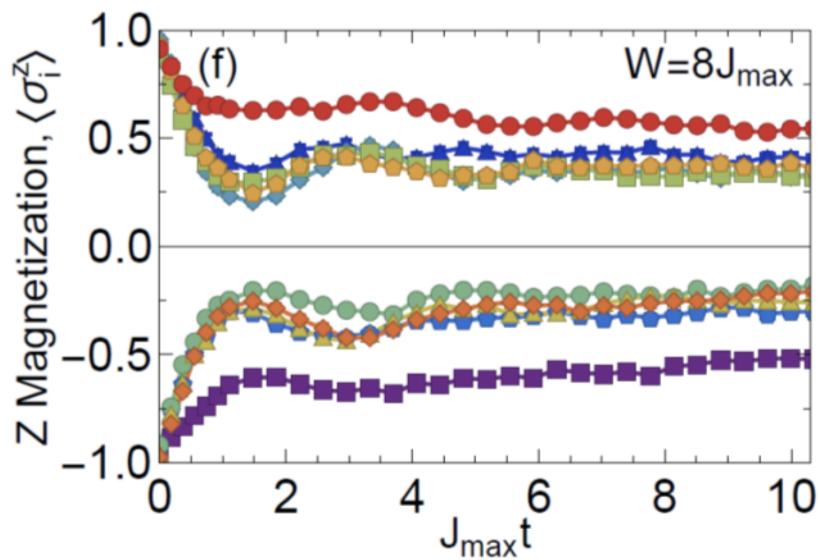
$$H = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B\sum_i \sigma_z^i + \sum_i \tilde{B}_z^i\sigma_z^i \qquad \tilde{B}_z^i \in [-W, W]$$

$$H = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_y\sin(\omega t)\sum_i \sigma_y^i$$

No disorder



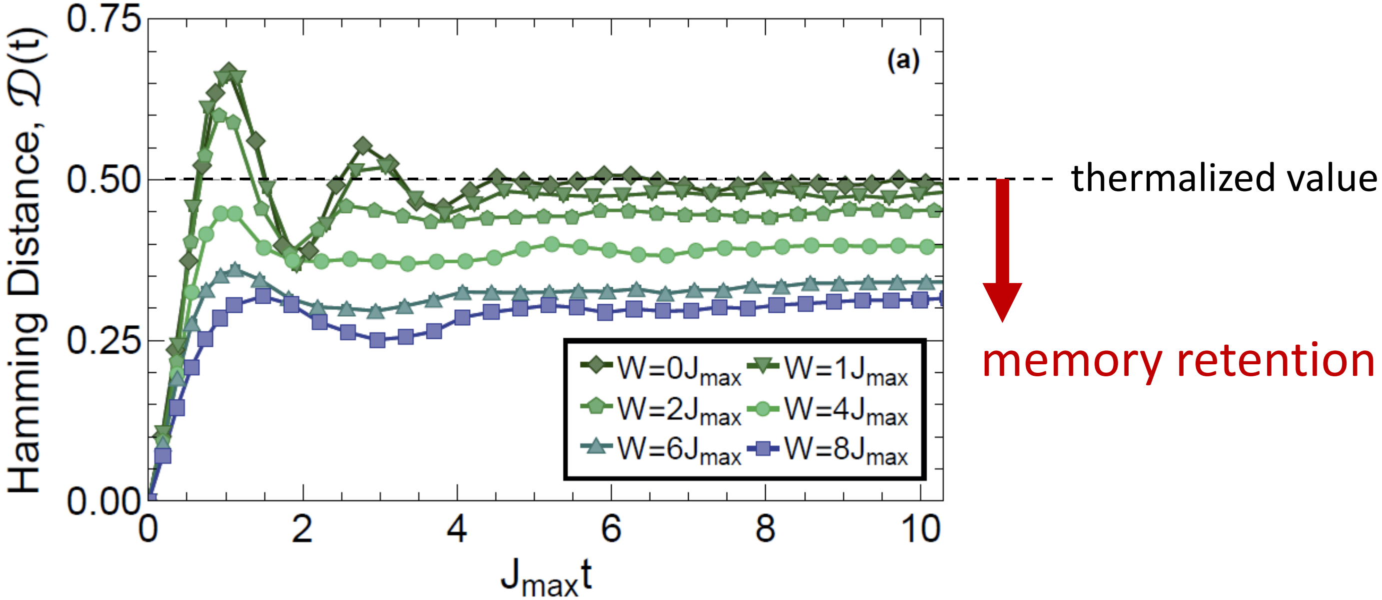
Some disorder



J. Smith et al., ArXiv 1508.07026 (2015)

Hamming distance from initial state:

$$\mathcal{D}(t) = \frac{1}{2} - \frac{1}{2N}\sum_i \langle\psi_0|\,\sigma_i^z(t)\sigma_i^z(0)\,|\psi_0\rangle$$

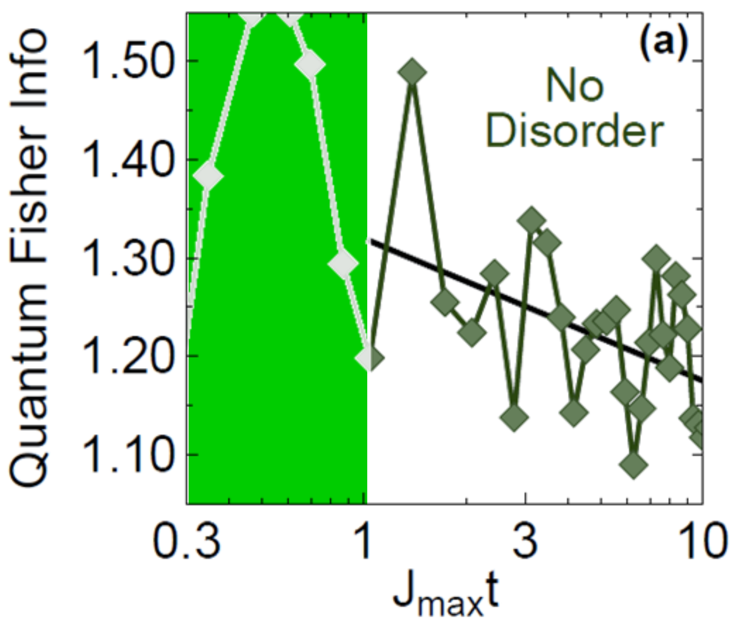


J. Smith et al., ArXiv 1508.07026 (2015)

Quantum Fisher Information: characterizes system entanglement

$$F_Q = 4N^2(\Delta\hat{\mathcal{D}})^2 = \sum_{i,j}[(-1)^{i+j}\langle\sigma_i^z\sigma_j^z\rangle] - [\sum_i(-1)^i\langle\sigma_i^z\rangle]^2$$

Braunstein and Caves Phys. Rev. Lett. 72, 3439 (1994)
Hauke, Heyl, Tagliacozzo, Zoller, arXiv:1509.01739 (2015)



J. Smith et al., ArXiv 1508.07026 (2015)

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

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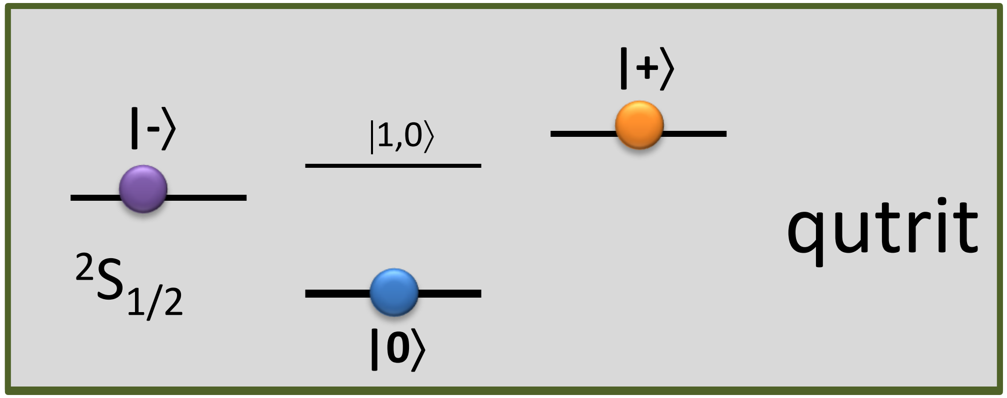
- Prethermalization
- Many-Body Localization

Spin-1

Extending to N~100 spins and beyond

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 $|0\rangle \leftrightarrow |-\rangle$

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

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

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., Phys. Rev. X 5, 021026 (2015)

Trapped Ion Spin Hamiltonian Engineering

Ground states and Adiabatic Protocols

Dynamics

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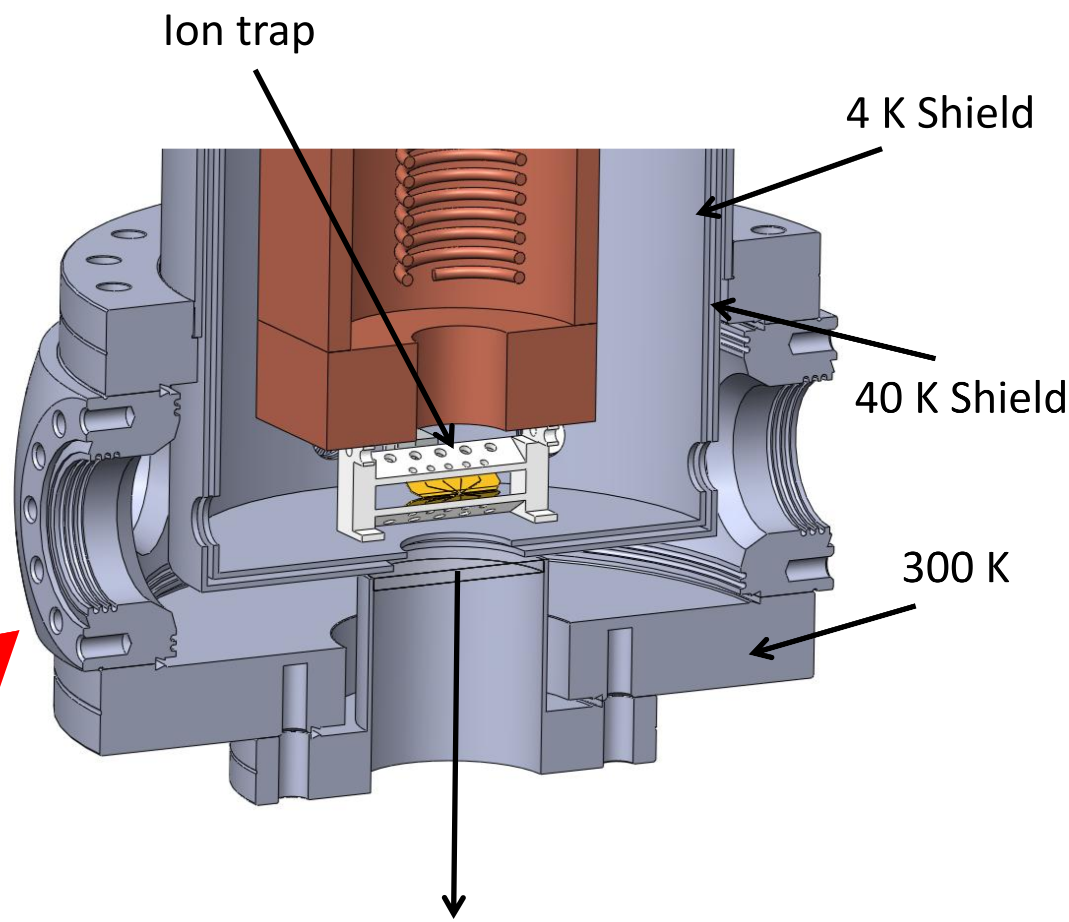
- Prethermalization
- Many-Body Localization

Spin-1

Extending to N~100 spins and beyond

Scaling Up: 4K to get lower pressure

50-100 spins SOON



P. Richerme
P. Hess

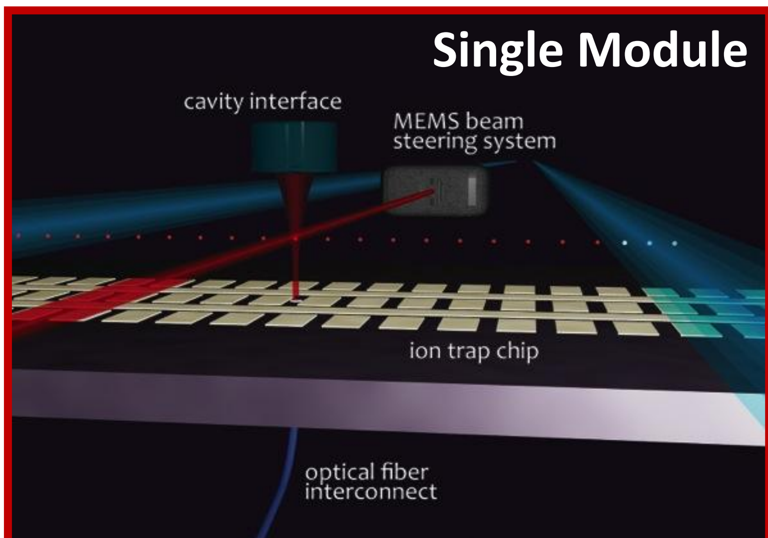
Modular Scaling to 10^6 qubits?

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

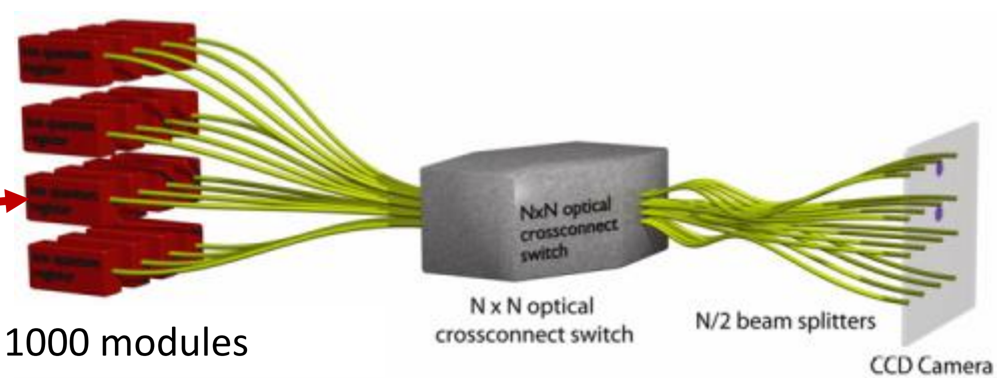
Interconnect of Multiple Such Registers via Photonic Channel

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

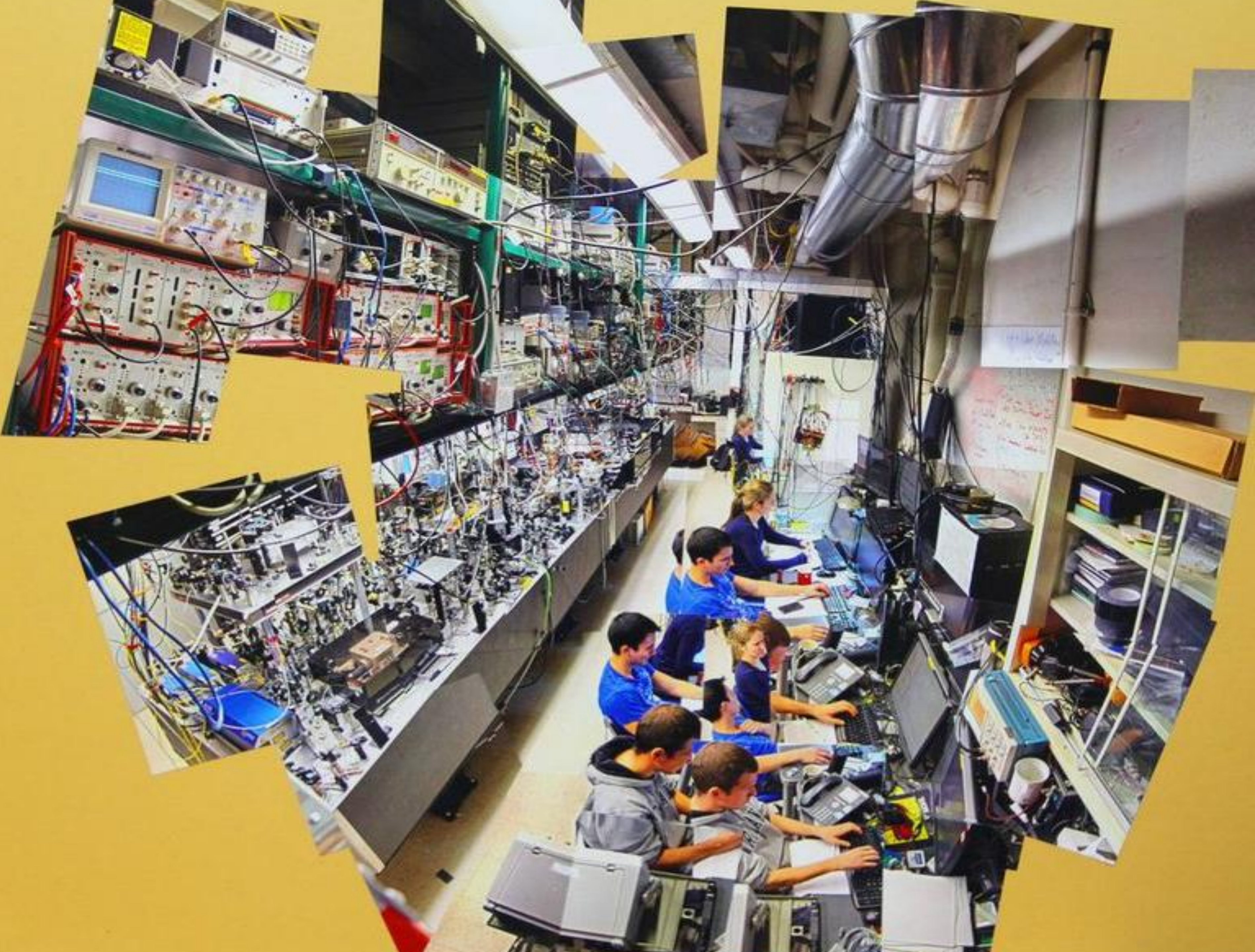


100 qubits / module

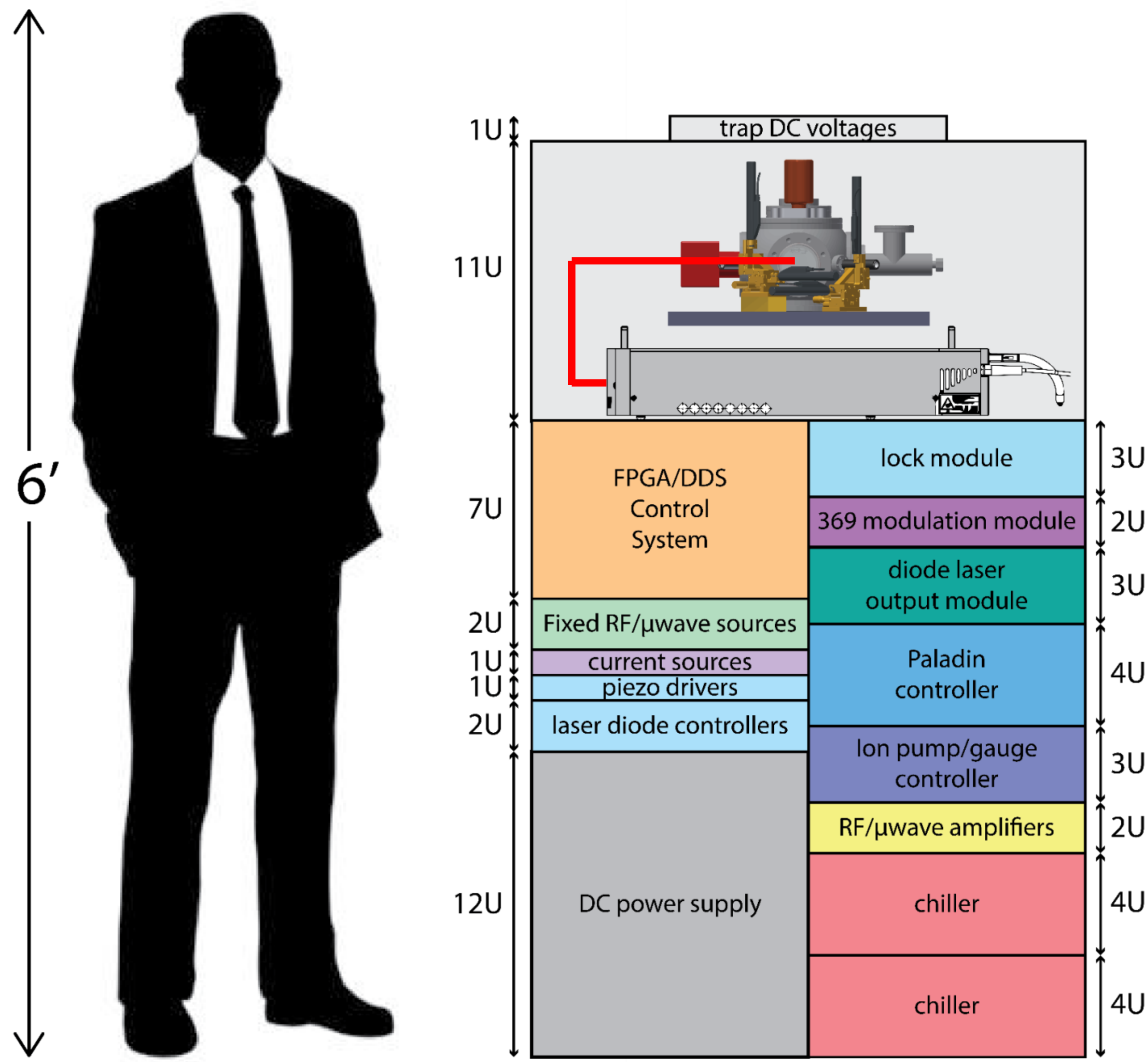
100,000 qubit quantum computer?



1000 modules

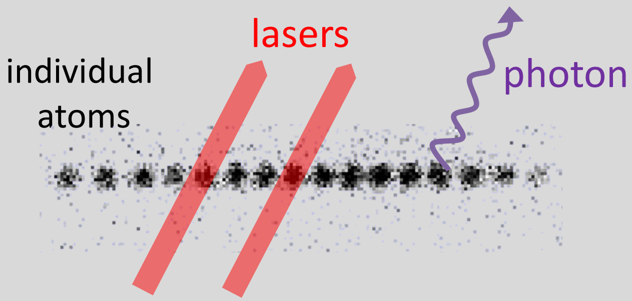


Single Module ~100 spins on 2 × 19” Racks



Leading Quantum Computer Hardware Candidates

Trapped Atomic Ions



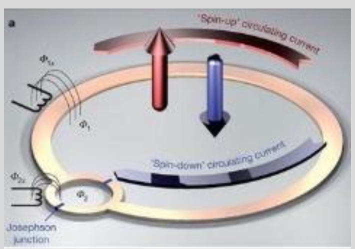
Atomic qubits connected through laser forces on motion or photons

FEATURES & STATE-OF-ART
- very long (>>1 sec) memory
- 5-20 qubits demonstrated
- **atomic qubits all identical**
- **connections reconfigurable**

CHALLENGES
- lasers & optics
- high vacuum
- 4K cryogenics
- **engineering needed**

Investments: IARPA, Lockheed, GTRI, UK Gov't, Sandia

Superconducting Circuits



Superconducting qubit: right or left current

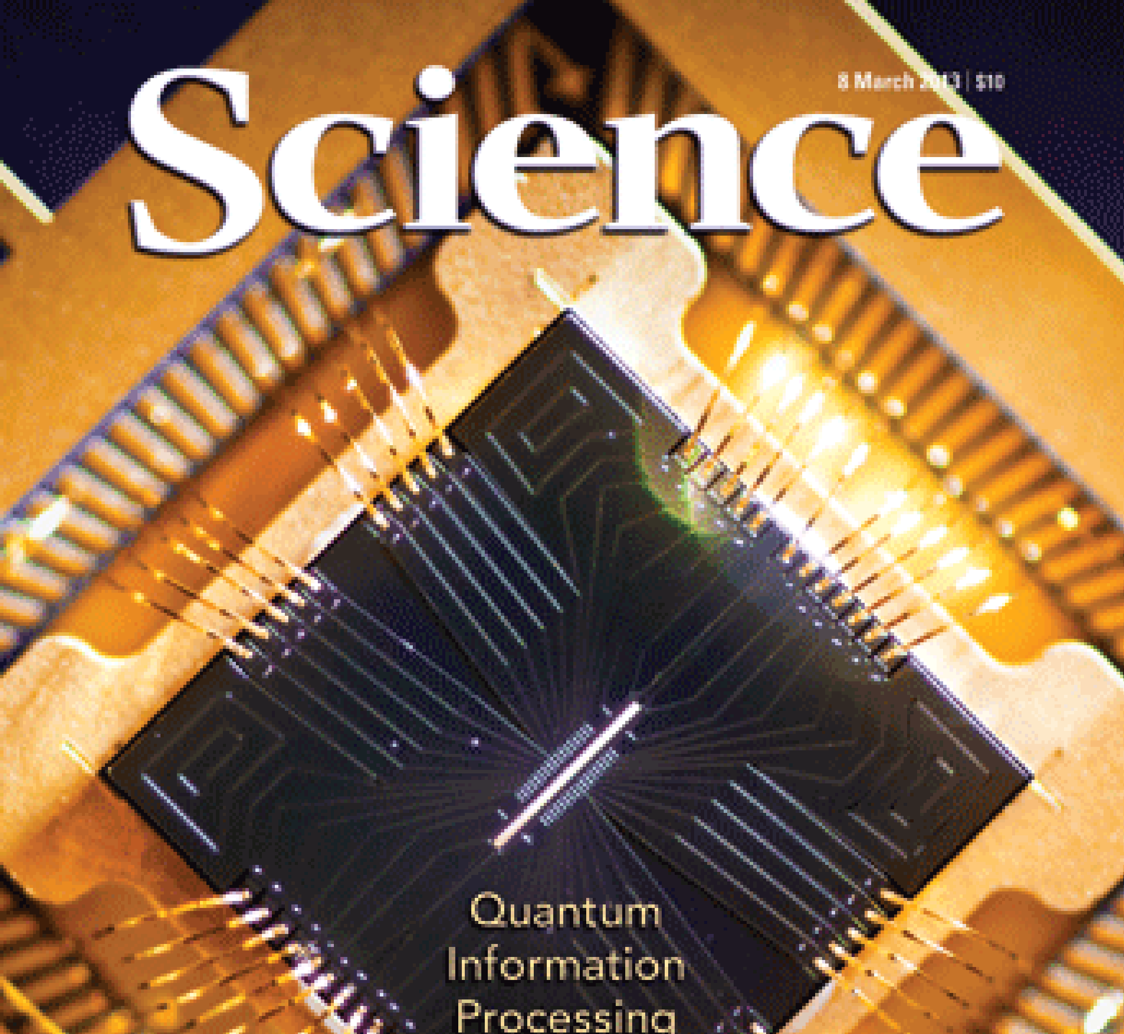
FEATURES & STATE-OF-ART
- connected with wires
- fast gates
- 5-10 qubits demonstrated
- **printable circuits and VLSI**

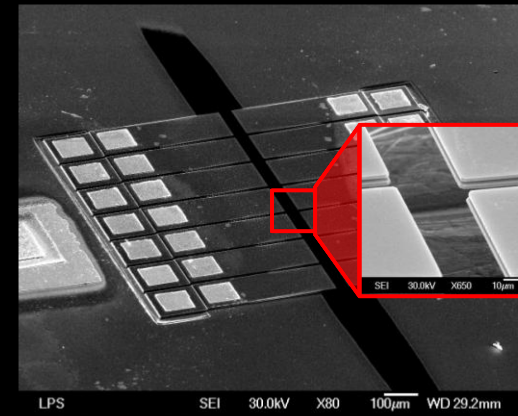
CHALLENGES
- short (10^{-6} sec) memory
- 0.05K cryogenics
- **all qubits different**
- **not reconfigurable**

LARGE Investments: Google/UCSB, IBM, Lincoln Labs, Intel/Delft

Others: still exploratory

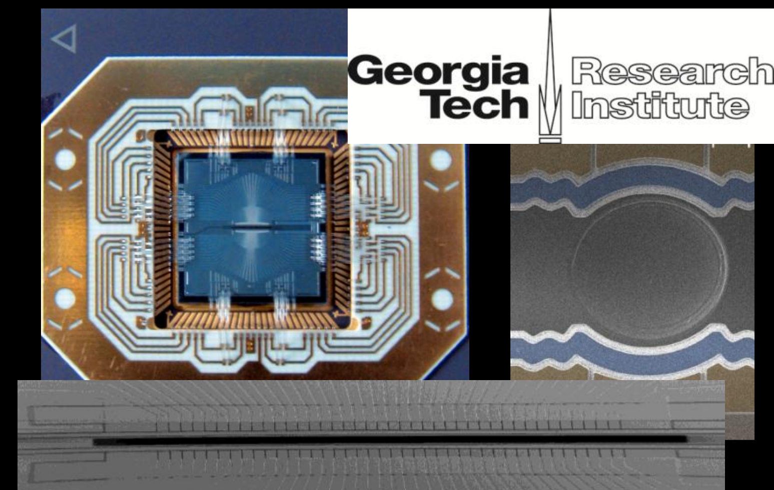
- NV-Diamond
- Semiconductor quantum dots
- Atoms in optical lattices



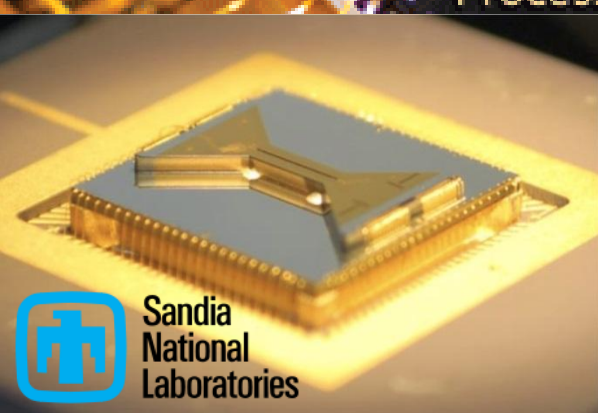


Univ. of Maryland

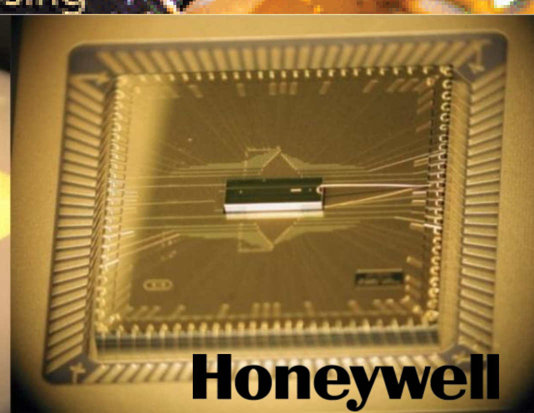
LPS
The Laboratory for Physical Sciences



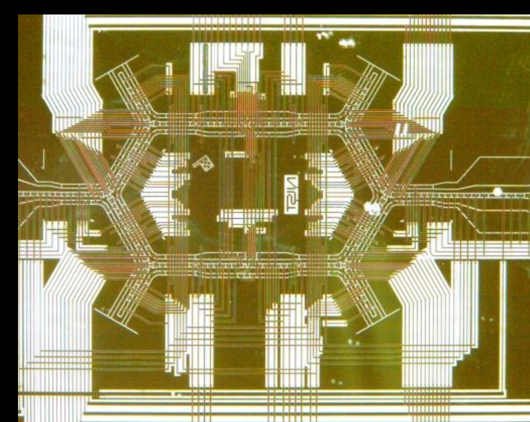
Georgia Tech Research Institute



Sandia National Laboratories



Honeywell



NIST Boulder

T1Q1 Trapped Ion Quantum Information

www.iontrap.umd.edu

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