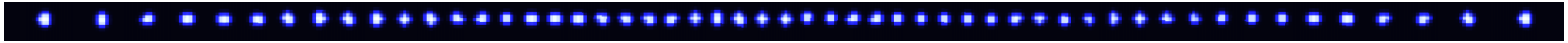
Quantum simulations:
advances in ion spin chains

Jiehang Zhang

Christopher Monroe group,

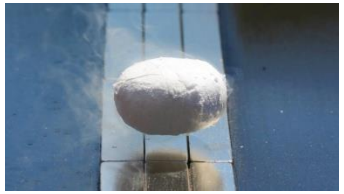
Joint Quantum Institute (JQI) and Department of Physics, University of Maryland

INT workshop, UW Seattle, 2017/11/14

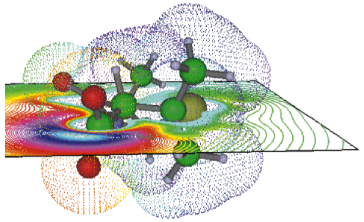


Quantum Simulation

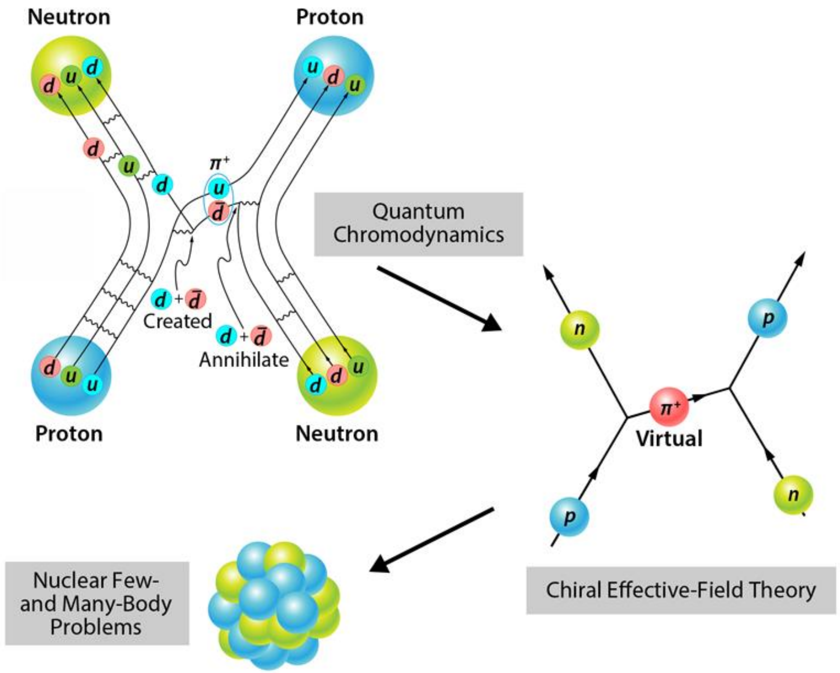
Study complex quantum many-body phenomena



High T_c superconductivity



Quantum Chemistry



Nuclear many-body problems

Quantum Simulation

Classical Algorithms

N spin ½ particles

↕

2^N complex amplitudes

Quantum Simulation

Classical Algorithms

N spin ½ particles

↕

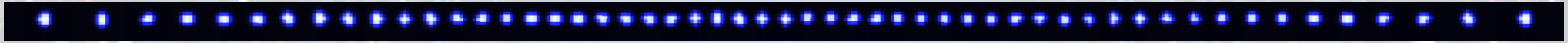
2^N complex amplitudes

Quantum Simulation

N spin ½ particles

↕

N qubits



- **Toolbox**

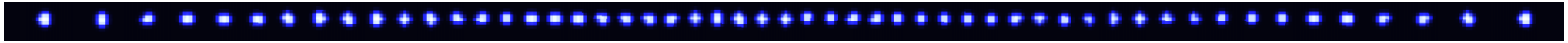
Quantum engineering with atomic ions

- **Non-equilibrium spin dynamics**

50+ qubit quantum simulator

- **Outlook**

Plenty of room at the bottom



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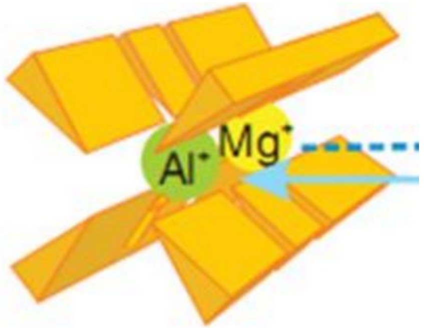
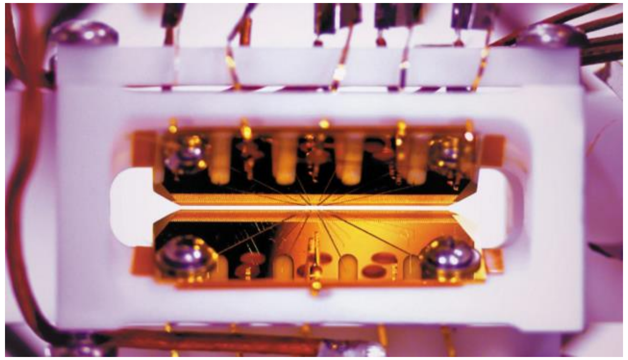
Ion trap quantum information processing

Ion clock
3×10^{-18}
accuracy

Precision measurements

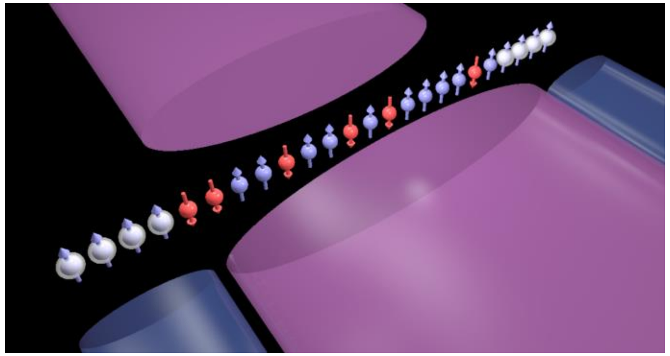


Quantum logic spectroscopy



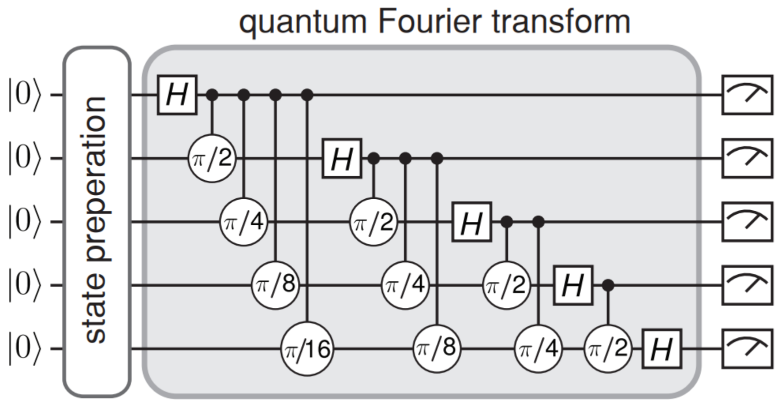
Program-
mable
quantum
gates

Quantum computing:
digital

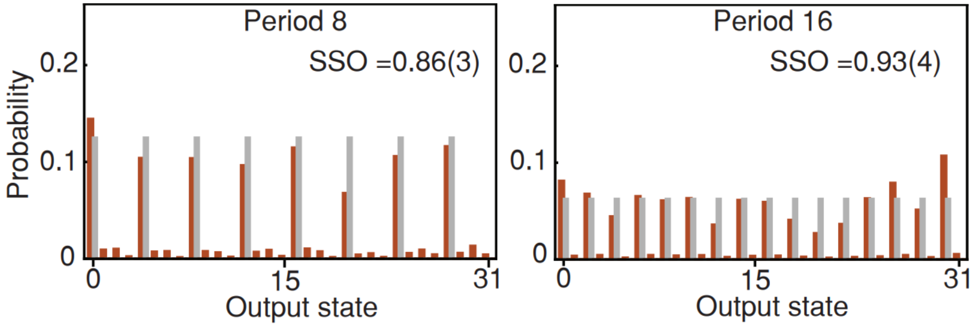


Synthetic quantum matter:
analog

Ion trap quantum information processing

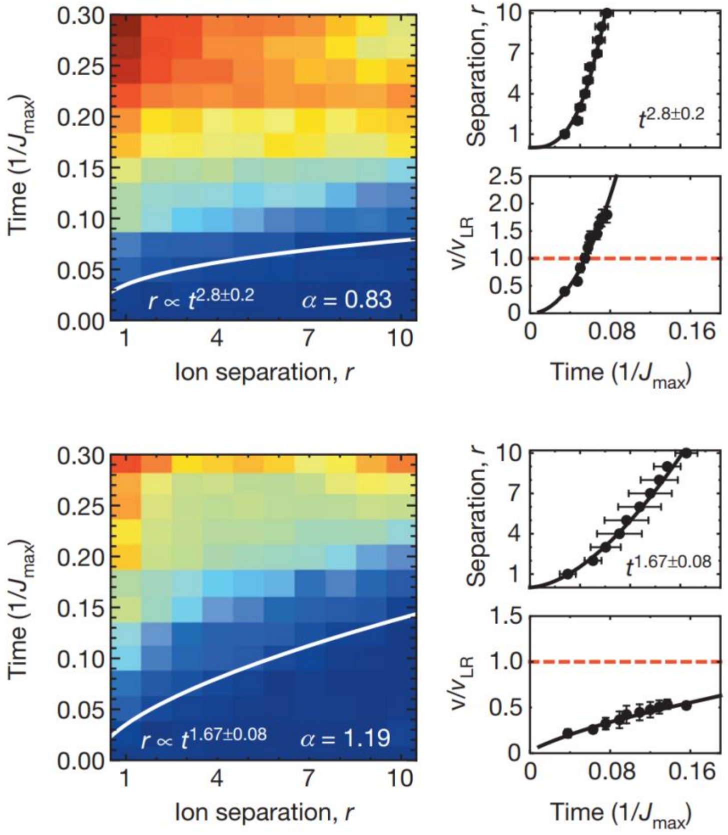


Quantum computing: digital



- Quantum algorithms

S. Debnath, *et al.*, Nature **536**, 63 (2016)



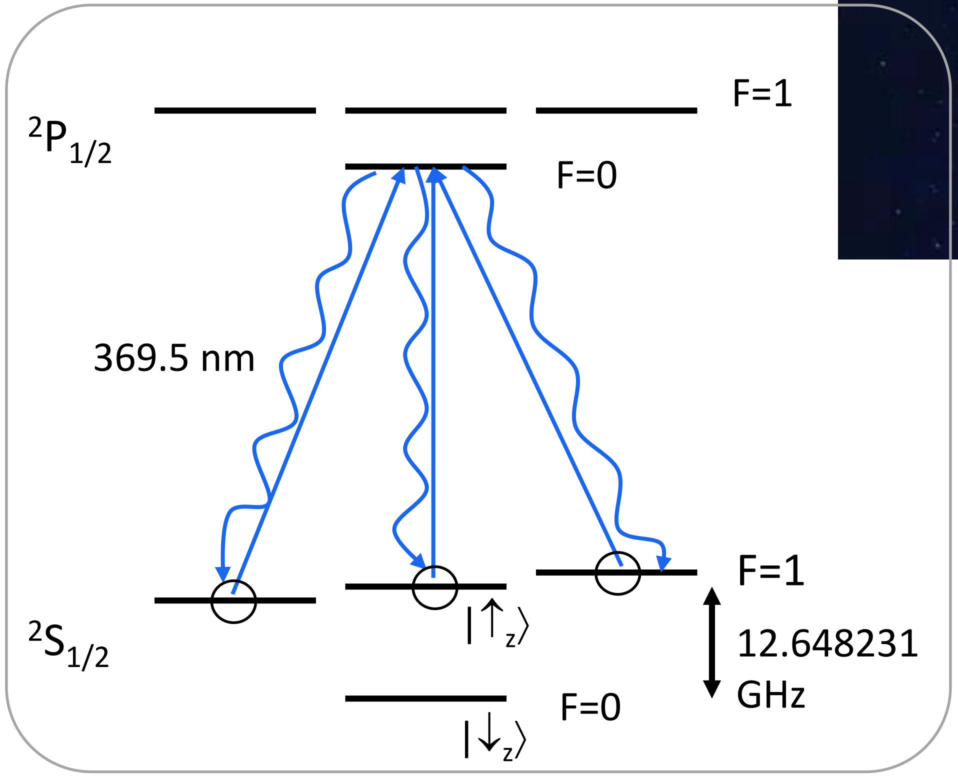
Synthetic quantum matter: analog

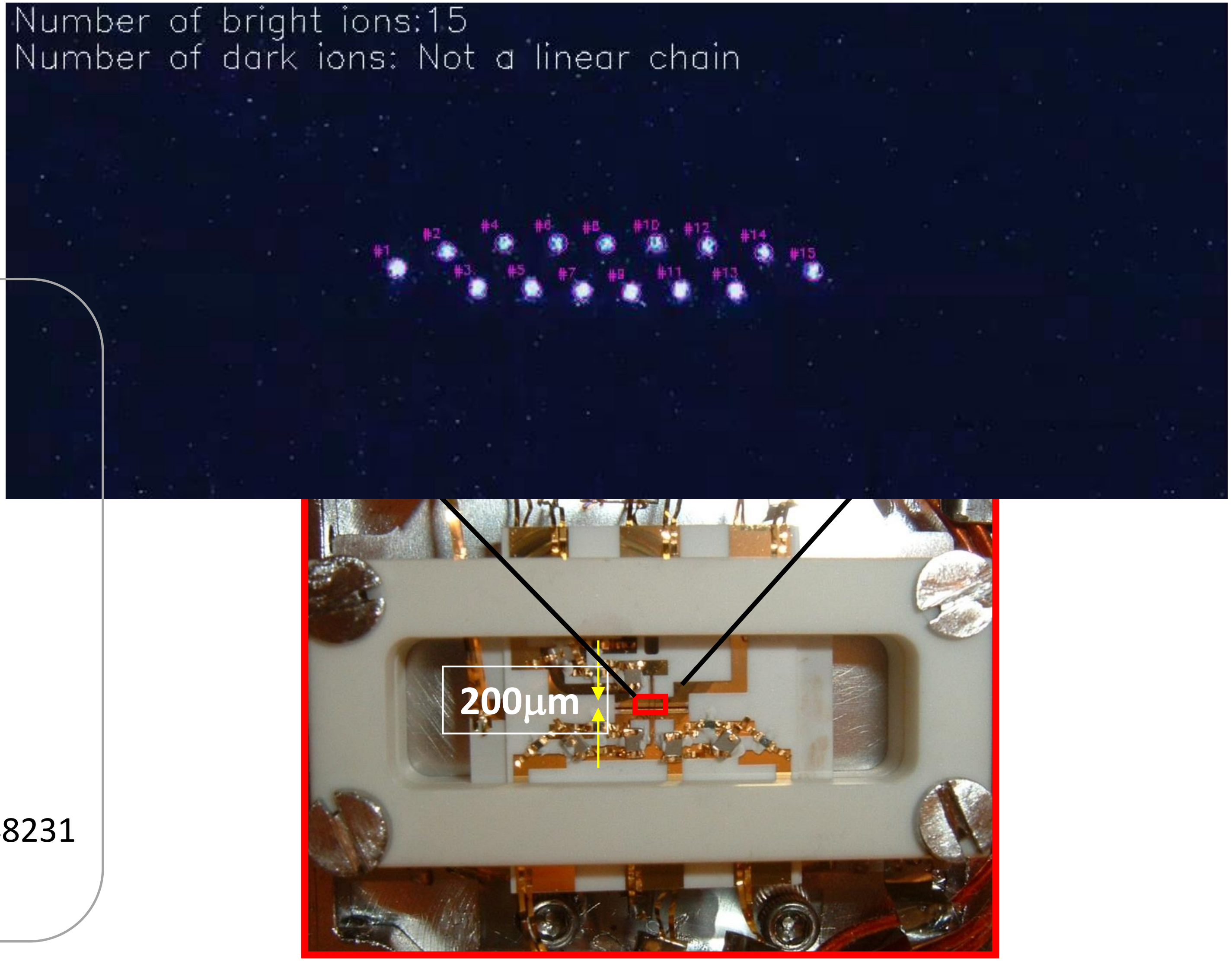
- Correlation propagation

P. Richerme, *et al.*, *Nature* **511**, 198–201 (2014)

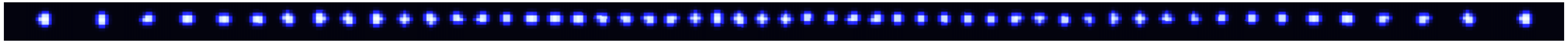
See also work by I. Bloch and R. Blatt groups

$^{171}Yb^{+}$ hyperfine clock qubits.

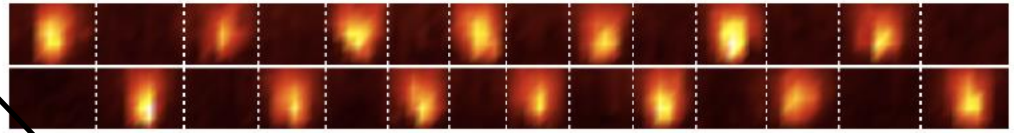




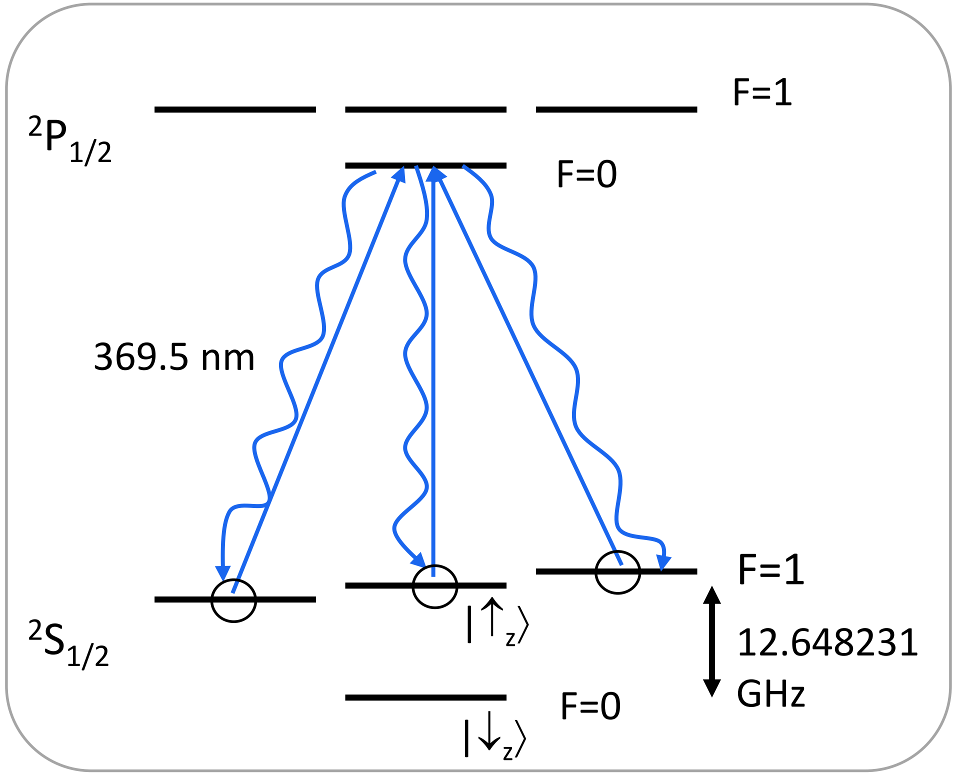
$^{171}Yb^+$ hyperfine clock qubits.

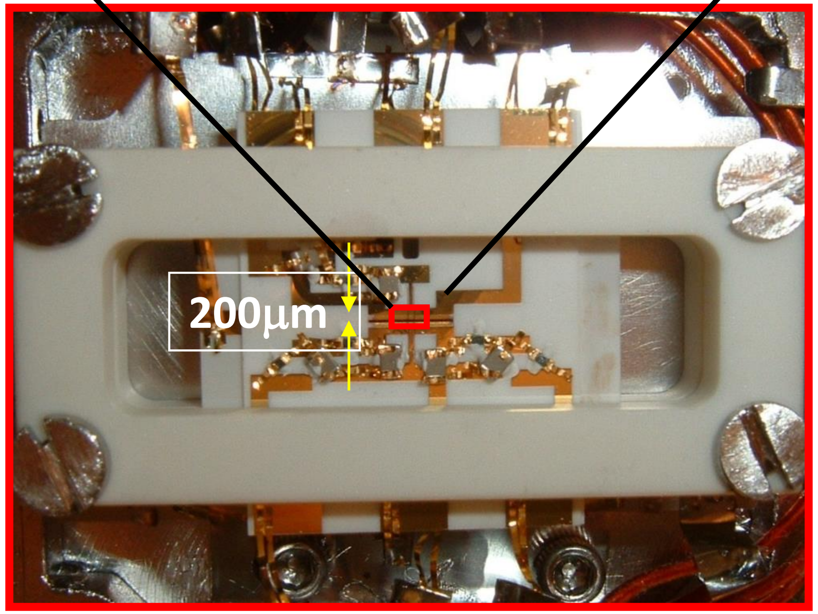


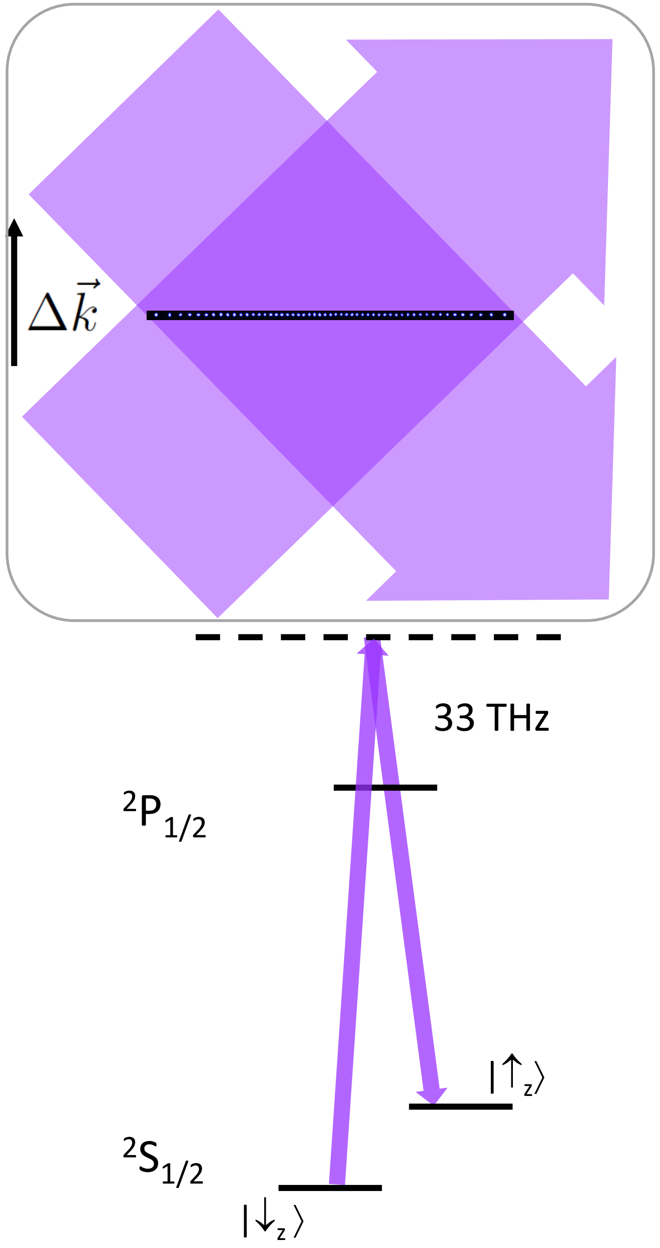
eg: AFM ordering of 14 spins



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







Universal toolbox: Global interactions and individual addressing

Transverse field Ising model

$$H_{\text{eff}} = \sum_{i<j} J_{ij}\sigma_i^x \sigma_j^x + B\sum_i \sigma_i^z + \sum_i D_i\sigma_i^z$$

- Long-range Ising interactions from spin-dependent dipole forces $J_{ij} \approx \frac{J_0}{|i-j|^\alpha}$ $(0 < \alpha < 3)$ J_0~ kHz
- Transverse fields by asymmetric detuning of force
- Individual local field via Stark shifts:

A. C. Lee, JZ, *et al.*, Phys. Rev. A **94**, 042308 (2016)

- Toolbox

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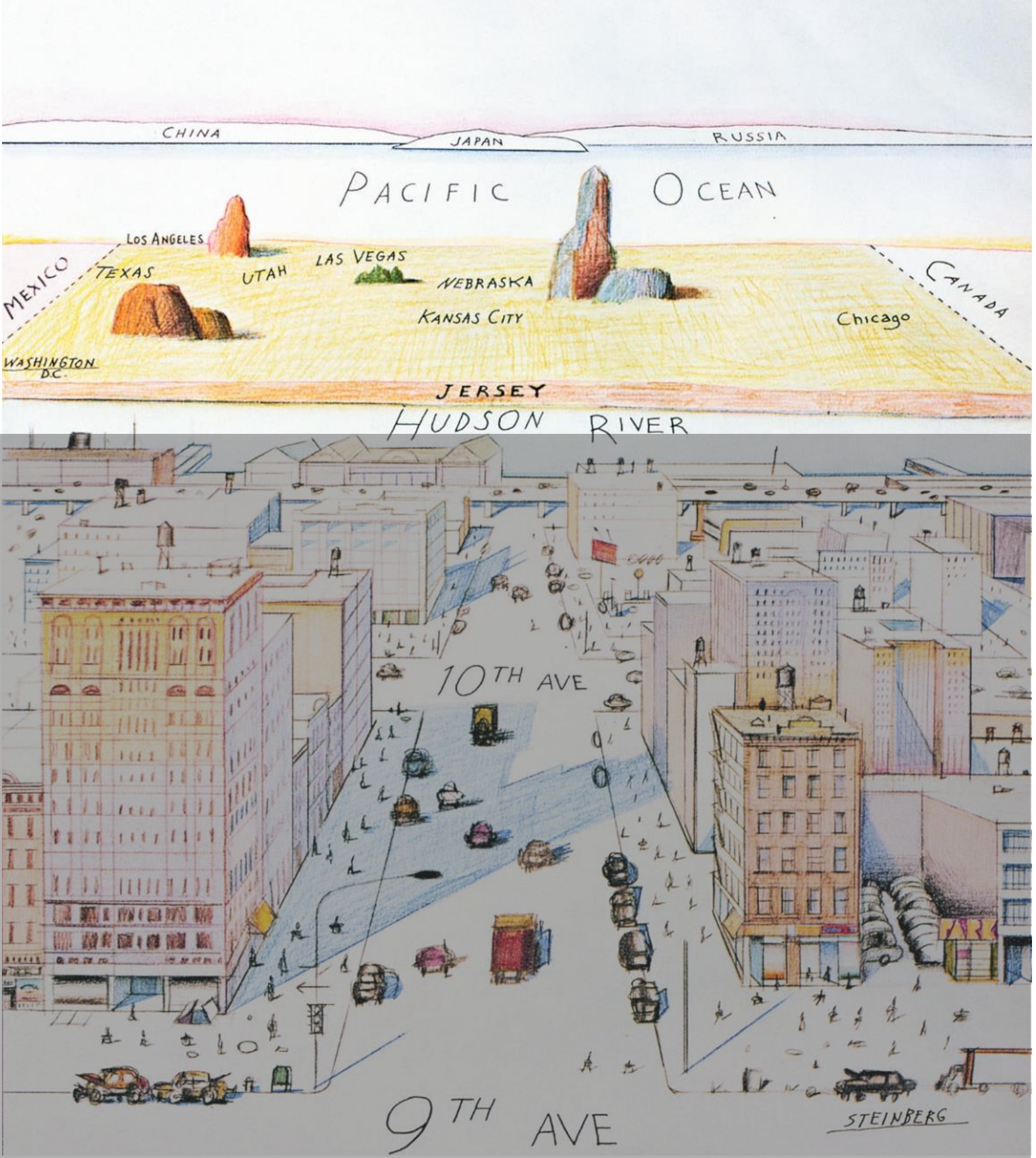
- **Non-equilibrium spin dynamics**

50+ qubit quantum simulator

- Outlook

Plenty of room at the bottom



Non-equilibrium

- Correlation propagation [1]

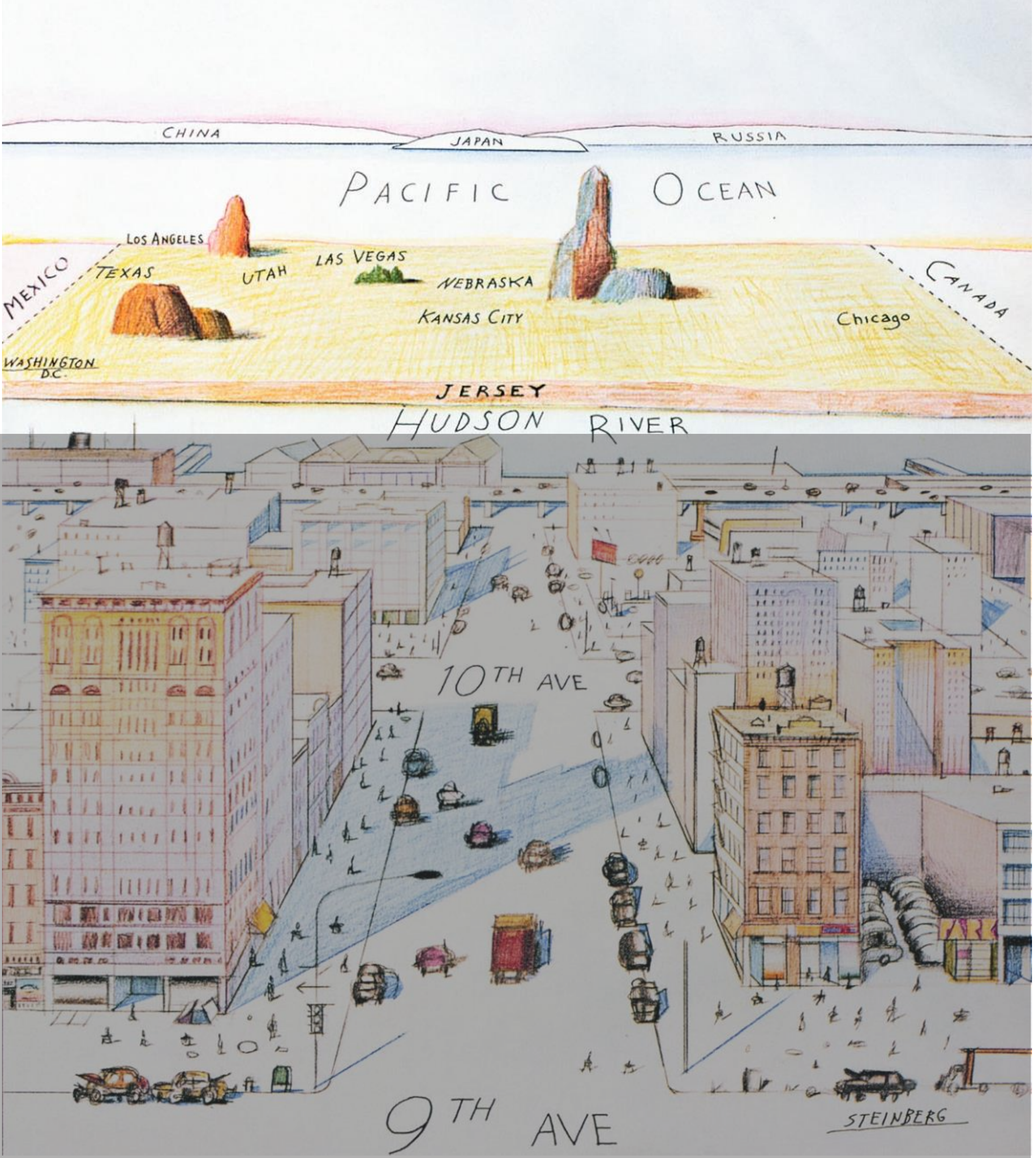
  Lieb-Robinson bounds
- Failures of quantum thermalization [2,3]

  Localization and Prethermalization
- Dynamical phase transition [4]

  50+ qubit quantum simulator
- Discrete time crystal [5]

  A novel driven phase of matter

[1] P. Richerme, *et al.*, *Nature* **511**, 198–201 (2014)
[2] J. Smith, *et al.*, *Nat. Phys.* **12**, 907–911 (2016)
[3] B. Neyenhuis, JZ *et al.*, *Science Advances* **3**(8), e1700672 (2017)
[4] JZ, *et al.*, arXiv 1708.01044 (2017), *Nature*, in press
[5] JZ *et al.*, *Nature* **543**, 217–220 (2017)



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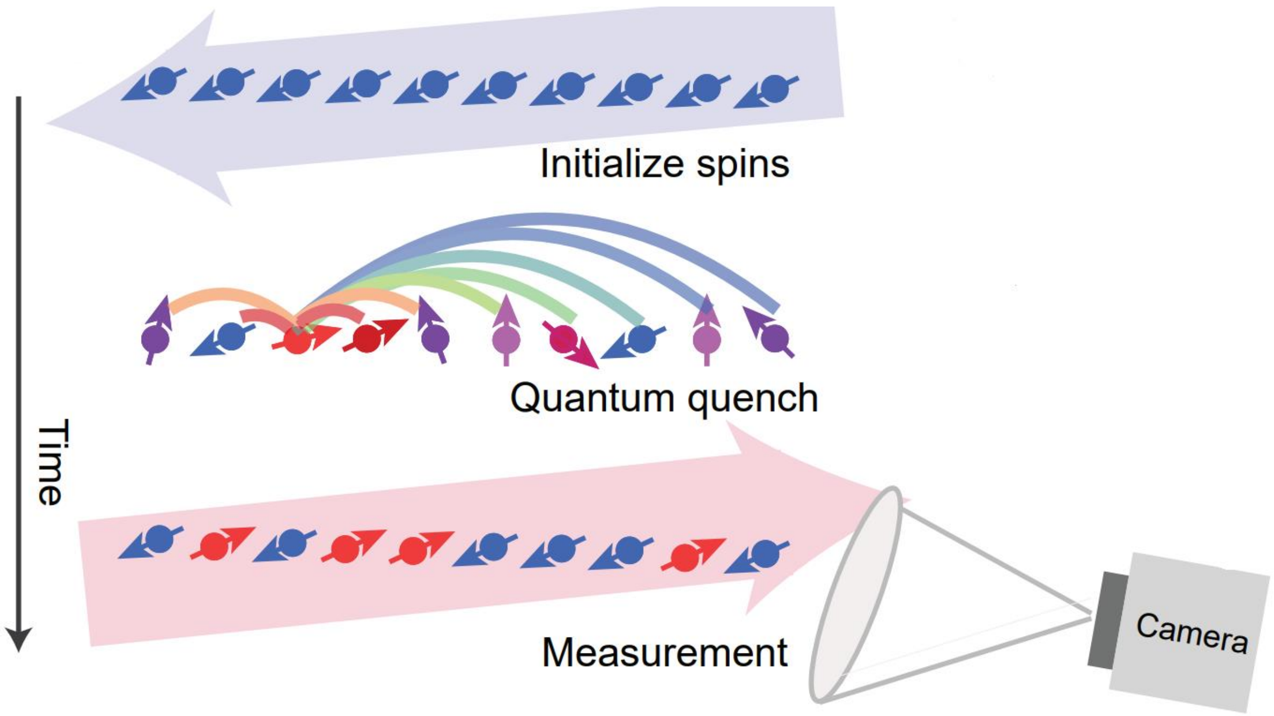
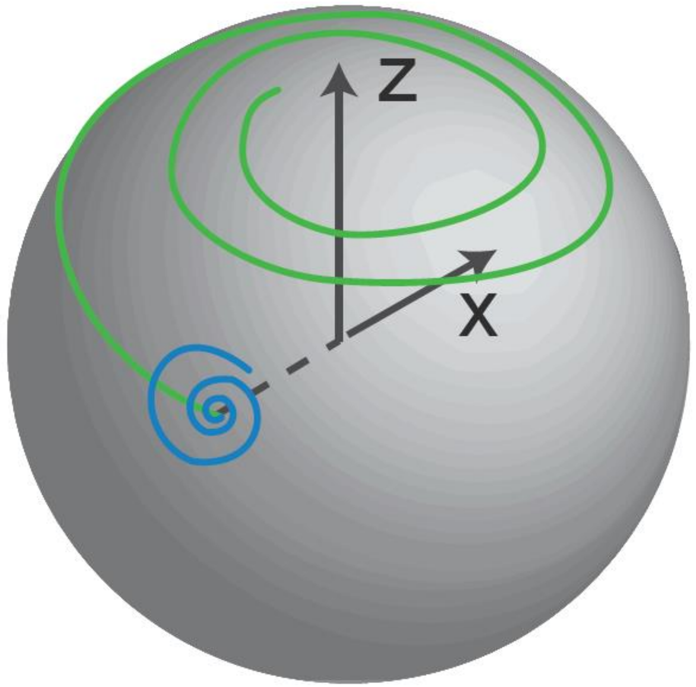
Dynamical phase transition

$$H = \sum_{i<j} J_{ij}\sigma_i^x \sigma_j^x + B \sum_i \sigma_i^z$$





J. Zhang *et al.*, arXiv 1708.01044 (2017), Nature, in press

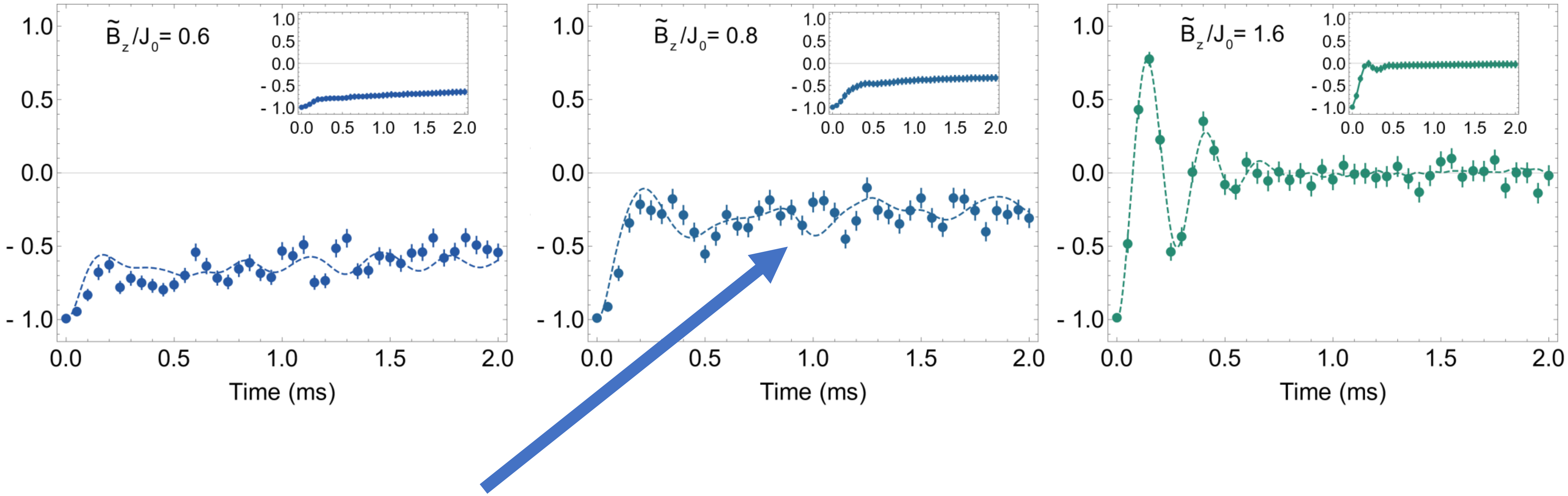
Evolution up to $(2\pi J_0)t \sim 5$ for different transverse field strengths

(N=16 spins, α ≈ 0.8)

$$H = \sum_{i<j} J_{ij}\sigma_i^x \sigma_j^x + B \sum_i \sigma_i^z$$

Average magnetization

$$\frac{1}{N}\sum_i \langle \sigma_i^x \rangle$$

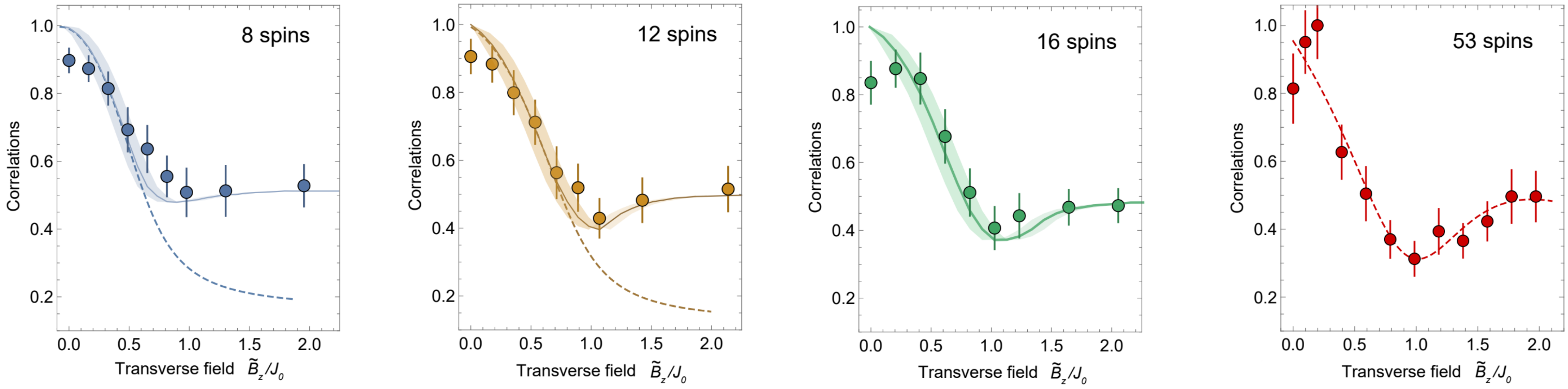


Plateau!

J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Dynamical phase transitions:

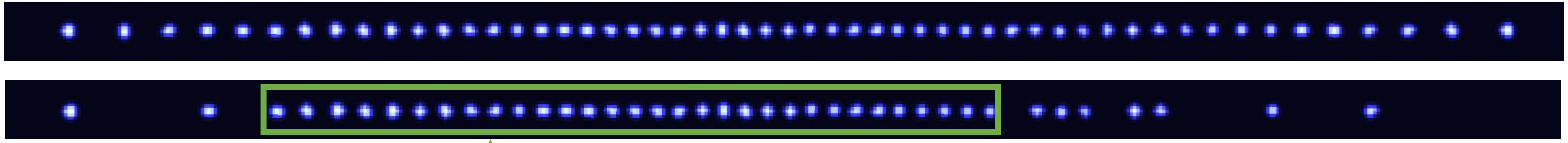
Second order correlations $\frac{1}{N^2}\sum_{i,j}\langle\sigma_i^x\sigma_j^x\rangle$

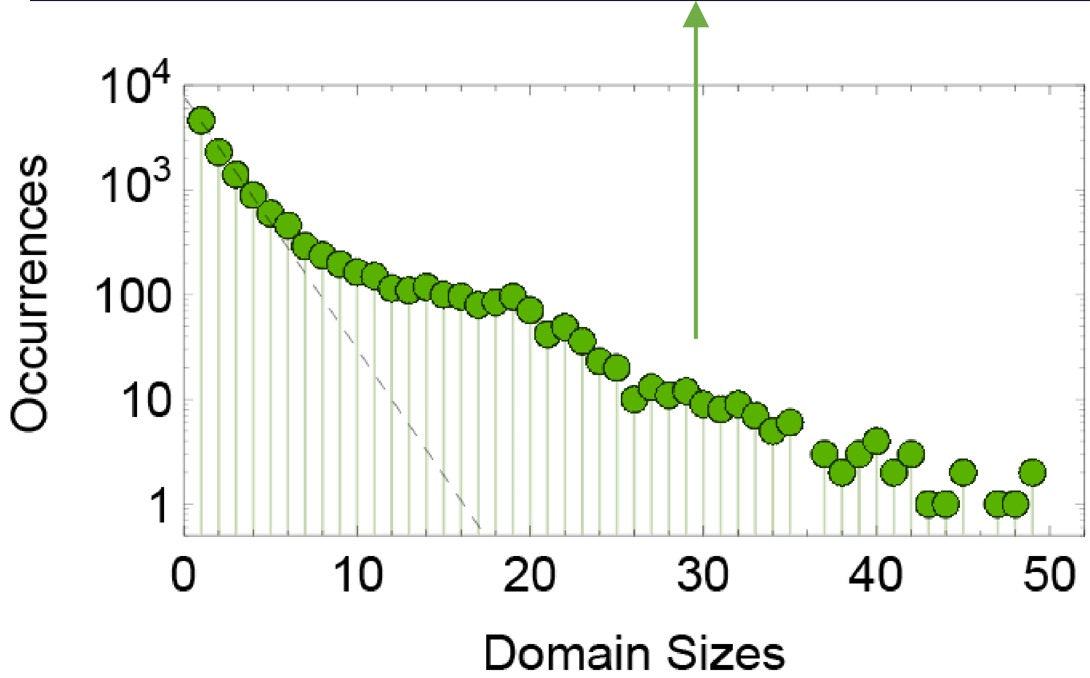


J. Zhang *et al.,* arXiv 1708.01044 (2017),
Nature, in press

Post-quench domain distributions.

Initial state:



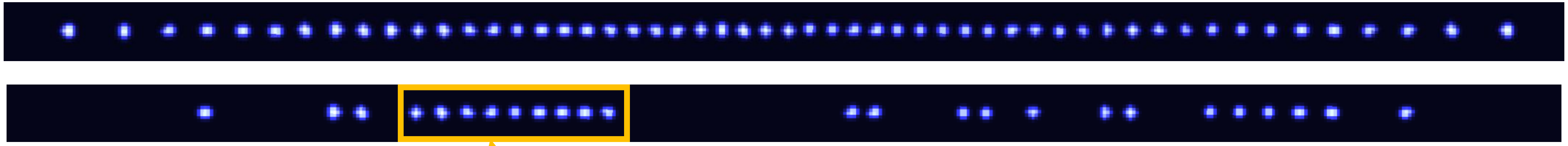


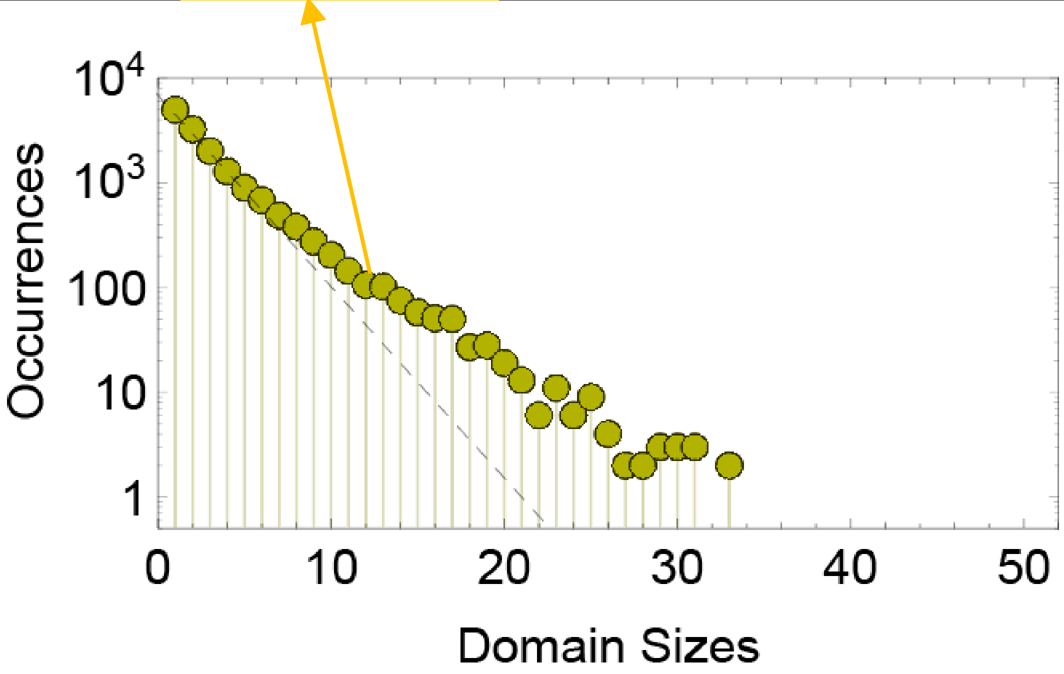
$\tilde{B}_z/J_0 = 0.1$

J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Post-quench domain distributions.

Initial state:



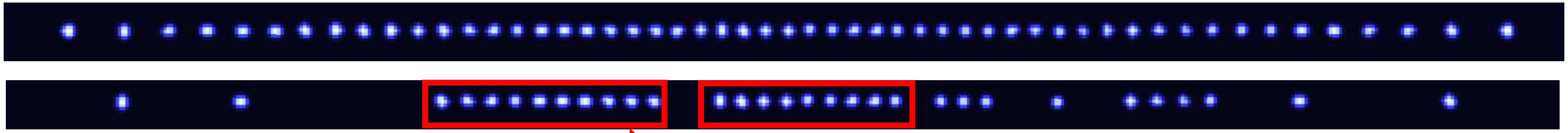


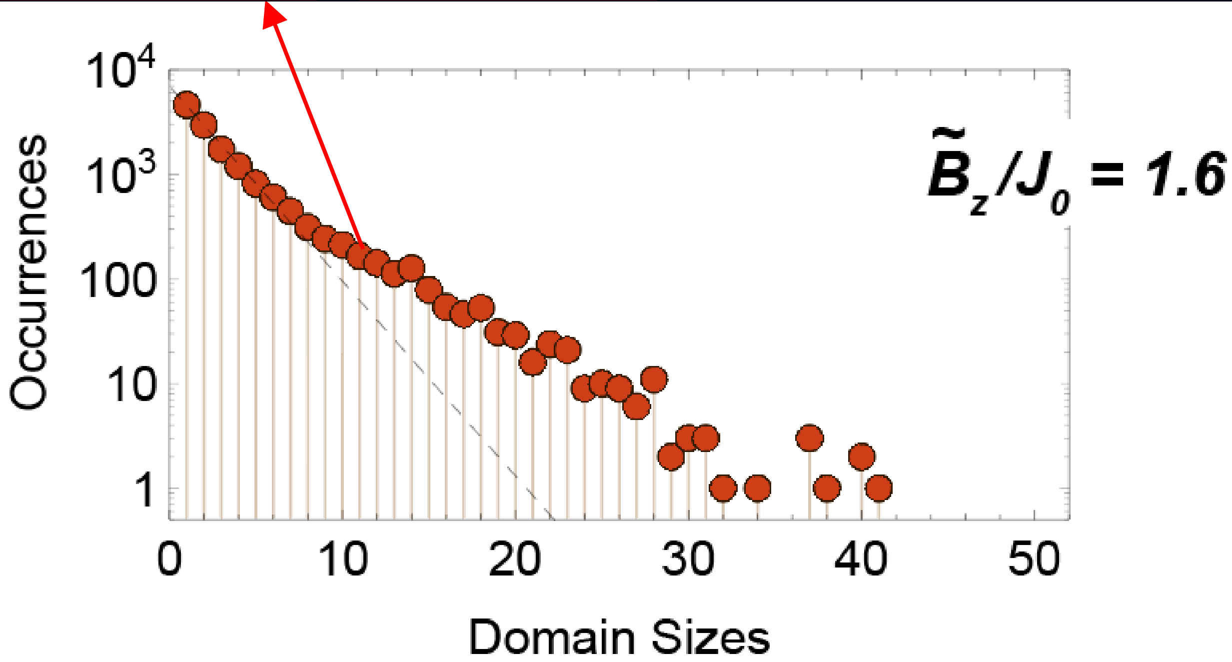
$\tilde{B}_z/J_0 = 1.0$

J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Post-quench domain distributions.

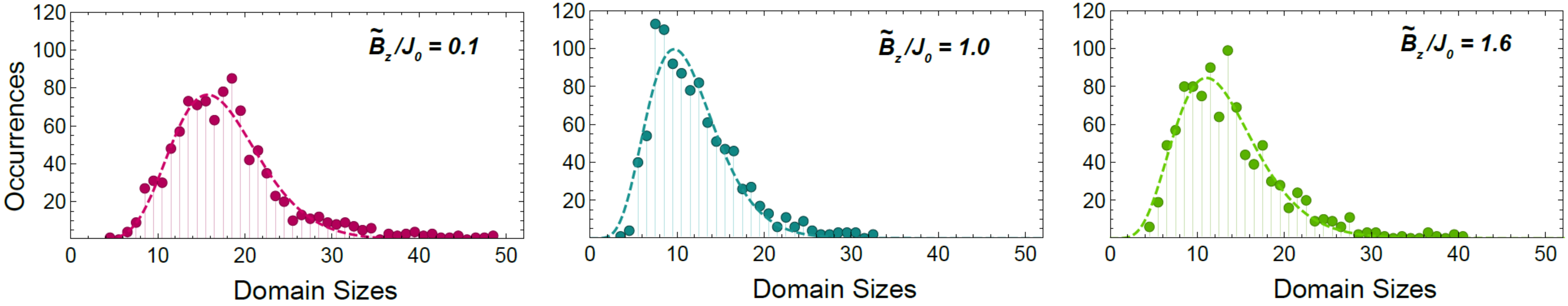
Initial state:





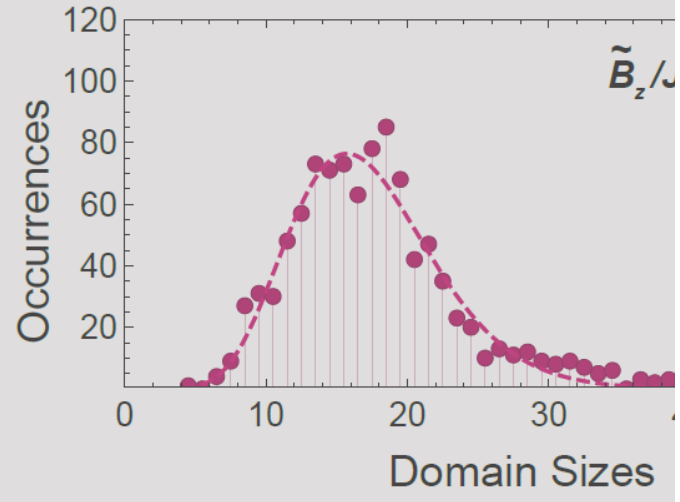
J. Zhang *et al.*, arXiv 1708.01044 (2017), Nature, in press

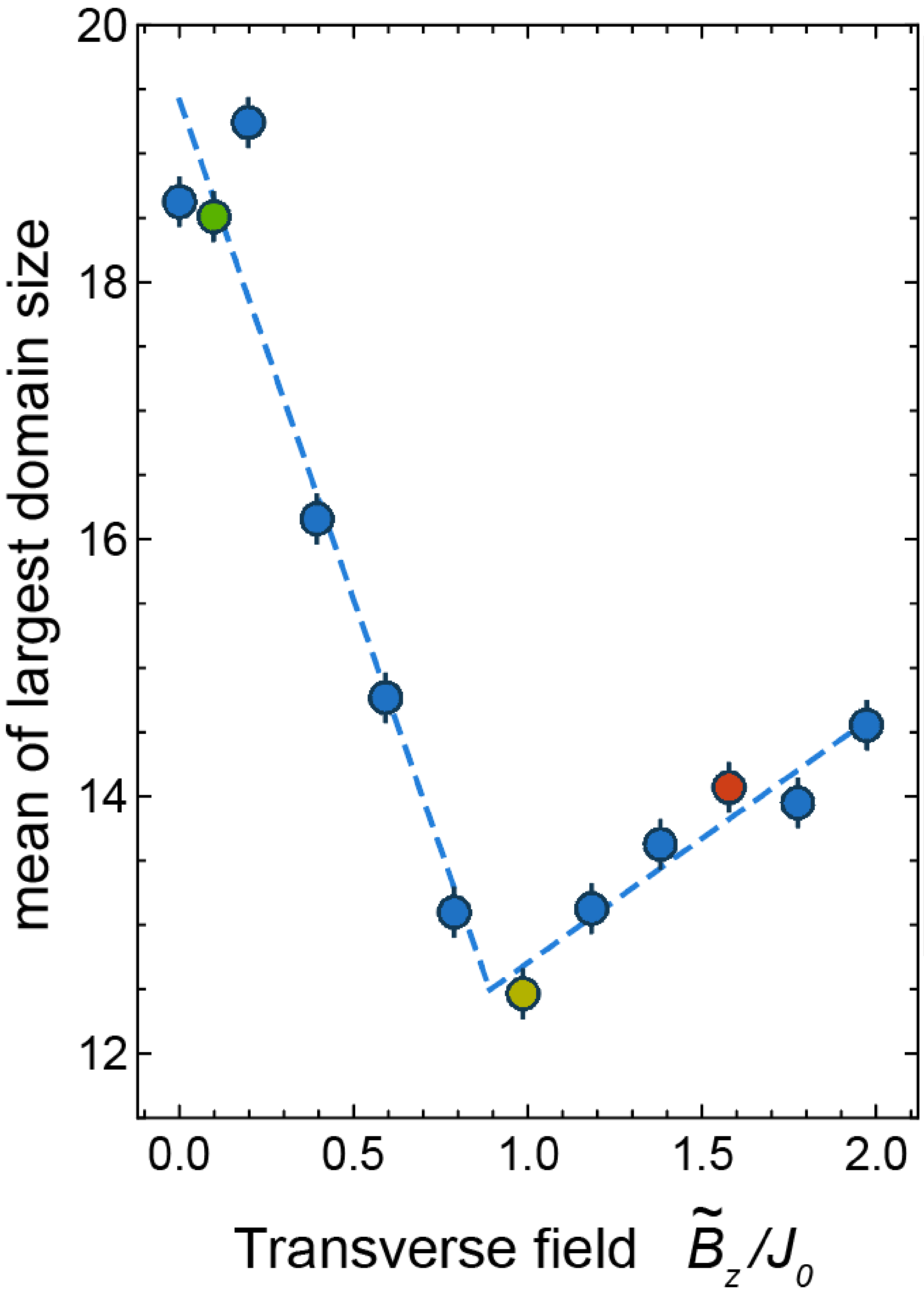
Distribution of large domains

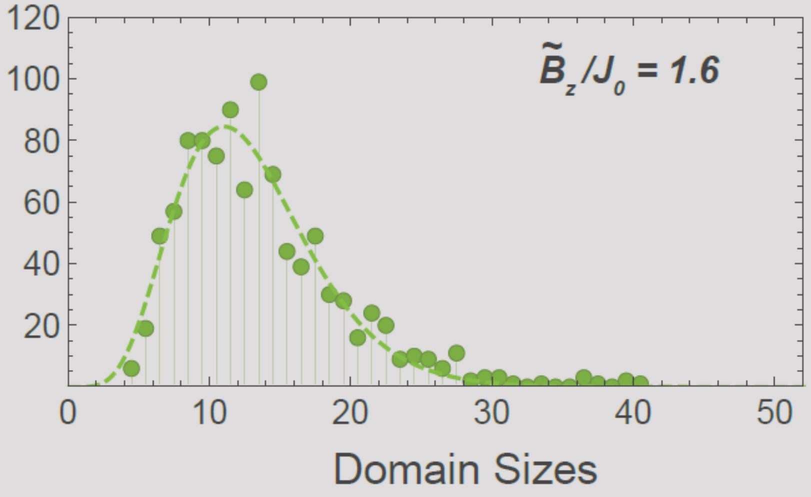


J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Distributio







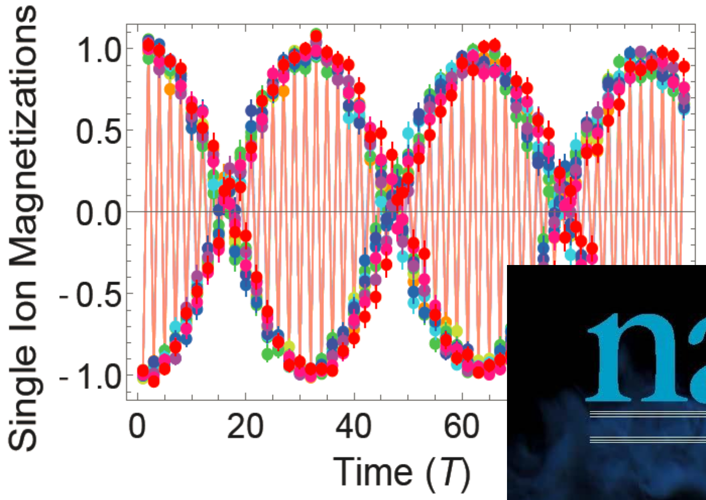
J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Analog-digital mixed approach

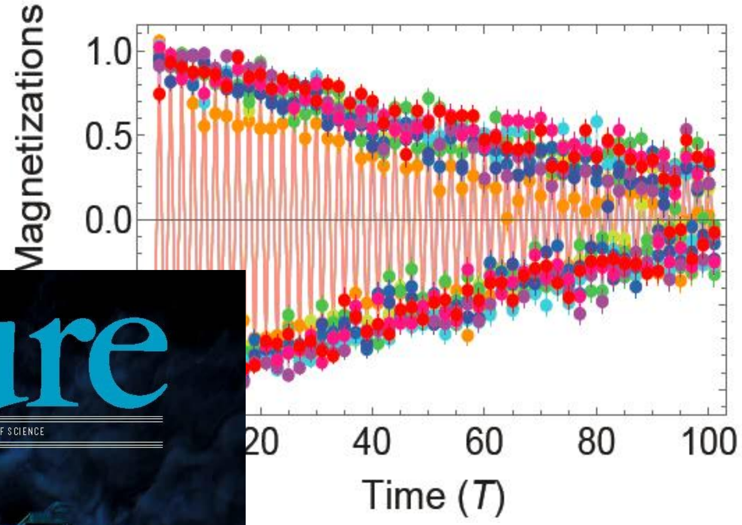
$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x \sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i \sigma_i^x & \text{time } t_3 \end{cases}$$

Analog-digital mixed approach

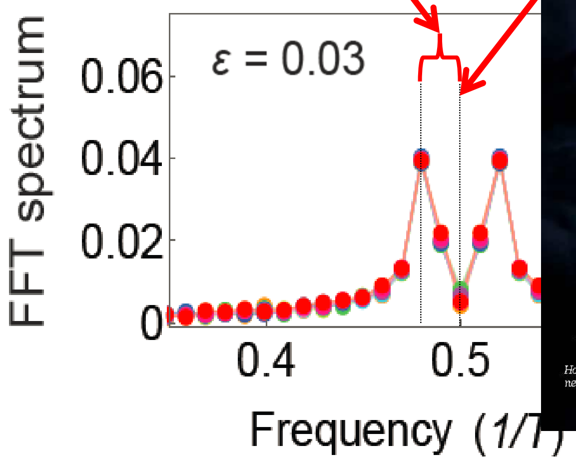
No Interactions (H_2) or Disorder (H_3)



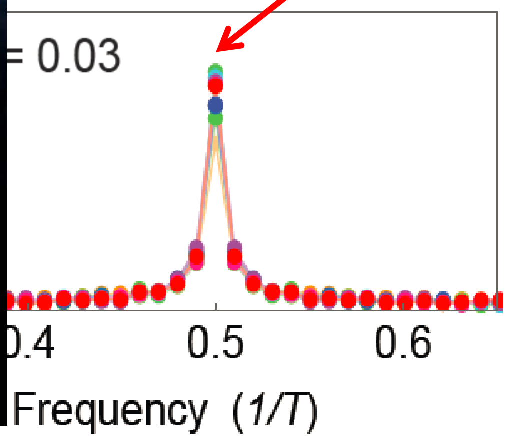
Many-body localization and interactions stabilizes time crystal



Fourier Peak Shifts by ε



$\omega = \frac{1}{2T}$



- **Toolbox**

Quantum engineering with atomic ions

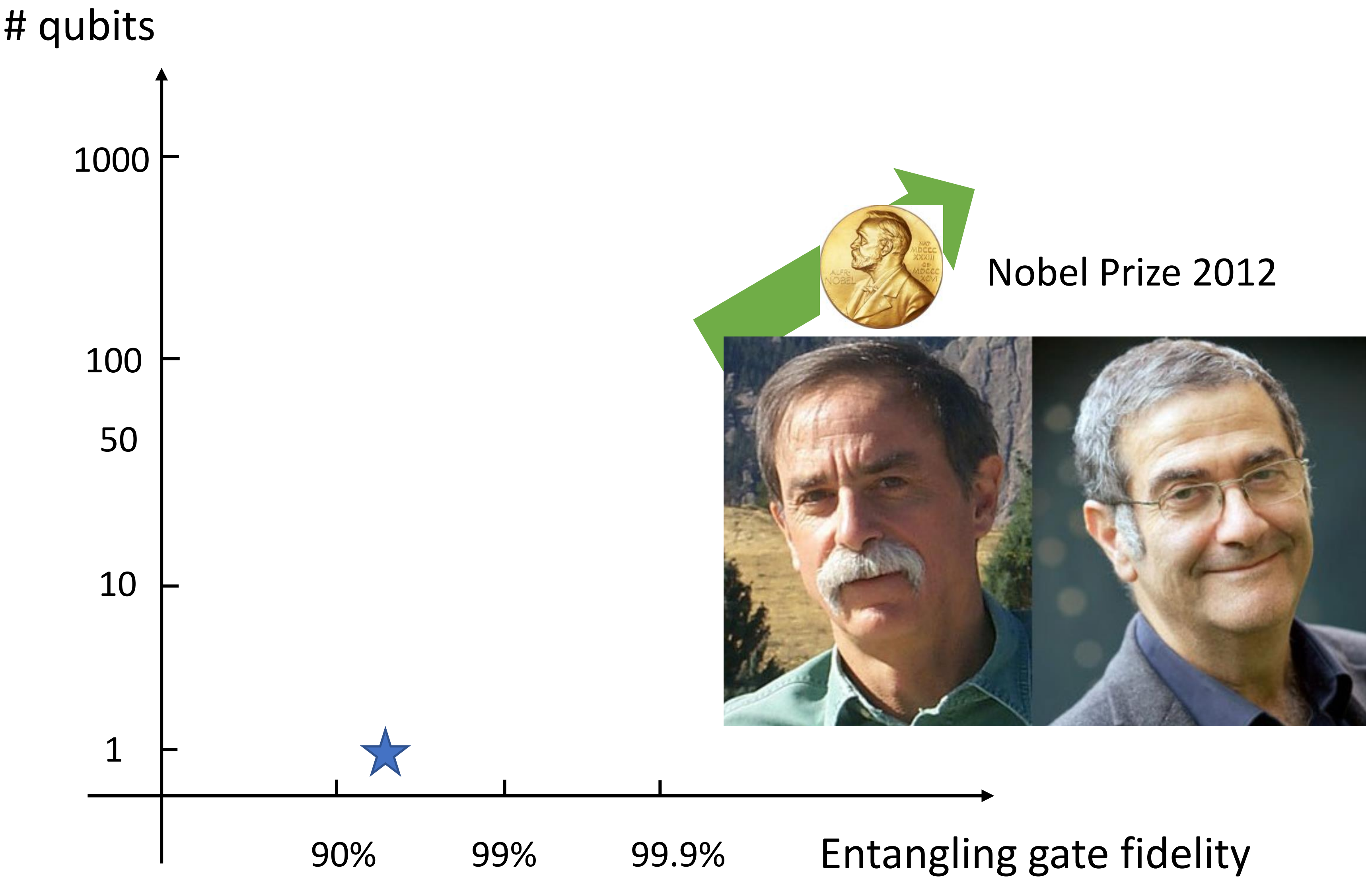
- **Non-equilibrium spin dynamics**

50+ qubit quantum simulator

- **Outlook**

Plenty of room at the bottom

Need both complexity and precision



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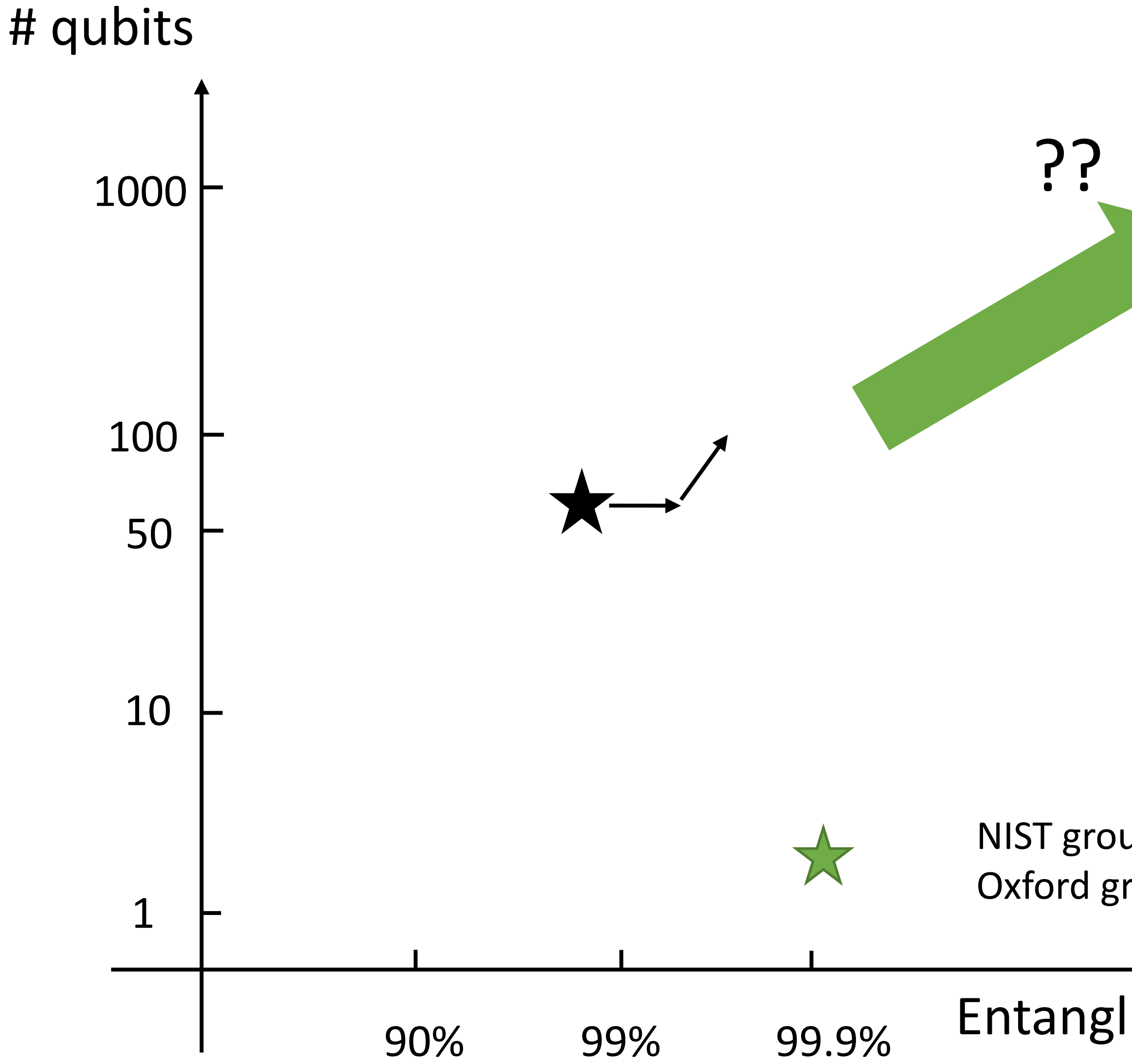
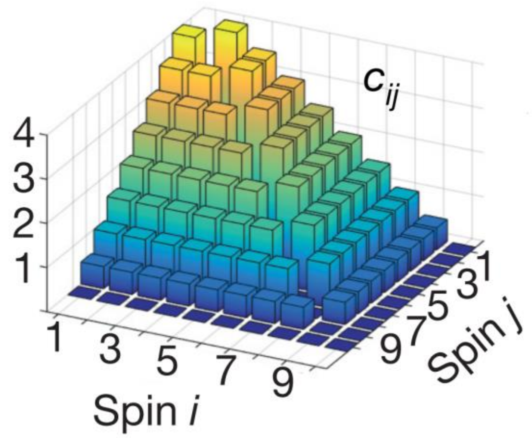


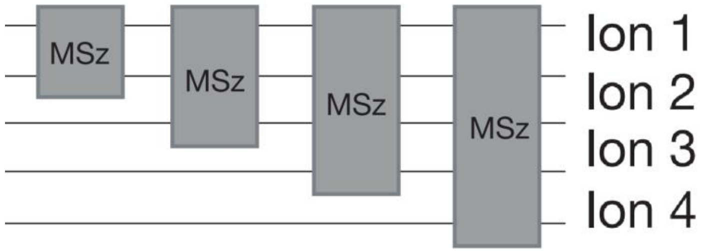
NIST group: J. P. Gaebler, *et al.*, Phys. Rev. Lett. **117**, 060505 (2016)
Oxford group: C. J. Balance, *et al.*, Phys. Rev. Lett. **117**, 060504 (2016)

How can we encode particle and nuclear physics?

Lattice gauge theories

Non-Abelian??





Blatt group: 1D QED
E. A. Martinez, et al., Nature **534**, 516 (2016)

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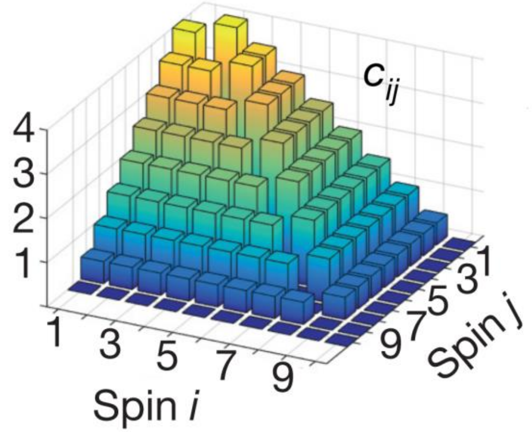
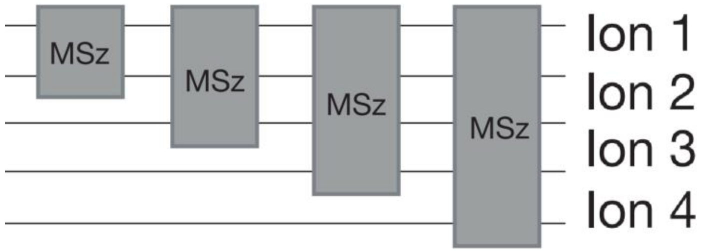
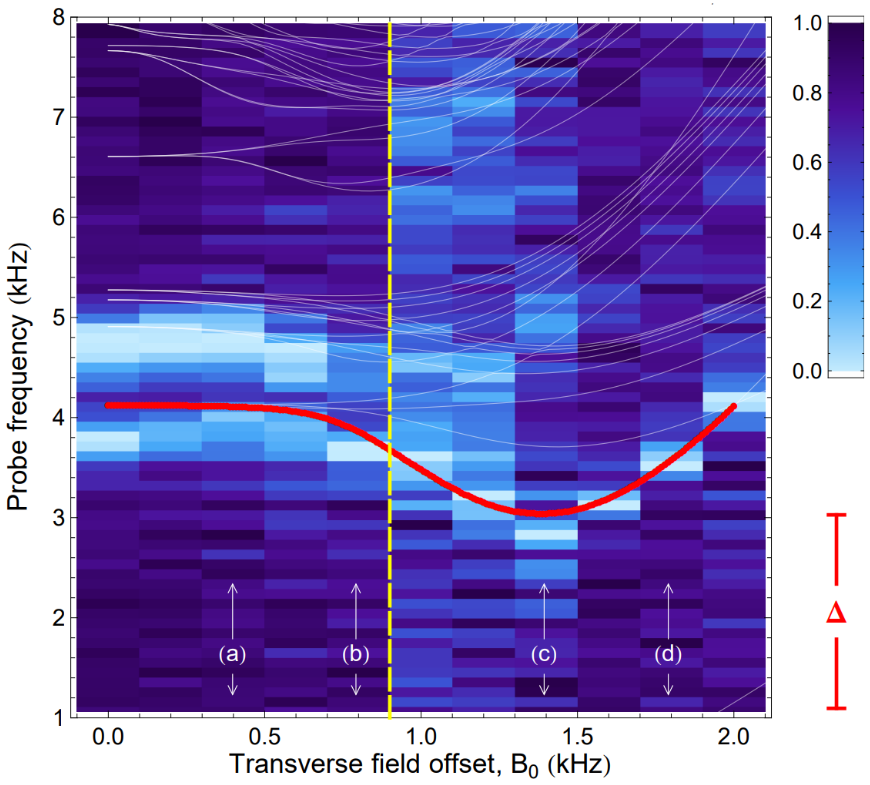




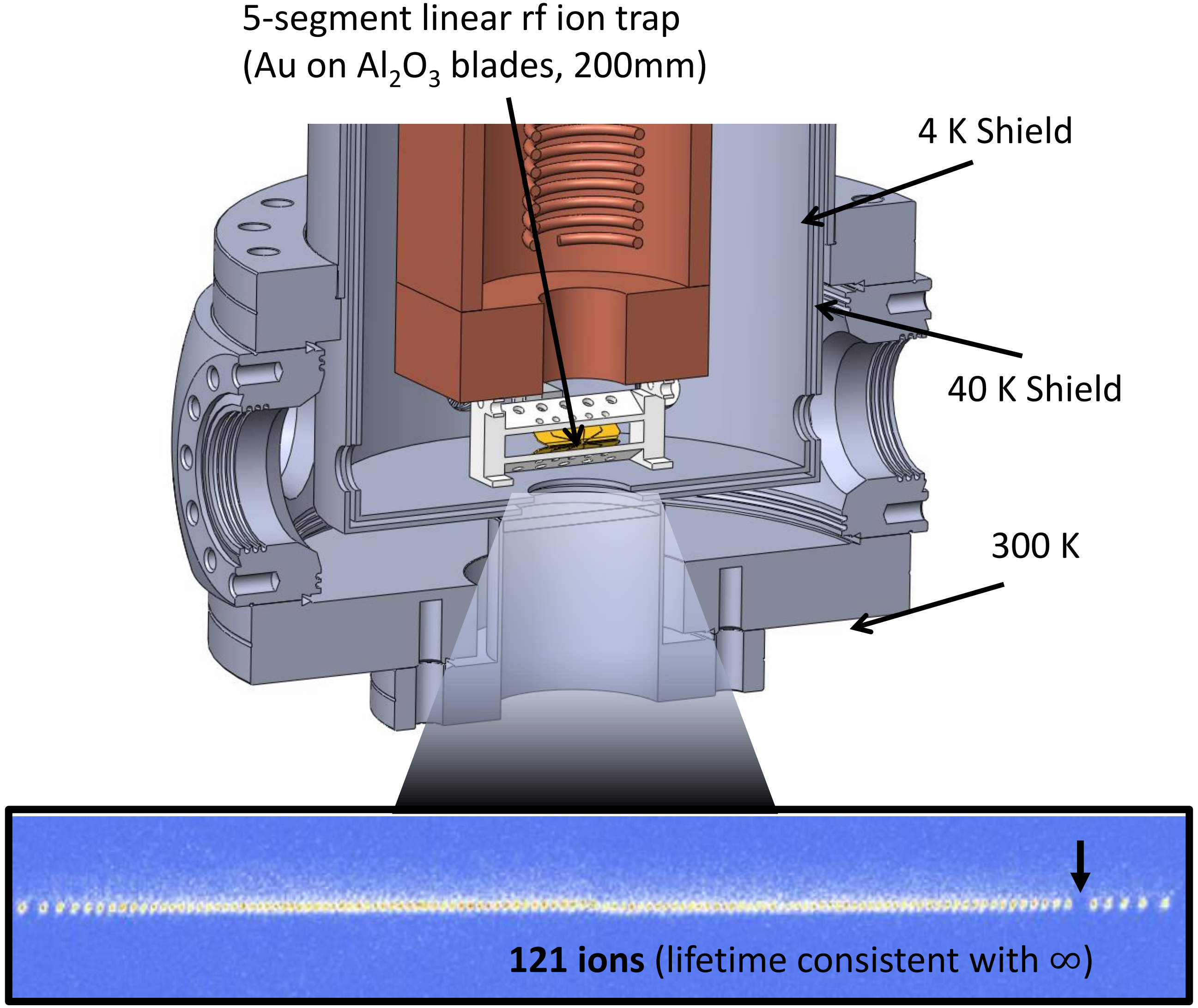
Blatt group: 1D QED
E. A. Martinez, et al., Nature **534**, 516 (2016)

Quantum advantage, sampling, connected to quantum chaos: Random matrix theory



Many-body spectroscopy:
C. Senko, et al., Science **345**, 430 (2014)

Scaling Up: 4K to get lower pressure



Qubit Control:
Programmable/*Reconfigurable* Quantum Computer Module

Classical Control (FPGAs, DACs, AWGs, DDSs)

Identify Multiqubit Quantum Algorithm

↓

Program Circuit in terms of universal sparse gate family (e.g., CNOT, H, T)

↓

Compile Circuit in terms of a native (physical) gate family (e.g., Ising, Rotations)

↓

Decompose Gates into interactions with communication bus (pulse shaped laser fields)

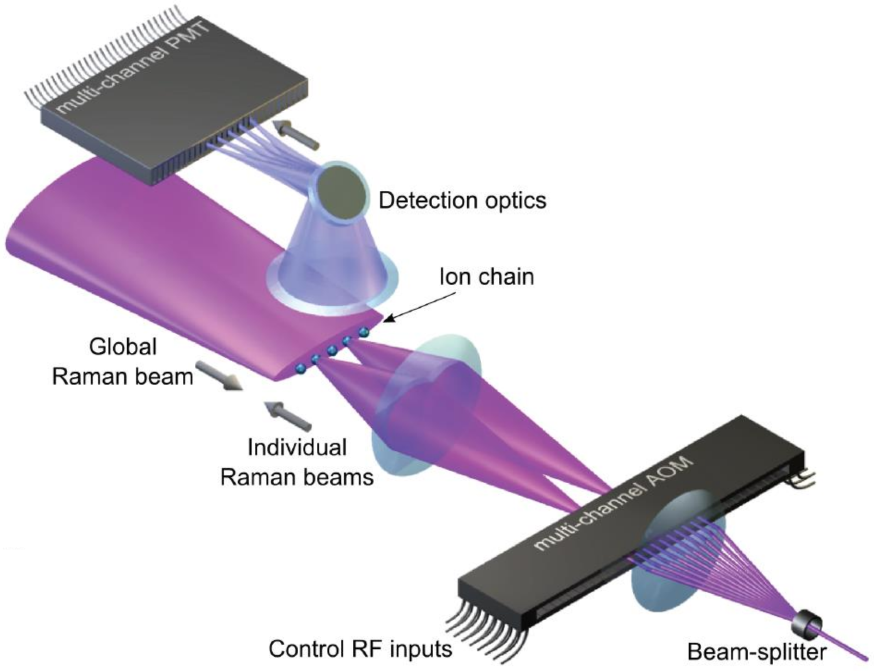
↓

Quantum Control

Apply Laser Pulses to couple qubits (ion spins) with bus (phonons)

↓

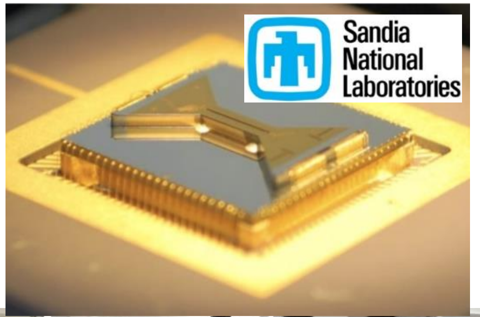
Measure Qubits



S. Debnath, *et al.*, Nature **536**, 63 (2016)
N. Linke, *et al.*, PNAS **114**, 13 (2017)

Engineering Meets Ion Traps

- Full control of up to 32 qubits
- Full connectivity/reconfigurability
- Dual species ($^{171}Yb^{+}$/$^{138}Ba^{+}$)
- Room temperature chamber
- NA 0.6 optical access



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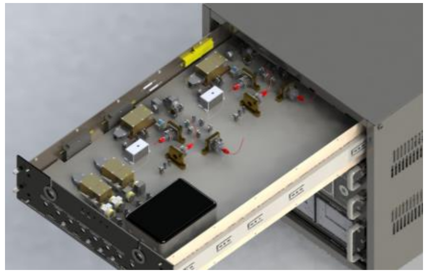
AOSense
ColdQuanta
HARRIS®
COHERENT®

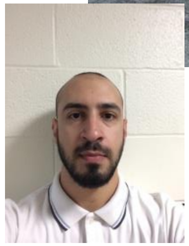
AOSense CW laser rack
- 6 wavelengths, all locked
- all modulators/switches
- fiber delivery



Acknowledgements

QSIM Team
PI: Chris Monroe

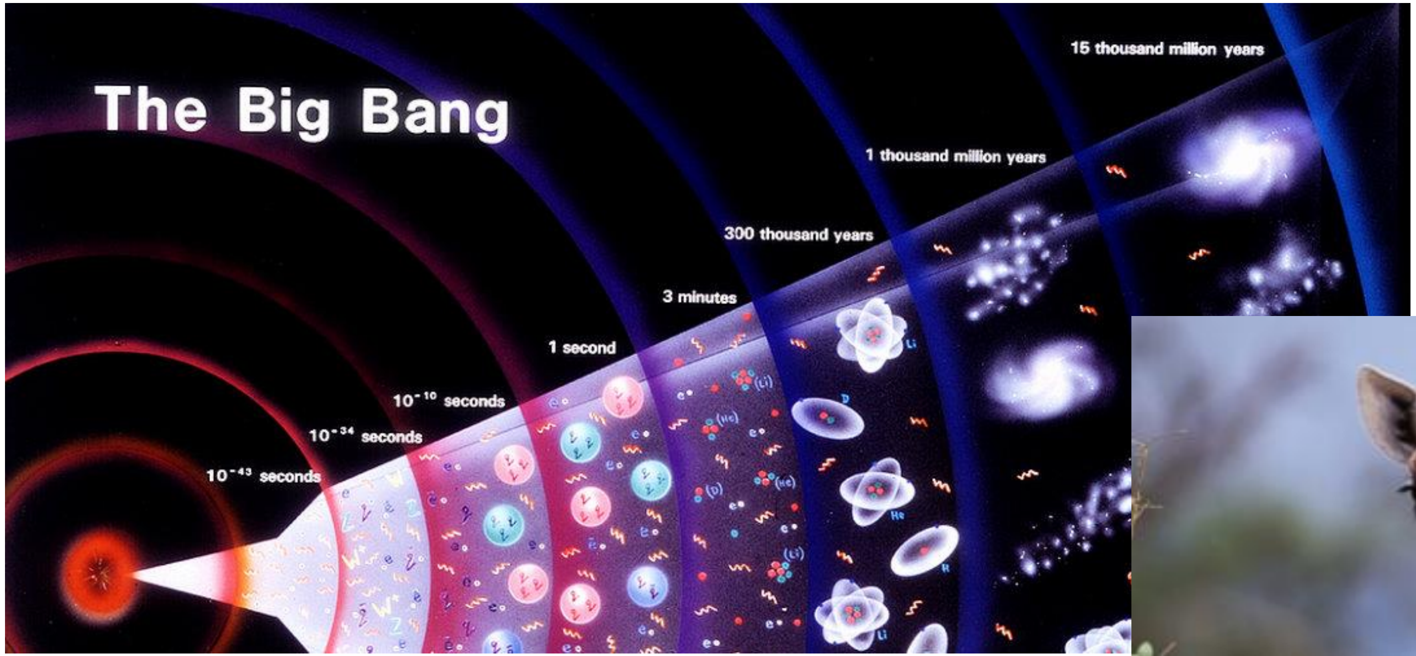
Post-docs:
- Jiehang Zhang
- Paul Hess
- Guido Pagano



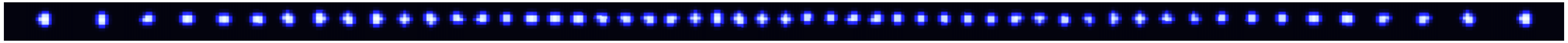
Graduate Students:
- Antonis Kyprianidis
- Patrick Becker
- Harvey Kaplan
- Wen Lin Tan

Theory Collaborator:
- Norman Yao
- Andrew Potter
- Ashvin Vishwanath
- Zhe-Xuan Gong
- Alexey Gorshkov

Nature: the fastest quantum computer

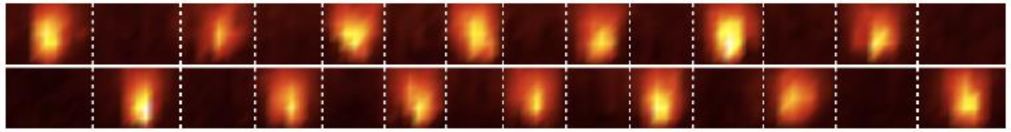


Spin detection:
High-resolution fluorescence imaging



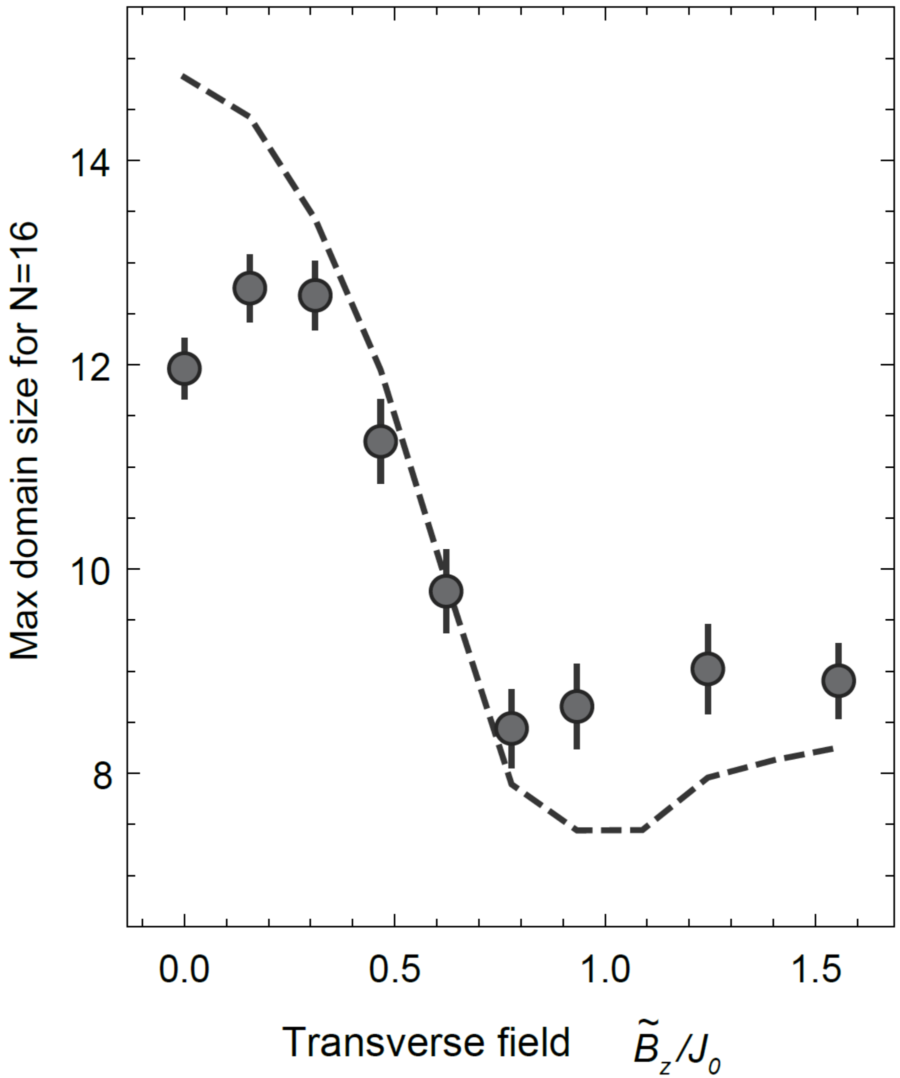
- Ion positions are determined by illuminating the chain for less than 20 ms.
- State of ***each spin*** is then measured in 300 μs detection time
- *All many-body correlations available in a single shot*

eg: AFM ordering of 14 spins



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

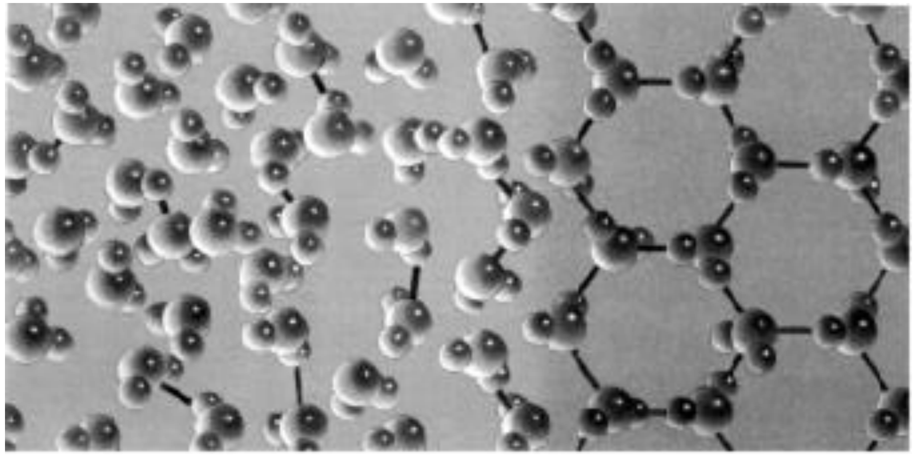
Formation probabilities for 16 spins



K. Naja and M. A. Rajabpour, Phys. Rev. B 93, 125139 (2016).

What are Time Crystals?

Hot ⟷ Cold



<u>Time Translational Symmetry Breaking?</u>

$$\hat{H} \xrightarrow{?} \langle \psi_0 | \hat{O} | \psi_0 \rangle = f(t)$$

Time independent Time dependent

Wilczek (PRL 2012), Li *et al.*, (PRL 2012), Bruno (PRL 2013), Watanabe &Oshikawa (PRL 2015)

Discrete Time Crystals

Periodically Driven (Floquet) Hamiltonian

$$\hat{H}(t) = \hat{H}(t+T) \quad \longrightarrow \quad \langle \hat{\mathcal{O}}(t) \rangle = \langle \hat{\mathcal{O}}(t + nT) \rangle$$

Khemani *et al*. (PRL 2016) ; Else, *et al.* (PRL 2016); N. Yao *et al.* (PRL 2016)
von Keyserlingk, *et al.* (PRB 2016); Sacha PRA (2015)

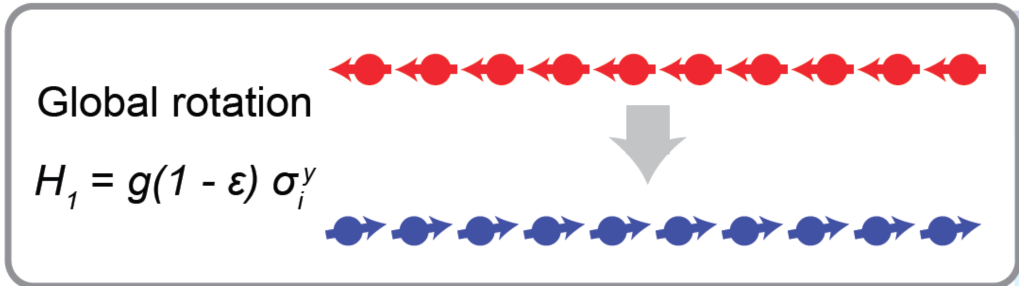
Requirements for Discrete Time Crystal definition:

- ✓ Periodic state dependence at sub-harmonic frequencies
- ✓ Robust to perturbations (no fine tuned parameters)
- ✓ Oscillations stabilized by many-body effects

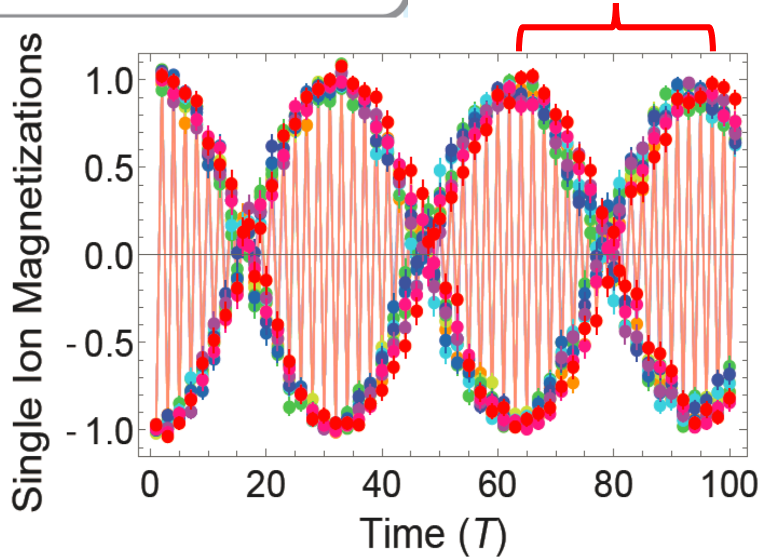
Eliminates most "trivial" Discrete Time Crystals

Spin chain Floquet evolution

$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x\sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i\sigma_i^x & \text{time } t_3 \end{cases}$$



Beatnote Period $1/\varepsilon$ (T)



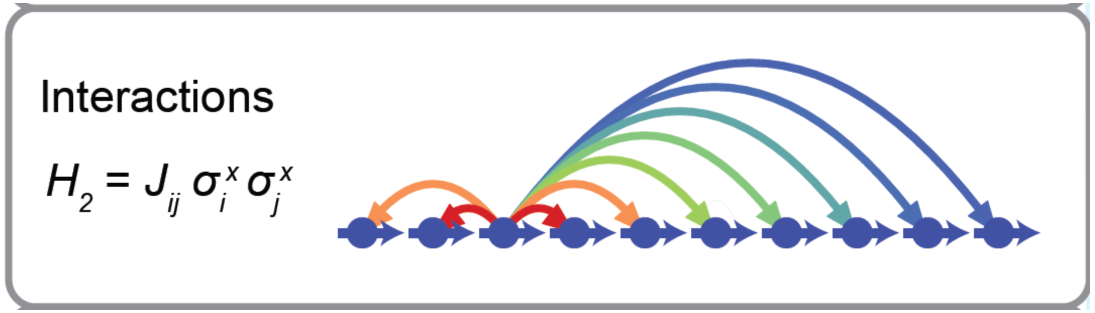
Perturbed
$(1-\varepsilon)\pi$ - pulses

$0 \leq \varepsilon \leq 15\%$

J. Zhang *et al.*, Nature 543, 217-220 (2017).
See also work by M. Lukin group.

Spin chain Floquet evolution

$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x\sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i\sigma_i^x & \text{time } t_3 \end{cases}$$



$$J_{ij} \approx \frac{J_0}{|i-j|^{\alpha}}$$

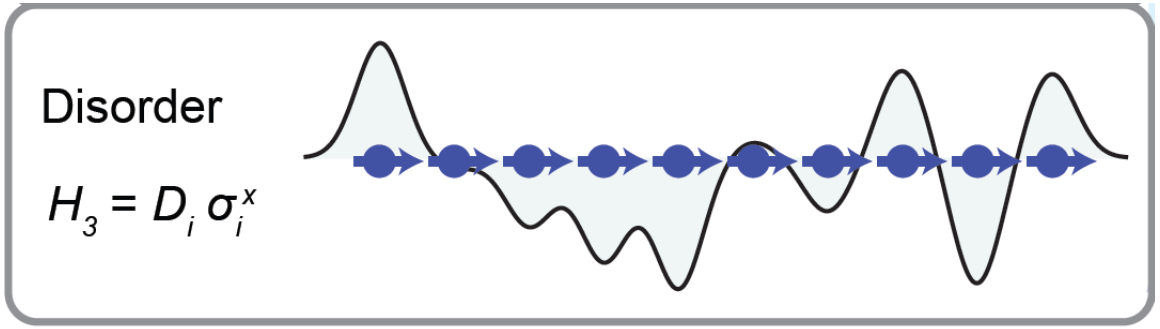
$\alpha = 1.5$

Interactions:
$0.006 < J_0\, t_2 < 0.04$

J. Zhang *et al.*, Nature 543, 217-220 (2017).

Spin chain Floquet evolution

$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x \sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i \sigma_i^x & \text{time } t_3 \end{cases}$$

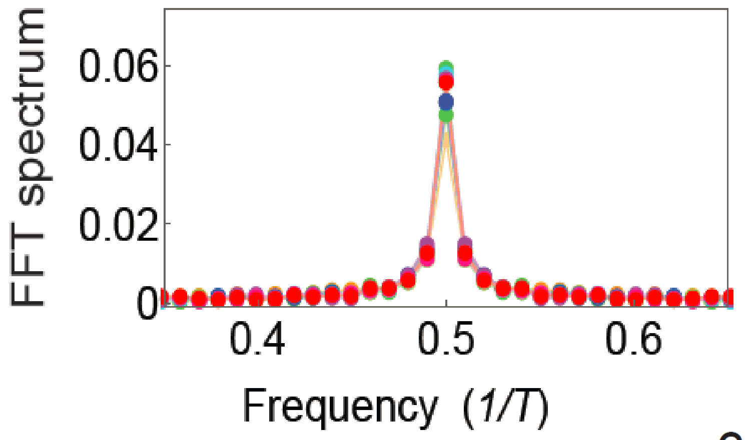


- Strong Disorder:

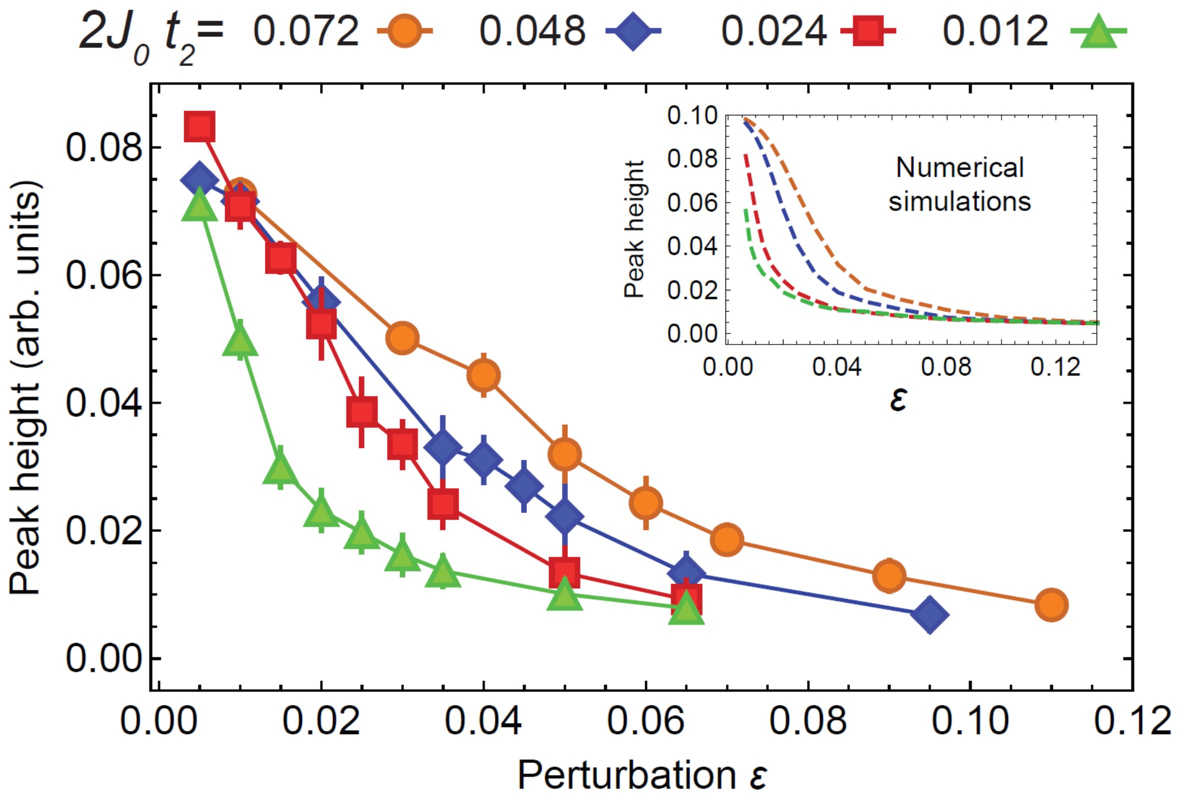
  $D_i\, t_3 \in [0, \pi]$
- Localization prevents heating

J. Zhang *et al.*, Nature 543, 217-220 (2017).

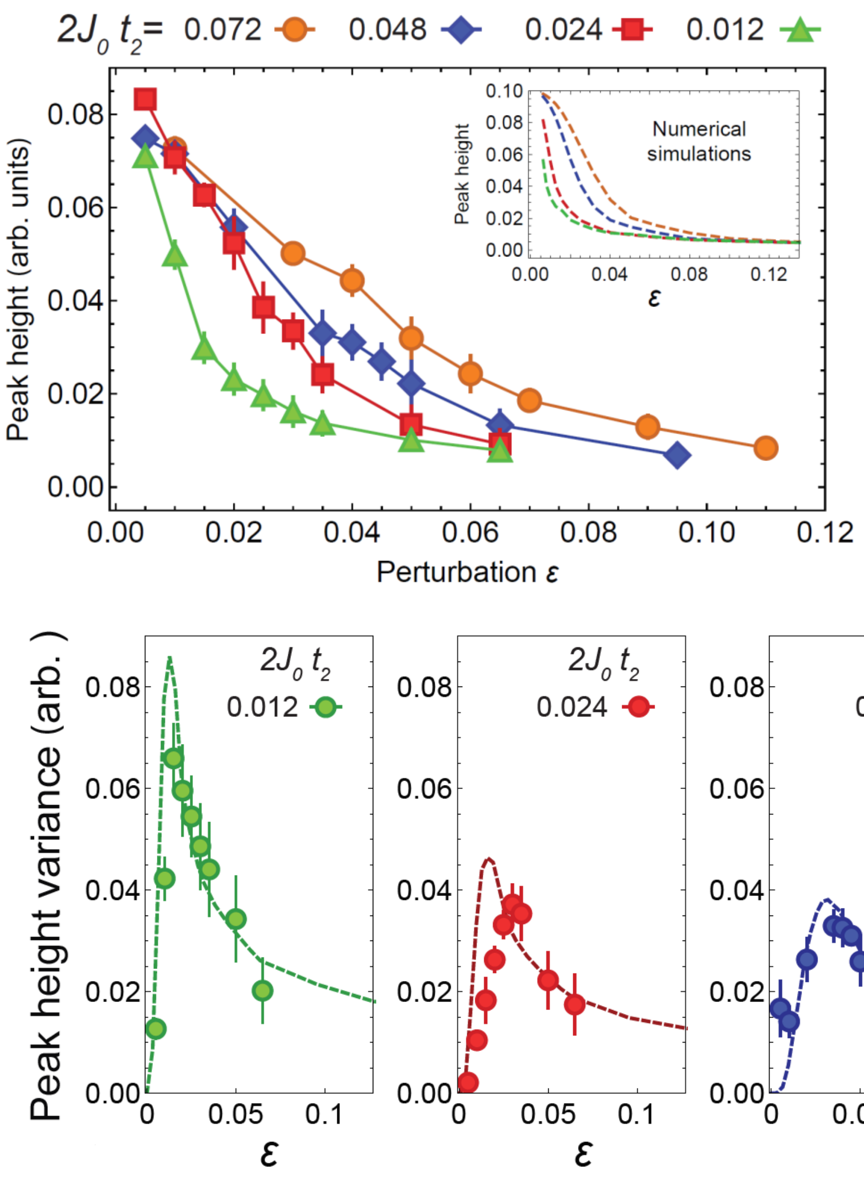
Sub-harmonic peak heights:
An order parameter



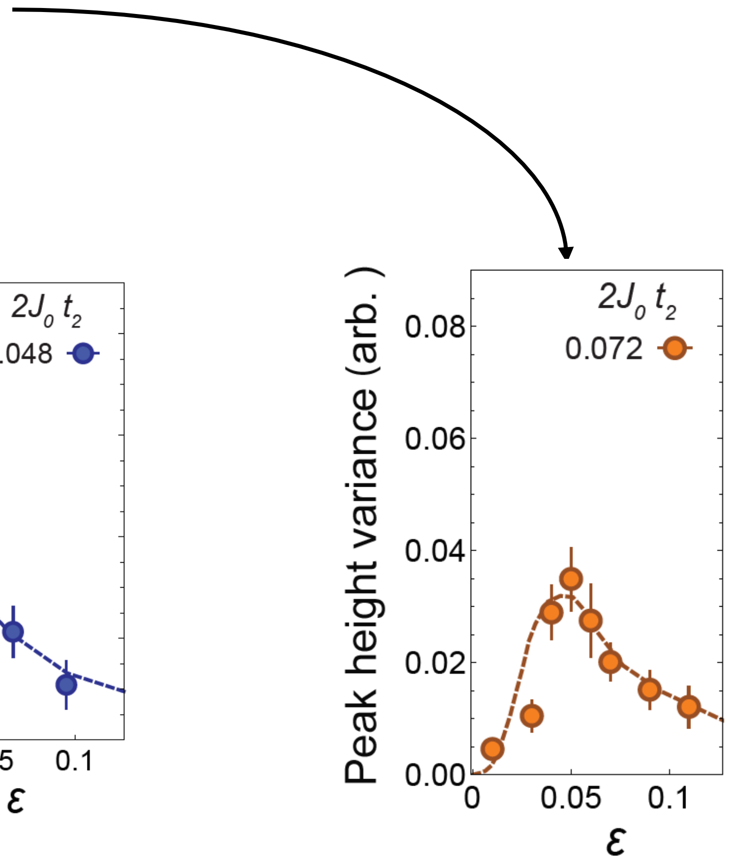
Average over 10 ions and 10 disorder instances



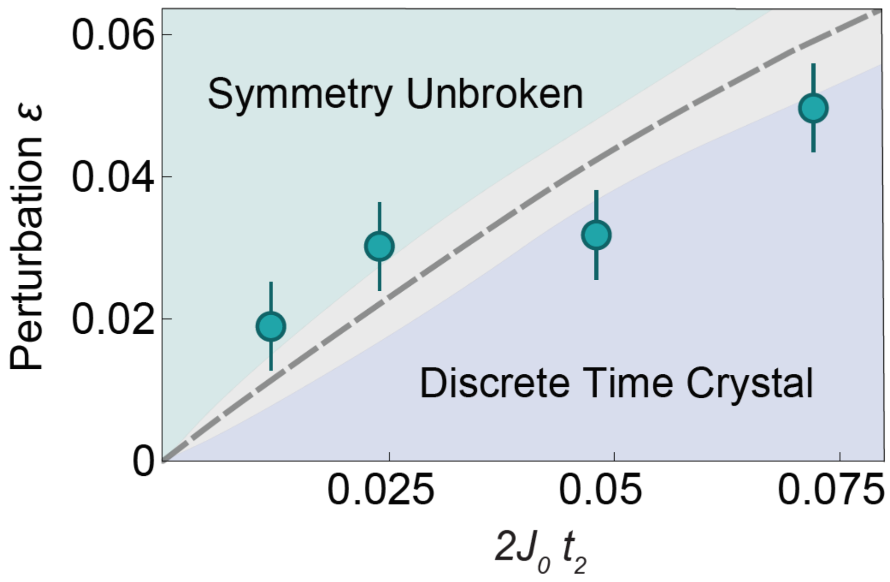
Variance: signature of cross-over



Order parameter variance blows up at phase boundary



“Phase diagram” and other signatures

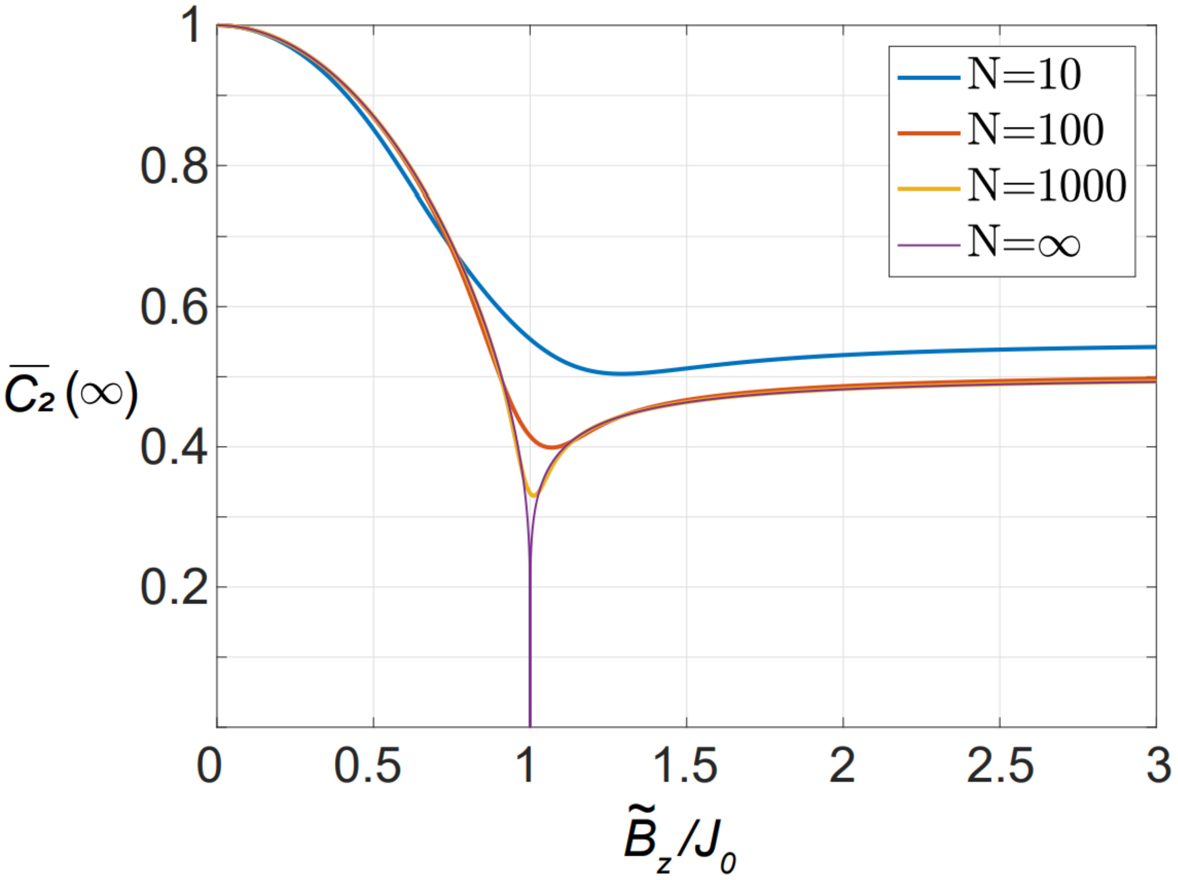


- Highest variance correspond to the phase transition points, which is rounded into a cross-over with finite size systems
- Agrees well with numerical simulations (dashed line)

We’ve also checked:

- Finite-size scaling
- Different initial states
- Disorder vs clean systems (more to come)

Theory at the all-to-all limit (α = 0)



- Special point where a permutation symmetry exist, i.e. all spins are interchangeable.
- Phase transition manifested in logarithmic “dip” in the second order correlation.
- α ≠ 0 remains an open question.

J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Possible connections to sampling experiments