Our-of-equilibrium Spin systems with a Quantum Simulator

Jiehang Zhang

NPQI workshop, Mar. 30, 2018

Christopher Monroe group,

University of Maryland

JZ *et al.*, *Nature*, **551**, 601–604 (2017).

The exponential beast: two rules of quantum mechanics

Rule # 1:

The Hilbert space scales exponentially.

Rule #2:

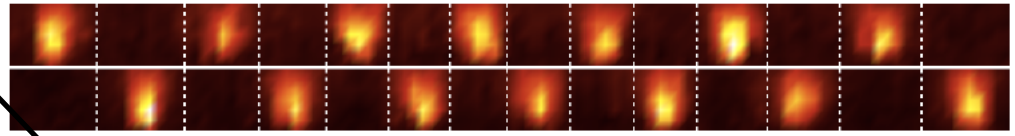
Rule #1 only works when you're not looking.

Niels Bohr:

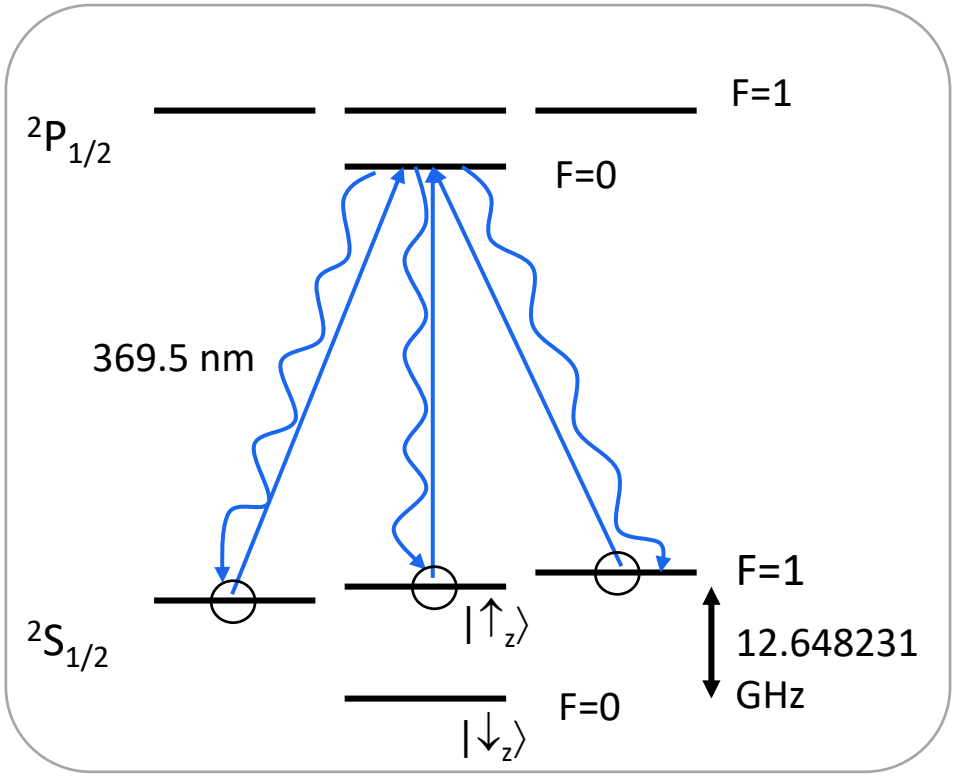
"We are all agreed that your theory is crazy." (1958)

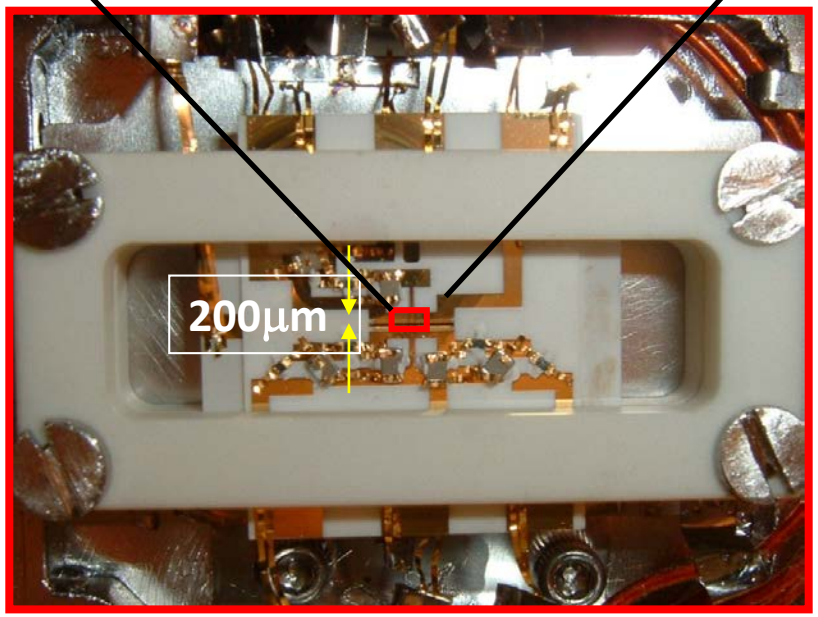
$^{171}Yb^{+}$ hyperfine clock qubits.

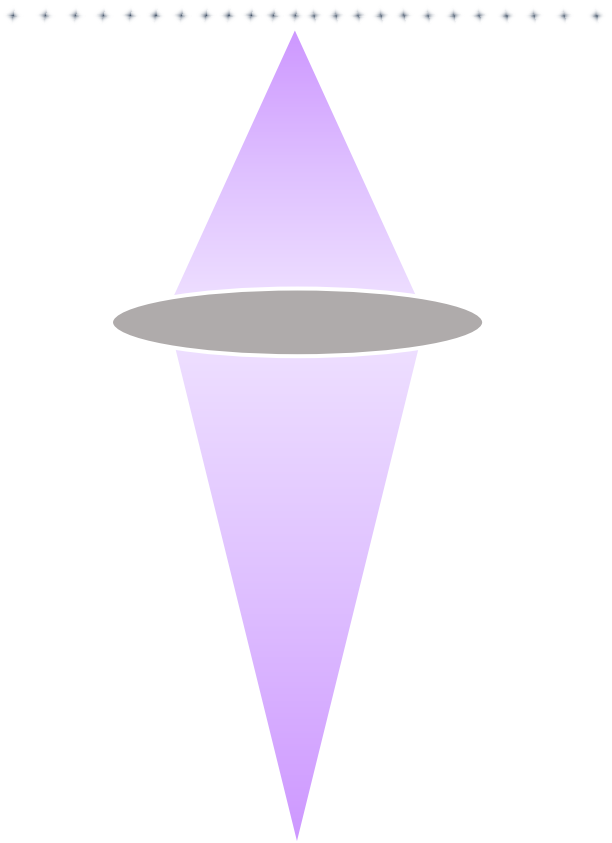
eg: AFM ordering of 14 spins



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







Effective Hamiltonian: 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

$$J_{ij} \approx \frac{J_0}{|i-j|^\alpha} \quad (0 < \alpha < 3)$$

J_0~ kHz

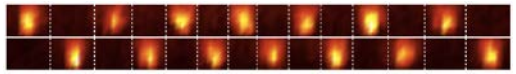
- Transverse fields by asymmetric detuning of force
- Individual local field via Stark shifts:

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

Equilibrium

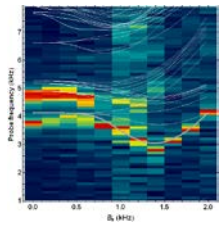
- Adiabatic processes [1]

  Frustrated ground states



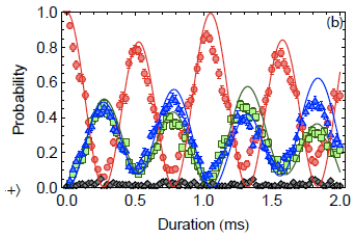
- Many-body spectroscopy [2]

  Probing low-lying excited states



- Spin-1 simulation [3]

  Interacting “qutrits”

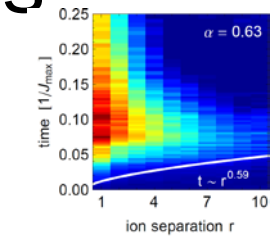


[1] R. Islam, *et al.*, Science **340**, 583 (2013).
[2] C. Senko, *et al.*, Science **345**, 430 (2014).
[3] C. Senko, *et al.*, PRX **5**, 021026 (2015).

Dynamical problems

- 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.*, *Nature*, **551**, 601–604 (2017).
[5] JZ *et al., Nature* **543**, 217–220 (2017).

Equilibrium

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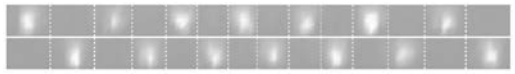

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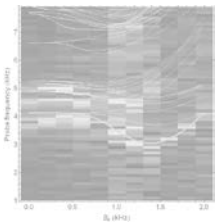

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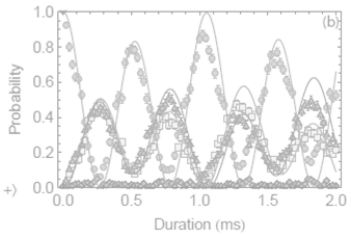

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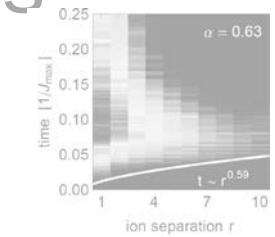
Dynamical problems



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  A novel driven phase of matter

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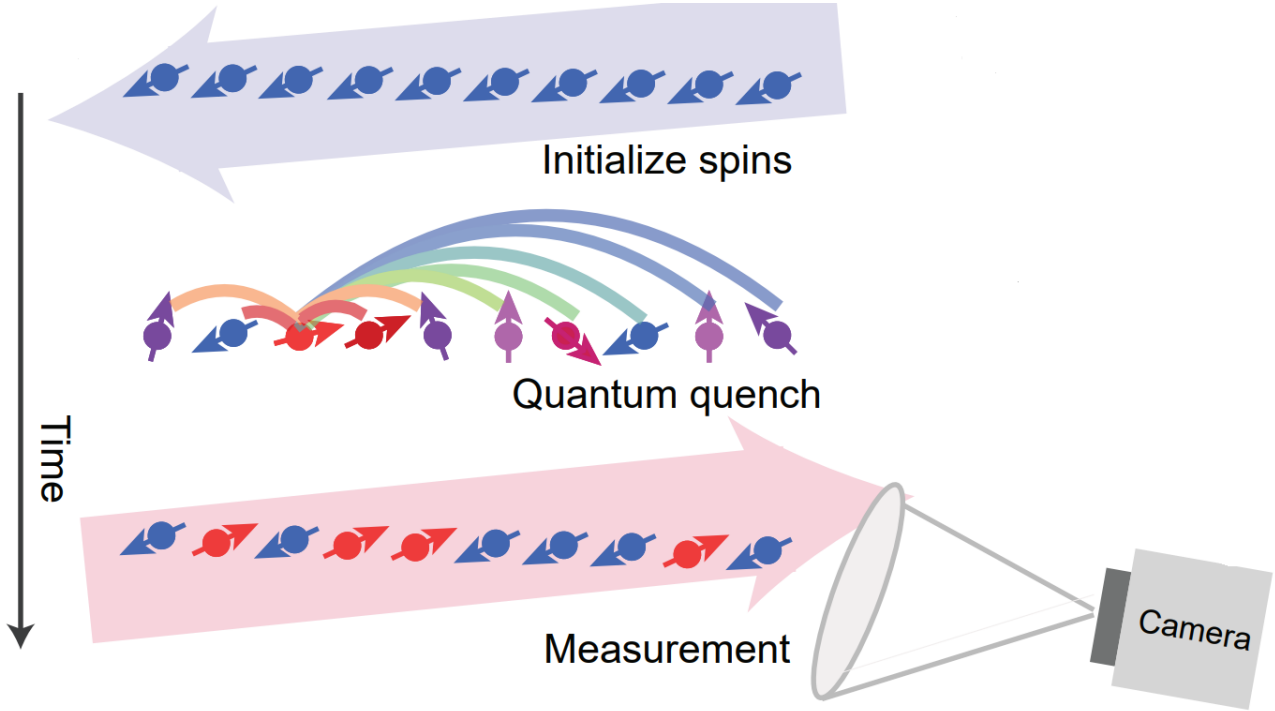
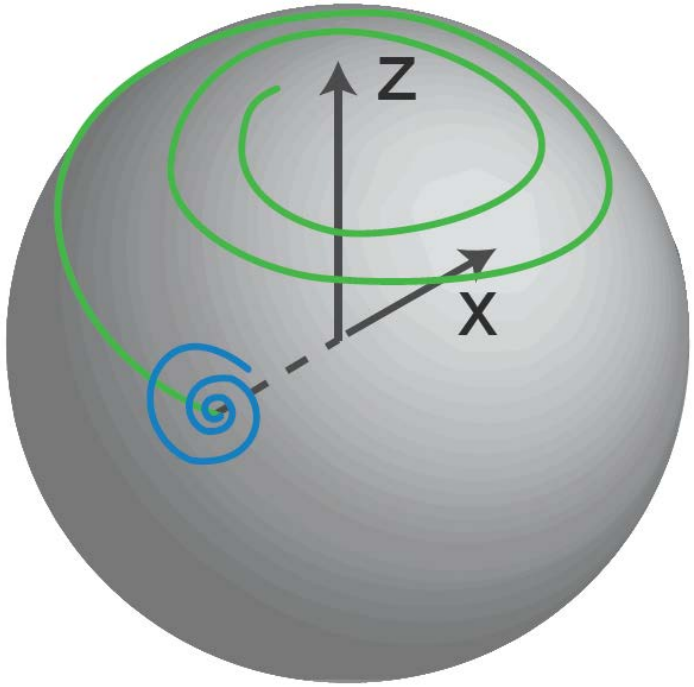
Dynamical phase transition

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

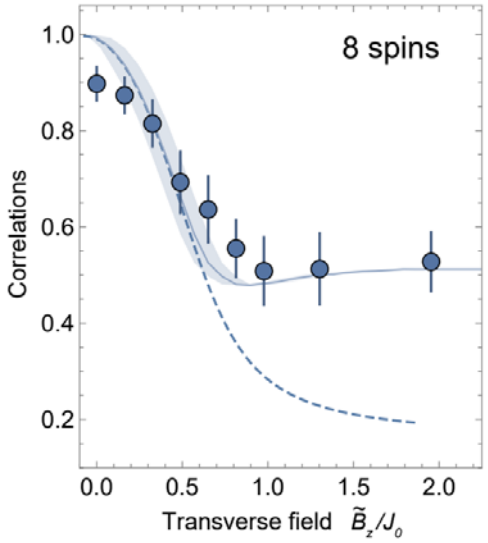


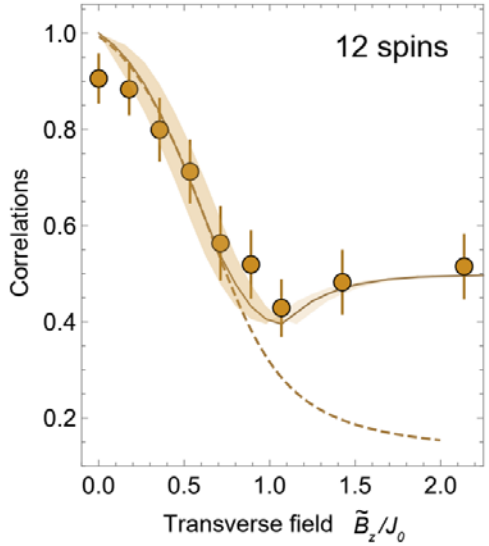


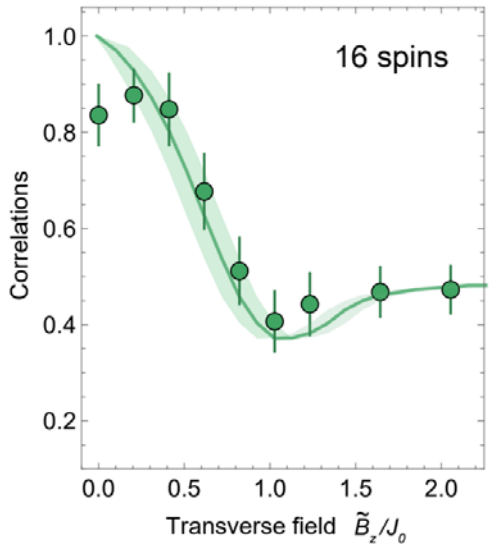
JZ *et al.*, *Nature*, **551**, 601–604 (2017).

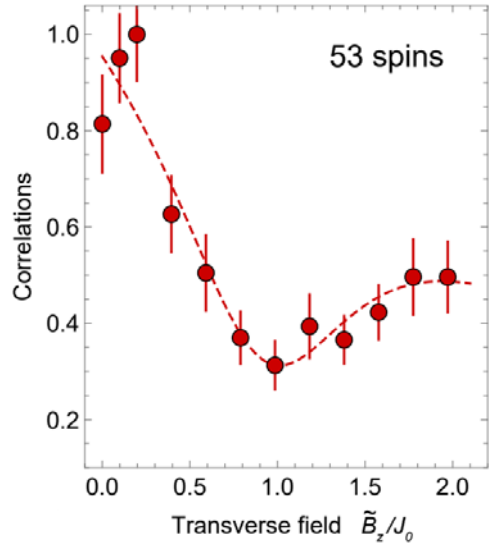
Dynamical phase transitions:
Second order correlations $\frac{1}{N^2}\sum_{i,j}\langle\sigma_i^x\sigma_j^x\rangle$

Evolution up to $(2\pi J_0)t \sim 5$
Interaction decay exponent
α ≈ 0.9





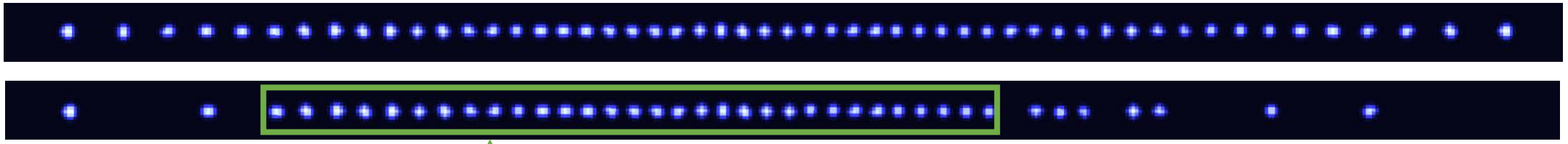


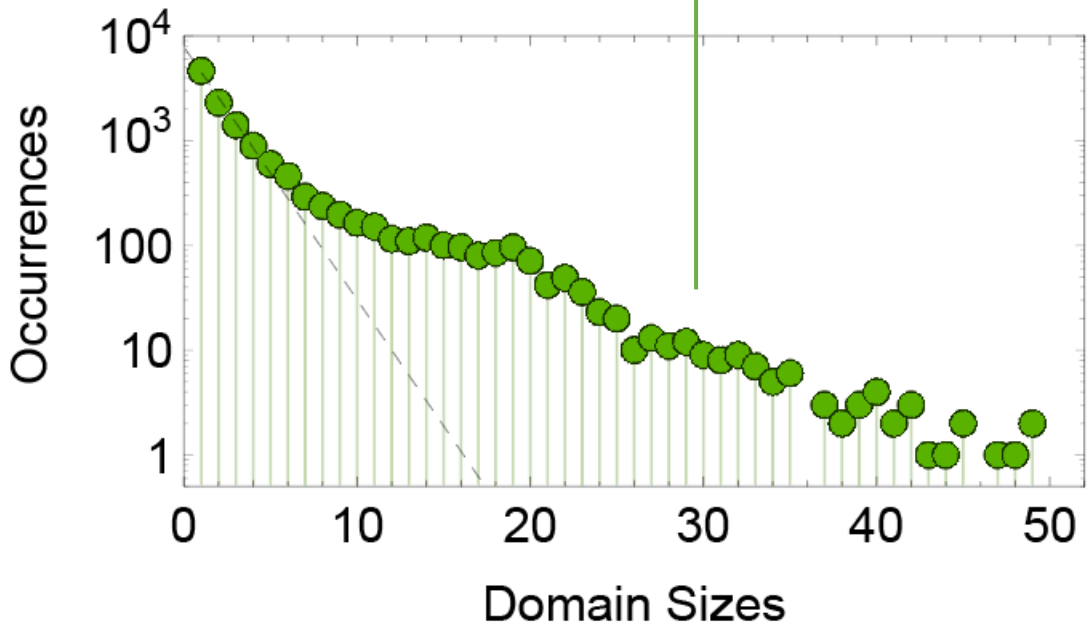


JZ *et al.*, *Nature*, **551**, 601–604 (2017).

Post-quench domain distributions.

Initial state:



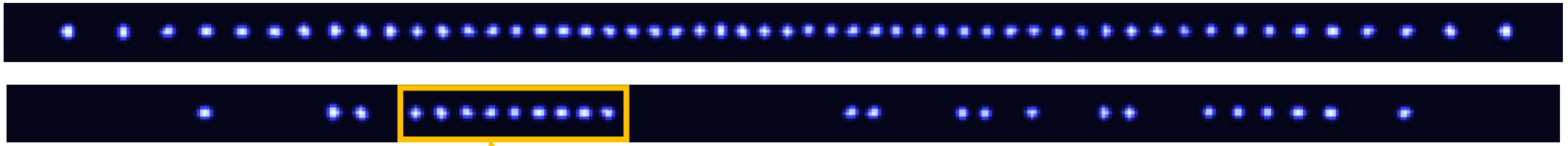


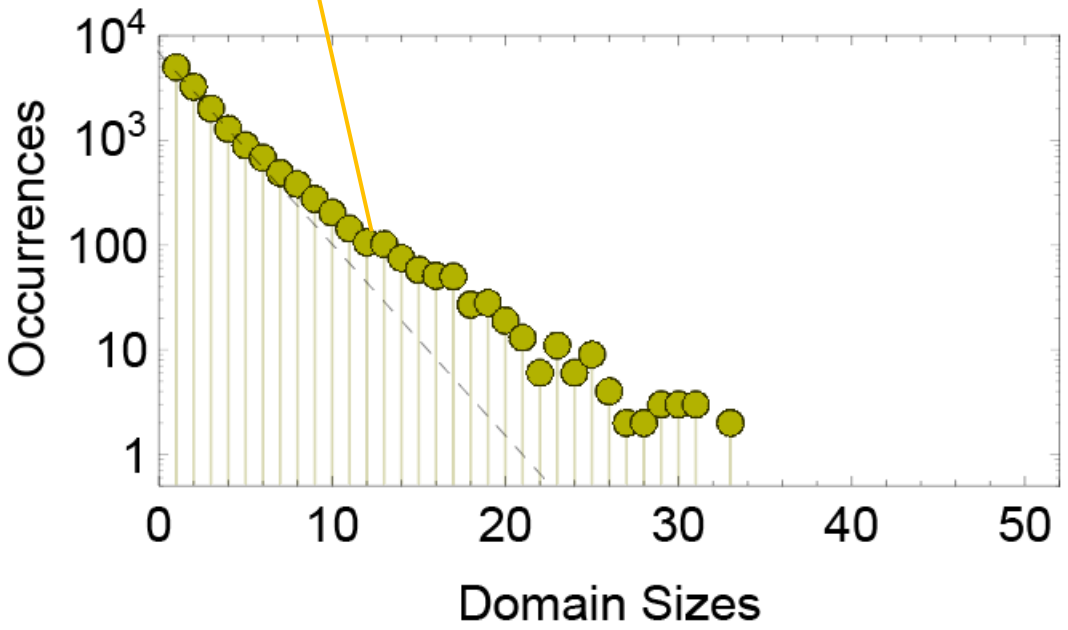
$\tilde{B}_z/J_0 = 0.1$

JZ *et al.*, *Nature*, **551**, 601–604 (2017).

Post-quench domain distributions.

Initial state:



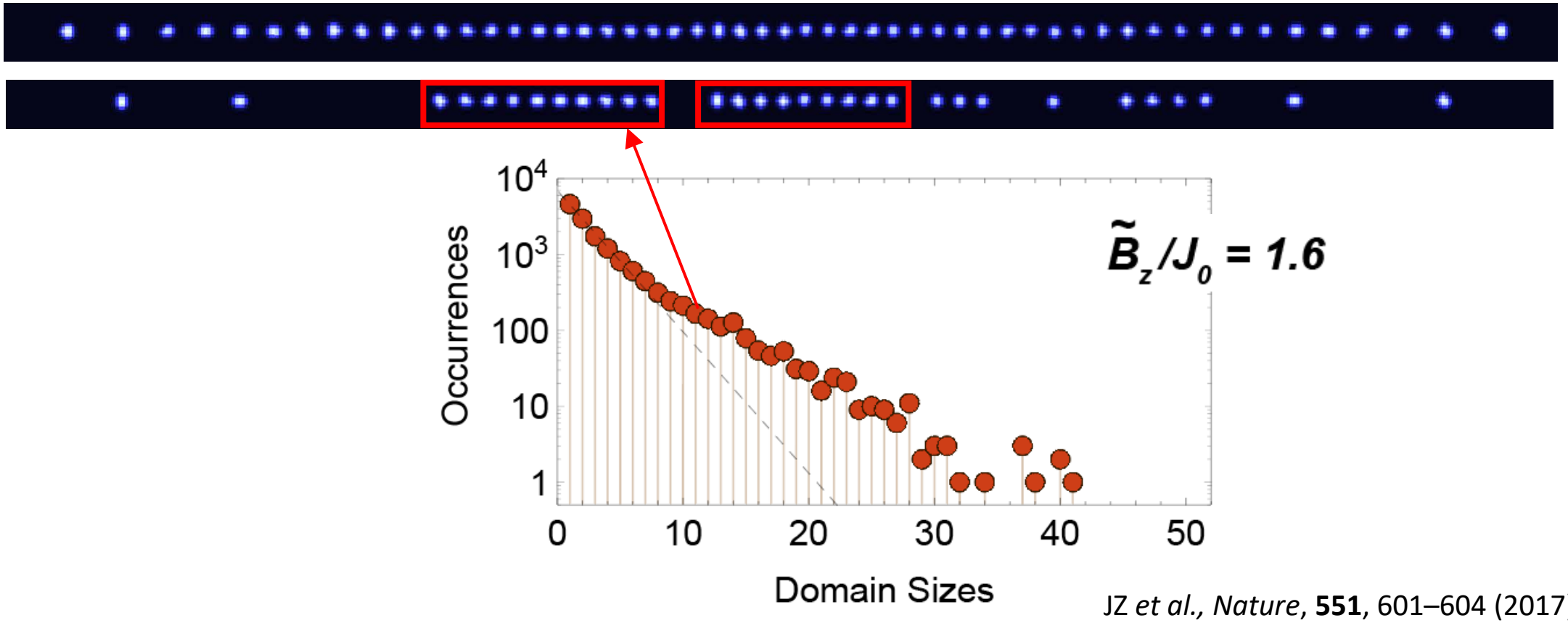


$\tilde{B}_z/J_0 = 1.0$

JZ *et al.*, *Nature*, **551**, 601–604 (2017).

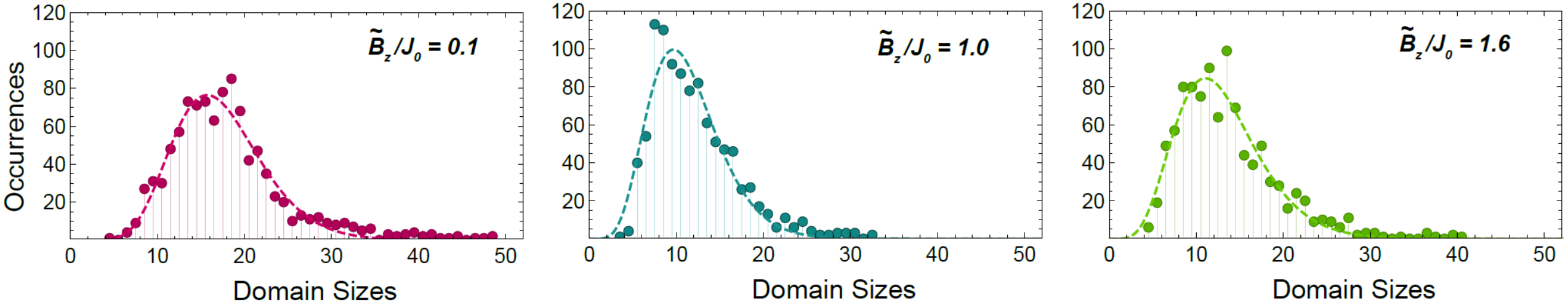
Post-quench domain distributions.

Initial state:



JZ *et al.*, *Nature*, **551**, 601–604 (2017).

Distribution of large domains



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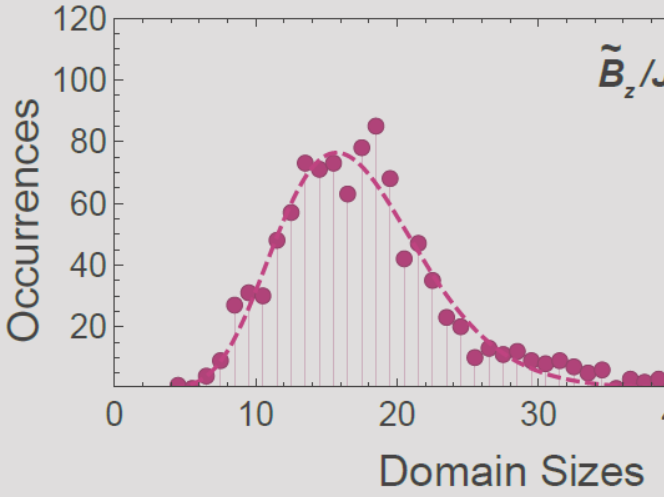
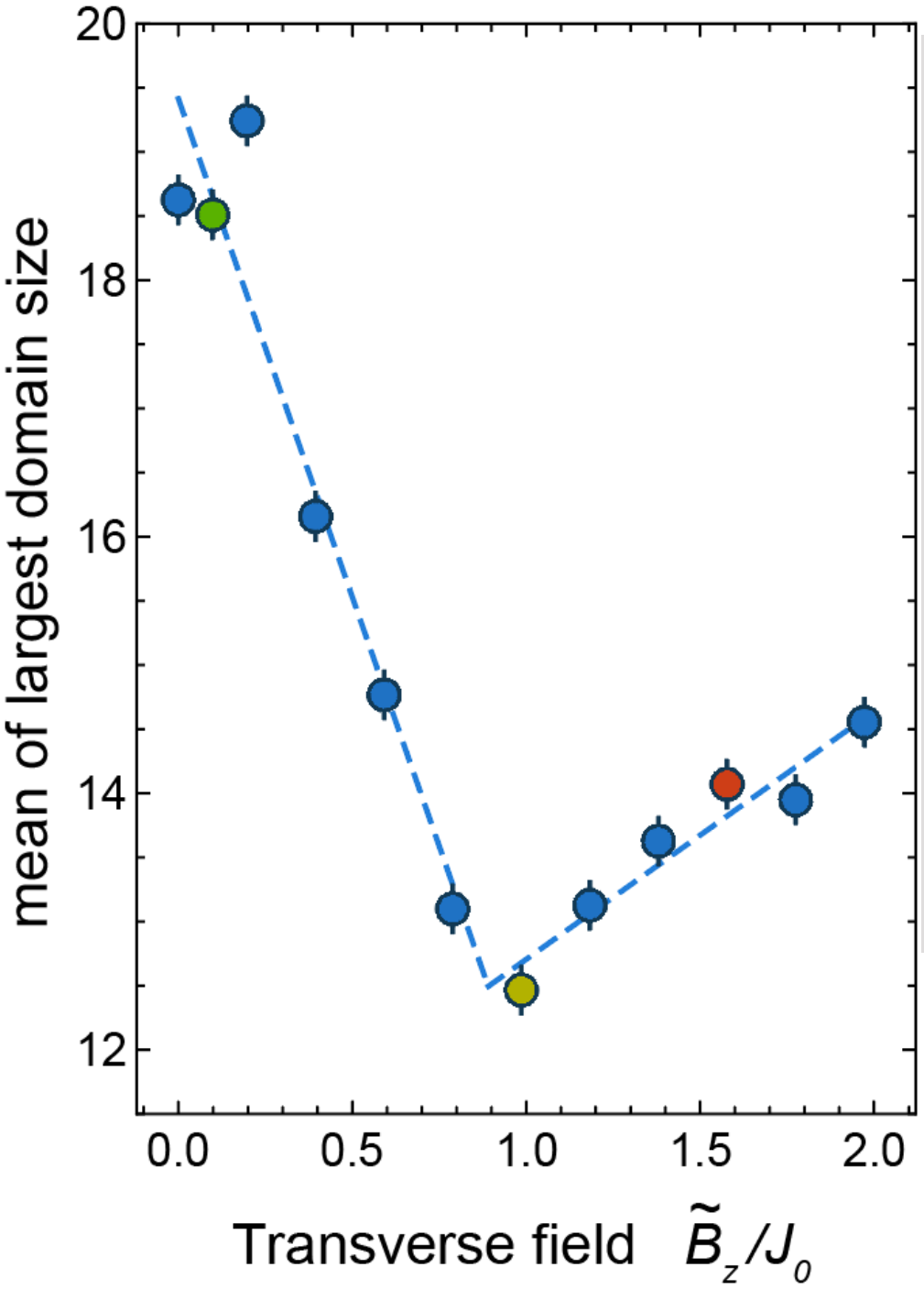
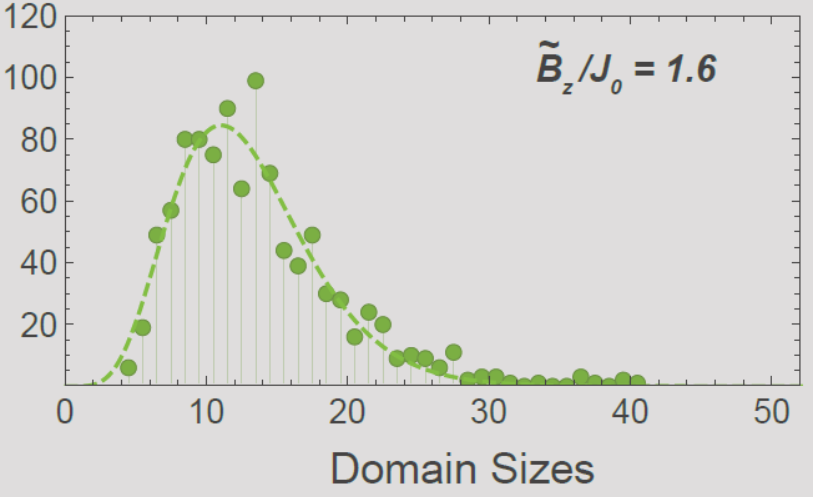
Distributio



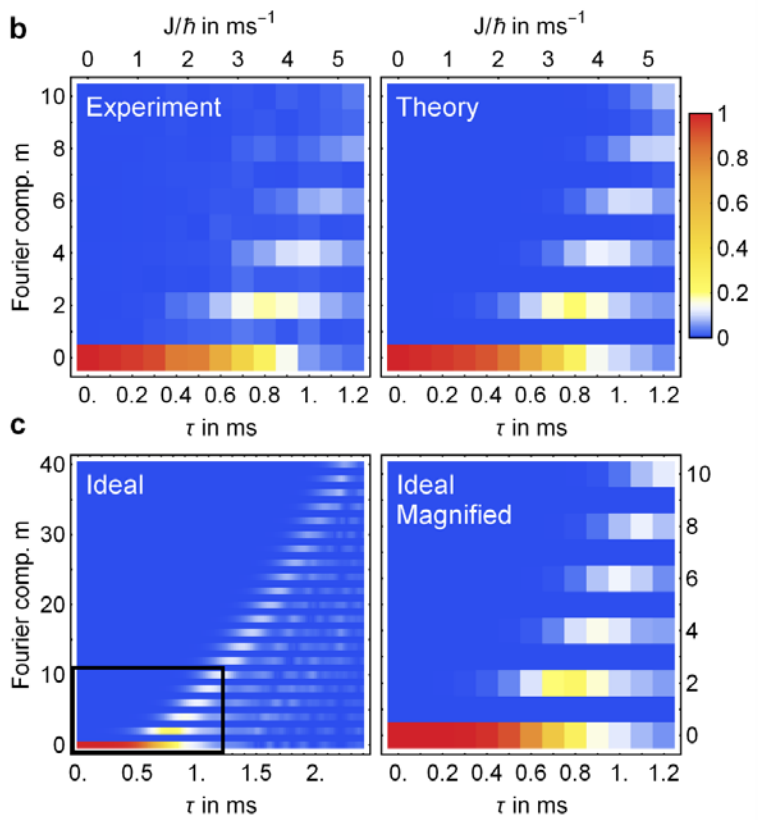




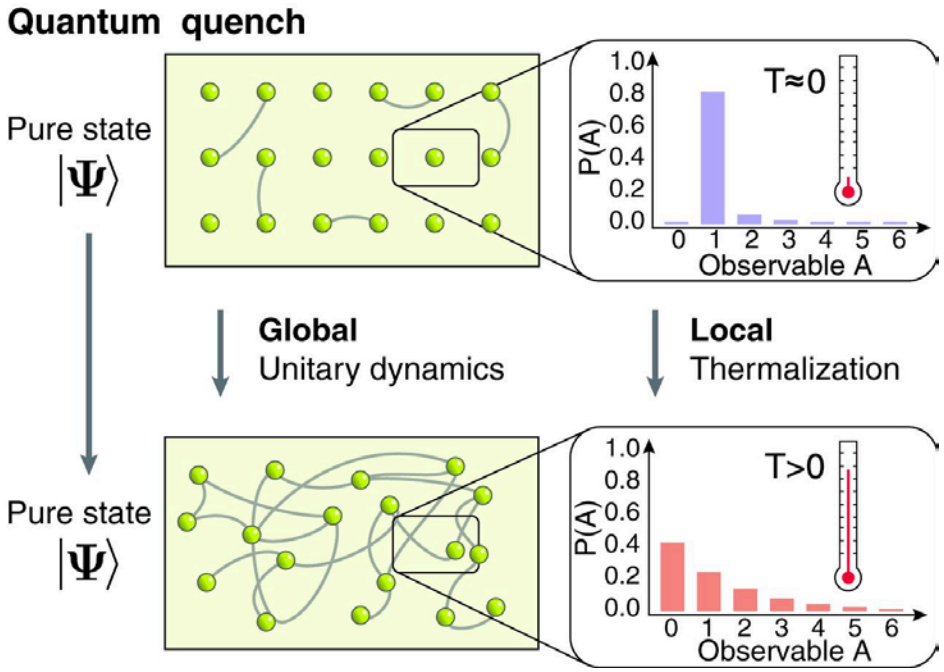
Colored dots correspond to the domain statistics shown before

JZ *et al.*, *Nature*, **551**, 601–604 (2017).

Quantum many-body chaos? Thermalization?

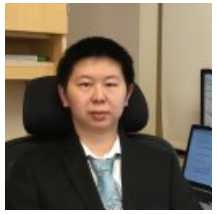


J. Bollinger group:
M. Gärttner, et al., Nat. Phys. 13, 781-785 (2017)



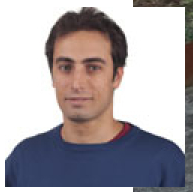
M. Greiner group:
Kaufman, et al., 353(6301) 794-800 (2016)

Acknowledgements

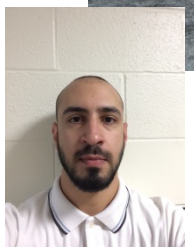


<u>QSIM Team</u>
PI: Chris Monroe

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



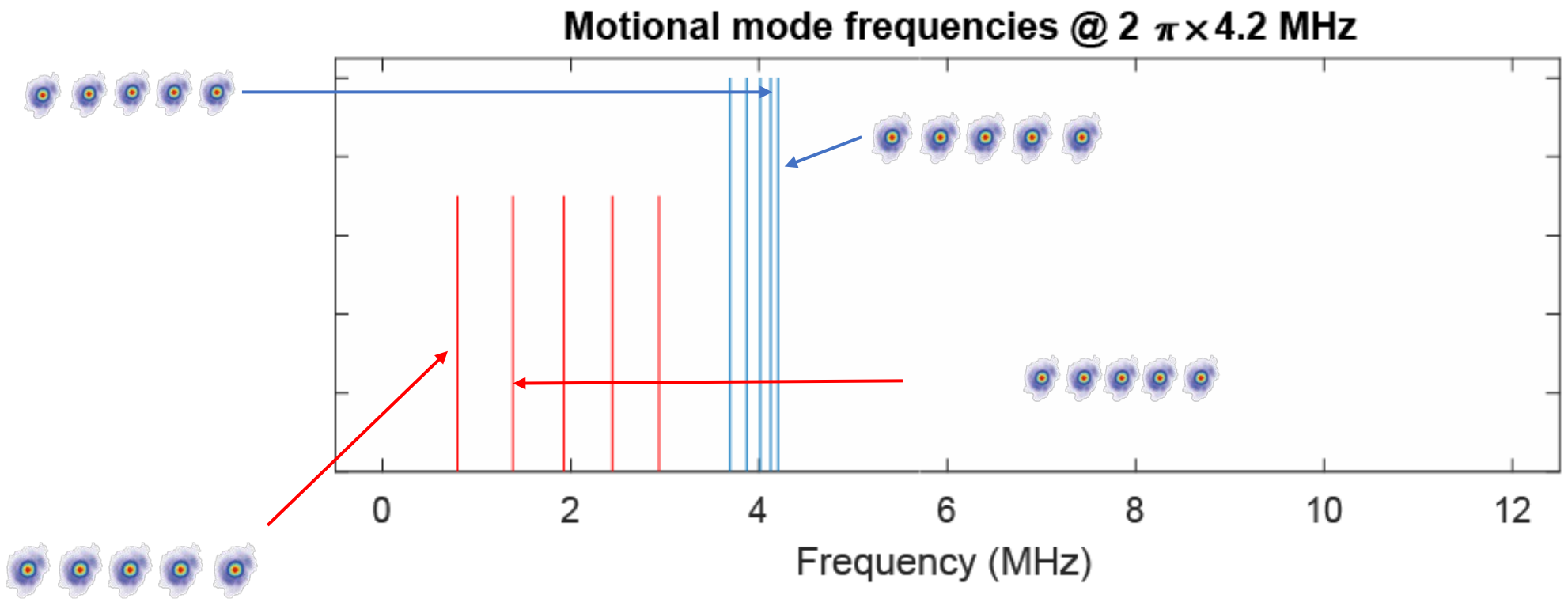
Graduate Students:
- Antonis Kyprianidis
- Patrick Becker
- Kate Collins
- Harvey Kaplan
- Wen Lin Tan

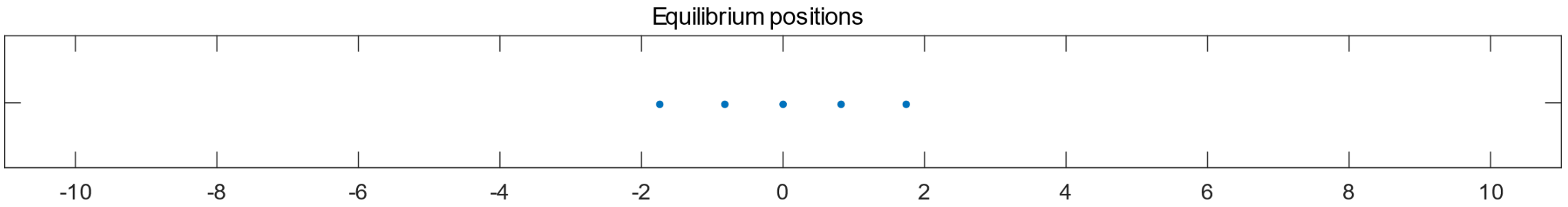


Theory Collaborations:
- Norman Yao
- Alexey Gorshkov
- Zhe-Xuan Gong
- Mohammad Hafezi
- Andrew Childs
- Andrew Potter
- Ashvin Vishwanath

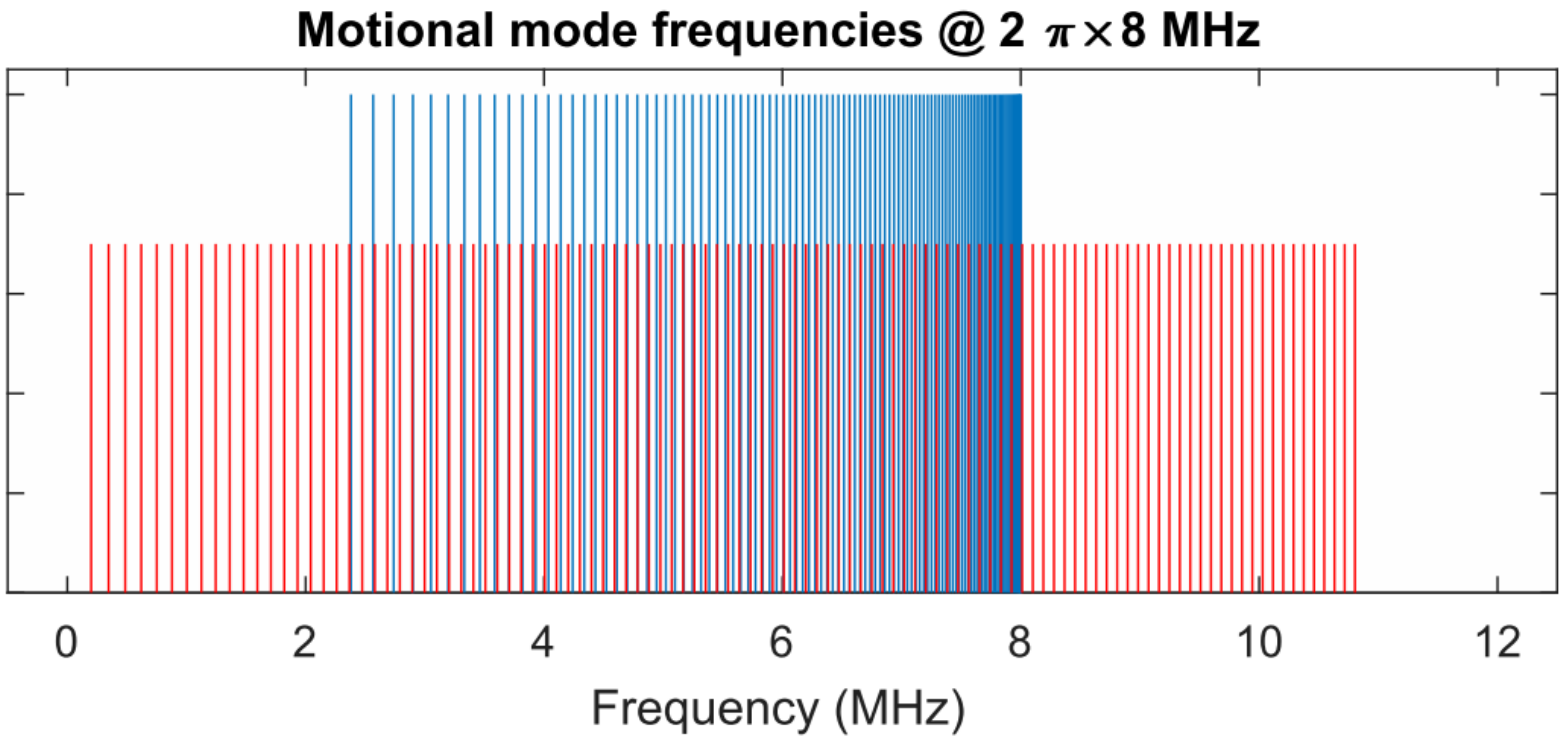

Thank you!

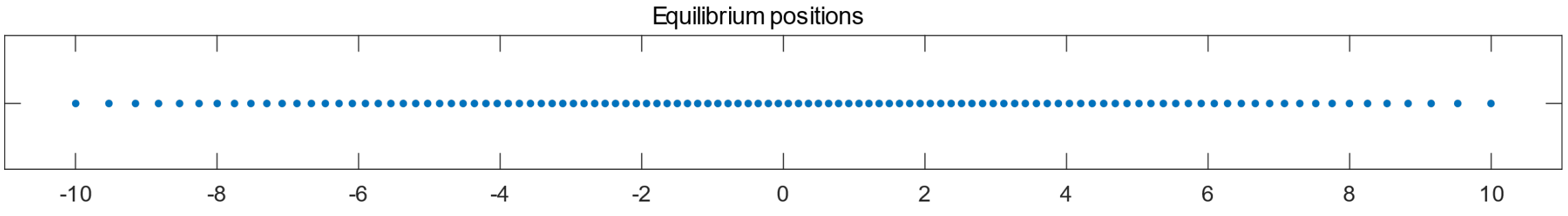
Arbitrary interactions: normal mode addressing



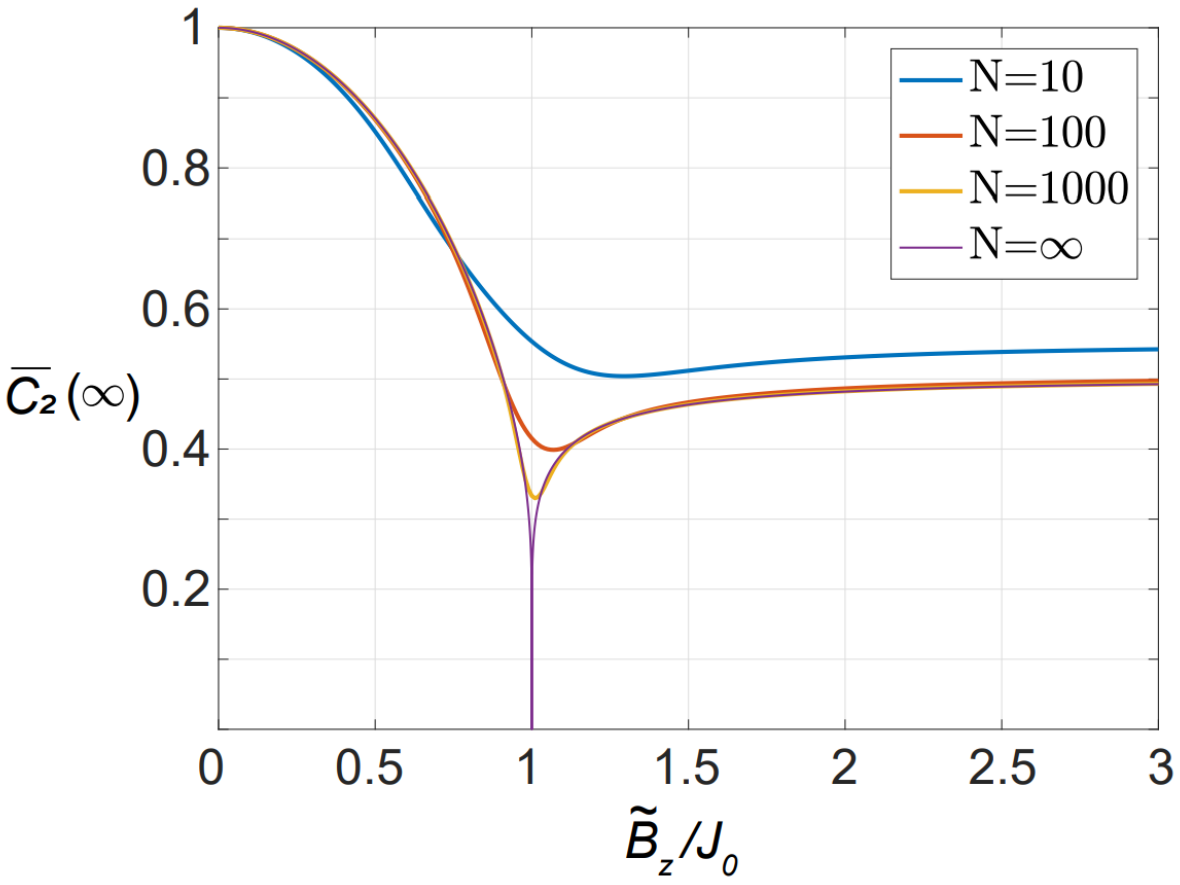


Motional mode spectrum for 100 ions





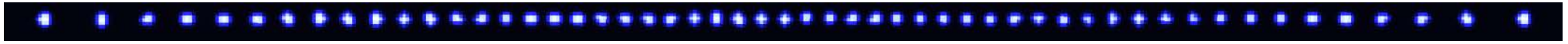
Theory at the all-to-all limit (α = 0)



- 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.

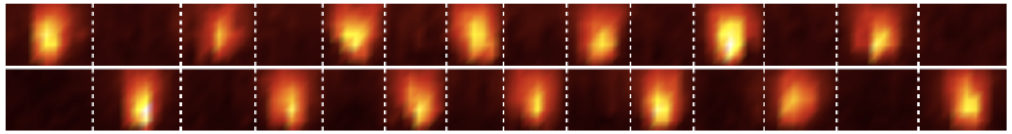
J. Zhang *et al.,* arXiv 1708.01044 (2017), Nature, in press

Spin detection:
High-resolution fluorescence imaging



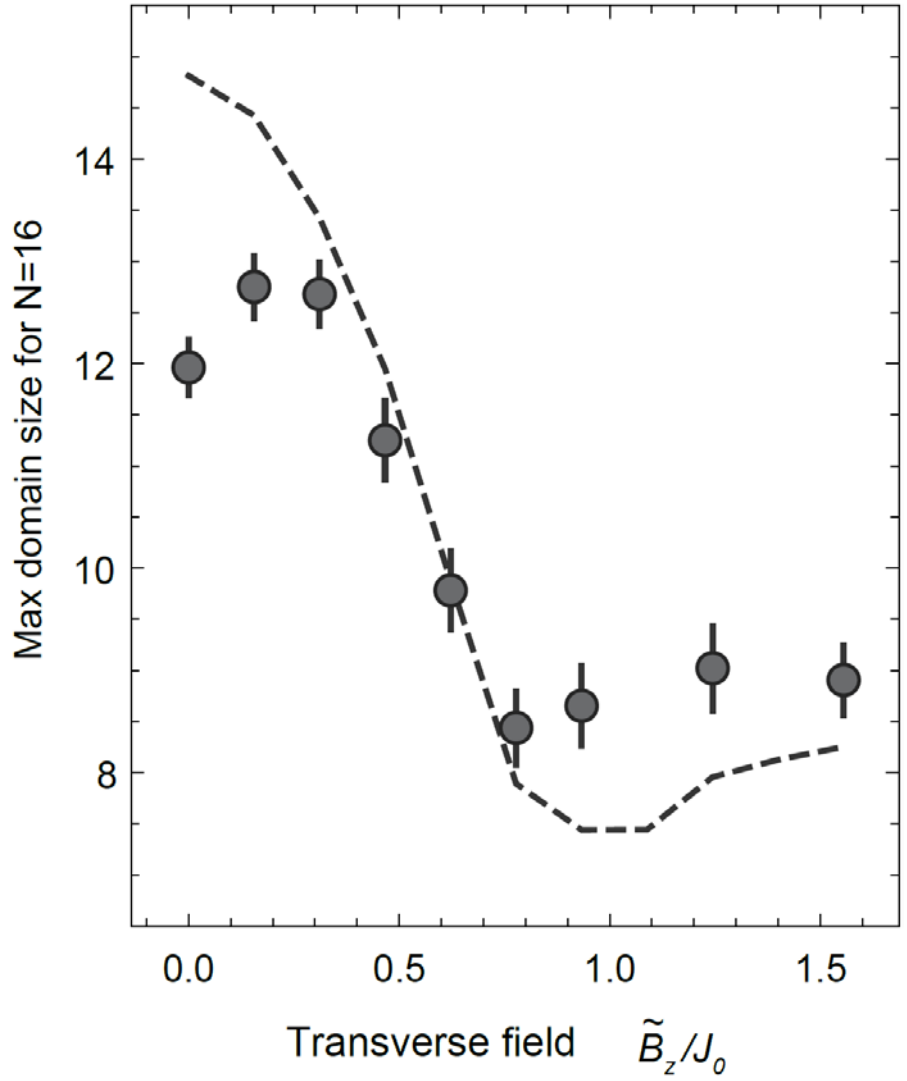
- Ion positions are determined by illuminating the chain for less than 20 ms.
- State of ***each spin*** is then measured in 300 μs detection time
- *All many-body correlations available in a single shot*

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 (20