Thermalization and Non-Thermalization in a Programmable Spin Chain of Trapped Ions

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Designer Quantum Systems Out of Equilibrium
KITP – Santa Barbara, CA

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Classical and Quantum Thermodynamics

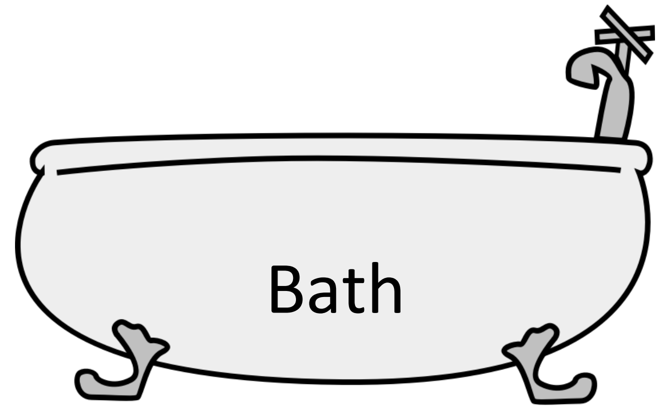
Classical Ergodic Hypothesis

$$X = \langle X \rangle$$

Long Time Average

Thermal Ensemble

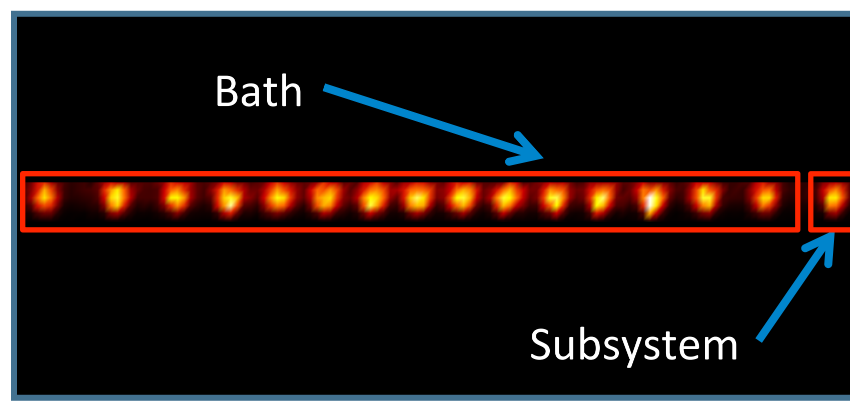
System



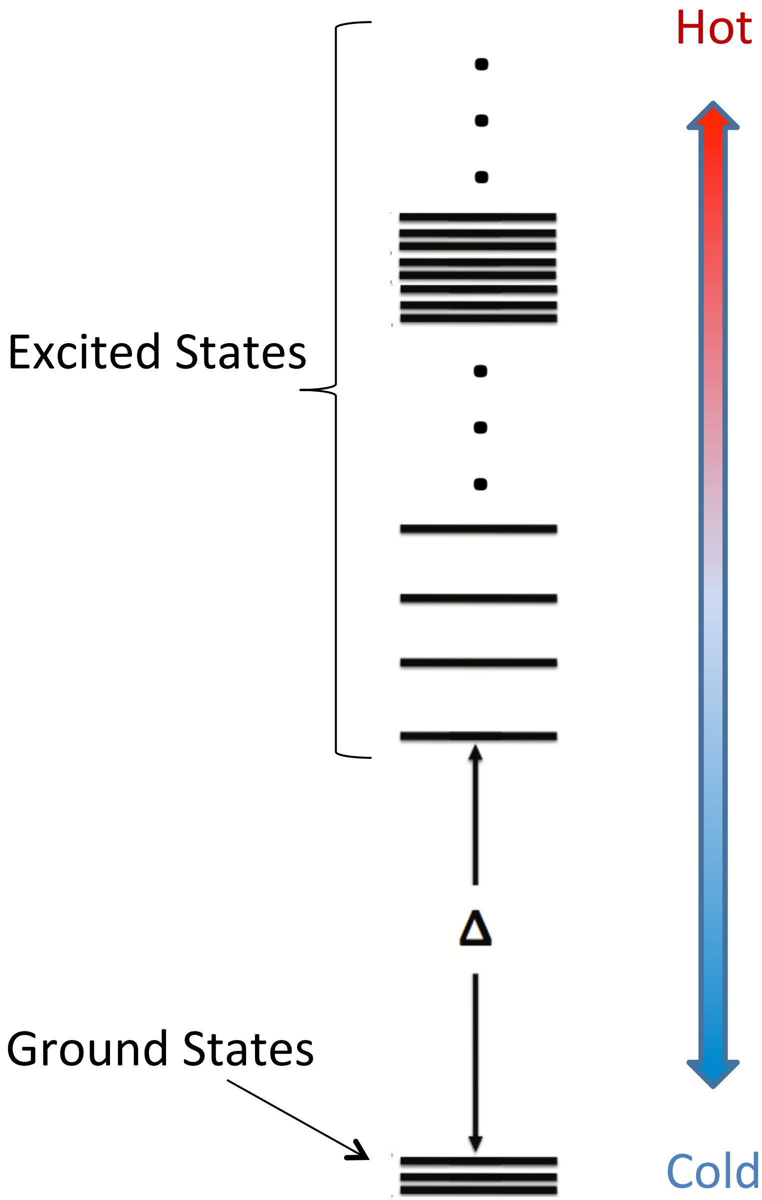
Closed Quantum Systems

Can a system thermalize anyway?

Yes! … If there is lots of entanglement

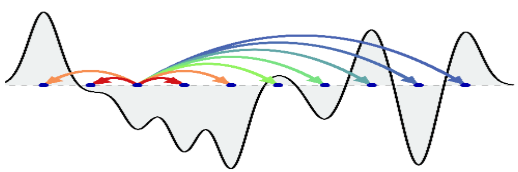


Excited States and Floquet Systems

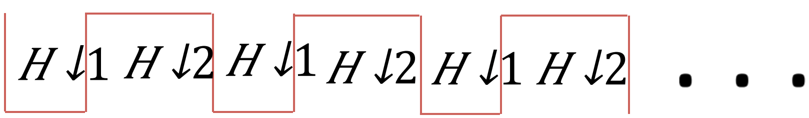


Unique Physics in Excited States:
- More generic part of the spectrum
- Necessary for describing thermal or out-of-equilibrium states
- Is there universal behavior in these states as well?

Interesting Cases:
- Many-body localization



- Floquet Systems



Preparation Schemes:
- Quantum Quenches
- Many-body excitations
- Periodic Hamiltonian Modulation

Non-Equilibrium Studies with Trapped Ions

Systems of trapped ions can exhibit tunable long range interactions

- Breaks Integrability
- Theoretically Challenging
- Model for quantum systems in nature

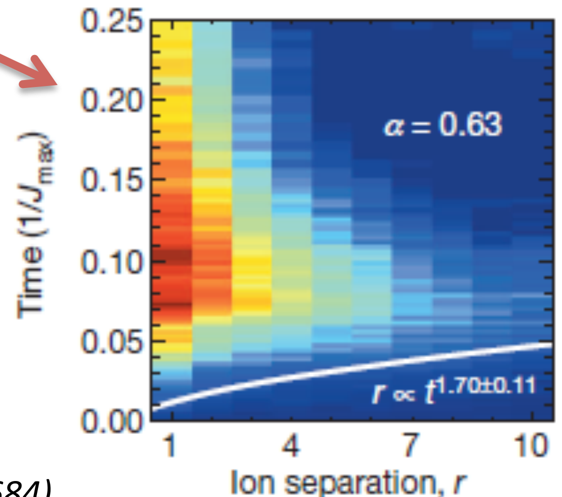
Long-Range Transverse Field Ising Model

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z$$

$$J^{i,j} \approx \frac{J_0}{|i-j|^{\alpha}}$$

Excited States and Out-Of-Equilibrium Phenomena

- Propagation of correlations after a global quench [1]
- Dynamics of excited state quasiparticles [2,3]
- Excited state many-body spectroscopy [4]
- **Many Body Localization [5] and Prethermalization [6]**
- **Floquet Systems and Discrete Time Crystals [7]**



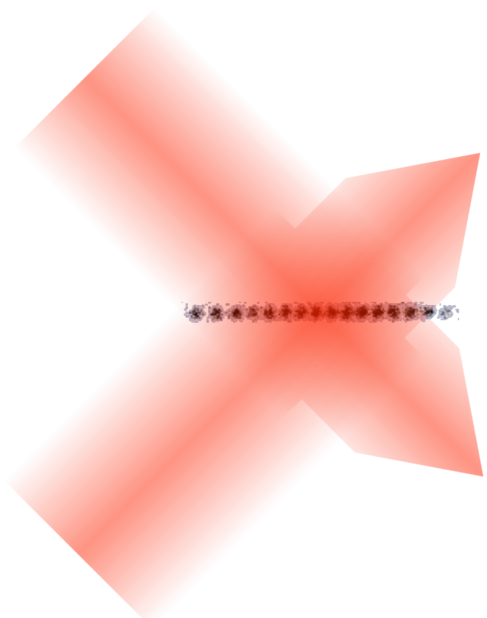
[1] Richerme *et al.*, (Nature 2014)
[2] Jurcevic *et al.*, (Nature 2014); [3] Jurcevic *et al.*, (PRL 2015)
[4] Senko *et al.*, (Science 2015); [5] Smith *et al.*, (Nphys 2016)
[6] Neyenhuis *et al.*, (*arXiv: 1608.00681*); [7] Zhang, Hess, *et al.* (*arXiv: 1609.08684)*

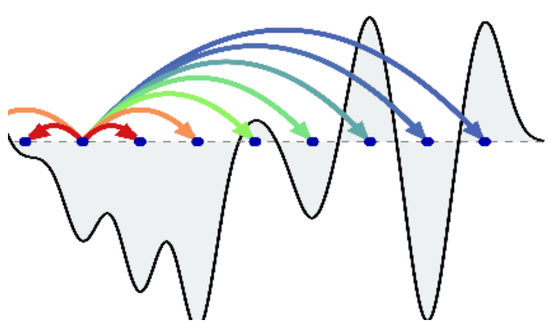
Overview

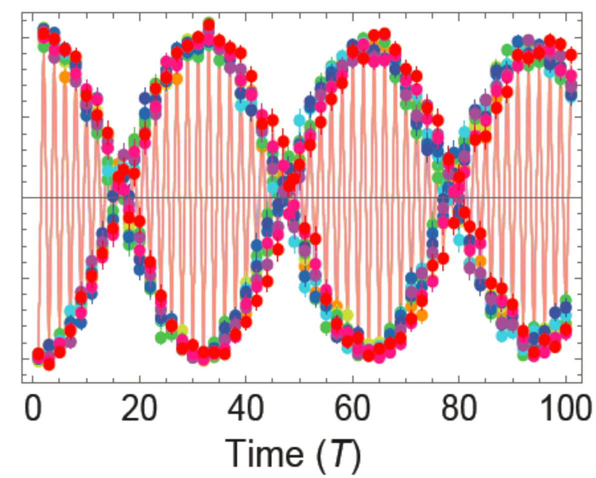
1. Generating Long Range Interacting Hamiltonians

2. Many Body Localization in Disordered Potentials

3. Observing Discrete Time Crystals in Driven Systems







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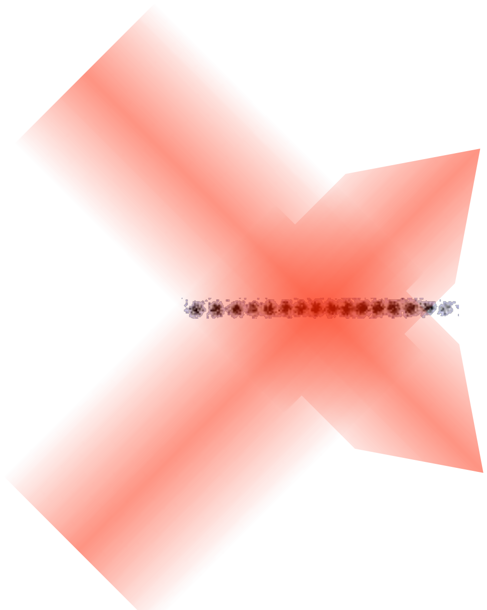
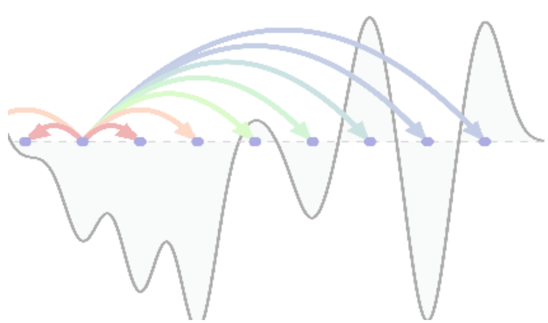
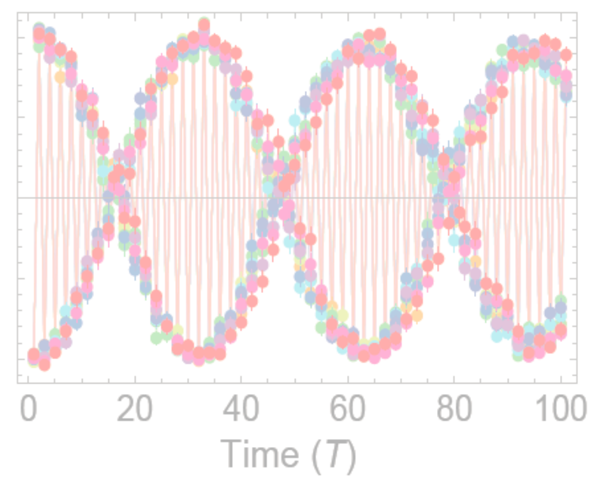




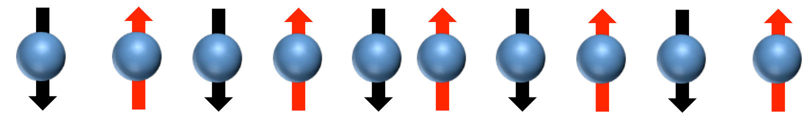


Trapped Ions for Quantum Simulation

<u>Necessary Ingredients</u>:

- ✓ Spin-1/2 degree of freedom for each ion
- ✓ Preparation of arbitrary product states

Néel State



- ✓ Readout of magnetization of each spin in a 'single shot'

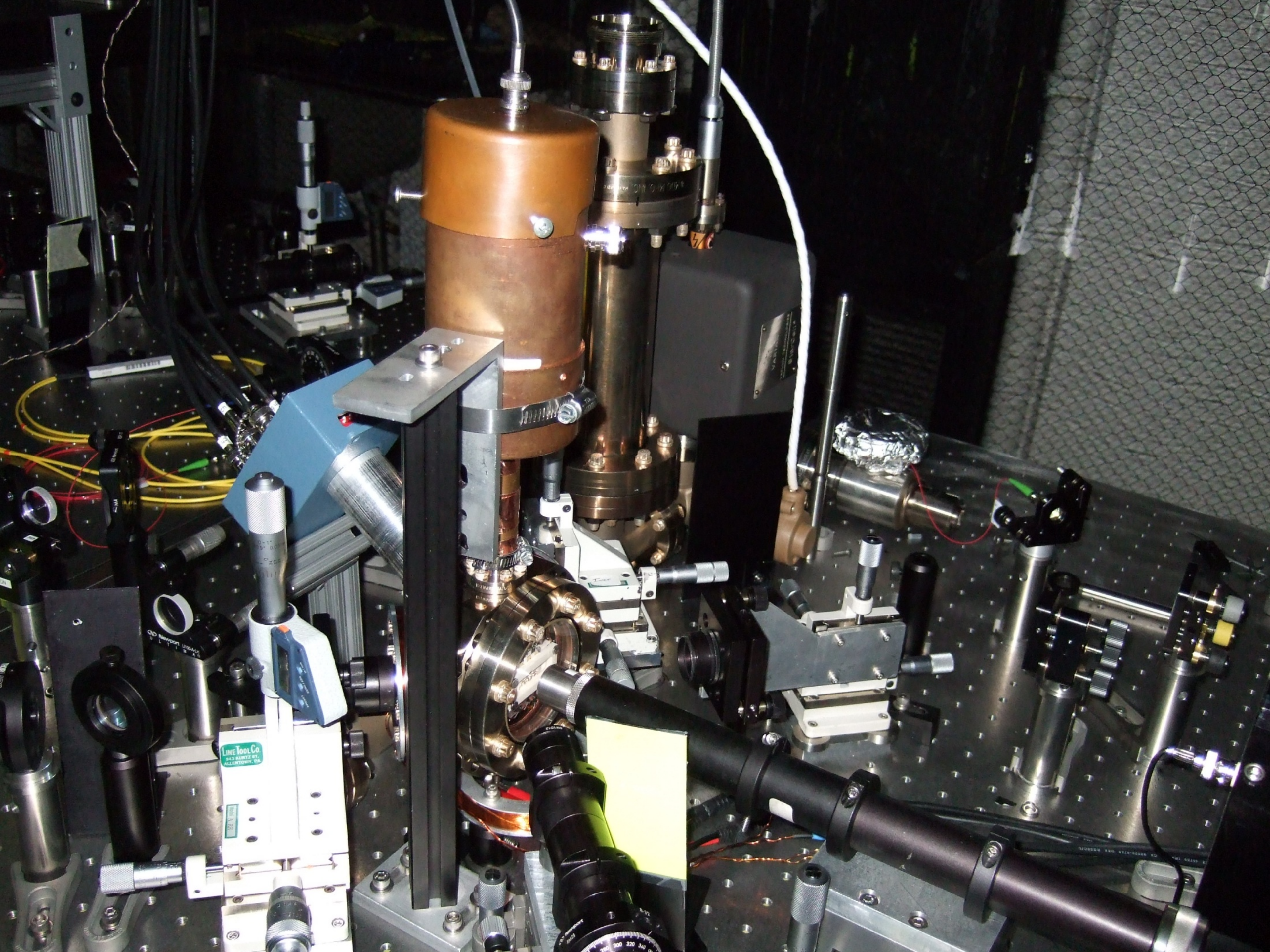
Ion Image

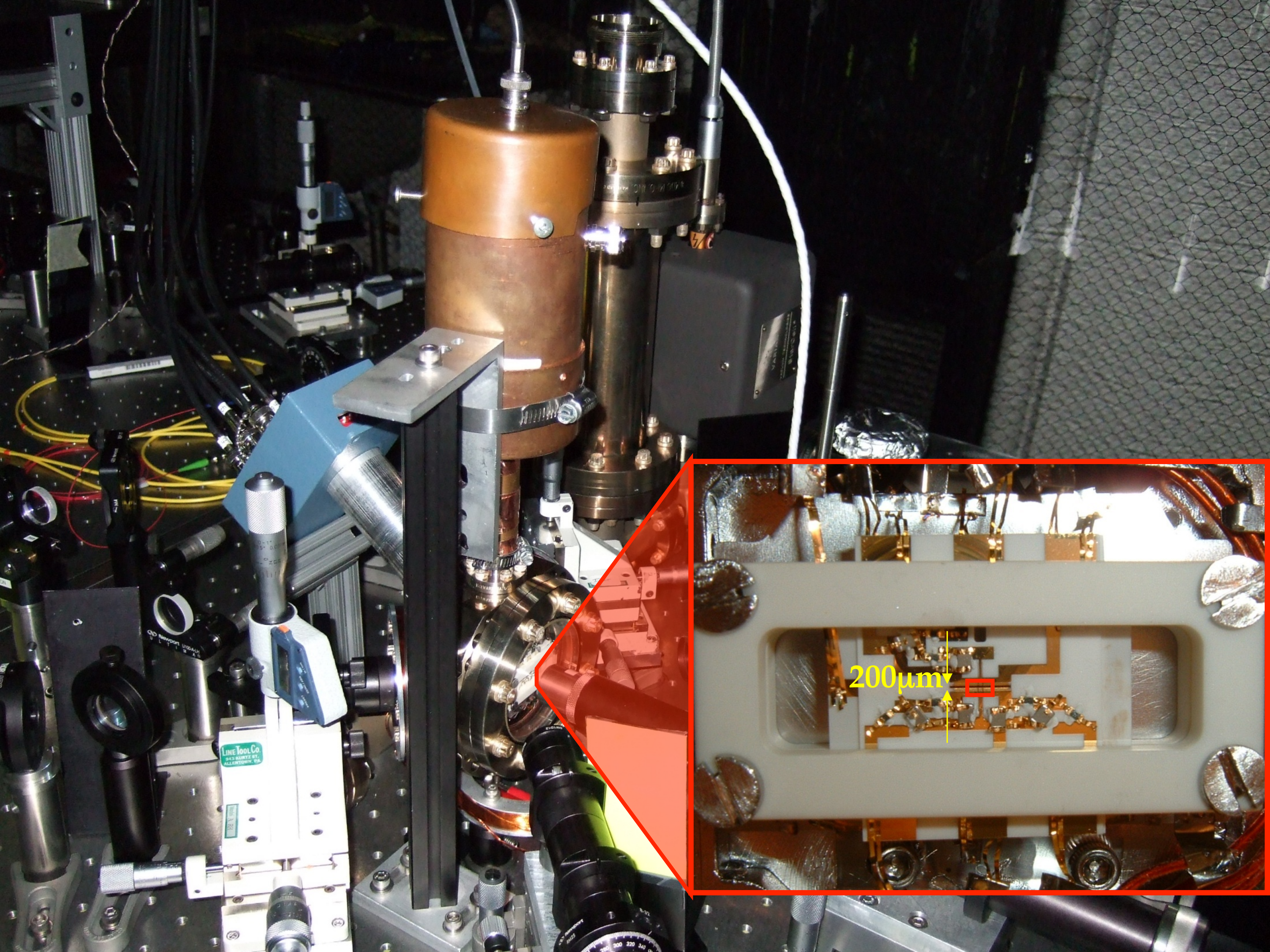
- ✓ Use optical dipole force to generate long range interaction between spins

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z$$

- ✓ Generating disordered potential for MBL work

$$+ \sum_i \frac{D_i}{2} \sigma_i^z$$


LINE TOOL CO.
943 BURTZ ST.
ALLENTOWN, PA


200μm
LINE TOOL CO.
943 BURTZ ST.
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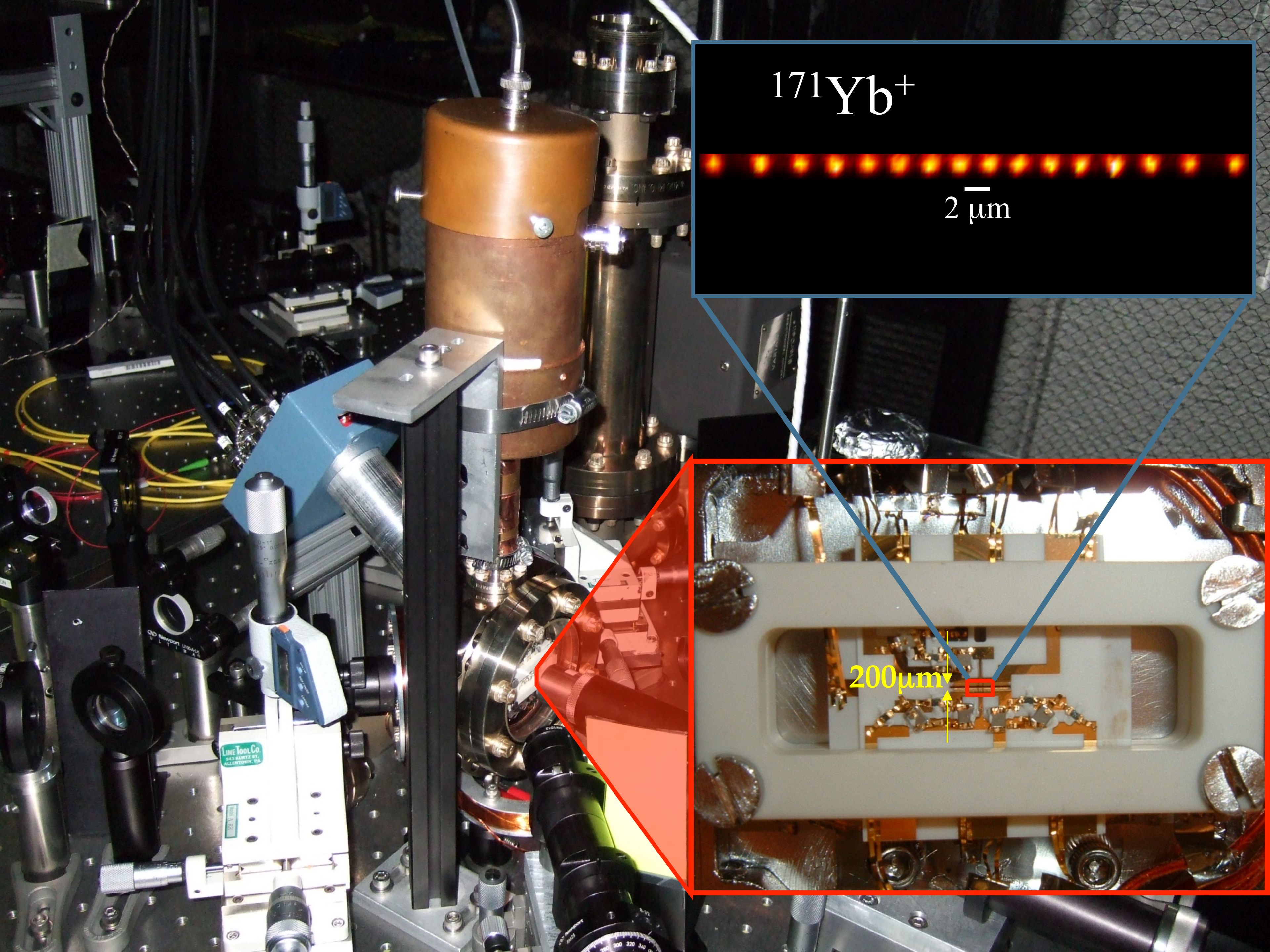
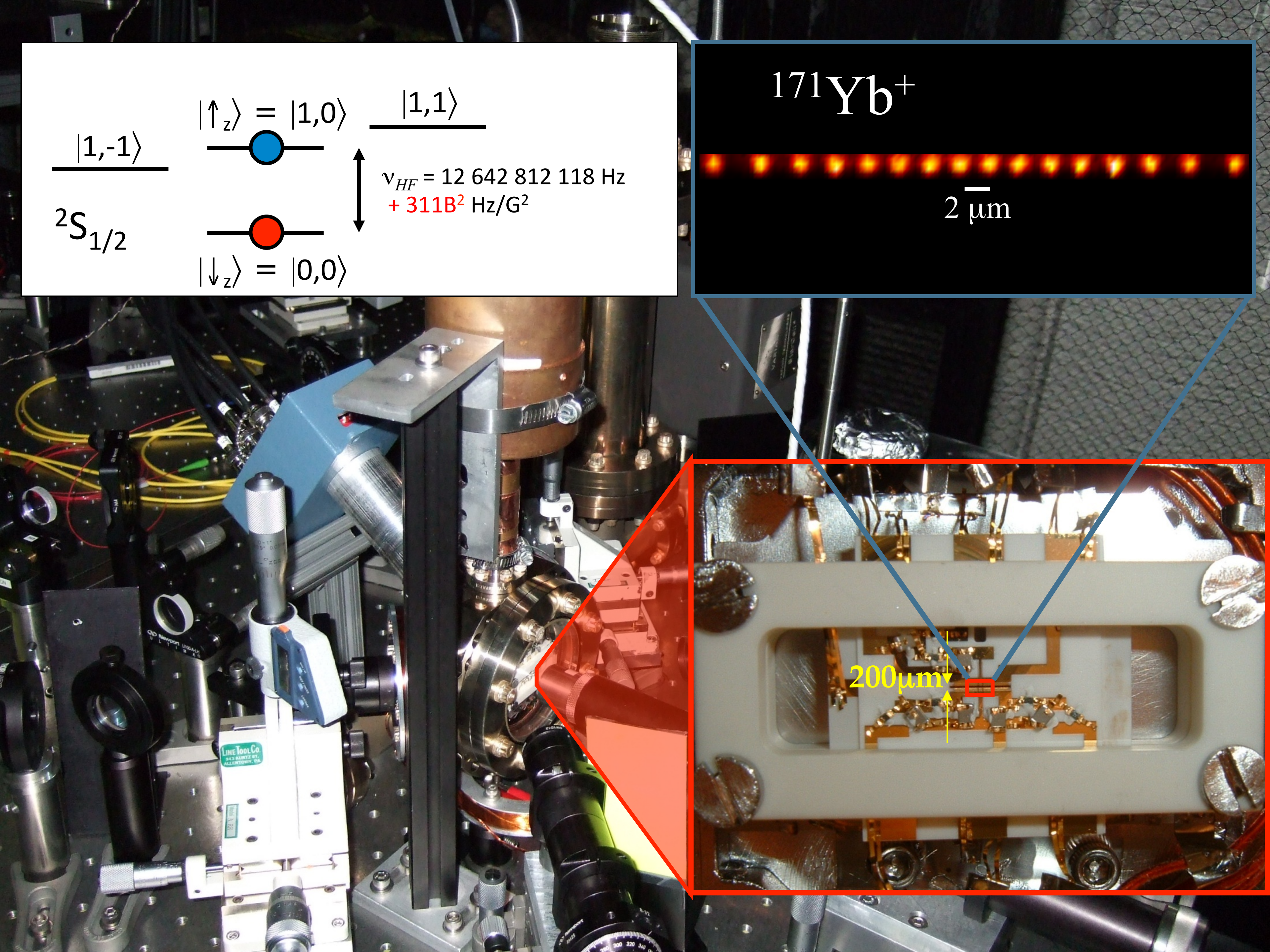
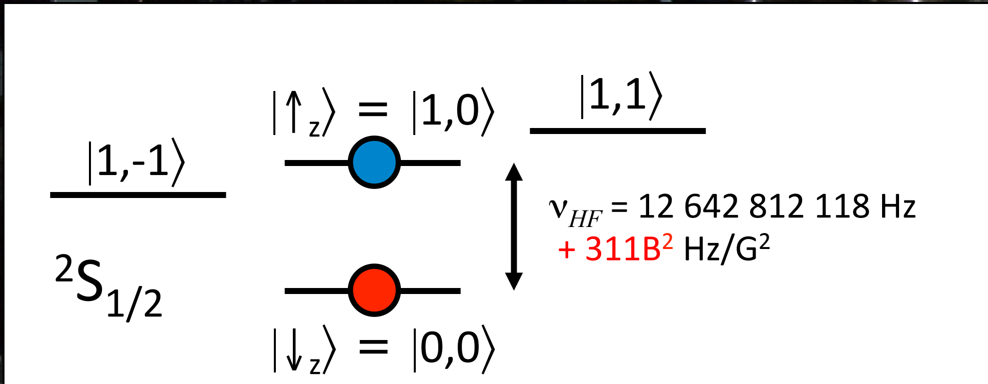


$^{171}Yb^+$
2 μm
200μm



|1,-1⟩
|↑z⟩ = |1,0⟩
|1,1⟩
²S1/2
νHF = 12 642 812 118 Hz
+ 311B² Hz/G²
|↓z⟩ = |0,0⟩
171Yb+
2 μm
200μm



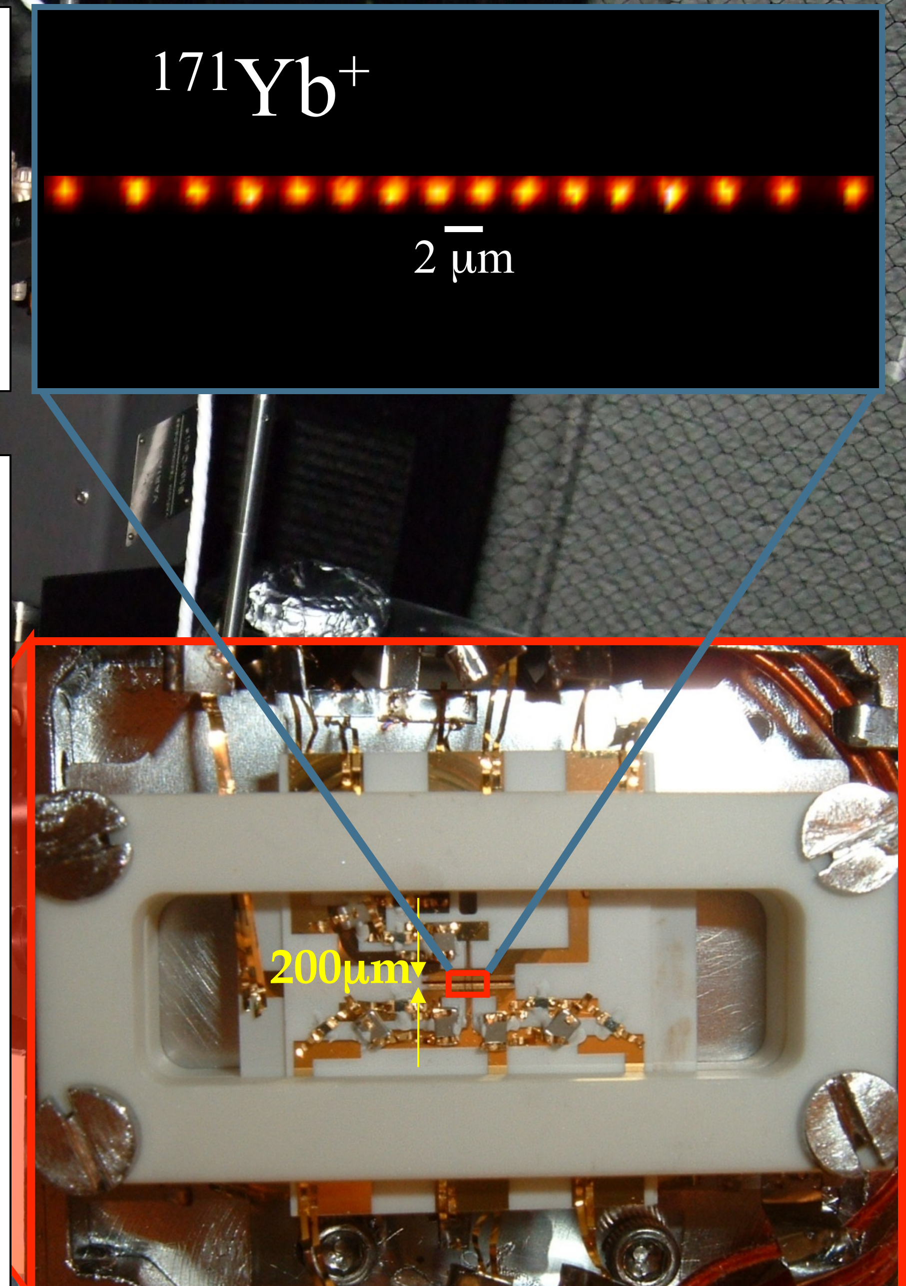
Quantum Operations from "Global Laser Beams"

1) State Preparation Via Optical Pumping

2) Coherent Rotations with Optical Raman Transitions

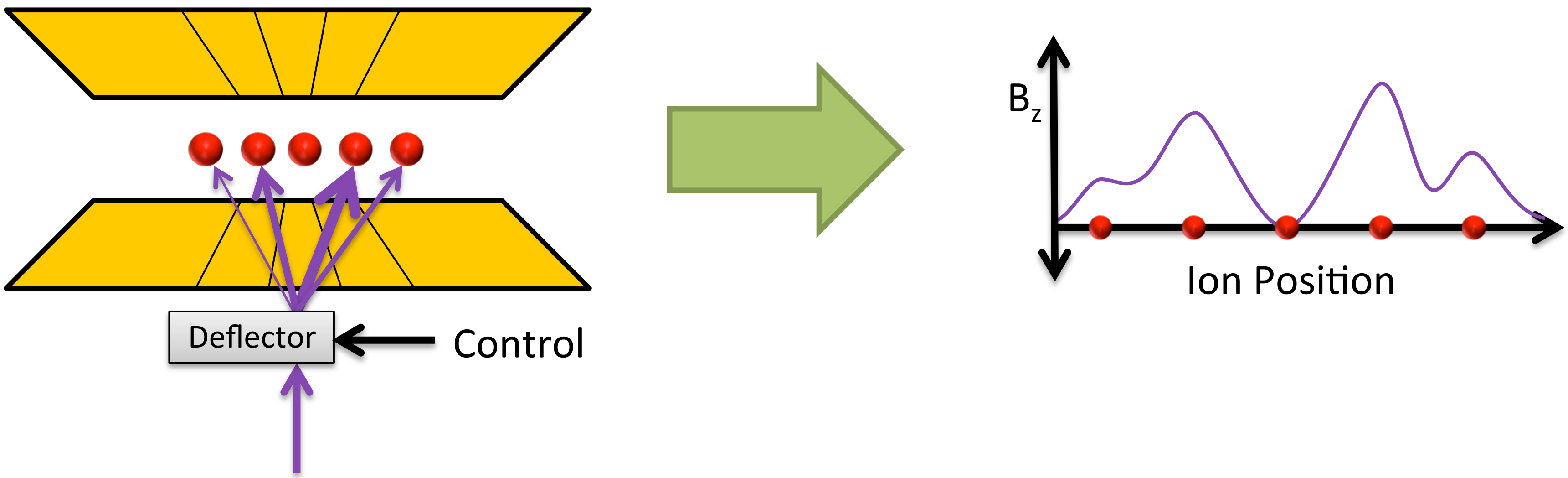
3) Single Shot State Readout Via Fluorescence

4) Single Site Imaging Resolution



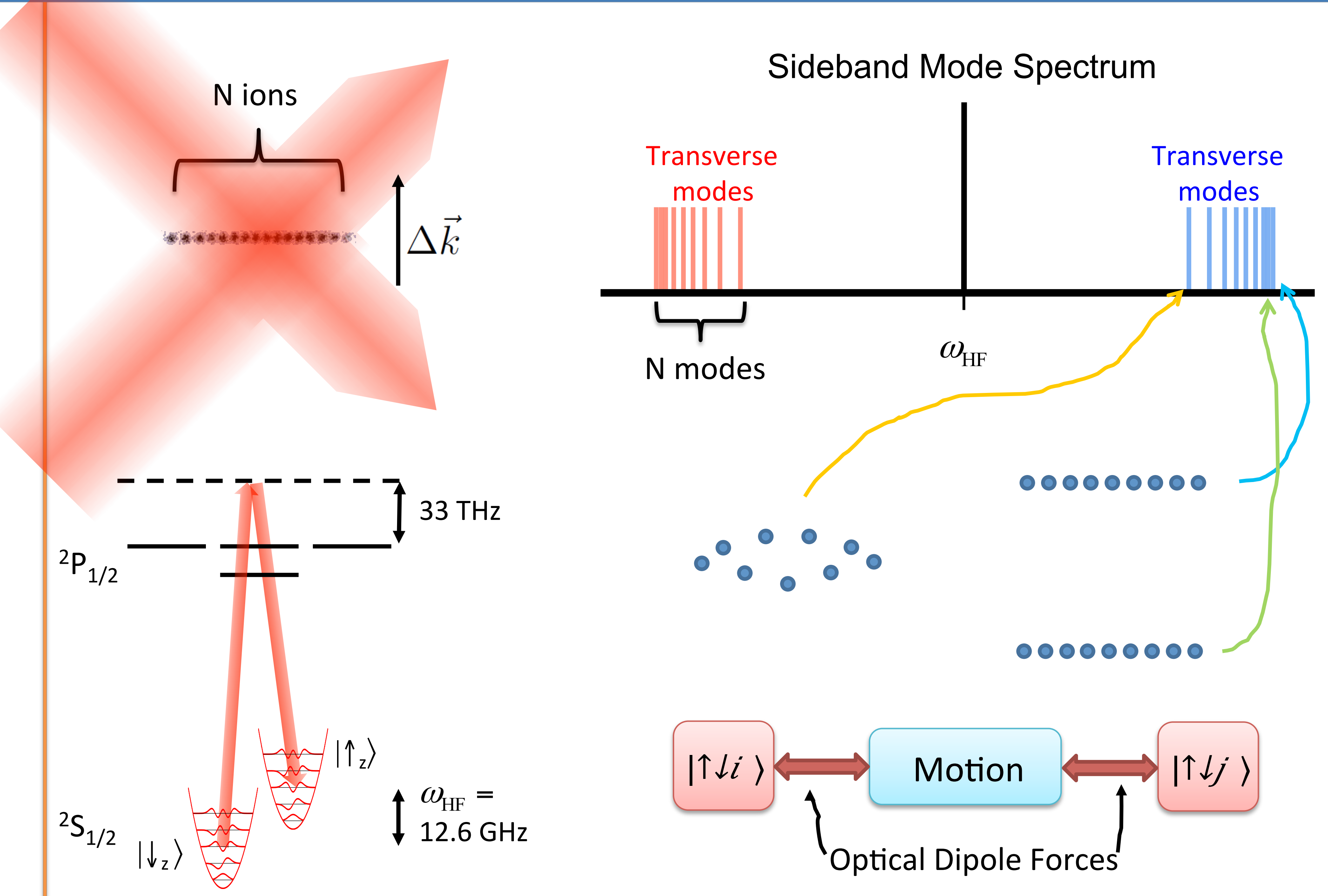
Programmable Local Fields

$$H = \frac{1}{2}\sum_i B_i^z \sigma_i^z$$

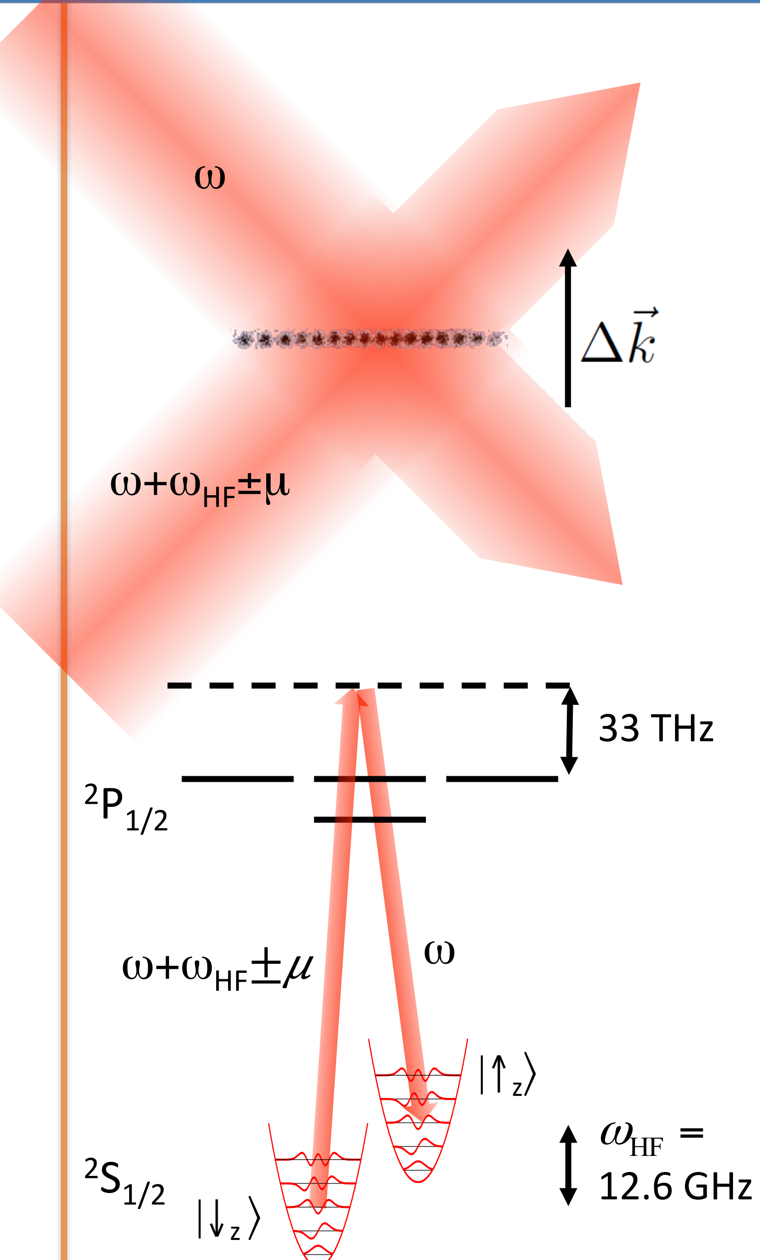


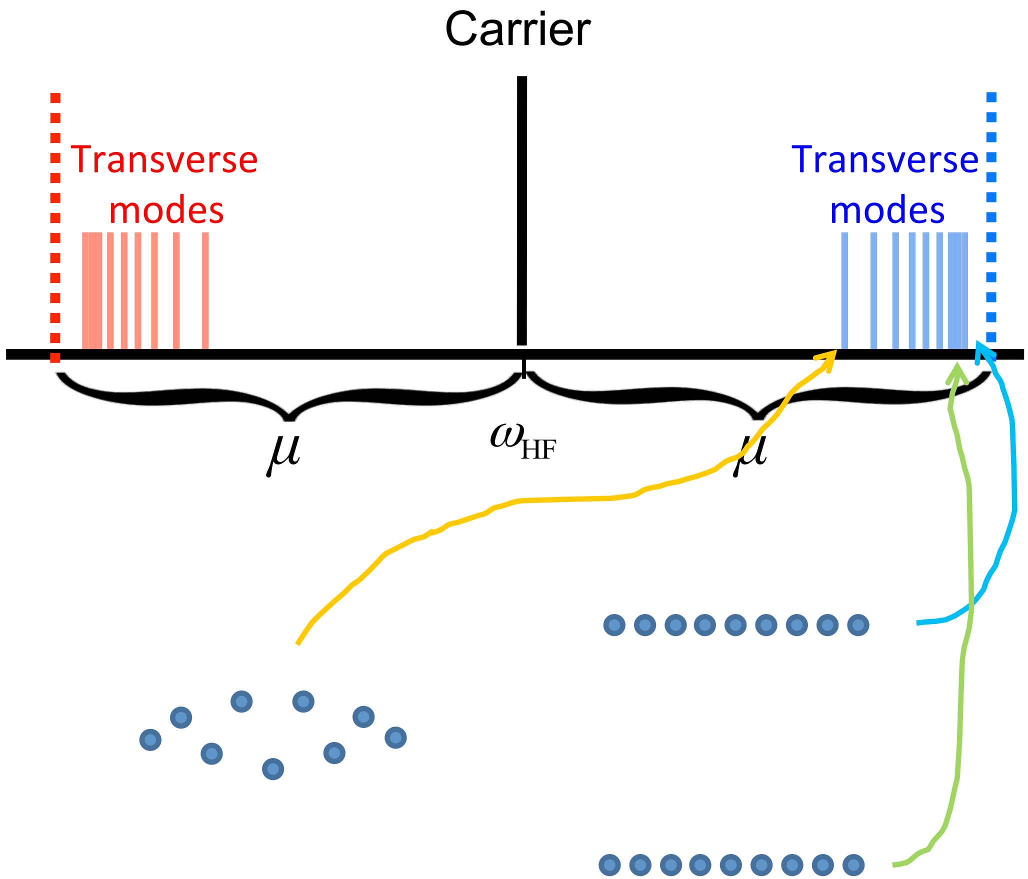
A. Lee *et al.*, PRA **94**, 042308 (2016)

Ion Motional Modes



Generating Spin-Spin Couplings





K. Mølmer and A. Sørensen, PRL **82**, 1835 (1999)
D. Porras and J.I. Cirac, PRL **92**, 207901 (2004)
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K. Kim *et al.*, PRL **103**, 120502 (2009)

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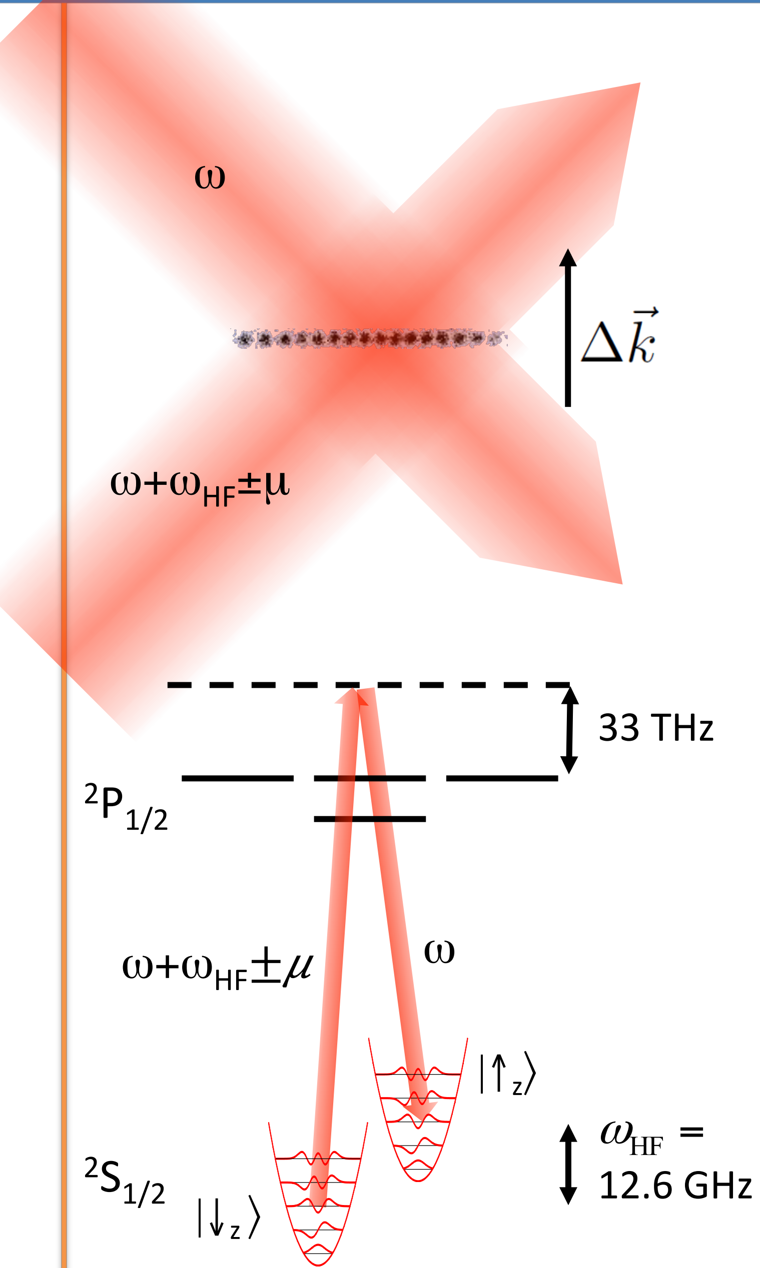

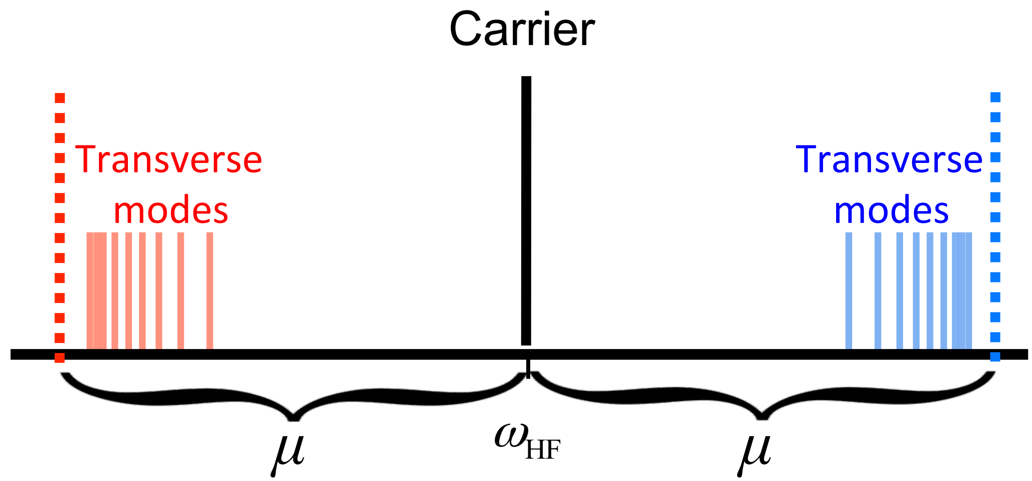

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x$$

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The Interaction Graph

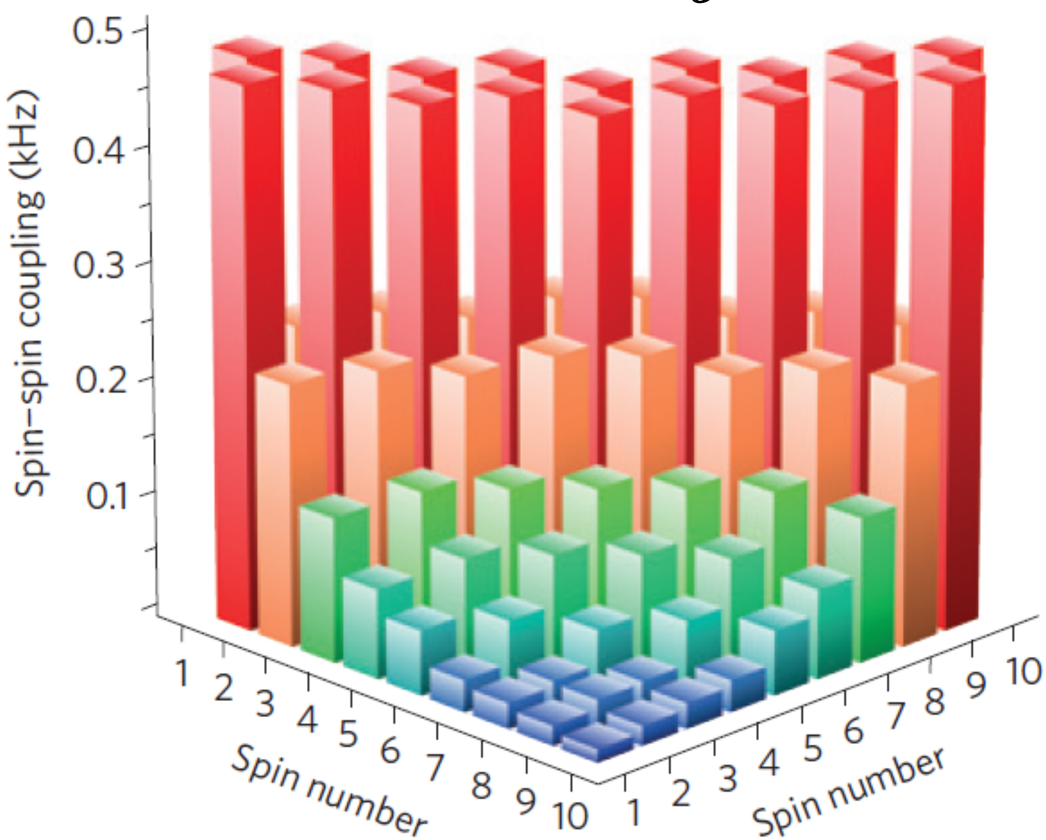
$$J^{i,j} \approx \frac{J_0}{|i-j|^{\alpha}}$$

Theoretical Range: $0 < \alpha < 3$

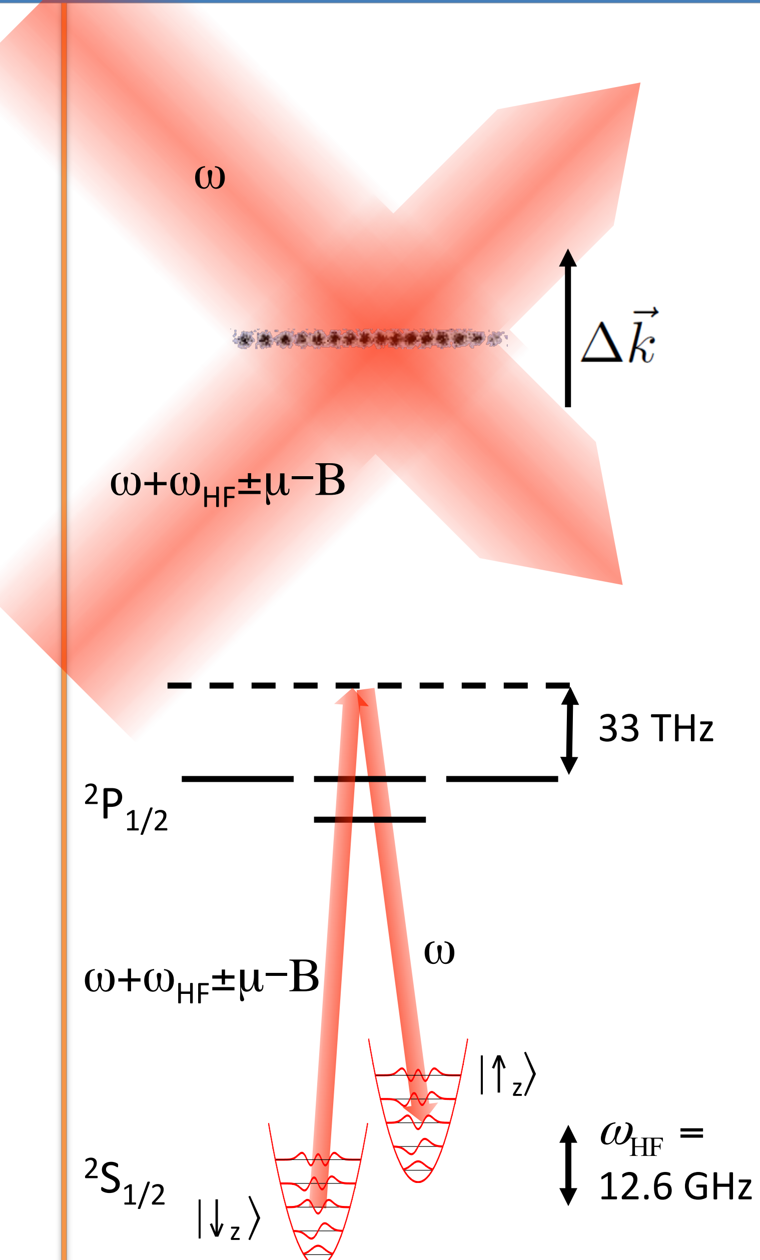
Practical Range: $0.5 < \alpha < 2$

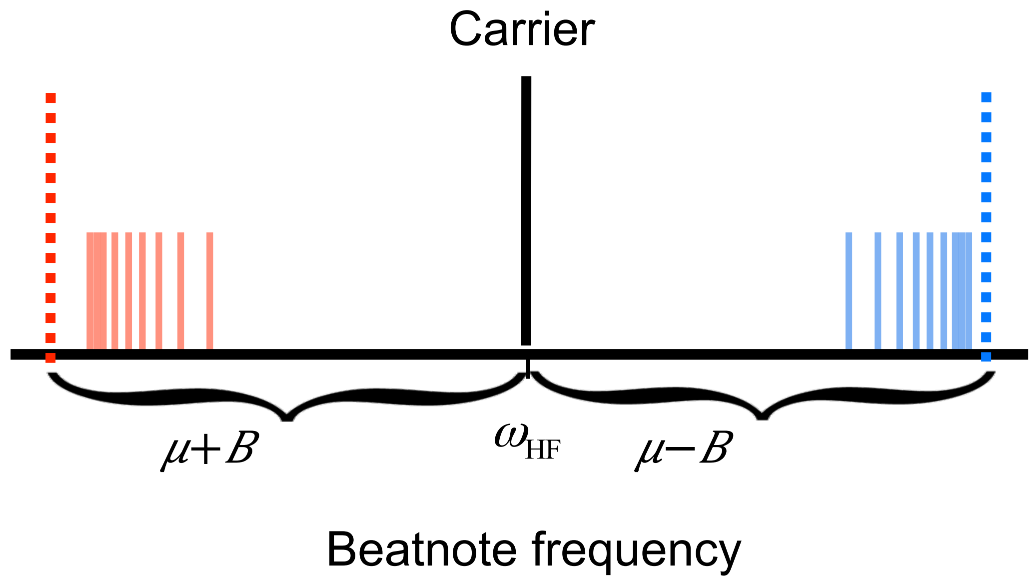
α controllable via sideband detunings and trap parameters

Measured $J^{i,j}$



Global Effective Magnetic Fields





$$H_{eff} = \sum_{i<j} J^{i,j}\sigma_i^x\sigma_j^x + \frac{B}{2}\sum_i \sigma_i^z$$

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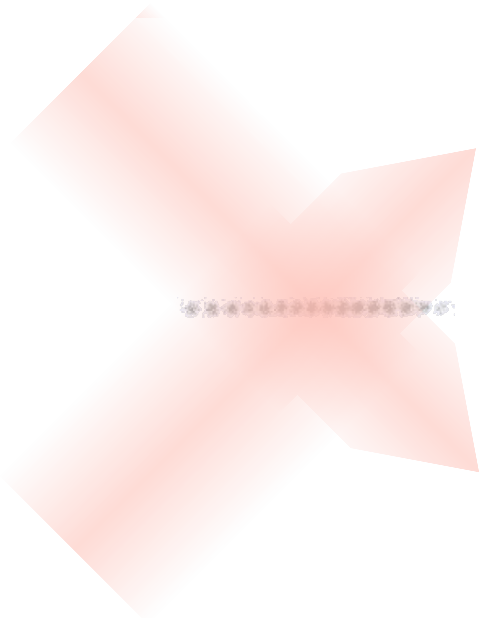
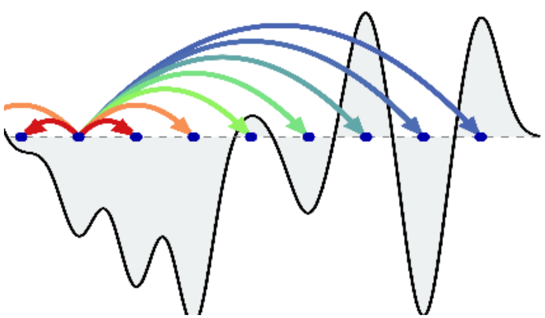
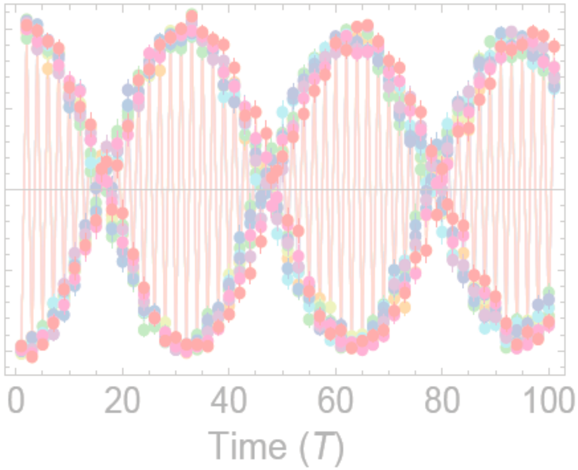






Localization and Disorder

How can closed quantum systems thermalize?

→ Eigenstate Thermalization Hypothesis

Rigol *et al.*, (Nature 2008); Srednicki (PRE 1994); Deutsch (PRA 1991)

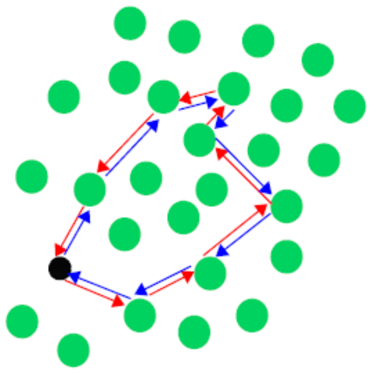
How can closed quantum systems fail to thermalize?

→ Conserved Quantities (Integrability) ⇒ "Prethermalization"

→ Disorder

Anderson Localization

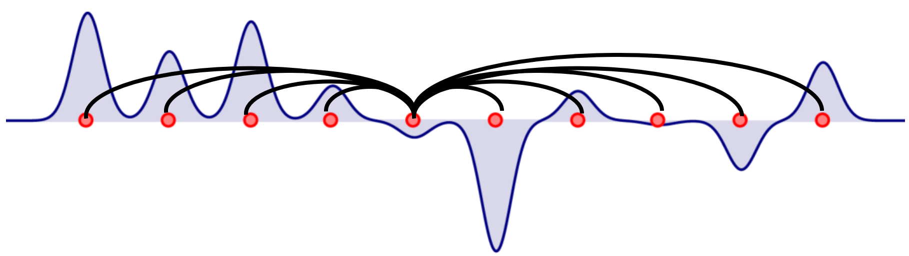
No Interactions



Anderson (Phys Rev 1957)

Many Body Localization

Strong Interactions + High Temperatures



Basko *et al.*, Ann. Of Phys. **321**, 1126 (2006)

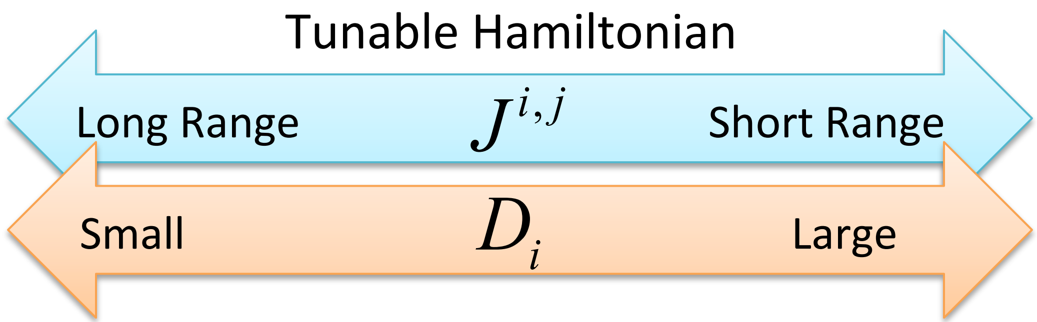
A. Pal and D. A. Huse, Phys. Rev. B **82**, 174411 (2010)

P. Hauke and M. Heyl, PRB **92**, 134204 (2015)

Signatures of MBL in our system

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z + \sum_i \frac{D_i}{2} \sigma_i^z$$

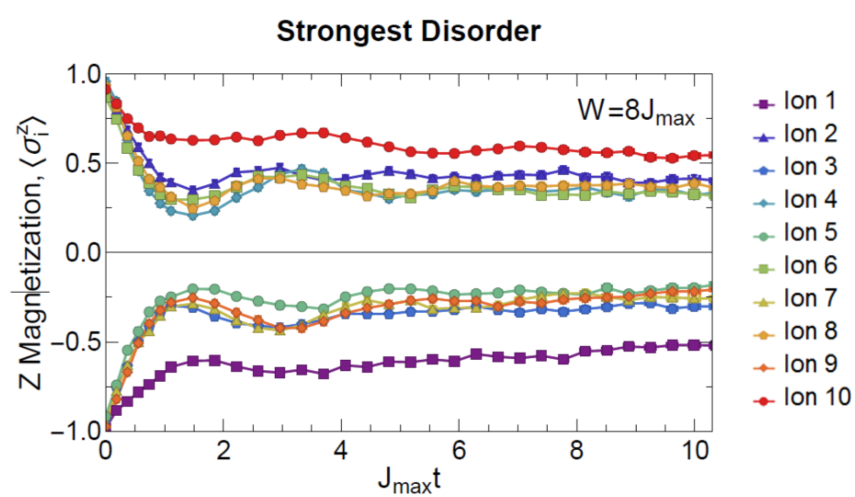
Thermalizing



Localizing

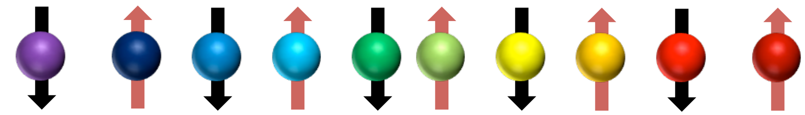
Observables

- Memory of initial conditions in spin magnetization
- Long-time growth of Quantum Fisher Information



Searching for Thermalization

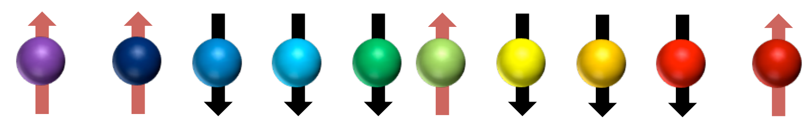
1. Initialize a product state along x or z



2. Apply Hamiltonian

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z$$

3. Measure either $\langle \sigma_i^x \rangle$ or $\langle \sigma_i^z \rangle$

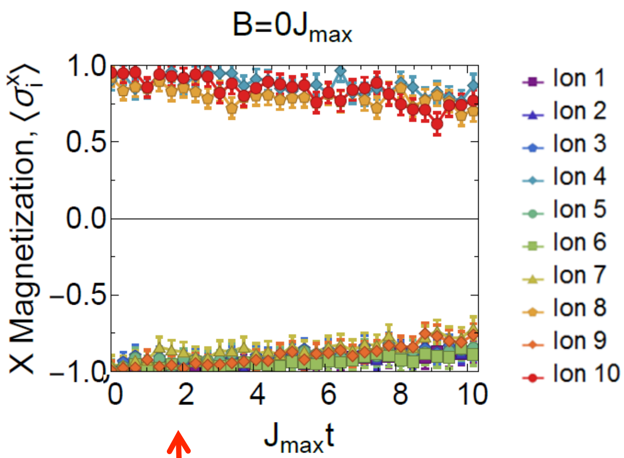


4. Repeat for different magnetic field strengths

If $\langle \sigma_i^{x,z} \rangle = 0$ → Thermal State

J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

Evidence of Thermalization

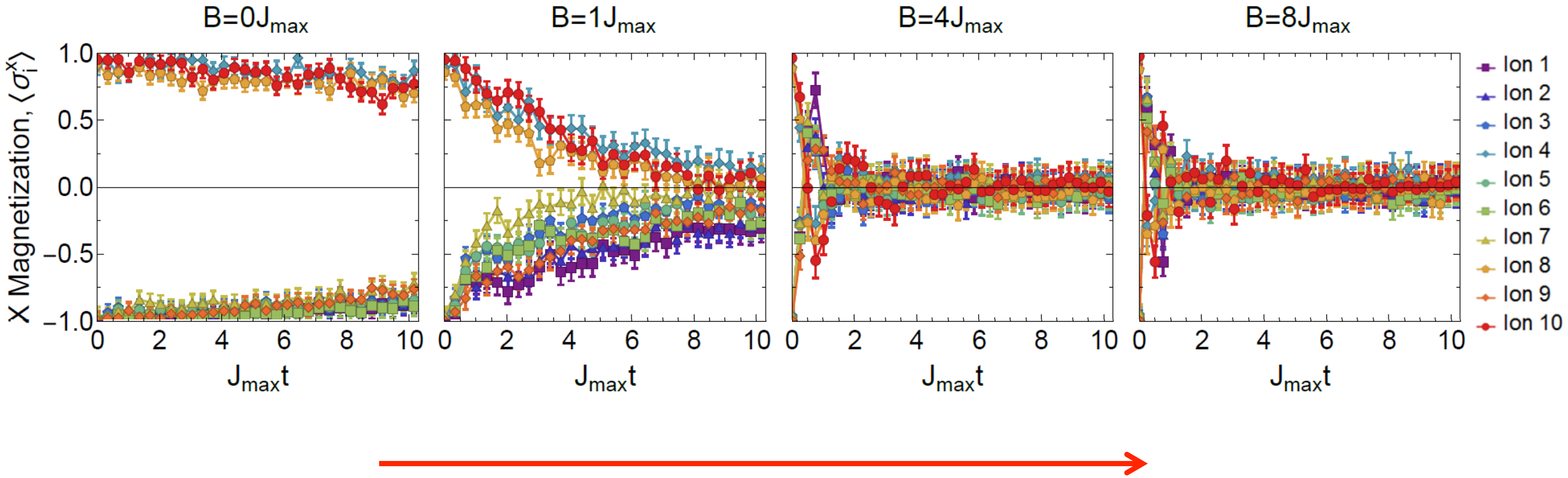


Prepared in an eigenstate

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x$$

J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

Evidence of Thermalization

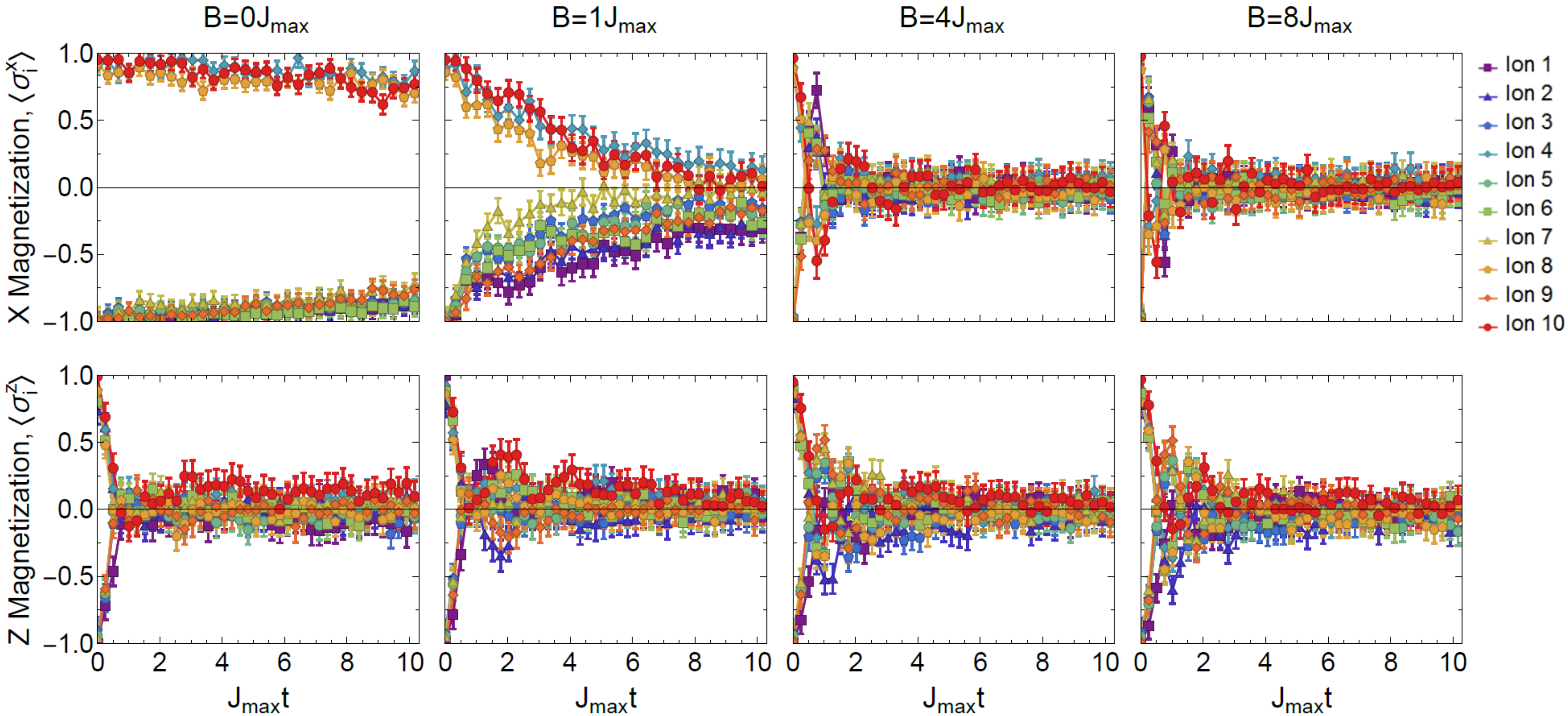


Faster Thermalization

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z$$

J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

Evidence of Thermalization



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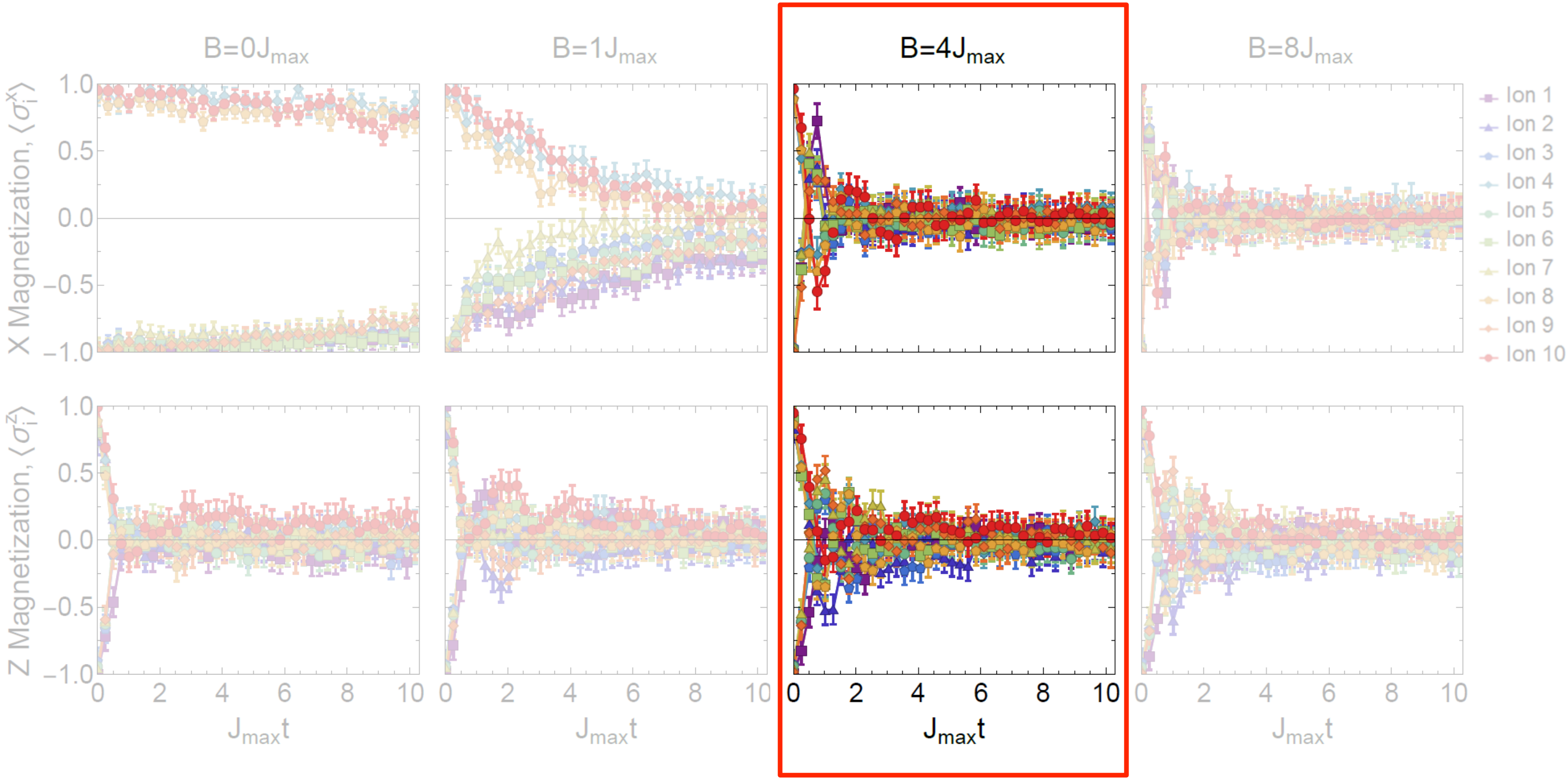

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Adding a Disordered Field

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z + \sum_i \frac{D_i}{2} \sigma_i^z$$

$$D_i \in [-W, W]$$

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Adding a Disordered Field

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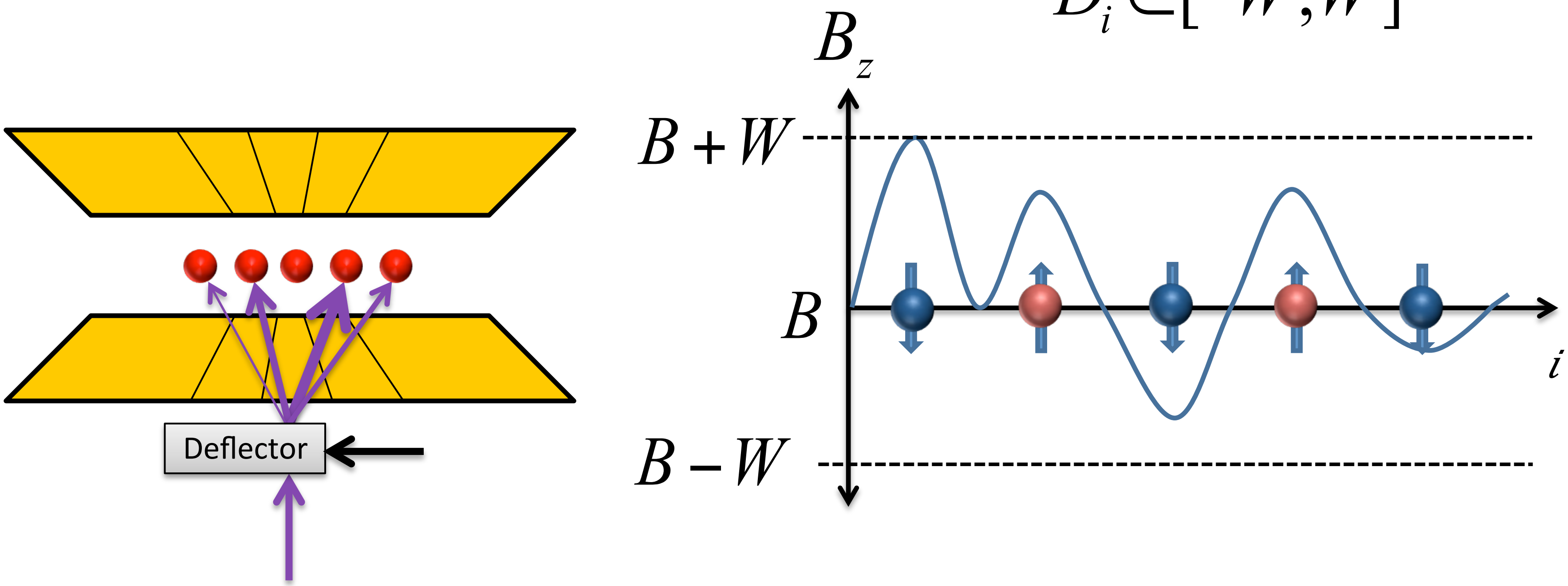
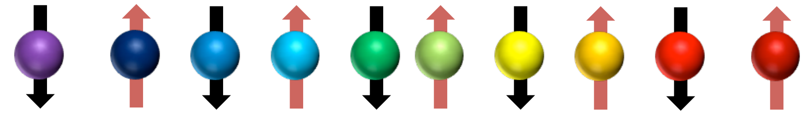


J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

Searching for Many-Body Localization

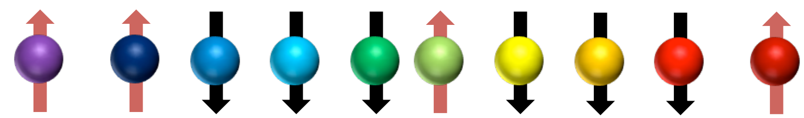
1. Initialize along z



2. Apply Hamiltonian

$$H_{eff} = \sum_{i<j} J^{i,j} \sigma_i^x \sigma_j^x + \frac{B}{2} \sum_i \sigma_i^z + \sum_i \frac{D_i}{2} \sigma_i^z$$

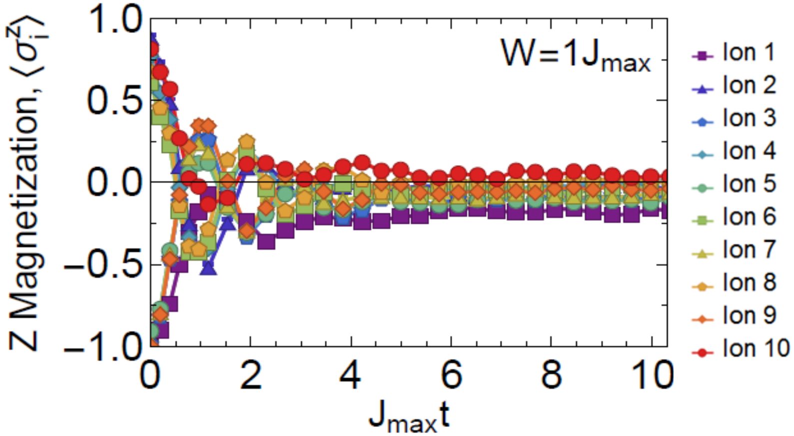
3. Measure $\langle \sigma_i^z \rangle$



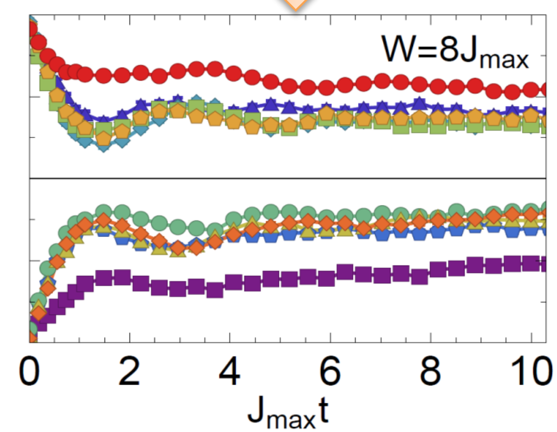
4. Repeat for different disorder strengths and instances

J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

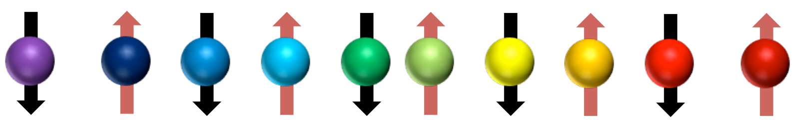
Increasing Localization with Disorder



Increase D_i



Initial Staggered State



$$H_{eff} = \sum_{i<j} J^{i,j}\sigma_i^x\sigma_j^x + \frac{B}{2}\sum_i \sigma_i^z + \sum_i \frac{D_i}{2}\sigma_i^z \qquad D_i \in [-W, W]$$

Localization in State Space

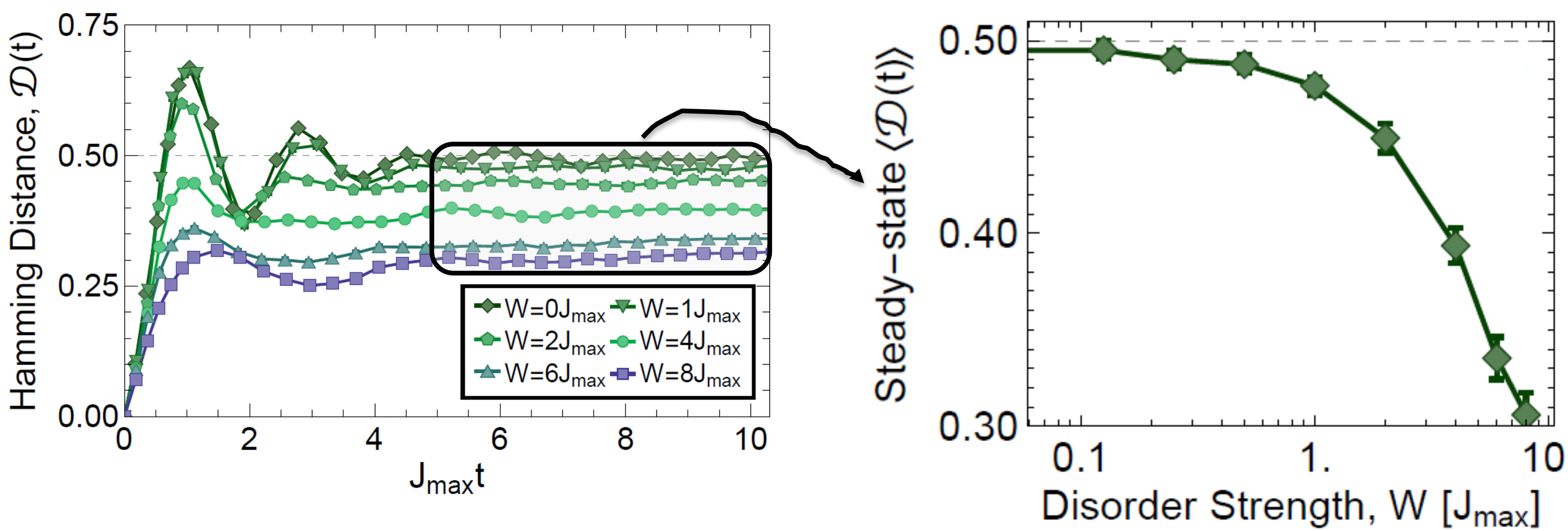
Observable: Normalized Hamming Distance between initial and final states

$$D(t) = \frac{1}{2}\left(1 - \frac{1}{N}\sum_{i}^{N}\langle\psi_0|\sigma_i^z(t)\sigma_i^z(0)|\psi_0\rangle\right)$$

→ Counts number of spin flips

→ $\mathcal{D}(t)$ = 0.5 for thermal systems

→ $\mathcal{D}(t)$ = 0 for fully localized states



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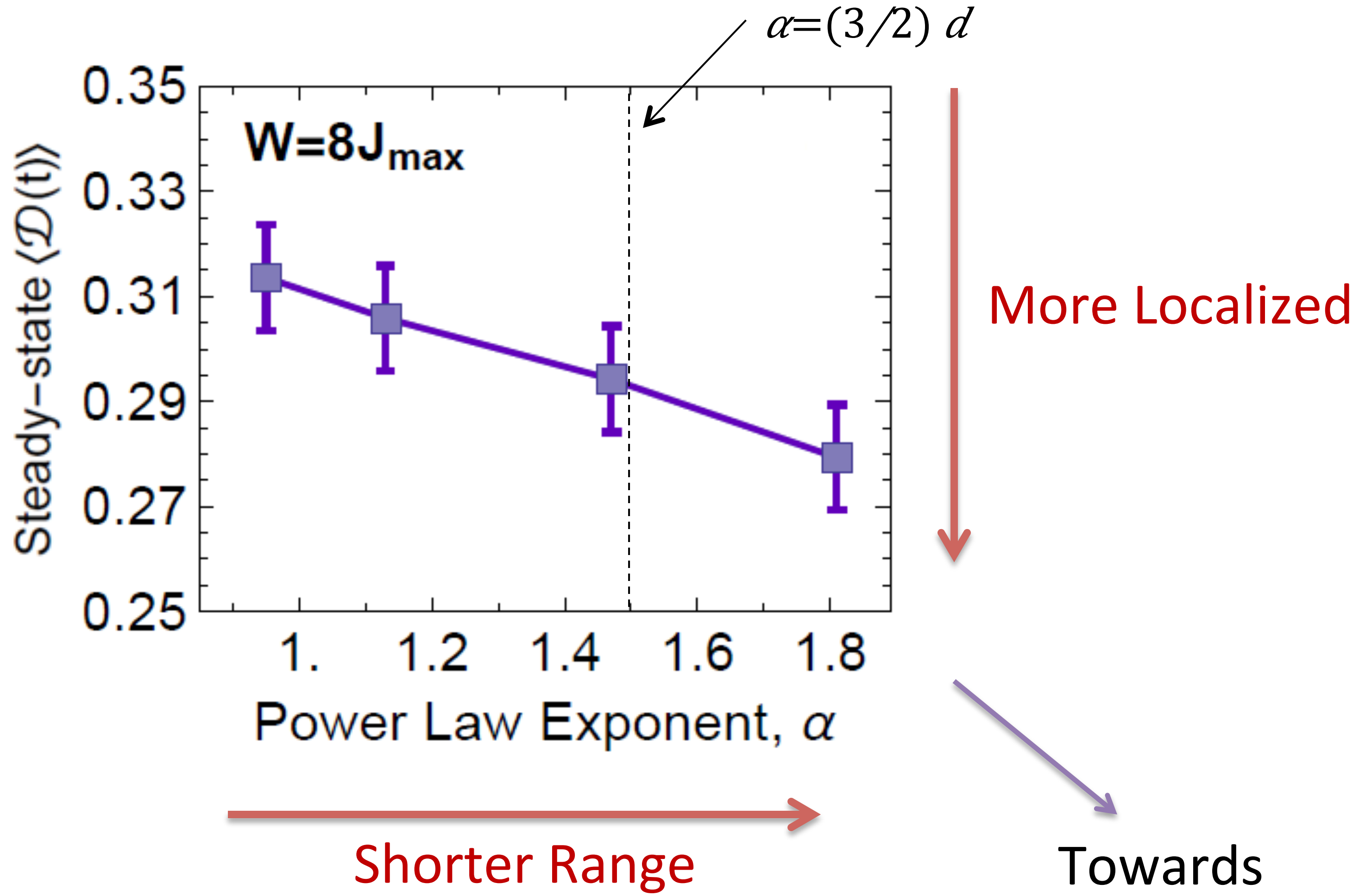
Long Range Interactions



Towards Anderson localized limit

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

J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

Quantum Fisher Information as a Witness

- Long-time entanglement growth in MBL state

$$O = \sum_{i=1}^{N} (-1)^i \frac{\sigma_i^z}{2}$$

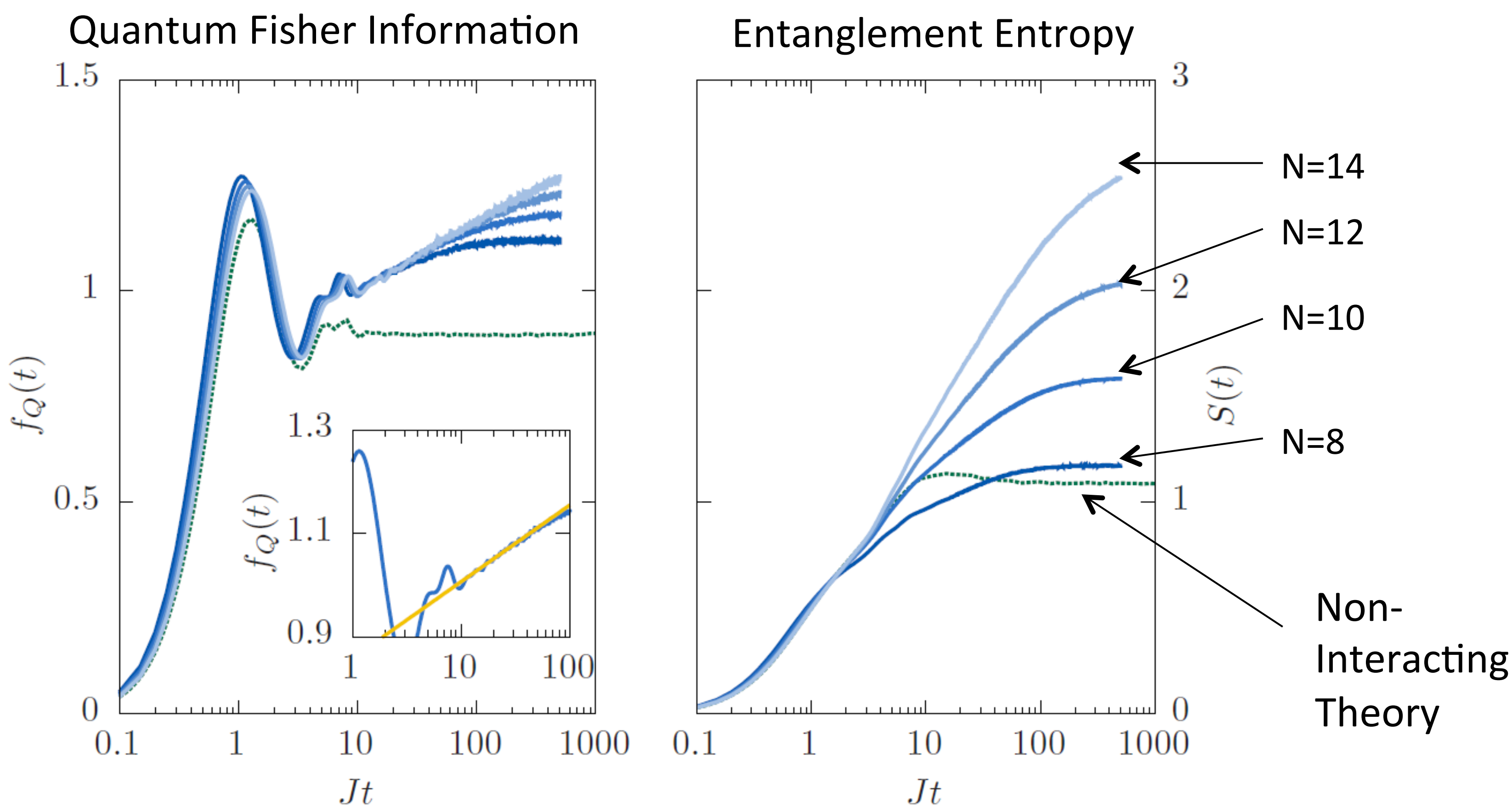
- Full tomography scales exponentially

$$QFI = \langle O^2 \rangle - \langle O \rangle^2$$

- Witness: Quantum Fisher Information easily accessible

J. H. Bardarson, PRL **109**, 017202 (2012)
M. Pino, PRB **90**, 174204 (2014)
G. Tóth, PRA **85**, 022322 (2012)

QFI vs. Entanglement Entropy

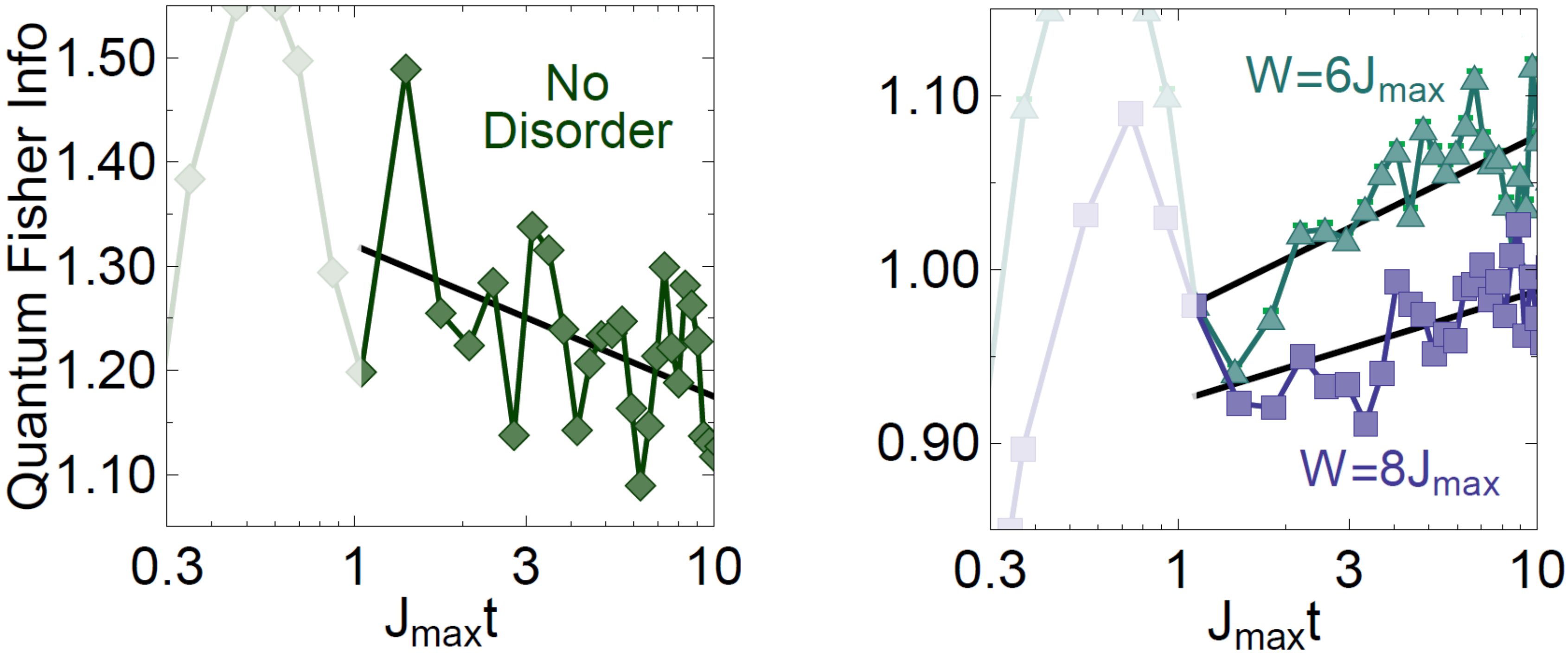


α=1.33 $W/J\downarrow max = 8$

Simulations by M. Heyl and P. Hauke

J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

Long Time Entanglement Growth



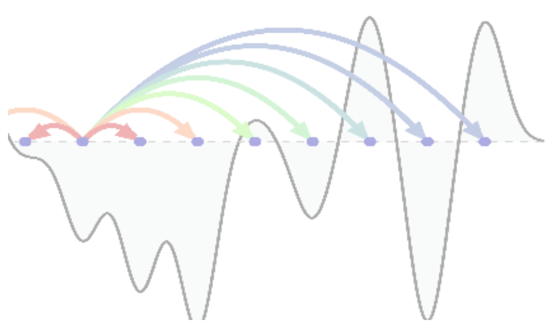
J. Smith *et al.* , Nature Physics, DOI: 10.1038 (2016)

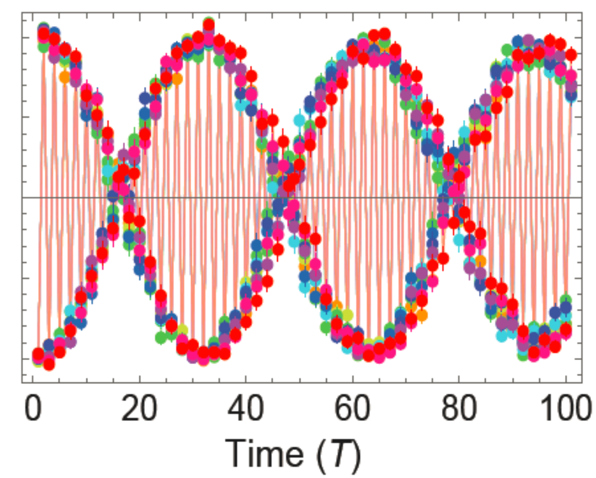
Overview

1. Generating Long Range Interacting Hamiltonians

2. Many Body Localization in Disordered Potentials

3. Observing Discrete Time Crystals in Driven Systems





What are Time Crystals?

Ion Trap?

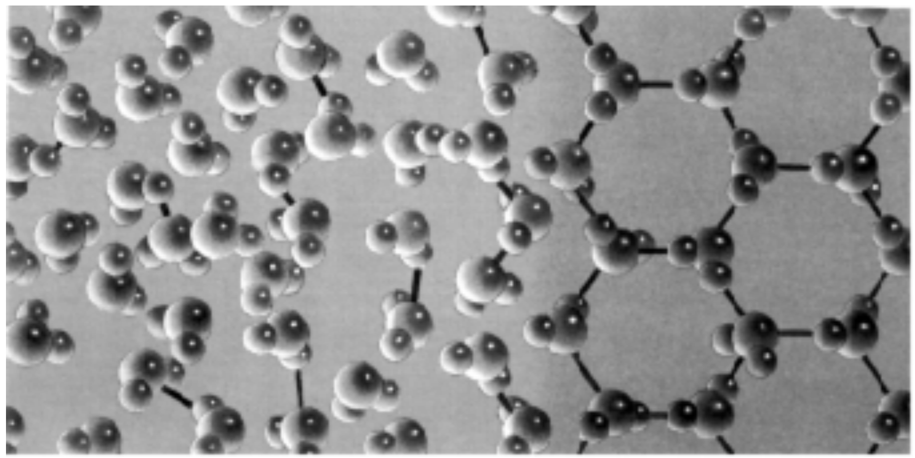
The Flux Capacitor

What are Time Crystals?

Consider a creating a spatial crystal of H_2O

Hot ⟷ Cold


Water



Ice


Continuous ⟺ Discrete

Spatial Symmetry

Can there be a similar broken symmetry in time?

Time Translational Symmetry Breaking (TTSB)

"Quantum Time Crystals"

Wilczek (PRL 2012)

H ⟹ ? $\langle \psi_0 | O | \psi_0 \rangle = f(t)$

Time Independent

Time Dependent

A Broader Definition of Time Crystals

<u>"No-Go Theorem" for Continuous Time Translational Symmetry Breaking (TTSB)</u>

~~$\langle \psi_0 | \phi(x,t) | \psi_0 \rangle = f(t)$~~ → Trivial in any eigenstate

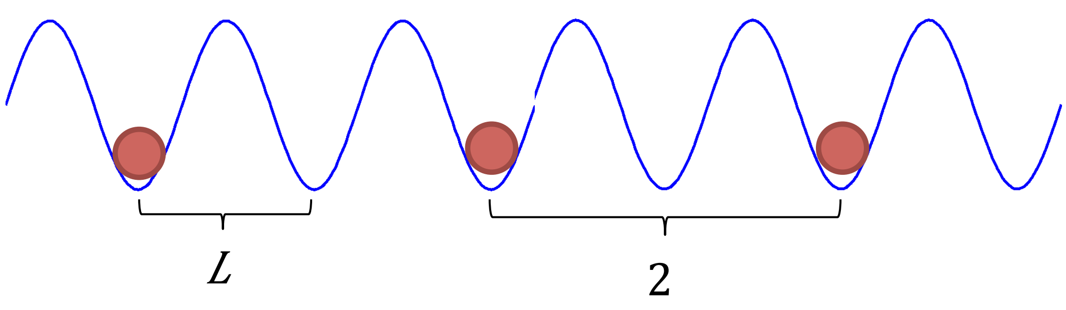
Long Range Correlations in time?

~~$\langle \psi_0 | \phi(x,t) \phi(0,0) | \psi_0 \rangle \rightarrow f(t)$~~ → No periodic time order in ground or thermal states

Watanabe & Oshikawa (2015)

What about states where symmetries are already broken?

Discrete Symmetry Breaking → Charge Density Wave



Discrete Time Crystals

Periodically Driven (Floquet) Hamilton

$H(t) = H(t+T)$ → $\langle \mathcal{O}(t)\rangle \neq \langle \mathcal{O}(t+T)\rangle$

Discrete TTSB

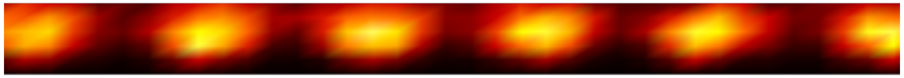
Khemani *et al*. (PRL 2016) ; Else, Bauer, Nayak (PRL 2016); N. Yao *et al.* (*arXiv: 1608.02589*)
von Keyserlingk, Khemani, Sondhi (PRB 2016)

Requirements for new Time Crystal definition:

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

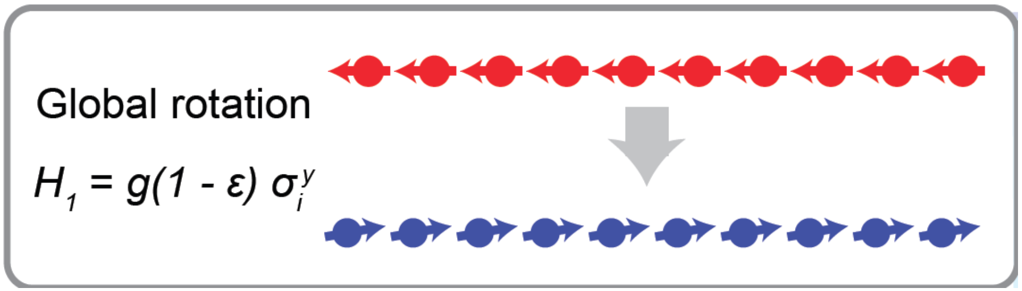
} Eliminates most "trivial" Discrete Time Crystals

Realize all three in our chain of trapped ions



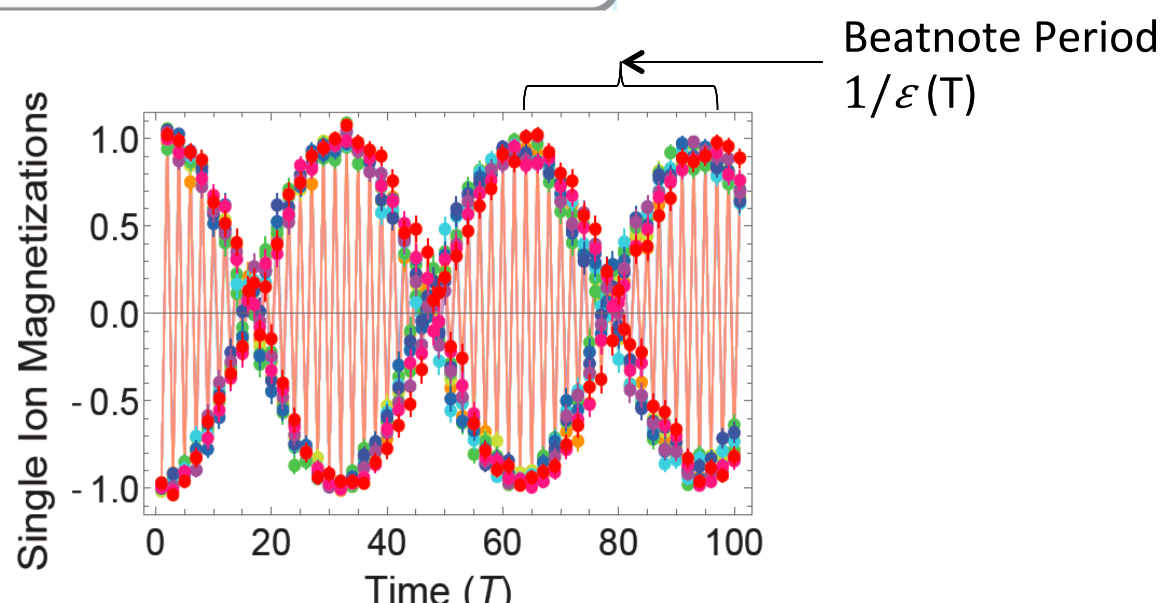
Trapped Ion Floquet Evolution

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



Perturbed

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

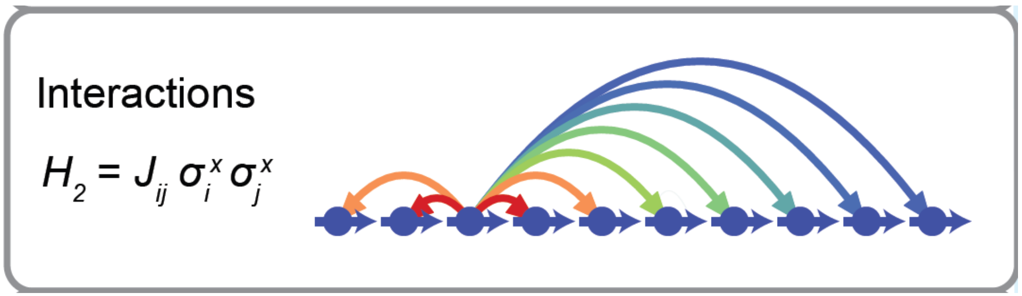


$0 \leq \varepsilon \leq 15\%$

Zhang, Hess, *et al. arXiv: 1609.08684*

Trapped Ion Floquet Evolution

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

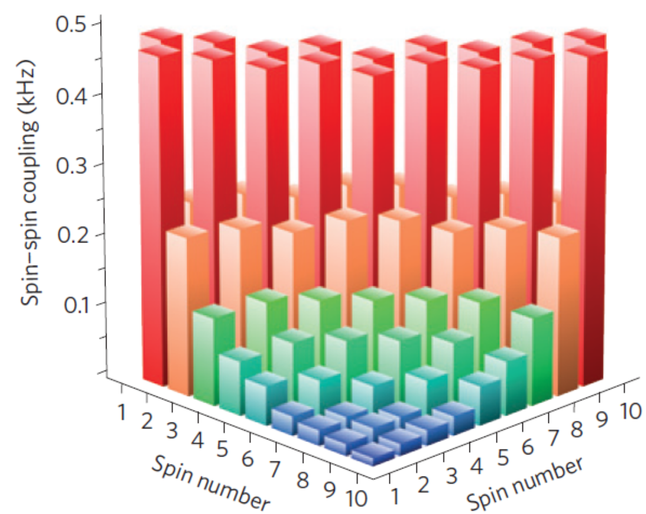


$$J_{ij} \approx \frac{J_0}{|i-j|^{\alpha}}$$

α=1.5

Weak Interactions:

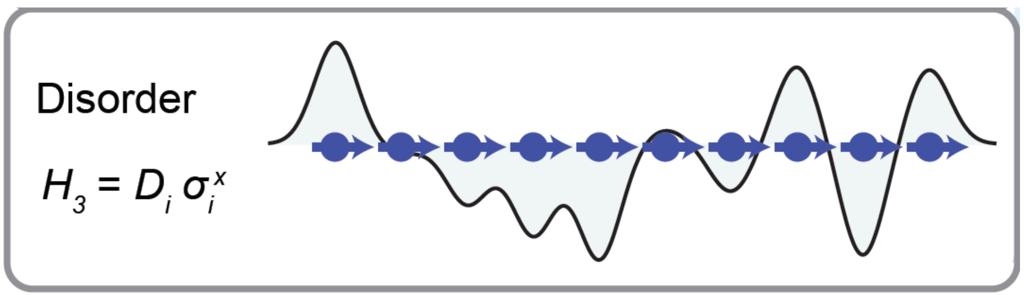
$$0.006 < J_0 t_2 < 0.04$$

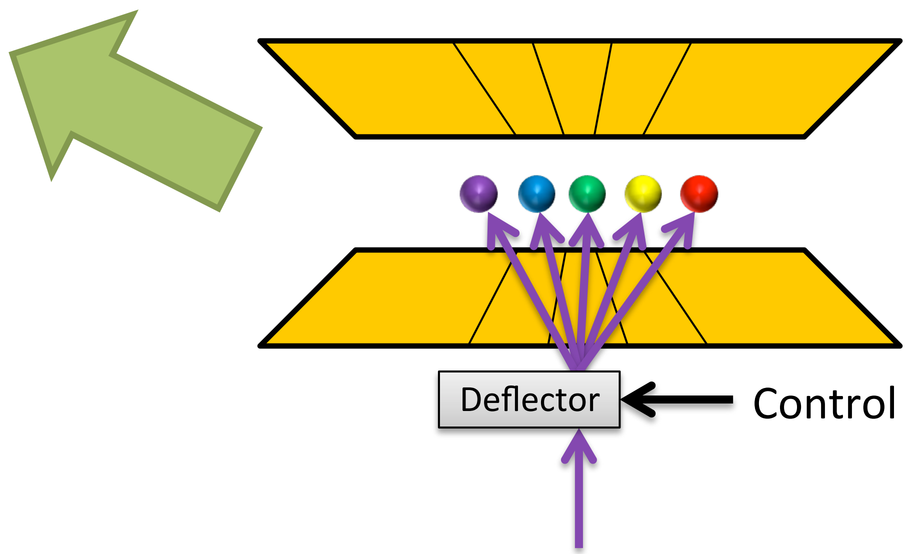


Zhang, Hess, *et al. arXiv: 1609.08684*

Trapped Ion Floquet Evolution

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





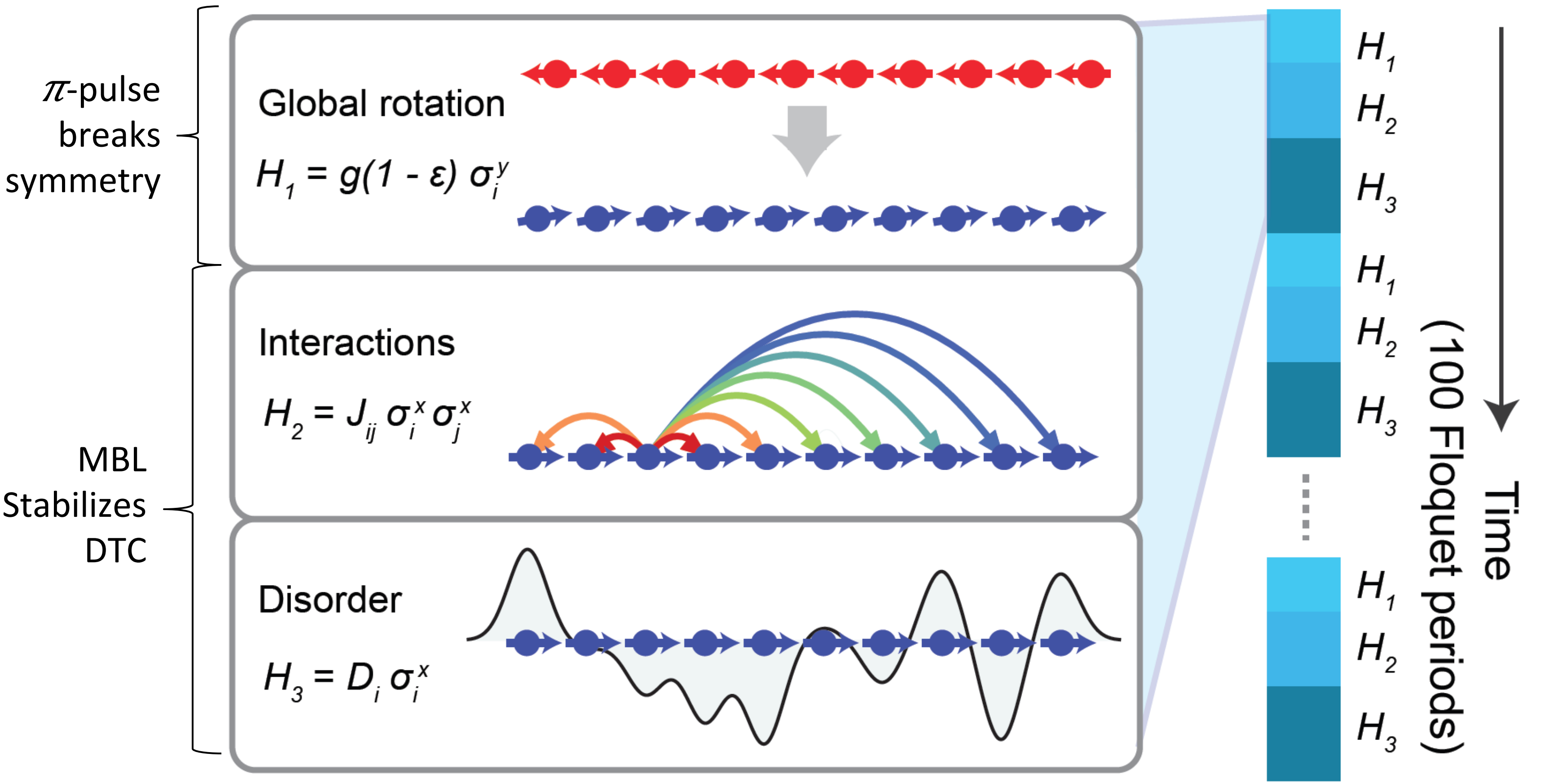
Strong Disorder:

$$D_i\, t_3 \in [0, \pi]$$

Zhang, Hess, *et al. arXiv: 1609.08684*

Trapped Ion Floquet Evolution

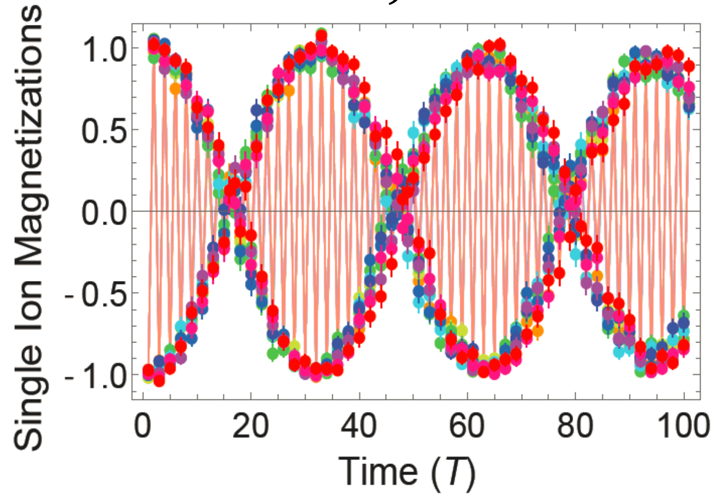
$$H = \begin{cases} H_1 = g(1-\varepsilon)\sum_i \sigma_i^y, & \text{time } t_1 \\ H_2 = \sum_i J_{ij}\sigma_i^x\sigma_j^x, & \text{time } t_2 \\ H_3 = \sum_i D_i\sigma_i^x & \text{time } t_3 \end{cases}$$



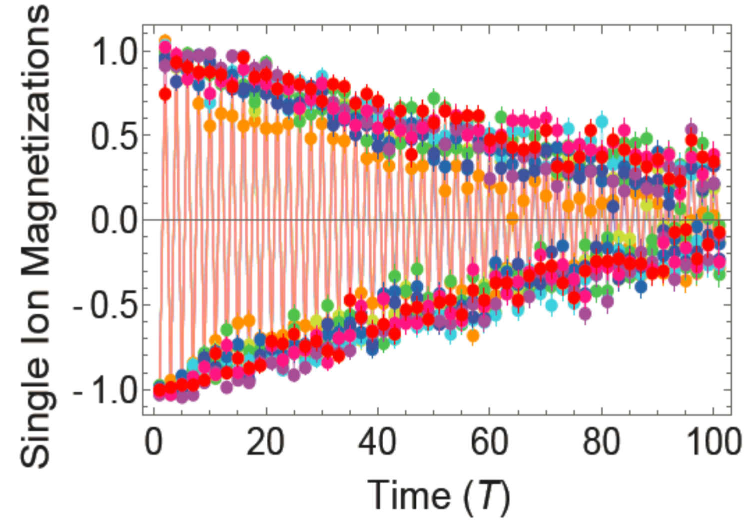
Zhang, Hess, *et al. arXiv: 1609.08684*

Stabilized Sub-Harmonic Response

No Interactions (H_2) or Disorder (H_3)

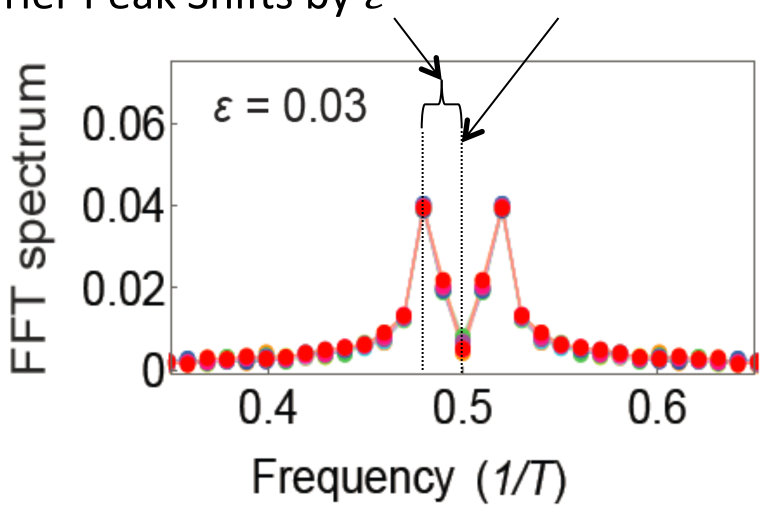


MBL Drive Stabilizes Time Crystal

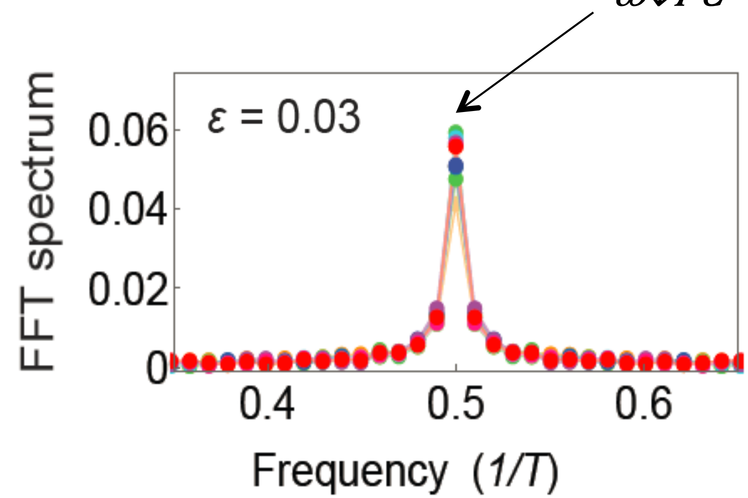


Fourier Peak Shifts by ε

$\omega_{TC} = 1/2T$

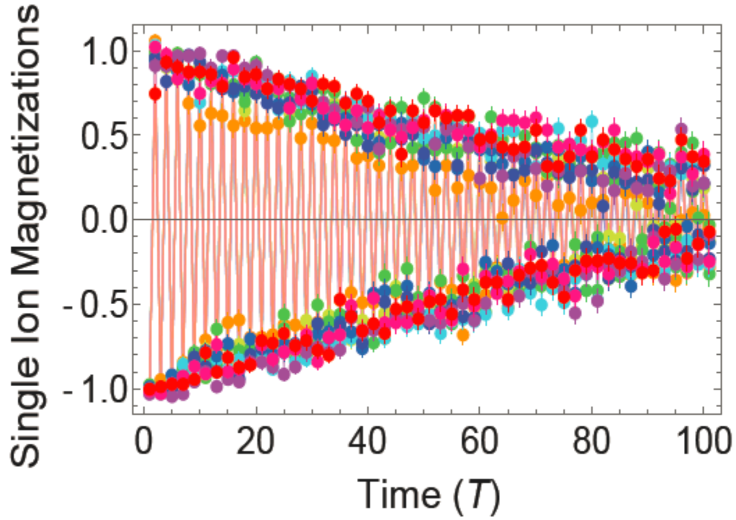


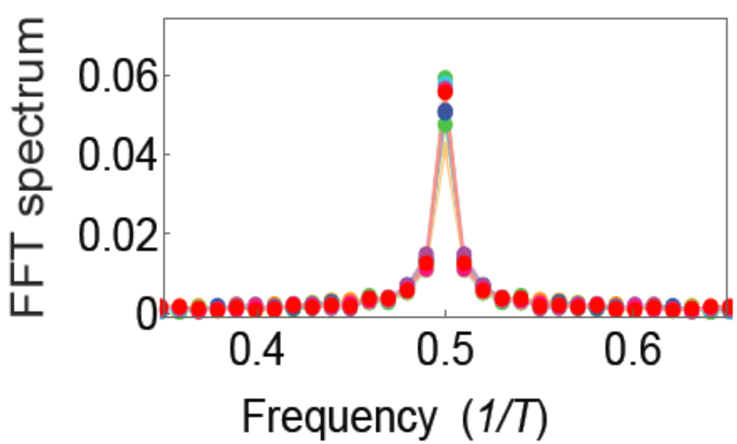
$\omega_{TC} = 1/2$



Robustness of Stabilized Response

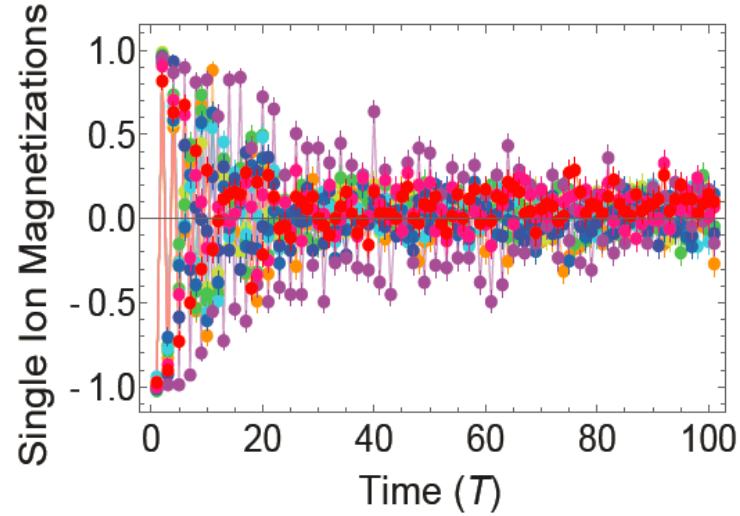
MBL Drive Stabilizes Time Crystal

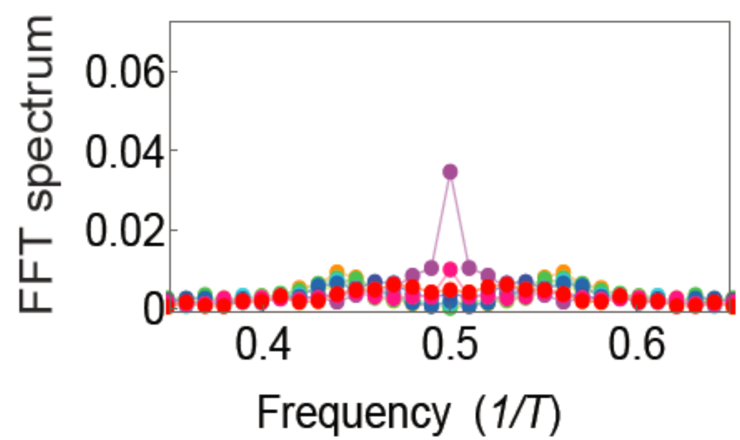




$\varepsilon = 0.03 < 2\pi J_0 t_2 / (W t_3)$

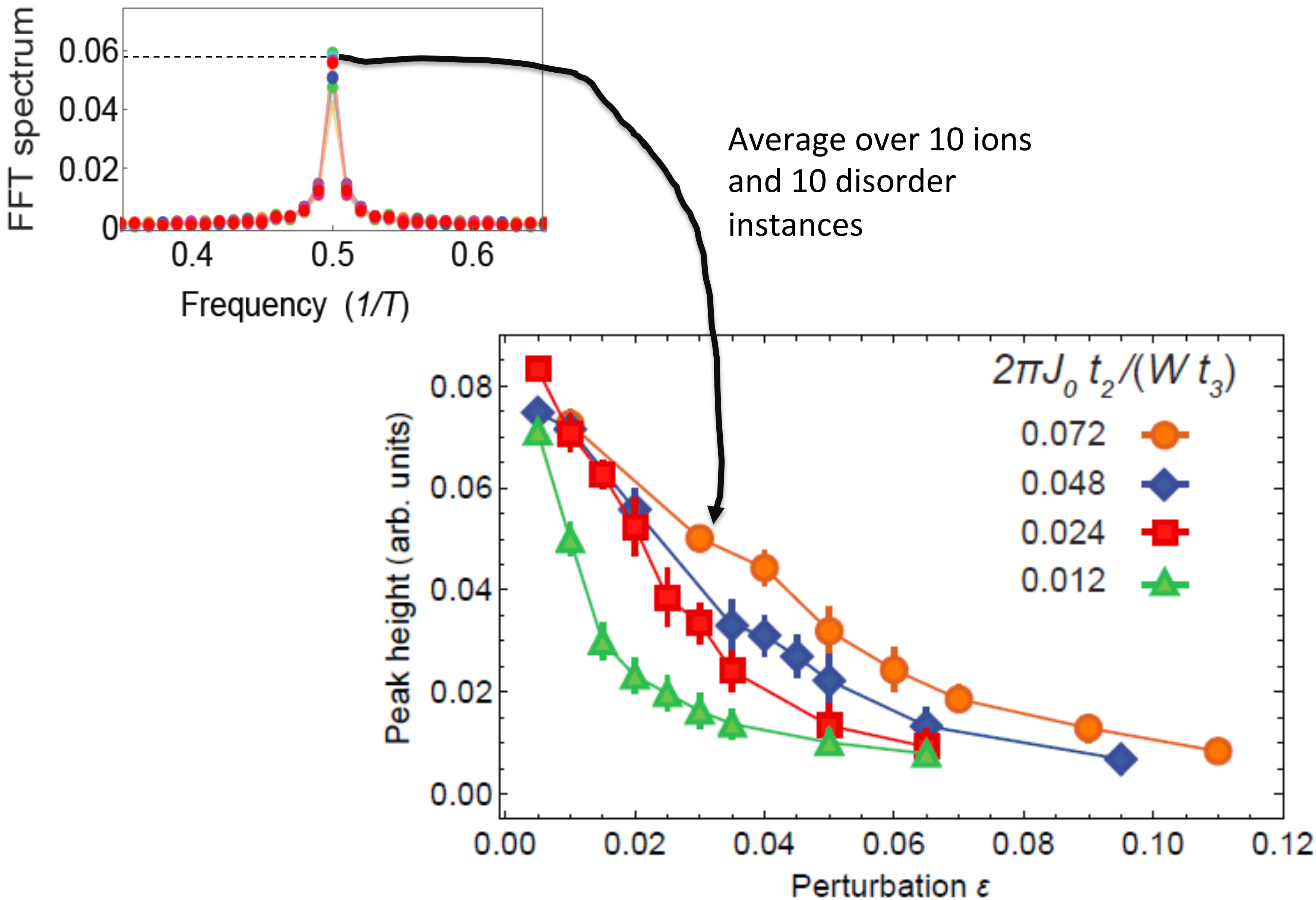
Up to a point . . .





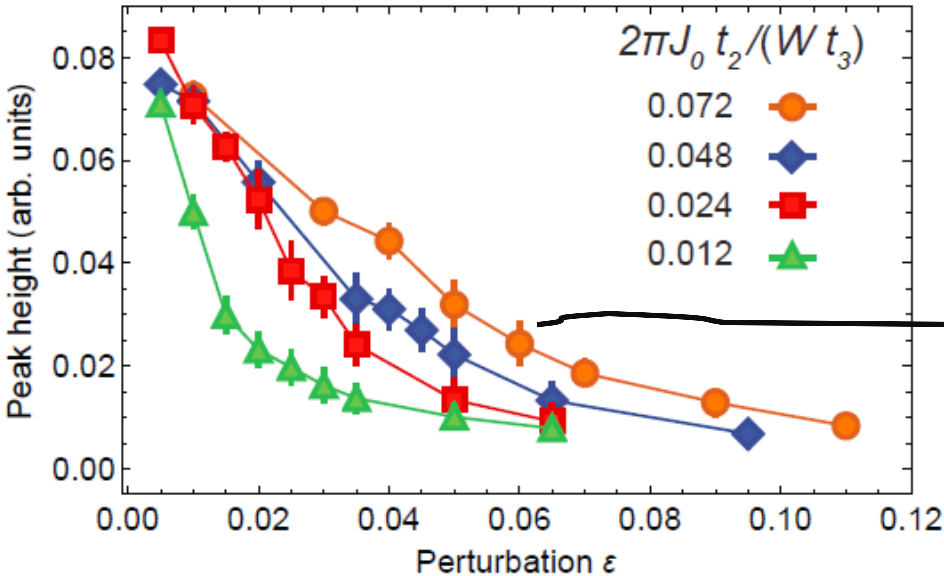
$\varepsilon = 0.11 > 2\pi J_0 t_2 / (W t_3)$

Sub-Harmonic Peak Heights: An Order Parameter

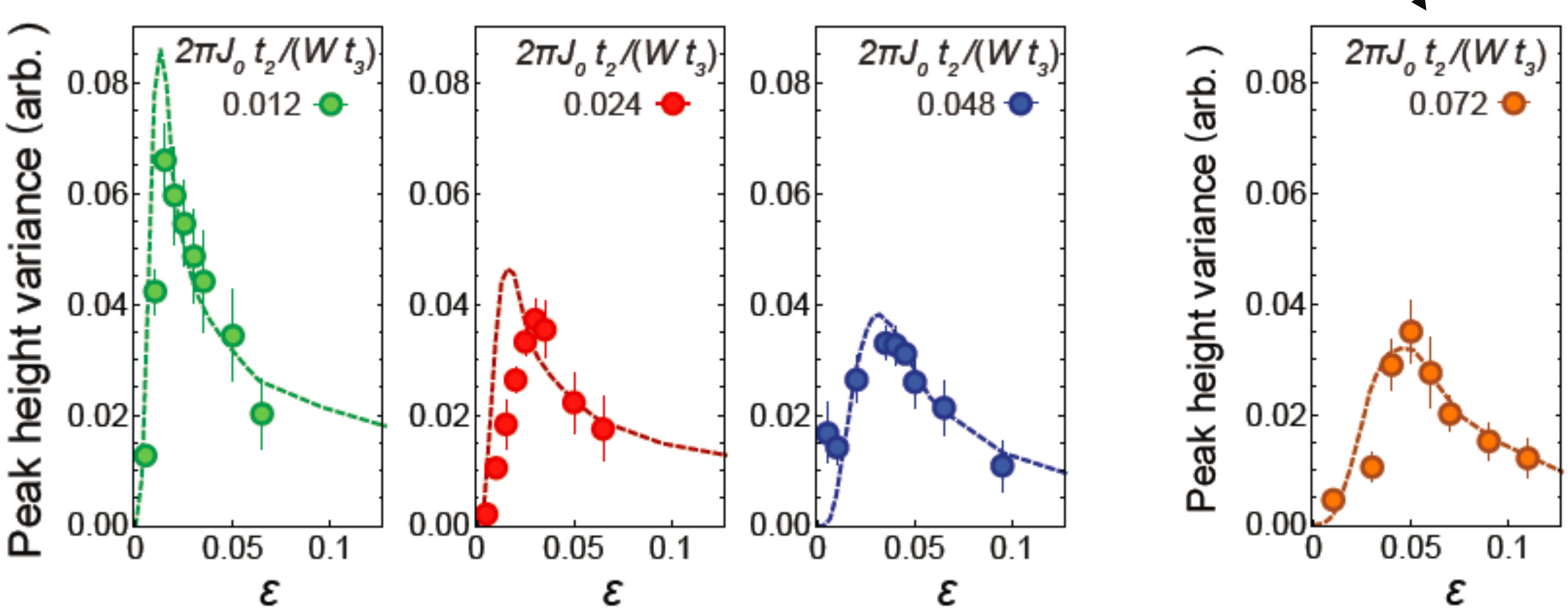


Average over 10 ions and 10 disorder instances

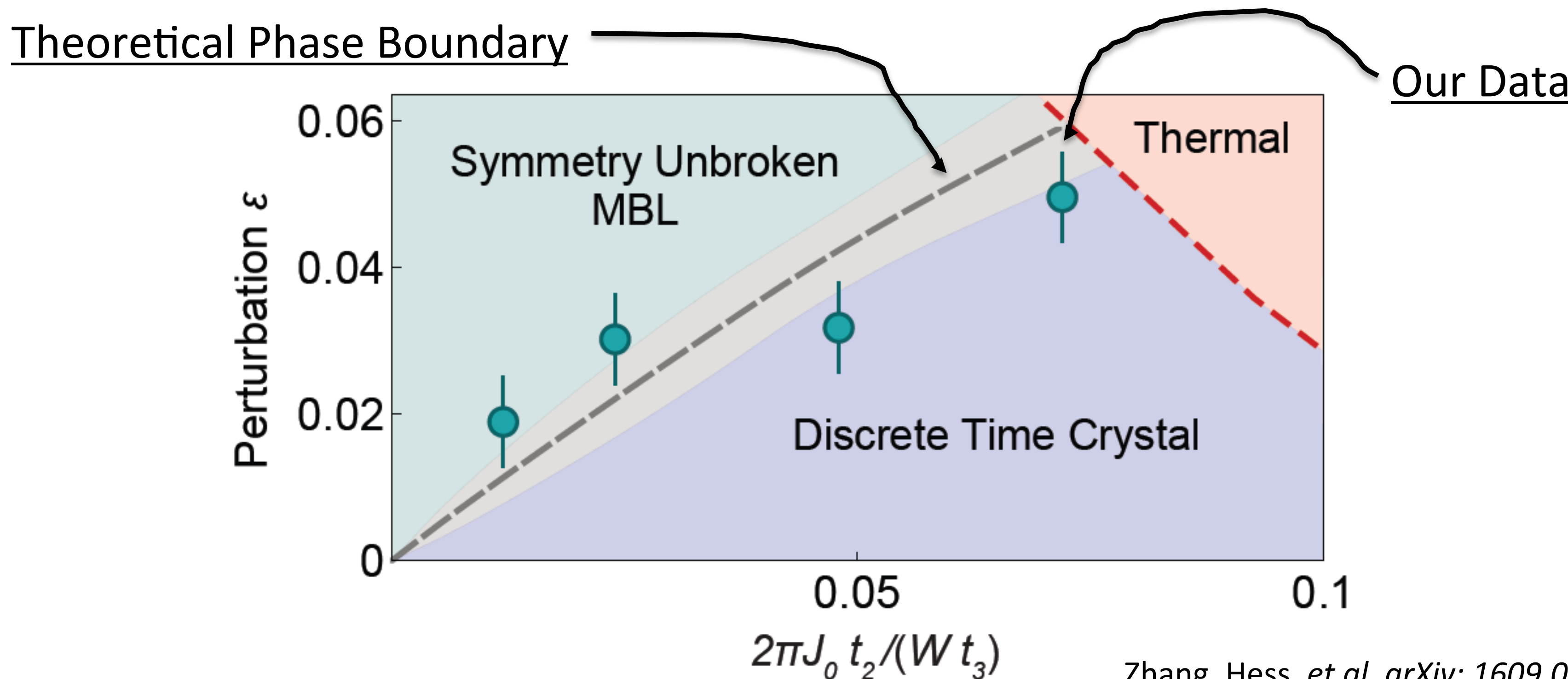
Variance: Signature of Cross-Over



Order parameter variance blows up at phase boundary



Phase Diagram



Zhang, Hess, *et al. arXiv: 1609.08684*

Observed Key Signatures of a Discrete Time Crystal:

- ✓ Periodic state dependence at sub-harmonic frequencies
- ✓ Robust to perturbations up to symmetry breaking phase boundary
- ✓ Oscillations stabilized by many-body interactions

See M. Lukin Talk on Thursday → Time Crystals (Choi *et al., arXiv:1610.08057*) and Localization (Kucsco *et al., arXiv: 1609.08216*)

Acknowledgements

PI: Chris Monroe

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- Jake Smith
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- Patrick Becker

<u>Undergraduates</u>:
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- Eric Brickelbaw

<u>Recent Alumni</u>:
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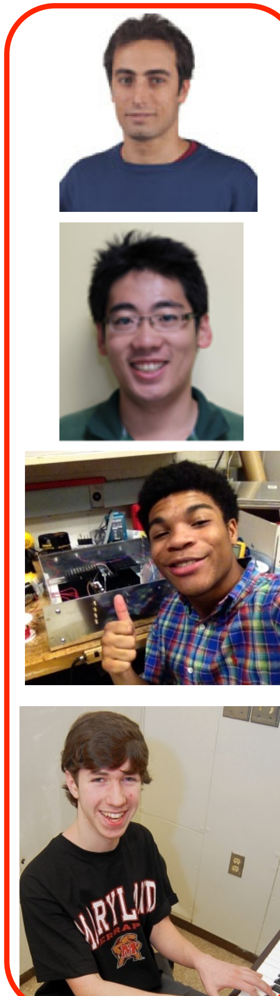
- Bryan Neyenhuis → LM



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- Markus Heyl
- David Huse
- Norm Yao
- Ashvin Vishwanath
- Andrew Potter
- Dragos Potirniche

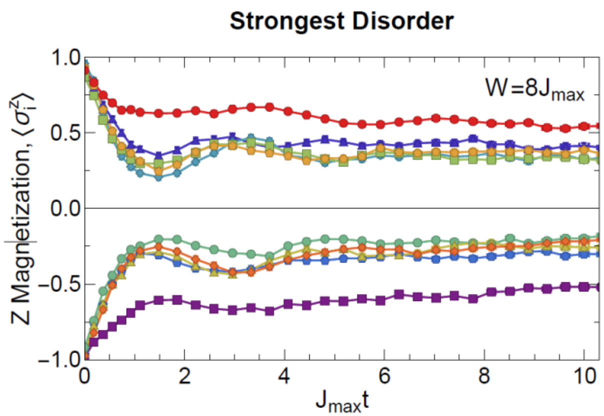
Joint Quantum Institute

Summary and References

Observation of Many Body Localization

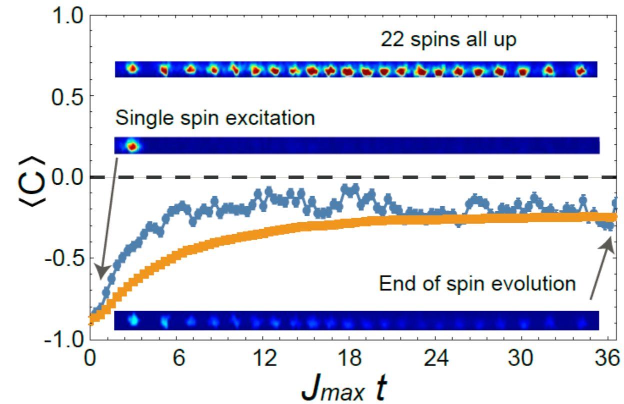
(J. Smith *et al.* Nature Physics (2016))

Memory of Initial Conditions



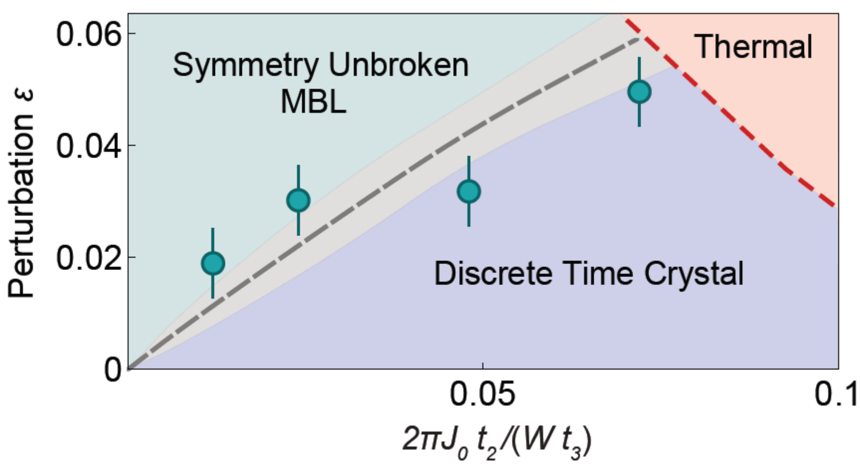
Prethermalization - Memory w/o disorder

(B. Neyenhuis *et al., arXiv: 1608.00681*)



Discrete TTSB and MBL Time Crystals

(J. Zhang, P.W. Hess, *et al. arXiv: 1609.08684)*



Come chat with Jiehang at our poster on Wednesday