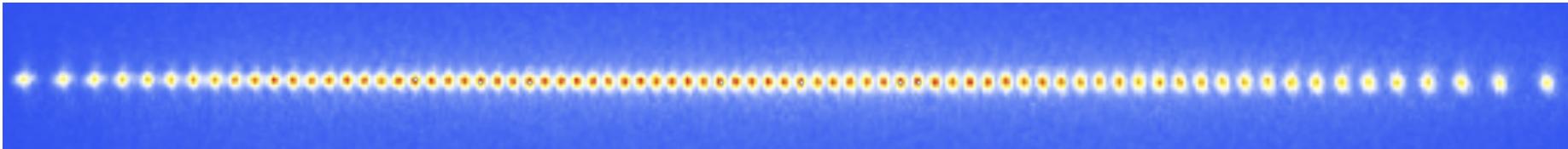


# Out-of-Equilibrium Phenomena in Trapped-Ion Spin Systems



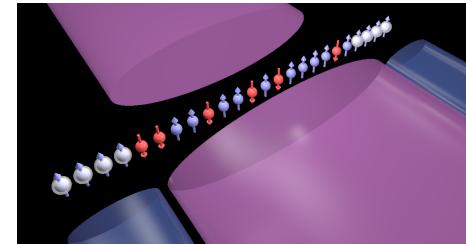
RICE

# Outline

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## Introduction:

- Trapped-Ion Quantum Systems



## Trapped-Ion Quantum Simulation:

- Prethermal time crystals, [A. Kyprianidis et al., Science 372, 6547 \(2021\)](#)
- Stark MBL, [W. Morong, et al., arXiv:2102.07250 \(2021\), \(to appear in Nature\)](#)

## Outlook

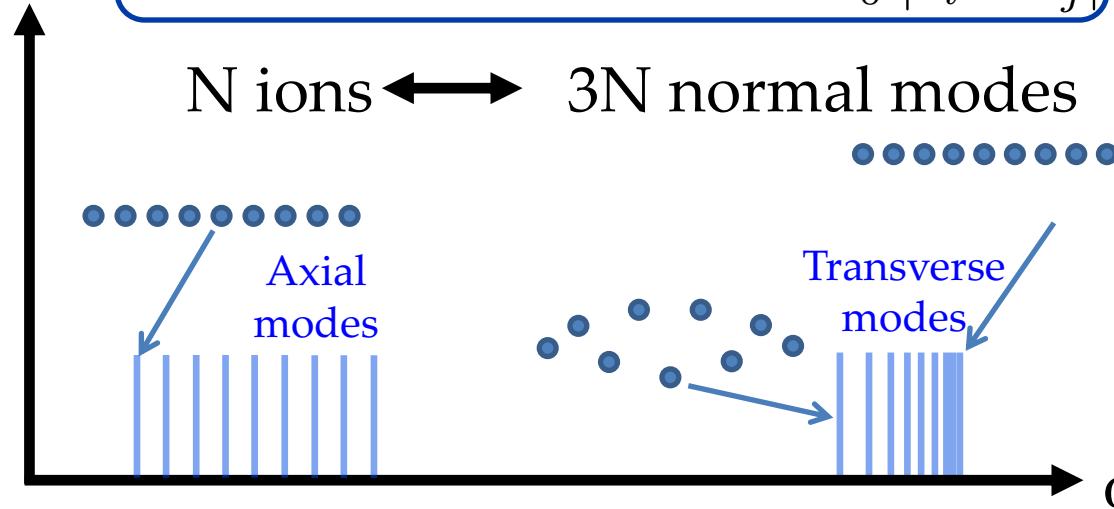
- Floquet Dissipative Systems, [P. Sierant et. al., arXiv:2107.05669 \(2021\)](#)

# Self-organized Ion crystals

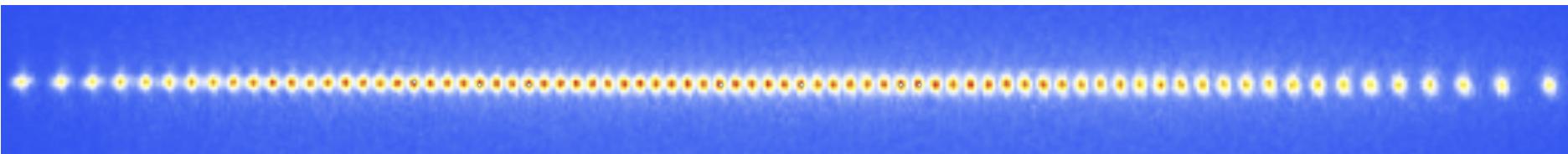
Number of bright ions: 15  
Number of dark ions: Not a linear chain



$$H_M = \frac{\hat{p}^2}{2m} + \frac{m}{2}\omega_{\alpha}^2 x_{\alpha i}^2 + \frac{q^2}{8\pi\epsilon_0} \frac{1}{|r_i - r_j|}$$



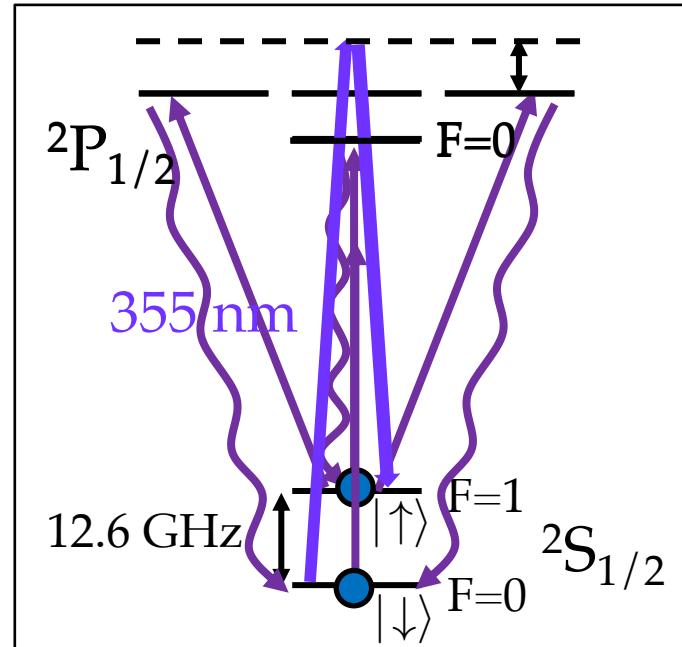
# A many-body system assembled atom by atom



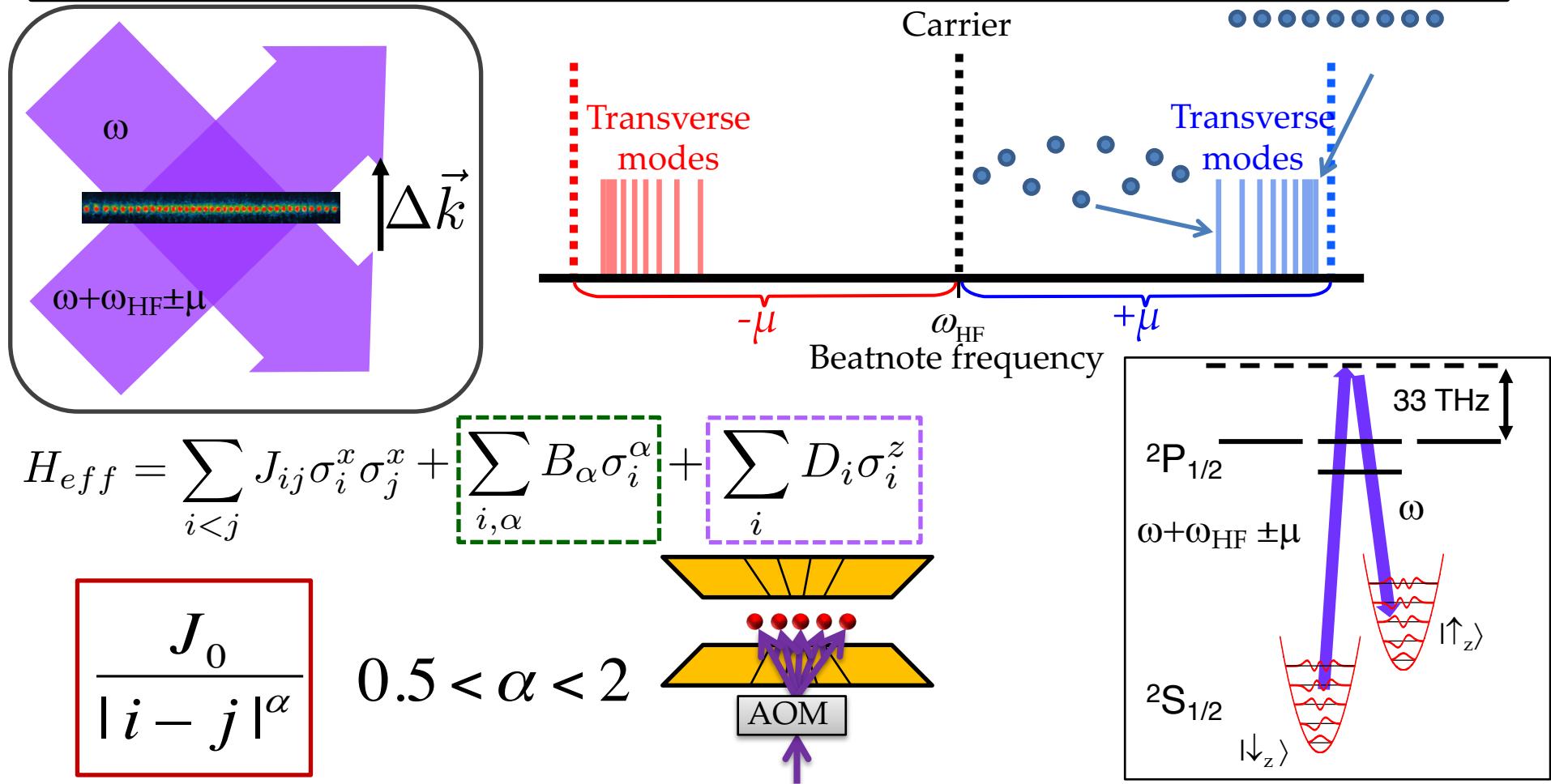
## $^{171}\text{Yb}^+$ Clock states qubit

- Coherence time:  $T_2 \sim 1$  hour [1]
- High fidelity state preparation: > 99.9% in  $\sim 10 \mu\text{s}$
- High speed readout: > 99.9% in  $\sim 100 \mu\text{s}$
- High Fidelity one (>99% in 1  $\mu\text{s}$ ) and two qubit gates (>98.5% in 500  $\mu\text{s}$ )

[1] P. Wang et al., Nat. Comm. **12**, 233 (2021)



# Generating Spin Hamiltonians



# Non-Equilibrium Studies with Trapped Ions

## Long-Range Transverse Field Ising Model

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

### Reviews

- C. Monroe, *et al.*, RMP **93** 025001 (2021)
- N. Defenu, *et al.*, arXiv 2109.01063 (2021)

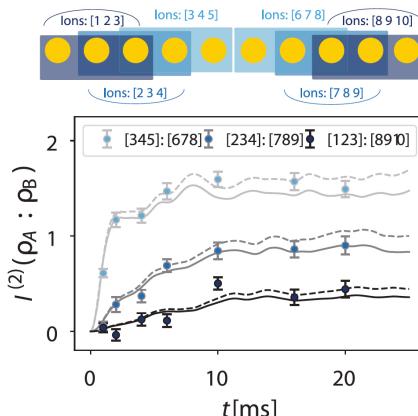
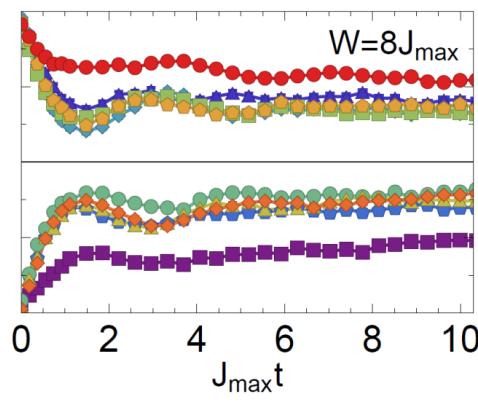
$$H_{\text{eff}} = \sum_{ij} J_{ij} \sigma_i^x \sigma_j^x + B \sum_i \sigma_i^z$$
$$J_{ij} \sim \frac{J_0}{|i - j|^\alpha}$$

## Quantum quenches and Thermalization in Spin LR Systems

### Many-Body Localization [1,2]

[1] Smith *et al.*, (Nature Phys. 2016),

[2] Bridges *et al.*, (Science 2019)



# Non-Equilibrium Studies with Trapped Ions

## Long-Range Transverse Field Ising Model

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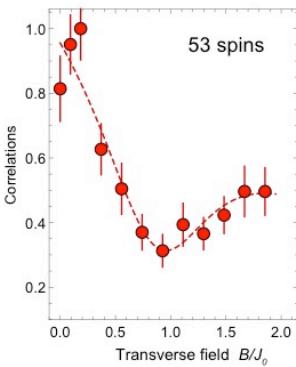
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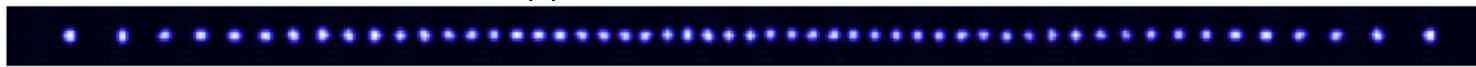
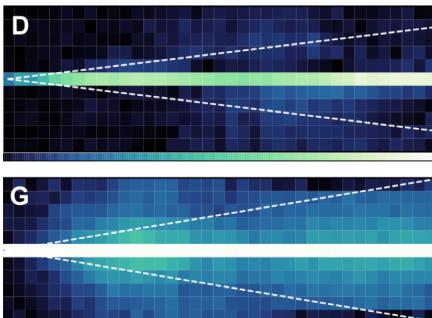
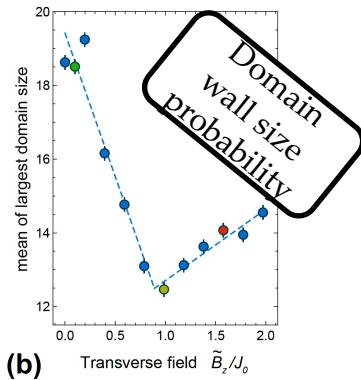
### Dynamical Phase transition [3,4]

[3] Zhang, GP, *et al.*, Nature (2017)

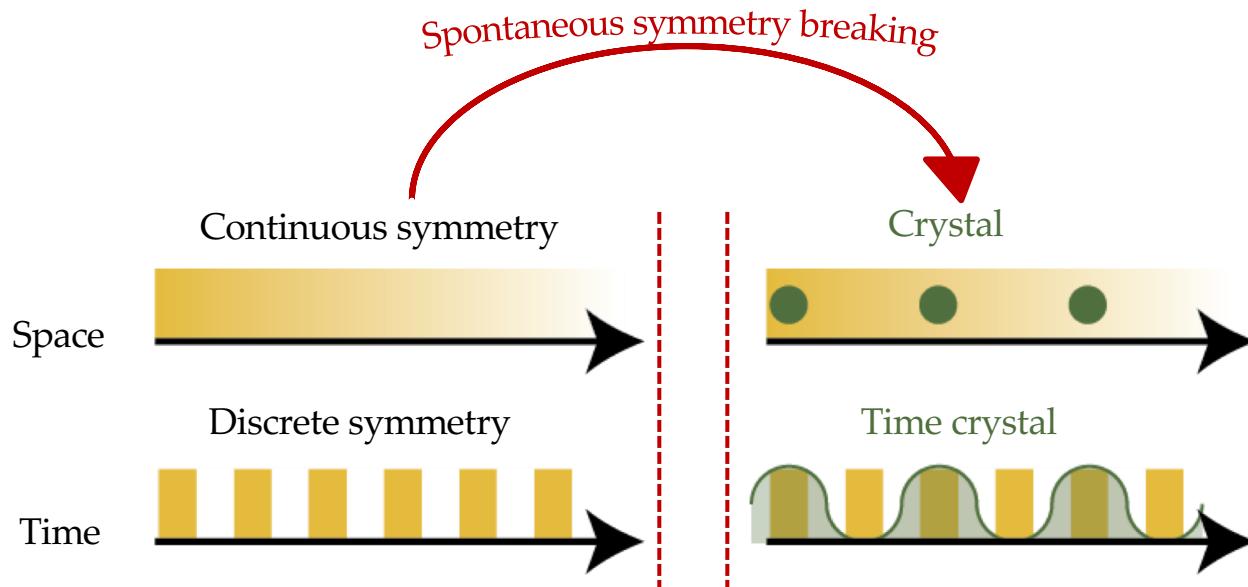
[4] Jurcevic, *et al.*, PRL (2017)

### Confinement of Domain Walls [5]

[5] Tan, Becker, *et al.*, Nature Phys. (2021)



# Floquet Discrete Time Crystal

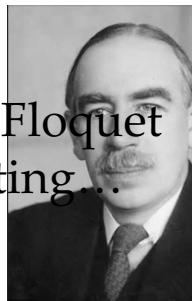


Robust  
subharmonic  
response  
stabilized by  
MB interactions

# Thermalization and lack thereof

	Eigenstate Thermalization Hypothesis (ETH)	Many-body localization (MBL)
Static Systems	$\rho_A \sim e^{-\beta H_A}$ $S_A \sim \text{vol}(A)$	$S_A \sim \partial A$
Floquet Systems	$T = \infty$ $\rho_A \sim \mathbf{1}$	$T < \infty$ $S_A \sim \partial A$

Fight Floquet heating...



Many-body Localization  
V. Khemani et al., arXiv 1910.10745  
N. Yao et al., Ann. Rev. C. M. Phys. 11, 467  
Google AI arXiv:2107.13571, Randall et al., arXiv:2107.00736

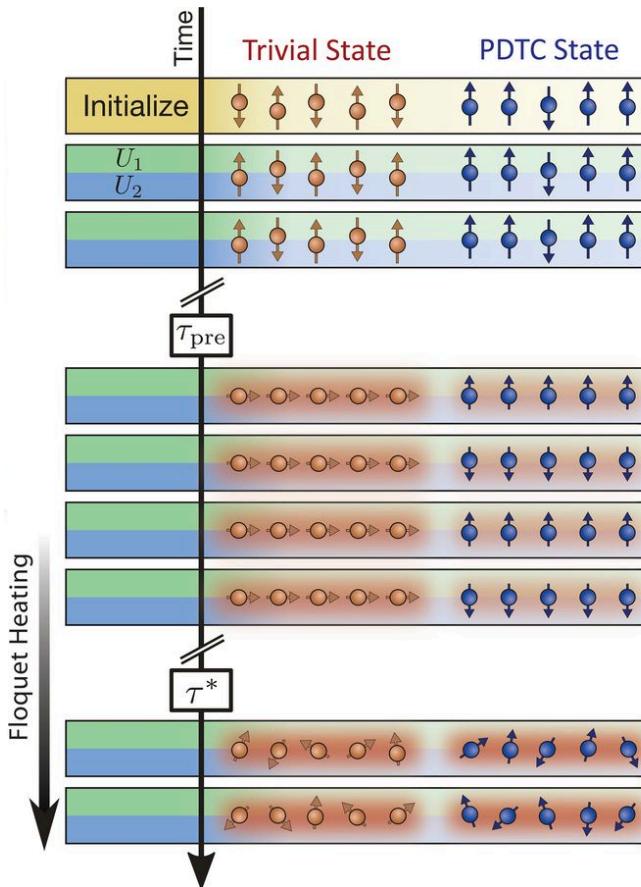
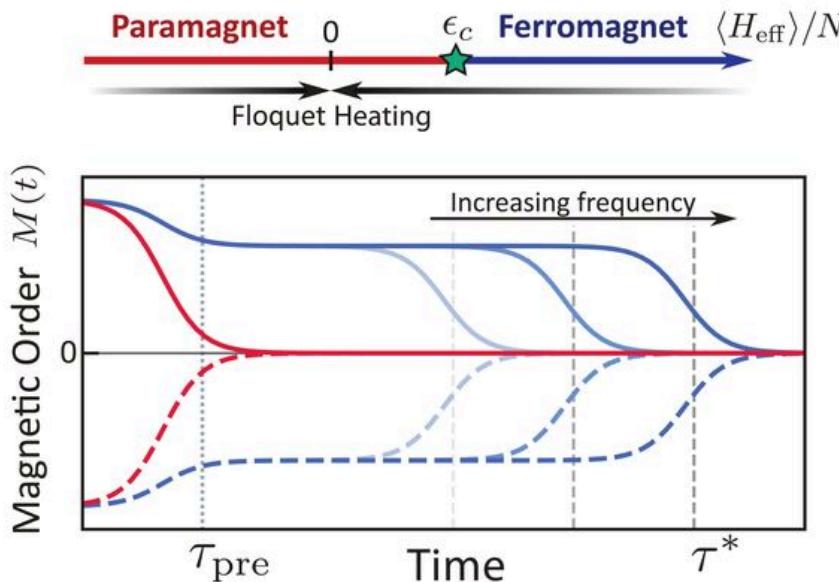
he long run, we are all dead.”  
Pritham Mallick (Jia)  
A. Kyprianidis et al., Science 372, 6547 (2021)

# Prethermalization and Time Crystals

- If  $\omega > J_{\text{loc}}$ , the system is described by an effective prethermal Hamiltonian  $H_{\text{eff}}$
  - Effective temperature is set by  $\langle H_{\text{eff}} \rangle / N$

T. Kuwahara, et al., Ann. Phys. 367, 96–124 (2016).

D. A. Abanin, et al., Phys. Rev. B 95, 014112 (2017).

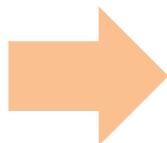


# Prethermalization

Floquet drive

$$U_1 = \exp \left[ i \frac{\pi}{2} \sum_i^N \sigma_i^y \right]$$

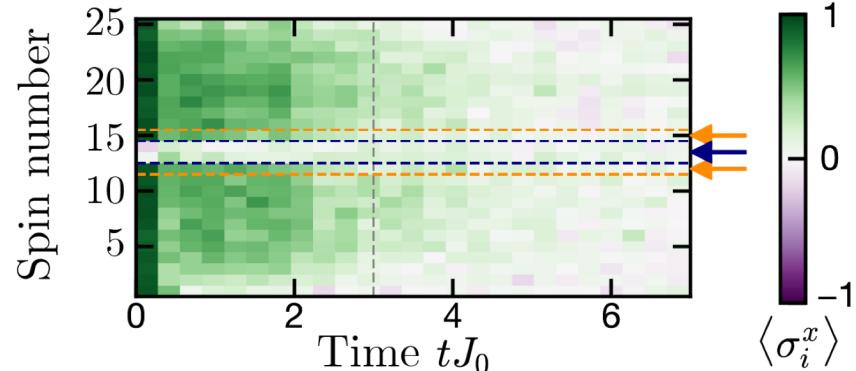
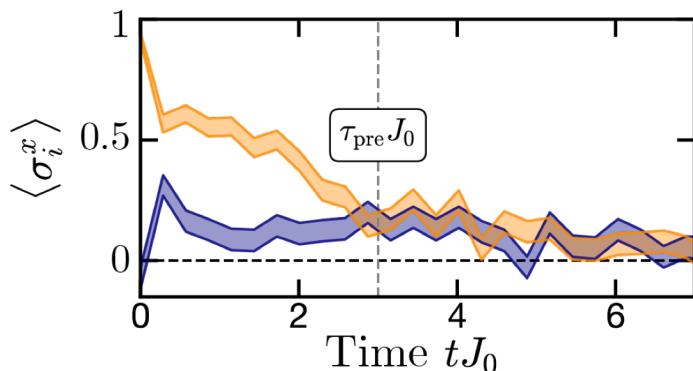
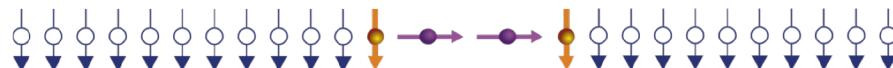
$$U_2 = \exp \left[ iT \left( \sum_{i < j}^N J_{ij} \sigma_i^x \sigma_j^x + B_y \sum_{i=1}^N \sigma_i^y + B_z \sum_{i=1}^N \sigma_i^z \right) \right]$$



Effective Hamiltonian (anti-ferro)

$$H_{\text{eff}} = \sum_{i < j}^N J_{ij} \sigma_i^x \sigma_j^x + B_y \sum_{i=1}^N \sigma_i^y$$

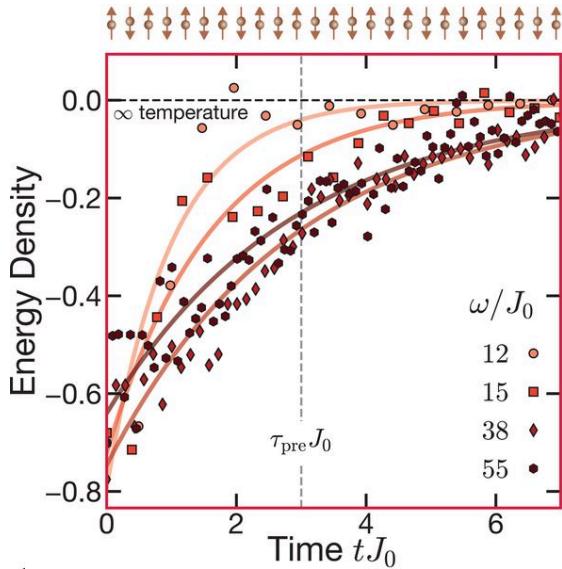
Initial state



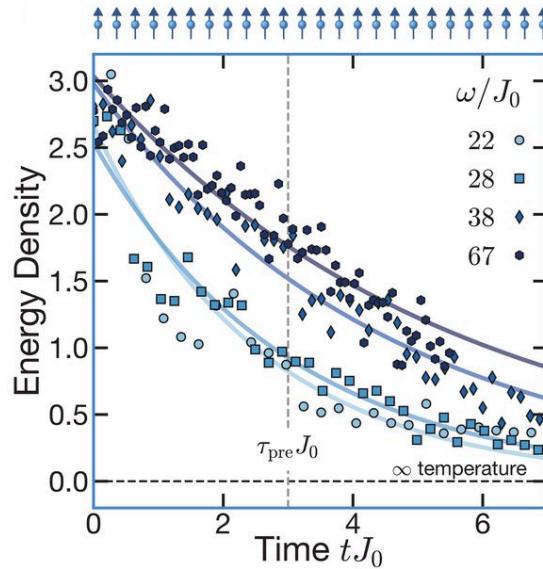
Local equilibration to a thermal ensemble of  $H_{\text{eff}}$

# Energy Density

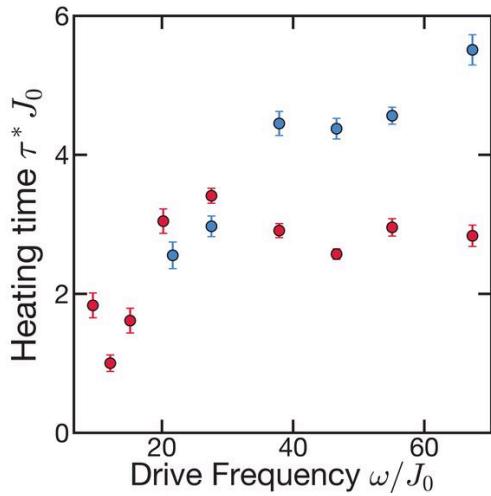
Low-energy  
Néel state



High-energy  
polarized state

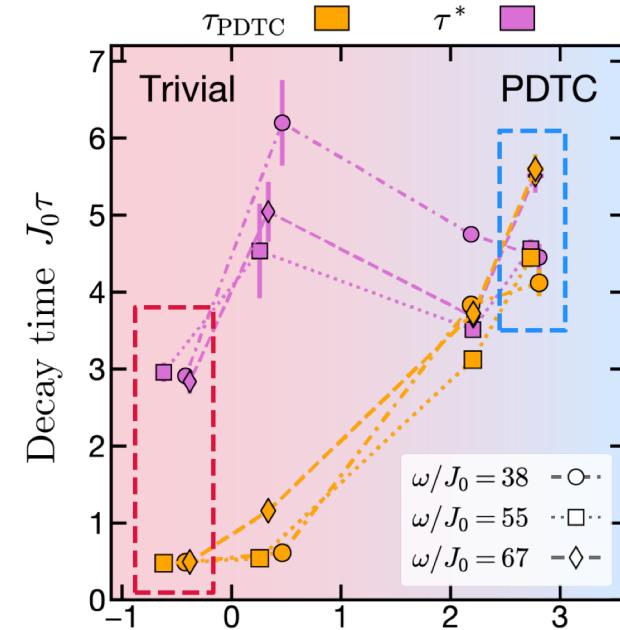
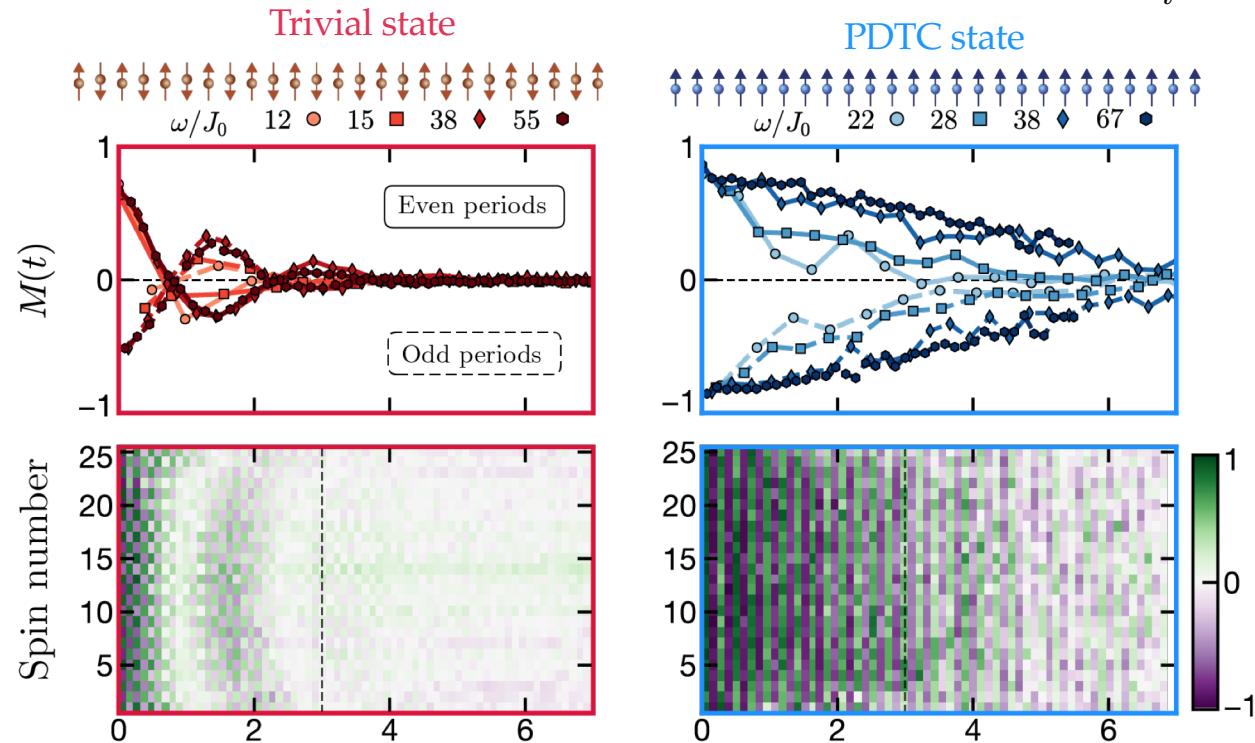


Heating  
dependence  
on drive frequency



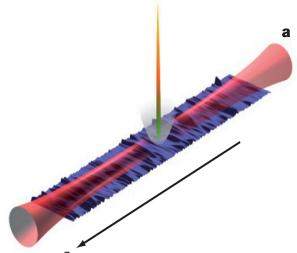
# Prethermal Discrete Time Crystal

$G \sim \prod_i \sigma_i^y$  is an emerging symmetry of the evolution, even if not a symmetry of the original Floquet evolution  $\rightarrow M(t) = \sum_i \langle \sigma_i^x \rangle$  is a good order parameter



# Stark Many-Body Localization

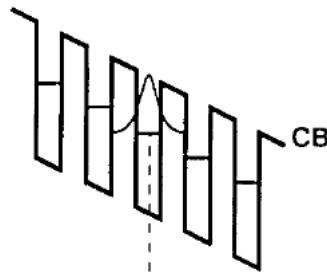
Longstanding question: is Many-Body Localization possible without disorder??



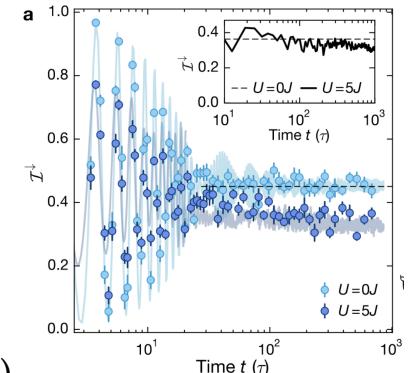
Anderson Localization + interactions



MBL



Wannier-Stark Localization + interactions → Stark-MBL?



## Theory:

- Van Nieuwenburg *et al.*, PNAS 116, 9269 (2019)  
Schulz *et al.*, PRL 122, 040606 (2019)  
Sala *et al.*, PRX 10, 011047 (2020)  
Khemani *et al.*, Phys. Rev. B 101, 174204 (2021)

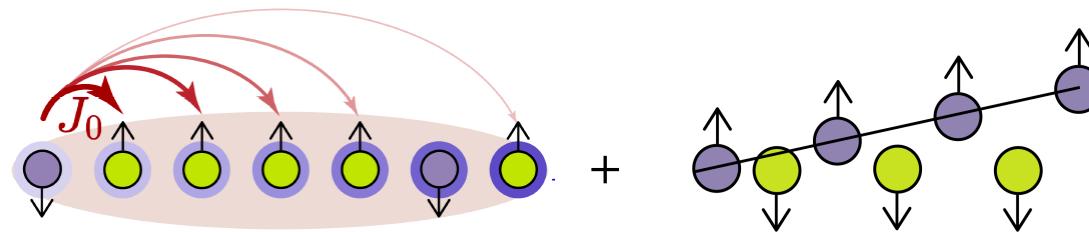
## Experiments:

- Scherg *et al.*, Nat. Comm. 12, 4490 (2021)  
Guo *et al.*, npj Quantum Information 7, 51 (2021)

# Stark Many-Body Localization

Experimental procedure:

- Prepare various product states of up and down spins  $|\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\rangle_z$
- Quench with  $H = \sum_{i < j} \frac{J_0}{r^\alpha} \sigma_i^x \sigma_j^x + \sum_j jg \sigma_j^z$

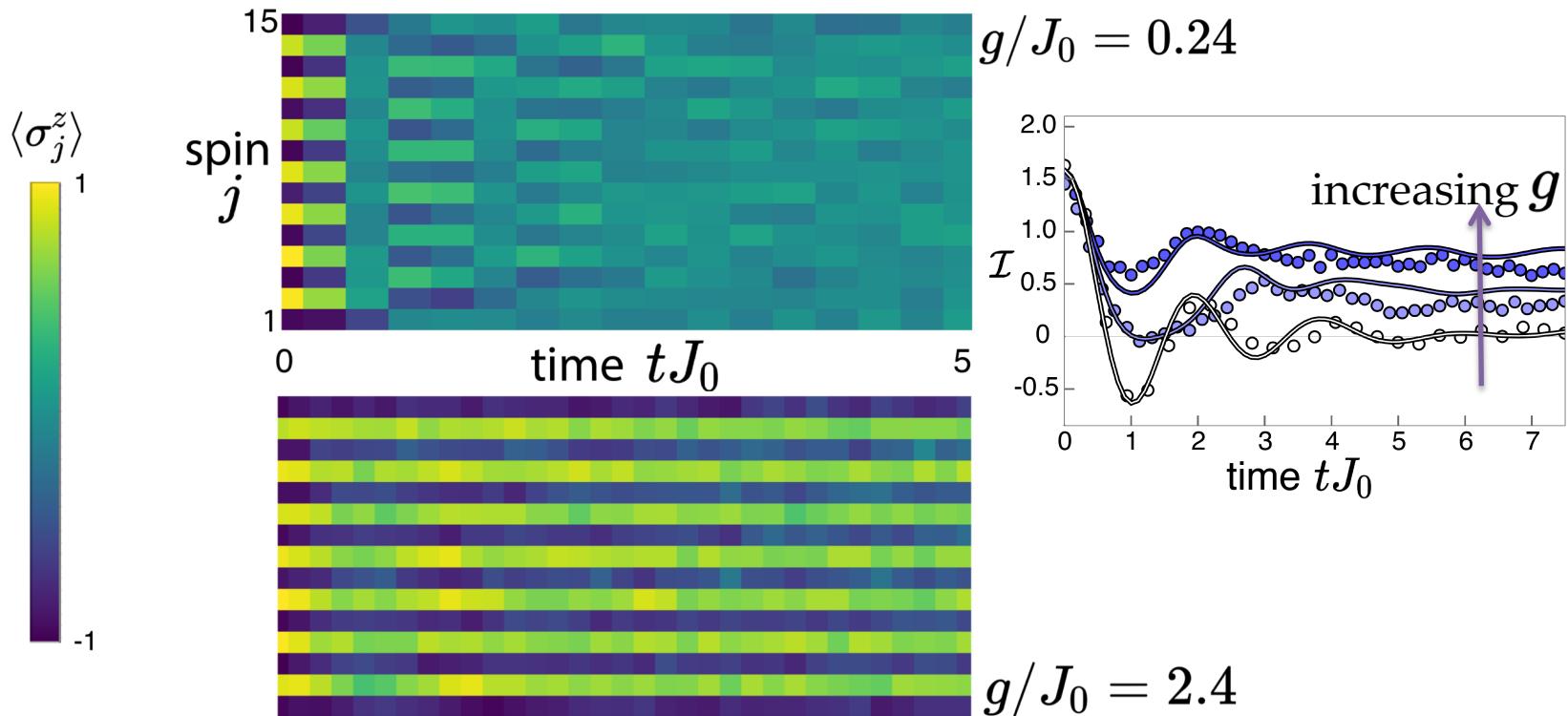


- Measure average magnetizations  $\langle \sigma_i^z \rangle$  and Imbalance

$$\mathcal{I}(t) = \frac{\left\langle \sum_{i=1}^{N_\uparrow} \sigma_i^z \right\rangle}{N_\uparrow} - \frac{\left\langle \sum_{i=1}^{N_\downarrow} \sigma_i^z \right\rangle}{N_\downarrow}$$

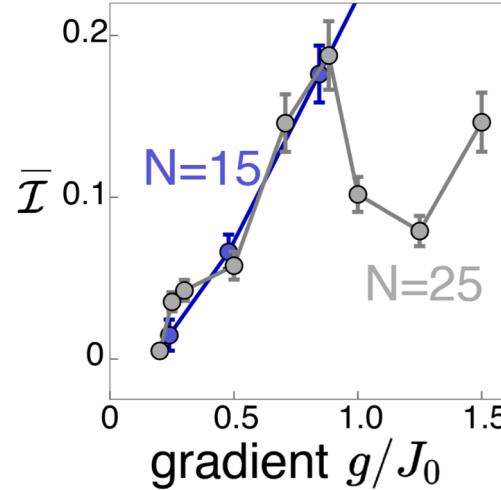
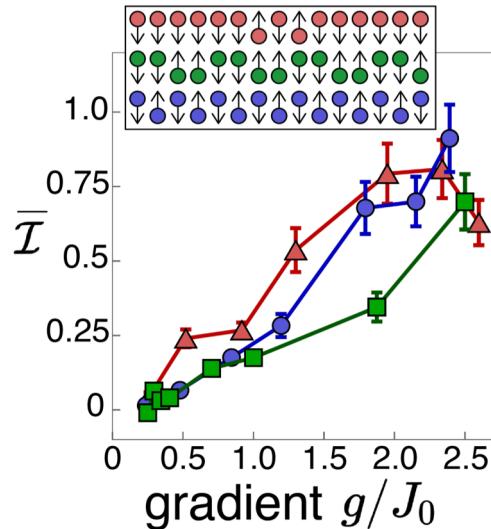
# Memory of the Initial State

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# Stark Many-Body Localization

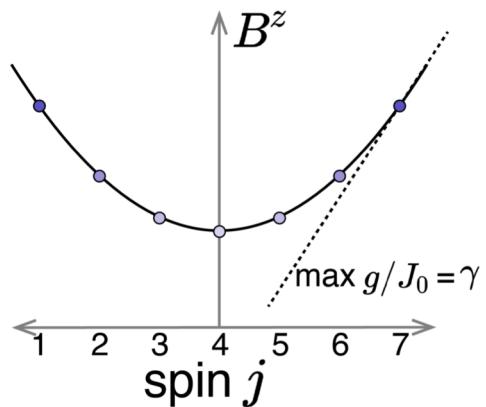
Steady-state imbalance  $\bar{\mathcal{I}}$  :



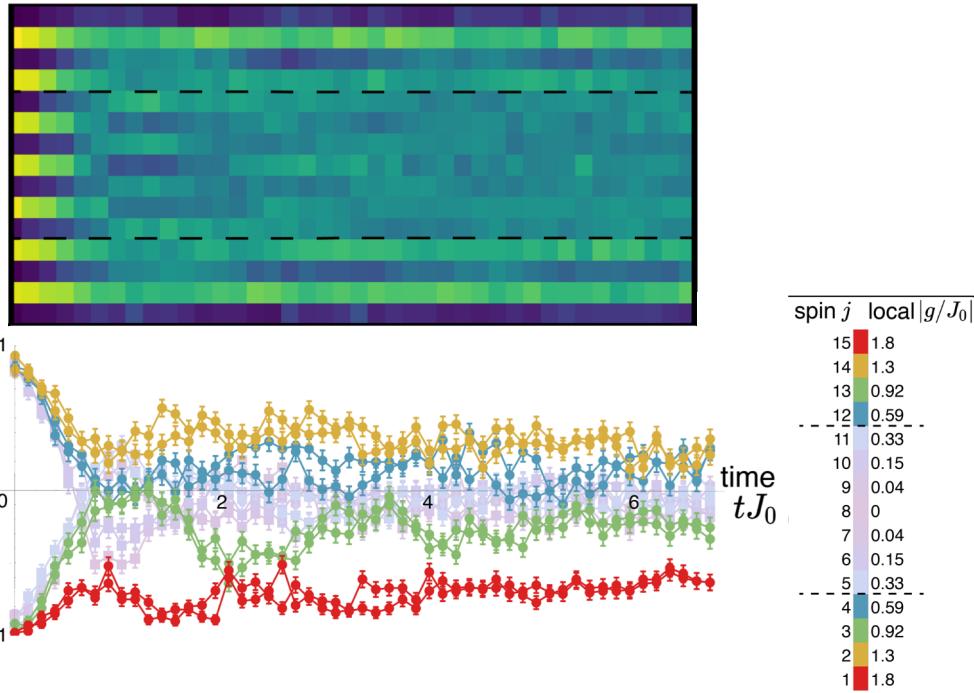
Localization for variety of initial states  
(differently from quantum many-body scars)

Localization persists  
up to 25 spins

# Quadratic potential: generalizing SMBL



Coexisting localized and thermal regions!



## Outlook:

- How SMBL depends on  $\alpha$  ?
- Related to Quadrupole conservation ?
- Can SMBL be used to avoid Floquet Heating?

# New Opportunities in Quantum Simulation

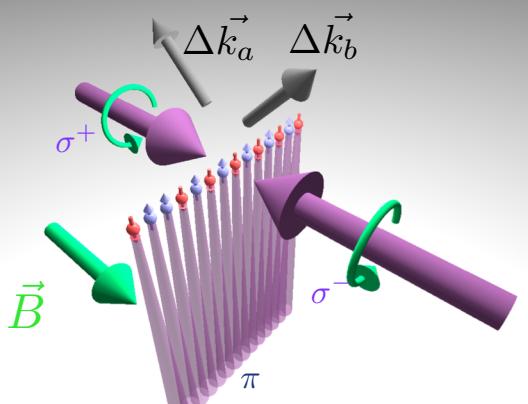
QAOA, [PNAS 117 \(41\), 25396 \(2020\)](#)

Confinement, [Nat. Phys. 17, 742 \(2021\)](#)

Prethermal TC, [Science 372, 6547 \(2021\)](#)

- Global Interaction Control
- One set of normal modes

Plenty of room at the bottom!



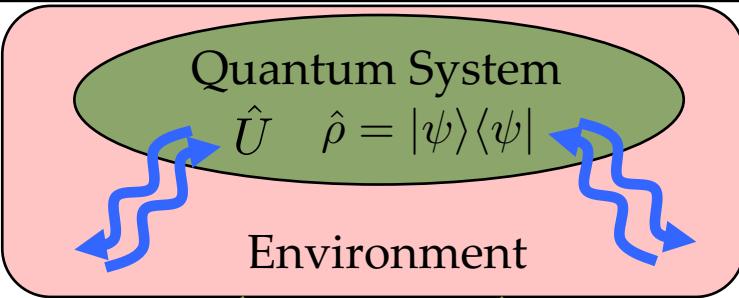
# RICE

- Quantum magnetism models
- Optimization problems
- Quantum Spin glasses
- High Energy Physics
- Driven-Dissipative quantum systems

[paganolab.rice.edu](http://paganolab.rice.edu)



# Dissipative Many-body Systems



Dissipative Phase Transitions (DPT)

$$\frac{\partial \rho}{\partial t} = \frac{1}{i\hbar} [H, \rho] + \mathcal{L}(\rho)$$

Properties of the Average state  
 $\langle O \rangle = \text{Tr}(\rho O)$

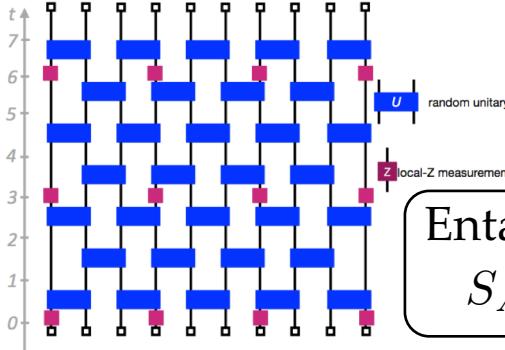
L. M. Sieberer, et al., Rep. Prog. in Phys. 79, 096001 (2016).

T. E. Lee, et al., Phys. Rev. Lett. 110, 257204 (2013).

J. Jin, et al., Phys. Rev. X 6, 031011 (2016).

M. F. Maghrebi, et al., Phys. Rev. B 93, 014307 (2016) ....

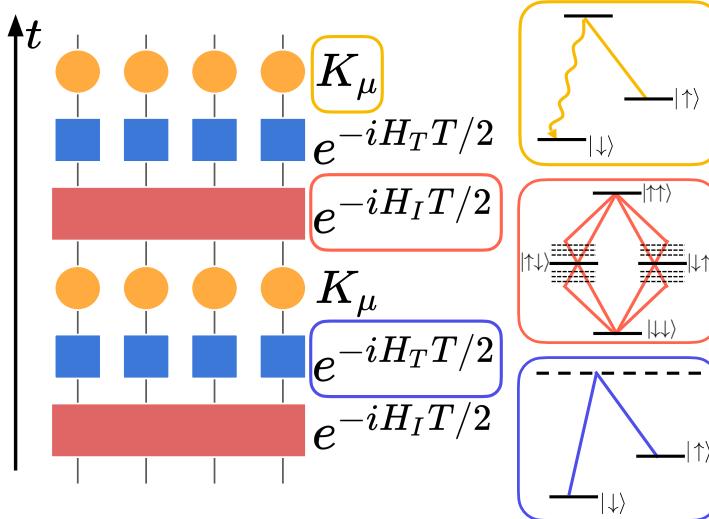
Measurement-induced phase transitions (MIPT)



- Nahum, et al., Phys. Rev. X 7, 031016 (2017)  
Y. Li, et al., Phys. Rev. B 98, 205136 (2018)  
Y. Li, et al., Phys. Rev. B 100, 134306 (2019) ...

Entanglement Entropy  
 $S_A = -\text{Tr}(\rho_A \log \rho_A)$

# Dissipative Floquet Systems



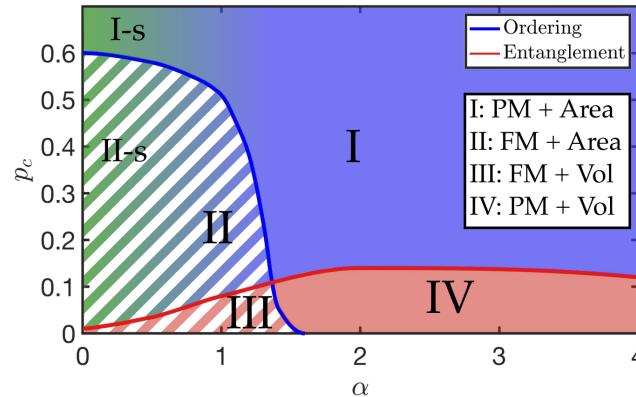
$$K_{i,0} = \sqrt{p} |\downarrow\rangle\langle\downarrow|_i \quad K_{i,1} = \sqrt{p} |\downarrow\rangle\langle\uparrow|_i \quad K_{i,2} = \sqrt{1-p} \mathbf{1}_i$$

$$H_I = \sum_{i < j} J_{ij} \sigma_i^x \sigma_j^x, \quad J_{ij} \sim \frac{J_0}{|i - j|^\alpha}$$

$$H_T = B_z \sum_i \sigma_i^z$$

DPT  
Order-Disorder ?

$$X^2 = \frac{1}{L} \text{Tr}(\rho_{ss} \sum_{i \neq j} \sigma_i^x \sigma_j^x)$$

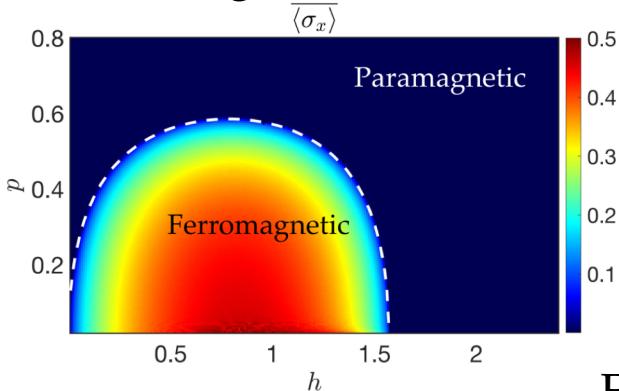


MIPT  
Volume-Area law ?

$$S_A = -\text{Tr}(\rho_A \log \rho_A)$$

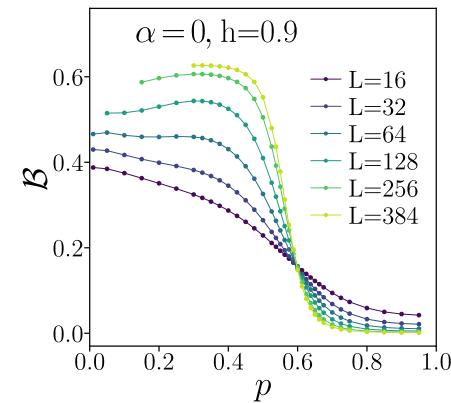
# Dissipative Symmetry-Breaking Phase transition

Magnetization

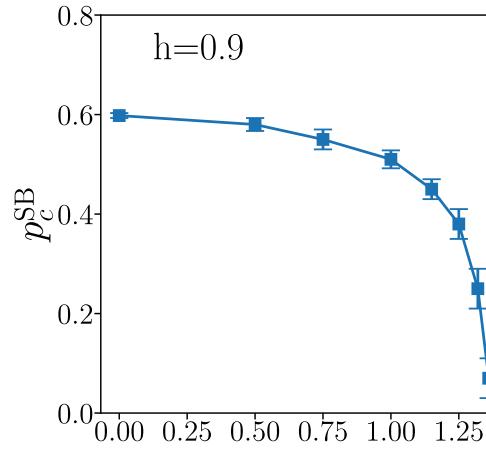
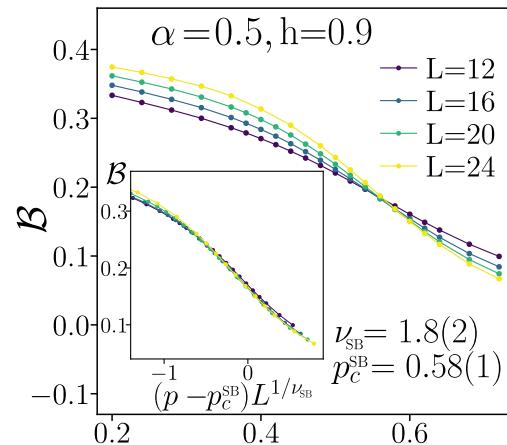


Cluster mean field  
for  $\alpha = 0$

Binder cumulant



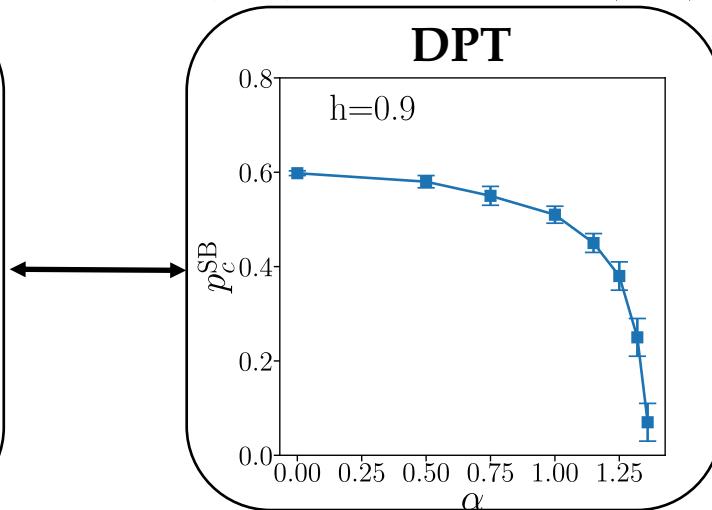
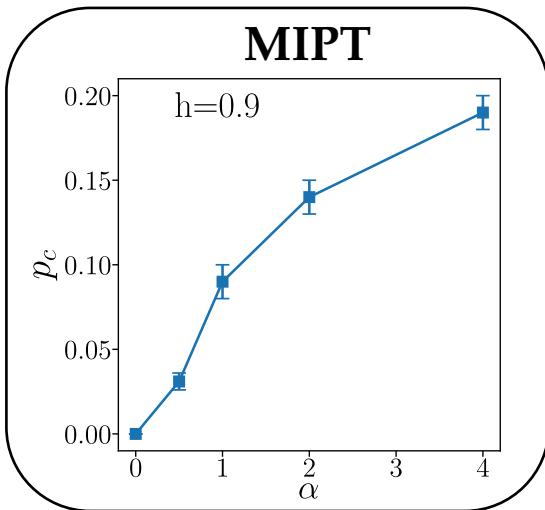
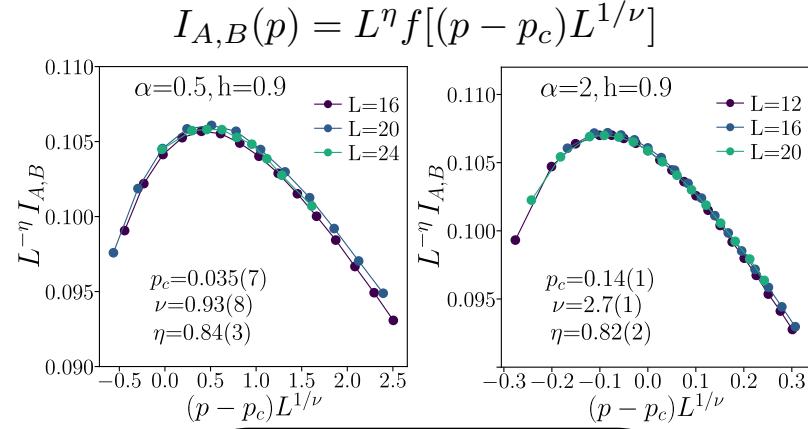
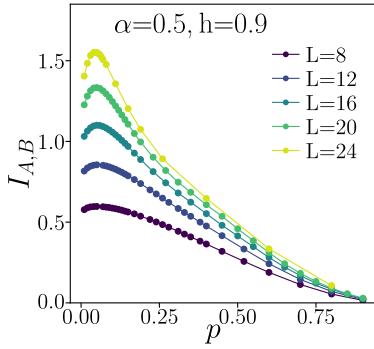
Exact Diagonalization  $\alpha > 0$



# Measurement Induced Phase Transitions

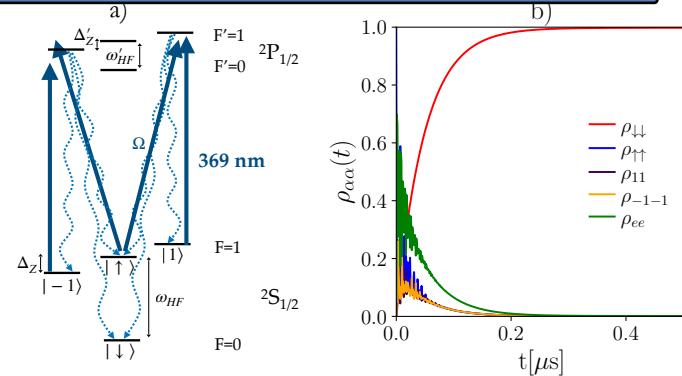
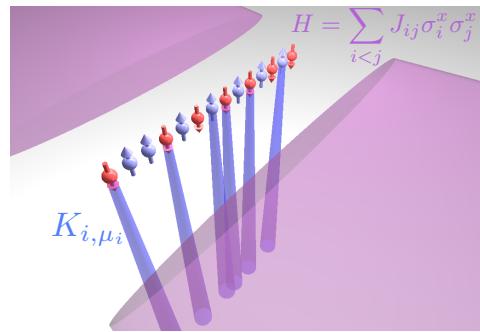
Quantum  
mutual  
information

$$I_{A,B} = S(A) + S(B) - S(A \cup B)$$



# Experimental Considerations

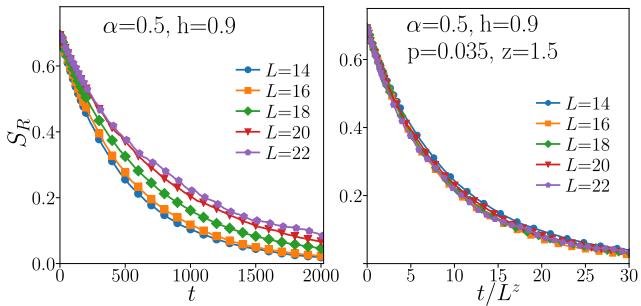
DPT:  
Global Long-range Interactions  
+  
Local Optical Pumping



MIPT:

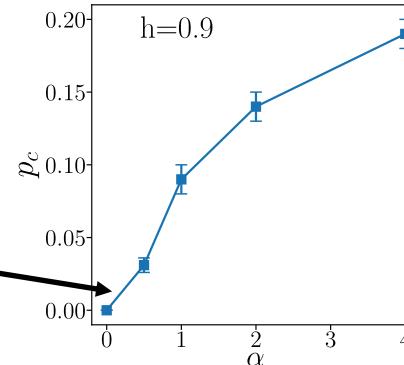
- 1) Detecting  $S(\rho_A)$
- 2) Postselect over quantum trajectories  $\rightarrow 2^{pLT}$  measurements
- 3) Detect individual qubits with negligible crosstalks

# Experimental Considerations

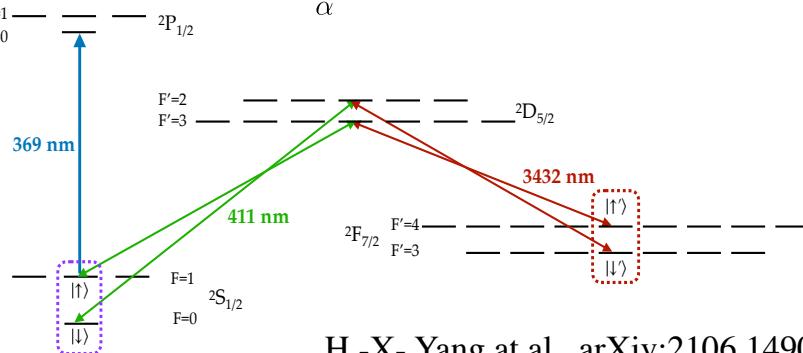


1) Detecting  $S(\rho_A)$  of an entangled Ancilla  
M. J. Gullans and D. A. Huse, PRL 125 (2020)  
C. Noel et al., arXiv:2106.05881 (2021)

2)  $2^{pLT}$  overhead manageable if  $\alpha$  and, therefore,  $p_c$  is decreased



3) Qubit hiding to avoid crosstalks during measurements



# Other Directions

## Lattice Gauge Theory with trapped ions

$$H = w \sum_{n=1}^{N-1} [\sigma_n^+ \sigma_{n+1}^- + \text{h.c.}] + \frac{m}{2} \sum_{n=1}^N c_n \sigma_n^z + \frac{J}{2} \sum_{n=1}^{N-2} \sum_{l=n+1}^{N-1} \sigma_n^z \sigma_l^z$$

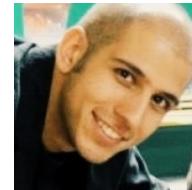
Particle-antiparticle hopping

Mass

Gauge field



Z. Davoudi



A. Seif



M. Hafezi

Z. Davoudi et al., PRR 2, 023015 (2020) – Multimode Quantum Simulation

Z. Davoudi, et al., arXiv, PRR in press (2021) Hybrid Spin-Phonon approach

B. Andreade et al., arXiv (2021), Engineering Three-body interactions

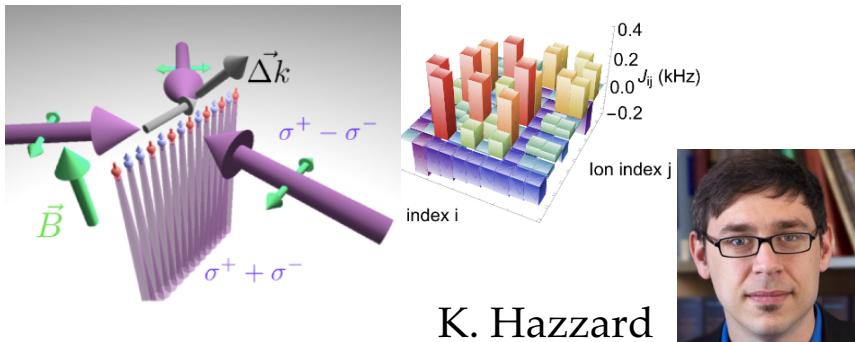


N. M. Linke



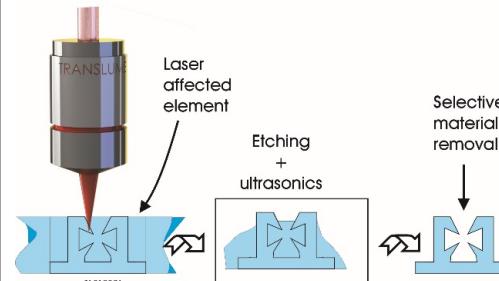
T. Grass

## Quantum Spin Glass/Variational Optimization

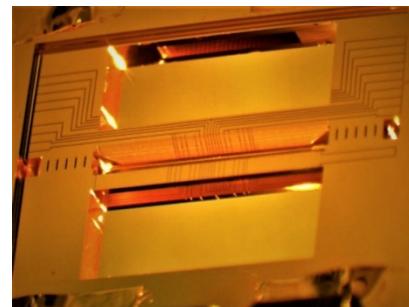


K. Hazzard

## Ion Trapping made easy: Monolithic trap



N. M. Linke + Translume

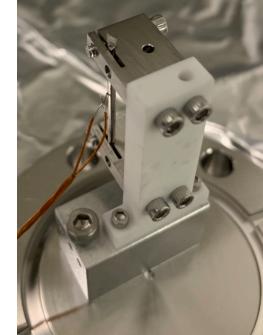
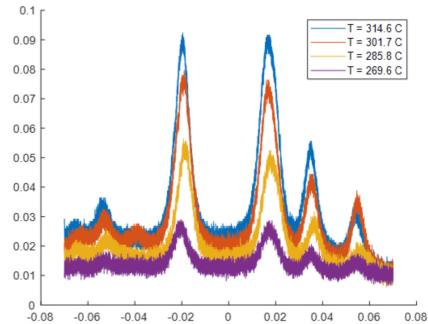


# Trapped ions @ Rice

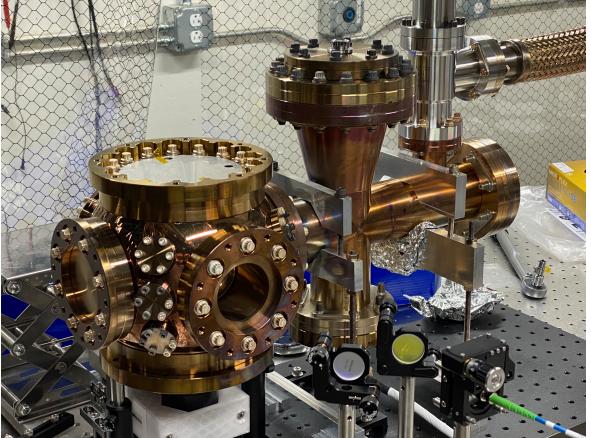
The Lab



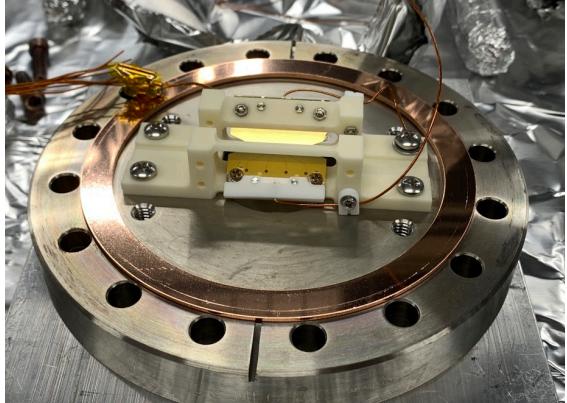
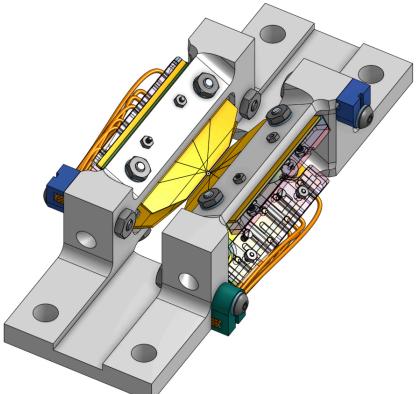
Atomic source characterization



Vacuum apparatus assembly



Paul Trap design and assembly



# Acknowledgments



A. Kyprianidis P. Becker K. Collins



QSIM



Cryo  
QSIM

H. Kaplan

W. L. Tan

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- Patrick Becker → Booze Allen
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- Arinjoy De



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- Fangli Liu → Quera
- Francisco Machado
- Norman Yao
- Chetan Nayak
- Dominique Else

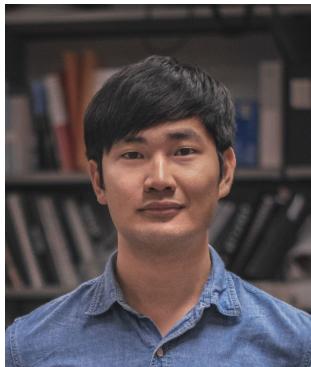
# Acknowledgments

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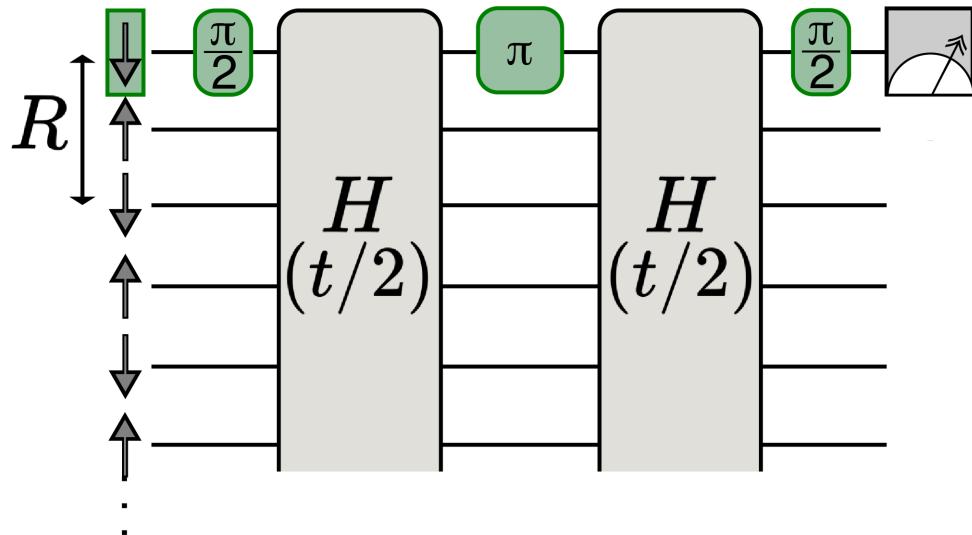
RICE

# DEER Protocol

Key aspect of a localized state: entanglement dynamics

Not revealed by typical observables such as magnetization

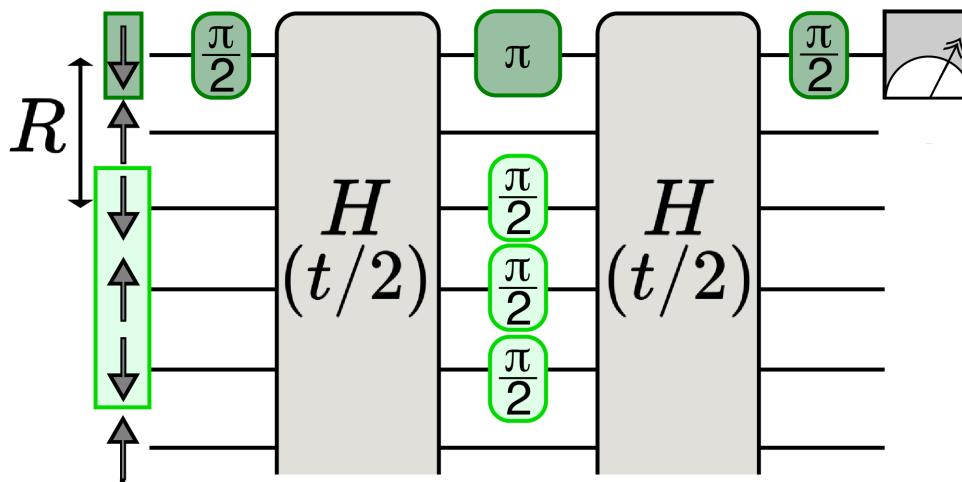
Scalable probe: DEER measurement:



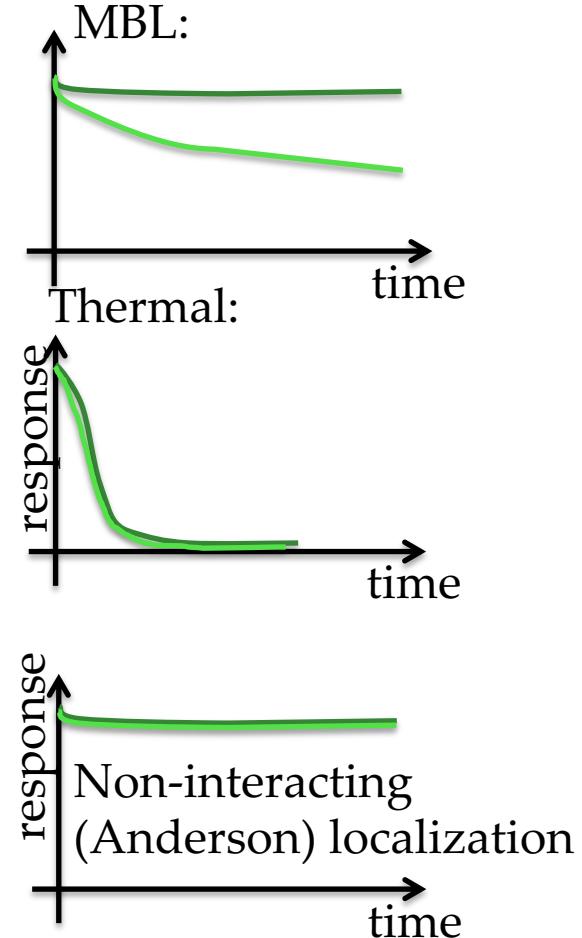
Requires local probing and  
measurement ability

# DEER Protocol

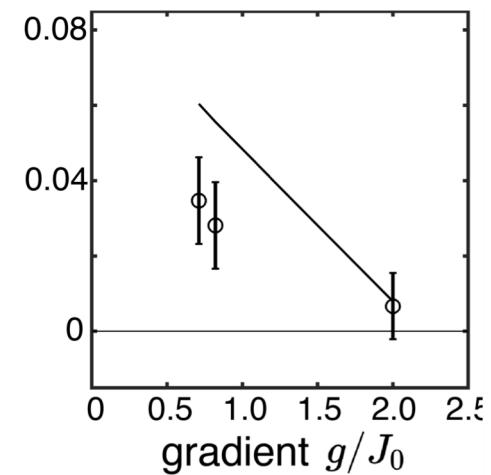
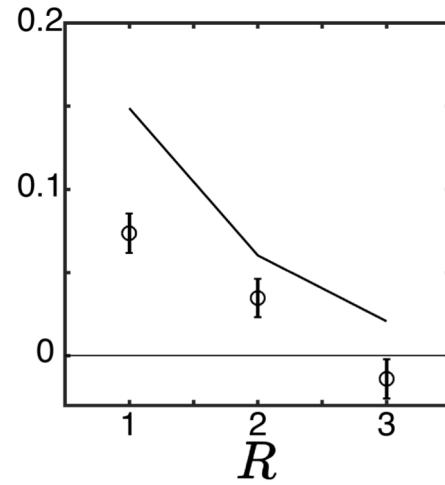
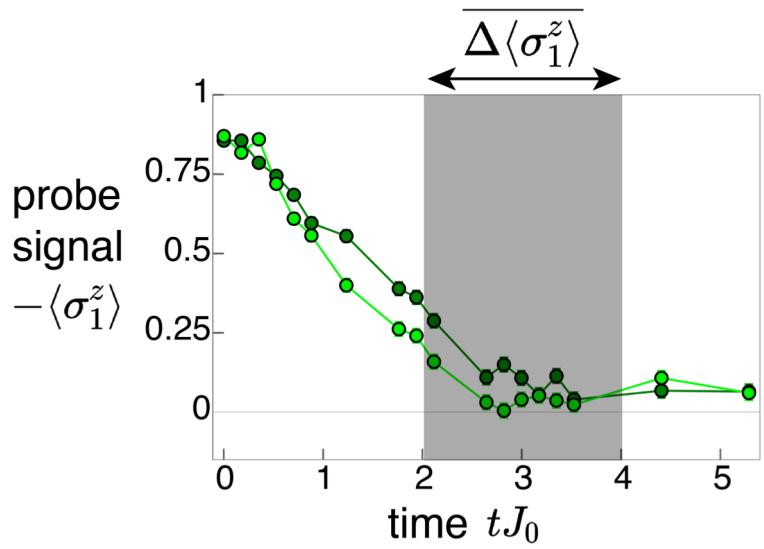
Key aspect of a localized state: entanglement dynamics  
Not revealed by typical observables such as magnetization  
Scalable probe: DEER measurement:



Requires local probing and measurement ability

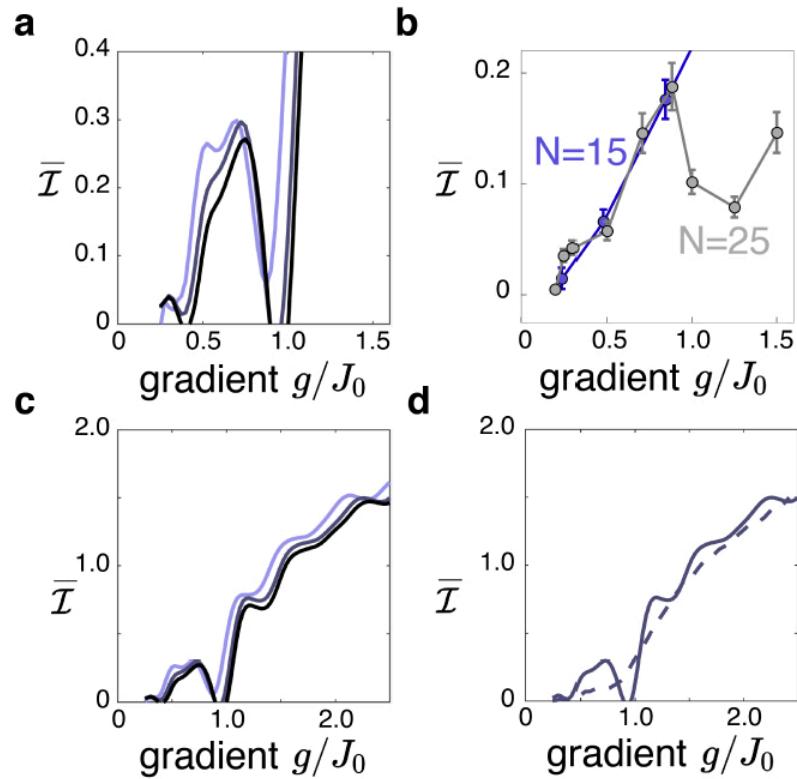


# DEER Protocol



Indication of slow entanglement dynamics  
after imbalance has stabilized

# SMBL N Scaling



# Participation Entropies

$$S_q = \frac{1}{1-q} \ln \left( \sum_{\beta=1}^{2^L} |\psi_{\beta}|^{2q} \right)$$

The scaling with  $L$  of  $S_q$  distinguishes if wave functions that are delocalized, multifractal and localized.

$$a_q(L) \sim a_q^{\infty} + b_1/L + b_2/L^2$$

