Many-body physics in the NISQ era: quantum programming a discrete time crystal

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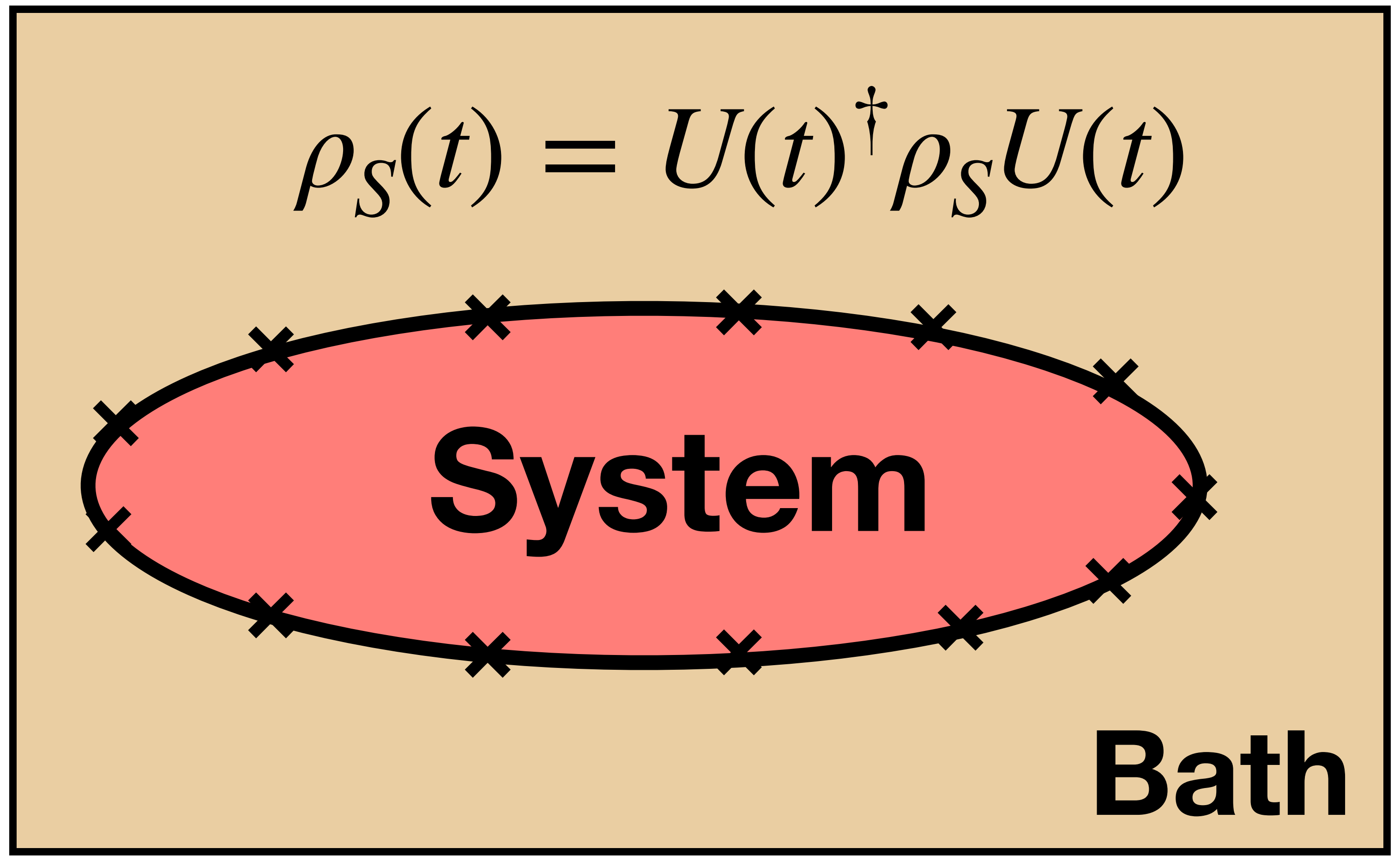
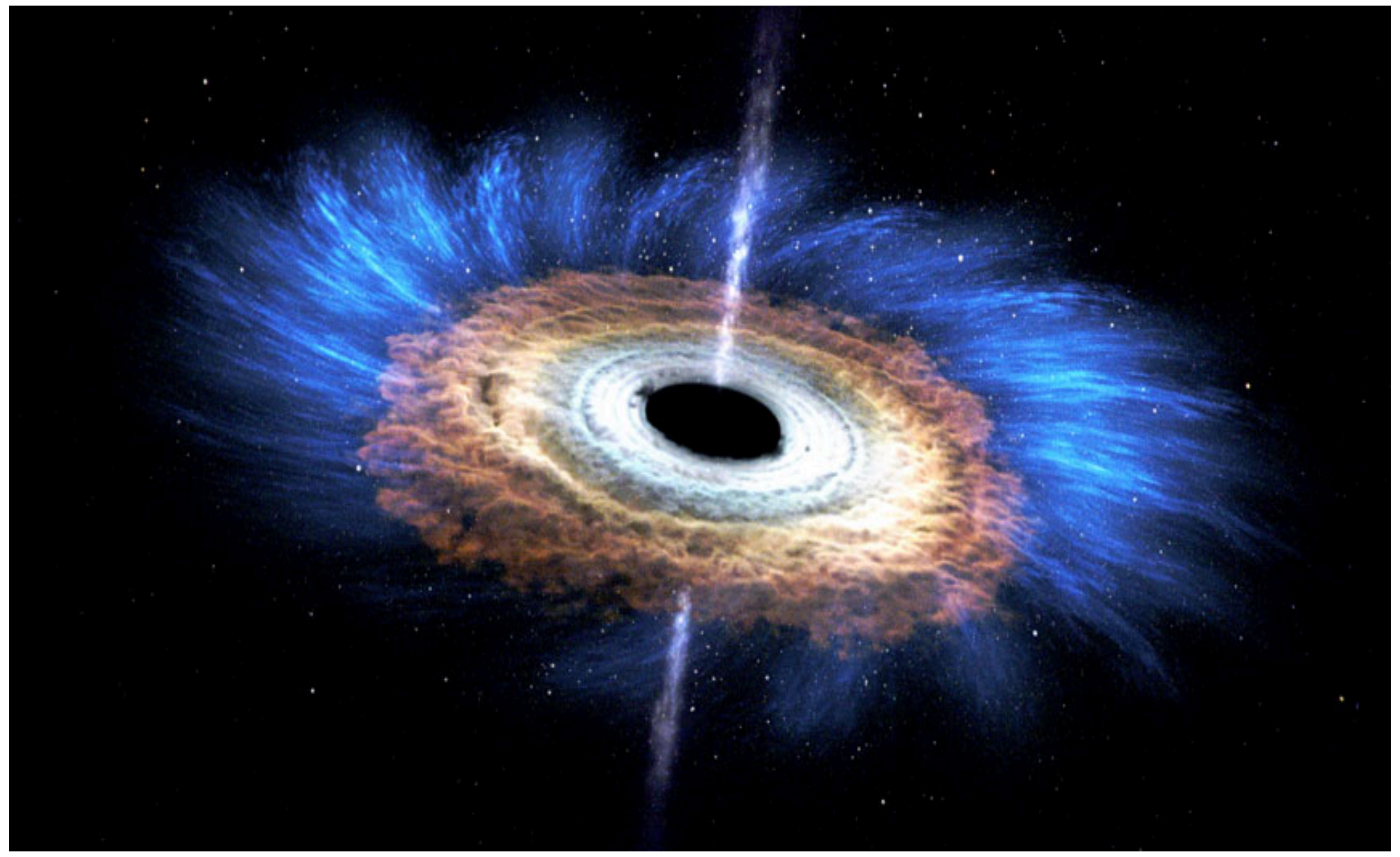
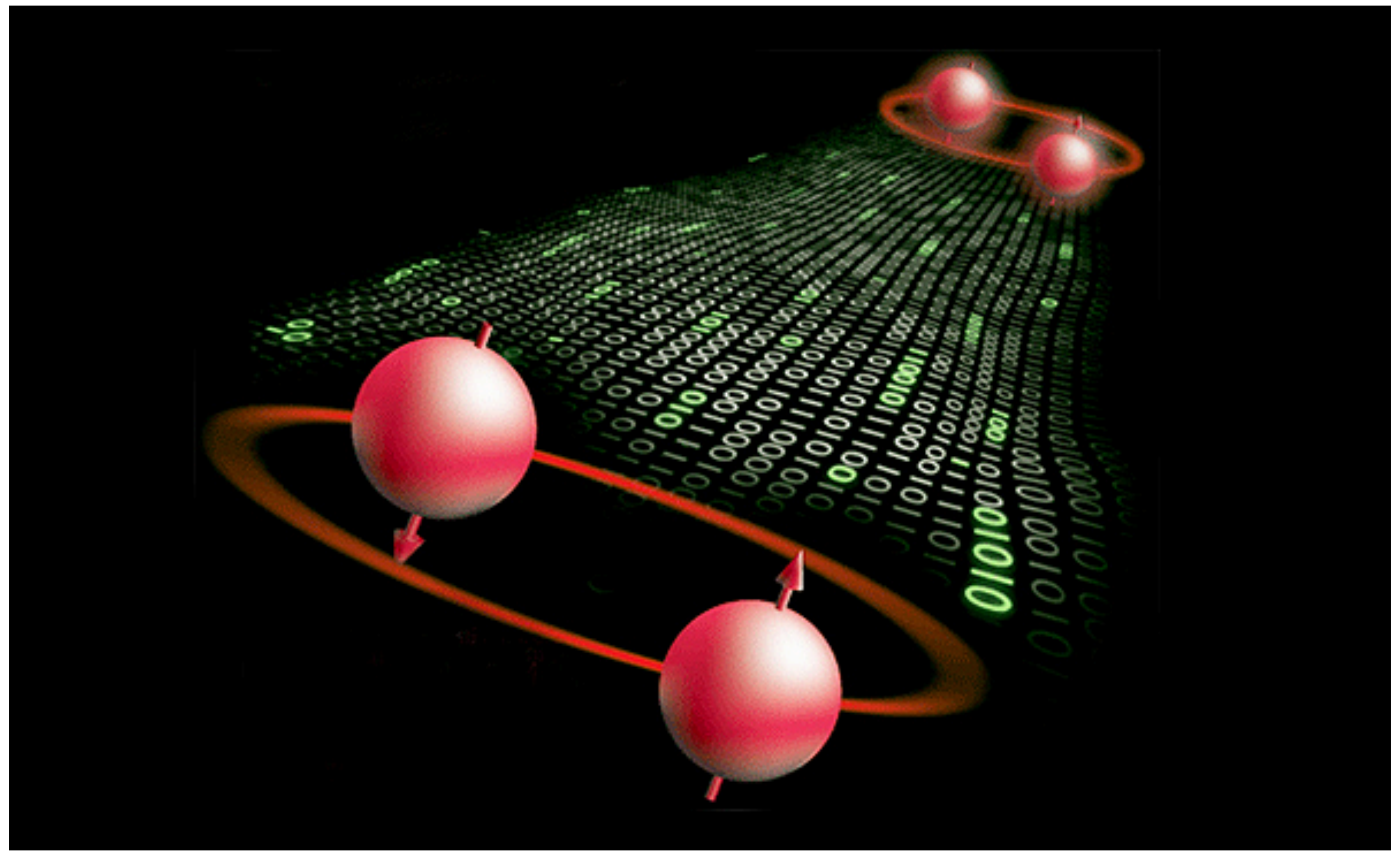
Ippoliti, Kechedzhi, Moessner, Sondhi, **VK**, arXiv: 2007.11602

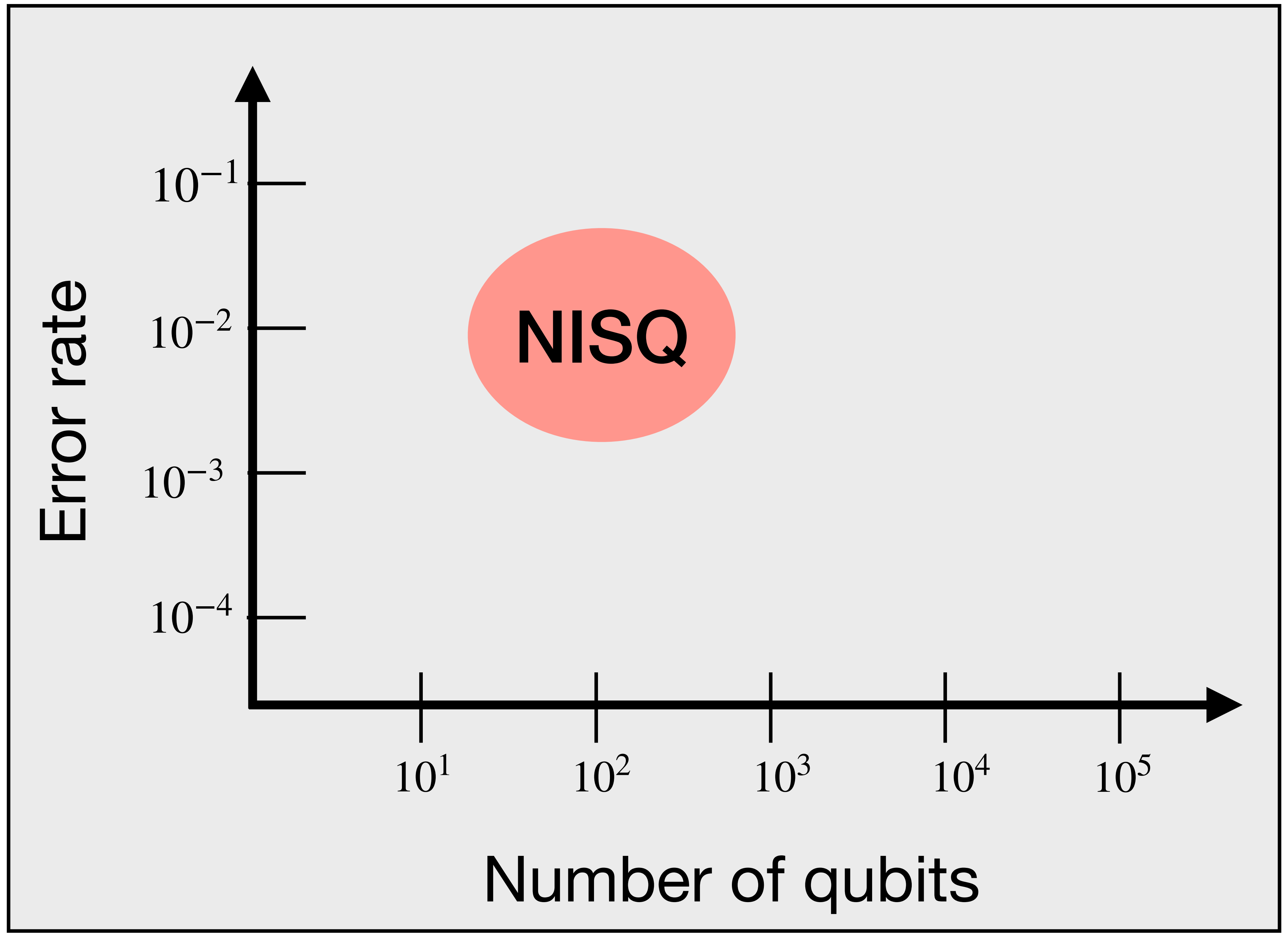
QI theoretic approaches to many-body physics







Noisy **I**ntermediate **S**cale **Q**uantum



Steadily pushing the boundary in the development of artificial "designer" many-body quantum systems across a variety of platforms: superconducting qubits, trapped ions, cavity QED, photonic circuits…

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical. And by golly it's a wonderful problem, because it doesn't look so easy." (Feynman 1981)

Preskill (2018)

Article

Quantum supremacy using a programmable superconducting processor

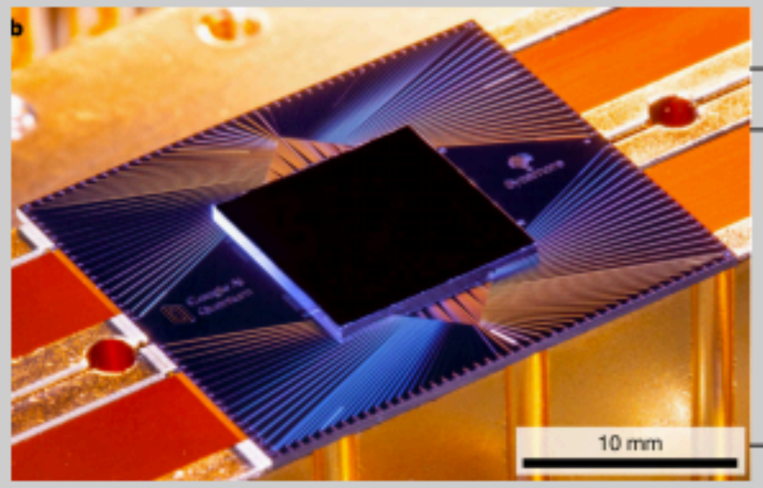
Task

Sample the output distribution from a random quantum circuit U

Quantum vs. Classical

Best quantum strategy:

Run circuit on quantum processor, take m samples



x_1

x_2

$\vdots$

x_m

Best classical strategy:

Simulate circuit using a supercomputer

p_U

Bench marking

Verify that quantum processor is working properly

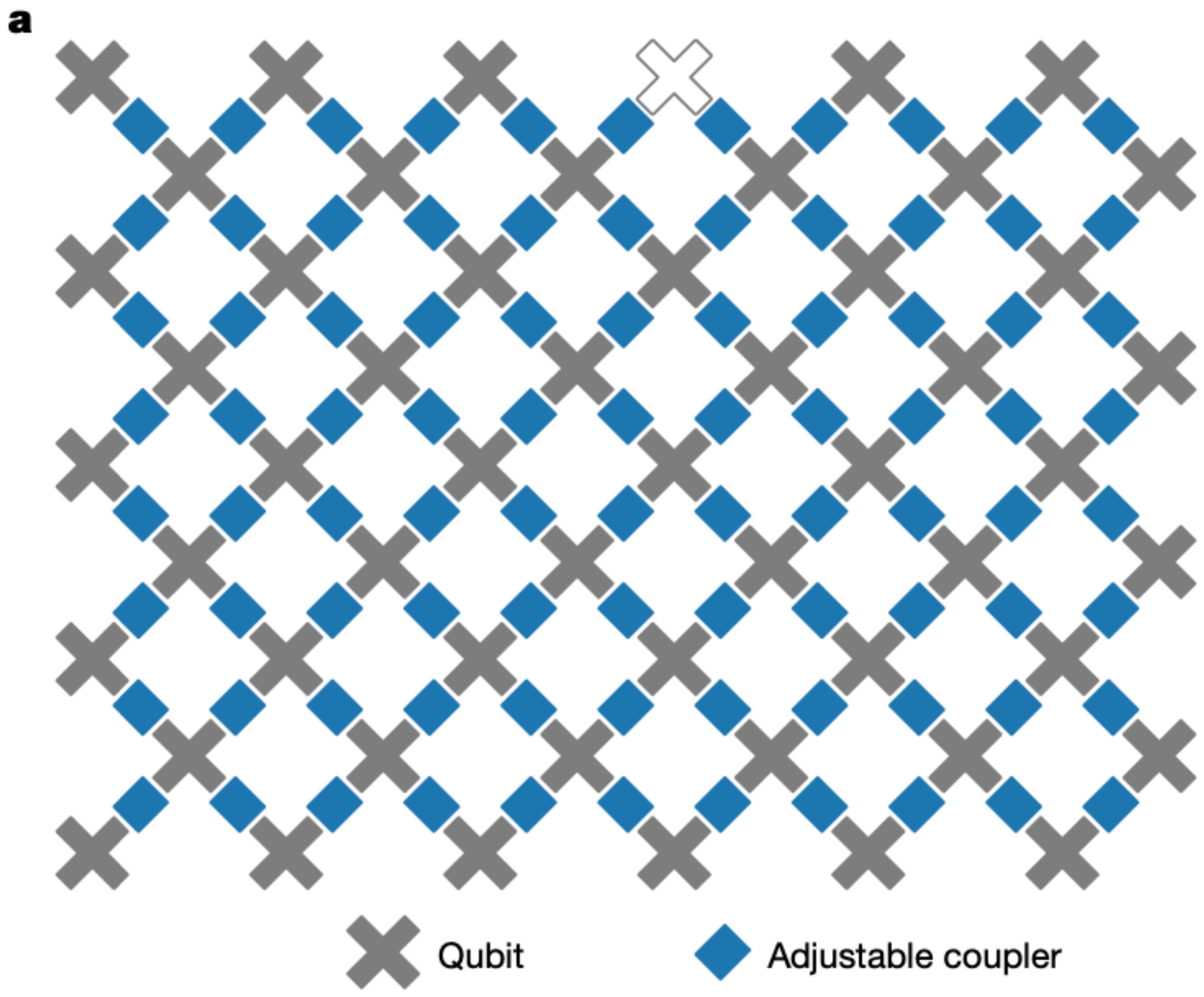
$$F_{XEB} = N\langle p_U(x_i)\rangle_i - 1$$

Evaluation

Quantum processing time: short

Classical processing time: Exponential in n

"Supremacy"



(Arute et. al. 2019)

Many-body physics in the NISQ era

Computational Devices ↔ Experimental Platforms for MB physics

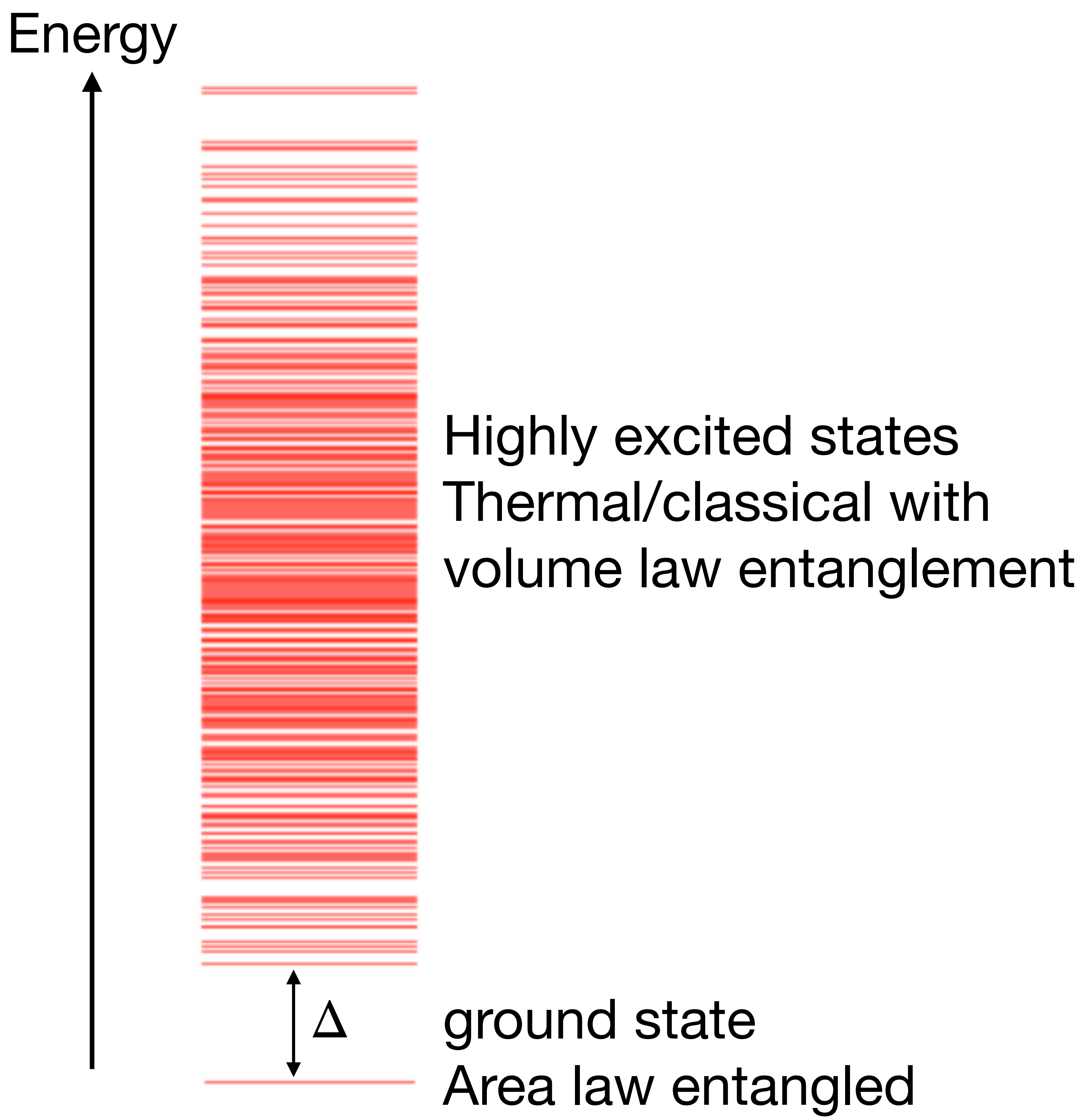
Broadly: What does the NISQ era of tunable, programmable quantum systems portend for many body physics?

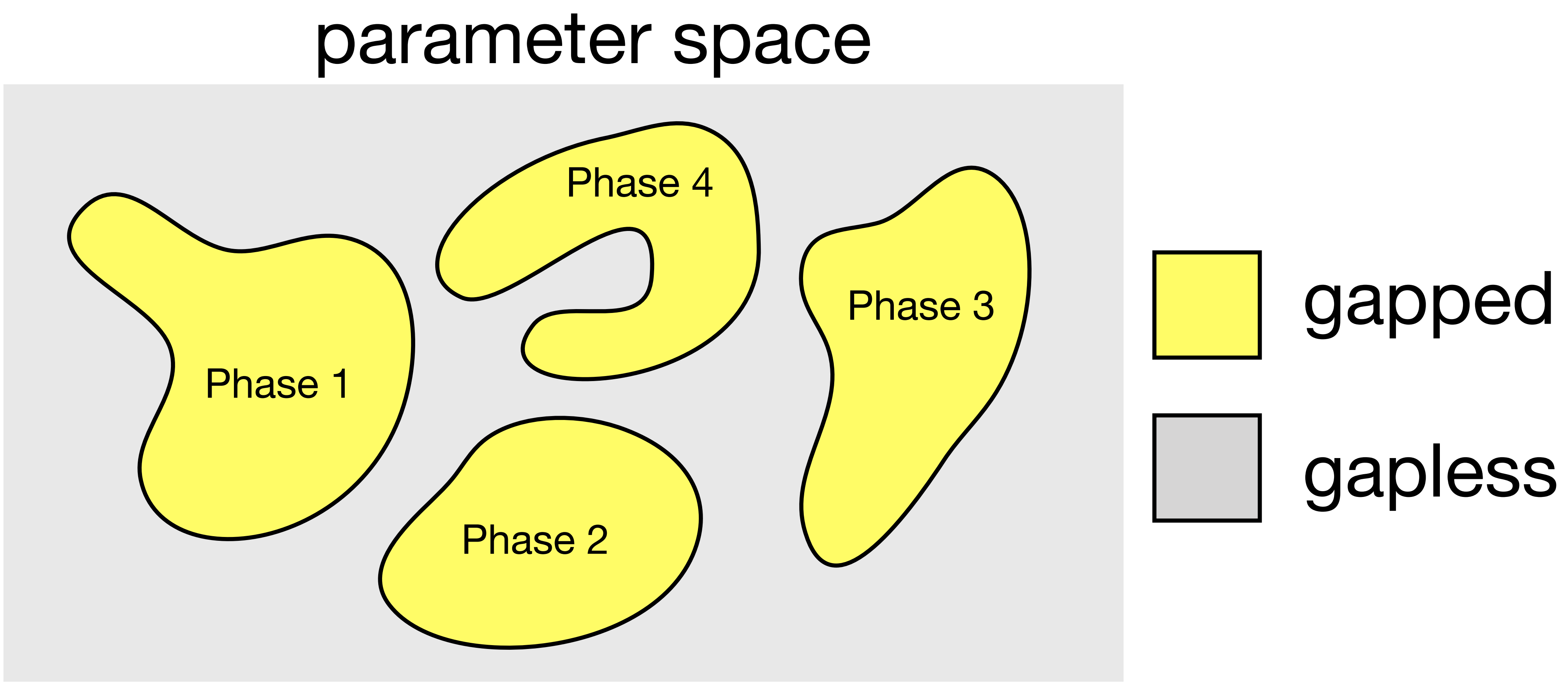
Which *physical phenomena* in the realm of quantum statistical mechanics can these devices realize, that have not been (or cannot be) as crisply demonstrated in any other setting?

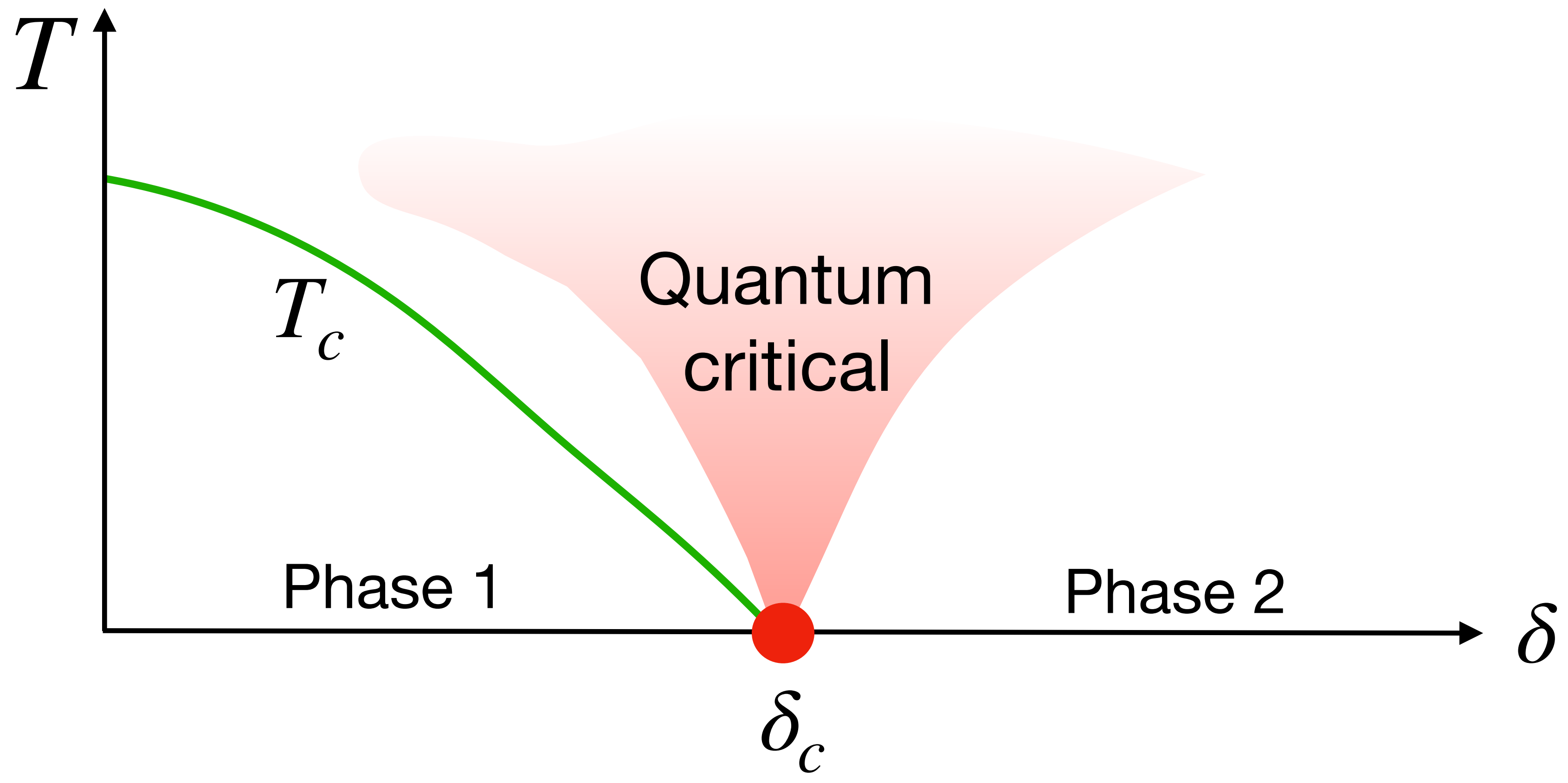
Narrowly: What interesting physics can be realized immediately with Google's Sycamore device?

Traditional CMT paradigms

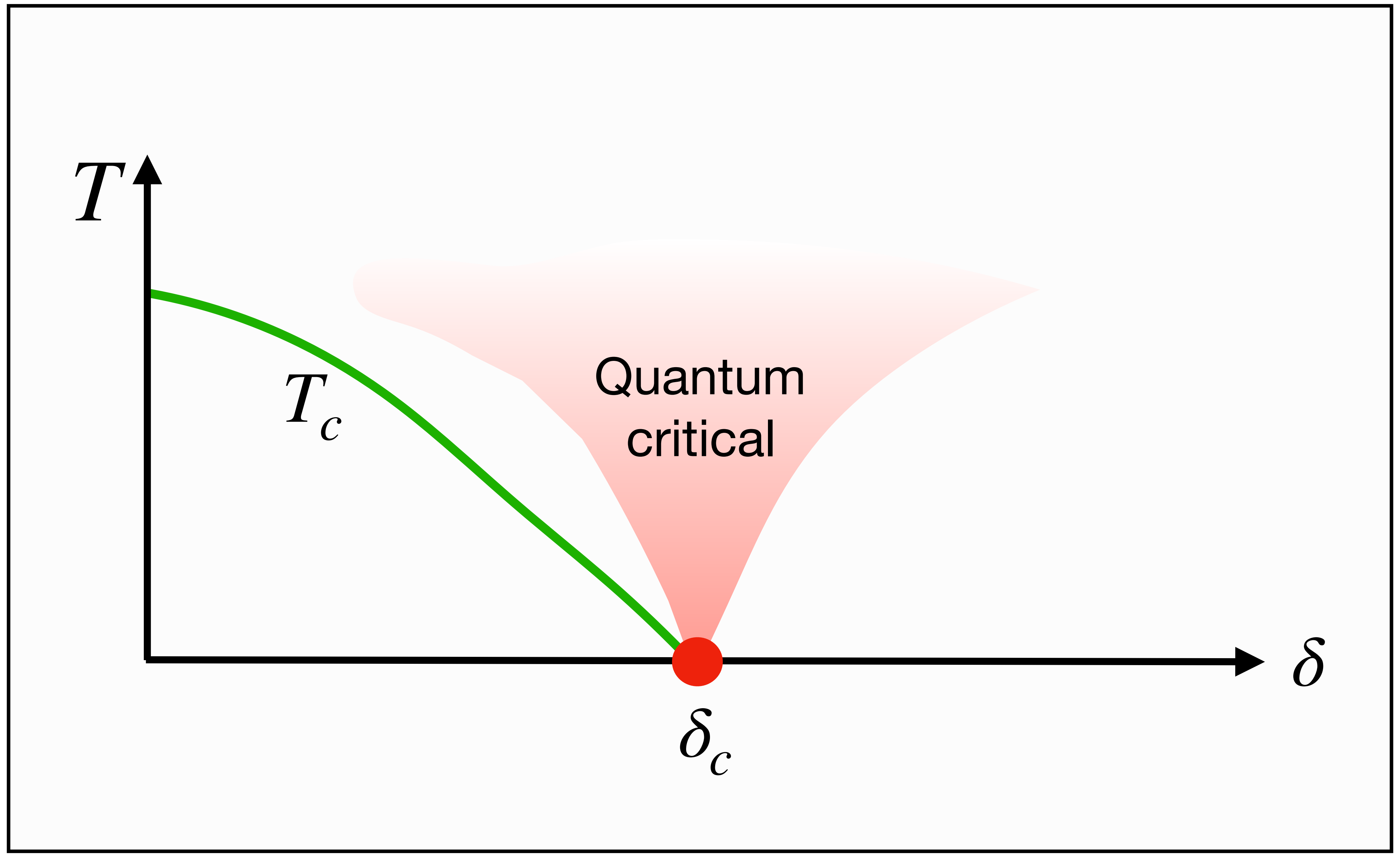
- Study time-independent Hamiltonians (Ising, Heisenberg, Hubbard…)
- Study universal (quantum) phases and phase transitions at zero/low temperatures

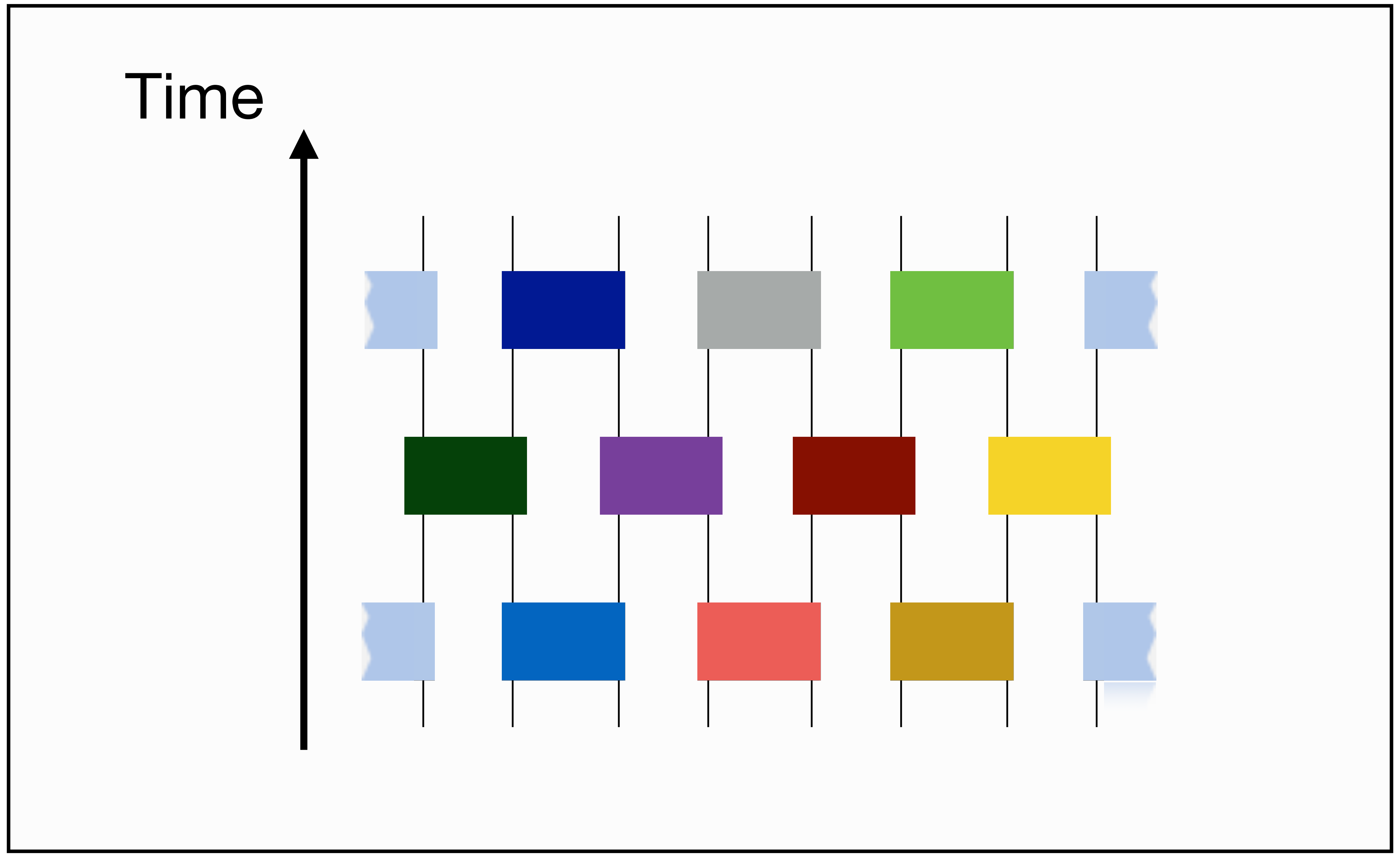






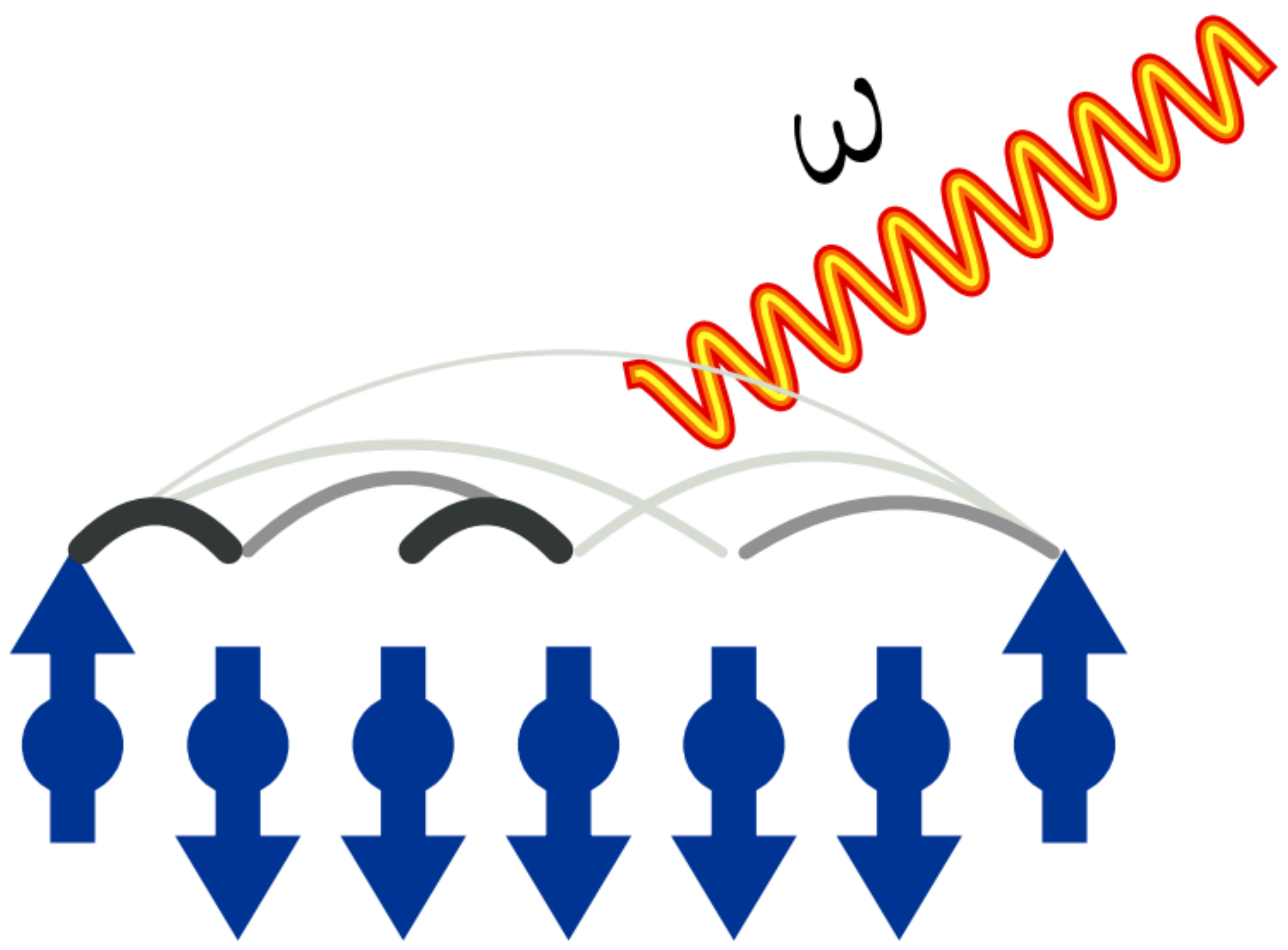
Many-body physics in the NISQ era

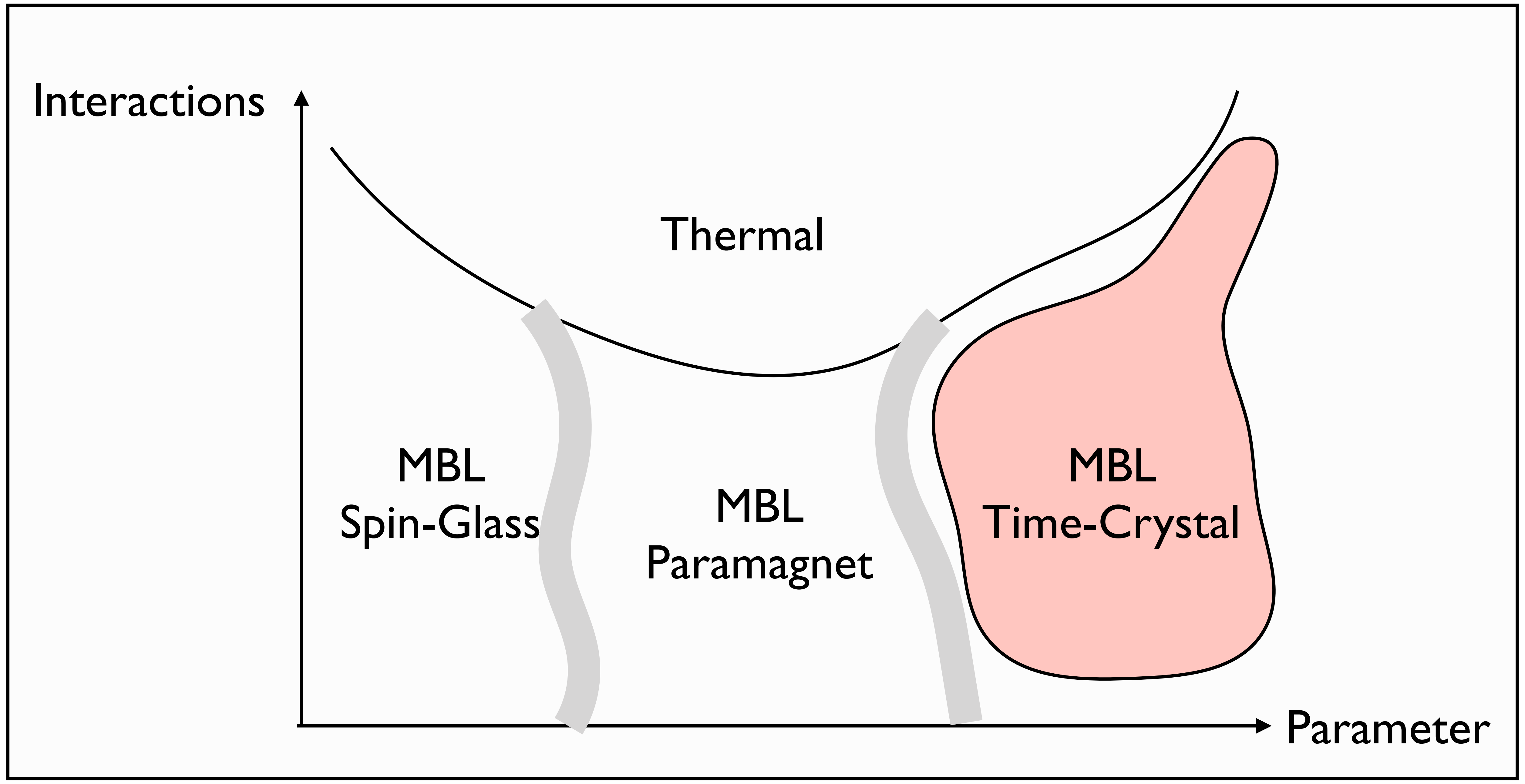




Hamiltonians → Unitary Circuits

Many-body phases out-of-equilibrium





Equilibrium Phases ➔ Dynamical nonequilibrium phases in Floquet systems

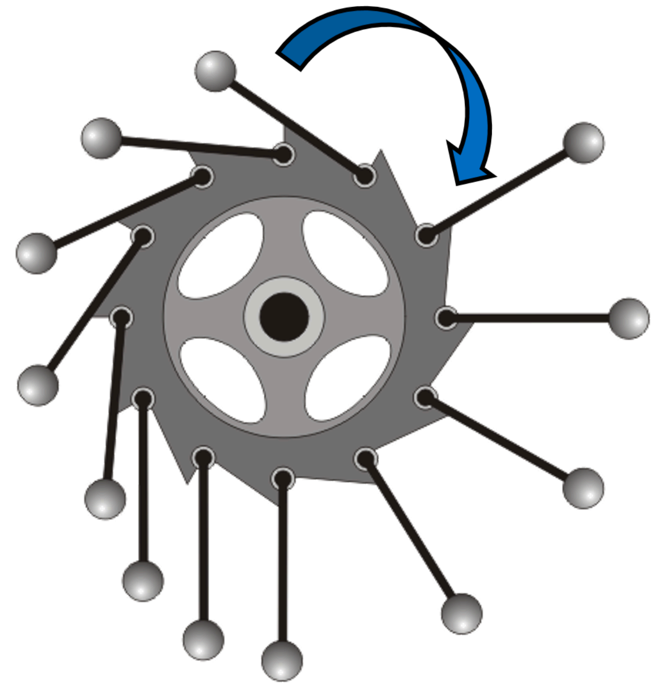
Can allow for "localization protected" quantum order

Huse et al (2014); **VK**, Lazarides, Moessner, Sondhi (2016)

Outline

- Review of the discrete time-crystal (DTC) phase
- Summary of state-of-the art DTC experiments
  - desired experimental capabilities
- Implementing a DTC on Sycamore:
  - model
  - phase diagram
  - diagnostics
  - noise

What is a time crystal?



- Spontaneously breaks time translation symmetry
  - The rules underlying the system are time independent, but the motion (state) is periodic in time.
  - Must consider *macroscopic* many-body systems. Few body systems routinely break TTS and exhibit recurrences and revivals
  - “Perilously close” to a perpetual motion machine

Forbidden in thermal equilibrium states or in ground states of many-body systems (Bruno, Nozieres, Oshikawa Watanabe…)

Review: VK, Moessner, Sondhi (2019)

Floquet (discrete) time crystal

$$H(t) = H(t + T)$$

- Period doubling in observables for infinitely long times (or other multiples of driving period)
  - spontaneously breaks *discrete* time-translation symmetry
  - sharp *subharmonic* peak in Fourier space.
- Robust over a range of parameters to define a *phase* of matter
- MBL to avoid heating to infinite temperature
- Spatiotemporal order: long-range order in space+ period doubling in time

Review: VK, Moessner, Sondhi (2019)

A zoo of "time-crystals"

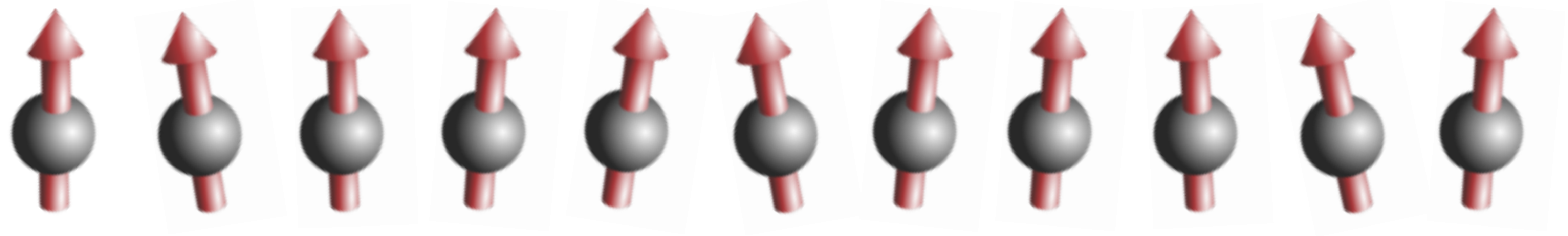
- Nominally similar period doubling behavior across a range of familiar systems (parametric oscillators, Faraday waves…)
- All are one- or few- or "effectively-few" body systems
- We are interested in a *genuine* many-body phase of matter in an isolated quantum system. This requires Floquet MBL.

Review: VK, Moessner, Sondhi (2019)

Why DTC for Sycamore?

- Novel nonequilibrium many-body phase of matter with spatiotemporal order
    - Bona-fide realization has <u>not</u> been achieved in experiment yet
- Circuit realizations of Floquet models of DTCs are natural
- Dynamical signatures, rather than diagnostics in equilibrium thermodynamics
- Disorder (say due to variations in circuit elements) is not only tolerated, but essential for stabilizing MBL

DTC in a driven Ising chain



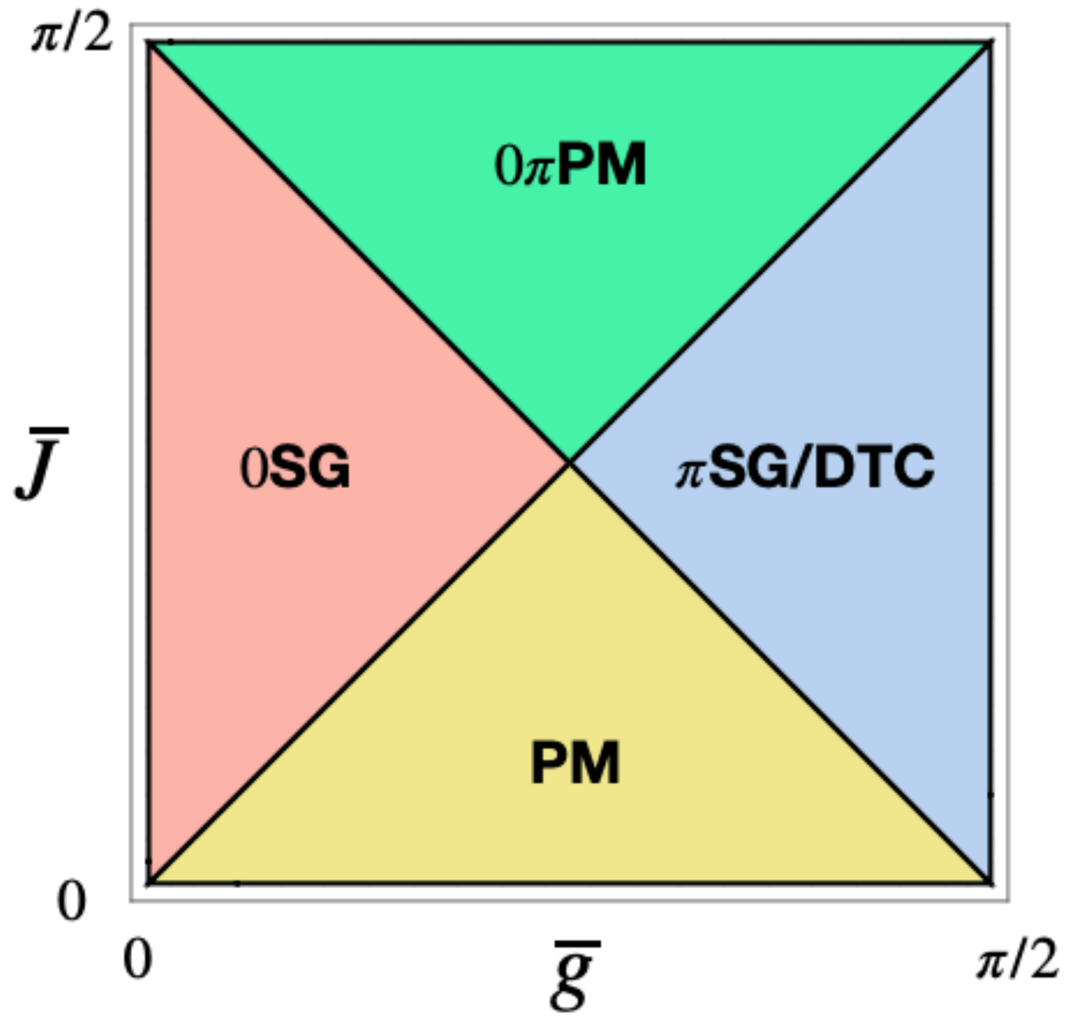
$$H(t) = \boxed{H_X}\,\boxed{H_z}$$

$$U_F = e^{-ig\sum_i X_i}\, e^{-iH_z}$$

$$U(n) =$$

$$\cdots$$

$$H_Z = \sum_{\langle ij\rangle} J_{ij} Z_i Z_j$$



VK Lazarides Moessner Sondhi (2016)

Spatiotemporal order in a “trivial” limit

$$g = \frac{\pi}{2}$$

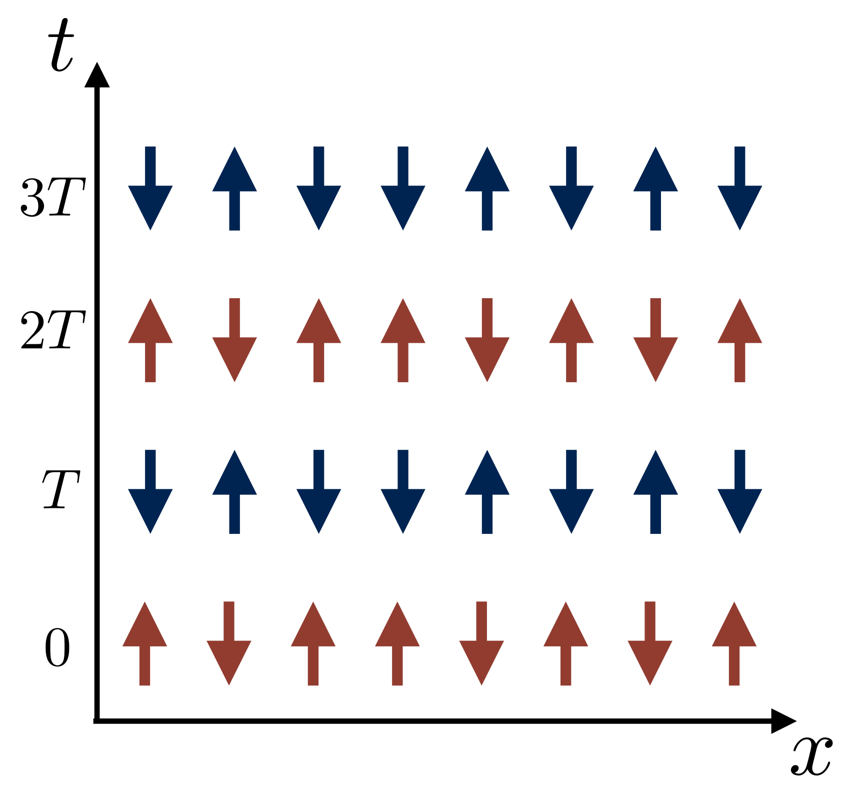
Perfect rotation by π about the x-axis

$$H_Z = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j$$

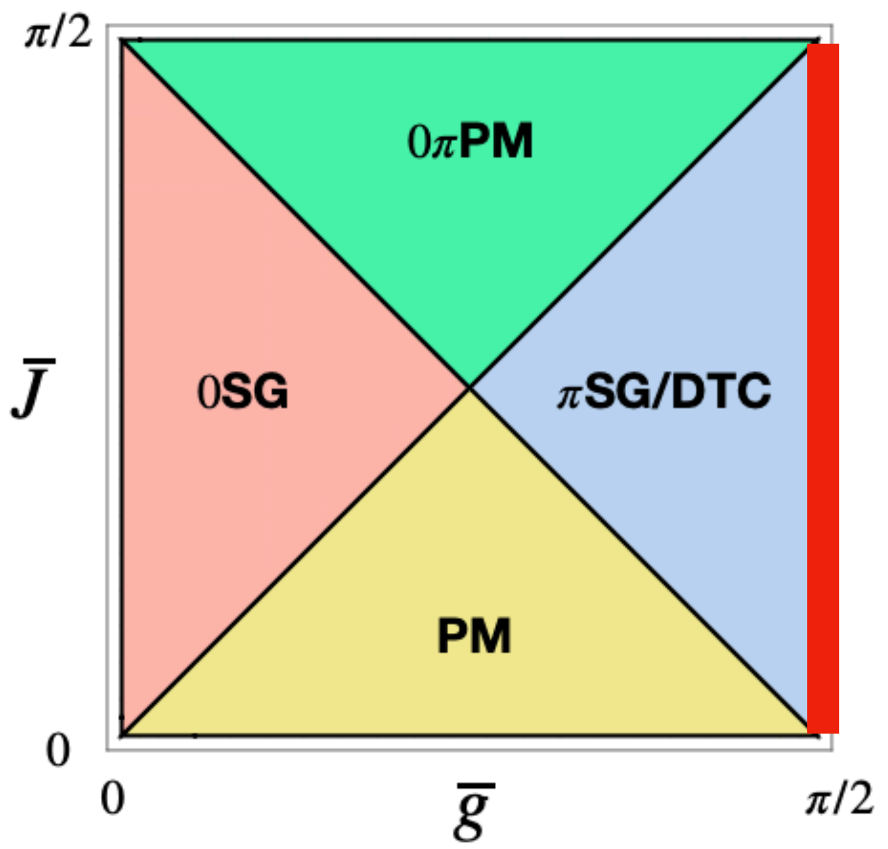
$$U_F = e^{-i\frac{\pi}{2}\sum_i X_i} e^{-iH_z} = P e^{-iH_z} \quad = \quad \pi \text{ rotation} \;\; H_z$$

$$e^{-i\frac{\pi}{2}\sum_i X_i} \propto \prod_i X_i \equiv P$$

- Period doubling: time translation symmetry breaking



$$Z(n) = (-1)^n Z$$

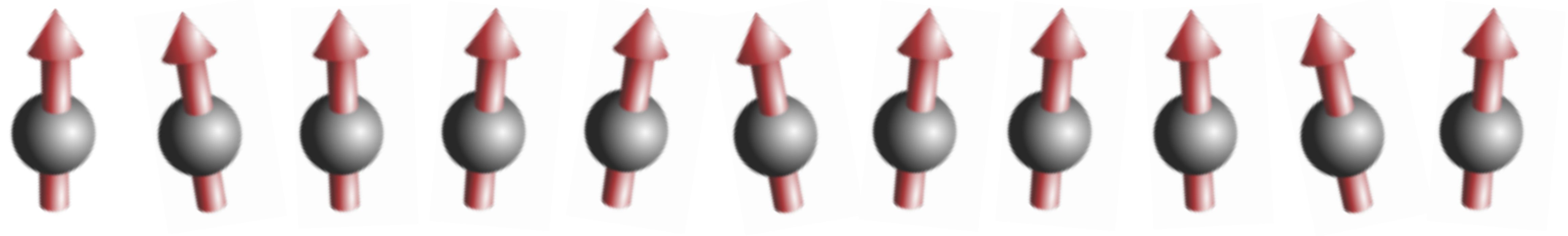


- *Glassy* Long-range spatial order:

$$\langle Z_i Z_j \rangle_c = s_{ij} \neq 0 \quad \text{for large} \quad |i-j|$$

VK Lazarides Moessner Sondhi (2016)

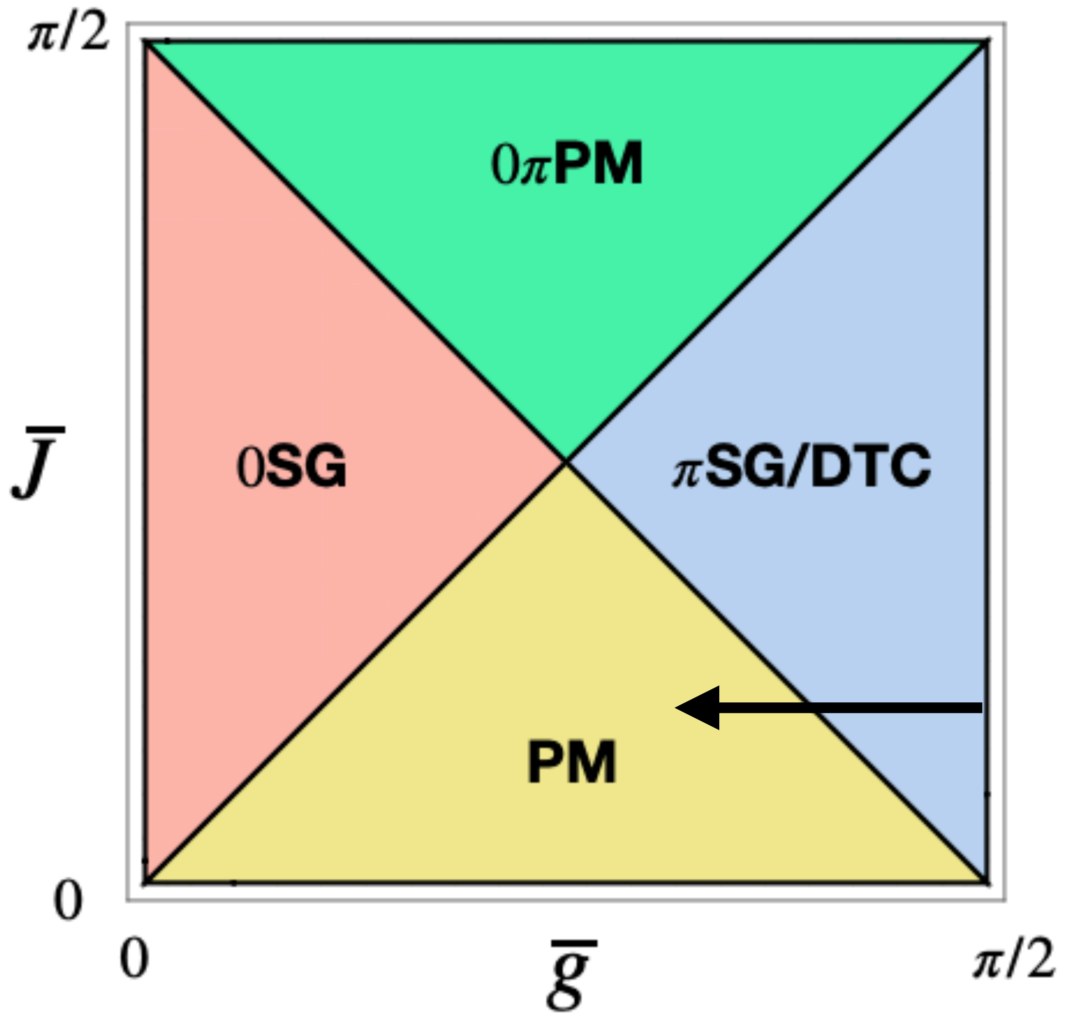
Robust phase of matter with spatiotemporal order

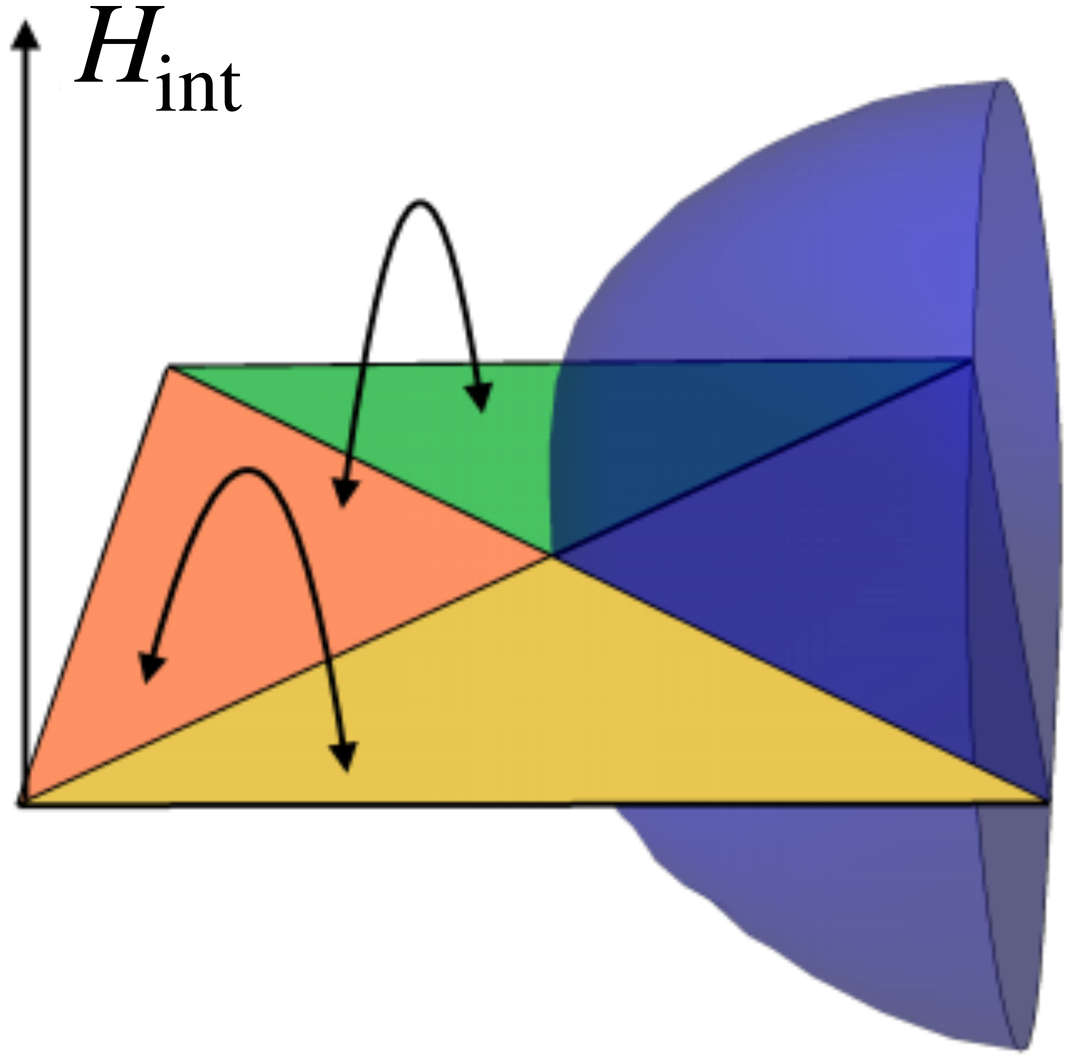


$$U_F = e^{-ig\sum_i X_i} e^{-i(H_z + H_{\text{int}})} \;=\;$$ Imperfect Rotation $H_z + H_{\text{int}}$

$$H_Z = \sum_{\langle ij \rangle} J_{ij} Z_i Z_j$$

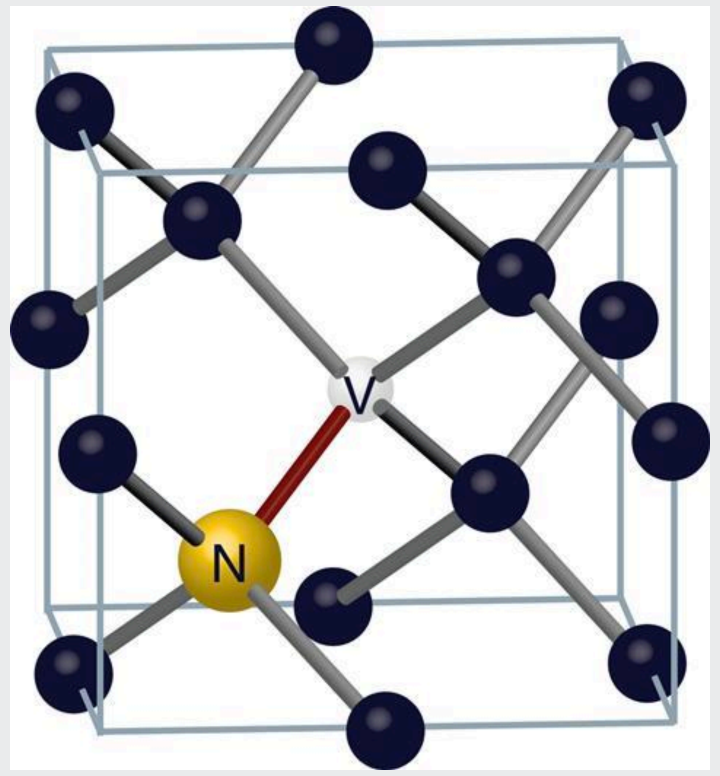
$$H_{\text{int}} = \sum_i h_i Z_i + J_{ij}^{\perp}(X_i X_j + Y_i Y_j) + \cdots$$





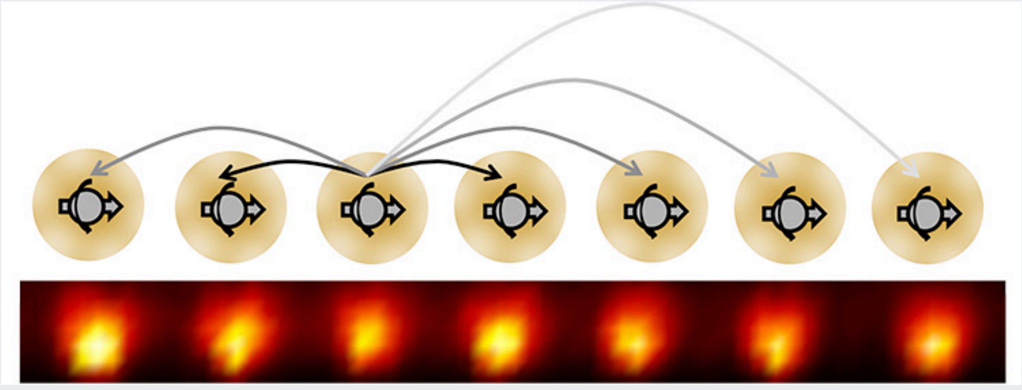
Vk, Lazarides, Moessner Sondhi (2016), Else Bauer Nayak (2016);
vonKeyserlingk **VK** Sondhi (2016)

DTC Experiments



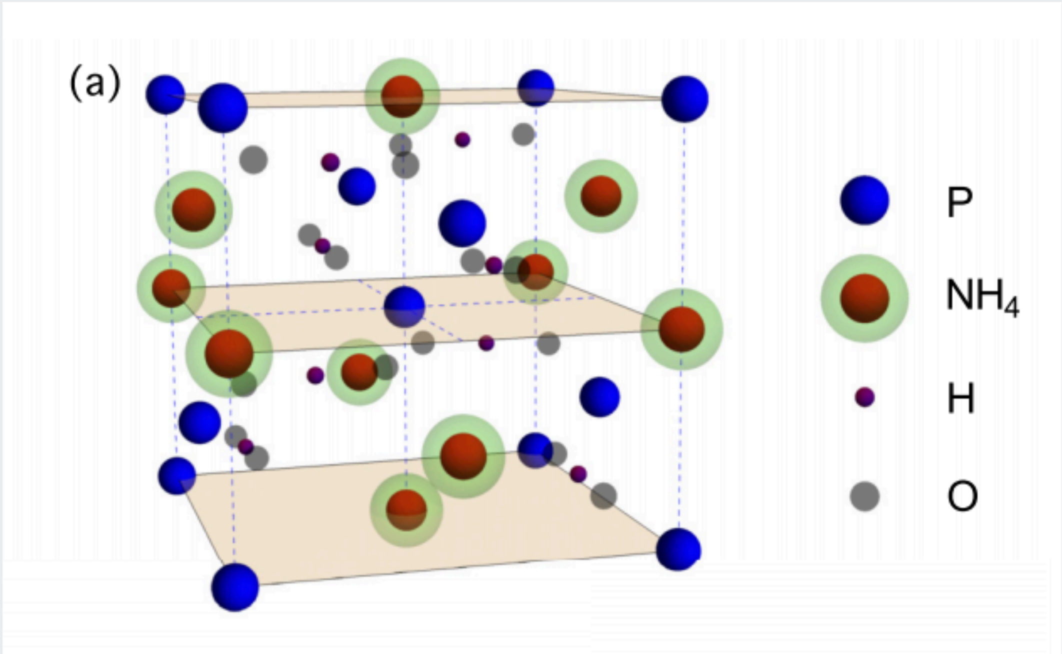
Disordered NV centers in 3D diamond (10^6)

Choi…Lukin (2017)



Disordered trapped Ions in 1D (10)

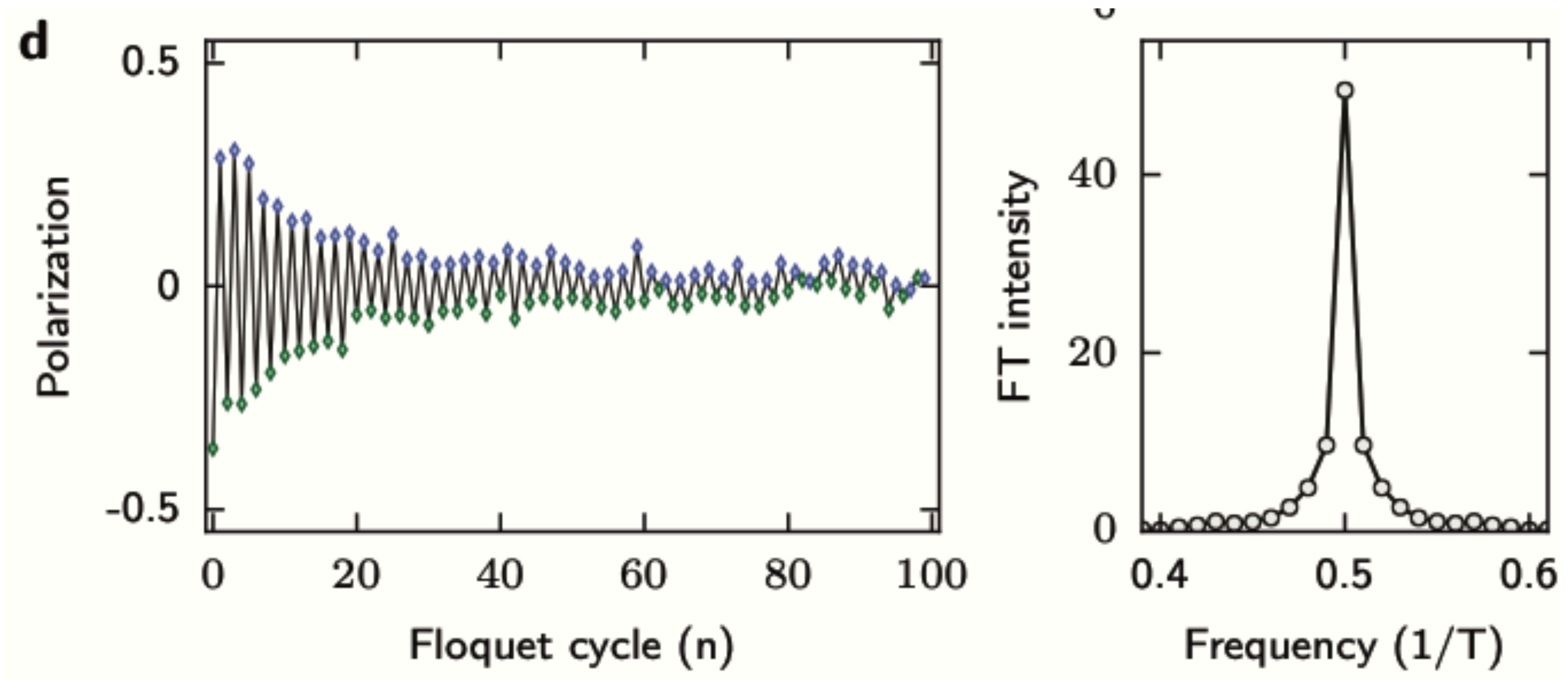
Zhang…Monroe (2017)



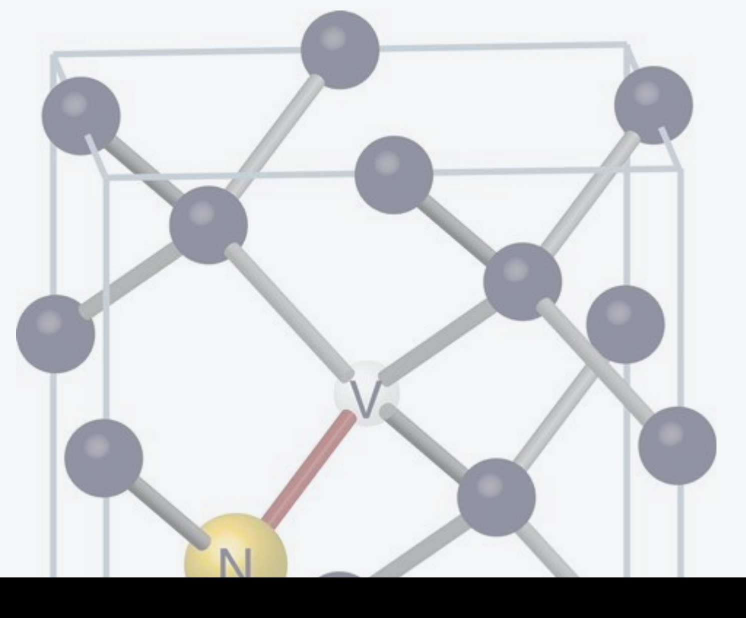
Ordered NMR 3D crystal (10^6)

Rovny…Barrett (2018)

$U(T) =$ Imperfect Rotation (Dominantly Ising) Interactions



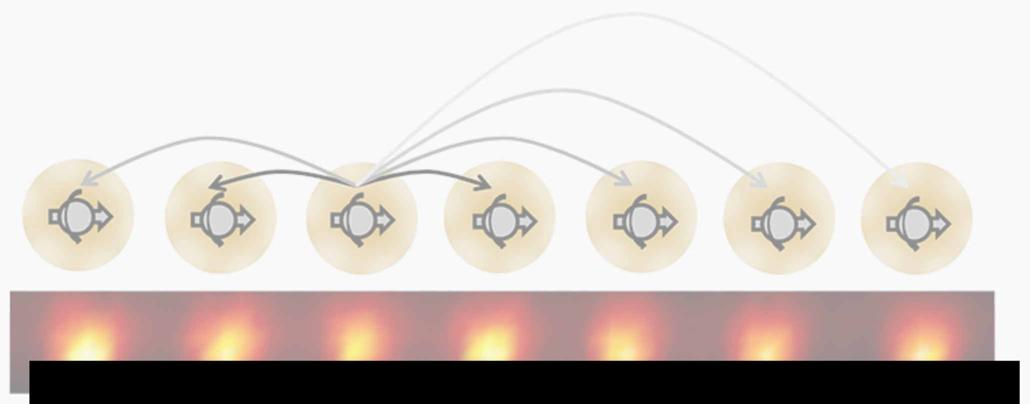
DTC Experiments



Critical TC

Disordered NV centers in 3D diamond (10^6)

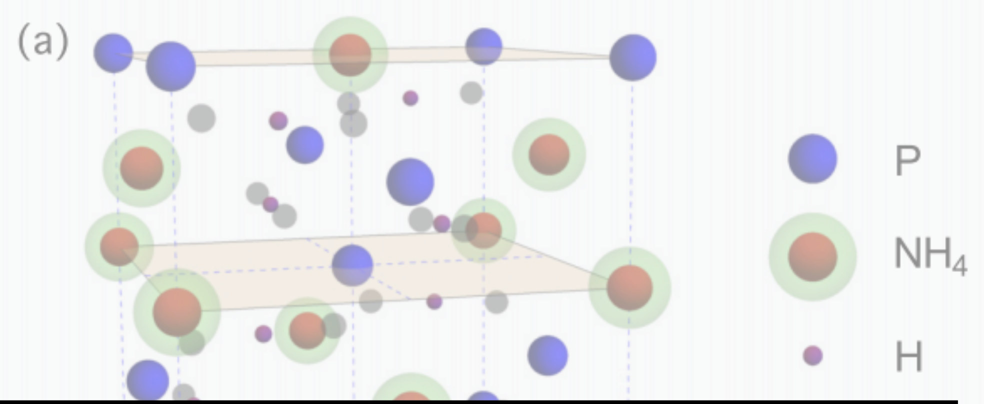
Choi…Lukin (2017)



Prethermal TC

Ions in 1D (10)

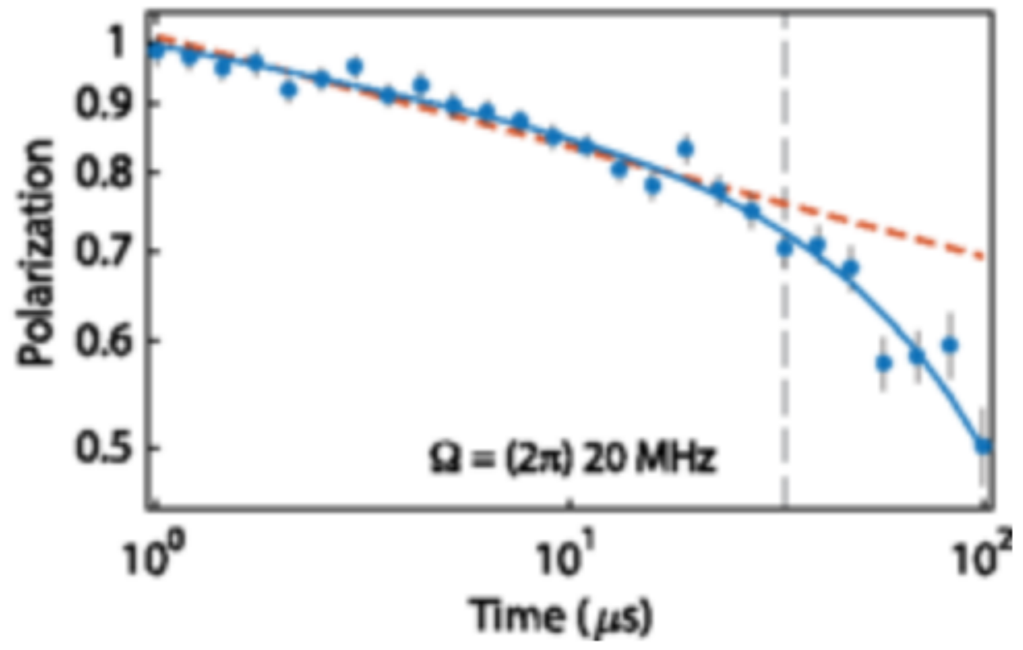
Zhang…Monroe (2017)



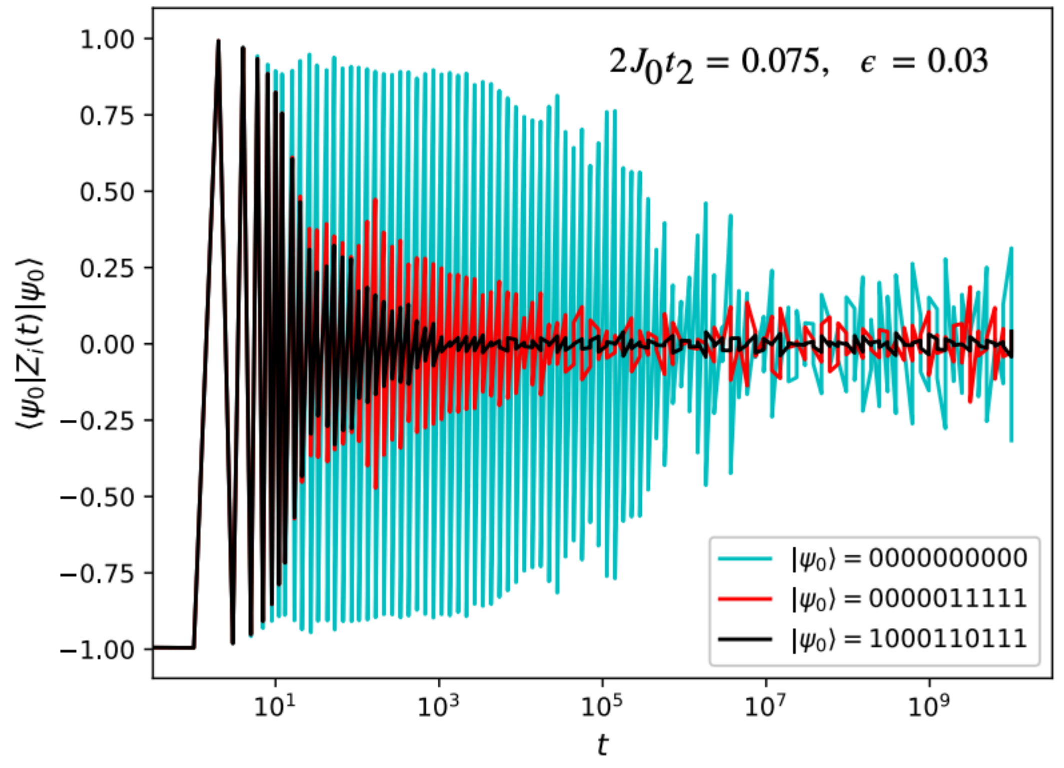
Prethermal U(1) TC

3D crystal (10^6)

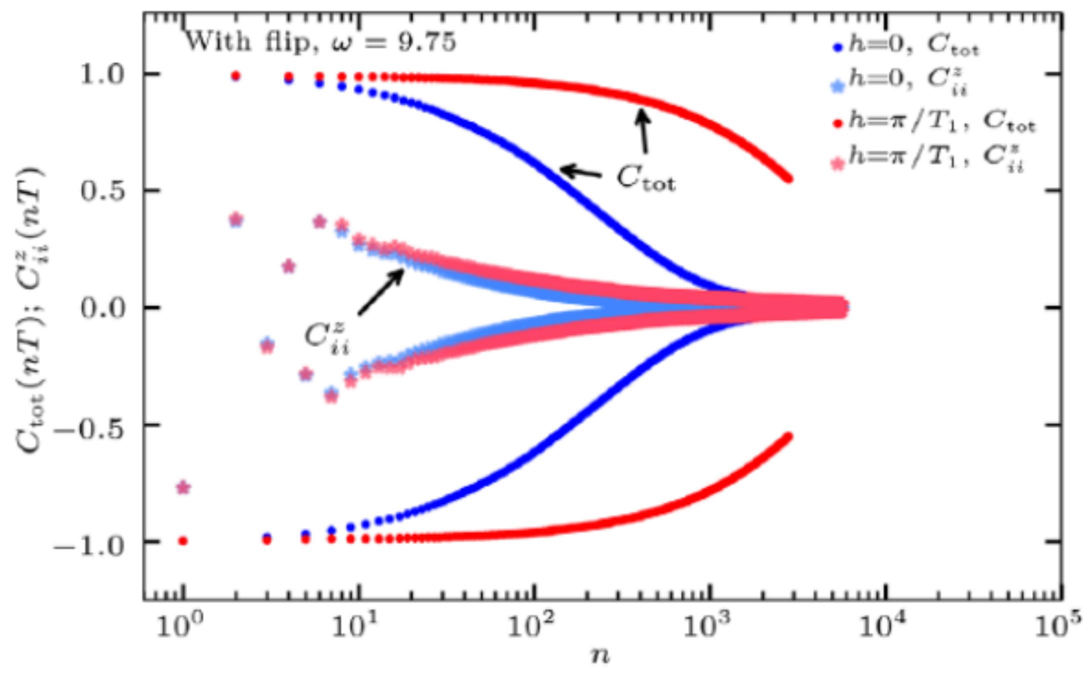
Rovny…Barrett (2018)



Kuscko et. al. (2018)
Ho et. al. (2018)



VK Moessner Sondhi (2019)



Luitz Moessner Sondhi **VK** (2019)

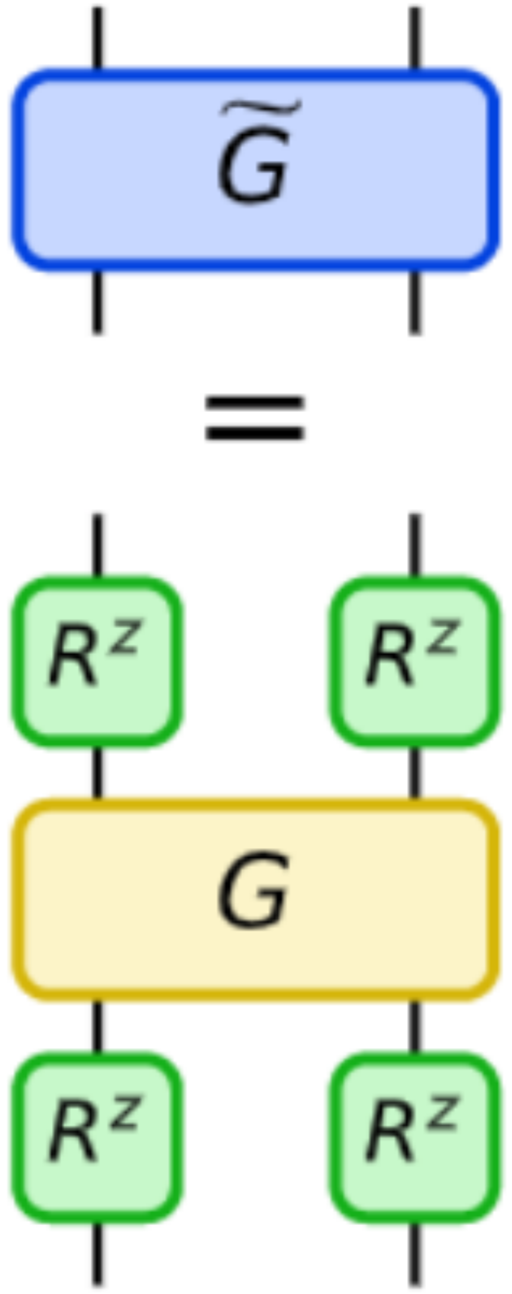
Desired experimental capabilities

- Large enough and generic enough to probe many-body physics
- Long enough coherence time to probe dynamical phases of matter
- For stabilizing MBL
  - Short-range interactions, $\alpha < \frac{3}{2}d$ [Only present in trapped-ion setup]
  - Disorder in Ising even couplings J_{ij} ; [**Not** present in trapped-ion setup]
    - Ising odd disorder (such as in longitudinal fields) “echoes out” over two periods.
- For measuring spatiotemporal order, and distinguishing asymptotic DTCs from “prethermal” variants
  - Site-resolved observables [Only present in trapped-ion setup]
  - Varying initial states [Present in trapped-ion setup, but not exploited]

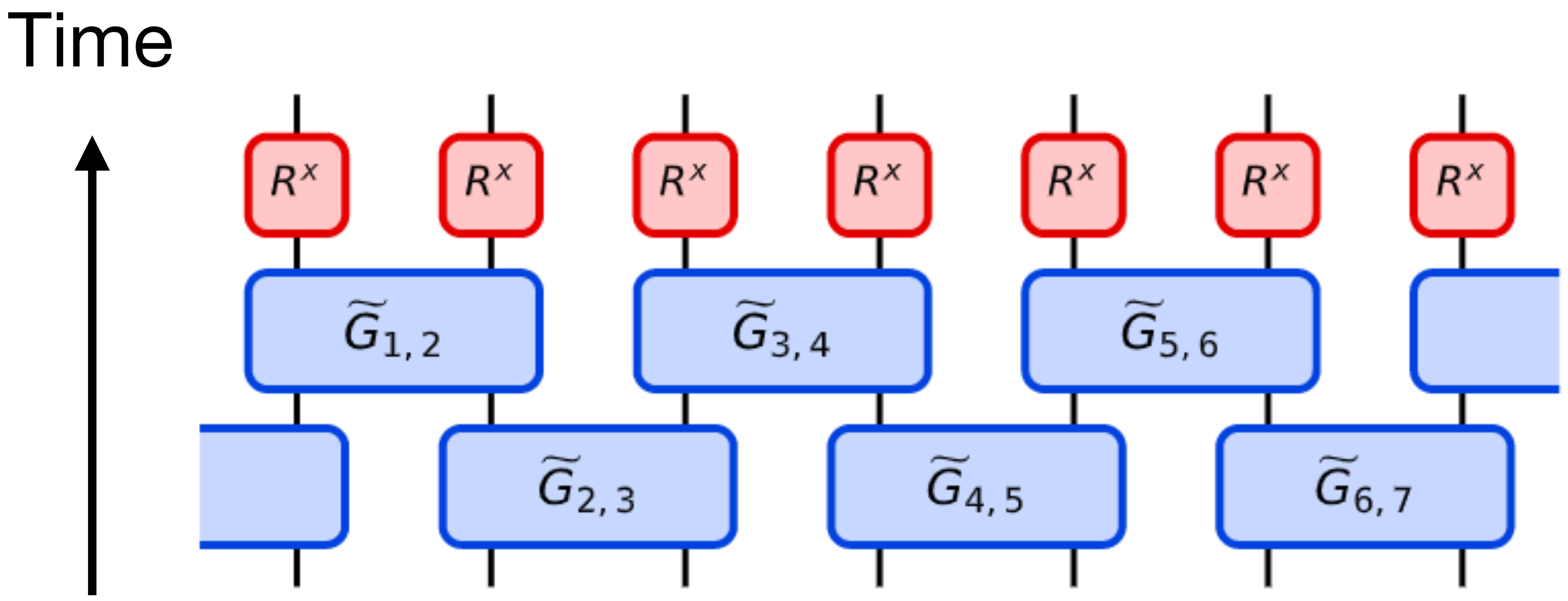
Desired experimental capabilities

Requirements	Experiments			
	NV centers	Trapped ions	NMR crystal	Sycamore
Definitional				
Long coherence time	✓	✓	✓	✓
Many-body	✓✓	∼	✓✓	✓
Stabilizing MBL				
Short-range int.	✗	?	✗	✓
Ising-even disorder	✓	✗	✗	✓
Detection				
Site-resolved meas.	✗	✓	✗	✓
Varied initial states	✗	∼	✗	✓

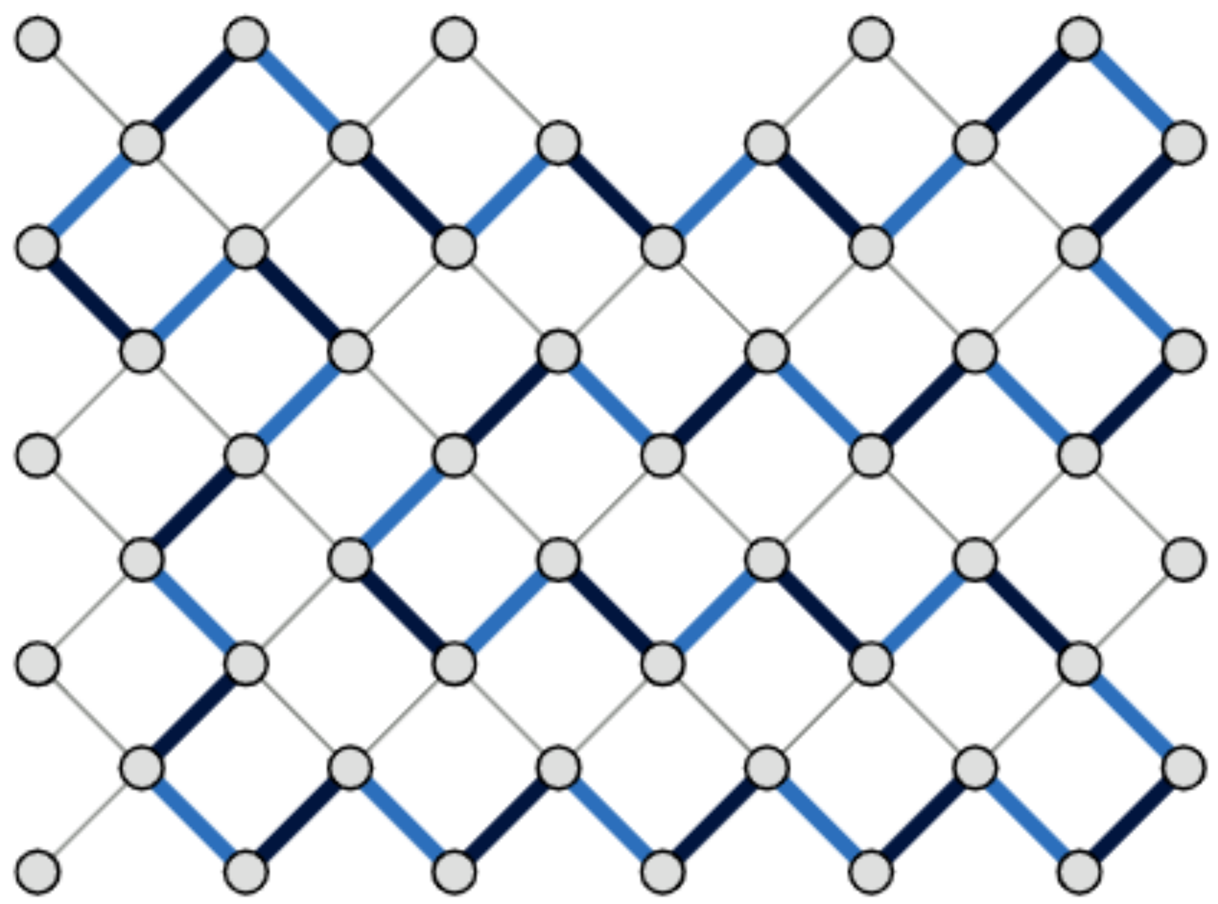
DTC on Sycamore



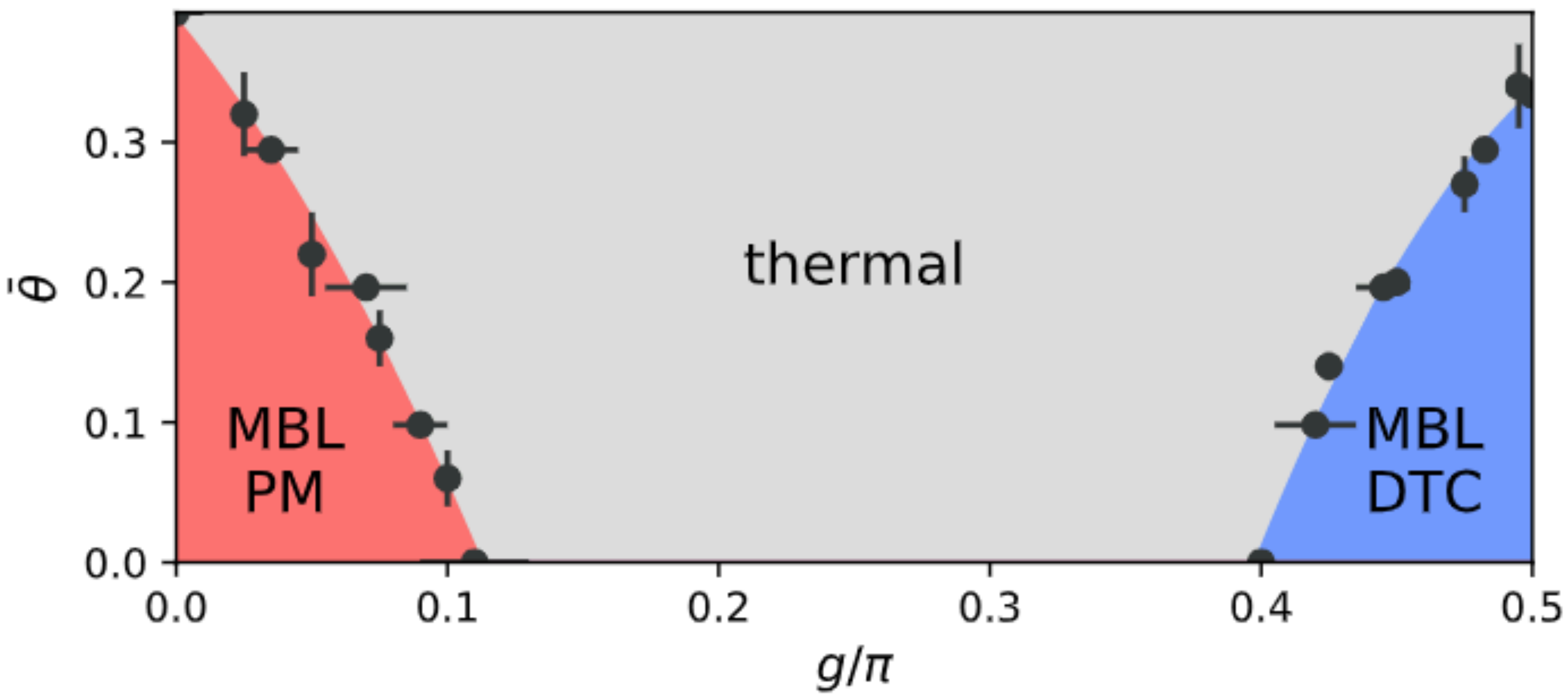
$$\widetilde{G} = R_1^z(\delta h_a)R_2^z(-\delta h_a)e^{-i(\theta/2)(XX+YY)-i(\phi/4)ZZ} \\ \times R_1^z(\delta h_{b,1})R_2^z(\delta h_{b,2})$$



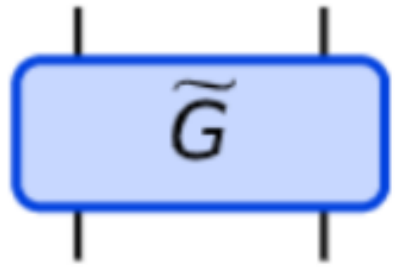
$U_F =$ Imperfect Rotation (Dominantly Ising) Interaction



DTC on Sycamore: Phase diagram



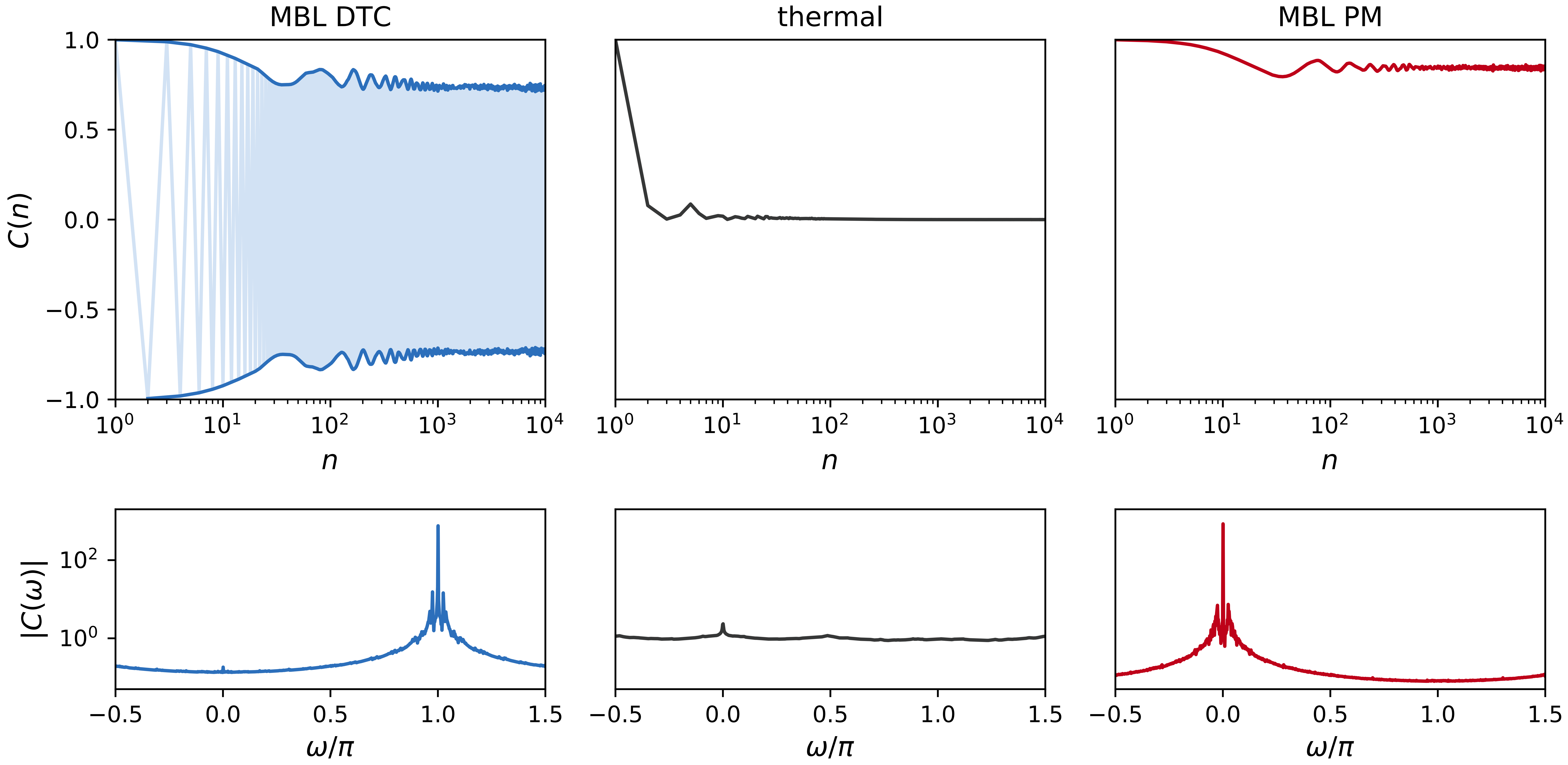
$$\phi_j \in \left[\frac{\pi}{2}, \frac{3\pi}{2}\right]$$



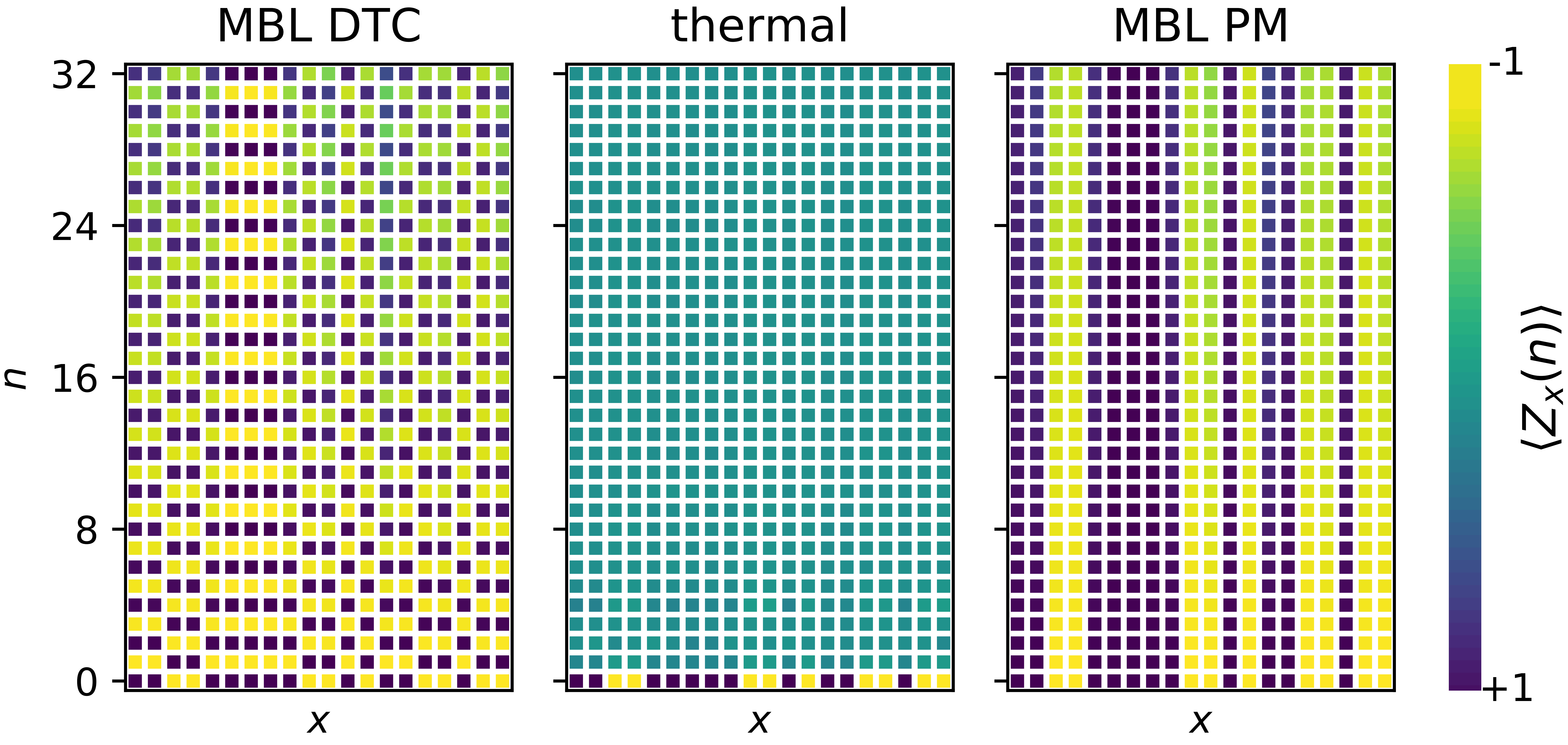
$$= R_1^z(\delta h_a) R_2^z(-\delta h_a) e^{-i(\theta/2)(XX+YY)-i(\phi/4)ZZ} \times R_1^z(\delta h_{b,1}) R_2^z(\delta h_{b,2})$$

$$= e^{-ig\sum_i X_i}$$

DTC on Sycamore: Time dynamics

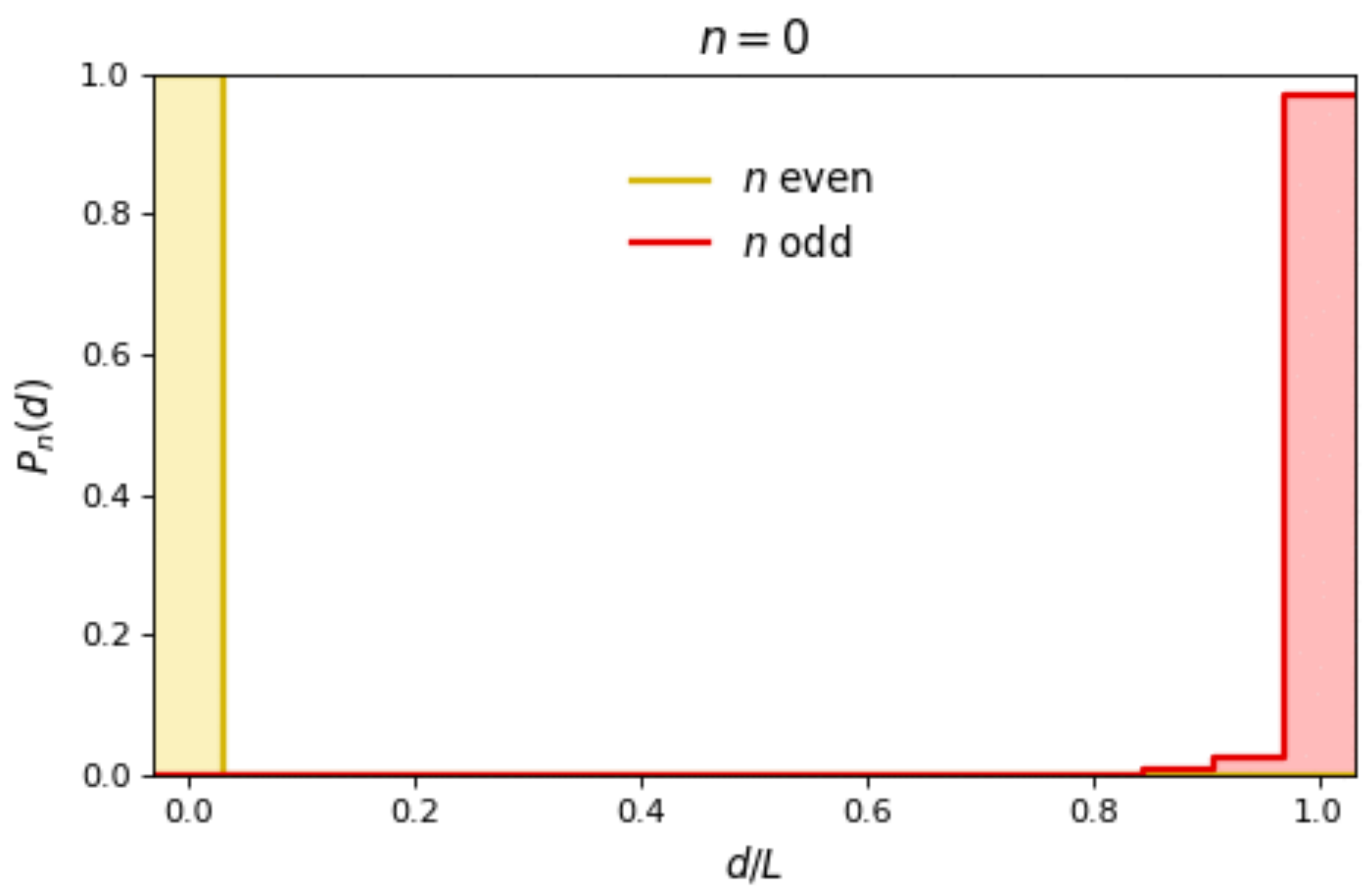


DTC on Sycamore: space-time snapshots

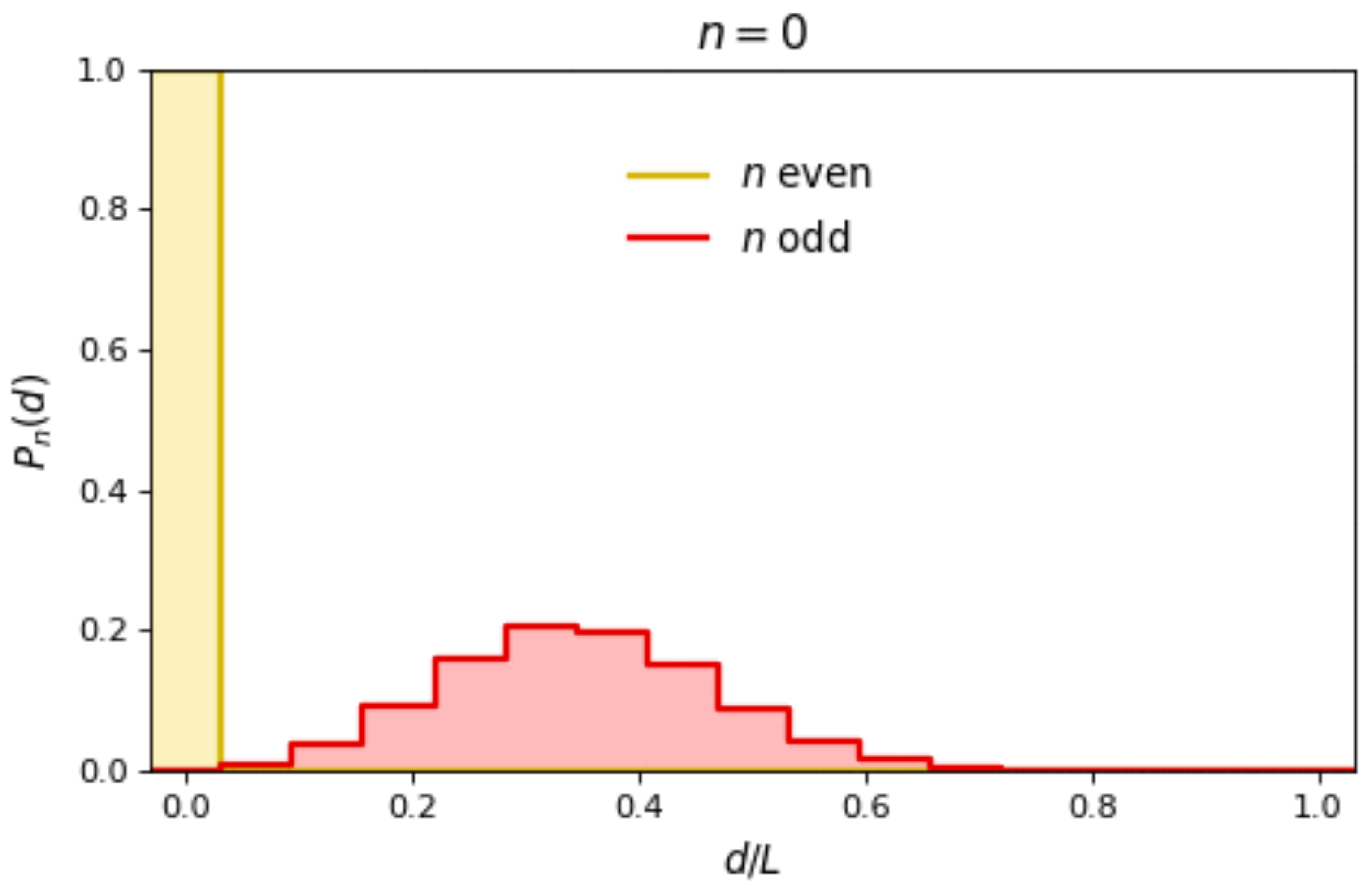


DTC on Sycamore: Hamming distance as a novel metric

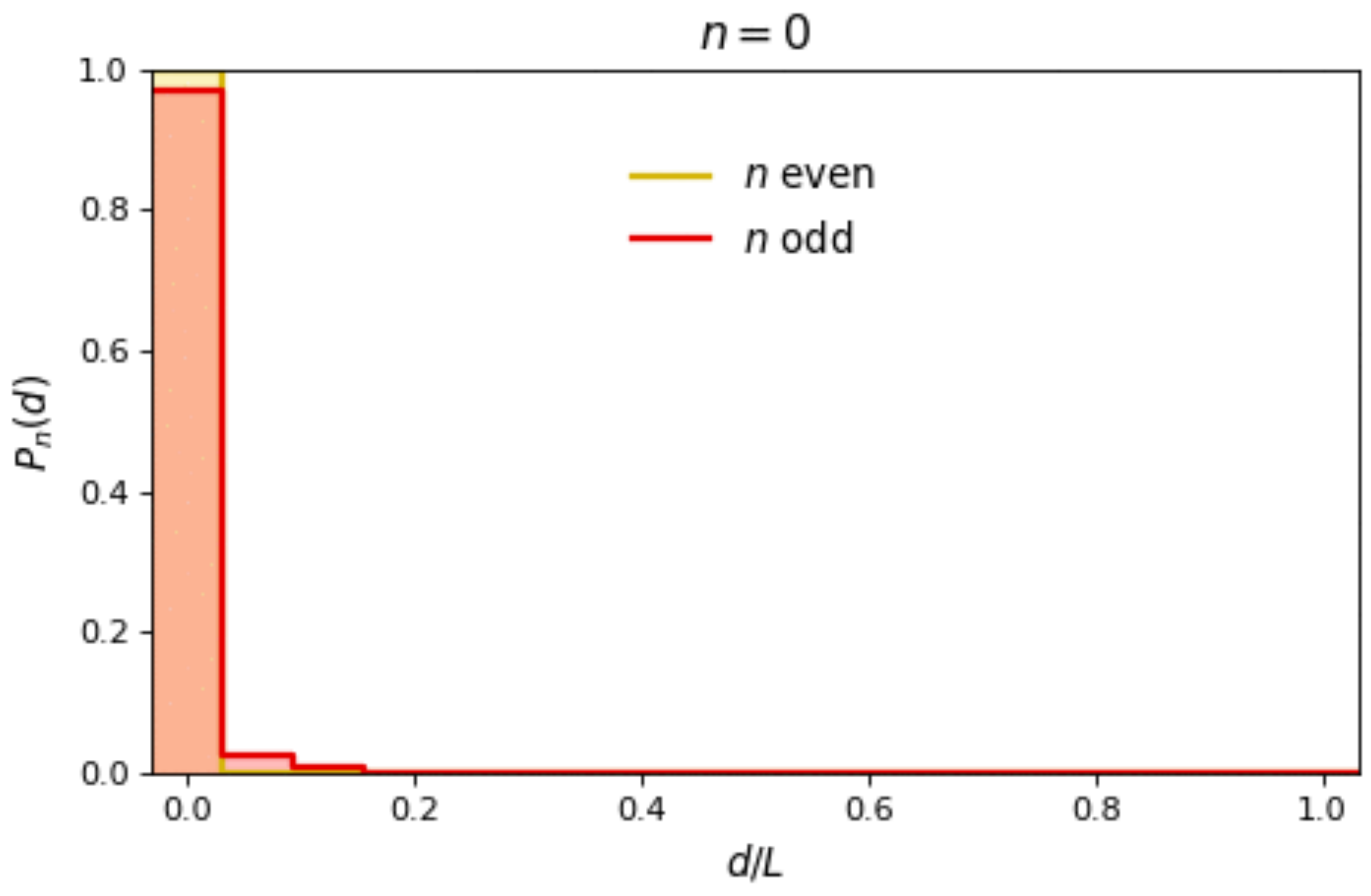
MBL DTC



Thermal

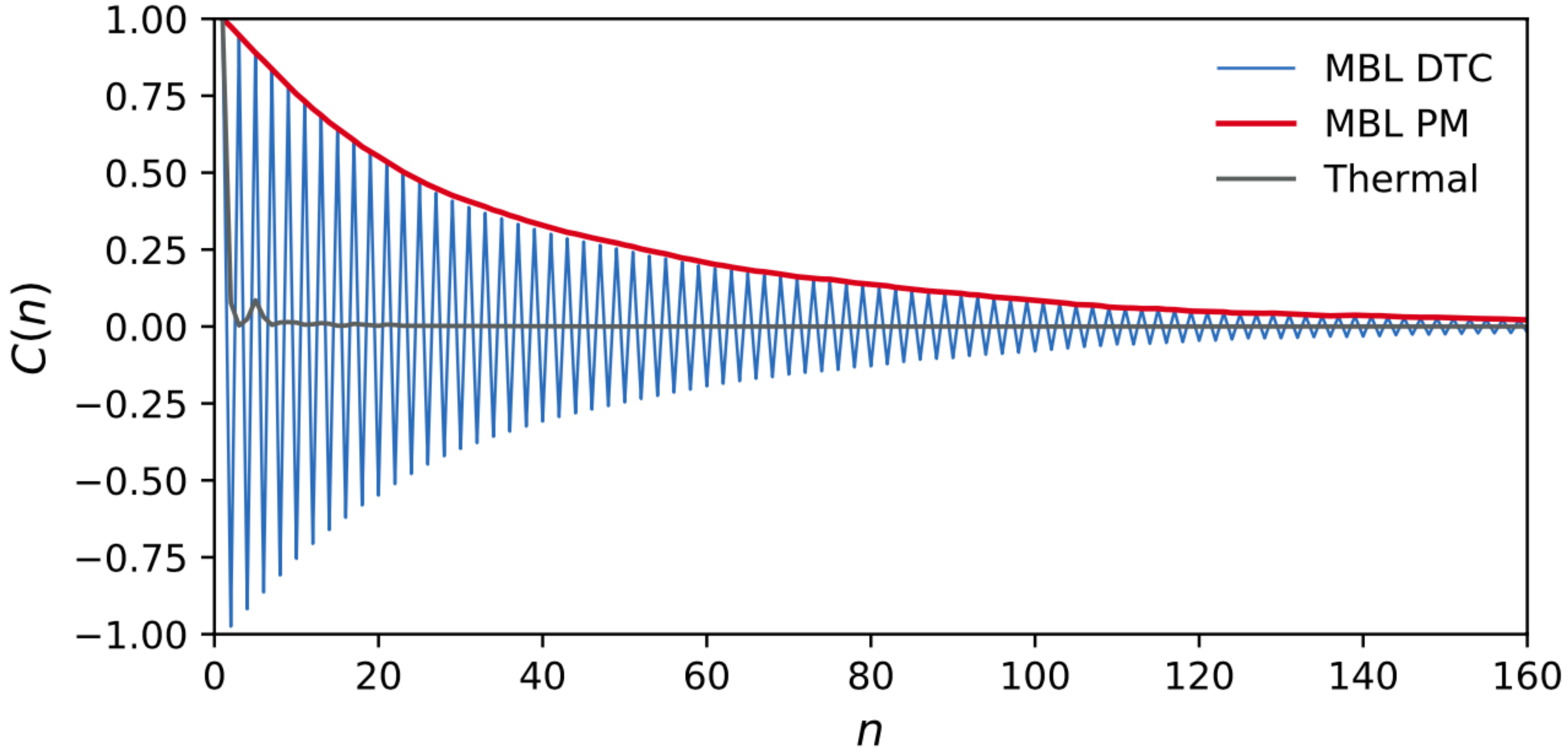


MBL PM



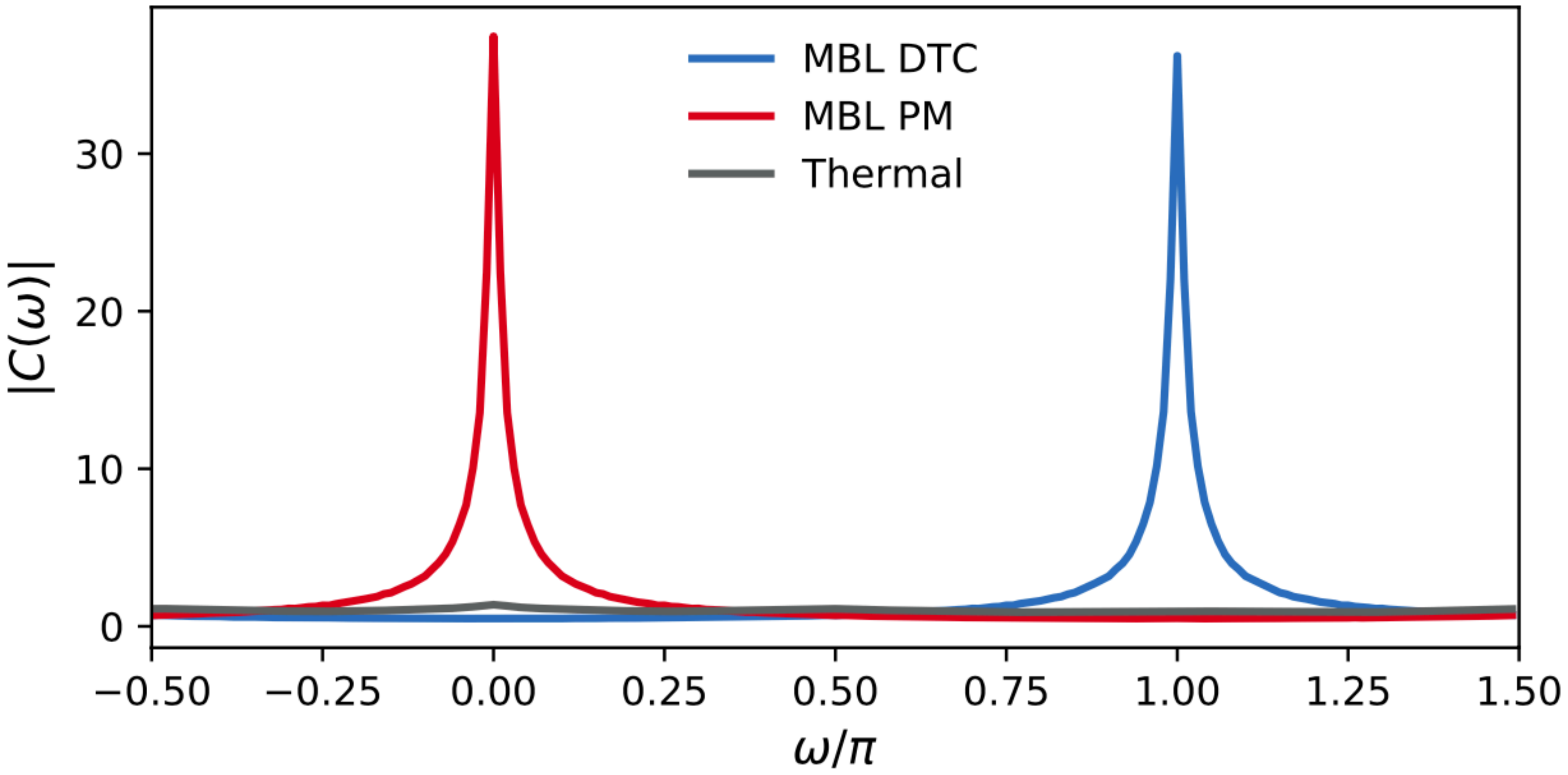
Distributions of Hamming-distance between initial and time-evolved states

The effect of noise



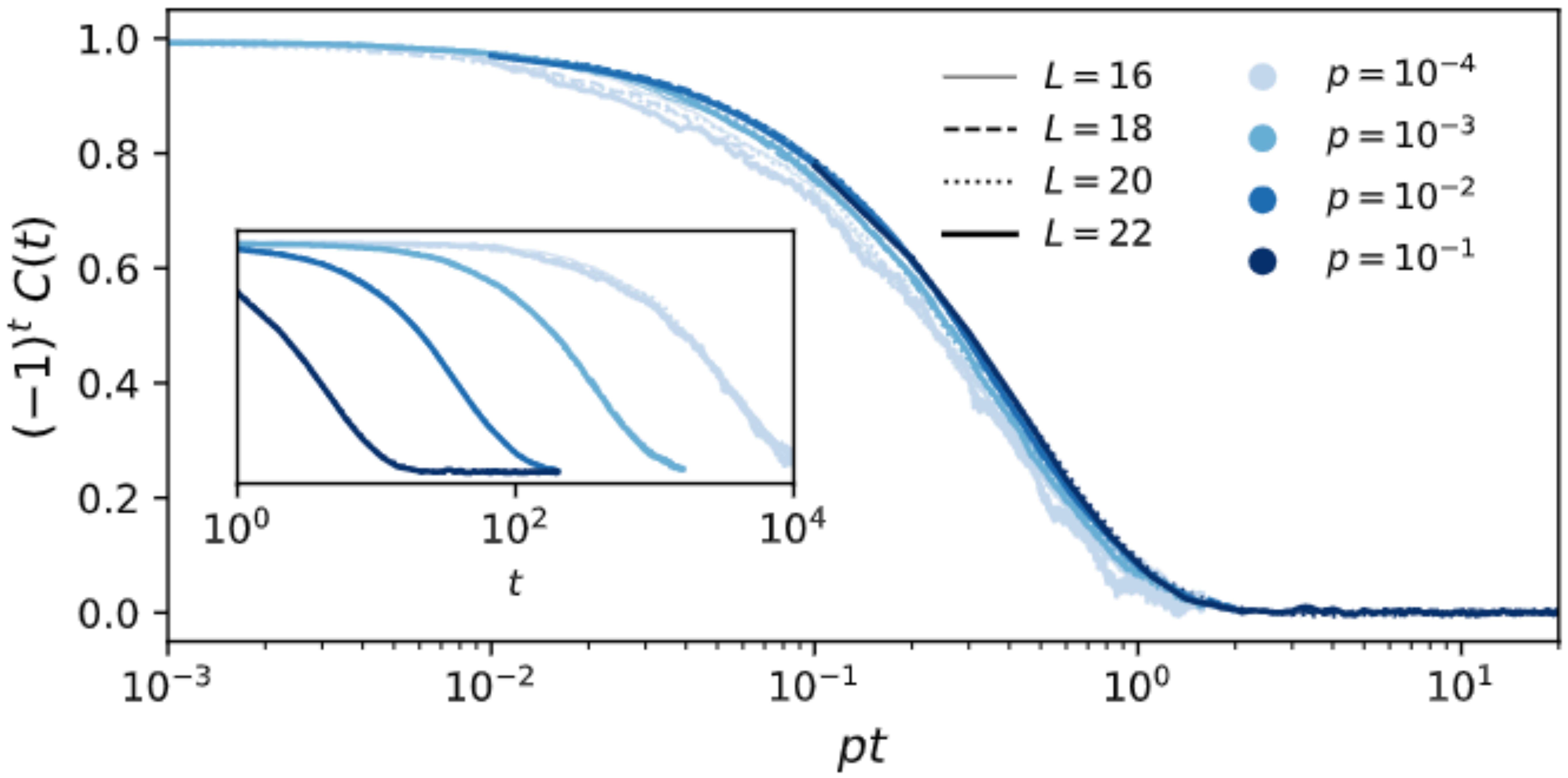
Depolarizing error model with two qubit error rate p, and one qubit error rate $p/10$.

Conservative estimate $p = 1\%$



Exquisite noise calibration in Sycamore helps disentangle contributions from “internal and “external” decoherence upon observing a decaying signal

The effect of noise



Signal decay does *not* care about system size. Contrast with fidelity decay in chaotic system, $F \sim (1-p)^{Lt}$

Outlook: Physics with Random Unitary circuits

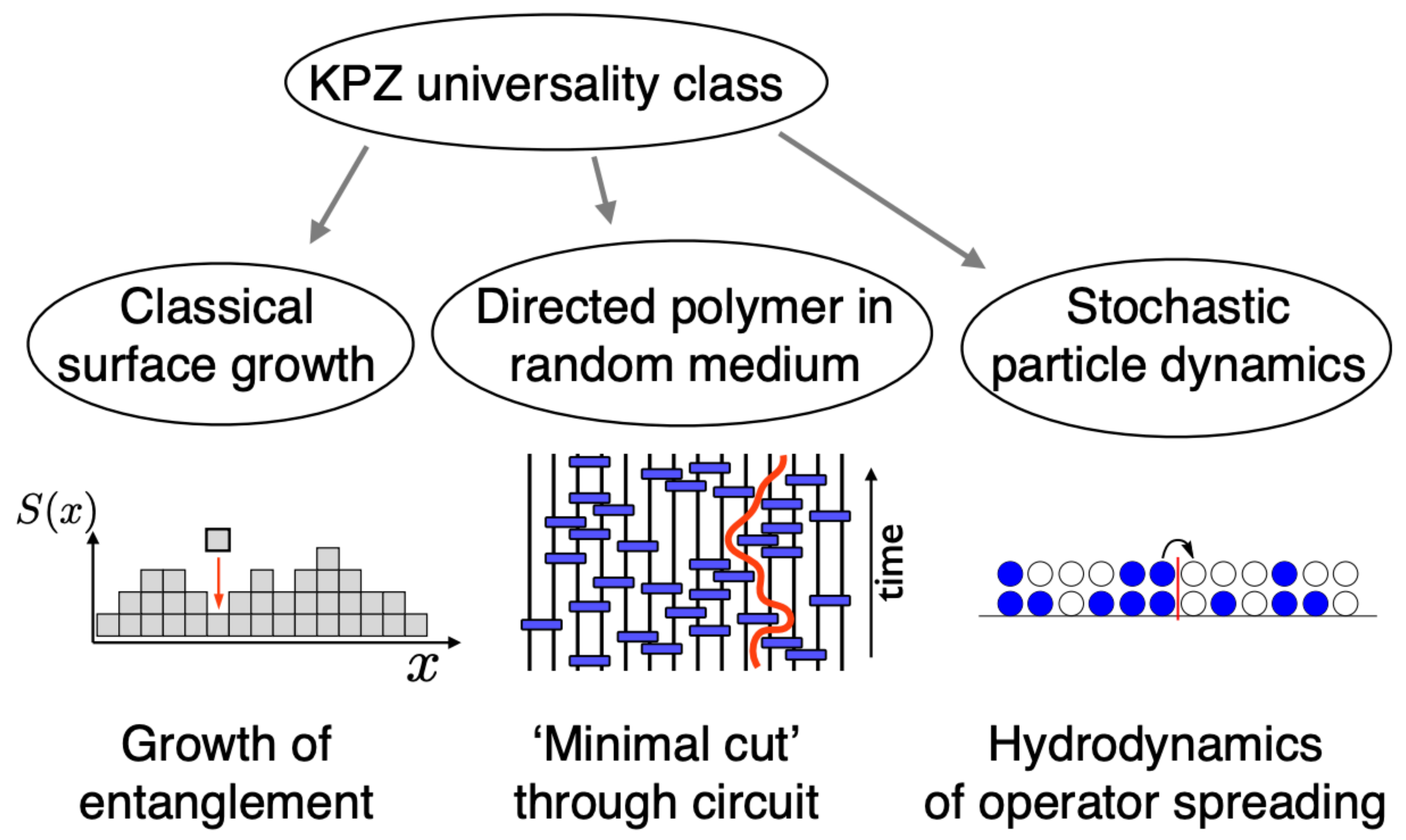
Dynamics of quantum entanglement (Nahum et. al. 2017)

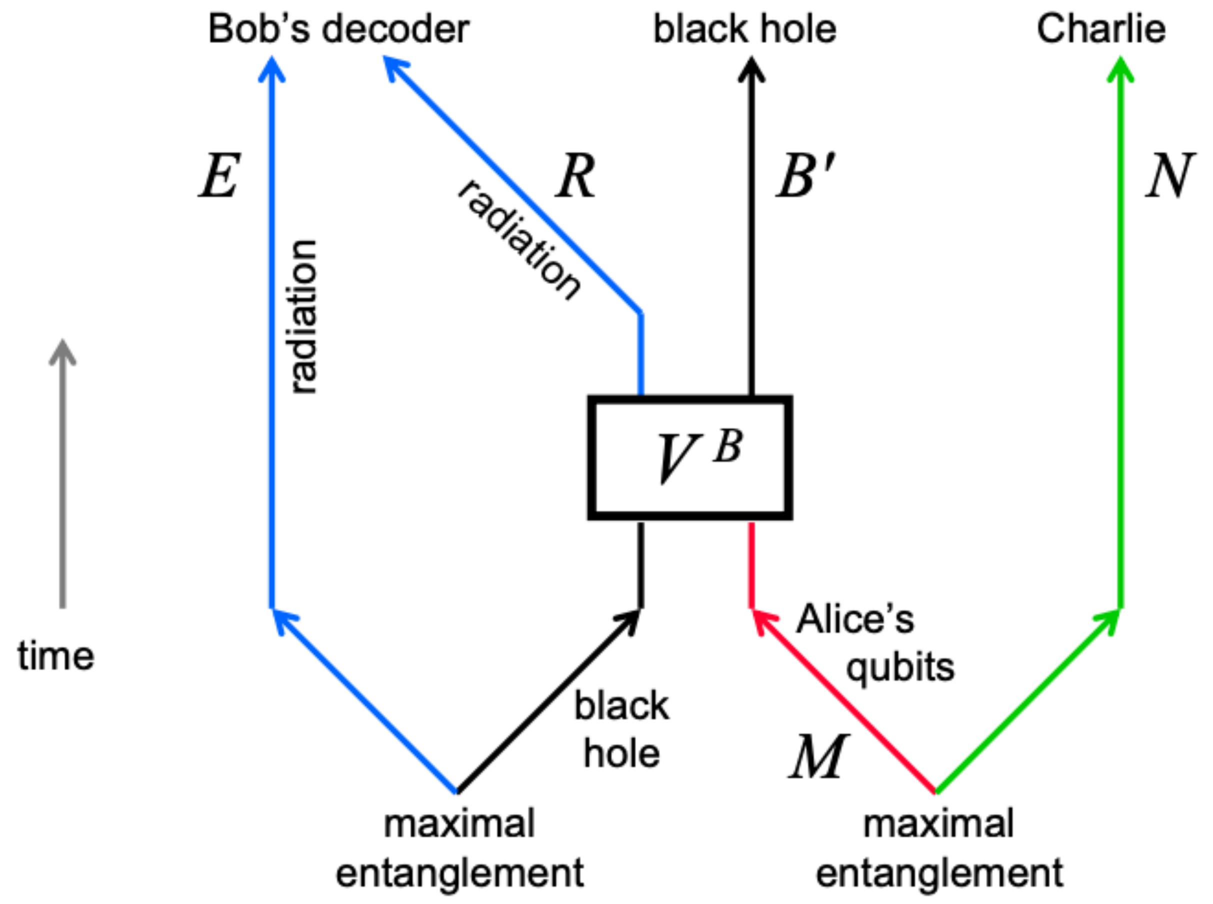
Operator spreading, scrambling and OTOCs (Nahum et. al. 2018; von Keyserlingk et. al. 2018)

Emergence of hydrodynamics under unitary dynamics with conservation laws (VK et. al. 2018; Rakovszky et. al. 2018)

Measurement-induced phase transitions Li, Chen, Fisher (2018); Skinner, Ruhman, Nahum (2018)… Ippoliti…VK (2020)

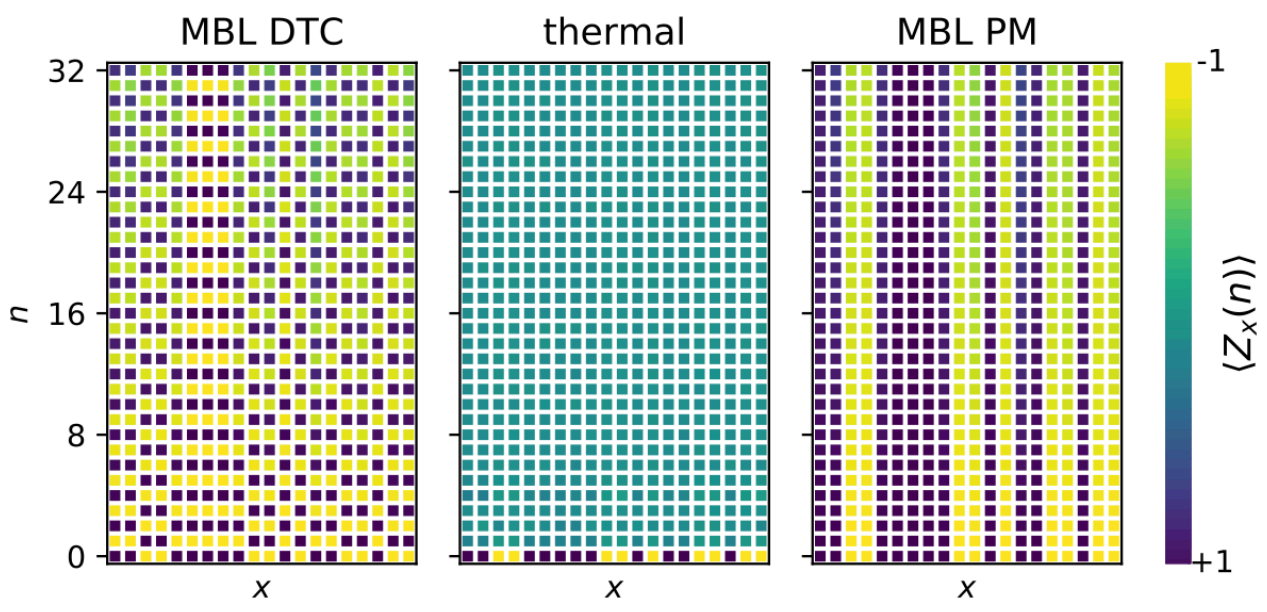
Models of black holes (Hayden Preskill 2007)



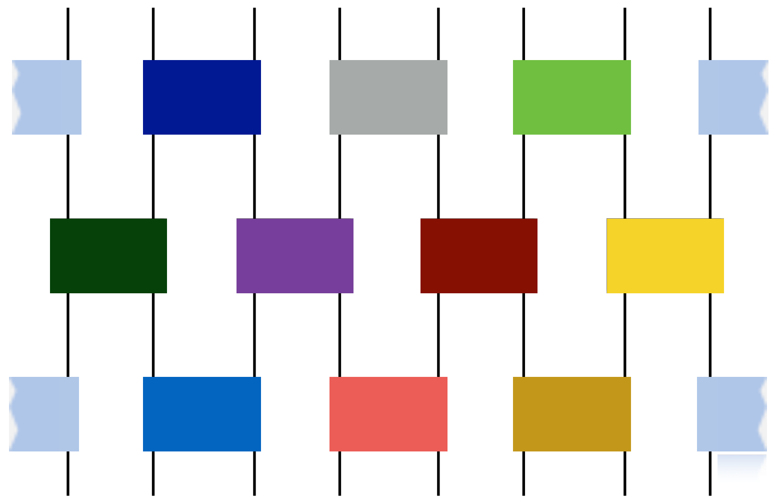


Summary and outlook

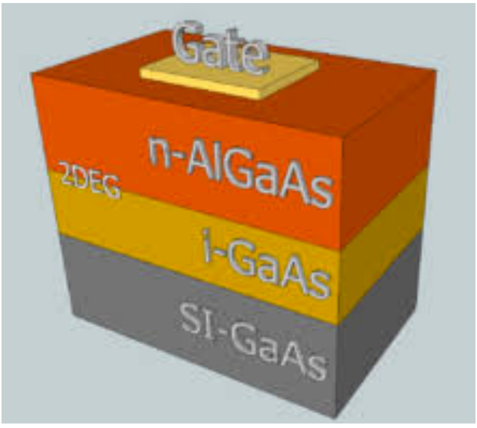
- Immediate near-term application of a NISQ device as a platform for MB experiments: observe DTC. Longer term: can insights from MB physics be used for benchmarking "quantumness" of devices?

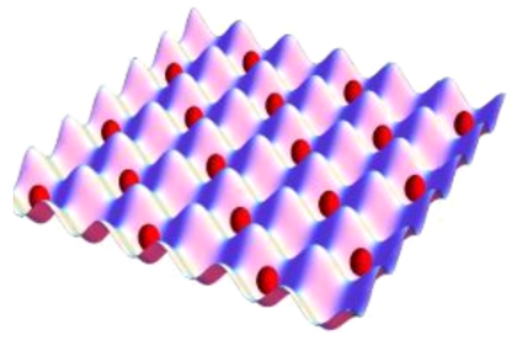


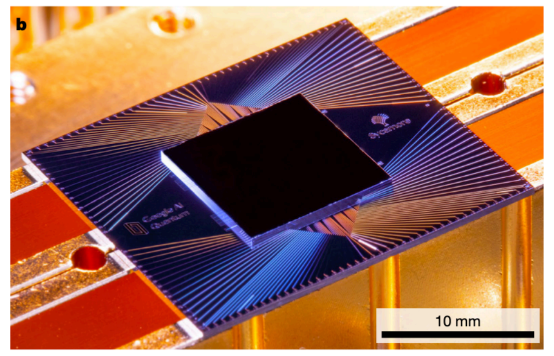
- Broader set of interesting MB problems with random circuits (entanglement dynamics, chaos, measurement induced phase transitions…)



- More broadly: view of NISQ devices as experimental platforms calls on many-body physicists to treat these setups with a level of attention commensurate to that normally devoted to other, more traditional systems.

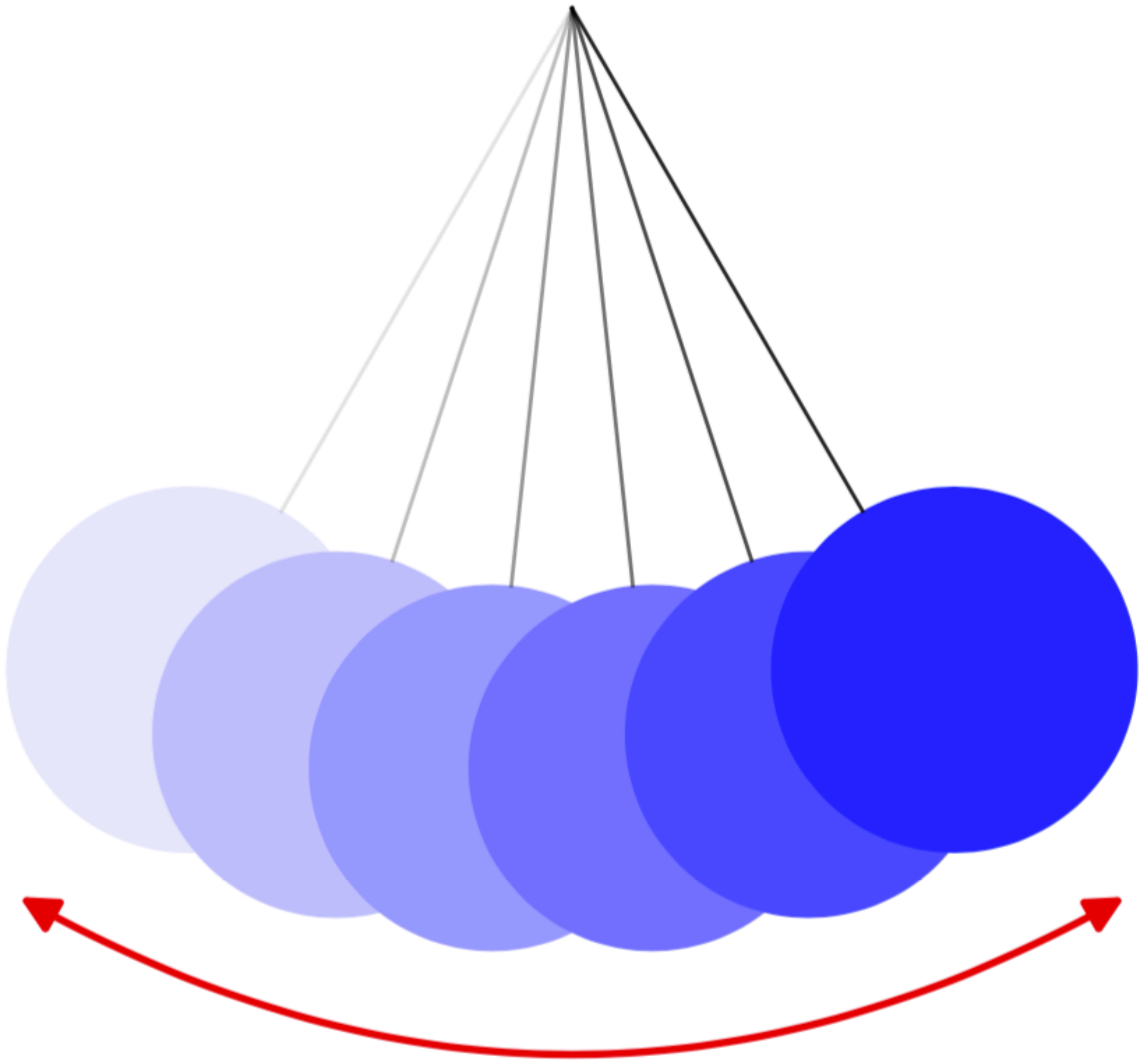




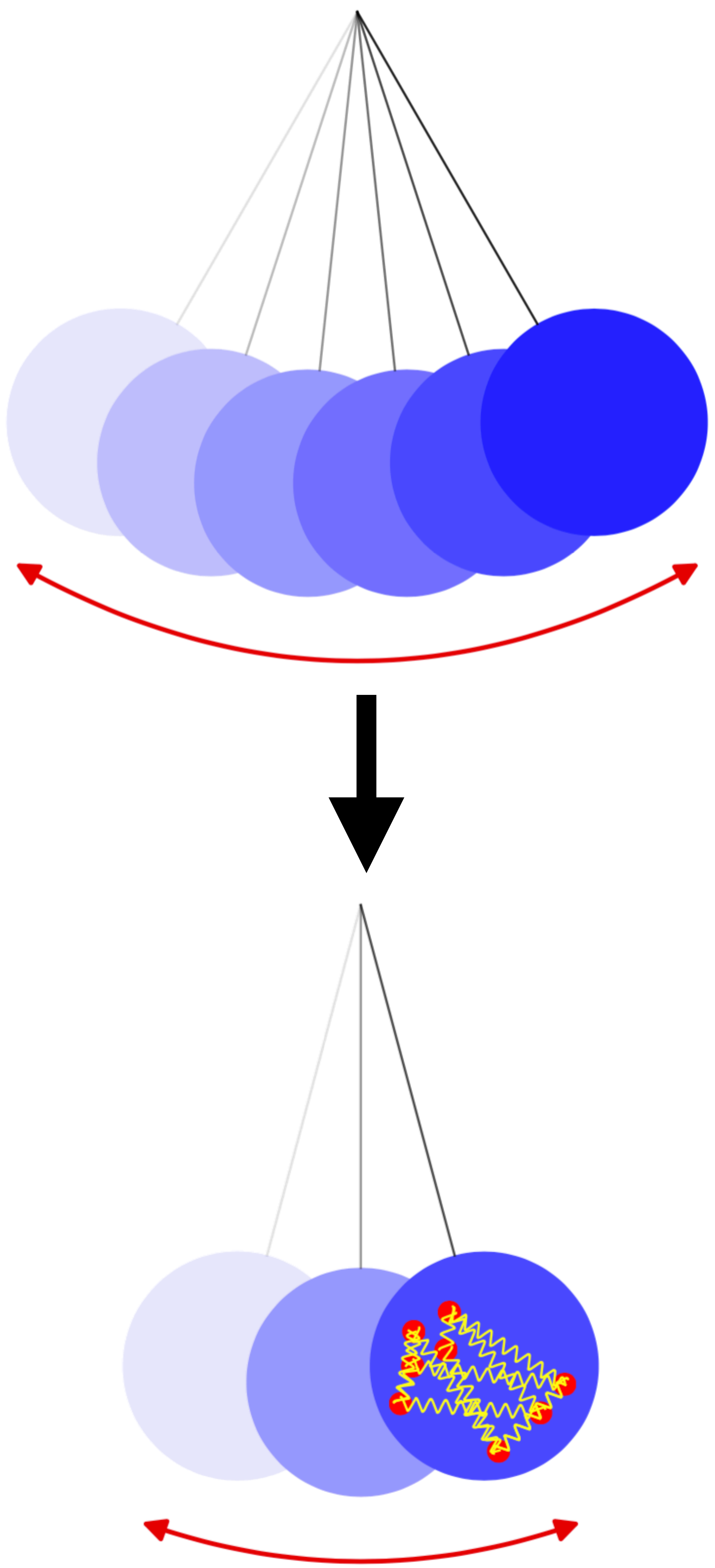


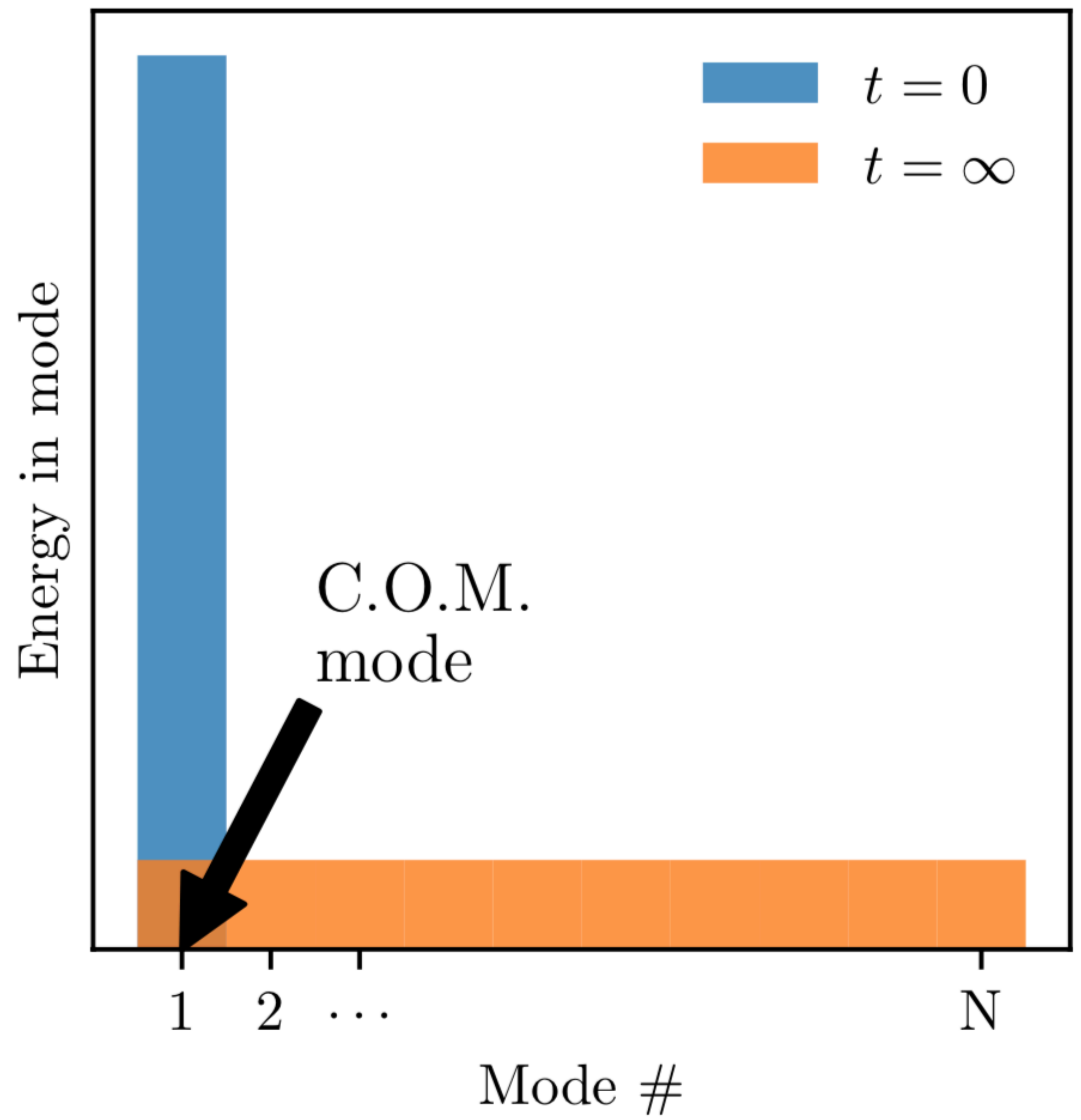
Ippoliti, Kechedzhi, Moessner, Sondhi, VK, arXiv: 2007.xxxxx

Why not a large pendulum?

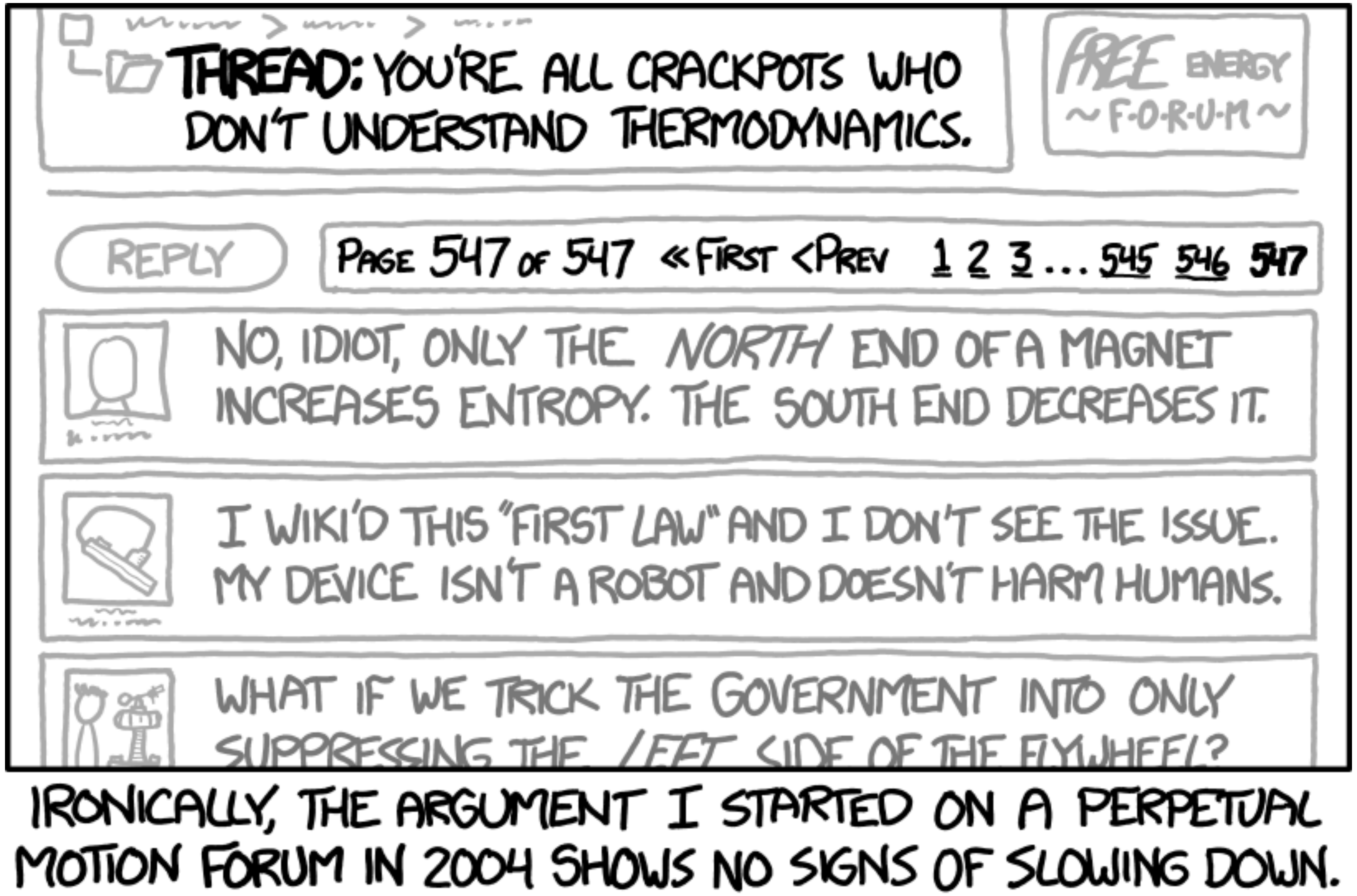


Equipartition in a *many-body* pendulum



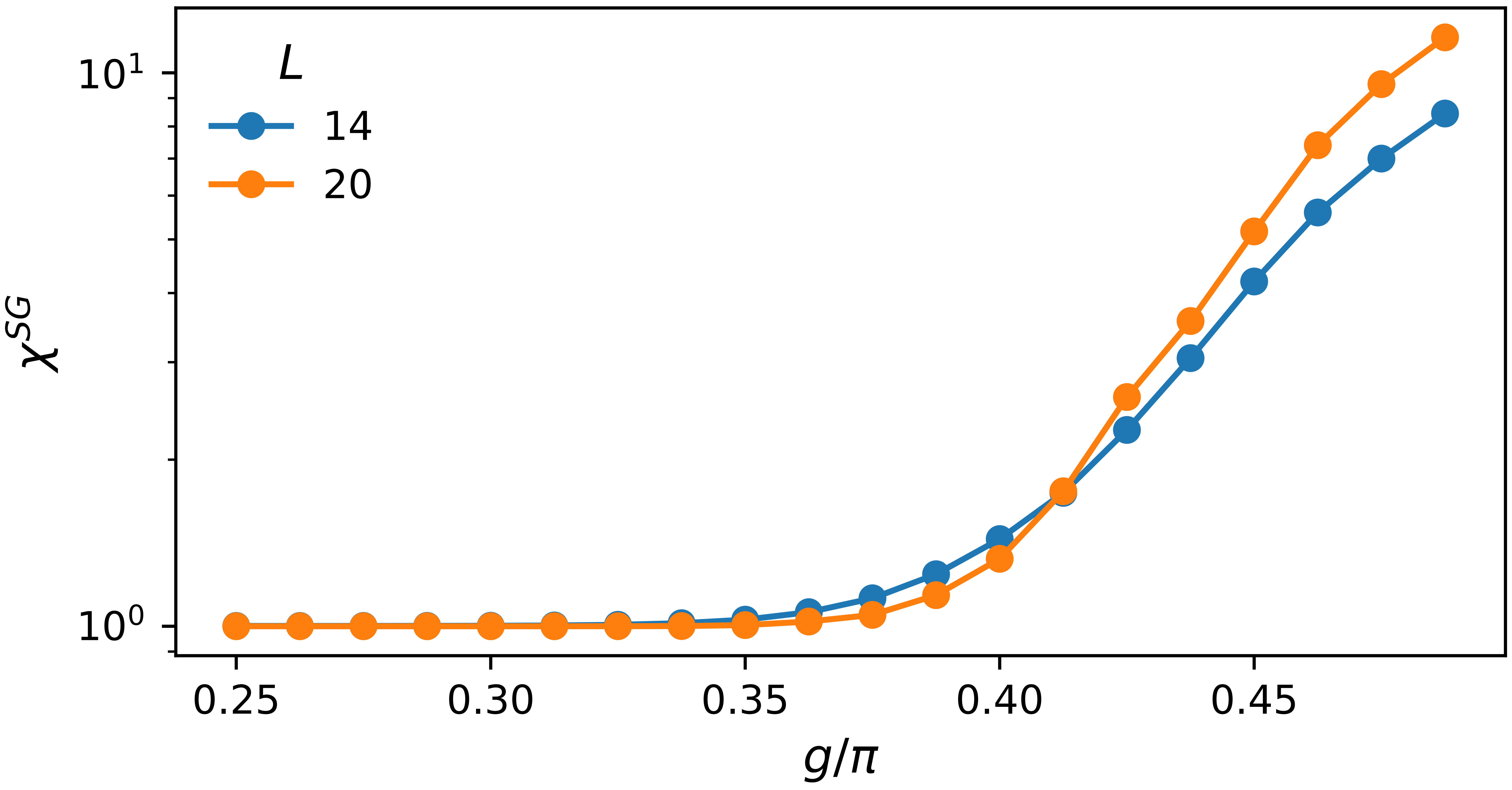


- 1st Law: perpetual motion needs a source of energy
- 2nd Law: macroscopic systems head to entropy maximizing equilibrium states



xkcd.com/1166

DTC on Sycamore: glassy spatial order



$$\chi^{SG} = \frac{1}{L}\sum_{i,j} \langle\psi|\, Z_i Z_j \,|\psi\rangle^2$$

Trapped Ions

- Disorder in onsite fields is <u>not</u> enough to stabilize MBL TC. Gets "echoed out" over two periods

$$U(2T) = P_x R^x_\epsilon e^{-i\sum_{ij} J_{ij} Z_i Z_j + h_i Z_i} P_x R^x_\epsilon e^{-i\sum_{ij} J_{ij} Z_i Z_j + h_i Z_i}$$

$$= R^x_\epsilon e^{-i\sum_{ij} J_{ij} Z_i Z_j - h_i Z_i} R^x_\epsilon e^{-i\sum_{ij} J_{ij} Z_i Z_j + h_i Z_i}$$

VK Moessner Sondhi (2019)

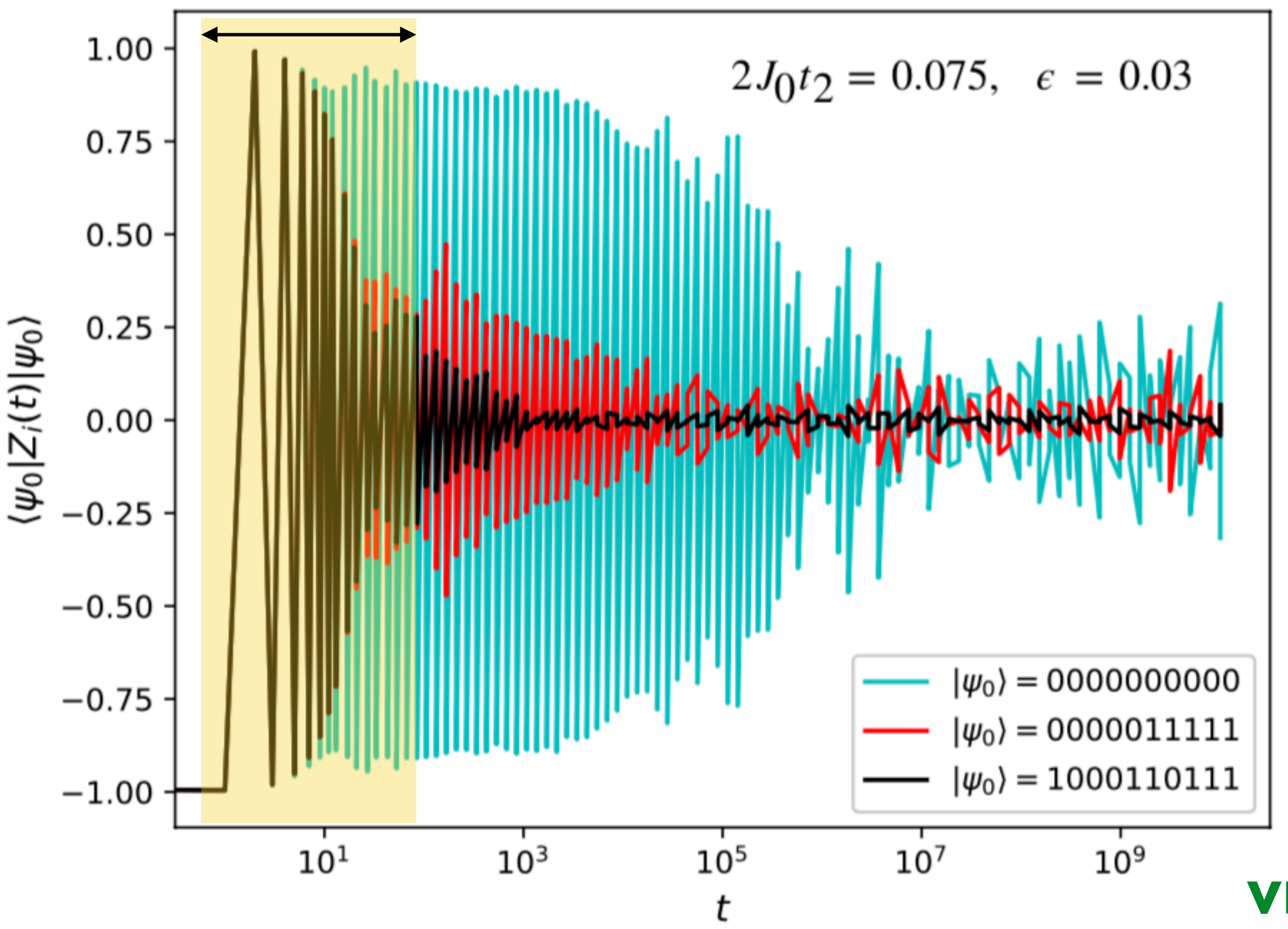
Trapped Ions

- Paremeters chosen to approximate an MBL TC

Yao et al (2017); Choi…Monroe (2017)

- However, disorder in onsite fields is <u>not</u> enough to stabilize MBL TC. Gets "echoed out" over two periods

- System appears to realize a "prethermal TC", with strong initial state dependence



VK Moessner Sondhi (2019)

Floquet Prethermalization

- Interacting MB Floquet systems generically heat up to infinite temperature. When the driving frequency is large compared to the local energy scales in the problem, this could take a time exponentially large in the separation:
$$t_* \sim \exp[\omega/J]$$

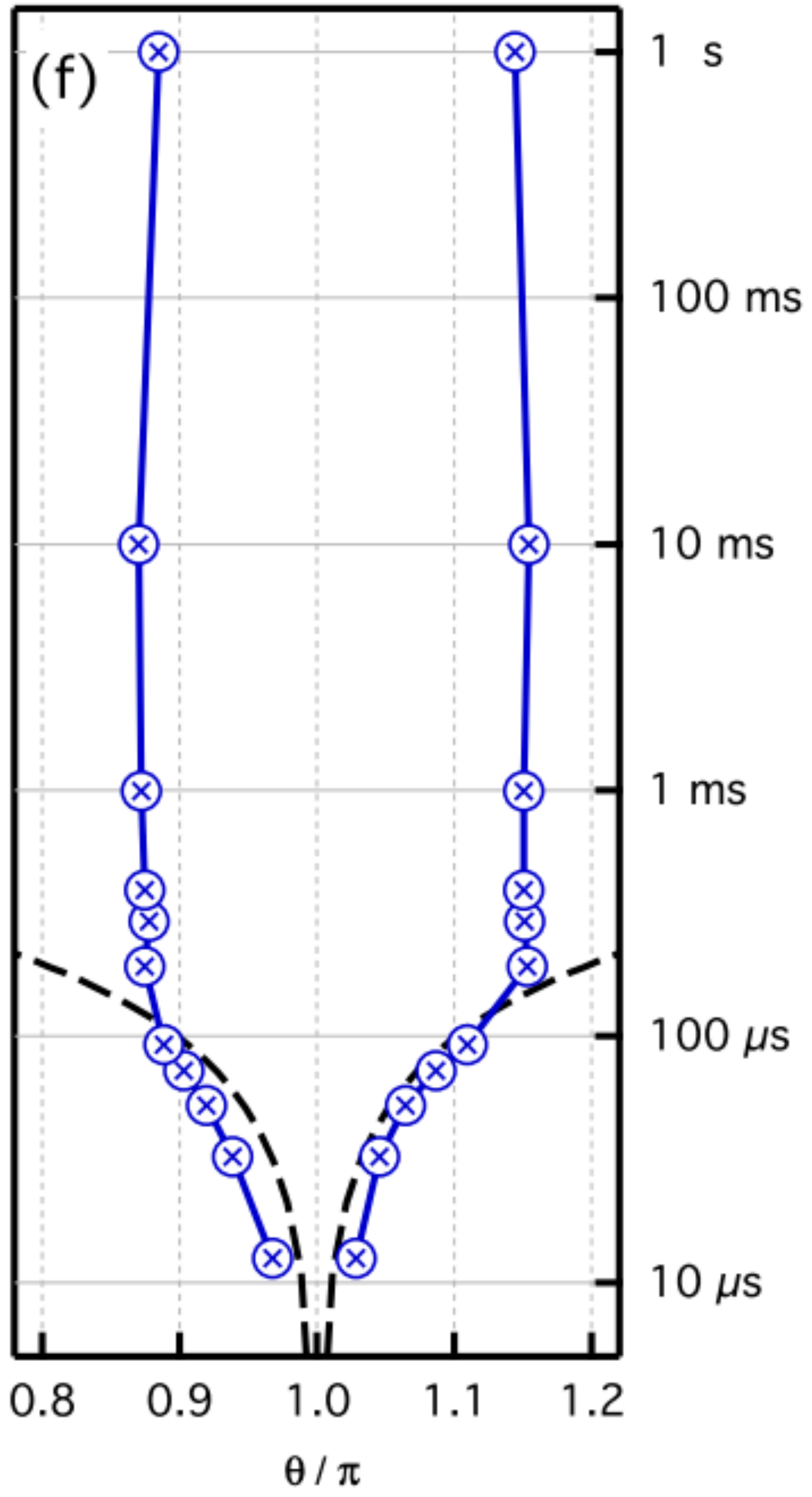
- Prior to this time, the system is described by an effective "prethermal" Hamiltonian, and looks like it conserves energy

Abanin et. al (2015, 2017); Kuwahara et. Al (2015); Mori et. al (2015)

- If the prethermal Hamiltonian has an ordering transition at a finite *Tc*, then initial states at low temperature can show symmetry breaking and TTSB for a long time

Else, Bauer, Nayak (2016)

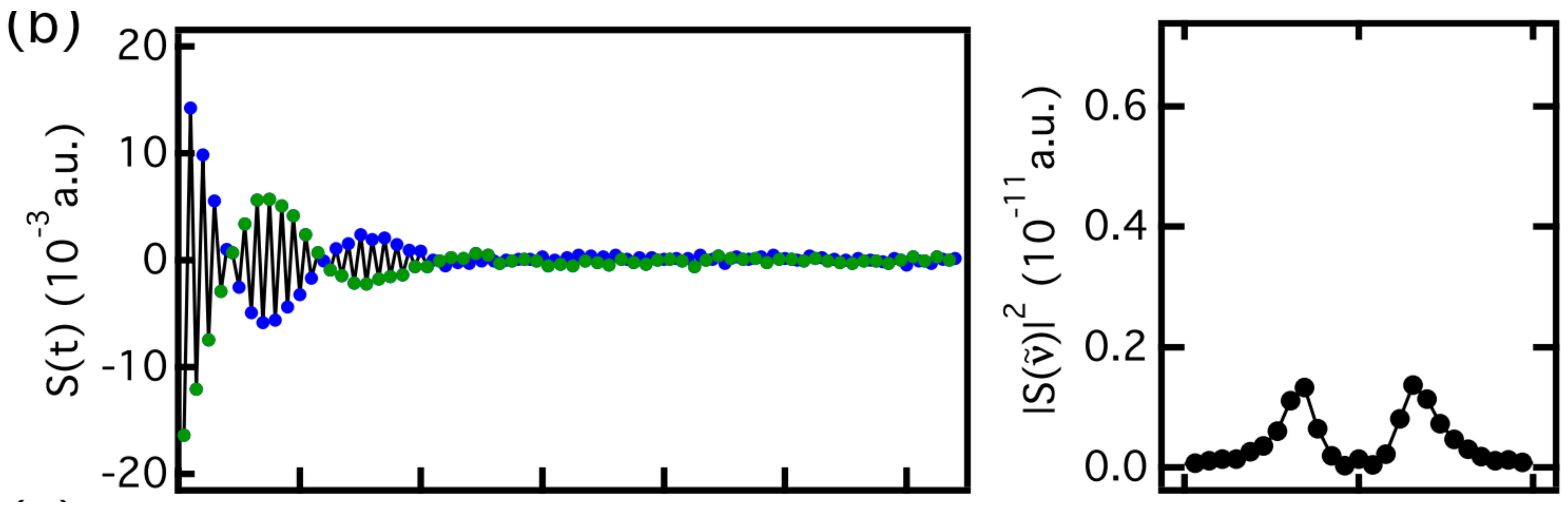
Clean NMR Solid



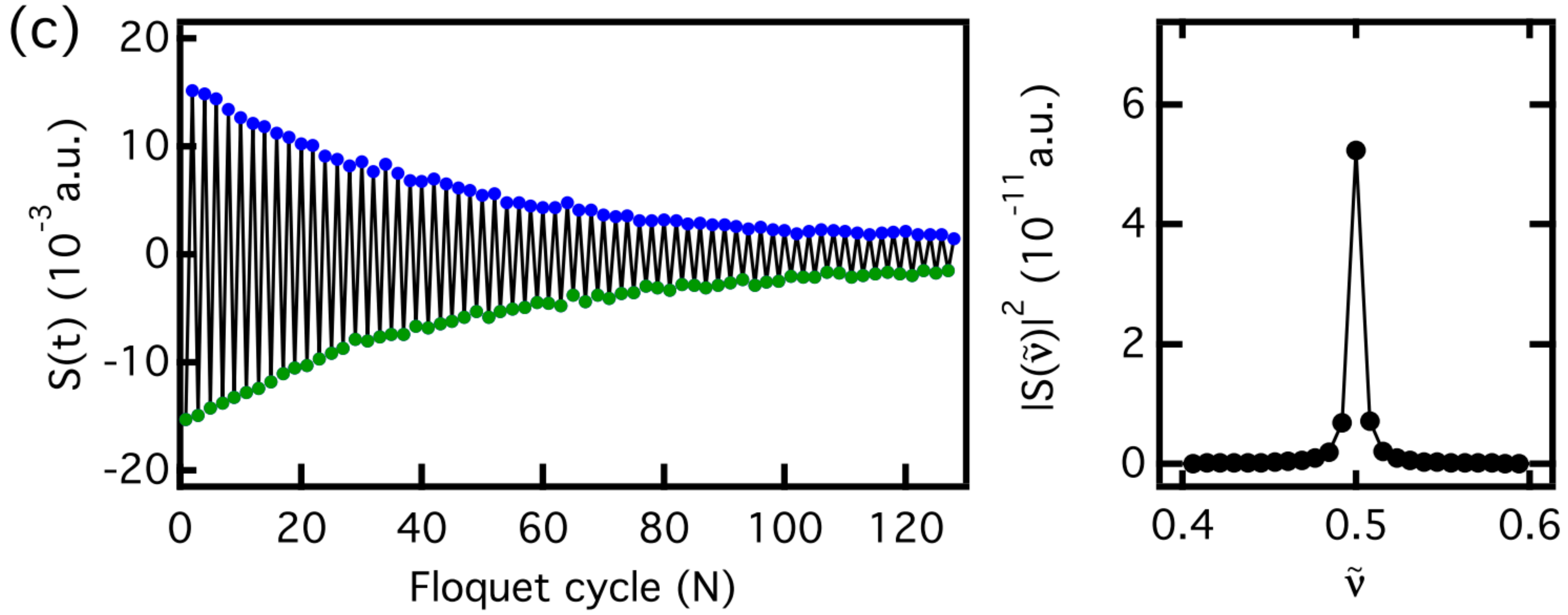
$$U(T) = R^x_{\pi-\theta}\, e^{-i\tau[\sum_{ij} J_{ij}(X_iX_j+Y_iY_j)-2Z_iZ_j+hZ_i]}$$

Rotation Interaction

Weak interactions



Stronger interactions



Rovny et. al. (2018)

Prethermalization *without* temperature

- NMR solid is clean, and initial state is very high temperature. Outside usual framework of MBL/prethermal TCs
- Can be understood via the emergence of an additional U(1) symmetry; temperature of initial state plays no role in this analysis
- A slightly modified (experimentally realizable) protocol can be used to engineer M_z conservation for much longer times, keeping all other parameters fixed.
- Not fine tuned — small deviations about new protocol still give enhancement
- Can distinguish between MBL TCs/SSB prethermal TCs/U(1) prethermal TCs by examining local autocorrelators for a variety of initial states

Luitz, Moessner, Sondhi, **VK** 2019

Localization Protected Quantum Order

How do we think of phase structure out-of-equilibrium?

- Highly excited (infinite "temperature") MBL eigenstates have low (area law) entanglement — look like gapped ground states at zero temperature

- *Individual* highly excited MB eigenstates can display "frozen" orders that may be forbidden in equilibrium

- Experimentally measurable dynamical signatures

Equilibrium Phases ➔ Eigenstate Phases

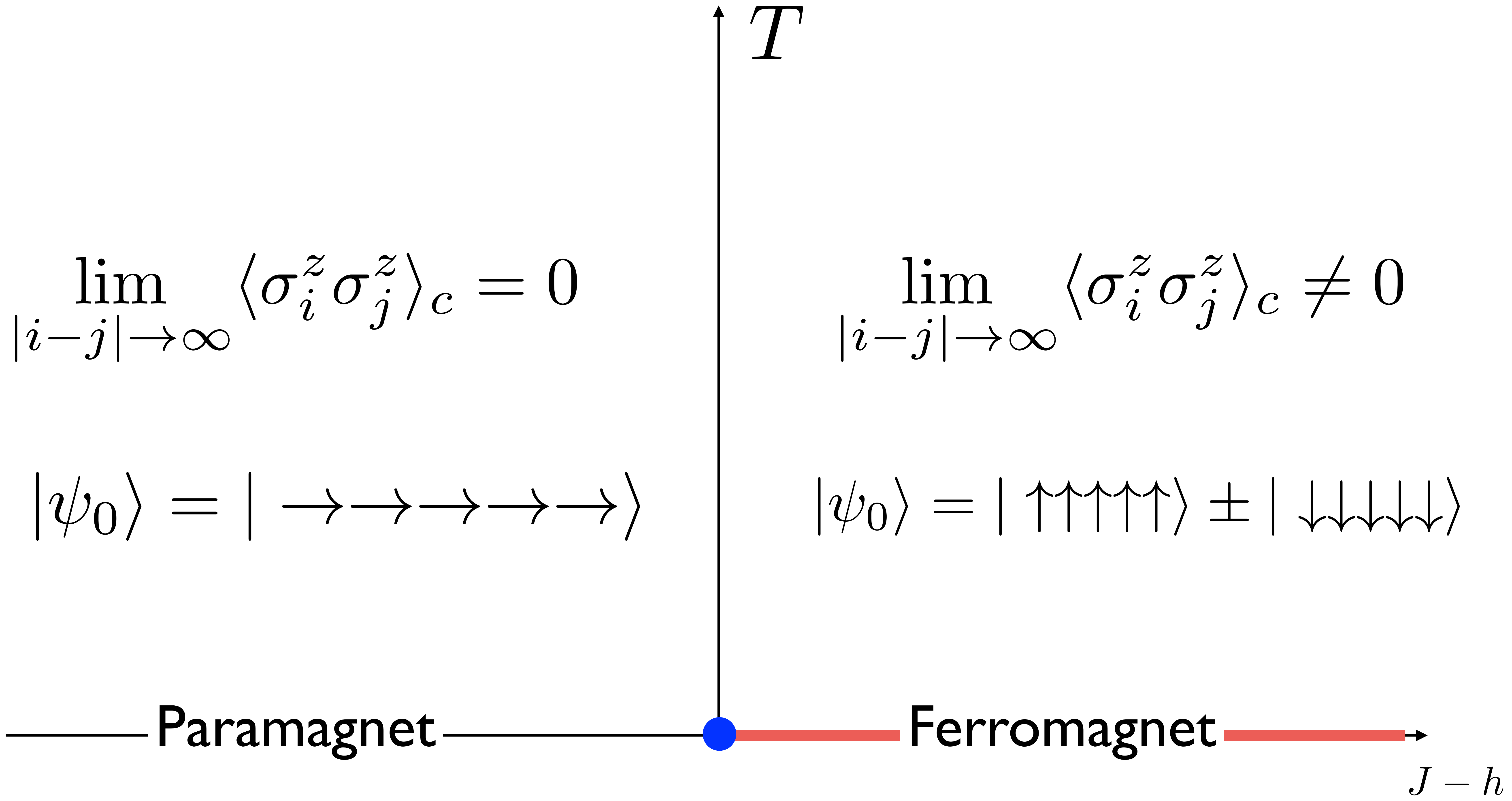
Huse et. al. (2013); Chandran, **VK**, Laumann, Sondhi (2014); Bahri, Altman, Vishwanath (2014)

Eigenstate Order: Ising example

1D transverse field Ising model

$$H = J \sum_i \sigma_i^z \sigma_{i+1}^z + h \sum_i \sigma_i^x$$

$$P = \prod_i \sigma_i^x$$



$$\lim_{|i-j|\to\infty} \langle \sigma_i^z \sigma_j^z \rangle_c = 0$$

$$|\psi_0\rangle = |\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rangle$$

$$\lim_{|i-j|\to\infty} \langle \sigma_i^z \sigma_j^z \rangle_c \neq 0$$

$$|\psi_0\rangle = |\uparrow\uparrow\uparrow\uparrow\uparrow\rangle \pm |\downarrow\downarrow\downarrow\downarrow\downarrow\rangle$$

Eigenstate Order: Ising example

1D transverse field Ising model

$$P = \prod_i \sigma_i^x$$

$$H = \sum_i J_i \sigma_i^z \sigma_{i+1}^z + h_i \sigma_i^x$$

Energy Density

Paramagnet

$$\langle \sigma_i^z \sigma_j^z \rangle = 0$$

$$\text{for} \quad |i-j| \to \infty$$

$$|\psi\rangle_\epsilon = |\leftarrow\rightarrow\rightarrow\leftarrow\rightarrow\rangle$$

Spin Glass

$$\langle \sigma_i^z \sigma_j^z \rangle \neq 0$$

$$\text{for} \quad |i-j| \to \infty$$

$$|\psi\rangle_\epsilon = |\uparrow\downarrow\downarrow\uparrow\downarrow\rangle \pm |\downarrow\uparrow\uparrow\downarrow\uparrow\rangle$$

$J - h$

D. Fisher(1995)