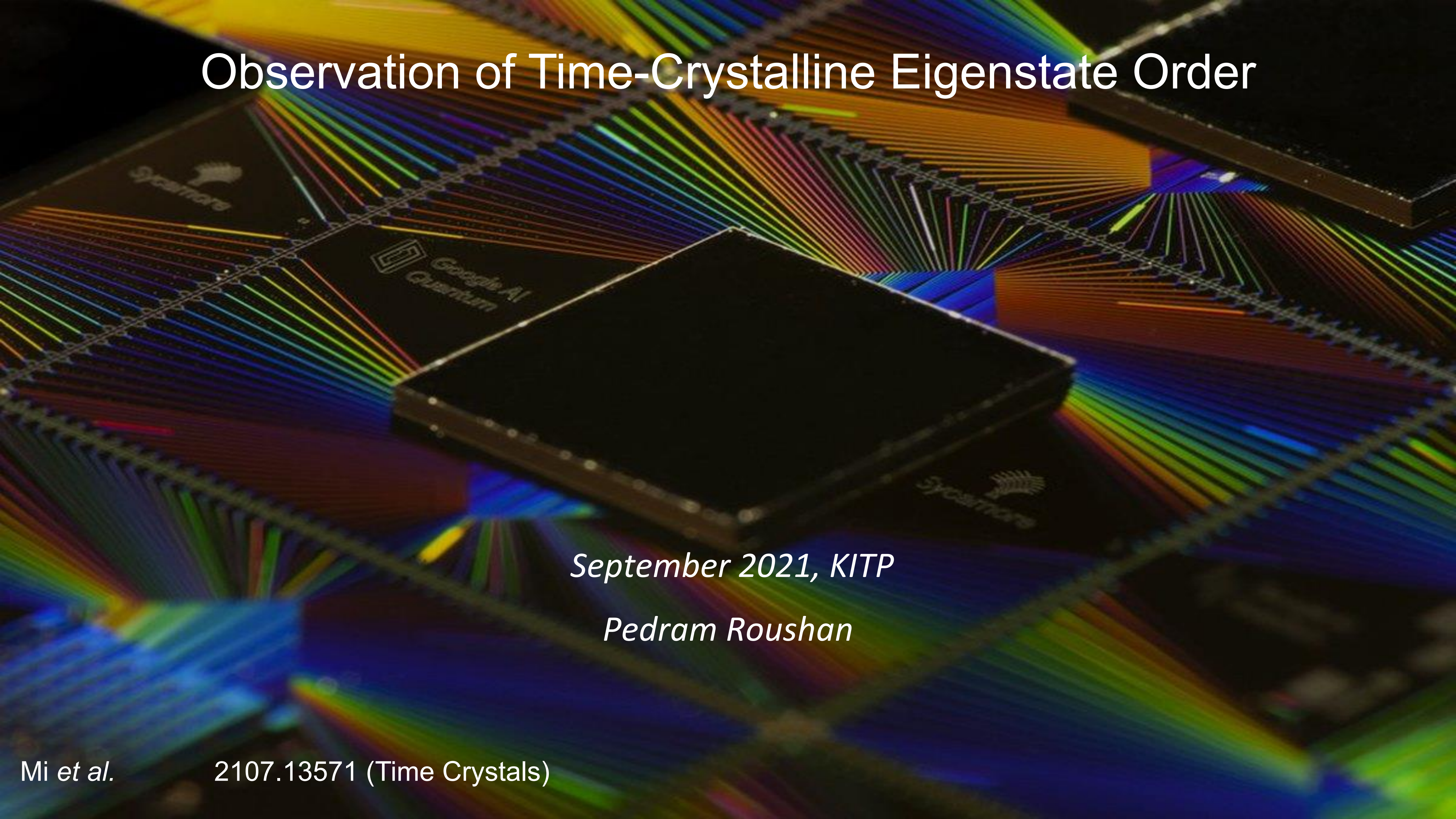
Observation of Time-Crystalline Eigenstate Order



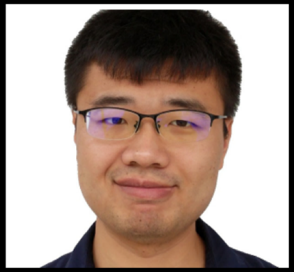
September 2021, KITP

Pedram Roushan

Mi *et al.* 2107.13571 (Time Crystals)

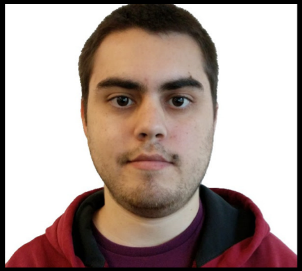
Dramatis Personae

Xiao Mi



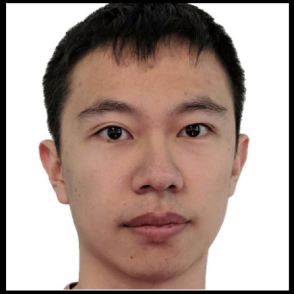
Kostyantyn Kechedzhi

Chris Quintana



Ami Greene

Jimmy Chen



Jonathan Gross

Vadim Smelyanskiy

Yu Chen

External Collaborators

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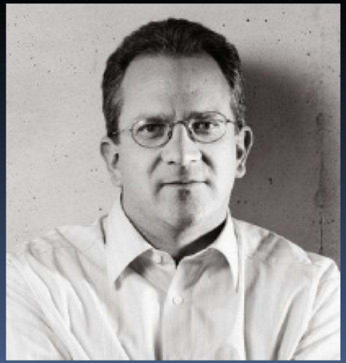
(Stanford)

Vedika Khemani
(Stanford)

Shivaji Sondhi
(Princeton→ Oxford)

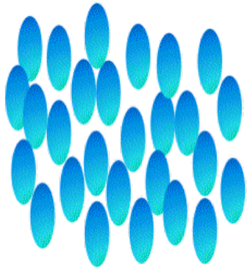
Roderich Moessner
(Max-Planck)

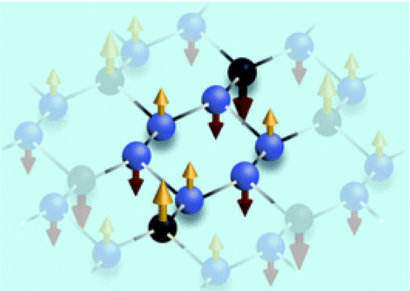


References: theory (to appear PRX Quantum 2021) and experiment

Time Crystal: indefinite oscillation in a many-body isolated system

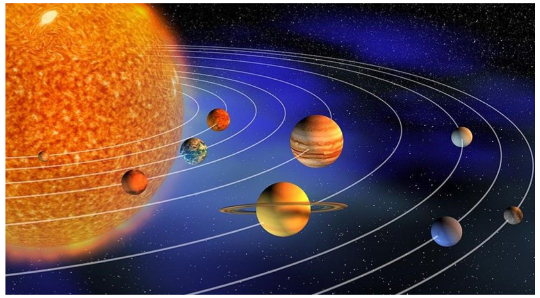
spatial ordering...



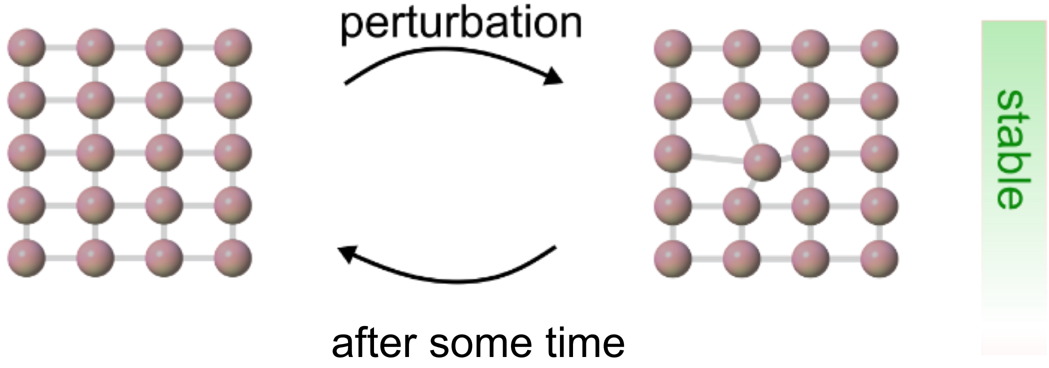


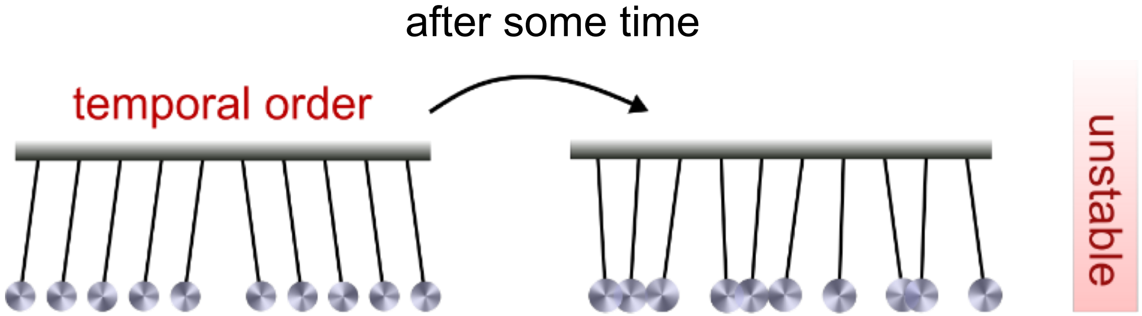
...stable for any number of interacting particles

temporal ordering...



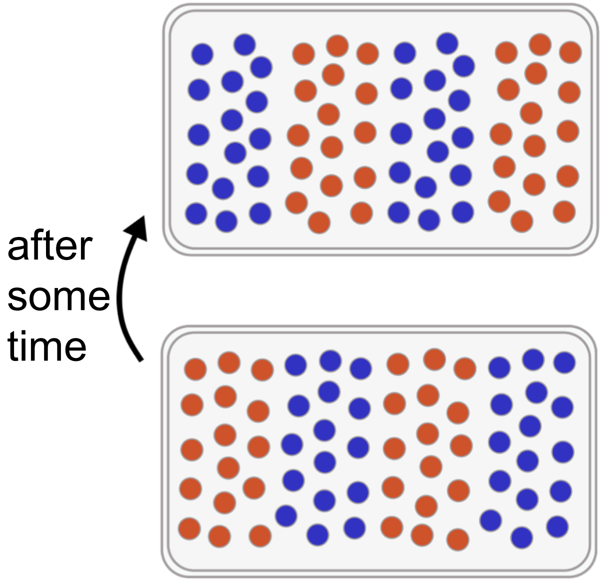
...too few degrees of freedom



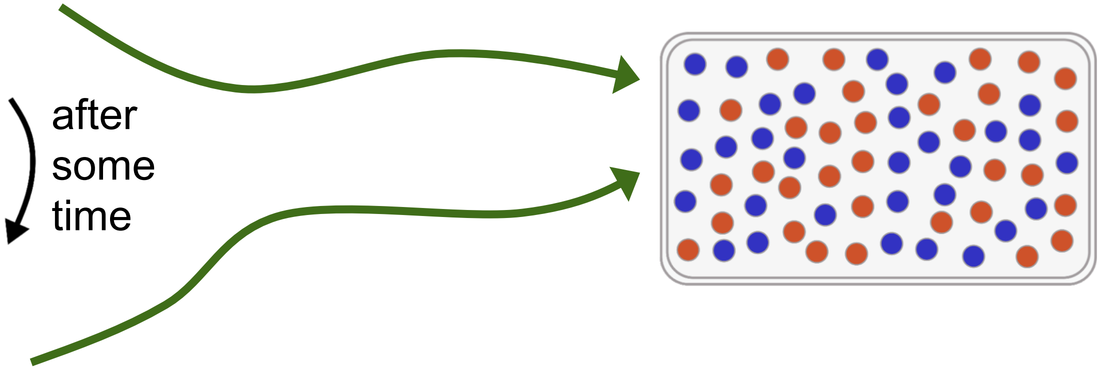


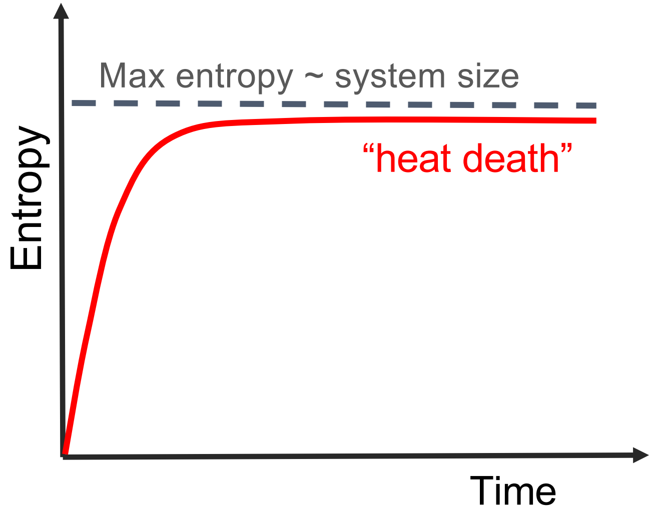
[If stable → need energy injection or fine-tuned]

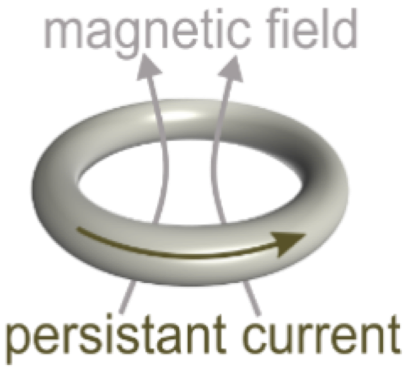
A challenge and an impossibility

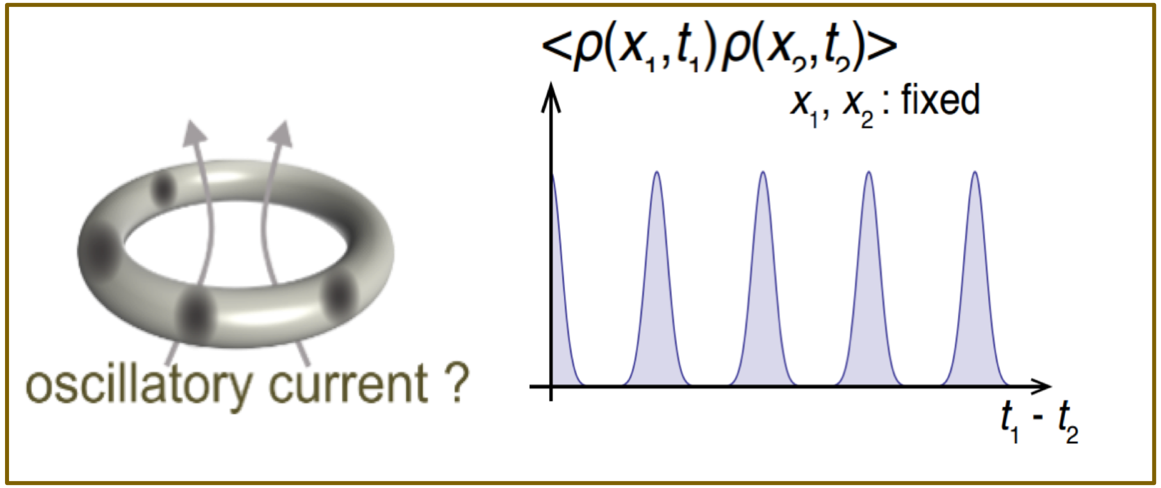


The second law of thermodynamics:
Entropy cannot decrease in time.









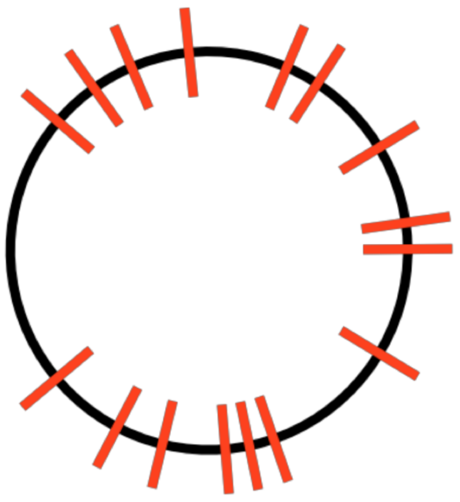
Impossible: breaking time-translational symmetry spontaneously at equilibrium

F. Wilczek, "Quantum Time Crystals," PRL (2012). P. Bruno, "Comment on "Quantum Time Crystals"," PRL (2013). H. Watanabe and M. Oshikawa, "Absence of Quantum Time Crystals," PRL (2015)

Discrete Time Crystals (DTC): Rigid oscillation in isolation

$\hat{H}(t) = \hat{H}_0$

$\hat{H}(t+T) = \hat{H}(t)$



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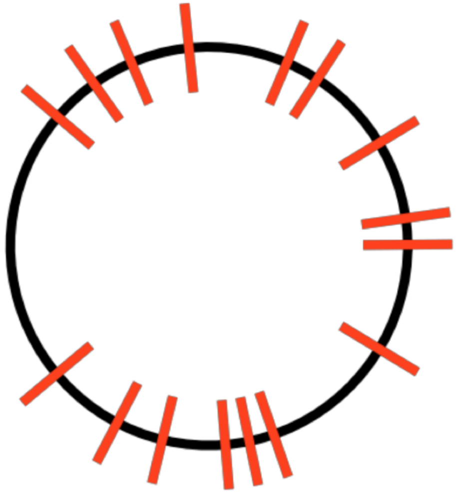
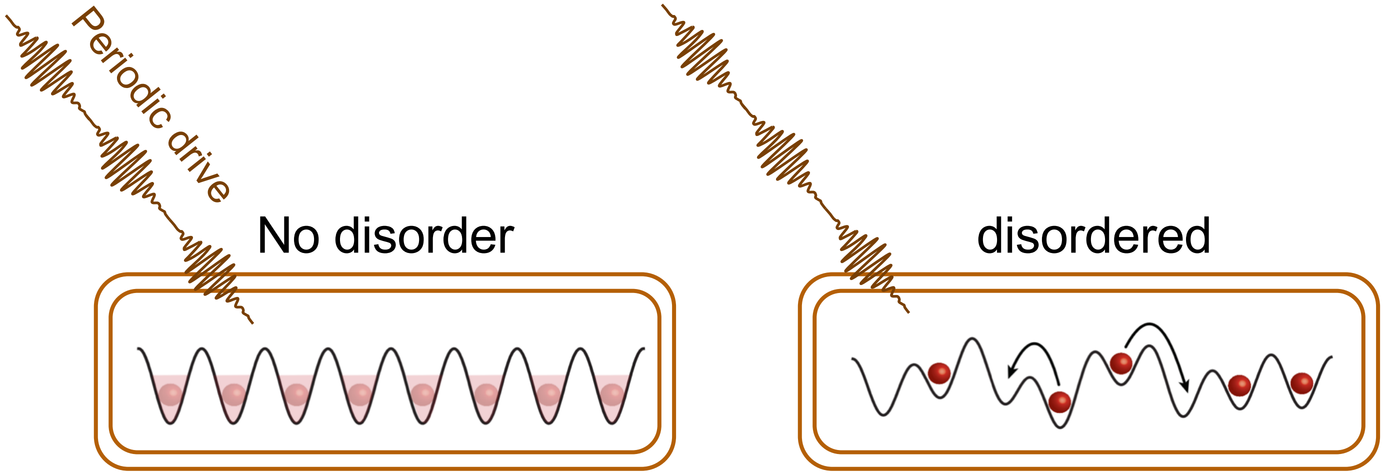
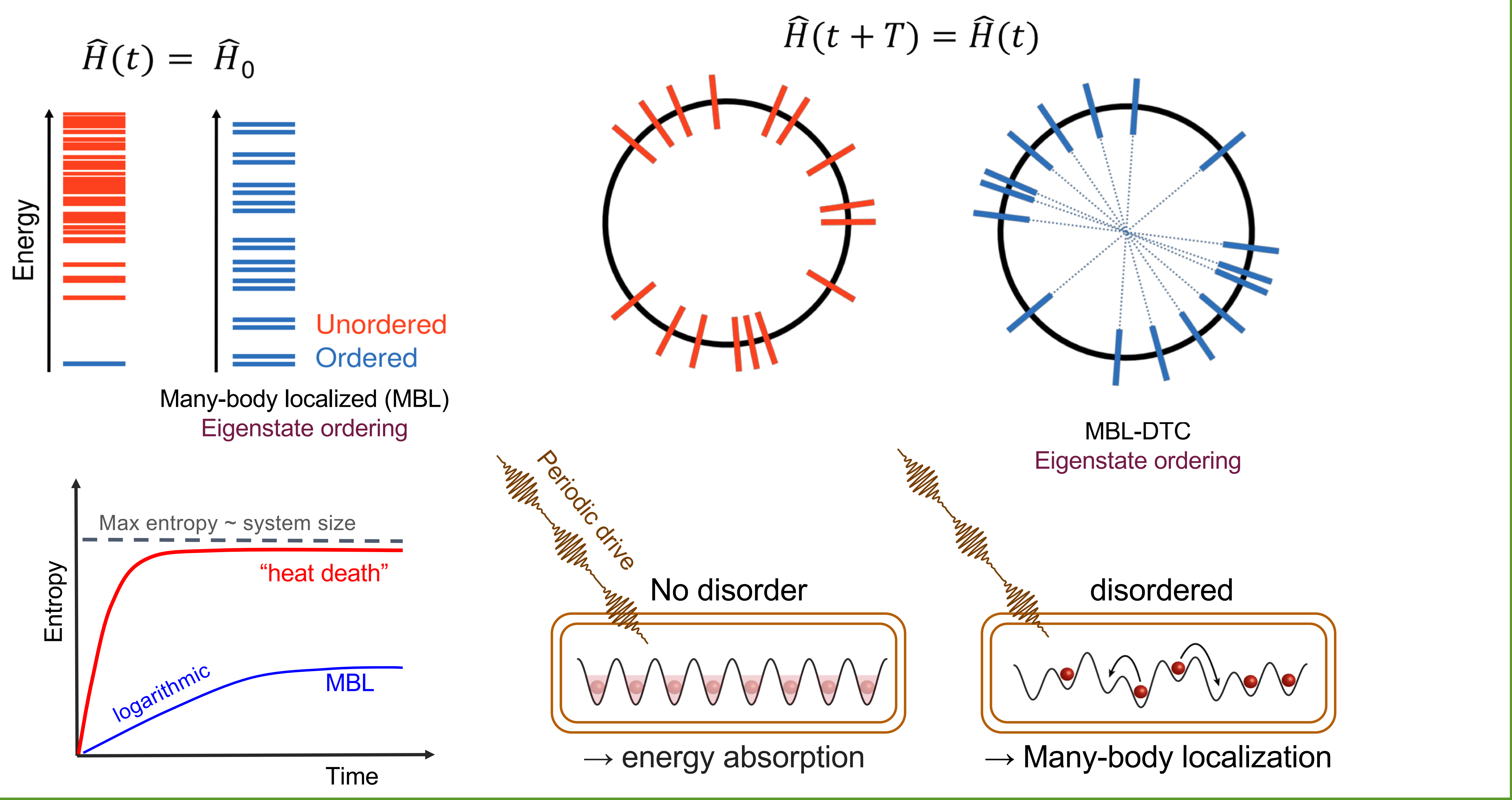




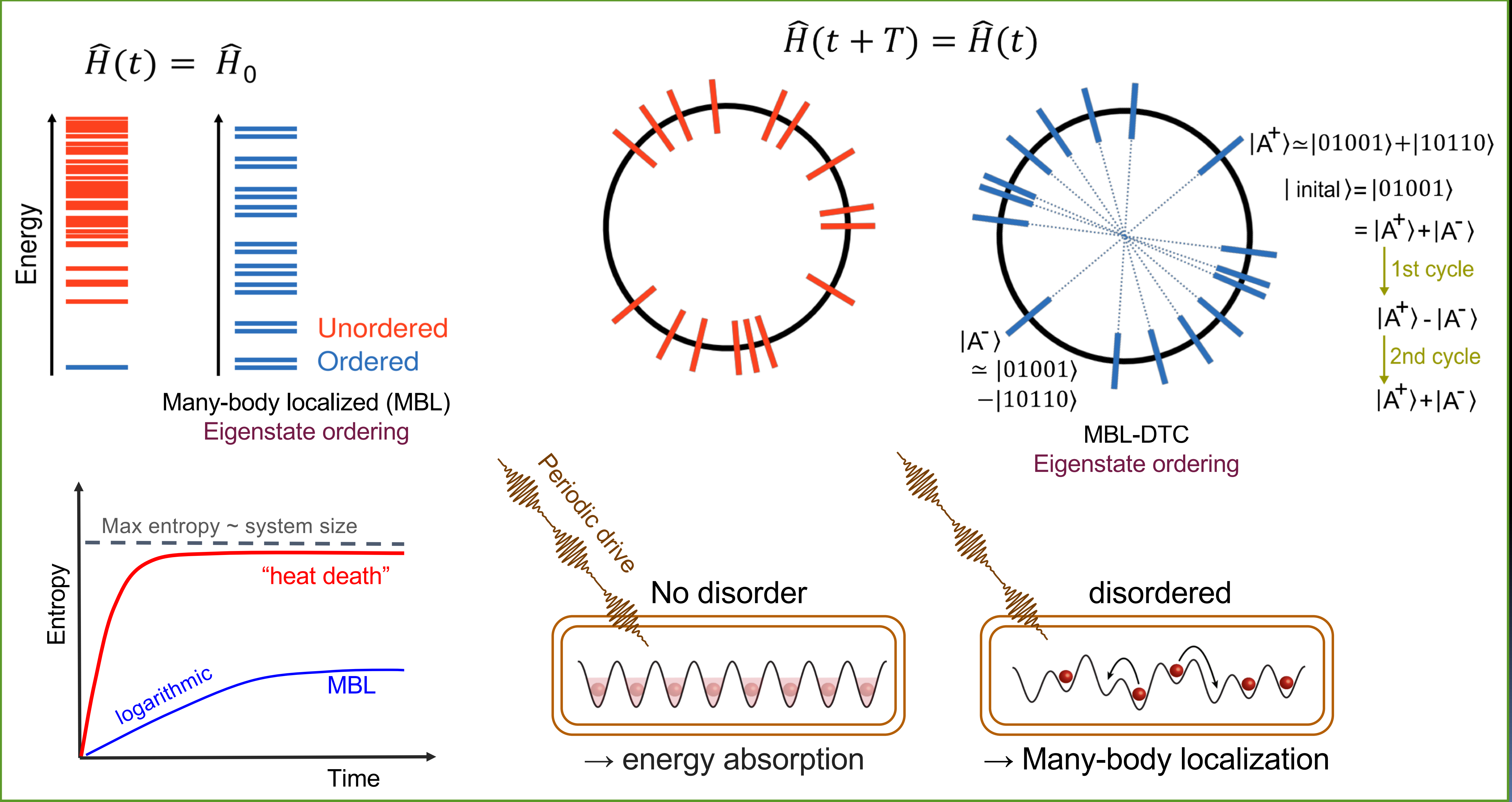
→ energy absorption

→ Many-body localization

Discrete Time Crystals (DTC): Rigid oscillation in isolation

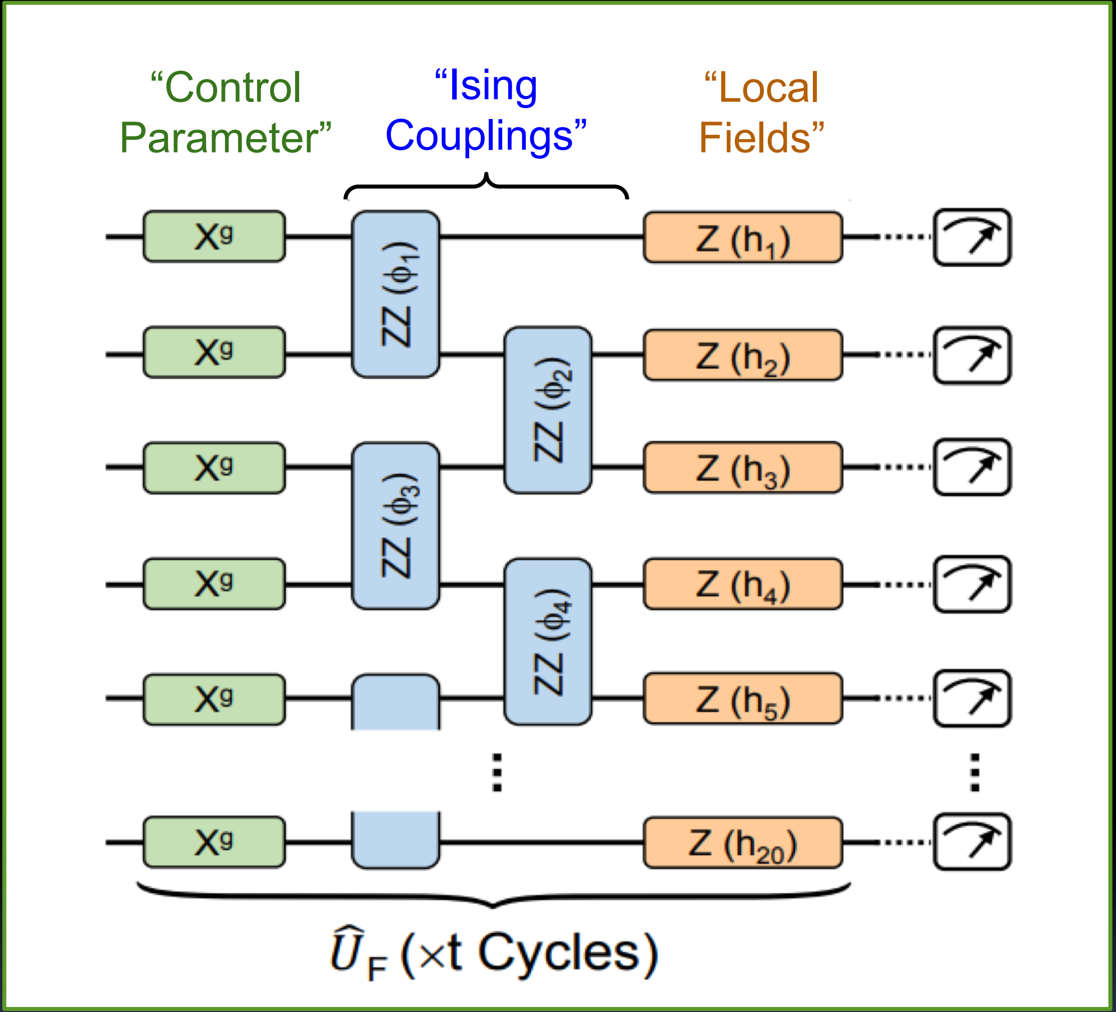


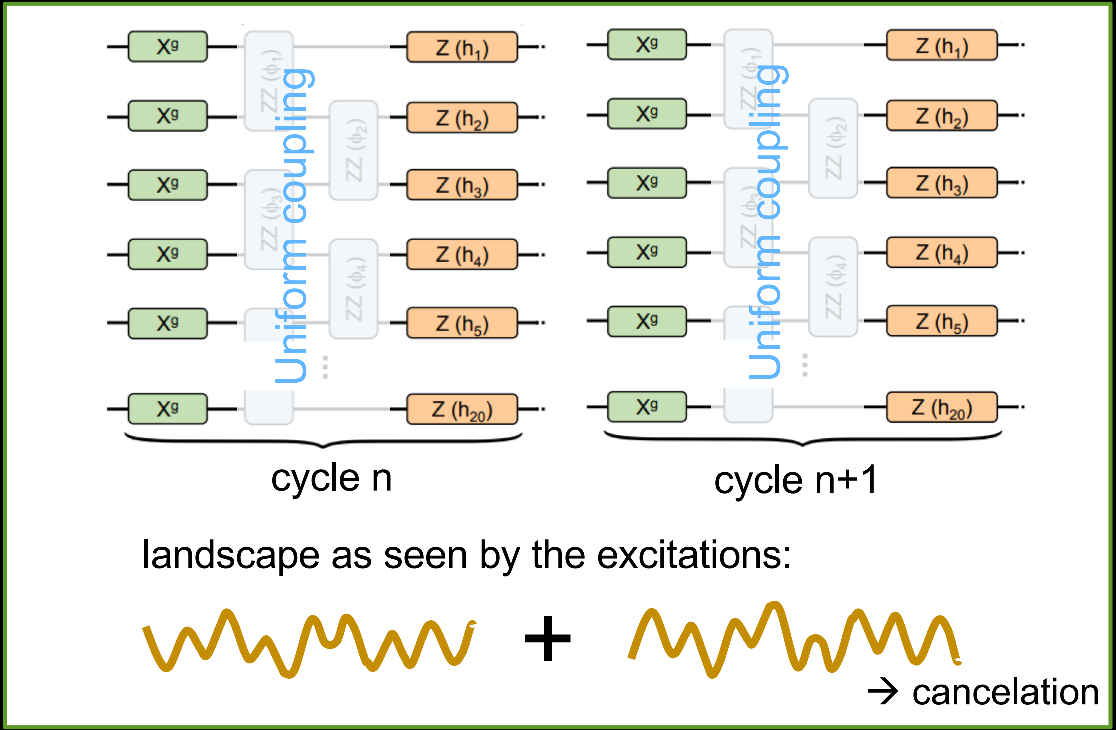
Discrete Time Crystals (DTC): Rigid oscillation in isolation



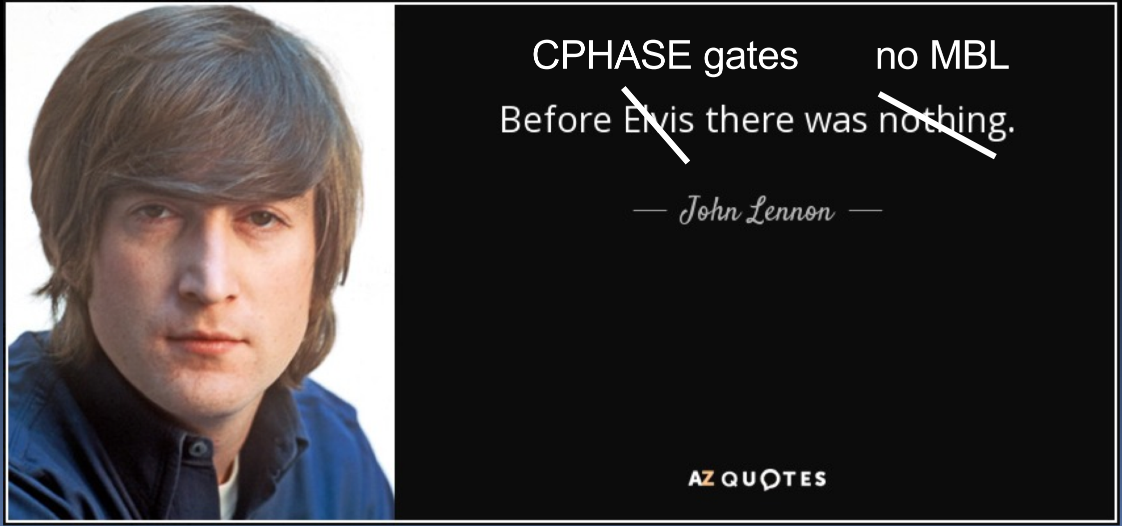
Transverse field Ising model

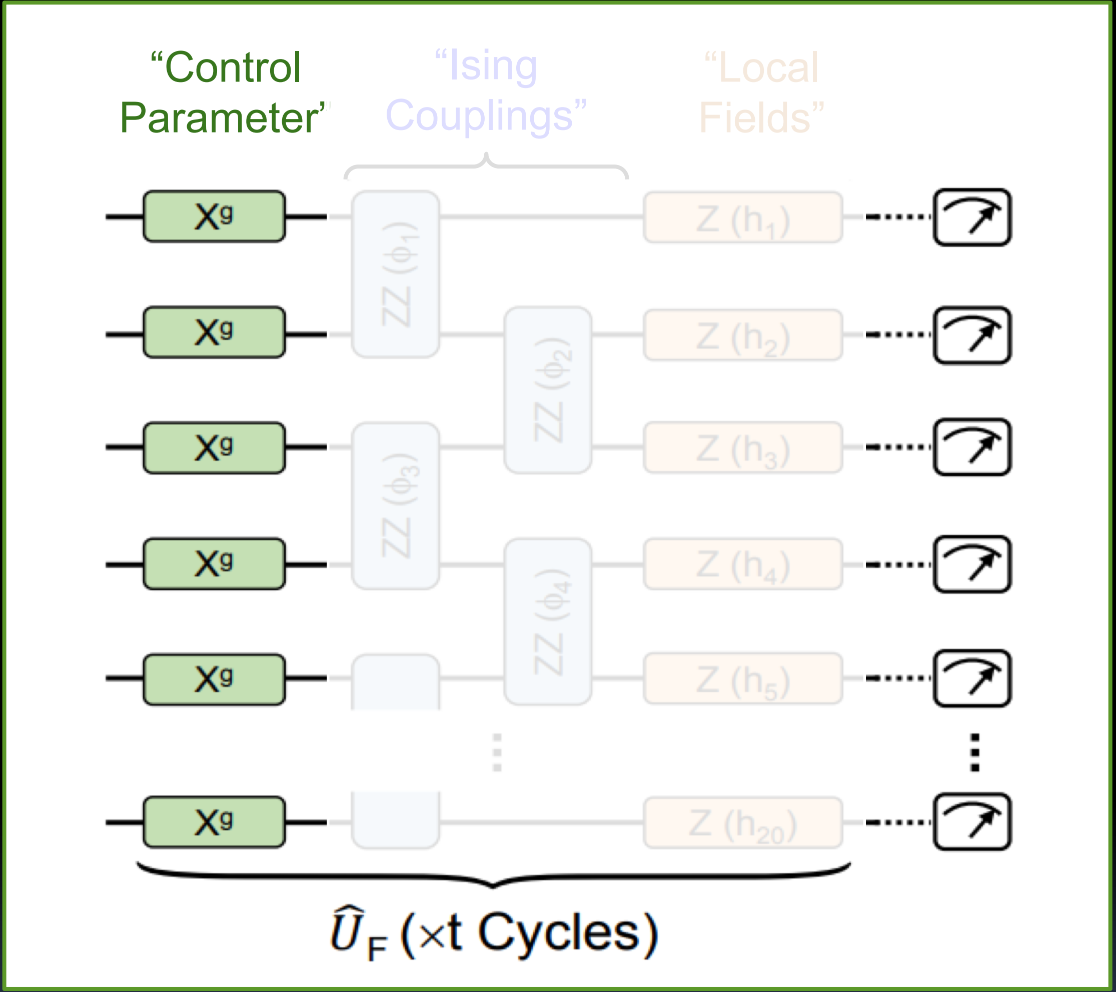
Non-integrability: $h_i \in [0, 2\pi]$, MBL: $\phi_i \in [-1.5\pi, -0.5\pi]$





$$\hat{U}_F = \underbrace{e^{-\frac{i}{2}\sum_i h_i \hat{Z}_i}}_{\text{longitudinal fields}} \underbrace{e^{-\frac{i}{4}\sum_i \phi_i \hat{Z}_i \hat{Z}_{i+1}}}_{\text{Ising interaction}} \underbrace{e^{-\frac{i}{2}\pi g \sum_i \hat{X}_i}}_{x \text{ rotation by } \pi g}$$





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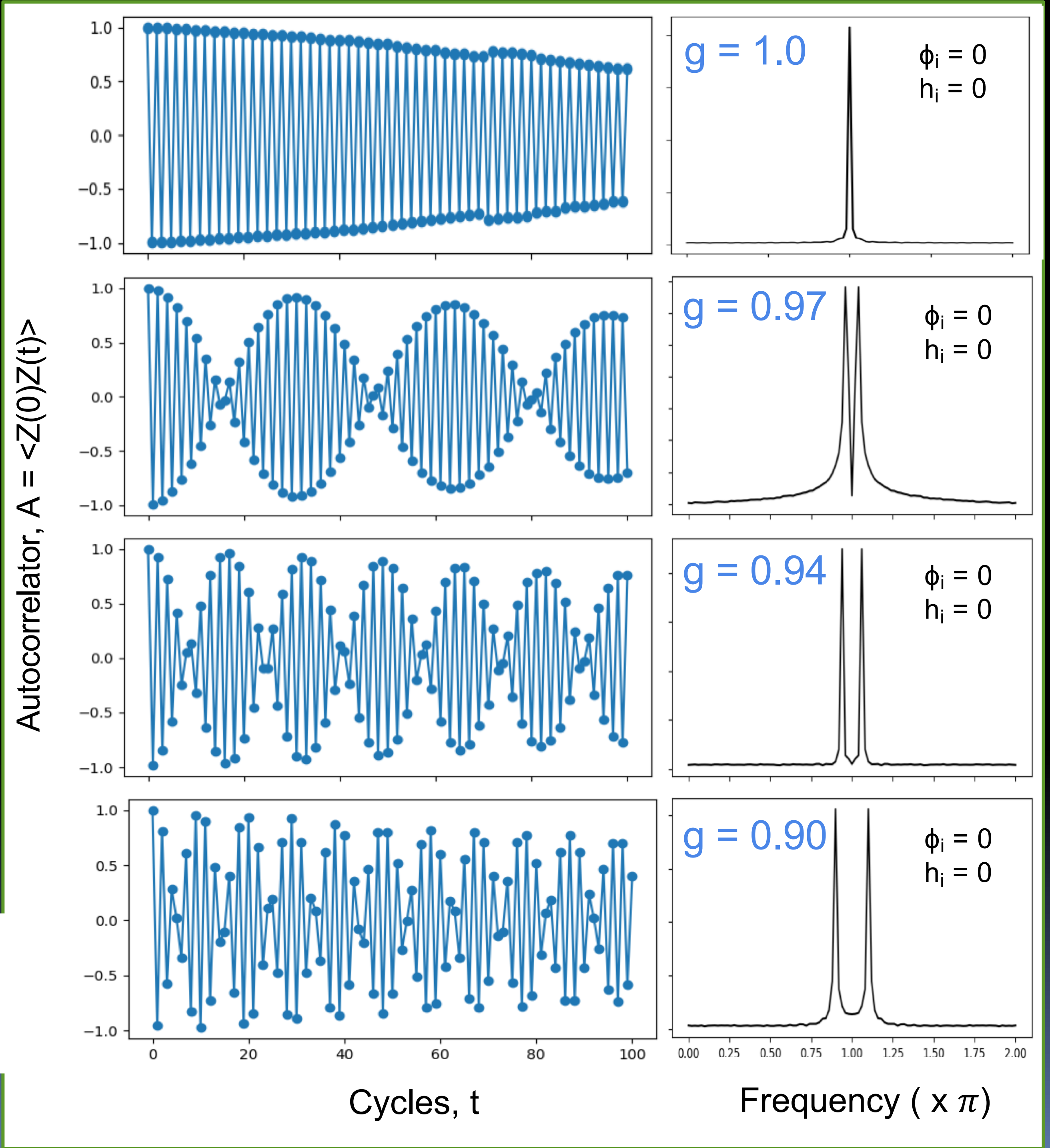
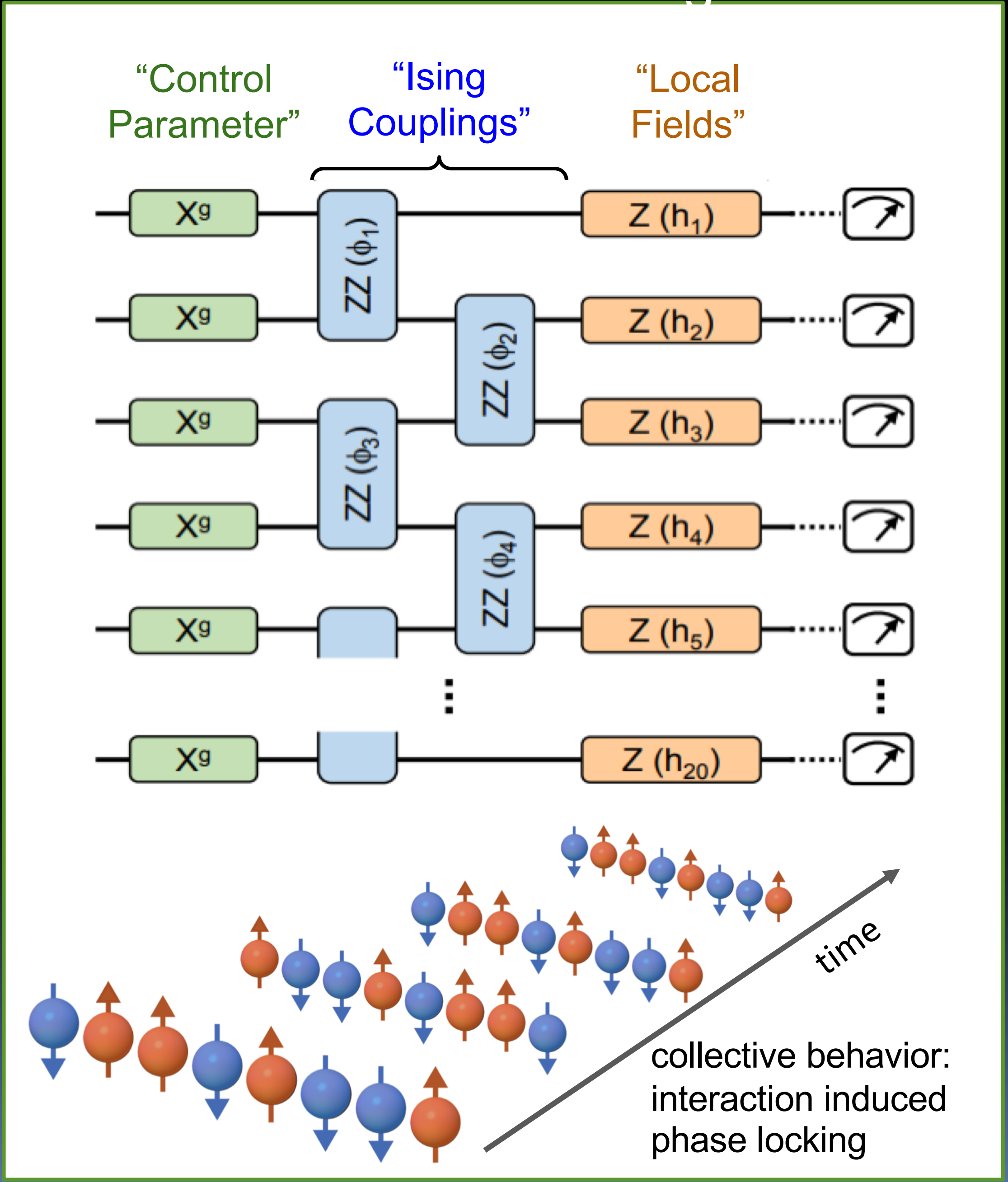
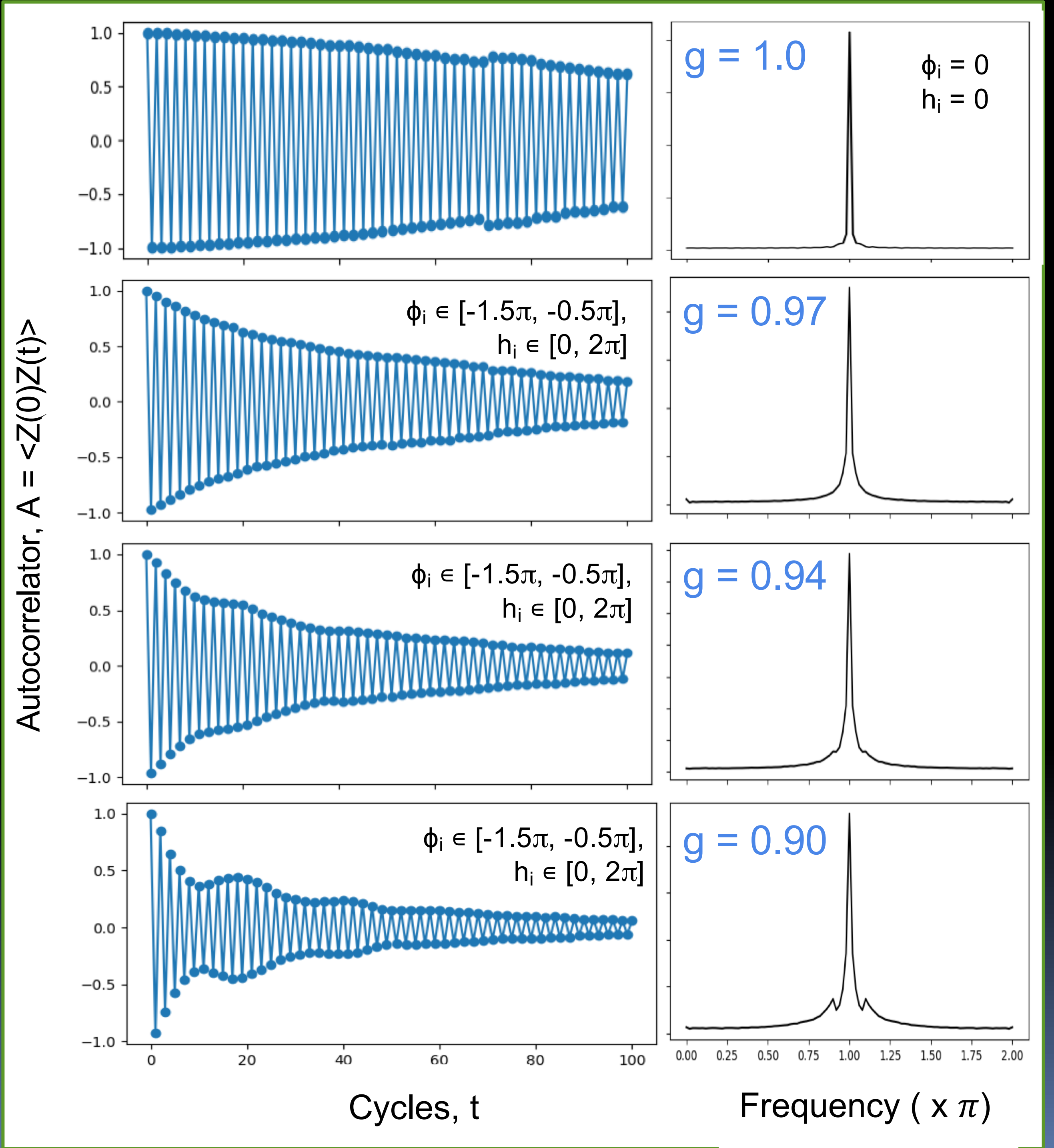
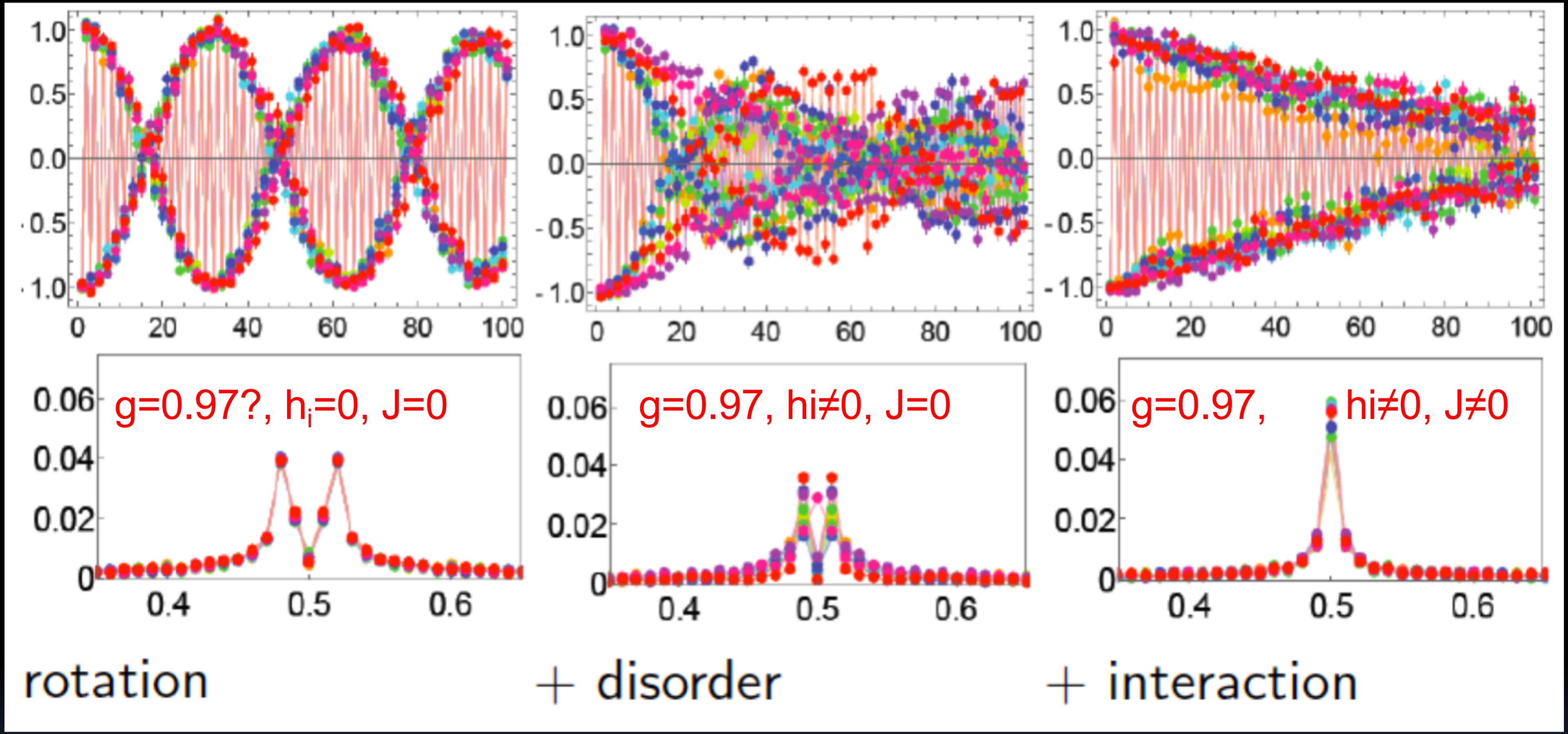


Transverse field Ising model





First generation experiments: observing period doubling response



Observation of sub-harmonic response

- over range of parameters
- few initial states

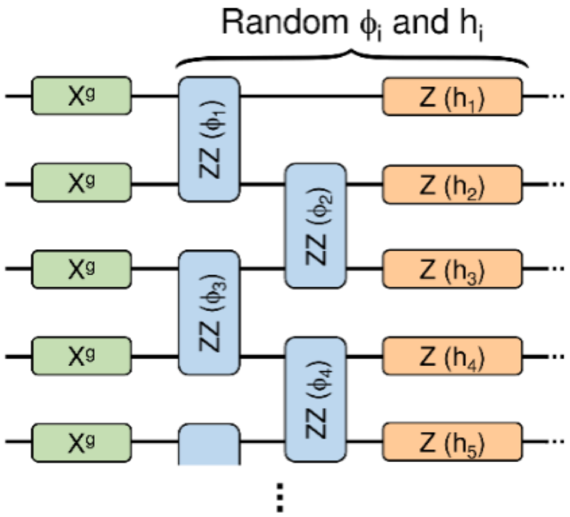
interactions induced mode locking

Challenges: going beyond response and verifying formation of a phase

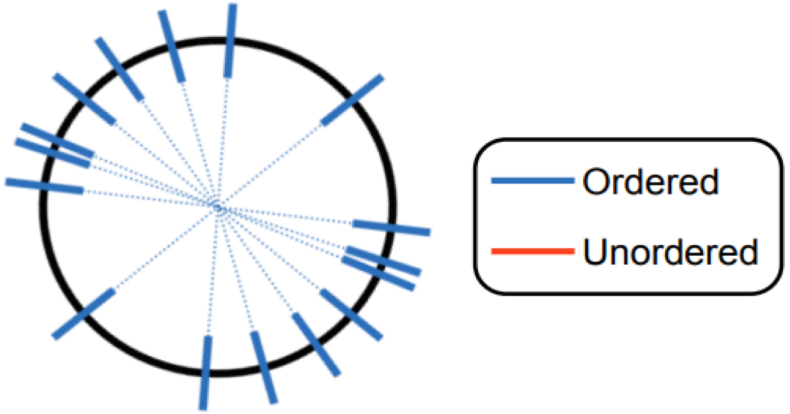
- Establishing MBL
- Long-lived oscillation
- Check all initial states

Choi *et al.* Nature 543 (2017), Zhang *et al.* Nature 543 (2017), Rovny *et al.* PRL. 120 (2018), Pal *et al.* PRL 120 (2018)

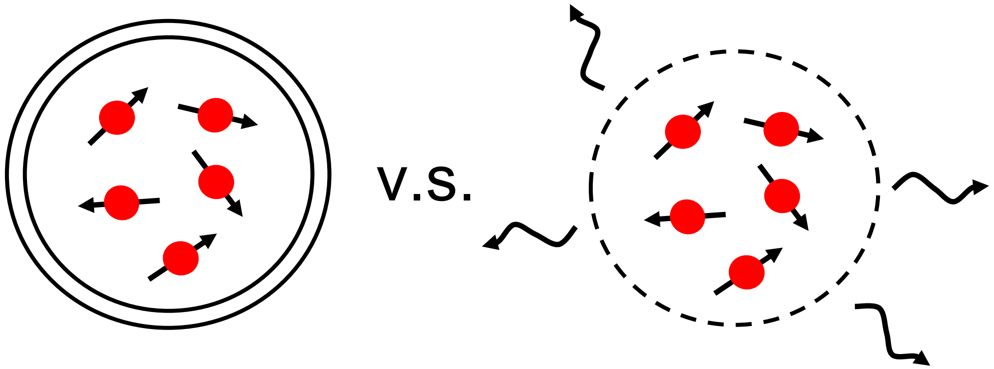
Stable Phase Structure showing MBL



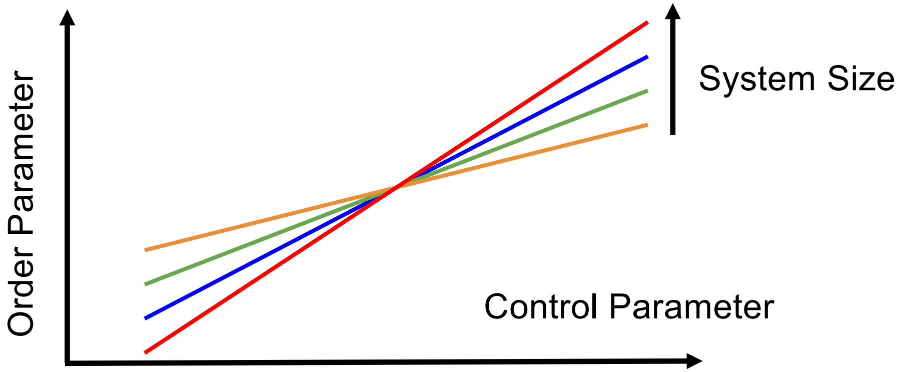
Quantum Order in all Eigenstates



Separating Decoherence and Thermalization



Finite Size Effects & Phase Transition



Definition of DTC: a phase that shows indefinite temporal ordering with no heating in a Hamiltonian system for all initial states.

↓ Stable to perturbation, infinite size

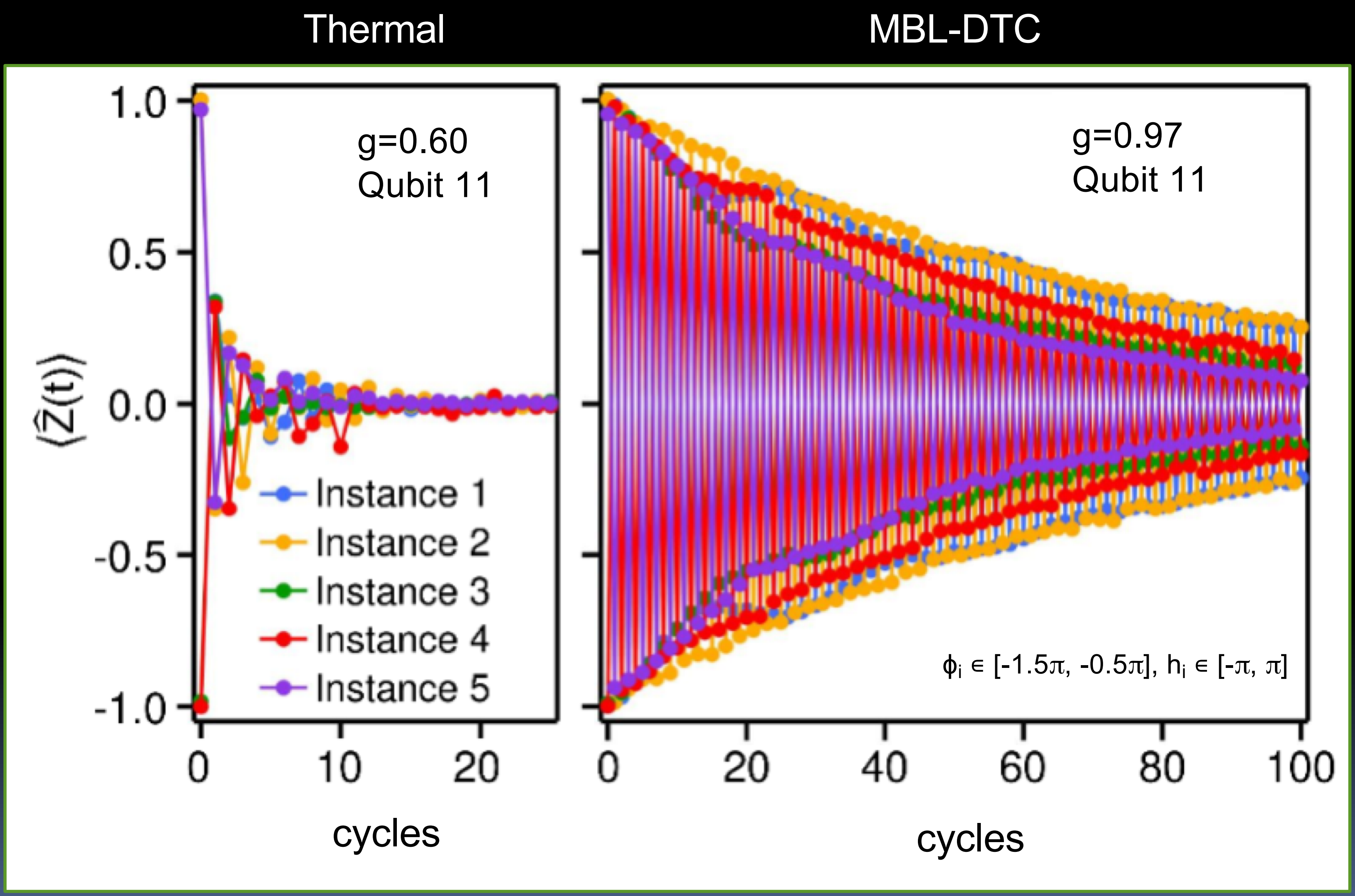
↓ Indefinite period doubling

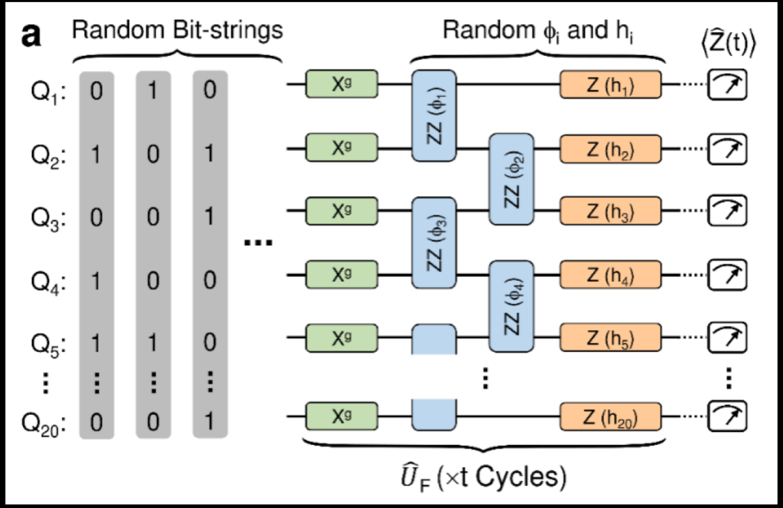
↓ MBL, Periodically driven

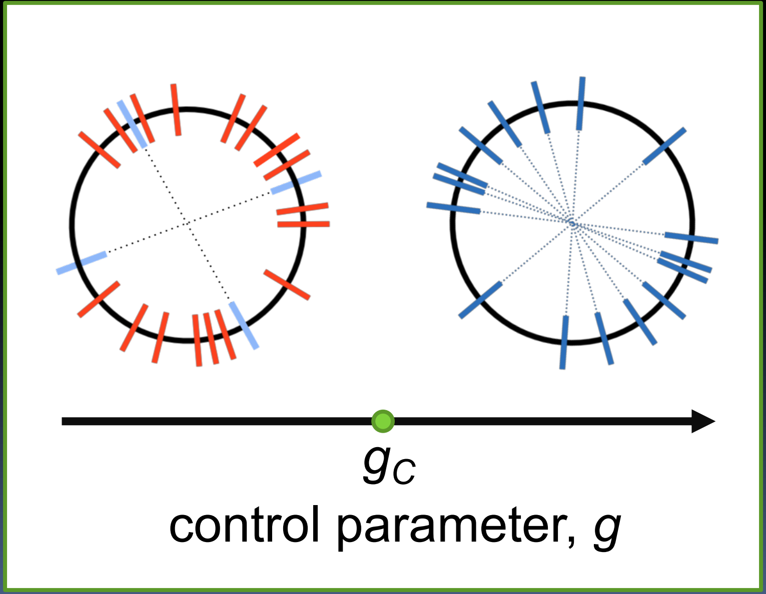
↓ Isolated

↓ Eigenstate order

Extended over a parameter range







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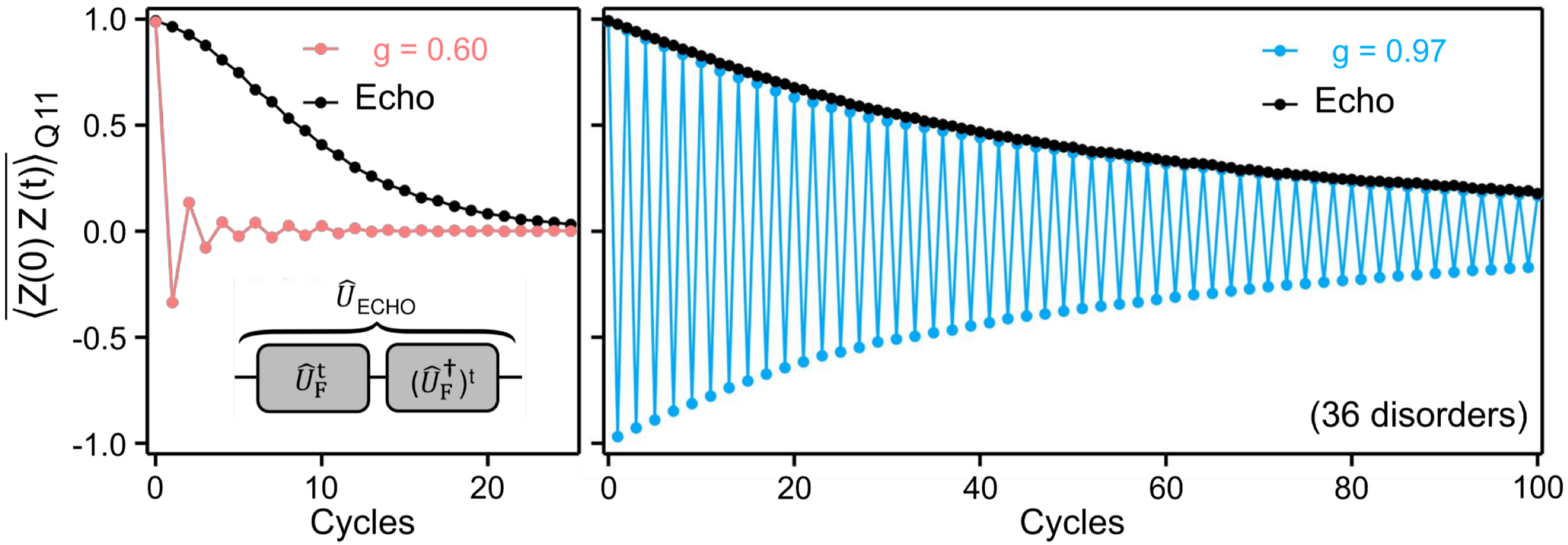
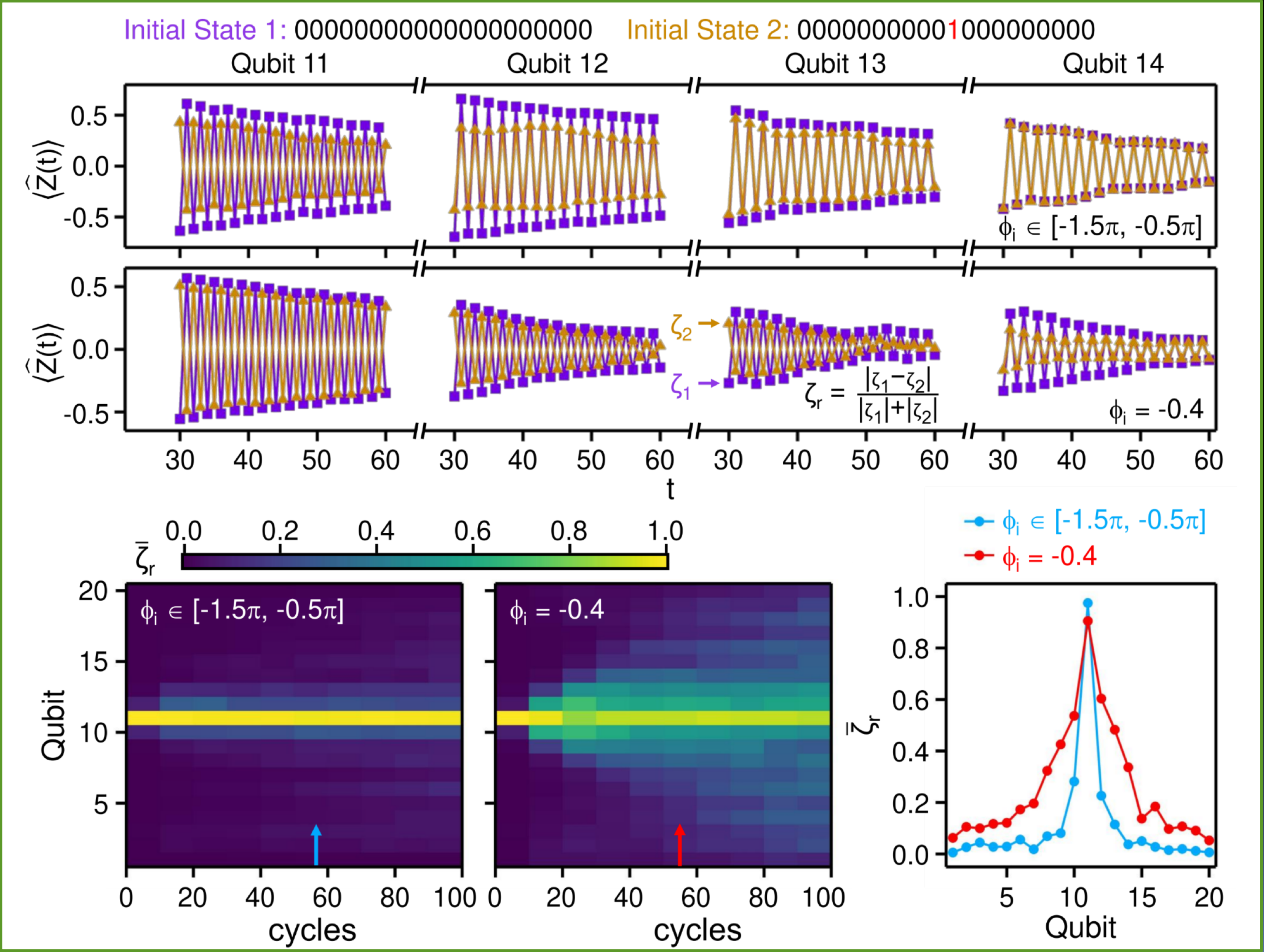
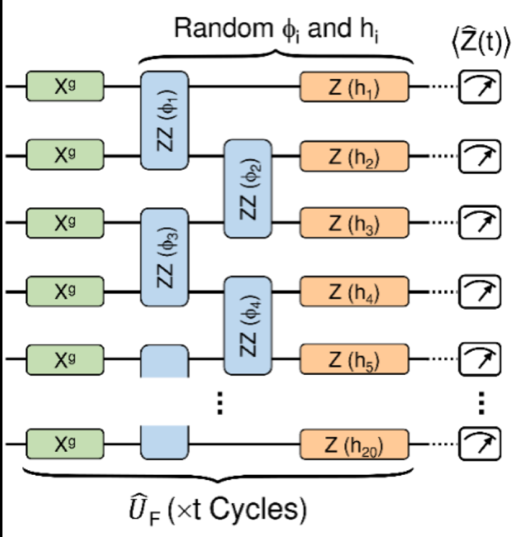
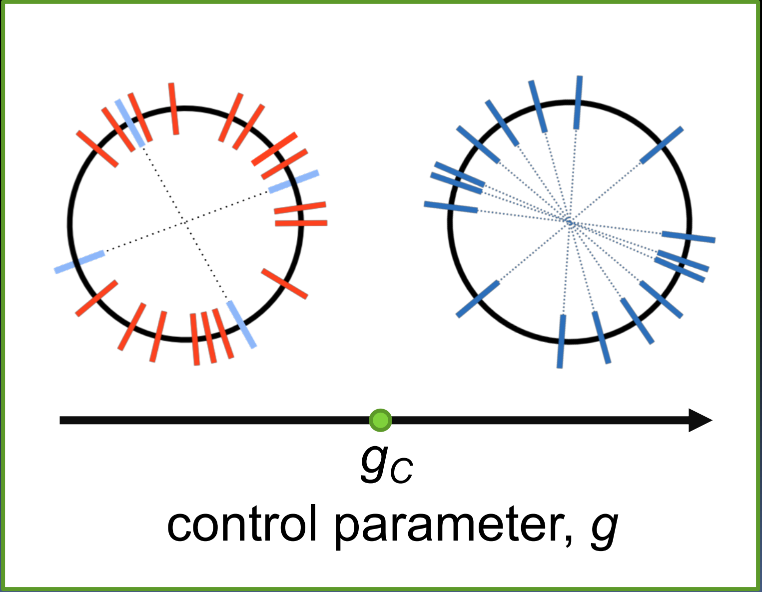


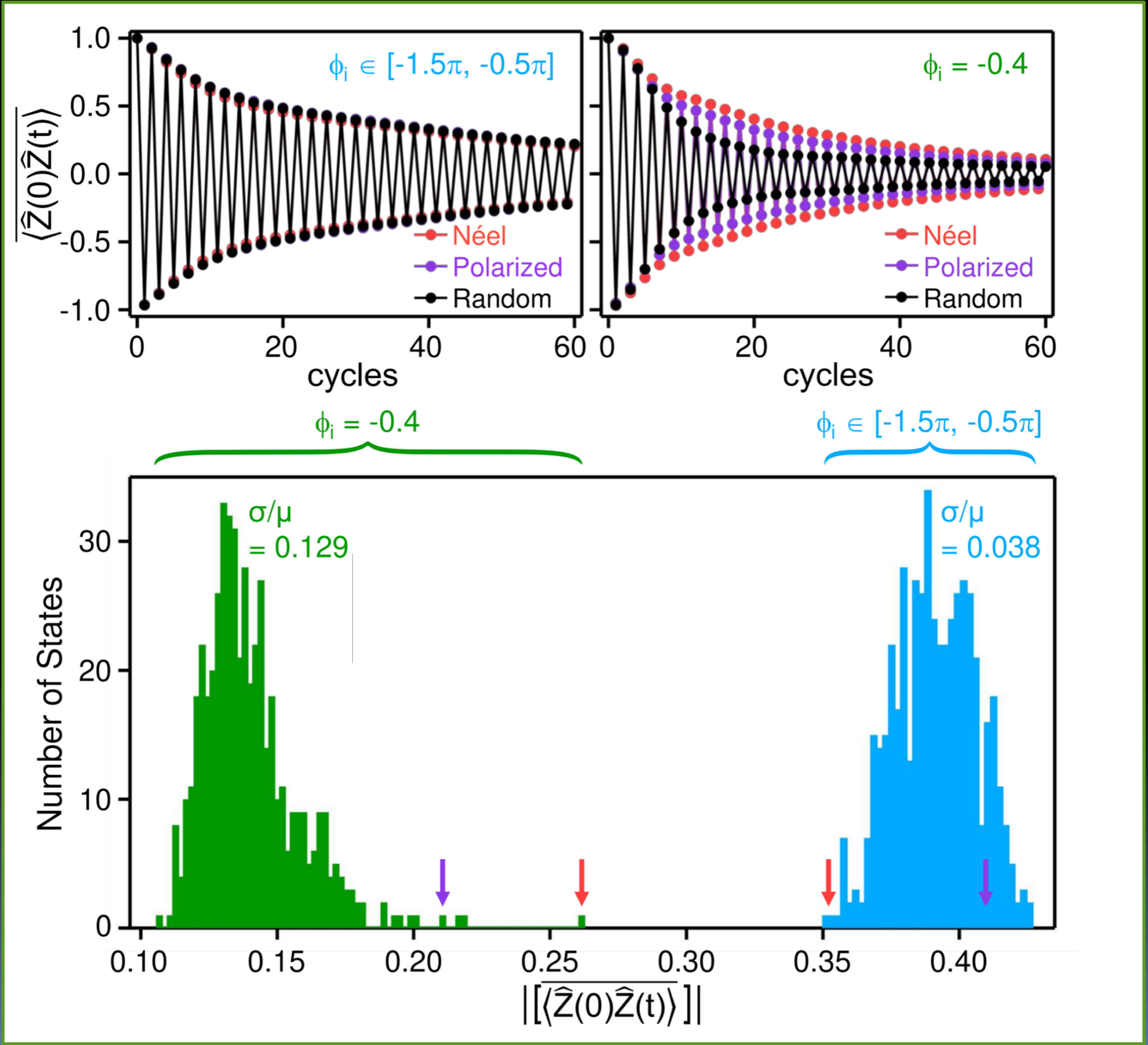
Establishing MBL

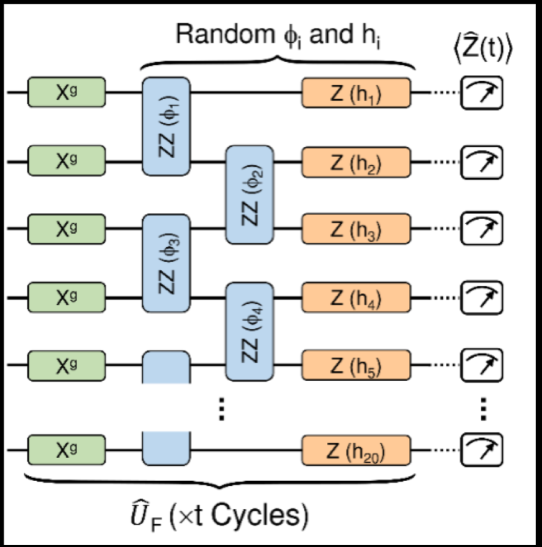


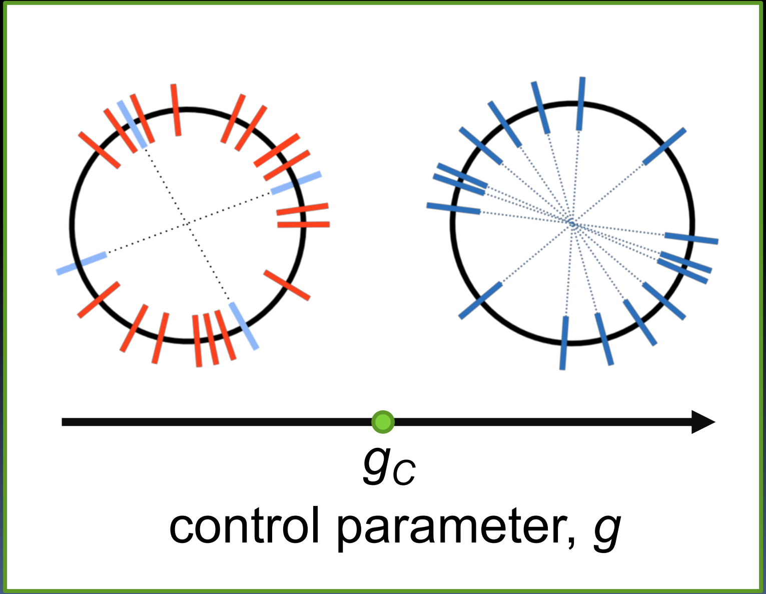




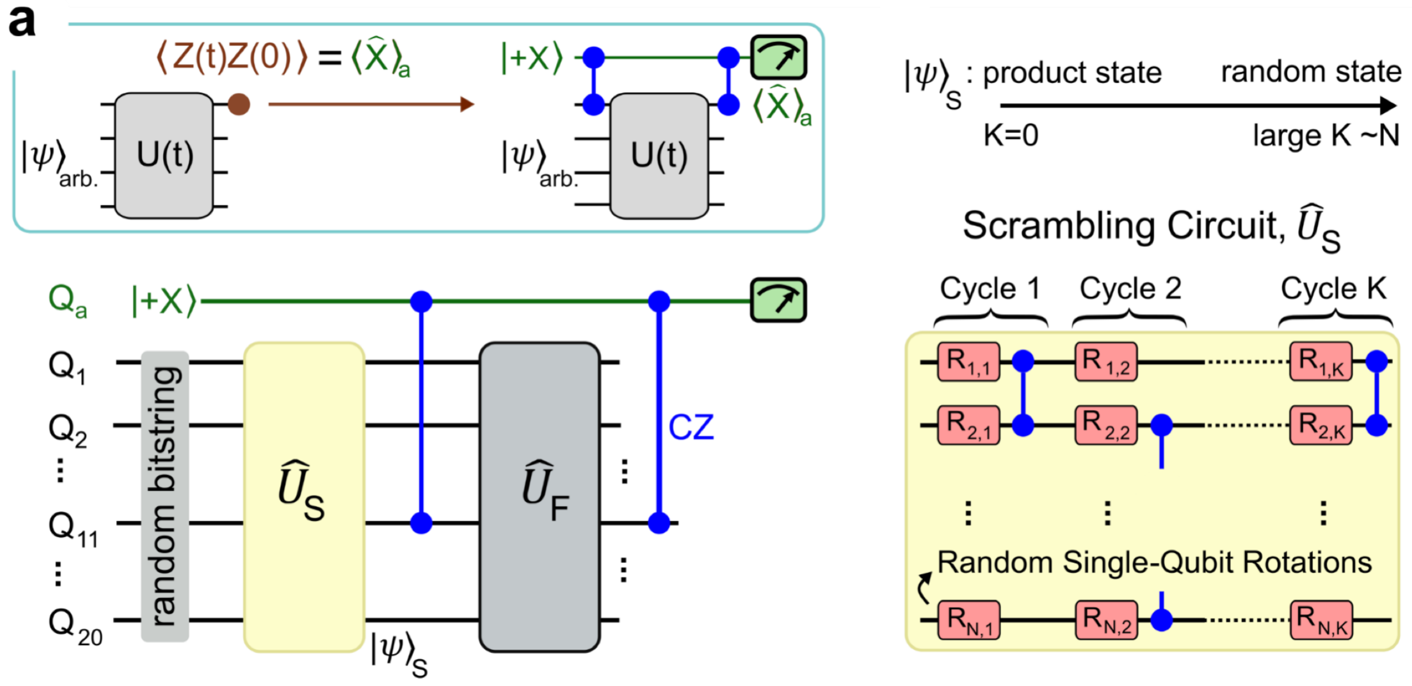
Signatures of eigenstate ordering

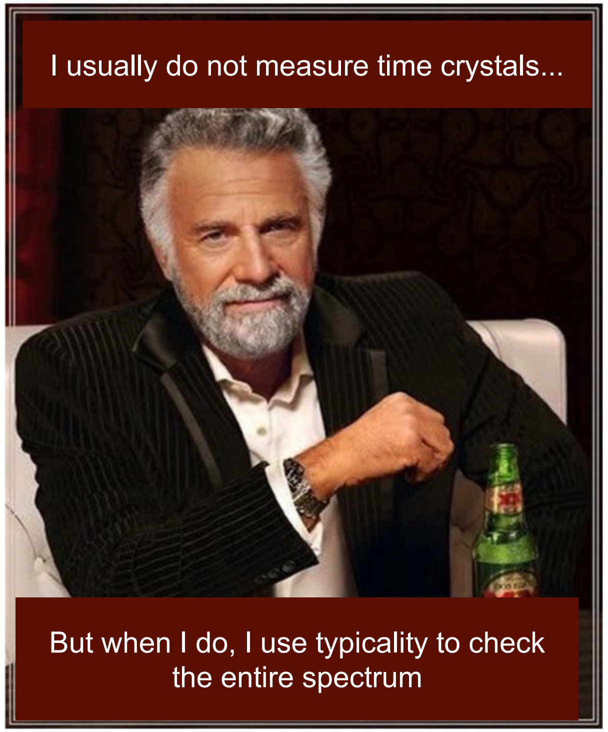


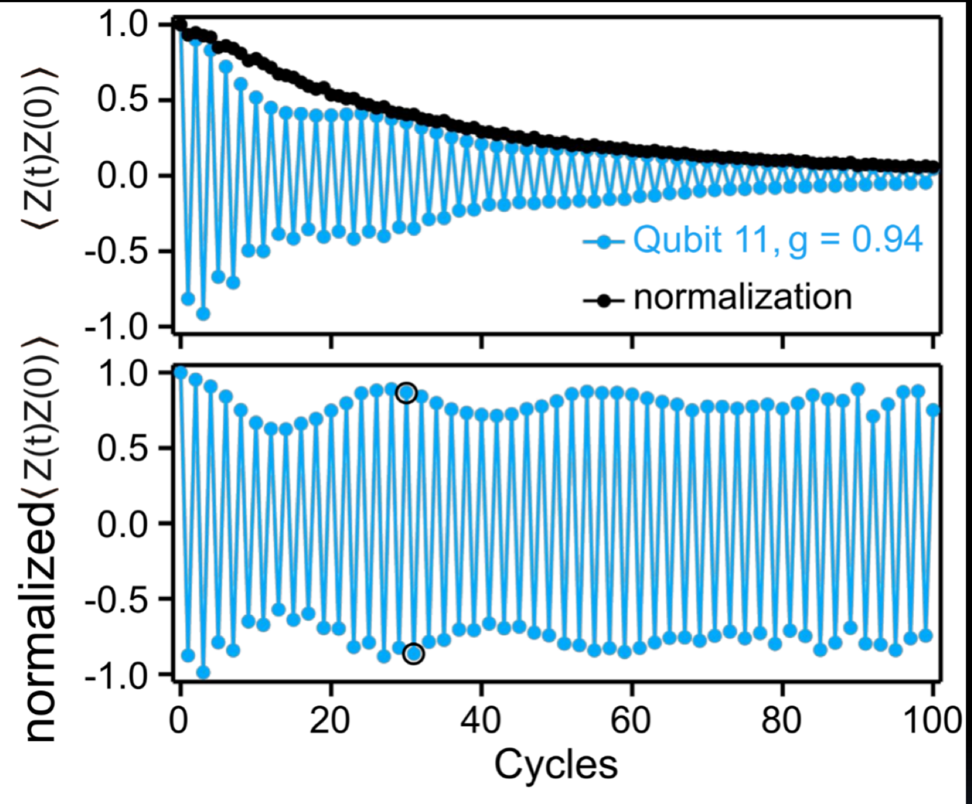




Average spectral response via quantum typicality







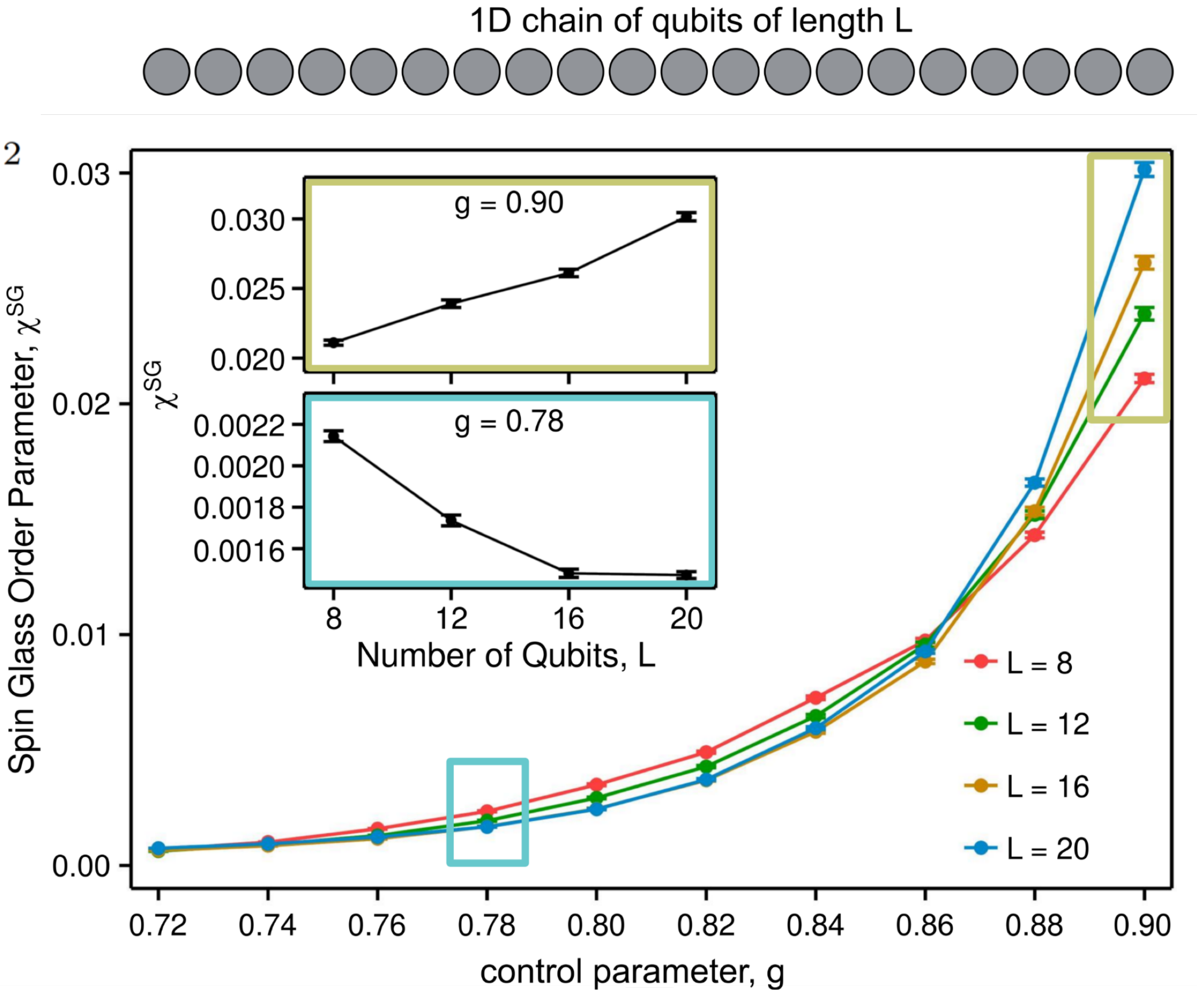
Ensemble average behavior → fully mixed state

Typicality:
→ pure state randomly from Hilbert space.

Estimating phase-transition by varying system size

$$\chi^{SG} = \frac{1}{L-2} \sum_{i \neq j}' \langle \hat{Z}_i \hat{Z}_j \rangle^2$$

Edwards-Anderson order parameter



average of cycles 51 to 60
40 disorder instances
40,000 stats at cycle and disorder

Did Google team realized a time crystal? *NO!*

SCIENCE

Google Claims It Created a New Phase of Matter That's In Perpetual Motion

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Google researchers made a time crystal inside a quantum computer

Google's 'time crystals' could be the greatest scientific achievement of our lifetimes

EurekaEurekaEurekaEureka!

Google says it has created a time crystal in a quantum computer, and it's weirder than you can imagine

Fresco at Apostolic Palace, Vatican

thermodynamical phase → Bose-Hubbard
vs.
Dynamical phase → Time crystals

Study of non-equilibrium phenomena is challenging
(limited programmability, coherence, and size of NISQ hardware)

…establish a scalable approach to studying non-equilibrium phases of matter on current quantum processors.