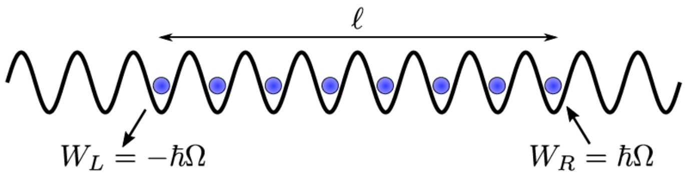
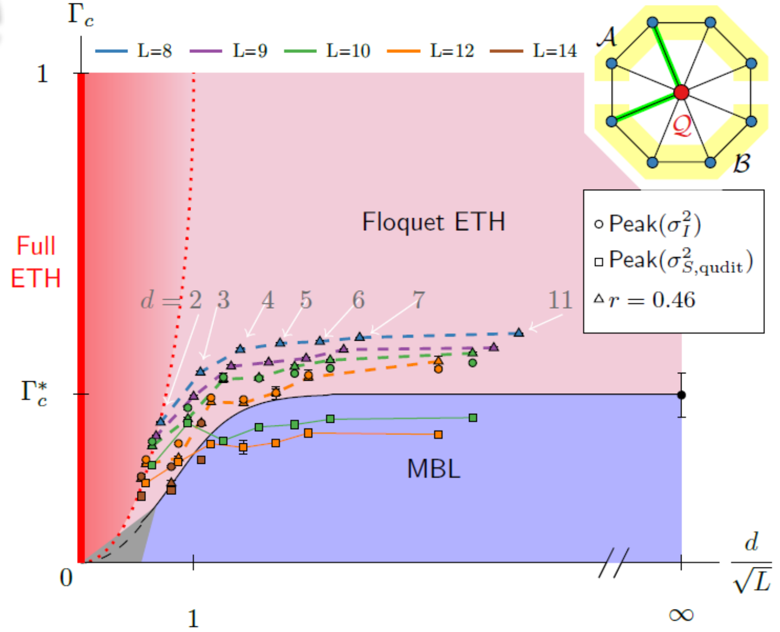
Backaction of Floquet systems on quantized drive





Michael Kolodrubetz, UT Dallas

In collaboration with…

UC Berkeley: Takahiro Morimoto[A], Snir Gazit[A], Joel Moore[A], **Nathan Ng[B]**

Neils Bohr Institute: **Frederik Nathan[A],** Mark Rudner[A]

UT Dallas: **Saeed Rahmanian**

References: [A]Phys. Rev. Lett. 120, 150601 (2018); [B]arXiv:1809.02606

From Floquet to photons

- Periodic (Floquet) driving gives rise to a wide variety of new phenomena
  - Time crystals
  - Pi-Majoranas
  - Floquet SPTs
- What does the driving? Photon
- Let’s quantize them and see what happens!

Example: Quantized time crystal

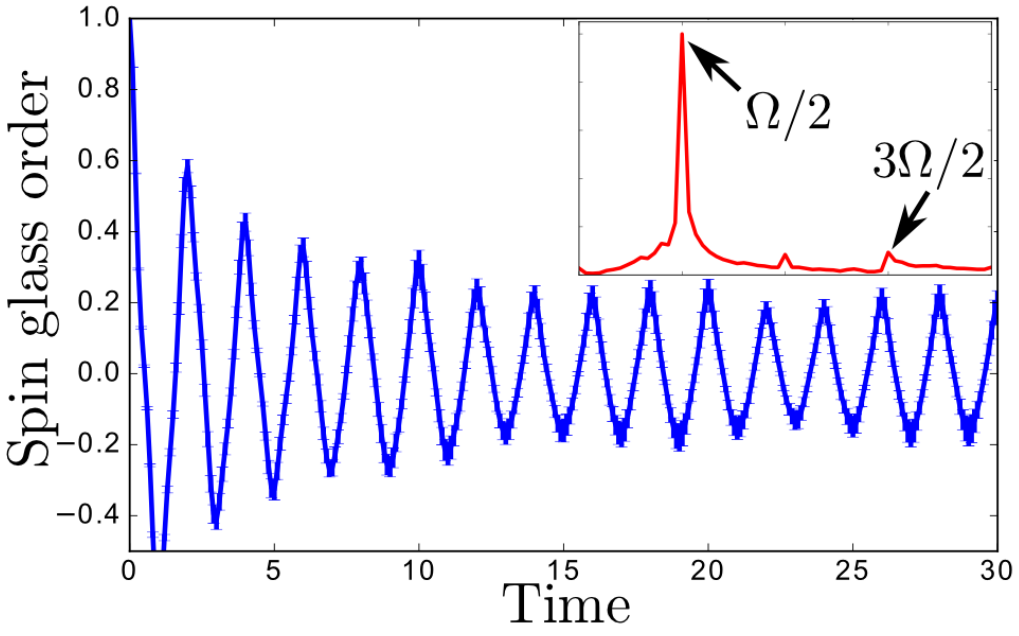
- Consider monochromatic version of time crystal:

$$H(t) = H_0 + H_1 \cos(\Omega t)$$

$$H_0 = \sum\left(h_{x0} X_j + J Z_j Z_{j+1} + g_j Z_j\right); H_1 = \sum h_{xd} X_j$$

- Extended zone:

$$\begin{pmatrix} \ddots & & & & \\ & H_0 - \hbar\Omega & H_1 & 0 & \\ & H_1 & H_0 & H_1 & \\ & 0 & H_1 & H_0 + \hbar\Omega & \\ & & & & \ddots \end{pmatrix}$$



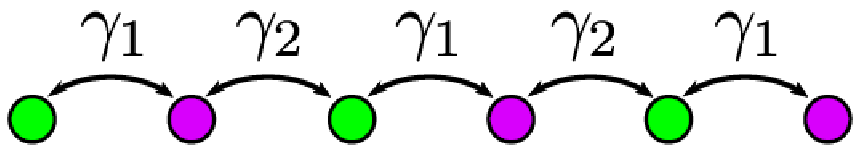
- Time crystal in equilibrium
  - Breaks Watanabe & Oshikawa?

Outline

- Intro to Floquet-Thouless energy pump
  [MK, Nathan, Gazit, Morimoto, Moore, PRL 120, 150601 (2018)]
- Quantizing photons in energy pump
  - Topological photon creation/conversion
  - Closed cycle energy/charge pump
- Quantizing photons in Floquet MBL
  [Ng, MK, arXiv:1809.02606]
  - Localization in present of global coupling
  - Effect of Floquet cutoff
  - Inverted mobility edge?

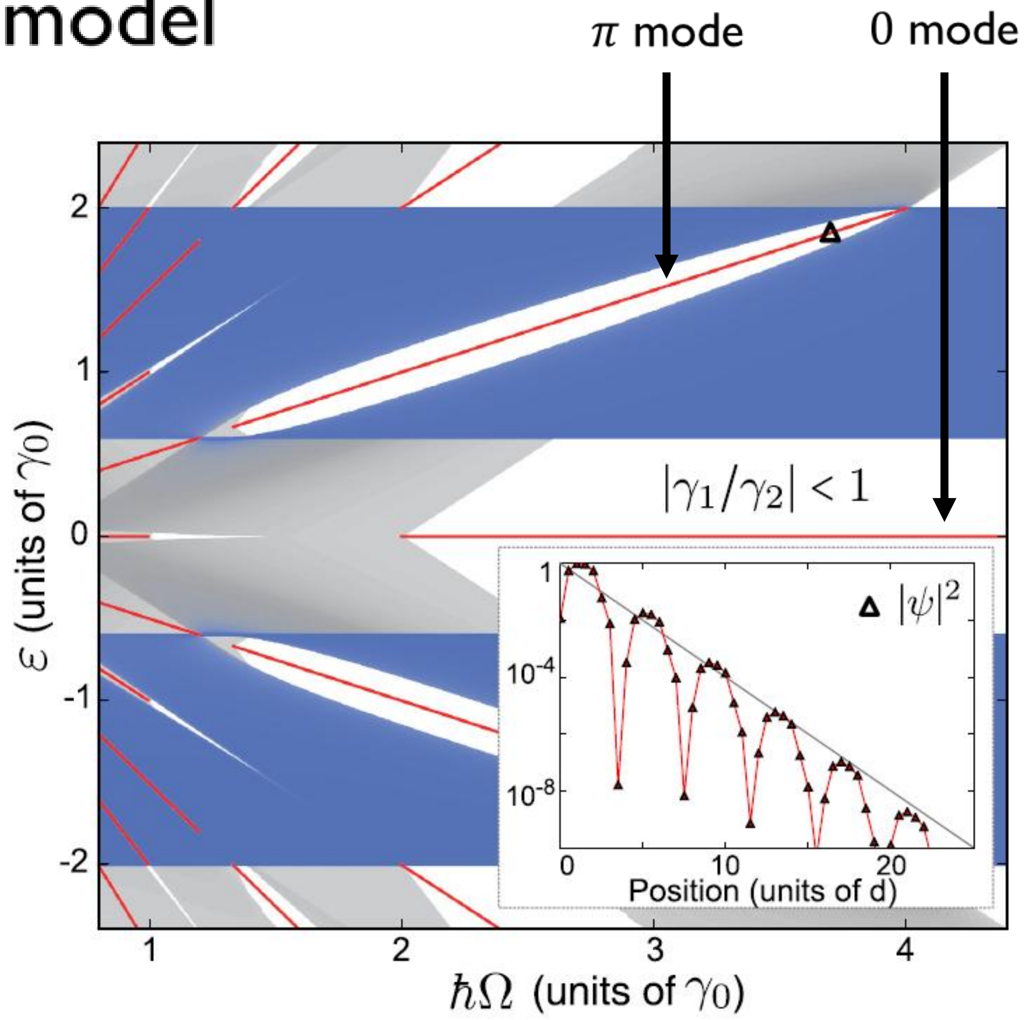
Floquet-Thouless energy pump

- Starting point: Floquet-SSH model



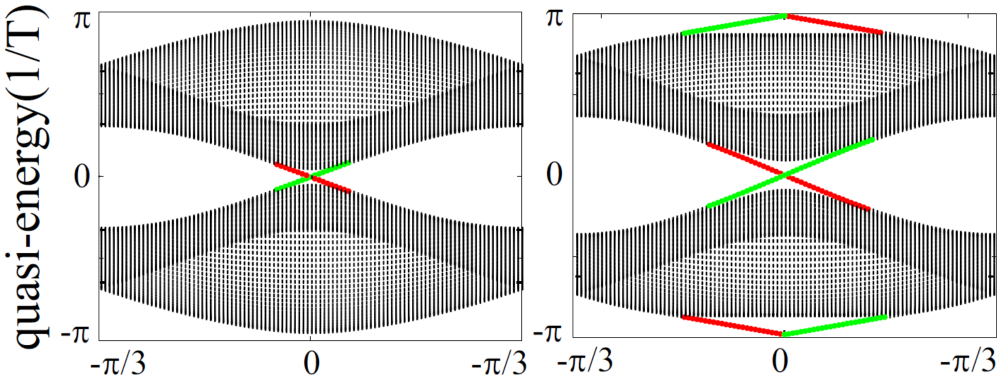
$$\gamma_1(t) = \gamma_0 + \delta + 2A\cos(\Omega t)$$
$$\gamma_2(t) = \gamma_0 - \delta - 2A\cos(\Omega t)$$

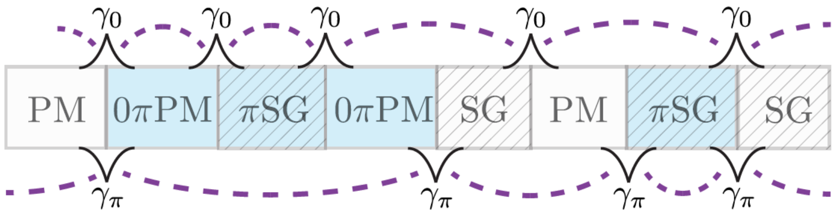
  - Chiral symmetry means $\epsilon_F = 0, \pi/T$ special
  - Tuning parameters gives both 0 and π modes



Floquet-Thouless energy pump

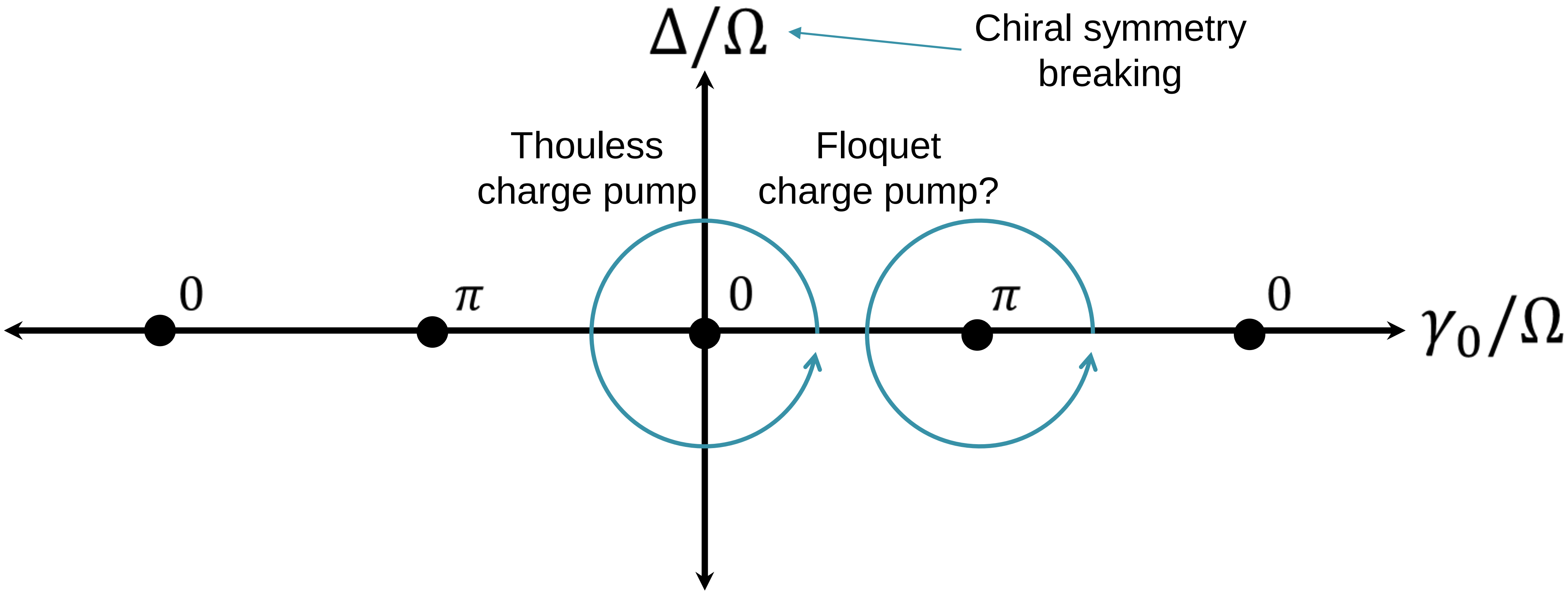
- These π modes play important role in Floquet systems
  - $\mathbb{Z}_2$ time crystal / π spin glass is dual to π Majorana chain [Khemani et al, PRL 116, 250401 (2016); Keyserlingk and Sondhi, PRB 93, 245146 (2016); Else et al, PRL 117, 090402 (2016)]
  - π modes distinguish anomalous Floquet insulator from Chern insulator [Kitagawa et al, PRB 82, 235114 (2010); Rudner et al, PRX 3, 031005(2013)]
  - Hybridization of π modes gives rise to Floquet criticality [Berdanier et al, arXiv:1803.00019]





Floquet-Thouless energy pump

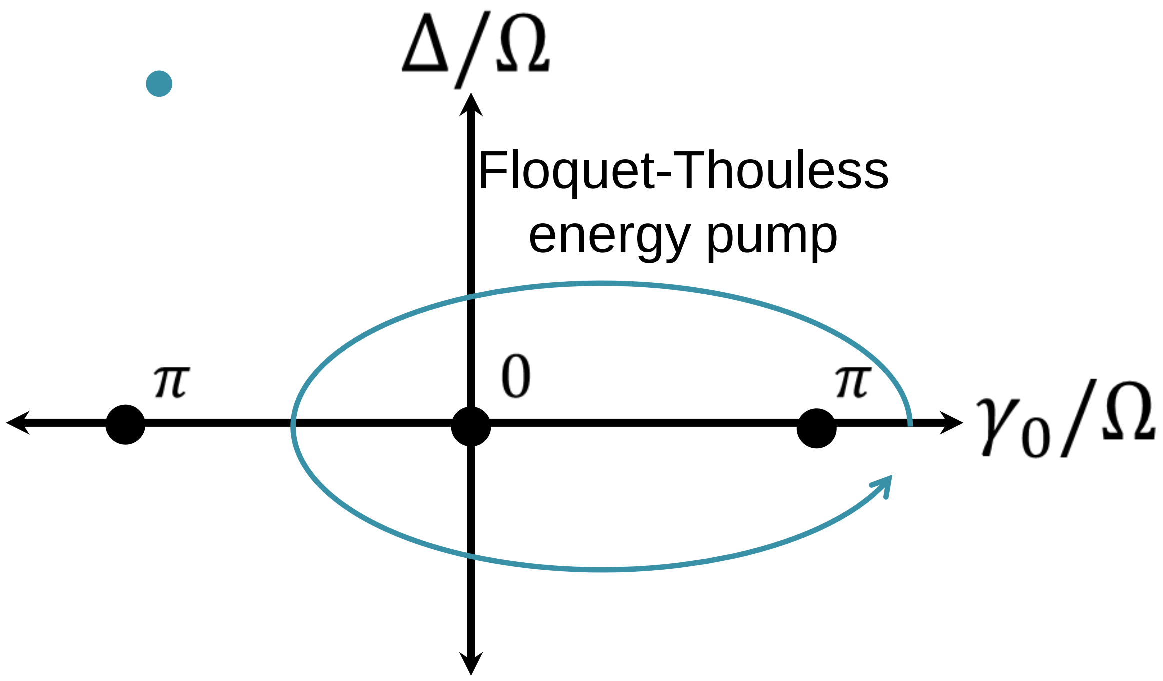
- These π modes play important role in Floquet systems
  - We ask the question of what happens to a Thouless charge pump when π modes are involved

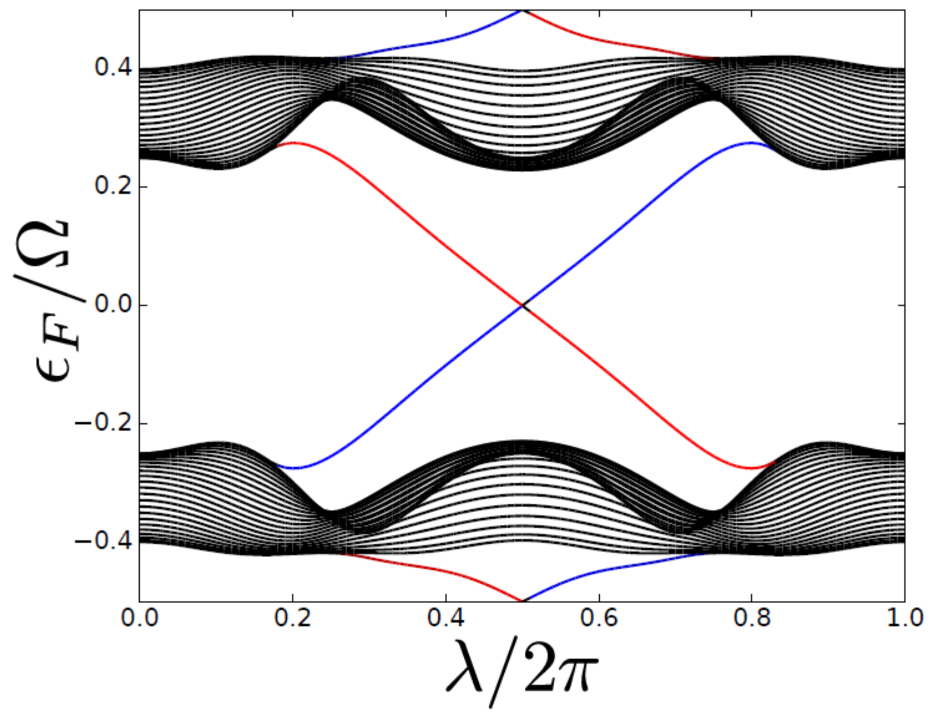


Floquet-Thouless energy pump

- Test using Floquet version of Rice-Mele model
  - Result: Surrounding a π mode gives rise to a conventional Thouless charge pump
  - Reason: The charge pump does not require any symmetry besides charge conservation, so can just deform π gap to arbitrary quasienergy
  - But in the process uncover new type of pumping cycle: Floquet-Thouless energy pump

Floquet-Thouless energy pump

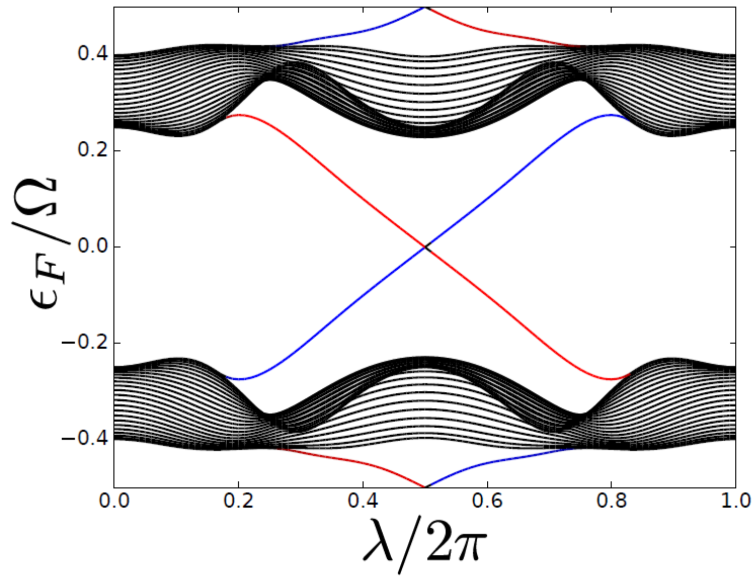
- 

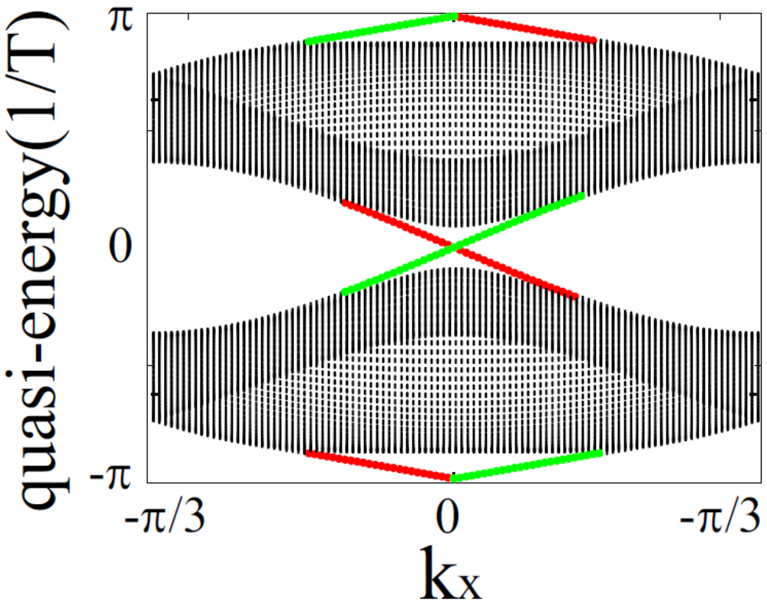


- Surround both 0 and π degeneracies $\Rightarrow C_1 = 0$
- But topological edge states remain

Floquet-Thouless energy pump

- Looks very similar to anomalous Floquet insulator
  [Kitagawa et al, PRB 82, 235114 (2010)]

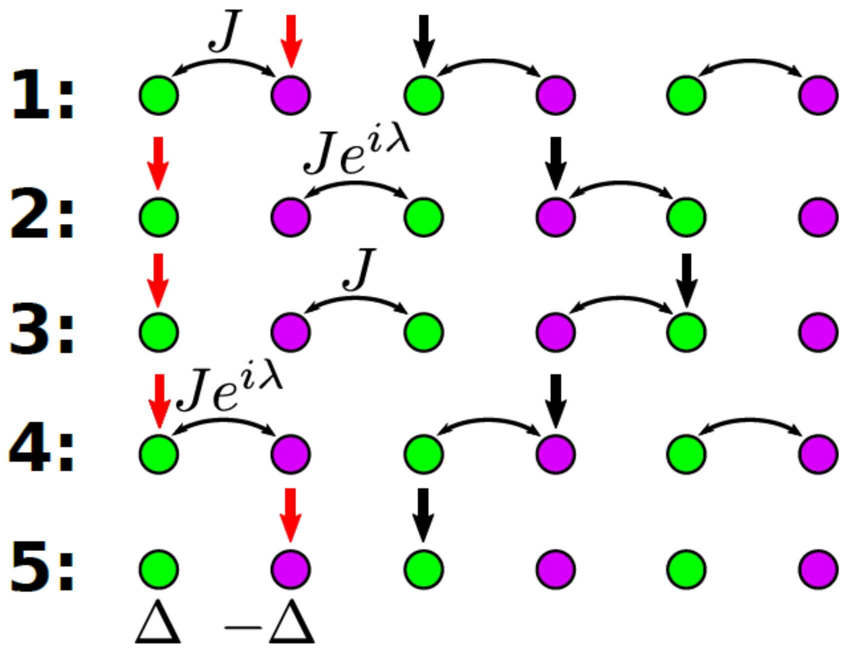




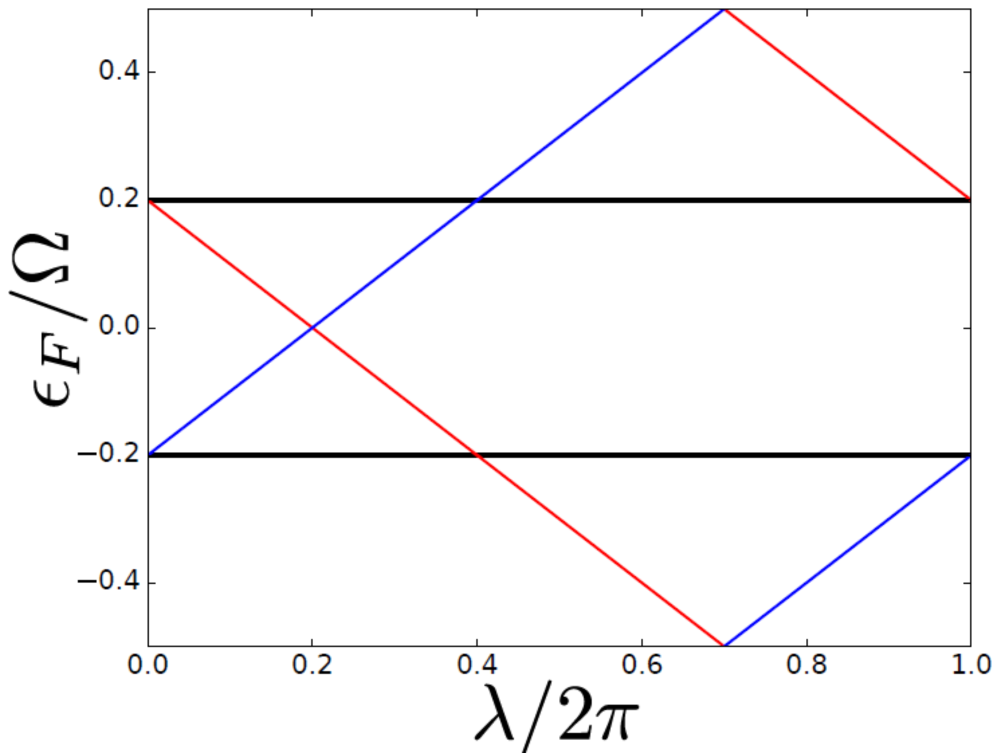
- Floquet-Thouless energy pump is dimensional reduction of anomalous Floquet insulator

Floquet-Thouless energy pump

- Use this intuition to get simpler flat band model…*

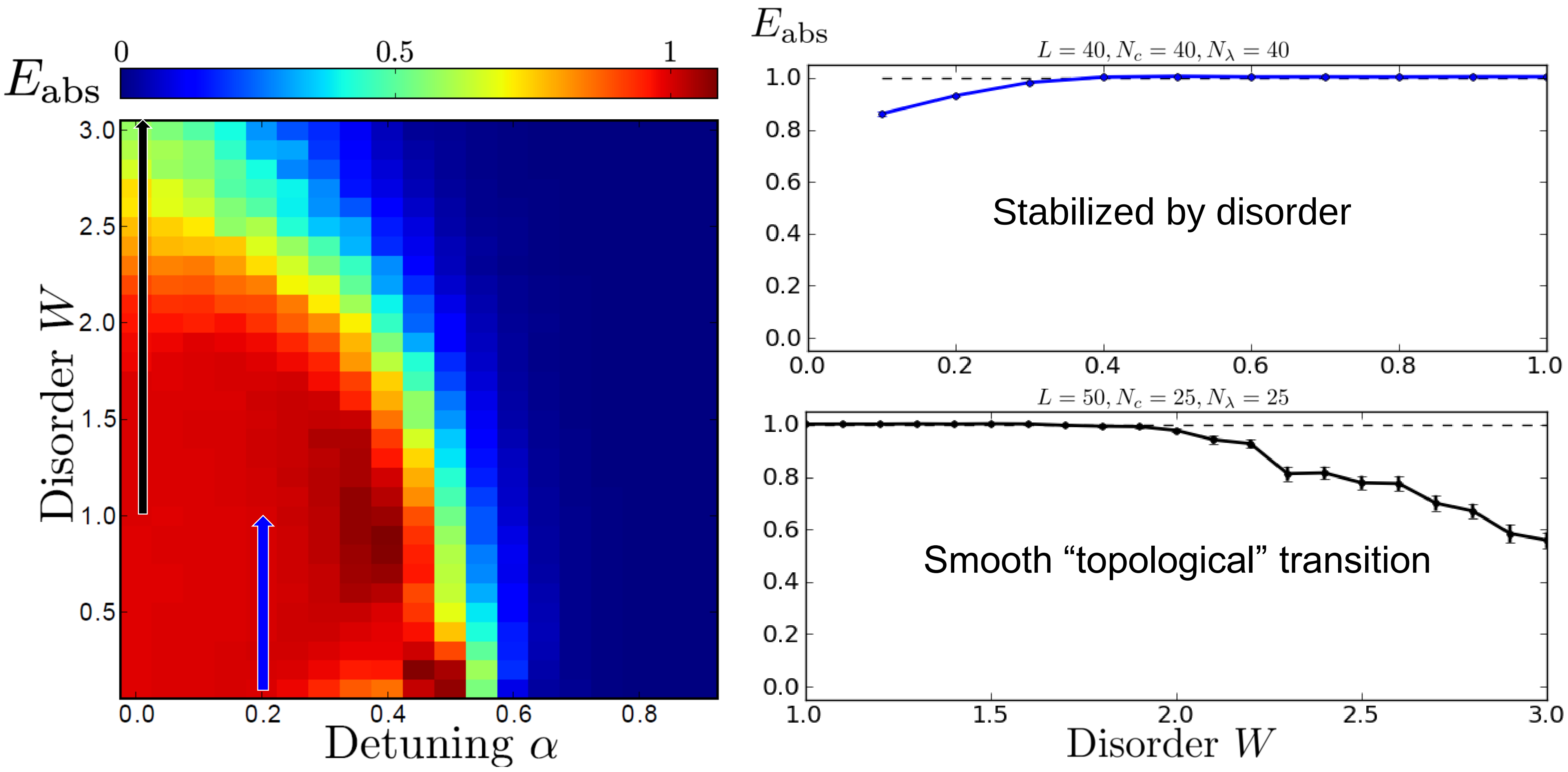


For $J = J_{tuned}$, hops one site per step



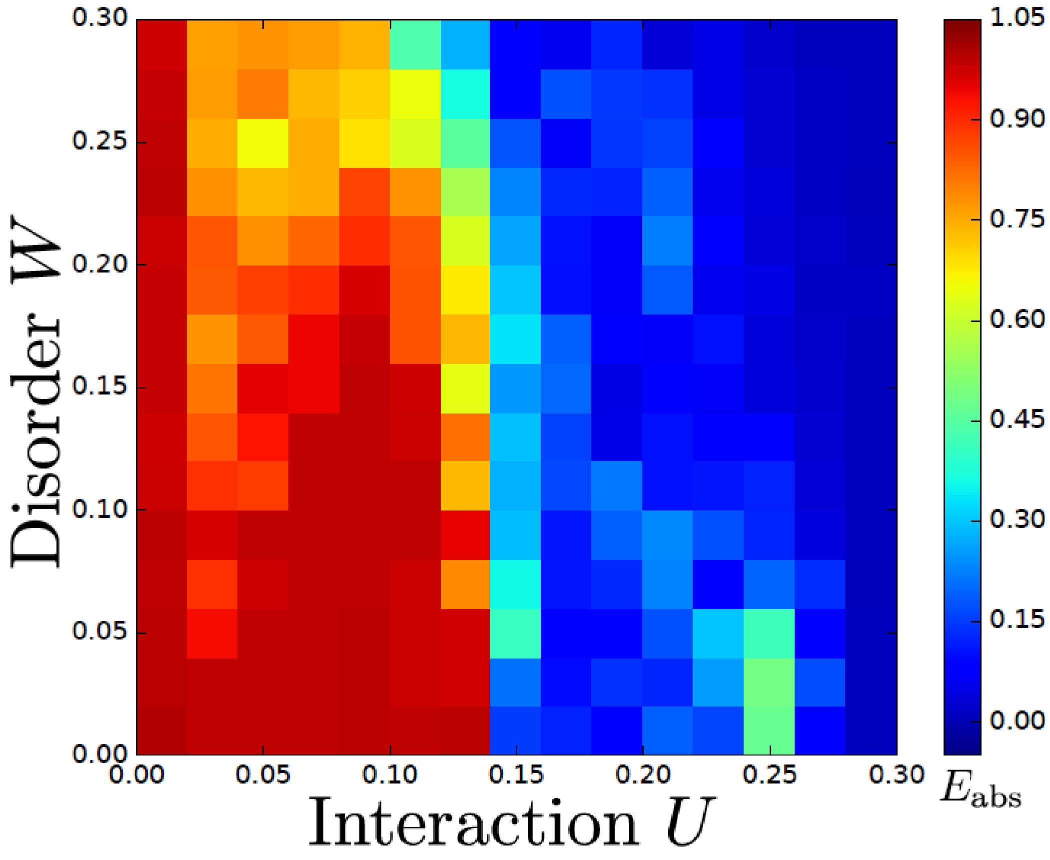
*Inspired by Rudner et al, PRX 3, 031005(201

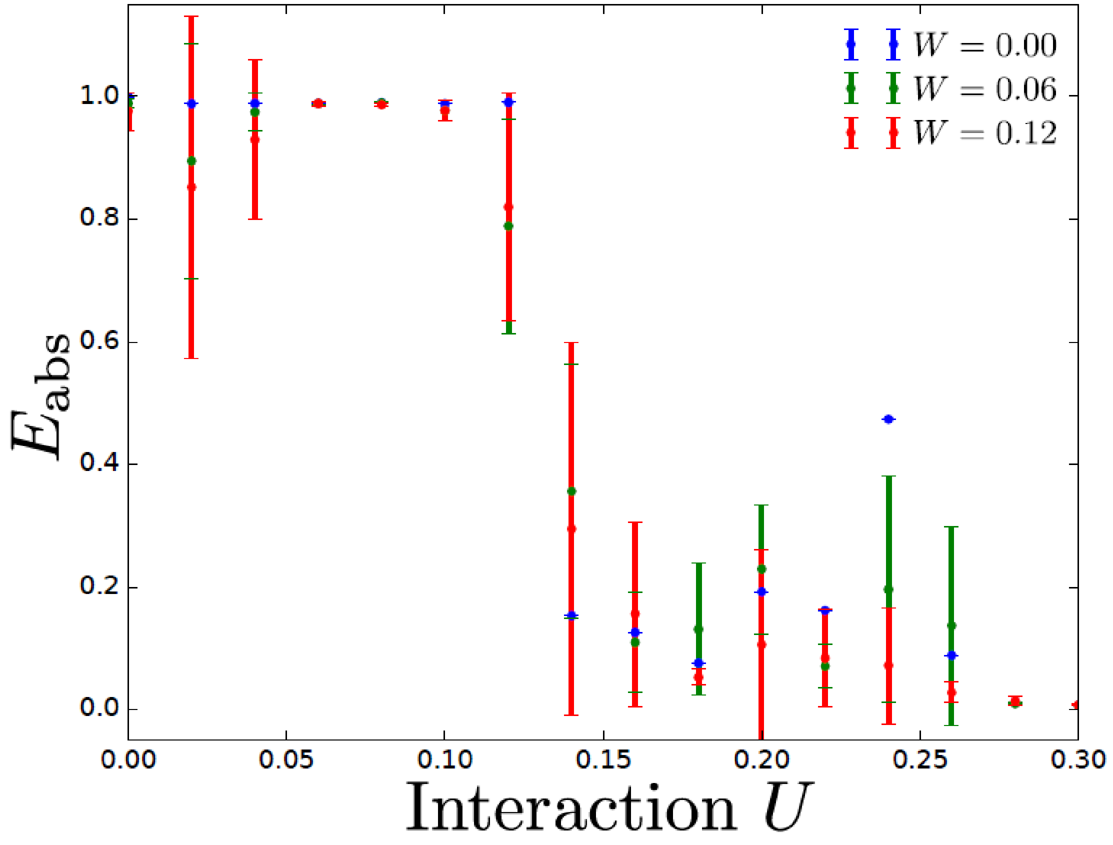
Floquet-Thouless energy pump



Floquet-Thouless energy pump

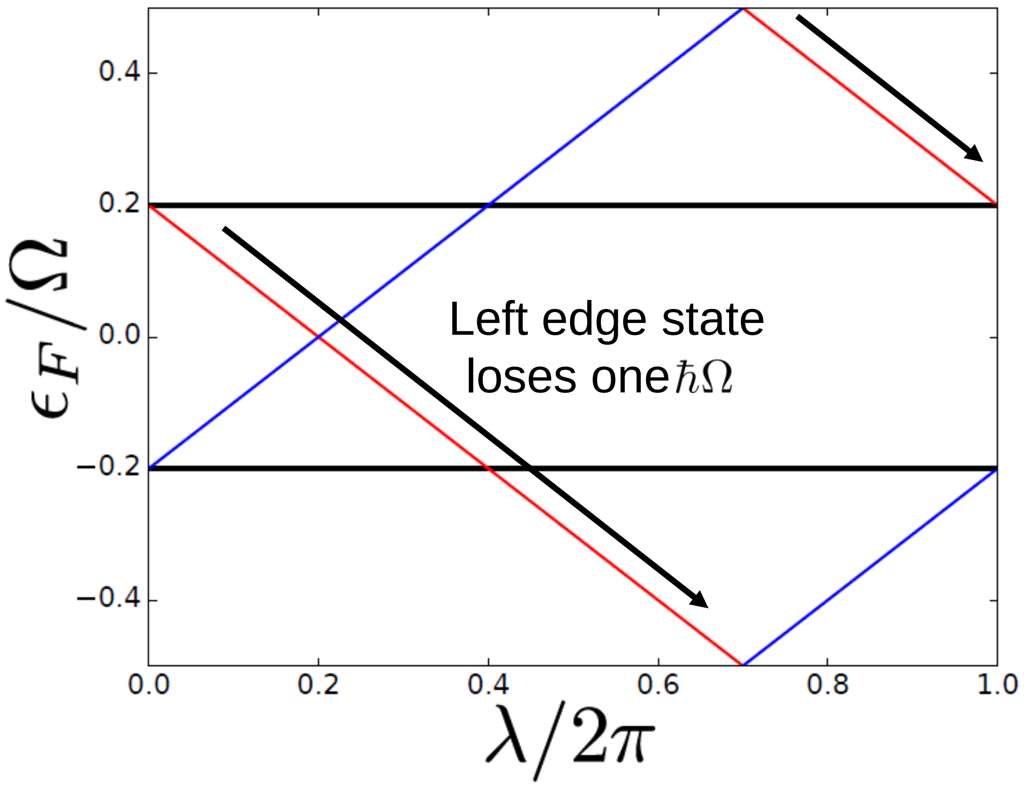
Stable to MBL (within numerical uncertainty)

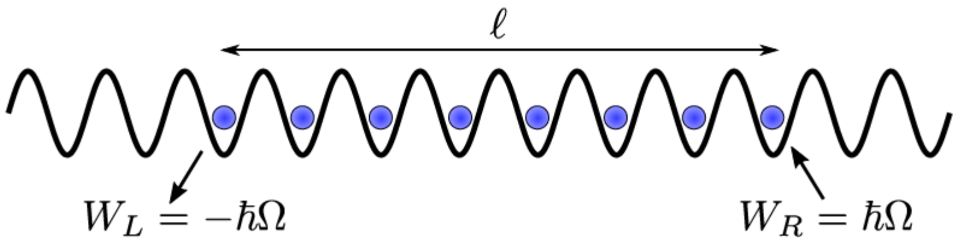




Floquet-Thouless energy pump

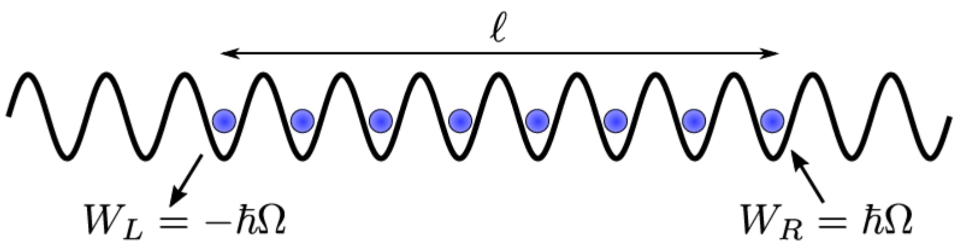
- Physical consequences?
  - Particles themselves do not move (stroboscopically)





Floquet-Thouless energy pump

- Physical consequences?
  - Particles themselves do not move (stroboscopically)
  - Pumps photon quanta from one side of system to the other

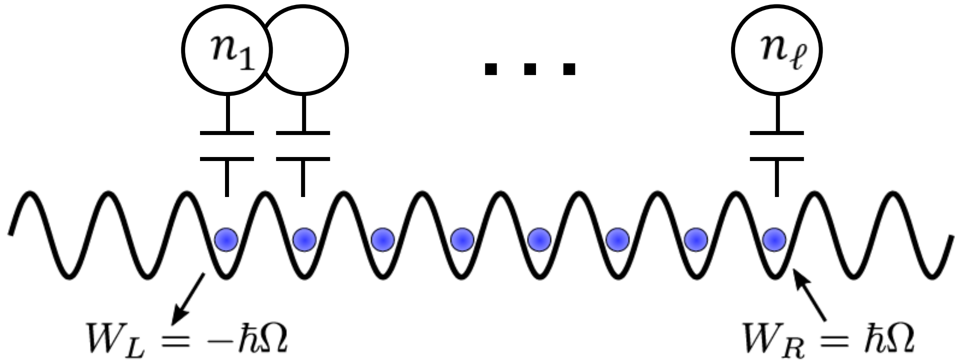


  - Pump involves quantized backaction (work) on the bath

$$\frac{\nu}{T} = \frac{1}{2\pi\hbar L}\left[\int d\lambda \sum_n \left(\frac{1}{T}\int_0^T dt \langle\psi_n|\hat{x}\partial_\lambda H|\psi_n\rangle\right)\right]$$

Energy pump with quantized photons

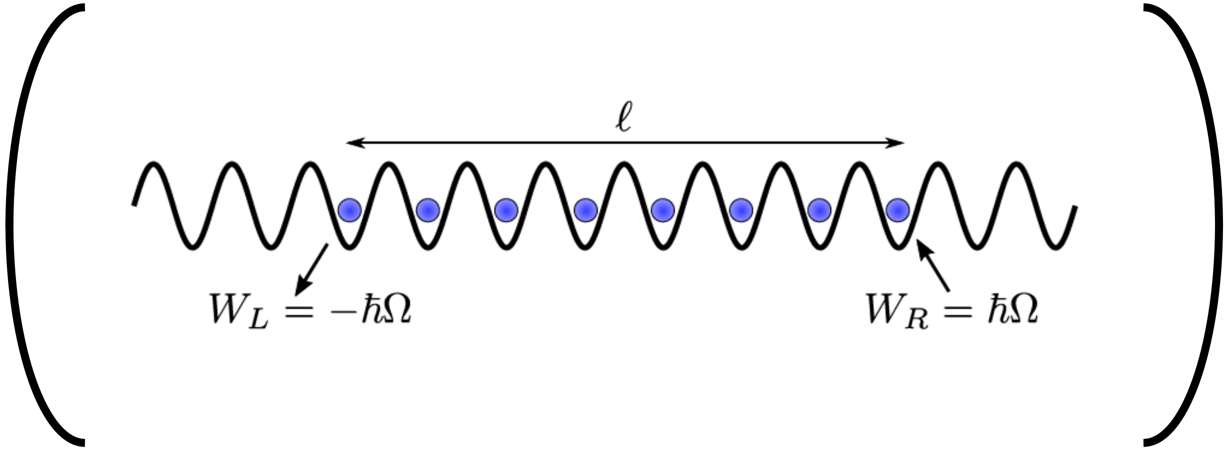
- Option 1: local photon "baths"



- $|n_1, n_2, \cdots, MBL\rangle \rightarrow |n_1 - 1, n_2, \cdots, n_\ell + 1, MBL\rangle$

Energy pump with quantized photons

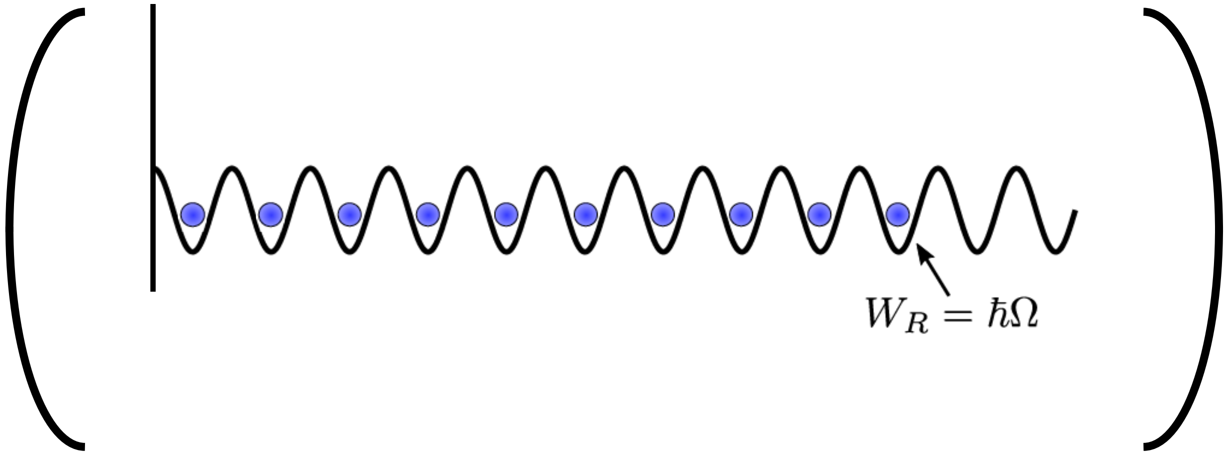
- Option 2: stick it in a cavity



- $|n, MBL\rangle \rightarrow |n+1, L\rangle + |n-1, R\rangle + |n, MBL_{bulk}\rangle$?
- Position-dependent entanglement with photons?

Energy pump with quantized photons

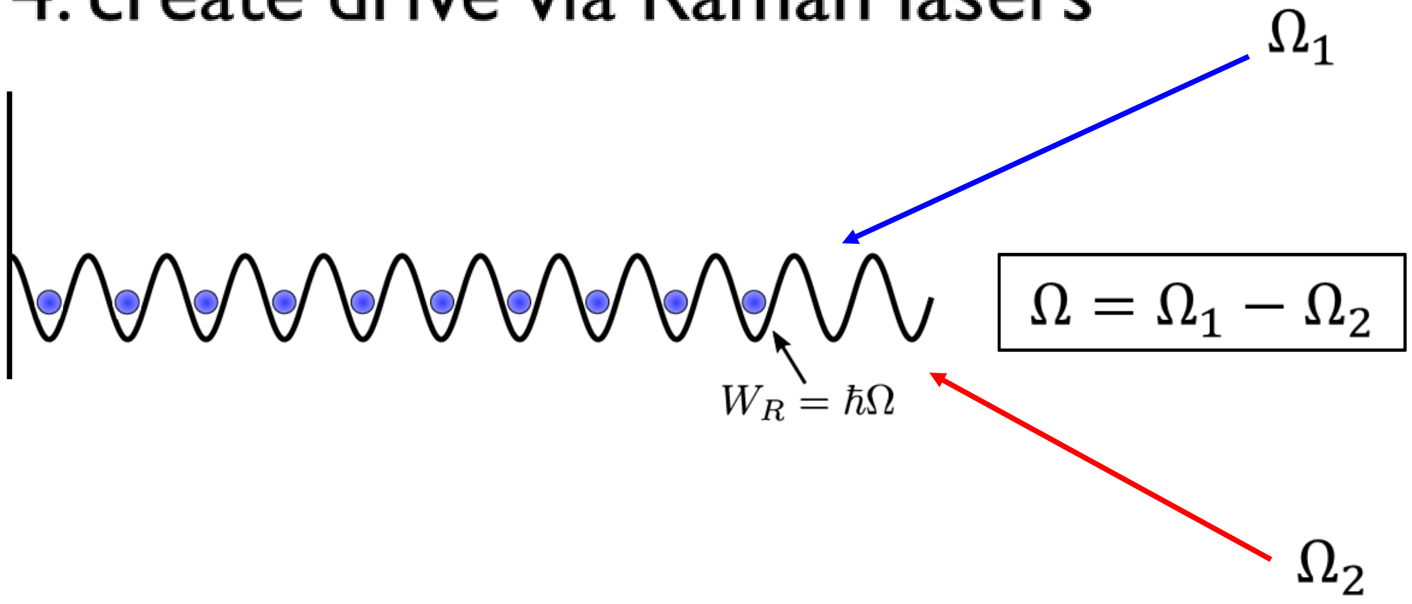
- Option 3: fill half the system, including the edge state



- $|n, MBL\rangle \rightarrow |n-1, MBL\rangle$
- Topological pumping of photons out of cavity

Energy pump with quantized photons

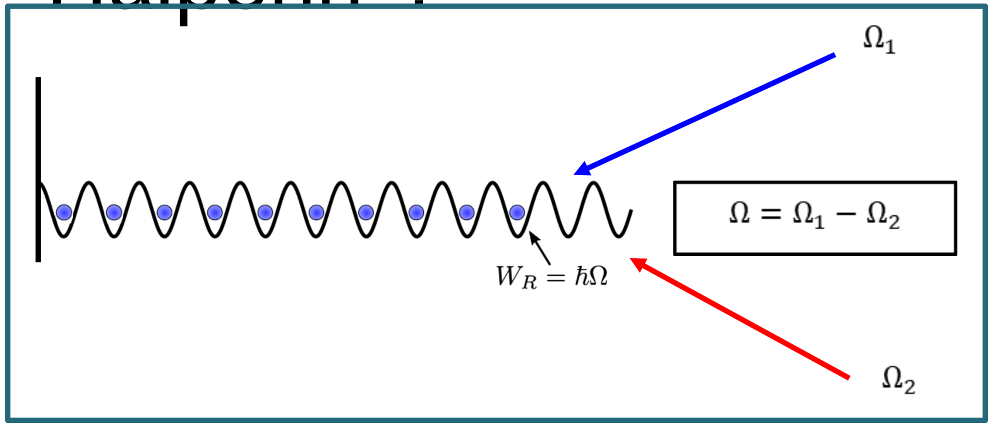
- Option 4: create drive via Raman lasers

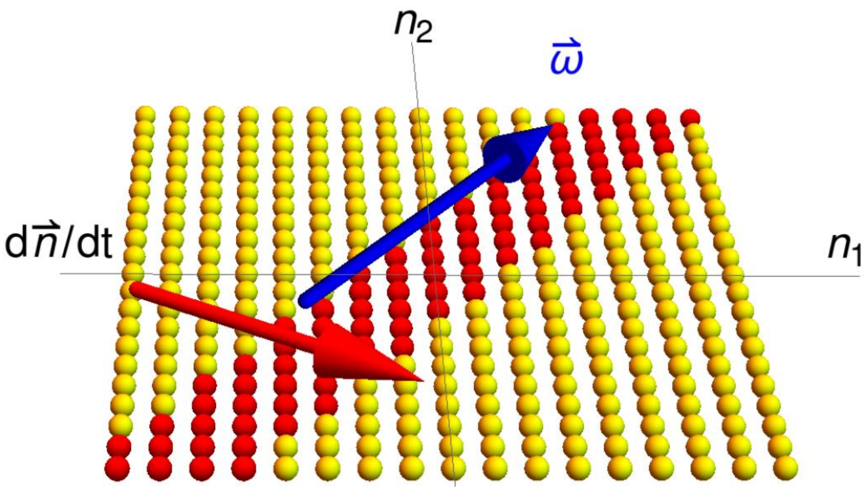


- $|n_1, n_2, MBL\rangle \to |n_1 + 1, n_2 - 1, MBL\rangle$
- Topological frequency conversion

Energy pump with quantized photons

- How does this differ from Martin, Refael and Halperin*?





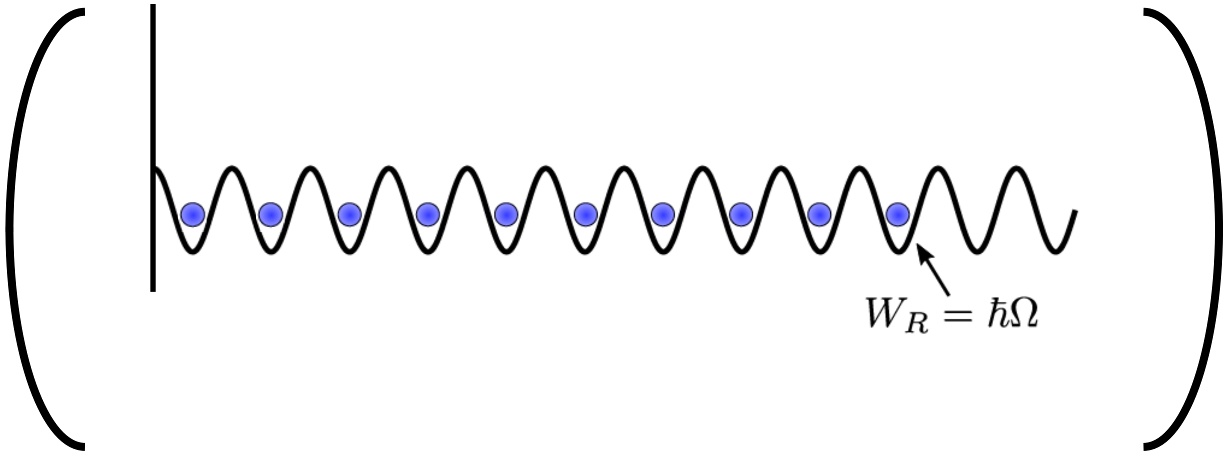
- Requires adiabatic ramping
- Works for arbitrary frequencies
- Many body effect throughout spectrum
- Protected by winding number

- Photons “pump” themselves
- Works for low frequencies
- Few body ground state effect
- Protected by Chern number

* PRX 7, 041008 (2017)

Energy pump with quantized photons

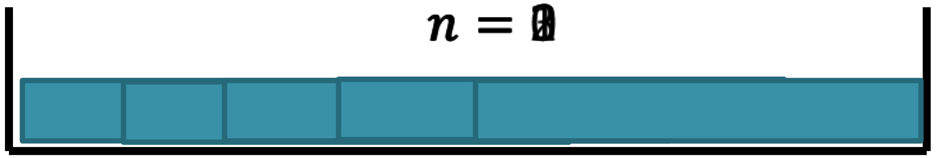
- Option 3: fill half the system, including the edge state

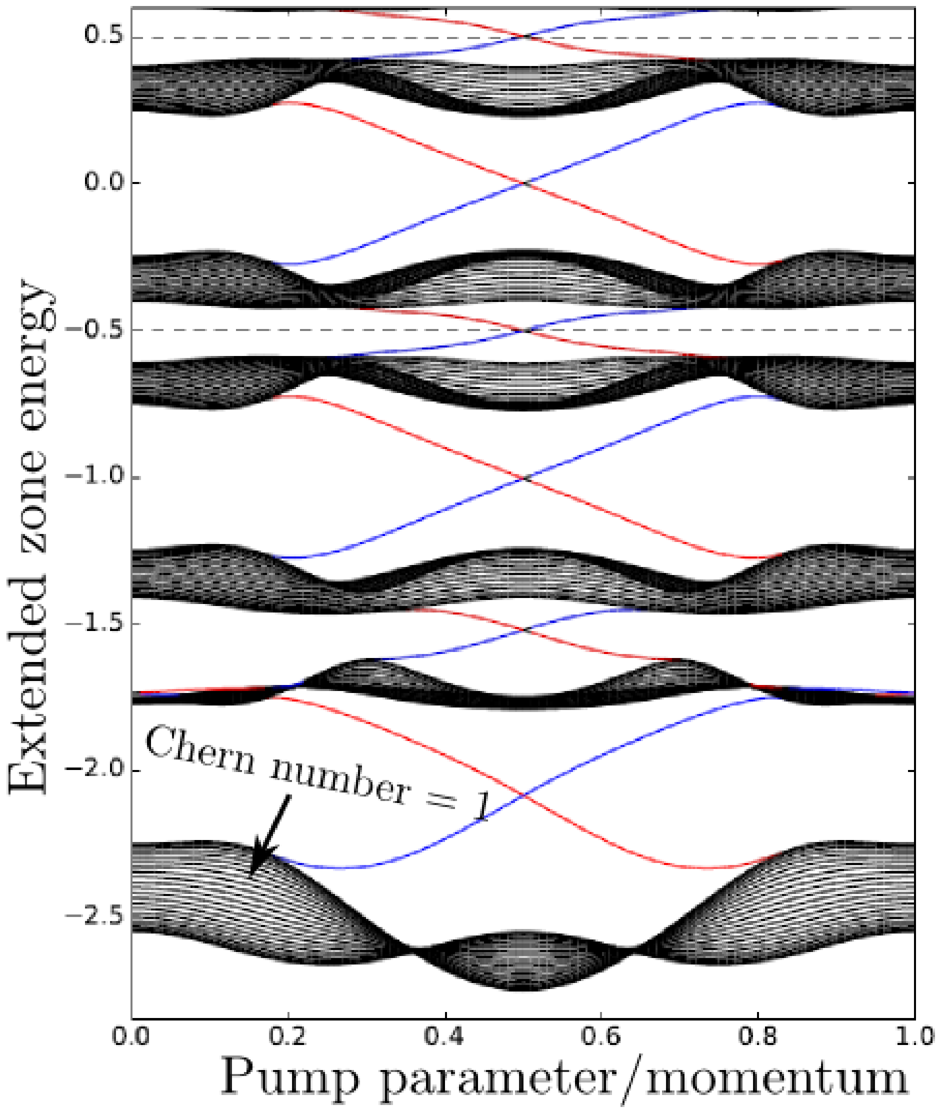


- $|n, MBL\rangle \rightarrow |n-1, MBL\rangle$
- Topological pumping of photons out of cavity
  - What happens when we pump down to $n = 0$?

Energy pump with quantized photons

- Floquet winding numbers originate from non-zero Chern numbers in "artificial" bands near cutoff
- Upon reaching $n \approx 0$, Chern number initiates charge pumping





Quantized Floquet MBL

- At some point I used the fact that the 1D chain was localized, consistent with what we know about Floquet MBL
- But with cavity photon, have localized spins/atoms/electrons coupled to a *global* mode
- Rest of talk: How to reconcile localization with global coupling to photons?

Quantized Floquet MBL

- Start with Hamiltonian of Zhang, Khemani and Huse* and monochromatize it:

$$H = \frac{H_z + H_x}{2} + \cos(\Omega t)\frac{H_z - H_x}{2}$$

$$H_z = \sum_i (h + g\sqrt{1-\Gamma^2}G_i)\tau_i^z + \tau_i^z\tau_{i+1}^z$$

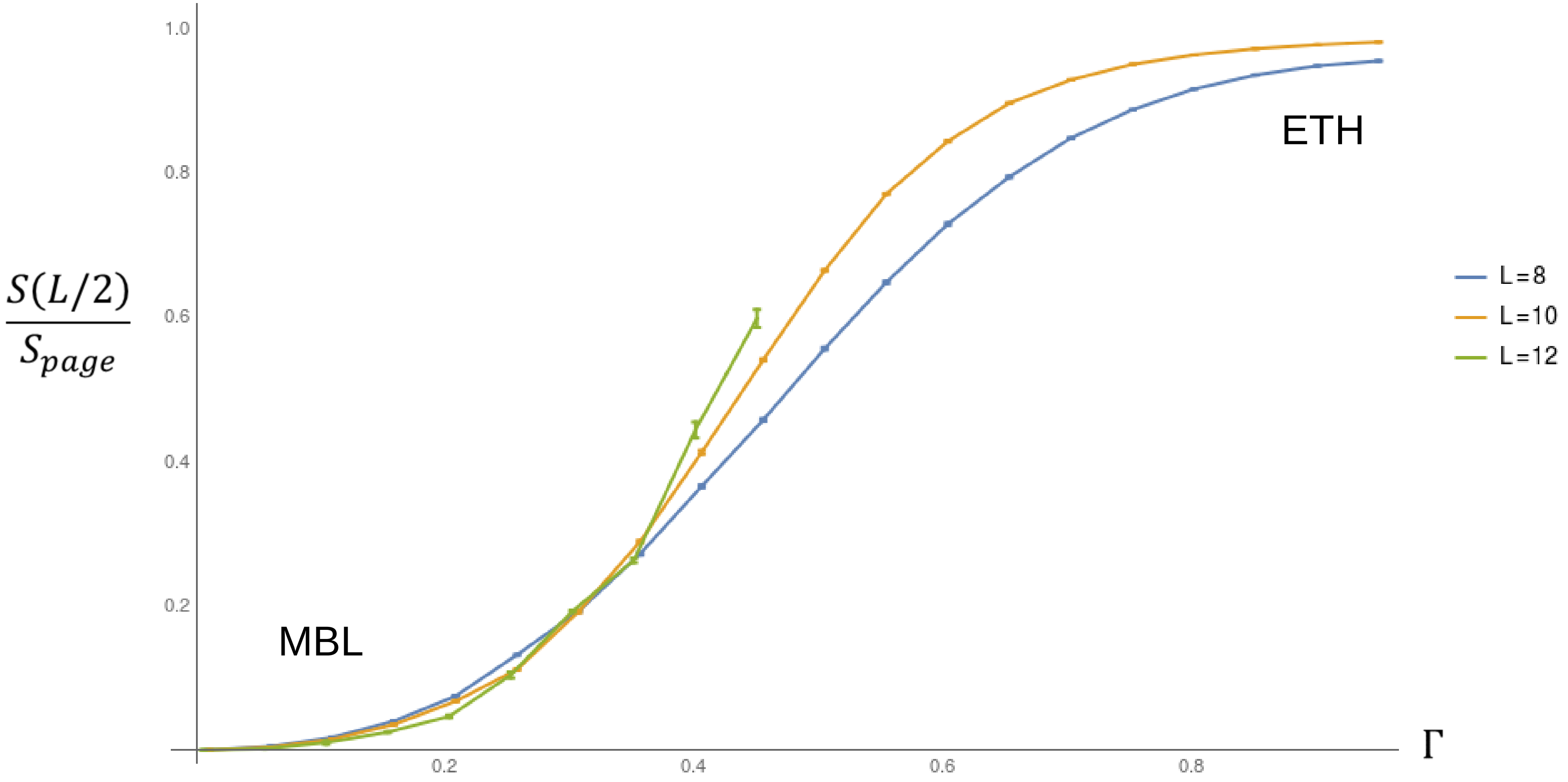
$$H_x = g\Gamma\sum_i \tau_i^x$$

- Important parameter: Γ = quantum fluctuations
- Other parameters: $h = 0.809, g = 0.9045, \Omega = 3.927$

* PRB 94, 224202 (2016)

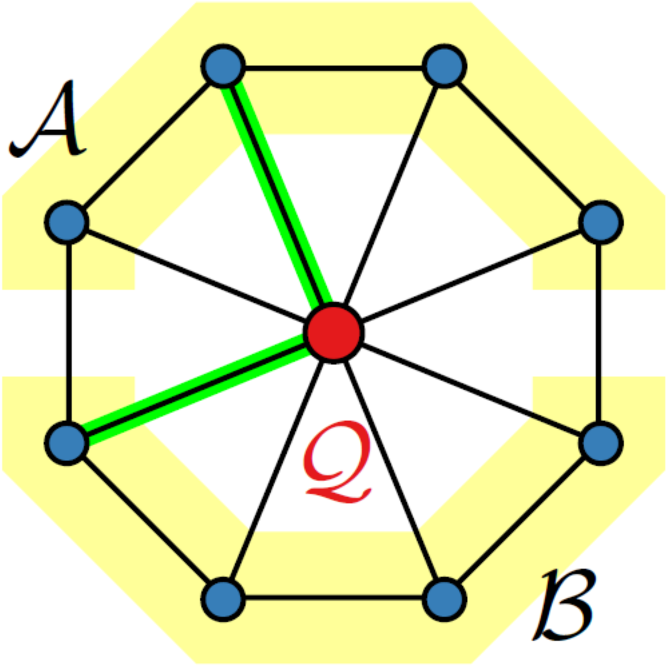
Quantized Floquet MBL

- MBL/ETH transition seems to survive at $\Gamma_c \sim 0.3$



Quantized Floquet MBL

- When looking at Floquet extended zone, we often will impose a cutoff on photon number: $-N_c \leq n \leq N_c$
  - Equivalent to global coupling of spin chain to central qudit with dimension $d = 2N_c + 1$
  - For Floquet, should be independent of d, i.e., take the limit $d \to \infty$ first
- We will try to understand dependence on both d and L



Quantized Floquet MBL

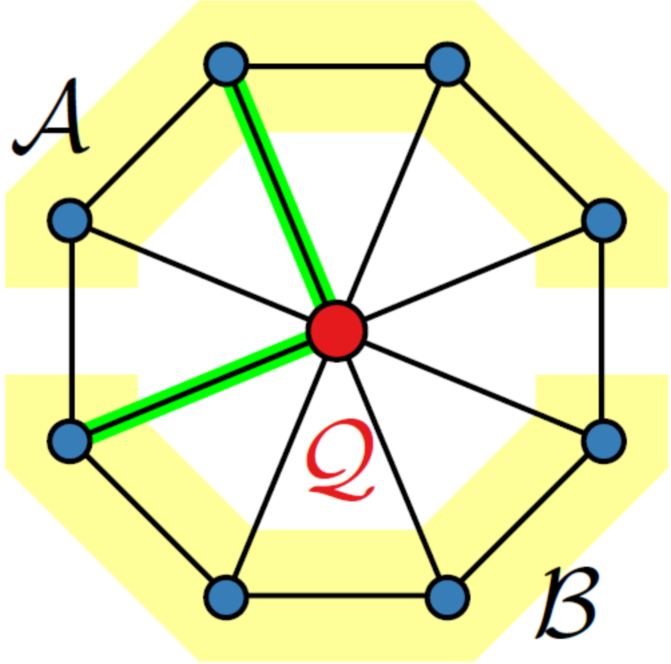
- Central qudit Hamiltonian:

$$H_{\mathrm{EZ}} = \sum_n \left(\frac{1}{2} H_+ + \Omega n \right) \otimes |n\rangle\langle n| + \frac{1}{4} H_- \otimes \left(\sum_n |n+1\rangle\langle n| + \mathrm{h.c.} \right)$$

$$H_\pm = H_z \pm H_x$$

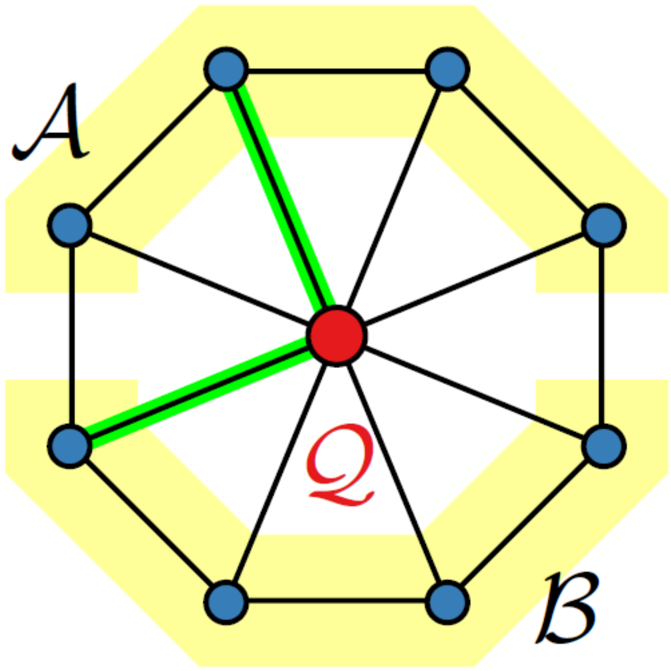
$$H_z = \sum_i (h + g\sqrt{1-\Gamma^2} G_i) \tau_i^z + \tau_i^z \tau_{i+1}^z$$

$$H_x = g\Gamma \sum_i \tau_i^x$$

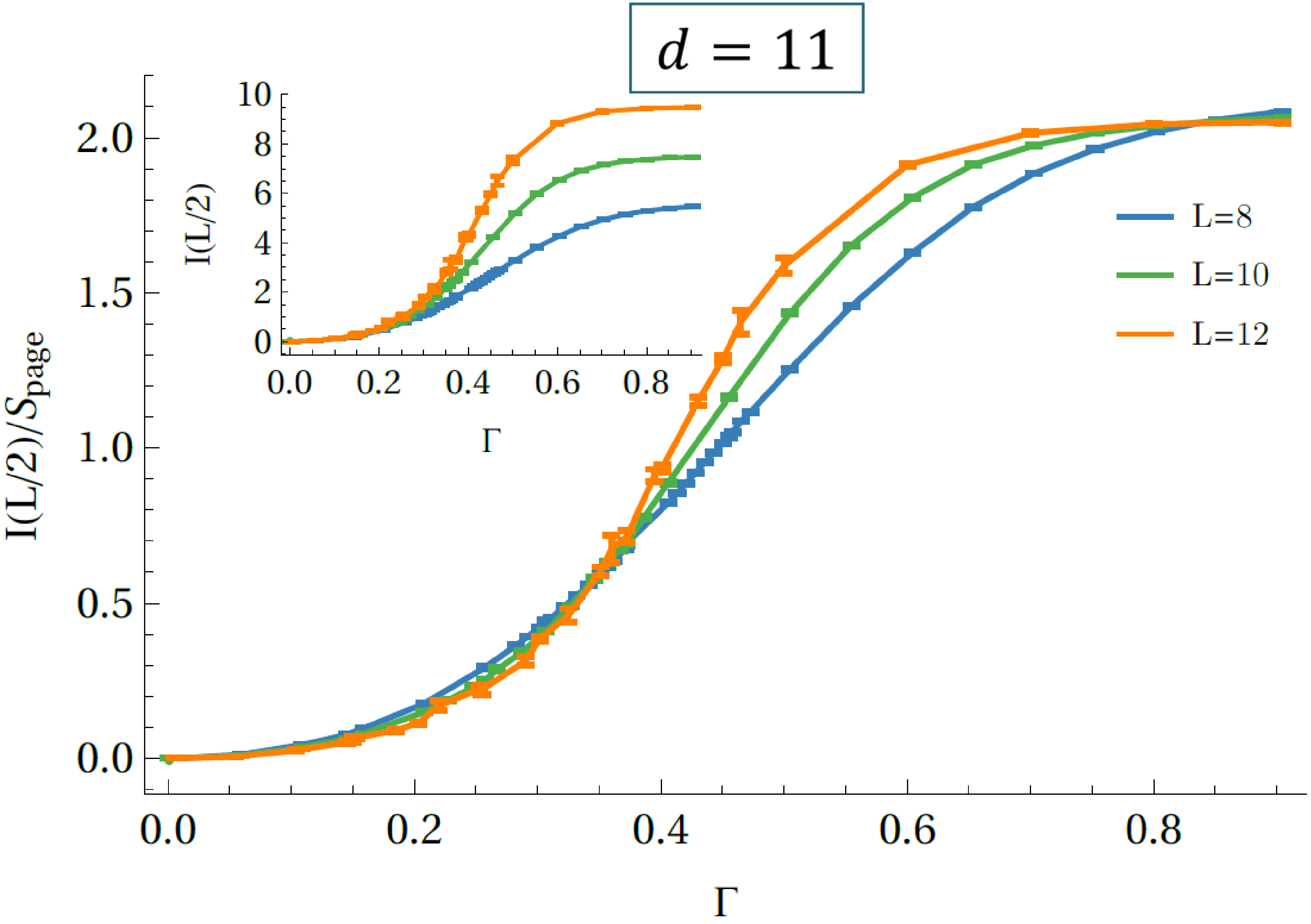


Quantized Floquet MBL

- Methods:
  - Shift-inverse target 10 states in middle of spectrum
  - Measure…
    - Level statistics
      $$r = \frac{\min(E_n - E_{n-1}, E_{n+1} - E_n)}{\max(E_n - E_{n-1}, E_{n+1} - E_n)}$$
    - Half-system mutual information
      $$I(A,B) = S(A) - S(B) - S(A \cup B)$$
    - Qudit entanglement



Quantized Floquet MBL



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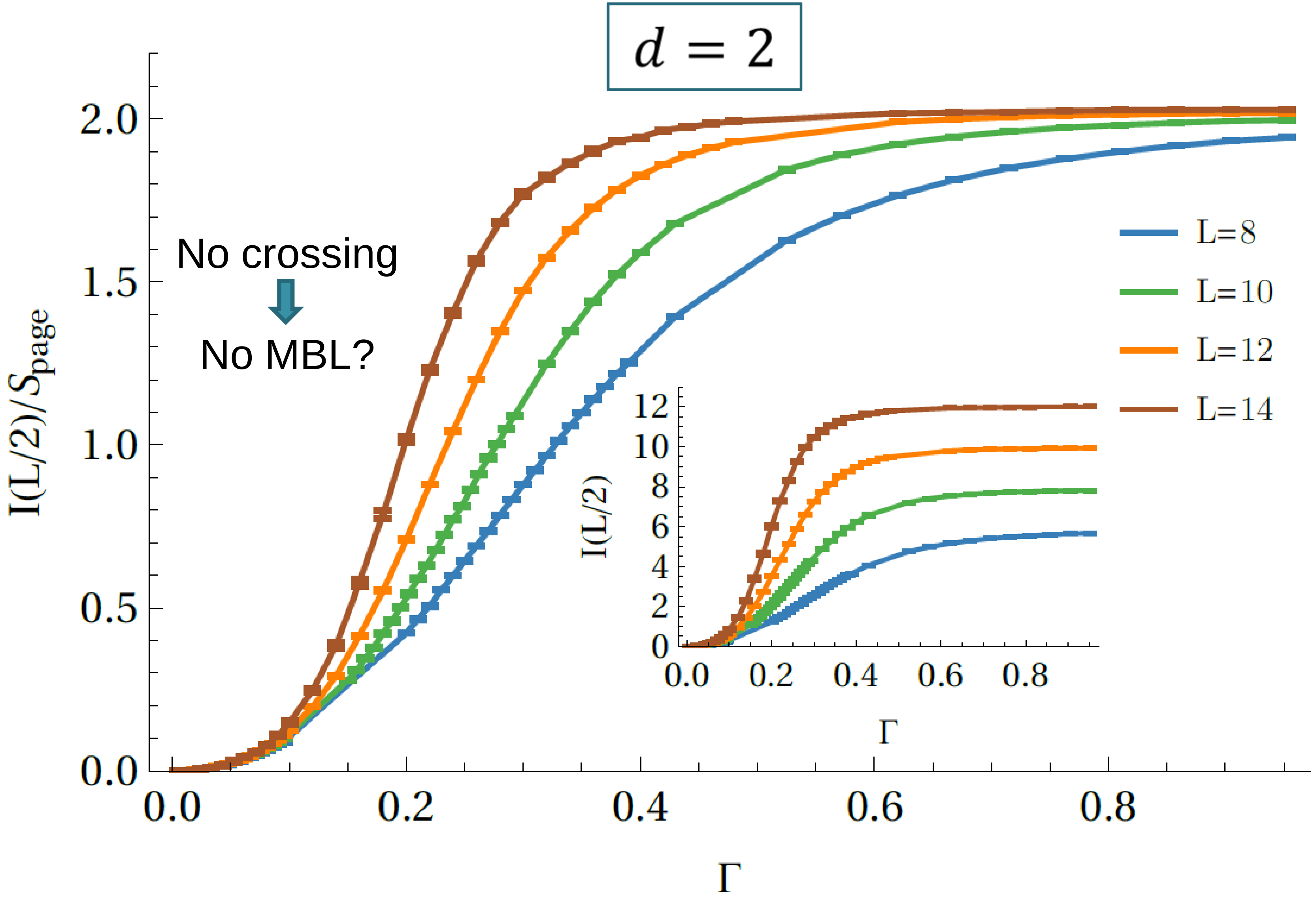
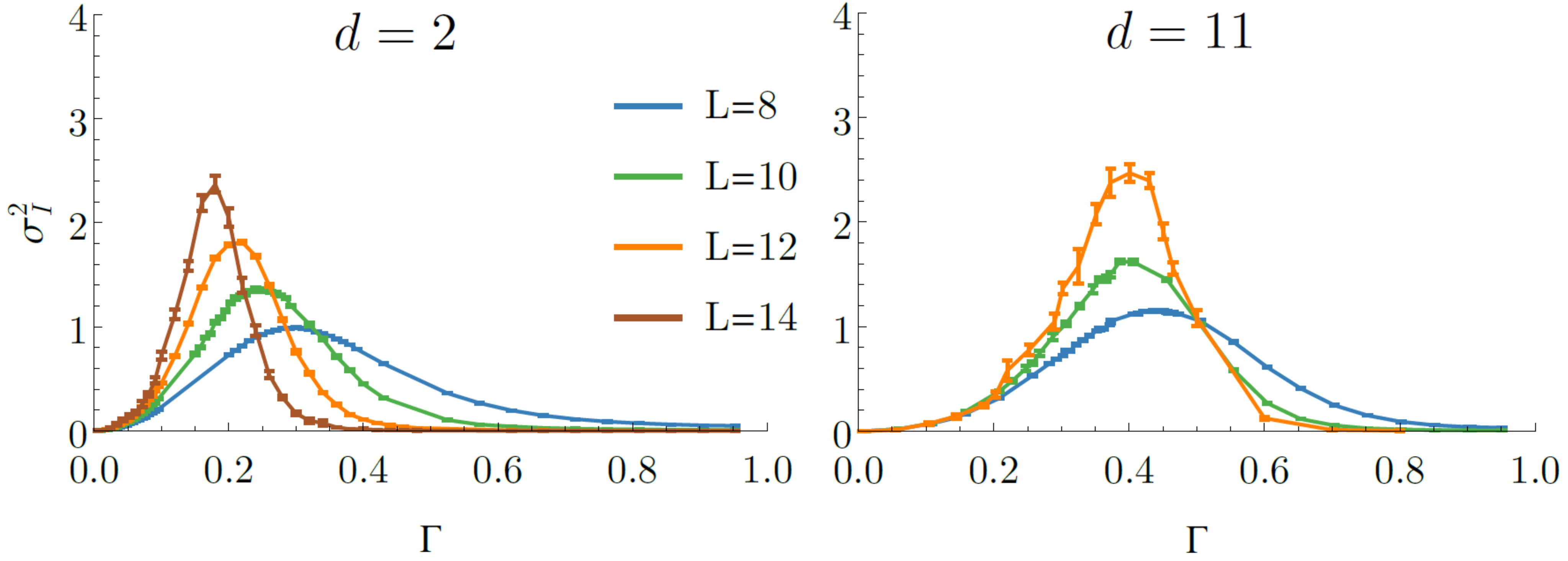


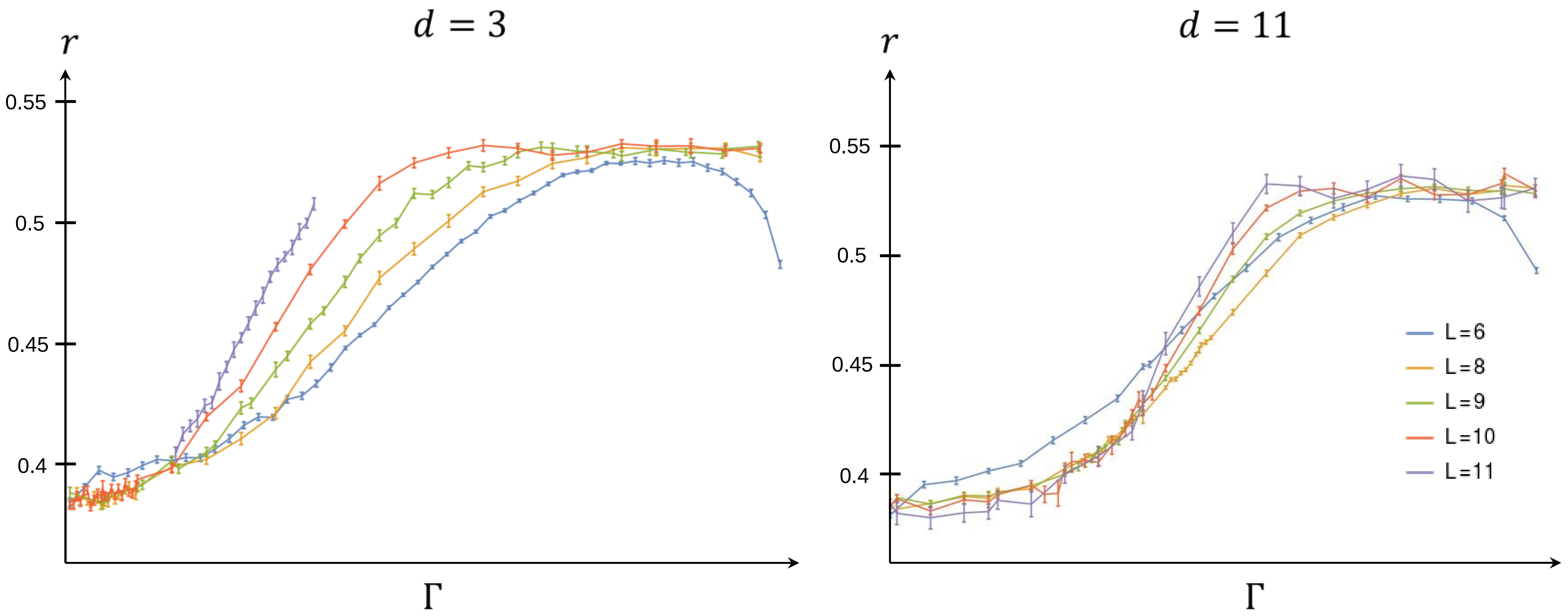
Quantized Floquet MBL

- σ_I^2 = fluctuations over disorder/eigenstates

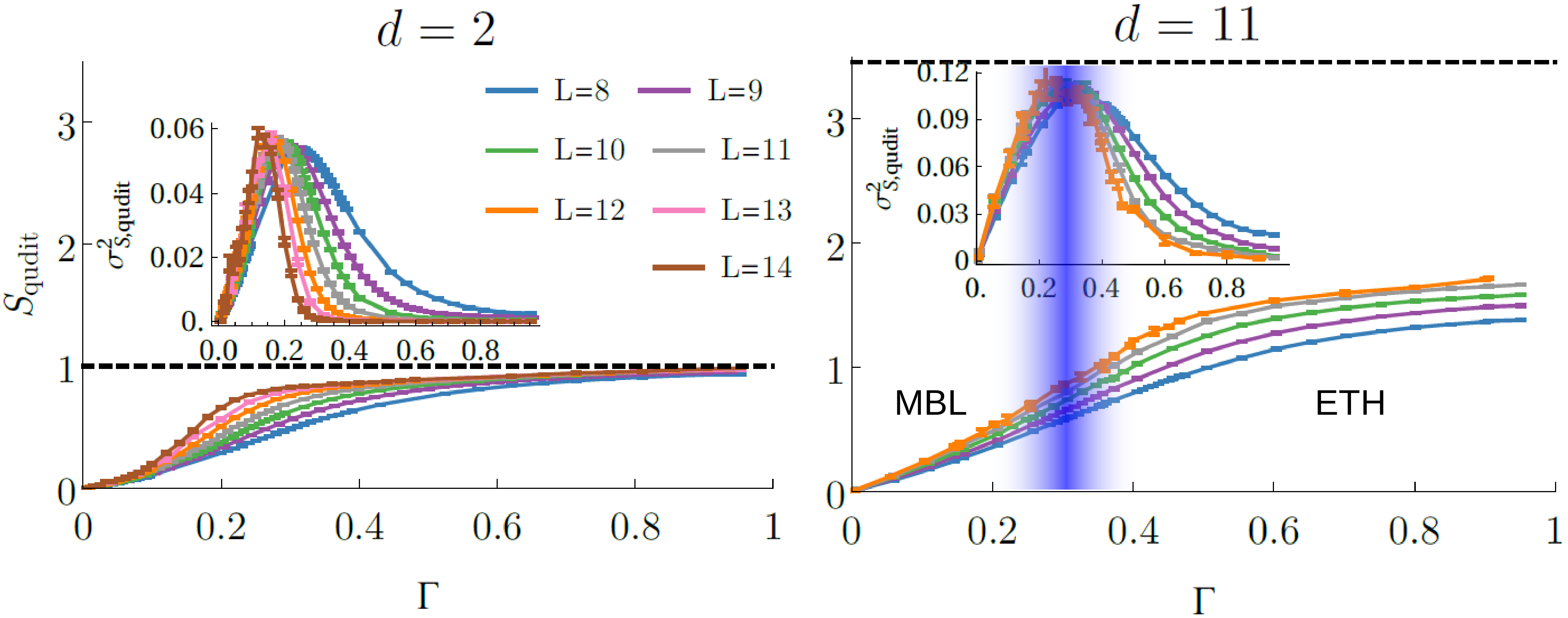


- No MBL at $d = 2$: Ponte et al., Phil. Trans. R. Soc. A 375, 20160428 (2017); Hetterich et al., arXiv:1806.08316

Quantized Floquet MBL



Quantized Floquet MBL



Consistent with thermalization at all Γ in the thermodynamic limit

Spin chain thermalizes for large Γ, but qudit does not

Quantized Floquet MBL

- What is going on?
  - At large d, qudit becomes Wannier-Stark localized, exactly like photons in Floquet extended zone
  - Qudit does not explore all accessible states: athermal
  - At smaller d, qudit explores more of its Hilbert space, eventually begins to notice that its Hilbert space is bounded
  - Arguments from Ponte et al. suggest that this can lead to thermalization

Quantized Floquet MBL

- How much does qudit spread?

$$H_{\text{EZ}} = \sum_n \left(\frac{1}{2}H_+ + \Omega n\right) \otimes |n\rangle\langle n| + \frac{1}{4}H_- \otimes \left(\sum_n |n+1\rangle\langle n| + \text{h.c.}\right)$$

$$H_\pm = H_z \pm H_x$$

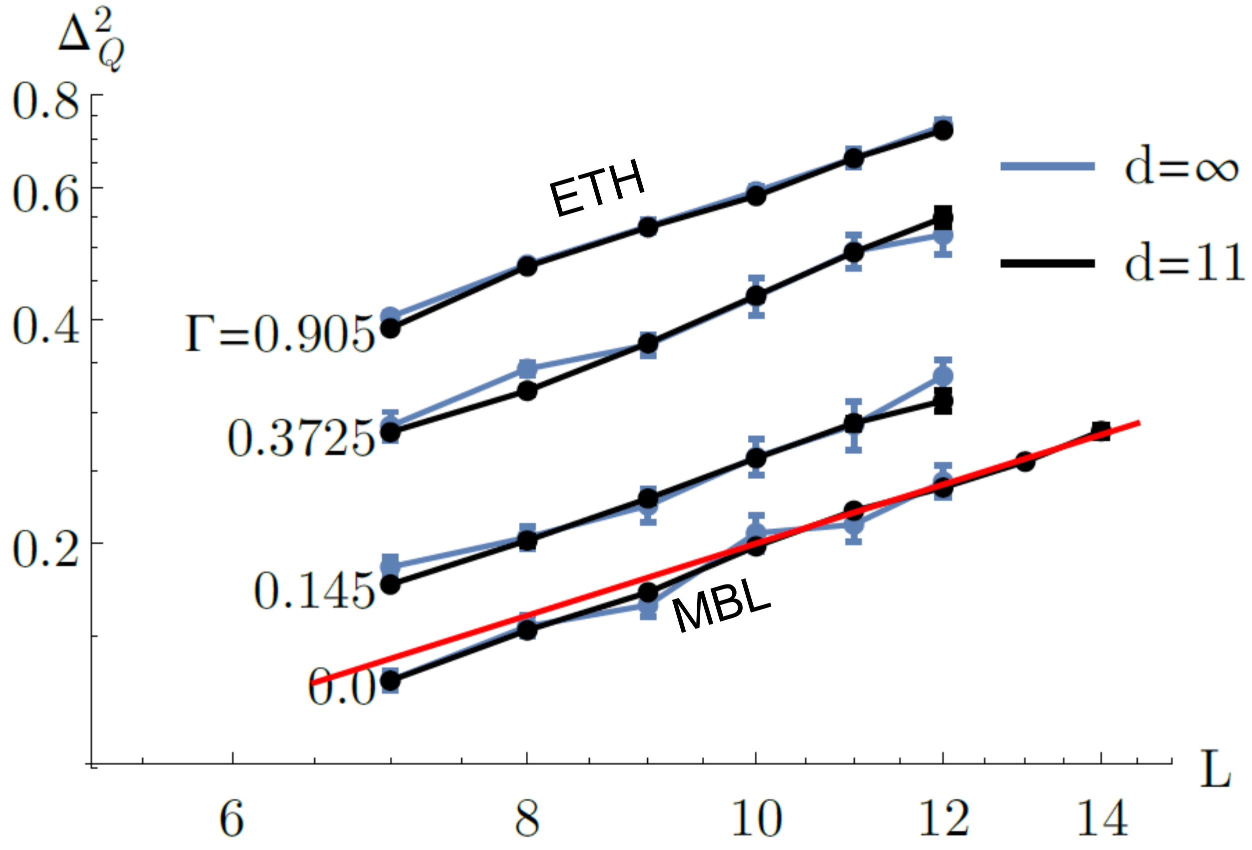
$$H_z = \sum_i (h + g\sqrt{1-\Gamma^2}G_i)\tau_i^z + \tau_i^z \tau_{i+1}^z$$

$$H_x = g\Gamma \sum_i \tau_i^x$$

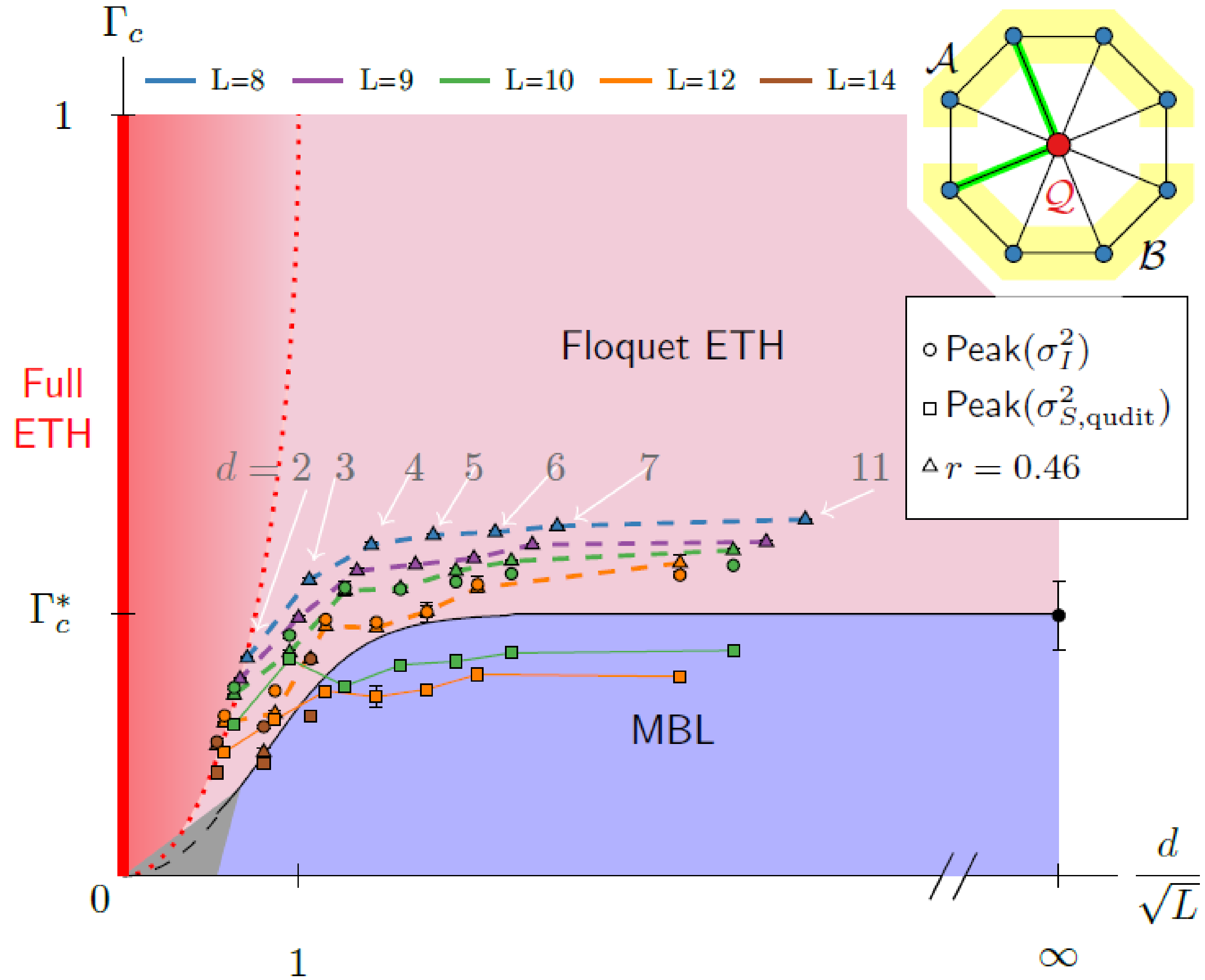
- Now exact Wannier-Stark: $\sigma_n^2 = \frac{\langle H_Z \rangle^2}{2\Omega^2} \sim L$

Quantized Floquet MBL

- Can argue perturbatively stable in Γ. But what about $\Gamma = O(\Gamma_c)$?

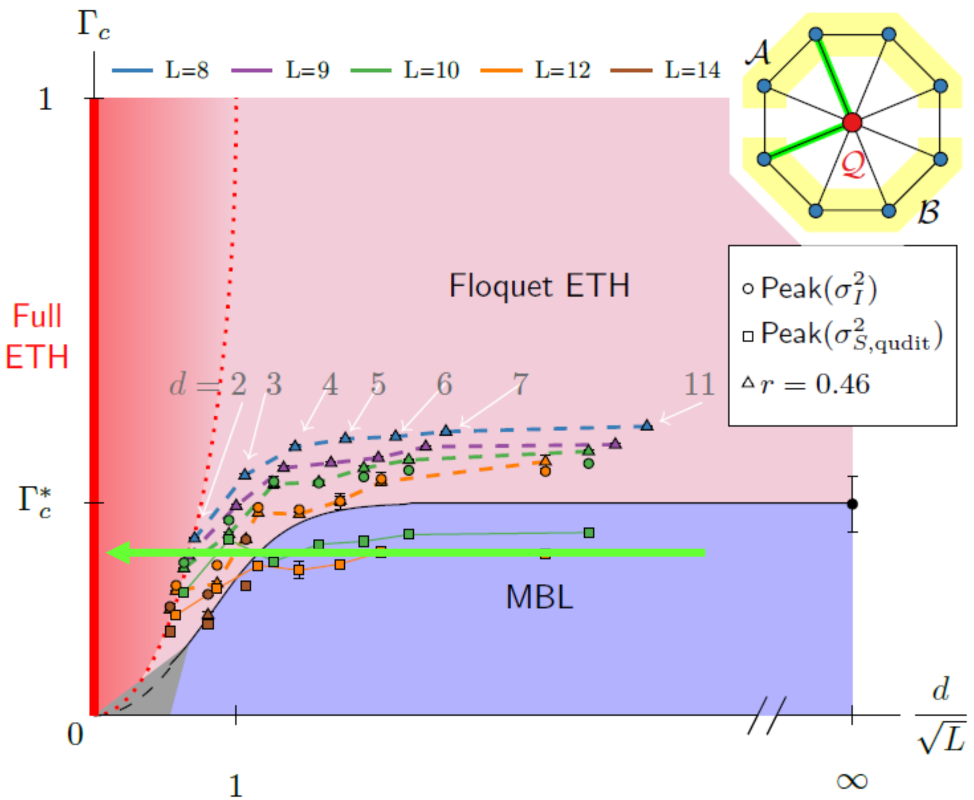


Quantized Floquet MBL



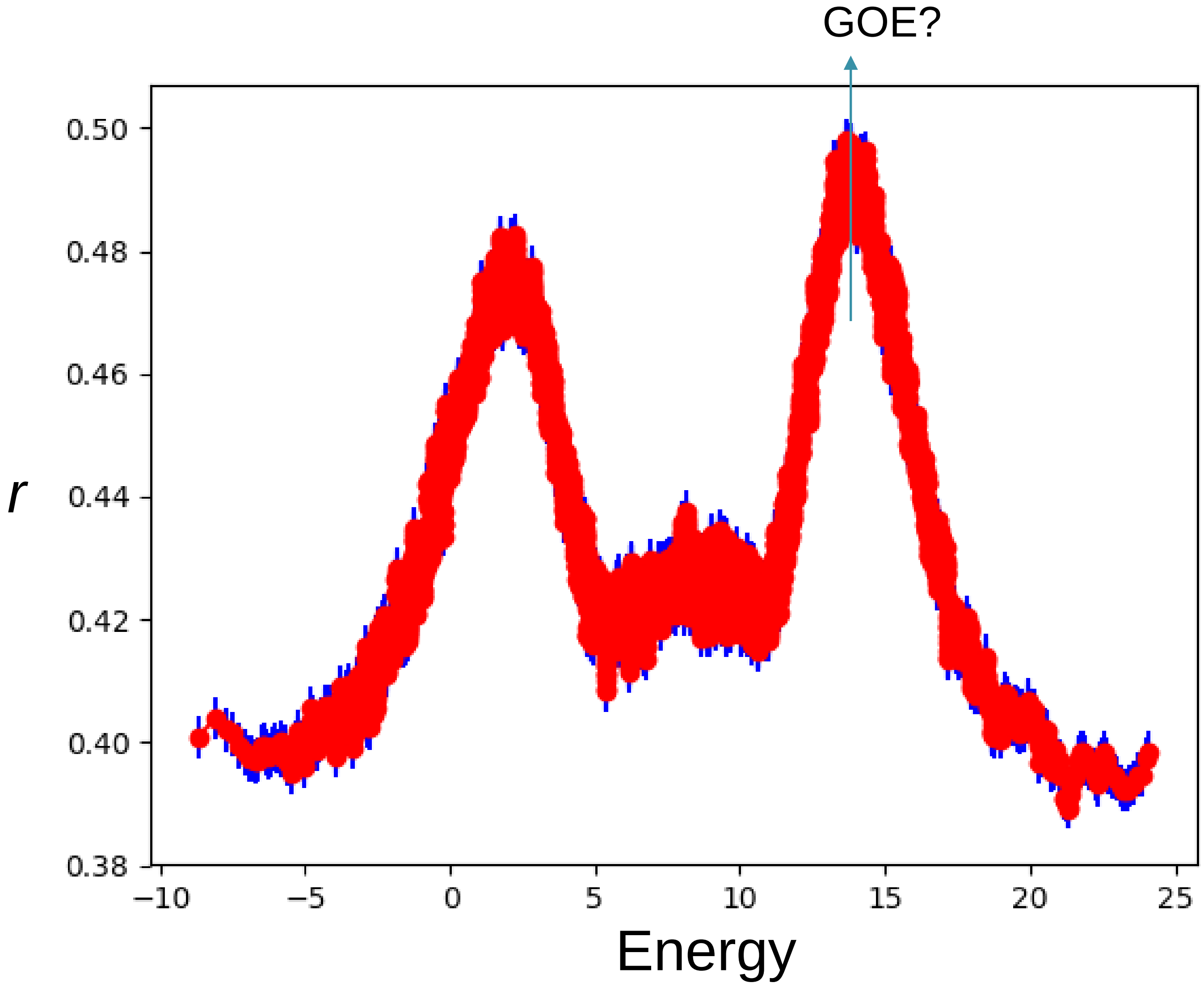
Quantized Floquet MBL

- "Anomalous" behavior
  - Localization survives the presence of a global mode
  - Larger quantum "bath" allows localization ($d = \infty$) while smaller "bath" causes thermalization
  - Localization of chain is not one-to-one with localization of qudit
  - Transition from MBL to ETH as energy is lowered?



Quantized Floquet MBL

$L = 10$
$d = 5$
$\Gamma = 0.3$



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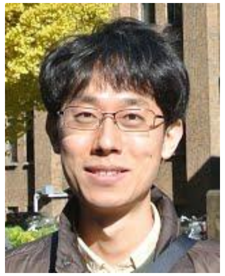
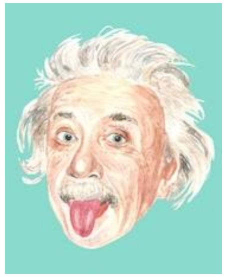
Acknowledgments

Berkeley


Joel Moore


Takahiro Morimoto


Snir Gazit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Copenhagen


Frederik Nathan


Mark Rudner

UT Dallas


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VELUX FONDEN