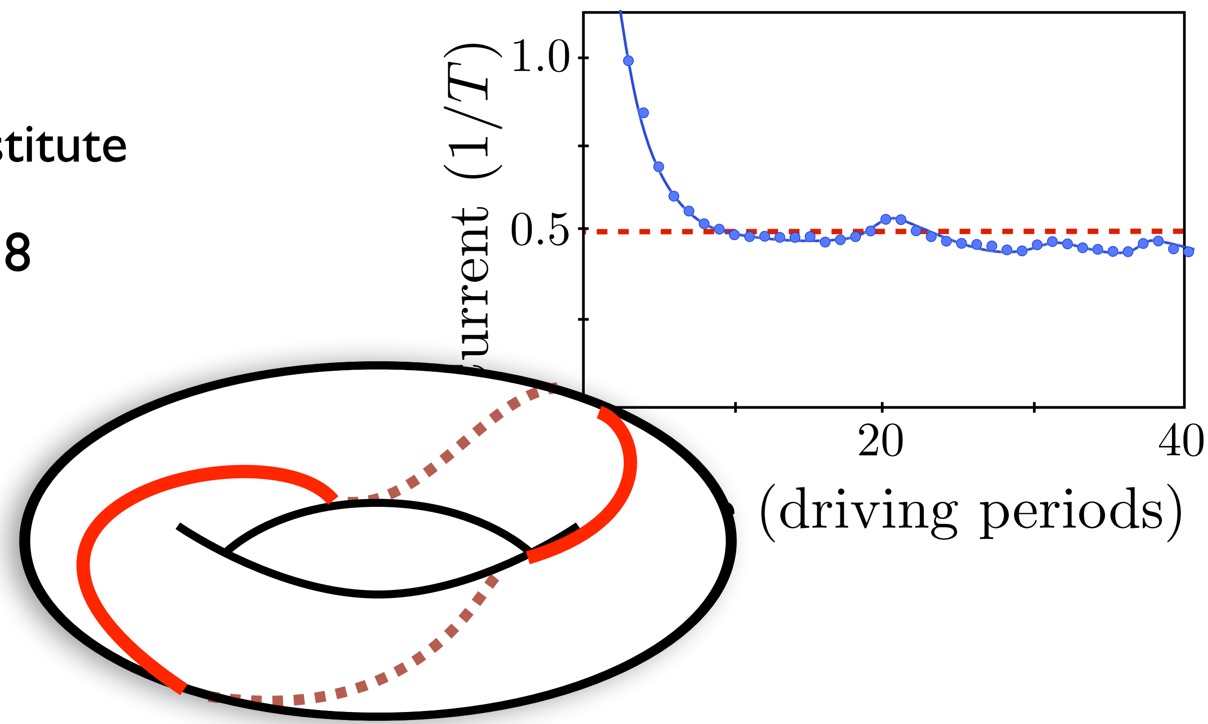
# Universal quasi-steady states in periodically driven many-body systems


Mark Rudner

Niels Bohr Institute


27 August 2018




In collaboration with Erez Berg, Netanel Lindner, Tobias Gulden, and Raffael Gawatz

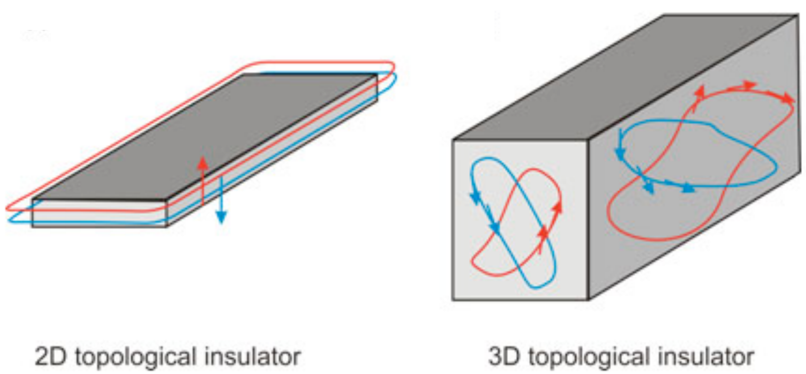
*For details see: N. Lindner, E. Berg, and MR, PRX **7**, 011018 (2017)


MARIE CURIE FELLOWSHIPS VILLUM FONDEN erc

# Advances of the past decade bring new tools, opportunities

## Theory

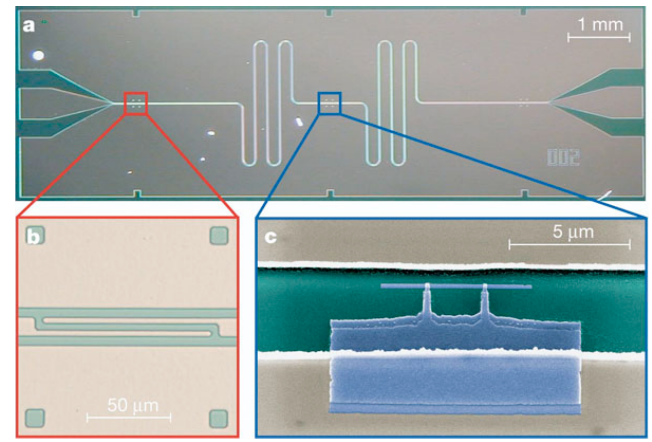
New phases, topological phenomena




M. Z. Hasan, SSRL Science Highlight, March 2009

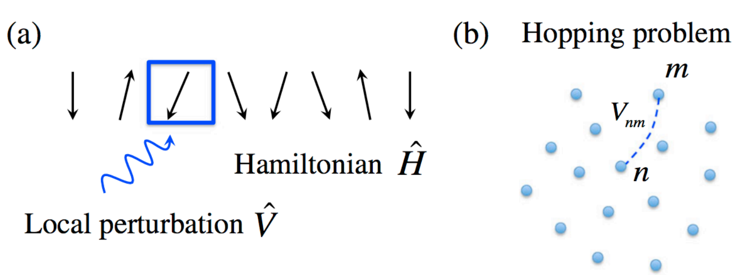
## Experiment

Quantum control: MWs, lasers




A. Wallraff. *et al.*, Nature **431**, 162 (2004)

Quantum dynamics, thermalization




M. Serbyn, Z. Papic, and D. Abanin, Phys. Rev. X **5**, 041047 (2015).

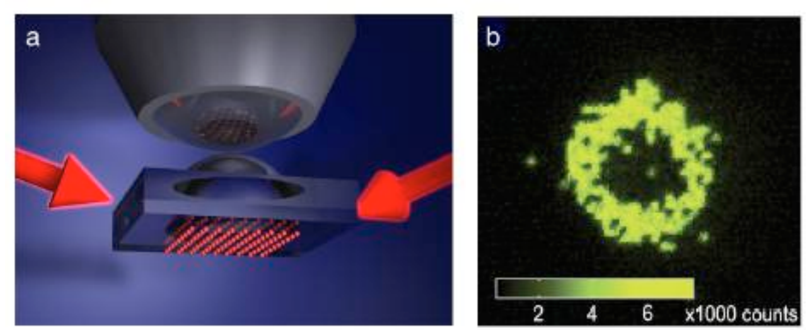
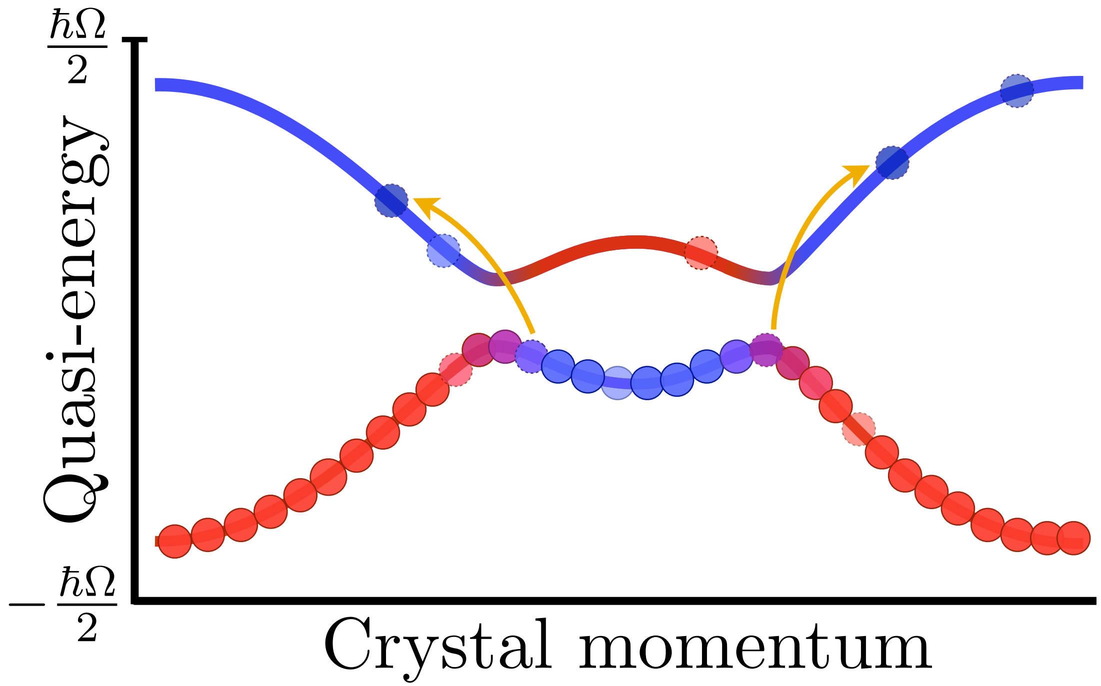



Image from `http://greiner.physics.harvard.edu`

# A <u>closed</u>, interacting, periodically driven system generically absorbs energy, tends to high entropy state




See for example:


L. D'Alessio, M. Rigol, Phys. Rev. X **4**, 041048 (2014).

A. Lazarides, A. Das, and R. Moessner, Phys. Rev. Lett. **112**, 150401 (2014).

P. Ponte, A. Chandran, Z. Papic, D. A. Abanin, Annals of Physics **353**, 196 (2015).

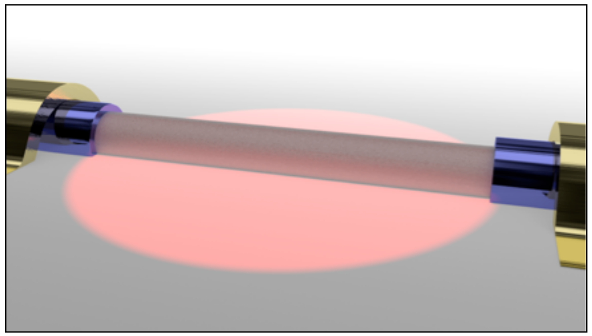

Exceptions being explored:

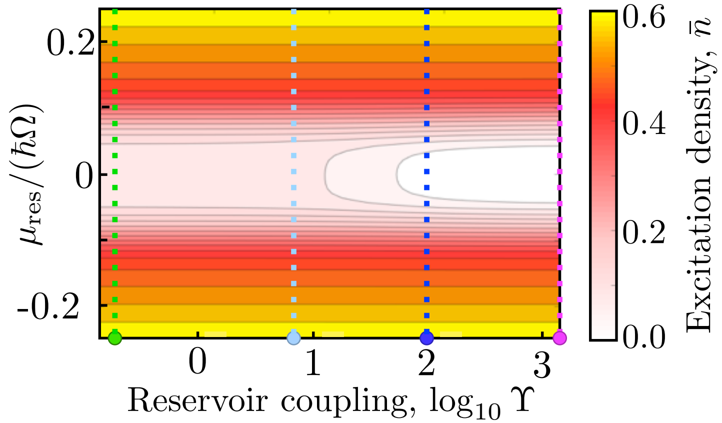

R. Citro *et al.*, Annals of Physics **360**, 694 (2015).

A. Chandran and S. L. Sondhi, arXiv:1506.0883 (2015).

# Must develop strategies to realize nontrivial behavior

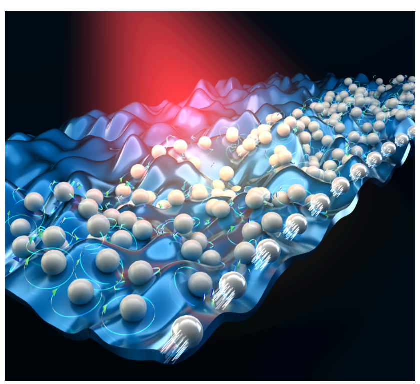
## Tailored coupling to baths






K. Seetharam, C.-E. Bardyn, N. Lindner, MR, and G. Refael, PRX (2015).
H. Dehghani, T. Oka, and A. Mitra, PRB (2015).
T. Iadecola, T. Neupert, and C. Chamon, PRB (2015).

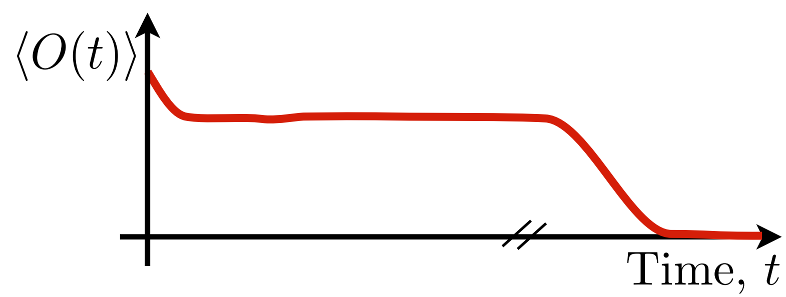
## Disorder, localization



Many-body localization + driving:

P. Ponte, A. Chandran, Z. Papic, D. Abanin, Annals of Phys. (2015).
A. Lazarides, A. Das, and R. Moessner, PRL (2015).
V. Khemani, A. Lazarides, R. Moessner, S. L. Sondhi, PRL (2016).

## (Long) transient dynamics



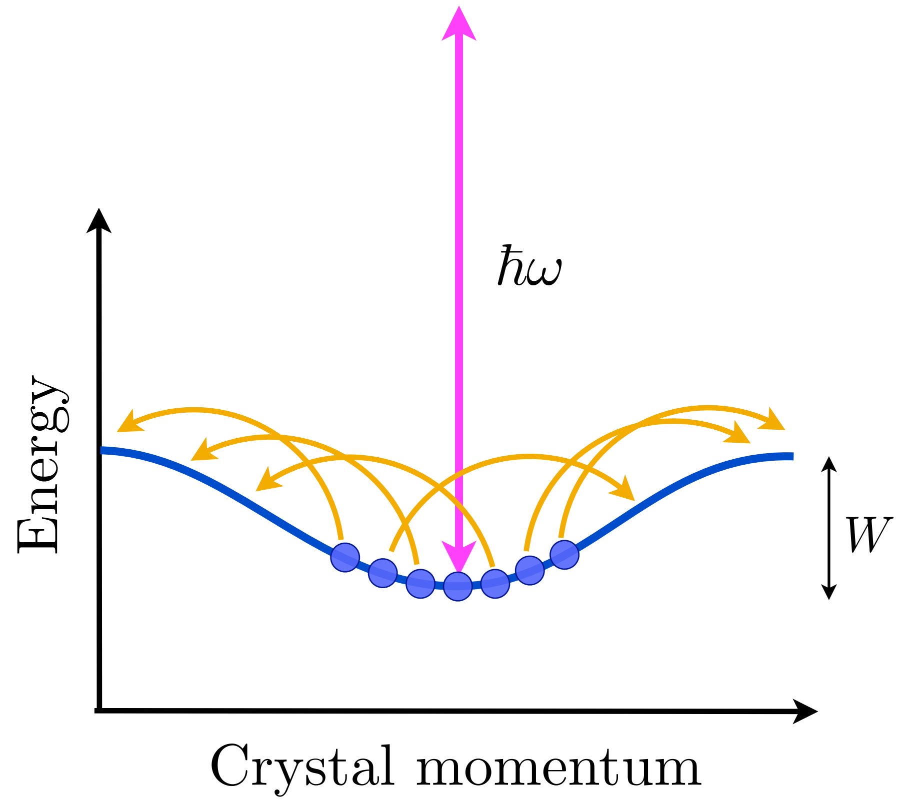

High frequency driving limit:

M. Bukov, L. D'Alessio, A. Polkovnikov, Adv. in Phys. (2015).

Examples: pre-thermal Floquet steady states:

M. Bukov, S. Gopalakrishnan, M. Knap, and E. Demler, PRL (2015).
E. Canovi, M. Kollar, and M. Eckstein, PRE (2016).
D. A. Abanin, W. De Roeck, W. W. Ho, PRB (2017).

# Energy absorption exponentially suppressed at high frequency




System ***prethermalizes*** with respect to a static, effective Hamiltonian

See, for example:

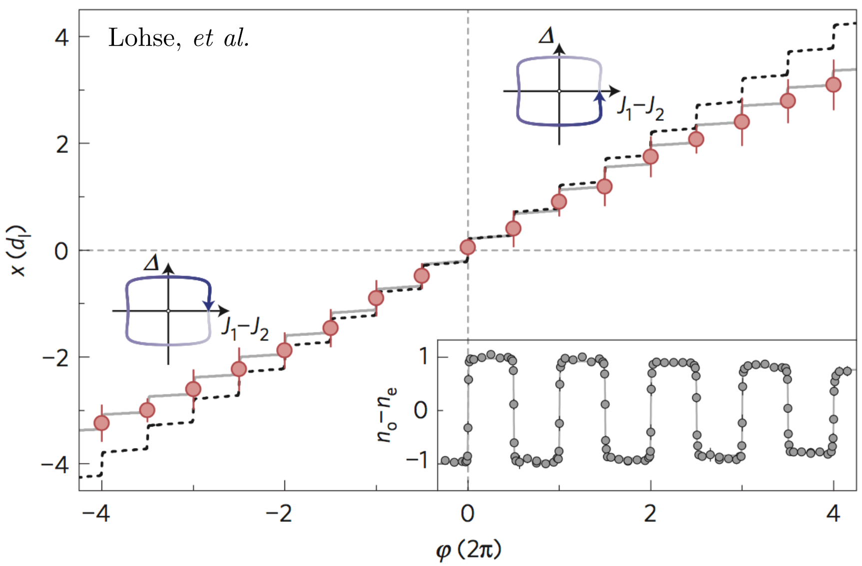

D. A. Abanin, W. De Roeck, and F. Huveneers, PRL (2015).

M. Bukov, L. D'Alessio, A. Polkovnikov, Adv. in Phys. (2015).

D. A. Abanin, W. De Roeck, W. W. Ho, and F. Huveneers, PRB (2017).

# Periodically-driven systems may host new types of topological phenomena, with no equilibrium analogues

## Quantized pumping




*Original theory (1D):*

Thouless, PRB (1983)

*Experiments(1D):*

Lohse *et al.*, Nature Physics (2015)

Nakajima *et al.*, Nature Physics (2015)

*Extensions to 3D (theory):*

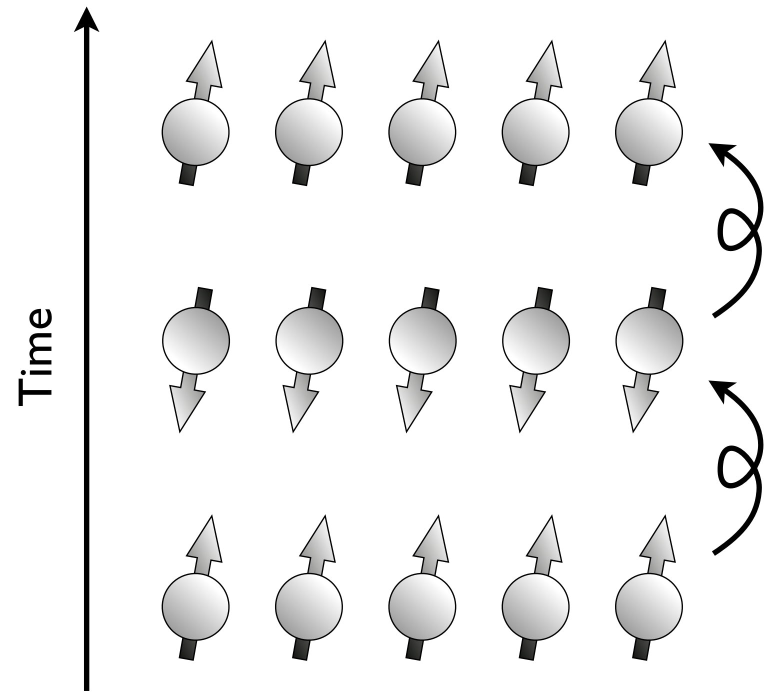
Kitagawa, Berg, MR, Demler, PRB (2010)

Sun, Xiao, Bzdusek, Zhang, Fan, arXiv:1806.09296

Higashikawa, Nakagawa, Ueda, arXiv:1806.06868

⋮

## Micromotion phase transitions




*Examples in 1D ("time crystals"):*

Khemani, Lazarides, Moessner, Sondhi, PRL (2016)

Else, Bauer, Nayak, PRL (2016)

*Examples in 2D (quantized magnetization, edge transport):*

MR, Lindner, Berg, Levin, PRX (2013)

Po, Fidkowski, Morimoto, Potter, Vishwanath, PRX (2016)

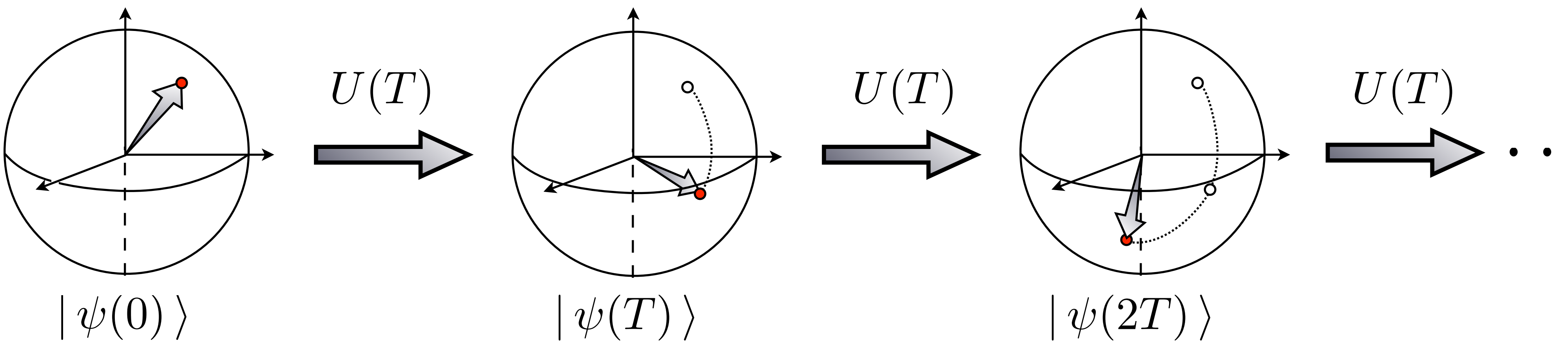
Nathan, MR, Lindner, Berg, Refael, PRL (2017)

⋮

# Universal chiral quasi-steady states emerge from interactions and unique topology of Floquet bands

# Quasi-energy is conserved for system with discrete time translation symmetry

$$U(T) = \mathcal{T} e^{-i\int_0^T H(t)dt} \qquad H(t+T) = H(t)$$

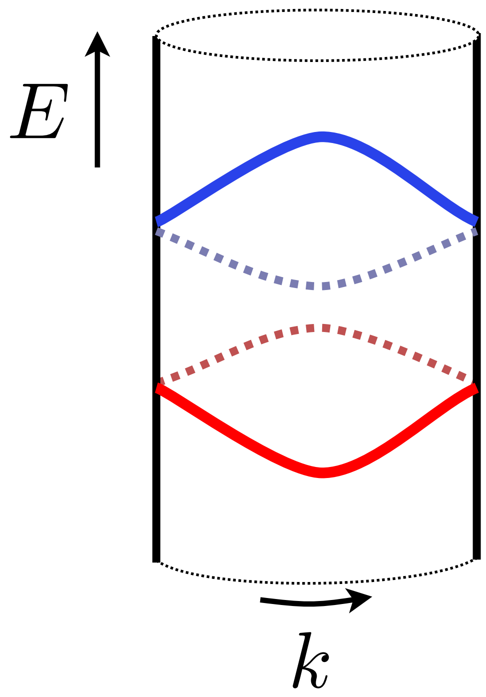



$$U(T)|\,\psi_n\,\rangle = e^{-i\varepsilon_n T}|\,\psi_n\,\rangle$$

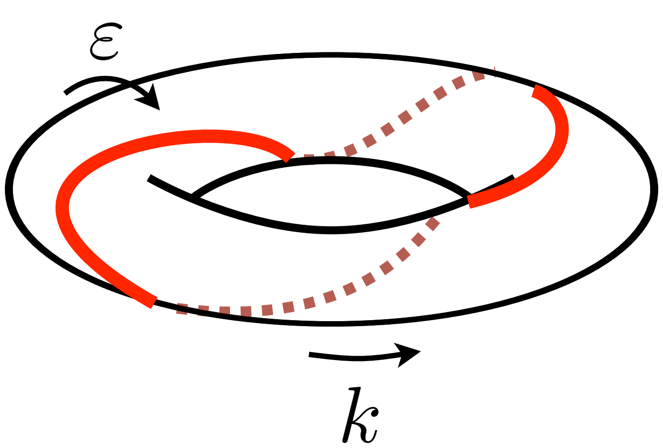
Eigenvalue invariant under $\varepsilon_n \to \varepsilon_n + 2\pi N/T$: quasi-energy lives on a circle

# New types of topological bands possible in driven systems

Normal band structure: <u>cylinder</u>




Quasi-band structure: <u>torus</u>



# Quasi-energy winding related to quantized adiabatic transport

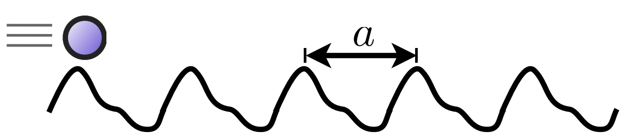
Average group velocity <u>quantized</u>

$$\bar{v}_g = \overline{\frac{d\varepsilon_k}{dk}} = a/T$$

Average current:

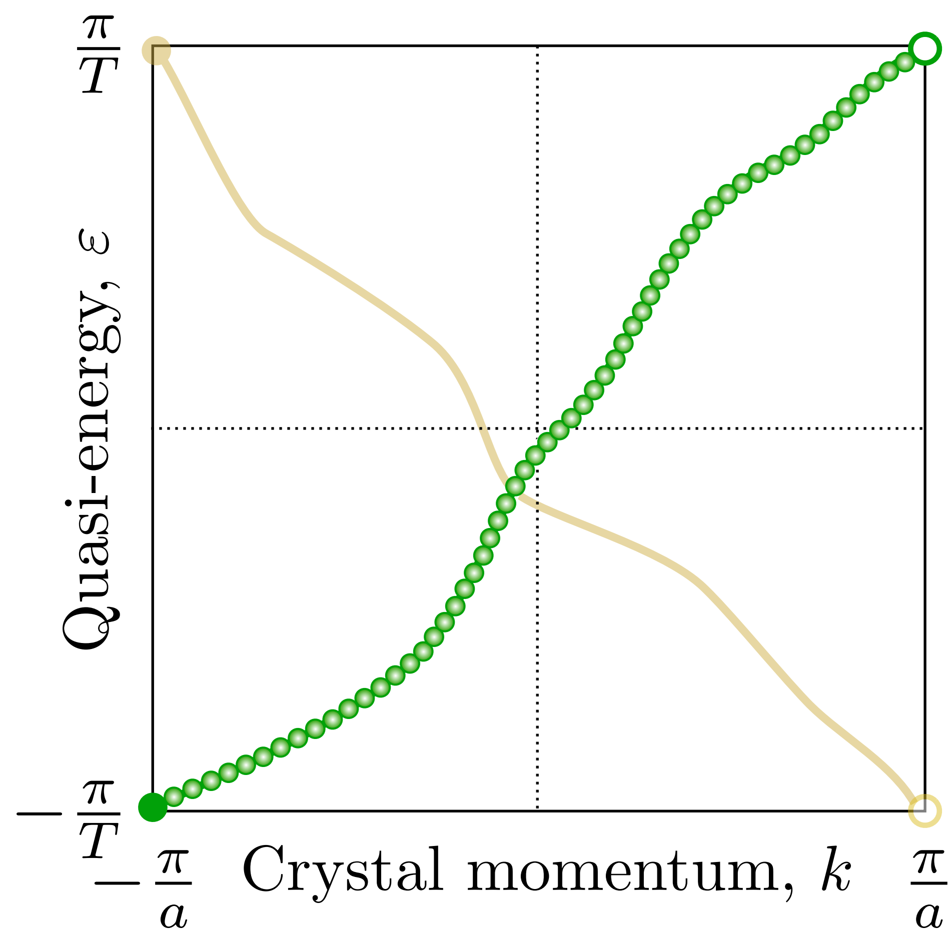
$$I = \rho\,\bar{v}_g = 1/T$$

particle density: $\rho = 1/a$



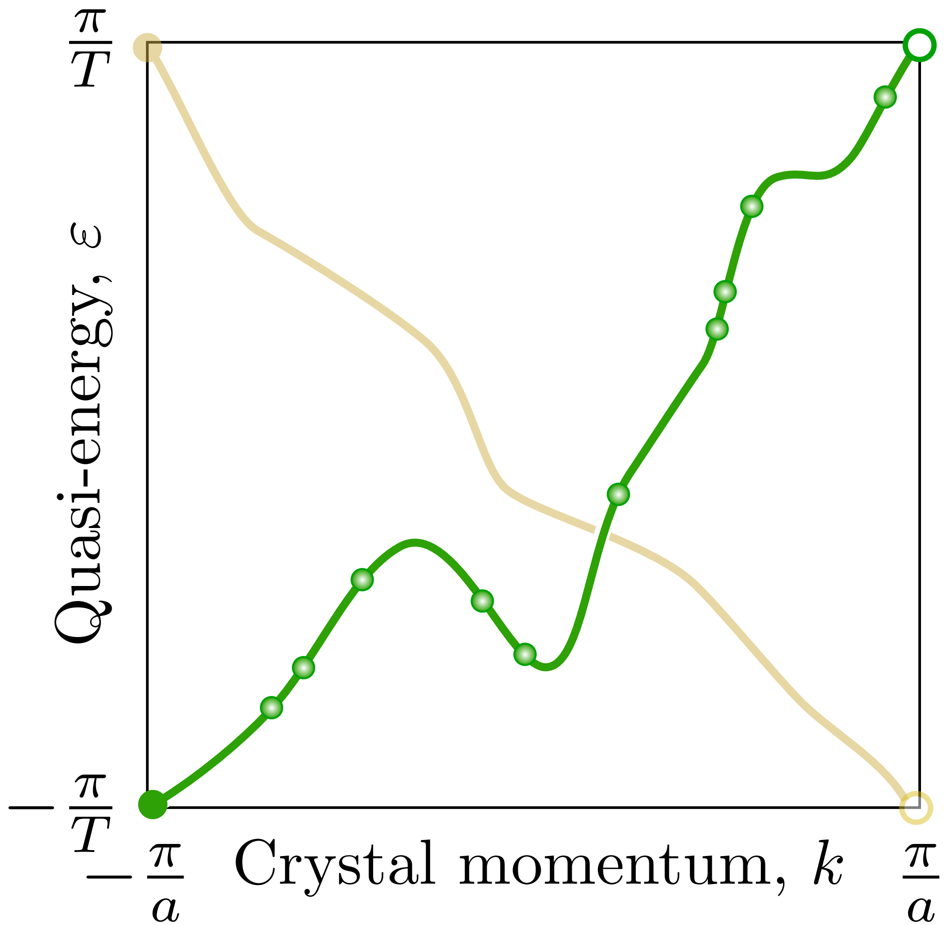

$$V(x+a) = V(x)$$

$$U(T)|\,\psi(k)\,\rangle = e^{-i\varepsilon_k T}|\,\psi(k)\,\rangle$$

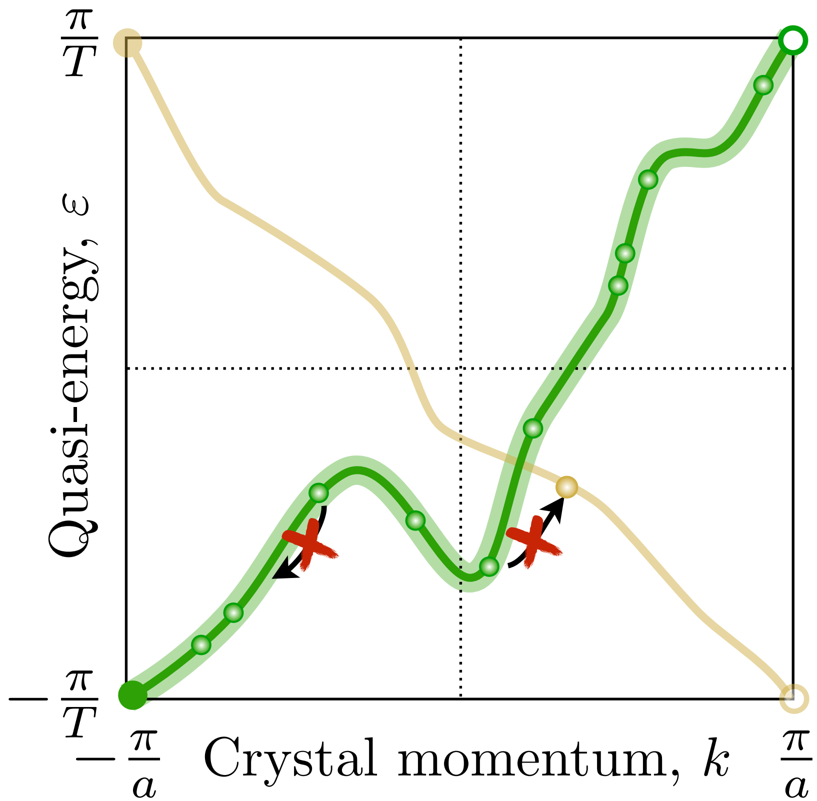



T. Kitagawa, E. Berg, MR, and E. A. Demler, Phys. Rev. B 82, 235114 (2010).

# Current carried by partially-filled band can be anything



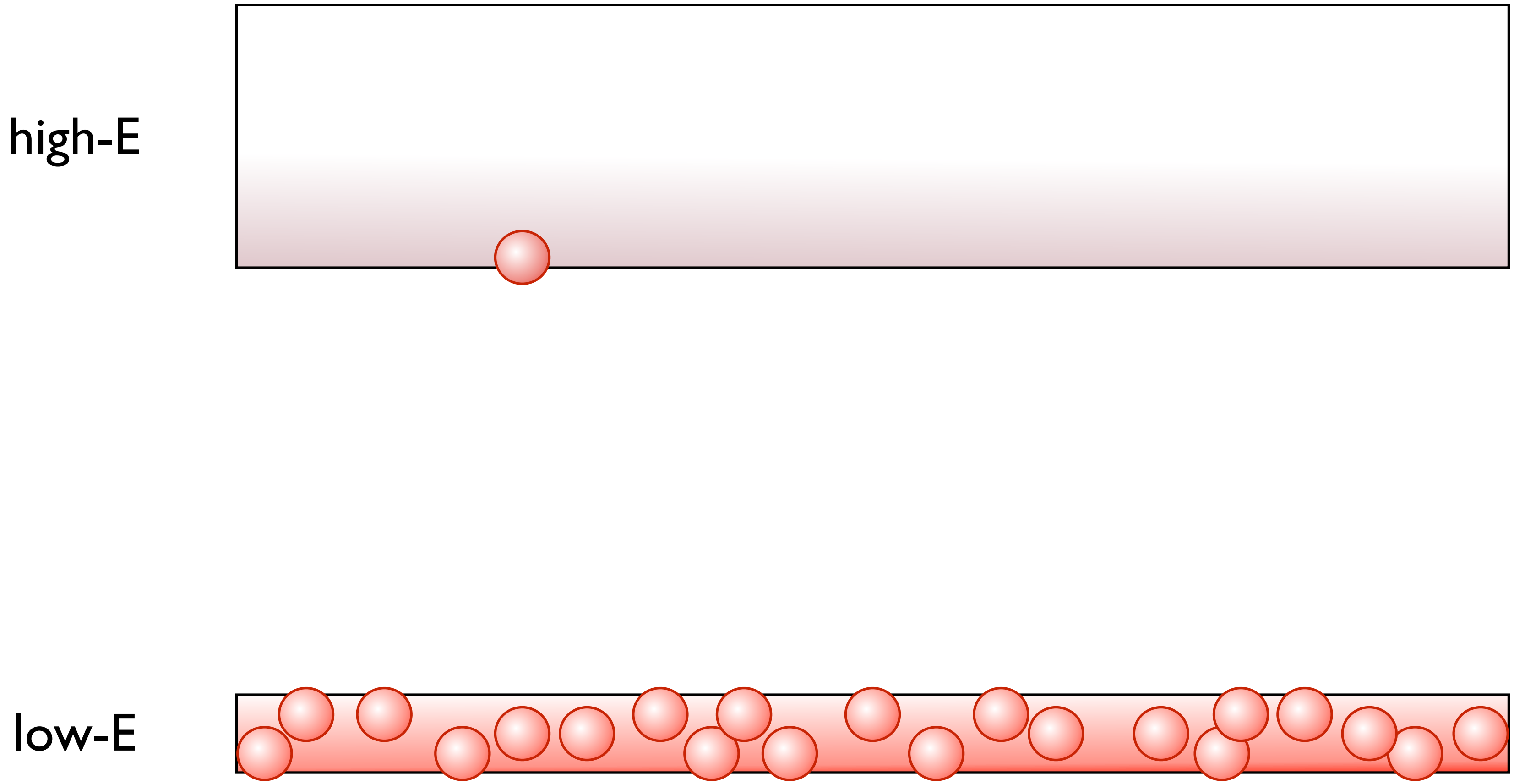
# Restricted infinite-temperature-like state within a band yields uniform averages, restores universality




* Universal quantized pumping coefficient!

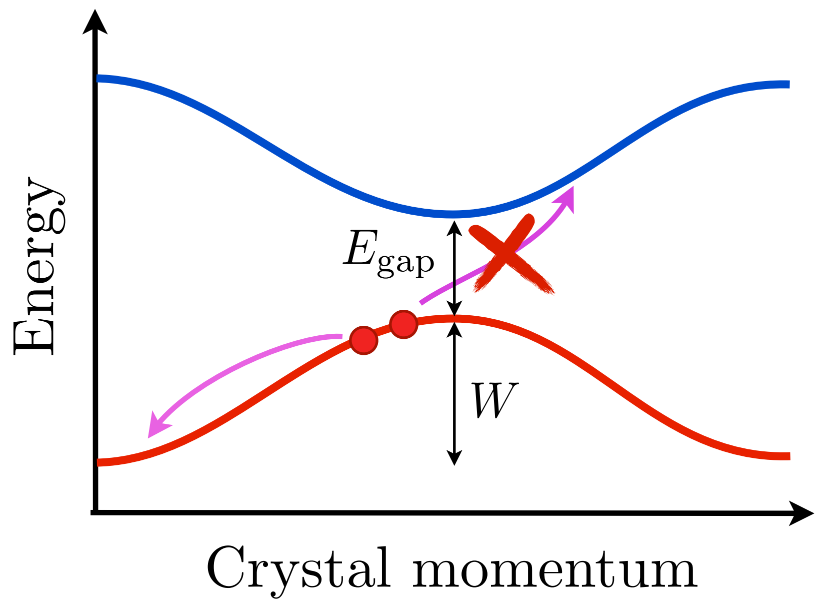
$$(\text{current}) = (1/T) \times (\text{density})$$

# Restricted heating of low energy degrees of freedom reveals universal (topological) features of low-energy sector



# Must suppress both direct and photon-assisted processes

Direct scattering

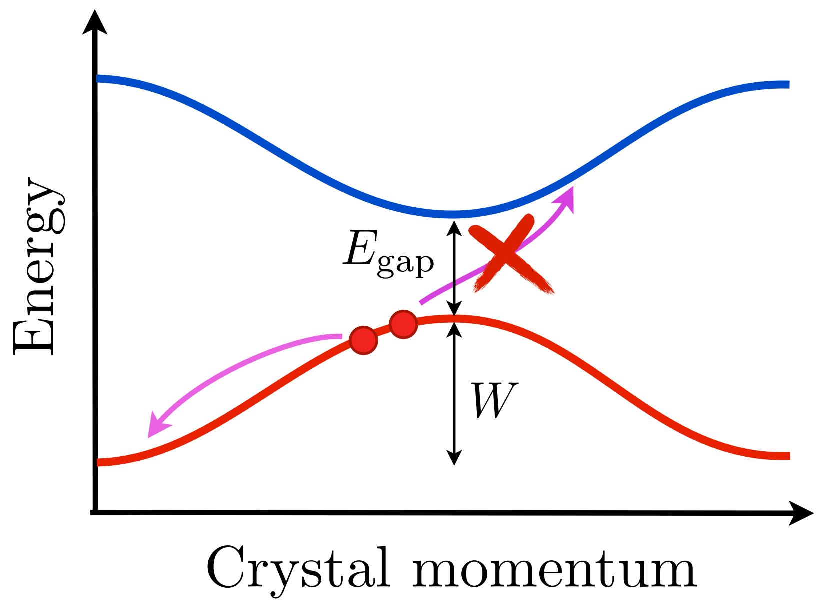



Small bandwidth

$$W/E_{\text{gap}} \ll 1$$

# Must suppress both direct and photon-assisted processes

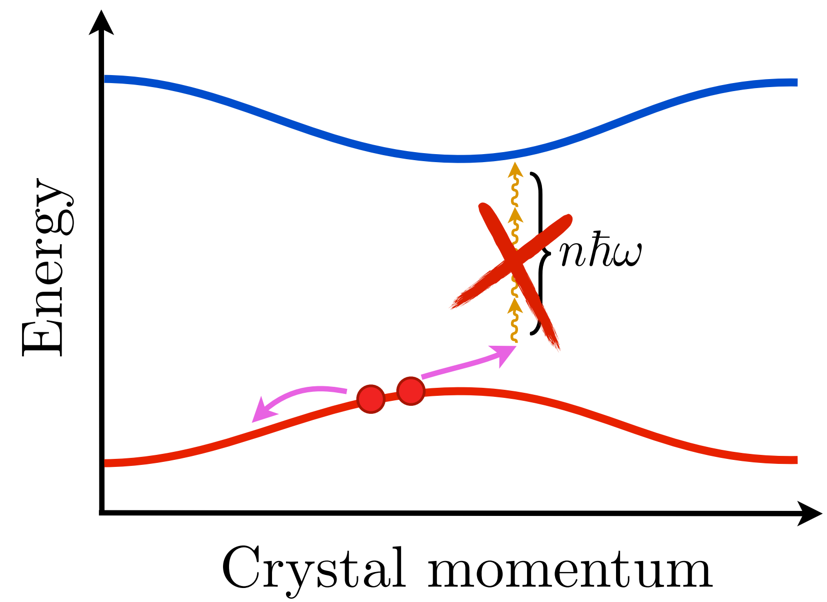
## Direct scattering




**Small bandwidth**

$$W/E_{\text{gap}} \ll 1$$

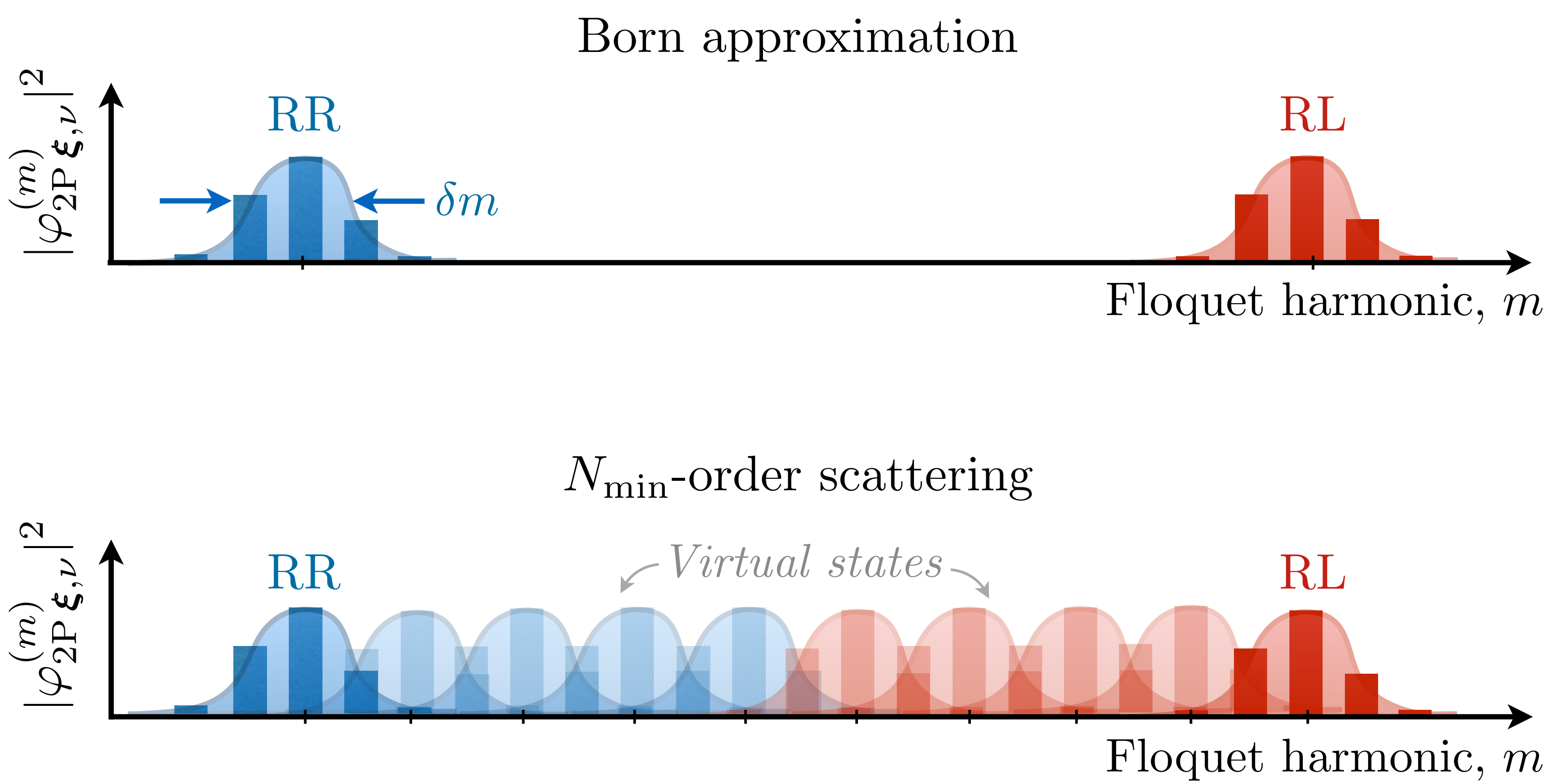
## Photon-assisted scattering




**Single-particle adiabaticity**

$$\hbar\omega/E_{\text{gap}} \ll 1$$

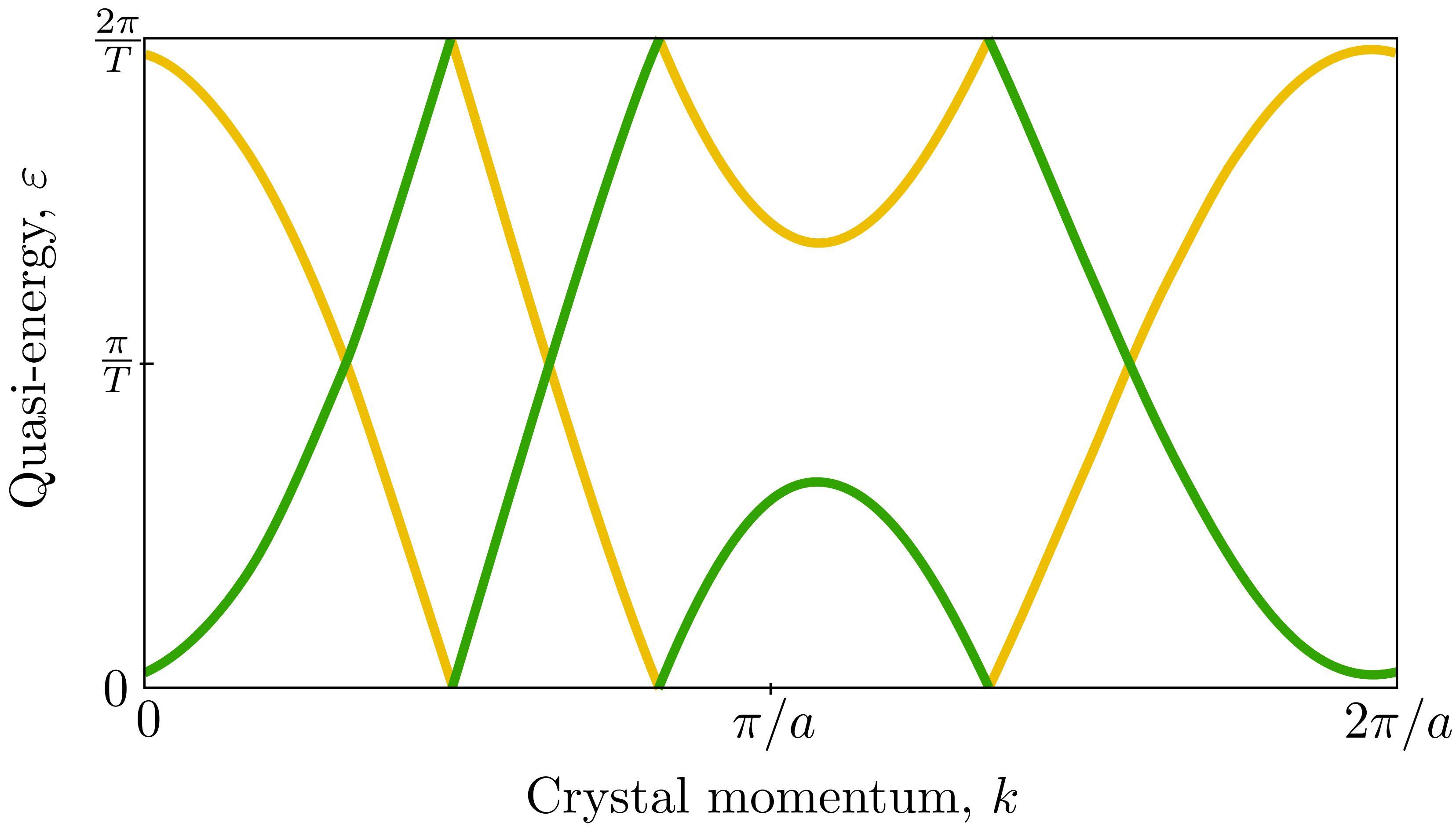
# High-order perturbation theory predicts exponential suppression of scattering in $1/\omega$




Rigorous bound on decay rate obtained via rotating frame, Lieb Robinson bounds

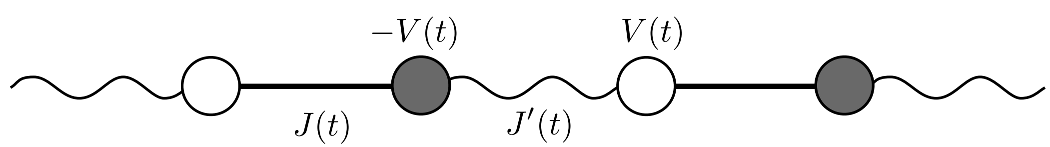
T. Gulden, E. Berg, MR, N. H. Lindner (to appear)

# Study dynamics in system with winding Floquet bands, nearest neighbor interactions




$$\frac{V_1}{\hbar\omega} = 8.2$$

$$\frac{J_0}{\hbar\omega} = 4.1$$

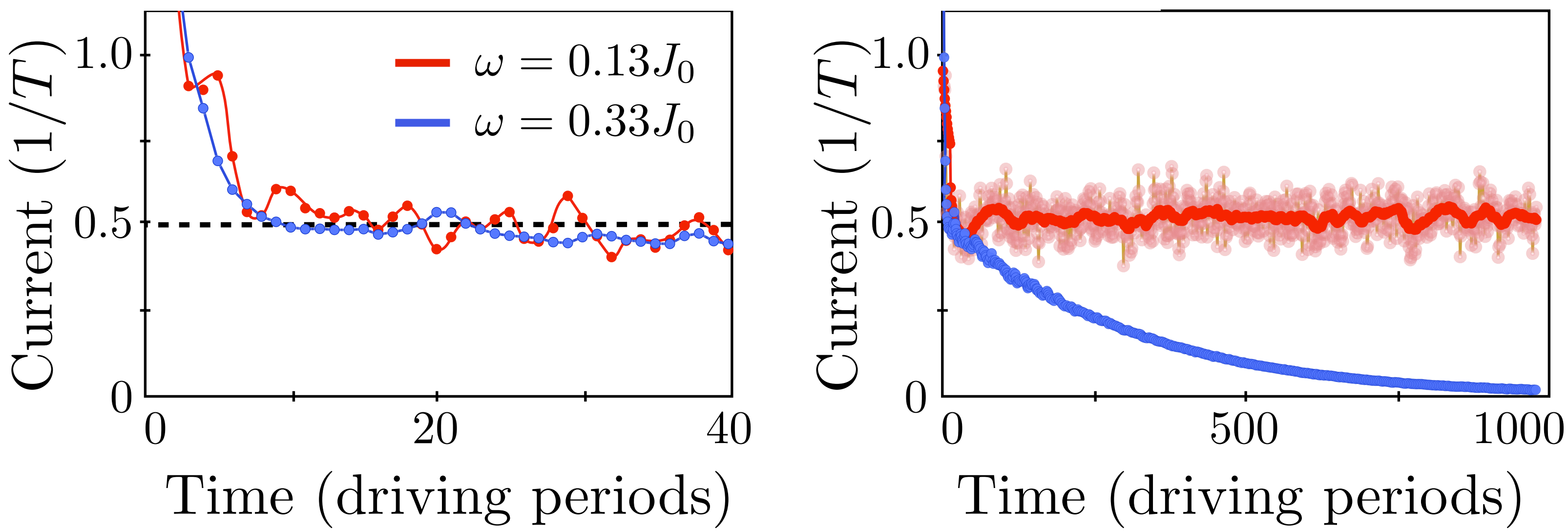


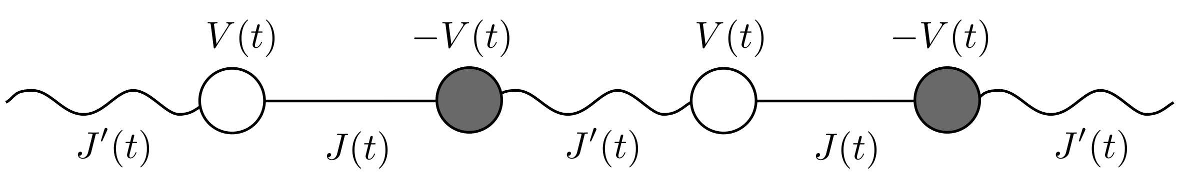

$$V(t) = V_1 \sin\omega t \qquad J(t) = J_0(1+\cos\omega t) \qquad J'(t) = J_0(1-\cos\omega t)$$

$$H_{\text{int}} = U\sum_j n_j(n_j - 1),\ n_j = \hat{c}^\dagger_{j,A}\hat{c}_{j,A} + \hat{c}^\dagger_{j,B}\hat{c}_{j,B}$$

# Two timescales emerge for intraband equilibration and interband scattering (decay of current)

Numerics: 8 fermionic particles, 32 sites (16 unit cells)



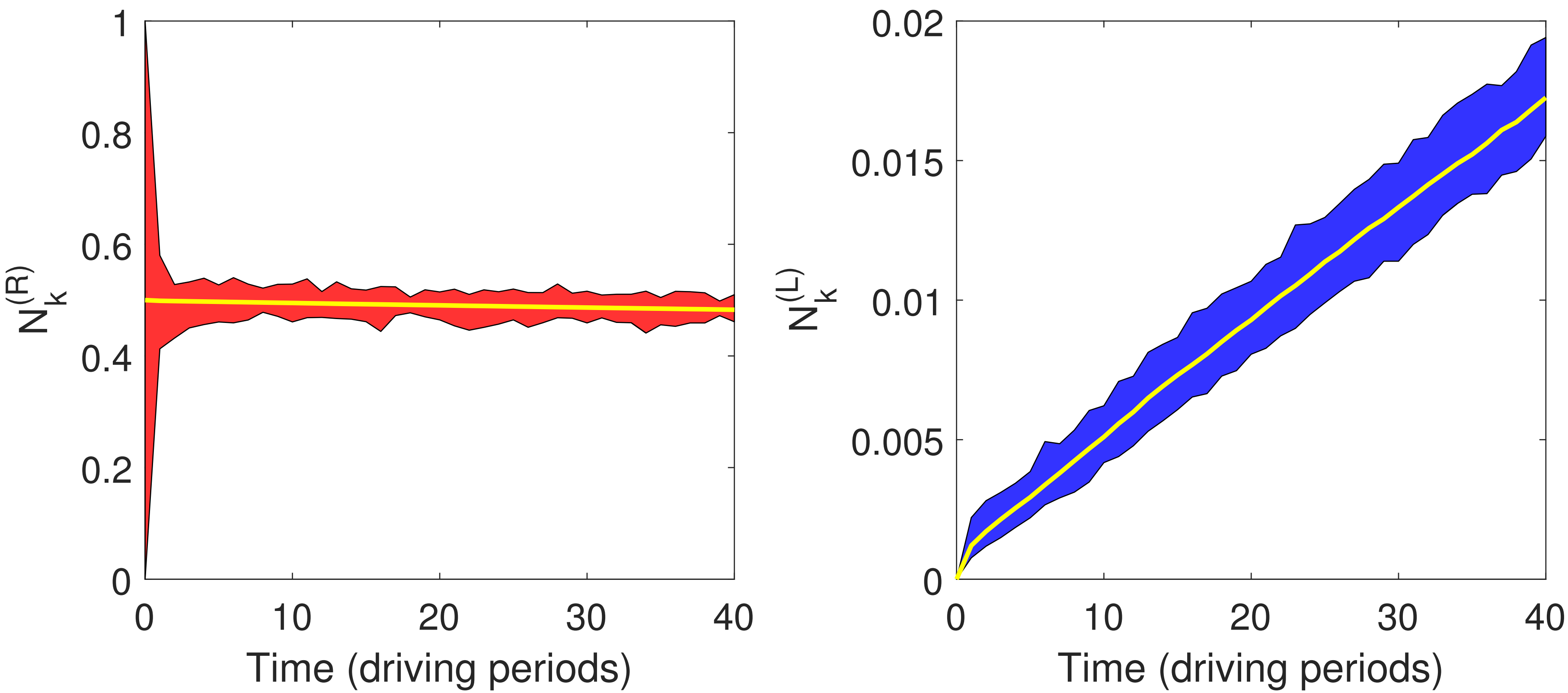

$$J_1 = \tfrac{2}{3} J_0$$

$$V_1 = 2 J_0$$

$$\omega = \tfrac{1}{3} J_0$$

$J(t) = J_0 + J_1 \cos \omega t \qquad J'(t) = J_0 - J_1 \cos \omega t \qquad V(t) = V_1 \sin \omega t$

# Populations rapidly converge to quasi-steady distribution



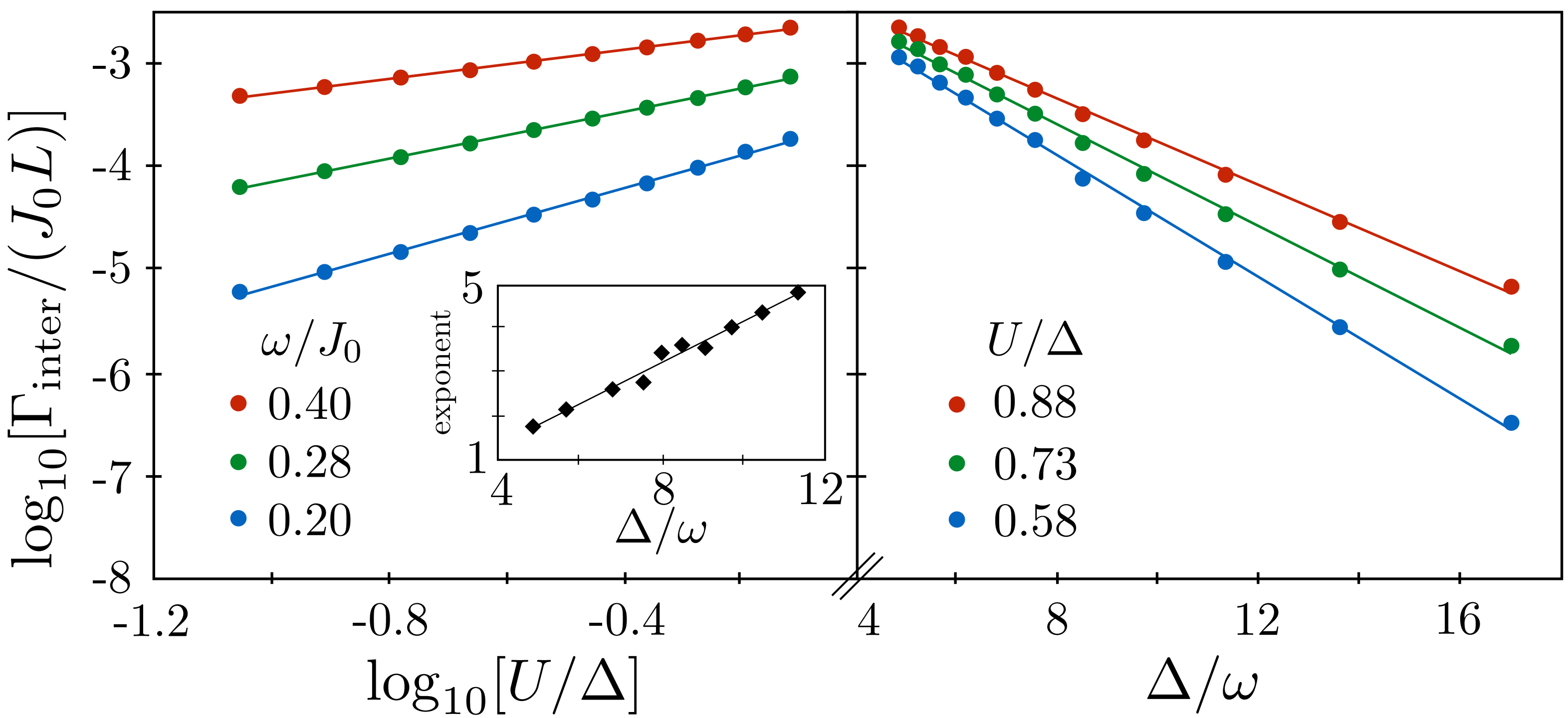
# High-order perturbation theory predicts exponential suppression of scattering in $1/\omega$

$$\Gamma_{\text{inter}} \sim \left(\frac{\alpha U}{\Delta}\right)^{\frac{\Delta}{\delta m \omega}}$$

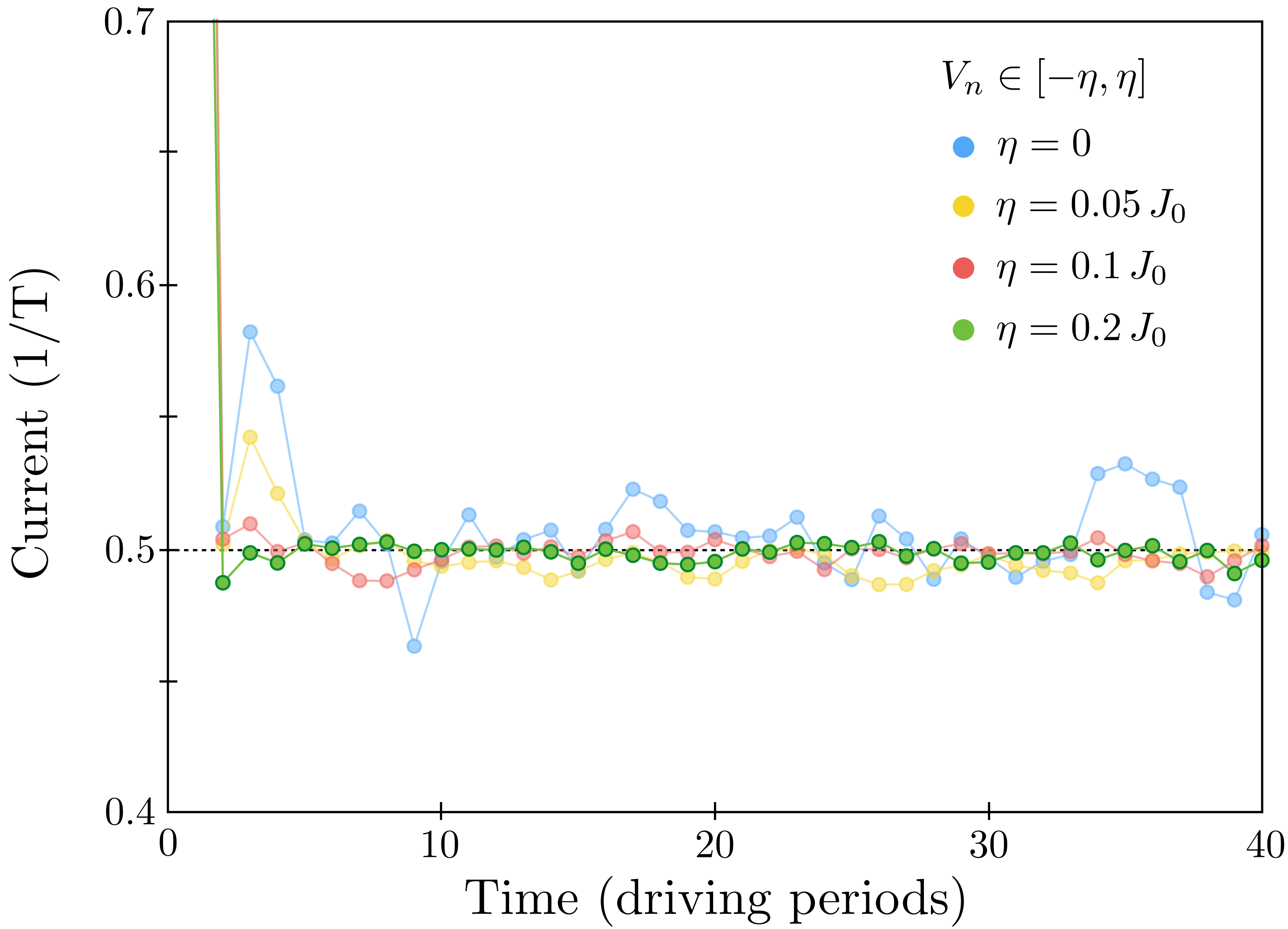
interaction

minimal order of photon absorption

minimal instantaneous band gap



# Disorder *improves* current quantization for finite system size




R. Gawatz (in progress)

# Summary and open questions

Prethermalization due to slow driving can lead to new regimes of universal dynamics

Universality of quasi-steady behavior apparently persists even when intraband scattering is fast compared with driving frequency

Questions to study: What sets fidelity of quantization? How does chirality/nontrivial topology affect thermalization/many-body chaos? Generalizations to other dimensions/phenomena…

For details see: N. Lindner, E. Berg, and MR, PRX 7, 011018 (2017)

Contact: rudner@nbi.dk

Support for this work provided by:

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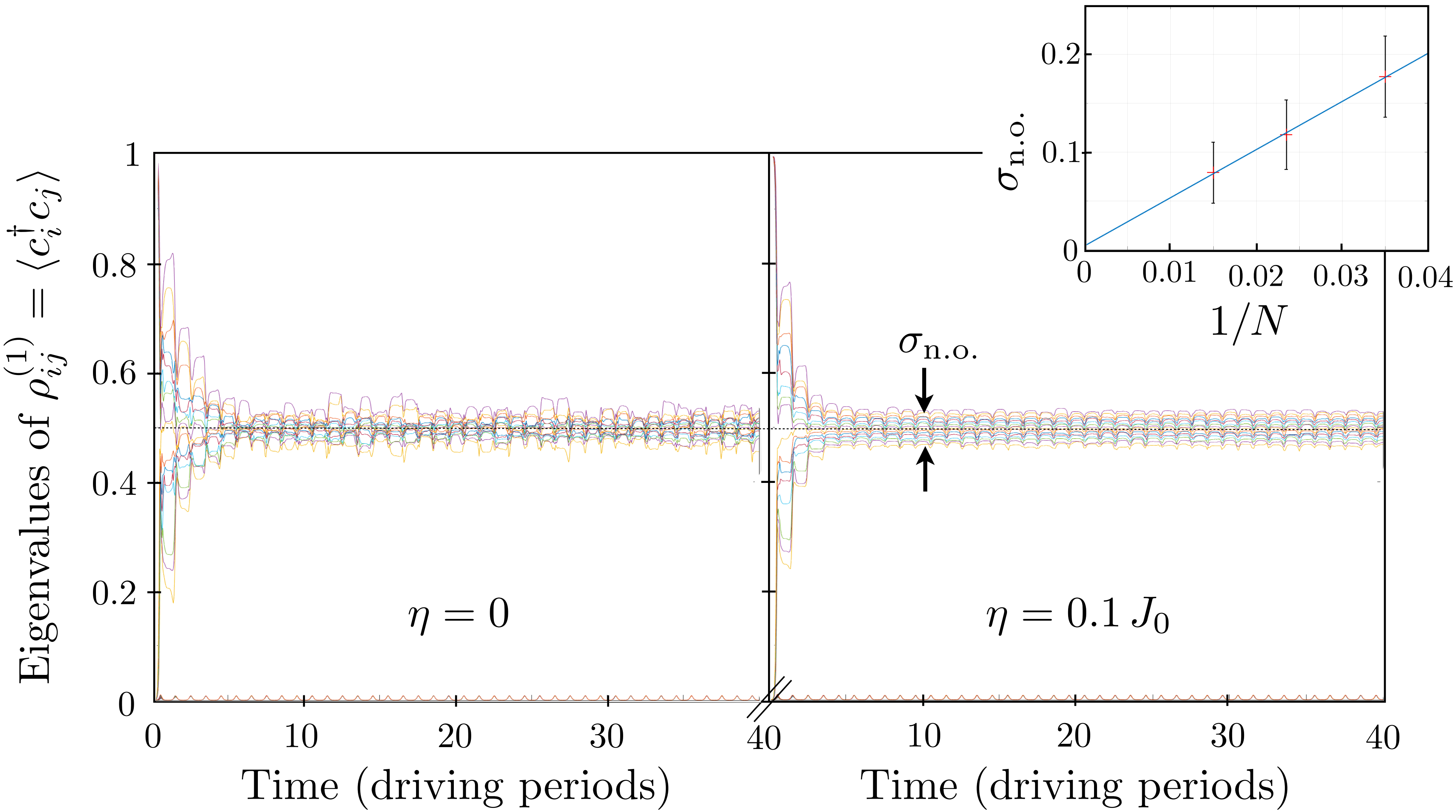
# "Natural orbital" occupation converges to uniform distribution with system size; disorder smoothens fluctuations




R. Gawatz (in progress)