Photon Inhibited and Enabled Topological Transport

Tami Pereg-Barnea
McGill University

August 14, 2015 - KITP
arXiv:1505.05578
arXiv:1505.05584

צדיקים מלאכתם נעשית בידי אחרים

- Saints, their work is done by others

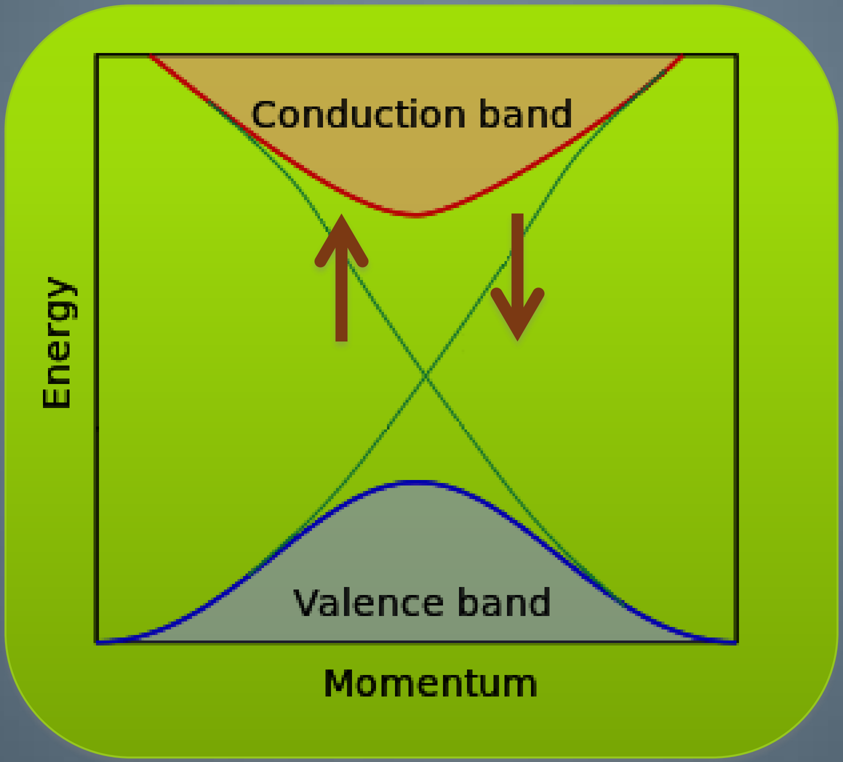
Aaron Farrell

- Acknowledgment: Aash Clerk and Jean-Rene Soquet

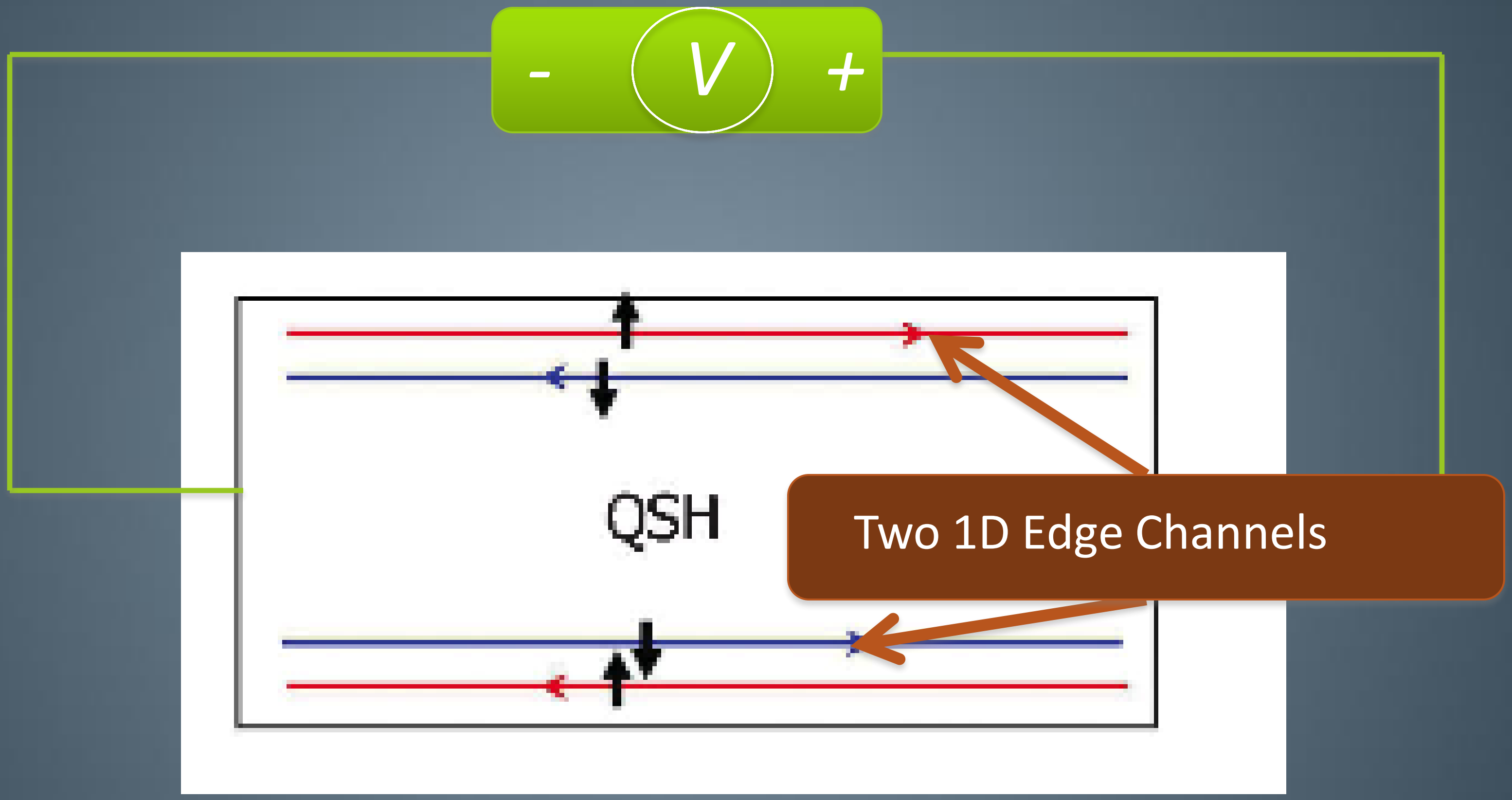
Outline

- Floquet topological insulators
- Nonequilibrium transport results
- Photon inhibition of edge-states
- Photon enabling of edge states
- Summary and outlook

Topological Insulators
Quantum Spin Hall

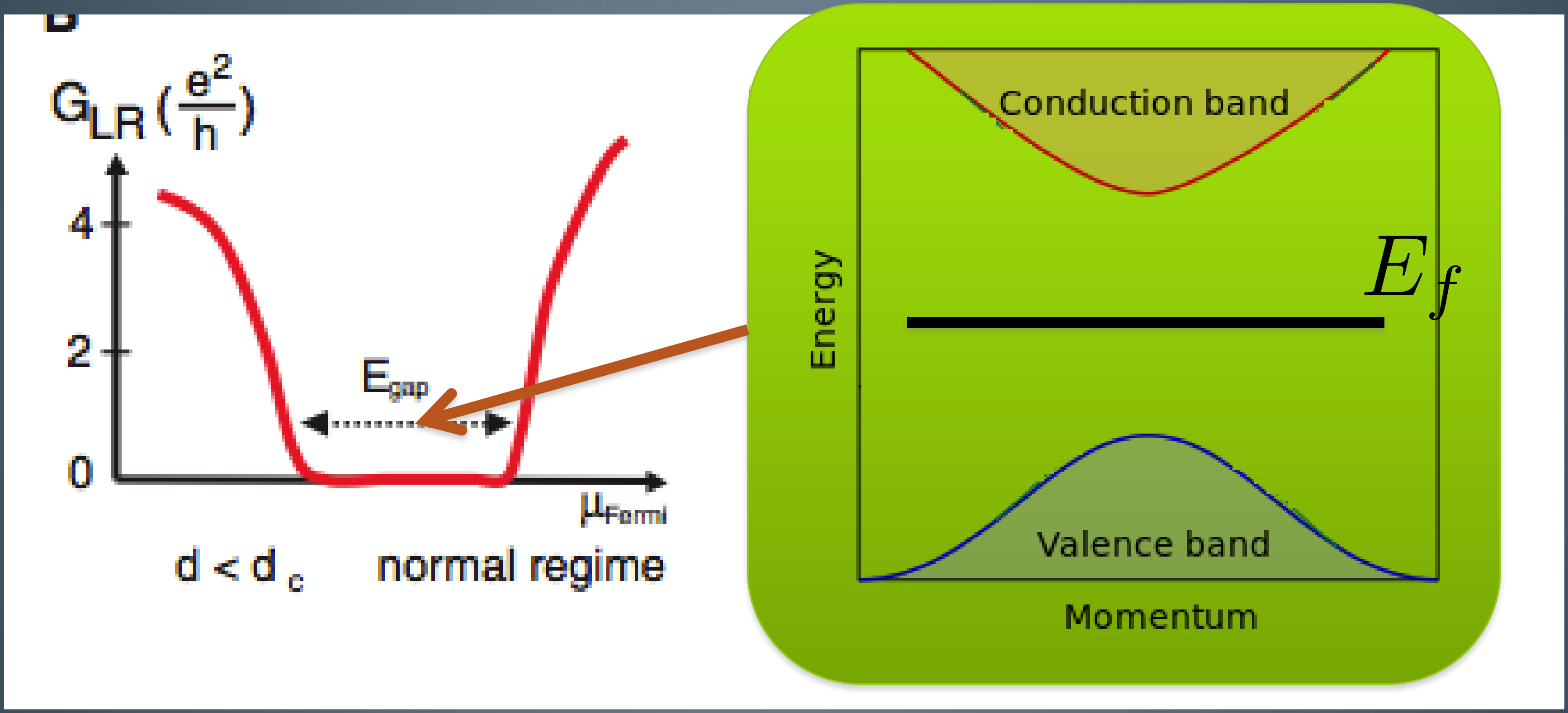


Topological Insulators



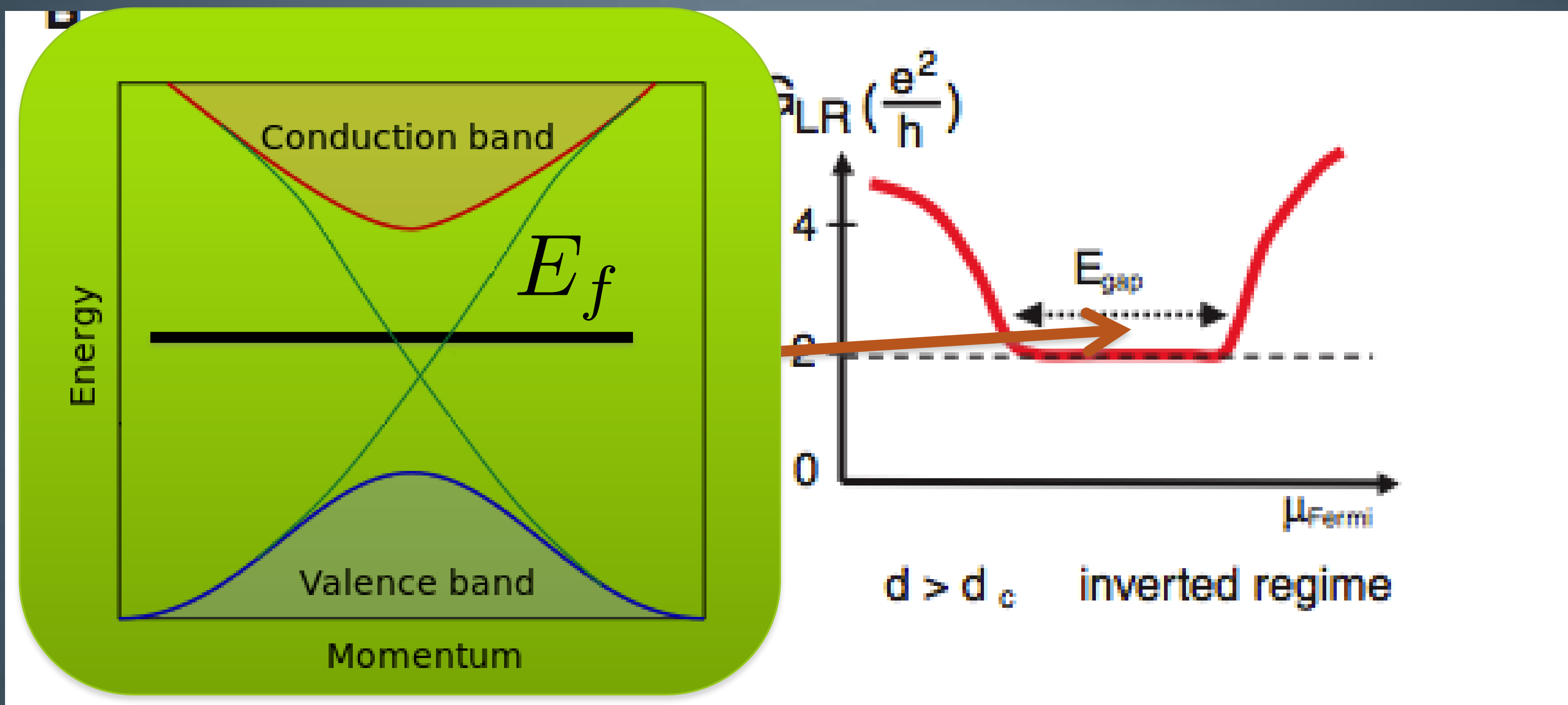
Qi and Zhang, RMP, **83** (2011)

Probes of Topological Insulators



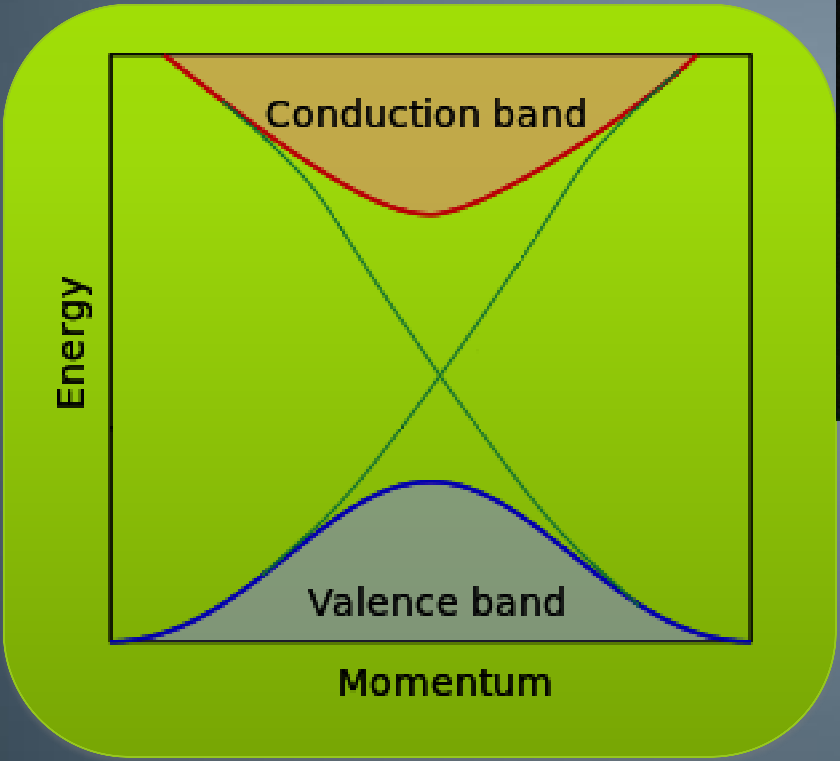
Bernevig *et al*, Science, **314** (2006)

Probes of Topological Insulators



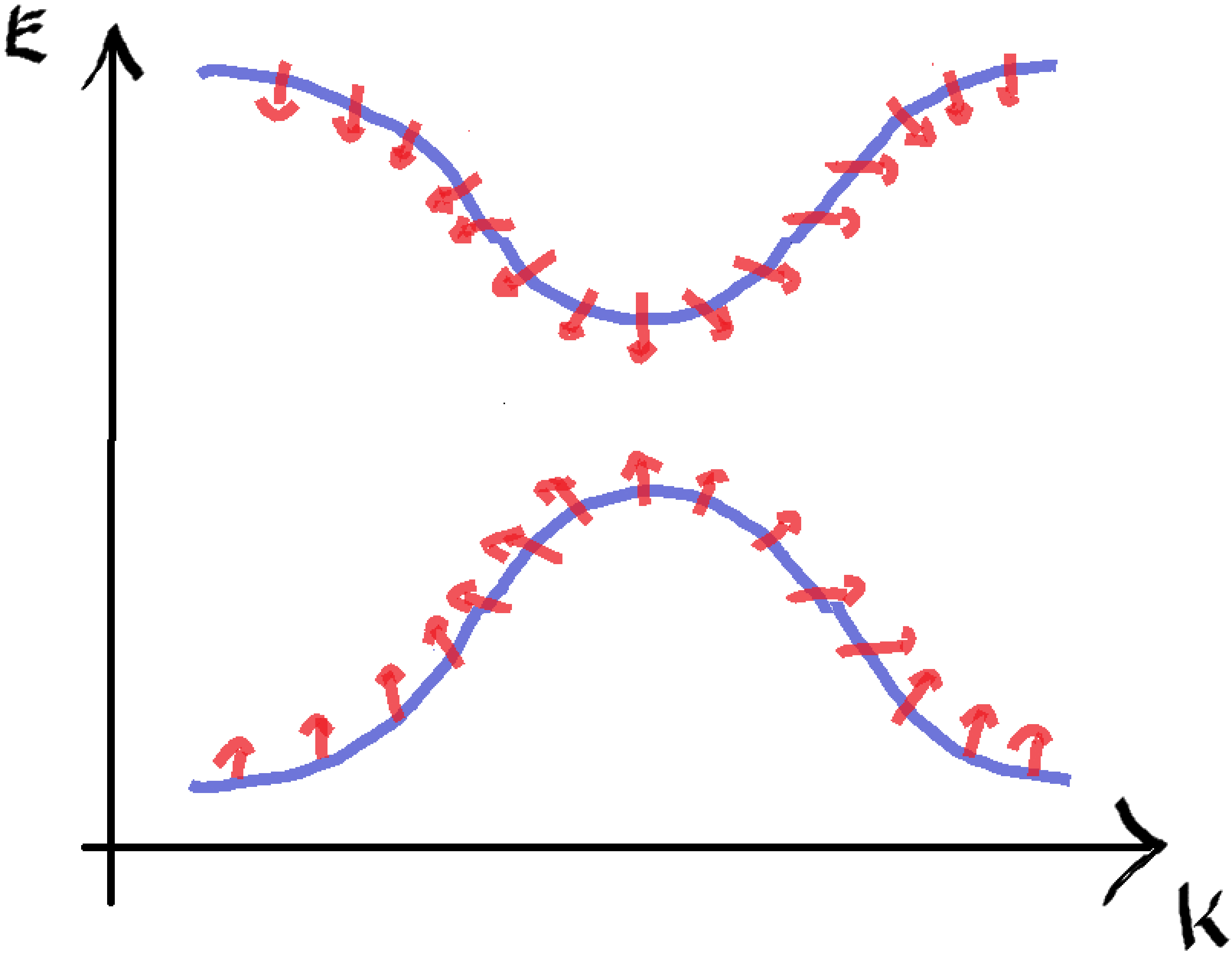
Bernevig *et al*, Science, **314** (2006)

Floquet Topological Insulators



$$V(t) = V(t + \tau)$$

Lindner, Refael and Galitsky, Nature Physics **7** (2011)


E
k

Time Periodic Quantum Mechanics

$$i\hbar\partial_t|\psi(t)\rangle = H(t)|\psi(t)\rangle$$

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

Time Periodic Quantum Mechanics

$$i\hbar\partial_t|\psi(t)\rangle = H(t)|\psi(t)\rangle$$

$$|\psi(t)\rangle = e^{-i\epsilon t/\hbar}|\phi\rangle$$

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Additional Time Dependence

Time Periodic Quantum Mechanics

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$$|\phi(t+T)\rangle = |\phi(t)\rangle$$

Time Periodic Quantum Mechanics

$$i\hbar\partial_t|\psi(t)\rangle = H(t)|\psi(t)\rangle$$

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Bloch: $\psi(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}}u_{\mathbf{k}}(\mathbf{r})$

$$u_{\mathbf{k}}(\mathbf{r}+\mathbf{R}) = u_{\mathbf{k}}(\mathbf{r})$$

Time Periodic Quantum Mechanics

$$i\hbar\partial_t|\psi(t)\rangle = H(t)|\psi(t)\rangle$$

$$|\psi(t)\rangle = e^{-i\epsilon t/\hbar}|\phi(t)\rangle$$

$$|\phi(t+T)\rangle = |\phi(t)\rangle$$

$$(H(t) - i\hbar\partial_t)|\phi(t)\rangle = \epsilon|\phi(t)\rangle$$

Time Periodic Quantum Mechanics

$$i\hbar\partial_t|\psi(t)\rangle = H(t)|\psi(t)\rangle$$

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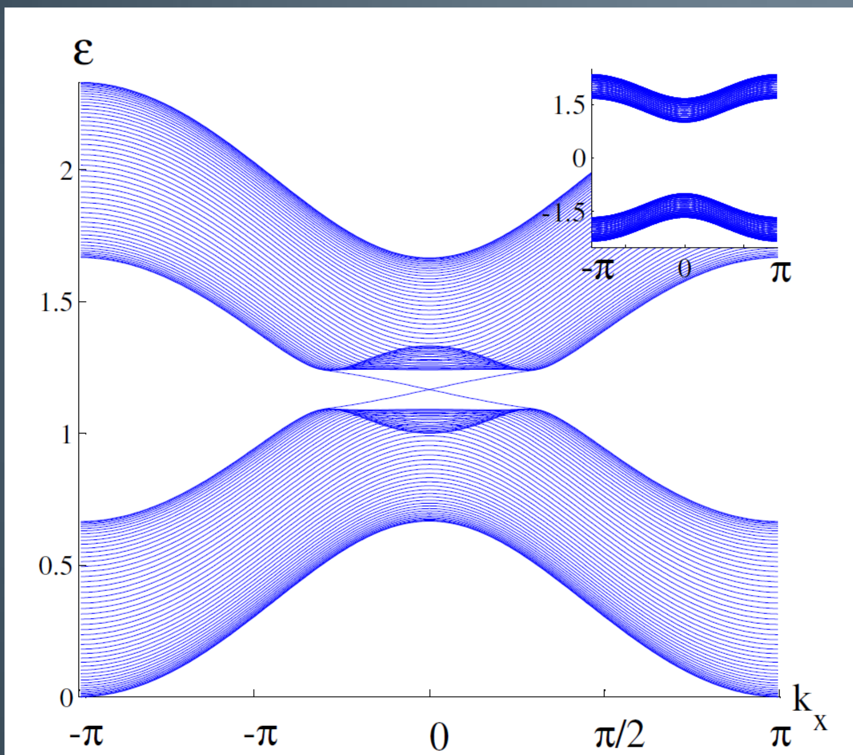
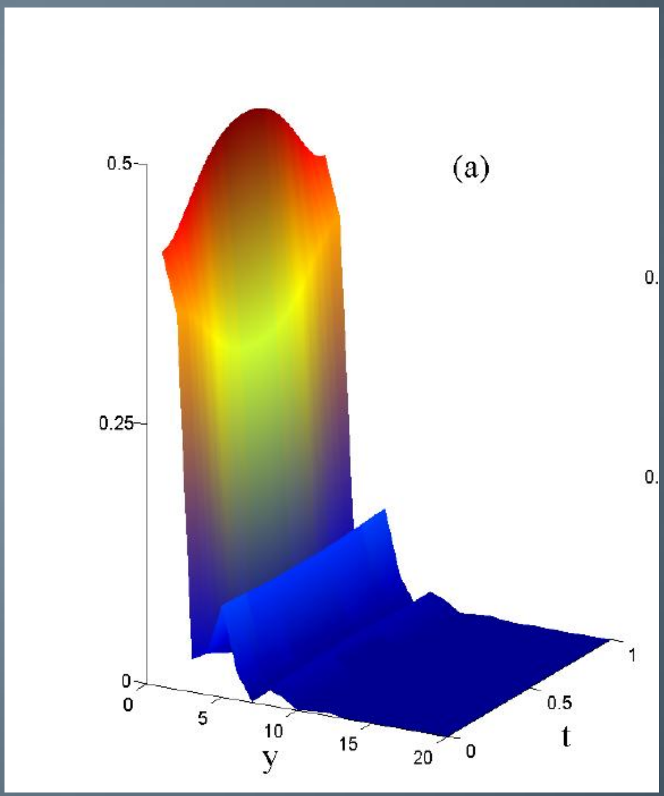
$$(H(t) - i\hbar\partial_t)|\phi(t)\rangle = \epsilon|\phi(t)\rangle$$

Quasi-energy

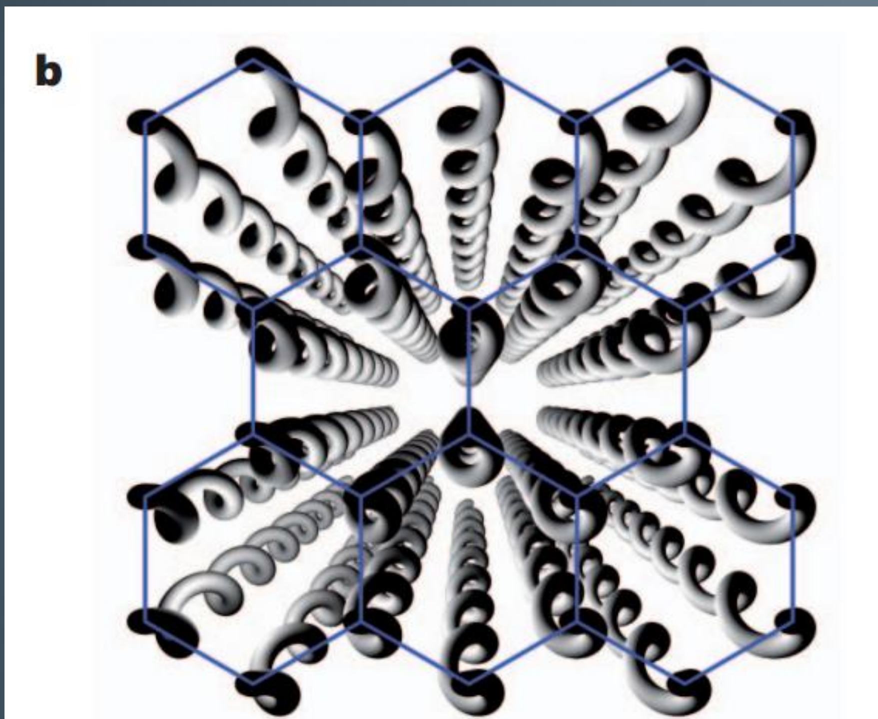
Floquet Topological Insulators

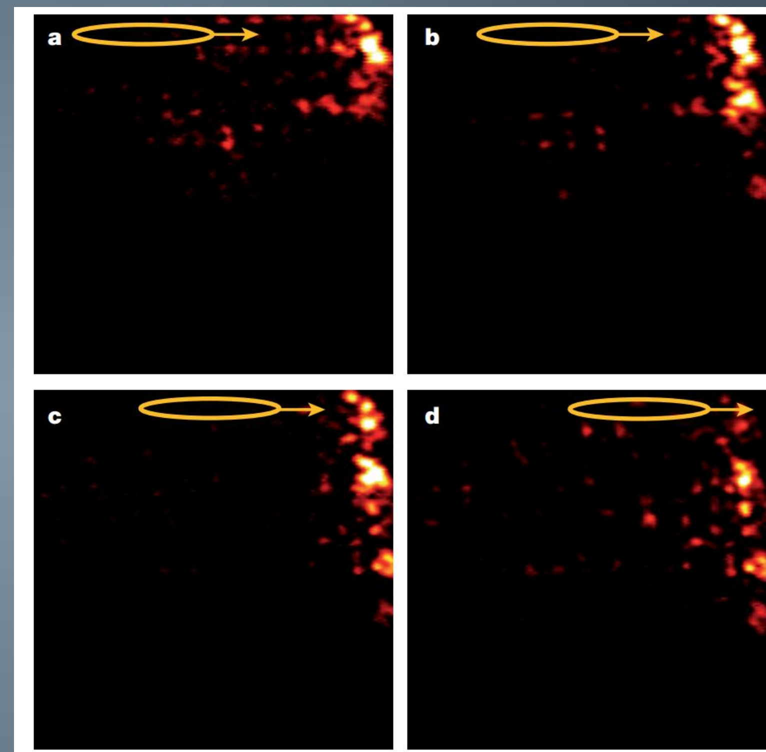




Lindner *et al*, Nature Physics **7** (2011)

Photonic Floquet TI





$$i\partial_z \psi(x,y,z) = -\frac{1}{2k_0}\nabla^2 \psi(x,y,z) - \frac{k_0 \Delta n(x,y,z)}{n_0}\psi(x,y,z)$$

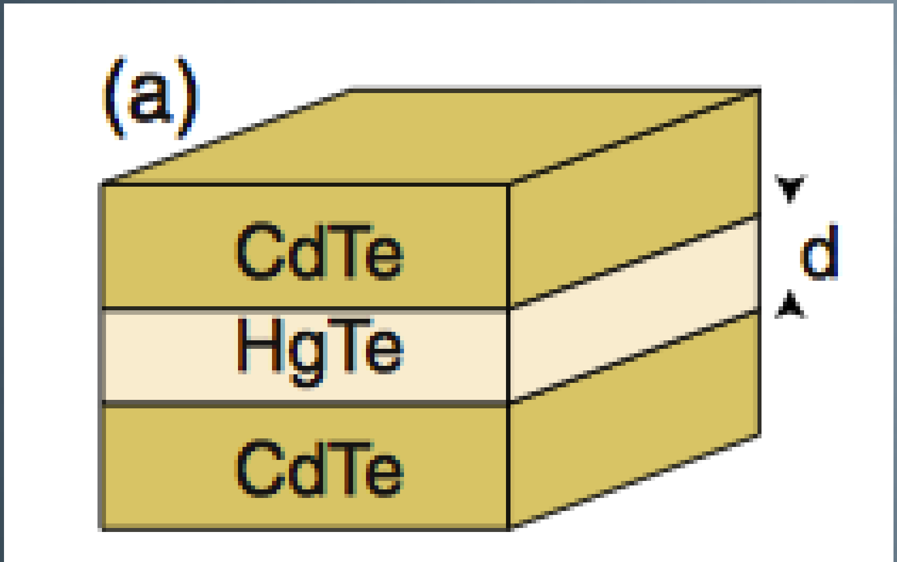
Rechtsman *et al.,* Nature **496**, 196 (2013)

Goal

- Study transport properties of topological edge states in the presence of time periodic potential
- Study both forms of edge states: naturally occurring and driven.

Quantum Well Heterostructures

- For concreteness we study quantum well heterostructures



Hasan and Kane, RMP **82** (2010)

$$\tilde{H}(\mathbf{k}) = \begin{pmatrix} H(\mathbf{k}) & 0 \\ 0 & H^*(-\mathbf{k}) \end{pmatrix}$$

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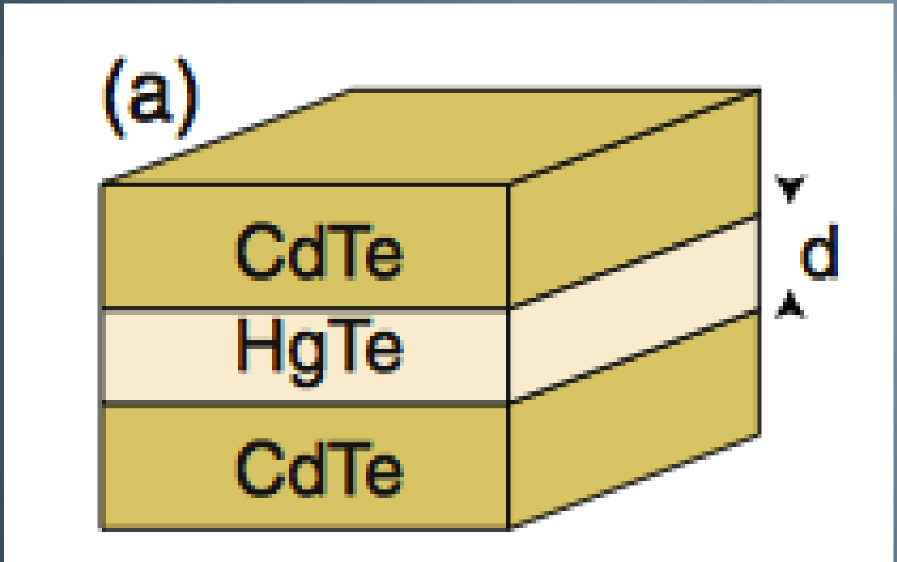

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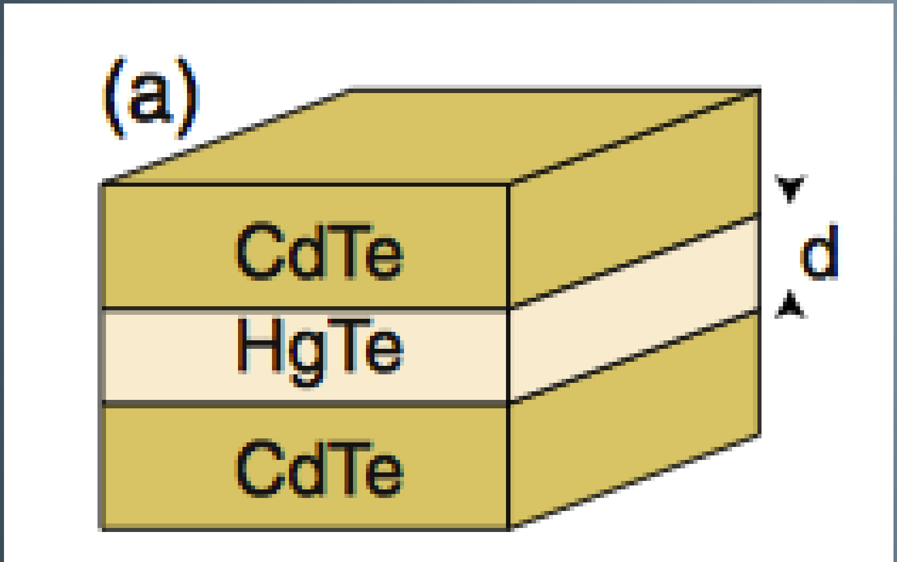

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$$V(t) = 2V_{ext}\sigma_z \cos \Omega t$$

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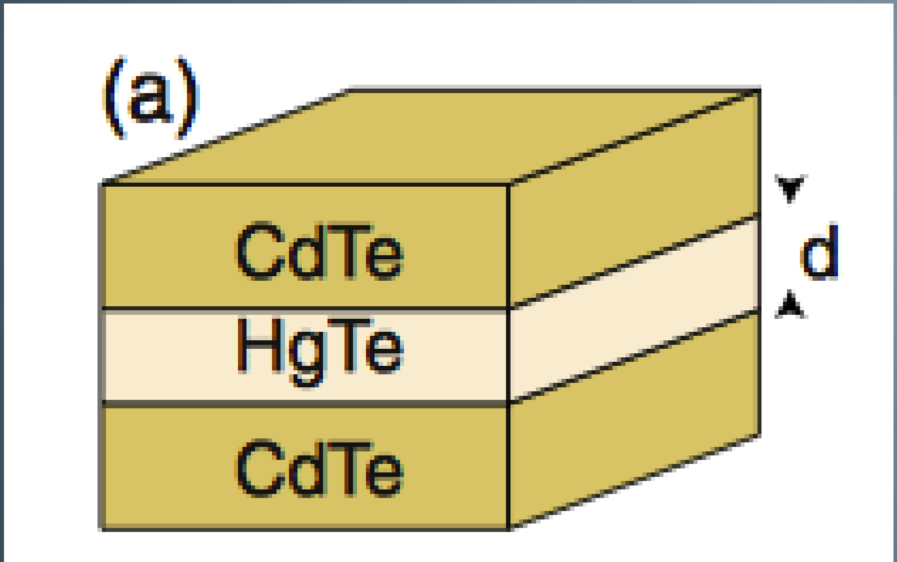

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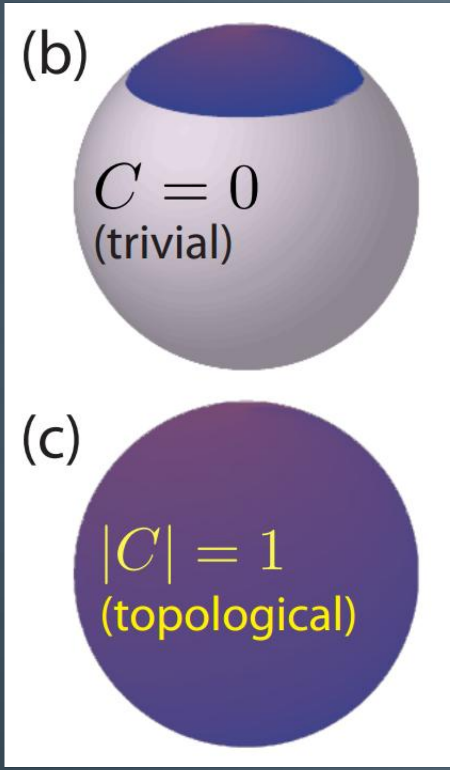

$$H(\mathbf{k}) = \epsilon(\mathbf{k})I + \vec{d}_{\mathbf{k}} \cdot \vec{\sigma}$$

$$\vec{d}_{\mathbf{k}} = (A \sin k_x, A \sin k_y, M + 2B(\cos k_x + \cos k_y - 2))$$

Alicea, *Rep. Prog. Phys.* **75** (2012) 076501

Quantum Well Heterostructures

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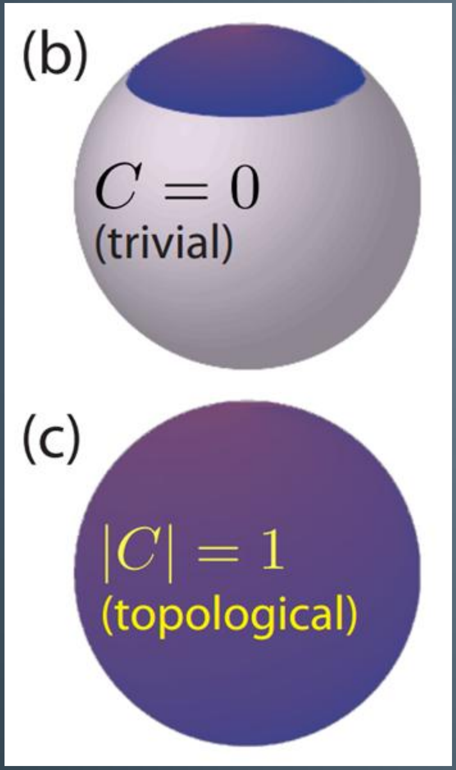

Alicea, *Rep. Prog. Phys.* **75** (2012) 076501

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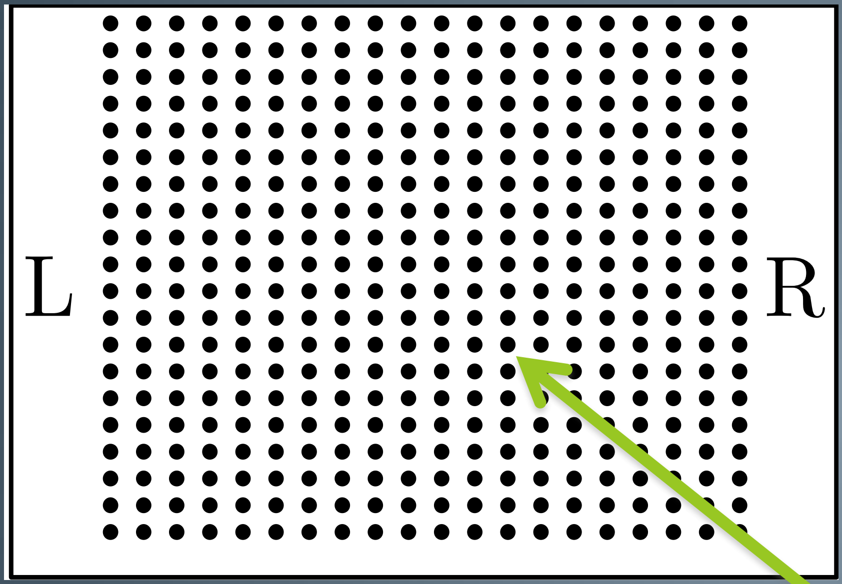
$$\vec{d}_{\mathbf{k}} = (A\sin k_x, A\sin k_y, M + 2B(\cos k_x + \cos k_y - 2))$$

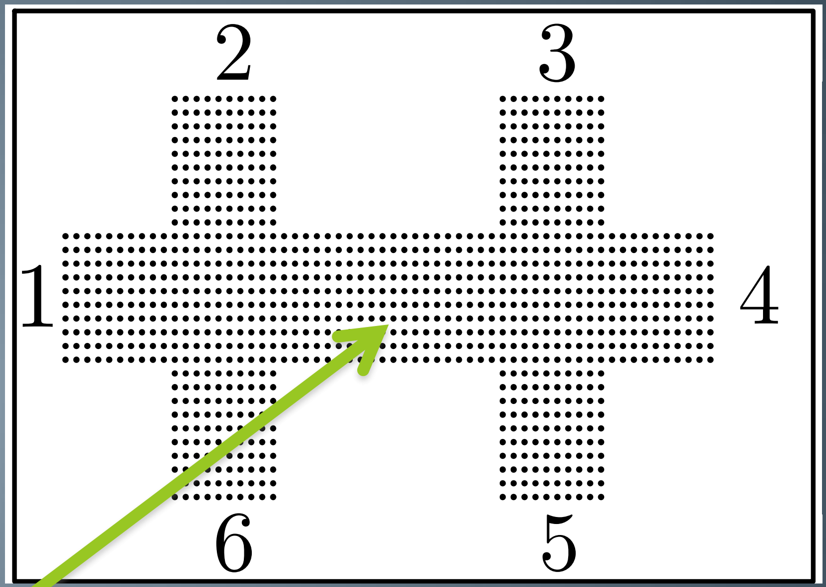
sign(*MB*)>0 → Topological
sign(*MB*)<0→ Trivial

Quantum Well Heterostructures

- Focus on topological parameter regime to gain insight.
- Look for signature transport values and robustness

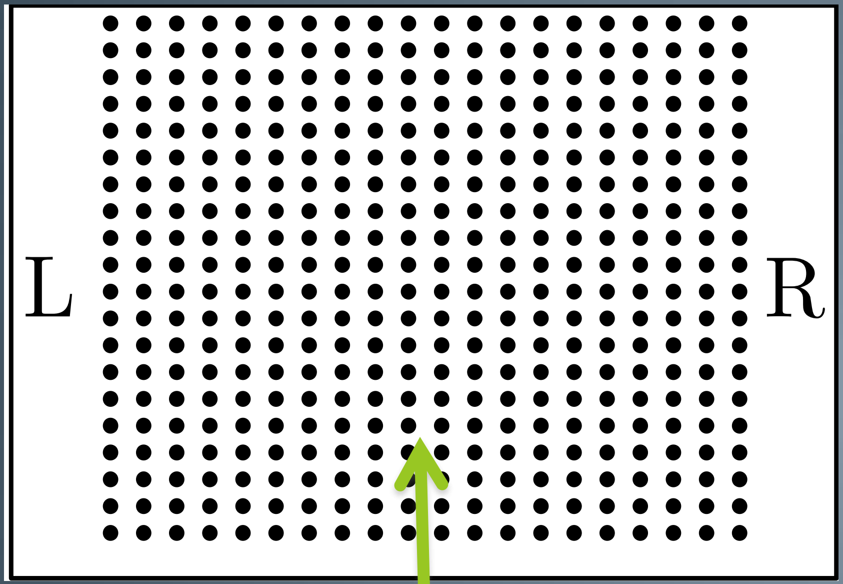
Time Periodic Landauer Formalism





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

Time Periodic Landauer Formalism



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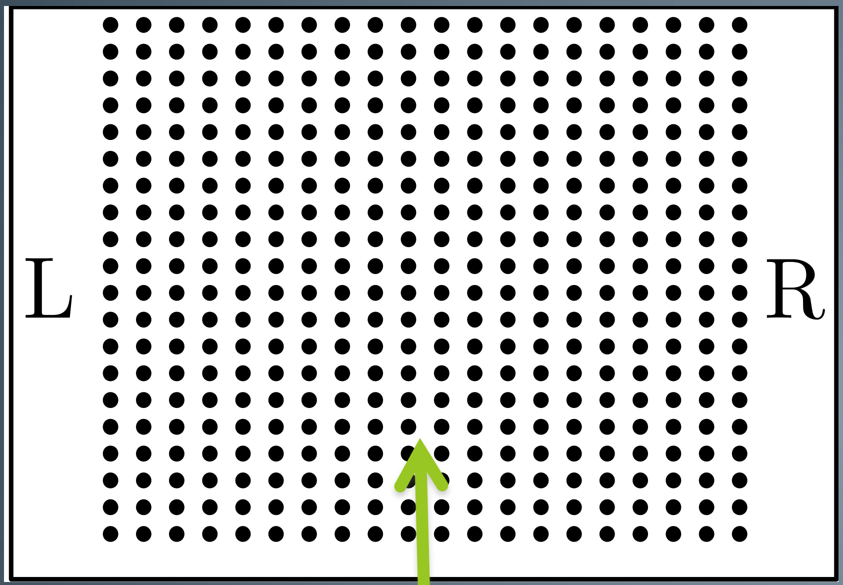
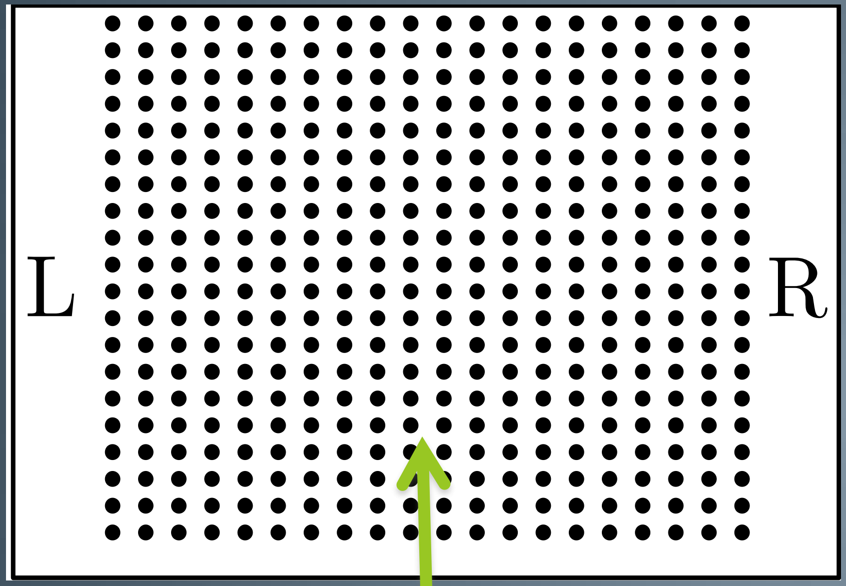


Lead $\alpha \to \Sigma_\alpha$

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

Time Periodic Landauer Formalism

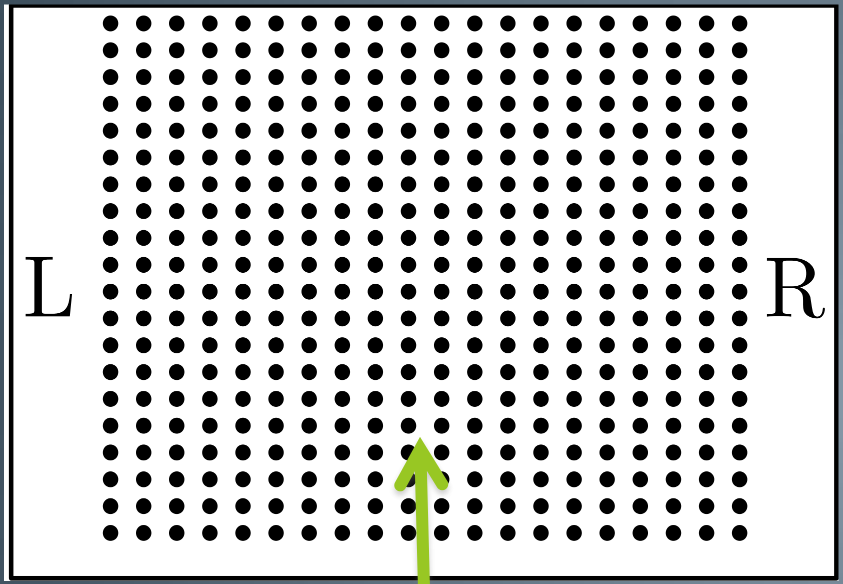


$$H(t+T) = H(t)$$

$$\text{Lead } \alpha \to \Sigma_\alpha$$

$$H(t) \to H(t) + \Sigma$$

Time Periodic Landauer Formalism



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

$$\text{Lead } \alpha \to \Sigma_\alpha$$

$$H(t) \to H(t) + \Sigma$$

$$\Sigma = \sum_\alpha \Sigma_\alpha = \frac{i}{2}\Gamma$$

Landauer Formalism

$$\bar{I}_\lambda = \frac{e}{h} \sum_{\lambda'} \int d\epsilon \left(T_{\lambda,\lambda'}(\epsilon) f_{\lambda'}(\epsilon) - T_{\lambda',\lambda}(\epsilon) f_\lambda(\epsilon) \right)$$

Landauer Formalism

$$\bar{I}_\lambda = \frac{e}{h} \sum_{\lambda'} \int d\epsilon \left(T_{\lambda,\lambda'}(\epsilon) f_{\lambda'}(\epsilon) - T_{\lambda',\lambda}(\epsilon) f_\lambda(\epsilon) \right)$$

$$G(\epsilon) = \int dt' e^{i\epsilon(t-t')} G(t,t')$$

Landauer Formalism

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$$G(t,t') = G(t-t')$$

Time Periodic Landauer Formalism

$$\bar{I}_\lambda = \frac{e}{h} \sum_{\lambda'} \int d\epsilon \left(T_{\lambda,\lambda'}(\epsilon) f_{\lambda'}(\epsilon) - T_{\lambda',\lambda}(\epsilon) f_\lambda(\epsilon) \right)$$

$$G^{(n)}(\epsilon) = \frac{1}{T} \int_0^T dt e^{-in\Omega t} \int dt' e^{i\epsilon(t-t')} G(t,t')$$

Time Periodic Landauer Formalism

$$\bar{I}_\lambda = \frac{e}{h}\sum_{\lambda'}\int d\epsilon\,(T_{\lambda,\lambda'}(\epsilon)f_{\lambda'}(\epsilon) - T_{\lambda',\lambda}(\epsilon)f_\lambda(\epsilon))$$

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Green's function of $H(t) + \Sigma$

Time Periodic Landauer Formalism

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$$T_{\lambda,\lambda'}(\epsilon) = \sum_n \mathrm{Tr}\left[\Gamma_\lambda G^{(n)}(\epsilon)\Gamma_{\lambda'}(G^{(n)}(\epsilon))^\dagger\right]$$

Time Periodic Landauer Formalism

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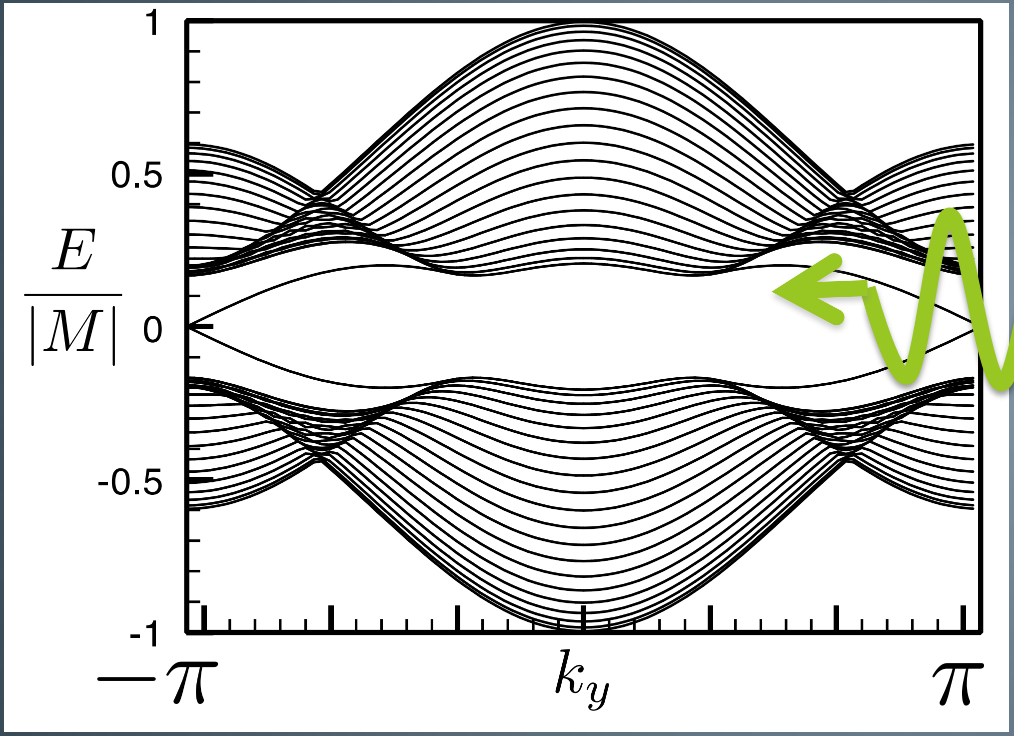
$$\sigma = \frac{d\bar{I}_\lambda}{dV_{bias}}$$

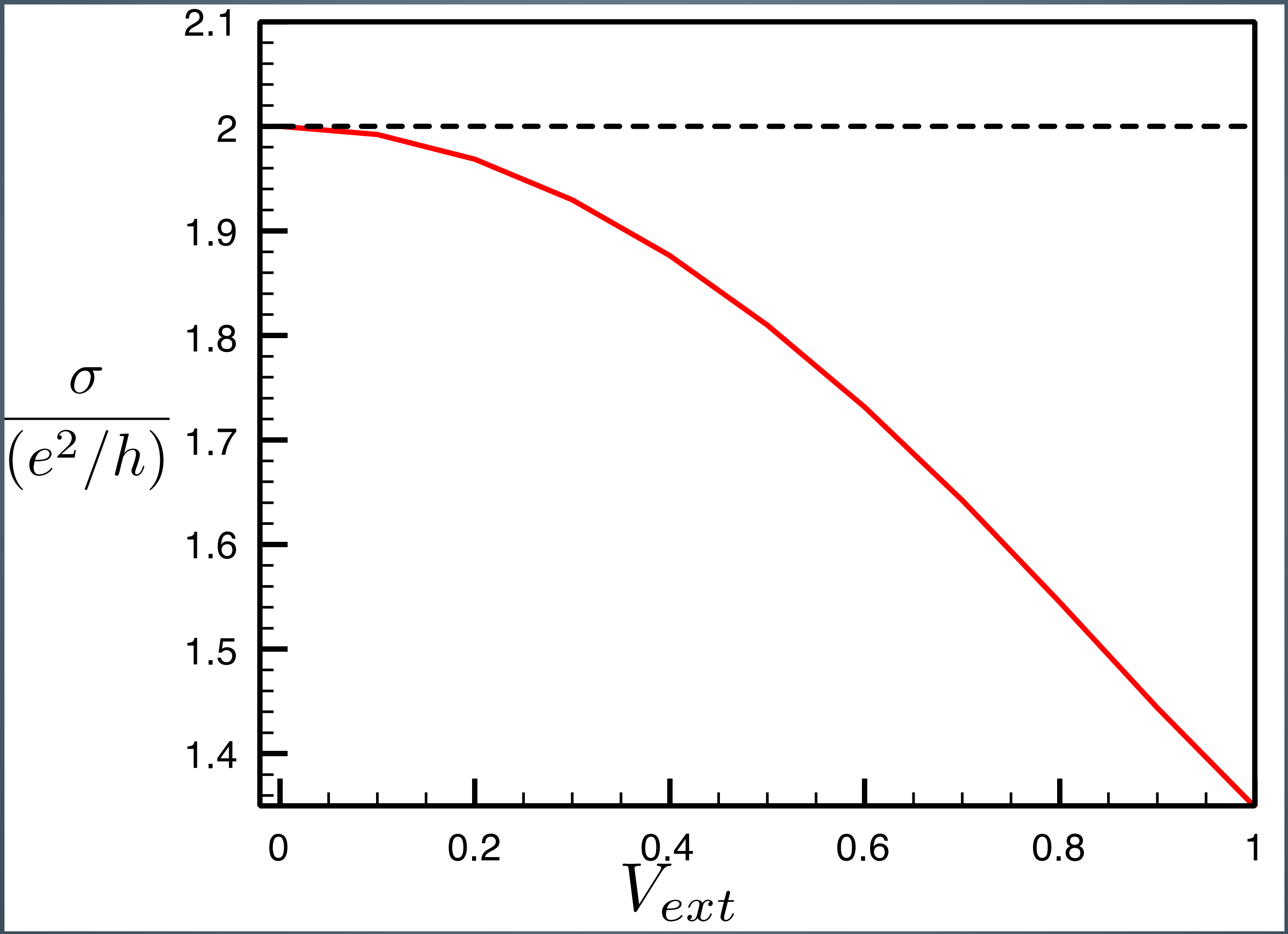
Numerical Calculation



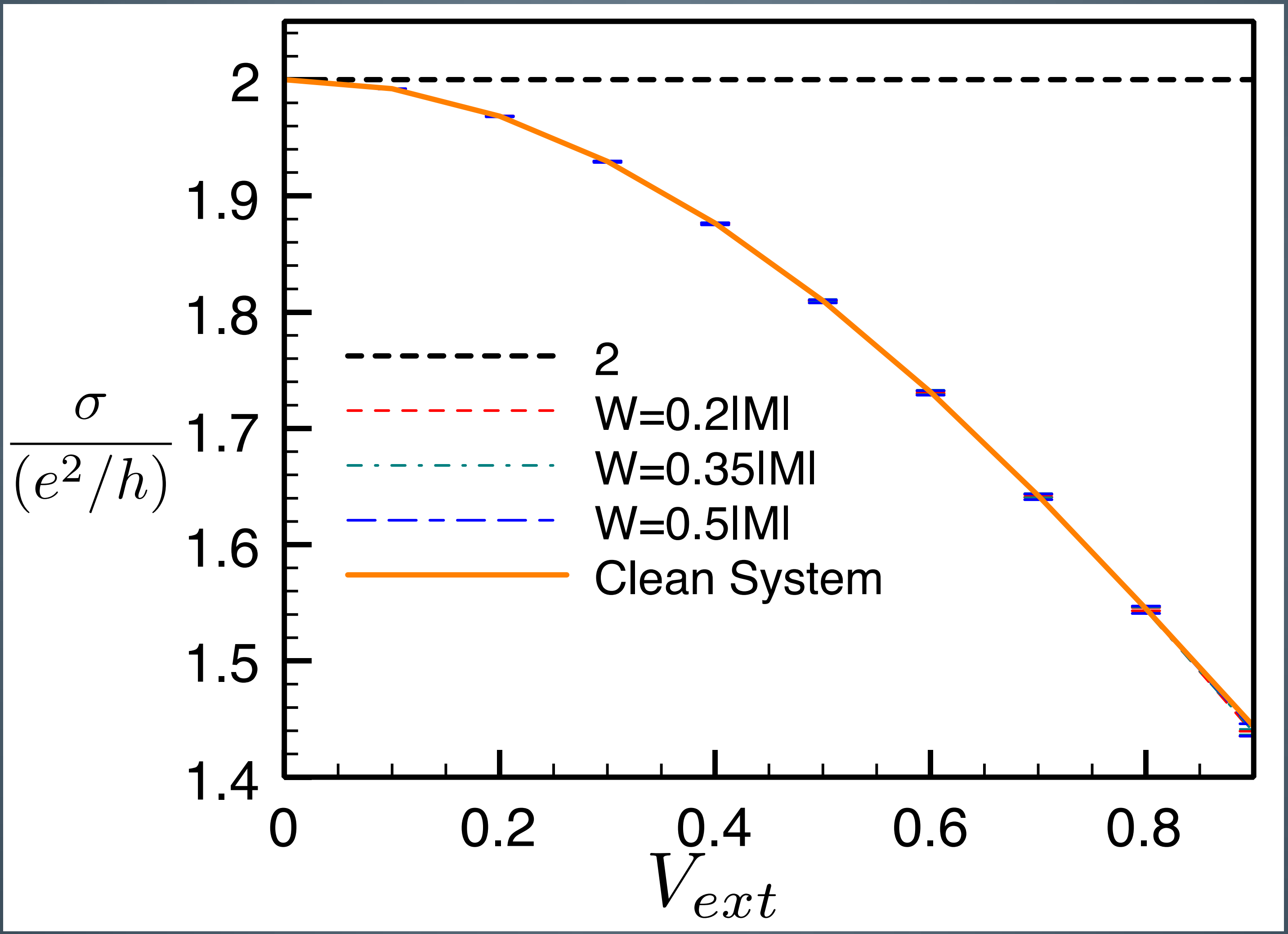
$V(t) = V(t+T)$

$\text{Strength} = V_{ext}$

Numerical Calculation



Insensitivity to Disorder



Periodic Topological Insulator

- No quantized conductivity
- Insensitive to disorder and material parameters
- Still “topologically robust”
- Where did the lost conductivity go?

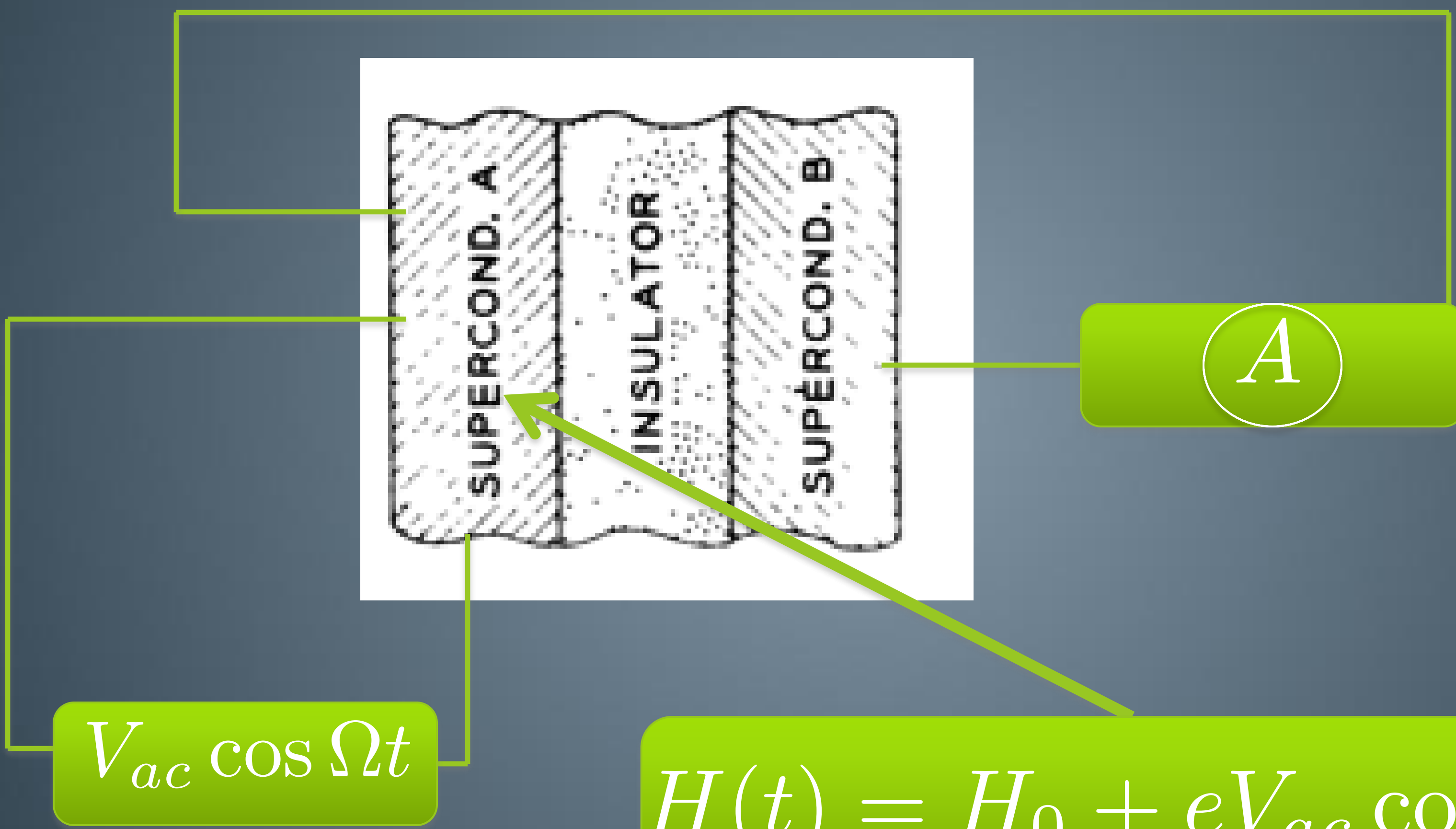
Photon Assisted Tunneling

PHYSICAL REVIEW VOLUME 129, NUMBER 2 15 JANUARY 1963

Multiphoton Process Observed in the Interaction of Microwave Fields with the Tunneling between Superconductor Films

P. K. Tien and J. P. Gordon
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 28 August 1962)

Photon Assisted Tunneling



$$H(t) = H_0 + eV_{ac}\cos\Omega t$$

P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

Photon Assisted Tunneling

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Photon Assisted Tunneling

$$H(t) = H_0 + eV_{ac} \cos \Omega t$$

$$|\psi(t)\rangle = e^{-i \frac{eV_{ac}}{\hbar\Omega} \sin \Omega t} |\psi_0(t)\rangle$$

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$$i\hbar\partial_t |\psi_0(t)\rangle = H_0 |\psi_0(t)\rangle$$

$$e^{-i\alpha \sin \Omega t} = \sum_m J_m(\alpha) e^{-im\Omega t}$$

P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

Photon Assisted Tunneling

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$$|\psi_0(t)\rangle = e^{-iEt/\hbar}|\psi_0^E\rangle$$

P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

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$$|\psi(t)\rangle = \sum_m J_m(\alpha)e^{-i(\hbar m\Omega+E)t/\hbar}|\psi_0\rangle$$

P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

Photon Assisted Tunneling

E →

⋮	
$E + 2\hbar\Omega$	$J_2^2(\alpha)$
$E + \hbar\Omega$	$J_1^2(\alpha)$
E	$J_0^2(\alpha)$
$E - \hbar\Omega$	$J_{-1}^2(\alpha)$
$E - 2\hbar\Omega$	$J_{-2}^2(\alpha)$
⋮	

$$|\psi(t)\rangle = \sum_m J_m(\alpha) e^{-i(\hbar m\Omega + E)t/\hbar} |\psi_0\rangle$$

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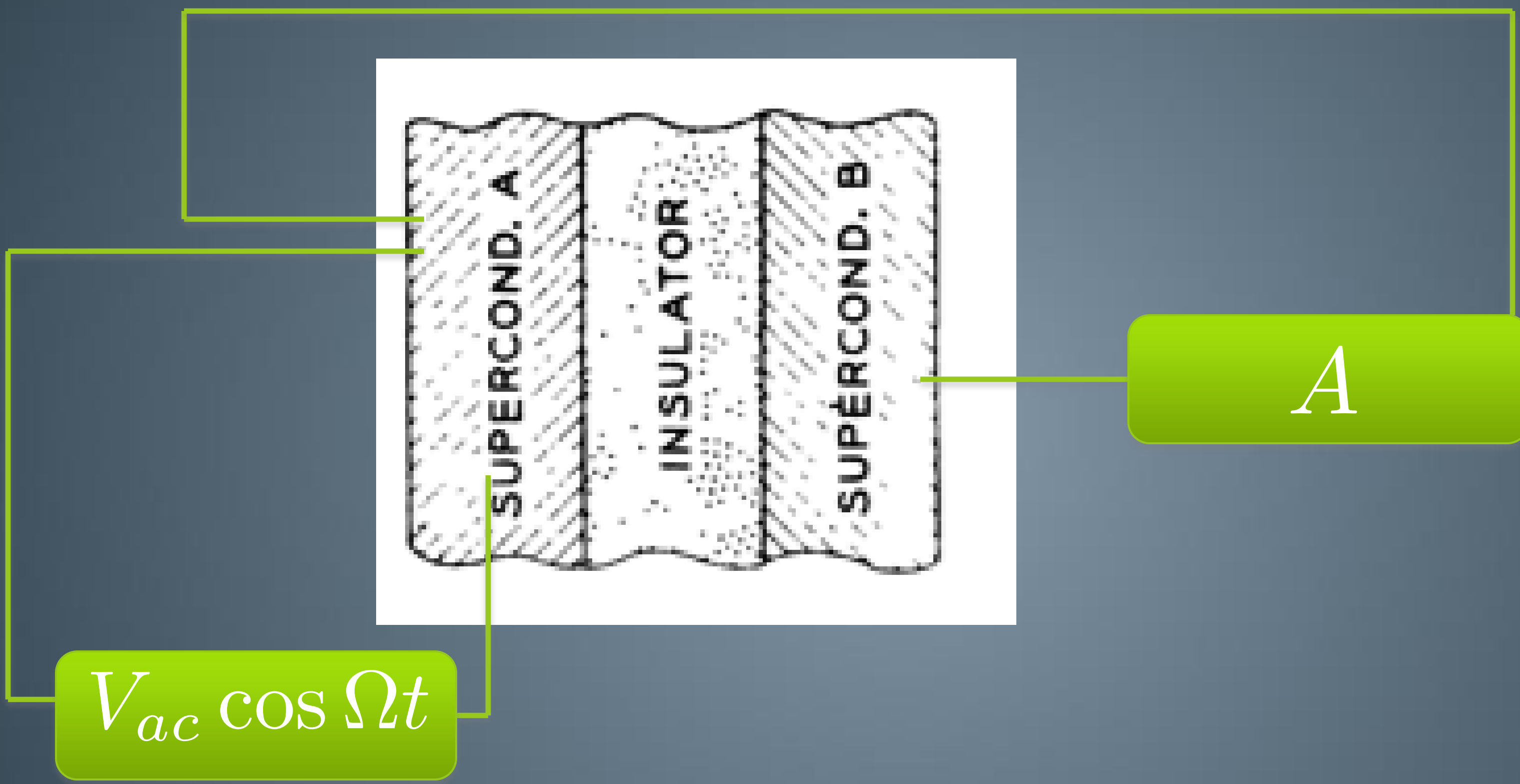
Photon Assisted Tunneling



$$I_{dc}(V_{dc}) = \sum_m J_m^2\left(\frac{eV_{ac}}{\hbar\Omega}\right) I_{dc}^0(V_{dc} + \frac{m\hbar\Omega}{e})$$

P. K. Tien and J. P. Gordon, Phys. Rev. 129, 647 (1963).

Photon Inhibited Topological Transport

- How does this help us….?

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Photon Inhibited Topological Transport

- How does this help us….?

$$H_{\mathbf{k}}(t) = H(\mathbf{k}) + V(t)$$

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Photon Inhibited Topological Transport

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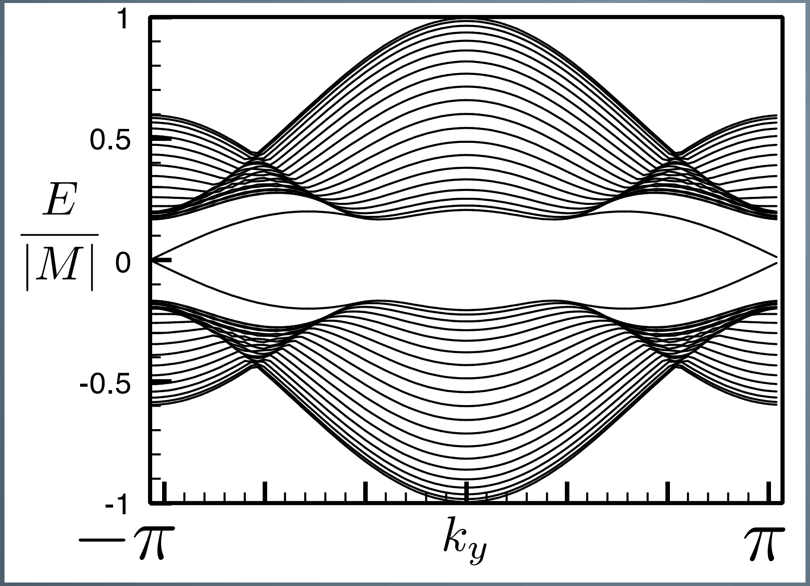
$$\tilde{H}_{\mathbf{k}}(t) = e^{i\frac{\mathbf{V}\cdot\vec{\sigma}}{\hbar\Omega}\sin\Omega t}H(\mathbf{k})e^{-i\frac{\mathbf{V}\cdot\vec{\sigma}}{\hbar\Omega}\sin\Omega t}$$

Photon Inhibited Topological Transport



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$$\tilde{H}_{\mathbf{k}}(t) \rightarrow H_{\mathbf{k}}^{eff} = \frac{1}{T}\int_0^T dt\tilde{H}_{\mathbf{k}}(t)$$

Photon Inhibited Topological Transport

- For off-resonant light the underlying static Hamiltonian is modified
- Modified Hamiltonian is split into sidebands

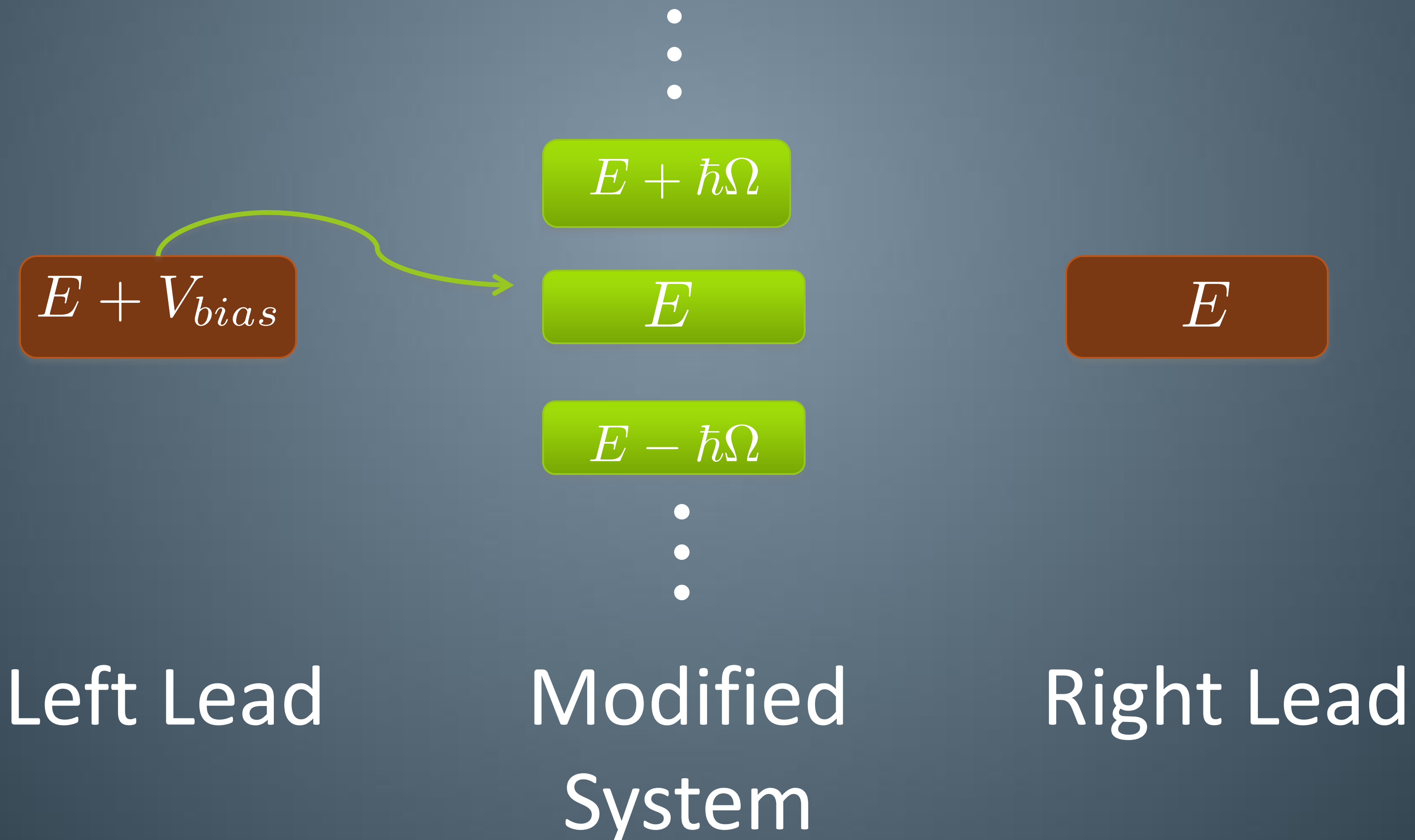
Photon Inhibited Topological Transport

Left Lead

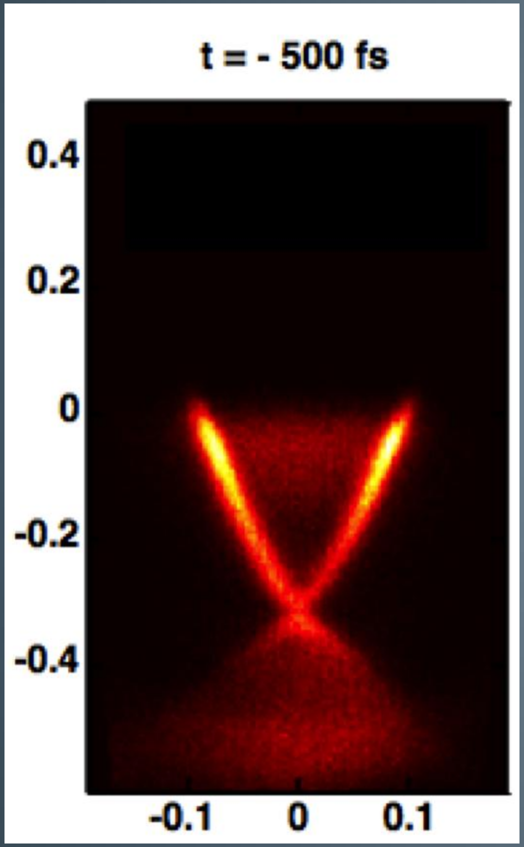
Modified System

Right Lead

Photon Inhibited Topological Transport

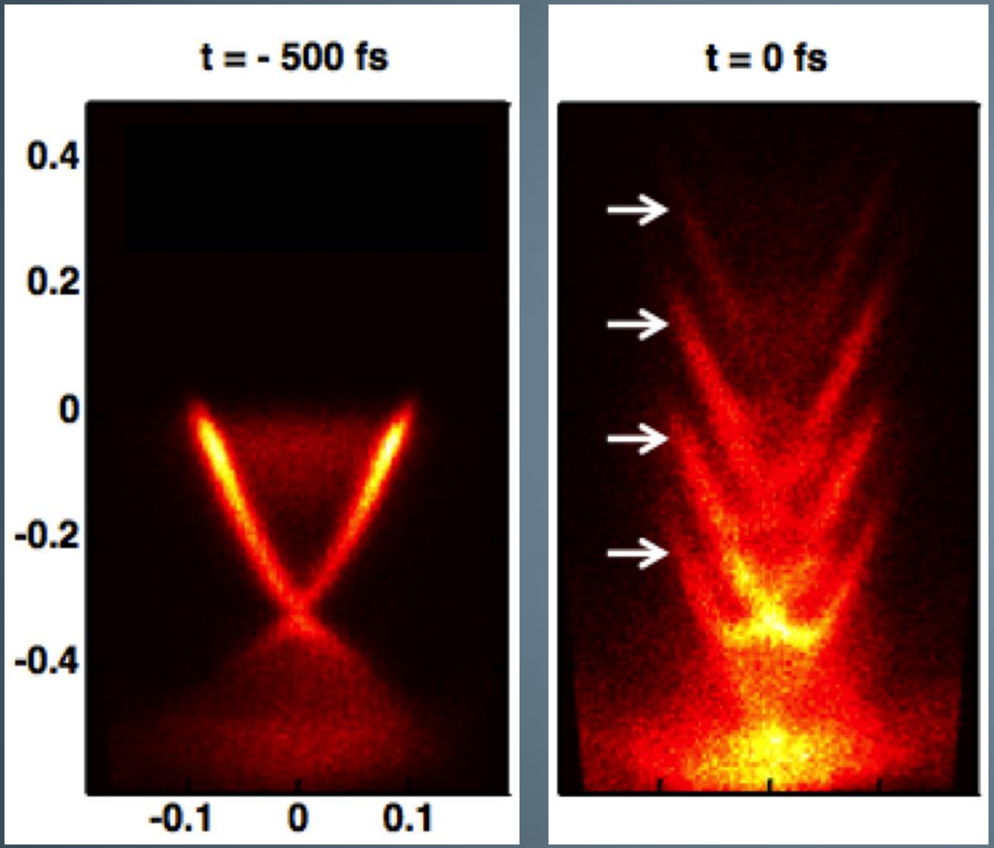


Side bands in time resolved ARPES



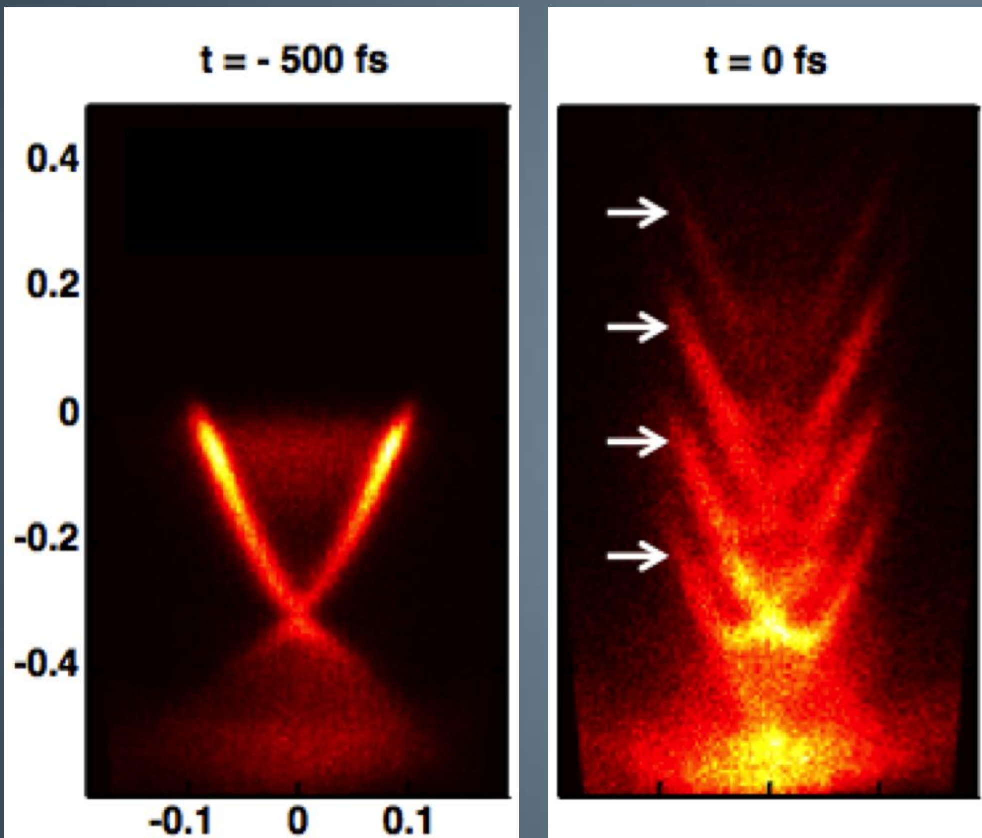
Y.H. Wang *et al*, Science, **342** (2013)

Side bands in time resolved ARPES



Y.H. Wang *et al*, Science, **342** (2013)

Photon Inhibited Topological Transport



Y.H. Wang *et al*, Science, **342** (2013)

⋮

$E + \hbar\Omega$

E

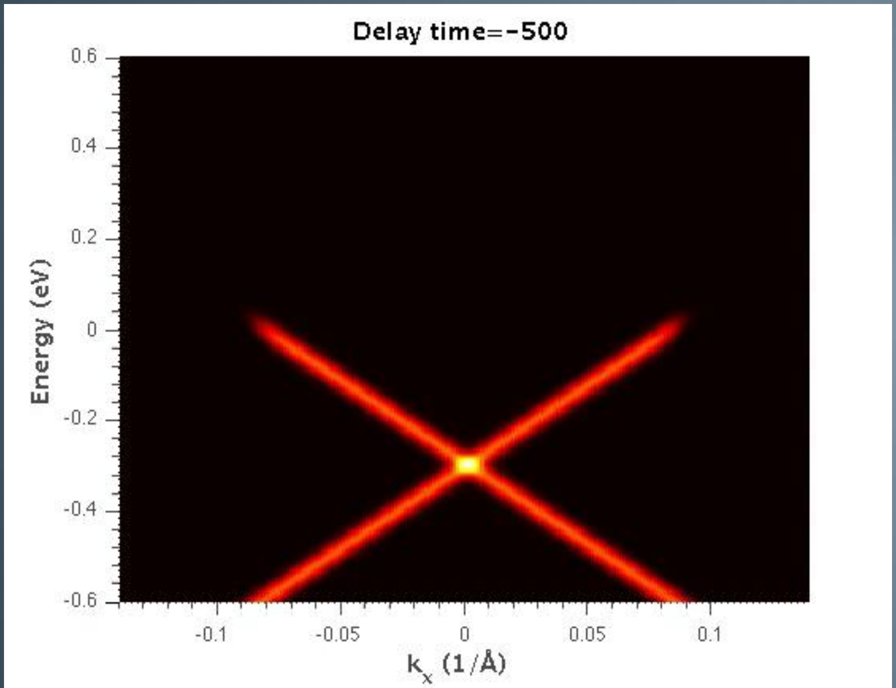
$E - \hbar\Omega$

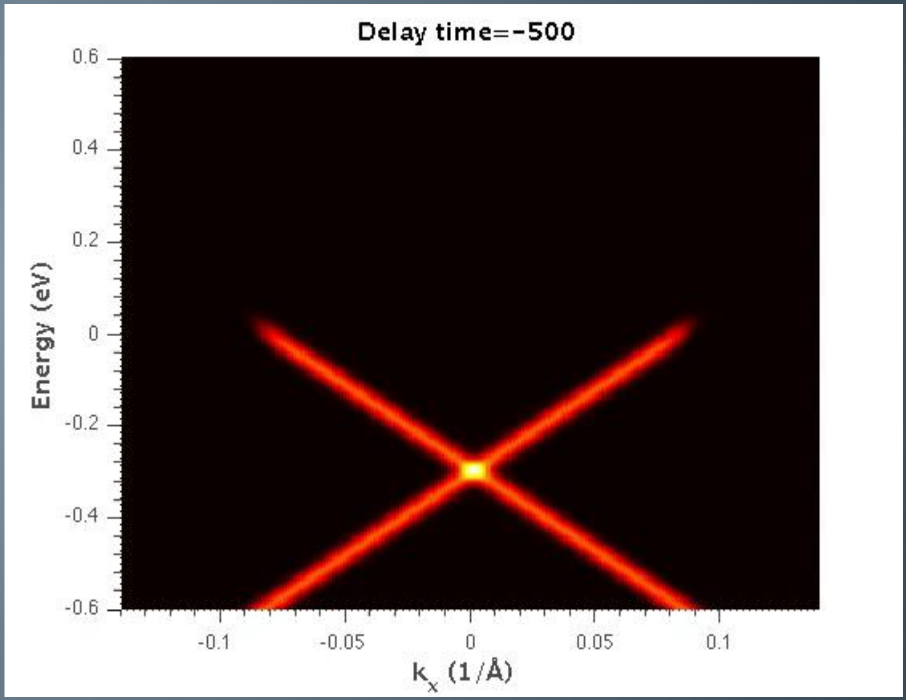
⋮

Aaron Farrell and TPB

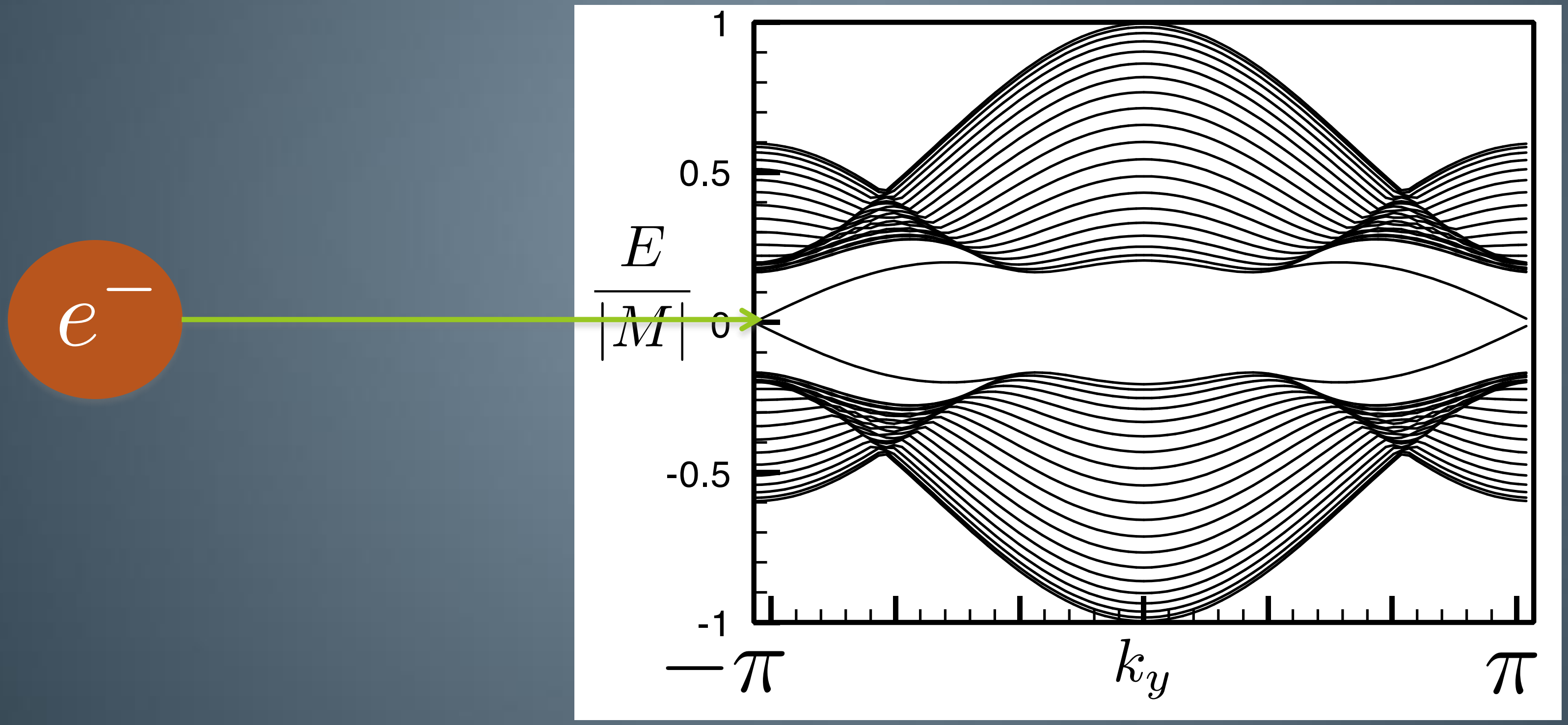
Work in Progress

Time Resolved ARPES simulation



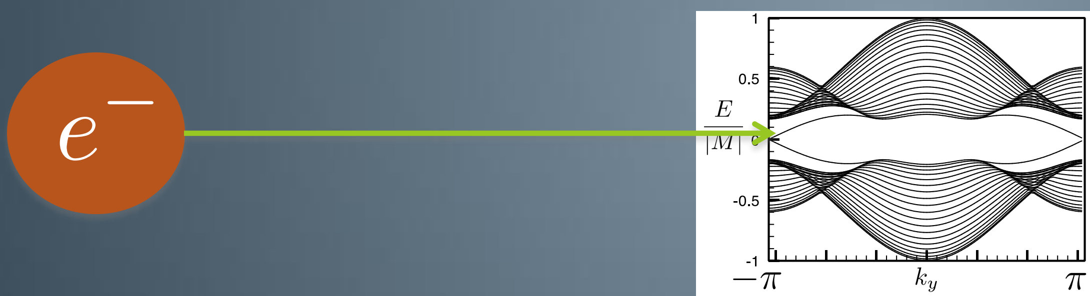


Photon Inhibited Topological Transport



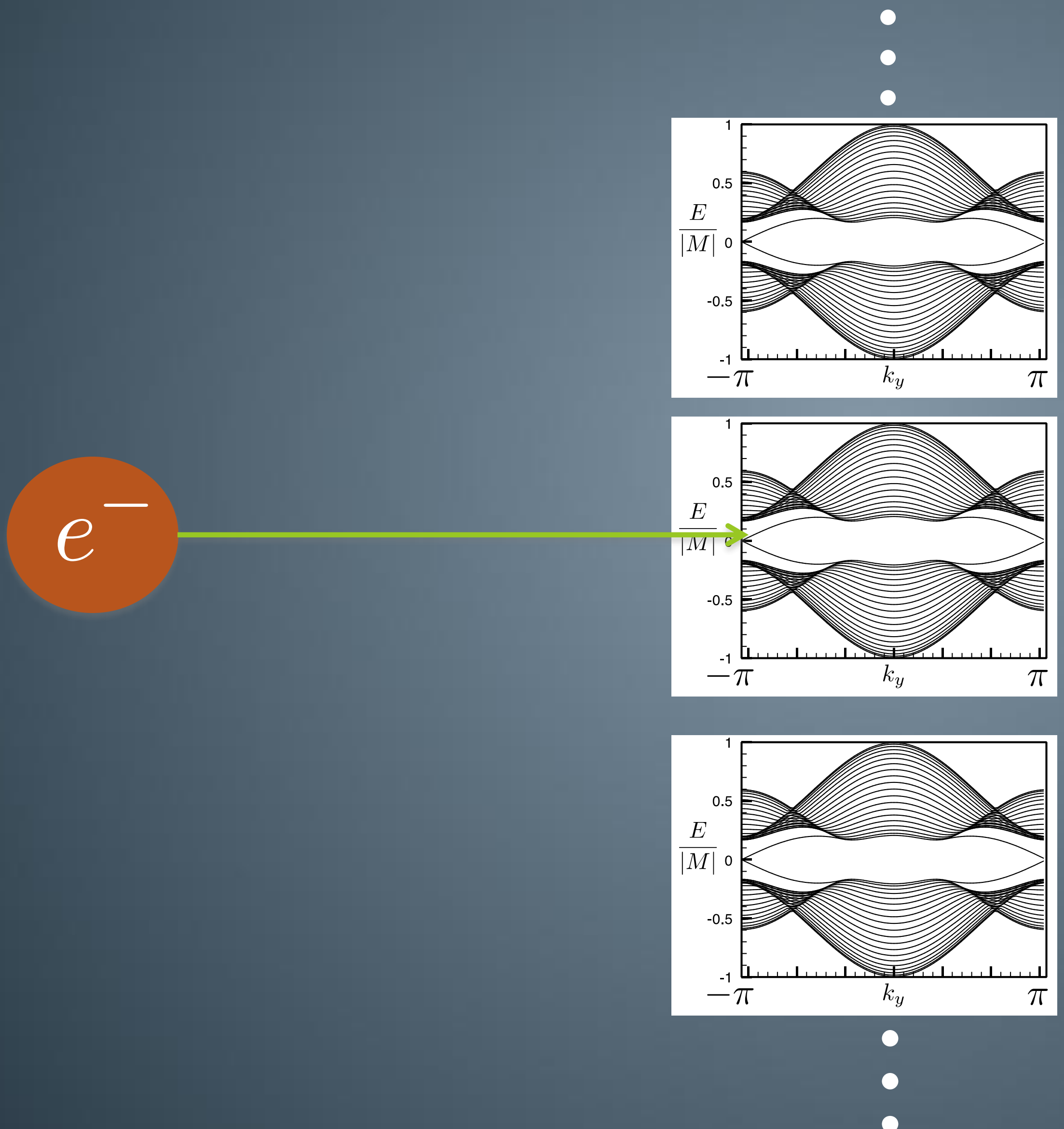
Bands of $H_{\mathbf{k}}^{eff}$

Photon Inhibited Topological Transport



Bands of $H_{\mathbf{k}}^{eff}$

Photon Inhibited Topological Transport

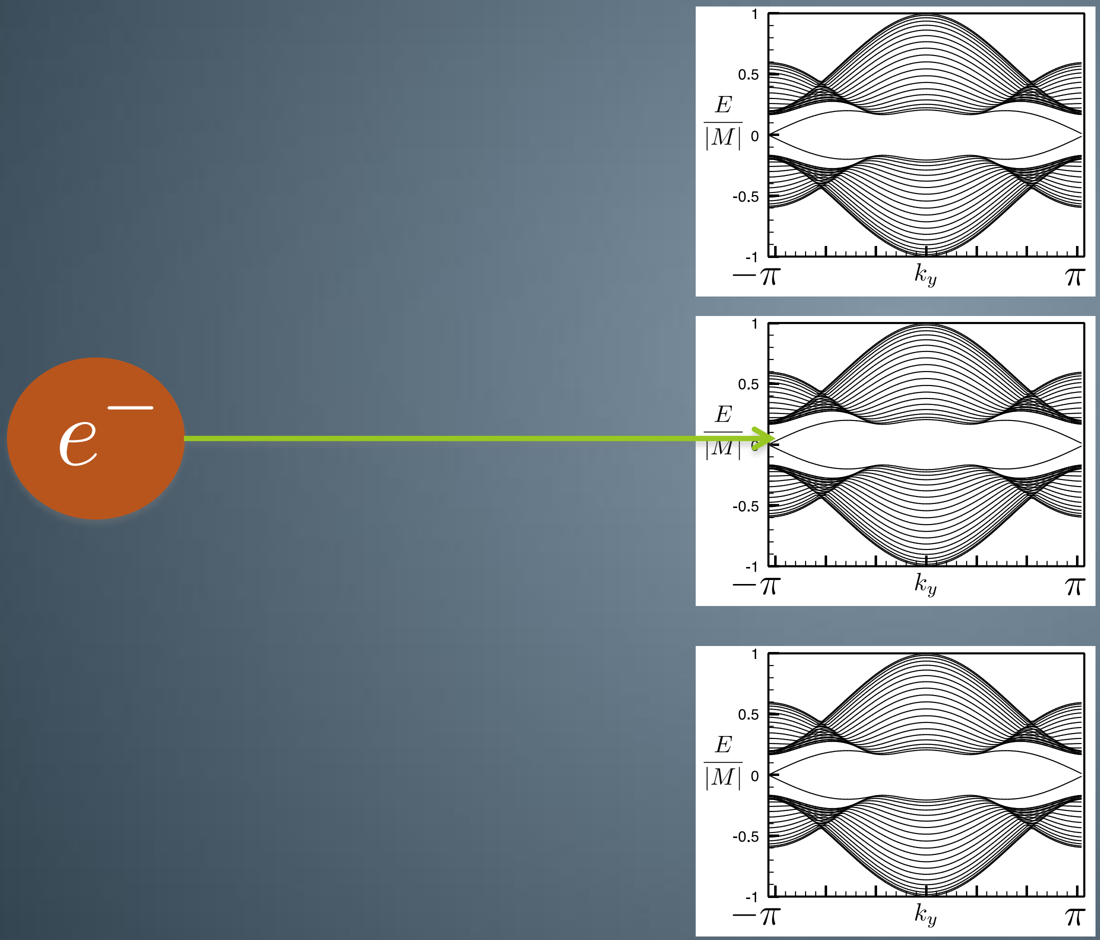


Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

Bands of $H_{\mathbf{k}}^{eff}$

Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

Photon Inhibited Topological Transport



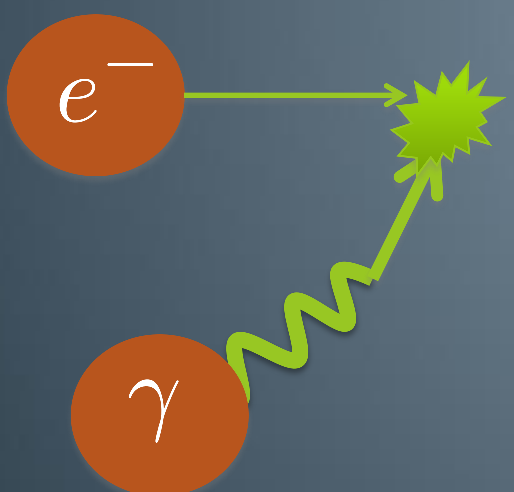
Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

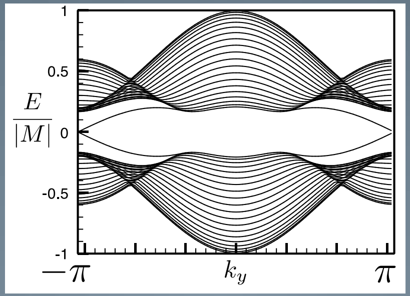
Bands of $H_{\mathbf{k}}^{eff}$

P_0

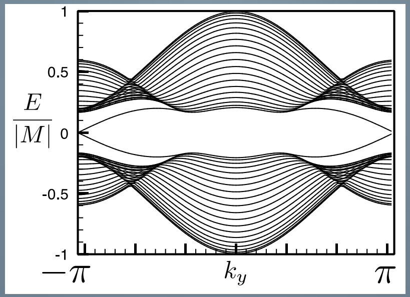
Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

Photon Inhibited Topological Transport



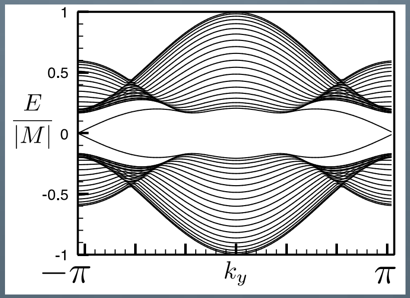


Bands of $H^{eff}_{\mathbf{k}} + \hbar\Omega$



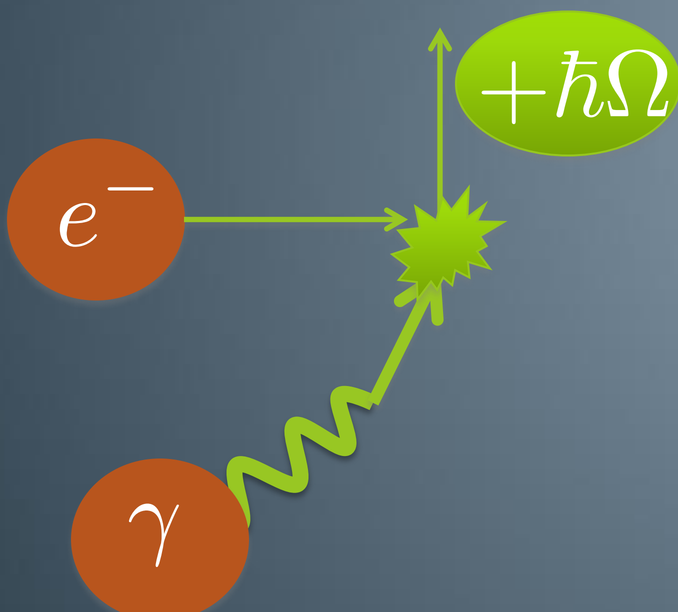
Bands of $H^{eff}_{\mathbf{k}}$

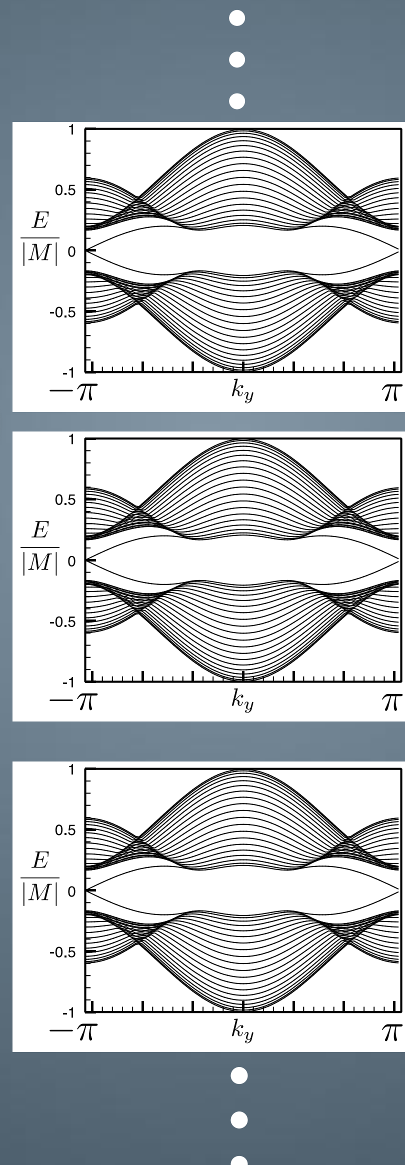
P_0



Bands of $H^{eff}_{\mathbf{k}} - \hbar\Omega$

Photon Inhibited Topological Transport





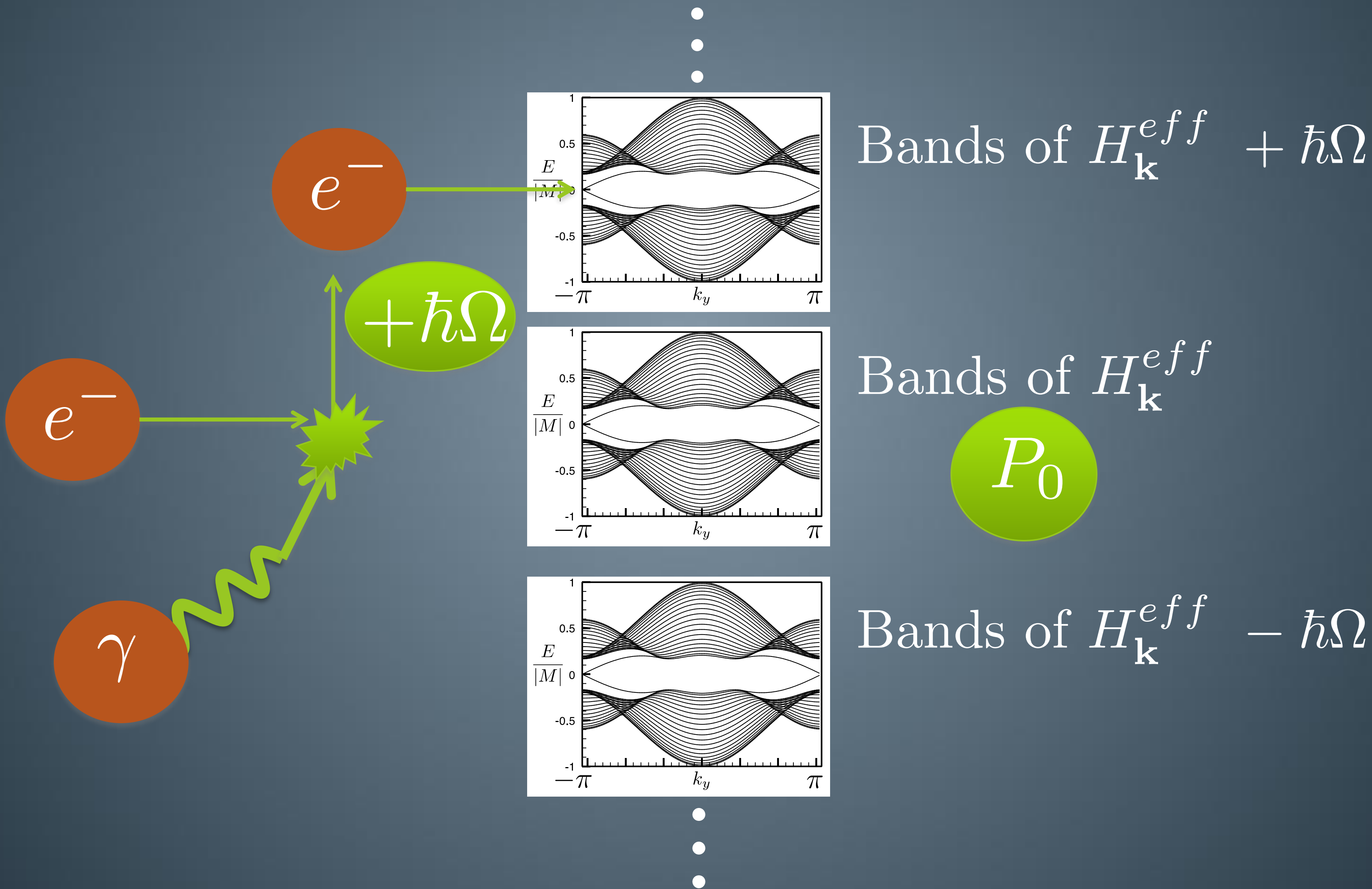
Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

Bands of $H_{\mathbf{k}}^{eff}$

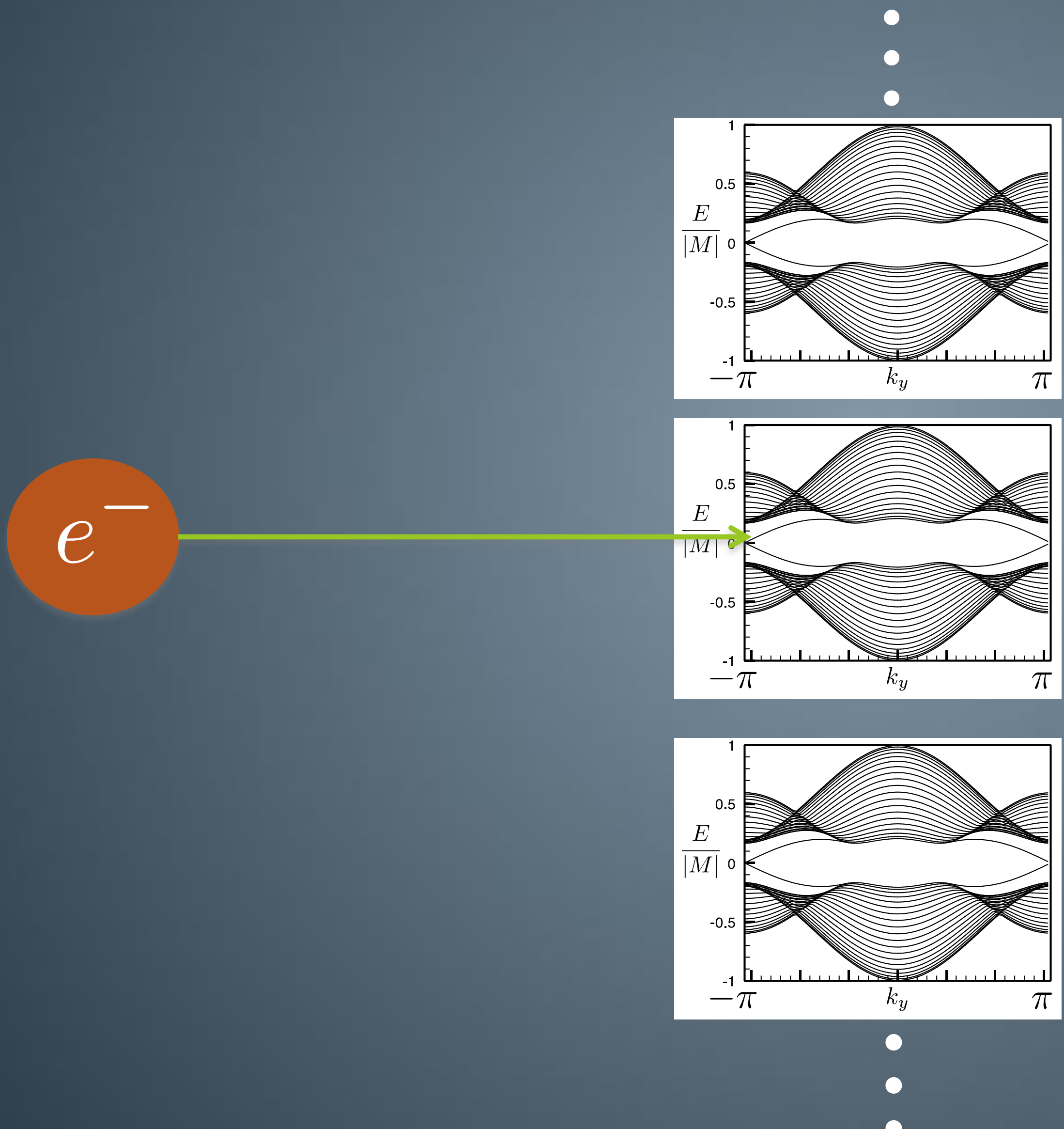
P_0

Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

Photon Inhibited Topological Transport



Photon Inhibited Topological Transport



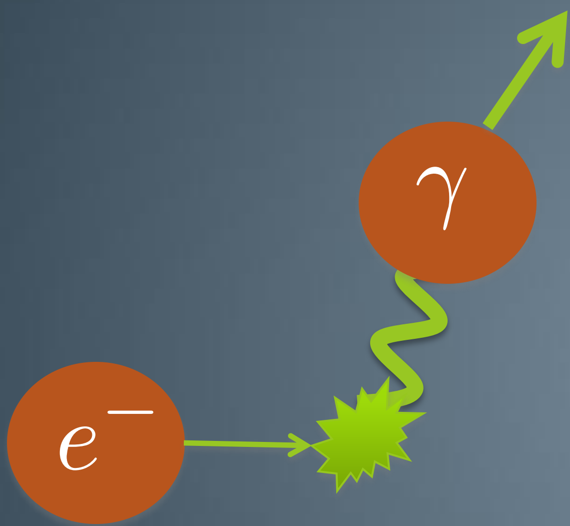
Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

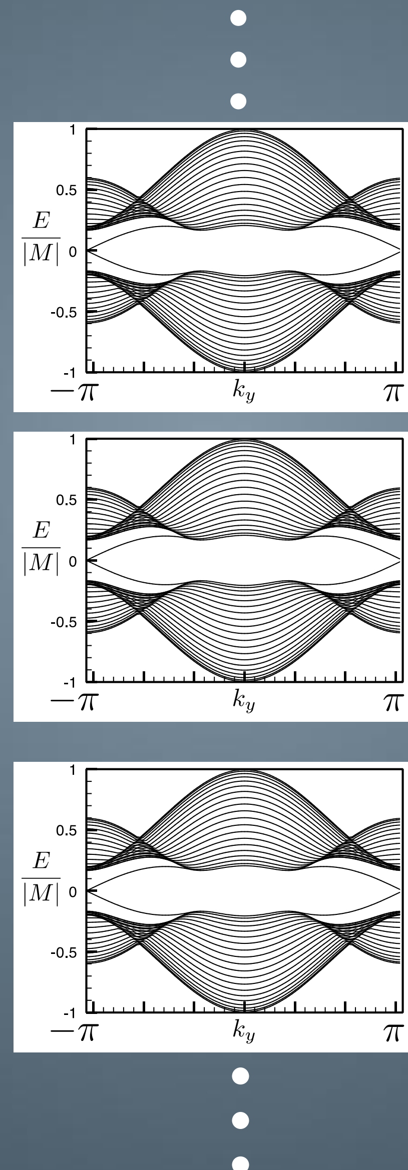
Bands of $H_{\mathbf{k}}^{eff}$

P_0

Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

Photon Inhibited Topological Transport





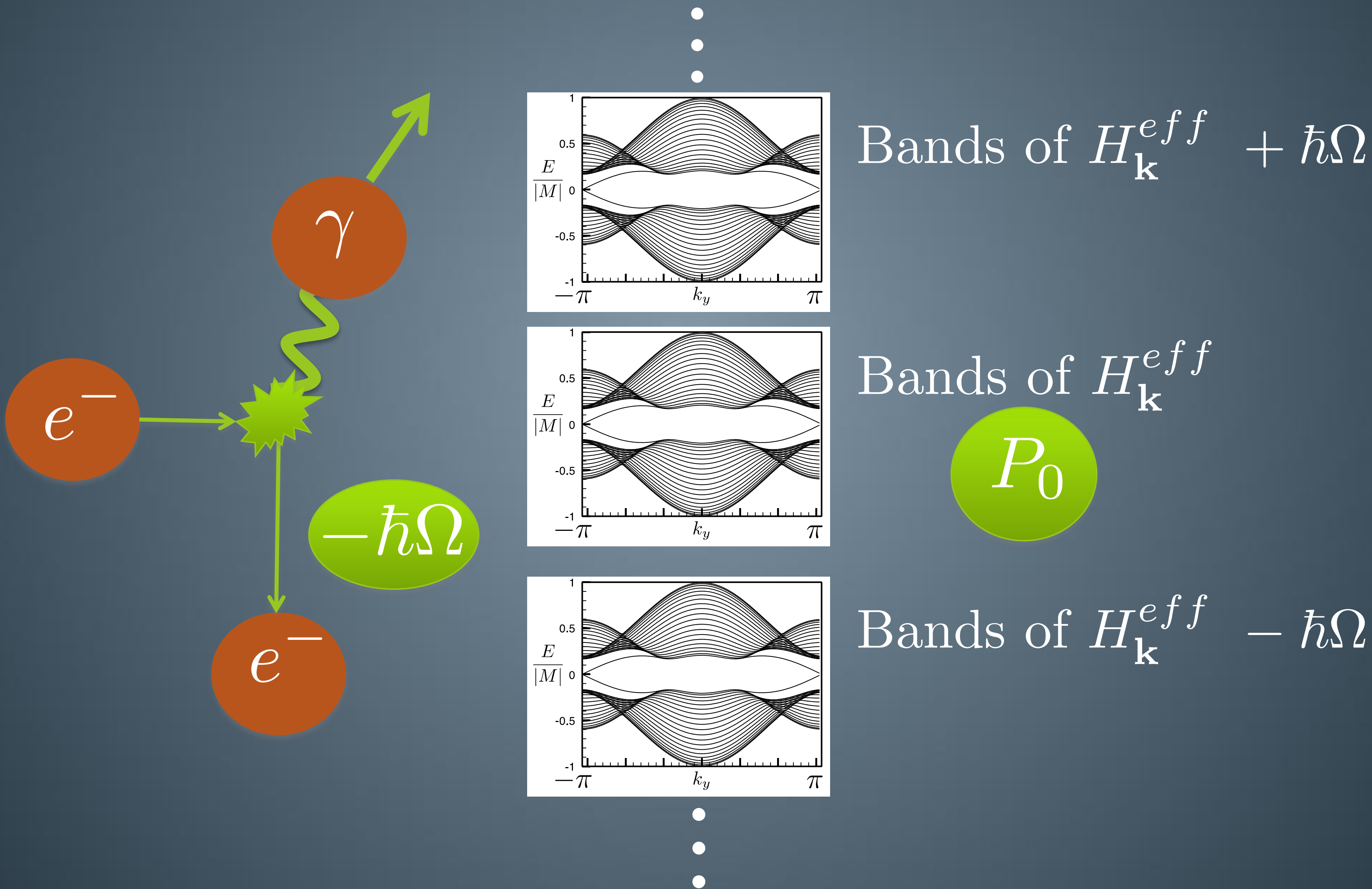
Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

Bands of $H_{\mathbf{k}}^{eff}$

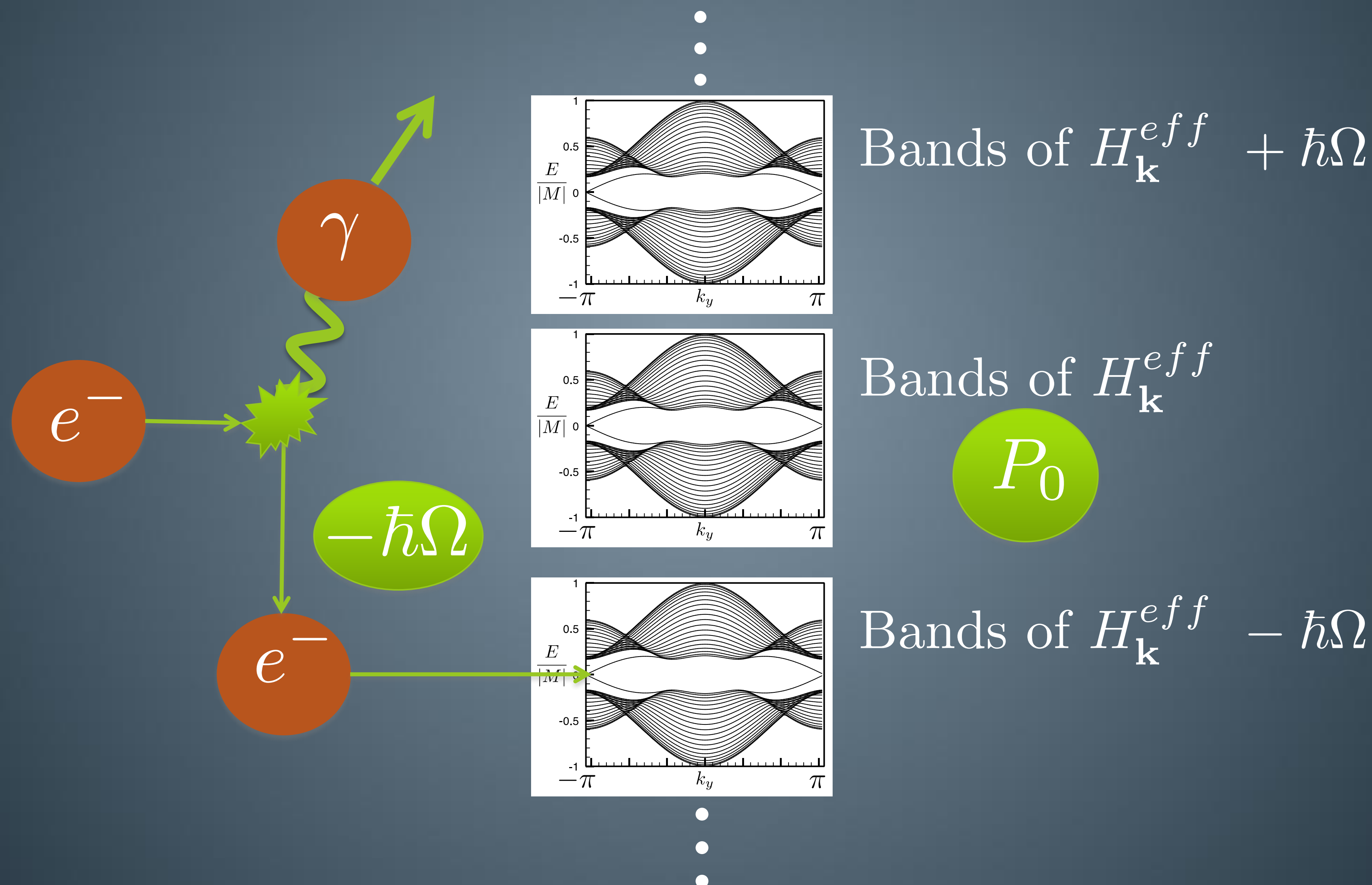
P_0

Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

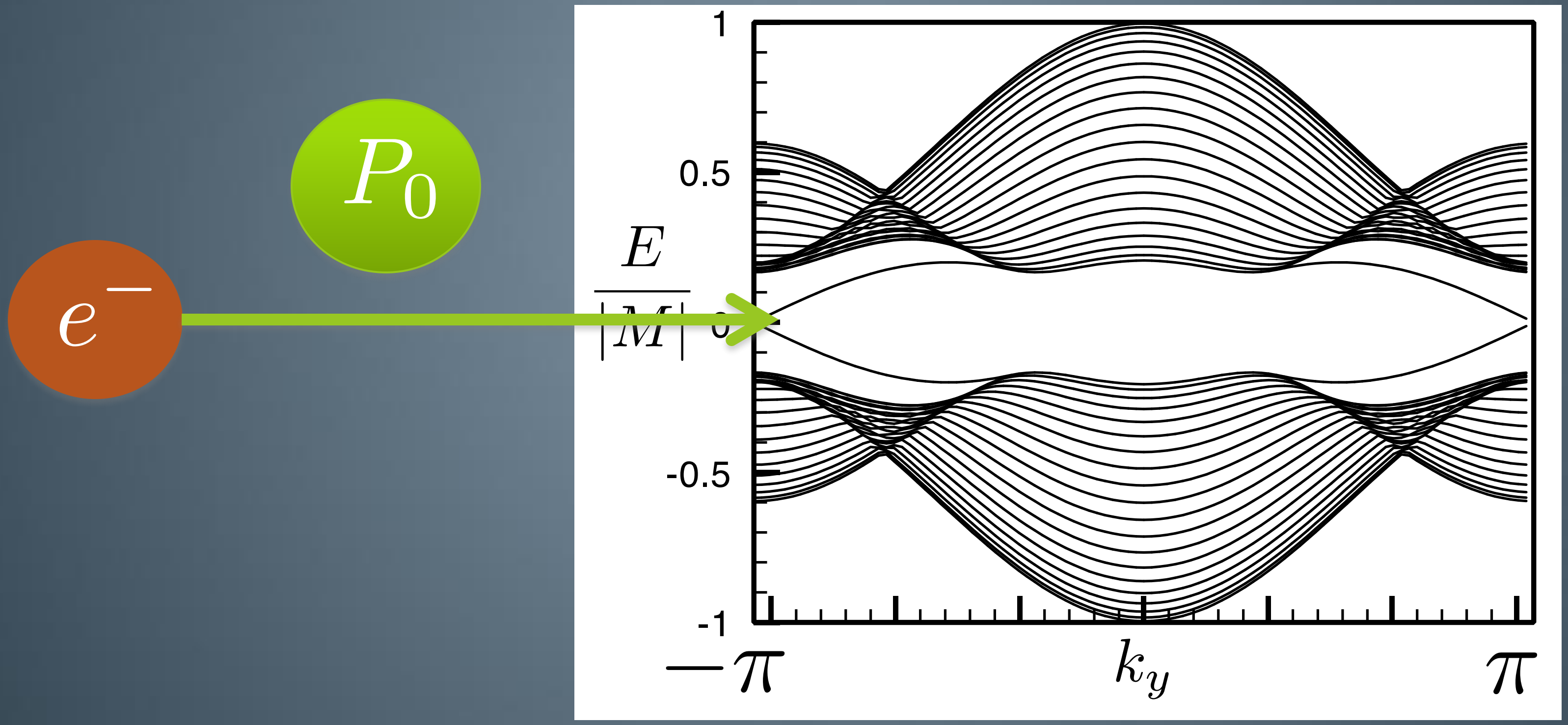
Photon Inhibited Topological Transport



Photon Inhibited Topological Transport



Photon Inhibited Topological Transport



Bands of $H_{\mathbf{k}}^{eff}$

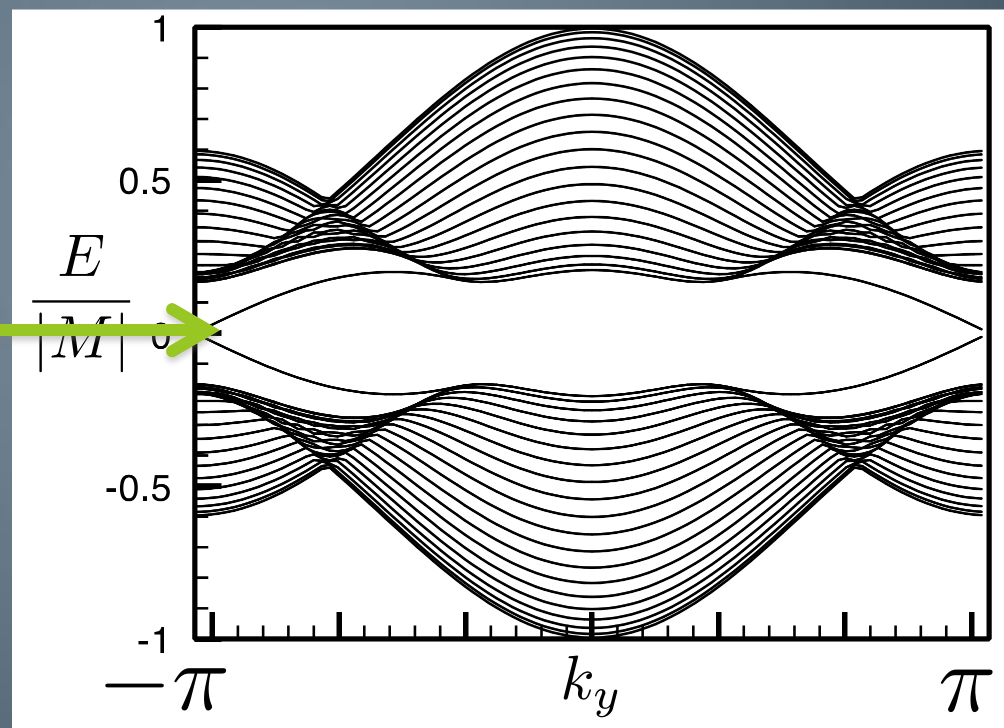
Photon Inhibited Topological Transport

P_0

e^-

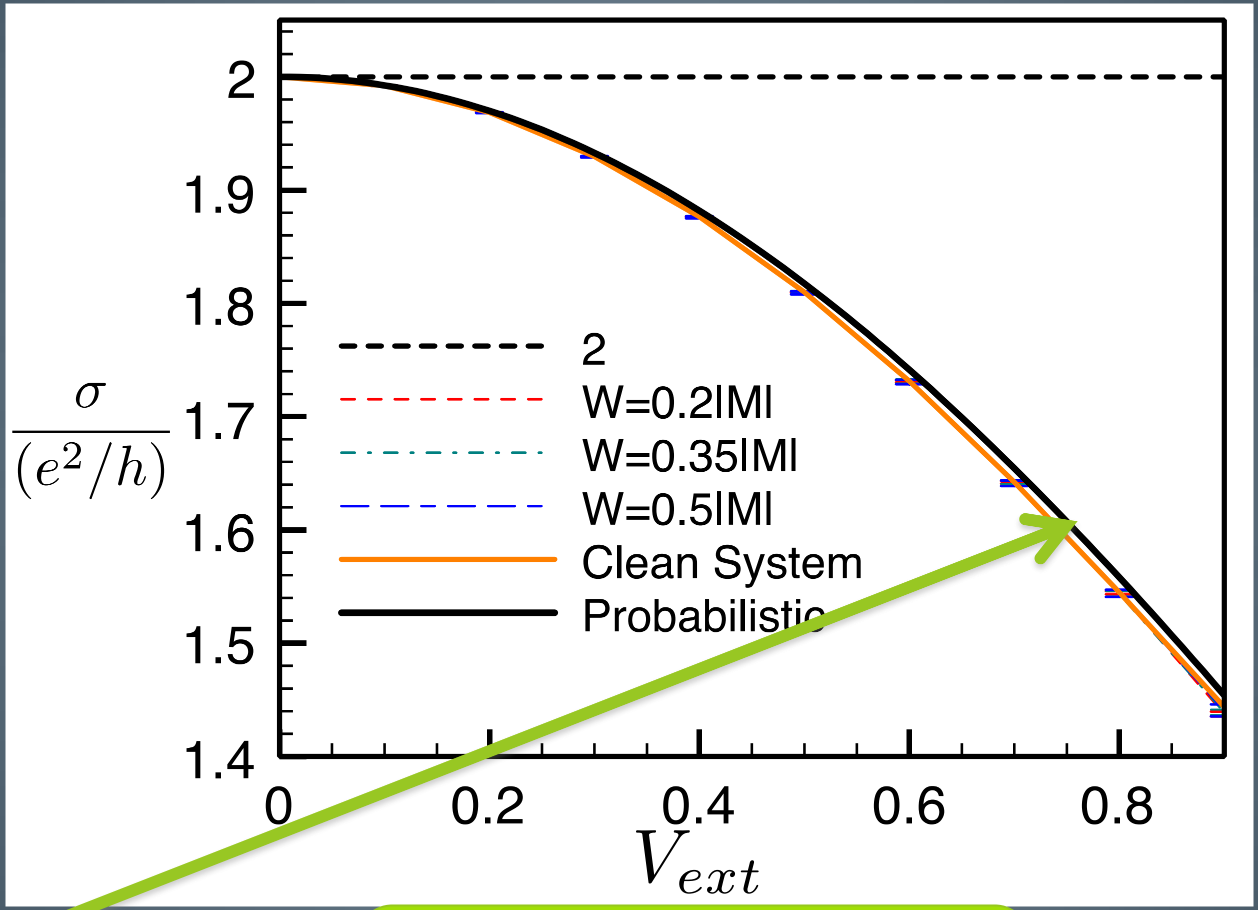
$$\sigma(E) = P_0 \tilde{\sigma}(E)$$

Conductivity of $H_{\mathbf{k}}^{eff}$



Bands of $H_{\mathbf{k}}^{eff}$

Photon Inhibited Topological Transport



$$\sigma(E) = P_0\tilde{\sigma}$$

$$P_0 = J_0^2\left(\frac{2V_{ext}}{\hbar\Omega}\right)$$

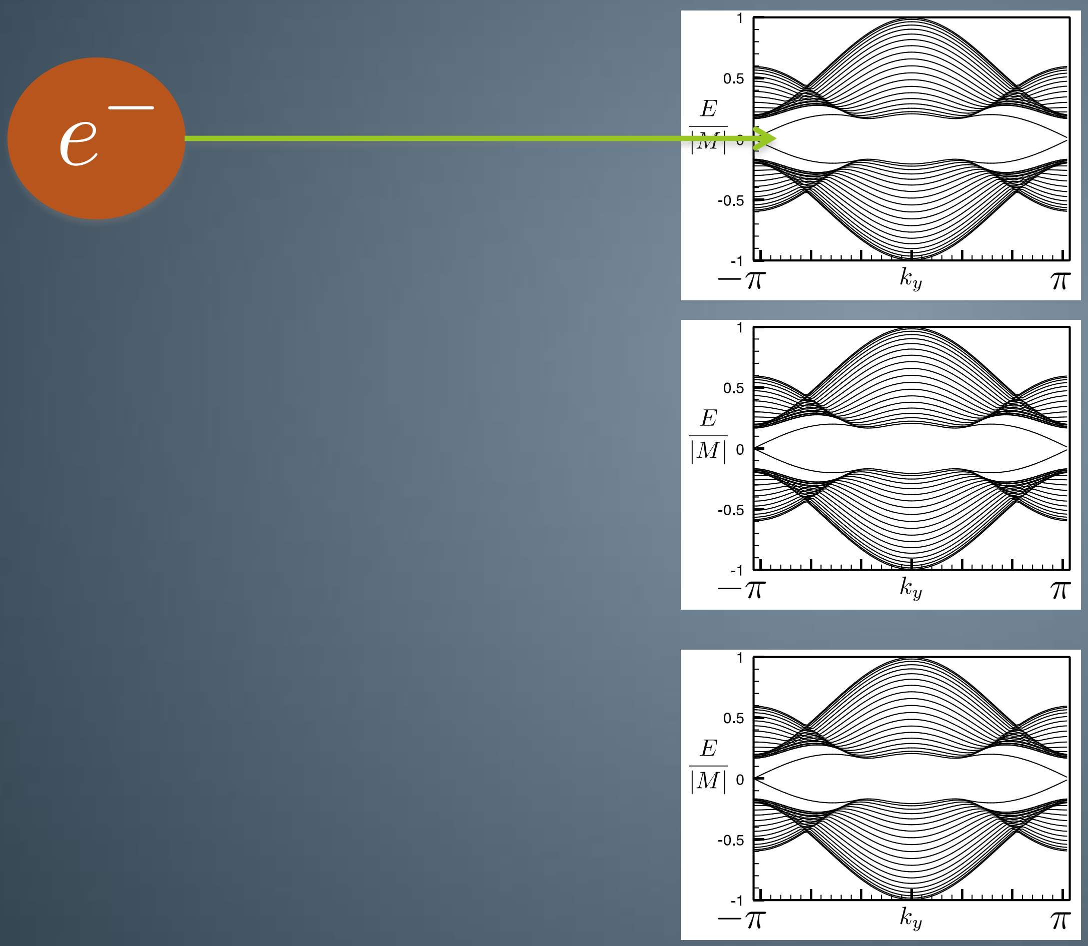
$$\tilde{\sigma} = 2e^2/h$$

Floquet Sum Rule

$$\sigma_F(E) = \sum_n \sigma(E + n\hbar\Omega)$$

Kundu and Seradjeh, PRL **111** (2013)

Photon Inhibited Topological Transport

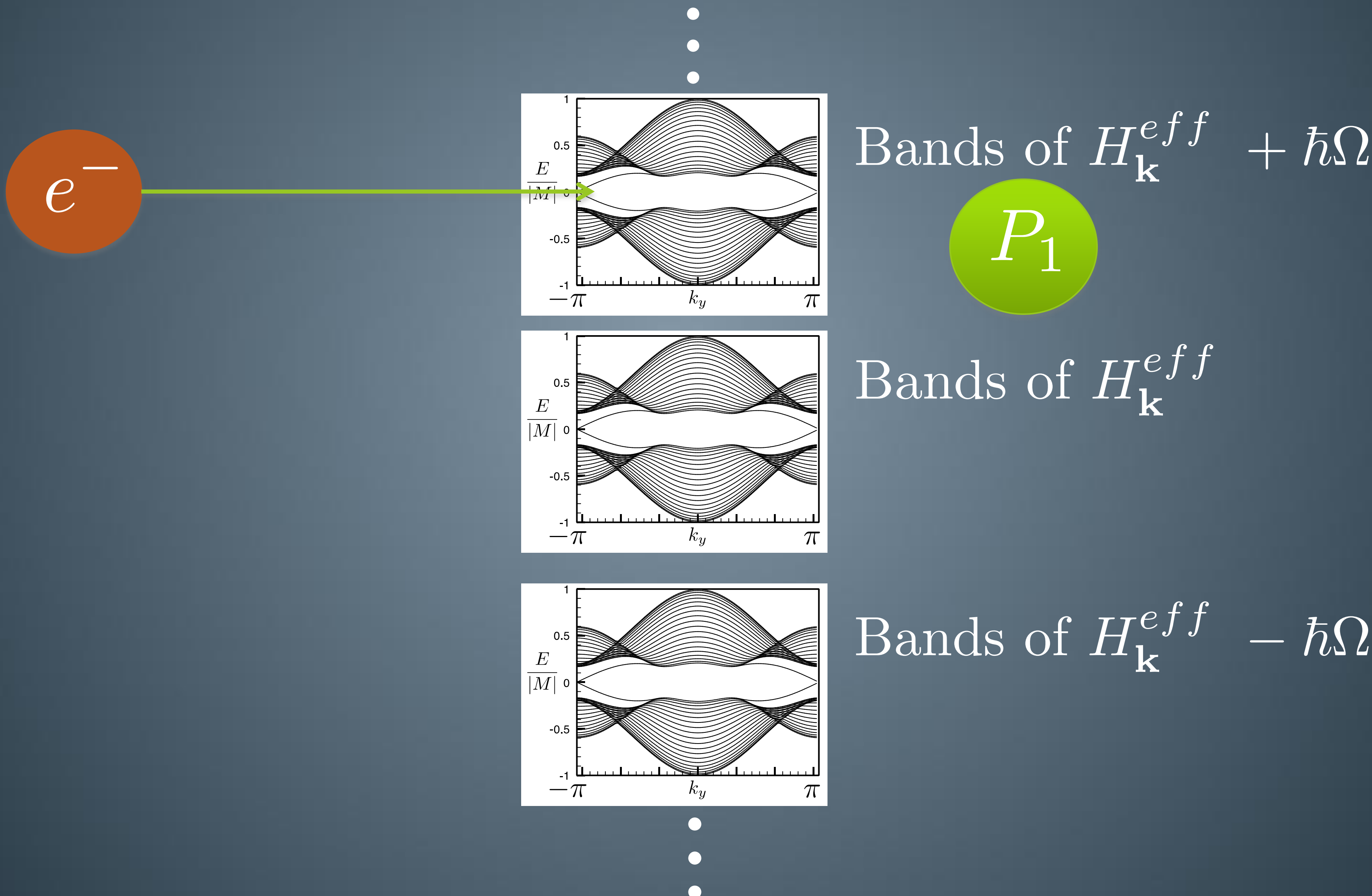


Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

Bands of $H_{\mathbf{k}}^{eff}$

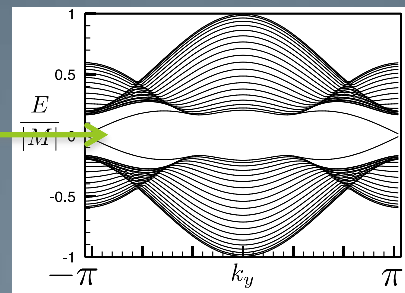
Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

Photon Inhibited Topological Transport



Photon Inhibited Topological Transport

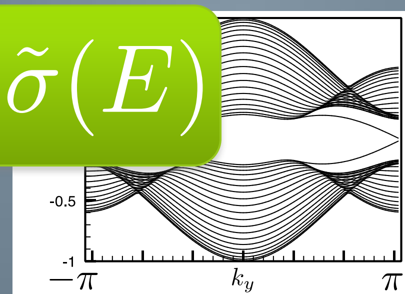
e^-



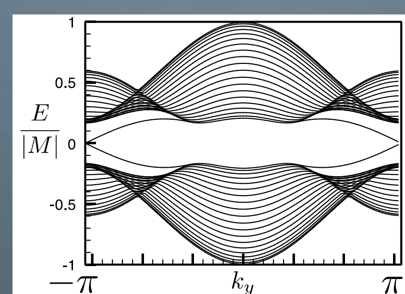
Bands of $H_{\mathbf{k}}^{eff} + \hbar\Omega$

P_1

$$\sigma(E + \hbar\Omega) = P_1 \tilde{\sigma}(E)$$



Bands of $H_{\mathbf{k}}^{eff}$



Bands of $H_{\mathbf{k}}^{eff} - \hbar\Omega$

Floquet Sum Rule

$$\sigma(E + n\hbar\Omega) = P_n \tilde{\sigma}(E)$$

Floquet Sum Rule

$$\sigma(E + n\hbar\Omega) = P_n \tilde{\sigma}(E)$$

$$\sigma_F(E) = \sum_n \sigma(E + n\hbar\Omega)$$

Floquet Sum Rule

$$\sigma(E + n\hbar\Omega) = P_n \tilde{\sigma}(E)$$

$$\sigma_F(E) = \sum_n \sigma(E + n\hbar\Omega)$$

$$\sigma_F(E) = \tilde{\sigma}(E) \sum_n P_n = \tilde{\sigma}(E)$$

Floquet Sum Rule

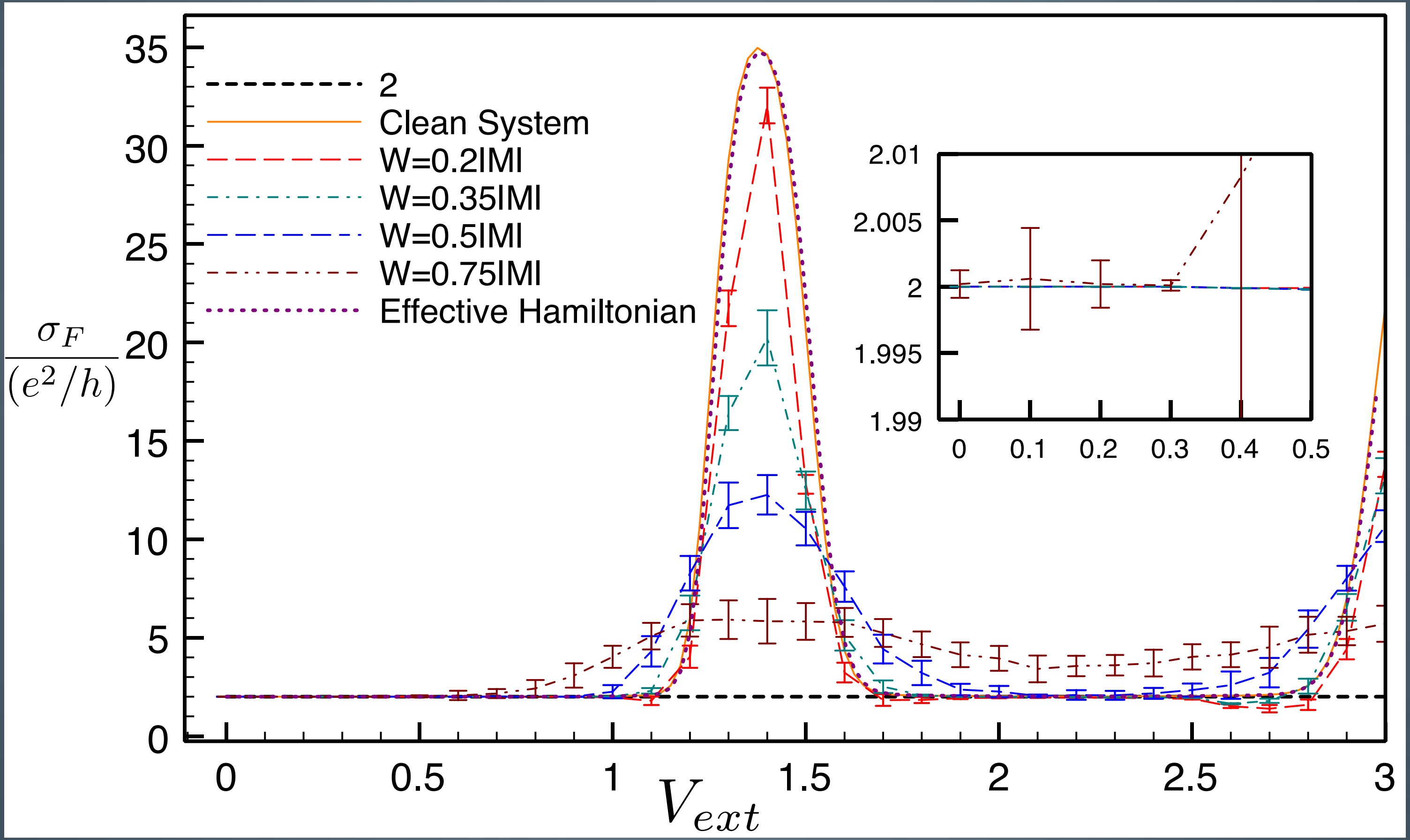
$$\sigma(E + n\hbar\Omega) = P_n \tilde{\sigma}(E)$$

$$\sigma_F(E) = \sum_n \sigma(E + n\hbar\Omega)$$

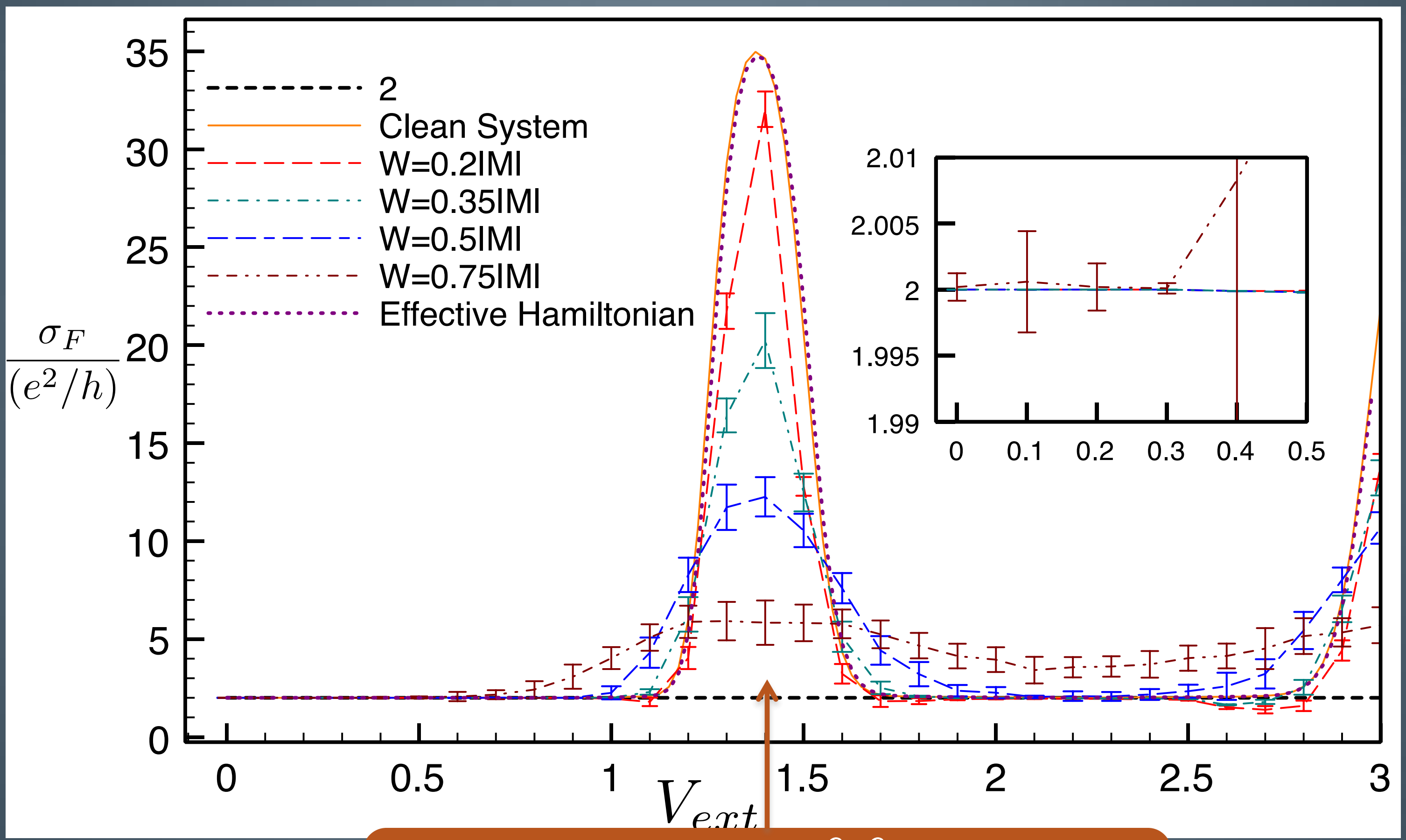
$$\sigma_F(E) = 2e^2/h$$

When edge states are present at energy *E* in effective Hamiltonian

Floquet Sum Rule

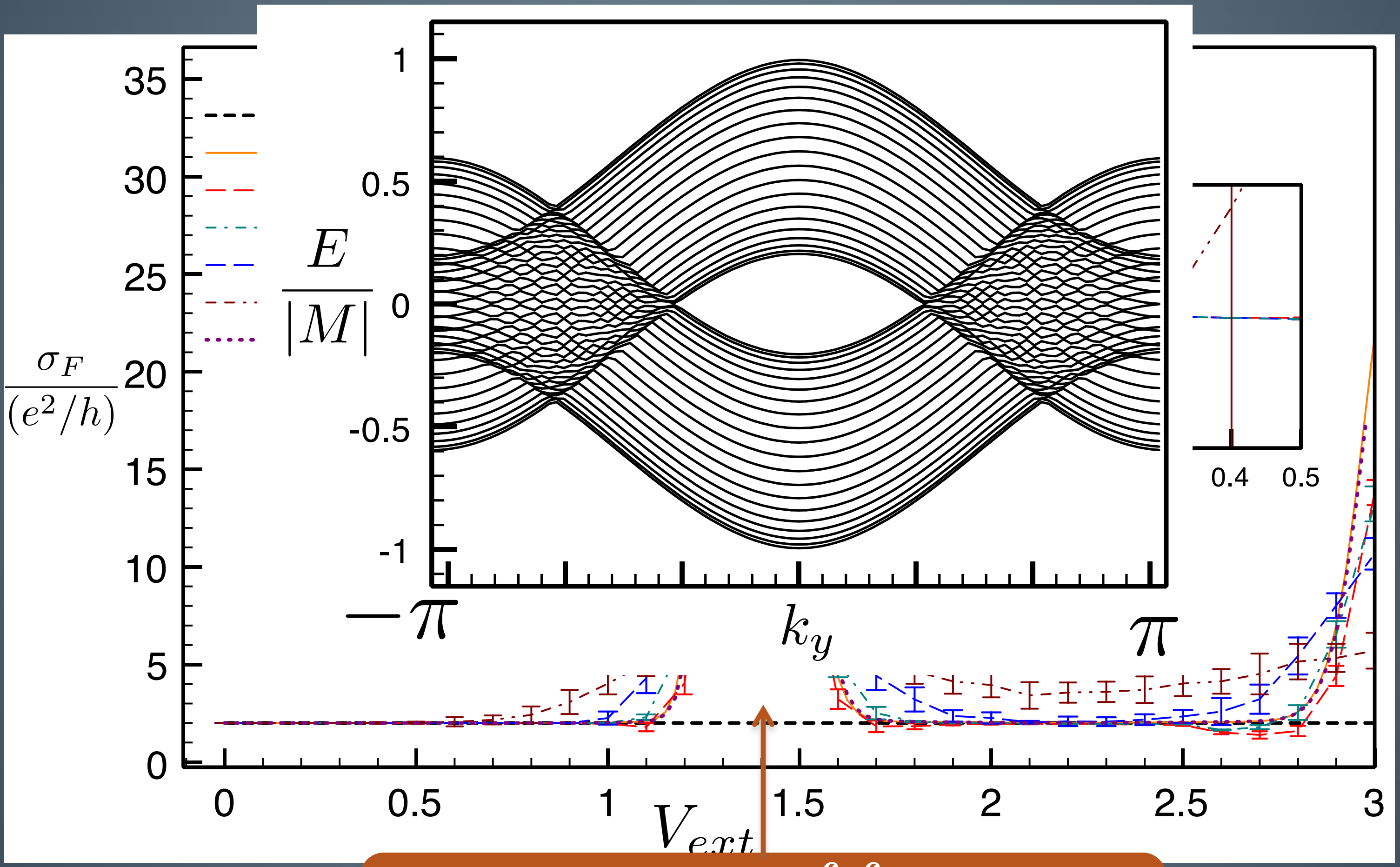


Floquet Sum Rule



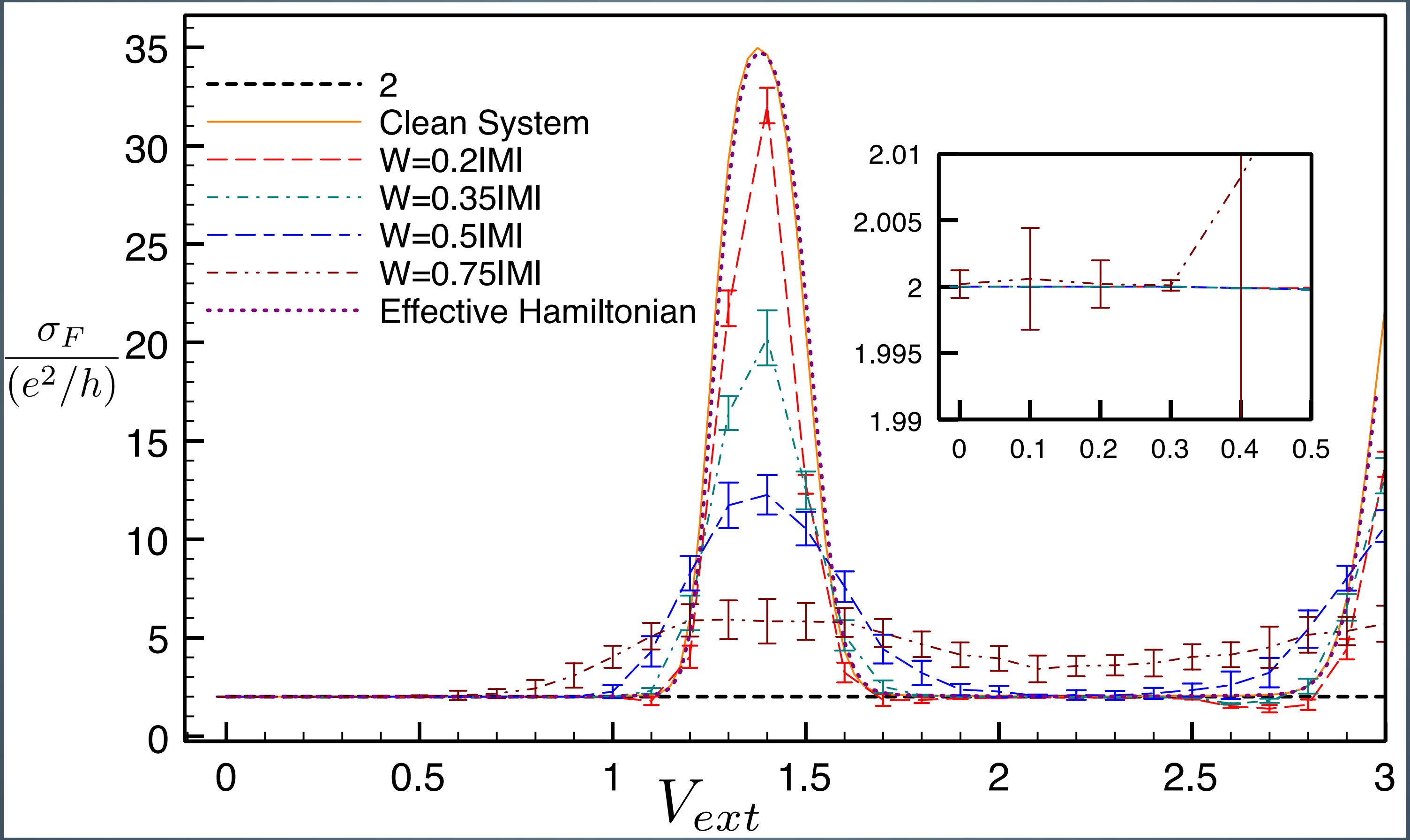
Gap in $H_{\mathbf{k}}^{eff}$ closes

Floquet Sum Rule

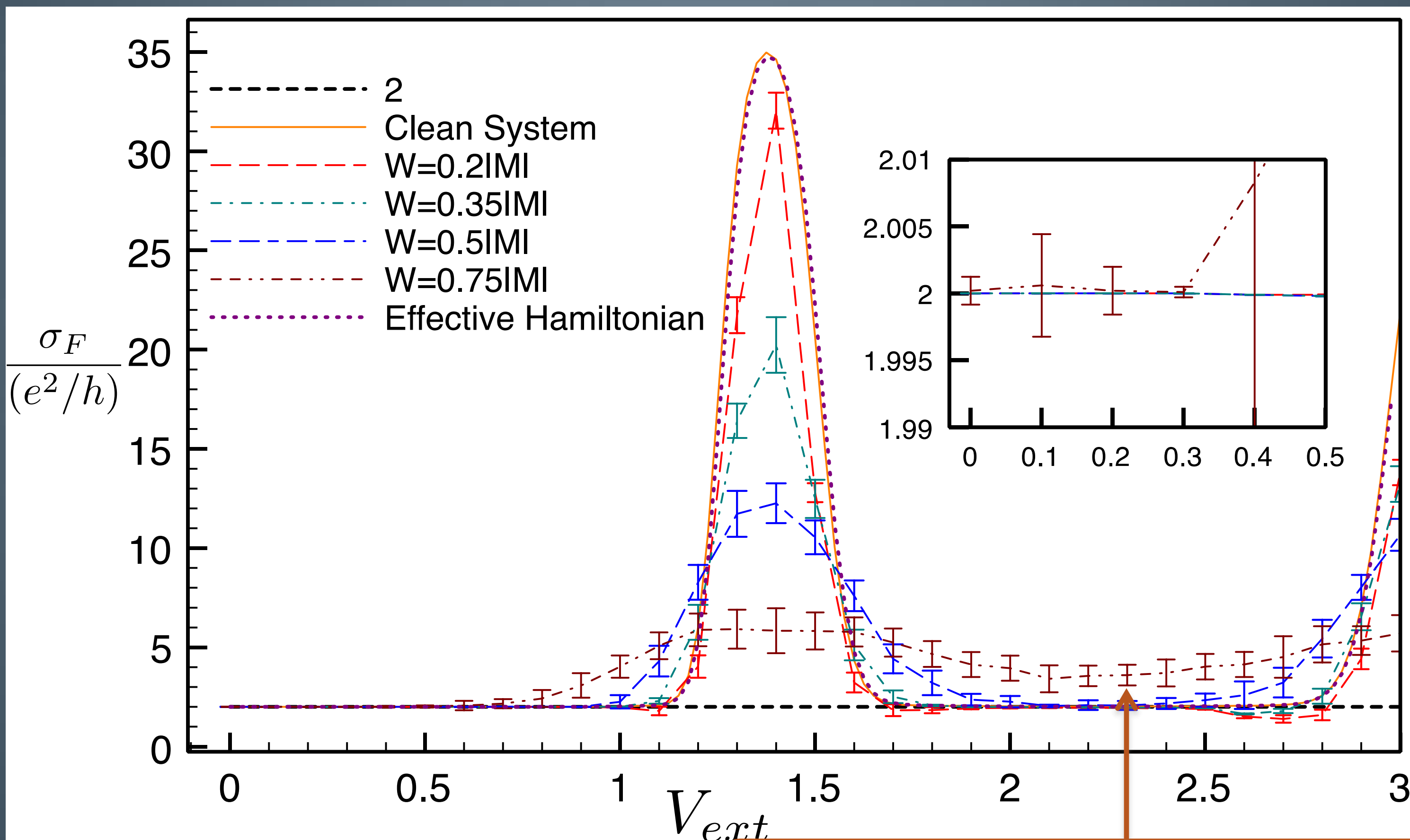


Gap in $H_{\mathbf{k}}^{eff}$ closes

Floquet Sum Rule

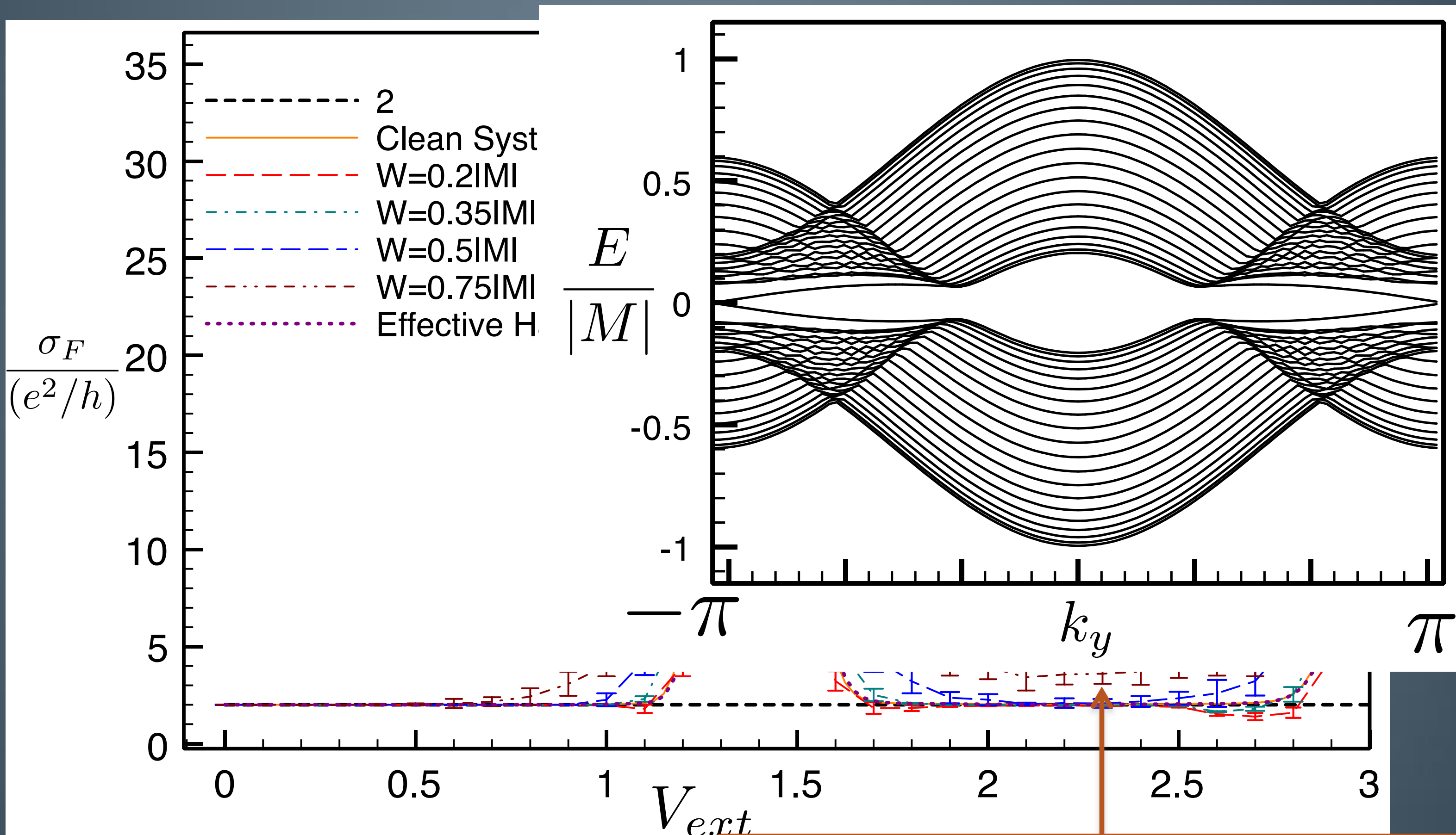


Floquet Sum Rule



Gap in $H_{\mathbf{k}}^{eff}$ opens

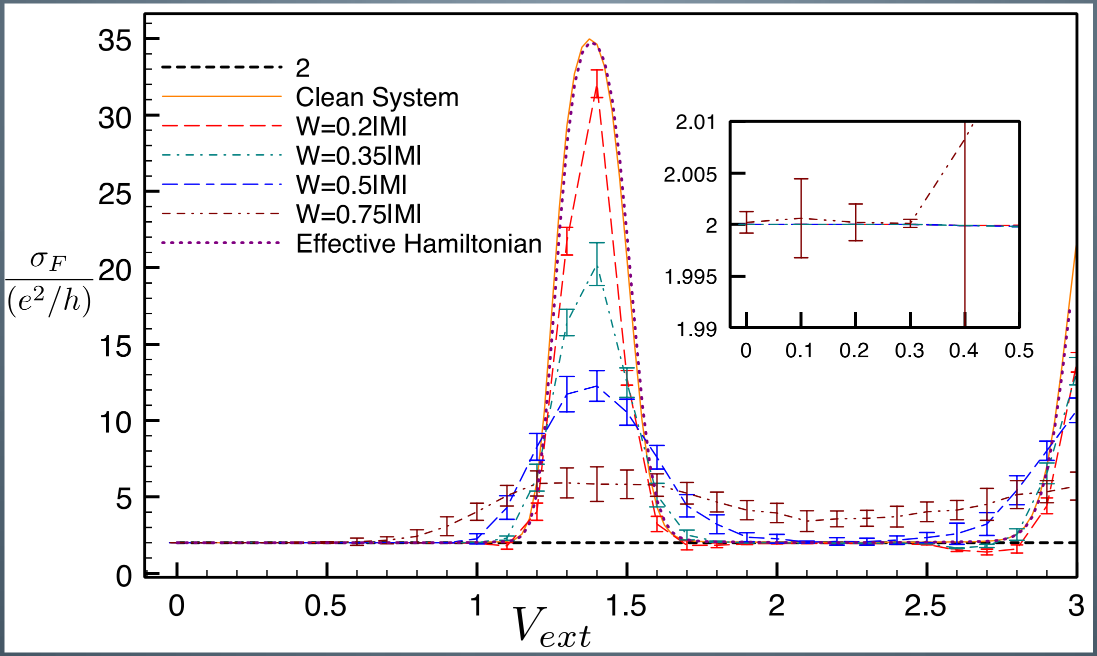
Floquet Sum Rule



Gap in $H_{\mathbf{k}}^{eff}$ opens

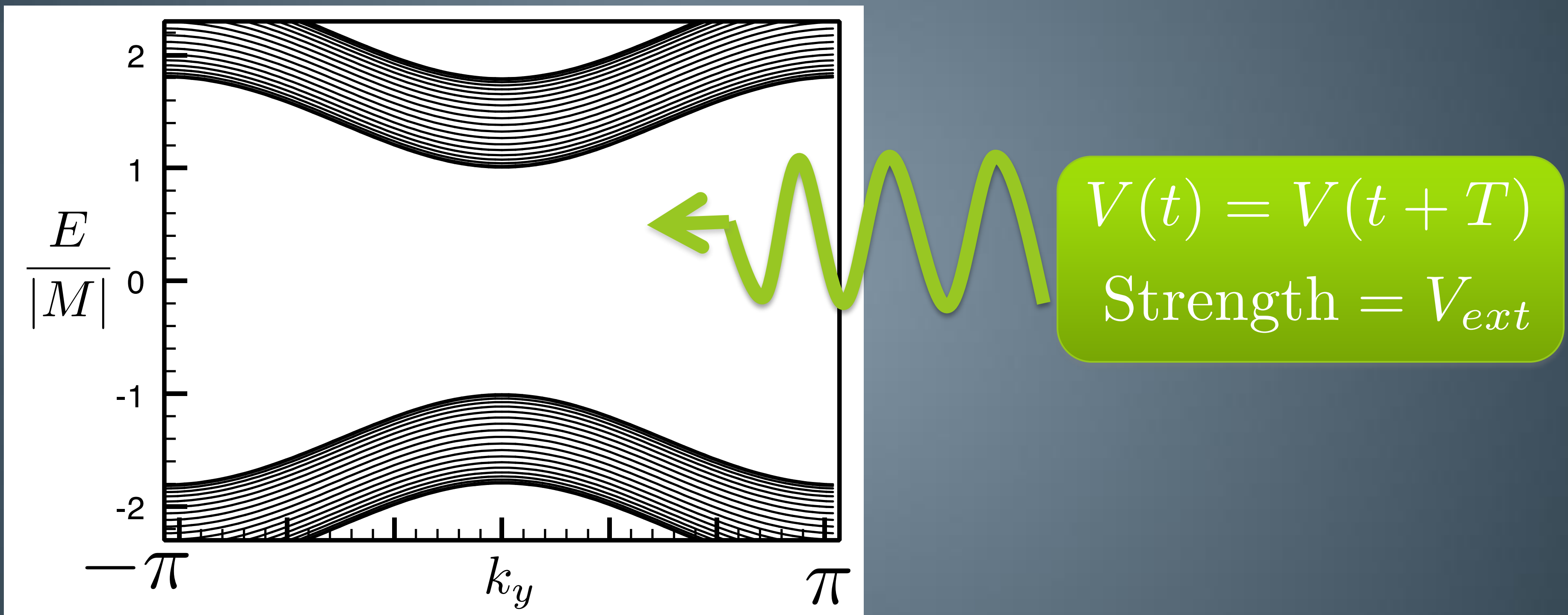
Periodic Topological Insulator

- Conductivity lost due to photon scattering
- Conductivity is still robust
- Lost conductivity reclaimed by sum rule

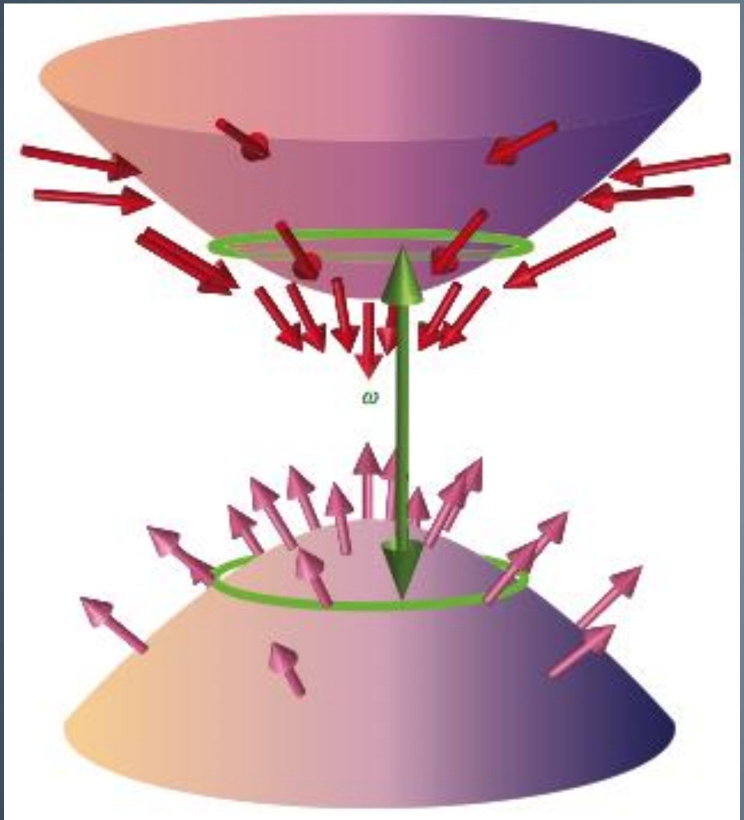


arXiv:1505.05578

Floquet Edge States and Transport



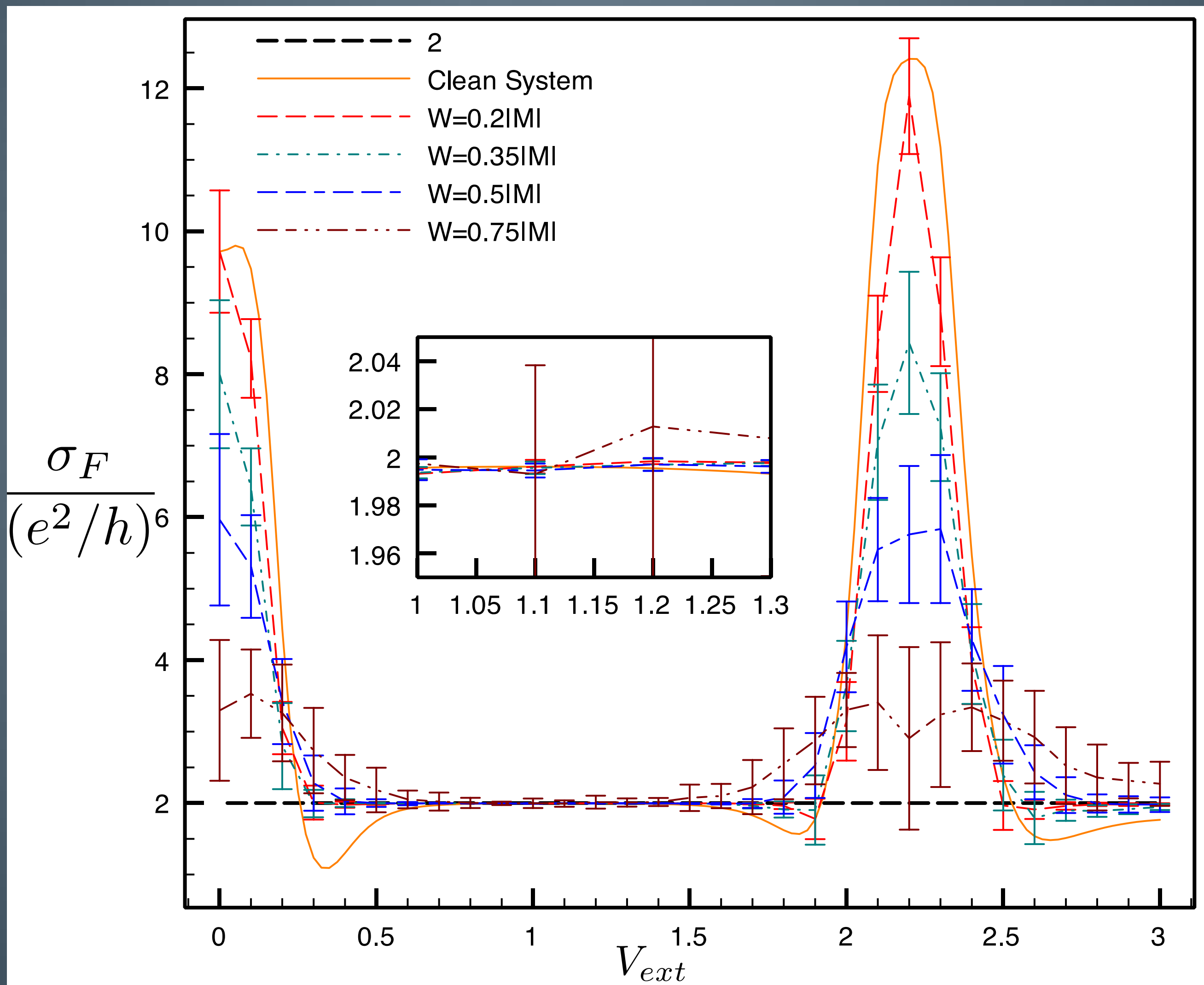
Floquet Edge States and Transport



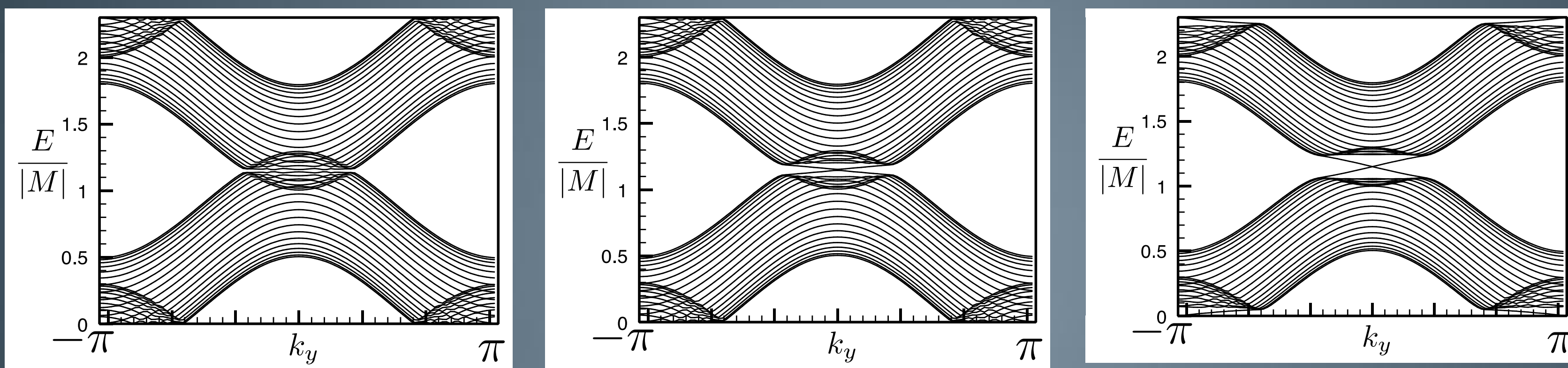
Lindner *et al*, Nature Physics **7** (2011)

- “On-resonant” light induces edge states
- Effective Hamiltonian description now not possible
- Edge states still occupied probabilistically
- Begin with the sum rule

Floquet Edge States and Transport



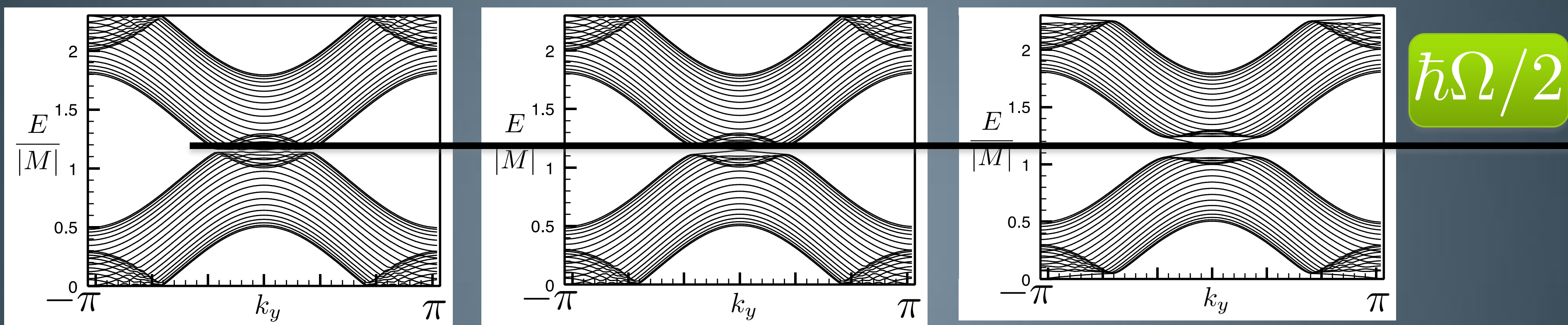
Floquet Edge States and Transport



Increasing V_{ext}

How do these states effect transport?

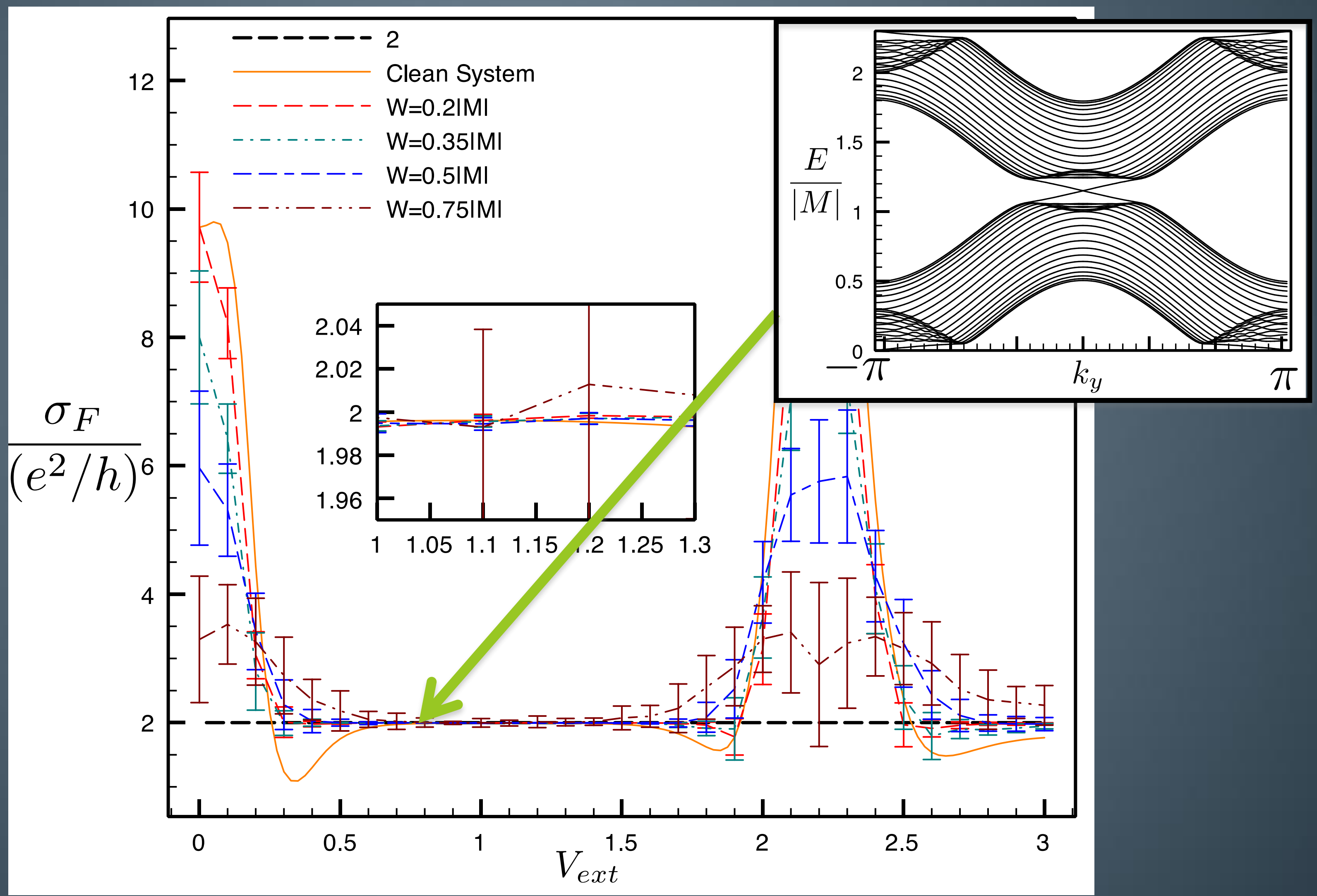
Floquet Edge States and Transport



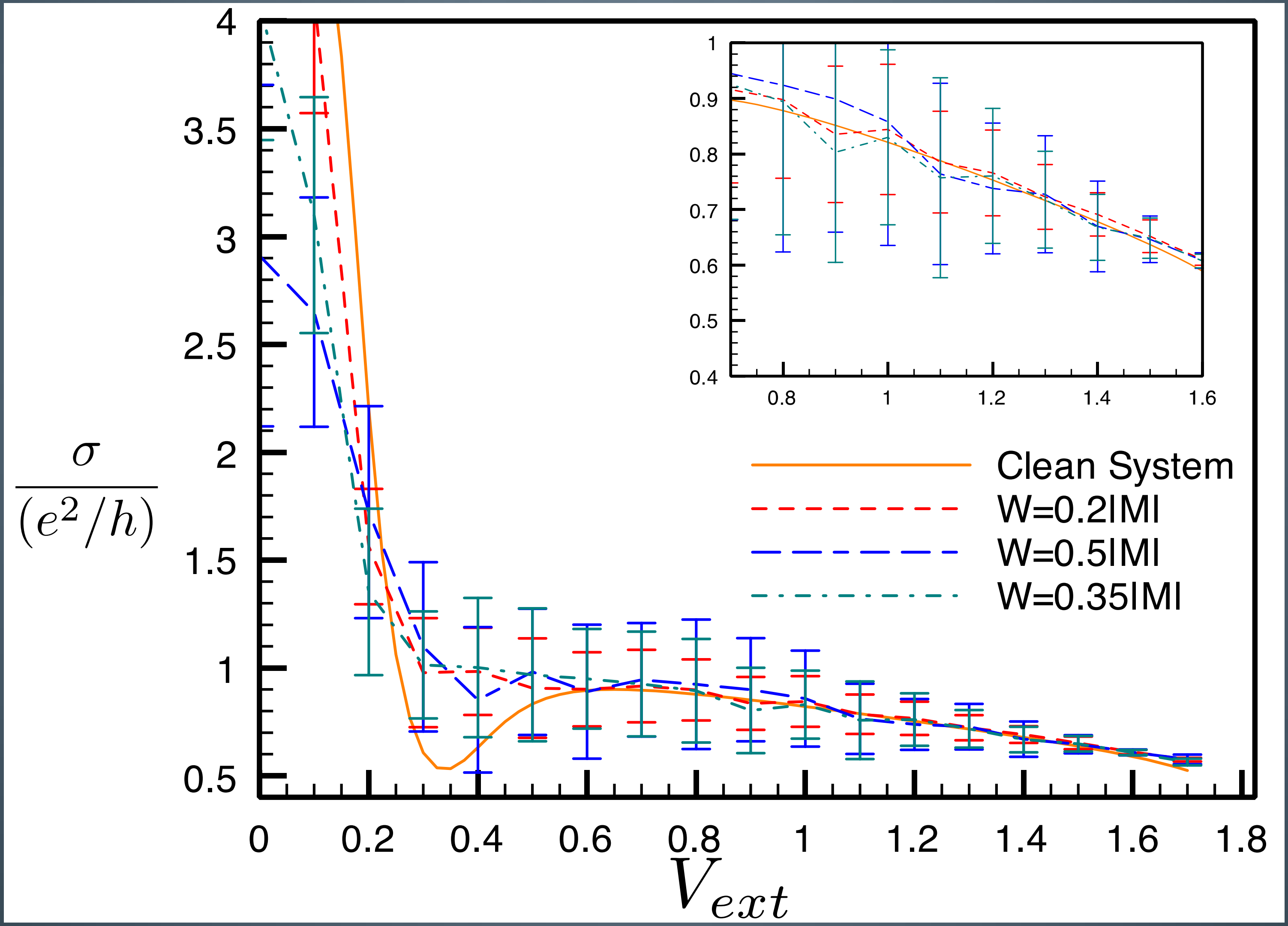
Increasing V_{ext}

How do these states effect transport?

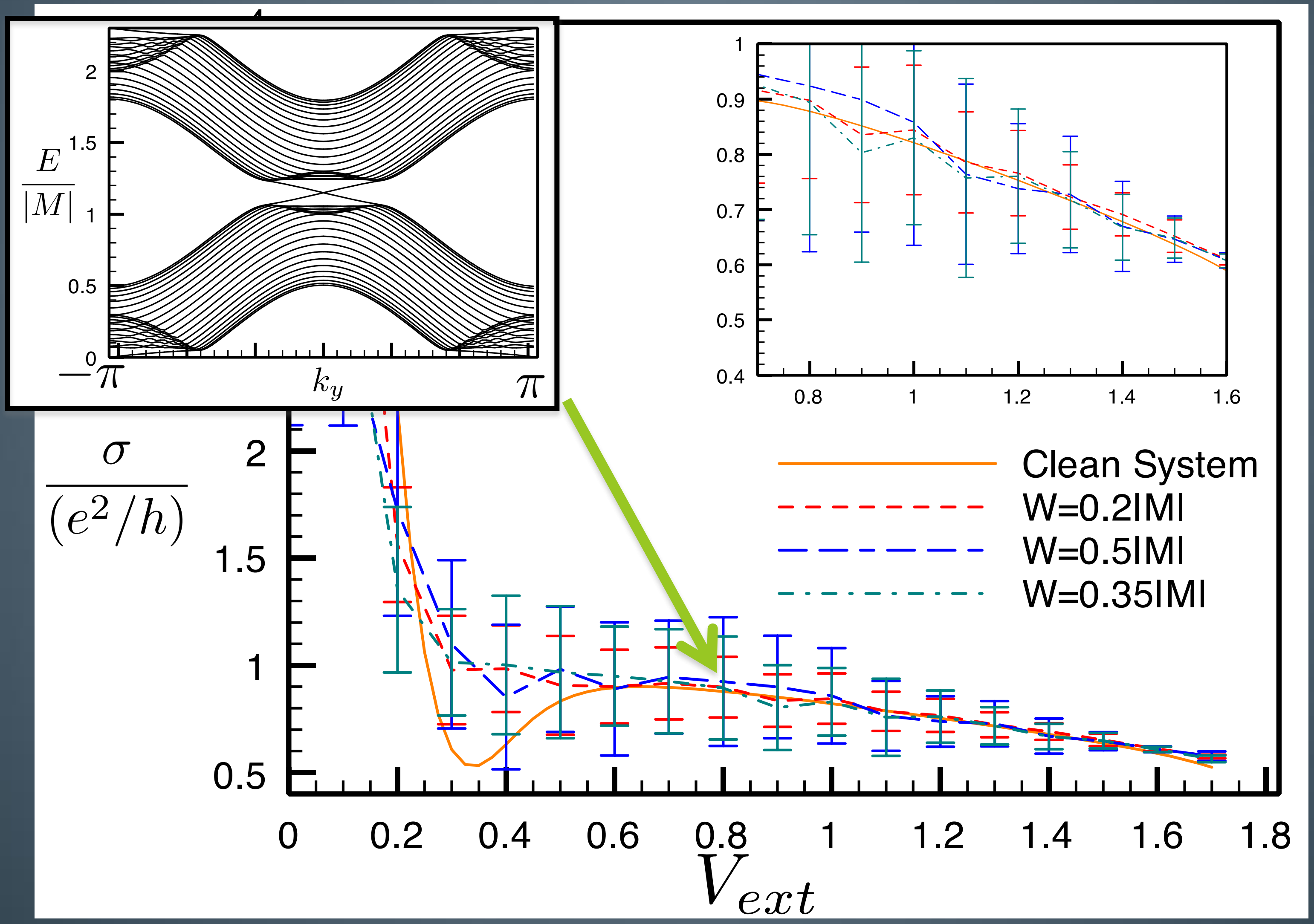
Summed Conductivity



Conductivity (not summed)



Floquet Edge States and Transport



Floquet Edge States and Transport

$$\sigma(E + n\hbar\Omega) = \frac{1}{2}\left(J_n^2(\alpha) + J_{n+1}^2(\alpha)\right)\tilde{\sigma}(E)$$

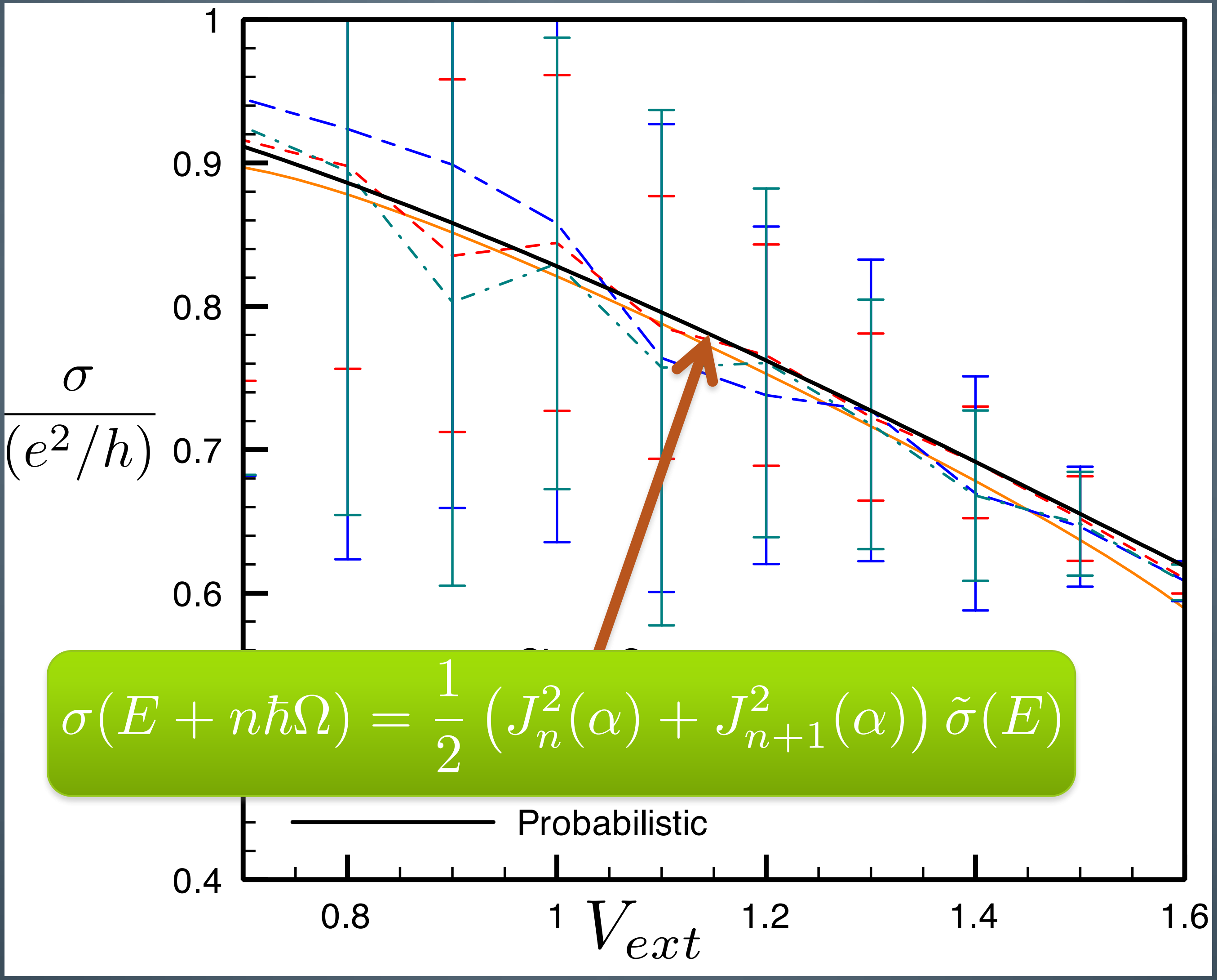
Probability of accessing edge states

Floquet Edge States and Transport

$$\sigma(E + n\hbar\Omega) = \frac{1}{2}\left(J_n^2(\alpha) + J_{n+1}^2(\alpha)\right)\tilde{\sigma}(E)$$

Conductivity of edge states (complicated)

Floquet Edge States and Transport



$$\sigma(E + n\hbar\Omega) = \frac{1}{2}\left(J_n^2(\alpha) + J_{n+1}^2(\alpha)\right)\tilde{\sigma}(E)$$

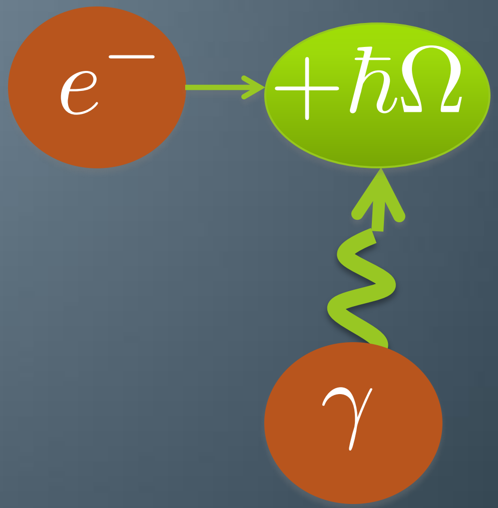
Floquet Edge States and Transport

- Edge states induced using “on-resonant” light
- Quantization of Floquet sum rule, presence of edge states and robustness coexist
- Edge states are accessed with a certain probability

arXiv:1505.05584

Summary

- Periodic driving reduces transport signatures of topological edge states, maintains robustness
- Can recollect these lost signatures using a "Floquet sum rule"



arXiv:1505.05578
arXiv:1505.05584

Outlook

- Effects of additional bands
- Transport signatures at small frequency
- Signatures in the AC conductivity