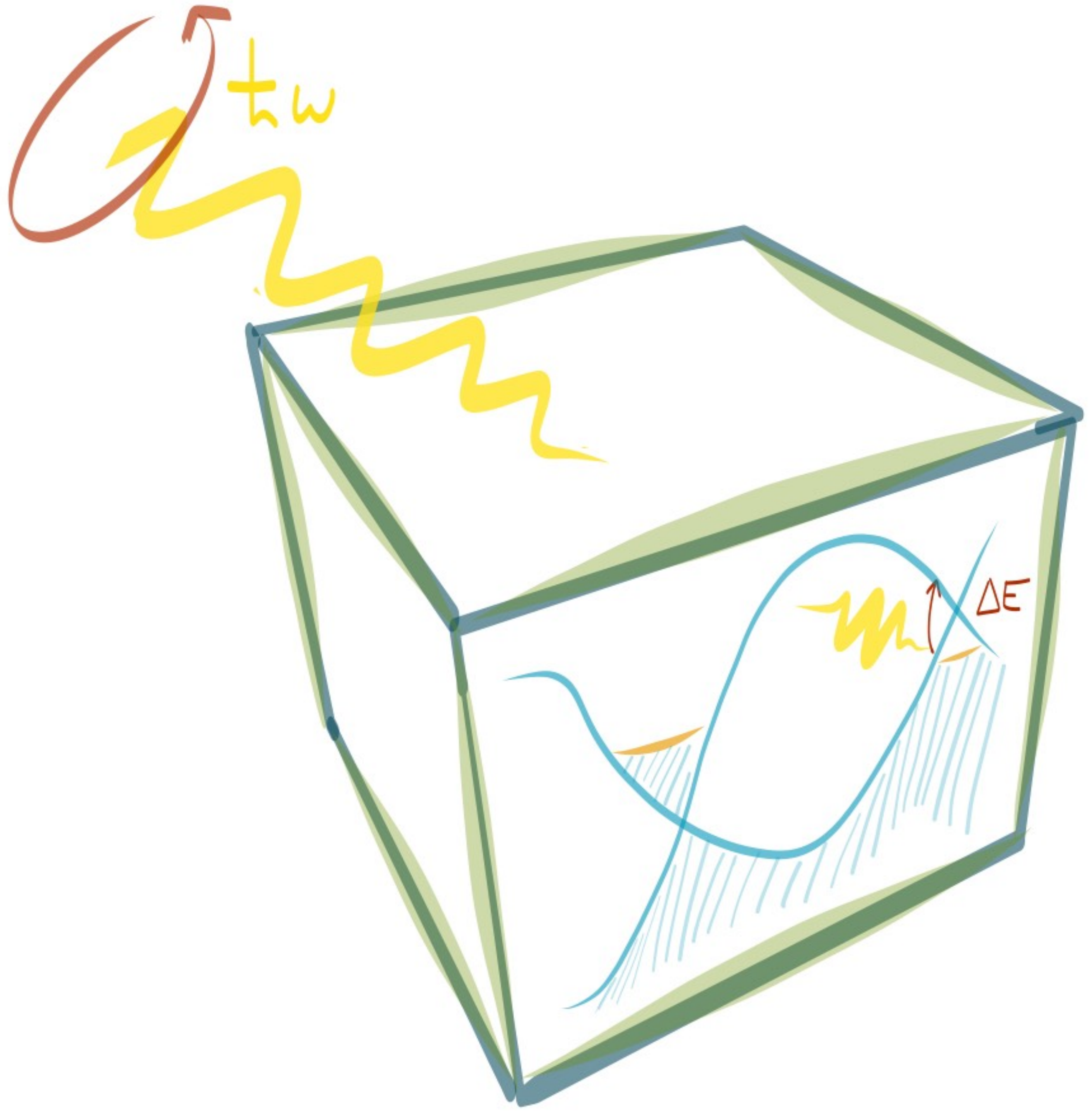
Quantized optical responses in chiral insulators and metals

Adolfo G. Grushin (Néel / CNRS) KITP 10/12/2019

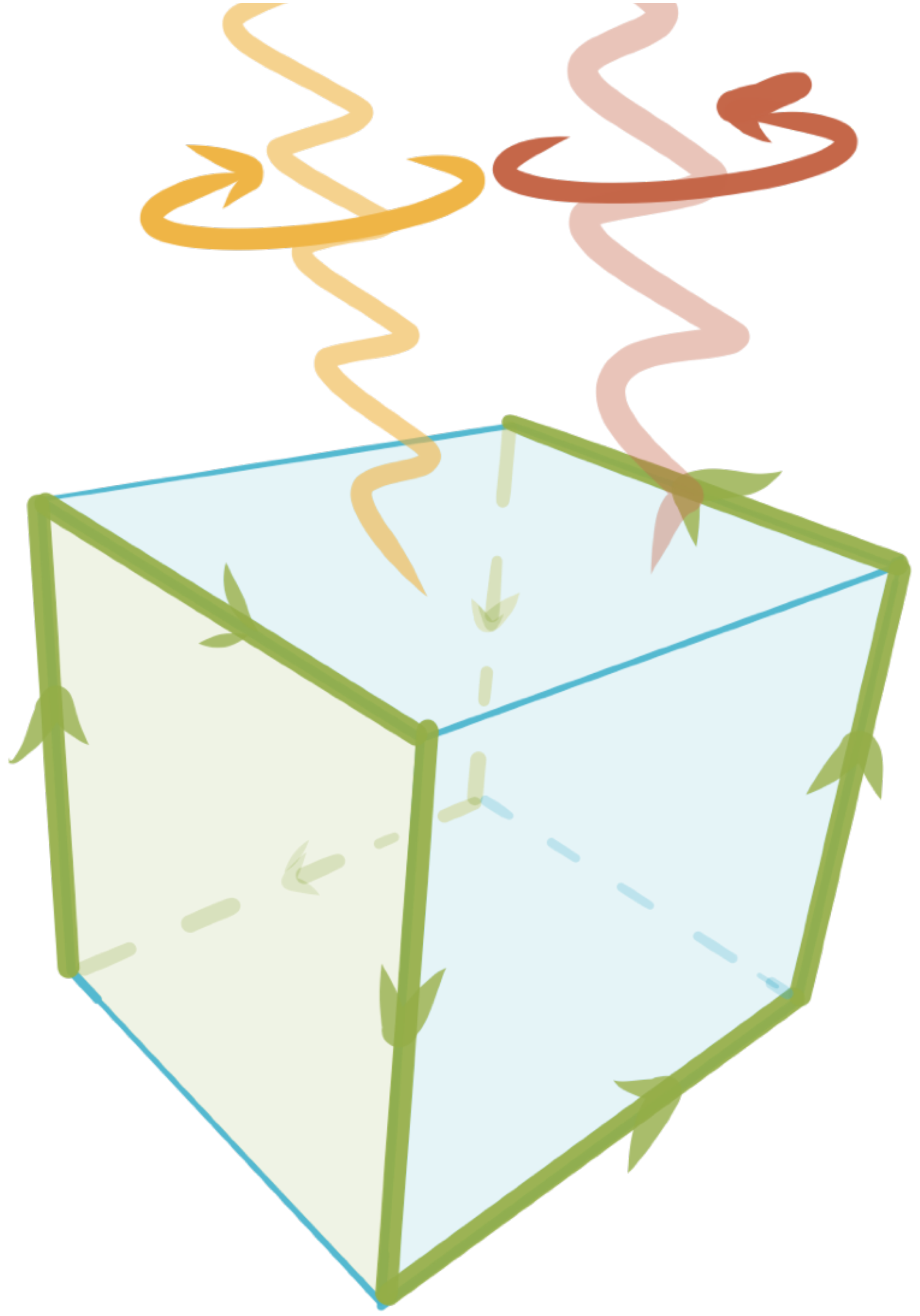


1907.02537
(to appear in PRR)

metallic

1906.05863
(to appear in PRL)

insulating



F. Flicker, F. de Juan, T. Morimoto, B. Bradlyn, M. Vergniory, AGG PRB (2018)
F. de Juan, AGG, T. Morimoto, J. E. Moore Nat. Comm (2017)
M.A. Sanchez-Martinez, F. de Juan, AGG PRB (2019)

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European Commission

Quantization

Quantization

...not so often experimentally observed

$$j_i = \sigma_{ij} E_j$$

Quantum Hall effect

von Klitzing, Tsui, Stormer (80's)

Rotation of plane of polarization

L. Wu, et al Science (2016)

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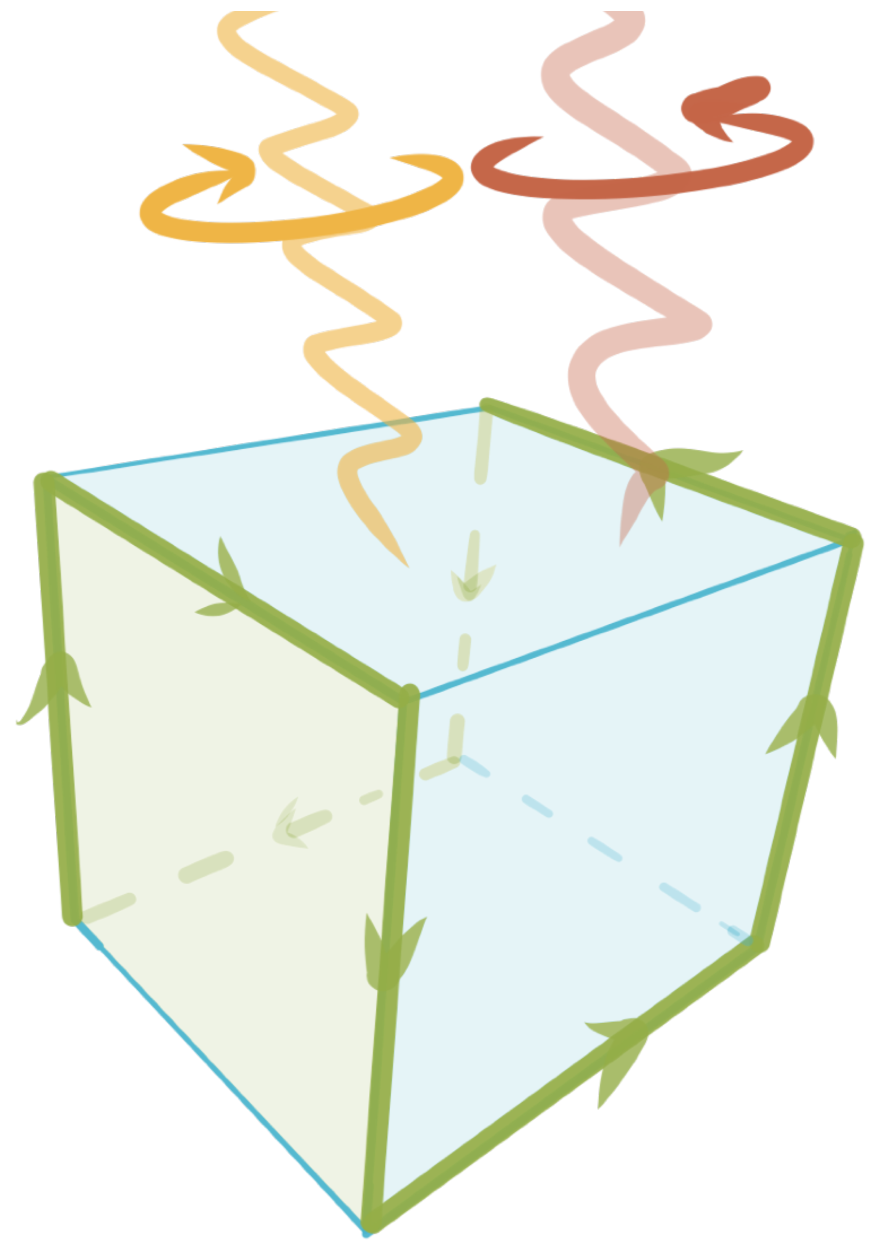

Quantization

...not so often experimentally observed

$$j_i = \sigma_{ij} E_j + \sigma_{ijl} E_j E_l + \cdots$$

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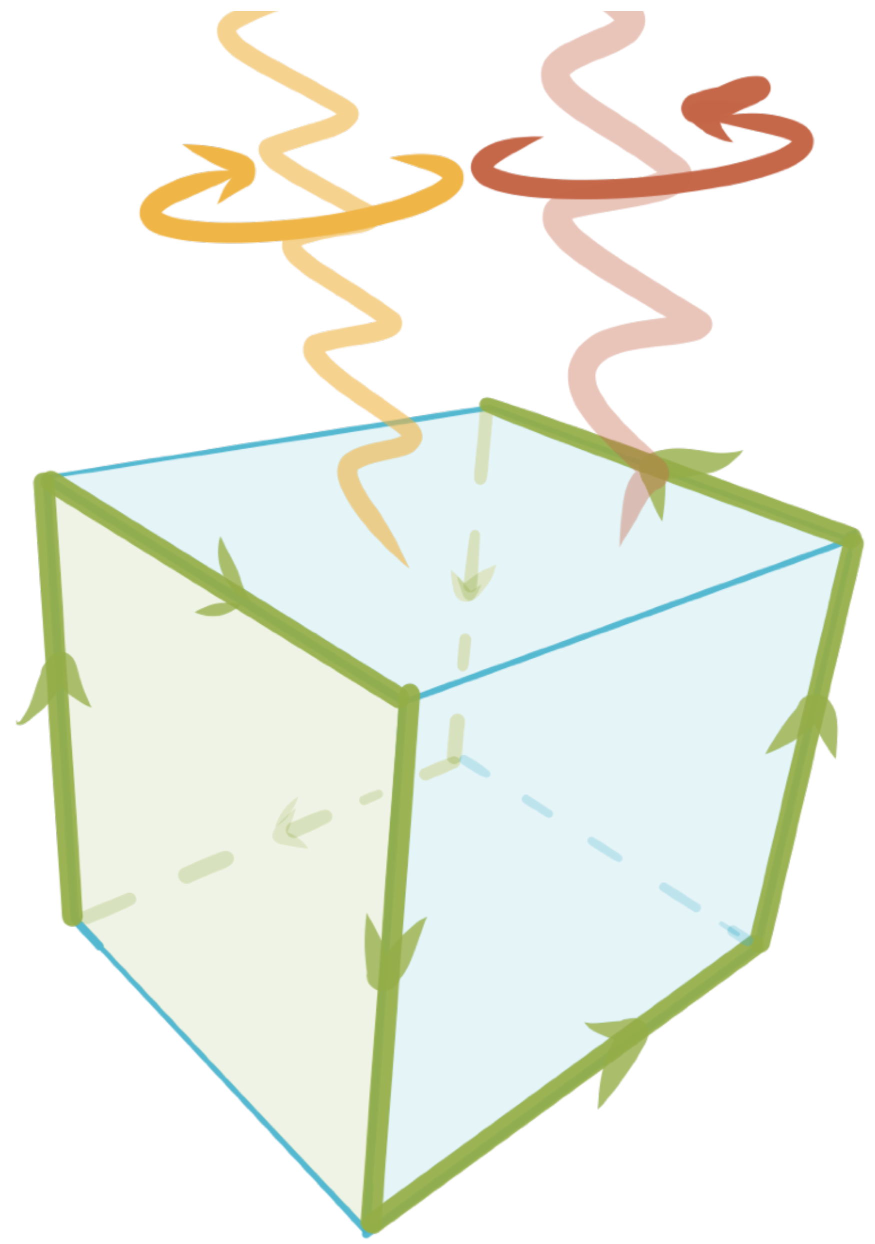
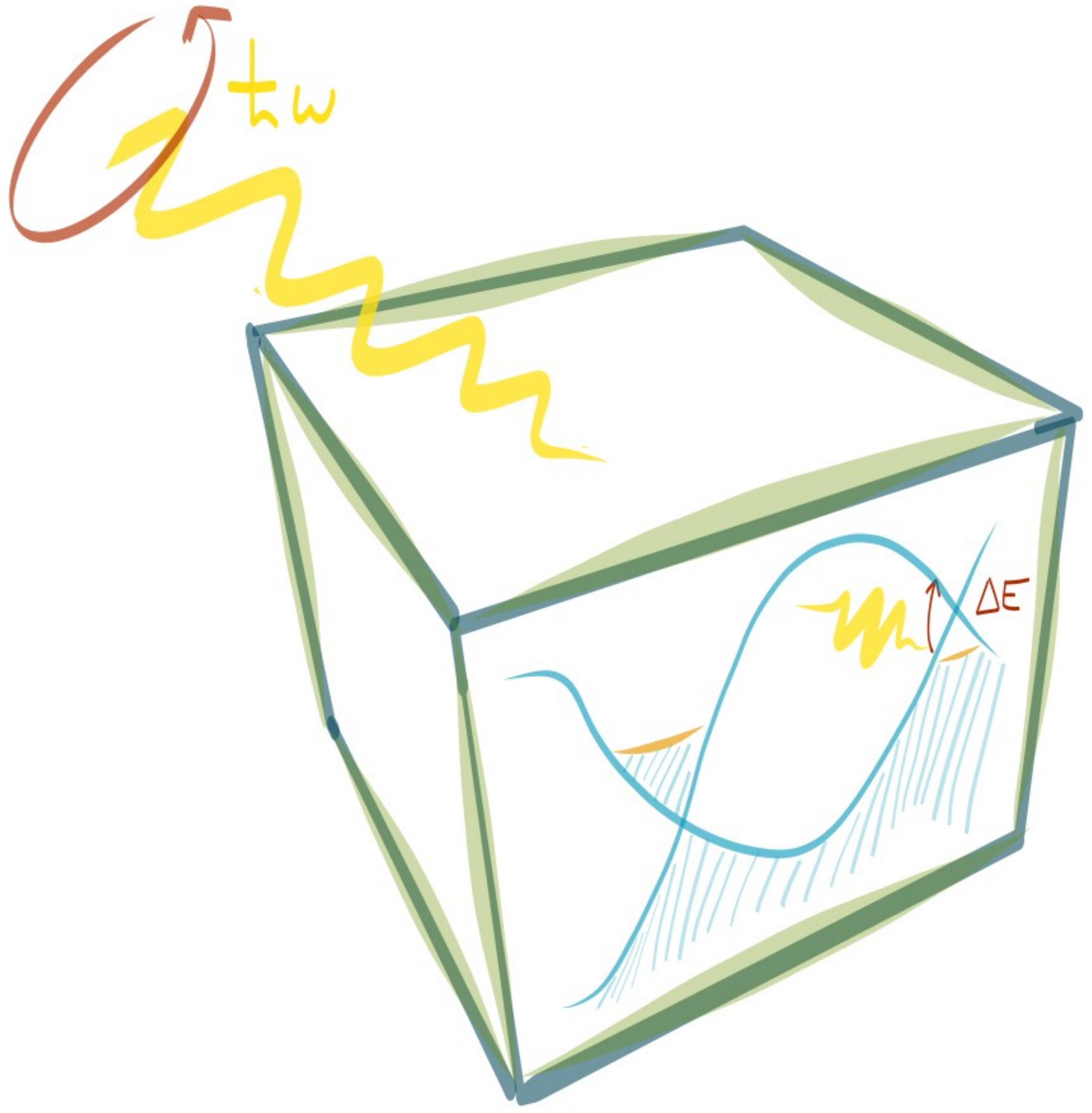
Quantized photogalvanic effect

F. De Juan et al Nat. Comm (2017)

D. Rees et al arXiv: 1902.03230





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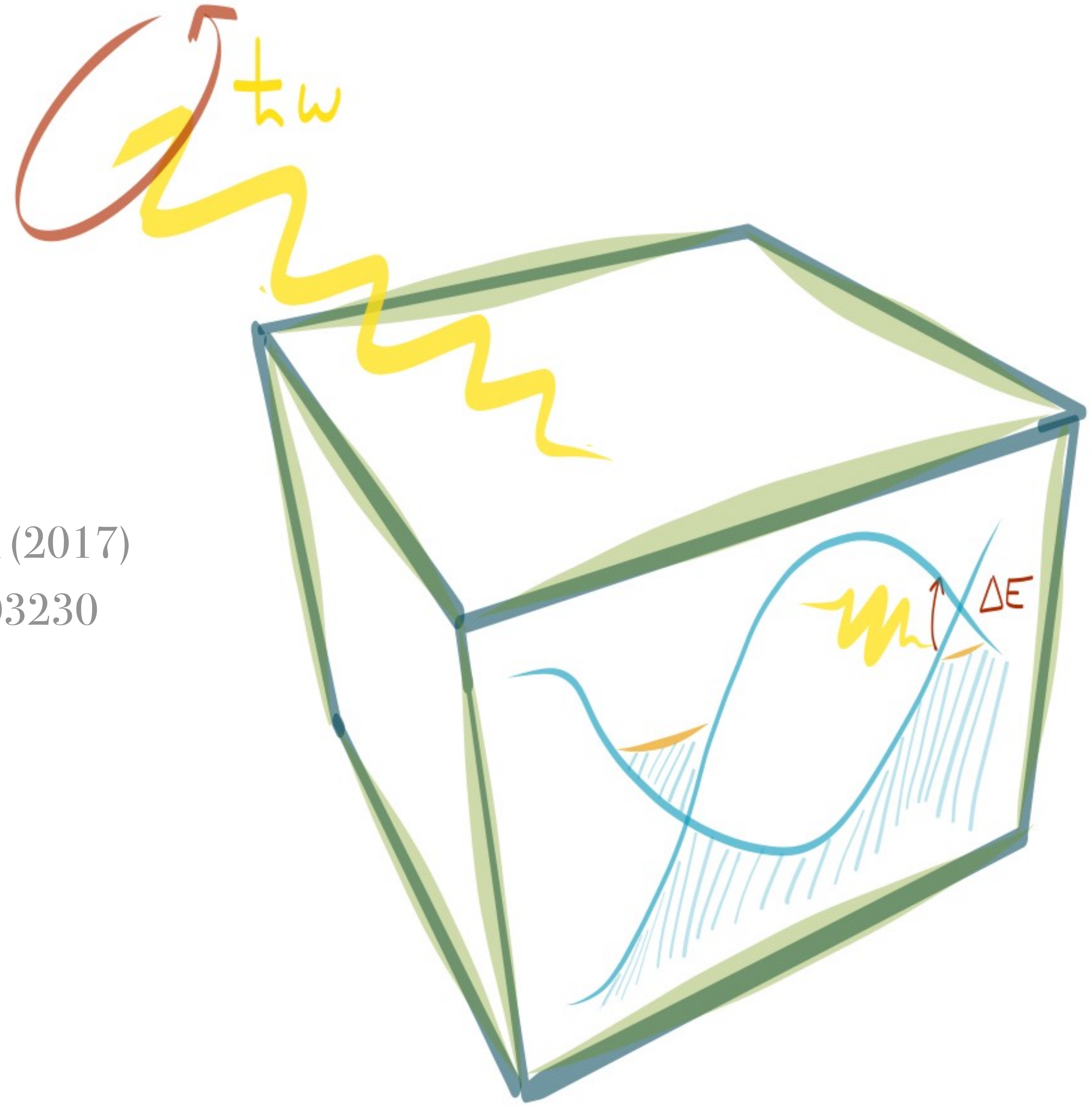

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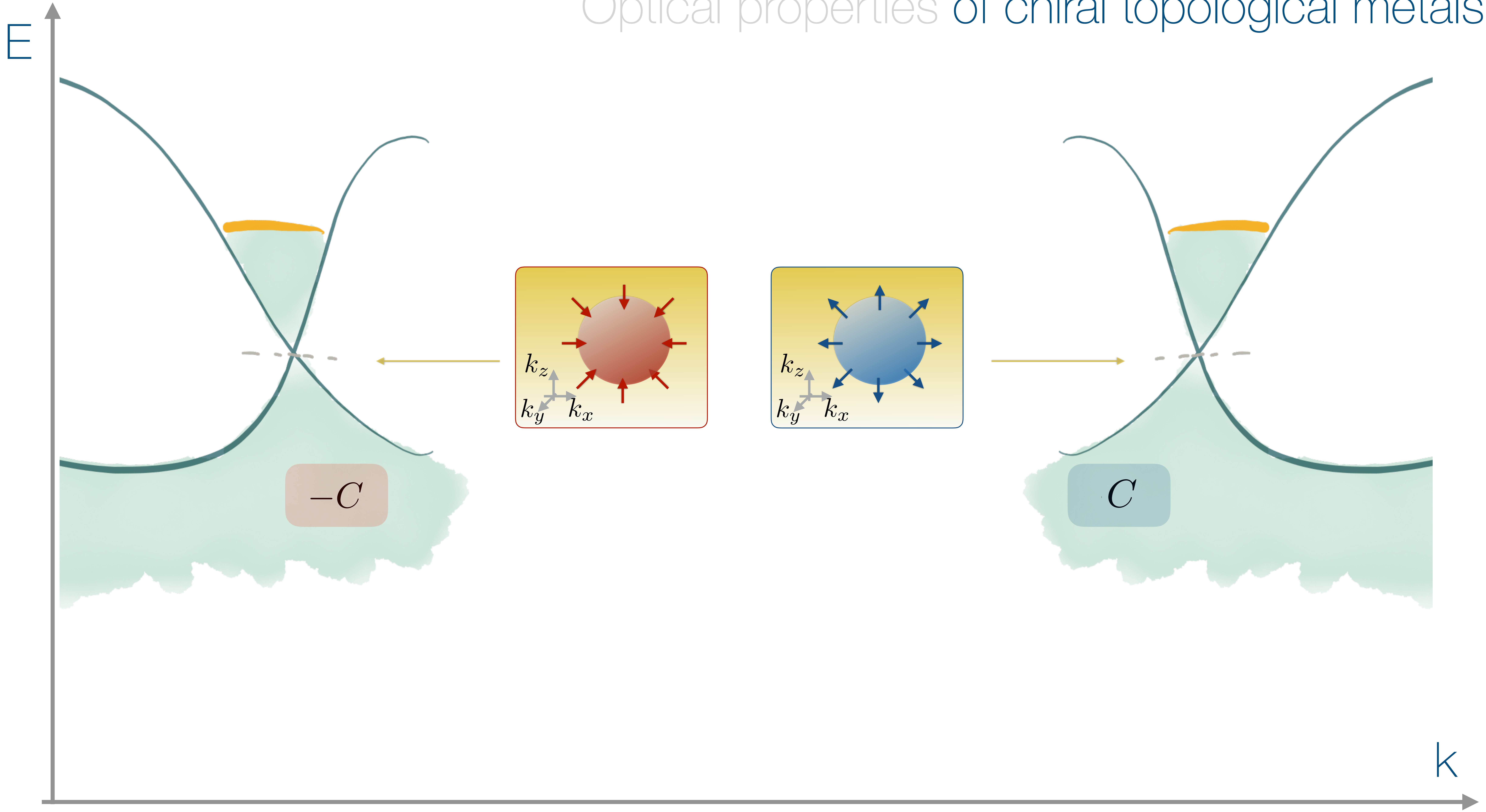
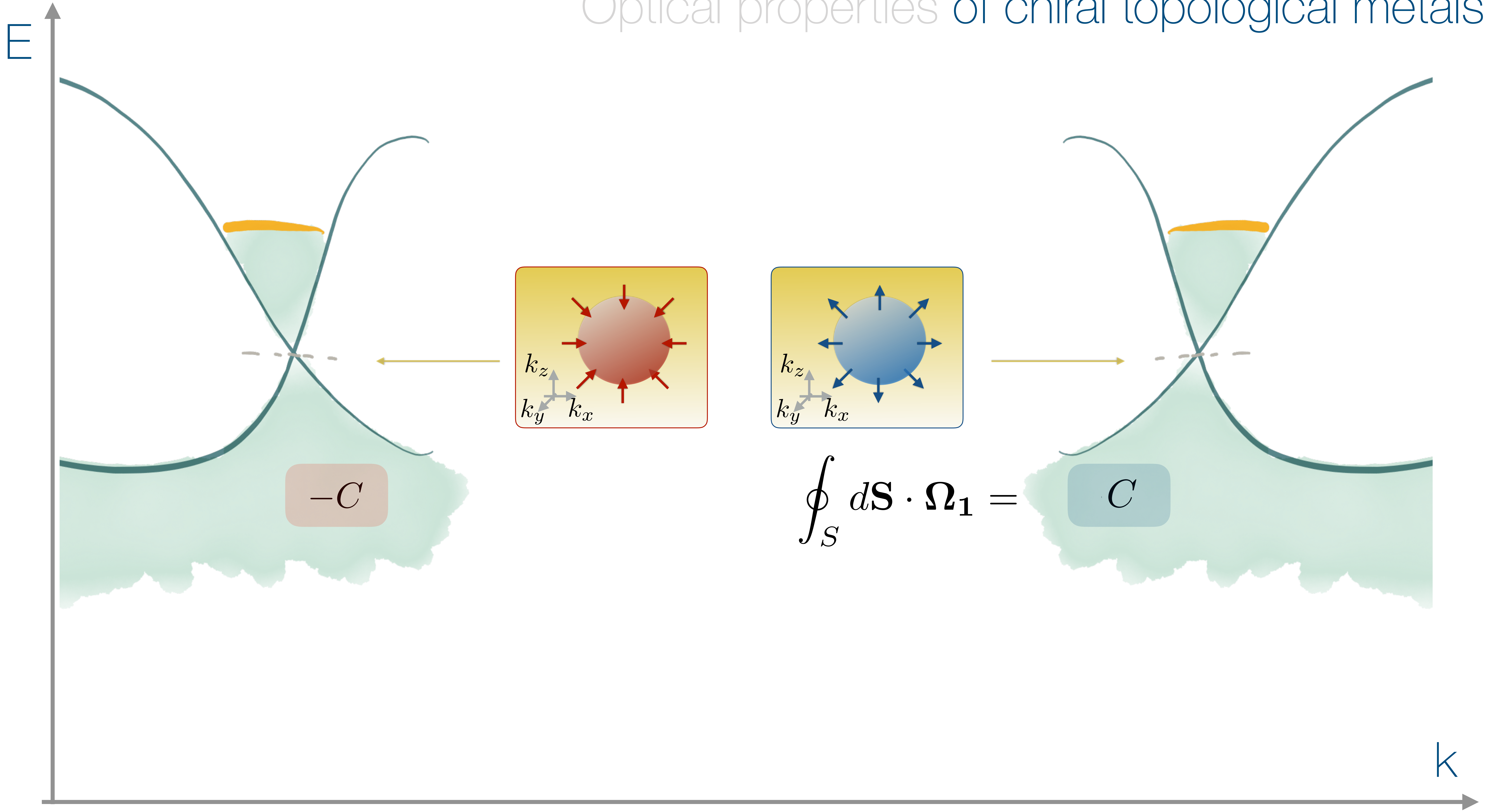
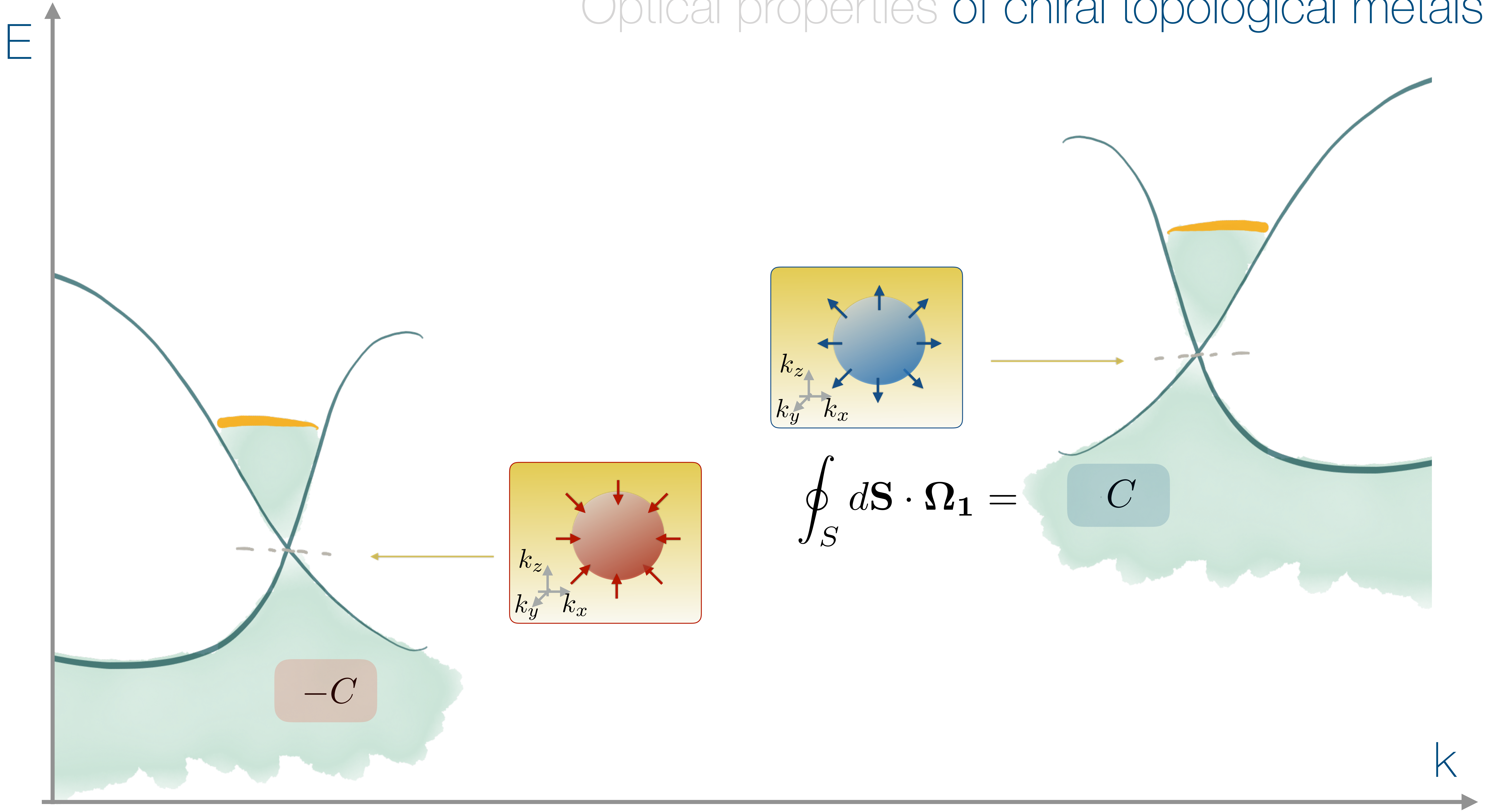
Optical properties of chiral topological metals

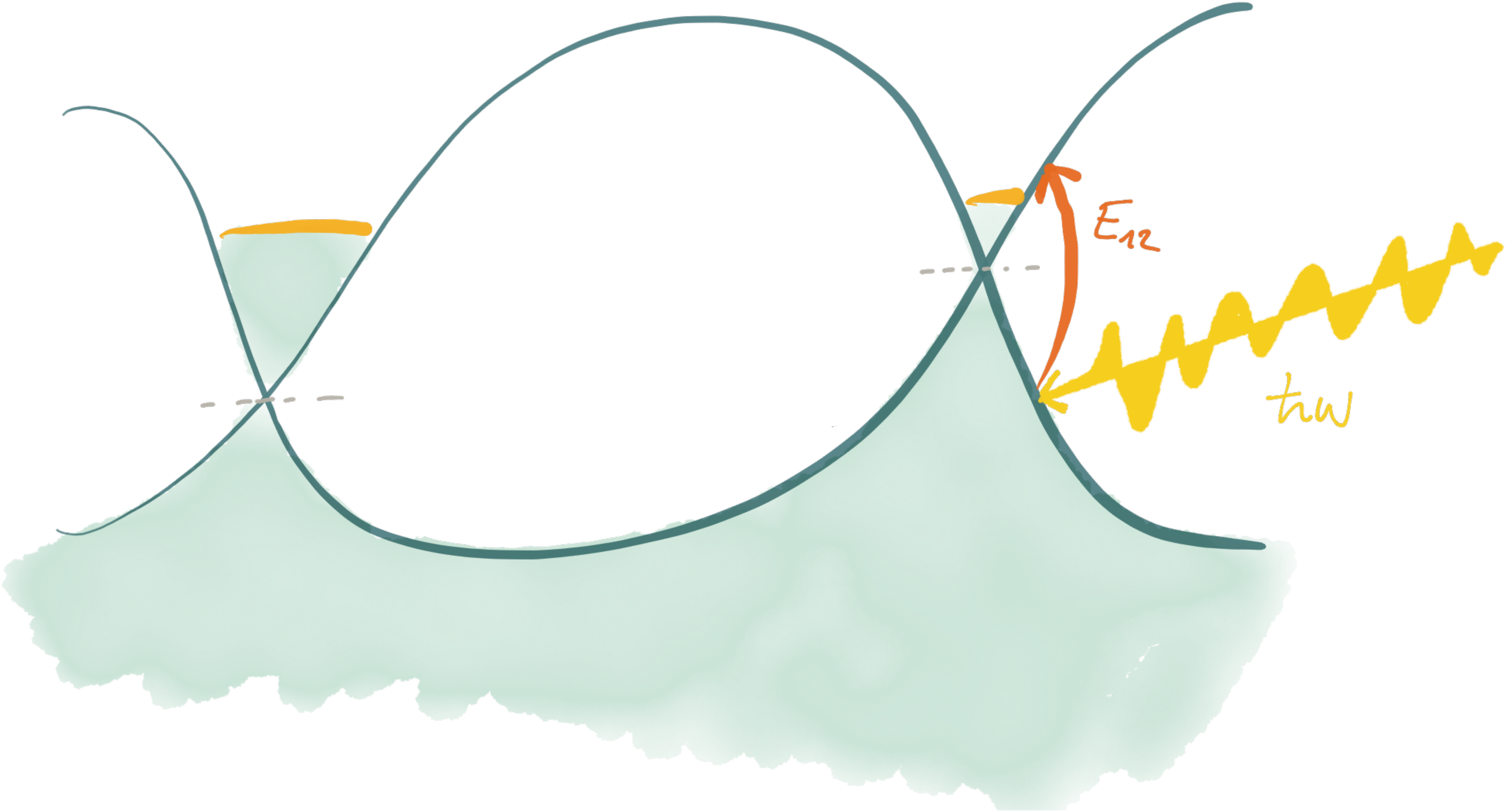



E
k
$-C$
C
k_z
k_y
k_x
k_z
k_y
k_x
$\oint_S d\mathbf{S} \cdot \mathbf{\Omega_1} =$

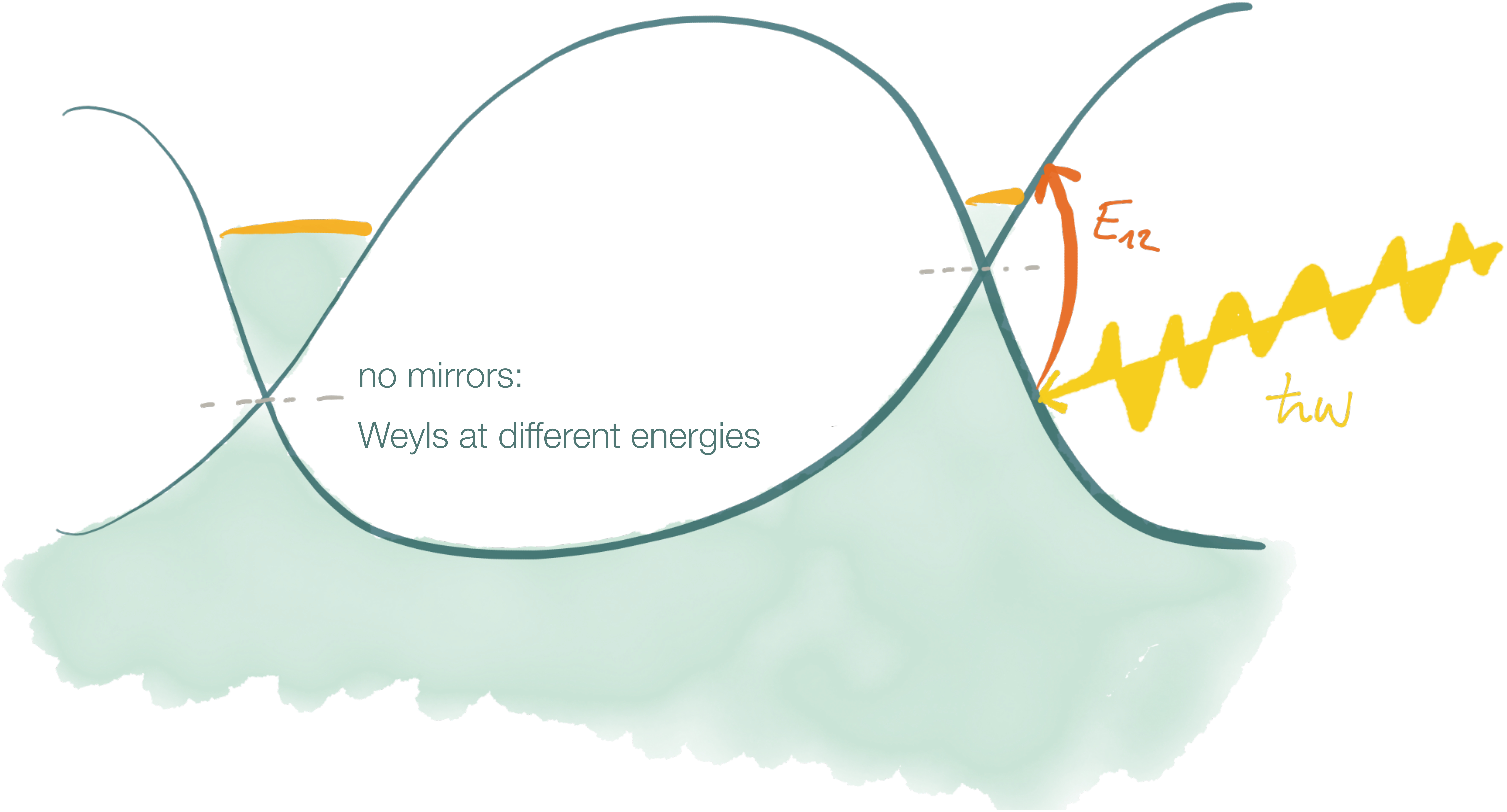
Optical properties of chiral topological metals



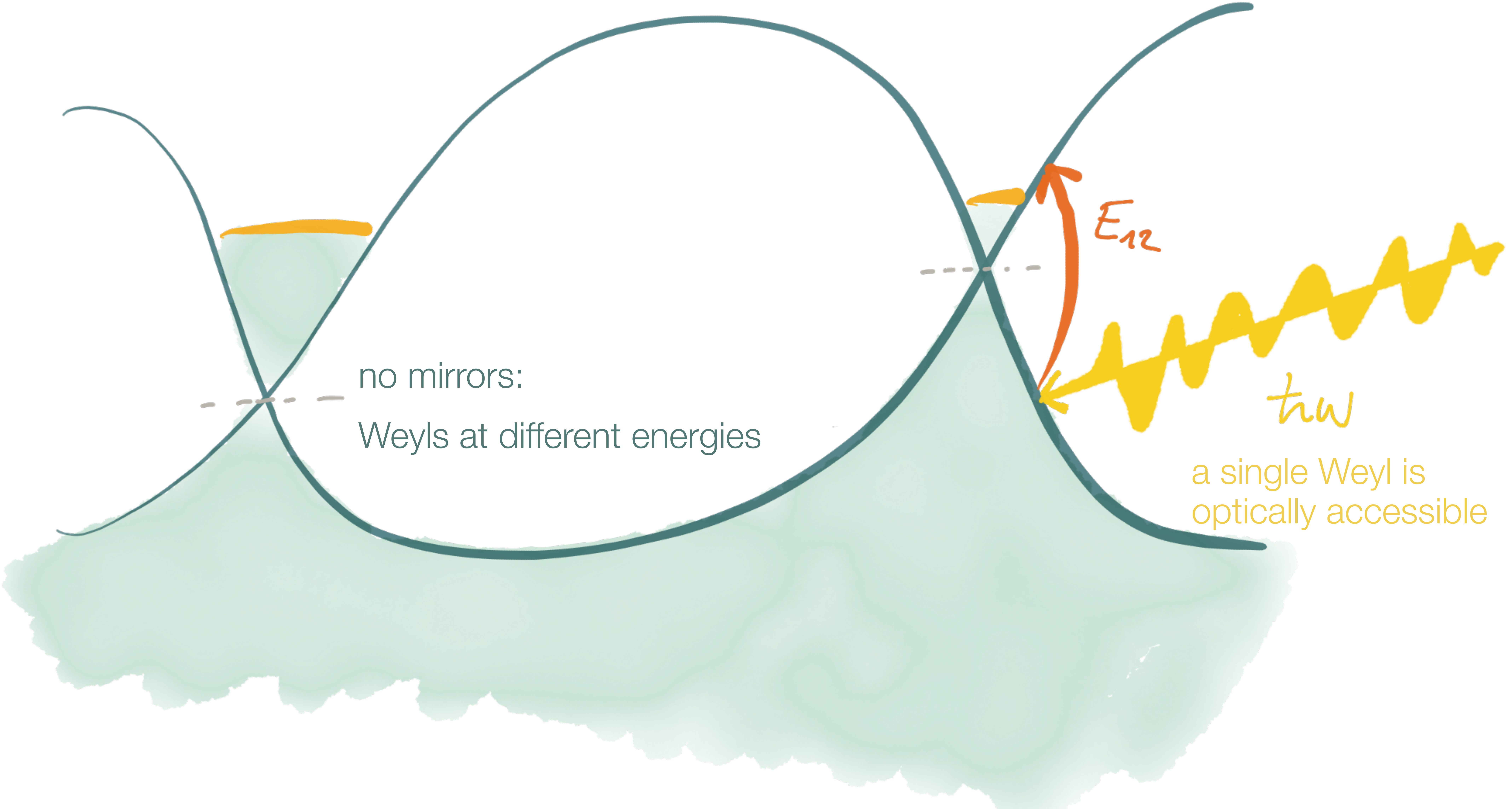
Optical properties of chiral topological metals

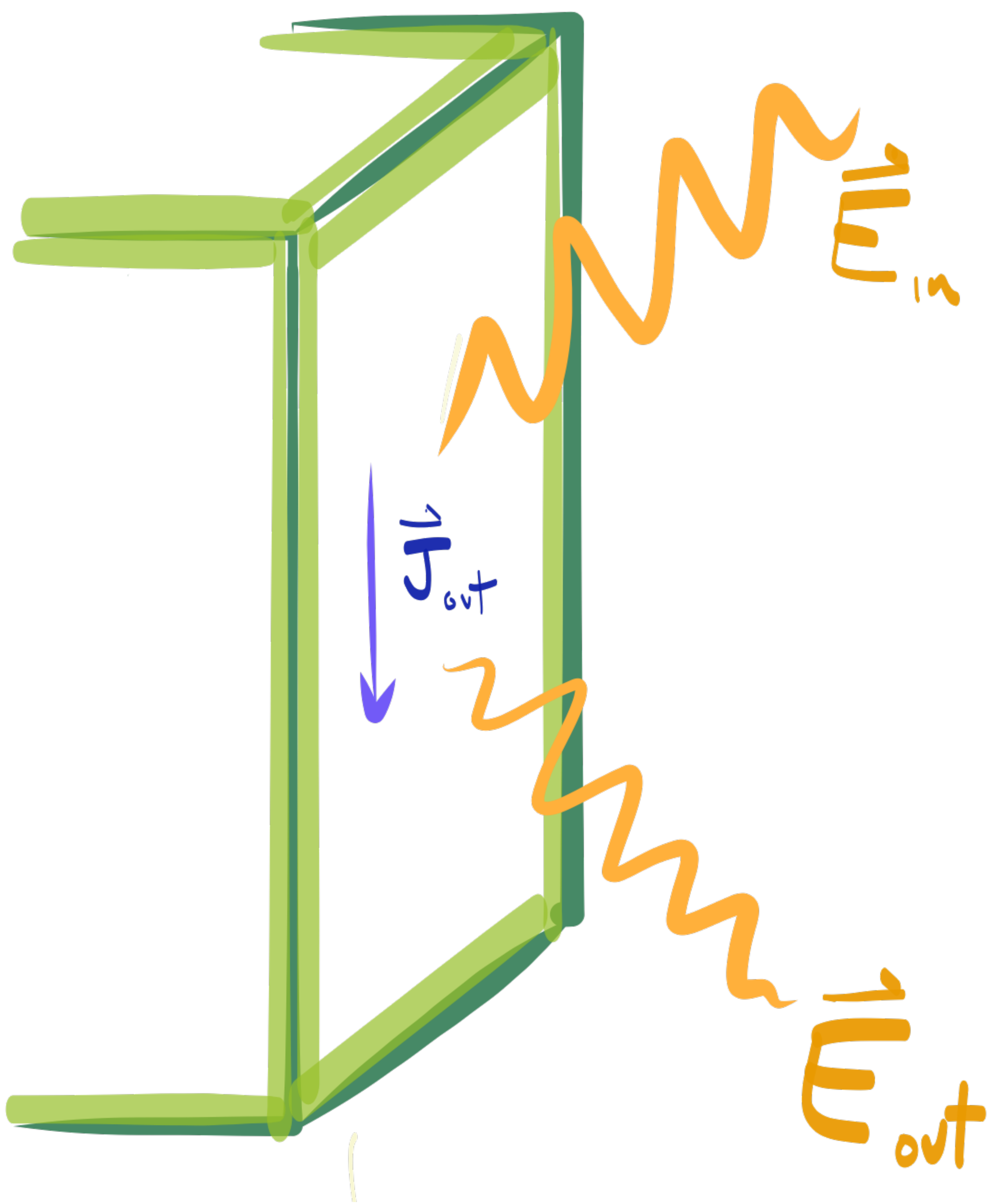


Optical properties of chiral topological metals



Optical properties of chiral topological metals





$$j_i \propto \sigma_{ijl} E_j E_l$$

Second order zoo

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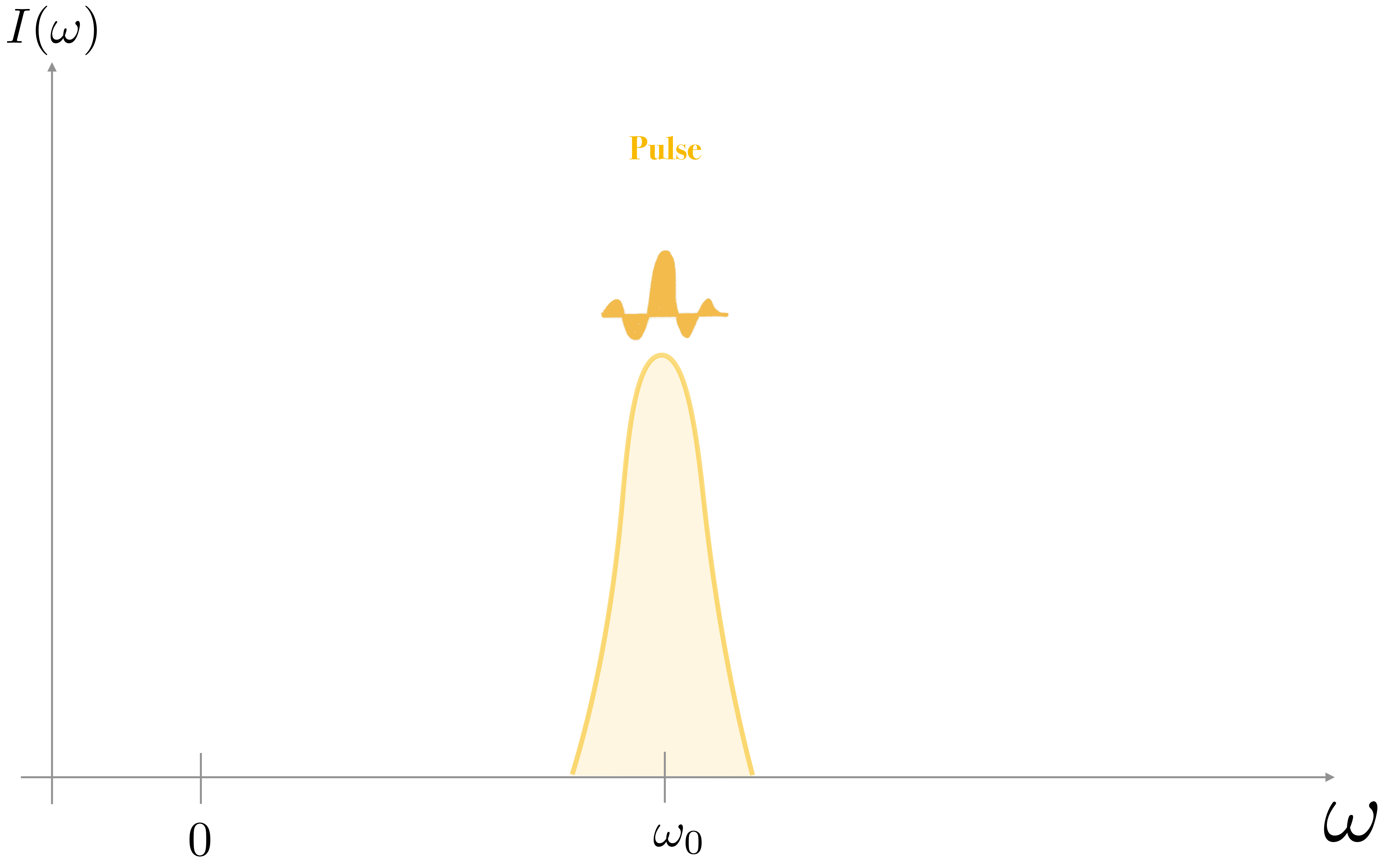

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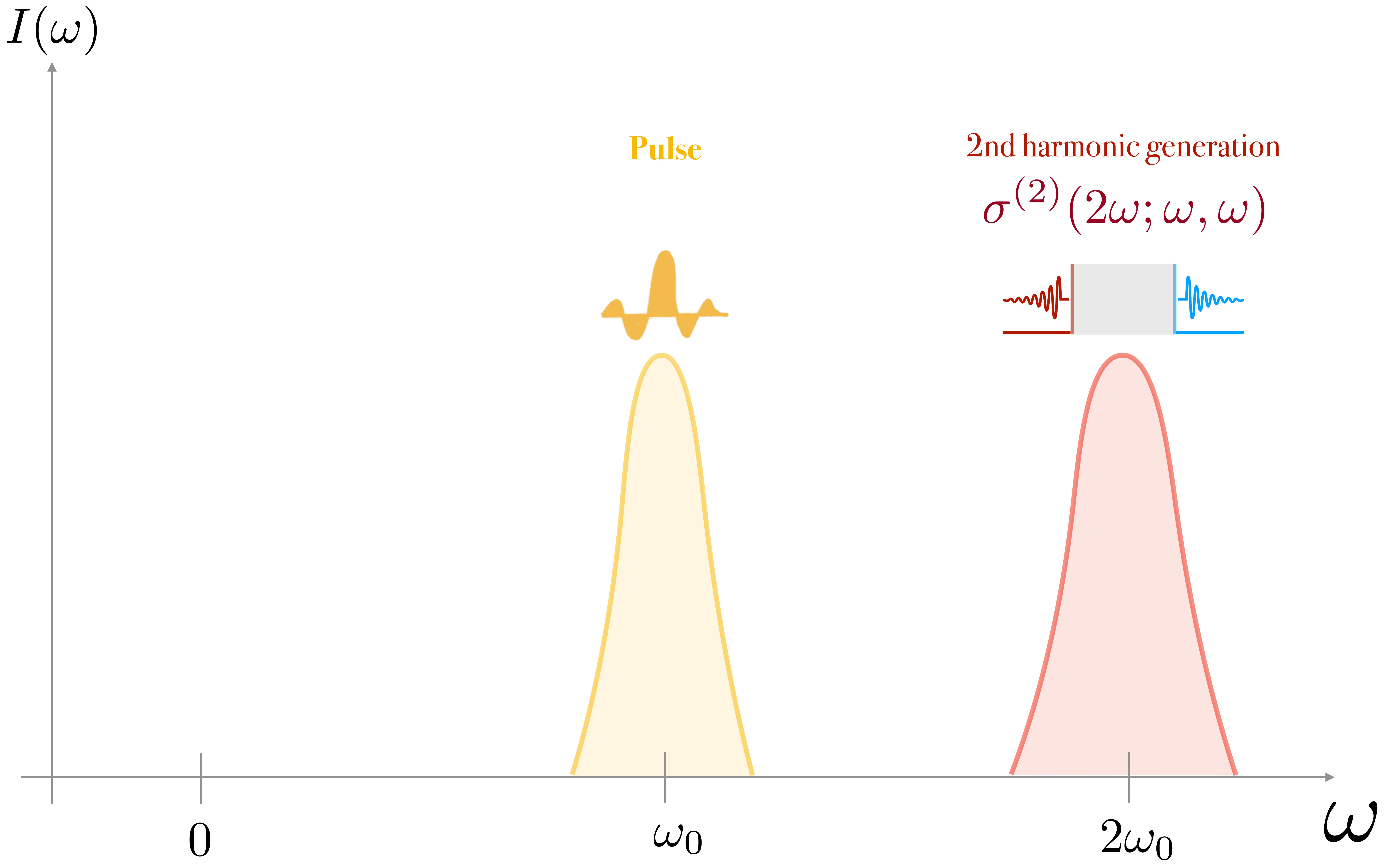

S. Patankar et. al. PRB '18

Second order zoo

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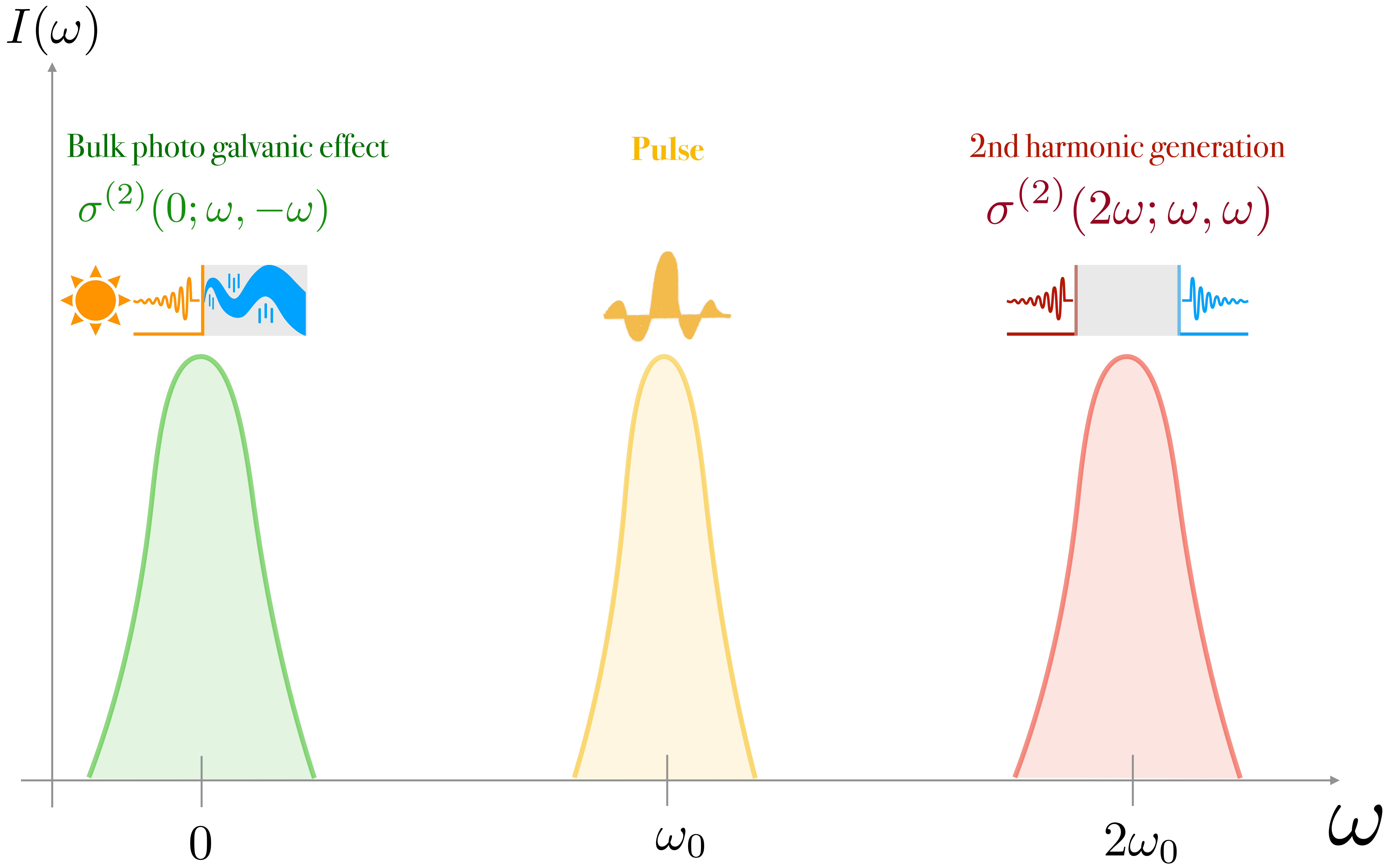

S. Patankar et. al. PRB '18

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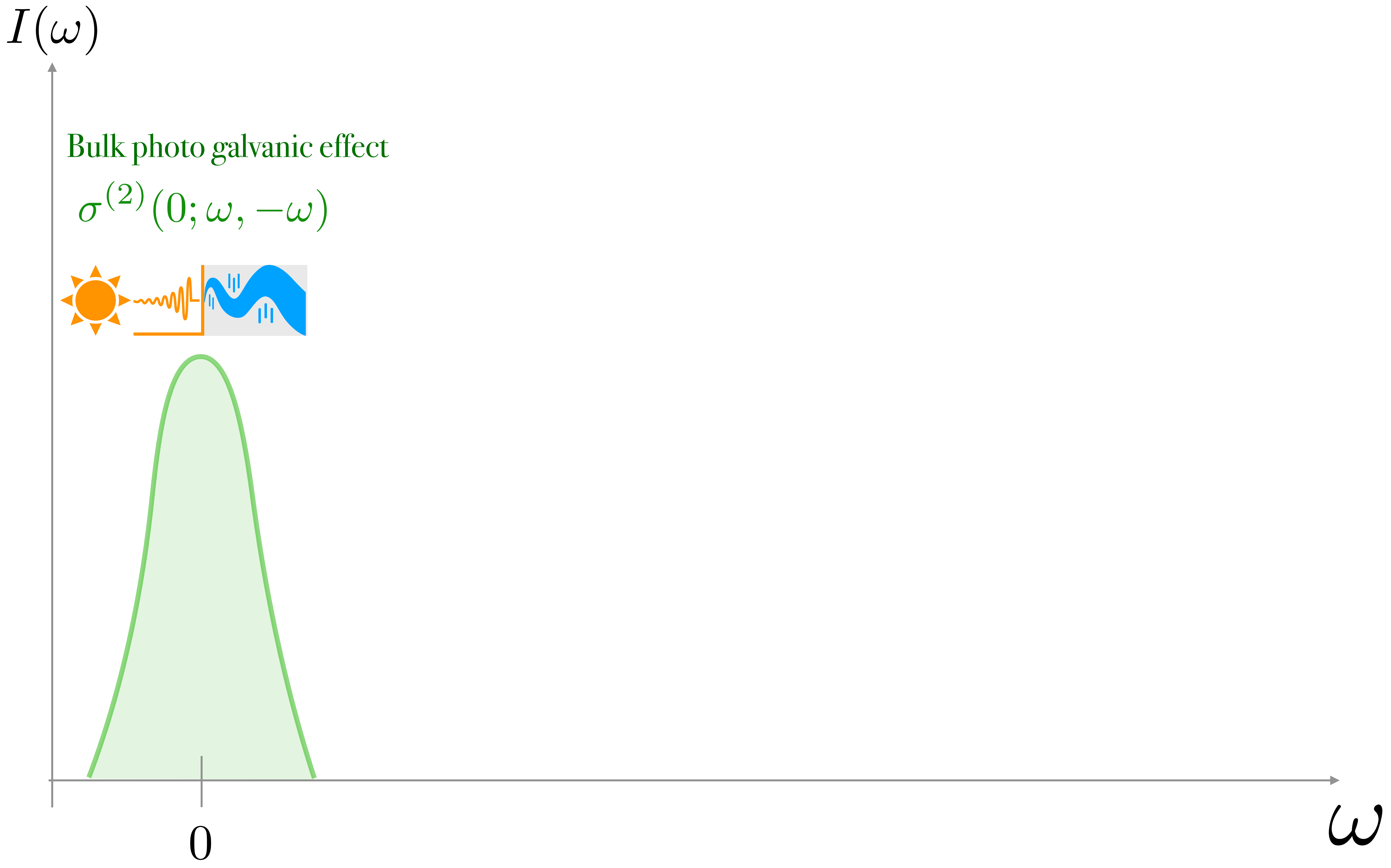

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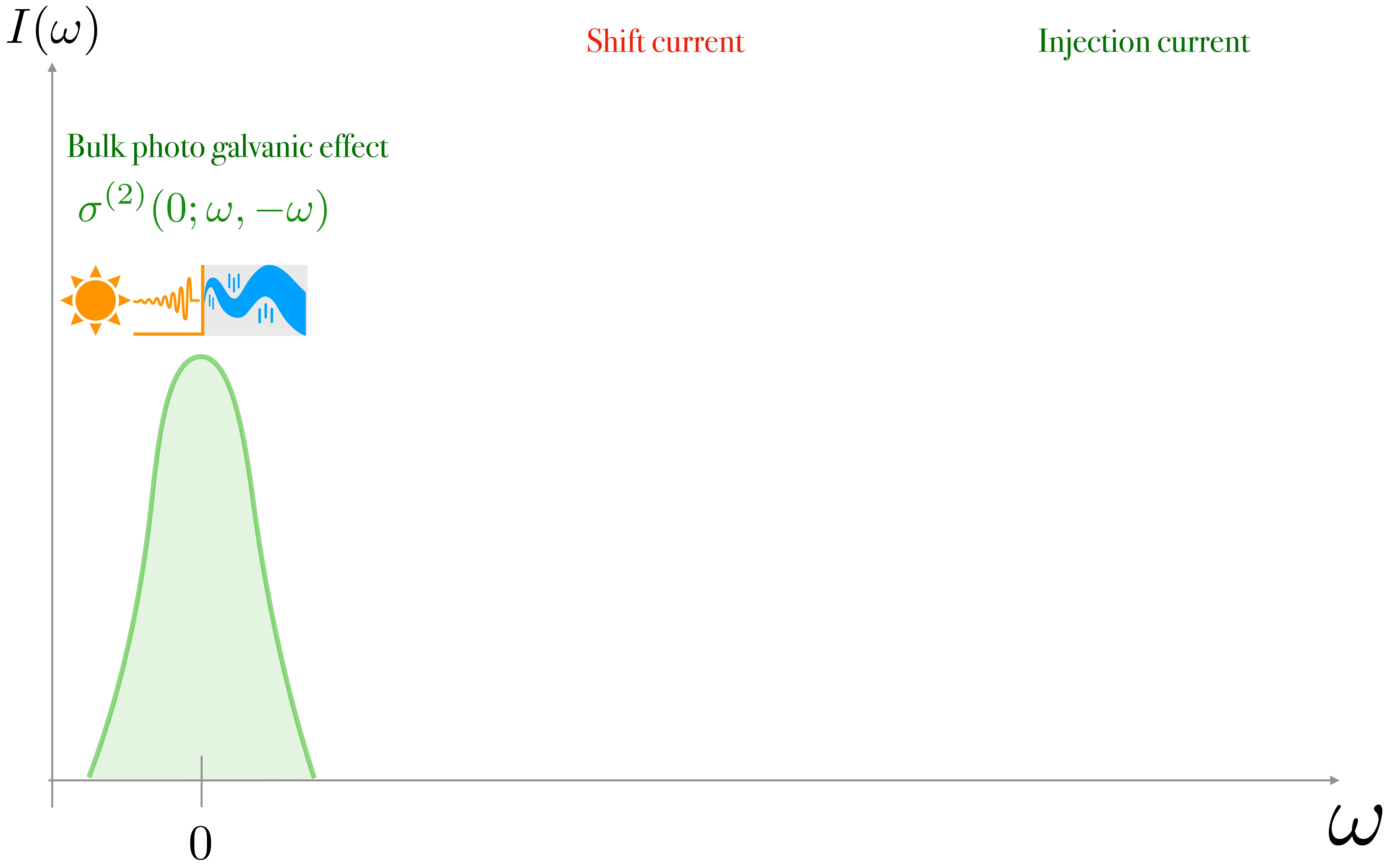

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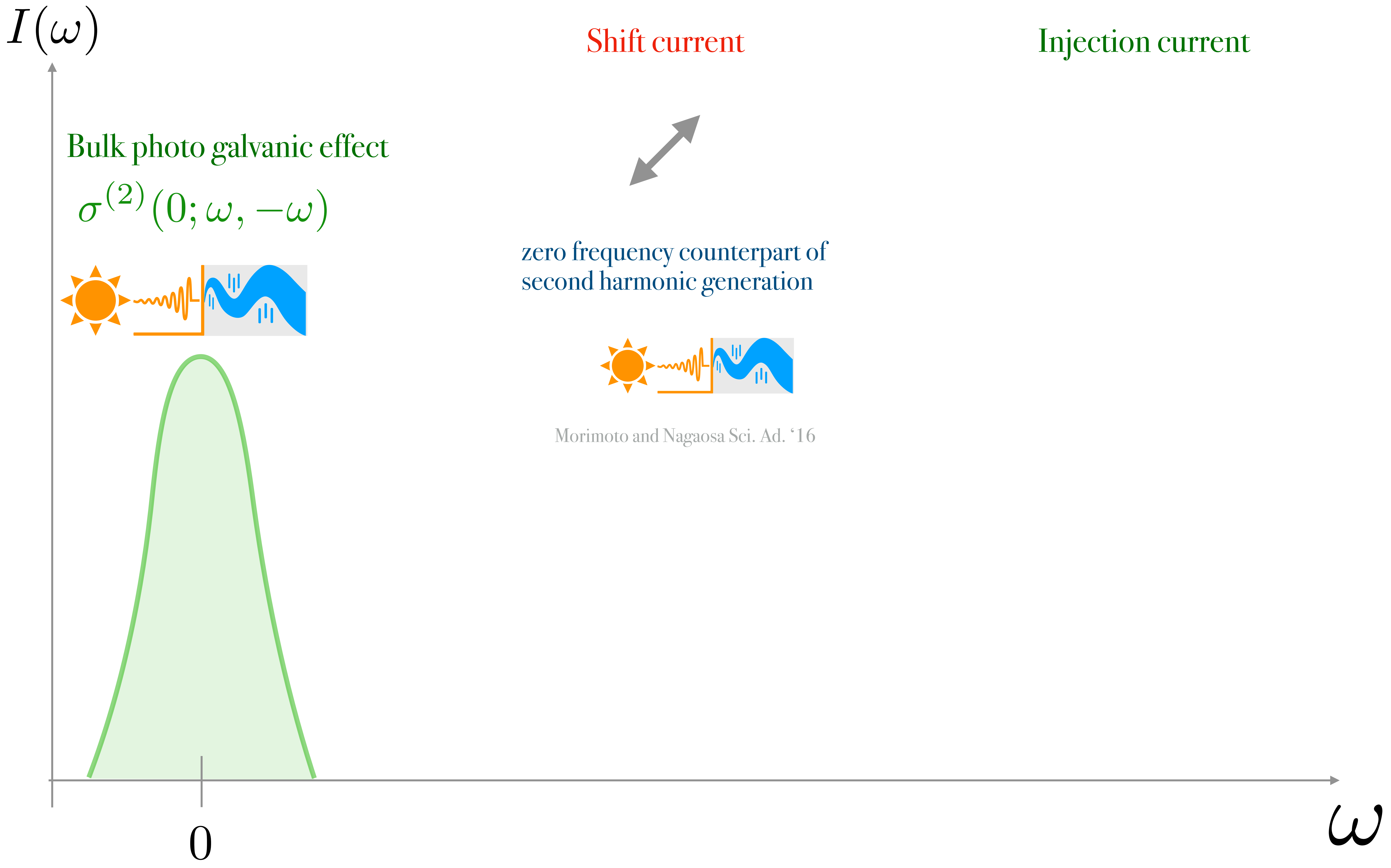

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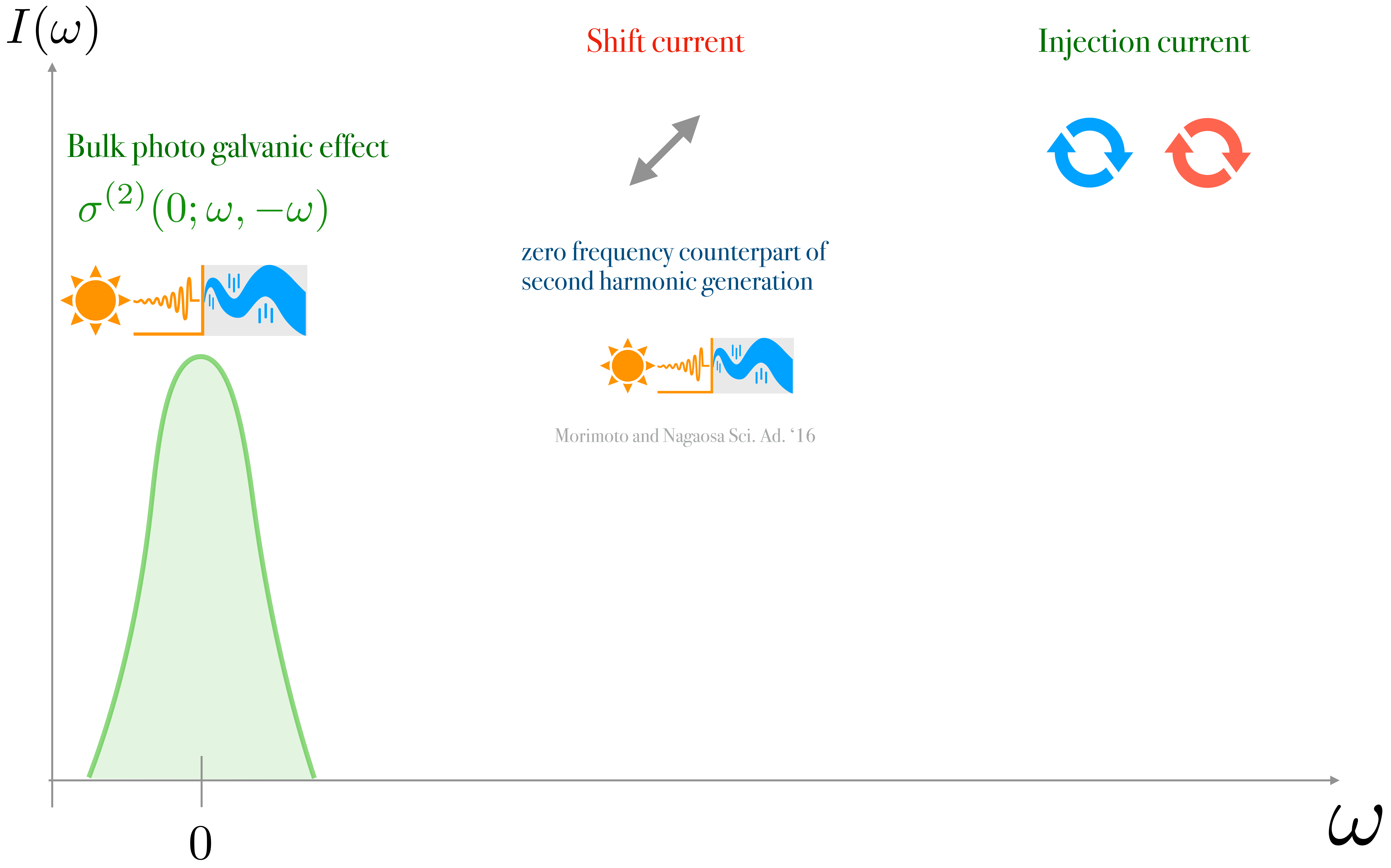

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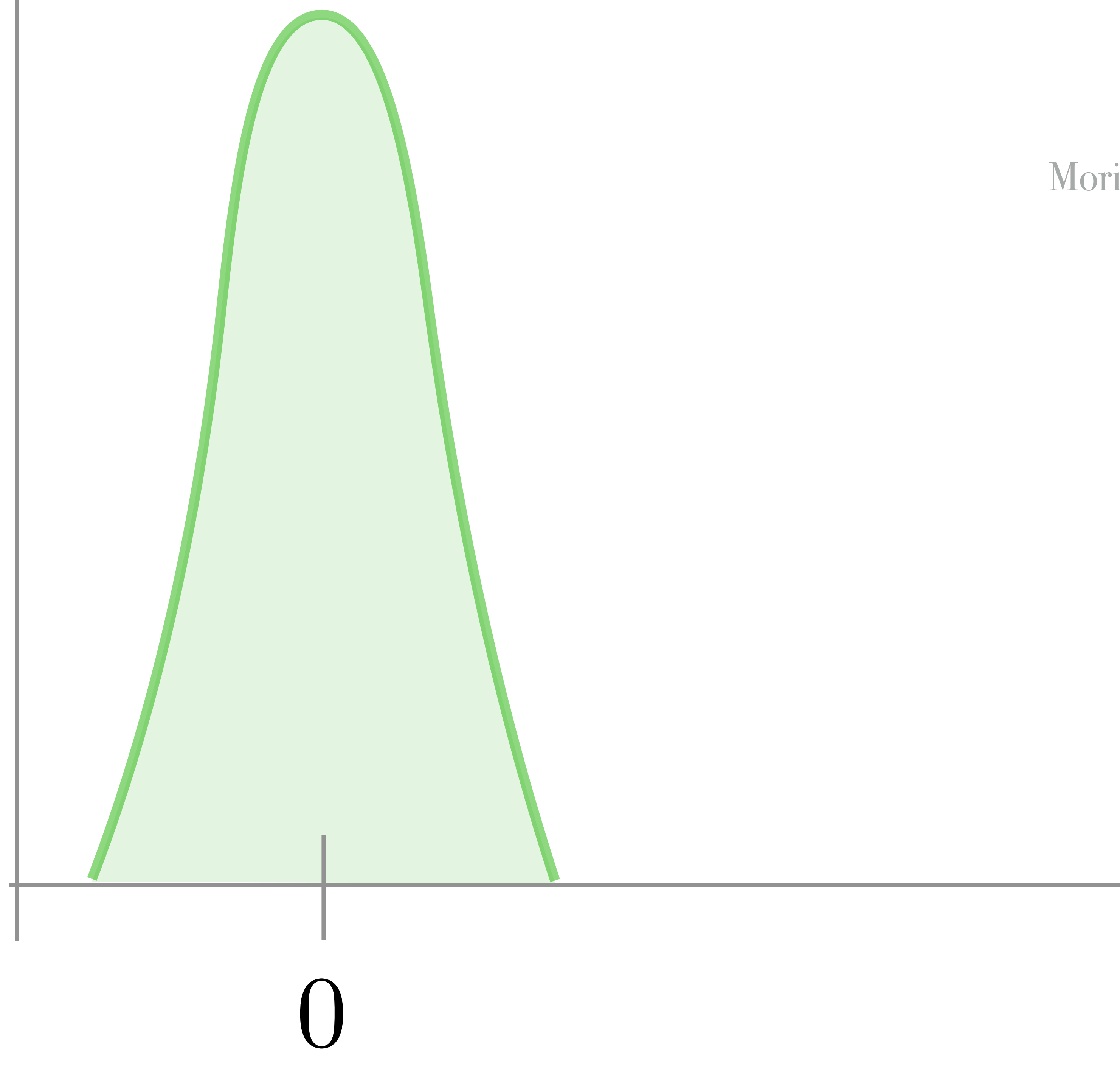
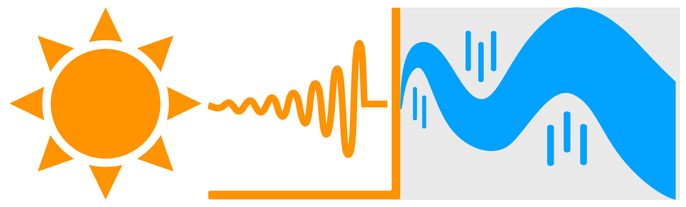


$I(\omega)$

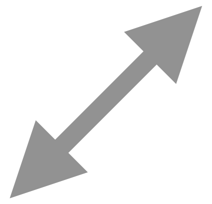
ω

Bulk photo galvanic effect

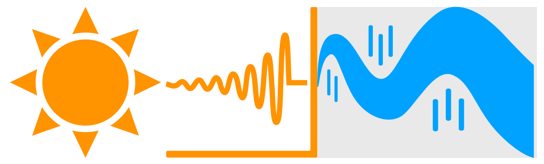
$\sigma^{(2)}(0; \omega, -\omega)$



Shift current

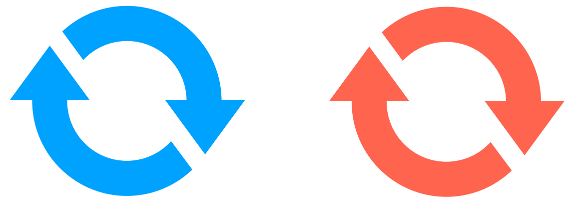


zero frequency counterpart of
second harmonic generation



Morimoto and Nagaosa Sci. Ad. '16

Injection current

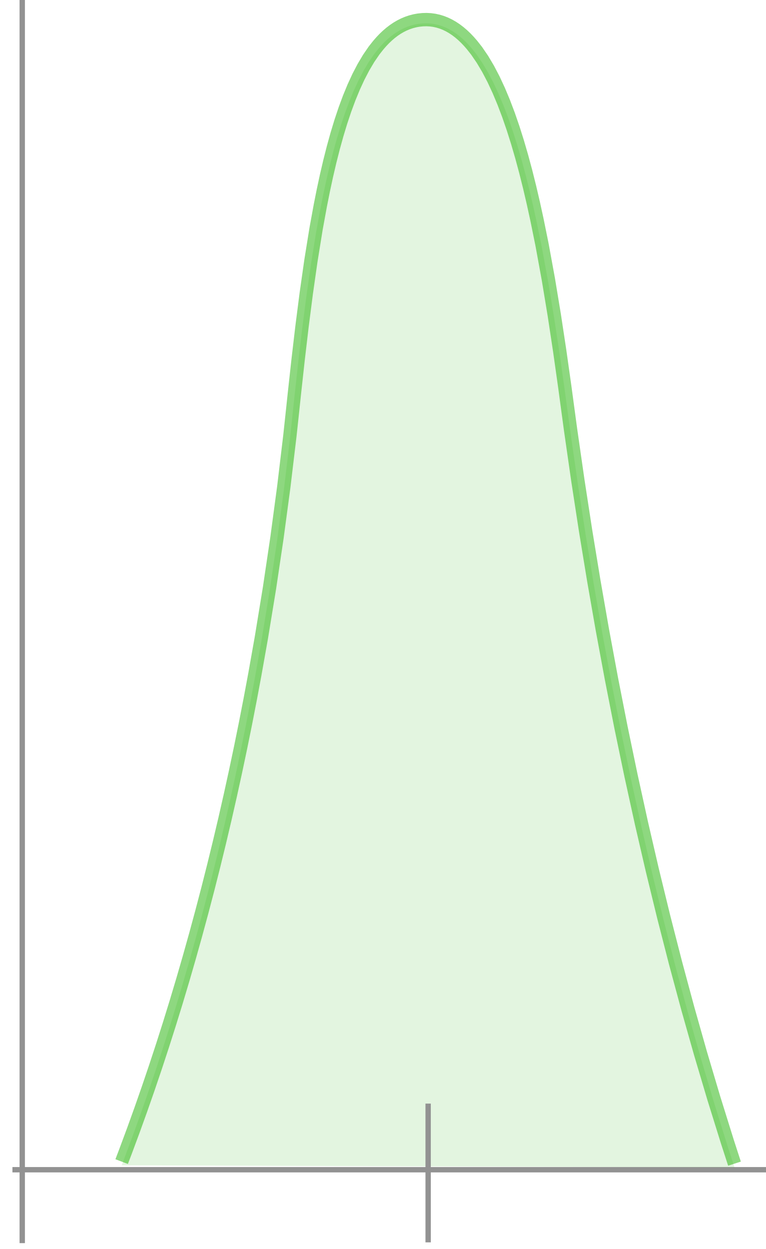


part that flips sign with polarization:
large and quantized

$$\frac{e^3}{h^2}$$

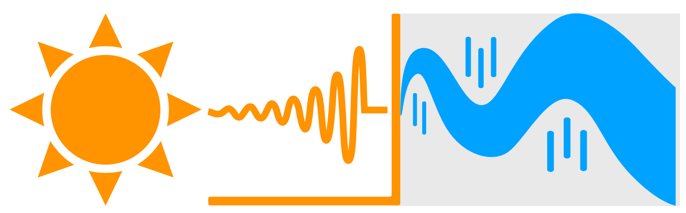
Second order zoo

$$j_i \propto \sigma_{ijl} E_j E_l$$



Bulk photo galvanic effect

$\sigma^{(2)}(0; \omega, -\omega)$



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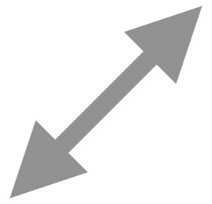

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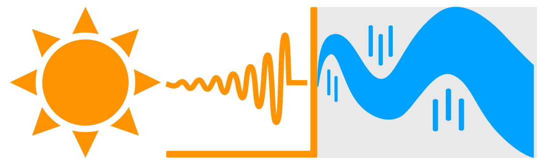

Morimoto and Nagaosa Sci. Ad. '16

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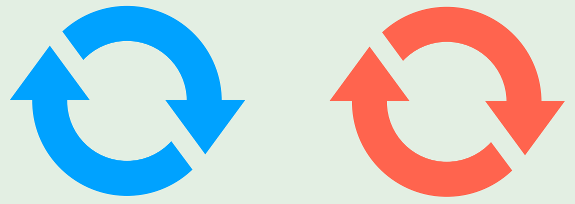

part that flips sign with polarization:
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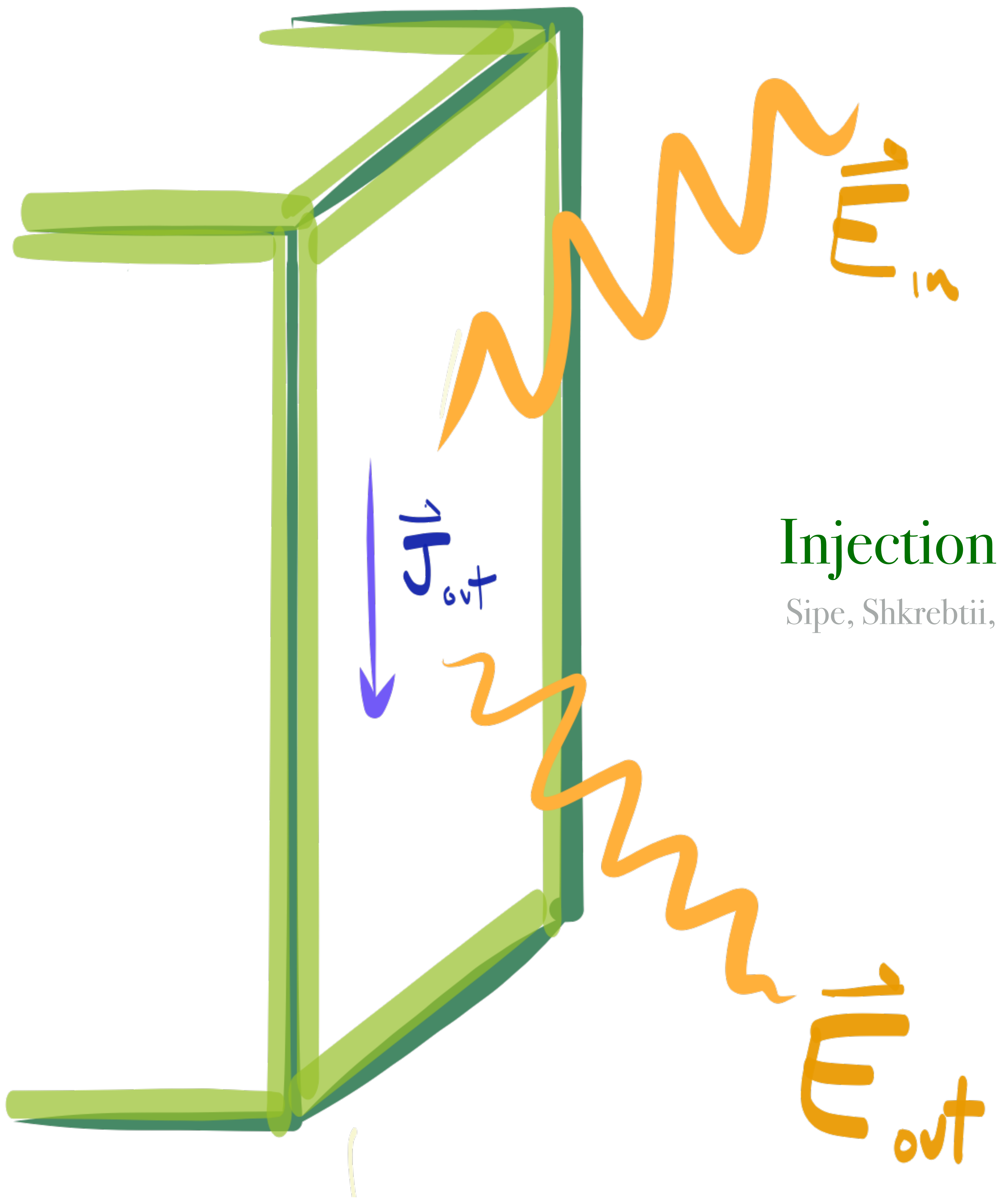
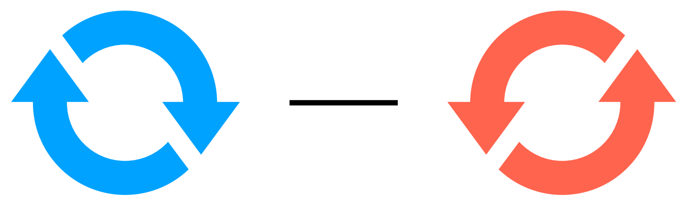


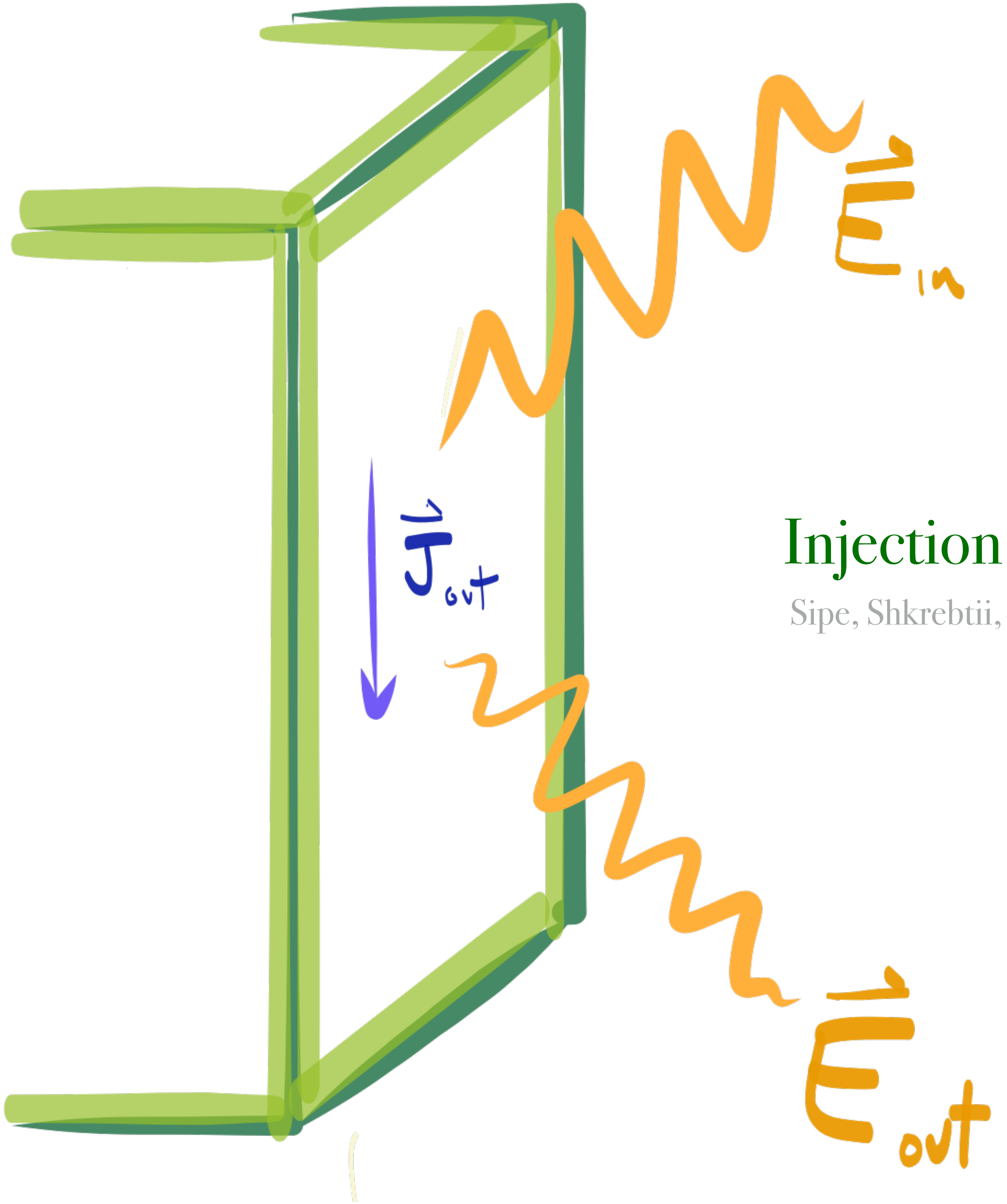
Injection current

Sipe, Shkrebtii, PRB (2000)

$$j_i \propto \sigma_{ijl} E_j E_l$$



$$\boxed{(\mathbf{E} \times \mathbf{E}^*)_j}$$



Injection current

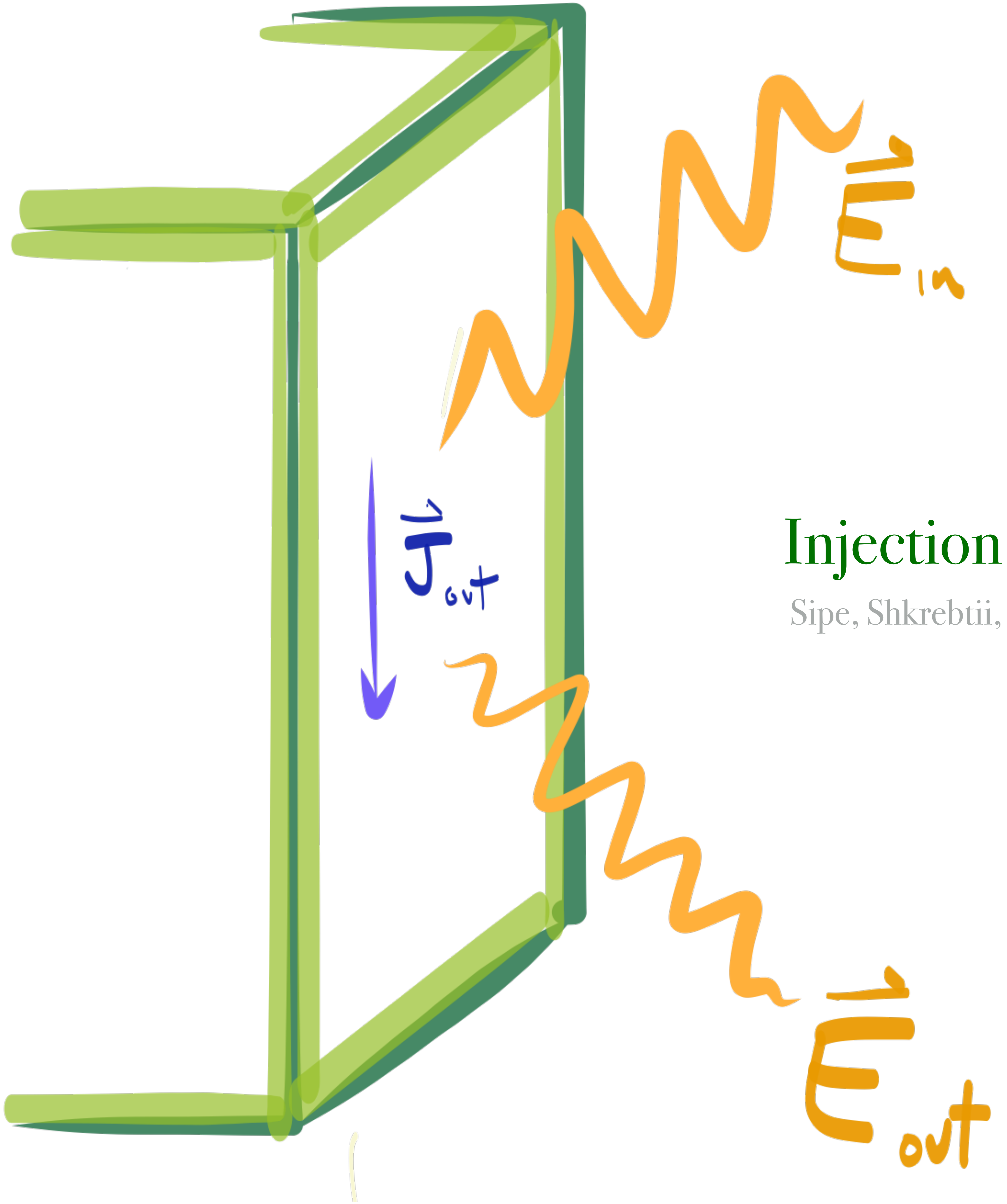
Sipe, Shkrebtii, PRB (2000)

$$j_i \propto \sigma_{ijl} E_j E_l$$

$\propto (i\omega)^{-1}$

$$\boxed{\frac{dj_i}{dt}} \qquad \boxed{(\mathbf{E} \times \mathbf{E}^*)_j}$$

—



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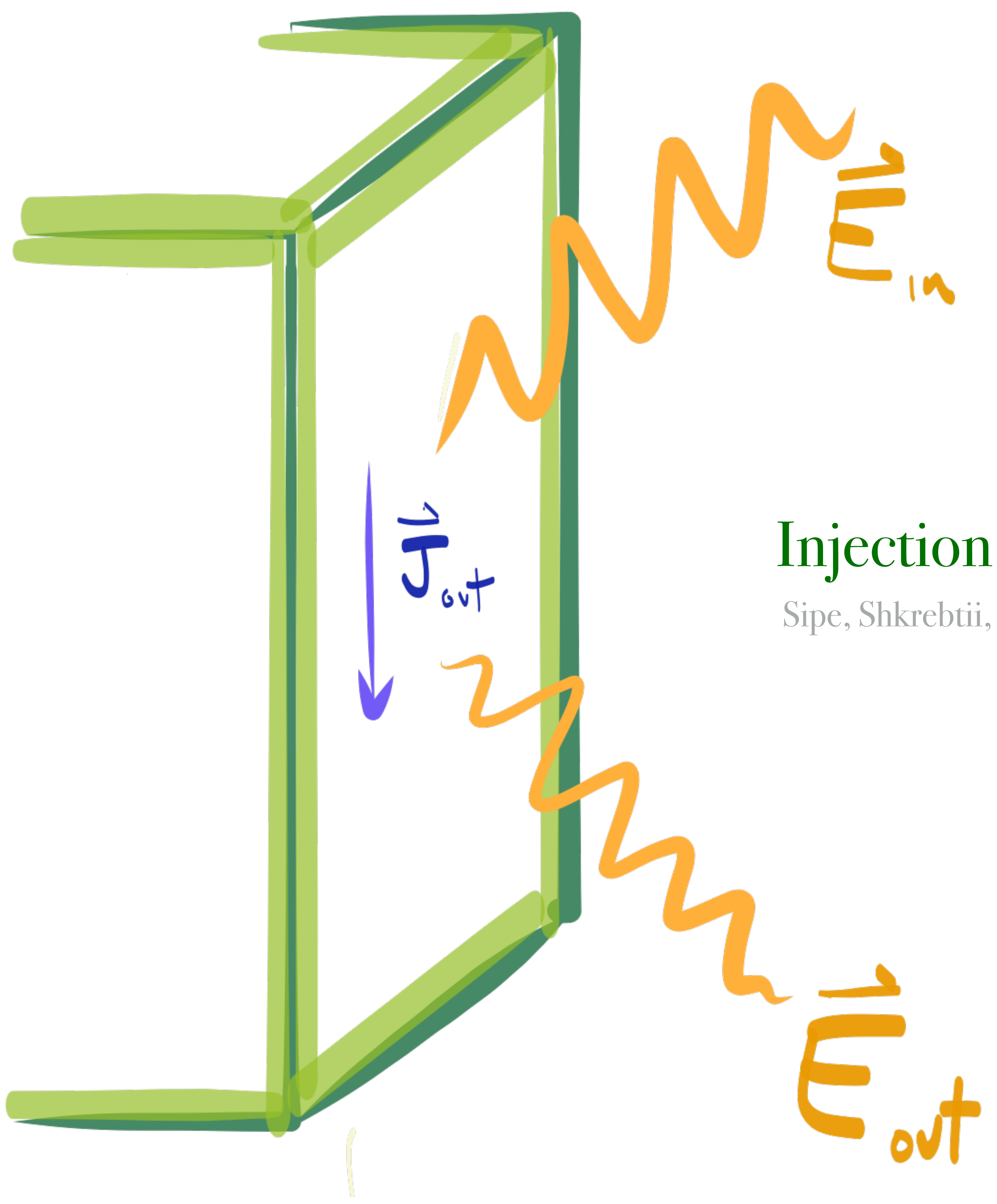
$$\boxed{\frac{dj_i}{dt}} = \beta_{ij}(\omega)\boxed{(\mathbf{E} \times \mathbf{E}^*)_j}$$



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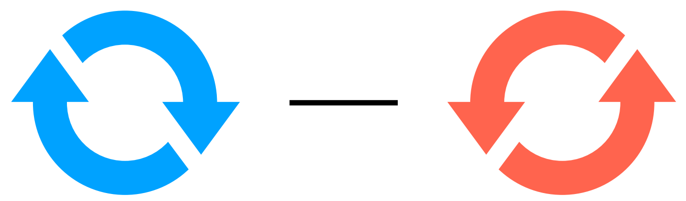


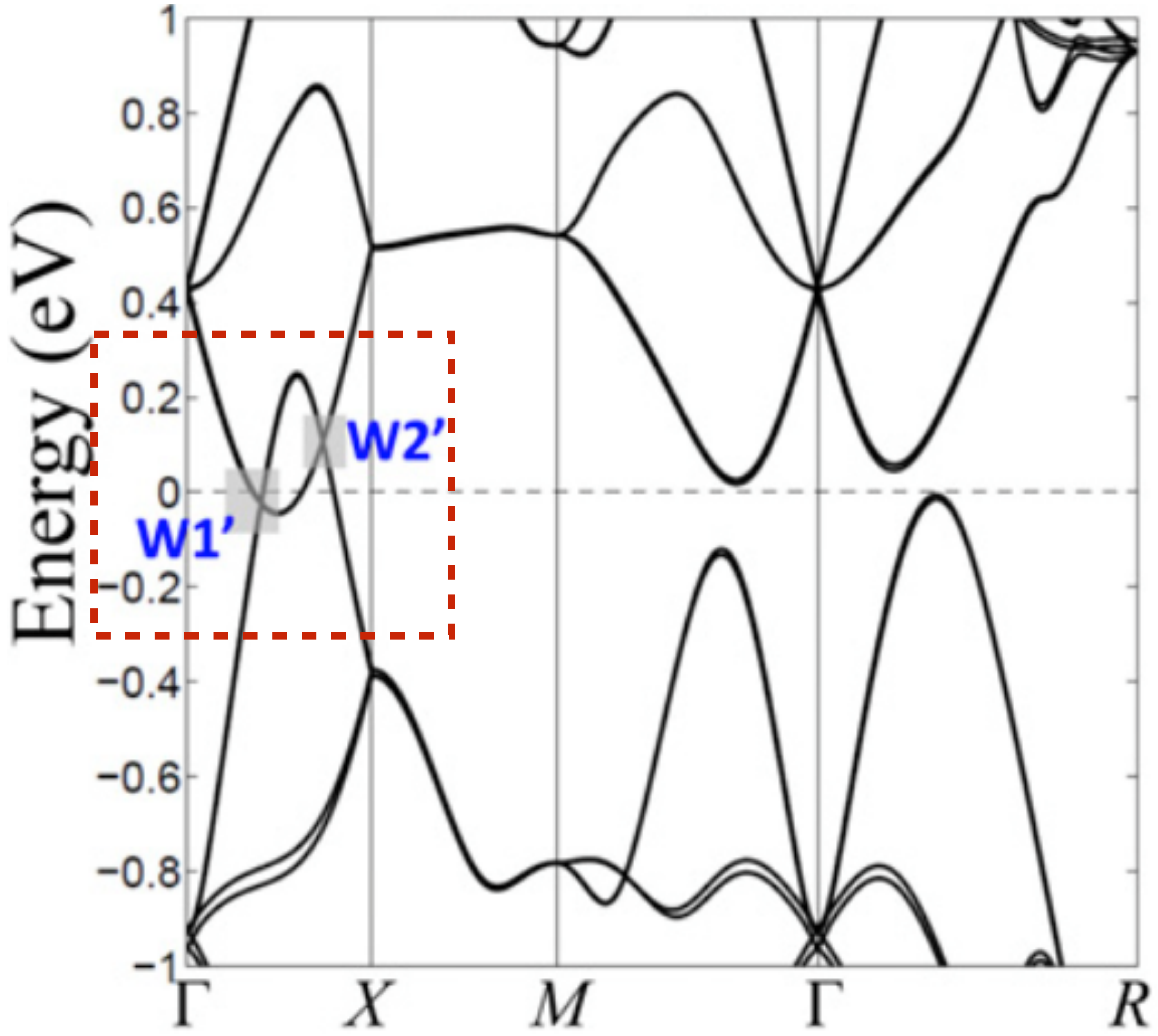
$$\boxed{\frac{dj_i}{dt}} = \beta_{ij}(\omega)\boxed{(\mathbf{E} \times \mathbf{E}^*)_j}$$

$$\boxed{\mathrm{Tr}[\beta] = i\frac{e^3}{2h^2}\oint_S d\mathbf{S} \cdot \mathbf{\Omega_1}}$$

F. de Juan, AGG, T. Morimoto, J. E. Moore Nat. Comm (2017)

$SrSi_2$

Huang, et al. PNAS **113** 1180 (2015)



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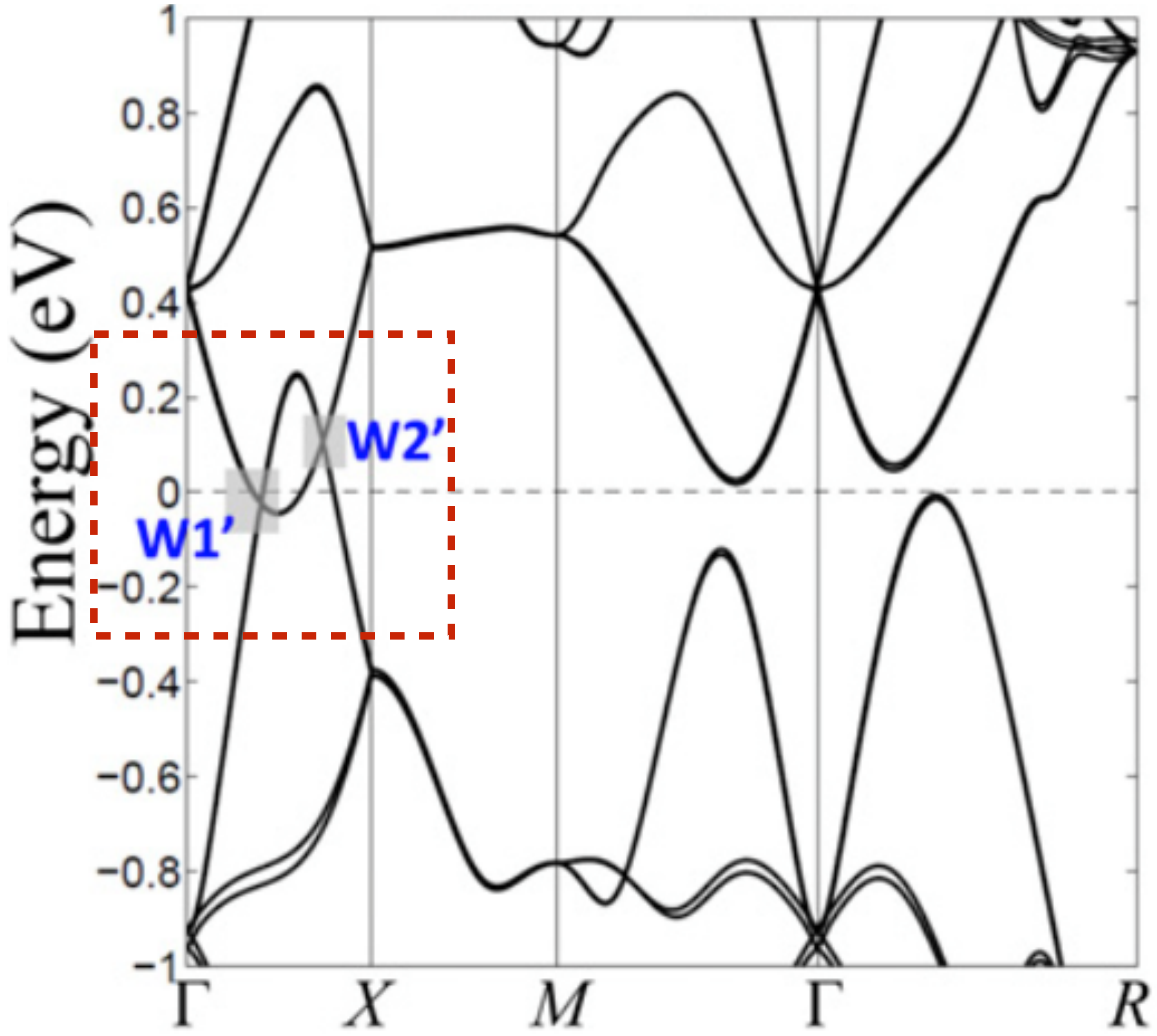

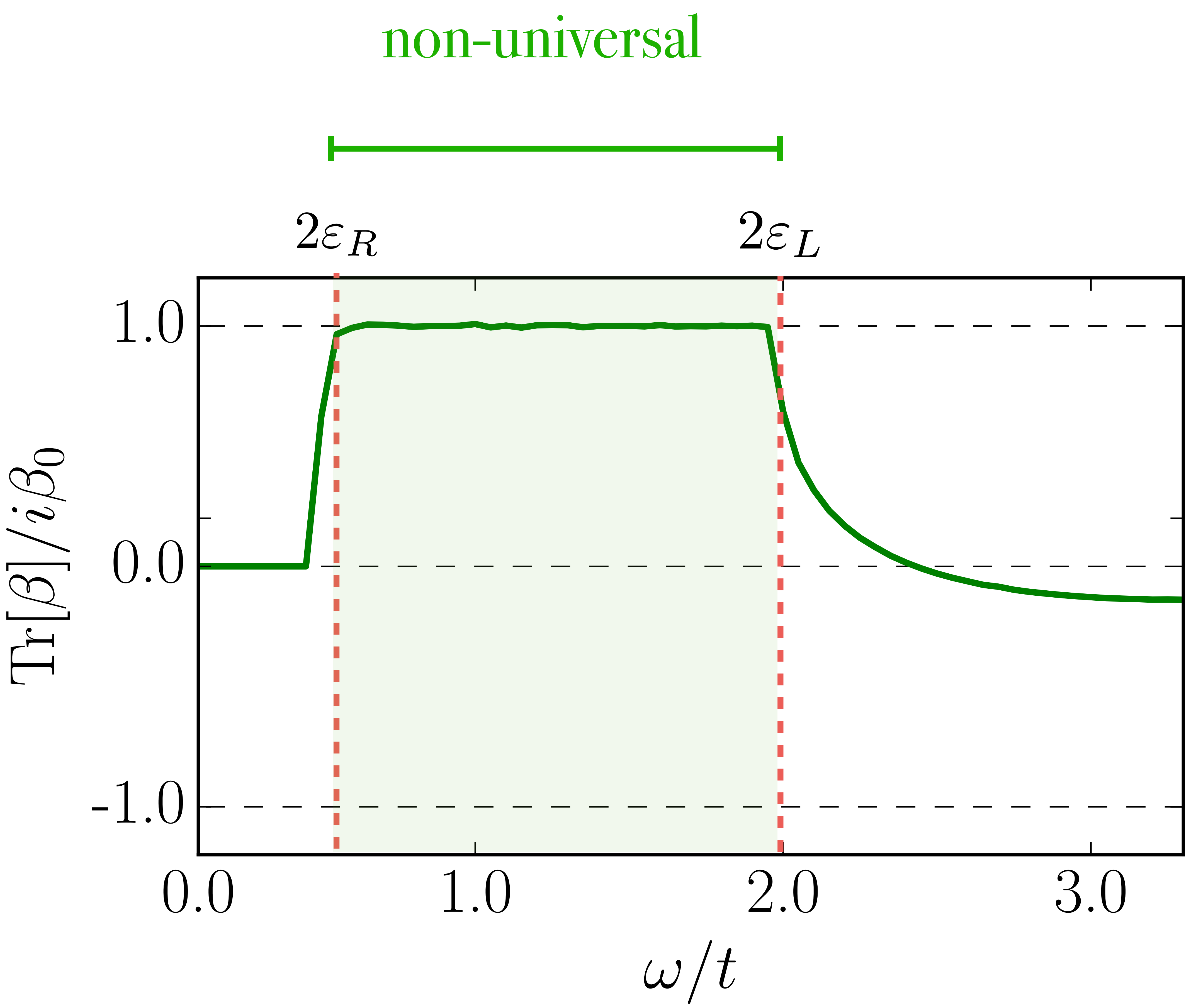

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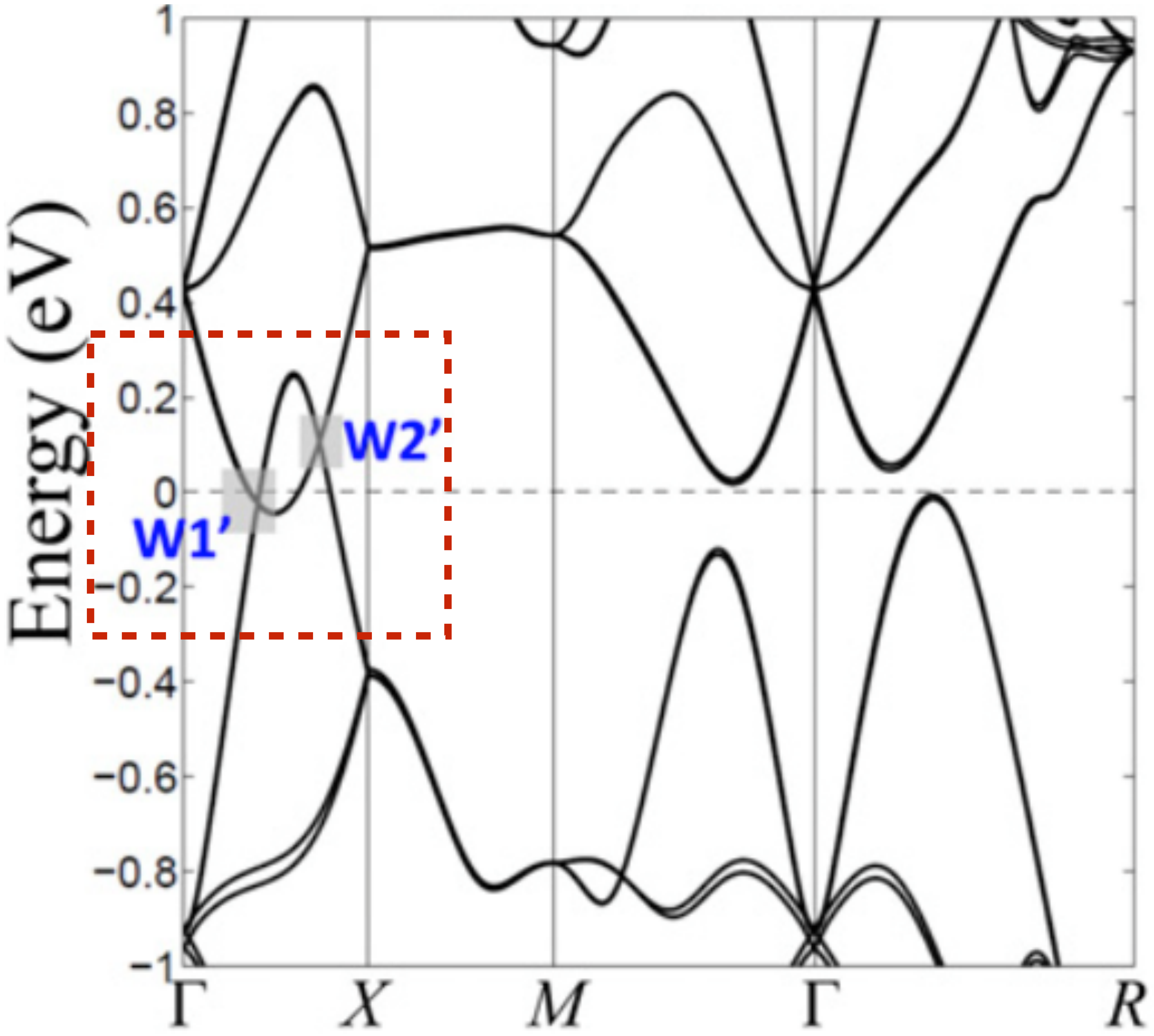
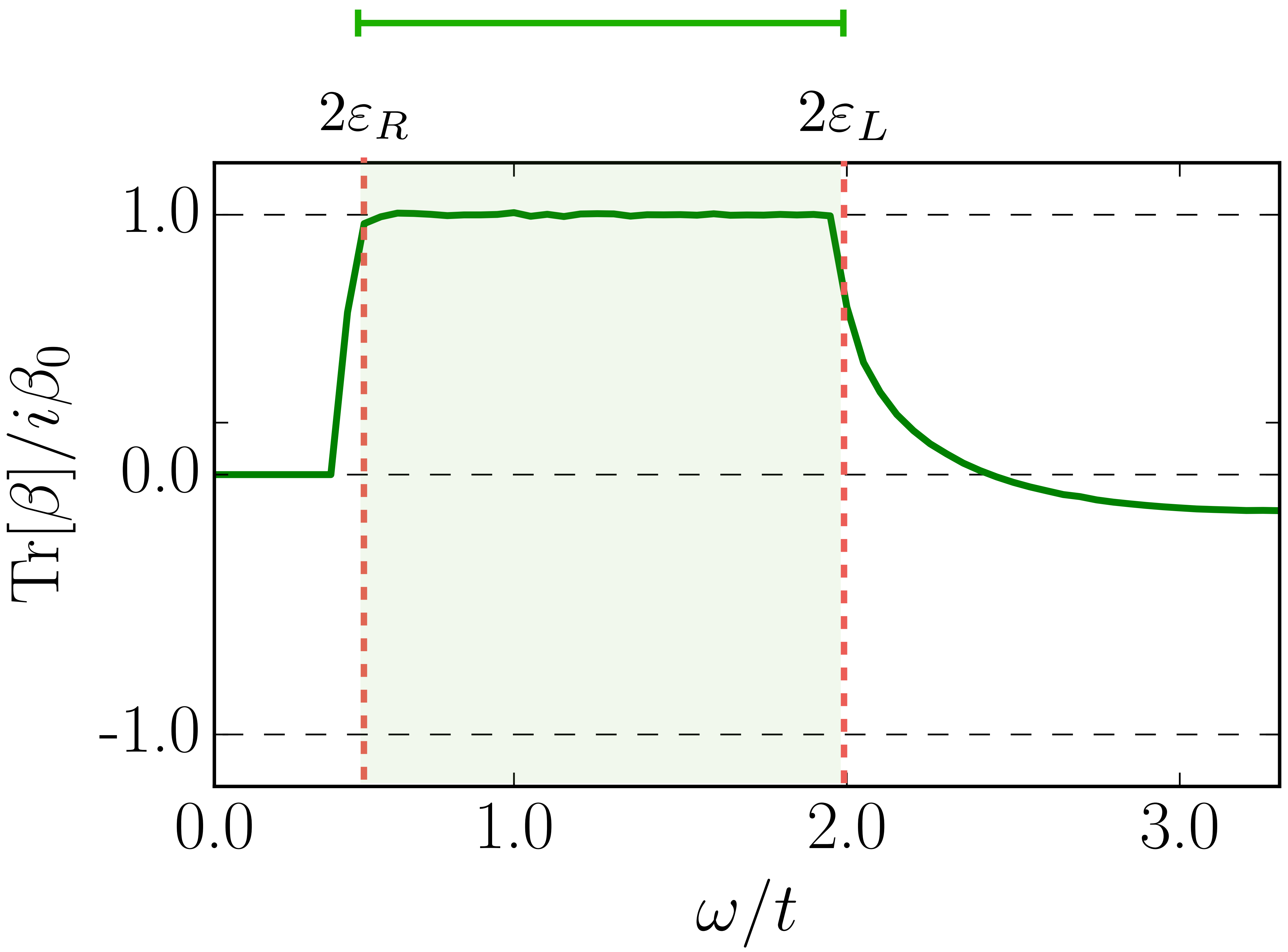


non-universal

universal



$$\pi \frac{e^3}{h^2} C$$

F. de Juan, AGG, T. Morimoto, J. E. Moore Nat. Comm (2017)

$SrSi_2$

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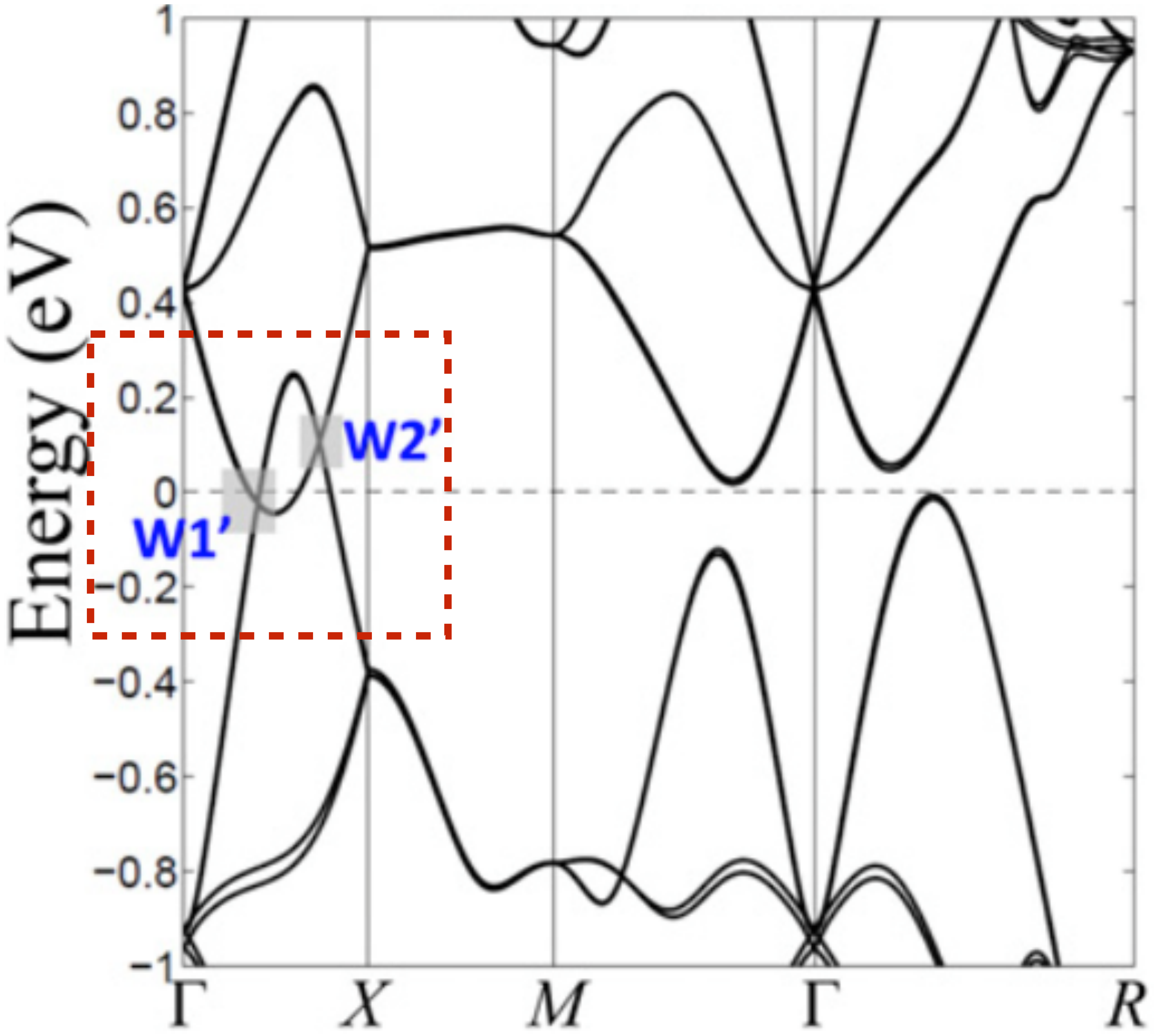
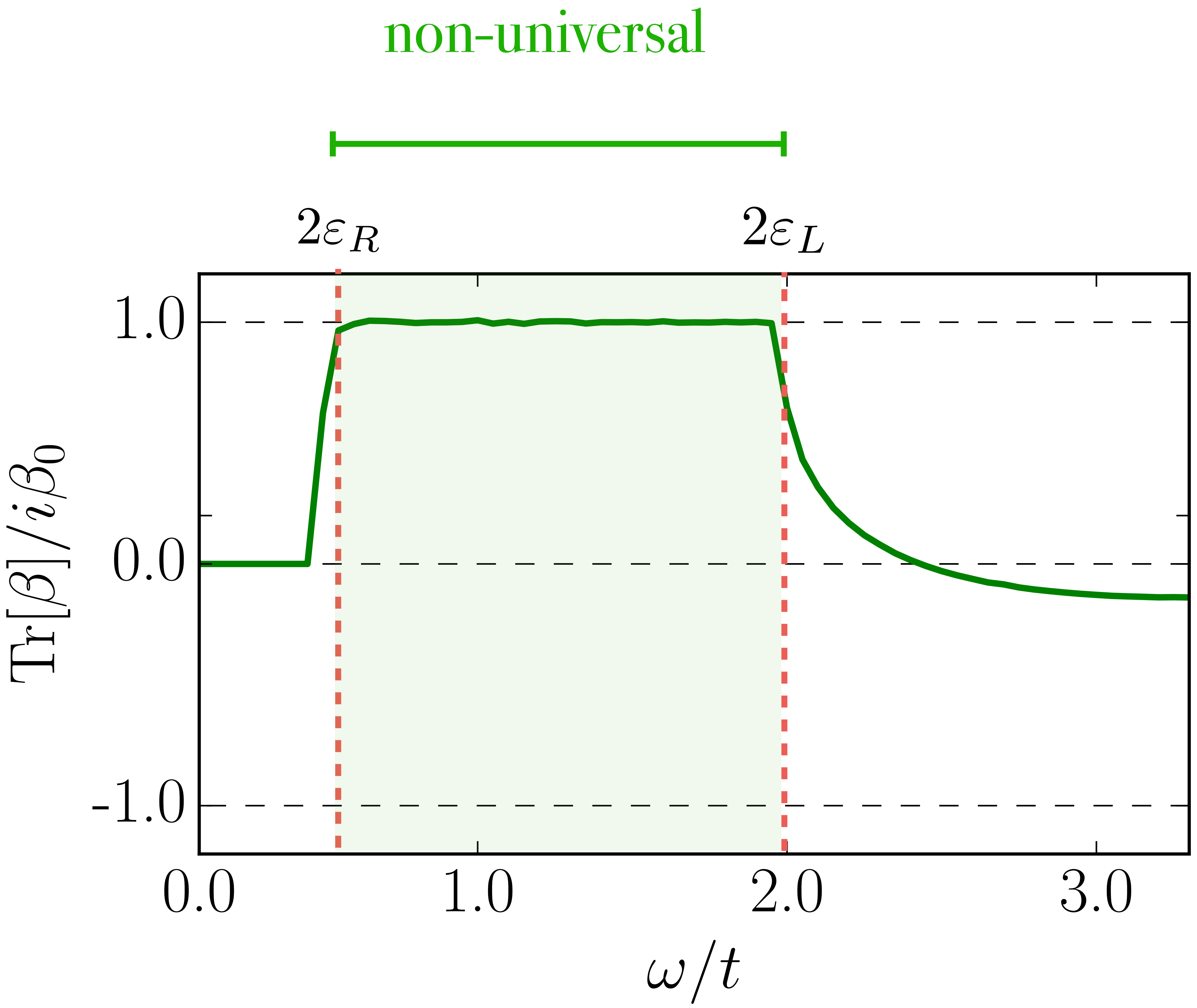




universal

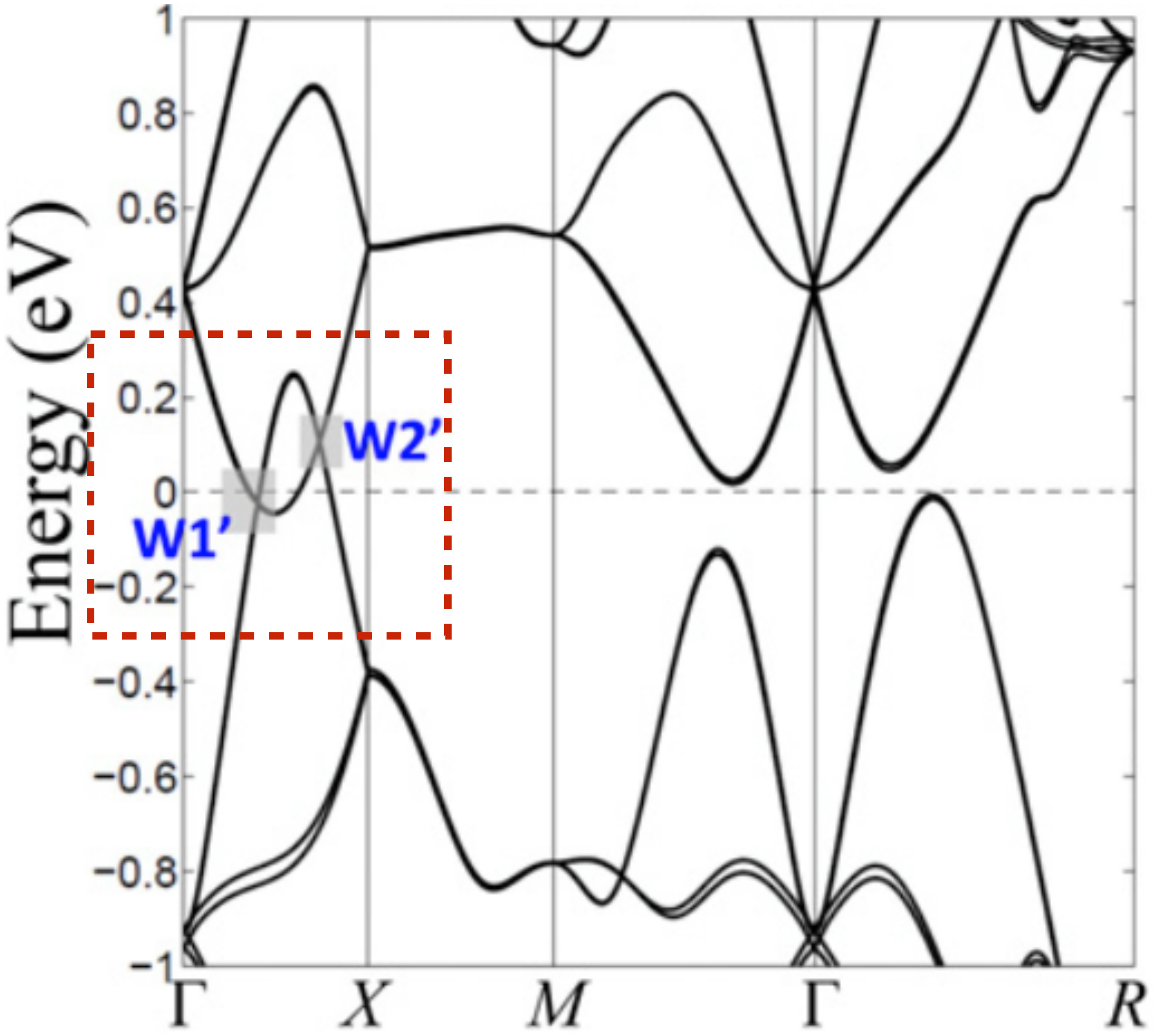
$$\pi \frac{e^3}{h^2} C \quad + \mathcal{O}\left(\frac{\omega^2}{\Delta E^2}\right)$$

multi-band correction

F. de Juan, AGG, T. Morimoto, J. E. Moore Nat. Comm (2017)

$SrSi_2$

Huang, et al. PNAS **113** 1180 (2015)



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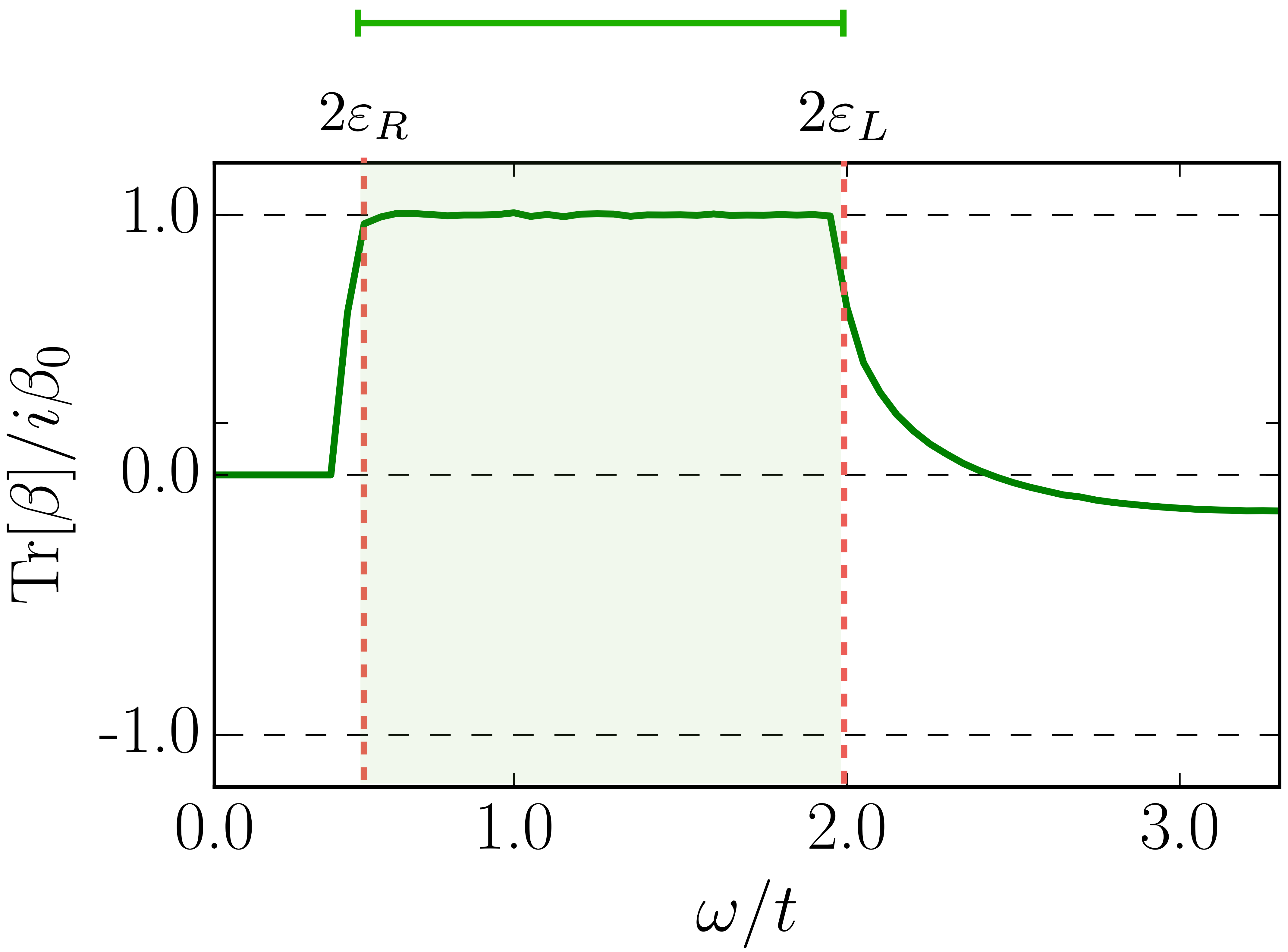

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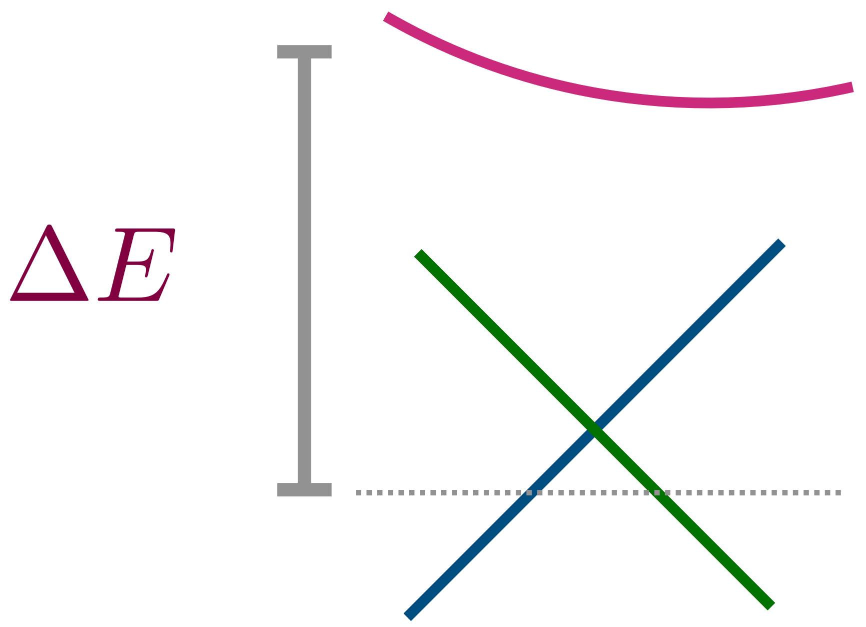
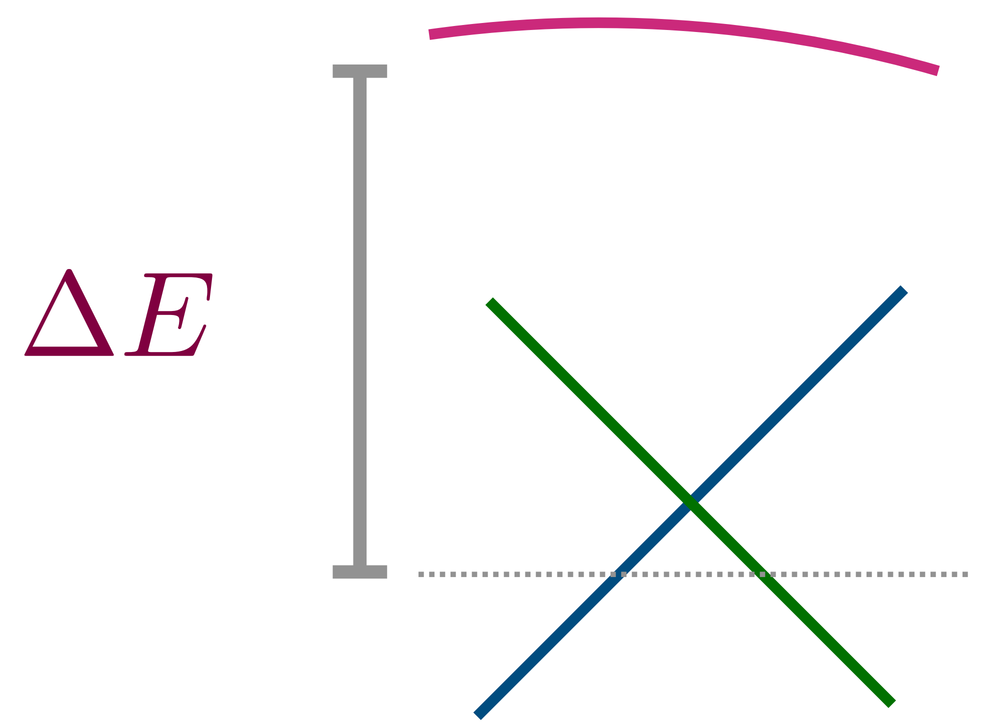


F. de Juan, AGG, T. Morimoto, J. E. Moore Nat. Comm (2017)

Reality

Many bands



$$\delta\beta = M_{13}\frac{\omega^2}{\Delta E_{13}^2}$$

F. De Juan et al Nat. Comm (2017)

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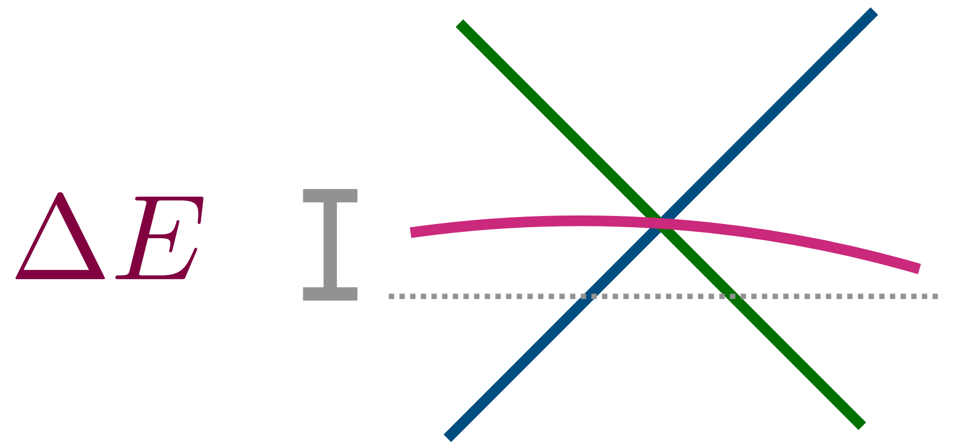

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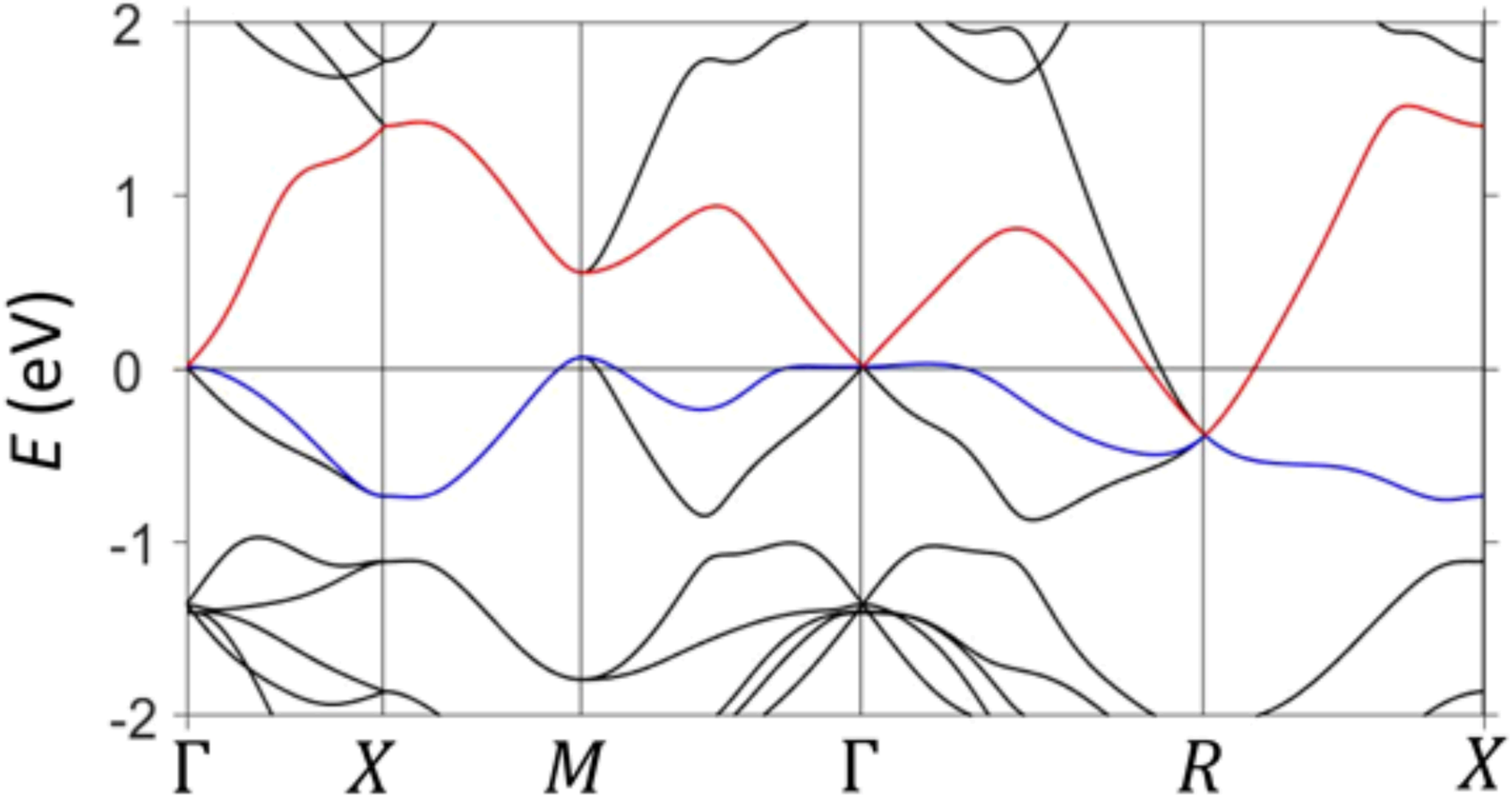
Nodal crossings with three or more bands[51], however, are not expected to display quantization of this type as the corrections from equation (8) cannot be made small.

F. De Juan et al Nat. Comm (2017)

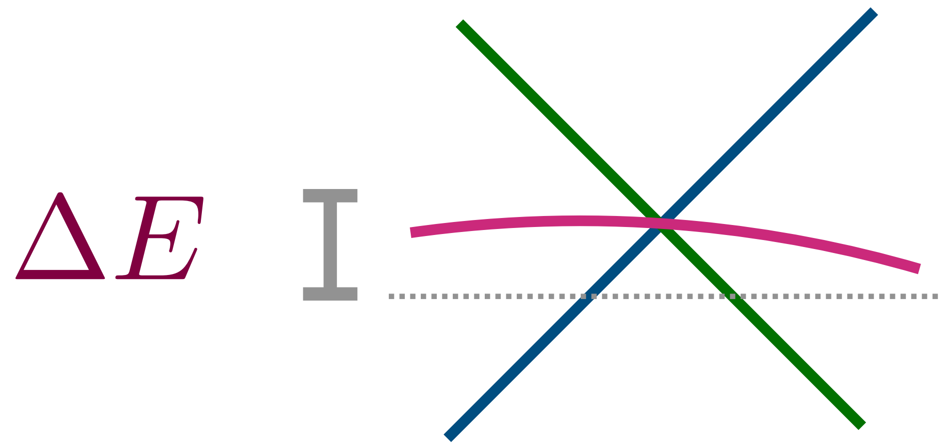
Reality

RhSi

Chang et. al PRL '17



Many bands



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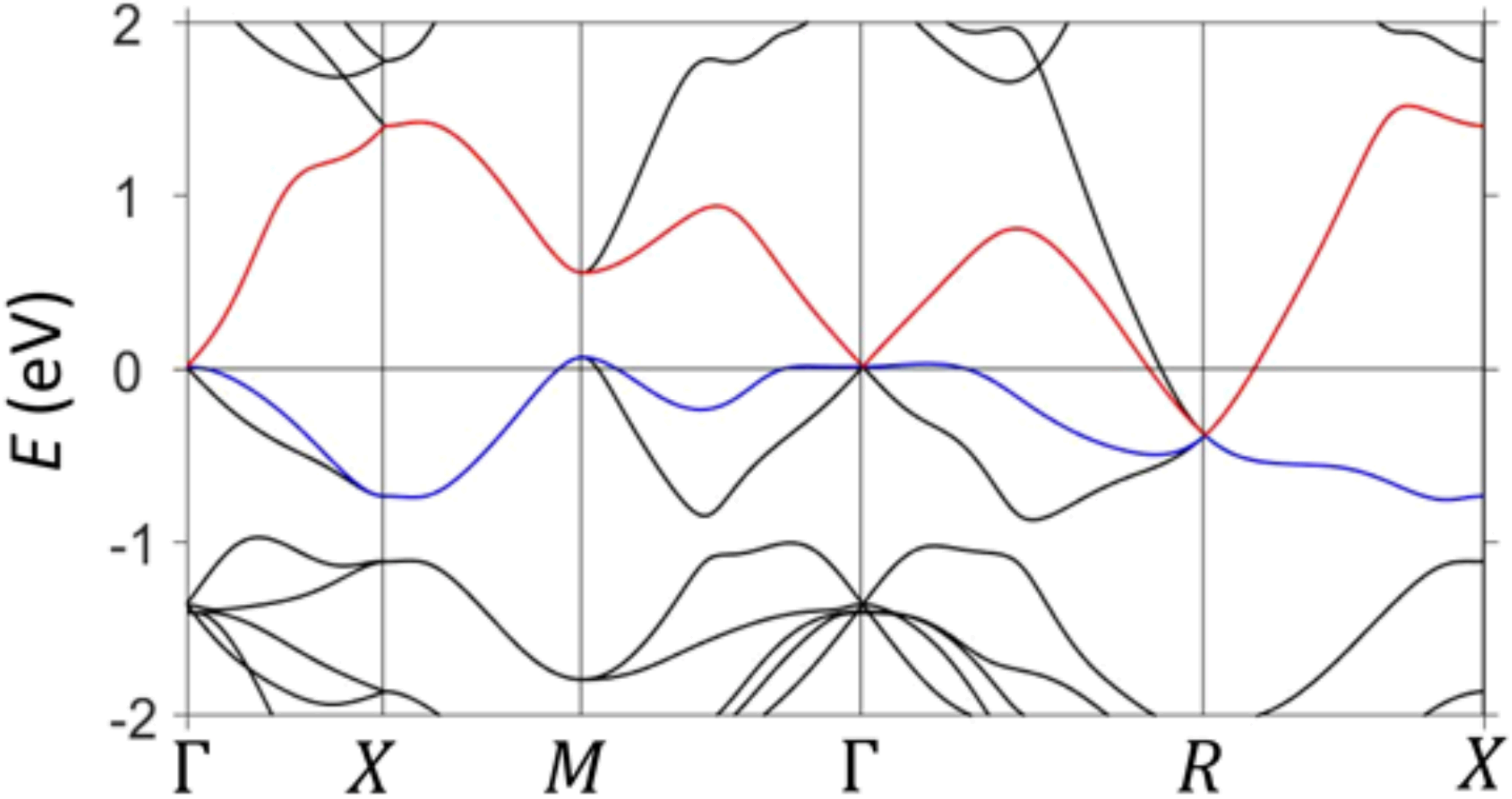

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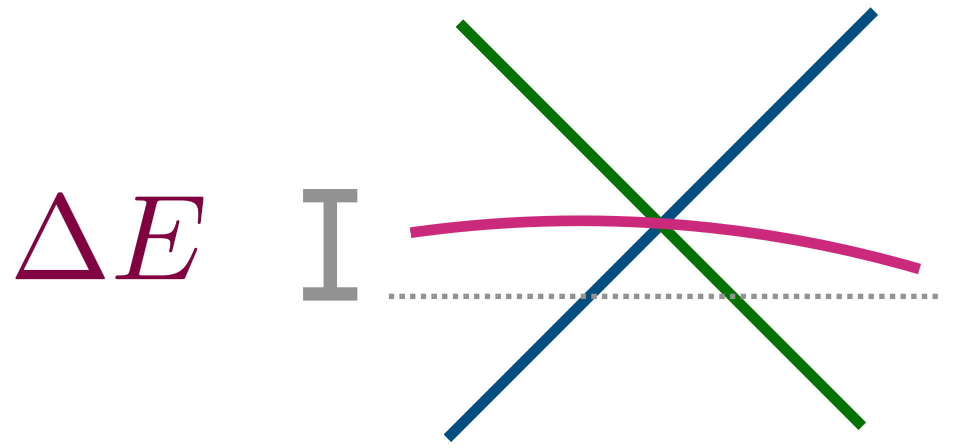

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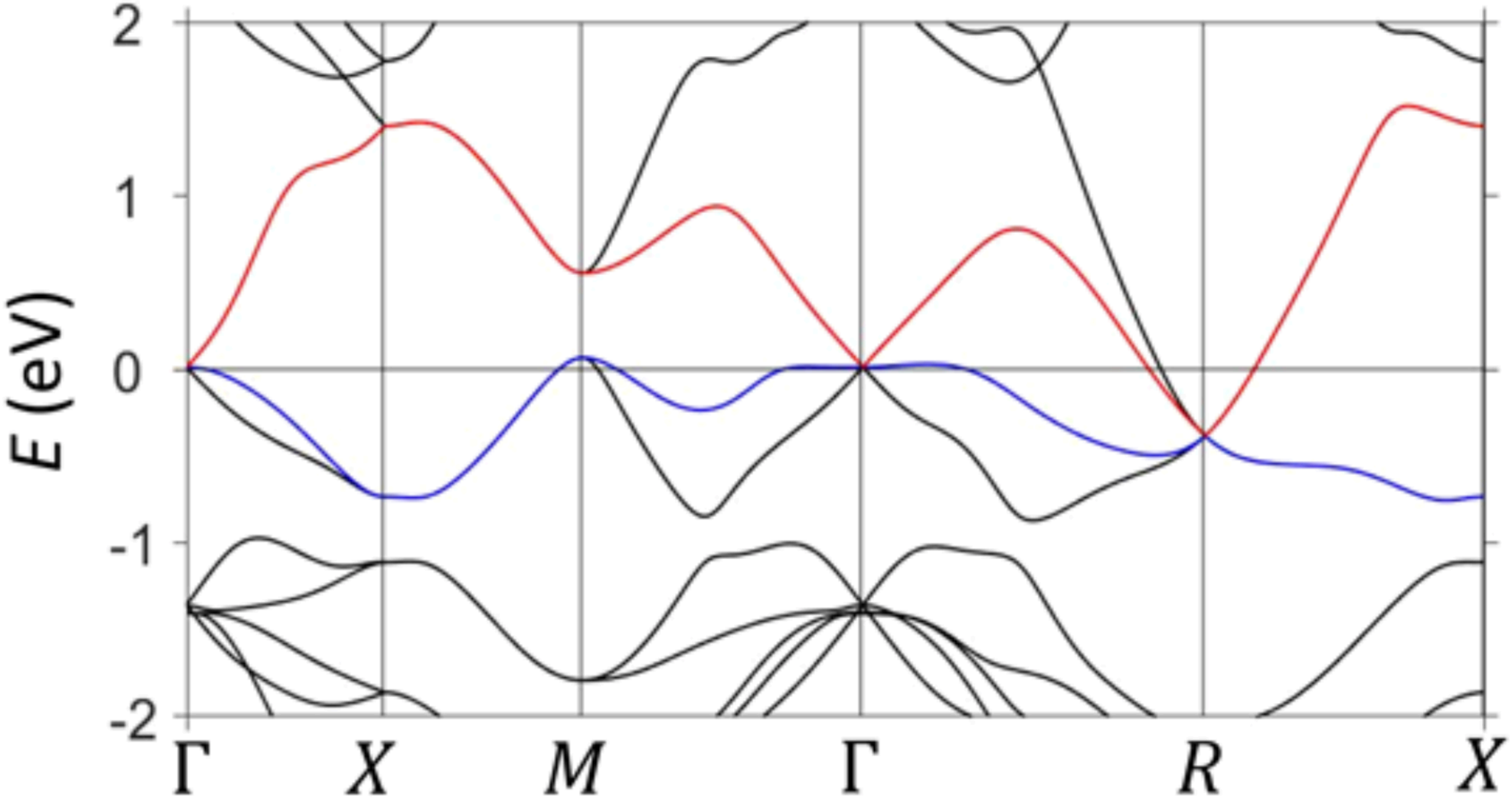
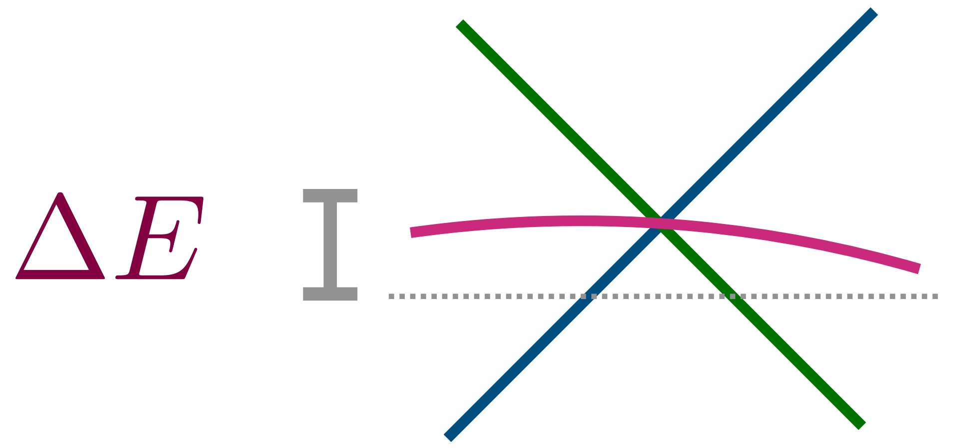


$$H(\phi, \vec{k}) = \vec{S}(\phi) \cdot \vec{k}$$

Many bands



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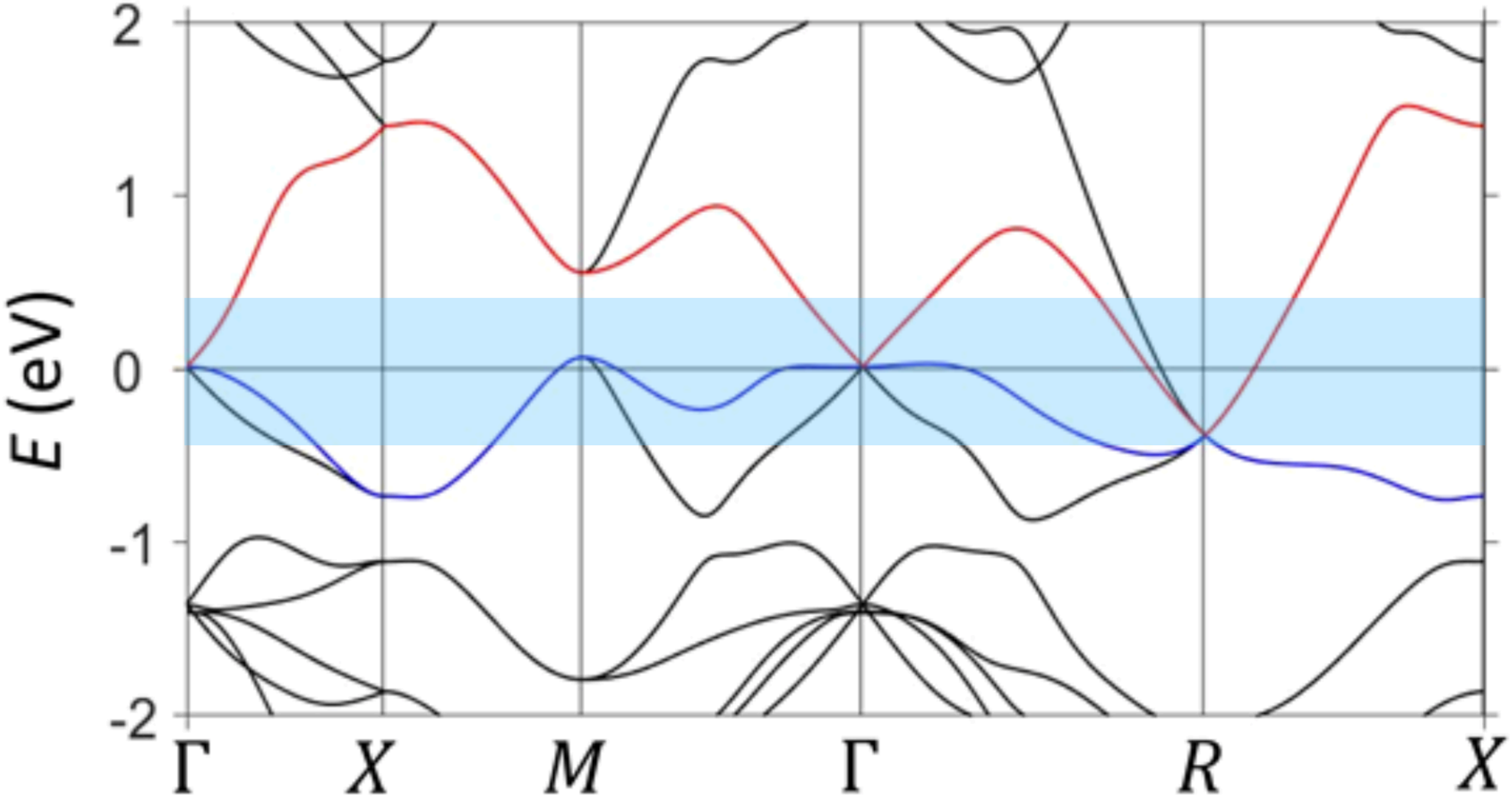
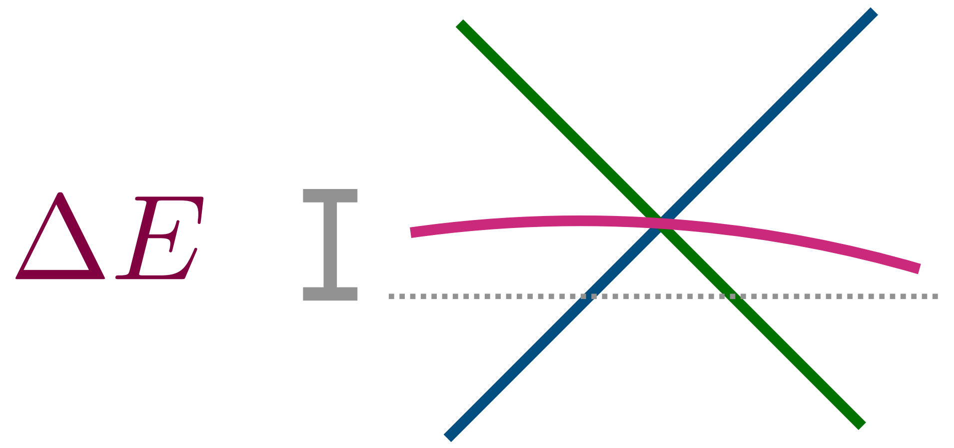


Many bands



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Nodal crossings with three or more bands[51], however, are not expected to display quantization of this type as the corrections from equation (8) cannot be made small.

$$H(\phi, \vec{k}) = \vec{S}(\phi)\cdot\vec{k}$$

$$\beta(\omega) = 4\pi^2\beta_0 C_\Sigma$$

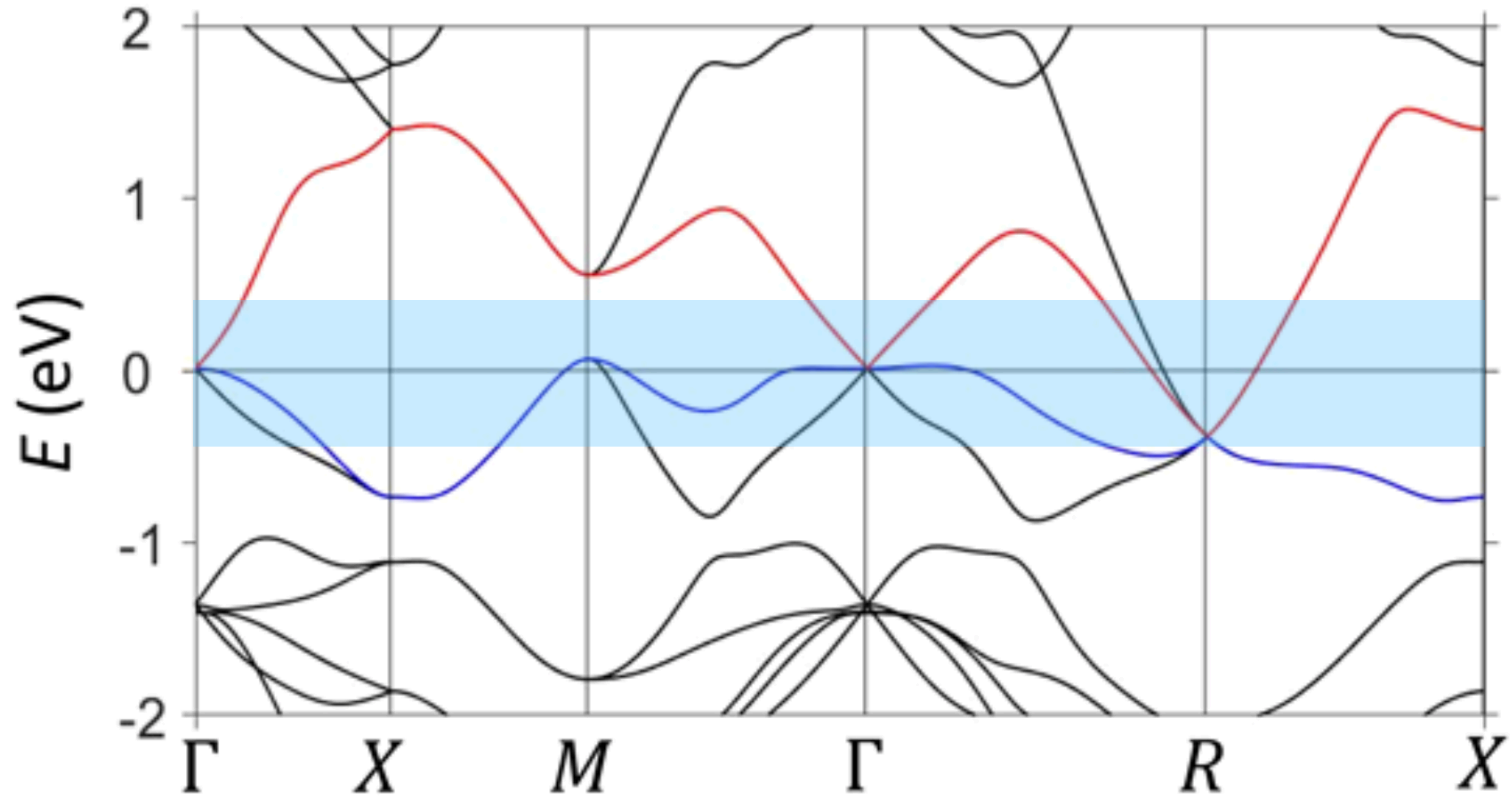
F. Flicker, F. de Juan, T. Morimoto, B. Bradlyn, M. Vergniory, AGG PRB (2018)

F. De Juan et al Nat. Comm (2017)

Reality

RhSi

Chang et. al PRL '17



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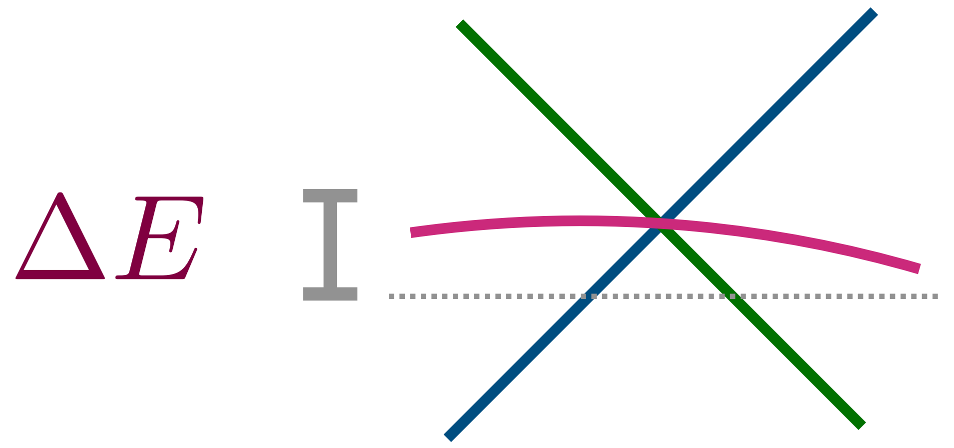

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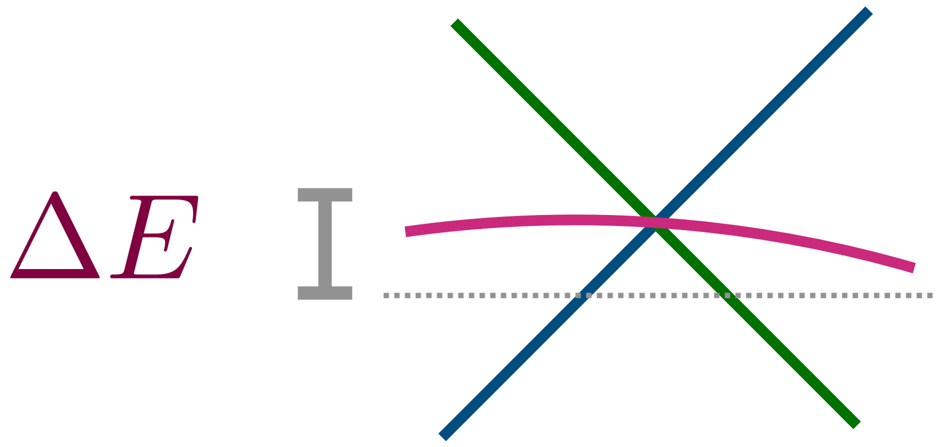

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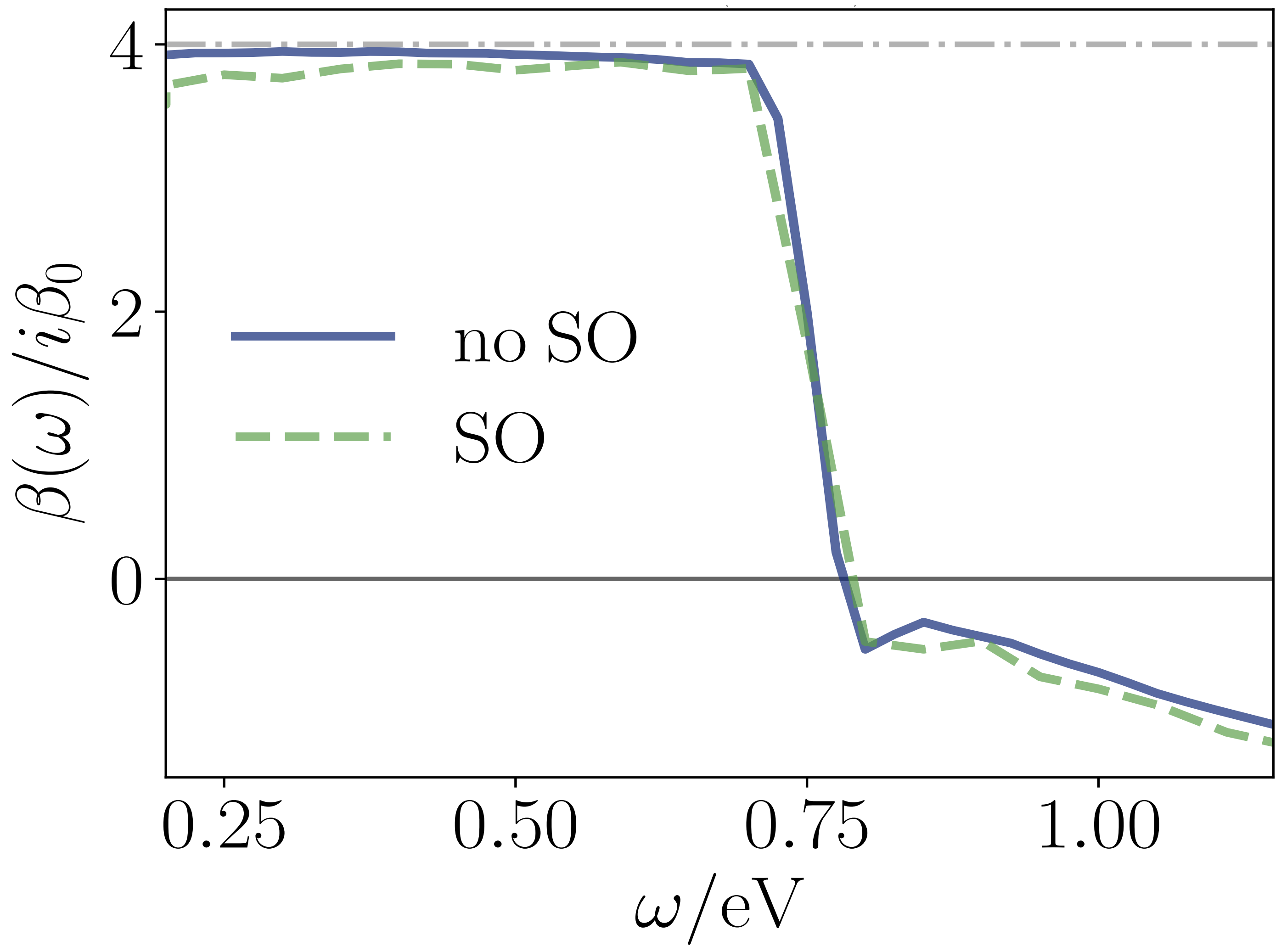


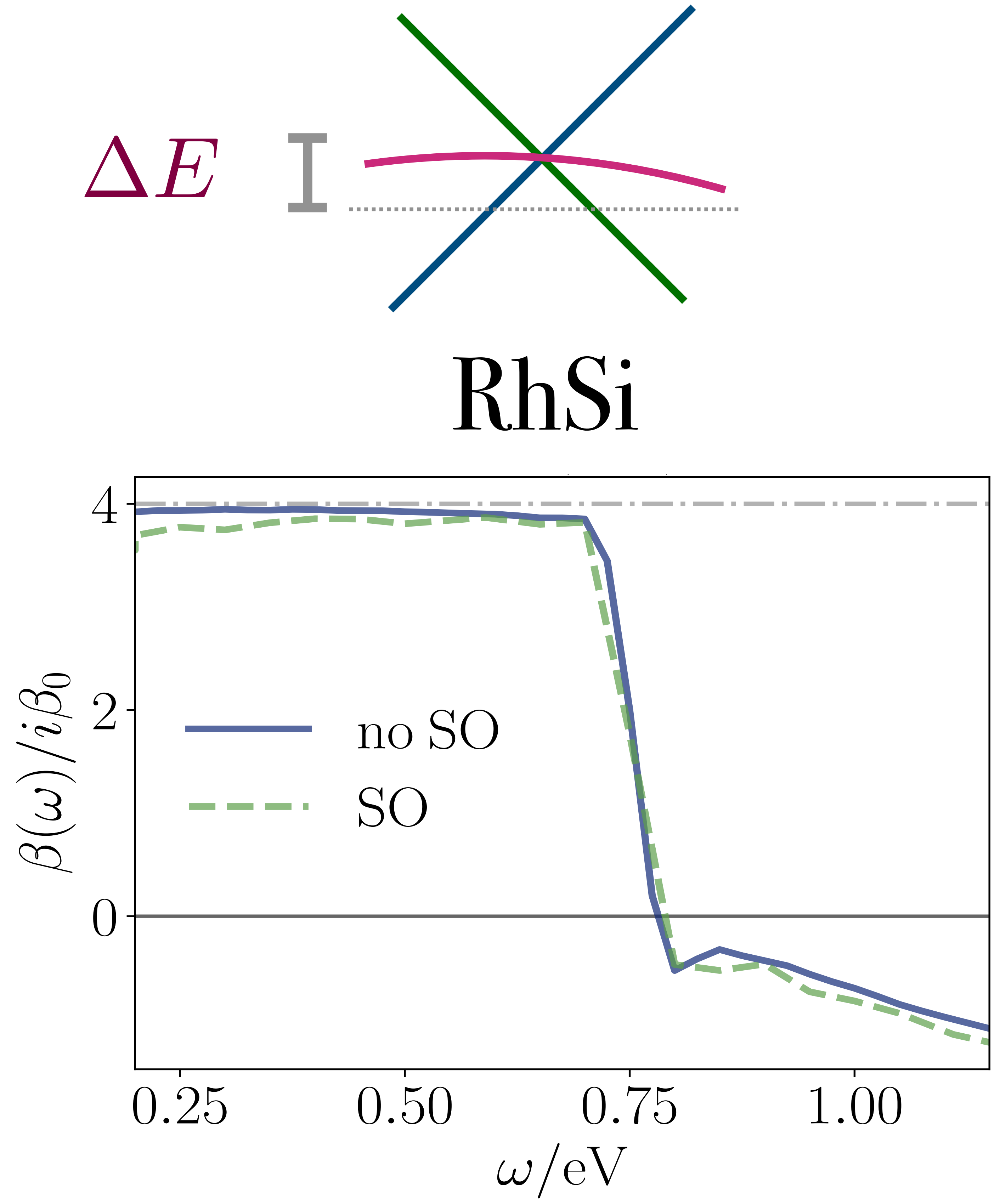
F. Flicker, F. de Juan, T. Morimoto, B. Bradlyn, M. Vergniory, AGG PRB (2018)

F. De Juan et al Nat. Comm (2017)

Reality

Disorder τ

Many bands



F. Flicker, F. de Juan, T. Morimoto, B. Bradlyn, M. Vergniory, AGG PRB (2018)

F. De Juan et al Nat. Comm (2017)

Disorder τ

$$\frac{dj_i}{dt} = \beta_{ij}(\omega)(\mathbf{E} \times \mathbf{E}^*)_j$$

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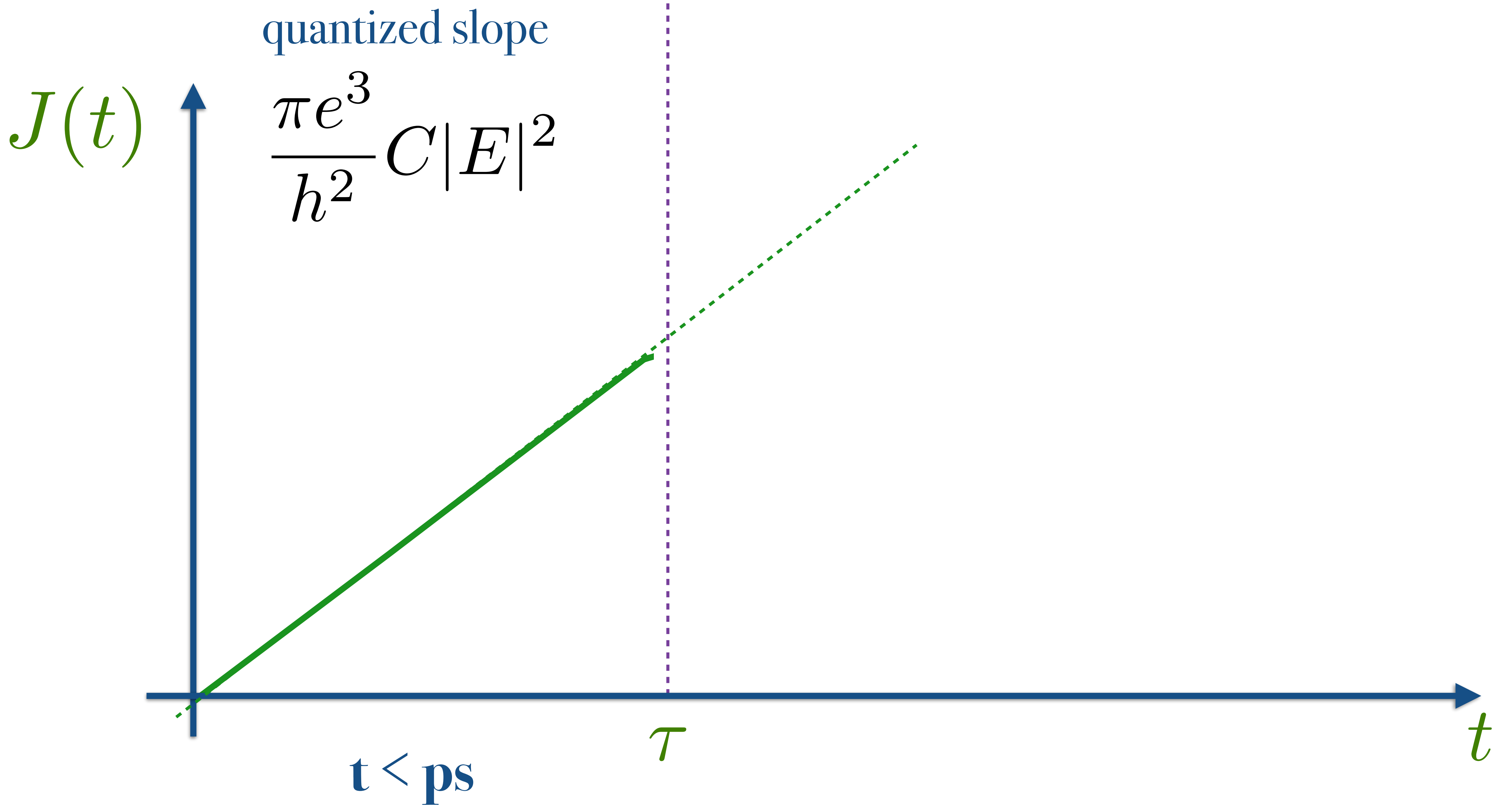

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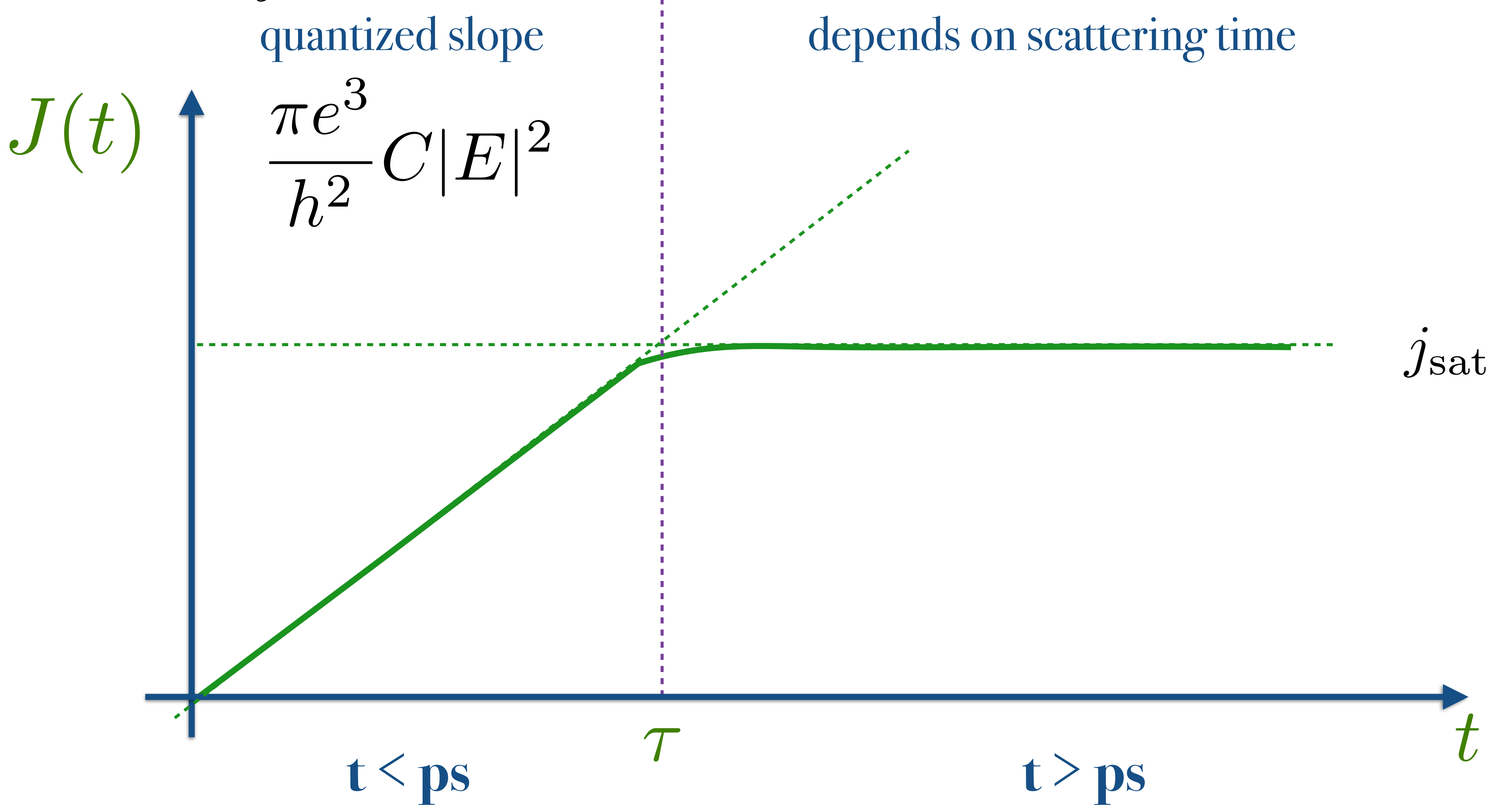

$$j_{\text{sat}} = \tau \frac{\pi e^3}{h^2} C|E|^2$$

E. J. König et al. PRB'17

Quantized non-linear response in RhSi

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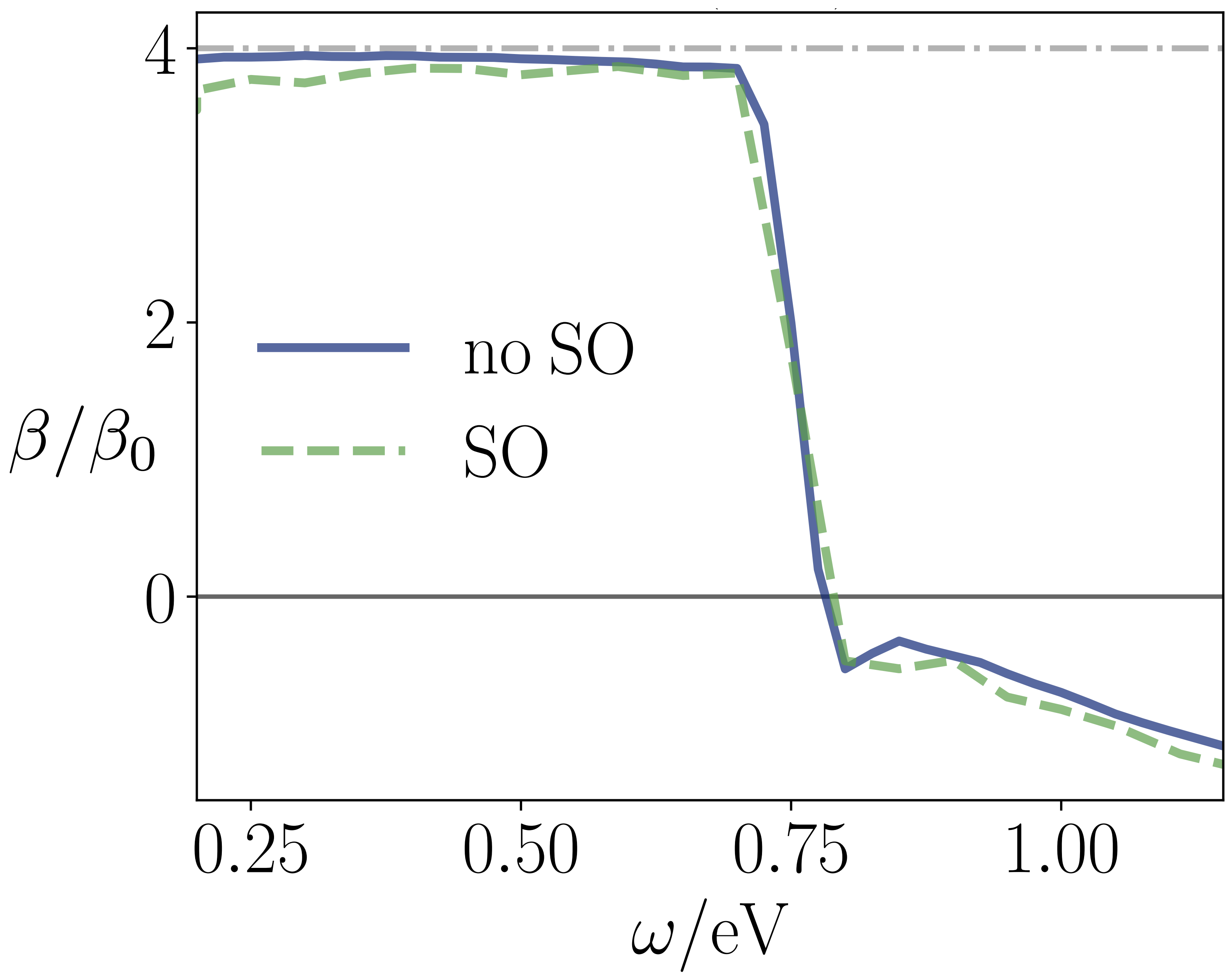
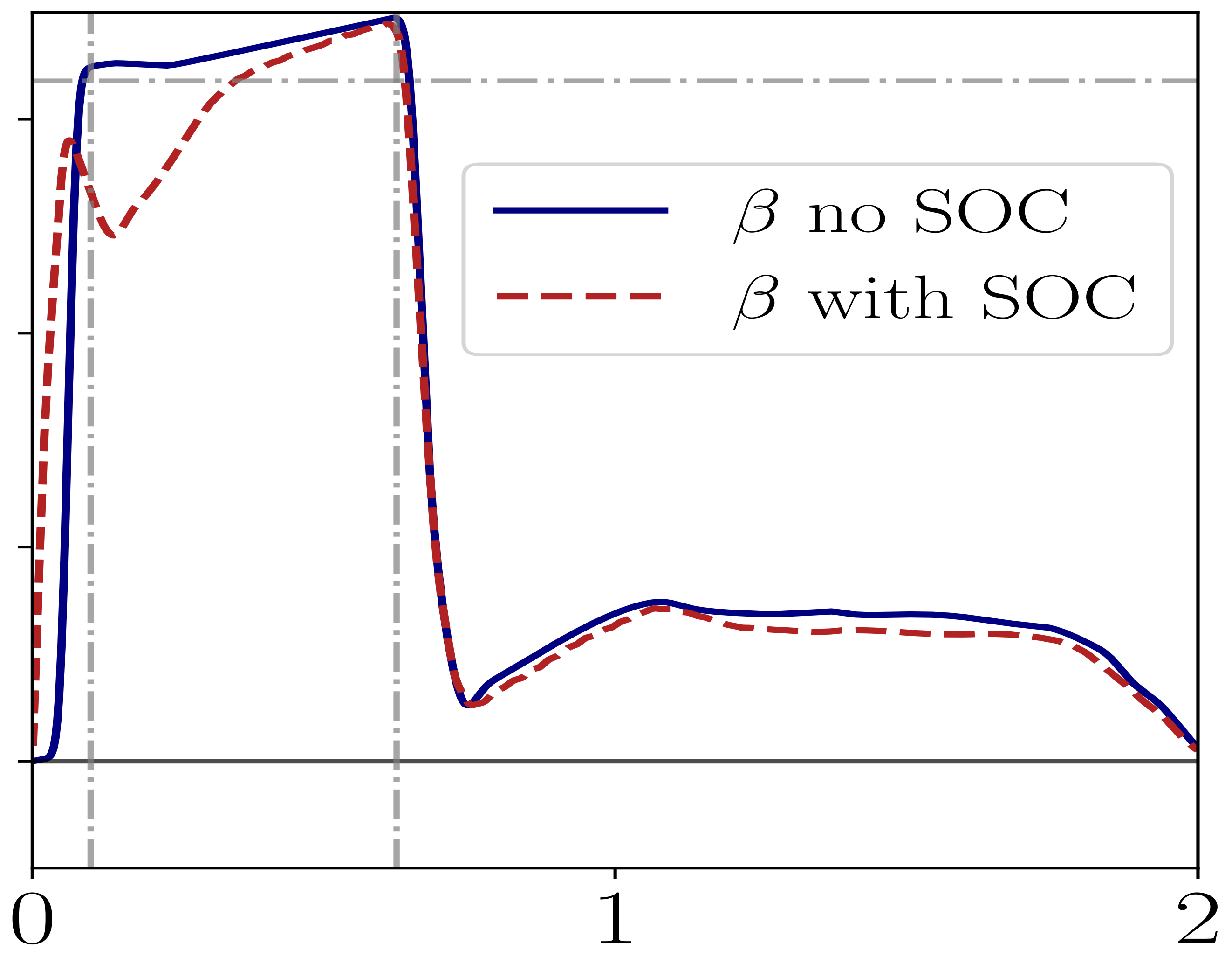
Tight binding



F. Flicker et. al. PRB (2018)

DFT



F. De Juan, Y. Zhang, et. al. arXiv: 1907.02537

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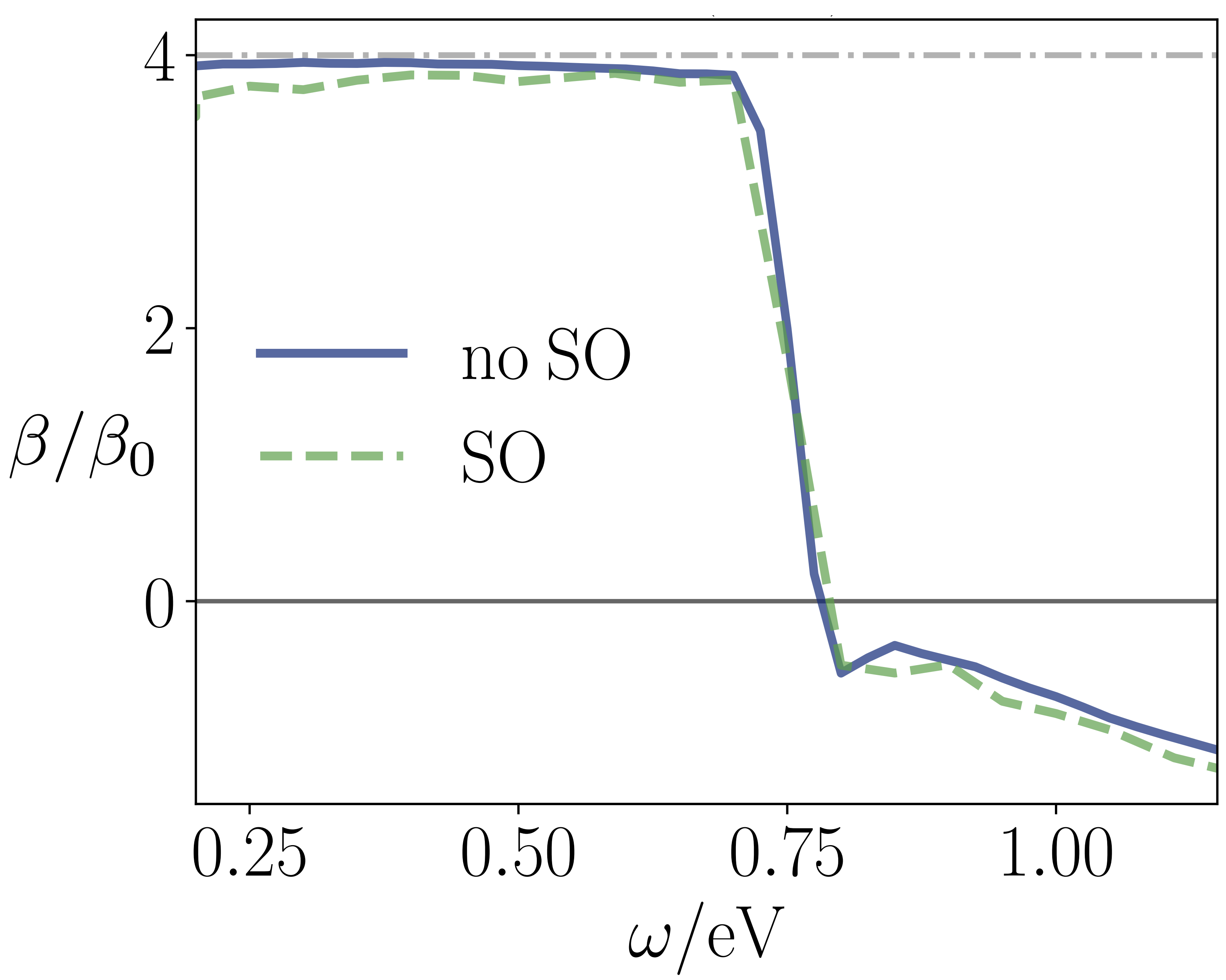

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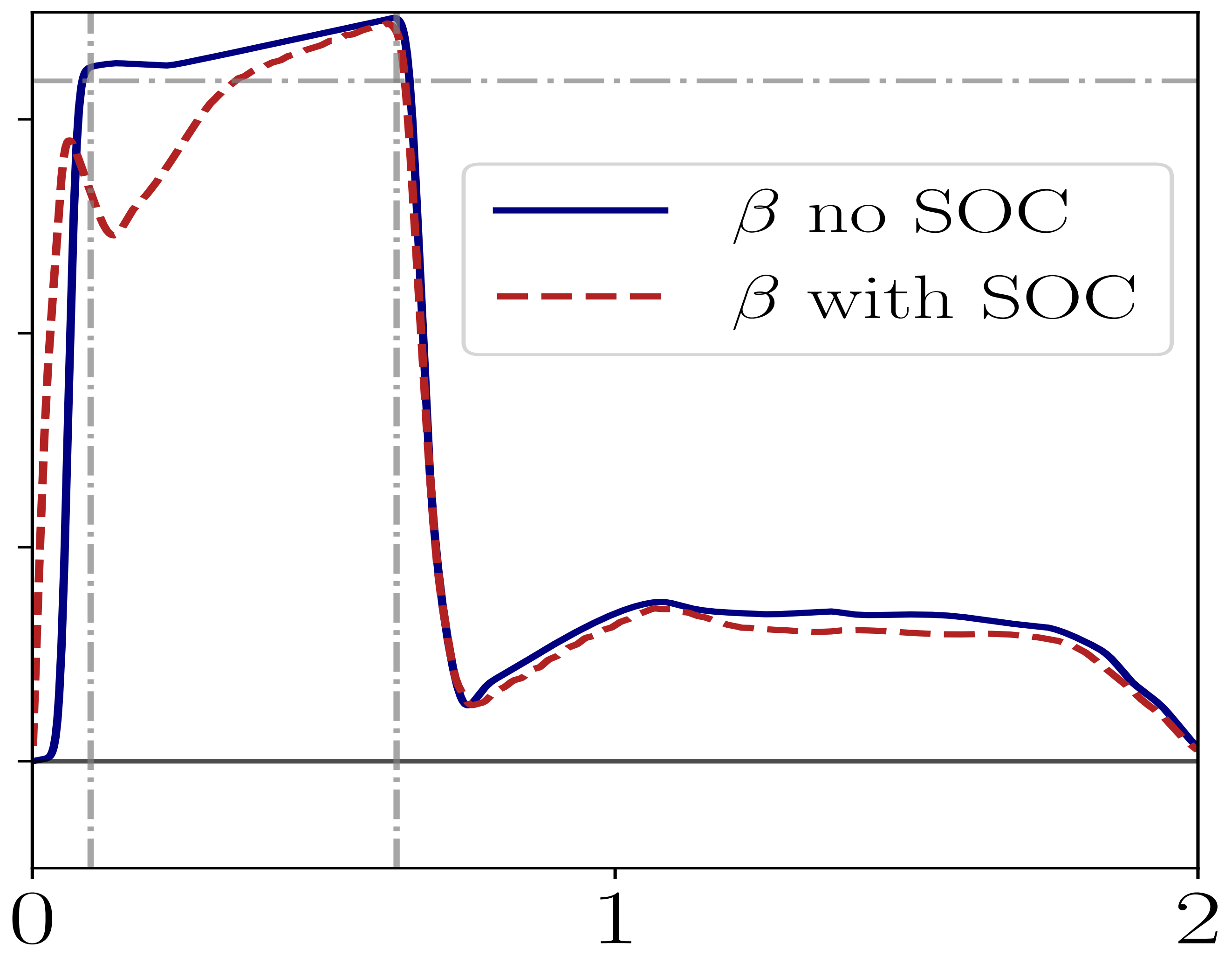

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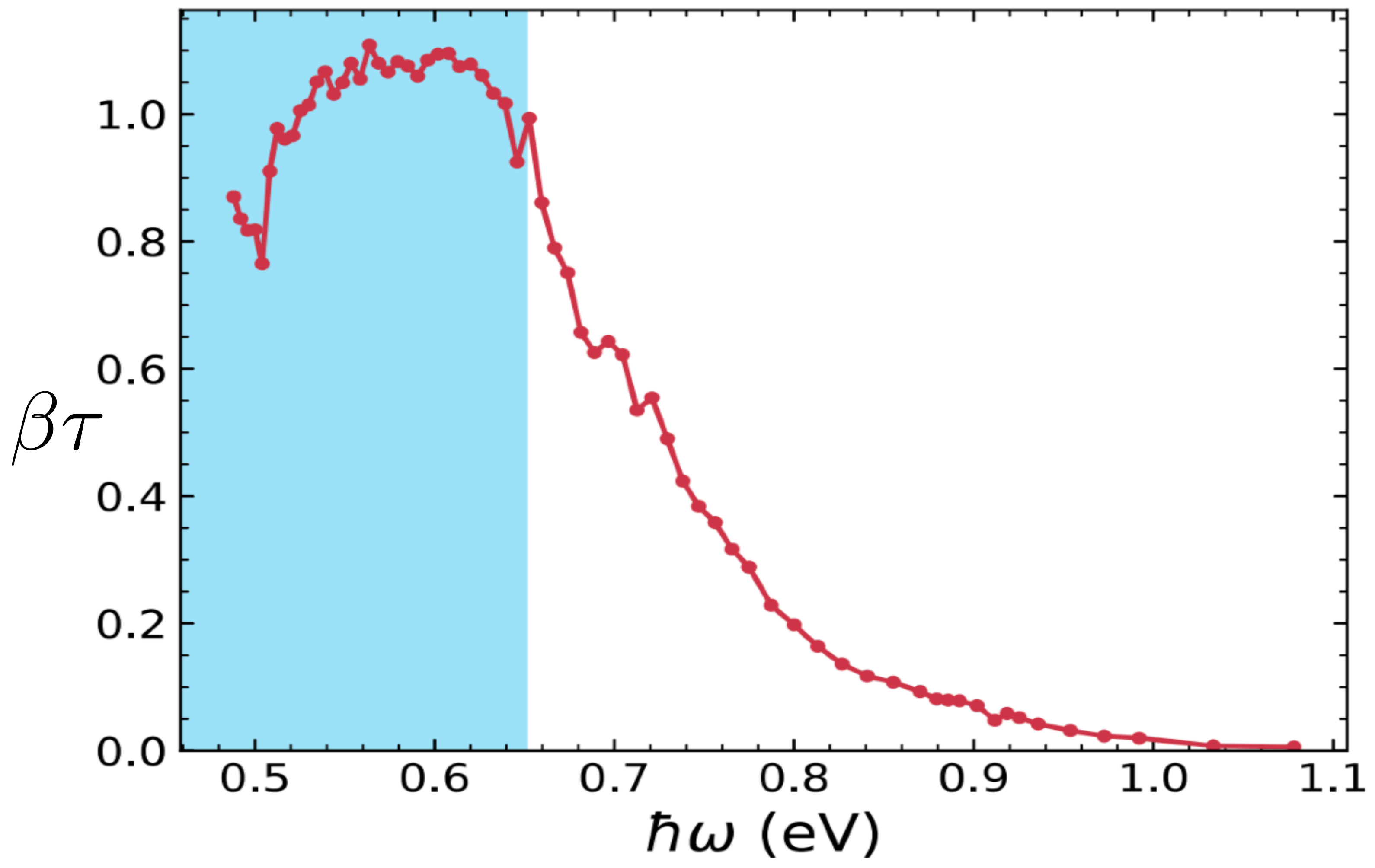
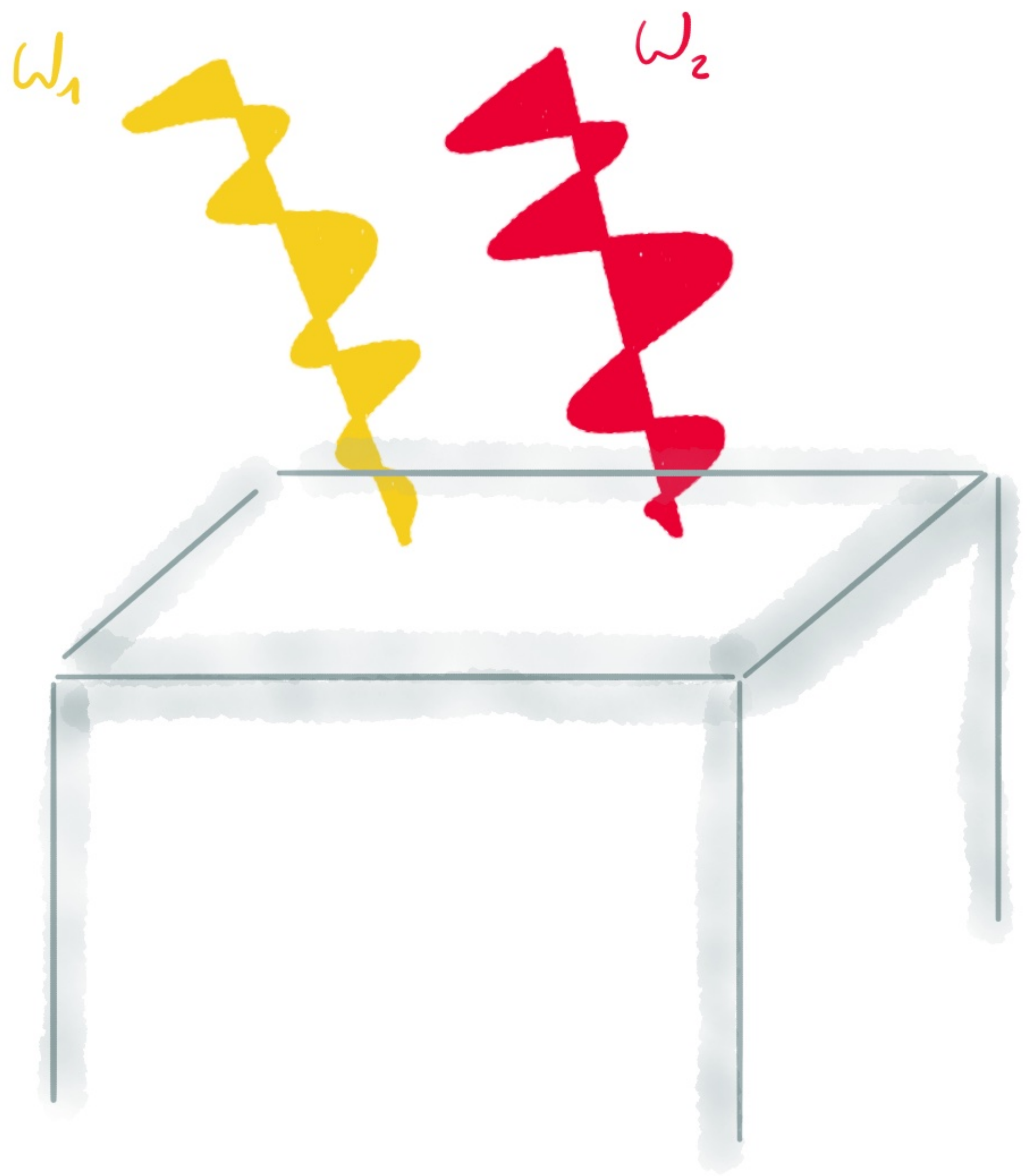
Experiment



D. Rees. arXiv: 1902.03230

An alternative: difference frequency generation

signal that oscillates with the frequency difference $$\Delta\omega = \omega_1 - \omega_2$$



Genkin & Mednis , Sov. Phys. JETP **27**, 609 (1968)

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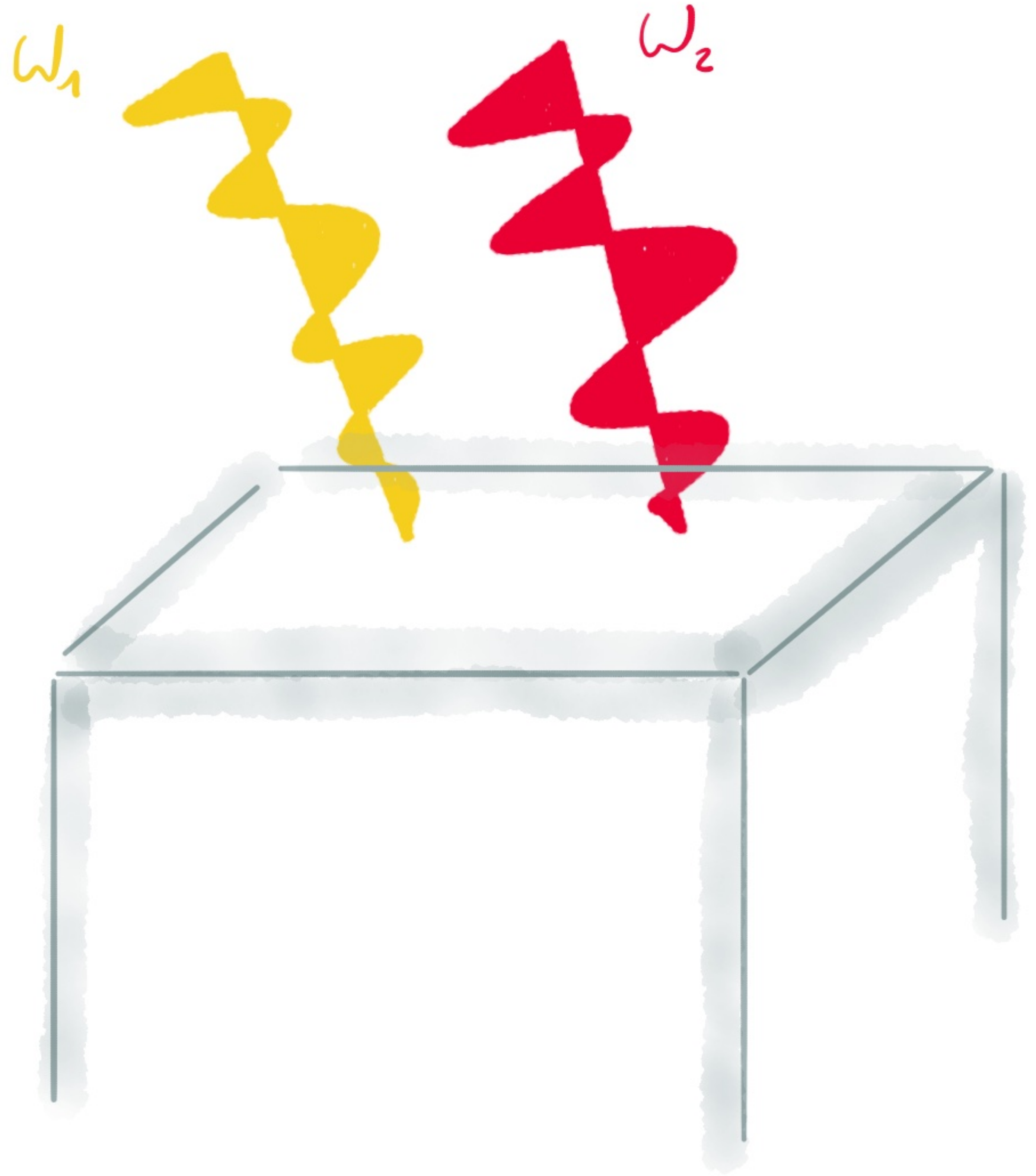

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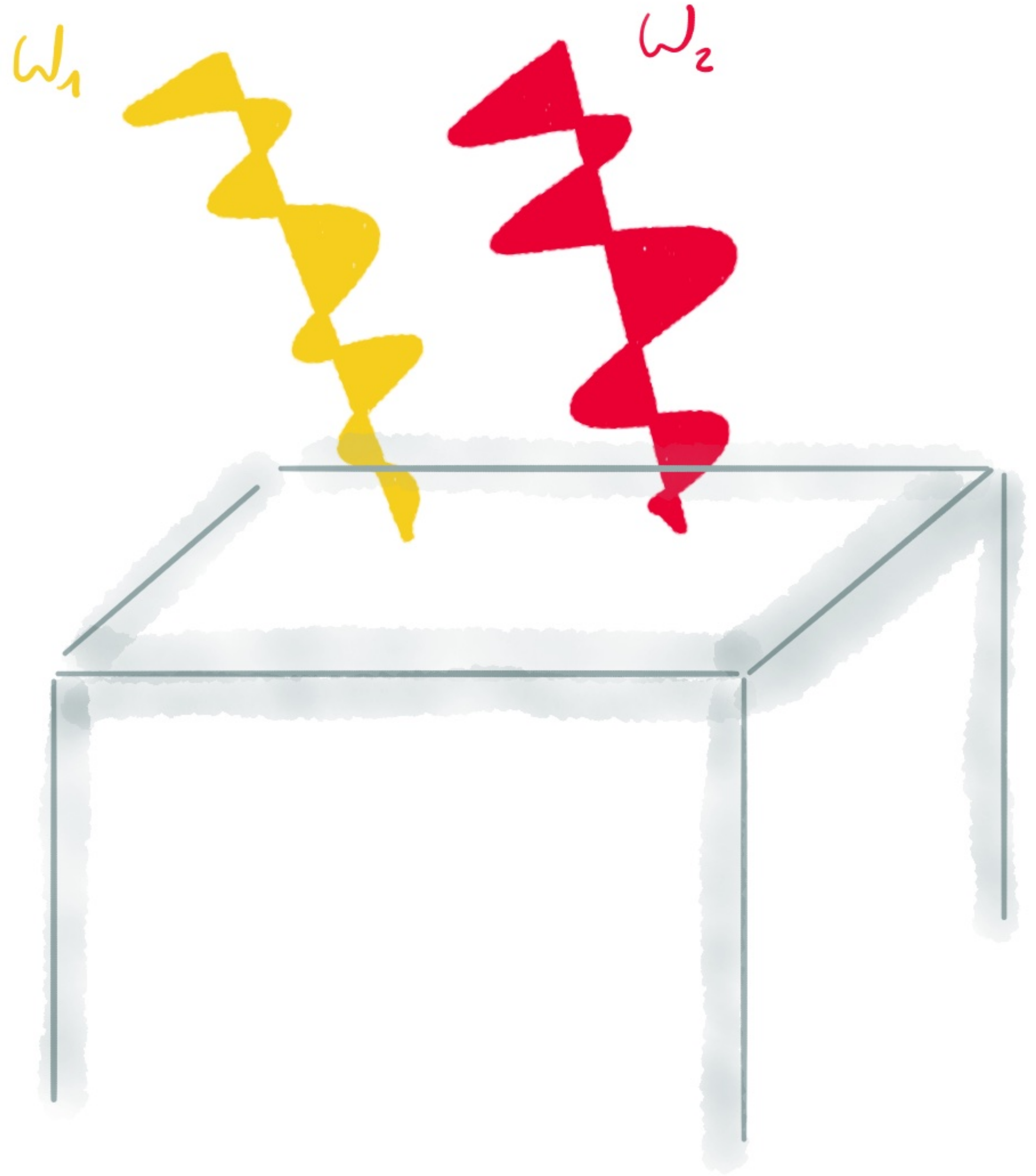

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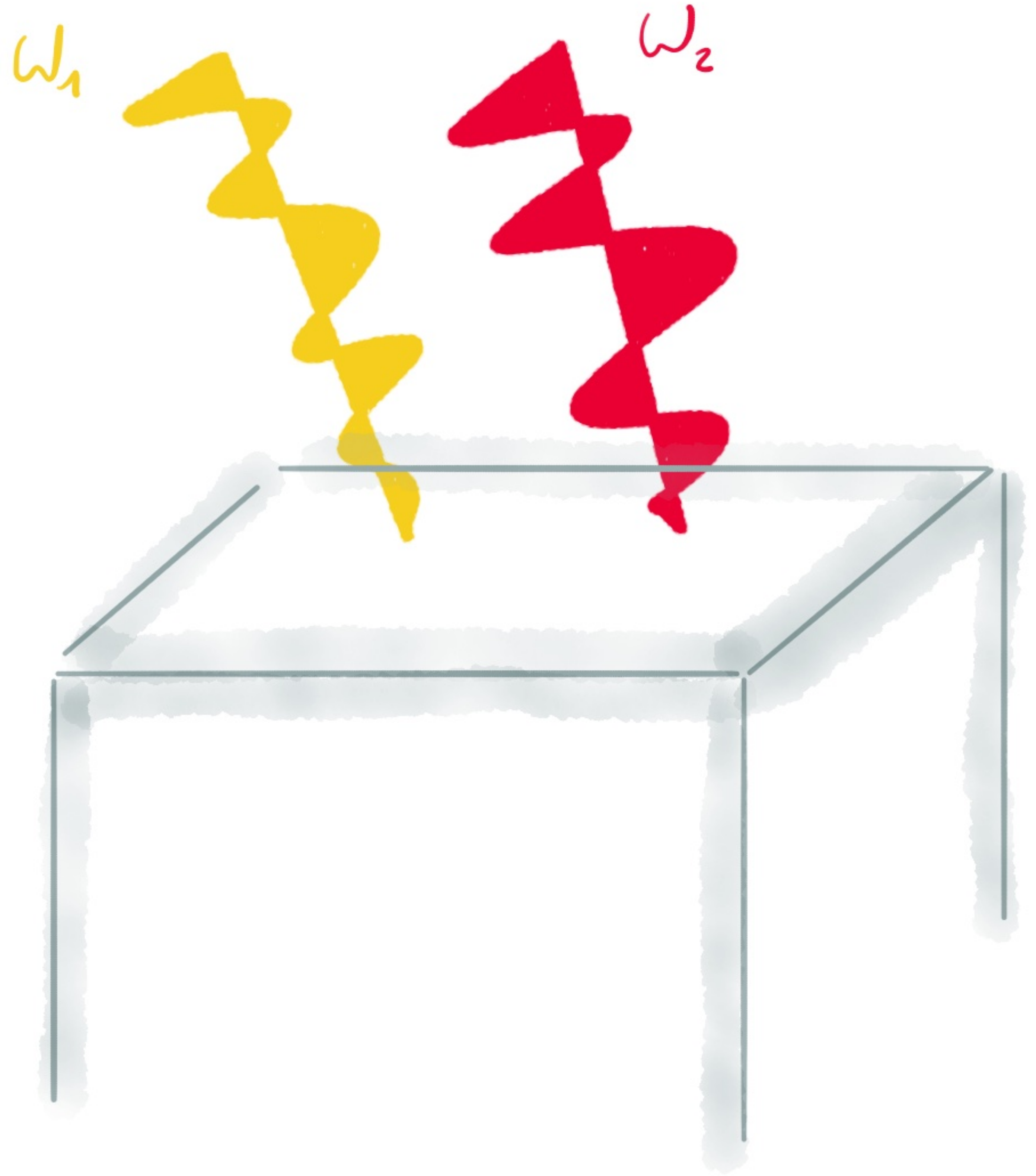

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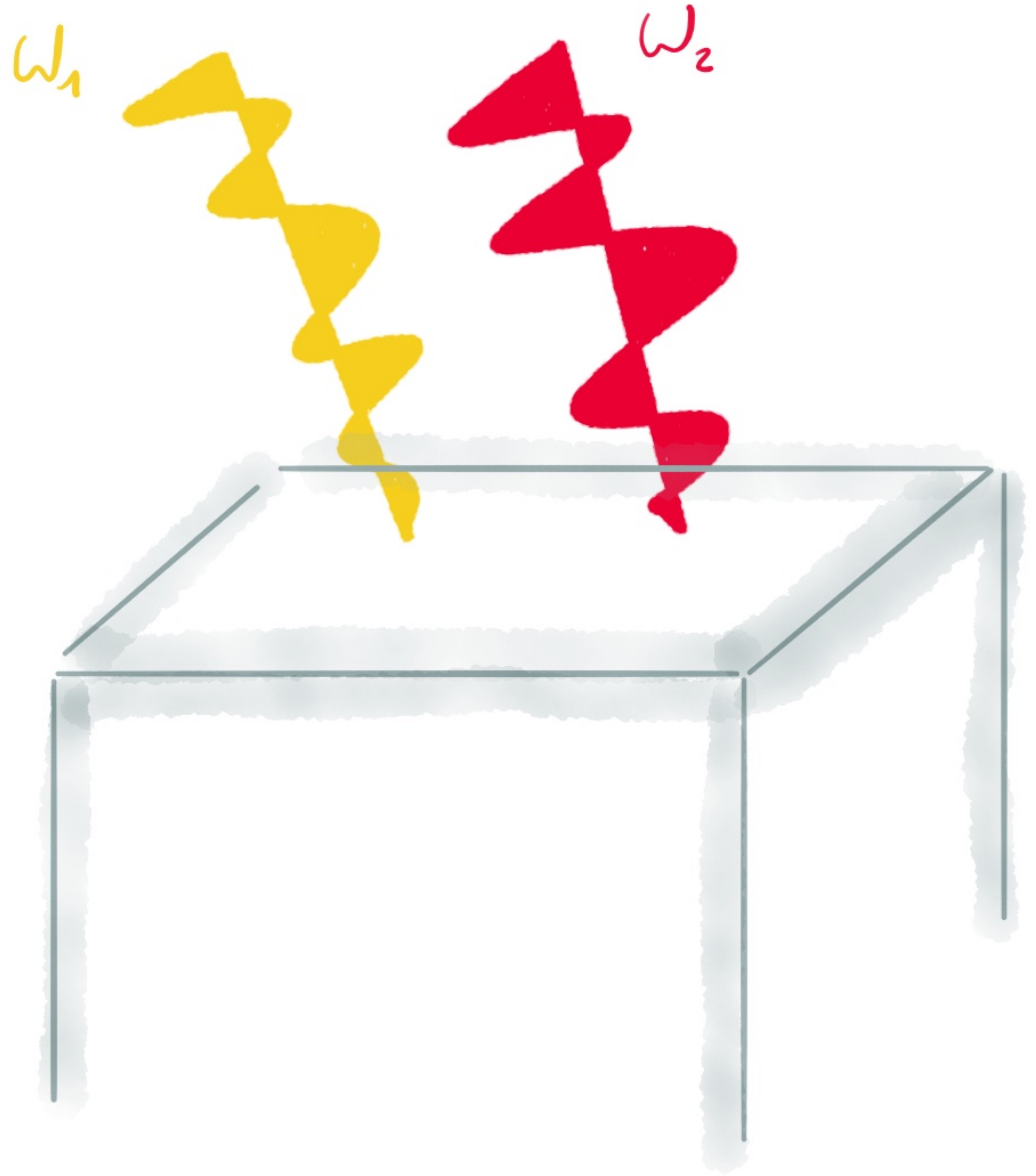

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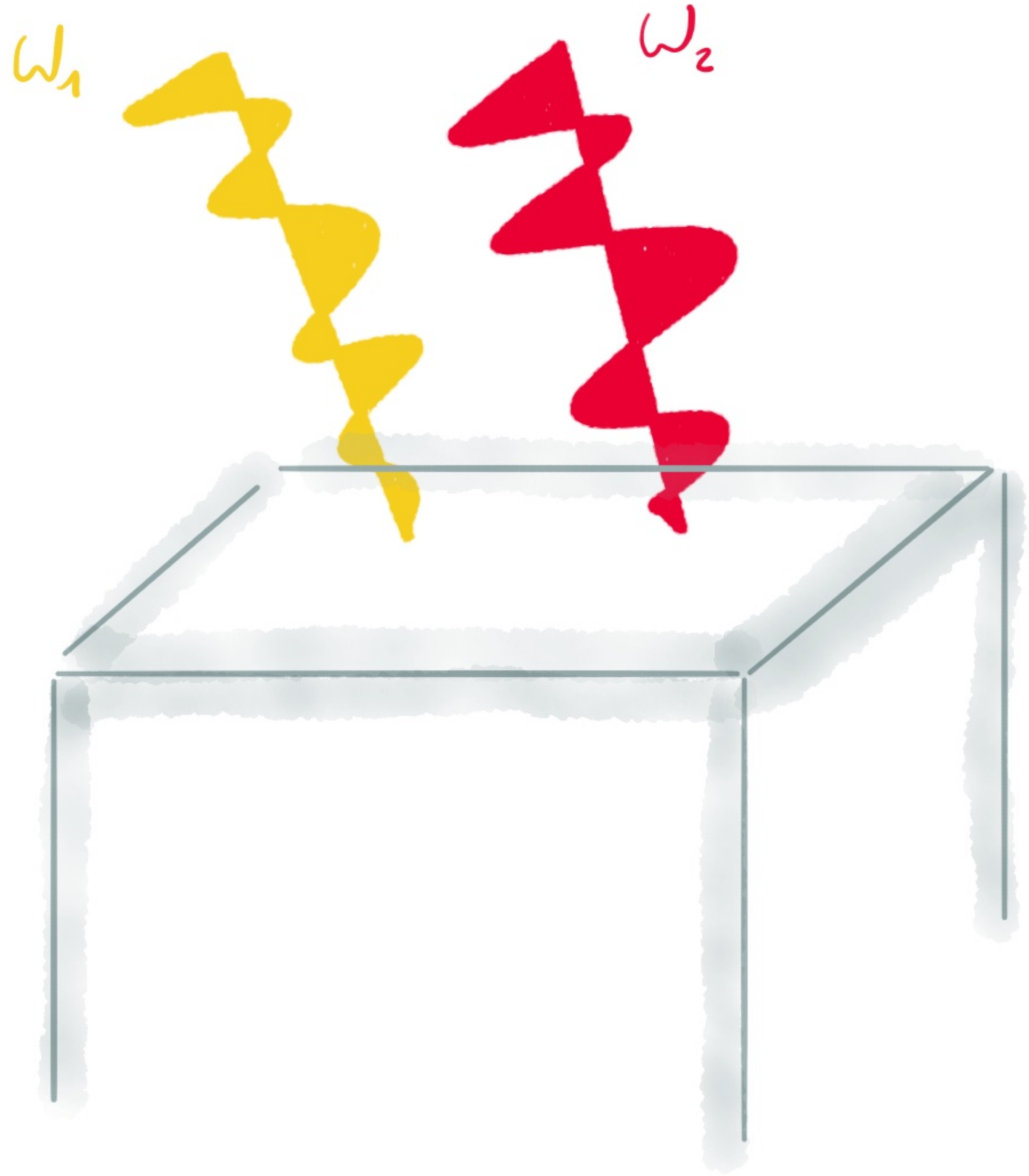

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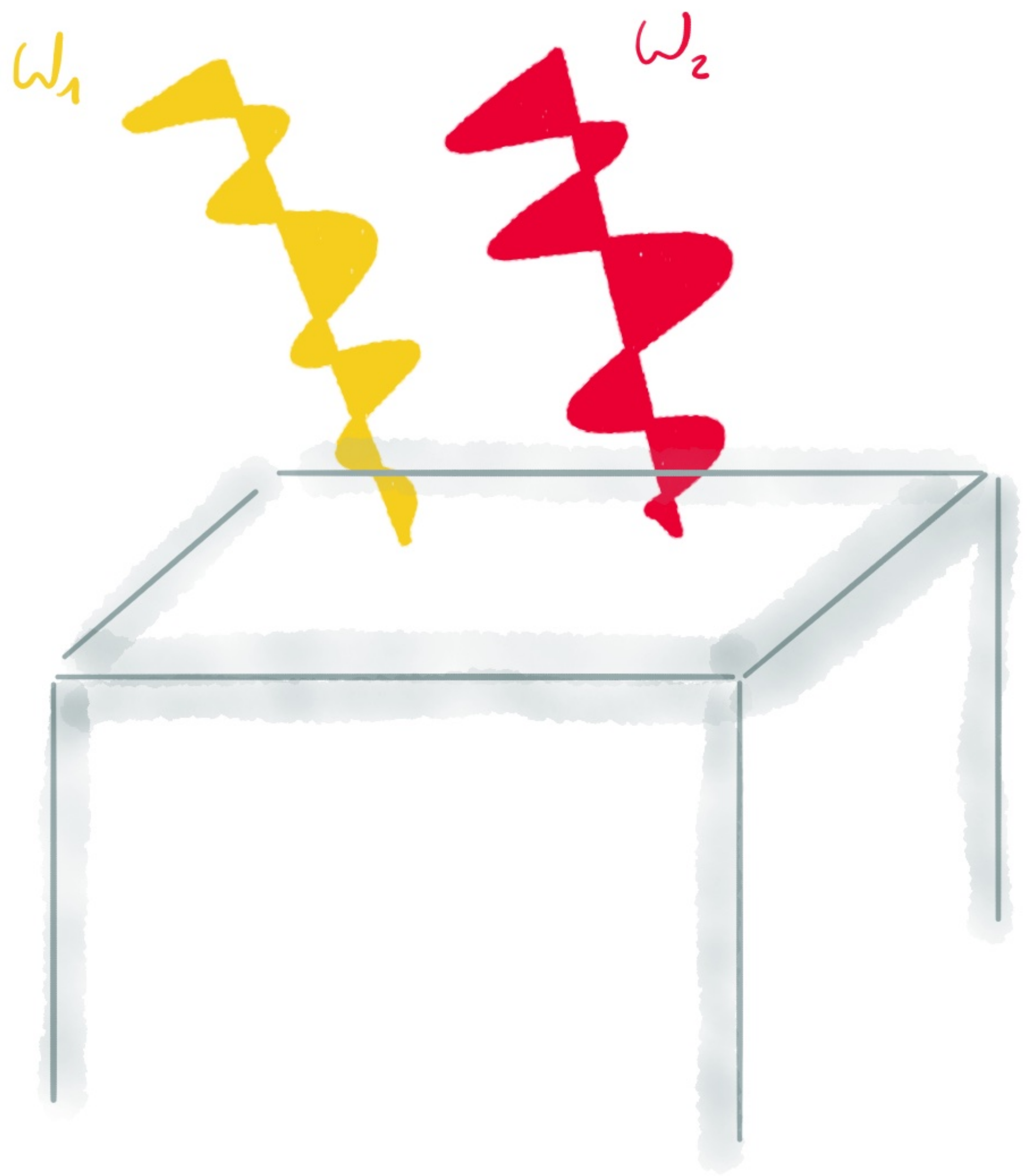

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CPGE

Free carrier

k derivative of the integrand of the reactive part of the linear conductivity

$$\sigma^{ab}_{\text{rea}} = \sigma^{ab} - (\sigma^{ba})^*$$

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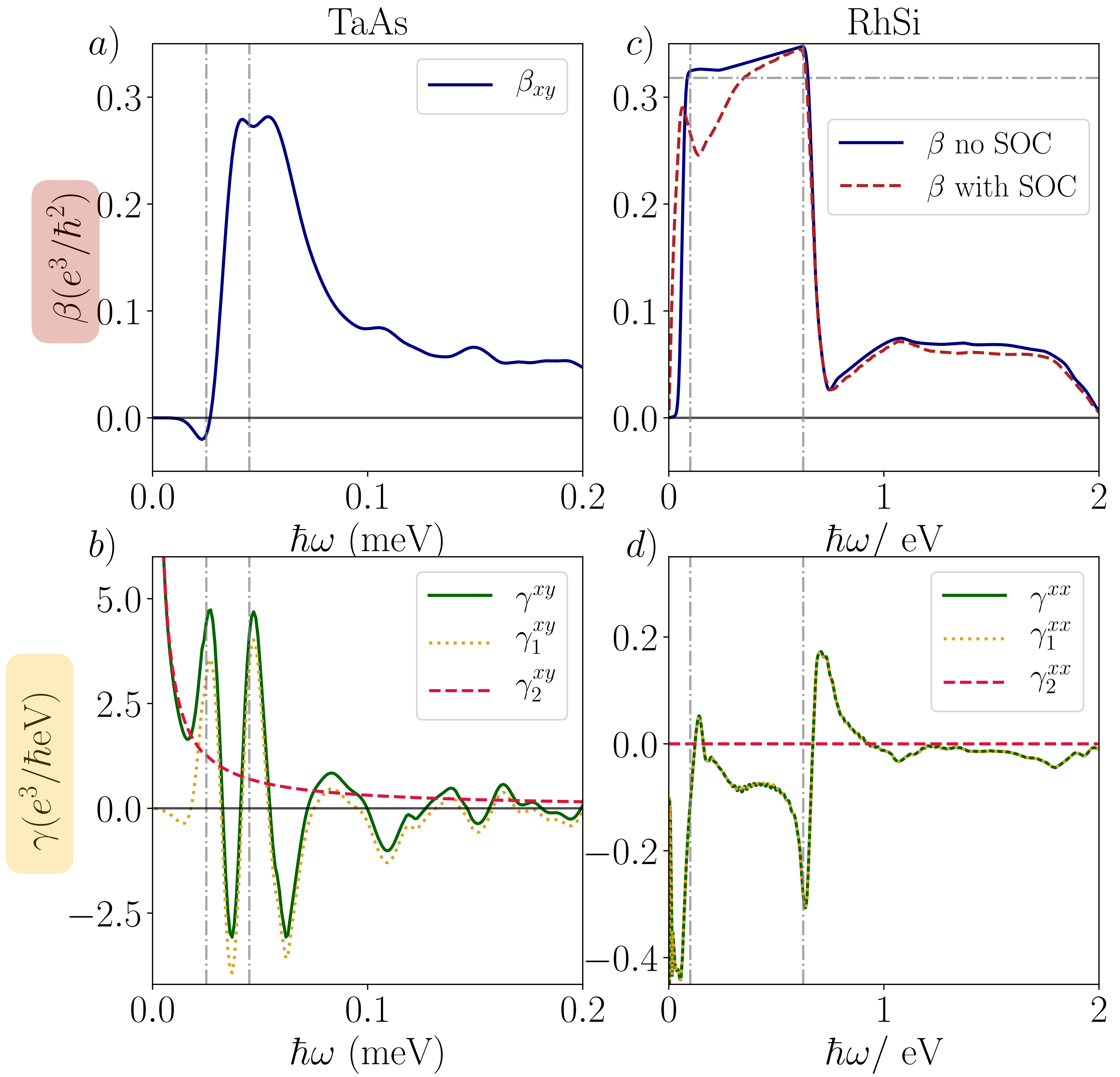

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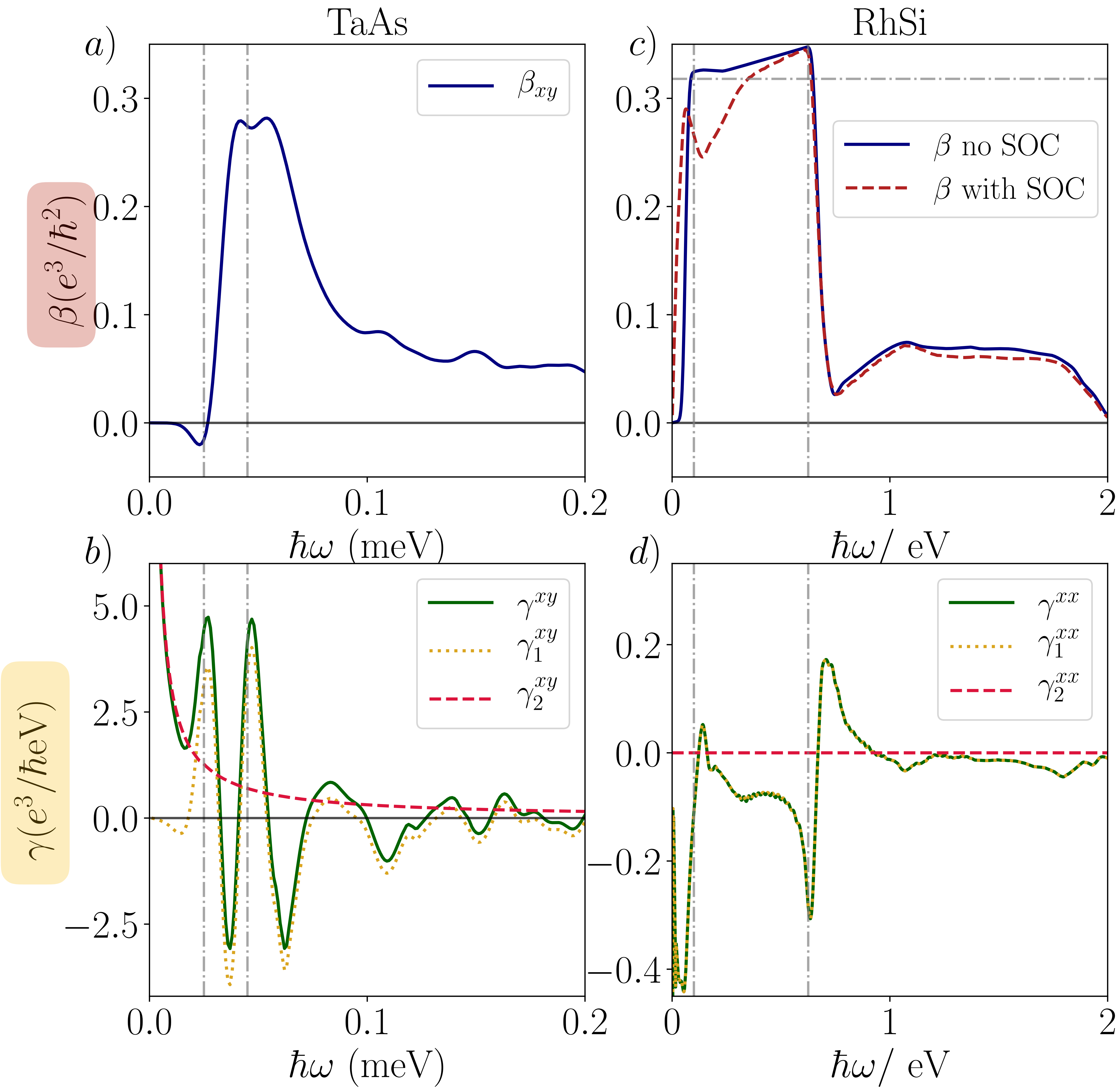

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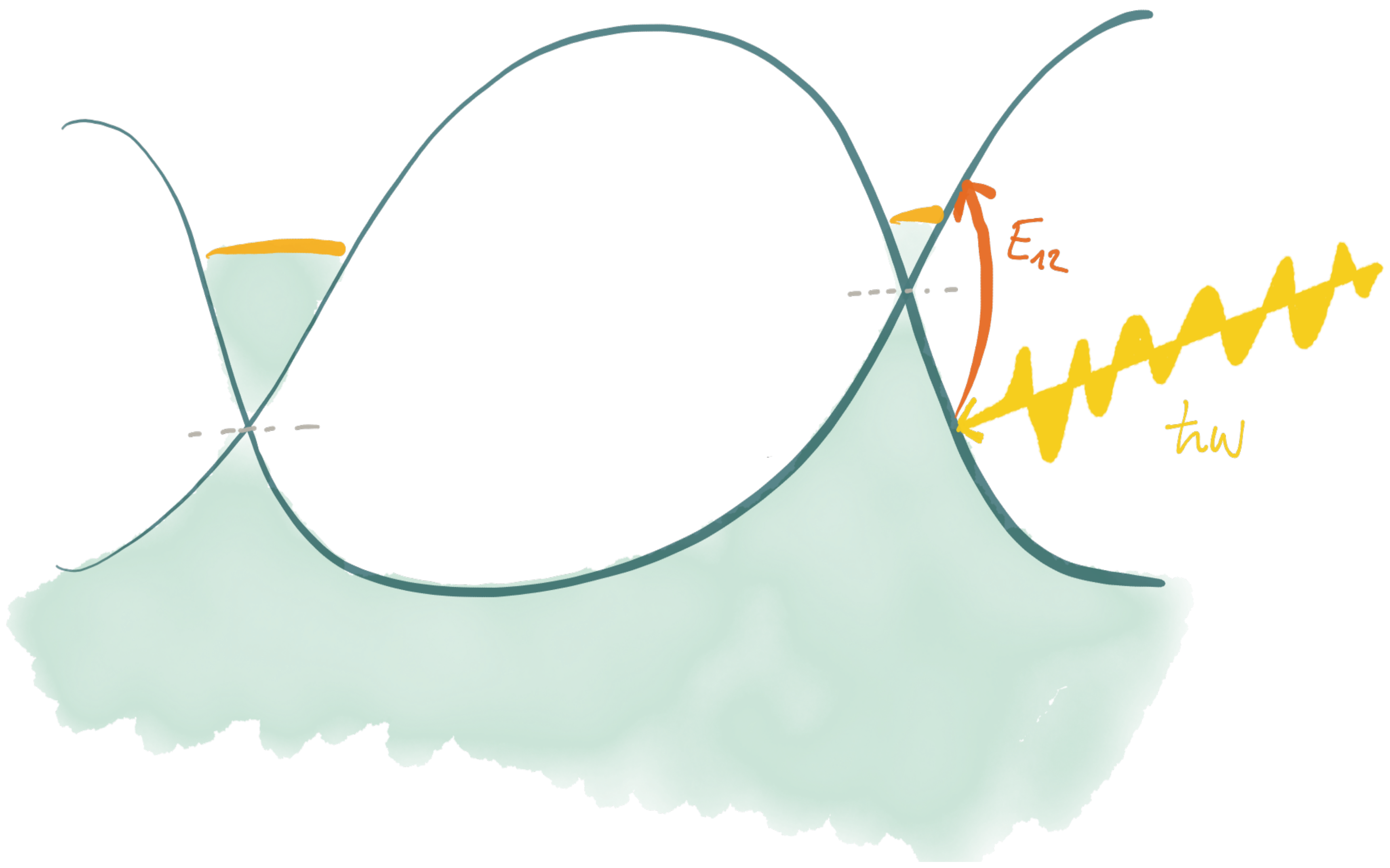
CPGE Free carrier

Divergences and plateaus appear at node activation frequencies



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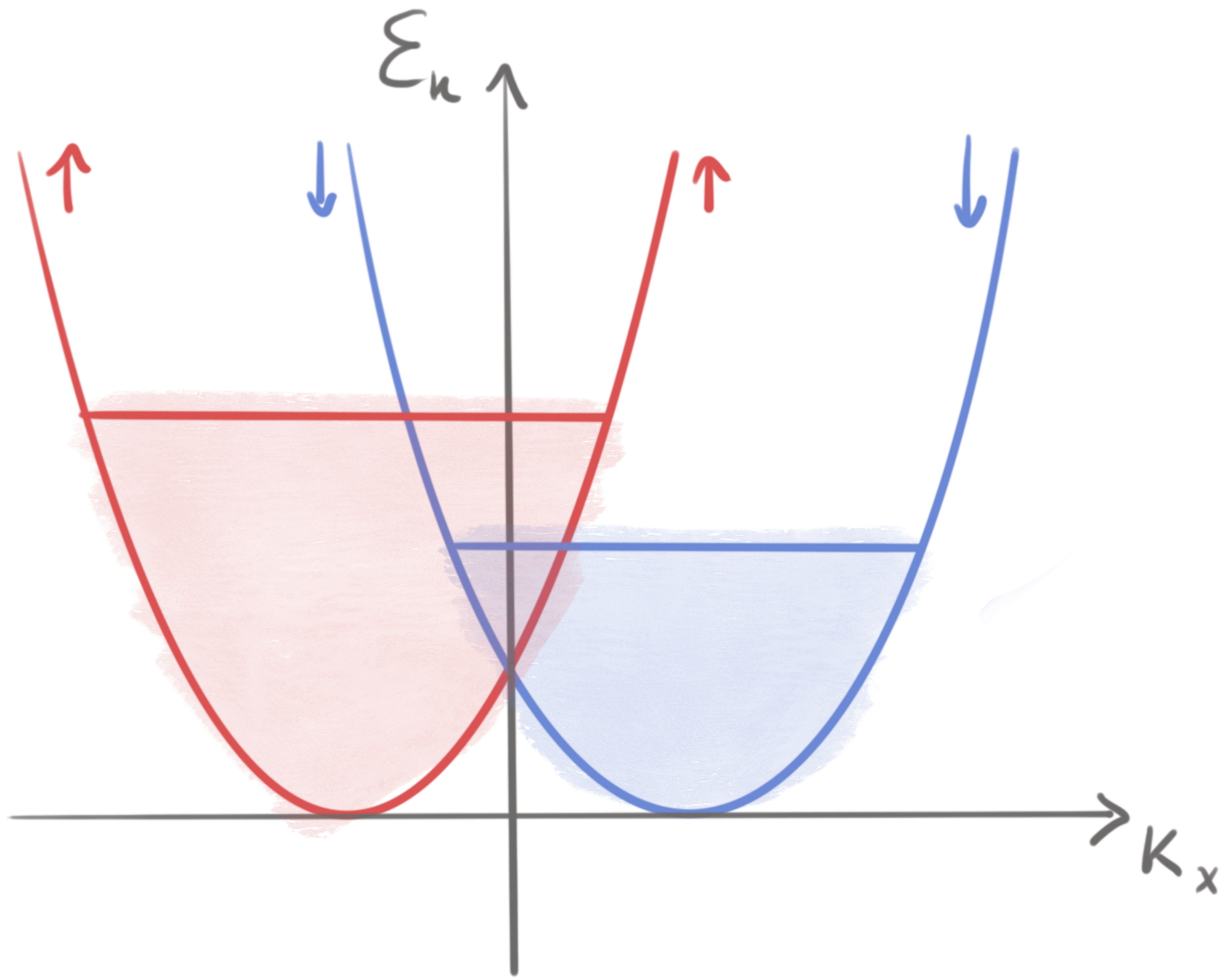
Food for spin-thought: Spin-galvanic effect

Asymmetric spin populations and scattering induces electric current



S. D. Ganichev et. al. Nature 417, 153 (2002)

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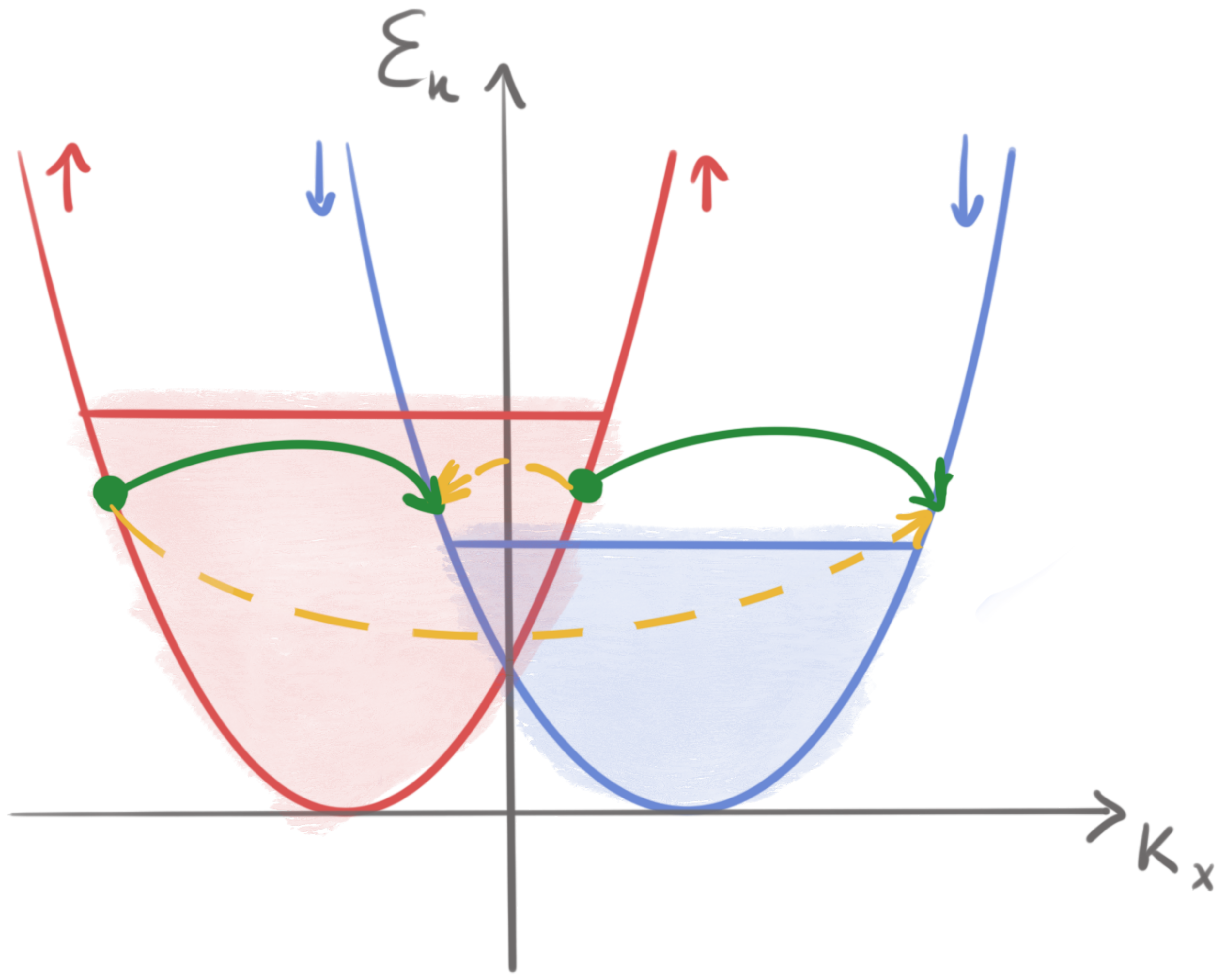

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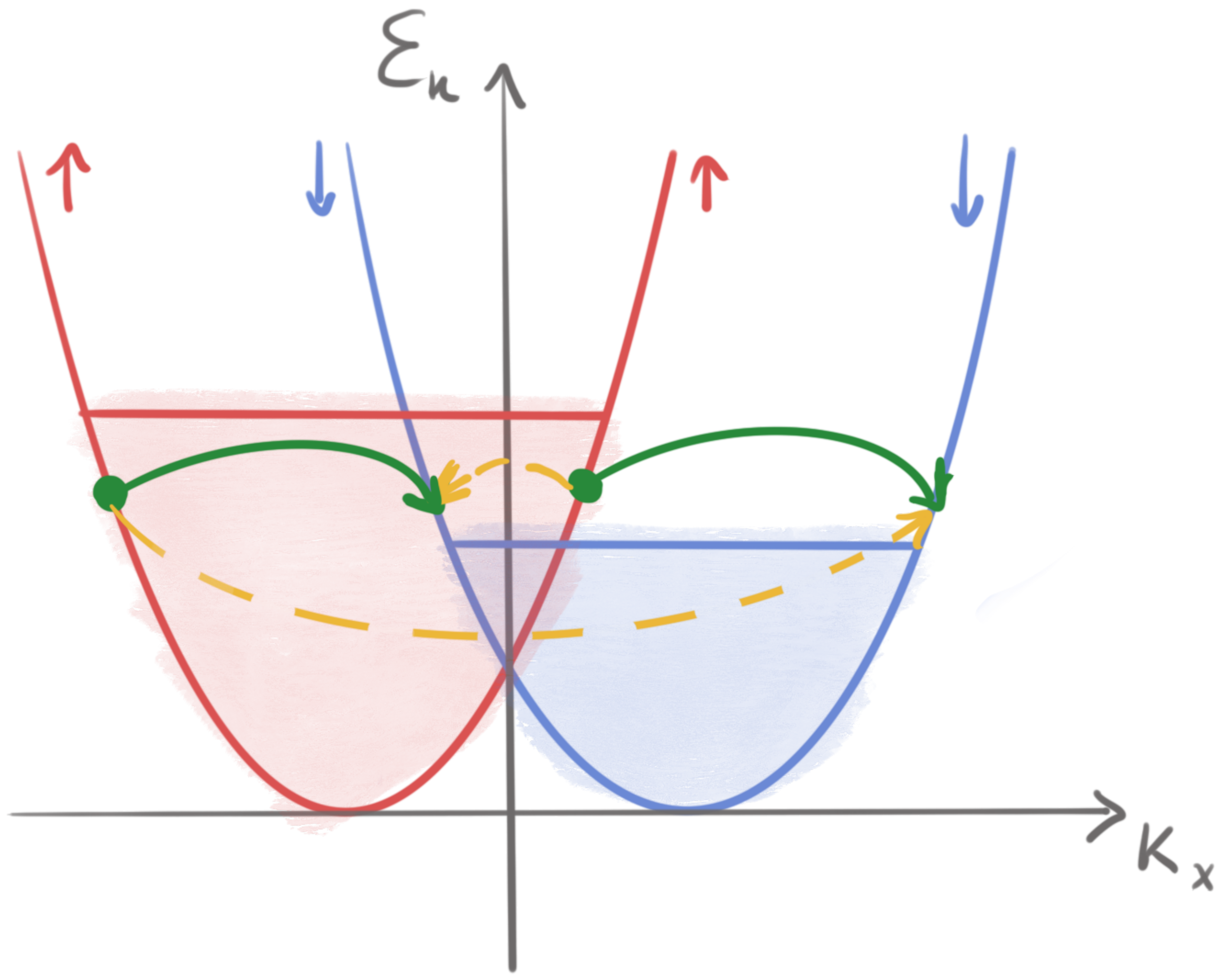

$$j_i = \tau_s Q_{ij} S_j$$

electron spin

allowed in gyrotropic point groups

S. D. Ganichev et. al. Nature 417, 153 (2002)

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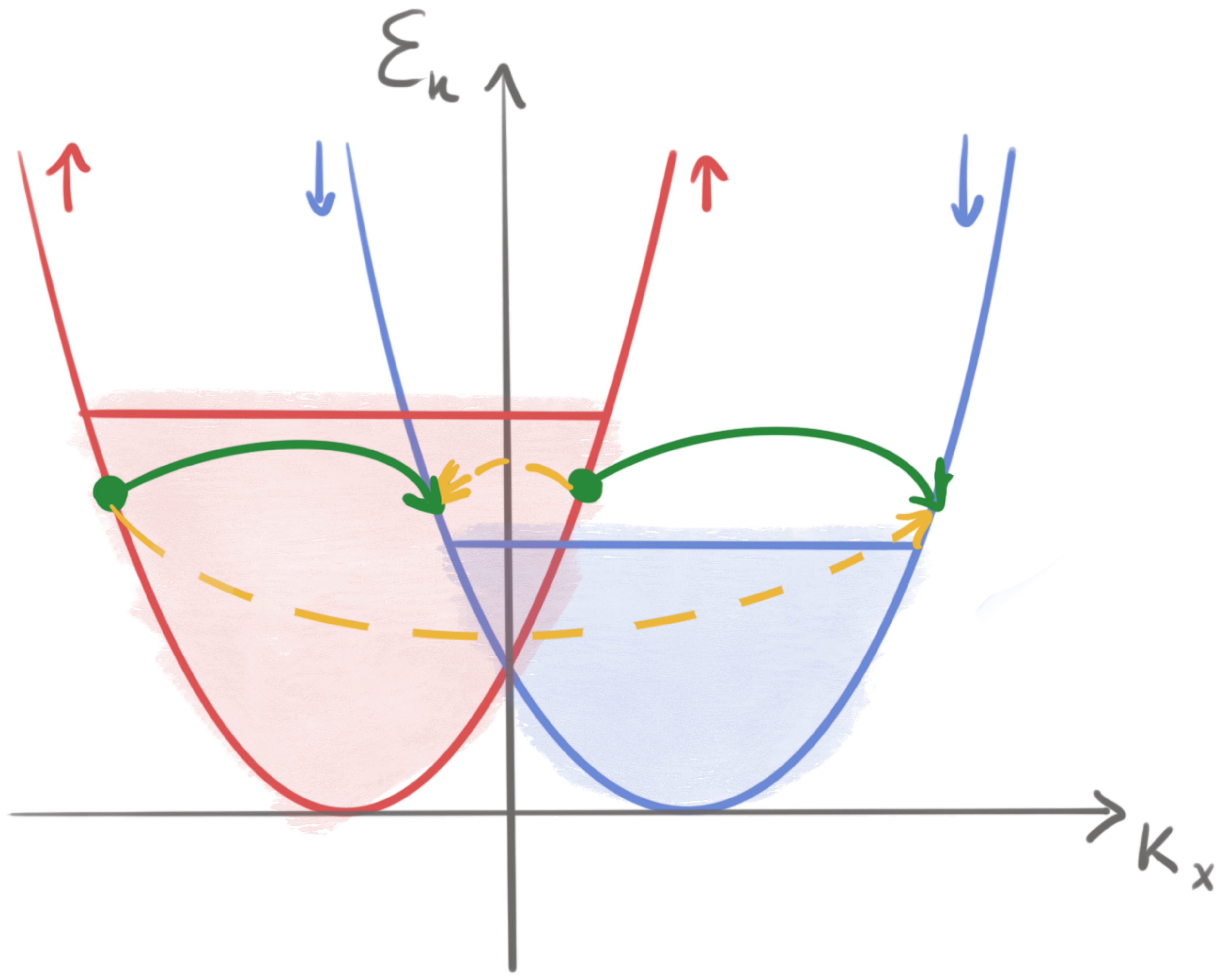

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electron spin

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photon angular momentum

$$j_i = \tau \beta_{ij} (\mathbf{E} \times \mathbf{E}^*)_j$$

S. D. Ganichev et. al. Nature 417, 153 (2002)

Quantization

...not so often experimentally observed

$$j_i = \sigma_{ij} E_j + \sigma_{ijl} E_j E_l + \cdots$$

Quantum Hall effect

von Klitzing, Tsui, Stormer (80's)

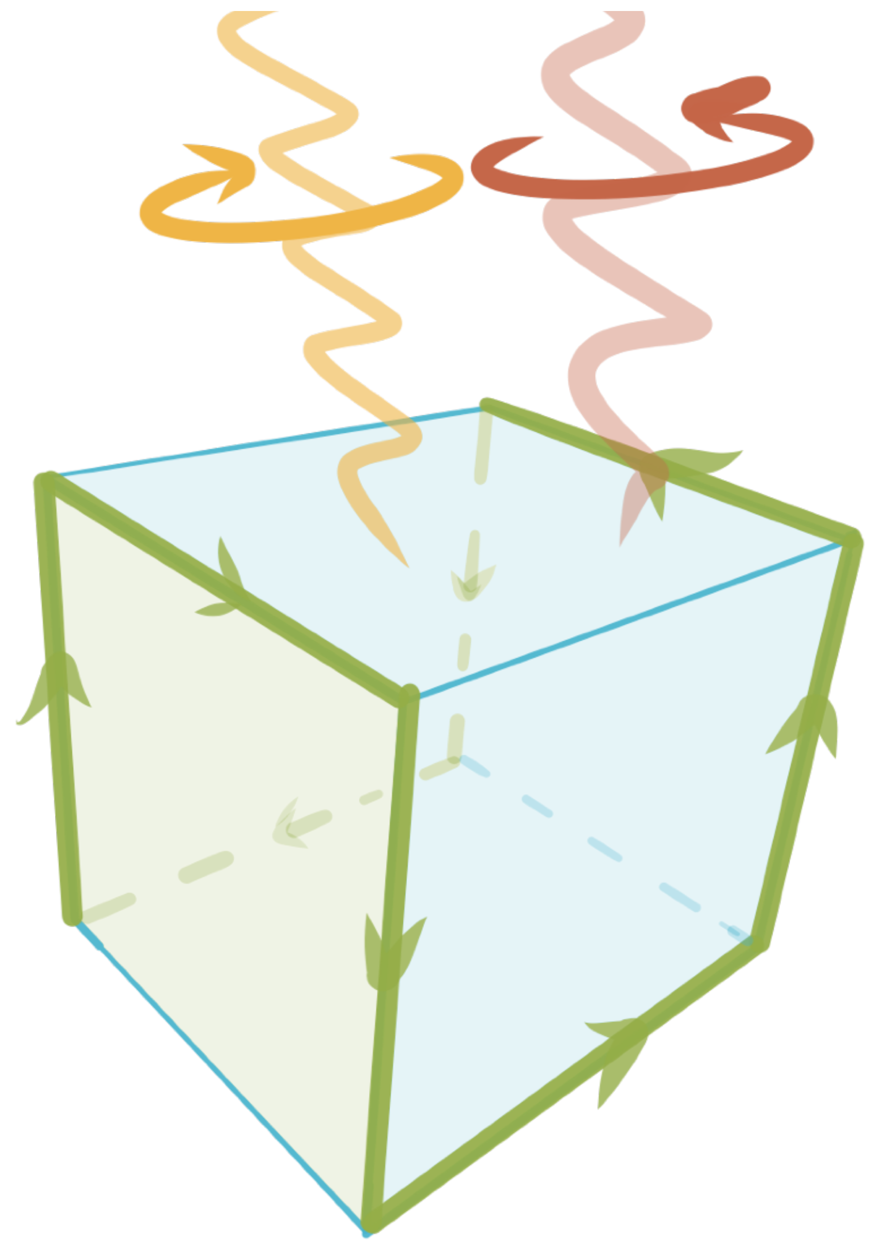
Rotation of plane of polarization

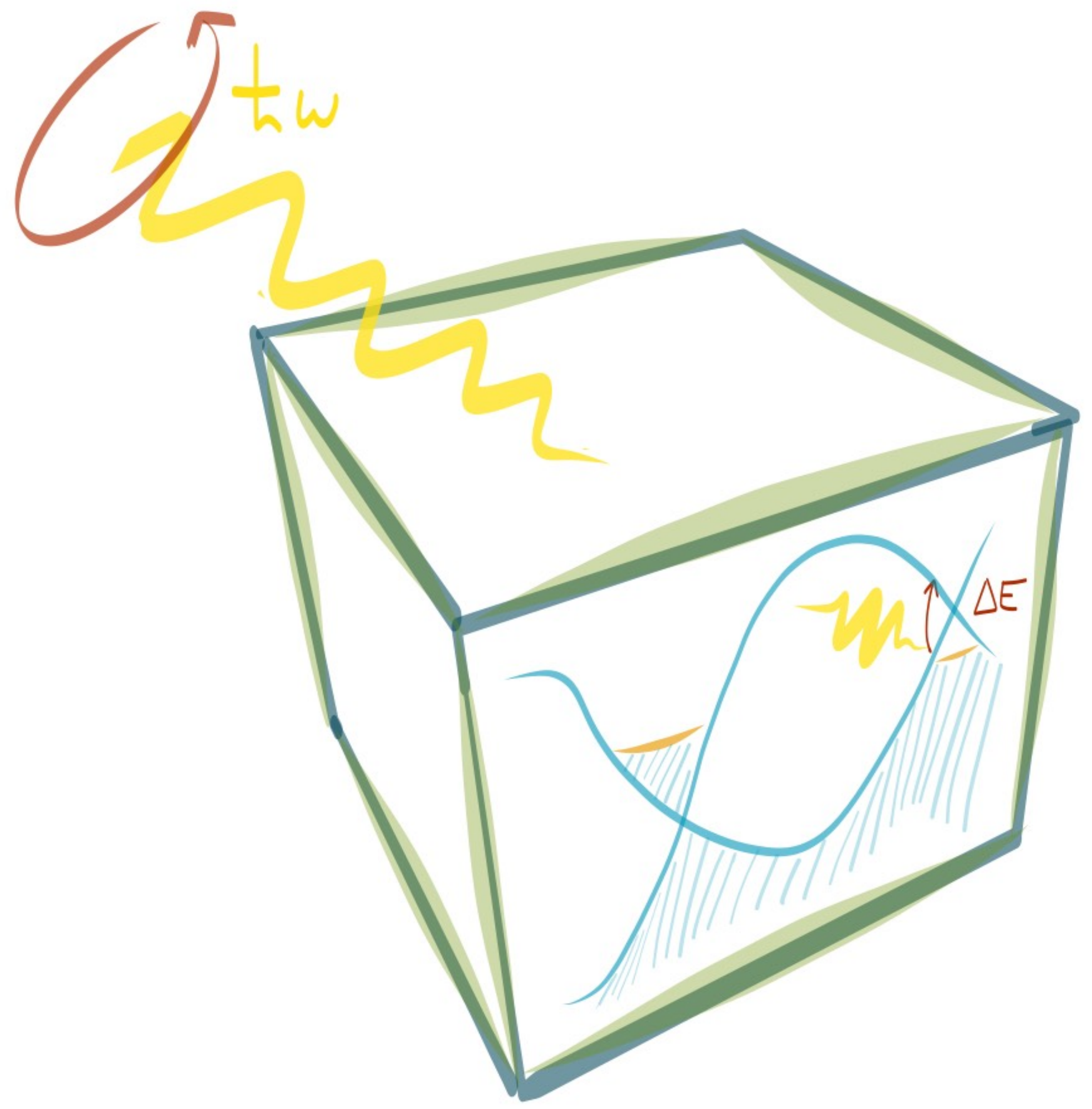
L. Wu, et al Science (2016)

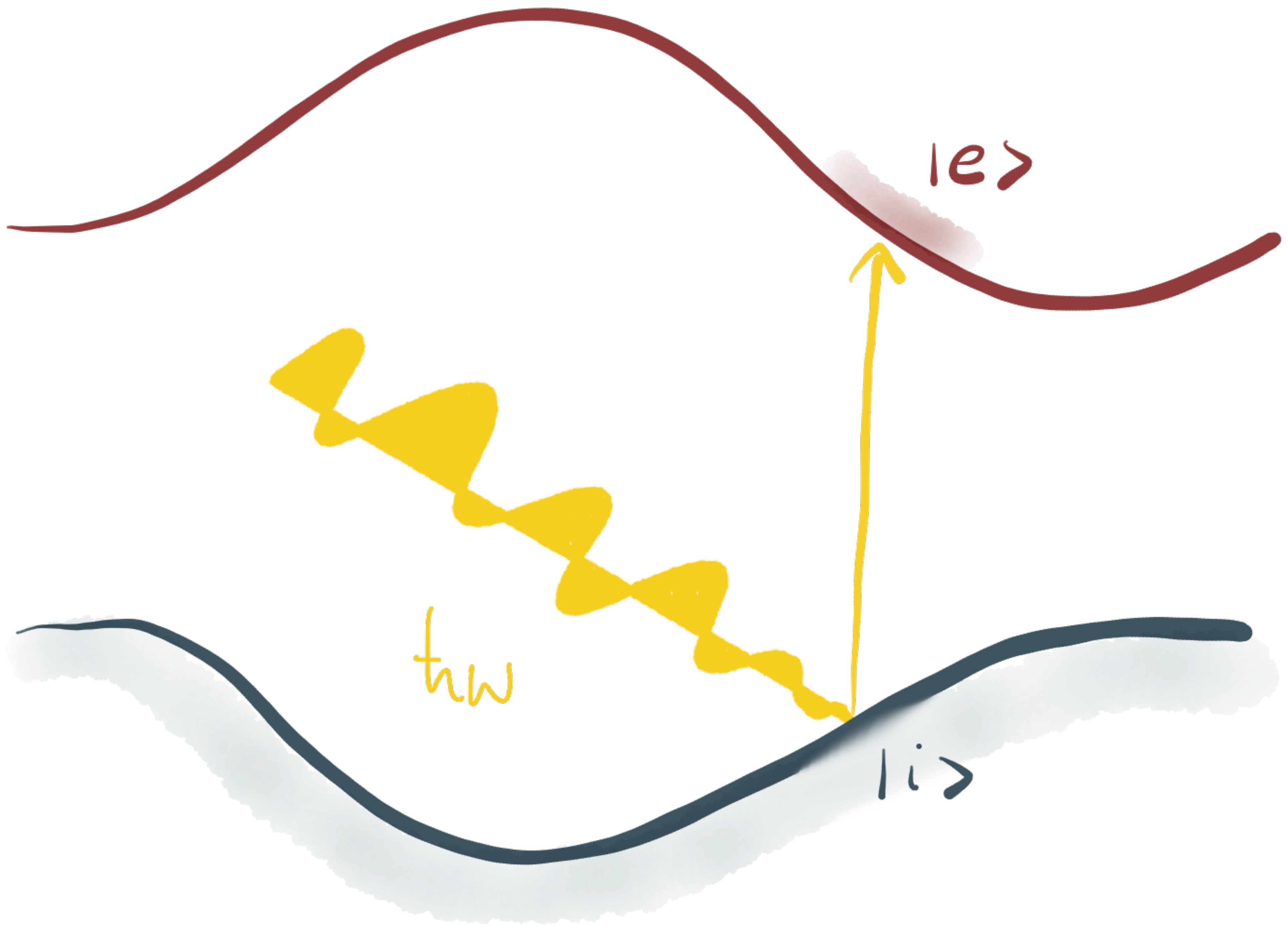
Quantized photogalvanic effect

F. De Juan et al Nat. Comm (2017)

D. Rees et al arXiv: 1902.03230



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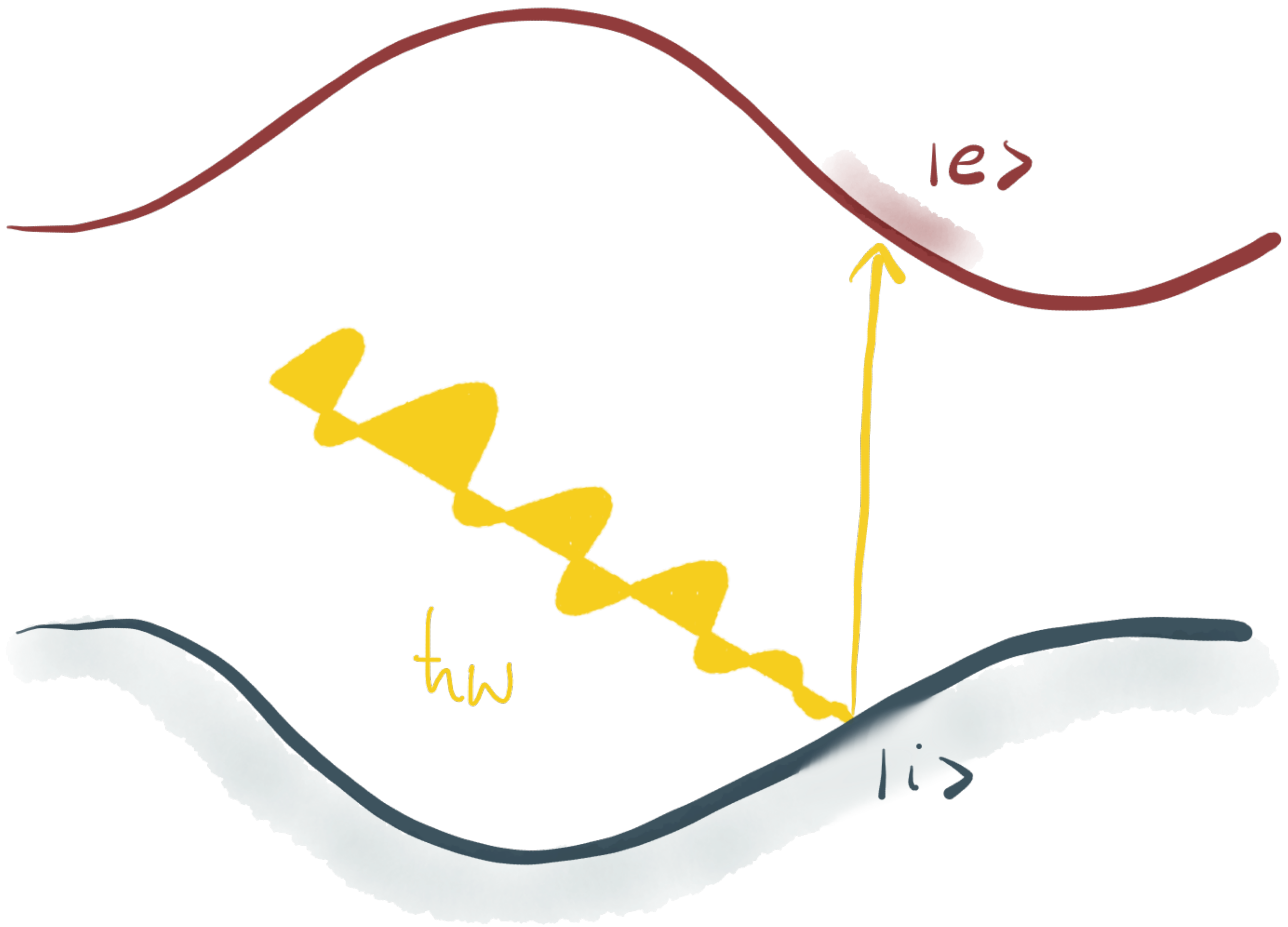
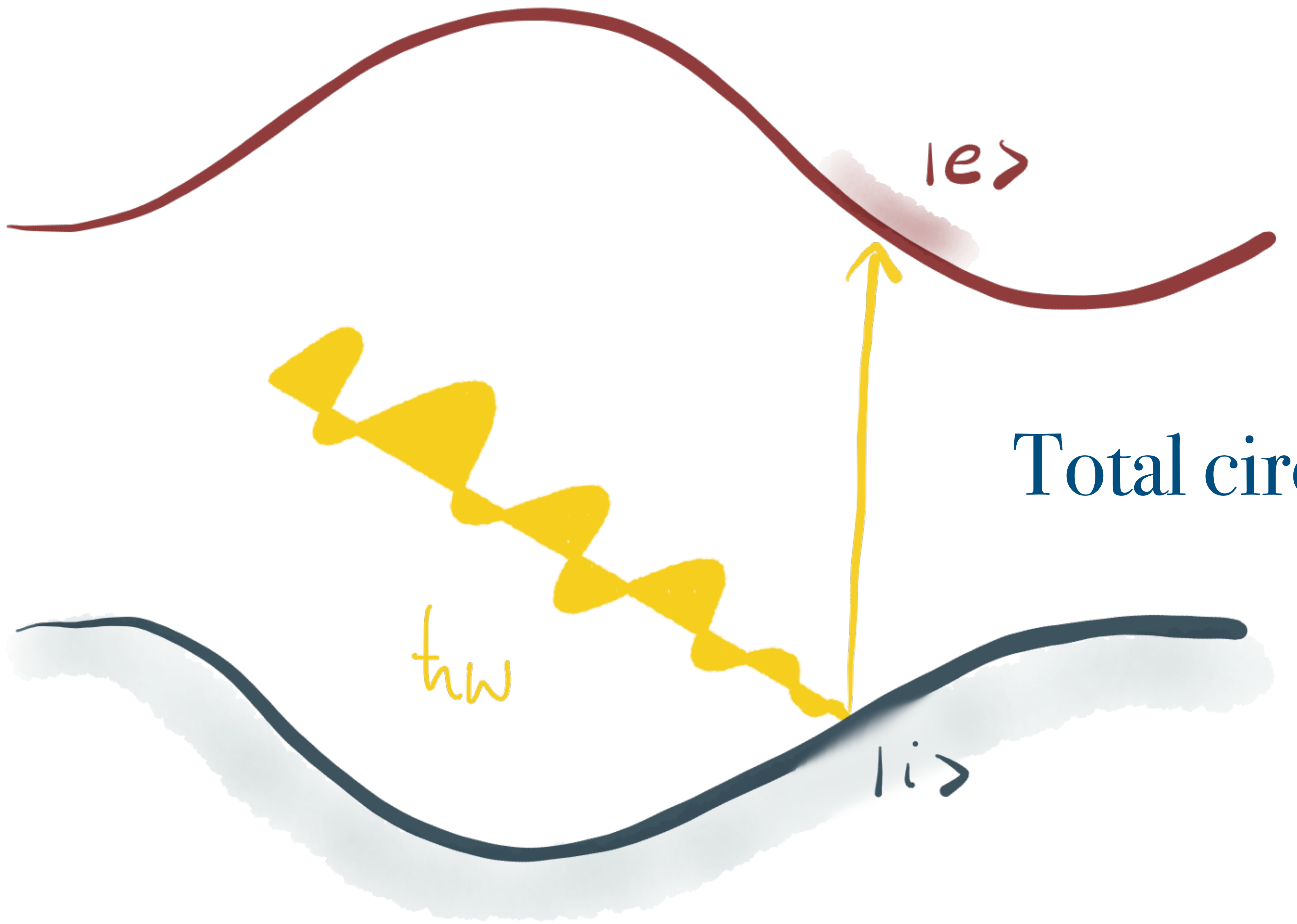


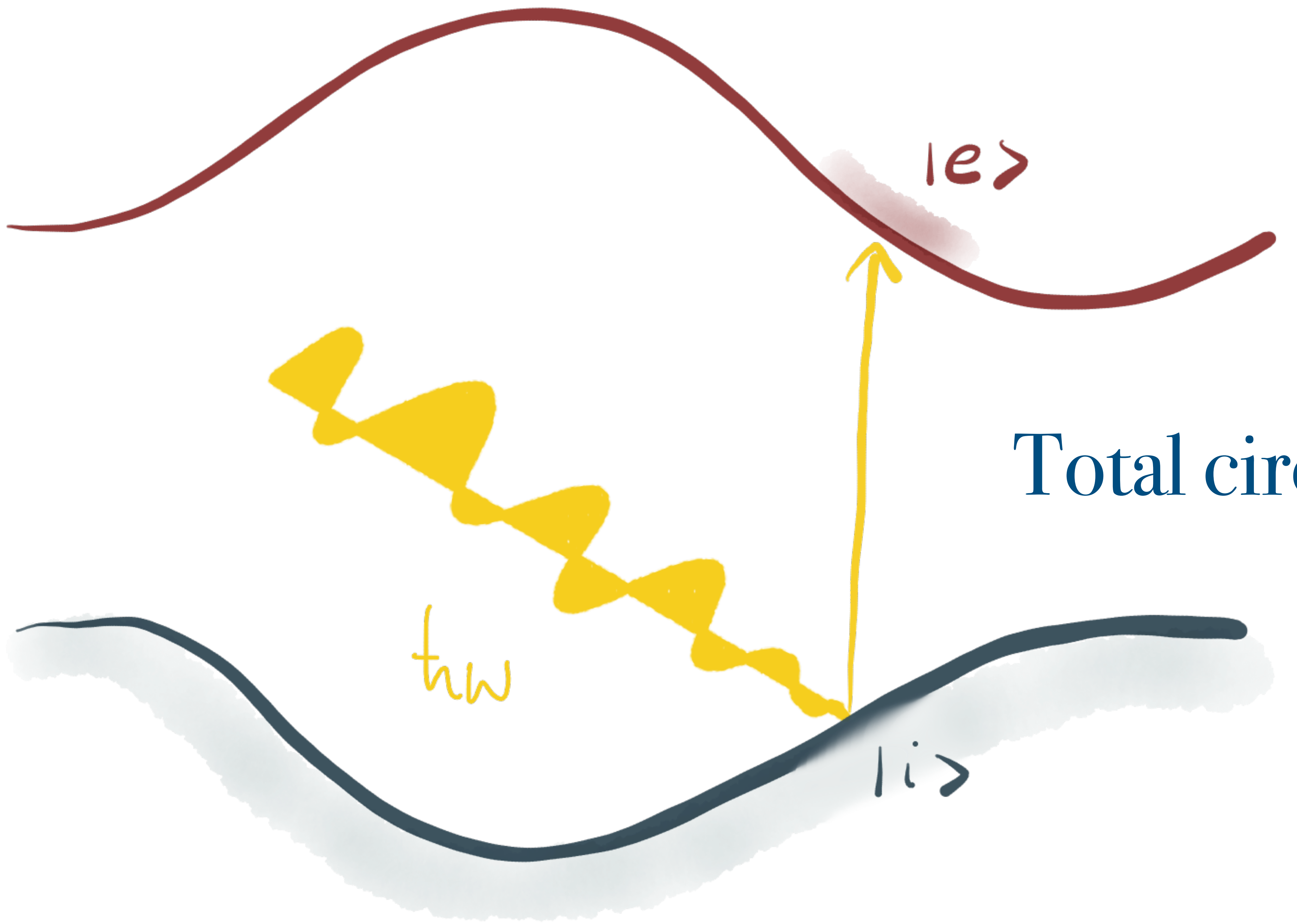
Circular dichroism of chiral 3D-HOTIs
is quantized to integers, and
distinguishes different HOTIs



Total circular dichroism measures the DC Hall conductivity

Bennett and Stern PRA (1965)
Souza and Vanderbilt PRB (2008)

Absorbed power $$\frac{P}{A} = \mathrm{Re}\,\langle J_i^* E_i \rangle$$



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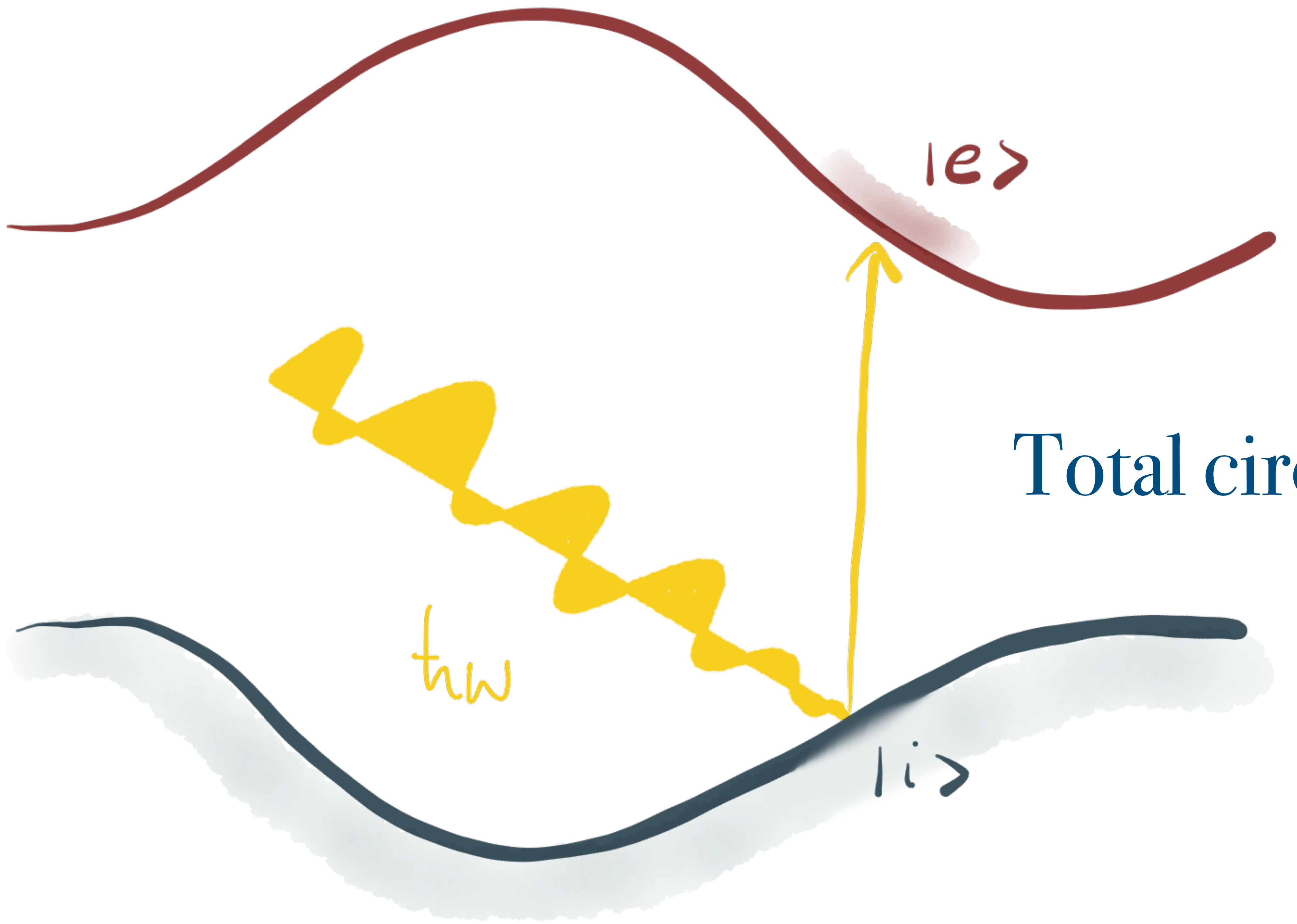

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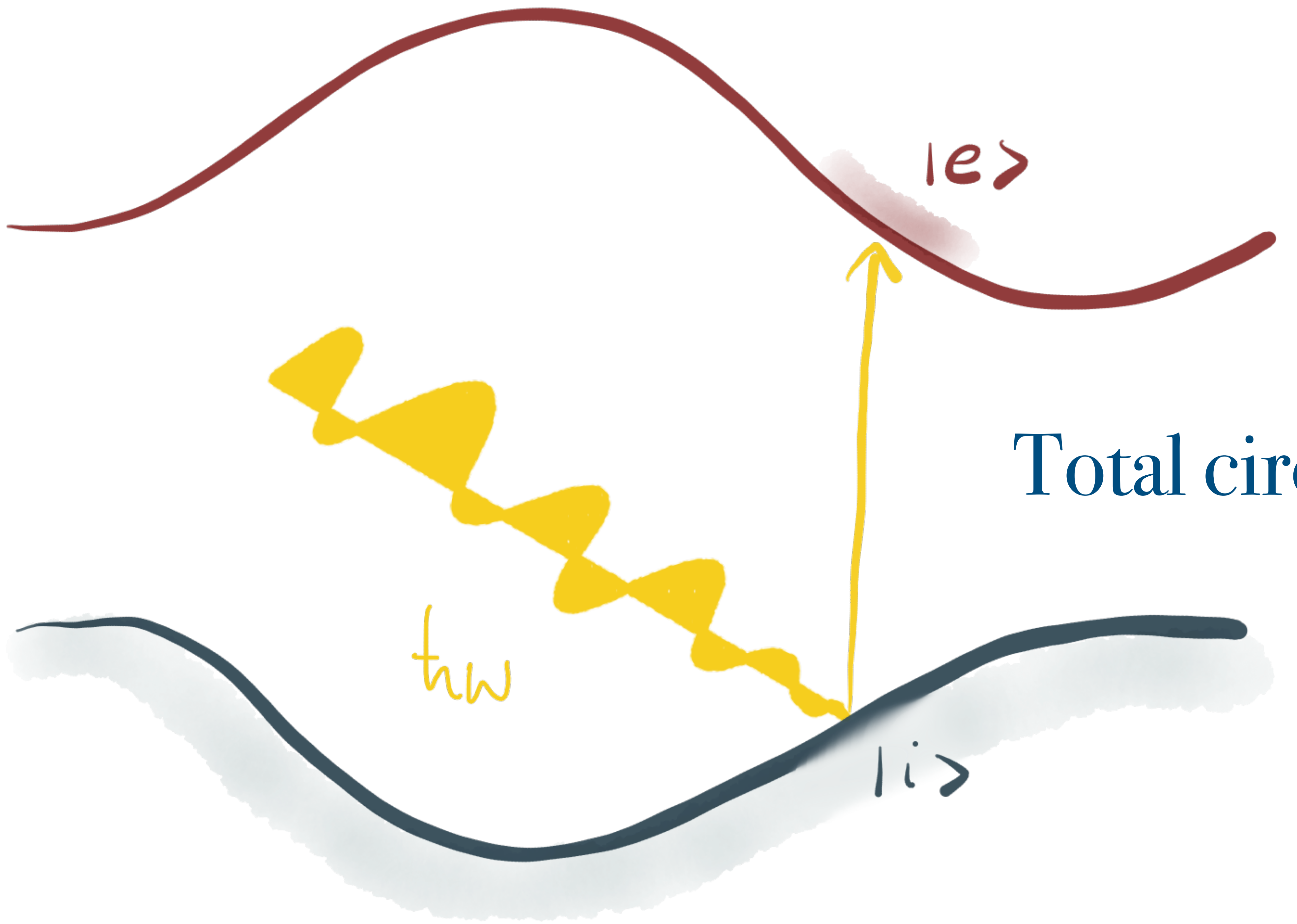

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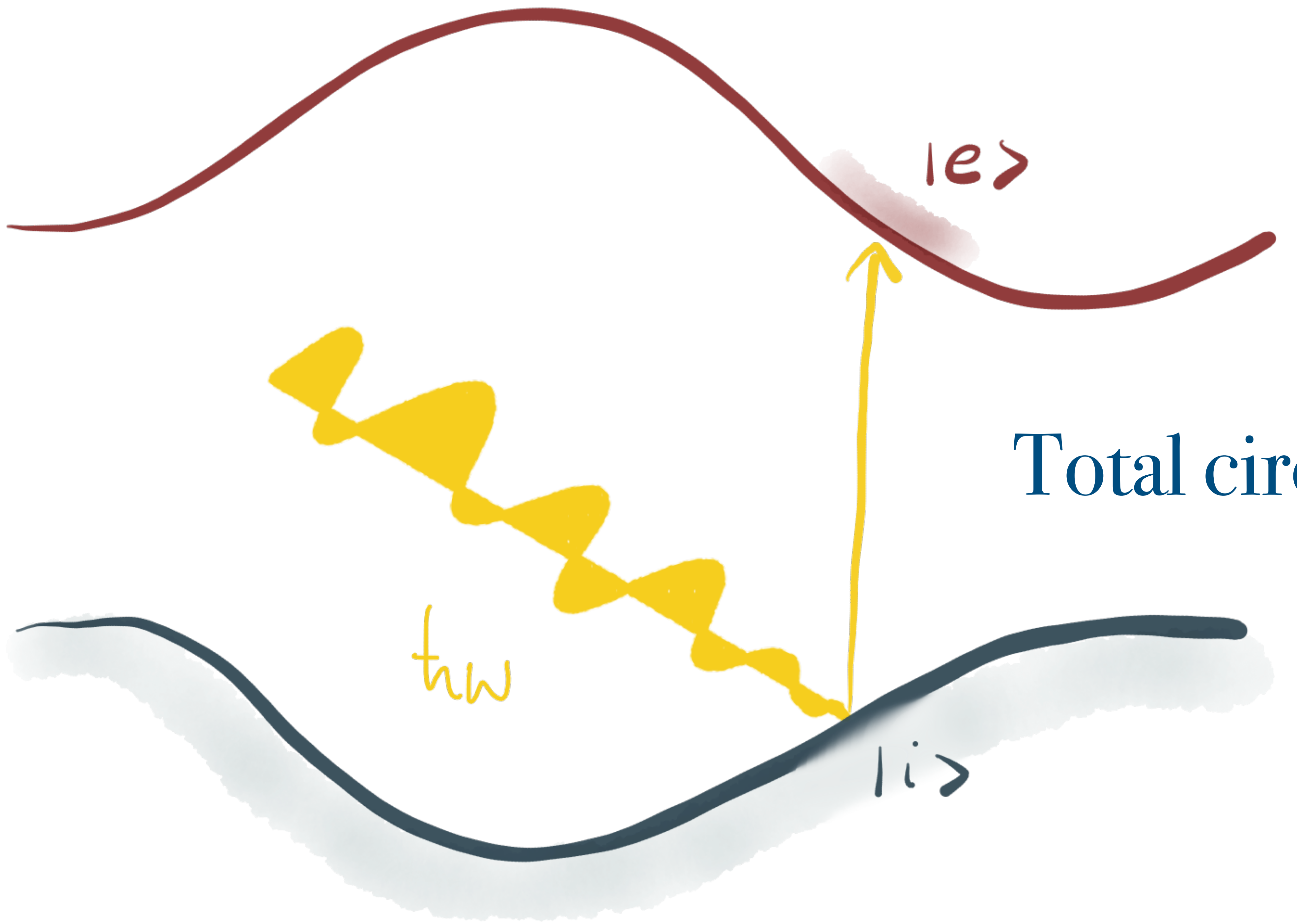
electric field
$E = 2|E|(1, \pm i, 0)e^{i\omega t}$



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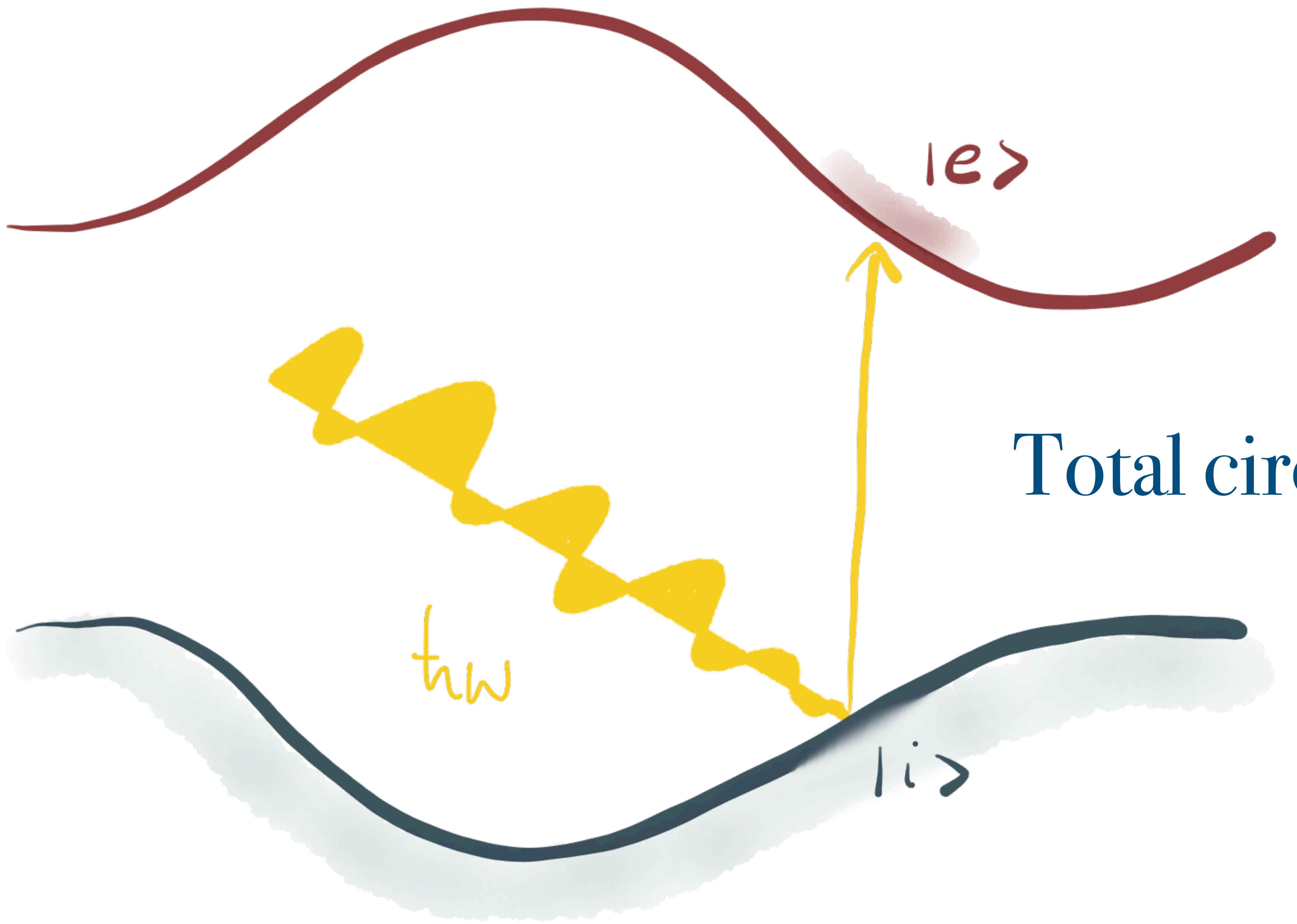

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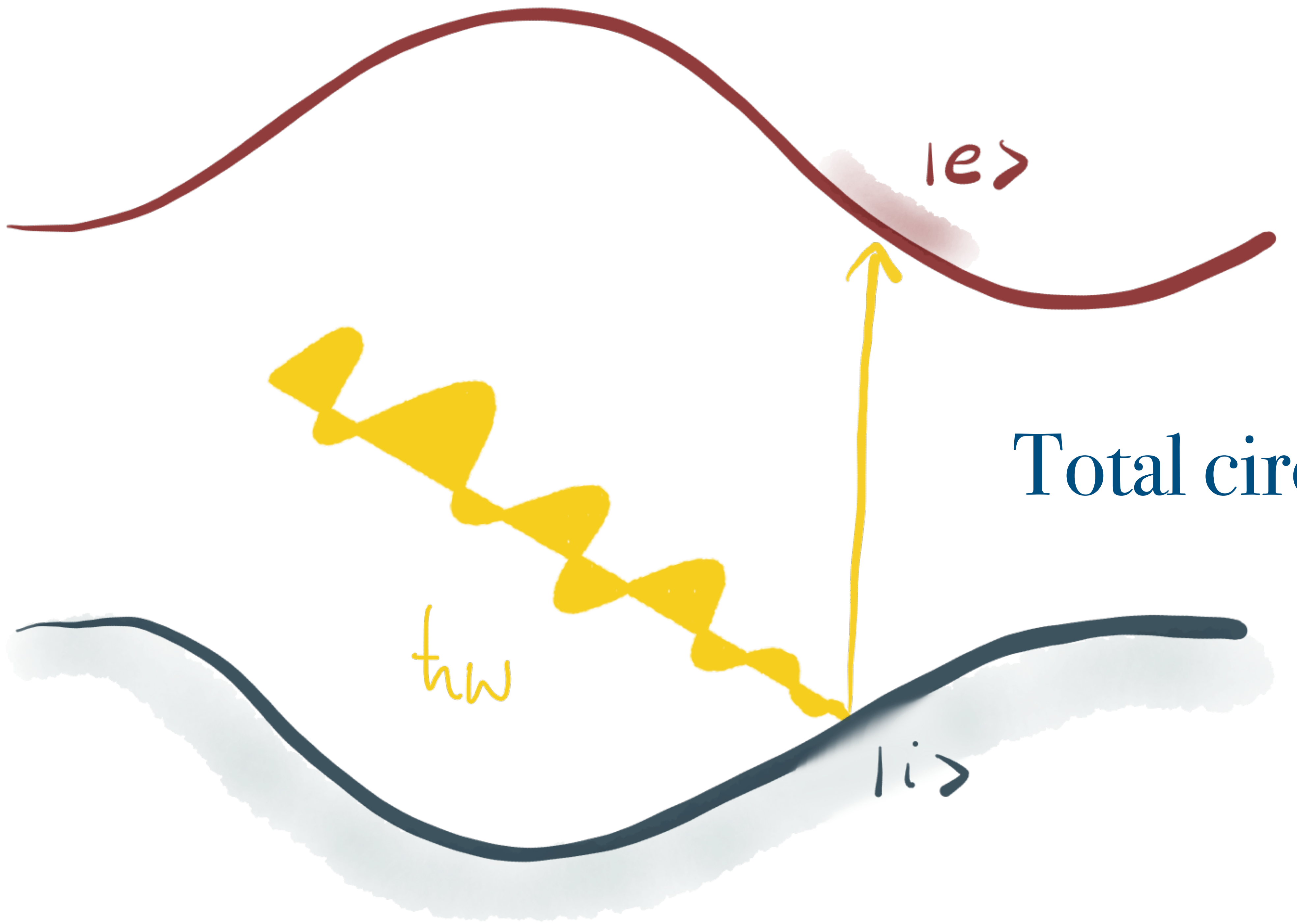

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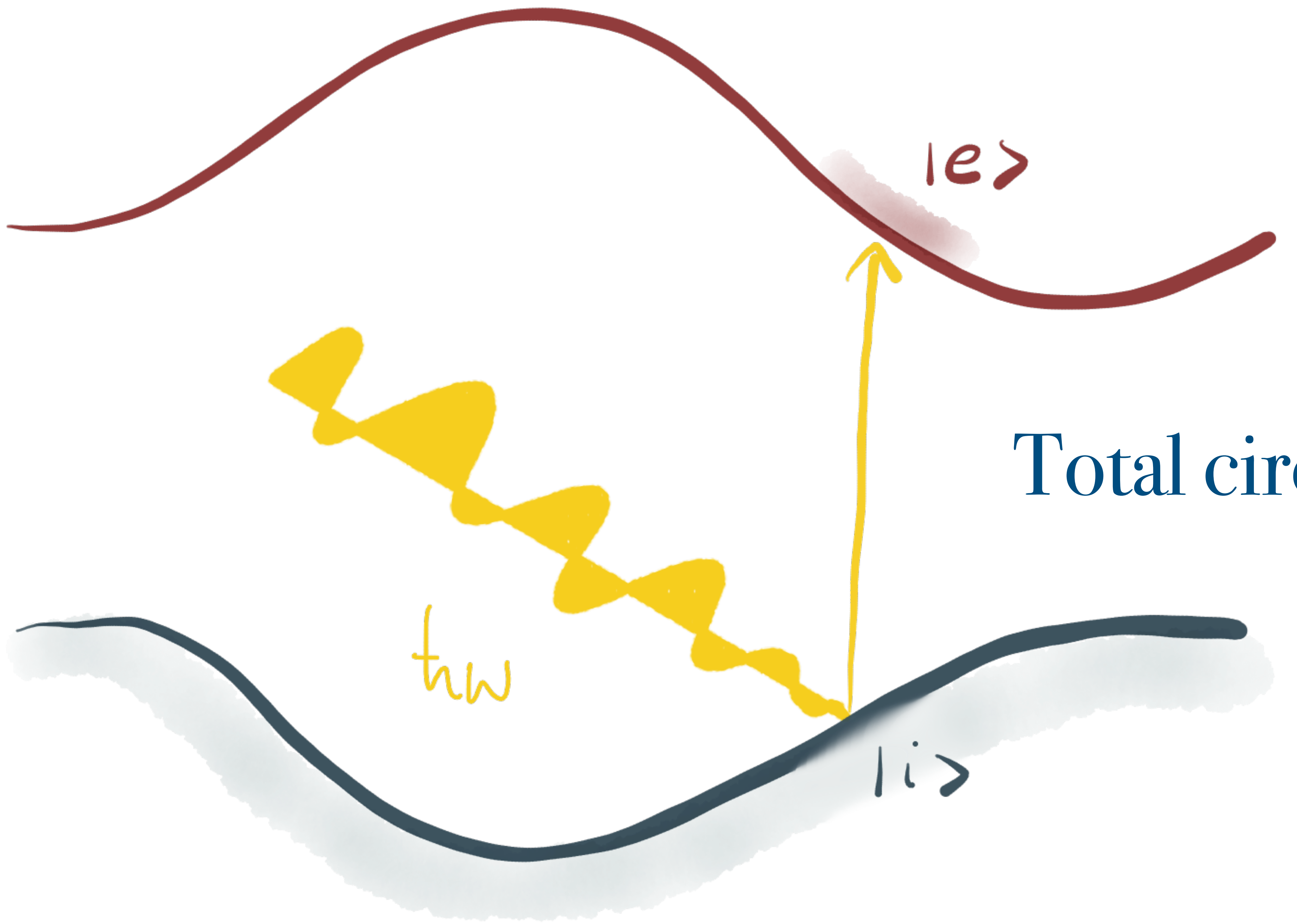

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Total circular dichroism measures the DC Hall conductivity

$$\frac{\Delta\Gamma}{A} = \frac{1}{A}\int d\omega(\Gamma_+ - \Gamma_-)/2$$

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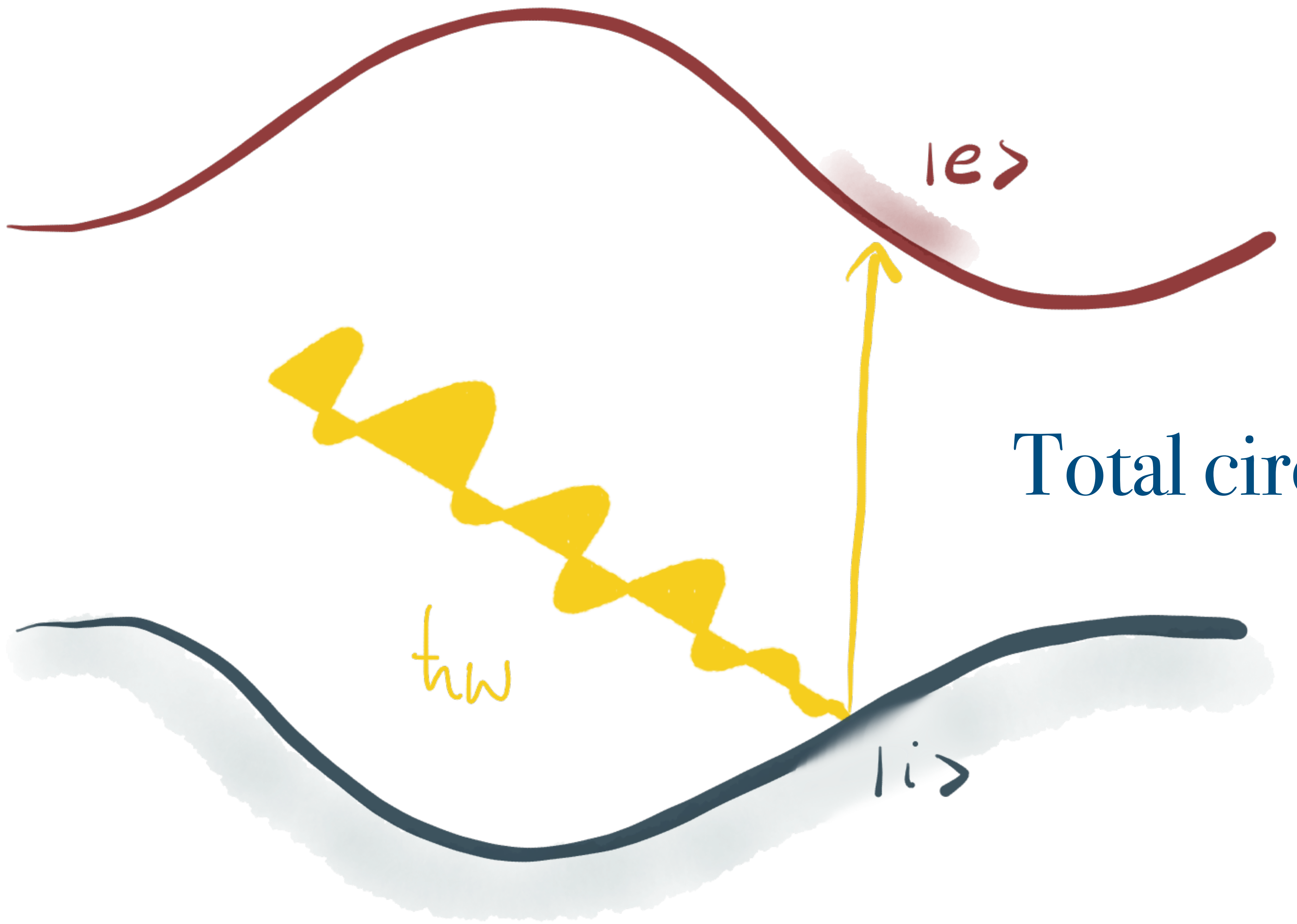
electric field
$E = 2|E|(1, \pm i, 0)e^{i\omega t}$



Power absorbed $P_\pm = \hbar\omega\Gamma_\pm$

Total circular dichroism measures the DC Hall conductivity

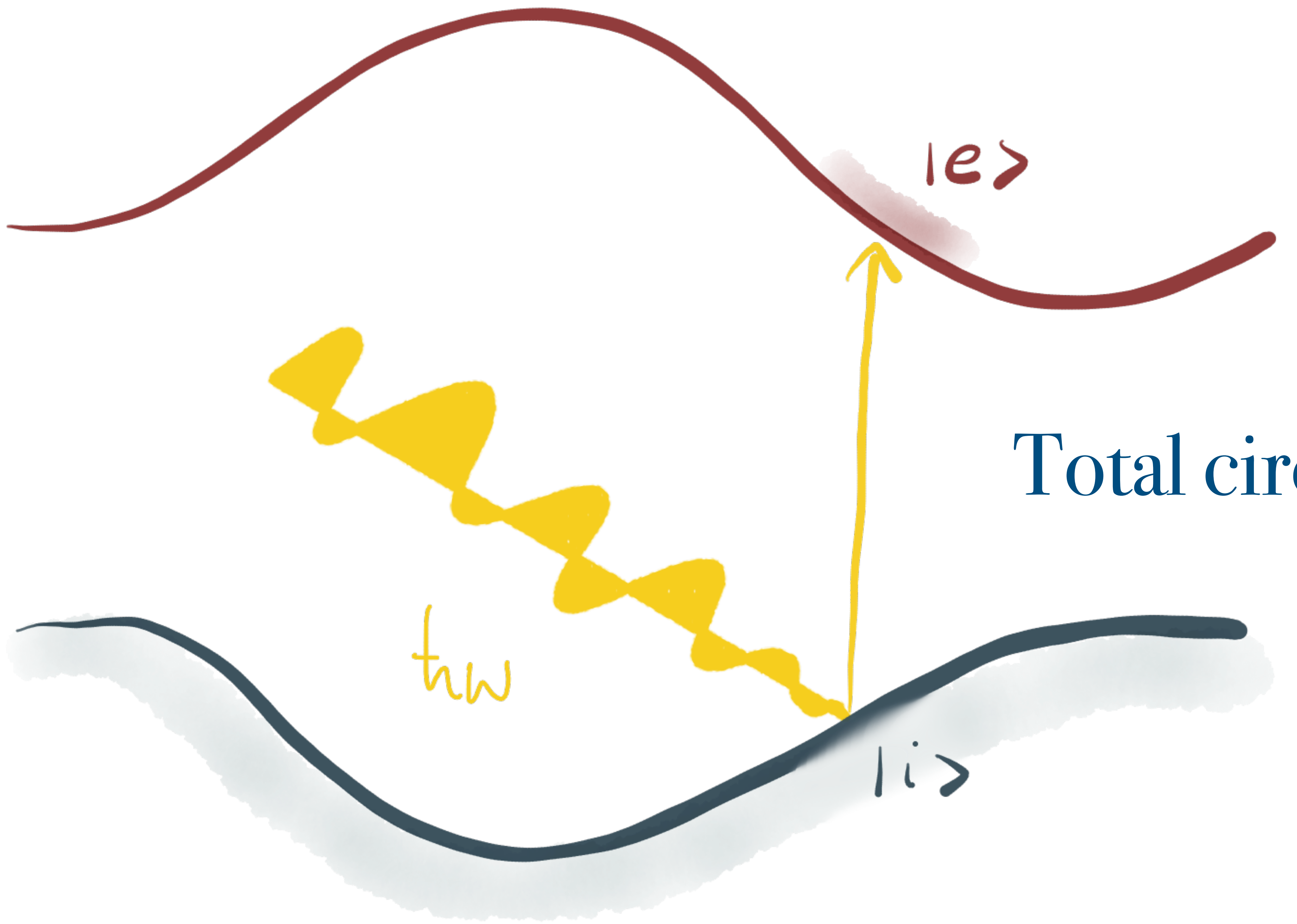
$$\frac{\Delta\Gamma}{A} = \int d\omega\, \frac{4|E|^2 \mathrm{Im}\left[\sigma_{xy}(\omega)\right]}{\hbar\omega}$$

Bennett and Stern PRA (1965)
Souza and Vanderbilt PRB (2008)

Absorbed power $\frac{P}{A} = \mathrm{Re}\langle J_i^* E_i \rangle = \mathrm{Re}\left[\sigma_{ij}^* E_i^* E_j\right] = 4|E|^2\left(\mathrm{Re}[\sigma_{xx}(\omega)] \pm \mathrm{Im}[\sigma_{xy}(\omega)]\right)$

current
$J_i = \sigma_{ij} E_j$

electric field
$E = 2|E|(1, \pm i, 0)e^{i\omega t}$



Power absorbed $P_{\pm} = \hbar\omega\Gamma_{\pm}$

Total circular dichroism measures the DC Hall conductivity

$$\frac{\Delta\Gamma}{A} = 2\pi\,\mathrm{Re}[\sigma_{xy}(\omega = 0)]\,\frac{E^2}{\hbar}$$

Bennett and Stern PRA (1965)
Souza and Vanderbilt PRB (2008)

Absorbed power $$\frac{P}{A} = \mathrm{Re}\,\langle J_i^* E_i \rangle = \mathrm{Re}\left[\sigma_{ij}^* E_i^* E_j\right] = 4|E|^2\left(\mathrm{Re}[\sigma_{xx}(\omega)] \pm \mathrm{Im}[\sigma_{xy}(\omega)]\right)$$

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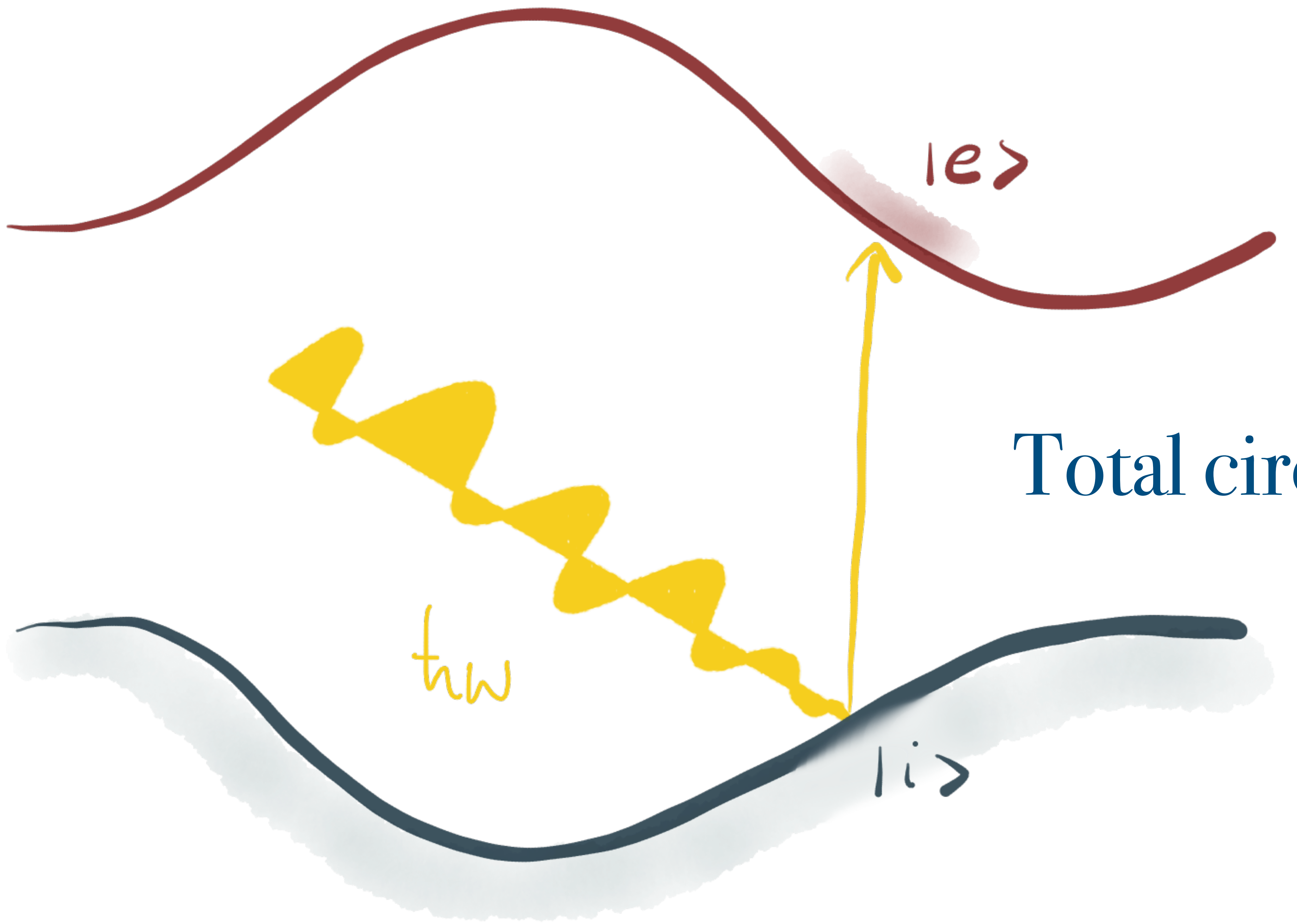


Power absorbed $P_\pm = \hbar\omega\Gamma_\pm$

Total circular dichroism measures the DC Hall conductivity

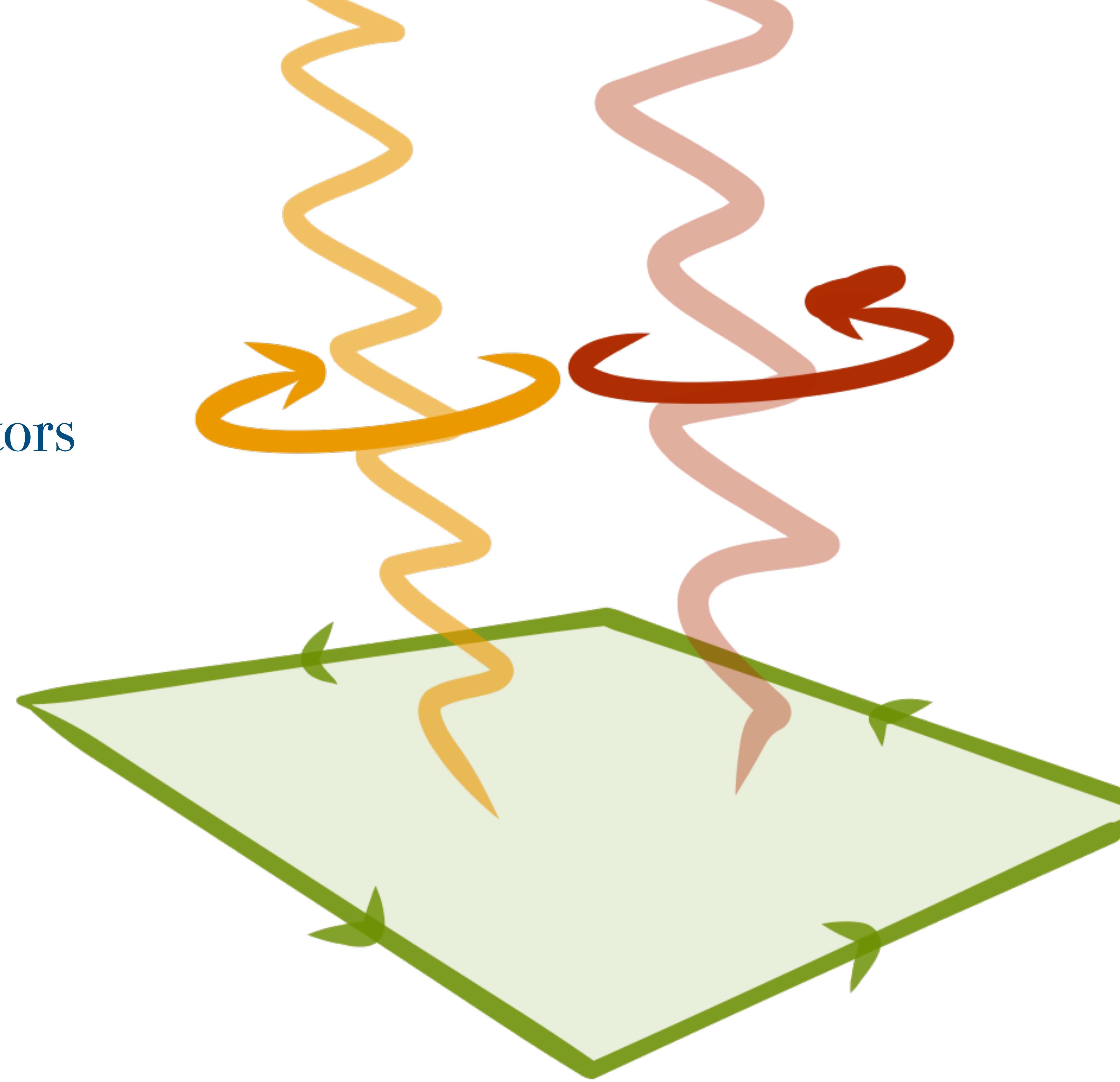
$$\frac{\Delta\Gamma}{A} = \nu\frac{e^2 E^2}{\hbar^2}$$

2D insulator

Bennett and Stern PRA (1965)
Souza and Vanderbilt PRB (2008)

Total circular dichroism is quantized in Chern insulators

$$\frac{\Delta\Gamma}{A} = \nu \frac{e^2 E^2}{\hbar}$$



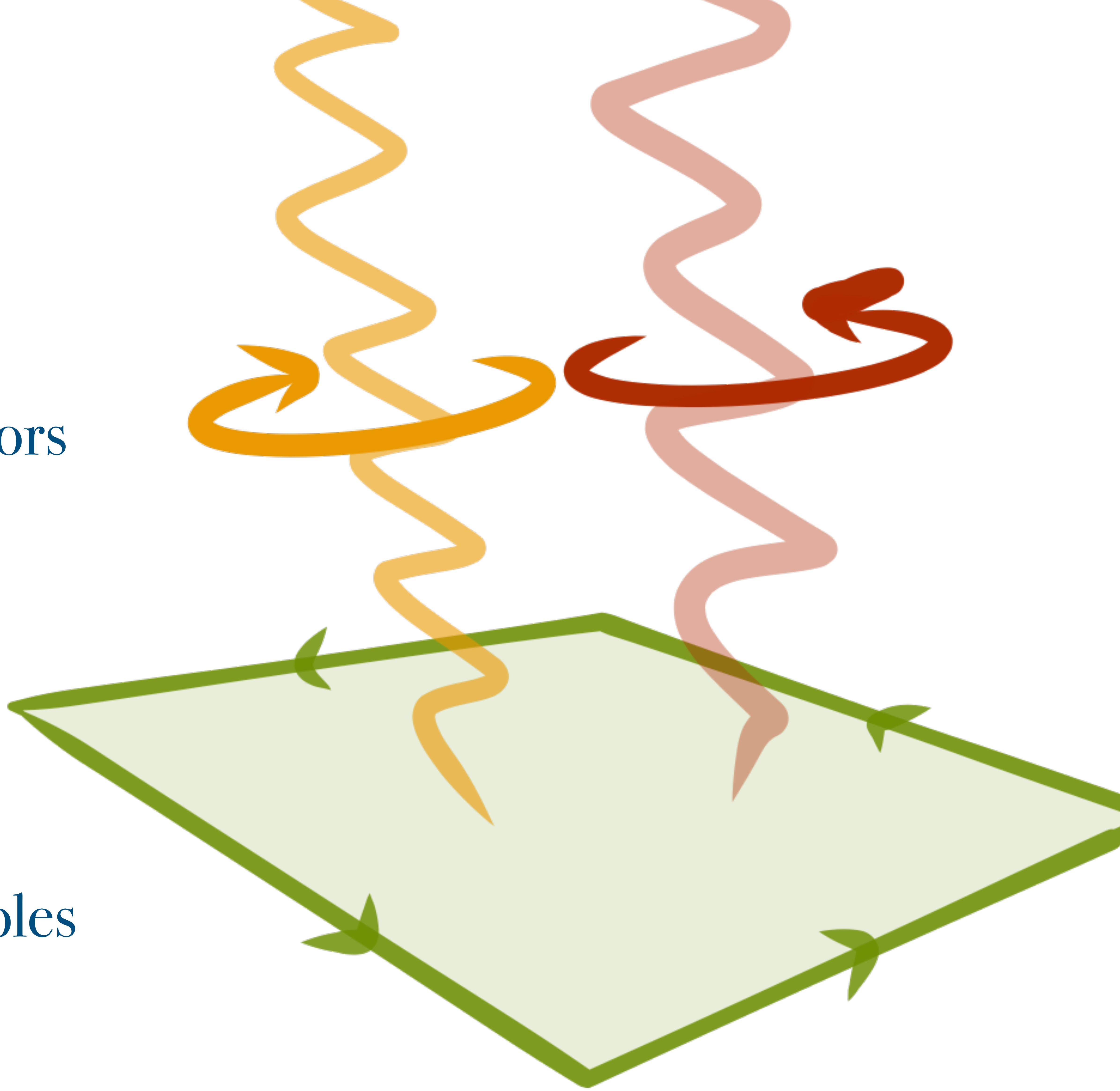
D. T. Tran, A. Dauphin, AGG, P. Zoller, N. Goldman Science Advances (2017)

L. Asteria et al Nat. Phys. (2019)

Total circular dichroism is quantized in Chern insulators

$$\frac{\Delta\Gamma}{A} = \nu \frac{e^2 E^2}{\hbar}$$

...but the total circular dichroism is zero in finite samples



D. T. Tran, A. Dauphin, AGG, P. Zoller, N. Goldman Science Advances (2017)
L. Asteria et al Nat. Phys. (2019)

the total circular dichroism is zero in finite samples (real space picture)

$$\nu = \frac{1}{A} \sum_{\mathbf{r}} C_{xy}(\mathbf{r}) = 0$$

$$C_{xy}(\mathbf{r}) = 2\pi \mathrm{Im} \langle \mathbf{r} | \left[\hat{Q}\hat{x}, \hat{P}\hat{y} \right] | \mathbf{r} \rangle$$

Wannier basis

ground-state
projector operator

Bianco, Resta PRB (2011)

the total circular dichroism is zero in finite samples (real space picture)

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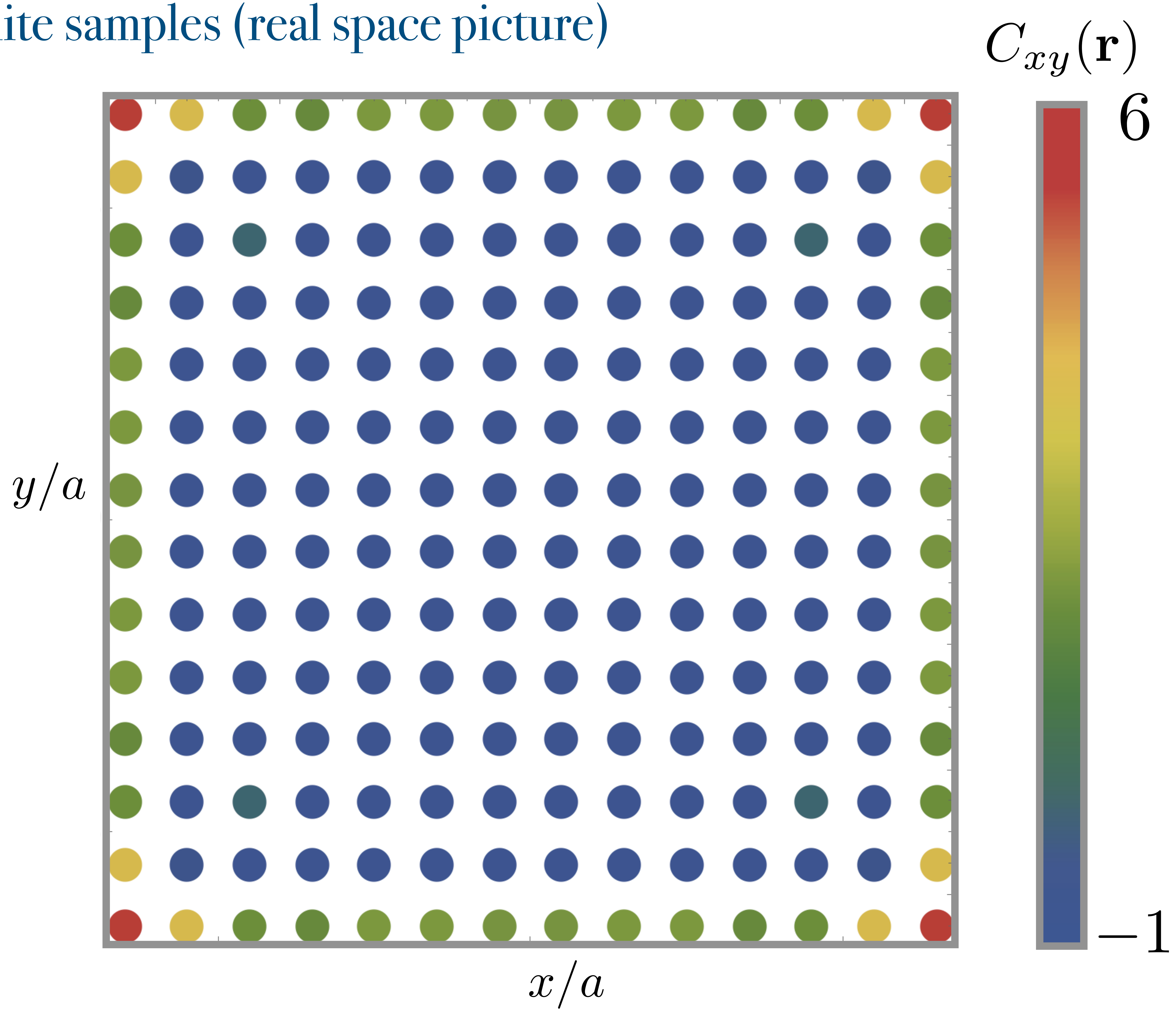
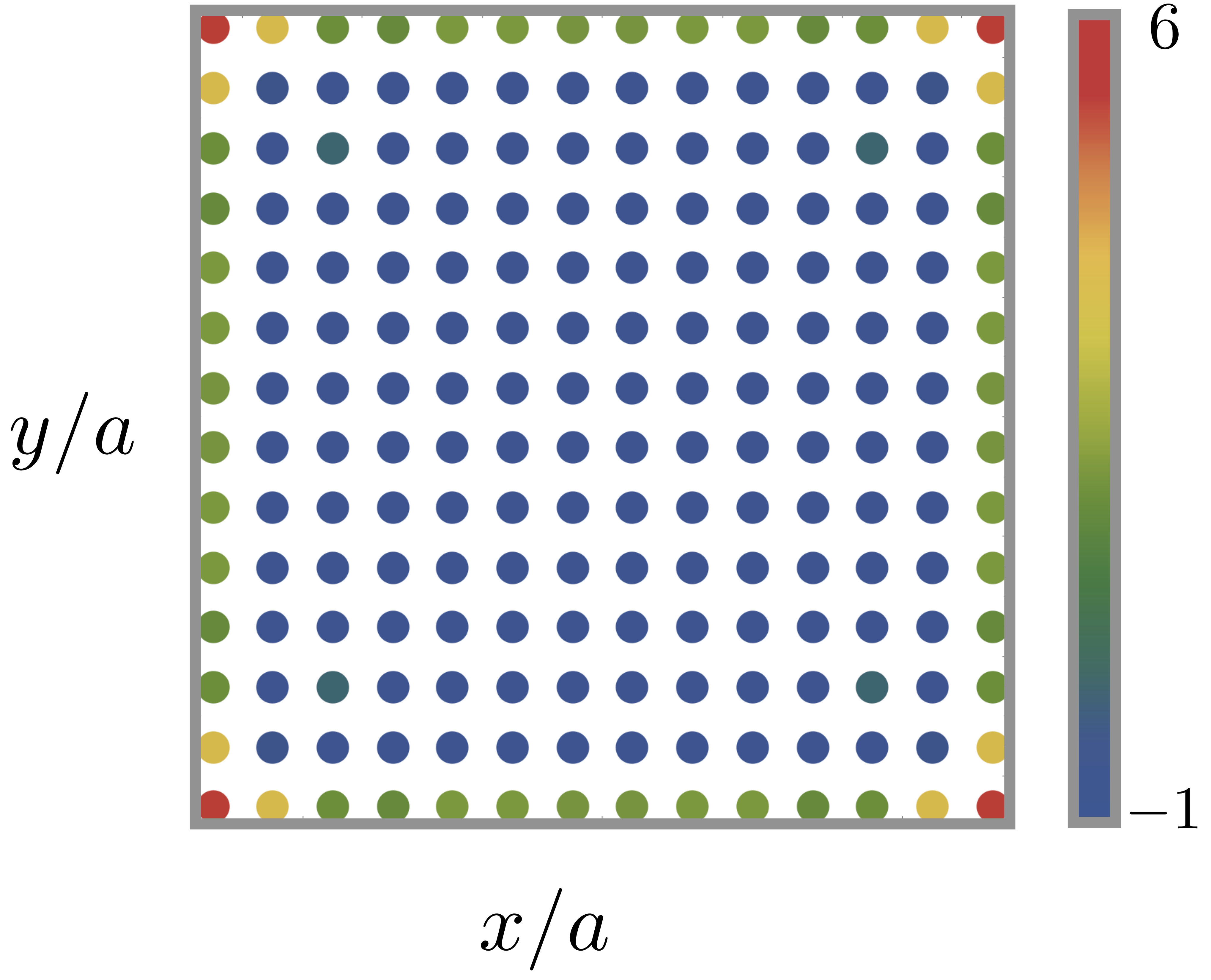


Bianco, Resta PRB (2011)

the total circular dichroism is zero in finite samples (real and energy space picture)

Real space

$$\Delta\Gamma = \frac{e^2 E^2}{\hbar^2} \sum_{\mathbf{r}} C_{xy}(\mathbf{r}) = 0$$



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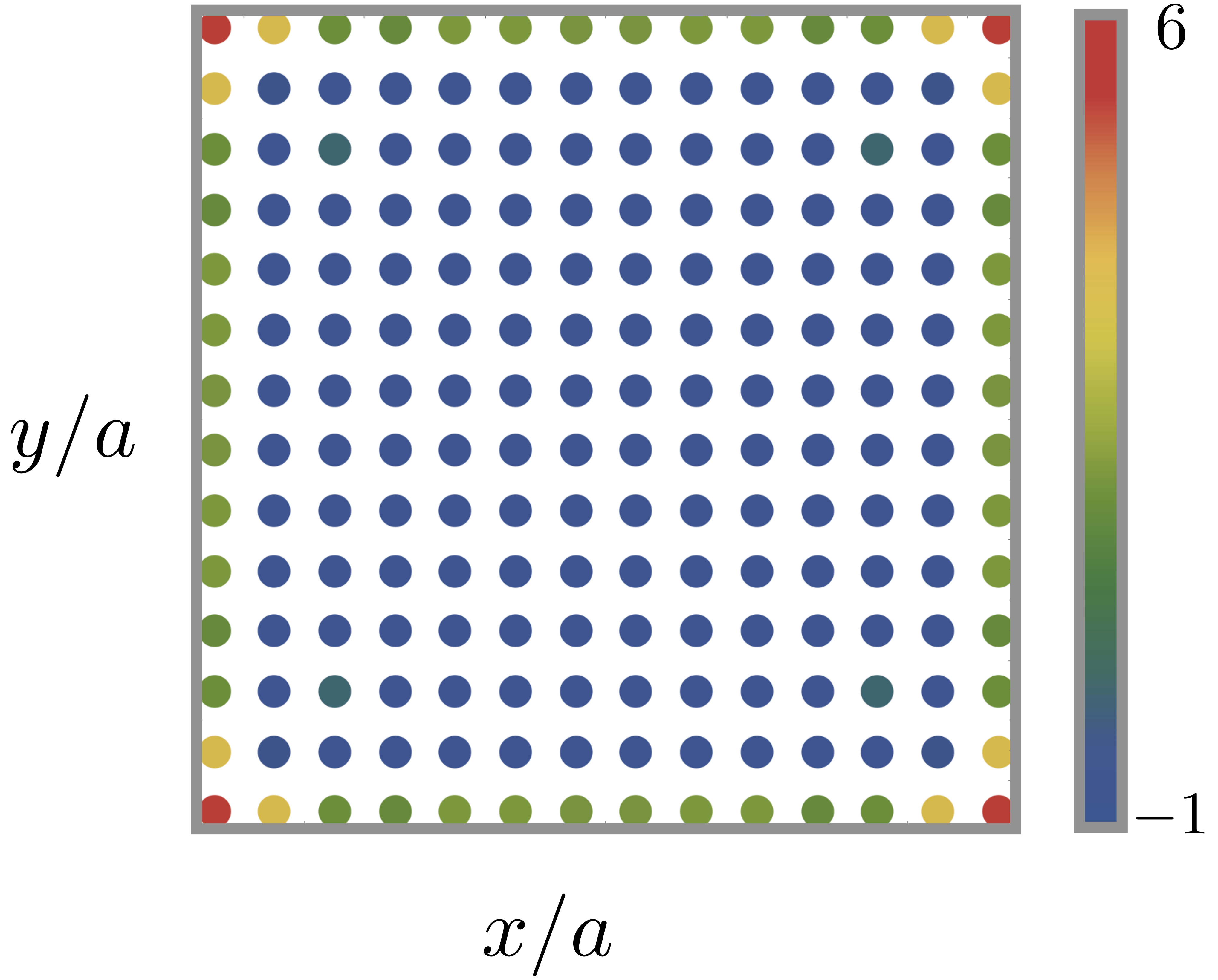
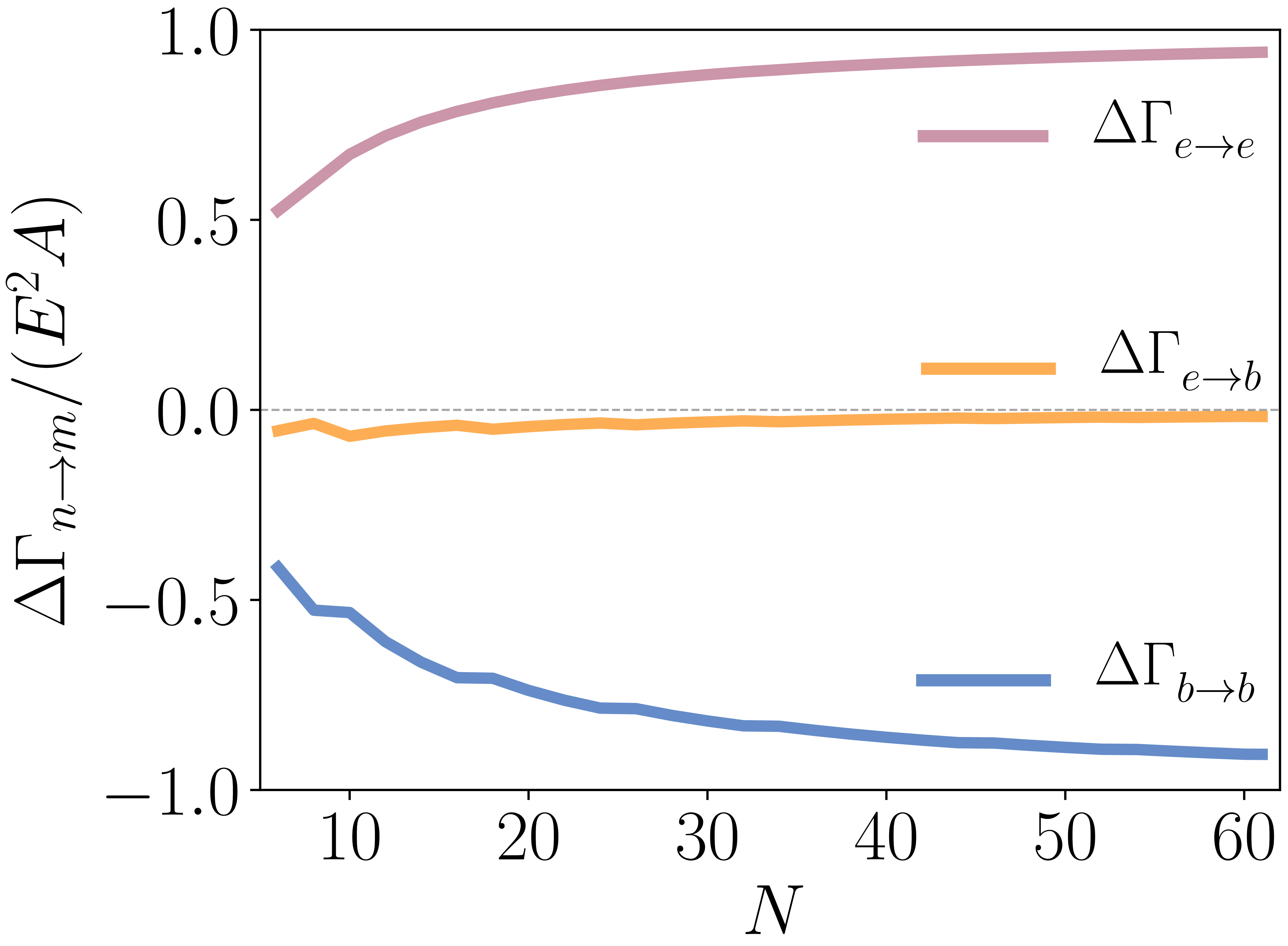


Energy space

$$\Delta\Gamma = \sum_{n,m\in\{e,b\}} \Gamma_{n\to m} = 0$$

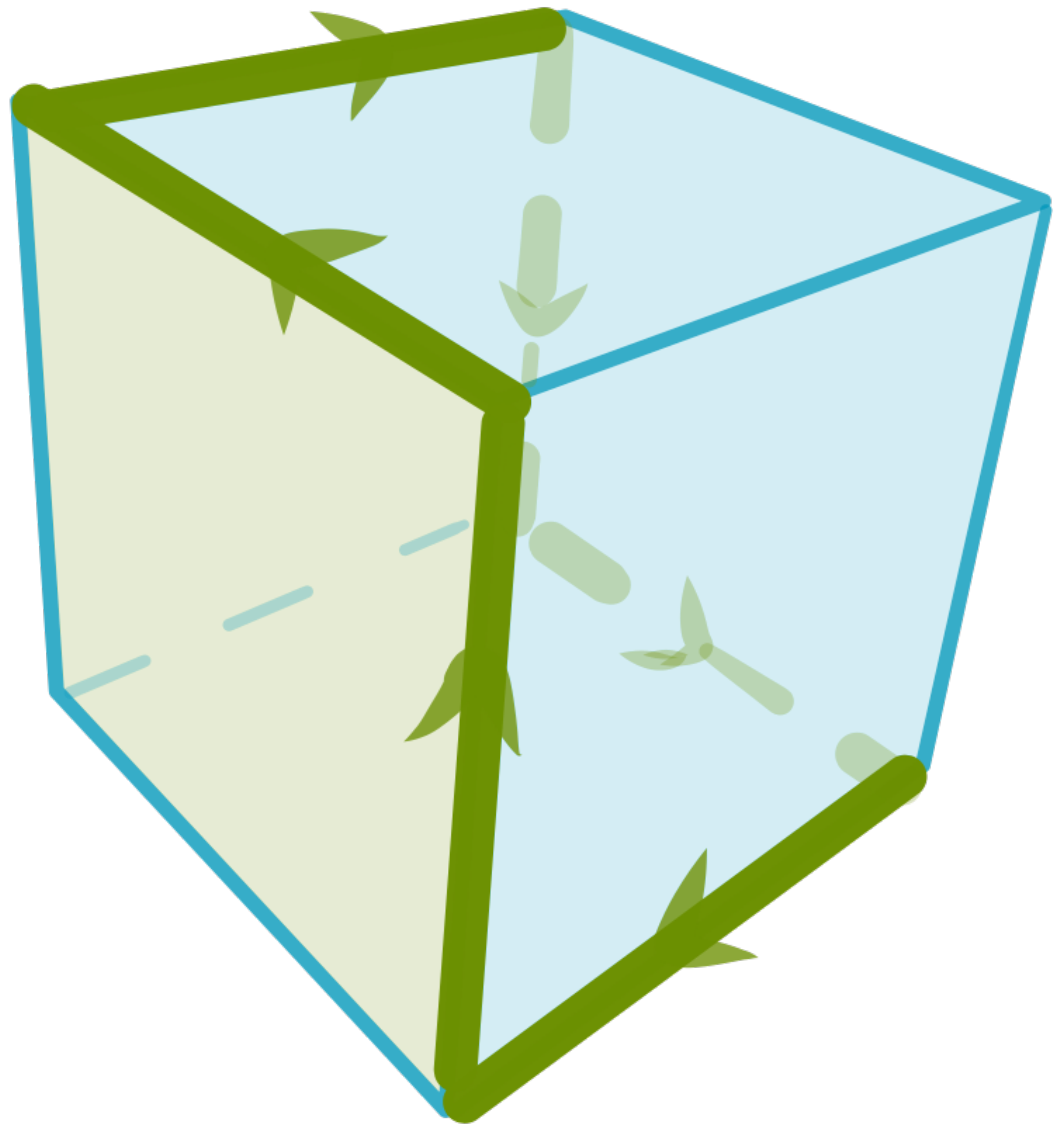


Calculated using Fermi's Golden Rule $\frac{\Gamma_{\pm}(\omega)}{2\pi E^2} = \sum_{n,m} \left| \langle m| (\hat{x} \pm i\hat{y}) |n\rangle \right|^2 \delta(E_m - E_n - \hbar\omega)$

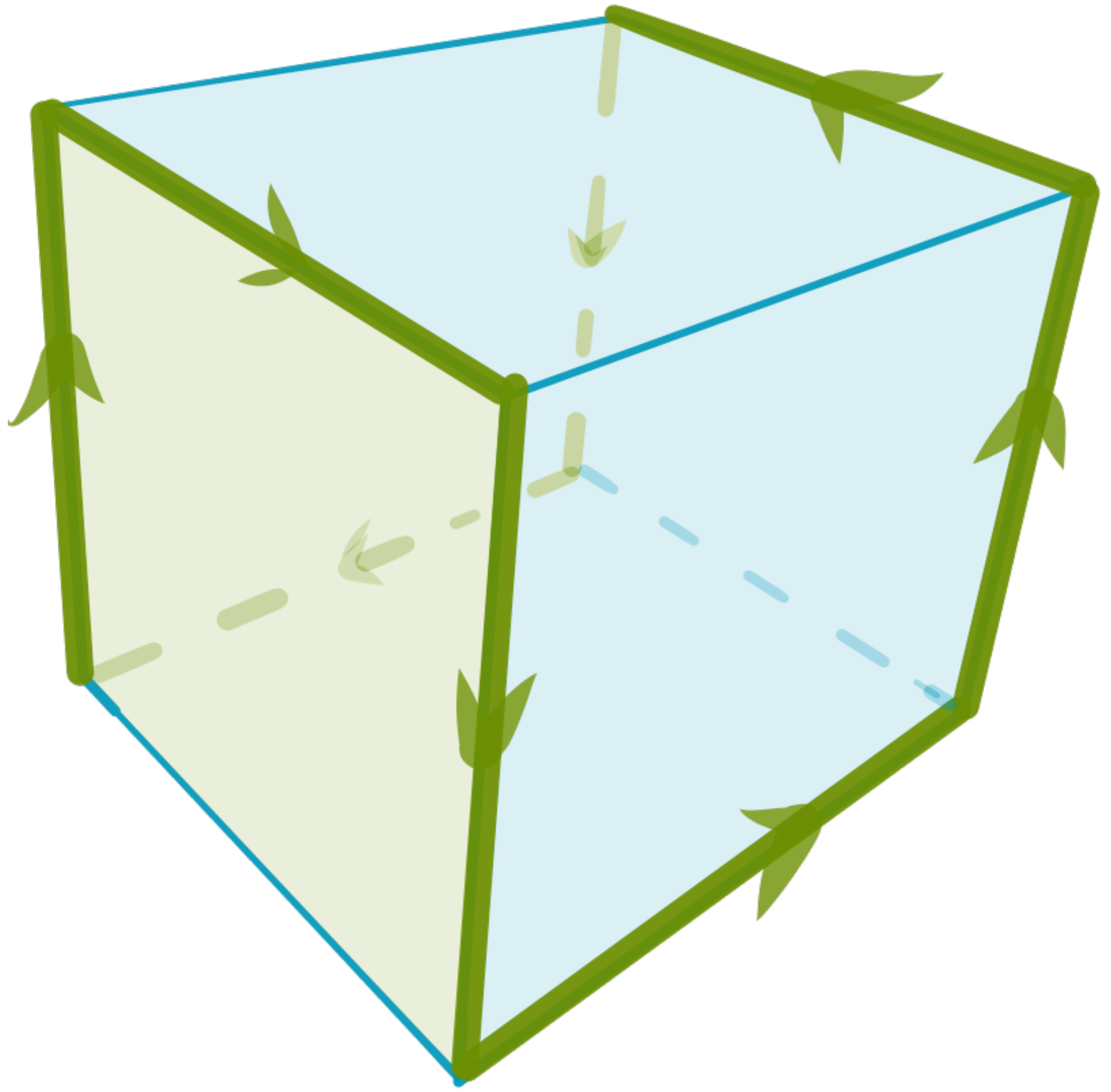
Model: F. Schindler et. al Science Advances (2018) + M. Ezawa Phys Rev. B (2018)

Chiral higher order topological insulators

$$H = H_{\mathrm{TI}} + H_{C_4^z \mathcal{T}} + H_{\mathrm{Zeeman}}$$

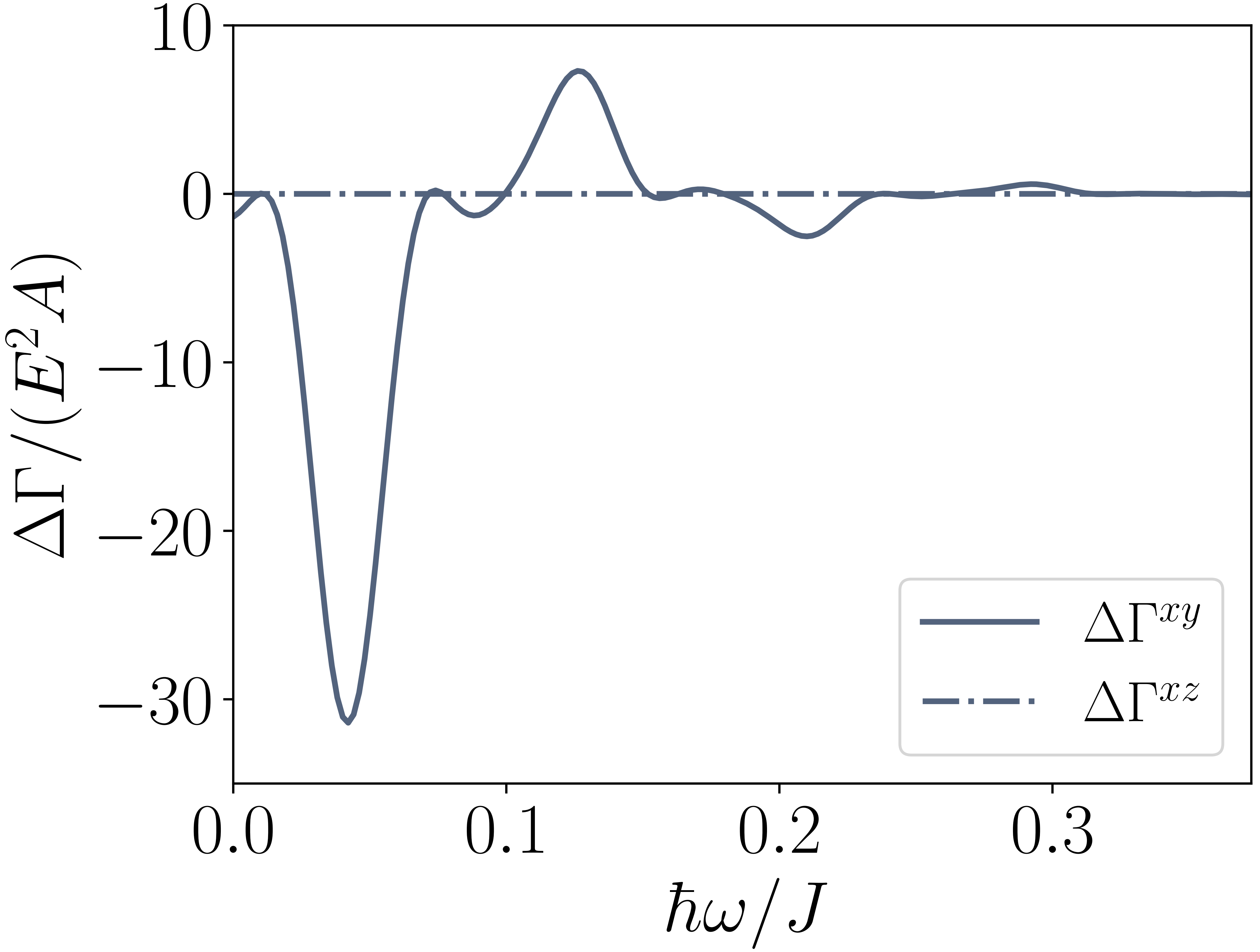


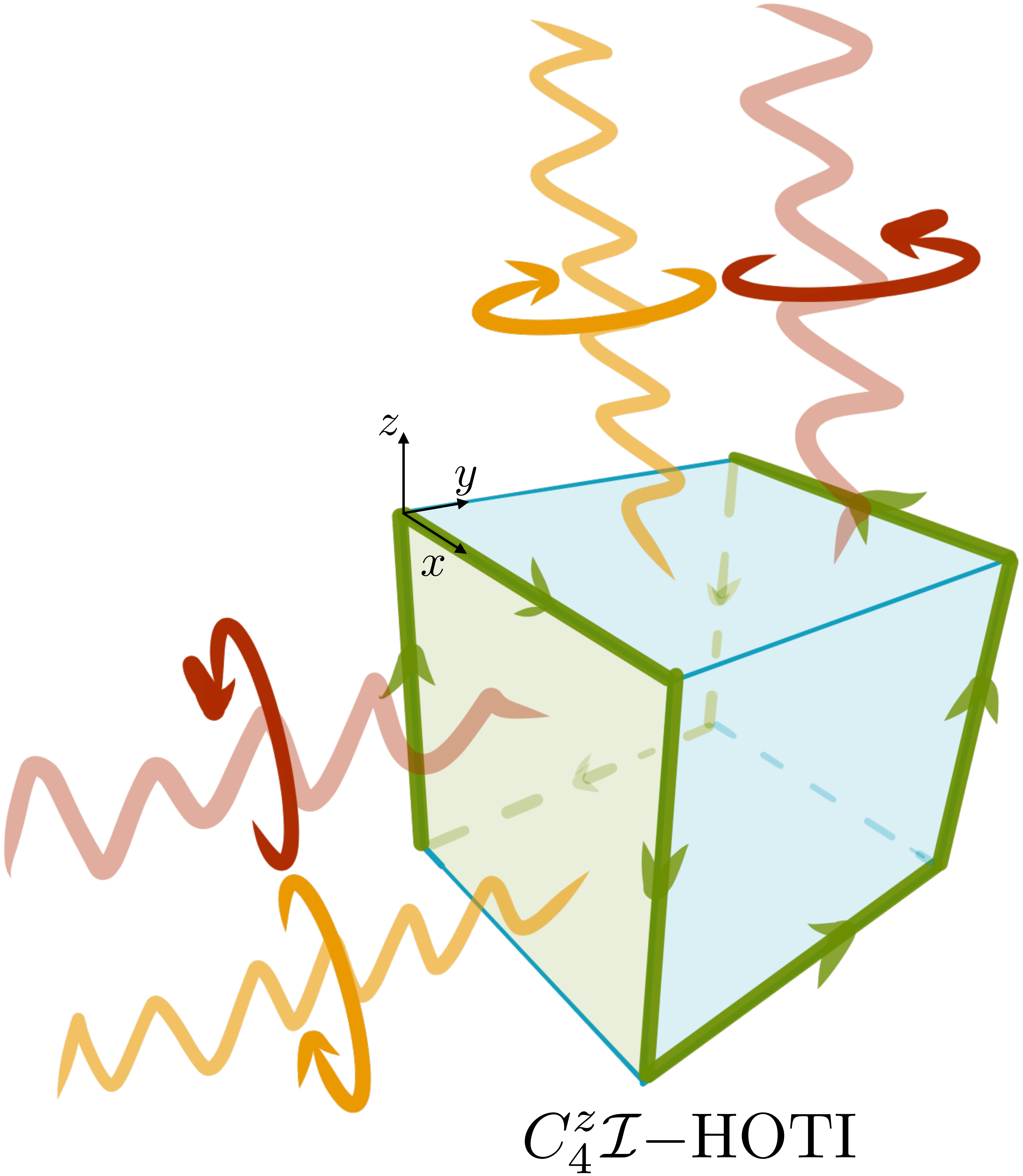
$\mathcal{I}$–HOTI



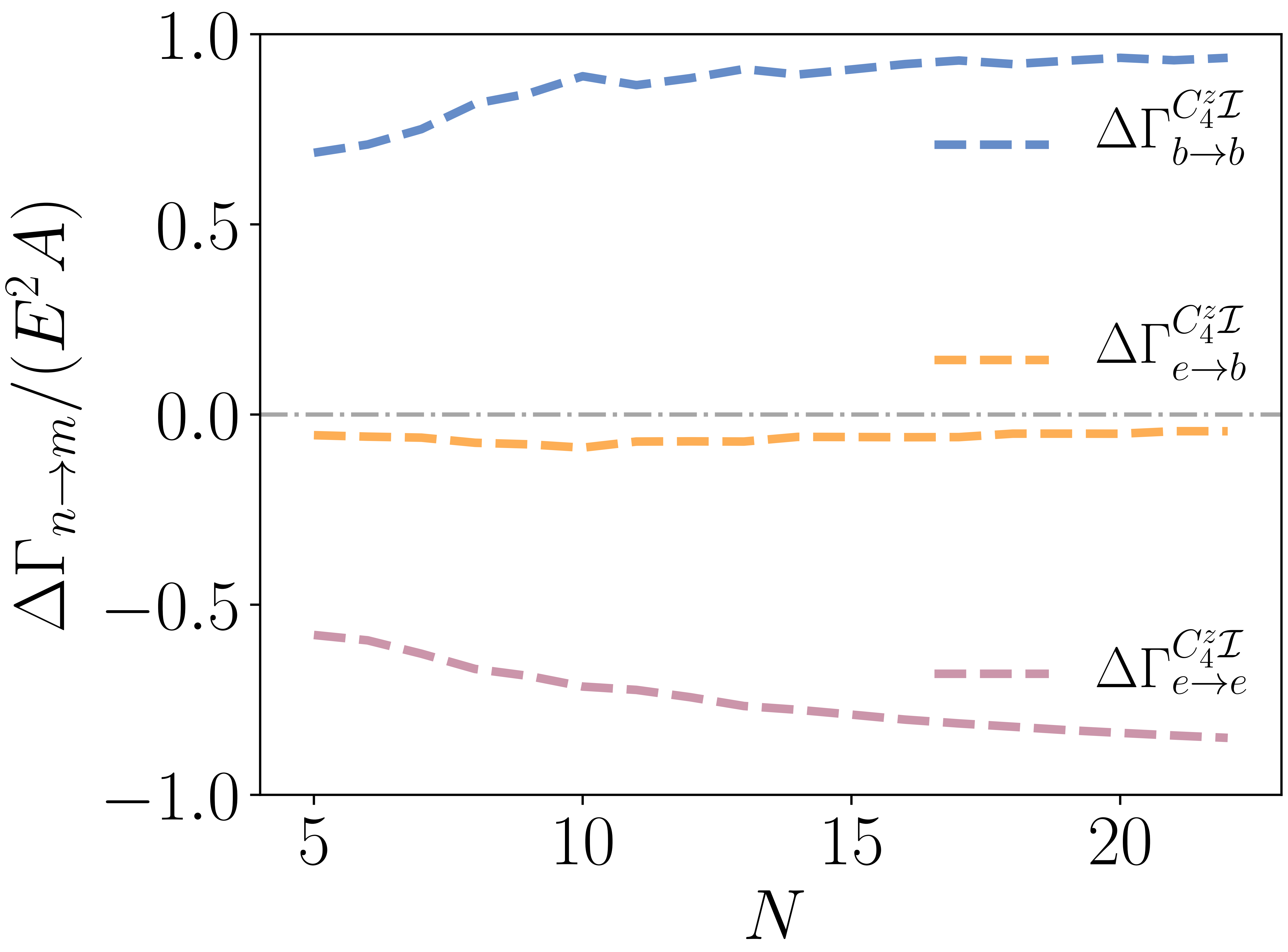
$C_4^z \mathcal{I}$–HOTI

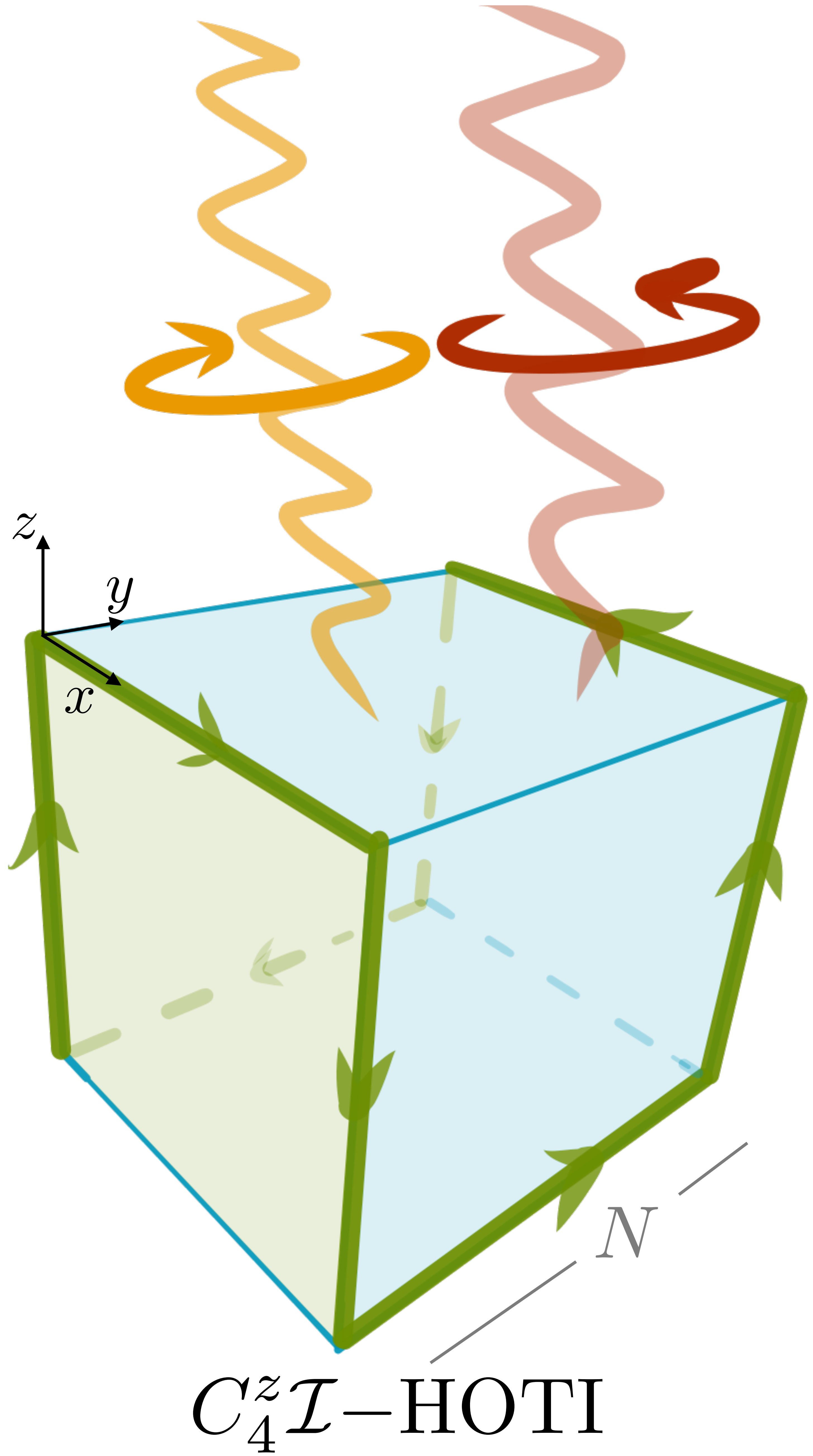
Quantized circular dichroism depends on irradiated surface





Quantized circular dichroism depends on irradiated surface





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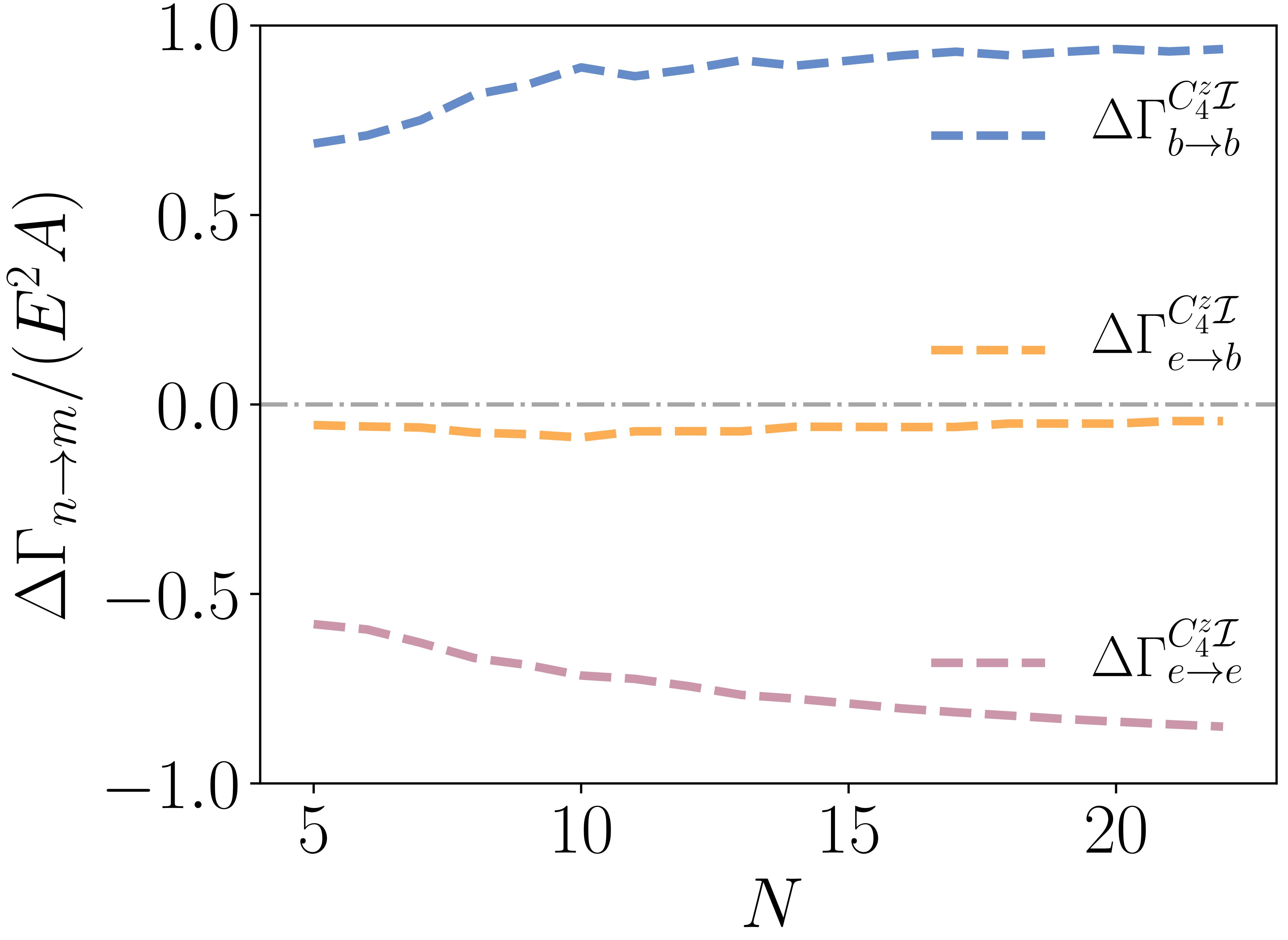
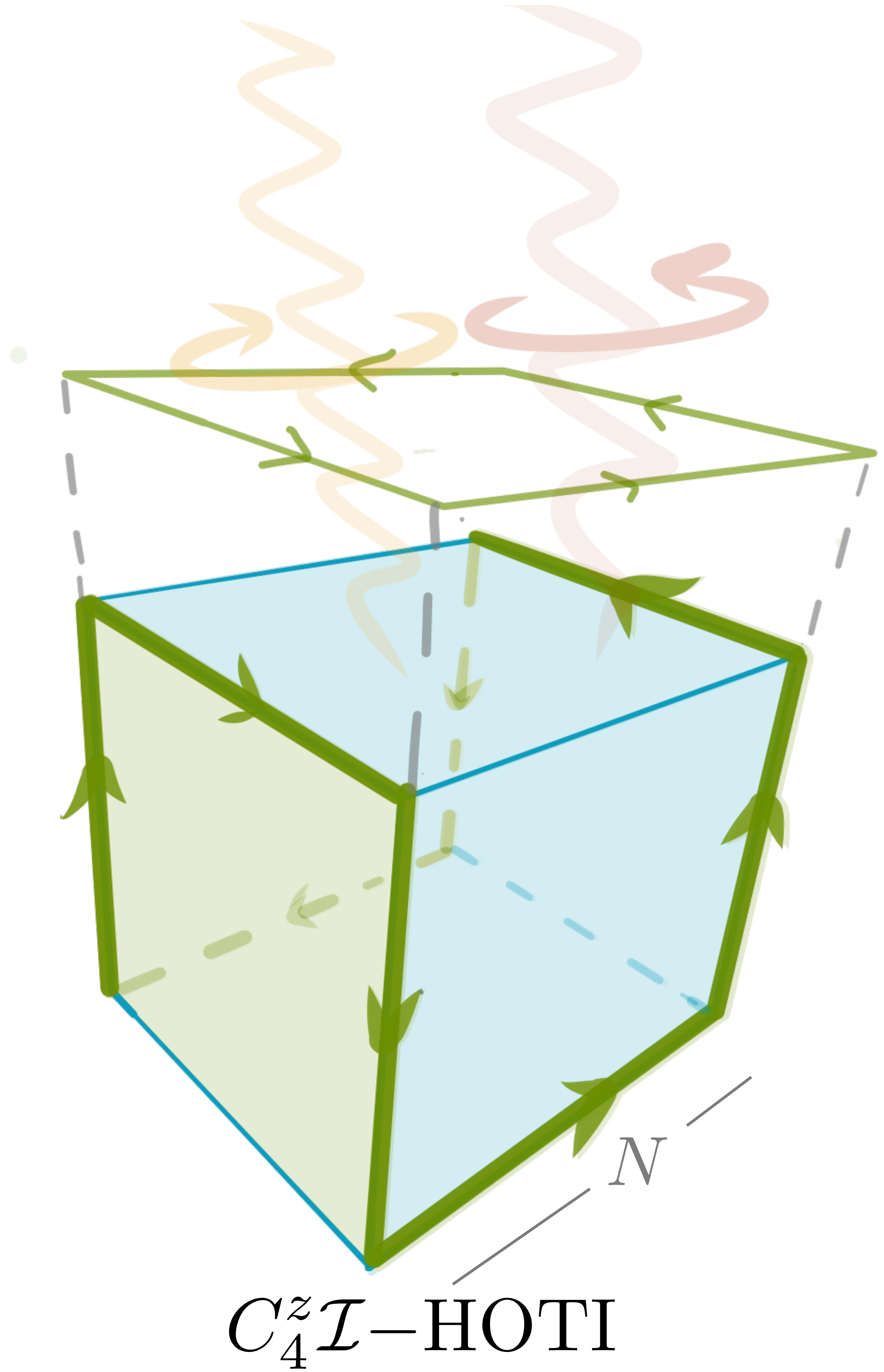
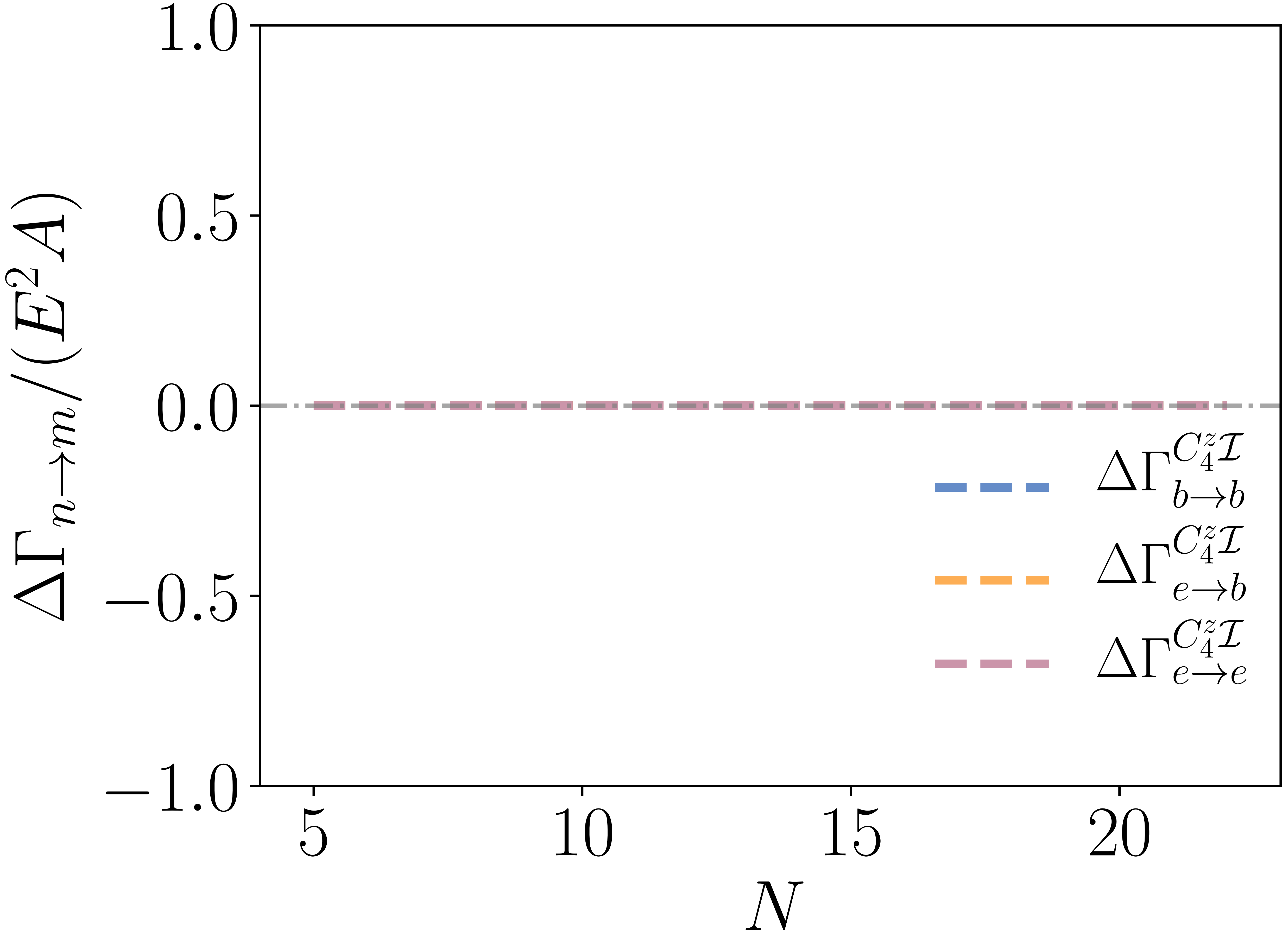
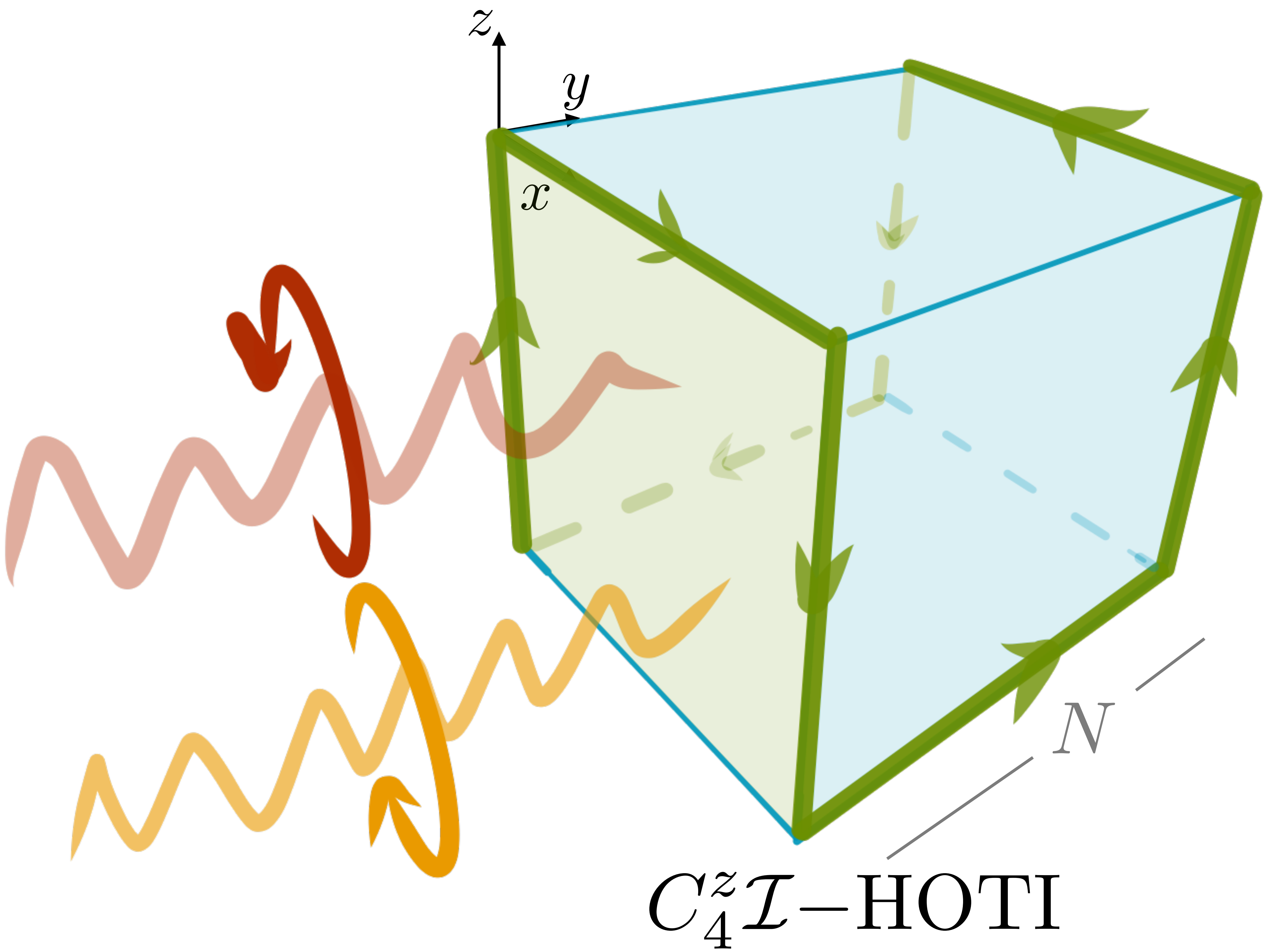




Quantized circular dichroism depends on irradiated surface





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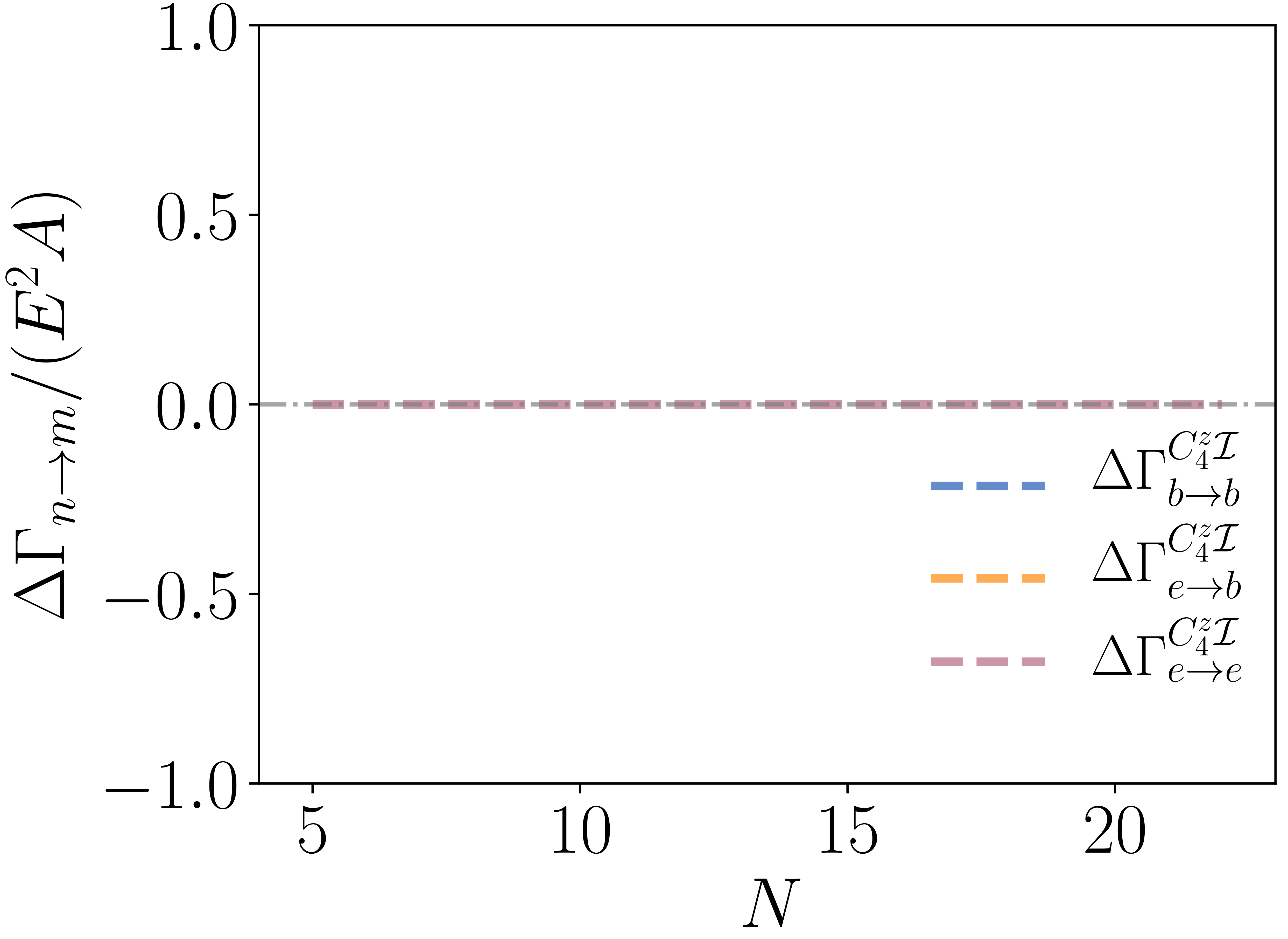
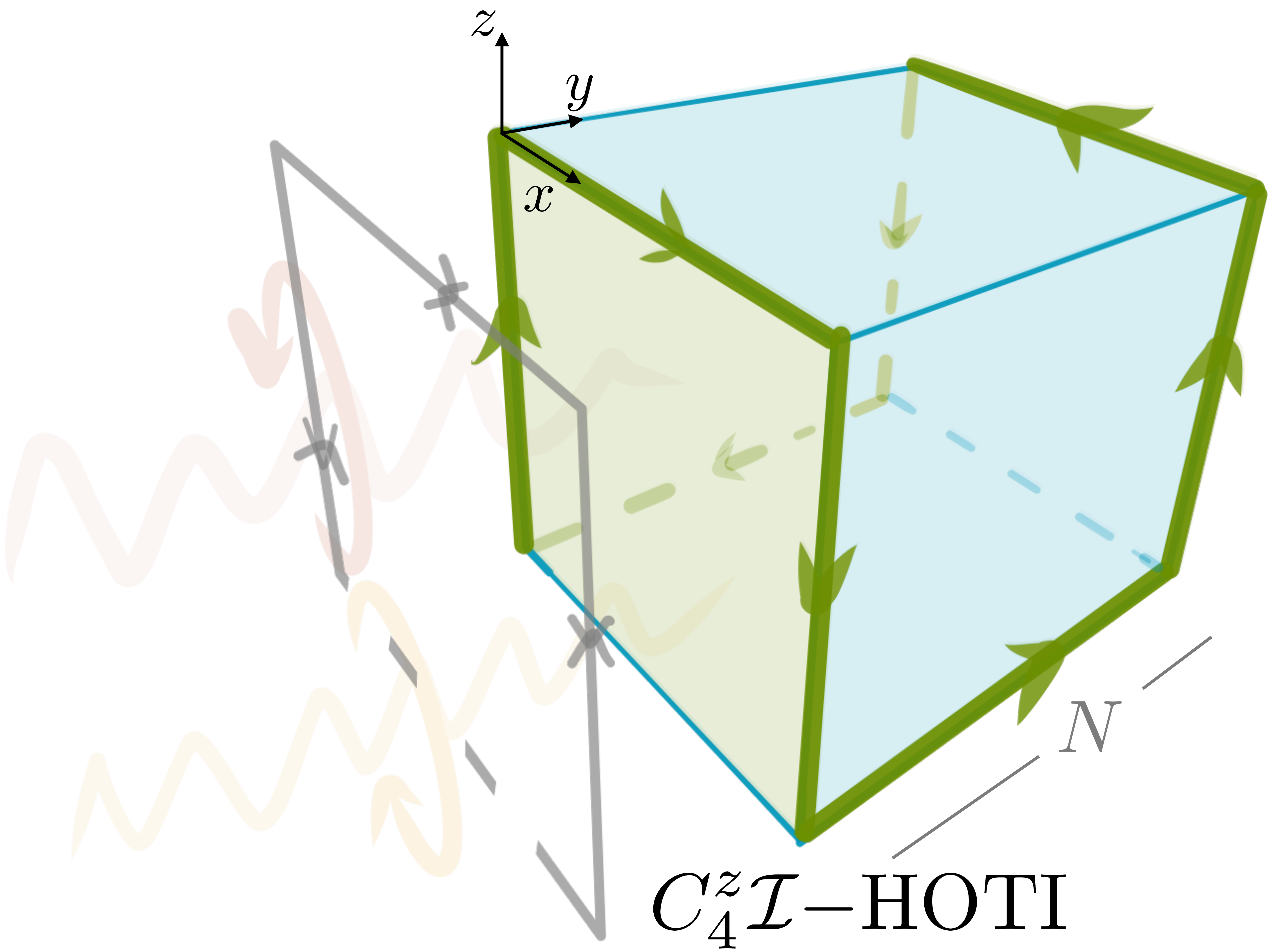
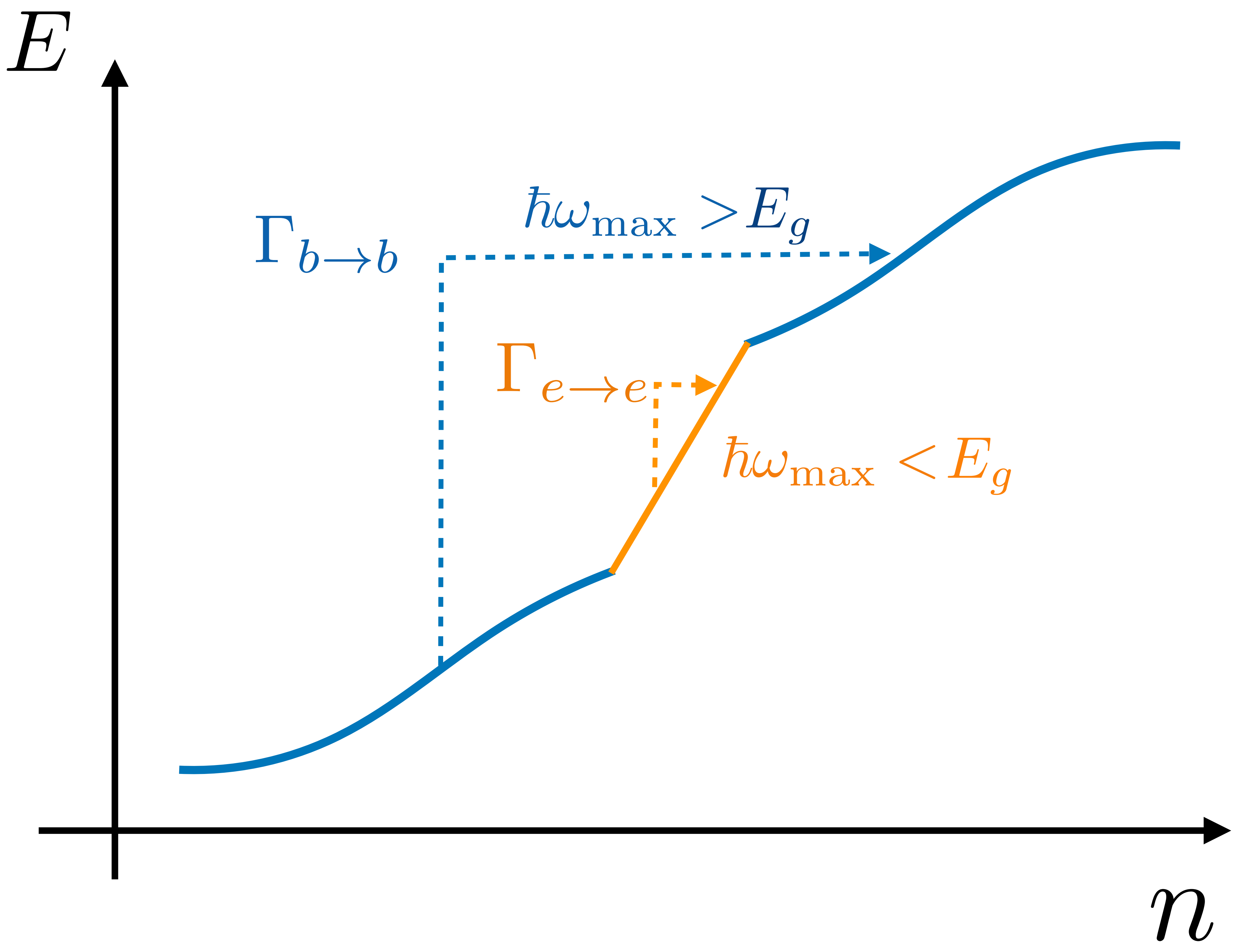




…but how can one measure quantization?

Edge state signal can be filtered out to measure quantization

$$\Delta\Gamma(\omega_{\max}) \equiv \int_0^{\omega_{\max}} d\omega(\Gamma_+(\omega) - \Gamma_-(\omega))/2.$$



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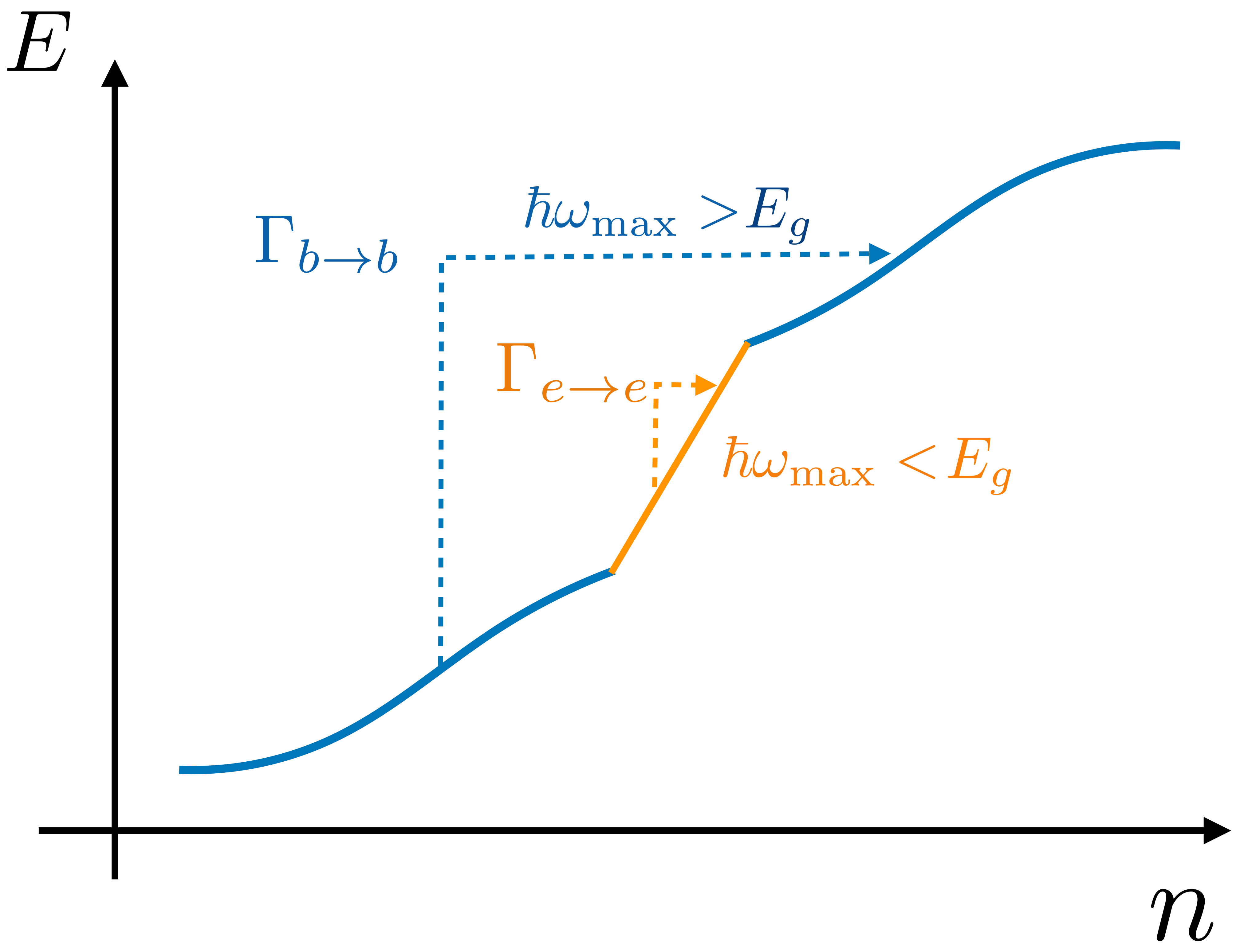
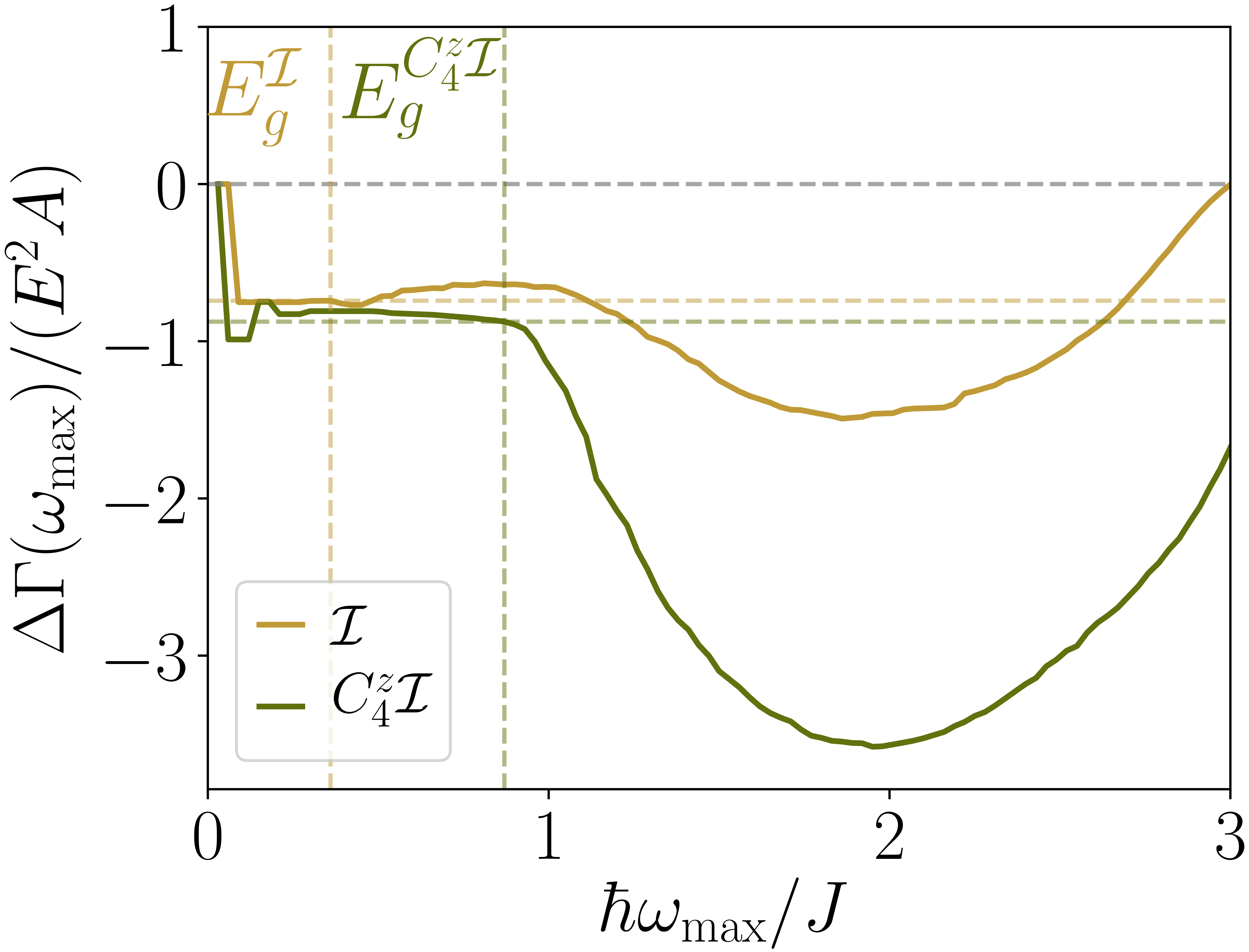
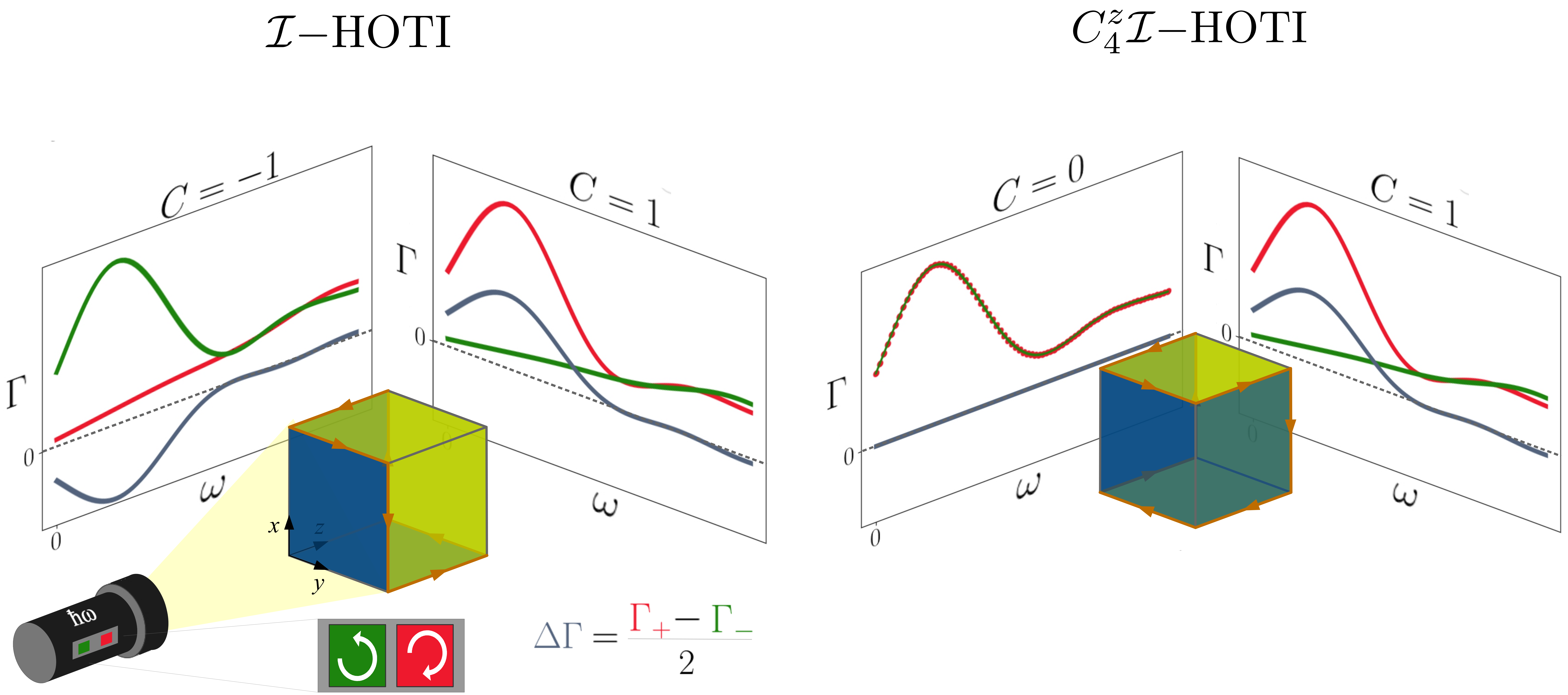


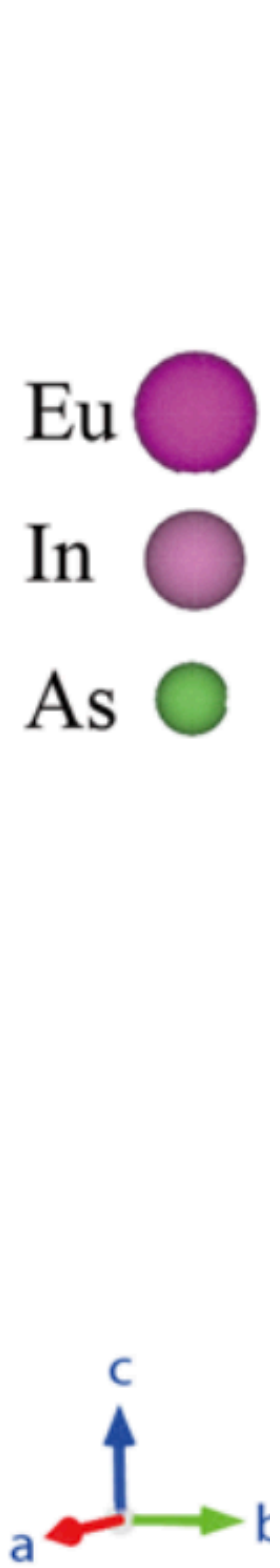


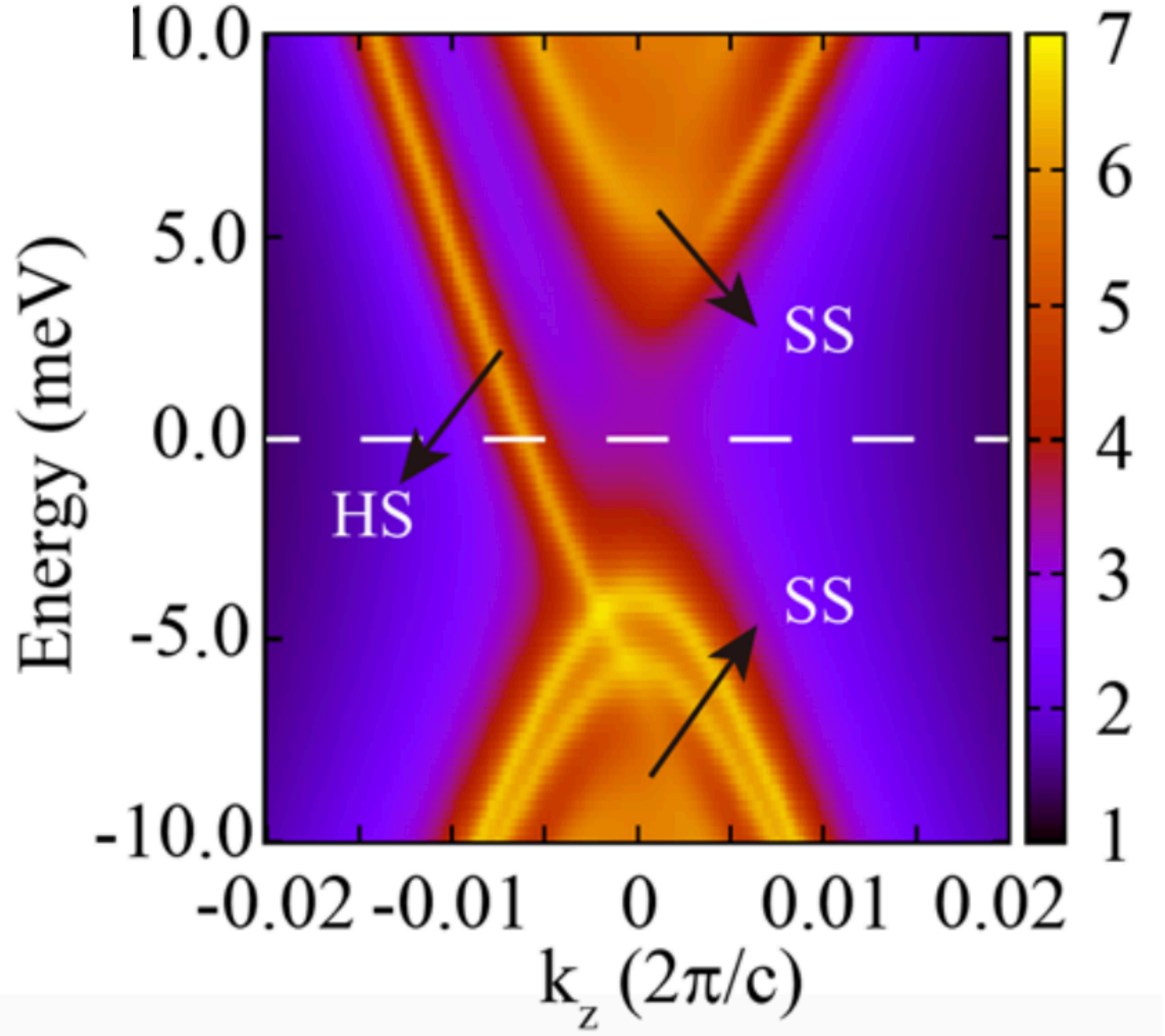
Quantized circular dichroism distinguishes chiral higher order topological insulators

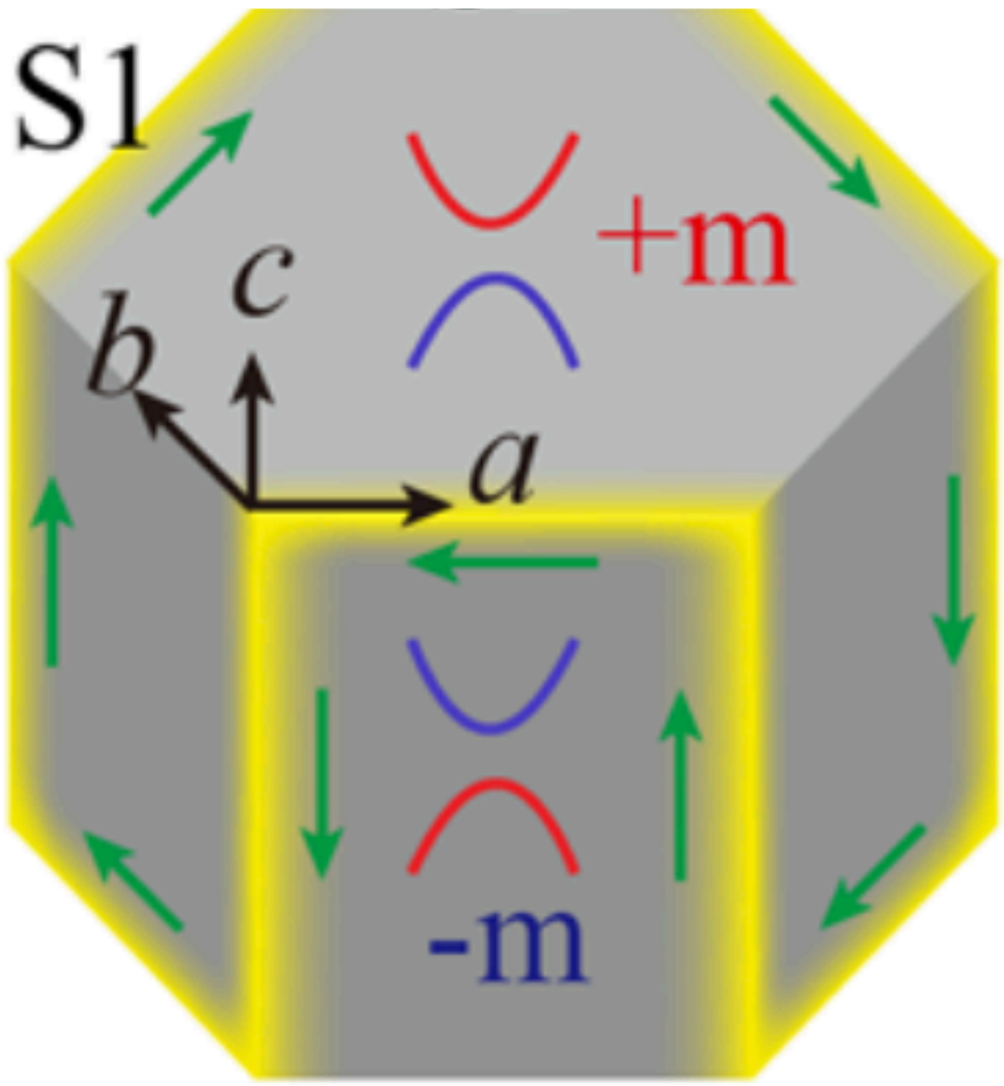


Experiments?

$EuIn_2As_2$



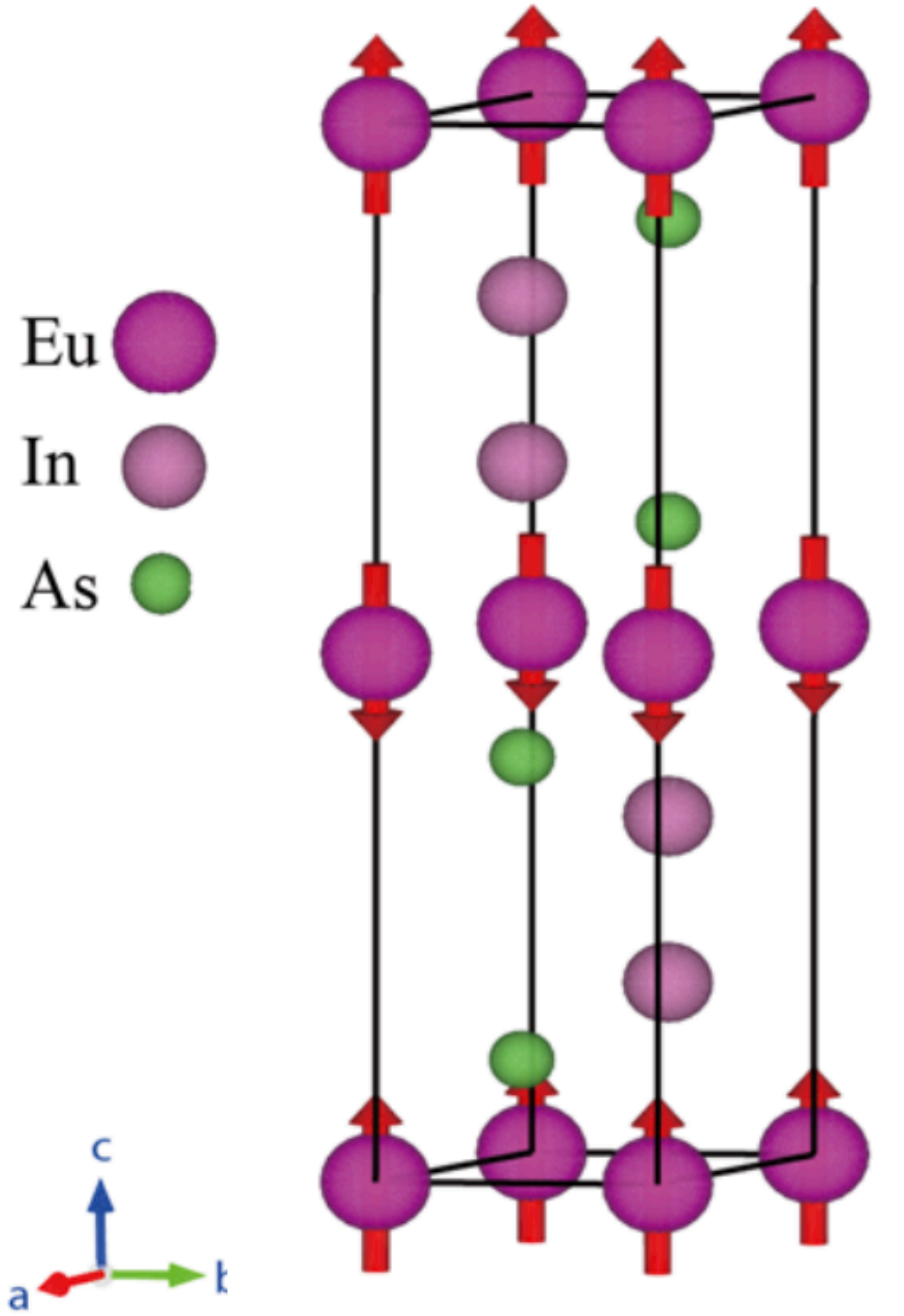


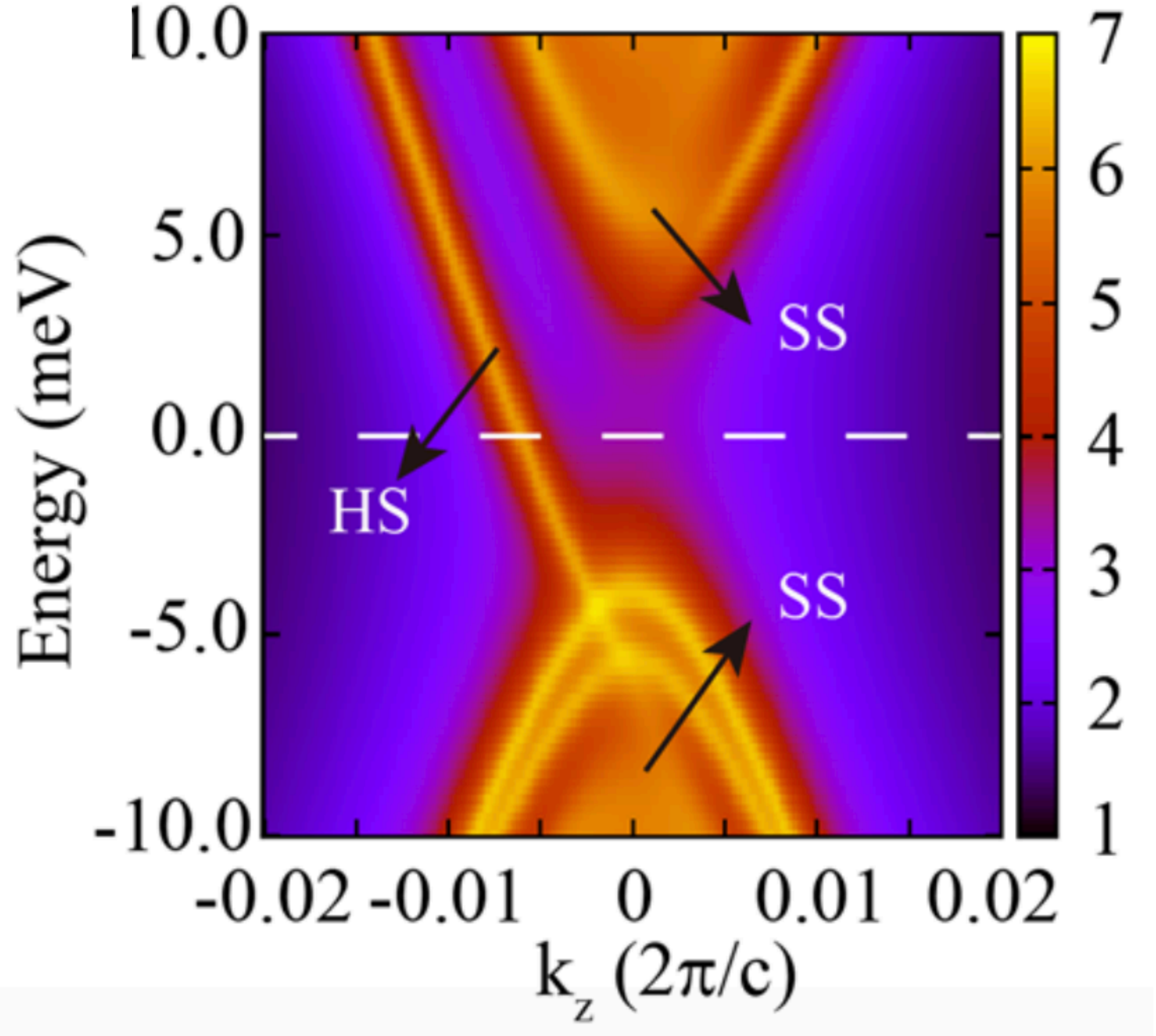


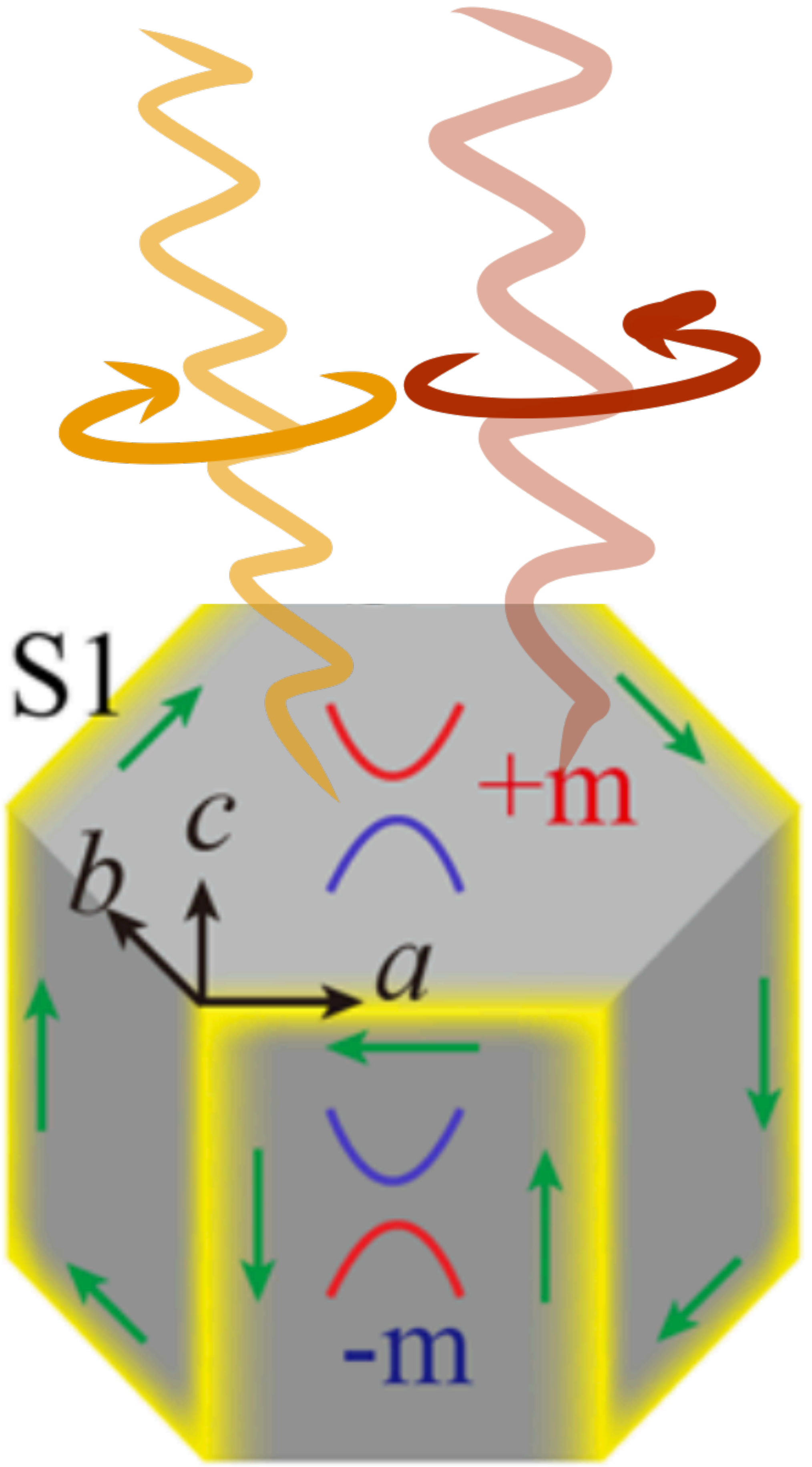
Y Xu et al. PRL 122, 256402 (2019)

Experiments?

$$EuIn_2As_2$$



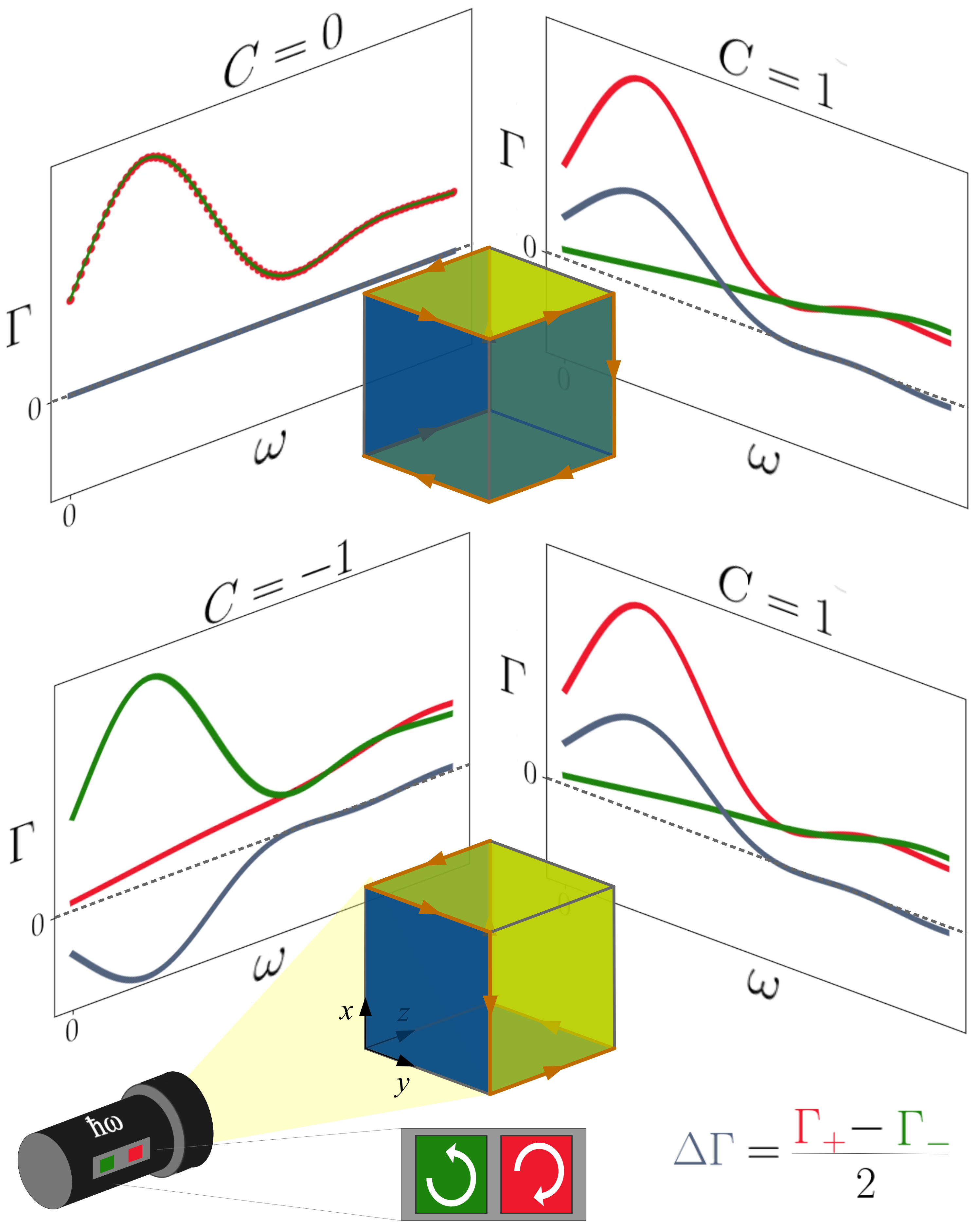




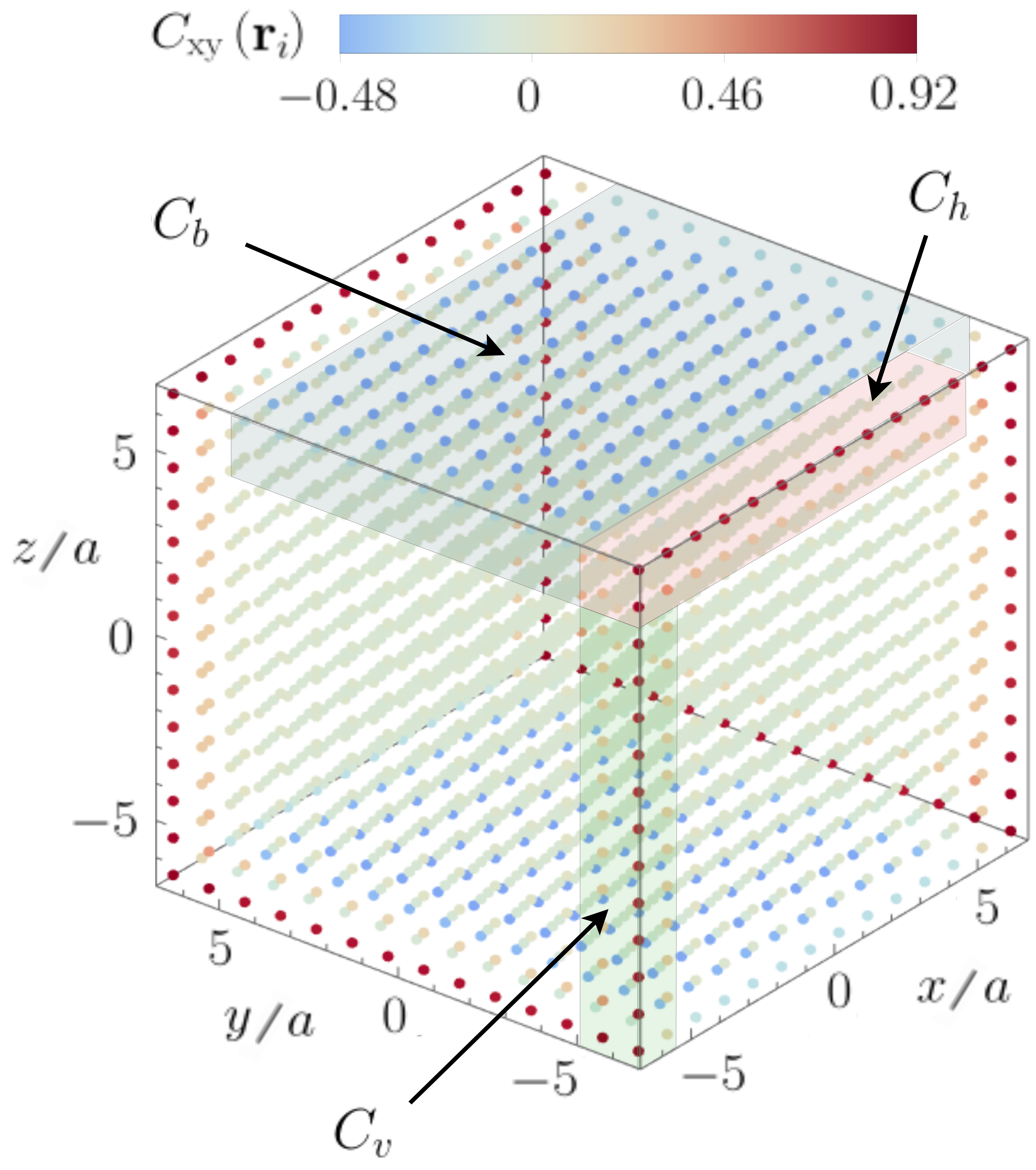
Y Xu et al. PRL 122, 256402 (2019)

Quantization in chiral higher order topological insulators

Quantized circular dichroism distinguishes HOTIs

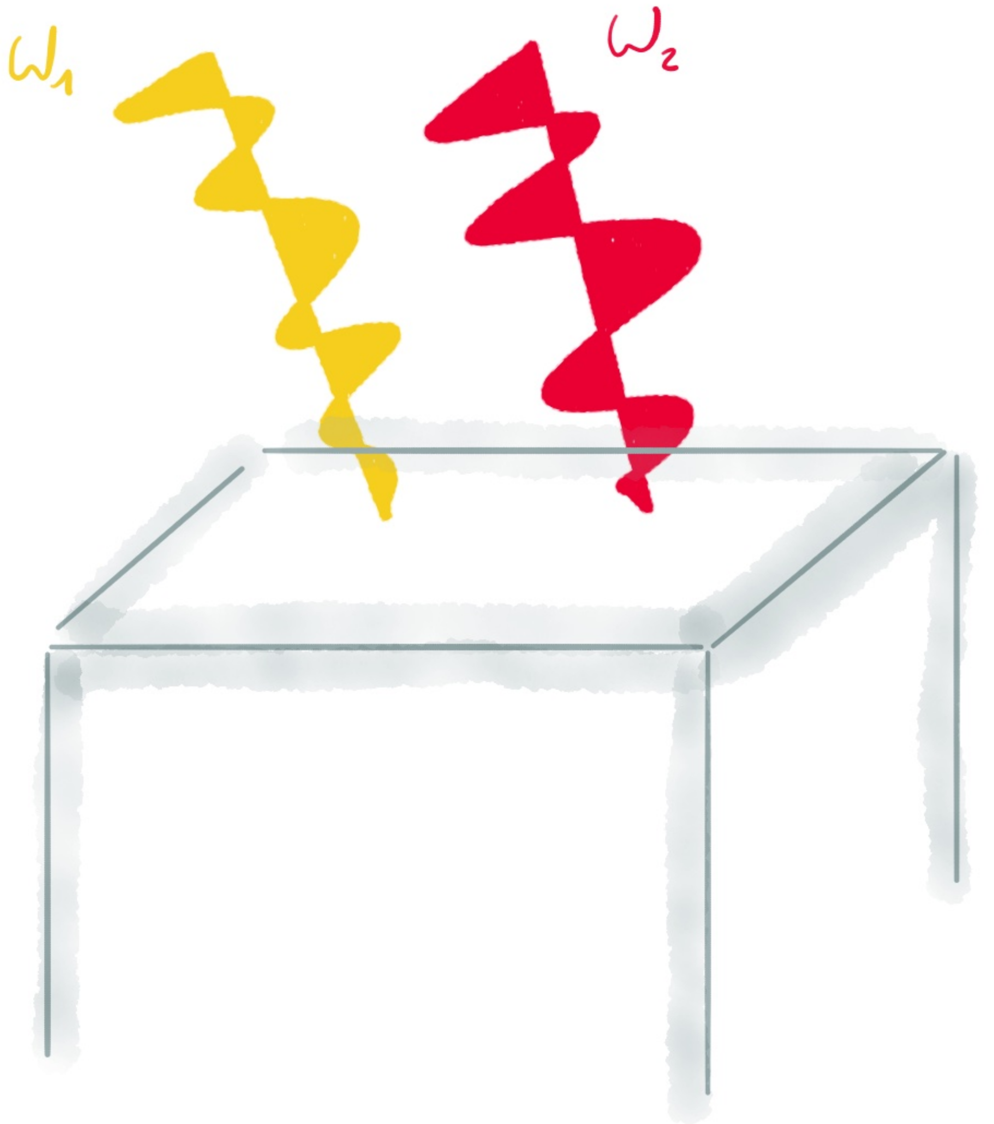


Non-universal surface average of the local Chern marker



Quantized optical responses in chiral insulators and metals

Difference frequency generation reveals quantization and a free carrier response



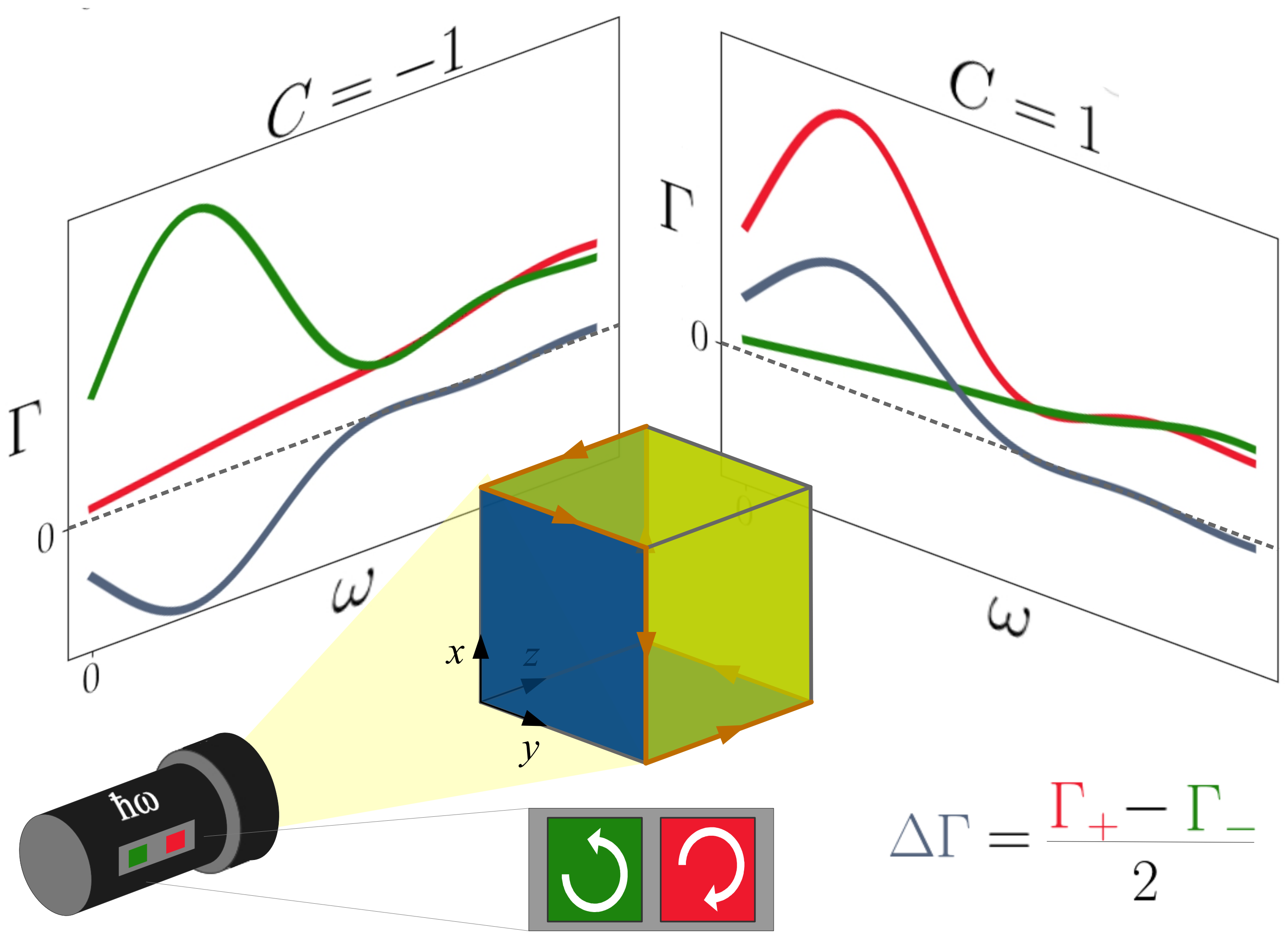
metallic

1907.02537.
(to appear in PRR)

Quantized circular dichroism distinguishes HOTIs

insulating

1906.05863
(to appear in PRL)



It is still worth looking for chiral Weyls to find exact quantization!

F. Flicker, F. de Juan, T. Morimoto, B. Bradlyn, M. Vergniory, AGG PRB (2018)

F. de Juan, AGG, T. Morimoto, J. E. Moore Nat. Comm (2017)

M.A. Sanchez-Martinez, F. de Juan, AGG PRB (2019)

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$$\gamma_{ab} = \epsilon^{abc}\rho^{dbc}$$