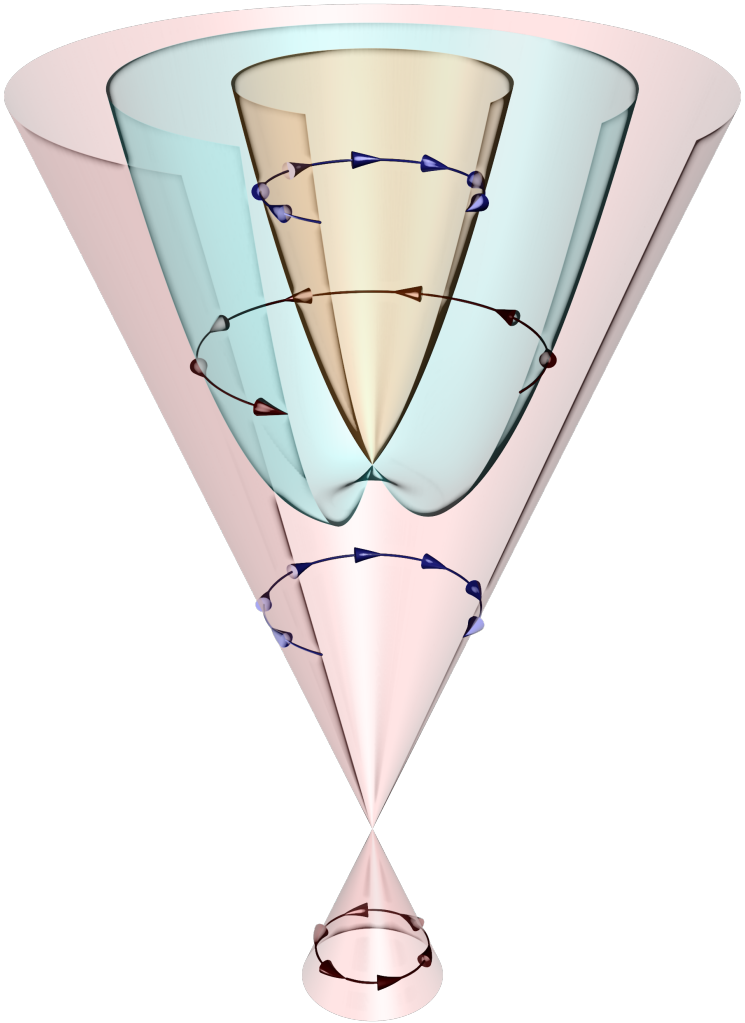

FLOQUET ENGINEERING OF DIRAC CONES ON THE SURFACE OF A TOPOLOGICAL INSULATOR

ÁLVARO DÍAZ FERNÁNDEZ


FRANCE
GALICIA
Oviedo
Bilbao
PYRENNEES
Zaragoza
ARAGON
CATALONIA
Barcelona
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Salamanca
Madrid
PORTUGAL
EXTREMADURA
Valencia
N
W
E
S
Cordoba
Granada
ANDALUSIA
SPAIN




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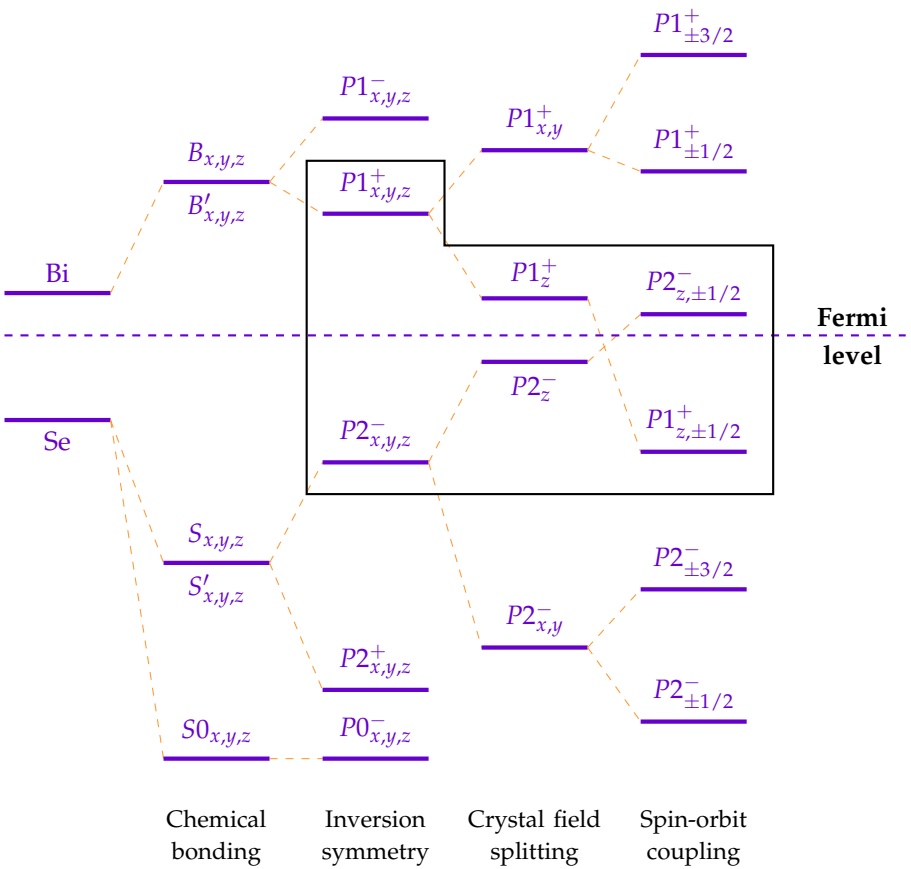
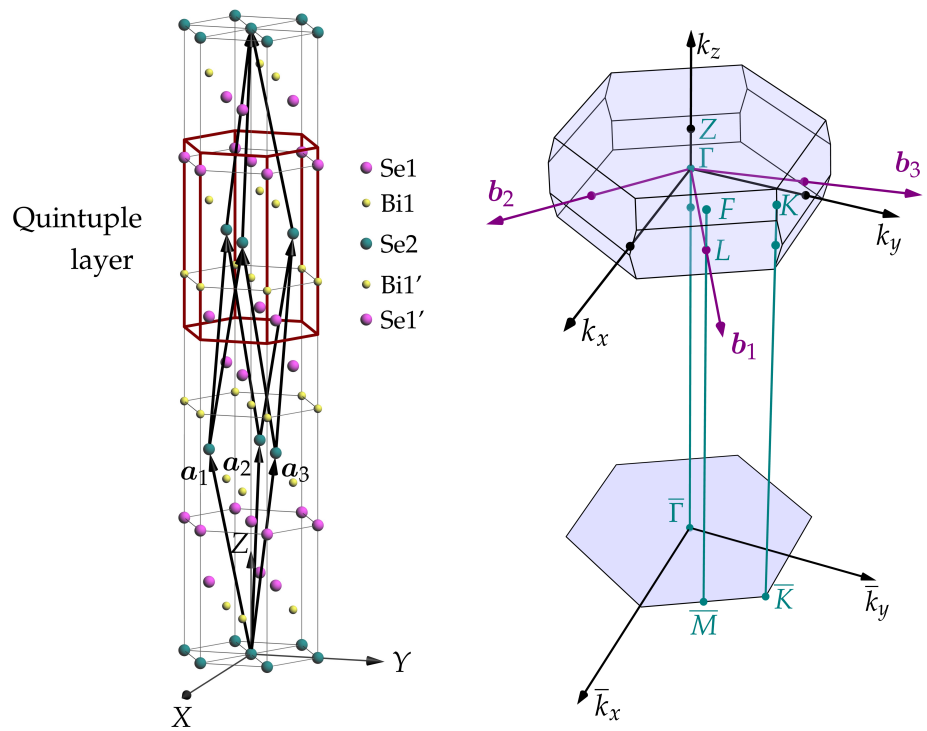
Bi_2Se_3

H Zhang *et al.*, *Nat. Phys.* **5**, 438 (2009)
CX Liu *et al.*, *PRB* **82**, 045122 (2010)





Parity inversion due to SOC at Γ−point

Bulk

Hamiltonian in orbital-spin basis $\{\tau, \sigma\}$

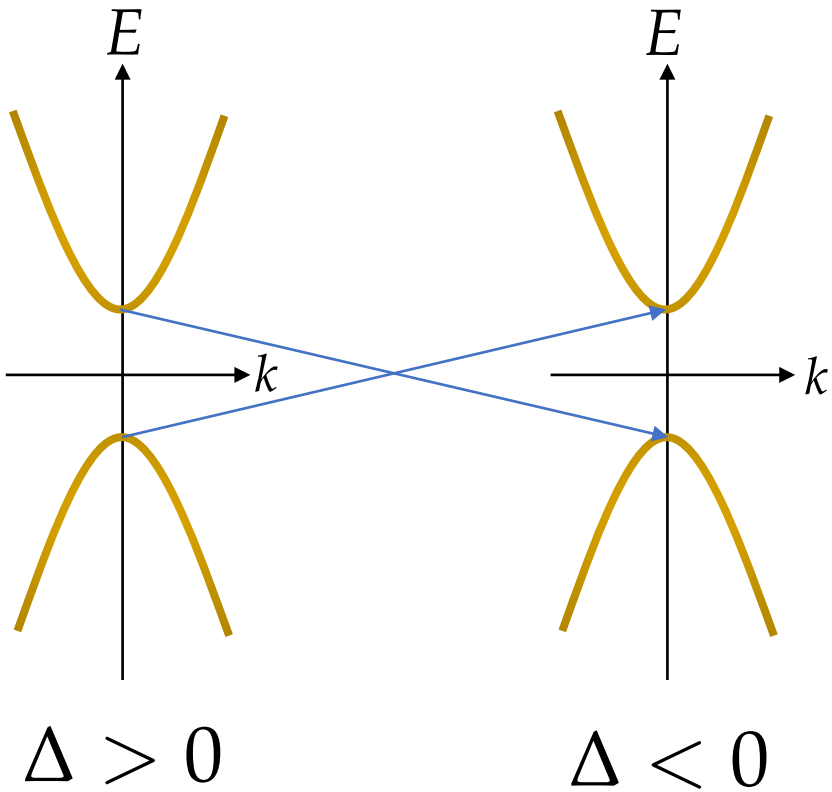
$$\mathcal{H} = v_F \boldsymbol{\alpha} \cdot \boldsymbol{p} + \Delta\beta$$

Massive Dirac fermions in the bulk

$$E = \pm\sqrt{(v_F k)^2 + \Delta^2}$$

$\mathbb{Z}_2$ **topological index**

$$\nu = \mathrm{sgn}(\Delta)$$



Surface

Topological boundary

$$\mathcal{H} = v_F \boldsymbol{\alpha} \cdot \boldsymbol{p} + \Delta(z)\beta \qquad \Delta(-\infty)\Delta(\infty) < 0$$

Massless Dirac fermions at the boundary

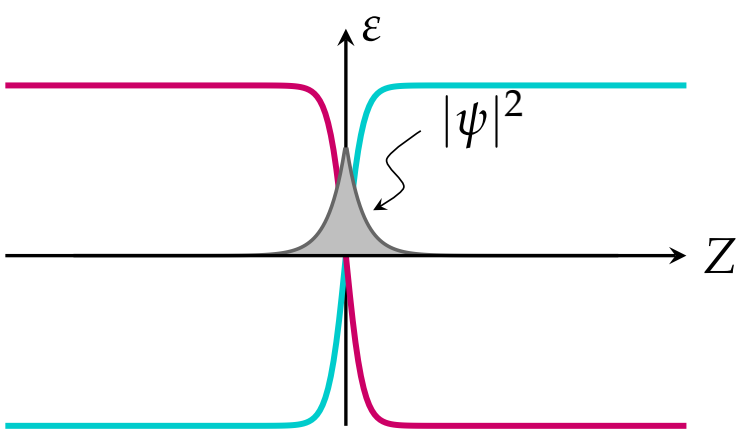
$$E = \pm v_F k_\perp$$

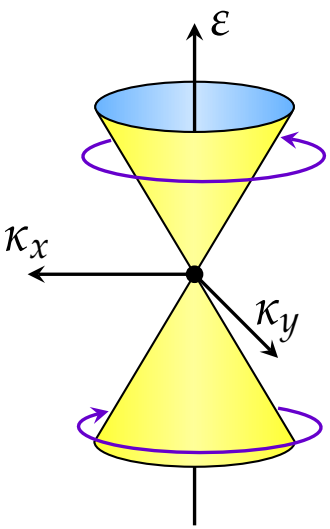
Localization length

$$d = \frac{v_F}{\Delta}$$

Surface effective Hamiltonian

$$\mathcal{H}_S = v_F (\boldsymbol{\sigma} \times \boldsymbol{k})_z$$





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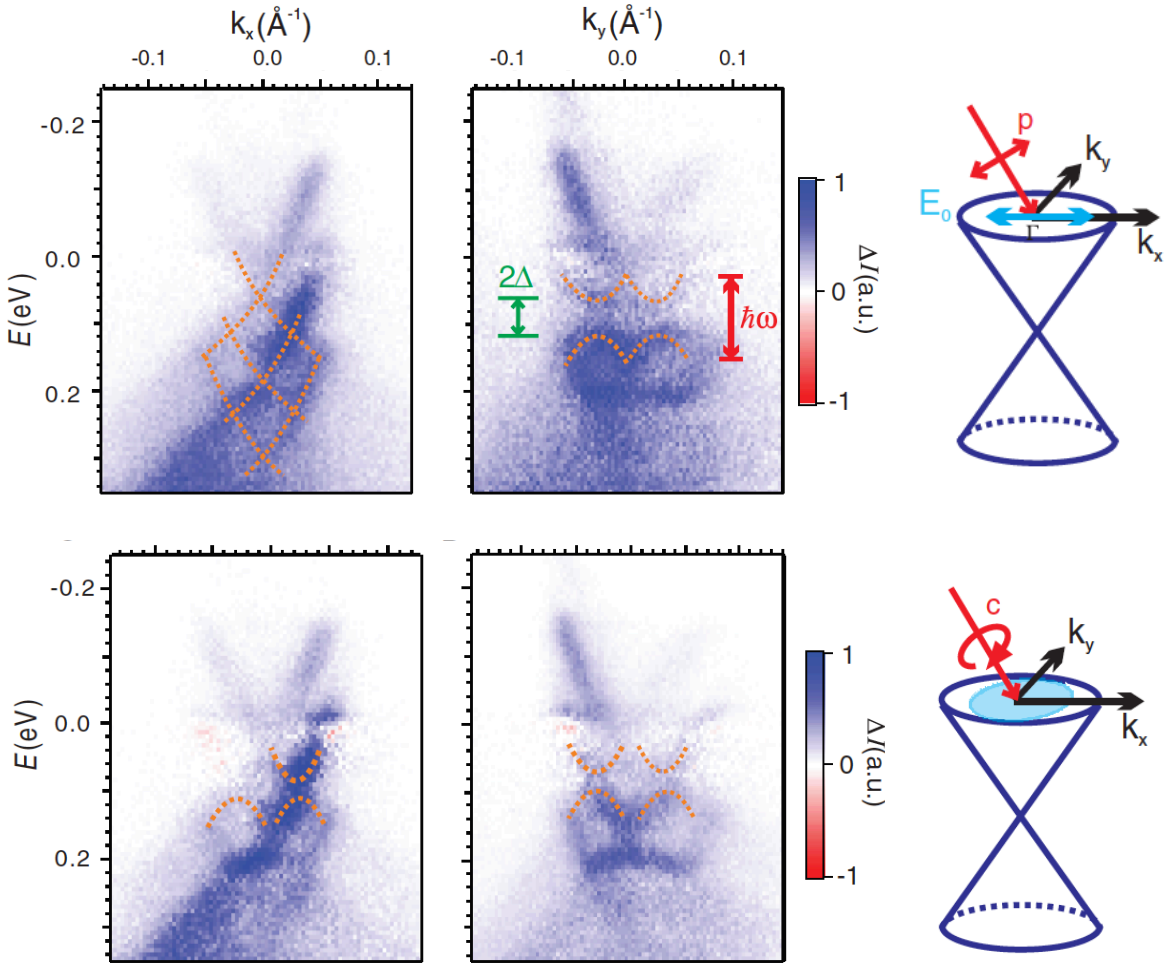

Periodic driving

$$\boldsymbol{k} \to \boldsymbol{k} + \boldsymbol{A}(t)$$

Circularly polarized light

$$\mathcal{H}_S = (\boldsymbol{\sigma} \times \boldsymbol{k})_z \pm \left(\frac{f}{\omega}\right)^2 \sigma_z$$

T Kitagawa *et al.*, *PRB* **84**, 235108 (2011)
NH Lindner *et al.*, *Nat. Phys.* **7**, 490 (2011)
P Delplace *et al.*, *PRB* **88**, 245422 (2013)
SV Syzranov *et al.*, *PRB* **88**, 241112 (2013)
G Usaj *et al.*, *PRB* **90**, 115423 (2014)
YH Wang *et al.*, *Science* **342**, 453 (2013)

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Model

Dirac Hamiltonian

$$\mathcal{H} = \boldsymbol{\alpha} \cdot \boldsymbol{\kappa} + \beta \Delta(z)$$

Minimal coupling

$$\boldsymbol{\kappa} \to \boldsymbol{\kappa} + \boldsymbol{A}(t)$$

Small-sized sample (disregard spatial dependence)

$$\boldsymbol{A}(t) = \boldsymbol{a} e^{\mathrm{i}\,\omega t} + \boldsymbol{a}^* e^{-\mathrm{i}\,\omega t}$$

$$a_j = \frac{f_j}{2\omega} e^{\mathrm{i}\,\theta_j}$$

Approach

Floquet Theory

$$\boldsymbol{\Psi}(\boldsymbol{r},t) = e^{-i\varepsilon t} e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \boldsymbol{\Phi}(z,t) \qquad \boldsymbol{\Phi}(z,t) = \sum_{l=-\infty}^{\infty} \boldsymbol{\varphi}_l(z) e^{-il\omega t}$$

Result similar to a NN-tight-binding in Floquet index

$$\varepsilon \boldsymbol{\varphi}_l(z) = \left[\boldsymbol{\alpha}\cdot\boldsymbol{k} + \beta\Delta(z) - l\omega \mathbf{1}_4\right] \boldsymbol{\varphi}_l(z) + J\boldsymbol{\varphi}_{l+1}(z) + J^\dagger \boldsymbol{\varphi}_{l-1}(z)$$

Hoppings

$$J = \boldsymbol{\alpha}\cdot\boldsymbol{a} \qquad a_j = \frac{f_j}{2\omega} e^{\mathrm{i}\,\theta_j}$$

Non-Hermitian hoppings for circularly polarized-light: TR-symmetry breaking

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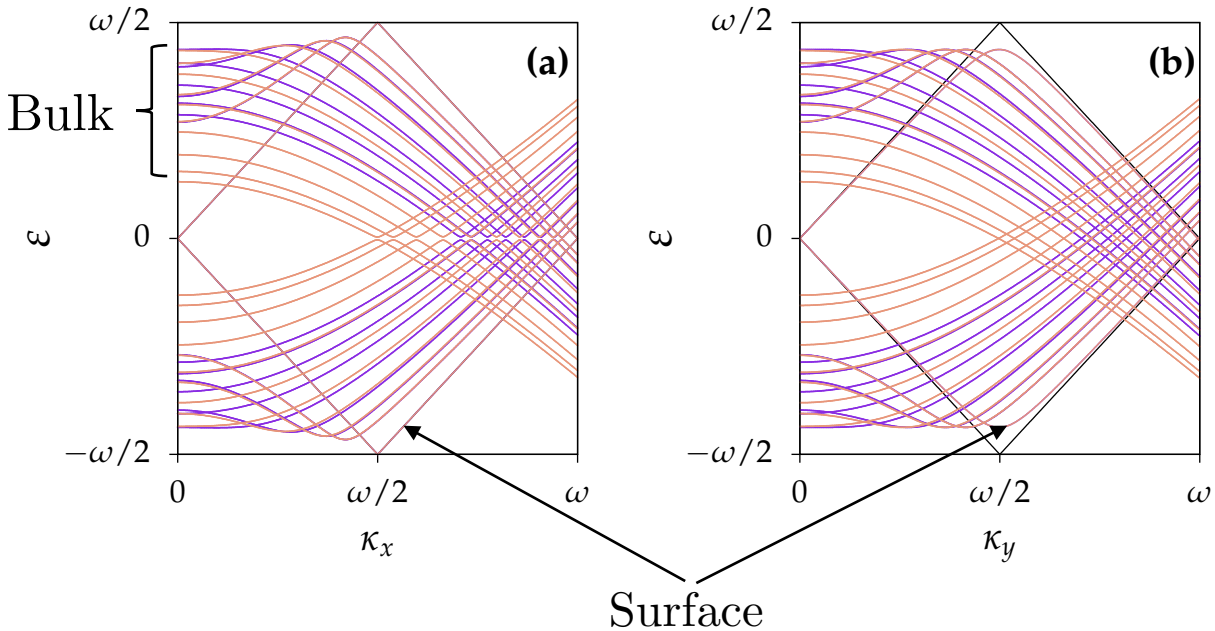
PHYSICAL REVIEW B **100**, 075412 (2019)

Floquet engineering of Dirac cones on the surface of a topological insulator

A. Díaz-Fernández,[1] E. Díaz,[1] A. Gómez-León,[2] G. Platero,[2] and F. Domínguez-Adame[1]
[1]*GISC, Departamento de Física de Materiales, Universidad Complutense, E-28040 Madrid, Spain*
[2]*Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC), Cantoblanco, E-28049 Madrid, Spain*

In-Plane, Linear

In-plane along X, linear



Remember $J = \boldsymbol{\alpha} \cdot \boldsymbol{a}$

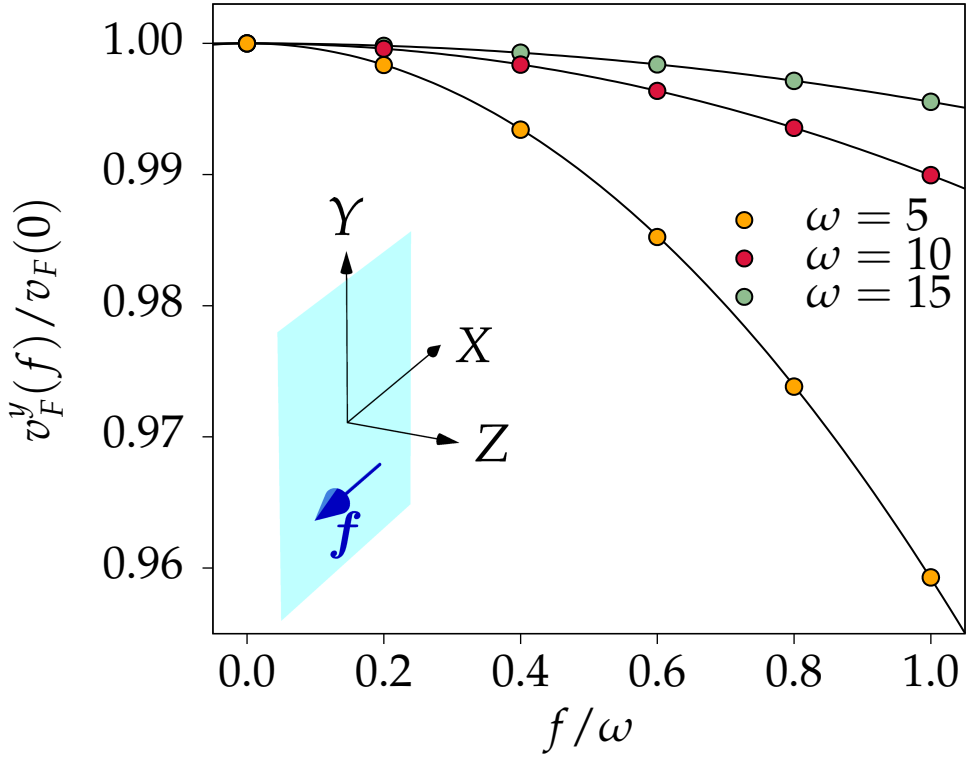
No avoided crossings at FB zone edge along X

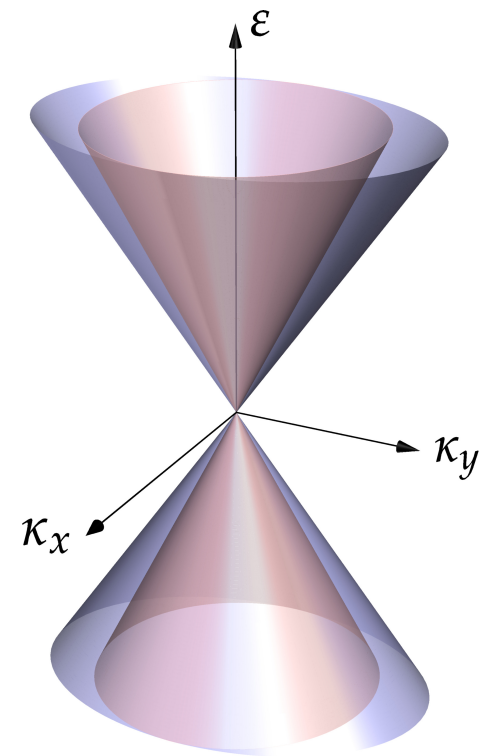
Avoided crossings along Y reduce the slope

Surface states unchanged upon changing discretization step and/or system size

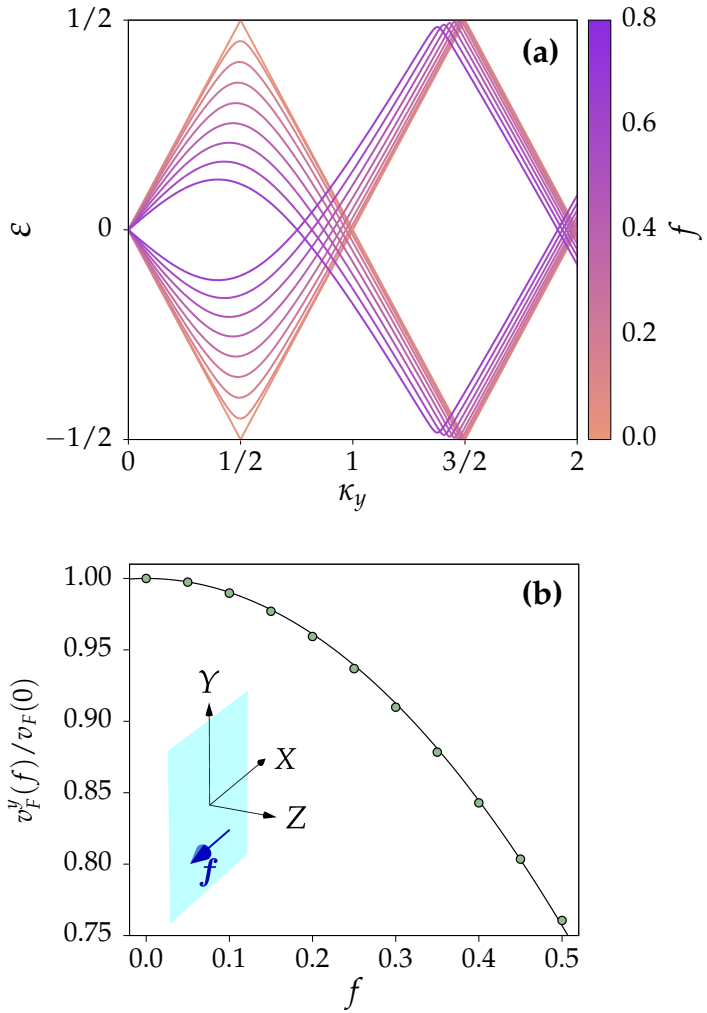
No hybridization

In-plane along X, linear

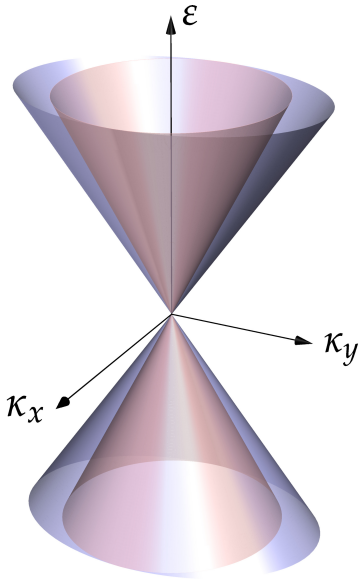




SV Syzranov *et al.*, *PRB* **88**, 241112 (2013)



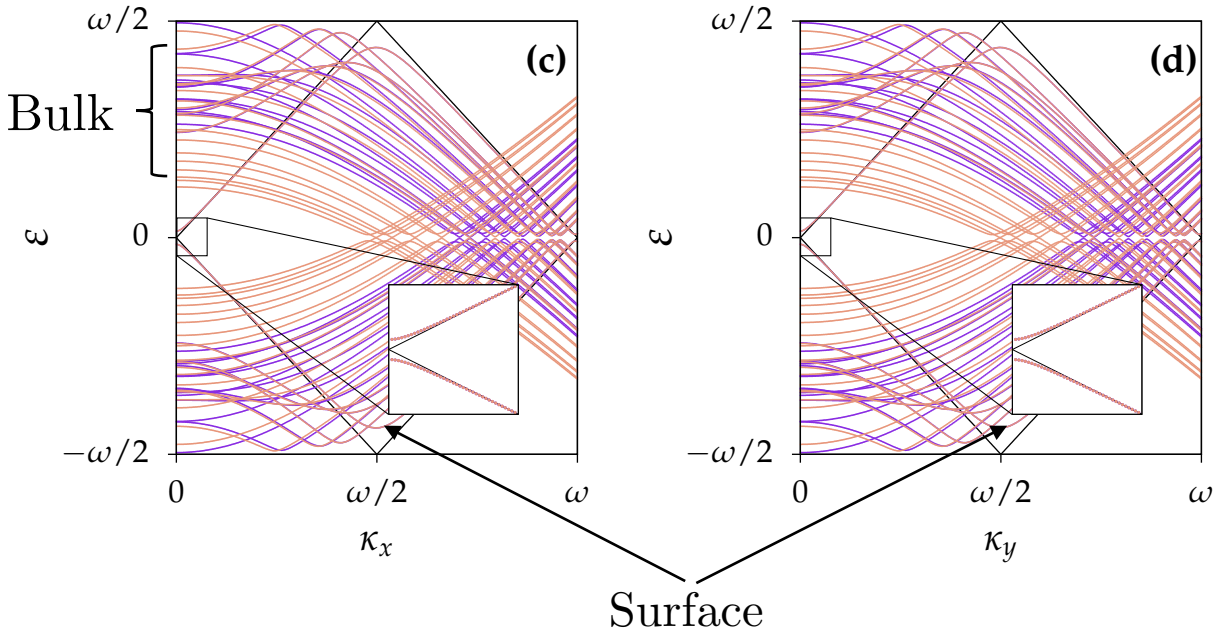
In-plane, linear, graphene (bulk)



See also: SV Syzranov *et al.*, *PRB* **88**, 241112 (2013)

In-Plane, Circular

In-plane, circular



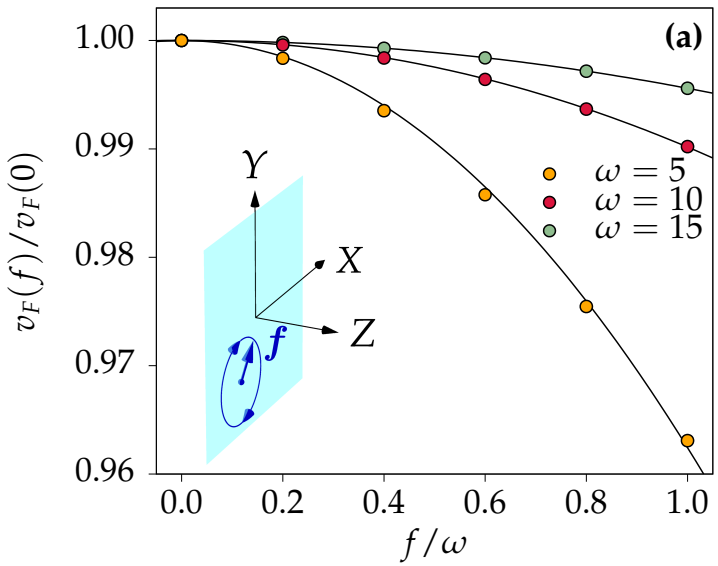
Remember $J = \boldsymbol{\alpha} \cdot \boldsymbol{a}$

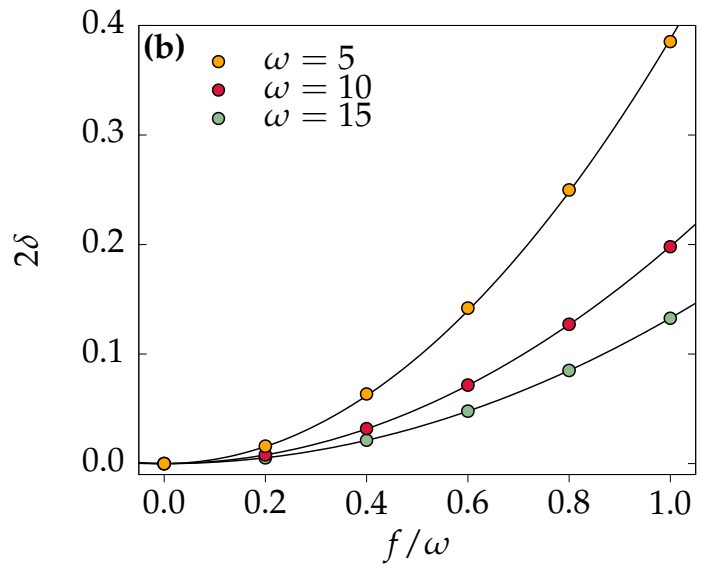
Avoided crossings at FB edge reduce the slope

Gap opening at Dirac point

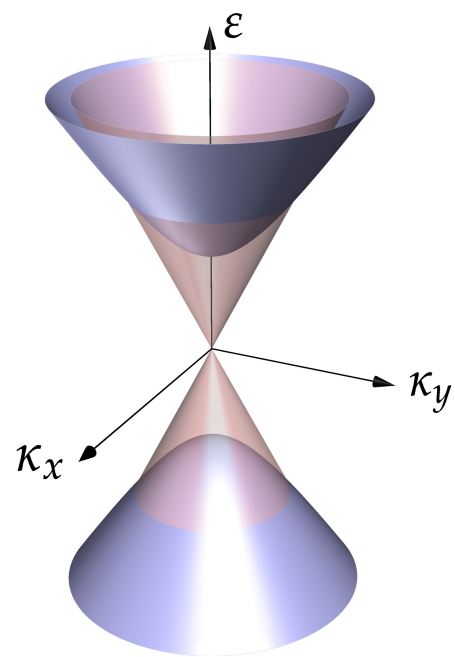
Surface states unchanged upon changing discretization step and/or system size

No hybridization





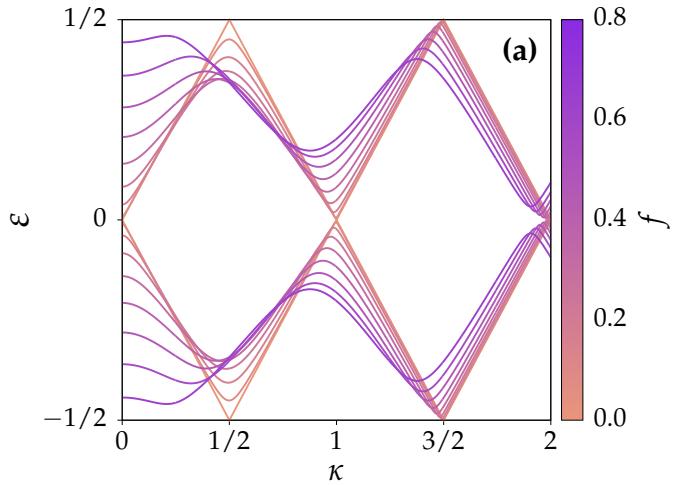
In-plane, circular

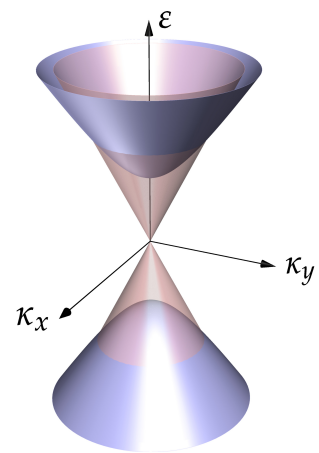


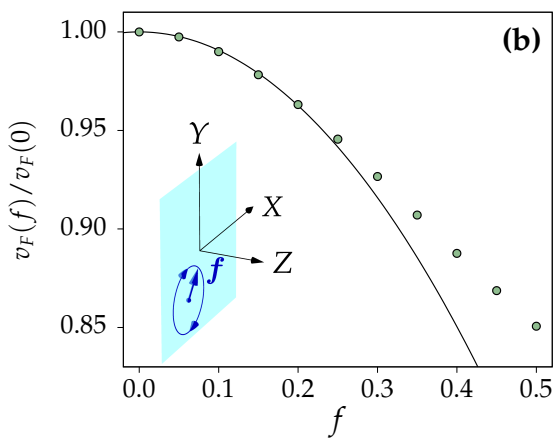
T Kitagawa *et al.*, *PRB* **84**, 235108 (2011)

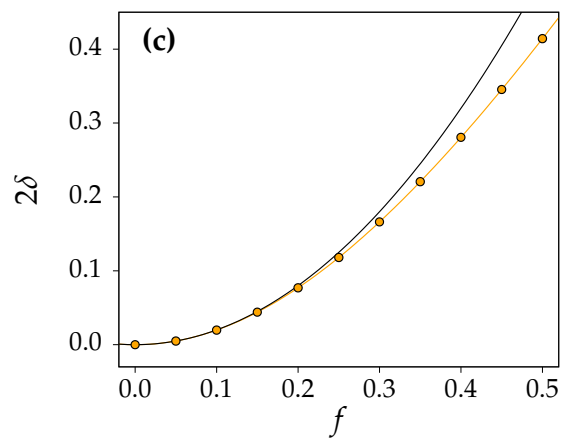
$$\mathcal{H}_S = (\boldsymbol{\sigma} \times \boldsymbol{k})_z \pm \left(\frac{f}{\omega}\right)^2 \sigma_z$$

In-plane, circular, graphene (bulk)









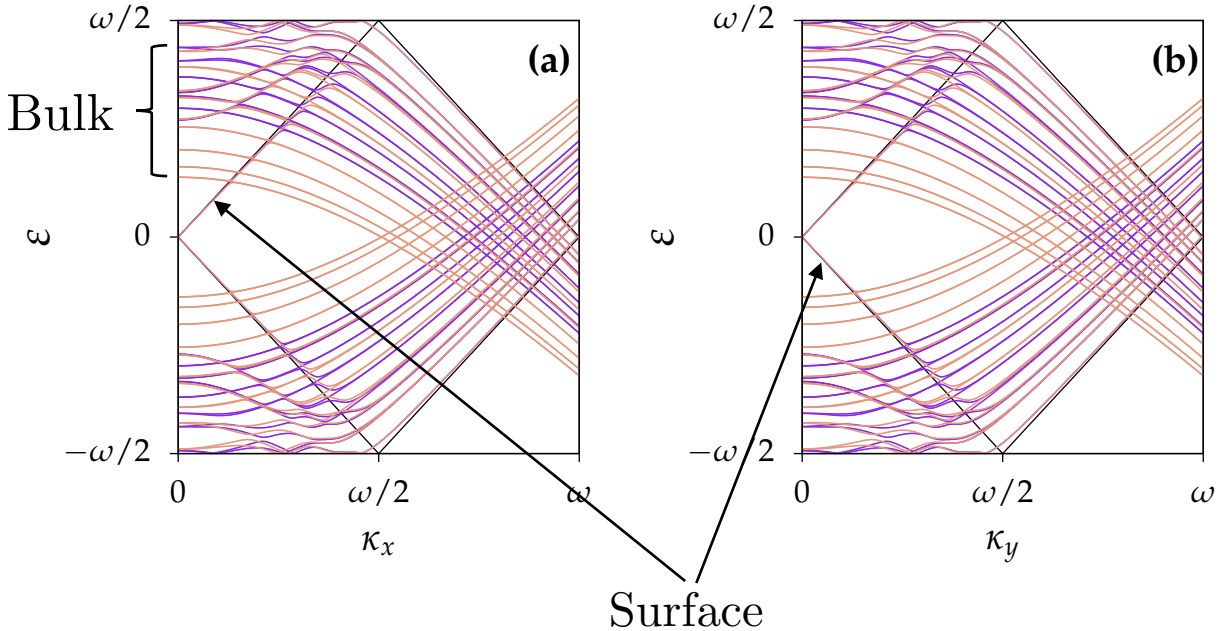
T Kitagawa *et al.*, *PRB* **84**, 235108 (2011)

$$\mathcal{H} = (\sigma_y k_x - \sigma_x k_y \tau_z) \pm \left(\frac{f}{\omega}\right)^2 \sigma_z \tau_z$$

See also: SV Syzranov *et al.*, *PRB* **88**, 241112 (2013)

Out-of-plane, Linear

Out-of-plane, linear

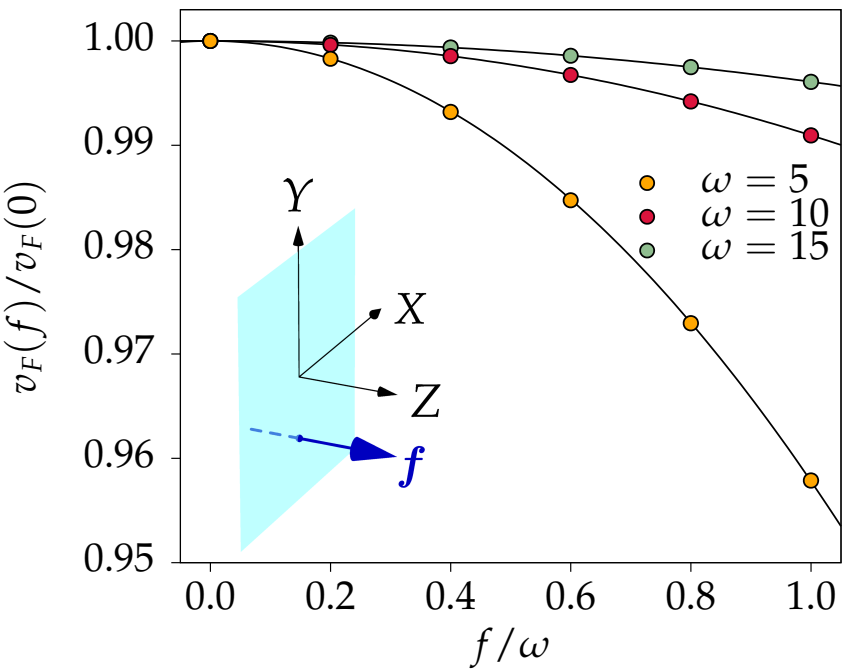


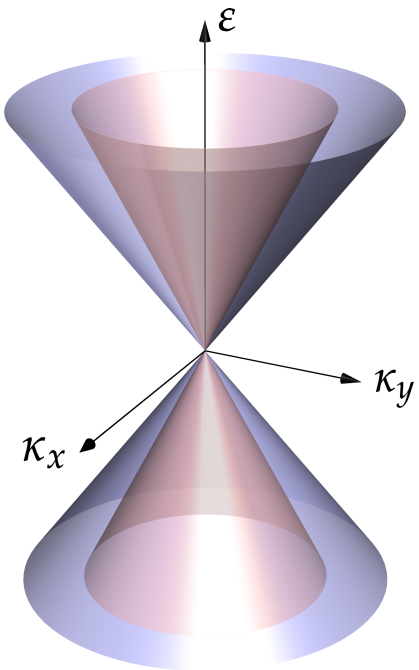
Complicated spectrum with hybridizations between bulk and surface

States close to Dirac point remain unchanged when changing step (no smaller than real lattice spacing)

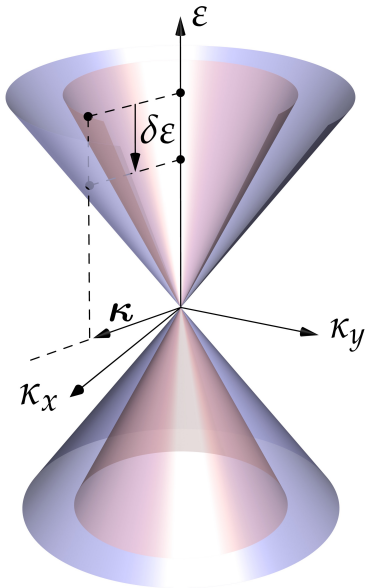
Isotropic reduction of slope

Out-of-plane, linear

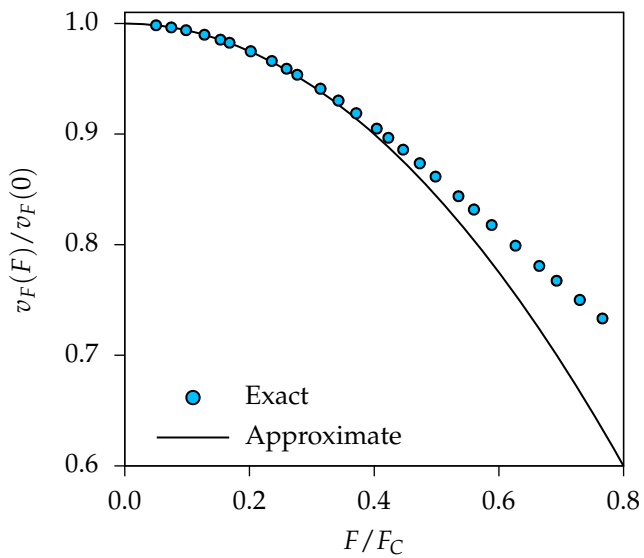




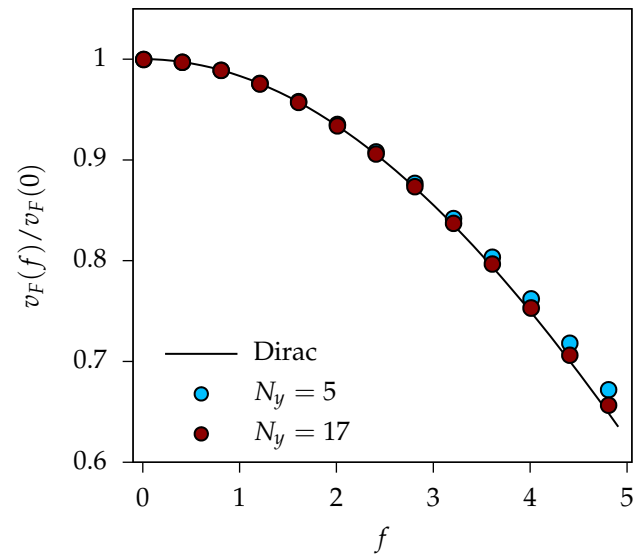
Static fields, similar behaviour



Topological Insulator



aGNR

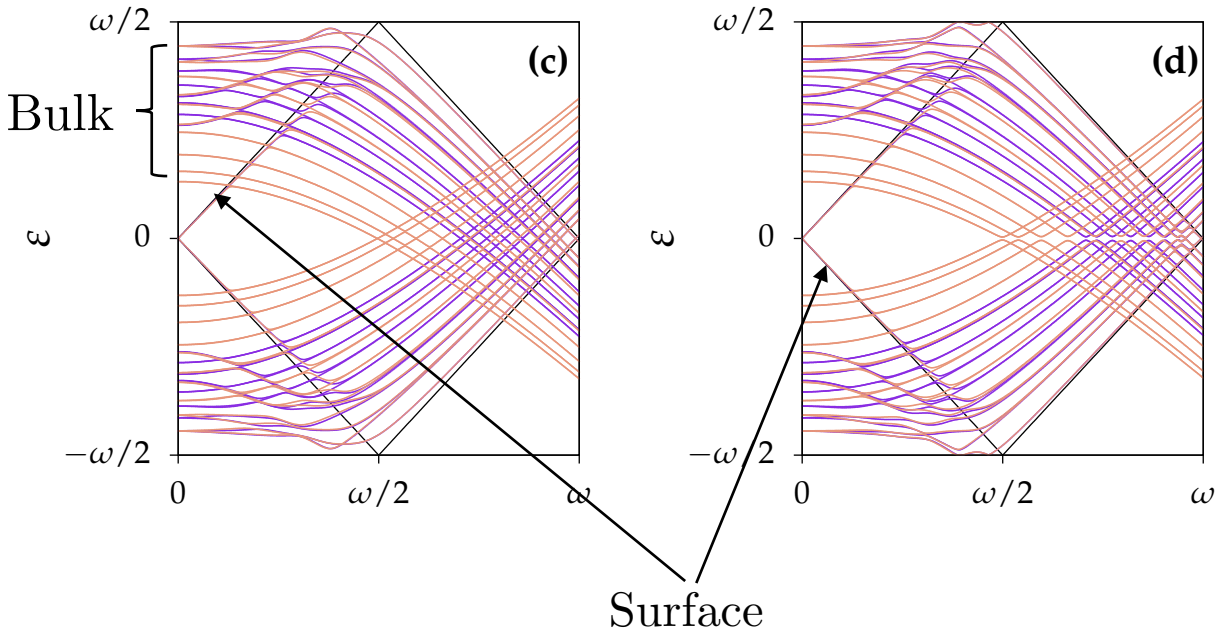


$$v_F(f) = v_F(0)\left(1 - \frac{5f^2}{8}\right)$$

ADF, L. Chico, J. W. González & FDA, *Sci. Rep.* **7**, 8058 (2017)

Out-of-plane, Circular

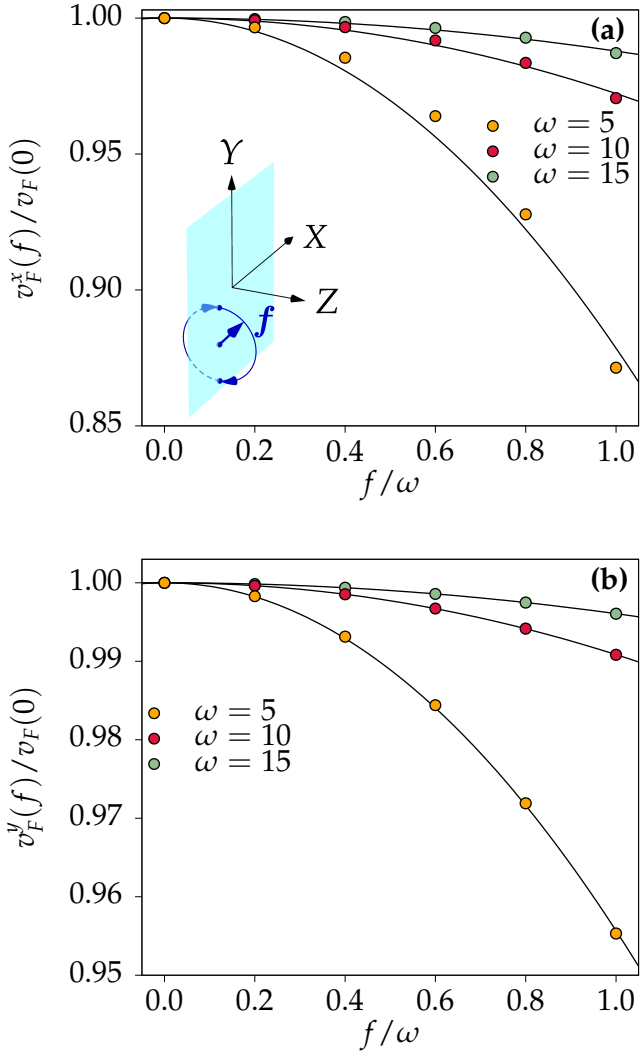
Out-of-plane, circular



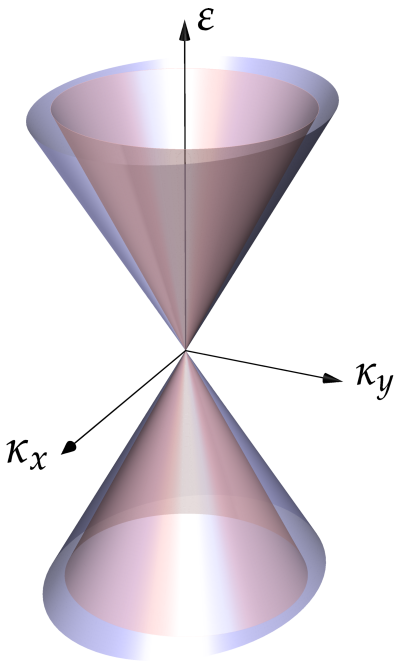
Complicated spectrum with hybridizations between bulk and surface

States close to Dirac point remain unchanged when changing step (no smaller than real lattice spacing)

Anisotropic reduction of slope: out-of-plane linear + in-plane linear



Out-of-plane, circular



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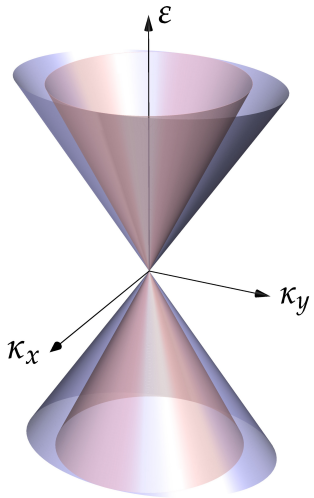
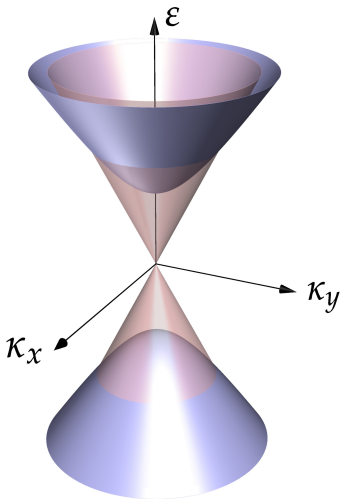
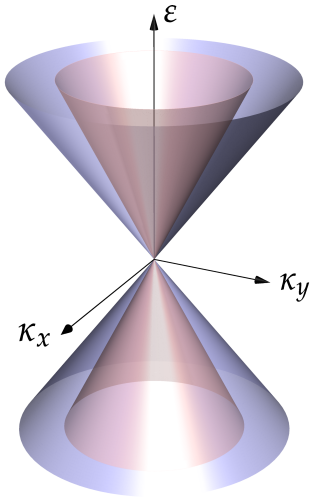
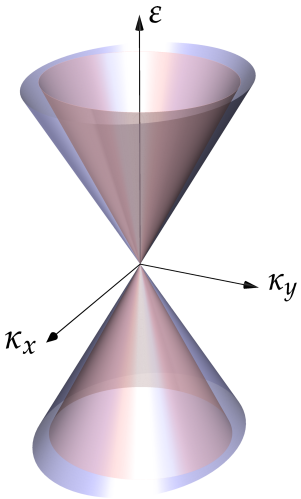
	Linear	**Circular**
In-plane		
Out-of-plane		

- **Corroboration of previous studies with surface effective Hamiltonians**
- **Anisotropic modulation of Dirac dispersion**
- **Results applicable to both graphene and TIs, so maybe other Dirac materials as well**

PHYSICAL REVIEW B **100**, 075412 (2019)

Floquet engineering of Dirac cones on the surface of a topological insulator

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[1]*GISC, Departamento de Física de Materiales, Universidad Complutense, E-28040 Madrid, Spain*
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