Weyl semimetals — from chiral anomaly to fractional chiral metal

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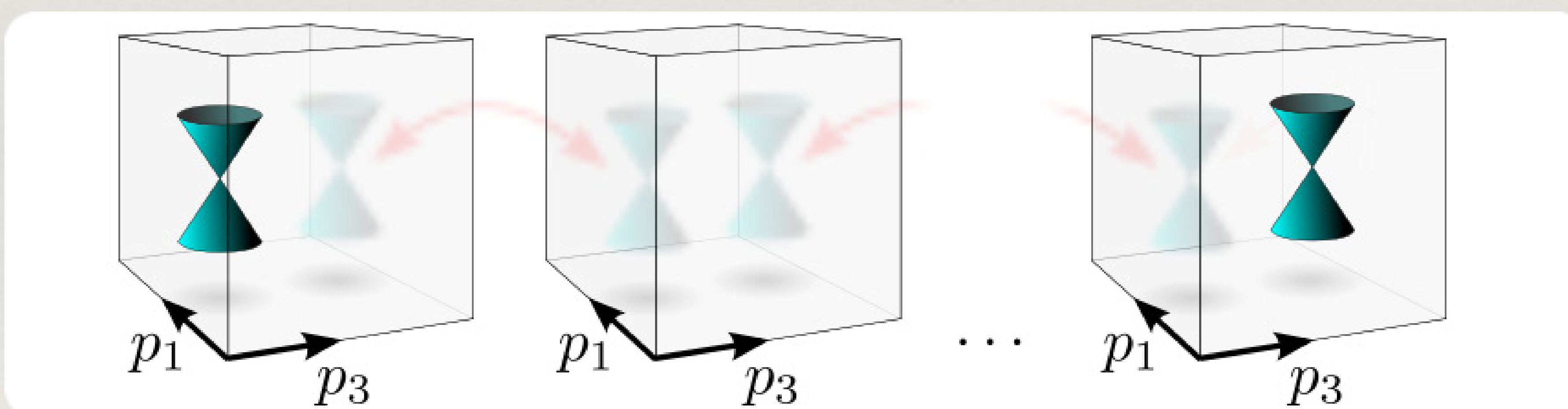


J. Behrends, A. G. Grushin, T. Ojanen, JHB Phys. Rev. B **93**, 075114 (2016)
F. Arnold, …A. G. Grushin, JHB, … C. Felser, E. Hassinger, B. Yan Nat. Comm. **7**, 11615 (2016)
T. Meng, A. G. Grushin, K. Shtengel JHB arXiv:1602.08856 (to appear in PRB)

Weyl Fermions

Weyl fermions

Hermann Weyl (1885-1955)

PhD Göttingen 1908 with Hilbert

1908 - 1913 — Göttingen

1913 - 1930 — ETH Zürich

1930 - 1933 — Göttingen

1930 - 1951— Princeton

— My work always tried to unite the truth with the beautiful, but when I had to choose one or the other, I usually chose the beautiful —

Dirac equation

$$(i\gamma^\mu \partial_\mu - m)\,\psi = 0$$

$$\gamma^0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix} \qquad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$$

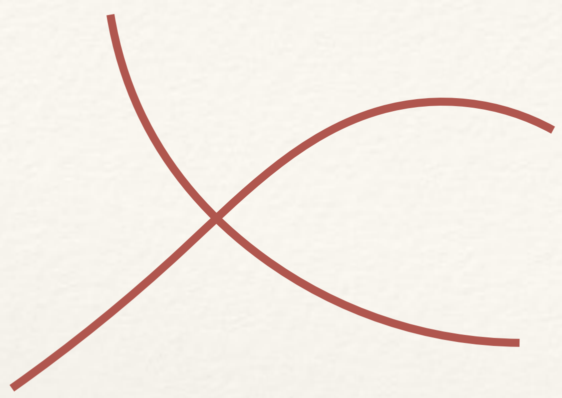
Massless Weyl fermions: $m = 0$

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} \psi_1 + \psi_2 \\ \psi_1 - \psi_2 \end{pmatrix} = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

$$(i\partial_t \pm \mathbf{p} \cdot \boldsymbol{\sigma})\psi_{R/L} = 0$$

H. Weyl Z. Phys. 1929

Accidental crossing of two bands in 3D band structure is a Weyl point



$$H = \begin{pmatrix} A & B \\ B^* & C \end{pmatrix} = a + \mathbf{b} \cdot \boldsymbol{\sigma}$$

$$H(p_x, p_y, p_z) = a(\mathbf{p}) + \mathbf{b}(\mathbf{p}) \cdot \boldsymbol{\sigma}$$

$$\mathbf{b}(\mathbf{p}_*) = 0$$

Note $a(p)$!

Type II Weyl semimetals

see, e.g., Soluyanov et al Nature 2015

$$b_i(\mathbf{p}) = \sum_j b_{ij}(\mathbf{p} - \mathbf{p}_*)_j + \mathcal{O}((\mathbf{p} - \mathbf{p}_*)^2)$$

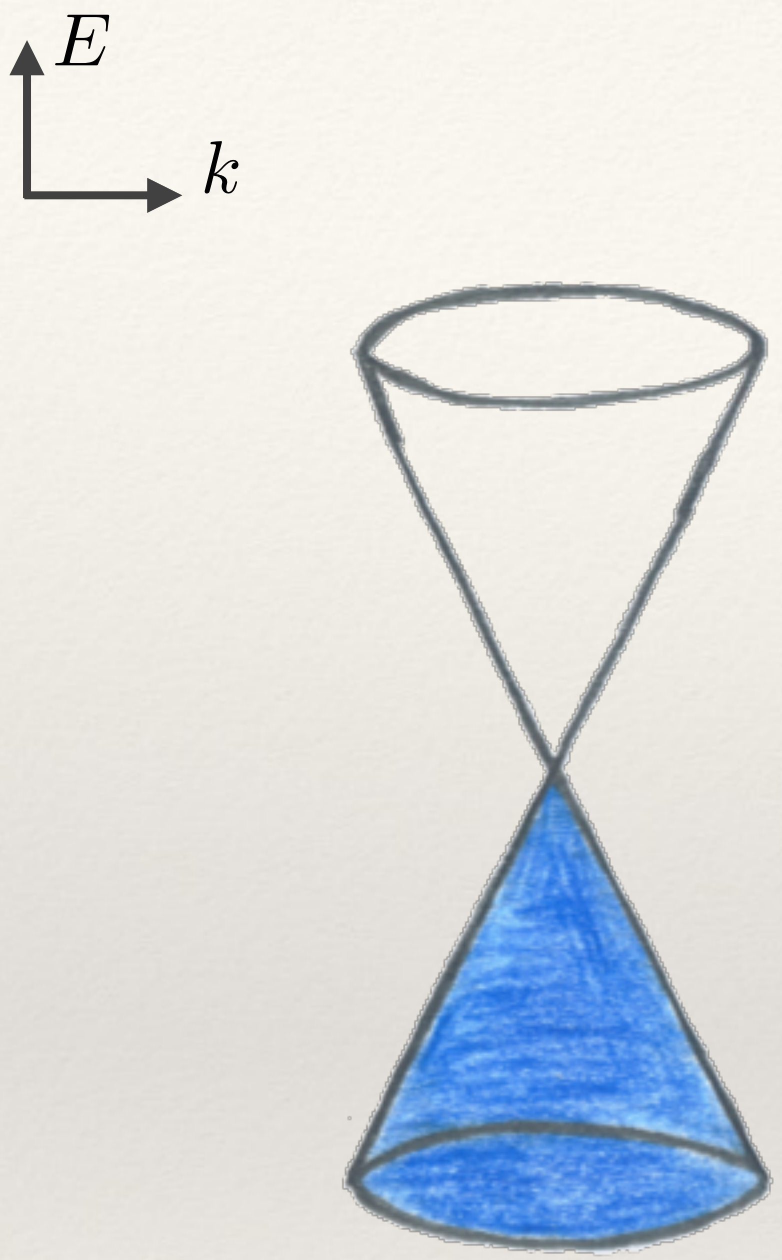
$$b_{ij} = \left. \frac{\partial b_i}{\partial p_j} \right|_{\mathbf{p}=\mathbf{p}_*}$$

$$H' = \sum_{i,j} \sigma_i b_{ij} (\mathbf{p} - \mathbf{p}_*)_j \quad \rightarrow \mathbf{p} \cdot \boldsymbol{\sigma}$$

C. Herring, Phys. Rev. 1937

E. Witten arXiv:1510.07698

At low energy Weyl semimetals are described by Weyl fermions

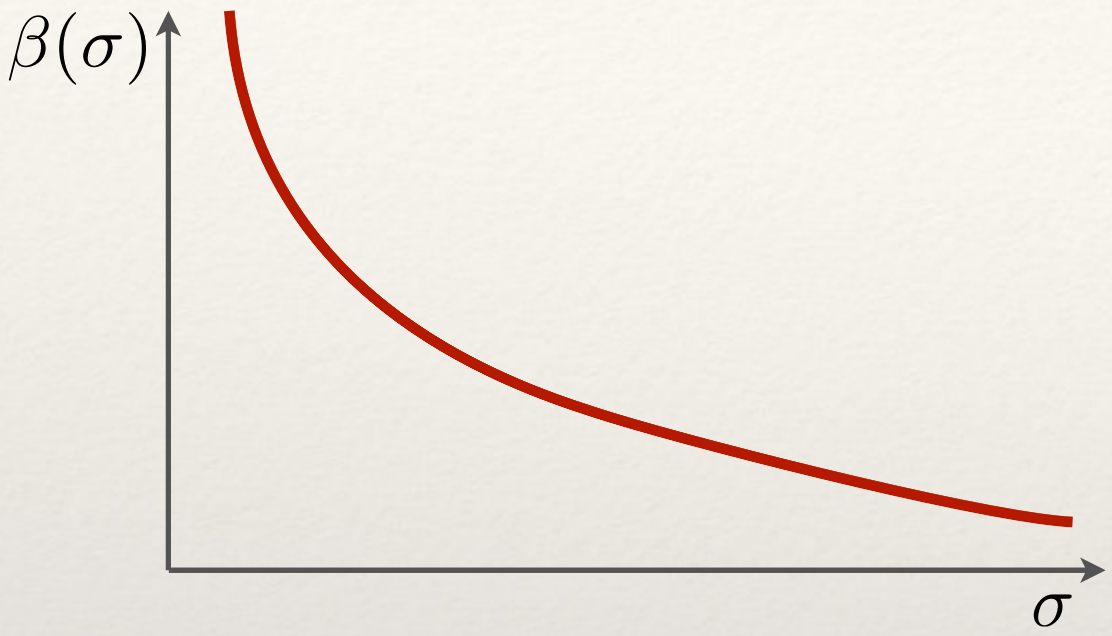


$$H = \mathbf{p}\cdot\sigma \; = p_x\sigma_x + p_y\sigma_y + p_z\sigma_z$$

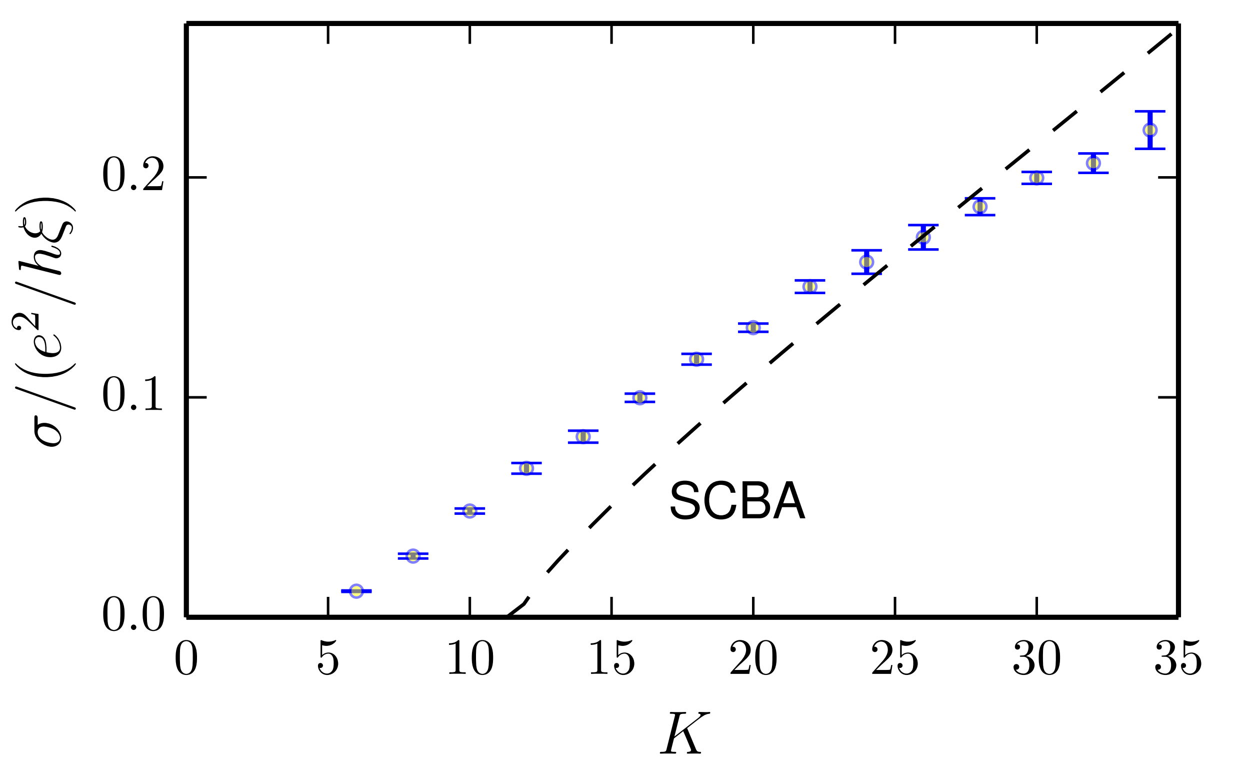
Reviews: Turner and Vishwanath arXiv:1301.0330; Hosur and Xi *C. R. Phys.* 2013

Scalar disorder is irrelevant for 3D Weyl nodes

2D



3D



JHB, Tworzydlo, Brouwer, Beenakker, PRL 2007
Nomura, Koshino, Ryu PRL 2007

Fradkin PRB 1986 (x2)
Sbierski, Pohl, Bergholtz, Brouwer PRL 2014

Weyl node is a topologically stable monopole of Berry flux

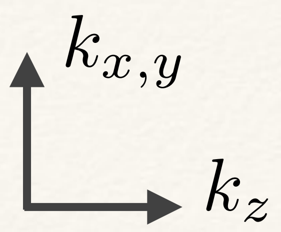
$$\mathbf{A_p} = i\langle u_\mathbf{p} | \boldsymbol{\nabla} u_\mathbf{p} \rangle$$ Berry phase

$$\boldsymbol{\Omega}_\mathbf{p} = \boldsymbol{\nabla}_p \times \mathbf{A_p}$$ Berry curvature

$$\nu^{(i)} = \frac{1}{2\pi\hbar} \oint d\mathbf{S} \cdot \boldsymbol{\Omega}^{(i)}_\mathbf{p} \quad \in \mathbb{Z}$$ topological invariant

Volovik JETP Lett. 2014; *The Universe in a Helium Droplet* 2003

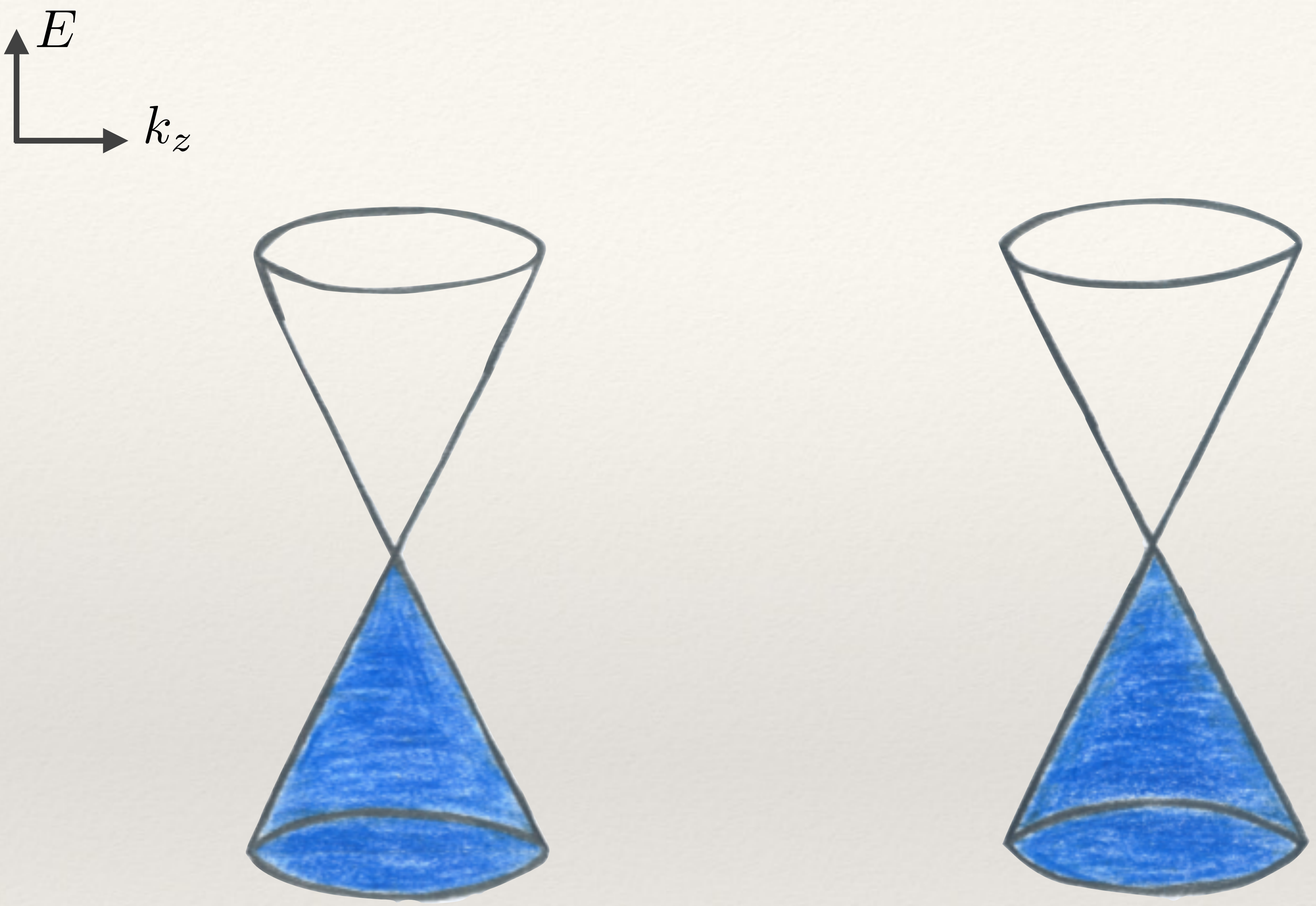
In momentum space the monopoles always come in pairs



Nielsen & Ninomiya Nucl. Phys. B 1981

Volovik JETP Lett. 2014; *The Universe in a Helium Droplet* 2003

The minimal model of a Weyl semimetal has two Weyl nodes

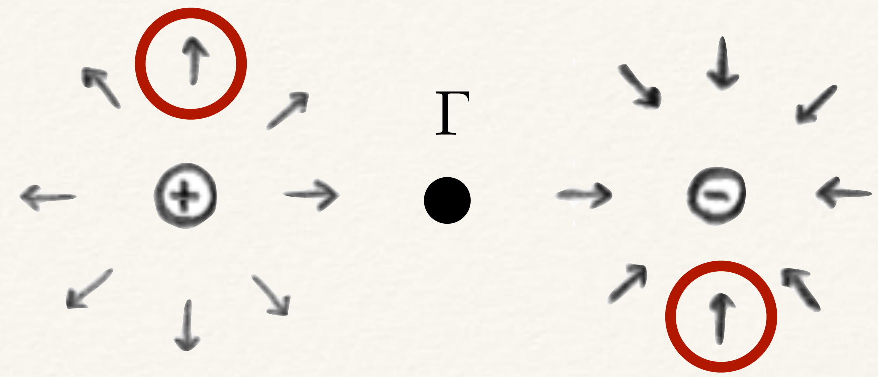


Reviews: Turner and Vishwanath arXiv:1301.0330; Hosur and Xi *C. R. Phys.* 2013

Weyl semimetals necessarily break time reversal and/or inversion symmetry

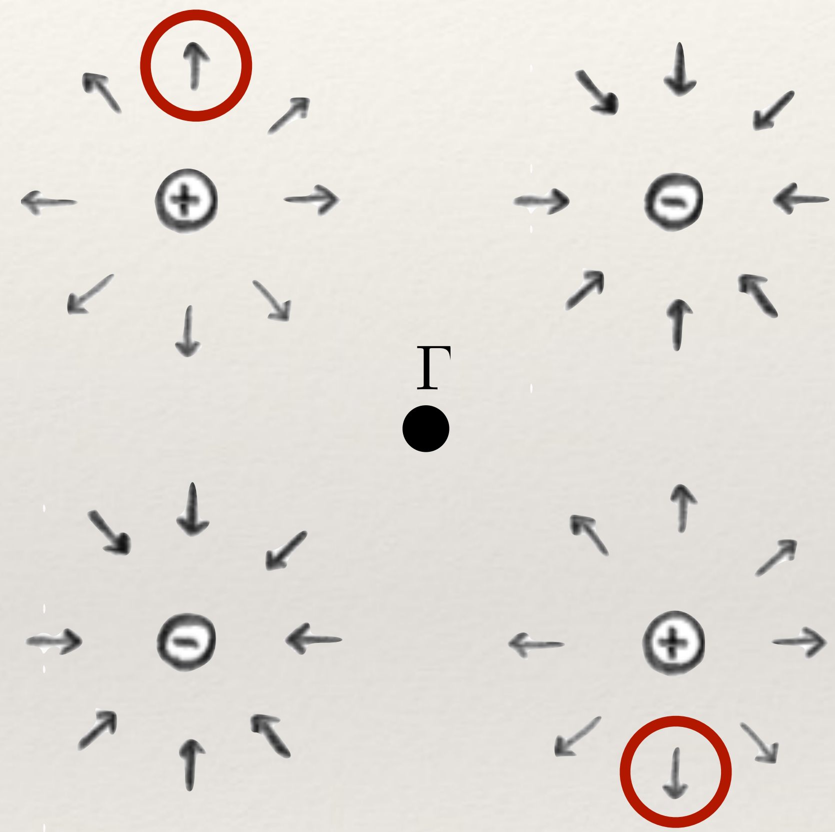
Inversion symmetry

$$\mathbf{k} \rightarrow -\mathbf{k}$$
$$\sigma \rightarrow \sigma$$
$$\varepsilon_{\uparrow}(\mathbf{k}) = \varepsilon_{\uparrow}(-\mathbf{k})$$



Time reversal symmetry

$$\mathbf{k} \rightarrow -\mathbf{k}$$
$$\sigma \rightarrow -\sigma$$
$$\varepsilon_{\downarrow}(\mathbf{k}) = \varepsilon_{\uparrow}(-\mathbf{k})$$



TRS + IS Dirac semimetal

$$\varepsilon_{\uparrow}(\mathbf{k}) = \varepsilon_{\uparrow}(-\mathbf{k}) = \varepsilon_{\downarrow}(\mathbf{k})$$

Wan, Turner, Vishwanath, Savrasov PRB (2011)

Weyl (and Dirac) semimetals exist!

Dirac semimetals — 2014

Na_3Bi

Xu et al. Science 2015
Liu et al. Science 2014
Kushwaha et al. APL Mat. 2015
…

Cd_3As_2

Neupane et al. Nature Comm. 2014
Borisenko et al. PRL 2014
Yi et al. Sci. Rep. 2014
Liu et al. Nature Mater. 2014
Liang et al. Nature Mater. 2014
He et al. PRL 2014
…

…

See Claudia Felser's talk!

Weyl semimetals — 2015

Weng et al. PRX 2015 (th)

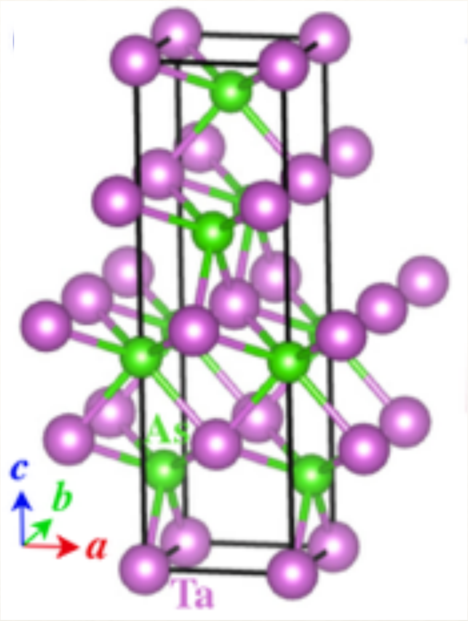
TaAs

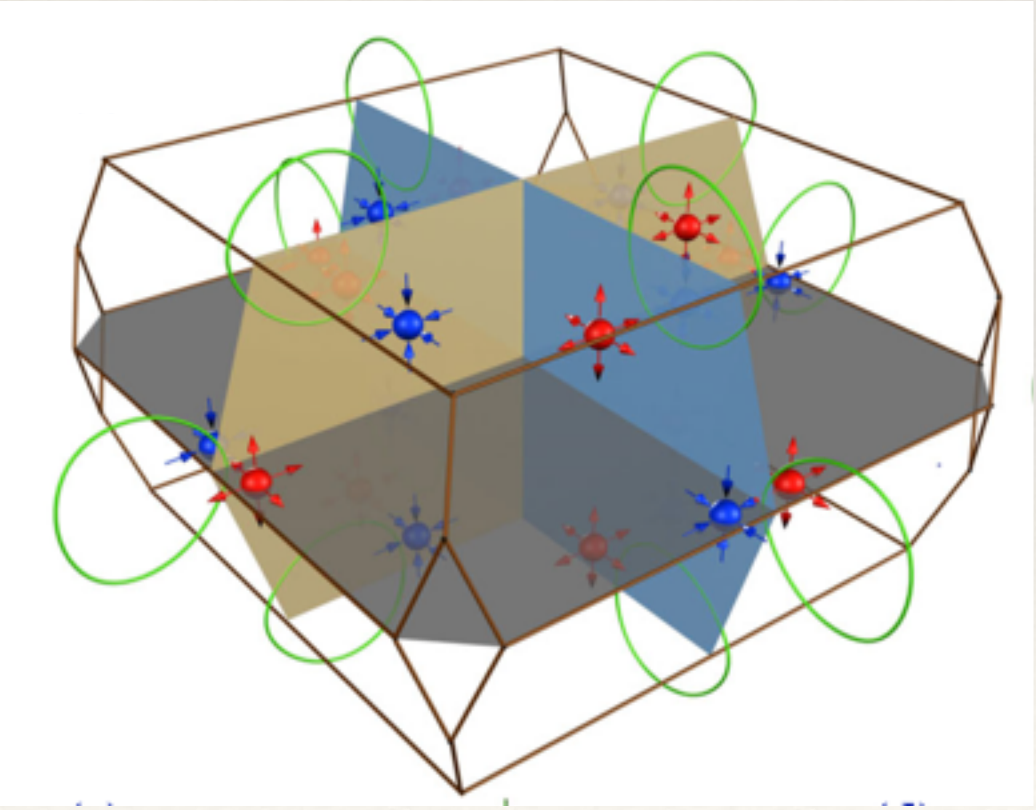
Xu et al. Science 2015
Yang et al. Nature Physics 2015,
Lv et al. Nature Physics 2015, PRX 2015
…

NbAs

Xu et al. Nature Physics 2015
…

…

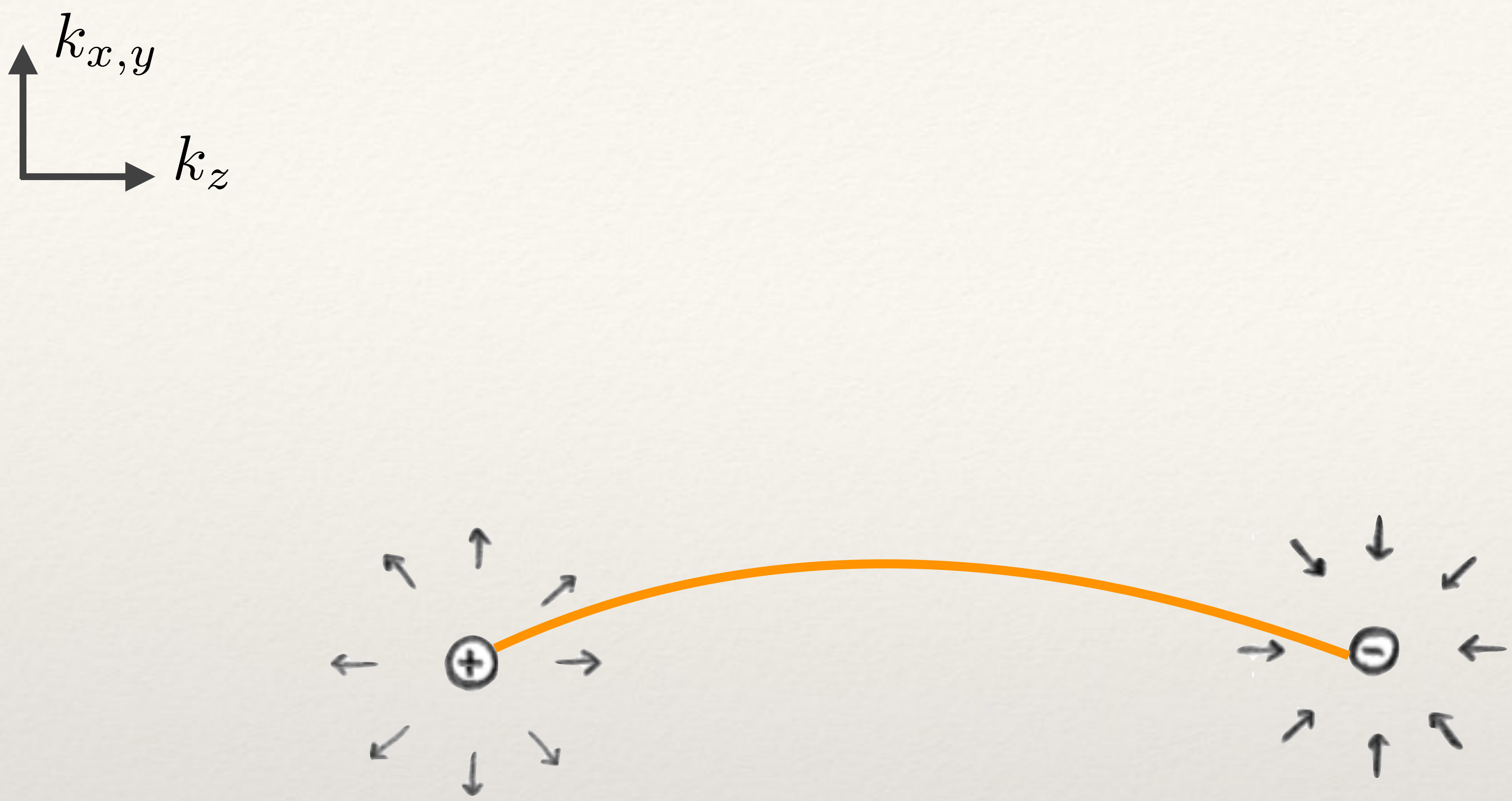




Images from: Weng et al. PRX 2015

Fermi Arcs

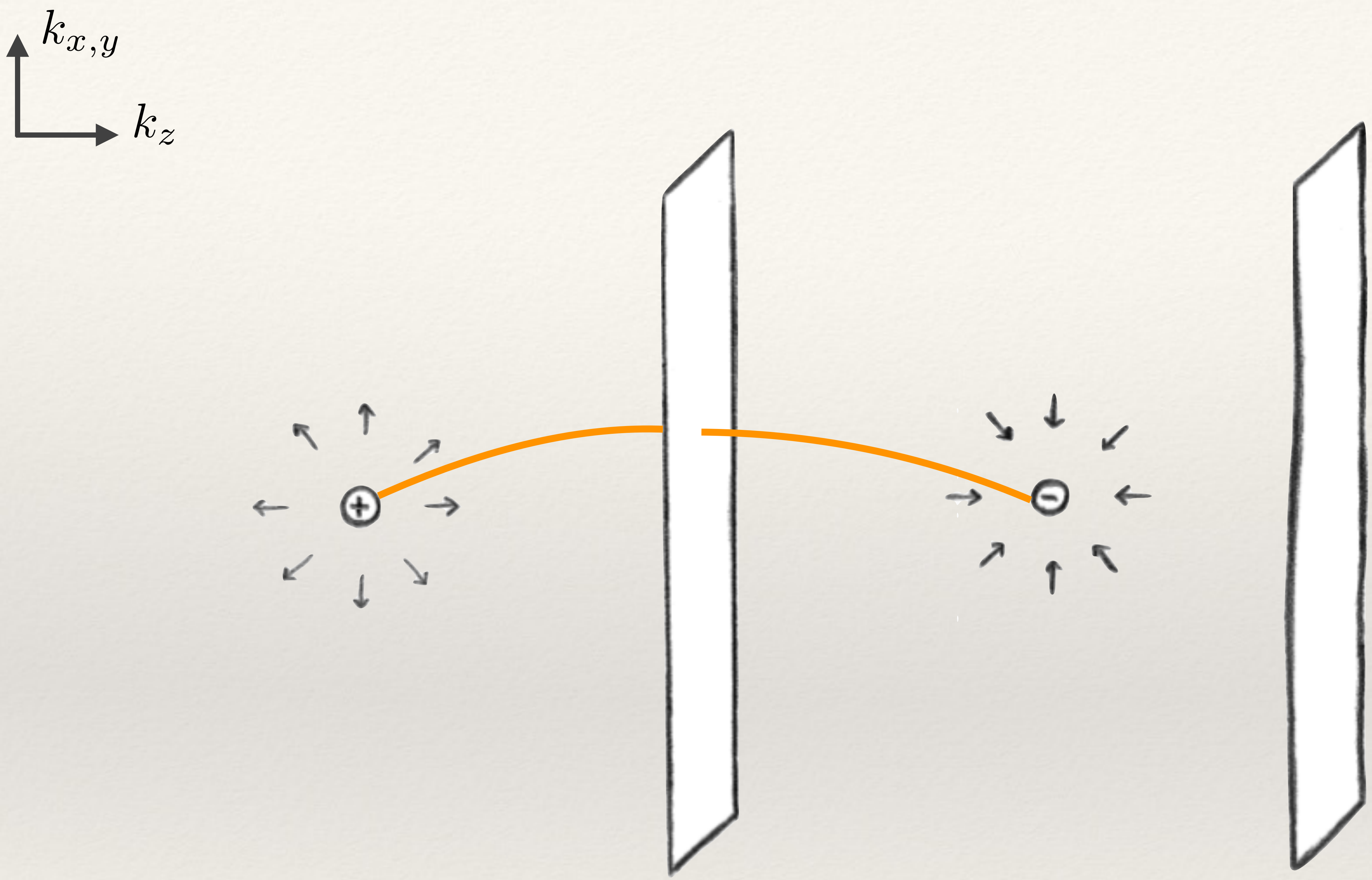
In momentum space the monopoles always come in pairs



Nielsen & Ninomiya Nucl. Phys. B 1981

Volovik JETP Lett. 2014; *The Universe in a Helium Droplet* 2003

In some parts of momentum space, Dirac string cuts a plane odd times



Volovik JETP Lett. 2014; *The Universe in a Helium Droplet* 2003

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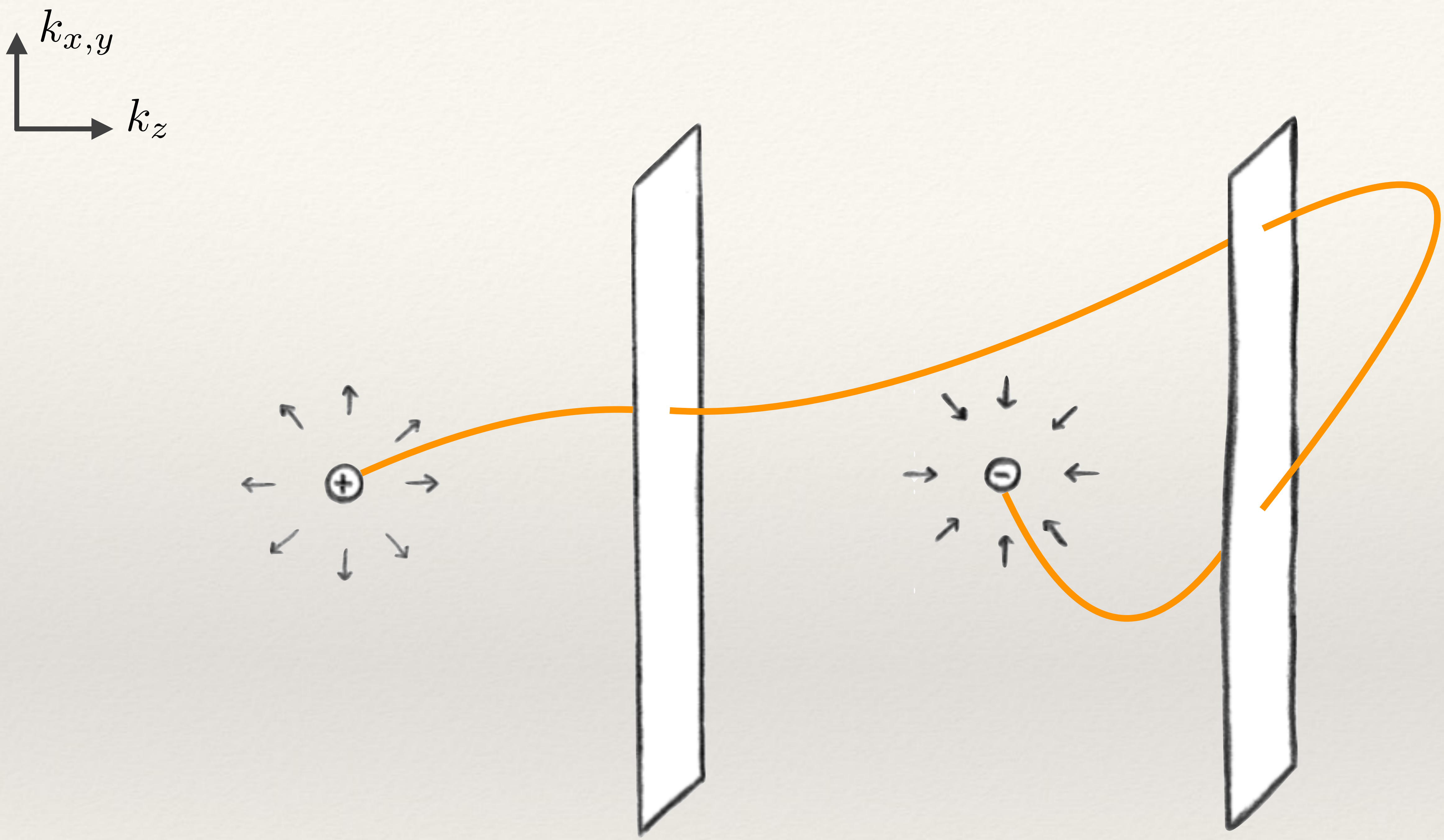
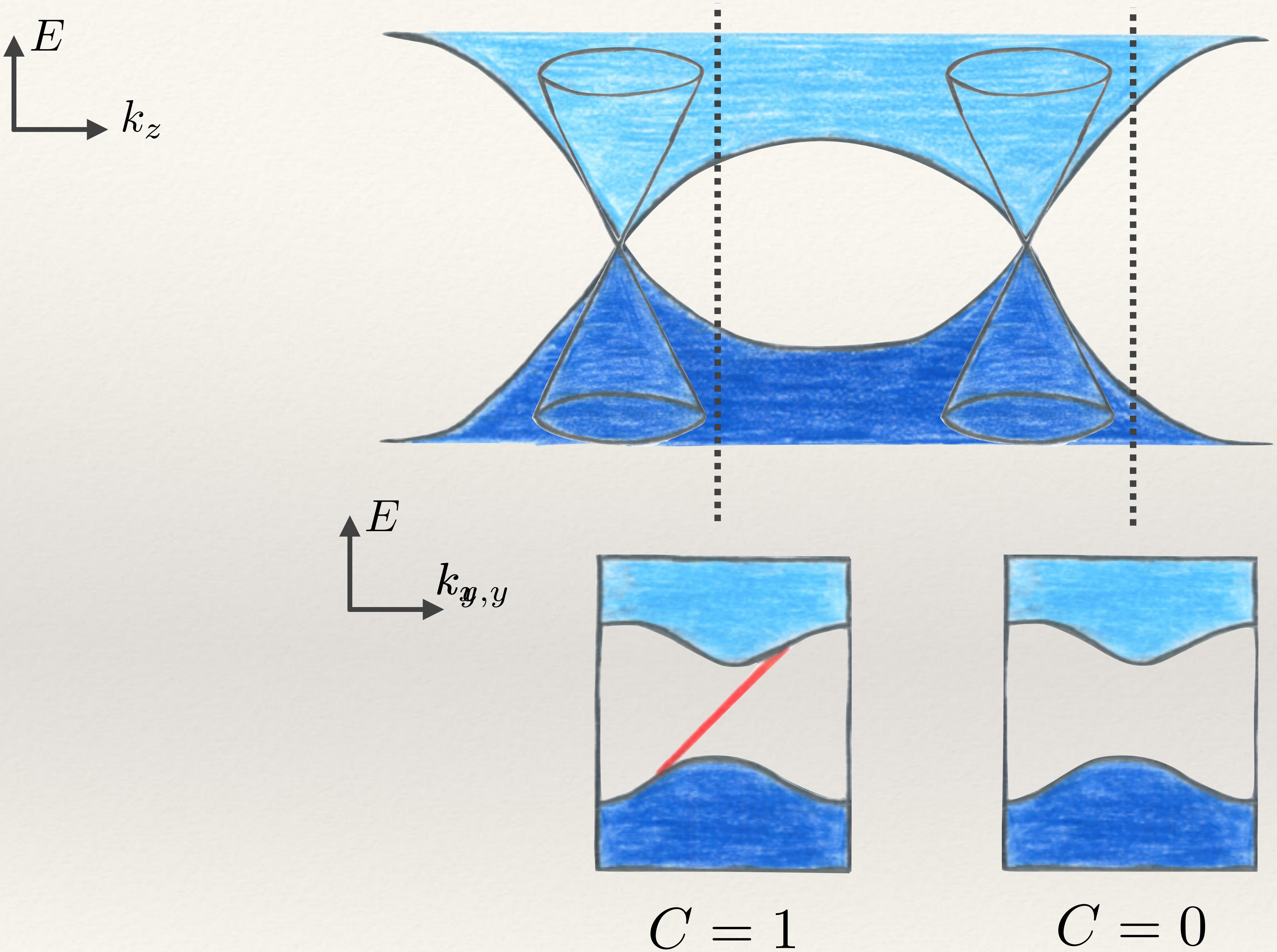


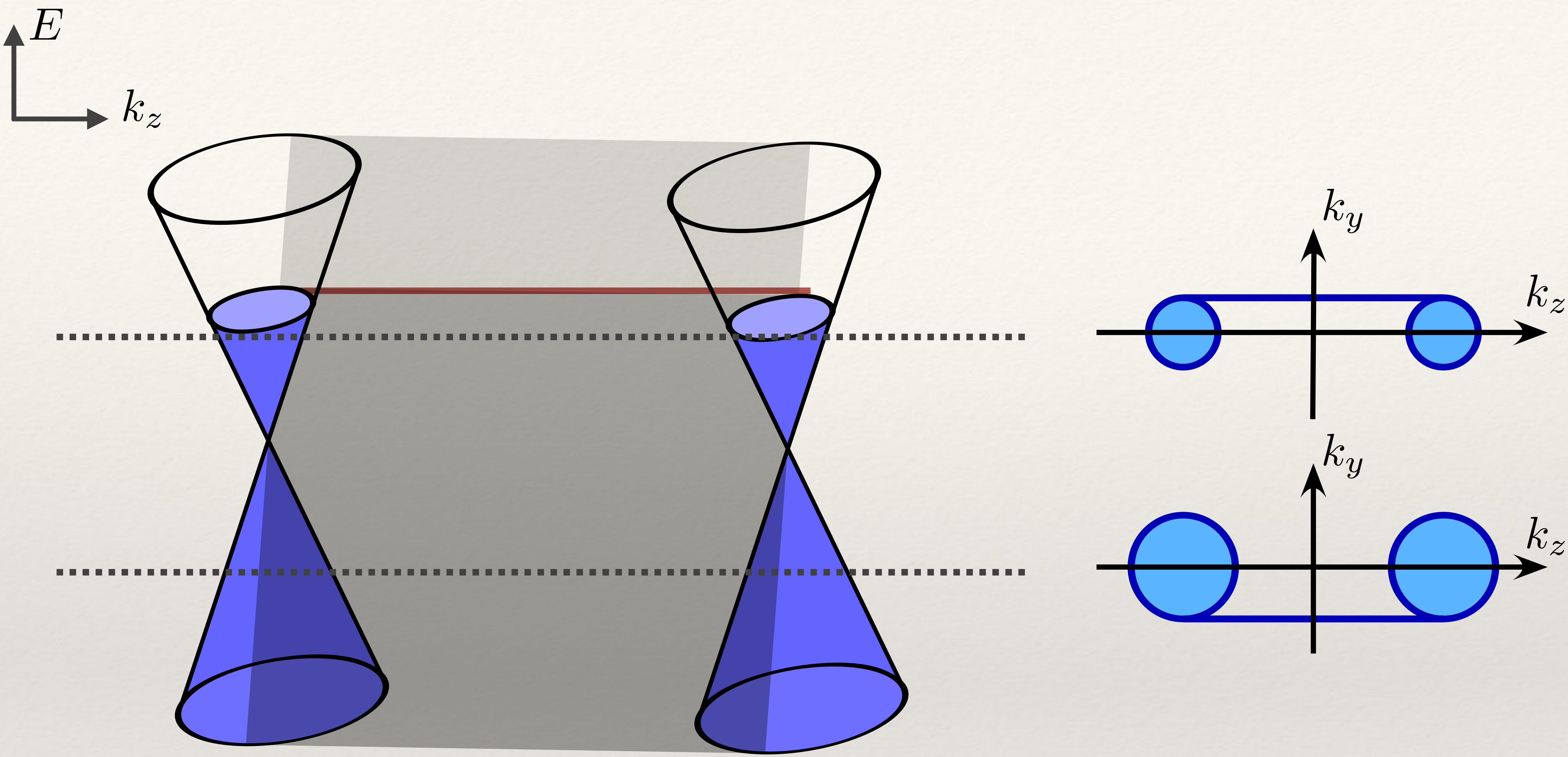
Volovik JETP Lett. 2014; *The Universe in a Helium Droplet* 2003

Topological surface states appear for certain momentum values



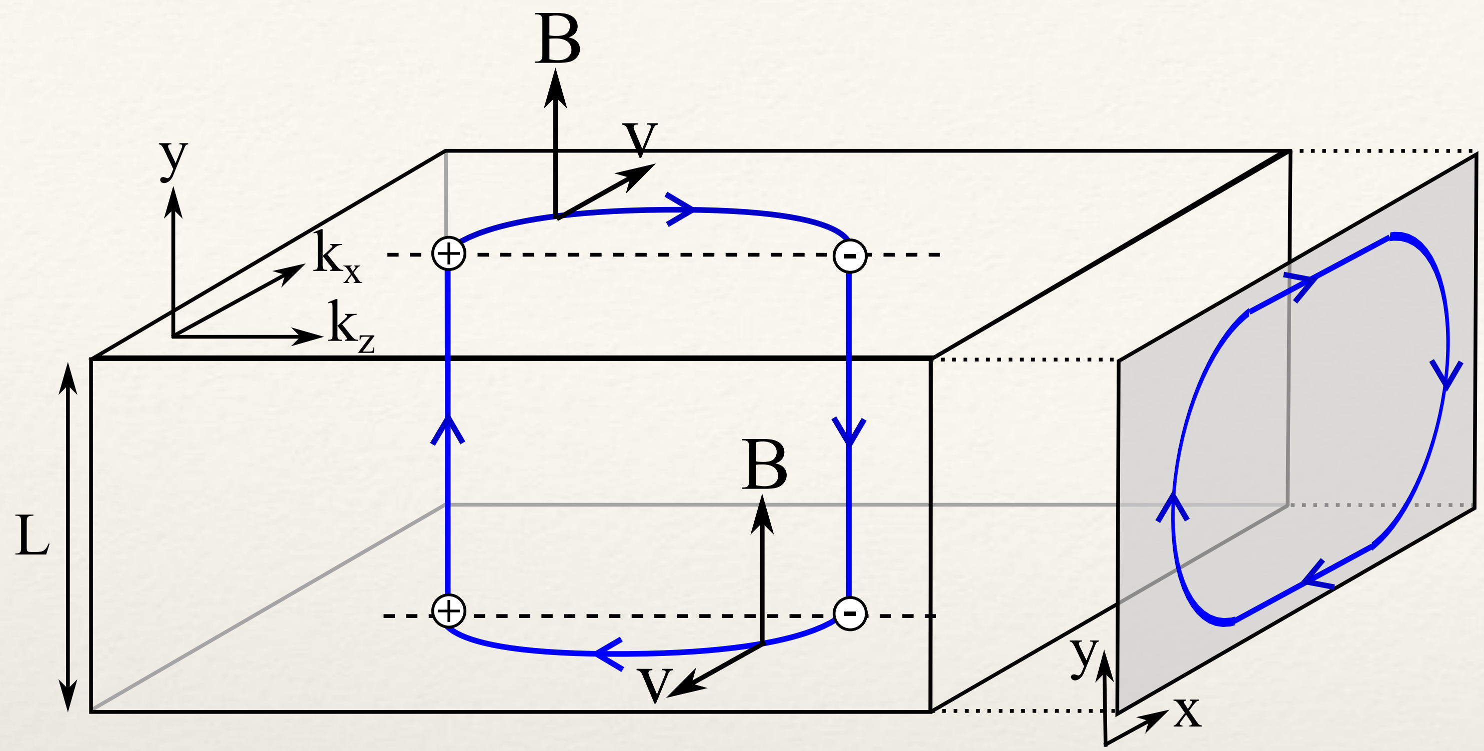
Reviews: Turner and Vishwanath arXiv:1301.0330; Hosur and Xi *C. R. Phys.* 2013

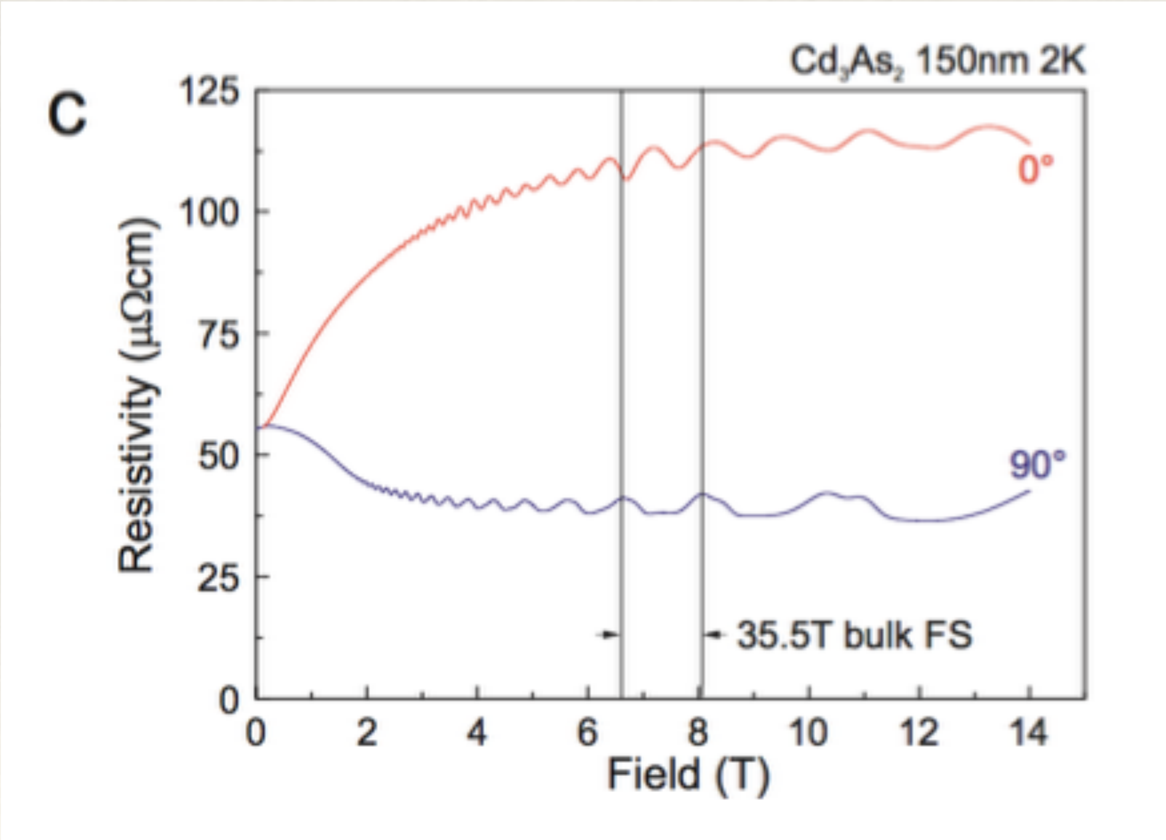
The Fermi arc separates occupied and unoccupied surface states

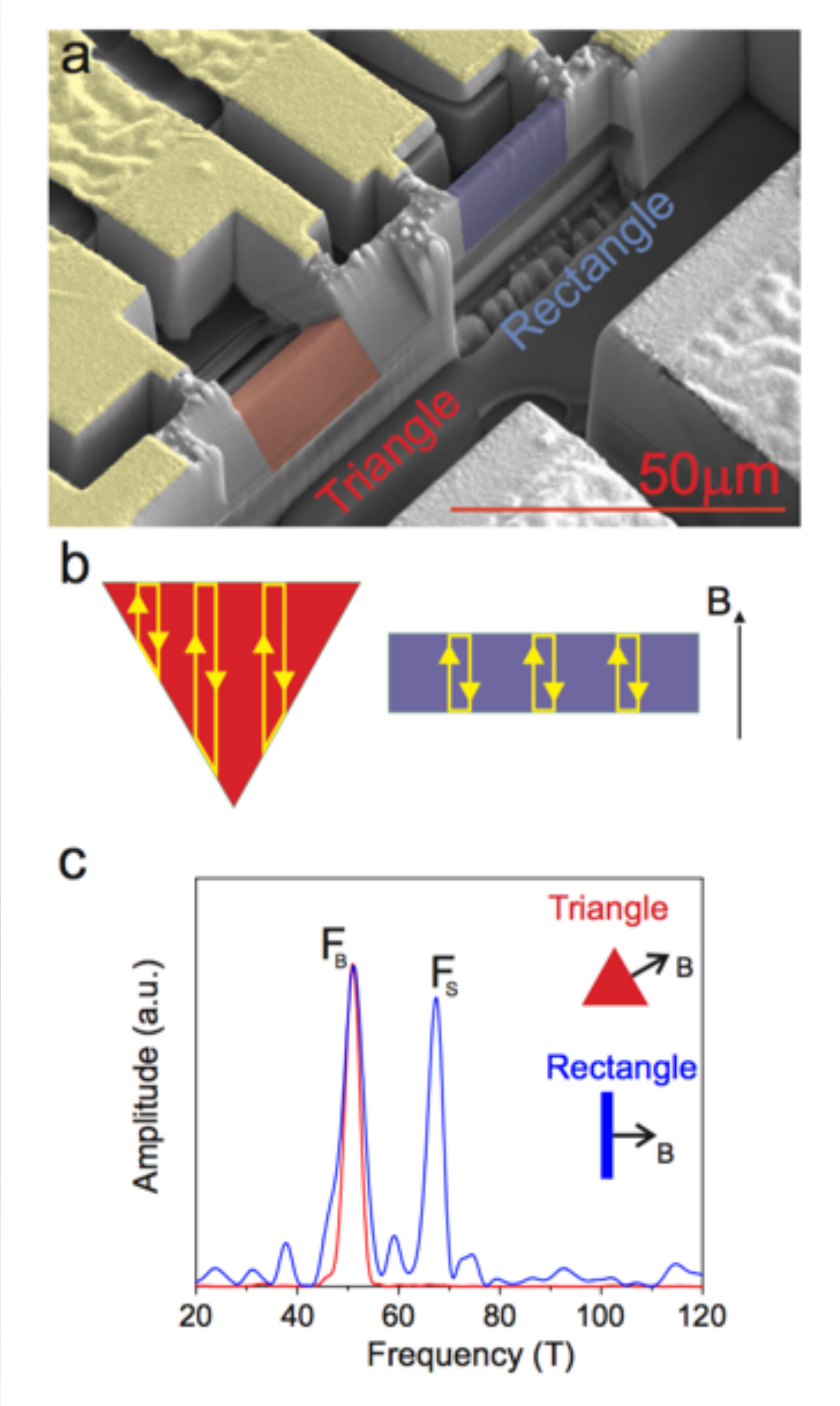


Wan, Turner, Vishwanath, and Savrasov PRB 2011

Quantum oscillations from Fermi arcs



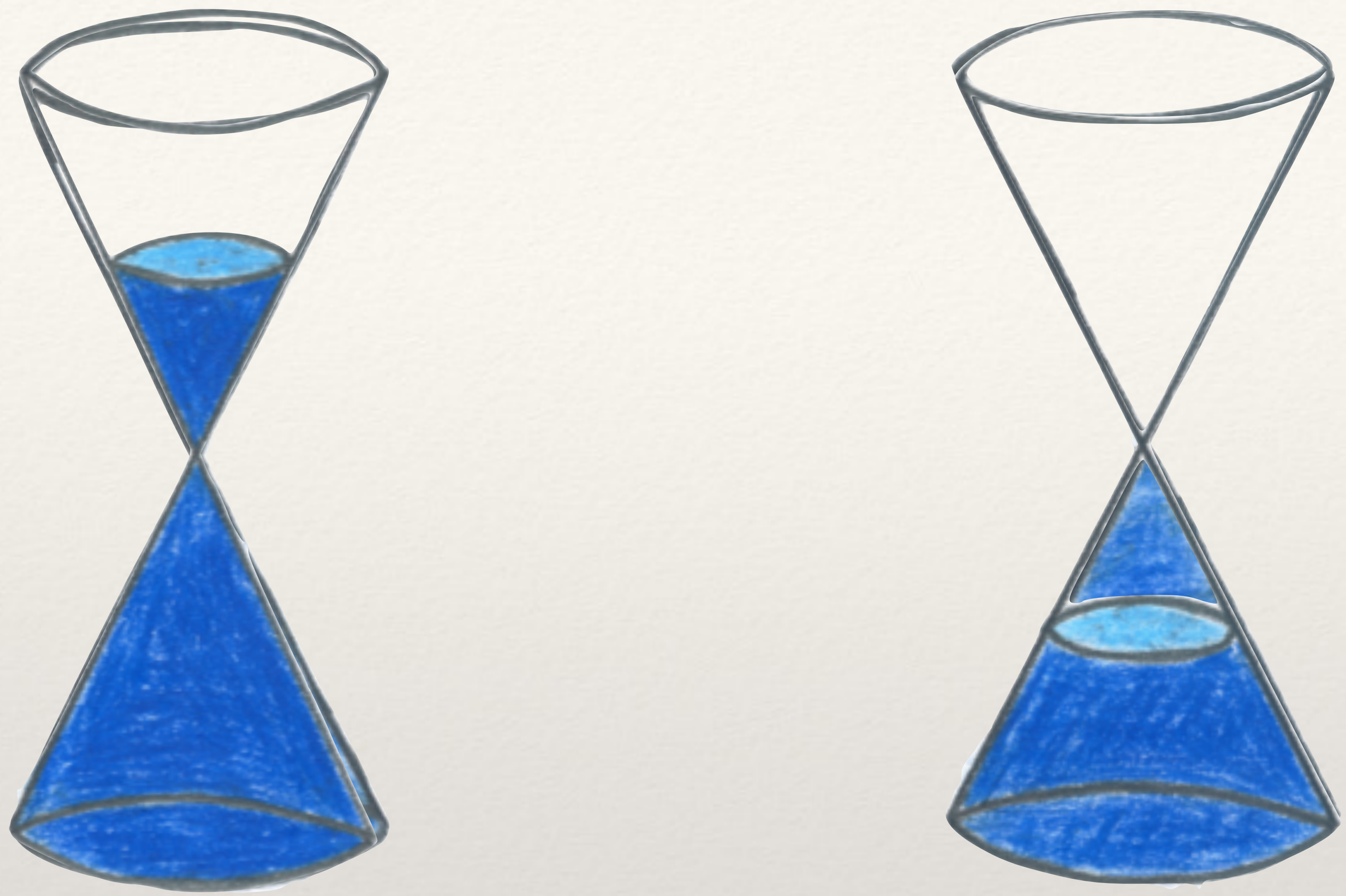




Potter, Kimchi, Vishwanath, Nature Comm. 2014
Baum, Berg, Parameswaran, Stern PRX 2015
Moll, Nair, Helm, Potter, Kimchi, Vishwanath, Analytis, Nature 2016

Chiral anomaly

Chiral anomaly in a Weyl semimetal



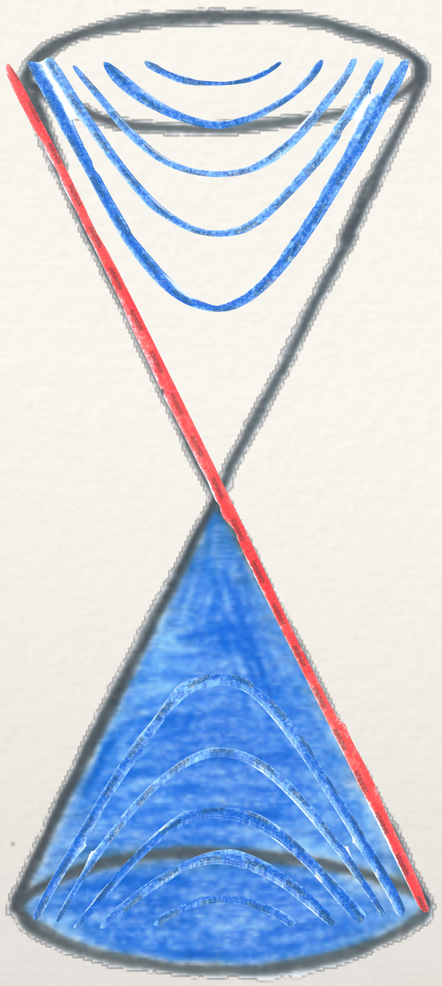
$$\frac{\partial}{\partial t}(n_L + n_R) = 0$$

$$\frac{\partial}{\partial t}(n_L - n_R) = \frac{e^2}{2\pi^2\hbar^2}\mathbf{E}\cdot\mathbf{B} - \frac{n_L - n_R}{\tau_v}$$

Nielsen & Ninomiya Phys. Lett. B 1983; Volovik JETP Lett 1999; Aji PRB 2012

see also Burkov 1502.07609 and references within

Zero Landau level is chiral



$$H = \chi(\mathbf{p} - e\mathbf{A}) \cdot \boldsymbol{\sigma} \qquad \chi = \pm \qquad \mathbf{B} = B\mathbf{e}_3$$

$$a_{p_2} = \frac{1}{\sqrt{2}}\left(\frac{x_1 - p_2\ell_B^2}{\ell_B} + ip_1\ell_B\right)$$

$$[a_{p_2}, a_{p_2}^\dagger] = 1$$

$$H = \chi\begin{pmatrix} p_3 & i\sqrt{2}a_{p_2}^\dagger/\ell_B \\ -i\sqrt{2}a_{p_2}/\ell_B & -p3 \end{pmatrix}$$

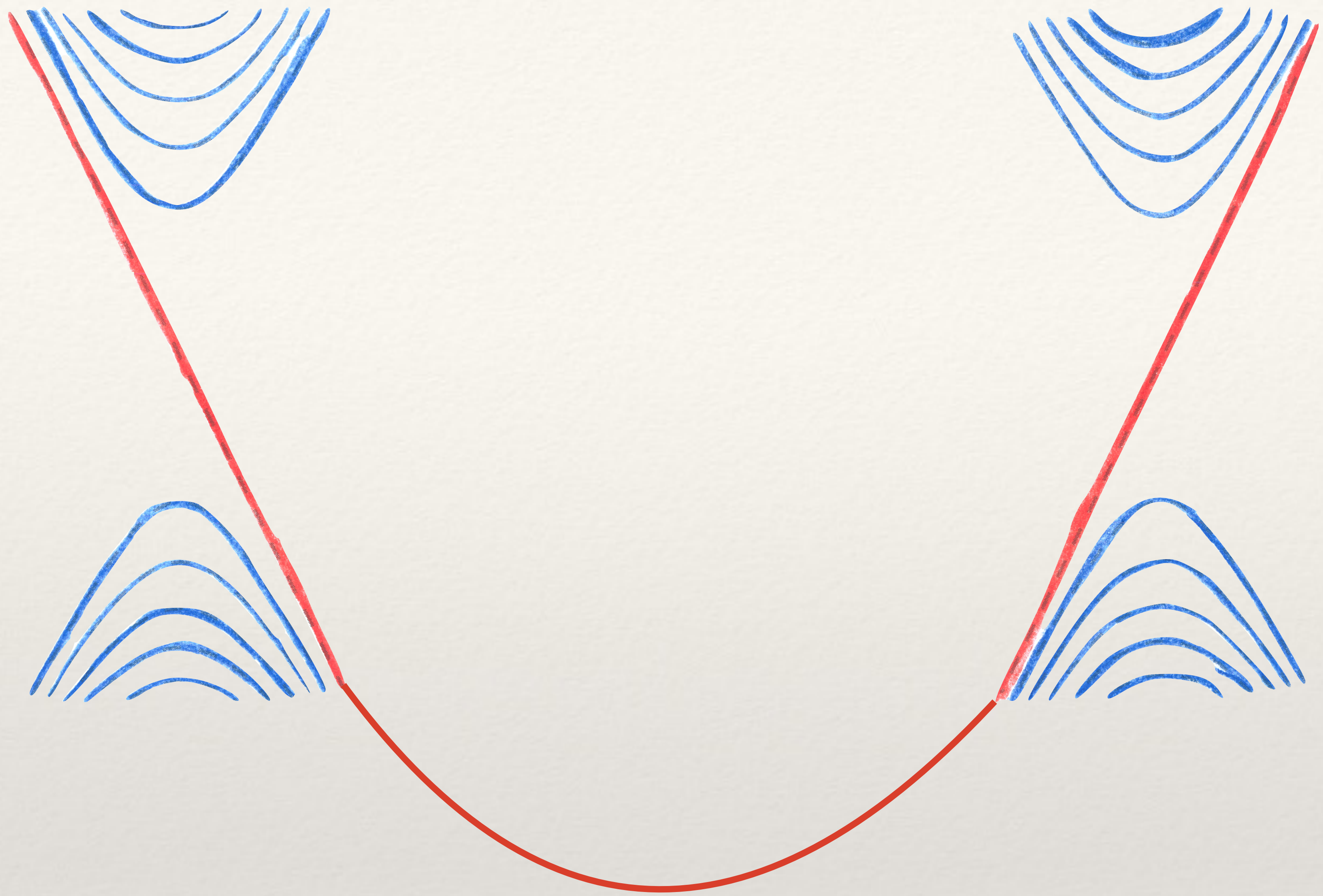
$$\psi_n = \begin{pmatrix} |n\rangle \\ \lambda|n-1\rangle \end{pmatrix}$$

$$E_n = \pm\chi\sqrt{p_3^2 + 2n\ell_B^2}$$

$$\psi_0 = \begin{pmatrix} |0\rangle \\ 0 \end{pmatrix} \qquad E_0 = \chi p_3$$

Nielsen & Ninomiya Phys. Lett. B 1983

Zero Landau level is chiral



$$\frac{\partial p_3}{\partial t} = eE$$

$$\frac{\partial n}{\partial t} = \frac{eE}{2\pi\hbar}\frac{eB}{2\pi\hbar} = \frac{e^2}{4\pi^2\hbar^2}\mathbf{E}\cdot\mathbf{B}$$

Nielsen & Ninomiya Phys. Lett. B 1983

Semiclassical Boltzmann theory gives the same answer

$$\frac{\partial n_{\mathbf{p}}}{\partial t} + \dot{\mathbf{r}} \cdot \frac{\partial n_{\mathbf{p}}}{\partial \mathbf{r}} + \dot{\mathbf{p}} \cdot \frac{\partial n_{\mathbf{p}}}{\partial \mathbf{p}} = I_{\text{coll}}\{n_{\mathbf{p}}\}$$

$$\dot{\mathbf{r}} = \frac{\partial \epsilon_{\mathbf{p}}}{\partial \mathbf{p}} + \dot{\mathbf{p}} \times \mathbf{\Omega}_{\mathbf{p}} \qquad \mathbf{\Omega}_{\mathbf{p}} = \mathbf{\nabla}_p \times \mathbf{A}_{\mathbf{p}} \qquad \mathbf{A}_{\mathbf{p}} = i\langle u_{\mathbf{p}} | \mathbf{\nabla} u_{\mathbf{p}} \rangle$$

$$\dot{\mathbf{p}} = e\mathbf{E} + \frac{e}{c}\dot{\mathbf{r}} \times \mathbf{B}$$

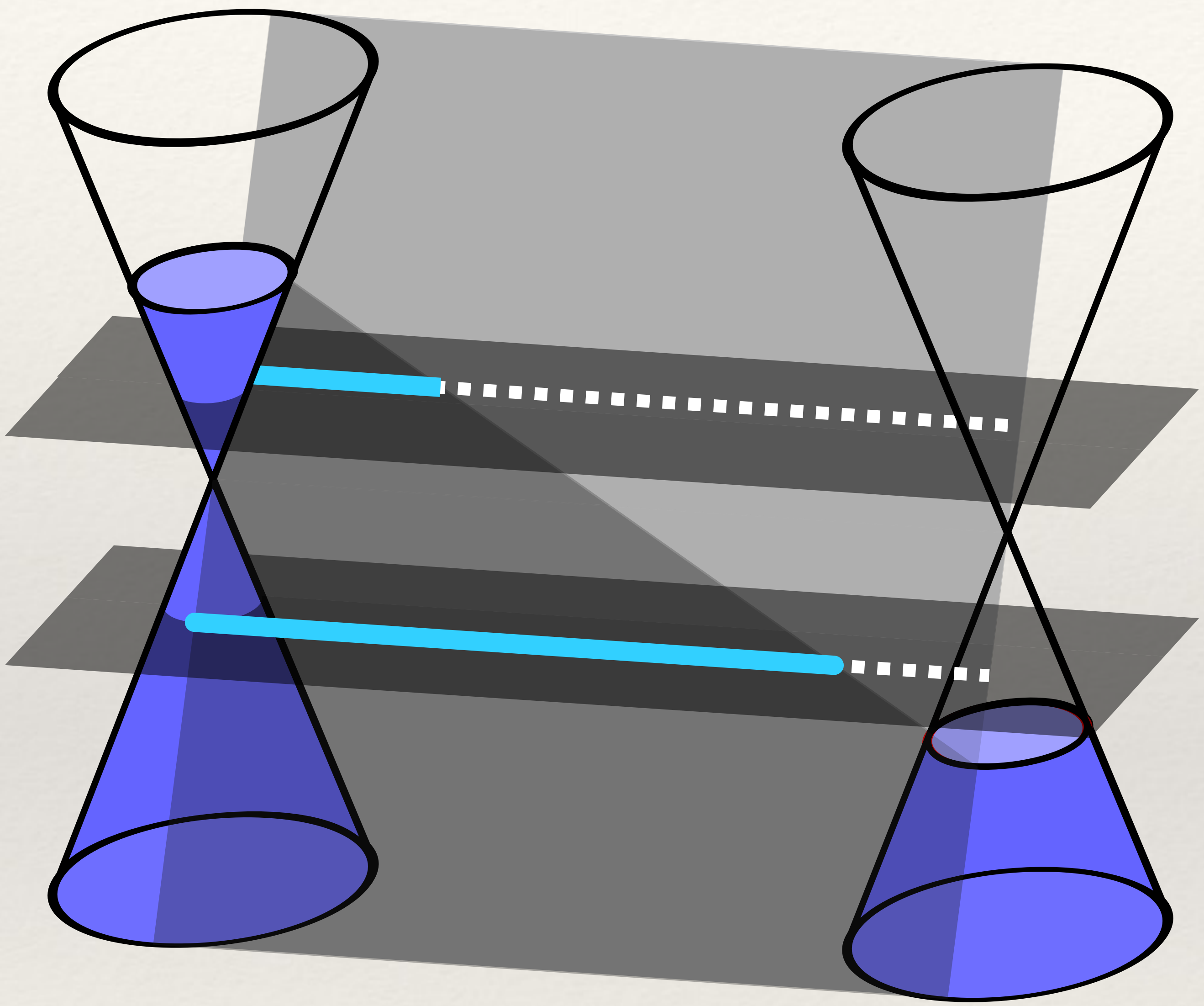
$$\nu^{(i)} = \frac{1}{2\pi\hbar} \oint d\mathbf{S} \cdot \mathbf{\Omega}_{\mathbf{p}}^{(i)} \quad \in \mathbb{Z}$$

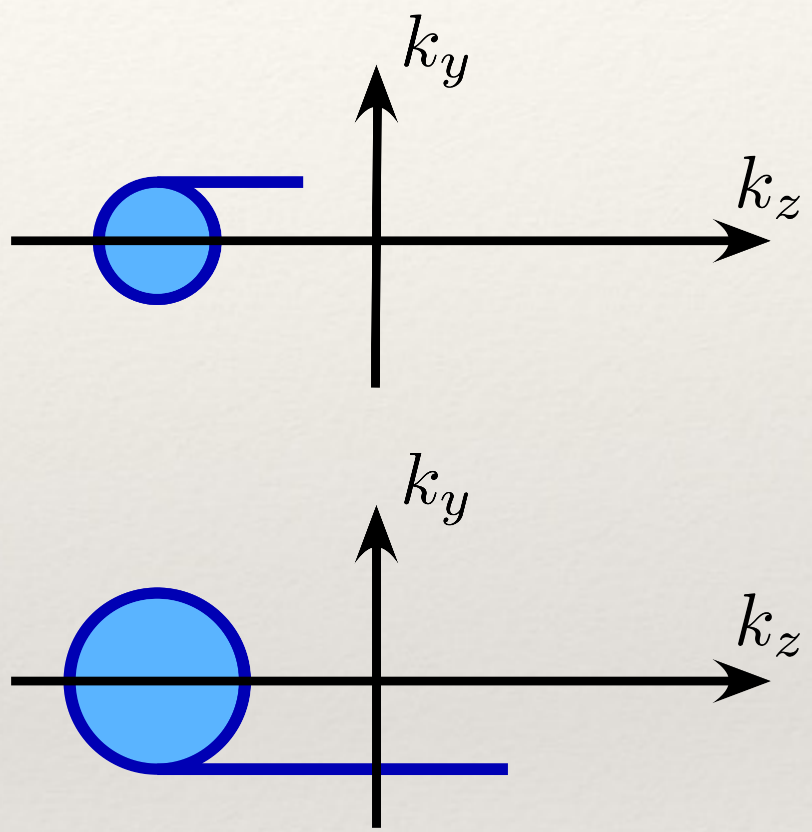
$\dots$

$$\frac{\partial n^{(i)}}{\partial t} + \mathbf{\nabla} \cdot \mathbf{j}^{(i)} = \nu^{(i)} \frac{e^2}{4\pi^2\hbar^2} \mathbf{E} \cdot \mathbf{B} - \frac{\delta n^{(i)}}{\tau}$$

D. T. Son and B. Z. Spivak PRB (2013)

The chiral anomaly induced chiral chemical potential tilts the Fermi arc

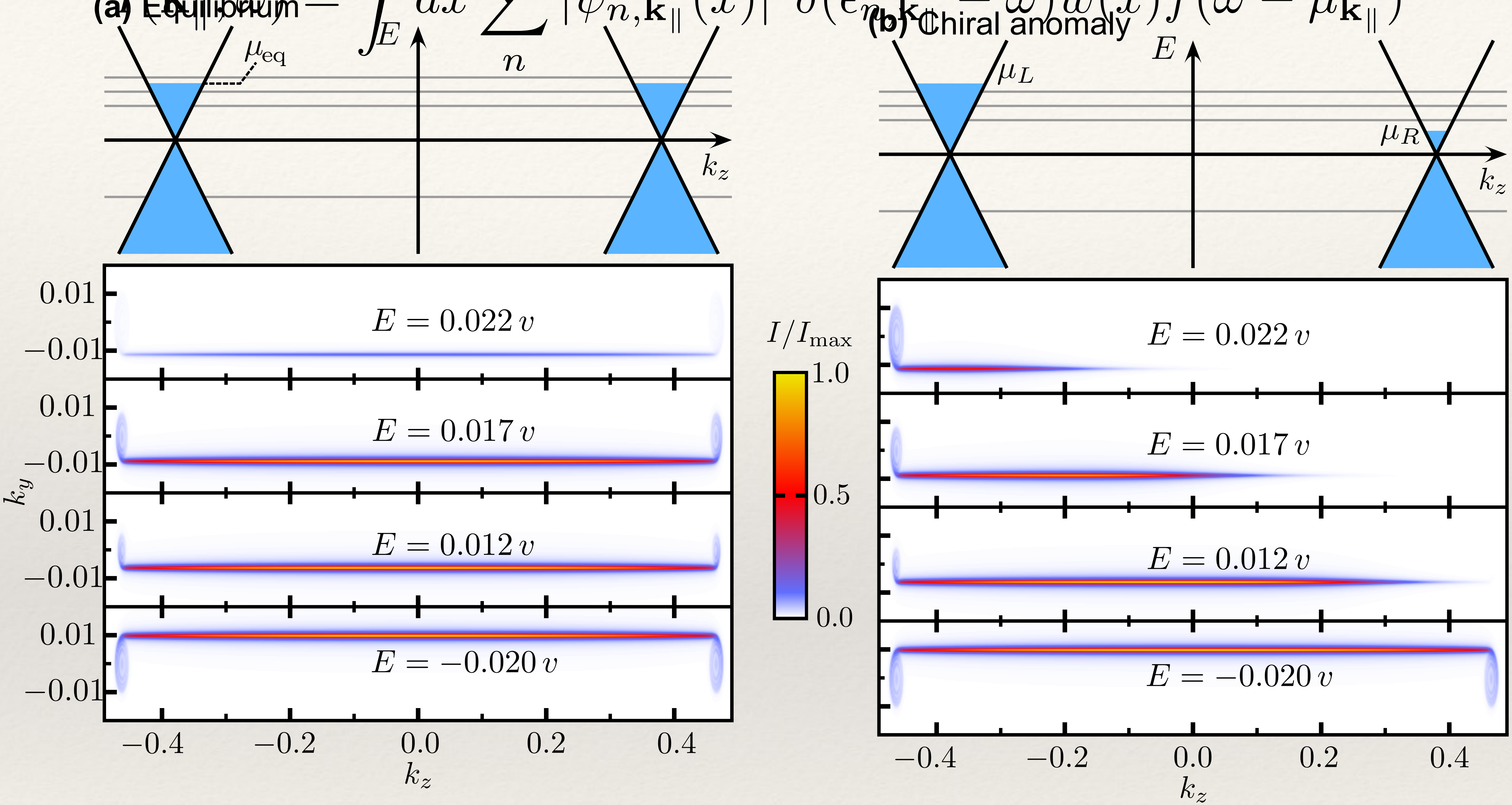




Behrends, Grushin, Ojanen, **JHB** PRB 2016

ARPES — Weyl semimetal

$$I(\mathbf{k}_\parallel,\omega) = \int dx \sum_n |\psi_{n,\mathbf{k}_\parallel}(x)|^2 \delta(\epsilon_{n,\mathbf{k}_\parallel} - \omega)\, w(x)\, f(\omega - \mu_{\mathbf{k}_\parallel})$$



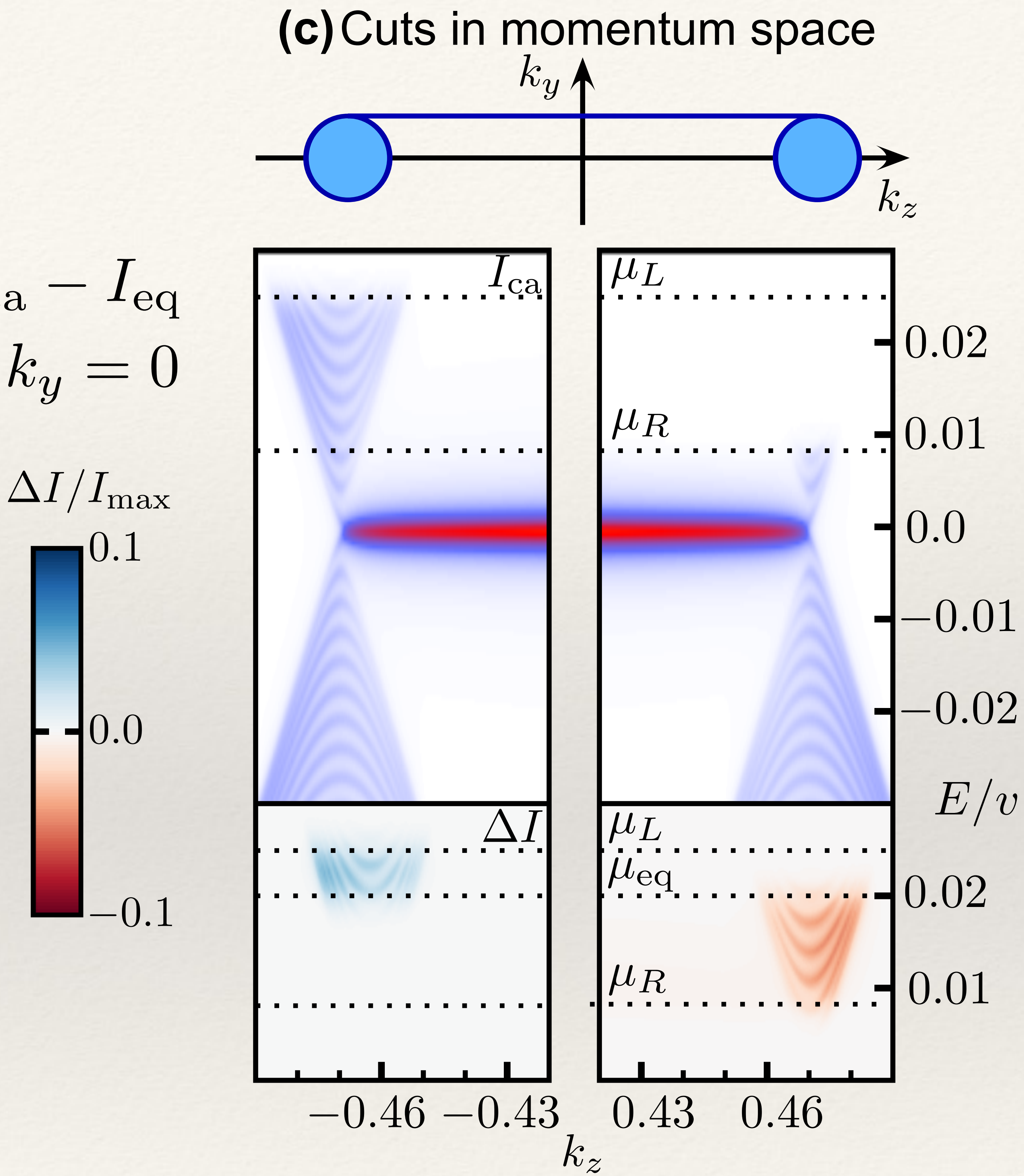
use tight binding model from Vazifeh and Franz PRL 2013

Behrends, Grushin, Ojanen, **JHB** PRB 2016

ARPES — Weyl semimetal

$$\Delta I = I_{\mathrm{ca}} - I_{\mathrm{eq}}$$

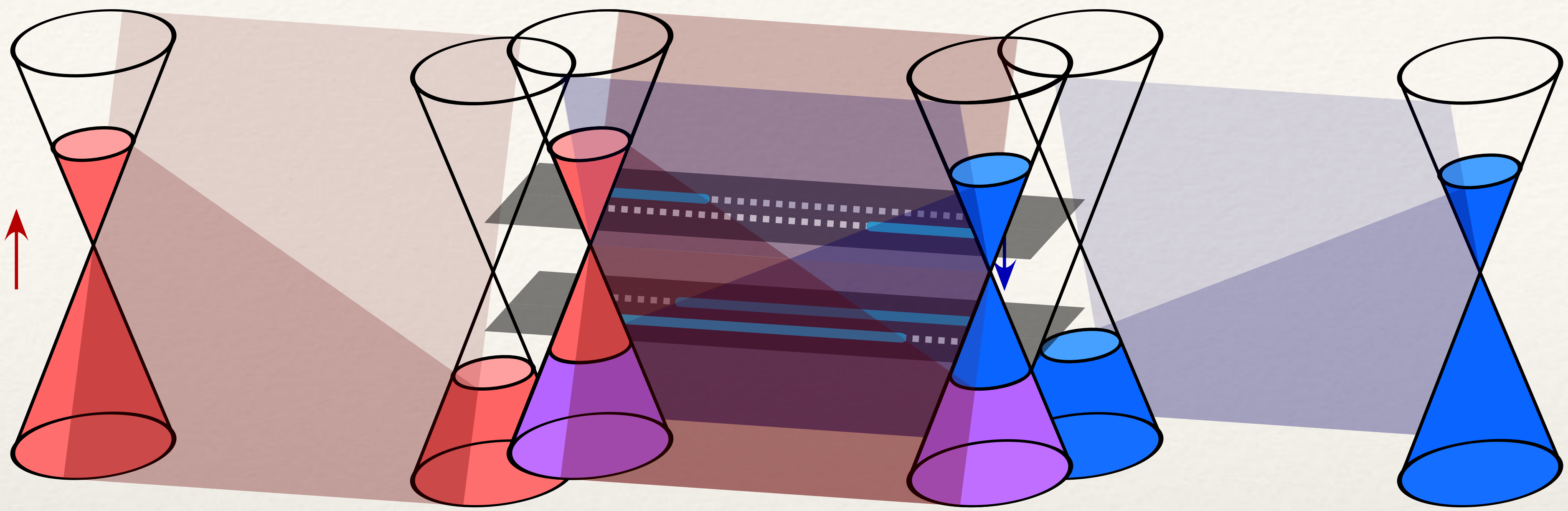
$$k_y = 0$$

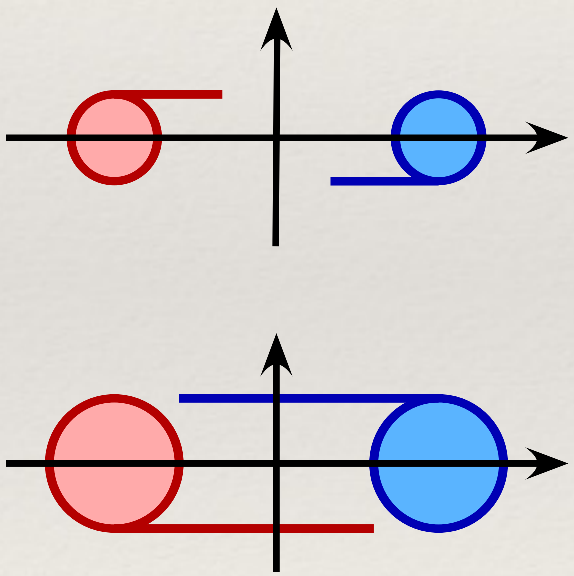


use tight binding model from Vazifeh and Franz PRL 2013

Behrends, Grushin, Ojanen, **JHB** PRB 2016

Dirac semimetal as two copies of a Weyl semimetal

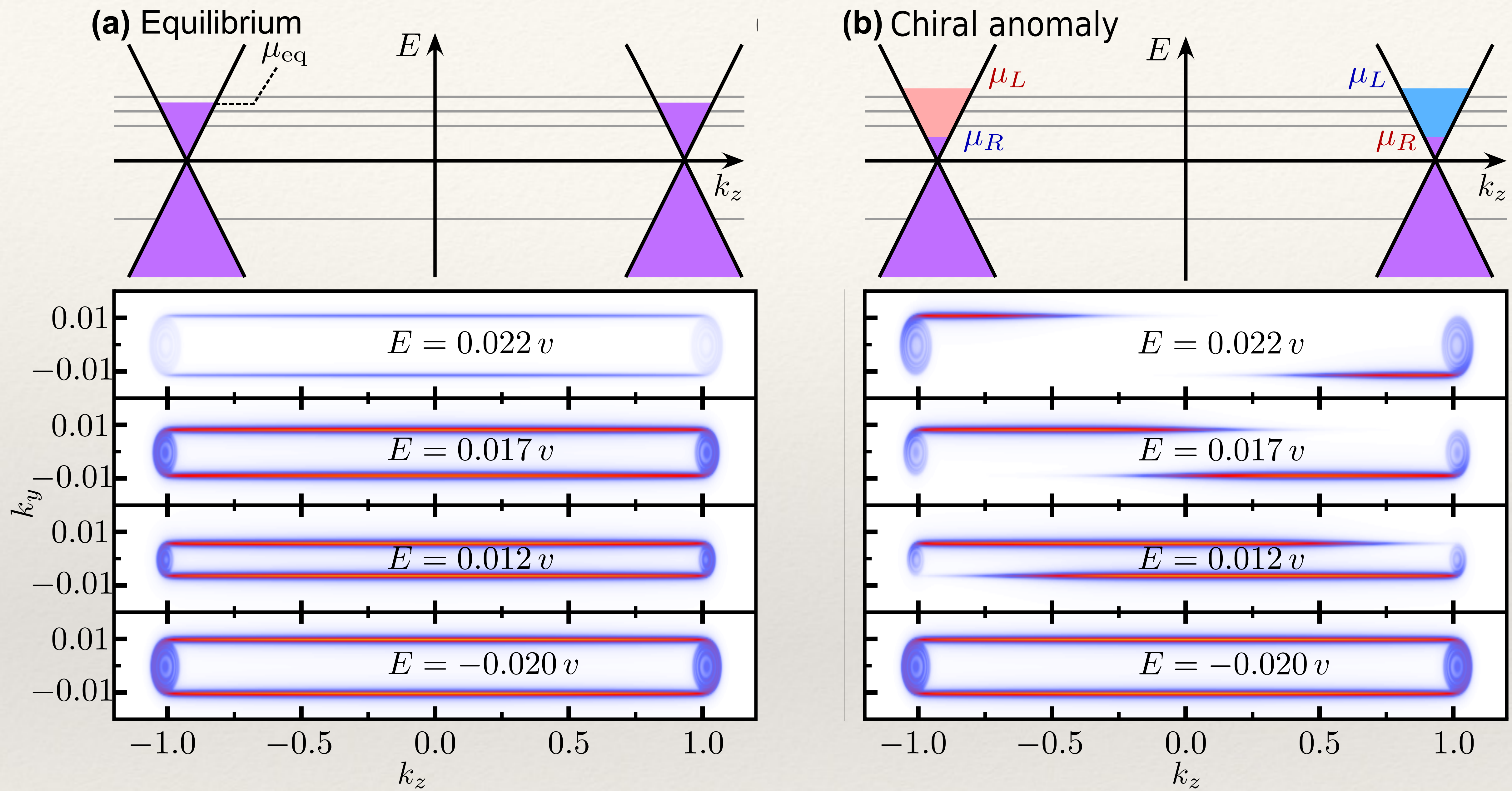




Young et al. PRL 2012,…

Behrends, Grushin, Ojanen, **JHB** PRB 2016

ARPES — Dirac semimetal



use tight binding models from Wang et al. PRB 2012; PRB 2013

Behrends, Grushin, Ojanen, **JHB** PRB 2016

Experimental estimates

Na_3Bi

$$E = 10^4 \text{ V m}^{-1}$$

$$B = 1 \text{ mT}$$

$$\tau_v/\tau_c = 10^4$$

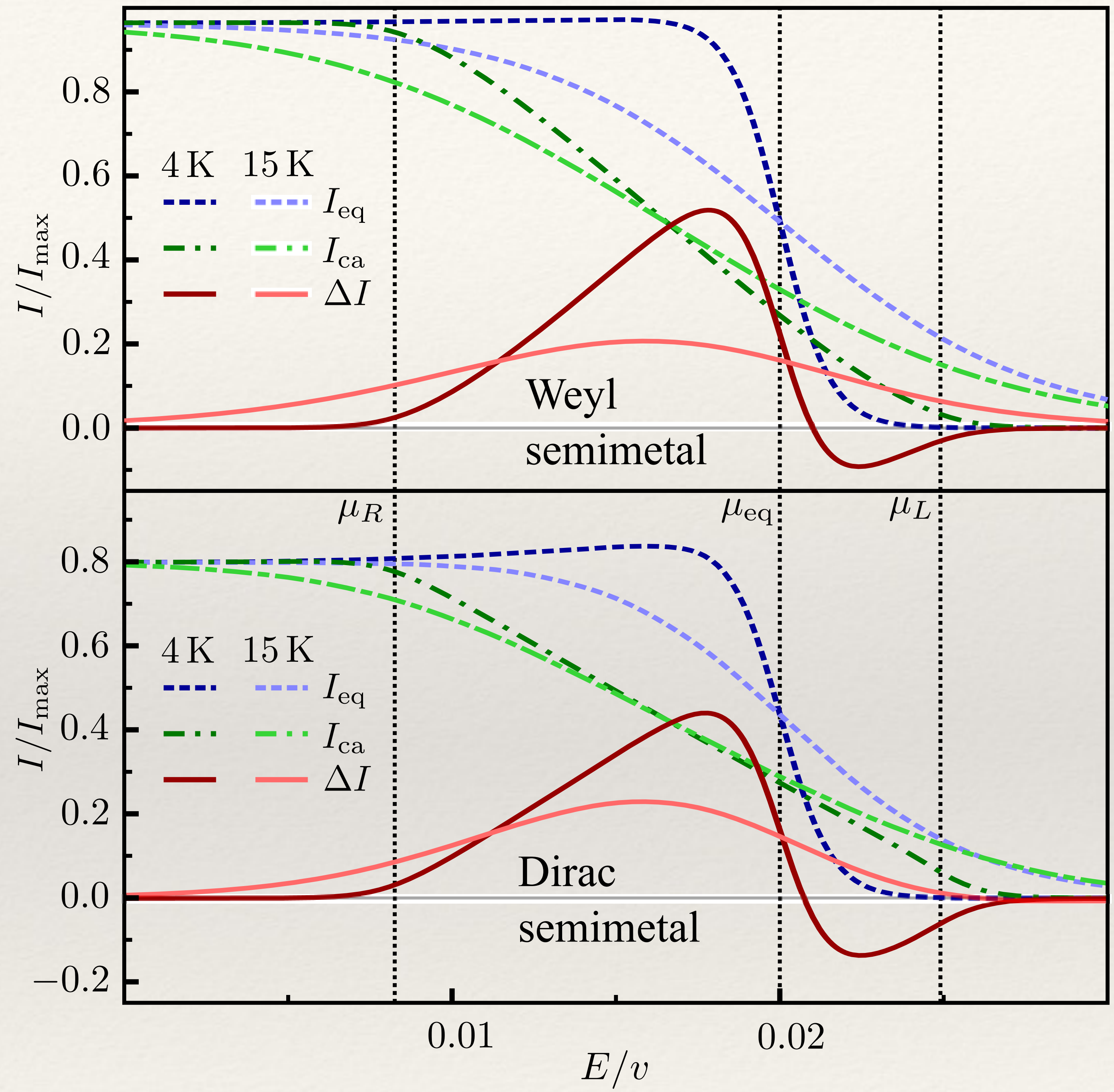
$$\delta\mu = \mu_L - \mu_R \approx 10 \text{ meV}$$

But, ARPES doesn't like B!

Magnetic substrate

Pump-probe

…



discussion of scattering times: Parameswaran et al. PRX 2014

Behrends, Grushin, Ojanen, **JHB** PRB 2016

Transport: negative magnetoresistance

Semiclassical Boltzmann theory and conductance

$$\frac{\partial n^{(i)}}{\partial t} + \boldsymbol{\nabla} \cdot \mathbf{j}^{(i)} = \nu^{(i)} \frac{e^2}{4\pi^2\hbar^2} \mathbf{E} \cdot \mathbf{B} - \frac{\delta n^{(i)}}{\tau}$$

Chiral magnetic effect:

$$\mathbf{j} = \frac{e^2}{4\pi^2\hbar^2 c} \mathbf{B} \sum_i k^{(i)} \mu^{(i)}$$

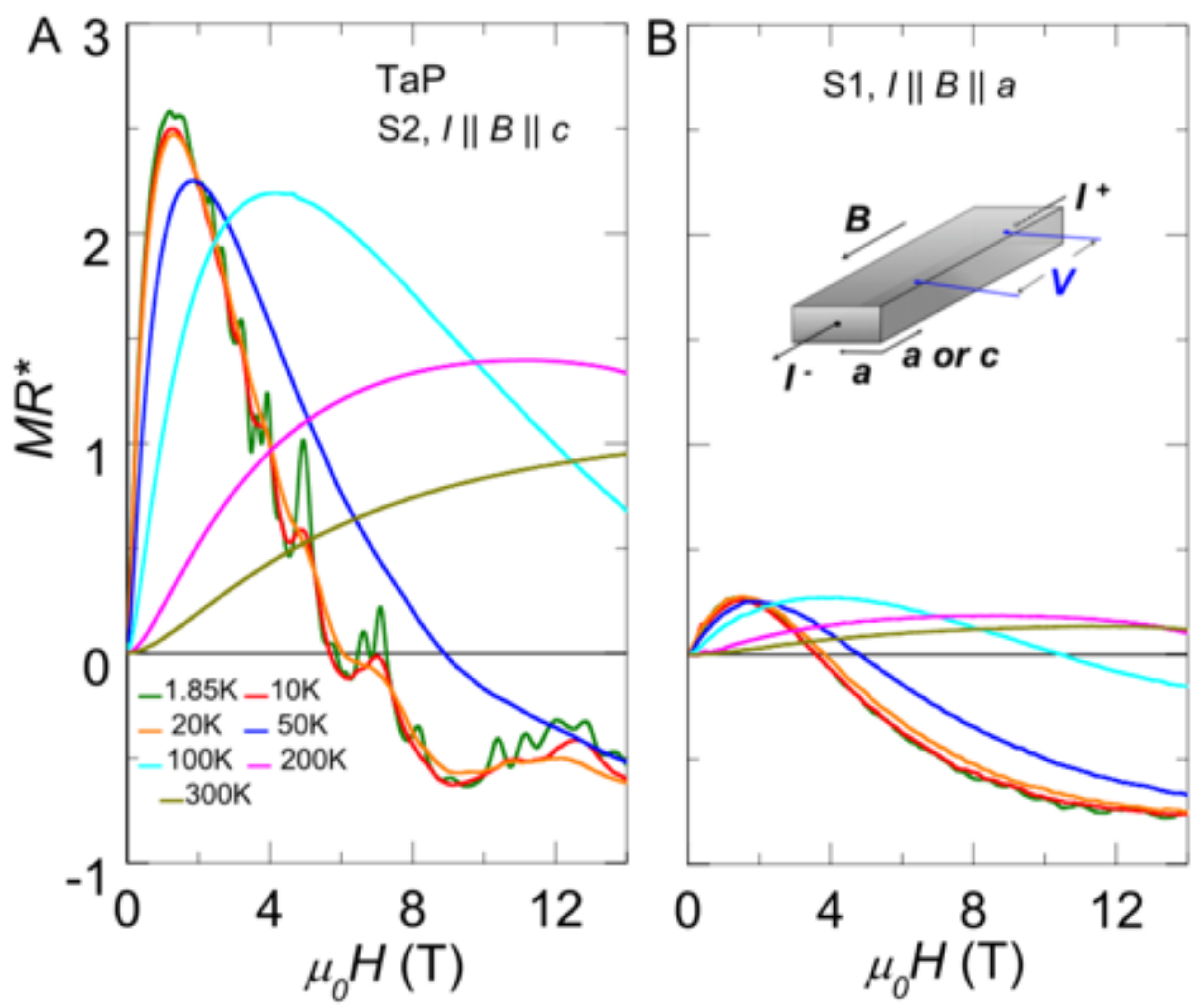
Negative magnetoresistance

$$\sigma_{zz} = \frac{e^2}{4\pi^2\hbar} \frac{(eB)^2 v^3}{\mu^2} \tau \qquad \tau \gg \tau_{\rm tr}$$

D. T. Son and B. Z. Spivak PRB (2013)

Negative magnetoresistance in TaP

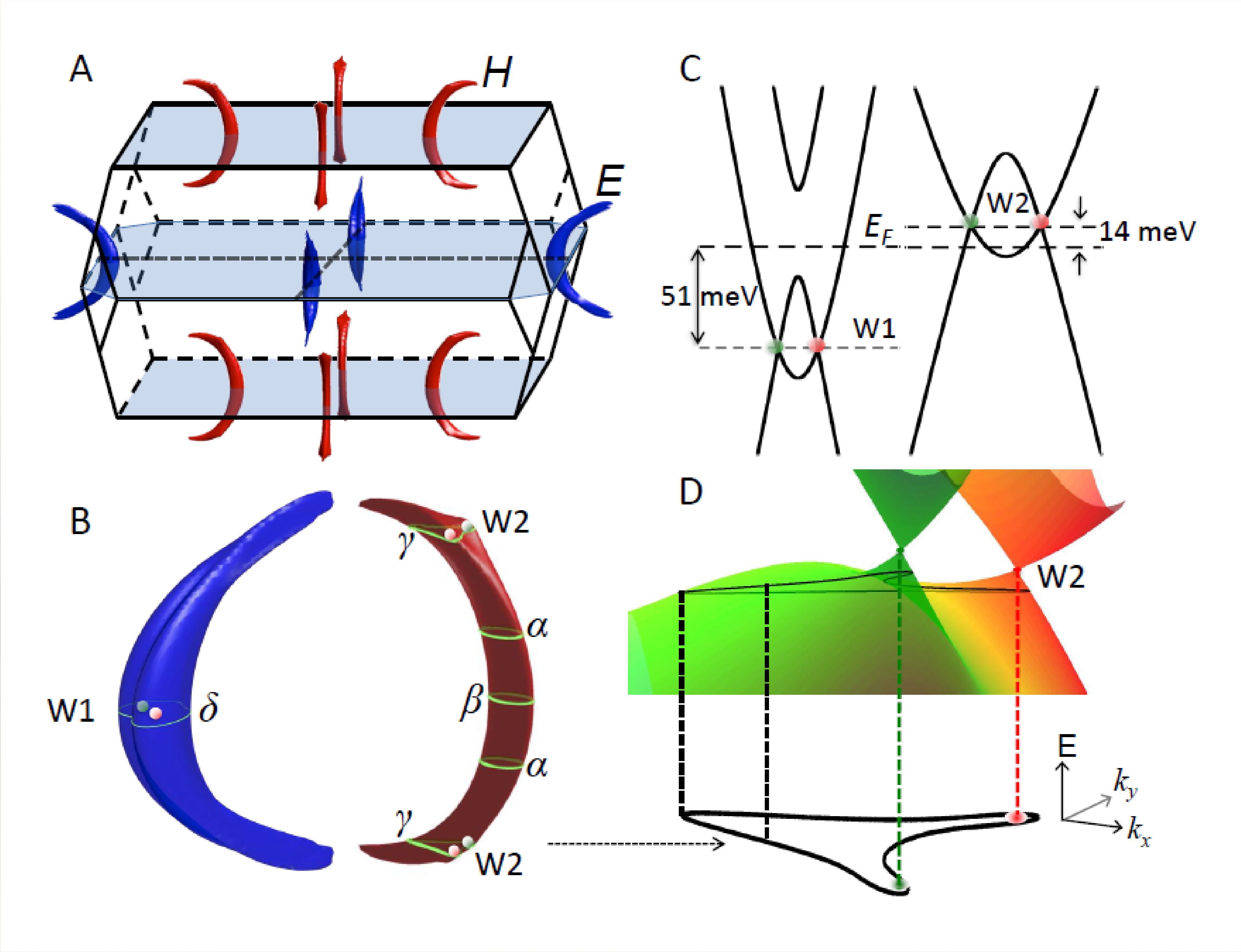
$$\sigma = \sigma_0 + \frac{e^4 B^s \tau_a}{4\pi^4 g(E_F)}$$



Nielsen & Ninomiya Phys. Lett. B 1983,
Aji PRB 2012, Son and Spivak PRB 2013, Burkov PRL 2014, PRB 2015

Arnold, …Grushin, JHB, … Felser, Hassinger, Yan Nat. Comm. **7**, 11615 (2016)

TaP has several electron and hole pockets and no well defined chirality



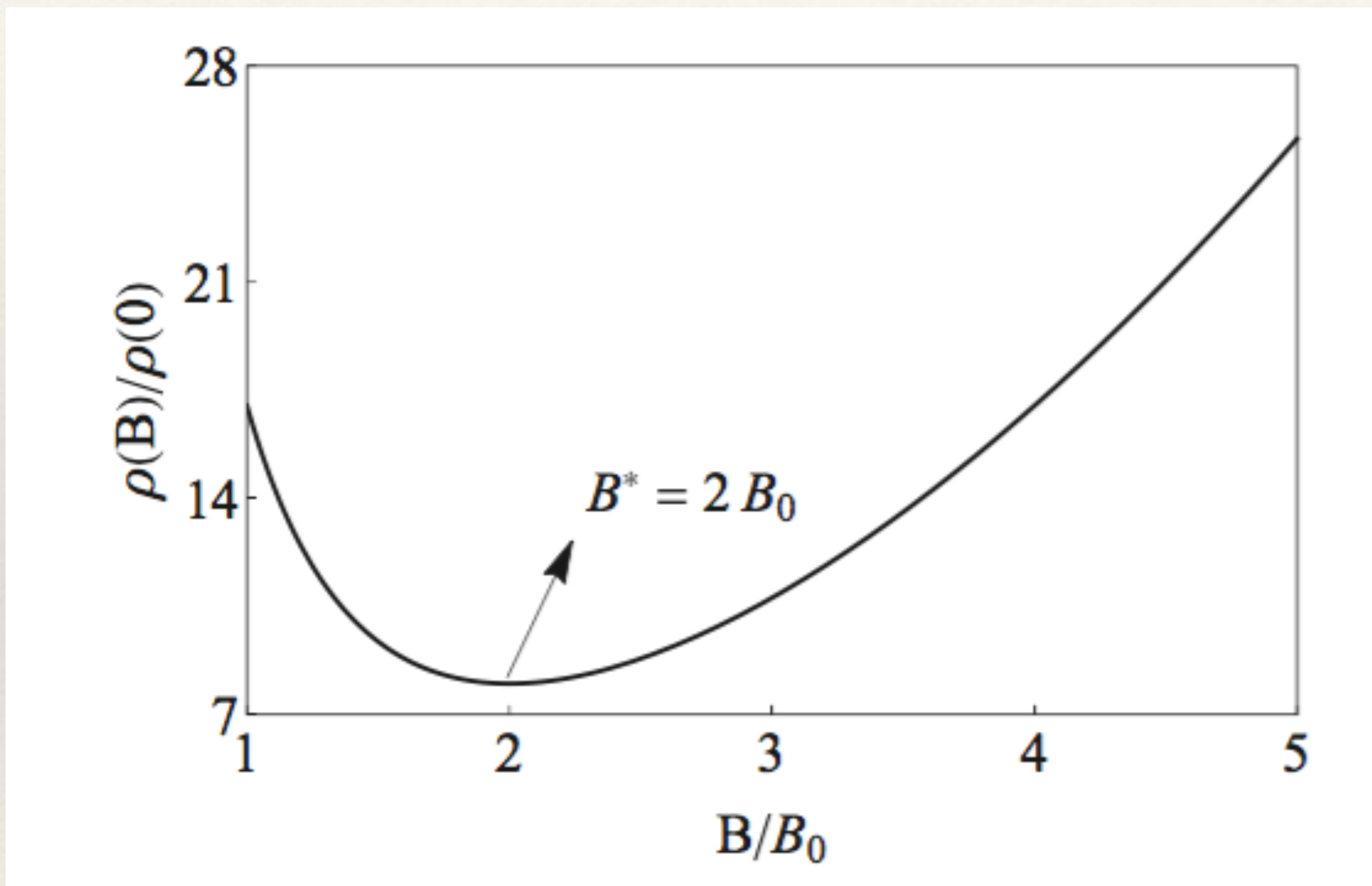
Arnold, …Grushin, JHB, … Felser, Hassinger, Yan Nat. Comm. **7**, 11615 (2016)

Negative magnetoresistance also for electron pockets in quantum limit

PHYSICAL REVIEW B **92**, 075205 (2015)

Axial anomaly and longitudinal magnetoresistance of a generic three-dimensional metal

Pallab Goswami, J. H. Pixley, and S. Das Sarma



Gyrotropic magnetic effect

$$j_i = \alpha_{ij}^{\mathrm{GME}} B_j$$

$$\alpha_{ij}^{\mathrm{GME}} = \frac{i\omega\tau}{i\omega\tau - 1} \frac{e}{(2\pi)^2 h} \sum_{n,a} \int_{S_{n,a}} dS \hat{v}_{F,i} m_{\mathbf{k}n,j}$$

$$\mathbf{m}_{\mathbf{k}n} = -(e g_s / 2m_e) \mathbf{S}_{\mathbf{k}n} + \mathbf{m}_{\mathbf{k}n}^{\mathrm{orb}}$$

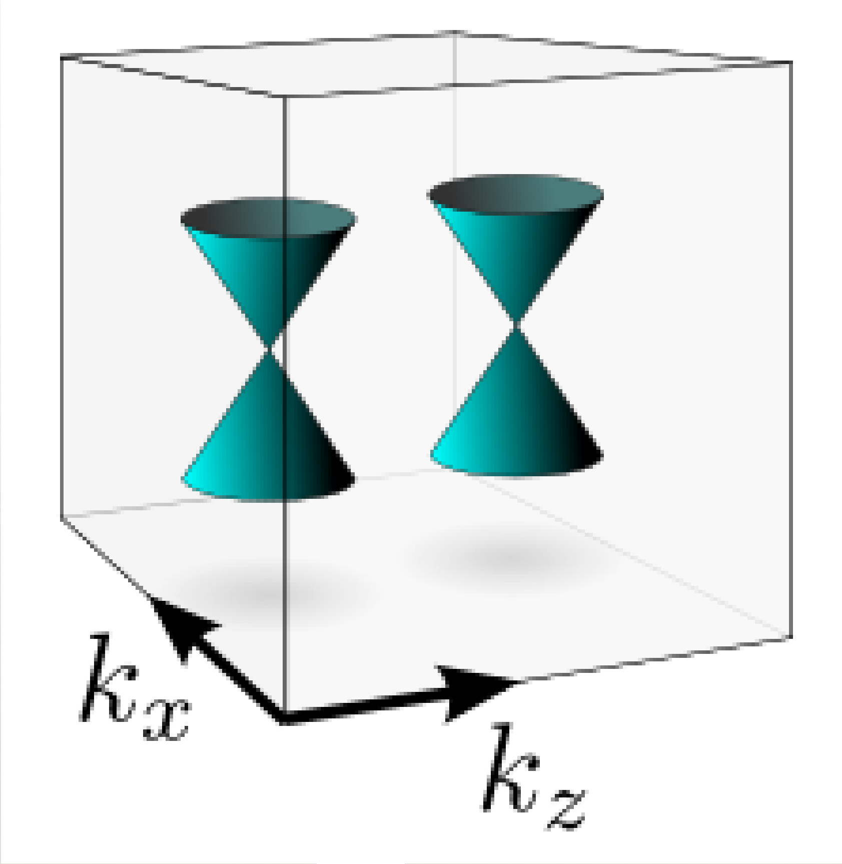
$$\mathbf{m}_{\mathbf{k}n}^{\mathrm{orb}} = \frac{e}{2\hbar} \mathrm{Im} \langle \partial_{\mathbf{k}} u_{\mathbf{k}n} | \times (H_{\mathbf{k}} - \epsilon_{\mathbf{k}n}) | \partial_{\mathbf{k}} u_{\mathbf{k}n} \rangle$$

Zhong, Moore, Souza PRL 2016
Ma, Pesin PRB 2015

Fractional chiral metal

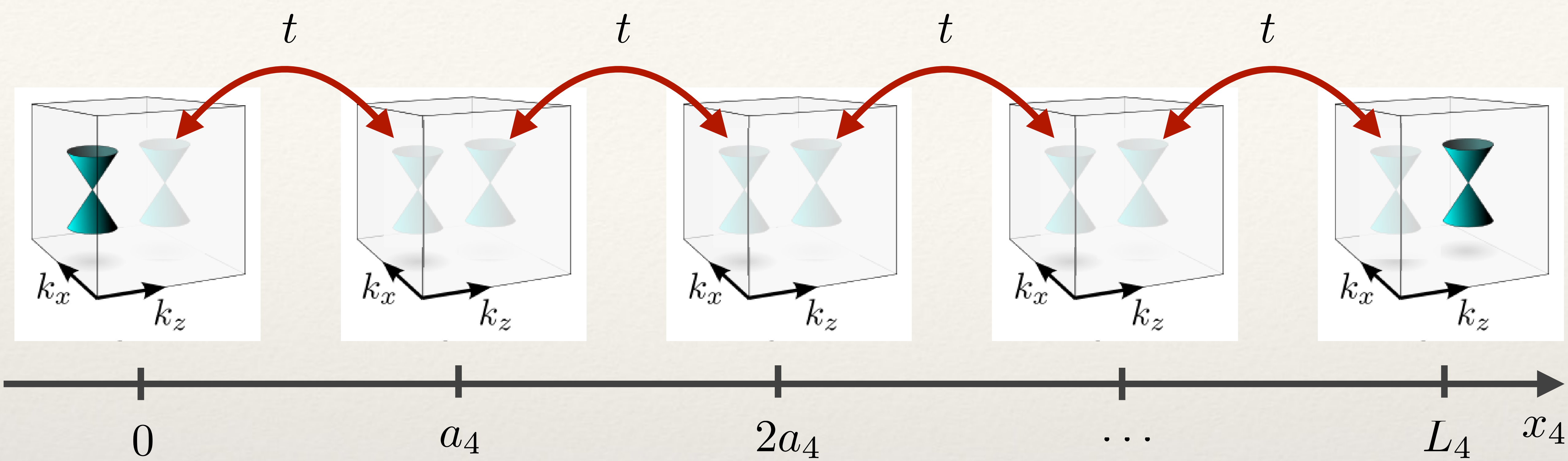
Meng, Grushin, Shtengel, JHB arXiv:1602.08856 (to appear in PRB)

A 4D construction of a Weyl semimetal



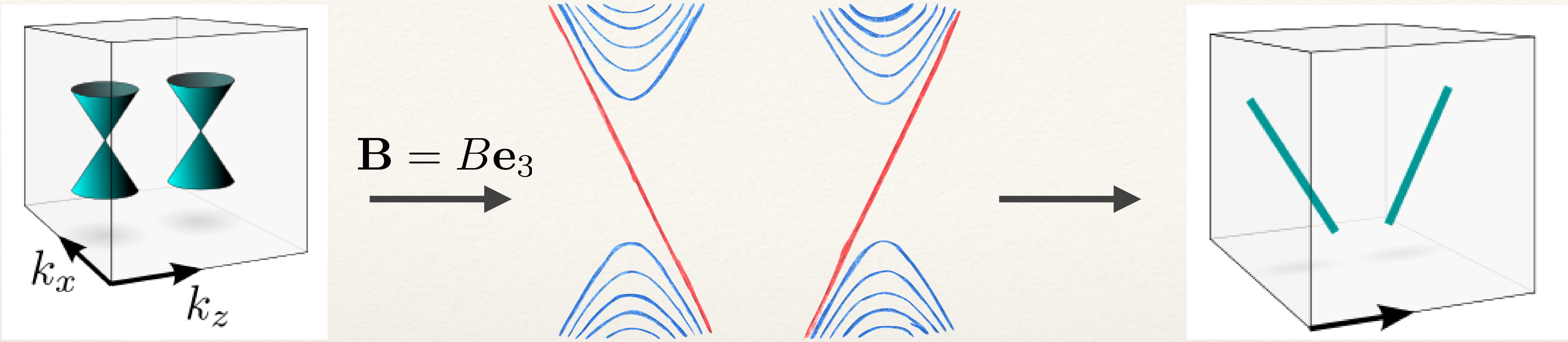
Meng, Grushin, Shtengel, JHB arXiv:1602.08856

A 4D construction of a Weyl semimetal



Meng, Grushin, Shtengel, JHB arXiv:1602.08856

In presence of interactions first go to quantum limit and bosonize



$$H_0 = \sum_{x_4,p_2} \int dx_3 \left(R^\dagger_{p_2}(x_3,x_4)(-i\partial_3) R_{p_2}(x_3,x_4) + L^\dagger_{p_2}(x_3,x_4)(i\partial_3) L_{p_2}(x_3,x_4) \right)$$

$$H_0^{\mathrm{bos}} = \sum_{r,q,q',p_2} \int dx_3 \, (\partial_3 \Phi_{rp_2}(q,x_4))^T V_{p_2,q,q'} (\partial_3 \Phi_{rp_2}(q',x_4))$$

$$V_{p_2,q,q'} = \frac{v_F}{4\pi} \delta_{q,q'} \mathbb{1} + \tilde{U}_{p_2,q,q'}$$

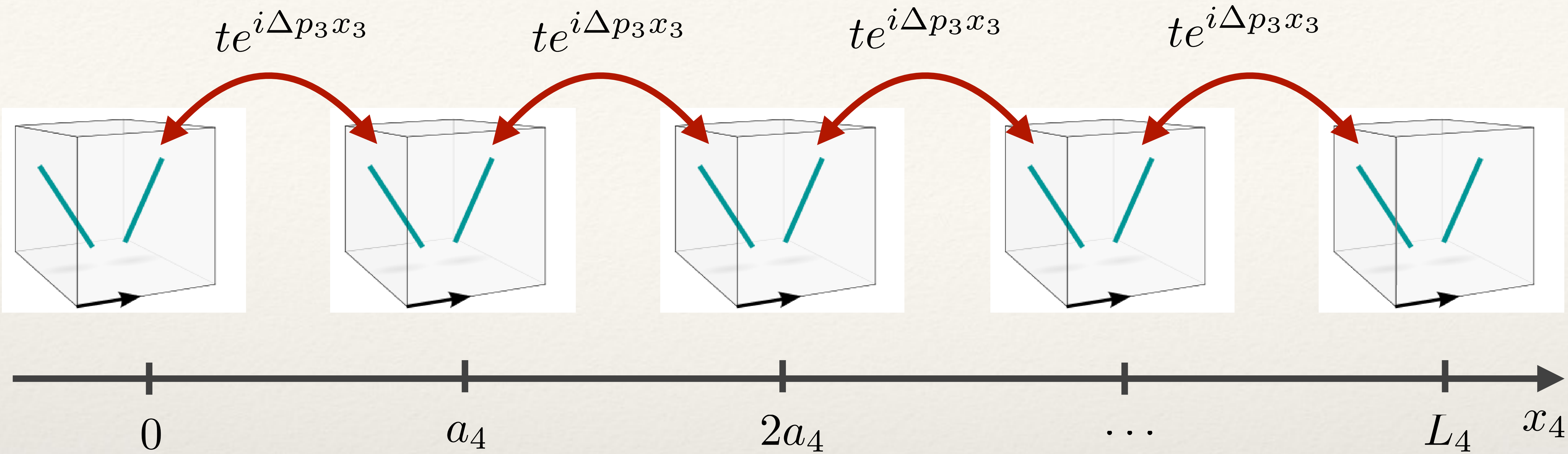
$$c_{p_2}(x_3,x_4) = e^{-ix_3 b/2} L_{p_2}(x_3,x_4) + e^{ix_3 b/2} R_{p_2}(x_3,x_4)$$

$$r_{p_2}(x_3,x_4) = \frac{U_{rp_2x_4}}{\sqrt{2\pi\alpha}} e^{-i\Phi_{rp_2}(x_3,x_4)}$$

$$[\Phi_{rp_2}(x_3,x_4), \Phi_{r'p_2'}(x_3',x_4')] = \delta_{rr'} \delta_{p_2p_2'} \delta_{x_4x_4'} i\pi\hat{r}\mathrm{sgn}(x_3 - x_3')$$

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

Coupled wires construction

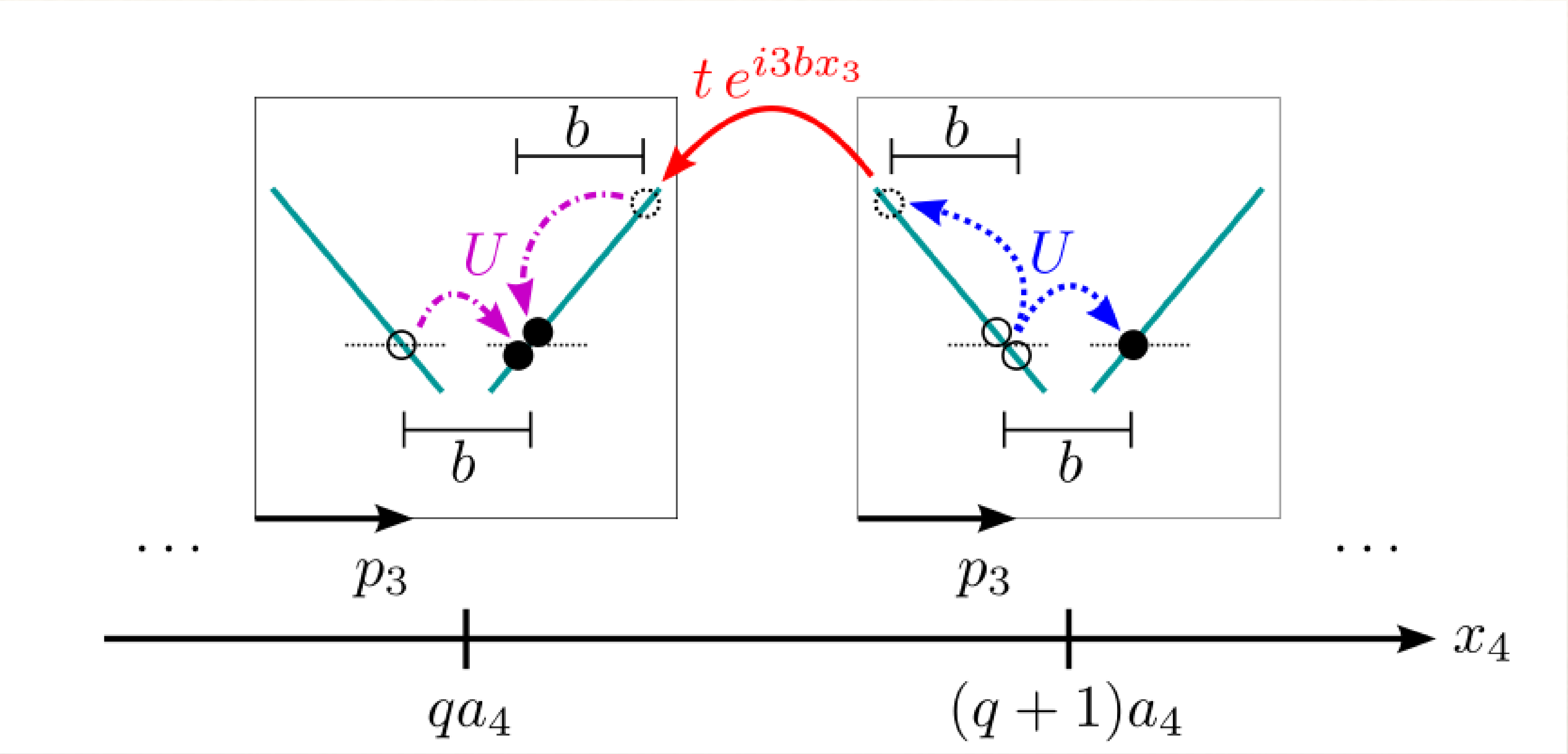


$$H_{\text{tun}} = \sum_{q,p_2,p_3} t c^\dagger_{p_2,p_3+\Delta p_3}((q+1)a_4) c_{p_2,p_3}(qa_4) + \text{h.c.}$$

$$H_{\text{int}} = \int dx_3 \sum_{p_2,x_4} U c^\dagger_{p_2}(x_3,x_4)(\partial_3 c^\dagger_{p_2}(x_3,x_4))(\partial_3 c_{p_2}(x_3,x_4))c_{p_2}(x_3,x_4)$$

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

Fractional quantum Hall state obtained for correlated hopping



$$\tilde{\Phi}_{Lp_2}(x_3, x_4) = (m+1)\Phi_{Lp_2}(x_3, x_4) - m\Phi_{Rp_2}(x_3, x_4)$$

$$\tilde{\Phi}_{Rp_2}(x_3, x_4) = (m+1)\Phi_{Rp_2}(x_3, x_4) - m\Phi_{Lp_2}(x_3, x_4)$$

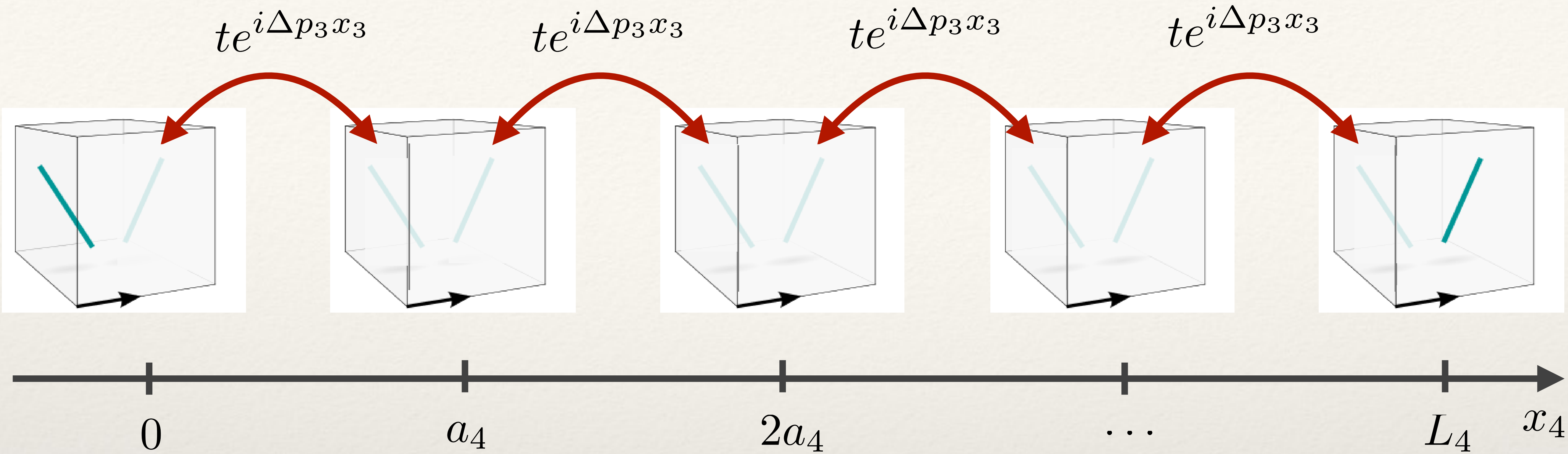
$$[\tilde{\Phi}_{rp_2}(x_3, x_4), \tilde{\Phi}_{r'p_2'}(x_3', x_4')] = \delta_{rr'}\delta_{p_2p_2'}\delta_{x_4x_4'}(2m+1)i\pi\hat{r}\mathrm{sgn}(x_3 - x_3')$$

$$H^{(2m)}_{\mathrm{tun}} \sim tU^{2m}\sum_{q,p_2}\int dx_3 \cos\Big(\tilde{\Phi}_{Lp_2}(x_3, (q+1)a_4) - \tilde{\Phi}_{Rp_2}(x3, qa_4)\Big)$$

C. L. Kane, R. Mukhopadhyay, and T. C. Lubensky, PRL 2002

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

The bulk is gapped out by the correlated hopping



$$H_{\text{tun}}^{(2m)} \sim tU^{2m} \sum_{q,p_2} \int dx_3 \cos\left(\tilde{\Phi}_{Lp_2}(x_3,(q+1)a_4) - \tilde{\Phi}_{Rp_2}(x3, qa_4)\right)$$

Electromagnetic response: $$j^4 = -\frac{e^3}{4\pi^2(2m+1)}\mathbf{E}\cdot\mathbf{B}$$

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

Field theory from minimal coupling and gauge invariance

$$\mathcal{S} = \mathcal{S}_0[\Phi] + \mathcal{S}_1[\Phi, A_4] + \mathcal{S}_2[\Phi, A_\alpha]$$

$$\mathcal{S}_1[\Phi, A_4] \sim tU^{2m} \sum_{q,p_2} \int dx_0 dx_3 \cos\left(\tilde{\Phi}_{Lp_2}((q+1)a_4) - \tilde{\Phi}_{Rp_2}(qa_4) + ea_4 A_4(qA_4)\right)$$

$$\mathcal{S}_2[\Phi, A_\alpha] = e \sum_{x_4} \int dx_0 dx_3 j^\alpha A_\alpha \qquad \alpha = 0, 3$$

$$= \sum_{p_2, x_4} \frac{e}{2\pi(2m+1)} \int dx_0 dx_3 \epsilon^{\alpha\beta} \partial_\alpha (\tilde{\Phi}_{Rp_2} - \tilde{\Phi}_{Lp_2}) A_\beta$$

$$\partial_\alpha j^\alpha = 0$$

$$\rho = \sum_{p_2} \frac{1}{2\pi} \partial_3 (\Phi_{Lp_2} - \Phi_{Rp_2}) = \sum_{p_2} \frac{1}{2\pi(2m+1)} \partial_3 (\tilde{\Phi}_{Lp_2} - \tilde{\Phi}_{Rp_2})$$

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

Strong coupling and electromagnetic response: fractional chiral anomaly

$$\tilde{\Phi}_{Rp_2}(qa_4) - \tilde{\Phi}_{Lp_2}((q+1)a_4) = ea_4 A_4(qa_4)$$

$$\mathcal{S}_2[A_4, A_\alpha] = \sum_{p_2} \frac{-e^2}{2\pi(2m+1)} \int dx_0 dx_3 dx_4 \epsilon^{\alpha\beta} A_4 \partial_\alpha A_\beta$$

$$\sum_{p_2} \to N_{\mathrm{LL}} = eB_3 L_1 L_2 / 2\pi$$

$$j^4 = \frac{\delta \mathcal{S}}{\delta A_4} = -\frac{e^3}{4\pi^2(2m+1)} B_3 E_3$$

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

Action is an anisotropic part of the isotropic 4+1D Chern-Simons action

$$N_{\rm LL} = \frac{B_3 L_1 L_2}{2\pi/e} = \int dx_1 dx_2 \frac{1}{2\pi/e} \epsilon^{\gamma\delta} \partial_\gamma A_\delta$$

$$\mathcal{S}_2[A_\mu] = \frac{-e^3}{(2\pi)^2(2m+1)} \int d^5x \epsilon^{\alpha\beta} \epsilon^{\gamma\delta} A_4 (\partial_\alpha A_\beta)(\partial_\gamma A_\delta)$$

compare with

$$\mathcal{S}_{\rm CS}^{(4+1)}[A_\mu] = \frac{-e^3}{6(2\pi)^2(2m+1)} \int d^5x \epsilon^{\mu\nu\rho\sigma\eta} A_\mu \partial_\nu A_\rho \partial_\sigma A_\eta$$

$$j^4 = -\frac{e^3}{4\pi^2(2m+1)} \mathbf{E} \cdot \mathbf{B}$$

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

Surface field theory — fractional chiral metal

3+1D surface state constructed from $N_{\rm LL}$ copies of the edge theory of 2+1D Chern-Simons theory, labeled by p_2

$$\mathcal{S}_{\rm surface}[\Phi_{R,L}] = \frac{2m+1}{4\pi} N_{\rm LL} \int_{\partial\Sigma} \Big[\partial_0 \Phi_L \partial_3 \Phi_L - v_F (\partial_3 \Phi_L)^2 - (\partial_0 \Phi_R \partial_3 \Phi_R + v_F (\partial_3 \Phi_R)^2) \Big]$$

$$\partial_0 \rho_{R,L} + \hat{r} v_F \partial_3 \rho_{R,L} = 0 \qquad \hat{r} = \pm 1$$

Consistent with current algebra analysis of the 4+1D Chern-Simons field theory

$$S_{\phi F} = \kappa \int_{\partial\Sigma} \partial_0 \phi d\phi \wedge F$$

K. Gupta and A. Stern, Nucl. Phys. B 1995

Meng, Grushin, Shtengel, JHB arXiv:1602.08856

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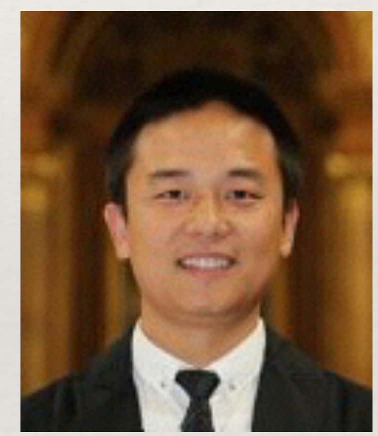
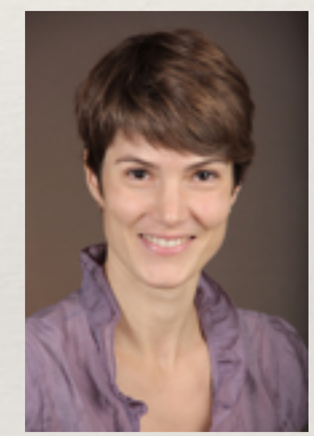


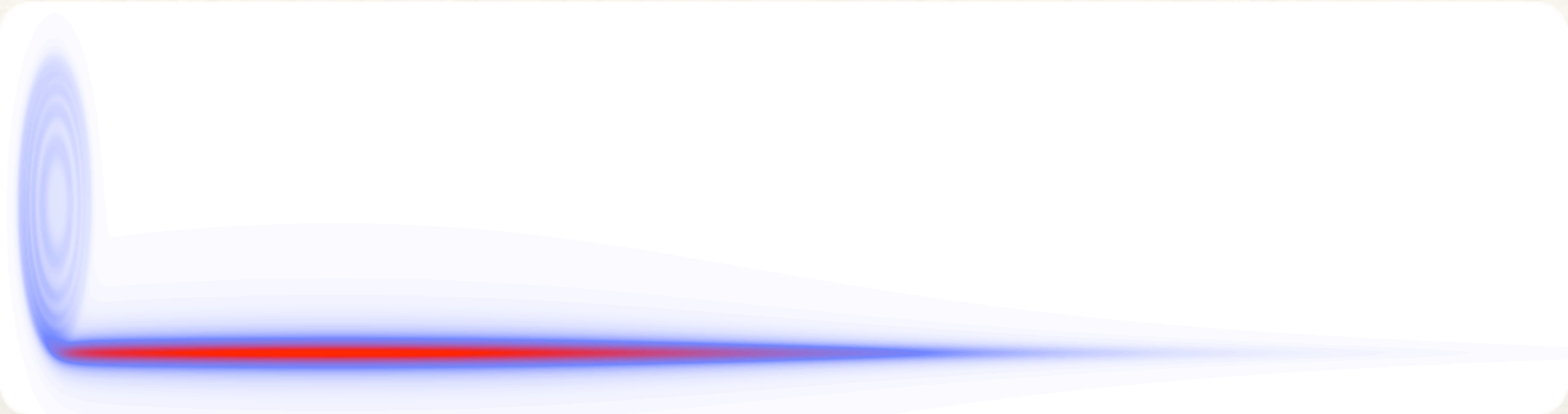
Binghai Yan
(颜丙海)

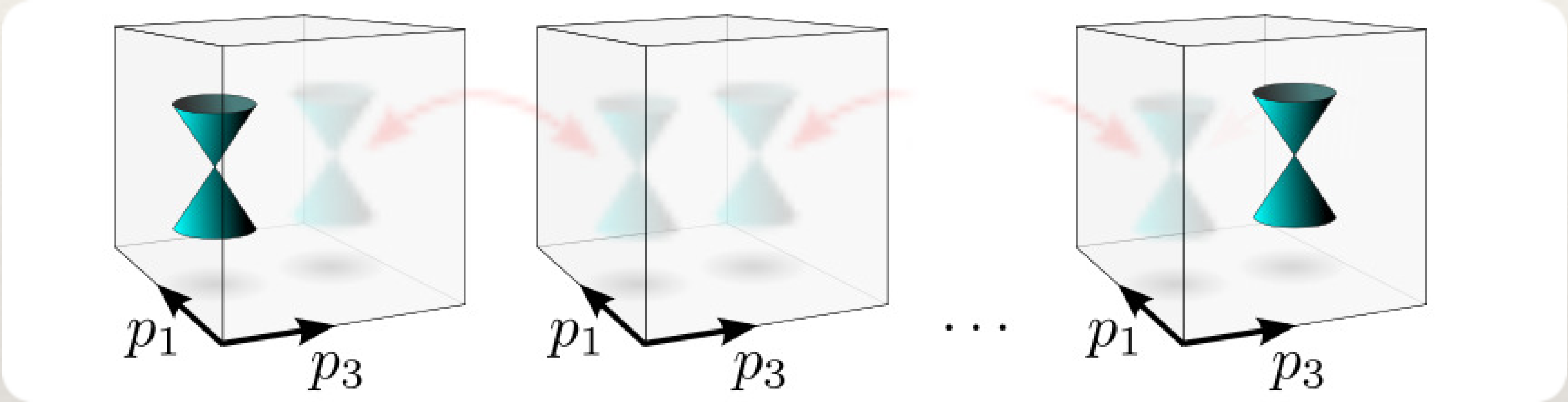


Elena Hassinger

and more

Summary: chiral anomaly visualized through the blue note and fractional chiral metals





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F. Arnold, …A. G. Grushin, JHB, … C. Felser, E. Hassinger, B. Yan Nat. Comm. **7**, 11615 (2016)
T. Meng, A. G. Grushin, K. Shtengel JHB arXiv:1602.08856 (to appear in PRB)