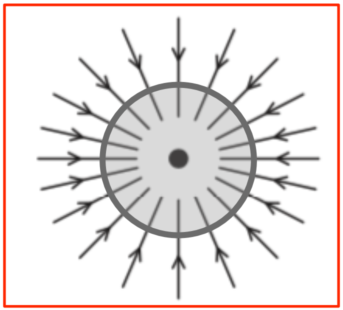
Chiral anomaly: Second viewpoint (Text 5.4.3)

$$\dot{\mathbf{r}} = \mathbf{v}_{\mathrm{g}} - \dot{\mathbf{k}} \times \boldsymbol{\Omega}\,, \tag{5.11a}$$

$$\dot{\mathbf{k}} = -\frac{e}{\hbar}\mathcal{E} - \frac{e}{\hbar c}\,\dot{\mathbf{r}} \times \mathbf{B}\,, \tag{5.11b}$$

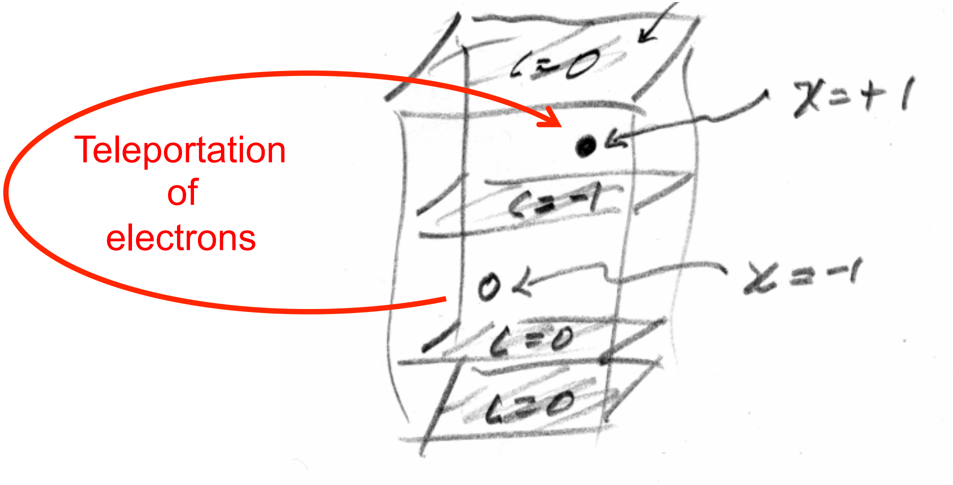
$$\left(1 + \frac{e}{\hbar c}\mathbf{B}\cdot\boldsymbol{\Omega}\right)\dot{\mathbf{r}} = \mathbf{v}_{\mathrm{g}} + \frac{e}{\hbar}\,\mathcal{E} \times \boldsymbol{\Omega} + \frac{e}{\hbar c}\,(\mathbf{v}_{\mathrm{g}}\cdot\boldsymbol{\Omega})\,\mathbf{B}\,, \tag{5.39a}$$

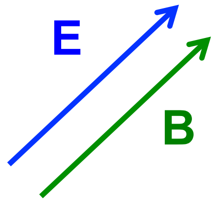
$$\left(1 + \frac{e}{\hbar c}\mathbf{B}\cdot\boldsymbol{\Omega}\right)\boxed{\dot{\mathbf{k}}} = -\frac{e}{\hbar}\mathcal{E} - \frac{e}{\hbar c}\mathbf{v}_{\mathrm{g}} \times \mathbf{B} - \frac{e^2}{\hbar^2 c}\,(\mathcal{E}\cdot\mathbf{B})\,\boxed{\boldsymbol{\Omega}}\,. \tag{5.39b}$$



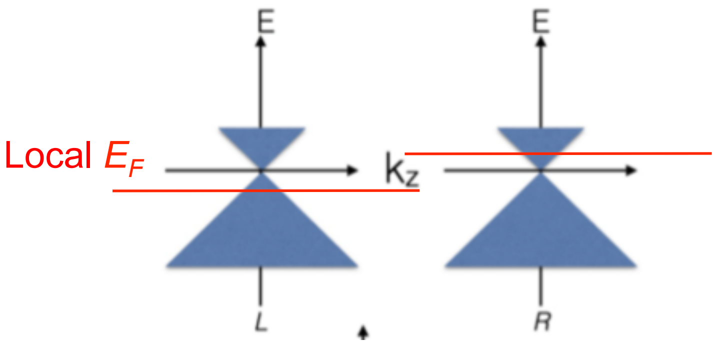
$$\frac{dn}{dt} = \frac{-1}{(2\pi)^3}\,\frac{e^2}{\hbar^2 c}\,(\mathcal{E}\cdot\mathbf{B})\int_{S_{\mathrm{F}}} \boldsymbol{\Omega}\cdot\hat{\mathbf{v}}_{\mathrm{F}}\,d^2k$$

$$= \frac{e^2}{h^2 c}\,(\mathcal{E}\cdot\mathbf{B})\,\chi_i$$





One consequence:

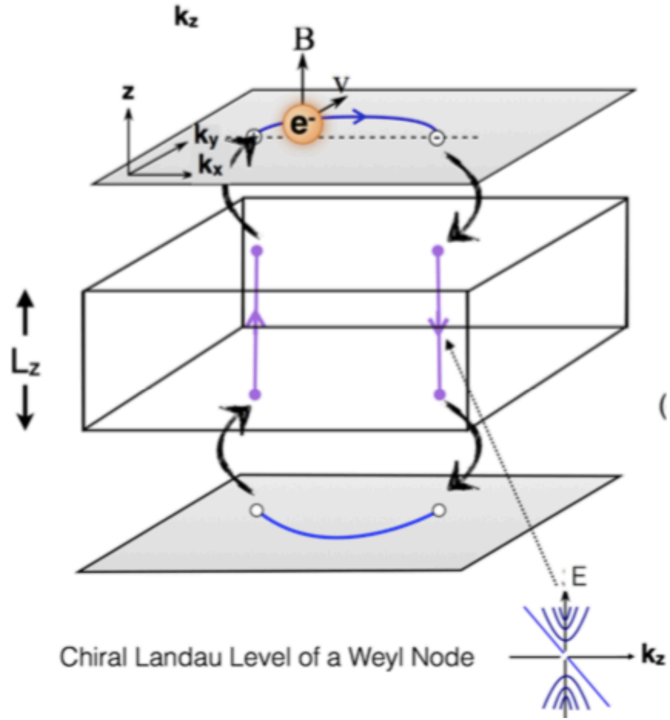


Chiral magnetic effect

$$\mathbf{J} = \left(\frac{e^2}{h^2 c} \sum_i \mu_i \chi_i \right) \mathbf{B}$$

Local E_F
of i^{th} Weyl node

Landau orbits



<u>More on Weyl semimetals</u>

See reviews by

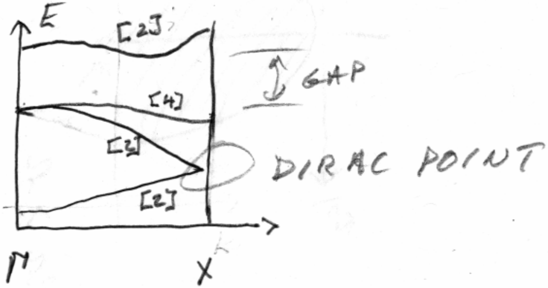
- Hasan et al. (2017)
- Yan and Felser (2017)
- Armitage et al. (2018)

Dirac semimetals

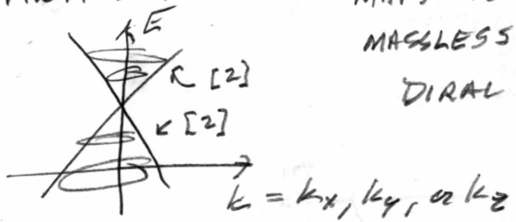
IF I AND TR ARE BOTH GOOD SYMMETRIES,

$\underline{k} \xrightarrow[I]{} -\underline{k} \xrightarrow[TR]{} \underline{k}$ SO $H_{\underline{k}}$ = HAM OF TR-INVAR 0D SYSTEM FOR ANY $\underline{k}$

Si



DEFINITION:



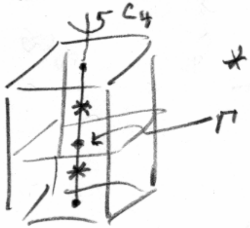
MAPS TO MASSLESS DIRAC THEORY

CAN IT OCCUR AT E_F, AS TOUCHING OF VB & CB?

YES, E.G., Na_3Bi, Cd_3As_2, ETC.

3 fold rotational axis for Na3B
4 fold rotational axis for Cd3As2

OCCURS ON ROTATIONAL SYMMETRY AXIS:



$*$ = DIRAC POINTS

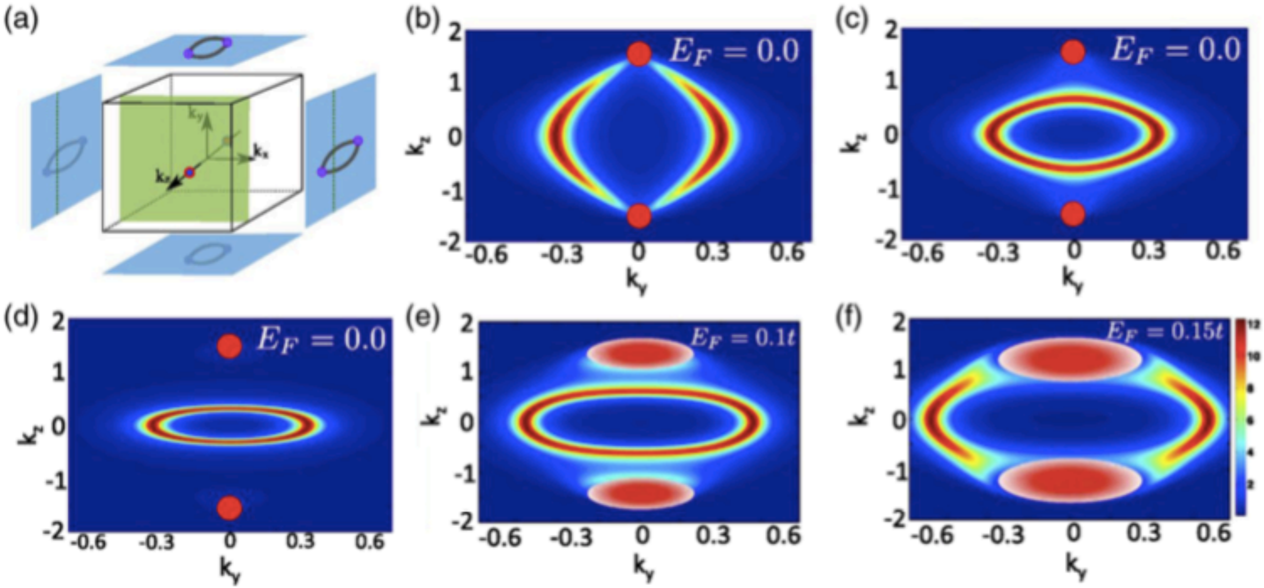


FIG. 13. Fermi arcs on the surface of DSMs. (a) A schematic of a DSM showing Dirac nodes along the k_z axis in the bulk BZ and double Fermi arcs on the surface BZs. Note that surfaces perpendicular to the z axis have no arcs. A 2D slice of the bulk BZ perpendicular to the k_z axis is shown as a shaded (green) plane, which projects to the dashed (green) line on the surface BZ. (b)–(d) A symmetry-allowed mass term at the surface admits backscattering between these branches at the contact point which dissociates the surface band from the projected Dirac point. These surface branches can be deformed but not removed from the time reversal symmetric plane at $k_z = 0$. If the chemical potential is not aligned with the bulk Dirac points the surface Fermi arcs disappear by merging with the bulk continuum (e), (f). Adapted from Kargarian, Randeria, and Lu, 2016.

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TOPICAL REVIEW — Topological electronic states

Topological nodal line semimetals*

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2.2. Nodal lines protected by inversion, time-reversal, and SU(2) spin-rotation symmetries

Here we first assume that all the three symmetries are present in our system. Since SU(2) is a symmetry, we can redefine time-reversal operator, combining it with a π spin rotation about the y-axis,

$$T \to T\,\mathrm{e}^{\mathrm{i}s_y\pi}, \tag{7}$$

after which we have $T^2 = +1$ instead of -1 for fermions. Since both inversion, P and T, reverse the momentum $\boldsymbol{k} \to -\boldsymbol{k}$, $P*T$ is an anti-unitary symmetry that preserves the momentum. Since $[P,T]=0$, we have

$$(P*T)^2 = P^2T^2 = 1. \tag{8}$$

Equation (8) dictates that it can be represented as

$$P*T = K, \tag{9}$$

where K is the complex conjugation, in a proper orbital basis. In this basis, $P*T$-symmetry ensures that

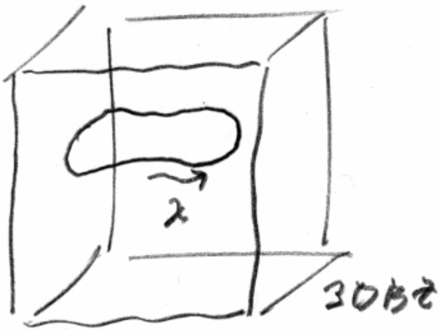
$$H(\boldsymbol{k}) = H^*(\boldsymbol{k}), \tag{10}$$

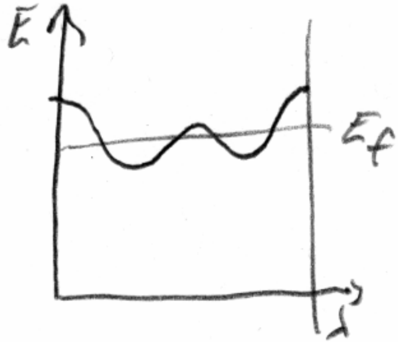
or that $H(\boldsymbol{k})$ is real at each $\boldsymbol{k}$.

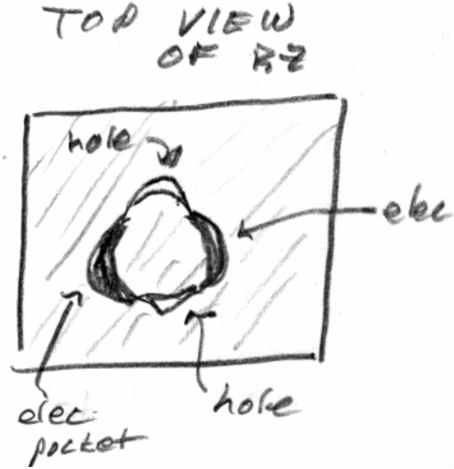
$$H_{2\times 2} = \begin{pmatrix} a & c \\ c & b \end{pmatrix} = \frac{a+b}{2}\mathbb{I} + \underbrace{\frac{a-b}{2}}_{=}\sigma_3 + \underbrace{c}_{=}\,\sigma_1$$

Codimension of 2 is enough! Nodal lines can occur in 3D BZ.

(also can occur due to symmetries)


3DBZ


E
E_f


TOP VIEW OF BZ
hole
elec
elec pocket
hole

Symmorphic Intersecting Nodal Rings in Semiconducting Layers

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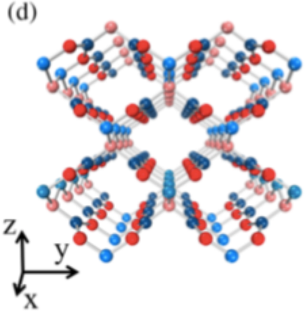

Hypothetical structures of BN, AlP, GaP, SiC, BP, etc.