Wave Propagation as a Probe of the Chiral Anomaly in Weyl Matter

Pavlo O. Sukhachov

Conference on Symmetry Breaking Phenomena in Quantum Field Theory,
May 17, 2026

Chapter 0

2016 - Ph.D., Theoretical physics, BITP, Kyiv, Ukraine

Topics:

- Interaction effects on **3D Dirac and Weyl systems**: magnetic catalysis [P. O. Sukhachov, Ukr. J. Phys. 59, 696 (2014); J. Phys. Stud. 18, 2071 (2014); E. V. Gorbar, V. A. Miransky, I. A. Shovkovy, and P. O. Sukhachov, Phys. Rev. B 94, 115429 (2016)]
- Quantum oscillations [E. V. Gorbar, **V. A. Miransky**, I. A. Shovkovy, and P. O. Sukhachov, Phys. Rev. B 90, 115131 (2014)]
- Surface states [E. V. Gorbar, **V. A. Miransky**, I. A. Shovkovy, and P. O. Sukhachov, Phys. Rev. B 91, 121101(R) (2015); Phys. Rev. B 91, 235138 (2015); Phys. Rev. B 93, 235127 (2016); Phys. Rev. B 93, 235127 (2016)]
- Chiral separation and chiral magnetic effect [E. V. Gorbar, **V. A. Miransky**, I. A. Shovkovy, and P. O. Sukhachov, Phys. Rev. B 92, 245440 (2015)]

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Four "Musketeers"

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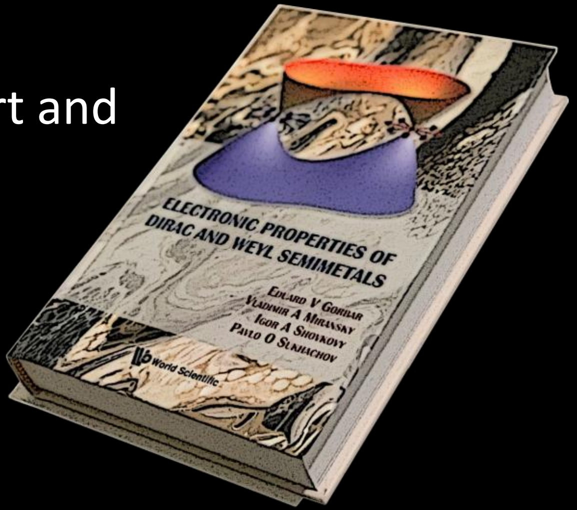
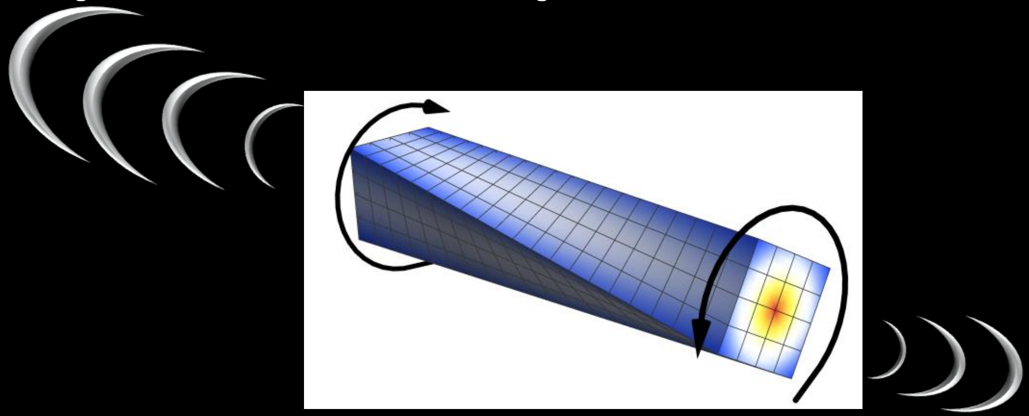


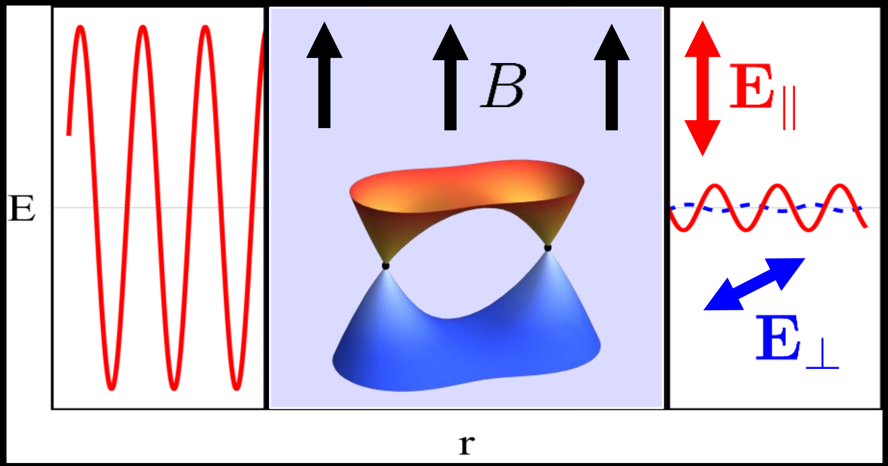
In total, 24 publication, including a book

[E. V. Gorbar, **V. A. Miransky**, I. A. Shovkovy, and P. O. Sukhachov, Electronic properties of Dirac and Weyl semimetals (World Scientific, 2021)]

Outline

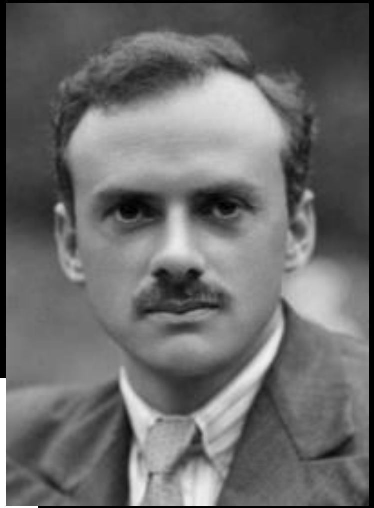
1. Quantum anomalies → **reduction of sound attenuation** in Weyl semimetals subject to magnetic fields.
2. Static strains → **sound attenuation dichroism – nonreciprocal propagation** of sound.
3. The chiral anomaly → **nonlocal response** to light.
4. Anomalous nonlocal regime → **enhancement of electromagnetic wave penetration depth.**

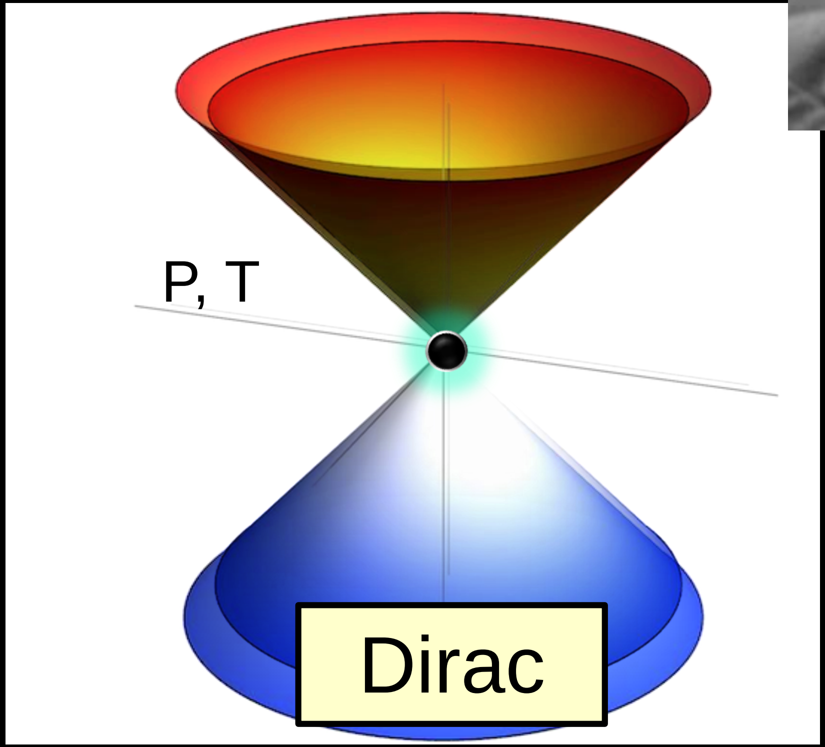




Dirac and Weyl Hamiltonians

$$H(\mathbf{k}) = \begin{pmatrix} v\boldsymbol{\sigma}\cdot\mathbf{k} & 0 \\ 0 & -v\boldsymbol{\sigma}\cdot\mathbf{k} \end{pmatrix}$$





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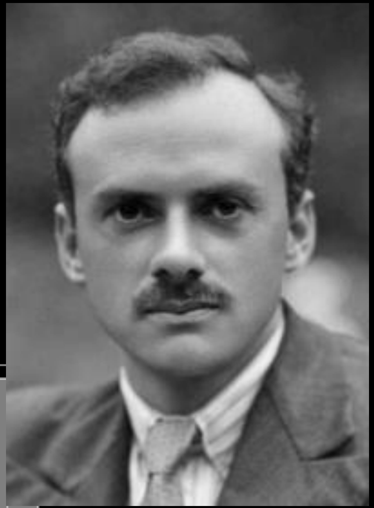

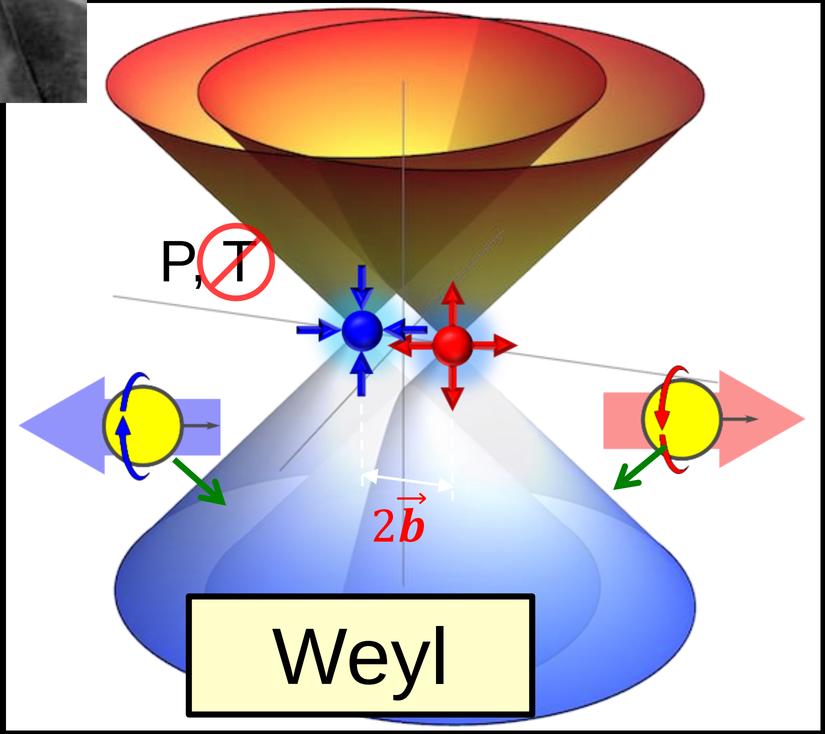

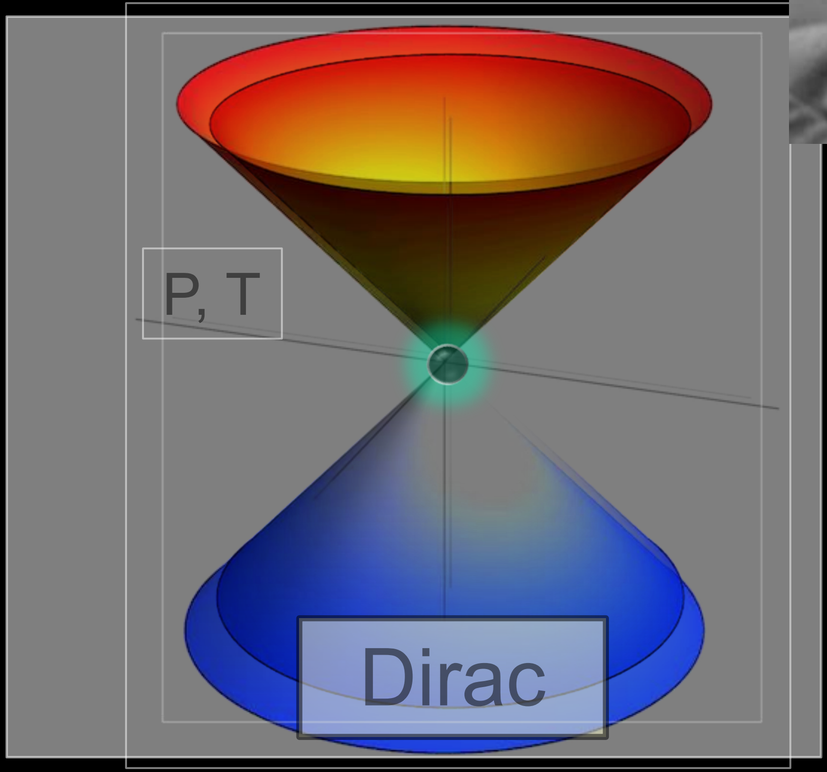

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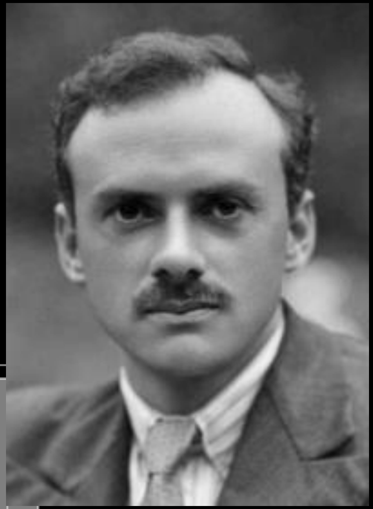
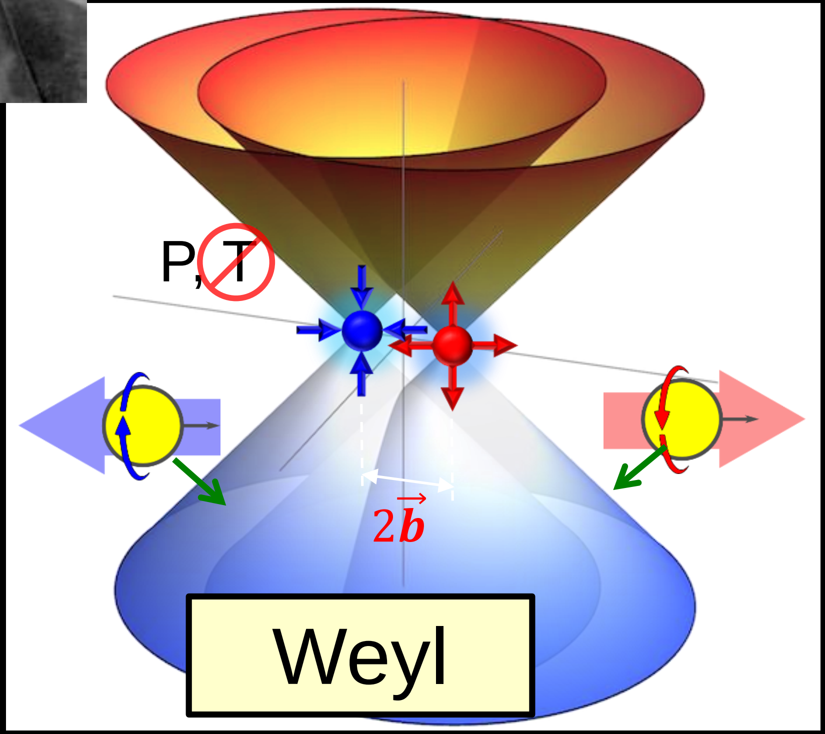
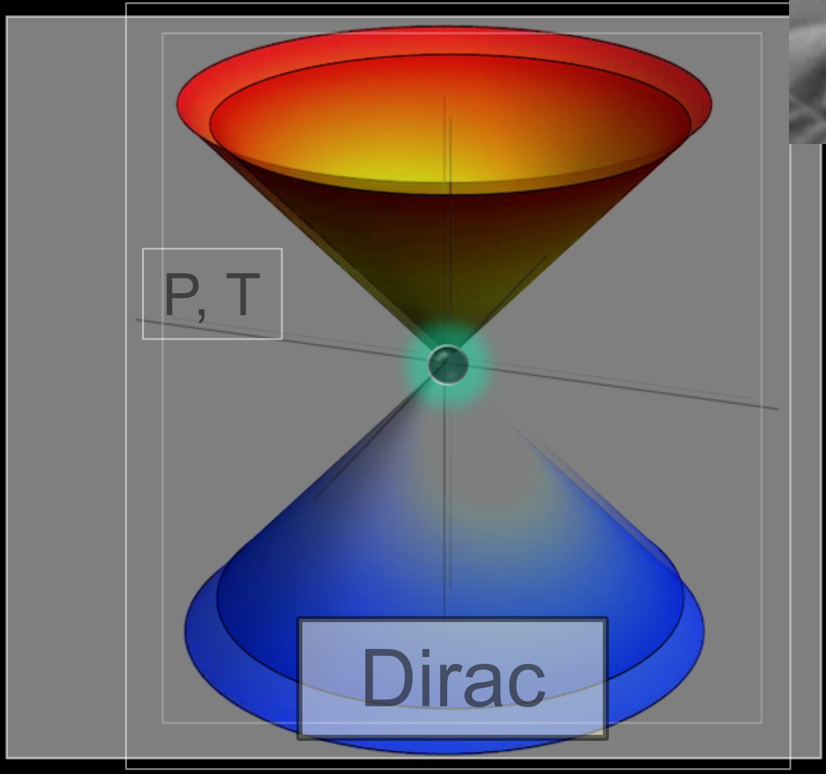
Chiral shift parameter







[H. Weyl, Z. Phys. **56**, 330 (1929); P.A.M. Dirac, Proc. R. Soc. A 117, 610 (1928); R. Jackiw and V. Alan Kostelecky, Phys. Rev. Lett. 82, 3572 (1999)]

Electrons in solids: Primer

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Determines quantum geometry (topology)

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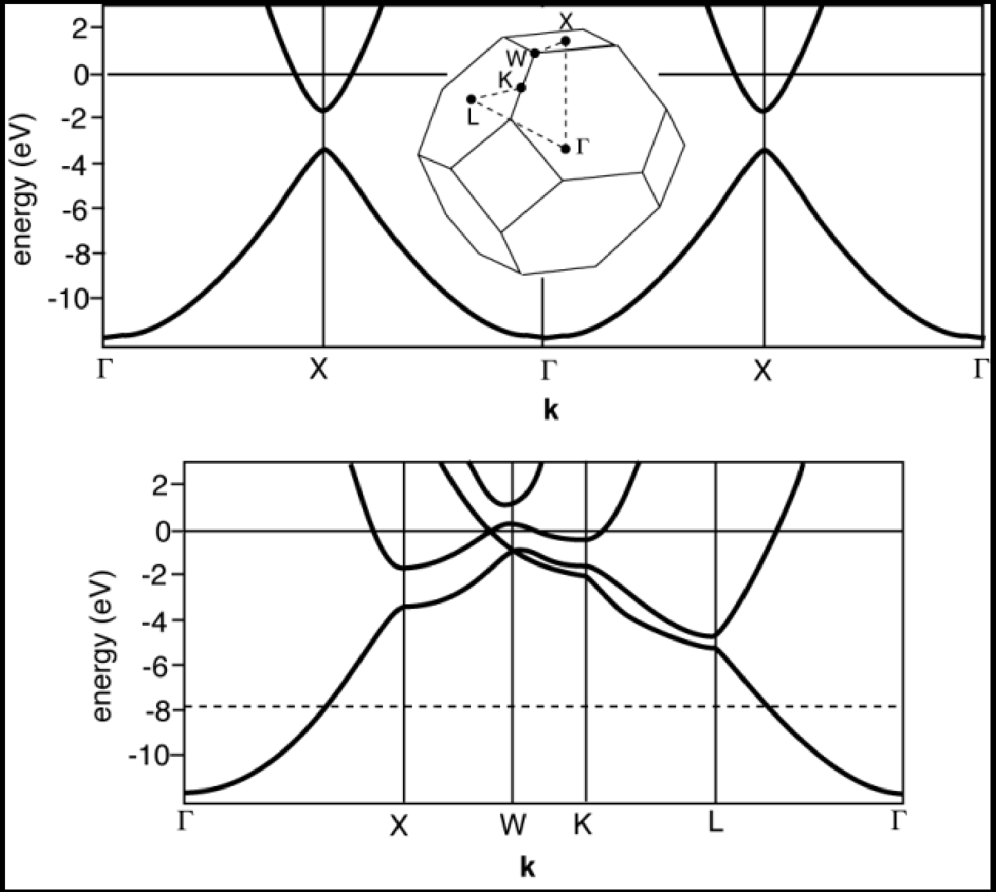

Band structure of Al

[B. Segall, Phys. Rev. **124**, 1797 (1961)]

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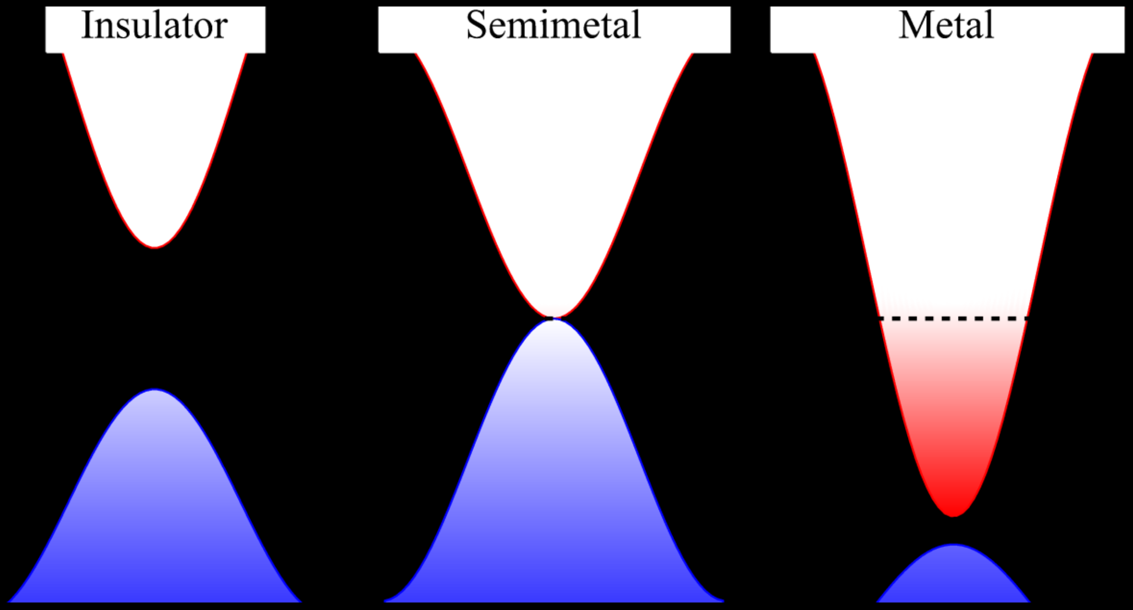
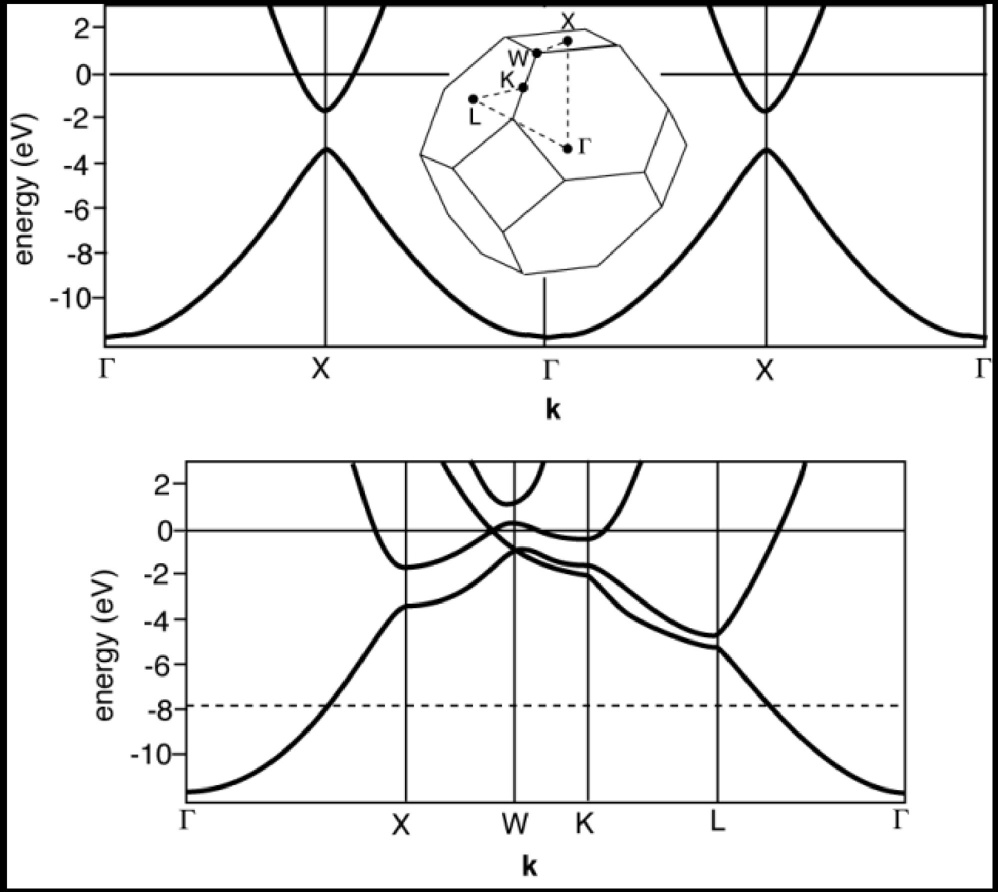
Quasi-momentum defined in the Brillouin zone





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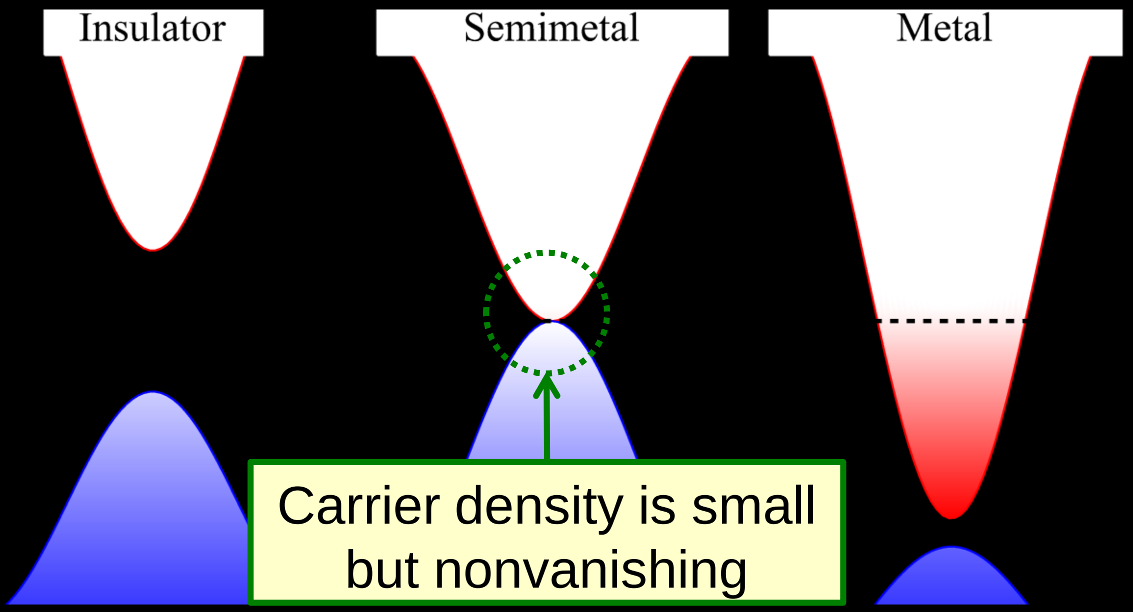

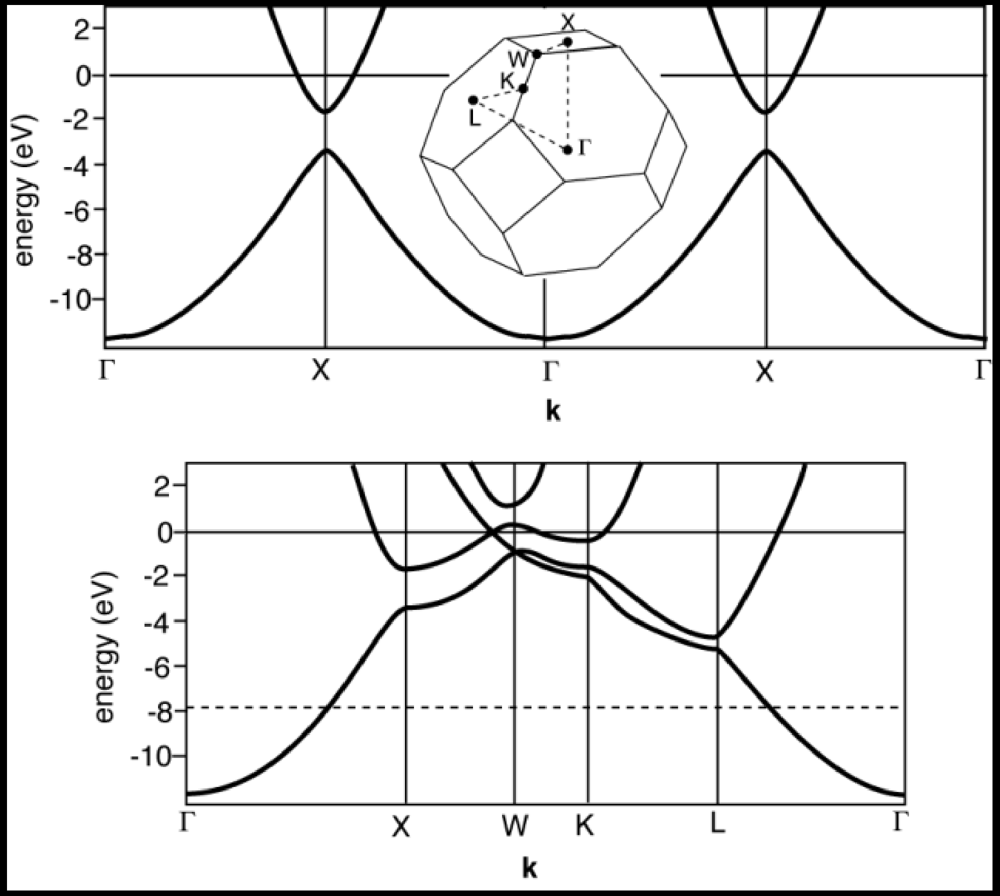

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Linear band crossings: Weyl semimetals

Hamiltonian (two bands → 2x2): $$H(\mathbf{k}) = \epsilon_0(\mathbf{k}) + \mathbf{d}(\mathbf{k}) \cdot \boldsymbol{\sigma}$$

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$$H_W(\mathbf{k}) = \pm v \boldsymbol{\sigma} \cdot \delta\mathbf{k}$$

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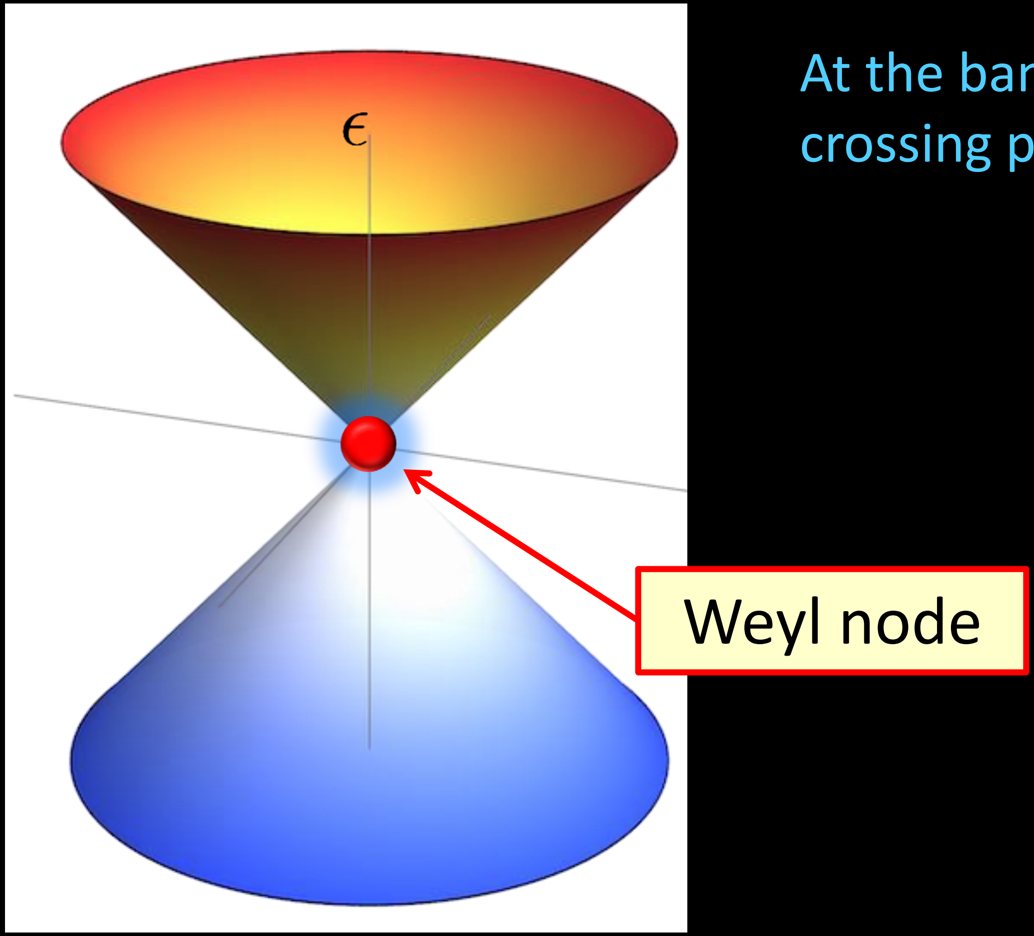

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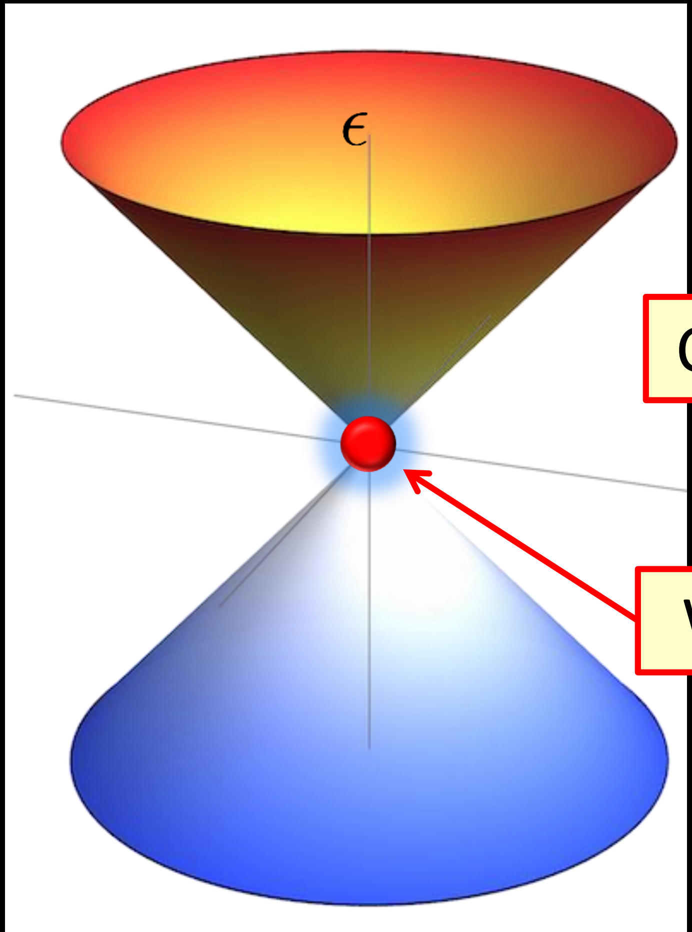

Chirality

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Weyl Hamiltonian

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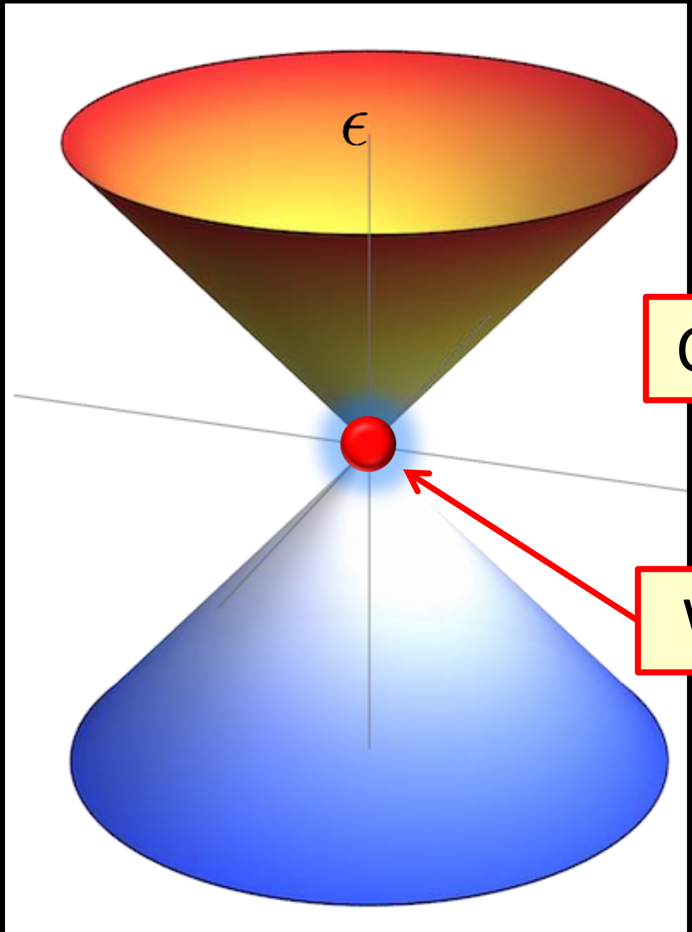

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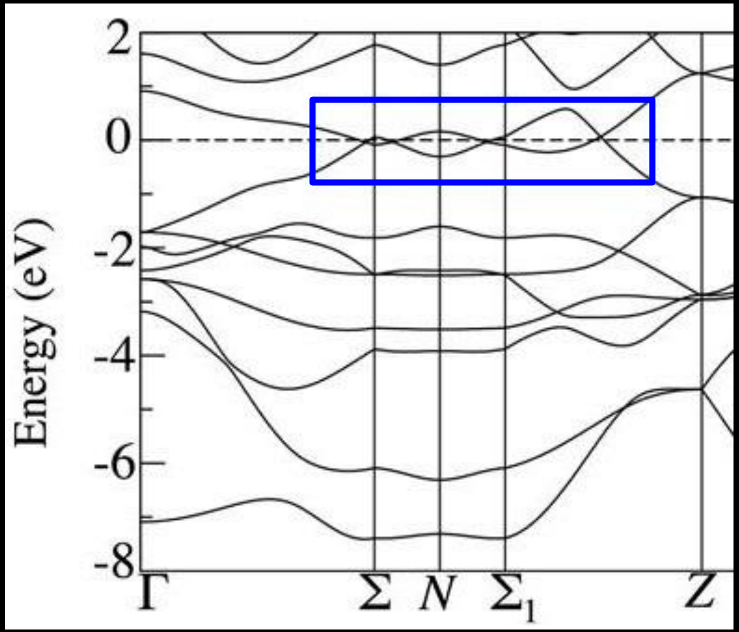
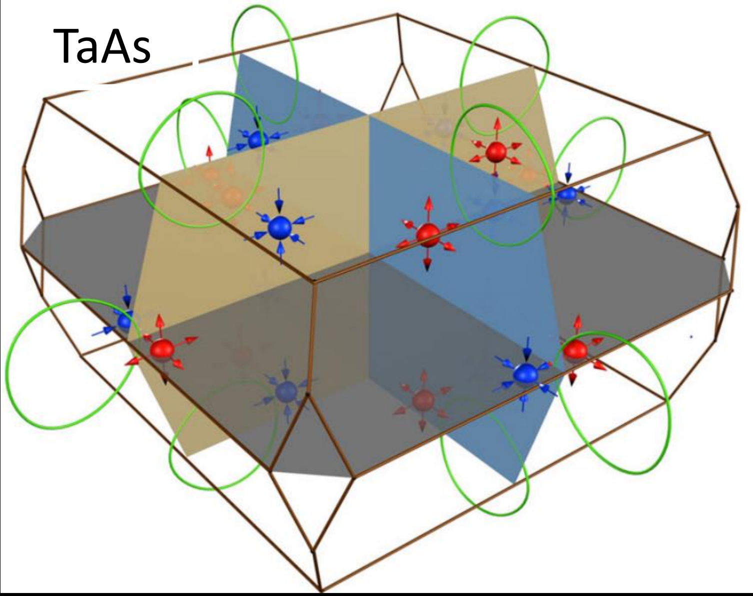
First mention of linear energy spectrum in solids:

[C. Herring, Phys. Rev. **52**, 365 (1937)]

3D Weyl materials: ab initio results and experiment





[H. Weng, et al., Phys. Rev. X **5**, 011029 (2015)]

- TaAs, TaP, NbAs, NbP

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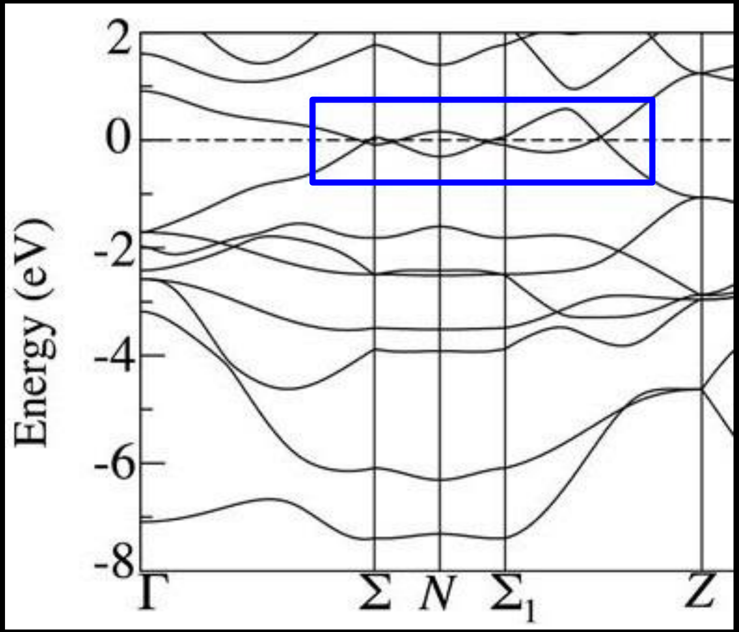

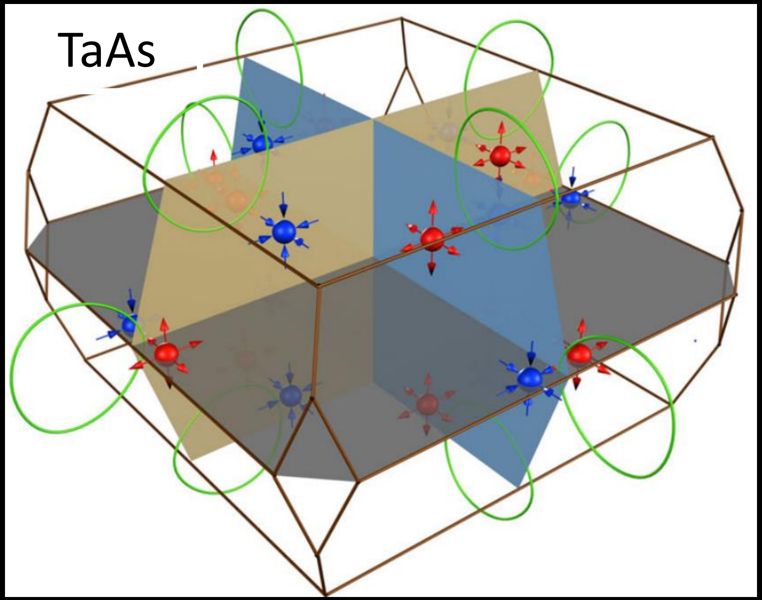

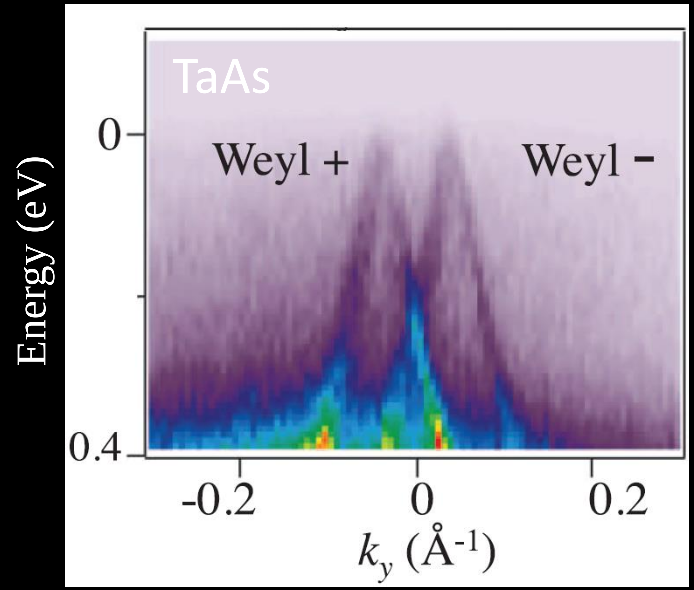

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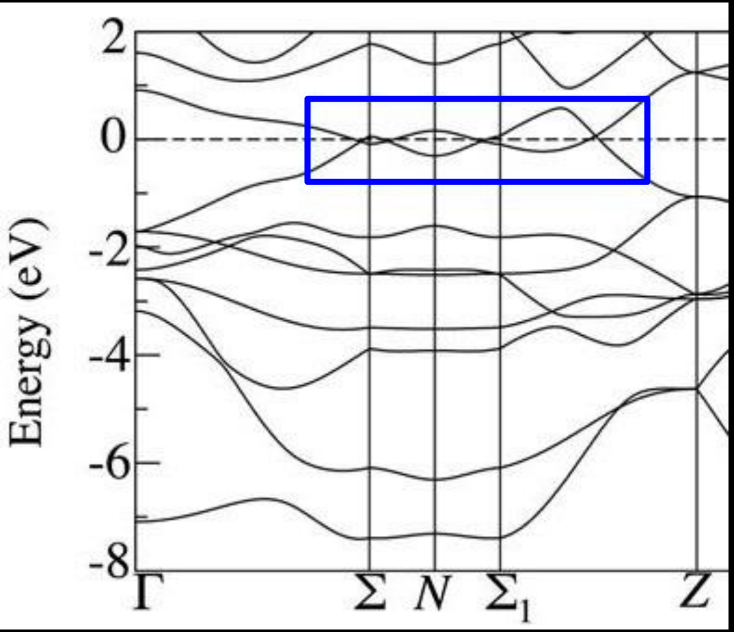

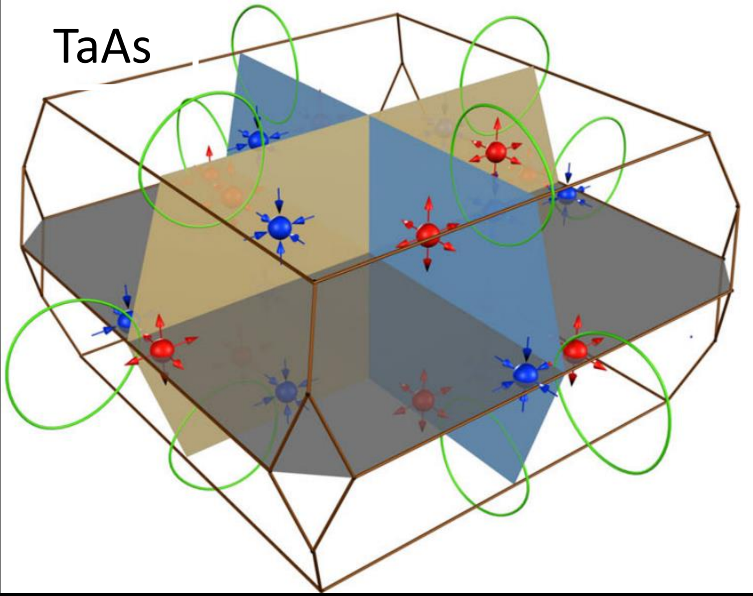

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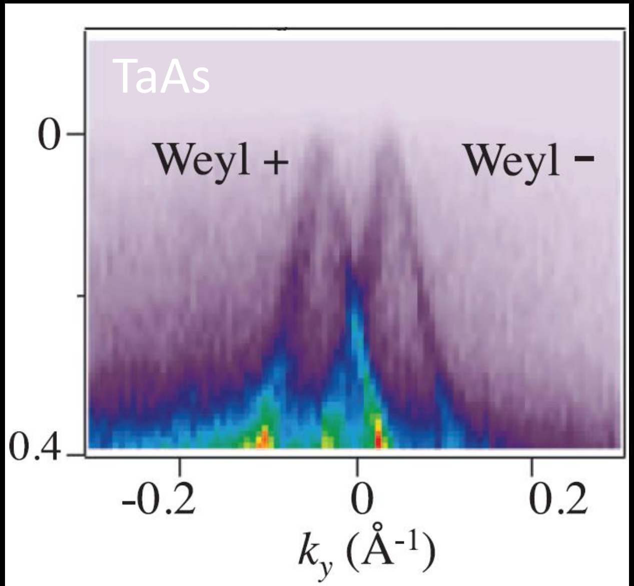

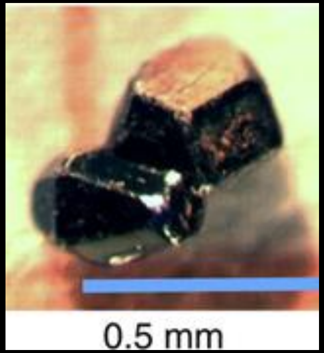

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Topology of electron states: Berry curvature

- Adiabatic evolution [M.V. Berry, Proc. R. Soc. A **392**, 45 (1984)]:

$$H = H(\mathbf{k}(t)) \qquad H(\mathbf{k})\,|u_n(\mathbf{k})\rangle = \epsilon_n(\mathbf{k})\,|u_n(\mathbf{k})\rangle$$

- Closed trajectory in the parameter space → rate-independent phase factor:

$$e^{-i\gamma}\,|u_n(\mathbf{k})\rangle$$

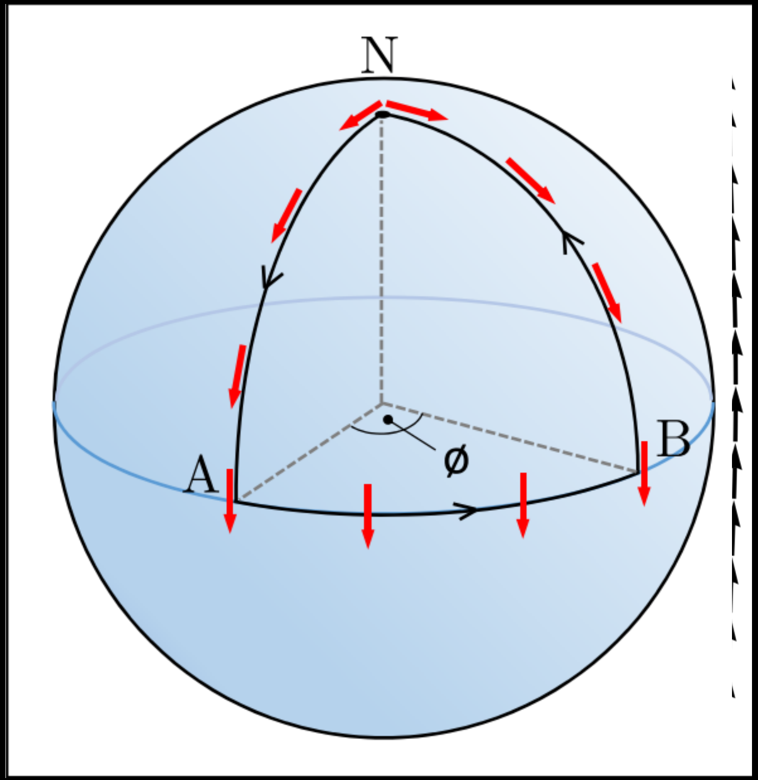
- The Berry phase and the Berry connection:

$$\gamma = \oint d\mathbf{k}\cdot\boldsymbol{\mathcal{A}}(\mathbf{k}), \qquad \boldsymbol{\mathcal{A}}(\mathbf{k}) = i\,\langle u_n(\mathbf{k}) \mid \partial_{\mathbf{k}} u_n(\mathbf{k})\rangle$$

- The Berry curvature:

$$\boldsymbol{\Omega} = \partial_{\mathbf{k}} \times \boldsymbol{\mathcal{A}}(\mathbf{k}) \qquad \boldsymbol{A}(\mathbf{r})$$ Vector potential

$$\mathrm{B} = \nabla_{\mathbf{r}} \times \boldsymbol{A}(\mathbf{r})$$ Magnetic field



[A.T. Boothroyd, Contemp. Phys. **63**, 305 (2022)]

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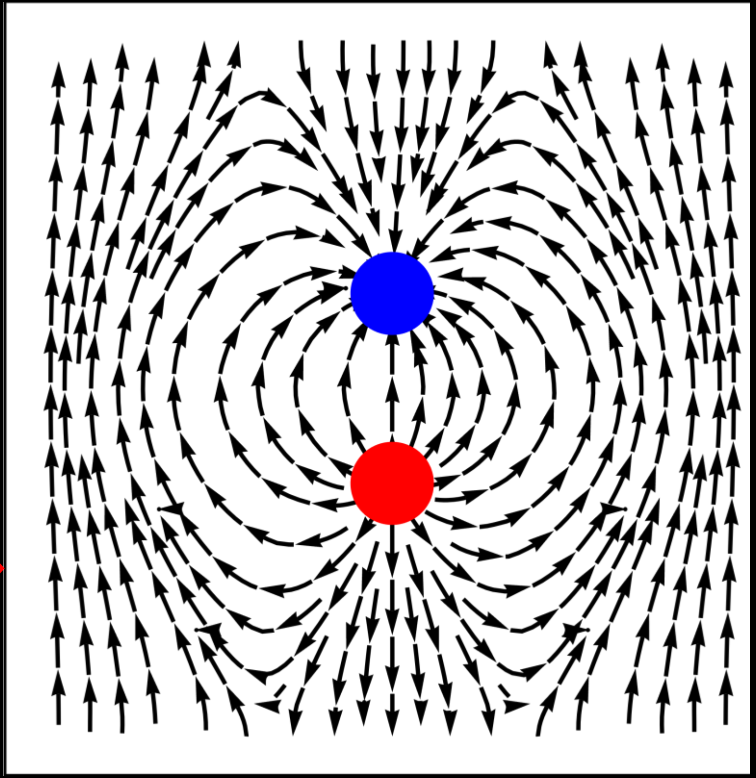
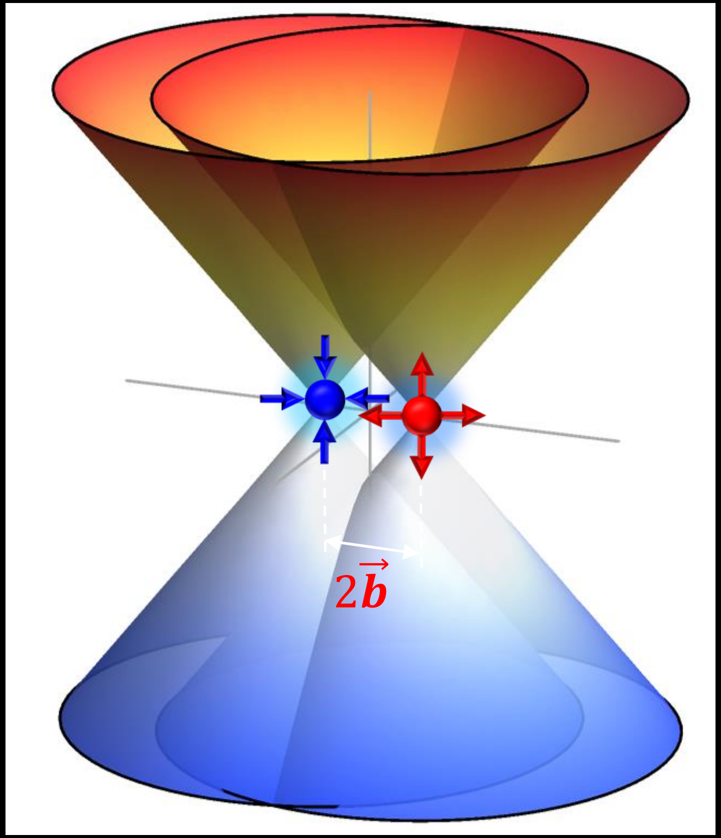
Field lines of the Berry curvature for a Weyl semimetal → dipole structure



Strain-induced axial gauge fields

$$H_0(\mathbf{k}) = \begin{pmatrix} v_F \boldsymbol{\sigma} \cdot (\mathbf{k} - \mathbf{b}) & 0 \\ 0 & -v_F \boldsymbol{\sigma} \cdot (\mathbf{k} + \mathbf{b}) \end{pmatrix}$$



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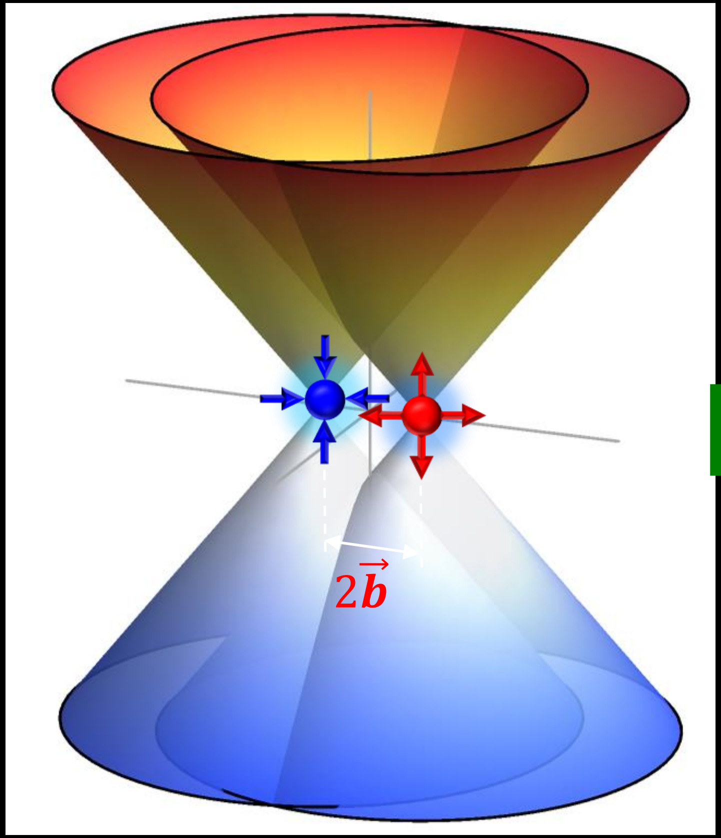

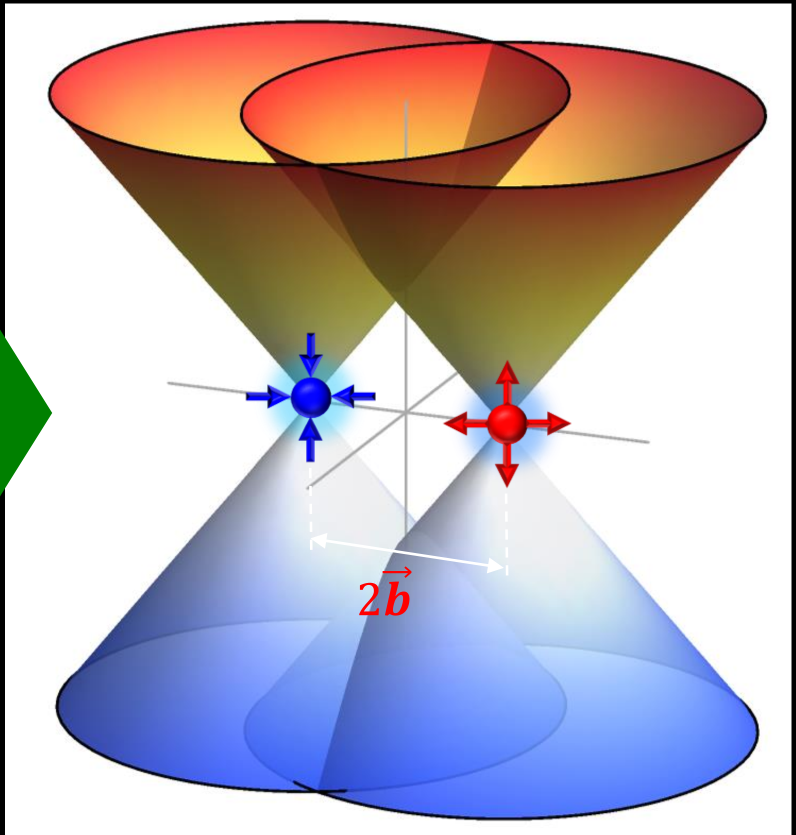

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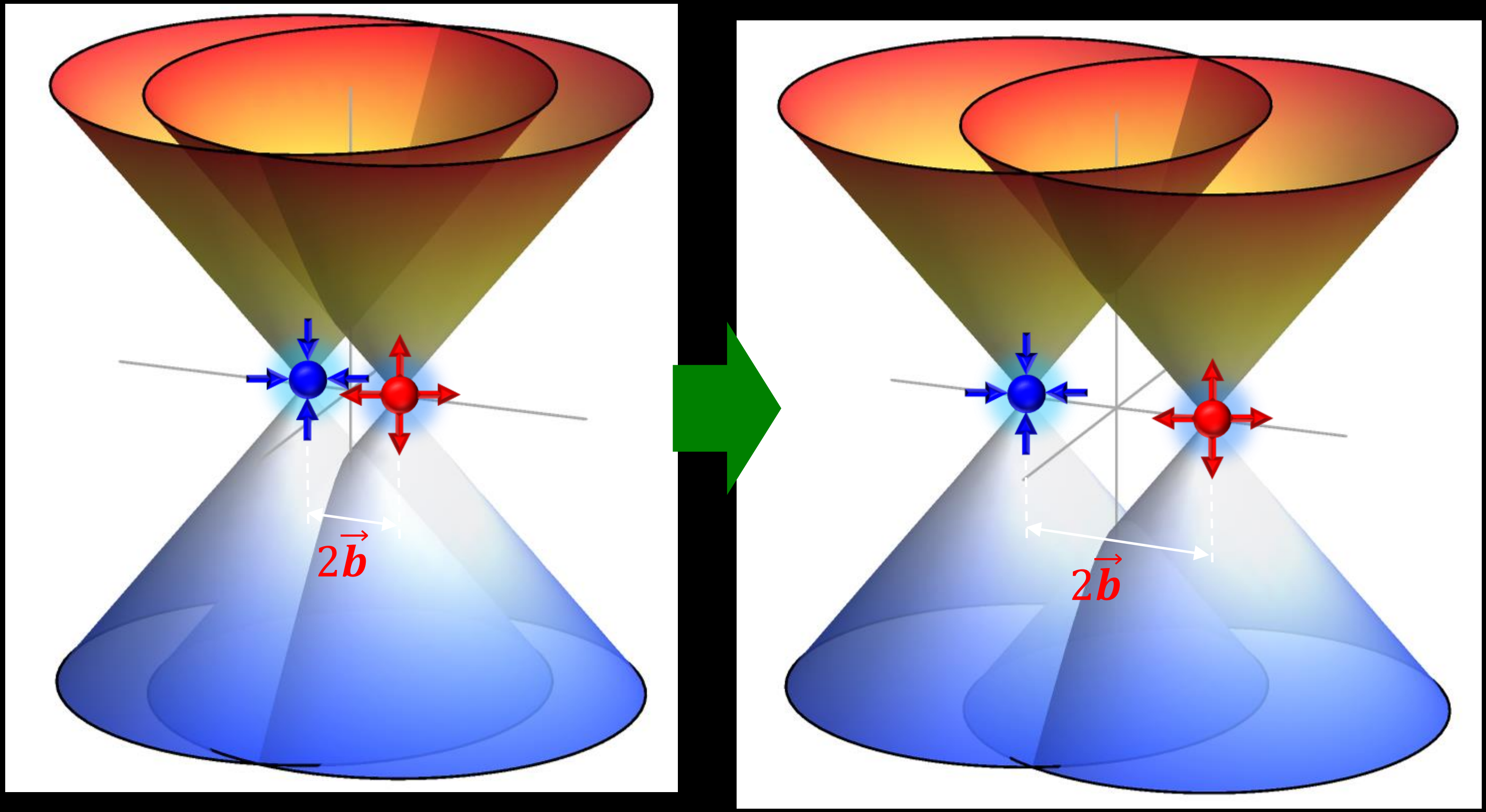
[A. Cortijo et al., PRL **115**, 177202 (2015); R. Ilan, A.G. Grushin, and D.I. Pikulin, Nat. Rev. Phys. **2**, 29 (2020)]



Pseudomagnetic (axial) field

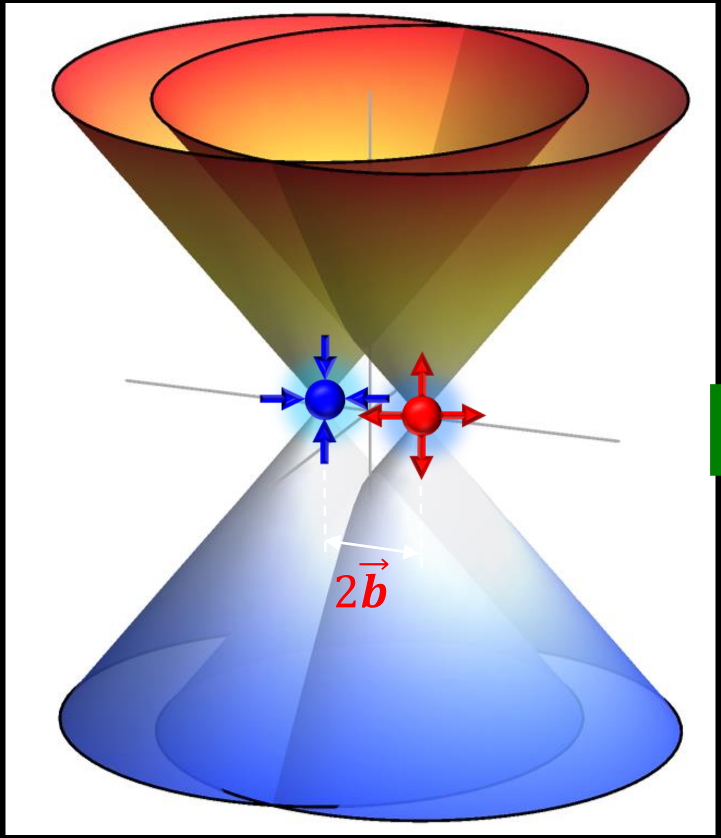
$$\pm\mathbf{b}(\mathbf{r}) \equiv \pm e\mathbf{A}_5(\mathbf{r}) \leftrightarrow e\mathbf{A}(\mathbf{r})$$

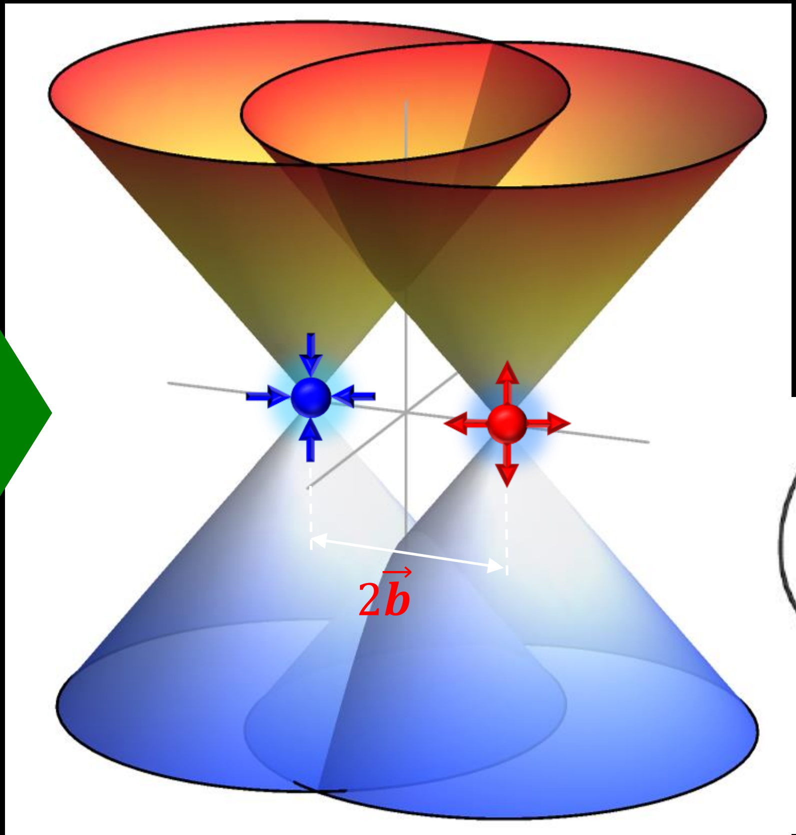
Strain-induced axial gauge fields

$$H_0(\mathbf{k}) = \begin{pmatrix} v_F \boldsymbol{\sigma} \cdot (\mathbf{k} - \mathbf{b}) & 0 \\ 0 & -v_F \boldsymbol{\sigma} \cdot (\mathbf{k} + \mathbf{b}) \end{pmatrix}$$

[A. Cortijo et al., PRL **115**, 177202 (2015); R. Ilan, A.G. Grushin, and D.I. Pikulin, Nat. Rev. Phys. **2**, 29 (2020)]

$$\mathbf{b} \rightarrow \mathbf{b}(\mathbf{r})$$

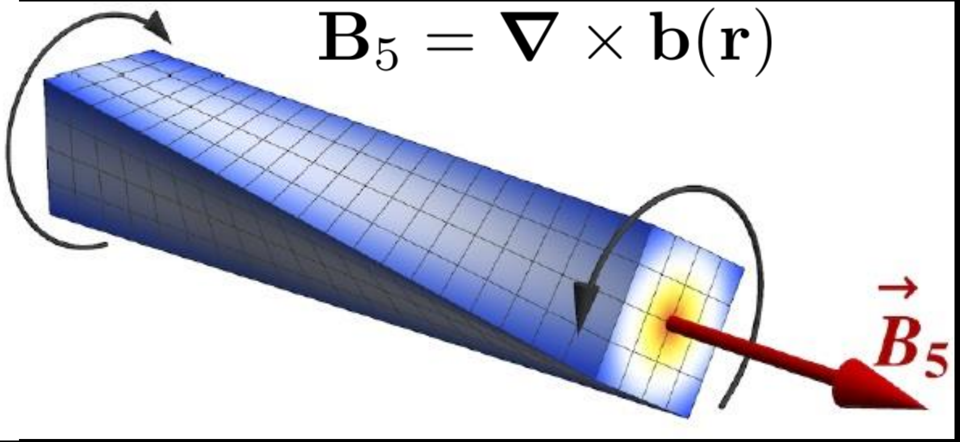




Pseudomagnetic (axial) field

$$\pm\mathbf{b}(\mathbf{r}) \equiv \pm e\mathbf{A}_5(\mathbf{r}) \leftrightarrow e\mathbf{A}(\mathbf{r})$$

$$\mathbf{B}_5 = \boldsymbol{\nabla} \times \mathbf{b}(\mathbf{r})$$



Quantum (chiral) anomaly

Anomaly = breakdown of classical symmetry by quantum effects

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Classical chiral systems: numbers of left- and right-handed particles are **separately** conserved

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[P. Danaisawadi, et al. Sci. Rep. **6**, 23832 (2016)]

Quantum (chiral) anomaly

Anomaly = breakdown of classical symmetry by quantum effects

Classical chiral systems: numbers of left- and right-handed particles are **separately** conserved

[P. Danaisawadi, et al. Sci. Rep. **6**, 23832 (2016)]

→ Currents of left- and right-handed particles are **separately** conserved

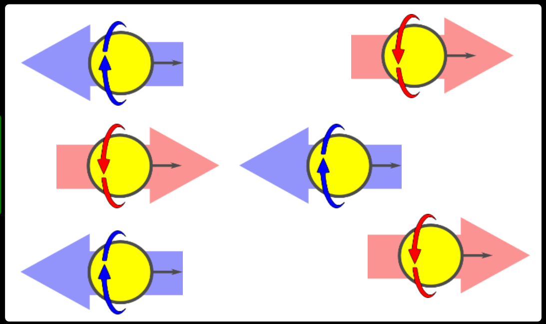
Quantum (chiral) anomaly

Anomaly = breakdown of classical symmetry by quantum effects

Classical chiral systems: numbers of left- and right-handed particles are **separately** conserved

[P. Danaisawadi, et al. Sci. Rep. **6**, 23832 (2016)]

Quantum systems:



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Chiral Anomaly

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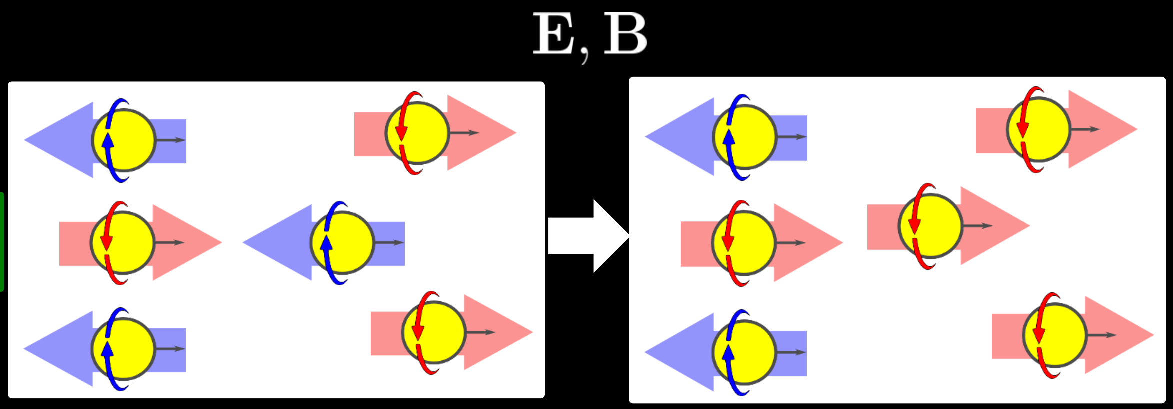

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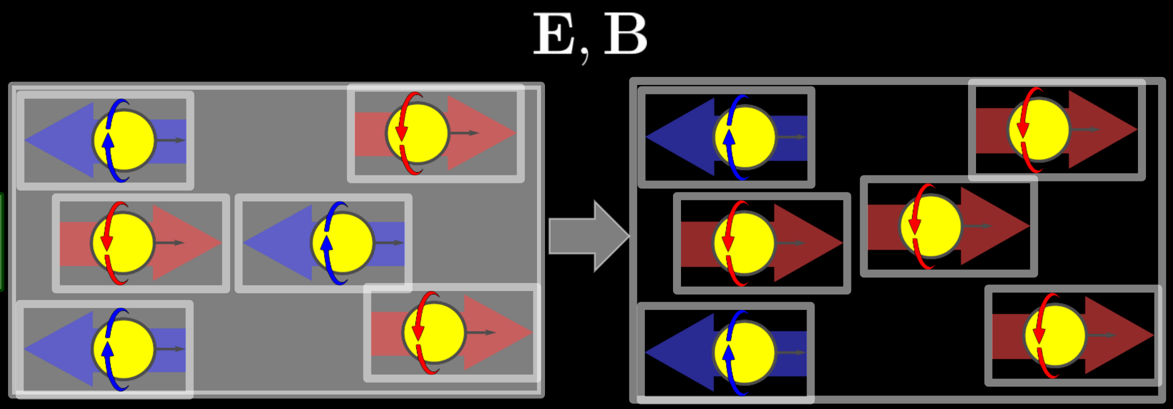
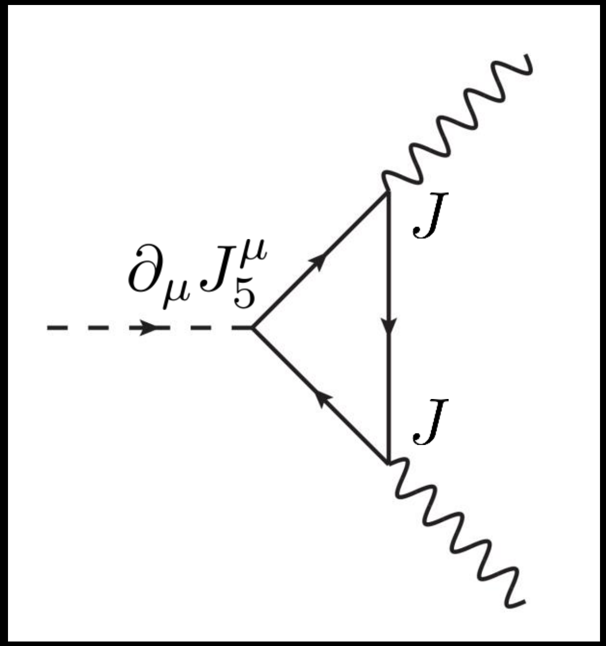
Quantum systems:



High-energy physics:

$$\pi^0 \to \gamma + \gamma$$

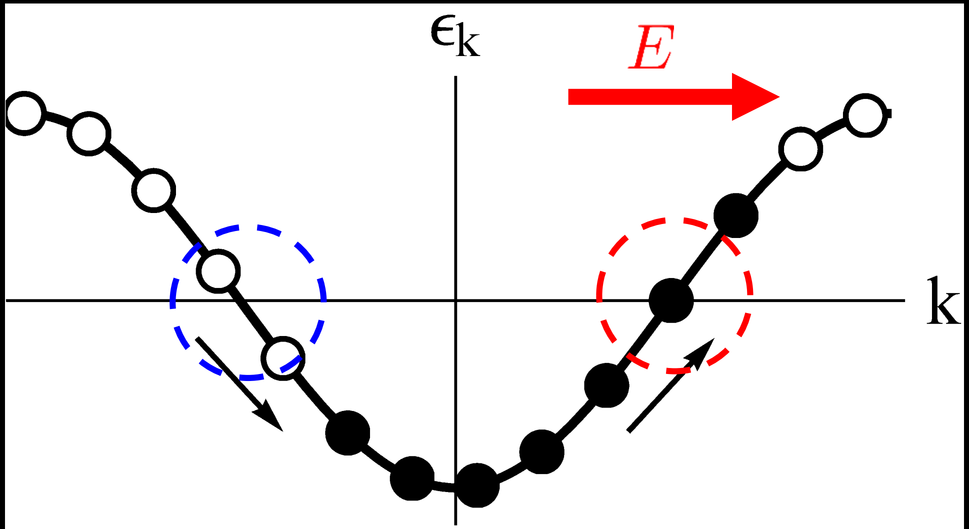
Allowed by the chiral anomaly!



[S.L. Adler, Phys. Rev. **177**, 2426 (1969), J.S. Bell and R. Jackiw, Nuovo Cim. A **60**, 47 (1969)]

Quantum (chiral) anomaly: solid state viewpoint

1D crystal:



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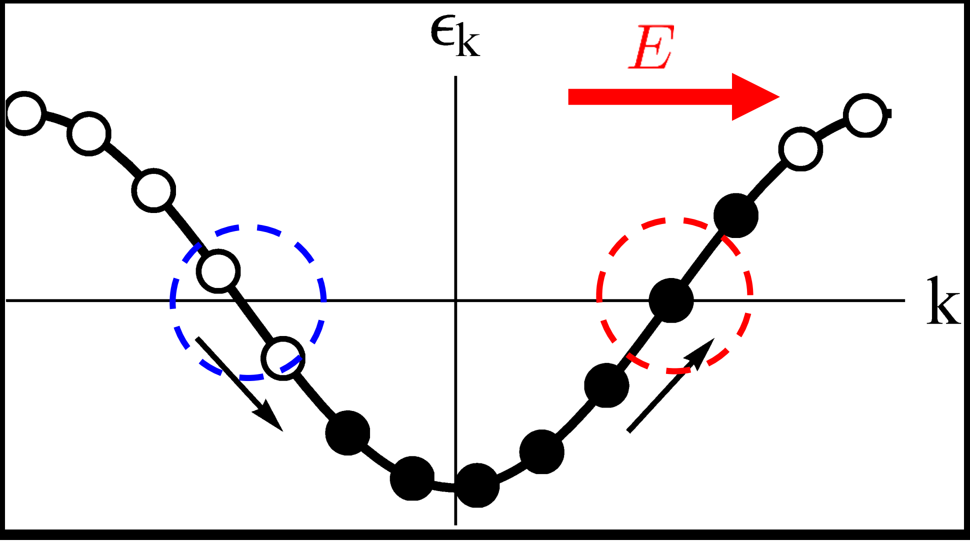
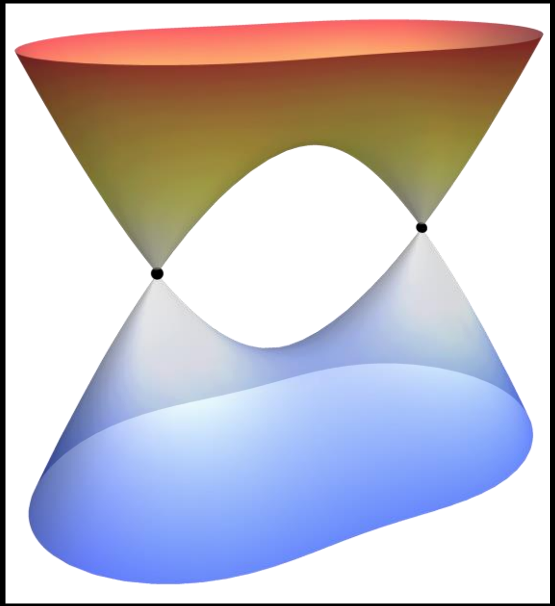
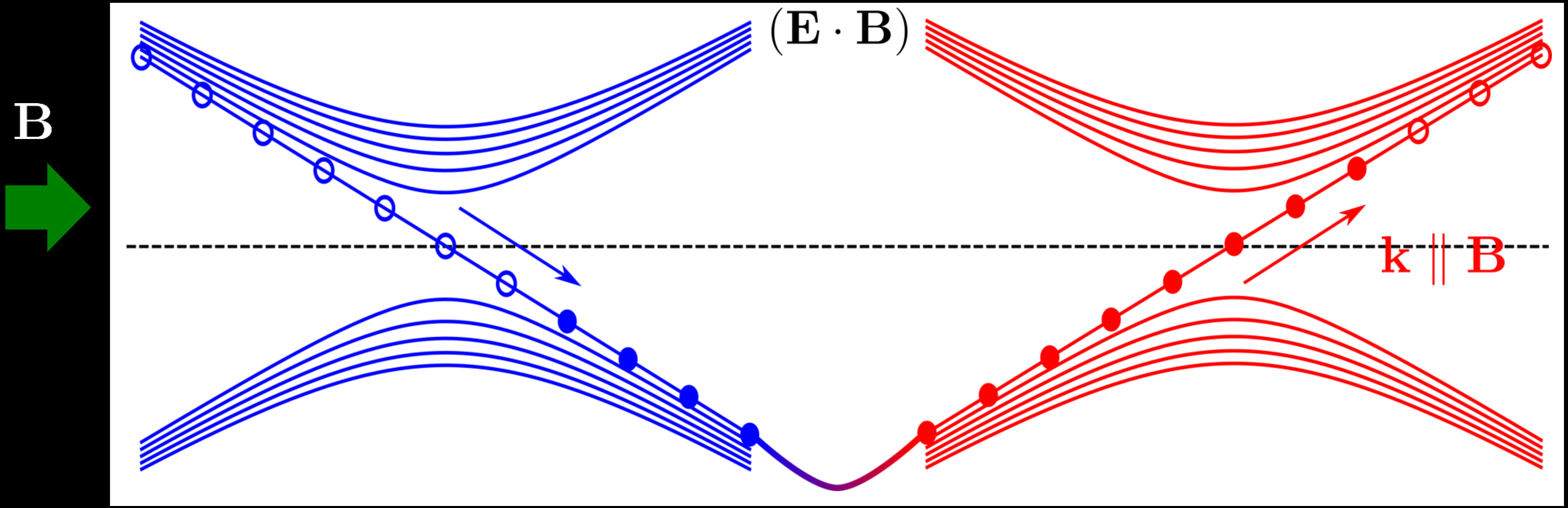


3D crystal:



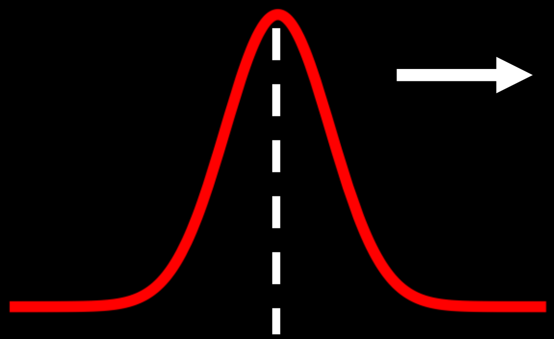


[H. Nielsen and M. Ninomiya, Phys. Lett. B **130**, 389 (1983)]

Semiclassical approach

[N.W. Ashcroft and N.D. Mermin, Solid State Physics (1976)]

Wave packet:



$$\Delta r \Delta p \geq \hbar/2$$

Coordinate and momentum are well defined

Equations of motion:

$$\begin{aligned} \partial_t \mathbf{r} &= \mathbf{v_p}, \\ \partial_t \mathbf{p} &= -e\mathbf{E} - \frac{e}{c}\left[(\partial_t \mathbf{r}) \times \mathbf{B}\right], \\ \mathbf{v_p} &= \partial_{\mathbf{p}} \epsilon \end{aligned}$$

Semiclassical approach

[N.W. Ashcroft and N.D. Mermin, Solid State Physics (1976)]

[D. Xiao, M.-C. Chang, and Q. Niu, Rev. Mod. Phys. **82**, 1959 (2010)]
[D.T. Son and N. Yamamoto, Phys. Rev. D **87**, 085016 (2013)]
[M.A. Stephanov and Y. Yin, Phys. Rev. Lett. **109**, 162001 (2012)]

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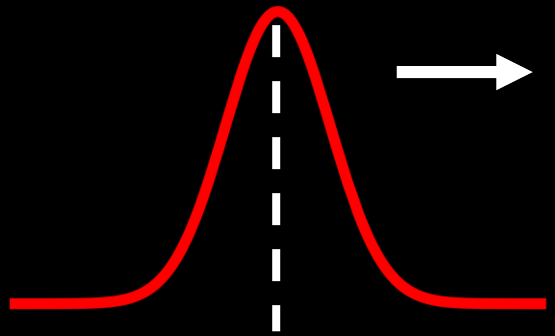

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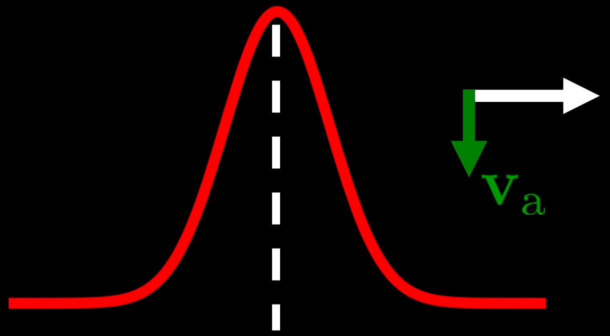

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$$\begin{aligned} \partial_t \mathbf{r} &= \mathbf{v}_{\mathbf{p}} + \left[(\partial_t \mathbf{p}) \times \mathbf{\Omega}(\mathbf{p})\right], \\ \partial_t \mathbf{p} &= -e\mathbf{E} - \frac{e}{c}\left[(\partial_t \mathbf{r}) \times \mathbf{B}\right], \\ \mathbf{v}_{\mathbf{p}} &= \partial_{\mathbf{p}} \epsilon \end{aligned}$$

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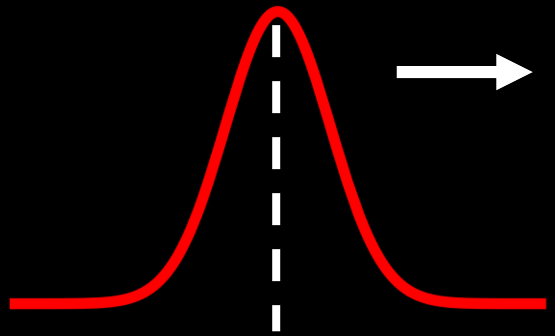

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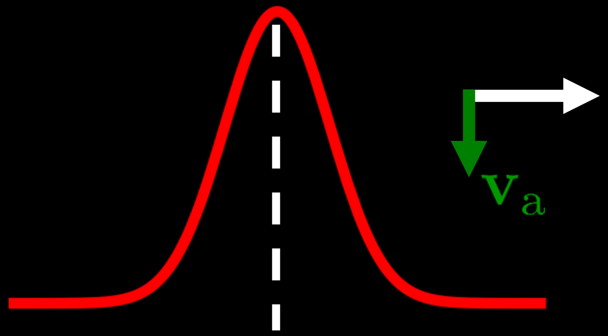

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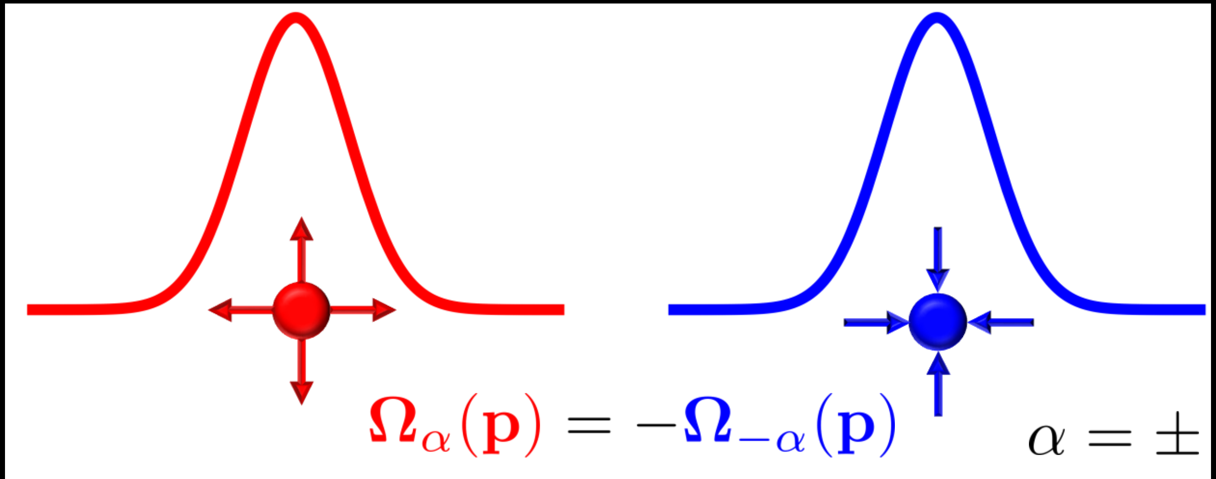
$A(\mathbf{r}) \longleftrightarrow \mathcal{A}(\mathbf{p})$

Transport effect of chiral anomaly

Multiple Weyl nodes:



$$\partial_t \mathbf{r}_\alpha = \mathbf{v}_\alpha - \frac{e}{c}\mathbf{B}\left(\mathbf{v}_\alpha \cdot \mathbf{\Omega}_\alpha\right) + \ldots$$

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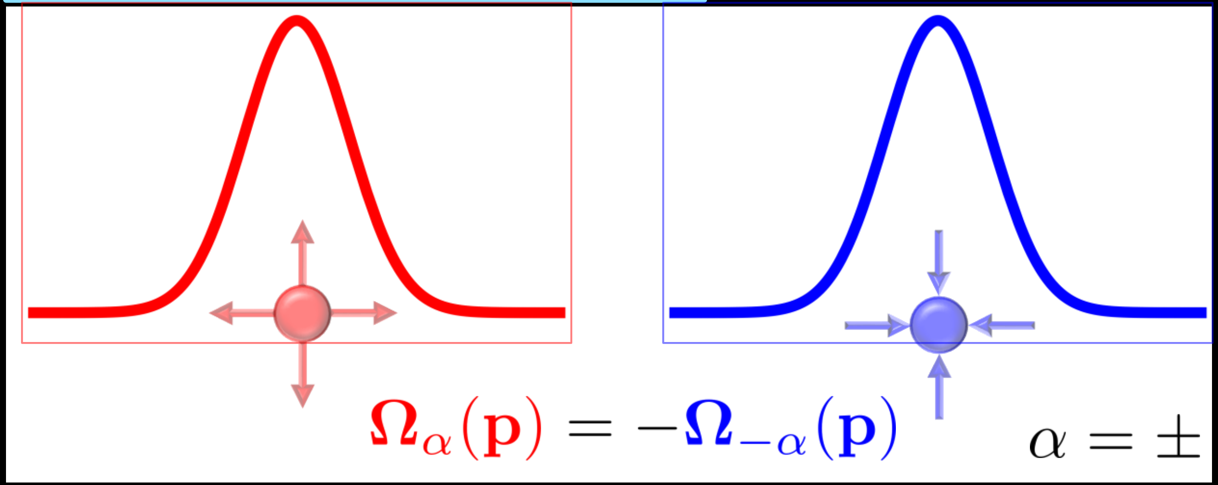

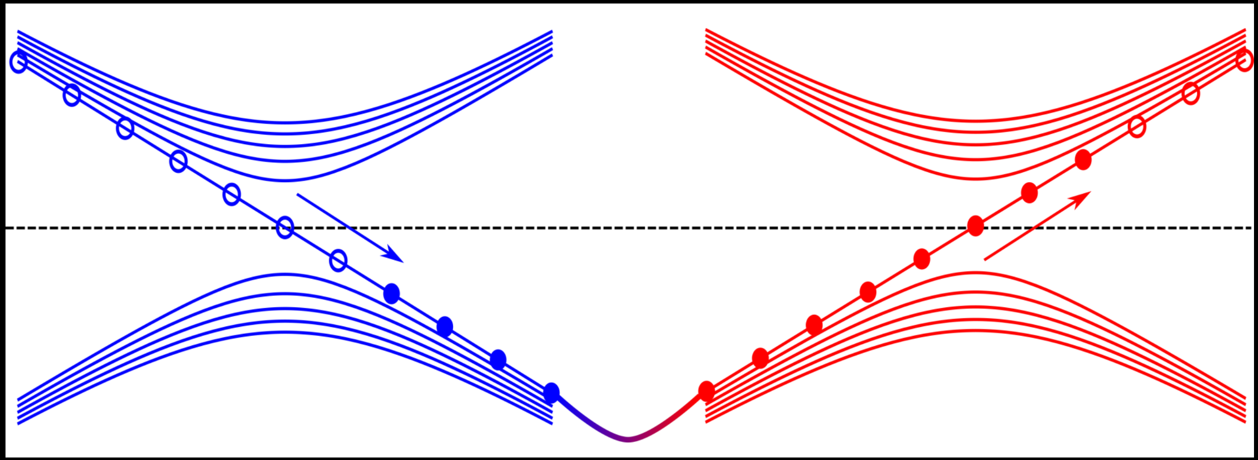

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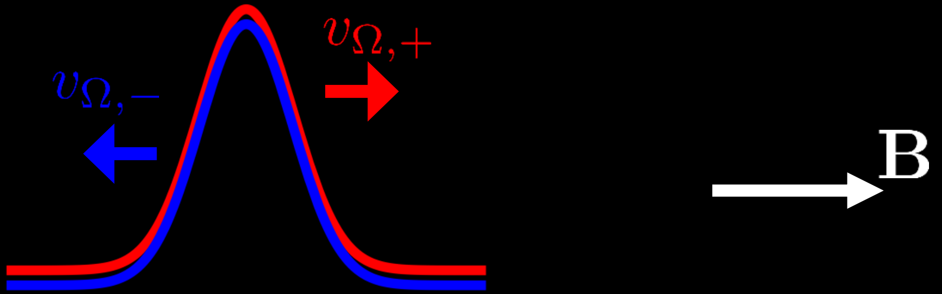

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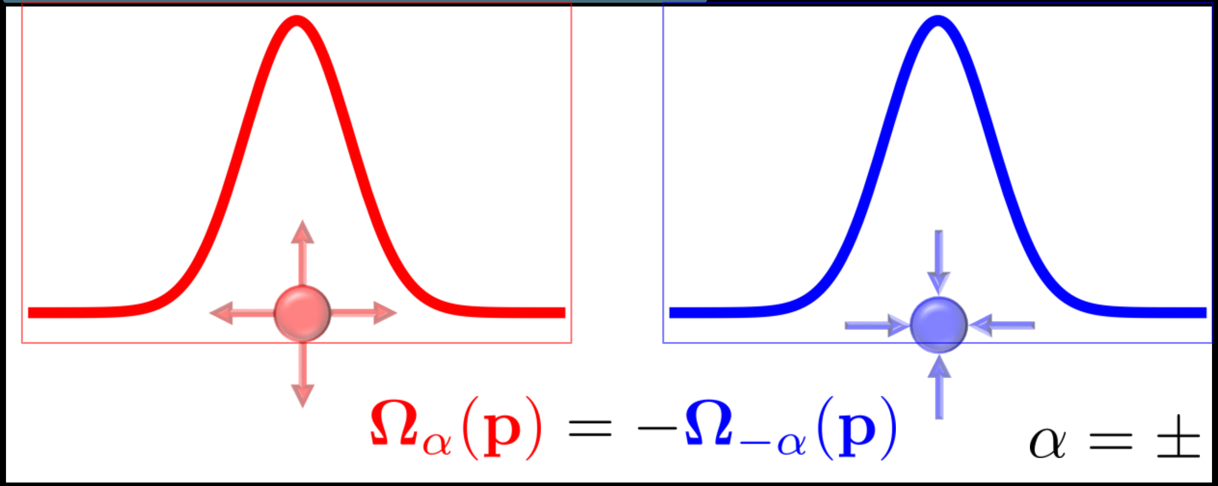
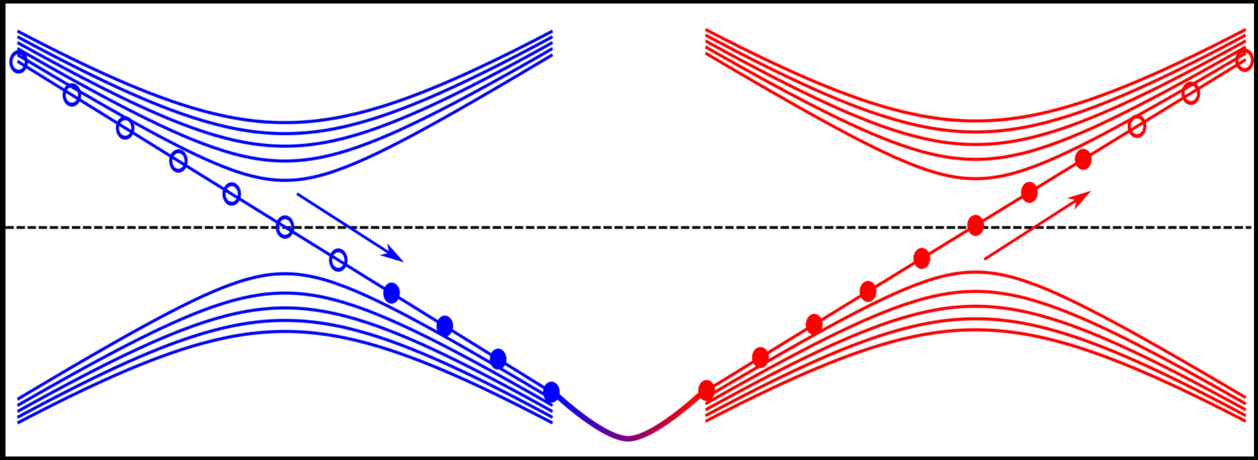




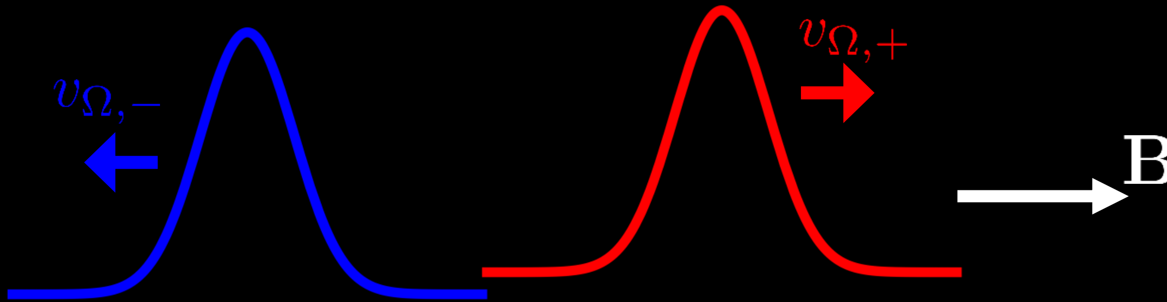
$$N_+ - N_- \propto (\mathbf{E}\cdot\mathbf{B})$$

$$\partial_t \mathbf{r}_\alpha = \mathbf{v}_\alpha - \frac{e}{c}\mathbf{B}\left(\mathbf{v}_\alpha\cdot\boldsymbol{\Omega}_\alpha\right) + \ldots$$

Chiral magnetic effect:

$$\mathbf{j} \propto (N_+ - N_-)\,\mathbf{B}$$

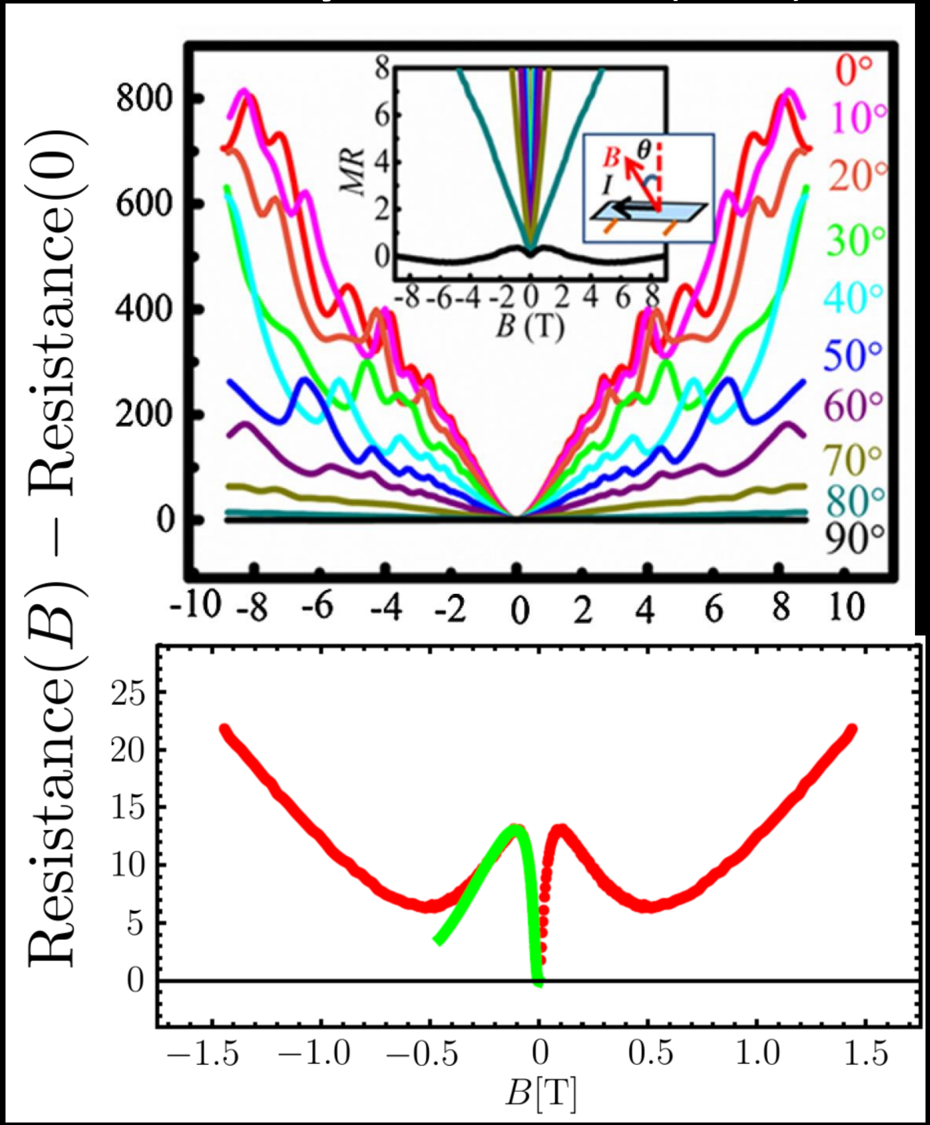
[A. Vilenkin, Phys. Rev. D **22**, 3080 (1980); K. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D **78**, 074033 (2008)]



Separation of wave packets → electric current

Transport in magnetic fields

Weyl semimetals (TaAs)



[X. Huang, L. Zhao, Y. Long, et al., Phys. Rev. X **5**, 031023 (2015)]

[C.-L. Zhang, S.-Y. Xu, I. Belopolski, Z. Yuan, et al., Nat. Commun. **7**, 10735 (2016)]

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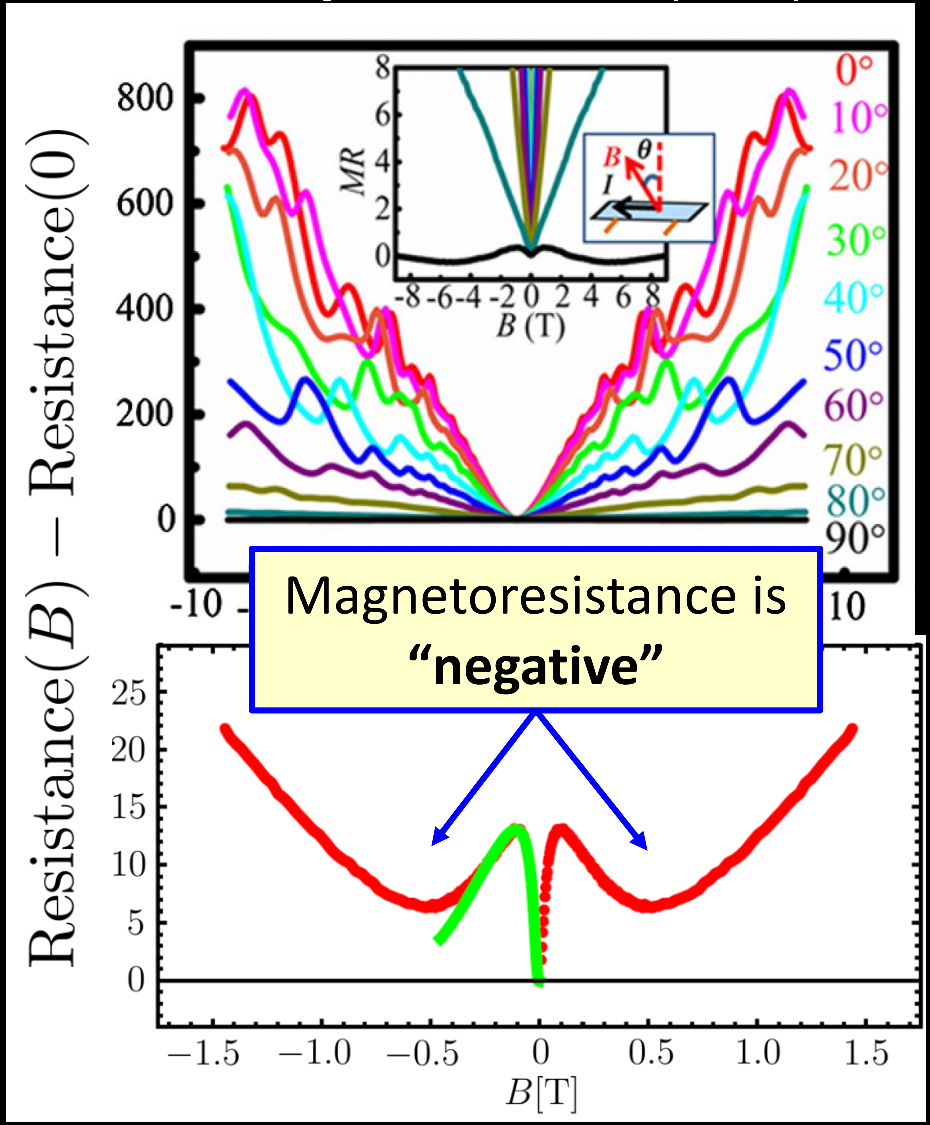

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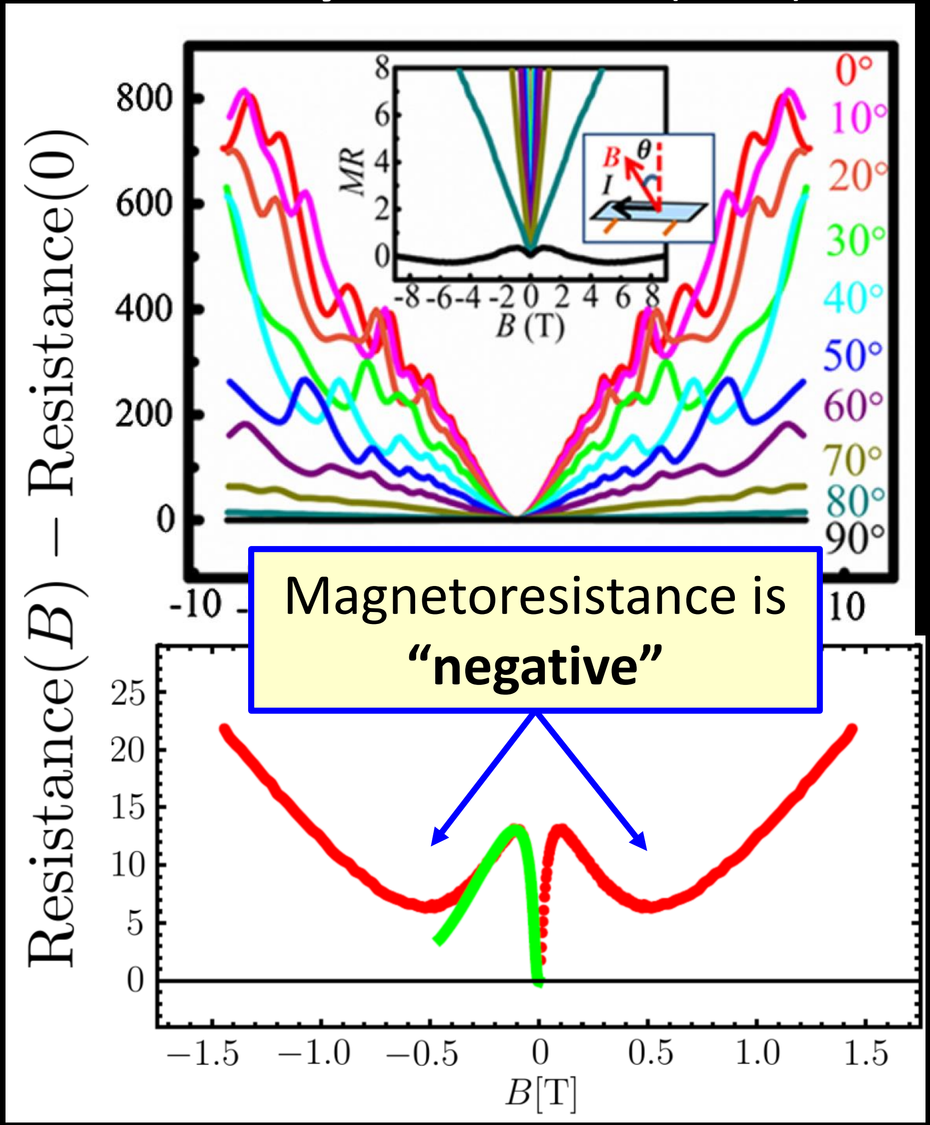

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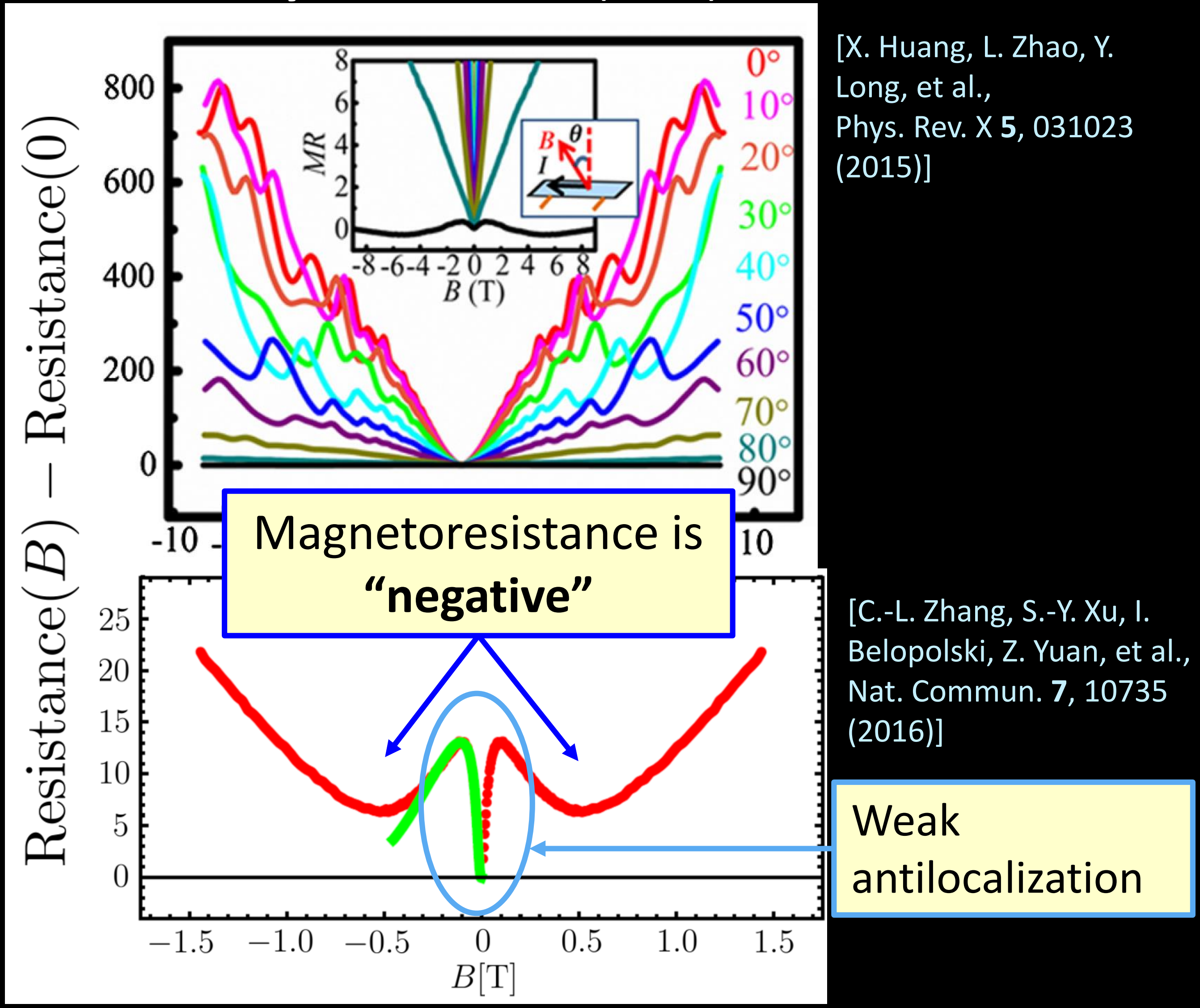

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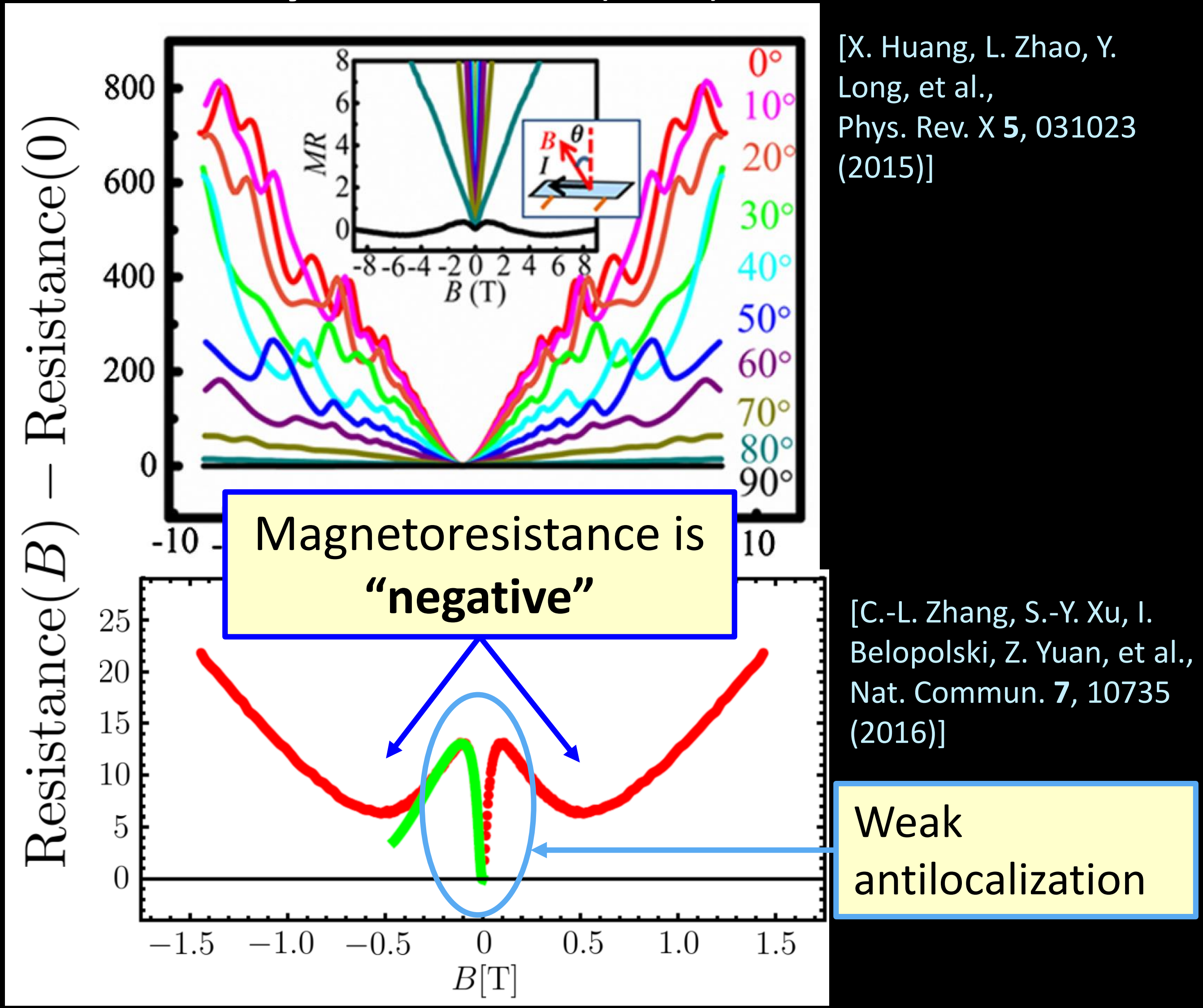

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Other mechanisms:

- Current jetting [R. D. dos Reis, et al., New J. Phys. **18**, 085006 (2016)]
- Weak antilocalization-localization crossover
- Scattering off charged disorder

[P. Goswami, J. H. Pixley, and S. Das Sarma, Phys. Rev. B **92**, 075205 (2015)]

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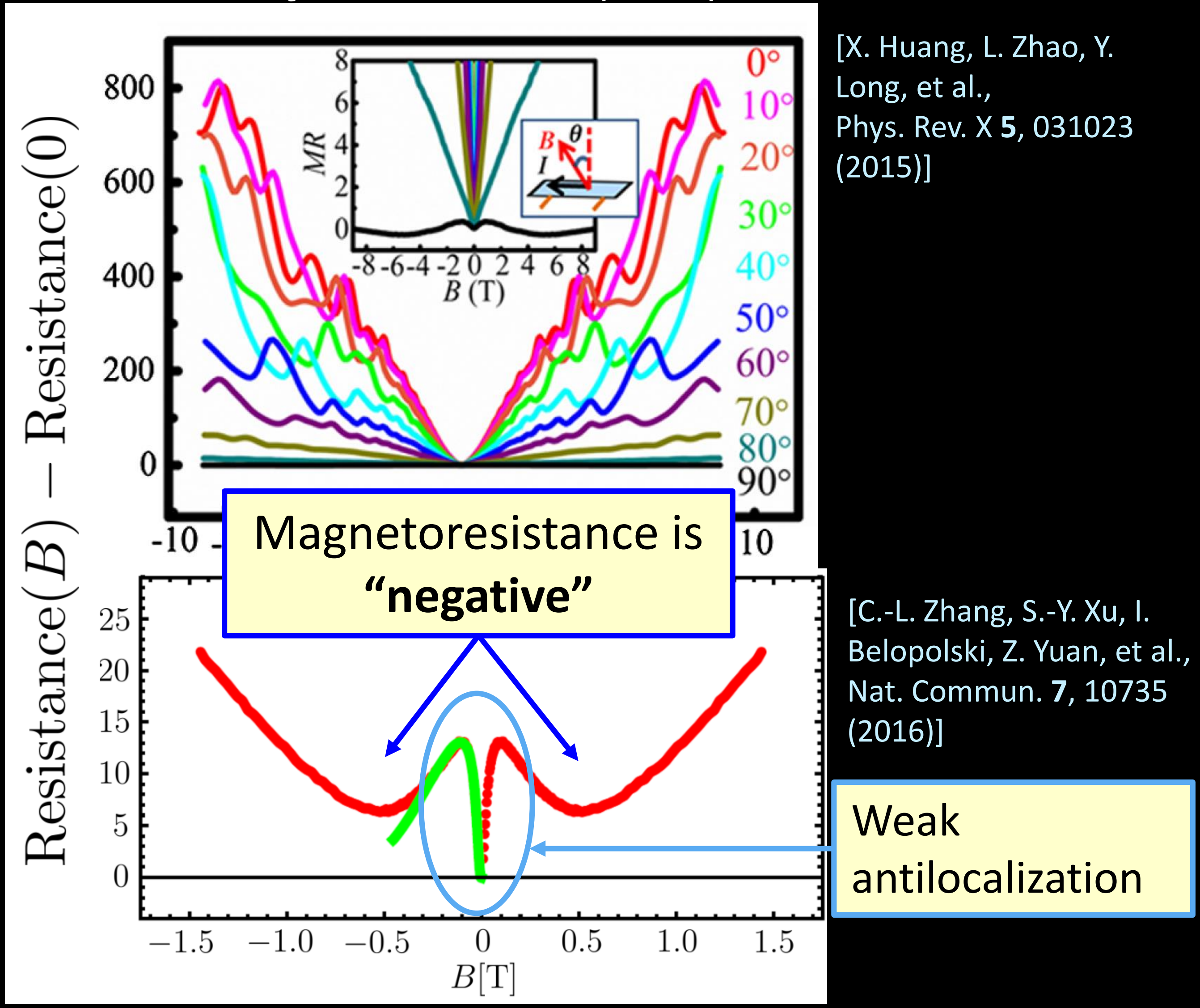

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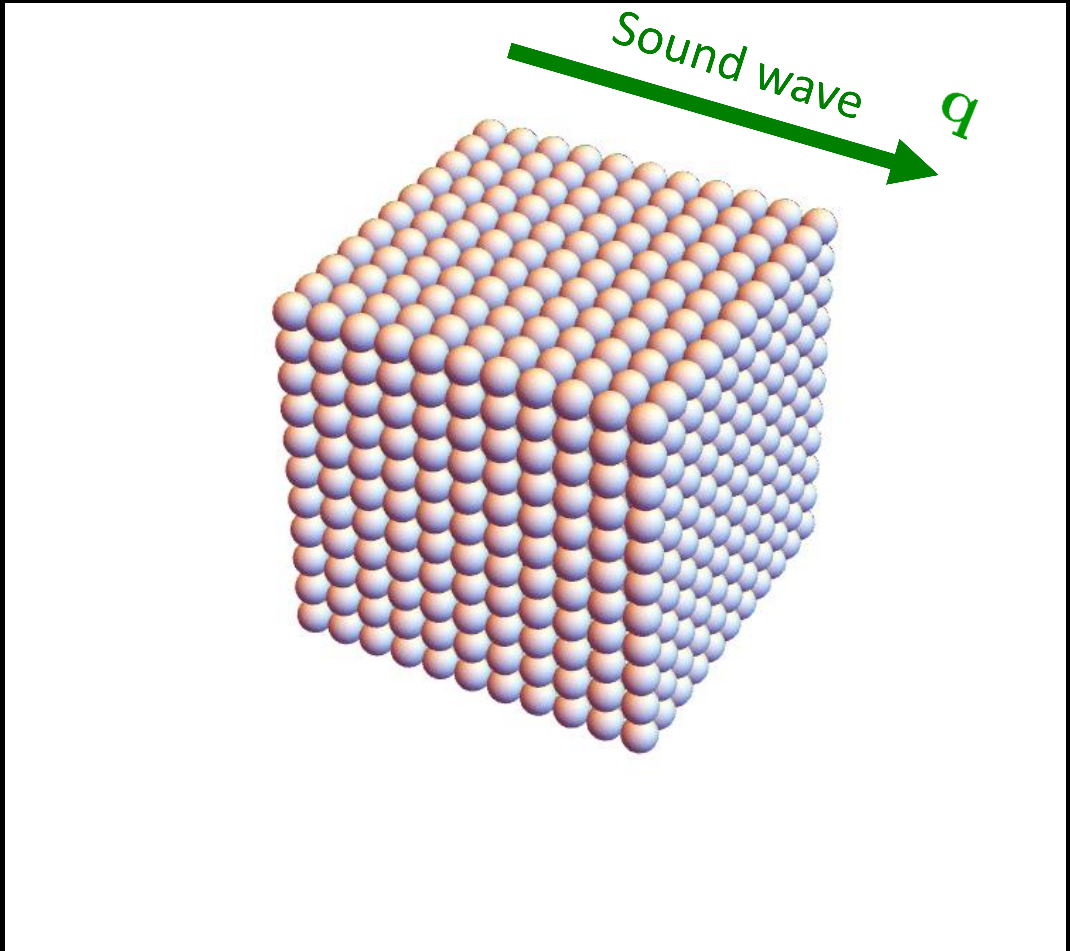
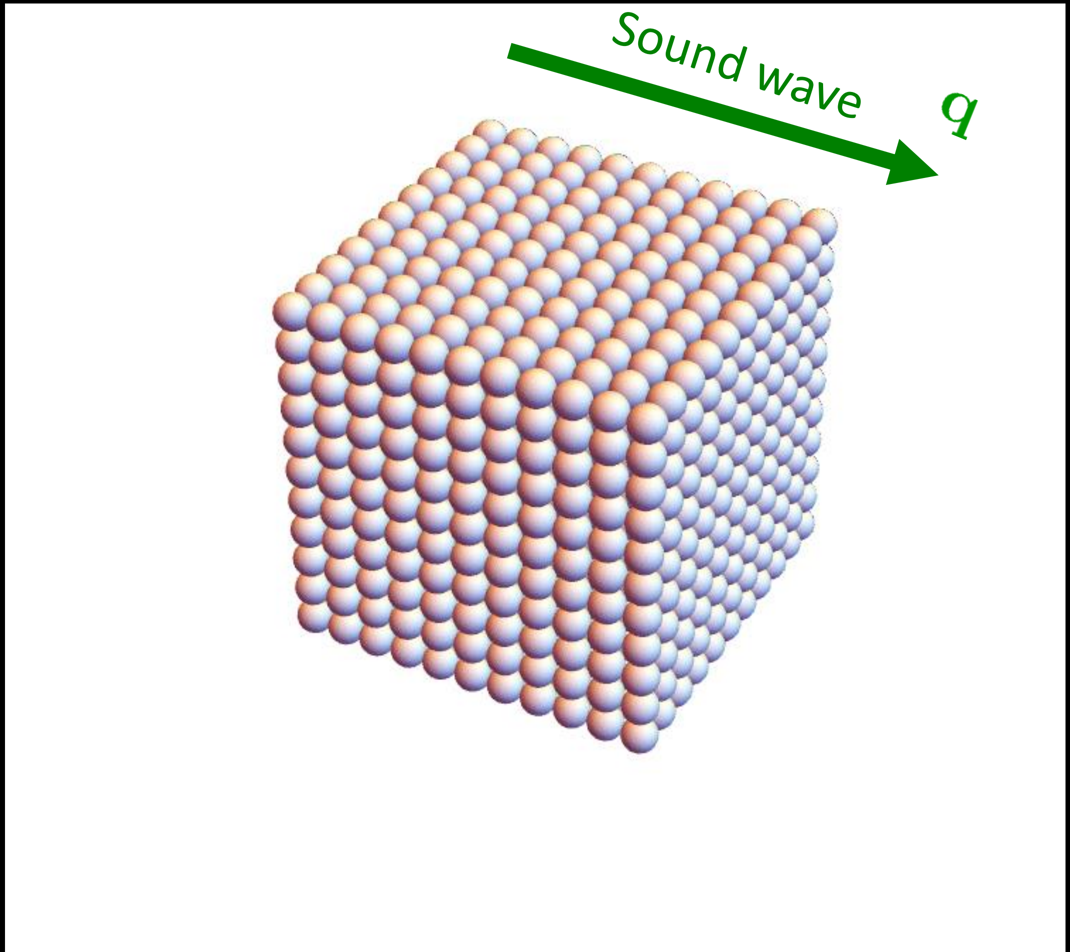
- **New approaches** are needed to verify chiral anomaly
- Novel effects await in the **ac regime**

Sound propagation

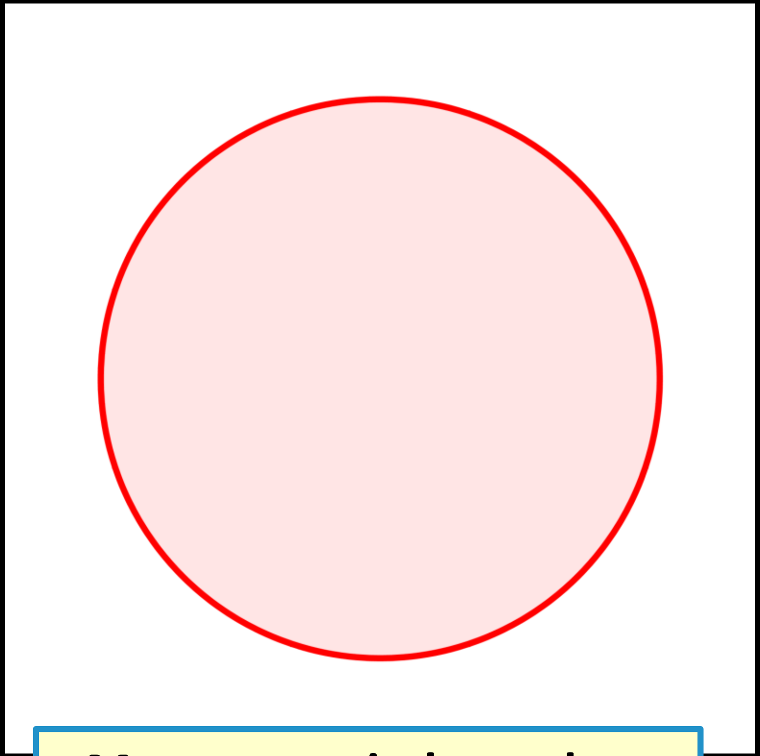


Sound propagation



Deformation potential:
Sound → modifies the potential acting on electrons

Sound propagation

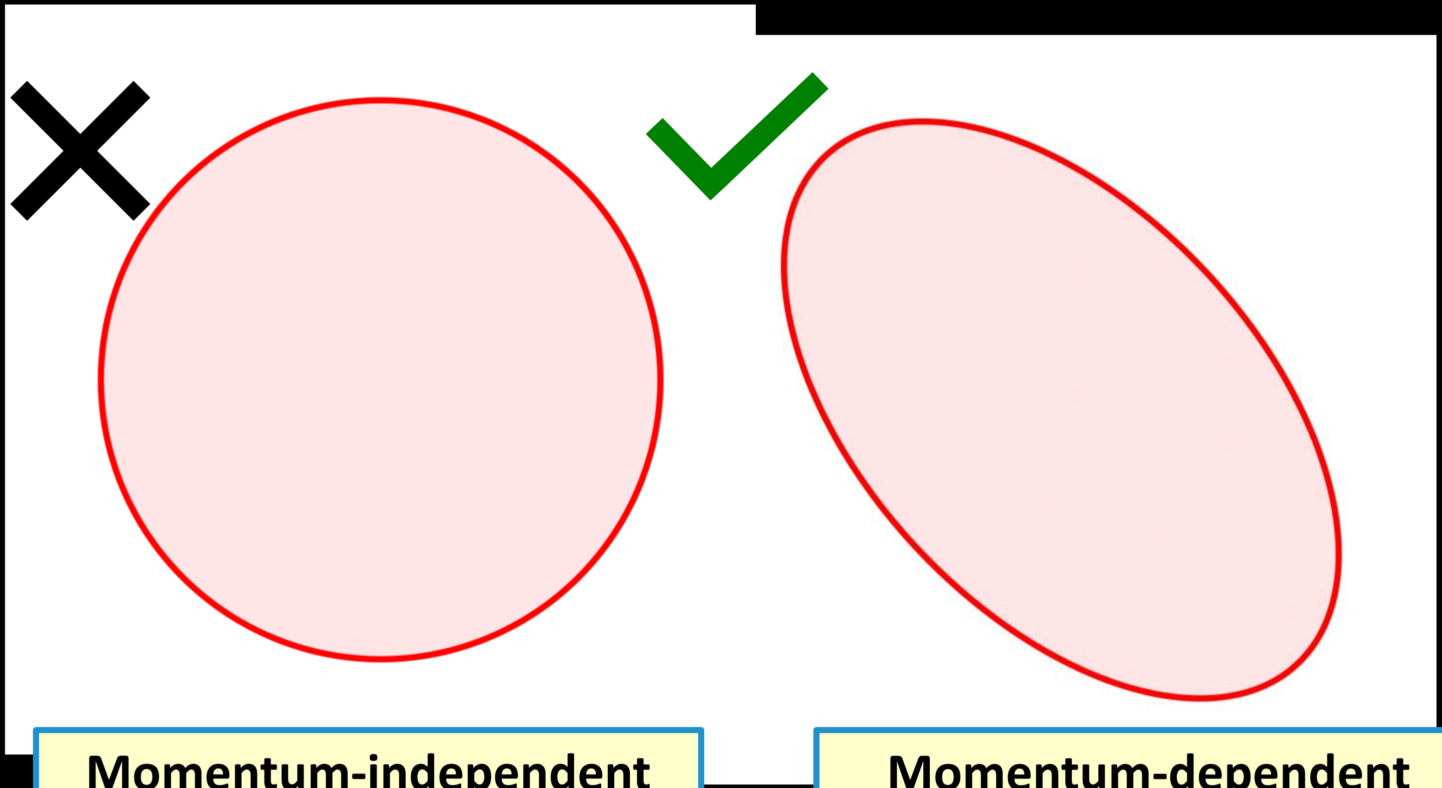


Momentum-independent
deformation potential

$$U(k_F, t, \mathbf{r})$$

Sound propagation

Strong screening $\Longrightarrow$ **local** charge neutrality $\Longrightarrow$ only **volume-preserving** deformations allowed



Momentum-independent deformation potential

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Momentum-dependent deformation potential

$$U\left(k_F \cos\left(2\theta\right), t, \mathbf{r}\right)$$

Sound propagation

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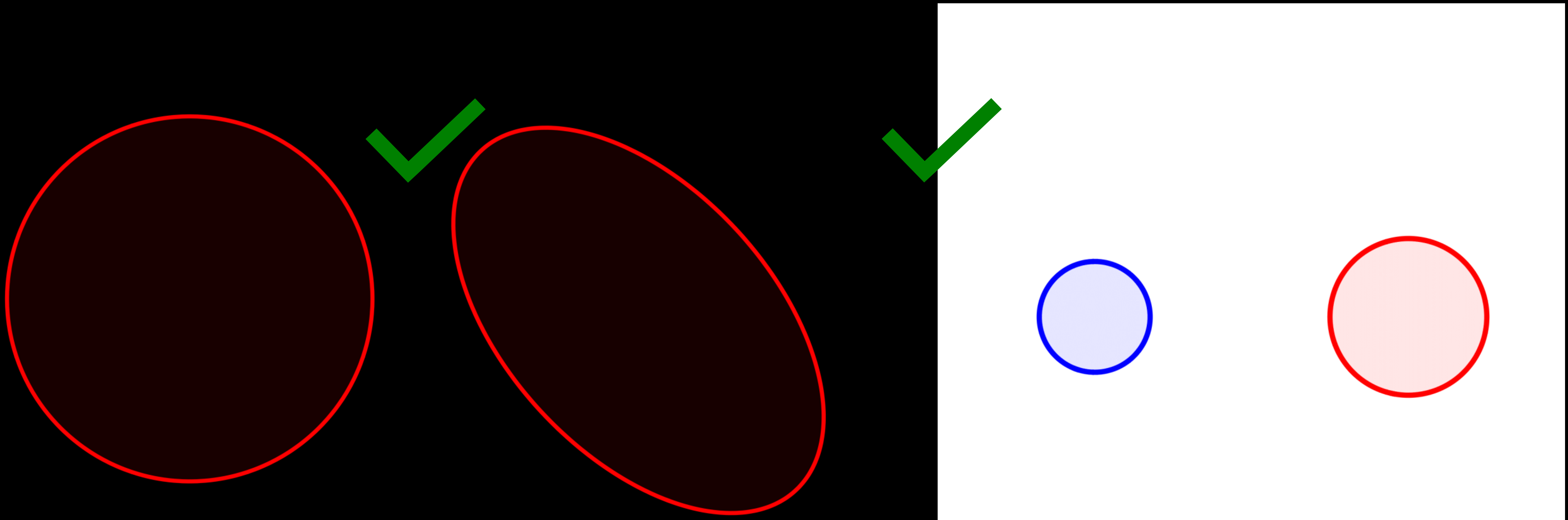


Momentum-independent
deformation potential

$$U(k_F, t, \mathbf{r})$$

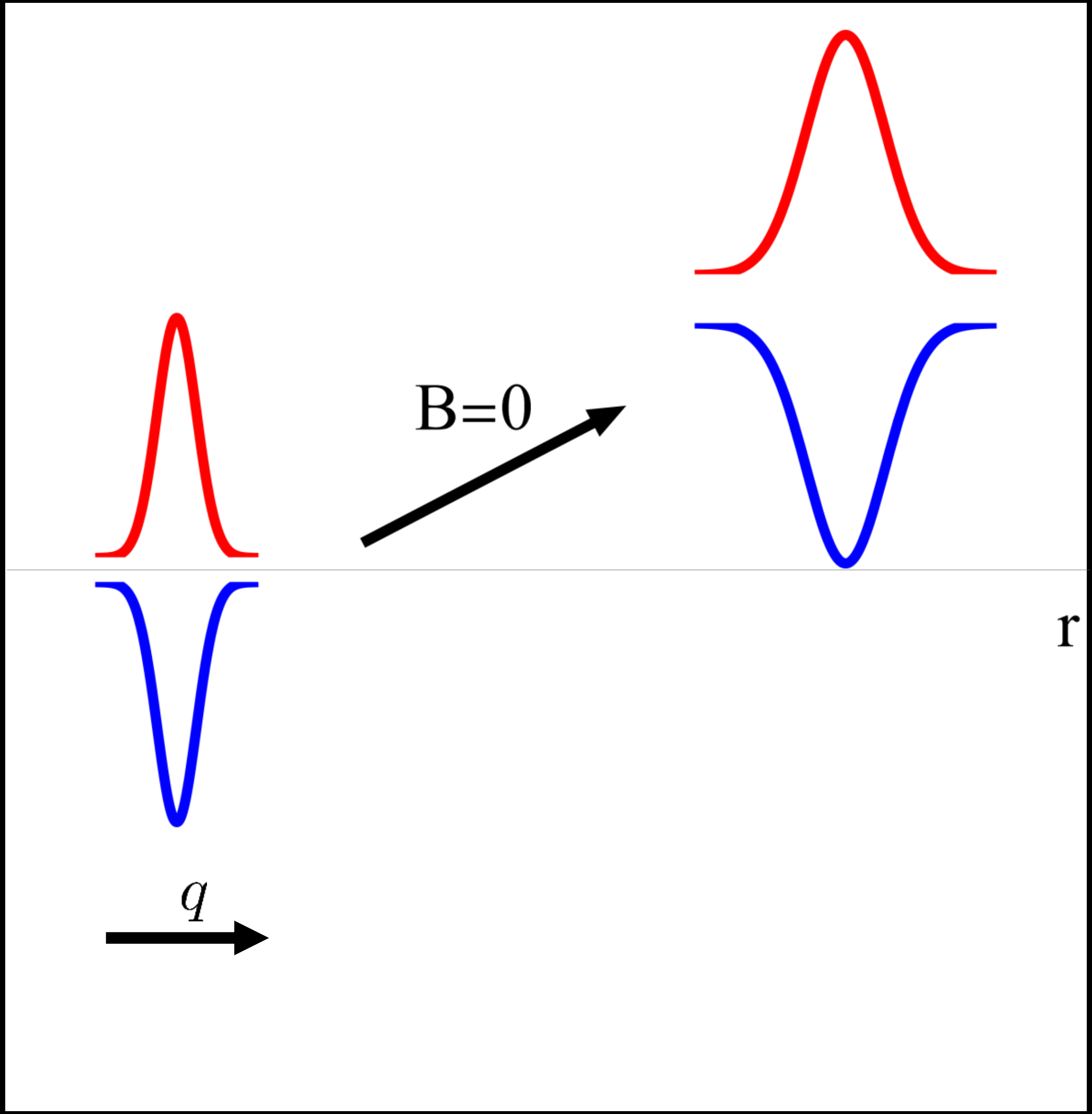
Momentum-dependent
deformation potential

$$U\left(k_F \cos\left(2\theta\right), t, \mathbf{r}\right)$$

Valley-dependent
deformation potential

$$U_+(k_F, t, \mathbf{r}) = -U_-(k_F, t, \mathbf{r})$$

Symmetric Weyl nodes in magnetic field



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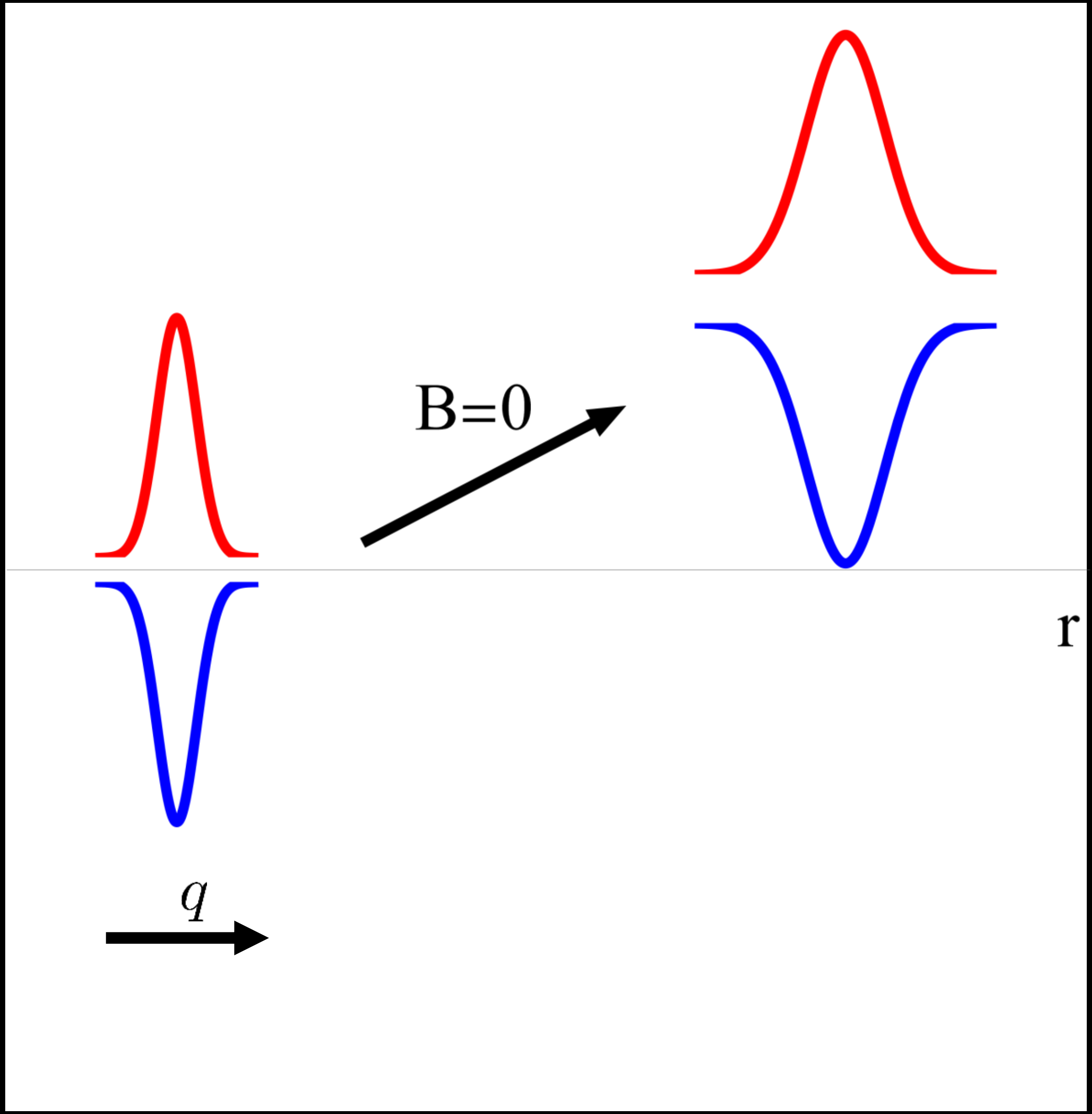

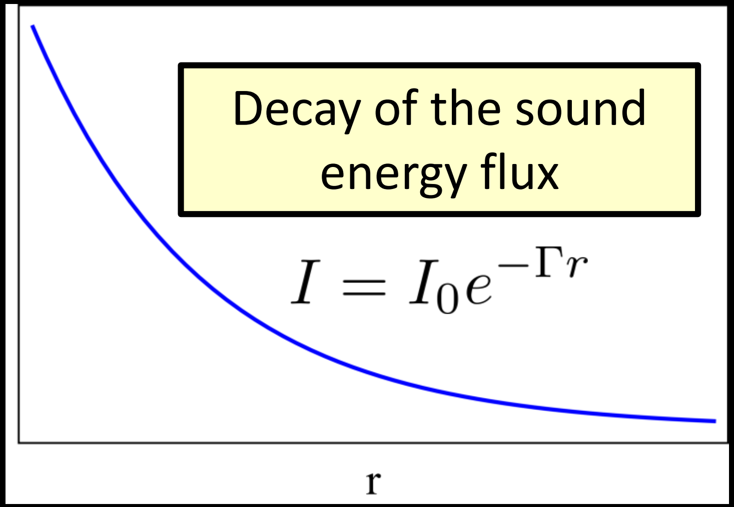

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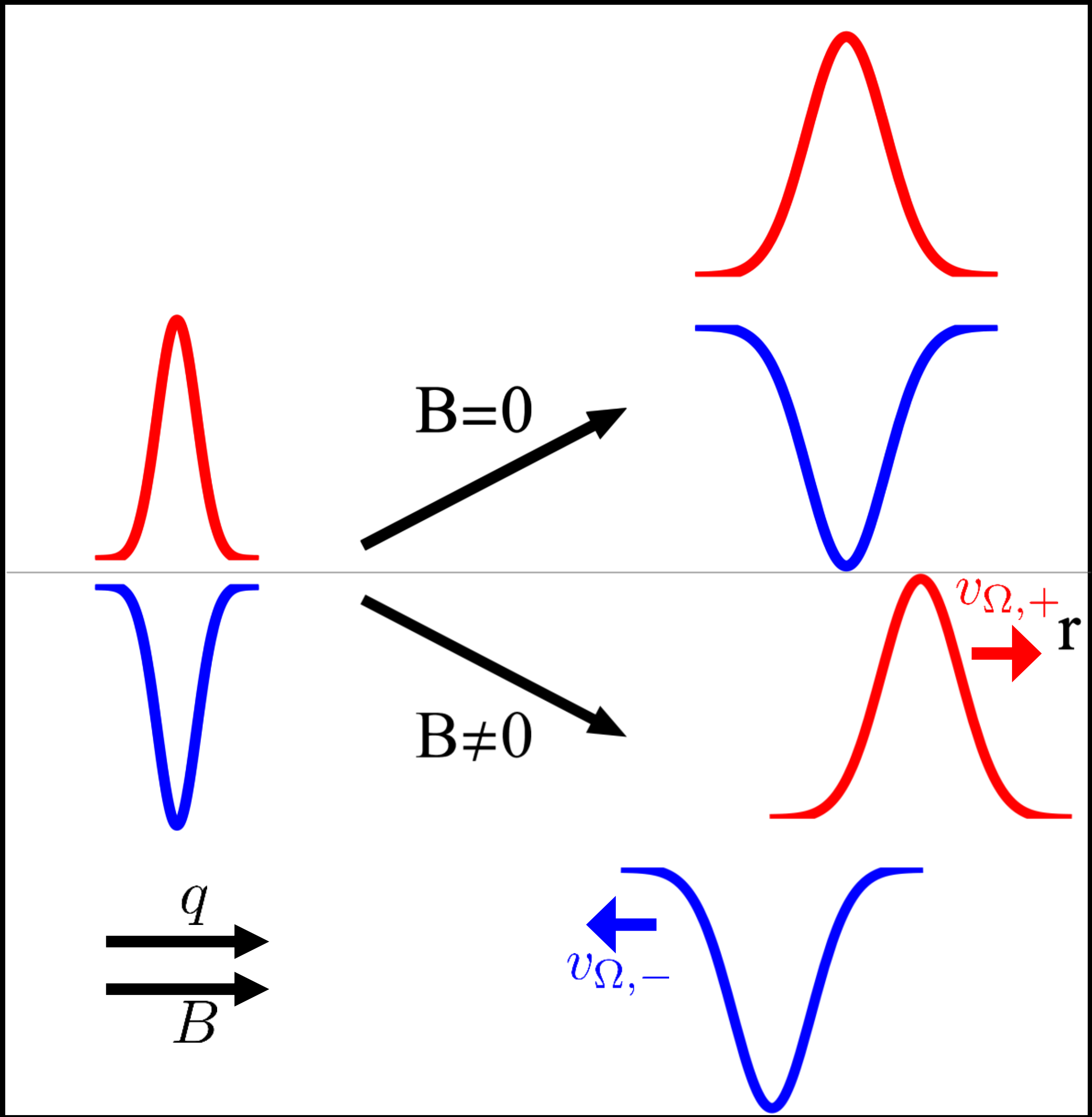
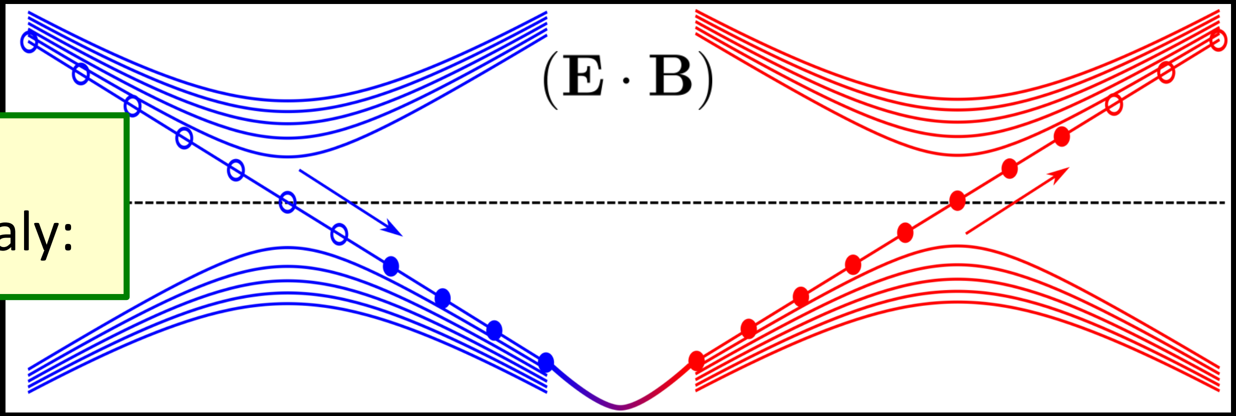


Chiral anomaly:



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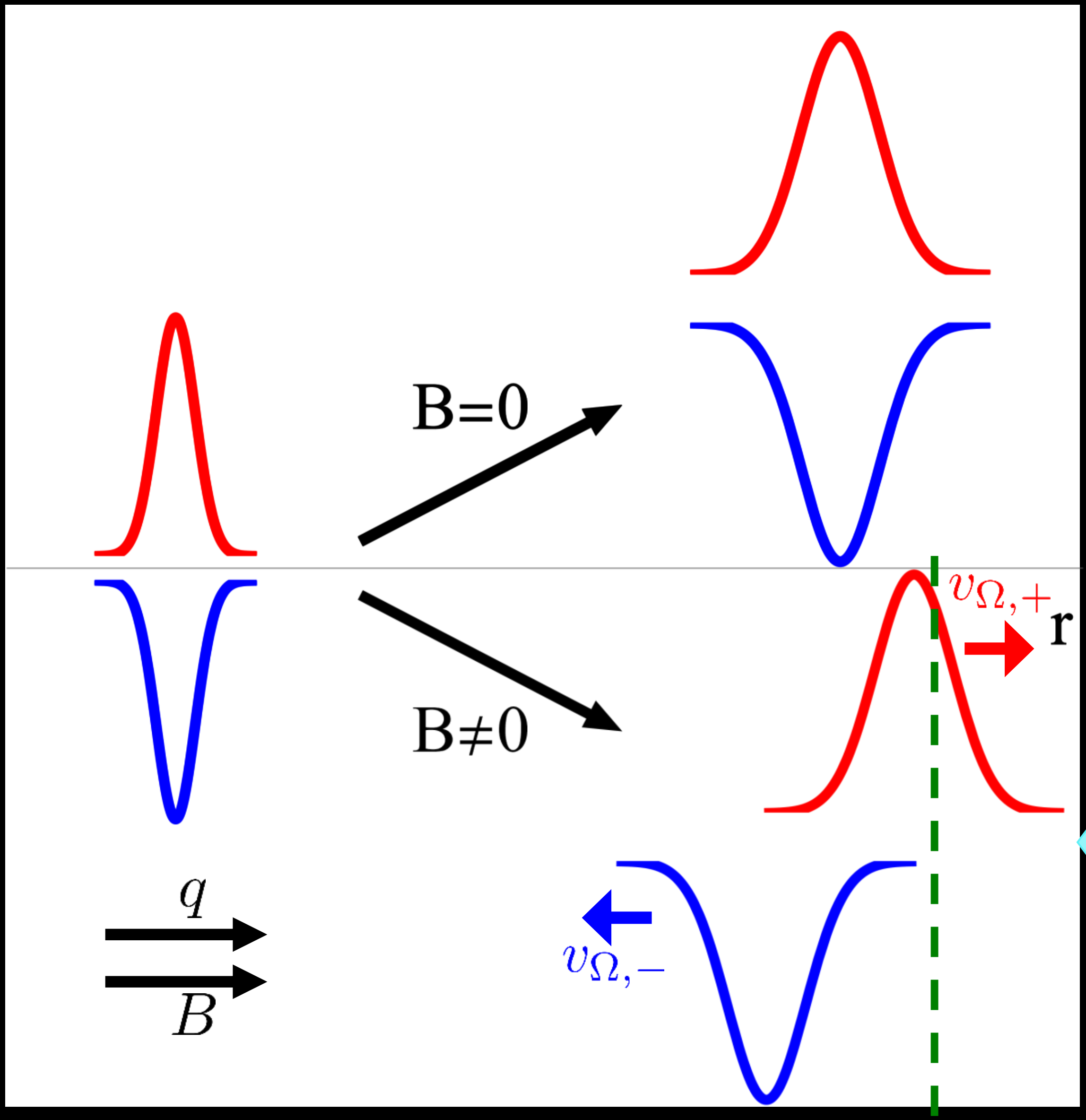

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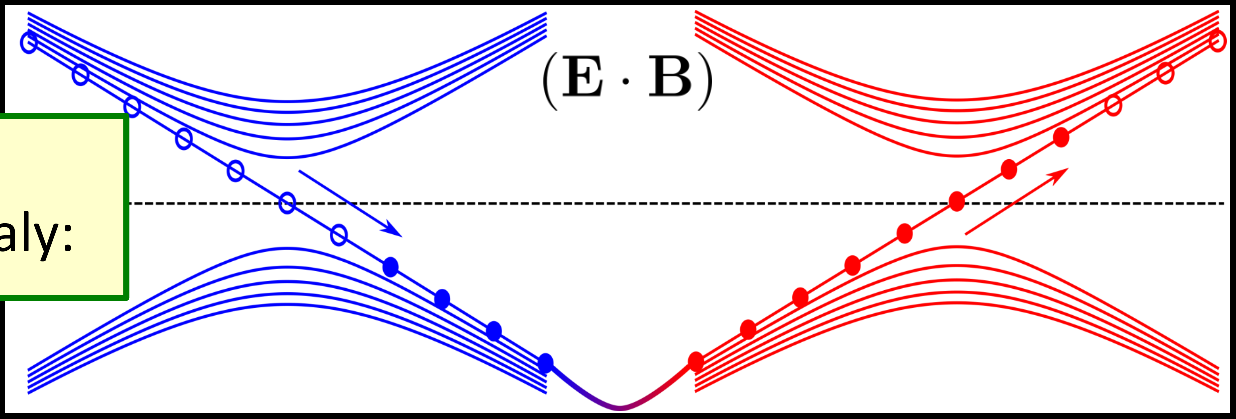
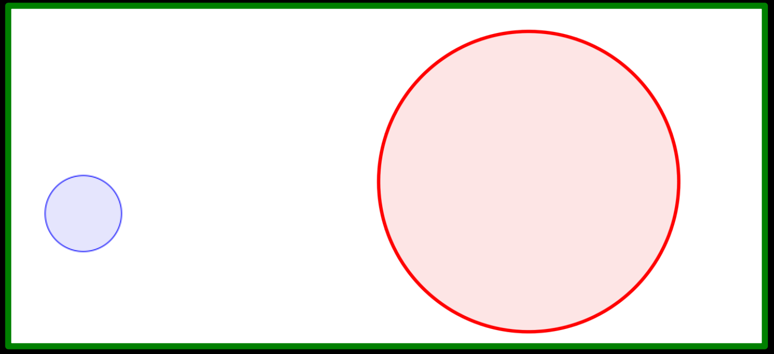
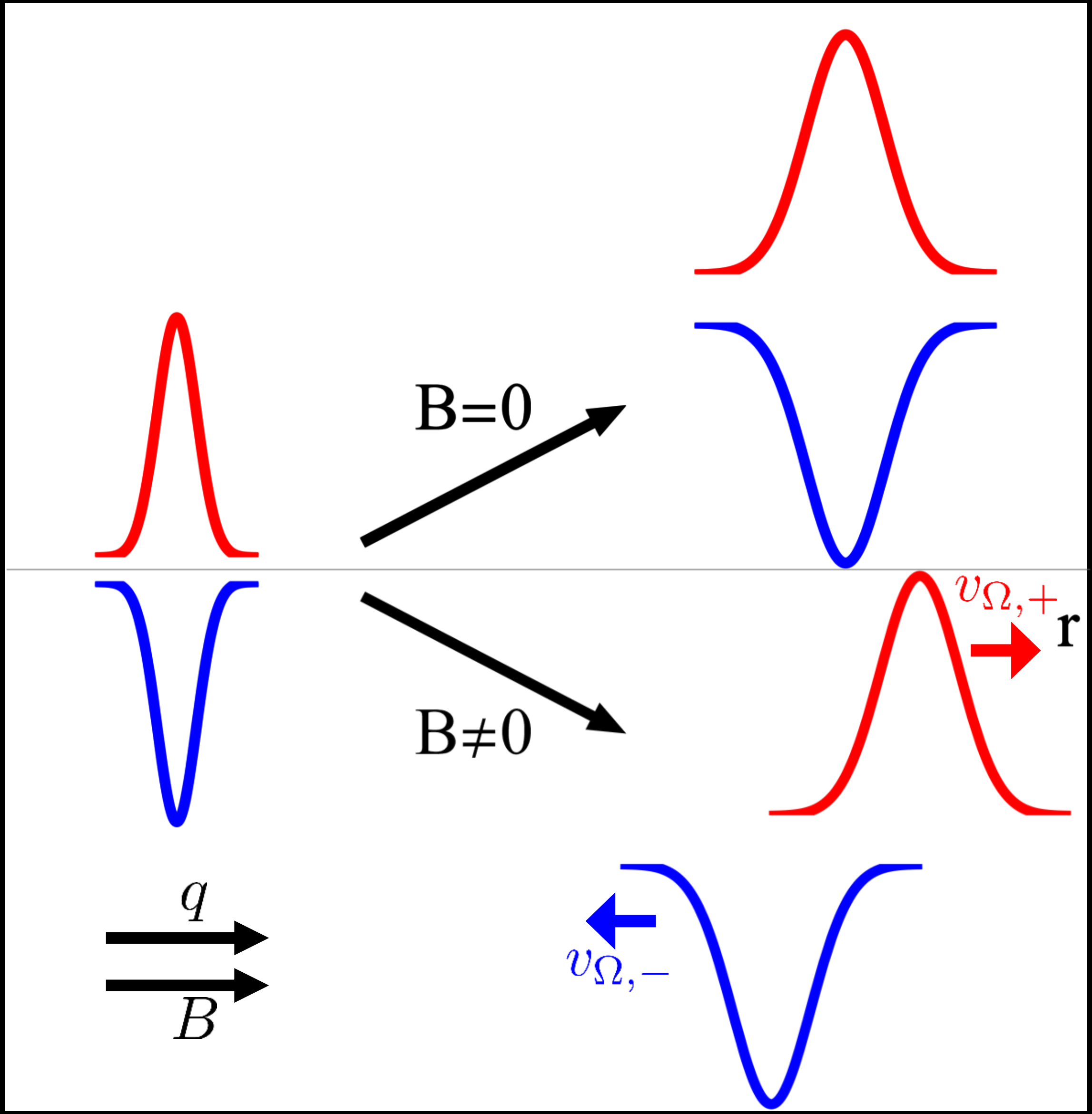




No longer locally neutral!

Symmetric Weyl nodes in magnetic field



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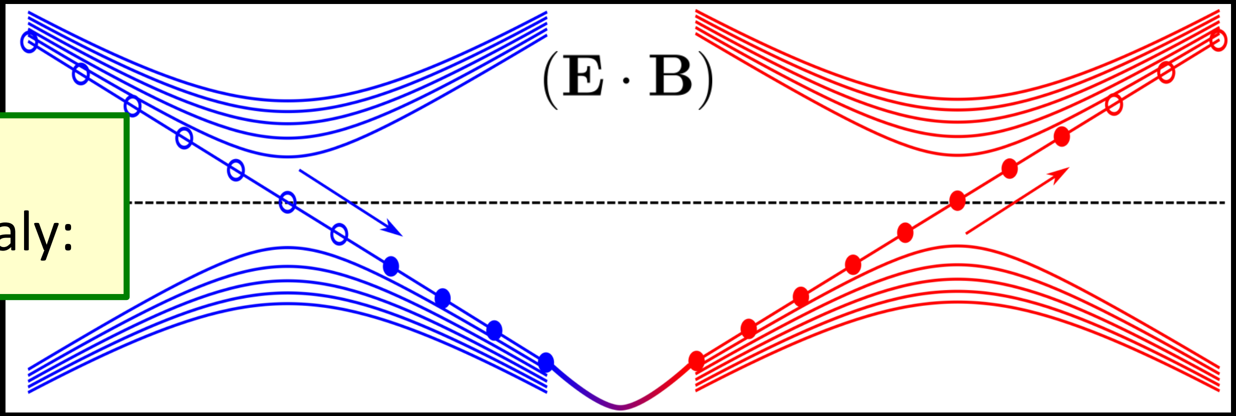

Anomaly-induced drift of chiral wave packets violates local charge neutrality → screening of the valley-odd deformation potential

Magnetic field reduces the sound attenuation

Sound attenuation coefficient

$$\Gamma = \frac{Q}{VI},$$

Sound attenuation coefficient

$$Q = \frac{1}{T}\int_0^T dt \langle \frac{d}{dt}\hat{H} \rangle,$$

Dissipated energy

$$I = v_s \frac{\rho_m \langle |\partial_t \mathbf{u}|^2 \rangle_T}{2} = v_s \frac{\rho_m \omega^2 u_0^2}{2}.$$

Sound energy flux

Sound attenuation coefficient

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Dissipated energy

$$I = v_s \frac{\rho_m \langle |\partial_t \mathbf{u}|^2 \rangle_T}{2} = v_s \frac{\rho_m \omega^2 u_0^2}{2}.$$

Sound energy flux

$$\frac{Q}{V} = -\sum_{\alpha}^{N_W} \frac{1}{2e} \mathrm{Re}\left\{ i\omega \left(\lambda_{ij}^{(\alpha)} u_{ij} \right)^* N_\alpha \right\}.$$

Sound attenuation coefficient

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$$Q = \frac{1}{T}\int_0^T dt \langle \frac{d}{dt}\hat{H} \rangle,$$

Dissipated energy

$$I = v_s \frac{\rho_m \langle |\partial_t \mathbf{u}|^2 \rangle_T}{2} = v_s \frac{\rho_m \omega^2 u_0^2}{2}.$$

Sound energy flux

$$\frac{Q}{V} = -\sum_{\alpha}^{N_W} \frac{1}{2e} \mathrm{Re}\left\{ i\omega \left(\lambda_{ij}^{(\alpha)} u_{ij} \right)^* N_\alpha \right\}.$$

$$\Gamma = -\frac{q}{e v_s \rho_m \omega u_0} \mathrm{Re}\left\{ \lambda N + \lambda^{(5)} N_5 \right\}, \quad \text{at} \quad \nu_\alpha = \nu, \quad \lambda_{ij}^{(\alpha)} = \lambda_{ij} + \chi_\alpha \lambda_{ij}^{(5)}.$$

Sound attenuation is determined by the non-equilibrium part of the charge densities

Kinetic equations

Diffusive approximation: $\tau_{\alpha,\alpha} \ll \tau_{\alpha,\beta}$ and $\tau_{\alpha,\alpha}\omega \ll 1$

$$\partial_t N_\alpha + (\boldsymbol{\nabla}\cdot\mathbf{j}_\alpha) - e^2\nu_\alpha\left(\left[\mathbf{E} + \frac{1}{e}\lambda_{ij}^{(\alpha)}\boldsymbol{\nabla}u_{ij}\right]\cdot\mathbf{v}_{\Omega,\alpha}\right) = -\sum_\beta^{N_W} T_{\alpha,\beta}N_\beta - u_{ij}\sum_\beta^{N_W}\frac{\lambda_{ij}^{(\alpha)} - \lambda_{ij}^{(\beta)}}{\tau_{\alpha,\beta}}.$$

$$\mathbf{v}_{\Omega,\alpha} = \chi_\alpha\frac{e}{4\pi^2 c\hbar^2\nu_\alpha}\mathbf{B}_\alpha.$$

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Currents in each of the nodes:

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Anomalous part of the current

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Anomalous part of the current

Gauss law:

$$\boldsymbol{\nabla}\cdot\mathbf{E} = 4\pi\sum_{\alpha}^{N_W}N_\alpha.$$

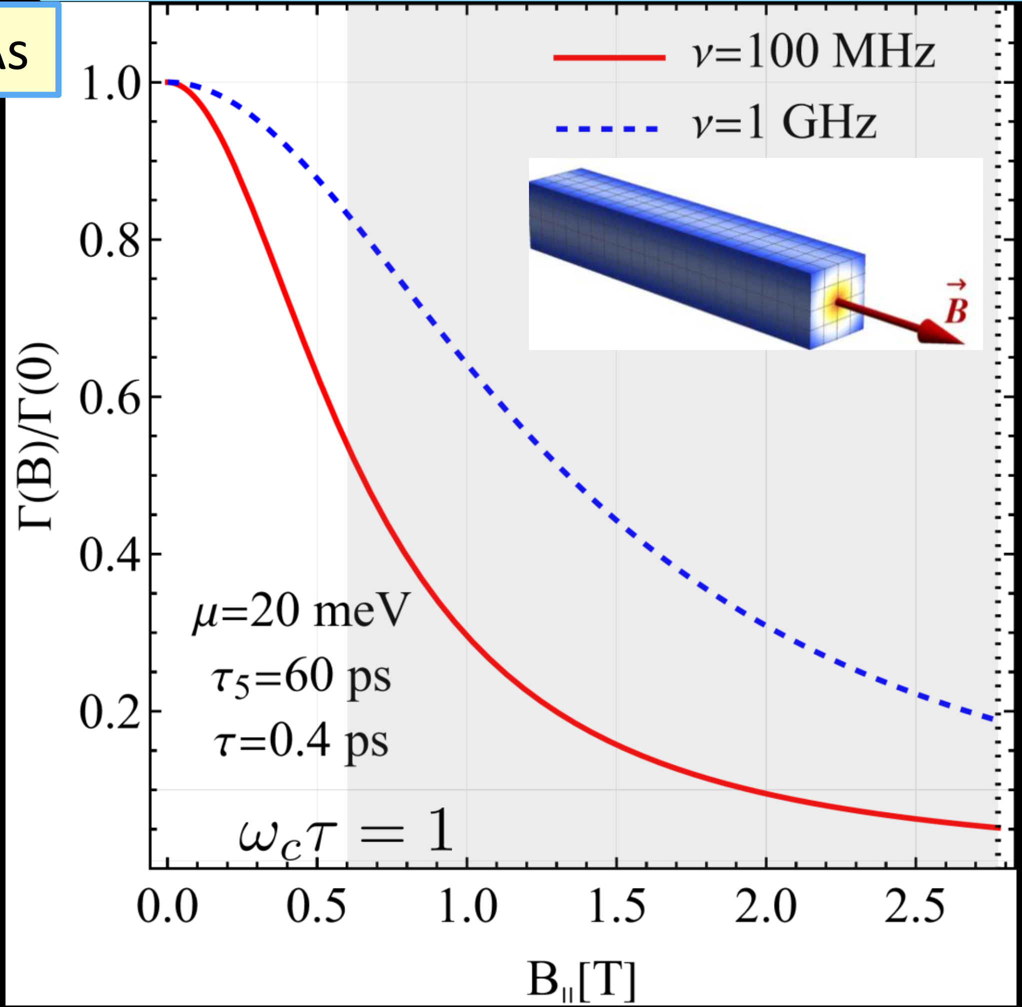
Inclusion of the Gauss law is the key difference from the previous studies

[B. Z. Spivak and A. V. Andreev, Phys. Rev. B **93**, 085107 (2016).]

Results of the chiral kinetic approach

Screening is strong even in semimetals
($\mu \approx 10 - 20$ meV)

TaAs



[P. O. Sukhachov and L. I. Glazman, Phys. Rev. B **103**, 214310 (2021)]

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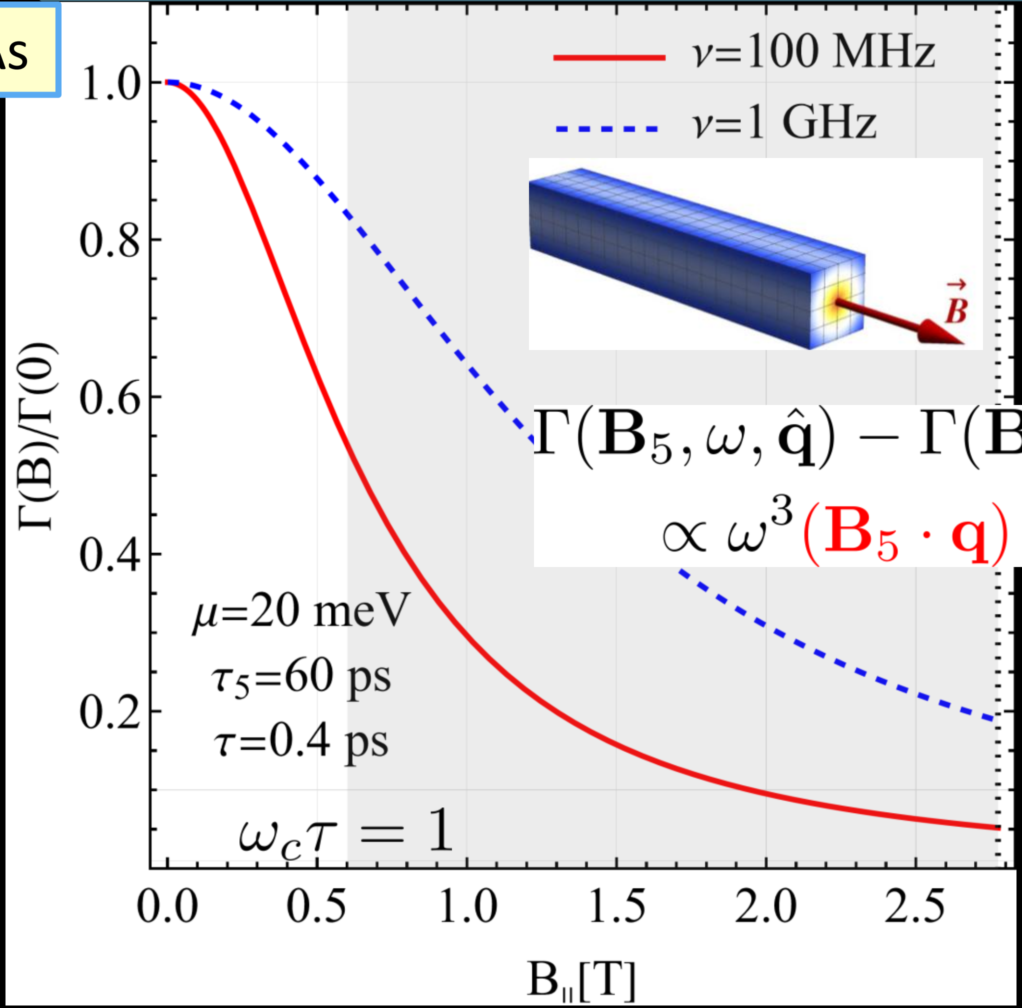
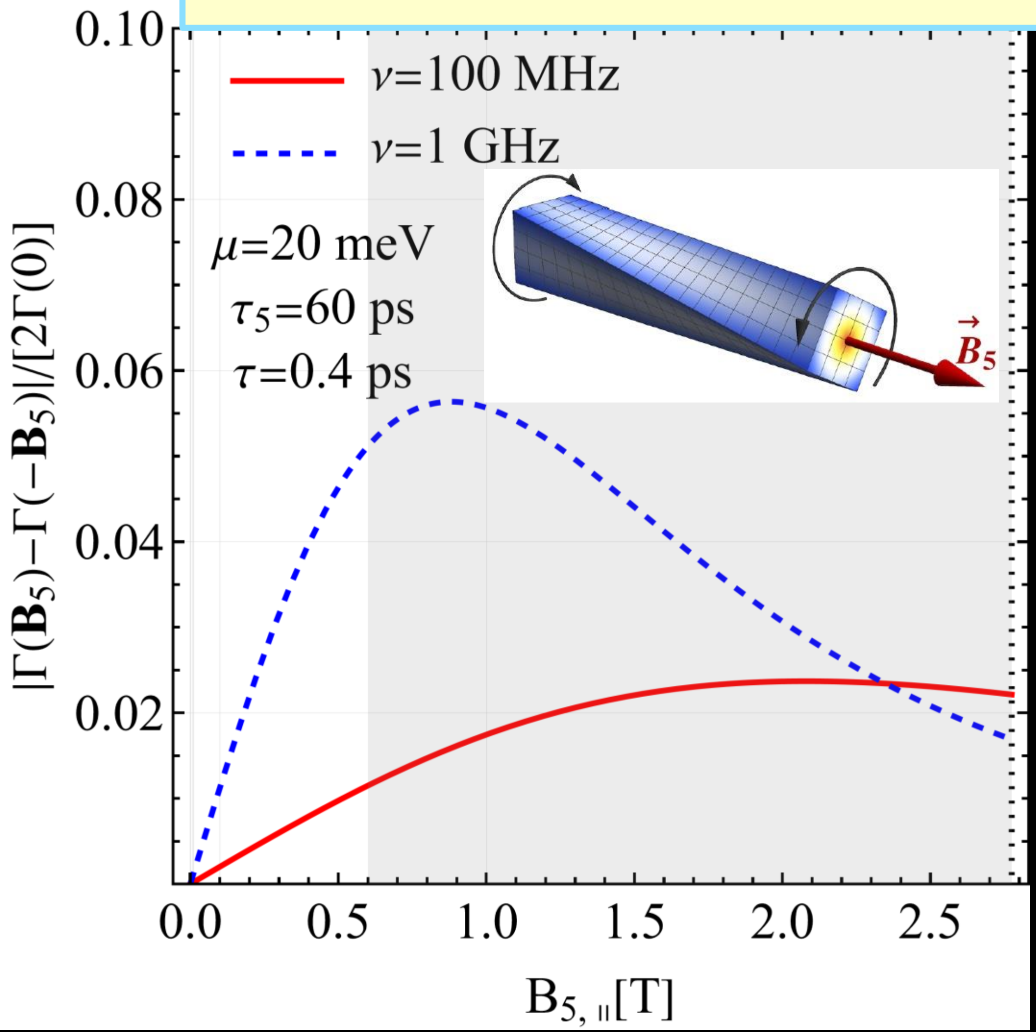


$$\Gamma(\mathbf{B}_5, \omega, \hat{\mathbf{q}}) - \Gamma(\mathbf{B}_5, \omega, -\hat{\mathbf{q}}) \propto \omega^3 (\mathbf{B}_5 \cdot \mathbf{q})$$

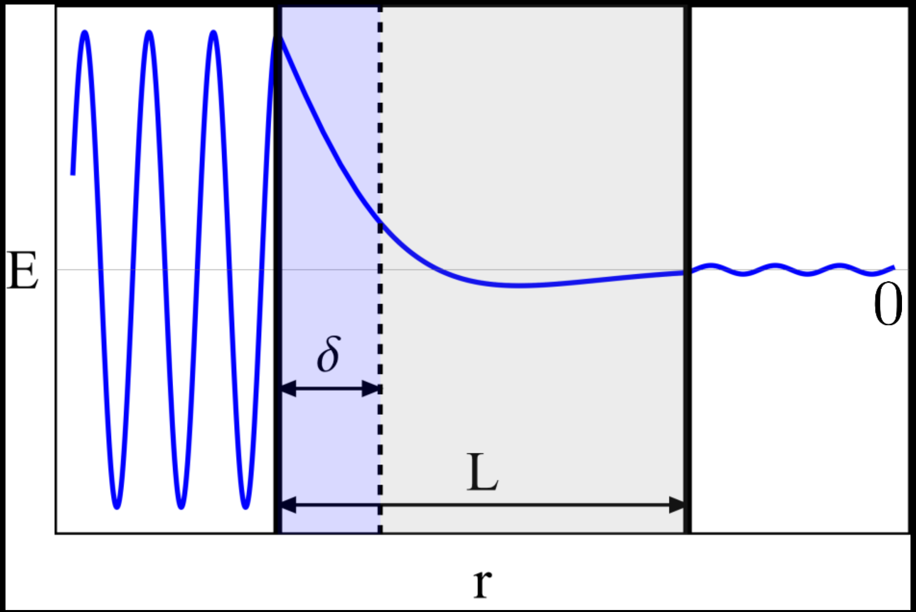
Pseudomagnetic field → **sound attenuation dichroism**

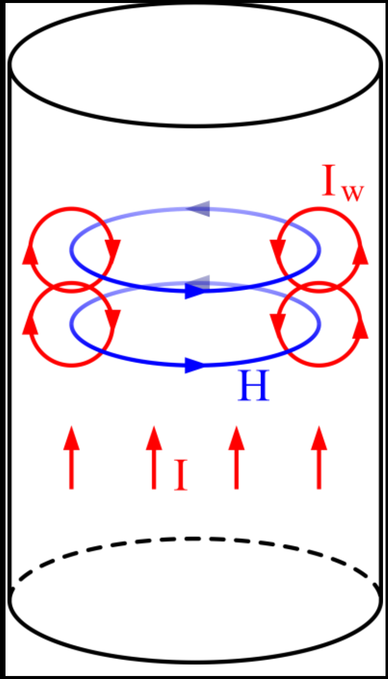


[P. O. Sukhachov and L. I. Glazman, Phys. Rev. B **103**, 214310 (2021)]

Light propagation: Skin effect

Conventional skin effect:





$$E \sim e^{-z/\delta(\omega)}, \qquad \delta(\omega) = \frac{c}{\sqrt{2\pi\omega\sigma_0}}$$

$$l_{\mathrm{mfp}} = v_F \tau \ll \delta(\omega)$$

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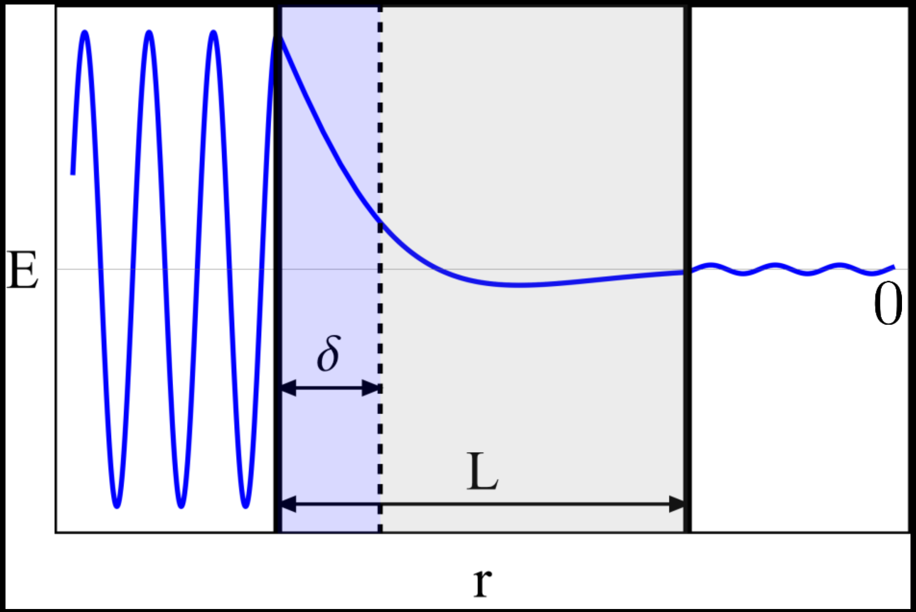

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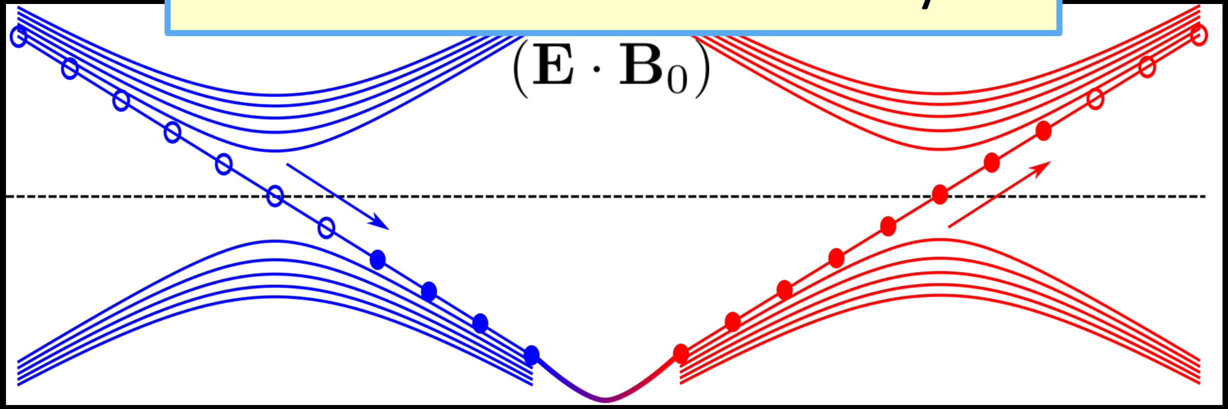
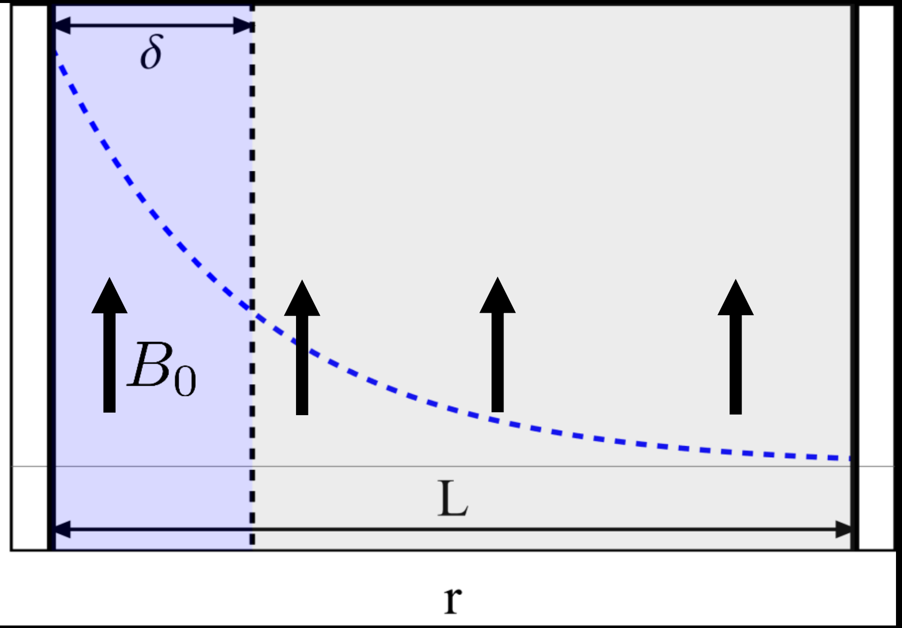
Role of the chiral anomaly:



$N_+ - N_-$



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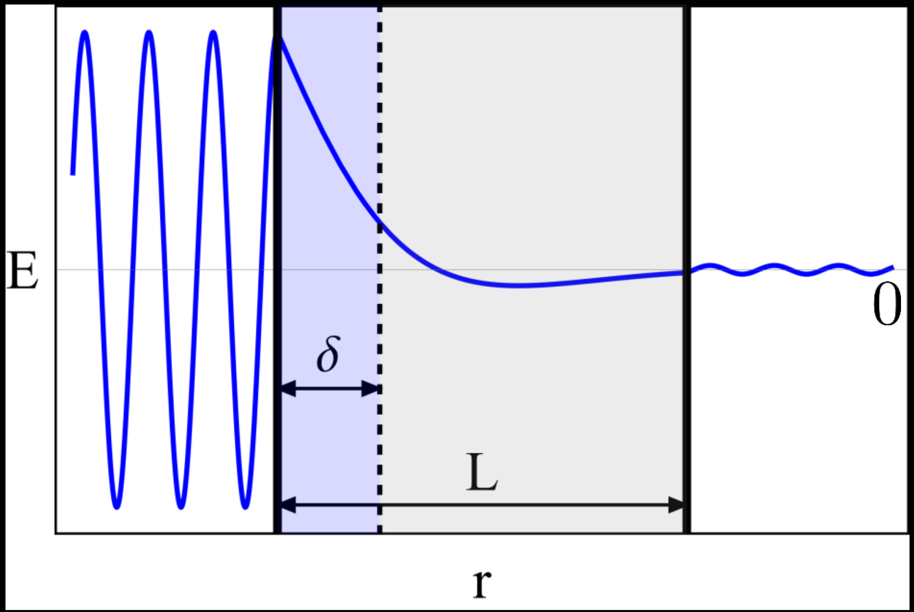

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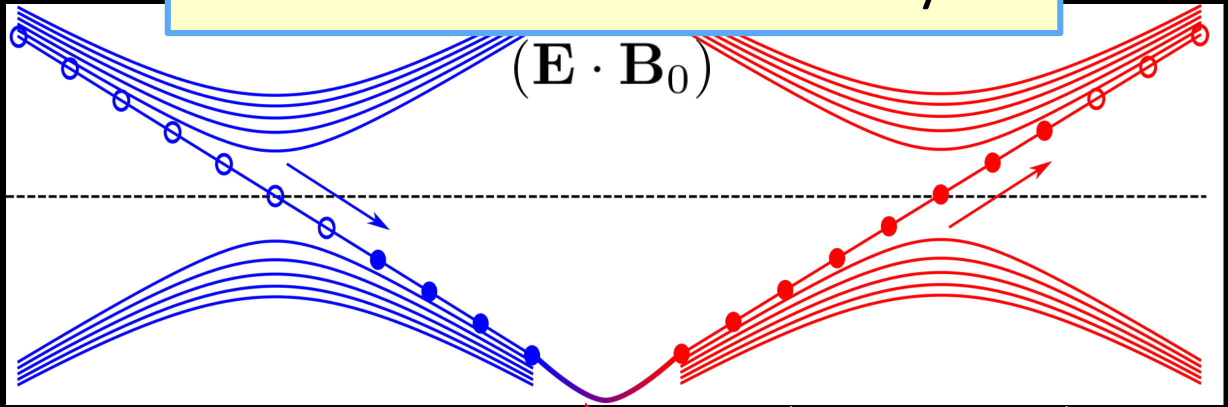

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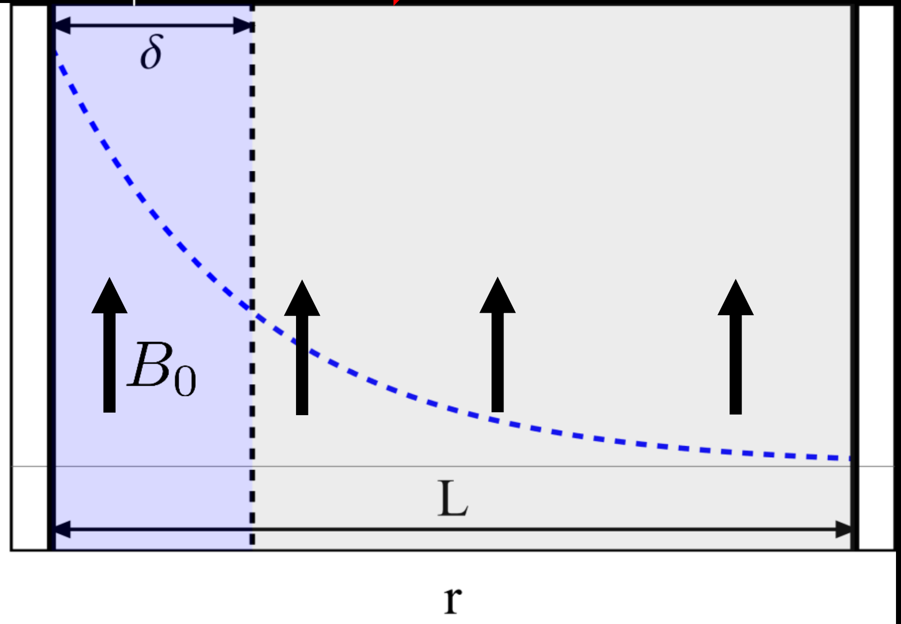

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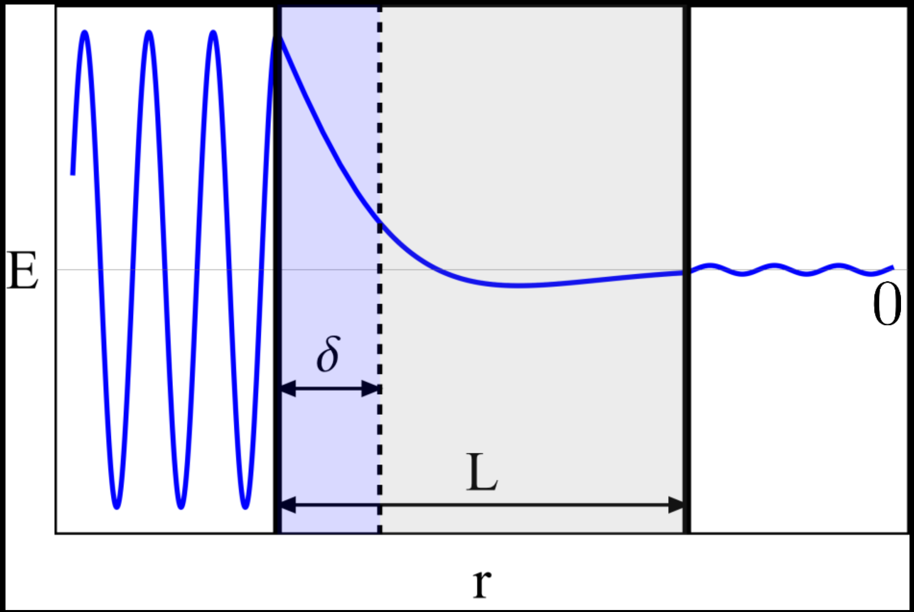

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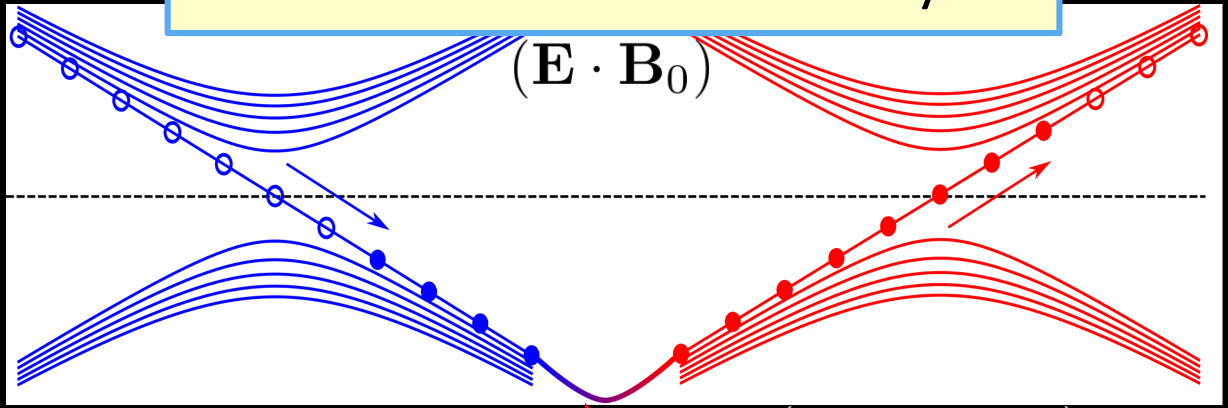

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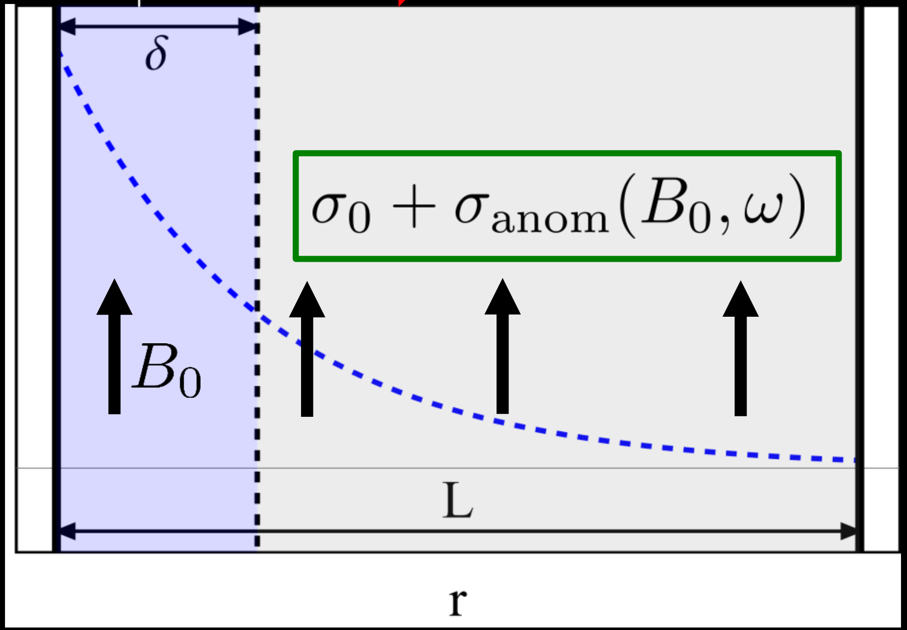
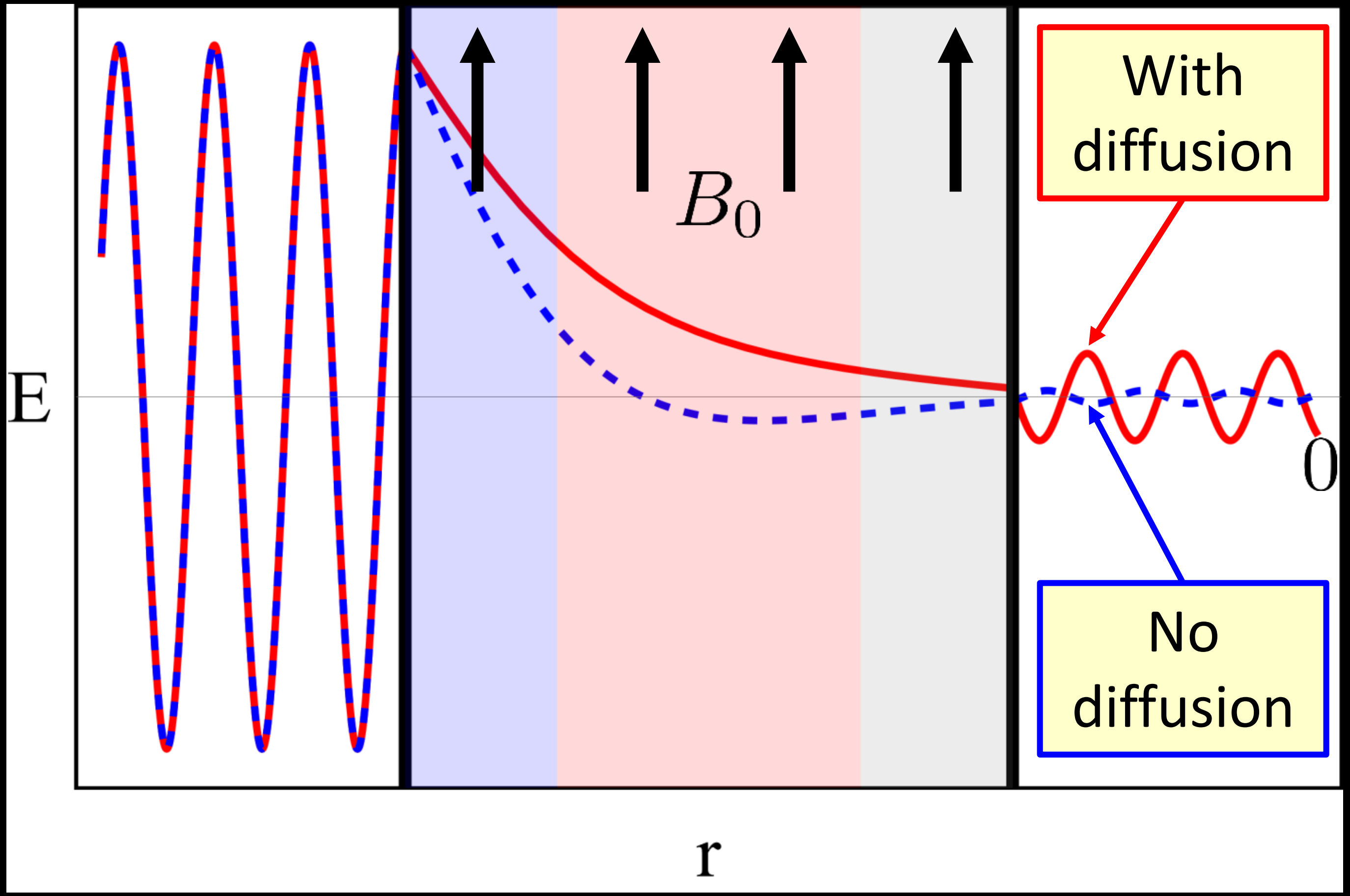


Enhancement of light transmission

Chiral anomaly + diffusion of the chiral charge

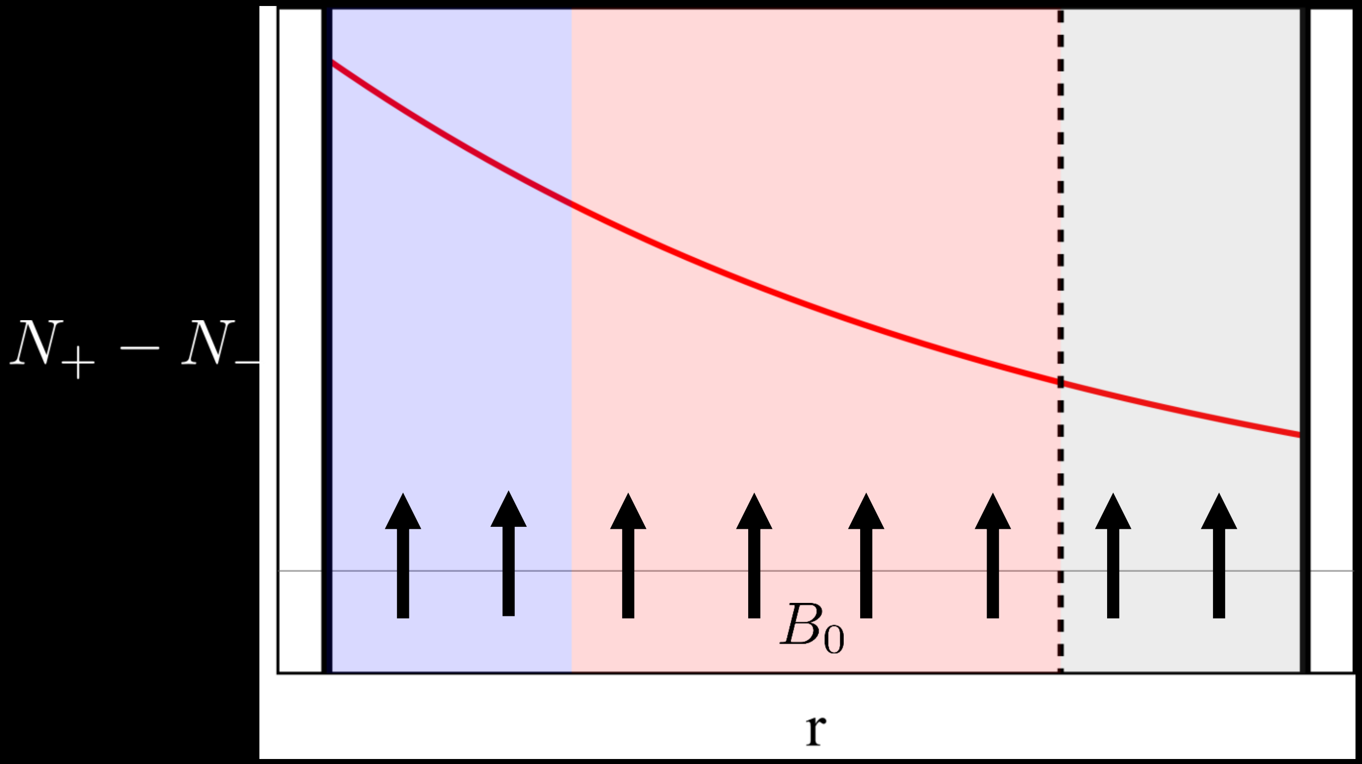
Anomalous nonlocal regime

Transmission of electromagnetic field is **enhanced**



[P. O. Sukhachov and L. I. Glazman, Phys. Rev. Lett. **128**, 146801 (2022)]

Nonlocal regime



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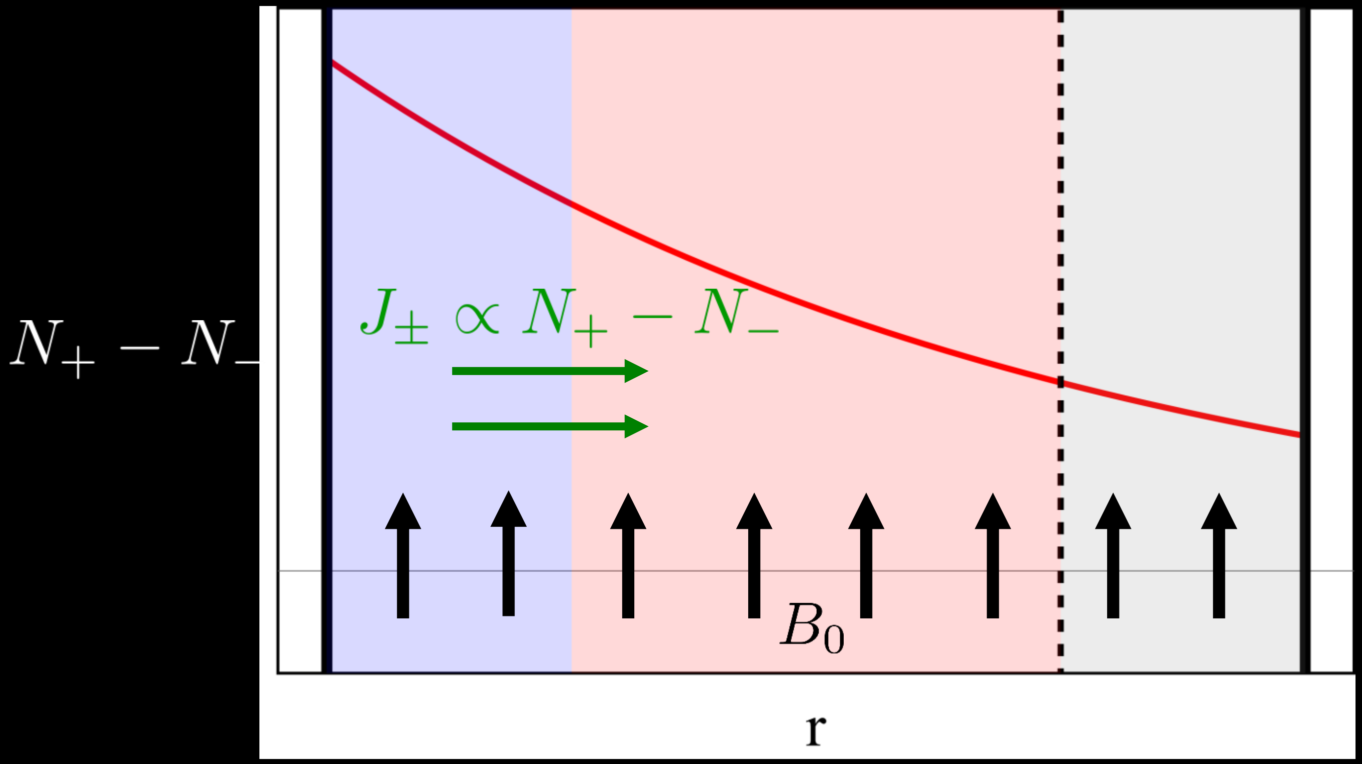

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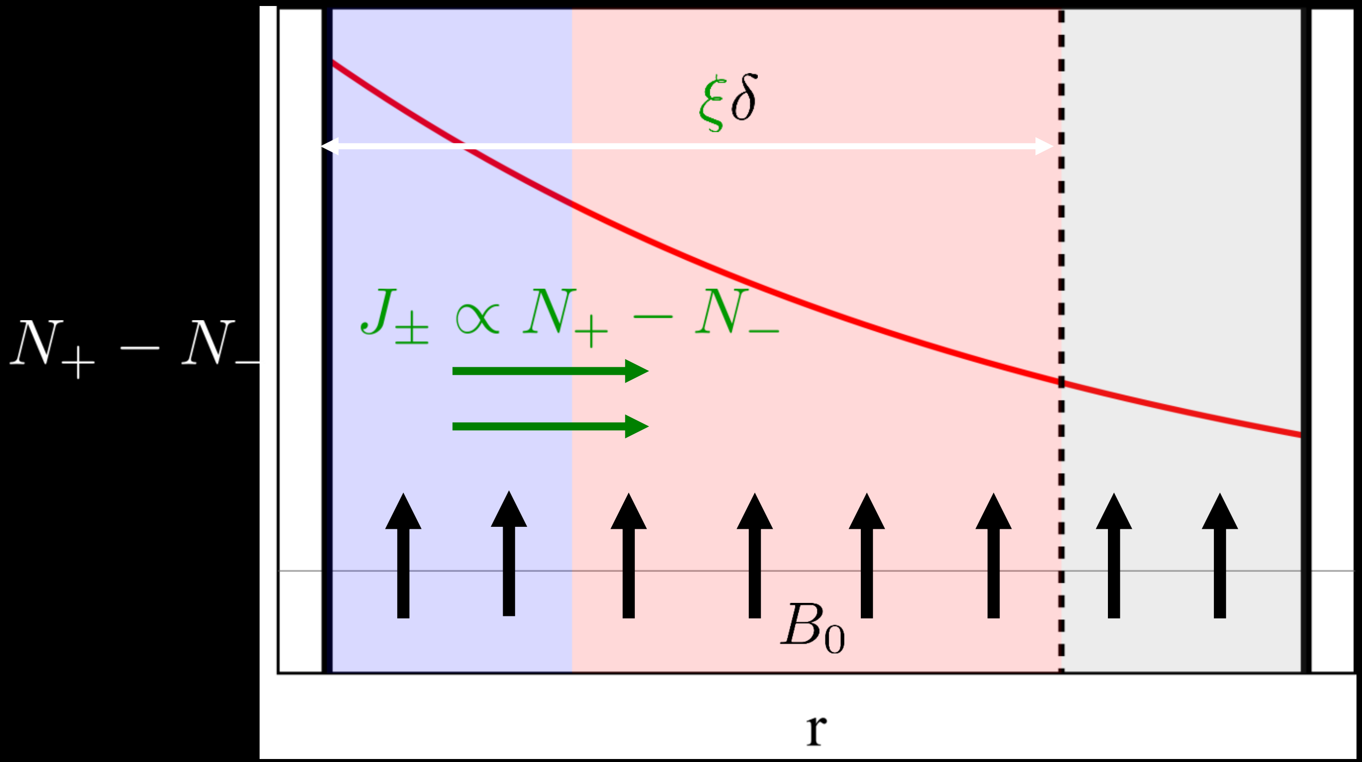

Nonlocality parameter:

$$\xi = \frac{\sqrt{4\pi\sigma_0 D}}{c}$$

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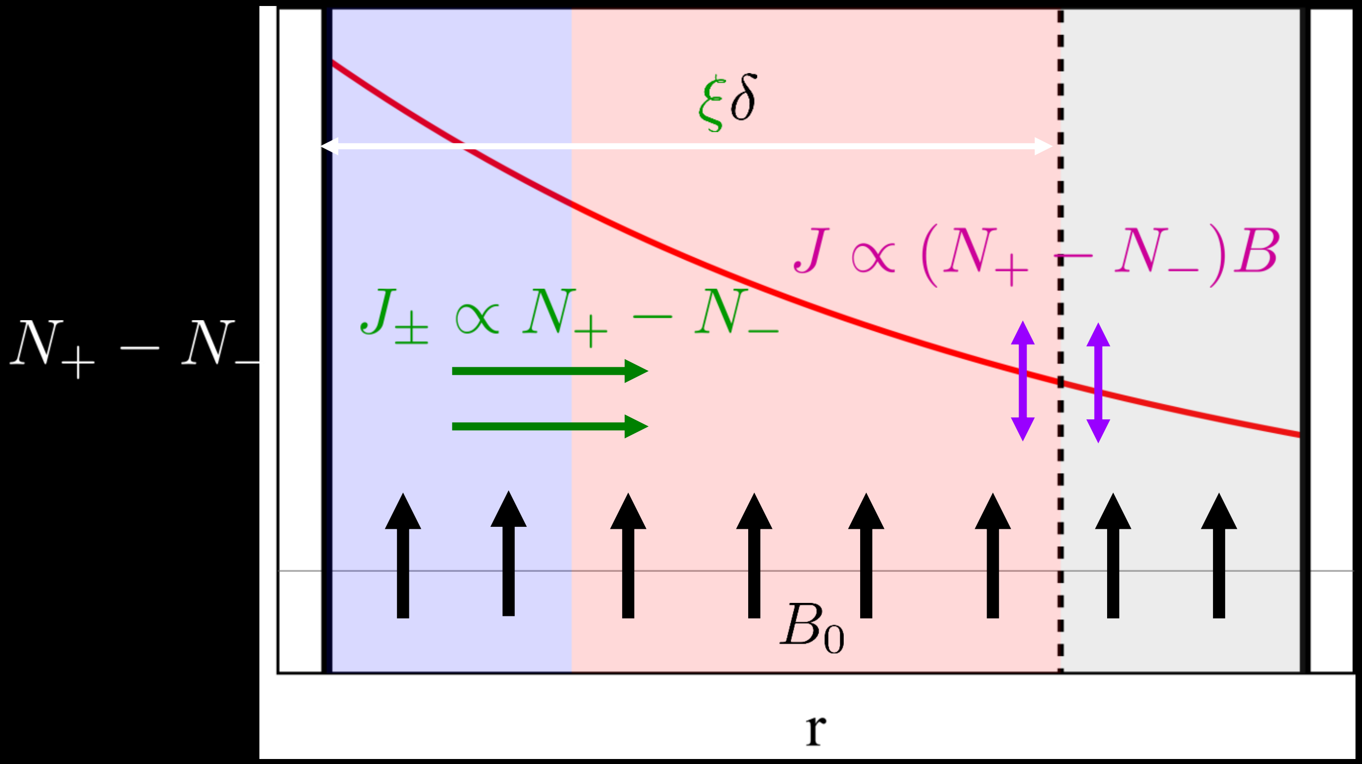

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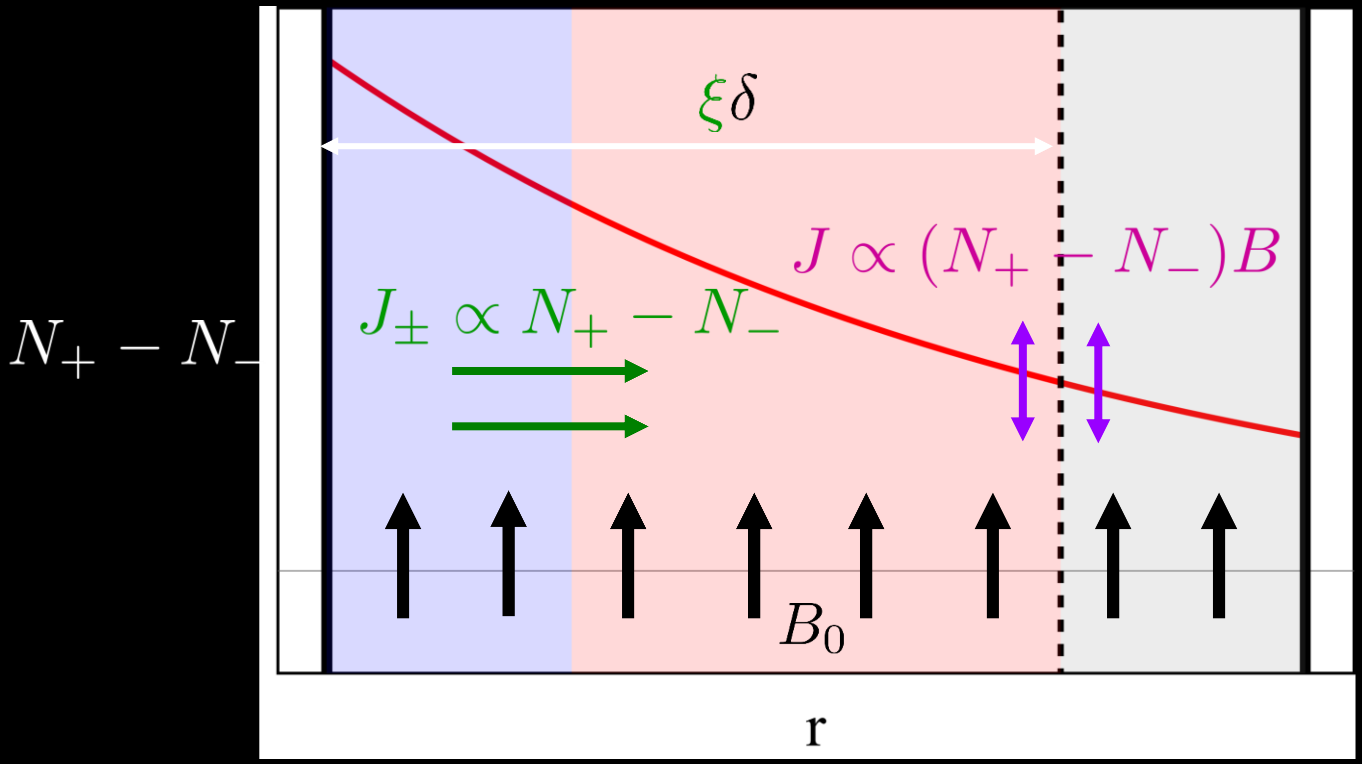
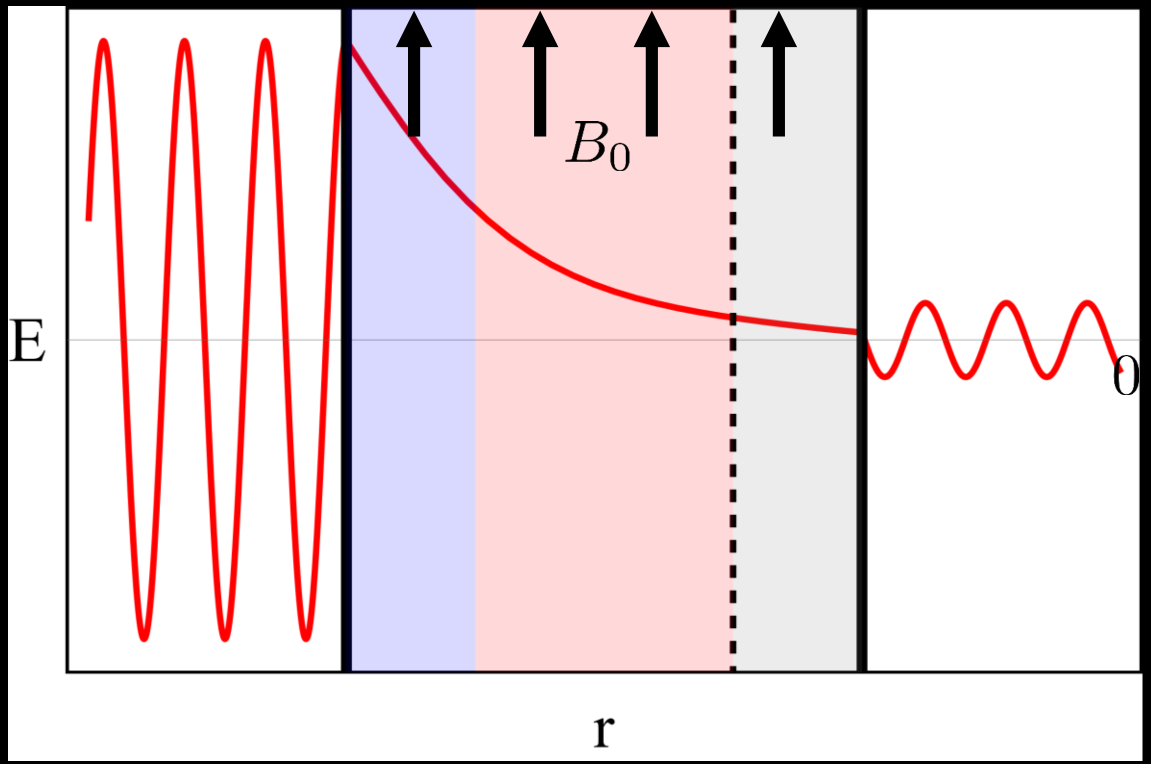
[P. O. Sukhachov and L. I. Glazman, Phys. Rev. Lett. **128**, 146801 (2022)]

Nonlocal regime

Chiral imbalance diffuses away from the skin layer → skin depth increases

Electromagnetic field penetration enhances





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Summary

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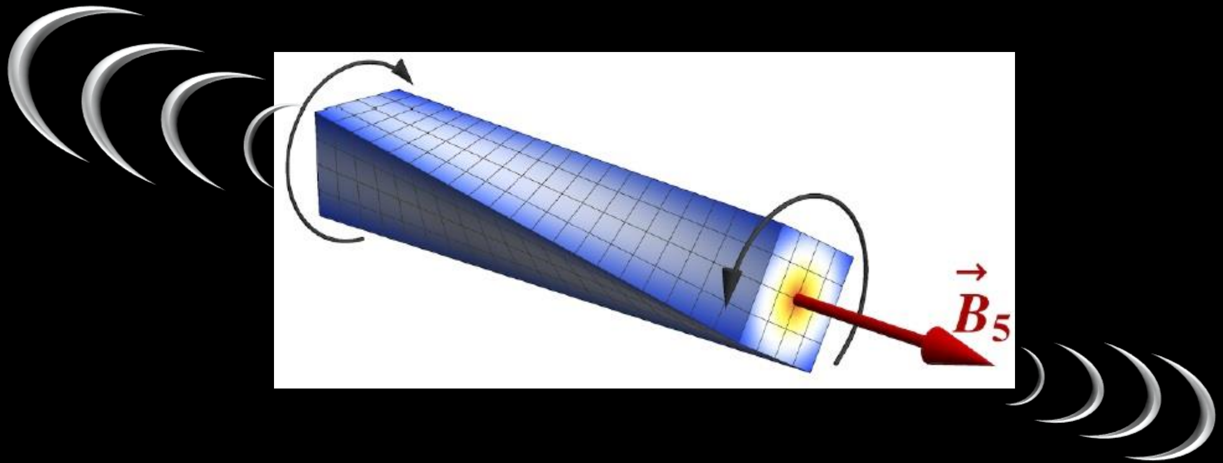
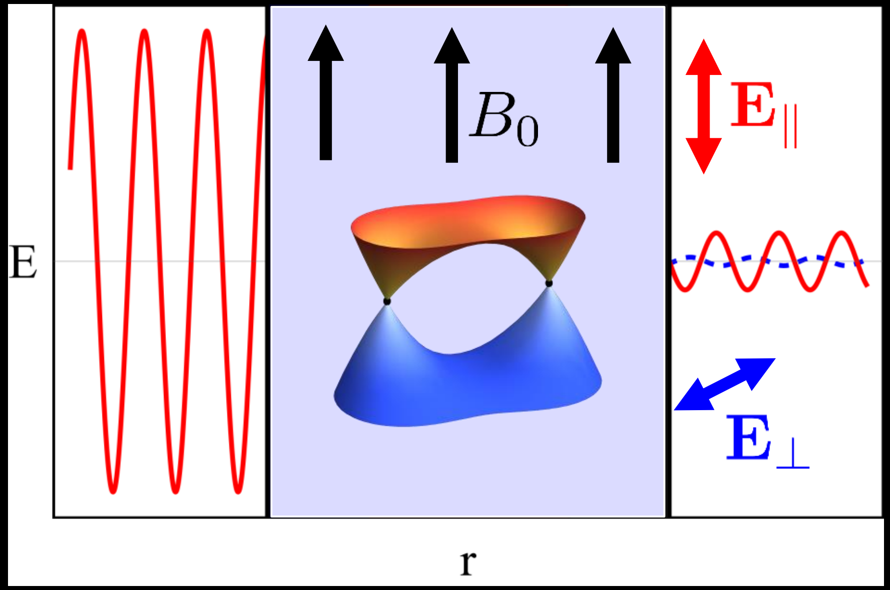
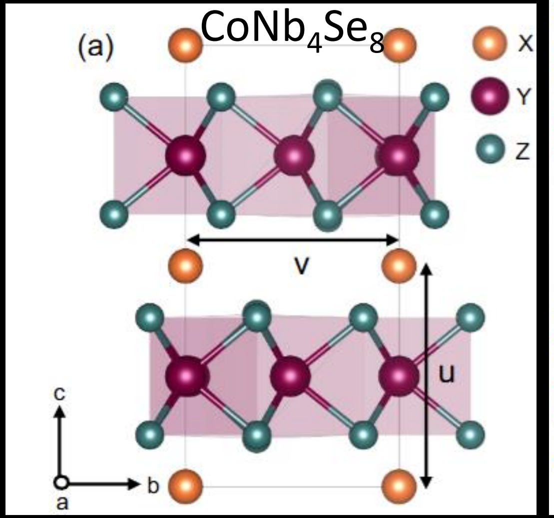
Possible applications

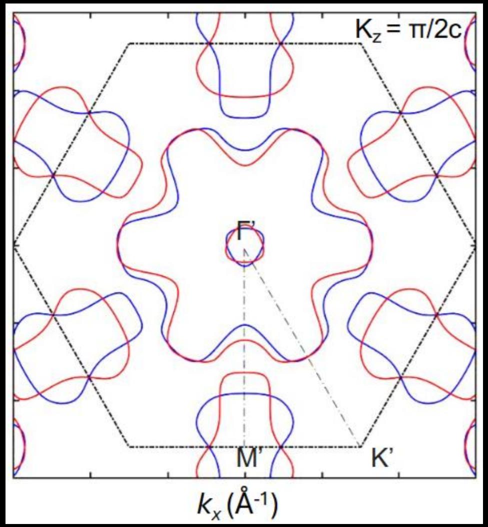
1. New experimental methods to **identify quantum anomalies**
2. Magnetic and pseudomagnetic fields as **control knobs for sound propagation** and attenuation
3. Sound attenuation dichroism as an **indicator of pseudomagnetic fields**
4. Enhancement of the penetration depth as a way to **measure light polarization**





New directions: Weyl altermagnets





Definitions:

- Altermagnets: unconventional magnets with spin-split energy bands
- Intercalated TMDs → platforms combining altermagnetism and Weyl physics

[A. Sah, et al., npj Quantum Materials (2026), arXiv:2510.21968]

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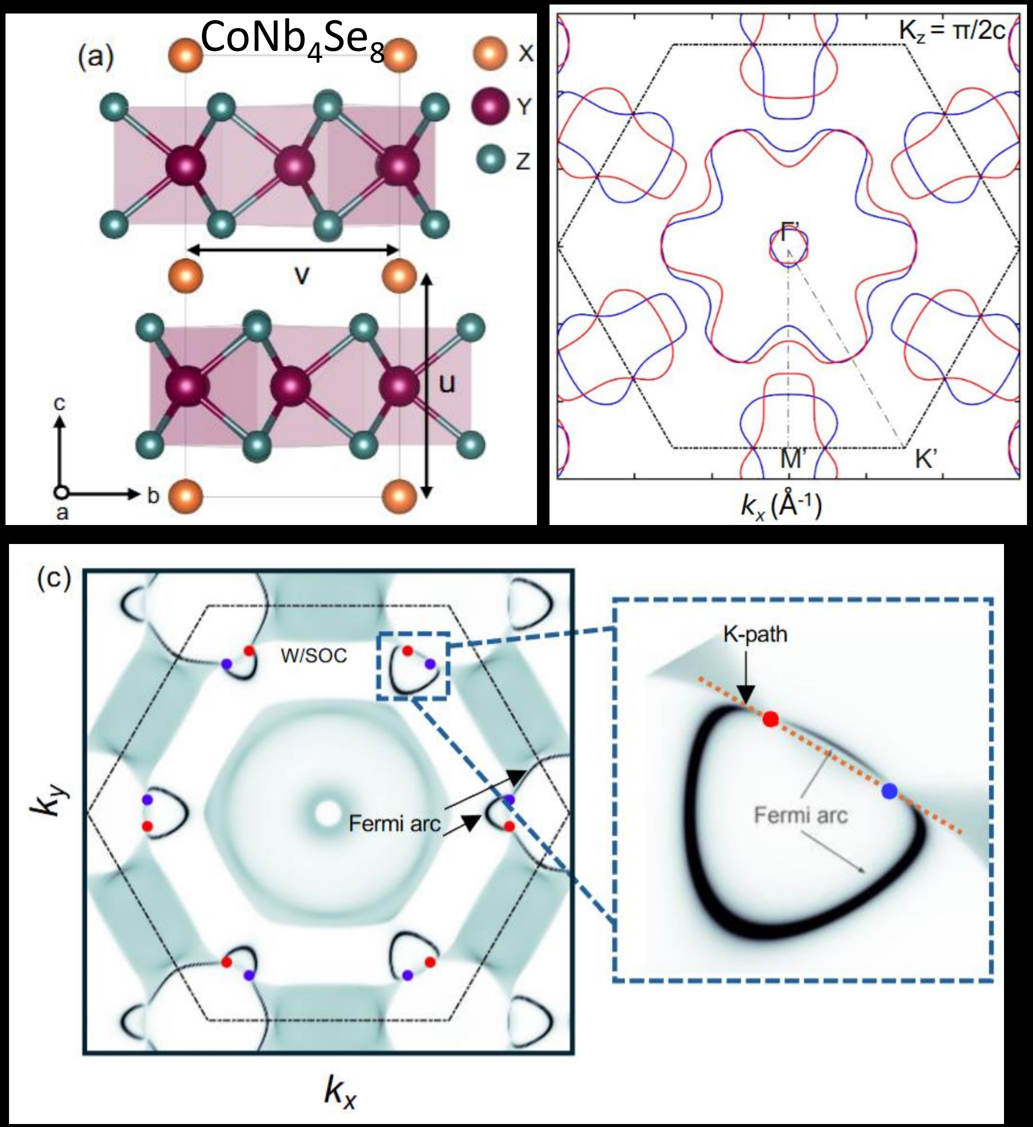

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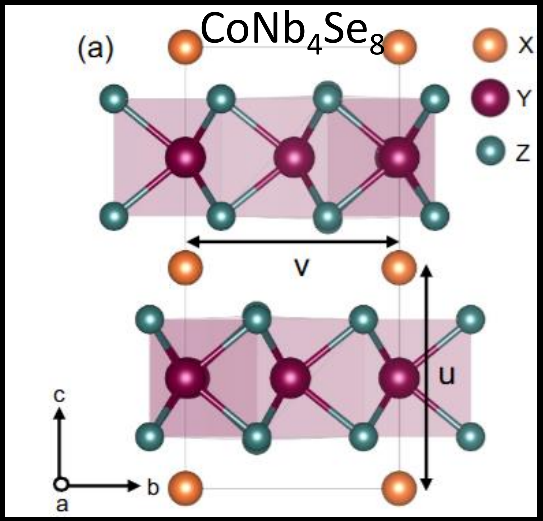

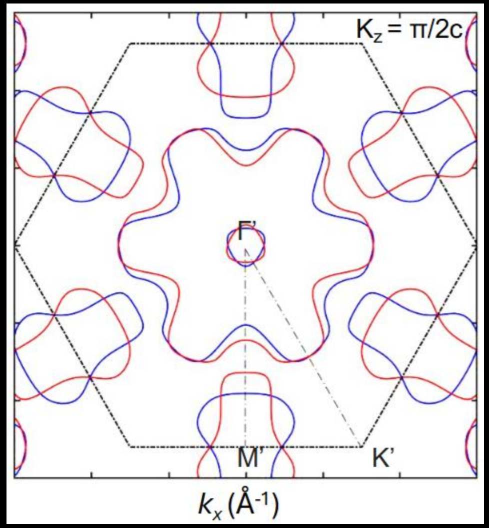

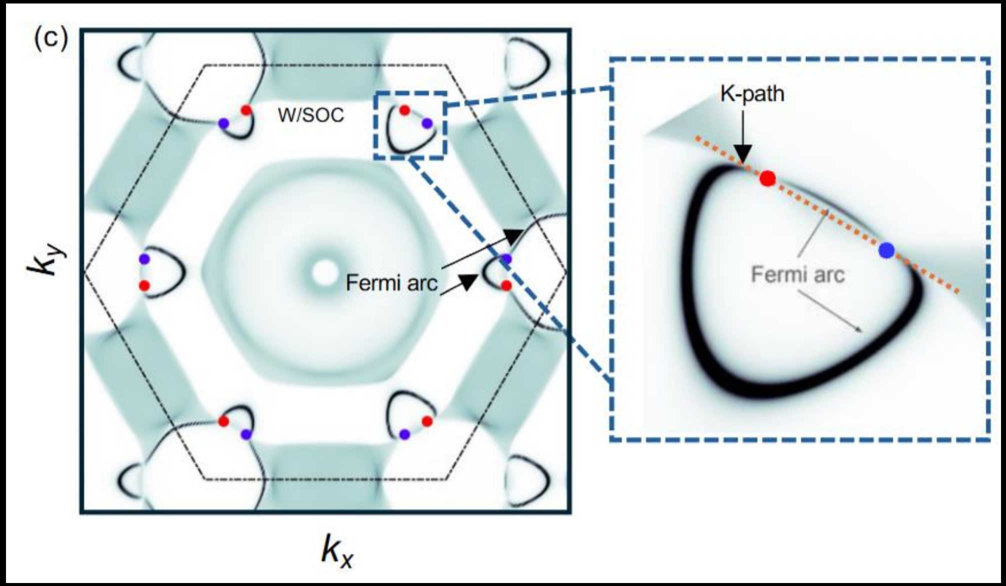

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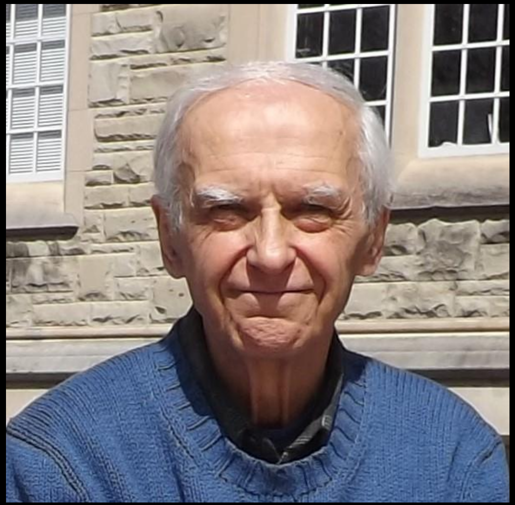
Open questions:

- Interplay of altermagnetism and quantum anomalies
- Electric and spin transport properties of Weyl altermagnets
- Interaction effects: magnetic catalysis and superconductivity

[A. Sah, et al., npj Quantum Materials (2026), arXiv:2510.21968]

Acknowledgements



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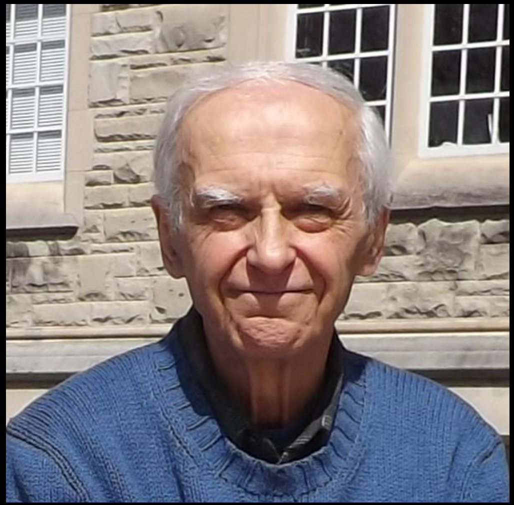
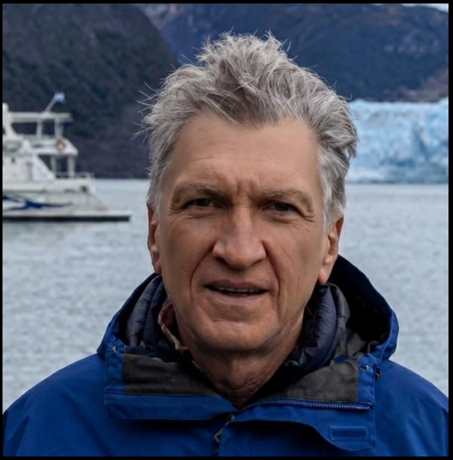

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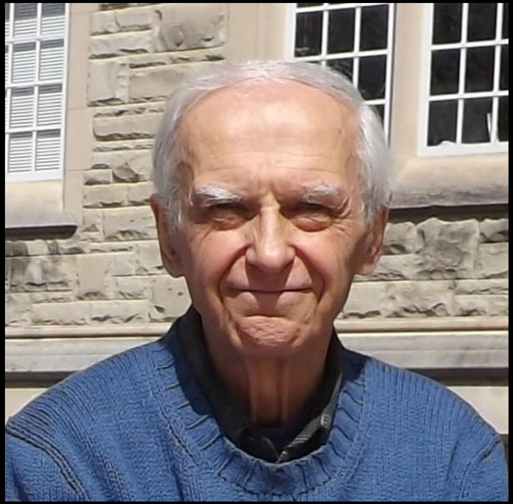
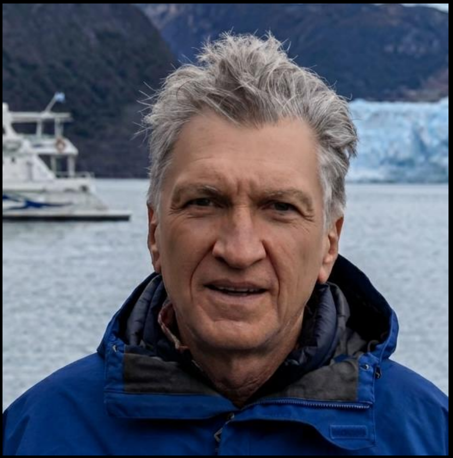
Acknowledgements







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Mizzou






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