Weyl Semimetals

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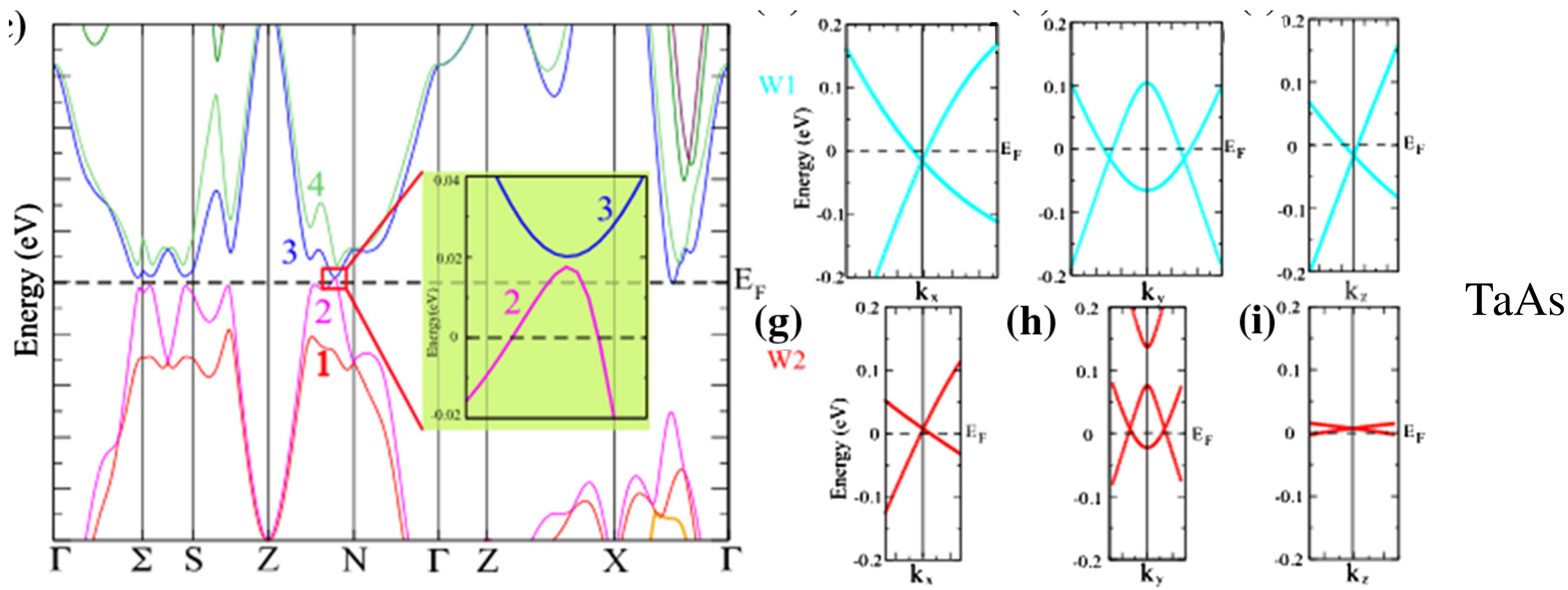
Based on work with
K. Landsteiner, E. Megias, L. Melgar, G. Grignani, S. Speziali, A. Marini, R. Dantas, B. Roy and P. Surowka

What is a Weyl semimetals?

- Is a semiconductor with an even number of singular points in the band structure, where valence and conduction bands touch
- A Weyl semimetal exists if time reversal, Parity or both are broken
- Each singular point has associated an integer monopole charge source of Berry curvature
- The sign of the monopole charge is connected to the helicity of the excitations around this point
- The simplest and best understood case has charge unity
- In my language a Weyl semimetal only contains doubly degenerate singular points!

Some pictures of Weyl semimetals



Phys. Rev. X 5, 031023 (2015)

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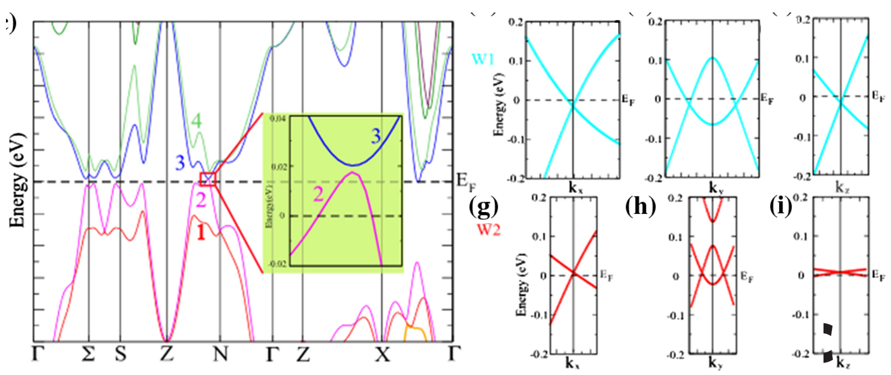
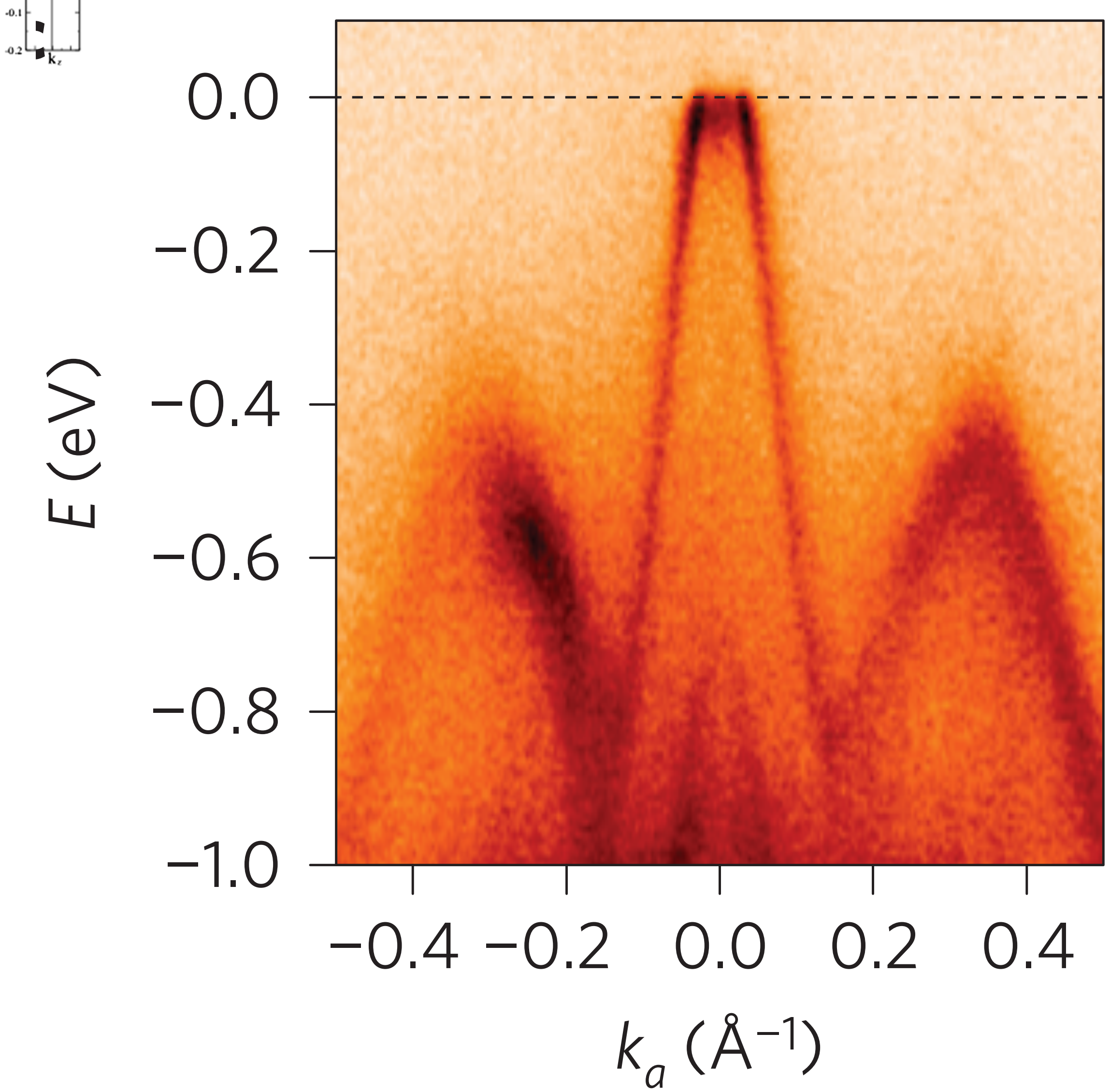


TaAs

Phys. Rev. X 5, 031023 (2015)



$ZrTe_5$

Nature Physics vol 12, pages 550–554 (2016)

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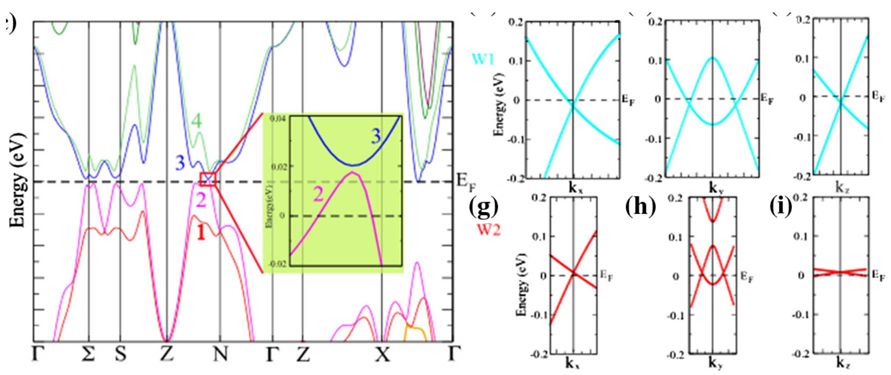

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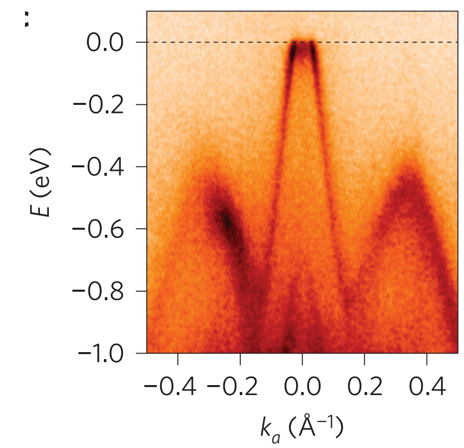
Phys. Rev. X 5, 031023 (2015)



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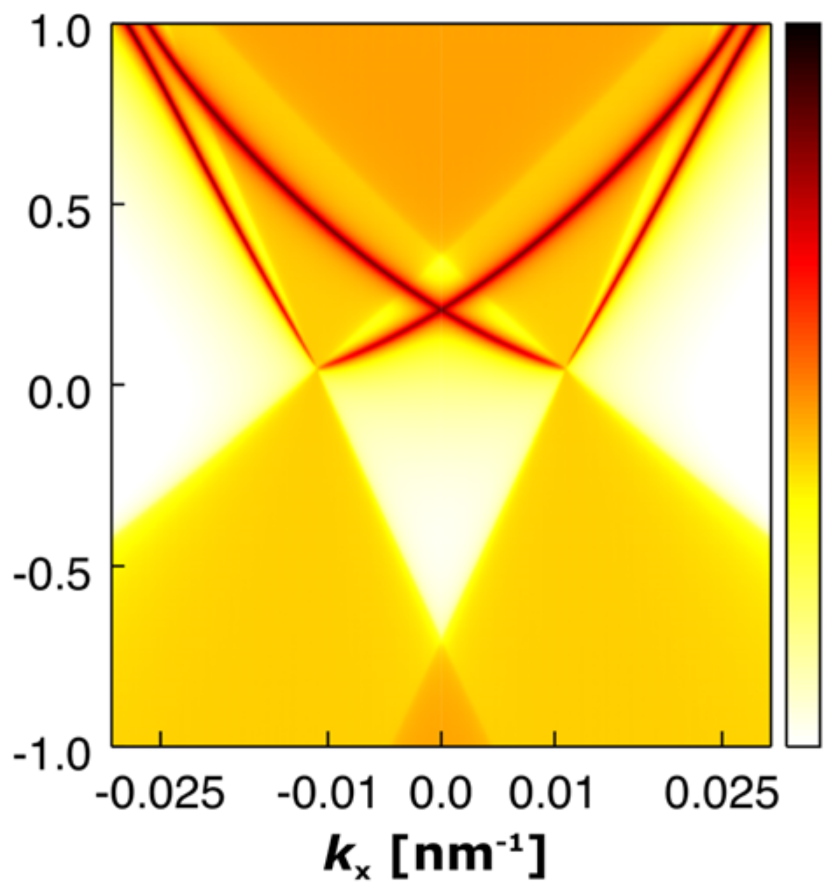


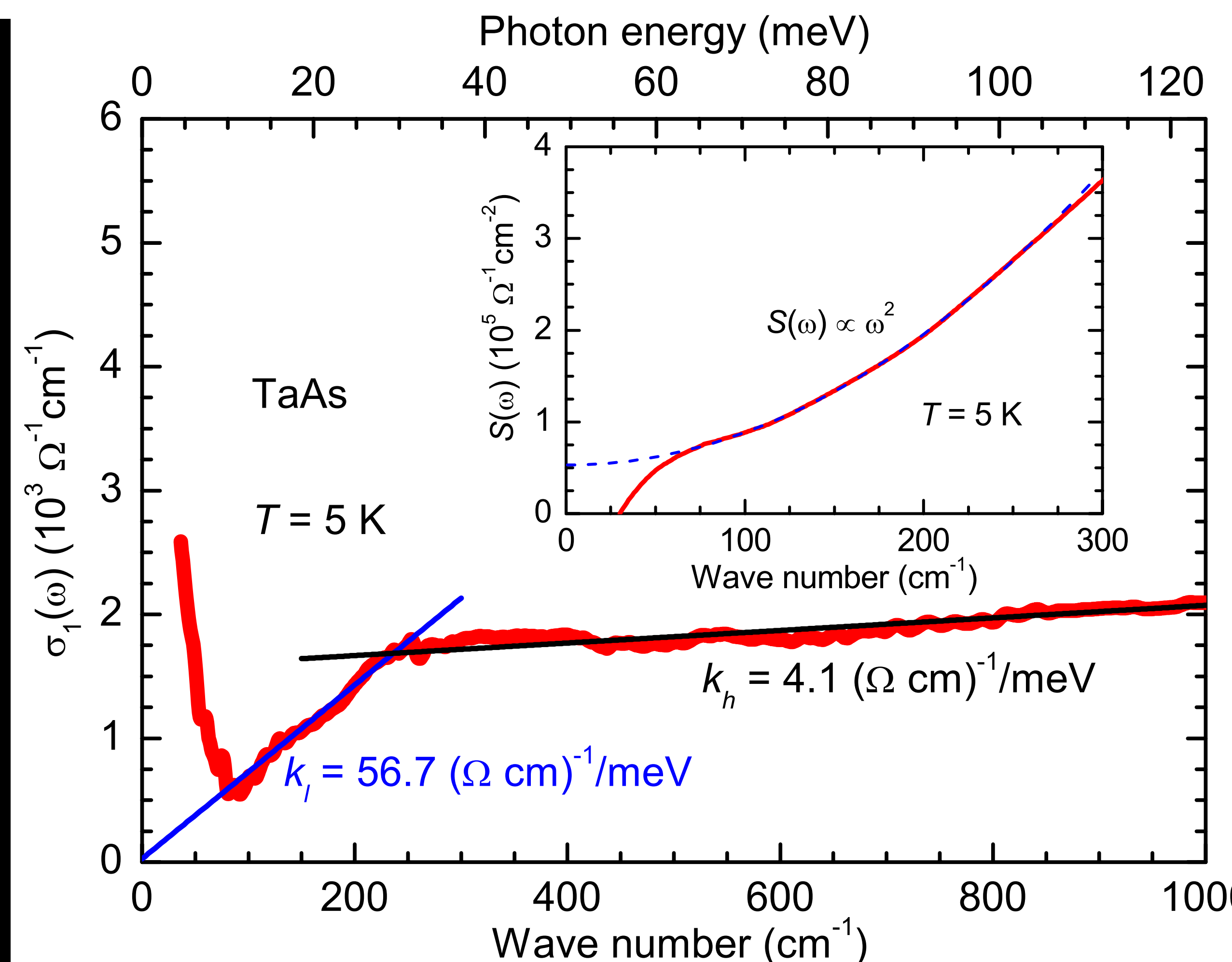
HgTe

Under compressive strain

Phys. Rev. X 9, 031034 (2019)

Optical conductivity

Optical conductivity



Phys. Rev. B 93, 121110(R) (2016)

$$\sigma(\omega) = N\frac{e^2}{12h}\frac{\omega}{v_f}\dots$$

Phys. Rev. Lett. 108, 046602

ANOMALIES

SOME WELL ESTABLISHED FACTS...

ANOMALIES

SOME WELL ESTABLISHED FACTS...

- In a field theory global symmetries can be violated at the quantum level
- Theories with massless fermions have axial and vector global symmetries
- Is not possible to preserve in the QFT both symmetries
- In 3+1d there are two types of axial anomalies

Argument 2:

$$iW_{eff}[A, A_5] = \log \int \mathscr{D}\bar{\psi}\mathscr{D}\psi\, e^{iS[\bar{\psi},\psi]} \exp\left[i \int d^4x \left(A_\mu J^\mu + A^5_\nu J^\mu_5\right)\right]$$

$$\mathscr{D}\bar{\psi}\mathscr{D}\psi \to \mathscr{D}\bar{\psi}'\mathscr{D}\psi' \exp\left[ic_A \int d^4x \lambda(x)\epsilon^{\mu\nu\rho\alpha}(F_{\mu\nu}F_{\rho\alpha} + \frac{1}{3}F^5_{\mu\nu}F^5_{\rho\alpha})\right]$$

$$\delta W_{eff} = \int d^4x \left(\lambda^5(x)\partial_\mu J^\mu_5 + \lambda(x)\partial_\mu J^\mu\right) = c_A \int d^4x \lambda^5(x)\epsilon^{\mu\nu\rho\alpha}\left(F_{\mu\nu}F_{\rho\alpha} + \frac{1}{3}F^5_{\mu\nu}F^5_{\rho\alpha}\right)$$

$$\partial_\mu J^\mu = 0$$

$$\partial_\mu J^\mu_5 = c_A\epsilon^{\mu\nu\rho\alpha}\left(F_{\mu\nu}F_{\rho\alpha} + \frac{1}{3}F^5_{\mu\nu}F^5_{\rho\alpha}\right) = 8c_A\left(\vec{E}\cdot\vec{B} + \frac{1}{3}\vec{E}_5\cdot\vec{B}_5\right)$$

$$c_A = \frac{1-(-1)}{32\pi^2\hbar^2 c}$$

That automatically implies that the following three point function

$$\frac{\delta^3 W_{eff}}{\delta A_\mu(x)\delta A_\nu(y)\delta A_\rho(z)} = \langle J_5^\mu(x) J^\nu(y) J^\rho(z)\rangle \text{ satisfies}$$

$$\langle \partial_\mu J_5^\mu(x) J^\nu(y) J^\rho(z)\rangle = c_A \epsilon^{\nu\rho\alpha\beta}\partial_\alpha \delta(x-y)\partial_\beta \delta(x-z)$$

The famous triangle diagram, which is one loop exact!

s_b

s_a

s_c

That automatically implies that the following three point function

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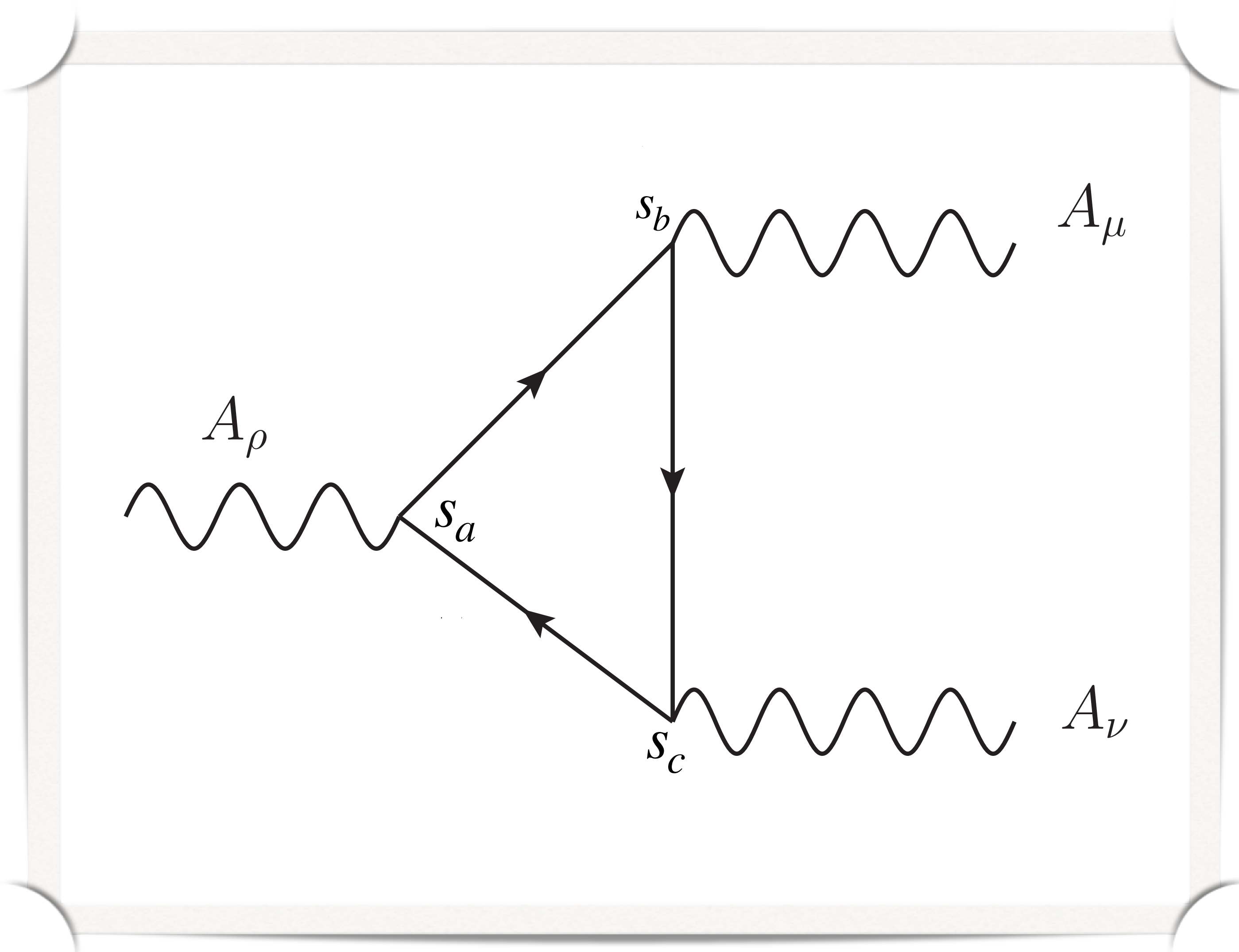
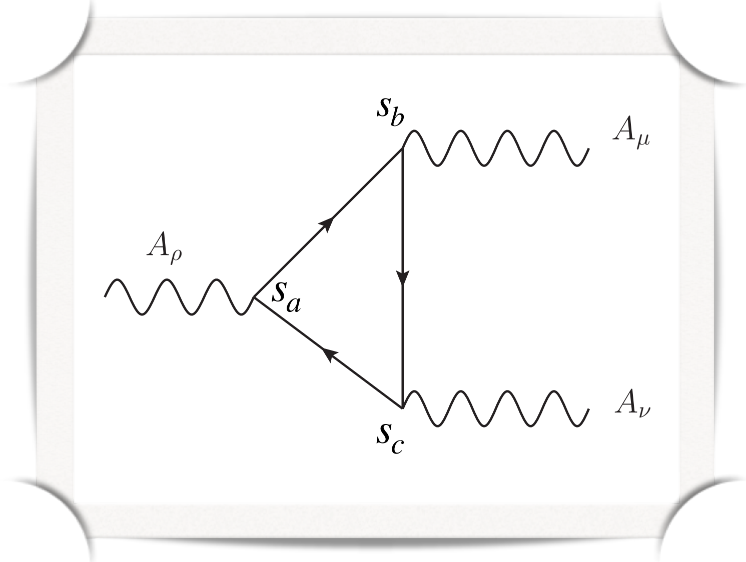
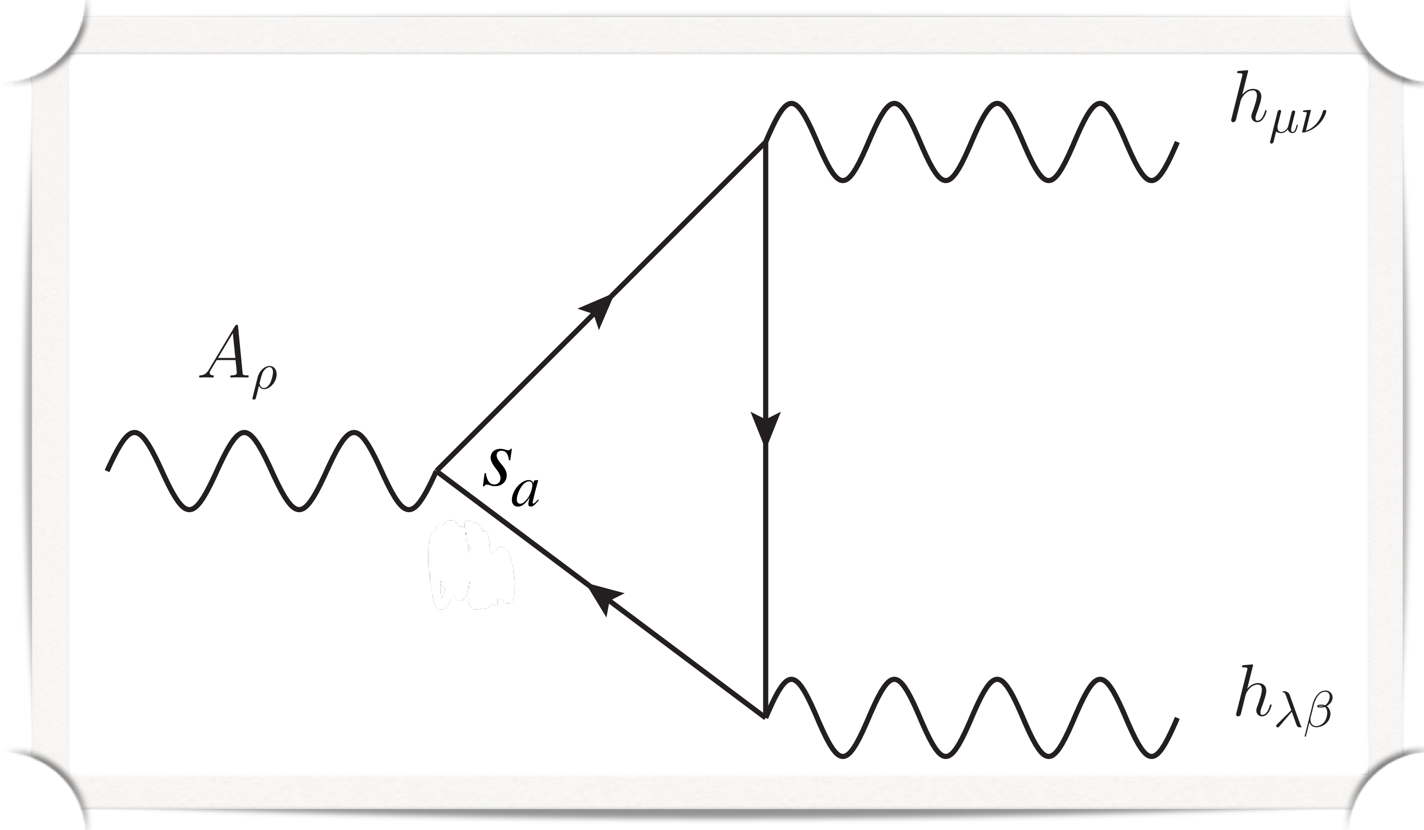




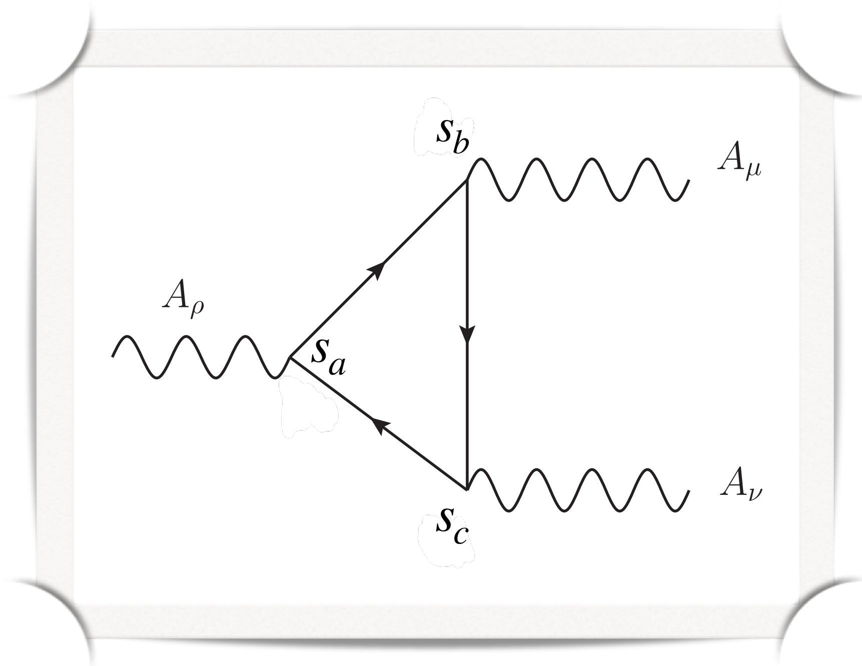


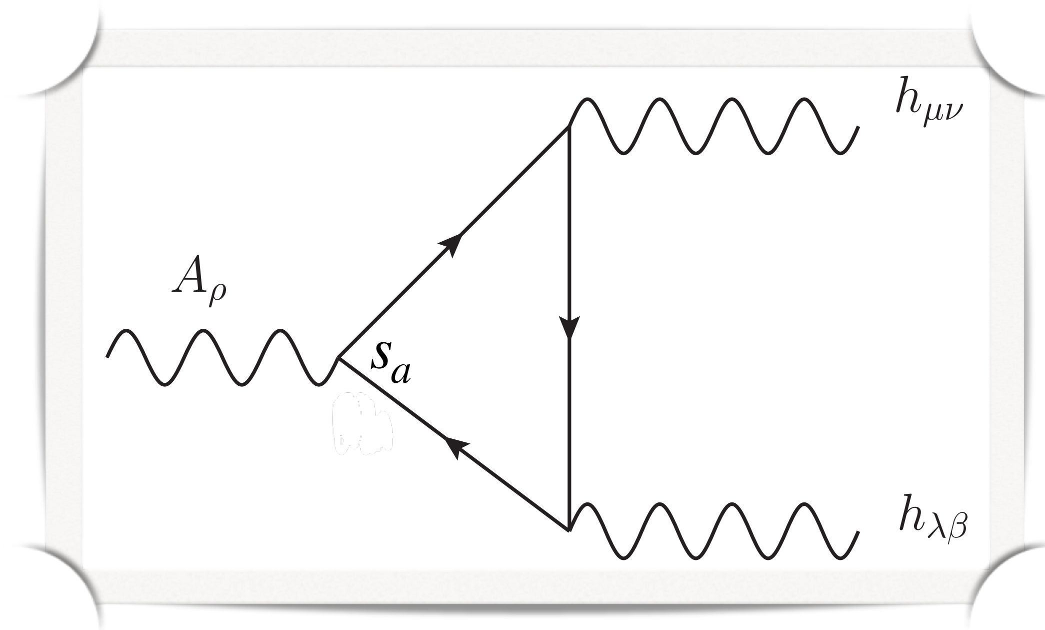
However there is another diagram which is not vanishing!

Finally the full anomaly (non)-conservation law is

$$\nabla_\mu J_5^\mu = \epsilon^{\mu\nu\rho\alpha}\left(c_A F_{\mu\nu}F_{\rho\alpha} + \frac{1}{3}c_A F^5_{\mu\nu}F^5_{\rho\alpha} + c_g R^\alpha{}_{\beta\mu\nu}R^\beta{}_{\alpha\rho\alpha}\right)$$

$$c_A = \frac{1^3-(-1)^3}{32\pi^2\hbar^2 c} \quad , \quad c_g = \frac{1-(-1)}{768\pi^2\hbar^2 c}$$





In general the anomaly takes the form

$$(\mathcal{D}_\mu \tilde{J}^\mu)_a = \frac{1}{24\pi^2}\epsilon^{\mu\nu\rho\sigma} tr\left[s_a \partial_\mu \left(A_\nu \partial_\rho A_\sigma + \frac{1}{2} A_\nu A_\rho A_\sigma\right)\right] + \frac{b_a}{768\pi^2}\epsilon^{\mu\nu\rho\lambda} R^\alpha{}_{\beta\mu\nu} R^\beta{}_{\alpha\rho\lambda}$$

$$d_{abc} = \tfrac{1}{2}\mathrm{Tr}\left[\{s_a, s_b\}\, s_c\right] \qquad b_a = \mathrm{Tr}\left[s_a\right]$$

Anomalies and Transport

$$J_a^\mu = \sigma_{ab}^B B_b^\mu + \sigma_a^V \omega^\mu + K_a^\mu + P_a^\mu$$

$$\sigma_{ab}^B = \frac{1}{4\pi^2} d_{abc} \mu^c$$

$$\sigma_a^V = \frac{1}{8\pi^2} d_{abc} \mu^b \mu^c + \frac{T^2}{24} b_a$$

Returning to Weyl semimetals

A single particle Hamiltonian

$$H_n\left(\mathbf{p}\right) = \alpha_n p_\perp^n \left[\cos\left(n\phi_p\right)\sigma_x + \sin\left(n\phi_p\right)\sigma_y\right] + v p_z \sigma_z$$

A single particle Hamiltonian

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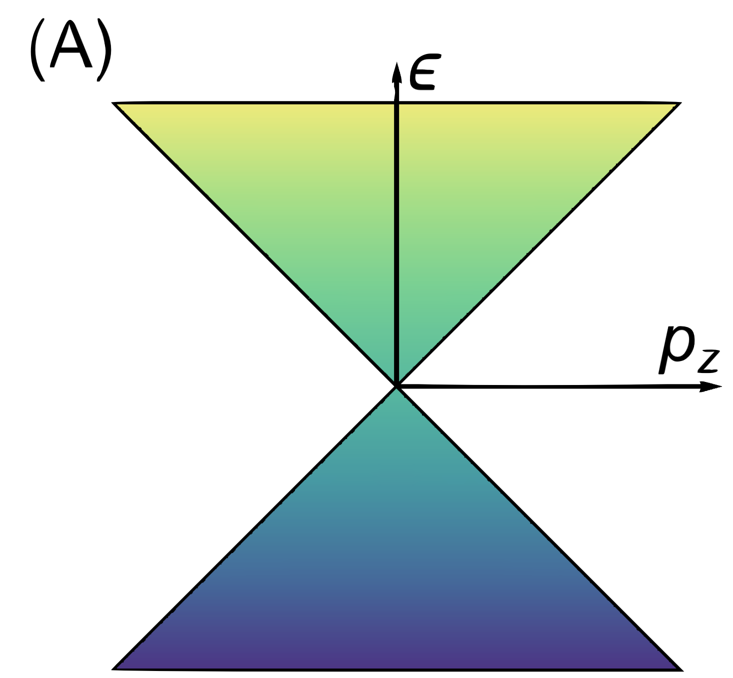
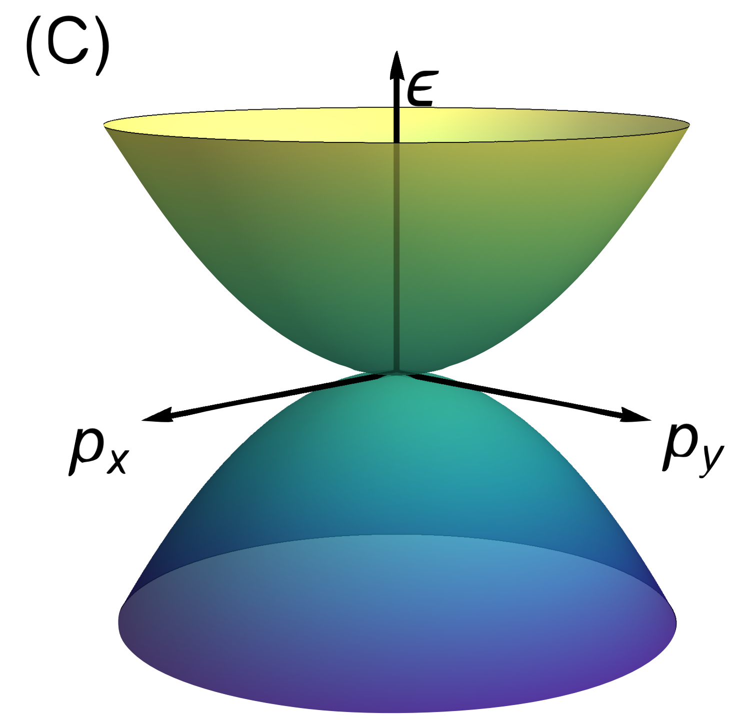


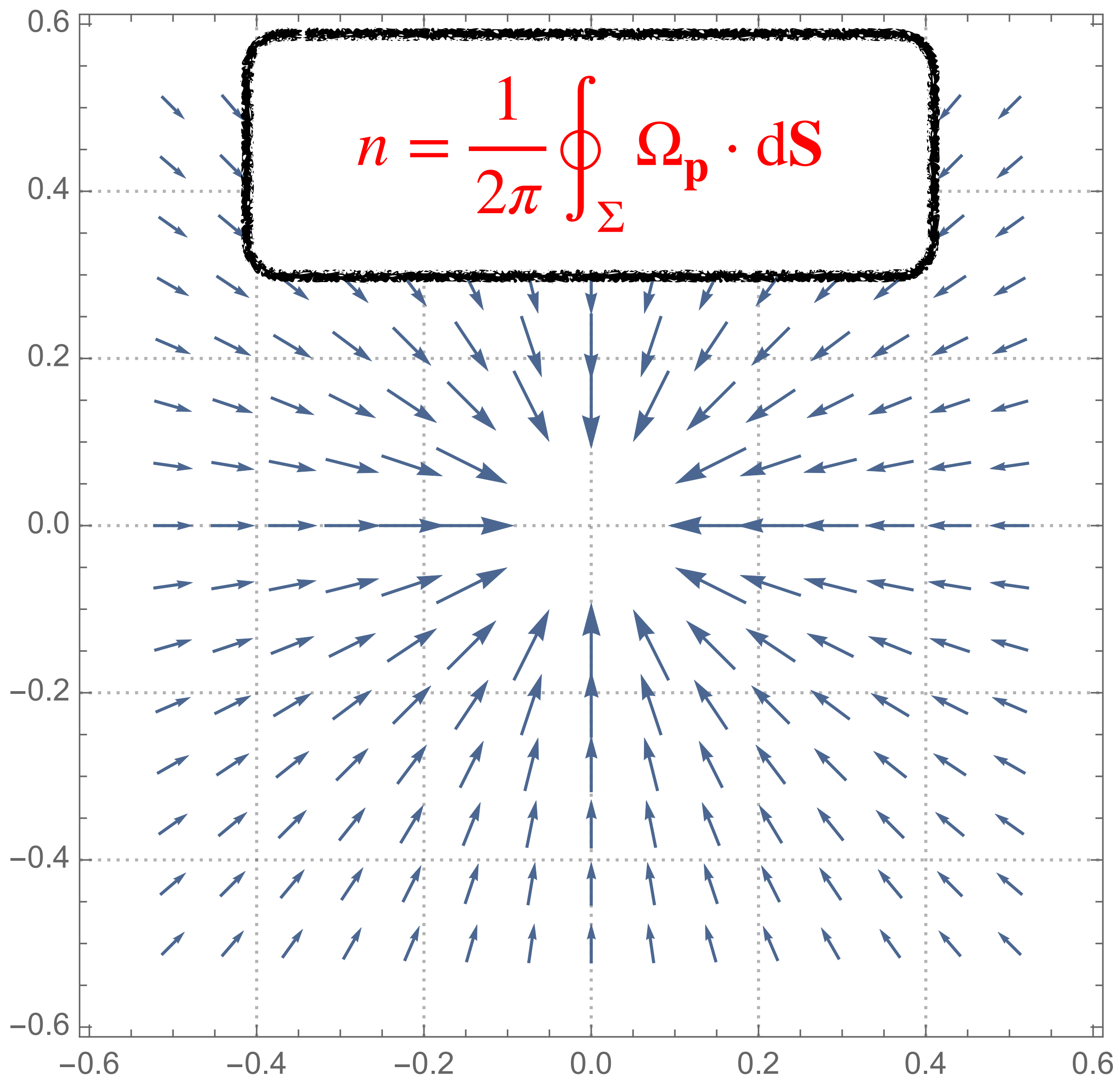
$$\epsilon_{\mathbf{p}} = \sqrt{\alpha_n^2 p_\perp^{2n} + v^2 p_z^2}$$



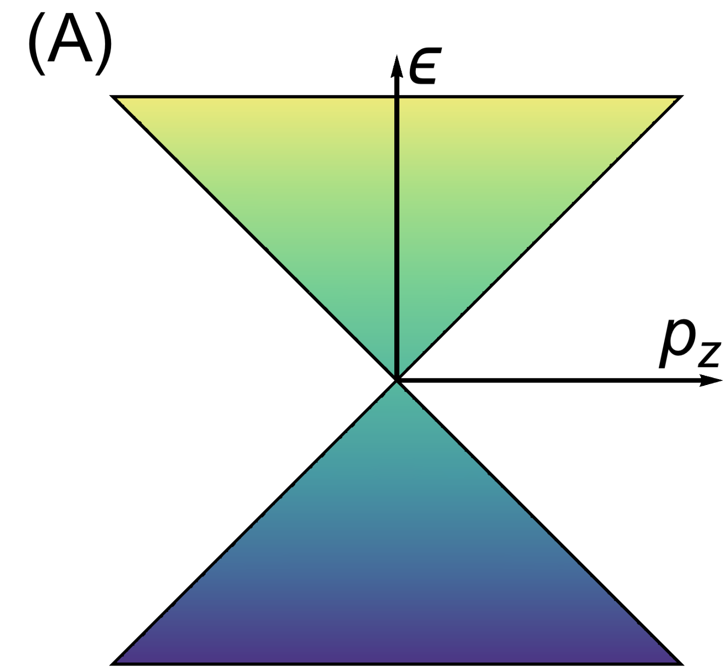
A single particle Hamiltonian

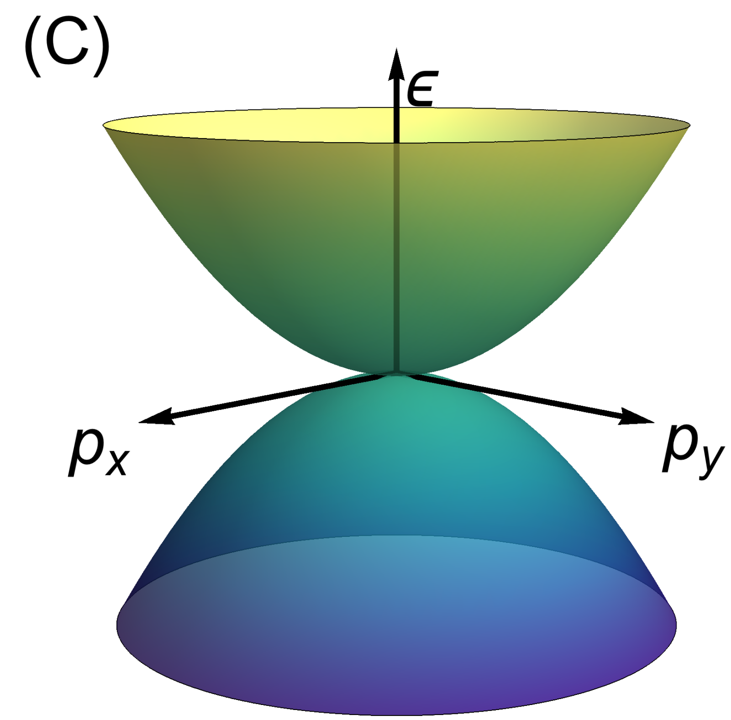
The Berry curvature $\Omega_{\mathbf{p}} = \mathrm{d}\langle\psi|\mathrm{d}\psi\rangle$

$$\boldsymbol{\Omega}_{\mathbf{p}} = \frac{1}{2}\frac{nv\alpha_n^2(p_x^2+p_y^2)^{n-1}}{\left[\alpha_n^2(p_x^2+p_y^2)^n+v^2p_z^2\right]^{3/2}}\,(p_x,p_y,np_z)$$



$$n = \frac{1}{2\pi}\oint_{\Sigma}\boldsymbol{\Omega}_{\mathbf{p}}\cdot \mathrm{d}\mathbf{S}$$





A QFT model I

Minimal T breaking Weyl semimetal

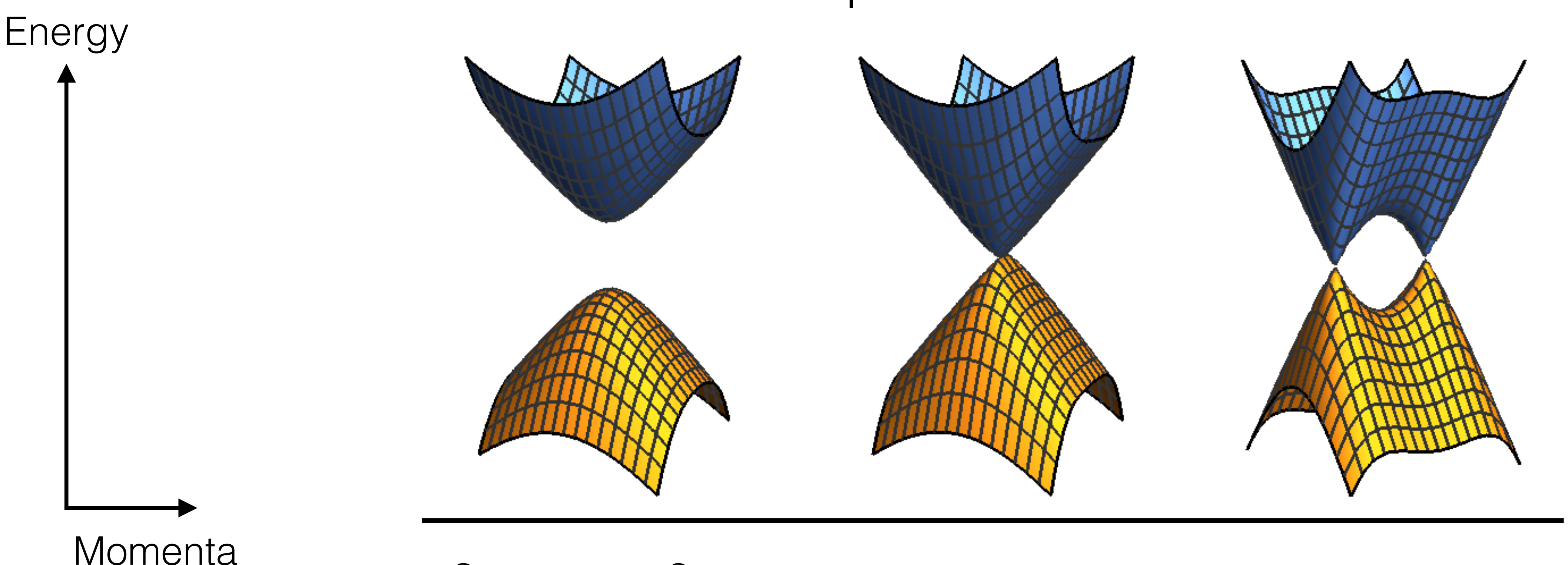
$$\mathcal{L} = \bar{\Psi}\left(i\partial\!\!\!/ - eA\!\!\!/ - \gamma_5\gamma_z b + M\right)\Psi\,.$$

A QFT model I

Minimal T breaking Weyl semimetal

$$\mathcal{L} = \bar{\Psi}\left(i\partial\!\!\!/ - eA\!\!\!/ - \gamma_5\gamma_z b + M\right)\Psi\,.$$

Dispersion relation



$b^2 < M^2$ $\qquad$ $b = M$ $\qquad$ $b^2 > M^2$

$M_{\text{eff}} = \sqrt{M^2 - b^2}$ $\qquad$ $b_{\text{eff}} = \sqrt{b^2 - M^2}$

Anomalous currents for a pair of Weyl cones

$$U(1)_L \times U(1)_R$$

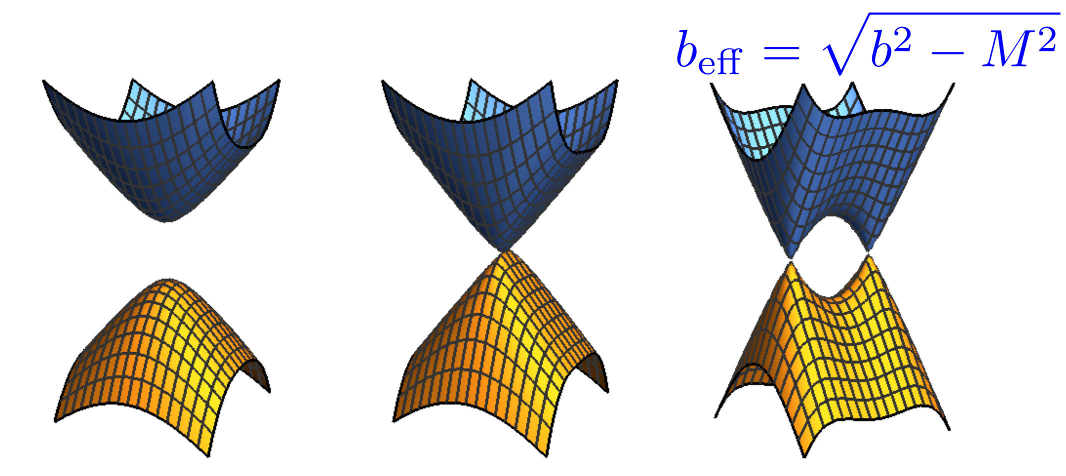
For $M = 0$

$$\begin{aligned}
\rho_e &= \frac{1}{2\pi^2}\vec{b}\cdot\vec{B} \\
\vec{j}_e &= \frac{1}{2\pi^2}\mu\vec{B}_5 + \frac{1}{2\pi^2}\mu\mu_5\vec{\omega} + \frac{1}{2\pi^2}\vec{E}\times\vec{b} \\
\rho_5 &= \frac{1}{6\pi^2}\vec{b}\cdot\vec{B}_5 \\
\vec{j}_5 &= \frac{1}{2\pi^2}\mu\vec{B} + \frac{1}{3\pi^2}\mu_5\vec{B}_5 + \left(\frac{\mu^2+\mu_5^2}{4\pi^2} + \frac{T^2}{12}\right)\vec{\omega} + \frac{1}{6\pi^2}\vec{E}_5\times\vec{b}
\end{aligned}$$

And the chiral magnetic effect in the electric current cancel!

Anomalous currents for a pair of Weyl cones

$$U(1)_L \times U(1)_R$$



$$\rho_e = \frac{1}{2\pi^2}\vec{b}\cdot\vec{B}$$

$$\vec{j}_e = \frac{1}{2\pi^2}\mu\vec{B}_5 + \frac{1}{2\pi^2}\mu\mu_5\vec{\omega} + \frac{1}{2\pi^2}\vec{E}\times\vec{b}$$

$$\rho_5 = \frac{1}{6\pi^2}\vec{b}\cdot\vec{B}_5$$

$$\vec{j}_5 = \frac{1}{2\pi^2}\mu\vec{B} + \frac{1}{3\pi^2}\mu_5\vec{B}_5 + \left(\frac{\mu^2+\mu_5^2}{4\pi^2} + \frac{T^2}{12}\right)\vec{\omega} + \frac{1}{6\pi^2}\vec{E}_5\times\vec{b}$$

Phys. Rev. Lett. 82, 3572 (1999)
Phys. Lett. B 461, 138 (1999)
Phys. Rev. Lett. 83, 2518 (1999)

Phys Rev. D 86, 045001 (2012)
JHEP vol. 2017, 138 (2017)

A QFT model II ($n > 1$)

Let's start with the Hamiltonian $H_{L,R} = \pm \vec{k} \cdot \vec{\tau} \otimes \mathbb{I}_{2\times 2}$

And find the perturbations which are invariant under C_4 $R_z = e^{-i\alpha\tau_z} \otimes e^{-i\alpha s_z}$

$\tau_z \otimes s_z$ Two Weyl points with the same chirality

$$\tau_x \otimes s_x + \tau_y \otimes s_y$$
$$\tau_x \otimes s_y - \tau_y \otimes s_x$$

Two gapped bands and two gapless

$$\epsilon = \pm\sqrt{2\Delta^2 - 2\Delta\sqrt{\Delta^2 + k_\perp^2} + k_\perp^2 + k_\parallel^2} \longrightarrow \epsilon_{\mathbf{p}} = \sqrt{\alpha_n^2 p_\perp^{2n} + v^2 p_z^2}$$

Phys.Rev.Res. 2 (2020) 1, 013007

Previous Hamiltonian can be written in terms of a covariant Lagrangian

$$\mathcal{L}_L = i\psi_L^\dagger \tau^\mu \left[\partial_\mu - i\Delta\left(\delta_\mu^1 s_1 + \delta_\mu^2 s_2\right)\right]\psi_L \longrightarrow \mathcal{L}_L = i\psi_L^\dagger \tau^\mu \left[\partial_\mu - iA_\mu^a s_a\right]\psi_L$$

$$A_\mu^a = \Delta\left(\delta_\mu^x \delta_a^1 + \delta_\mu^y \delta_a^2\right)$$

$$\mathbf{R}^{3,1} \times SO(3,1) \times U(1) \times SU(2)$$

$$\mathbf{R}^{3,1} \times SO(1,1) \times U(1) \times U(1)_3$$

We explicitly break the symmetry

The lattice $C_{4,6}$ **is included here**

Allow me for a while simplify the picture removing the gauge field and remain classical

$$\mathcal{L} = i\psi^\dagger \tau^\mu \partial_\mu \psi$$

This system has the following symmetry

$$\mathbf{R}^{3,1} \times SO(3,1) \times U(1) \times SU(2)$$

$$\updownarrow \qquad \updownarrow \qquad \updownarrow \qquad \updownarrow$$

$$T^{\mu\nu} \qquad L^{\mu\nu\rho} \qquad J^\mu \qquad J^\mu_a$$

Noether theorem implies

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu J^\mu = 0$$

$$\partial_\mu L^{\mu\nu\rho} = 0 \qquad \partial_\mu J^\mu_a = 0$$

Now we play the same game for the theory

$$U(1)_L \times U(1)_R \times SU(2)_L \times SU(2)_R$$

$$\mathcal{L} = i\psi_L^\dagger \tau^\mu \partial_\mu \psi_L + i\psi_R^\dagger \bar{\tau}^\mu \partial_\mu \psi_R$$

The abelian currents are

$$\rho_e = \frac{n}{2\pi^2}\mathbf{b} \cdot \mathbf{B} \qquad \mathbf{j}_e = \frac{n}{2\pi^2}\mu \mathbf{B}_5 + \frac{c(n)}{2\pi^2}\mu_3 \mathbf{B}_{3_5} + \frac{n}{2\pi^2}\mathbf{E} \times \mathbf{b}$$

$$\rho_5 = \frac{n}{6\pi^2}\mathbf{b} \cdot \mathbf{B}_5 \qquad \mathbf{j}_5 = \frac{n}{2\pi^2}\mu \mathbf{B} + \frac{n}{3\pi^2}\mu_5 \mathbf{B}_5 + \frac{c(n)}{2\pi^2}\mu_3 \mathbf{B}_3 + \frac{c(n)}{3\pi^2}\mu_{3_5} \mathbf{B}_{3_5} + \frac{c(n)}{6\pi^2}\mathbf{E}_5 \times \mathbf{b}$$

Now we play the same game for the theory

$$U(1)_L \times U(1)_R \times SU(2)_L \times SU(2)_R$$

$$\mathcal{L} = i\psi_L^\dagger \tau^\mu \partial_\mu \psi_L + i\psi_R^\dagger \bar{\tau}^\mu \partial_\mu \psi_R$$

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$$\rho_5 = \frac{n}{6\pi^2}\mathbf{b}\cdot\mathbf{B}_5 \qquad \mathbf{j}_5 = \frac{n}{2\pi^2}\mu\mathbf{B} + \frac{n}{3\pi^2}\mu_5\mathbf{B}_5 + \frac{c(n)}{2\pi^2}\mu_3\mathbf{B}_3 + \frac{c(n)}{3\pi^2}\mu_{3_5}\mathbf{B}_{3_5} + \frac{c(n)}{6\pi^2}\mathbf{E}_5\times\mathbf{b}$$

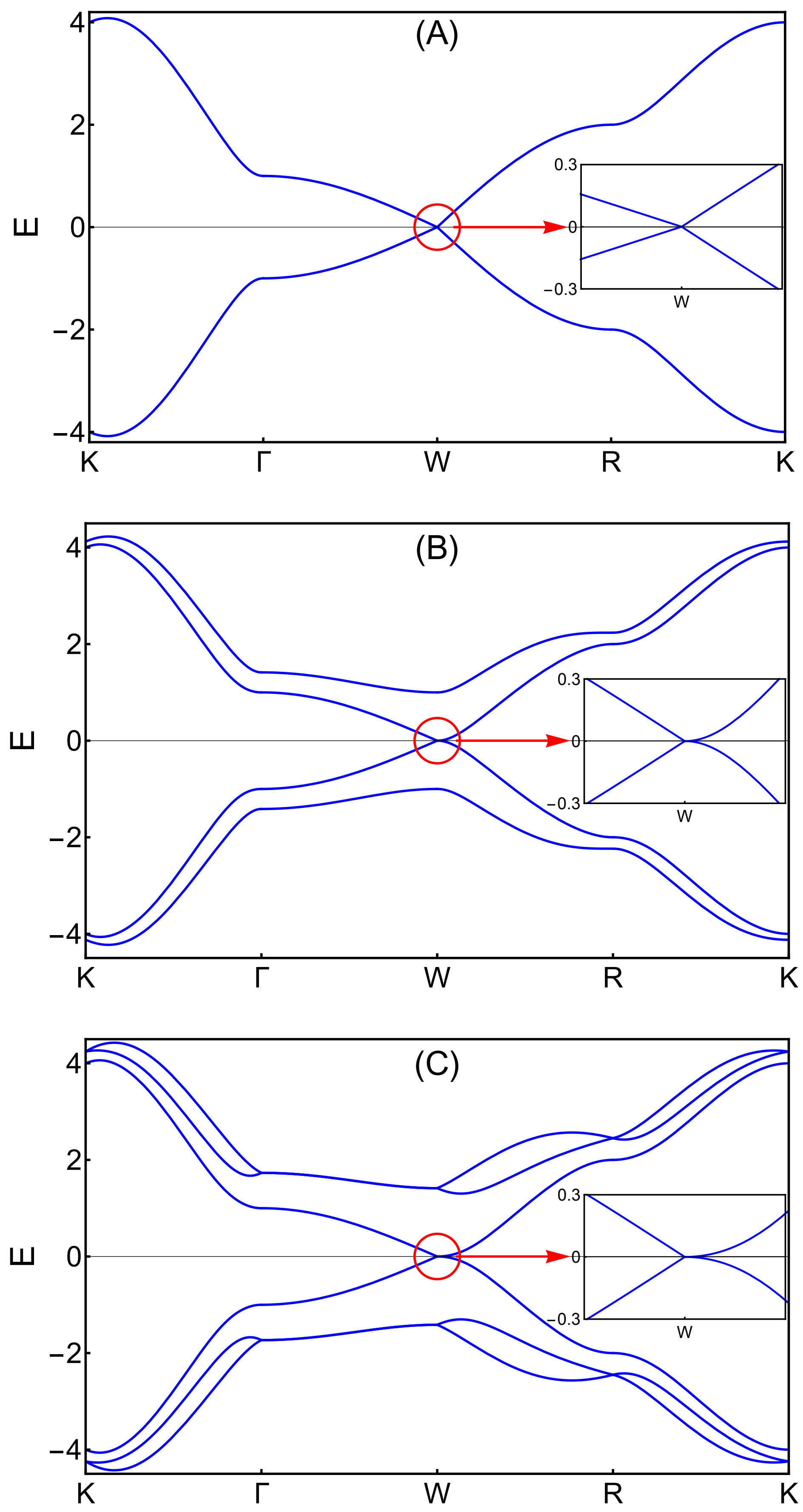
The non-abelian currents are

$$\rho_3 = \frac{c(n)}{2\pi^2}\mathbf{b}\cdot\mathbf{B}_3 \qquad \mathbf{j}_3 = \frac{c(n)}{2\pi^2}\mu\mathbf{B}_{3_5} + \frac{c(n)}{2\pi^2}\mu_3\mathbf{B}_5 + \frac{c(n)}{2\pi^2}\mathbf{E}_3\times\mathbf{b}$$

$$\rho_{3_5} = \frac{c(n)}{2\pi^2}\mathbf{b}\cdot\mathbf{B}_3 + \frac{c(n)}{6\pi^2}\mathbf{b}\cdot\mathbf{B}_{3_5}$$

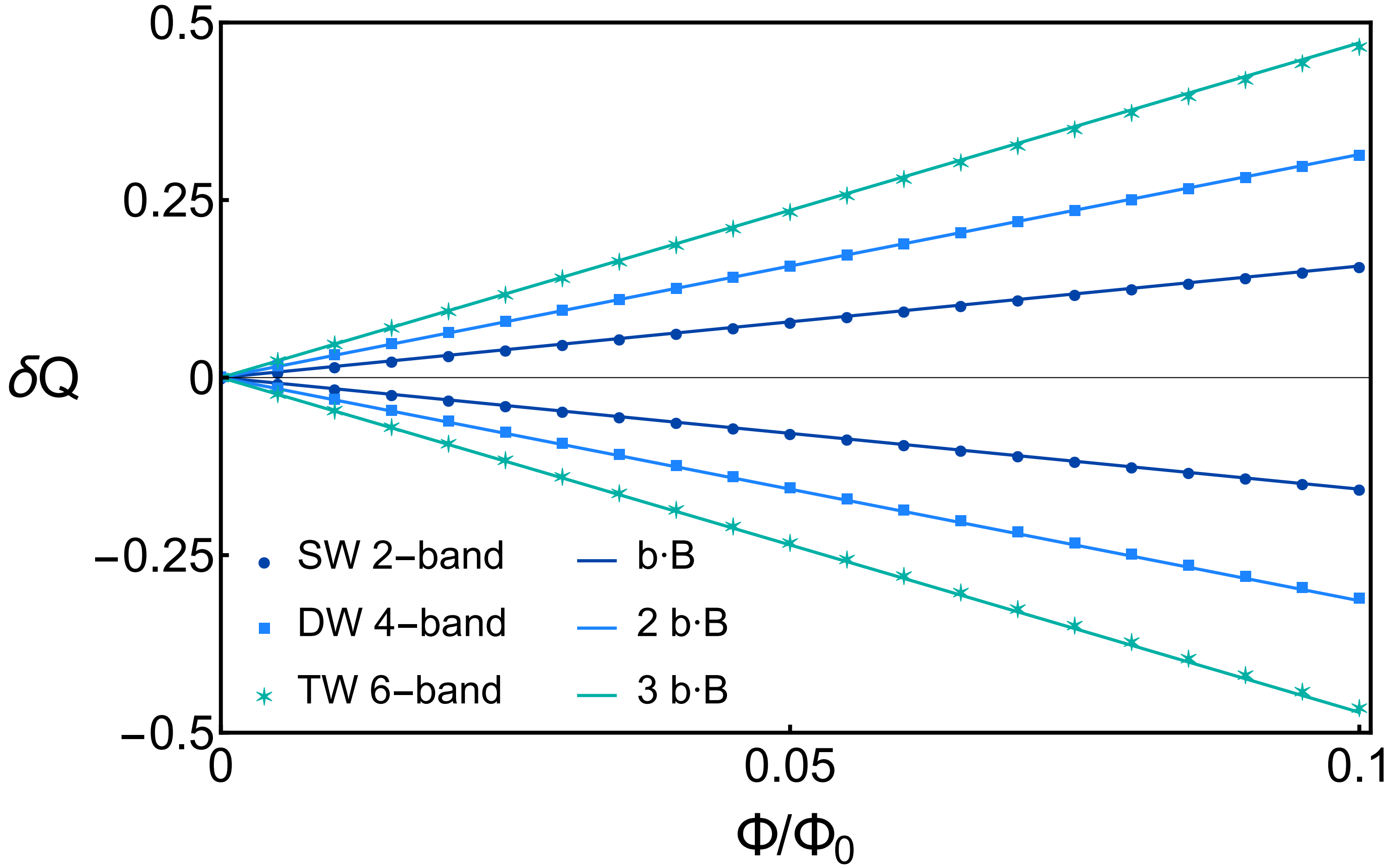
$$\mathbf{j}_{3_5} = \frac{c(n)}{2\pi^2}\mu_3\mathbf{B} + \frac{c(n)}{3\pi^2}\mu_{3_5}\mathbf{B}_5 + \frac{c(n)}{2\pi^2}\mu\mathbf{B}_3 + \frac{c(n)}{3\pi^2}\mu_5\mathbf{B}_{3_5} + \frac{c(n)}{6\pi^2}\mathbf{E}_{3_5}\times\mathbf{b}$$

Testing the QFT with a tight binding model

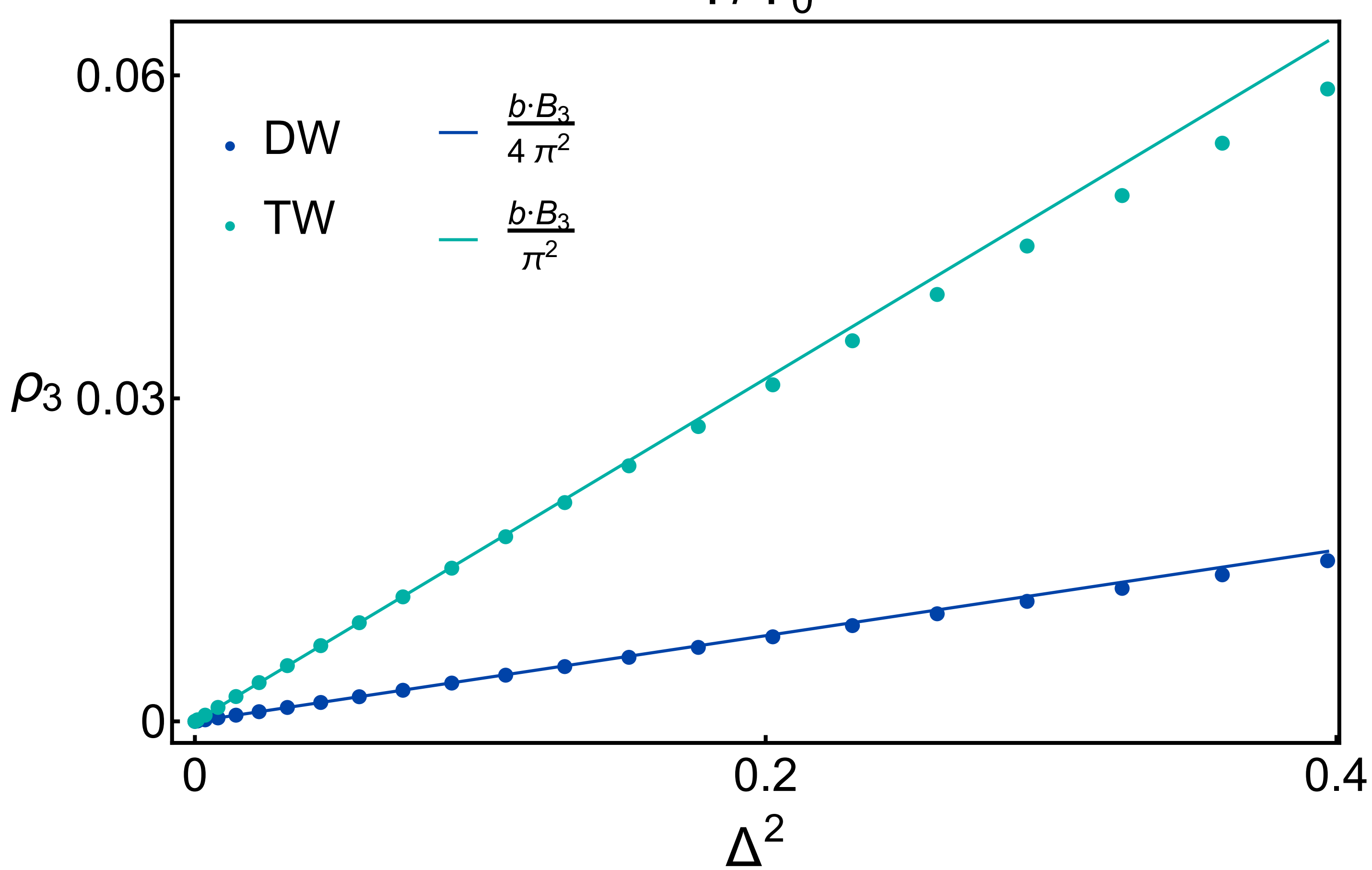


$$H_{SW} = t\left[\sin k_x\,\sigma_1 + \sin k_y\,\sigma_2 + (\cos k_z - m_z)\,\sigma_3\right] + t_0\left[2 - \cos k_x - \cos k_y\right],$$

$$H_{MW} = H_{SW} \otimes \mathbb{I}_n + \Delta\left(\sigma_1 \otimes s_1 + \sigma \otimes s_2\right)$$



$$\rho_e \;=\; \frac{n}{2\pi^2}\vec{b}\cdot\vec{B}$$

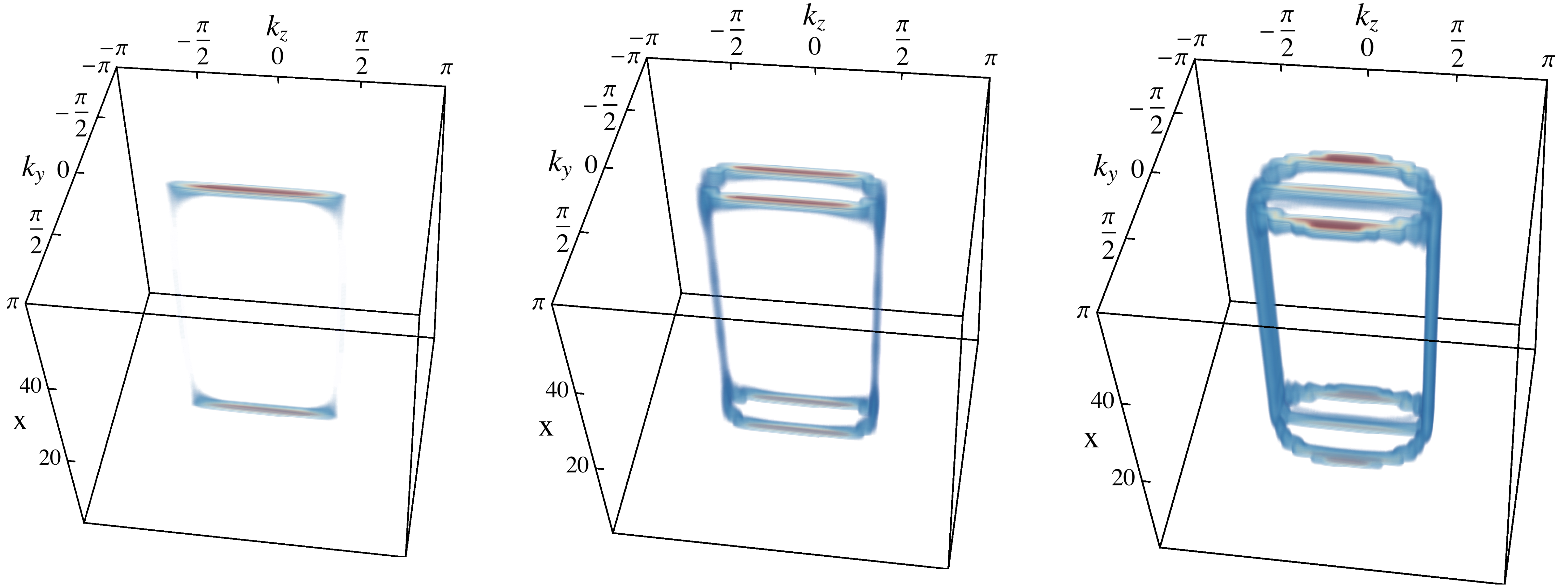


$$\rho_3 \;=\; \frac{c(n)}{2\pi^2}\vec{b}\cdot\vec{B}_3$$

Fermi arcs for simple, double and triple Weyl semimetals

As expected each case shows as many Fermi arcs as the value of the monopole charge

$$H_{MW} = H_{SW} \otimes \mathbb{I}_n + \Delta \left(\sigma_1 \otimes s_1 + \sigma \otimes s_2 \right)$$



Magneto-Transport

$$\dot{\rho} + \nabla \cdot \vec{J}_\rho = a_\chi \vec{E} \cdot \vec{B} \qquad \vec{J}_\rho = a_\chi \mu \vec{B}$$

$$\dot{\epsilon} + \nabla \cdot \vec{J}_\epsilon = \vec{J}_\rho \cdot \vec{E} \qquad \vec{J}_\epsilon = \left(\frac{a_\chi}{2} \mu^2 + a_g T^2 \right) \vec{B}$$

assuming a steady state via a relaxation time approximation

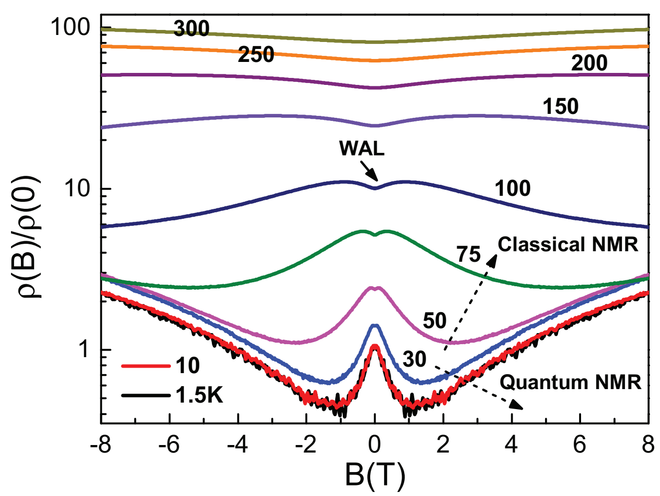
$$(\dot{\rho}, \dot{\epsilon}) \to M \cdot (\delta\mu, \delta T)$$

$$\vec{J} = G\vec{E} + G_T \nabla T$$

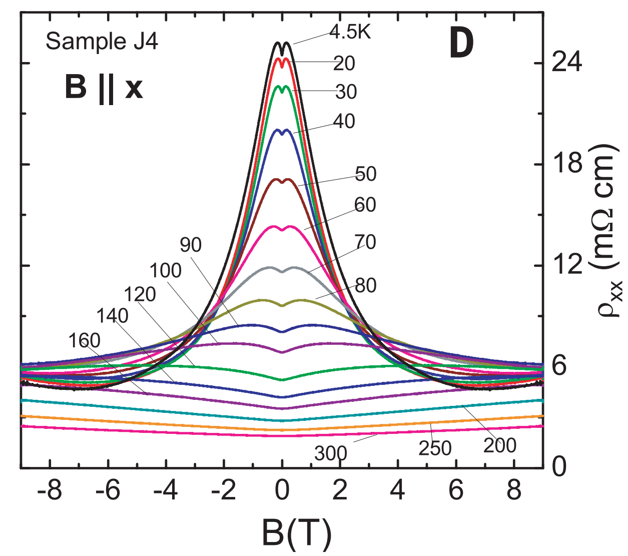
$$G = d_e + c_1 a_\chi^2 B^2 \qquad G_T = d_{th} + c_2 a_\chi a_g B^2$$

Kinetic theory single Weyl: [Son, Spivak]
Kinetic theory single multi-Weyl: [Dantas,P-B,Roy,Surowka]
Hydro: [Lucas, Davison, Sachdev]

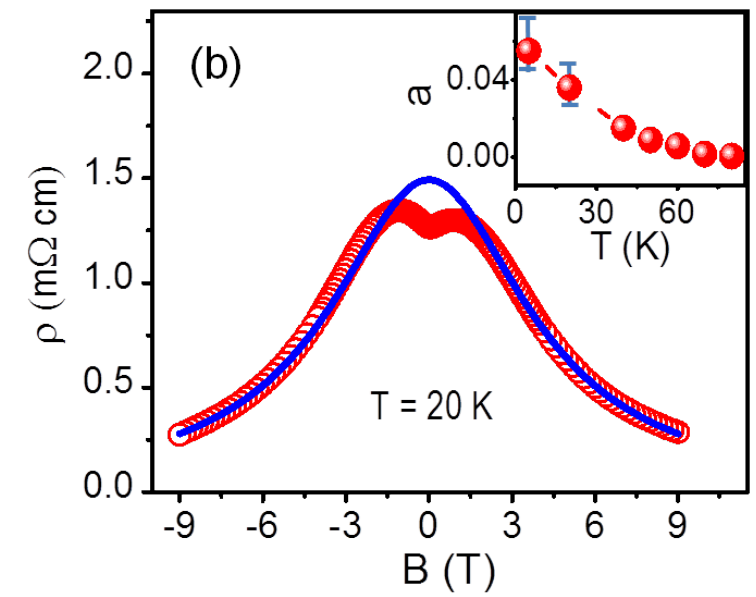
Some experimental signals



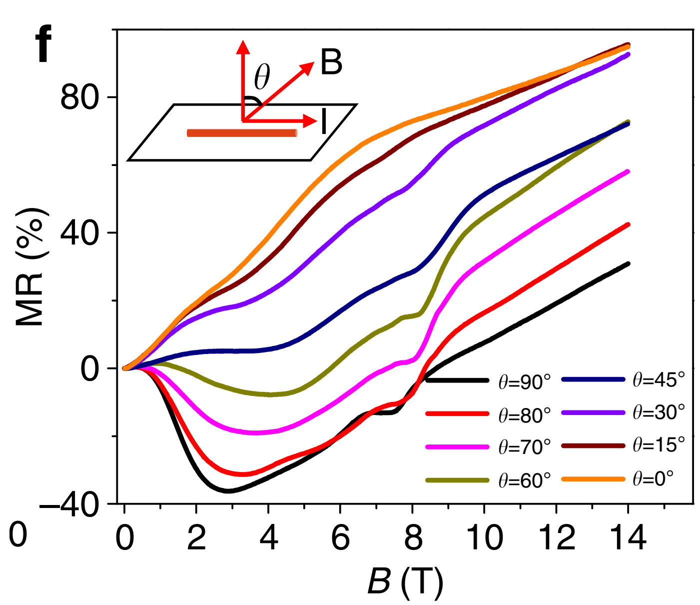
Phys. Rev. B 93, 121112(R) (2016)



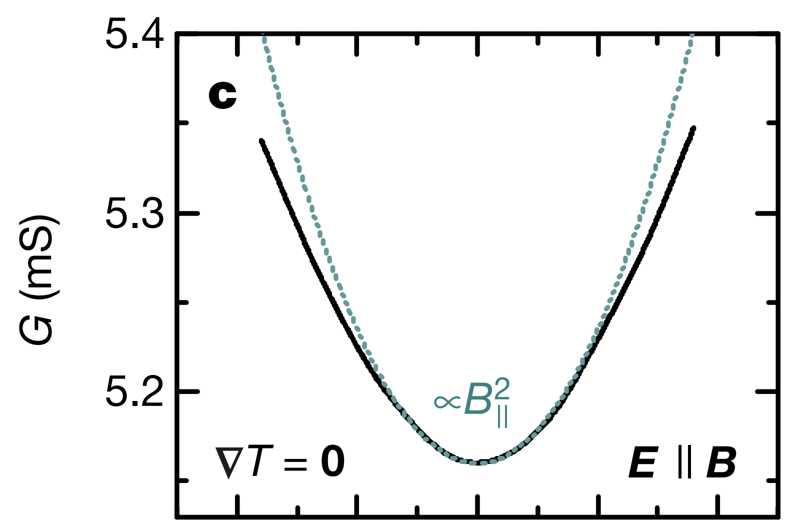
Science 23, 350 Issue 6259
413-416 (2015)



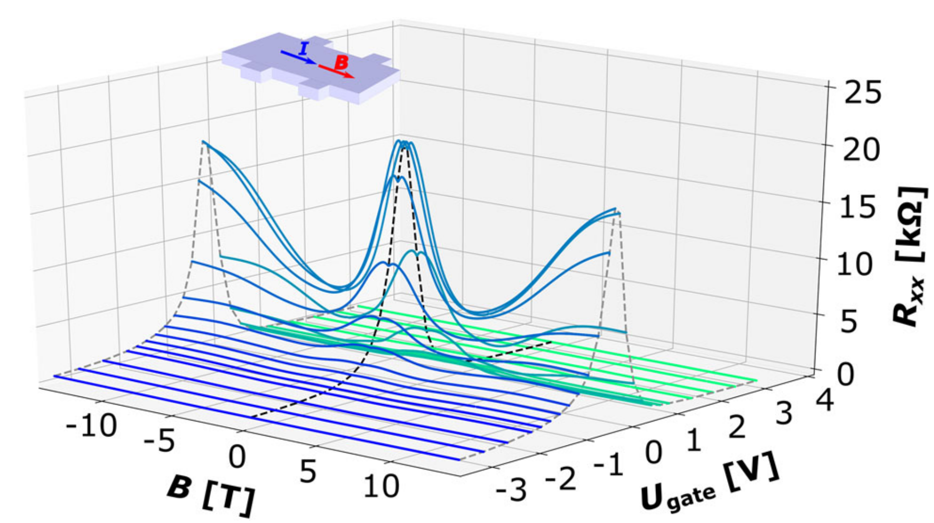
Nature Physics volume 12, pages 550–554 (2016)



Nature Comm. vol. 6, 10137 (2015)

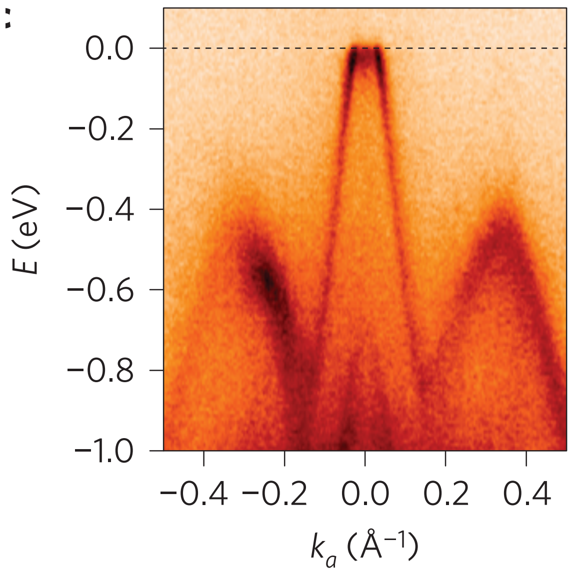


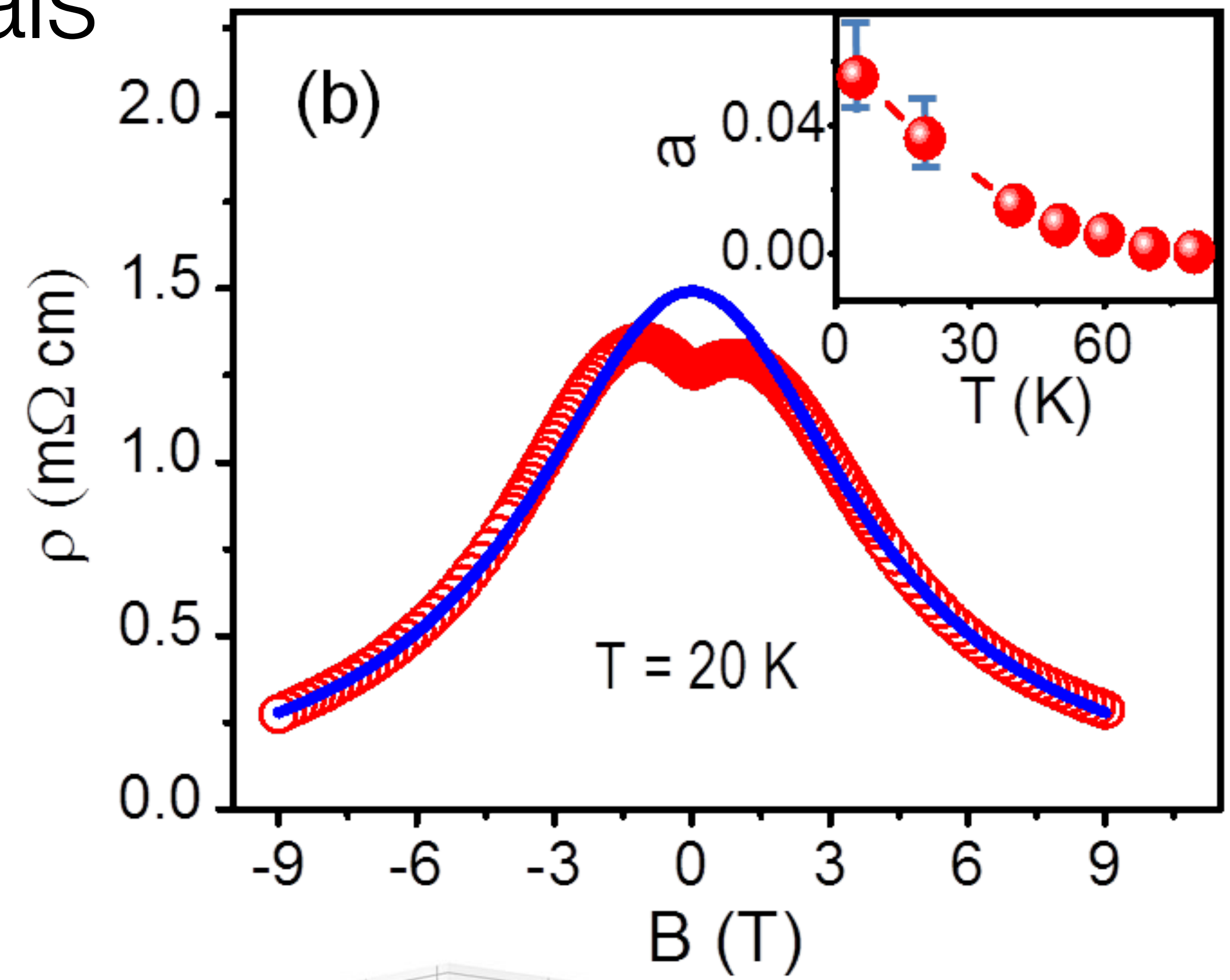
Nature volume 547, 324–327 (2017)

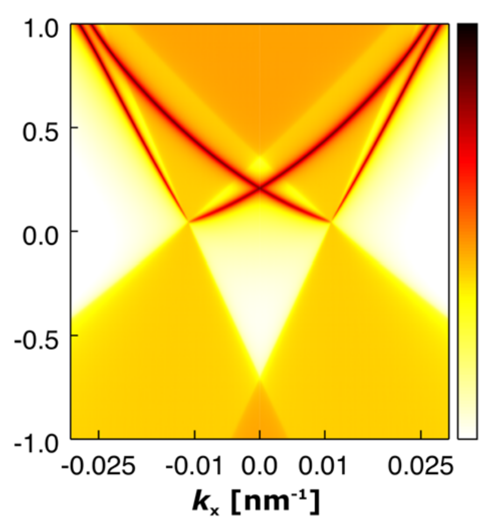


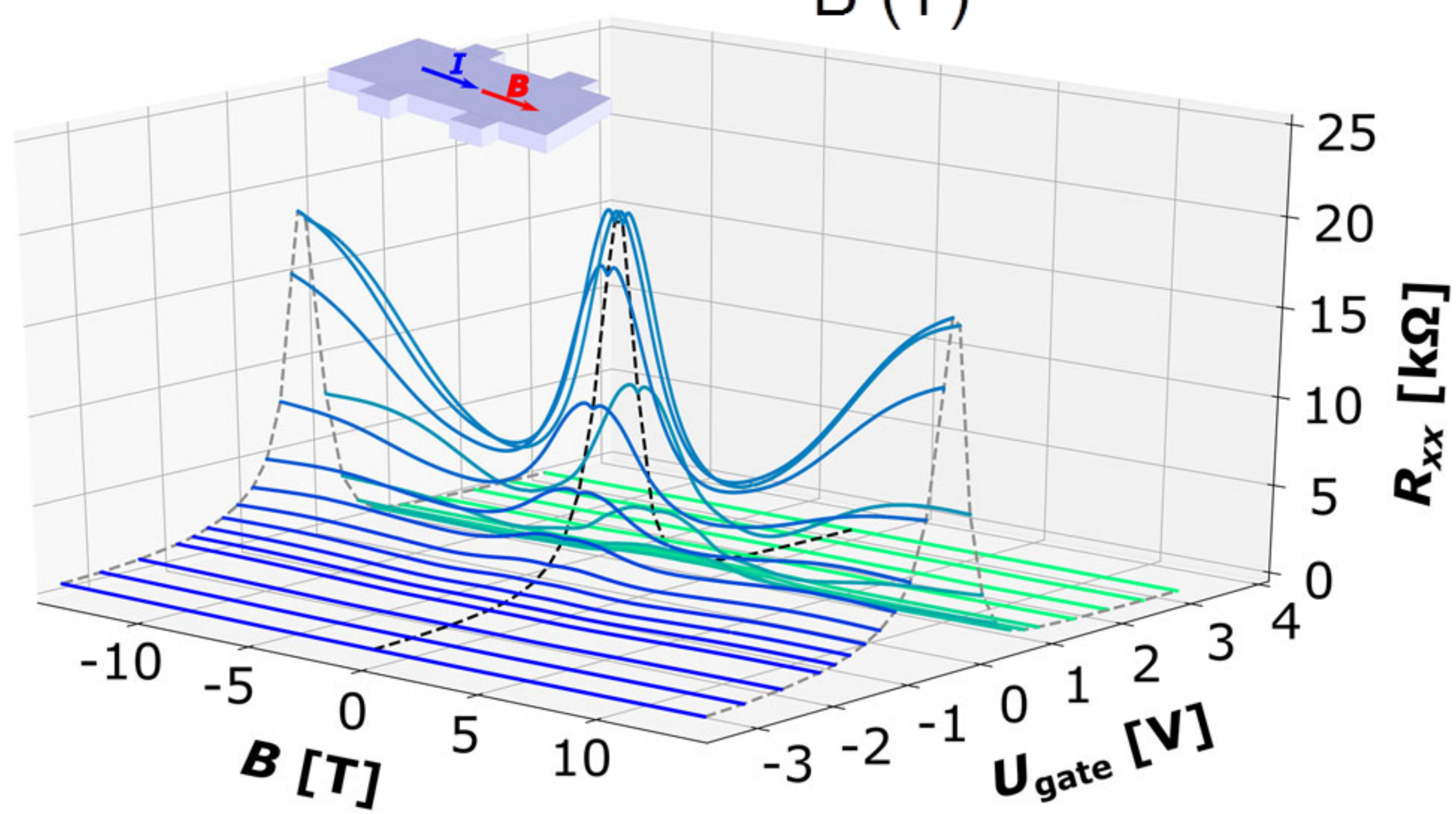
Phys. Rev. X 9, 031034 (2019)

Some experimental signals

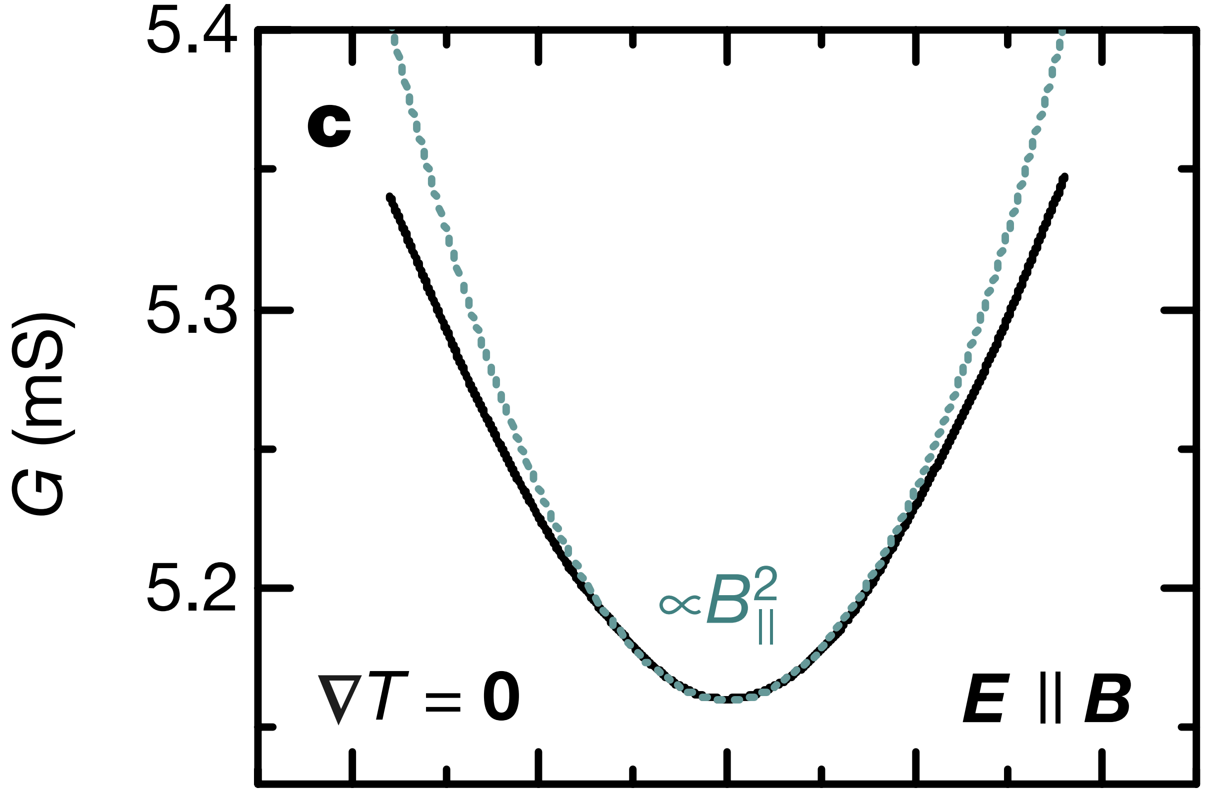


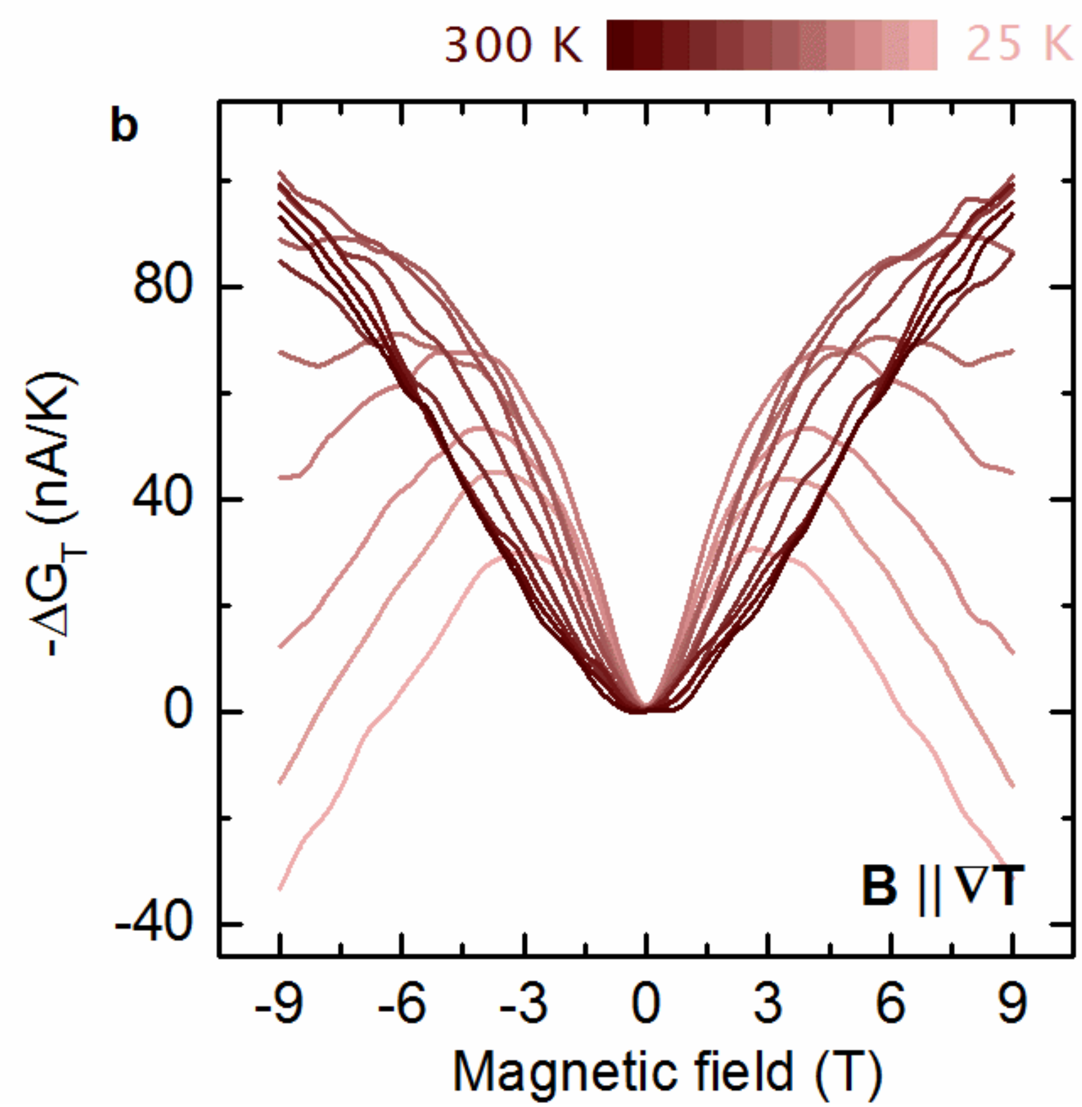


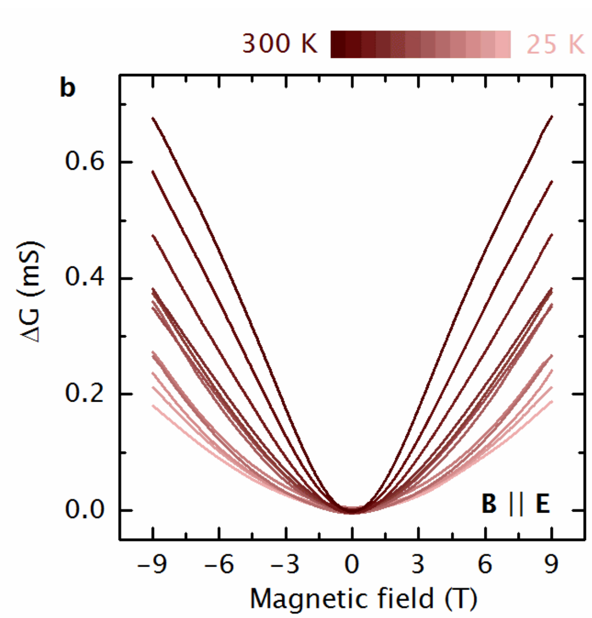




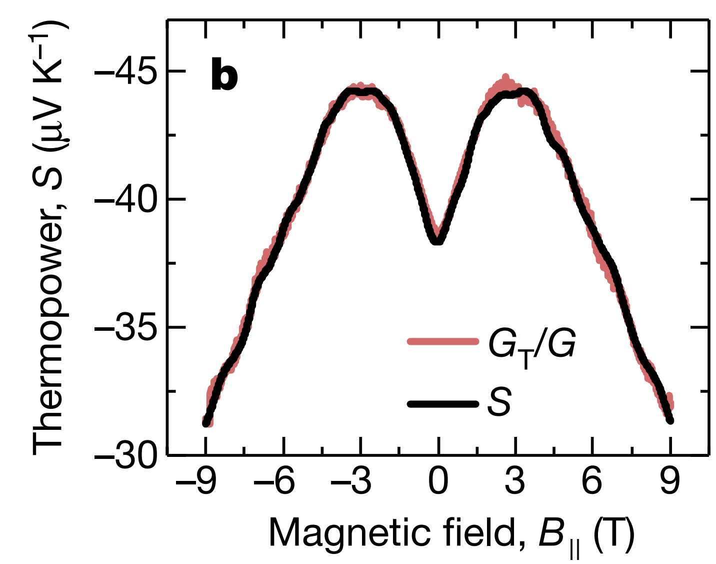
Some experimental signals



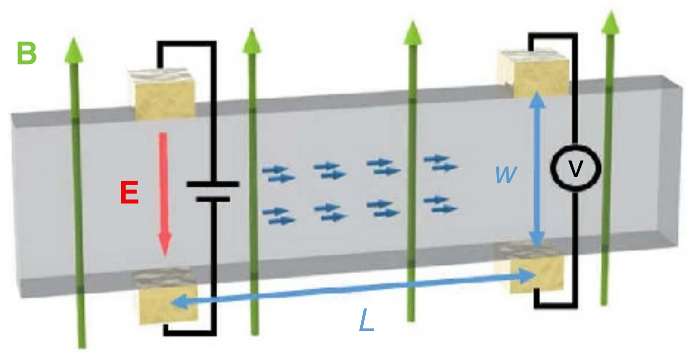


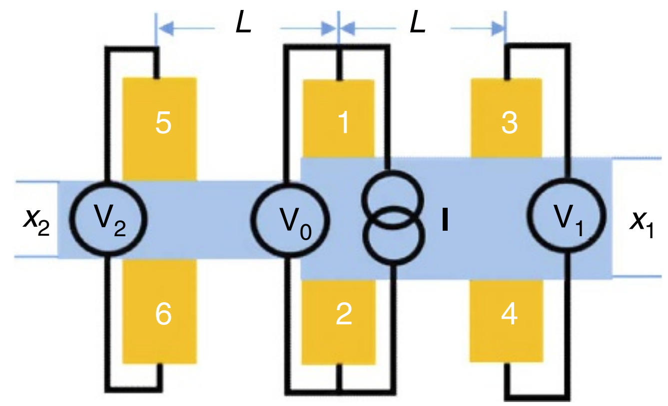


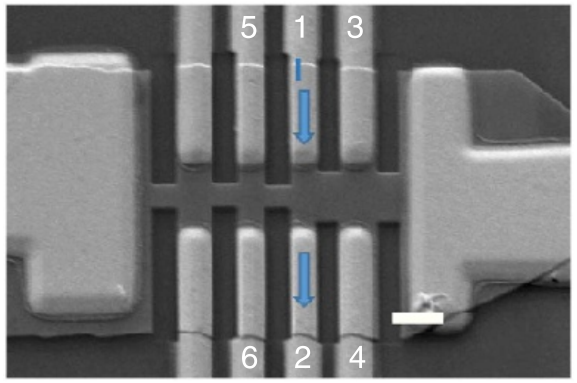
Nature volume 547, 324–327 (2017)

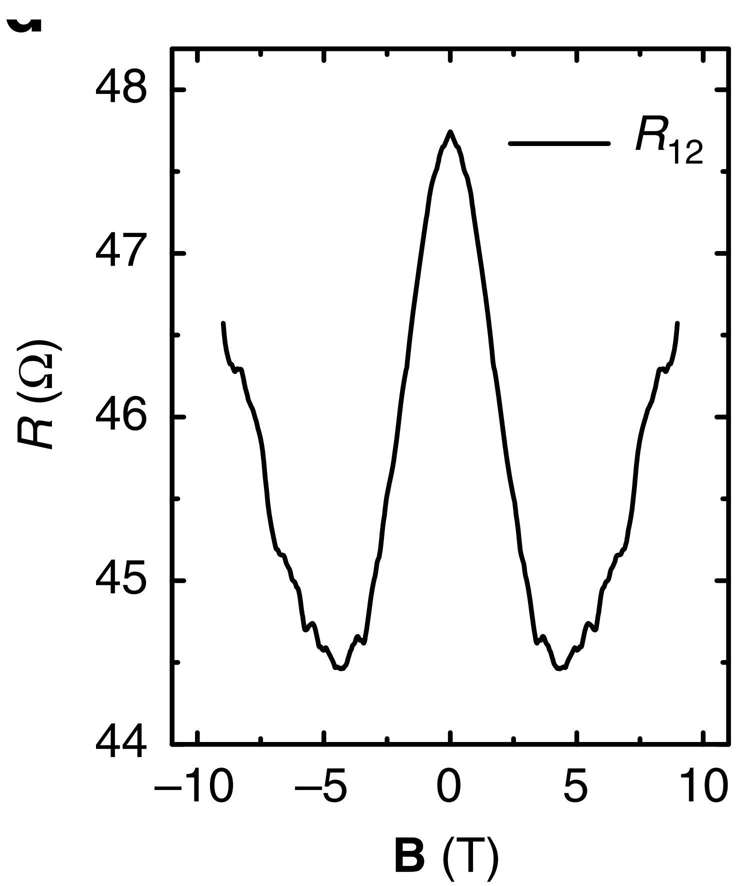


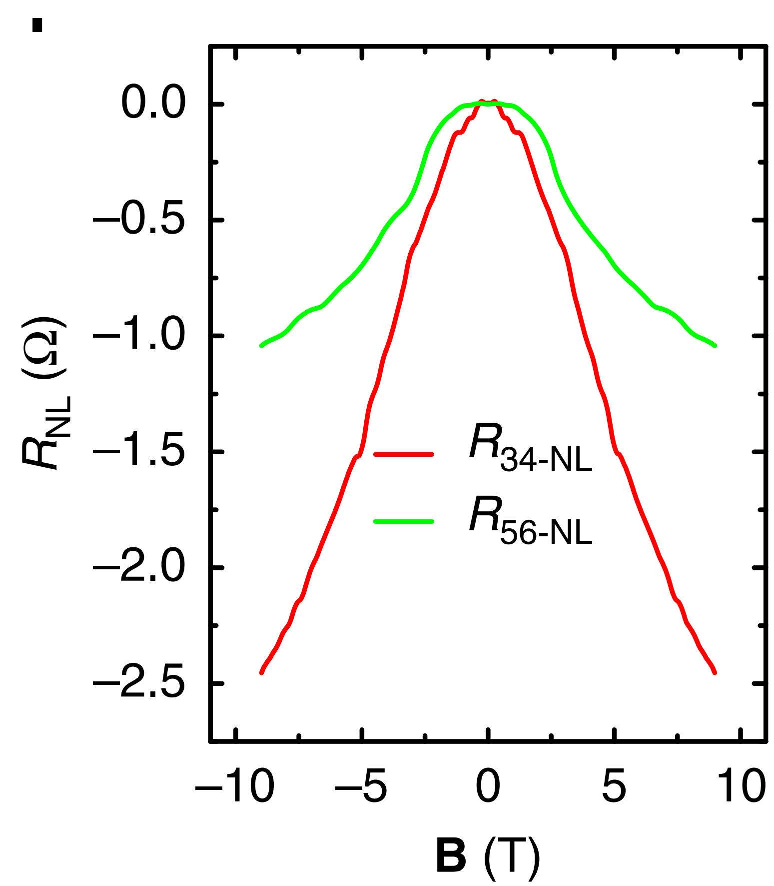
More experimental evidence!











Nature Communications vol. 8, 13741 (2017)

strong coupling

Ingredients:

- Gauge field dual to the vector current
- Gauge field dual to the axial current
- Axial anomaly
- background axial field
- mass deformation

$$\mathcal{L} = \bar{\Psi}\left(i\partial\!\!\!/ - eA\!\!\!/ - \gamma_5\gamma_z b + M\right)\Psi\,.$$

$$\partial_\mu J_5^\mu = \frac{1}{16\pi^2}\epsilon^{\mu\nu\rho\lambda}F_{\mu\nu}F_{\rho\lambda} + 2M\bar{\Psi}\gamma_5\Psi$$

the model

$$S = \int d^5x\sqrt{-g}\left[\frac{1}{2\kappa^2}\Big(R + \frac{12}{L^2}\Big) - \frac{1}{4}F^2 - \frac{1}{4}F_5^2 + \frac{\alpha}{3}\epsilon^{\mu\nu\rho\sigma\tau}A_\mu\Big(F^5_{\nu\rho}F^5_{\sigma\tau} + 3F_{\nu\rho}F_{\sigma\tau}\Big) + \right.$$
$$\left. + (D_\mu\Phi)^*(D^\mu\Phi) - V(\Phi)\,, \right. \qquad (2.1)$$

$$V = -\tfrac{12}{L^2} + m^2\phi^2 + \tfrac{\lambda}{2}\phi^4$$

If the Scalar runs to a constant value

$$ds^2 = B_0 r^2(-dt^2 + dr^2 + dx^2 + dy^2) + C_0 r^{2\beta}dz^2$$

$$A_z = r^c \qquad , \qquad \phi = \phi_{IR}$$

Anomalous Hall conductivity

$$\sigma_{xy} = 8\alpha A_z^5(r_0)$$

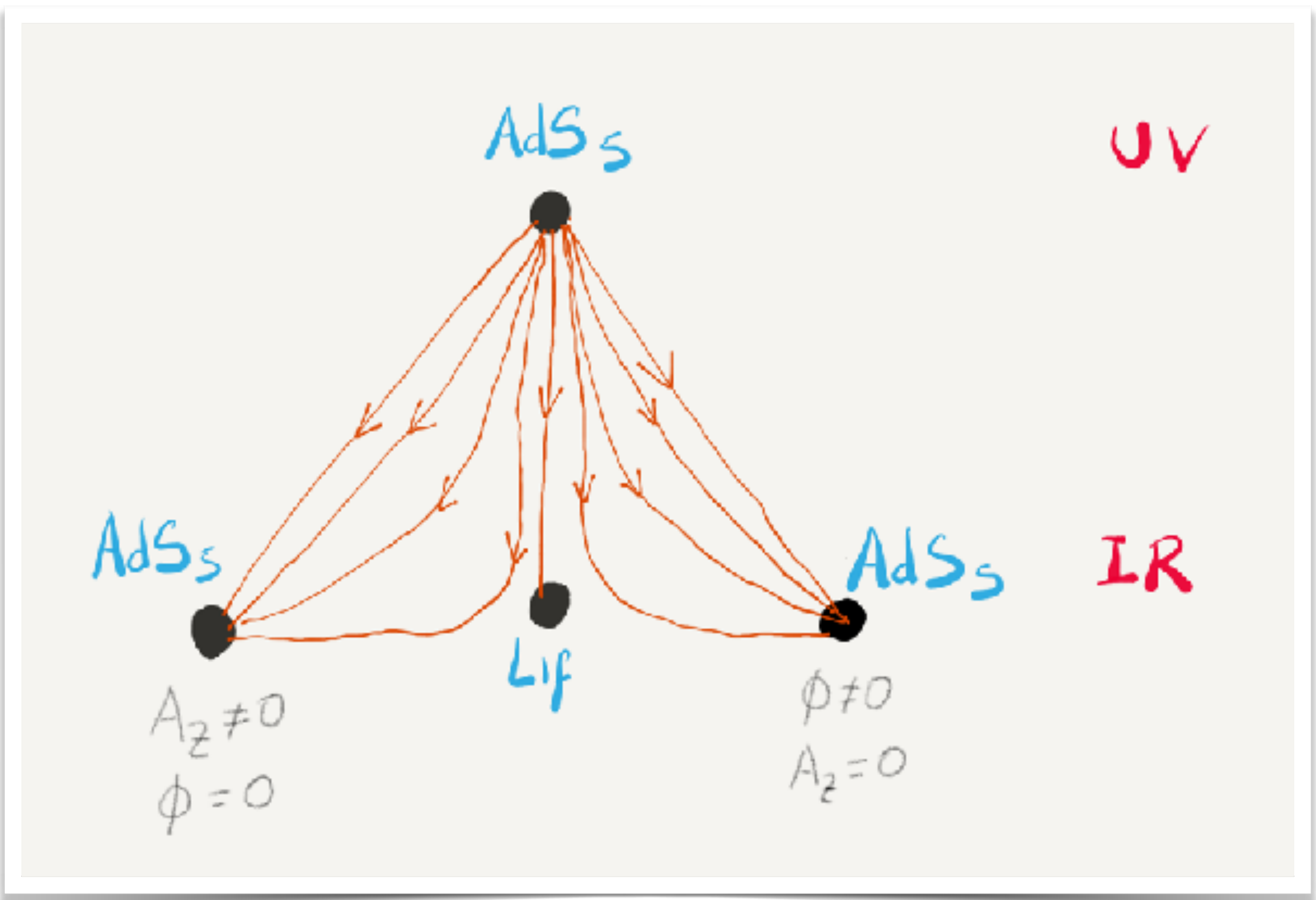
[Landsteiner, Liu, Sun]

general models

case of scalar running to a constant value

$$ds^2 = B_0 r^2(-dt^2 + dr^2 + dx^2 + dy^2) + C_0 r^{2\beta} dz^2$$

$$A_z = r^c \qquad , \qquad \phi = \phi_{IR}$$



optical conductivity
(small frequency)

longitudinal conductivity $\Re(\sigma) \propto \omega^{2-\beta}$

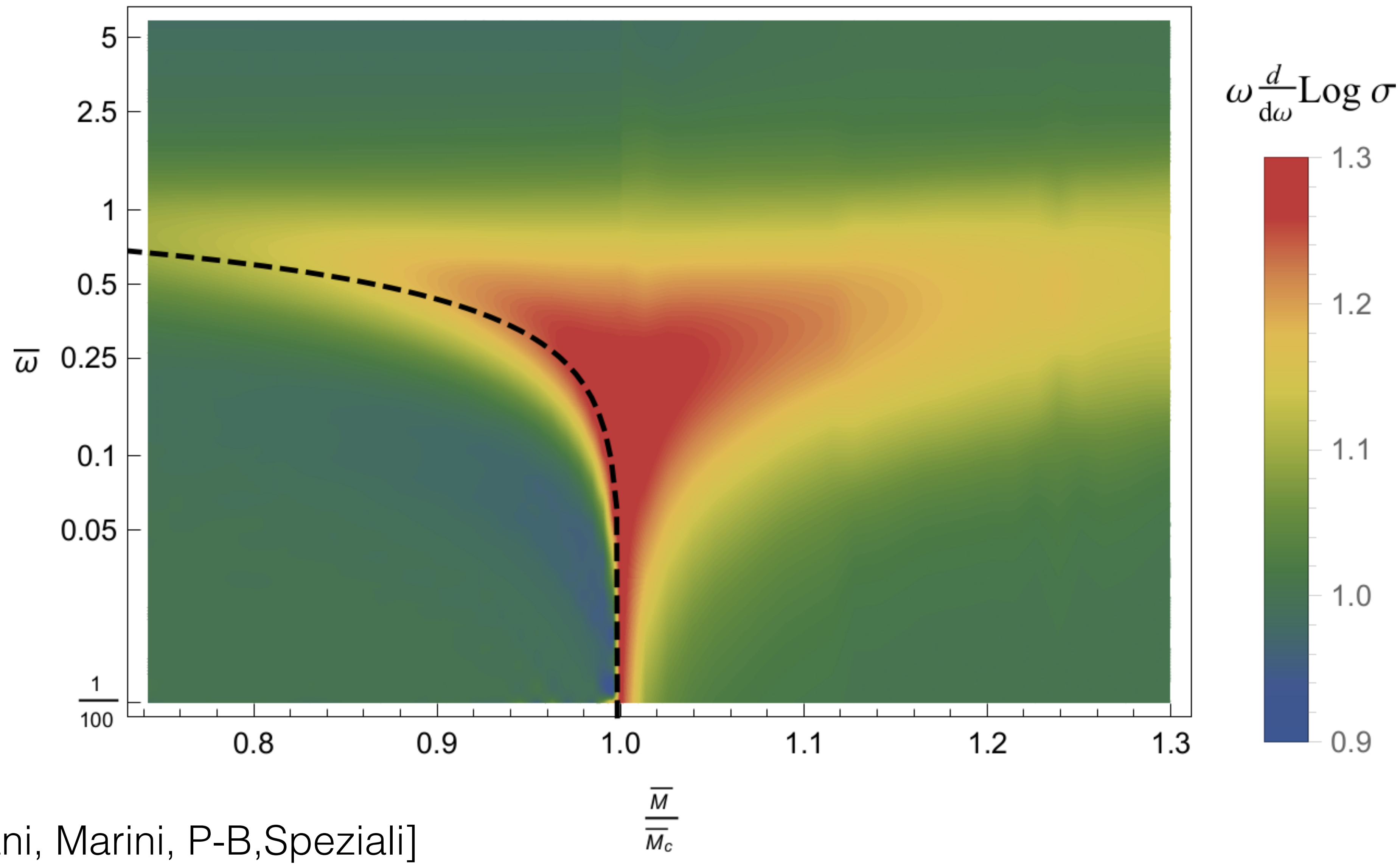
transvers conductivity $\Re(\sigma_{\pm}) \propto \omega^{\beta}$

consistency requires

$$0 < \beta \leq 1$$

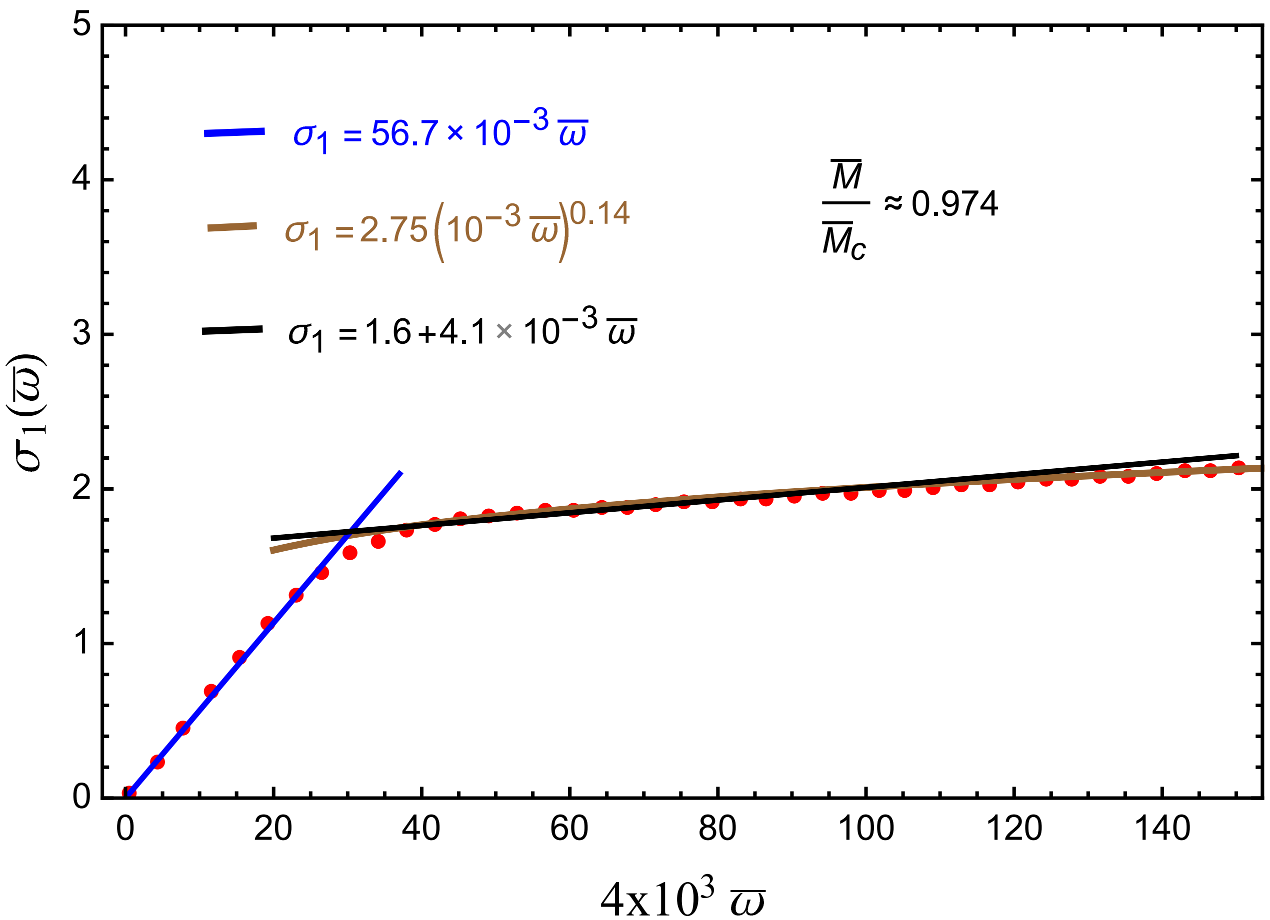
Quantum phase diagram

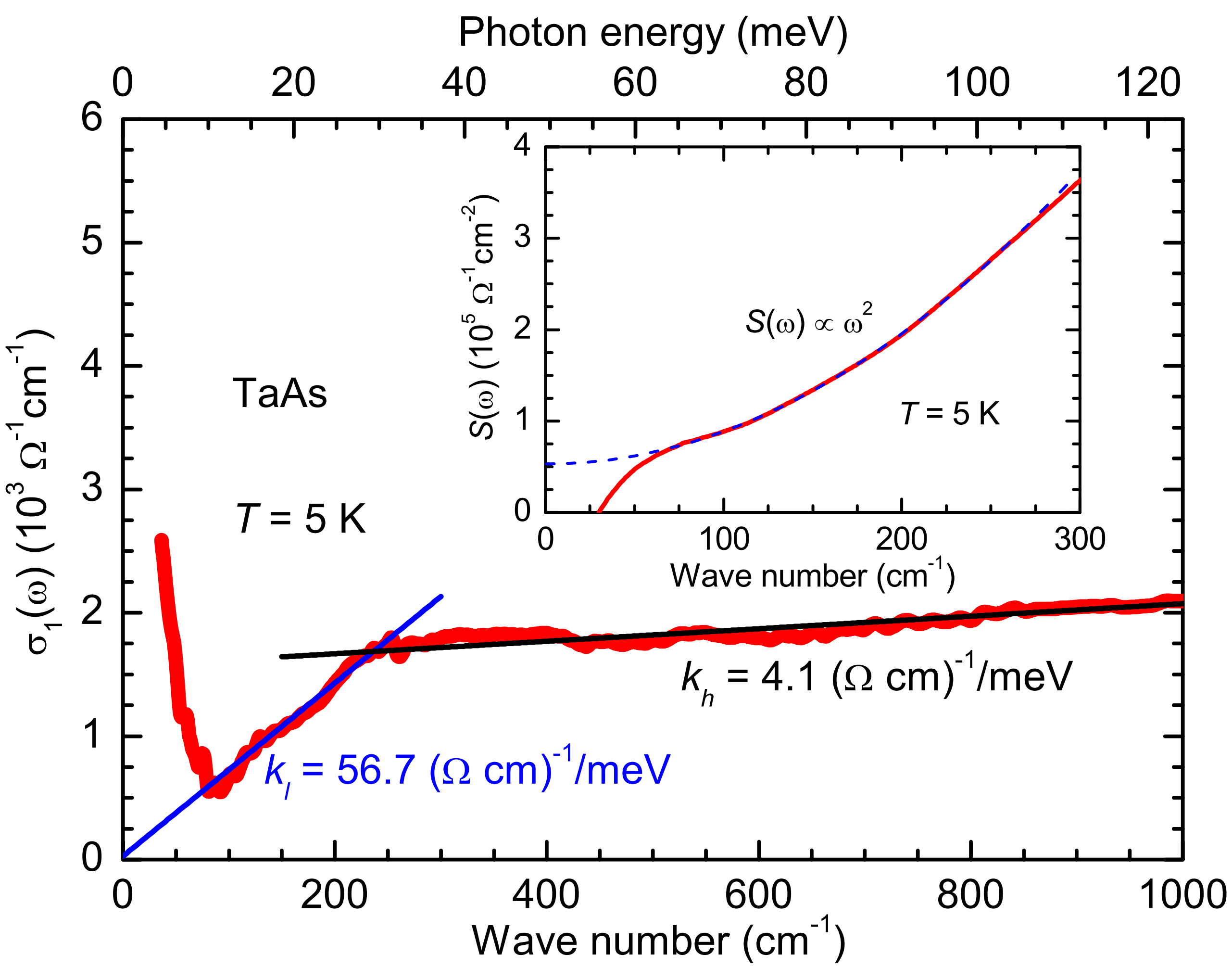
Taking advantage of the scaling symmetry around the fix points we construct the phase diagram studying the conductivity as a function of the frequency and mass parameter



[Grignani, Marini, P-B,Speziali]

Comparing the model and the experiment

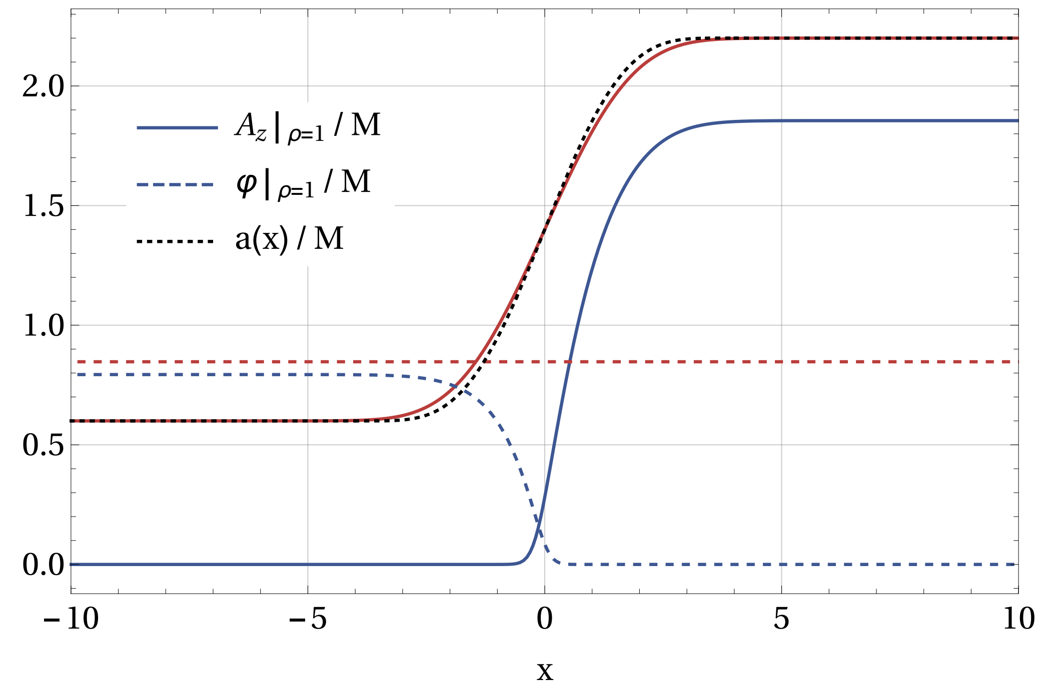


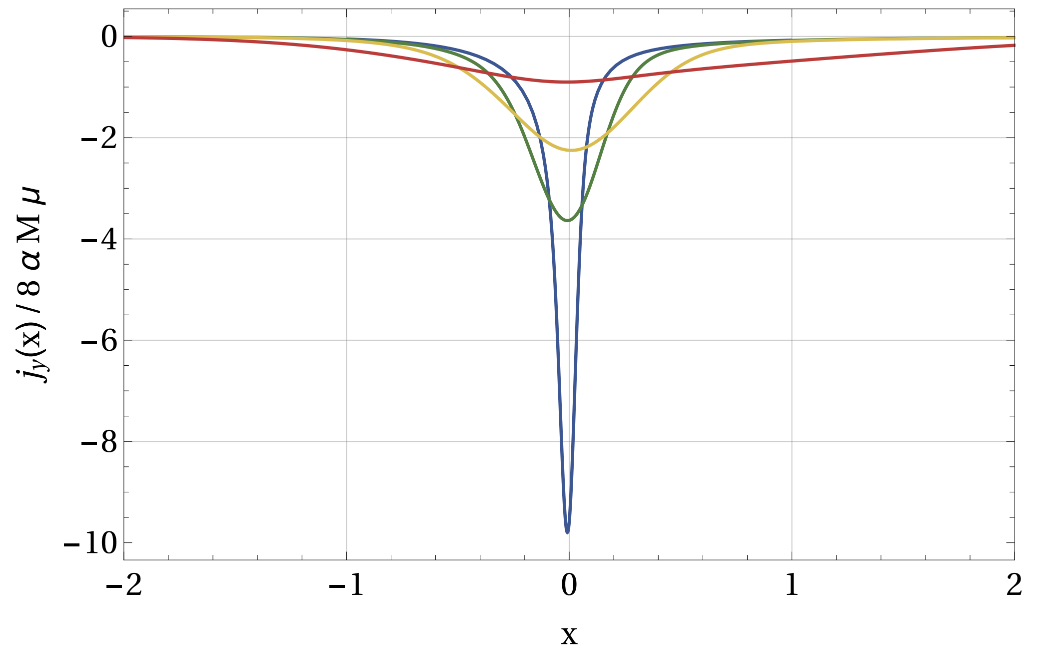


$$\beta \approx 0.14$$

[Grignani, Marini, P-B,Speziali]

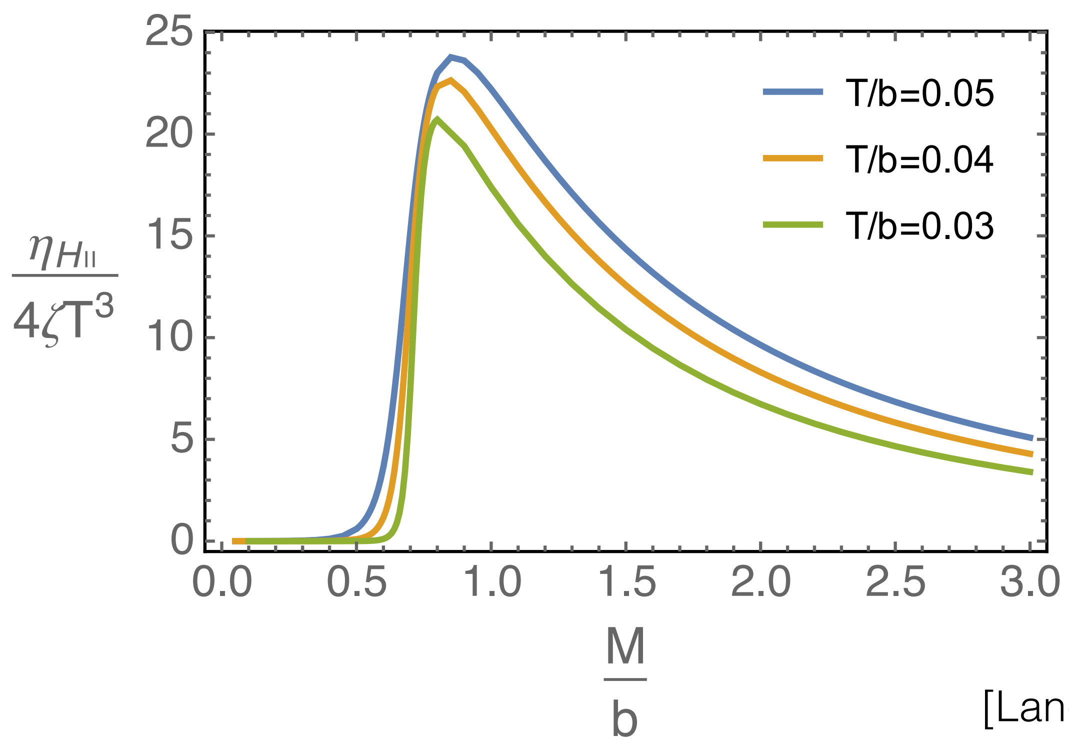
Holographic Fermi Arcs

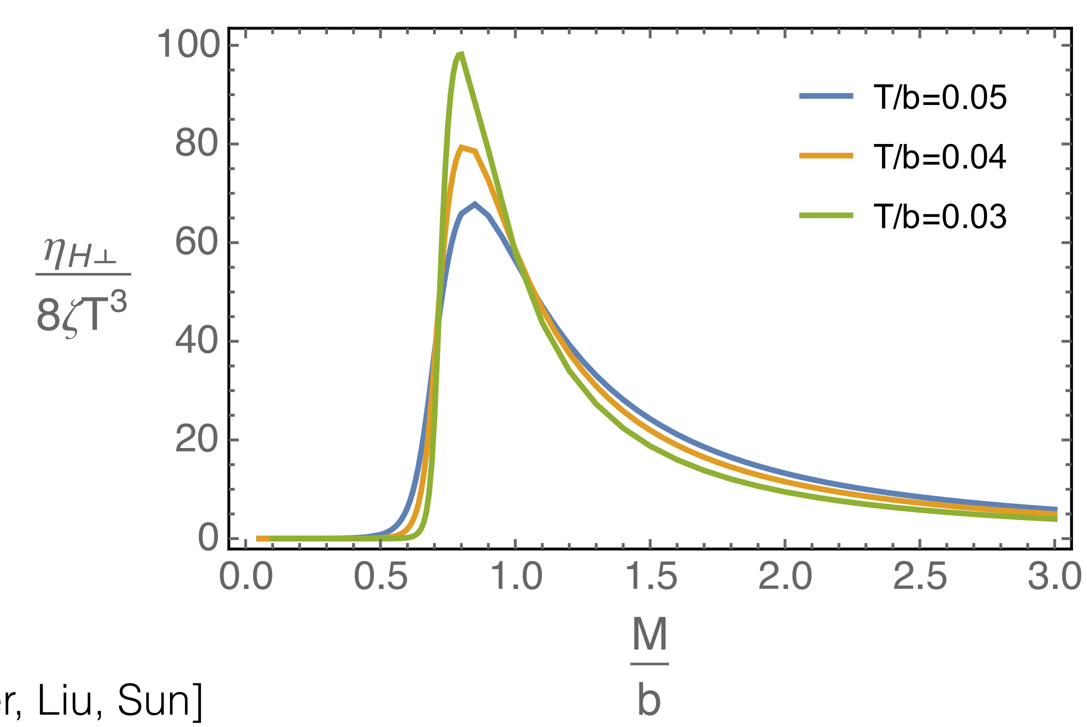




[Ammon, Jimenez-Alba, Heinrich, Moeckel]

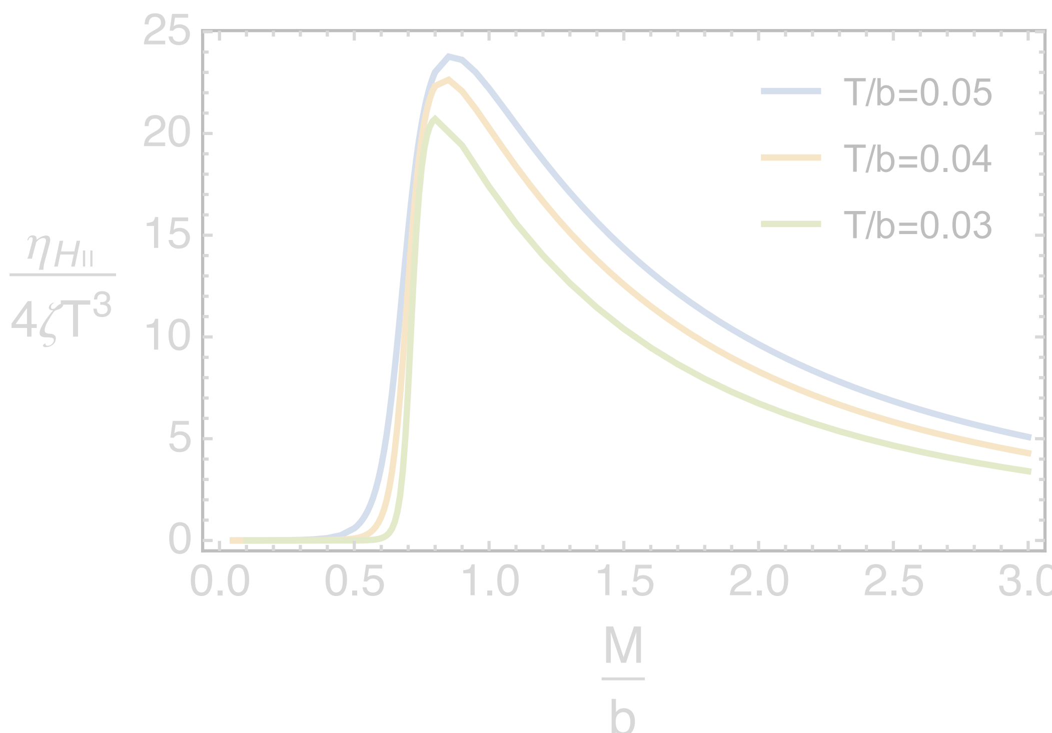
Holographic Hall viscosity

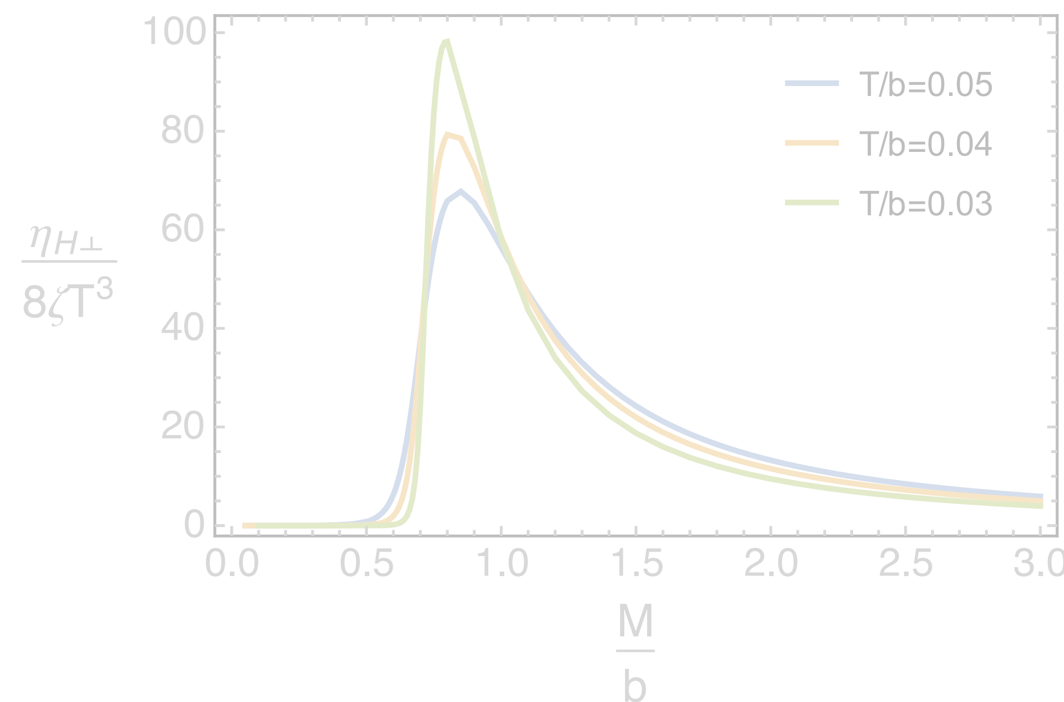




[Landsteiner, Liu, Sun]

Hall viscosity



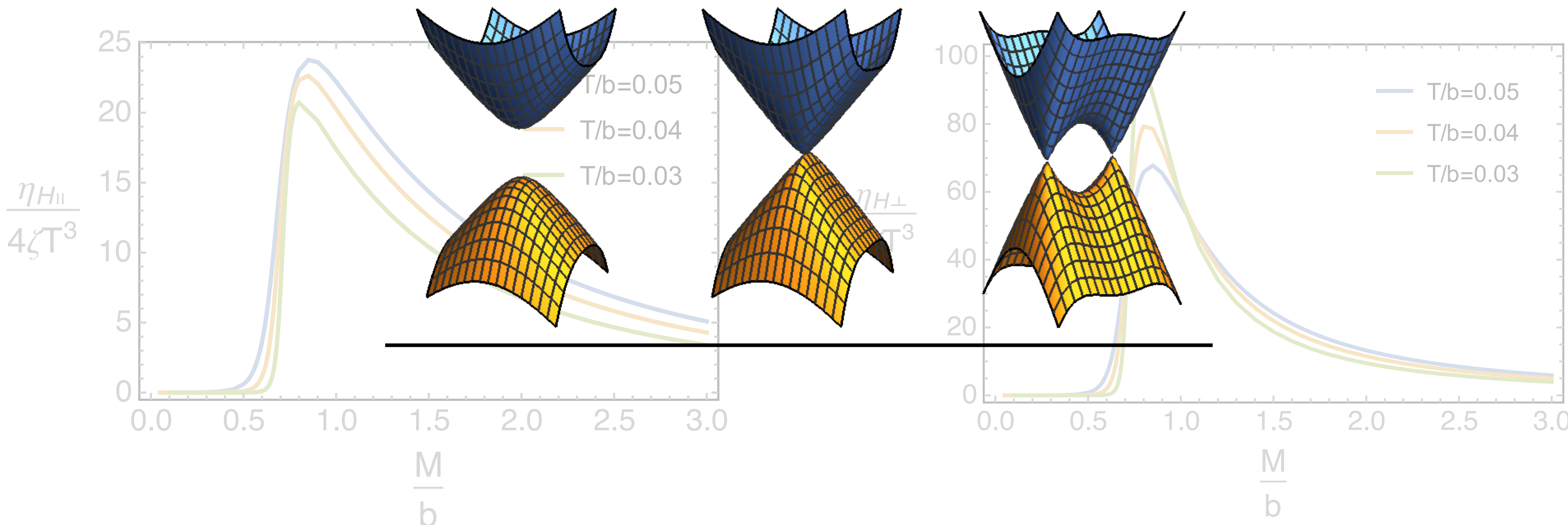


$$\eta = \frac{s}{4\pi^2}\frac{\beta}{3\beta+1}T^{3\beta}\Gamma(3\beta)\eta_D(3\beta) =_{\beta\to 0} \frac{s}{24\pi^2}$$

[Copetti,Landsteiner]

Afterwards Coppetti argued that in such a limit translations become an anomalous symmetry [JHEP vol. 2020, 190 (2020)]

Hall viscosity



$$\eta = \frac{s}{4\pi^2}\frac{\beta}{3\beta+1}T^{3\beta}\Gamma(3\beta)\eta_D(3\beta) =_{\beta\to 0} \frac{s}{24\pi^2}$$

[Copetti,Landsteiner]

Afterwards Coppetti argued that in such a limit translations become an anomalous symmetry [JHEP vol. 2020, 190 (2020)]

The higher monopole charge case

$$S \ = \ -\int \mathrm{Tr}\left[\frac{1}{2n}F\wedge{}^\star F+\frac{1}{2c(n)}G\wedge{}^\star G+\ \lambda\left(\mathcal{A}\wedge(d\mathcal{A})^2+\frac{3}{2}\mathcal{A}^3\wedge\mathrm{d}\mathcal{A}+\frac{3}{5}\mathcal{A}^5\right)\right]$$

$$A=A^{(0)}s_0 \quad , \quad \mathbb{A}=\mathbb{A}^{(a)}s_a \quad , \quad \mathcal{A}=A+\mathbb{A} \qquad\qquad F=dA \quad , \quad G=d\mathbb{A}-i\mathbb{A}^2$$

$$\mathcal{A} \ = \ \left(\mathcal{A}_t(r)s_0+\mathcal{A}_t^3(r)s_z\right)\mathrm{d}t+\mathcal{Q}(r)\left(s_x\mathrm{d}x+s_y\mathrm{d}y\right)+\left(\mathcal{A}_z(r)s_0+\mathcal{A}_z^3(r)s_z\right)\mathrm{d}z+xBs_0\mathrm{d}y$$

For the non holographers

$$\mathcal{L}=\mathcal{L}_{CFT}+\mu Q+\mu_3 Q^3+\Delta\left(\delta_x^\mu J_\mu^1+\delta_y^\mu J_\mu^2\right)$$

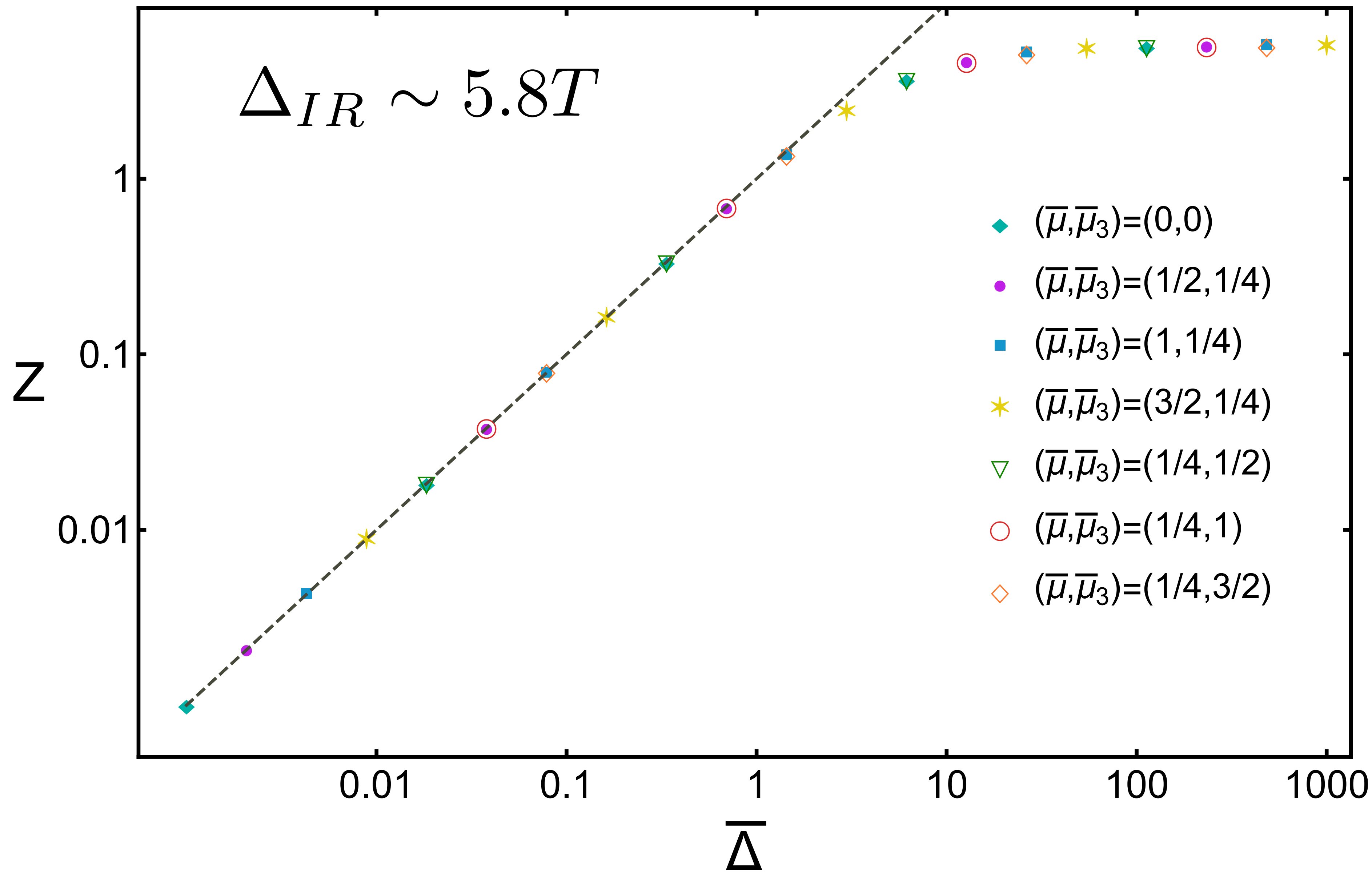
The equations of motion automatically imply

$$J^z=\frac{n}{4\pi^2}\mu B+\frac{c(n)}{4\pi^2}\mu_3\Delta^2$$

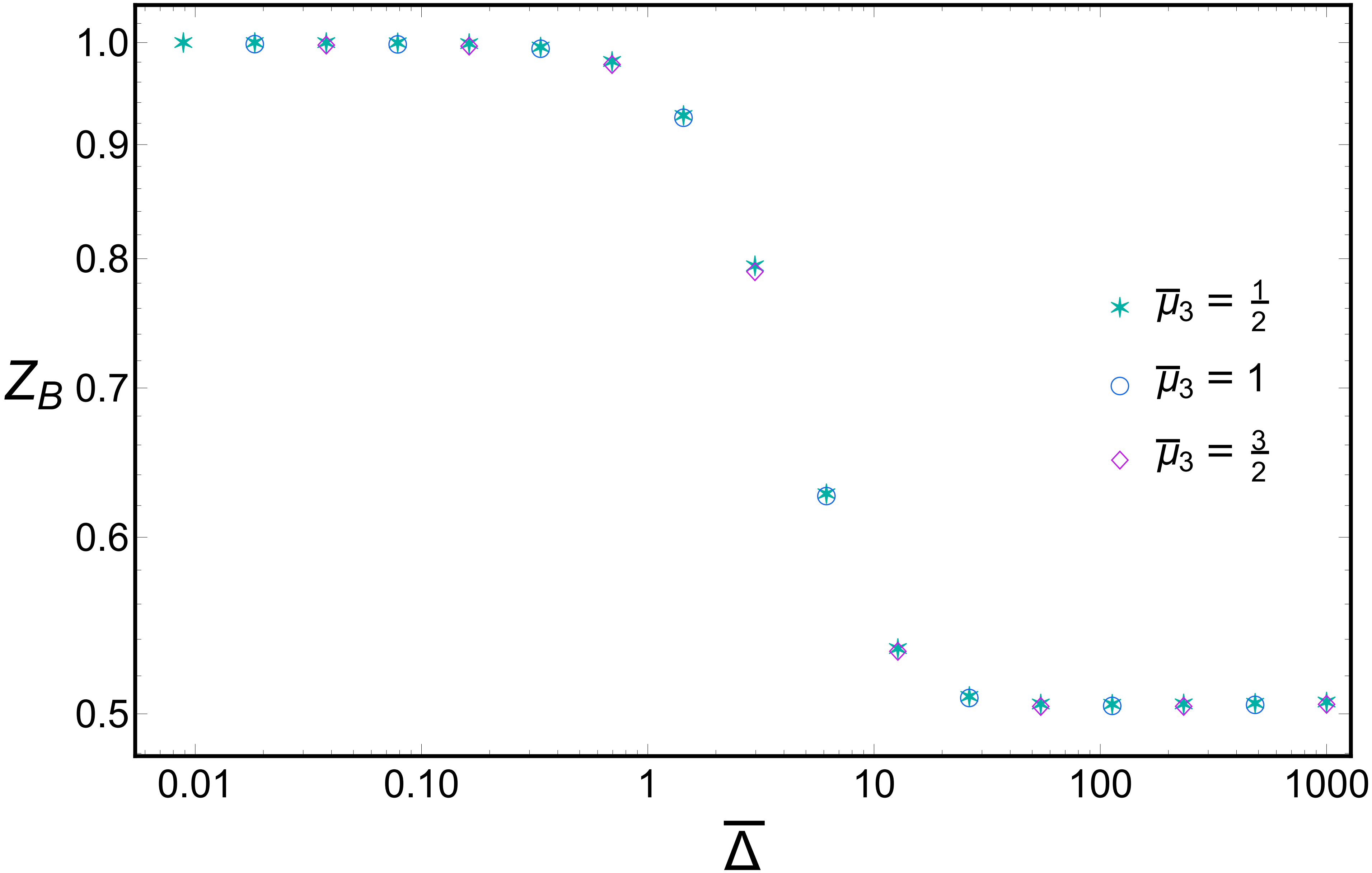
The non abelian sector has to be solved numerically

The non-abelian symmetry is explicitly broken, therefore Δ will renormalise

$$\Delta_{IR} = Z(\Delta/T)T$$

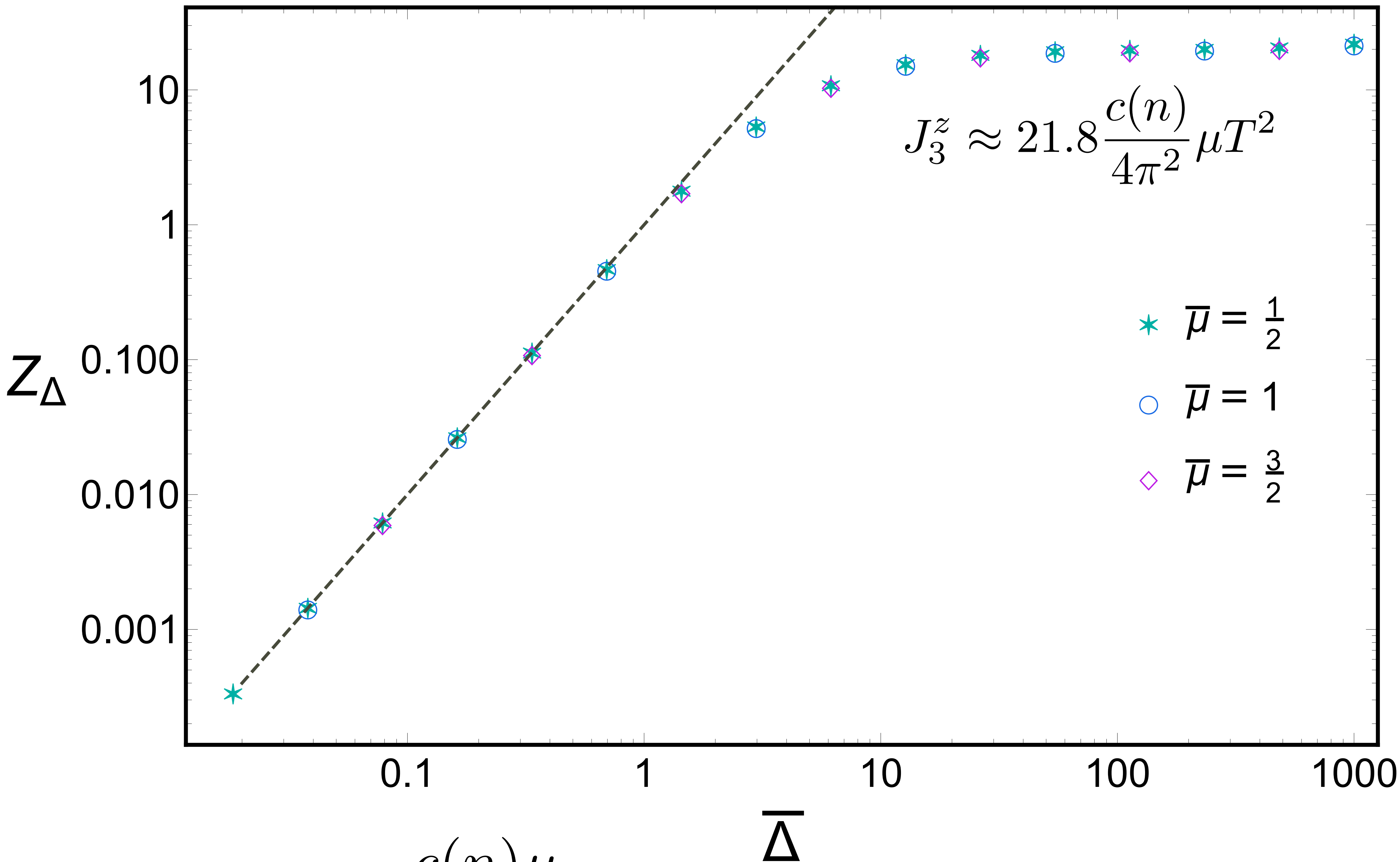


Same thing happens with the current



$$\vec{J}_3 = Z_B(\Delta/T)\frac{n\mu_3}{4\pi^2}\vec{B}$$

Same thing happens with the current



$$J_3^z = Z_\Delta(\Delta/T) \frac{c(n)\mu}{4\pi^2} T^2$$

To summarise I hope I convinced you that Weyl semimetals are cool because…

- They are a minimal copy of our Universe.
  - They can be used to test several high energy ideas and phenomena of different acmes otherwise
  - They host Abelian and “non-Abelian” anomalies
  - They are nearly scale invariant
- In multi-Weyl systems the non-Abelian current is related to a spin current, issue that needs to be understood.
- They are a source of interesting strongly coupled dynamics
- Conformal anomalies manifest also in transport (**Not discussed in this talk**).
  - See: *Generation of a Nernst Current from the Conformal Anomaly in Dirac and Weyl Semimetals*, Phys. Rev. Lett. 120, 206601 (2018)
- Allow me to conclude with a provocative question. Could it be possible that with live inside a crystal?