Chiral transport in strong fields from holography

Tuna Demircik

Department of Physics, Ben-Gurion University of the Negev, Beer-Sheva, Israel

September 2, 2019

[1] Y. Bu, T. Demircik and M. Lublinsky, JHEP **05** (2019) 071, arXiv:1903.00896v2.

Outline:

- Hydrodynamics
- Chiral Transport
- Holography
- **Holographic Model**
- **Gradient Expansion**
- **Gradient Resummation**
- **Conclusion**

Hydrodynamics:

- **Hydrodynamics** is an effective low energy description of many interacting QFTs which is valid for fluctuations about global equilibrium under long wavelength limit.

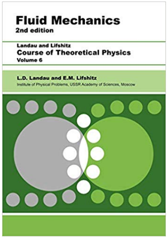
- **Dynamical content of hydro: Continuity equations**

e.g. : $\partial_t \rho = -\vec{\nabla} \cdot \vec{J}$

(Needs extra input to be able solve!)

$\Downarrow$

Constitutive relations (e.g.: $\vec{J} = -\mathcal{D}\vec{\nabla}\rho + \sigma\vec{E} + \cdots$)



- **Constitutive relations** are written as gradient expansion of hydro variables.

$$\text{e.g.}: \quad \vec{J} = -\mathcal{D}\vec{\nabla}\rho + \sigma\vec{E} + \cdots$$

Any term which respects **symmetries of underlying theory** and **thermodynamical constraints** can be written up to a **coefficients**.

$\Downarrow$

Transport coefficients

(TCs should be determined either from the underlying microscopic theory or experimentally.)

- **Truncation at fixed order** leads **violation of causality !**

(Ideally, one needs to include all orders of gradients $\Rightarrow$ **Ressummation**!)

Chiral Transport:

• For massless Dirac fermions, independent phase rotations of **left handed** and **right handed** spinors are independent symmetries of the classical theory ($U(1)_L$ and $U(1)_R$):

$$i\gamma^\mu \partial_\mu \Psi = 0, \quad \Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}, \quad \psi_L \to e^{i\theta_L}\psi_L \quad \text{and} \quad \psi_R \to e^{i\theta_R}\psi_R.$$

At the classical level:

$$\partial_\mu J^\mu_{L,R} = 0 \quad \text{where} \quad J^\mu_{L,R} = \bar{\Psi}\gamma^\mu P_\pm \Psi \text{and} \quad P_\pm = (1 \pm \gamma^5)/2.$$

At the quantum level, in the presence EM-field, only one linear combination of these to symmetries preserved:

$$\partial_\mu J^\mu = 0 \qquad \text{and} \qquad \partial_\mu J^\mu_5 = 12\kappa \vec{E}\cdot\vec{B}$$

$$\Downarrow$$

Chiral Anomaly!

• **Chiral Anomaly** leads **chiral asymmetry** ($\mu_5 \neq 0$) in a relativistic plasma. $\Rightarrow$ Modifies the contstitutive relation!*

$$\begin{aligned}
&\text{Chiral **M**agnetic **E**ffect (**CME**)} : && \vec{J} \propto \mu_5 \vec{B} \\
&\text{Chiral **S**eparation **E**ffect (**CSE**)} : && \vec{J}_5 \propto \mu \vec{B} \\
&\text{Chiral **E**lectric **S**eparation **E**ffect (**CESE**)} : && \vec{J}_5 \propto \mu_5 \vec{E}
\end{aligned}$$

$$+$$

Zoo of anomaly **induced nonlinear transports**

e.g. : Chiral **H**all **E**ffect (**CHE**) : $\vec{J} \propto \mu \vec{E} \times \vec{B}$

Anomalous **C**hiral **H**all **E**ffect : $\vec{J} \propto \mu \vec{E} \times \vec{\nabla} \mu_5$

Hall **D**iffusion : $\vec{J} \propto \vec{B} \times (\mu \vec{\nabla} \mu + \mu_5 \vec{\nabla} \mu_5)$

$$\vdots$$

• Note that some of these transports are Non-dissipative!

$$\left(\begin{array}{c} \mathcal{T}\text{-even TC} \Rightarrow \text{Nondissipative} \\ \mathcal{T}\text{-odd TC} \Rightarrow \text{Dissipative} \end{array} \right), \quad \text{e.g. CME, CHE, Hall Diffusion}, \cdots$$

*CME: [A. Vilenkin, 1980],[K. Fukushima, D.E. Kharzeev, H.J. Waringa,2008]

- **Chiral Anomaly** leads **new collective modes** which propogate through chiral plasma:

$$\mu \to \delta\mu e^{-i(\omega t - \vec{q}\cdot\vec{x}))}, \qquad \mu_5 \to \delta\mu_5 e^{-i(\omega t - \vec{q}\cdot\vec{x})},$$
$$\omega = \pm v_{\chi B} q \pm v_{\chi E} q + v_{\chi S} q + iDq^2 + \cdots .$$

CME + CSE $\Rightarrow$ **C**hiral **M**agnetic **W**ave : $(v_{\chi B} \parallel \vec{B})$

CESE $\Rightarrow$ **C**hiral **E**lectric **W**ave : $(v_{\chi B} \parallel \vec{E})$

CHE $\Rightarrow$ **C**hiral **H**all **D**ensity **W**ave : $(v_{\chi S} \parallel \vec{S})$

- **Remark: Realistic plasmas are exposed strong E/M fields!** e.g. **Q**uark-**G**luon-**P**lasma [X.G. Huang, 2015], **Primordial plasma** in early universe [D. Grasso, H.R. Rubinstein, 2000]

Holography (AdS/CFT):

• **Holography (AdS/CFT)** is a duality between **strongly-coupled gauge theory in 4D** and **weakly-coupled gravity theory in 5D**. (It is a powerful tool to analyze strongly-coupled gauge theories by using classical gravitational theories!) $[N_c^2 \propto (L^3/G_5), \quad \lambda \propto (L/l_s)^4]$

• **Gubser-Klebanov-Polyakov-Witten**-relation:

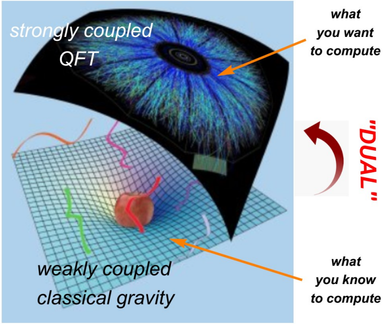
$$\mathcal{Z}_{gauge} = \mathcal{Z}_{AdS}$$

$$\left\langle exp\left(i\int \phi^{(0)} O\right)\right\rangle = exp\left(i\bar{S}[\phi|_{r=r_B} = \phi^{(0)}]\right)$$

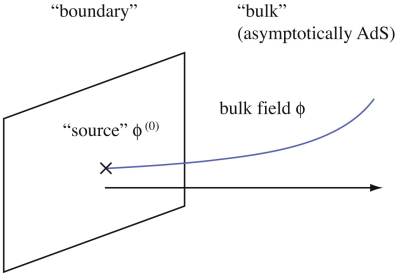
$$\Downarrow$$

(i.e. Bulk fields act as external sources of boundary operator!)

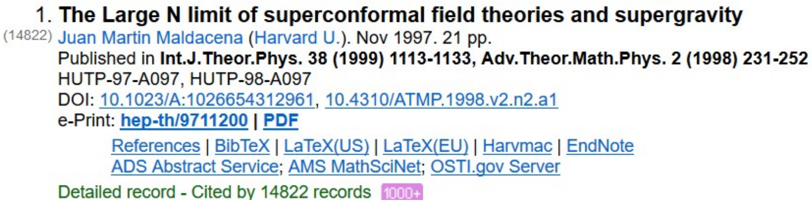
$$\left(\begin{array}{ccccc} \text{e.g. Boundary operator} & & \text{External sources} & & \text{Bulk fields} \\ T^{\mu\nu} & \leftrightarrow & g^{(0)}_{\mu\nu} & \rightarrow & g_{MN} \\ J^{\mu} & \leftrightarrow & A^{(0)}_{\mu} & \rightarrow & A_M \end{array}\right)$$



(a) Image: [M. Baggioli, 2019]



(b) Image: [M. Natsuume, 2014]



1. **The Large N limit of superconformal field theories and supergravity**

(14822) Juan Martin Maldacena (Harvard U.). Nov 1997. 21 pp.

Published in **Int.J.Theor.Phys. 38 (1999) 1113-1133, Adv.Theor.Math.Phys. 2 (1998) 231-252**

HUTP-97-A097, HUTP-98-A097

DOI: 10.1023/A:1026654312961, 10.4310/ATMP.1998.v2.n2.a1

e-Print: **hep-th/9711200** | **PDF**

References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

ADS Abstract Service; AMS MathSciNet; OSTI.gov Server

Detailed record - Cited by 14822 records 1000+

(c) The original AdS/CFT paper has been cited in all physics arXivs!

Holographic setup: $U(1)_V \times U(1)_A$

The Holographic model is **Maxwell-Chern-Simons theory** in the **Schwarzchild**-AdS_5. The bulk action

$$S = \int d^5x \sqrt{-g}\mathcal{L} + S_{\mathrm{c.t.}},$$

where

$$\mathcal{L} = -\frac{1}{4}(F^V)_{MN}(F^V)^{MN} - \frac{1}{4}(F^a)_{MN}(F^a)^{MN} + \frac{\kappa\,\epsilon^{MNPQR}}{2\sqrt{-g}} \times \left[3A_M(F^V)_{NP}(F^V)_{QR} + A_M(F^a)_{NP}(F^a)_{QR}\right],$$

$$S_{\mathrm{c.t.}} = \frac{1}{4}\log r \int d^4x\sqrt{-\gamma}\left[(F^V)_{\mu\nu}(F^V)^{\mu\nu} + (F^a)_{\mu\nu}(F^a)^{\mu\nu}\right],$$

and **the background metric** is

$$ds^2 = g_{MN}dx^M dx^N = 2dtdr - r^2 f(r)dt^2 + r^2\delta_{ij}dx^i dx^j,$$

where $f(r) = 1 - 1/r^4$, $\quad r \in [1,\infty)$. Temperature is $\quad \pi T = 1$.

Bulk equations can be split into **dynamical** ($\mathrm{EV}^\mu = \mathrm{EA}^\mu = 0$) and **constraint** components ($\mathrm{EV}^r = \mathrm{EA}^r = 0$), where

$$\mathrm{EV}^M \equiv \nabla_N (F^V)^{NM} + \frac{3\kappa\epsilon^{MNPQR}}{\sqrt{-g}} (F^a)_{NP} (F^V)_{QR},$$

$$\mathrm{EA}^M \equiv \nabla_N (F^a)^{NM} + \frac{3\kappa\epsilon^{MNPQR}}{2\sqrt{-g}} \left[(F^V)_{NP} (F^V)_{QR} + (F^a)_{NP} (F^a)_{QR} \right].$$

The boundary currents in terms **the bulk fiels** are

$$J^\mu = \lim_{r\to\infty} \sqrt{-\gamma} \left\{ (F^V)^{\mu M} n_{_M} + \frac{6\kappa\epsilon^{M\mu NQR}}{\sqrt{-g}} n_{_M} A_N (F^V)_{QR} - \widetilde{\nabla}_\nu (F^V)^{\nu\mu} \log r \right\},$$

$$J_5^\mu = \lim_{r\to\infty} \sqrt{-\gamma} \left\{ (F^a)^{\mu M} n_{_M} + \frac{2\kappa\epsilon^{M\mu NQR}}{\sqrt{-g}} n_{_M} A_N (F^a)_{QR} - \widetilde{\nabla}_\nu (F^a)^{\nu\mu} \log r \right\},$$

Near boundary asymptotic expansion of the bulk gauge fields:

$$V_\mu = \mathcal{V}_\mu + \frac{V_\mu^{(1)}}{r} + \frac{V_\mu^{(2)}}{r^2} - \frac{2V_\mu^{\mathrm{L}}}{r^2}\log r + \mathcal{O}\left(\frac{\log r}{r^3}\right), \qquad A_\mu = \frac{A_\mu^{(2)}}{r^2} + \mathcal{O}\left(\frac{\log r}{r^3}\right),$$

where

$$V_\mu^{(1)} = \mathcal{F}_{t\mu}^V, \qquad 4V_\mu^{\mathrm{L}} = \partial^\nu \mathcal{F}_{\mu\nu}^V.$$

The currents in terms of **coefficients of near boundary expansion**:

$$J^\mu = \eta^{\mu\nu}(2V_\nu^{(2)} + 2V_\nu^{\mathrm{L}} + \eta^{\sigma t}\partial_\sigma \mathcal{F}_{t\nu}^V), \qquad J_5^\mu = \eta^{\mu\nu} 2A_\nu^{(2)}.$$

$$\Downarrow$$

(Near boundary coefficients at $\mathcal{O}(r^{-2})$ determine the boundary currents!)

Fluid/Gravity correspondence*:

The most general static and homogeneous profiles for the bulk gauge fields:

$$V_\mu = \mathcal{V}_\mu - \frac{\rho}{2r^2}\delta_{\mu t}, \qquad A_\mu = -\frac{\rho_5}{2r^2}\delta_{\mu t},$$

with the boundary currents:

$$J^t = \rho, \quad J^i = 0; \qquad J_5^t = \rho_5, \quad J_5^i = 0.$$

Promoting $\mathcal{V}_\mu$, ρ, ρ_5 into **arbitrary functions of the boundary coordinates**

$$\mathcal{V}_\mu \to \mathcal{V}_\mu(x_\alpha), \qquad \rho \to \rho(x_\alpha), \qquad \rho_5 \to \rho_5(x_\alpha),$$

causes them to cease to be solution. **Corrections** should be introduced

$$V_\mu(r, x_\alpha) = \mathcal{V}_\mu(x_\alpha) - \frac{\rho(x_\alpha)}{2r^2}\delta_{\mu t} + \mathbb{V}_\mu(r, x_\alpha),$$
$$A_\mu(r, x_\alpha) = -\frac{\rho_5(x_\alpha)}{2r^2}\delta_{\mu t} + \mathbb{A}_\mu(r, x_\alpha).$$

*:[S.Bhattacharyya, V.E. Hubeny, S. Minwalla, M. Rangamani, 2008]

BCs:
(i) regularity over $r \in [1,\infty)$
(ii) $\mathbb{V}_\mu \to 0, \quad \mathbb{A}_\mu \to 0 \quad \text{as} \quad r \to \infty$
(iii) the Landau frame convention $(J^t = \rho(x_\alpha), \quad J^t_5 = \rho_5(x_\alpha))$

Equations for the corrections:

$$0 = r^3\partial_r^2\mathbb{V}_t + 3r^2\partial_r\mathbb{V}_t + r\partial_r\partial_k\mathbb{V}_k + 12\kappa\epsilon^{ijk}\left[\partial_r\mathbb{A}_i\left(\partial_j\mathcal{V}_k + \partial_j\mathbb{V}_k\right) + \partial_r\mathbb{V}_i\partial_j\mathbb{A}_k\right],$$

$$\begin{aligned}0 &= (r^5 - r)\partial_r^2\mathbb{V}_i + (3r^4 + 1)\partial_r\mathbb{V}_i + 2r^3\partial_r\partial_t\mathbb{V}_i - r^3\partial_r\partial_i\mathbb{V}_t + r^2\left(\partial_t\mathbb{V}_i - \partial_i\mathbb{V}_t\right)\\
&+ r(\partial^2\mathbb{V}_i - \partial_i\partial_k\mathbb{V}_k) - \frac{1}{2}\partial_i\rho + r^2\left(\partial_t\mathcal{V}_i - \partial_i\mathcal{V}_t\right) + r\left(\partial^2\mathcal{V}_i - \partial_i\partial_k\mathcal{V}_k\right)\\
&+ 12\kappa r^2\epsilon^{ijk}\left(\frac{1}{r^3}\rho_5\partial_j\mathcal{V}_k + \frac{1}{r^3}\rho_5\partial_j\mathbb{V}_k + \partial_r\mathbb{A}_t\partial_j\mathcal{V}_k + \partial_r\mathbb{A}_t\partial_j\mathbb{V}_k\right)\\
&- 12\kappa r^2\epsilon^{ijk}\partial_r\mathbb{A}_j\left[\left(\partial_t\mathcal{V}_k - \partial_k\mathcal{V}_t\right) + \left(\partial_t\mathbb{V}_k - \partial_k\mathbb{V}_t\right) + \frac{1}{2r^2}\partial_k\rho\right]\\
&- 12\kappa r^2\epsilon^{ijk}\left\{\partial_r\mathbb{V}_j\left[\left(\partial_t\mathbb{A}_k - \partial_k\mathbb{A}_t\right) + \frac{1}{2r^2}\partial_k\rho_5\right] - \partial_j\mathbb{A}_k\left(\partial_r\mathbb{V}_t + \frac{1}{r^3}\rho\right)\right\},\end{aligned}$$

$$0 = r^3\partial_r^2\mathbb{A}_t + 3r^2\partial_r\mathbb{A}_t + r\partial_r\partial_k\mathbb{A}_k + 12\kappa\epsilon^{ijk}\left[\partial_r\mathbb{V}_i\left(\partial_j\mathcal{V}_k + \partial_j\mathbb{V}_k\right) + \partial_r\mathbb{A}_i\partial_j\mathbb{A}_k\right],$$

$$\begin{aligned}
0 = &(r^5 - r)\partial_r^2\mathbb{A}_i + (3r^4 + 1)\partial_r\mathbb{A}_i + 2r^3\partial_r\partial_t\mathbb{A}_i - r^3\partial_r\partial_i\mathbb{A}_t + r^2\left(\partial_t\mathbb{A}_i - \partial_i\mathbb{A}_t\right)\\
&+ r(\partial^2\mathbb{A}_i - \partial_i\partial_k\mathbb{A}_k) - \frac{1}{2}\partial_i\rho_5 + 12\kappa r^2\epsilon^{ijk}\left(\partial_j\mathcal{V}_k + \partial_j\mathbb{V}_k\right)\left(\partial_r\mathbb{V}_t + \frac{1}{r^3}\rho\right)\\
&- 12\kappa r^2\epsilon^{ijk}\partial_r\mathbb{V}_j\left[(\partial_t\mathcal{V}_k - \partial_k\mathcal{V}_t) + (\partial_t\mathbb{V}_k - \partial_k\mathbb{V}_t) + \frac{1}{2r^2}\partial_k\rho\right]\\
&- 12\kappa r^2\epsilon^{ijk}\left\{\partial_r\mathbb{A}_j\left[(\partial_t\mathbb{A}_k - \partial_k\mathbb{A}_t) + \frac{1}{2r^2}\partial_k\rho_5\right] - \partial_j\mathbb{A}_k\left(\partial_r\mathbb{A}_t + \frac{1}{r^3}\rho_5\right)\right\}.
\end{aligned}$$

I) Gradient expansion:

Introducing λ as a **gradient expansion parameter** ($\partial_\mu \to \lambda\partial_\mu$), the corrections of bulk fields are expandable in in powers of λ:

$$\mathbb{V}_\mu = \sum_{n=0}^{\infty} \lambda^n \mathbb{V}_\mu^{[n]}, \qquad \mathbb{A}_\mu = \sum_{n=0}^{\infty} \lambda^n \mathbb{A}_\mu^{[n]}.$$

Accordingly:

$$\vec{J} = \sum_{n=0}^{\infty} \lambda^n \vec{J}^{[n]}, \qquad \vec{J}_5 = \sum_{n=0}^{\infty} \lambda^n \vec{J}_5^{[n]}.$$

The background fields $\vec{\mathbf{E}}$ and $\vec{\mathbf{B}}$ are treated as *zeroth* order in the gradient expansion, as opposed to our previous studies!

$$\Downarrow$$

$$\vec{\mathbf{E}}, \vec{\mathbf{B}} \sim \mathcal{O}(\partial^0) \Rightarrow \textbf{TCs} \to \textbf{TCs}[\mathbf{E}^2, \mathbf{B}^2, (\vec{\mathbf{E}}\cdot\vec{\mathbf{B}})^2]$$

$\mathcal{O}(\lambda^0)$:

$$\vec{J}^{[0]} = \sigma_e^0 \vec{\mathbf{E}} + \sigma_\chi^0 \kappa \rho_5 \vec{\mathbf{B}} + \delta\sigma_\chi^0 \kappa^2 (\vec{\mathbf{E}} \cdot \vec{\mathbf{B}})\vec{\mathbf{B}} + \sigma_{\chi H}^0 \kappa^2 \rho \vec{\mathbf{B}} \times \vec{\mathbf{E}} + \sigma_{\chi e}^0 \kappa^3 \rho_5 (\vec{\mathbf{B}} \cdot \vec{\mathbf{E}})\vec{\mathbf{E}}$$

$$\vec{J}_5^{[0]} = \sigma_\chi^0 \kappa \rho \vec{\mathbf{B}} + \sigma_{\chi H}^0 \kappa^2 \rho_5 \vec{\mathbf{B}} \times \vec{\mathbf{E}} + \sigma_{\chi e}^0 \kappa^3 \rho (\vec{\mathbf{B}} \cdot \vec{\mathbf{E}})\vec{\mathbf{E}} + \sigma_s^0 \kappa^3 (\vec{\mathbf{E}} \cdot \vec{\mathbf{B}})\vec{\mathbf{B}} \times \vec{\mathbf{E}}$$

Except σ_s^0, all terms have already appeared in the literature. **The main novelty is:**

$$\sigma_e^0 = \sigma_e^0[\mathbf{E}^2, \mathbf{B}^2, (\vec{\mathbf{B}} \cdot \vec{\mathbf{E}})^2]; \qquad \sigma_\chi^0 = \sigma_\chi^0[\mathbf{E}^2, \mathbf{B}^2, (\vec{\mathbf{B}} \cdot \vec{\mathbf{E}})^2]; \qquad \text{etc...}$$

Alternatively:

$$J_i^{[0]} = \sigma_e^0 \left(\delta_{ij} - \frac{\mathbf{B}_i\mathbf{B}_j}{\mathbf{B}^2}\right) \mathbf{E}_j + \sigma_e^{0\mathrm{L}} \frac{\mathbf{B}_i\mathbf{B}_j}{\mathbf{B}^2} \mathbf{E}_j + \sigma_\chi^0 \kappa \rho_5 \left(\delta_{ij} - \frac{\mathbf{E}_i\mathbf{E}_j}{\mathbf{E}^2}\right) \mathbf{B}_j + \sigma_\chi^{0\mathrm{L}} \kappa \rho_5 \frac{\mathbf{E}_i\mathbf{E}_j}{\mathbf{E}^2} \mathbf{B}_j + \sigma_{\chi H}^0 \kappa^2 \rho (\vec{\mathbf{B}} \times \vec{\mathbf{E}})_i,$$

where: $\sigma_e^{0\mathrm{L}} = \sigma_e^0 + \kappa^2 \mathbf{B}^2 \delta\sigma_\chi^0, \qquad \sigma_\chi^{0\mathrm{L}} = \sigma_\chi^0 + \kappa^2 \mathbf{E}^2 \sigma_{\chi e}^0.$

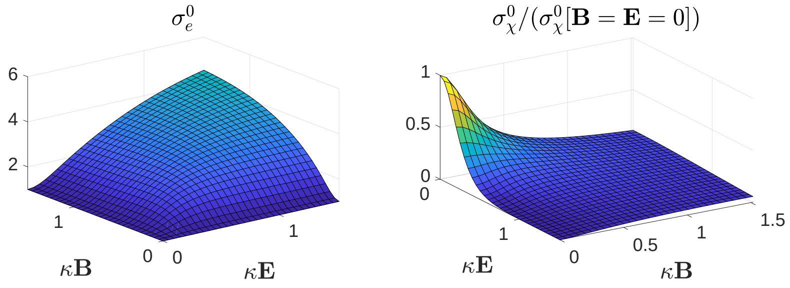


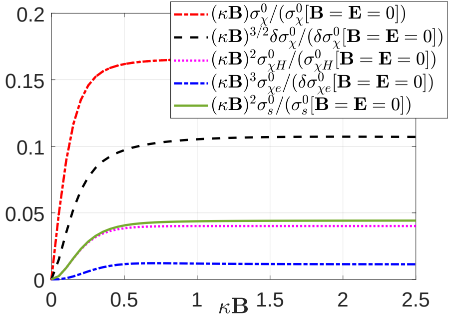
Figure: Zeroth order TCs as functions of e/m fields when $\vec{\mathbf{E}} \parallel \vec{\mathbf{B}}$

- Ohmic conductivity σ_e^0 gets enhancement!

$\Downarrow$

(Without Anomaly: [G.T. Horowitz, N. Iqbal, J.E. Santos, 2013],[H.B. Zeng, Y.Tian, Z.Y. Fan, C.M. Fan, 2016, 2017], **Anomaly induced**:**New!**)

- Other TCs behave similary as σ_χ^0, i.e. decrease dramatically and vanish asymptotically!



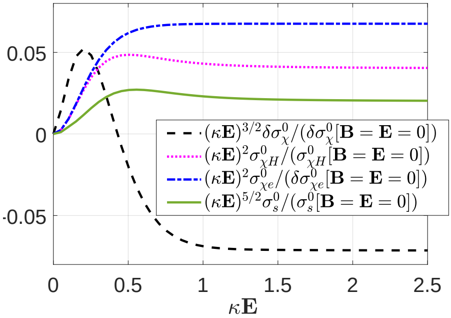
- For $\kappa\mathbf{E}=0$, asymptotic behaviors for large-$\kappa\mathbf{B}$ can be extracted numerically:

$$\sigma^0_\chi[\kappa\mathbf{B}\to\infty,\kappa\mathbf{E}=0]\to\frac{1}{\kappa\mathbf{B}},\quad \delta\sigma^0_\chi[\kappa\mathbf{B}\to\infty,\kappa\mathbf{E}=0]\to\frac{3.349}{(\kappa\mathbf{B})^{3/2}},$$

$$\sigma^0_{\chi H}[\kappa\mathbf{B}\to\infty,\kappa\mathbf{E}=0]\to-\frac{1}{(\kappa\mathbf{B})^2},\quad \sigma^0_{\chi e}[\kappa\mathbf{B}\to\infty,\kappa\mathbf{E}=0]\to\frac{0.977}{(\kappa\mathbf{B})^3},$$

$$\sigma^0_s[\kappa\mathbf{B}\to\infty,\kappa\mathbf{E}=0]\to-\frac{6.751}{(\kappa\mathbf{B})^2}.$$

(Note: σ^0_χ is consistent with analytic results of [K.Landsteiner, Y.Liu, Y.W.Sun, 2015], [M.Ammon, S.Grieninger, A.J. Alba, 2016], [Y.Bu, M.Lublinsky, A.Sharon, 2017].)



- For $\kappa\mathbf{B}=0$, asymptotic behaviors for large-$\kappa\mathbf{E}$ can be extracted numerically:

$$\delta\sigma^0_\chi[\kappa\mathbf{B}=0,\kappa\mathbf{E}\to\infty]\to-\frac{2.243}{(\kappa\mathbf{E})^{3/2}},\quad \sigma^0_{\chi H}[\kappa\mathbf{B}=0,\kappa\mathbf{E}\to\infty]\to-\frac{1}{(\kappa\mathbf{E})^2},$$

$$\sigma^0_{\chi e}[\kappa\mathbf{B}=0,\kappa\mathbf{E}\to\infty]\to\frac{6.04}{(\kappa\mathbf{E})^2},\qquad \sigma^0_s[\kappa\mathbf{B}=0,\kappa\mathbf{E}\to\infty]\to-\frac{3.069}{(\kappa\mathbf{E})^{5/2}}.$$

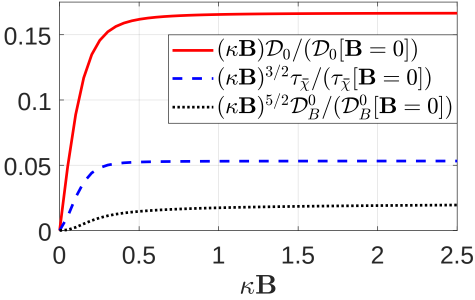
Except for $\sigma^0_\chi[\kappa\mathbf{B}=0]$ which decays much faster than any other TCs, and asymptotically does not scale as a power function of $\kappa\mathbf{E}$.

$\mathcal{O}(\lambda^1)$:

We consider the cases of either $\mathbf{E} = 0$ or $\mathbf{B} = 0$ separately:

a) $\mathbf{E} = \mathbf{0}$:

$$\vec{J}^{[1]} = -\mathcal{D}_0 \vec{\nabla}\rho + \tau_{\bar{\chi}} \kappa \partial_t \rho_5 \vec{\mathbf{B}} + \mathcal{D}_B^0 \kappa^2 (\vec{\mathbf{B}} \cdot \vec{\nabla}\rho)\vec{\mathbf{B}}, \quad \vec{J}_5^{[1]} : \rho \leftrightarrow \rho_5.$$

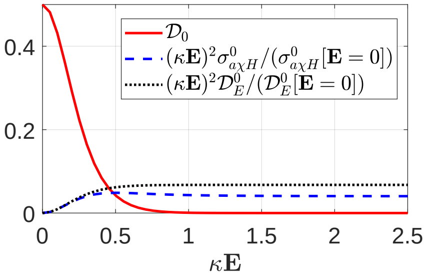


$$\mathcal{D}_0[\kappa\mathbf{B} \to \infty, \kappa\mathbf{E} = 0] \to \frac{0.083}{(\kappa\mathbf{B})}, \qquad \tau_{\bar{\chi}}[\kappa\mathbf{B} \to \infty, \kappa\mathbf{E} = 0] \to -\frac{0.36}{(\kappa\mathbf{B})^{3/2}},$$

$$\mathcal{D}_B^0[\kappa\mathbf{B} \to \infty, \kappa\mathbf{E} = 0] \to -\frac{0.269}{(\kappa\mathbf{B})^{5/2}}.$$

a) $\mathbf{B} = \mathbf{0}$:

$$\vec{J}^{[1]} = -\mathcal{D}_0 \vec{\nabla}\rho + \sigma^0_{a\chi H} \kappa \vec{\mathbf{E}} \times \vec{\nabla}\rho_5 + \mathcal{D}^0_E \kappa^2 (\vec{\mathbf{E}} \cdot \vec{\nabla}\rho)\vec{\mathbf{E}}, \quad \vec{J}_5^{[1]} \quad : \rho \leftrightarrow \rho_5.$$



$$\sigma^0_{a\chi H}[\kappa\mathbf{B} = 0, \kappa\mathbf{E} \to \infty] \to -\frac{0.141}{(\kappa\mathbf{E})^2}, \quad \mathcal{D}^0_E[\kappa\mathbf{B} = 0, \kappa\mathbf{E} \to \infty] \to -\frac{0.298}{(\kappa\mathbf{E})^2}.$$

- $\mathcal{D}_0$ was shown to receive **negative** $\mathbf{E}^2$- and $\mathbf{B}^2$-corrections induced by the chiral anomaly ([Y.Bu, M.Lublinsky, A.Sharon, 2016],[Y.Bu, T,Demircik, M.Lublinsky, 2018]). $\Rightarrow$ **Now it vanishes asymptotically!**

II) Gradient Ressumation :

• The framework of **all order resummation** was invented and improved through: [M.Lublinsky, E.Shuryak, 2009],
[Y.Bu, M.Lublinsky, 2014, 2014, 2015, 2015, 2016]

• The essence is: **T**ransport **C**oefficient **F**unctions

$\mathbf{TCs} \rightarrow \mathbf{TCFs}[\partial_t, \vec{\nabla}^2]$

i) contain information about **infinitely many gradients.**

ii) valid **beyond hydro limit** $(\omega, q^2 \ll 1)$.

iii) introduce **memory functions.**

• In this study, we **relax weak field assumption** ($\mathbf{E} = \mathbf{0}$) for and employ **linearization in** ρ, ρ_5:

$$\rho \rightarrow \epsilon\rho, \qquad \rho_5 \rightarrow \epsilon\rho_5, \qquad \mathbf{B} \sim \mathcal{O}(\epsilon^{\mathbf{0}}).$$

$$\Downarrow$$

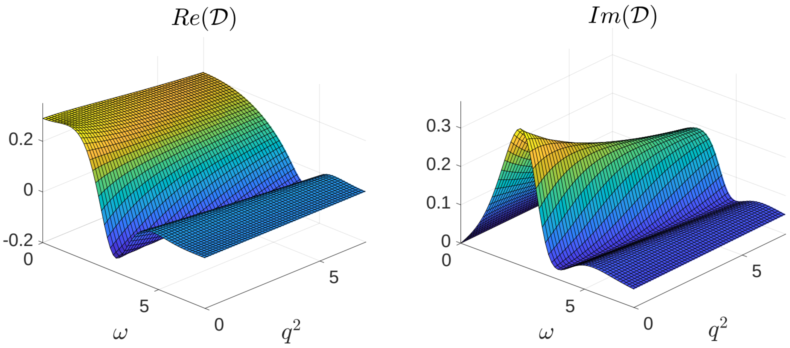
$$\mathbf{TCFs}[\partial_t, \vec{\nabla}^2] \rightarrow \mathbf{TCFs}[\partial_t, \vec{\nabla}^2, (\kappa\mathbf{B})^2, (\kappa\vec{\mathbf{B}} \cdot \vec{q})^2]$$

(The main **novelty!**)

$\mathcal{O}(\epsilon)$:

$$\vec{J} = -\mathcal{D}\vec{\nabla}\rho + \mathcal{D}_B\kappa^2\vec{\mathbf{B}}(\vec{\mathbf{B}}\cdot\vec{\nabla}\rho) + \bar{\sigma}_{\bar{\chi}}\kappa\vec{\mathbf{B}}\rho_5 + \mathcal{D}_\chi\kappa(\vec{\mathbf{B}}\cdot\vec{\nabla})\vec{\nabla}\rho_5, \quad \vec{J}_5 : \rho \leftrightarrow \rho_5.$$

where: $\mathcal{D}[\partial_t, \vec{\nabla}^2, (\kappa\mathbf{B})^2, (\kappa\vec{\mathbf{B}}\cdot\vec{q})^2]$, $\mathcal{D}_B[\partial_t, \vec{\nabla}^2, (\kappa\mathbf{B})^2, (\kappa\vec{\mathbf{B}}\cdot\vec{q})^2]$, etc..



- All the **TCFs** exhibit similar behavior: **relatively weak dependence** on q^2; **damped oscillations** in ω.

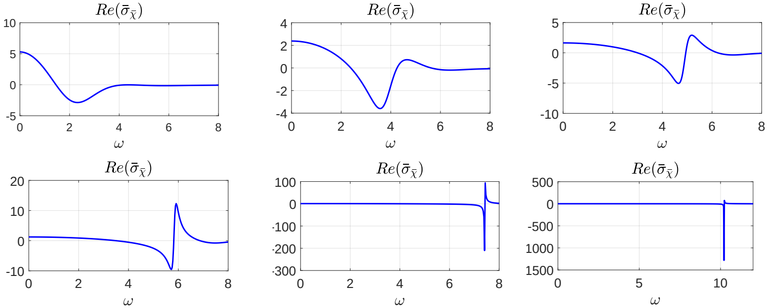


Figure: $Re(\bar{\sigma}_{\bar{\chi}})$ as a function of ω when $q = 0$ and
$\kappa\mathbf{B} = 0.1 \to \kappa\mathbf{B} = 0.4 \to \kappa\mathbf{B} = 0.6 \to \kappa\mathbf{B} = 0.8 \to \kappa\mathbf{B} = 1.2 \to \kappa\mathbf{B} = 2.2$.

- **TCFs** become **singular** when **magnetic field is large enough** ($\kappa\mathbf{B} \gtrsim 0.5$) !
- At larger values of $\kappa\mathbf{B}$, **additional singularities** emerge at larger ω.
- Locations of these additional singularities are **symmetric** about the origin.

- These singularities are the **Quasi Normal Modes!**

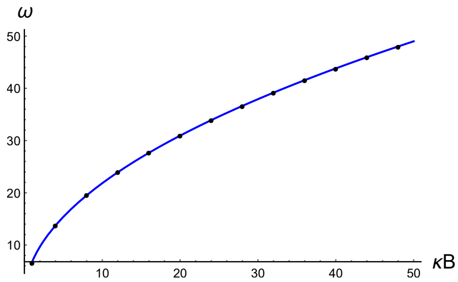


Figure: Location of the singularity as a function of $\kappa\mathbf{B}$: numerical result (black dots) is best fitted by $\omega = -0.155157 + 6.95306\sqrt{\kappa\mathbf{B}}$ (blue curve).

- The lowest **QNM** exhibit **Landau level** behavior:

$$Re[\omega] \sim \sqrt{\kappa\mathbf{B}}, \qquad Im[\omega] \rightarrow 0$$

[M.Ammon, S.Grieninger, A.J.Alba, R.P. Macedo, L.Melgar, 2016]

- Similar phenomenon was found recently and named as **"anomalous resonance"** in [M.Haack, D. Sarkar, A.Yarom, 2019].

- Modifications on **CMW:**

$$\omega = \pm \left(\bar{\sigma}_{\bar{\chi}} - q^2 \mathcal{D}_{\chi}\right) \kappa \vec{\mathbf{B}} \cdot \vec{q} - i \left(q^2 \mathcal{D} - \mathcal{D}_B (\kappa \vec{\mathbf{B}} \cdot \vec{q})^2\right).$$

- Can **CMW** be **fully non-dissipative** $\Rightarrow$ **Yes!**

[Y.Bu, M.Lublinsky, T.Demircik, 2018]

- Can **CMW** be **fully non-dissipative** at **large magnetic field**? $\Rightarrow$ **Yes!**

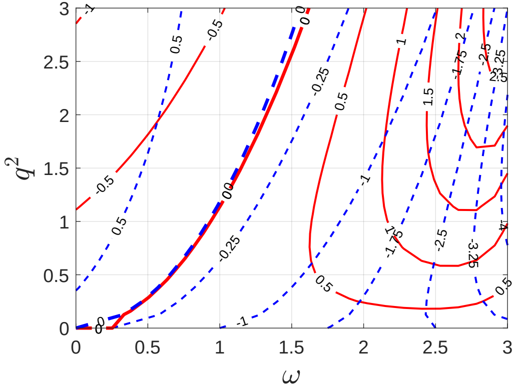


Figure: Contour plots for the functions ϕ_R (blue dashed) and ϕ_I (red solid) at $\kappa \mathbf{B} = 0.33$.

Conclusion:

- In this work we focused on **influence of strong background e/m fields on chiral anomaly-induced transport phenomena** for a holographically defined thermal plasma.
- Constitutive relations for $\vec{J}, \vec{J}_5$ were evaluated within two complimentary approximation schemes: a **fixed order gradient expansion** (up to first order) and an **all-order gradient resummation** (linear in ρ, ρ_5).
- **TCs** are found to be suppressed by the external fields and vanish at asymptotically strong fields, **except the Ohmic conductivity** which gets enhanced in parallel electrical and magnetic fields.
- When $\vec{\mathbf{E}} = 0$, **the all-order resummed constitutive relations** are parameterised by **four independent TCFs, which are functions of** $\omega, \vec{q}$ **and** $\vec{\mathbf{B}}$. The TCFs are found to show a common **singularity** at **B** is strong enough. This singularity is identified as **QNM** and obey **Landau level behavior**.
- Previously, discovered **non-dissipative and thus long-lived CMW mode** is examined CMW exactly without the weak field approximation.

Thanks!