

Energy loss and chiral magnetic effect

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Objective

Chiral media, such as quark-gluon plasma, possess a number of unique properties originating from the quantum phenomenon of the chiral anomaly. These properties can be measured by observing the propagation of fast charged particles through the medium and the radiation produced in the process.

We show how the chiral anomaly confers distinctive features onto the particle energy loss and its radiation spectrum. We argue then that this makes quantum tomography a powerful and versatile tool to investigate the properties of chiral systems ranging from the Weyl semimetals to the quark-gluon plasma to the axion stars.

Introduction

The chiral anomaly breaks axial symmetry defined by the transformation $\psi \rightarrow e^{i\gamma_5\theta}\psi$. It leads to a chiral imbalance such that

$$\frac{d(N_R - N_L)}{dt} = c \int \mathbf{E} \cdot \mathbf{B} dt$$

Studying the chiral anomaly may lead to a greater understanding of the characteristics of various media. The presence of the anomaly has been seen experimentally via the chiral magnetic effect in materials such as Weyl and Dirac semimetals.

The possible presence of the anomaly has a number of interesting implications for various areas such as

- possible charge separation via the chiral magnetic effect in quark-gluon plasma produced in heavy ion collision
- could be used as means for detecting dark matter in the form of axionic matter via the photon spectrum emitted by cosmic waves

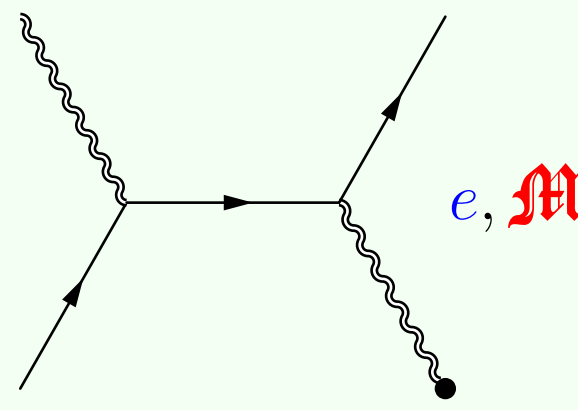
In QED the anomaly appears as the pseudoscalar θ in the Maxwell Chern Simons lagrangian

$$\mathcal{L}_{MCS} = \mathcal{L}_{QED} + c_A \theta \mathbf{E} \cdot \mathbf{B},$$

The presence of the anomaly In QED stems from QCD, however, we will restrict our study to the effect in QED due to its simplicity. We intend to extend our study to QCD in the future.

Radiative Loss

For the radiative energy loss we consider a fermion of mass m scattering off a center of charge e and magnetic moment \mathfrak{M} transferring some momentum q and irradiating a photon in a homogeneous with finite chiral conductivity.[2]



Double lines indicate photons in chiral medium.

Assuming that the magnetic moments are stochastically oriented, the cross-sectional contributions due to e and \mathfrak{M} separate into two parts, coupling to the zeroth, and spatial components of the photon propagator respectively.

$$D_{00} \propto \frac{1}{q^2}, D_{ij} \propto \frac{1}{q^2 - b_0^2}$$

The coulomb contribution gains a resonant behavior in the photon and fermion propagators due to the effect of the anomaly on the dispersion relation of the photon

$$\omega^2 = \mathbf{k}^2 + k^2 = \mathbf{k}^2 - \lambda b_0 |\mathbf{k}|.$$

In the small Debye mass limit both propagators may be regulated by the relaxation time τ . After regulating the divergent behavior the energy loss per length becomes

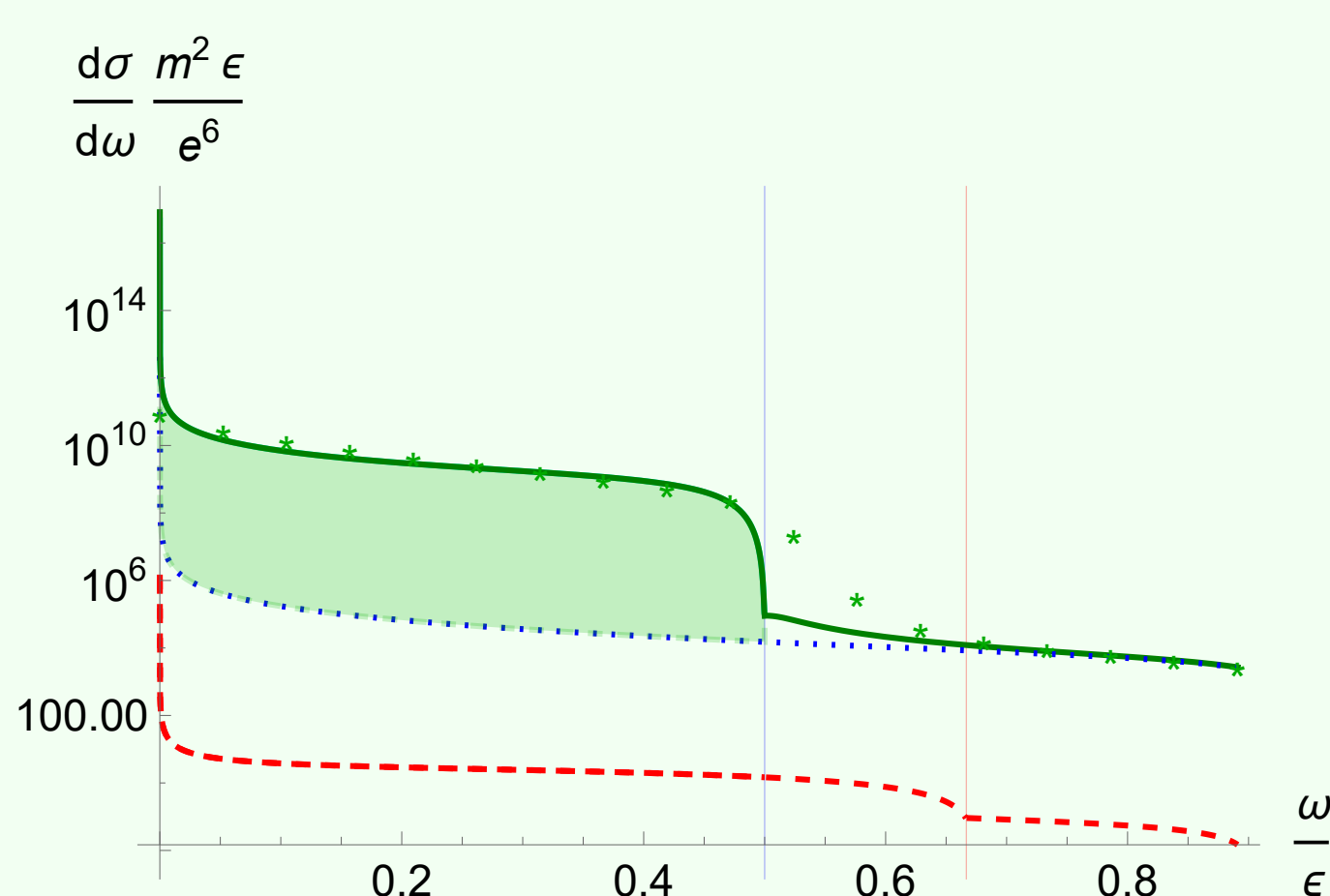
$$-\frac{dE}{dz} \approx \frac{e^2 E}{8\pi^2 \ell} \left\{ \ln \frac{2E}{m} - \frac{1}{3} + \tau E \arctan 2b_0 \tau \right\}$$

(BH) (anomaly)

The result due to a significantly large Debye mass may be computed similarly, however, the effects due to the anomaly may be suppressed in this case.

In addition to the effect due the photon's dispersion relation, the magnetic moment contribution therefore has a highly resonant behavior for $\mathbf{q} = b_0$ in the static limit.

This may be remedied similarly to the coulomb contribution by introducing a finite resonance width Γ which is related to the photon decay width. This behavior can be seen as the knee-like structure for the ultra-relativistic limit in the red line in the plot.



The coulomb and magnetic moment contributions are compared in the plot. Focusing on the coulomb plot, the anomaly dominates for frequencies less than

$$\omega^* = \frac{\lambda b_0 E^2}{\lambda b_0 E + m^2}$$

Focusing on QED, \mathcal{L}_{MCS} leads to an additional current in Maxwell's equations. In a homogeneous with finite chiral conductivity

$$\mathbf{j}_a = b_0 \mathbf{B}$$

where b_0 is the time derivative of $c_A \theta$ and leads to the chiral magnetic effect.

The sections of radiative and collisional energy loss will focus on such a media

We can study the chiral magnetic effect by considering a media such as QGP when probed by a fast-moving particle.

While the particle losses energy as it travels through the medium the anomaly appears as a resonant-like behavior in the collisional and radiative energy loss of the particle as it travels through the medium.

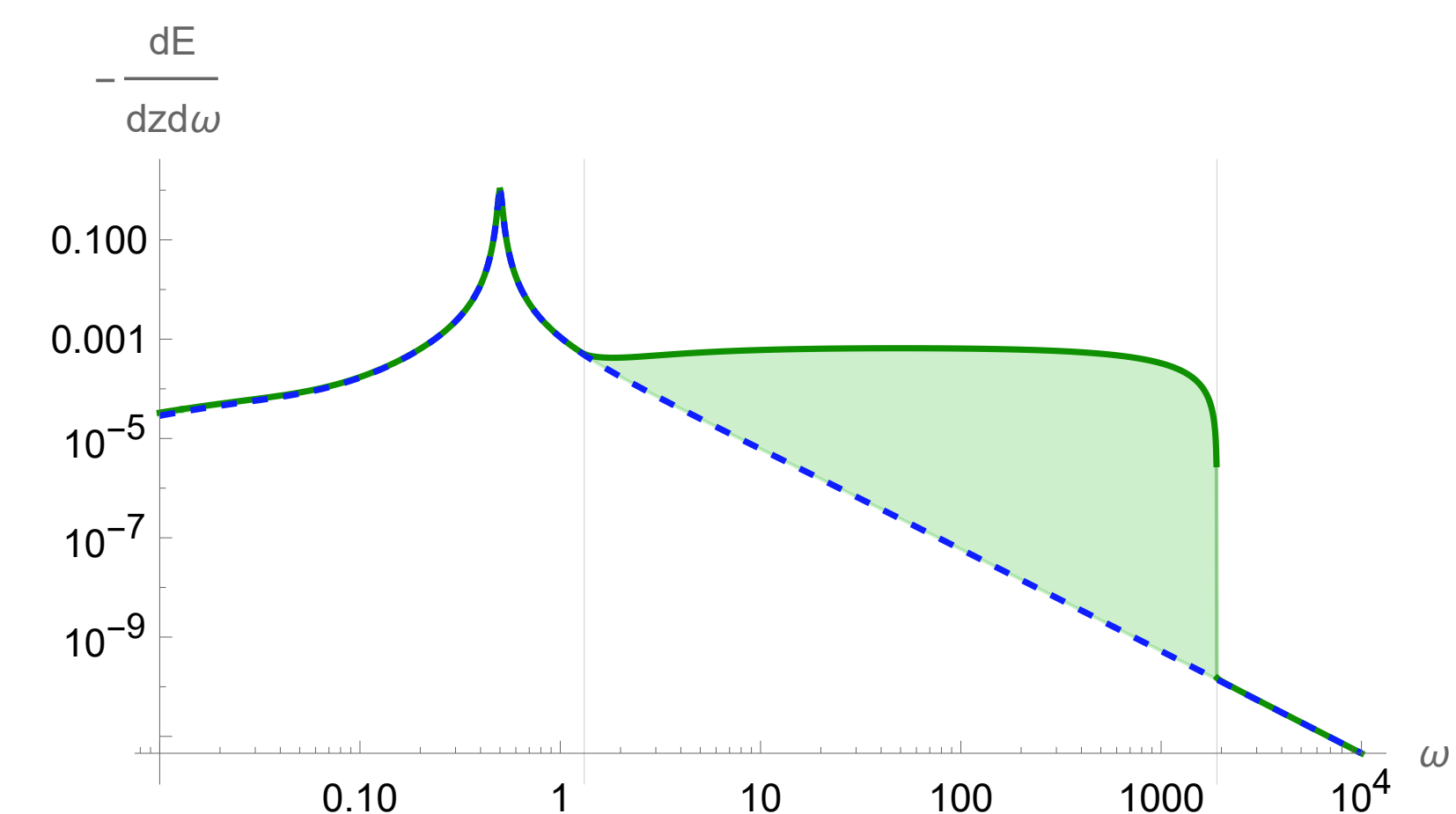
Studying the energy loss has a number of advantages. For example, globally QGP is chiral neutral. The chiral magnetic effect requires such a chiral imbalance and is therefore immeasurable in such cases. However, the enhancement due to the presence of any chiral magnetic effect for the rate of energy loss of a particle makes it sensitive to local chiral imbalances in the plasma. Moreover, if we focus on the radiation produced in such a process, overall the jets produced will be chiral neutral, however chirality of the radiated photons may oscillate depending on the local chiral imbalances in the plasma. Overall the chiral magnetic effect may still play a role in QGP.

Collisional loss

The collisional energy loss of a particle of mass m and charge q traveling with velocity v through a media under the influence of the anomaly[1] in the presence of and electromagnetic field.

The rate of energy loss for the particle can be computed from the modified Maxwell's equations as the flux of the Poynting vector out of a cylinder of radius a coaxial with the particle path.

The effect of the chiral conductivity can be seen in the following example of the rate of energy loss in frequency space



The effect due to the anomaly can be seen as an amplification of the original signal over the region in green. Integrating over all frequencies we upon the total rate of energy loss per unit length in the ultra relativist limit

$$-\frac{dE}{dz} = \frac{q^2}{4\pi v^2} \left(\omega_p^2 \ln \frac{v}{a\omega_p} + \frac{1}{4} \gamma^2 b_0^2 \right)$$

(Fermi) (anomaly)

In which case, the anomaly may have a significant effect on the collisional energy loss at high energies. It should be noted that this is a completely classical treatment of the rate of energy loss. When recoil is taken into account the enhancement due to the anomaly is reduced by a factor of γ .

Discussion

- The presence of a finite chiral conductivity has a potentially significant effect on the collisional energy loss including Weyl semimetals and QGP.
- In the radiative energy loss both the contributions due to electric charge and magnetic moment may be affected by the anomaly, however, the effect may be most noticeable in the coulomb contribution particularly when the Debye mass is small.
- Focus on the soft photon regime for the radiative energy loss the anomaly appears as an amplification of the original signal
- In the future, we hope to expand our discussion to QCD. This may be seen in the tree-level diagrams, via a modified Lipatov vertex in the ultra-relativistic limit.
 - most notable we hope to investigate the effects of the anomaly due to the dispersion relation of the gluon, and three gluon vertex.

References

- [1] Jeremy Hansen and Kirill Tuchin. *Phys. Rev. C*, 104(3):034903, 2021.
- [2] Jeremy Hansen and Kirill Tuchin. *Phys. Rev. D*, 105(11):116008, 2022.