Waves of Anomaly in QGP : Chiral Magnetic Wave and Chiral Shear Wave

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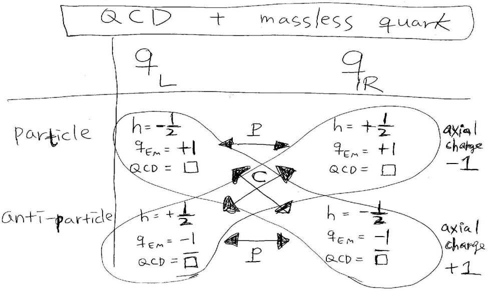
References : CMW : A work in progress with Dima Kharzeev
CSW : arXiv:0910.5915 [hep-th](with B.Sahoo)

P, C, and anomaly basics



- P and C are good symmetries of QCD with massless quarks
- $U(1)_A$ suffers from anomaly in QCD : it is not a true symmetry

$$\partial_\mu J^\mu_A \sim \epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}\left(G_{\mu\nu}G_{\alpha\beta}\right) \quad (1)$$

  One fact : this anomaly is $\frac{1}{N_c^2}$-suppressed in large N_c limit

- But, $SU(N_F)_A$ for multiple flavors are good global symmetries free of QCD anomaly
- There are also triangle anomaly of AVV and AAA

Why triangle anomalies can be interesting

- It is often said that results from anomalies are robust, independent of dynamics such as coupling constant. This is both good and bad.
- But, the important assumption in this statement is that we are considering low energy limits which results in various low energy theorems. For finite frequency or momentum $\omega, k \neq 0$, there are in general no such theorems, and we DO expect the results to depend on dynamics such as temperature, coupling constants, etc.
- For strongly coupled QGP with a lot of time/space dependent dynamics going on, it will be non-trivial to compute such effects

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A table of recent interesting discoveries

	$T < T_c$	$T > T_c$ (RHIC,LHC)
$B = 0$	- gauged WZW term $\pi^0 \to 2\gamma$, etc - $\mu \neq 0$, Quarkyonic spiral	- chiral vortex current ($\mu \neq 0$) $J^\mu \sim \epsilon^{\mu\nu\alpha\beta} u_\nu \partial_\alpha u_\beta$ - chiral shear wave ($\mu \neq 0$)
$B \neq 0$	- meson(pion) suppercurrent ($\mu \neq 0$) $\partial\pi \neq 0$ "chiral spiral" - chiral magnetic spiral ($\mu \neq 0$) $J^1 + iJ^2 \neq 0$	- chiral magnetic effect ($\mu \neq 0$) $\vec{J} \sim \vec{B}\mu$ -chiral magnetic wave ($\mu = 0$)

Important difference between chiral magnetic effect and chiral magnetic wave will be that CMW exists even in the average neutral plasmas

Chiral Magnetic Wave: Derivation

- Consider general deconfined QCD plasma with applied magnetic field $\vec{B} = B\hat{x}^1$. The plasma can be neutral in general.
- We will treat electromagnetism as non-dynamical external environment
- Let's start from the basic chiral magnetic effects

$$\vec{j}_V = \frac{N_c e\vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{j}_A = \frac{N_c e\vec{B}}{2\pi^2}\mu_V \quad , \tag{2}$$

$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c e\vec{B}}{2\pi^2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix} \quad . \tag{3}$$

- We are interested in small fluctuations out of neutral plasma, so let's expand $\mu_{V,A}$ in terms of small charge densities $j^0_{V,A}$ linearly

$$\begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix} = \begin{pmatrix} \frac{\partial\mu_V}{\partial j^0_V} & \frac{\partial\mu_V}{\partial j^0_A} \\ \frac{\partial\mu_A}{\partial j^0_V} & \frac{\partial\mu_A}{\partial j^0_A} \end{pmatrix}\begin{pmatrix} j^0_V \\ j^0_A \end{pmatrix} \equiv \begin{pmatrix} \alpha_{VV} & \alpha_{VA} \\ \alpha_{AV} & \alpha_{AA} \end{pmatrix}\begin{pmatrix} j^0_V \\ j^0_A \end{pmatrix} \quad . \tag{4}$$

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CMW Derivation continued

- Recall that chemical potentials are defined as $\mu_i = \frac{\partial \mathcal{F}}{\partial j_i^0}$, $i = V, A$ where $\mathcal{F}$ is free energy, so

$$\alpha_{ij} = \frac{\partial^2 \mathcal{F}}{\partial j_i^0 \partial j_j^0} \quad . \tag{5}$$

are in fact susceptabilities

- By parity invariance, $\alpha_{AV} = \alpha_{VA} = 0$. In a deconfined phase, one also has $\alpha_{VV} \sim \alpha_{AA} \equiv \alpha$, so at the end one arrives at

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- Diagonalize in terms of chiral basis

$$j_L^\mu \equiv \frac{1}{2}(j_V^\mu - j_A^\mu) \quad , \quad j_R^\mu \equiv \frac{1}{2}(j_V^\mu + j_A^\mu) \quad . \tag{7}$$

One can also rewrite

$$\alpha = \frac{1}{2}\left(\frac{\partial \mu_L}{\partial j_L^0}\right) = \frac{1}{2}\left(\frac{\partial^2 \mathcal{F}}{\partial j_L^0 \partial j_L^0}\right) = \frac{1}{2}\left(\frac{\partial \mu_R}{\partial j_R^0}\right) = \frac{1}{2}\left(\frac{\partial^2 \mathcal{F}}{\partial j_R^0 \partial j_R^0}\right) \quad . \tag{8}$$

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Continued...

The semi-final result is

$$\vec{j}_{L,R} = \mp \left(\frac{N_c e \vec{B} \alpha}{2\pi^2} \right) j^0_{L,R} - D_L \frac{\vec{B}(\vec{B} \cdot \vec{\nabla})}{B^2} j^0_{L,R} + \cdots \quad , \tag{9}$$

with a longitudinal diffusion constant D_L. This should be taken as a hydrodynamic constitutive equation in long wave-length expansion
A few comments are

- What we are claiming is that the above result is valid for arbitrarily large magnetic field B. Several previous literature considered only linear in B
- Note that α will be a non-trivial, non-linear function of B as well as temperature, coupling constant, etc. We will see this explicitly later for infinitely large B case and holographic QCD computation
- It might also be interesting to consider transverse diffusion coefficient D_T

New propagating modes out of this

Now, plug the above in the conservation laws $\partial_\mu j^\mu_{L,R} = 0$, and consider only longitudinal derivative ∂_1, which results in

$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0 \quad . \tag{10}$$

- This is a directional (chiral) wave with velocity

$$v_\chi = \frac{N_c e B \alpha}{2\pi^2} = \frac{N_c e B}{4\pi^2}\left(\frac{\partial \mu_L}{\partial j^0_L}\right) = \frac{N_c e B}{4\pi^2}\left(\frac{\partial \mu_R}{\partial j^0_R}\right) \quad . \tag{11}$$

- The momentum space dispersion relation looks as

$$\omega = \mp v_\chi k - i D_L k^2 + \cdots \quad , \tag{12}$$

The propagating leading part would be absent if there was no anomaly or magnetic field B, and it is essentially important to have them to find the propagating behavior

Large B limit and 1+1 dimensional reduction

We will consider one particular weak coupling limit, $eB \to \infty$

- At first, the expression

$$v_\chi = \frac{N_c eB}{4\pi^2}\left(\frac{\partial \mu_L}{\partial j_L^0}\right) \tag{13}$$

  looks worrisome in view of causality

- It is natural to expect that the quarks are sitting in the lowest Landau Levels, as the gap $\Delta = \sqrt{eB} \gg T$. We have an effective 1+1 dimensional reduction.

- For a chemical potential μ_L, 1+1 dimensional free fermion density is simply $\frac{\mu_L}{(2\pi)}$. We also have transverse space density of state of $\frac{eB}{(2\pi)}$, so that the net 3-dimensional density j_L^0 is

$$j_L^0 = \left(\frac{\mu_L}{(2\pi)}\right)\left(\frac{eB}{(2\pi)}\right) = \frac{eB}{4\pi^2}\mu_L \tag{14}$$

  or $\left(\frac{\partial \mu_L}{\partial j_L^0}\right) = \frac{4\pi^2}{eB}$ in the limit of $eB \to \infty$. This gives

$$v_\chi \to 1 \quad , \quad eB \to \infty \tag{15}$$

1+1 dimensional bosonization

Let's pursue further aspects of this 1+1 dimensional reduction

- From q_L one gets 1+1 dimensional chiral fermion in LLL, ψ_L. Vice Versa from q_R to get ψ_R. Together they form a single 1+1 dimensional massless Dirac fermion
- One has $U(1)_V \times U(1)_A$ symmetries with currents j_V^μ and j_A^μ. 1+1 dimensional γ-matrices imply that

$$j_V^\mu = \epsilon^{\mu\nu} j_{A\nu} \tag{16}$$

  This can be written in terms of a real scalar field ϕ by

$$j_V^\mu = \epsilon^{\mu\nu}\partial_\nu\phi \quad , \quad j_A^\mu = \partial^\mu\phi \tag{17}$$

  where conservation of j_V^μ is automatic.
- Then, the conservation of axial current j_A^μ implies

$$\partial_\mu j_A^\mu = \partial_\mu\partial^\mu\phi = 0 \tag{18}$$

  so ϕ is a massless scalar boson

Bosonization continued...

- Bosonization says that the two quantum theories are in fact equivalent with a dictionary

$$\psi_L \sim e^{i\phi_L} \quad , \quad \psi_R \sim e^{-i\phi_R} \tag{19}$$

where $\phi = \phi_L + \phi_R$, or

$$\bar{\psi}_R \psi_L \sim e^{i\phi} \tag{20}$$

- The mass term will be $cos(\phi)$ under this, which gives us sine-Gordon model

Our basic identification is : Chiral magnetic wave is a bosonized wave of ϕ

Holographic computation

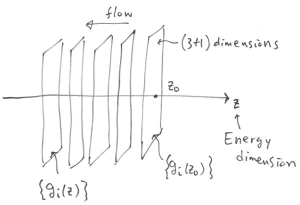
- One can study the same phenomena in the framework of holographic QCD for strongly coupled regime. We choose Sakai-Sugimoto model as it contains all the necessary ingredients of chiral symmetry and its triangle anomaly
- Triangle anomaly is encoded as a 5D Chern-Simons term in the bulk
- One can study v_χ as well as D_L systematically in the model

Very brief words about AdS/CFT ideas

- We have an effective theory for large N_c and strong t'Hooft coupling limit of a gauge theory living in five dimensions
- The additional dimension is roughly energy-scale of the theory. Recall RG still works in large N_c limit. 5D theory involves gravity :

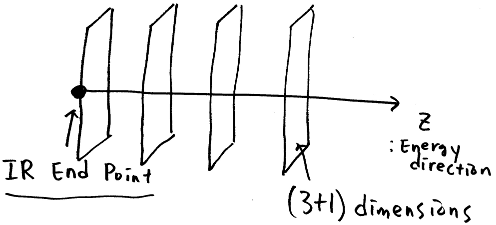
$$\text{Quantum RG invariance} \longleftrightarrow \text{Classical general covariance}$$

- Large N_c factorization implies classical or statistical description of master variables while RG still makes sense : **holography is one way of combining these two**



Finite temperature plasma is described by Black Hole

In the 5D gravity description, finite temperature plasma is described by Black Hole or more precisely, Black Brane



- There is no rigorous understanding of this
- It has been more like **"empirical"**
- Hawking temperature is identified with plasma temperature naturally

How to study physics in AdS/CFT ?

Just two facts we need from AdS/CFT dictionary

- Global symmetry in gauge theory $\longleftrightarrow$ Gauge symmetry in 5D

How it works?

$$A_\mu(x^\mu, Z) \sim A_\mu^{(0)} + \sum_n f_n(Z) A_\mu^{(n)} \tag{21}$$

where $A_\mu^{(0)}$ is interpreted as a source for the current J^μ in gauge theory, and $A_\mu^{(n)}$ are massive vector mesons that can be created by J^μ

It is a unified description of external sources and dynamical excitations

- An important ingredient for our purposes

  Triangle anomaly in 4D $\longleftrightarrow$ 5D Chern-Simons term $A \wedge F \wedge F$

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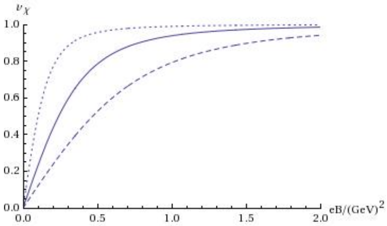
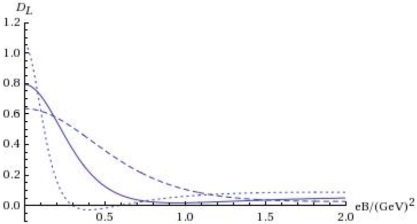


ν_χ
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
eB/(GeV)^2



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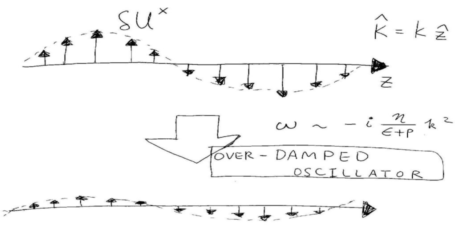
Our next subject : Chiral Shear Wave

Some pictorial cartoon of damping shear waves



- Shear modes are waves of transverse velocity field δu^i where $i = x$ or $i = y$ when the wave-vector is $\vec{k} = k\hat{z}$
- It is not a propagating mode, but exponentially damping
- From the constitutive relation of $T^{\mu\nu}$, the leading order dispersion relation starts as

$$\omega \approx -\frac{i\eta}{\epsilon + p} k^2 + \cdots \tag{22}$$

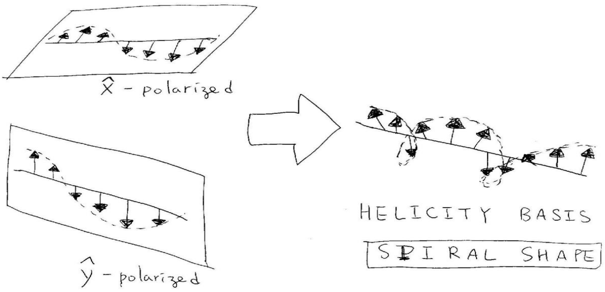
where η is the shear viscosity

Why anomaly affects this and how ?

Q : How come anomaly could affect these transverse shear modes ?

The basic reason : In the charged plasma, transverse velocity fluctuations δu^i induce charge current flow too, i.e. they are coupled with each other dynamically

Net effect : δu^x and δu^y mix with each other, and the correct eigen modes are definite helicity modes



The two opposite helicity modes turn out to have different sub-leading dispersion relations from anomaly

AdS/CFT computation of chiral shear waves

- As a model theory, we take

$$(16\pi G_5)\mathcal{L} = R + 12 - \frac{1}{4}F_{MN}F^{MN} - \frac{\kappa}{4\sqrt{-g_5}}\epsilon^{MNPQR}A_M F_{NP} F_{QR} \quad , \qquad (23)$$

  and consider a charged black-hole plasma background
- Study linear fluctuations, especially helicity ± 1 transverse shear modes. One finds that Chern-Simons effect (anomaly effect) appears only on these modes
- From analyzing these modes in AdS/CFT, one can obtain their dispersion relations. The result depends on the sign of helicity, which maybe called chiral shear waves
- Our result is

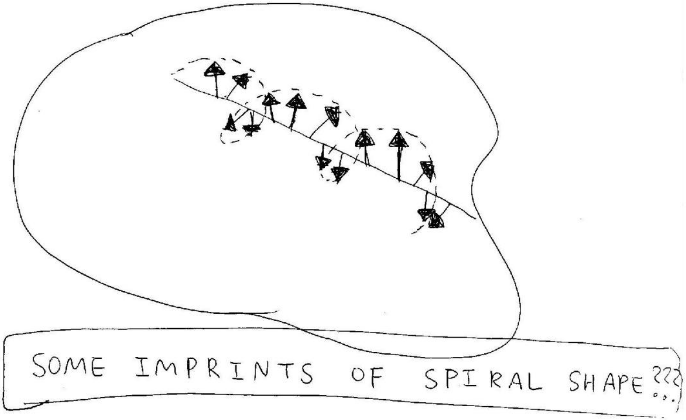
$$\omega \approx -i\frac{\eta}{\epsilon + p}k^2 \pm i\frac{\kappa Q^3}{8m^2 r_H^3}k^3 + \mathcal{O}\left(k^4\right) \quad : \quad \text{helicity} \pm 1 \quad , \qquad (24)$$

  where $\mathcal{O}(k^3)$ is the chiral term from anomaly. In fact, any term with odd powers of k comes from anomaly
- Domokos-Harvey and Nakamura-Ooguri-Park observed that for a sufficiently large κ, the anomaly-induced term can be big enough to overcome the leading piece, to induce an instability toward forming chiral shear waves

How to observe experimentally ?

- One helicity mode has a larger imaginary frequency than the other, so it would decay faster than the other
- After some time, only one helicity modes should dominate.

It will look like a SPIRAL SHAPE transverse fluctuation



Thank you very much

Thank you very much for listening