Collective Flow of Photons in Strongly Coupled Gauge Theories

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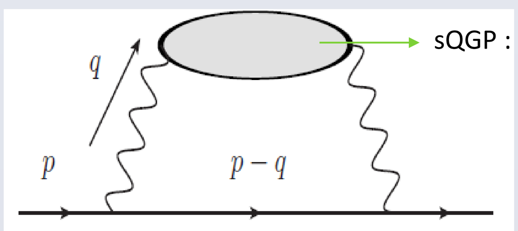
Abstract

In the quark gluon plasma (QGP), the transport properties of electromagnetic (EM) probes such as leptons and photons could be modified by the lepton/photon-parton scattering compared with the case in the QED plasma. In order to incorporate the non-perturbative effects from the strongly couple QGP on the lepton/photon-parton collisions, a semi-holographic approach which combines the Boltzmann equation and the gauge/gravity duality is applied to compute the shear viscosity of thermal leptons and photons. It is found that the lepton shear viscosity due to the lepton-quark scattering is inversely proportional to the ratio of electric conductivity of the QGP to temperature up to the leading logarithmic order of the EM coupling and is suppressed compared with the one from lepton-lepton scattering. On the other hand, the photon shear viscosity up to the leading order of the EM coupling is suppressed by the photon-parton scattering, where the suppression is favored by the strong coupling of the QGP. Such suppression stems from the blue shift of the thermal-photon spectrum at fixed temperature when the coupling of the QGP is increased. On the contrary, the lepton shear viscosity behaves oppositely due to the decrease of electric conductivity of the QGP at stronger coupling. Moreover, in a holographic model breaking conformal symmetry, both the conductivity and the amplitude of the thermal-photon spectrum scaled by temperature decrease rapidly near the deconfinement transition. Accordingly, a sharp enhancement of the shear viscosity of both thermal leptons and thermal photons close to the critical temperature is observed. In conclusion, our findings imply that the thermal leptons and photons in the QGP are less viscous than in the QED plasma. In particular, thermal photons may become fluid-like in the strongly coupled scenario. We argue that it may strengthen the anisotropic flow of direct photons in heavy ion collisions. The presentation is based on [1.2].

Viscous Leptons in the Quark Gluon Plasma

Here we address a subtle situation – the mixture of both weakly coupled and strongly coupled sectors of the plasma – which exists in the practical cases such as the QGP present in the early universe. The plasma comprises both leptons and colored quanta (quark and gluons), where the interactions among leptons are weakly coupled but the interactions among quarks and gluons are strongly coupled. The two sectors are connected by electroweak scattering between leptons and quarks.

The self-energy diagram for thermal leptons :



Since the collisional terms are additive in the linear Boltzmann equation, the complete shear viscosity of leptons, $\eta_c \approx \frac{\eta_{\rm mix}\eta_{\rm QED}}{\eta_{\rm mix}+\eta_{\rm QED}}$

will be always smaller than each individual contribution.

- The Strategy to Compute the Shear Viscosity :

In thermal equilibrium, the interaction rate of leptons in the relativistic Boltzmann approach can be written as

$$\frac{p^\mu}{E_p}\partial_\mu \tilde{f}(p,x) = -\tilde{f}(p,x)\Gamma^{>}(p) + (1-\tilde{f}(p,x))\Gamma^{<}(p)$$

Using the optical theorem, the Boltzmann equation is governed by the retarded current-current correlator,

$$p^\mu\partial_\mu\tilde{f}(p,x) = e^2\int\frac{d^3\mathbf{q}}{(2\pi)^3 4E_{p-q}}\frac{\epsilon(q_0){\rm Im}[\Pi^R_{\mu\nu}(q)]}{(q^2)^2}{\rm tr}\left[(\not{p}+m)\gamma^\mu((\not{p}-\not{q})+m)\gamma^\nu\right]D(q,p),$$

$$\Pi^R_{\mu\nu}(q) = \hat{P}^T_{\mu\nu}\Pi^T(q) + \hat{P}^L_{\mu\nu}\Pi^L(q) \qquad D(q,p) = \tilde{f}(p,x)(1+f(q,x))(1-\tilde{f}(p-q,x)) - (1-\tilde{f}(p,x))f(q,x)\tilde{f}(p-q,x).$$

Considering the shear fluctuation : $\delta\tilde{f}(p,x) = (1-\tilde{n}(p,x))\tilde{n}(p,x)\chi(p,x),$ $\chi(p,x) = \frac{B(p)}{T}\hat{p}^i\hat{p}^j\partial_i u_j$

Shear viscosity : $\eta = \frac{\beta}{15}\int\frac{d^3\mathbf{p}}{(2\pi)^3 2E_p}|\mathbf{p}|^2(1-\tilde{n}_p)\tilde{n}_p B(p)$

"The primary task is to solve the Boltzmann eq. for B(p)."

The low-energy scattering dominates : $q_0 < |\mathbf{q}| \ll T \le |\mathbf{p}|$ ⟶ long-wavelength approximation

We analytically derive B(p) with a proper ansatz depending on the current-current correlator under the long-wavelength approximation. In fact, since the collinear divergence dominates the q integral, the correlator is given by only the transverse part, which can be further written in terms of the electric conductivity of the medium under the long-wavelength approximation.

DC conductivity : $\sigma_c = -\left(\frac{\epsilon(q_0){\rm Im}[\Pi^T(q)]}{q_0}\right)_{q_0\to|\mathbf{q}|\ll T}$ $\xrightarrow[\text{(up to leading log order of } e)]{\text{corresponding ansatz}}$ $B(p) = \frac{\pi^2|p|^2}{2\sigma_c T e^2\ln(1/e)}$

Shear Viscosity : $\boxed{\eta_{\rm mix} \approx \frac{T^4 I_p}{120\sigma_c e^2\ln(1/e)}}$ $I_p \approx 116$

Weakly coupled scenarios:

$$\eta_{\rm QED} = \frac{T^3 I_p}{5\pi e^4\ln(1/e)} \qquad \eta^{\rm pQCD}_{\rm mix} \approx \frac{T^3 I_p(N_c^2-1)g^4\ln(1/g)}{c_0 N_c^2 N_f e^2 Q^2\ln(1/e)}$$

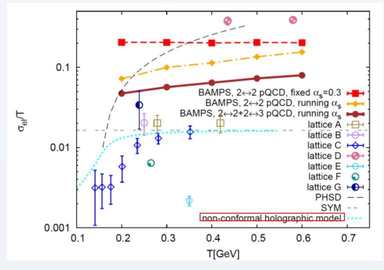
Strongly coupled scenarios :

$$\eta^{\rm D3/D7}_{\rm mix} \approx \frac{\pi T^3 I_p}{30 N_c N_f e^2 Q^2\ln(1/e)} \qquad \eta^{\rm SS}_{\rm mix} \approx \frac{9\pi I_p T^2 M_{\rm KK}}{40\lambda N_c e^2 Q^2\ln(1/e)}$$

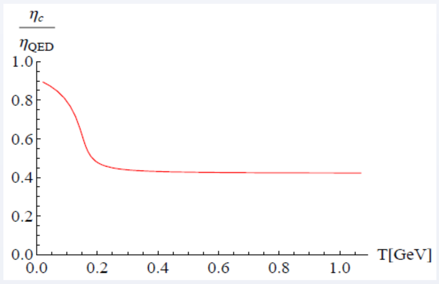
The D3/D7 system [3,4]: strongly coupled N=4 SYM plasma + quarks in fundamental rep.
The Sakai-Sugimoto model [5]: a strongly coupled non-conformal gauge theory.

A holographic model mimicking sQGP [6,7] :

The conductivity drops near Tc, which leads to an enhancement of lepton viscosity near the deconfinement transition. In summary, the lepton viscosity is suppressed in sQGP away from Tc compared with the one in QED.



comparison with lattice data [8]



Collective Flow of Photons in Strongly Coupled Gauge Theories

In QGP, the cross section of photon-parton scattering is quadratic in e, which dominates the photon-photon/lepton scattering from the power counting. To compute the shear viscosity of photons in the sQGP, we start from the Boltzmann approach. Considering only particle scattering, the relativistic Boltzmann equation of photons can be written as

$$\frac{p^\mu}{p^0}\partial_\mu f(p,x) = -f(p,x)\Gamma^{>}(p) + (1+f(p,x))\Gamma^{<}(p), \qquad \Gamma^{<(>)}(p) = (2\pi)^3\frac{d\tilde{\Gamma}^{<(>)}}{d^3p}.$$

⟵ production (absorption) rates per unit volume

Note that the production (absorption) rates are fully non-perturbative in g, which could be obtained from holography [9] (Here we actually work on the N=4 SYM plasma).

Introducing thermal fluctuations : $f(p,x) = n_b(p,x) + \delta f(p,x)$

Boltzmann eq : $\frac{p^\mu}{p^0}\partial_\mu f(p,x) = \frac{{\rm Im}\left[\Pi^R(p^0)\right]}{p^0}\delta f(p,x)$ ⟶ relaxation time : $\tau_\gamma = -\left(\frac{{\rm Im}\left[\Pi^R(p^0)\right]}{p^0}\right)^{-1} = 2p^0\chi(p^0)^{-1}$

The solution of the shear fluctuation : $\delta f(p,x) = (1+n_b(p,x))n_b(p,x)\frac{B(p)}{T}\hat{p}^i\hat{p}^j\partial_i u_j,$ $B(p) = -\frac{|\mathbf{p}|^2}{{\rm Im}\left[\Pi^R(p^0)\right]}$

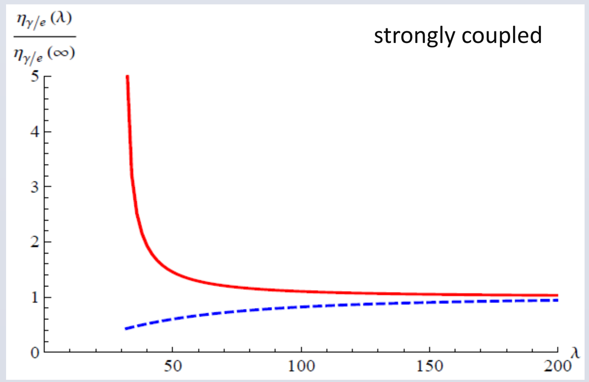
The shear viscosity of photons can now be written in terms of the production rate :

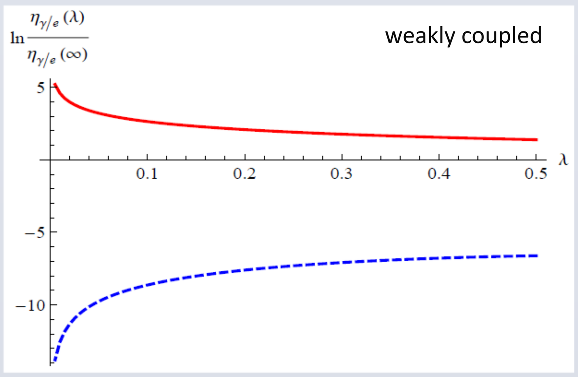
$$\eta_\gamma = \frac{1}{120T\pi^4}\int d|\mathbf{p}||\mathbf{p}|^6 n_b(p,x)^2(1+n_b(p,x))\left(\frac{d\tilde{\Gamma}^<}{dp}\right)^{-1}$$

For N=4 SYM at infinite t'Hooft coupling : $\eta^{SYM}_\gamma(\lambda=\infty) = \frac{1.46T^3}{e^2N_c^2}$ $\xrightarrow[N_c=3]{}$ $\boxed{\frac{\eta^{SYM}_\gamma(\lambda=\infty)}{s_\gamma} \approx \frac{25}{4\pi}}$

$(\lambda = g^2N_c)$

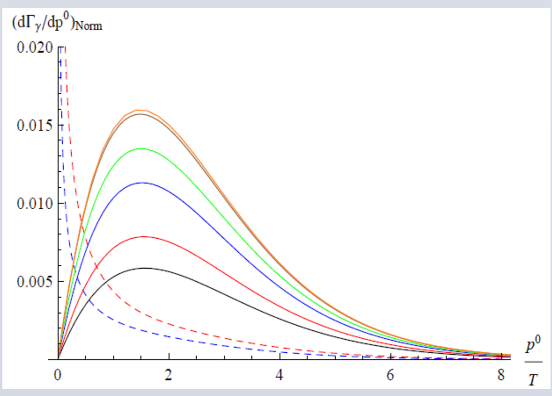
The photoemission rate at finite but large t'Hooft coupling can be obtained by the inclusion of $O(\alpha'^3)$ string-theory corrections, which results in the $O(\lambda^{-3/2})$ correction in the SYM theory. It is found that the maximum amplitude of the spectrum decreases when the t'Hooft coupling is increased [10]. However, the spectrum shifts to the UV regime at the strong coupling. Similar scenarios is also found in the perturbative calculation at weak coupling. The suppression of the amplitude, which corresponds to the reduction of electric conductivity, causes the enhancement of the shear viscosity of leptons. On the contrary, the blueshift of the spectrum gives rise to the suppression of the shear viscosity of photons.





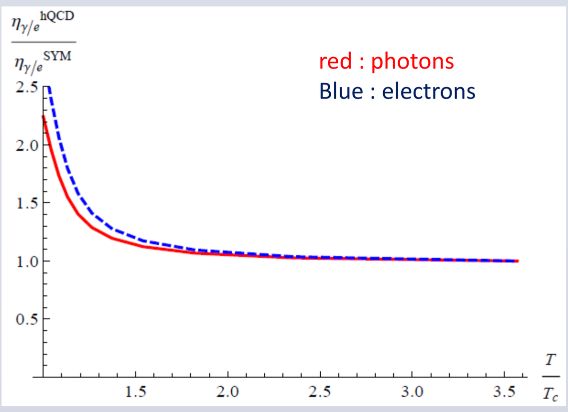
red : photons
Blue : electrons

In the holographic-QCD (hQCD) model mimicking the sQGP, we find that the amplitude of the photon spectrum decreases rapidly when T approaches Tc, while the peak of the spectrum remains unchanged. Therefore, both the shear viscosity of leptons and the shear viscosity of photons in the sQGP rise near the deconfinement transition.



solid curves from bottom to top :
T=(1, 1.08, 1.26, 1.54, 3.57, 7.4) Tc

dashed curves :
weakly coupled
(red : $\alpha_s = 0.1$, blue : $\alpha_s = 0.05$)



In phenomenology of heavy ion collisions, given that the η_γ/s is small, which could be slightly greater than the ratio of the sQGP itself, the photons emitted from the core are nearly "trapped" in the fireball. Near the critical temperature, these photons then become more viscous and "freeze-out" as hadrons. In other words, the thermal-photon production from the QGP in this scenario is thus delayed. Because most of photons are now emitted in late times, the anisotropic flow of direct photons may be amplified.

References

[1] B. Mueller and D.-L. Yang, Phys.Rev. D91, 125010 (2015), 1503.06967.
[2] D.-L. Yang and B. Mueller, 1507.04232.
[3] D. Mateos, R. C. Myers, and R. M. Thomson, Phys.Rev.Lett. 97, 091601 (2006), hep-th/0605046.
[4] D. Mateos and L. Patino, JHEP 0711, 025 (2007), 0709.2168.
[5] T. Sakai and S. Sugimoto, Prog.Theor.Phys. 113, 843 (2005), hep-th/0412141; Prog.Theor.Phys. 114, 1083 (2005), hep-th/0507073.
[6] S. S. Gubser and A. Nellore, Phys.Rev. D78, 086007 (2008), 0804.0434.
[7] S. I. Finazzo and J. Noronha, Phys.Rev. D89, 106008 (2014), 1311.6675.
[8] M. Greif, I. Bouras, C. Greiner, and Z. Xu, Phys.Rev. D90, 094014 (2014), 1408.7049.
[9] S. Caron-Huot, P. Kovtun, G. D. Moore, A. Starinets, and L. G. Yaffe, JHEP 0612, 015 (2006), hep-th/0607237.
[10] B. Hassanain and M. Schvellinger, Phys.Rev. D85, 086007 (2012), 1110.0526.