Collective modes of gluon in an anisotropic thermomagnetic medium

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Abstract

- We study the collective modes of gluon in an anisotropic thermal medium in presence of a constant background magnetic field using the **hard-thermal loop (HTL) perturbation theory**.
- The momentum space anisotropy of the medium has been incorporated through the **generalized 'Romatschke- Strickland' form** of the distribution function, whereas, the magnetic modification arising from the quark loop contribution has been taken into account in **the lowest Landau level approximation**.
- We consider two special cases: (i) a spheroidal anisotropy with the anisotropy vector orthogonal to the external magnetic field and (ii) an ellipsoidal anisotropy with two mutually orthogonal vectors describing aniostropies along and orthogonal to the field direction.

Introduction

- QGP created in ultra relativistic heavy-ion collisions (URHIC) possess substantial deviation from perfect local isotropic equilibrium.
- The rapid expansion of the QCD matter along the longitudinal direction (beam direction) which gives rise to **a large local rest frame momentum space anisotropy in the $p_T - p_L$ plane**.
- This anisotropic momentum distribution can cause plasma instabilities in the system. The anisotropic distribution function is usually parametrized by 'Romatschke-Strickland' (RS) form $f_{\rm aniso}(\mathbf{k}) = f_{\rm iso}\left(\frac{1}{\Lambda_T}\sqrt{\mathbf{k}^2 + \xi(\mathbf{k}\cdot\mathbf{a})^2}\right)$.

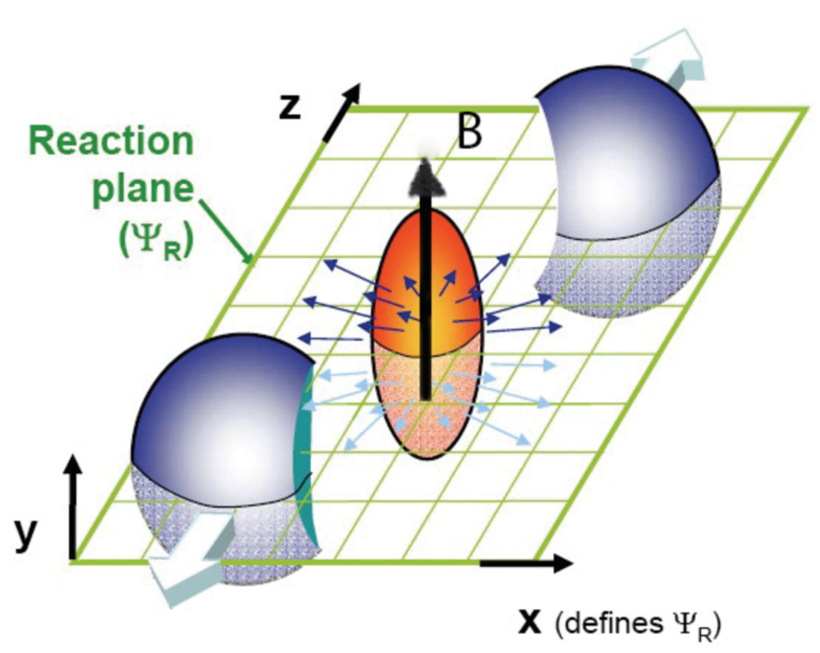

Figure 1: Non-central heavy ion collision

- Magnetic field of **strength upto** $\sim 20m_\pi^2$ is created in non-central heavy ion collision.
- The magnetic field is created **in a direction perpendicular to the reaction plane**. This magnetic field decreases with time. In this project, we consider strong magnetic field ($gT < T < \sqrt{|q_f B|}$).
- The production of strong magnetic field at early stages of collision naturally motivates one to investigate the magnetic field effects on anisotropic QGP.

Gluon self energy

- We follow the real-time Schwinger-Keldysh formalism based on contour Green's functions which is applicable for non-equilibrium field theories.
- Gluon self energy consists of quark and gluon loop contributions among which **only the quark loop is affected by the magnetic field**.
- **Gluon loop:** The anisotropic gluon distribution in presence of ellipsoidal anisotropy is parametrized as $f_{\rm aniso}(\mathbf{k}) = f_{\rm iso}\left(\frac{1}{\Lambda_T}\sqrt{\mathbf{k}^2 + \xi_1(\mathbf{k}\cdot\mathbf{a}_1)^2 + \xi_2(\mathbf{k}\cdot\mathbf{a}_2)^2}\right)$.
- **Quark loop:** In presence of strong magnetic field the energy of fermion becomes $E = \sqrt{k_z^2 + m_f^2}$ *i.e.,* **dimensional reduction** $(3+1 \rightarrow 1+1)$ **occurs in lowest Landau level**. In LLL, the nonequllibrium quark distribution is constructed as [1] $f^F_{\rm aniso}(k_z) = f^F_{\rm iso}\left(\frac{1}{\Lambda_T}\sqrt{k_z^2 + \xi_2 k_z^2}\right) = f^F_{\rm iso}(|k_z|/\lambda_T)$.
- The quark loop contribution in the retarded gluon polarization tensor can be obtained as

$$\bar{\Pi}^{\mu\nu}_{ab}(p) = \delta_{ab}\sum_f g_s^2 \frac{|e_f B|}{8\pi^2} \exp\left(-\frac{p_\perp^2}{2|e_f B|}\right) \sum_{{\rm sgn}(k_z)=\pm 1} \frac{v^\mu_\parallel v^l_\parallel}{1+\xi_2}\left[\eta^{\nu l}_\parallel - \frac{v^\nu_\parallel p^l}{(v_\parallel \cdot p_\parallel + i\epsilon)}\right]\Bigg|_{l=3}$$

- The general structure of gluon self energy [2] in the anisotropic magnetized medium is constructed as $\Pi^{\mu\nu} = \alpha A^{\mu\nu} + \beta B^{\mu\nu} + \gamma C^{\mu\nu} + \delta D^{\mu\nu} + \sigma E^{\mu\nu} + \lambda F^{\mu\nu}$.

Dispersion relation

- Dispersion relations can be found from **the pole of the gluon effective propagator** which includes the effect of the medium.

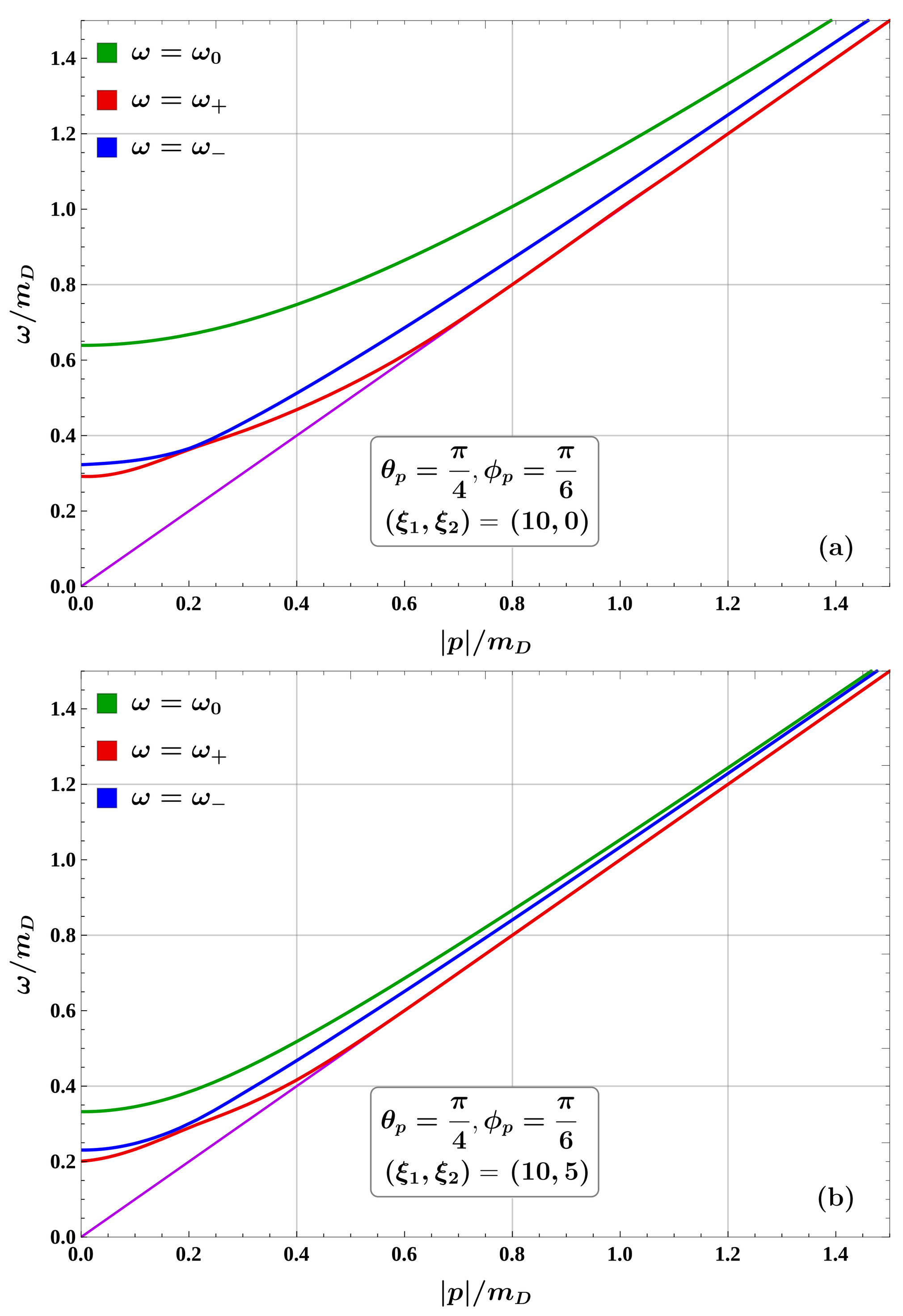

Figure 2: Dispersion relation of gluon in anisotropic thermomagnetic medium

Presence of instability

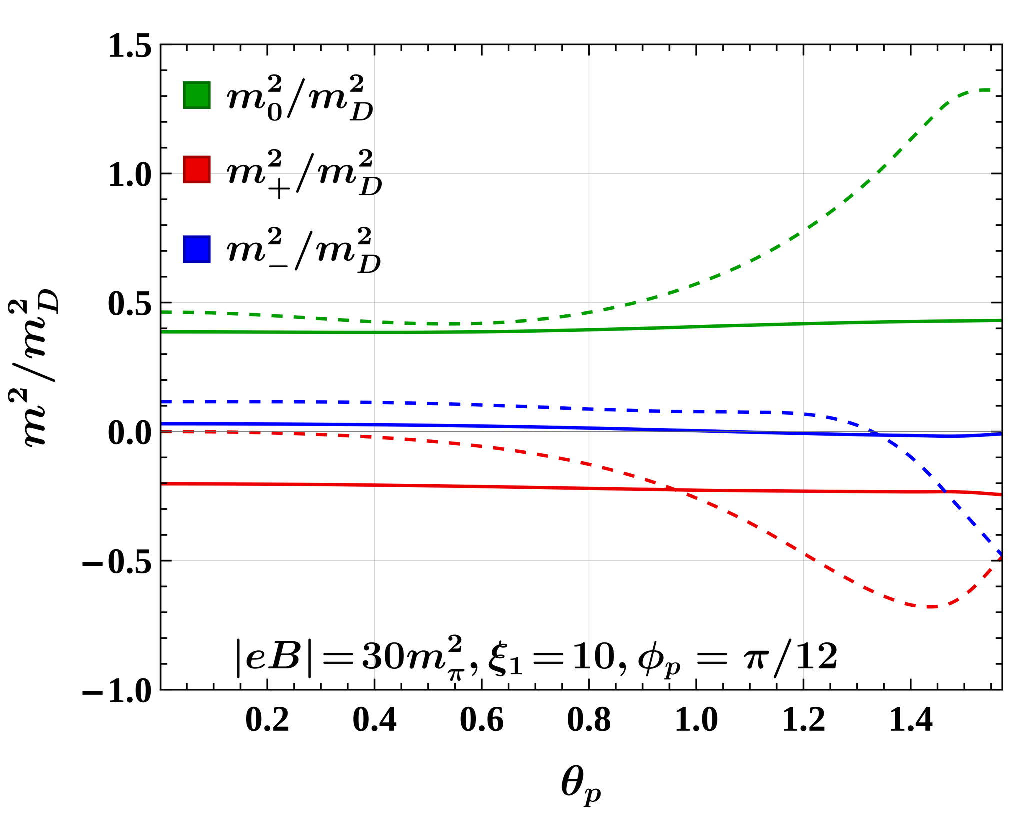

Figure 3: The continuous and the dashed curves represent $\xi_2 = 5$ and $\xi_2 = 0$ respectively.

- The presence of anisotropy in the system leads to unstable gluon modes. These instabilities can contribute in the thermalization and isotropization process.
- We define mass corresponding to each gluon modes **by taking the static limit** ($\omega \rightarrow 0$). A negative squared mass indicates the existence of an unstable mode.
- The growth rate of such instabilities *i.e.,* the imaginary part of the mode frequency can be obtained from the pole of the effective propagator.

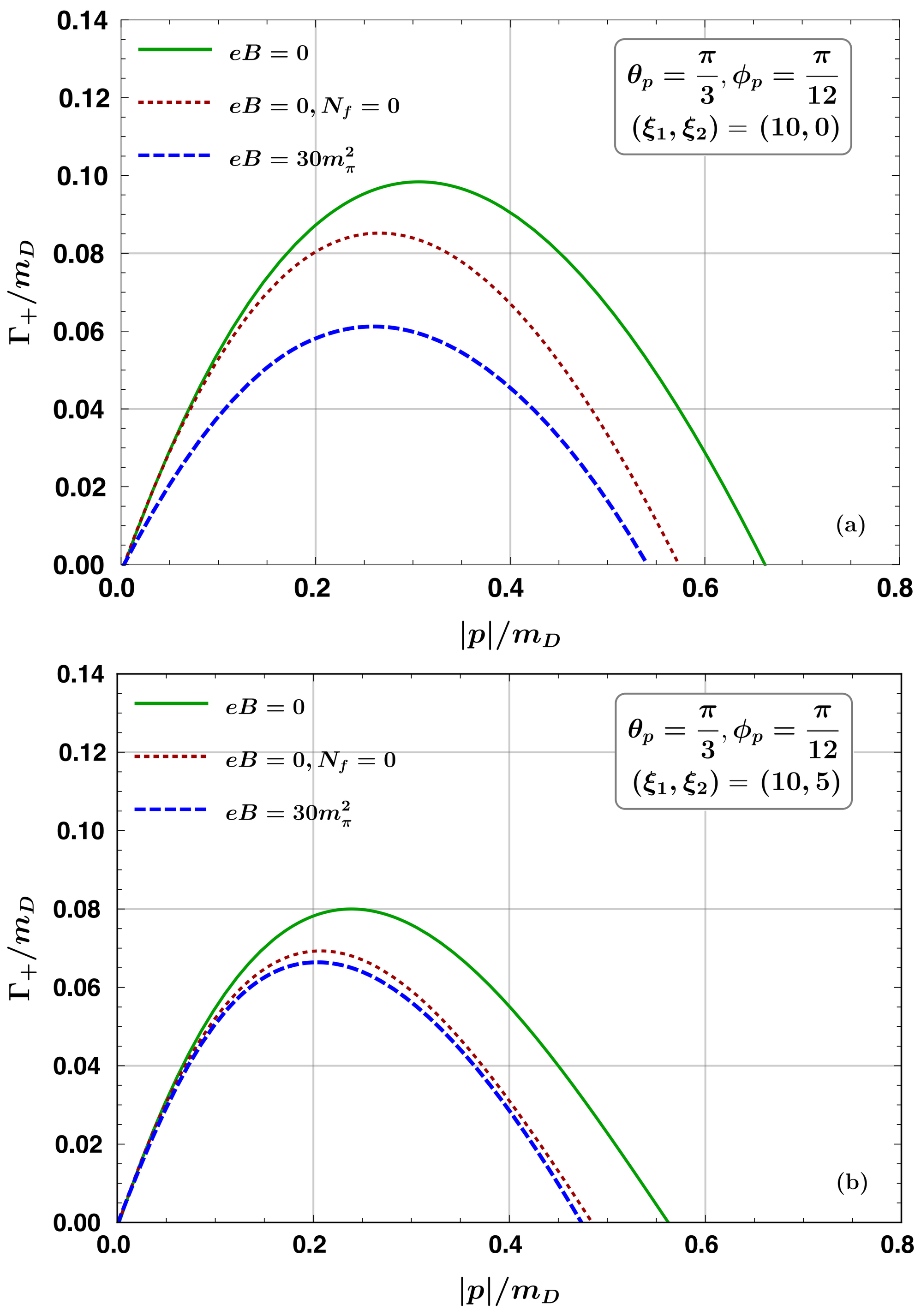

Figure 4: The growth rate of unstable gluon mode ω_+

Conclusions

- The collective modes of gluon in the presence of momentum space anisotropy along with a constant background magnetic field have been studied using the hard-thermal loop perturbation theory.
- The gluon loop of gluon self energy remains unaffected by the magnetic field. We find **three dispersive gluon modes** from the effective propagator.
- It is observed that due to the dimensional reduction in the LLL approximation, the parameter ξ_2 that characterizes the anisotropy along the magnetic field direction, **appears in the quark loop only in an overall suppressing factor**.
- We define mass scales for each mode to investigate the instability. **Depending upon the propagation direction, we found negative squared mass** which indicates presence of instability.
- The magnetic field has **strong influence on the growth rate of the unstable modes**. The amplitude as well as the critical momentum corresponding to the growth rate are significantly reduced.
- Although, any critical magnetic field strength above which the modes become stable, is unlikely to be present.

References

[1] B. Karmakar, R. Ghosh and A. Mukherjee, [arXiv:2204.09646 [hep-ph]].

[2] R. Ghosh, B. Karmakar and A. Mukherjee, Phys. Rev. D **102**, no.11, 114002 (2020).