Impact of anisotropy on transport coefficients of quark matter

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INTRODUCTION

- Ultrarelativistic heavy-ion collisions (uRHIC) at facilities like RHIC and LHC create a deconfined state of matter known as the Quark-Gluon Plasma (QGP).
- The initial geometry of non-central collisions and the rapid, asymmetric expansion of the medium lead to significant momentum-space anisotropy. This anisotropy may persist for a substantial part of the QGP's evolution.
- This intrinsic feature of the QGP is expected to heavily influence its bulk properties, particularly the transport coefficients that govern dissipation and flow.
- While many effective models of QCD assume an isotropic medium, a realistic phenomenological analysis requires the inclusion of momentum anisotropy.
- **This work:** We investigate the impact of momentum-space anisotropy on the shear viscosity (η) and electrical conductivity (σ_{el}) of quark matter. We employ the Polyakov Chiral SU(3) Quark Mean Field (PCQMF) model as our theoretical framework.

METHODOLOGY

- **PCQMF Model & Thermodynamic Potential:**
The grand thermodynamic potential per unit volume Ω in the PCQMF model is given by [1]

$$\Omega_{\text{PCQMF}} = \Omega_{q\bar{q}} + \Omega_{\text{vac}} + \mathcal{U}(\Phi, \bar{\Phi}, T) - \mathcal{L}_M - \mathcal{V}_{\text{vac}}$$

where $\Omega_{q\bar{q}}$ is the thermal contribution from quarks and antiquarks, Ω_{vac} is the fermionic vacuum term, $\mathcal{U}$ is the Polyakov loop potential, and $\mathcal{L}_M$ contains meson self-interactions. The quark thermal contribution is

$$\Omega_{q\bar{q}} = \sum_{i=u,d,s} \frac{-\gamma_i T}{(2\pi)^3} \int d^3k \left\{ \ln F_i^-(k) + \ln F_i^+(k) \right\}$$

with $F_i^{\pm}(k)$ encoding the Polyakov loop dynamics. The effective quark mass (m_i^*) and chemical potential (μ_i^*) are generated dynamically

$$m_i^* = -g_\sigma^i \sigma - g_\zeta^i \zeta - g_\delta^i \delta + \Delta m_i$$
$$\mu_i^* = \mu_i - g_\omega^i \omega - g_\phi^i \phi - g_\rho^i \rho$$

The quark chemical potentials μ_i are related to baryon μ_B, isospin μ_I, and strangeness μ_S chemical potentials.

- **Momentum-Space Anisotropy:**
We introduce anisotropy via a spheroidal deformation of the momentum distribution, quantified by the parameter [2]

$$\xi = \frac{\langle \mathbf{p}_\perp^2 \rangle}{2\langle p_\parallel^2 \rangle} - 1$$

This modifies the effective quark energy to become direction-dependent

$$E^*_{i,\text{aniso}}(k) = \sqrt{E_i^{*2}(k) + \xi k^2 \cos^2\theta}$$

- **Anisotropic Transport Coefficients:**
Derived from the Relativistic Boltzmann Equation (RBE) in the Relaxation Time Approximation (RTA), the anisotropic transport coefficients are obtained by replacing the standard distribution functions ($f_i, \bar{f}_i$) with their anisotropic counterparts ($f_{i,\text{aniso}}, \bar{f}_{i,\text{aniso}}$) in the defining integrals. The explicit expressions are [3]

$$\eta_{\text{aniso}} = \eta - \xi \frac{N_c \tau}{90 T^2 \pi^2} \sum_{i=u,d,s} \int dk \frac{k^8}{E_i^{*3}(k)} \Bigg(f_i(1-f_i) + \bar{f}_i(1-\bar{f}_i) - 4(f_i^2 + \bar{f}_i^2) + \frac{2\left(\bar{\Phi} e^{-2E_i^-(k)} + e^{-3E_i^-(k)}\right)}{F_i^-(k)}(1-2f_i) + \frac{2\left(\Phi e^{-2E_i^+(k)} + e^{-3E_i^+(k)}\right)}{F_i^+(k)}(1-2\bar{f}_i) \Bigg),$$

$$\sigma_{el,\text{aniso}} = \sigma_{el} - \xi \frac{N_c \tau}{18 T^2 \pi^2} \sum_{i=u,d,s} e_i^2 \int dk \frac{k^6}{E_i^{*3}(k)} \Bigg(f_i(1-f_i) + \bar{f}_i(1-\bar{f}_i) - 4(f_i^2 + \bar{f}_i^2) + \frac{2\left(\bar{\Phi} e^{-2E_i^-(k)} + e^{-3E_i^-(k)}\right)}{F_i^-(k)}(1-2f_i) + \frac{2\left(\Phi e^{-2E_i^+(k)} + e^{-3E_i^+(k)}\right)}{F_i^+(k)}(1-2\bar{f}_i) \Bigg).$$

Here, the dimensionless energies are defined as $E_i^{\pm}(k) = (E_i^*(k) \pm \mu_i^*)/T$ and $f_i(k)/\bar{f}_i(k)$ represent the Fermi distribution functions for quarks/antiquarks. The anisotropic corrections vanish as $\xi \to 0$.

RESULTS

- We calculated the specific shear viscosity η_{aniso}/s and scaled electrical conductivity $\sigma_{el,aniso}/T$ as functions of temperature for different anisotropy parameters ξ at both zero and finite baryon chemical potential μ_B.
- **Shear Viscosity:** As shown in Fig.1 (a) and 1 (c), η_{aniso}/s exhibits a minimum near the crossover temperature. For $\xi > 0$, a "squeezed" momentum distribution suppresses the ratio, while $\xi < 0$, a "stretched" distribution enhances it.
- **Electrical Conductivity:** Similarly, Fig.1 (b) and 1 (d) show that $\sigma_{el,aniso}/T$ is suppressed for $\xi > 0$ and enhanced for $\xi < 0$ relative to the isotropic case.
- **Baryon Density Effect:** A finite chemical potential $\mu_B = 400$ MeV increases the magnitude of both transport coefficients compared to the $\mu_B = 0$ case.

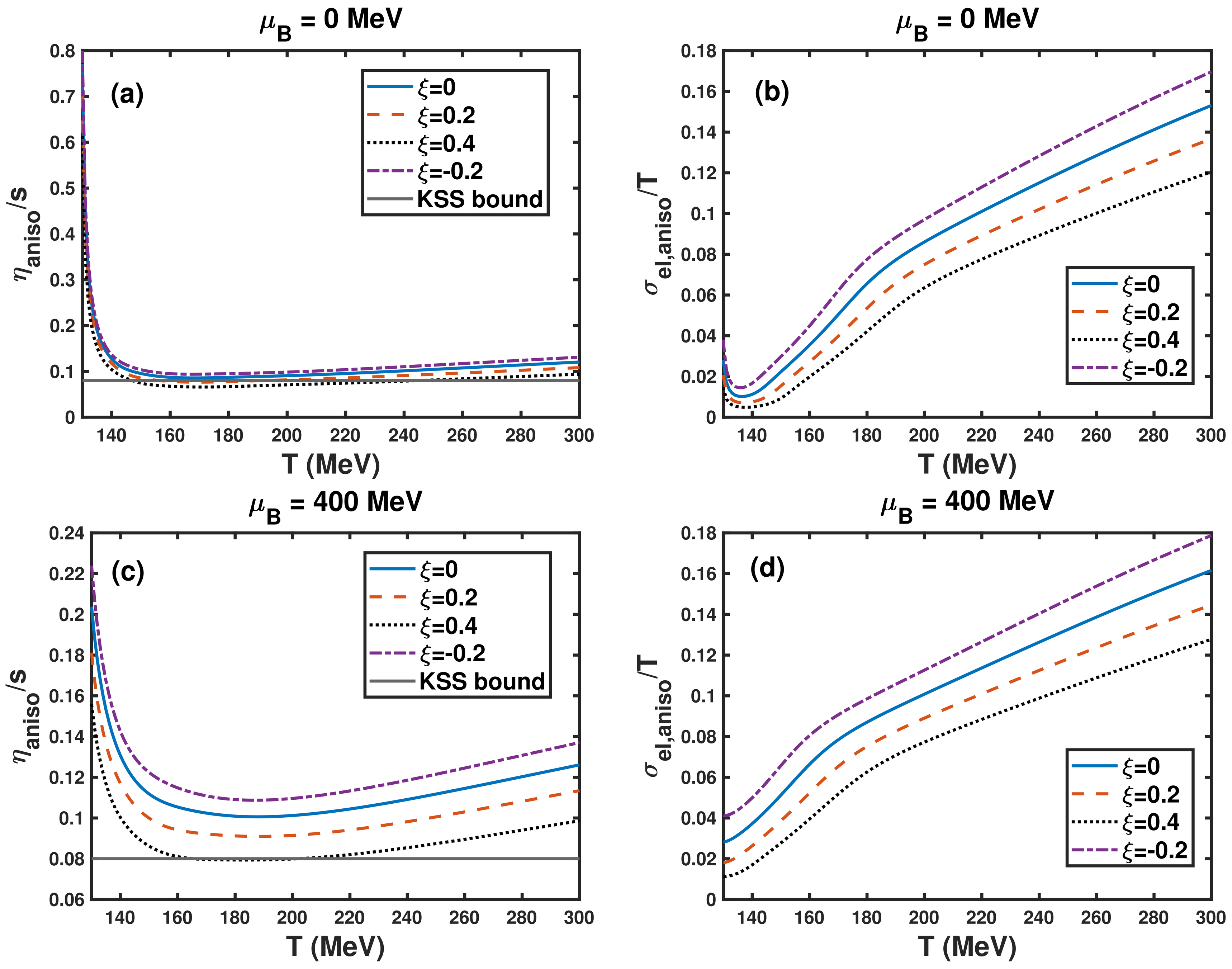

Figure 1: Specific shear viscosity, η_{aniso}/s (left panels), and scaled electrical conductivity, $\sigma_{el,aniso}/T$ (right panels), vs. Temperature for different ξ values. Top row: $\mu_B = 0$ MeV. Bottom row: $\mu_B = 400$ MeV.

CONCLUSIONS

- Momentum-space anisotropy has a significant and qualitatively similar impact on both shear viscosity and electrical conductivity in the QGP.
- $\xi > 0$, which is expected in the early stages of uRHICs, suppresses both η/s and σ_{el}/T. For strong anisotropy ($\xi = 0.4$), η/s approaches the Kovtun-Son-Starinets (KSS) conjecture bound.
- $\xi < 0$ enhances both transport coefficients.
- The presence of a finite baryon chemical potential increases the magnitude of both coefficients, highlighting the interplay between baryon density and anisotropic effects.
- These findings underscore that incorporating momentum anisotropy is crucial for accurately modeling the dissipative dynamics of the QGP.

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