Global Properties of the Quark Gluon Plasma

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Narrowing my focus

Global properties of the QGP
Transport coefficients

Transport coefficients at $\mu_B = 0$

Comparisons with a Hadron Resonance Gas
Transport Coefficient of the QGP

Shear Viscosity $\eta/s(T, \mu_B, \mu_S, \mu_Q)$

$\dot{q} = \frac{\langle p^2 \rangle}{L}$

Energy Loss $\dot{q}(T, \mu_B, \mu_S, \mu_Q)$

Bulk Viscosity $\zeta/s(T, \mu_B, \mu_S, \mu_Q)$

BSQ+C Diffusion $\kappa_{ij}(T, \mu_B, \mu_S, \mu_Q)$

+ Vorticity, 2nd-order, heat conductivity
Attempts from QCD

Recent algorithms made for Quantum Computers

Inversion Problem: correlation functions from Lattice QCD in Euclidean time, must convert to Minkowski time.

For overview, see Moore 2010.15704
Calculations in certain limits

Pure Yang Mills Theory


Perturbative QCD

Ghiglieri et al, JHEP 03 (2018) 179
Experimental probes of $\eta/s(T)$

AdS/CFT: Kovtun, Son, Starinets PRL94(2005)111601
Hadron resonance gas

Transport

\[ \eta = \frac{C_{xy}(0)V\tau}{T} \]


Minimum $\eta/s \sim 1$

Contains microscopic i.e. $\sigma$'s

Depends on # of particles, $\mu$'s
1. Determine radius from Lattice QCD

Assume all hadrons have the same volume

To relax this assumption, see Albright et al, Phys. Rev. C 90 (2014) 2, 024915
Hadron resonance gas

2. Calculate shear viscosity

\[ \eta^{HRG} = \frac{5}{64\sqrt{8}} \frac{1}{r^2 n} \sum_i n_i \left( \int_0^{\infty} p^3 e^{-\sqrt{p^2 + m_i^2/T + \tilde{\mu}_i}} dp + \int_0^{\infty} p^2 e^{-\sqrt{p^2 + m_i^2/T + \tilde{\mu}_i}} dp \right) \]

Excluded Volume


Minimum \( \eta/s \sim 0.7 \)
Hadron resonance gas

Transport

Excluded Volume

More (strongly interacting) states suppress $\eta/s$

Comparison to Bayesian Analysis

Hadron Resonance gas
PDG16+
$\eta/s \sim 0.7$

$pQCD$
$\eta/s \sim 0.5$

More (unmeasured) states and N-body interactions may be needed

Bulk Viscosity

Scales with \( \frac{\zeta}{s(T)} \propto \left( \frac{1}{3} - c_s^2 \right)^n \)

Expect a peak at the cross-over phase transition

[HotQCD] Phys. Rev. D 2014, 90, 094503

See review for more details
Czajka et al, JHEP 07 (2019) 145
Bulk viscosity

[See citations from] Rose et al., J. Phys. G 48 (2020) 1, 015005
Energy Loss $\hat{q}/T^3$ in the HRG

$$\hat{q}_{HRG}(T) = \frac{\hat{q}_N}{\rho_N} \left[ \frac{2}{3} \rho_M(T) + \rho_B(T) \right]$$


Saturation Density

$$\rho_N \sim (0.15 - 0.17) \text{fm}^{-3}$$

Extracted jet transport for a quark at the center of a large nucleus from HERMES

$$\hat{q}_N \sim (0.024 \pm 0.008) \text{GeV}^2/\text{fm}$$


Assume high inflection temperature
Energy Loss $\hat{q}/T^3$

$$\hat{q}_{\text{HRG}}(T) = \frac{\hat{q}_N}{\rho_N} \left[ \frac{2}{3} \rho_M(T) + \rho_B(T) \right]$$

Saturation Density

$$\rho_N \sim (0.15 - 0.17)\, \text{fm}^{-3}$$

Extracted jet transport for a quark at the center of a large nucleus from HERMES

$$\hat{q}_N \sim (0.024 \pm 0.008) \, \text{GeV}^2/\text{fm}$$

Does $\eta T/w \sim \hat{q}/T^3$ hold?


Maybe close to the phase transition, but it’s not so clear...
Conclusions and Outlook

• While general features of the transport coefficients are understood (minimum of $\eta/s$ and maximum $\zeta/s$ at the transition), the finer details demand more theoretical work.

• Theory calculations are more consistent with $\zeta/s$ than with $\eta/s$.

• Possible to smooth connect $\hat{q}/T^3$, consequences?