Holographic calculation of hydrodynamic transport coefficients for the QGP at the crossover transition

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Abstract

The holographic correspondence [1] is used to determine 13 transport coefficients of an Israel-Stewart-like hydrodynamic theory for the QGP at the crossover phase transition (at zero baryon chemical potential). Parametrizations of the temperature dependence of all the second-order transport coefficients that appear in this theory, which can be implemented in numerical hydrodynamic codes, can be found in [2].

Israel-Stewart-like 2nd order hydrodynamics for a non-conformal relativistic fluid

- The conserved energy-momentum tensor (i.e., $\nabla_\mu T^{\mu\nu}=0$) can be generically decomposed as

$$T^{\mu\nu}=\varepsilon\, u^\mu u^\nu+(P+\Pi)\Delta^{\mu\nu}+\pi^{\mu\nu} \tag{1}$$

where ε is the energy density, P is the pressure, the fluid flow obeys $u_\mu u^\mu=-1$, $\Delta^{\mu\nu}=g^{\mu\nu}+u^\mu u^\nu$, $g_{\mu\nu}$ is the 4-dimensional spacetime metric, Π is the bulk viscous pressure, and $\pi^{\mu\nu}$ is the shear stress tensor.

- We follow [3] and write the simplest relaxation-type theory that reduces to the 2nd order gradient expansion theory for a non-conformal fluid derived in [4]. In flat spacetime, one finds (see [2] for details)

$$\tau_\pi\left(D\pi^{\langle\mu\nu\rangle}+\frac{4\theta}{3}\pi^{\mu\nu}\right)+\pi^{\mu\nu}=-\eta\sigma^{\mu\nu}+\frac{\lambda_1}{\eta^2}\pi_\lambda^{\langle\mu}\pi^{\nu\rangle\lambda}-\frac{\lambda_2}{\eta}\pi_\lambda^{\langle\mu}\Omega^{\nu\rangle\lambda}-\lambda_3\Omega_\lambda^{\langle\mu}\Omega^{\nu\rangle\lambda}$$
$$+\,\tau_\pi\,\pi^{\mu\nu}\,D\,\ln\left(\frac{\eta}{s}\right)+\tau_\pi^*\pi^{\mu\nu}\,\frac{\Pi}{3\zeta}+\lambda_4\nabla^{\langle\mu}\ln s\,\nabla^{\nu\rangle}\ln s \tag{2}$$

and

$$\tau_\Pi\left(D\Pi+\Pi\theta\right)+\Pi=-\zeta\theta+\frac{\xi_1}{\eta^2}\pi_{\mu\nu}\pi^{\mu\nu}+\frac{\xi_2}{\zeta^2}\Pi^2+\xi_3\Omega_{\mu\nu}\Omega^{\mu\nu}+\tau_\Pi\,\Pi\,D\,\ln\left(\frac{\zeta}{s}\right)$$
$$+\,\xi_4\nabla_\mu^\perp\ln s\,\nabla_\perp^\mu\ln s\,. \tag{3}$$

- Eqs. (2) and (3) (together with energy-momentum conservation equations) define a set of equations that can be used to describe the non-conformal QGP. This 2nd order theory has 15 transport coefficients.

- Coefficients λ_3, λ_4, ξ_3, and ξ_4 can be determined via Kubo formulas involving only equilibrium quantities and Euclidean two- and three-point functions of the energy-momentum tensor components (suitable for lattice calculations).

- Coefficients η, ζ, τ_π, τ_π^*, τ_Π, λ_1, λ_2, ξ_1, and ξ_2 are associated with quantities that define the dissipative properties of the theory (for instance, η is proportional to the imaginary part of a retarded Green's function).

Non-conformal holographic model

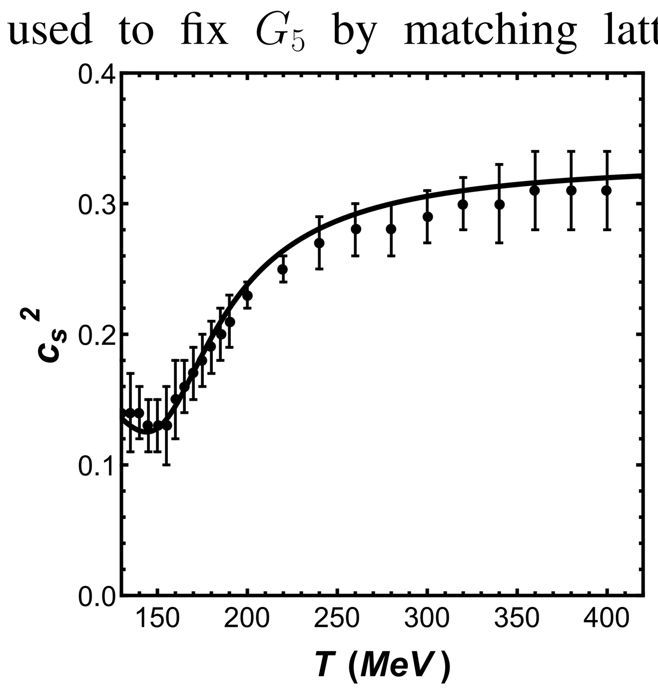
- We use a 5-dimensional holographic Einstein+Scalar model given by

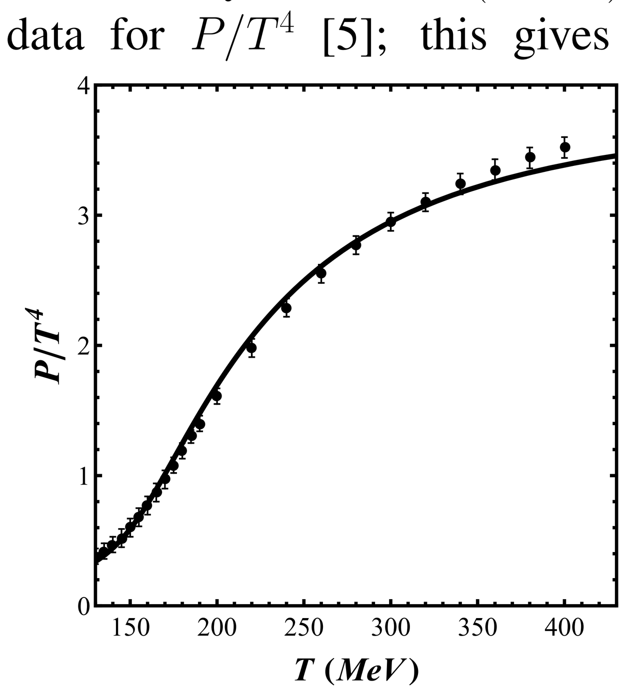
$$S_{\rm ES}^{\rm (bulk)}=\frac{1}{16\pi G_5}\int_{\mathcal{M}_5}d^5x\sqrt{-g}\left[R-\frac{(\partial_M\Phi)^2}{2}-V(\Phi)\right], \tag{4}$$

where Φ is the bulk scalar field and the scalar potential $V(\Phi)$ is

$$V(\Phi)=\frac{-12\cosh\gamma\Phi+b_2\Phi^2+b_4\Phi^4+b_6\Phi^6}{L^2}, \tag{5}$$

with $\gamma=0.606$, $b_2=0.703$, $b_4=-0.1$, $b_6=0.0034$ (and the asymptotic AdS_5 radius fixed as $L=1$). The thermodynamics of $(2+1)$-flavor QCD is used to fix G_5 by matching lattice data for P/T^4 [5]; this gives $G_5=0.5013$.

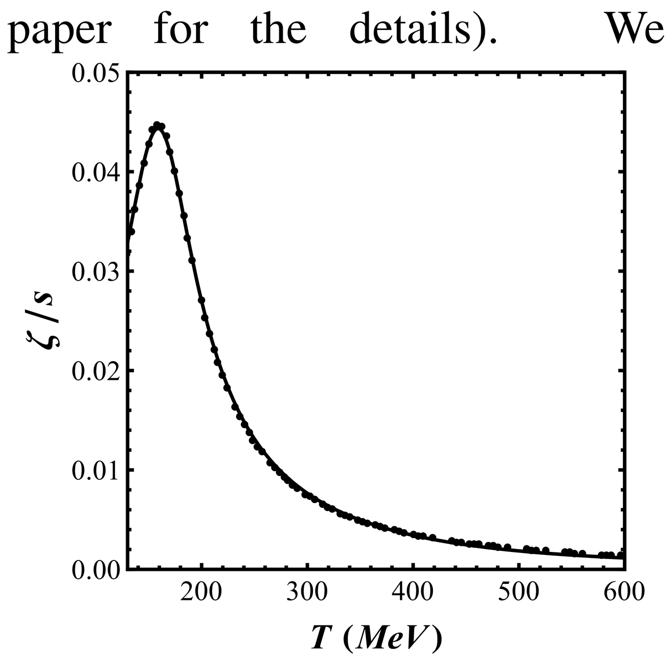


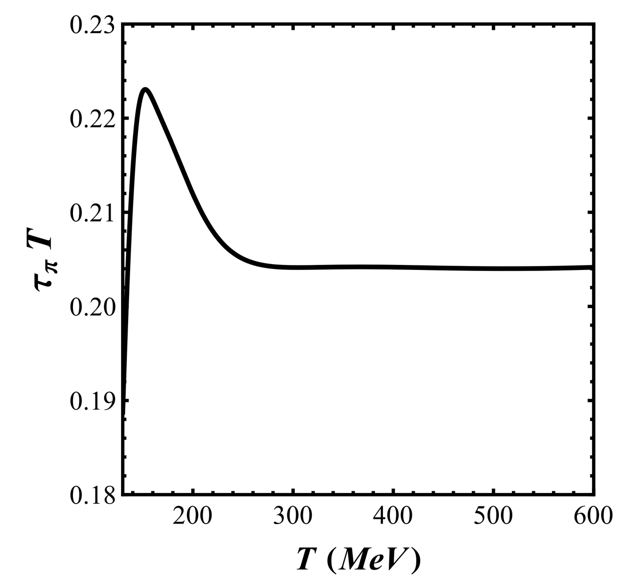


Holographic results for the transport coefficients

- Once all the parameters are fixed by thermodynamics, the model is used to compute transport coefficients at the crossover transition.

- Here we just show some of the coefficients computed in [2] (see the paper for the details). We note that $\eta/s=1/(4\pi)$ in this model.

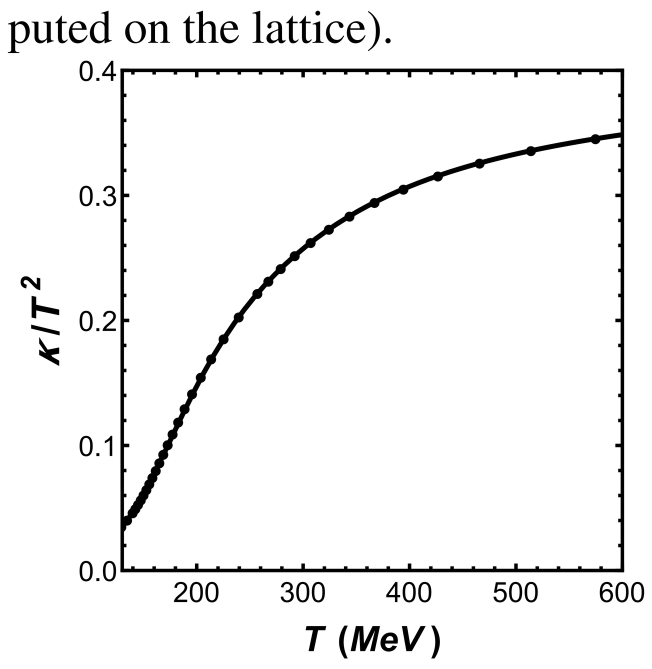


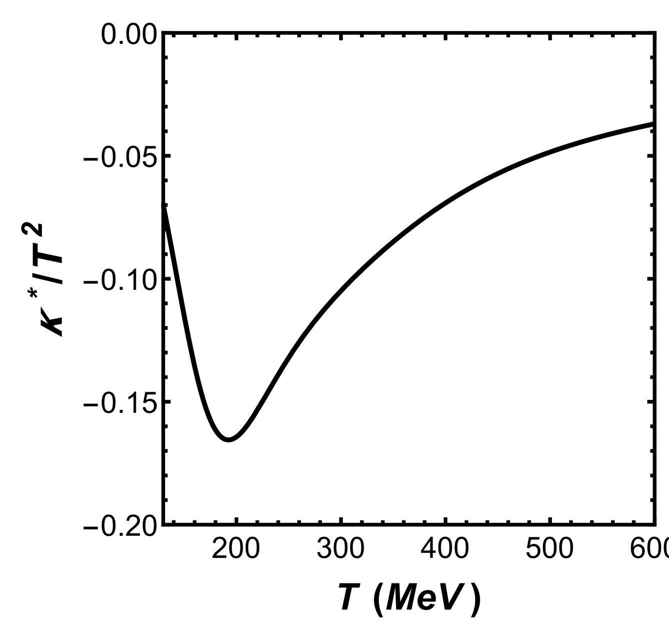


- Fit to the bulk viscosity for hydro codes $\frac{\zeta}{s}\left(x=\frac{T}{T_c}\right)=\frac{a}{\sqrt{(x-b)^2+c^2}}+\frac{d}{x^2+e^2}$ (and $T_c=143.8$ MeV) with $a=0.01162$, $b=1.104$, $c=0.2387$, $d=-0.1081$, $e=4.870$.

- Fit to $\tau_\pi\eta/T^2$ for hydro codes $\frac{\tau_\pi\eta}{T^2}\left(x=\frac{T}{T_c}\right)=\frac{a}{1+e^{b(c-x)}+e^{d(e-x)}+e^{f(g-x)}}$ with $a=0.2664$, $b=2.029$, $c=0.7413$, $d=0.1717$, $e=-10.76$, $f=9.763$, and $g=1.074$.

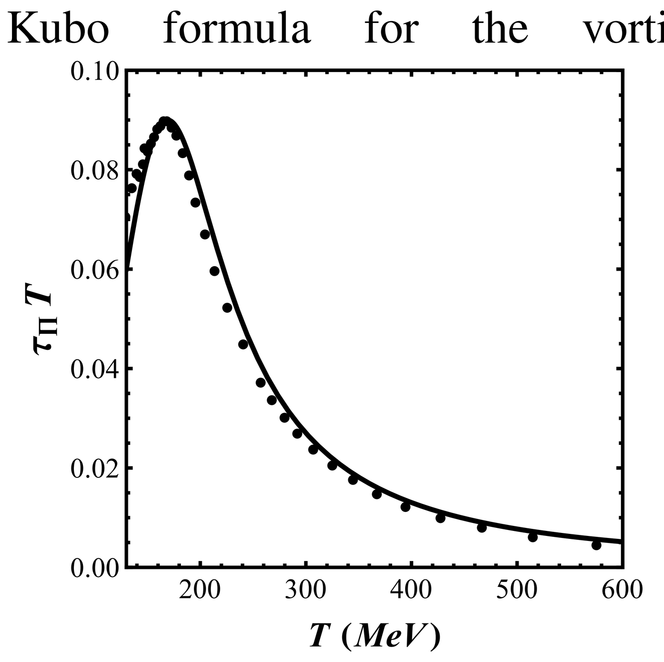
- $\lambda_3=-\lambda_4=2\kappa^*$ where $\kappa^*=\kappa-\frac{T}{2}\frac{d\kappa}{dT}$ and $\kappa=-\lim_{q\to 0}\lim_{\omega\to 0}\frac{\partial^2 G_R^{xy,xy}(\omega,q)}{\partial q^2}$ (can be computed on the lattice).

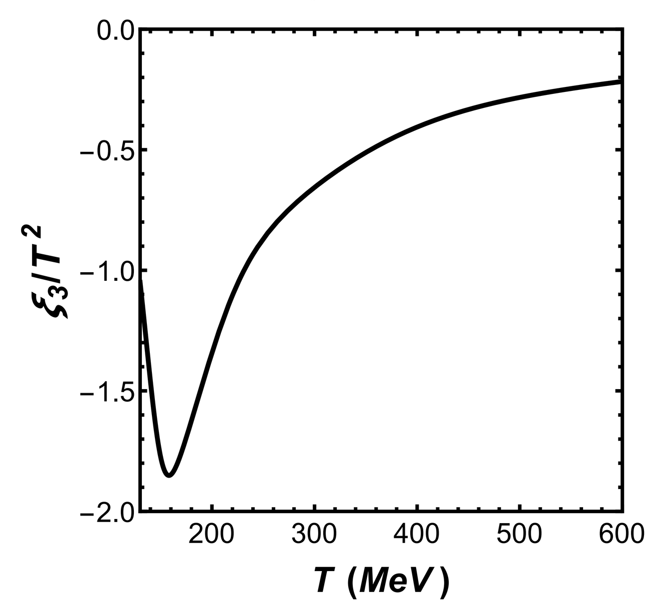




- Fit to $\tau_\Pi T$ for hydro codes $\tau_\Pi T\left(x=\frac{T}{T_c}\right)=\frac{a}{\sqrt{(x-b)^2+c^2}}+\frac{d}{x}$ with $a=0.05298$, $b=1.131$, $c=0.3958$, and $d=-0.05060$.

- Kubo formula for the vorticity coefficient ξ_3 can be found in [6].





Conclusions

- We computed 13 hydrodynamic transport coefficients of a holographic non-conformal plasma whose thermodynamics resembles the QGP. A parametrization of the T-dependence of these coefficients was given in [2].
- These coefficients may be relevant in the study of hydrodynamic behavior in small systems (such as pA collisions).
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References

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