Transport properties of the QGP: quark-flavour dependence within the quasiparticle model

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Motivation

QGP is a nearly perfect fluid $\rightarrow$ transport properties?

- Relativistic hydrodynamics [works of Bożek, Broniowski, Florkowski, Mrówczyński...]
- FRG estimation [Christiansen et al., PRL 115 '15]
- Lattice QCD [Astrakhantsev et al., JHEP 101 '17]
- Holographic QCD ($\eta/s \simeq 1/4\pi$) [Kovtun, Son, Starinets, PRL 94 '05]
- Kinetic theory: Boltzmann equation [Sasaki, Redlich, PRC 79 '09; Florkowski, Maksymiuk, Ryblewski, PRC 97'18]

  + Quasiparticle model [Bluhm, Kämpfer, Redlich, PRC 84 '11]

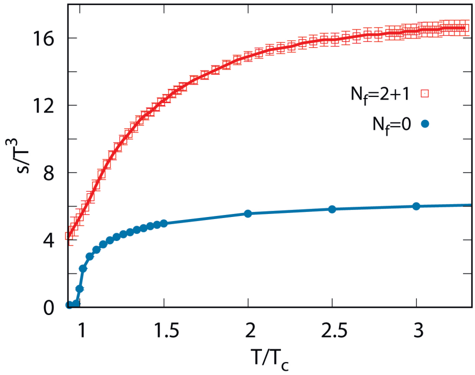
Quasiparticle Model

Weakly interacting particles with effective masses, $M[G(T), T]$:

$$M_q^2 = M_0^2 + 2M_0\sqrt{\frac{G^2T^2}{6}} + \frac{G^2T^2}{3}$$

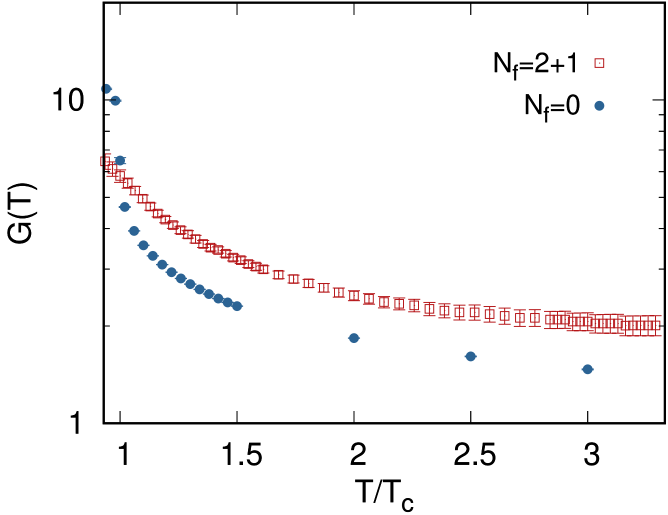
$$M_g^2 = \frac{1}{6}(3 + \frac{1}{2}N_f)G^2T^2$$

[Pisarski, Nucl. Phys. A498, 423C '89;
Bluhm, Kämpfer, Redlich, PRC 84 '11]



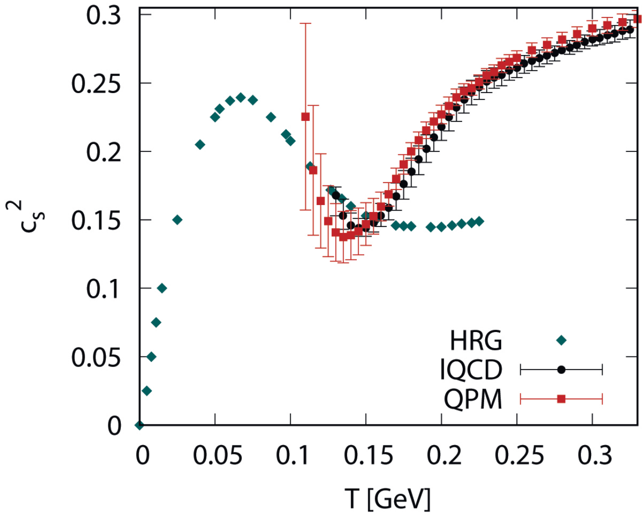
[lQCD: Nf=2+1: Borsanyi et al., Phys. Lett. B730 '14; Nf=0: Borsanyi et al., JHEP1207, 056 '12]

Effective running coupling



[V. M., Bluhm, Redlich, Sasaki, PRD 100 ’19]

Speed of sound: $N_f = 2 + 1$



[HRG, *M*<2.5 GeV: Castorina, Cleymans, Miller, Satz, Eur.Phys.J.C66 '10;
lQCD: HotQCD Collaboration, PRD 90 '14]

Kinetic theory under the relaxation time approximation

Transport parameters at $\mu = 0$ for one type of particles

Shear viscosity

$$\eta = \frac{d}{15\,T} \int \frac{d^3p}{(2\pi)^3} \frac{\bar{p}^4}{E^2} \tau f_0 (1 \pm f_0)$$

[Hosoya, Kajantie, NPB250 ’85; Danielewicz, Gyulassy, PRD31 ’85; Sasaki, Redlich, PRC 79 ’09]

Bulk viscosity

$$\zeta = \frac{d}{T} \int \frac{d^3p}{(2\pi)^3} \frac{\tau}{E^2} f_0 (1 \pm f_0) \left\{ \left(E^2 - T^2 \frac{\partial M^2}{\partial T^2} \right) \frac{\partial P}{\partial \epsilon} - \frac{1}{3} \bar{p}^2 \right\}^2$$

[Bluhm, Kämpfer, Redlich, PRC 84 ’11]

Electrical conductivity

$$\sigma = \frac{d\ q^2}{T} \int \frac{d^3p}{(2\pi)^3} \frac{\bar{p}^2}{E^2} \tau f_0 (1 - f_0)$$

[L. Thakur et al., PRD 95 ’17]

Relaxation time: $\tau^{-1} = d \cdot n \cdot \bar{\sigma}$

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Gluons in pure SU(3):

$$\tau_g^{-1}(G(T), T, M_g) = 16 n_g \bar{\sigma}_{gg \to gg}$$

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Light quarks in full QCD:

$$\tau_{\mathrm{u,d}}^{-1}(G(T), T, M_{\mathrm{u,d}}, M_s, M_g) = 12 n_{u,d}(\bar{\sigma}_{ud \to ud} + \bar{\sigma}_{uu \to uu}) +$$

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$$16 n_g \bar{\sigma}_{ug \to ug} + 6 n_s \bar{\sigma}_{us \to us} + 6 n_{\bar{s}} \bar{\sigma}_{u\bar{s} \to u\bar{s}}.$$

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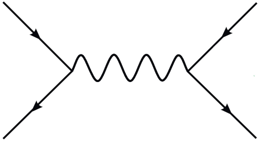
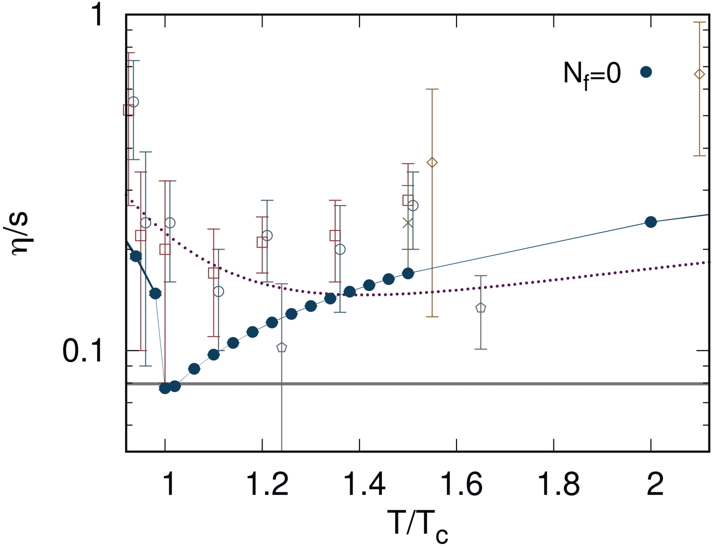


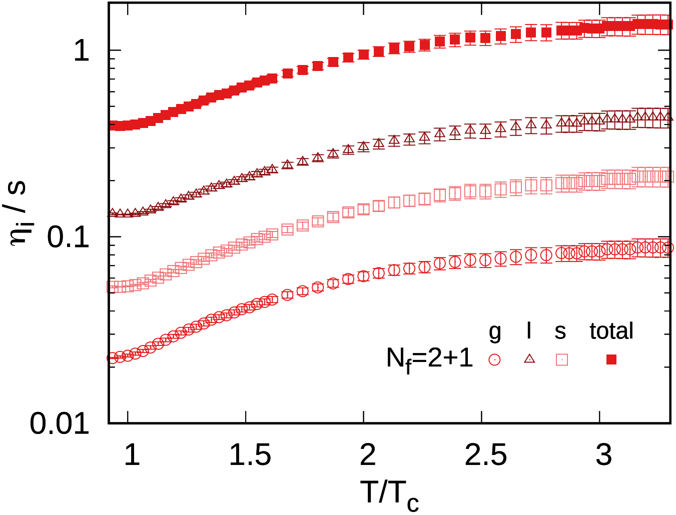
Feynman diaram for $qq' \to qq'$ scattering

Shear viscosity: $N_f = 0$



[dashed, FRG: Christiansen et al., PRL 115 '15 + various lQCD data cited in V. M., Bluhm, Redlich, Sasaki, PRD 100 '19]

Shear viscosity: $N_f = 2 + 1$



[V. M., Bluhm, Redlich, Sasaki, PRD 100 '19]

Perturbative QCD expectations for $N_f = 3$

Perturbative parametrization:

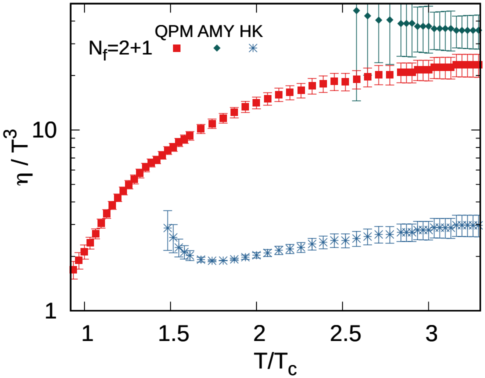
$$\eta_{\mathrm{HK}} = \frac{64\pi^4}{675} \frac{T^3}{g^4 \ln(4\pi/g^2)} \left[\frac{21 N_f}{6.8\,[1 + 0.12(2N_f + 1)]} + \frac{16}{15\,[1 + 0.06 N_f]} \right]$$

NLL expansion in g for $N_f = 3$:

$$\eta_{\mathrm{AMY}} = \frac{T^3}{g^4} \left[\frac{\eta_1}{\ln(\mu_*/m_D)} \right],$$

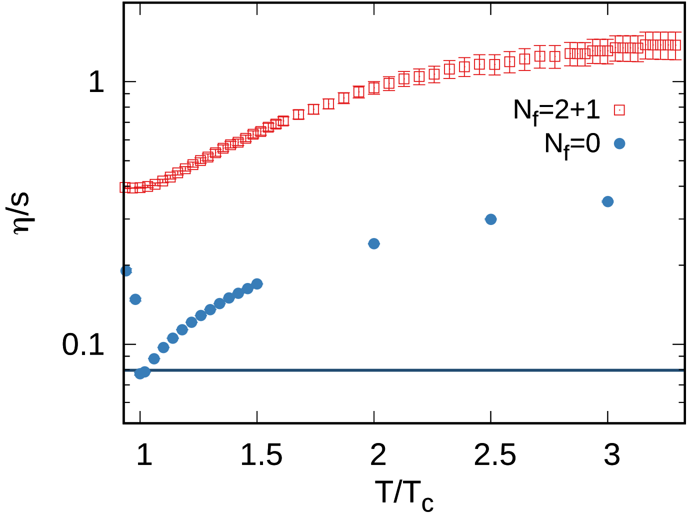
$\eta_1 = 106.66$, $\mu_*/T = 2.957$

$m_D^2 = \frac{1}{2} g^2 T^2$



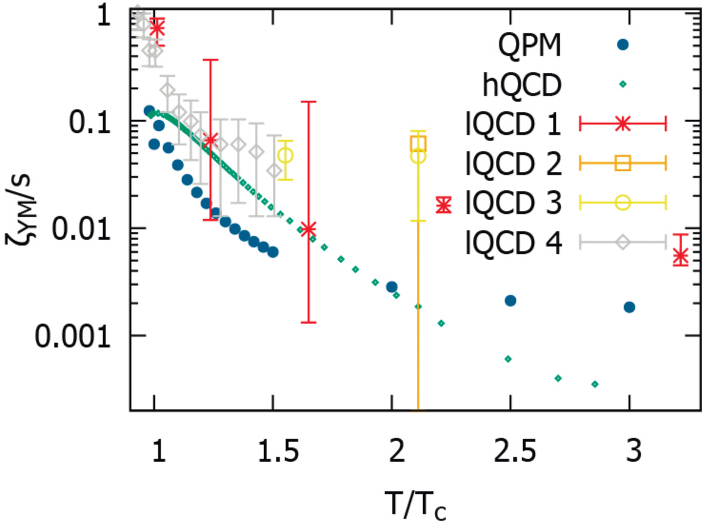
[Hosoya, Kajantie, Nucl.Phys. B 250 ’85; Arnold, Moore, Yaffe, JHEP 030 ’03]

Shear viscosity: $N_f = 0$ vs $N_f = 2 + 1$



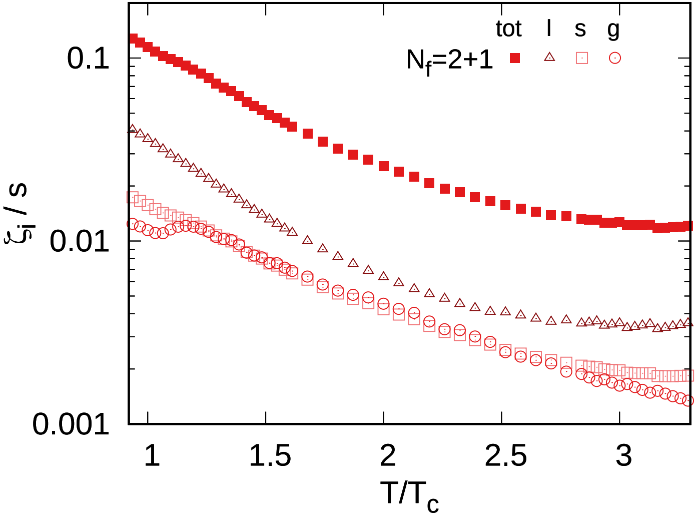
[V. M., Bluhm, Redlich, Sasaki, PRD 100 '19]

Bulk viscosity: $N_f = 0$



[hQCD: Li, He, Huang, JHEP 06 '15; lQCD 1: Meyer, PRL 100 '08; lQCD 2, lQCD 3: Sakai, Nakamura, PoS LAT2007 '07; lQCD 4: Astrakhantsev et al., JHEP 101 '17]

Bulk viscosity: $N_f = 2 + 1$



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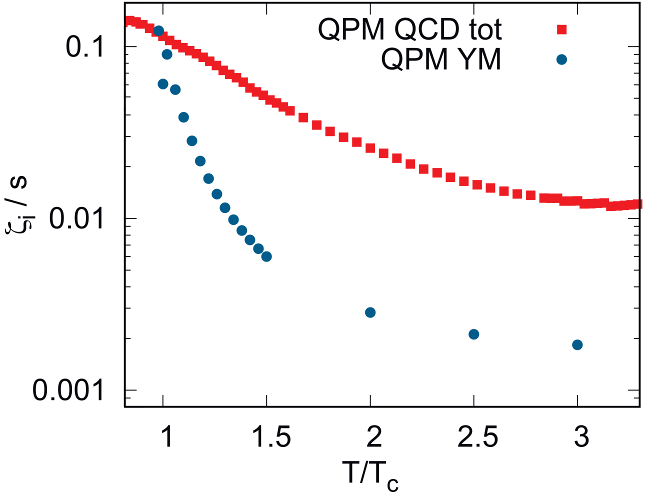
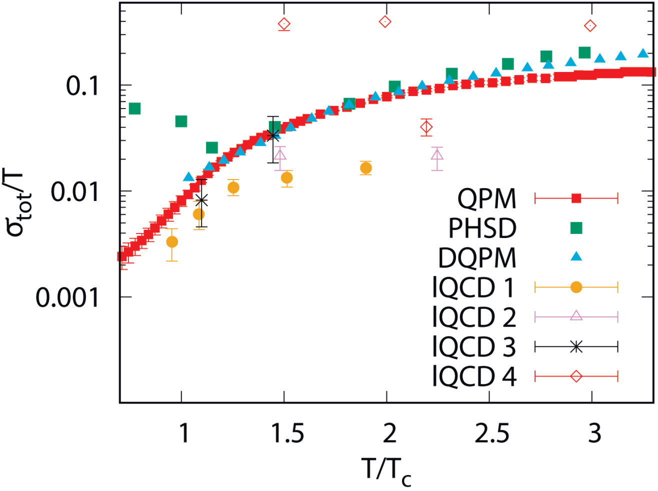


Electrical conductivity: $N_f = 2 + 1$



[PHSD, DQPM: Cassing et al., PRL 110 '13; lQCD1: Amato et al., PRL 111 '13;
lQCD2: Aarts et al., PRL 99 '07; lQCD3: Ding et al., PoS 185 '11; lQCD 4: Gupta et al., PLB 97' 04]

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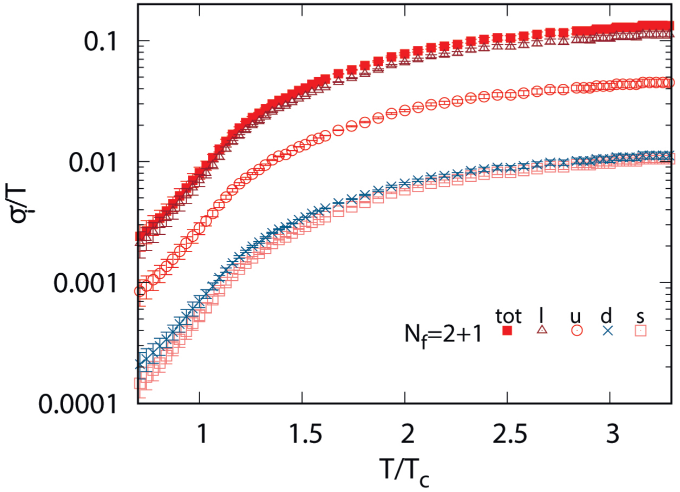

Summary

- Relevant d.o.f. increase viscosity and conductivity of the system;
- $\tau(\bar{\sigma}) \Rightarrow \eta/s$ does not reach the KSS bound for $N_f = 2+1$;
- $\eta/s, \zeta/s$ in agreement with FRG and lQCD for $N_f = 0$;
- Application of $\eta(T), \zeta(T)$ to viscous hydrodynamics.

$\star$ More flavours, non-zero chemical potential...