The role of the strange quasiquarks in transport properties of the QGP

Valeriya Mykhaylova

Institute of Theoretical Physics
University of Wrocław

V. M., C. Sasaki, PRD 103 '21 [arXiv:2007.06846]
V. M., EPJ ST 229 '20 [open access]
V. M., M. Bluhm, C. Sasaki, K. Redlich, PRD 100 '19 [arXiv:1906.01697]

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Uniwersytet Wrocławski

Motivation

Transport properties of QGP: $\eta,\ \zeta, ...$ – input for hydro simulations

- Lattice QCD
- Perturbative QCD
- AdS/CFT
- Effective models
- Green-Kubo formalism
- Kinetic theory
- ...

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Goal: impact of quark quasiparticles on transport parameters in hot QCD: $N_f = 2+1$ vs $N_f = 0$ at $\mu = 0$.

Quasiparticle Model

Propagating through the medium, particles become dressed with

$$m_i[G(T), T],\ i = g, (\underbrace{u, d}_{l}, s).$$

$\Longrightarrow$ Weakly-interacting massive particles with interactions encoded in $m_i[G(T), T]$:

$$P,\ \epsilon,\ s \sim \sum_i \int \frac{d^3p}{(2\pi)^3} f_i^0 \ \ldots;$$

$$f_i^0 = (\exp(E_i/T) \pm 1)^{-1};$$

$$E_i[G(T), T] = \sqrt{p^2 + m_i^2[G(T), T]}.$$

Effective coupling $G(T)$ extracted from the lattice entropy density.

Effective Coupling and Masses

$$s = \sum_{i=l,\bar{l},s,\bar{s},g} \frac{d_i}{\pi^2} \int dp\, 2p^2\, \frac{\frac{4}{3}p^2 + m_i^2[G(T),T]}{E_i(T)T} f_i^0 \;;$$

$$m_i^2[G(T),T] = (m_i^0)^2 + \Pi_i[G(T),T]\,;$$

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[R. Pisarski, NPA498 '89; M. Bluhm et al., EPJC49 '07]

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$$m_i^2[G(T),T] = (m_i^0)^2 + \Pi_i[G(T),T]\, ; \qquad \Pi_{l,s}[G(T),T] = 2\left[m_{l,s}^0 \sqrt{\frac{G^2(T)T^2}{6}} + \frac{G^2(T)T^2}{6}\right]$$

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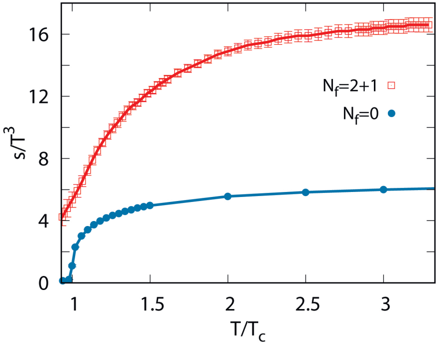

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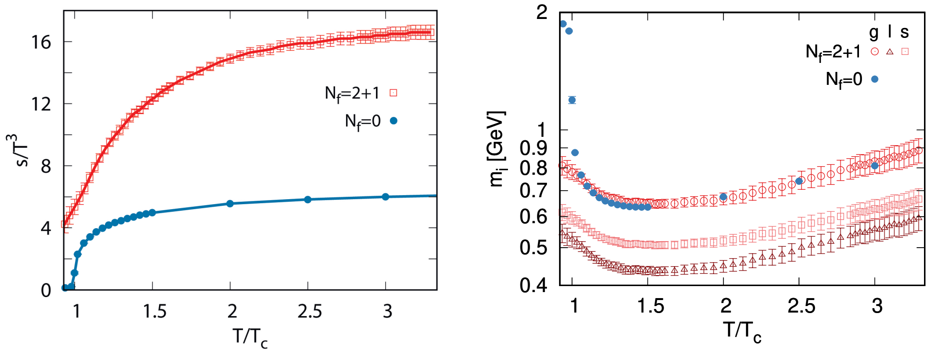
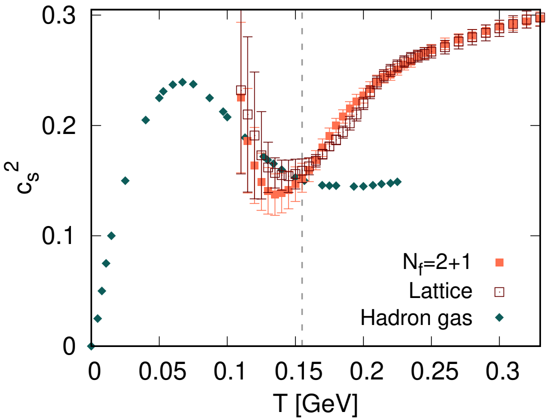


[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 '19; lQCD: Borsanyi et al., JHEP1207, 056 '12; Phys. Lett. '14]

Quasiparticle Model: Thermodynamic Consistency

$$c_s^2 = \frac{\partial P}{\partial \epsilon} = \frac{s}{T}\left(\frac{\partial s}{\partial T}\right)^{-1}$$

QCD with $N_f = 2 + 1$



[V.M and C. Sasaki, PRD 103 '21; lQCD: Borsanyi et al.,PLB730 '14; HRG, m<2.5 GeV: Castorina et al., EPJ C66 '10]

Kinetic Theory: Relaxation Time Approximation

Shear viscosity:

[Hosoya, Kajantie, NPB250 '85]

$$\eta = \frac{1}{15T} \sum_{i=l,\bar{l},s,\bar{s},g} d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} f_i^0 (1 \pm f_i^0) \tau_i$$

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Bulk viscosity:

[Bluhm, Kämpfer, Redlich, PRC 84 '11]

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Electrical conductivity:

[Srivastava, Thakur, Patra, PRC 91 '15]

$$\sigma = \frac{1}{3T} \sum_{i=u,\bar{u},d,\bar{d},s,\bar{s}} q_i^2 \, d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{E_i^2} f_i^0 (1 - f_i^0) \tau_i$$

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$*$ common relaxation time $\tau_i \to \tau_i$-indepedent ζ/η, $(\eta/s)/(\sigma/T)$ ratios

Relaxation Time Complexity: Pure Yang-Mills vs QCD

Pure Yang-Mills theory:

$$\tau_g^{-1} = n_g \bar{\sigma}_{gg \to gg}$$

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QCD:

→ Gluons:

$$\tau_g^{-1} = n_g (\bar{\sigma}_{gg \to gg} + \bar{\sigma}_{gg \to l\bar{l}} + \bar{\sigma}_{gg \to s\bar{s}}) +$$

$$n_l\, \bar{\sigma}_{gl \to gl} + n_{\bar{l}}\, \bar{\sigma}_{g\bar{l} \to g\bar{l}} + n_s\, \bar{\sigma}_{gs \to gs} + n_{\bar{s}}\, \bar{\sigma}_{g\bar{s} \to g\bar{s}}$$

Relaxation Time Complexity: Pure Yang-Mills vs QCD

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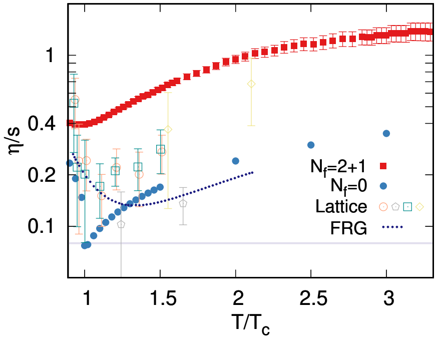
$$n_l\,\bar{\sigma}_{gl\to gl} + n_{\bar{l}}\,\bar{\sigma}_{g\bar{l}\to g\bar{l}} + n_s\,\bar{\sigma}_{gs\to gs} + n_{\bar{s}}\,\bar{\sigma}_{g\bar{s}\to g\bar{s}}$$

→ Strange quarks:

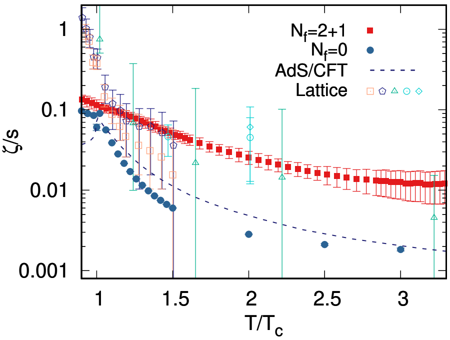
$$\tau_s^{-1} = n_l\,\bar{\sigma}_{sl\to sl} + n_{\bar{l}}\,\bar{\sigma}_{n\bar{l}\to s\bar{l}} + n_s\,\bar{\sigma}_{ss\to ss} + n_{\bar{s}}\,\bar{\sigma}_{s\bar{s}\to s\bar{s}} + n_g\,\bar{\sigma}_{sg\to sg}$$

∗ relaxation times τ_i are momentum-independent

Shear and Bulk Viscosities: $N_f = 2+1$ vs $N_f = 0$

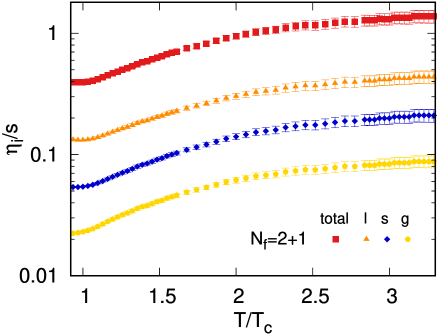


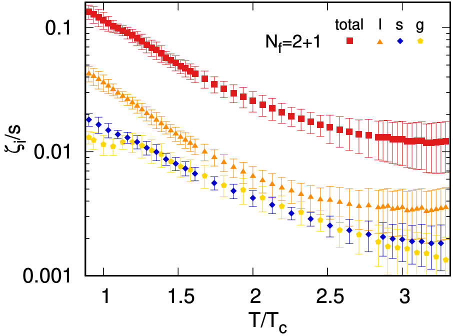
[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 '19; FRG: Christiansen et al., PRL 115 '15; lQCD: Nakamura, Sakai, PRL 94 '05; Meyer, PRD 76 '07; Astrakhantsev et al.,JHEP 1704 '17]



[V.M. and C. Sasaki, PRD 103 '21; AdS/CFT: Li et al., JHEP 06 '15; lQCD: Meyer, PRL 100 '08; Sakai, Nakamura, PoS LAT2007 '07; Astrakhantsev et al., JHEP 101 '17]

Individual Contributions to Shear and Bulk Viscosity





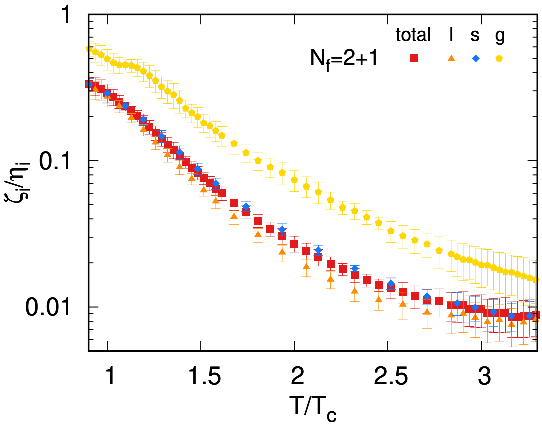
$$\eta = \frac{1}{T} \sum_{i=l,\bar{l},s,\bar{s},g} d_i \int \frac{d^3p}{(2\pi)^3} f_i^0(1 \pm f_i^0) \frac{\tau_i}{E_i^2} \frac{p^4}{15}$$

$$\zeta = \frac{1}{T} \sum_{i=l,\bar{l},s,\bar{s},g} d_i \int \frac{d^3p}{(2\pi)^3} f_i^0(1 \pm f_i^0) \frac{\tau_i}{E_i^2} \left\{ \left(E_i^2 - T^2 \frac{\partial m_i^2(T)}{\partial T^2} \right) c_s^2 - \frac{p^2}{3} \right\}^2$$

[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 '19; V.M. and C. Sasaki, PRD 103 '21]

Bulk to Shear Viscosity Ratio

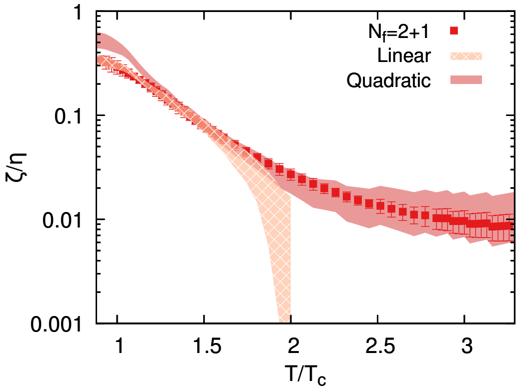
$$\frac{\zeta}{\eta} \text{ (total) vs } \frac{\zeta_g}{\eta_g} \text{ vs } \frac{\zeta_s}{\eta_s} \text{ vs } \frac{\zeta_l}{\eta_l}$$



Non-perturbative vs Perturbative QCD Regimes

Linear: $\frac{\zeta}{\eta} \propto \left(\frac{1}{3} - c_s^2\right)$ – AdS/CFT [Buchel, PRD 72 '05]

Quadratic: $\frac{\zeta}{\eta} \propto \left(\frac{1}{3} - c_s^2\right)^2$ – pQCD [Weinberg, Astrophys. J. 168 '71]



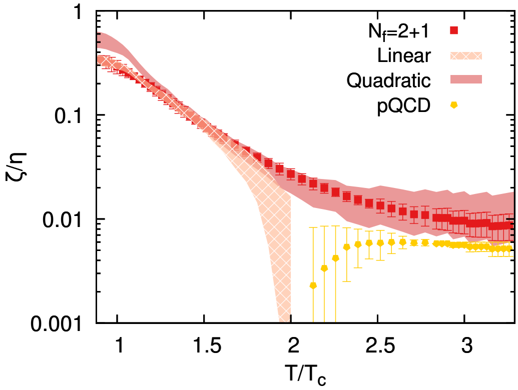
[V.M. and C. Sasaki, PRD 103 '21]

pQCD NLL Approximation

$$\eta_{\mathrm{NLL}} = \frac{T^3}{g^4} \frac{\eta_1}{\ln(\mu_1^*/m_D)}, \quad \zeta_{\mathrm{NLL}} = \frac{A g^4 T^3}{16\pi^2 \ln(\mu_2^*/m_D)}$$

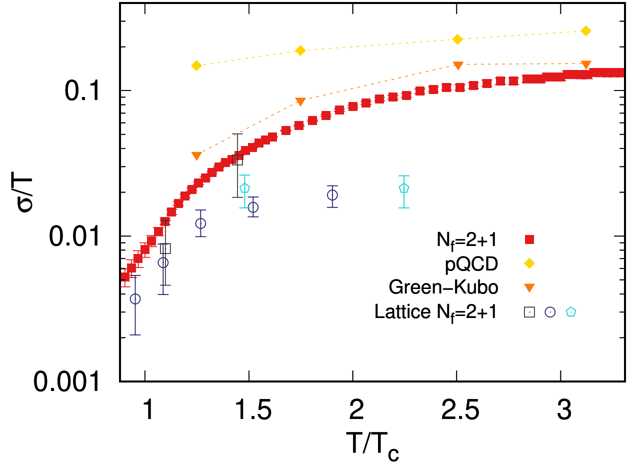
$$m_D^2 = (1 + N_f/6) g^2 T^2, \; g \to G(T)$$

[Arnold, Moore, Yaffe, JHEP 05 '03; Arnold, Dogan, Moore, PRD 74 '06]



[V.M. and C. Sasaki, PRD 103 '21]

Electrical Conductivity: $N_f = 2 + 1$



[V.M, C. Sasaki, PRD 103 '21; Puglisi et al., PRD 90 '14; Ding et al., PoS 185 '11; Amato et al., PRL 111 '13; Aarts et al., JHEP 02 '15]

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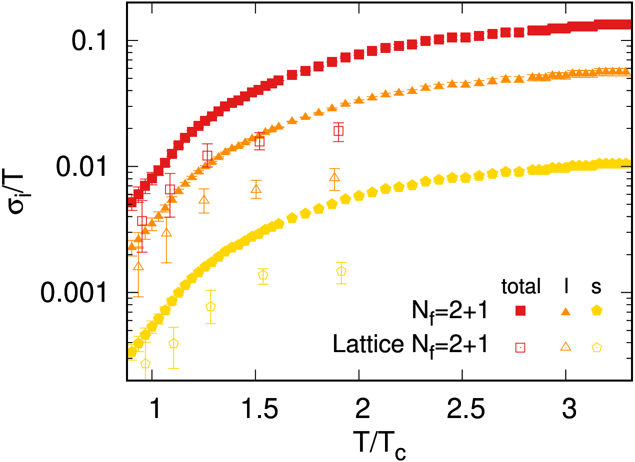
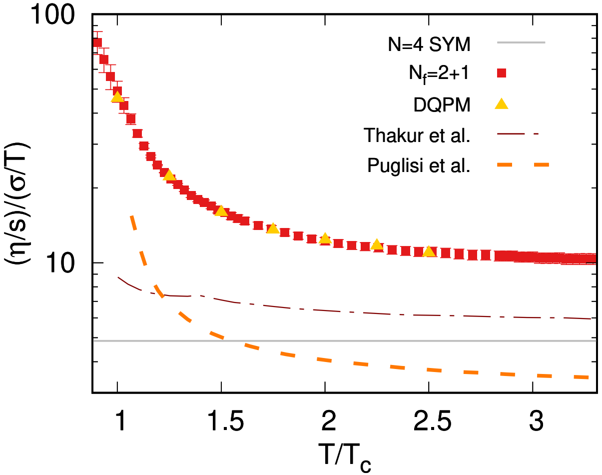


lQCD: $M_\pi \approx 384$ MeV $\implies$ larger quark masses

[V.M., EPJ ST 229 '20; lQCD: G. Aarts et al., JHEP 02 '15]

Shear viscosity to Electrical Conductivity: $N_f = 2 + 1$



$$\frac{\eta/s}{\sigma/T} \sim \frac{\tau_g}{\tau_l + \tau_s}$$

[V.M., EPJ ST 229 '20; DQPM: Soloveva et al., PRC 101 '20; L. Thakur et al. PRD 95 '17; A. Puglisi et al,. PLB 751 '15]

Summary

Quasiparticle Model:

- consistent with lattice EoS;
- accommodates non-perturbative effects around T_c;
- corresponds to the pQCD expectations at high T;
- gives transport parameters consistent with other approaches;
- investigates role of different quark flavors in $\zeta,\ \eta,\ \sigma$.

Perspective: $\mu \neq 0$, $\tau_\eta \neq \tau_\zeta$, heavy flavors...