Transport properties of the QGP with strange and charm quark quasiparticles

Valeriya Mykhaylova

Institute of Theoretical Physics
University of Wrocław

V. M., C. Sasaki, Phys.Rev.D 103 (2021) [arXiv:2007.06846]
V. M., M. Bluhm, C. Sasaki, K. Redlich, Phys.Rev.D 100 (2019) [arXiv:1906.01697]

Uniwersytet Wrocławski

Motivation

Transport properties of QGP: $\eta/s,\ \zeta/s, \ldots$ – input for hydro simulations

- Lattice QCD
- Perturbative QCD
- AdS/CFT
- Effective models
- Green-Kubo formalism
- Kinetic theory
- $\ldots$

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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

⋆ similar to massive quasielectron moving freely in solid states

QGP:		QGP:
$\sim$ massless,	$\longrightarrow$	massive,
strongly-interacting particles		weakly-interacting **quasi**particles

Quasiparticle Model

Particles propagate through the medium and become dressed with

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

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

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

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

Effective coupling $G(T)$ extracted from LQCD entropy density

Quasiparticle Model: Effective 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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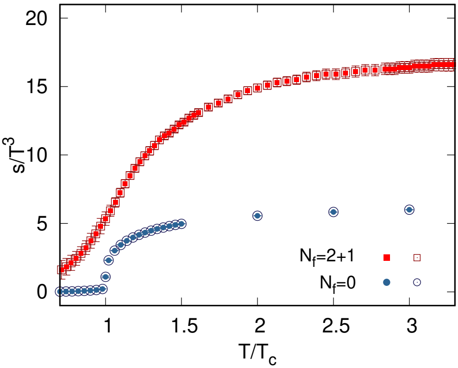

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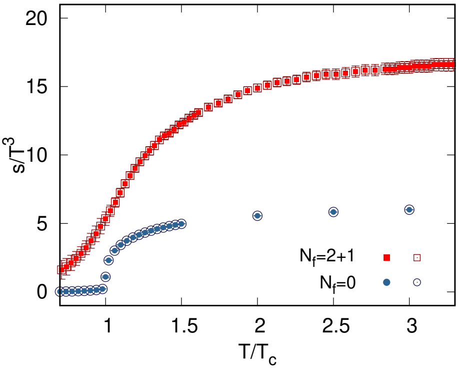

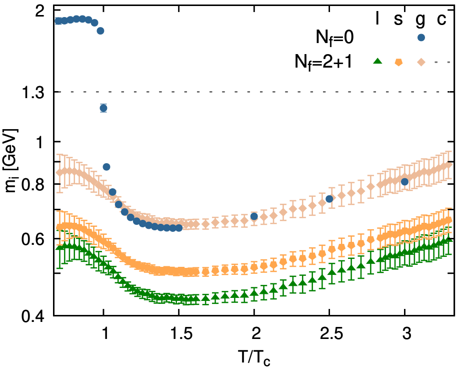

[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019); lQCD: Borsanyi et al., JHEP1207, 056 (2012); Phys. Lett. B 730 (2014)]

Transport coefficients in the relaxation time approximation

Shear viscosity $\sim$ longitudinal motion

$$\eta = \frac{2}{15T} \sum_{i=l,s,g} \int_0^\infty \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} d_i \tau_i f_{0,i}(1 \pm f_{0,i}) \quad \longrightarrow \quad \eta_g \text{ for } N_f = 0$$

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

Bulk viscosity $\sim$ volume expansion

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

[Bluhm, Kämpfer, Redlich, PRC 84 '11]

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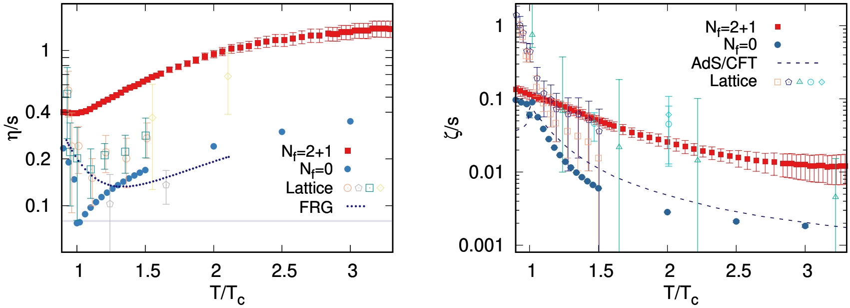
[Bluhm, Kämpfer, Redlich, PRC 84 '11] Relaxation time of strange quarks in $N_f = 2+1$ QGP:

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

Shear and bulk viscosities: $N_f = 0$ vs $N_f = 2+1$



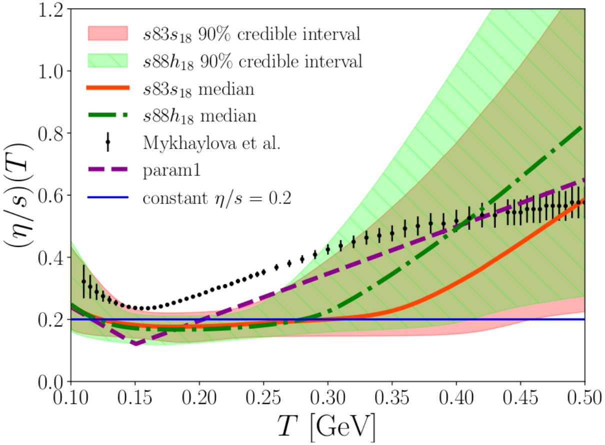
Based on transport cross-sections: $\sigma_{12\rightarrow 34}[sin^2(\theta)]$

[FRG: Christiansen, Haas, Pawlowski, Strodthoff, PRL 115 '15; lQCD: Nakamura, Sakai, PRL 94 '05; Meyer, PRD 76 '07; Astrakhantsev et al.,JHEP 1704 '17]

[AdS/CFT: Li et al., JHEP 06 '15; lQCD: Meyer, PRL 100 '08; Sakai, Nakamura, PoS LAT2007 '07; Astrakhantsev et al., JHEP 101 '17]

Specific Shear Viscosity - total cross sections

$\frac{\eta}{s}(\sigma_{tr}[sin^2\theta])$: min at $\simeq$ 0.4 vs $\frac{\eta}{s}(\sigma_{tot}[sin^2\theta = 1])$: min at $\simeq$ 0.2

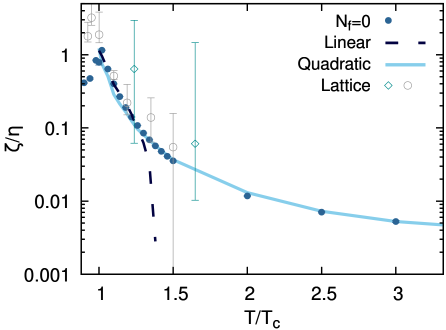


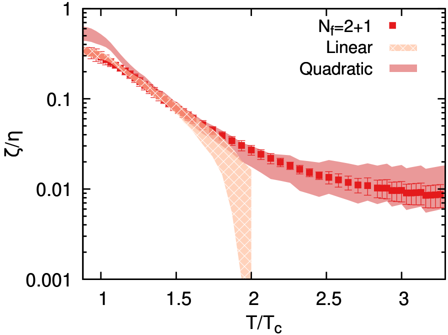
[J. Auvinen et al., Phys.Rev.C 102 (2020)]

Non-perturbative vs Perturbative QCD Regimes

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

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





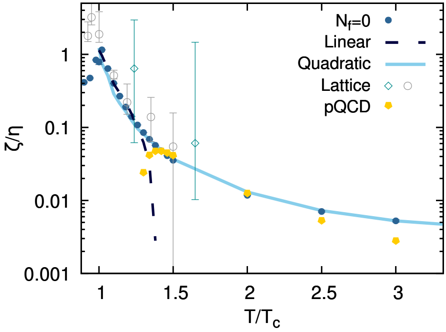
[V.M., C. Sasaki, PRD 103 '21; lQCD:Astrakhantsev et al., JHEP 1704 '17; JHEP 101 '17]

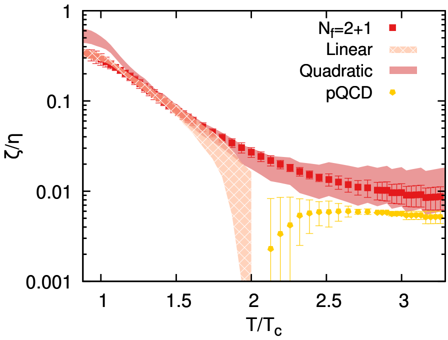
pQCD NLL Approximation

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

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

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





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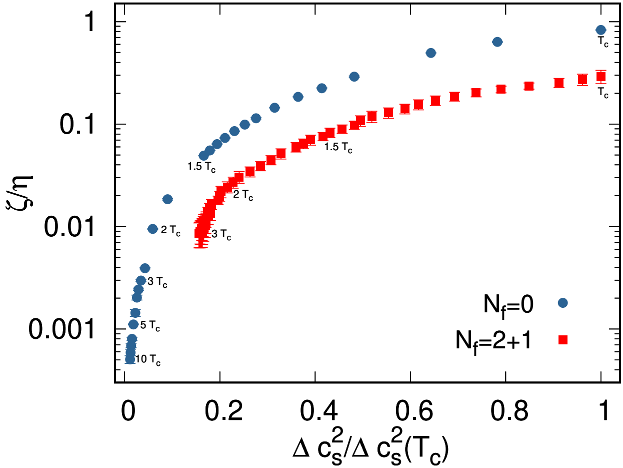
Conformal limit

Restoration of conformal invariance is delayed by quasiquarks

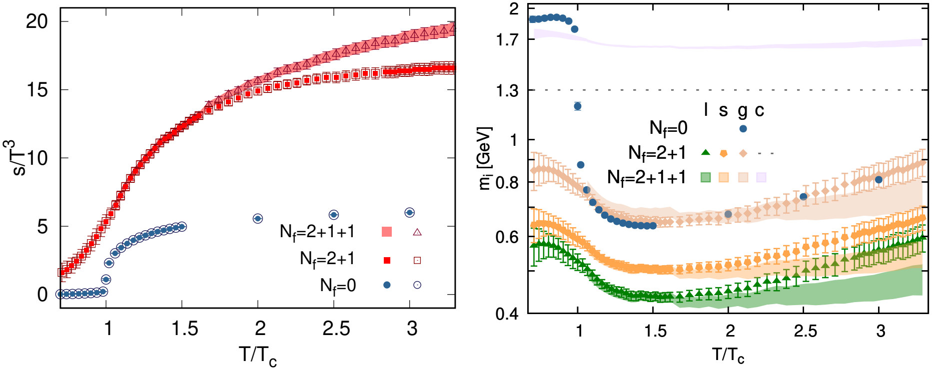


$\Delta c_s^2 = \frac{1}{3} - c_s^2$ – conformality measure

Quasiparticle model with thermalized charm quarks: $N_f = 2 + 1 + 1$

Charm quarks contribute to EoS at $T \geq 300$ MeV ($\simeq 2T_c$)

[Sz. Borsanyi et al., Nature 539 (2016)]



Preliminary

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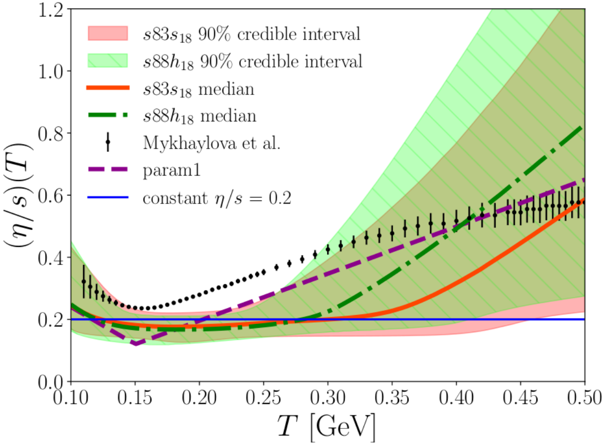

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Summary

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;
- phenomenological study of QCD for different N_f;

Perspectives: $\mu \neq 0$, magnetic field, anisotropy, higher-order cross sections, more inelastic scatterings, B flavor, hadronic phase...

Time evolution of the QGP: $T(\tau) = ?$

For longitudinally expanding boost-invariant medium ($\zeta = 0$)

$$\frac{\partial \epsilon}{\partial \tau} + (\epsilon + P)\frac{1}{\tau} = \frac{\Phi}{\tau}$$

Ideal hydro: $\Phi = 0 \quad \Rightarrow \quad s(\tau) \cdot \tau = s_0(\tau_0) \cdot \tau_0$

Second-order viscous hydro (Israel-Muller) [A. Muronga PRL 88 (2002)]:

$$\frac{\partial \Phi}{\partial \tau} = -\frac{\Phi(\epsilon + P)}{5\eta} - \frac{4\Phi}{3\tau} + \frac{4(\epsilon + P)}{15\tau}$$

$\star$ Same initial conditions for all: $\tau_0 = 0.2$ fm, $T_0 = 0.624$ GeV
[J. Auvinen et al., Phys.Rev.C 102 (2020)]

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