QUARK-GLUON PLASMA THROUGH THE PRISM OF QUASIPARTICLES

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Outlook

☞ Quark-gluon plasma and its transport properties

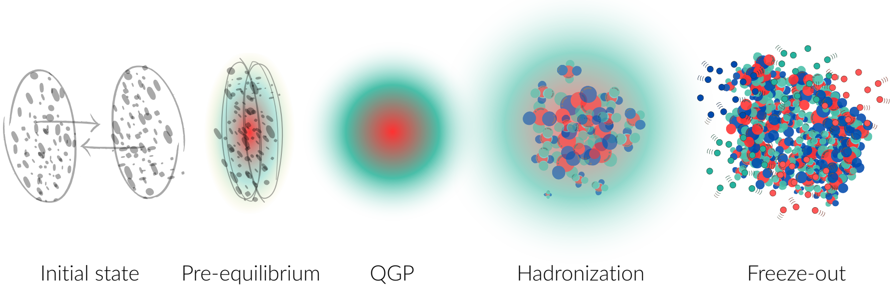
☞ Effective Tool – Quasiparticle approach

☞ What can be studied?

- ➢ Shear and bulk viscosities
- ➢ Electrical conductivity
- ➢ Charm production in quasiparticle picture

Quark-Gluon Plasma

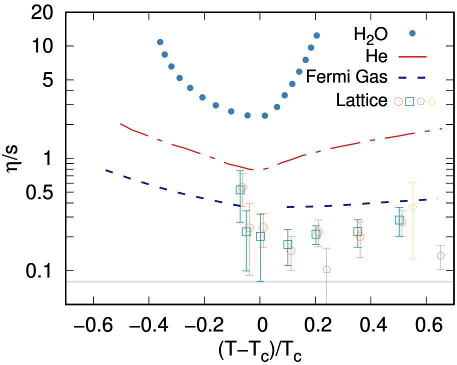
☞ strongly coupled fluid produced in heavy ion collisions:



☞ phase of matter in extreme conditions: $T \sim 10^{12}$ K, $\tau \sim 10^{-6}$ s

Transport Phenomena in Hot QCD

Longitudinal motion - friction between layers - shear viscosity η

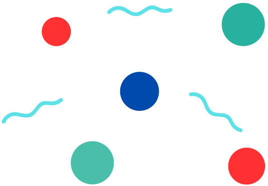


Lattice QCD data for pure SU(3) – no quarks

Quasiparticle Model - Effective Approach to QCD

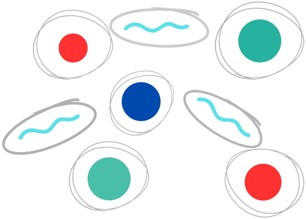
☞ similar to massive quasielectrone moving freely in solid states

Quark-gluon plasma:



Reality:
strongly-interacting particles,
constant (bare) masses m_i^0

$\longrightarrow$



Effective approach:
weakly-interacting **quasi**particles,
dynamical $m_i[T, G(T)]$

Quasiparticle Model

Quasiparticles are „dressed" with effective masses $m_i[G(T), T]$:

$$m_i[G(T), T] = \sqrt{(m_i^0)^2 + \Pi_i[G(T), T]} \tag{1}$$

self-energies Π_i:

$$\text{gluons:}\;\; \Pi_g[G(T), T] = \left(3 + \frac{N_f}{2}\right) \frac{G^2(T)}{6} T^2 \tag{2}$$

$$\text{quarks:}\;\; \Pi_{l,s}[G(T), T] = 2\left[m_{l,s}^0 \sqrt{\frac{G^2(T)T^2}{6}} + \frac{G^2(T)T^2}{6}\right] \tag{3}$$

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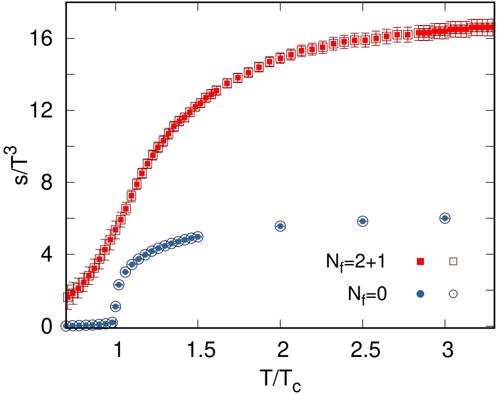
☞ effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

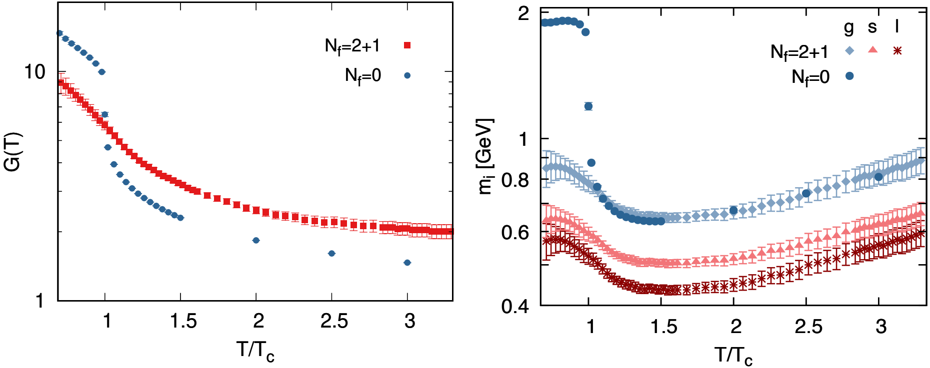
Quasiparticle Model

$$s(T) \sim \sum_{i=g,l,s,\ldots} \int f_i^0(m_i[G(T), T]) = \text{lattice data} \rightarrow G(T) \qquad (4)$$

$$E[G(T), T] = \sqrt{p^2 + m_i^2[G(T), T]} \qquad (5)$$



Effective Coupling and Masses



$$m_i[G(T), T] = \sqrt{(m_i^0)^2 + \Pi_i[G(T), T]} \tag{6}$$

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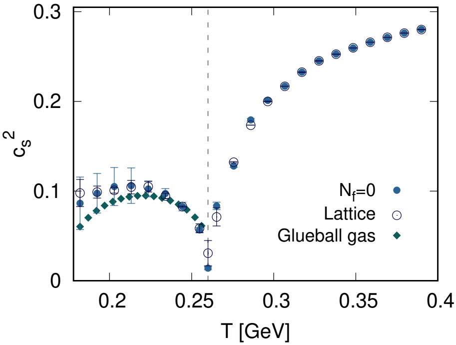
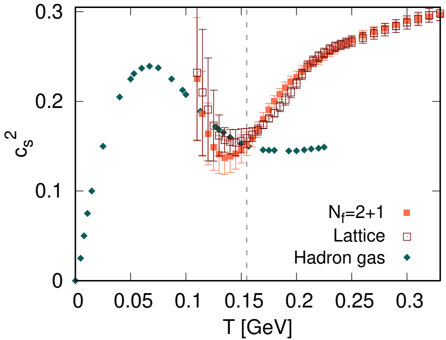
Thermodynamic Consistency

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

Pure SU(3), $N_f = 0$



QCD, $N_f = 2+1$



☞ Ideal gas: $c_s^2 = 1/3$ vs Quasiparticle model: $c_s^2 \to 1/3$ as $T \to \infty$

[V.M, C. Sasaki, PRD103 '21]

Kinetic Theory: Relaxation Time Approximation

Boltzmann Equation:

$$p^\mu \partial_\mu f_i = \mathcal{C}[f_i] \sim \int \omega(f_i' f_j' - f_i f_j) \tag{9}$$

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$$p^\mu \partial_\mu f_i = \mathcal{C}[f_i] \sim \int \omega(f_i' f_j' - f_i f_j) \simeq -\frac{f_i - f_i^0}{\tau_i} \tag{10}$$

Approximate solution: f_i relaxes to equilibrium value f_i^0 in time τ_i

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Pure gluon plasma ($N_f = 0$):

$$\tau_g = [n_g^0 \bar{\sigma}_{gg \to gg}]^{-1}; \qquad n_i^0 \sim \int f_i^0 \quad (11)$$

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$\rightarrow$ Get transport coefficients in the τ-approximation

Kinetic Theory: Relaxation Time Approximation

Shear viscosity (reaction to flow): $\rightarrow \eta_g,\ \zeta_g$ for gluon plasma ($N_f = 0$)

[Hosoya, Kajantie, NPB250 '85]

$$\eta = \frac{1}{15\,T} \sum_{i=g,l,s,\ldots} d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} f_i^0 (1 \pm f_i^0)\, \tau_i \tag{13}$$

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Bulk viscosity (reaction to volume expansion):

[Bluhm, Kämpfer, Redlich, PRC 84 '11]

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Electrical conductivity: $\rightarrow \sigma_g = 0$

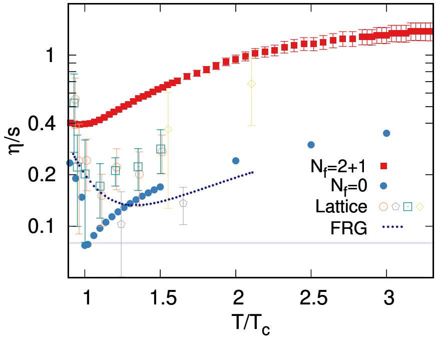
[Srivastava, Thakur, Patra, PRC 91 '15]

$$\sigma = \frac{1}{3T} \sum_{i=u,d,s,\dots} q_i^2\, d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{E_i^2} f_i^0 (1 - f_i^0)\, \tau_i \tag{14}$$

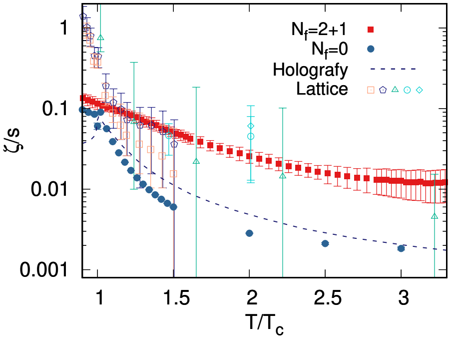
common relaxation times τ_i

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

Shear viscosity (flow)



Bulk viscosity (volume)



☞ Dynamical quarks increase viscosities of hot QCD matter

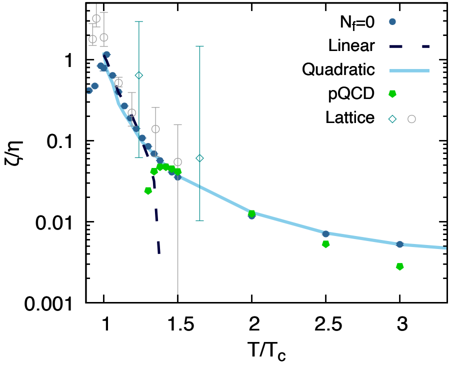
☞ Faster restoration of conformal invariance for gluon plasma

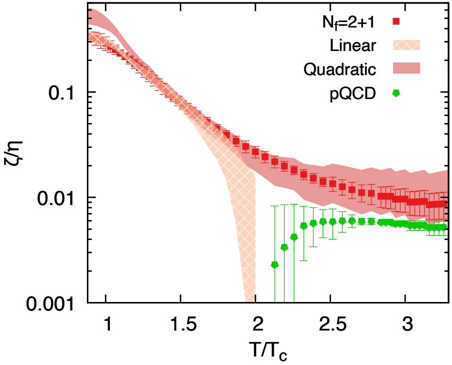
[V. M., C. Sasaki, PRD103 '21; V. M., M. Bluhm, K. Redlich, C. Sasaki, PRD100 '19]

Non-perturbative vs Perturbative QCD Regimes

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

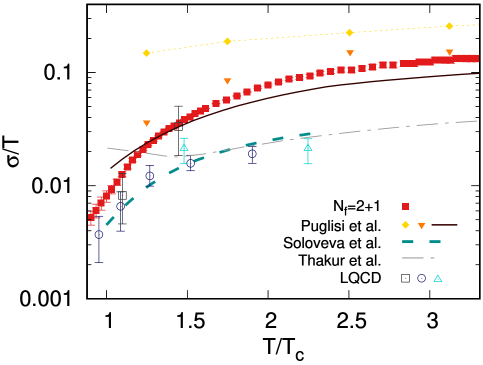
$$\text{Quadratic:} \quad \frac{\zeta}{\eta} \propto \left(\frac{1}{3} - c_s^2\right)^2 \; - \; \text{pQCD} \; \text{[Weinberg, Astrophys. J. 168 '71]}$$





[V.M., C. Sasaki, PRD 103 '21; pQCD w. G(T): Arnold, Moore, Yaffe, JHEP 05 '03; Arnold, Dogan, Moore, PRD 74 '06]

Electrical Conductivity: $N_f = 2 + 1$



☞ Overall agreement with other models and lattice at low T

Lattice: $m_\pi \approx 384\ \mathrm{MeV} \implies$ larger bare quark masses

[V. M. and C. Sasaki, PRD 103 '21; V.M. EPJ ST 229 '20]

Charm Quark Evolution

☞ Charm quarks survive through QGP lifetime

$$m_c^0 = 1300 \text{ MeV} > m_i[G(T), T] \simeq 400 - 900 \text{ MeV} \gg m_s^0, m_l^0$$

➛ Better understanding of QGP properties and evolution

☞ Production/Reduction of charm quarks

➛ Details of charm in-medium interactions

Task:

Add charm quarks as obstacles to QGP with $N_f = 2 + 1$ in equilibrium, see how their abundance change with time τ.

Charm Quark Evolution

Rate equation [Biro et al., PRC 48 '93; Zhang et al., PRC 77 '08]:

$$\partial_\mu n_c^\mu[\lambda(T)] = \left(1 - \frac{n_c^2[\lambda(T)]}{(n_c^0)^2}\right) R_{gain} \tag{15}$$

Fugacity $\lambda(T)$ shows how far is equilibrium, $n_c^0 = n_c[\lambda = 1]$

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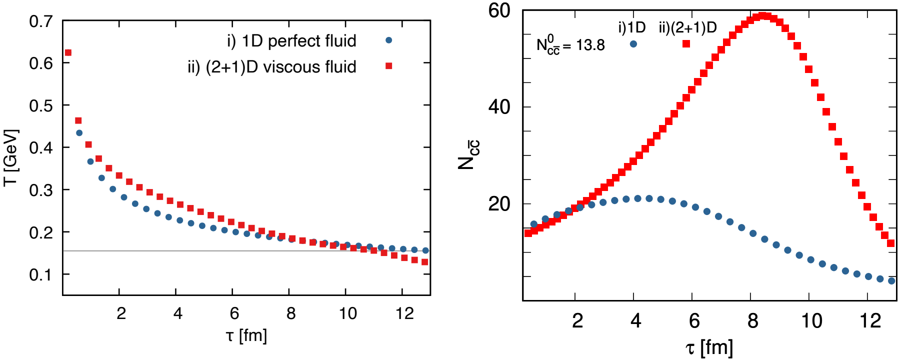
☞ Time evolution $T(\tau)$? Study 2 cases:

- ➛ Longitudinal propagation of ideal fluid (Bjorken flow)
- ➛ (2+1)D expansion of viscous fluid (+ shear viscosity η/s)

Charm Quark Evolution



☞ (2+1)D viscous expansion – initial and final charm numbers are roughly the same [Andronic, Braun-Munzinger, Redlich, Stachel, Vislavicius, JHEP 07 '21]

[(2+1)D viscous hydro: Auvinen, Eskola, Huovinen, Niemi, Paatelainen, Petreczky, PRC 102 '20; V.M., C. Sasaki, K. Redlich: preliminary, to appear on arXiv]

Summary

☞ **Quark-Gluon Plasma** – peculiar state of strongly interacting matter with unique properties and a lot of open questions.

☞ **Quasiparticle Model** – powerful tool connecting non-perturbative and perturbative QCD regimes (strong vs weak coupling).

☞ **Perspectives** – $\tau_\eta \neq \tau_\zeta$, exact solution of Boltzmann equation, momentum anisotropy, magnetic effects...

Thank you for attention! Stand with Ukraine!