EXPLORING THE PROPERTIES OF HOT QCD MATTER IN THE QUASIPARTICLE APPROACH

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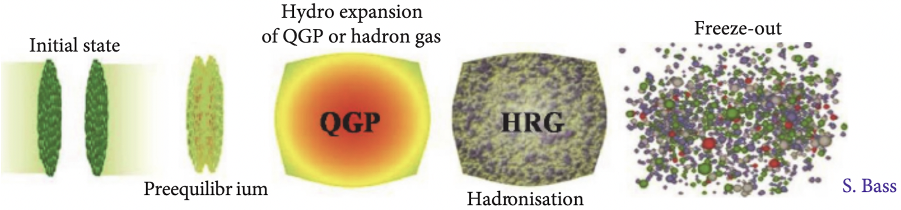
Outlook

1. What do we study?
   - Quark-gluon plasma & its transport properties
2. What do we use?
   - Quasiparticle model & kinetic theory
3. What did we find?
   - Transport parameters - shear & bulk viscosities, ...

Quark-Gluon Plasma

- Subject of Quantum ChromoDynamics (QCD) – theory of strong interactions
- Strongly coupled fluid produced in heavy ion collisions:



- Phase of matter in extreme conditions: $T \geq 155$ MeV, $\tau \simeq 10$ fm
- Mixture of *deconfined* quarks and gluons

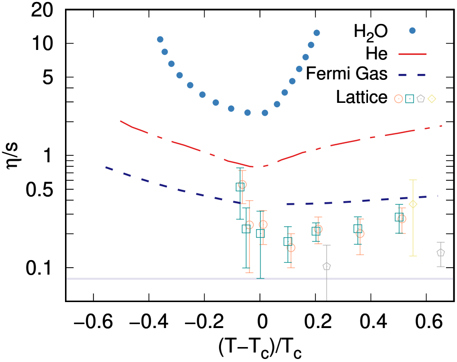
Transport Phenomena in hot QCD

Longitudinal motion - friction between layers - shear viscosity η

Resistance to volume expansion/compression- bulk viscosity ζ

+ electrical conductivity, heat conductivity ...

Transport Phenomena in Hot QCD



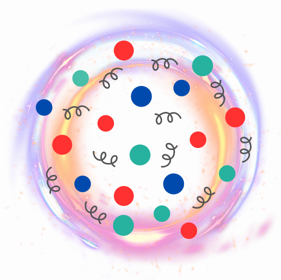
Lattice QCD data for gluon plasma (no quarks)

[V.M., "Transport Properties of Hot QCD Matter in the Quasiparticle Approach", PhD Thesis]

Quasiparticle Model

☞ similar to massive quasielectron moving freely in solid states

Real QGP:



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

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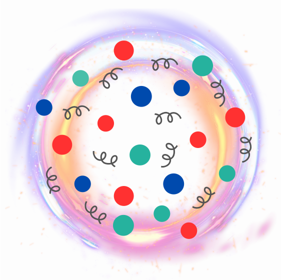
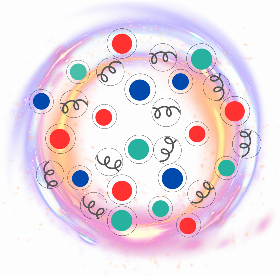


strongly-interacting particles, constant (bare) masses m_i^0

$\longrightarrow$

Effective approach:



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

Quasiparticle Model

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

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

self-energies Π_i from perturbative QCD:

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

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

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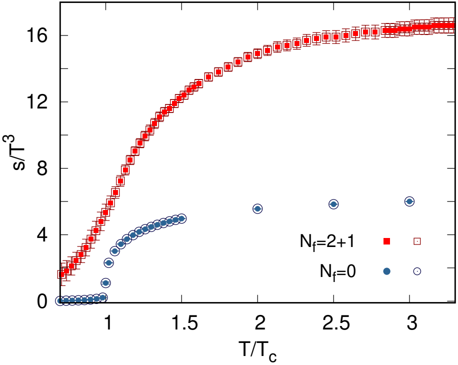
☞ effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

Quasiparticle Model

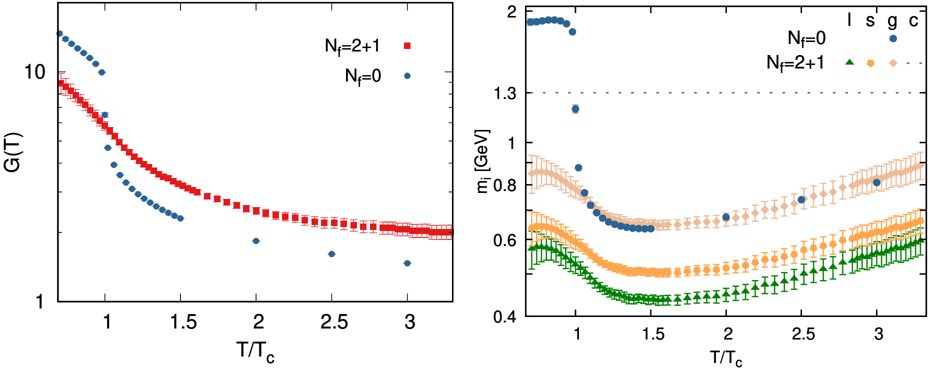
$$s(T) \simeq \sum_{i=g,l,s,..} \int d^3p\,([1 \pm f_i^0]\ln[1 \pm f_i^0] \mp f_i^0 \ln f_i^0) = \text{lattice data} \to G(T)$$

$$f_i^0(E_i): \quad E_i[G(T),T] = \sqrt{p^2 + m_i^2[G(T),T]} \qquad (4)$$



[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019); lattice: Wuppertal-Budapest]

Effective Coupling and Masses

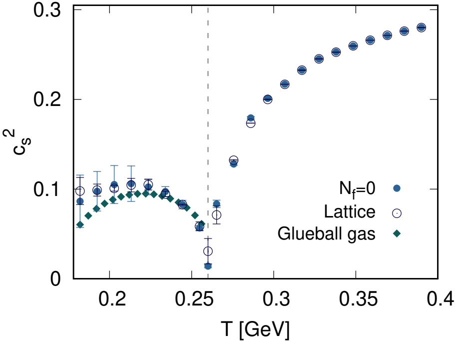


$$\mathrm{m}_i[G(T), T] \gg m_l^0 = 5 \text{ MeV}, \; m_s^0 = 95 \text{ MeV}$$

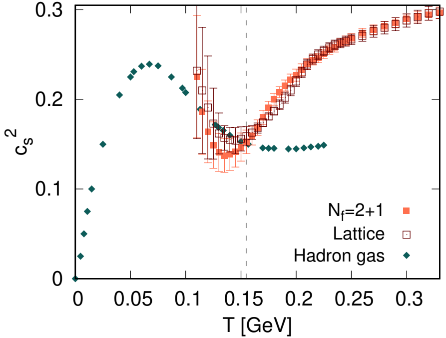
Thermodynamic Consistency

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

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:

$$p^\mu \partial_\mu f_i = \mathcal{C}[f_i] \sim \int \omega(f_i' f_j' - f_i f_j) \tag{5}$$

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

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Pure gluon plasma ($N_f = 0$):

$$\tau_g = \frac{1}{n_g^0 \bar{\sigma}_{gg\to gg}} = [n_g^0 \bar{\sigma}_{gg\to gg}]^{-1}; \qquad n_i^0 \sim \int f_i^0 \tag{7}$$

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$\rightarrow$ Compute 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]

$$\eta = \frac{1}{15\,T} \sum_{i=g,l,s,\ldots} d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} f_i^0 (1 \pm f_i^0)\, \tau_i \tag{9}$$

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Electrical conductivity: $\rightarrow \sigma_g = 0$

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

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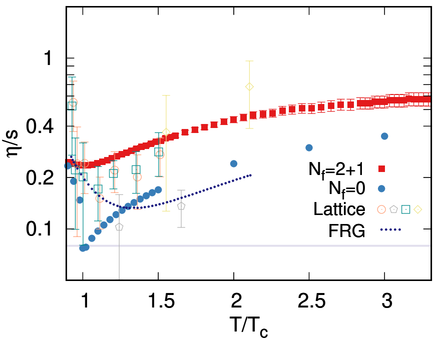
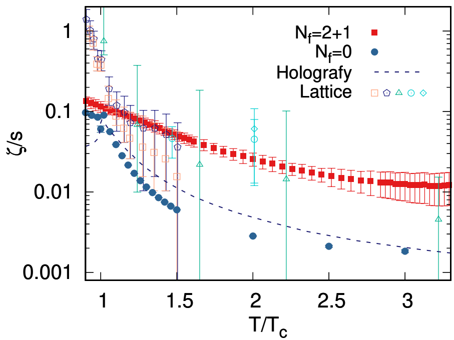
$\ast$ common relaxation times τ_i

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

Shear viscosity (flow)



Bulk viscosity (volume)



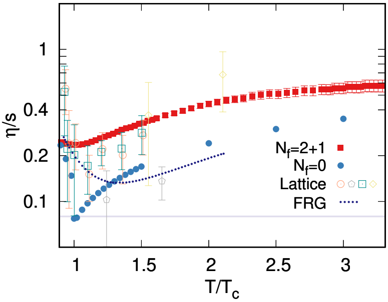
⟵ time

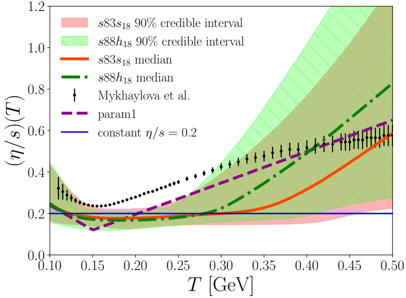
⋆ Dynamical quarks increase viscosities of hot QCD matter

⋆ Faster restoration of conformal invariance for gluon plasma

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

Specific Shear Viscosity



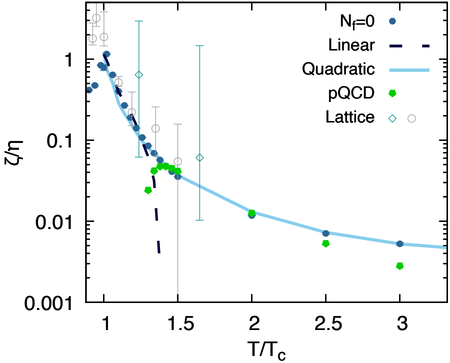


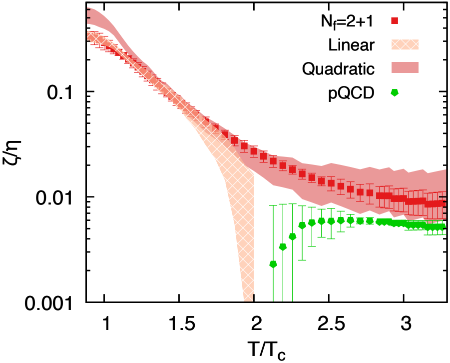
[V.M., M. Bluhm, K. Redlich, C. Sasaki, PRD100 '19; Auvinen, Eskola, Huovinen, Niemi, Paatelainen, Petreczky, PRC 102 '20]

Non-Perturbative vs Perturbative QCD Regimes

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

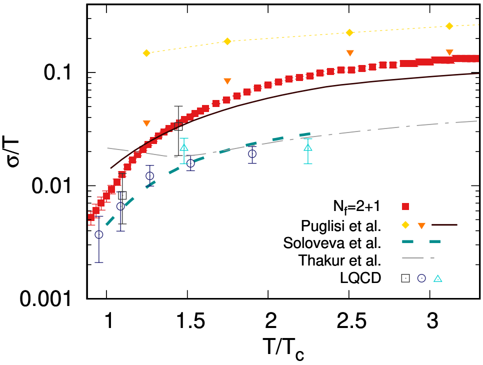
$$\text{Quadratic:} \quad \frac{\zeta}{\eta} \propto \left(\frac{1}{3} - c_s^2\right)^2 \; - \; \text{pQCD (weak G)} \; \text{[Weinberg, Astrophys. J. 168 '71]}$$





[V.M., C. Sasaki, PRD 103 '21; pQCD: Arnold, Moore, Yaffe, JHEP 05 '03; Arnold, Dogan, Moore, PRD 74 '06]

Electrical Conductivity of QGP



⋆ Overall agreement with other models and with lattice at low T

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

[V. M. and C. Sasaki, PRD 103 '21; V.M. EPJ ST 229 '20, Lattice: G. Aarts et al., JHEP 02 (2015)]

Summary

☞ **Quark-gluon plasma** – peculiar state of matter with unique properties and a lot of open questions.

☞ **Quasiparticle model** – well-established tool connecting non-perturbative and perturbative QCD regimes (strong vs weak coupling).

☞ **Possibilities** – finite μ, quasiquarks out of chemical equilibrium, $N_f = 2 + 1 + 1$, momentum anisotropy...

THANK YOU FOR ATTENTION!