EVOLUTION OF CHARM QUARKS IN THE EXPANDING QUARK-GLUON PLASMA

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Task

☞ Add charm quarks as obstacles to QGP with $N_f = 2 + 1$ in equilibrium. See how $N_{c\bar{c}}$ evolves with time under various conditions:

$\mathbf{I}_{id}$: Longitudinal expansion (1D) of perfect fluid

$\mathbf{II}_{vis}$: (2+1)-D expansion of viscous fluid (+ $(\eta/s)(T)$ from QPM).

☞ Quasiparticle model

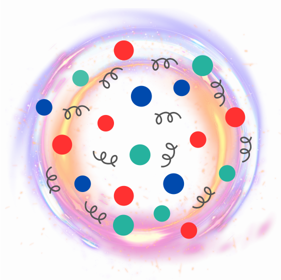
☞ Transport properties of the QGP: shear viscosity

☞ Charm quark production in hot deconfined matter

Quasiparticle Model - Effective Approach to QCD

☞ similar to massive quasielectron moving freely in solid states

Real QGP:



strongly-interacting particles,
constant (bare) masses m_i

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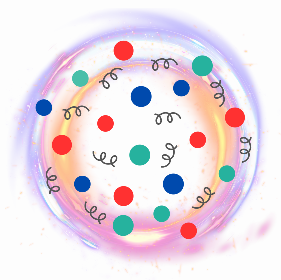
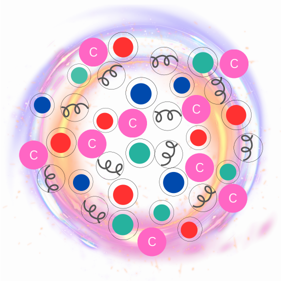


$\longrightarrow$

Effective approach:



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

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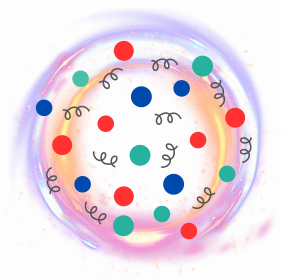

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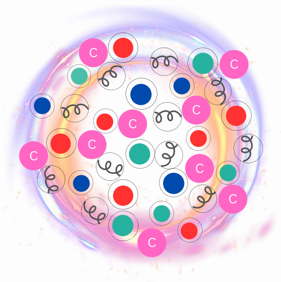

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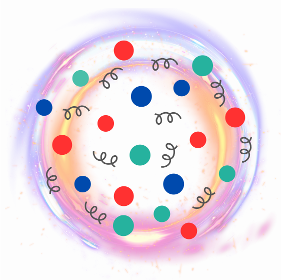

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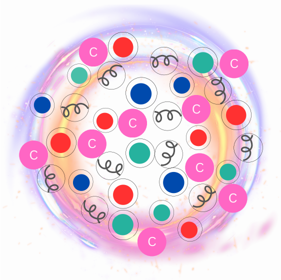

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$G(T)$ *from lattice QCD EoS*

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 pQCD (Hard Thermal Loops):

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

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

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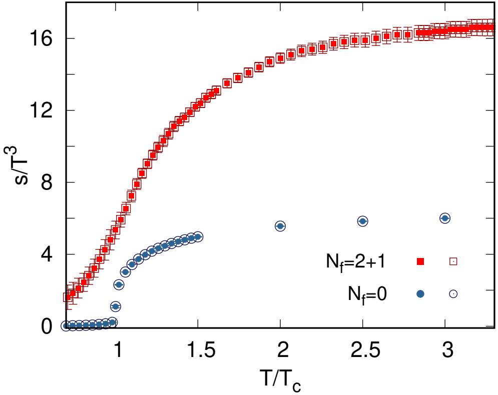
☞ effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

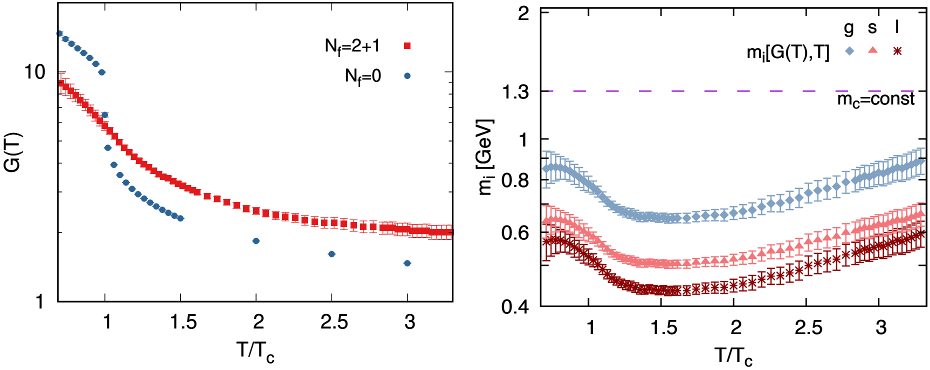
Quasiparticle Model

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

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



Effective Coupling and Masses

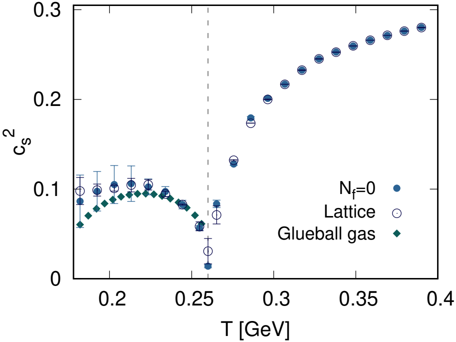


$$\mathrm{m}_i[G(T),\, T] \gg m_l^0 = 5 \text{ MeV},\; m_s^0 = 95 \text{ MeV}$$

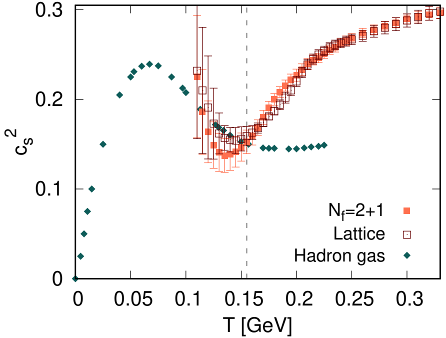
QGP Thermodynamics

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

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 $T \to \infty$

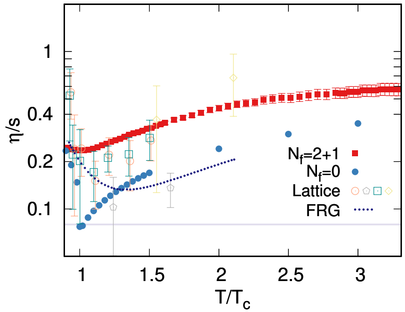
[V.M, C. Sasaki, PRD103 '21]

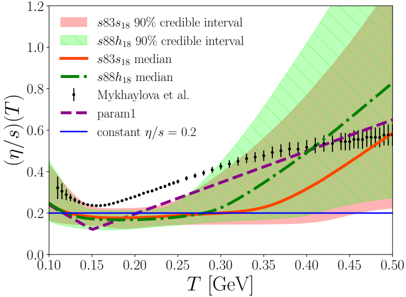
Shear Viscosity

(reaction to flow) [Hosoya, Kajantie, NPB250 ’85]

$$\eta = \frac{1}{15\,T} \sum_{i=g,l,s,\ldots} d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} f_i^0 (1 \pm f_i^0)\, \tau_i \tag{5}$$

$$\text{e.g. } \tau_g = [n_g^0(\bar{\sigma}_{gg\to gg} + \bar{\sigma}_{gg\to l\bar{l}} + \bar{\sigma}_{gg\to s\bar{s}}) + n_l^0\,\bar{\sigma}_{gl\to gl} + n_s^0\,\bar{\sigma}_{gs\to gs}]^{-1} \tag{6}$$





☞ Dynamical quarks increase viscosity of hot deconfined matter.

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

Charm Quark Evolution

How number of charm quarks changes in hot QCD medium?
Rate equation [Biro et al., PRC 48 '93; Zhang et al., PRC 77 '08]:

$$\partial_\mu(n_c u^\mu) = [\bar{\sigma}_{l\bar{l}\to c\bar{c}}\,(n_l^0)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\,(n_s^0)^2 + \frac{1}{2}\,\bar{\sigma}_{gg\to c\bar{c}}\,(n_g^0)^2]\Big(1 - \frac{n_c^2}{(n_c^0)^2}\Big) \quad (7)$$

LHS changes depending on a scenario:

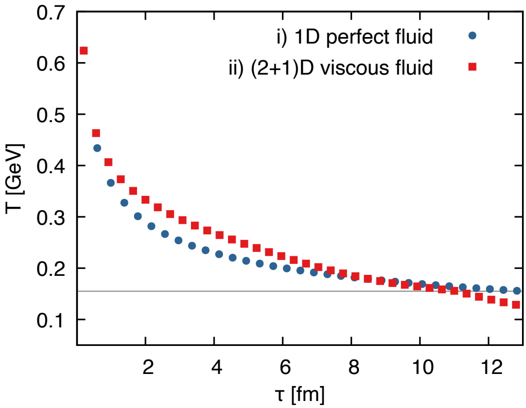
$\mathbf{I}_{id}$: Longitudinal expansion (1D) of perfect fluid = Bjorken flow,

$$T(\tau) = T_0\,\Big(\frac{\tau_0}{\tau}\Big)^{1/3} \quad (8)$$

$\mathbf{II}_{vis}$: (2+1)-D expansion of viscous fluid – 2^{nd} order hydro + η/s from QPM.

QGP Evolution in Time

1D propagation of ideal fluid vs (2+1)D expansion of viscous fluid (+ shear viscosity η/s):



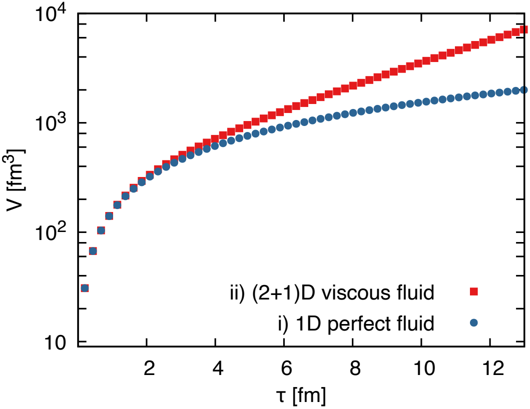
☞ Common initial conditions: $T_0 = 0.624$ GeV, $\tau_0 = 0.2$ fm.

[taken from (2+1)D viscous hydro: Auvinen, Eskola, Huovinen, Niemi, Paatelainen, Petreczky, PRC 102 '20]

QGP Evolution in Space

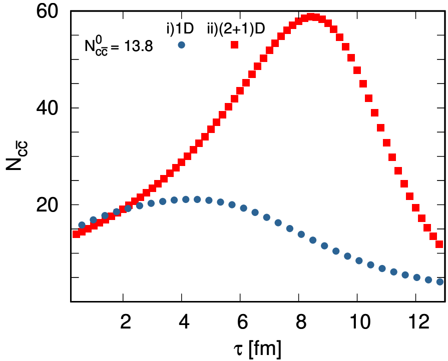
$$V(\tau) = \pi R^2(\tau)\tau = \pi[R_0 + a(\tau - \tau_0)^2]^2\tau \qquad (9)$$

$R_0 = 7$ fm; transverse acceleration parameter: $a_{\mathbf{II}_{vis}} = 0.15\ \text{fm}^{-1}$.



Charm Quark Evolution

$$n_{c\bar{c}}(\tau)V(\tau) = N_{c\bar{c}}(\tau) \quad (10)$$



Statistical Hadronization Model: $dN_{c\bar{c}}/dy = 13.8$ [Andronic et al., JHEP 07 '21]

[V.M., K. Redlich, C. Sasaki, to appear on arXiv]

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...