

CHARM QUARK EVOLUTION IN HOT QCD

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Outlook

- Quasiparticle model
- Transport properties of the QGP: shear viscosity
- Charm quark production in hot deconfined matter

Charm Quark Evolution

- ☞ Charm quarks witness the whole QGP lifetime: $m_c^0 = 1.3$ GeV.
 - Can probe the QGP properties.
- ☞ Changes in number of charm quarks (production/reduction?)
 - Details of charm in-medium interactions

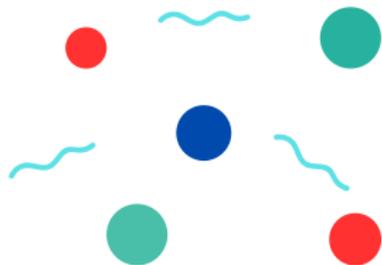
Task:

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.

Quasiparticle Model - Effective Approach to QCD

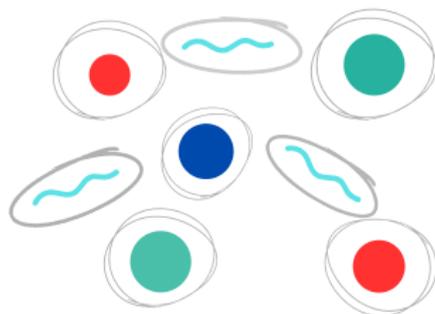
☞ similar to massive quasidelectron moving freely in solid states

Quark-gluon plasma:



Reality:

strongly-interacting particles, \longrightarrow
bare masses $m_i^0 = \text{const}$



Effective approach:

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

Quasiparticle Model

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

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

self-energies Π_i from pQCD (HTL):

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

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

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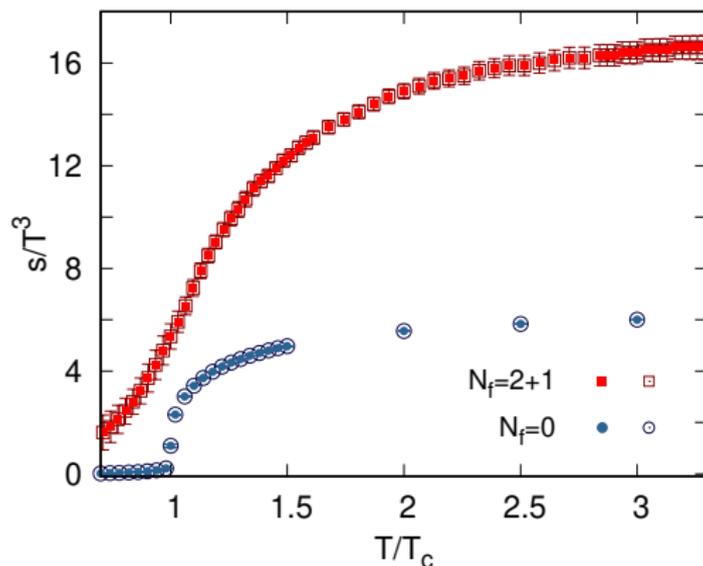
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➤ effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

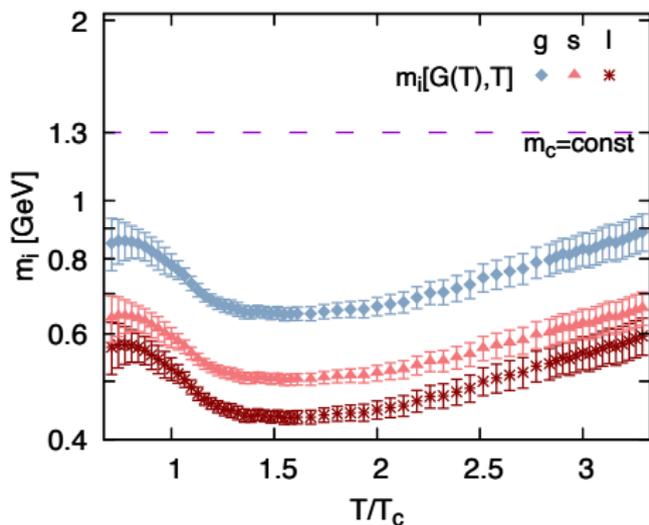
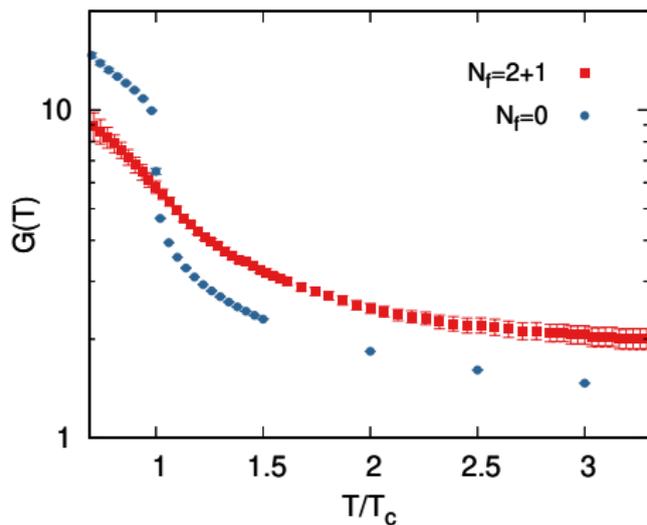
Quasiparticle Model

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

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



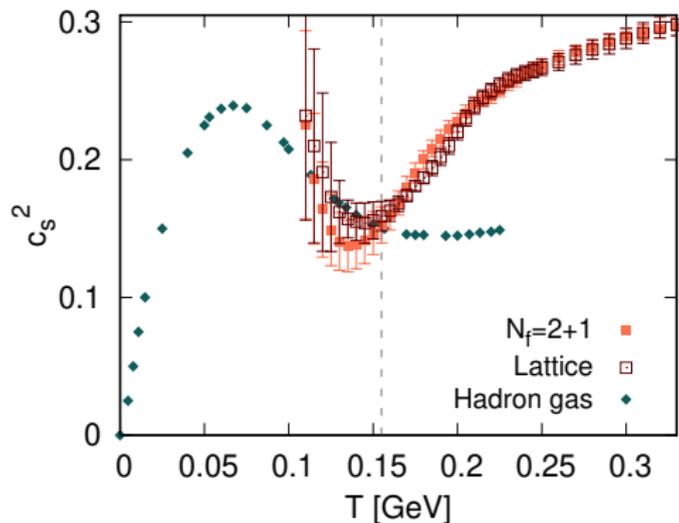
Effective Coupling and Masses



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

QGP Thermodynamics

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



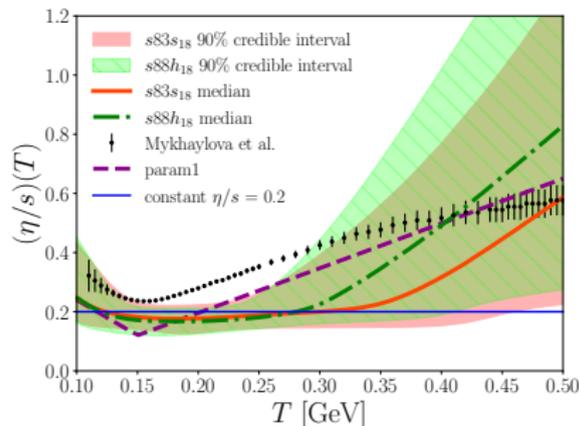
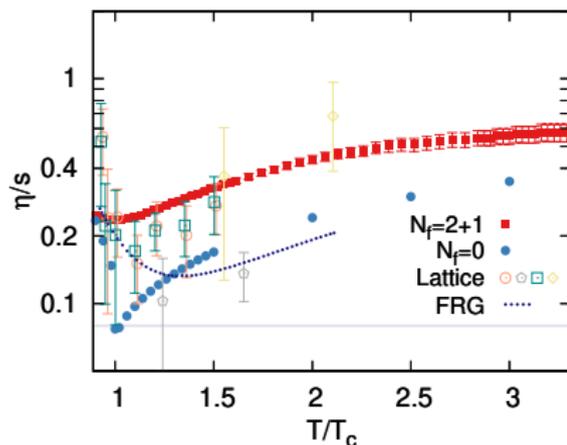
☞ Ideal gas: $c_s^2 = 1/3$ vs Quasiparticle model: $c_s^2 \rightarrow 1/3$ as $T \rightarrow \infty$

Shear Viscosity

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

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

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

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

LHS changes depending on a scenario:

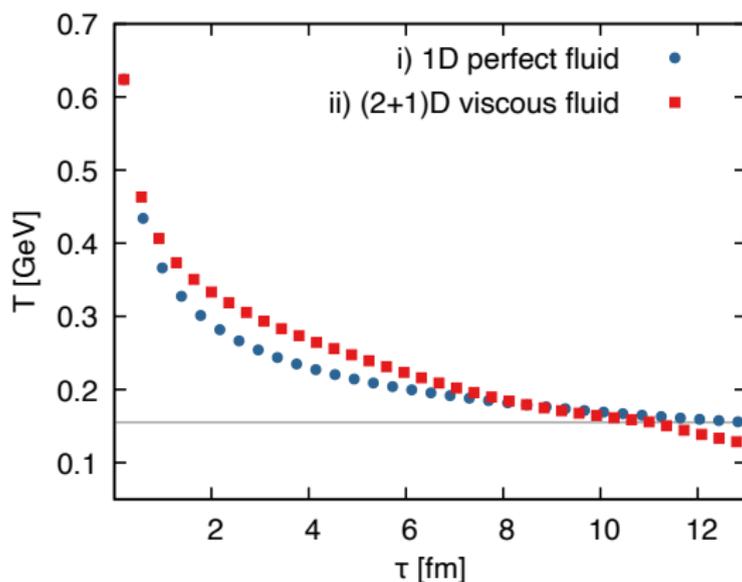
I_{id}: Longitudinal expansion (1D) of perfect fluid = Bjorken flow,

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

II_{vis}: (2+1)-D expansion of viscous fluid – 2nd 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):



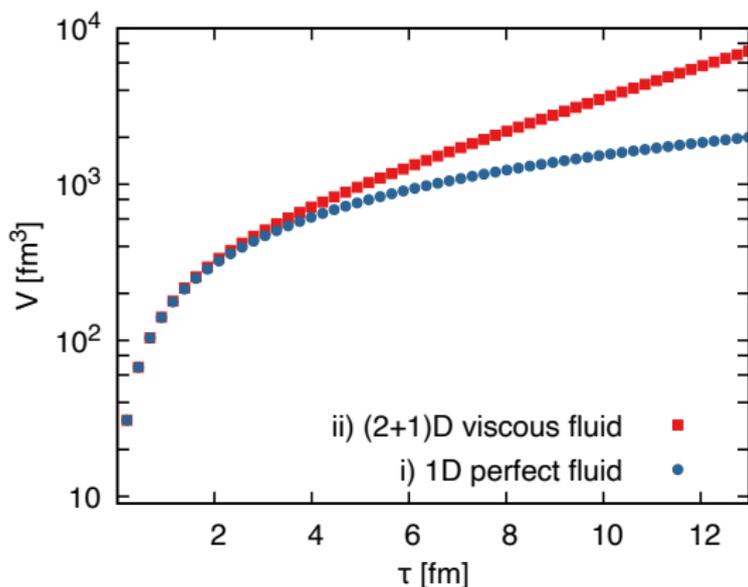
☞ Common initial conditions: $T_0 = 0.624$ GeV, $\tau_0 = 0.2$ fm.

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

QGP Evolution in Space

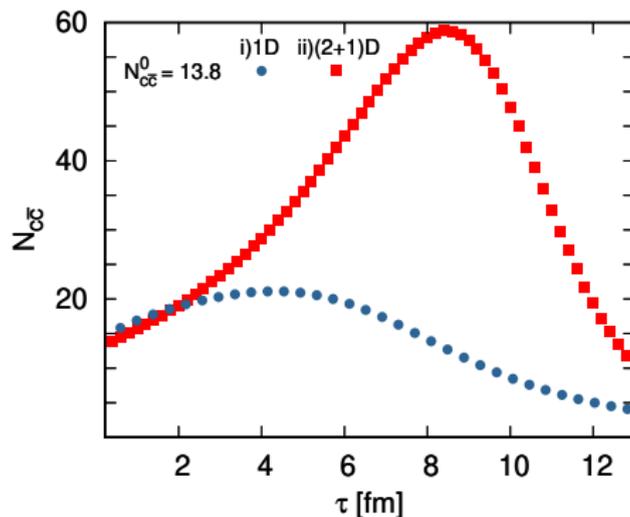
$$V(\tau) = \pi R^2(\tau)\tau = \pi[R_0 + a(\tau - \tau_0)]^2\tau \quad (9)$$

$R_0 = 7$ fm; transverse acceleration parameter: $a_{\parallel vis} = 0.15$ 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]

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...