# CHARM QUARK PRODUCTION IN HOT QCD FROM THE QUASIPARTICLE PERSPECTIVE

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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 survive through the QGP lifetime,

$$m_c^0 = 1.3 \text{ GeV} \gg m_l^0 = 0.005 \text{ GeV}, \; m_s^0 = 0.095$$

➛ Better understanding of QGP properties and evolution

☞ Production/Reduction of charm quarks

➛ Details of charm in-medium interactions

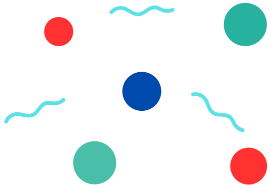
*Task:*

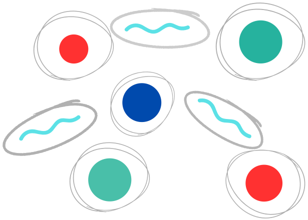
Add charm quarks as obstacles to QGP with $N_f = 2 + 1$ in equilibrium, see how their abundance change with time $\tau$.

# 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 $\Pi_i$:

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

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

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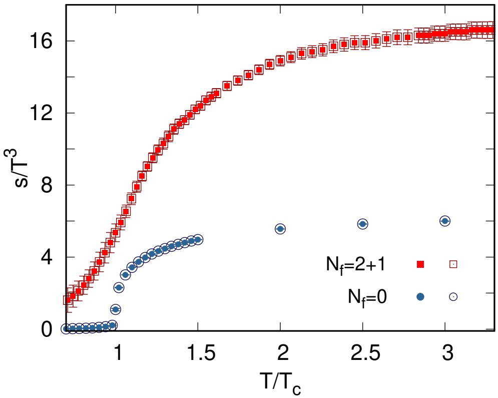
☞ effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

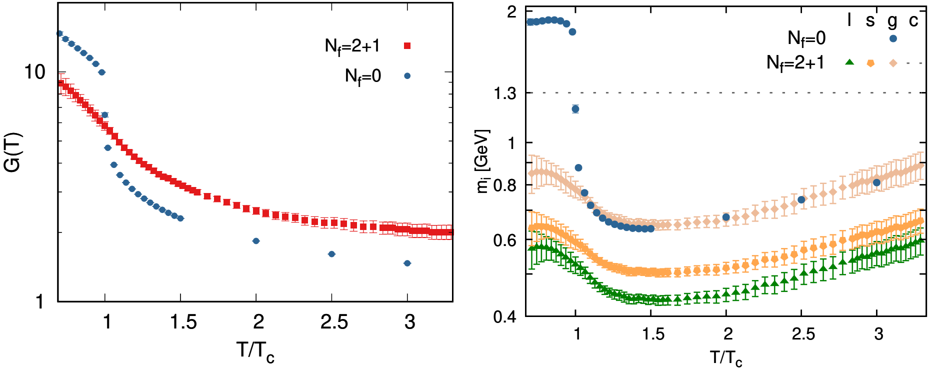
# Quasiparticle Model

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

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



# Effective Coupling and Masses

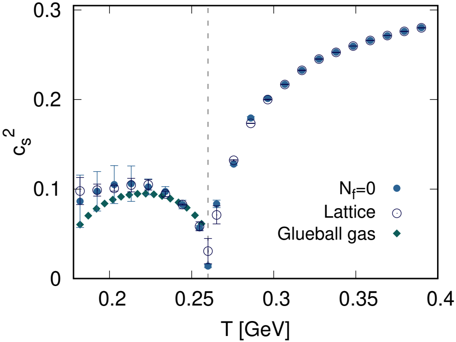



$$m_i[G(T), T] \gg m_l^0 = 0.005 \text{ GeV}, \; m_s^0 = 0.095 \text{ GeV}$$

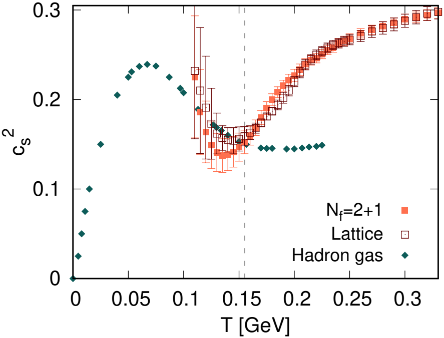
# Thermodynamic Consistency

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

Pure SU(3), $N_f = 0$




QCD, $N_f = 2 + 1$

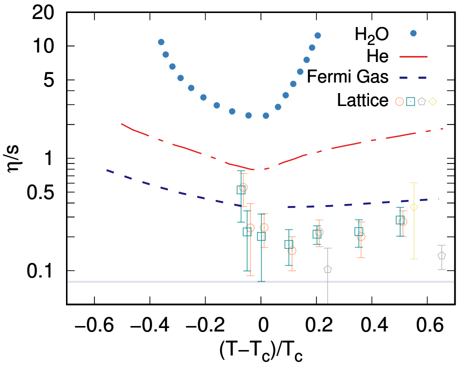



☞ Ideal gas: $c_s^2 = 1/3$ vs Quasiparticle model: $c_s^2 \to 1/3$ as $T \to \infty$

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

# Transport Phenomena in Hot QCD

Longitudinal motion - friction between layers - shear viscosity $\eta$




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

# Kinetic Theory: Relaxation Time Approximation

Boltzmann Equation:

$$p^\mu \partial_\mu f_i = \mathcal{C}[f_i] \simeq -\frac{f_i - f_i^0}{\tau_i} \tag{5}$$

Approximate solution: $f_i$ relaxes to equilibrium value $f_i^0$ in time $\tau_i$

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Pure gluon plasma ($N_f = 0$):

$$\tau_g = [n_g^0 \bar{\sigma}_{gg \to gg}]^{-1}; \qquad n_i^0 \simeq \int d^3p \, f_i^0 \qquad (6)$$

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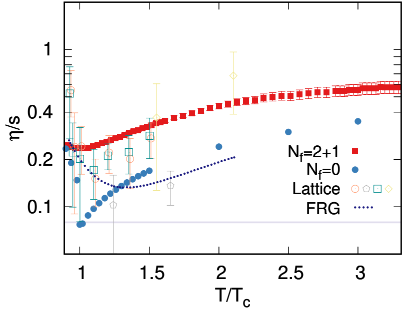
Quark-gluon plasma ($N_f = 2+1$):

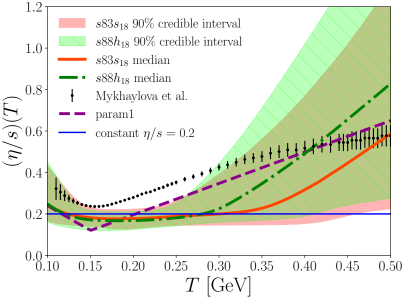
$$\tau_g = [n_g^0(\bar{\sigma}_{gg\to gg} + \bar{\sigma}_{gg\to l\bar{l}} + \bar{\sigma}_{gg\to s\bar{s}}) + n_l^0\,\bar{\sigma}_{gl\to gl} + n_s^0\,\bar{\sigma}_{gs\to gs}]^{-1} \tag{7}$$

# Shear Voscosity

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

$$\eta = \frac{1}{15\,T} \sum_{i=g,l,s,\dots} d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} f_i^0 (1 \pm f_i^0)\, \tau_i \qquad (8)$$




☞ 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

Rate equation for fugacity parameter $\lambda(T)$ [Biro et al., PRC 48 '93; Zhang et al., PRC 77 '08]:

$$\partial_\mu n_c^\mu[\lambda(T)] = \left(1 - \frac{n_c^2[\lambda(T)]}{(n_c^0)^2}\right) R_{gain} \tag{9}$$

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

$$n_c(\lambda) \simeq \int d^3p \, f_c(\lambda) = \int d^3p \, \lambda(e^{E_c/T} - \lambda)^{-1} \tag{10}$$

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$$R_{gain} = \bar{\sigma}_{l\bar{l}\to c\bar{c}}\,(n_l^0)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\,(n_s^0)^2 + \frac{1}{2}\,\bar{\sigma}_{gg\to c\bar{c}}\,(n_g^0)^2 \tag{11}$$

# Charm Quark Evolution

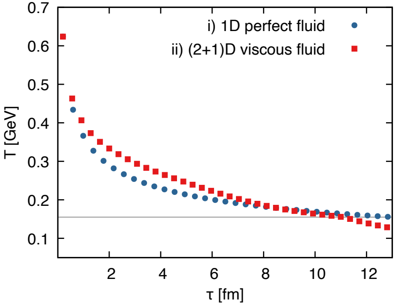
$$n_c[\lambda(T)]V(T) = N_c(T) \quad (12)$$

➛ Longitudinal propagation of ideal fluid (Bjorken flow):

$T(\tau) = T_0\left(\frac{\tau_0}{\tau}\right)^{1/3}$, initial conditions: $T_0 = 0.624$ GeV, $\tau_0 = 0.2$ fm.

➛ (2+1)D expansion of viscous fluid (+ shear viscosity $\eta/s$)

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



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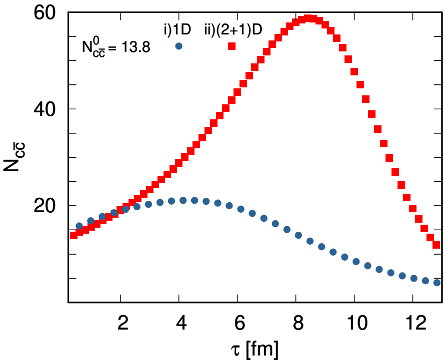


☞ (2+1)D viscous expansion – similar initial and final number of charm quarks – agrees with SHM:

$dN_{c\bar{c}}/dy = 13.8$ [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).

☞ **Nearest perspectives** – charm quark diffusion coefficient, $N_f = 2 + 1 + 1$, momentum anisotropy, magnetic effects...