

# Heavy Flavor Kinetics in HIC

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# Motivation

☞ Charm quarks probe the properties of the QGP

Task: study the  $c\bar{c}$  production in equilibrated QGP,  $N_f = 2 + 1$ , two evolution scenarios:

- 1D ideal fluid (Bjorken flow)

-(2+1)D viscous QGP +  $(\eta/s)(T)$

☞ Quasiparticle model

☞ Rate equation: cross sections, charm production rate

☞ Number of  $c\bar{c}$  pairs in hot deconfined matter

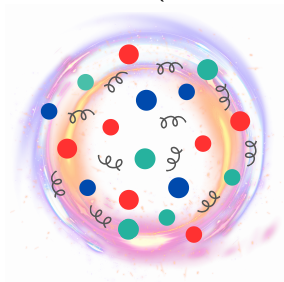
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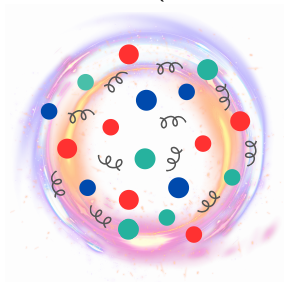


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constant (bare) masses  $m_j$

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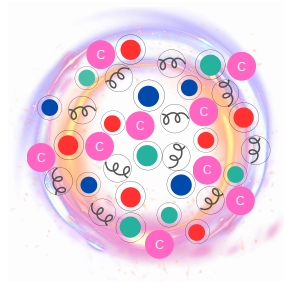
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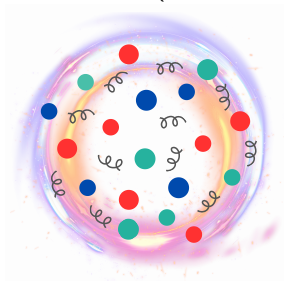


weakly-interacting **quasi**particles,  
dynamical  $m_i^{eff} [T, G(T)]$

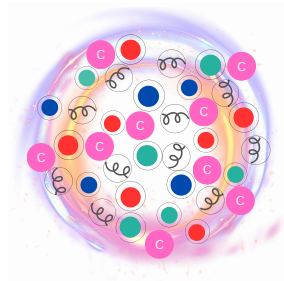
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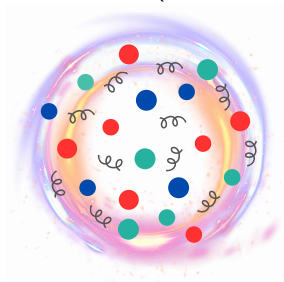
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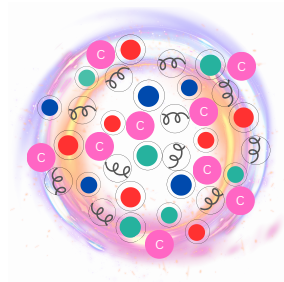
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$G(T)$  from lattice QCD EoS

# Quasiparticle Model

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

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

self-energies  $\Pi_i$  from pQCD (Hard Thermal Loops):

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

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



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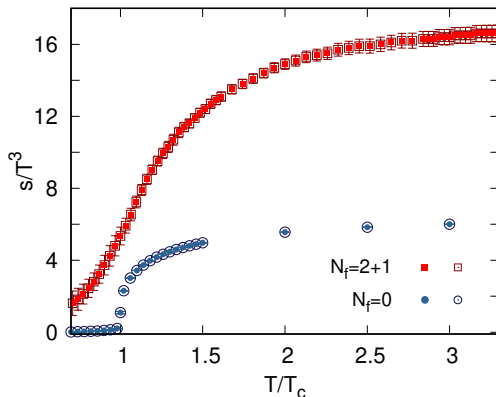
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➡ effective coupling  $G(T)$  – reliable thermodynamics – lattice QCD

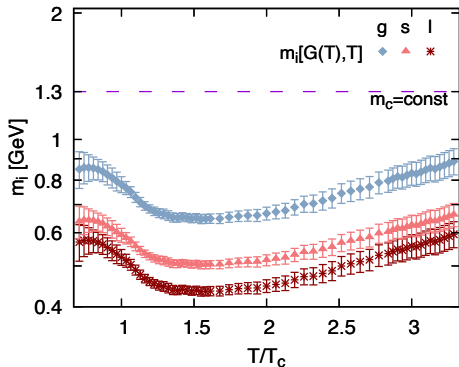
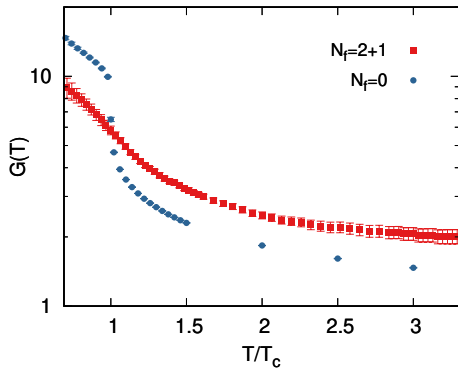
# Quasiparticle Model

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

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



# Effective Coupling and Masses



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

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

# Charm Quark Evolution

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

describes time/temperature evolution of the number density function

$$\partial_\mu (n_c u^\mu) = R_{l\bar{l} \rightarrow c\bar{c}} + R_{s\bar{s} \rightarrow c\bar{c}} + R_{gg \rightarrow c\bar{c}} - R_{c\bar{c} \rightarrow l\bar{l}} - R_{c\bar{c} \rightarrow s\bar{s}} - R_{c\bar{c} \rightarrow gg} \quad (5)$$

Applying the detailed balance:

$$\partial_\mu (n_c u^\mu) = [\bar{\sigma}_{l\bar{l} \rightarrow c\bar{c}} (n_l^0)^2 + \bar{\sigma}_{s\bar{s} \rightarrow c\bar{c}} (n_s^0)^2 + \frac{1}{2} \bar{\sigma}_{gg \rightarrow c\bar{c}} (n_g^0)^2] \left(1 - \frac{n_c^2}{(n_c^0)^2}\right) \quad (6)$$

$$n_i^0 = d_i \int d^3 p f_i^0 [E_i(T)] \quad (7)$$

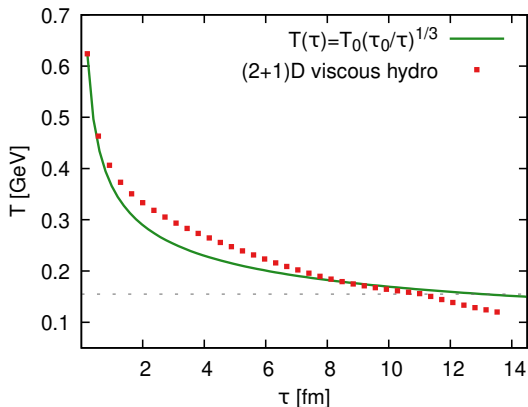
$$n_c = \lambda_c(\tau) n_c^0 \quad (8)$$

\* LHS depends on the QGP evolution:

- i) 1D Bjorken flow, ideal fluid;
- ii) (2+1)D expansion  $+(\eta/s)(T)$

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

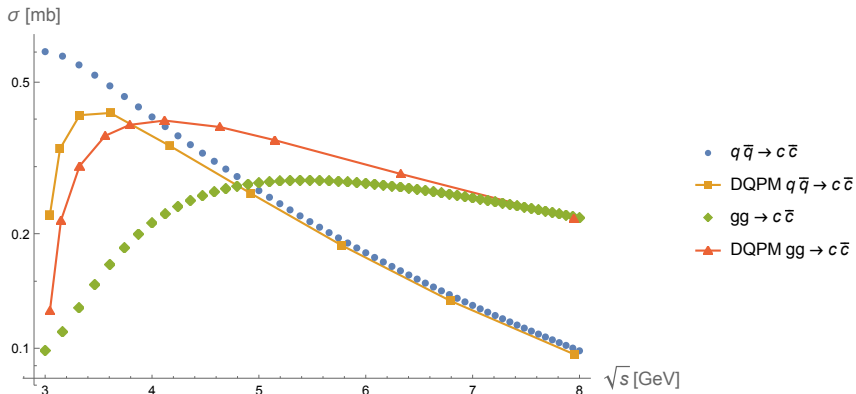
# QGP Evolution



$$T_0 = 0.624 \text{ GeV}, \tau_0 = 0.2 \text{ fm}$$

[Auvinen, Eskola, Huovinen, Niemi, Paatelainen, Petreczky, PRC 102 '20]

# Total Cross Sections at $T_c = 0.155$ GeV



DQPM: T. Song, I. Grishmanovskii, O. Soloveva, E. Bratkovskaya, arXiv:2404.00425

# Thermal-Averaged Cross Sections

$$\sigma(\sqrt{s}) \rightarrow \bar{\sigma} = \langle \sigma v \rangle \quad (9)$$

For Boltzmann statistics:

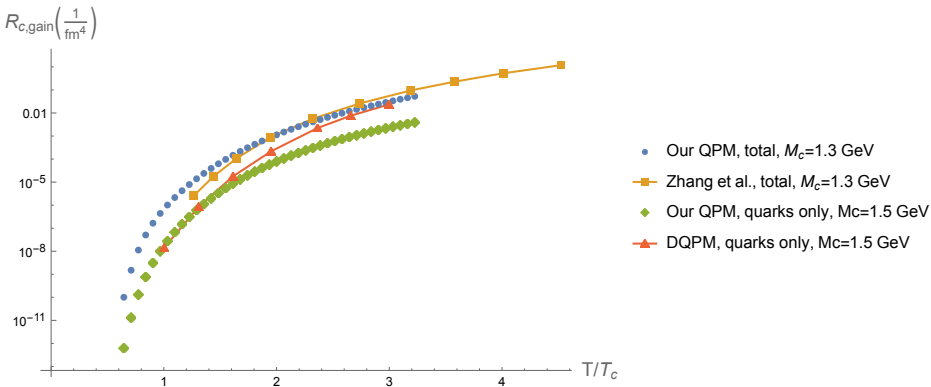
$$\bar{\sigma}_{ab \rightarrow cd} = \frac{\int d^3 p_a d^3 p_b f_a f_b \sigma_{ab \rightarrow cd} v_{ab}}{\int d^3 p_a d^3 p_b f_a f_b} = \quad (10)$$

$$\left[ 4 \frac{M_a^2}{T^2} \frac{M_b^2}{T^2} K_2\left(\frac{M_a}{T}\right) K_2\left(\frac{M_b}{T}\right) \right]^{-1} \times$$

$$\int_{\sqrt{s_0}}^{\infty} d(\sqrt{s}) K_1\left(\frac{\sqrt{s}}{T}\right) \sigma_{ab \rightarrow cd} \left[ \frac{s}{T^2} - \left( \frac{M_a^2}{T^2} + \frac{M_b^2}{T^2} \right)^2 \right] \left[ \frac{s}{T^2} - \left( \frac{M_c^2}{T^2} + \frac{M_d^2}{T^2} \right)^2 \right];$$

$$\sqrt{s_0} = \max[M_a + M_b, M_c + M_d]$$

# Charm Quark Production Rate

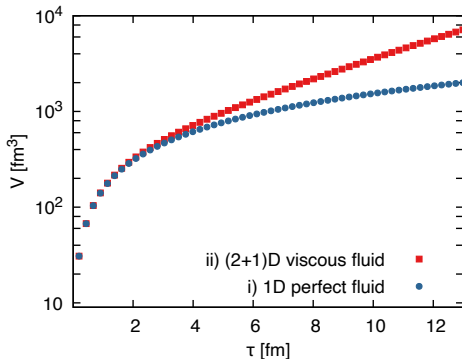


DQPM: T. Song, I. Grishmanovskii, O. Soloveva, E. Bratkovskaya, arXiv:2404.00425 (2024);  
Zhang et al., Phys. Rev. C 77 (2008)



# Volume of the QGP

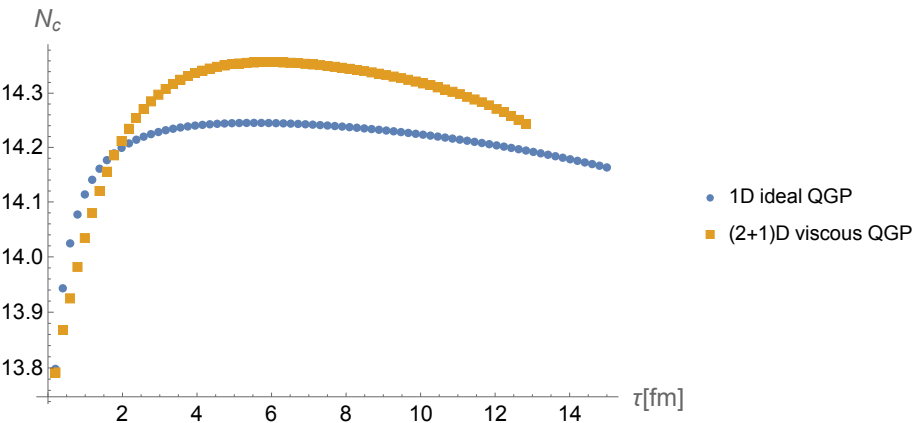
$$V(\tau) = \pi R^2 \tau \quad (11)$$



i) 1D ideal Bjorken dynamics:  $R = R_0 = 7 \text{ fm}$

ii) (2+1)D viscous expansion:  $R(\tau) = R_0 + (\tau - \tau_0)^2 a/2$ ,  $a = 0.01 \text{ fm}$

# Charm Quark Production



$$\frac{dN_c}{dy} = 13.8 \quad (12)$$

[Andronic, Braun-Munzinger, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius, JHEP 07 '21]

# Summary

- ☞ **Quasiparticle model** – effective well-established tool connecting non-perturbative and perturbative QCD regimes.
- ☞ **Charm quarks** – minor thermal production in both ideal 1D- and viscous (2+1)D-expanding plasma.
- ☞ **Possibilities** – quasihadrons out of chemical equilibrium, finite  $\mu$ ,  
 $N_f = 2 + 1 + 1\dots$