Probes in holographic plasmas with unquenched quarks

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based on:
A. Magaña, J. Más, LM, J. Tarrío [arXiv:1205.xxxx]

University of Crete, May 16, 2012

We start from: ...

Benini et al 06, Bigazzi et al 08, 09, 11 ... (top-down)
Mateos et al 06, 07 ..., Erdmenger et al 06 ...

Quark-gluon plasma	$\Leftrightarrow$	Holographic plasma
Finite temperature		Black hole
Unquenched quarks		Smeared flavor branes
Running coupling		Dilaton profile
Chemical potential		Bulk gauge field
T		$r_h \simeq 1/\pi T$
$N_f \sim N_c$		N_f backreacted branes
$\lambda = \lambda(\varepsilon)$		$\lambda = 4\pi g_s N_c e^{\Phi(r)}$
μ		A_t

. . . and want to go:

Casalderrey-Solana et al 11

Quark-gluon plasma ?	⇔	Holographic plasma
• Quarkonia • Quarkonia (+lattice) • (SC) • Energy loss • Transv. mom. broad.		• Meson melting • Screening length • Conductivity • Drag force • Diffusion constant
• J/ψ spectrum dN/d^3p • " • σ • Nucl. mod. factor $R_{AA}^{\pi^0}$ • "		• c vs. M_q • $V_{\bar{q}q}$ • $\sigma_{\rm DC}$ • M_k and μ • $\hat{q}$

Outline

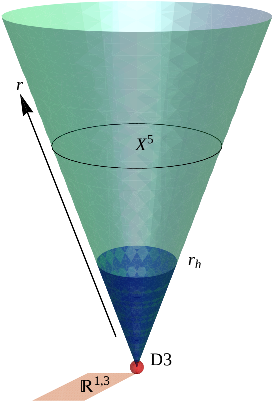
Review: D3/D7 plasmas

D7 probes

- Constituent mass
- Quark condensate
- Conductivity at finite chemical potential
- Quark-antiquark potential
- Drag force for a moving heavy quark
- Kinetic mass
- Jet quenching parameter

Conclusions

D3 black hole Witten 98



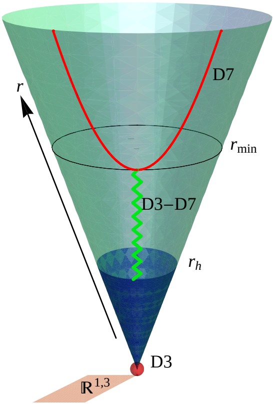
- N_c D3 at the tip of a Calabi-Yau cone with base X^5 (e.g. $S^5, T^{1,1}$)
- D3 extend over $\mathbb{R}^{1,3}$
- at finite temperature $T \leftrightarrow r_h$

$$\Downarrow$$

near horizon Scwarzchild AdS$_5 \times X^5$

$$ds^2 = \frac{r^2}{R^2}\left[-(1-\frac{r_h^4}{r^4})dt^2 + d\vec{x}_3^2\right] + \frac{R^2}{r^2}\left[\frac{dr^2}{\left(1-\frac{r_h^4}{r^4}\right)} + r^2 ds^2_{KE} + r^2\left(d\tau + A_{KE}\right)^2\right]$$

Probe D7 in the D3 black hole Karch Katz 02



- probe D7 wrapping $X^3 \subset X^5$ (ξ, θ, ϕ)
- D7 extends over $\mathbb{R}^{1,3}$ and r
- quark mass M_c: string stretching from the D7 to the D3

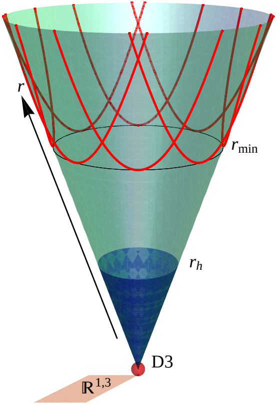
$$\Downarrow$$

embedding $\tau = \tau_0, \chi = \chi(r)$

$$\chi(r) \simeq \frac{m}{r} + \frac{c}{r^3} + \dots \quad , \qquad r \to \infty$$

Smeared D7 in the D3 black hole

Benini Canoura Cremonesi Nuñez Ramallo 07 ...



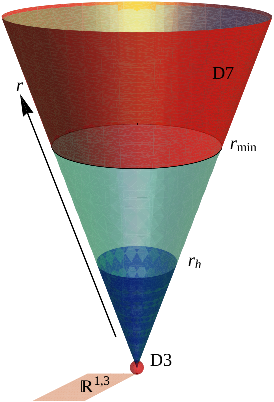
- N_f smeared D7 along X^5/X^3 $(\chi(r))$
- $N_f \sim N_c \gg 1$
- smearing preserves $\mathcal{N} = 1$ susy (broken)
- $r_{\min}$ still determines the quark mass

$\Downarrow$

smeared embedding form Ω_2

$$\sum^{N_f} \int d^8x \longrightarrow N_f \int d^8x \, \Omega_2$$

Backreacted D3/D7 black hole



- N_f backreacted D7 smeared on X^5
- running dilaton $\lambda(r) = 4\pi g_s N_c e^{\Phi(r)}$
- Landau pole in the far UV: $r_{\rm LP} \gg r_h$

$$\Downarrow$$

backreaction expansion in $\epsilon_h = \frac{\mathrm{Vol}(X^3)}{\mathrm{Vol}(X^5)} \frac{\lambda_h}{16\pi} \frac{N_f}{N_c}$

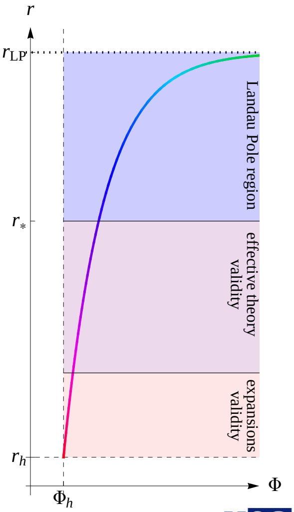
$$G_{rr} = \frac{R^2}{r^2}\left(1 - \frac{r^4}{r_h^4}\right)^{-1}\left(1 + \frac{\epsilon_h}{4} + \mathcal{O}(\epsilon_h^2)\right), \qquad \Phi = \Phi_h + \epsilon_h \log\left(\frac{r}{r_h}\right) + \mathcal{O}(\epsilon_h^2),$$

$$G_{KE} = R^2\left(1 + \frac{\epsilon_h}{12} + \mathcal{O}(\epsilon_h^2)\right), \qquad G_{\tau\tau} = R^2\left(1 - \frac{\epsilon_h}{12} + \mathcal{O}(\epsilon_h^2)\right)$$

Scales in the D3/D7 plasma

- r_h sets the temperature
- $r_{\rm min} = 0$ for background $\Rightarrow$ massless quarks
- effective and full theory coincide for $r < r_*$
- Landau Pole $r_{\rm LP} \approx r_* e^{1/\epsilon_h} \ll 1$
- boundary conditions at r_*: $G, \phi = G^{(0)}, \phi^{(0)}$
- validity of expansions: $\epsilon_h \left| \log \frac{r_h}{r_*} \right| \ll 1$

our range: $r_h \leq r \ll r_h e^{1/\epsilon_h}$



Flavored vs. unflavored background: temp and energy

Unflavored

$$r_h^{(0)} = \pi T R^2$$

$$N_c^{(0)} = \sqrt{\frac{2\varepsilon}{3}\frac{2}{\pi T^2}}$$

Flavored

$$r_h = \pi T R^2 \left(1 + \frac{\epsilon_h}{8} + \mathcal{O}(\epsilon_h^2)\right)$$

$$N_c = \sqrt{\frac{2\varepsilon}{3}\frac{2}{\pi T^2}} \left(1 - \frac{\epsilon_h}{4} + \mathcal{O}(\epsilon_h^2)\right)$$

Comparison scheme

Fixed observables: temperature T, energy density ε
Varying parameters: horizon size r_h, number of colors N_c
As the number of flavors $N_f \Leftrightarrow \epsilon_h$ varies

$$\Rightarrow \quad \lambda = 8 g_s \sqrt{\frac{2\varepsilon}{3T^4}} \left[1 + \epsilon_h \left(\log \frac{r}{\pi T R^2} - \frac{1}{4}\right) + \mathcal{O}(\epsilon_h^2)\right]$$

Parameters in the D3/D7 plasma

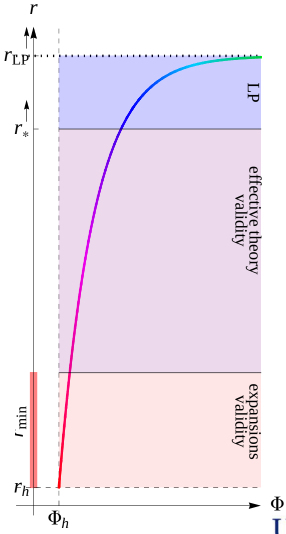
- realistic setup:
  - coupling $\lambda_h \sim 6\pi$
  - number of colors $N_c \sim 3$
  - number of flavors $N_f \sim 3$

$$\Downarrow$$

- perturbative parameter $\epsilon_h \sim 0.24$

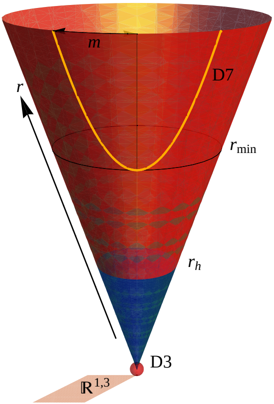
$$\Downarrow$$

UV cutoff range $r \lesssim 10\, r_h$



Probe D7 embedding in the flavored background

Magaña Más LM Tarrío



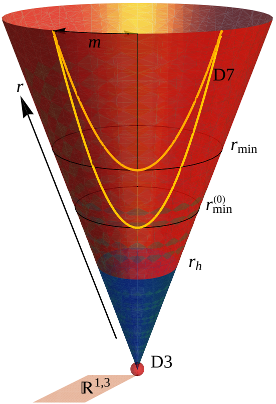
- probe D7 wrapping $X^3 \subset X^5$ (ξ, θ, ϕ)
- D7 extends over $\mathbb{R}^{1,3}$ and r
- m as boundary condition at ∞
- bare mass $M_q = \frac{1}{2}\sqrt{\lambda_h} T\, m$

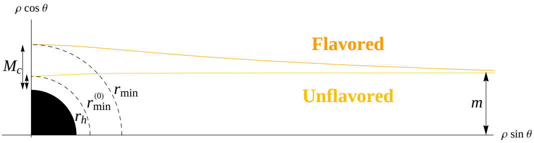
$$\Downarrow$$

embedding $\tau = \tau_0, \psi = \sin\frac{\chi(r,\epsilon_h)}{2}$

$$\psi(\infty) \simeq \frac{r_h}{r}\left[m_0 + c_0\frac{r_h^2}{r^2} + \epsilon_h\left[m_1 + m_0\log\frac{r_h}{r} + \frac{r_h^2}{r^2}\left(c_1 + \frac{5}{6}c_0\log\frac{r_h}{r} + \dots\right)\right] + \mathcal{O}(\epsilon_h^2)\right]$$

Flavored vs. unflavored embedding





Quark bare mass (dimension-less)

$$m = m_0 + \epsilon_h m_1 + \dots$$

from holographic renormalization

$$\psi(\infty) \simeq \frac{r_h}{r}\left[m_0 + c_0\frac{r_h^2}{r^2} + \epsilon_h\left[m_1 + m_0\log\frac{r_h}{r} + \frac{r_h^2}{r^2}\left(c_1 + \frac{5}{6}c_0\log\frac{r_h}{r} + \dots\right)\right] + \mathcal{O}(\epsilon_h^2)\right]$$

Flavored vs. unflavored background: mass

Unflavored

$$r_h^{(0)} = \pi T R^2$$

$$N_c^{(0)} = \sqrt{\frac{2\varepsilon}{3}\frac{2}{\pi T^2}}$$

$$r_{\rm min}^{(0)} = r_{\rm min}^{(0)}(m)$$

Flavored

$$r_h = \pi T R^2 \left(1 + \frac{\epsilon_h}{8} + \mathcal{O}(\epsilon_h^2)\right)$$

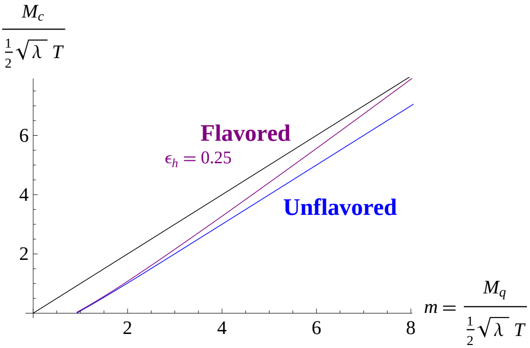
$$N_c = \sqrt{\frac{2\varepsilon}{3}\frac{2}{\pi T^2}} \left(1 - \frac{\epsilon_h}{4} + \mathcal{O}(\epsilon_h^2)\right)$$

$$r_{\rm min} = r_{\rm min}^{(0)}(m) + \epsilon_h r_{\rm min}^{(1)}(m) + \mathcal{O}(\epsilon_h^2)$$

Comparison scheme

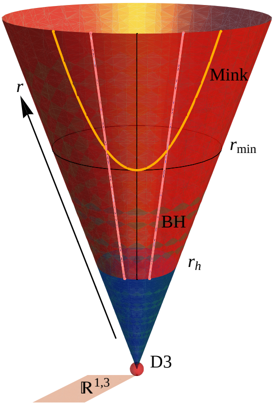
Fixed observables: T, ε, rest mass $m \equiv m_0 + \epsilon_h m_1 + \ldots$
Varying parameters: r_h, N_c, UV cutoff $r_{\rm min}$
As the number of flavors $N_f \Leftrightarrow \epsilon_h$ varies

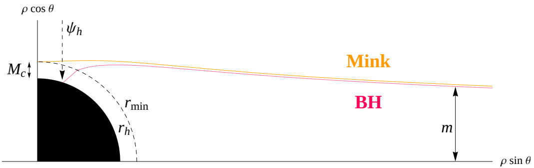
Constituent mass



$$M_c = \frac{1}{2\pi\alpha'}\int_{r_h}^{r_{\rm min}} dr\, e^{\frac{\Phi}{2}}\sqrt{-G_{tt}G_{rr}}$$
$$= \frac{1}{2R^2}\sqrt{\lambda_h(\varepsilon)}\left[\left(1+\frac{3\epsilon_h}{8}\right)\left(r_{\rm min}(m)-r_h(T)\right)+\frac{\epsilon_h}{2}r_{\rm min}(m)\log\frac{r_{\rm min}(m)}{r_h(T)}+\dots\right]$$

Minkowski vs. black-hole embedding





- Mink: constituent mass $M_c (m > m_*)$
- BH: no M_c, $m < m_* + \delta m_*$
- both Mink and BH for $m_* \leq m \leq m_* + \delta m_*$

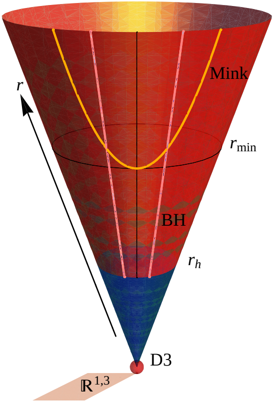
$\Downarrow$

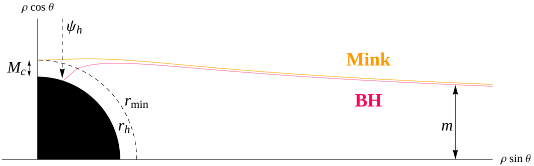
renormalized DBI+CS D7 action onshell $I_{\rm ren}$

Karch O'Bannon Skenderis 05, Albash Johnson 11

$$\frac{\partial I_{\rm ren}}{\partial r_{\rm min}} = -\frac{1}{8}\sqrt{\lambda_h} N_c T^3 \left[2c_0 + \epsilon_h \left(2c_1 + \frac{7}{6}c_0\right) + \mathcal{O}(\epsilon_h^2)\right] \left(\frac{\partial m_0}{\partial r_{\rm min}} + \epsilon_h \frac{\partial m_1}{\partial r_{\rm min}} + \mathcal{O}(\epsilon_h^2)\right)$$

Minkowski vs. black-hole embedding





- Mink: constituent mass $M_c (m > m_*)$
- BH: no M_c, $m < m_* + \delta m_*$
- both Mink and BH for $m_* \leq m \leq m_* + \delta m_*$

$\Downarrow$

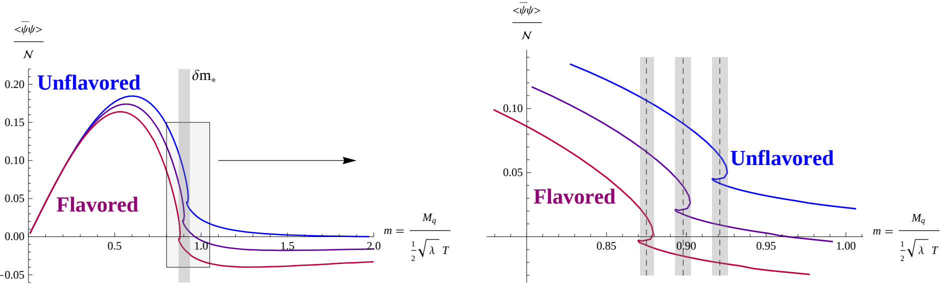
renormalized DBI+CS D7 action onshell $I_{\rm ren}$

Karch O'Bannon Skenderis 05, Albash Johnson 11

$$\frac{\partial I_{\rm ren}}{\partial \psi_h} = -\frac{1}{8}\sqrt{\lambda_h} N_c T^3 \left[2c_0 + \epsilon_h \left(2c_1 + \frac{7}{6}c_0\right) + \mathcal{O}(\epsilon_h^2)\right] \left(\frac{\partial m_0}{\partial \psi_h} + \epsilon_h \frac{\partial m_1}{\partial \psi_h} + \mathcal{O}(\epsilon_h^2)\right)$$

Quark condensate (negative as in Albash et al 07, Erdmenger Meyer and Shock 07)

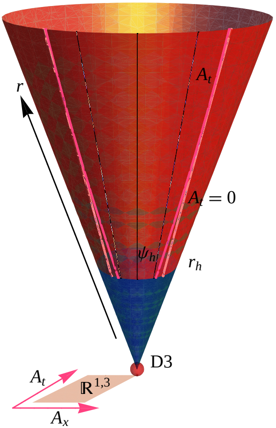
$$\epsilon_h = 0, 0.25, 0.5$$



$$\langle\bar\psi\psi\rangle = \frac{1}{2}\sqrt{\lambda_h}T\frac{\partial I_{\rm ren}}{\partial M_q} = \frac{\partial I_{\rm ren}}{\partial((m_0+\epsilon_h m_1+\dots)}$$

$$= -\frac{1}{8}\sqrt{\lambda_h(\varepsilon)}N_c(\varepsilon)T^3\left[2c_0(m)+\epsilon_h\left(2c_1(m)+\frac{7}{6}c_0(m)\right)+\mathcal{O}(\epsilon_h^2)\right]$$

Chemical potential



- gauge field $A = A_t dt + (Et + A_x)dx$
- only BH embedding
- density perturbative parameter $\delta \propto n_q$

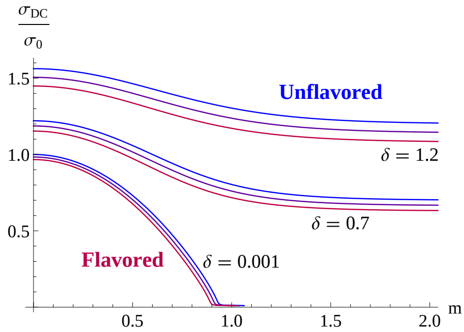
$$\Downarrow$$

regularity of DBI D7 action at $r_{ss} = r_h + \ell(E)$

$$\langle J \rangle = \sqrt{\tilde{\mathcal{N}}^2 G_{\mathrm{D7},xx} G_{\mathrm{D7},X^3} + e^{-\Phi} G_{\mathrm{D7},xx}^{-2} n_q^2}\Big|_{r_{ss}} 2\pi\alpha' E$$

Conductivity Karch O'Bannon 07

$$\epsilon_h = 0, 0.25, 0.5$$

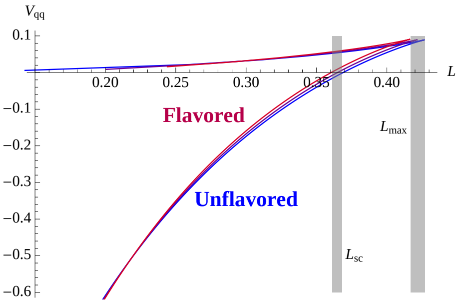


$$\sigma_{DC} = \sigma_0 \sqrt{\left(1 - \frac{\epsilon_h}{6}\right) (1 - \psi_h^2)^3 + \delta_0{}^2 \left(1 - \frac{\epsilon_h}{4}\right)}$$

$$\sigma_0 = \frac{N_f' N_c^{(0)}}{4\pi} T \ , \quad \delta_0 = \frac{8 n_q}{N_f' N_c^{(0)} \sqrt{\lambda_h^{(0)}} T}$$

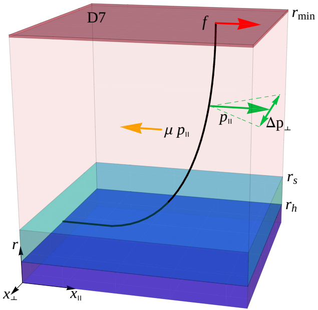
$\bar{q}q$ potential

$\epsilon_h = 0, 0.25, 0.5$



Screening ⇒ pair of disconnected strings beyond $L_{sc}(m, \epsilon_h)$

Trailing string



$$\frac{d\vec{p}}{dt} + \mu\vec{p} = \vec{f} + \vec{\xi}, \quad \langle \xi^i \xi^j \rangle = \kappa^{ij}\delta(t-t')$$

viscous force   diffusion constants

$$\mu = -\frac{1}{\gamma M \omega}\mathrm{Im}G_R(\mathcal{F})|_{\omega=0}, \ \kappa = G_{sym}(\mathcal{F})|_{\omega=0}$$

Son Starinets 02, Gubser 06, Son Teaney 09, Giecold Iancu Müller 09

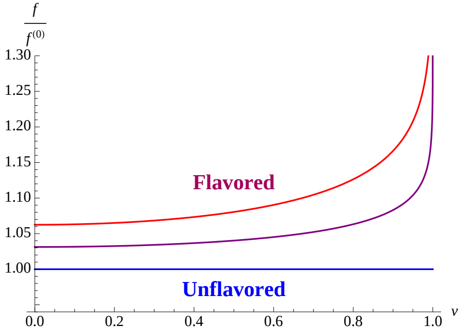
$X^1 = vt + x + \delta X^1,\ X^2 = \delta X^2,\ X^3 = \delta X^3 \quad \Leftrightarrow \quad \mathcal{F}$ (istantaneous force)

Worldsheet horizon

$$T_s = \frac{T}{\sqrt{\gamma}}\left(1 + \frac{1}{8}\epsilon_h v^2 + \dots\right), \quad r_s = r_h\sqrt{\gamma}, \quad \gamma = \frac{1}{\sqrt{1-v^2}}$$

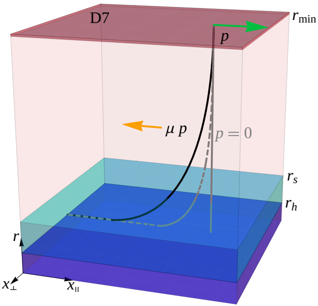
Drag force

$$\epsilon_h = 0, 0.25, 0.5$$



$$f = \mu M_k(m)\gamma v = \frac{e^{\frac{\Phi}{2}}}{2\pi\alpha'}\sqrt{-G_{xx}G_{tt}}\Big|_{r_s} = \frac{\pi}{2}\sqrt{\lambda_s(\varepsilon)}\, T^2 \left[1 + \frac{\epsilon_h}{4}\log\gamma + \mathcal{O}(\epsilon_h^2)\right]$$

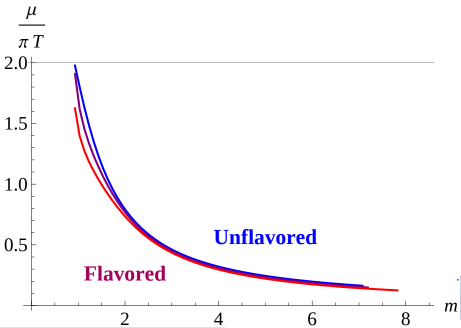
QNM



$$\frac{dp}{dt} + \mu p = 0 \quad \Rightarrow \quad \frac{dx}{dt} \propto e^{-\mu t}$$

- non-relativistic $\dot{X}_1 = \dot{x} \ll 1$
- arbitrary mass m (numeric)

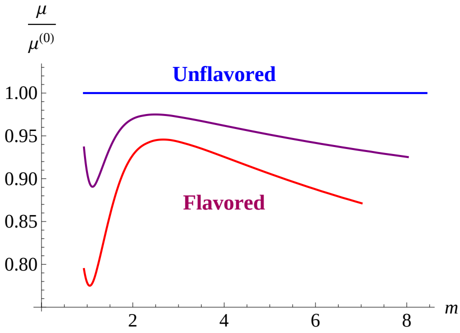
$$\epsilon_h = 0, 0.25, 0.5$$



- decreasing with flavors
- μ bounded by $2\pi T$

Drag coefficient

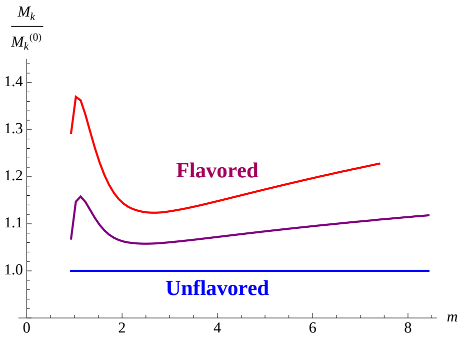
$$\epsilon_h = 0, 0.25, 0.5$$

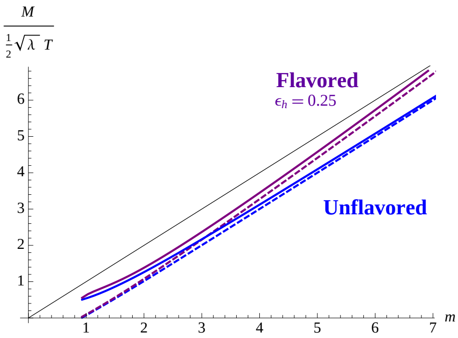


$$\mu = \frac{f}{M_k(m)\gamma v} = \frac{1}{M_k(m)} \frac{\pi}{2\gamma v} \sqrt{\lambda_s(\varepsilon)}\, T^2 \left[1 + \frac{\epsilon_h}{4} \log \gamma + \mathcal{O}(\epsilon_h^2)\right]$$

Kinetic mass

$\epsilon_h = 0, 0.25, 0.5$

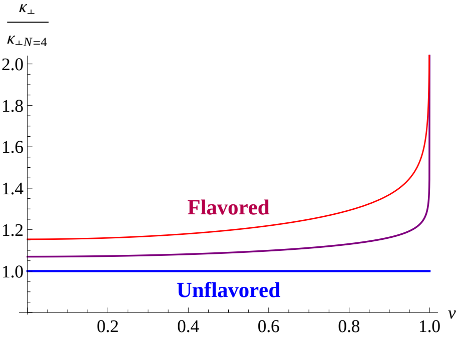


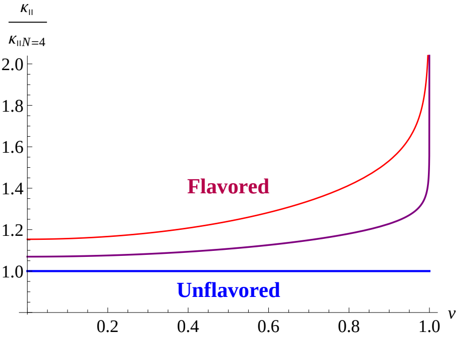


$$M_k = \frac{f}{\mu\gamma v} = \frac{\pi}{2\gamma v}\sqrt{\lambda_s(\varepsilon)}\,\frac{T^2}{\mu(m,\epsilon_h)}\left[1 + \frac{\epsilon_h}{4}\log\gamma + \mathcal{O}(\epsilon_h^2)\right]$$

Diffusion constants

$$\epsilon_h = 0, 0.25, 0.5$$

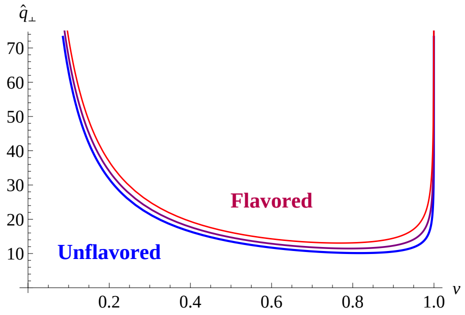


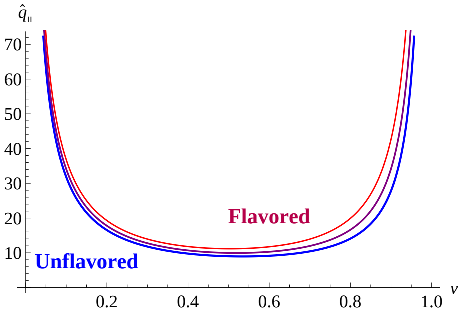


$$\kappa_\perp = \frac{e^{\frac{\Phi}{2}}}{\pi\alpha' T_s G_{xx}} = \gamma^{1/2}\pi^2\sqrt{\lambda_s(\varepsilon)}\,T^3\left(1+\epsilon_h\frac{3\gamma^2-1}{8\gamma^2}+\frac{\epsilon_h}{4}\log\gamma\right)$$

Jet quenching parameters

$\epsilon_h = 0, 0.25, 0.5$





$$\hat{q}_\perp = \frac{2\kappa_\perp}{v} = 2\frac{\gamma^{1/2}}{v}\pi^2\sqrt{\lambda_s(\varepsilon)}\,T^3\left(1+\epsilon_h\frac{3\gamma^2-1}{8\gamma^2}+\frac{\epsilon_h}{4}\log\gamma\right)$$

Summary of results

Comparison w.r.t. the unflavored plasma

qualitative trend of physical quantities increasing N_f (decreasing N_c)

constituent mass	$M_c/(\sqrt{\lambda}T)$	↗
meson melting point	$M_q/(\sqrt{\lambda}T)$	↘
conductivity	σ/σ_0	↘
screening length	$L_{\rm sc}$	↘
drag force	μ/T	↗
kinetic mass	$M_k/(\frac{1}{2}\sqrt{\lambda}T)$	↗
jet quenching	$\hat{q}/(\sqrt{\lambda}T^2)$	↗

Thank you