D3-D7 quark-gluon plasmas

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Outline

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Holographic plasmas as toy models for QCD plasmas

Why we want to include “quarks"

What do we look for?

- Solutions duals to plasmas with fundamental matter

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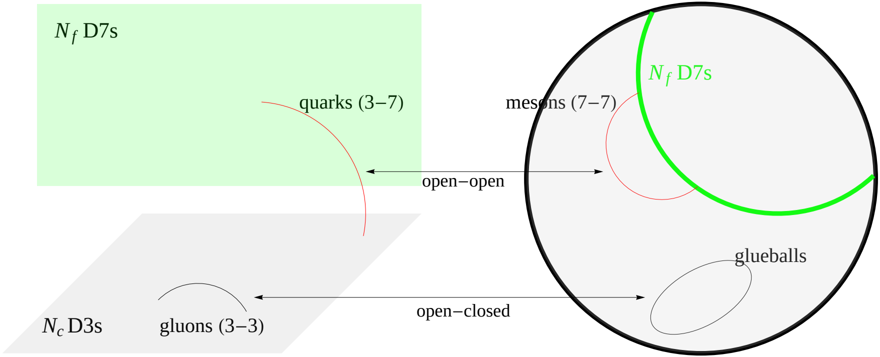
- Answer: in several features, but ...
- ...the absence of fundamental matter is a prominent one among them

Outline

Flavor Branes Introduce Fundamental Matter

Karch, Katz (02), . . .



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- Why? Because we want to know how they affect the physics of the plasma
- How? We must look for a solution coupled to D7-brane sources

Unquenched and Smeared

Bigazzi, Casero, Cotrone, Kiritsis, Paredes (05)

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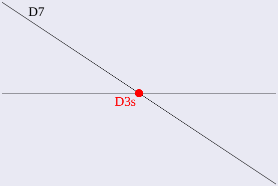
A few flavor branes



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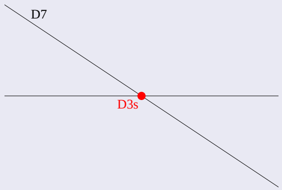

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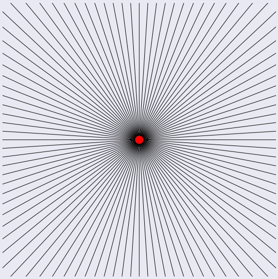

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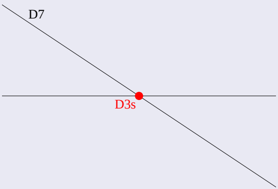

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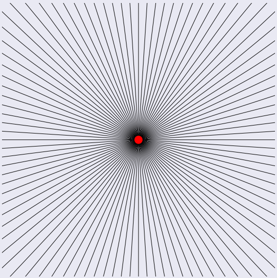
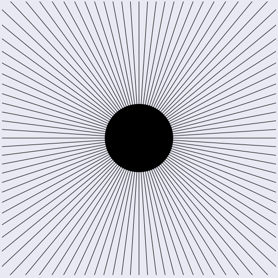


The black hole



Outline

What we look for: a solution of type IIB string theory

We need a deformation of $AdS_5 \times S^5$ with:

- Backreaction of N_f D7 flavor branes
- A black hole horizon

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Note: It can be easily generalized to $AdS_5 \times X^5$

The action

Defining the problem

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  $S_{IIB} = \frac{1}{2\kappa_{10}^2} \int d^{10}x \sqrt{-g_{10}} \left[R - \frac{1}{2}\partial_M\Phi\partial^M\Phi - \frac{1}{2}e^{2\Phi}F_{(1)}^2 - \frac{1}{2}\frac{1}{5!}F_{(5)}^2 \right]$

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- The source terms
  $S_{fl} = -T_7 \sum_{N_f} \left(\int d^8x \, e^{\Phi} \sqrt{-g_8} - \int C_8 \right)$
  Since we will consider a smeared situation, these contributions become 10d integrals.

Outline

The ansatz

The non-extremal generalization of Benini et al. (hep-th/0612118)

The metric and forms

$$ds_{10}^2 =$$

$$-\frac{r^2}{R^2} \qquad dt^2 + \frac{r^2}{R^2} d\vec{x}_3^2 + \frac{R^2}{r^2} \qquad \frac{dr^2}{\qquad} + R^2 \quad ds_{CP^2}^2 + R^2 \quad (d\tau + A_{CP^2})^2$$

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$$F_{(5)} = Q_c(1+*)\varepsilon(S^5)\,, \qquad F_{(1)} = Q_f(d\tau + A_{CP^2})\ , \qquad \Phi(r)$$

- Non-trivial temperature requires non-extremality factor
- Flavor D7 branes require $F_{(1)}$, running dilaton and squashing of the sphere

The flavor brane embeddings

They must be solved too

How the family of embeddings looks like

- $\sum_{i=1}^{3} a_i Z^i = 0 \qquad \rightarrow \qquad W = \cdots + \tilde{q} \left(\sum_{i=1}^{3} a_i \Phi_i \right) q$

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The associated charge density

- $dF_{(1)} = -g_s \Omega = 2 Q_f J_{CP^2}$

The explicit background solution

an awful slide...

$$\epsilon_* = \frac{\lambda_*}{8\pi^2}\frac{N_f}{N_c}$$

$$\begin{aligned}
\tilde{F} &= 1 - \frac{\epsilon_*}{24}\left(1 + \frac{2r^4 - r_h^4}{6r_*^4 - 3r_h^4}\right) + \frac{\epsilon_*^2}{1152}\left(17 - \frac{94}{9}\frac{2r^4 - r_h^4}{2r_*^4 - r_h^4} + \frac{5}{9}\frac{(2r^4 - r_h^4)^2}{(2r_*^4 - r_h^4)^2} + \right. \\
&\left. -\frac{8}{9}\frac{r_h^8(r_*^4 - r^4)}{(2r_*^4 - r_h^4)^3} - 48\log\left(\frac{r}{r_*}\right)\right) + O(\epsilon_*^3)\ , \\
\tilde{S} &= 1 + \frac{\epsilon_*}{24}\left(1 - \frac{2r^4 - r_h^4}{6r_*^4 - 3r_h^4}\right) + \frac{\epsilon_*^2}{1152}\left(9 - \frac{106}{9}\frac{2r^4 - r_h^4}{2r_*^4 - r_h^4} + \frac{5}{9}\frac{(2r^4 - r_h^4)^2}{(2r_*^4 - r_h^4)^2} + \right. \\
&\left. -\frac{8}{9}\frac{r_h^8(r_*^4 - r^4)}{(2r_*^4 - r_h^4)^3} + 48\log\left(\frac{r}{r_*}\right)\right) + O(\epsilon_*^3)\ , \\
\Phi &= \Phi_* + \epsilon_* \log\frac{r}{r_*} + \frac{\epsilon_*^2}{72}\left(1 - \frac{2r^4 - r_h^4}{2r_*^4 - r_h^4} + 12\log\frac{r}{r_*} + 36\log^2\frac{r}{r_*} + \right. \\
&\left. +\frac{9}{2}\left(Li_2\left(1 - \frac{r_h^4}{r^4}\right) - Li_2\left(1 - \frac{r_h^4}{r_*^4}\right)\right)\right) + O(\epsilon_*^3)\ ,
\end{aligned}$$

The integration constants

Integration constants were fixed requiring:

- Regularity at the horizon
- The solution coincides with the backreacted susy one at $r = r_*$

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A perturbative expansion (far below the LP):

The solution is a small deformation of the unflavored one, controlled by $\epsilon_* \sim N_f$

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Energy scales

How to deal with the Landau pole

Usual notion of renormalization

We introduce an arbitrary UV scale Λ_{UV}. IR physics is independent of this choice.

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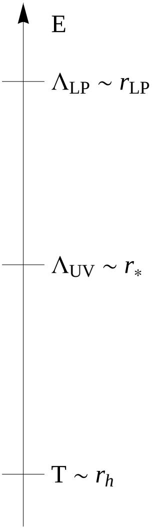

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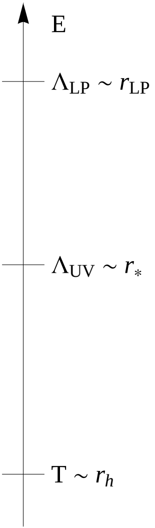

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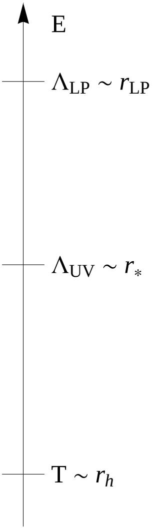

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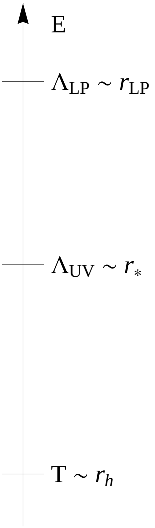

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- For the UV completion corrections to be subleading
  $\epsilon_* \gg \frac{r_h}{r_*}$
- Putting everything together

$$\boxed{e^{-\frac{1}{\epsilon_*}} \ll \frac{r_h}{r_*} \ll \epsilon_* \ll 1}$$

Introducing ϵ_h and regime of validity

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Putting together the previous slide and usual considerations:

Regime of validity

$$N_c \gg 1 \ , \qquad \lambda_h \gg 1 \ , \qquad N_f \gg 1 \ , \qquad \epsilon_h = \frac{\lambda_h}{8\pi^2}\frac{N_f}{N_c} \ll 1$$

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The rest of this talk

I will discuss some of its physical properties (thermodynamics and energy loss within the plasma)

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Temperature, Entropy, Energy, Free Energy

Temperatue

Regularity of euclideanized metric

$$T = \frac{r_h}{\pi R^2}\left[1 - \frac{1}{8}\epsilon_h - \frac{13}{384}\epsilon_h^2\right]$$

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Free energy

On-shell euclidean action

$$f = -\frac{1}{8}\pi^2 N_c^2 T^4 \left[1 + \frac{1}{2}\epsilon_h + \frac{1}{6}\epsilon_h^2\right]$$

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$$s = -\partial_T f \qquad\qquad f = \varepsilon - T\, s$$

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  (where we need to use $\partial_T \epsilon_h = \epsilon_h^2 / T$)
- At first order in ϵ_h, the probe limit of Mateos, Myers, Thomson (07) is recovered

Heat Capacity, Speed of Sound, Shear Viscosity

Heat capacity

$$c_V = \partial_T \varepsilon$$

$$c_V = \frac{3}{2}\pi^2 N_c^2 T^3 \left[1 + \frac{1}{2}\epsilon_h + \frac{11}{24}\epsilon_h\right]$$

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Shear and bulk viscosities

$$\eta = \frac{1}{4\pi} s \,, \qquad \frac{\varsigma}{\eta} = 2\left(\frac{1}{3} - v_s^2\right) = \frac{\epsilon_h^2}{9}$$

Outline

The jet quenching parameter
Liu, Rajagopal, Wiedemann (06)

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$$\hat{q} = \left(\pi\,\alpha' \int_{r_h}^{r_*} e^{-\frac{\Phi}{2}} \frac{\sqrt{g_{rr}}}{g_{xx}\sqrt{g_{xx}+g_{tt}}} dr\right)^{-1} = \frac{\pi^{\frac{3}{2}}\sqrt{\lambda_h}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})} T^3 \left[1 + \frac{1}{8}(2+\pi)\epsilon_h + \gamma\,\epsilon_h^2\right]$$

where $\gamma = \frac{11}{96} + \frac{\pi}{48} + \frac{3\pi^2}{128} + \frac{1}{8}\mathcal{C} + \frac{1}{48}\,{}_4F_3\left(1,1,1,\frac{3}{2};\frac{7}{4},2,2;1\right) \approx 0.5565.$

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An (unjustified) numerical estimate:

Take:

$N_c = N_f = 3$
$\alpha_s = \frac{1}{2}; \lambda_h = 6\pi$
$\epsilon_h = 0.24$
$T = 300 MeV$

$\Rightarrow$

The result is:

$\hat{q} = 5.3 \text{ (GeV)}^2/\text{fm}$
(for $N_f = 0$ it is $\hat{q} = 4.5 \text{ (GeV)}^2/\text{fm}$)

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- The field theory has a Landau pole, but IR physical properties can be consistently computed
- We have extracted the thermodynamics and started analysing energy loss of partons

Outlook

Many interesting open problems can be addressed!

- Backreaction of massive quarks
- Transport coefficients (bulk viscosity, . . .) (0912.3256)
- Phase transitions, meson spectra, . . .
- Chemical potential, baryon number
- Other set-ups (D2-D6, D4-D6, . . .)

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Thanks !