Aspects of D3/D7 plasmas at finite baryon density

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based on Bigazzi, Cotrone, JT arXiv:1304.4802
Motivation

- QCD has a rich phase diagram at finite $T$ and $\mu$
- Details only known in certain regimes
- Strong coupling physics dominates an important region
- Use holography to study systems at finite $\mu$ and possibly low $T$
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Cartoon of QCD phase diagram
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Cartoon of QCD phase diagram
• Introduction
• Finite baryon density and the probe
• Going beyond the probe limit
• Physical aspects and limitations
• Conclusions
AdS/CFT

• Most reliable tool in generic regions of the phase diagram (finite $\mu$)

• As a weak/strong duality allows us to learn strong coupling effects from classical gravity

• Provides geometric interpretation of field theory features or vice versa

• Fields in gravity provide sources and vevs of the field theory operators

• No known dual for QCD
Finite charge on the probe

- Take $N_c$ D3-branes, this is SU($N_c$) SYM
  \[ N_c \to \infty \]
- Strings represent fields in the adjoint
- Add $N_f$ D7-branes
- New strings give fields in the fundamental

Karch, Katz hep-th/0205236
Basic dictionary

- **RG flow = radial dependence**
- **Finite temperature = black D3-branes**
- **Non dynamic flavor = probe D7-branes on black D3-branes background**
  - Background AdS$_5 \times$S$_5$, D7’s wrap S$^3$ in S$^5$
  - No running dilaton
- **Massive flavor = D7’s separated a finite distance from D3’s**
- **Finite baryon chemical potential = U(1) gauge field on the D7’s worldvolume**
Probe brane at $T=0$

- We focus in the low $T$, finite baryon charge setup
- Probe approximation can be studied analytically
  \[ L = -N r^3 \sqrt{1 + y'^2 - (2\pi \alpha') A'^2_t} \]
- Charged system expected to be unstable
  - Charged scalars in the field theory: BE cond.
  - Charged fermions (chiral density wave)
  - CS-like couplings trigger instabilities

Karch, O’Bannon \textit{arXiv:0709.0570}

Ammon, Erdmenger, Lin, Müller, O’Bannon, Shock \textit{arXiv:1108.1798}
Fluctuations

- All bosonic worldvolume fields studied in the probe approximation: no instabilities found
Fluctuations

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**Figure 6:** (Color online) The complex $\tilde{\omega}$ plane, where each line indicates the motion, as a function of momentum $\tilde{k} \in (0,9)$, of the $\Phi^-(\tilde{\rho})$, $m = 1$ QNM that starts on the imaginary axis at small $\tilde{k}$, our “R-spin diffusion” mode. The different lines are for $\varepsilon = M/\mu = (0, 0.1, 0.3, 0.5, 0.7, 0.8, 0.9)$. 
Considering backreaction of the flavor branes
Beyond the probe limit

- Bottom-up vs. top-down models

<table>
<thead>
<tr>
<th>Nc(&gt;&gt;)1</th>
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<tbody>
<tr>
<td>‘t Hooft vs Veneziano</td>
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N=4 SYM with multiplets in the fundamental
Beyond the probe limit

- Bottom-up vs. top-down models

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<td>fixed phenomenology</td>
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$N=4$ SYM with multiplets in the fundamental
Beyond the probe limit

Bigazzi, Casero, Cotrone, Kiritsis, Paredes  hep-th/0505140

see review arXiv:1002.1088 for references

\[ S = \frac{1}{2\kappa_{10}^2} \left( \int L_{IIB} - \#\lambda \frac{N_f}{N_c} \int L_{D7} \right) \]

I will consider the Veneziano limit

\[ L_{D7} \sim \sqrt{-P[G]} \delta^2(D7) + WZ \]

\[ L_{D7} \sim \sqrt{-P[G]} \Omega_2 + WZ \]
Beyond the probe limit

• Finite baryon chemical potential = DBI action for the flavor branes

\[ \mathcal{L}_{D7} \sim \sqrt{-P[G]} \Omega_2 \rightarrow \sqrt{-P[G] + F \Omega_2} \]

• Analytic solutions at finite T and \( \mu \) available perturbatively in the backreaction parameter

\[ \epsilon \sim \lambda \frac{N_f}{N_c} \]

Bigazzi, Cotrone, Mas, Paredes, Ramallo, JT arXiv:0909.2865
Bigazzi, Cotrone, Mas, Mayerson, JT arXiv:1101.3560
Bigazzi, Cotrone, JT arXiv:1304.4802
Beyond the probe limit

- Not so complicate effective action describing the system

\[ S = \frac{1}{2\kappa_5^2} \int \left[ (R - V) \ast 1 - \frac{40}{3} df \wedge \ast df - 20 dw \wedge \ast dw - \frac{1}{2} d\Phi \wedge \ast d\Phi \\
- \frac{1}{2} e^{\Phi+4f+4w} \left( dC_0 - 2\sqrt{2}C_1 \right) \wedge \ast \left( dC_0 - 2\sqrt{2}C_1 \right) \\
- \frac{1}{2} e^{\Phi-\frac{4}{3}f-8w} \left( dC_1 - Q_7F_2 \right) \wedge \ast \left( dC_1 - Q_7F_2 \right) - \frac{1}{2} e^{\Phi-\frac{20}{3}f} dC_2 \wedge \ast dC_2 \\
- 4Q_7 e^{\Phi+\frac{16}{3}f+2w} \sqrt{-g + e^{-\frac{\Phi}{2}-\frac{10}{3}F_2}} \right], \]
Beyond the probe limit

• The solution is analytic but too large to write it down

• Possesses a horizon and depends on the value of the charge density from the $U(1)_B$

• It is perturbative in the backreaction parameter (explicitly built up to second order)

• The solution breaks down at a given UV scale due to the presence of a Landau pole
Physical aspects and limitations
Landau pole

- Perturbative beta function is positive

\[ \beta \propto \lambda^2 \frac{N_f}{N_c} \Rightarrow g_{YM}^2(Q^2) = \frac{16\pi^2}{N_f \log \frac{\Lambda^2}{Q^2}} \]

- The running of the coupling dual to a running dilaton

\[ \Phi = \Phi_* + \epsilon \log \frac{r}{r_*} + \mathcal{O}(\epsilon^2) \]
Landau pole

- Consider two scales associated to $r_1$ and $r_2$ and using

$$\epsilon_1 \propto \lambda_1 \frac{N_f}{N_c} = 4\pi g_S N_f e^{\Phi(r_1)}$$

- Then under a change of scale, from the solution, we have

$$\epsilon_1 = \epsilon_2 e^{\Phi_2 - \Phi_1} = \epsilon_2 + \epsilon_2^2 \frac{r_1}{r_2} \log \frac{r_1}{r_2} + \cdots$$

and in particular

$$g_{YM}^2 = \frac{4\pi g_s}{1 - \epsilon \left( \log \frac{r}{r_*} + \cdots \right)}$$
Effective IR dynamics

• Available description order by order in

\[ S_{\text{eff}} = \frac{1}{2\kappa_5^2} \int d^5 x \left( R + 12 - 4\epsilon_h \sqrt{1 + \frac{F^2}{2}} \right) \]

Pal arXiv:1209.3559

\[ s = \frac{\pi^3}{4G_5} T^3 \left( 1 - \frac{\epsilon_h}{2} + \epsilon_h \sqrt{1 + \frac{r_d^6}{\pi^3 T^3}} \right) \]

Bigazzi, Cotrone, JT arXiv:1304.4802

• Thermodynamics determined analytically and stable
more physical consequences

• Corrections to transport coefficients or energy loss effects are available
  - increased loss of energy of probes through the plasma due to additional scattering centers
    \[
    \hat{q} = \hat{q}_0 \left( 1 + \frac{2 + \pi}{8} \epsilon + 0.5565 \epsilon^2 + \cdots \right)
    \]
  - Positive bulk viscosity
    \[
    \frac{\zeta}{\eta} = \frac{1}{9} \epsilon^2 + \cdots
    \]
  - Unusual optical properties
  - etc
Fluctuations (again)

• Charged system expected to be unstable, but no instability found in the probe limit. However there is a mode with $m_{BF}^2$ mass.

Ammon, Erdmenger, Lin, Müller, O’Bannon, Shock arXiv:1108.1798

• In this setup we include supergravity couplings and might see corrections driving the mode unstable.

• However we can NOT go to zero temperature and everything remains stable.

• The system is stable under fluctuations for finite temperature (not all fluctuations studied, though).

Bigazzi, Cotrone, JT arXiv:1304.4802
Problem: it is a perturbation on top of a neutral black hole solution

- Inner horizon at radius $O(\epsilon)$
- Increasing baryon density requires the whole resummation of the solution and/or instanton effects

Physically: energy density of D7-branes always dominates in the IR

Hartnoll, Polchinski, Silverstein, Tong arXiv:0912.1061

- This is true also in the ‘t Hooft limit and in particular this problem persists for massless probe calculations
Summary & conclusions

• We studied SYM theory with fundamental matter with symmetry $U(1)^{N_f}$

• Reasonable analytic control to include phenomenological features

• Possibility to study plasma observables perturbatively in $N_f/N_c$

• IR physics obtained from simpler system

• A different approach to study extremality in the charged black hole must be taken
Thank you