Holographic Quark-Gluon Plasmas at Finite Quark Density

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June 1, 2011

Contents:

- Motivations.
- D3D7 Charged Quark-Gluon Plasmas.
- Physical Properties.
- Conclusions.

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Holographic methods provide an effective (qualitative and semi-quantitative) complementary approach to the ordinary (pQCD, Lattice, ...) theoretical studies of the QCD Quark-Gluon Plasma.

Motivations

Holography (AdS/CFT): a quantum field theory in d dimensions may be modeled by gravity in $d+n$ dimensions.

Example [Maldacena 1997]:

$\mathcal{N}=4$ $SU(N_c)$ SYM in 4d equivalent to Type IIB on $AdS_5 \times S^5$.

Gravity regime: $N_c \gg 1$,
$\lambda = g_{YM}^2 N_c \gg 1$.

Classical computations determine quantum field theories at strong coupling.

Motivations

- "Revolutionary" for formal aspects: new way of looking at strongly coupled QFTs.
- "Undelivered" for applied aspects:
    - Asymptotic freedom has no gravitational dual (weak coupling).
    - QCD has no gravitational dual even in the IR (different vacuum structure).

  But:
    - Can (toy) model QCD to some extent (AdS/QCD).
    - Possible evolutions in understanding the string (beyond gravity).
    - Can be applied to other QFTs (Condensed Matter).
    - QCD at finite temperature.

Quark-Gluon Plasma

- QCD at $T > T_c$: quarks and gluons not in hadrons (deconfined), but still strongly coupled.
- Realized in experiments: RHIC, LHC, SPS (FAIR, NICA, J-PARC).
- Strong coupling $\Rightarrow$ no(t only) pQCD $\Rightarrow$ lattice.
- RHIC and LHC QGP described fairly well as fluids.
- Real-time physics (transport coefficients, probe partons) $\Rightarrow$ no lattice (Euclidean formulation).

Motivations

Holographic approach: a theoretical tool for the QGP

What is the gain?

- QGPs at strong coupling (toy models for QCD).
- Can include dynamical flavors at finite chemical potential.
- Real-time physics readily accessible.

What is the price?

- Planar limit.
- Very large coupling.
- Not QCD.

Motivations

The price is not that high (an example):

- Hydrodynamic transport coefficients (e.g. shear viscosity η) must be calculated in microscopic theory.
- Calculations in pQCD and lattice not compatible with experiments/questionable.
- Holography: $\mathcal{N} = 4$ SYM Plasma $\Leftrightarrow$ $AdS_5 \times S^5$-Black Hole.
- From gravity [Policastro-Son-Starinets 2002]: $\frac{\eta}{s} = \frac{1}{4\pi}$.

Gravity result compatible with RHIC experiment.

- Numerical simulations of QGP evolution use holographic values for η, ζ: interpret QCD data at RHIC and LHC.

PRL **105**, 252302 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 201

(NRF), South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW); Ukraine Ministry of Education and Science; United Kingdom Science and Technology Facilities Council (STFC); The U.S. Department of Energy, the U.S. National Science Foundation, the State of Texas, and the State of Ohio.

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Motivations

Why does it work?

- Vacuum structures not so different at $1.5T_c < T < 4T_c$: (near) conformal, no supersymmetry, no chiral condensate, screening...
- Some observables are poorly sensitive to details of the theory: strong coupling in deconfined regime more important than specific theory.

Contents:

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There exist gravity solutions dual to QGPs with dynamical flavors and at finite quark density.

[Bigazzi-Cotrone-Mas-Paredes-Ramallo-Tarrio 2009] [Bigazzi-Cotrone-Mas-Mayerson-Tarrio 2011]

D3D7 Charged Quark-Gluon Plasmas

Quark-Gluon Plasma at RHIC, LHC, SPS (FAIR, NICA, J-PARC): thermalized systems at $T > T_c$, $\mu > 0$.

μ: light flavor chemical potential.

Theoretically even more difficult:

- Strong coupling $\Rightarrow$ no(t only) pQCD $\Rightarrow$ lattice.
- Dynamical flavors: unquenched.
- Finite chemical potential: sign problem.

D3D7 Charged Quark-Gluon Plasmas

Holographic approach to flavor physics

- Flavors (fundamental) in $\mathcal{N} = 4$ SYM: D7-branes on $AdS_5 \times S_5$ −BH.
- Baryon charge: gauge field on D7-branes.
- Quenched flavors $\Longleftrightarrow$ probe approximation [Karch-Katz 2002].
- Many infos but no flavor vacuum effects (non-dynamical), while QGP at RHIC and LHC does contain a significant fraction of dynamical degrees of freedom in fundamental representation.

D3D7 Charged Quark-Gluon Plasmas

The technique:

- Flavors beyond quenched approximation $\Leftrightarrow$ backreaction of D7-branes $\Rightarrow$ difficult (PDEs).
- "Smearing technique" takes advantage of parameter regime:
  $N_f \gg 1$ D7-branes
  $\Rightarrow$ homogeneous distribution in transverse space
  $\Rightarrow$ recover (part of) symmetry
  $\Rightarrow$ ODEs.

  [Bigazzi-Casero-Cotrone-Kiritsis-Paredes 2005, Casero-Nunez-Paredes 2006]
- Flavor group is Abelian.

D3D7 Charged Quark-Gluon Plasmas

Backreacted AdS-BH
(Charged flavored $\mathcal{N} = 4$ SYM)

$$ds^2 = -\frac{r^2}{R^2} b dt^2 + \frac{r^2}{R^2} d\vec{x}_3^2 + \frac{R^2}{r^2}\left[bS^8 F^2 j^2 dr^2 + S^2 ds^2_{CP^2} + F^2 (d\tau + A_{CP^2})^2 \right]$$

T=0 solution in [Benini-Canoura-Cremonesi-Nunez-Ramallo 2006].

Parameters: $\epsilon_h = \frac{\lambda_h}{8\pi^2}\frac{N_f}{N_c}, \qquad \delta = \frac{4}{\sqrt{\lambda_h}}\frac{\mu}{T}\left(1 - \frac{5}{24}\epsilon_h\right).$

Solution analytic at order ϵ_h^2, δ^2.

[Bigazzi-Cotrone-Mas-Paredes-Ramallo-Tarrio 2009] [Bigazzi-Cotrone-Mas-Mayerson-Tarrio 2011]

D3D7 Charged Quark-Gluon Plasmas

The solution:

$$b(r) = 1 - \frac{r_h^4}{r^4} - \frac{\epsilon_h \delta^2}{2}\left(\left(2 - \frac{r_h^4}{r^4}\right)\left(\frac{r_h^2}{r^2} - \log\left[1 + \frac{r_h^2}{r^2}\right]\right) - \frac{r_h^4}{r^4}(1 - \log 2)\right) + \mathcal{O}(\epsilon_h^2 \delta^2)$$

$$S(r) = r\left[1 + \frac{\epsilon_h}{24} + \epsilon_h^2\left(\frac{9}{1152} - \frac{1}{24}\log\frac{r_h}{r}\right)\right.$$
$$\left. + \frac{\epsilon_h \delta^2}{40}\left(3 - 2\frac{r^2}{r_h^2} - 3\left(1 - 2\frac{r^4}{r_h^4}\right)\log\left[1 + \frac{r_h^2}{r^2}\right] - \frac{1}{2}G(r)\right) + \mathcal{O}(\epsilon_h^2 \delta^2)\right]$$

$$F(r) = r\left[1 - \frac{\epsilon_h}{24} + \epsilon_h^2\left(\frac{17}{1152} + \frac{1}{24}\log\frac{r_h}{r}\right)\right.$$
$$\left. + \frac{\epsilon_h \delta^2}{40}\left(3 - 22\frac{r^2}{r_h^2} + 5\frac{r_h^2}{r^2} - 3\left(1 - 2\frac{r^4}{r_h^4}\right)\log\left[1 + \frac{r_h^2}{r^2}\right] + 2G(r)\right) + \mathcal{O}(\epsilon_h^2 \delta^2)\right]$$

$$\phi(r) = \phi_h + \epsilon_h \log\frac{r}{r_h} - \frac{\epsilon_h^2}{48}\left(8\left(1 + 3\log\frac{r}{r_h}\right)\log\frac{r_h}{r} - 3\,\mathrm{Li}_2\left[1 - \frac{r_h^4}{r^4}\right]\right) + \mathcal{O}(\epsilon_h^2 \delta^2)$$

where:

$$j(r) = \frac{1}{r(r^4 - r_h^4)} + \frac{\epsilon_h \delta^2}{4r^3(r^4 - r_h^4)^2}\left(r_h^2(2r^2 - r_h^2)(r^2 + r_h^2) - 2r^6\log\left(1 + \frac{r_h^2}{r^2}\right)\right) + \mathcal{O}(\epsilon_h^2 \delta^2)$$

$$G(r) = 2\pi\frac{r_h^6}{r^6}\,{}_2F_1\left(\frac{3}{2}, \frac{3}{2}, 1, 1 - \frac{r_h^4}{r^4}\right)$$

Regime of validity:

- $N_c \gg 1$, $\lambda_h \gg 1$: gravity approximation of string theory.
- $N_f \gg 1$: brane distribution dense enough.
- $\epsilon_h \ll 1$: Landau pole far in the UV.
- $\delta \ll 1$: solution in analytic form (can be relaxed with numerics).

Contents:

From gravity "toy models" extract informations for QCD: enhancement of jet quenching by flavors, estimates of transport coefficients, ...

Consistent Thermodynamics

Grand-canonical ensemble:

$$
\begin{aligned}
s &= \frac{1}{2}\pi^2 N_c^2 T^3 \left[1 + \frac{1}{2}\epsilon_h(1+\delta^2) + \frac{7}{24}\epsilon_h^2(1+\delta^2)\right] \\
\varepsilon &= \frac{3}{8}\pi^2 N_c^2 T^4 \left[1 + \frac{1}{2}\epsilon_h(1+2\delta^2) + \frac{1}{3}\epsilon_h^2(1+\frac{7}{4}\delta^2)\right] \\
\omega &= -\frac{1}{8}\pi^2 N_c^2 T^4 \left[1 + \frac{1}{2}\epsilon_h(1+2\delta^2) + \frac{1}{6}\epsilon_h^2(1+\frac{7}{2}\delta^2)\right]
\end{aligned}
$$

Note: $\frac{d\epsilon_h}{dT} = \frac{\epsilon_h^2}{T} + \mathcal{O}(\epsilon_h^3)$, $\left(\frac{d\,\delta}{dT}\right)_\mu = -\frac{\delta}{T}\left(1 + \frac{\epsilon_h}{2} + \mathcal{O}(\epsilon_h^2)\right)$.

Physical Properties

Thermodynamic stability

Susceptibilities:

$$
\begin{aligned}
-\frac{\partial^2\omega}{\partial\mu^2} &= \frac{N_f N_c}{2}\;T^2\left(1+\frac{1}{6}\epsilon_h\right)\\
-\frac{\partial^2\omega}{\partial\mu\partial T} &= -\frac{\partial^2\omega}{\partial T\partial\mu} = N_f N_c\;\mu\;T\left(1+\frac{1}{6}\epsilon_h\right)\\
-\frac{\partial^2\omega}{\partial T^2} &= \frac{3\pi^2 N_c^2}{2}\;T^2\left(1+\frac{1}{2}\epsilon_h+\frac{11}{24}\epsilon_h^2\right)+\frac{N_f N_c}{2}\;\mu^2\left(1+\frac{1}{6}\epsilon_h\right)
\end{aligned}
$$

Positive determinant of susceptibility matrix.

Note: $\frac{\chi_\infty}{\chi_0} = \frac{1}{2}\left(1+\frac{1}{6}\epsilon_h\right)$.

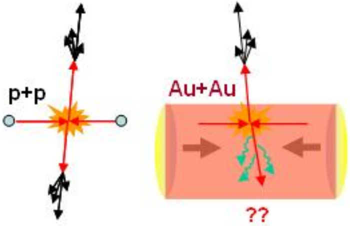
Physical Properties

Breaking of conformality at second order in ϵ_h

$$\begin{aligned} \varepsilon - 3p &= \frac{1}{16}\pi^2 N_c^2 T^4 \epsilon_h^2 \\ c_s^2 &= \frac{1}{3}\left[1 - \frac{1}{6}\epsilon_h^2\right] \end{aligned}$$

Jet quenching parameter

- Transport coefficient characterizing probe energy loss.



- In string theory calculated by light-like Wilson loop.

[Liu-Rajagopal-Wiedemann 2006, Armesto-Edelstein-Mas 2006]

Physical Properties

In flavored $\mathcal{N} = 4$ SYM:

$$\hat{q} = \frac{\pi^{3/2}\Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})}\sqrt{\lambda_h}\, T^3 \left[1 + \frac{2+\pi}{8}\epsilon_h(1 + 0.87\,\delta^2)\right]$$

Flavors enhance jet quenching!

- Naive: $N_c = 3, \;\lambda_h = 6\pi, \;T = 300$ MeV, $\;\mu = 10$ MeV.

$$\hat{q}_{\mathcal{N}=4} \sim 4.5 \text{ GeV}^2/\text{fm} \quad \longrightarrow \quad \hat{q}_{N_f=3} \sim 5.3 \text{ GeV}^2/\text{fm}.$$

At RHIC: $\hat{q}$ in the range 5-15 GeV^2/fm.

Physical Properties

- Less naive: fix number of degrees of freedom (entropy density s or energy density ε or pressure p).

  Fix N_c, vary T:

  - Flavors enhance jet quenching.
  - Chemical potential reduces the enhancement.

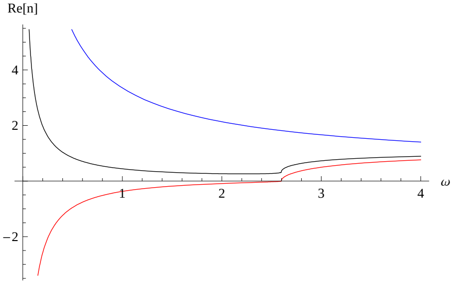
  Fix T, vary N_c: Flavors enhance jet quenching but chemical potential increases the enhancement.

Important to consider effect of flavors in phenomenology!

[Muller-Nagle 2006]

Optical properties

- System: charged relativistic fluid.
- From [Amariti-Forcella-Mariotti-Policastro 2010, Amariti-Forcella-Mariotti 2010]:
  - Negative refraction of light (opposite direction of phase velocity and energy) for frequencies $\omega < \frac{2\sqrt{2}q}{\pi N_c} \frac{\rho}{T^2} \left(1 - \frac{1}{4}\epsilon_h\right)$.
  - Additional Light Waves: simultaneous propagation of 2 waves with same polarization, different velocity and dumping.



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- From gravity "toy models" extract informations for QCD: enhancement of jet quenching by flavors, estimates of transport coefficients, ...

Conclusions

Future directions:

- Explore large μ/T regime (extremality?).
- Extend to massive flavors.
- Extend to models with confinement and chiral symmetry breaking: phase diagram at large N_c, N_f.

Informations for phase diagram of QCD?