Holographic Quark-Gluon Plasmas at Finite Quark Density

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Contents:

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

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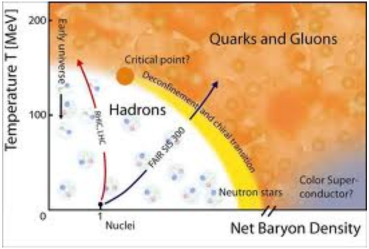
There are no first-principle methods to investigate the physics of relevant parts of the QCD phase diagram.

Motivations

QCD phase diagram, possibly:



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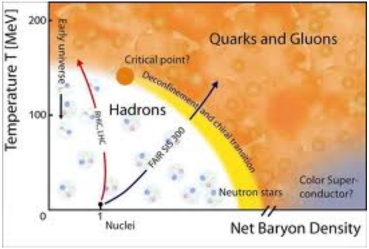

- Phenomenology beyond hadronic phase:
  - Early universe evolution.
  - Neutron stars.
  - Experiments (RHIC, LHC, SPS, FAIR, NICA, J-PARC).

Motivations

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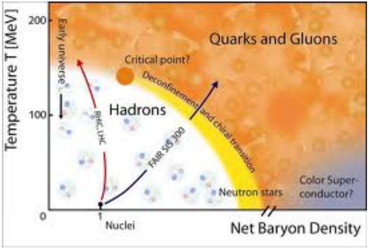

- Theory results:
  - pQCD: very large temperature or charge.
  - Lattice: small charge, mostly equilibrium physics.
  - Effective models.

Motivations

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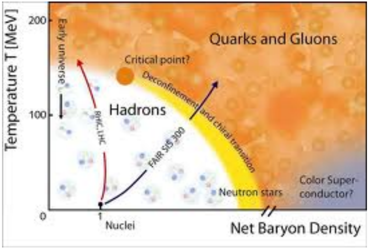
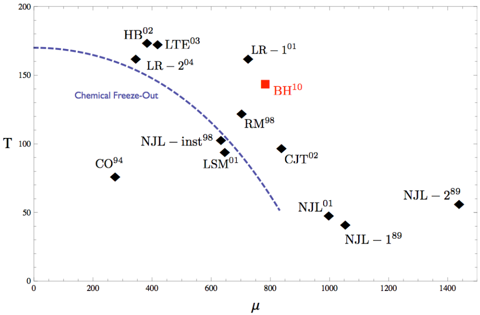


- Bulk of the phase diagram?
  - Not pQCD: strong coupling.
  - Not lattice: sign problem, non-equilibrium physics.
  - Effective models: assumptions.

The critical point, theoretically:

Figure from [DeWolfe-Gubser-Rosen 2010]



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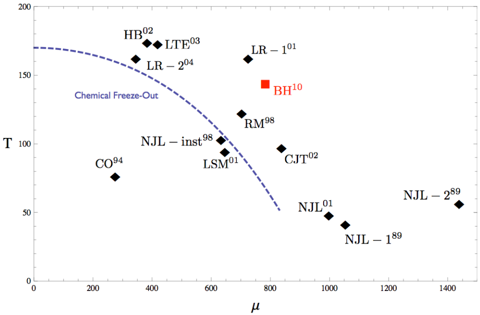

"There are no first-principle methods to investigate the physics of relevant parts of the QCD phase diagram."

Motivations

Holographic approach:
A theoretical tool for the physics of the QCD phase diagram?

What is the gain?

- Strong coupling.
- No sign problem.
- Real-time physics readily accessible.
- First principle constructions (top-down).

What is the price?

- Planar limit.
- Very large coupling.
- Not QCD.
- Difficulties with flavor physics.

Motivations

Further motivation: AdS/CM.

- Electron systems at finite density near Fermi surfaces.

  Can model holographically as:

  - Electrons $\rightarrow$ matter in fundamental.
  - Finite density $\rightarrow$ density for fundamentals.
  - Fermi surface $\rightarrow$ horizon near extremality.
- Superconductivity/superfluidity.

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First step: simplest gravity solutions dual to systems with dynamical flavors at finite temperature and quark density.

[Bigazzi-Cotrone-Mas-Mayerson-Tarrio 2011]

D3D7 Charged Quark-Gluon Plasmas

Holographic approach to flavor physics:

- Flavors (fundamental) in $\mathcal{N} = 4$ SYM: D7-branes on $AdS_5 \times S_5(-\text{BH})$.
- Baryon charge: gauge field on D7-branes.
- Flavors beyond quenched approximation $\Leftrightarrow$ backreaction of D7-branes.
- "Smearing technique": uniform distribution of D7s $\Rightarrow$ flavor group is Abelian.

[Bigazzi-Casero-Cotrone-Kiritsis-Paredes 2005, Casero-Nunez-Paredes 2006]

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]

The solution:

$$
\begin{aligned}
b(r) &= 1 - \frac{r_h^4}{r^4} - \frac{\epsilon_h \delta^2}{2}\left(\left(2 - \frac{r_h^4}{r^4}\right)\left(\frac{r_h^2}{r^2} - \log\left[1 + \frac{r_h^2}{r^2}\right]\right) - \frac{r_h^4}{r^4}(1 - \log 2)\right) + \mathcal{O}(\epsilon_h^2 \delta^2) \\
S(r) &= r\left[1 + \frac{\epsilon_h}{24} + \epsilon_h^2\left(\frac{9}{1152} - \frac{1}{24}\log\frac{r_h}{r}\right)\right. \\
&\quad \left. + \frac{\epsilon_h \delta^2}{40}\left(3 - 2\frac{r^2}{r_h^2} - 3\left(1 - 2\frac{r^4}{r_h^4}\right)\log\left[1 + \frac{r_h^2}{r^2}\right] - \frac{1}{2}G(r)\right) + \mathcal{O}(\epsilon_h^2\delta^2)\right] \\
F(r) &= r\left[1 - \frac{\epsilon_h}{24} + \epsilon_h^2\left(\frac{17}{1152} + \frac{1}{24}\log\frac{r_h}{r}\right)\right. \\
&\quad \left. + \frac{\epsilon_h \delta^2}{40}\left(3 - 22\frac{r^2}{r_h^2} + 5\frac{r_h^2}{r^2} - 3\left(1 - 2\frac{r^4}{r_h^4}\right)\log\left[1 + \frac{r_h^2}{r^2}\right] + 2G(r)\right) + \mathcal{O}(\epsilon_h^2\delta^2)\right] \\
\phi(r) &= \phi_h + \epsilon_h \log\frac{r}{r_h} - \frac{\epsilon_h^2}{48}\left(8\left(1 + 3\log\frac{r}{r_h}\right)\log\frac{r_h}{r} - 3\,\mathrm{Li}_2\left[1 - \frac{r_h^4}{r^4}\right]\right) + \mathcal{O}(\epsilon_h^2\delta^2)
\end{aligned}
$$

where:

$$
\begin{aligned}
j(r) &= \frac{1}{r(r^4 - r_h^4)} + \frac{\epsilon_h \delta^2}{4r^3(r^4 - r_h^4)^2}\left(r_h^2(2r^2 - r_h^2)(r^2 + r_h^2) - 2r^6 \log\left(1 + \frac{r_h^2}{r^2}\right)\right) + \mathcal{O}(\epsilon_h^2\delta^2) \\
G(r) &= 2\pi \frac{r_h^6}{r^6}\, {}_2F_1\left(\frac{3}{2}, \frac{3}{2}, 1, 1 - \frac{r_h^4}{r^4}\right)
\end{aligned}
$$

D3D7 Charged Quark-Gluon Plasmas

Regime of validity:

- $N_c \gg 1$, $\lambda_h \gg 1$: gravity approximation of string theory.
- $\lambda_h^{1/2} \gg N_f \gg 1$: brane distribution dense enough; Abelian DBI reliable.
- $\epsilon_h \ll 1$: Landau pole far in the UV.
- $\delta \ll 1$: solution in analytic form (can be relaxed).

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What physics from this gravity "toy models"?

Properties

- Consistent Thermodynamics.
- Thermodynamic stability.
- Susceptibility:

$$\chi_\infty \equiv -\frac{\partial^2 \omega}{\partial \mu^2} = \frac{N_f N_c}{2} T^2 \left(1 + \frac{1}{6}\epsilon_h\right)$$

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

QCD: $\frac{\chi}{\chi_0} \sim 0.7$ at $T \sim 2T_c$ (reduced by flavors from $\frac{\chi}{\chi_0} \sim 1$) [Borsanyi et al. 2010].

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- Enhancement of jet quenching due to flavors.
- Optical properties (charged fluid):

[Amariti-Forcella-Mariotti-Policastro 2010, Amariti-Forcella-Mariotti 2010]

  - Negative refraction of light.
  - Additional Light Waves.

Properties

- Stability (preliminary).

  Reduced 5d theory contains:

  - $\mathcal{A}_\mu$ vector from world-volume gauge field;
  - $\mathcal{A}$ scalar from world-volume gauge field;
  - $C^{(4)}_\mu$ from $C_{(4)}$;
  - $C^{(2)}_{\mu\nu}$ from $C_{(2)}$;

  $$S_5 \supset \int \mathcal{F} \wedge \mathcal{F} \wedge C^{(4)} + \mathcal{F} \wedge \partial \mathcal{A}^2 \wedge C^{(2)} \, .$$

  (see also [Chen-Hashimoto-Matsuura 2009])

  5d CS terms can give instabilities.

  [Domokos-Harvey 2007, Nakamura-Ooguri-Park 2009]

  Invisible in probe approximation in [Ammon-Erdmenger-Lin-Muller-O'Bannon-Shock 2011]: no instability.

Conclusions

Future directions:

- Explore large μ/T regime (extremality? stability?).
- 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?