Holographic modeling of hot and cold QCD

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[arXiv:1112.1261, 1210.4516, 1312.5199 with
Alho, Kajantie, Kiritsis, Rosen, Tuominen]
[ongoing work with Jokela, Nijs, Remes]

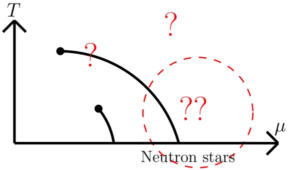
Outline

1. Introduction and motivation
2. The V-QCD models
3. Comparing V-QCD with QCD data
4. Conclusions

1. Introduction

Motivation

- Behavior of QCD unclear at intermediate chemical potentials and small temperatures
  - Region relevant for neutron stars
- Large uncertainties also elsewhere (except for certain well known regions)
  - In particular in the EoS at finite μ and T
- Can (bottom-up) holography be used to reduce the uncertainties or to pick a favored EoS?

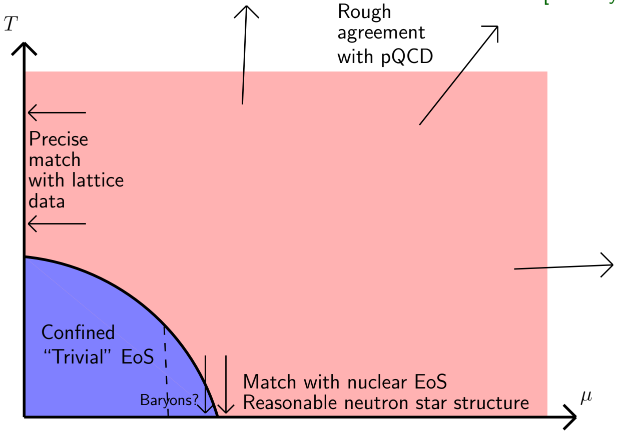


Modeling QCD in bottom-up holography

Idea: constrain holographic model using available data

- In particular, extrapolate lattice data to finite μ
- Complementary to the top-down approach

[Talk by C. Hoyos]



Goal: a good model of the (deconfined) QCD EoS for all T and μ

Warning: work in progress!

2. V-QCD

Holographic V-QCD: the fusion

The fusion:

1. IHQCD: model for glue inspired by string theory (dilaton gravity)

   [Gursoy, Kiritsis, Nitti; Gubser, Nellore]

2. Adding flavor and chiral symmetry breaking via tachyon brane actions

   [Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

Consider 1. + 2. in the Veneziano limit with full backreaction:
$N_c \to \infty$ and $N_f \to \infty$ with $x \equiv N_f/N_c$ fixed
$\Rightarrow$ V-QCD models

[MJ, Kiritsis arXiv:1112.1261]

V-QCD at finite T and μ

Two bulk scalars: $\lambda \leftrightarrow g^2 N_c$, $\tau \leftrightarrow \bar{q}q$

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$
$$- N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) e^{-\tau^2}$$
$$\times \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

$$F_{rt} = \Phi'(r) \qquad \Phi(0) = \mu$$

- Four functions V_g, V_{f0}, κ, w and two parameters: M and the dynamical energy scale Λ to be determined
- Find numerically black brane/horizonless saddle points with/without tachyon and compare free energies

[Alho,Kajantie,Kiritsis,MJ,Tuominen arXiv:1210.4516;
Alho,Kajantie,Kiritsis,MJ,Rosen,Tuominen arXiv:1312.5199]

Constraining the potentials

In the UV ($\lambda \to 0$):

- UV expansions of potentials matched with perturbative QCD beta functions $\Rightarrow$ asymptotic freedom and logarithmic flow of the coupling and quark mass, as in QCD

[Gürsoy, Kiritsis arXiv:0707.1324; MJ, Kiritsis arXiv:1112.1261]

In the IR ($\lambda \to \infty$): various qualitative constraints

- Linear confinement, discrete glueball & meson spectrum, linear radial trajectories
- Existence of a "good" IR singularity
- Correct behavior at large quark masses
- Working potentials often string-inspired power-laws, multiplied by logarithmic corrections (i.e, first guesses usually work!)

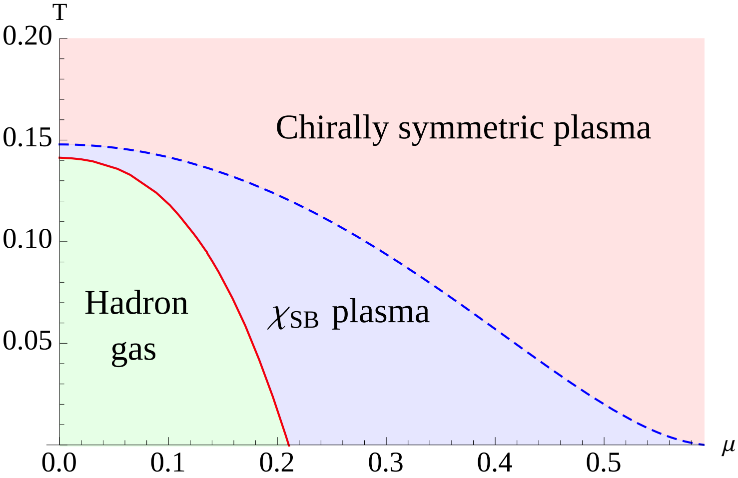
[Gürsoy, Kiritsis, Nitti arXiv:0707.1349; MJ, Kiritsis arXiv:1112.1261; Arean, Iatrakis, MJ, Kiritsis arXiv:1309.2286, arXiv:1609.08922; MJ arXiv:1501.07272]

Final task: determine the potentials in the middle, $\lambda = \mathcal{O}(1)$

- Qualitative comparison to lattice/experimental data

Phase diagram: example

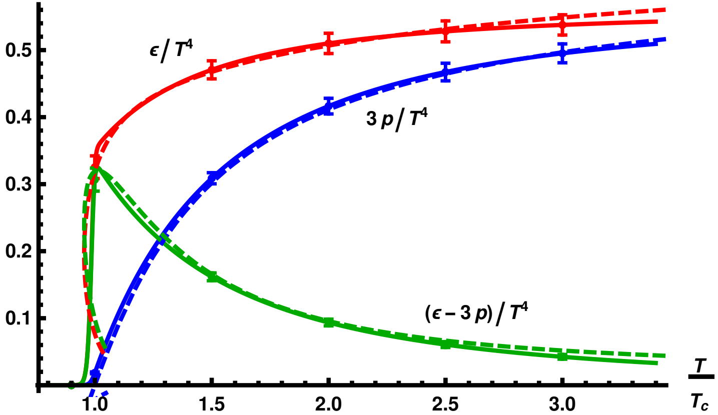
Choosing a set of potentials satisfying asymptotic constraints at $x = N_f/N_c = 1$: [Alho,Kajantie,Kiritsis,MJ,Rosen,Tuominen, arXiv:1312.5199]



(Fit to data will reduce the region of intermediate phase)

3. V-QCD: data comparison

Fitting: glue sector



- Determine precise form of $V_g(\lambda)$ with UV and IR asymptotics fixed (at $N_f = 0$)
- Follow roughly the strategy in [Gürsoy, Kiritsis, Mazzanti, Nitti arXiv:0903.2859]
- Stiff fit to large N_c YM lattice data [Panero, arXiv:0907.3719]

Fitting flavor sector: strategy

The different ongoing projects:

1. Overall fit to the properties of QCD: spectrum of mesons, glueballs, baryons, thermodynamics, decay constants,. . .
   - Not covered in this talk (results too preliminary)
2. Precision fit of QCD EoS at finite μ and T
   - The rest of the talk
   - Fit to lattice data at $\mu = 0$ as well as possible + require agreement with pQCD at large μ and T
   - Predict the EoS elsewhere
   - "Guided analytic continuation"
   - Rather constrained description even at $\mu = \mathcal{O}(\Lambda_{QCD})$
   - Related approach describes the critical point using Einstein-Maxwell-dilaton gravity

[DeWolfe, Gubser, Rosen, arXiv:1012.1864]

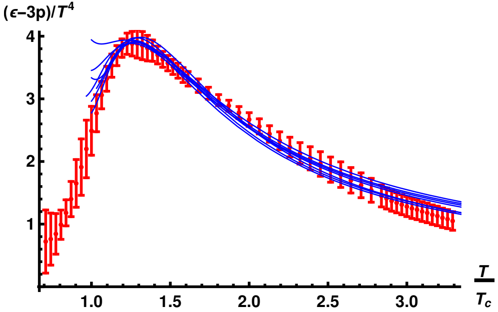
Possible caveats

- Comparing to data at $N_c = 3$: what about $\mathcal{O}(1/N_c)$ corrections?
- Issues due to sizeable N_f/N_c:
  - Unsuppressed open string loop corrections not properly treated?
  - Maybe I should write a different (more general?) Ansatz for the flavor/DBI action?
- Lattice data for $2+1$ quarks, whereas I will set all quark masses to zero
- No critical point, 1st order transition at $\mu = 0$, so how to fit lattice data which has a crossover?
  - Could matching with hadron resonance gas help? [Alho,Kajantie,Kiritsis,MJ,Tuominen, arXiv:1501.06379]
- All $T = 0$ solutions have finite entropy, sign of instabilities?

Fitting: flavor sector

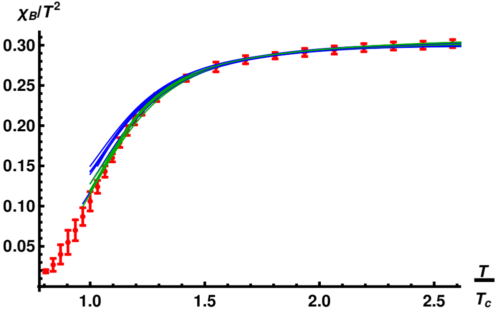
Interaction measure: constrains $V_{f0}(\lambda)$ (and a bit $\kappa(\lambda)$)

Lattice data: Borsanyi et al. arXiv:1309.5258



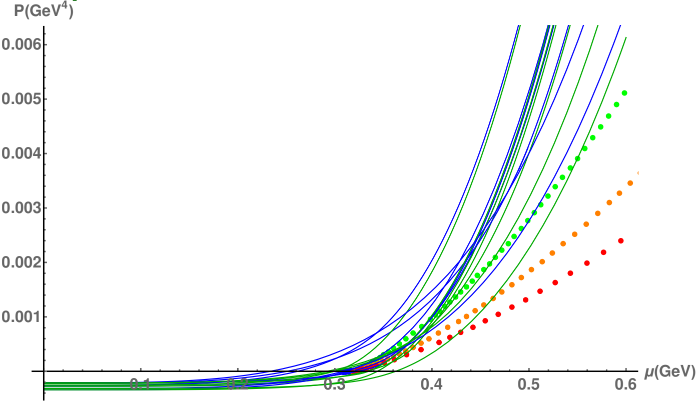
Baryon number susceptibility: constrains $w(\lambda)$

Lattice data: Borsanyi et al. arXiv:1112.4416



Extrapolated EoS of cold QCD

After fit to lattice data, critical μ is close to 300 MeV
Compared to stiff, intermediate, and soft nuclear EoSs
[K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk arXiv:1303.4662]

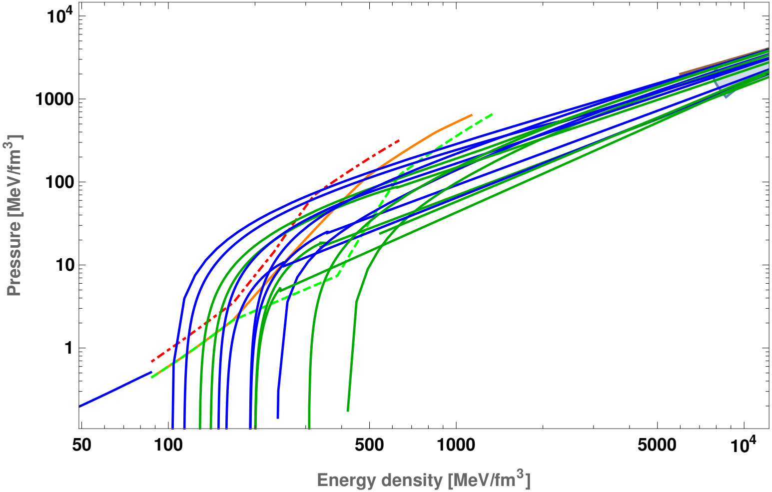


Ongoing work with N. Jokela and J. Remes: determine EoS which can be matched with nuclear EoS – are neutron stars with (holographic) quark matter cores possible, unlike in D3-D7?
[Hoyos, Rodriguez, Jokela, Vuorinen arXiv:1603.02943]

Limit of high μ

All holographic EoSs hit the pQCD band

[A. Kurkela, P. Romatschke, A. Vuorinen arXiv:0912.1856]



Conclusions and outlook

- V-QCD EoS in the deconfined phase can be tuned to agree with lattice data and pQCD
  $\Rightarrow$ a rough model for all (μ, T)
- The model is more general than just EoS
  - Dynamics can be studied directly in the model
  - Also finite B and CP-odd physics can be "turned on"
    [Arean, Iatrakis, MJ, Kiritsis arXiv:1609.08922; Gürsoy, Iatrakis, MJ, Nijs arXiv:1611.06339]
- Other ongoing projects:
  - Including baryons on the holographic side [with T. Ishii and G. Nijs]
  - Overall fit to QCD data, taking into account also meson and glueball spectra, decay constants, baryon mass
- Future work (?): flavor dependent quark masses

Extra slides

Limit of high T and μ