Dense holographic QCD and neutron stars

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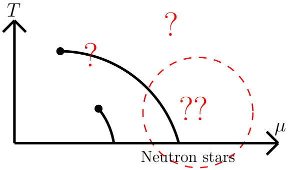
[ongoing work with Jokela, Remes (Helsinki);
Ishii, Nijs (Utrecht)]

Outline

1. Introduction and motivation
2. The V-QCD models
3. V-QCD at finite μ and neutron stars
4. Conclusions

Motivation

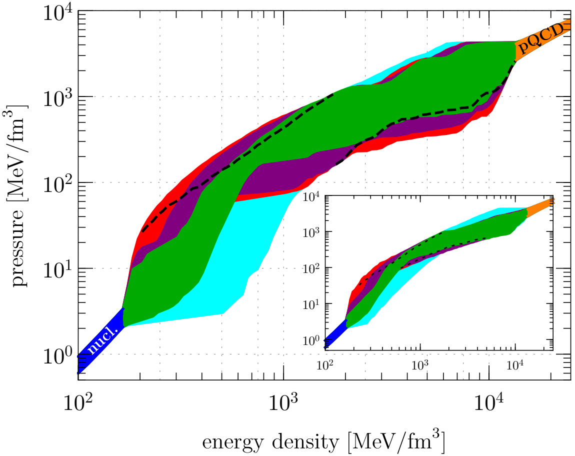
- Behavior of QCD unclear at intermediate chemical potentials and small temperatures
  - Region relevant for neutron stars (typically $T \ll \Lambda_{\mathrm{QCD}}$)
- Large uncertainties also elsewhere (except for certain well known regions)
  - In particular in the EoS at nonzero μ and T
- Can (bottom-up)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



State of the art for QCD EoS at $T = 0$: interpolations between nuclear EoS and pQCD, constrained by

[Annala, Gorda, Kurkela, Vuorinen arXiv:1711.02644]

- Speed of sound $< c$
- Highest observed neutron star mass $\approx 2.0\, M_\odot$ (cyan area)
- LIGO observation of neutron star merger GW170817: upper bound on tidal deformability (red area)



Holographic V-QCD: the fusion

I consider a specific model with dynamical quarks, obtained by fusing together:

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

   [Gursoy, Kiritsis, Nitti; Gubser, Nellore]

2. Method for 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]

- A very good overall model for physics of QCD over most of the parameter space (N_f/N_c, m_q, T, μ, B, θ ...)

V-QCD at finite T and μ

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

- Model physics in chirally symmetric phase (zero m_q): set $\tau = 0$

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

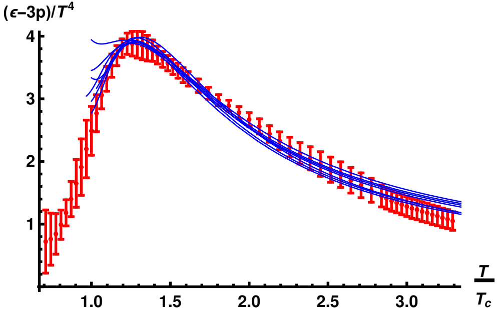
$$- N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) \sqrt{-\det(g_{ab} + w(\lambda) F_{ab})}$$

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

- Functions V_g, V_{f0}, w and two parameters: M and the dynamical energy scale Λ to be determined
  - Use both qualitative features (e.g. confinement, asymptotic freedom) and fit to lattice/experimental data
- Find numerically black brane/horizonless saddle points and compare free energies
- Use standard holographic dictionary to compute observables

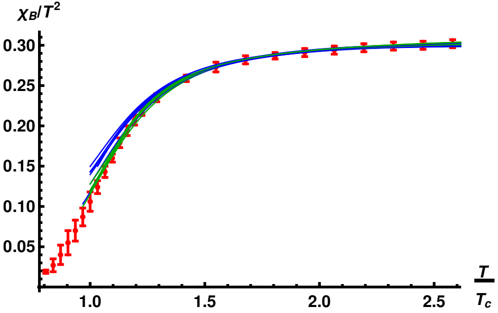
[Alho,Kajantie,Kiritsis,MJ,Tuominen arXiv:1210.4516; Alho,Kajantie,Kiritsis,MJ,Rosen,Tuominen arXiv:1312.5199]

Fitting to full QCD data at $\mu = 0$



Interaction measure: constrains $V_{f0}(\lambda)$

Lattice data: Borsanyi et al. arXiv:1309.5258



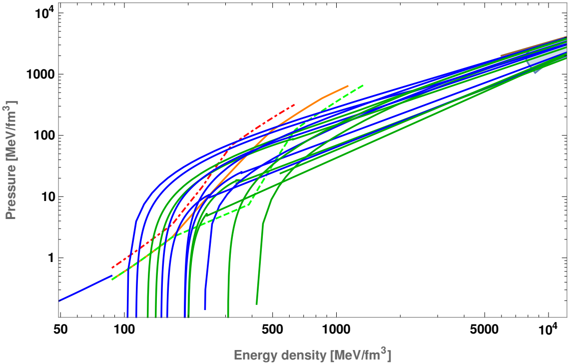
Baryon number susceptibility: constrains $w(\lambda)$

Lattice data: Borsanyi et al. arXiv:1112.4416

Extrapolated EoS of cold QCD

After fit to lattice data at $\mu = 0$, holographic EoS at $T = 0$ compared to stiff, intermediate, and soft nuclear EoSs
[K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk arXiv:1303.4662]

- All holographic EoSs hit the pQCD band
[A. Kurkela, P. Romatschke, A. Vuorinen arXiv:0912.1856]

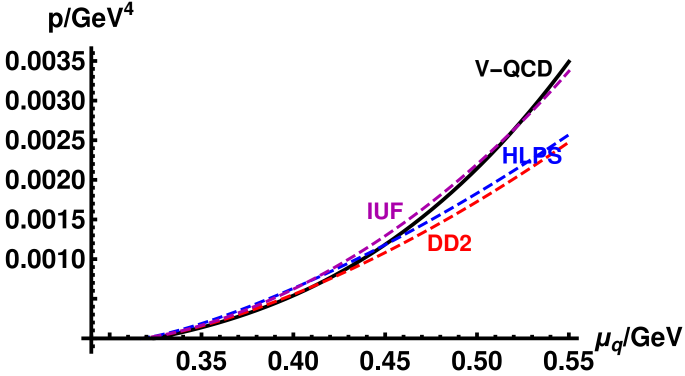


- Similar extrapolations carried out earlier within perturbative and simpler holographic models
[Rebhan,Romatschke hep-ph/0304294; DeWolfe,Gubser,Rosen 1012.1864;. . .]

Matching with nuclear models

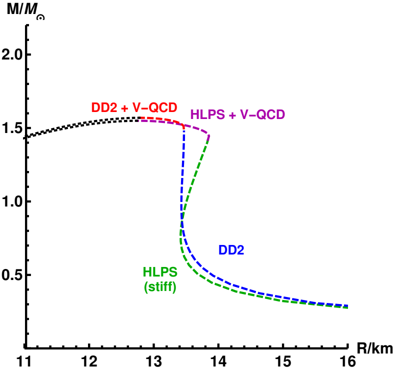
We choose potentials which have critical μ_q near vacuum – nuclear matter transition (at $T = 0$) [ongoing work with Jokela, Remes]

- V-QCD (deconfined phase) EoS “automatically” matches well with nuclear matter EoSs from various models



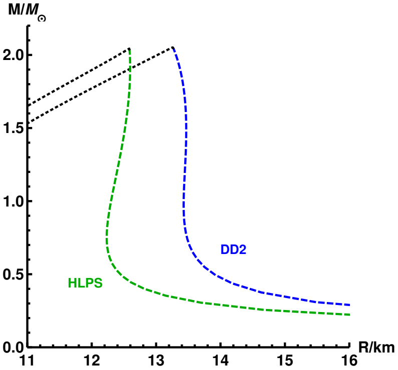
- We use nuclear models for the baryonic phase and V-QCD to model deconfined phase

Mass – radius relations



(Cold) stars with stable holographic matter possible but maximum mass too low $\ll 2M_\odot$

- Fix by fine tuning of parameters?



More realistic scenario: instability induced by V-QCD EoS

[Hoyos et al. arXiv:1603.02943]

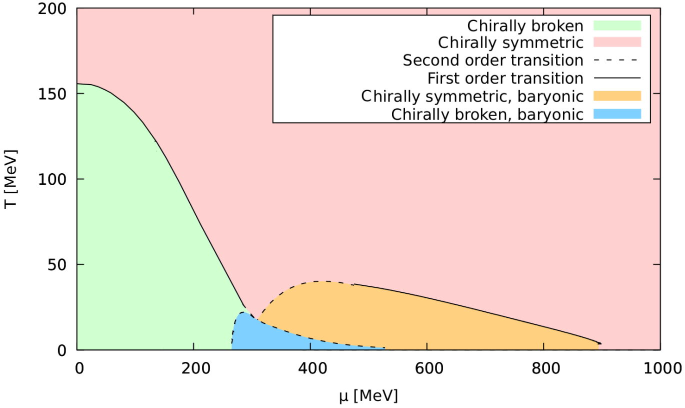
- Final state of GW170817 a black hole (?) $\Rightarrow$ maximal neutron star mass $2 \,..\, 2.2M_\odot$ $\Leftarrow$ location of instability?

Next step: baryonic matter in V-QCD?

Replace nuclear models by holographic baryons?

[ongoing work with Ishii, Nijs]

- We study this in the simplest approximation: pointlike solitons in the bulk [Bergman, Lifschytz, Lippert arXiv:0708.0326; Roshali, Shieh, Van Raamsdonk, Wu arXiv:0708.1322]



- Baryons appear in the expected region of the phase diagram

Conclusions

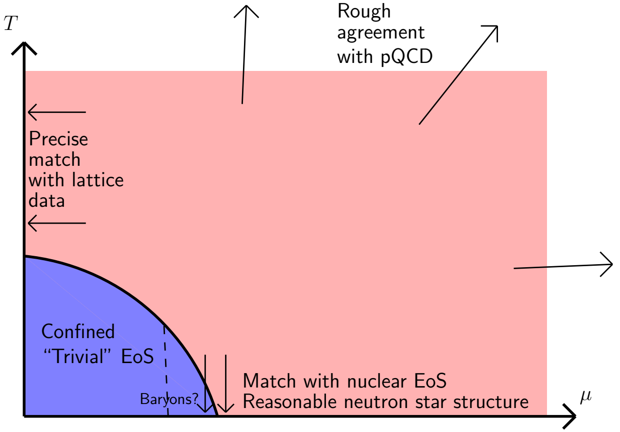
- Our main results:
  - ✓ V-QCD EoS matches nicely both with lattice data ($\mu = 0$) and nuclear EoSs ($T = 0$)
  - ✗ Cold neutron stars with stable "holographic" matter in tension with constraints from observations, as in earlier D3-D7 analysis [Hoyos, Rodriguez, Jokela, Vuorinen arXiv:1603.02943]
  - ✓ After matching with lattice + nuclear models + pQCD, a well-constrained EoS of deconfined phase for all T and μ: relevant for neutron star collisions
- Several possible extensions
  - Holographic baryon physics under study
  - Finite B and CP-odd physics can be "turned on"
  - Effects of flavor dependent quark masses

Extra slides

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



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

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!)

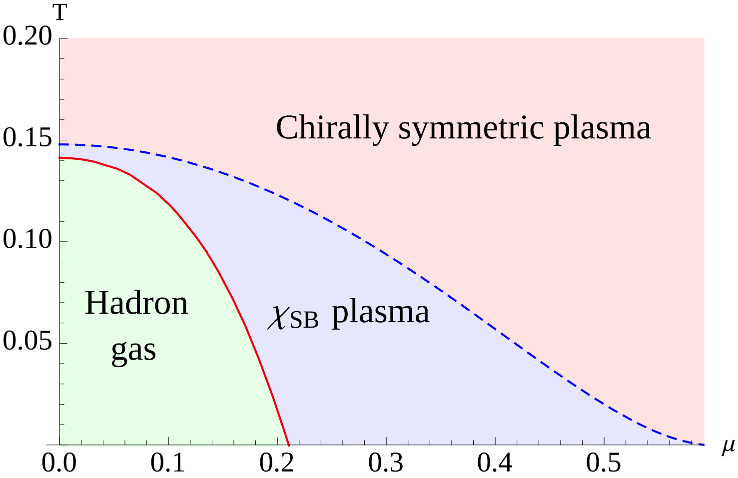
[Gürsoy, Kiritsis, Nitti arXiv:0707.1349; MJ, Kiritsis arXiv:1112.1261; Arean, Iatrakis, MJ, Kiritsis arXiv:1309.2286, arXiv:1609.08922; MJ arXiv:1501.07272]

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

- Qualitative comparison to lattice/experimental data

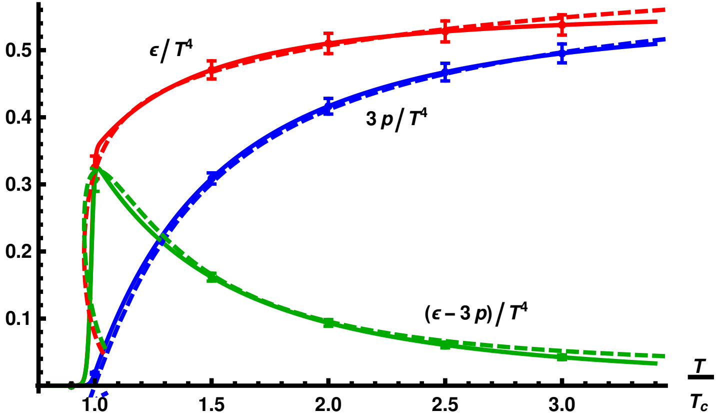
Phase diagram: example

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)

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]

Limit of high T and μ