Neutron Star Equation of State from Holographic QCD

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Based on

- T. Ishii, M. Järvinen, G. N., arXiv:1903.06169

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Motivation

Neutron stars occupy the small temperature, intermediate chemical potential region of the QCD phase diagram.

- Perturbative QCD converges only at much larger densities.
- Lattice QCD has the sign problem.
- EFTs of baryons converge only at small densities.

Because of this quantities like the equation of state are not well known.
We want to try a different approach: holography.

Holography

Holography establishes a duality between a QFT on one side and a gravitational dual on the other side:

QFT	Holographic dual
4D boundary	5D bulk
strongly coupled	weakly coupled

Advantages:

- Inherently strongly coupled.
- Several explicity examples are known from string theory.
- Gives access to otherwise inaccessible observables.

Disadvantages:

- It is necessary to take the limit $N_c \to \infty$.
- Holographic dual to QCD is not known.

Holographic Dictionary I: Field-Operator Correspondence

Operators in the boundary correspond to fields in the bulk. We build the bulk theory out of fields dual to operators which are most relevant in QCD.

QFT	Holographic dual
$T_{\mu\nu}$	$g_{\mu\nu}$ (metric)
$\mathrm{Tr}(F^2)$	λ (dilaton)
$\bar{q}q$	τ (tachyon)
μ_B	A_0 (gauge field)

With these fields, we can correctly obtain features of QCD such as:

- Correct running of the coupling strength.
- Chiral symmetry breaking.
- Confinement/Deconfinement transition.
- ...

V-QCD

The resulting model is V-QCD:

$$S_{\text{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{-g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$
$$- N_c N_f M^3 \int d^5x \, V_f(\lambda, \tau)$$
$$\times \sqrt{-\det(g_{\mu\nu} + \kappa(\lambda)\partial_\mu\tau\partial_\nu\tau + w(\lambda)F_{\mu\nu})}$$
$$+ \dots$$

- We compute at $N_f = N_c = \infty$ to incorporate backreaction of quark sector onto the glue sector.
- Action contains potentials V_g, V_f, κ and w, which can be chosen to match real QCD.

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Holographic Dictionary II: Thermodynamics

Homogeneous solutions can have a horizon. In that case

QFT	Holographic dual
T	Hawking temperature
s	Bekenstein-Hawking entropy
p	On-shell action

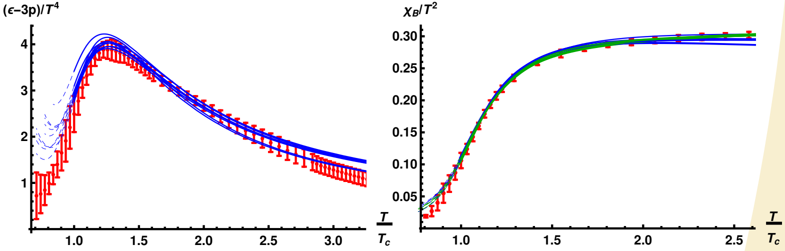
Using this, we can compute thermodynamical quantities at $\mu_B = 0$, where we can compare with lattice data.

Matching V-QCD to Lattice Data

To define our theory, we must choose the potentials V_g, V_f, κ and w.

- At $\mu_B = 0$, lattice data is available.
- One can then choose the potentials such that we match lattice data.

[Jokela, Järvinen, Remes, arXiv:1809.07770]



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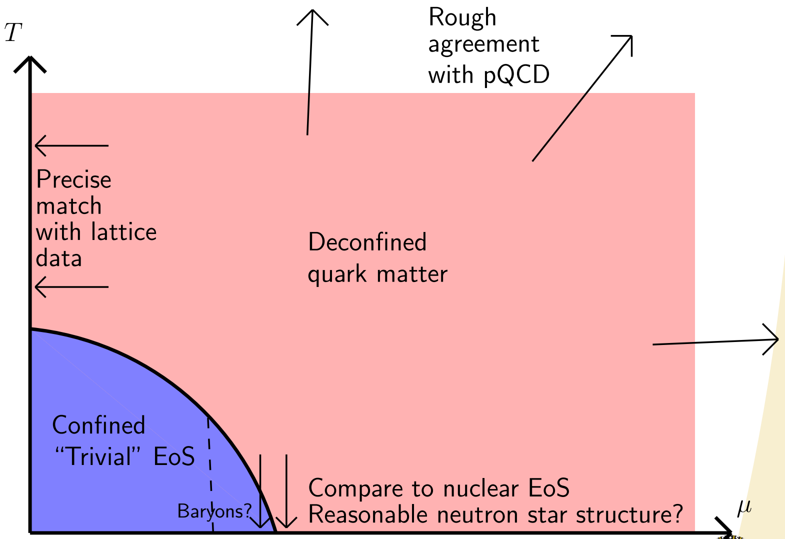
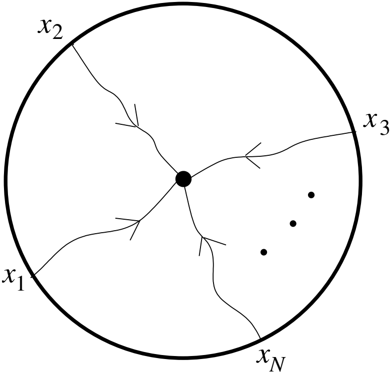
Matching V-QCD to Lattice Data



Holographic Dictionary III: Baryons

So far, we only considered homogeneous solutions.

- Baryons in QCD are dual to solitonic objects in the bulk.
  [Witten, hep-th/9805112; Gross, Ooguri, hep-th/9805129]



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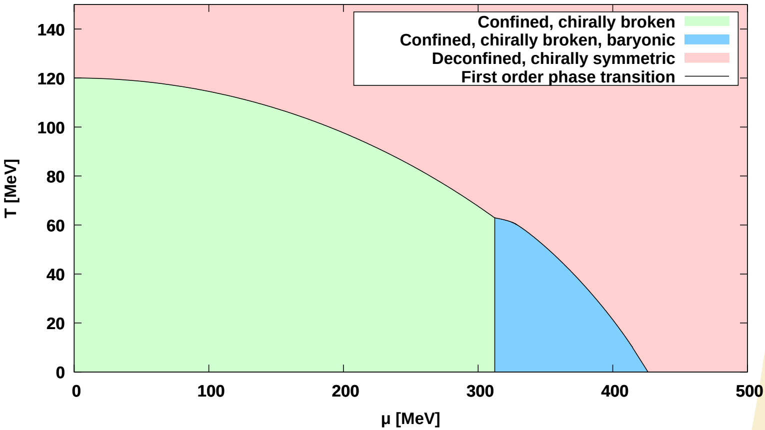
Homogeneous Approximation for Holographic Baryons

Computing the full inhomogeneous solutions is for now too hard. Therefore we use a homogeneous approximation:

- Baryonic phase should consist of dense configuration of solitons.
- At some distance the field configuration is expected to be homogeneous.
- Approximate baryons as a homogeneous field with a discontinuity.

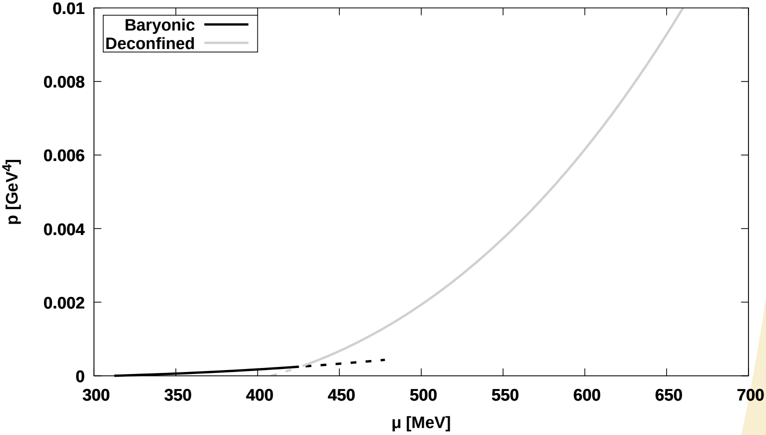
[Rozali, Shieh, Van Raamsdonk, Wu, arXiv:0708.1322]

Phase diagram



- Phase diagram looks qualitatively reasonable.
- Baryons appear at finite $\mu \approx m_{\text{proton}}/3$ for $b \approx 10$.

Equation of state



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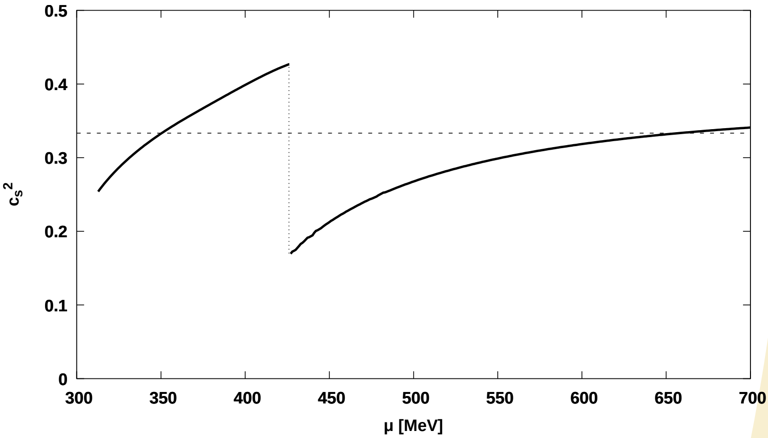
Speed of Sound



- Speed of sound violates conformal bound in two places.

Conclusions and outlook

Conclusions:

- We can construct a qualitatively reasonable phase diagram/EoS in holography.
- The resulting EoS has a large speed of sound.

Outlook:

- The approximations in the computation of the EoS can be improved.
- Apply a magnetic field to the nuclear matter.
- Add temperature dependence.
- . . .