Neutron stars meet AdS/CFT

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From quarks to gravitational waves:
Neutron stars as a laboratory for fundamental physics
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Outline

Based on. . . collaborators. . .

- Holographic quark matter and neutron stars 1603.02943(PRL)
- Breaking the sound barrier in AdS/CFT 1609.03480(PRD)

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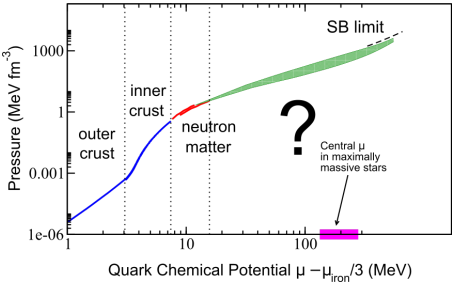
1. Introduction

Matter in neutron stars



[Kurkela, Fraga, Schaffner-Bielich, Vuorinen 1402.6618]

Traditionally two choices

- Pheno models, eg. MIT bag model
- Controlled interpolation between two limits

No-man's land

- Theoretical uncertainties welcome alternative approaches

Insights from string theory

The greenhouse effect

- Theoretical greenhouse where new ideas grow to be transplanted elsewhere

Recent idea

- Super-Yang-Mills is secrectly a theory of closed strings
- Low energy effective theory (strong coupling of SYM) is dual to a supersymmetric classical gravity theory in $AdS_5 \times S^5$

Duality

- Two theories containing very different dofs and interactions (w/ and w/o gravity) turn out to be the same
- Mapped to each other by a very complicated coordinate trafo
- Action related to expansion about a point

Example of a duality via bosonization

$$\int d^2x \bar{\psi}(i\partial\!\!\!/ - m_F)\psi - \frac{g}{2}(\bar{\psi}\gamma^\mu\psi)^2 = \int d^2x (\partial\phi)^2 + \frac{m}{\beta^2}(\cos\phi - 1)$$

if $\frac{\beta}{4\pi^2} = \frac{1}{1+g\pi}$ (S-duality) + details w/ renormalization

[S. Coleman '75]

Practical application: AdS/QCD

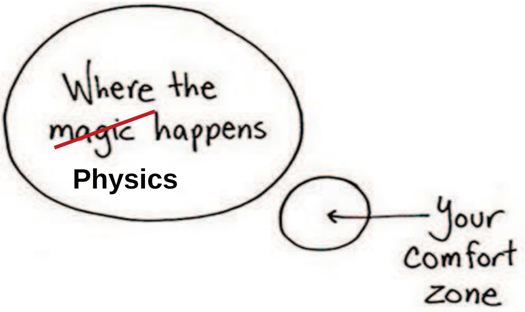
Quark-gluon plasma

- Surprising results from RHIC: QCP behaves more like an opaque strongly coupled fluid instead of hot gas
- The fluid has extremely low viscosity, hydro good approx
- Strongly coupled $\mathcal{N} = 4$ SYM is not QCD but has similar universal features at RHIC regime
- Calculations in strongly coupled SYM are hard, but very easy in SUGRA
- SUGRA gives surprisingly good effective description for various aspects of heavy ion collisions!

Another practical application of AdS/CFT

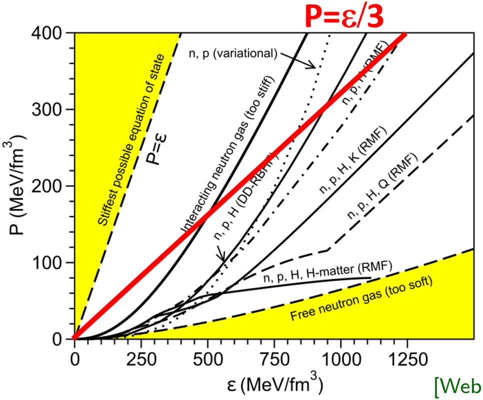
Can holography be useful in studying quark/nuclear matter relevant for neutron stars?

2. Proof of concept



Equation of state

- Fixed relation between P and ε
- In a CFT $\langle T^{\mu}_{\mu} \rangle = -\varepsilon + 3P = 0 \ \rightarrow \ v_s^2 = \frac{\partial P}{\partial \varepsilon} = \frac{1}{3}$.
- Causality $v_s \leq 1$ restricts EoS: $P \leq \varepsilon$.



[Weber astro-ph/0612054]

Break conformal symmetry

- Simplest generalization of $\mathcal{N} = 4$ works!
- Add massive fundamentals

Conditions on quark matter

- Baryon chemical potential $\mu_B = \mu_u + \mu_d + \mu_s$ and $m_u = m_d = m_s$
- Chemical equilibrium under weak processes:

$$u \to d + \bar{e} + \nu_e \ , \ d, s \to u + e + \bar{\nu}_e$$

$$\mu_u = \mu_d - \mu_e \ , \ \mu_d = \mu_s = \mu_u + \mu_e$$

- Leads to $\mu_u = (\mu_B - 2\mu_e)/3 \ , \ \mu_d = \mu_s = (\mu_B + \mu_e)/3$
- Assume charge neutrality $\mu_e = 0$:

$$\mu_u = \mu_d = \mu_s = \mu_B/3 \equiv \mu_q$$

- Quiescent neutron stars $T \sim 100\mathrm{keV} \ll \mu_q \sim 100\mathrm{MeV}$

Field theory $\leftrightarrow$ gravity dual

Field theory

- $\mathcal{N}=4$ Super-Yang-Mills at $N_c \to \infty, \lambda_{YM} = g_{YM}^2 N_c \gg 1$
- $\mathcal{N}=2$ quenched massive flavor hypermultiplets $N_f \ll N_c$
- Global $U(N_f) \sim SU(N_f) \times \underbrace{U(1)_B}_{baryon}$ flavor symmetry
- Optional: finite T

Gravity dual

- Spacetime $AdS_5 \times S^5$
- Embed identical N_f probe D7-branes
- Optional: Schwarzschild black hole in $AdS_5 \times S^5$

Equation of State

- Pressure:[a]

[Karch-O'Bannon 0709.0570]

$$P = \frac{N_f N_c}{4\gamma^3 \lambda_{YM}} (\mu_q^2 - m^2)^2 + \mathcal{O}(\mu_q^3 T) \ , \ \gamma \approx 1.4$$

- EoS:

$$\varepsilon = \mu_q \frac{\partial P}{\partial \mu_q} - P = 3P + m^2 \sqrt{\frac{N_f N_c}{4\gamma^3 \lambda_{YM}}} \sqrt{P}$$

- Speed of sound:

$$v_s^2 = \frac{\partial P}{\partial \varepsilon} = \frac{1 - \left(\frac{m}{\mu_q}\right)^2}{3 - \left(\frac{m}{\mu_q}\right)^2} < \frac{1}{3}$$

[a] At finite temperature and/or magnetic field, the EoS is obtained numerically from ODE.

Extrapolation to QCD

- $N_c = N_f = 3$
- Stefan-Boltzmann limit ($\mu_q \to \infty$)

$$P \sim \frac{N_f N_c}{12\pi^2}\mu_q^4$$

- This fixes

$$\lambda_{YM} = \frac{3\pi^2}{\gamma^3} \approx 10.74$$

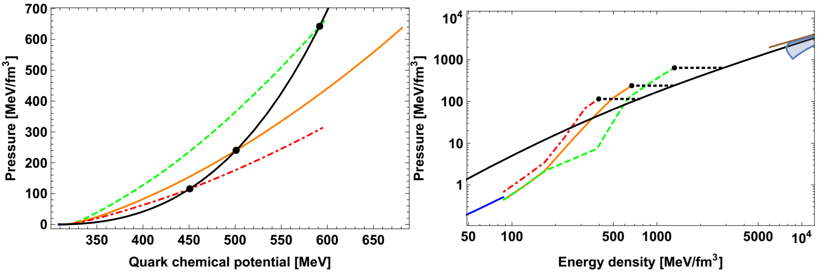
- $P(\mu_q = m) = 0 \to m \sim m_p/3$:

$$m \approx 308.55 \text{ MeV}$$

Equation of State

$$\varepsilon = 3P + \frac{\sqrt{2}}{2\pi}(308.55 \text{ MeV})^2\sqrt{P}$$

Comparison to nuclear matter models



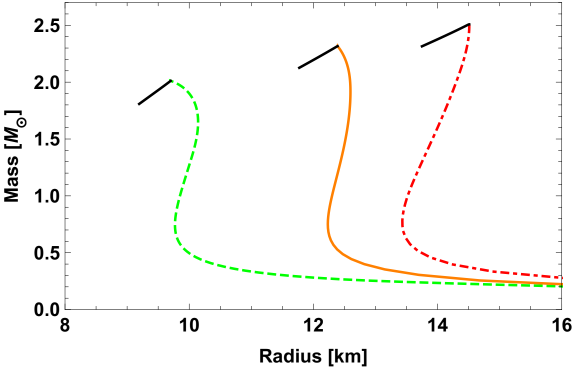
[soft,intermediate,stiff EoS curves from Hebeler-Lattimer-Pethick-Schwenk 1303.4662]

Hybrid construction

- High μ_q use holographic EoS for quark matter and match with CET at low μ_q
- Results in a very strong 1st order phase transition $(n_{\rm crit}, \Delta Q)$:

$$(6.9 n_s, (331 \mathrm{MeV})^4), (3.8 n_s, (265 \mathrm{MeV})^4), (2.4 n_s, (229 \mathrm{MeV})^4)$$

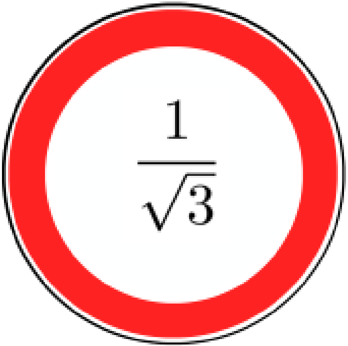
Solutions from TOV



Conclusion from extrapolation

- Upper bound on most massive stars
- Naively: no stable star with pure quark matter at the core

3. Breaking the sound barrier



Bound on speed limits and neutron stars

Massive stars are in tension with models

- Largest mass of stable neutron star depends on EoS
- Observations find up to $\sim 2M_\odot$
- Requires a stiff EoS
- Upper bound of speed of sound strongly disfavored

[Bedaque-Steiner 1408.5116]

Shedding light via AdS/CFT

Can the bound be violated in holographic models?

Trivial breaking

"Trivial breaking"

- UV is not CFT. Several D-brane examples.

  [NJ et al. + many others]

- Non-relativistic Lifshitz scaling ($t \to \lambda^z t$, $x^i \to \lambda x^i$), EoS $P = \frac{z}{3}\varepsilon$, stiffer than CFT, sound dispersion:

  [Hoyos-O'Bannon-Wu 1007.0590]

$$\omega^2 = \frac{z}{3} C_z \rho^{2(z-1)/3} k^2 \ , \ 1 \leq z < 2 \text{ no sound for z} > 2$$

- QCD at finite isospin $\mu_I > m_\pi \to$ pion condensate

  [Son-Stephanov hep-ph/0005225]

$$v_s^2 = \frac{\mu_I^2 - m_\pi^2}{\mu_I^2 + 3m_\pi^2} \to 1 \ , \ m_\pi/\mu_I \to 0$$

Conjecture: universal bound

Holographic models always below conformal bound

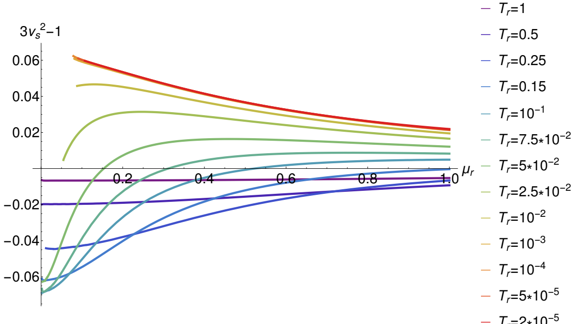
[Cherman-Cohen-Nellore 0905.0903]

~~Conjecture: universal bound~~

~~Holographic models always below conformal bound.~~

Family of examples

- Scalar field coupled to gravity at low temperature and density
- Stable: no homogeneous condensate
- SUGRA example: R-charged black hole



Quark matter at the core

- Finite magnetic field and temperature
- Mixed phases
  - Consider isospin chemical potential
  - Surface tension in bubble phases
- Neutron star phenomenology with stiffer holographic EoS

Strongly coupled nuclear matter

- Large-N_c makes baryonic matter hard to study
- Solitons in D3-D7
  [Ammon-Jensen-Kim-Laia-O'Bannon 1208.3197]

  or in Sakai-Sugimoto
  [Bergman-Lippert-Lifschytz 0708.0326,Li-Schmitt-Wang 1505.04886,. . .]
- However, alternative large-N_c limit recently available!
  [Hoyos-Itsios-Vasilakis 1611.07029]

Other quantities easily obtainable using AdS/CFT

- Correlation functions, emissivities
- Thermo-electric conductivities
- Shear, bulk viscosities
- Love parameter, I-Love-Q universality

Stringy, quantum (gravity) corrections to dual SUGRA

- N-corrections: practically impossible
- λ-corrections: doable in certain cases
- N_f/N_c-corrections: done, but not yet in QCD-like scenarios

More realistic holographic QCD model

- Top-down: pick a top-down model closer to QCD at the UV (eg. Klebanov-Strassler)
- Bottom-up holographic QCD in the Veneziano limit
  [Alho-Järvinen-Kajantie-Rosen-Tuominen 1312.5199]
  - Try to follow principles from string theory as closely as possible
  - Fix model by hand and tune potentials to match QCD physics and data