Realistic neutron stars from holography

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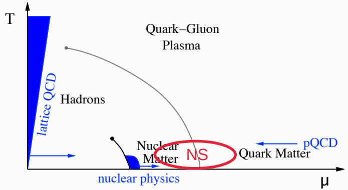
Introduction and motivation

QCD

- Various techniques for examining regions of the phase diagram
- How to describe properties of non-asymp. dense QCD?



Holography [Maldacena '97]

- Equivalence between weakly coupled gravity in d dimensions and strongly coupled field theory in $(d-1)$ dimensions
- Weakly coupled gravity calc. $\implies$ insight into dense QCD

Main Idea: Apply holographic model for QCD to the physics of neutron stars - natural QCD laboratories

Holographic QCD - Neutron Star applications

"Top down" - First principles

- $D3/D7$ models **[Hoyos et al. '16, Annala et. al '18, Fadafan-Rojas-Evans '20, '21]**
- $D4/D8$ models **[Ghoroku et al. '14, Zhang et al. '20, AP-Kovensky-Schmitt '21]**

"Bottom-up" - Phenomenology

- V-QCD model **[Jokela et al. '19,'21, Järvinen et al. '19, '20]**
- Gravity + CSC phase **[Ghoroku et al. '21]**
- Recent review **[Jokela '21, Jokela-Järvinen-Reims '21]**

Drawbacks of holography:

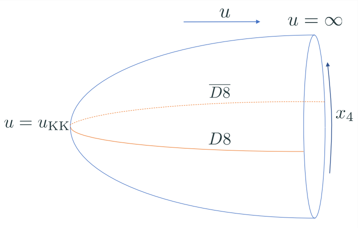
- Dual theories defined in $N_c \to \infty$, real-world QCD has $N_c = 3$
- Precise dual theory to QCD is not known

Can still expect to capture qualitative (and sometimes quantitative) non-perturbative physics relevant for $N_c = 3$ QCD

Our model - Confined [Witten '98, Sakai-Sugimoto '05] WSS

Top down model based on type IIA string theory - N_c $D4$-branes and N_f "probe" $D8/\overline{D8}$-branes

- $x_4 \sim x_4 + 2\pi M_{\mathrm{KK}}^{-1}$ (BCs break SUSY)
- u: holographic dir. (dual theory lives at $u = \infty$)
- Confined: $(x_4, u) \approx$ cigar



Further particulars & benefits:

- $N_f = 2$ - $U(2)$ gauge group, no strangeness
- Consider antipodally separated 8-branes at ∞: $L = \pi M_{\mathrm{KK}}^{-1}$
- 2 parameters: λ - 't Hooft coupling, M_{KK} - KK mass scale
- Isospin asymmetric baryonic matter [Kovensky-Schmitt - '21] crucial for systems with more n than p - Neutron stars!

Baryons in holography

Action on the flavor branes boils down to a simple 1d model:

$$S_{D8/\overline{D8}} = S_{\mathsf{DBI}} + S_{\mathsf{CS}} = \int du\, L(\hat{a}_0, a_0, a_i; \hat{a}_0', a_0', a_i')$$

- Baryons in the dual theory correspond to instantons in the bulk **[Hata et al. '07, Hashimoto et al. '08]**
- We use a homogeneous ansatz **[Rozali et al. '08]**

$$a_i(u) = -\frac{\lambda h(u)}{8\pi}\sigma_i$$

- Isospin asymmetry via boundary conditions **[Kovensky-Schmitt - '21]**: $\hat{a}_0(\infty) = \mu_B$, $a_0(\infty) = \mu_I$, $h(\infty) = 0$
- Ignore kaon/pion condensation **[Sawyer '72, Migdal '73, Akmal-Pandharipande '97]** - Difficult to separate (pions) from baryons **[Kovensky-Schmitt - '21]**

Neutron star physics

Static, spherically symmetric star with matter described by cold, strongly coupled QCD

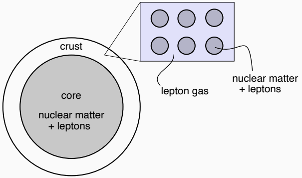
$$G_{\mu\nu} = (P+\epsilon)u_\mu u_\nu + P g_{\mu\nu}$$

Symmetry $\implies$ TOV equations

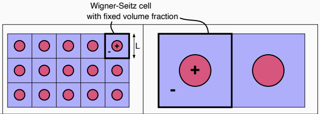
Can also compute the tidal Love number, k_2, and tidal deformability $\Lambda = \frac{2k_2}{3c^5}$ ($c = \frac{GM}{R}$ is the compactness of the star)

- Need an equation of state $P = P(\epsilon)$ to close the system
- Idea: Derive the equation of state for the entire star from holography **[AP-Kovensky-Schmitt - '21]**
- Add leptons to construct realistic NS matter - neutralise!
- Interpret holographic isospin components as n and p ($\mu_\nu \approx 0$)

Holographic star - Core and crust



- Core: β-equilibrated, locally neutral baryonic matter (+leptons)



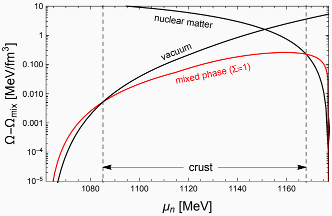
surface energy (~ 1/L)	LARGE	SMALL
Coulomb energy (~ L^2)	SMALL	LARGE

- Crust: Mixed phase ($\Omega_B = 0$), globally neutral - Surface tension Σ enters as an additional parameter

Dynamical determination of crust-core transition:

$$\Omega_{\text{core}} = \Omega_B + \Omega_\ell$$

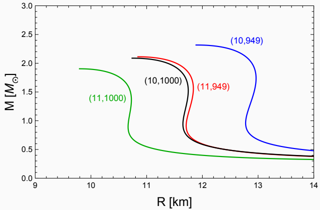
$$\Omega_{\text{crust}} = \Omega_\ell + \Delta_\Sigma \Omega$$

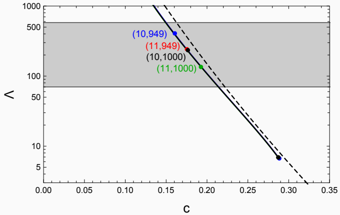


Equation of state - Solving TOV

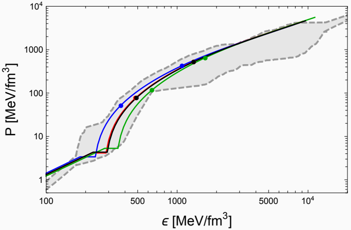
- Ω in each phase gives EoS: $P = -\Omega$, $\epsilon = \sum \mu_a n_a - P$
- Each triple $(\lambda, M_{\mathsf{KK}}, \Sigma = 1\,\mathsf{MeV/fm}^2)$ gives an EoS
- Fit with QCD **[Sakai-Sugimoto '05], [Brünner et al. '16]**

$\implies (\lambda, M_{\mathsf{KK}}) \simeq (7-17, (949-1000)\,\mathsf{MeV})$





- Systematic comparison of EoS with χ-EFT and pQCD
- Intermediate band **[Annala et al. '18]** is EoS which give $M_{\mathsf{max}} > 2M_\odot, \Lambda_{1.4} < 580$



Astrophysical constraints - LIGO and NICER

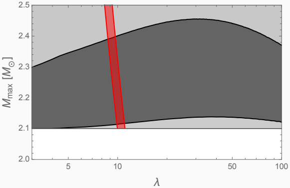
We can further test our model using astro constraints from:

Q: Can we find a region of (λ, M_{KK}) space which satisfies

- $M_{\text{max}} \geq 2.1 M_\odot$ from heaviest known NS **[Fonseca et al. '21]**
- $70 \leq \Lambda_{1.4} \leq 580$ from GW170817 **[Abbott et al. '19]**
- $\left.\begin{array}{l} 11.4\text{km} \leq R_{2.1} \leq 16.3\text{km} \\ 11.5\text{km} \leq R_{1.4} \leq 14.3\text{km} \end{array}\right\}$ from NICER **[Riley et al. '19, '21]**?

A: Yes! New predictions for NS e.g. $M_{\text{max}} \leq 2.46 M_\odot$

Advantage over pointlike baryons **[Zhang et al. '20]**



Summary

- Constructed entire neutron star EoS using the WSS model **[Sakai-Sugimoto '05]** with isospin asymmetry **[Kovensky-Schmitt '21]**

- Crust/core transition dynamically determined

- Astrophysical constraints **[Fonseca et al. '20], [Abbott et al. '19], [Riley et al. '19, '21]** all satisfied by model with just 3 parameters - $(\lambda, M_{\mathsf{KK}}, \Sigma)$

Future directions

- Include Pion condensation **[Kovensky-Schmitt '21]** and Pion mass **[Kovensky-Schmitt '20]**
- Reduce large-N_c effects in particular high proton fraction - bulk quantisation **[Hata et al. '05]**
- Include finite T effects (deconfined WSS geometry) - could model a quark(yonic) core **[Kovensky-Schmitt '20]** or simulate a full NS merger from WSS EoS (as has already been done for V-QCD **[Ecker et al. '20]**)
- Include strangeness ($N_f = 3$) - determine whether holographic hyperons play a role in NS
- Construct an inner crust (near symmetric nuclear & neutron fluid) and consider different "pasta phases" **[Pearson et al. '20]**
- Dynamical computation of Σ