Holographic construction and predictions for neutron stars

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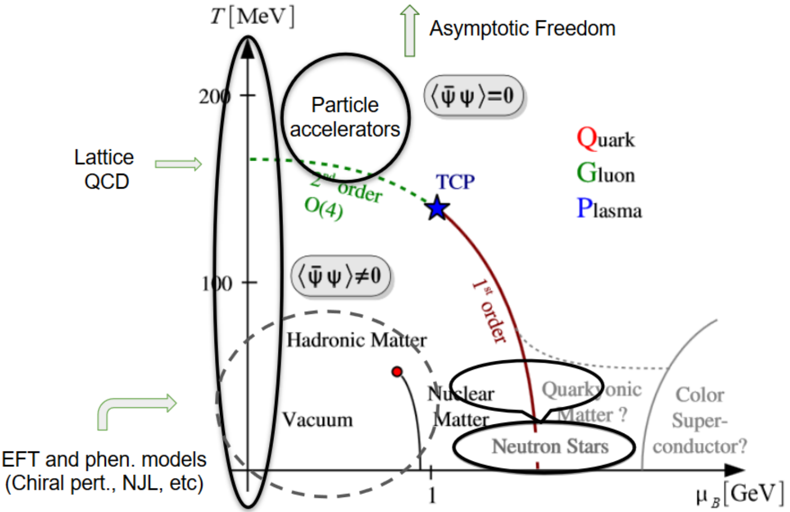
in collaboration with **Andreas Schmitt** and **Aaron Poole**. Funded by the Leverhulme Trust.

Introduction and motivations

QCD phase and Neutron Stars $(m_q = 0)$ [de Forcrand et al '15]

NS lie in the cold and dense region where most analytic methods fail



What we know about Neutron Stars

NS matter: isospin-asymmetric, β-eq, neutral + the crust.

Most massive stars:

$M_{\max} > 2.1 M_\odot$ (or $2.5 M_\odot$?)

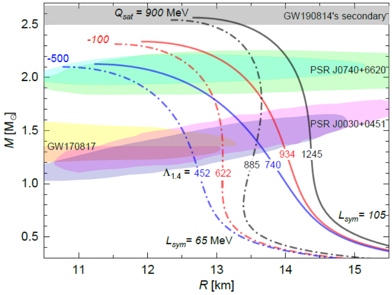
[Cromartie+ 19, Fonseca+ 21]
[GW190814 LIGO 20]

Tidal deformability:

$70 \leq \Lambda[1.4 M_\odot] \leq 580$

[GW170817 LIGO 18]

NICER constraints on Radii [Li et al 21]

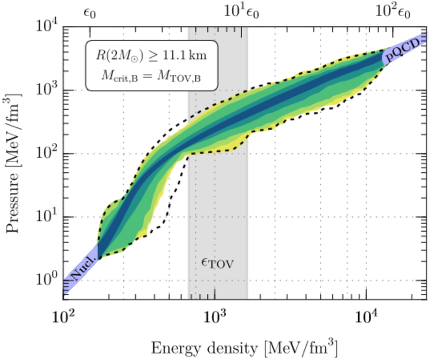


Constraints on the Equation of State

By combining [Annala et al 21]

- Perturbative QCD at high densities ($n_B > 40n_0$),
- Chiral effective theory at very low densities ($n_B < 1.1n_0$), and
- **Astrophysical constraints** ($M_{\mathrm{max}} > 2M_\odot$, $\Lambda_{1.4} < 580$),

with a piecewise polytropic interpolation, one finds



Neutron stars (NS) and holography

Neutron star matter is dense, but not asymptotically dense.
Strong coupling makes AdS/CFT a valuable tool in this context.

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Most applications to NS so far use holography for a description of quark and very dense baryonic matter, combining it with "ordinary" nuclear matter in the low-density outer layers.

- Instantons/Pointlike baryons [Ghoroku et al 19,21][Zhang et al 19]
- D3D7 model for quark matter [Hoyos et al 16][Annala et al 17][Bitaghsir Fadafan et al 19,20]
- V-QCD model for quark/dense baryonic matter [Chesler,Demerick,Ecker,Ishii,Järvinen,Jokela,Loeb,Nijs, Remes,Vuorinen 18+]
- Recent reviews: [Jokela; Jokela, Järvinen,Remes,21]

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We use our description of isospin asymmetry to construct a 'realistic' Neutron Star within holography, including the crust!

Baryons, Pions and Isospin asymmetry in holography

Pros / Cons of holographic models:

Witten-Sakai-Sugimoto and related models [W 98, SS 04]

Pros / Cons of holographic models:

- Provide **analytic methods** at strong coupling.
- Give a **geometric description** of QCD phenomena.
- *Top-down* model in string theory with **only 2 free parameters**.
- (We will add 1 more external parameter for the **NS crust**.)

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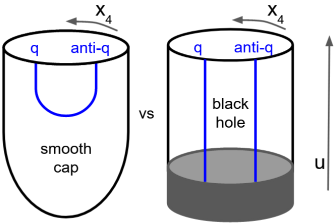
- The precise dual to QCD is not known.
- Works (mostly) at large N_c. (We will see some effects)
- No asymptotic freedom (in general, see however V-QCD).
- Requires some work to include the pion mass. [NK-A.Schmitt 19]

Confinement: gluon physics and holographic grav background



Geometric interpretation

[Witten-Sakai-Sugimoto 98-04/5]

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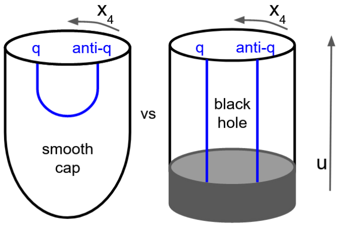
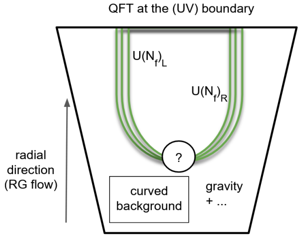


Chiral sym. breaking: flavor physics and D-branes



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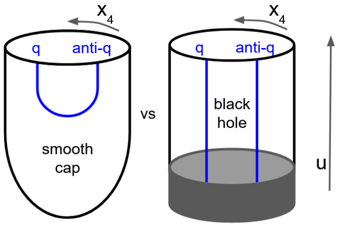

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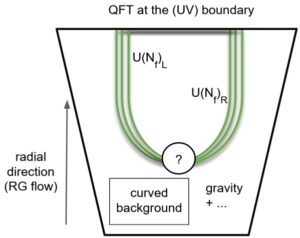
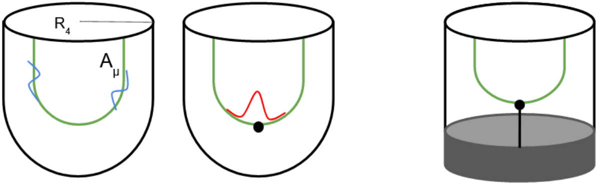


Holographic matter: Gauge fields, strings, instantons



mesons = gauge fields baryons = instantons quarks = strings

χPT and Skyrmyons from HQCD

The low-energy D8-$\overline{\text{D8}}$-brane action reproduces the **Chiral Lagrangian**:

$$\mathcal{L}_{\chi\mathrm{PT}} = \frac{f_\pi^2}{4}\,\mathrm{Tr}\left[D_\mu U D^\mu U^\dagger\right] + \cdots\,, \quad \mu_{L,R} \subset D_\mu$$

where the **pion matrix** is

$$U \equiv \mathcal{P}\exp\left(i\int_{-\infty}^{\infty} dz\, A_z\right),$$

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We can use *bulk* U(2) gauge fields for all ingredients:

1. Fluctuations are **pion dynamics/condensation**. [Aharony 07]
2. Boundary condition for A_0 encode **chemical potential** $\mu_{L/R}$.
3. Topologically non-trivial configurations produce **baryons**.

   BPST instantons as h-**Skyrmions** [Hata,S,S,Yamato 07]

   [Adkins,Nappi,Witten 83, Atiyah,Manton 89]

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We approximate a homogeneous distribution of baryons [Rozali+ 07].

$$\hat{A}_0(z \to \pm\infty) = \mu_B , \quad A_0^{(3)}(z \to \pm\infty) = \pm\mu_I , \quad A_i(z) = \lambda\, h(z)\, \sigma_i , \quad A_z = 0.$$

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- **Pure baryonic phase (B)**
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We can **compare all phases dynamically** and also include **temperature**.

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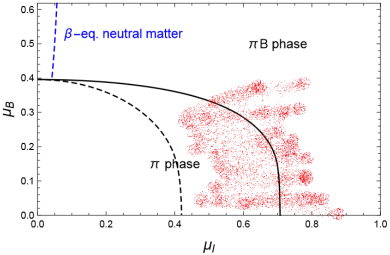

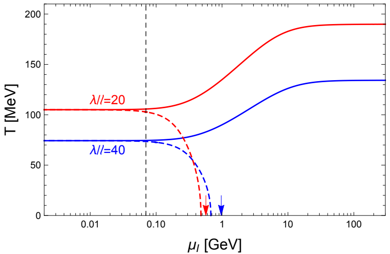

A model for Neutron Stars

The core of the Neutron Star

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and construct β-equilibrated, locally neutral matter by imposing

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where $\mu_\nu \approx 0$ and we have defined

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A couple of disclaimers

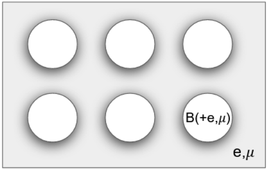
- The simplest model has no asymp freedom. No quark core.
- We do not really have protons + neutrons, only a homogeneous distribution of instanton-like objects deformed by μ_I (this is a large N_c effect, w.i.p.).

The crust: global neutrality instead [NK,Poole,Schmitt 21]

For the (outer) crust we employ a very simple model [Glendenning 00, Schmitt 20]: we consider a mixed phase with

- **bubbles** of h-nuclear matter
- separated from a charged **lepton gas**.

and impose global neutrality.



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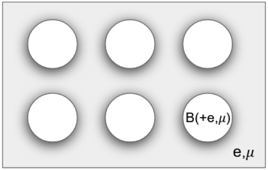

We also include surface and Coulomb effects by assuming a step-like profile at the phase boundaries, employing the Wigner-Seitz approx and using the surface tension Σ as an **external parameter**.

$$\Delta\Omega = \frac{3}{2}(\rho_1 - \rho_2)^{2/3}\Sigma^{2/3}(1-\chi)[d^2 f_d(1-\chi)]^{1/3}\,.$$

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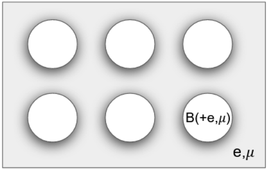

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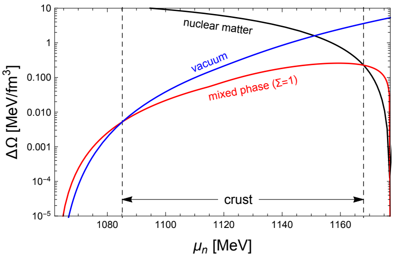
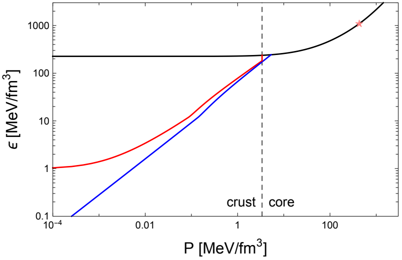
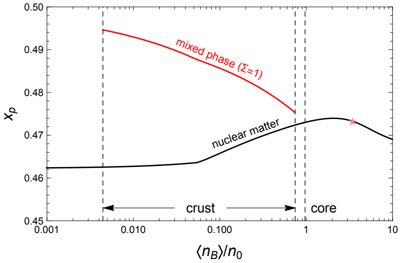
Since we construct the entire star from holography, this enables us to determine the crust-core transition fully dynamically.

Results: Free energy, thermodynamics and proton fraction



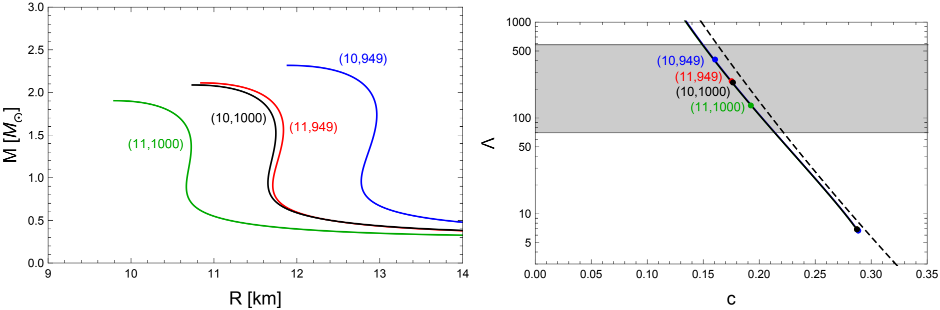
- Mixed phase interpolates between vacuum and β-eq matter.
- All 1^{st} order for $\Sigma > 0$.
- Dynamical crust-core transition.
- Non-monotonic speed of sound.
- Too large x_P.





We then combine this EoS with the TOV equations to construct NS.

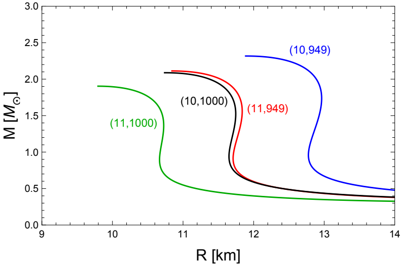
Results: MR curves, radii and deformabilities $(\lambda, M_{\mathrm{KK}})$

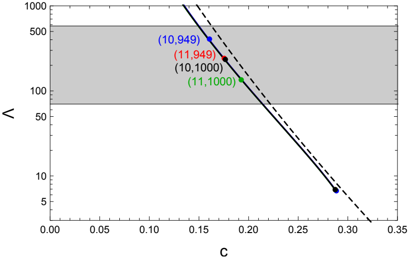


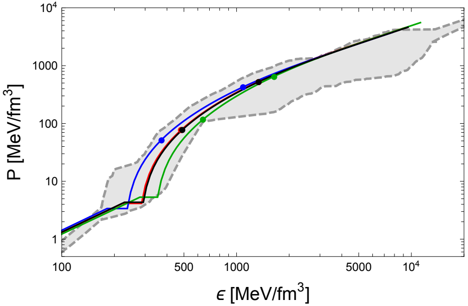
fit to	λ	M_{KK}
$f_\pi,\ m_\rho$	16.63	949 MeV
$\sigma,\ m_\rho$	12.55	949 MeV
$n_0,\ \mu_0$	7.09	1000 MeV

Model parameters are chosen close to the fits to QCD vacuum properties [SS 04-05, Brünner+16] and to nuclear saturation properties.

We also set ($\Sigma = 1$ MeV/fm^2 in these plots).







- All values are realistic!
- The crust is essential.
- Reasonable parameter values.
- $\Lambda, \bar{R}_{\rm cc}(c) \sim$ universality [Yagi+ 16]
- High E: no asymptotic freedom.
- Low E: simplistic crust?

New predictions for M, R and Λ

Systematics + astrophysical constraints = predictions

Only 2+1 parameters: λ, M_{KK} and Σ. We **scan** for values consistent with astrophysical constraints $(M_{\max}, \Lambda_{1.4}, R_{1.4}, R_{2.1})$ to derive predictions!

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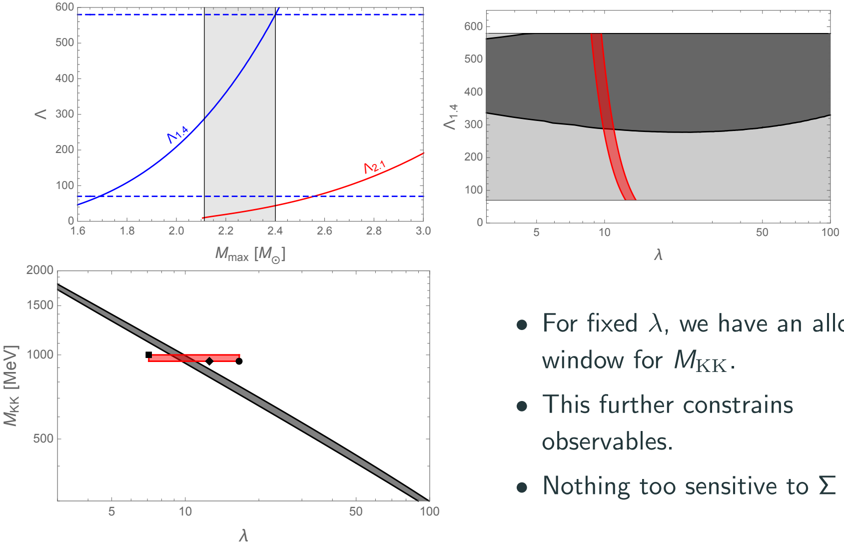

- For fixed λ, we have an allowed window for M_{KK}.
- This further constrains observables.
- Nothing too sensitive to $\Sigma \approx 1$.

New predictions for NS observables

We obtain new parameter independent bounds for:

1. The upper bound for $M_{\rm max}$.
2. The lower bound for $R_{1.4}$.
3. The upper bound for $R_{2.1}$.
4. The lower bound for $\Lambda_{1.4}$
5. The allowed window for $\Lambda_{2.1}$

Even more stringent constraints from restricting to the QCD window

	parameter-independent		QCD window	
	lower bound	upper bound	lower bound	upper bound
$M_{\rm max}$ [$M_\odot$]	(2.1)	2.46	2.11	2.40
$R_{1.4}$ [km]	11.9 (11.5)	(14.3)	12.4	14.1
$R_{2.1}$ [km]	(11.4)	13.7 (16.3)	(11.4)	13.7
$\Lambda_{1.4}$	277 (70)	(580)	286	(580)
$\Lambda_{2.1}$	9.13	49.3	10.1	43.7

Future work

We are interested in ...

- including the pion mass and condensate (importance?), allow for a more realistic response from baryons (*in preparation* [NK,Schmitt 19])
- computing Σ dynamically and constructing an inner crust.
- analysing the effect of temperature and the possibility of quark cores (NS from deconfined model). What about mergers? [Ecker et al 19]
- can quarkyonic matter play a role? [NK,Schmitt 20]
- Constructing a more realistic protons+neutrons dense matter (w.i.p.)

- studying systematically the EOS and the comparison to Lattice QCD and V-QCD. [Jokela et al 20]
- computing transport properties of our NS matter. [Hoyos et al 20,21]
- considering magnetic fields [Rehban et al 08+] and the possibility of color superconductivity [Bitaghsir Fadafan et al 18] [Henriksson et al 19]

Thank you! Any questions?

A systematic study of the parameter space [NK,Poole,Schmitt 21]

The model has only 2+1 parameters: λ, M_{KK} and Σ!

We can **scan** for values consistent with astrophysical constraints:

1. Mass: Existence of $M = 2.1 M_\odot$ stars.
2. Tidal def $1.4 M_\odot$: $70 < \Lambda_{1.4} < 580$ [LIGO 18]
3. Radius $1.4 M_\odot$: $11.5\,\mathrm{km} < R_{1.4} < 14.3\,\mathrm{km}$ [Riley+ 19 , Miller+ 19]
4. Radius $2.1 M_\odot$:$11.4\,\mathrm{km} < R_{2.1} < 16.3\,\mathrm{km}$ [Riley+ 21 , Miller+ 21]

From the GW170817 and GW19081 events, ant the NICER collaboration.

Can we combine these with our model to
derive more stringent predictions? Yes!

We keep in mind the QCD vacuum properties fits [SS 04-05, Brünner+ 16]