Realistic Neutron Stars from Holography

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in collaboration with **Andreas Schmitt** and **Aaron Poole** at U. of Southampton.

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Introduction and motivations

Astrophysics and constraints on the Equation of State

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

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Observations: [LIGO-GW170817+GW190814, NICER 21]

- Masses: $M_{\mathrm{max}} > 2.08\, M_{\odot}$ (or $2.5\, M_{\odot}$?),
- Tidal deformabilities: $70 < \Lambda_{1.4} < 580$,
- Radii: 11.5 km $< R_{1.4} < 14.3$ km and 11.4 km $< R_{2.1} < 16.3$ km,

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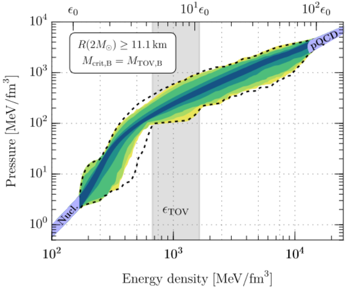
w/ pQCD and χEFT for a piecewise polytropic interp: [Annala et al 21]



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- Instantons/Pointlike baryons [Ghoroku et al 19,21][Zhang et al 19]
- D3D7 model for quark matter [Hoyos+ 16][Annala+ 17][B Fadafan+ 19,20]
- Hard-Wall AdS/QCD [Bartolini+ 21]
- 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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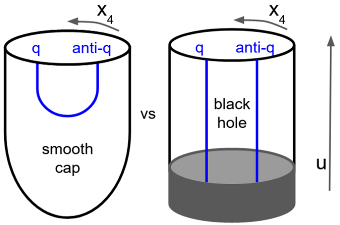
We use our description of isospin asymmetry to construct a 'realistic' Neutron Star within holography, including the crust!

Baryons, Pions and Isospin asymmetry in holography

Confinement: gluon physics and holographic gravity background



The geometry of strong coupling [Witten-Sakai-Sugimoto 98-04/5]

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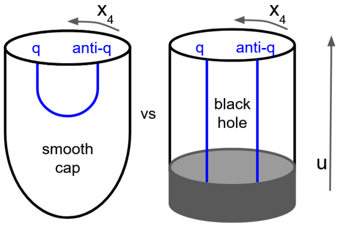
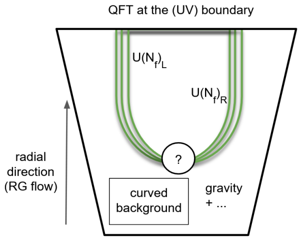


Chiral sym. breaking:
flavor physics and D-branes



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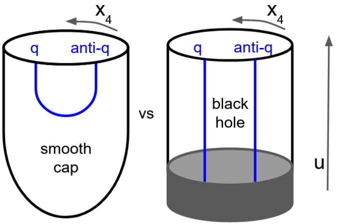

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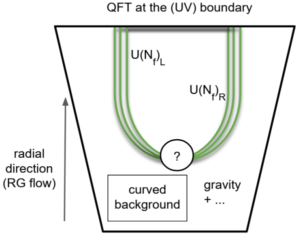
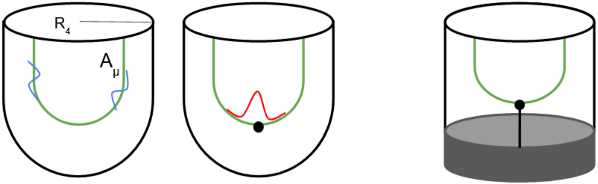


Holographic matter: Gauge fields, strings, instantons



mesons = gauge fields baryons = instantons quarks = strings

Isospin asymmetry in baryonic matter [NK, Schmitt 21]

Many-instanton systems are hard to work with ...

We use a homogeneous approximation for baryons [Rozali+ 07].

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

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This leads to four possible configurations:

- **Vacuum**
- **Pion-condensed phase**: reproduces χPT.
- **Baryonic phase**: includes isospin asymmetry.
- **Coexistence phase**: π-cond interacting with dense B-medium.

We can **compare all phases dynamically** and also include **temperature**!

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Top-down model, with strongly coupled physics – only 2 parameters!,

Large N_c (no $p + n$) and no asymptotic freedom (no quark cores).

A model for Neutron Stars

Our holographic Neutron Star [NK,Poole,Schmitt 21]

The CORE: (no pion condensate)

$\boxed{\text{isospin-asymmetric h-baryons}} + \boxed{\text{Fermi gas of electrons and muons}}$

to construct β-equilibrated, locally neutral matter by imposing

$$\mu_\mu = \mu_e \,, \qquad \mu_e + \mu_p = \mu_n + \mu_\nu \,, \qquad n_p = n_e + n_\mu \,,$$

where $\mu_\nu \approx 0$ and we have defined $n_{n/p} \equiv (n_B \pm n_I)/2$.

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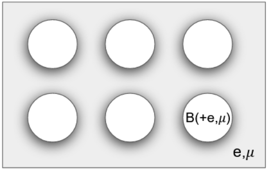
The CRUST: (mixed phase) [Glendenning 00, Schmitt 20]

- **bubbles** of h-nuclear matter
- separated from a charged **lepton gas**.
- impose global neutrality instead
- $+$ surface and Coulomb effects $\Rightarrow \Sigma$.



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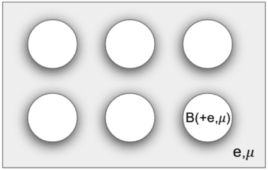
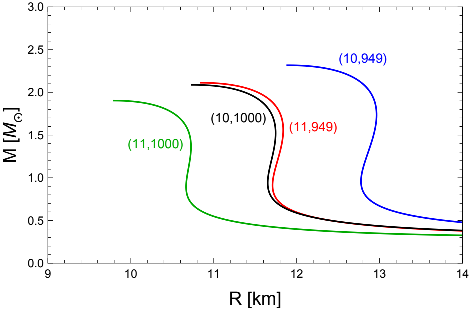
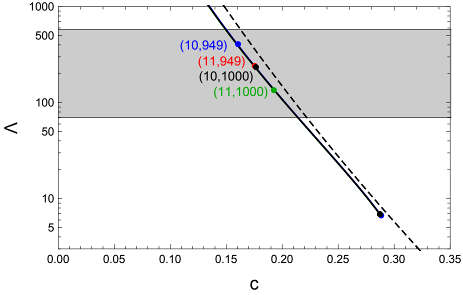


h-EoS + TOV Eqs. $\Rightarrow$ Crust-core transition fully dynamical!

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





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

Fits of to QCD vacuum properties [SS 04-05, Brunner+15] and to nuclear saturation properties.

- Here $\Sigma = 1$ MeV/fm^2.
- All values are realistic!
- The crust is essential.
- Reasonable parameter values.
- $\Lambda(c)$ universality [Yagi+ 16]

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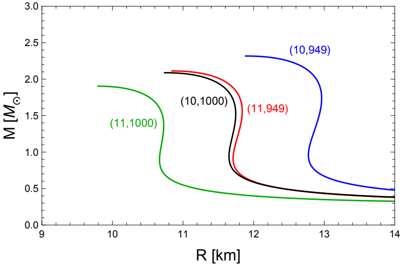

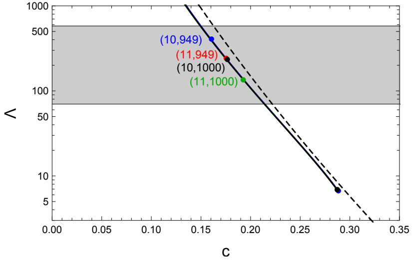

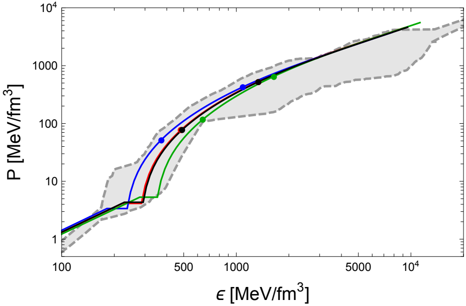

- Microscopic EoS fits nicely!
- and with only $2 + 1$ parameters!
- High E: no asymptotic freedom.
- Low E: simplistic crust?
- However, x_P is too large.

New predictions for M, R and Λ

Systematics (2+1 parameters) + astrophysics = predictions!

We obtain new parameter-independent bounds:

Scan $(M_{\mathrm{KK}}, \lambda)$-space for reasonable values of Σ, check phenomenology.

Even more stringent constraints from restricting to the QCD window

	parameter-independent		QCD window	
	lower bound	upper bound	lower bound	upper bound
$M_{\mathrm{max}}\ [M_\odot]$	(2.1)	**2.46**	2.11	2.40
$R_{1.4}\ [\mathrm{km}]$	11.9 (11.5)	(14.3)	12.4	14.1
$R_{2.1}\ [\mathrm{km}]$	(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 (important?), allowing 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]
- checking if quarkyonic matter can play a role. [NK,Schmitt 20]
- constructing more realistic protons+neutrons (w.i.p.)

- 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?