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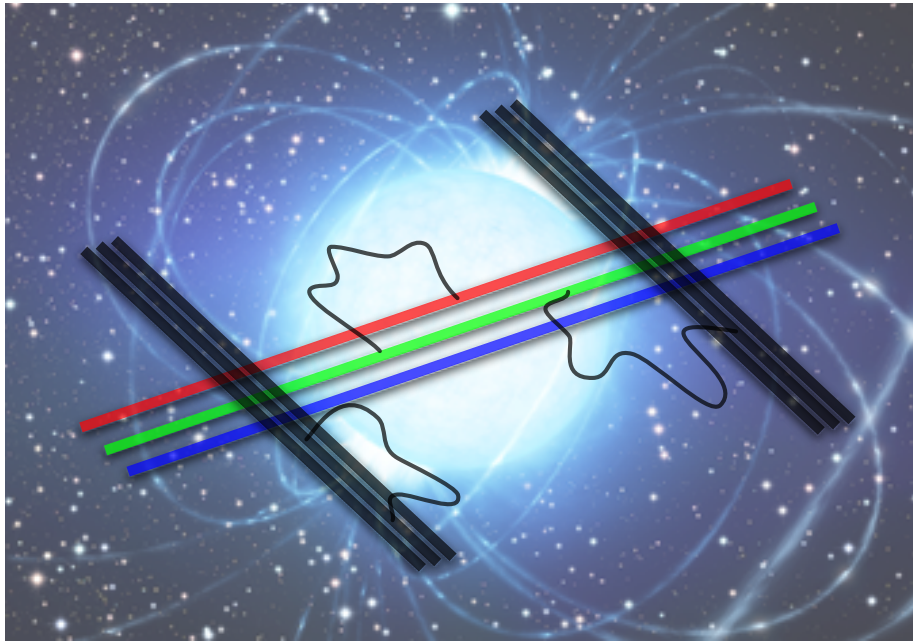
Building a realistic neutron star from holography

N. Kovensky, A. Poole, A. Schmitt



A. Schmitt (foreground); ESO/L. Calçada (neutron star)

Outline

- Witten-Sakai-Sugimoto model:
  holography as close as possible to QCD

- μ_B-μ_I phase diagram ($T = 0, N_f = 2$):
  baryonic matter + meson condensation
  N. Kovensky, A. Poole, A. Schmitt, arXiv:2302.10675 [hep-ph]

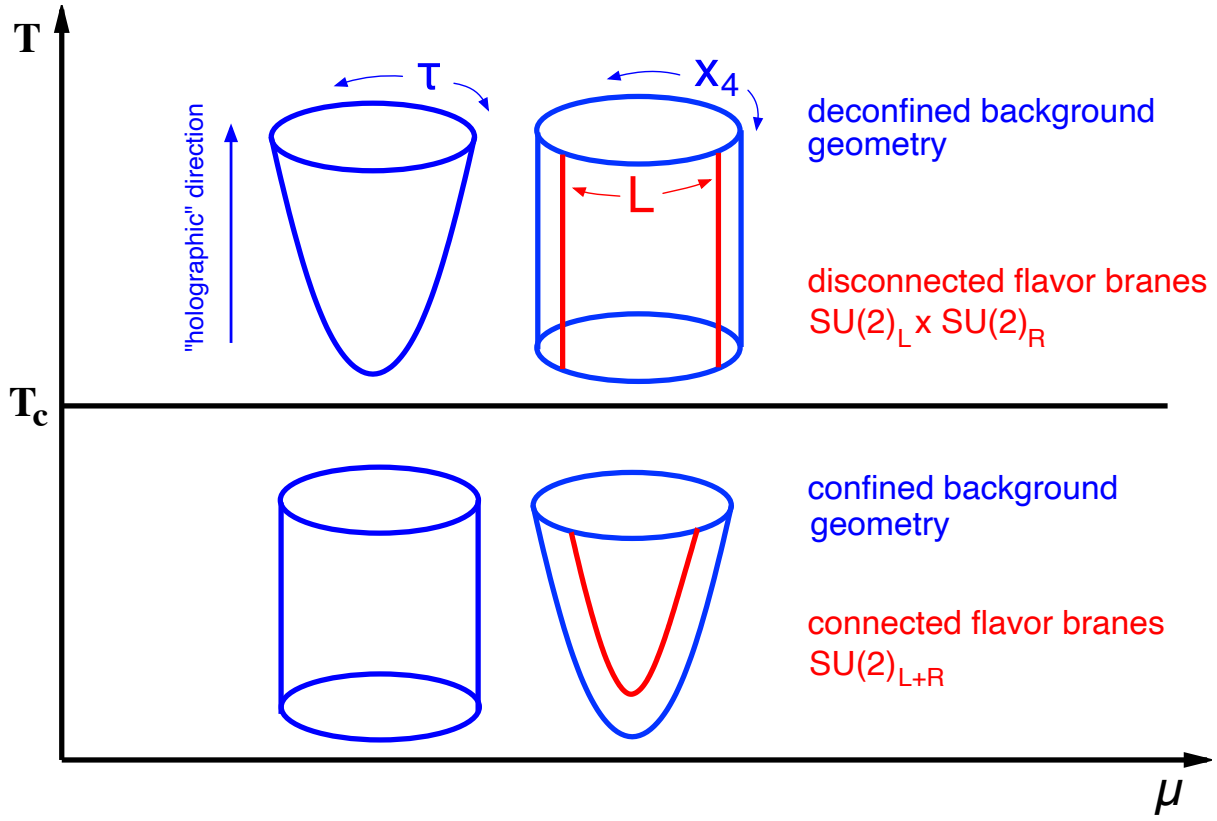
- Construct neutron star (including crust) from holographic baryonic matter (+leptons) and compare with astrophysical data
  N. Kovensky, A. Poole, A. Schmitt, PRD 105, 034022 (2022); SciPost Phys. Proc. 6, 019 (2022)

Witten-Sakai-Sugimoto model

E. Witten, Adv. Theor. Math. Phys. 2, 505 (1998)

T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)

- top-down approach with only 2 (or 3) parameters: λ, $M_{\rm KK}$ (and L)
- supersymmetry and conformal symmetry broken
- successfully applied to meson, baryon, glueball spectra



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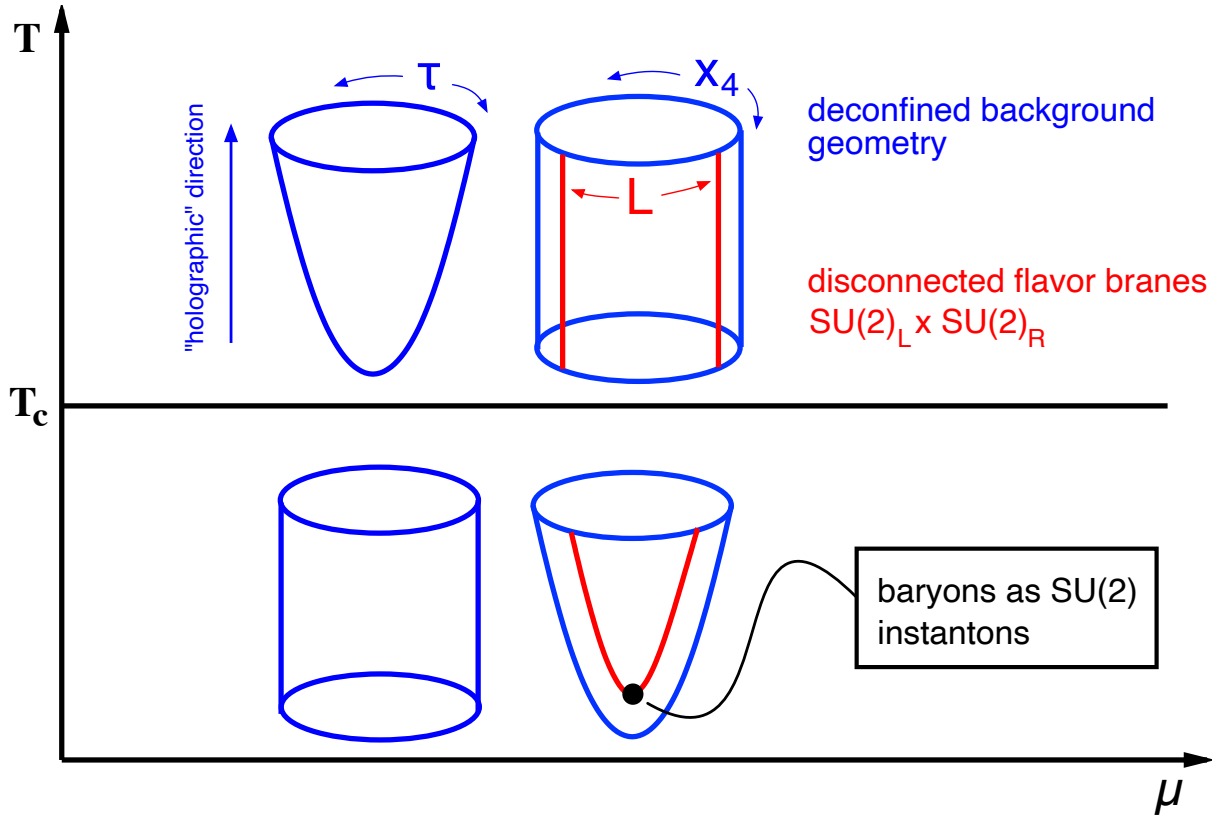


Isospin-asymmetric matter: setup

- D8-brane action (YM + CS) for $U(2)$ gauge fields, $F_{\mu\nu} = \hat{F}_{\mu\nu} + F^a_{\mu\nu}\sigma_a$, confined geometry, maximal separation L
- add effective mass term for m_π from open Wilson line
  N. Kovensky and A. Schmitt, JHEP 02, 096 (2020)
- include pion condensate θ via global rotation
- chemical potentials in boundary

$$\begin{aligned}\hat{A}_0(\pm\infty) &= \mu_B \\ A^1_0(\pm\infty) &= \mp\mu_I \sin\theta \\ A^2_0(\pm\infty) &= \pm\mu_I \sin\theta \\ A^3_0(\pm\infty) &= \mu_I \cos\theta\end{aligned}$$

- homogeneous, diagonal ansatz for baryons

$$A^a_i(z) = h_i(z)\delta^a_i$$

anisotropy → rho meson condensation

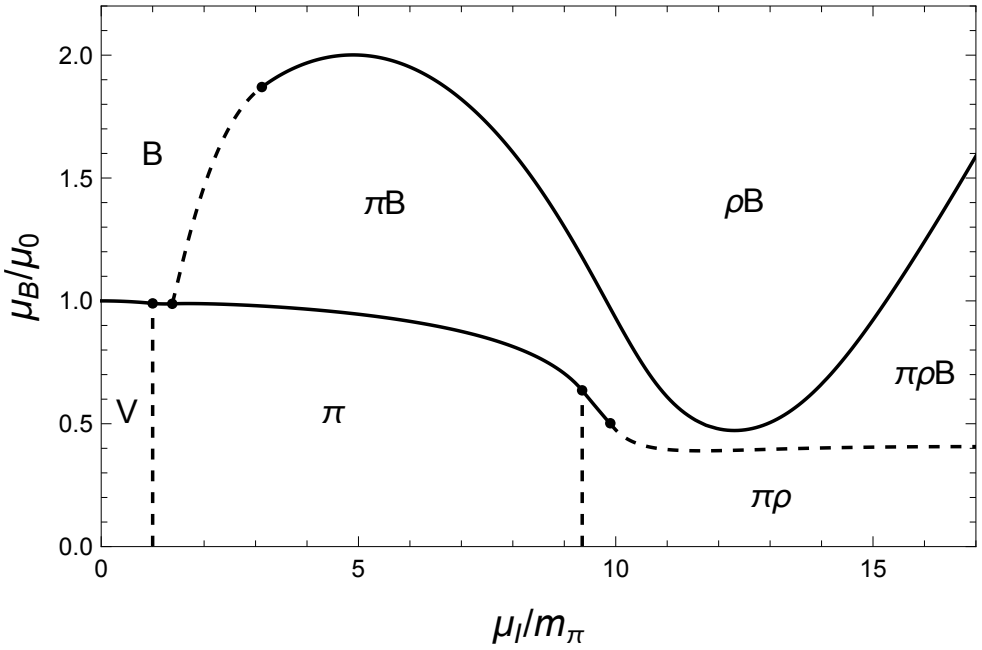
for given μ_B, μ_I solve classical EOMs for $\hat{A}_0$, $\hat{A}_i$, A^a_0, h_i and minimize free energy with respect to θ

compare free energies of vacuum, pion-condensed phase, baryonic phase, ...

Isospin-asymmetric matter: phase diagram

N. Kovensky, A. Poole, A. Schmitt, arXiv:2302.10675 [hep-ph]

- parameters fitted to reproduce m_π, m_ρ, f_π



- no baryons at low μ_B

  O. Aharony, K. Peeters, J. Sonnenschein and M. Zamaklar, JHEP 02, 071 (2008)

  D. T. Son and M. A. Stephanov, PRL 86, 592-595 (2001)

- effective pion mass increases in baryonic medium

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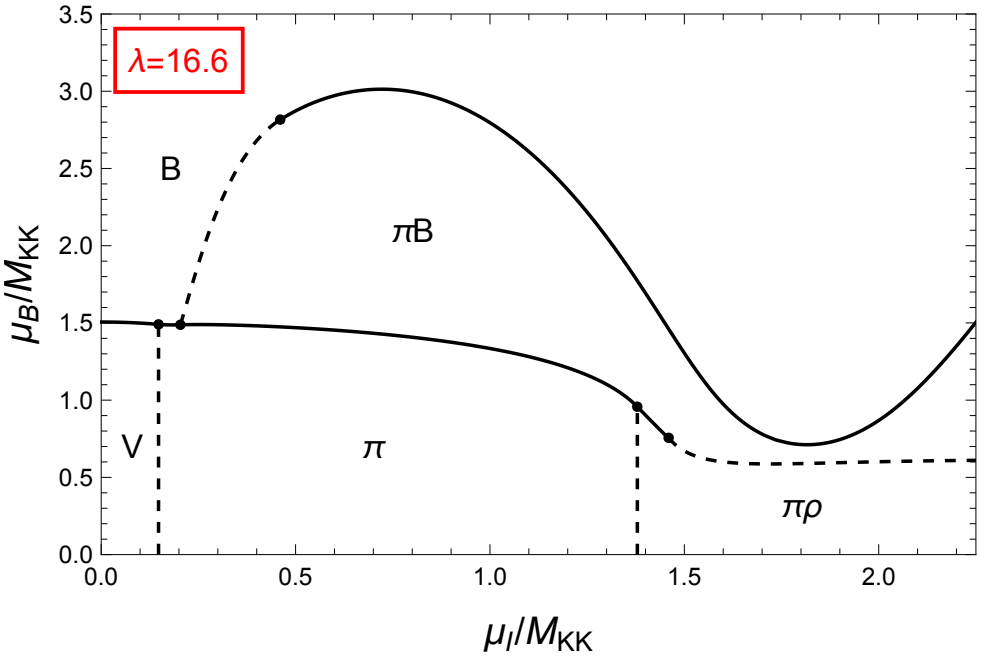

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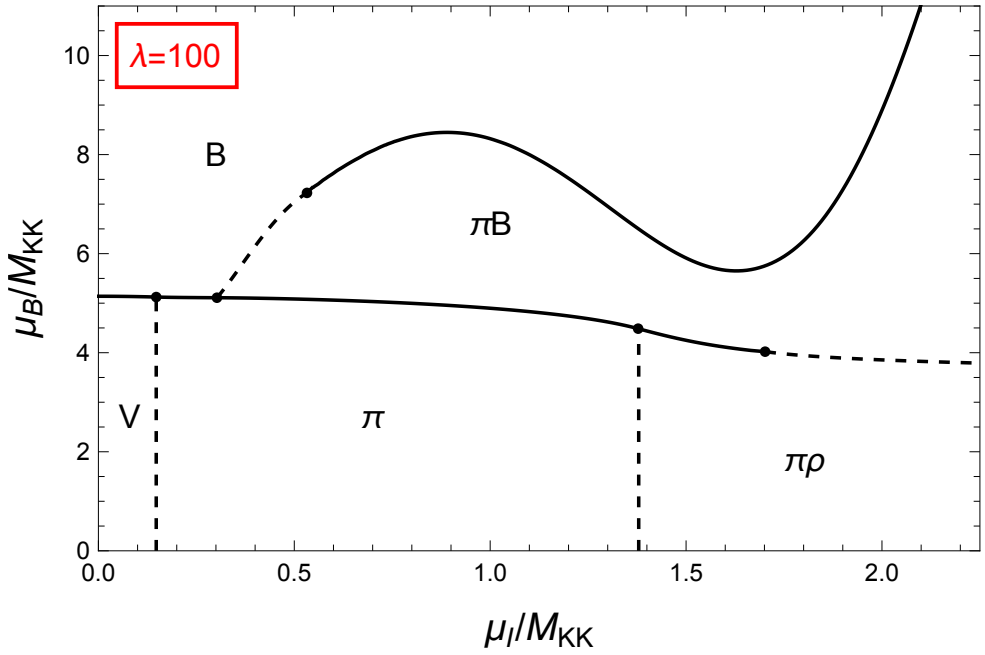

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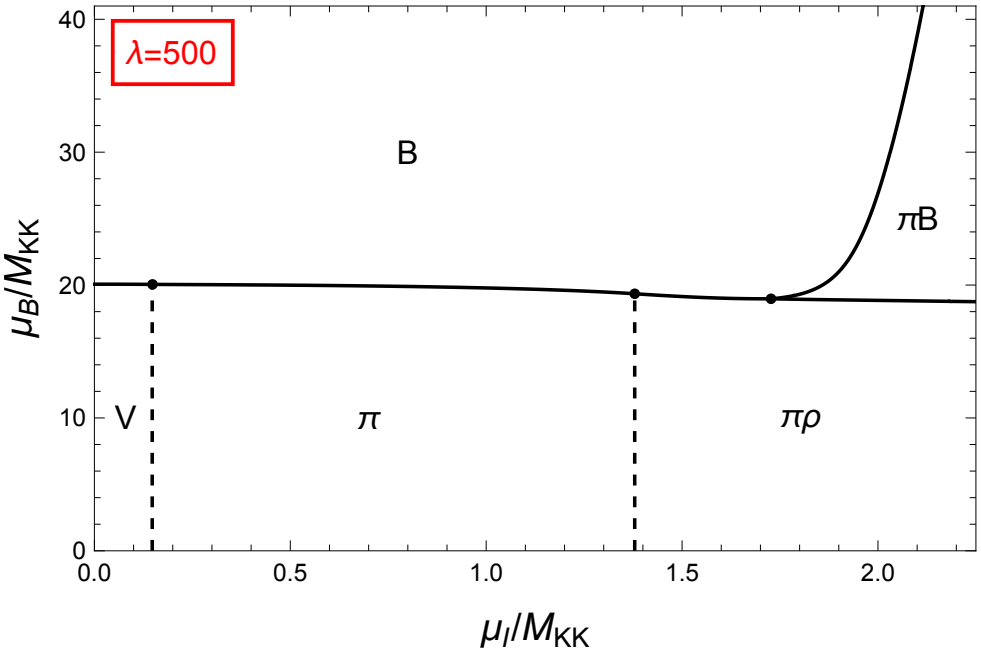

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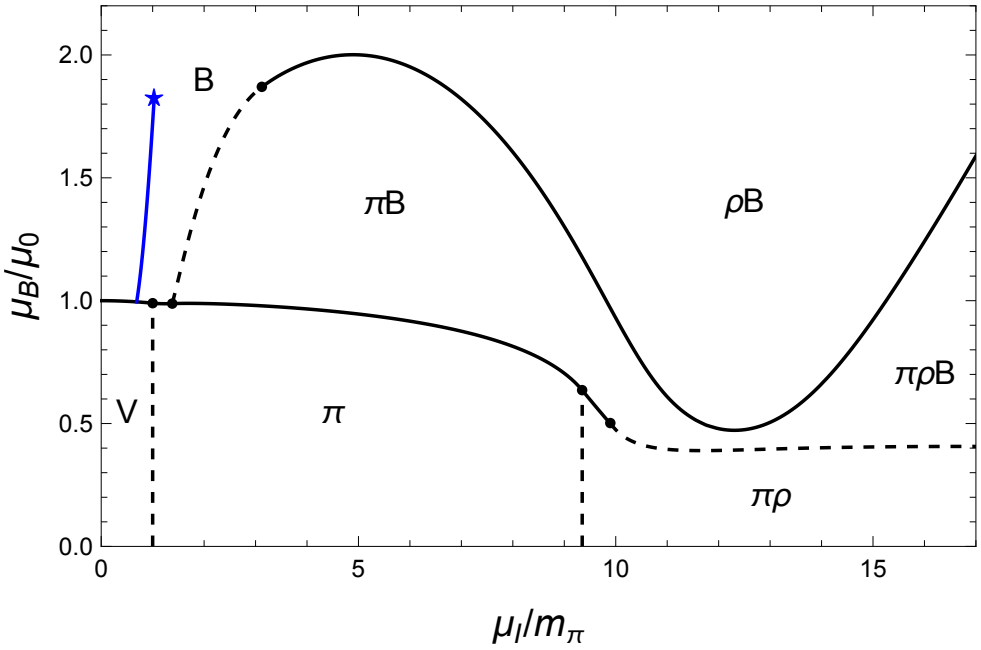

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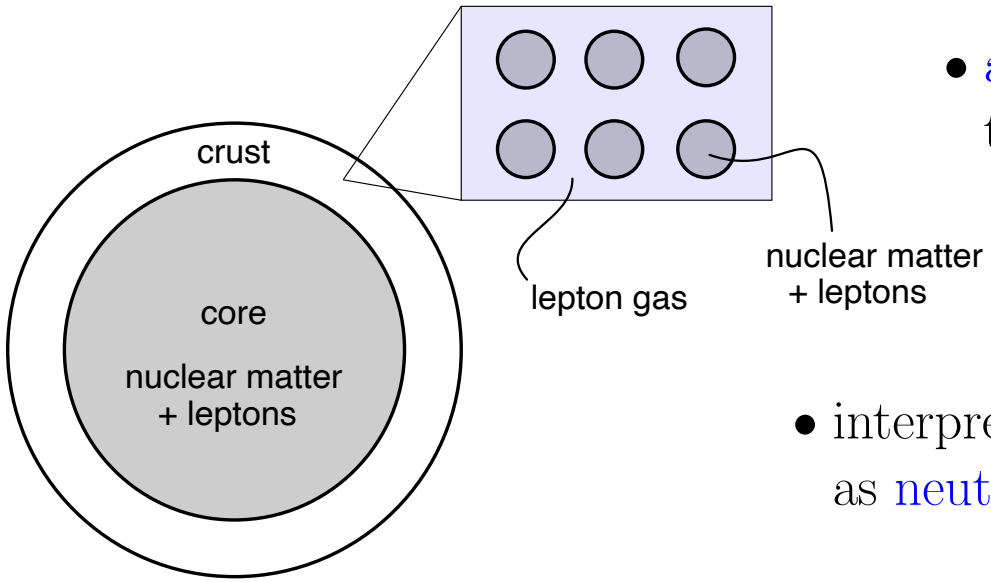
- β-equilibrium + charge neutrality
  $\rightarrow$ no pion condensation in neutron stars

Building a neutron star from holography (page 1/5)

N. Kovensky, A. Poole, A. Schmitt, Phys. Rev. D 105, 034022 (2022)



- add leptons (electrons + muons) to holographic nuclear matter

- interpret holographic isospin components as neutron and proton

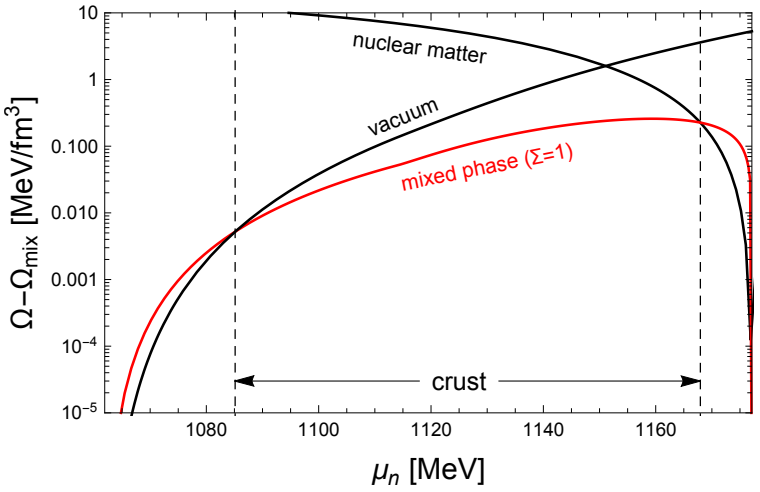
- construct uniform (locally neutral) and mixed (globally neutral) phases in β-equilibrium

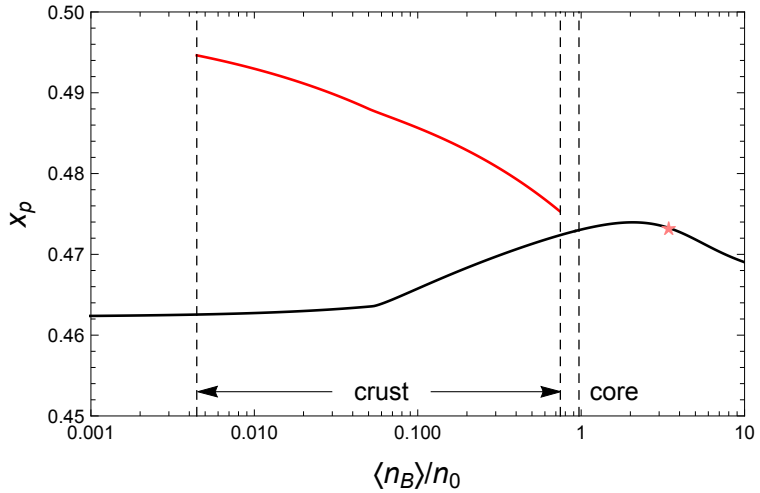
- use Wigner-Seitz approximation and step-like interfaces (surface tension Σ as input)

dynamic calculation of clusters and crust-core transition

Building a neutron star from holography (page 2/5)

- mixed phase energetically preferred for small μ_n





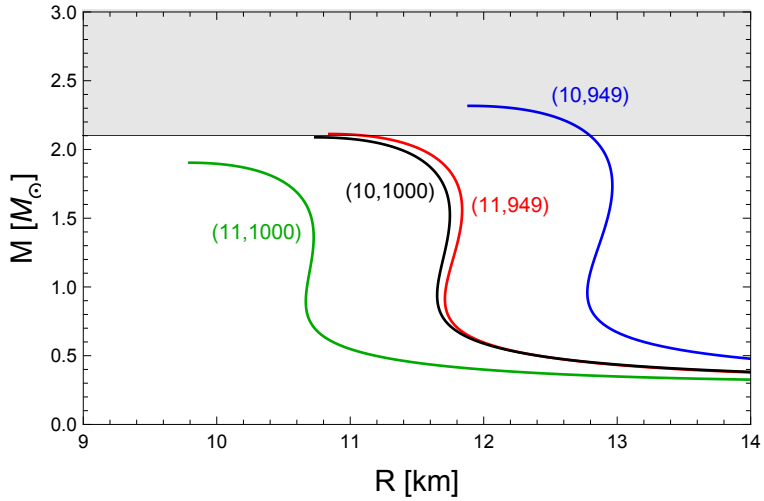
- large-N_c artifact:
  continuous isospin spectrum
  → large proton fraction
  → muons in inner crust

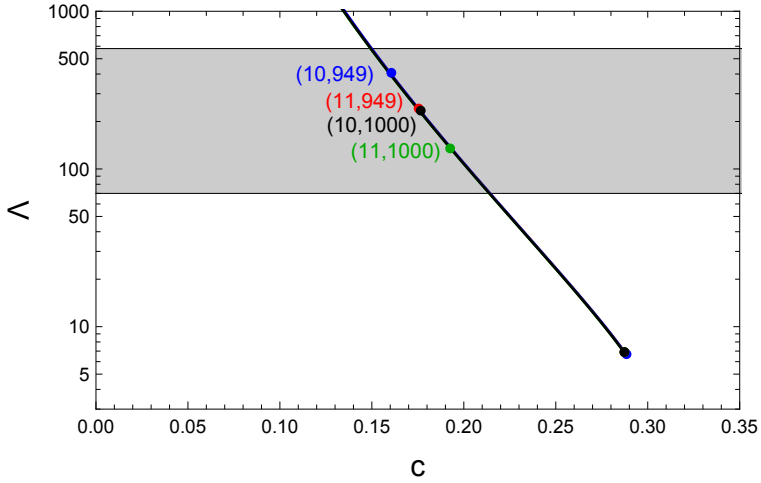
possible improvement:
L. Bartolini, S. B. Gudnason, 2209.14309 [hep-ph]

Building a neutron star from holography (page 3/5)

couple to gravity ("TOV equations") → mass-radius curves
for different parameter pairs $(\lambda, M_{\rm KK})$ with $\Sigma = 1\,\mathrm{MeV/fm}^2$

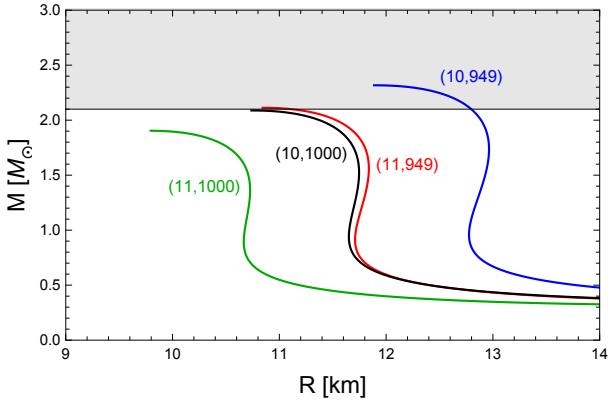
fit to	λ	$M_{\rm KK}$
f_π, m_ρ	16.63	949 MeV
σ, m_ρ	12.55	949 MeV
n_0, E_B	7.09	1000 MeV

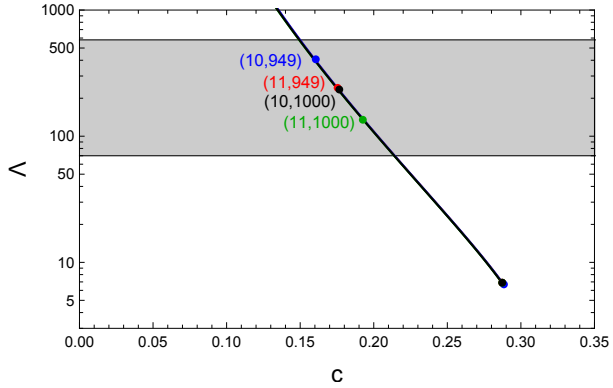




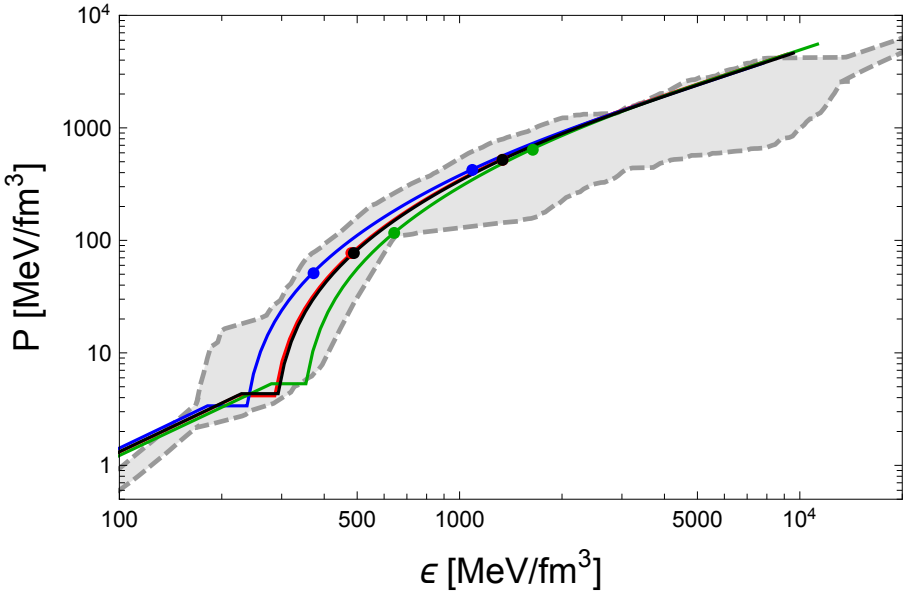
- realistic maximal masses and 1.4-solar-mass deformabilities

Building a neutron star from holography (page 4/5)



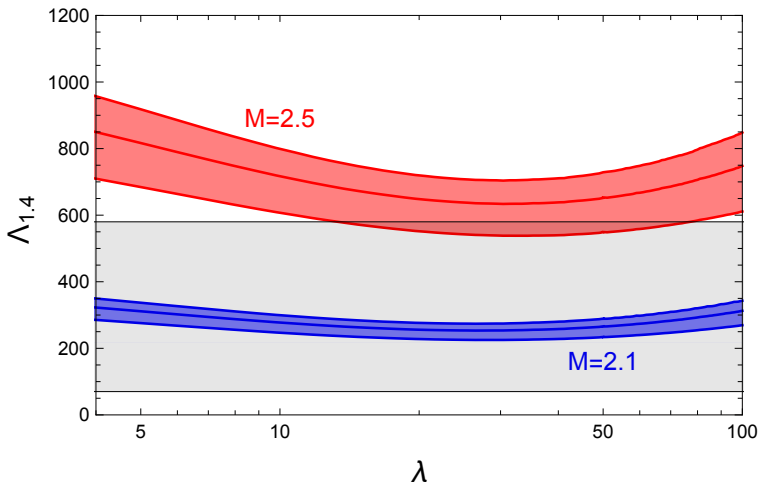


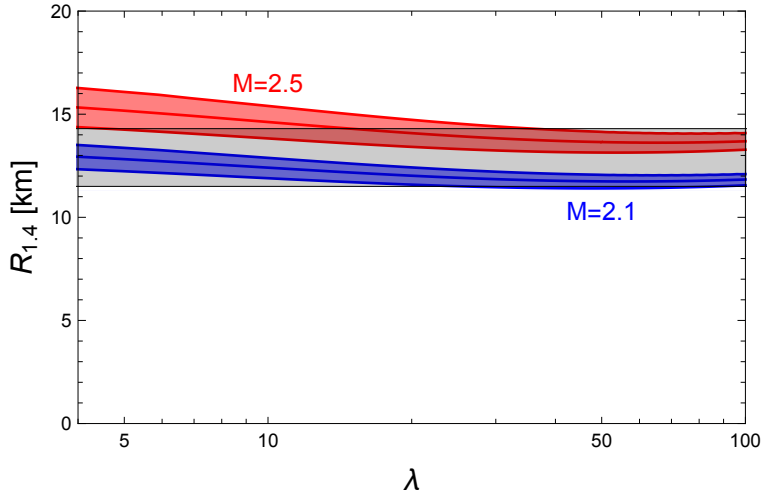
Can our results be connected to perturbative QCD?



grey band taken from E. Annala, T. Gorda, A. Kurkela, and A. Vuorinen, PRL 120, 172703 (2018)

Building a neutron star from holography (page 5/5)





- astrophysical constraints from GW170817 + NICER
- 2.5-solar-mass stars barely possible
- parameter-independent prediction for lower bounds on $\Lambda_{1.4}$ and radius $R_{1.4}$

  more systematic predictions: N. Kovensky, A. Poole and A. Schmitt, SciPost Phys. Proc. 6, 019 (2022)

other holographic approaches to compact stars (combined with "traditional" methods), see reviews
M. Järvinen, EPJC 82, 282 (2022)
C. Hoyos, N. Jokela and A. Vuorinen, Prog. Part. Nucl. Phys. 126, 103972 (2022)

Summary

- holographic Witten-Sakai-Sugimoto model gives a "QCD-like" theory with all necessary ingredients
  (chiral transition, baryons, pion condensation, ...)

- introducing isospin-asymmetric baryonic matter allows us to
  - study phase structure for finite μ_B, μ_I (and T)
  - construct neutron stars from a single model
    (unlike most other holographic and non-holographic approaches)

Outlook

- improve holographic description of baryons (large-N_c artifacts?)
- improve holographic crust (pasta structures, inner crust)
- allow for anisotropic pion condensation and chiral density wave
  N. Kovensky, A. Schmitt, work in progress
- include strangeness (kaon condensation, hyperons)
  N. Kovensky, A. Schmitt, work in progress
- holographic quark-hadron (quarkyonic-hadron) phase transition in compact stars?
- compute $T > 0$ equation of state for merger simulations
- compute transport properties