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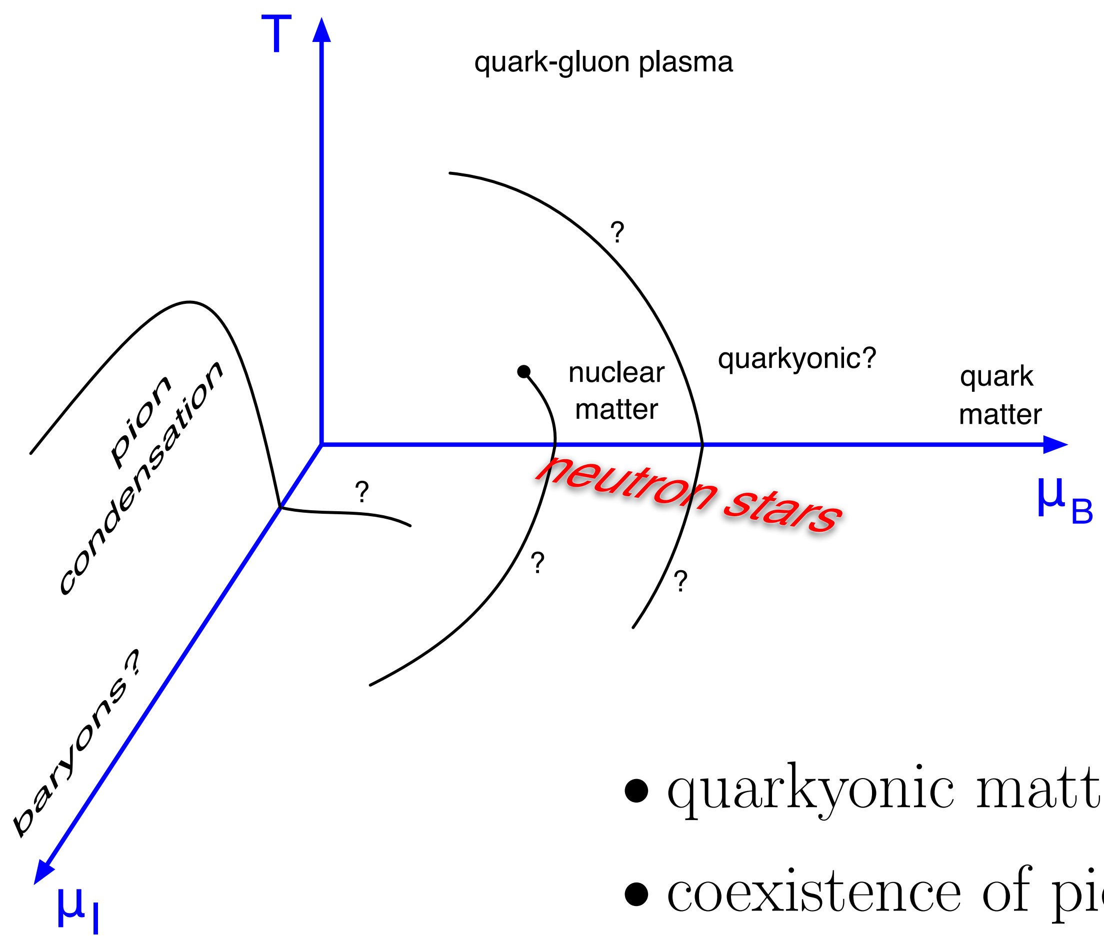
STAG RESEARCH CENTRE

Holographic nuclear matter with isospin asymmetry

N. Kovensky and A. Schmitt, SciPost Phys. 11, 029 (2021)
N. Kovensky, A. Poole, and A. Schmitt, arXiv:2111.03374 [hep-ph]

- holographic Sakai-Sugimoto model: basics and phases
  e.g., quarkyonic matter N. Kovensky, A. Schmitt, JHEP 09, 112 (2020)
- isospin asymmetric matter
  - nuclear matter + pion condensation
  - phase structure in μ_B-μ_I-T space
- building a realistic neutron star from holography

Phases of QCD



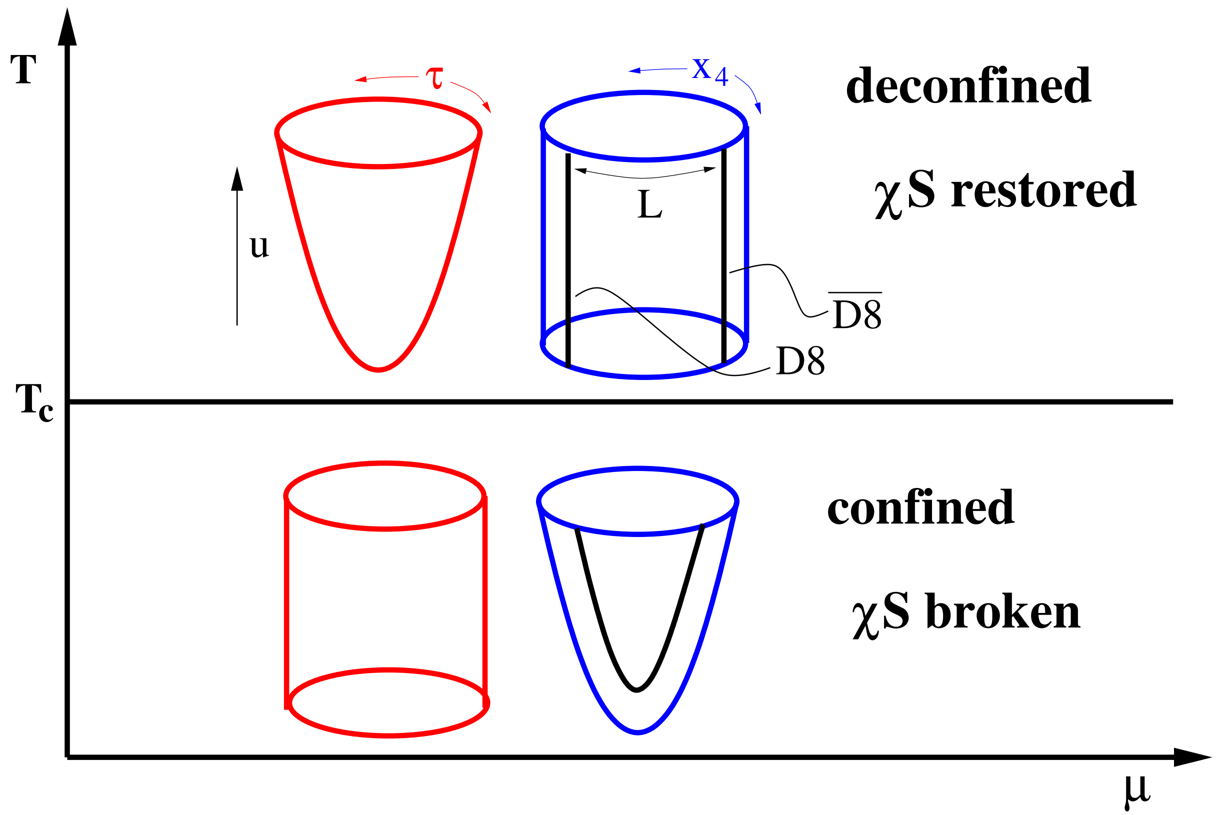
- quarkyonic matter for $N_c = 3$?
- coexistence of pion condensate and baryons?
- composition of neutron star matter?

Can holography help?

- dual of QCD: probably exists, but currently out of reach
- reliable strong-coupling calculation (usually infinite coupling)
- successful (qualitative) predictions for heavy-ion collisions (supersymmetric YM plasma instead of quark-gluon plasma)

- 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 3 parameters
  - supersymmetry and conformal symmetry broken
  - dual to large-N_c QCD, however in inaccessible limit
  - successfully applied to meson, baryon, glueball spectra
    ... and phase structure, e.g., inverse magnetic catalysis
    F. Preis, A. Rebhan and A. Schmitt, JHEP 03, 033 (2011)

Phases in the Sakai-Sugimoto model (page 1/3)



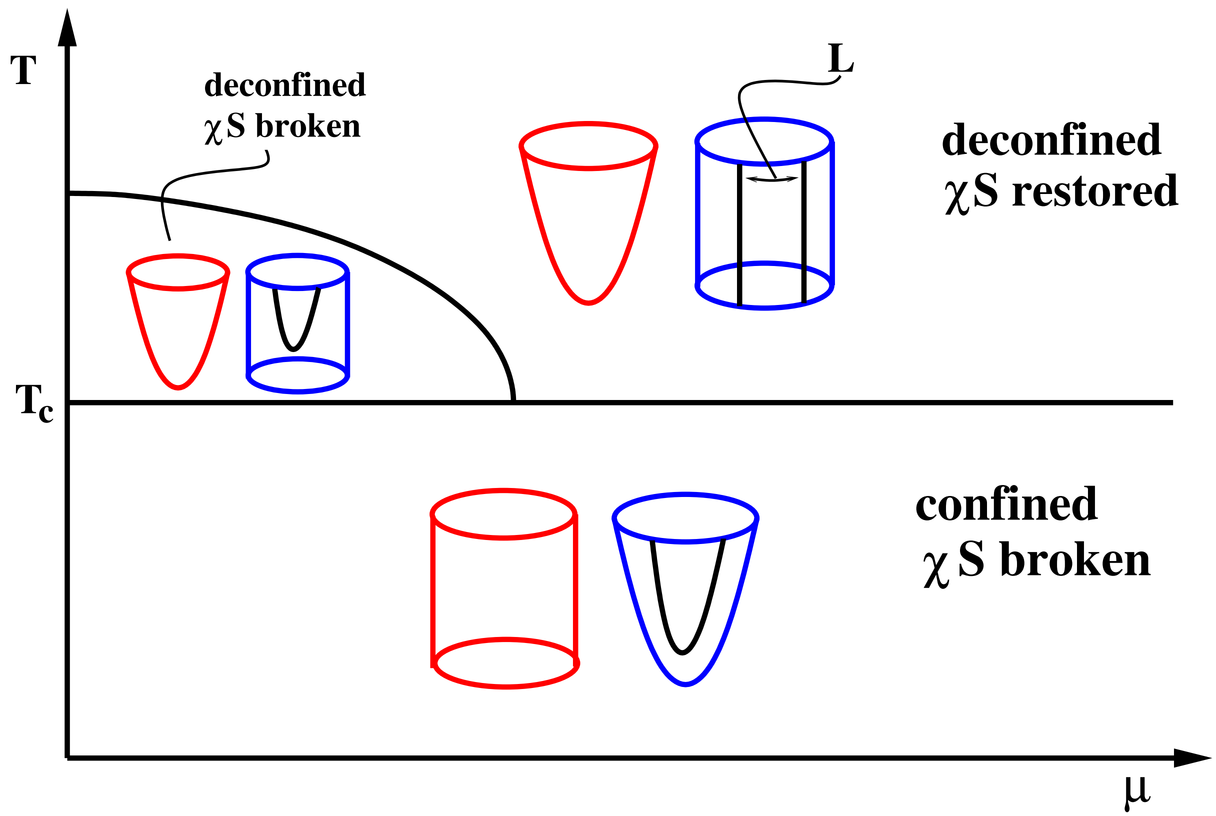
- in probe brane ("quenched") approximation: phase transition unaffected by quantities on flavor branes (μ, B, ...)
- not unlike expectation from large-N_c QCD

Phases in the Sakai-Sugimoto model (page 2/3)

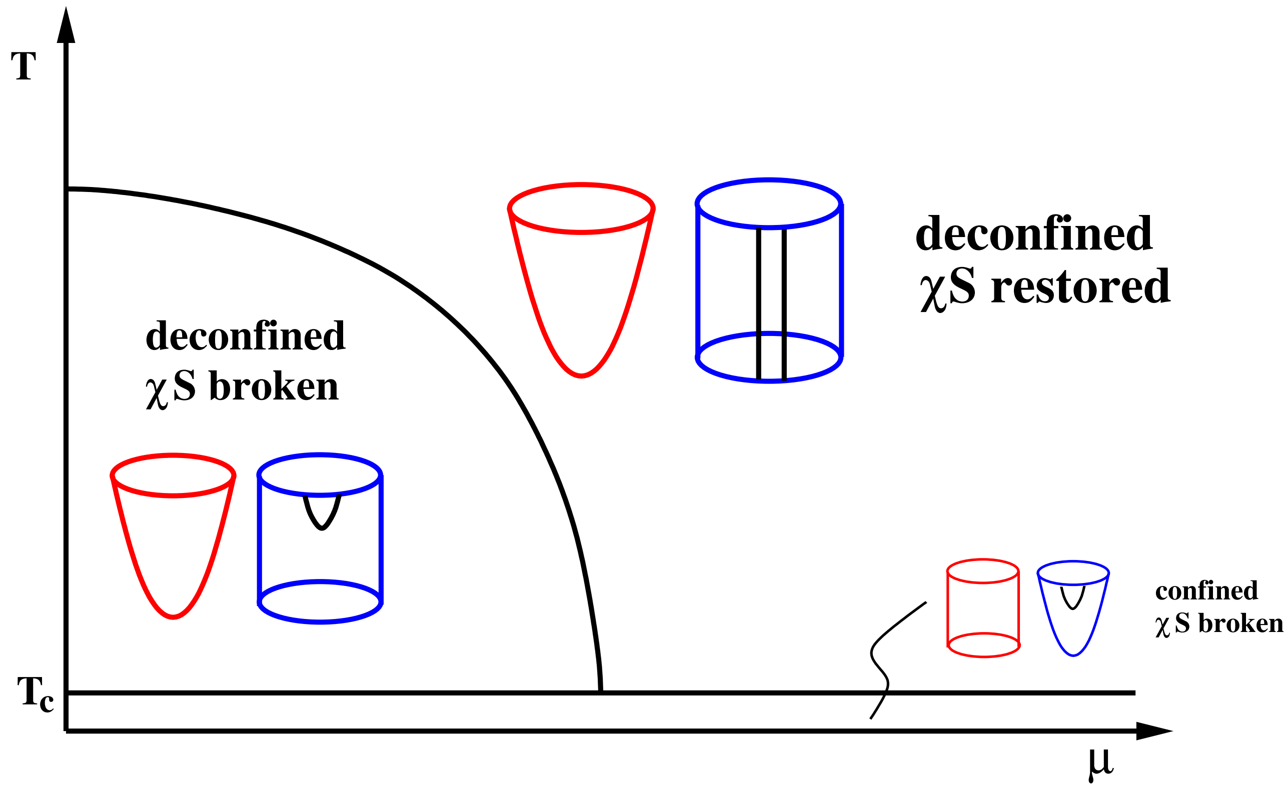
- less "rigid" behavior for smaller L
- deconfined, chirally broken phase for $L < 0.3\,\pi/M_{\rm KK}$

O. Aharony, J. Sonnenschein, S. Yankielowicz, Annals Phys. 322, 1420 (2007)

N. Horigome, Y. Tanii, JHEP 0701, 072 (2007)



Phases in the Sakai-Sugimoto model (page 3/3)



- "decompactified" limit → gluon dynamics decouple
- "NJL-like" dual field theory

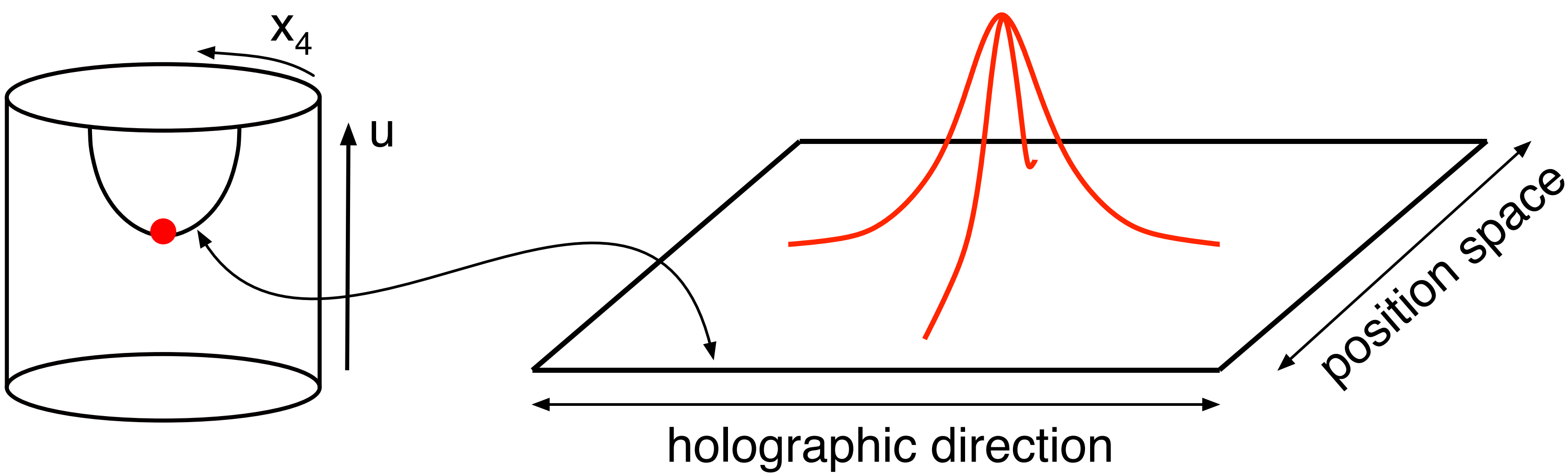
E. Antonyan, J. A. Harvey, S. Jensen, D. Kutasov, hep-th/0604017

J. L. Davis, M. Gutperle, P. Kraus, I. Sachs, JHEP 0710, 049 (2007)

F. Preis, A. Rebhan and A. Schmitt, Lect. Notes Phys. 871, 51 (2013)

Adding baryons

- baryons in AdS/CFT: wrapped D-branes with N_c string endpoints
  E. Witten, JHEP 9807, 006 (1998); D. J. Gross, H. Ooguri, PRD 58, 106002 (1998)
- baryons in Sakai-Sugimoto:
  – D4-branes wrapped on S^4
  – equivalently: instantons on D8-branes ($\rightarrow$ skyrmions)
  T. Sakai, S. Sugimoto, Prog. Theor. Phys. 113, 843-882 (2005)
  H. Hata, T. Sakai, S. Sugimoto, S. Yamato, Prog. Theor. Phys. 117, 1157 (2007)



Approximations for holographic nuclear matter

- Pointlike approximation
  O. Bergman, G. Lifschytz, M. Lippert, JHEP 0711, 056 (2007)
  quarkyonic matter: N. Kovensky and A. Schmitt, JHEP 09, 112 (2020)

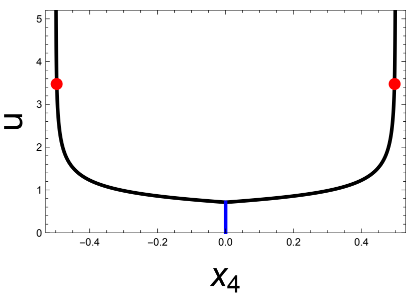
- Finite-width instantons
  - Non-interacting
    K. Ghoroku, K. Kubo, M. Tachibana, T. Taminato and F. Toyoda, PRD 87, 066006 (2013)
    S.-w. Li, A. Schmitt, Q. Wang, PRD 92, 026006 (2015)
    F. Preis, A. Schmitt, JHEP 1607, 001 (2016); EPJ Web Conf. 137, 09009 (2017)
  - Two-body interactions from exact two-instanton solution
    K. Bitaghsir Fadafan, F. Kazemian, A. Schmitt, JHEP 1903, 183 (2019)

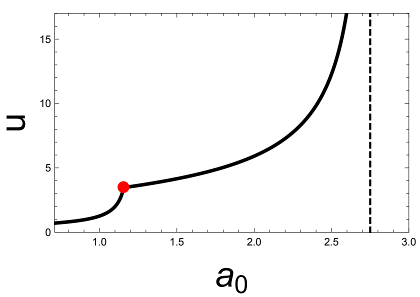
- "Homogeneous ansatz" (not based on single-instanton solution)
  M. Rozali, H. H. Shieh, M. Van Raamsdonk and J. Wu, JHEP 0801, 053 (2008)
  S.-w. Li, A. Schmitt, Q. Wang, PRD 92, 026006 (2015)
  M. Elliot-Ripley, P. Sutcliffe and M. Zamaklar, JHEP 1610, 088 (2016)
  with isospin asymmetry: N. Kovensky and A. Schmitt, SciPost Phys. 11, 029 (2021)

Holographic quarkyonic matter

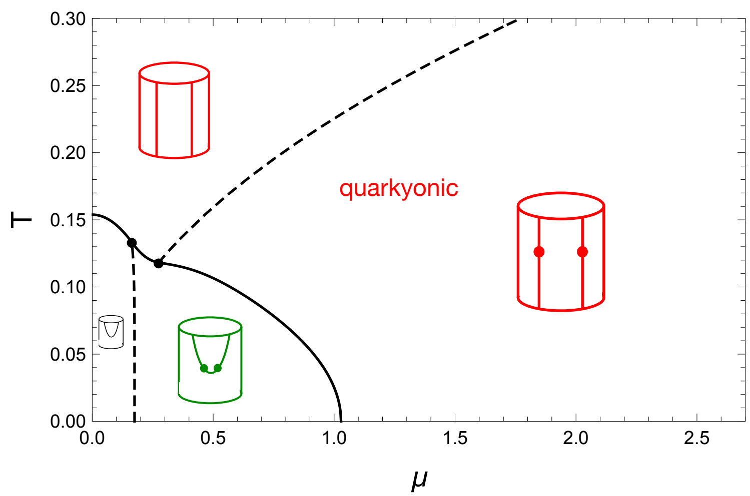
N. Kovensky and A. Schmitt, JHEP 09, 112 (2020)

large-N_c QCD L. McLerran and R. D. Pisarski, NPA 796, 83 (2007)

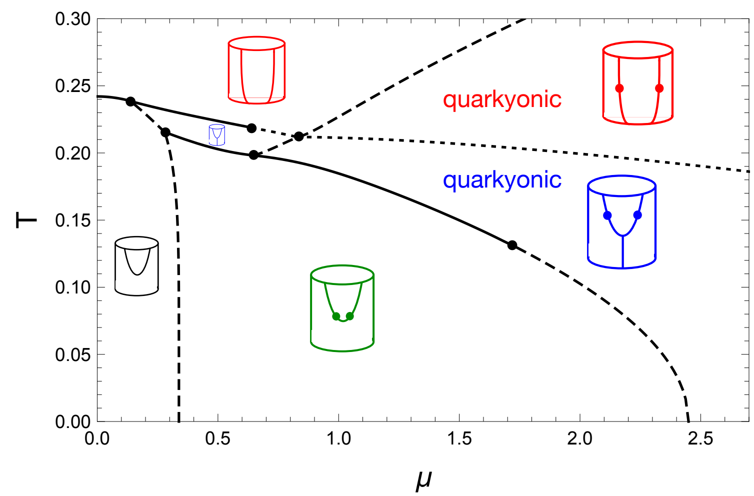




quarks and baryons separated in holographic direction



$m_\pi = 0$



$m_\pi > 0$

Isospin-asymmetric matter: setup (page 1/2)

- D8-brane action

$$S = \underbrace{T_8 V_4 \int_{x^\mu} \int_z e^{-\Phi} \sqrt{\det(g + 2\pi\alpha' F)}}_{\text{Dirac-Born-Infeld (DBI)}} + \underbrace{\frac{N_c}{8\pi^2} \int_{x^\mu} \int_z \hat{A}_0 \mathrm{Tr}[F_{ij} F_{kz}] \epsilon_{ijk}}_{\text{Chern-Simons (CS)}}$$

- gauge fields in the bulk ($\to$ global symmetry at the boundary)

$$N_f = 2: \qquad F_{\mu\nu} = \hat{F}_{\mu\nu} + F^a_{\mu\nu} \sigma_a$$

- baryon chemical potential

$$\mu_B = \hat{A}_0(z = \pm\infty)$$

- (topological) baryon number

$$N_B = -\frac{1}{8\pi^2} \int_{\vec{x}} \int_z \mathrm{Tr}[F_{ij} F_{kz}] \epsilon_{ijk}$$

Isospin-asymmetric matter: setup (page 2/2)

- include isospin chemical potential

$$(\pm)\mu_I = A_0^3(z = \pm\infty)$$

- allow for pion condensation (→ different boundary conditions)
  O. Aharony, K. Peeters, J. Sonnenschein and M. Zamaklar, JHEP 02, 071 (2008)

- assume $m_\pi = 0$

- homogeneous ansatz for non-abelian gauge fields

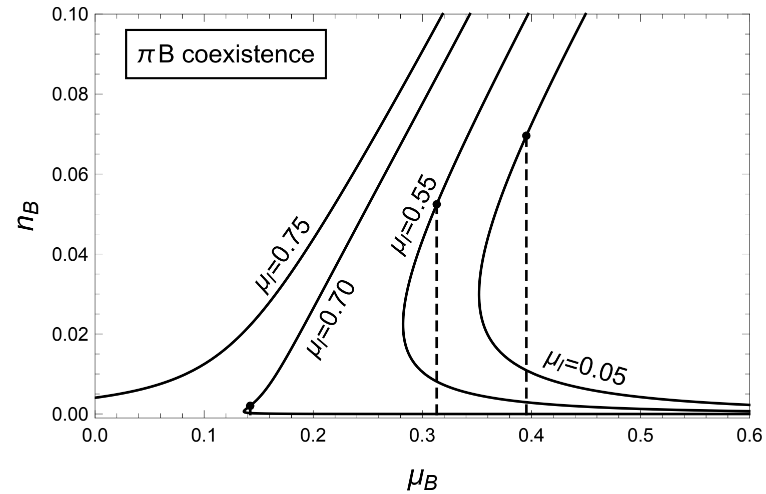
$$A_i(z) = h(z)\sigma_i$$

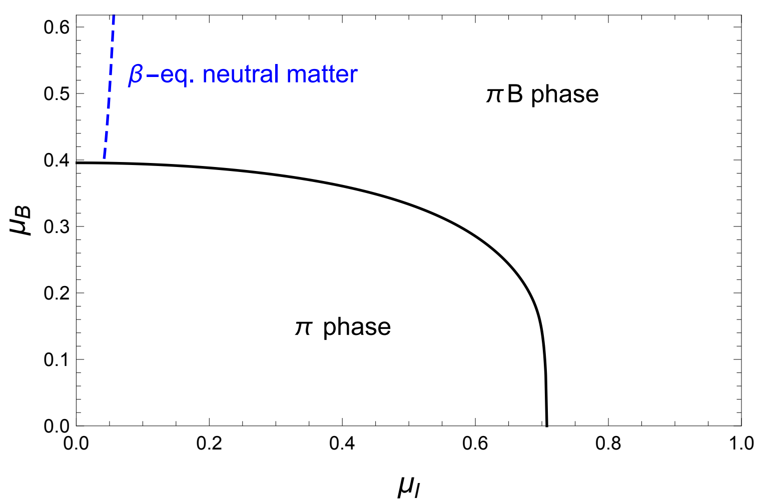
→ solve classical EOMs for $\hat{A}_0$, A_0^3, h (and x_4) for given μ_B, μ_I, T

→ compare free energies of vacuum, pion condensed phase, baryonic phase, coexistence phase (and chirally symmetric phase)

Isospin-asymmetric matter: results (page 1/2)

- simplest version:
  confined geometry, antipodal branes, YM approximation
- first-order transition from pion to coexistence phase

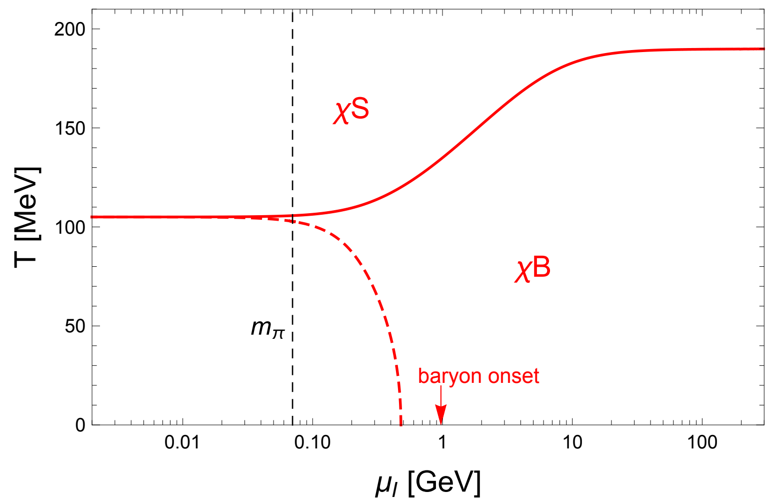


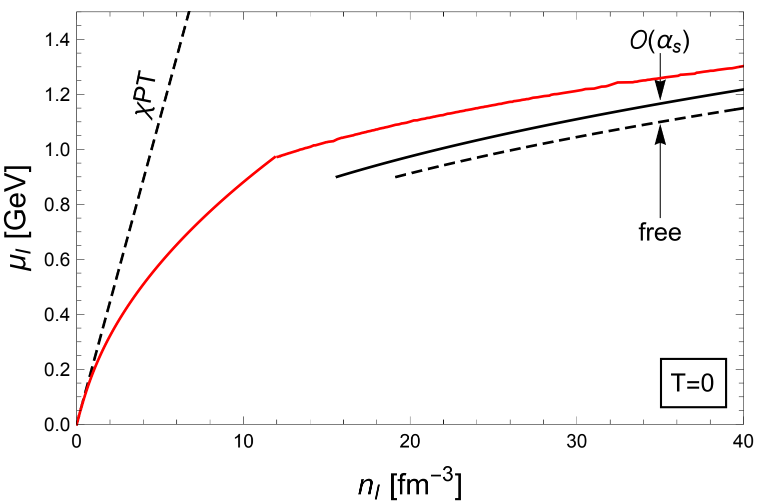


- baryons appear even for $\mu_B = 0$ (degenerate with anti-baryon phase)

Isospin-asymmetric matter: results (page 2/2)

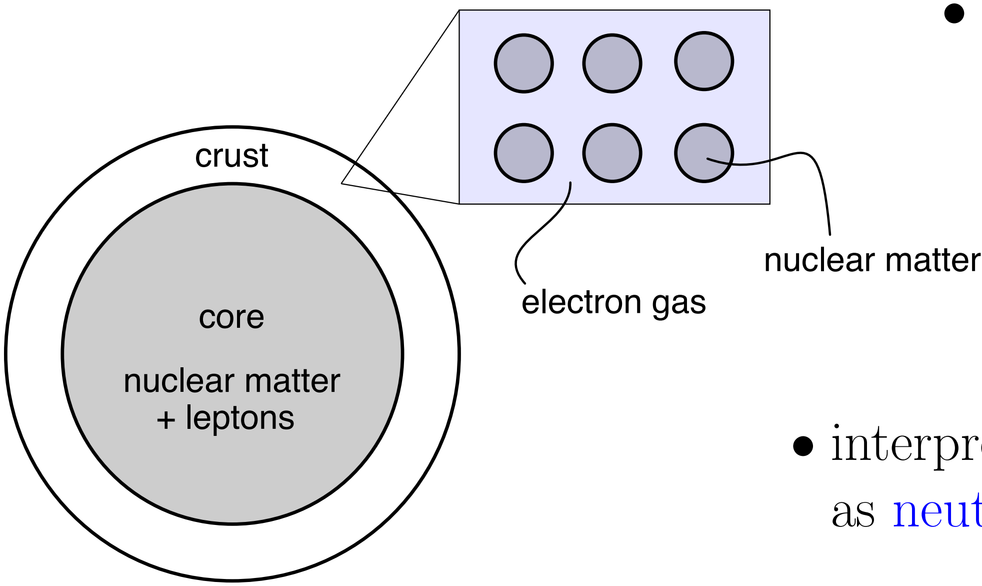
- deconfined geometry, "decompactified limit" (→ T-dependence, chiral transition)





- interpolation between chiral perturbation theory and pQCD

Building a neutron star from holography (page 1/3)

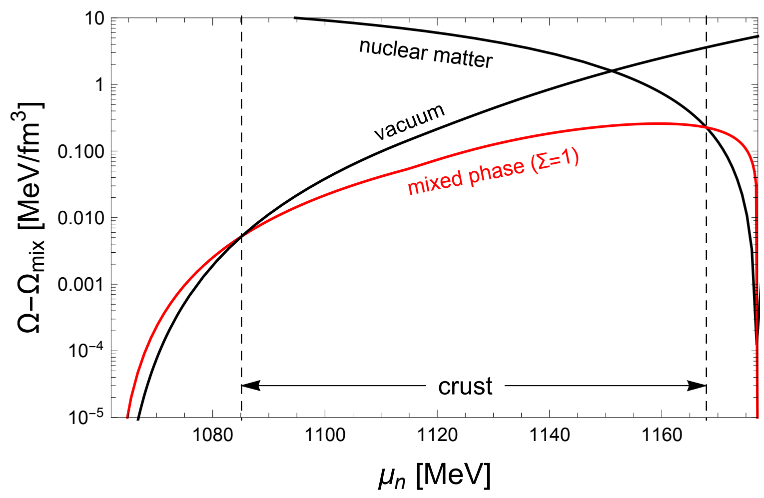


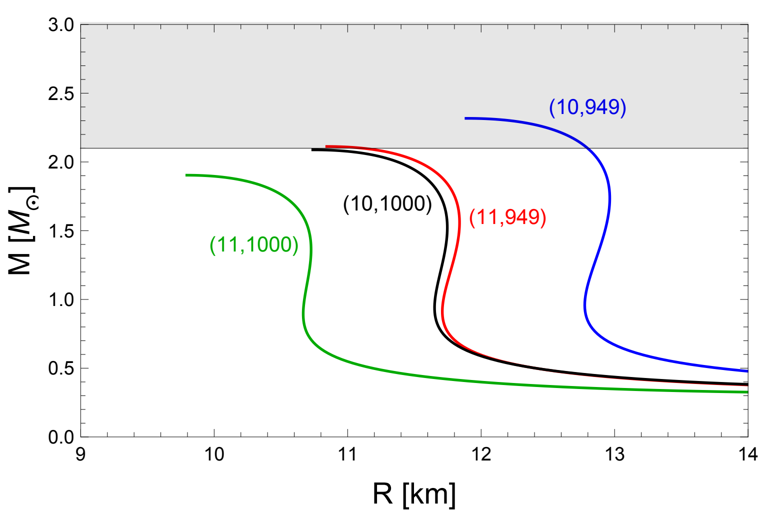
- add leptons to holographic nuclear matter
- interpret holographic isospin components as neutron and proton
- construct uniform (locally neutral) and mixed (globally neutral) phases in β-equilibrium
- use Wigner-Seitz approximation and step-like interfaces (surface tension Σ as input)

dynamic calculation of clusters and crust-core transition

Building a neutron star from holography (page 2/3)

- mixed phase energetically preferred for small μ_n

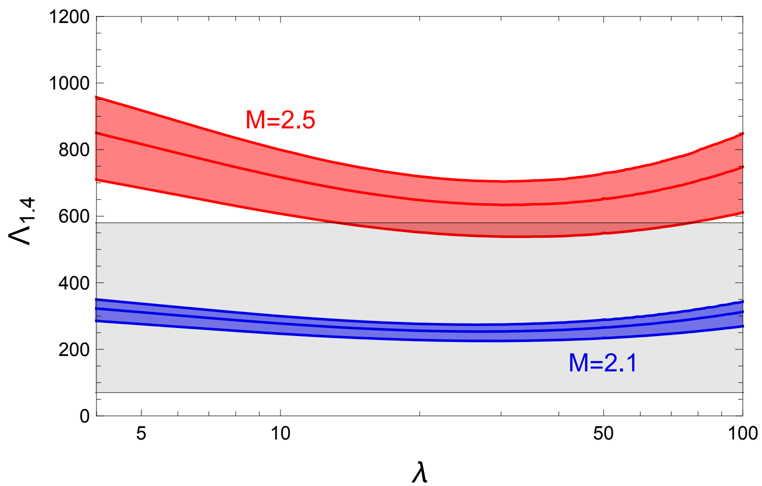


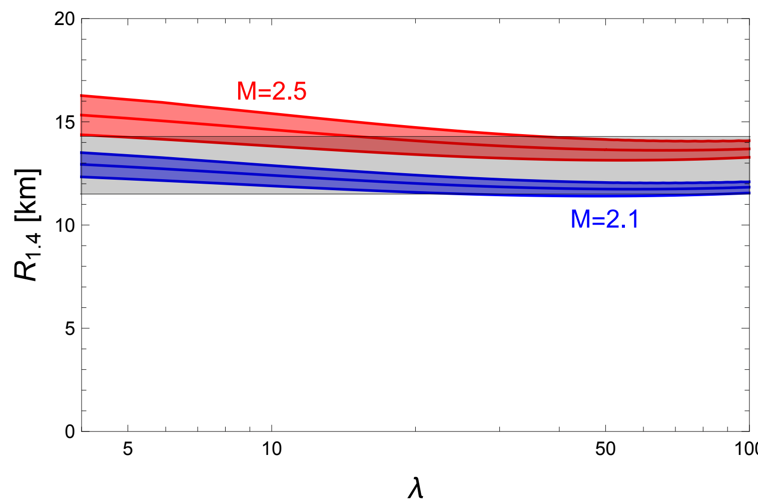


- couple to gravity ("TOV equations")

→ mass-radius curves for different parameter pairs (λ, M_{KK}) with $\Sigma = 1\,\text{MeV/fm}^2$

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





- deformability Λ and radius R in agreement with astrophysical constraints (GW170817 + NICER)
- parameter-independent prediction for lower bounds on $\Lambda_{1.4}$ and radius $R_{1.4}$

other holographic approaches to compact stars (combined with "traditional" methods):
D3-D7: C. Hoyos, D. Rodríguez Fernández, N. Jokela and A. Vuorinen, PRL 117, 032501 (2016)
D3-D7 + running coupling: K. Bitaghsir Fadafan, J. Cruz Rojas and N. Evans, PRD 101, 126005 (2020)
V-QCD: N. Jokela, M. Järvinen and J. Remes, JHEP 03, 041 (2019)
C. Ecker, M. Järvinen, G. Nijs and W. van der Schee, PRD 101, 103006 (2020)

Summary

- holographic 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, 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?)

- include pion mass in phase structure (comparison to lattice)

- include magnetic field
  pointlike baryons: F. Preis, A. Rebhan and A. Schmitt, JPG 39, 054006 (2012)

- compute surface tension dynamically

- include strangeness ($SU(3)$ gauge theory in the bulk
  $\rightarrow$ holographic hyperons in compact stars?)

- holographic quark-hadron (quarkyonic-hadron) phase transition in compact stars?