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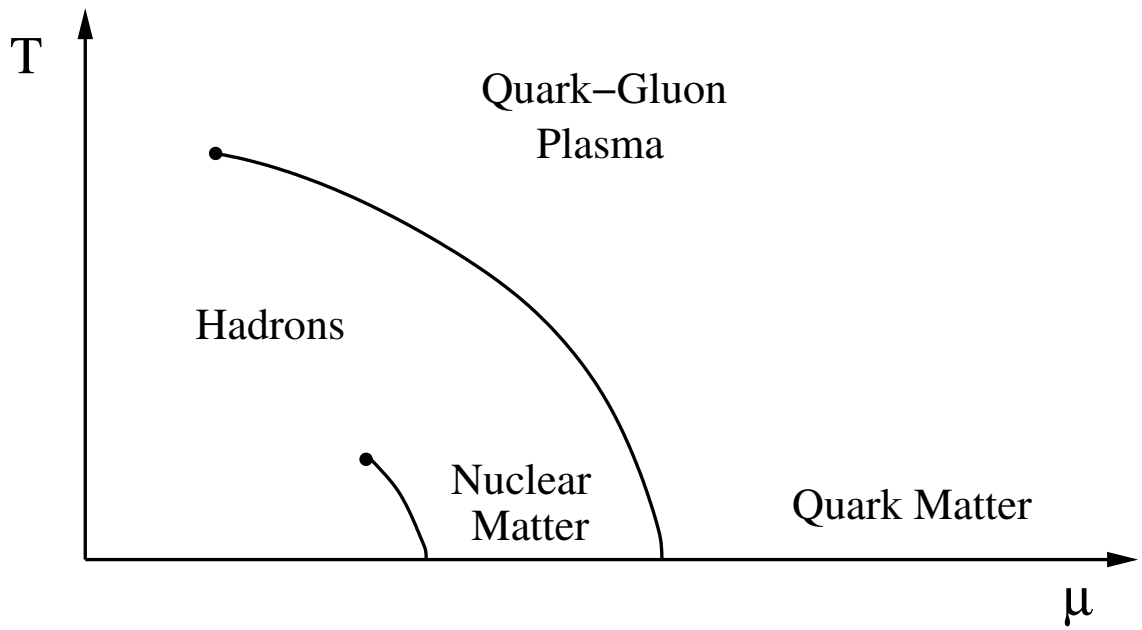
Dense nuclear and quark matter in holographic QCD

S.-w. Li, A. Schmitt, Q. Wang, PRD 92, 026006 (2015)
F. Preis, A. Schmitt, JHEP 1607, 001 (2016)

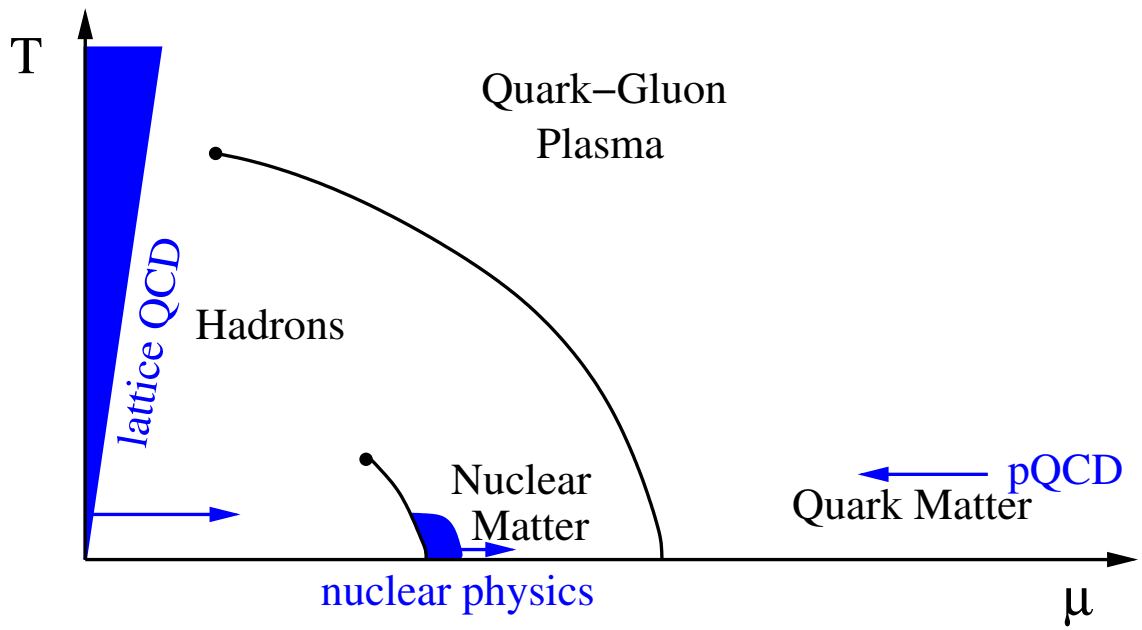
- motivation: theoretical challenges in dense matter and relevance for compact stars
- the Sakai-Sugimoto model: holography as close to QCD as currently possible
- realistic nuclear matter and transition to quark matter in the Sakai-Sugimoto model?

• Dense QCD matter: what we know



- first-order onset of nuclear matter at $\mu = 308\,\mathrm{MeV}$
- weakly interacting quark matter at asymptotically large μ
- as a consequence: must be chiral/deconfinement transition in between (presumably in strongly coupled regime)

• Dense QCD matter: rigorous methods



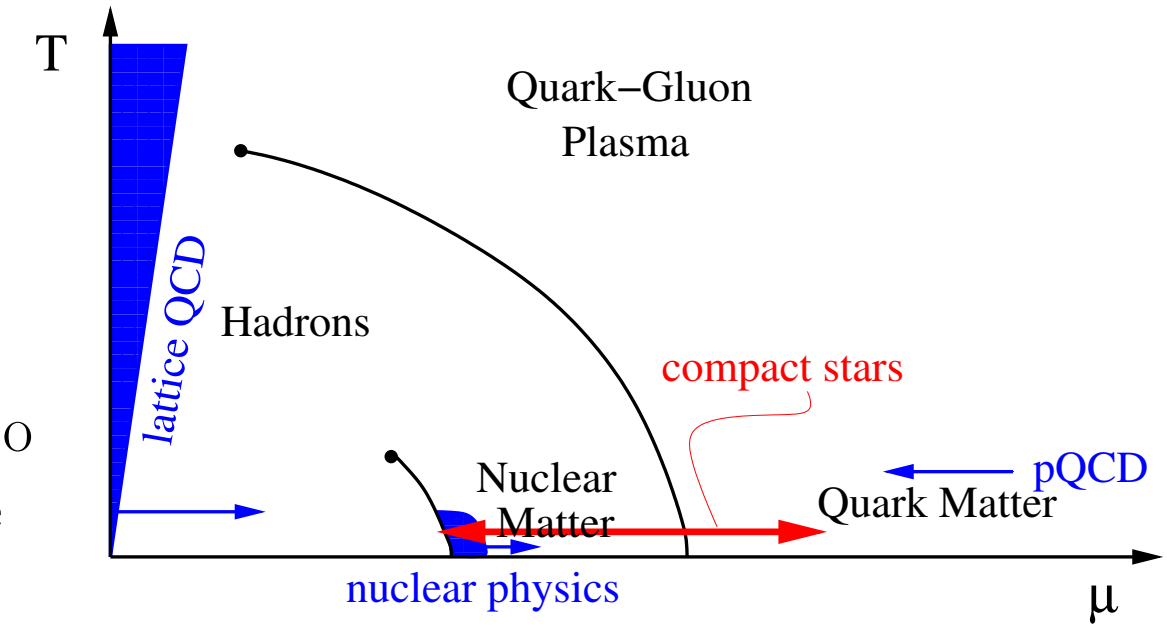
- QCD on the lattice: sign problem at nonzero μ, but recent progress
- perturbative QCD: restricted to ultra-high densities
- "standard" nuclear physics: input from experiment, restricted to nuclear saturation density

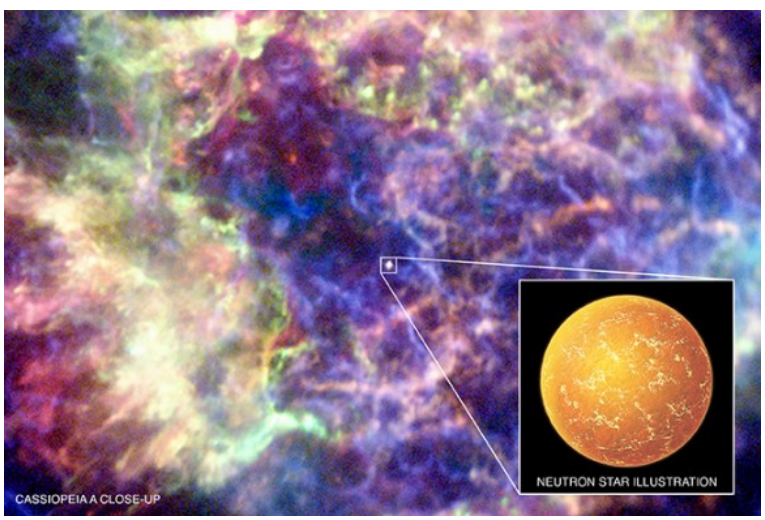
• Dense QCD matter in compact stars

- density *profile* in a compact star

$$n_B \sim (1-10)\, n_0$$

- phase transition to quark matter possible

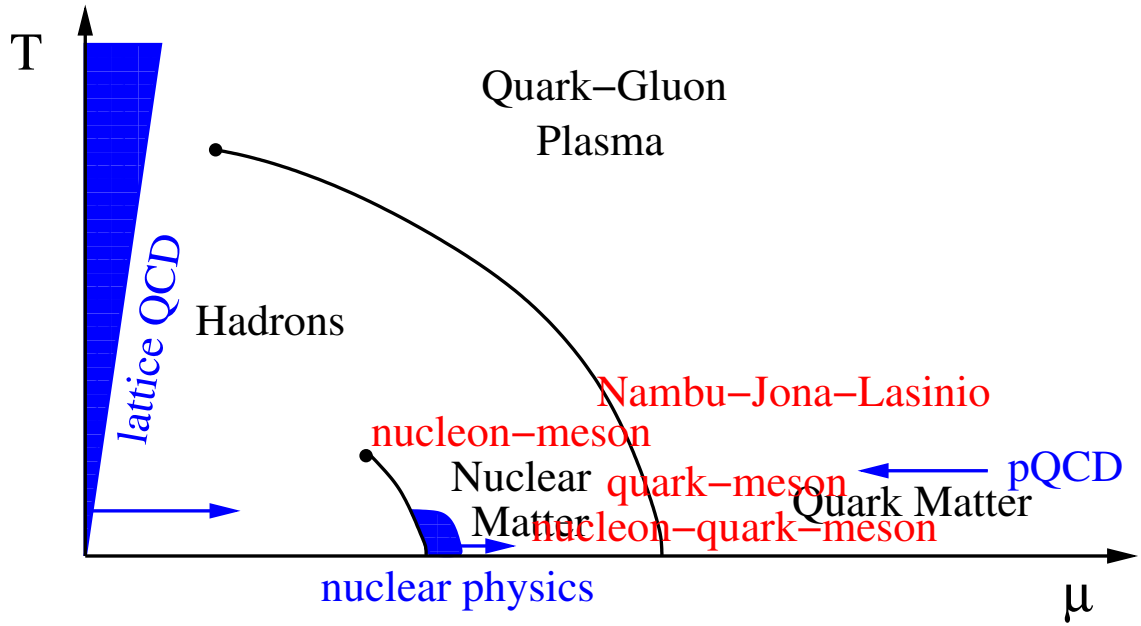




- equation of state + gravity
  → mass/radius of the star

equation of state over wide density regime highly desired!

• Dense QCD matter: models



- Nambu–Jona-Lasinio (usually no nuclear matter)
- quark-meson (no nucleons), nucleon-meson (no quarks)
- nucleon-quark-meson (patched together, many parameters)
- extrapolations from nuclear to weakly interacting quark matter

→ even without rigor: models for compact stars hard to construct!

• Can holography help? (page 1/2)

J. M. Maldacena, Adv. Theor. Math. Phys. 2, 231 (1998)

string theory (in higher dimensions)	$\Leftrightarrow$	gauge theory (on boundary)

original "AdS/CFT correspondence":

string theory on $AdS_5 \times S^5 \Leftrightarrow \mathcal{N} = 4$ $SU(N_c)$ SYM theory on $\mathbb{R}^{3,1}$

(super)gravity limit (*easy!*)	$\Leftrightarrow$	strong coupling limit (*difficult!*)

• Can holography help? (page 2/2)

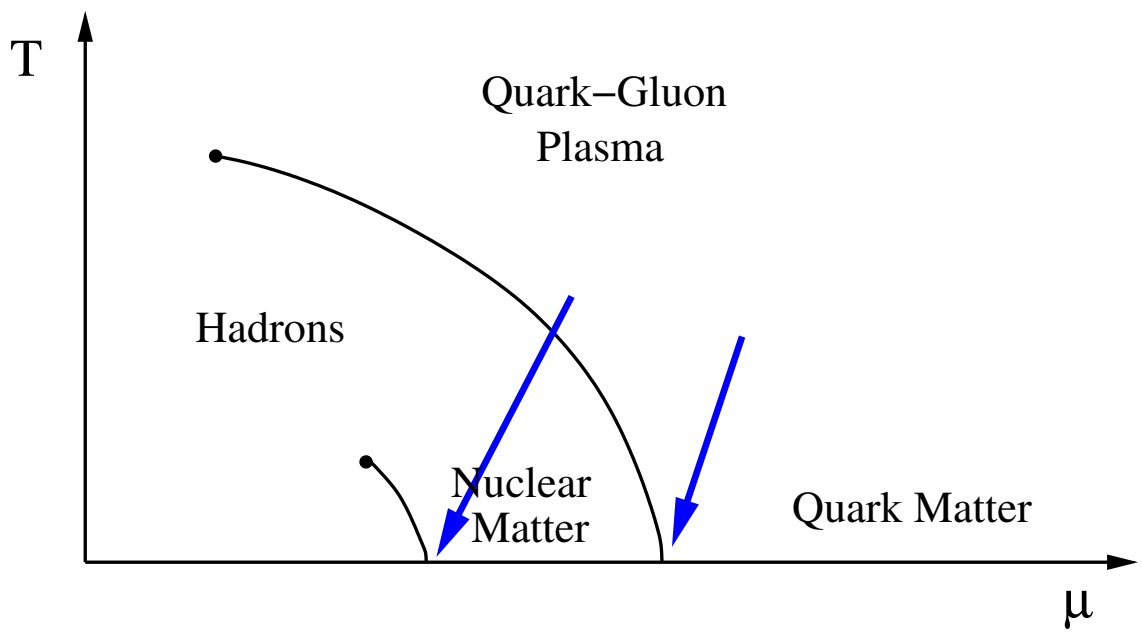
J. M. Maldacena, Int. J. Theor. Phys. 38, 1113 (1999) [Adv. Theor. Math. Phys. 2, 231 (1998)]

- dual of QCD: probably exists, but currently out of reach
- reliable strong-coupling calculation (usually infinite coupling)

- Sakai-Sugimoto model:
  T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)
  - top-down approach with only 3 parameters
  - dual to large-N_c QCD, however in inaccessible limit
  - contains all necessary ingredients:
    baryons, quark matter, chiral/deconfinement phase transitions

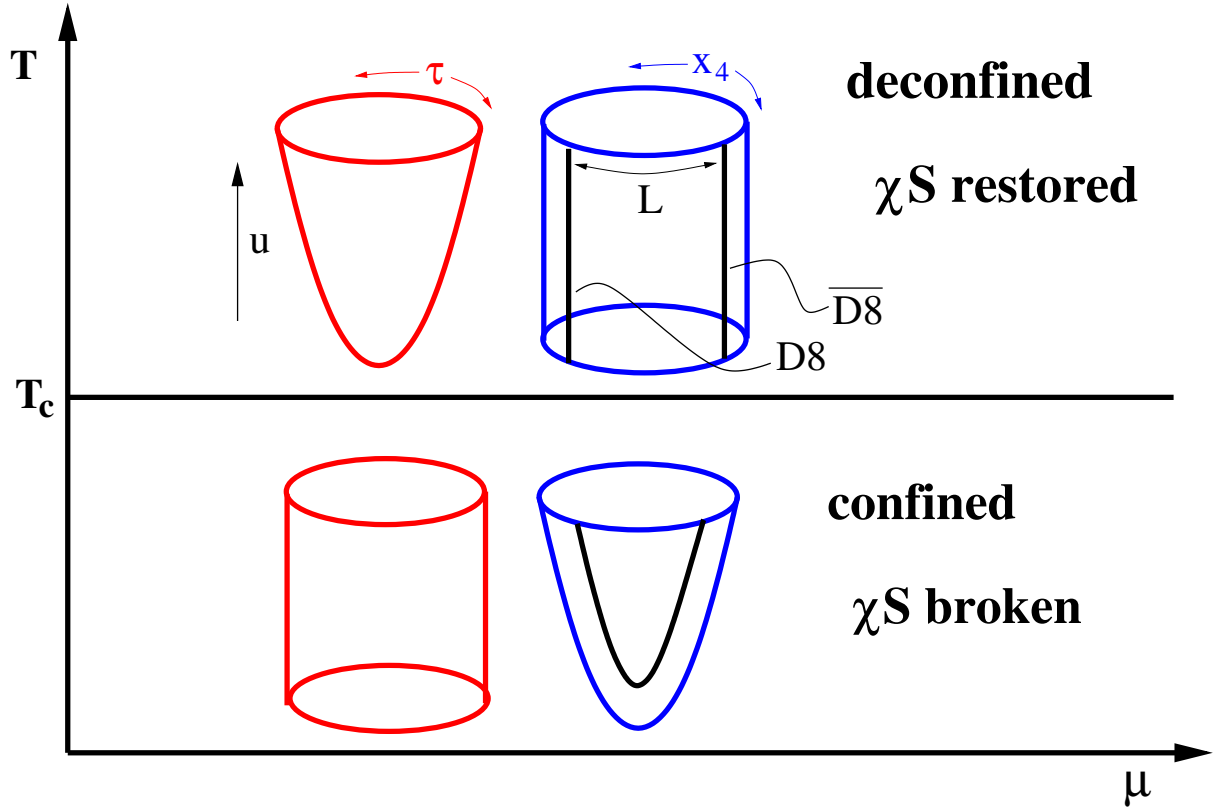
- **Goal**

Does cold and dense holographic matter show
a first-order baryon onset
and
a chiral phase transition to quark matter?



(ignore superfluidity in nuclear matter and color superconductivity)

• Chiral transition in the Sakai-Sugimoto model (p. 1/3)

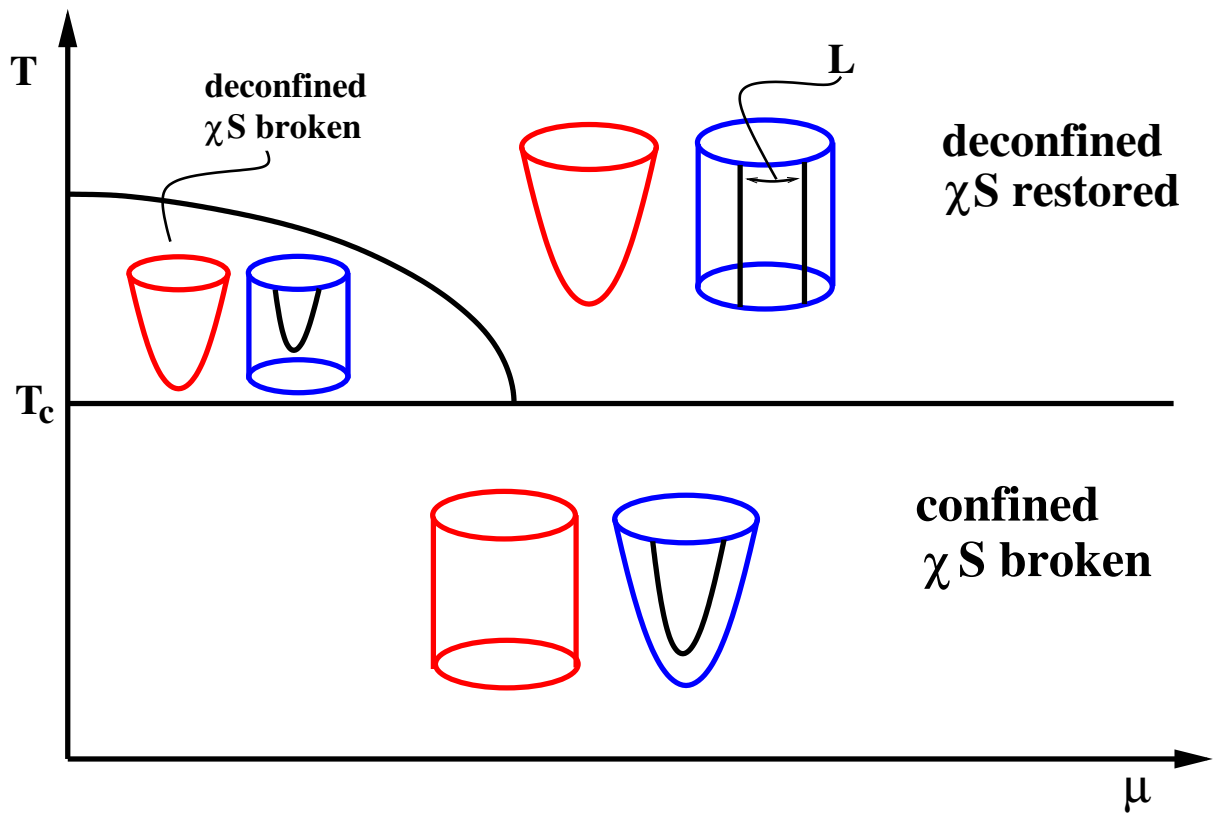


- in probe brane ("quenched") approximation: phase transition unaffected by quantities on flavor branes (μ, B, ...)
- not unlike expectation from large-N_c QCD

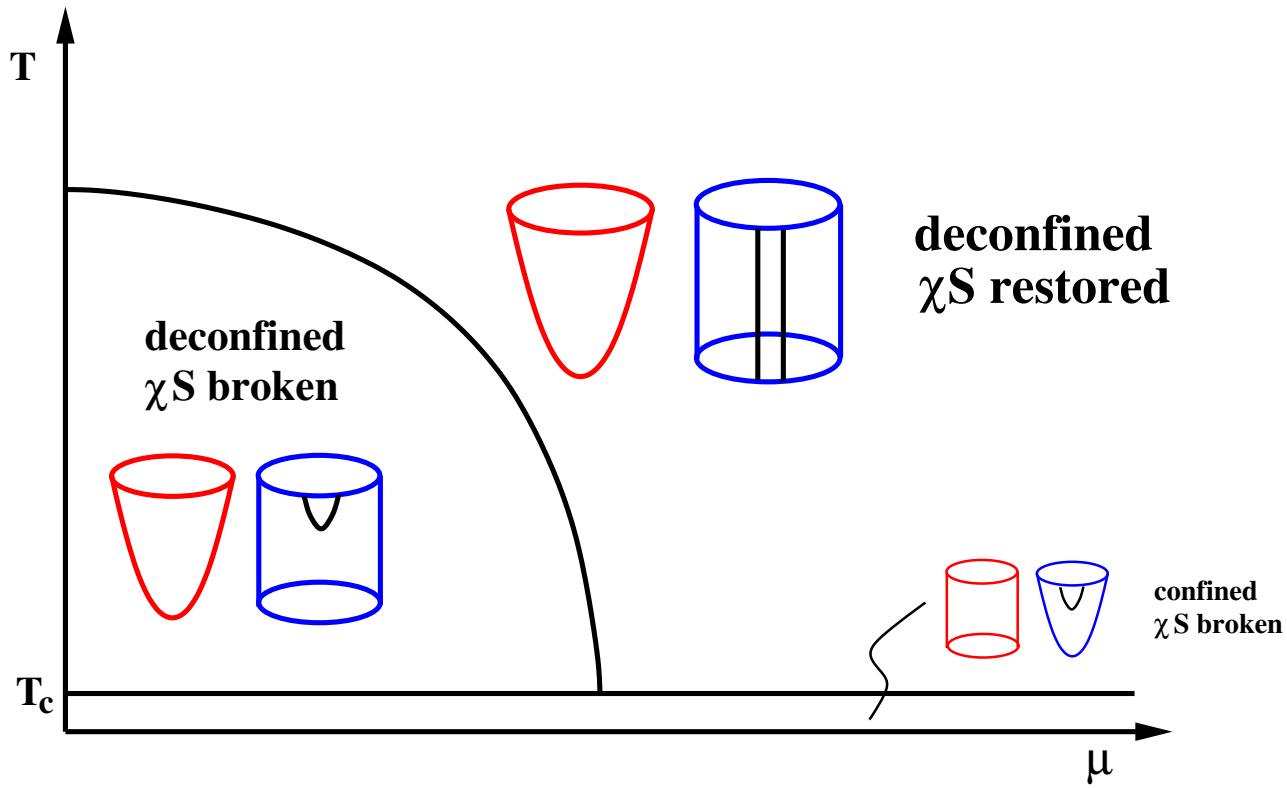
• Chiral transition in the Sakai-Sugimoto model (p. 2/3)

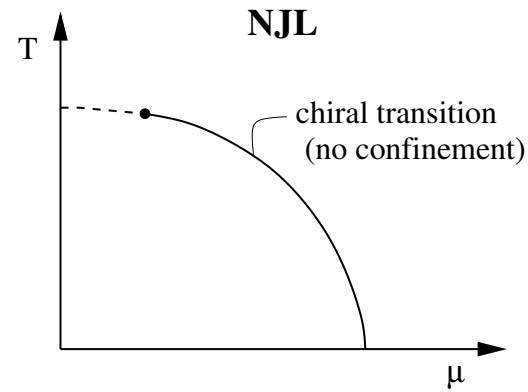
- less "rigid" behavior for smaller L
- deconfined, chirally broken phase for $L < 0.3\,\pi/M_{\rm KK}$

O. Aharony, J. Sonnenschein, S. Yankielowicz, Annals Phys. 322, 1420 (2007)
N. Horigome, Y. Tanii, JHEP 0701, 072 (2007)



• Chiral transition in the Sakai-Sugimoto model (p. 3/3)





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

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

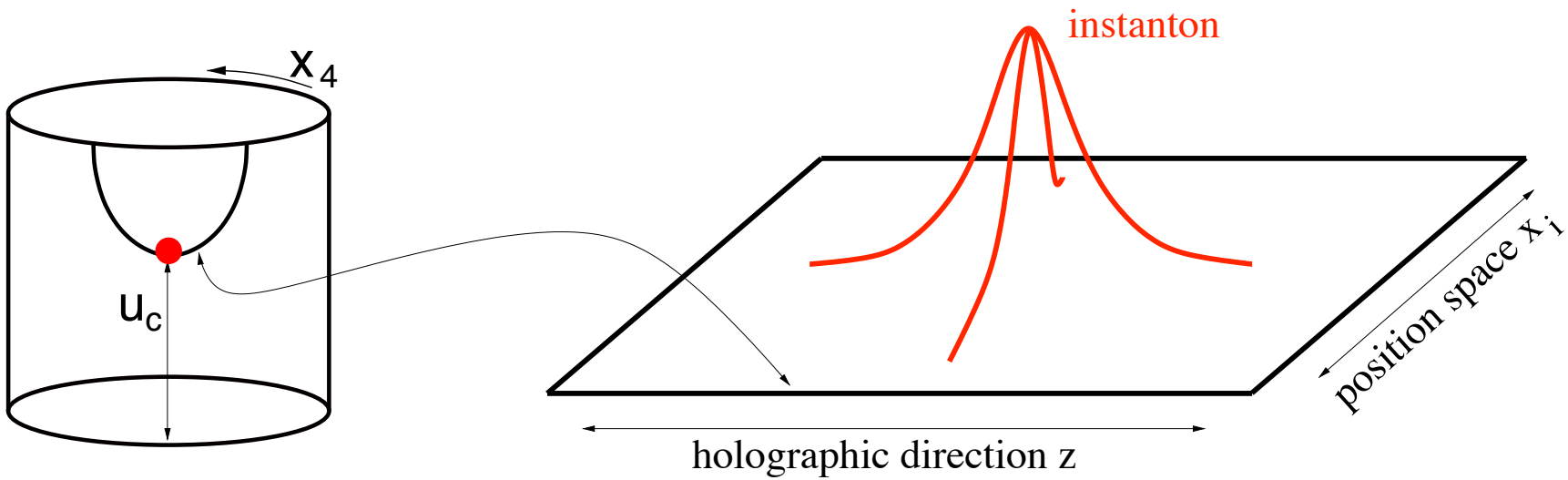
  J. L. Davis, M. Gutperle, P. Kraus, I. Sachs, JHEP 0710, 049 (2007)

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

• Baryons in the Sakai-Sugimoto model (page 1/2)

- 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)

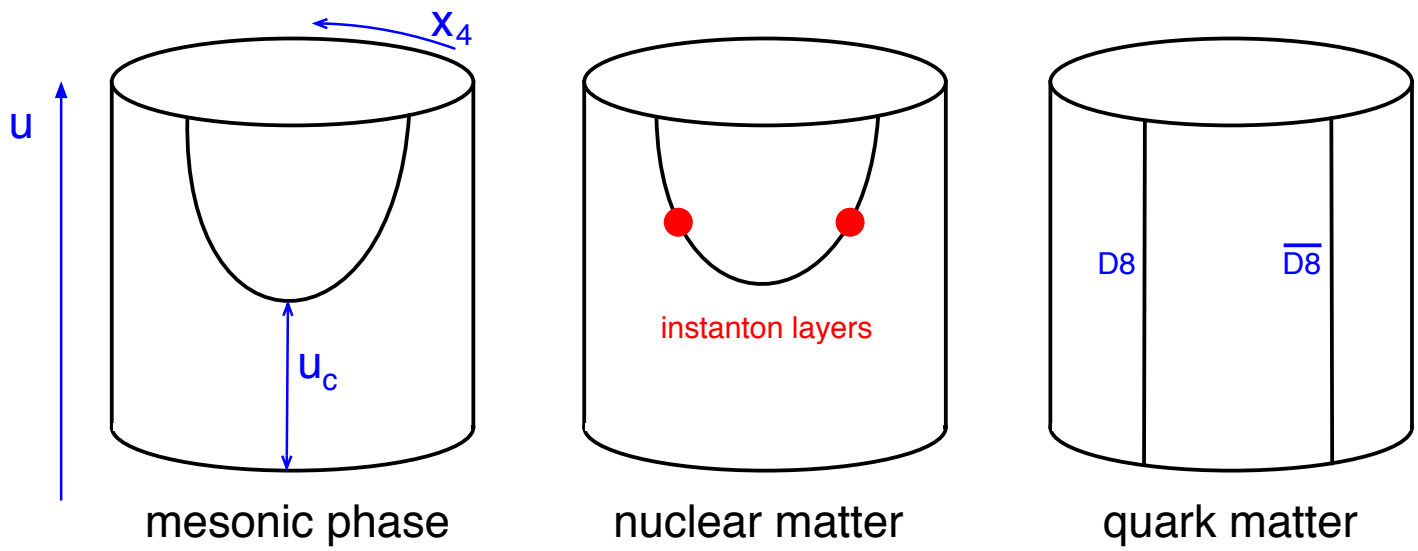


• Baryons in the Sakai-Sugimoto model (page 2/2)

- instanton solution for $SU(2)$ gauge fields in the bulk

$$F^2 \sim \frac{\rho^4}{[(\vec{x}-\vec{x}_0)^2 + \frac{(z-z_0)^2}{\gamma^2} + \frac{\rho^2}{\gamma^2}]^4} \rightarrow \sum_{n=1}^{N_I} \frac{\rho^4}{[(\vec{x}-\vec{x}_0)^2 + \frac{(z-z_0)^2}{\gamma^2} + \frac{\rho^2}{\gamma^2}]^4}$$

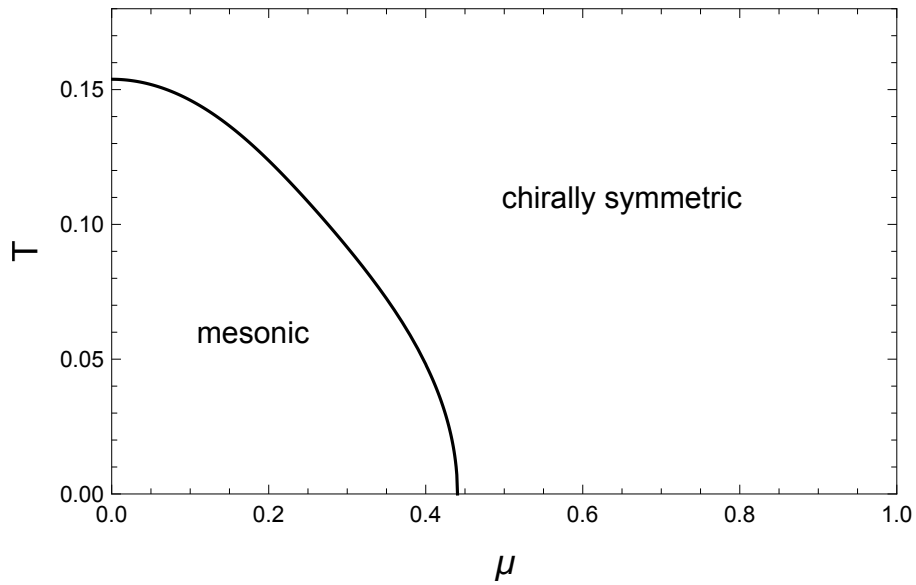
- solve EOMs for $U(1)$ gauge field $\hat{A}_0(u)$ and embedding $x_4(u)$
- minimize free energy wrt ρ, γ, N_I, u_c, and # of instanton layers



- compare free energy of all three phases

• Phase diagrams with holographic baryons (page 1/4)

- first: without baryons
  N. Horigome and Y. Tanii,
  JHEP 0701, 072 (2007)

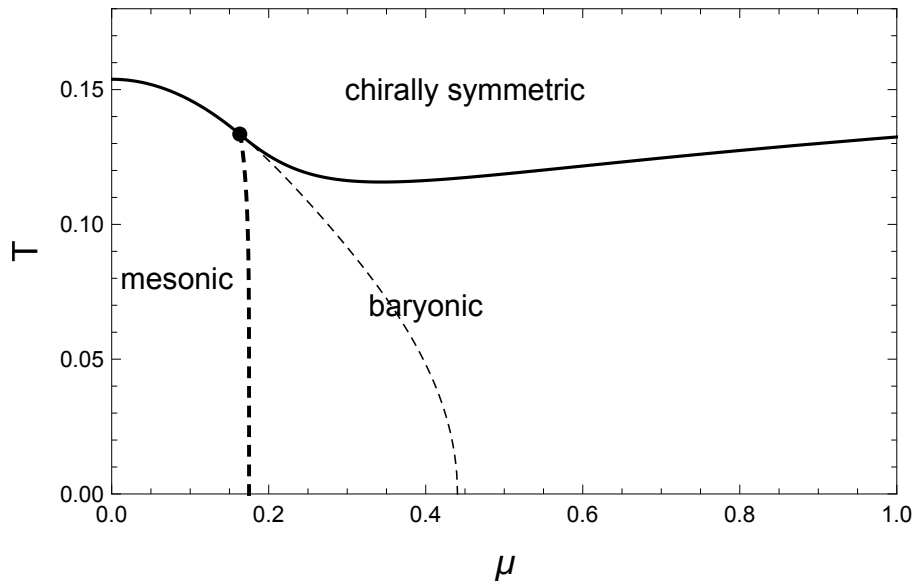


- first-order chiral phase transition

(dimensionless temperature $T \to TL$ and quark chemical potential $\mu \to 4\pi\lambda^{-1}L^2 M_{\rm KK}\mu$)

• Phase diagrams with holographic baryons (page 2/4)

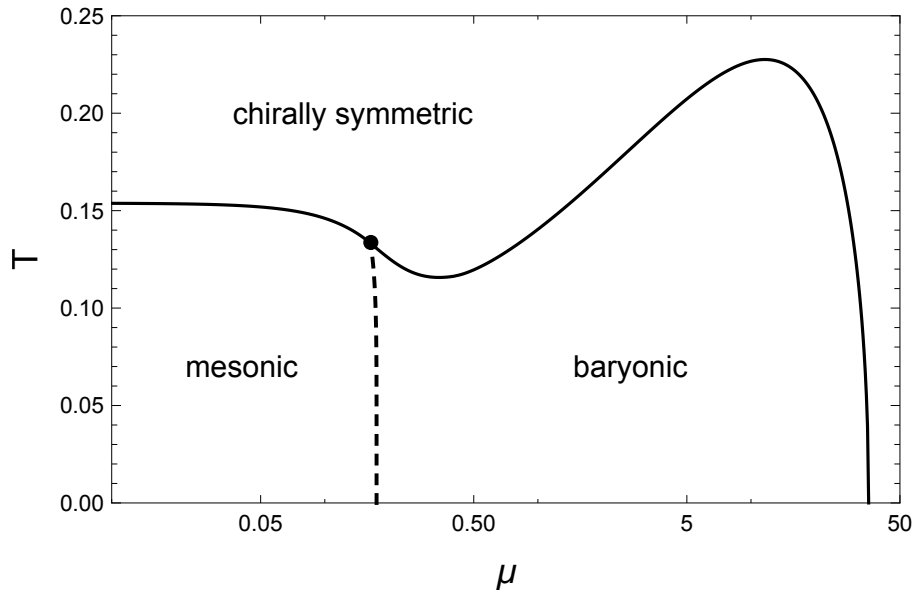
- pointlike approximation: delta function instead of instanton profile
  O. Bergman, G. Lifschytz, M. Lippert, JHEP 0711, 056 (2007)



- second-order baryon onset
- no chiral restoration of dense matter at small T

• Phase diagrams with holographic baryons (page 3/4)

- finite-size instantons with dynamically determined width ρ
  S.-w. Li, A. Schmitt, Q. Wang, PRD 92, 026006 (2015)

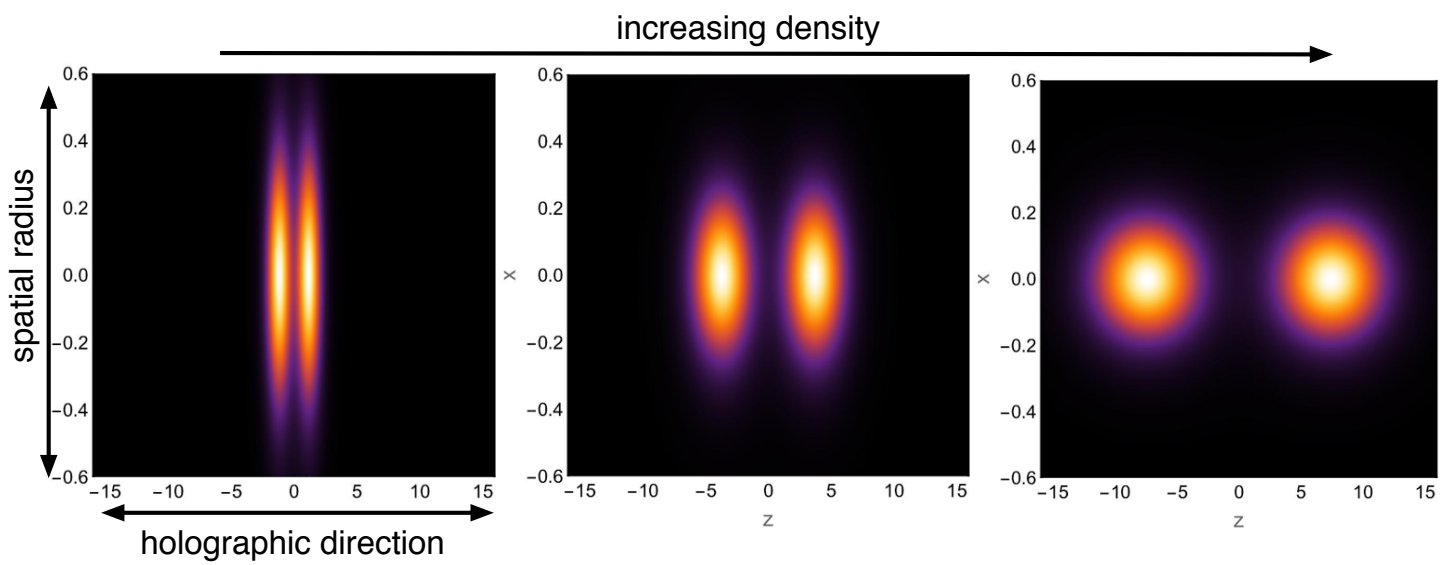


- second-order baryon onset
- chiral restoration of dense matter at (very!) large μ

• Further improving the instanton approximation

F. Preis, A. Schmitt, JHEP 1607, 001 (2016)

- include instanton deformation γ and dynamic distribution of layers
- motivated by vacuum results: constraints $\rho = \rho_0 u_c$, $\gamma = \gamma_0 u_c^{3/2}$



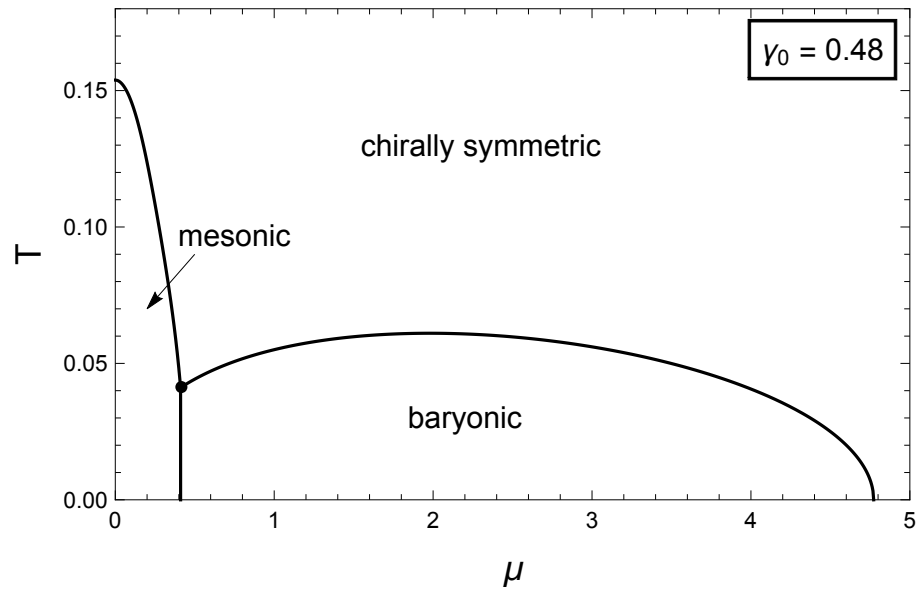
- agreement with complementary approximations

  "baryonic popcorn": V. Kaplunovsky, D. Melnikov, J. Sonnenschein, JHEP 1211, 047 (2012)

  M. Elliot-Ripley, P. Sutcliffe and M. Zamaklar, arXiv:1607.04832 [hep-th]

• Phase diagrams with holographic baryons (page 4/4)

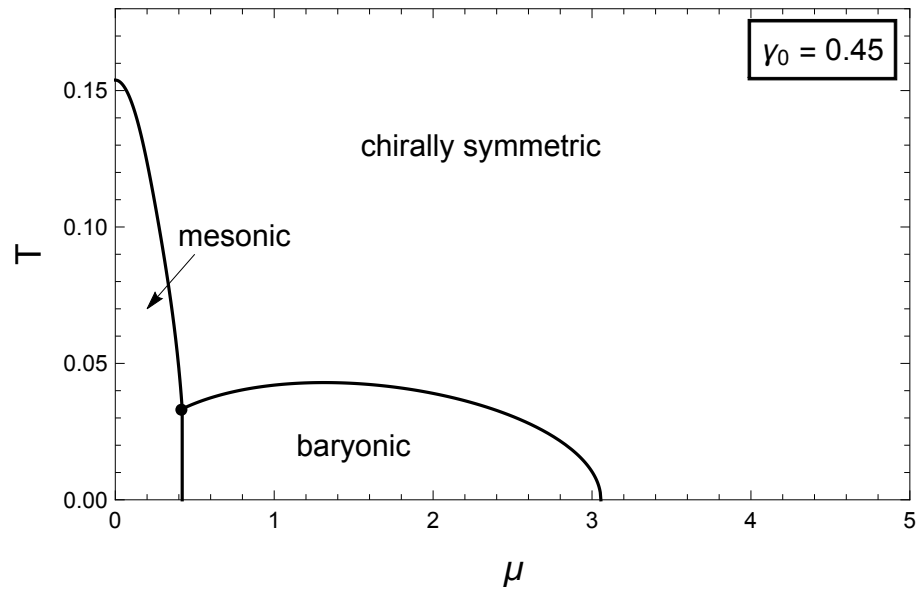
- deformed instanton layers
  F. Preis, A. Schmitt, JHEP 1607, 001 (2016)



- first-order baryon onset
- chiral restoration occurs, but very sensitive to ρ_0, γ_0,
  → improvements necessary

• Phase diagrams with holographic baryons (page 4/4)

- deformed instanton layers
  F. Preis, A. Schmitt, JHEP 1607, 001 (2016)



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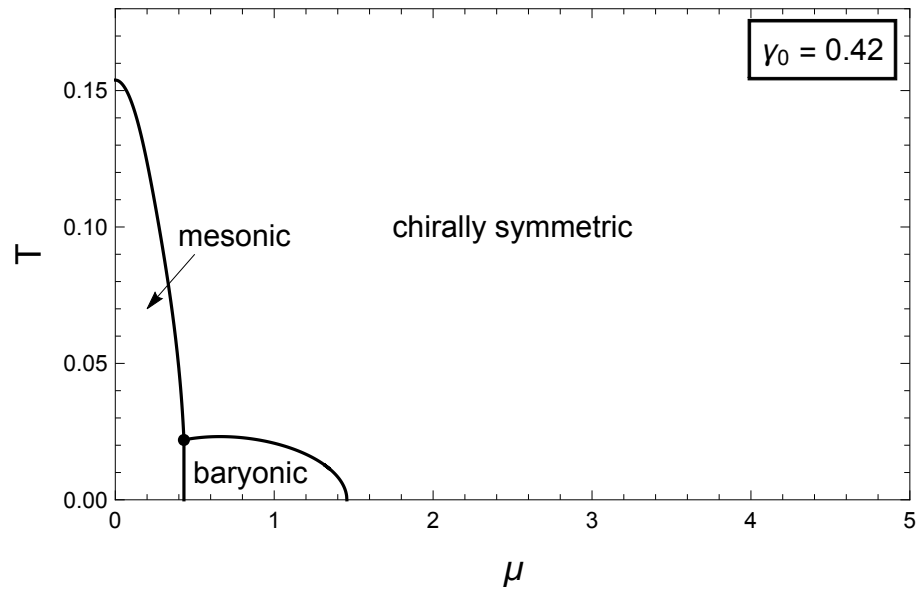

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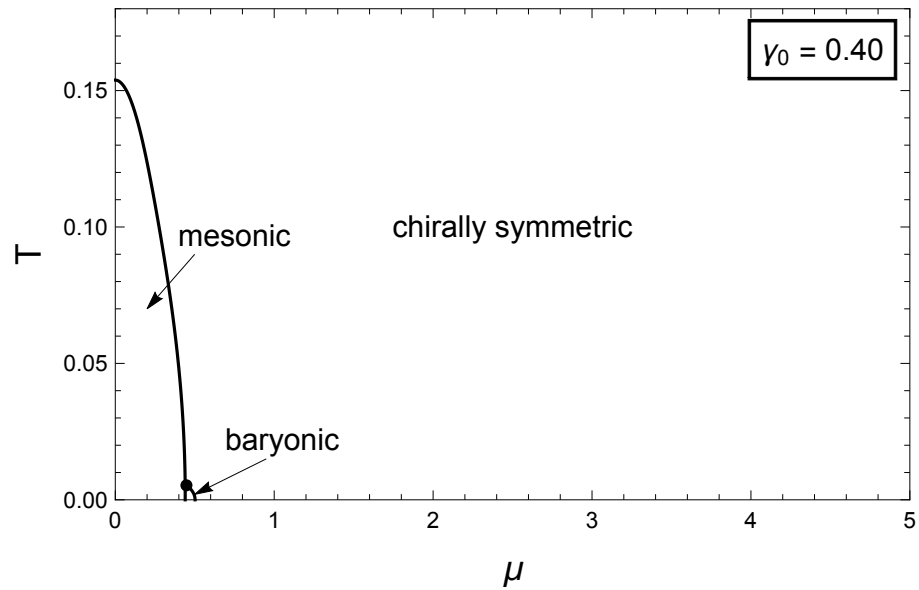

- first-order baryon onset
- chiral restoration occurs, but very sensitive to ρ_0, γ_0,
  → improvements necessary

- **Summary**

  - compact stars: need to understand nuclear *and* quark matter over fairly wide density regime
  - currently no first-principle calculations and very few/crude models that cover *both* phases
  - holography: useful because of strong coupling, however (more or less) different from QCD
  - Sakai-Sugimoto model (in the decompactified limit): nucleons as instantons in the bulk + quark matter + transition between them

• Outlook

- alternative, homogeneous ansatz (not based on instanton solutions)
  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, arXiv:1607.04832 [hep-th]

- improve approximation for instanton repulsion in position space
  A. Schmitt, F. Preis, work in progress

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

- goal: fit parameters to nuclear saturation properties,
  compute high-density EoS, mass/radius curve for hybrid stars