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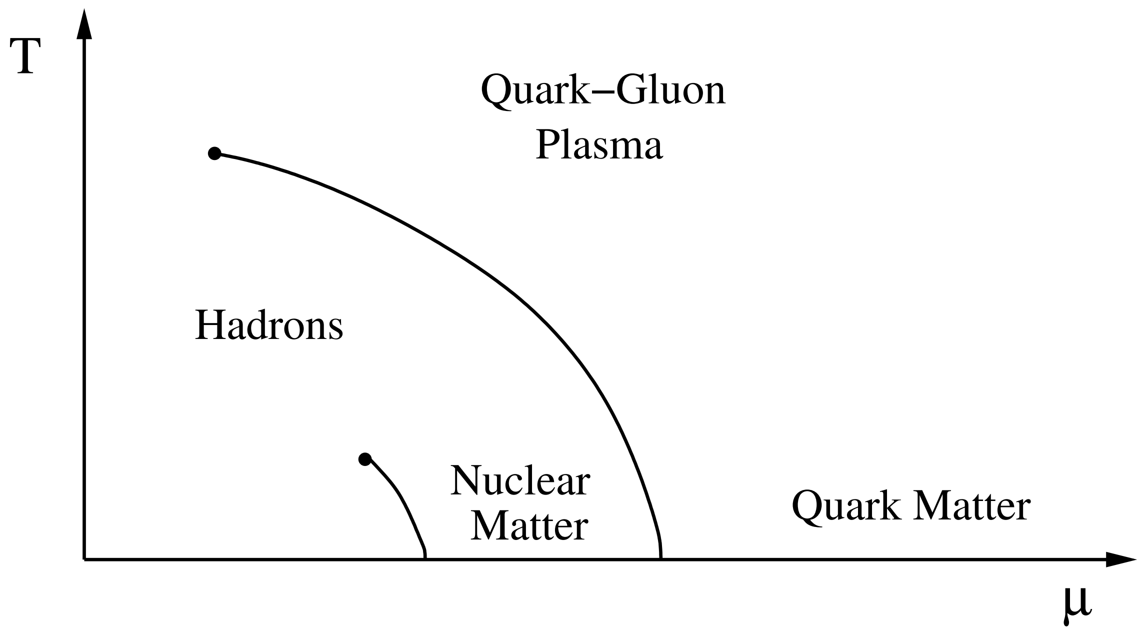
From holography towards real-world nuclear matter

Si-wen Li, Andreas Schmitt, Qun Wang, arXiv:1505.04886 [hep-ph]

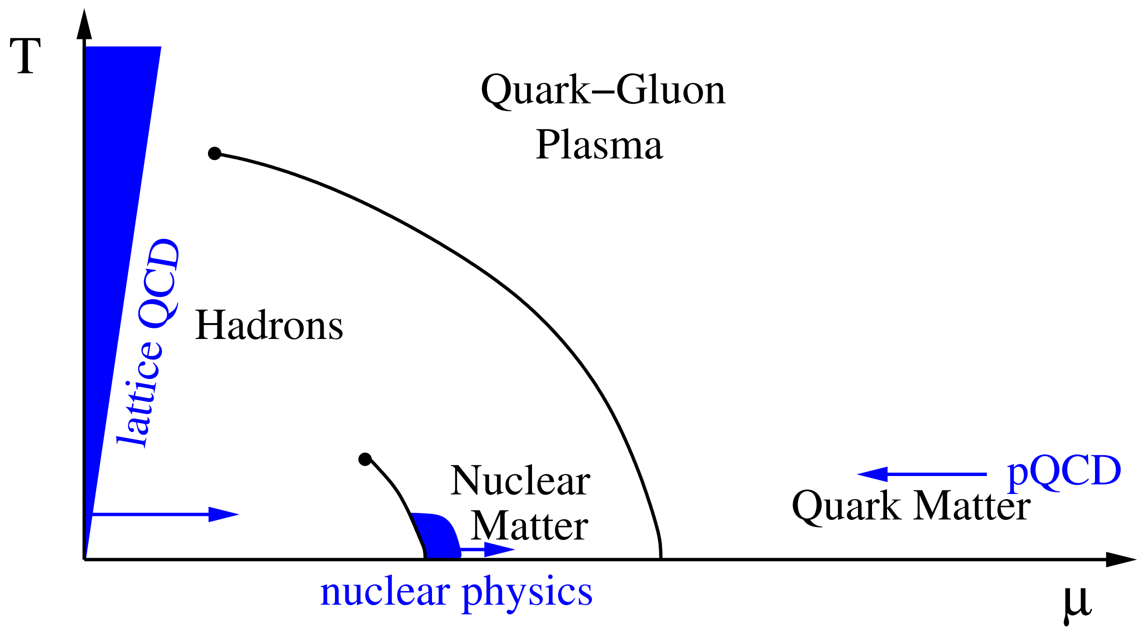
- dense QCD matter: theoretical challenges
- the Sakai-Sugimoto model:
  holography as close to QCD as currently possible
- realistic nuclear matter in the Sakai-Sugimoto model?

• Dense QCD matter: what we know



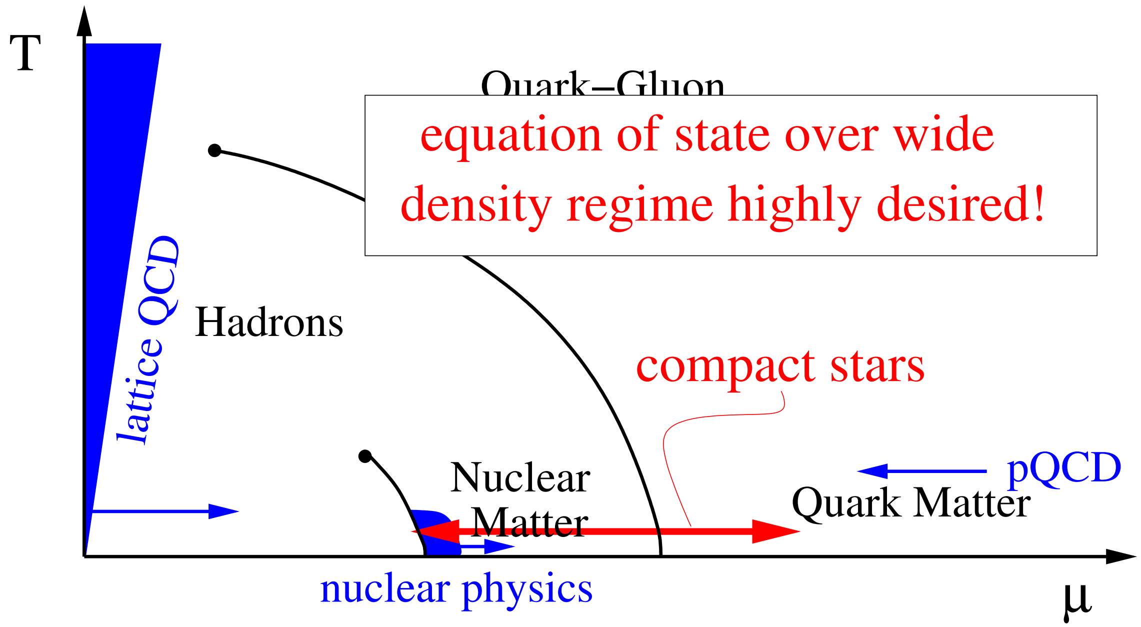
- first-order onset of nuclear matter at $\mu = 308\,\text{MeV}$
- weakly interacting quark matter at asymptotically large μ
- as a consequence: must be chiral/deconfinement transition in between (presumably in strongly coupled regime)

• Dense QCD matter: rigorous approaches



- 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: rigorous approaches



- QCD on the lattice: sign problem at nonzero μ, but recent progress
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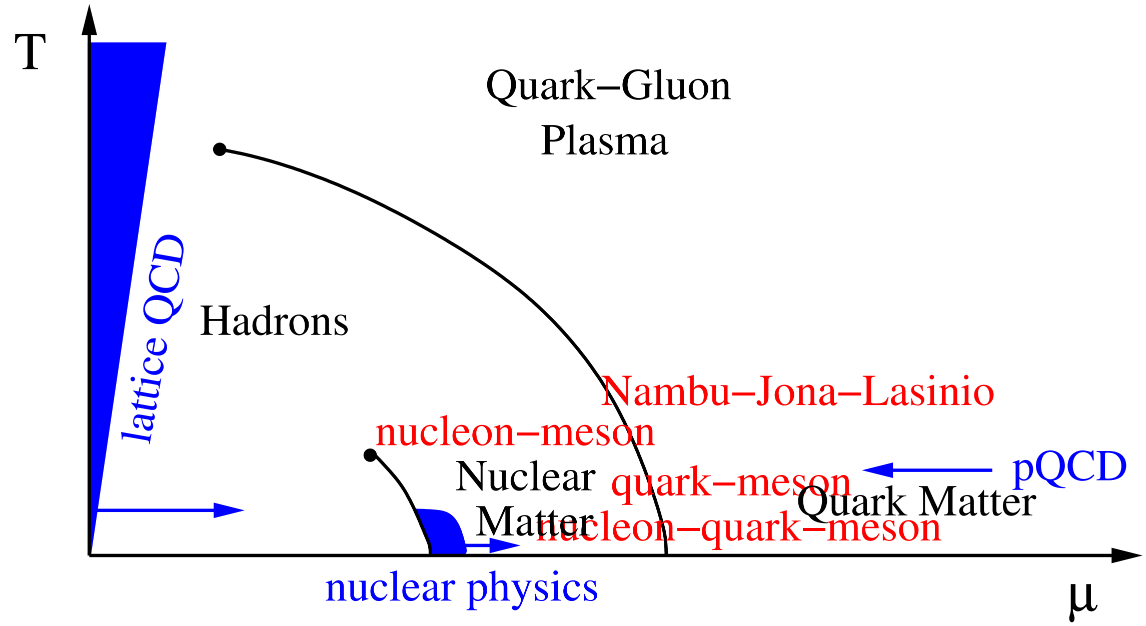
• Dense QCD matter: models



- 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 $\mathbb{R}^{3,1}$

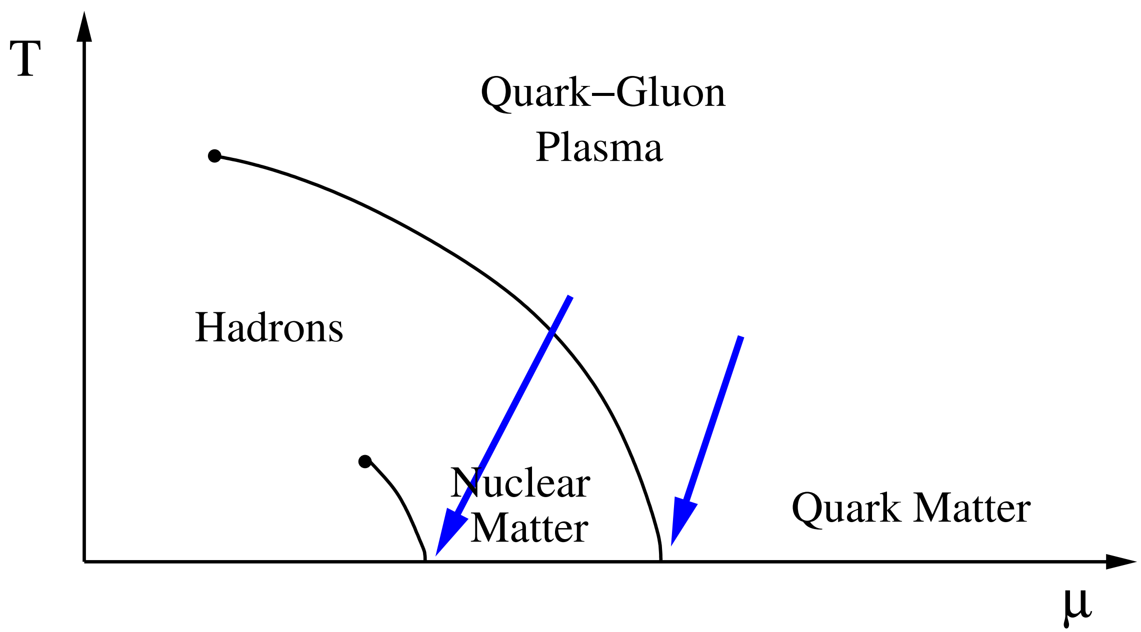
(super)gravity limit (*easy!*)	$\Leftrightarrow$	strong coupling limit (*difficult!*)

• Can holography help? (page 2/2)

- 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

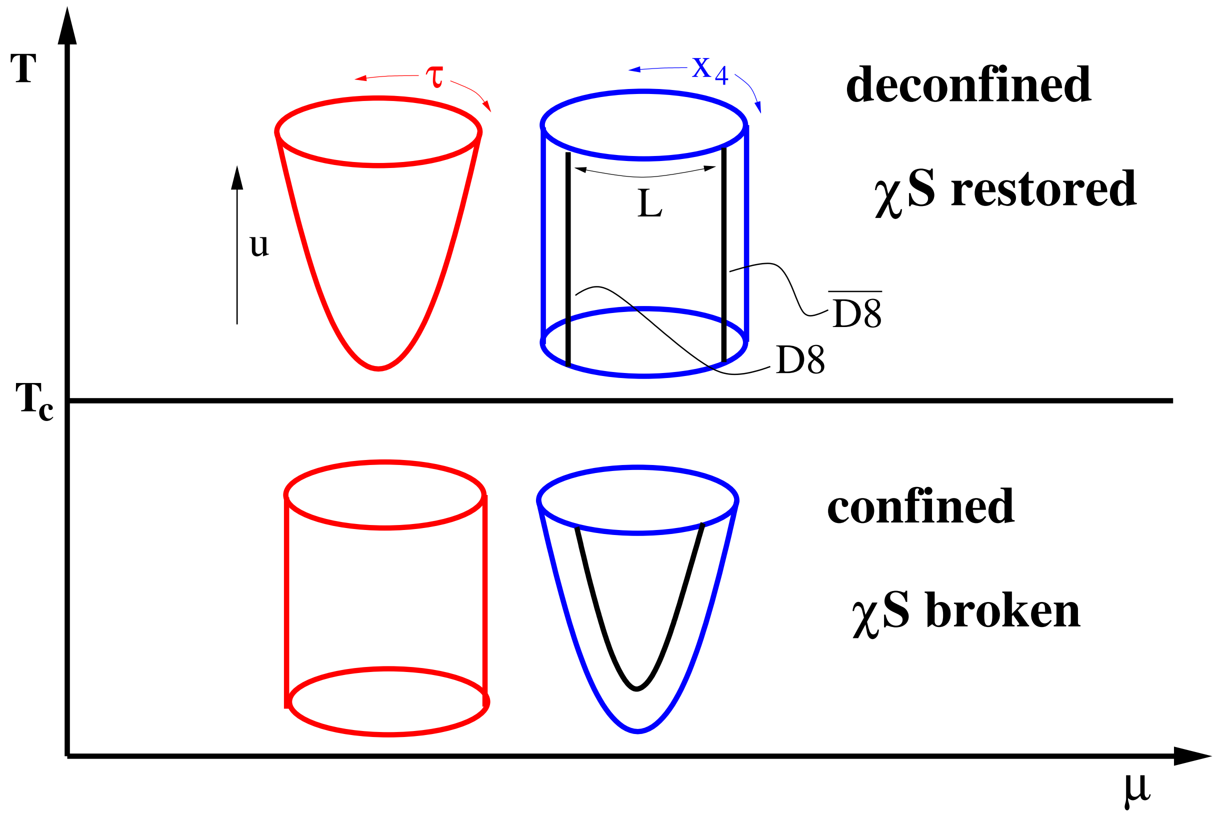
- **Goal**

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)



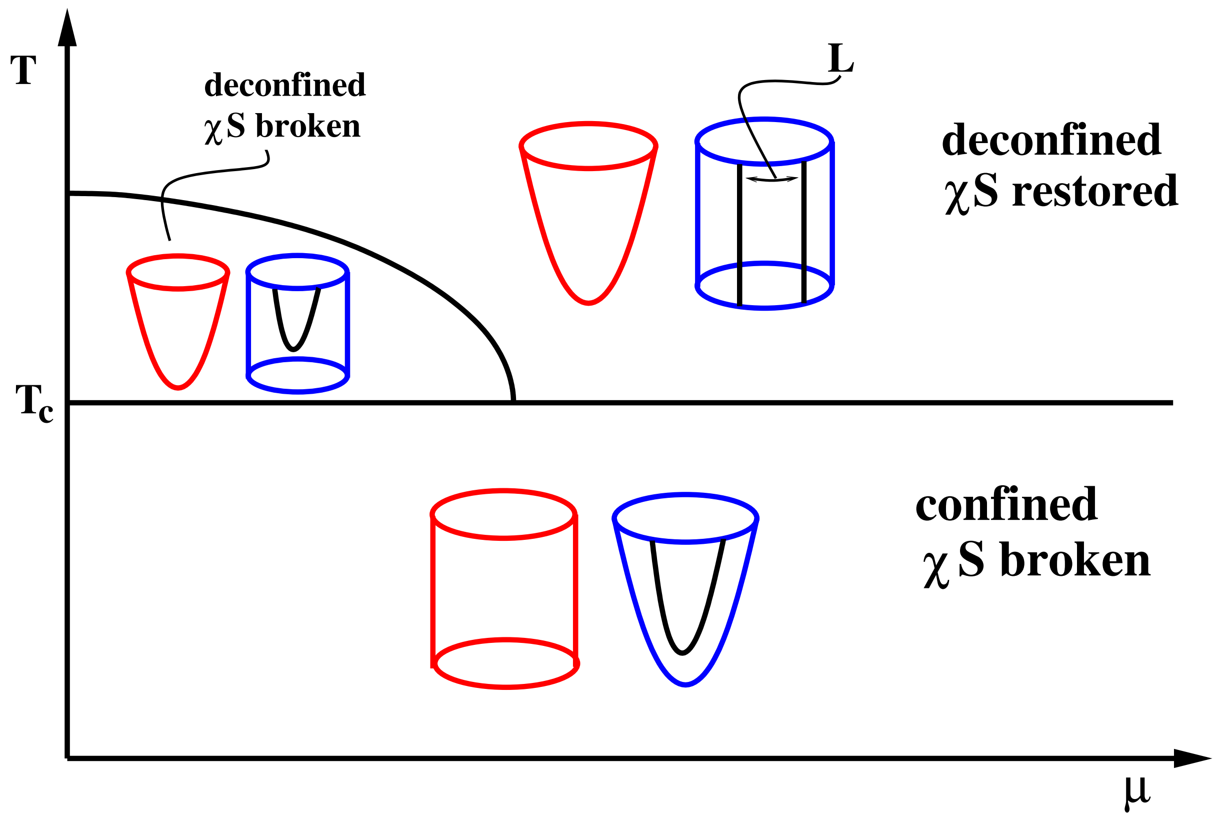
- in probe brane ("quenched") approximation: phase transition unaffected by quantities on flavor branes (μ, B, ...)
  beyond probe brane: F. Bigazzi, A. L. Cotrone, JHEP 1501, 104 (2015)
- not unlike expectation from large-N_c QCD

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

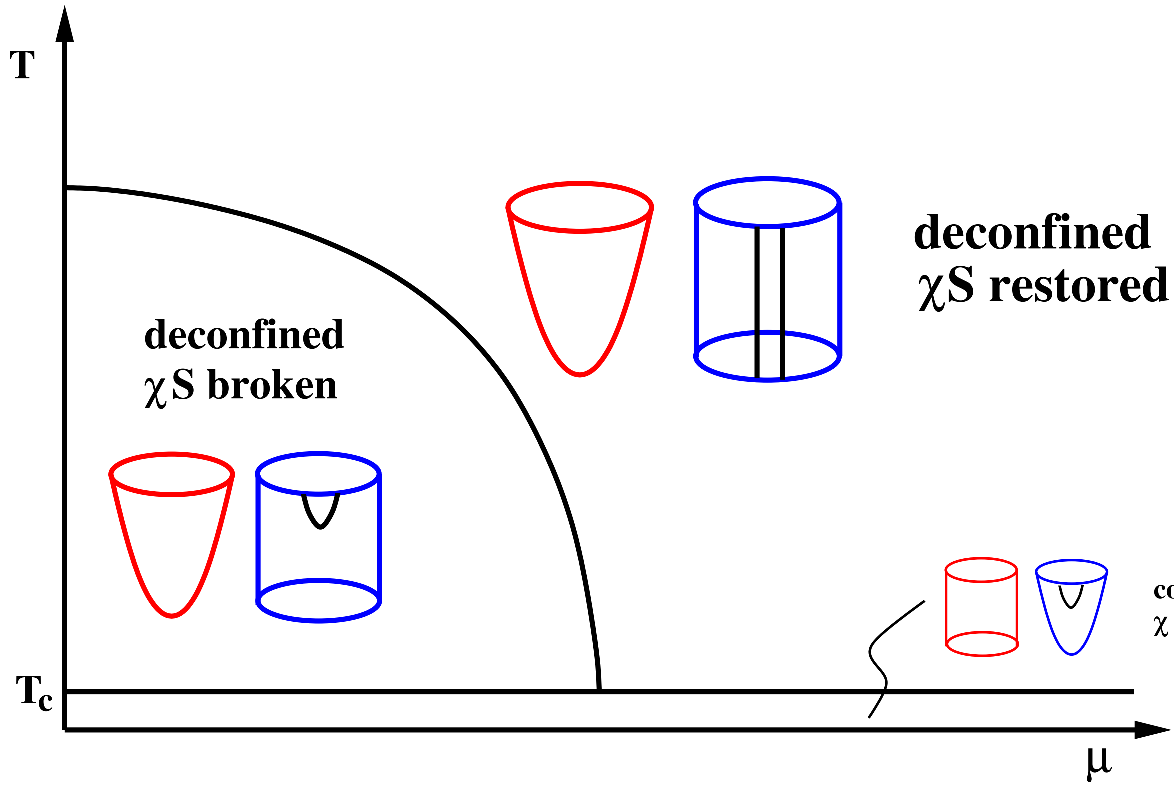
- less "rigid" behavior for smaller L
- deconfined, chirally broken phase for $L < 0.3\,\pi/M_{\rm KK}$

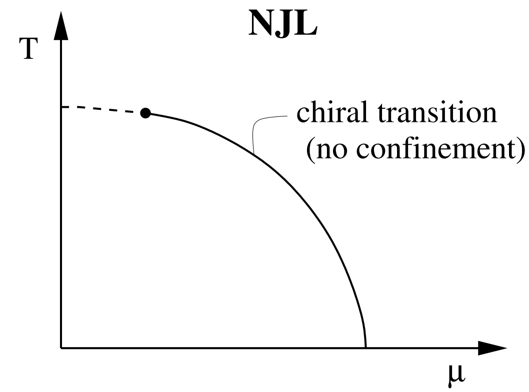
O. Aharony, J. Sonnenschein, S. Yankielowicz, Annals Phys. 322, 1420 (2007)

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

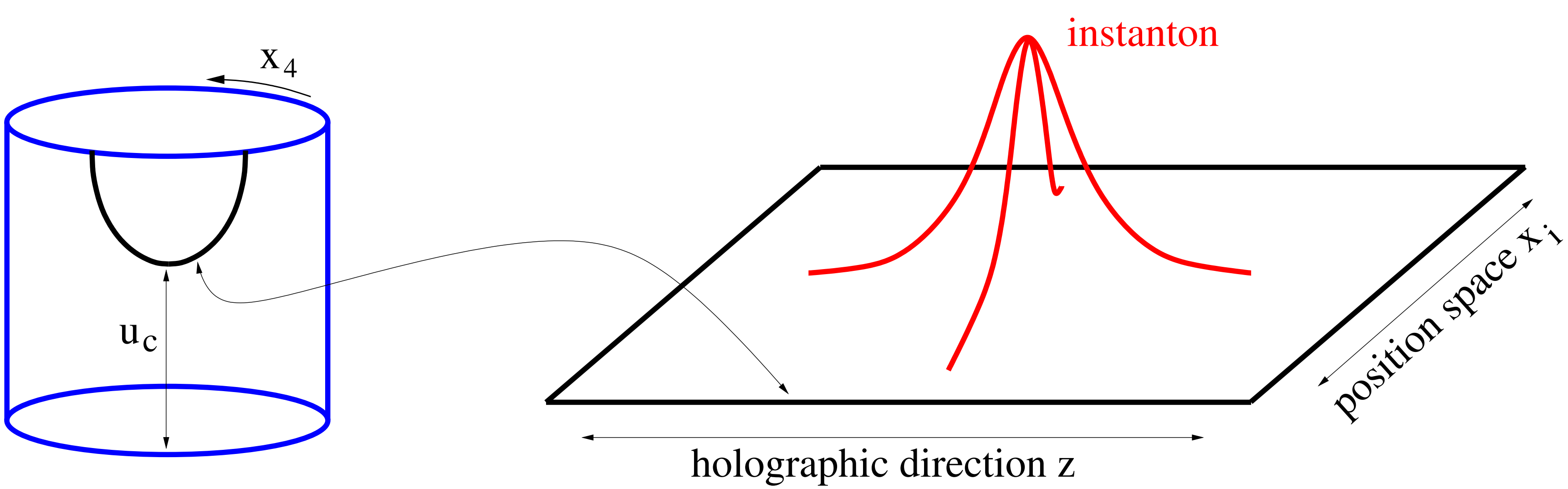
  J. L. Davis, M. Gutperle, P. Kraus, I. Sachs, JHEP 0710, 049 (2007)

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

• Baryons in Sakai-Sugimoto

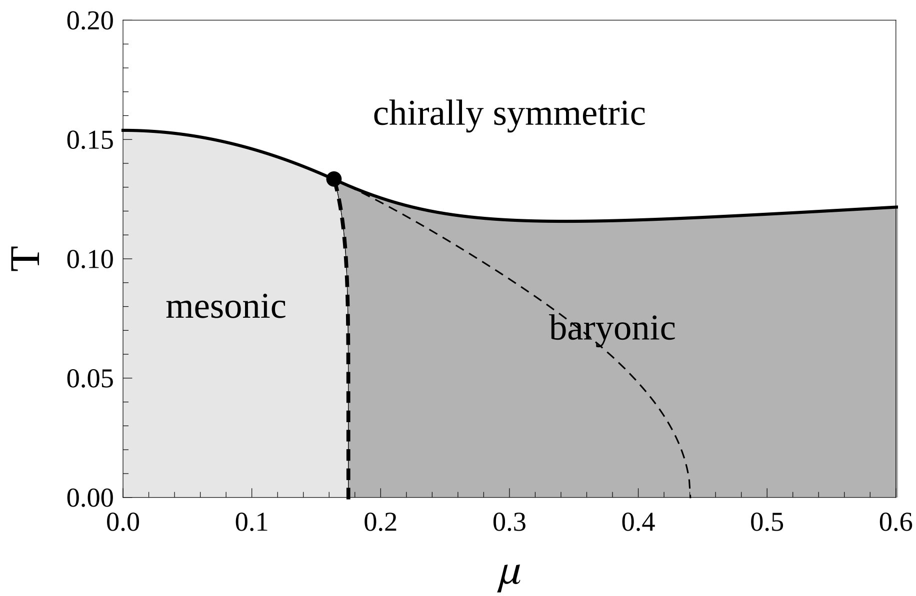
- baryons in AdS/CFT: wrapped D-branes with N_c string endpoints
  E. Witten, JHEP 9807, 006 (1998); D. J. Gross, H. Ooguri, PRD 58, 106002 (1998)
- baryons in Sakai-Sugimoto:
  – D4-branes wrapped on S^4
  – equivalently: instantons on D8-branes ($\rightarrow$ skyrmions)

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)



• Baryonic matter: pointlike approximation

O. Bergman, G. Lifschytz, M. Lippert, JHEP 0711, 056 (2007)



- second-order baryon onset
- no quark matter at small T

• Baryonic matter: beyond the pointlike approximation

Si-wen Li, Andreas Schmitt, Qun Wang, arXiv:1505.04886 [hep-ph]

1. Instanton gas approximation

   K. Ghoroku, K. Kubo, M. Tachibana, T. Taminato and F. Toyoda, PRD 87, 066006 (2013)

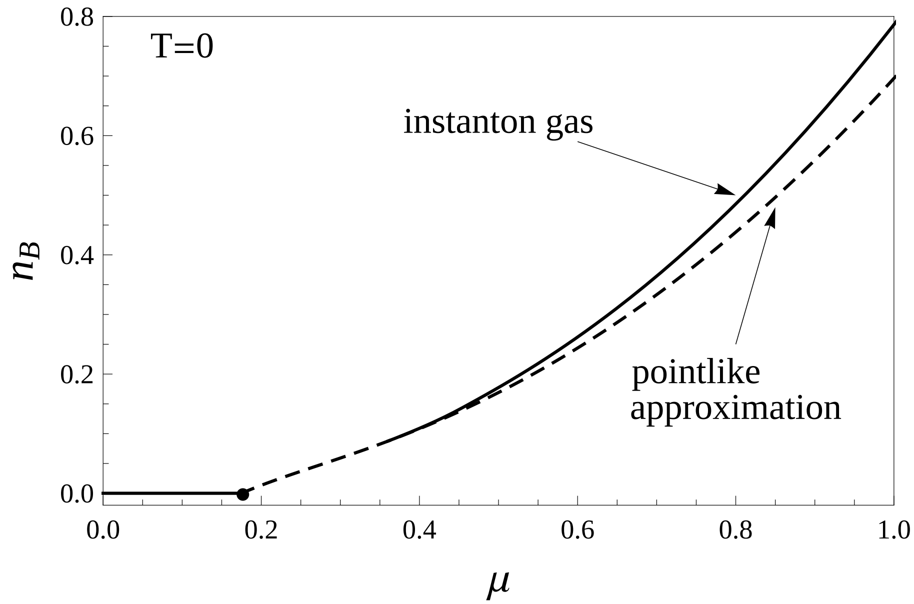
   - non-abelian gauge fields $A_z(\vec{x}, z)$, $A_i(\vec{x}, z)$ as flat-space instantons
   - average over space, place all instantons at tip of connected D8-branes
   - determine instanton width, density and location of tip dynamically

2. "Homogeneous ansatz"

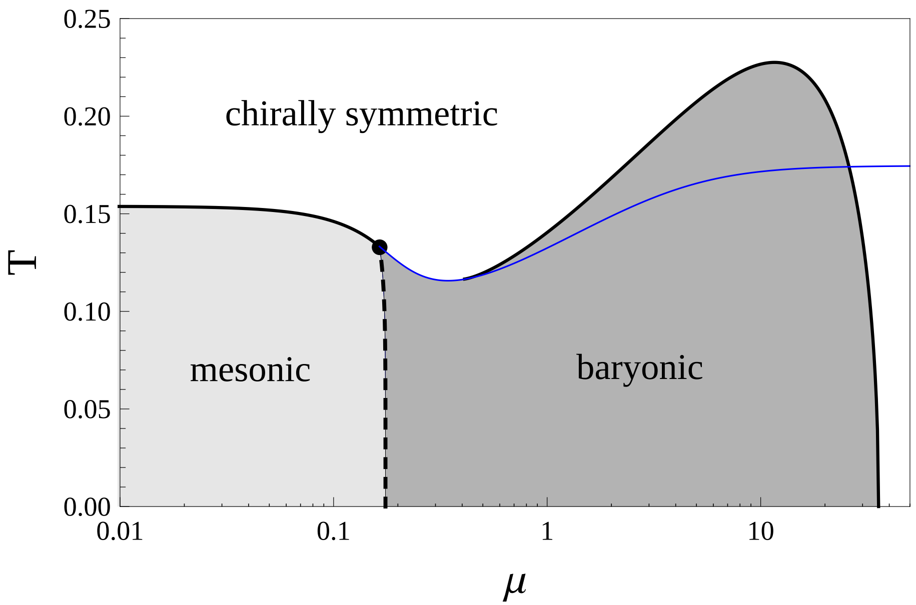
   M. Rozali, H. H. Shieh, M. Van Raamsdonk and J. Wu, JHEP 0801, 053 (2008)

   - start from homogeneous non-abelian gauge fields $A_z = 0$, $A_i(z) = -\sigma_i h(z)$
   - determine $h(z)$ dynamically

• Instanton gas approximation

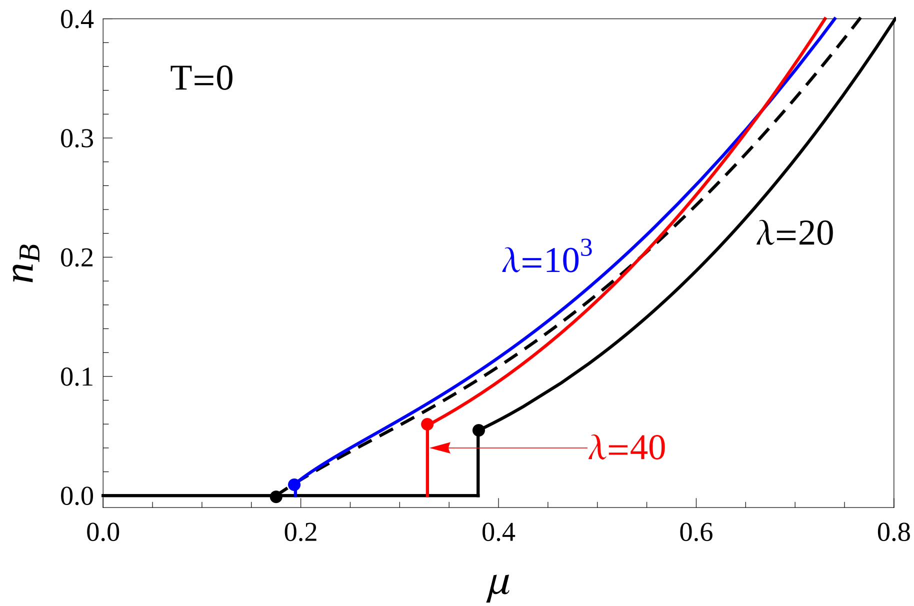


- pointlike approximation recovered for small n_B
- second-order baryon onset

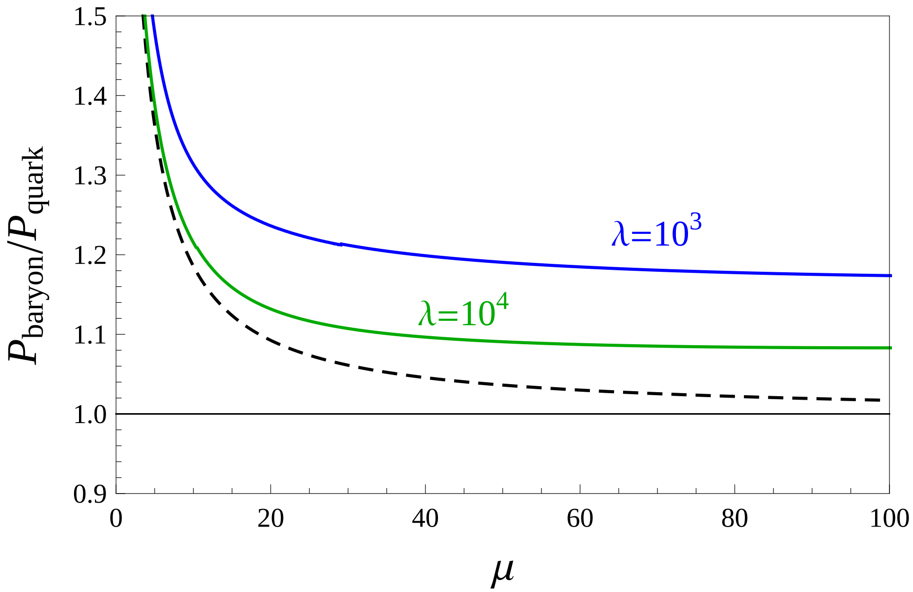


- (very) large μ: chiral restoration $\rightarrow$ quark matter

• Homogeneous ansatz (page 1/2)



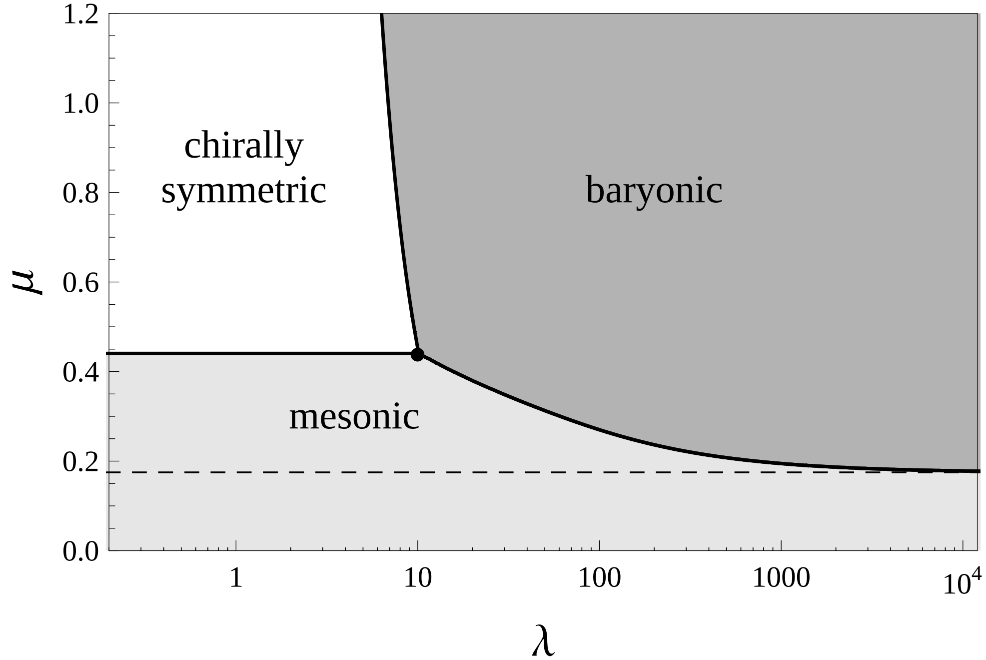
- first-order baryon onset
- pointlike approximation recovered for $\lambda \to \infty$



- no chiral restoration for any μ

• Homogeneous ansatz (page 2/2)

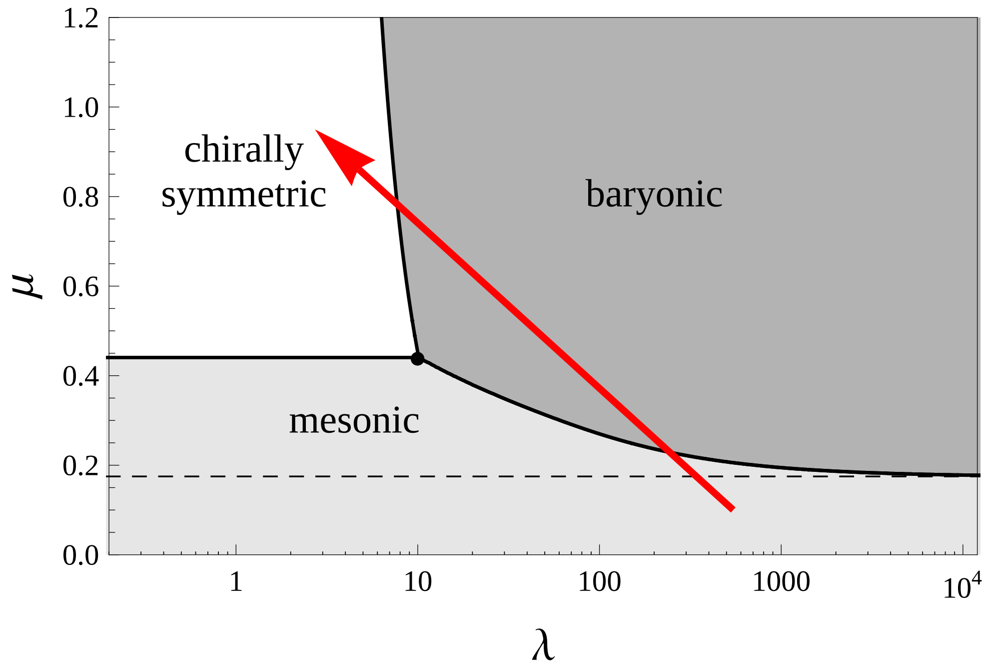
- phases in μ-λ plane at $T = 0$:



- large λ: baryon onset approaches pointlike approximation
- $\lambda \gtrsim 10$: vacuum $\to$ baryons
- $\lambda \lesssim 10$: vacuum $\to$ quark matter ($\to$ baryons)

• Homogeneous ansatz (page 2/2)

- phases in μ-λ plane at $T = 0$:



- large λ: baryon onset approaches pointlike approximation
- $\lambda \gtrsim 10$: vacuum $\rightarrow$ baryons
- $\lambda \lesssim 10$: vacuum $\rightarrow$ quark matter ($\rightarrow$ baryons)
- running coupling: vacuum $\rightarrow$ baryons $\rightarrow$ quark matter

• 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
- nuclear matter in Sakai-Sugimoto ("decompactified" limit):

	first-order baryon onset	chiral restoration
pointlike approximation	x	x
instanton gas	x	✓
homogeneous ansatz	✓	x

• Outlook

- improve on present results:
  - understand relation between instanton gas and homogeneous ansatz
  - instantons without $SO(4)$ symmetry (λ dependence!)
    vacuum: M. Rozali, J. B. Stang and M. van Raamsdonk, JHEP 1402, 044 (2014)
  - determine distribution of instantons in the bulk dynamically

- use (improved) results for phenomenology:
  - fit 3 parameters to nuclear saturation and compute equation of state
  - nuclear matter in a magnetic field
    pointlike: F. Preis, A. Rebhan, A. Schmitt, JPG 39, 054006 (2012)