Holographic quark hadron continuity

Farideh Kazemian
Shahrood University of Technology(SUT)

Kazem Bitaghsir Fadafan
(SUT)
Andreas Schmitt
(U. of Southampton)
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Shahrood University of Technology
HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
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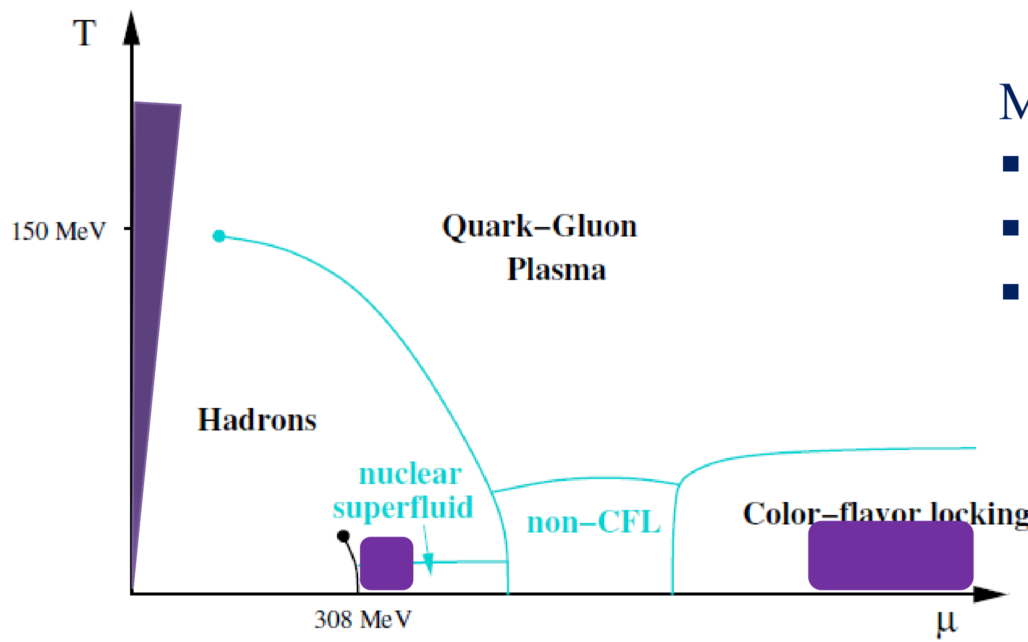
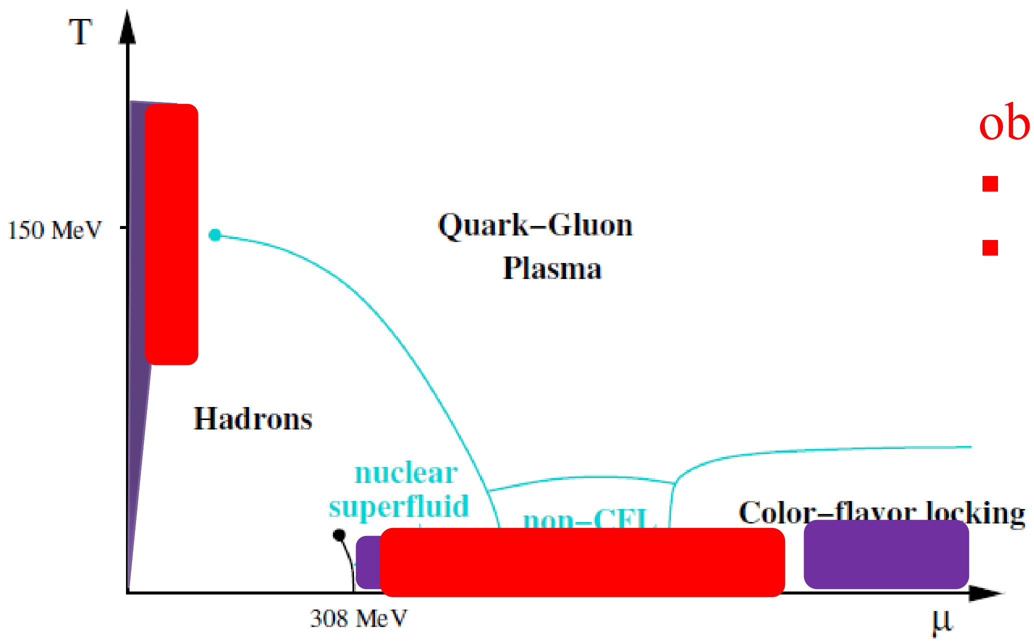
QCD at nonzero densities and temperatures



Method

- Pertubative QCD
- Lattice QCD
- Nuclear physics

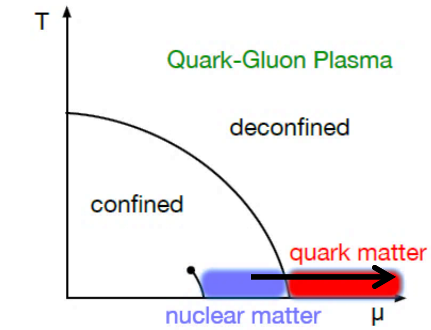
QCD at nonzero densities and temperatures

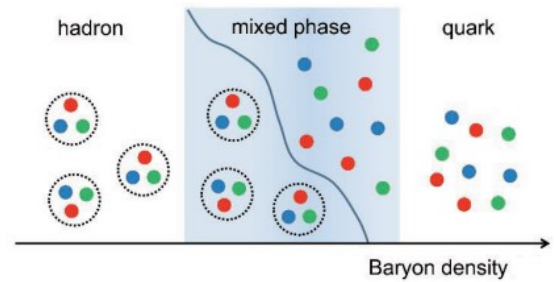


observations
- heavy-ion collisions
- Neutron star

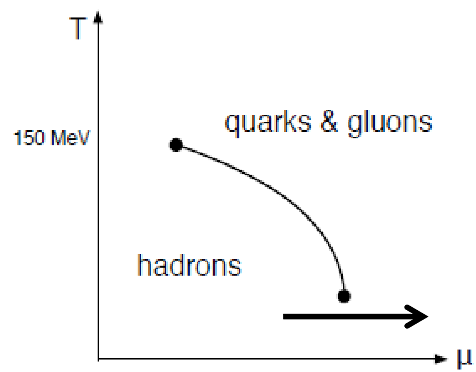
QCD phase diagram

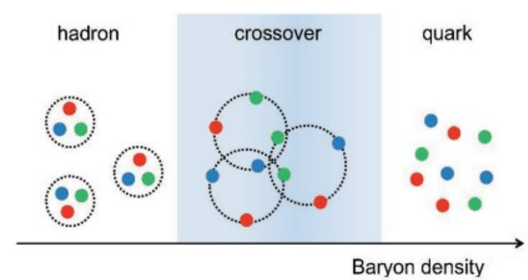
First order Phase transition





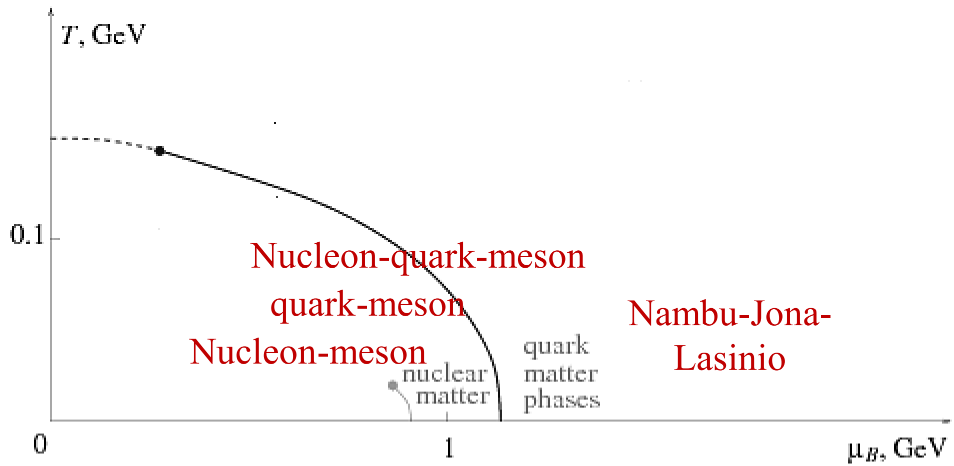
Crossover





K. Masuda, T. Hatsuda and T. Takatsuka, Eur. Phys. J. A 52 (2016) 65

Theoretical approaches



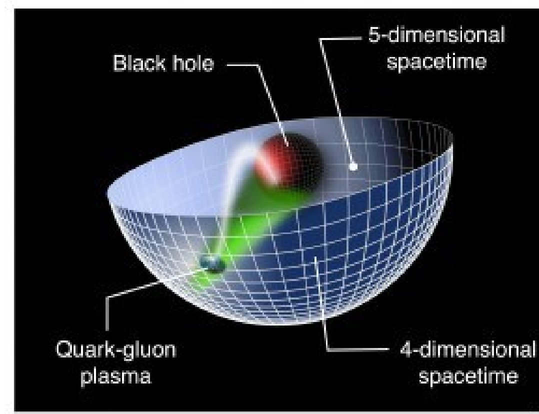
- Nambu-Jona-Lasinio (usually no nuclear matter)
- quark-meson (no nucleons), nucleon-meson (no quarks)
- nucleon-quark-meson (patched together, many parameters)

What is Holography?

- Holography refers to a duality between a string theory (in the bulk)and a field theory (on the boundary)

- Original example: Maldacena duality(conjecture):N = 4 SYM in3 + 1dim. is dual to type IIB strings on AdS5

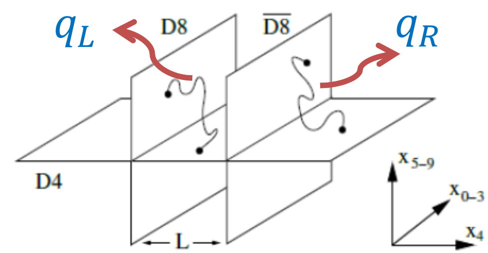
- Strong-weak coupling duality



Maldacena (1997), Gubser, Klebanov,Polyakov;Witten (1998)

Sakai-Sugimoto model of holographic QCD

- N_f D8-branes at $X_4 = 0$
  N_f D8-branes at X_4 = L,
- Global chiral symmetry visible
  as gauge theory on $D8\text{-}\overline{D8}$



Quark masses are neglected → Chiral symmetry exact

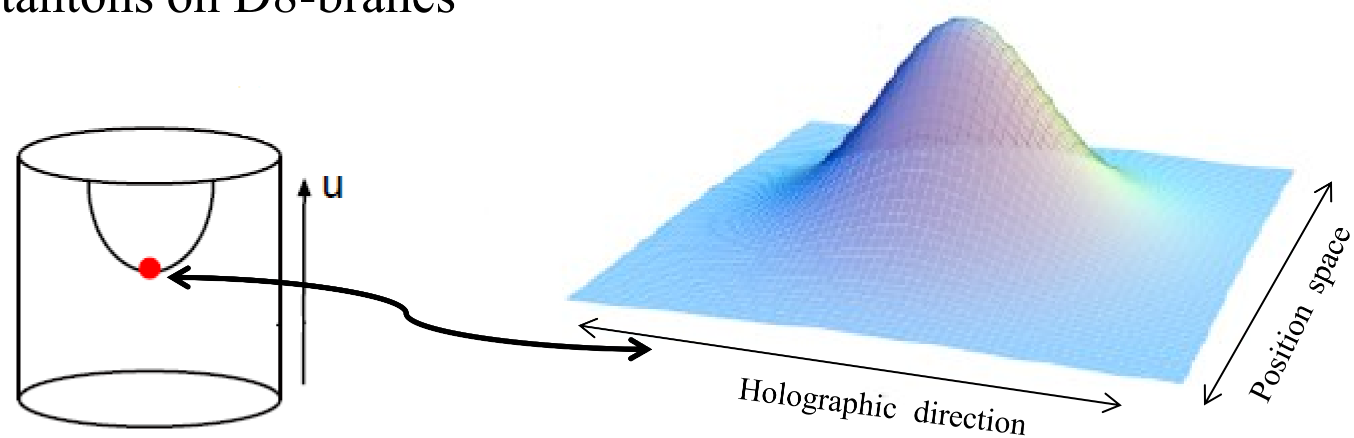
- Originally used for meson ,baryon ,glueball spectra
- Also employed for phase diagrams
- We can account for nuclear and quark matter in a single model
- Model only has a few parameters

E. Witten, Adv. Theor. Math. Phys. 2, 505 (1998)
T. Sakai and S. Sugimoto, Prog. Theor. Phys. 113, 843 (2005)

Baryon in Sakai-Sugimoto model

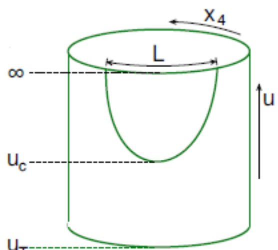
Baryons in Sakai-Sugimoto:

- D4-brane wrapped on S^4= instantons on D8-branes

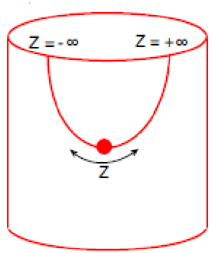


T. Sakai, S. Sugimoto, Prog. Theor. Phys. 113, 843-882 (2005)
H. Hata, T. Sakai, S. Sugimoto, S. Yamato, Prog. Theor. Phys. 117, 1157 (2007)

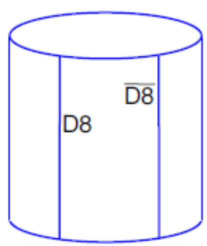
Phases



chirally broken
"mesonic phase"



chirally broken
"nuclear matter"



chirally symmetric
"quark matter"

- Insert instanton ansatz for non-abelian $SU(2)$ part into DBI+CS action

$$S = \underbrace{T_8 V_4 \int_{x^\mu} \int_z e^{-\varphi} \sqrt{\det(g + 2\pi \acute{\alpha} F)}}_{DBI} + \underbrace{\frac{N_c}{8\pi^2} \int_{x^\mu} \int_z \widehat{A_0}\, Tr[F_{ij}\ F_{kz}]\epsilon_{ijk}}_{CS}$$

$$F_{\mu\nu} = \widehat{F_{\mu\nu}} + F_{\mu\nu}{}^{a} \sigma_a \qquad N_f = 2$$

abelian ← → Non-abelian

- Solve EOMs for abelian $U(1)$ gauge field and embedding $x_4(u)$
- Minimize free energy wrt u_c ,parameters of ansatz etc
- Compare free energies of all three phases for all μ and T

Interaction from two-instanton solution

- construct N-instanton system from 2-instanton solution
  - define interaction energy

$$I^2_{(1,2)} = \mathcal{F}^2_{(1,2)} - F^2_{(1)} - F^2_{(2)}$$

  - approximation for N-instanton field strength

$$\mathcal{F}^2 = \sum_{n}^{N} F^2_{(n)} + \frac{1}{2}\sum_{n}^{N}\sum_{m\neq n}^{N} I_{n,m}$$

Single instanton

$$F_{(n)}{}^2 \sim \frac{\rho^4}{\left((\vec{x}-\overrightarrow{x_n})^2+\frac{z^2}{\gamma^2}+\frac{\rho^2}{\gamma^2}\right)^4}$$

deformation instanton

Width instanton

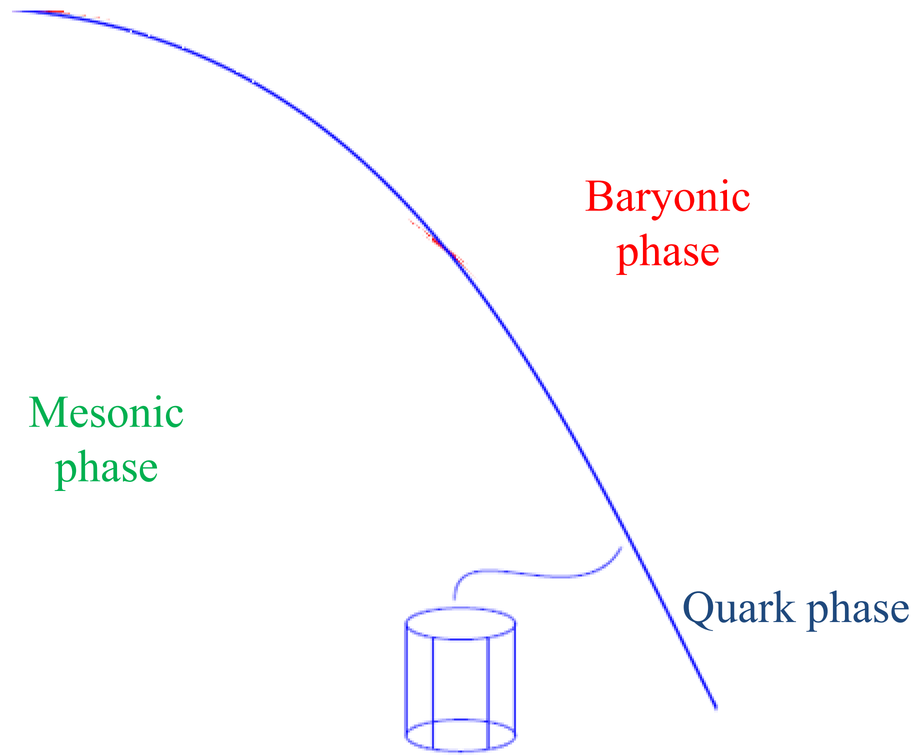
$\mathcal{F}^2_{(1,2)}$ =2-body interaction from exact 2 instanton

Solution in flat space: (ADHM)

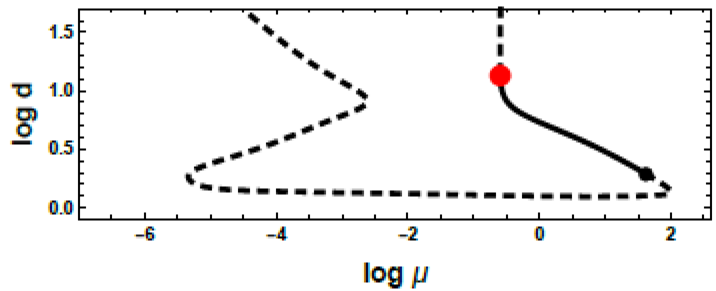
M. F. Atiyah, N. J. Hitchin,
V. G. Drinfeld and Y. I. Manin, PLA 65, 185 (1978)

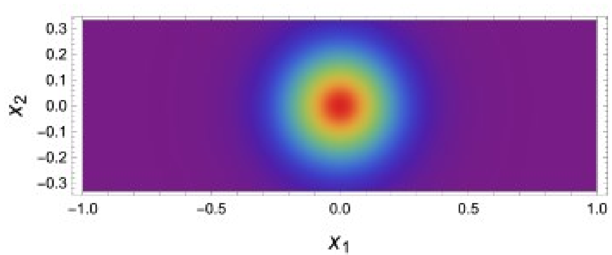
- employ nearest-neighbor approximation

Main result

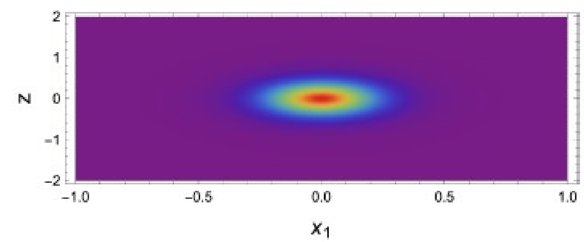


Instanton profile



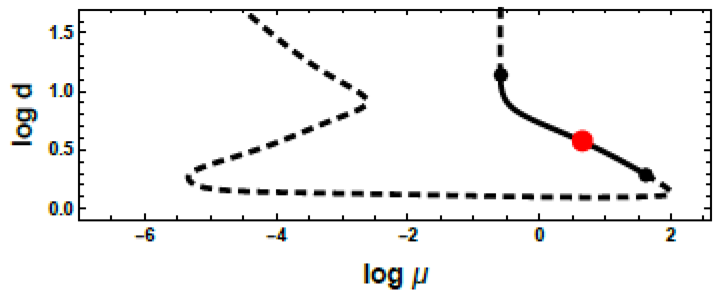


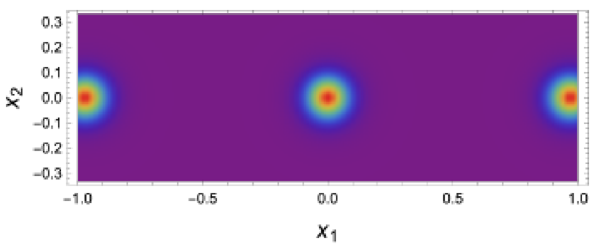
Cubic instanton lattice



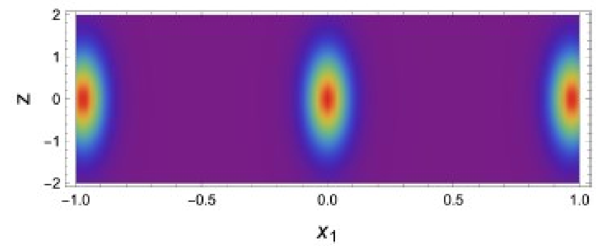
Deformation from $so(4)$

Instanton profile



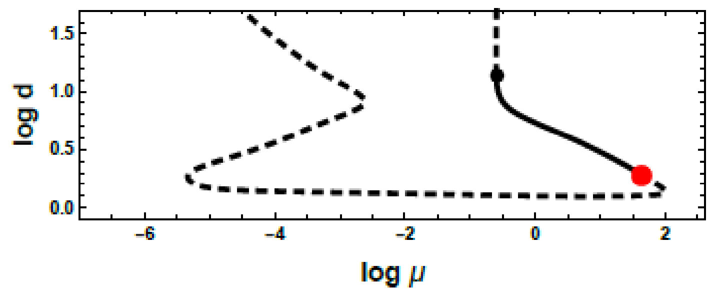


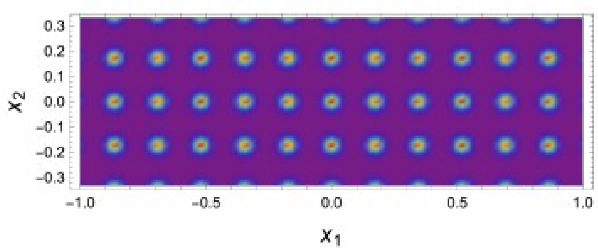
Cubic instanton lattice



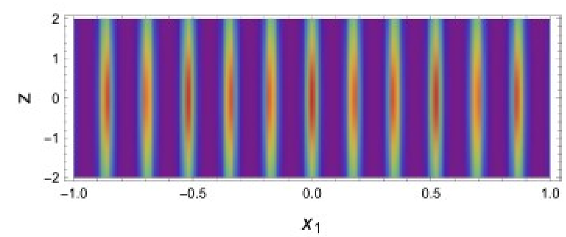
Deformation from $so(4)$

Instanton profile





Cubic instanton lattice



Deformation from $so(4)$

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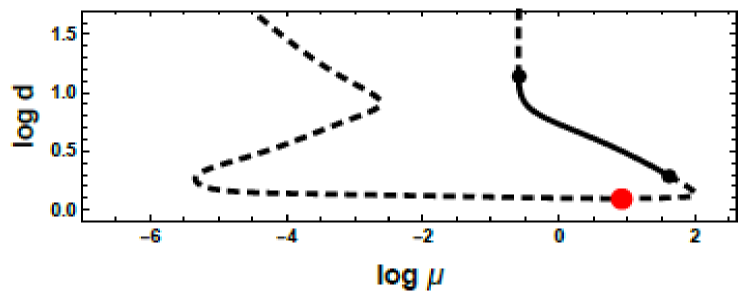
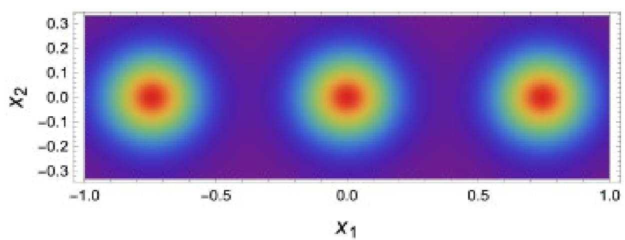
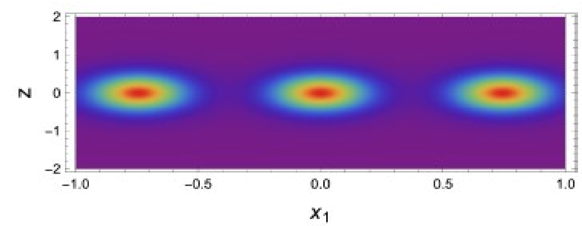


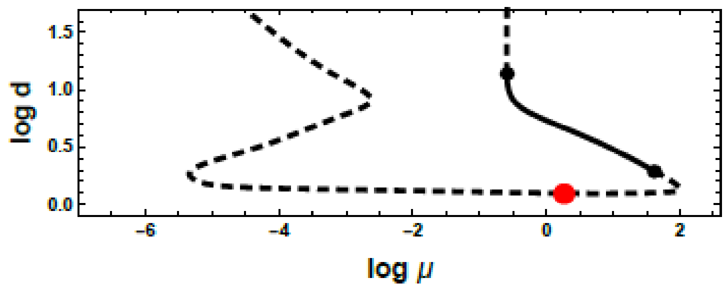


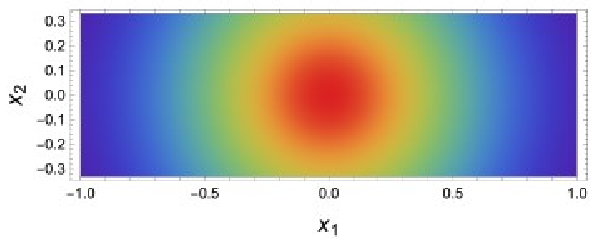
Cubic instanton lattice



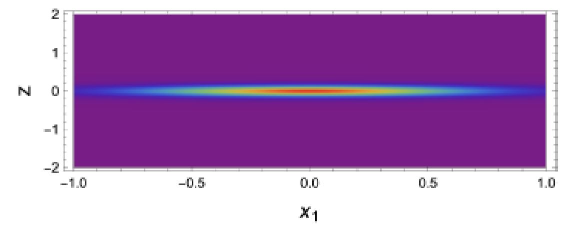
Deformation from $so(4)$

Instanton profile





Cubic instanton lattice

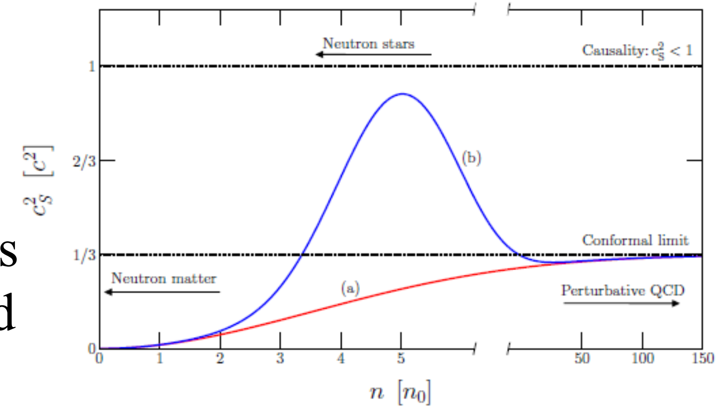


Deformation from $so(4)$

Speed of sound

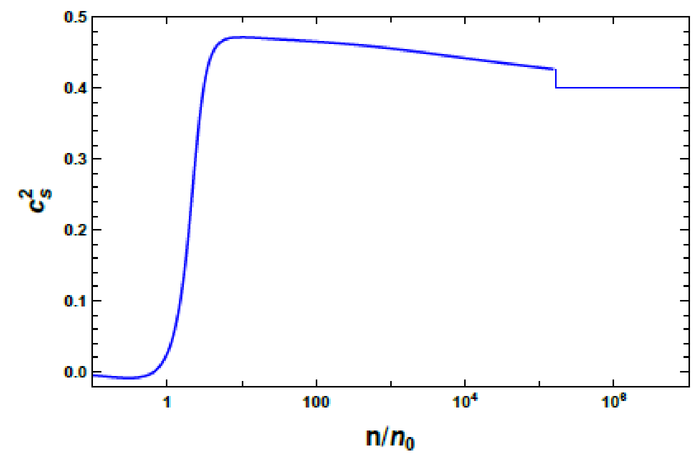
Two scenarios:

a: obey conformal limit for all densities
b: QCD violating this conformal bound



schematic plot from I. Tews et al., Astrophys. J. 860, 149 (2018)

Our model



- Fit Sakai-Sugimoto parameters to low-density nuclear matter
- Non monotonic speed of sound

Summary

1) Chirally broken and chirally symmetric phases in Sakai -Sugimoto model can be continuously connected (in previous studies just included instantons only in the confined geometry or did not include interaction between them)
2) Instanton become infinitesimally thin in holographic direction but spread out to become infinitely wide in spatial direction

3) Parameters of the model can be fitted to reproduce properties of nuclear matter at saturation
4) Non-monotonic behavior of speed of sound in nuclear matter

Out look

1) Include nonzero quark masses

2) Non zero temperature and/or magnetic field

3) Equation of state ⟷ Neutron star mass/radius

Thank you