Holographic quark hadron continuity

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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

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 in $3 + 1$ dim. 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 $D8$-$\overline{D8}$

Quark masses are neglected  \[ \text{Chiral symmetry exact} \]

- 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

Baryon in Sakai-Sugimoto model

Baryons in Sakai-Sugimoto:

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

Phases

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

\[ S = T_8 V_4 \int_{x^\mu} \int_{z} e^{-\varphi} \sqrt{\det(g + 2\pi\alpha' F)} + \frac{N_c}{8\pi^2} \int_{x^\mu} \int_{z} \bar{A}_0 \text{Tr}[F_{ij} F_{kz}] \epsilon_{ijk} \]

\[ F_{\mu\nu} = \widehat{F}_{\mu\nu} + F_{\mu\nu}^a \sigma_a \quad N_f = 2 \]

- 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 $\mu$ and $T$
Interaction from two-instanton solution

- construct N-instanton system from 2-instanton solution
  - define interaction energy
    \[ I_{(1,2)}^2 = \mathcal{F}^2_{(1,2)} - F^2_{(1)} - F^2_{(2)} \]
  - approximation for N-instanton field strength
    \[ \mathcal{F}^2 = \sum_{n}^{N} F^2_{(n)} + \frac{1}{2} \sum_{n}^{N} \sum_{m \neq n} I_{n,m} \]

Single instanton
\[ F(n)^2 \sim \frac{\rho^4}{((x - x_n)^2 + \frac{z^2}{\gamma^2} + \frac{\rho^2}{\gamma^2})^4} \]

- employ nearest-neighbor approximation

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

Solution in flat space: (ADHM)
M. F. Atiyah, N. J. Hitchin, V. G. Drinfeld and Y. I. Manin, PLA 65, 185 (1978)
Main result

Mesonic phase

Baryonic phase

Quark phase
Instanton profile

Cubic instanton lattice

Deformation from $so(4)$
Instanton profile

Cubic instanton lattice

Deformation from $so(4)$
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Deformation from $so(4)$
Instanton profile

Cubic instanton lattice

Deformation from $\text{so}(4)$
Instanton profile

Cubic instanton lattice

Deformation from $\mathfrak{so}(4)$
Speed of sound

Two scenarios:

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


- 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 $\leftrightarrow$ Neutron star mass/radius
Thank you