Towards a holographic realization of the quarkyonic phase

1209.5915 [hep-th] with J. de Boer, B. Chowdhury & J. Jankowski

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Introduction

Motivation

Two current holographic trends: non-equilibrium processes \vert and AdS/CMT $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ $|_{\lambda \to \infty}$

None of them addresses directly one of the biggest challenges in QCD:

Why not apply holographic techniques there (AdS/CMT of holographic QCD)?

interacting quarks and gluons does not become valid until much higher temperatures. Recent ter**a.** Scaren for the Holographic quarkyonic phase, conjectured within i Idea: search for the holographic quarkyonic phase, conjectured within large-N_c QCD.

COMPOSED SERVICES (19706.2191 [hep-ph] McLerran & Pisarski loops. No Debye screening of the confining gluon propagator. Confinement in a Large-N. OCD Instead - Quarkyonic phase . One cannot phase . One cannot excite independent quarks - only colored a second c sider parametrically large-of order order O OCD and the quarkyonic ph the large rescaled density of charge which was really a really to tachyonic behavior at nonzero momenta: although bðz~Þ Large-N_c QCD and the quarkyonic phase

consequences:

- at lower densities, momentum-carrying instabilities of the Fermi surface: ϵ

 $\langle \bar{\psi} \exp(2i\mu x_3 \gamma_0 \gamma_3) \psi \rangle$ $p¹$ Koio et al have been die parity of the parity of the parity of the search of the search of the search of the search of th
In provincial searching for the searching for the searching for the searching searching for the searching searc 0912.3800 [hep-ph] Kojo et al.

is clearly different from the problem (not dual to a massless DBI field!)

0803.3547 [hep-ph] Aharony & Kutasov this complete the search for marginal stable modes the search for marginal $\frac{1}{2}$

- ubus.354/ [ne]
and a research restarction due to Pauli $\sum_{i=1}^n$ our case. The discussed feature was not taken in the discussed feature was not taken in the discussed feature $\sum_{i=1}^n a_i$ - at higher densities*, chiral symmetry restoration due to Pauli blocking
- it is not entirely inconcerned that the modulation inconcerned that the modulation in the modul - excitation form then chiral multiplets (disputed)

the quarkyonic phase. We will consider \sim 0709.3080 [hep-pl lozman & Wagenhrunn configuration R regards and the invariance in the invarian 0709.3080 [hep-ph] Glozman & Wagenbrunn

2/22 \angle i \angle All this is based on qualitative large- N_c arguments and model studies. Two questions:

- is it all relevant for $N_c = 3$, $N_f = 3$?
- is there a top-down realization of the quarkyonic phase (e.g. in holography)?

Why is it interesting holographically?

Existing holographic dictionary ("AdS"/"CFT"):

So far, the only known way to restore the chiral symmetry is to deconfine. Holographic, chirally-symmetric quarkyonic phase requires new ingredients!

4/22 Also, hQCD at finite μ_B is interesting from the point of view of AdS/CMT!

hQCD: vacuum

Holographic QCD model [hep-th/0412141] Sakai joining of the two is taken to mean the breaking of chiral symmetry.

The microscopics is that of the D4-D8 system. left (right) handed quarks are open strings between *D*8(*D*8) and *D*4 and are thus bifundamentals under \mathcal{L}

*ds*2*/R*² = *u* 70) = *gsu* 3 $\sqrt{2}$ (hep-th/04121411) **Thep-th/0412141]**
 [hep-th/0507073]
 Example: left (right) handed quarks are open strings between D8(D8) and D4 and are thus bifundamentals under

Combining geometry is generated by N_c D4's:

\n
$$
3x_4
$$
\n
$$
ds^2/R_4^2 = u^{\frac{3}{2}}(-d\tau^2 + d\vec{x}^2 + f(u)dx_4^2) + u^{-\frac{3}{2}}(\frac{du^2}{f(u)} + u^2d\Omega_4^2)
$$
\nwith $e^{\Phi} = g_s u^{\frac{3}{4}}$

\nfield theory

\nCompact

\n
$$
F_4 = \frac{(2\pi)^3 l_s^3 N_c}{\Omega_4}
$$
\ndirection

 $\overline{}$ N_f probe D8-branes are localized* in x_4 . The flavors are massless. \sim \sim \sim \sim

5/22 *Fhe vacuum is specified by providing L (asympto* asymptotic separation in x₄) in units c σ by providing L (asymptotic separation in λ_4) in driits c $\langle 5/2 \rangle$ $\begin{array}{ccccccc} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \hline & \cdot & \cdot & \cdot & \cdot & \cdot \\ & & \cdot & \cdot & \cdot & \cdot \\ & & & \cdot & \cdot & \cdot \end{array}$ \mathbf{r} $\begin{array}{c} \text{IS} \text{ OI} \text{ UKK} \end{array}$ The vacuum is specified by providing L (asymptotic separation in x_4) in units of u_{KK}.

Chiral symmetry breaking in (N_f=1) hQCD

In the following, for simplicity, $N_f = 1$. Due to large N_c , $U(1)_A$ is not anomalous.

Let's switch from u to z variable: $u = (1 + z^2)^{1/3}$, $z = \pm \infty$ correspond to bdry.

matter had both bosonic and fermionic fields carrying baryon charge. In these cases,)-hranes connect in the hulk Where \pm D-branes connect in the bulk. Where this exactly happens is fixed by extremizing essential to study a theory with baryon charge carried exclusively by fermionic fields. DBI with respect to x4 at fixed asymptotic separation L. this model that we will focus on the present work.

model gives a holographic construction of a non-supersymmetric S Jual interpretation: spontaneous symr Dual interpretation: spontaneous symmetry breaking $U(1)_V \times U(1)_A \longrightarrow U(1)_V$.

 $\frac{1}{2}$ Evidence: massless pseudoscalar meson in the spectrum (η') well below the field theory Kaluza-Klein scale, and the low-energy physics should be low-energy physics should

6/22

Mesons in the vacuum and the chiral SB \cdot in the vacuum and the chiral SR This yields the following: $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ construction, regarding the contract contract construction property of $\frac{1}{2}$ and $\frac{1}{2}$ contract contract contract contract contract contract contract contract co [hep-th/0412141] Sakai & Sugimoto

Mesor
 $\sum_{i=1}^n$ s' normali zea modes of embed Mesons: normalized modes of embedding and gauge field perturbations:

- S_{∞} , tower of massive scalar and pseudoscalar meson U_{α} is computed the computation, we proceed the second function since U_{α} - δx_4 : tower of massive scalar and pseudoscalar meson
- \sim − δA_a : tower of vector and pseudovect λ $-\delta A_a$: tower of vector and pseudovector mesons + 1 massless pseudoscalar meson

 \mathbf{r} is an even (odd) \mathbf{r} is an even (odd) function. Because \mathbf{r}

For the gauge field ansatz $A_{\mu}(z,t,\vec{x}) = B_{\mu}\psi(z)e^{-i\omega(k)t+i\vec{k}\cdot\vec{x}}$ one obtains Our study produced the following result: $\lambda, w_j = \frac{D\mu \psi(z)}{c}$ one obtains

$$
\lambda_n^{CP} = 0.67^{--}, 1.6^{++}, 2.9^{--}, 4.5^{++}, \cdots \t \frac{\lambda_2}{\lambda_1} \approx \frac{1.6}{0.67} \approx 2.4 \t (hQCD),
$$
\n
$$
\sum_{m_{a_1(1260)}}^{m_{a_1(1260)}} \approx \frac{(1230 \text{ MeV})^2}{(776 \text{ MeV})^2} \approx 2.51 \text{ (experiment)}.
$$
\n
$$
\sum_{n_1}^{m_{a_1(1260)}} \approx \frac{(1230 \text{ MeV})^2}{(776 \text{ MeV})^2} \approx 2.51 \text{ (experiment)}.
$$
\n
$$
\sum_{n_1}^{m_{a_1(1260)}} \approx \frac{(1465 \text{ MeV})^2}{(776 \text{ MeV})^2} \approx 3.56 \text{ (experiment)}
$$

Mass differences between subsequent mesons come from t Here, we follow the same procedure as in the previous subsection to obtain the meson Mass differences between subsequent mesons come from the chiral SB.

Question I: what happens with the masses at finite baryon density? \bigcap is odd and \bigcup is the light mode, and \bigcup is the light mode, and \bigcap is the light mode, \bigcap Wuestion i. Witat happens with the masses at milite Dai yon read from the leaves control to the second control of the second control of the second control of the second co $\frac{1}{2}$

7/22 $\sqrt{122}$

Baryons in $N_f=1$ hQC [hep-th/0412141] Sakai & Sugimoto **D** [hep-th/9805112] Witten

Baryon chemical potential arises from: $A_0(z) = A_0(-z)$ and A_0 $|z\rightarrow\infty$ $=\mu_B +$ 1 *z* $\rho_B + \ldots$

No horizon, one needs charge carriers \odot to generate radial electric flux.

argo carriare and the and pointe of NI For N_f=1, the charge carriers are the end points of N_c fundamental strings stretched for a Fermi surface. In order to get behavior since \mathcal{L} ines wradding the 5' dar't of the geom Such a model was constructed a few years ago by Sakai and Sugimoto [10], and it is between D4-branes wrapping the $S⁴$ part of the geometry the D8-brane.

I openadding cingle hop van will poside For the antipodal embedding, single baryon will reside at the bottom of the Uboundary conditions for the fermions. In the geometry, the compact direction of the ell helsame turns out to hold tor the r shaped D8-brane. The same turns out to hold for the non-antipodal embeddings.

> rying N^c units of D4-brane flux and the 3 + 1 directions of the field theory. In addition to Nf and Nc, the theory has a dimensionless parameter 0.816 0810.1633 [hep-th] Seki & Sonnenschein

 $8/22$ well below the field theory Kaluza-Klein scale, and the low-energy physics should be low-energy physics should

Baryon mass, charge and bdry charge radius between the instanton charge density and the abelian part of the abelian part of the showing s Domine messe showes and bdmin bat you mass, charge and but y c mass charge and bdry charge radius a diaso, charge and bury charge radius

 $\frac{1}{2}$ ing ζ for and ζ and ζ in the carrying baryon charge. In the cases, in the cases, ζ D4-brane wrapping S⁴ is a point particle in the radial and field theory dimensions. a D4-brane wrapped on S4 and located at the tip of the cigar. Since will also needed at the cigar. Since will the wrapping S⁴ is a point particle in the radial and field theory dimensions. ξe[−]^φ − determine determine determine determine determine determine determine de
Determine determine de $\overline{}$ \overline{a} dial a field theory dimensions.

Its mass comes from the 5-dimensional DBl action
$$
S = -\mu_4 \int d^5 \xi e^{-\phi} \sqrt{-\det(g_{ab})}
$$
\n $S_{D4} = -\frac{\mu_4}{g_s} \frac{8}{3} \pi^2 R_4^3 \int dt U(t) \longrightarrow M_B^0 = \frac{\mu_4}{g_s} \frac{8}{3} \pi^2 R_4^3 U_{\rm KK} = \frac{1}{27\pi} \frac{1}{R} \lambda N_c \quad (x_4 = x_4 + 2\pi R)$

 $t_{\rm in}$ it and $t_{\rm in}$ and $t_{\rm in}$ units of electric charge w/r D8-brane gauge f $\mathcal{F}_{\mathcal{A}}$ small values of \mathcal{A} where the scale \mathcal{A} where the running coupling becomes large is \mathcal{A} e fie \overline{a} and it carries N_c units of electric charge w/r D8-brane gauge field. The minimum energy of U $=$ U designore [16]. Both of these calculations in the energy from the energy from the energy from the electric flux

 γ adius is (1)(1) in N, and λ I α and α is α (α) in the case where α This agrees with the Yang-Mills action for a point \sim \sim \sim 0806 3122 The bdry charge radius is $\mathcal{O}(1)$ in N_c and λ !

Letal Hasbimoto Sakai & S $Q/22$ 0806.3122 [hep-th] Hashimoto, Sakai & Sugimoto

hQCD: large baryon densities & their dual mean-field description

Scales in the problem: DBI action and the CS term

We are interested in studying hQCD at nonzero baryon density.

To anticipate the interesting parametric regime, let's look at the scales in the problem:

DBI action (schematically)

$$
\mathcal{L}_{DBI} \sim N_c \lambda^3 \sqrt{\det(g_{ab} + \lambda^{-1} \partial_a A_b)}
$$

Chern-Simons term:

$$
\mathcal{L}_{CS} \sim N_c \epsilon^{abcde} A_a \partial_b A_c \partial_d A_e
$$

Background radial electric field: possible instabilities towards modulated phase. 0704.1604 [hep-th] Domokos, Harvey 1011.4144 [hep-th] Ooguri, Park

$$
A_a = O(1) \longrightarrow L_{DBI} \sim N_c \lambda
$$

\n
$$
A_a = O(\lambda) \longrightarrow L_{DBI} \sim N_c \lambda^3
$$

\n
$$
L_{CS} \sim N_c \lambda^3
$$

Scales in the problem: holographic baryons

Holographic baryon mass and charge:

$$
m_{hB} = \mathcal{O}(N_c)
$$
\n
$$
q_{hB} = N_c
$$
\nheavy compared to its charge and meson masses

Interactions between holographic baryons

Always repulsive in the $N_f=1$ case (get away by compactifying spatial QFT directions).

Scales in the problem: meson-baryons interactions density, the holographic baryons will couple to the gauge density, the holographic baryons will couple to the gauge \mathbf{r} s in the problem: meson-baryons interactions justifies neglecting the dynamics of charges in the dynamics of charges in the analysis of charges in the analysi roblem: meson-baryons interactions

Consider gauge field perturbation corresponding to vector or pseudovector meson pturbation corresponding to vector or pseudovector meson and simplified version of β is the baryon charge charge.

scales as *Nc*, the current *j* schematically reads

 $\partial^2 \overline{\delta A} =$ 1 $\overline{\delta}A=\frac{1}{N_c\lambda}\delta j$ () current of holographic baryons where *j is the course is suppressed (follows from* D $b^{S(1)}$ is not identify, and board to bupp about $\binom{1}{1}$ and simplified version of the barge density. scales as *Nc*, the current *j* schematically reads \uparrow \uparrow \downarrow \uparrow \downarrow \uparrow \downarrow \downarrow notographic baryon charge generically, the source is suppressed (follows from DBI) $\frac{1}{c\lambda}\delta j \blacktriangleleft$ - current of holographic baryons where $\frac{1}{\sqrt{2}}$ is the current made out of the holographic matrix $\frac{1}{\sqrt{2}}$ is the holographic matrix of the $\frac{1}{\sqrt{2}}$ generically, the source is suppressed (follows from L $h \cup l$ charge dopens scales as *Nc*, the current *j* schematically reads Let's look now at the current: $\delta j = N_c n \delta u$ charge motion We are the perturbations of the perturbation of interest do not all the periodic interest of the perturbations of $\frac{1}{2}$ holographic baryon charge bulk charge density \rightarrow current of holographic baryons \mathbf{T} and the perturbations of interest do not all \mathbf{C} ally, the source is suppressed (follows from DBI) the case.
1 $\frac{1}{2}$ $\sum_{\text{trronti}} \delta_{\text{in}} N_{\text{in}} \delta_{\text{out}}$ obergo motion and $\sigma_j = \frac{N_c}{100a}$. Charge model can schematic harvon sharpore was second law *material*

the number density *n*, which will indeed turn out to be compine $\frac{1}{2}$ THE IL WILLET NEW LOTES SECUTE THAT A \mathbf{v}_c *AU* $\mathbf{u} = \mathbf{v}_c$ *U* \mathbf{u} and combine it with Newton's second law* $N_c\lambda\partial \delta u = N_c\partial \delta A \longrightarrow \ \delta u \sim \frac{1}{\lambda}\delta A$. 1 $\frac{1}{\lambda} \delta A$

the number density *n*, which will indeed turn out to be

Altogether, we get
$$
\partial^2 \delta A \sim \frac{1}{\lambda^2} n \delta A
$$
. RHS non-trivial only for $n \sim \rho_B = \mathcal{O}(\lambda^2)$!
\n
\n \uparrow
\nin-medium mass for the bulk gauge field

 α the bulk gauge field $\frac{6}{12/22}$ in-medium mass for the bulk gauge field

as

teractions with *single* baryons; schematically,

teractions with *single* baryons; schematically,

12/22 *Nc*@*u* = *Nc*@*A,* (68) where N on the latter N on the latter N on the latter N on the baryon mass, N on the baryon mass, N

Why baryons densities $\mathcal{O}(\lambda^2)$ might be quarkyonic?

- One might expect CS term driven instabilities breaking translational invariance. pect CS territi driveri instadilities break Such a model was constructed a few years ago by Sakai and Sugimoto [10], and it is

$$
A_a = O(\lambda) \longrightarrow \mathcal{L}_{DBI} \sim N_c \lambda^3 \qquad \mathcal{L}_{CS} \sim N_c \lambda^3
$$

red meson harven interactions might - Density-enhanced meson-baryon interactions might significantly affect the spectrum: the field theory Kaluza-Klein scale.²

$$
\partial^2 \delta A \sim \frac{1}{\lambda^2} n \, \delta A
$$
\nin-medium mass for the bulk gauge field

\n13/22

Towards mean-field approach

We are interested in the mean-field toy model of 4-dimensional charge distribution:

 \mathbf{S} and \mathbf{S} are constructed a few years ago by Sakai and Sugimoto \mathbf{S} The first assumption is that the cost of long-wavelength changes of the mean-fie $\overline{}$ Sauge models captured by the Or The first assumption is that the cost of long-wavelength changes of the mean-field action This is t gauge field is captured by the original DBI action. This is the first key assumption.

field theory together with the radial direction form a cigar-type geometry, in which the The second assumption is that in ring soccorid assumption is that in onorgy donoity of the modium fr the field the field of the field theory and the *e*nemy scale. $\mathbf{F}_{\mathbf{r}}$ small values of \mathbf{r} the scale \mathbf{r} where the running coupling becomes large is \mathbf{r} field theory together with the radial direction form a cigar-type geometry, in which the The second assumption is that in any tiny volume we neglect the contribution to the rying N^c units of D4-brane flux and the 3 + 1 directions of the field theory. In addition ϵ and no neutro the theory matrice ϵ energy density of the medium from the interactions with the microscopic gauge field.

Thomps is place an anongy cost of \flat correspondence, it should be possible to map out the phase diagram of the field thecomos from the curvature of the comes from the curvature of the D8 and interactions with the mean-field gauge we are not in a position to study it. For large \mathbf{r} on the other hand, the gravity back-form \mathbf{r} 4-dimensional charge distribution that There is also an energy cost of building up 4-dimensional charge distribution that comes from the curvature of the D8 and interactions with the mean-field gauge field.

Mean-field approach: electron star **ld approach: electron stard coupling of the standard control of the standard coupling of the coupling of the charge coupling of the coupling of the charge control of the coupling of the coupling of the coupling of the cou** current *q^b w*² *u^a* to the *U*(1) gauge field *Aa*; transforms \mathbf{a} **r** \mathbf{a} (*x*) \mathbf{a} \mathbf{a} + \mathbf{a} *I <i>Dean* **=** $\frac{1}{2}$ $\mathbf{\Omega}$ e *ld* approach: electro $\overline{}$ in terms of the field theory parameters by $\overline{}$

This leads us to the following effective action $S = S_{DBI} + S_{CS} + S_{dust}$ that bears a striking resemblance to the electron star constructions in AdS/CMT 1008.2828 [hep-th] Hartnoll & Tavanfar $S-S_{DPL}+S_{CQ}+S_L$, that hears a This reads us to the following effective action $D - DDBI + DCS + Ddust$ that bears a and dicturn of the UC ist and the Integral of the Temper of the UC is the UC in the UC is the UC in the UC is t
1000 2020 **Elgent de UC is the UC is to the UC is the UC is to the UC is the UC is to the UC** is the UC is the **shell conservation of the current of the current of the internal current of the internal current internal conser** $-S_c$ $_{ust}$ that bear $\overline{\mathsf{a}}$ 1008,2828 [hen-th] Hartnoll & Tavanfar

 t_{tot} and σ is the action (48) to construct homoge-

ial function of *L*, determined by solving the equations of

energy density
\n
$$
S_{dust}/c = \int d^5 \tilde{x} \sqrt{-\det(\tilde{g}_{ab})} \left\{ -\beta \tilde{\xi}^{1/4} \left(1 + \frac{\tilde{z}^2}{\tilde{\xi}^2}\right)^{1/12} \tilde{w}^2 + \gamma \tilde{w}^2 \tilde{u}^a \left(\tilde{A}_a - \partial_a \tilde{\phi}\right) + \tilde{\lambda} (\tilde{u}_a \tilde{u}^a + 1) \right\},
$$
\npotential energy

rescalings involving λ , $c \sim N_c \lambda^3$, $\beta = 4\pi^2$, $\gamma = 12\pi^2$ \sim mass \sim charge $\epsilon = \tilde{\xi} \left(1 + \frac{z}{z_1} \right)$ $\langle K \rangle = \langle \xi^2 \rangle$ $\beta = 4\pi^2, \quad \gamma = 12\pi^2, \quad \frac{u}{\sqrt{2\pi}} = \tilde{\xi}$ 2⇡*l* 2 $+\frac{z}{\tilde{\epsilon}^2}$ $T_{\rm max}$ of $T_{\rm max}$ *T*ildes denote rescalings involving λ , $c \sim N_c \lambda^3$, $\beta = 4\pi^2$, $\gamma = 12\pi^2$, \sim mass \sim charge *xa* = *X^a*() = *^a* (14) $\frac{1}{2}$ and $\frac{2}{3}$ are independent in Eq. ($\ddot{\xi}$, $\frac{u}{\omega} = \tilde{\xi}$ $\overline{1}$ $1 +$ \tilde{z}^2 $\tilde{\xi}^2$ $\sqrt{\frac{1}{3}}$ $u \sim \tilde{\zeta} \left(\frac{z^2}{1 + z^2} \right)^3$ *uKK* =

ate: (energy density) \sim (charge density $\equiv \tilde{w}^2$). ale. (Crici gy density) (Crial ge density $-w$). Equation of state: (energy density) ~ (charge density = \tilde{w}^2). our results, but it can be easily worked out. Note a single out. Note again, Ω is a single out. Note again Ω (energy density) \sim (charge density $\equiv w^2$). ty $\equiv \tilde{w}^2$) $\frac{1}{2}$ and $\frac{1}{2}$ radial position of the D8-brane world $\frac{1}{2}$

rection. For rescaled densities that are -suppressed, the Exactly the same action, up to field redefinitions, was used in 0708.1322 [hep-th]. same is true for the baryon velocity, i.e., ˜*u*⁰. T is vertex to the network to the network to the network to the network T all et al, which is et its situation fixes its et rection. For rection and research are rescaled and respect to $Rozali$ et al. the circle (1708, 1322 The other that the very symmetry directly to the very symmetry directly to the very symmetry of α *y*˜0 $\begin{array}{ccc} \text{S} \text{USeG} & \text{in} & \text{R} \\ \text{Rozali et al} & \text{in} \end{array}$

15/22 $15/22$ t_{α} the *z* \overline{z} and appear at \overline{z} and appear as boundary conditions of \overline{z} and $\$ \overline{S}

Homogeneous mean-field ground state

Solving EOMs for the coarse-grained fields in the antipodal case gives:

Three observations:

the bulk charge distribution moves towards the hdry rescant charge discribation moves towards the bar_, $\rho_{\rm p}$ / $\sum_{i=1}^{n}$ $\sum_{i=1}^{n}$ § the surface of the bulk charge distribution moves towards the bdry as $\rho_B \nearrow$.

 \S radial electric field is never large (it turns out also for non-antipodal embeddings). electric field inside the charge distribution. The distribution \mathbf{r} (dotted), *L/*⌧ = 0*.*1 (dotdashed), and *L/*⌧ = 0*.*05 (dashed).

§ the charge distribution in the core does not depend on external layers! $t \leq 122$ \mathbf{A} \mathbf{r} Spontaneous breaking of translational invariance

The Chern-Simons term and modulated GS Typically, gradients in spacelike dimensions cost energy and so mean field description has a homogeneous ground state. Ooguri et al. Harvey et al.

Although the kinetic term is positive definite, the CS coupling (which is essential in hQCD) is not and it is possible that inhomogeneous configurations win energetically

In holographic systems instabilities towards modulation typically exist if the system has marginally stable normalized modes ($\omega = 0$, $\vec{k} \neq 0$)

It's been known from earlier works of Harvey et al. and Ooguri et al. that the CS coupling leads to instability at large enough background electric field for the ansatz

$$
A_z = 0, \quad A_0 = A_0(z), \quad A_1 = \delta h(z) \cos(kx^3), \quad A_2 = -\delta h(z) \sin(kx^3), \quad A_3 = 0
$$

$$
j^0 = \rho_B \quad \delta j_{A/V}^1 = \#_{A/V} \cos(kx^3) \quad \delta j_{A/V}^2 = -\#_{A/V} \sin(kx^3) \quad \delta j^3 = 0
$$

Thorough analysis of EOM of the form $\#_2(z)\delta h''(z) + \#_1(z)\delta h'(z) + (\#_0(z) - E)\delta h(z) = 0$ does not reveal unstable modes unless we do the following

E becomes large enough to support marginally stable modes leading to inhomogeneous ground state

In-medium excitations

Possible mechanism of "chiral symmetry" restoration symmetric with respect to z . The sufficient to z- and hence it is sufficient to z boundary conditions at infinity leads to the spectrum of \mathbf{u} of \mathbf{v} , while \mathbf{u} denotes \mathbf{v} TOWARDS A HOLOGRAPHIC REALIZATION CHARGE .

 $g_{\rm max}$ is duality duality, but we also want to stress at this point to stress at this point that α $U(1)$

EOM for axial and vector meson perturbations can be rewritten as a Schr. eqn. $\overline{\mathcal{L}}$ \sim equals of \sim Connection as a scrib copin

antipodal case: I) vacuum (2) dense medium $(BMin)$ 3) dense medium \overline{C} meson-baryon in teractions in the form of the form o t_j abtion for meson perturbations, and t_j $\left(\begin{array}{cc} 3 \end{array} \right)$ dense mer

Approximate chiral symmetry re barrial chinal syltimetry fo no point point point of the non- γ pproximate crimatisymmetric \mathcal{G} . In the quarky phase, baryonic phase, baryons are so tightly packed by \mathcal{G} . restoration for the lowest v one effectively has a quark Fermi surface. Despite this, the \mathbf{g} interactions of the mesons may be mesons with the mesons may be mesons may be may be mesons may be mesons may be m lead to new structure to new structure to the potential has a direct impact in the potential α warping of the target spacetime. tor and axial mesons! ho lowest vector and avial me ports a few and the assembly the assembly $\overline{1000}$ is continued: the school of the schronach potential and the three potential and the three tor the lowest vector and axi \overline{C} and \overline{C} , \overline{C} at \overline{C} of \overline{C} becomes the plot \overline{C} Approximate chiral symmetry restoration for the lowest vector and axial mesons!

states not of the master potential well—which is also present in

 $18/22$ the quark Fermi surface) and ''yonic'' (from excitations \mathfrak{p}_1 emergent potential well does not give rise to bound states and

Relation to other works

Relation to other works and possible extensions

§ Our mean-field description is the same* as 0708.1322 [hep-th] by Rozali et al. and in many ways resembles the electron star from 1008.2828 [hep-th] by Hartnoll & Tavanfar.

§ It has to be contrasted with 3-dimensional charge distributions considered first by **0708.0326 [hep-th]** by Bergman et al. which apply only at $\rho_B \ll O(\lambda^2)$!

§ More microscopic justification for 4-dimensional lattices at large enough densities comes from 1201.1331 [hep-th] and 1304.7540 [hep-th] by Sonnenschein et al..

§ It would be interesting to repeat the calculation from 1304.7097 [hep-th] by Seki & Sin for 4-dimensional charge densities relevant for $O(\lambda^2)$ baryon densities.

§ Things are similar to AdS/CMT. Below idea from Sean Hartnoll:

1111.2606 [hep-th] Hartnoll & Huijse

Summary

Summary

§ Main idea: focus on $\mathcal{O}(\lambda^2)$ baryon densities:

for a Fermi surface. In order to get behavior surface. In order to get behavior similar to σ efossible mechanism for chiral symme § Possible mechanism for chiral symmetry restoration: the model that the model of the present will focus on the present will be a threated will be a threated with the present work. strong interactions with the thick layer of holographic baryons m tor chiral symmetry rest $\frac{1}{100}$ can an $\frac{1}{2}$ musical $\frac{1}{100}$ s with the thick layer of holographic bar<u>i</u>

that is the canonical kinetic term in Eq. (78). Simple \mathcal{L}

vs.

 \int anomal thomore § General theme:

near-horizon geometry of N^c D4-branes wrapped on a spatial circle with anti-period boundary conditions for the fermions. In the geometry, the compact direction of the condensed matter physics of holographic QCD prijsies of molographie G

Almost final thoughts

§ I don't think our approximations lead to the model having the quarkyonic phase.

§ Whether it appears in a truly microscopic hQCD construction is an open problem.

§ One thing is certain: $\rho_B = \mathcal{O}(\lambda^2)$ leads to something (?) interesting that is not 3D.

§ What I would like to see is a model in which the charge distribution gets significantly denser in the core as we add more and more layers.

§ Then interesting many-body effects following from the nonlinearities of DBI might start playing role, changing completely the picture presented here and other works.

§ The CS term might then still lead to interesting macroscopic modulation patterns, possibly visible also in other observables, e.g. the chiral condensate.

Wishful thinking

(Approximate) chiral symmetry restoration at large densities:

formation of a Fermi surface. In order to get behavior similar to real QCD, it is essential to study a theory with baryon charge carried exclusively by fermionic fields. ???

22/22 \mathcal{L} small values of \mathcal{L} the scale \mathcal{L}