Axionic Strings, Domain Walls and Baryons via Holography

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Based on:
F. Bigazzi, A. L. Cotrone, A.O. JHEP **02**, 194 (2023).
F. Bigazzi, A. L. Cotrone, A.O. Phys. Rev. D **108**, 026019 (2023).
F. Bigazzi, A. L. Cotrone, A.O. ongoing work

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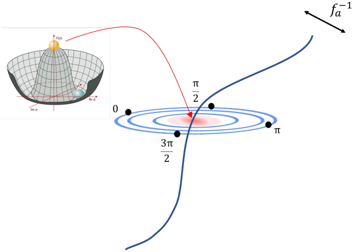
Axionic Strings

Strings & Topology

Non-simply connected vacuum manifold $\mathcal{M}$ (Ex. $\mathcal{M} = S^1$): existence of strings.



Global Strings

Ex. Spontaneous Symmetry Breaking of Global $U(1)$ at scale f_a

Core size: $\delta \sim f_a^{-1}$,

Tension: $T \sim \pi f_a^2 \log(f_a R)$, R cutoff.

"*Axionic Strings, Domain Walls and Baryons*" PRD 108, 026019 (2023)

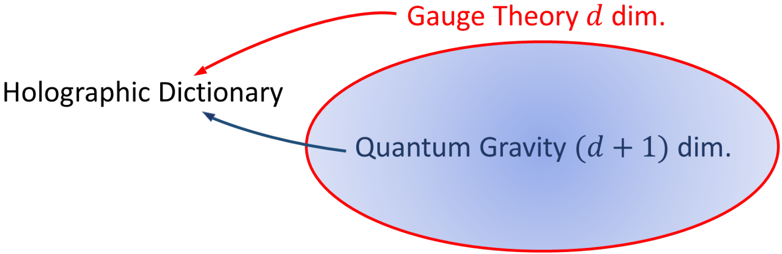
Composite Axion Model $T \neq 0$: $SU(N)$ gauge group + $N_f = 1$ extra-flavor.

Axionic string effective action from an UV complete theory (Holography!)

Holographic Correspondence

J. M. Maldacena, Adv.Theor.Math.Phys. 2 (1998) 231-252.

Gauge Theory in d dim. $\Longleftrightarrow$ Quantum Gravity theory in $(d+1)$ dim.



Weak/Strong Duality

Strongly-Coupled Gauge Theory $\Longleftrightarrow$ Classical Gravity Theory

Holographic Yang-Mills at High Temperature

Witten, Adv. Theor. Math. Phys. 2, 505 (1998). Aharony et al., Annals Phys. 322, 1420 (2007).

4-dim. $SU(N)$ YM $N \gg 1$, $\lambda = g_{YM}^2 N \gg 1$ + massive modes $\Leftrightarrow$ Witten background

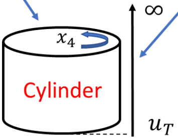
Witten Background at high temperature $T > \Lambda$ (confining scale).

$\Downarrow$

$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left[-f_T(u)dt^2 + dx^i dx^i + f_T(u)dx_4^2\right] + \left(\frac{R}{u}\right)^{3/2}\left[\frac{du^2}{f_T(u)} + u^2 d\Omega_4^2\right]$$

$$f_T(u) = 1 - \frac{u_T^3}{u^3}$$

Minkowski Space



Four-Sphere

$R_{x_4} \sim M_{KK}^{-1}$

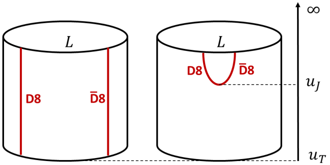
$u_T \sim T^2$ Black Hole Horizon

Confinement/Deconfinement Phase Transition $T_c \sim M_{KK}$.

Flavors

Sakai, Sugimoto, Prog. Theor. Phys. 113, 843 (2005). Aharony et al., Annals Phys. 322, 1420 (2007). Bigazzi et al., JHEP 12, 056 (2019).

- $N_f = 1$ probe D8/$\overline{\text{D}}$8 - branes (wrapped on the background four-sphere).
- $U(1)_L \otimes U(1)_R \to U(1)_V$: geometrical chiral symmetry breaking.



- L sets $u_J \sim f_a \gg \Lambda$.
- $T_c < T < f_a$: Model of Composite Axion!

χ-symmetry Broken/Preserved Phase Transition $T_a \sim L^{-1}$.

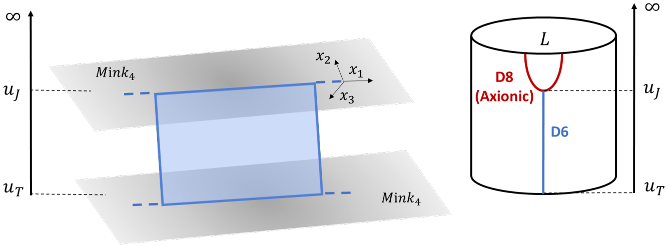
Theory on $N_f = 1$ D8-brane world-volume:
Maxwell-Chern-Simons theory in a five-dimensional curved space-time.

$$S \sim \lambda N \int_{M_5} \mathcal{F} \wedge \star d\mathcal{F} + N \int_{M_5} \mathcal{A} \wedge \mathcal{F} \wedge \mathcal{F}$$

Holographic Axionic String

F. Bigazzi, A. L. Cotrone, A.O., Phys. Rev. D 108, 026019 (2023).

Axionic string as D6-brane wrapped on S^4



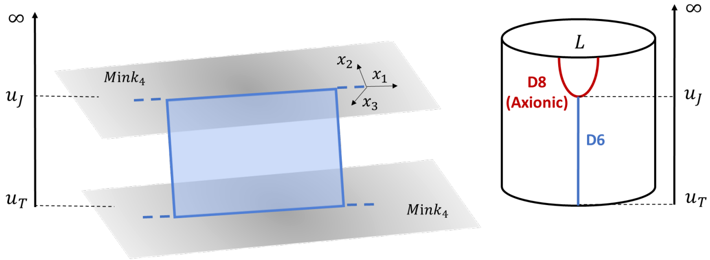
D6-brane as a Magnetic Source

D6 brane is a source for the Maxwell-Chern-Simons theory on the D8-branes

$$d\mathcal{F} = \delta_3$$ Magnetic Source

Holographic Axionic String

F. Bigazzi, A. L. Cotrone, A.O., Phys. Rev. D 108, 026019 (2023).



Maxwell-Bianchi system of equations from Maxwell-Chern-Simons theory:

$$d \star \mathcal{F} = a\, \mathcal{F} \wedge \mathcal{F},$$
$$d\mathcal{F} = -2\pi\delta(x_2)\delta(x_3)\delta(u - u_J)dx_2 \wedge dx_3 \wedge du.$$

Ansatz to solve the equations of motion:

$$\mathcal{F}_{x_2 x_3} = l(u)\partial_u H, \qquad \mathcal{F}_{x_2 u} = m(u)\partial_{x_3} H, \qquad \mathcal{F}_{x_3 u} = n(u)\partial_{x_2} H.$$

Holographic Axionic String

F. Bigazzi, A. L. Cotrone, A.O., Phys. Rev. D 108, 026019 (2023).

Series Solution: $H(u,r) = \sum_{n=0}^{\infty} \zeta_n(u) Y_n(r)$, $r = \sqrt{x_2^2 + x_3^2}$

Complete and orthonormal basis of eigenfunction $\zeta_n(u)$ with eigenvalues λ_n.

$Y_0(r) \sim \log(T_a r)$, $\lambda_0 = 0 \rightarrow$ Axion, $Y_n(r) \sim K_0(T_a\sqrt{\lambda_n}\, r)$ $n \geq 1$, Y_n mesonic modes.

D8-brane action $\Rightarrow$ Global string effective action derived, not postulated!

$$S = -\frac{1}{2}\sum_{n=0}^{\infty}\int d^4x \left[(\partial_r Y_n)^2 + T_a^2 \lambda_n {Y_n}^2\right].$$

Tension and Core Thickness of the string:

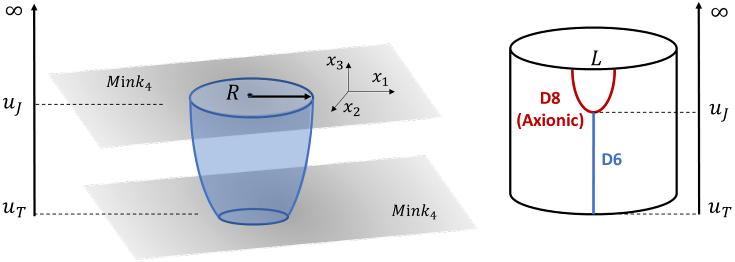
$$T \sim \lambda N T_c^2 \log\left(\frac{R}{\delta}\right), \qquad \delta \sim \left(\lambda T^3 T_c\right)^{-1/2}.$$

Near string divergence $\rightarrow$ presence of a hard-core, i.e. the D6-brane.

Holographic Vorton

Work in Progress.

$\sqrt{x_1^2 + x_2^2} = \rho = \rho(u)$ non-trivial embedding function.



$$d \star \mathcal{F} = a\, \mathcal{F} \wedge \mathcal{F},$$
$$d\mathcal{F} = -2\pi\delta(\rho(u) - R)\delta(x_3)\delta(u - u_J) d\rho \wedge dx_3 \wedge du.$$

Ansatz:

$$\mathcal{F}_{\rho x_3} = l(u)\partial_u H, \qquad \mathcal{F}_{\rho u} = m(u)\partial_{x_3} H, \qquad \mathcal{F}_{x_3 u} = n(u)\partial_\rho H.$$

Holographic Vorton

Work in Progress.

Series Solution:

$$H(u,\rho,x_3;R)=\sum_{n=0}^{\infty}\zeta_n(u)Y_n(\rho,x_3;R),\quad Y_n \text{ mesonic modes (numerical solution).}$$

Effective action:

$$\boxed{S=-\frac{1}{2}\sum_{n=0}^{\infty}\int d^4x\left[(\partial_\rho Y_n)^2+(\partial_3 Y_n)^2+\left(\frac{1}{\rho^2}+T_a^2\lambda_n\right){Y_n}^2\right]}$$

Tension is not divergent at large distances!

Vorton Stability (to be studied quantitatively)

$\mathcal{A}_t\neq 0$: Coulomb repulsion prevents the collapse.

(Qualitatively) Vorton Energy: $E(R)\sim TR+A/R \;\Rightarrow\; R_{stable}$.

$\mathcal{A}_t \iff J_t^B$: Vorton stabilized by a conserved baryonic current.

Holographic Domain Walls & A-Baryons

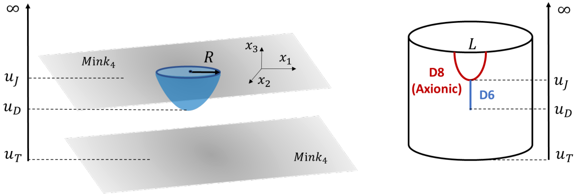
F. Bigazzi, A. L. Cotrone, A.O., JHEP 02, 194 (2023) + Work in Progress.

String-Wall Network

$\mathcal{M}$ (vacuum manifold) with disconnected components: Domain Walls (DW) arise.
DW attached to strings (Ex: axion mass switches on).

The holographic model allows us to study DW in the deconfined phase (unusual feature)!

Domain Wall as D6-brane wrapped on S^4

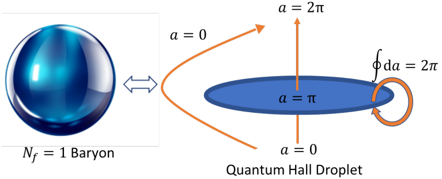


If charged $\Rightarrow$ Axionic-Baryons in the holographic model!

Holographic Domain Walls & A-Baryons

F. Bigazzi, A. L. Cotrone, A.O., JHEP 02, 194 (2023) + Work in Progress.

Low-energy description of $N_f = 1$ baryons: the baryon number is associated to the current flowing along the boundary (Z. Komargodski, arXiv:1812.09253 [hep-th]).



DWs as D6-branes can be studied also in the confined phase:

- Infinite DW & DW bounded by a string (Bigazzi, Cotrone, A.O., JHEP 02, 194 (2023)).
- Charged DW (Work in Progress).

Future Developments

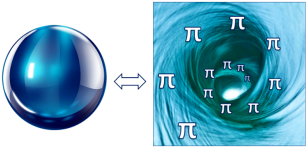
Phenomenological applications: Charged DWs & Vortons as Dark Matter candidates

Thank you for your time!

Baryons in Low-Energy QCD

Z. Komargodski, arXiv:1812.09253 [hep-th].

Low-energy QCD $\to$ Chiral Lagrangian (pionic degrees of freedom)



Baryon   Pion-field vortex

No low-energy description of $N_f = 1$ Baryons

One-flavored baryons require an alternative low-energy description.

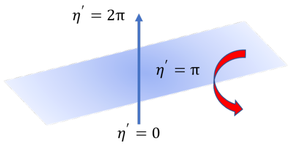
Chiral Lagrangian of $N_f = 1$ QCD $(\theta = 0)$ in the large N limit
$\to$ Effective field theory for η' phase of the chiral condensate

$$\mathcal{L}_{\eta'} = \frac{1}{2}(\partial\eta')^2 - \frac{1}{2}m\Lambda\cos(\eta') - \frac{1}{2}m_{WV}^2 \min_{k\in\mathbb{Z}}(\eta' + 2\pi k)^2 .$$

Extended excitation of the η' meson: sheets.

Baryons as Quantum Hall droplets

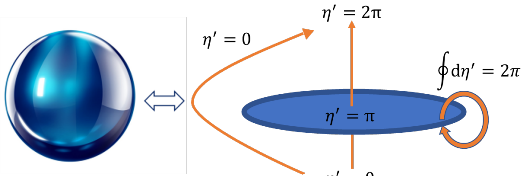
Z. Komargodski, arXiv:1812.09253 [hep-th].



Effective field theory on the sheet

$\eta' = \pi \rightarrow U(1)_N$ Chern-Simons (CS) theory

$$\frac{N}{4\pi}\int a \wedge da \;\Rightarrow\;$$ Fractional Quantum Hall effect!



$N_f = 1$ Baryon

Quantum Hall Droplet

Chiral effective field theory is Incomplete $\Rightarrow$ Holographic approach!

Holographic Yang-Mills (Witten)

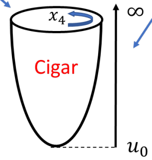
Witten, Adv. Theor. Math. Phys. 2, 505 (1998).

- (IIA Super String Theory) N D4-branes wrapped on a cycle with anti-periodic boundary conditions for fermions.
- Low-energy theory: four-dimensional Non-Supersymmetric $SU(N)$ Yang-Mills + tower of massive Kaluza-Klein modes.
- Parameters: $N \gg 1$, $\lambda = g_{YM}^2 N \gg 1$, $\Lambda_{QCD} \sim u_0$.

$$ds^2 = \left(\frac{u}{R}\right)^{3/2} \left[\eta_{\mu\nu} dx^\mu dx^\nu + f(u) dx_4^2\right] + \left(\frac{R}{u}\right)^{3/2} \left[\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right]$$

$$f(u) = 1 - \frac{u_0^3}{u^3}$$

Minkowski Space



Four-Sphere

$u_0 \sim \Lambda_{QCD}$ Confinement scale

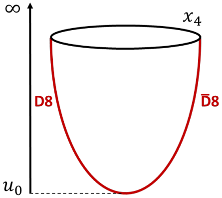
$R_{x_4} \sim M_{KK}^{-1}$

$\Rightarrow$ Confinement, Mass Gap.

Holographic QCD (Sakai-Sugimoto)

Sakai, Sugimoto, Prog. Theor. Phys. 113, 843 (2005).

- N_f probe D8/$\overline{\text{D}}$8 - branes (wrapped on the background four-sphere).
- $U(N_f) \otimes U(N_f) \to U(N_f)$: spontaneous symmetry breaking of chiral symmetry realized geometrically.
- Mesons arise from fluctuations of the D8-brane gauge field $\mathcal{A}$.



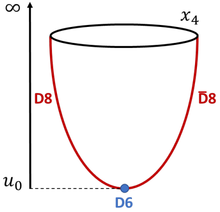
$$N_f = 1 \;\; \to \;\; S \sim \lambda N \int_{M_5} \mathcal{F} \wedge \star d\mathcal{F} + N \int_{M_5} \mathcal{A} \wedge \mathcal{F} \wedge \mathcal{F}.$$

Maxwell-Chern-Simons (MCS) theory in a five-dimensional curved space-time.

Hall Droplet Sheets in Holographic QCD

F. Bigazzi, A. L. Cotrone, A.O., JHEP 02, 194 (2023).

Sheet ⇔ D6-brane wrapped on S^4



Effective field theory on the Holo-sheet

$U(1)_N$ CS theory D6-brane world-volume.

$$\Rightarrow \quad \frac{N}{4\pi}\int_{M_3} a \wedge da,$$

where $M_3 = (t, x_1, x_2)$.

D8-brane gauge field perspective

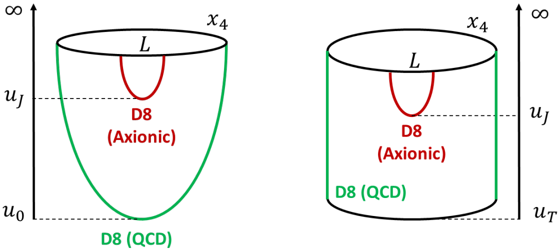
D6-brane is a source for the MCS theory ⇒ non-trivial η' profile.

D6-brane with a boundary in M_2 $\rightarrow$ $d\mathcal{F} = \delta_3$ Magnetic charge source.

Holographic QCD Axion

Bigazzi, Caddeo, Cotrone, Di Vecchia, Marzolla, JHEP 12, 056 (2019).

- Non antipodal extra probe D8/$\overline{\text{D}}$8 - branes.
- $U(1)_A$ anomalous and spontaneously broken (NJL-like term).
- Brane separation L sets $f_a \sim u_J \gg u_0 \sim \Lambda_{QCD}$.



- If $T \neq 0$ and $T_c < T < f_a$ axion survives $\Rightarrow$ Model of Composite Axion.
- $m_a^2(T)$ grows with the temperature!