The Holographic QCD Axion

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Plan

- Reminder: strong CP problem & axion
- Holographic QCD axion model
- CP-odd coupling to nucleons
- Deconfined phase
- Gravitational waves

Strong CP problem & axion

$$\mathcal{L}_{YM} = \frac{1}{2g_{YM}^2} TrF_{\mu\nu}F^{\mu\nu} - \theta\frac{i}{16\pi^2}TrF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Theta-term breaks CP

With only massive quarks physical parameter is $\bar{\theta} = \theta + \arg\det M$

M: quark mass matrix

With a massless quark θ non-physical (removed by chiral rotation)

Strong CP problem:

Experimentally: $|\bar{\theta}| \leq 10^{-10}$

Strong CP problem & axion

QCD axion:

Suppose exists global $U(1)_{PQ}$ which is:

- Spontaneously broken ⇒ Goldstone a (the axion)
- Anomalous ⇒ axion couples to $TrF_{\mu\nu}\tilde{F}^{\mu\nu}$

Then: $$\mathcal{L} \sim \left(\theta + \frac{a}{f_a}\right) \frac{i}{16\pi^2} TrF_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{L}(\partial_\mu a)$$

⇒ $\dfrac{\langle a \rangle}{f_a} = -\theta$ <u>solves strong CP-problem</u>

[Peccei-Quinn 1977]
[Wilczek 1978]
[Weinberg 1978]

Moreover: <u>good candidate for dark matter</u> if $10^8 \leq \dfrac{f_a}{\text{GeV}} \leq 10^{17}$

“Invisible axion”: weakly interacting and light $m_a \sim \dfrac{1}{f_a}$

Witten, Sakai-Sugimoto model

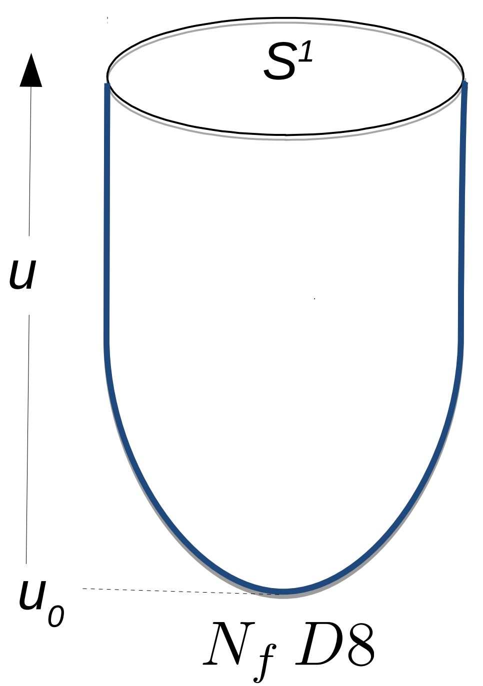
"Holographic QCD"

[Witten 1998, Sakai-Sugimoto 2004]

IIA background from N_c $D4$ wrapped on S^1 with N_f antipodal probe $D8$/anti-$D8$ pairs

Low energy: dual to 4d $SU(N_c)$ YM + KK modes + N_f quark flavors

Quark mass from world-sheet instantons [Aharony-Kutasov 2008, Hashimoto et al 2008]



$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(dx^\mu dx_\mu + f(u)dx_4^2\right) + \left(\frac{R}{u}\right)^{3/2}\frac{du^2}{f(u)} + R^{3/2}u^{1/2}d\Omega_4^2$$

Parameters:

- $N_c \gg 1 \qquad \lambda = g_{YM}^2 N_c \gg 1$
- $\Lambda_{QCD} \sim u_0$
- $\theta + 2\pi k = \int_{S^1} C_1$ → RR 1-form

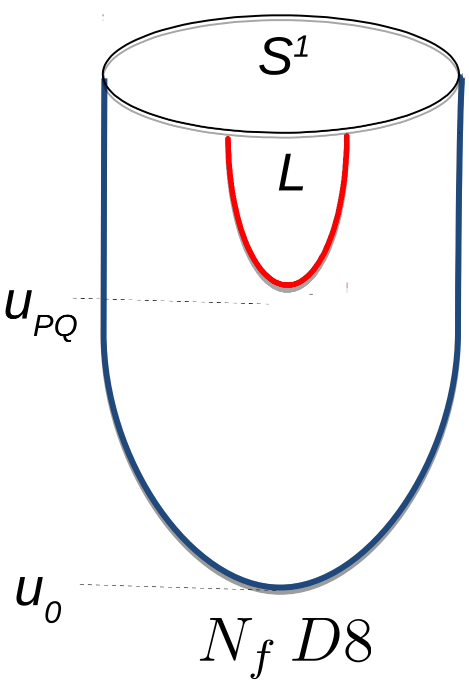
Holographic QCD axion

- Add extra probe D8/anti-D8 pair, non-antipodal
- Crucial: if no ws instantons → quarks massless → no Strong CP-problem

$U(1)_{PQ} = U(1)_A$ of extra flavor: anomalous and spontaneously broken

- Extra parameter L: extra scale, $f_a(\sim u_{PQ}) \gg \Lambda_{QCD}$ if $L \ll R_{S^1}$

→ only low energy effect from the (pseudo-)Goldstone: the (composite) axion



- Quark condensation at strong coupling from $D8$ embedding solution
- At weak coupling related to NJL-like term
[Antonyan et al. 2006]

Holographic QCD axion

Low energy physics derived from:

- *D*8 actions for QCD flavor and extra PQ flavor ($\mathcal{A}_{D8}$: gauge field on *D8*)
- QCD quark mass term (world-sheet instantons)
- F_2 term in IIA: $dF_2 \sim \mathcal{F}_{D8} \wedge \omega_1 \;\Rightarrow\; F_2^2 \sim (\theta + \eta' + a)^2$

$$\mathcal{L}_{\rm eff} = -\frac{f_\pi^2}{4} Tr\left[\partial_\mu U \partial^\mu U^\dagger\right] - \frac{1}{2}\partial_\mu a \partial^\mu a + c\, Tr\left[M U^\dagger + h.c.\right] - \frac{\chi_{YM}}{2}\left(\theta + \frac{\sqrt{2N_f}}{f_\pi}\eta' + \frac{\sqrt{2}}{f_a} a\right)^2 + \frac{1}{32 e^2} Tr\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]^2$$

$$U = e^{2i(\Pi^a T^a + (2N_f)^{-1/2}\eta')/f_\pi} = \mathcal{P} e^{i f_\pi \int_{QCD D8} \mathcal{A}_u}\,, \quad a = f_a \int_{PQD8} \mathcal{A}_u\,, \quad m_a^2 = \frac{\chi}{f_a^2}\,, \quad c \sim \langle \bar{q} q \rangle$$

Axion-extended Chiral Lagrangian with Skyrme term

[e.g. Di Vecchia et al. 2017]

CP-odd coupling to nucleons

- Axion very light: can mediate long range forces between macroscopic bodies
- CP-odd non-derivative interactions with nucleons particularly interesting

$$\bar{c}_N a \bar{N} N, \;\; N = (p, n)$$

- Leading CP-odd interactions if PQ mechanism not perfect: “residual” θ from explicit (small) breaking of $U(1)_{PQ}$
- Consider two flavors, rotate θ dependence in mass matrix
- Couplings from mass term on-shell on nucleon state (axion as external field):

$$\mathcal{L}_M = c\, Tr\left[M e^{-i\theta/2}\left(U_N - 1_2\right) + h.c.\right]$$

Instanton solution describing nucleon:
[Hata et al. 2007]

$$U_N = Exp\left[i\pi \frac{\vec{\tau}\cdot\vec{x}}{|\vec{x}|}\left(1 - \frac{1}{\sqrt{1+\rho^2/|\vec{x}|^2}}\right)\right]$$

CP-odd coupling to nucleons

- From axion mixing with mesons (also directly in chiral perturbation theory):

$$\bar{c}_p = -\bar{g}_{\eta' NN}\frac{\sqrt{2}\chi f_\pi}{4cf_a}[M^{-1}] - \bar{g}_{\pi NN}\frac{\sqrt{2}\chi f_\pi}{4cf_a}[M^{-1}\tau^3]$$
$$\bar{c}_n = -\bar{g}_{\eta' NN}\frac{\sqrt{2}\chi f_\pi}{4cf_a}[M^{-1}] + \bar{g}_{\pi NN}\frac{\sqrt{2}\chi f_\pi}{4cf_a}[M^{-1}\tau^3]$$

- Can be written as:

$$\bar{c}_p = \frac{\theta}{4f_a}\left[\sigma_{\pi N}\left(1-\epsilon^2\right) + \frac{1}{2}\Delta M\left(1-\epsilon^2\right)\right]$$
$$\bar{c}_n = \frac{\theta}{4f_a}\left[\sigma_{\pi N}\left(1-\epsilon^2\right) - \frac{1}{2}\Delta M\left(1-\epsilon^2\right)\right]$$

$$\Delta M = (M_n - M_p)_{strong} \qquad \epsilon = \frac{m_d - m_u}{m_d + m_u}$$

$\sigma_{\pi N}$: pion-nucleon sigma-term, quark mass contribution to nucleon mass

Leading term already in [Moody-Wilczek 1984]

CP-odd coupling to nucleons

- Use directly these formulae once $\sigma_{\pi N}$ and ΔM are known

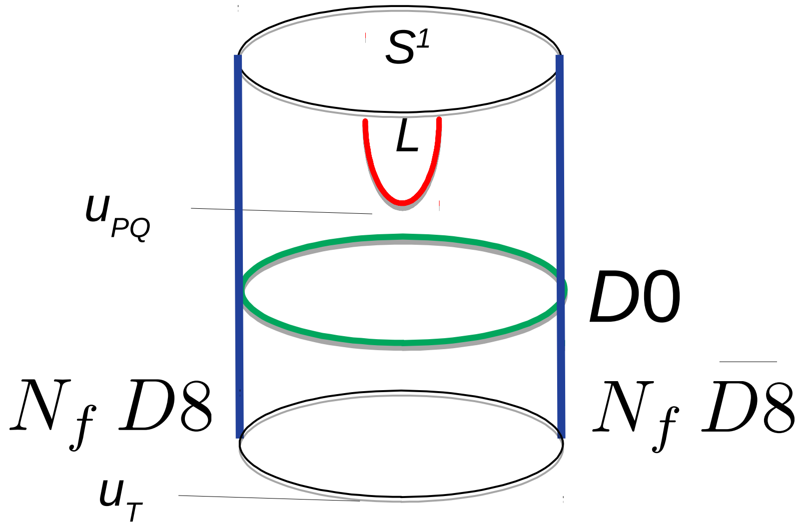
ΔM from lattice

$\sigma_{\pi N}$ from lattice or from πN scattering: large disagreement (50%)

	CL+lattice	CL+pheno	Holo axion	Skyrme
$\bar{c}_p$	14.9(9)	18.5(1.1)	16.3(4)	18.7(4)
$\bar{c}_n$	14.3(9)	17.9(1.1)	16.3(4)	18.7(4)

Values in MeV times θ/f_a

Deconfined phase



- Black brane background, <u>horizon</u> at u_T
- Cigar in geometry replaced by cylinder
- QCD branes fall into horizon: chiral symmetry restoration
- If $T_c < T < f_a$ PQ brane connected: axion survives
- Solution for $C_1 \sim const \;\Rightarrow\; F_2 = 0$: no effects of θ at leading order in $1/N_c$
- <u>Instantons give leading effects</u>: euclidean *D0* wrapped on S^1

$$S_{D0} = \int_{S^1} e^{-\phi}\sqrt{g} - i\int_{S^1} C_1 = \frac{8\pi^2}{g_{YM}^2} - i\theta$$

Deconfined phase

- Instanton corrections in IIA on S^1 from M-theory on torus (for $N_f=0$)

$$\delta S = -\frac{1}{k_{11}^{2/3}} \int d^{11}x \sqrt{g_{11}}\, W \left[\frac{2\pi^2}{3} + \mathcal{V}_2^{-3/2} f(\rho, \bar{\rho}) \right]$$

[Green-Gutperle-Vanhove 1997]

- $W \sim C^4$ (Weyl tensor) known [Gubser-Klebanov-Tseytlin 1998]
- $\mathcal{V}_2 \sim$ torus volume
- $f(\rho, \bar{\rho})$ modular form includes instanton contributions

$$f(\rho, \bar{\rho}) = 2\zeta(3)\rho_2^{3/2} + \frac{2\pi^2}{3}(\rho_2)^{-1/2} + 4\pi\left(e^{2\pi i\rho} + e^{-2\pi i\bar{\rho}}\right) + \ldots$$

$$\rho = \rho_1 + i\rho_2 \sim S_{D0} \sim \frac{\theta}{2\pi} + i\frac{4\pi}{g_{YM}^2}$$

Deconfined phase

- Gravity action: field theory free energy $f(\theta)$
- Topological susceptibility of Witten's model $\left(\chi = \frac{d^2 f(\theta)}{d\theta^2}|_{\theta=0}\right)$

$$\chi_{YM} = \frac{821 \cdot 2^9 \pi^{11/2}}{7 \cdot 3^5} \sqrt{\frac{N_c}{\lambda}} \Lambda_{YM} T^3 e^{-\frac{8\pi^2}{g_{YM}^2}}$$

- Axion mass (important for axion energy density in Universe): $m_a^2(T) = \frac{\chi}{f_a^2}$
- Note: g_{YM} constant in deconfined phase ⇒ axion mass increases with T!

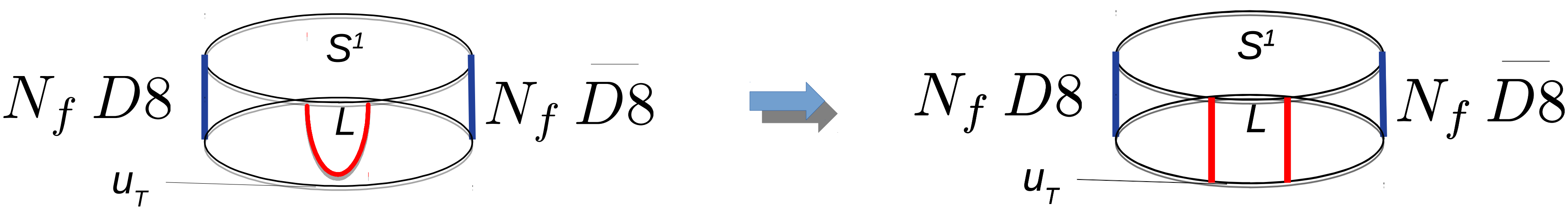
  The opposite behavior is expected!

- Similar computation in IIB gives topological susceptibility of $\mathcal{N} = 4$ SYM

$$\chi_{SYM} = \frac{15}{128} \pi^{3/2} \sqrt{N_c} T^4 e^{-\frac{8\pi^2}{g_{YM}^2}}$$

Gravitational waves

- In this model Peccei-Quinn transition is first order:



Gravitational waves:

when Universe cools down at $T < T_{PQ}$ bubbles of true vacuum are nucleated, expand, collide and percolate

bubble collisions and interactions with plasma (sound waves and turbulence) generate GWs

- Mechanism very general in first order transitions (plenty of them in holography!)

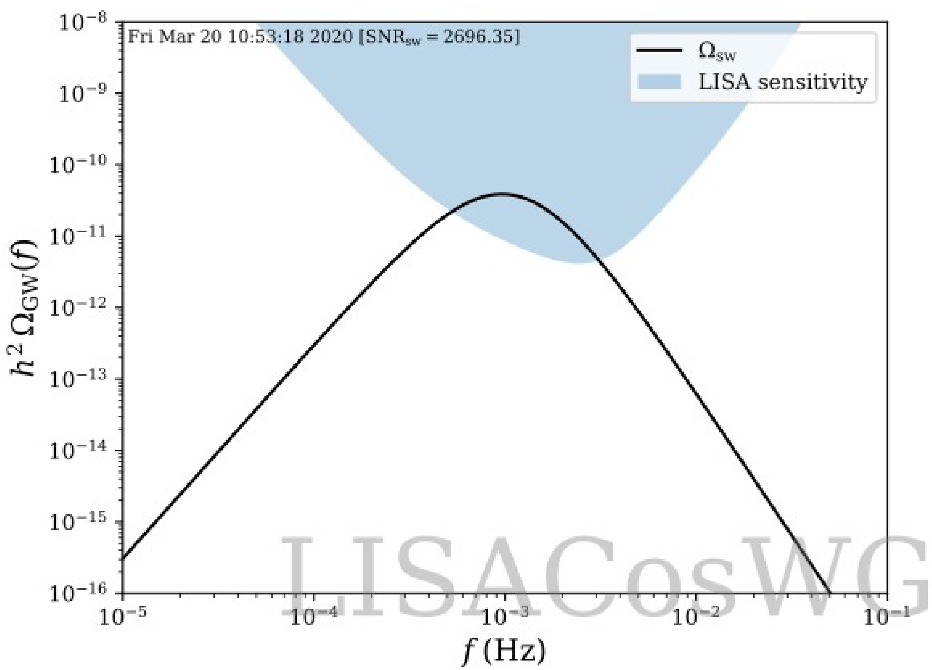
Gravitational waves

An "easier" example

Strongly coupled YM or QCD-like dark sectors can be <u>reliably</u> modeled with Witten, Sakai-Sugimoto (fixing a couple of issues in literature)

Confinement/deconfinement transition is first order → GWs

Preliminary result from sound waves with $\Lambda_{WSS} = 10\ \mathrm{GeV},\ \lambda N_c^2 = 10^8$



PTPlot from http://www.ptplot.org/ptplot/

LISA Cosmology Working Group

Thank you for your time!