Holographic QCD and Gravitational Waves

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arXiv:2008.02579 [hep-th] & to appear

Plan

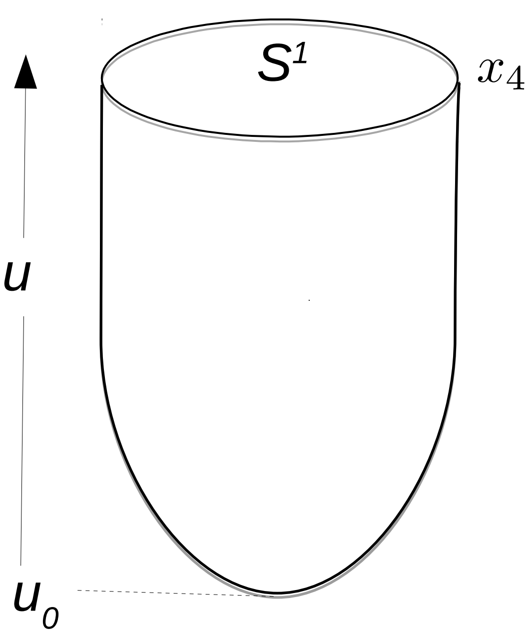
- Review of Holographic QCD
- Extensions: baryons and deconfinement
- Gravitational waves and cosmology
- Dark holograms
- GWs from Confinement and Chiral symmetry breaking transitions
- Overview

Review of Holographic QCD

Holographic Yang-Mills

[Witten 98]

- IIA background from N_c D4 wrapped on S^1 with anti-periodic b.c. for fermions
- Low energy: dual to non-susy 4d $SU(N_c)$ YM + KK modes
- Confined phase:



Minkowski

Four-sphere

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

Cigar

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

$$u_0 \neq 0 \;\Rightarrow\; g_{tt}(u_0) \neq 0 \;\Rightarrow$$ confinement, mass gap for glueballs

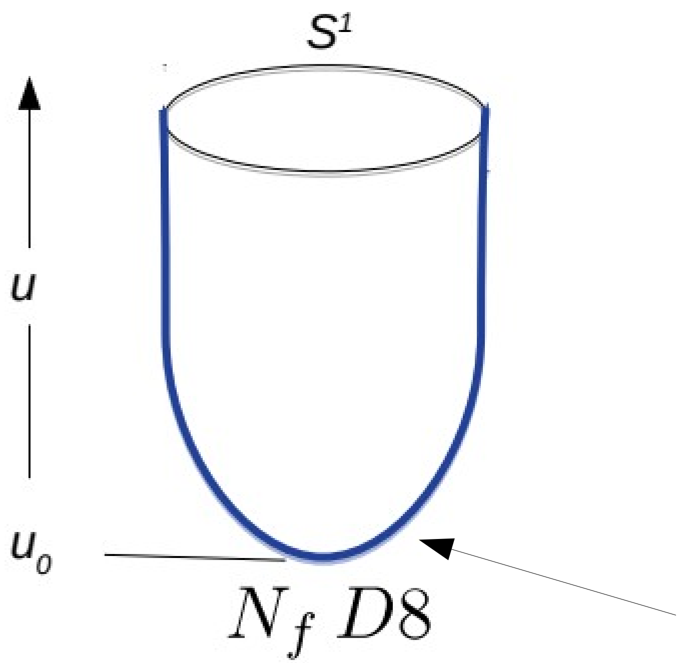
Parameters:

- $N_c \gg 1 \qquad \lambda = g_{YM}^2 N_c \gg 1$
- $\Lambda_{YM} \equiv M_{KK} \sim \sqrt{u_0}$

Review of Holographic QCD

Holographic QCD
[Sakai-Sugimoto 04]

- Add N_f probe D8/anti-D8 pairs, at antipodal points on circle
- From D4-D8 strings: (only) chiral quarks
- $U(N_f) \times U(N_f) \to U(N_f)$ chiral symmetry breaking from geometry



D8 embedding from Dirac-Born-Infeld action:

$$S_{DBI} = \frac{T_8}{g_s} \int d^9x \left(\frac{u}{R}\right)^{-3/2} u^4 \sqrt{\frac{1}{f(u)} + f(u) \left(\frac{u}{R}\right)^3 (\partial_u x_4)^2}$$

Equation of motion:

$$\left(\frac{u}{R}\right)^{-3/2} u^4 \frac{f(u)\left(\frac{u}{R}\right)^3 (\partial_u x_4)}{\sqrt{\frac{1}{f(u)} + f(u)\left(\frac{u}{R}\right)^3 (\partial_u x_4)^2}} = \text{constant}$$

Solution connected at tip of cigar!

Review of Holographic QCD

Holographic QCD
[Sakai-Sugimoto 04]

- Add N_f probe D8/anti-D8 pairs, at antipodal points on circle
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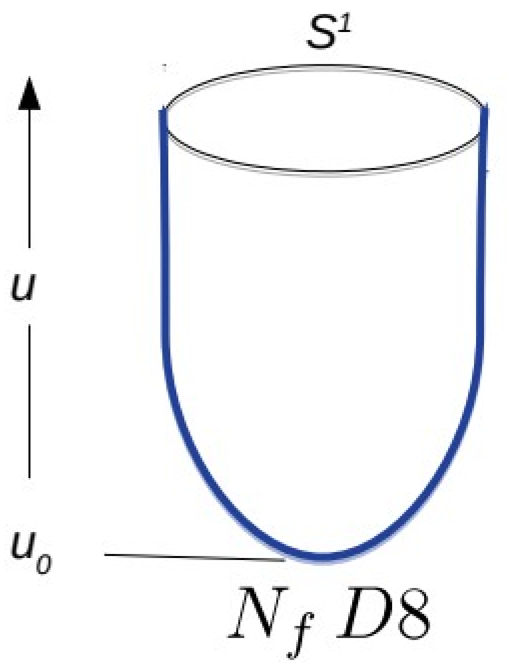


D8 world-volume scalar field (transverse direction):

- Mesons from fluctuating modes

D8 world-volume gauge field $\mathcal{A}_\mu$:

- Mesons from fluctuating modes
- Baryons from instantonic configurations

Review of Holographic QCD

Mesons

- DBI action for the D8-branes (gauge field only)

$$S_{DBI} = \frac{T_8}{g_s} \int d^9x \, e^{-\phi} \sqrt{\det(g + \mathcal{F})}$$

- Expanded to first order and reduced on four-sphere

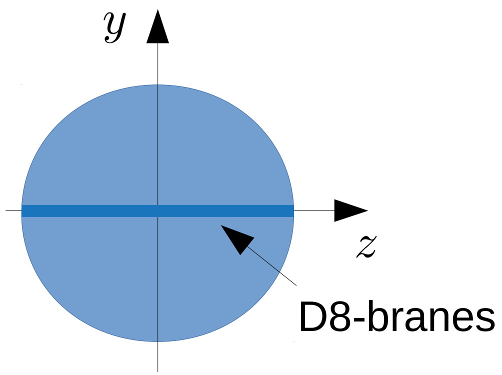
$$S_{DBI} = \kappa \int d^4x dz \left(\frac{1}{2} h(z) \mathrm{Tr} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu} + k(z) \mathrm{Tr} \mathcal{F}_{\mu z} \mathcal{F}^{\mu}_{z} \right)$$

$$\kappa = \frac{\lambda N_c}{216\pi^3}$$

$$h(z) = (1 + z^2)^{-1/3}$$

$$k(z) = (1 + z^2)$$

Coordinates on cigar:



Review of Holographic QCD

Mesons

- Expand (N_f=1) $\mathcal{A}_z = \sum_n \varphi^{(n)}(x_\mu)\phi_n(z)$

  $\mathcal{A}_\mu = \sum_n B_\mu^{(n)}(x_\mu)\psi_n(z)$

  Complete normalized sets

- Get

$$S_{DBI} = \kappa \int d^4x \left[\left(\sum_{n=1} \frac{1}{4} F_{\mu\nu}^{(n)} F^{\mu\nu(n)} + \frac{1}{2} m_n^2 B_\mu^{(n)} B^{\mu(n)} \right) + \frac{1}{2} \partial_\mu \varphi^{(0)} \partial^\mu \varphi^{(0)} \right]$$

$B_\mu^{(n)}$: tower of (axial) vector mesons (ρ , a_1, …), $F^{(n)} = dB^{(n)}$

$\varphi^{(0)}$: Goldstone of chiral symmetry breaking, the pion

- Masses $m_n^2 = \lambda_n M_{KK}^2$ from equation of motion

$$-h(z)^{-1}\partial_z \left(k(z)\partial_z \psi_n(z)\right) = \lambda_n \psi_n(z)$$

Review of Holographic QCD

Low-energy effective action for $N_f > 1$

- Define pion matrix

$$U = \mathcal{P}e^{i\int \mathcal{A}_z} = e^{i\Pi(x)/f_\pi}$$

$$f_\pi = 2\sqrt{\frac{\kappa}{\pi}}$$

$$\mathcal{F}_{\mu z} \approx U^{-1}\partial_\mu U \qquad \mathcal{F}_{\mu\nu} \approx \left[U^{-1}\partial_\mu U, U^{-1}\partial_\nu U\right]$$

- Get

$$e = -\frac{1}{2.5\kappa}$$

$$\mathcal{L}_{\rm eff} = -\frac{f_\pi^2}{4} Tr\left[\partial_\mu U \partial^\mu U^\dagger\right] + \frac{1}{32e^2} Tr\left[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U\right]^2$$

Chiral Lagrangian with Skyrme term, derived from gravity!

Review of Holographic QCD

Incomplete list of extensions:

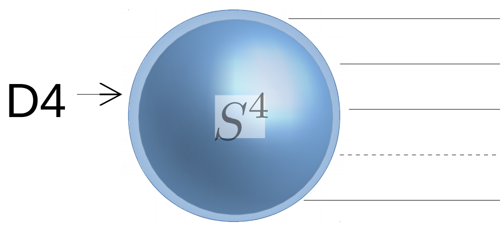
- Vector mesons in Chiral Lagrangian
- Chiral anomaly from D8-brane Chern-Simons term (WZW term)
- Witten-Veneziano formula for η' mass
- Interactions among mesons (vector meson dominance) [Sakai-Sugimoto 05]
- Addition of (small) quark mass [Aharony-Kutasov 08, Hashimoto et al 08]
- θ - angle [Sakai-Sugimoto 04, Bartolini et al 16]
- Finite baryon density [Horigome-Tanii 06]
- Further meson modes from oscillating strings [Imoto-Sakai-Sugimoto 10]
- Baryons
- Deconfinement

Extensions: baryons and deconfinement

Baryons

- Microscopic point of view: D4-branes wrapped on four-sphere + strings [Witten 98]

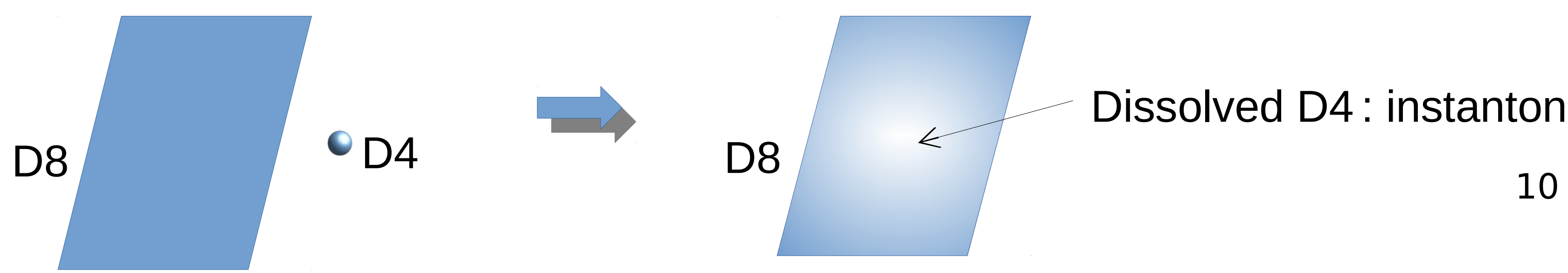
$$S_{D4} = \frac{T_4}{g_s}\int d^9x\, e^{-\Phi}\sqrt{\det g} = m_B \int dt \qquad \text{with} \quad m_B = \frac{\lambda N_c}{27\pi} M_{KK}$$



N_c strings to account for flux of F_4

View recently employed for excited baryons [Hayashi et al. 20]

- Macroscopic point of view: instantonic configurations on D8-brane world-volume [Hata et al. 07, Hong et al. 07]



Extensions: baryons and deconfinement

Baryons

- Macroscopic point of view (N_f=2) [Hata et al. 2007]

Standard instanton solution in directions $x_{i=1,2,3}, z$ describing nucleon

$$\mathcal{A}_M^{nAb} = -if(\xi)g\partial_M g^{-1} \qquad \mathcal{A}_0^{Ab} = \frac{N_c}{8\pi^2\kappa}\frac{1}{\xi^2}\left[1 - \frac{\rho^4}{(\rho^2+\xi^2)^2}\right]$$

$$f(\xi) = \frac{\xi^2}{\rho^2+\xi^2} \qquad g = \frac{(z-Z)\mathbf{1} - i(\vec{x}-\vec{X})\cdot\vec{\tau}}{\xi} \qquad \xi^2 = (\vec{x}-\vec{X})^2 + (z-Z)^2$$

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

Energy coincides with baryon mass m_B

Can extract many observables (radii, couplings, etc.)

Other baryons from quantization of (pseudo) moduli $\rho, Z, \vec{X}, \vec{a}$

Extensions: baryons and deconfinement

How does the WSS model perform?

Some meson masses:
(table from [Rebhan 14])

Isotriplet Meson	$\lambda_n = m^2/M^2_{KK}$	m/m_ρ	$(m/m_\rho)^{exp.}$	m/m_ρ [30]
0^{-+} (π)	0	0	0.174 |0.180	0
1^{--} (ρ)	0.669314	1	1	1
1^{++} (a_1)	1.568766	1.531	1.59(5)	1.86(2)
1^{--} (ρ^*)	2.874323	2.072	1.89(3)	2.40(4)
1^{++} (a_1^*)	4.546104	2.606	2.12(3)	2.98(5)

Some nucleon properties:
(table from [Hashimoto et al 08])

	WSS	Skyrmion	experiment
$\langle r^2\rangle^{1/2}_{I=0}$	0.742 fm	0.59 fm	0.806 fm
$\langle r^2\rangle^{1/2}_{M,I=0}$	0.742 fm	0.92 fm	0.814 fm
$\langle r^2\rangle_{E,p}$	(0.742 fm)^2	∞	(0.875 fm)^2
$\langle r^2\rangle_{E,n}$	0	$-\infty$	-0.116 fm^2
$\langle r^2\rangle_{M,p}$	(0.742 fm)^2	∞	(0.855 fm)^2
$\langle r^2\rangle_{M,n}$	(0.742 fm)^2	∞	(0.873 fm)^2
$\langle r^2\rangle^{1/2}_{A}$	0.537 fm	–	0.674 fm
μ_p	2.18	1.87	2.79
μ_n	-1.34	-1.31	-1.91
$\left\lvert\frac{\mu_p}{\mu_n}\right\rvert$	1.63	1.43	1.46
g_A	0.734	0.61	1.27
$g_{\pi NN}$	7.46	8.9	13.2
$g_{\rho NN}$	5.80	–	4.2 ~ 6.5

Extensions: baryons and deconfinement

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On top of geometrizing qualitative features of large N_c QCD, exhibiting the correct symmetry (breaking) pattern, the model gives some quantitatively reasonable observables in the IR

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Extensions: baryons and deconfinement

Deconfined phase

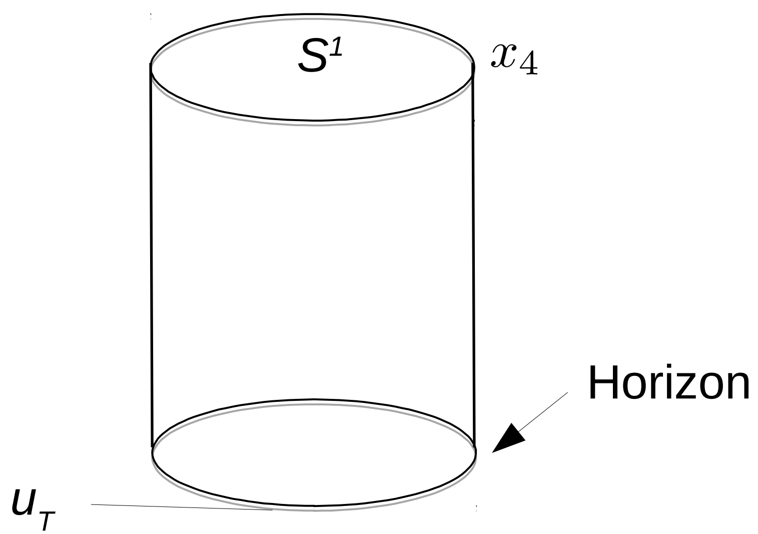
- In Holographic YM: D4 black-brane solution [Witten 98]

$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(-f_T(u)dt^2 + dx^i dx_i + dx_4^2\right) + \left(\frac{R}{u}\right)^{3/2}\frac{du^2}{f_T(u)} + R^{3/2}u^{1/2}d\Omega_4^2$$

Cylinder

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

$g_{tt}(u_T) = 0 \;\Rightarrow$ deconfinement



$$T \sim \sqrt{u_T}$$

Extensions: baryons and deconfinement

Deconfined phase

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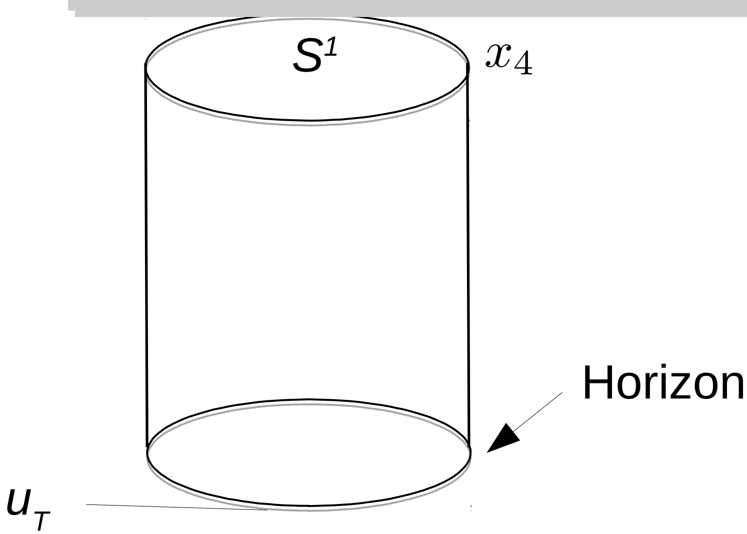
Confinement / deconfinement: first order transition at $T_c = M_{KK}$

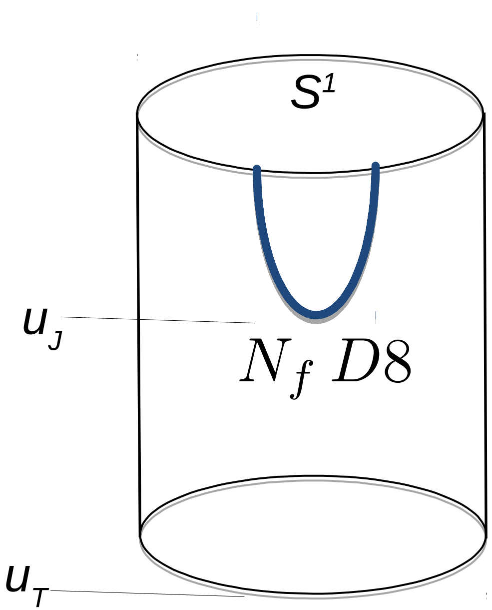
$$T \sim \sqrt{u_T}$$



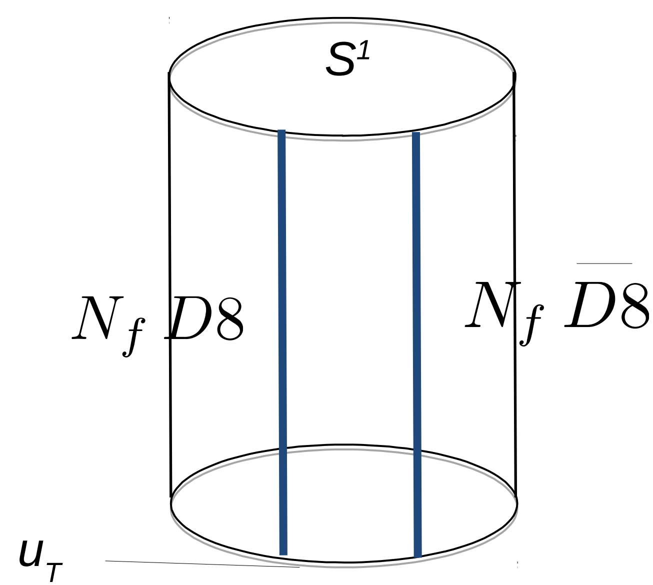
Extensions: baryons and deconfinement

Deconfined phase

- In Holographic QCD: chiral symmetry can persist if D8 non-antipodal [Aharony-Sonnenschein-Yankielowicz 06]
- Chiral symmetry breaking transition at new scale $f_\chi \sim u_J$
- Chiral symmetry broken phase:



- Chiral symmetry unbroken phase:

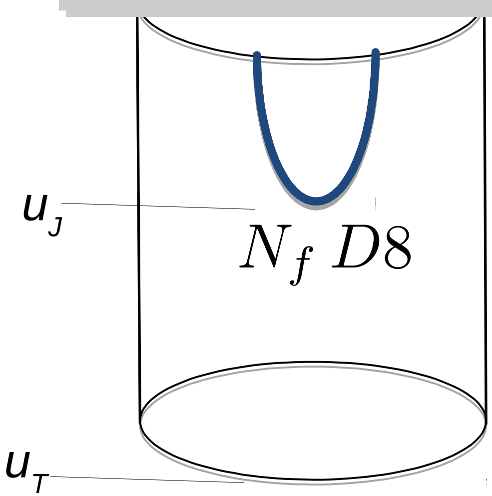


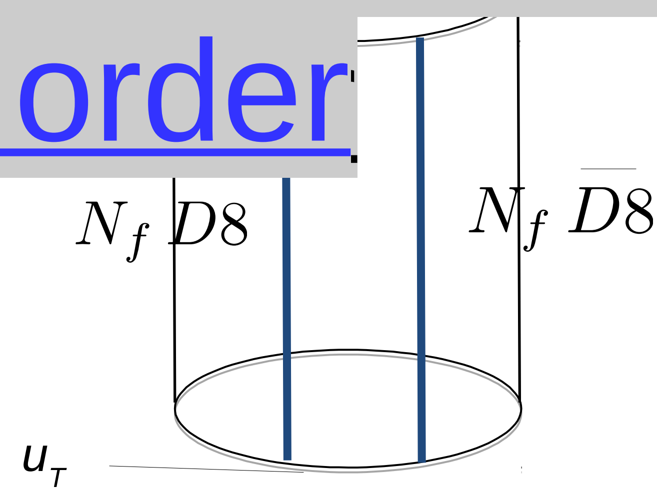
Extensions: baryons and deconfinement

Deconfined phase

- In Holographic QCD: chiral symmetry can persist if D8 non-antipodal [Aharony-Sonnenschein-Yankielowicz 06]
- Chiral symmetry breaking transition at new scale $f_\chi \sim u_J$
- Chiral symmetry b... unbroken phase:

Chiral symmetry breaking/restoration transition is first order





Gravitational waves and cosmology

Abstract

I. We are in an era of Gravitational Wave (GW) observations

II. Cosmological first order transitions generate GWs

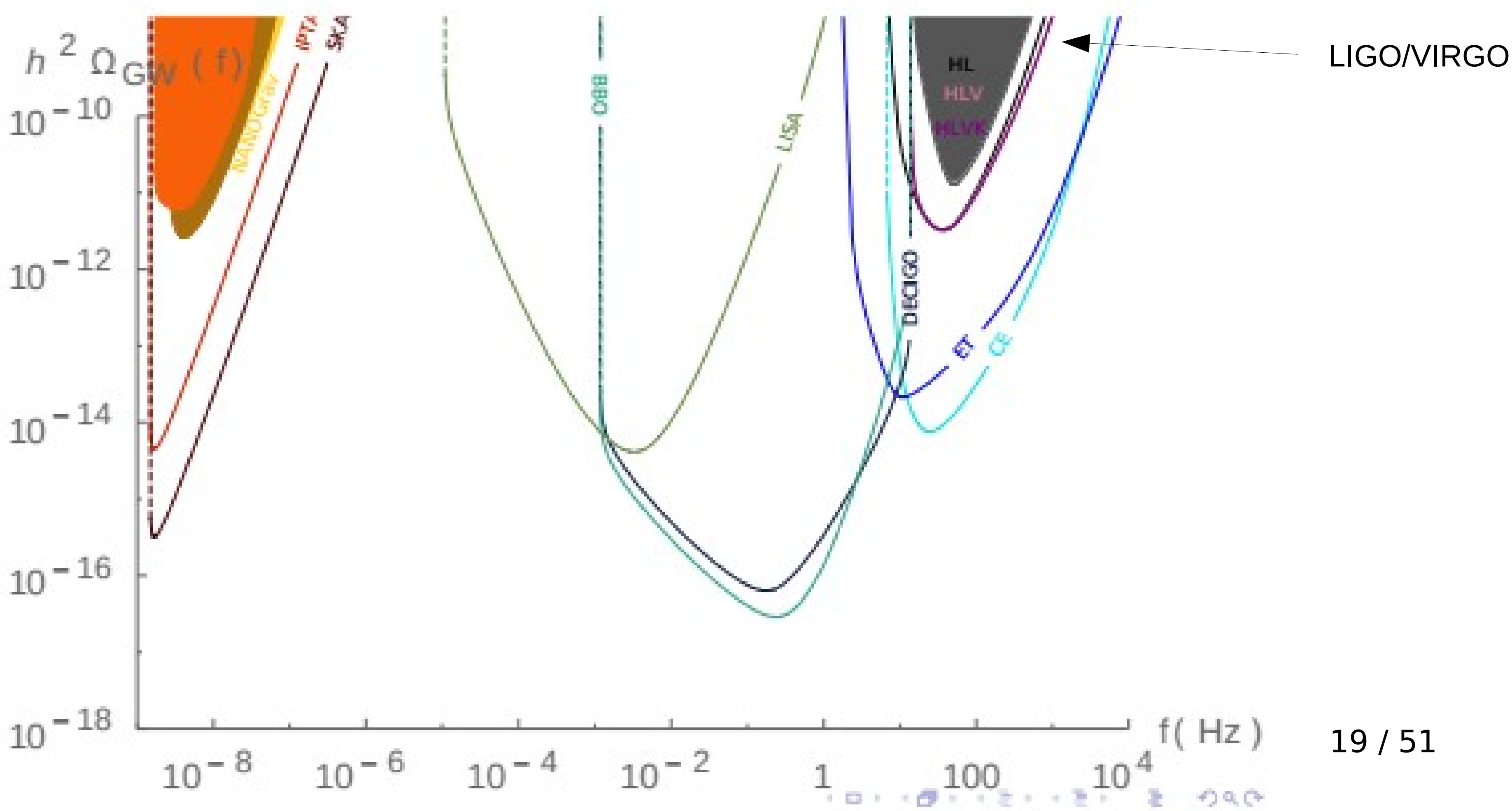
III. “Dark sectors” (hidden sectors) can undergo cosmological first order transitions

IV. If dark sectors holographic: calculate GW spectra from dual string description

V. These GW spectra can be within reach of future experiments

Gravitational waves and cosmology

Zoo of experimental sensitivity curves

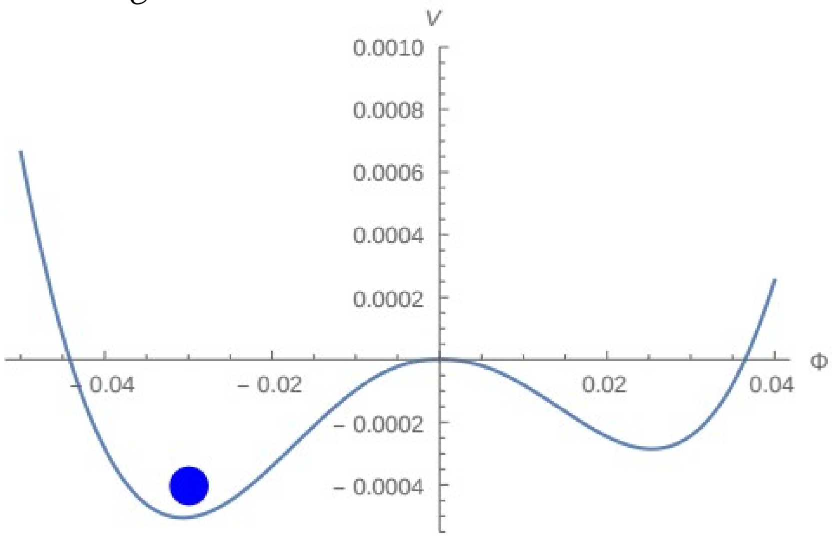


Gravitational waves and cosmology

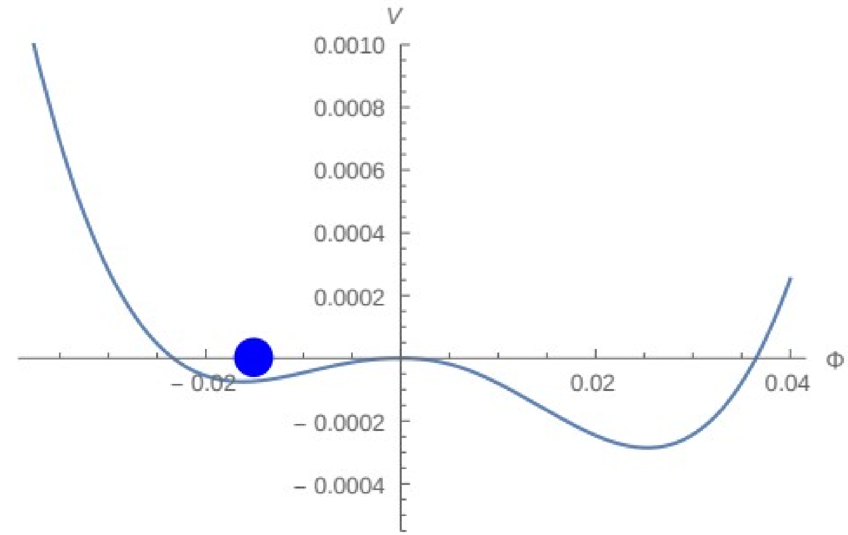
Bubbles in first order transitions

[Coleman 77, Callan-Coleman 77, Coleman-DeLuccia 78, Linde 81-83]

$T > T_c$



$T < T_c$



- Single scalar potential

$$V = -\left(5\Phi^3 + T(-\Phi)^{5/2}\right)\Theta(-\Phi) + \left(5\Phi^3 - M_{KK}\Phi^{5/2}\right)\Theta(\Phi)$$

- Universe expands and cools down

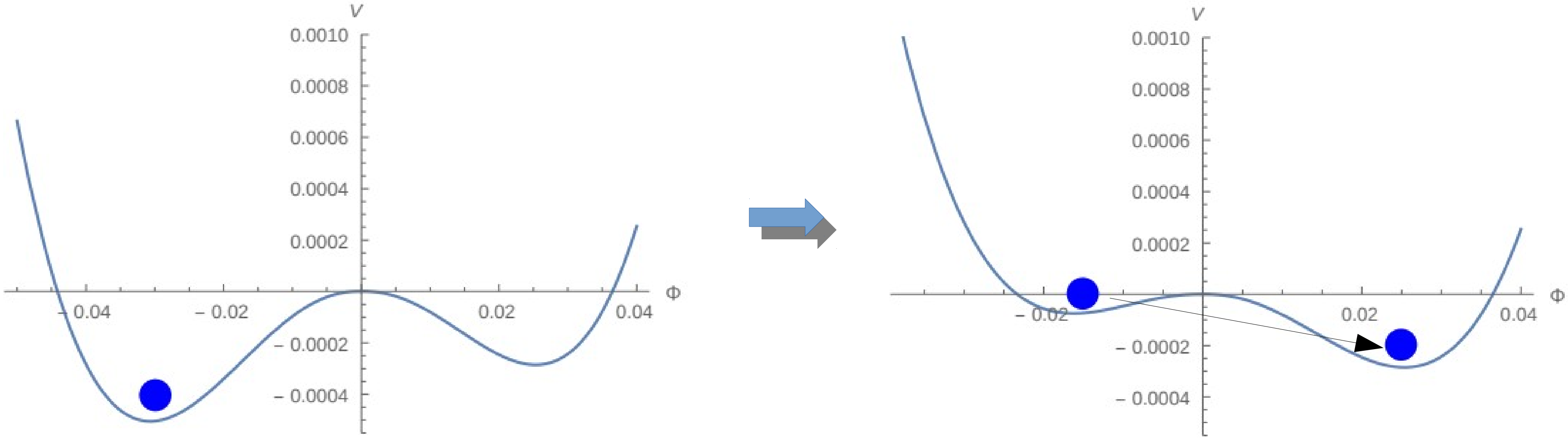
- First order transition at $T = T_c = M_{KK}$

Gravitational waves and cosmology

Bubbles in first order transitions

[Coleman 77, Callan-Coleman 77, Coleman-DeLuccia 78, Linde 81-83]

$T > T_c$ $\qquad\qquad$ $T < T_c$



- When $T < T_c$ Universe is in the “false vacuum”
- Starts nucleation of bubbles of “true vacuum” with rate

$$\Gamma \sim T^4 \ \mathrm{Exp}[-S(\Phi_{bubble})]$$

Gravitational waves and cosmology

Bubbles in first order transitions

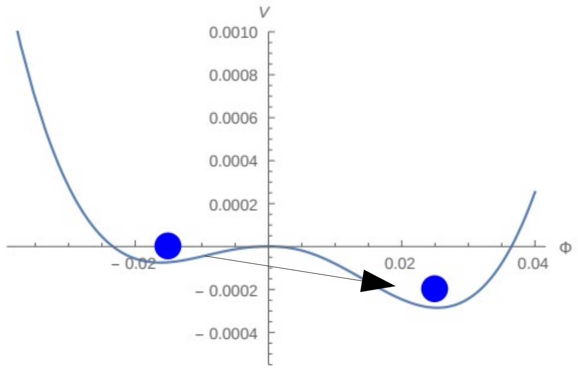
[Coleman 77, Callan-Coleman 77, Coleman-DeLuccia 78, Linde 81-83]

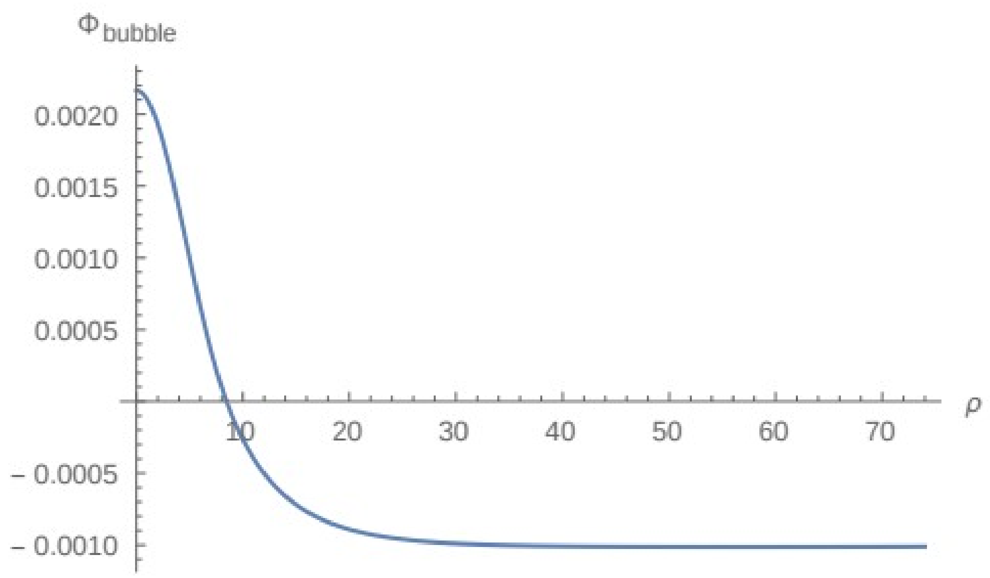
Radial direction in Minkowski

$\Phi_{bubble}(\rho)$: bubble configuration interpolating

between "true vacuum" for $\rho \to 0$

and "false vacuum" for $\rho \to \infty$





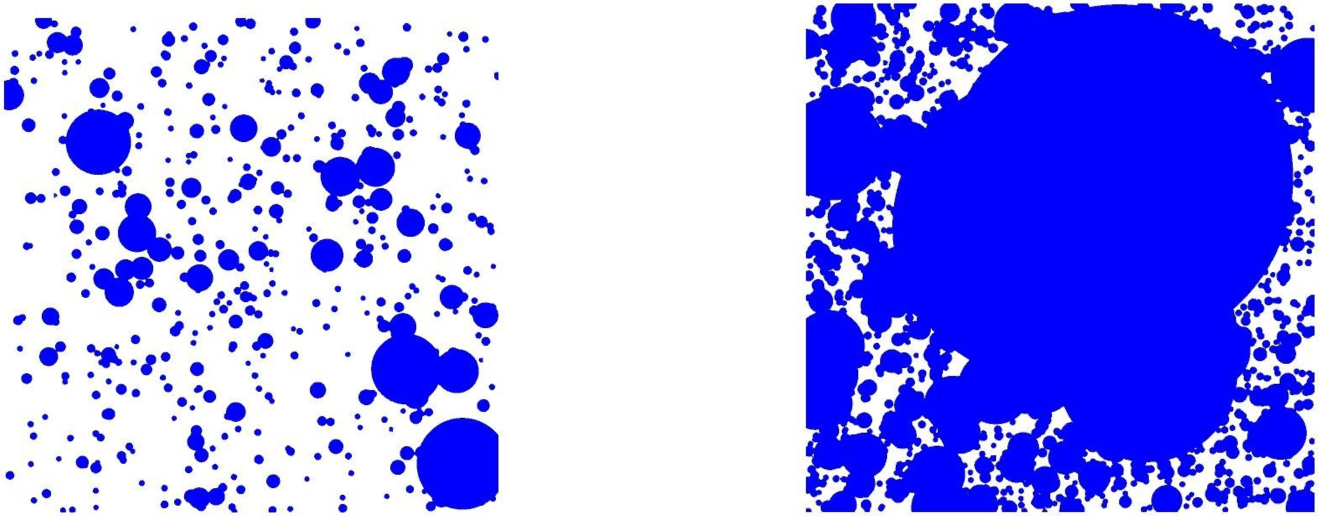
Gravitational waves and cosmology

- After nucleation, bubbles expand
- At "nucleation temperature" T_n such that

$$\frac{\Gamma}{H^4}\Big|_{T_n} \sim 1$$

Hubble parameter

bubbles percolate, leaving whole Universe in "true vacuum"



Images from [Freivogel-Kleban 09]

Gravitational waves and cosmology

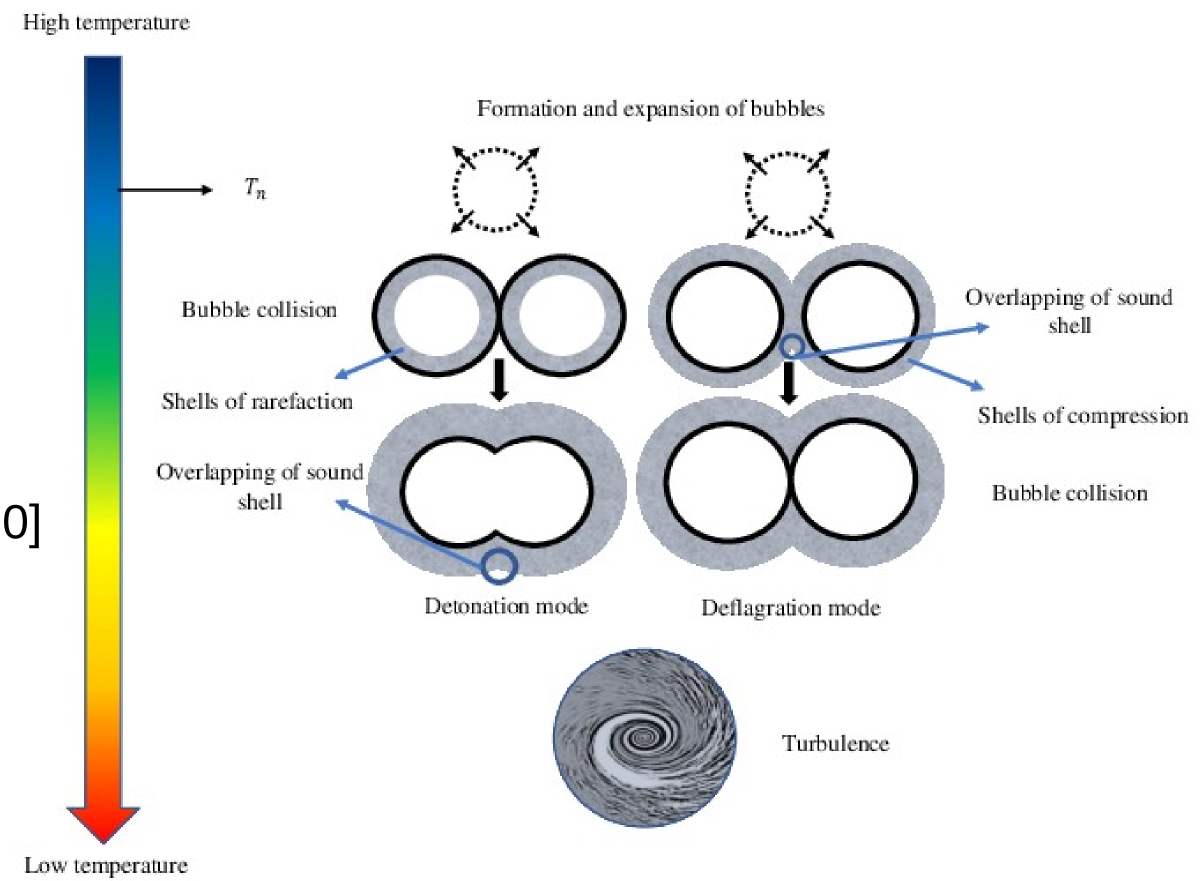
Bubbles excite plasma modes. GW produced by:

I. Bubble collisions

II. Sound wave collisions

III. Turbulence in plasma

Image from [Wang-Huang-Zhang 20]



Sound wave component dominates spectrum: let's focus on it

Gravitational waves and cosmology

$$h^2\Omega_{sw}(f) \sim 8.5 \cdot 10^{-6} \left(\frac{\beta}{H}\right)^{-1} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} v\, S_{sw}(f)$$

[Hindmarsh-Huber-Rummukainen-Weir 17]

$f =$ wave frequency

$\frac{\beta}{H} = -\frac{T}{\Gamma}\frac{d\Gamma}{dT}|_{T_n} =$ inverse phase transition duration

$\kappa_v = \frac{\alpha}{0.73 + 0.083\sqrt{\alpha} + \alpha} =$ efficiency factor

$\alpha = \frac{\Delta\rho - 3\Delta p}{4\rho_{radiation}} =$ phase transition strength

$g_* =$ # of relativistic degrees of freedom

$v =$ bubble velocity

Quantities in blue to be computed in microscopic model

$$S_{sw} = \left(\frac{f}{f_{sw}}\right)^3 \left(\frac{7}{4 + 3(f/f_{sw})^2}\right)^{7/2} = \text{ spectral shape}$$

$$f_{sw} = 8.9 \cdot 10^{-6}\mathrm{Hz}\frac{1}{v}\left(\frac{\beta}{H}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} = \text{ peak frequency}$$

Gravitational waves and cosmology

$$h^2\Omega_{sw}(f) \sim 8.5 \cdot 10^{-6} \left(\frac{\beta}{H}\right)^{-1} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} v\, S_{sw}(f)$$

[Hindmarsh-Huber-Rummukainen-Weir 17]

$f =$ wave frequency

β ... $T\, d\Gamma$ ...

We calculate the parameters with holography

$\kappa_v =$ ... $0.73 + 0.0$...

...o be computed in ...microscopic model

$\alpha = \dfrac{\Delta\rho - 3\Delta p}{4\rho_{radiation}}$

$g_* =$ # of relativistic degrees of freedom

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$$S_{sw} = \left(\frac{f}{f_{sw}}\right)^3 \left(\frac{7}{4+3(f/f_{sw})^2}\right)^{7/2} = \text{ spectral shape}$$

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Dark holograms

Motivations:

- A number of proposed “Dark sectors” are Yang-Mills or QCD-like theories
- Strong dynamics is crucial
- If gauge group rank sufficiently large, theory might admit gravity dual
- Holography describes strong dynamics in <u>reliable</u> way, or models it effectively

Let’s model Dark sector with the (top-down) holographic theory closest to QCD:

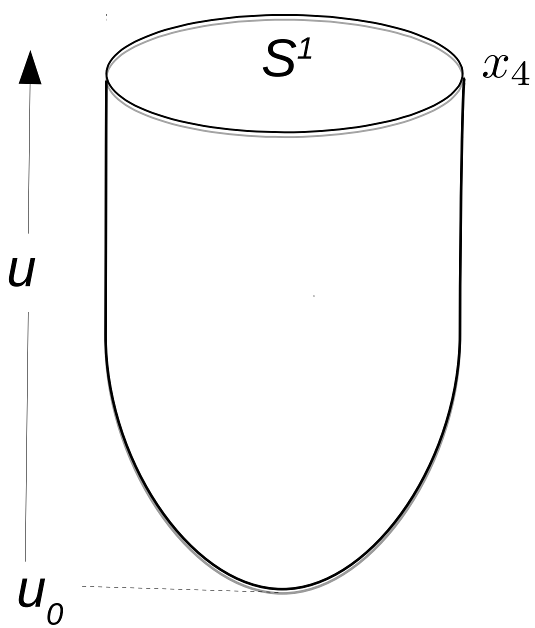
Witten-Sakai-Sugimoto model

Dark holograms

"Dark glueball scenario"
[Witten 98]

- IIA background from N_c $D4$ wrapped on S^1
- Low energy: dual to 4d $SU(N_c)$ YM + KK modes
- Confined phase:

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



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

Parameters:

- $N_c \gg 1 \qquad \lambda = g_{YM}^2 N_c \gg 1$
- $\Lambda_{YM} \equiv M_{KK} \sim \sqrt{u_0}$

Dark holograms

“Dark glueball scenario”
[Witten 98]

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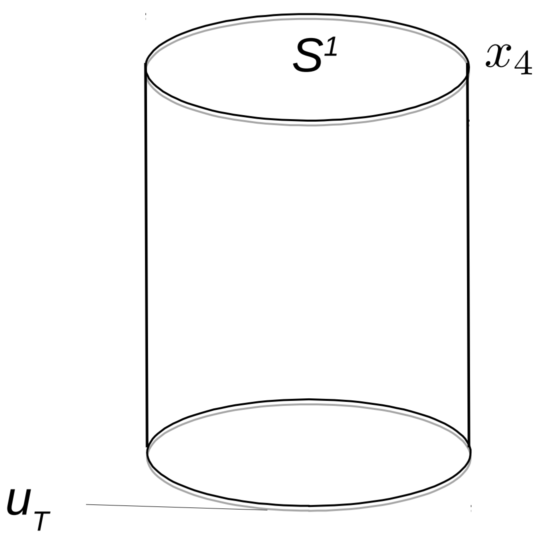
- Low energy: dual to 4d $SU(N_c)$ YM + KK modes
- Deconfined phase:

$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(-f_T(u)dt^2 + dx^i dx_i + dx_4^2\right) + \left(\frac{R}{u}\right)^{3/2}\frac{du^2}{f_T(u)} + R^{3/2}u^{1/2}d\Omega_4^2$$



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

Parameters:

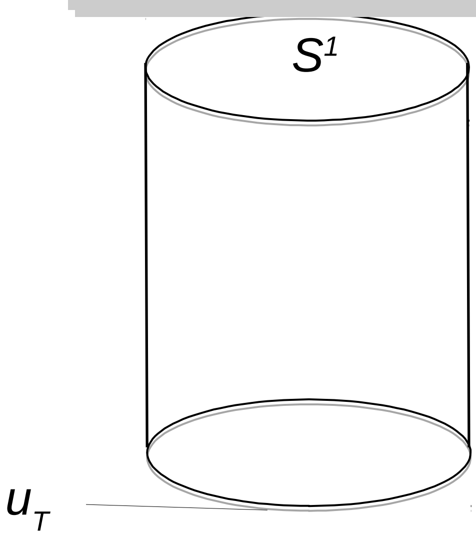
- $N_c \gg 1 \qquad \lambda = g_{YM}^2 N_c \gg 1$
- $T \sim \sqrt{u_T}$

Dark holograms

"Dark glueball scenario"
[Witten 98]

- IIA background from N_c $D4$ wrapped on S^1

Confinement / deconfinement first order transition at $T_c = M_{KK}$



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

Parameters:

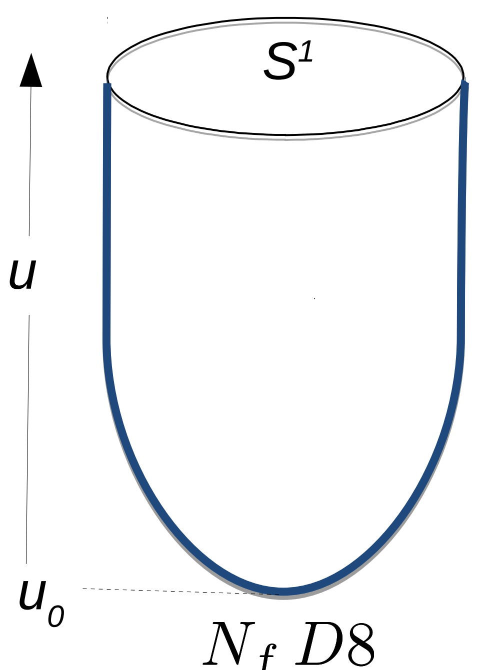
- $N_c \gg 1 \qquad \lambda = g_{YM}^2 N_c \gg 1$
- $T \sim \sqrt{u_T}$

Dark holograms

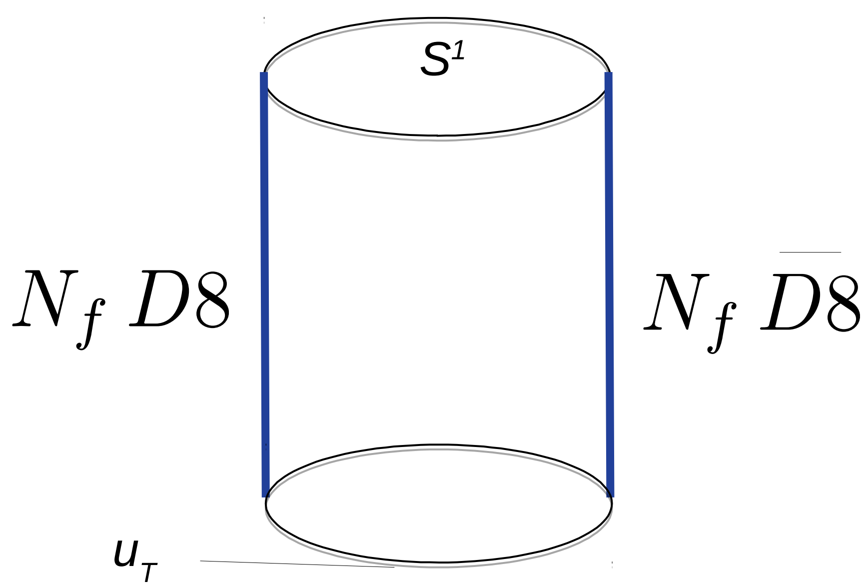
"Dark QCD scenario"

[Sakai-Sugimoto 04, Aharony-Sonnenschein-Yankielowicz 06]

- Add N_f antipodal probe $D8$/anti-$D8$ pairs
- Low energy: dual to 4d $SU(N_c)$ YM + KK modes + N_f quark flavors
- Confined phase:



- Deconfined phase:

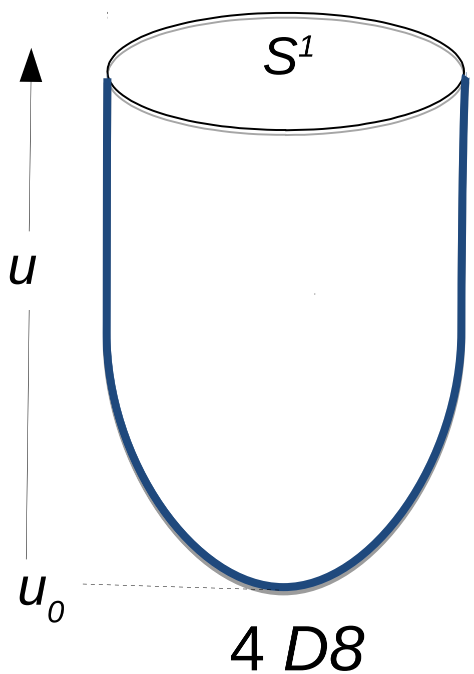


Dark holograms

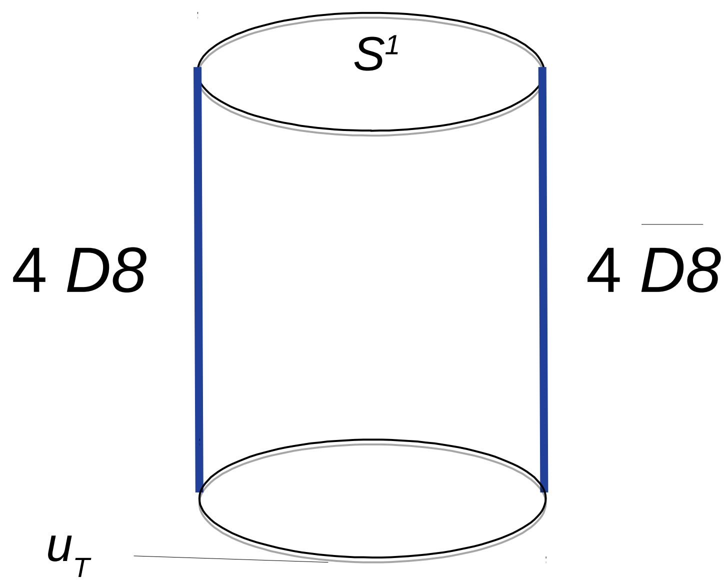
"Dark Axion scenario"

[Kim, Choi-Kim, Kaplan 1985, Bigazzi-Caddeo-ALC-Paredes 20]

- Add N_f=3+1 antipodal probe $D8$/anti-$D8$ pairs, realize composite axion as PNGB
- Flavors are in triplet and singlet of ordinary color $SU(3)_c$
- Confined phase:



- Deconfined phase:



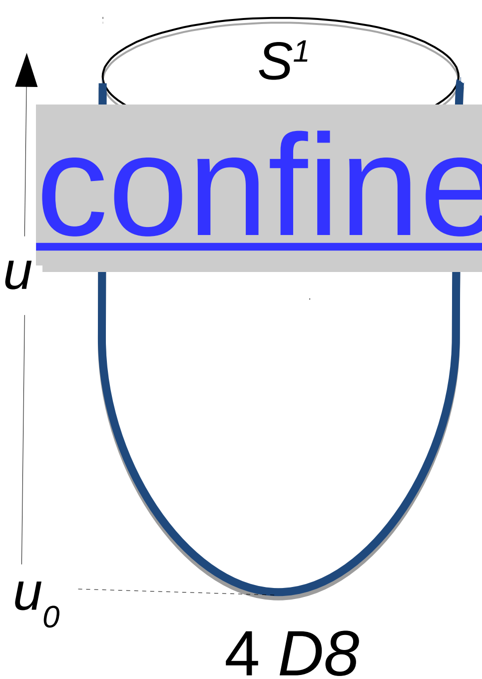
Dark holograms

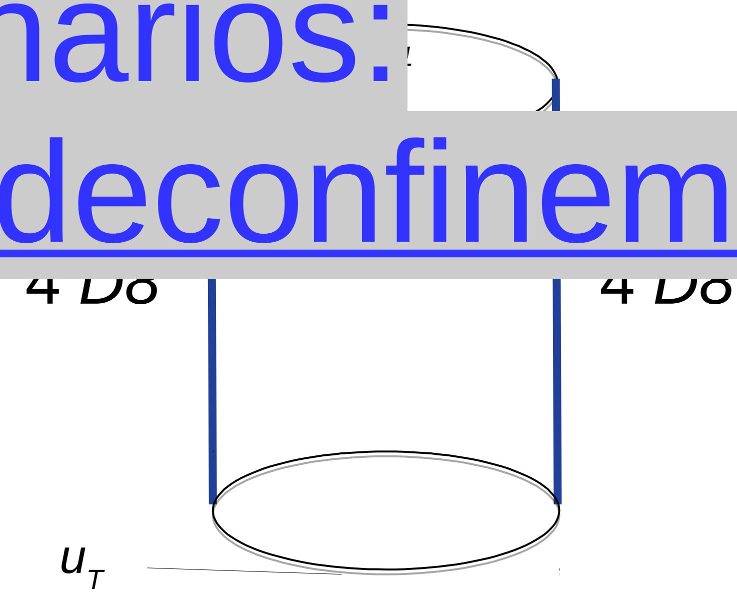
"Dark Axion scenario"

[Kim, Choi-Kim, Kaplan 1985, Bigazzi-Caddeo-ALC-Paredes 20]

- Add N_f=3+1 antipodal probe $D8$/anti-$D8$ pairs, realize composite axion as PNGB

Same first order transition in all 3 scenarios: confinement / deconfinement



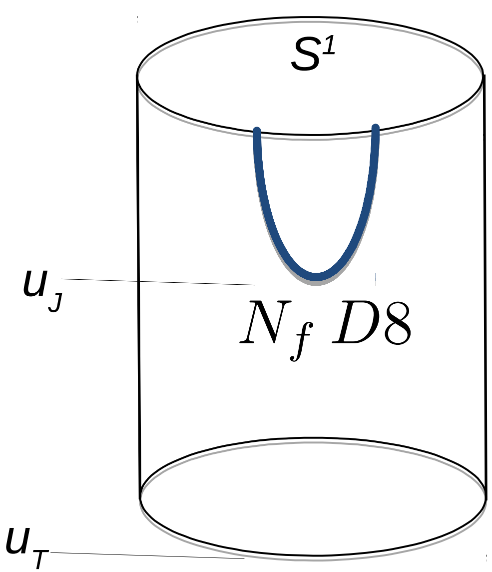


Dark holograms

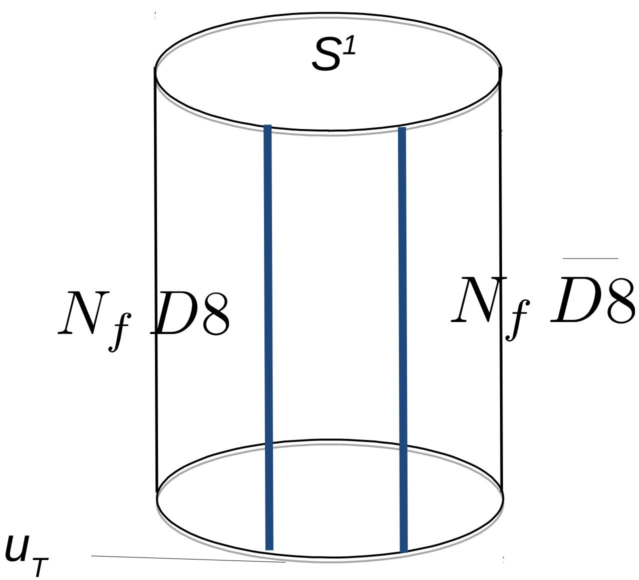
"Dark QCD ChiSB scenario"

[Aharony-Sonnenschein-Yankielowicz 06]

- Add N_f non-antipodal probe $D8$/anti-$D8$ pairs
- Chiral symmetry breaking transition at new scale $f_\chi \sim u_J$ (in deconfined phase)
- Chiral symmetry broken phase:



- Unbroken phase:



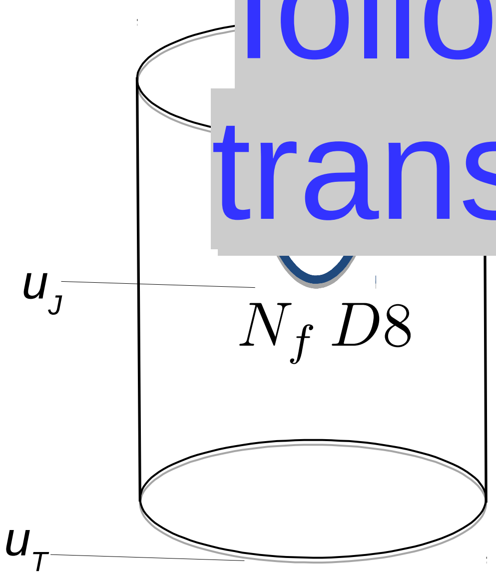
Dark holograms

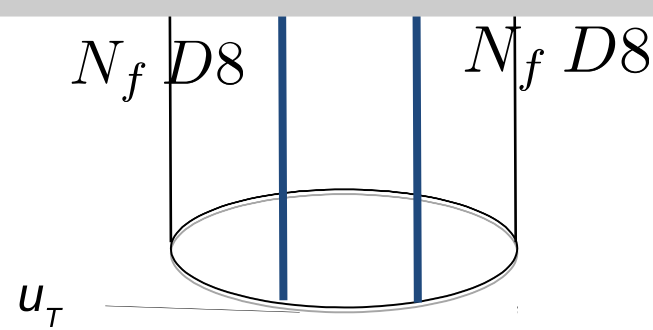
“Dark QCD ChiSB scenario”

[Aharony-Sonnenschein-Yankielowicz 06]

- Add N_f non-antipodal probe $D8$/anti-$D8$ pairs
- Chira … hase)
- Chiral s …

Chiral symmetry breaking followed by confinement transition: both first order



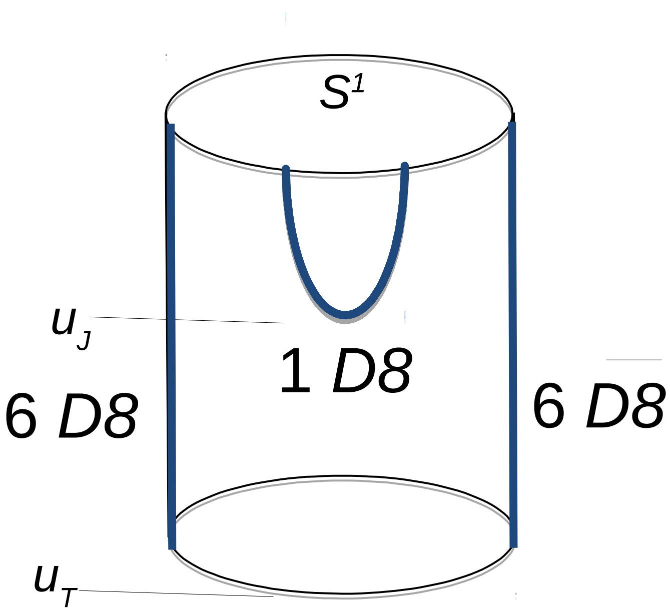


Dark holograms

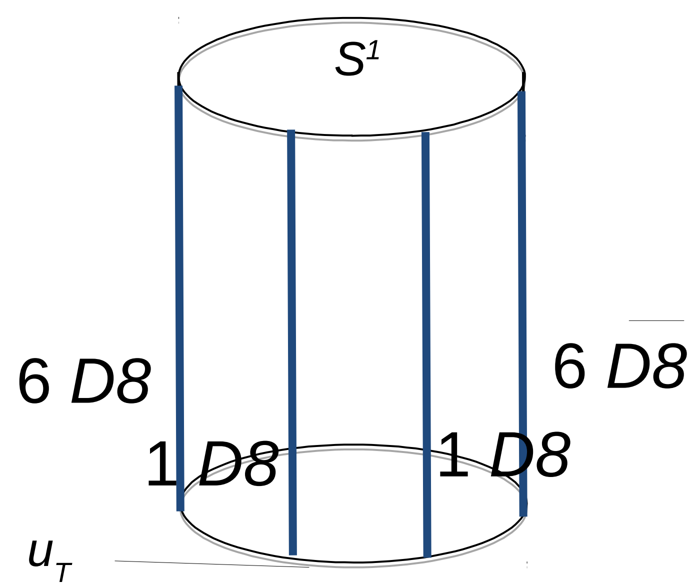
"Holo-Axion scenario"

[Bigazzi-Caddeo-ALC-Di Vecchia-Marzolla 19]

- Add 6 antipodal and 1 non-antipodal probe *D*8/anti-*D*8 pairs
- Model of QCD + axion, $f_\chi = f_a =$ axion decay constant
- Chiral symmetry broken phase:



- Unbroken phase:



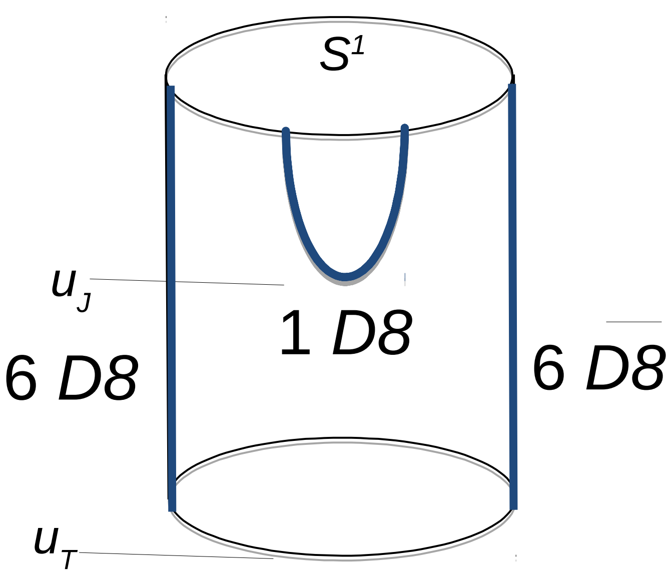
Dark holograms

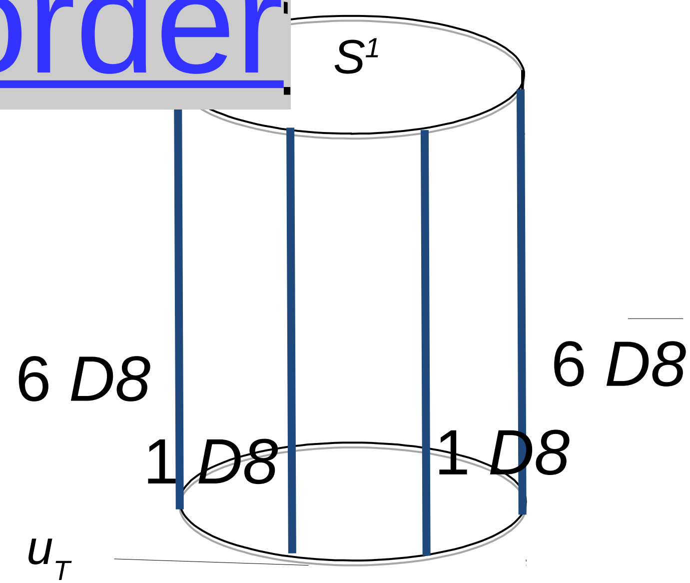
“Holo-Axion scenario”

[Bigazzi-Caddeo-ALC-Di Vecchia-Marzolla 19]

- Add *6* antipodal and 1 non-antipodal probe *D*8/anti-*D*8 pairs
- Mode
- Chiral symmetry broken ph ... en phase.

Peccei-Quinn transition is first order





GWs from Confinement transition

$$h^2\Omega_{sw}(f) \sim 8.5 \cdot 10^{-6} \left(\frac{\beta}{H}\right)^{-1} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} v\, S_{sw}(f)$$

- Thermodynamic-related parameters easily determined from standard relation

$$f = \frac{S^{ren}_{gravity} T}{V_3}$$

Renormalized on-shell gravitational action

Free energy density

Three dimensional volume

obtaining α, g_*, κ_v, v

- Difficult part: bubble configuration $\Phi_{bubble}(\rho)$ to get $\beta/H, T_*$

In principle: solve full set of 10d supergravity equations ← extremely challenging!

In practice: model bubble with single scalar mode

GWs from Confinement transition

Model bubble with single scalar mode [Creminelli-Nicolis-Rattazzi 2001]

- Bubble has to interpolate between two metrics

1) Conf:
$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(dx^\mu dx_\mu + f(u) dx_4^2\right) + \left(\frac{R}{u}\right)^{3/2}\frac{du^2}{f(u)} + R^{3/2}u^{1/2}d\Omega_4^2$$
$$f(u) = 1 - \frac{u_0^3}{u^3}$$

2) Deconf:
$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(-f_T(u) dt^2 + dx^i dx_i + dx_4^2\right) + \left(\frac{R}{u}\right)^{3/2}\frac{du^2}{f_T(u)} + R^{3/2}u^{1/2}d\Omega_4^2$$
$$f_T(u) = 1 - \frac{u_T^3}{u^3}$$

- Idea: main contribution from modes u_0 (conf phase) and u_T (deconf phase)

  Combine them in a single scalar field $\Phi(\rho)$

  Potential and kinetic term given by gravity action

GWs from Confinement transition

$$u_T(\rho) \sim T_h^2(\rho)$$

- Potential ([Creminelli-Nicolis-Rattazzi 01] in AdS case)

When $T_h = T$ black brane geometry is regular, free energy

$$f_{BB} = -\frac{1}{2}\left(\frac{2}{3}\right)^7 \pi^4 \lambda N_c^2 \frac{T_h^6}{M_{KK}^2}$$

When $T_h \neq T$ geometry has conical singularity: extra free energy contribution

estimated by replacing singularity with spherical cap [Fursaev-Solodukhin 95]

$$f_{sing} = -\frac{T}{2\kappa_{10}^2 V_3}\int d^{10}x\sqrt{g}e^{-2\phi}\mathcal{R}_{S^2} = 3\left(\frac{2}{3}\right)^7 \pi^4 \lambda N_c^2 \frac{T_h^6}{M_{KK}^2}\left(1 - \frac{T}{T_h}\right)$$

$\Rightarrow$ $$V(T_h) = \frac{1}{2}\left(\frac{2}{3}\right)^7 \pi^4 \lambda N_c^2 \frac{1}{M_{KK}^2}\left(5T_h^6 - 6TT_h^5\right)$$

GWs from Confinement transition

$$u_T(\rho) \sim T_h^2(\rho)$$

- <u>Kinetic term</u> [Bigazzi-Caddeo-ALC-Paredes 20]

From gravity action term

$$S_{kin} = -\frac{1}{2\kappa_{10}^2} \int d^{10}x\sqrt{g}\left[e^{-2\phi}\left(\mathcal{R} + 4\partial_\rho\phi\partial^\rho\phi\right)\right] \sim \int d^4x\ \partial_\mu T_h \partial^\mu T_h$$

Divergence from integration in *u* ➡ holographic renormalization

Add counter-term

$$S_{kin\,ct} = -\frac{1}{2\kappa_{10}^2}\left(-\frac{40R}{9g_s^{1/3}}\right)\int_{u=u_{UV}} d^9x\,\sqrt{h}\,e^{-\frac{5}{3}\phi}\,h^{mn}\,\partial_m\phi\,\partial_n\phi$$

GWs from Confinement transition

- Similar story for $u_0(\rho) \sim M_h^2(\rho)$ ("radion" in Randall-Sundrum set-ups)
- Define $\Phi = (-T_h^2 \text{ for } \Phi < 0, +M_h^2 \text{ for } \Phi > 0)$
- Full action

$$\frac{S_3}{T} = \frac{32\pi^4}{3^5 \bar{T}} \lambda N_c^2 \int_0^\infty d\bar{\rho}\bar{\rho}^2 \left[\left(5 - \frac{\pi}{2\sqrt{3}}\right) \Phi'^2 + V(\Phi) \right]$$

with

$$V(\Phi) = \frac{16\pi^2}{9} \left[-\left(5\Phi^3 + \frac{3}{\pi}\bar{T}(-\Phi)^{5/2}\right)\Theta(-\Phi) + \left(5\Phi^3 - \frac{3}{\pi}\Phi^{5/2}\right)\Theta(\Phi) \right]$$

⇒ Just solve for this system

$$\Phi_{bubble} \;\Rightarrow\; \Gamma \;\Rightarrow\; \beta/H, T_* \;\Rightarrow\; \Omega_{GW}$$

GWs from Confinement transition

Bonus track: same story in Randall-Sundrum (AdS)

- Potential known from [Creminelli-Nicolis-Rattazzi 01]
- Kinetic term in deconfined phase [Bigazzi-Caddeo-ALC-Paredes 20]

$$S_{deconf} = \frac{N_c^2}{16\pi^2}\, p \int d^4x \left[6\pi^2 (\partial_\mu T_h)^2 + 2\pi^4 (3T_h^4 - 4T_h^3 T)\right]$$

p determined by 10d embedding

$$p = \frac{\pi^3}{V(X_5)}$$

Volume of compact manifold

e.g. $p = 1$ for $X_5 = S^5$

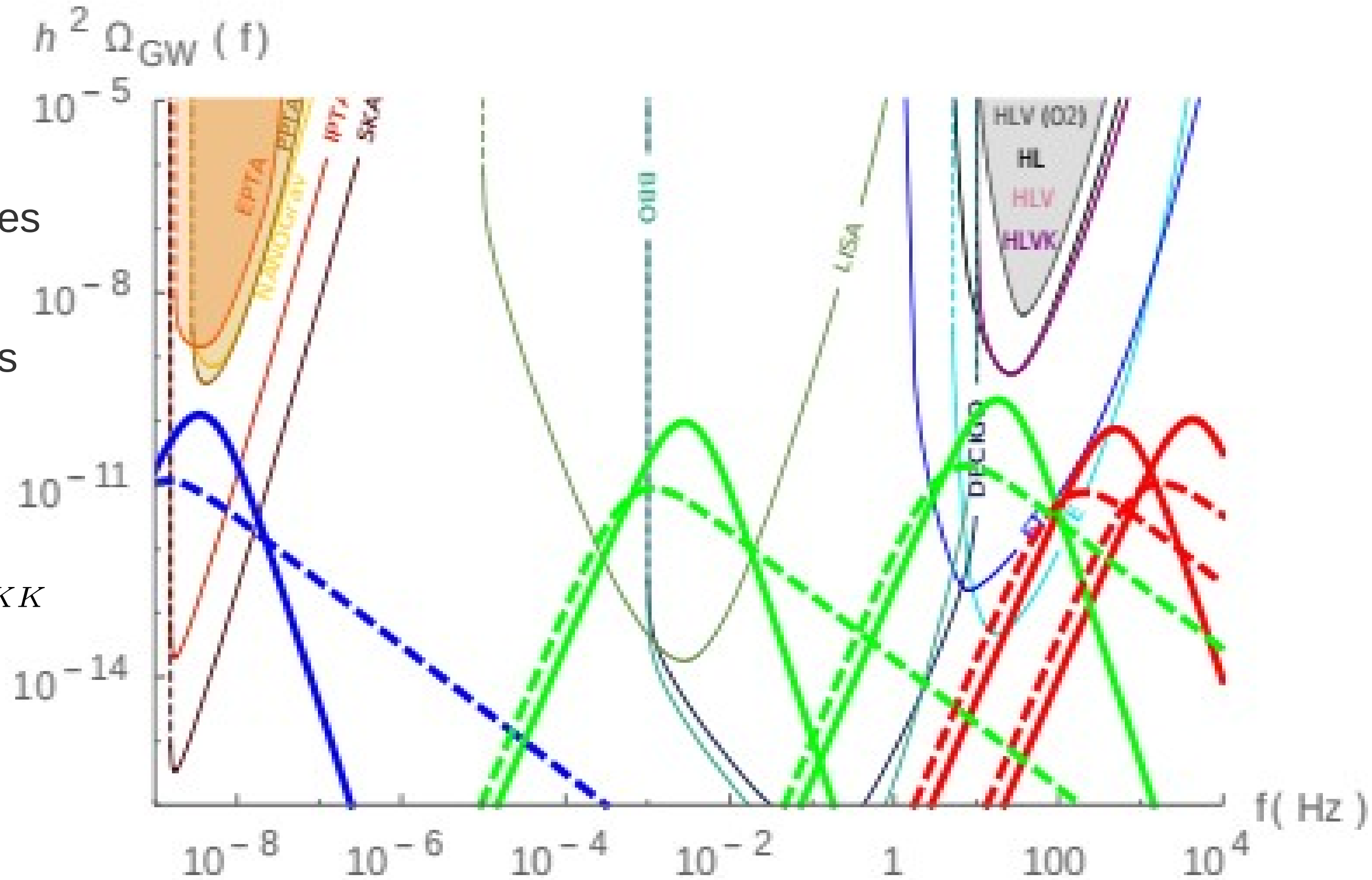
GWs from Confinement transition

Results:

Solid lines: sound waves

Dashed lines: collisions

Parameters: $\lambda N_c^2,\ M_{KK}$



- Blue: "Dark glueball scenario", $1\ \mathrm{KeV} \leq M_{KK} \leq 10\ \mathrm{MeV}$, detectable in next experiments
- Green: "Dark QCD scenario",$10^2\ \mathrm{MeV} \leq M_{KK} \leq 10^6\ \mathrm{GeV}$, detectable in next experiments
- Red: "Dark axion scenario", $f_a > 10^8\ \mathrm{GeV}$, non-detectable in next experiments

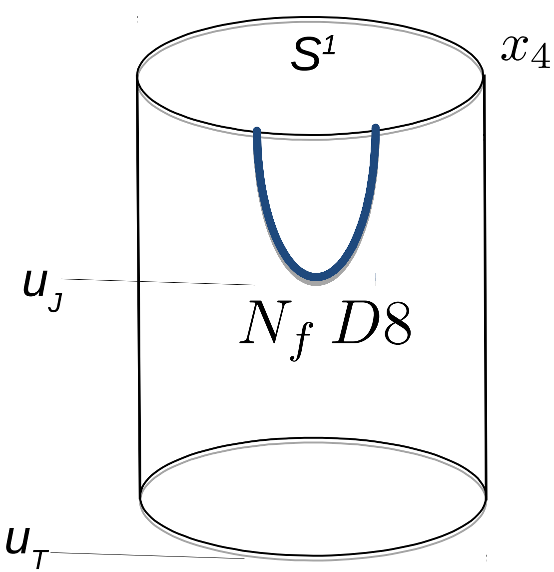
GWs from Chiral symmetry breaking

True bubble profile can be computed from DBI action!

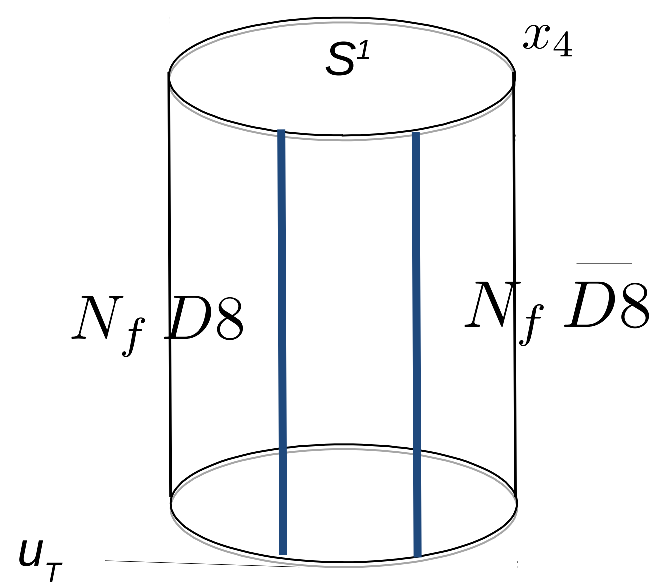
$$S_{DBI} = \frac{T_8}{g_s}\int d^9x\rho^2\left(\frac{u}{R}\right)^{-\frac{3}{2}}u^4\sqrt{1+f_T(u)\left(\frac{u}{R}\right)^3(\partial_u x_4(\rho,u))^2+(\partial_\rho x_4(\rho,u))^2}$$

Describes profile of the branes

- Chiral symmetry broken phase:



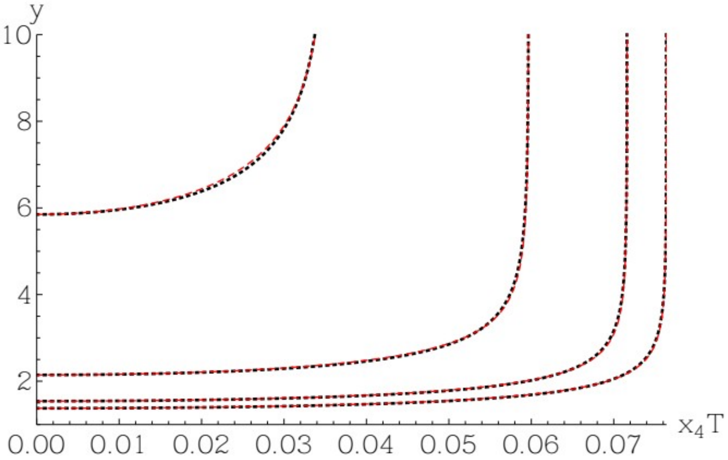
- Unbroken phase:



GWs from Chiral symmetry breaking

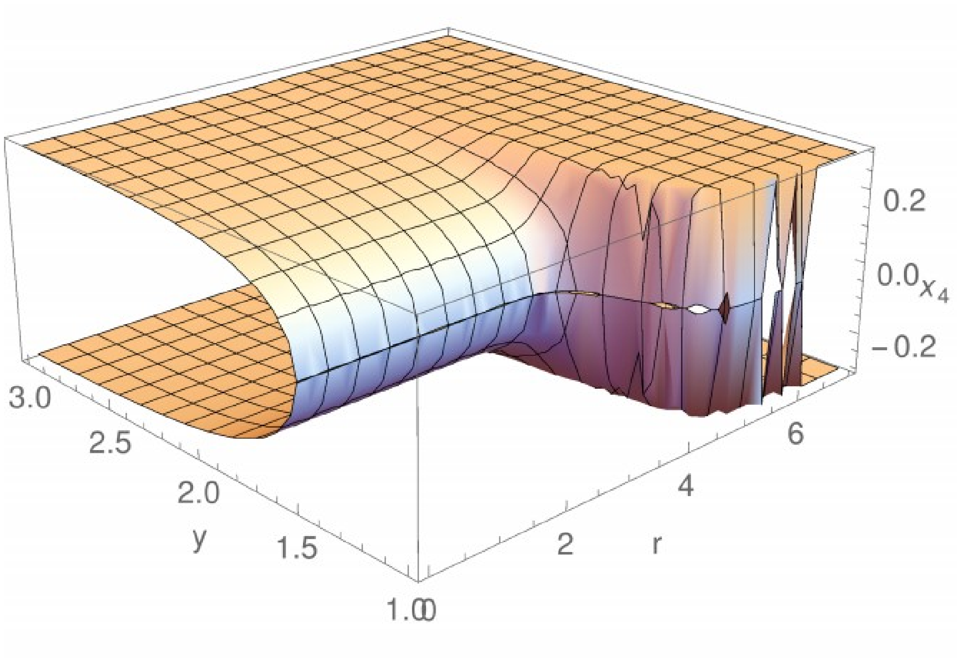
- Solve equations of motion with variational ansatz

$$x_4 \sim \tanh\left(\frac{\sqrt{y - y_0(r)}}{\sqrt{B(r)}}\right) \ , \qquad y = u/u_T \ , \quad r = \frac{4\pi T}{3}\rho$$



- Gives excellent approximation to true solution in connected and disconnected cases

- Bubble solution



GWs from Chiral symmetry breaking

Observations:

- "Dark QCD ChiSB scenario":
  - Chiral symmetry breaking transition followed by confinement transition: modifies formulae for spectra
  - Probe approximation: flavor contribution subleading ⇒ weaker signal
  - If confinement transition dominated by collisions: signal of ChiSB covered
- "Holo-Axion scenario": parameters are constrained as in Sakai-Sugimoto

$$M_{KK} \sim 1 \text{ GeV}, \quad \lambda \sim 33, \quad N_c = 3, \quad N_f = 6, \quad f_a > 10^8 \text{ GeV}$$

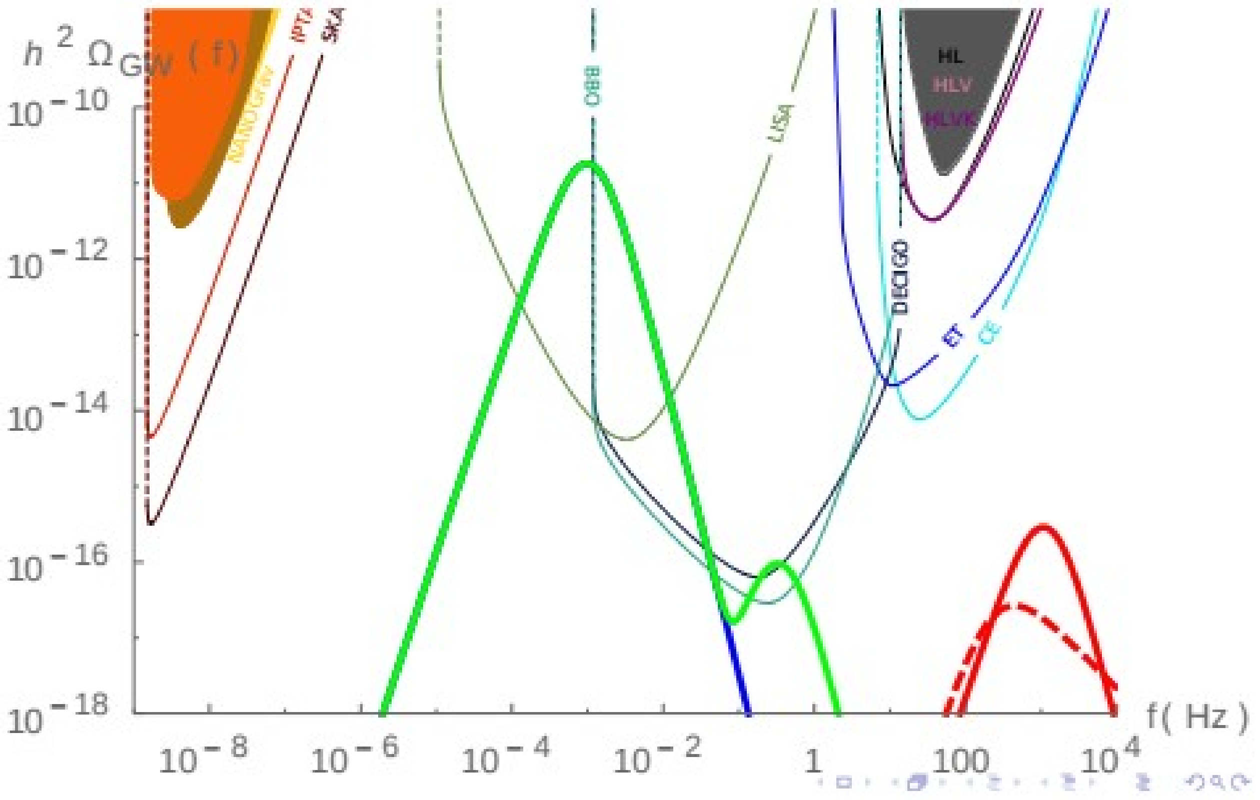
GWs from Chiral symmetry breaking

Results:

Solid lines: sound waves

Dashed line: collisions

Parameters: $\lambda, N_c, N_f, M_{KK}, f_\chi$



- Blue: “Dark QCD scenario”, confinement transition only
- Green: “Dark QCD scenario”, confinement+ChiSB, detectable in next experiments
- Red: “Holo-Axion scenario”, non-detectable in next experiments

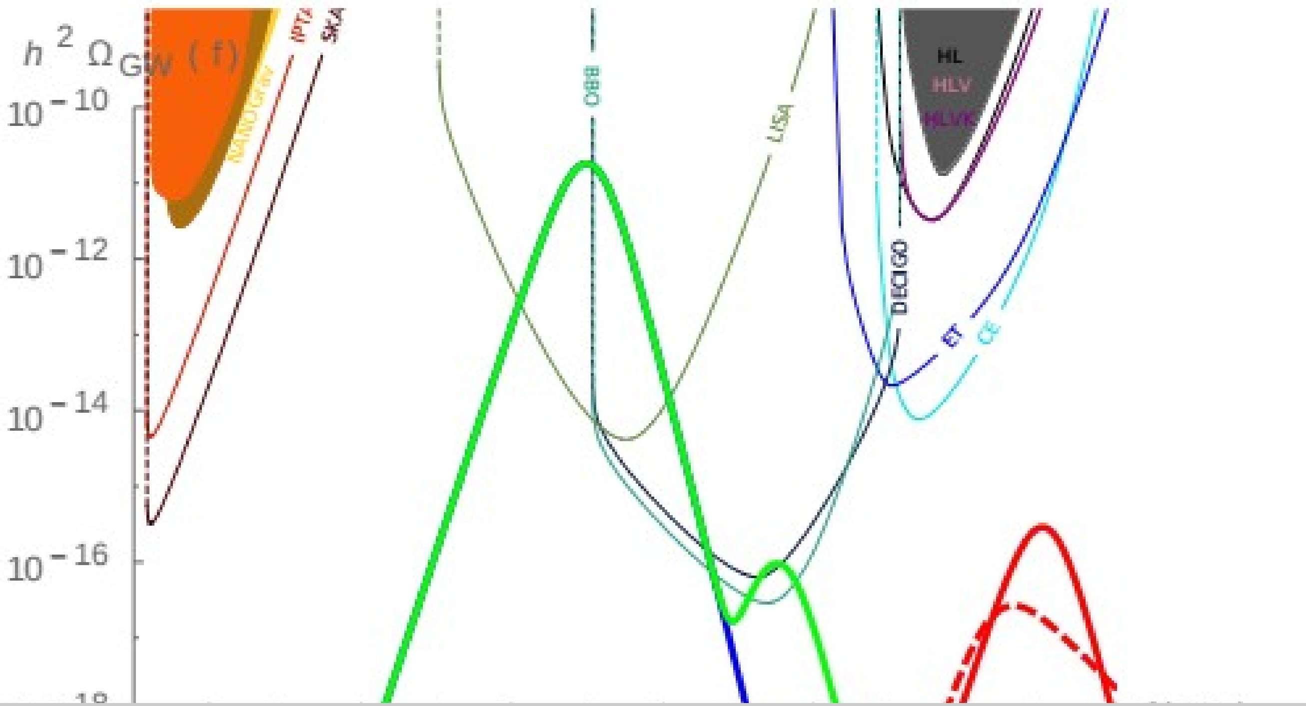
GWs from Chiral symmetry breaking

Results:

Solid lines: sound waves

Dashed line: collisions

Parameters: $\lambda, N_c, N_f, M_{KK}, f_\chi$



Double peak “smoking gun” for this type of models

- Blue: “Dark QC
- Green: “Dark Q xperiments
- Red: “Holo-Axion scenario”, non-detectable in next experiments

Overview

- YM or QCD-like holographic dark sectors (“Dark Holograms”) can generate detectable GW signals in a wide range of near future experimental facilities
- Holographic Peccei-Quinn transitions are non-detectable in near future
- Two peaks from ChiSB and confinement transitions single out this kind of models

➢ Determining peak correlations would provide very distinctive predictions

Thank you for your time!