Dark Holograms and Gravitational Waves

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arXiv:2008.02579 [hep-th] & arXiv:2011.08757 [hep-ph]

Plan

- Basics of Holography
- Review of Holographic QCD
- Gravitational waves and cosmology
- Dark holograms
- GWs from confinement and chiral symmetry breaking transitions

Basics of Holography

Holography

[Maldacena 97, Gubser-Klebanov-Polyakov 97, Witten 97]

Some classes of (strongly coupled) quantum field theories in *d* dimensions are secretly theories of (classical) gravity – or strings - in *d*+*n* dimensions

- Classical computations determine quantum field theories at strong coupling

- First example:

$$\mathcal{N}=4\ SU(N_c)\ SYM \text{ in } 4d \quad \Longleftrightarrow \quad IIB \text{ string theory on } AdS_5 \times S^5$$

Regime where gravity is a good approximation:

$$N_c \gg 1, \quad \lambda \equiv g_{YM}^2 N_c \gg 1$$

Basics of Holography

Is it true?

- No mathematical proof but infinite number of checks

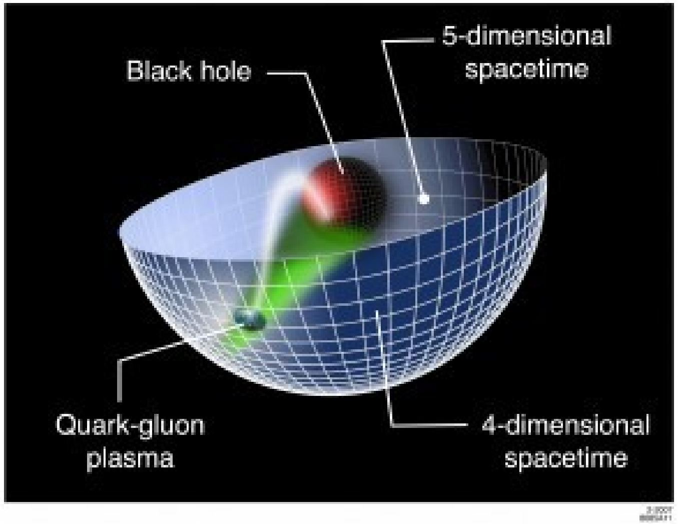
What is the gain?

- Can study systems at strong coupling
- Can study systems at finite charge density
- Real-time physics readily accessible

What is the price?

- Exact control only for certain theories with:
  - large number of degrees of freedom (e.g. planar limit)
  - few important operators: large gap in anomalous dimensions

Basics of Holography



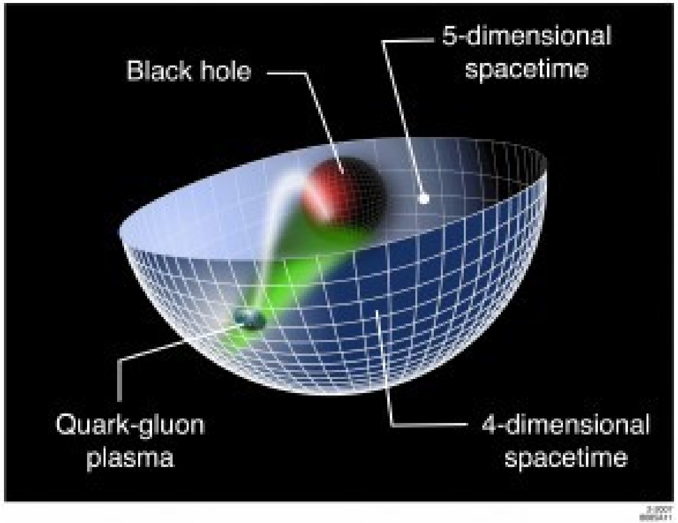
<u>How does it work</u>?

Every physical ingredient in quantum field theory (FT) is translated (⇒) in the dual gravity theory

"Dictionary":

- A state of the FT ⇒ a background gravity solution
- An operator $\mathcal{O}$ of the FT ⇒ a gravity field Φ
- RG scale ⇒ extra space-time (radial) dimension u
- Temperature T, charge density ρ ⇒ charged Black Hole with temperature T and non-trivial gravity gauge field A_t

Basics of Holography



How do we compute?

$$\langle e^{-\int \Phi_0 \mathcal{O}} \rangle_{FT} = e^{-S_{gravity}(\Phi_0)}$$

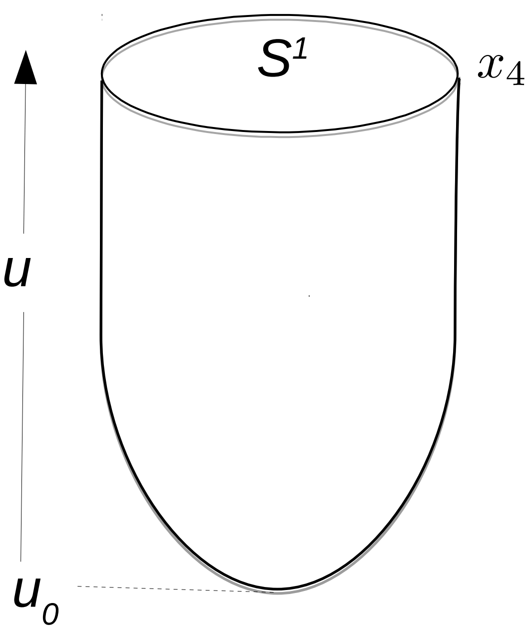
- $\mathcal{O} \Rightarrow \Phi$ and $\Phi_0 = \lim_{u \to \infty} \Phi$
- Φ_0 determines Φ via equations of motion
- Plug solution in gravity action: $S_{gravity}(\Phi_0)$
- LHS is generating functional: *n*-point functions from functional derivatives w.r.t. Φ_0 on the RHS

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 4*d* $SU(N_c)$ YM + KK modes
- Confined phase:



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

Minkowski; Cigar; Four-sphere

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

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

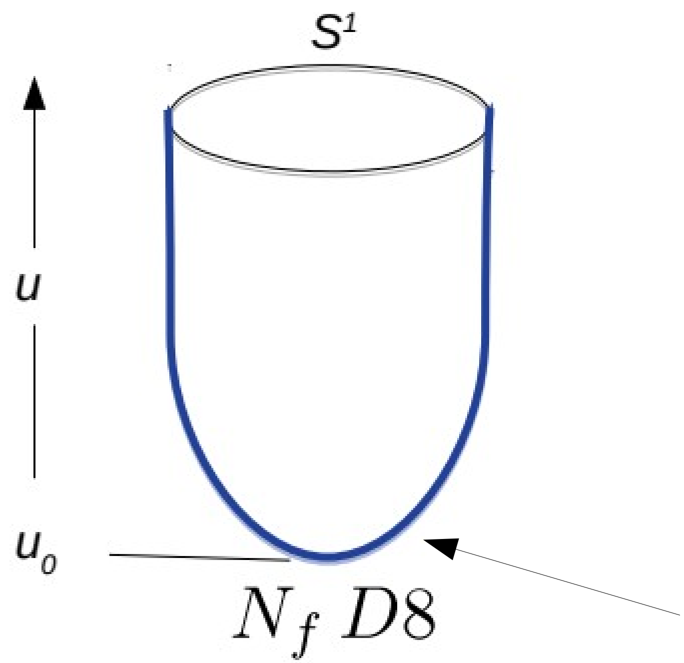
Parameters:

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

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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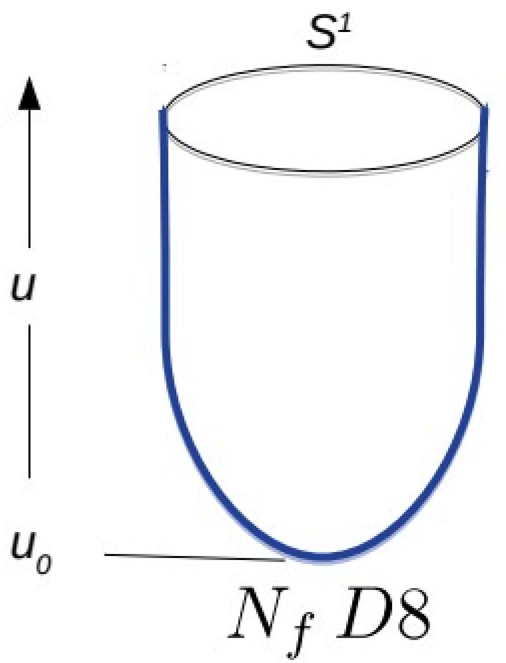


D8 world-volume scalar field (transverse direction):

- Mesons from fluctuating modes

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

- Mesons from fluctuating modes
- Baryons from instantonic configurations

Review of Holographic QCD

Low-energy effective action for N_f>1

- DBI for D8-branes (gauge field only), expanded to first order and reduced on four-sphere contains:

1) tower of (axial) vector mesons

2) Goldstones of chiral symmetry breaking, the pions

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

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

- Define pion matrix $U = \mathcal{P}e^{i\int \mathcal{A}_u} = e^{i\Pi(x)/f_\pi}$

- Get

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

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

Chiral Lagrangian with Skyrme term, derived from gravity!

Deconfined phase

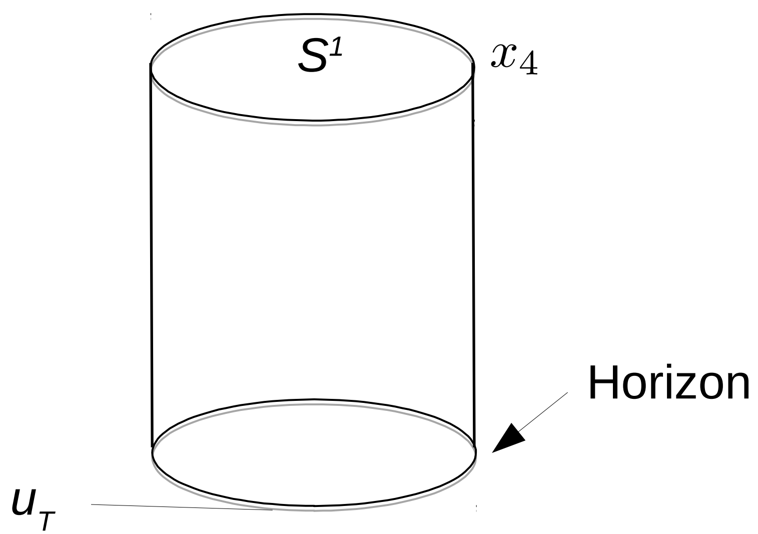
- In Holographic YM: D4 black-brane solution [Witten 98]

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

Cylinder

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

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



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

Review of Holographic QCD

Deconfined phase

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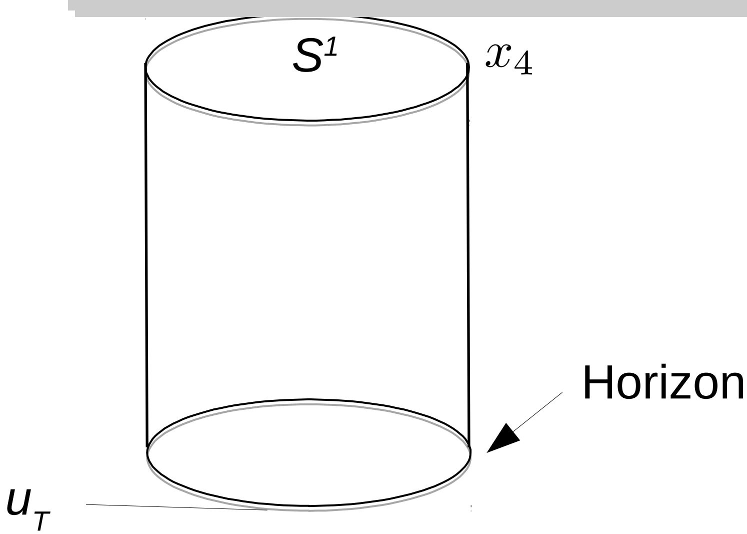
Confinement / deconfinement

first order transition at $T_c = M_{KK}$

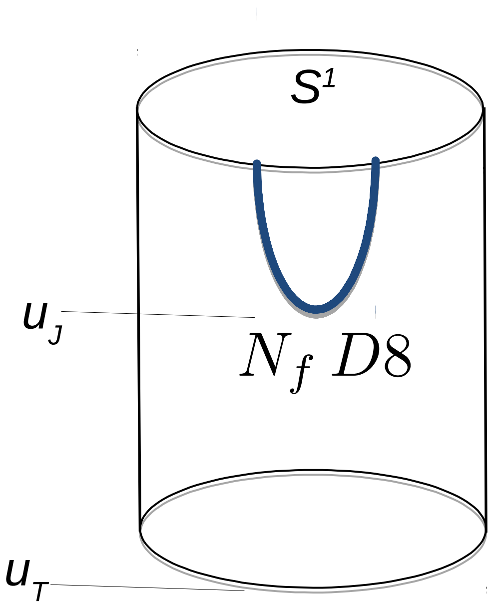


$$T \sim \sqrt{u_T}$$

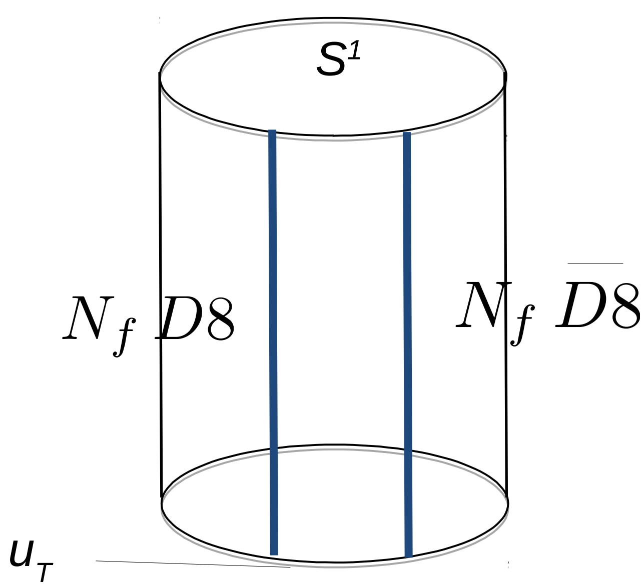
Review of Holographic QCD

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:



Review of Holographic QCD

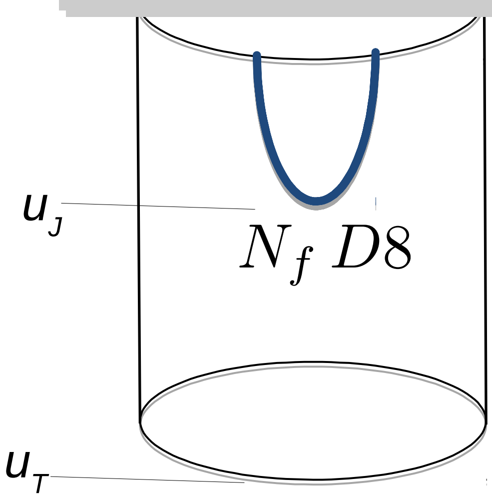
Deconfined phase

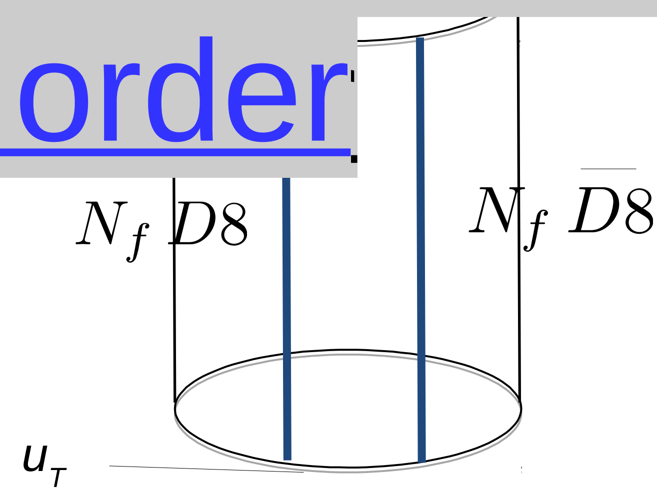
- In Holographic QCD: chiral symmetry can persist if D8 non-antipodal [Aharony-Sonnenschein-Yankielowicz 06]

- 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

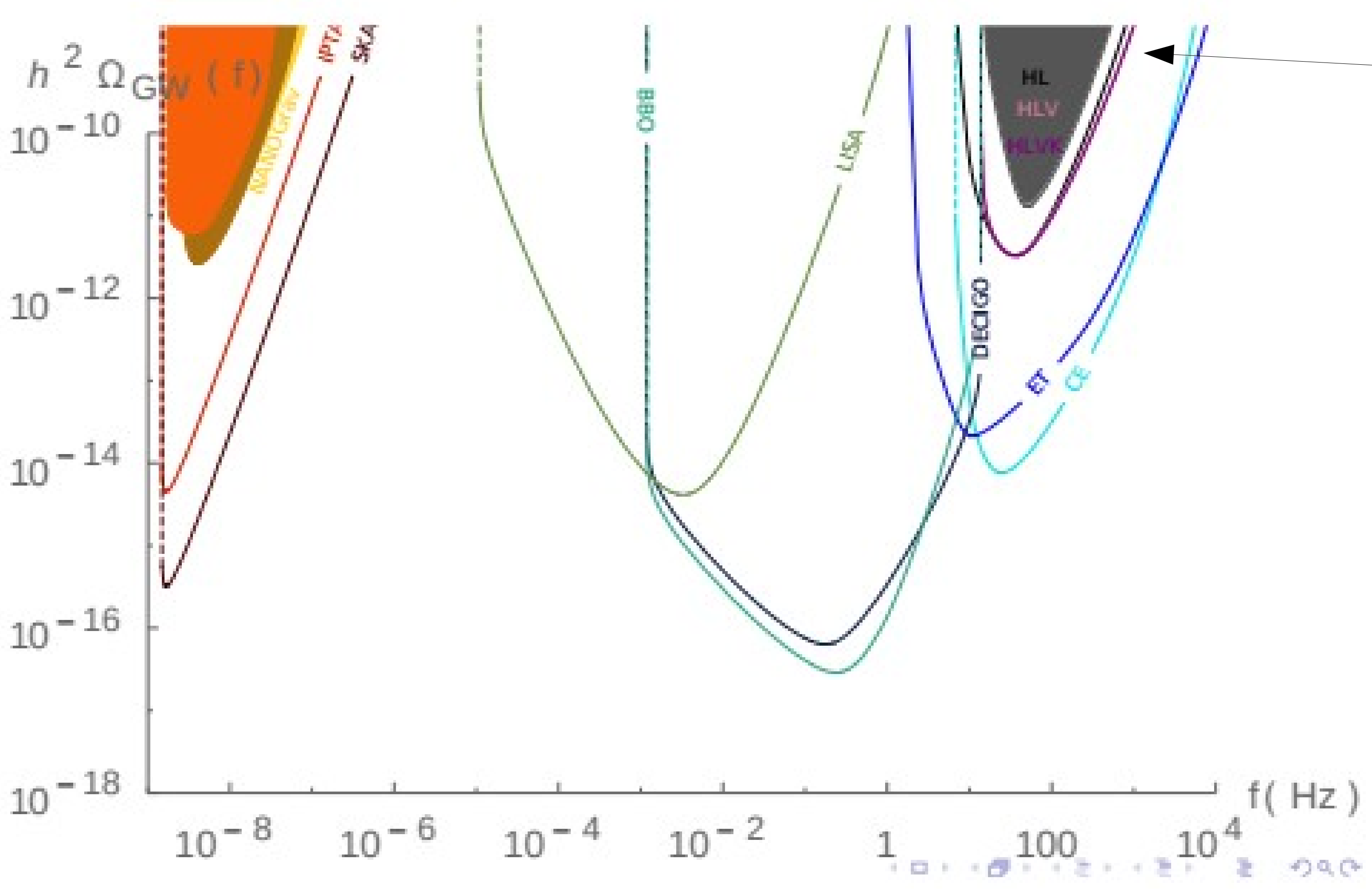
III. “Dark sectors” (hidden sectors) can undergo cosmological first order transitions

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



LIGO/VIRGO

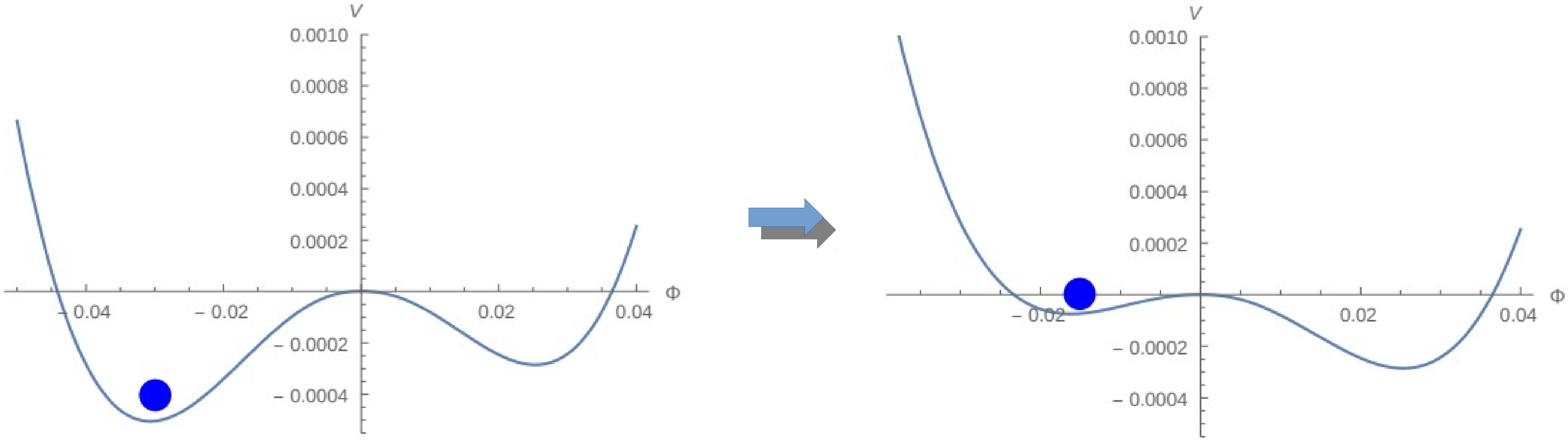
Image from [Schmidt 20]

Gravitational waves and cosmology

Bubbles in first order transitions

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

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



- 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

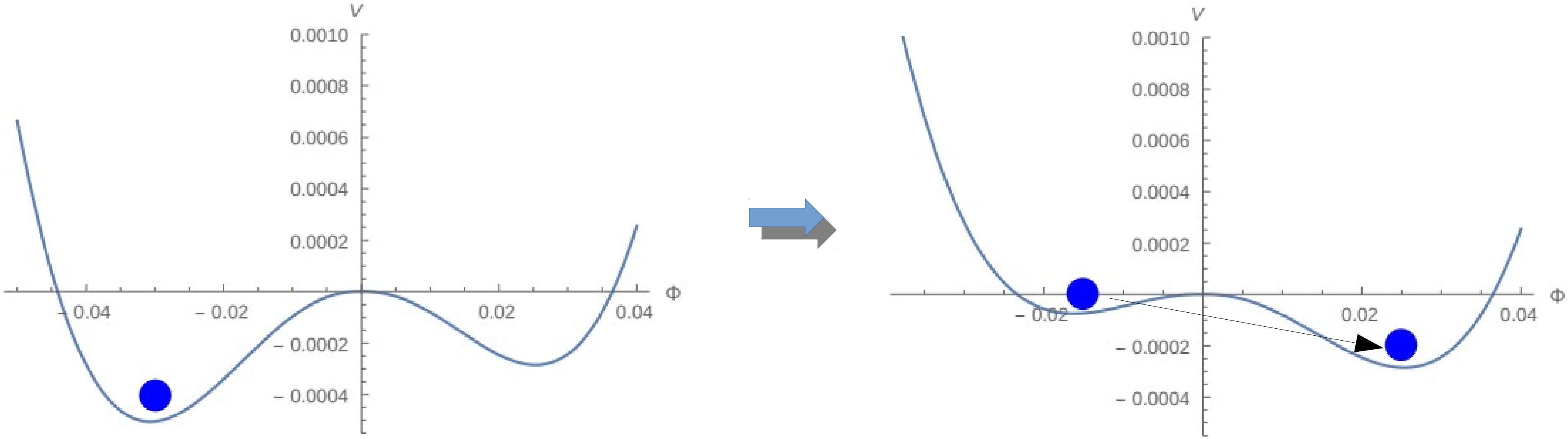
- First order transition at $T = T_c = M_{KK}$

Gravitational waves and cosmology

Bubbles in first order transitions

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

$T > T_c$ $T < T_c$



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

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

Bubbles in first order transitions

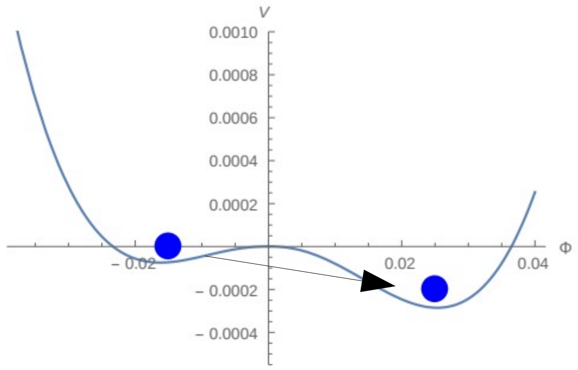
[Coleman 77, Callan-Coleman 77, Coleman-DeLuccia 78, Linde 81-83]

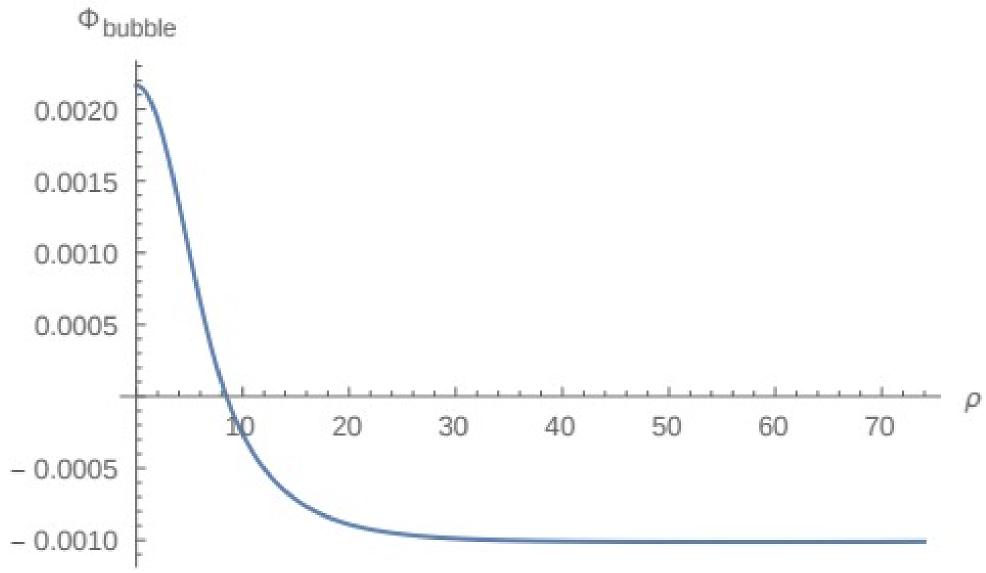
Radial direction in Minkowski

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

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

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





Gravitational waves and cosmology

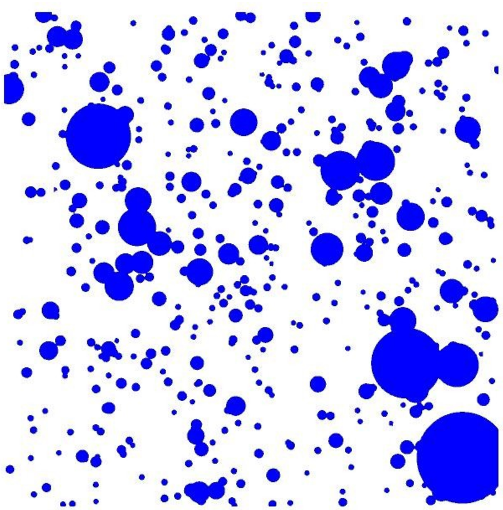
- After nucleation, bubbles expand
- At “nucleation temperature” T_n such that

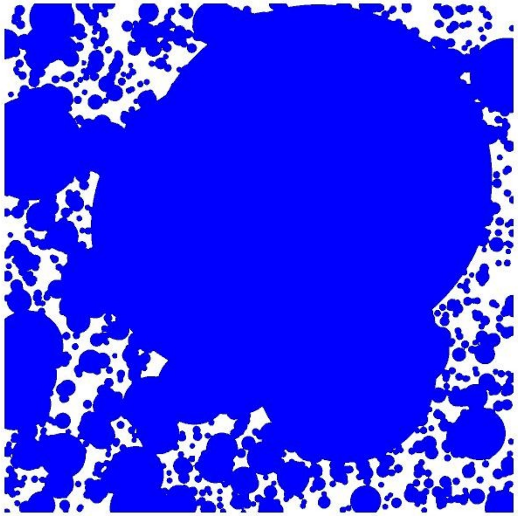
$$\frac{\Gamma}{H^4}\Big|_{T_n} \sim 1$$

Hubble parameter → H

bubbles percolate, leaving whole Universe in “true vacuum”

Image 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

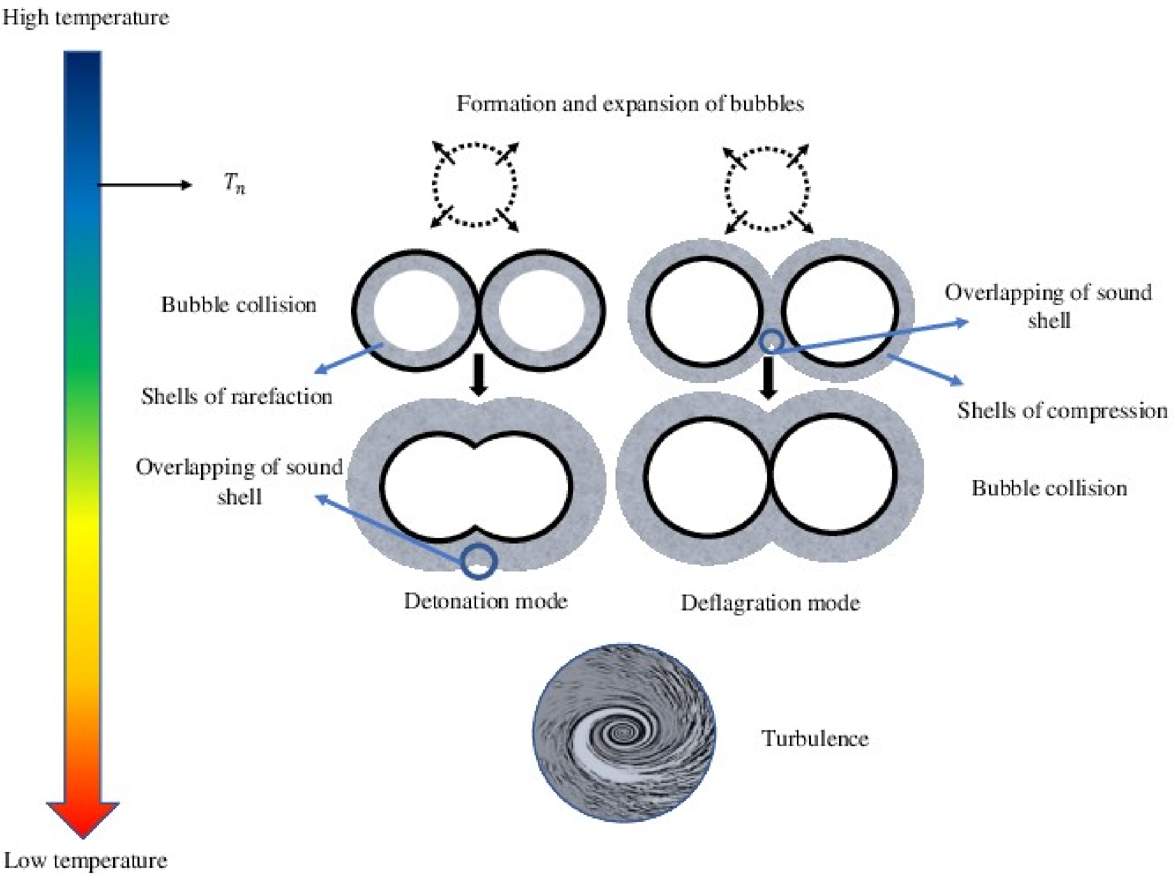


Image from [Wang-Huang-Zhang 20]

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

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

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

Quantities in blue to be computed in microscopic model

Gravitational waves and cosmology

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

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$f =$ wave frequency

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

$g_* =$ # of relativistic c

$v =$ bubble velocity

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If transition duratio short, suppressed by

$$\Sigma \equiv (8\pi)^{1/3} v \left(\frac{\beta}{H}\right)^{-1} \left(\frac{\kappa_v\alpha}{1+\alpha}\right)^{-1/2}$$

e.g. [Caprini et al. 19]

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

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

$\kappa_v =$ ... $0.73 + 0.08$...

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

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

$g_* =$ # of relativistic degrees of freedom

$v =$ bubble velocity

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

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

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 reliable way, or models it effectively

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

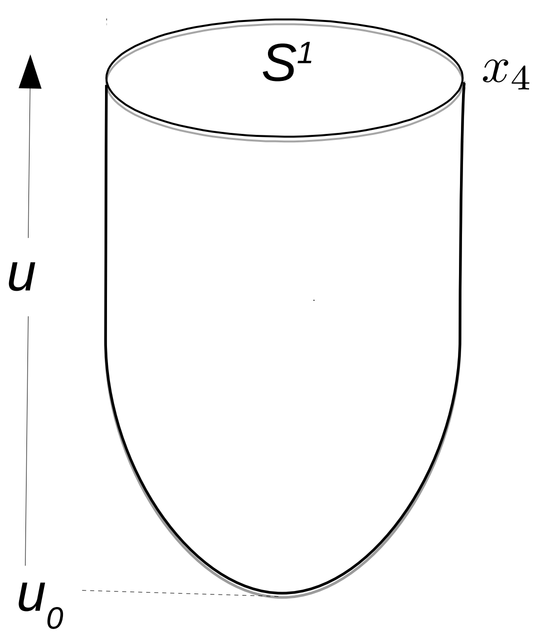
Witten-Sakai-Sugimoto model

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:

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

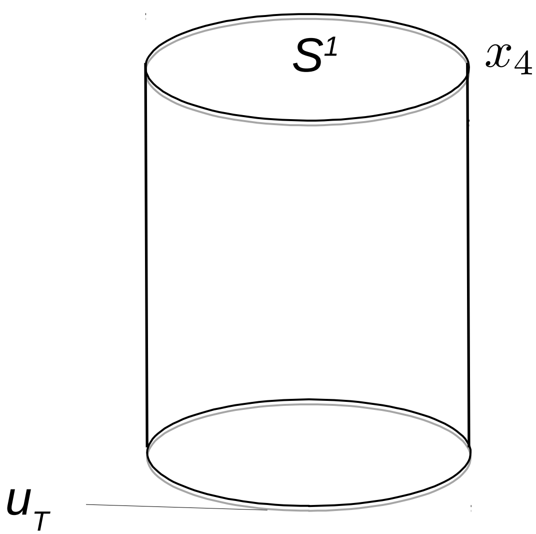
Dark holograms

"Dark glueball scenario"

[Witten 98]

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

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

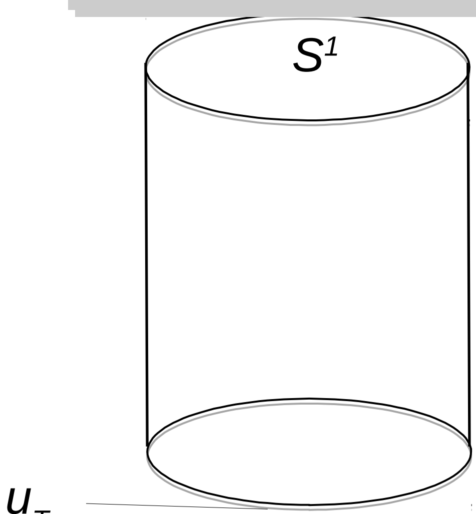
Dark holograms

"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:

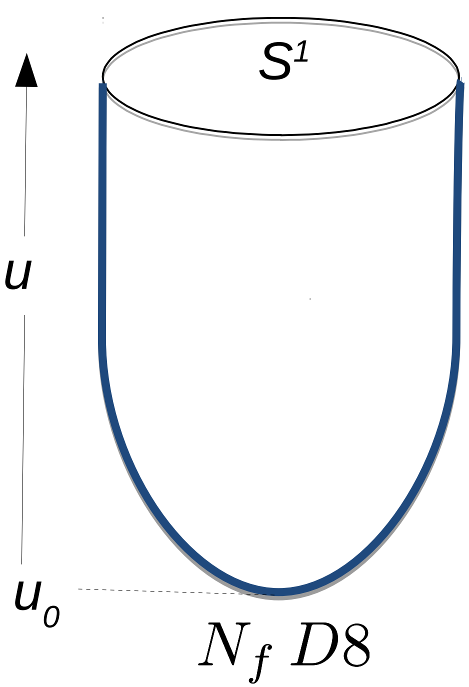
- $N_c \gg 1 \qquad \lambda = g_{YM}^2 N_c \gg 1$
- $T \sim \sqrt{u_T}$

Dark holograms

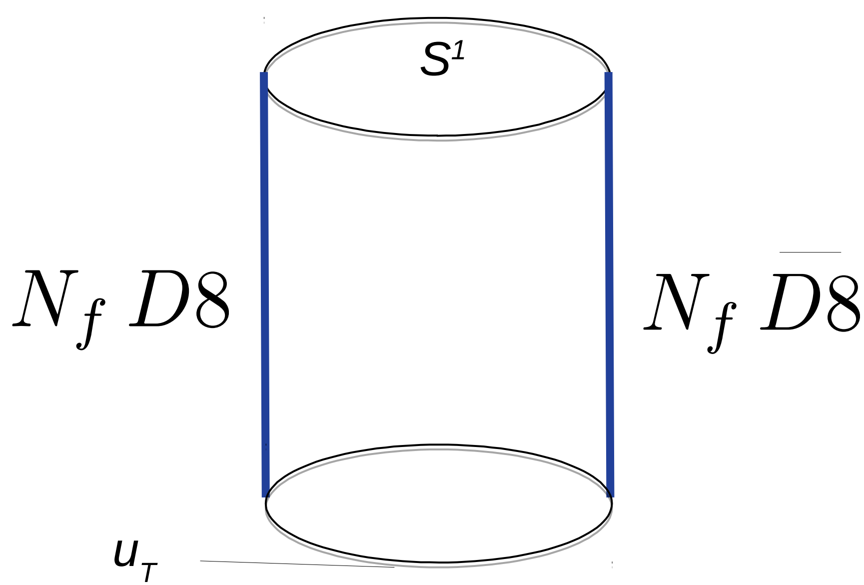
"Dark HQCD scenario"

[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:

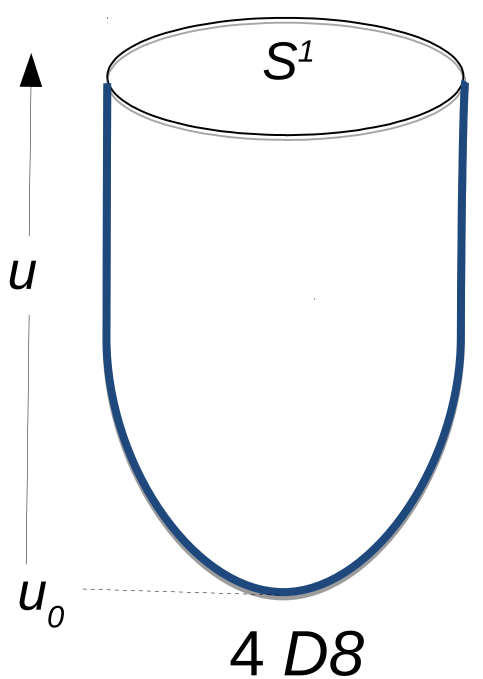


Dark holograms

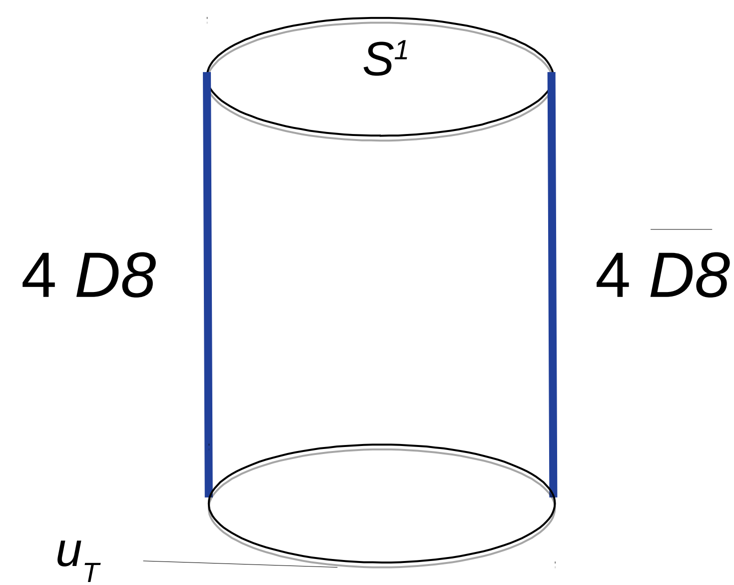
"Dark Axion scenario"

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

- Add N_f=3+1 <u>antipodal</u> probe *D*8/anti-*D*8 pairs, realize <u>composite axion</u> as PNGB
- Flavors are in triplet and singlet of ordinary color $SU(3)_c$
- <u>Confined phase</u>:



- <u>Deconfined phase:</u>



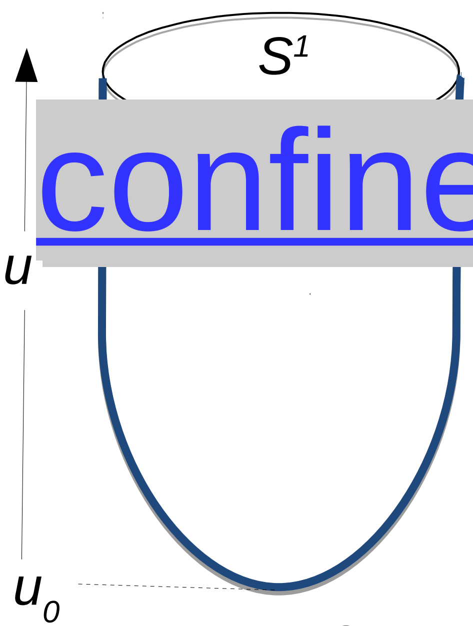
Dark holograms

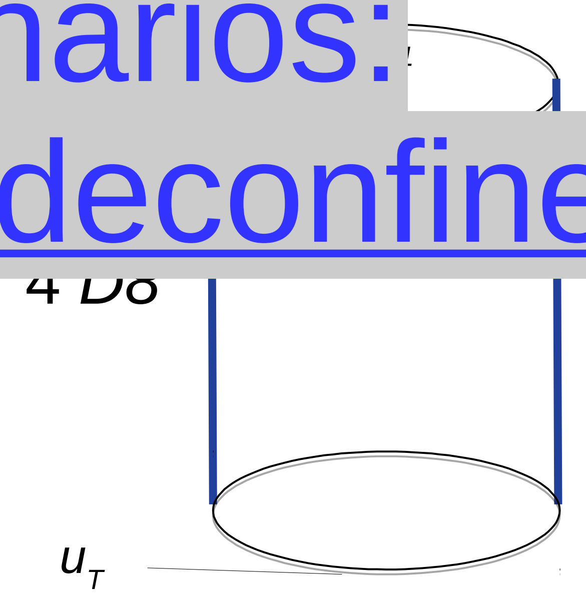
"Dark Axion scenario"

[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



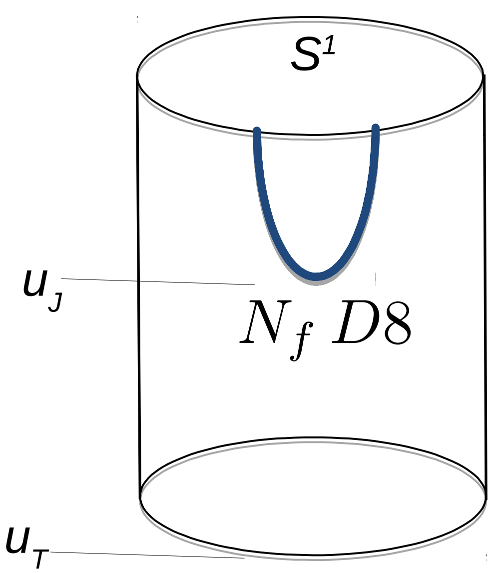


Dark holograms

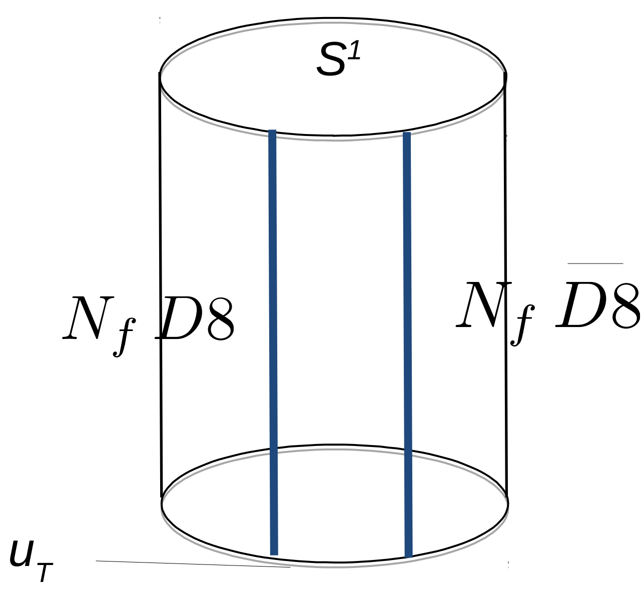
"Dark HQCD ChiSB scenario"

[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:



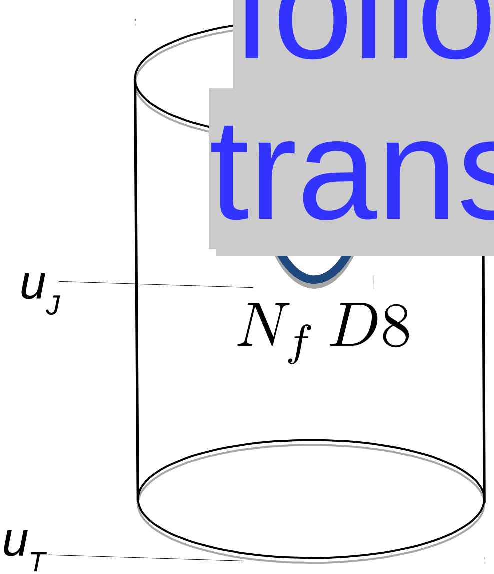
Dark holograms

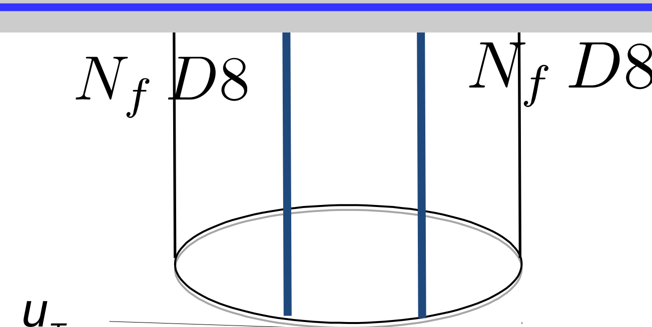
"Dark HQCD ChiSB scenario"

[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



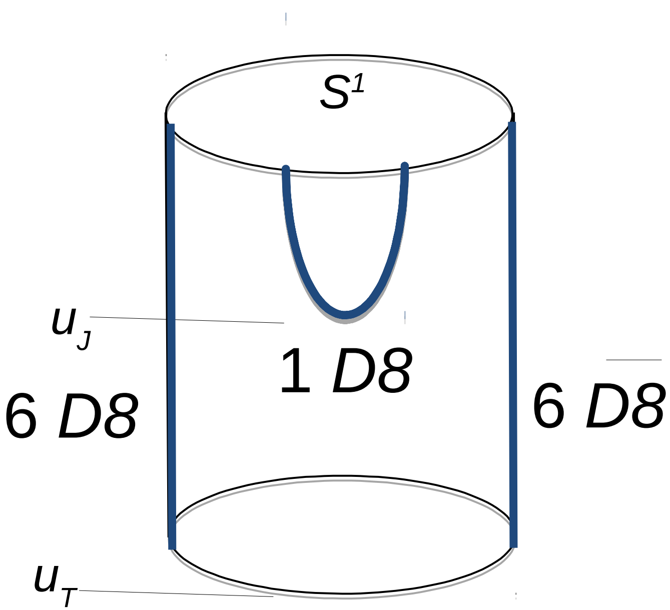


Dark holograms

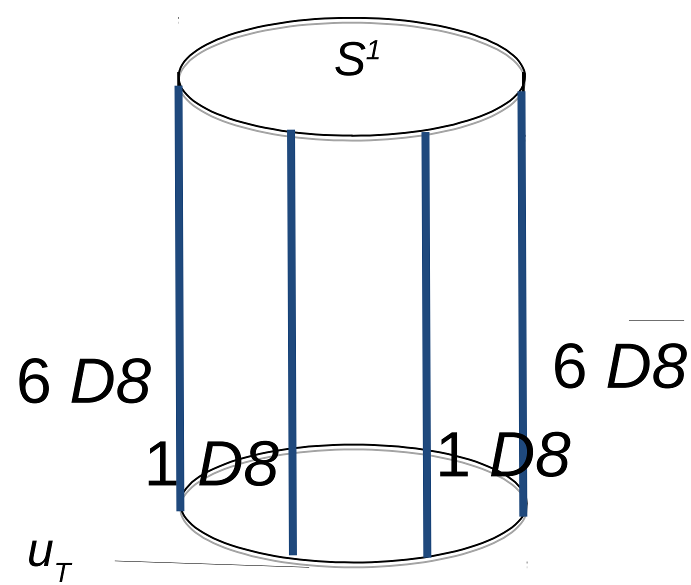
“[Holo-Axion scenario]”

[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:



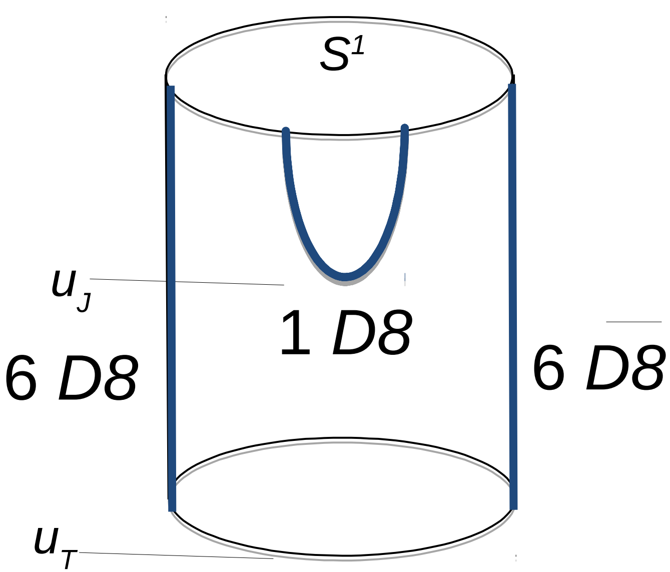
Dark holograms

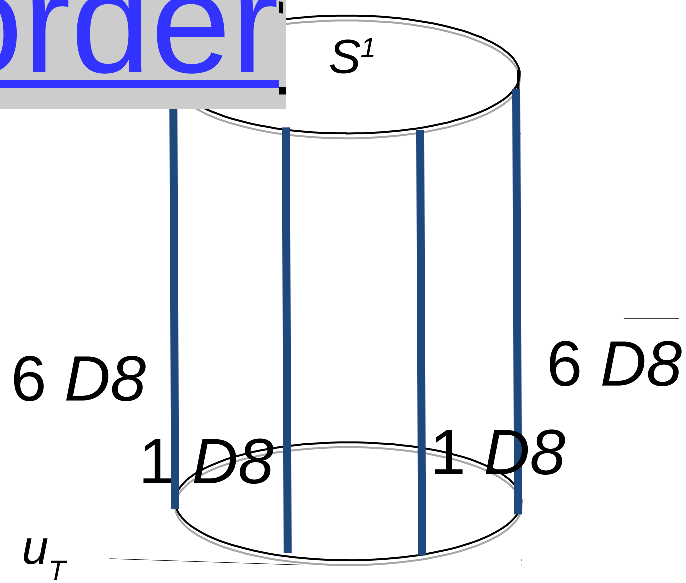
"Holo-Axion scenario"

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

- Add *6* antipodal and 1 non-antipodal probe *D*8/anti-*D*8 pairs
- Mode
- Chira... ...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 derivative 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]

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

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

GWs from Confinement transition

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

- Derivative term [Bigazzi-Caddeo-ALC-Paredes 20]

From gravity action term, $O(3)$ configuration

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

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]
- Derivative term in deconfined phase [Bigazzi-Caddeo-ALC-Paredes 20]

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

p determined by 10d embedding

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

Volume of compact manifold

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

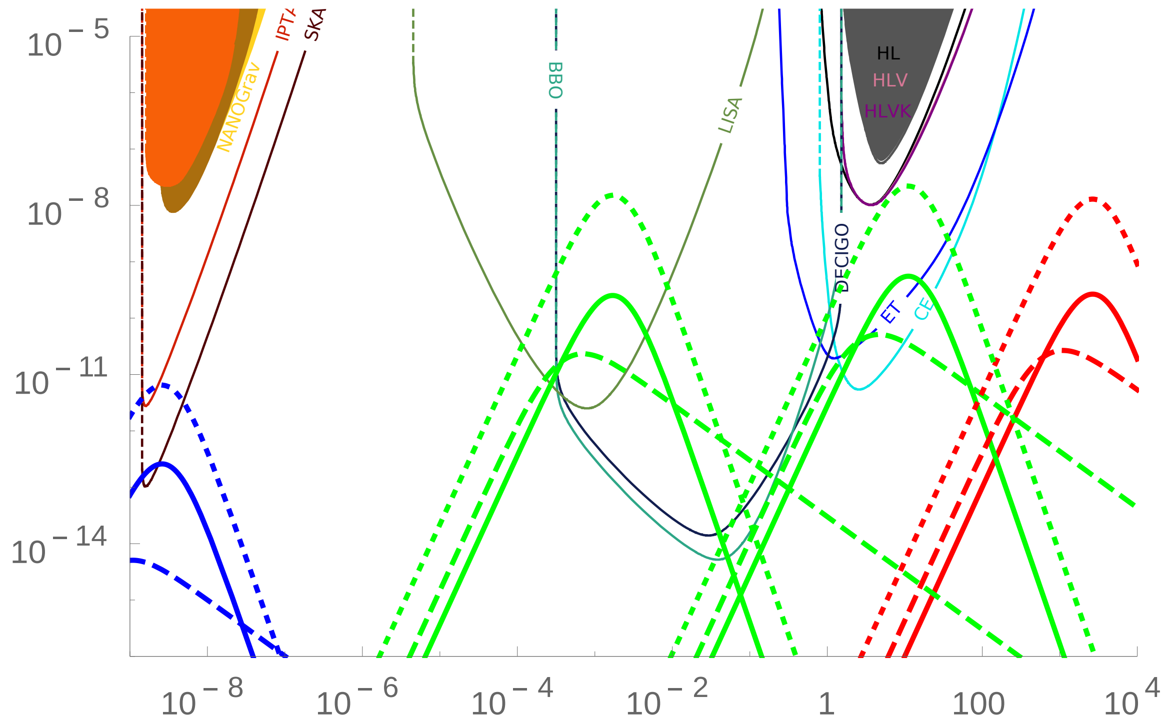
GWs from Confinement transition

Results:

Solid: sound waves, suppressed by Σ

Dotted: sound waves, no suppression

Dashed: collisions



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

$(g, M_{KK}/GeV) = (10^3, 10^{-4})$ $(10^6, 10^2)$ $(10^6, 10^6)$ $(10^3, 10^9)$

- Blue: "Dark glueball scenario", $1\ \text{KeV} \leq M_{KK} \leq 10\ \text{MeV}$, detectable (NANOGrav?)
- Green: "Dark HQCD scenario", $10^2\ \text{MeV} \leq M_{KK} \leq 10^6\ \text{GeV}$, detectable
- Red: "Dark axion scenario", $f_a > 10^8\ \text{GeV}$, non-detectable

GWs from Confinement transition

Results:

Detection prospects by number of facilities:

Blue: none

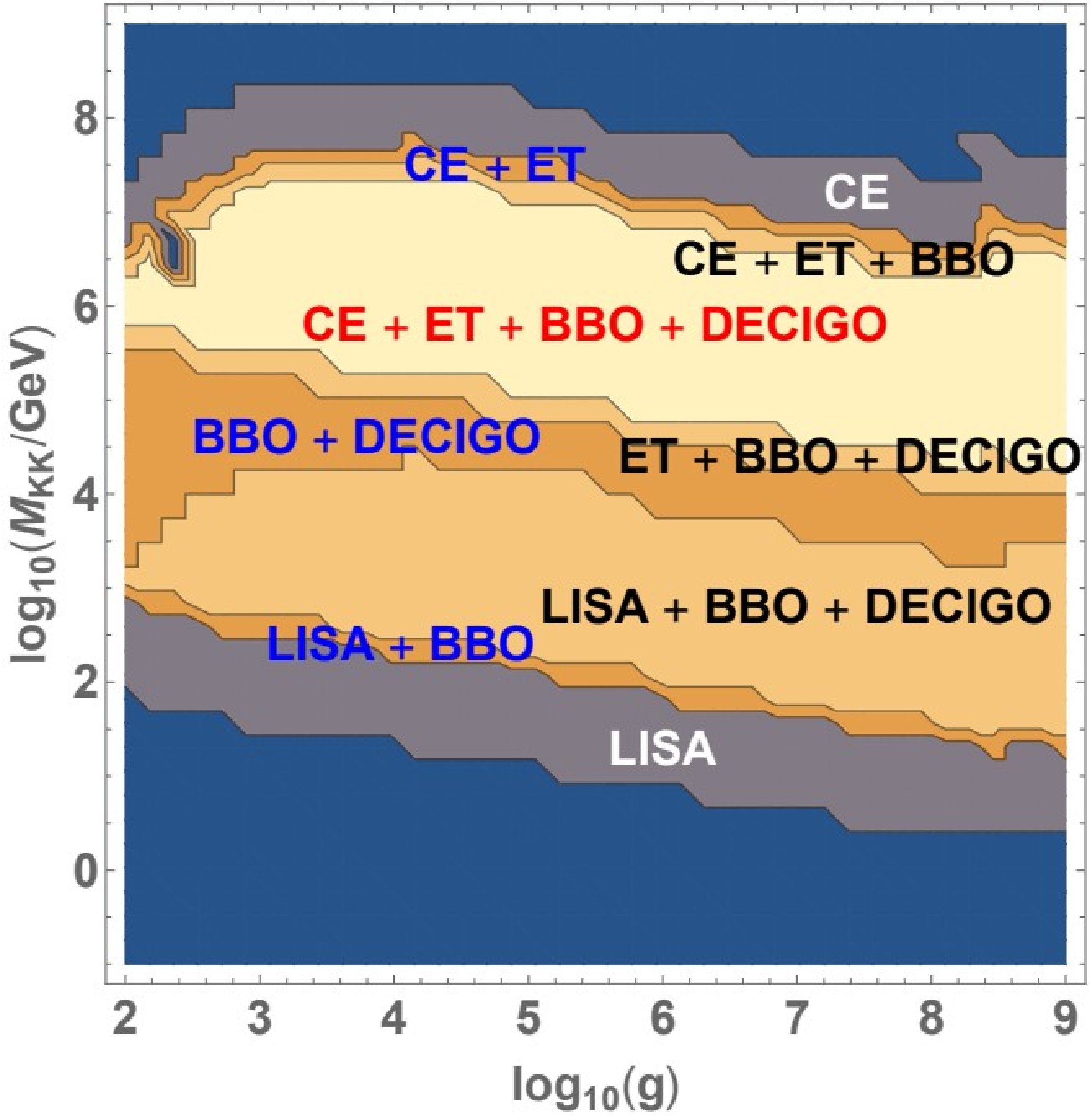
Grey: one

Dark orange: two

Light orange: three

Yellow: four

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



“Dark HQCD” scenario, sound waves, suppressed by Σ

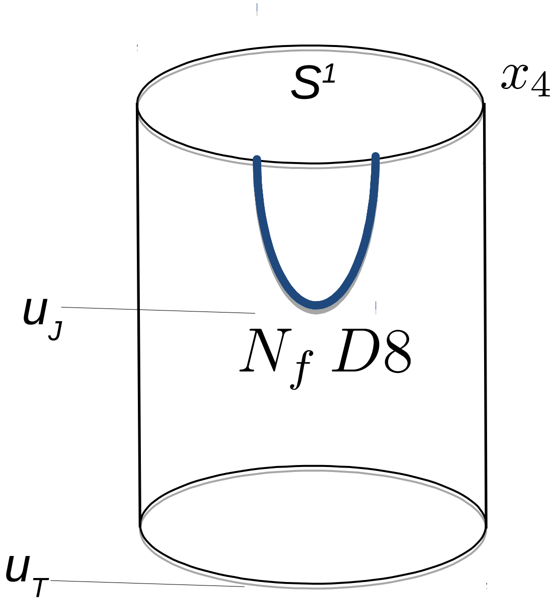
GWs from Chiral symmetry breaking

True bubble profile can be computed from DBI action!

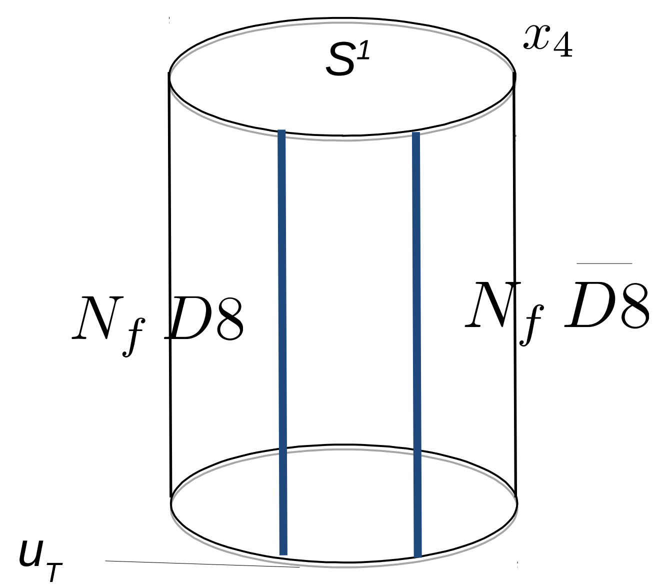
$$S_{DBI} = \frac{T_8}{g_s} \int d^9 x \rho^2 \left(\frac{u}{R}\right)^{-\frac{3}{2}} u^4 \sqrt{1 + f_T(u) \left(\frac{u}{R}\right)^3 (\partial_u x_4(\rho, u))^2 + (\partial_\rho x_4(\rho, u))^2}$$

Describes profile of the branes

- Chiral symmetry broken phase:



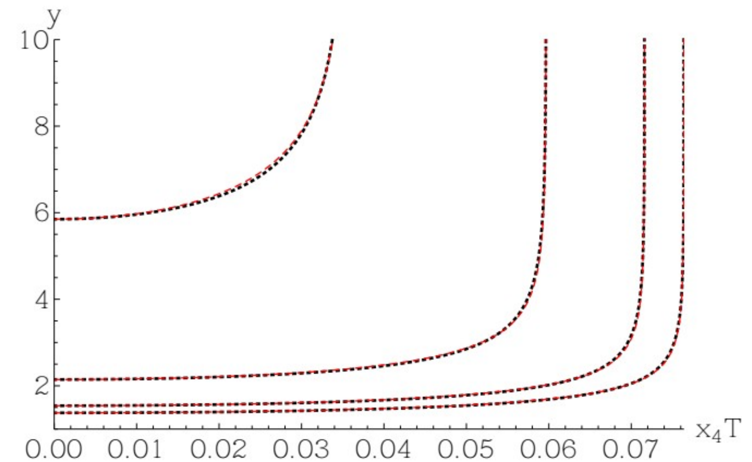
- Unbroken phase:



GWs from Chiral symmetry breaking

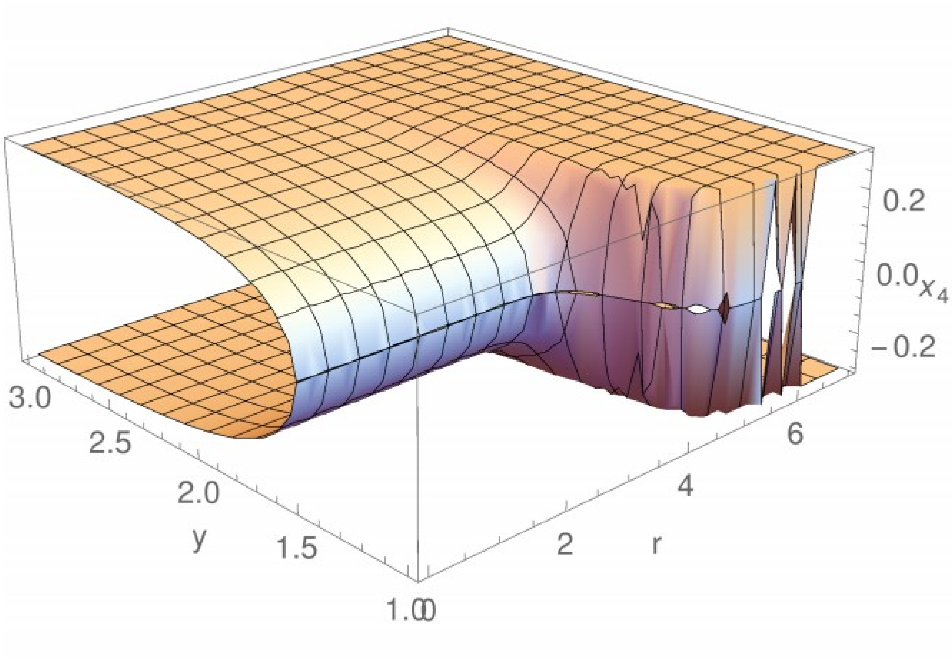
- Solve equations of motion with variational ansatz

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



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

- Bubble solution



GWs from Chiral symmetry breaking

Observations:

- "Dark HQCD 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

Observations:

- "Dark HQCD ChiSB scenario":
  - Chiral symmetry breaking transition followed by confinement transition:

    modifies formulae for spectra

Expansion of Universe adiabatic up to chiral transition epoch.

Fast reheating ➡ redshift formulae modified as:

frequency: $f \to f \cdot \delta$

energy density: $h^2\Omega \to h^2\Omega \cdot \delta^4$

rel dof at percolation temp of conf trans (entropy)

Percolation temperature of confinement transition

$$\delta \equiv \frac{(g^S_{*,p,conf})^{1/3} T_{p,conf}}{(g^S_{*,R,conf})^{1/3} T_{R,conf}}$$

rel dof at reheating temp of conf trans (entropy)

Reheating temperature of confinement transition

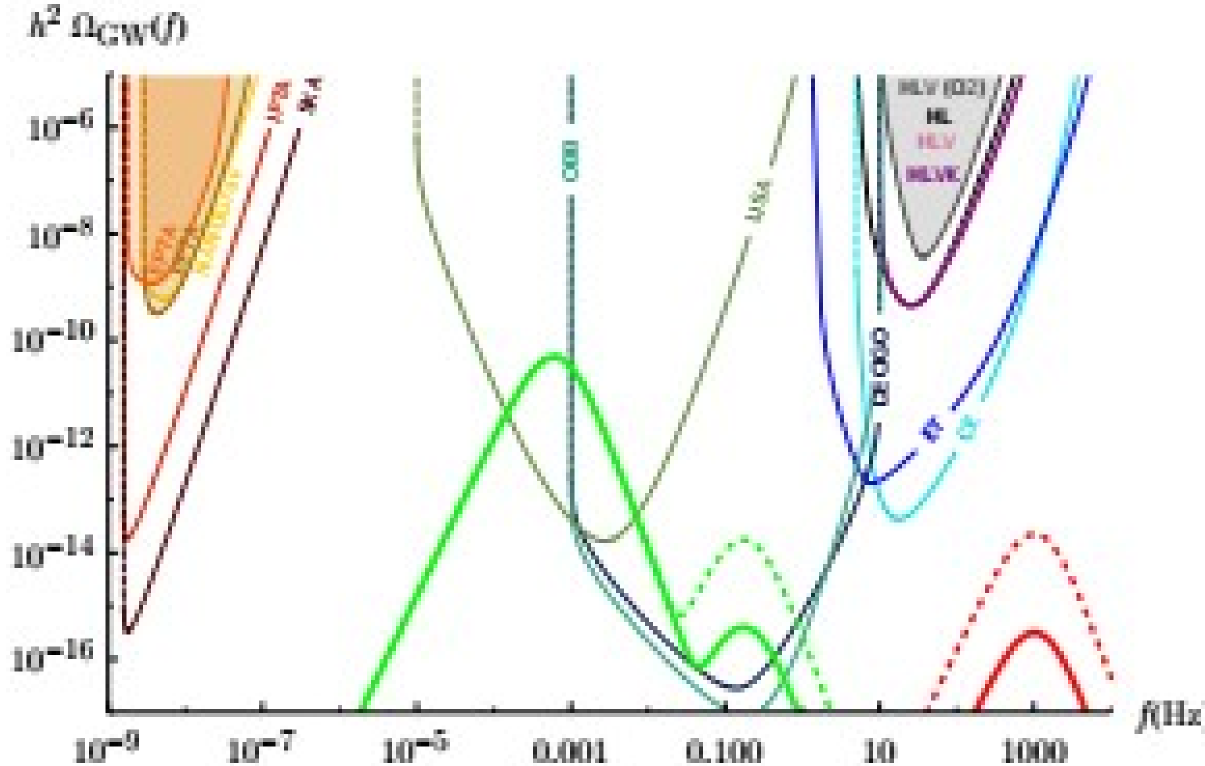
GWs from Chiral symmetry breaking

Results:

<u>Solid</u>: sound waves, suppressed by Σ

<u>Dotted</u>: sound waves, no suppression (only for ChiSB)

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



$(\lambda = 10, N_c = 10, N_f = 1, M_{KK} = 100\ \text{GeV}, f_\chi = 6 \cdot 10^3\ \text{GeV})$ $\quad (f_a = 10^8\ \text{GeV})$

- Green: “Dark HQCD scenario”, confinement+ChiSB, detectable
- Red: “Holo-Axion scenario”, non-detectable

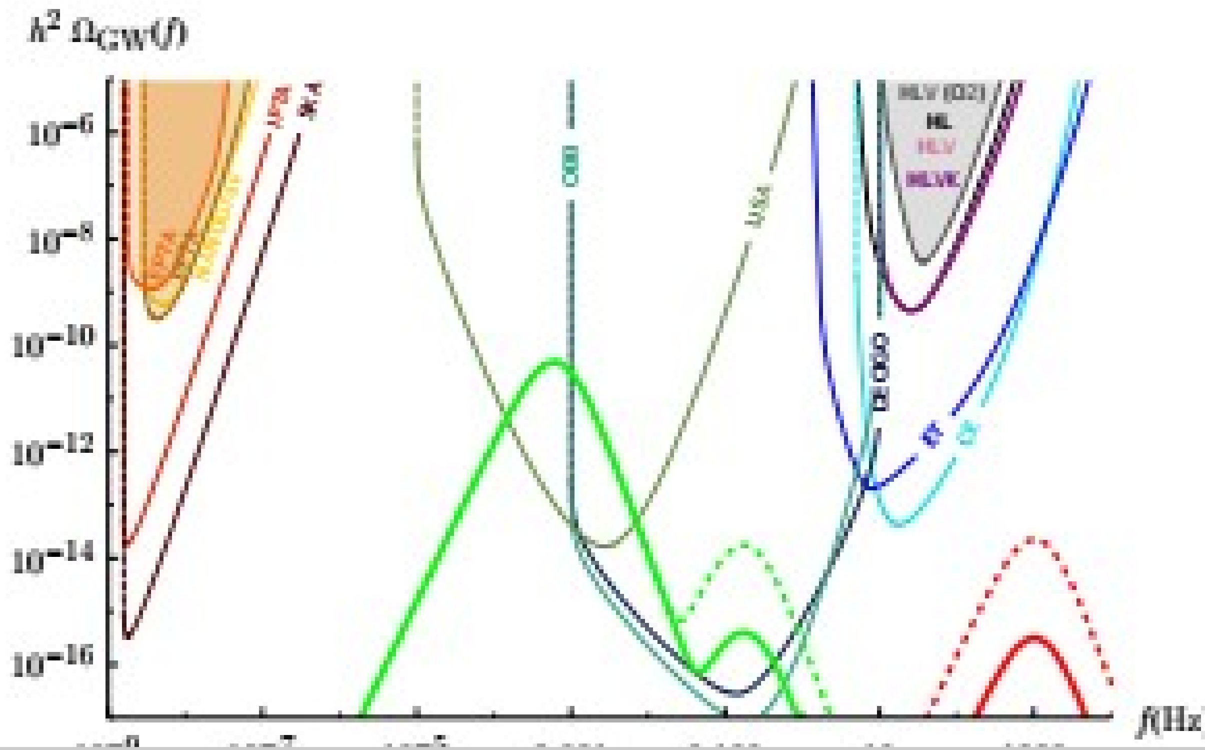
GWs from Chiral symmetry breaking

Results:

Solid: sound waves, suppressed by Σ

Dotted: sound waves, no suppression
(only for ChiSB)

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



Double peak “smoking gun” for two-transition models

- Green: “Da
- Red: “Holo

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

Directions:

- Determining peak correlations would provide very distinctive predictions
- Pheno constraints on model
- Finite charge density
- Better modeling of bubbles

Thank you for your time!

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

Review of Holographic QCD

How does the WSS model perform?

Some <u>meson masses</u>:
(table from [Rebhan 14])

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

<u>Some nucleon properties</u>:
(table from [Hashimoto et al 08])

	WSS	Skyrmion	experiment
$\langle r^2\rangle_{I=0}^{1/2}$	0.742 fm	0.59 fm	0.806 fm
$\langle r^2\rangle_{M,I=0}^{1/2}$	0.742 fm	0.92 fm	0.814 fm
$\langle r^2\rangle_{E,p}$	$(0.742\ \text{fm})^2$	∞	$(0.875\ \text{fm})^2$
$\langle r^2\rangle_{E,n}$	0	$-\infty$	$-0.116\ \text{fm}^2$
$\langle r^2\rangle_{M,p}$	$(0.742\ \text{fm})^2$	∞	$(0.855\ \text{fm})^2$
$\langle r^2\rangle_{M,n}$	$(0.742\ \text{fm})^2$	∞	$(0.873\ \text{fm})^2$
$\langle r^2\rangle_{A}^{1/2}$	0.537 fm	−	0.674 fm
μ_p	2.18	1.87	2.79
μ_n	−1.34	−1.31	−1.91
$\lvert\frac{\mu_p}{\mu_n}\rvert$	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

Review of Holographic QCD

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$1^{--}(\rho^*)$	2.874323	2.072	1.89(3)	2.40(4)

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

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

$\langle r^2\rangle^{1/2}_{M,I=0}$	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
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