Dark Holograms and Gravitational Waves

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University of Florence

Based on:

F. Bigazzi, AC, A. L. Cotrone, A. Paredes, 2008.02579
F. Bigazzi, AC, A. L. Cotrone, A. Paredes, to appear

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Motivations

- 2015: LIGO and VIRGO observe a signal from gravitational waves (GWs) produced by two merging black holes
- GW experiments will span a wide range of frequencies in the near future
- Cosmological first-order phase transitions (PT) source GWs
- No first-order phase transitions in the Standard Model
- Several Beyond-Standard Model scenarios involve strongly-coupled hidden gauge sectors where first-order phase transitions take place

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We use holography to study the gravitational waves produced in these first-order PTs

Outline

- Cosmological first-order PTs
- Review of the Witten-Sakai-Sugimoto (WSS) model
- Gravitational waves from confinement PT
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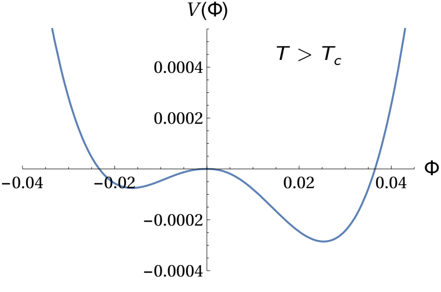
GW from first-order PT in a nutshell



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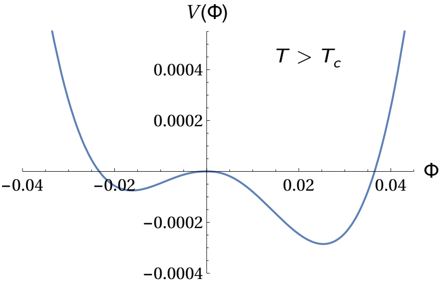

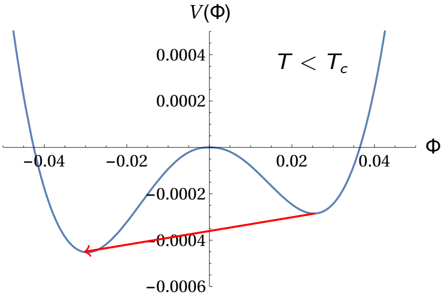

Bubbles of true vacuum nucleate in the plasma

Efficiency of the transition:

- Important ratio: Γ/H^4
- $\Gamma =$ bubble nucleation rate
- $H(t) =$ Hubble scale

Three sources of GWs:

- Bubble collisions
- Sound waves from the plasma
- Turbulence of the plasma

GW from first-order PT in a nutshell

Known formulae for the GW spectra in terms of few relevant parameters to be derived from a microscopic theory [Caprini et al. '15, Caprini et al. '19]:

- Nucleation, percolation and reheating temperatures T_n, T_p
- PT inverse duration β:

$$\beta = \frac{1}{\Gamma}\frac{d\Gamma}{dt} \qquad (\Gamma = Ae^{-S_B} \;\; \text{[Coleman '77]})$$

- Released energy α and reheating temperature T_R
- Number of relativistic d.o.f., velocity of the bubble walls

The formulae for the GW spectra involve several approximations

Top-down holography for reliable computations
in the strongly-coupled regime

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Backreaction of N D4-branes wrapped on S^1 with inverse radius M_{KK}:

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

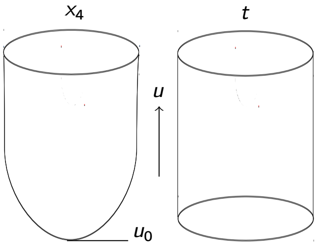
$$f(u) = 1 - \frac{u_0^3}{u^3} \qquad u_0 = \frac{4}{9}R^3 M_{KK}^2$$

Physics encoded in the cigar geometry ($\lambda = g_{YM}^2 N$)

- Mass gap $\sim M_{KK}$
- Confinement: $g_{00}(u_0) \neq 0$
- The free energy density is

$$f_{conf} = -\frac{1}{3^7\pi^2}\lambda N^2 M_{KK}^4$$

- Dominant at low temperatures



High-temperature phase

At high temperatures the dominant background is the black hole one:

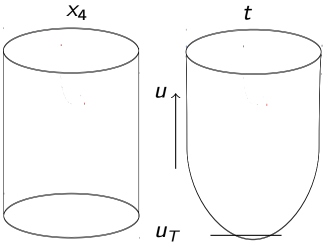
$$ds^2 = \left(\frac{u}{R}\right)^{3/2}\left(f_T(u)dt^2 + dx^i dx^i + dx_4^2\right) + \left(\frac{R}{u}\right)^{3/2}\frac{du^2}{f(u)} + R^{3/2}u^{1/2}d\Omega_4^2$$

$$f_T(u) = 1 - \frac{u_T^3}{u^3} \qquad u_T = \frac{16}{9}\pi^2 R^3 T^2$$

- Deconfinement: $g_{00}(u_0) = 0$
- The free energy density is

$$f_{deconf} = -\frac{2^6\pi^4}{3^7}\lambda N^2 \frac{T^6}{M_{KK}^2}$$

- First-order phase transition at temperature $T_c = M_{KK}/2\pi$



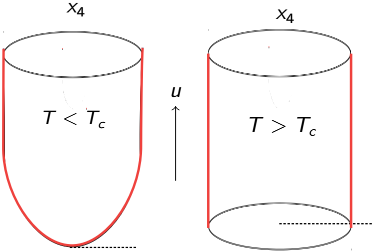
Flavours *[Sakai, Sugimoto '04]:*

Quark flavours introduced by N_f $D8/\overline{D8}$ pairs with a profile $x_4 = x_4(u)$

- Weyl fermions from $D4/D8$ and $D4/\overline{D8}$ strings
- If $N_f \ll N$, probe approximation: DBI action

$$S_{DBI} = -T_8 \int d^9x \sqrt{-\det(g_{ab} + 2\pi\alpha' F_{ab})}$$

- Branes bound to join in the IR: chiral symmetry breaking
- Decay constant $f_\chi^2 \sim \lambda N M_{KK}^2$
- Chiral symmetry restoration at $T > T_c = M_{KK}/2\pi$



Confinement PT implies chiral symmetry PT

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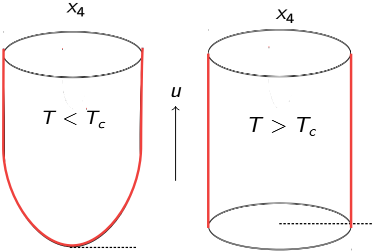


Confinement PT implies chiral symmetry PT

Flavours in non-antipodal configuration

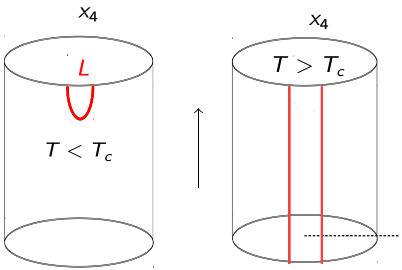
The $D8/\overline{D8}$ pairs can be placed in a non-antipodal configuration [Antonyan et al. '06, Aharony et al. '07]

- Decay constant $f^2_{\chi,L} \sim N\lambda/M_{KK}L^3$ (L free parameter)
- Holographic Axion [Bigazzi, AC, Cotrone, Di Vecchia. Marzolla '19]

- If $L < 0.97 M_{KK}^{-1}$, χSb PT at:

$$T_c^{\chi} = \frac{0.154}{L} > \frac{M_{KK}}{2\pi}$$

- First-order chiral symmetry PT
- Confinement PT at $T_c = M_{KK}/2\pi$



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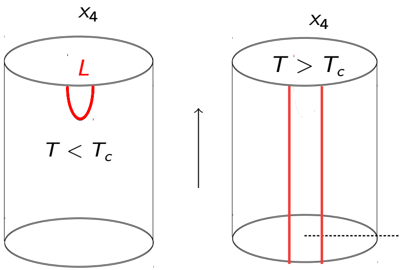

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Confinement bubbles *[Bigazzi, AC, Cotrone, Paredes '20]*

In principle: solution of 10d SUGRA (challenging!)

- Effective approach: transition described by a single field
  [Creminelli, Nicolis, Rattazzi '01] in Randall-Sundrum context
- $u_0 \sim M_h^2$ and $u_T \sim T_h^2$ promoted to functions of a radial coordinate ρ

Using holographic renormalisation: $(g = \lambda N^2)$

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

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

$$(\Phi = T_h^2 / M_{KK}^2 \text{ for } \Phi \geq 0 \text{ and } \Phi = M_h^2 / 4\pi^2 M_{KK}^2 \text{ for } \Phi \leq 0)$$

Byproduct: derivative term in the Randall-Sundrum scenario!

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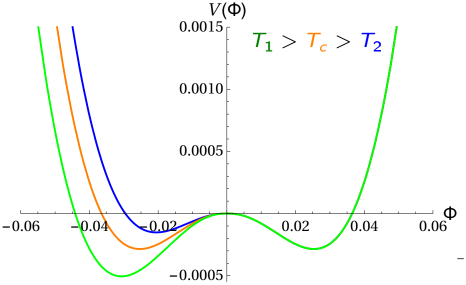

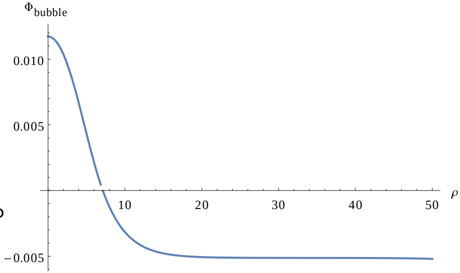

- Numerical solution of the e.o.m. with boundary conditions:

$$\Phi_B'(0) = 0 \qquad\qquad \lim_{\rho\to\infty} \Phi_B(\rho) = \Phi_{deconf}$$

- Two parameters: M_{KK} and $g = \lambda N^2$
- Thermal/quantum decay: $O(3)$-bubbles vs. $O(4)$-bubbles

Confinement bubbles *[Bigazzi, AC, Cotrone, Paredes '20]*

Bubble nucleation rate from on-shell action [Coleman '77, Linde '81, Linde '83]

$$\Gamma = \mathrm{Max}\left[T^4\left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T}, \left(\frac{S_4}{2\pi\rho_w^2}\right)^2 e^{-S_4}\right]$$

Holography allows us to reliably calculate all the parameters needed for the GW spectrum's computation

Plan:

- To explore known dark matter scenarios
- To compute the GW spectra for benchmark parameters' values
- To compare with experimental sensitivity curves

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Confinement/deconfinement scenarios

Dark QCD 1:

- $SU(N)$ Yang-Mills + N_f flavours
- Dynamical scale: 100 MeV $\lesssim M_{KK} \lesssim$ 100 TeV
- Confinement PT → Chiral Symmetry PT

Dark glueballs:

- Pure $SU(N)$ Yang-Mills
- Dynamical scale: 1 KeV $\lesssim M_{KK} \lesssim$ 1 GeV
- Negligible coupling with Standard Model [Breitbach et al. '18] :

$$\xi = \frac{T_D}{T_V} \leq 1$$

- GWs may be the only experimental tool to probe these models

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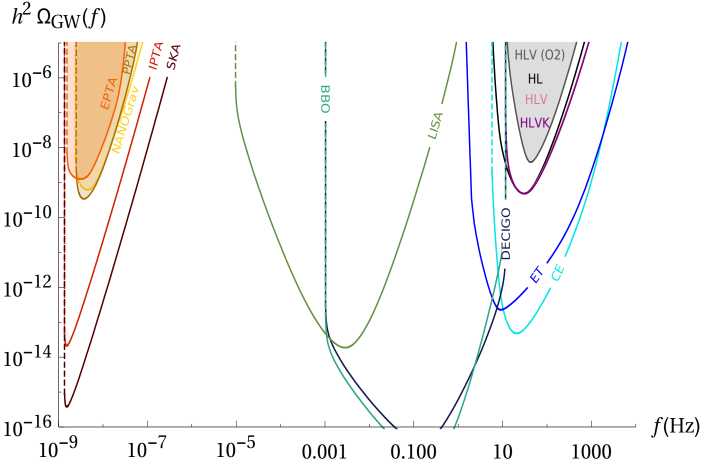
Dark Axion:

- $SU(3)$ YM$_{QCD}$ + $SU(N)$ YM$_{dark}$ + 4 flavours [Kim '79, Kaplan '85]
- Composite axion from anomalous $U(1)_A$
- Confinement PT $\rightarrow$ Peccei-Quinn PT
- Flavours as D8-branes in probe approximation ($\lambda \lesssim \sqrt{3}N$)
- Axion decay constant

$$f_a = \frac{1}{3\pi^2}\sqrt{\frac{\lambda}{N}}M_{KK} \quad (\gtrsim 10^8\text{GeV by phenomenology})$$

- Dynamical scale: $M_{KK} \gtrsim 10^9$GeV

Comparison with experimental sensitivity curves



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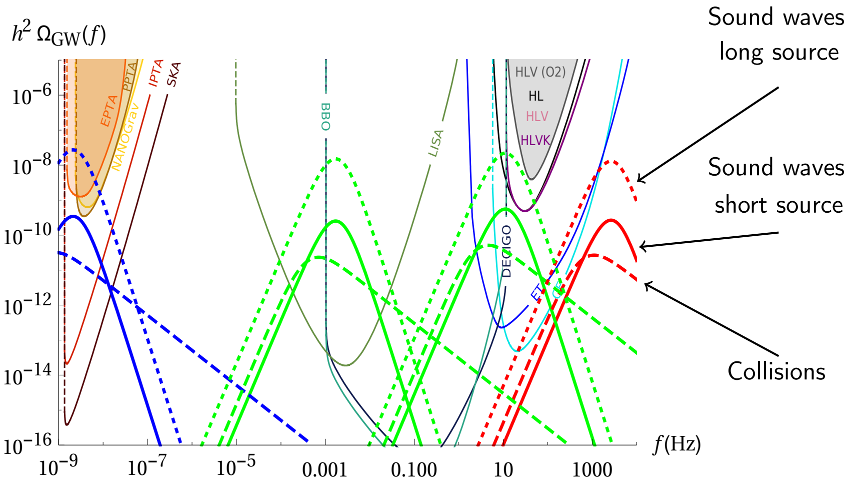

Dark Glueball — Dark QCD 1 — Dark Axion

$M_{KK} = 1$ KeV — $M_{KK} = 100$ GeV — $M_{KK} = 10^6$ GeV — $M_{KK} = 10^9$ GeV

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Chiral symmetry bubbles *[Bigazzi, AC, Cotrone, Paredes '20]*

In principle: to find bubble-like solution ($x = x(\sigma, y)$) from

$$S_{DBI} = \frac{NT^3\lambda^3}{486 M_{KK}^3} \int d\sigma dy\, \sigma^2 y^{5/2} \sqrt{1 + (y^3 - 1)(\partial_y x)^2 + (\partial_\sigma x)^2}$$

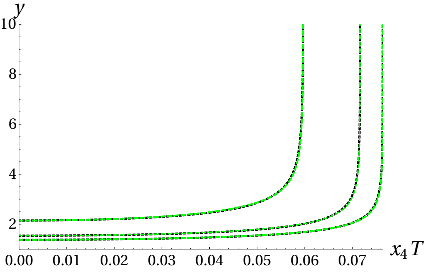
Extremely hard task!

Effective variational approach

- Test for vacuum solutions
- Ansatz for brane profile:

$$x(y) = \frac{\tilde{L}}{2} \tanh\left(\frac{\sqrt{y - y_J}}{\sqrt{B}}\right)$$

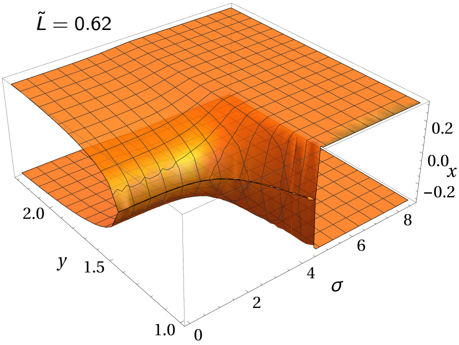
- Disconnected conf: $B \to 0$, $y_J = 1$
- Impressive fit of the exact profiles

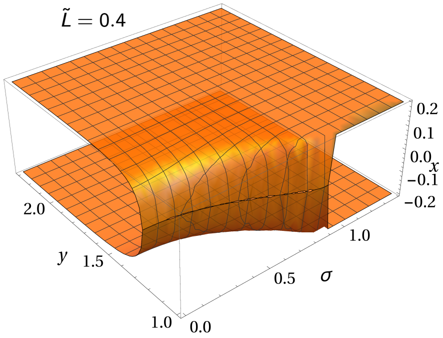


Chiral symmetry bubbles [Bigazzi, AC, Cotrone, Paredes '20]

We promote y_J and B to functions of radial coordinate σ

$$x(y,\sigma) = \frac{\tilde{L}}{2} \tanh\left(\frac{\sqrt{y - y_{J,tv} + (y_{J,tv} - 1)\alpha(\sigma)}}{\sqrt{B_{tv}(1-\alpha(\sigma))}}\right)$$





Chiral symmetry breaking/restoration scenarios

Dark QCD 2:

- $SU(N)$ Yang-Mills + N_f flavours
- Non-antipodal configuration: $f_\chi \gg M_{KK}$
- Two separated first-order PTs
- Two-peaks GW spectrum

HoloAxion:

- $SU(3)$ Yang-Mills + 6 antipodal flavours + 1 non-antipodal flavour
- Composite axion from chiral symmetry breaking
- Dynamical scale: $f_a \gtrsim 10^8$ GeV
- Gauge sectors describes QCD:

$$\lambda = 33.26 \qquad M_{KK} = 0.949 \text{ GeV}$$

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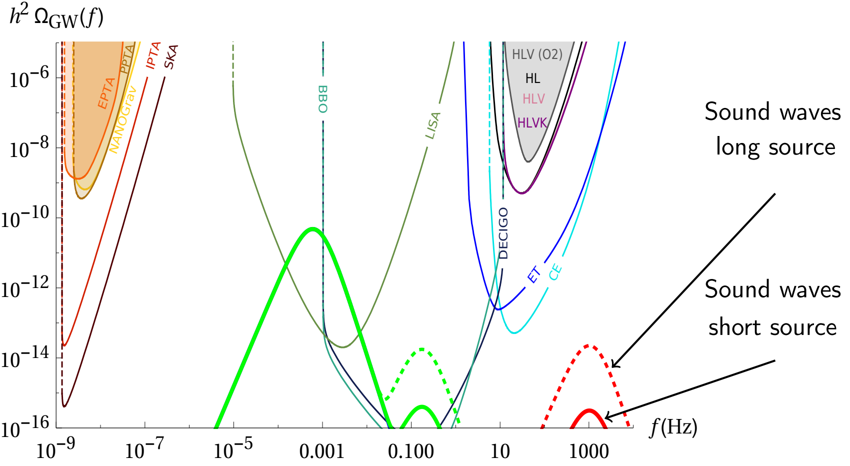

Dark QCD 2

$M_{KK} = 100$ GeV $\quad f_\chi = 6$ TeV

HoloAxion

$f_a = 10^9$ GeV

Conclusions and Outlook

- GWs allows us to probe beyond Standard Model physics
- We used the Witten-Sakai-Sugimoto model to describe dark sectors
- Effective approach for studying first-order PTs
- Dark QCD 1,2 and Dark Glueball scenarios expected to be detectable in near-future experiments

For the future:

- QCD at large baryon density
- Applications to quark-gluon-plasma physics

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Thank you for your attention!

Backup slides

Formulae for the spectra from collisions:

$$h^2\Omega_c(f) \sim 1.67 * 10^{-5} \left(\frac{\beta}{H_*}\right)^{-2} \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{0.48v^3}{1+5.3v^2+5v^4}\right) S_{env}(f)$$

$$S_{env}(f) \sim \left[0.064\left(\frac{f}{f_{env}}\right)^{-3} + 0.456\left(\frac{f}{f_{env}}\right)^{-1} + 0.48\left(\frac{f}{f_{env}}\right)\right]$$

$$f_{env} \sim 16.5 * 10^{-6}\mathrm{Hz}\left(\frac{f_*}{\beta}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

where

$$\frac{f_*}{\beta} \sim \frac{0.35}{1+0.069v+0.69v^4}$$

$$\begin{aligned} v &= \text{average velocity of the bubbles} \\ H_* &= \text{Hubble scale at percolation temperature } T_p \\ g_* &= \text{number of relativistic degrees of freedom at } T_p \end{aligned}$$

Backup slides

Formulae for the spectra from sound waves:

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

$$\begin{aligned} S_{sw}(f) &\sim \left(\frac{f}{f_{sw}}\right)^3 \left(\frac{7}{4+3(f/f_{sw})^2}\right)^{7/2} \\ f_{sw} &\sim 8.9 \cdot 10^{-6}\mathrm{Hz}\frac{1}{v}\left(\frac{\beta}{H_*}\right)\left(\frac{z_p}{10}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} \end{aligned}$$

If duration of source is short, we multiply by

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

Efficiency factor given by $\kappa_v = \alpha/(0.73 + 0.083\sqrt{\alpha} + \alpha)$