Cosmological Phase Transitions in Warped Space: Gravitational Waves and Collider Signatures

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E.M., O.Pujolàs JHEP1408(2014) 081; E.M., O.Pujolàs, M.Quirós, JHEP1605(2016) 137; E.M., G.Nardini, M.Quirós, 1806:04877.

Issues

1 The Radion Effective Potential
- General Formalism
- The effective potential in the warped model
- The effective potential at finite temperature

2 The phase transition
- The dilaton phase transition
- The electroweak phase transition

3 Gravitational waves

4 Heavy Radion Phenomenology
- Radion couplings
- LHC constraints on the radion signal strengths

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The Model

- Scalar-gravity system with UV and IR branes:

$$
S = \int d^5x \sqrt{|\det g_{MN}|} \left[-\frac{1}{2\kappa^2} R + \frac{1}{2} g^{MN}(\partial_M \phi)(\partial_N \phi) - V(\phi) \right]
$$
$$
- \sum_\alpha \int_{B_\alpha} d^4x \sqrt{|\det \bar{g}_{\mu\nu}|} \Lambda_\alpha(\phi) - \frac{1}{\kappa^2} \sum_\alpha \int_{B_\alpha} d^4x \sqrt{|\det \bar{g}_{\mu\nu}|} K_\alpha
$$

- Metric: $ds^2 = g_{MN}dx^M dx^N \equiv \underbrace{e^{-2A(r)}\eta_{\mu\nu}}_{\bar{g}_{\mu\nu}} dx^\mu dx^\nu - dr^2$,

- $V(\phi)$ bulk potential.
- Λ_α $(\alpha = 0, 1) \equiv$ UV, IR 4-dim brane potentials at $(r(\phi_0), r(\phi_1))$.
- Extrinsic curvature $K_{\mu\nu} = \frac{1}{2}\frac{d}{dr}(\bar{g}_{\mu\nu}) = -e^{-2A}A'\eta_{\mu\nu}$.
- Solve the hierarchy problem ➡ Brane dynamics should fix (ϕ_0, ϕ_1) to get $A(\phi_1) - A(\phi_0) \approx 35 \Longrightarrow M_{\mathrm{Planck}} \simeq 10^{30} M_{\mathrm{TeV}}$.

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The Model

- Introduce the superpotential

$$V(\phi) = \frac{1}{8} \left(\frac{\partial W}{\partial \phi} \right)^2 - \frac{\kappa^2}{6} W^2(\phi) .$$

- Equations of Motion (2 EoM of 1st order):

$$\phi'(r) = \frac{1}{2} \frac{\partial W}{\partial \phi} , \qquad A'(r) = \frac{\kappa^2}{6} W .$$

- Boundary conditions in the branes:

$$\Lambda_\alpha(\phi(r_\alpha)) = (-1)^\alpha W(\phi(r_\alpha)) , \qquad \frac{\partial \Lambda_\alpha(\phi(r_\alpha))}{\partial \phi} = (-1)^\alpha \frac{\partial W(\phi(r_\alpha))}{\partial \phi} .$$

- Brane potentials: $\Lambda_\alpha(\phi) = \Lambda_\alpha + \frac{\gamma_\alpha}{2}(\phi - v_\alpha)^2 .$

- In the limit $\gamma_\alpha \to \infty$ (stiff wall), the BCs simplify to

$$\phi(r_\alpha) = v_\alpha , \quad \Lambda_\alpha(\phi(r_\alpha)) = \Lambda_\alpha , \qquad \alpha = 0, 1 .$$

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The Effective Potential

- Action:

$$S = S_{\text{bulk}} + S_{\text{brane}} + S_{\text{GHY}} = - \int d^4 x \, V_{eff} \, .$$

- Effective Potential:

$$V_{eff} = \left[e^{-4A} \left(W + \Lambda_1 \right) \right]_{r_1} + \left[e^{-4A} \left(-W + \Lambda_0 \right) \right]_{r_0} \, .$$

- Fixing: $r_0 = 0$ and $A(0) = 0$ ➡ r_1 is the brane distance, and

$$\kappa^2 M_P^2 = 2\ell \int_0^{\bar{r}_1} d\bar{r} \, e^{-2A(\bar{r})} \, ,$$

with $\bar{r} \equiv r/\ell$ and $M_P = 2.4 \times 10^{18}$ GeV.

- In the holographic theory:

$$N^2 \simeq \frac{8\pi^2 \ell^3}{\kappa^2} \, .$$

$\ell \equiv$ radius of AdS.

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The Effective Potential

A novel technique to compute the effective potential:

- The EoM for W

$$V(\phi) = \frac{1}{8}\left(\frac{\partial W}{\partial \phi}\right)^2 - \frac{\kappa^2}{6} W^2(\phi)$$

  admits an arbitrary integration constant $\equiv s \longrightarrow$ expand in s
  [I. Papadimitriou '07], [EM,Pujolas '14]:

$$W = \sum_{n=0}^{\infty} s^n W_n$$

- W_n can be computed iteratively from W_0. For $n = 1$:

$$W_1(\phi) = \frac{1}{\ell\kappa^2}\exp\left(\frac{4\kappa^2}{3}\int^\phi \frac{W_0(\bar\phi)}{W_0'(\bar\phi)}d\bar\phi\right).$$

- Solution of EoM for ϕ and A:

$$\phi(r) = \phi_0(r) + s\,\phi_1(r) + \mathcal{O}(s^2), \qquad A(r) = A_0(r) + s\,A_1(r) + \mathcal{O}(s^2).$$

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- Choose s to fulfill the BCs:

$$\phi(0) = v_0, \quad \phi(r_1) = v_1 \qquad \longrightarrow \qquad s(r_1) = \frac{v_1 - \phi_0(r_1)}{\phi_1[\phi_0(r_1)]}.$$

- The superpotential gets explicit dependence on the brane distance r_1:

$$W(v_\alpha) = W_0(v_\alpha) + s(r_1)W_1(v_\alpha) + \cdots, \qquad \alpha = 0, 1.$$

- Effective potential (up to first order in $s(r_1)$):

$$V_{eff}(r_1) = \Lambda_0 - W_0(v_0)$$
$$+ e^{-4A_0(r_1)} \left\{ [\Lambda_1 + W_0(v_1)] [1 - 4A_1 s(r_1)] + s(r_1) \left[W_1(v_1) - e^{4A_0(r_1)} W_1(v_0) \right] \right\}$$

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The soft-wall model

- Consider the soft-wall phenomenological models:

$$W_0(\phi) = \frac{6}{\ell\kappa^2}\left(1 + e^{\gamma\phi}\right).$$

- W_0 is an exact solution for bulk scalar potential:

$$V(\phi) = -\frac{6}{\ell^2\kappa^2}\left[1 + 2e^{\gamma\phi} + \left(1 - \frac{3\gamma^2}{4\kappa^2}\right)e^{2\gamma\phi}\right].$$

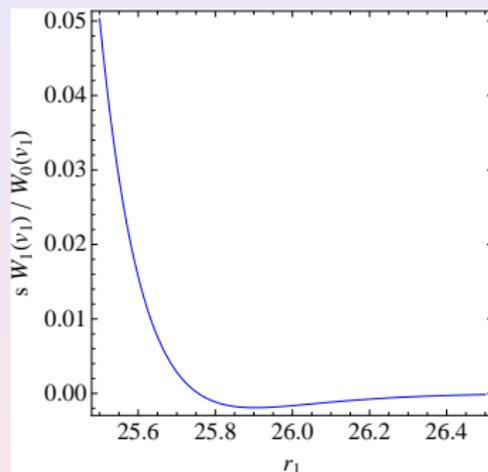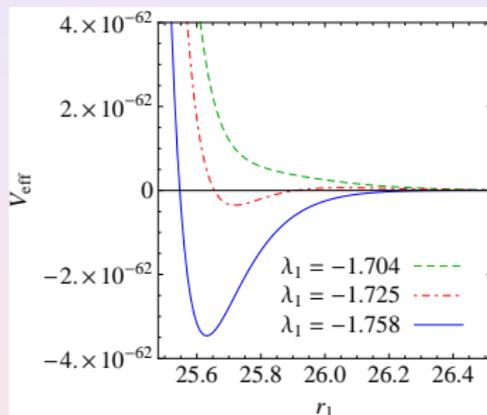- A solution is also $W(\phi) = W_0(\phi) + sW_1(\phi) + \cdots$, with

$$W_1(\phi) = \frac{1}{\ell\kappa^2}\exp\left[\frac{4\kappa^2}{3\gamma^2}\left(\gamma\phi - e^{-\gamma\phi}\right)\right].$$

- Scalar field and warp factor:

$$\phi_0(r) = v_0 - \frac{1}{\gamma}\log\left(1 - \frac{r}{r_S}\right), \qquad A_0(r) = \frac{r}{\ell} - \frac{\kappa^2}{3\gamma^2}\log\left(1 - \frac{r}{r_S}\right),$$

with naked singularity at $r_S = \frac{\kappa^2\ell}{3\gamma^2}e^{-\gamma v_0}$.

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$$s(r_1)W_1(v_1) \ll W_0(v_1) \quad \Rightarrow \quad W(\phi) = W_0(\phi) + sW_1(\phi) + \cdots \text{ reliable.}$$

Brane tensions: $\lambda_\alpha = \frac{\ell\kappa^2}{6}\Lambda_\alpha, \quad \alpha = 0, 1.$

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The radion field

- Perturbation of the metric:

$$ds^2 = -[1 + 2F(x,r)]^2 dr^2 + e^{-2[A+F(x,r)]}\bar{g}_{MN}dx^M dx^N ,$$
$$\phi(x,r) = \phi_{\text{Background}}(x) + \varphi(x,r) .$$

- Radion ansatz $F(x,r) = F(r)R(x)$.
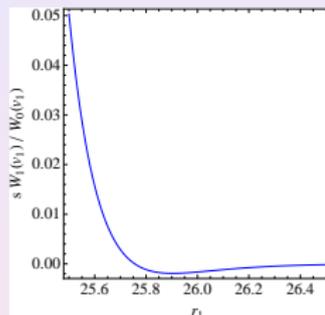
- For the canonically normalized radion field $\mu(r)$:
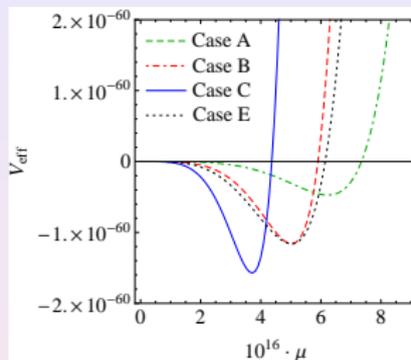
$$\mathcal{L}_{\text{rad}} = \frac{6\ell^3}{\kappa^2} \int d^4x \sqrt{|\det \bar{g}_{\mu\nu}|} \left(\frac{1}{2}(\partial\mu)^2 - \frac{1}{2}m_{\text{rad}}^2 \mu^2 \right) ,$$

with

$$\mu(r) = \ell^{-3/2} \int_r^{r_S} d\bar{r} X_F[\bar{r}]^{-1/2} , \qquad X_F(r) = 2 \int_0^r dr\, e^{2A(r)} ,$$

where we have used that $F(r) \simeq e^{2A(r)}$ for 'light' dilaton/radion.

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$s(r_1)W_1(v_1) \ll W_0(v_1)$ ➡ $W(\phi) = W_0(\phi) + sW_1(\phi) + \cdots$ reliable.

- Radion mass from mass formula
  [Cabrer,Gersdorff,Quiros '11], [EM,Pujolas,Quiros '16]:

$$m_{\rm rad}^2 \simeq \frac{\rho_1^2}{\Pi_{\rm rad}(r_1)}, \quad \rho_1 \equiv (1/\ell)e^{-A(r_1)},$$

$$\Pi_{\rm rad}(r_1) = \frac{1}{\ell^2} \int_0^{r_1} dr e^{4(A-A_1)} \left(\frac{W}{W'}\right)^2 \left[\frac{2}{W[\phi(r_1)]} + \int_r^{r_1} d\bar{r} e^{-2(A-A_1)} \left(\frac{W'}{W}\right)^2\right]$$

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- Graviton KK modes from mass formula
  [EM,Pujolas,Quiros '16]:

$$m_G^2 \simeq \frac{\rho_1^2}{\Pi_G(r_1)} \,,$$

$$\Pi_G(r_1) = \frac{1}{\ell^2} \frac{\int_0^{r_1} dr e^{-2(A-A_1)} \int_r^{r_1} dr' e^{4(A-A_1)} \int_{r'}^{r_1} dr'' e^{-2(A-A_1)}}{\int_0^{r_1} dr e^{-2(A-A_1)}} \,.$$

$$
\begin{array}{llll}
\text{(class A):} & m_{\text{rad}} \simeq 0.2\,\rho_1, & m_G \simeq 2.9\,\rho_1\,, \\
\text{(class B):} & m_{\text{rad}} \simeq 0.9\rho_1, & m_G \simeq 4.8\,\rho_1\,, \\
\text{(class C):} & m_{\text{rad}} \simeq 1.6\rho_1, & m_G \simeq 5.6\,\rho_1\,, \\
\text{(class D):} & m_{\text{rad}} \simeq 1.0\rho_1, & m_G \simeq 9.6\,\rho_1\,, \\
\text{(class E):} & m_{\text{rad}} \simeq 0.7\,\rho_1, & m_G \simeq 4.7\,\rho_1\,.
\end{array}
$$

- $A \equiv$ small back-reaction.
- B, C, D, E $\equiv$ large back-reaction.

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- Black-hole metric:

$$ds_{BH}^2 = -\frac{1}{h(r)}dr^2 + e^{-2A(r)}(h(r)dt^2 - d\vec{x}^2)\,.$$

- 4 EoM with boundary conditions:

$$h(0) = 1\,, \quad h(r_h) = 0\,, \quad \phi(0) = v_0 \quad A(0) = 0\,.$$

- Temperature and entropy of the BH:

$$T_h = \frac{1}{4\pi}e^{-A(r_h)}\big|h'(r)\big|_{r=r_h}\,, \qquad S = \frac{4\pi}{\kappa^2}e^{-3A(r_h)}\,.$$

- Free energy:

$$F(T_h) = (T_h - T)S(T_h) - \int_0^{T_h} S(\bar{T}_h)d\bar{T}_h\,.$$

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- Minimum of the free energy at $T_h = T$:

$$F_{\mathrm{min}} = F(T) = -\int_0^T S(\bar{T}_h)d\bar{T}_h = -\frac{4\pi^4\ell^3}{\kappa^2}\int_0^T a_h \bar{T}_h^3 d\bar{T}_h,$$

- a_h measures deviation from conformal limit ($a_h = 1$ is conformal):

$$S(T) = \frac{4\pi^4\ell^3}{\kappa^2}T^3 a_h(T) \quad \Longrightarrow \quad F_{\mathrm{min}} \simeq -\frac{\pi^4\ell^3}{\kappa^2}a_h(T)T^4.$$
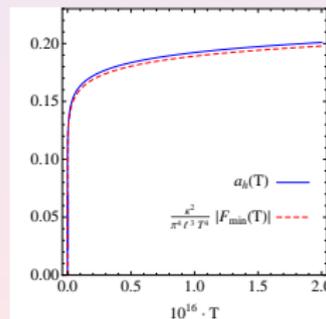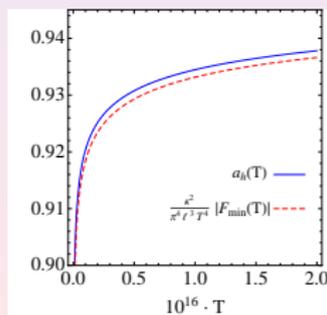

Figure : Left: Small back-reaction. Right: Large back-reaction.

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- Phase transition starts when $F_{\text{deconfined}} < F_{\text{confined}}$:

$$F_d(T) = E_0 + F_{min} - \frac{\pi^2}{90} g_d^{eff} T^4, \qquad F_c(T) = -\frac{\pi^2}{90} g_c^{eff} T^4,$$

where $E_0 = V_{eff}(\mu = 0) - V_{eff}(\mu = \langle\mu\rangle) > 0$.

- Number of degrees of freedom ($\mathcal{R}$, H and t_R in IR brane):

$$g_c^{eff} = g_B + \frac{7}{8} g_F = 106.75 \qquad \text{and} \qquad g_d^{eff} = 97.5.$$

- Critical temperature ➡ $F_d(T_c) = F_c(T_c)$
- Action driven by thermal fluctuations is $O(3)$ sym (high T):

$$S_3 = 4\pi \int d\rho \rho^2 \frac{6\ell^3}{\kappa^2} \left(\frac{1}{2}\mu'^2 + V_{rad}(\mu) \right) \qquad \text{with} \quad V_{rad} \equiv \frac{\kappa^2}{6\ell^3} V_{eff}.$$

- Action driven by quantum fluctuations is $O(4)$ sym (low T):

$$S_4 = 2\pi^2 \int d\rho \rho^3 \frac{6\ell^3}{\kappa^2} \left(\frac{1}{2}\mu'^2 + V_{rad}(\mu) \right),$$

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Bounce equation

- Solution of the bounce equation **[Coleman '77; Linde '81]**

$$\frac{\partial^2 \mu}{\partial \rho^2} + \frac{2}{\rho}\frac{\partial \mu}{\partial \rho} - \frac{\partial V_{\mathrm{rad}}}{\partial \mu} = 0\,, \qquad \rho = \sqrt{\vec{x}^2}\,,$$

with BCs

$$\frac{3\ell^3}{\kappa^2}\mu'^2(\rho)\bigg|_{\mu=0} = |F_{\min}(T)|\,, \quad \mu(0) = \mu_0\,, \quad \frac{d\mu}{d\rho}\bigg|_{\rho=0} = 0\,.$$

- Bubble nucleation from the false BH minimum to the true vacuum is given by

$$\Gamma/\mathcal{V} = \mathcal{A}e^{-S_E} \quad \simeq \quad e^{-S_3/T} + e^{-S_4}\,, \qquad \mathcal{A} \simeq T_c^4\,.$$

- Nucleation happens when

$$S_E \lesssim 4\log\left(M_P/\langle\mu\rangle\right) \approx 140\,.$$

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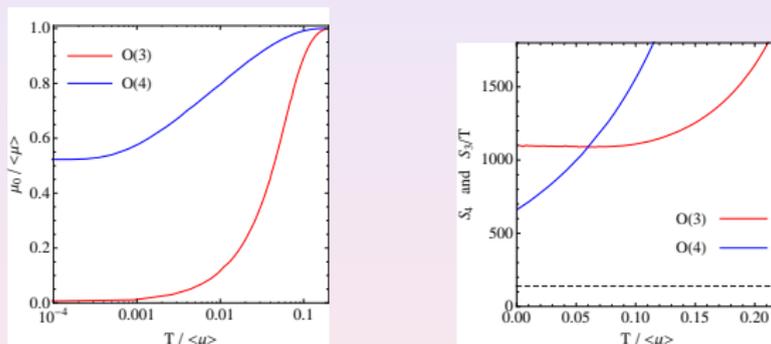
Figure : Case A: Small back-reaction ➡ No nucleation.

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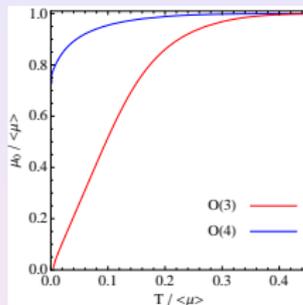
Figure : Case B: $\lambda_1 = -2.125$.

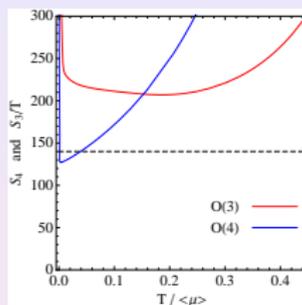Figure : Case B: $\lambda_1 = -2.583$.

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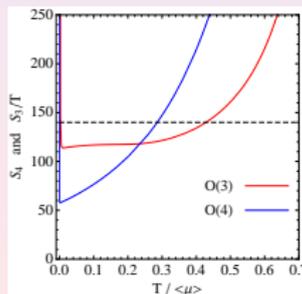
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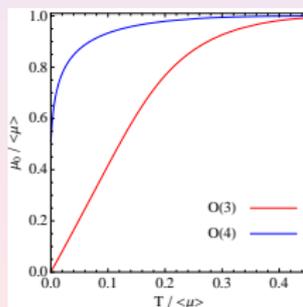| Scen.	λ_1	ℓ^{-1}/M_P	$m_{\rm rad}/m_G$	ρ_1/TeV	$m_{\rm rad}$/TeV	$\langle\mu\rangle$/TeV	$\mu_0/\langle\mu\rangle$	$T_c/\langle\mu\rangle$	$T_n/\langle\mu\rangle$
A_1	-1.250	0.501	0.0645	0.758	0.1998	0.750	-	0.305	-
B_1	-3.000	0.554	0.1969	1.085	1.018	0.828	0.9995	0.903	0.609
B_2	-2.583	0.554	0.1905	1.007	0.915	0.767	0.989	0.825	0.428
B_3	-2.500	0.554	0.1888	0.989	0.890	0.752	0.974	0.806	0.367
B_4	-2.438	0.554	0.1874	0.973	0.870	0.741	0.937	0.790	0.297
B_5	-2.375	0.554	0.1859	0.957	0.849	0.728	0.982	0.774	0.193
B_6	-2.292	0.554	0.1836	0.934	0.818	0.710	0.971	0.750	0.149
B_7	-2.208	0.554	0.1809	0.908	0.784	0.690	0.949	0.724	0.0990
B_8	-2.125	0.554	0.1776	0.879	0.745	0.667	0.890	0.694	0.0388
B_9	-2.096	0.554	0.1763	0.8675	0.7303	0.6585	0.827	0.682	0.0122
B_{10}	-2.092	0.554	0.1761	0.8658	0.7281	0.6572	0.808	0.680	0.0073
B_{11}	-2.090	0.554	0.1760	0.8650	0.7270	0.6565	0.793	0.679	0.0039
C_1	-3.125	0.377	0.289	0.554	0.890	0.378	0.989	1.123	0.601
C_2	-2.604	0.377	0.271	0.496	0.751	0.336	0.937	0.976	0.098
D_1	-3.462	1.49	0.106	0.468	0.477	0.250	0.9996	1.007	0.445
E_1	-2.429	0.554	0.155	0.877	0.643	0.667	0.895	0.694	0.142

A: $\kappa^2 = \frac{1}{4}\ell^3$ ($N \simeq 18$)
B: $\kappa^2 = \frac{1}{4}\ell^3$ ($N \simeq 18$)
C: $\kappa^2 = \frac{1}{8}\ell^3$ ($N \simeq 25$)
D: $\kappa^2 = \ell^3$ ($N \simeq 9$)
E: $\kappa^2 = \frac{1}{4}\ell^3$ ($N \simeq 18$)

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The dilaton phase transition

- Inflation starts when E_0 dominates over thermal corrections:

  Energy density: $\qquad \rho_d(T_i) = E_0 + \dfrac{3\pi^4 \ell^3}{\kappa^2} a_h T_i^4 + \dfrac{\pi^2}{30} g_d^{eff} T_i^4 \simeq E_0 \,.$

- Inflation finishes when bubbles percolate $\simeq T_n$.
- Number of e-folds of inflation is $N_e \approx \log(T_i/T_n)$.
- During the phase transition the energy density is approx. conserved. At the end of the phase transition the universe ends up in the confined phase at the reheating temperature

  $$\rho_c(T_R) = \rho_d(T_n)\,, \qquad \text{with} \qquad \rho_c = \frac{\pi^2}{30} g_c^{eff} T^4 \,.$$

- The reheating temperature is close to TeV.

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Scen.	$T_i/\langle\mu\rangle$	N_e	$T_R/\langle\mu\rangle$	T_R/GeV	α	$\log_{10}(\beta/H_\star)$
B_1	0.663	0.09	1.272	1053	1.60	2.36
B_2	0.605	0.35	1.071	821.8	4.61	1.99
B_3	0.591	0.48	1.024	770.4	7.86	1.79
B_4	0.580	0.67	0.986	730.6	17.1	1.48
B_5	0.568	1.08	0.953	694.0	90.1	1.97
B_6	0.551	1.31	0.921	654.2	228	1.86
B_7	0.531	1.68	0.887	612.0	1047	1.67
B_8	0.509	2.57	0.849	566.4	$4.0 \cdot 10^4$	1.23
B_9	0.5004	3.71	0.834	549.3	$4.1 \cdot 10^6$	0.64
B_{10}	0.4991	4.22	0.832	546.8	$3.3 \cdot 10^7$	0.34
B_{11}	0.4985	4.86	0.831	545.6	$4.5 \cdot 10^8$	-0.32
C_1	0.828	0.32	1.531	578.4	4.3	2.03
C_2	0.718	1.99	1.239	416.2	$5.0 \cdot 10^3$	1.45
D_1	–	–	0.535	133.7	5.0	1.05
E_1	0.509	1.28	0.850	567.2	203	1.89

Table : *Some physical parameters for the cases B_i, C_i, D and E.*

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The electroweak phase transition

When the BH moves beyond the IR brane, the Higgs field appears:

$$V(\mu, \mathcal{H}) = V_{eff}(\mu) + \left(\frac{\mu}{\langle\mu\rangle}\right)^4 V_{SM}(\mathcal{H}, T),$$

leads to **[Nardini, Quiros, Wulzer '07]**

$$v(T) = \begin{cases} 0 & \text{for } T > T_{EW} \\ v\sqrt{1 - T^2/T_{EW}^2} & \text{for } T \leq T_{EW} \end{cases}$$

and $T_{EW} \simeq 150\,\text{GeV}$.

- $T_n > T_{EW}$ ➡ EW remains unbroken during the dilaton PT.
- $T_n < T_{EW}$ ➡ EW sym broken at the same time that dilaton PT.

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- $T_R > T_{EW}$:
  At the end of the reheating process ➡ Higgs in sym phase ➡
  Universe evolves along a radiation dominated era
  ➡ EWSB as in SM ➡ No EW baryogenesis.

- $T_R < T_{EW}$:
  Reheating does not restore EW sym ➡ Higgs at minimum of
  $V(\mathcal{H}, T_R)$. EW baryogenesis condition

$$\frac{v(T_R)}{T_R} \gtrsim 1 \qquad \longrightarrow \qquad T_R \lesssim T_{\mathcal{H}} \simeq 140 \, \text{GeV} \, .$$

- $T_{\mathcal{H}} < T_R \lesssim T_{EW}$ ➡ EWPT too weak for EW baryogenesis.

- $T_R = 133.7 \, \text{GeV} < T_{\mathcal{H}} < T_{EW}$ ➡ EW baryogenesis.
  This is scenario D_1. EW and dilaton PT simultaneously at
  $T = T_n = 112$ GeV, and ends up with $T = T_R = 133.7$ GeV.

Gravitational waves

- Envelope approximation **[Kosowsky, Tuner '93]**, $\cdots$:

$$h^2 \Omega_{\mathrm{GW}}(f) \simeq h^2 \overline{\Omega}_{\mathrm{GW}} \, \frac{3.8(f/f_p)^{2.8}}{1 + 2.8(f/f_p)^{3.8}} \, ,$$

with

$$h^2 \overline{\Omega}_{\mathrm{GW}} \simeq 0.80 \times 10^{-4} \left(\frac{H_\star}{\beta} \frac{\alpha}{\alpha+1} \right)^2 \frac{\xi(v_w)}{\sqrt[3]{g_c(\overline{T}_R)}} \, ,$$

and

$$\alpha \simeq \frac{E_0}{3(\pi^4 \ell^3 / \kappa^2) a_h(T_n) T_n^4} \, ,$$

$$\frac{\beta}{H_\star} \simeq T_n \left. \frac{dS_E}{dT} \right|_{T=T_n} .$$
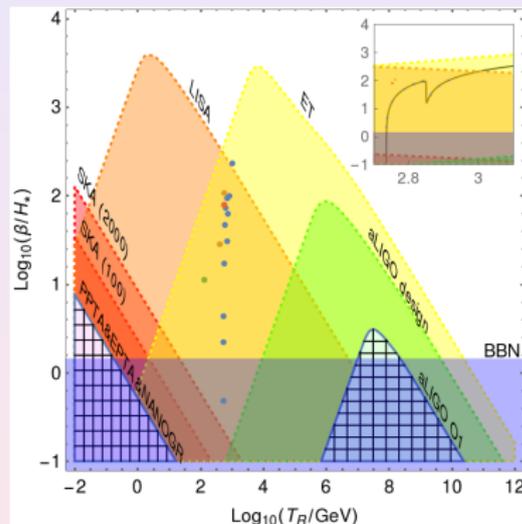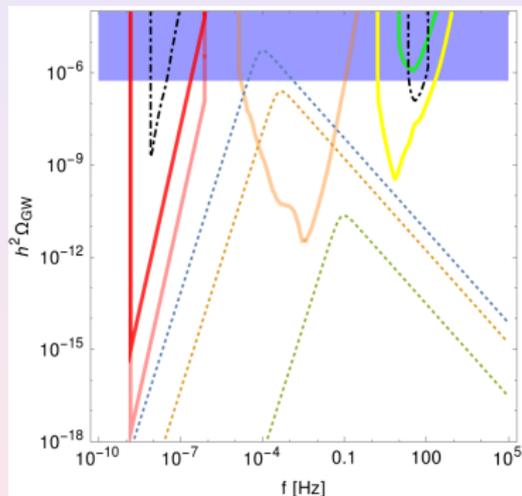
Gravitational waves

Figure : Right: Signal-to-Noise Ratio (SNR) > 10 in next ~ 20 years.

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Heavy Radion Phenomenology

- Large back-reaction $\Rightarrow$ Confined/Deconfined Phase Transition.
- Radion lighter than any KK resonance and $m_{\mathrm{rad}} \sim \mathcal{O}(\mathrm{TeV})$.
- $\Rightarrow$ Radion can decay only into SM-like fields.
- Radion couples to the Energy-Momentum tensor $\Rightarrow$ Radion channels are those of the SM Higgs, but with different strengths.
- 4D action for the radion:

$$S_4 = 2 \int_0^{r_1} dr \left[(1 - F)\bar{\psi}_{L,R} i\slashed{D} \psi_{L,R} - \left(\frac{1}{4} + \frac{F}{2} \right) \mathrm{tr} F_{\mu\nu}^2 - e^{-A}(1 - 2F)M(\phi)\bar{\psi}\psi \right.$$
$$\left. + \delta(r - r_1) \left\{ -\frac{\ell h_f}{\sqrt{2}}(1 - 4F)(H\bar{\psi}_L \psi_R + h.c.) + (1 - 2F)\frac{1}{2}(D_\mu H)^2 - (1 - 4F)V(H) \right\} \right]$$

Assume the 125-GeV Higgs in the IR brane.

- Compute the couplings to i) fotons, ii) gluons, iii) fermions, iV) massive gauge bosons, and V) the Higgs boson.

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Radion couplings

- Example: Couplings to fermions:

$$\mathcal{L}_{r\bar{f}f} = -\frac{\mathcal{R}(x)}{v} c_f m_f \bar{f} f \,,$$

with

$$c_f = \sqrt{\frac{8}{3}} \left(\frac{\int_0^{r_1} dr \, e^{-2A}}{\int_0^{r_1} dr \, e^{2(A-A_1)}} \right)^{1/2} \frac{v}{e^{-A_1} M_P} \,.$$

- For a Higgs of mass $m_H = m_{rad} \implies c_f = 1$.

Scen.	$m_{\rm rad}$/TeV	m_G/TeV	c_γ	c_g	c_V	$c_{\mathcal{H}}$	c_f
B$_2$	0.915	4.80	0.472	0.164	0.0649	0.259	0.259
B$_8$	0.745	4.19	0.542	0.146	0.0744	0.298	0.298
C$_1$	0.890	3.08	0.532	0.179	0.0904	0.362	0.362
C$_2$	0.751	2.77	0.595	0.162	0.101	0.404	0.404
D$_1$	0.477	4.50	3.791	0.475	0.397	1.586	1.586
E$_1$	0.643	4.16	0.562	0.124	0.0746	0.298	0.298

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Consider radion with masses: $m_{\mathcal{R}} = (0.915, 0.745, 0.477)$ TeV corresponding to scenarios B_2, B_8 and D_1.

*Production of the heavy radion at the LHC by:

- Gluon fusion:

$$\sigma^{ggF}(gg \to \mathcal{R}) \simeq |c_g|^2 \sigma_{SM}^{ggF}(gg \to H) \implies \sigma_{\mathcal{R}}^{ggF} \simeq (5.88, 14.6, 1270) \, \text{fb}$$

- Vector-boson fusion:

$$\sigma^{VBF}(VV \to \mathcal{R}) \simeq |c_V|^2 \sigma_{SM}^{VBF}(VV \to H) \implies \sigma_{\mathcal{R}}^{VBF} \simeq (0.59, 1.22, 86) \, \text{fb}$$

*Radion can decay into SM particles:

$$\Gamma(\mathcal{R} \to X\bar{X}) \simeq |c_X|^2 \Gamma_{SM}(H \to X\bar{X}), \quad X = \gamma, g, W, Z, f.$$

*It can decay also in a pair of 125-GeV Higgses:

$$\Gamma(\mathcal{R} \to \mathcal{H}\mathcal{H}) = \frac{|c_{\mathcal{H}}|^2}{16\pi} \frac{m_{\mathcal{H}}^4}{v^2 \, m_r} \sqrt{1 - \frac{4m_{\mathcal{H}}^2}{m_r^2}},$$

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- Radion branching fraction:

$$\mathcal{B}^{\mathcal{R}}_{XX} \simeq \frac{|c_X|^2 \Gamma_{SM}(H \to X\bar{X})}{\Gamma(\mathcal{R} \to \mathcal{H}\mathcal{H}) + \sum_Y |c_Y|^2 \Gamma_{SM}(H \to Y\bar{Y})}, \qquad Y = \gamma, g, W, Z, f.$$

Scen.	$\Gamma_{\mathcal{R} \to WW}$	$\Gamma_{\mathcal{R} \to ZZ}$	$\Gamma_{\mathcal{R} \to hh}$	$\Gamma_{\mathcal{R} \to t\bar{t}}$	$\Gamma_{\mathcal{R} \to b\bar{b}}$	$\Gamma_{\mathcal{R} \to \tau\bar{\tau}}$	$\Gamma_{\mathcal{R} \to \gamma\gamma}$
B_2	1220	610	5.70	2670	0.825	0.129	0.0385
B_8	786	389	9.01	2680	0.917	0.138	0.0143
D_1	4960	2350	362	28000	17.73	2.49	0.378

Table : *Partial widths of the radion in the scenarios B_2, B_8 and D_1. All widths are in MeV units.*

- Radion is a narrow resonance (total width):

$$\frac{\Gamma_{\mathcal{R}}}{m_r} \simeq (4.9, 5.2, 75) \times 10^{-3}.$$

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Experimental bounds

Scen.	$\mathcal{B}_{WW}^{\mathcal{R}}$	$\mathcal{B}_{ZZ}^{\mathcal{R}}$	$\mathcal{B}_{hh}^{\mathcal{R}}$	$\mathcal{B}_{t\bar{t}}^{\mathcal{R}}$	$\mathcal{B}_{b\bar{b}}^{\mathcal{R}}$	$\mathcal{B}_{\tau\bar{\tau}}^{\mathcal{R}}$	$\mathcal{B}_{\gamma\gamma}^{\mathcal{R}}$
B_2	0.271	0.135	$1.26 \cdot 10^{-3}$	0.592	$1.83 \cdot 10^{-4}$	$2.85 \cdot 10^{-5}$	$8.55 \cdot 10^{-6}$
B_8	0.203	0.101	$2.33 \cdot 10^{-3}$	0.693	$2.37 \cdot 10^{-4}$	$3.58 \cdot 10^{-5}$	$3.70 \cdot 10^{-6}$
D_1	0.139	$6.58 \cdot 10^{-2}$	$1.01 \cdot 10^{-2}$	0.785	$4.97 \cdot 10^{-4}$	$6.99 \cdot 10^{-5}$	$1.06 \cdot 10^{-5}$

- Cross section:

$$\mathcal{S}_{XX}^{ggF(VBF)} \equiv \sigma^{ggF(VBF)}(pp \to \mathcal{R} \to X\bar{X}) \simeq \sigma_{\mathcal{R}}^{ggF(VBF)}(gg \to \mathcal{R}) \cdot \mathcal{B}_{XX}^{\mathcal{R}}(\mathcal{R} \to X\bar{X}).$$

Scen.	$\mathcal{S}_{WW}^{ggF}$	$\mathcal{S}_{ZZ}^{ggF}$	$\mathcal{S}_{\tau\bar{\tau}}^{ggF}$	$\mathcal{S}_{\gamma\gamma}^{ggF}+\mathcal{S}_{\gamma\gamma}^{VBF}$	$\mathcal{S}_{WW}^{VBF}$	$\mathcal{S}_{ZZ}^{VBF}$	$\mathcal{S}_{\tau\bar{\tau}}^{VBF}$
B_2 (predic.)	1.59	0.80	$1.7 \cdot 10^{-4}$	$(5.0 + 0.5) \cdot 10^{-5}$	0.16	0.080	$1.7 \cdot 10^{-5}$
B_2 (bound)	52	14	11	0.29	12	8	–
B_8 (predic.)	2.96	1.47	$5.2 \cdot 10^{-4}$	$(5.4 + 0.5) \cdot 10^{-5}$	0.25	0.12	$4.4 \cdot 10^{-5}$
B_8 (bound)	91	42	20	0.34	19	19	–
D_1 (predic.)	176	83	0.09	0.013+0.001	12	6	0.006
D_1 (bound)	1100	300	90	2	200	130	–

Table : *The predictions of $\mathcal{S}_{XX}^{ggF(VBF)}$ and their corresponding 95% C.L. upper bounds. ATLAS searches [1709.07242, $\cdots$, 1710.07235].*

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Conclusions

- We have studied the cosmological phase transition in a 5D warped model. In particular:
    - Effective potential at zero temperature by using a novel technique, and the radion field.
    - Effective potential at finite temperature.
    - The dilaton phase transition.
- Confinement/deconfinement phase transition demands large back-reaction.
- Gravitational waves ➡ detectable by LISA and ET.
- Possibility of heavy radion detection at the LHC in full agreement with current bounds.

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Thank You!