Electroweak Phase Transition and Baryogenesis in Composite Higgs Models

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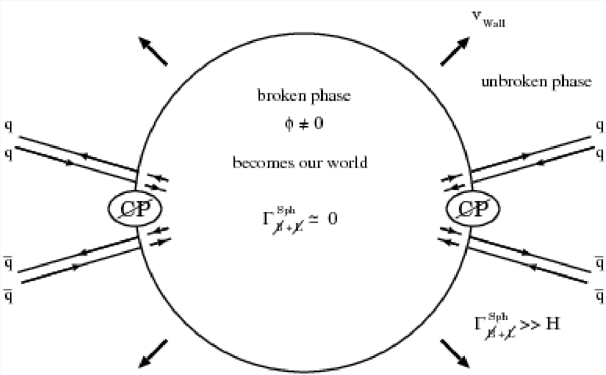
based on 1612.02447 w/ G. Servant
1803.08546 & 1804.07314 w/ S. Bruggisser, O. Matsedonskyi & G. Servant

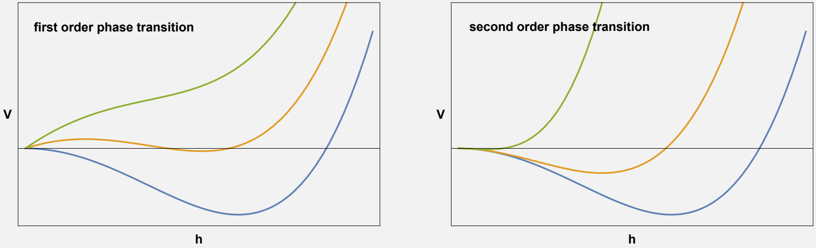
Electroweak baryogenesis in a nutshell

figure from `hep-ph/0205279`



- Appealing scenario to generate baryon asymmetry of the universe
- *CP*-violating effects in bubble wall create *CP*-asymmetry
- Then turned into baryon asymmetry by sphalerons in front of wall
- Inside bubble sphalerons are inactive and baryon asymmetry is frozen in

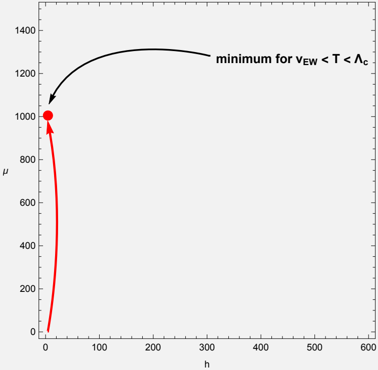
Electroweak baryogenesis in a nutshell



But electroweak baryogenesis does not work in SM because

- a) EW phase transition not first-order
- b) *CP*-violation from CKM too small

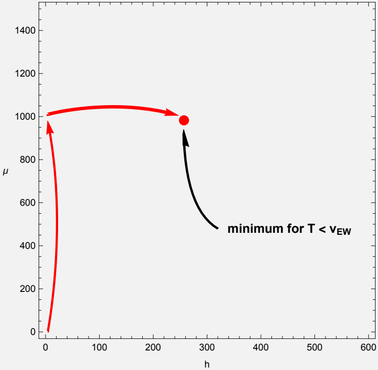
Electroweak baryogenesis with composite Higgs



Make electroweak baryogenesis work in composite Higgs with

- higher-dimensional operators
  `[Grinstein, Trott, 0806.1971]`
- additional singlet scalar
  `[Espinosa, Gripaios, Konstandin, Riva, 1110.2876]`

Electroweak baryogenesis with composite Higgs



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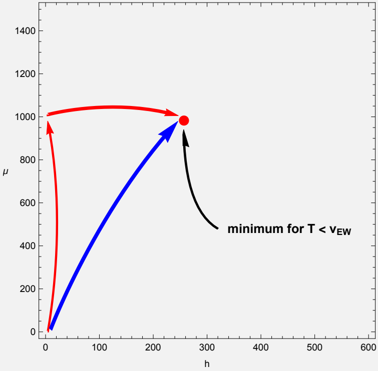
Electroweak baryogenesis with composite Higgs



Here instead: Assume supercooling and single-step phase transition. Then

- confining phase transition first-order ⇒ electroweak phase transition first-order too
- additional CP-violation from varying Yukawas during phase transition

Overview

1. The composite Higgs and its potential
2. The dilaton and its potential
3. Combining the Higgs and dilaton potentials
4. Results of numerical study
5. Experimental tests

Outline

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The composite Higgs and its potential

- Higgs emerges as bound state from confining sector
- Higgs pseudo-Nambu-Goldstone boson from confining sector
  ⇒ lighter than confinement scale (similar to pion in QCD)
- Solves (most of the) hierarchy problem
- Often assumed coset $SO(5)/SO(4)$ ⇒ custodial symmetry
- $SO(5)$ explicitly broken by coupling to SM sector ⇒ Higgs potential

$$V[\theta] \supset g_\star^2 f^4 \frac{3\,\xi^2}{(4\pi)^2}\left(c_\alpha \sin^2\theta + c_\beta \sin^4\theta\right)$$

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} f^2 (\partial_\mu \theta)^2$$

- ⇒ Canonically normalized field is $h \equiv f\theta$
- $g_\star$ sets masses of composite states: $m_\star \approx g_\star f$

Yukawa couplings from partial compositeness

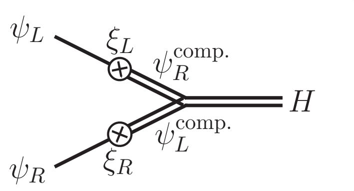
- SM fermions couple to fermionic operators $\mathcal{O}_{L,R}$,

$$\mathcal{L} \supset \frac{1}{\Lambda_{\mathrm{UV}}^{\gamma_{L,R}}}\mathcal{O}_L\psi_R + \frac{1}{\Lambda_{\mathrm{UV}}^{\gamma_{L,R}}}\mathcal{O}_R\psi_L$$

with $\gamma_{L,R} =$ dim. of $\mathcal{O}_{L,R} - 5/2$. At energies $\ll$ confinement scale Λ_c

$$\mathcal{L}_{\text{eff.}} \supset \xi_L\Lambda_c\,\psi_R\psi_L^{\text{comp.}} + \xi_R\Lambda_c\,\psi_L\psi_R^{\text{comp.}} \qquad \text{with} \quad \xi_{L,R} = \left(\frac{\Lambda_c}{\Lambda_{\mathrm{UV}}}\right)^{\gamma_{L,R}}$$

- Composite fermions couple to Higgs ⇒ Yukawa couplings:



Yukawa couplings from partial compositeness

- Integrate out $\psi_L^{\text{comp.}}$ and $\psi_R^{\text{comp.}}$ $\Rightarrow$ Yukawa coupling:

$$y \sim \frac{1}{g_\star} \xi_L \xi_R \sim \frac{1}{g_\star} \left(\frac{\Lambda_c}{\Lambda_{\text{UV}}} \right)^{\gamma_L} \left(\frac{\Lambda_c}{\Lambda_{\text{UV}}} \right)^{\gamma_R}$$

- For $y_t \sim 1$ need operators with $|\gamma_{L,R}| \ll 1$ and thus dim. $\approx 5/2$
- If composite sector contains only fermions (scalars reintroduce hierarchy problem!), $\mathcal{O}_{L,R} \sim \psi\bar{\psi}\psi$ and dim. $\sim 9/2$ at weak coupling
- $\Rightarrow$ Strong coupling to get large anomalous dimension and dim. $\sim 5/2$
- Confining sector near fixed point during most of RG evolution
- $\Rightarrow$ Confining sector is (weakly-broken, strongly-coupled) CFT

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2. **The dilaton and its potential**
3. Combining the Higgs and dilaton potentials
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The dilaton and its potential

- Need to break CFT. ⇔ Some condensate χ develops. But in CFT

$$V[\chi] \,=\, c_\chi g_\chi^2 \chi^4$$

- $\Rightarrow$ No spontaneous breaking. Instead break CFT explicitly

$$\mathcal{L} \,=\, \mathcal{L}_{\mathrm{CFT}} \,-\, \epsilon_{\mathrm{UV}} \Lambda_{\mathrm{UV}}^{\gamma_\epsilon}\, \mathcal{O}_{\mathrm{C\not{F}T}}$$

with dimension of $\mathcal{O}_{\mathrm{C\not{F}T}} = 4 - \gamma_\epsilon$ and $0 < \gamma_\epsilon \ll 1$.

$$\Rightarrow V[\chi] \,\supset\, c_\chi g_\chi^2 \chi^4 \,-\, \epsilon_{\mathrm{UV}} \Lambda_{\mathrm{UV}}^{\gamma_\epsilon} \chi^{4-\gamma_\epsilon}$$

$$\Rightarrow \chi_0 = \Lambda_c \,\sim\, \left(\frac{\epsilon_{\mathrm{UV}}}{c_\chi g_\chi}\right)^{1/\gamma_\epsilon} \Lambda_{\mathrm{UV}}$$

- Identify χ with dilaton, the pNGB of broken conformal invariance.

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Combining the Higgs and dilaton potentials

- So far:

$$V[\theta] \supset g_\star^2 f^4 \frac{3\,\xi^2}{(4\pi)^2}\left(c_\alpha \sin^2\theta + c_\beta \sin^4\theta\right) \quad \text{with} \quad \xi = \left(\frac{\Lambda_c}{\Lambda_{\rm UV}}\right)^{\gamma_{L,R}}$$

$$V[\chi] \supset c_\chi g_\chi^2 \chi^4 - \epsilon_{\rm UV} \Lambda_{\rm UV}^{\gamma_\epsilon} \chi^{4-\gamma_\epsilon}$$

- χ sets all mass scales in composite sector $\Rightarrow$ $\Lambda_c \to \chi$ and $f \to f[\chi]$
- Dimensional analysis and large-N counting $\Rightarrow$ $g_\star f = g_\chi \chi$
- Similarly find kinetic terms:

$$\mathcal{L}_{\rm kin} = \frac{1}{2}\frac{g_\chi^2}{g_\star^2}\chi^2(\partial_\mu\theta)^2 + \frac{1}{2}(\partial_\mu\chi)^2$$

Valleys in the potential

- Higgs potential now:

$$V[\theta,\chi] \supset \left(\frac{g_\chi}{g_\star}\chi\right)^4 \left(\kappa_\alpha[\chi]\sin^2\theta + \kappa_\beta[\chi]\sin^4\theta\right)$$

$$\text{with} \quad \kappa_{\alpha,\beta}[\chi] = \sum_{n_f} c^f_{\alpha,\beta}\, g_\star^2 \frac{3\,\xi_f^2[\chi]}{(4\pi)^2} \quad \text{and} \quad \xi_f[\chi] = \left(\frac{\chi}{\Lambda_{\mathrm{UV}}}\right)^{\gamma_{f_{L,R}}}$$

- Observed Higgs mass and vev require tuning. Take into account by

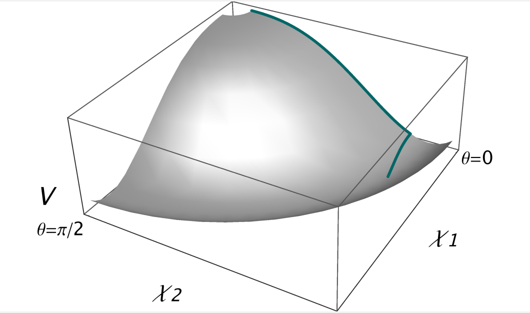
$$\kappa_\alpha[\chi] \to -\frac{1}{4} m^2_{\mathrm{Higgs}} + \kappa_\alpha[\chi] - \kappa_\alpha[\chi_0]$$

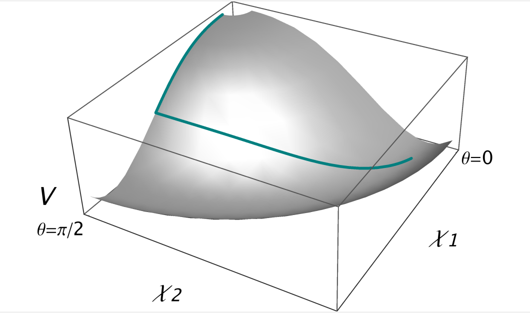
$$\kappa_\beta[\chi] \to \frac{1}{8} m^2_{\mathrm{Higgs}}/\sin^2(v_{\mathrm{EW}}/f_0) + \kappa_\beta[\chi] - \kappa_\beta[\chi_0]$$

$\Rightarrow$ local minima: $\theta = v_{\mathrm{EW}}/f_0$ (Higgs vev today)

$\theta = 0, \frac{\pi}{2}, \sim \frac{\pi}{4}$ (for $\chi \neq \chi_0$ and depending on signs of $c_{\alpha,\beta}$)

Valleys in the potential





The potential at finite temperature

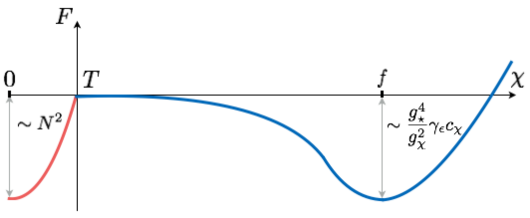
- For CFT with N colors, free energy given by

$$F_{\mathrm{CFT}}[\chi = 0] \sim -N^2 T^4$$

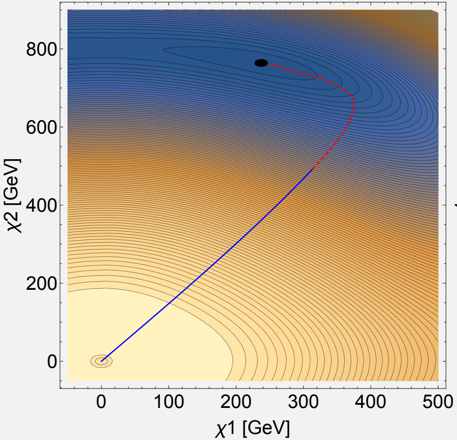
- For $\chi > T/g_\chi$, composite states heavy, contribution negligible:

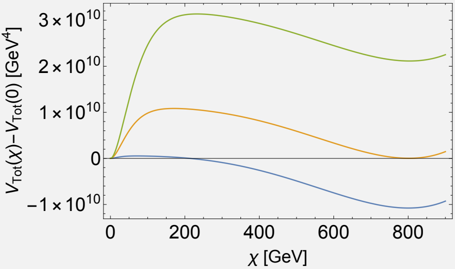
$$F_{\mathrm{conf.}}[\chi > T/g_\chi] \simeq V[\theta, \chi]$$

- Interpolate between $F_{\mathrm{CFT}}[\chi = 0]$ and $F_{\mathrm{conf.}}[\chi > T/g_\chi]$:



Tunneling in the (θ, χ)-potential





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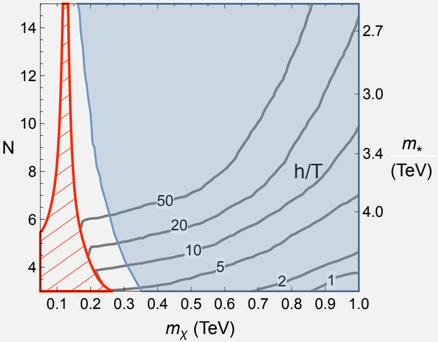
Numerical study

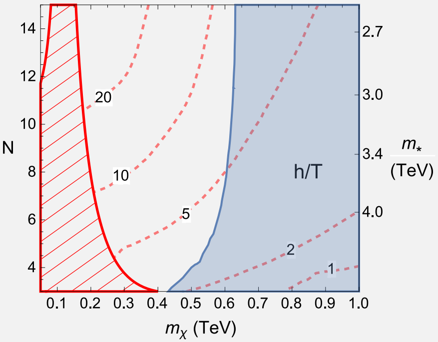
When phase transition sufficiently strong for electroweak baryogenesis, i.e. $h[T_n]/T_n \gtrsim 1$? Fix parameters for scan:

- $f_0 = 800\,\mathrm{GeV}$ (experimental constraints: $v_{\mathrm{EW}}^2/f_0^2 \lesssim 0.1 \ldots 0.2$)
- Large-N estimates: $g_\star = 4\pi/\sqrt{N}$ and $g_\chi = 4\pi/\sqrt{N}$ (meson-like dilaton) or $g_\chi = 4\pi/N$ (glueball-like dilaton)
- Focus on charm with $\gamma_{c_L} = -0.735$ for $E < \chi_0$ (see later)
- Trade γ_ϵ and ϵ_{UV} for dilaton mass m_χ and χ_0 $(= g_\star f_0/g_\chi)$
- Choose $c_\chi = 0.5$
- For charm choose $c_\alpha = -c_\beta = 1 \Rightarrow$ valley in potential along $\theta = \pi/4$
- Scan over free parameters $m_\chi(50\,\mathrm{GeV} \ldots .1\,\mathrm{TeV})$ and $N(3\ldots 15)$

Results: phase transition strength $h[T_n]/T_n$

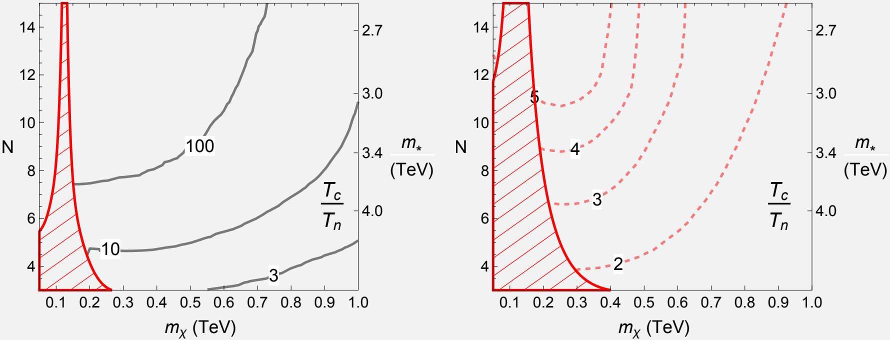
For electroweak baryogenesis need $h[T_n]/T_n \gtrsim 1$ to suppress sphalerons inside bubbles.





Results: supercooling T_c/T_n

In order to avoid runaway bubbles, phase transition should not be too supercooled, $T_c/T_n \sim \mathcal{O}(\text{few})$.

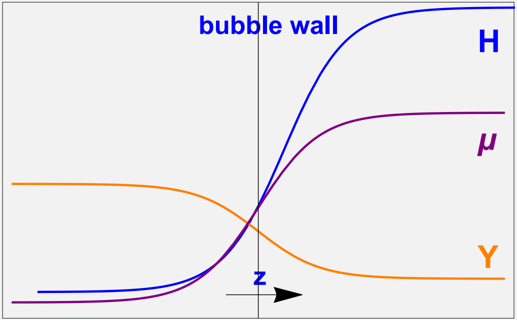


CP-violation from varying Yukawas

Phase transition can be strongly first-order. What about *CP*-violation?

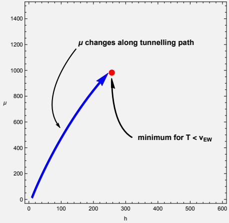
CP-violating term in transport equation: $S_{\not{C}P} \propto \mathrm{Im}\left[V^\dagger M^{\dagger\prime\prime} M\, V\right]$

`[S. Bruggisser, T. Konstandin, G. Servant, 1706.08534]`



- $M = Y\, H(z) \quad \Rightarrow \quad S_{\not{C}P} \propto \mathrm{Im}\left[V^\dagger Y^\dagger Y\, V\right] = 0$
- $M = Y(z)\, H(z) \quad \Rightarrow \quad S_{\not{C}P} \neq 0$
- Here: $Y = Y(\chi(z)) \neq$ const. , where χ is the dilaton

Varying Yukawas in composite Higgs



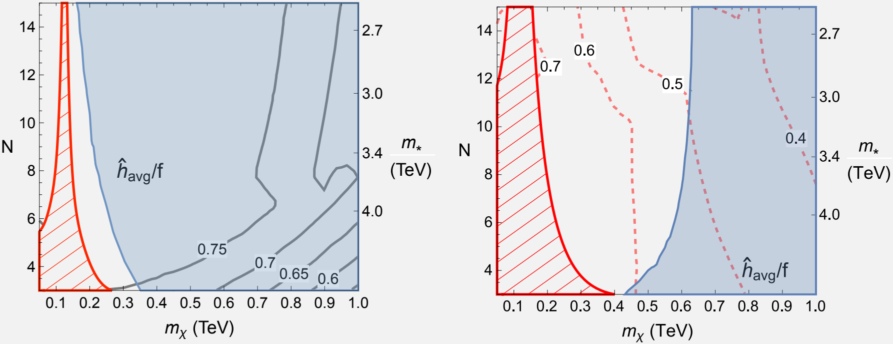
- Yukawa couplings for constant $\gamma_{L,R}$ $(\Lambda_c \to \chi)$

$$y \sim \frac{1}{g_\star}\xi_L \xi_R \sim \frac{1}{g_\star}\left(\frac{\chi}{\Lambda_{\mathrm{UV}}}\right)^{\gamma_L}\left(\frac{\chi}{\Lambda_{\mathrm{UV}}}\right)^{\gamma_R}$$

- For *CP*-violation interested in Yukawa couplings for $0 \lesssim \chi \lesssim \chi_0$
- Top has $|\gamma_{t_{L,R}}| \ll 1 \Rightarrow y_t$ only weakly dependent on χ
- Charm has $y_c \ll 1$ for $\chi = \chi_0$ and even smaller for $\chi \lesssim \chi_0$ if $\gamma_{c_{L,R}} > 0 \Rightarrow$ Not enough *CP*-violation
- Instead assume $\gamma_{c_{L,R}} < 0$ for $\chi \lesssim \chi_0 \Rightarrow$ Large charm Yukawa in IR

Results: tunneling direction θ_{avg}

Tunneling direction should be sufficiently far away from $\theta_{\mathrm{avg}} = \frac{\hat{h}_{\mathrm{avg}}}{f} = 0$ for enough CP-violating during phase transition.



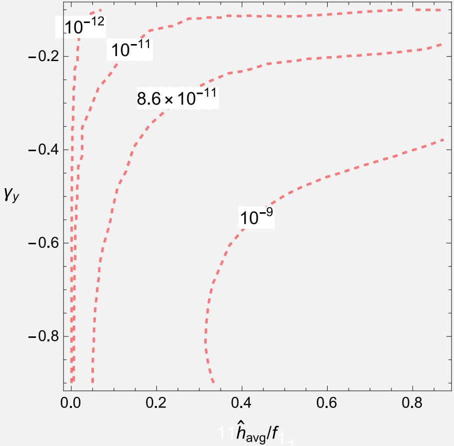
Electroweak baryogenesis

- Now have strong phase transition and new source of *CP*-violation.
- Yukawa couplings for several flavours can be written as:

$$y_{ij} \;=\; (\mathbb{I}_L)_{ik}\,(\xi_L)_{kk}\,(g_\star^{-1})_{kl}\,(\xi_R)^\dagger_{ll}\,(\mathbb{I}_R)_{lj}$$

- $f_0 = 800\,\mathrm{GeV} \Rightarrow$ Need to impose flavour symmetry, choose $U(1)$.
  $\Rightarrow (\mathbb{I}_L)_{ik}, (\mathbb{I}_R)_{lj}$ diagonal $\Rightarrow$ Need at least 2 ξ which grow with χ.
- Choose charm, $\gamma_{c_L} = -0.735$ and scan over negative γ_{c_R}.
- Meson with $m_\chi = 500\,\mathrm{GeV}$ and $N = 5$, other parameters as before.
- Bubble nucleation rate: $\Gamma_n \sim e^{S_E}$. $S_E(\theta_{\mathrm{avg}})$ shallow near $\theta_{\mathrm{avg}}^{\mathrm{min}}$. $\Rightarrow \Gamma_n$ for bubbles with $\theta_{\mathrm{avg}} \neq \theta_{\mathrm{avg}}^{\mathrm{min}}$ not very suppressed. $\Rightarrow$ Scan over θ_{avg}.
- Assume wall velocity $v_{\mathrm{wall}} = 0.1$.

Results: Baryon asymmetry



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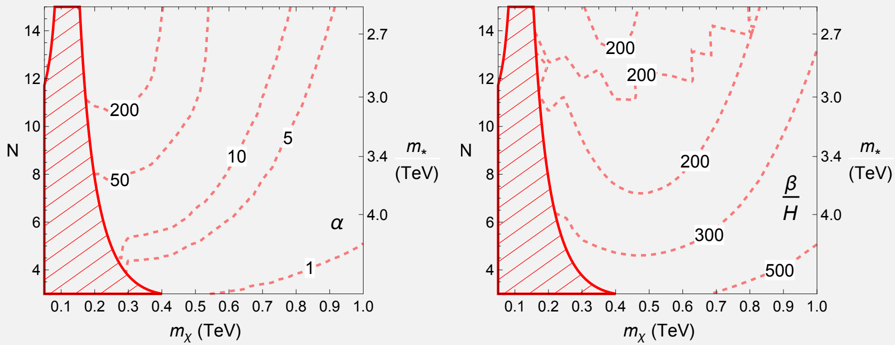
Experimental tests

- Bound on dilaton mass: $m_\chi \gtrsim 100\,\mathrm{GeV}$
- Flavour symmetry ⇒ flavour-changing processes suppressed
- *CP*-violation from varying charm Yukawa ⇒ today suppressed by size of Yukawa (large for varying top Yukawa ⇒ electron EDM)
- More promising: Gravitational waves
- Spectrum controlled by two parameters:

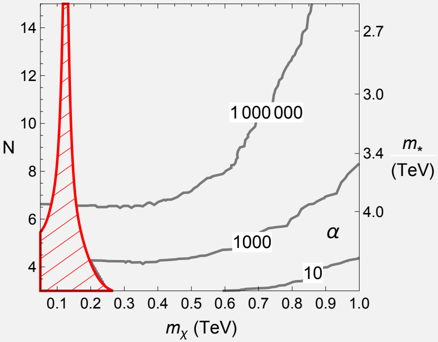
$$\alpha \simeq \frac{(V_{\text{tot}}[0,0] - V_{\text{tot}}[v_{\mathrm{EW}},\chi_0])_{T_n}}{3\pi^2 N^2 T_n^4/8}\,, \qquad \frac{\beta}{H} \simeq T_n \, \frac{\mathrm{d}S_E}{\mathrm{d}T}\bigg|_{T_n}$$

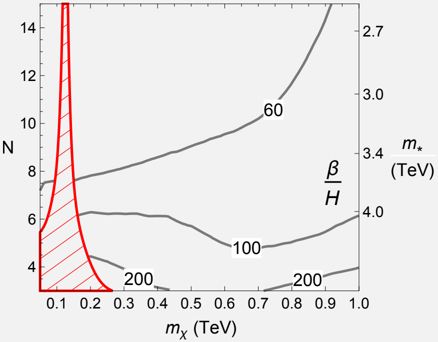
- Signal from phase transition at $T_n = 100\,\mathrm{GeV}$ detectable by LISA if $1 \lesssim \beta/H \lesssim 10^4$ and $\alpha \gtrsim 0.1$.

Results: Gravitational waves, meson



Results: Gravitational waves, glueball





Conclusions

- Derived joint potential for Higgs and dilaton in composite Higgs models to describe simultaneously confinement and electroweak phase transitions.
- Allows for novel realization of electroweak baryogenesis with composite Higgs:
  - Confining and electroweak phase transition simultaneous ⇒ first-order
  - CP-violation from varying Yukawas during phase transition
- Prefers composite Higgs sector with $N \sim \mathcal{O}(\text{few})$ and meson-like dilaton with mass $\sim 300 - 500\,\text{GeV}$.
- Signatures: Light dilaton and gravitational waves from phase transition.