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Cosmological Dynamics of Higgs Fine Tuning



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main suggestion

If the Higgs potential is fine-tuned, there might be cosmological implications from the early universe: eq. of state + gravitational waves

LHC: Standard Model Higgs but nothing else ...



LHC: Standard Model Higgs — tuned Higgs mass/ potential





no new particles, does not necessarily rule out SUSY

Higgs mass/potential is "tuned" (Higgs is accidentally light)

SUSY: field-dependent Higgs mass/potential



 $\phi =$ modulus = could be the inflaton

accidentally light/tuned Higgs = precarious balance between broken and unbroken phase





fine tuned / weakly broken potential: possible if global min. *close to* symmetry breaking point



light Higgs: possible if global min. *close to* symmetry breaking point



M = SUSY breaking scale

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* we take this to be the quantum corrected effective potential rather than the treelevel potential; we do not have to compute shifts in VEVs induced by loop corrections.

how would we know today ?

we cannot really go exploring in this field space, fixed couplings/masses



Necessary Fine Tuning \Leftrightarrow

$$\frac{\phi_{\rm m} - \phi_0}{f} \ll 1$$

how would we know? early universe to the rescue

a displaced modulus will naturally explore different Higgs potentials



 $\frac{\phi_{\rm m} - \phi_0}{f} \ll 1$

Necessary Fine Tuning \Leftrightarrow

complex dynamics of the Higgs-modulus system

tachyonic particle production and backreaction



 $\frac{\phi_{\rm m} - \phi_0}{f} \ll 1$ Necessary Fine Tuning \Leftrightarrow

* related, but not identical dynamics in hybrid inflation, Dufaux et. al (2006)

modulus dynamics



* under certain conditions, later in the talk

Higgs dynamics



* under certain conditions, later in the talk

complex dynamics of the Higgs-modulus system



time \longrightarrow

* under certain conditions, later in the talk

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* 3D simulation with "real" Higgs, actual Higgs is complex— higher dimension in field space

fine tuning — non-perturbative dynamics — implications



an important parameter in the Higgs-modulus potential

$$V(\phi, h) = \frac{1}{2}m_{\phi}^{2}\phi^{2} + M^{2}\frac{(\phi - \phi_{0})}{f}h^{\dagger}h + \lambda(h^{\dagger}h)^{2} + V_{0}$$

$$V_{ridge} - V_{valley} = b \times V_{ridge}$$

$$0 \leq \text{fragmentation efficiency parameter} \qquad b \equiv \frac{M^{4}}{2\lambda f^{2}m_{\phi}^{2}} \leq 1$$

for violent nonlinear dynamics: 2 conditions



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* b ~ O(I) is possible, but non-trivial for model building. Use flat directions in SUSY

non-perturbative dynamics -

non-trivial eq. of state

$$V(\phi,h) = \frac{1}{2}m_{\phi}^{2}\phi^{2} + M^{2}\frac{(\phi-\phi_{0})}{f}h^{\dagger}h + \lambda(h^{\dagger}h)^{2} + V_{0}$$

fragmentation efficiency

 $b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2}$





* likely returns to matter domination at late times, unless there are other decay channels. We cannot simulate very long times

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non-perturbative dynamics — stochastic gravitational waves

$$V(\phi,h) = \frac{1}{2}m_{\phi}^{2}\phi^{2} + M^{2}\frac{(\phi-\phi_{0})}{f}h^{\dagger}h + \lambda(h^{\dagger}h)^{2} + V_{0}$$

fragmentation efficiency

$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$$





for high frequency gw-detection ideas see:

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Akutsu et. al (2010), Goryachev & Tobar (2014), Arvanitaki & Geraci (2016)

non-perturbative dynamics — stochastic gravitational waves

$$V(\phi,h) = \frac{1}{2}m_{\phi}^{2}\phi^{2} + M^{2}\frac{(\phi-\phi_{0})}{f}h^{\dagger}h + \lambda(h^{\dagger}h)^{2} + V_{0}$$

fragmentation efficiency

$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1)$$



* IF universe becomes matter dominated for N_{mod} e-folds again before BBN

$$f_{0} \sim 30 \,\mathrm{kHz} \times e^{-\frac{N_{\mathrm{mod}}}{4}(1-3w_{\mathrm{mod}})} \sqrt{\frac{m_{\phi}}{10^{2} \,\mathrm{TeV}}} \qquad 10^{-8} \qquad 10^{-8} \qquad 10^{-8} \qquad 10^{-10} \qquad 10^{-10} \qquad 10^{-10} \qquad 10^{-10} \qquad 10^{-10} \qquad 10^{-12} \qquad 10^{-12} \qquad 10^{-12} \qquad 10^{-14} \qquad 1$$

caveats and future directions

* we are not necessarily *explaining* the fine tuning; we are exploring the implications of fine tuning

- * inclusion of gauge fields + complex Higgs
- * initial conditions
- * model building

caveats and future directions

- * we are not necessarily explaining the fine tuning, we are exploring the implications of fine tuning
- * inclusion of gauge fields + complex Higgs
- * model building
- * inclusion of self-interactions in the moduli: oscillons



summary: Cosmological Dynamics of Higgs Fine Tuning

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extra slides

(with $b = 1, q = 10^2, f = m_{\rm pl}$).

The Thraphiculie of the background fields power spectra for the orange curve in Fig. 3 (with $b = 1, q = 10^2, f = m_{\rm pl}$). Experimentally, the each field $F(\mathbf{x})$ is $P_F(k) \equiv \phi_{\rm osc}^{-2}(d/d\ln k)\overline{F^2(\mathbf{x})}$, where $\phi_{\rm osc}$ is the amplitude of the background as oscillations. For this normalization, when $P_{\phi}(k) = \mathcal{O}(1)$, the modulus becomes inhomogeneous. Initially, the tachyonic become values of the background by excitations in the modulus (due to re-scattering). Comoving modes $k < m_{\phi}q^{1/2}$ ctra then set le down and power of the modules (due to re-scattering). Comoving modes $k < m_{\phi}q^{1/2}$ propagatest towards in generation of the modules (due to re-scattering).

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other implications of

non-trivial eq. of state

* assuming an inflationary model, the eq. of state can significantly affect the lower bound on the modulus mass

$$m_{\phi}^2 \gtrsim \frac{3(1+w_{\rm mod})}{2c} m_{\rm pl}^2 \exp\left(-\frac{6(1+w_{\rm mod})}{1-3w_{\rm mod}} \left(-N_k + 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_k}{\rho_{\rm end}}\right)\right)\right)$$



model building

$$V(\phi,h) = \frac{1}{2}m_{\phi}^{2}\phi^{2} + M^{2}\frac{(\phi-\phi_{0})}{f}h^{\dagger}h + \lambda(h^{\dagger}h)^{2} + V_{0}$$

$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim \mathcal{O}(1) \qquad \text{fragmentation efficiency}$$

$$a)m_{\phi} \lesssim M \ll f \sim M_{\rm pl}, \lambda \ll 1$$
$$b)m_{\phi} \ll M \ll f \sim M_{\rm pl}, \lambda \sim 1$$

D-flat directions in SUSY can help with small λ

gravitational waves: scalings

$$f_{0} = \frac{1}{2\pi} \frac{k}{a_{0}} = \frac{1}{2\pi} \left(\frac{k}{a_{g}H_{g}}\right) \sqrt{H_{g}H_{0}} \left(\frac{a_{g}}{a_{th}}\right)^{(1-3w_{mod})/4} \left(\frac{g_{th}}{g_{0}}\right)^{-1/12} \Omega_{r,0}^{1/4}$$
scale at production red-shifting
$$\Omega_{gw,0} = \Omega_{gw} \times \left(\frac{a_{g}}{a_{th}}\right)^{1-3w_{mod}} \left(\frac{g_{th}}{g_{0}}\right)^{-1/3} \Omega_{r,0}$$

$$\Omega_{gw} \sim \left(\frac{a_{g}H_{g}}{k}\right)^{2} \delta_{\pi}^{2} \qquad \delta_{\pi} \sim 1/3 \qquad \text{gradients/total}$$

$$\Omega_{\rm gw} = \frac{1}{\rho_{\rm g}} \frac{d\ln\rho_{\rm gw}}{d\ln k}$$

fragmentation: a closer look



power spectrum: higgs/modulus



