

Unified Emergence of Energy Scales and Cosmic Inflation

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Based on 2012.09706
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Energy scales in high-energy physics



- M_{Pl} and m_h are known \rightarrow **gauge hierarchy problem**

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$$V^{1/4} \lesssim 10^{16} \text{ GeV} \quad [\text{Planck 2018}]$$

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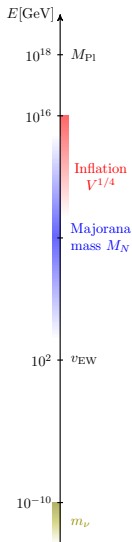
- **Light active neutrinos**

$$\sum_i m_{\nu_i} < 0.12 \text{ eV} \quad [\text{Planck 2018}]$$

- **Seesaw mechanism:** adding ν_R with Majorana mass M_N

$$m_\nu \simeq -m_D M_N^{-1} m_D^T$$

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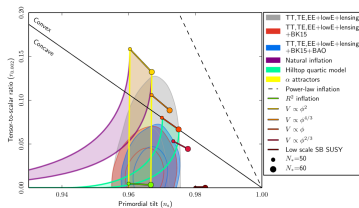
- \rightarrow **Dynamical generation of all scales**
- \rightarrow **All scales vanish at tree-level (classical scale invariance)**

Scale invariance

Classical action invariant under rescalings

$$g_{\mu\nu} \rightarrow e^{2\sigma} g_{\mu\nu}, \quad \Phi \rightarrow e^{-w_{\Phi}\sigma} \Phi$$

- Symmetry of SM at high energies: $E \gg m_i$
- CMB power spectrum $n_S \sim 1$ [Planck '18]



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- 1 Introduction
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The Model

$$\frac{\mathcal{L}_{CW}}{\sqrt{-g}} = \frac{1}{2}g^{\mu\nu}\partial_\mu S\partial_\nu S + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_\sigma\sigma^4 - \frac{1}{4}\lambda_{S\sigma}S^2\sigma^2$$

$$\frac{\mathcal{L}_{GR}}{\sqrt{-g}} = -\frac{1}{2}(\beta_S S^2 + \beta_\sigma\sigma^2 + \beta_H H^\dagger H)R + \gamma R^2 + \kappa W_{\mu\nu\alpha\beta}W^{\mu\nu\alpha\beta}$$

$$\frac{\mathcal{L}_{SM}}{\sqrt{-g}} = \mathcal{L}_{SM}|_{\mu_H=0} - \frac{1}{4}(\lambda_{HS}S^2 + \lambda_{H\sigma}\sigma^2)H^\dagger H$$

$$\frac{\mathcal{L}_N}{\sqrt{-g}} = \frac{i}{2}\overline{N_R}\not{\partial}N_R - \left(\frac{1}{2}y_M S\overline{N_R}(N_R)^c + y_\nu\bar{L}\tilde{H}N_R + \text{h.c.}\right)$$

- ① Additional scalar sector for Coleman-Weinberg mechanism $\rightarrow \langle S \rangle = v_S$
- ② Gravity with global scale invariance \rightarrow identification of M_{Pl} and inflation
- ③ SM interactions + Higgs portals
- ④ type-I seesaw \rightarrow Higgs and light active neutrino mass scale

Dimensional transmutation

Coleman-Weinberg mechanism [Coleman, Weinberg '73]

e.g. massless sQED $V_{\text{eff}}(\varphi) = \frac{\lambda}{4!}\varphi^4 + 3\frac{(g\varphi)^4}{64\pi^2} \left[\log\left(\frac{(g\varphi)^2}{\mu^2}\right) - \frac{5}{6} \right]$

$$\mathcal{O}(\lambda) \sim \mathcal{O}(g^4) \quad \rightarrow \quad \langle \varphi \rangle \neq 0$$

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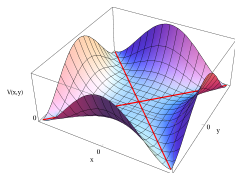
Coleman-Weinberg mechanism [Coleman, Weinberg '73]

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Approximation tool for multi-scalar potential: **Gildener-Weinberg approach**

[Gildener, Weinberg '76]



$$V_{\text{tree}}(S, \sigma) = \frac{1}{4} (\lambda_S S^4 + \lambda_\sigma \sigma^4 + \lambda_{S\sigma} S^2 \sigma^2) + \frac{1}{4} (\lambda_{HS} S^2 + \lambda_{H\sigma} \sigma^2) H^\dagger H$$

Desired flat direction ($S \neq 0, \sigma = 0$) for $\lambda_S \ll \lambda_{S\sigma}$ and $\lambda_S \ll \lambda_\sigma$

SSB of scale invariance

$$\frac{\mathcal{L}_{\text{GR}}}{\sqrt{-g}} = -\frac{1}{2}(\beta_S S^2 + \beta_\sigma \sigma^2 + \beta_H H^\dagger H) R + \gamma R^2 + \kappa W_{\mu\nu\alpha\beta} W^{\mu\nu\alpha\beta}$$

- Coleman-Weinberg potential in background $\sigma = 0$, $S \neq 0$ and $R \neq 0$:

$$U_{\text{eff}}(S, R) = V_{\text{tree}}(S, 0) + \frac{1}{64\pi^2} (\tilde{m}_s^4 \ln[\tilde{m}_s^2/\mu^2] + \tilde{m}_\sigma^4 \ln[\tilde{m}_\sigma^2/\mu^2])$$

$$\tilde{m}_s^2 = 3\lambda_S S^2 + \beta_S R, \quad \tilde{m}_\sigma^2 = \frac{1}{2}\lambda_{S\sigma} S^2 + \beta_\sigma R$$

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- During Inflation $\beta_S R < 3\lambda_S S^2$ and $\beta_\sigma R < (1/2)\lambda_{S\sigma} S^2$

$$\tilde{U}_{\text{eff}}(S, R) = U_{\text{eff}}(S, R) - U_0 = U_{\text{CW}}(S) + U_{(1)}(S)R + U_{(2)}(S)R^2 + \mathcal{O}(R^3)$$

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- Subtracting induced cosmological constant U_0 such that

$$U_{\text{CW}}(S = v_S) = 0$$

- Identification of **Planck mass**: $M_{\text{Pl}} = v_S \sqrt{\beta_S + 2U_{(1)}(v_S)/v_S^2}$
For inflation $\beta_S \sim 10^{(2-3)} \Rightarrow v_S \sim 10^{(16-17)}$ GeV

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Effective action for inflation

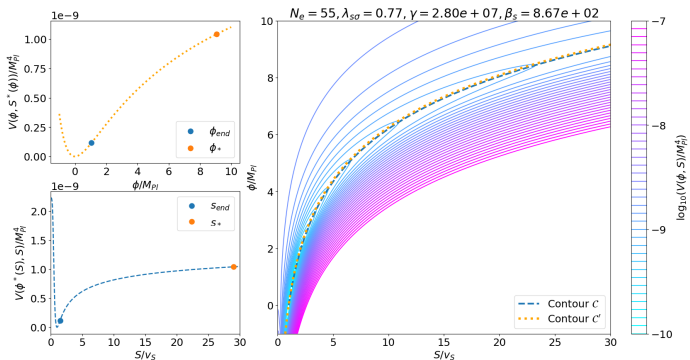
Jordan frame: $\frac{\mathcal{L}_{\text{eff}}}{\sqrt{-g_J}} = -\frac{1}{2}B(S)R_J + G(S)R_J^2 + \frac{1}{2}g_J^{\mu\nu} \partial_\mu S \partial_\nu S - U_{\text{CW}}(S)$

Einstein frame: $\frac{\mathcal{L}_{\text{eff}}^E}{\sqrt{-g}} = -\frac{M_{\text{Pl}}^2}{2} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2} e^{-\sqrt{2/3} \frac{\phi}{M_{\text{Pl}}}} g^{\mu\nu} \partial_\mu S \partial_\nu S - V(S, \phi)$

Effective action for inflation

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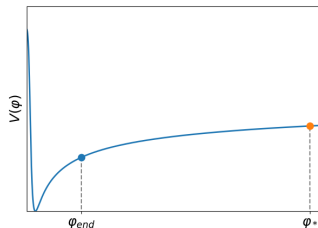
Contour $\mathcal{C} = \{S, \tilde{\phi}(S)\} \rightarrow \frac{\mathcal{L}_{\text{eff}}^E}{\sqrt{-g}} = -\frac{1}{2}M_{\text{Pl}}^2 R + \frac{1}{2}F(S)^2 g^{\mu\nu}\partial_\mu S\partial_\nu S - V_{\text{inf}}(S)$

Slow-roll approximation

- Potential slow-roll parameters

$$\varepsilon(S) = \frac{M_{\text{Pl}}^2}{2 F^2(S)} \left(\frac{V'_{\text{inf}}(S)}{V_{\text{inf}}(S)} \right)^2$$

$$\eta(S) = \frac{M_{\text{Pl}}^2}{F^2(S)} \left(\frac{V''_{\text{inf}}(S)}{V_{\text{inf}}(S)} - \frac{F'(S)}{F(S)} \frac{V'_{\text{inf}}(S)}{V_{\text{inf}}(S)} \right)$$



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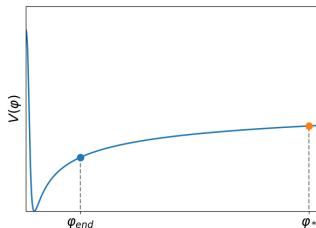
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- CMB observables

$$A_s = \frac{V_{\text{inf}}(S_*)}{24\pi^2 \varepsilon(S_*) M_{\text{Pl}}^4}, \quad n_s = 1 + 2\eta(S_*) - 6\varepsilon(S_*), \quad r = 16\varepsilon(S_*)$$



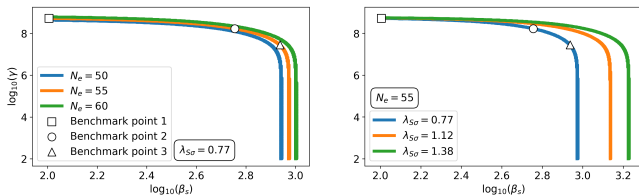
Inflation results

- Free parameters in V_{inf} :
$$\begin{cases} \lambda_S, \lambda_{S\sigma} & \text{tree-level potential} \\ \beta_\sigma, \beta_S & \text{non-minimal couplings} \\ \gamma & R^2 - \text{coefficient} \end{cases}$$

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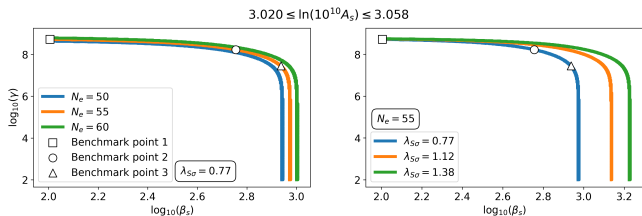
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- Scalar amplitude constraint [Planck 2018]

$$3.020 \leq \ln(10^{10} A_s) \leq 3.058$$

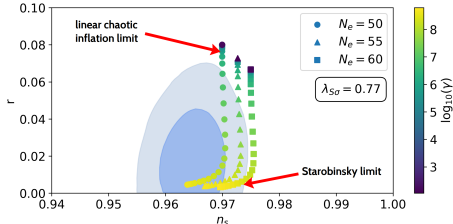


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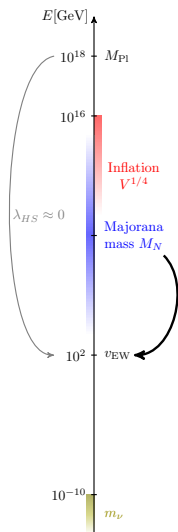
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How to connect the Planck and EW scale?

- New approach to hierarchy problem: **Neutrino Option**

[Brivio, Trott, 1703.10924]



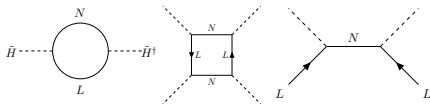
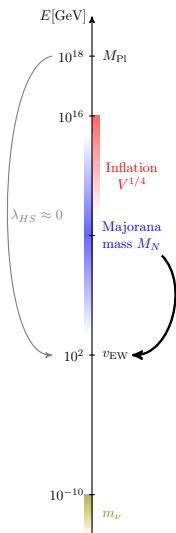
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- Higgs potential is radiatively generated

$$\mu_H = 0 \text{ (tree level)}, \quad \Delta\mu_H^2 \sim -\frac{y_\nu^2 m_N^2}{16\pi^2}, \quad \Delta\lambda \sim \frac{y_\nu^4}{64\pi^2}$$



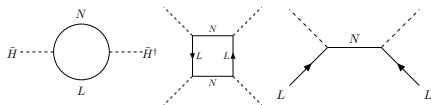
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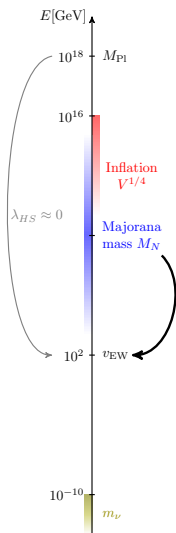
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- Type-I seesaw mechanism

$$m_\nu \simeq y_\nu^2 v_h^2 / m_N \sim 0.1 \text{ eV}$$



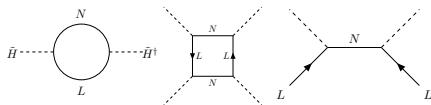
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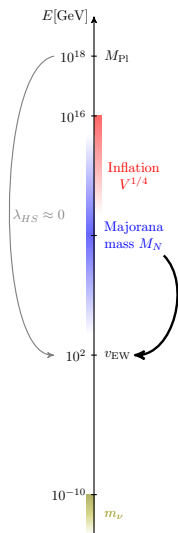
$$m_\nu \simeq y_\nu^2 v_h^2 / m_N \sim 0.1 \text{ eV}$$

- Correct Higgs mass and active neutrino masses scale obtained for

$$m_N \sim 10^7 \text{ GeV}, \quad y_\nu \sim 10^{-4} \quad [\text{Brivio, Trott, 1809.03450}]$$

- Embedding in scale-invariant theory ($m_N = y_m v_S$)

[Brdar et al, 1807.11490]



Embedding of neutrino option

$$\mathcal{L} \supset \frac{i}{2} \overline{N_R} \not{\partial} N_R - \left(\frac{1}{2} y_M S \overline{N_R} (N_R)^c + y_\nu \bar{L} \tilde{H} N_R + \text{h.c.} \right) - \frac{1}{4} (\lambda_{HS} S^2 + \lambda_{H\sigma} \sigma^2) H^\dagger H$$

- **Induced Majorana mass (Yukawa coupling fixed by Planck scale and inflation)**

$$m_N = y_M v_S \simeq 10^7 \text{ GeV} \quad (\text{neutrino option})$$

$$y_M = \frac{m_N \beta_S^{1/2}}{M_{\text{Pl}}} \simeq 10^{-10} \left(\frac{\beta_S}{10^3} \right)^{1/2}$$

- $y_M \rightarrow 0$ technically natural ($U(1)_{B-L}$ restored) [t Hooft '80]

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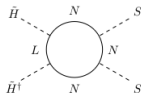
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- **Another contribution to the Higgs mass**

$$\lambda_{HS} S^2 (H^\dagger H) \rightarrow \lambda_{HS} v_S^2 (H^\dagger H)$$

$$\Delta \lambda_{HS} \sim y_\nu^2 y_M^2 / 16\pi^2$$

- $\lambda_{HS} \ll 1$ but not fine-tuned to special value
- $\{\lambda_{HS}, \lambda_{H\sigma}, y_M\} \ll 1$ stable under RG running
- preserved with gravitational interactions (RGE of [Salvio, Strumia '14])



Summary & conclusion

- Classically scale invariant model with dynamical generation of all scales
- Extended scalar sector for Coleman-Weinberg-type breaking
- VEV $v_S = 10^{16-17}$ GeV generates Planck scale $M_{\text{Pl}} \approx \beta_S^{1/2} v_S$
- Inflation predictions consistent with Planck observations
- Majorana mass scale $M_N = y_M v_S \sim 10^7$ GeV
- Higgs mass realized by neutrino option (+ light active neutrinos)

Thank you!

Inflation

Inflaton potential

$$V(S, \phi) = e^{-2\sqrt{2/3} \frac{\phi}{M_{\text{Pl}}}} \left[U_{\text{CW}}(S) + \frac{M_{\text{Pl}}^4}{16 G(S)} \left(B(S) - e^{\sqrt{2/3} \frac{\phi}{M_{\text{Pl}}}} \right)^2 \right]$$

$$B(S) = \beta_S S^2 + 2U_{(1)}(S), \quad G(S) = \gamma - U_{(2)}(S)$$

Contours

$$\textcircled{1} \quad \mathcal{C} = \{S, \tilde{\phi}(S)\} \quad \text{where} \quad \left. \frac{\partial V(S, \phi)}{\partial \phi} \right|_{\phi=\tilde{\phi}(S)} = 0, \quad V_{\text{inf}}(S) = V(S, \tilde{\phi}(S))$$

$$\rightarrow \frac{\mathcal{L}_{\text{eff}}^E}{\sqrt{-g}} = -\frac{1}{2} M_{\text{Pl}}^2 R + \frac{1}{2} F(S)^2 g^{\mu\nu} \partial_\mu S \partial_\nu S - V_{\text{inf}}(S)$$

$$V_{\text{inf}}(S) = V(S, \tilde{\phi}(S)) = \frac{U_{\text{CW}}(S)}{B(S)^2 + 16 G(S) U_{\text{CW}}(S) / M_{\text{Pl}}^4}$$

$$\textcircled{2} \quad \mathcal{C}' = \{\tilde{S}(\phi), \phi\}, \quad \text{where} \quad \left. \frac{\partial V(S, \phi)}{\partial S} \right|_{S=\tilde{S}(\phi)} = 0, \quad V_{\text{inf}}(\phi) = V(\tilde{S}(\phi), \phi)$$

Inflationary observables

Power spectrum of adiabatic and Gaussian scalar fluctuations

$$\langle \mathcal{R}\mathcal{R} \rangle = (2\pi)^3 \delta(k + k') P_{\mathcal{R}}(k), \quad \Delta_s^2(k) = \frac{k^3}{2\pi^2} P_{\mathcal{R}}(k)$$

$$\Delta_s^2(k) = A_s(k_*) \left(\frac{k}{k_*} \right)^{n_s(k_*)-1} \begin{cases} A_s & \text{scalar power spectrum amplitude} \\ n_s & \text{scalar spectral-tilt} \\ k_* & \text{pivot scale} \end{cases}$$

Tensor perturbations (sum of two polarizations: h_x, h_+)

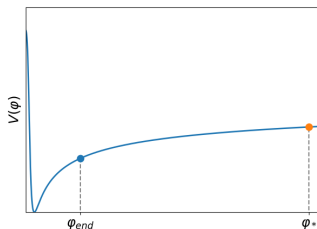
$$\Delta_t^2(k) = A_t(k_*) \left(\frac{k}{k_*} \right)^{n_t(k_*)} \left\{ r = \frac{\Delta_t^2}{\Delta_s^2} \right. \text{ tensor-to-scalar ratio}$$

Slow-roll approximation

- Potential slow-roll parameters

$$\varepsilon(S) = \frac{M_{\text{Pl}}^2}{2 F^2(S)} \left(\frac{V'_{\text{inf}}(S)}{V_{\text{inf}}(S)} \right)^2$$

$$\eta(S) = \frac{M_{\text{Pl}}^2}{F^2(S)} \left(\frac{V''_{\text{inf}}(S)}{V_{\text{inf}}(S)} - \frac{F'(S)}{F(S)} \frac{V'_{\text{inf}}(S)}{V_{\text{inf}}(S)} \right)$$



- End of inflation

$$\varepsilon(S = S_{\text{end}}) = 1 \quad \text{or} \quad |\eta(S = S_{\text{end}})| = 1$$

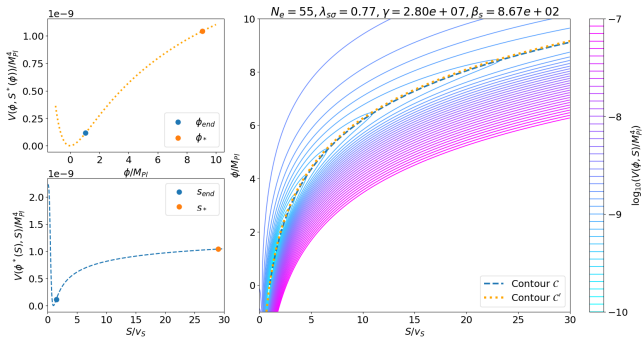
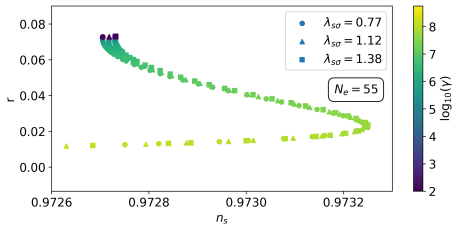
- Field value at horizon crossing S_* fixed by e-folds $N_e = 50 - 60$

$$N_e = \int_{t_*}^{t_{\text{end}}} H dt = \int_{S_*}^{S_{\text{end}}} \frac{dS}{\sqrt{2\varepsilon(S)}}$$

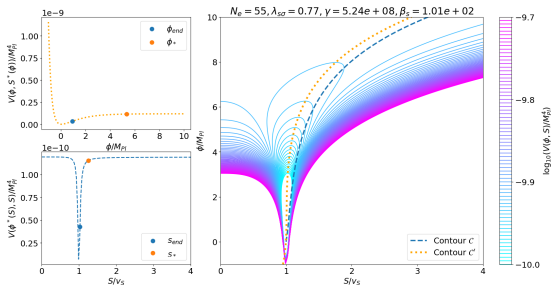
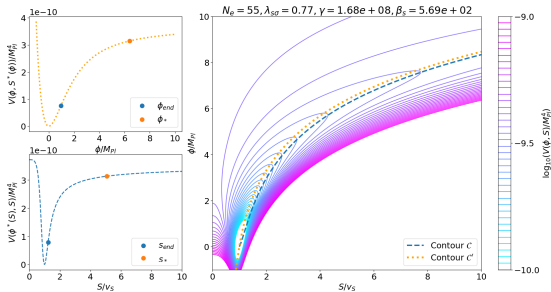
- CMB observables

$$A_s = \frac{V_{\text{inf}}(S_*)}{24\pi^2 \varepsilon(S_*) M_{\text{Pl}}^4}, \quad n_s = 1 + 2\eta(S_*) - 6\varepsilon(S_*), \quad r = 16\varepsilon(S_*)$$

Inflation



Inflation



Neutrino option

Figure 1: Schematic illustration of the main idea underlying the Neutrino Option: (1) the Higgs potential is generated by new physics states at a scale $M \gg \text{TeV}$ ($M = 10^6 \text{ GeV}$ in the figure). (2) At $E < M$ the Higgs parameters run according to the SM RGEs, with boundary conditions fixed by the threshold matching contributions $\Delta\sqrt{m_h^2}$, $\Delta\lambda$. The figure shows in two overlapping plots the 1-loop SM running of the Higgs mass (blue line, right axis) and of the quartic coupling λ (red line, left axis) for a top quark mass $m_t = 173.2 \text{ GeV}$ [4].

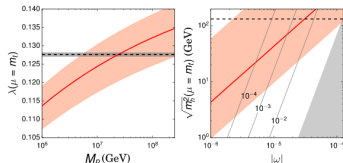
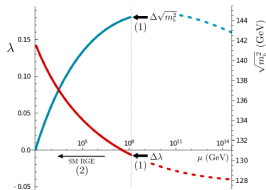
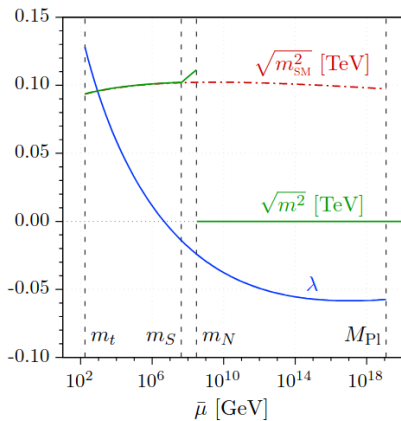


Figure 3: Values of the parameters λ (left) and $\sqrt{m_h^2}$ (right) extrapolated at the scale $\mu = m_t$ as a function of the two seesaw parameters M and ω respectively, in the preliminary study of Ref. [1]. The dashed lines and surrounding bands indicate the values consistent with the measured Higgs mass within $\pm 1\sigma$ [15]. Left panel: the red line assumes $m_t = 173.2 \text{ GeV}$ and the orange band corresponds to varying m_t between 171 and 175 GeV. Right panel: the solid red line assumes $M = 10^{7.4} \text{ GeV}$. The grey region is disfavoured by the Λ CDM cosmology limit $\sum m_\nu \leq 0.23 \text{ eV}$. The three solid lines indicate, for reference, the sum of neutrino masses predicted, in eV.

Figures taken from [Brivio, 1904.07029]

Neutrino option



Figures taken from [Brdar et al, 1807.11490]

RGE of [Salvio, Strumia '14]

$$\Delta(M_H^2/M_{\text{Pl}}^2) \sim \frac{\beta_H}{2(4\pi)^2} \left(\frac{5}{4\kappa^2} + \frac{1}{36\gamma^2} (3\beta_H + 1) \right) + O(M_H^2/M_{\text{Pl}}^2),$$

$$\Delta \beta_H \sim \frac{2\lambda_{\text{HS}}\beta_S}{(4\pi)^2} + \dots$$

$$\Delta \lambda_{\text{HS}} \sim \frac{\beta_H\beta_S}{(4\pi)^2} \frac{5}{16\kappa^2} + O(\lambda_{\text{HS}})$$