Unified Emergence of Energy Scales and Cosmic Inflation

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Based on 2012.09706
(Jisuke Kubo, Jeff Kuntz, Manfred Lindner, J. R., Philipp Saake, Andreas Trautner)

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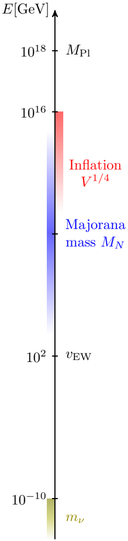
Energy scales in high-energy physics



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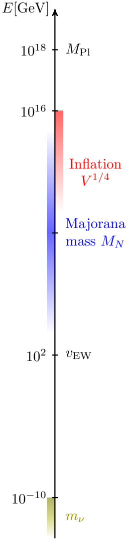

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$$V^{1/4} \lesssim 10^{16}\ \text{GeV}$$ [Planck 2018]

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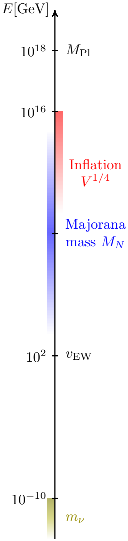

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- **Light active neutrinos**

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

- **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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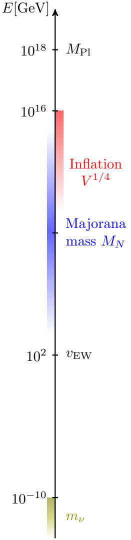

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$\rightarrow$ **Dynamical generation of all scales**
$\rightarrow$ **All scales vanish at tree-level (classical scale invariance)**

Scale invariance

Classical action invariant under rescalings

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

- Symmetry of SM at high energies: $E \gg m_i$

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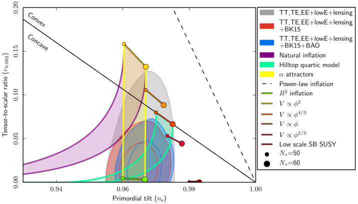

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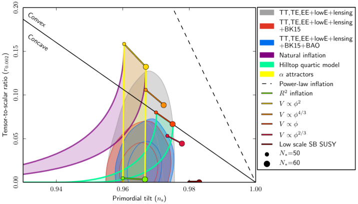

- If scale invariance broken by scale anomaly, $M_{\rm Pl}$ and $v_{\rm EW}$ exponentially separated and radiatively stable if: no intermediate scales [Bardeen '95] [Meissner, Nicolai, hep-th/0612165]

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The Model

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

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

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

$$\frac{\mathcal{L}_N}{\sqrt{-g}} = \frac{i}{2}\overline{N_R}\partial\!\!\!/ N_R - \left(\frac{1}{2}y_M S\overline{N_R}(N_R)^c + y_\nu\bar{L}\tilde{H}N_R + \text{h.c.}\right)$$

1. Additional scalar sector for Coleman-Weinberg mechanism ($\langle S\rangle = v_S$)
2. Gravity with global scale invariance (identifcation of $M_{\rm Pl}$ and inflation)
3. SM interactions + Higgs portals
4. type-I seesaw (also inducing Higgs mass)

Dimensional transmutation

Coleman-Weinberg mechanism [Coleman, Weinberg '73]

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

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

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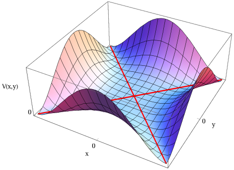
Approximation tool for multi-scalar potential: **Gildener-Weinberg approach**

[Gildener, Weinberg '76]



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

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

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

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

$$U_{\rm eff}(S, R, \sigma) = \frac{\lambda_S}{4} S^4 + \frac{\lambda_\sigma}{4}\sigma^4 + \frac{\lambda_{S\sigma}}{4} S^2\sigma^2 + \frac{1}{64\pi^2}\left(\tilde{m}_s^4 \ln[\tilde{m}_s^2/\mu^2] + \tilde{m}_\sigma^4 \ln[\tilde{m}_\sigma^2/\mu^2]\right)$$

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- During Inflation $\sigma = 0$, $\beta_S R < 3\lambda_S S^2$ and $\beta_\sigma R < (1/2)\lambda_{S\sigma} S^2$

$$\tilde{U}_{\rm eff}(S, R) = U_{\rm eff}(S, R, 0) - U_0 = U_{\rm CW}(S) + U_{(1)}(S) R + U_{(2)}(S) R^2 + \mathcal{O}(R^3)$$

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- Subtracting induced cosmological constant

$$U_{\rm CW}(S = v_S) = 0\,, \quad U_0 = -\mu^4 \frac{\beta_{\lambda_S}}{16} \exp\left[-1 - 16C/\beta_{\lambda_S}\right]$$

- Identification of **Planck mass**: $M_{\rm Pl} = v_S \sqrt{\beta_S + 2U_{(1)}(v_S)/v_S^2}$
  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: $\frac{\mathcal{L}_{\rm eff}}{\sqrt{-g_J}} = -\frac{1}{2}B(S)R_J + G(S)R_J^2 + \frac{1}{2}g_J^{\mu\nu}\partial_\mu S\partial_\nu S - U_{\rm CW}(S)$

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

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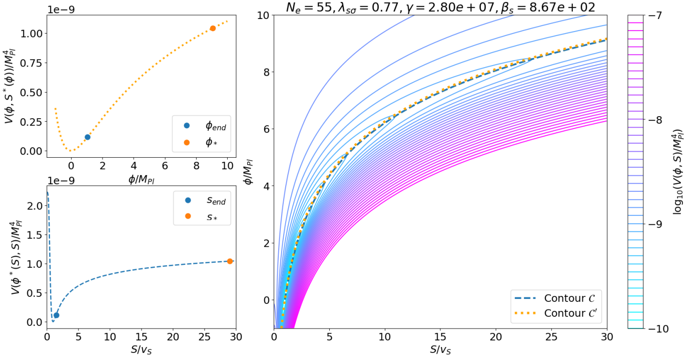


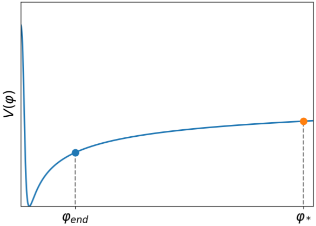
Contour $\mathcal{C} = \{S, \tilde{\phi}(S)\} \to \frac{\mathcal{L}^E_{\rm eff}}{\sqrt{-g}} = -\frac{1}{2}\,M_{\rm Pl}^2\,R + \frac{1}{2}\,F(S)^2\,g^{\mu\nu}\,\partial_\mu S\,\partial_\nu S - V_{\rm inf}(S)$

Slow-roll approximation

- Potential slow-roll parameters

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

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



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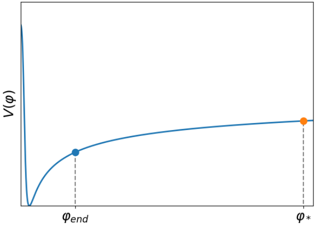

- CMB observables

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

Inflation results

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

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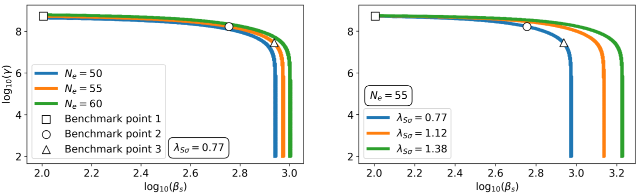
- Scalar amplitude constraint [Planck 2018]

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



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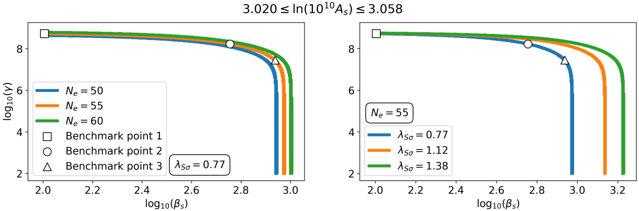
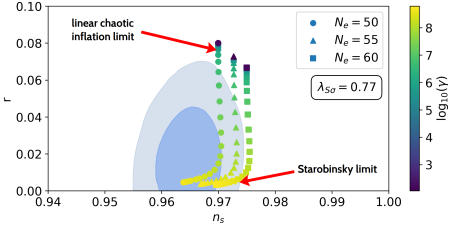


- Free parameters: $\{\gamma, \lambda_{S\sigma}\}$



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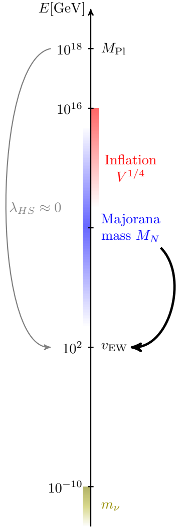

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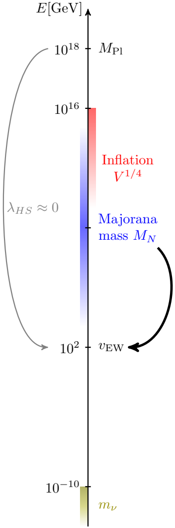

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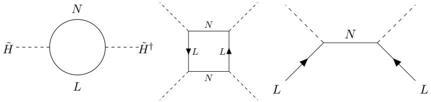
$$\mu_H = 0 \,(\text{tree level}), \quad \Delta\mu_H^2 \sim -\frac{y_\nu^2 m_N^2}{16\pi^2}, \quad \Delta\lambda \sim \frac{y_\nu^4}{64\pi^2}$$



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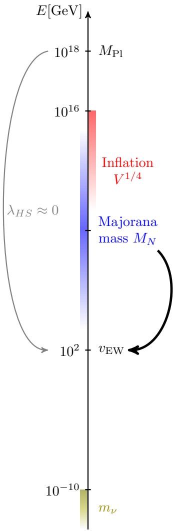

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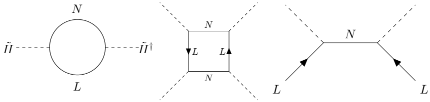

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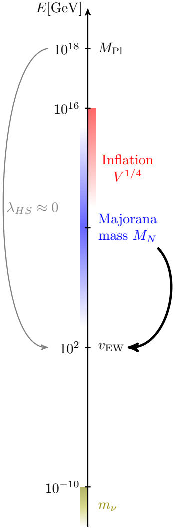

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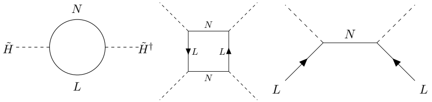

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- Correct Higgs mass and active neutrino masses scale obtained for

$$m_N \sim 10^7\,\text{GeV}, \quad y_\nu \sim 10^{-4}$$

[Brivio, Trott, 1809.03450]

- Embedding in scale-invariant theory $(m_N = y_m v_S)$
  [Brdar et al, 1807.11490]

Fine-tuning

$$\mathcal{L} \supset \frac{i}{2}\overline{N_R}\partial\!\!\!/ N_R - \left(\frac{1}{2}y_M S\overline{N_R}(N_R)^c + y_\nu \bar{L}\tilde{H}N_R + \text{h.c.}\right) - \frac{1}{4}(\lambda_{HS}S^2 + \lambda_{H\sigma}\sigma^2)H^\dagger H$$

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

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

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

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

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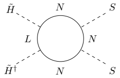
- **Another contribution to the Higgs mass**

$$\lambda_{HS}S^2(H^\dagger H) \to \lambda_{HS}v_S^2(H^\dagger H)$$
$$\Delta\lambda_{HS} \sim y_\nu^2 y_M^2/16\pi^2$$



- $\lambda_{HS} \ll 1$ but not fine-tuned to special value
- $\{\lambda_{HS}, \lambda_{H\sigma}, y_M\} \sim 0$ stable under RG (in absence of gravity)

Summary & conclusion

- Classically scale invariant model with dynamical generation of all scales
- VEV $v_S = 10^{16-17}$ GeV generates Planck scale $M_{\mathrm{Pl}} \approx \beta_S^{1/2} v_S$
- 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

$$U_{\rm eff}(S,R,\sigma) = \frac{\lambda_S}{4}S^4 + \frac{\lambda_\sigma}{4}\sigma^4 + \frac{\lambda_{S\sigma}}{4}S^2\sigma^2 + \frac{1}{64\pi^2}\left(\tilde{m}_s^4\ln[\tilde{m}_s^2/\mu^2] + \tilde{m}_\sigma^4\ln[\tilde{m}_\sigma^2/\mu^2]\right)$$

$$\tilde{m}_s^2 = 3\lambda_S S^2 + \beta_S R$$

$$\tilde{m}_\sigma^2 = \frac{1}{2}\lambda_{S\sigma}S^2 + \beta_\sigma R$$

Inflaton potential

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

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

Contours

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

$$\to \frac{\mathcal{L}^E_{\rm eff}}{\sqrt{-g}} = -\frac{1}{2}M_{\rm Pl}^2\,R + \frac{1}{2}F(S)^2\,g^{\mu\nu}\,\partial_\mu S\,\partial_\nu S - V_{\rm inf}(S)$$

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

Inflationary observables

Power spectrum of adiabatic and Gaussian scalar fluctuations

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

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

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

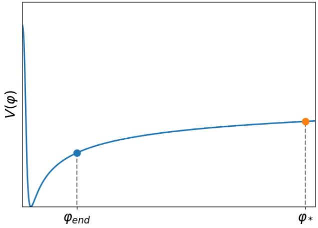
$$\Delta_t^2(k) = A_t(k_*) \left(\frac{k}{k_*}\right)^{n_t(k_*)} \begin{cases} r = \frac{\Delta_t^2}{\Delta_s^2} & \text{tensor-to-scalar ratio} \end{cases}$$

Slow-roll approximation

- Potential slow-roll parameters

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

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



- End of inflation

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

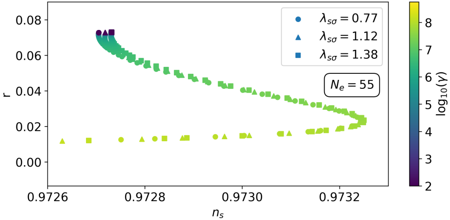
- Field value at horizon crossing S_* fixed by e-folds $N_e = 50 - 60$

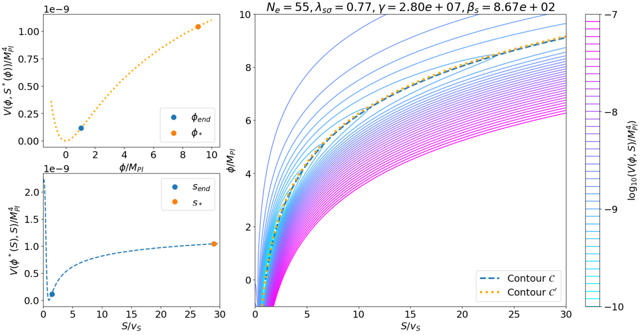
$$N_e = \int_{t_*}^{t_{\rm end}} H {\rm d}t = \int_{S_*}^{S_{\rm end}} \frac{{\rm d}S}{\sqrt{2\varepsilon(S)}}$$

- CMB observables

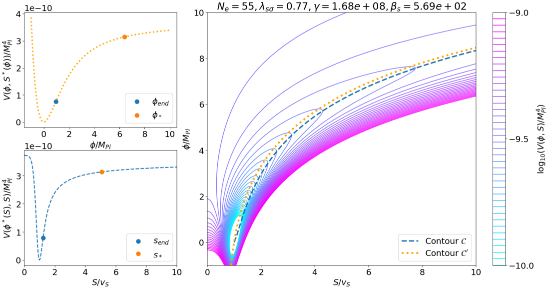
$$A_s = \frac{V_{\rm inf}(S_*)}{24\pi^2\,\varepsilon(S_*)\,M_{\rm Pl}^4}\,, \quad n_s = 1 + 2\,\eta(S_*) - 6\,\varepsilon(S_*)\,, \quad r = 16\,\varepsilon(S_*)$$

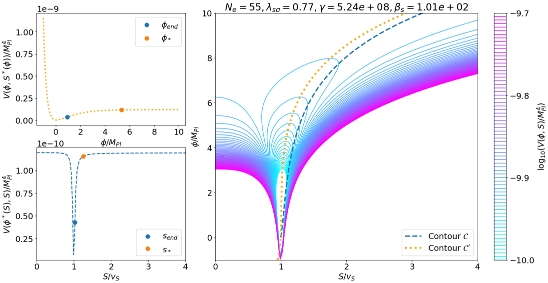
Inflation


$\lambda_{s\sigma} = 0.77$
$\lambda_{s\sigma} = 1.12$
$\lambda_{s\sigma} = 1.38$
$N_e = 55$
r
n_s
$\log_{10}(\gamma)$


$N_e = 55, \lambda_{s\sigma} = 0.77, \gamma = 2.80e+07, \beta_s = 8.67e+02$
$V(\phi, S^*(\phi))/M_{Pl}^4$
ϕ/M_{Pl}
ϕ_{end}
ϕ_*
$V(\phi^*(S), S)/M_{Pl}^4$
S/v_S
S_{end}
S_*
Contour $\mathcal{C}$
Contour $\mathcal{C}'$
$\log_{10}(V(\phi, S)/M_{Pl}^4)$

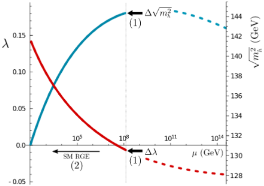
Inflation


1e−10
$V(\phi, S^*(\phi))/M_{Pl}^4$
ϕ/M_{Pl}
ϕ_{end}
ϕ_*
1e−10
$V(\phi^*(S), S)/M_{Pl}^4$
S/v_S
s_{end}
s_*
$N_e = 55, \lambda_{s\sigma} = 0.77, \gamma = 1.68e+08, \beta_s = 5.69e+02$
ϕ/M_{Pl}
S/v_S
Contour $\mathcal{C}$
Contour $\mathcal{C}'$
$\log_{10}(V(\phi, S)/M_{Pl}^4)$
−9.0
−9.5
−10.0


1e−9
$V(\phi, S^*(\phi))/M_{Pl}^4$
ϕ/M_{Pl}
ϕ_{end}
ϕ_*
1e−10
$V(\phi^*(S), S)/M_{Pl}^4$
S/v_S
s_{end}
s_*
$N_e = 55, \lambda_{s\sigma} = 0.77, \gamma = 5.24e+08, \beta_s = 1.01e+02$
ϕ/M_{Pl}
S/v_S
Contour $\mathcal{C}$
Contour $\mathcal{C}'$
$\log_{10}(V(\phi, S)/M_{Pl}^4)$
−9.7
−9.8
−9.9
−10.0

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 $M \gg$ TeV ($M = 10^8$ 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 $m_t = 173.2\,$GeV [4].



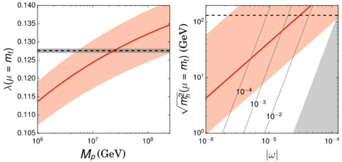
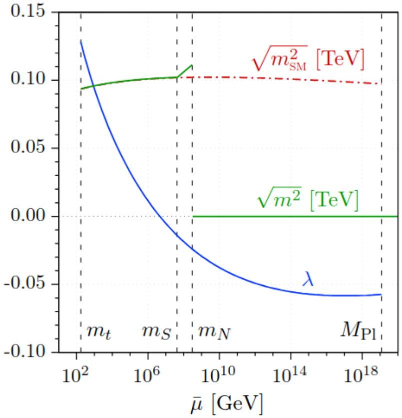


Figure 3: Values of the parameters λ (left) and $\sqrt{m_h^2}$ (right) extrapolated at the scale $\mu = m_t$ as a function of the two seesaw parameters M and ω respectively, in the preliminary study of Ref. [1]. The dashed lines and surrounding bands indicate the values consistent with the measured Higgs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