Pre-heating, Higgs stability and leptogenesis

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BLV, October 2019
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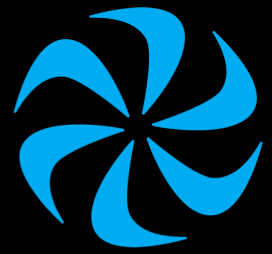


Based on
DC, N. Fernandez, D. McKeen, G. White
[JHEP, arXiv:1903.08658]

A minimal model for high-scale leptogenesis

Imagine a minimal model explaining inflation, neutrino masses, and the BAU:

Inflaton potential

Inflaton-Higgs couplings, at tree or one loop level

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial\phi)^2 - V(\phi) + \frac{g}{2}\phi^2|H|^2 - \sigma\phi|H|^2$$

$$+ i\bar{N}_i \not{\partial} N_i - \left(\frac{1}{2} M_{ij} \bar{N}_i^c N_j + Y_{ij} \bar{L}_i \tilde{H} N_j + \tilde{\lambda}_{ij} \phi \bar{N}_i^c N_j + \text{h.c.} \right)$$

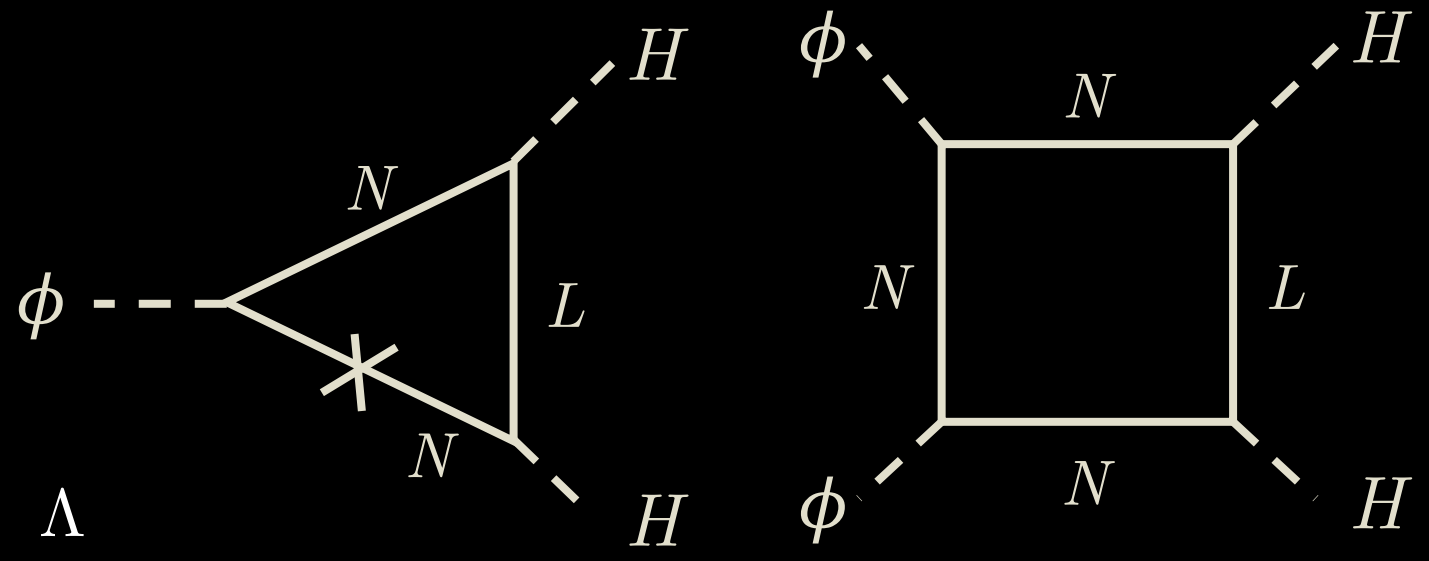
Neutrino mass terms

$$Y = \frac{1}{v} U \sqrt{m_\nu} R^T \sqrt{M}$$

Inflaton-sterile coupling, through which to reheat

Higgs-inflaton couplings

- Even if vanishing at some scale, Higgs-inflaton couplings are introduced at one-loop,



- Of the form,

$$\delta g = \frac{1}{2\pi^2}\mathrm{Tr}\left[\tilde{\lambda}^\dagger\tilde{\lambda}Y^\dagger Y\right]\log\frac{\Lambda}{m_\phi}$$

$$\delta\sigma = -\frac{1}{4\pi^2}\mathrm{Tr}\left[\mathrm{Re}\left(\tilde{\lambda}M + M\tilde{\lambda}\right)Y^\dagger Y\right]\log\frac{\Lambda}{m_\phi}$$

BAU in the type-I seesaw mechanism

- Solving the Boltzmann equations,

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi\,\rho_\phi,$$

$$\frac{d\rho_{N_1}}{dt} + 3H\rho_{N_1} = -\Gamma_{N_1}\left(\rho_{N_1} - \rho_{N_1}^{\rm eq}\right) + \Gamma_{\phi\to N_1 N_1}\,\rho_\phi,$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_{N_1}\left(\rho_{N_1} - \rho_{N_1}^{\rm eq}\right) + \Gamma_{\phi\to R}\,\rho_\phi.$$

- B-L asymmetry is generated from sterile neutrino decays,

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = \epsilon_1\frac{\Gamma_{N_1}}{M_i}\left(\rho_{N_1} - \rho_{N_1}^{\rm eq}\right) - W n_{B-L}$$

Asymmetry parameter

Washout

Preheating with the Higgs

- Consider $V(\phi, h) = \frac{1}{2} m_\phi^2 \phi^2 + \frac{g}{4} \phi^2 h^2 + \frac{\sigma}{2} \phi h^2 + \frac{\lambda_h}{4} h^4$
- At the bottom of the inflaton potential, $\begin{cases} \phi(t) = \Phi(t) \cos(m_\phi t) \\ \Phi(t) \sim \dfrac{\Phi_0}{m_\phi t} \end{cases}$
- Such that the following (Mathieu) mode-equation describes the (comoving) Higgs modes in the oscillating background,

$$\ddot{\tilde{h}}_k + \omega_k^2 \tilde{h}_k = 0 \,,$$

$$\omega_k^2 = \left[\frac{k^2}{a^2} + \frac{g}{2} \Phi^2 \cos^2(m_\phi t) + \sigma \Phi \cos(m_\phi t) + 3 a^{-3} \lambda_h(h) \langle \tilde{h}^2 \rangle + \Delta \right]$$

Parametric resonance

- At some scale, the Higgs quartic becomes negative,

$$V_{\rm eff}(h) \approx \frac{1}{2} m^2_{h_{\rm eff}} h^2 - \frac{|\lambda_h(\tilde{\mu})|}{4} h^4$$

- Let's first consider the mixed quartic coupling, g
  - The Higgs variance grows as

$$\langle h^2 \rangle \approx \frac{\Phi(t)}{32\pi^{3/2}} \sqrt{\frac{g m_\phi}{\mu t}} e^{(2\mu m_\phi - \Gamma_{h\to\bar{t}t})t}$$

$\mu \approx (\ln 3)/2\pi$

$\Gamma_{h\to tt}$ Higgs decay rate into tops

  - Then, $\lambda_h \langle h^2 \rangle$ (Harttree approximation) acts as a mass term
  - The effective Higgs mass is negative for a time interval $\Delta t = \sqrt{\frac{6\lambda_h(\tilde{\mu})\langle h^2 \rangle}{g\Phi^2 m_\phi^2}}$ around $\phi = 0$ → tachyonic amplification of the Higgs field

See also Enqvist, Karciauskas, Lebedev, Rusak and Zatta [JCAP, arXiv:1608.08848]

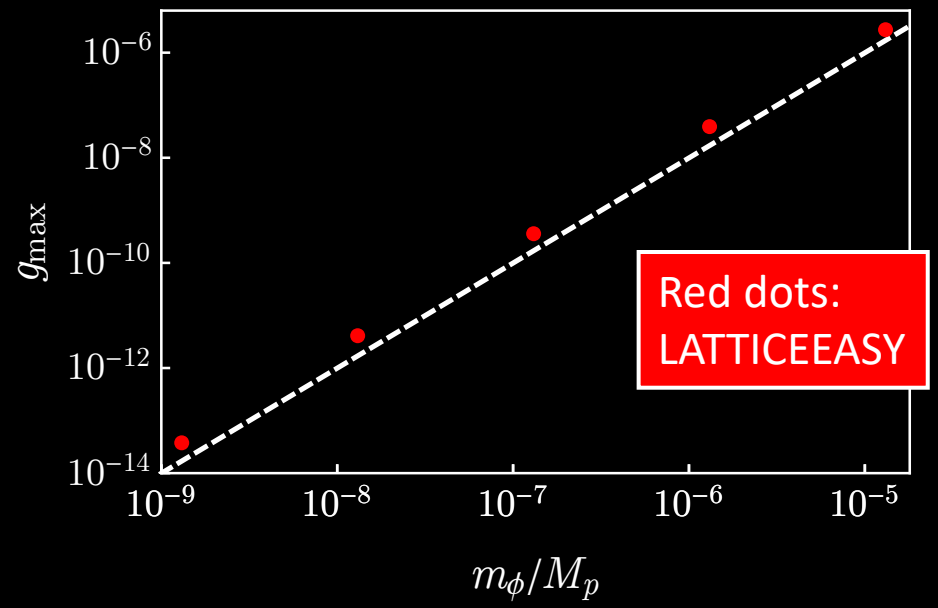
Upper bounds

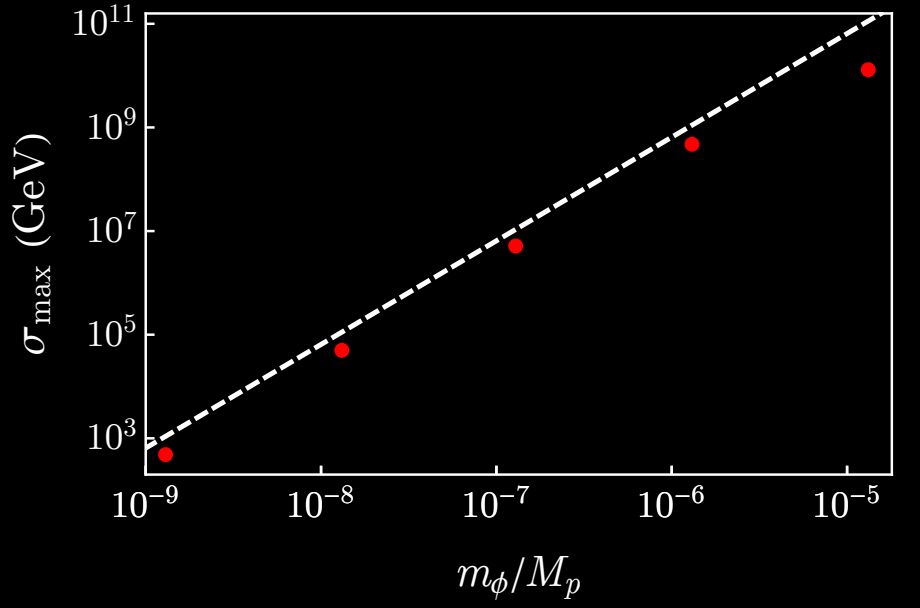
- Insisting that the vacuum decay time is longer than the duration of parametric resonance leads to an upper bound,

$$g < \frac{6\pi}{4\mu^2}\left[\frac{m_\phi}{M_{\rm Pl}}\ln\left(\frac{16\pi^{3/2}}{3|\lambda_h(\tilde{\mu})|}\right)\right]^2 \times \left(1-\frac{y_t^2}{96\sqrt{2}\pi^2\mu}\right)^{-2}$$

- Repeating this analysis for σ yields,

$$\sigma < \frac{\sqrt{3\pi}}{4\mu^*}\left(\frac{m_\phi^2}{M_{\rm Pl}}\right)\ln\left(\frac{16\pi^{3/2}}{3|\lambda_h(\tilde{\mu})|}\right)$$





Leptogenesis + Higgs stability

For two sterile neutrino species, where the inflaton couples dominantly to the lightest sterile neutrino (conservative scenario)

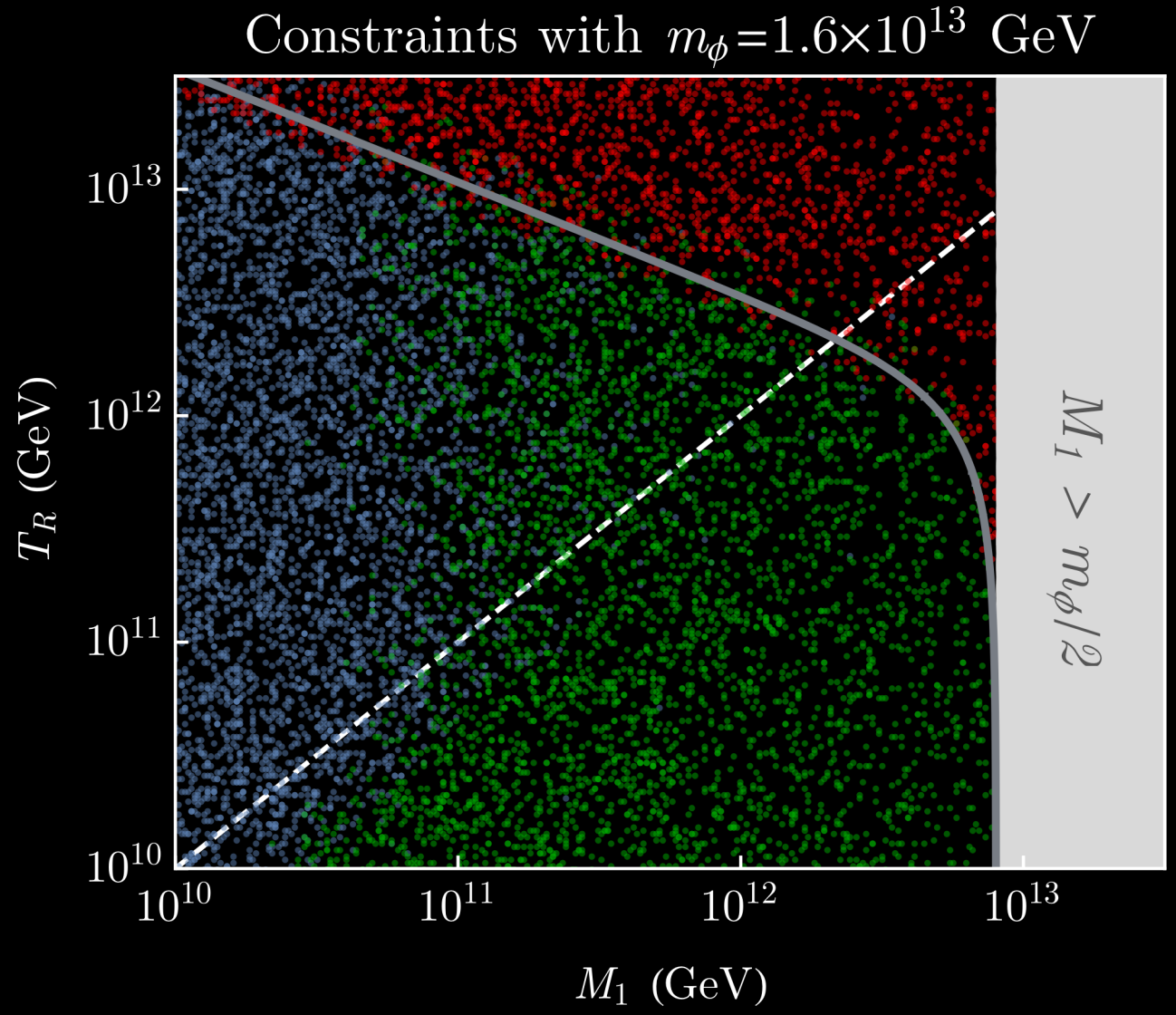
Perturbative reheating into sterile neutrinos

$$T_R = (M_p\,\Gamma)^{1/2} \times (45/4g_*\pi^3)^{1/4}$$

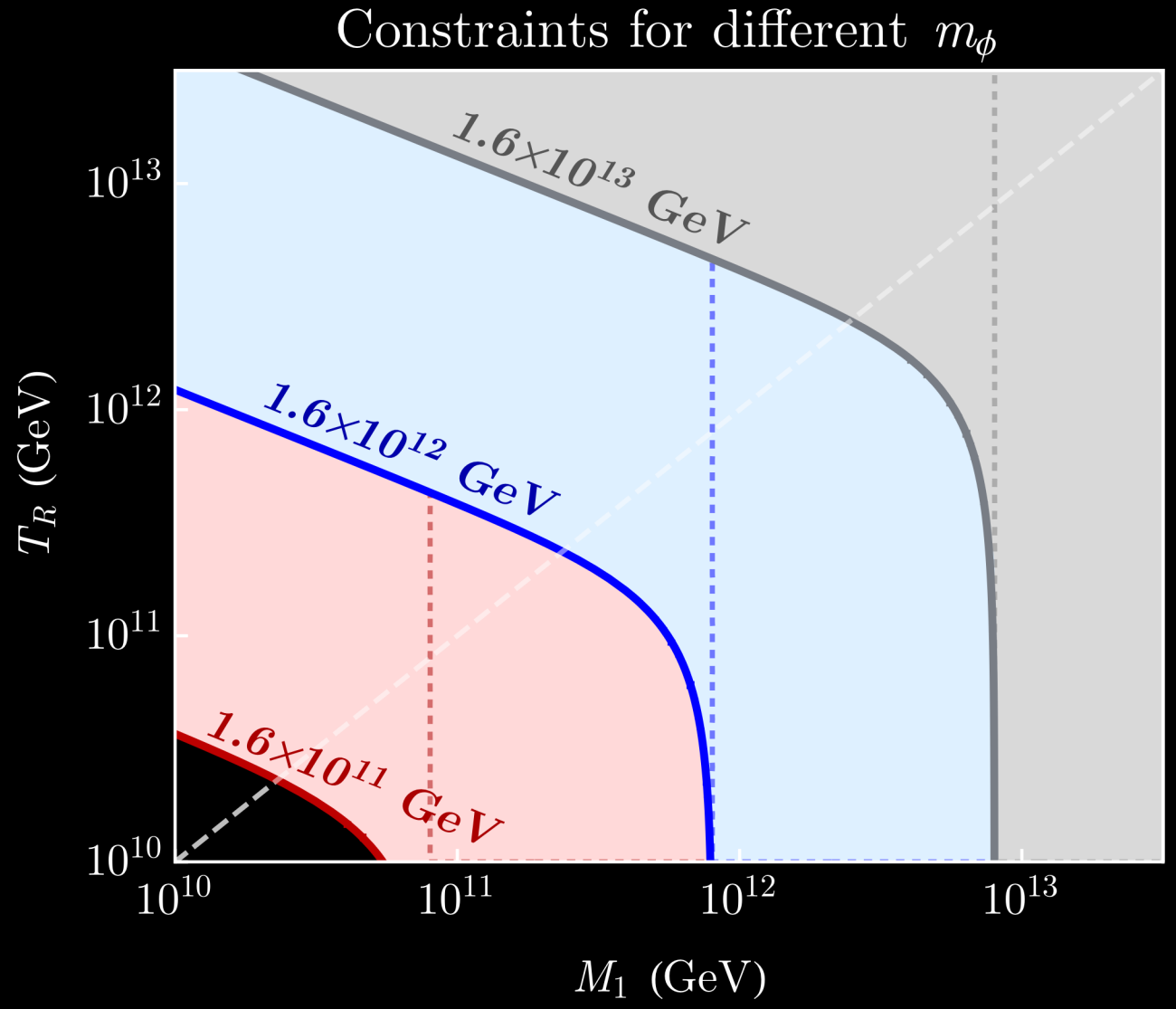
$$T_R \lesssim 4.7\times10^{16}\ \mathrm{GeV}\left(\frac{106.75}{g_*}\right)^{1/4}\left(\frac{\sigma_{\max}}{5\times10^{8}\ \mathrm{GeV}}\right)\left(\frac{14}{\log M_{\mathrm{Pl}}/m_\phi}\right)$$
$$\times\left(\frac{10^{11}\ \mathrm{GeV}}{M_1}\right)^{2}\left(\frac{m_\phi}{1.6\times10^{13}\ \mathrm{GeV}}\right)^{1/2}\left(1-\frac{4M_1^2}{m_\phi^2}\right)^{3/4}$$

$$T_R \lesssim 1.1\times10^{13}\ \mathrm{GeV}\left(\frac{106.75}{g_*}\right)^{1/4}\left(\frac{g_{\max}}{2\times10^{-8}}\right)^{1/2}\left(\frac{14}{\log M_{\mathrm{Pl}}/m_\phi}\right)^{1/2}$$
$$\times\left(\frac{10^{11}\ \mathrm{GeV}}{M_1}\right)^{1/2}\left(\frac{m_\phi}{1.6\times10^{13}\ \mathrm{GeV}}\right)^{1/2}\left(1-\frac{4M_1^2}{m_\phi^2}\right)^{3/4}$$

Results


Constraints with m_ϕ=1.6×10^{13} GeV
T_R (GeV)
M_1 (GeV)
10^{10}
10^{11}
10^{12}
10^{13}
$M_1 > m_\phi/2$

Results


Constraints for different m_ϕ
1.6×10^{13} GeV
1.6×10^{12} GeV
1.6×10^{11} GeV
10^{13}
10^{12}
10^{11}
10^{10}
T_R (GeV)
10^{10}
10^{11}
10^{12}
10^{13}
M_1 (GeV)

Conclusions

- Vanilla leptogenesis relies on CP-violating decays of sterile neutrinos
- Any coupling between sterile neutrinos and the inflaton induces an inflaton-Higgs coupling at the loop level
- Stability constraints on the size of this coupling imply constraints on the parameter space of vanilla leptogenesis
  - Complementary to zero-temperature constraints from Higgs stability

See e.g. Bambhaniya, Bhupal Dev, Goswami, Khan and Rodejohann [PRD, arXiv:1611.03827]
Ipek, Plascencia, Turner [JHEP, arXiv:1806.00460]