Type II Seesaw Leptogenesis

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NDB, C. Han, H. Murayama, Phys. Rev. Lett. 128 (2022) 14, 141801; arxiv:2106.03381
NDB, C. Han, H. Murayama, JHEP 05 (2022) 160; arxiv:2204.08202

The Neutrino Masses and Seesaw Mechanisms

The origin of the observed non-zero neutrino masses remains unknown.

The types of Seesaw Mechanism, extend the SM by:

I At least two right-handed neutrinos,

II A $SU(2)_L$ triplet scalar,

III At least two $SU(2)_L$ fermion triplets.

None of these models, or mixtures, have been experimentally observed.

Matter-antimatter Asymmetry

Unknowns of neutrino sector could explain observed baryon asymmetry,

$$\eta = \frac{n_b - n_{\bar{b}}}{s} \simeq 8.5 \times 10^{-11}$$

- Equilibrium sphalerons can transfer an asymmetry from the leptons to baryons.
- Thermal Leptogenesis possible in Type I and III Seesaw Mechanisms.
- Type II Seesaw requires additional triplet scalar or RH neutrino.
- Consider other mechanisms for Leptogenesis:
  Affleck-Dine mechanism

Affleck-Dine Mechanism

Consider a complex field ϕ with a global $U(1)$ charge Q.

The charge density of ϕ is,

$$n_\phi = j^0 = 2Q\mathrm{Im}[\phi^\dagger \dot{\phi}] = Q\phi_r^2\dot{\theta} \ ,$$

where $\phi = \frac{1}{\sqrt{2}}\phi_r e^{i\theta}$.

Required ingredients:

- A scalar that is charged under some mixture of the global $U(1)_L$ or $U(1)_B$ symmetries,
- A small term in the Lagrangian that breaks this symmetry,
- A displaced vacuum value during the early universe.

Affleck-Dine Mechanism

Standard Case:

- Originally explored in the context of SUSY,
- Scalar superpartners carry B and L,
- Flat directions in scalar potential,
- Scalars displaced from potential minimum during inflationary epoch,
- Motion in complex phase via B and L violating interactions.

We want to instead consider ϕ to be the Triplet Higgs, giving,

- A minimal framework that does not require Supersymmetry, or new particles beyond the Triplet Higgs.
- A natural way to transfer the asymmetry from scalar to SM fermions.

The Type II Seesaw Mechanism

SM Higgs doublet and Triplet Higgs,

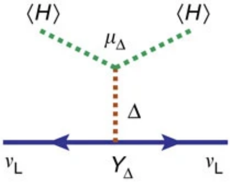
$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix},$$

Adds a neutrino yukawa coupling,

$$\mathcal{L}_{\text{yukawa}} = -\frac{1}{2} y_{ij} \bar{L}_i^c \Delta L_j + h.c.$$

Making Δ doubly charged under $U(1)_L$ with lepton violation terms,

$$\mathcal{L}_{\not{L}} = \mu h^2 {\Delta^0}^* + \frac{1}{M_P}\left(\lambda_5 |h|^2 h^2 {\Delta^0}^* + \lambda_5' |\Delta^0|^2 h^2 {\Delta^0}^*\right) + h.c.$$



Nature Commun. 5 (2014) 5153

Triplet Higgs Phenomenology

- The neutral component of the triplet has a non-zero vev,

$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\rm EW}^2}{2m_\Delta^2} \ ,$$

  for $m_\Delta \gg v_{\rm EW}$. Able to generate the observed m_ν for $\mathcal{O}(1)\ {\rm GeV} > \langle \Delta^0 \rangle \gtrsim 0.05$ eV, while ensuring y_ν is perturbative.

- $m_\Delta \gtrsim 800$ GeV from searches for the doubly-charged Higgs.

- Lepton Flavour violating interactions.

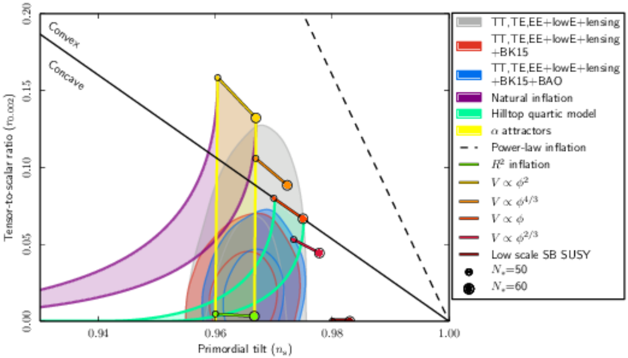
- Neutrinoless double beta decay,

- Vacuum stability.

To fulfill the third Affleck-Dine mechanism criteria we can take the Δ^0 to play a role in inflation.

Inflation

- Explains homogeneity, flatness, and primordial perturbations.
- Scalar field with a very flat potential, satisfying slow roll parameters.



Astron.Astrophys. 641 (2020) A10

Starobinsky inflation, matches well with current observional constraints.

Higgs Inflation

- The SM Higgs has been considered as a possible inflaton candidate,
- The Higgs potential is too steep to be consistent with observation,
- Require flattening by non-minimal coupling to gravity,

$$M_p^2\left(1+\frac{\xi_H|H|^2}{M_p^2}\right)R\ ,$$

- Gives the Starobinsky potential in Einstein frame,

$$U(\chi)=\frac{3}{4}m_S^2M_p^2(1-e^{-\sqrt{2/3}\chi/M_p})^2\ ,$$

where $m_S=\frac{\lambda_H M_p^2}{3\xi_H^2}\simeq 3\cdot 10^{13}$ GeV, fitting observations.

Model Framework

Simple extension of the SM motivated by the unknown origins of Inflation, Baryogenesis, and the neutrino masses.

Explain by addition of a Triplet Higgs to SM,

- Two-field inflation (H and Δ), with Starobinsky-like observables,
- Lepton number phase motion, n_L, induced during inflationary phase,
- Baryon asymmetry via sphaleron redistribution,
- Neutrino masses via triplet higgs vacuum expectation value,
- Rich phenomenological implications.

Inflationary Setting

Reparametrise in polar coordinates $h \equiv \frac{1}{\sqrt{2}}\rho_H e^{i\eta}$, $\Delta^0 \equiv \frac{1}{\sqrt{2}}\rho_\Delta e^{i\theta}$, and

$$\rho_H = \varphi \sin\alpha,\ \ \rho_\Delta = \varphi\cos\alpha,\ \ \xi \equiv \xi_H \sin^2\alpha + \xi_\Delta \cos^2\alpha \ .$$

Giving the Lagrangian,

$$\begin{aligned}\frac{\mathcal{L}}{\sqrt{-g}} \;\; &= \;\; -\frac{1}{2}M_P^2 R - \frac{1}{2}\xi\varphi^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi \\ &\quad\; -\frac{1}{2}\varphi^2\cos^2\alpha\ g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\varphi,\theta)\ ,\end{aligned}$$

where

$$V(\varphi,\theta) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2\varphi^3\left(\tilde{\mu} + \frac{\tilde{\lambda}_5}{M_P}\varphi^2\right)\cos\theta\ .$$

The inflationary trajectory is approximately fixed by,

$$\frac{\rho_H}{\rho_\Delta} \equiv \tan\alpha \simeq \sqrt{\frac{2\lambda_\Delta\xi_H - \lambda_{H\Delta}\xi_\Delta}{2\lambda_H\xi_\Delta - \lambda_{H\Delta}\xi_H}}\ ,$$

and the Jordan frame inflaton is defined by φ.

Assumptions

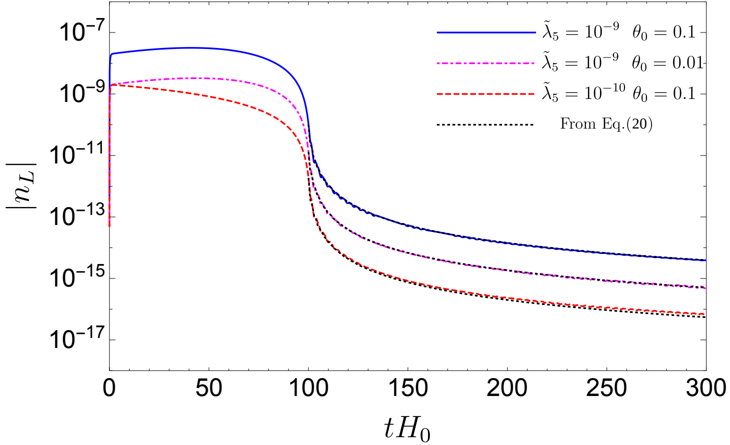
The inflaton is defined as χ with potential,

$$U(\chi) = \frac{3}{4} m_S^2 M_p^2 \left(1 - e^{-\sqrt{\frac{2}{3}}(\chi/M_p)}\right)^2 \ .$$

- Cubic term is suppressed relative to the Dim-5 term throughout inflation and reheating,
- Initial $\theta_0 \neq 0$,
- The mixing angle α is approximately constant,
- The Dim-5 term has a negligible effect on the inflationary trajectory.

Solve numerically and analytically to determine the generated $\dot{\theta}$.

The Lepton Number Density



Parameter Space

Parameter Requirements

- Successful Leptogenesis - $\eta_B \simeq \eta_B^{\rm obs}$,
- Neutrino masses - At least one satisfying $m_\nu \simeq y \frac{\mu v_{ew}^2}{2m_\Delta^2} \gtrsim 0.05$ eV ,
- Perturbative neutrino yukawa coupling - $y \lesssim 1$,
- Avoiding lepton number washout effects:

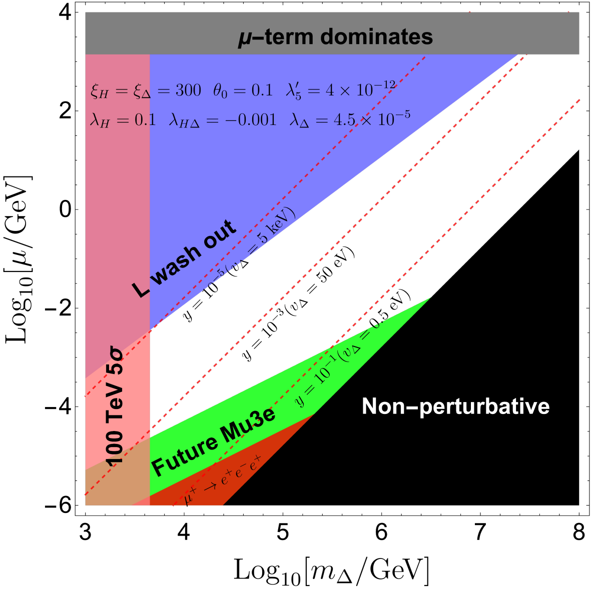
  $LL \leftrightarrow HH \Rightarrow m_\Delta < 10^{12}$ GeV,

  Combination of $LL \leftrightarrow \Delta$ and $HH \leftrightarrow \Delta \Rightarrow \langle\Delta^0\rangle < 10\ \mathrm{keV}$,
- LHC triplet Higgs mass constraints - $m_\Delta \gtrsim 800$ GeV,
- Triplet Higgs VEV - $10\ \mathrm{keV} > \langle\Delta^0\rangle \gtrsim 0.05$ eV .

Parameter Requirements

- Inflationary observables - n_s, r, N_e, $\frac{\lambda}{\xi^2} \simeq 5 \cdot 10^{-10}$; consistent with Starobinsky inflation predictions,
- Avoid unitarity violation during preheating - $\lambda\xi^2 < 300$,
- Sub-dominance of $\tilde{\lambda}_5$ term - $\frac{\tilde{\lambda}_5}{\xi^2} \ll 6 \cdot 10^{-11}\sqrt{\xi}e^{-\frac{\chi_0}{\sqrt{6}M_p}}$,
- Asymmetry conservation during oscillatory epoch - $\tilde{\mu} \lesssim \frac{m_S n_{L\mathrm{reh}}}{4\varphi^3_{\mathrm{reh}}}$,
- Isocurvature Perturbations,
- No stable Q-ball formation.

Allowed Parameter Space



Summary of Phenomenological Implications

- 100 TeV collider searches, probe up to $\sim$ 4 TeV at 5σ,
- $v_\Delta = 0.05$ eV - 10 keV, decays dominantly into Leptonic channel,
- Lepton violating interactions constrained by future Mu3e searches,
- Neutrinoless double beta decay,
- Vacuum Stability,
- Non-Gaussianties and Isocurvature Perturbations,
- Possible gravitational wave implications - r by LiteBIRD, Preheating, and First Order Phase Transition.

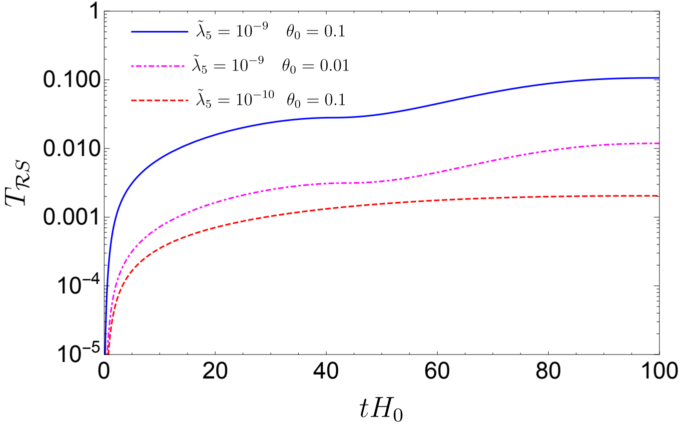
Conclusion

Simple extension of the SM by the triplet Higgs of the Type II Seesaw Mechanism, unified solution to multiple unknowns.

- Successful Type II Seesaw Leptogenesis scenario,
- Explains the observed neutrino masses,
- Inflationary measurements consistent with observations,
- Unique phenomenology to be probed at future experiments.

Thank You! :)

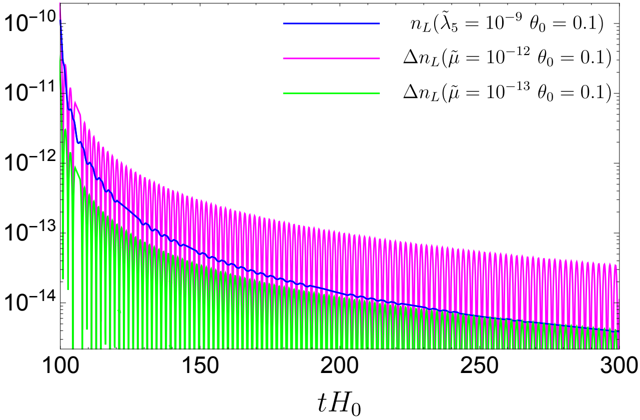
Parameter Requirements - Isocurvature Perturbations



The evolution of $T_{\mathcal{R}S}$ during inflation for different input parameters. The input parameters are fixed to $\xi = 300$ and $\lambda = 4.5 \cdot 10^{-5}$, with initial conditions $\chi_0 = 6.0M_p$, $\dot{\chi}_0 = 0$, and $\dot{\theta}_0 = 0$ chosen.

Parameter Requirements -

We must ensure that $\Delta n_L \lesssim n_L$ before reheating completed,



For these example parameters we require $\tilde{\mu} \lesssim 10^{-13} M_p$.

Parameter Requirements - $\tilde{\mu}$ upper bound