TeV Scale Leptogenesis, Inflaton Dark Matter & Neutrino Mass in the Scotogenic Model

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Debasish Borah, P.S. Bhupal Dev & AK; arXiv: 1810.03645 [hep-ph]

Sandhya Choubey & AK; JHEP 11 (2017) 080

The Universe… Many puzzles

Homogeneous and isotropic at large scales. A very fast expansion phase in the early universe – primordial inflation. Models often consider a field called the inflaton as responsible for causing it.

More baryonic matter than antimatter. Baryon number violation, C & CP violation, Out of equilibrium interactions are the 3 necessary conditions for it to occur. These are called Sakharov Conditions.

Almost five times more mass than can be accounted for by luminous matter. Dark matter, a non-baryonic new particle makes 20% of the universe.

Neutrinos are not massless, they oscillate. Right handed neutrinos can give SM neutrinos mass.

Scotogenic Model

$\Phi_1 = \frac{1}{\sqrt{2}}(\chi, h), \Phi_2 = \frac{1}{\sqrt{2}}(q, x\, e^{i\theta}) \rightarrow$ The Higgs doublet and the Inert doublet respectively.

$N_i, i = 1,2,3 \rightarrow$ The three right handed neutrinos

An extra $\mathbb{Z}_2$ symmetry $\Phi_2 \rightarrow -\Phi_2, N_i \rightarrow -N_i$ while SM particles are even.

Model details:

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}M_{\rm Pl}^2 R - D_\mu\Phi_1 D^\mu\Phi_1^\dagger - D_\mu\Phi_2 D^\mu\Phi_2^\dagger - V(\Phi_1,\Phi_2) - \xi_1\Phi_1^2 R - \xi_2\Phi_2^2 R\right]$$

$$V(\Phi_1,\Phi_2) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \text{H.c.}\right] .$$

$$\mathcal{L} \supset \frac{1}{2}(M_N)_{ij}N_iN_j + \left(Y_{ij}\,\bar{L}_i\tilde{\Phi}_2 N_j + \text{H.c.}\right)$$

We consider that inflation occurs in the Φ_2 direction i.e. $\frac{\lambda_2}{\xi_2^2} \ll \frac{\lambda_1}{\xi_1^2}$

Inflation

- First, perform a conformal transformation on the action to get a canonical one without explicit gravity couplings. $\phi_i = \{\chi, h, q, x\}$

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu},$$

$$\Omega^2 = 1 + \frac{\xi_1}{M_{Pl}^2}(\chi^2 + h^2) + \frac{\xi_2}{M_{Pl}^2}(q^2 + x^2),$$

$$G_{ij} = \frac{1}{\Omega^2}\delta_{ij} + \frac{3}{2}\frac{M_{Pl}^2}{\Omega^4}\frac{\partial\Omega^2}{\partial\phi_i}\frac{\partial\Omega^2}{\partial\phi_j},$$

$$\tilde{V} = \frac{V}{\Omega^4}.$$

- G_{ij} = coefficient of kinetic term $\tilde{\partial}_\mu \phi_i \, \tilde{\partial}^\mu \phi_j$
- Mixed kinetic terms present.
- Redefine the fields to get a diagonal kinetic term i.e. no kinetically mixed terms:

$$A = \sqrt{\frac{3}{2}} M_{Pl} \log\left(\Omega^2\right),$$

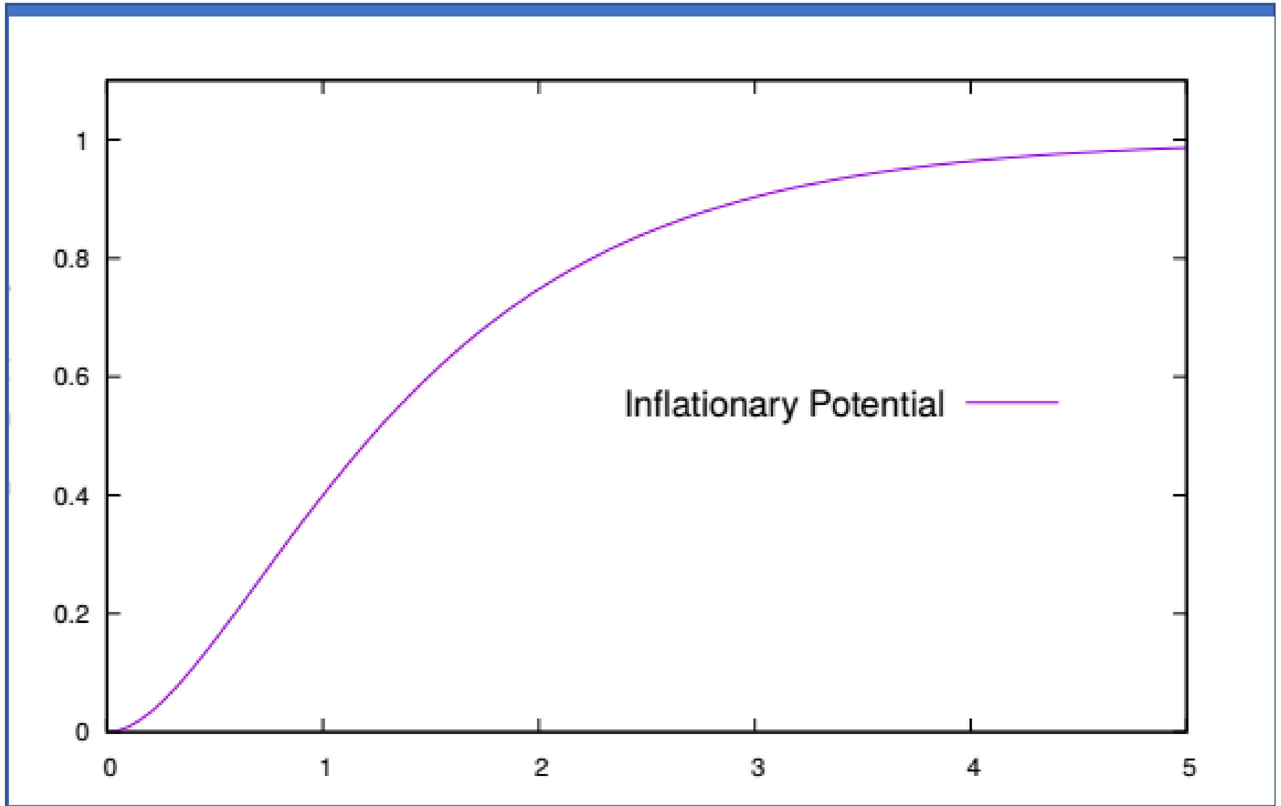
$$B = M_{Pl}\frac{x}{q}.$$

Inflation

- The potential in terms of the new fields:

$$V_e \approx \frac{\lambda_2 M_{Pl}^4}{4\xi_2^2}\left[1-\exp\left(-\sqrt{\frac{2}{3}}\frac{A}{M_{Pl}}\right)\right]^2.$$

- This potential belongs to the Starobinsky class and is sufficiently flat for slow-roll inflation.



The y-axis shows the potential V_e multiplied by $\frac{4\xi^2}{\lambda_2 M_{Pl}^4}$, x-axis is field value multiplied by $\sqrt{\frac{2}{3}}\frac{1}{M_{Pl}}$.

Inflationary parameters

- The predicted scalar spectral index $n_s = 0.9678$.
- The observed scalar spectral index $n_s = 0.9649 \pm 0.0042$ at 68% CL (Planck 2018)
- The predicted tensor to scalar perturbation ratio $r = 0.0029$.
- The observed tensor to scalar perturbation ratio $r < 0.11$ at 95% CL (Planck 2018)
- The scalar power spectrum $P_s = 5.57\frac{\lambda_2}{\xi_2^2}$.
- The observed scalar power spectrum $\log(10^{10}P_s) = 3.047 \pm 0.014$ at 68% CL (Planck 2018)
- Gives us $\xi_2 \simeq 5.33 \times 10^4\, \lambda_2^{1/2}$.
- The model satisfies the inflationary observations very nicely.

Reheating

- Occurs during a potential that can be approximated as quadratic.
- Sol: $A(t) = A_0(t)\cos(\omega t),\ A_0 = \frac{2\sqrt{2}\xi_2}{\lambda_2^{1/2}\,t}$
- Occurs until the inflaton amplitude A_0 falls below $A_{\rm cr} = \frac{\sqrt{\frac{2}{3}}M_{Pl}}{\xi_2}$ where this approximation breaks down.

$$V_e = \frac{\lambda_2 M_{Pl}^4}{4\,\xi_2^2}\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{A}{M_{Pl}}\right)\right]^2,$$

$$\simeq \frac{\lambda_2 M_{Pl}^2}{6\xi_2^2}A^2,$$

$$V_e = \frac{1}{2}\omega^2 A^2, \quad \text{where } \omega^2 = \frac{\lambda_2 M_{Pl}^2}{3\xi_2^2},$$

- Radiation production can proceed through three ways:
  - 1st is the linear production of bosons when their number density is small. The bosons decay to relativistic fermions.
  - 2nd is through parametric resonance production of bosons when their number density is large. In this regime, bosons annihilate to relativistic fermions.
  - 3rd Direct production of fermions through the Yukawa coupling.

Reheating via the bosons

$$\frac{d(n_W a^3)}{dt} = \begin{cases} \frac{P}{2\pi^3}\omega K_1^3 a^3, & \text{(linear)}, \\ 2a^3\omega Q n_W, & \text{(resonance)}, \end{cases}$$

$$\frac{d(n_h a^3)}{dt} = \begin{cases} \frac{P}{2\pi^3}\omega K_2^3 a^3, & \text{(linear)}, \\ 2a^3\omega Q n_h. & \text{(resonance)}, \end{cases}$$

The above equations give the linear and parametric resonance production of gauge bosons n_W and Higgs n_h where,

$$K_1 = \left[\frac{g^2 M_{Pl}^2}{6\xi_2^2}\sqrt{\frac{\lambda_2}{2}}A_0(t_i)\right]^{1/3}$$

$$K_2 = \left[\frac{\lambda_3 M_{Pl}^2}{3\xi_2^2}\sqrt{\frac{\lambda_2}{2}}A_0(t_i)\right]^{1/3}$$

The parameters $P \approx 0.0455$ and Q ≈ 0.045

Reheating via the bosons

- Higgs contribution to relativistic fermion production $\ll$ Gauge boson contribution
- Radiation production in the linear regime of boson production through decay.
- Radiation production during parametric resonance production of gauge bosons by annihilations
- Parametric resonance starts when the decay rate falls below the resonance production rate
- Radiation production during parametric resonance phase $\gg$ radiation production during linear phase.
- Lower bound on λ_2

$$\Gamma_W = 0.75 \frac{g^2}{4\pi} m_W$$

$$\sigma_{WW} \approx \frac{g^4}{16} \frac{2N_l + 2N_q N_c}{8\pi \langle m_W^2 \rangle} \approx 10\pi \frac{g^4}{16\pi^2 \langle m_W^2 \rangle}$$

$$A_0 < \frac{2}{0.5625\,\pi} \frac{Q^2 \lambda_2}{\alpha_W^3} A_{cr} \approx 61.88\, \lambda_2\, A_{cr}$$

$$\lambda_2 \gtrsim \frac{1}{60}$$

$$\rho_r \simeq \frac{1.06 \times 10^{57}\ \mathrm{GeV}^4}{\lambda_2}$$

Reheating via direct decay to fermions

$$Y_{ij}\sqrt{\frac{M_{Pl}A}{\sqrt{24}}}\;\bar{L}_i N_j + h.c.$$

With this coupling between the inert doublet particles, the SM leptons and the right handed neutrinos N_i the radiation energy density produced is given as follows:

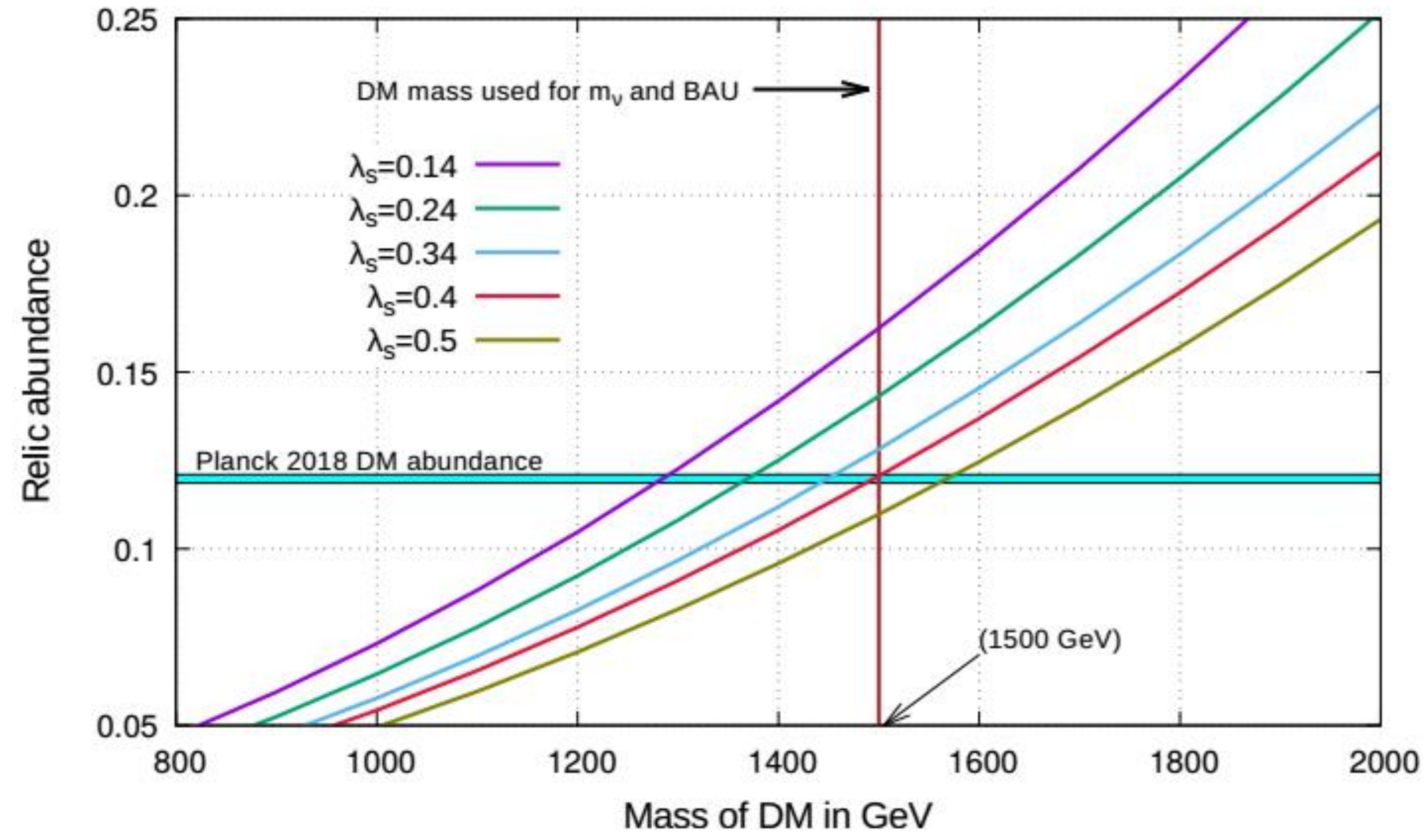
$$\rho_r = \sqrt{\frac{3}{\lambda_2}}\frac{Y^2 M_{\rm Pl}\omega^3}{4\pi} \simeq \frac{6.16\times 10^{49}\ {\rm GeV}^4}{\sqrt{\lambda_2}}$$

For a typical Yukawa value of 10^{-4}, we find that the energy density created by direct decays is much smaller than via the gauge bosons for λ_2 of the order of 1.

Dark Matter

- The inert doublet particles become part of the thermal plasma after reheating to freeze-out of the equilibrium in later stages of the universe
- The lightest neutral particle is a dark matter (DM) candidate. We assume it is the scalar without loss of generality.
- We infer the mass of the DM and its couplings $\lambda_s = \lambda_3 + \lambda_4 + \lambda_5$ through relic density bounds and direct detection limits.
- TeV scale DM, $\lambda_s \lesssim O(0.5)$ satisfies relic density with freeze-out around EW scale. RG run constrains λ_s beyond 0.5.
- Existing phenomenology for high mass DM tells us that the degeneracy between the scalar and pseudo-scalar should be very small $(\lambda_5 \ll 1)$. Also beneficial for BAU.
- Within range of direct detection experiments XENONnT, LZ, DARWIN, PandaX-3T.

Dark Matter



$\lambda_4 = \lambda_5$ in the analysis

Neutrino Masses

$$(M_\nu)_{ij} = \sum_k \frac{Y_{ik}Y_{jk}M_k}{32\pi^2}\left(\frac{m_{H^0}^2}{m_{H^0}^2 - M_k^2}\ln\frac{m_{H^0}^2}{M_k^2} - \frac{m_{A^0}^2}{m_{A^0}^2 - M_k^2}\ln\frac{m_{A^0}^2}{M_k^2}\right)$$

The Casas-Ibarra parameterization:

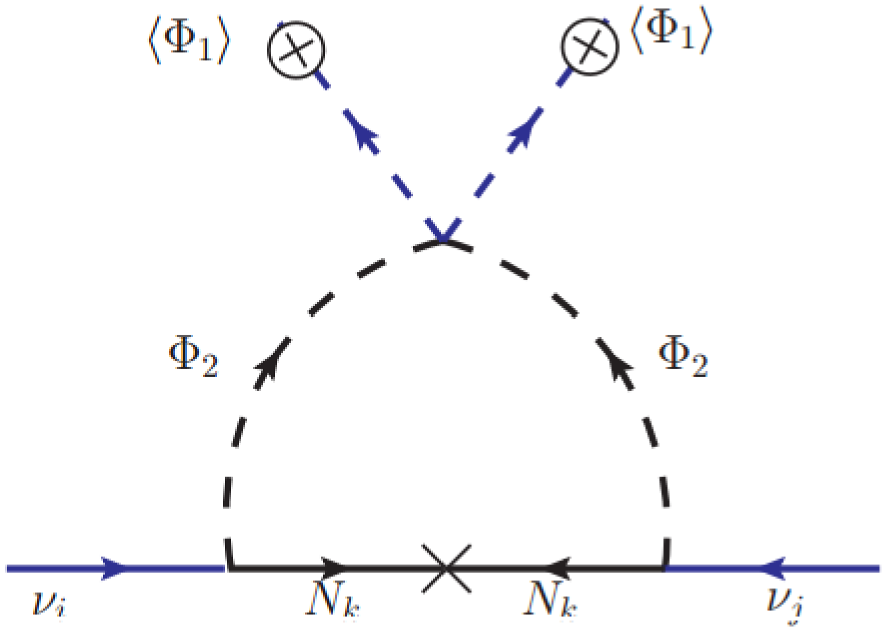
$$\widetilde{M}_i = \frac{2\pi^2}{\lambda_5}\zeta_i\frac{2M_i}{v^2},$$

$$\text{and} \quad \zeta_i = \left(\frac{M_i^2}{8(m_{H^0}^2 - m_{A^0}^2)}\left[L_i(m_{H^0}^2) - L_i(m_{A^0}^2)\right]\right)^{-1}$$

$$M_\nu = Y\widetilde{M}^{-1}Y^T$$

$$D_\nu = U^\dagger M_\nu U^* = \mathrm{diag}(m_1, m_2, m_3)$$

$$Y = UD_\nu^{1/2}O\widetilde{M}^{1/2}$$



Baryon Asymmetry

- A lepton asymmetry is created by out-of-equilibrium CP asymmetric decay of the right handed neutrino.
- The leptonic asymmetry is converted to the baryon asymmetry of the universe by sphaleron processes at the electroweak phase transition.
- Usual leptogenesis and 2 RHN leptogenesis in scotogenic model need $M_N > 10^9$ GeV.
- 3 RHN leptogenesis in scotogenic model can reduce lower bound on mass to 10 TeV*.
- Successful production of observed baryon asymmetry with RHN masses in the 10 TeV range require lightest active neutrino around 10^{-11} eV.
- Simultaneous Boltzmann eq. for n_{N_1} and $n_{N_{B-L}}$ used to obtain B-L number density. Initial equilibrium distribution for RHN required to numerically solve the equation.

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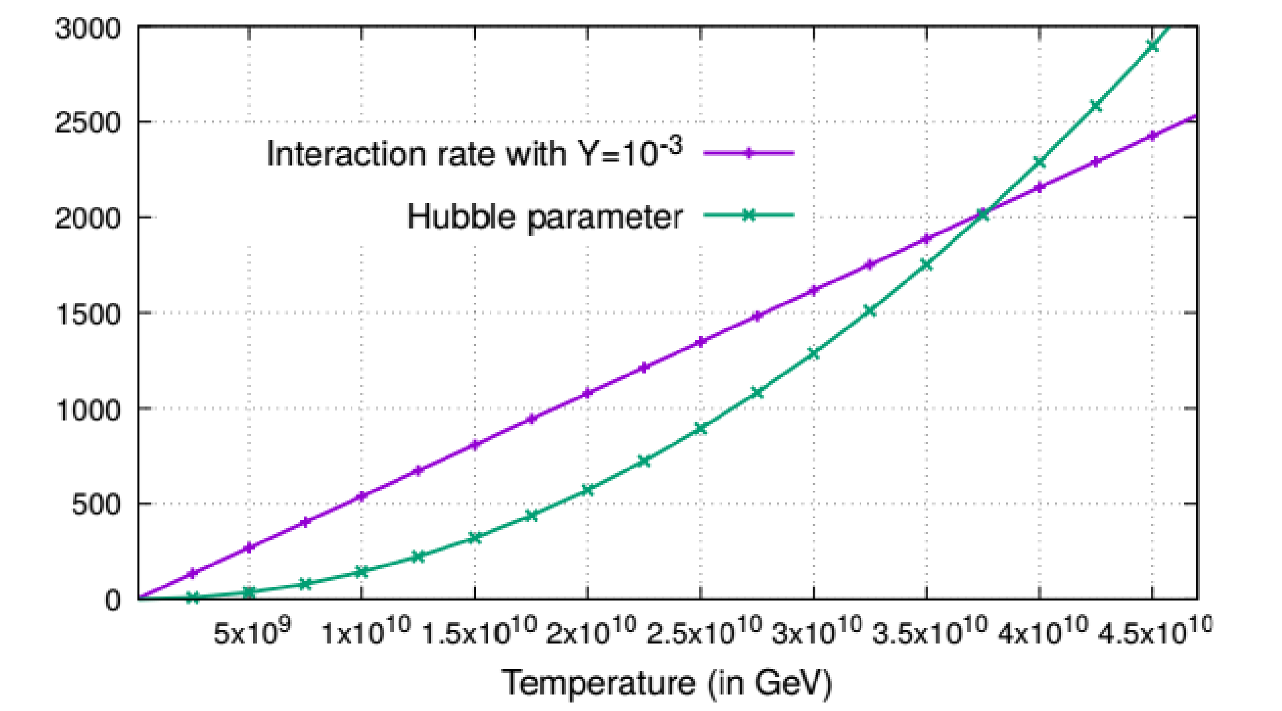
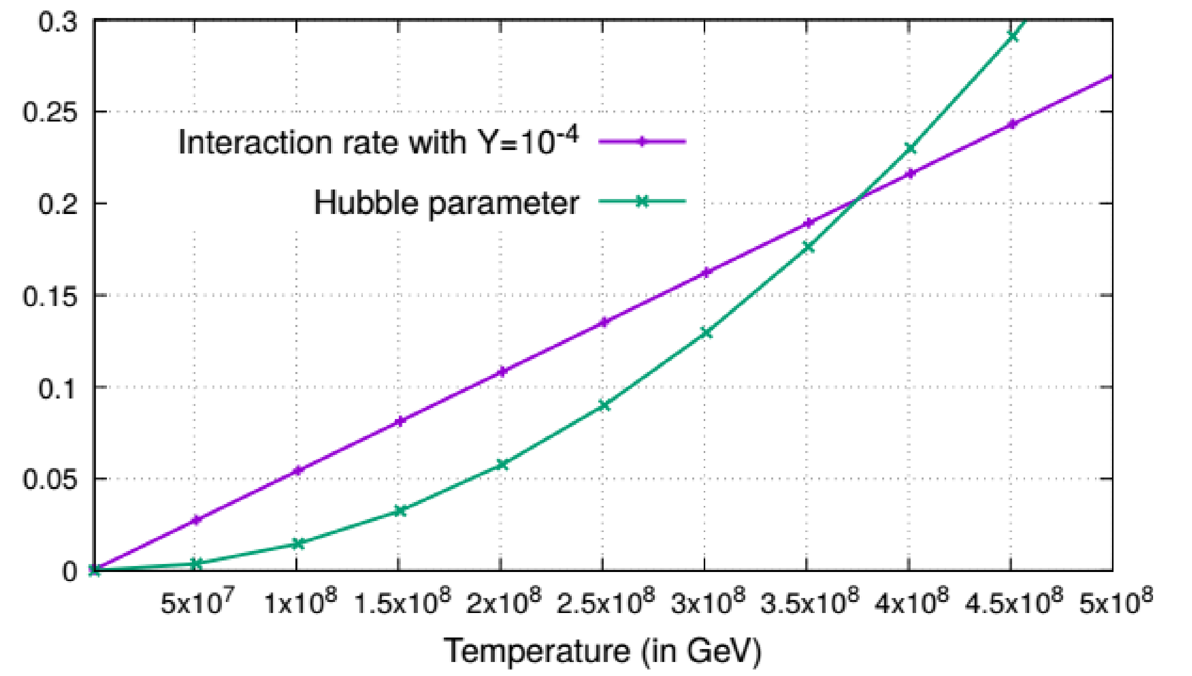
Baryon Asymmetry

Interactions that help create an initial equilibrium distribution for RHN

$$W/Z, H^{\pm}/H_0/A_0 \rightarrow N, \ell^{\pm}/\nu$$



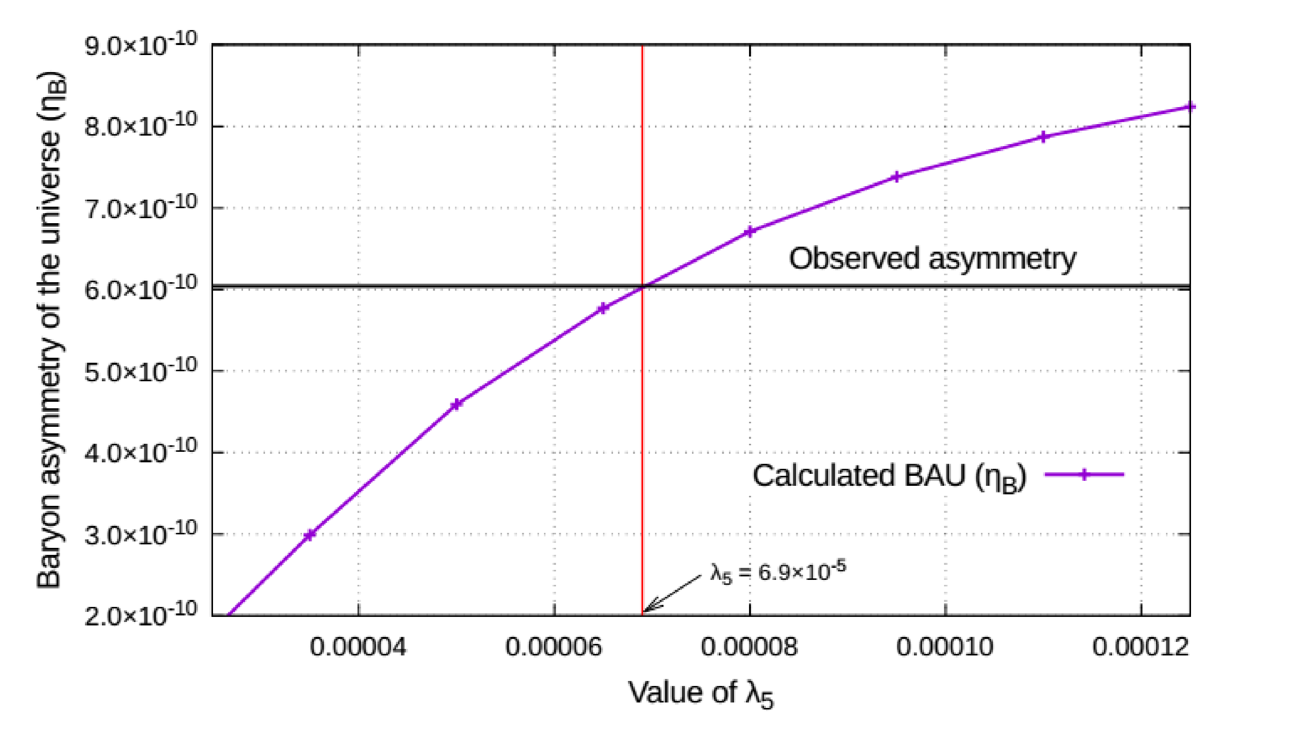


Baryon Asymmetry

- After solving the Boltzmann equation, we get an asymmetry in the lepton sector.
- Sphaleron processes during EW phase transition convert the lepton asymmetry to baryon asymmetry

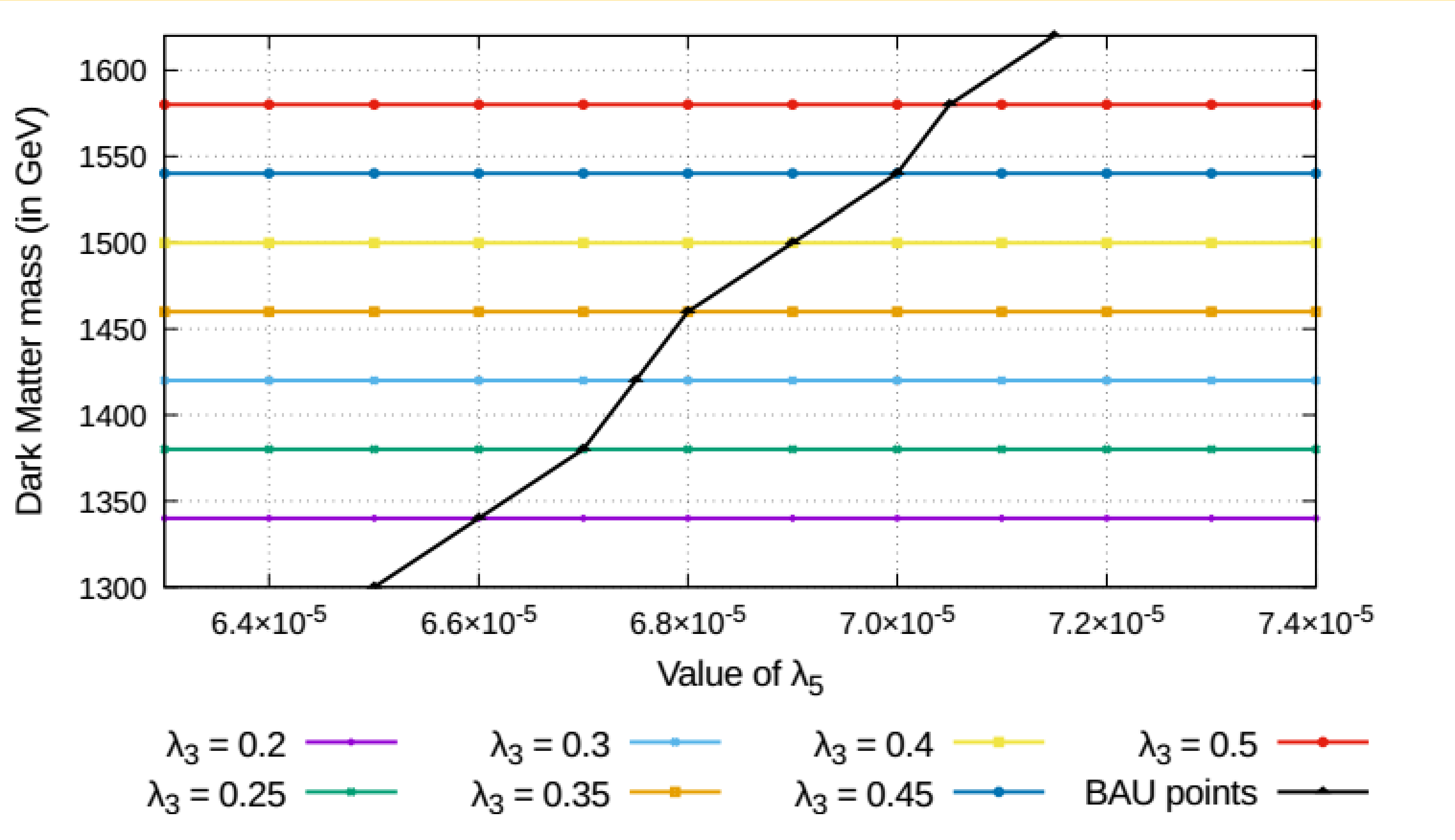
$$\eta_B = \frac{3}{4}\frac{g_*^0}{g_*} a_{\rm sph} n^f_{B-L} \simeq 9.2 \times 10^{-3}\, n^f_{B-L}$$

$a_{sph} = \frac{8}{23}$ is the sphaleron factor.



- Dark Matter mass has been fixed at 1.5 TeV in the figure. N_1 mass is 10 TeV.
- Requires lightest neutrino mass $O(10^{-11})$ eV.

Baryon Asymmetry



Baryon asymmetry and DM mass as functions of λ_5. The black line shows the BAU satisfying points.

Final Remarks:

- Made a successful unified model for inflation, dark matter, baryogenesis and neutrino masses.
- Used the inert doublet particles coupled non-minimally to gravity to achieve inflation. Found $n_s = 0.9678,\ r = 0.0029$. Very good agreement with Planck 2018.
- Reheating by production of relativistic fermions via parametric resonance production of gauge bosons. Require $\lambda_2 \gtrsim \frac{1}{60}$ and $\xi_2 \simeq 5.33 \times 10^4 \lambda_2^{1/2}$.
- Dark matter freeze-out around the EW symmetry breaking scale with $m_{DM} = O(1\ TeV), \lambda_s = \lambda_3 + \lambda_4 + \lambda_5 \lesssim 0.5$ satisfies Planck 2018 relic abundance. The DM direct detection cross-section is within range of near future experiments like XENONnT, LZ, DARWIN, PandaX-30T.
- Obtained baryon asymmetry matching with Planck 2018 for $\lambda_5 \approx 7 \times 10^{-5}$, with N_1 mass of 10 TeV and DM mass of 1.5 TeV.
- Requirement of lightest active neutrino mass $O(10^{-11})$ eV.
- Other neutrino masses obey neutrino oscillation data.

Inflation - backups

- Inflation along Φ_2 if $\frac{\lambda_2}{\xi_2^2} \ll \frac{\lambda_1}{\xi_1^2}$. Ensured by taking ξ_1 of the same order as λ_1 while λ_2, ξ_2 relation will be obtained using power spectrum data.
- $n_s = 1 - 6\epsilon + 2\eta = 0.9678$

$$\epsilon = \frac{1}{2} M_{Pl}^2 \left(\frac{1}{V_e} \frac{dV_e}{dA} \right)^2 = \frac{4}{3} \left[-1 + \exp\left(\sqrt{\frac{2}{3}} \frac{A}{M_{Pl}} \right) \right]^{-2}$$

$$\eta = M_{Pl}^2 \frac{1}{V_e} \frac{d^2 V_e}{dA^2} = \frac{4}{3} \frac{\left[2 - \exp\left(\sqrt{\frac{2}{3}} \frac{A}{M_{Pl}} \right) \right]}{\left[-1 + \exp\left(\sqrt{\frac{2}{3}} \frac{A}{M_{Pl}} \right) \right]^2} .$$

$$\frac{1}{2\Omega^2} \left((\partial_\mu \chi)^2 + (\partial_\mu h)^2 \right) + \left[\frac{1}{2} + \frac{1}{12\xi_2 F(A)} \right] (\partial_\mu A)^2 + \left[\frac{F(A)}{2\xi_2 (1 + B^2/M_{Pl}^2)^2} \right] (\partial_\mu B)^2 + \left[\frac{F(A)\, B^2}{2\xi_2 (1 + B^2/M_{Pl}^2)} \right] (\partial_\mu \theta)^2$$

$$F(A) = 1 - \exp\left(-\sqrt{\frac{2}{3}} \frac{A}{M} \right)$$

Dark Matter - backups

$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = -\langle\sigma v\rangle \left[n_{\rm DM}^2 - (n_{\rm DM}^{\rm eq})^2\right]$$

$$\langle\sigma v\rangle = \frac{1}{8m_{\rm DM}^4 T K_2^2\left(\frac{m_{\rm DM}}{T}\right)} \int_{4m_{\rm DM}^2}^{\infty} \sigma(s - 4m_{\rm DM}^2)\sqrt{s}\, K_1\left(\frac{\sqrt{s}}{T}\right) ds$$

$$x_f \equiv \frac{m_{\rm DM}}{T_f} = \ln\left(0.038 \frac{g}{g_*^{1/2}} M_{\rm Pl} m_{\rm DM} \langle\sigma v\rangle_f\right)$$

$$\Omega_{\rm DM} h^2 = \left(1.07 \times 10^9 \ {\rm GeV}^{-1}\right) \frac{x_f g_*^{1/2}}{g_{*s} M_{\rm Pl} \langle\sigma v\rangle_f}$$

Baryon Asymmetry - backups

$$r_{j1} = \left(\frac{M_j}{M_1}\right)^2, \ \eta_1 \equiv \left(\frac{m_{\rm DM}}{M_1}\right)^2$$

$$\Gamma_{N_1} \ = \ \frac{M_1}{8\pi}(Y^\dagger Y)_{11}\left[1 - \left(\frac{m_{\rm DM}}{M_1}\right)^2\right]^2 \ \equiv \ \frac{M_1}{8\pi}(Y^\dagger Y)_{11}\,(1-\eta_1)^2$$

$$K_{N_1} \ = \ \frac{\Gamma_{N_1}}{H(z=1)}$$

Baryon Asymmetry - backups

$$\varepsilon_1 = \frac{1}{8\pi(Y^\dagger Y)_{11}} \sum_{j\neq 1} \mathrm{Im}\left[(Y^\dagger Y)^2_{1j}\right] \left[f(r_{j1},\eta_1) - \frac{\sqrt{r_{j1}}}{r_{j1}-1}(1-\eta_1)^2\right]$$

$$\text{where} \quad f(r_{j1},\eta_1) = \sqrt{r_{j1}}\left[1 + \frac{1-2\eta_1+r_{j1}}{(1-\eta_1)^2}\ln\left(\frac{r_{j1}-\eta_1^2}{1-2\eta_1+r_{j1}}\right)\right],$$

$$\frac{dn_{N_1}}{dz} = -D_1(n_{N_1} - n_{N_1}^{\rm eq}),$$

$$\frac{dn_{B-L}}{dz} = -\varepsilon_1 D_1(n_{N_1} - n_{N_1}^{\rm eq}) - W_1 n_{B-L}$$

$$W_{\rm ID} = \frac{1}{4} K_{N_1} z^3 K_1(z)$$

$$W_{\Delta L=2} \simeq \frac{18\sqrt{10}\,M_{\rm Pl}}{\pi^4 g_\ell \sqrt{g_*} z^2 v^4}\left(\frac{2\pi^2}{\lambda_5}\right)^2 M_1 \bar{m}_\zeta^2$$

$$W_1 = W_{ID} + W_{\Delta L=2}$$