Creating matter-antimatter asymmetry with non-standard cosmology

Based on DM, Debasish Borah; JCAP 04 (2020) 032; arXiv:1912.09726

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Outline

1. Introduction: Matter-antimatter asymmetry
   Dark Matter
2. Standard calculation of asymmetry
3. Non-standard cosmology
4. Results and conclusions

Matter-antimatter (baryon) asymmetry

- The observed BAU is often quoted in terms of baryon to photon ratio

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.04 \pm 0.08 \times 10^{-10}$$

(**Planck 2018**)

- The three basic ingredients necessary to generate a net baryon asymmetry from an initially baryon symmetric Universe (Sakharov 1967):

1. **Baryon number (B) violation** $X \longrightarrow Y + B$
2. **C and CP violation** $\Gamma(X \longrightarrow Y + B) \neq \Gamma(\bar{X} \longrightarrow \bar{Y} + \bar{B})$
3. **Departure from thermal equilibrium.**

Baryogenesis from Leptogenesis

- Out of equilibrium decays of right handed neutrinos (Fukugita and Yanagida 1986)

$$Y_{ij}\bar{L_i}\tilde{H}N_j + \frac{1}{2}M_{ij}N_iN_j$$

- CP violation due to phases in Yukawa couplings Y, leads to a lepton asymmetry.

$$\epsilon_{N_k} = \frac{\Gamma(N_k \longrightarrow lH) - \Gamma(N_k \longrightarrow \bar{l}H^*)}{\Gamma(N_k \longrightarrow lH) + \Gamma(N_k \longrightarrow \bar{l}H^*)}$$

- At least two N are required to generate an asymmetry due to the presence of interference between tree and one loop diagrams namely, vertex diagram (Fukugita and Yanagida'86) and self energy diagram (Liu and Segre'93).

- The lepton asymmetry gets converted into baryon asymmetry through electroweak sphalerons (Khlebnikov and Shaposhnikov'88)

Dark matter

- Evidence of non-luminous matter in galaxy cluster by **Fritz Zwicky (1933)**.
- In **1970 V.C. Rubin** provided strong evidence for existence of dark matter from galaxy rotation curve observation.
- The power spectrum of cosmic microwave background radiation (CMBR) also provide powerful evidence in support of existence of dark matter.

$$\Omega_{DM}h^2 = 0.12 \pm 0.001 \qquad \textbf{Planck 2018}$$

- Dark matter plays a crucial role in structure formation.

However, the standard model of particle physics lacks a suitable candidate for dark matter!

Particle dark matter: **WIMP** miracle

The abundance of DM which was in thermal equilibrium in the early universe can be calculated by solving the Boltzmann equation.

$$\frac{dY}{dx} = -\frac{\lambda}{z^2}(Y^2 - Y_{eq}^2) \tag{1}$$

Where, $Y = \frac{n_{DM}}{T}$, $z = \frac{m_{DM}}{T}$, $\lambda = \frac{m_{DM}^3 \langle \sigma v \rangle}{H(m_{DM})}$ and $H(T) = \sqrt{\frac{8\pi^3 g*}{90}} \frac{T^2}{M_{Pl}}$.

Approximate analytical solution gives

$$\Omega h^2 \approx \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle} \tag{2}$$

To satisfy the correct relic, interaction of the same strength as weak interaction is required. No overwhelming evidence from dark matter searches in experiments.

Alternate possibilities: FIMP DM/non-standard cosmology?

Non-standard cosmology: motivation

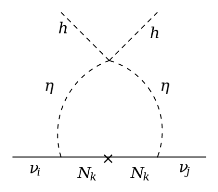
- Generation of DM relic and baryon asymmetry usually occurs at very high scale when the Universe was radiation dominated (in standard cosmology).
- There is no experimental evidence to suggest that the Universe was radiation dominated prior to the epoch of $T_{BBN} \sim 1s$.
- In terms of temperature $T_{BBN} \sim \mathcal{O}(1MeV)$.
- We expect dark-matter results to get changed significantly in different cosmological history [**Stefano Profumo et al (2018), Nicolas Bernal et al(2019), Paola Arias et al (2019)**].
- Possibility of lowering leptogenesis scale with non-standard cosmology?

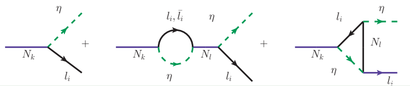
Standard leptogensis in Scotogenic model

Ernest Ma (2006)

T. Hugle et al(2018), D. Borah et al (2019)

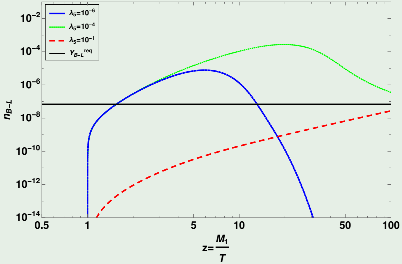
$N_i \to -N_i, \eta \to -\eta, SM \to SM$

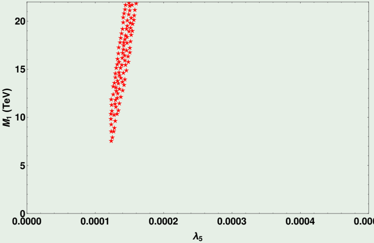




$$\frac{dN_1}{dt} = -D_1(n_{N_1} - n_{N_1}^{eq})$$

$$\frac{dn_{B-L}}{dt} = -\epsilon_1 D_1(n_{N_1} - n_{N_1}^{eq}) - W^{Tot} n_{B-L}$$





Leptogenesis at a scale of 10 TeV

Early matter domination (EMD)

- Prior to BBN era, Universe was dominated by a scalar field.
- In priciple this field can decay to both dark sector and visible sector particles.
- This cosmological model can be characterised by two parameters, T_{end} and
$k = \dfrac{\rho_\phi(T = M_1)}{\rho_{rad}(T = M_1)}$
- The T_{end} can be constrained to the decay width of ϕ in a model independent way, $T_{end}^4 = \dfrac{90}{\pi^2 g_*(T_{end})} M_{Pl}^2 \Gamma_\Phi^2$.
- BBN constraints , $T_{end} \gtrsim 4$ MeV
- The Hubble parameter can be written as $H(T) = \sqrt{\dfrac{\rho_\phi(T) + \rho_{rad}(T)}{3M_{Pl}^2}}$,

$$H(z) = \begin{cases} \frac{\pi}{3}\sqrt{\frac{g_*}{10}}\frac{M_1^2}{M_{\rm Pl}}\frac{1}{z^2}, & \text{if } z \le z_{\rm eq} \\ \frac{\pi}{3}\sqrt{\frac{g_*}{10}}\frac{M_1^2}{M_{\rm Pl}}\sqrt{\frac{k}{z^{3(1+\omega)}}}, & \text{if } z_{\rm eq} \le z \le z_{\rm end} \\ \frac{\pi}{3}\sqrt{\frac{g_*}{10}}\frac{M_1^2}{M_{\rm Pl}}\frac{1}{z^2}, & \text{if } z \ge z_{\rm end}. \end{cases}$$

- This new scalar field, SM radiation (entropy density), DM density and Matter-Antimatter asymmetry evolve according to the following coupled Boltzmann equations:

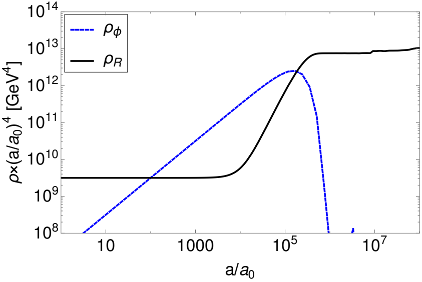
$$\frac{d\rho_\phi}{dt} + 3(1+\omega)H\rho_\phi = -\Gamma_\phi \rho_\phi, \tag{3}$$

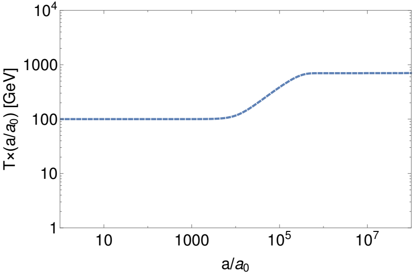
$$\frac{ds}{dt} + 3Hs = \frac{\Gamma_\phi \rho_\phi}{T}\left(1 - b\frac{E}{m_\phi}\right) + 2\frac{E}{T}\langle \sigma v_{\rm rel}\rangle \left(n^2 - n_{\rm eq}^2\right), \tag{4}$$

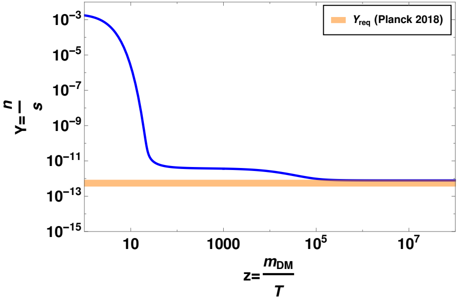
$$\frac{dn}{dt} + 3Hn = \frac{b}{m_\phi}\Gamma_\phi \rho_\phi - \langle \sigma v_{\rm rel}\rangle (n^2 - n_{\rm eq}^2), \tag{5}$$

$$\frac{dn_{B-L}}{dz} + \frac{n_{B-L}}{s}\frac{ds}{dz} + \frac{3n_{B-L}}{z} = -\epsilon_1 D_1 (n_{N_1} - n_{N_1}^{\rm eq}) - W^{\rm Total} n_{B-L} \tag{6}$$

$$\frac{dn_{N_1}}{dz} + \frac{n_{N_1}}{s}\frac{ds}{dz} + \frac{3n_{N_1}}{z} = -D_1 (n_{N_1} - n_{N_1}^{\rm eq}). \tag{7}$$

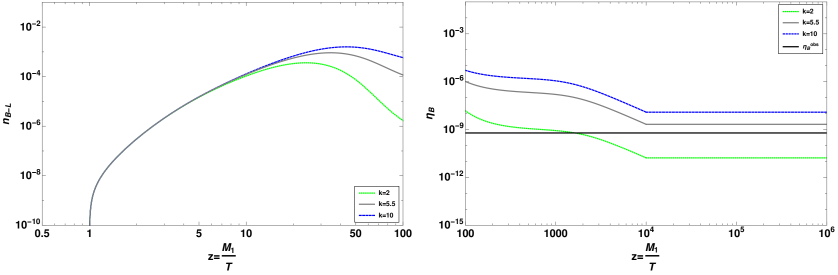






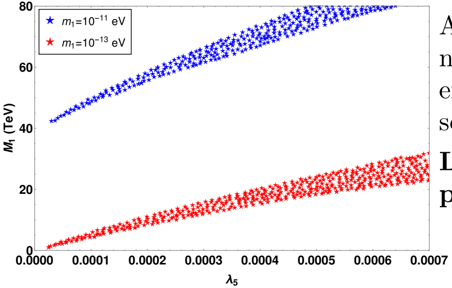
Freeze-out abundance of DM gets depleted at late epochs due to entropy injection from decays of ϕ into radiation. Even with weaker interaction, one may be able to generate the correct relic.

Leptogenesis with EMD



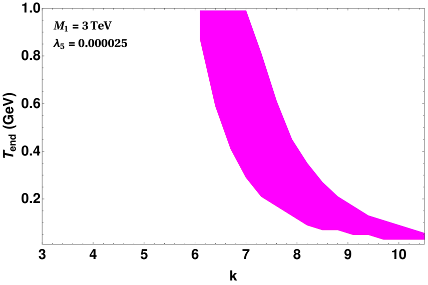
$T_{end} << T_{sphaleron} << T_{eq}$

For higher values of k more asymmetry is generated (Less washout effects). Entropy dilution and washouts decreases the asymmetry after ϕ decay.



A larger value of the lightest active neutrino mass makes the washout effects stronger pushing the leptogensis scale up.

Leptogenesis below 10 TeV is possible.



A larger value of T_{end} requires a smaller value of k, as the entropy dilution effects are more dominant for earlier epochs.

Fast expanding Universe

- Prior to the BBN era, Universe was dominated by a scalar field whose energy density red-shifts faster than radiation

$$\rho_\phi \propto a^{-(4+n)}$$

$$\rho(T) = \rho_\phi(T) + \rho_{rad}(T) = \rho_{rad}(T)\left[1 + \frac{g_*(T_r)}{g_*(T)}\left(\frac{g_{*s}(T)}{g_{*s}(T_r)}\right)^{(4+n)/3}\left(\frac{T}{T_r}\right)^n\right]$$

$$H(T) \simeq \frac{\pi g_*^{1/2}(T)T^2}{3\sqrt{10}M_{\rm Pl}}\left[1 + \left(\frac{g_*(T)}{g_*(T_{\rm r})}\right)^{(1+n)/3}\left(\frac{T}{T_{\rm r}}\right)^n\right]^{1/2}$$

- The energy density drops below that of radiation before the BBN epoch.
- The field behaves like a spectator only, affecting total energy density and hence the Hubble expansion rate.

Boltzmann equation for DM

$$\frac{dY}{dz} = -A\frac{\langle \sigma v_{\rm rel}\rangle}{z^3 L\left[n,z,z_r\right]}\left[Y^2 - Y_{\rm eq}^2\right], A = \frac{s(z=1)}{H_{\rm rad}(z=1)} = \frac{2\sqrt{2}\pi}{3\sqrt{5}} g_*^{1/2} m_{\rm DM} M_{\rm Pl}$$

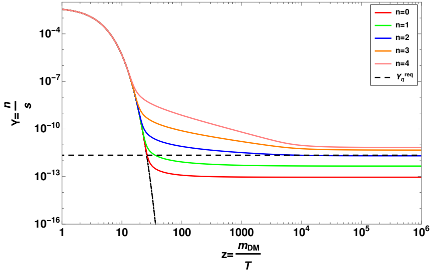
$$L\left[n,z,z_r\right] = (n+4)\left[\frac{1}{z^4} + \left(\frac{g_*(z)}{g_*(z_r)}\right)^{(1+n)/3}\frac{z_r^n}{z^{n+4}}\right]^{3/2}\left[\frac{4}{z^5} + (4+n)\left(\frac{g_*(z)}{g_*(z_r)}\right)^{(1+n)/3}\frac{z_r^n}{z^{n+5}}\right]^{-1}$$

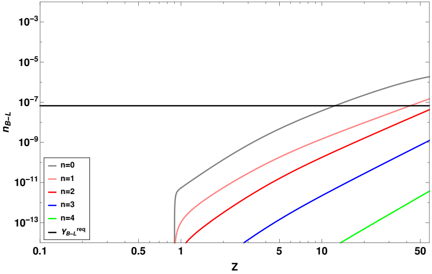
Boltzmann equations for Leptogensis

$$\frac{dn_{N_1}}{dz} = D_1^{'}(n_{N_1} - n_{N_1}^{\rm eq}), \quad \frac{dn_{B-L}}{dz} = -\epsilon_1 D_1^{'}(n_{N_1} - n_{N_1^{eq}}) - W_{\rm Total}^{'} n_{B-L}$$

$$D_1^{'} = K_1 \frac{\kappa_1(z)}{\kappa_2(z)}\frac{1}{L\left[n,z,z_r\right]}$$

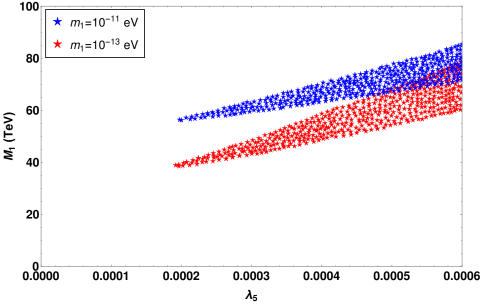
$T_r(z_r)$ **corresponds to the epoch at which radiation overcomes** ϕ

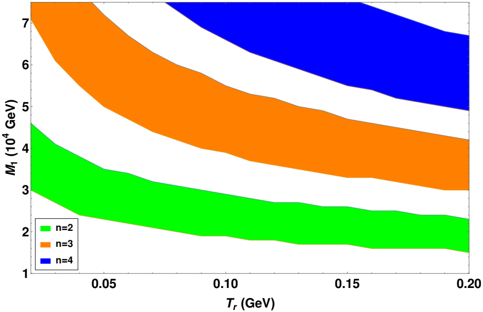




DM annihilation redshifts slower than Hubble and hence can keep annihilating even after freeze-out, further depleting the abundance!
An under-abundant DM scenario in standard scenario can be revived in FEU.

The generation of asymmetry slowed down because of faster expansion.





The scale of leptogenesis is pushed up slightly compared to the standard scenario.

Since required asymmetry must be created before sphaleron temperature it puts strong constraints on the FEU scenario.

For larger values n, we require large M_1 to satisfy the correct baryon asymmetry.

Large T_r pushes the Leptogenesis more towards usual radiation like.

Conclusions

- Non-standard cosmology can significantly affect high scale phenomena before the epoch of BBN like generation of baryon asymmetry, dark matter.
- The scale of leptogenesis can be either lower or higher compared to the standard scenario, depending upon the details of non-standard history.
- Non-standard cosmological phase can arise in several inflationary models after the end of slow roll (e.g., Quintessential inflation, Starobinsky inflation, see 2006.02442, 2004.13706)
- Non-standard cosmology can have interesting implications for gravitational waves generated primordially or at cosmic phase transitions (see 1905.10410, 2007.08537).
- Non-standard cosmology has also received attention in the light of Hubble tension (discrepancies between low and high redshift measurements, see 1908.03663).


Thank you