Leptogenesis in non-standard cosmologies

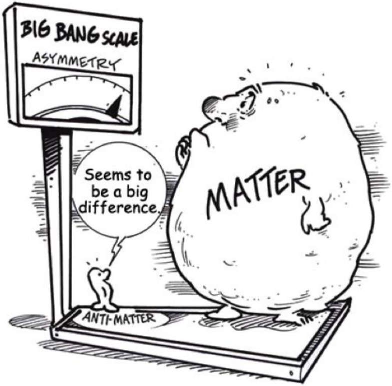
Mehran Dehpour

Department of Physics, Shahid Beheshti University
PO Box 19839-63113, Tehran, Iran

Oral Defence in Partial Fulfillment of
Master of Science in Particle Physics
January 9, 2024

Outline

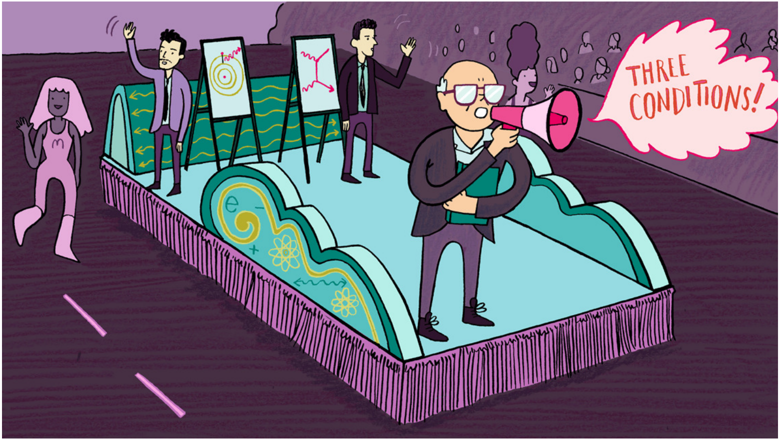
Baryon Asymmetry of Universe



$$Y_B^{\rm obs} \equiv \left.\frac{n_B - \overline{n}_B}{s}\right|_0 = (8.73 \pm 0.35) \times 10^{-11}$$

V. Simha et al., JCAP 06 (2008) 016

Sakharov's conditions



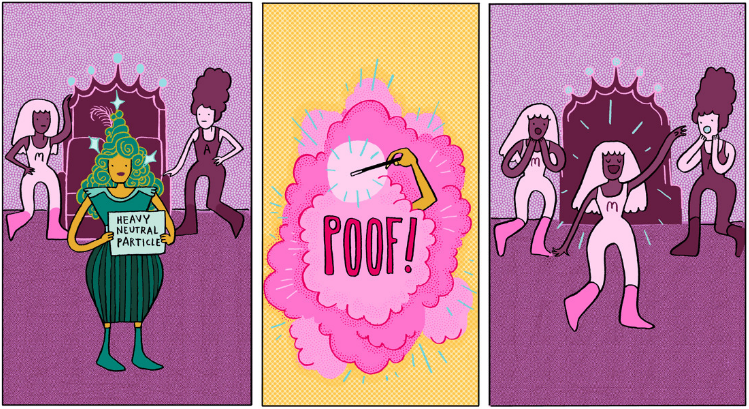
1. violation of baryon number conservation,
2. C and CP violation,
3. and the presence of out-of-equilibrium dynamics.

Searching Beyond Standard Model

The Standard Model has all the basic ingredients, but cannot produce the desired baryon asymmetry!

M.B. Gavela et al., Nucl.Phys.B 430 (1994) 345-381, 345-426

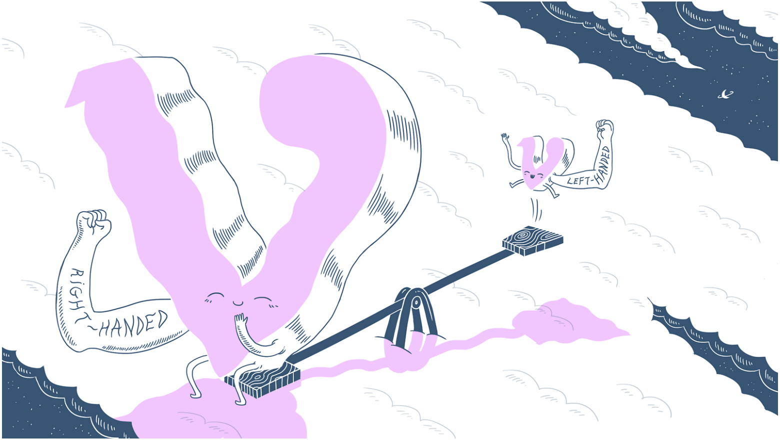
Thermal leptogenesis



Through extension of the standard model by adding at least two right-handed neutrinos.

M.A. Luty, Phys.Rev.D 45 (1992) 455-465

Right-Handed Neutrinos



The seesaw mechanism introduces these new particles.

P. Minkowski, Nucl.Phys.B 67 (1977) 421-428

Free parameters of theory

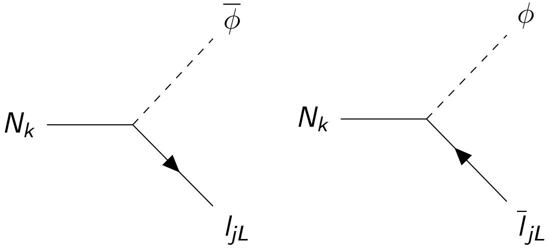
M_1/GeV	M_3/GeV	M_3/GeV
10^{11}	$10^{11.6}$	10^{12}

In the seesaw type-1 framework, Yukawa coupling parameterized as Casas-Ibarra formalism

$$y = -iU\sqrt{D_m}R^T(z_1, z_2, z_3)\sqrt{D_M}\frac{\sqrt{2}}{v}$$

m/GeV	$x_1/^\circ$	$y_1/^\circ$	$x_2/^\circ$	$y_2/^\circ$	$x_3/^\circ$	$y_3/^\circ$
10^{-11}	12	51.4	33	11.4	180	11

Right-Handed Neutrino decay



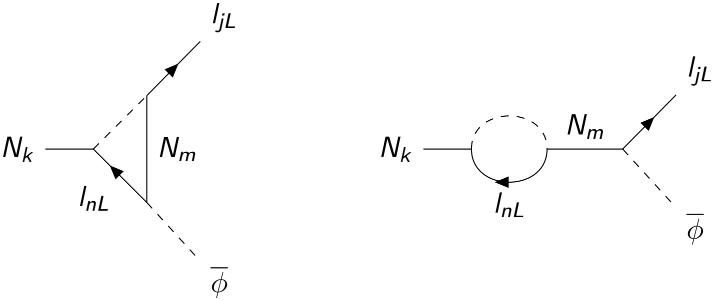
By considering $k = 1$ and summation on j, one can calculate the tree-level decay rates as

$$\Gamma_1 = \overline{\Gamma}_1 = \frac{M_1}{16\pi}(yy^\dagger)_{11},$$

where M_1 is mass of N_1, and y is Yukawa coupling matrix.

CP violation

$$\epsilon_1 \equiv \frac{\Gamma_1 - \overline{\Gamma}_1}{\Gamma_1 + \overline{\Gamma}_1}$$



$$\epsilon_1 = \sum_{k \neq 1} \frac{1}{8\pi} \frac{\Im \left(yy^\dagger\right)^2_{1k}}{(yy^\dagger)_{11}} \left[f\left(\frac{M_k^2}{M_1^2}\right) + \frac{M_1 M_k}{M_1^2 - M_k^2} \right]$$

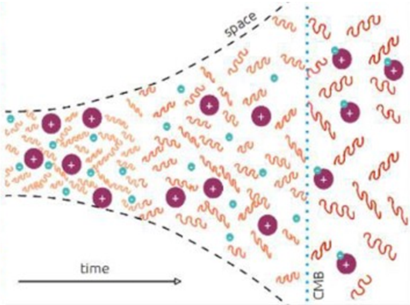
Dynamics of the $Y_{B-L} = (\overline{n}_l - n_l)/s^q$ and $Y_{N_1} \equiv n_{N_1}/s^q$

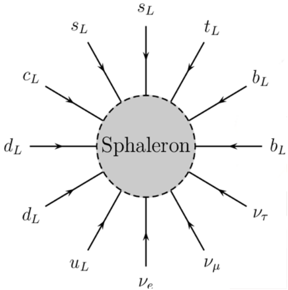
$$\frac{dY_{N_1}}{dz} = -D_1 \left(Y_{N_1} - Y_{N_1}^{\mathrm{eq}} \right)$$
$$\frac{dY_{B-L}}{dz} = -\epsilon_1 D_1 \left(Y_{N_1} - Y_{N_1}^{\mathrm{eq}} \right) - W_1 Y_{B-L}$$

$$D_1 \equiv \frac{2\langle \Gamma_1 \rangle}{Hz}, \quad W_1 \equiv \frac{1}{2} \frac{Y_{N_1}^{\mathrm{eq}}}{Y_l^{\mathrm{eq}}} D_1$$

$$Y_{N_1}^{\mathrm{eq}} = \frac{45}{4\pi^4} \frac{g_{N_1}}{g_\star} z^2 K_2(z), \quad Y_l^{\mathrm{eq}} \simeq \frac{45}{4\pi^4} \frac{g_l}{g_\star} \frac{3}{2} \zeta(3)$$

Relation between Y_{B-L} and the baryon asymmetry





$$Y_B = \frac{28}{79} Y_{B-L}.$$

Davidson-Ibarra bound

$$M_1 > 10^9 \text{ GeV}$$

S. Davidson et al., Phys.Lett.B 535 (2002) 25-32

Thermal leptogenesis in nonextensive cosmology

Modified distribution function

The generalized distribution function is parameterized by a real number $q \in [0, 2]$ known as the Tsallis parameter

$$f^q = \left[\frac{1}{e_q^{-\left(\frac{E-\mu}{T}\right)}} + \xi \right]^{-1}$$

$$e_q^x \equiv [1 + (q-1)\,x]^{\frac{1}{1-q}}$$

C. Tsallis, J.Statist.Phys. 52 (1988) 479-487

Modified Hubble expansion rate

$$H^q = \frac{1.66}{M_{\mathrm{Pl}}} (g_\star^q)^{1/2} T^2$$

$$g_\star^q = \left[\frac{15}{\pi^4} \int_0^\infty d\gamma \gamma^3 \left(\frac{1}{e_q^{-\gamma}} - 1 \right)^{-q} \right] \sum_b g_b$$
$$+ \left[\frac{15}{\pi^4} \int_0^\infty d\gamma \gamma^3 \left(\frac{1}{e_q^{-\gamma}} + 1 \right)^{-q} \right] \sum_f g_f$$

M.E. Pessah et al., Physica A 297 (2001) 164-200

Modified entropy density

$$s^q = \frac{2\pi^2}{45} g^q_{\star,s} T^3$$

$$\begin{aligned} g^q_{\star,s} = & \left[\frac{45}{4\pi^4} \int_1^\infty d\gamma \left(\frac{4}{3}\gamma^3 + \frac{\sqrt{\gamma^2 - 1}}{3} \right) \left(\frac{1}{e_q^{-\gamma}} - 1 \right)^{-q} \right] \sum_b g_b \\ & + \left[\frac{45}{4\pi^4} \int_1^\infty d\gamma \left(\frac{4}{3}\gamma^3 + \frac{\sqrt{\gamma^2 - 1}}{3} \right) \left(\frac{1}{e_q^{-\gamma}} + 1 \right)^{-q} \right] \sum_f g_f \end{aligned}$$

M.E. Pessah et al., Physica A 297 (2001) 164-200

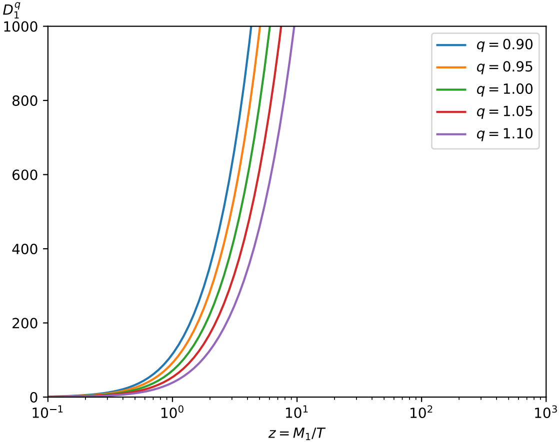
Modified quilibrium amount of particles

$$n_{\chi}^{\mathrm{eq},q} = g_{\chi} \int \frac{d^3 p}{(2\pi)^3} f_{\chi}^{\mathrm{eq},q},$$

$$Y_{\chi}^{\mathrm{eq},q} = \frac{45}{4\pi^4} \frac{g_{\chi}}{g_{\star,s}^{q}} \frac{z^3}{M_1^3} \int_0^{\infty} dp\ p^2 \left[\frac{1}{e_q^{-\left(\frac{E_{\chi} z}{M_1}\right)}} + \xi_{\chi} \right]^{-1}.$$

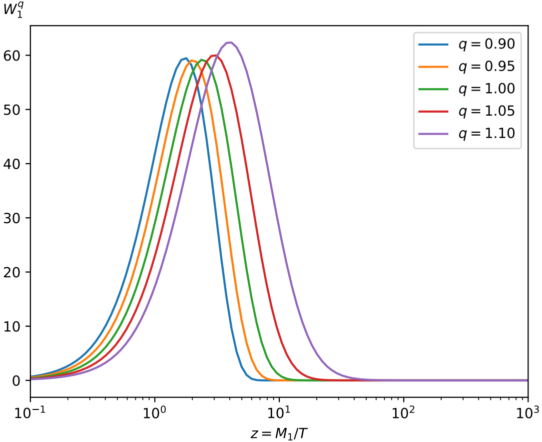
Modified decay parameter

$$D_1^q \equiv \frac{2\langle\Gamma_1\rangle}{H^q z}$$

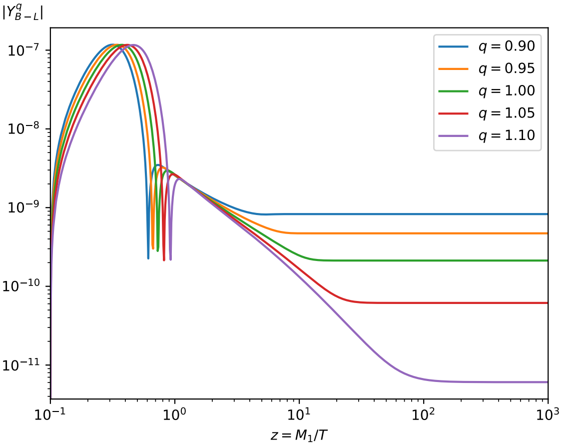


Modified washout parameter

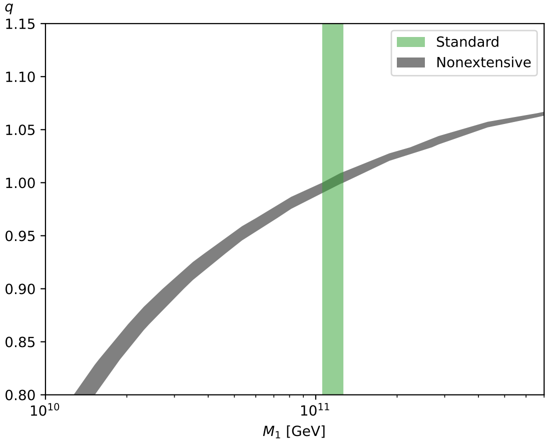
$$W_1^q \equiv \frac{1}{2}\frac{Y_{N_1}^{\mathrm{eq},q}}{Y_l^{\mathrm{eq},q}} D_1^q,$$



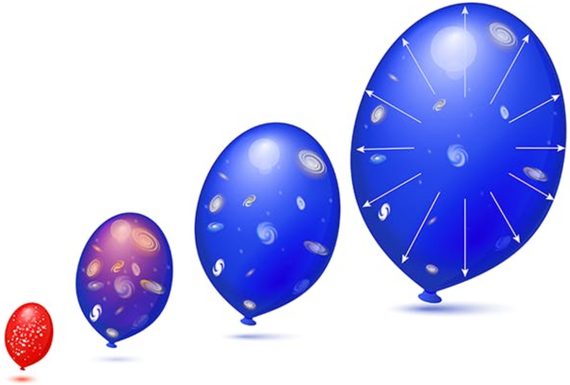
Numerical results I



Numerical results II



Thermal leptogenesis in anisotropic cosmology



Bianchi type-I metric and Friedmann equation

$$ds^2 = -dt^2 + a_1^2(t)dx^2 + a_2^2(t)dy^2 + a_3^2(t)dz^2$$

$$H^2 = \frac{8\pi G}{3}\epsilon_r + \frac{1}{3}\sigma^2$$

$$a \equiv (a_1 a_2 a_3)^{1/3}\,, \quad H \equiv \dot{a}/a = \frac{1}{3}(H_1 + H_2 + H_3)$$

$$\sigma^2 \equiv \frac{1}{6}\left[(H_1 - H_2)^2 + (H_2 - H_3)^2 + (H_3 - H_1)^2\right]$$

E. Russell et al., Mon.Not.Roy.Astron.Soc. 442 (2014) 3

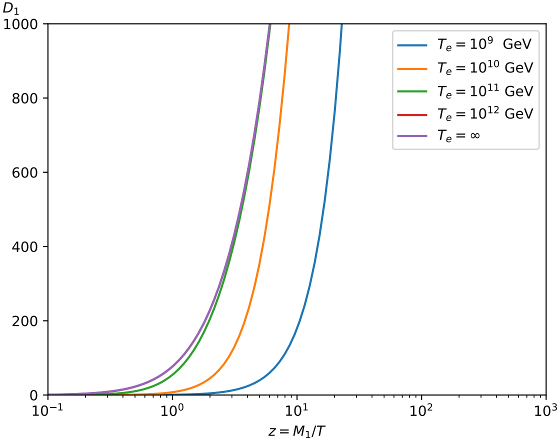
Modified Hubble expansion rate

$$H = \frac{1.66}{M_{\mathrm{Pl}}} (g_\star)^{1/2} T^2 \sqrt{1 + \frac{g_\star}{g_\star^e} \frac{T^2}{T_e^2}},$$

M. Kamionkowski et al., Phys. Rev. D 42 (1990) 3310

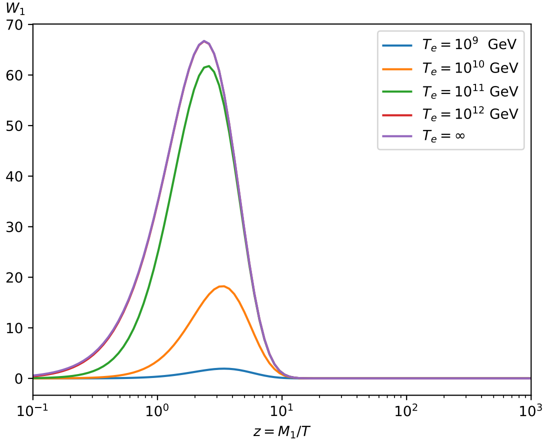
Modified decay parameter

$$D_1 \equiv \frac{2\langle\Gamma_1\rangle}{Hz}$$

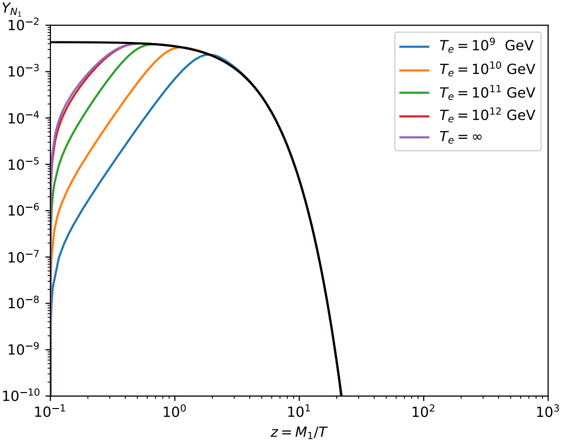


Modified washout parameter

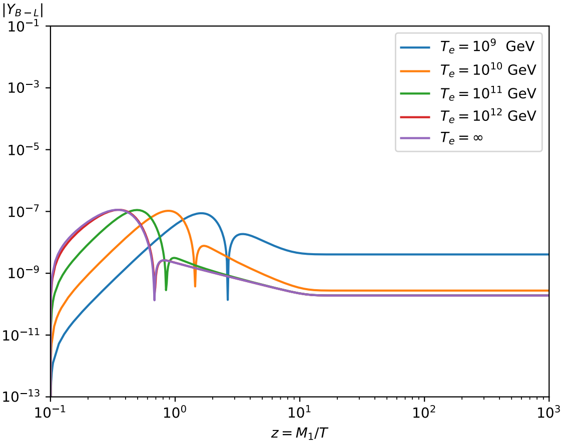
$$W_1 \equiv \frac{1}{2}\frac{Y_{N_1}^{\mathrm{eq}}}{Y_l^{\mathrm{eq}}} D_1,$$



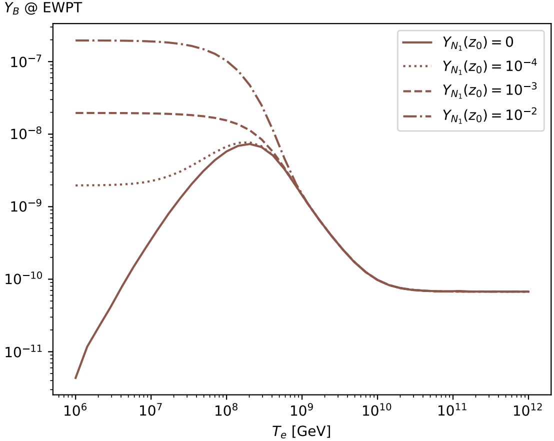
Numerical results I



Numerical results II



Numerical results III



Conclusion

In this study, by referring to nonstandard cosmologies, we attempt to reach low-scale leptogenesis through two methods:

1. Modifying standard statistical mechanics to nonextensive statistical mechanics
2. Neglecting the isotropic cosmological principle with Bianchi type-I metric in the early universe

Thanks for your attention!

Backup slides

PMNS matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

NuFIT 5.2 (2022)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.142 \to 0.155 \\ 0.233 \to 0.505 & 0.460 \to 0.693 & 0.630 \to 0.779 \\ 0.262 \to 0.525 & 0.473 \to 0.702 & 0.610 \to 0.762 \end{pmatrix}$$

$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.143 \to 0.155 \\ 0.244 \to 0.498 & 0.502 \to 0.693 & 0.632 \to 0.768 \\ 0.272 \to 0.517 & 0.473 \to 0.672 & 0.623 \to 0.761 \end{pmatrix}$$

R matrix

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{z_1} & s_{z_1} \\ 0 & -s_{z_1} & c_{z_1} \end{pmatrix} \begin{pmatrix} c_{z_2} & 0 & s_{z_2} \\ 0 & 1 & 0 \\ -s_{z_2} & 0 & c_{z_2} \end{pmatrix} \begin{pmatrix} c_{z_3} & s_{z_3} & 0 \\ -s_{z_3} & c_{z_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violation

$$\epsilon_1 = \sum_{k \neq 1} \frac{1}{8\pi} \frac{\Im \left(yy^\dagger\right)_{1k}^2}{\left(yy^\dagger\right)_{11}} \left[f\left(\frac{M_k^2}{M_1^2}\right) + \frac{M_1 M_k}{M_1^2 - M_k^2} \right]$$

$$f(x) = \sqrt{x}\left[1 - (1+x)\ln\left(\frac{1+x}{x}\right)\right]$$

Equilibrium conditions

$$\mu_{q_{iL}} + \mu_\phi - \mu_{u_{jR}} = 0$$
$$\mu_{q_{iL}} - \mu_\phi - \mu_{d_{jR}} = 0$$
$$\mu_{l_{iL}} - \mu_\phi - \mu_{e_{jR}} = 0$$

$$\sum_i \left(2\mu_{q_{iL}} - \mu_{u_{iR}} - \mu_{d_{iR}}\right) = 0$$
$$\sum_i \left(3\mu_{q_{iL}} + \mu_{l_{iL}}\right) = 0$$

$$\sum_i \left(\mu_{q_{iL}} + 2\mu_{u_{iR}} - \mu_{d_{iR}} - \mu_{l_{iL}} - \mu_{e_{iR}} + \frac{2}{3}\mu_\phi\right) = 0$$

Gravitino overproduction problem

The thermal production of RHN requires a T_{reh} larger than M_1. A typical value might be $T_{\mathrm{reh}} \sim 10 M_1$. So according to Davidson-Ibarra bound required T_{reh} is

$$T_{\mathrm{reh}} > 10^{10}\ \mathrm{GeV}$$

While gravitino production upper bound on T_{reh} is

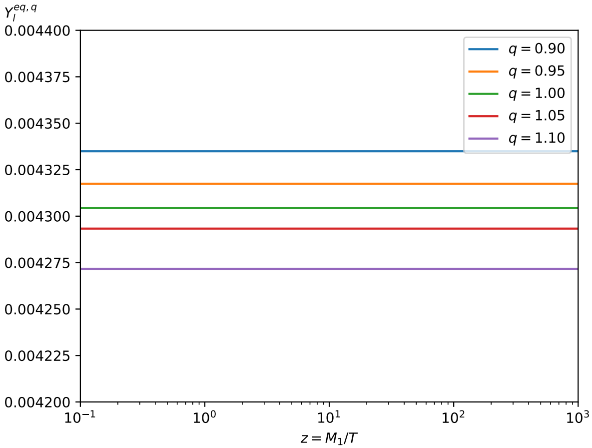
$$T_{\mathrm{reh}} < 10^{9} - 10^{12}\ \mathrm{GeV}$$

High and low energy cutoff

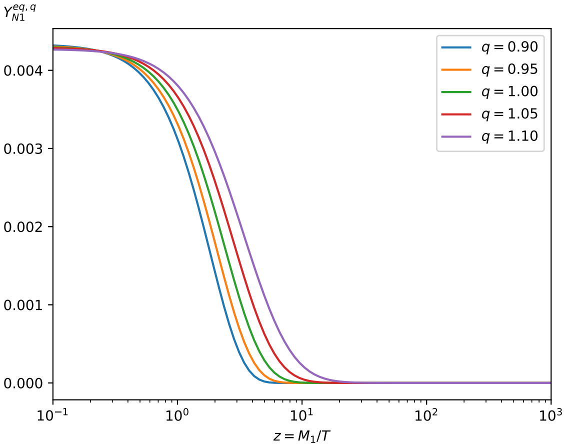
We would define $e_q^x \equiv 0$ in two cases of

1. $q < 1$ and $x < 1/(q-1)$: interpreted as a cutoff distribution function at high energies $E \geq \mu - T/(q-1)$,
2. $q > 1$ and $x \geq 1/(q-1)$: interpreted as a cutoff distribution function at low energies $E \leq \mu - T/(q-1)$.

Equilibrium amount of particles I



Equilibrium amount of particles II



Decay parameter

$$D_1^q \equiv \frac{2\langle\Gamma_1\rangle}{H^q z}$$

$$D_1^q = \frac{2}{H^q z} \frac{\int_0^\infty \frac{dp\ \ p^2}{E} \left[\frac{1}{e_q^{-(\frac{E_{N_1} z}{M_1})}}\right]^{-1}}{\int_0^\infty dp\ \ p^2 \left[\frac{1}{e_q^{-(\frac{E_{N_1} z}{M_1})}}\right]^{-1}} \frac{M_1^2}{16\pi}(yy^\dagger)_{11}.$$

Shear versus radiation

By useful relation $\dot{H}_i - \dot{H}_j = -3H(H_i - H_j)$ which is equivalent to $H_i - H_j \propto a^{-3}$, one can obtain the square of the shear scalar dependence on effective scale factor $\sigma^2 \propto a^{-6}$. Therefore, the square of the shear scalar falls off faster than the radiation energy density.

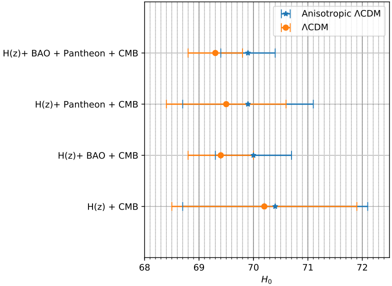
Definition of T_e

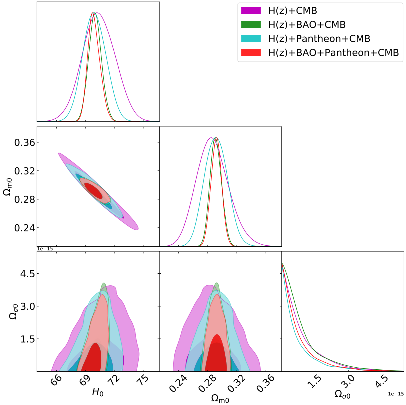
We define the temperature at which $8\pi G\epsilon_r = \sigma^2$ to be T_e.

- For $T \gg T_e$ the universe is shear dominated: $H \propto a^{-3}$ and $a \propto t^{1/3}$ then $H = 1/3t$;
- for $T \ll T_e$ the universe is radiation dominated: $H \propto a^{-2}$ and $a \propto t^{1/2}$ then $H = 1/2t$.

As we did not see any signature of anisotropy in BBN, we want that anisotropy does not affect it. So, we have a constraint as $T_e \gg 2.5\ \mathrm{MeV}$.

Constraints on a Bianchi type-I





Ö. Akarsu et al., Phys. Rev. D 100 (2019) 023532

Modification of Boltzmann Eqs.

The Liouville operator is affected which in the relativistic form is given by

$$\boldsymbol{L} = p^\alpha \frac{\partial}{\partial x^\alpha} - \Gamma^\alpha_{\beta\gamma} p^\beta p^\gamma \frac{\partial}{\partial p^\alpha},$$

where $\Gamma^\alpha_{\beta\gamma}$ are Christoffel symbols of the related metric. For BI metric, nonzero Christoffel symbols are equal to

$$\Gamma^1_{01} = \Gamma^1_{10} = \frac{\dot{a}_1}{a_1}, \quad \Gamma^2_{02} = \Gamma^2_{20} = \frac{\dot{a}_2}{a_2}, \quad \Gamma^3_{03} = \Gamma^3_{30} = \frac{\dot{a}_3}{a_3},$$
$$\Gamma^0_{11} = a_1 \dot{a}_1, \quad \Gamma^0_{22} = a_2 \dot{a}_2, \quad \Gamma^0_{33} = a_3 \dot{a}_3.$$