Baryon asymmetry of the universe and new neutrino states

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Introduction

Why additional neutrino species?

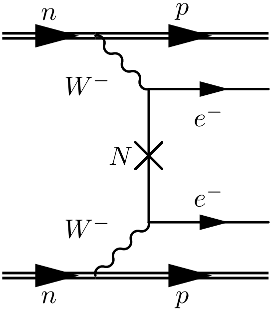
- neutrino oscillation anomalies (LSND, MiniBooNE)
  $\longrightarrow$ mixing with sterile SU(2) singlet neutrinos
- warm dark matter candidates (νMSM)
  $\longrightarrow$ sterile right-handed neutrinos with $m \sim$ keV
- fourth generation models
  $\longrightarrow$ generic addition of SU(2) lepton doublet

Constraining mass of 4th generation neutrino:

- $|m_{\ell_4} - m_{\nu_4}| < 140\,\mathrm{GeV}$ (Eberhardt, Lenz, Rohrwild: arXiv:1005.3505)
  $\Rightarrow$ charged and neutral lepton have similar masses
- ℓ_4 gains mass via Yukawa coupling to Higgs
  $\Rightarrow\ m_{\nu_4} \sim m_{\ell_4} = y_{\ell_4} \cdot v < \mathcal{O}(1\,\mathrm{TeV})$
- SU(2) doublet neutrino must avoid LEP Z decay measurement
  $\Rightarrow\ m_{\nu_4} > \frac{m_Z}{2} \approx 45\,\mathrm{GeV}$

$$\Rightarrow m_{\nu_4} \sim \mathcal{O}(100\,\mathrm{GeV})$$

Constraining Majorana mass term by $0\nu\beta\beta$ (Lenz, Päs, Schalla: arXiv:1104.2465)



contribution of heavy neutrino:

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\frac{m_p}{\langle m_N\rangle}\right)^2 C_{mm}^{NN}$$

with $\langle m_N\rangle^{-1} = U_{e4}^2 m^{-1}$

and using 2σ-fits from Lacker, Menzel: 1003.4532

$$0.021 \leq U_{e4} \leq 0.089$$

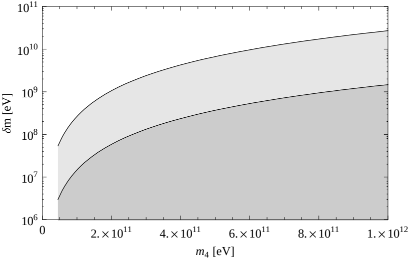
$\Rightarrow$ $m > \mathcal{O}(10^4\,\mathrm{GeV})$ to avoid signal in current experiments

contributions from light neutrinos too small

$\Rightarrow$ M must cancel contribution of m

efficient cancellation $\Leftrightarrow$ $m \sim M$ $\Leftrightarrow M_R$ small

$$\Rightarrow \left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\frac{m_p}{\langle m\rangle} - \frac{m_p}{\langle M\rangle}\right)^2 C_{mm}^{NN}$$



$\Rightarrow$ $\delta m \equiv M - m < \mathcal{O}(1\,\mathrm{GeV})$

thus a fourth generation neutrino must be either a pure Dirac or a pseudo-Dirac particle

$\Rightarrow$ lepton number violating processes are allowed but suppressed

Baryon asymmetry of the universe

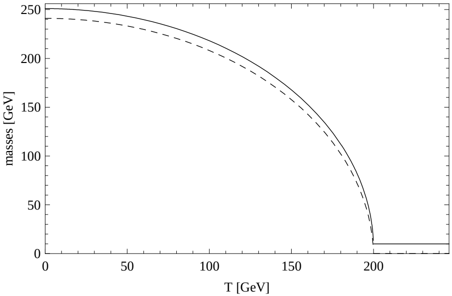
Our universe today:

number of baryons $\neq$ number of antibaryons

$$Y_{\Delta B} \equiv \frac{n_B - n_{\overline{B}}}{s} = (8.75 \pm .23) \cdot 10^{-11}$$

numerous viable models to explain this value
($\rightarrow$ Baryogenesis/Leptogenesis scenarios)
most of them create this asymmetry at high temperatures $\sim T_{GUT}$
The fourth generation neutrino is too light/freezes out too early to actively produce this asymmetry, but might erase any pre-existing asymmetry in the early universe due to their lepton number violating interactions.

above the electroweak phase transition the Higgs-vev vanishes and the two mass eigenstates decouple



$$m \xrightarrow{T > T_{EW}} 0$$

$$M \xrightarrow{T > T_{EW}} M_R$$

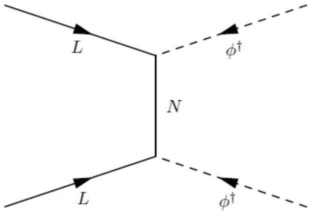
the mass splitting is unaffected:

$$\delta m = M_R = \text{const.}$$

$\Rightarrow$ above the EW phase transition a heavy pseudo-Dirac and a light sterile neutrino with mass δm are indistinguishable
$\Rightarrow$ following discussion not solely applies to fourth generation neutrinos

We will not specify the mechanism of baryogenesis
$\rightarrow$ assume pre-existing $B - L_\alpha$ asymmetry of the right amount at T_{GUT}.
LNV processes mediated by additional neutrino species may dilute such asymmetry

$$\Delta L = 2$$



$$\langle \sigma \, | \, v \, | \rangle \sim \sum_{\beta,\gamma} \kappa_{\alpha\beta\gamma 4} \frac{\delta m^2}{(T^2 + \delta m^2)^2} = \sum_{\beta,\gamma} \kappa_{\alpha\beta\gamma 4} \frac{1}{\delta m^2} \frac{z^4}{(1+z^2)^2}$$

with $z \equiv \delta m / T$

$$\kappa_{\alpha\beta\gamma 4} = \sum_{\beta,\gamma} y^2_{\alpha\beta} y^2_{\alpha\gamma} U^2_{\beta 4} U^2_{\gamma 4}$$

Such processes are efficient in thermal equilibrium

No-washout-criterion

The strongest constraint is obtained by demanding that no washout should occur at all.
$\Rightarrow$ Process should not reach equilibrium while sphaleron transitions are effective

$$\Rightarrow \; H(T) > \Gamma(T) \text{ for } T_{EW} < T < T_{GUT}$$

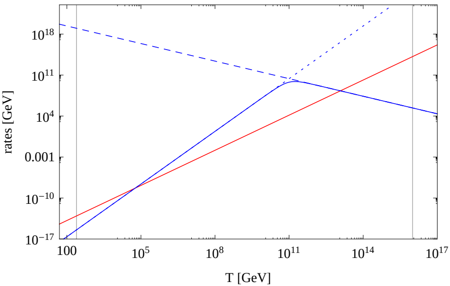
$$H(T) = \sqrt{\frac{8\pi^3 g_*}{90}} \frac{T^2}{m_{Pl}} \qquad \Gamma(T) \sim n_\phi \langle \sigma \, | \, v \, | \rangle \text{ with } n_\phi \approx 2\zeta(3) T^3/\pi^2$$

$$\Rightarrow \; \left(\frac{\delta m}{10\,\mathrm{keV}}\right)^2 < 1 \times \sum_{\beta\gamma} \frac{1}{\kappa_{\alpha\beta\gamma 4}} \times \left(\frac{T}{246\,\mathrm{GeV}}\right)^3$$

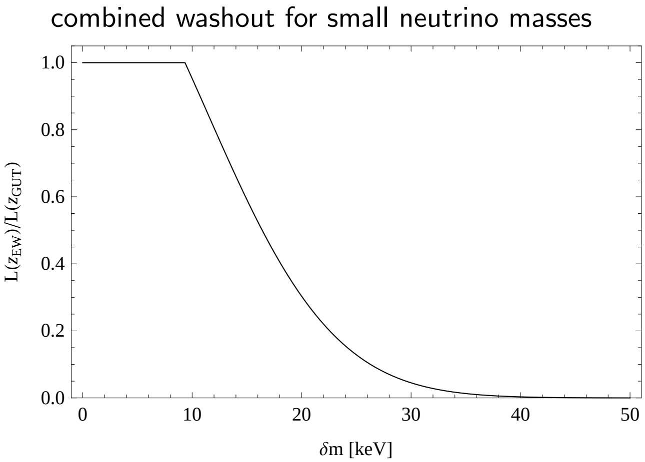
Small washout

When the scattering rate exceeds the expansion rate while sphaleron transitions are effective LNF depletes the existing asymmetry

$$\ln\left(\frac{L(z_{EW})}{L(z_{GUT})}\right) = -\frac{1}{H(z=1)}\int_{z_{GUT}}^{z_{EW}} \mathrm{d}z'\, z' n_\gamma \langle \sigma\, |\, v\, |\, \rangle (z')$$



careful treatment of integration limits crucial



Amount of allowed washout depends on capability of model

Summary

- electroweak fits contrain mass range of additional SU(2) doublet neutrino
- $0\nu\beta\beta$ constrains its Majorana mass to $< 1\,\mathrm{GeV}$
- "light" neutrinos tend to erase existing baryonasymmetries in the early universe
- preserving prominent baryogenesis models the Majorana mass ist constrained to $< 10\,\mathrm{keV}$
- due to vanishing Higgs potential this also applies to additional sterile neutrinos (e.g. dark matter candidates)