Flavoured scalar triplet leptogenesis

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Based on work done in collaboration with Stéphane Lavignac (to appear)

Introduction

Baryon asymmetry of the universe

$$\frac{n_B}{n_\gamma} = \begin{cases} (5.1 - 6.5) \times 10^{-10} \text{ (BBN)} \\ 6.04 \pm 0.8 \times 10^{-10} \text{ (CMB)} \end{cases}$$

$\Rightarrow$ 3 Sakharov's conditions

Leptogenesis

- ($\not{L}$, $\not{CP}$)-decay of a heavy field $\to$ L asymmetry
- L asymmetry

  $\downarrow$ EW sphalerons

  B asymmetry

Leptogenesis scenarios can involve

- Right-handed neutrinos [Fukugita, Yanagida, '86]
- Scalar triplets [Ma & Sarkar '98, Hambye & Senjanovic '03]
  flavour effects considered only recently
  $\hookrightarrow$ { [Felipe, Joaquim & Serodio '13]
  [Aristizabal Sierra, Dhen & Hambye '14] }

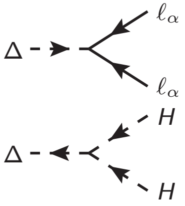
Type II seesaw

[Schechter & al. - Lazarides & al. - Mohapatra & al. - Wetterich]

Complex scalar triplet $\boldsymbol{\Delta} = (\boldsymbol{\Delta}^{++}, \boldsymbol{\Delta}^{+}, \boldsymbol{\Delta}^{0})$ $(M_\Delta \gg v)$ with couplings

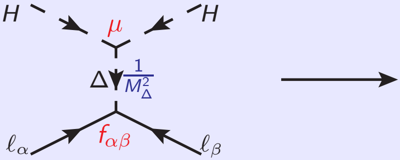
$f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$:

$\mu\Delta^\dagger HH$:



$\Delta L = 2, \quad \alpha,\, \beta = e,\, \mu,\, \tau$

Neutrino Majorana mass matrix



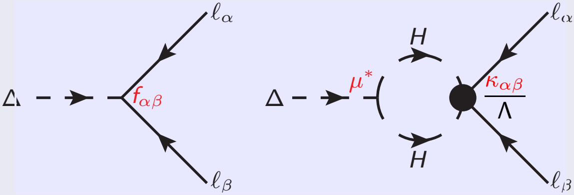
$$(m_\nu)_{\alpha\beta} = \frac{1}{2}\mu f_{\alpha\beta}\frac{v^2}{M_\Delta^2}$$

- The decay $\Delta \to \overline{\ell}\overline{\ell}$ violates L but not CP...
- ...Unless we add more fields

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2}\frac{\kappa_{\alpha\beta}}{\Lambda}\ell_\alpha \ell_\beta HH$$

Now $(m_\nu)_{\alpha\beta} = \mu f_{\alpha\beta}\frac{v^2}{2M_\Delta^2} + \kappa_{\alpha\beta}\frac{v^2}{2\Lambda}$

CP asymmetry [Ma & Sarkar '98, Hambye & Senjanovic '03]



$$\epsilon = \frac{\Gamma(\bar{\Delta} \to \ell\ell) - \Gamma(\Delta \to \overline{\ell}\overline{\ell})}{\Gamma_\Delta^{\text{tot}}} = \frac{M_\Delta}{8\pi\Lambda}\frac{\Im[\mu^* f_{\alpha\beta}^* \kappa_{\alpha\beta}]}{\text{tr}(ff^\dagger) + \mu^2/M_\Delta^2}$$

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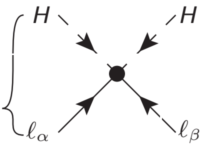

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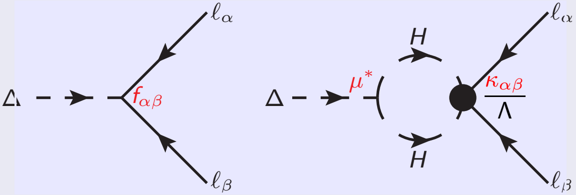

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Boltzmann equations

[Hambye, Raidal & Strumia, '06]

- Equation for the scalar density $\Sigma_\Delta = Y_\Delta + Y_{\bar{\Delta}}$

$$sHz\frac{d\Sigma_\Delta}{dz} = -(D + A), \quad z = \frac{M_\Delta}{T}$$

$D \propto \Gamma_\Delta$: decays and inverse decays
A: EW annihilations

- Equations for the asymmetries $\Delta_a = Y_a - Y_{\bar{a}}, \quad a = \ell, H, \ldots$

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a D - W_a$$

ϵ_a: CP asymmetry in the decay of Δ into $a + \ldots$
W_a: washout due to inverse decays and scatterings

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Flavour dependance

[R. Barbieri, P. Creminelli, A. Strumia &N. Tetradis '99]

[A. Abada, S. Davidson, F.-X. Josse-Michaux, M. Losada & A. Riotto '06]

3 temperature regimes

- Lepton lavours distinguished **only by their Yukawa couplings**
- $T < 10^9$ GeV: τ and μ Yukawa in equilibrium
  $\rightarrow$ 3 distinguishable flavours
- $T > 10^{12}$ GeV: no Yukawa in equilibrium
  $\rightarrow$ τ, μ and e undistinguishable

Density matrix

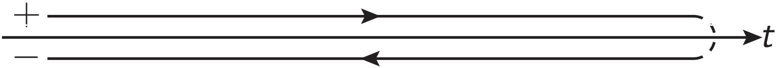
$$\Delta n_{\ell_\alpha} = n_{\ell_\alpha} - n_{\bar{\ell}_\alpha} = \langle : \ell_\alpha^\dagger \ell_\alpha : \rangle \rightarrow \Delta n_{\alpha\beta} = \langle : \ell_\alpha^\dagger \ell_\beta : \rangle$$

$$(\Delta_\ell)_{\alpha\beta} = \frac{\Delta n_{\alpha\beta}}{s} = \begin{pmatrix} (\Delta_\ell)_{ee} & (\Delta_\ell)_{e\mu} & (\Delta_\ell)_{e\tau} \\ (\Delta_\ell)_{\mu e} & (\Delta_\ell)_{\mu\mu} & (\Delta_\ell)_{\mu\tau} \\ (\Delta_\ell)_{\tau e} & (\Delta_\ell)_{\tau\mu} & (\Delta_\ell)_{\tau\tau} \end{pmatrix}$$

Closed time-path formalism

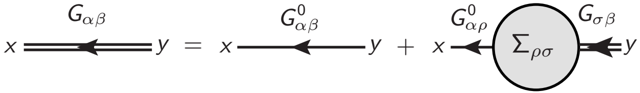
[W. Buchmüller & al. '00, De Simone & al. '07, Garbrecht & al. '10]

$\mathcal{C}$ = time-path that goes from 0 to ∞ and back



$G_{\alpha\beta}(x,y) = \langle \mathcal{T}_{\mathcal{C}}\, \ell_\alpha(x)\bar{\ell}_\beta(y)\rangle$ Green's function, time-ordered **following the contour**.

Schwinger-Dyson equation expresses G as a function of the free Green's function G^0 and the 1PI self-energy Σ



1°) $\mathrm{Tr}[(\overrightarrow{\not\partial}_x + \overleftarrow{\not\partial}_y)\mathbf{SD}] \longrightarrow$ Quantum Boltzmann equation for $(\Delta_\ell)_{\alpha\beta}$

2°) Classical limit $\longrightarrow sHz\dfrac{d(\Delta_\ell)_{\alpha\beta}}{dz} = \epsilon_{\alpha\beta}D - \mathcal{W}_{\alpha\beta}$

Chemical equilibriums

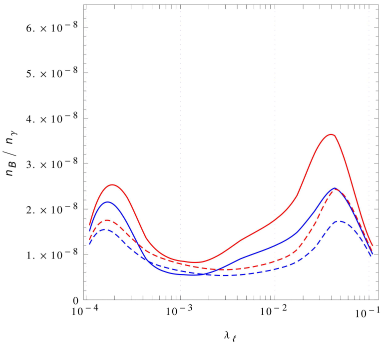
[Aristizabal Sierra, Dhen & Hambye '14]

Various SM processes affect the lepton asymmetry:

- EW sphalerons ($\not{B}$, $\not{L}$, $\not{B+L}$, $B-L$)
- Yukawa-mediated scatterings
  e.g. $W + \ell_\tau \to \tau_R + H, \; T < 10^{12}\text{GeV}$
- QCD sphalerons

Simplification: processes either negligible or very fast $\Rightarrow$ conditions on chemical potentials

Results



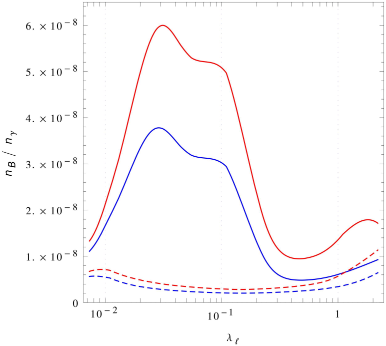


Figure: Comparisons of the final BAU as a function of $\lambda_\ell = \sqrt{\mathrm{tr}(ff^\dagger)}$ for different computations, for $M_\Delta = 5 \times 10^{12}\mathrm{GeV}$.

Results

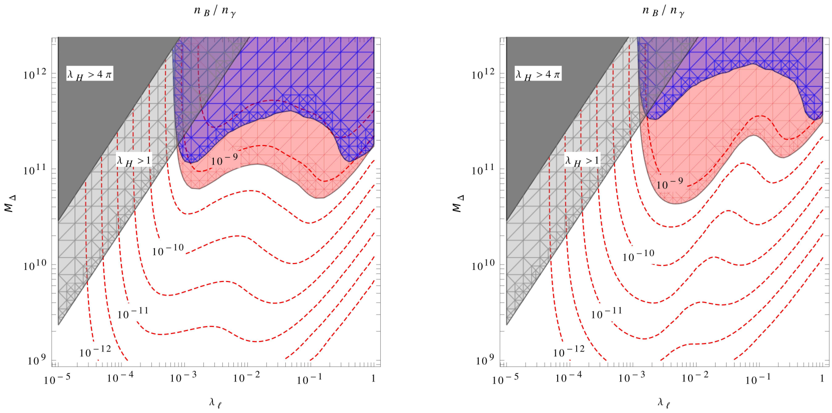


Figure: Final baryon asymmetry as a function of $\lambda_\ell = \sqrt{\mathrm{tr}(ff^\dagger)}$ and M_Δ.

Conclusion

- Scalar triplet leptogenesis successfully explains the BAU
- A correct description of the high-temperature regime should involve a 3×3 density matrix in flavour space
- The final baryon asymmetry can be greatly enhanced (up to 2 orders of magnitude) if one includes flavour effects and chemical equilibriums