A predictive scheme for triplet leptogenesis

Benoît Schmauch

IPhT - CEA Saclay

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

Introduction

Baryon asymmetry of the universe

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

Sakharov's conditions

- B violation
- CP violation
- Processes that violate B and CP out of equilibrium

In the Standard Model

- Sphaleron: non pertubative process that violates $B + L$ but conserves $B - L$
  [Kuzmin, Rubakov, Shaposhnikov]
  $\rightarrow$ electroweak baryogenesis
  [Cohen, Kaplan, Nelson]
- But $m_{Higgs} \lesssim 40\text{GeV}$ is required

Introduction

Baryon asymmetry of the universe

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

Sakharov's conditions

- B violation
- CP violation
- Processes that violate B and CP out of equilibrium

In the Standard Model

- Sphaleron: non pertubative process that violates $B + L$ but conserves $B - L$ [Kuzmin, Rubakov, Shaposhnikov] $\rightarrow$ electroweak baryogenesis [Cohen, Kaplan, Nelson]
- But $m_{Higgs} \lesssim 40\text{GeV}$ is required

Introduction

Baryon asymmetry of the universe

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

Sakharov's conditions

- B violation
- CP violation
- Processes that violate B and CP out of equilibrium

In the Standard Model

- Sphaleron: non pertubative process that violates $B + L$ but conserves $B - L$ [Kuzmin, Rubakov, Shaposhnikov] $\rightarrow$ electroweak baryogenesis [Cohen, Kaplan, Nelson]
- But $m_{Higgs} \lesssim 40\text{GeV}$ is required

Introduction

Baryon asymmetry of the universe

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

Sakharov's conditions

- B violation
- CP violation
- Processes that violate B and CP out of equilibrium

In the Standard Model

- Sphaleron: non pertubative process that violates $B + L$ but conserves $B - L$ [Kuzmin, Rubakov, Shaposhnikov] $\rightarrow$ electroweak baryogenesis [Cohen, Kaplan, Nelson]
- But $m_{Higgs} \lesssim 40\mathrm{GeV}$ is required

Introduction

Alternative way: baryogenesis through leptogenesis [Fukugita, Yanagida]

- Creation of a lepton asymmetry in a first place

$$Y_{B-L} \neq 0$$

- Then conversion to a baryon asymmetry through sphalerons

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

Appealing feature: leptogenesis can be realized in a framework that also explains neutrino masses

Introduction

Alternative way: baryogenesis through leptogenesis [Fukugita, Yanagida]

- Creation of a lepton asymmetry in a first place

$$Y_{B-L} \neq 0$$

- Then conversion to a baryon asymmetry through sphalerons

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

Appealing feature: leptogenesis can be realized in a framework that also explains neutrino masses

Introduction

Alternative way: baryogenesis through leptogenesis [Fukugita, Yanagida]

- Creation of a lepton asymmetry in a first place

$$Y_{B-L} \neq 0$$

- Then conversion to a baryon asymmetry through sphalerons

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

Appealing feature: leptogenesis can be realized in a framework that also explains neutrino masses

Introduction

Alternative way: baryogenesis through leptogenesis [Fukugita, Yanagida]

- Creation of a lepton asymmetry in a first place

$$Y_{B-L} \neq 0$$

- Then conversion to a baryon asymmetry through sphalerons

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

Appealing feature: leptogenesis can be realized in a framework that also explains neutrino masses

Neutrino masses and leptogenesis

Seesaw mechanism

Heavy particles Φ_i couple both to lepton and Higgs doublets. At low energy, these heavy fields can be integrated out of the Lagrangian, resulting in an effective coupling between neutrinos and the Higgs vev.

Possible choices of Φ_i are:

-Majorana neutrinos (Type I seesaw) [Minkowski - Mohapatra & al. - Gell-Mann & al. - Yanagida]

-Scalar triplets (Type II seesaw) [Schechter & al. - Lazarides & al. - Mohapatra & al. - Wetterich]

-Vector-like fermion triplets (Type III seesaw) [Foot & al.]

Neutrino masses and leptogenesis

Seesaw mechanism

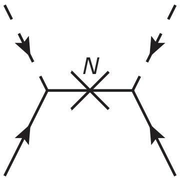
Heavy particles Φ_i couple both to lepton and Higgs doublets. At low energy, these heavy fields can be integrated out of the Lagrangian, resulting in an effective coupling between neutrinos and the Higgs vev.

Possible choices of Φ_i are:

-Majorana neutrinos (Type I seesaw) [Minkowski - Mohapatra & al. - Gell-Mann & al. - Yanagida]

-Scalar triplets (Type II seesaw) [Schechter & al. - Lazarides & al. - Mohapatra & al. - Wetterich]

-Vector-like fermion triplets (Type III seesaw) [Foot & al.]



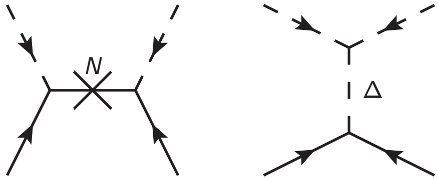
Neutrino masses and leptogenesis

Seesaw mechanism

Heavy particles Φ_i couple both to lepton and Higgs doublets. At low energy, these heavy fields can be integrated out of the Lagrangian, resulting in an effective coupling between neutrinos and the Higgs vev.

Possible choices of Φ_i are:

-Majorana neutrinos (Type I seesaw) [Minkowski - Mohapatra & al. - Gell-Mann & al. - Yanagida]
-Scalar triplets (Type II seesaw) [Schechter & al. - Lazarides & al. - Mohapatra & al. - Wetterich]
-Vector-like fermion triplets (Type III seesaw) [Foot & al.]



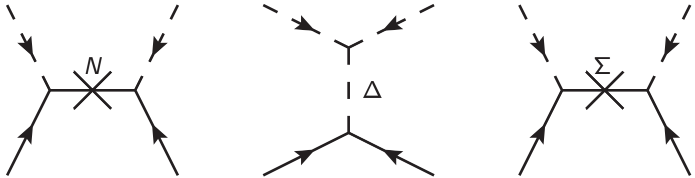
Neutrino masses and leptogenesis

Seesaw mechanism

Heavy particles Φ_i couple both to lepton and Higgs doublets. At low energy, these heavy fields can be integrated out of the Lagrangian, resulting in an effective coupling between neutrinos and the Higgs vev.

Possible choices of Φ_i are:

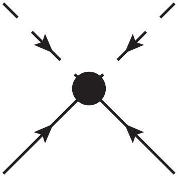
-Majorana neutrinos (Type I seesaw) [Minkowski - Mohapatra & al. - Gell-Mann & al. - Yanagida]
-Scalar triplets (Type II seesaw) [Schechter & al. - Lazarides & al. - Mohapatra & al. - Wetterich]
-Vector-like fermion triplets (Type III seesaw) [Foot & al.]



Neutrino masses and leptogenesis

All 3 choices lead to the same effective operator at low energy:

$$\mathcal{L}_{Weinberg} = -\frac{g}{\Lambda}(\ell^T \sigma_2 H) C (H^T \sigma_2 \ell) + h.c.$$



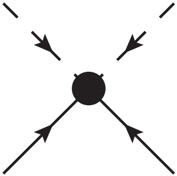
Thus, after the EWSB, neutrinos get Majorana masses:

$$\mathcal{L}_{m_\nu} = -\frac{g v^2}{\Lambda} \nu^T C \nu + h.c.$$

Neutrino masses and leptogenesis

All 3 choices lead to the same effective operator at low energy:

$$\mathcal{L}_{Weinberg} = -\frac{g}{\Lambda}(\ell^T \sigma_2 H) C (H^T \sigma_2 \ell) + h.c.$$



Thus, after the EWSB, neutrinos get Majorana masses:

$$\mathcal{L}_{m_\nu} = -\frac{g v^2}{\Lambda} \nu^T C \nu + h.c.$$

Neutrino masses and leptogenesis

Sakharov's conditions

- B violation: the decays of the heavy states violate $B - L$
- CP violation: this condition will be satisfied if $\Gamma(\Phi_i \to \text{leptons} + \ldots) \neq \Gamma(\Phi_i^c \to \text{antileptons} + \ldots)$
- Out of equilibrium: this is controlled by the dynamics of the decays as well as other relevant reactions (inverse decays, L-violating scatterings,...) in the early universe
  $\to$ Boltzmann equations describing $n_{\Phi_i}(t)$, $n_\ell(t)$, ... $\to \frac{n_B}{n_\gamma}(t_0)$

Neutrino masses and leptogenesis

Sakharov's conditions

- B violation: the decays of the heavy states violate $B - L$
- CP violation: this condition will be satisfied if $\Gamma(\Phi_i \to \text{leptons} + \ldots) \neq \Gamma(\Phi_i^c \to \text{antileptons} + \ldots)$
- Out of equilibrium: this is controlled by the dynamics of the decays as well as other relevant reactions (inverse decays, L-violating scatterings,...) in the early universe
  $\to$ Boltzmann equations describing $n_{\Phi_i}(t)$, $n_\ell(t)$, ... $\to \frac{n_B}{n_\gamma}(t_0)$

Neutrino masses and leptogenesis

Sakharov's conditions

- B violation: the decays of the heavy states violate $B - L$
- CP violation: this condition will be satisfied if $\Gamma(\Phi_i \to \text{leptons} + ...) \neq \Gamma(\Phi_i^c \to \text{antileptons} + ...)$
- Out of equilibrium: this is controlled by the dynamics of the decays as well as other relevant reactions (inverse decays, L-violating scatterings,...) in the early universe
  $\to$ Boltzmann equations describing $n_{\Phi_i}(t)$, $n_\ell(t)$, ... $\to \frac{n_B}{n_\gamma}(t_0)$

Neutrino masses and leptogenesis

Sakharov's conditions

- B violation: the decays of the heavy states violate $B - L$
- CP violation: this condition will be satisfied if $\Gamma(\Phi_i \to \text{leptons} + ...) \neq \Gamma(\Phi_i^c \to \text{antileptons} + ...)$
- Out of equilibrium: this is controlled by the dynamics of the decays as well as other relevant reactions (inverse decays, L-violating scatterings,...) in the early universe
  $\to$ Boltzmann equations describing $n_{\Phi_i}(t)$, $n_\ell(t)$, ... $\to \frac{n_B}{n_\gamma}(t_0)$

Neutrino masses and leptogenesis

Sakharov's conditions

- B violation: the decays of the heavy states violate $B - L$
- CP violation: this condition will be satisfied if $\Gamma(\Phi_i \to \text{leptons} + \ldots) \neq \Gamma(\Phi_i^c \to \text{antileptons} + \ldots)$
- Out of equilibrium: this is controlled by the dynamics of the decays as well as other relevant reactions (inverse decays, L-violating scatterings,...) in the early universe
  $\to$ Boltzmann equations describing $n_{\Phi_i}(t)$, $n_\ell(t), \ldots \to \frac{n_B}{n_\gamma}(t_0)$

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S \text{ or } T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta}R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S \text{ or } T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S$ or $T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S \text{ or } T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S$ or $T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ ($\Delta L = 2$)
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ ($\Delta L = 2$)
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ ($R = S$ or T)

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S$ or $T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ ($\Delta L = 2$)
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ ($\Delta L = 2$)
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ ($R = S$ or T)

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta}R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S \text{ or } T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Model based on a Grand Unified Theory with gauge group $SO(10)$.
[M. Frigerio, P. Hosteins, S. Lavignac, A. Romanino (2009)]

Particle content

- 1 complex scalar triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- 3 pairs of vector-like heavy lepton doublets

$$\underbrace{\mathcal{L}_\alpha = \begin{pmatrix} \mathcal{N}_\alpha \\ \mathcal{E}_\alpha \end{pmatrix}}_{L=1}, \underbrace{\bar{\mathcal{L}}_\alpha = \begin{pmatrix} \bar{\mathcal{N}}_\alpha \\ \bar{\mathcal{E}}_\alpha \end{pmatrix}}_{L=-1}$$

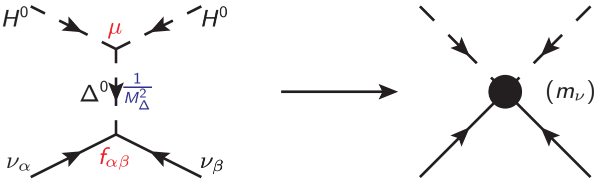
- 1 real scalar triplet $T = (T^{+}, T^{0}, T^{-})$ & 1 real scalar singlet S

New couplings

- $f_{\alpha\beta}\Delta\ell_\alpha\ell_\beta$ $(\Delta L = 2)$
- $f_{\alpha\beta}\Delta^\dagger\bar{\mathcal{L}}_\alpha\bar{\mathcal{L}}_\beta$ $(\Delta L = 2)$
- $\mu\Delta^\dagger HH$
- $c_R f_{\alpha\beta} R\bar{\mathcal{L}}_\alpha\ell_\beta$ $(R = S$ or $T)$

The Yukawa couplings are related by $SO(10)$ symmetry

Integrating out the heavy field Δ, one obtains the neutrino Majorana mass matrix:

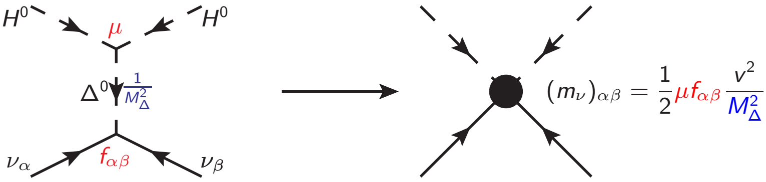


$$(m_\nu)_{\alpha\beta} = \frac{1}{2}\mu f_{\alpha\beta}\frac{v^2}{M_\Delta^2}$$

Coupling matrix

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

Integrating out the heavy field Δ, one obtains the neutrino Majorana mass matrix:



Coupling matrix

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

The violations of *CP* in the *L*-violating decays are encoded in the quantities

$$\epsilon_a = n_\ell \frac{\Gamma(a \to n_\ell \ell + ...) - \Gamma(a^c \to n_\ell \ell^c + ...)}{\Gamma a + \Gamma a^c}$$

Here, we consider the *CP* asymmetries in the decays of the three scalars.

CP asymmetries

$$\epsilon_\Delta = 2\frac{\Gamma(\Delta^\dagger \to \ell\ell) - \Gamma(\Delta \to \ell^c\ell^c)}{\Gamma_\Delta + \Gamma_{\Delta^\dagger}}$$

$$\epsilon_R = \frac{\Gamma(R \to \ell\bar{\mathcal{L}}) - \Gamma(\bar{R} \to \ell^c\bar{\mathcal{L}}^c)}{\Gamma_R} \qquad R = S,\ T$$

The violations of *CP* in the *L*-violating decays are encoded in the quantities

$$\epsilon_a = n_\ell \frac{\Gamma(a \to n_\ell \ell + ...) - \Gamma(a^c \to n_\ell \ell^c + ...)}{\Gamma a + \Gamma a^c}$$

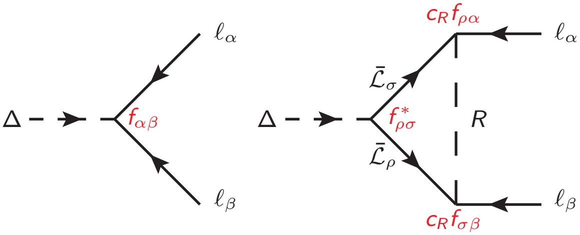
Here, we consider the *CP* asymmetries in the decays of the three scalars.

CP asymmetries

$$\epsilon_\Delta = 2\frac{\Gamma(\Delta^\dagger \to \ell\ell) - \Gamma(\Delta \to \ell^c \ell^c)}{\Gamma_\Delta + \Gamma_{\Delta^\dagger}}$$

$$\epsilon_R = \frac{\Gamma(R \to \ell\bar{\mathcal{L}}) - \Gamma(R \to \ell^c \bar{\mathcal{L}}^c)}{\Gamma_R} \quad R = S,\ T$$

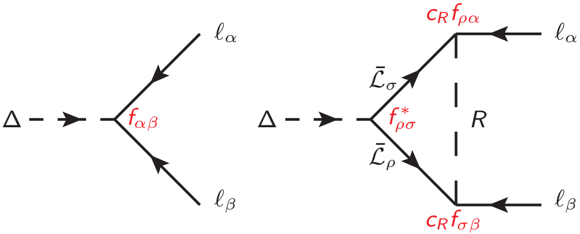
For instance, the asymmetry in $\Delta^\dagger \to \ell\ell$ comes from the interference between 2 diagrams:



$$\epsilon(\Delta \to \ell_\alpha \ell_\beta) = \frac{1}{4\pi}\frac{1}{\mathrm{Tr}(ff^\dagger)} \sum_{\rho,\sigma} \mathcal{I}m[f_{\rho\sigma} f^*_{\rho\alpha} f_{\alpha\beta} f^*_{\beta\sigma}] \sum_{R=S,T} c_R^2 g\left(\frac{M_R^2}{M_\Delta^2}, \frac{M_\rho^2}{M_\Delta^2}, \frac{M_\sigma^2}{M_\Delta^2}\right)$$

ϵ_Δ is non-zero only if:
-the product of coupling has a nonvanishing imaginary part
-the existence of an onshell intermediate state is allowed.

For instance, the asymmetry in $\Delta^\dagger \to \ell\ell$ comes from the interference between 2 diagrams:



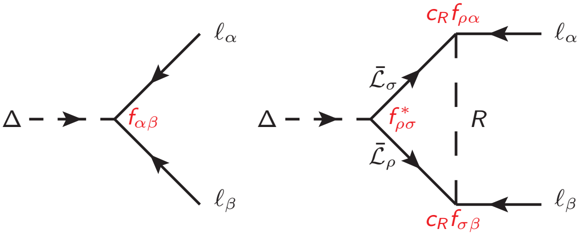
$$\epsilon(\Delta \to \ell_\alpha \ell_\beta) = \frac{1}{4\pi} \frac{1}{\mathrm{Tr}(ff^\dagger)} \sum_{\rho,\sigma} \mathcal{I}m[f_{\rho\sigma} f^*_{\rho\alpha} f_{\alpha\beta} f^*_{\beta\sigma}] \sum_{R=S,T} c_R^2 g\left(\frac{M_R^2}{M_\Delta^2}, \frac{M_\rho^2}{M_\Delta^2}, \frac{M_\sigma^2}{M_\Delta^2}\right)$$

ϵ_Δ is non-zero only if:

-the product of coupling has a nonvanishing imaginary part

-the existence of an onshell intermediate state is allowed.

For instance, the asymmetry in $\Delta^\dagger \to \ell\ell$ comes from the interference between 2 diagrams:



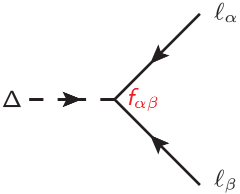
$$\epsilon(\Delta \to \ell_\alpha \ell_\beta) = \frac{1}{4\pi}\frac{1}{\mathrm{Tr}(ff^\dagger)}\sum_{\rho,\sigma}\mathcal{I}m[f_{\rho\sigma}f^*_{\rho\alpha}f_{\alpha\beta}f^*_{\beta\sigma}]\sum_{R=S,T}c_R^2 g\left(\frac{M_R^2}{M_\Delta^2},\frac{M_\rho^2}{M_\Delta^2},\frac{M_\sigma^2}{M_\Delta^2}\right)$$

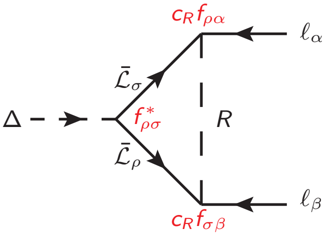
ϵ_Δ is non-zero only if:

-the product of coupling has a nonvanishing imaginary part

-the existence of an onshell intermediate state is allowed.

For instance, the asymmetry in $\Delta^\dagger \to \ell\ell$ comes from the interference between 2 diagrams:





$$\epsilon(\Delta \to \ell_\alpha \ell_\beta) = \frac{1}{4\pi}\frac{1}{\mathrm{Tr}(ff^\dagger)} \sum_{\rho,\sigma} \mathcal{I}m[f_{\rho\sigma} f^*_{\rho\alpha} f_{\alpha\beta} f^*_{\beta\sigma}] \sum_{R=S,T} c_R^2 \underbrace{g\left(\frac{M_R^2}{M_\Delta^2}, \frac{M_\rho^2}{M_\Delta^2}, \frac{M_\sigma^2}{M_\Delta^2}\right)}_{0 \ \text{if} \ M_\rho + M_\sigma > M_\Delta}$$

ϵ_Δ is non-zero only if:
-the product of coupling has a nonvanishing imaginary part
-the existence of an onshell intermediate state is allowed.

The asymmetry vanishes if $M_{\bar{\mathcal{L}}_1}, M_{\bar{\mathcal{L}}_2}, M_{\bar{\mathcal{L}}_3} > M_\Delta$ or if $M_{\bar{\mathcal{L}}_1}, M_{\bar{\mathcal{L}}_2}, M_{\bar{\mathcal{L}}_3} \ll M_\Delta$ (similarly for S and T).

CP asymmetries

With the assumption $M_{\bar{\mathcal{L}}_1} \ll M_{\Delta,S,T} \ll M_{\bar{\mathcal{L}}_{2,3}}$ (so that $\bar{\mathcal{L}}_2$ and $\bar{\mathcal{L}}_3$ decouple from the dynamics) one gets

$$\epsilon_\Delta = \frac{1}{4\pi} \frac{\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}]}{\mathrm{Tr}(f f^\dagger)} \sum_{R=S,T} c_R^2 g\left(\frac{M_R^2}{M_\Delta^2}\right)$$

$$\epsilon_S = -\frac{3}{16\pi} \frac{\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}]}{(f f^\dagger)_{11}} g\left(\frac{M_\Delta^2}{M_S^2}\right)$$

$$\epsilon_T = -\frac{1}{16\pi} \frac{\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}]}{(f f^\dagger)_{11}} g\left(\frac{M_\Delta^2}{M_T^2}\right)$$

The asymmetry vanishes if $M_{\bar{\mathcal{L}}_1}, M_{\bar{\mathcal{L}}_2}, M_{\bar{\mathcal{L}}_3} > M_\Delta$ or if $M_{\bar{\mathcal{L}}_1}, M_{\bar{\mathcal{L}}_2}, M_{\bar{\mathcal{L}}_3} \ll M_\Delta$ (similarly for S and T).

CP asymmetries

With the assumption $M_{\bar{\mathcal{L}}_1} \ll M_{\Delta,S,T} \ll M_{\bar{\mathcal{L}}_{2,3}}$ (so that $\bar{\mathcal{L}}_2$ and $\bar{\mathcal{L}}_3$ decouple from the dynamics) one gets

$$\epsilon_\Delta = \frac{1}{4\pi} \frac{\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}]}{\mathrm{Tr}(ff^\dagger)} \sum_{R=S,T} c_R^2 g\left(\frac{M_R^2}{M_\Delta^2}\right)$$

$$\epsilon_S = -\frac{3}{16\pi} \frac{\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}]}{(ff^\dagger)_{11}} g\left(\frac{M_\Delta^2}{M_S^2}\right)$$

$$\epsilon_T = -\frac{1}{16\pi} \frac{\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}]}{(ff^\dagger)_{11}} g\left(\frac{M_\Delta^2}{M_T^2}\right)$$

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.

Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger f f^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right.$$
$$\left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma - \rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma\right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses) $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of CP)

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.
Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger ff^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right.$$
$$\left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma - \rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma\right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses) $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of CP)

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.
Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger ff^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right.$$
$$\left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma - \rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma \right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses) $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of CP)

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.
Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger ff^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right. \\ \left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma - \rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma\right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses) $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of *CP*)

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.
Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger ff^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right. \\ \left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma - \rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma \right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses)
  $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of CP)

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.
Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger ff^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right.$$
$$\left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma - \rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma \right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses) $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of *CP*)

We define $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$, $\bar{m} = \sqrt{\mathrm{Tr}(m_\nu m_\nu^\dagger)}$.
Then, once λ_ℓ is fixed, $f_{\alpha\beta} = (\lambda_\ell/\bar{m})(m_\nu)_{\alpha\beta}$ is fully defined in terms of neutrino parameters.

In particular

$$\mathcal{I}m[f_{11}(f^\dagger ff^\dagger)_{11}] = \frac{\lambda_\ell^4}{\bar{m}^4}\left(-m_1 m_2 \Delta m_{21}^2 c_{12}^2 c_{13}^4 s_{12}^2 \sin 2\rho \right.$$
$$\left. + m_1 m_3 \Delta m_{31}^2 c_{12}^2 c_{13}^2 s_{13}^2 \sin 2(\sigma-\rho) + m_2 m_3 \Delta m_{32}^2 c_{13}^2 s_{12}^2 s_{13}^2 \sin 2\sigma\right),$$

- m_i: eigenvalues of m_ν (physical neutrino masses)
  $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2}$
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$
- ρ and σ are Majorana phases (we choose them in order to have a large enough violation of CP)

1. Presentation of the model
2. *CP* asymmetries
3. Boltzmann equations
4. Results

Boltzmann equations

- 3 equations for the scalar densities $Y_a = n_a/s$ with the general form

$$sHz\frac{dY_a}{dz} = -(D_a + S_a), \quad z = \frac{M_\Delta}{T}$$

$D_a \propto \Gamma_a$: decays and inverse decays of particle a
S_a: scatterings consuming a (typically electroweak annihilations)

- We also need the asymmetries $\Delta_a = Y_a - Y_{a^c}$ in Standard Model leptons Δ_ℓ, in heavy leptons $\Delta_{\bar{\mathcal{L}}_1}$, in Higgs doublets Δ_H and in triplets Δ_Δ

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a^b D_b - W_a$$

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

Boltzmann equations

- 3 equations for the scalar densities $Y_a = n_a/s$ with the general form

$$sHz\frac{dY_a}{dz} = -(D_a + S_a), \quad z = \frac{M_\Delta}{T}$$

$D_a \propto \Gamma_a$: decays and inverse decays of particle a

S_a: scatterings consuming a (typically electroweak annihilations)

- We also need the asymmetries $\Delta_a = Y_a - Y_{a^c}$ in Standard Model leptons Δ_ℓ, in heavy leptons $\Delta_{\bar{\mathcal{L}}_1}$, in Higgs doublets Δ_H and in triplets Δ_Δ

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a^b D_b - W_a$$

ϵ_a^b: *CP* asymmetry in the decay of b into $a + \ldots$

W_a: washout due to inverse decays and scatterings

Boltzmann equations

- 3 equations for the scalar densities $Y_a = n_a/s$ with the general form

$$sHz\frac{dY_a}{dz} = -(D_a + S_a), \quad z = \frac{M_\Delta}{T}$$

$D_a \propto \Gamma_a$: decays and inverse decays of particle a
S_a: scatterings consuming a (typically electroweak annihilations)

- We also need the asymmetries $\Delta_a = Y_a - Y_{a^c}$ in Standard Model leptons Δ_ℓ, in heavy leptons $\Delta_{\bar{\mathcal{L}}_1}$, in Higgs doublets Δ_H and in triplets Δ_Δ

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a^b D_b - W_a$$

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

Boltzmann equations

- 3 equations for the scalar densities $Y_a = n_a/s$ with the general form

$$sHz\frac{dY_a}{dz} = -(D_a + S_a), \quad z = \frac{M_\Delta}{T}$$

  $D_a \propto \Gamma_a$: decays and inverse decays of particle a
  S_a: scatterings consuming a (typically electroweak annihilations)

- We also need the asymmetries $\Delta_a = Y_a - Y_{a^c}$ in Standard Model leptons Δ_ℓ, in heavy leptons $\Delta_{\bar{\mathcal{L}}_1}$, in Higgs doublets Δ_H and in triplets Δ_Δ

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a^b D_b - W_a$$

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

Boltzmann equations

- 3 equations for the scalar densities $Y_a = n_a/s$ with the general form

$$sHz\frac{dY_a}{dz} = -(D_a + S_a), \quad z = \frac{M_\Delta}{T}$$

  $D_a \propto \Gamma_a$: decays and inverse decays of particle a
  S_a: scatterings consuming a (typically electroweak annihilations)

- We also need the asymmetries $\Delta_a = Y_a - Y_{a^c}$ in Standard Model leptons Δ_ℓ, in heavy leptons $\Delta_{\bar{\mathcal{L}}_1}$, in Higgs doublets Δ_H and in triplets Δ_Δ

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a^b D_b - W_a$$

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

Boltzmann equations

- 3 equations for the scalar densities $Y_a = n_a/s$ with the general form

$$sHz\frac{dY_a}{dz} = -(D_a + S_a), \quad z = \frac{M_\Delta}{T}$$

$D_a \propto \Gamma_a$: decays and inverse decays of particle a
S_a: scatterings consuming a (typically electroweak annihilations)

- We also need the asymmetries $\Delta_a = Y_a - Y_{a^c}$ in Standard Model leptons Δ_ℓ, in heavy leptons $\Delta_{\bar{\mathcal{L}}_1}$, in Higgs doublets Δ_H and in triplets Δ_Δ

$$sHz\frac{d\Delta_a}{dz} = \epsilon_a^b D_b - W_a$$

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

Flavour dependance

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

- If charged lepton Yukawa interactions are in equilibrium ($T < 10^{12}$ GeV for τ, $T < 10^9$ GeV for μ) lepton flavours are distinguishable
  $\Rightarrow$ For $T < 10^9$ GeV, write 3 Boltzmann equations for Δ_{ℓ_e}, Δ_{ℓ_μ} and Δ_{ℓ_τ}.
- In the opposite case, lepton flavors are undistinguishable
  $\Rightarrow$ For $T > 10^{12}$ GeV, computations are often done in the **single flavour approximation**: in the minimal leptogenesis scenario involving right-handed neutrinos, if only the decay of the lightest right-handed neutrino N_1 is responsible for the lepton asymmetry, then

$$\sum_\alpha y_{1\alpha} \bar{N}_1 \ell_\alpha H \to y \bar{N}_1 \ell_0 H$$

$$y = \sqrt{\sum_\alpha |y_{1\alpha}|^2}, \quad \ell_0 = \sum_\alpha \frac{y_{1\alpha}}{y} \ell_\alpha$$

$\Rightarrow$ one single flavour ℓ_0 couples to the heavy state responsible for leptogenesis

Flavour dependance

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

- If charged lepton Yukawa interactions are in equilibrium ($T < 10^{12}$ GeV for τ, $T < 10^9$ GeV for μ) lepton flavours are distinguishable
  $\Rightarrow$ For $T < 10^9$ GeV, write 3 Boltzmann equations for Δ_{ℓ_e}, Δ_{ℓ_μ} and Δ_{ℓ_τ}.

- In the opposite case, lepton flavors are undistinguishable
  $\Rightarrow$ For $T > 10^{12}$ GeV, computations are often done in the **single flavour approximation**: in the minimal leptogenesis scenario involving right-handed neutrinos, if only the decay of the lightest right-handed neutrino N_1 is responsible for the lepton asymmetry, then

$$\sum_\alpha y_{1\alpha} \bar{N}_1 \ell_\alpha H \to y \bar{N}_1 \ell_0 H$$

$$y = \sqrt{\sum_\alpha |y_{1\alpha}|^2}, \quad \ell_0 = \sum_\alpha \frac{y_{1\alpha}}{y} \ell_\alpha$$

  $\Rightarrow$ one single flavour ℓ_0 couples to the heavy state responsible for leptogenesis

Flavour dependance

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

- If charged lepton Yukawa interactions are in equilibrium ($T < 10^{12}$ GeV for τ, $T < 10^9$ GeV for μ) lepton flavours are distinguishable
  $\Rightarrow$ For $T < 10^9$ GeV, write 3 Boltzmann equations for Δ_{ℓ_e}, Δ_{ℓ_μ} and Δ_{ℓ_τ}.

- In the opposite case, lepton flavors are undistinguishable
  $\Rightarrow$ For $T > 10^{12}$ GeV, computations are often done in the **single flavour approximation**: in the minimal leptogenesis scenario involving right-handed neutrinos, if only the decay of the lightest right-handed neutrino N_1 is responsible for the lepton asymmetry, then

$$\sum_\alpha y_{1\alpha} \bar{N}_1 \ell_\alpha H \to y \bar{N}_1 \ell_0 H$$

$$y = \sqrt{\sum_\alpha |y_{1\alpha}|^2}, \quad \ell_0 = \sum_\alpha \frac{y_{1\alpha}}{y} \ell_\alpha$$

$\Rightarrow$ one single flavour ℓ_0 couples to the heavy state responsible for leptogenesis

Flavour dependance

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

- If charged lepton Yukawa interactions are in equilibrium ($T < 10^{12}$ GeV for τ, $T < 10^9$ GeV for μ) lepton flavours are distinguishable
  $\Rightarrow$ For $T < 10^9$ GeV, write 3 Boltzmann equations for Δ_{ℓ_e}, Δ_{ℓ_μ} and Δ_{ℓ_τ}.
- In the opposite case, lepton flavors are undistinguishable
  $\Rightarrow$ For $T > 10^{12}$ GeV, computations are often done in the **single flavour approximation**: in the minimal leptogenesis scenario involving right-handed neutrinos, if only the decay of the lightest right-handed neutrino N_1 is responsible for the lepton asymmetry, then

$$\sum_\alpha y_{1\alpha} \bar{N}_1 \ell_\alpha H \to y \bar{N}_1 \ell_0 H$$

$$y = \sqrt{\sum_\alpha |y_{1\alpha}|^2}, \quad \ell_0 = \sum_\alpha \frac{y_{1\alpha}}{y} \ell_\alpha$$

$\Rightarrow$ one single flavour ℓ_0 couples to the heavy state responsible for leptogenesis

Flavour dependance

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

- If charged lepton Yukawa interactions are in equilibrium ($T < 10^{12}$ GeV for τ, $T < 10^9$ GeV for μ) lepton flavours are distinguishable
$\Rightarrow$ For $T < 10^9$ GeV, write 3 Boltzmann equations for Δ_{ℓ_e}, Δ_{ℓ_μ} and Δ_{ℓ_τ}.

- In the opposite case, lepton flavors are undistinguishable
$\Rightarrow$ For $T > 10^{12}$ GeV, computations are often done in the **single flavour approximation**: in the minimal leptogenesis scenario involving right-handed neutrinos, if only the decay of the lightest right-handed neutrino N_1 is responsible for the lepton asymmetry, then

$$\sum_\alpha y_{1\alpha} \bar{N}_1 \ell_\alpha H \to y \bar{N}_1 \ell_0 H$$

$$y = \sqrt{\sum_\alpha |y_{1\alpha}|^2}, \quad \ell_0 = \sum_\alpha \frac{y_{1\alpha}}{y} \ell_\alpha$$

$\Rightarrow$ one single flavour ℓ_0 couples to the heavy state responsible for leptogenesis

Flavour dependance

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

- If charged lepton Yukawa interactions are in equilibrium ($T < 10^{12}$ GeV for τ, $T < 10^9$ GeV for μ) lepton flavours are distinguishable
  $\Rightarrow$ For $T < 10^9$ GeV, write 3 Boltzmann equations for Δ_{ℓ_e}, Δ_{ℓ_μ} and Δ_{ℓ_τ}.

- In the opposite case, lepton flavors are undistinguishable
  $\Rightarrow$ For $T > 10^{12}$ GeV, computations are often done in the **single flavour approximation**: in the minimal leptogenesis scenario involving right-handed neutrinos, if only the decay of the lightest right-handed neutrino N_1 is responsible for the lepton asymmetry, then

$$\sum_\alpha y_{1\alpha} \bar{N}_1 \ell_\alpha H \to y \bar{N}_1 \ell_0 H$$

$$y = \sqrt{\sum_\alpha |y_{1\alpha}|^2}, \quad \ell_0 = \sum_\alpha \frac{y_{1\alpha}}{y} \ell_\alpha$$

$\Rightarrow$ one single flavour ℓ_0 couples to the heavy state responsible for leptogenesis

Flavour dependance

No such thing in our scenario: because of the structure of Yukawa couplings

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

impossible to define one single linear combination of lepton flavours involved in leptogenesis.

For $T > 10^{12}$ GeV, there are quantum correlations between the various flavours to take into account.

Density matrix

$$\Delta n_{\ell_\alpha} = n_{\ell_\alpha} - n_{\ell^c_\alpha} = \langle : \ell^\dagger_\alpha \ell_\alpha : \rangle \rightarrow \Delta n_{\alpha\beta} = \langle : \ell^\dagger_\alpha \ell_\beta : \rangle$$

We need to derive the Boltzmann equation for $(\Delta_\ell)_{\alpha\beta} = \dfrac{\Delta n_{\alpha\beta}}{s}$

Flavour dependance

No such thing in our scenario: because of the structure of Yukawa couplings

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

impossible to define one single linear combination of lepton flavours involved in leptogenesis.

For $T > 10^{12}$ GeV, there are quantum correlations between the various flavours to take into account.

Density matrix

$$\Delta n_{\ell_\alpha} = n_{\ell_\alpha} - n_{\ell^c_\alpha} = \langle : \ell^\dagger_\alpha \ell_\alpha : \rangle \rightarrow \Delta n_{\alpha\beta} = \langle : \ell^\dagger_\alpha \ell_\beta : \rangle$$

We need to derive the Boltzmann equation for $(\Delta_\ell)_{\alpha\beta} = \frac{\Delta n_{\alpha\beta}}{s}$

Flavour dependance

No such thing in our scenario: because of the structure of Yukawa couplings

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

impossible to define one single linear combination of lepton flavours involved in leptogenesis.

For $T > 10^{12}$ GeV, there are quantum correlations between the various flavours to take into account.

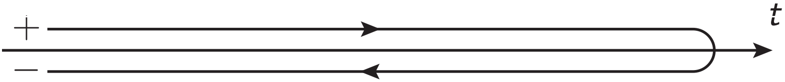
Density matrix

$$\Delta n_{\ell_\alpha} = n_{\ell_\alpha} - n_{\ell^c_\alpha} = \langle : \ell^\dagger_\alpha \ell_\alpha : \rangle \rightarrow \Delta n_{\alpha\beta} = \langle : \ell^\dagger_\alpha \ell_\beta : \rangle$$

We need to derive the Boltzmann equation for $(\Delta_\ell)_{\alpha\beta} = \dfrac{\Delta n_{\alpha\beta}}{s}$

Closed time-path formalism

Formalism used to describe quantum out of equilibrium phenomena, applied to leptogenesis [W. Buchmüller & al., De Simone & al., Garbrecht & al.]
$\mathcal{C}$ = time-path that goes from 0 to ∞ and back



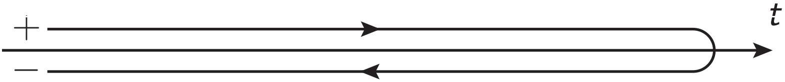
$G_{\alpha\beta} = -i\langle \mathcal{T}_{\mathcal{C}} \ell_\alpha \bar{\ell}_\beta \rangle$ Green's function, time-ordered **following the contour**.

$$G = \begin{pmatrix} G^{++} & -G^{+-} \\ G^{-+} & -G^{--} \end{pmatrix}$$

For instance $G^{-+}_{\alpha\beta}(x,y) = -i\langle \ell_\alpha(x)\bar{\ell}_\beta(y)\rangle$
Idea: Deduce the evolution equation of $\Delta n_{\alpha\beta} = \langle : \ell^\dagger_\alpha \ell_\beta : \rangle$ From the equation of motion of $G_{\beta\alpha}$

Closed time-path formalism

Formalism used to describe quantum out of equilibrium phenomena, applied to leptogenesis [W. Buchmüller & al., De Simone & al., Garbrecht & al.]
$\mathcal{C}$ = time-path that goes from 0 to ∞ and back



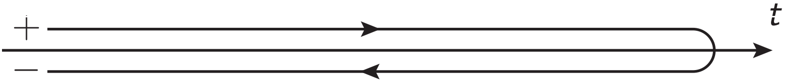
$G_{\alpha\beta} = -i\langle \mathcal{T}_{\mathcal{C}} \ell_\alpha \overline{\ell}_\beta \rangle$ Green's function, time-ordered **following the contour**.

$$G = \begin{pmatrix} G^{++} & -G^{+-} \\ G^{-+} & -G^{--} \end{pmatrix}$$

For instance $G^{-+}_{\alpha\beta}(x,y) = -i\langle \ell_\alpha(x) \overline{\ell}_\beta(y) \rangle$
Idea: Deduce the evolution equation of $\Delta n_{\alpha\beta} = \langle : \ell^\dagger_\alpha \ell_\beta : \rangle$ From the equation of motion of $G_{\beta\alpha}$

Closed time-path formalism

Formalism used to describe quantum out of equilibrium phenomena, applied to leptogenesis [W. Buchmüller & al., De Simone & al., Garbrecht & al.]
$\mathcal{C}$ = time-path that goes from 0 to ∞ and back

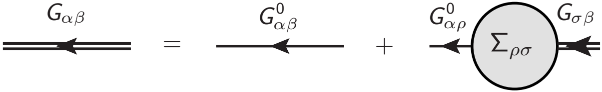


$G_{\alpha\beta} = -i\langle \mathcal{T}_{\mathcal{C}} \ell_\alpha \overline{\ell}_\beta \rangle$ Green's function, time-ordered **following the contour**.

$$G = \begin{pmatrix} G^{++} & -G^{+-} \\ G^{-+} & -G^{--} \end{pmatrix}$$

For instance $G^{-+}_{\alpha\beta}(x,y) = -i\langle \ell_\alpha(x)\overline{\ell}_\beta(y)\rangle$
Idea: Deduce the evolution equation of $\Delta n_{\alpha\beta} = \langle : \ell^\dagger_\alpha \ell_\beta : \rangle$ From the equation of motion of $G_{\beta\alpha}$

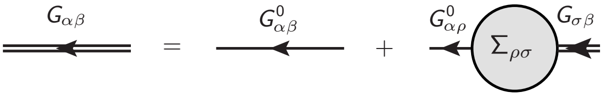
- **Schwinger-Dyson equation** expresses G as a function of the free Green's function G^0 and the 1PI self-energy Σ



- One obtains the evolution equation for the density matrix by noticing that $\frac{d\Delta n_{\alpha\beta}}{dt} = -\mathrm{Tr}((i\overrightarrow{\partial\!\!\!/}_x + i\overleftarrow{\partial\!\!\!/}_y)G^{-+}_{\beta\alpha}(x,y))_{|y=x}$
- In the end, from the equation for $\Delta n(t)$ we obtain a Boltzmann equation for $\Delta_\ell(z)$

$$sHz\frac{d(\Delta_\ell)_{\alpha\beta}}{dz} = \epsilon^{\Delta}_{\alpha\beta}D_\Delta + \epsilon^{S}_{\alpha\beta}D_S + \epsilon^{T}_{\alpha\beta}D_T - \mathcal{W}_{\alpha\beta}$$

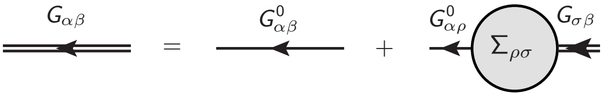
- **Schwinger-Dyson equation** expresses G as a function of the free Green's function G^0 and the 1PI self-energy Σ



- One obtains the evolution equation for the density matrix by noticing that $\dfrac{d\Delta n_{\alpha\beta}}{dt} = -\mathrm{Tr}((i\overrightarrow{\not\partial}_x + i\overleftarrow{\not\partial}_y)G^{-+}_{\beta\alpha}(x,y))_{|y=x}$
- In the end, from the equation for $\Delta n(t)$ we obtain a Boltzmann equation for $\Delta_\ell(z)$

$$sHz\frac{d(\Delta_\ell)_{\alpha\beta}}{dz} = \epsilon^\Delta_{\alpha\beta}D_\Delta + \epsilon^S_{\alpha\beta}D_S + \epsilon^T_{\alpha\beta}D_T - \mathcal{W}_{\alpha\beta}$$

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



- One obtains the evolution equation for the density matrix by noticing that $\frac{d\Delta n_{\alpha\beta}}{dt} = -\mathrm{Tr}((i\overrightarrow{\partial\!\!\!/}_x + i\overleftarrow{\partial\!\!\!/}_y)G^{-+}_{\beta\alpha}(x,y))_{|y=x}$
- In the end, from the equation for $\Delta n(t)$ we obtain a Boltzmann equation for $\Delta_\ell(z)$

$$sHz\frac{d(\Delta_\ell)_{\alpha\beta}}{dz} = \epsilon^{\Delta}_{\alpha\beta}D_\Delta + \epsilon^{S}_{\alpha\beta}D_S + \epsilon^{T}_{\alpha\beta}D_T - \mathcal{W}_{\alpha\beta}$$

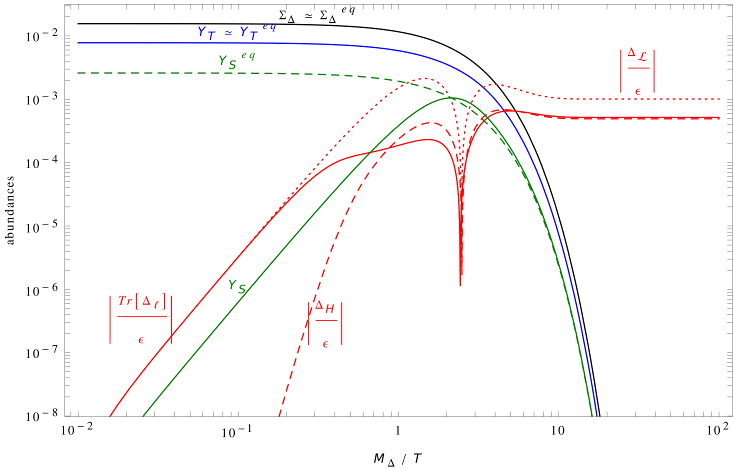


Figure: Evolution of the abundances for $M_\Delta = M_S = M_T = 10^{13}$ GeV, $m_1 = 10^{-3}$ eV and $\mu/M_\Delta = 0.2$

Final baryon asymmetry

- Before the action of sphalerons

$$Y_{B-L} = \Delta_{\bar{\mathcal{L}}_1} - \mathrm{Tr}(\Delta_\ell)$$

- In the end, we obtain the BAU

$$\frac{n_B}{n_\gamma} = 7.04 \times C \times Y_{B-L}$$

- To be viable, the model must accomodate

$$\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

Final baryon asymmetry

- Before the action of sphalerons

$$Y_{B-L} = \Delta_{\bar{\mathcal{L}}_1} - \mathrm{Tr}(\Delta_\ell)$$

- In the end, we obtain the BAU

$$\frac{n_B}{n_\gamma} = 7.04 \times C \times Y_{B-L}$$

- To be viable, the model must accomodate

$$\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

Final baryon asymmetry

- Before the action of sphalerons

$$Y_{B-L} = \Delta_{\bar{\mathcal{L}}_1} - \mathrm{Tr}(\Delta_\ell)$$

- In the end, we obtain the BAU

$$\frac{n_B}{n_\gamma} = 7.04 \times C \times Y_{B-L}$$

- To be viable, the model must accomodate

$$\frac{n_B}{n_\gamma} \sim 6 \times 10^{-10}$$

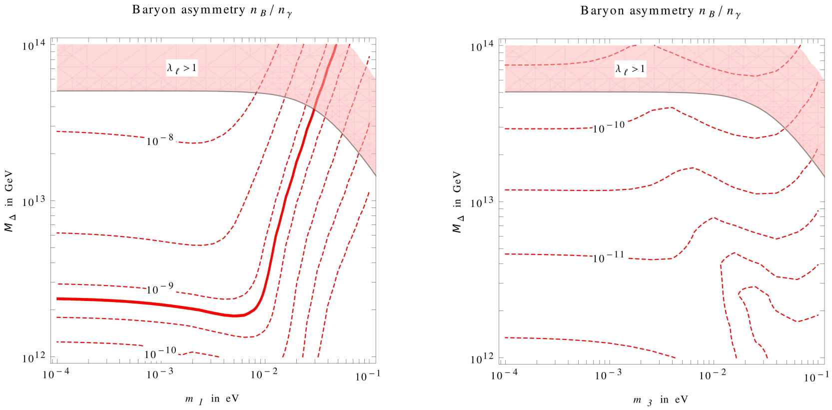


Figure: Final baryon asymmetry as a function of m_1 (normal hierarchy) or m_3 (inverted hierarchy) and $M_\Delta = M_S = M_T$ for $\mu / M_\Delta = 0.2$. The red line indicates the observed BAU $\sim 6 \times 10^{-10}$.

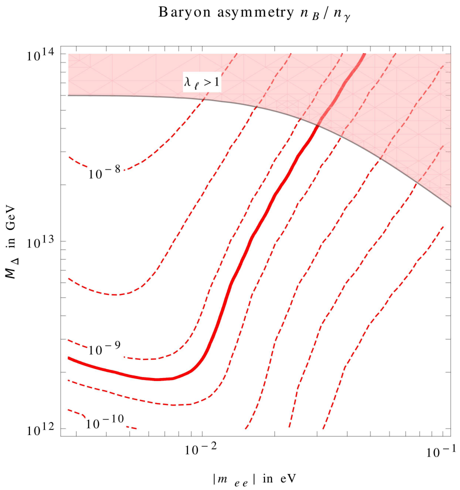


Figure: Final baryon asymmetry as a function of $|(m_\nu)_{ee}|$ and $M_\Delta = M_S = M_T$ for $\mu/M_\Delta = 0.2$.

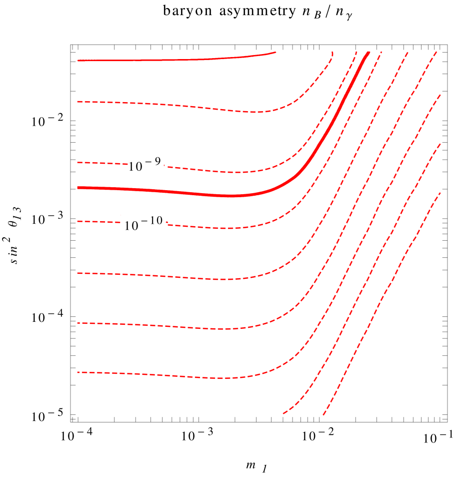


Figure: Final baryon asymmetry as a function of m_1 and $\sin^2 \theta_{13}$ for $M_\Delta = M_S = M_T = 10^{13}$ GeV, $\mu / M\Delta = 0.2$.

Conclusion

- This scenario can account for a successful baryogenesis
- The result is closely related to neutrino parameters thanks to the relation

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

- This scenario happens at a huge energy scale since $M_\Delta > 10^{12}$ GeV $\rightarrow$ it cannot be tested directly
- But this scenario could be ruled out
  -for too large values of $|(m_\nu)_{ee}|$ or m_1
  -if the hierarchy is inverted

Conclusion

- This scenario can account for a successful baryogenesis
- The result is closely related to neutrino parameters thanks to the relation

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

- This scenario happens at a huge energy scale since $M_\Delta > 10^{12}$ GeV
  $\rightarrow$ it cannot be tested directly
- But this scenario could be ruled out
  -for too large values of $|(m_\nu)_{ee}|$ or m_1
  -if the hierarchy is inverted

Conclusion

- This scenario can account for a successful baryogenesis
- The result is closely related to neutrino parameters thanks to the relation

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

- This scenario happens at a huge energy scale since $M_\Delta > 10^{12}$ GeV
$\rightarrow$ it cannot be tested directly
- But this scenario could be ruled out
-for too large values of $|(m_\nu)_{ee}|$ or m_1
-if the hierarchy is inverted

Conclusion

- This scenario can account for a successful baryogenesis
- The result is closely related to neutrino parameters thanks to the relation

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

- This scenario happens at a huge energy scale since $M_\Delta > 10^{12}$ GeV $\rightarrow$ it cannot be tested directly
- But this scenario could be ruled out
  -for too large values of $|(m_\nu)_{ee}|$ or m_1
  -if the hierarchy is inverted

The underlying $SO(10)$ model

$$\overbrace{16_i}^{SO(10)} = \overbrace{\underbrace{10_i^{16}}_{(Q_i, u_i^c, e_i^c)} \oplus \underbrace{\bar{5}_i^{16}}_{(\mathcal{L}_i, \bar{\mathcal{D}}_i)} \oplus \underbrace{1_i^{16}}_{\nu_i^c}}^{SU(5)}$$

$$10_i = \underbrace{5_i^{10}}_{(\bar{\mathcal{L}}_i, \mathcal{D}_i)} \oplus \underbrace{\bar{5}_i^{10}}_{(\ell_i, d_i^c)}$$

$$54 = \underbrace{15 \oplus \overline{15}}_{(\Delta, \Delta^\dagger)} \oplus \underbrace{24}_{(S, T)}$$

Lagrangian

$$\mathcal{L} = \frac{1}{2} f_{ij} 10_i \, 10_j \, 54 + \frac{1}{2} \mu 10_H \, 10_H \, 54 + \frac{1}{2} M_{54}^2 54^2$$

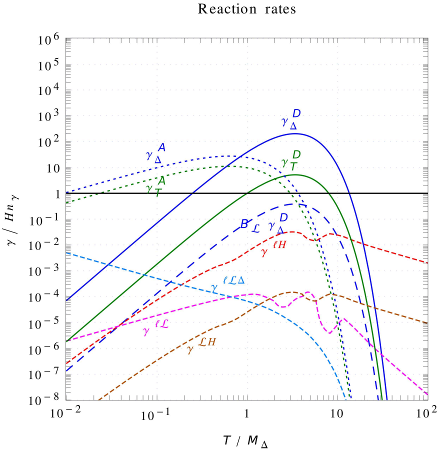


Figure: Space-time densities of reactions γ as a function of T/M_Δ, compared to Hn_γ

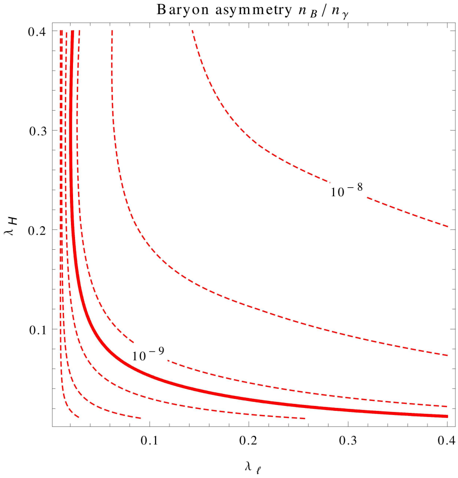


Figure: Final baryon asymmetry as a function of $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$ and $\lambda_H = \mu/M_\Delta$ for $m_1 = 10^{-3}$ eV (normal hierarchy).

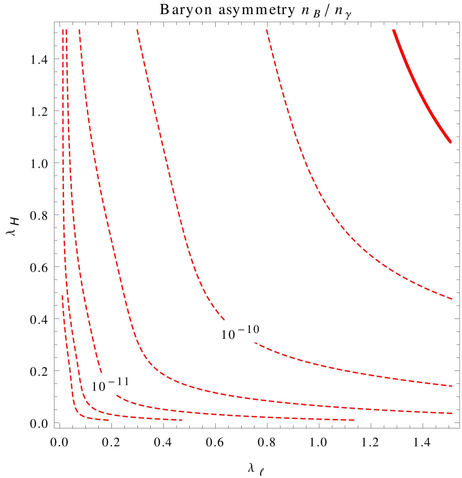


Figure: Final baryon asymmetry as a function of $\lambda_\ell = \sqrt{\mathrm{Tr}(ff^\dagger)}$ and $\lambda_H = \mu/M_\Delta$ for $m_3 = 10^{-3}$ eV (inverted hierarchy).