Leptogenesis on an S3 model

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Outline

1. Problem
2. The Model
   - S3 Model
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Introduction

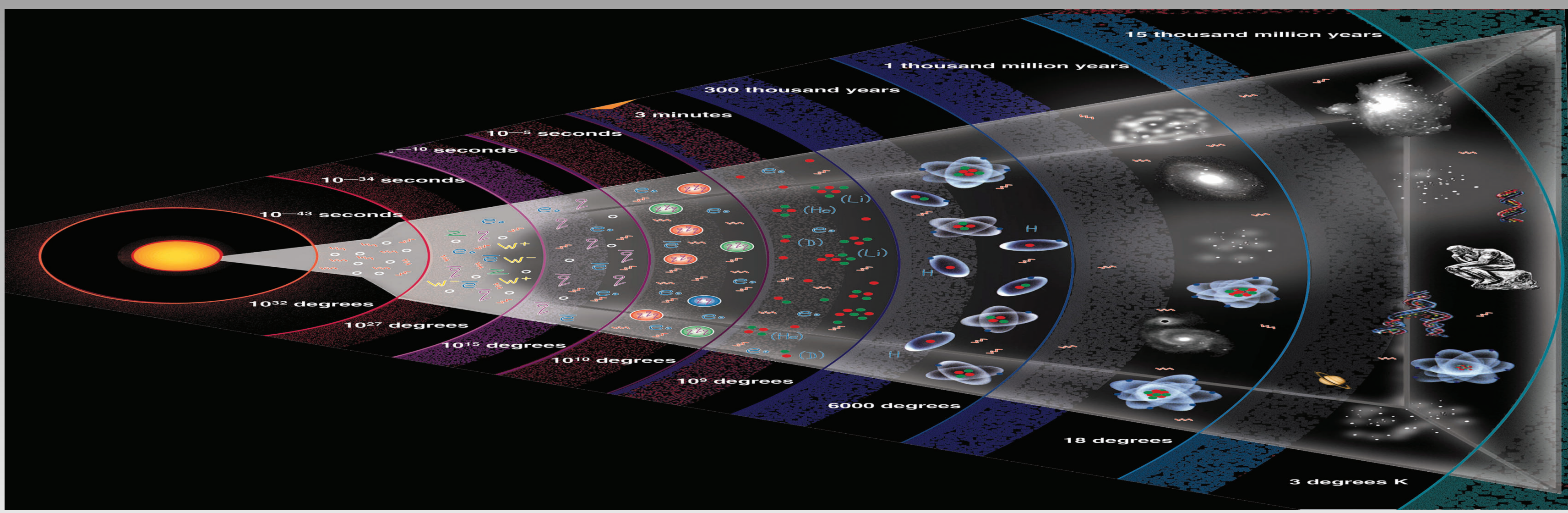
- Dirac predicted the existence of antimatter in the year 1928.
- The positron was first seen in the year 1932.
- The baryon asymmetry is $Y_B = \frac{\eta_B - \eta_{\overline{B}}}{s}$.

Introduction

- Exploring probes have not found antimatter in the solar system.
- The ratio of protons and anti-protons is $\frac{\overline{p}}{p} \approx 10^{-4}$.
- If large areas of the Universe were mainly constituted of antimatter, the interface between this areas would produce gamma ray radiation and distortions on the Microwave Background Radiation.
- $Y_B = (8.75 \pm 0.23) \times 10^{-11}$.
- There is more matter than antimatter!!!

Cosmological Importance

- The baryon asymmetry is very important for Cosmology.
- Nucleosynthesis is very sensitive to matter and antimatter values, if the baryon asymmetry would have been different, the formation of galaxies and stars would be different also.



S3 Model

- The Standard Model doesn't explain the baryon asymmetry.
- How to extend the Standard Model?
- The Standard Model is created by symmetries.
- We add a new flavour symmetry.
- The smallest non-abelian group is the S3.
- S3 is the permutational group of three objects.

S3 Symmetry

- The usual representation is the three dimensional one, it can be taken apart in two irreductible representations.
- Of dimension one.
- Of dimension two.

S3 Model

- The particles of the Standard Model are,

$$Q^T = (u_L, d_L), u_R, d_R, L^T = (\nu_L, e_L), e_R, \nu_R, H,$$

It is shown the SU(2) doublets explicitly.

- We add I,J indices for the doublets and 3 for the singlets.
- We add two Higgs doublets H_D.
- In order to guarantee the right values of Z,W bosons, the condition $< H_s >^2 + < H_1 >^2 + < H_2 >^2 = (246\text{GeV})^2/2$ is needed.

Modelo S3

- The most general Lagrangian is,
- $$L_Y = L_{Y_D} + L_{Y_U} + L_{Y_E} + L_{Y_\nu}$$
- $$\begin{aligned} L_{Y_D} &= -Y_I^d \overline{Q_I} H_S d_{IR} - Y_3^d \overline{Q_3} H_S d_{3r} \\ &\quad -Y_2^d [\overline{Q_I} \kappa_{IJ} H_I d_{JR} - \overline{Q_I} \eta_{IJ} H_2 d_{JR}] \\ &\quad -Y_4^d \overline{Q_3} H_I d_{IR} - Y_5^d \overline{Q_I} H_I D_{3R} + h.c. \\ L_{Y_U} &= -Y_1^u \overline{Q_I} (i\sigma_2 H_S^* u_{IR}) - Y_3^u \overline{Q_3} (i\sigma_2 H_S^* u_{3R}) \\ &\quad -Y_2^u [\overline{Q_I} \kappa_{IJ} (i\sigma_2 H_1^* u_{JR}) - \overline{Q_I} \eta_{IJ} (i\sigma_2 H_2^* u_{JR})] \\ &\quad -Y_4^u \overline{Q_3} (i\sigma_2 H_I^* u_{IR}) - Y_5^u \overline{Q_I} (i\sigma_2 H_I^* u_3 R) + h.c. \end{aligned}$$

S3 Model

- $$\begin{aligned} L_{Y_E} &= -Y_1^e \overline{L_I} H_S e_{IR}) - Y_3^e \overline{L_3} H_S e_{3R}) \\ &\quad -Y_2^e [\overline{L_I} \kappa_{IJ} H_1 e_{JR} - \overline{L_I} \eta_{IJ} H_2 e_{JR})] \\ &\quad -Y_4^e \overline{L_3} H_I e_{IR} - Y_5^e \overline{L_I} H_I D_{3R} + h.c. \\ L_{Y_\nu} &= -Y_1^\nu \overline{L_I} (i\sigma_2 H_S^* \nu_{IR}) - Y_3^\nu \overline{L_3} (i\sigma_2 H_S^* \nu_{3R}) \\ &\quad -Y_2^\nu [\overline{L_I} \kappa_{IJ} (i\sigma_2 H_1^* \nu_{JR}) - \overline{L_I} \eta_{IJ} (i\sigma_2 H_2^* \nu_{JR})] \\ &\quad -Y_4^\nu \overline{L_3} (i\sigma_2 H_I^* \nu_{IR}) - Y_5^\nu \overline{L_I} (i\sigma_2 H_I^* \nu_3 R) + h.c., \end{aligned}$$

where σ are the Pauli matrices

$$\kappa = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \eta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

S3 Model

- We are going to add a Majorana mass term for the right handed neutrinos,

$$L_M = -M_1 \nu_{IR}^T C \nu_{IR} - M_3 \nu_{3R}^T C \nu_{3R}. \quad (1)$$

- The model includes a Z2 symmetry.
- The Z2 symmetry vanishes some elements of the Lagrangian.

  some of them $Y_1^{\nu} = Y_5^{\nu} = 0$

S3 Model

- The S3 model is a good extension of the SM.
- The model predicts a non-zero mixing angle θ_{13}.
- The model explains the interactions of the Standard Model with less parameters.
- It has been added two Higgs doublets.

See-Saw Mechanism

- The neutrinos mass is:

$$\frac{m_{D_1}^2}{M_1}, \quad \frac{m_{D_2}^2}{M_2}, \quad \frac{m_{D_3}^2}{M_3}, \quad M_1, \quad M_2, \quad M_3.$$

where m_{D_i} and M_i are values of the matrices M_D and M_R.

- This mechanism explains why the neutrino's masses are so low.

Neutrinos

- The Dirac mass is:

$$L_D = m_D \overline{\nu}\nu = M_D \overline{\nu}_L N_R + h.c.$$

- The Majorana mass is:

$$L_M = -M_1 \nu_{IR}^T C \nu_{IR} - M_3 \nu_{3R}^T C \nu_{3R}.$$

- The two mass terms can be combined in to the Lagrangian

$$L_{\nu \text{mass}} = \frac{1}{2} \omega_L^T C^{-1} M_{D+M} \omega_L + h.c..$$

with

$$M_{D+M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \quad \omega_L = \begin{pmatrix} \nu_L \\ C(\overline{\nu}_R)^T \end{pmatrix}$$

Neutrinos

- From the Lagrangian of the S3 model we can read the neutrino matrix.

$$M_D = \begin{pmatrix} \mu_2^\nu & \mu_2^\nu & 0 \\ \mu_2^\nu & -\mu_2^\nu & 0 \\ \mu_4^\nu & \mu_4^\nu & \mu_3^\nu \end{pmatrix}.$$

enforcing $M_1 = M_2$

- The M_ν

$$M_\nu = \begin{pmatrix} 2(\rho_2^\nu)^2 & 0 & 2\rho_2^\nu\rho_4^\nu \\ 0 & 2(\rho_2^\nu)^2 & 0 \\ 2\rho_2^\nu\rho_2^\nu & 0 & 2(\rho_4^\nu)^2 + 2(\rho_3^\nu)^2 \end{pmatrix}$$

where $\rho_2^\nu = (\mu_2^\nu)/M_1^{1/2}, \rho_4^\nu = (\mu_4^\nu)/M_1^{1/2}, \rho_3^\nu = (\mu_3^\nu)/M_3^{1/2}$

Neutrinos On The S3 Model

- The mass matrix M_ν can be taken to diagonal form through the bi-unitary transformation U

$$U_\nu^T M_\nu U_\nu = diag(|m_{\nu 1}|e^{i\phi_1}, |m_{\nu 2}|e^{i\phi_2}, |m_{\nu 3}|e^{i\phi_3},)$$

where

$$|m_{\nu 1}|Sin\phi_1 = |m_{\nu 2}|Sin\phi_2 = |m_{\nu 3}|Sin\phi_3.$$

is required to ensure the unitary of U.

Neutrinos On The S3 Model

- For U to diagonalize the mass matrix

$$M_\nu = \begin{pmatrix} m_{\nu 3} & 0 & z \\ 0 & m_{\nu 3} & 0 \\ z & 0 & (m_{\nu 1} + m_{\nu 2} - m_{\nu 3}) e^{-2i\delta_\nu} \end{pmatrix},$$

$$\text{where } z = \sqrt{(m_{\nu 3} - m_{\nu 1})(m_{\nu 2} - m_{\nu 3})} e^{-i\delta_\nu}.$$

Md Matrix

- We can calculate the md matrix in terms of the neutrinos masses

$$M_d = \begin{pmatrix} \sqrt{\frac{m_3 M_2}{2}} & \sqrt{\frac{m_3 M_2}{2}} & 0 \\ \sqrt{\frac{m_3 M_2}{2}} & -\sqrt{\frac{m_3 M_2}{2}} & 0 \\ \frac{\sqrt{M_2(m_3-m_1)(m_2-m_3)e^{i\delta}}}{\sqrt{2m_3}} & \frac{\sqrt{M_2(m_3-m_1)(m_2-m_3)e^{i\delta}}}{\sqrt{2m_3}} & a \end{pmatrix}.$$

With

$$a = \sqrt{M_3(e^{-2i\delta}(m_1 + m_2 - m_3) - \frac{e^{-2i\delta}(m_2 - m_3)(-m_1 + m_3)}{m_3})}.$$

Baryogenesis

- Baryogenesis is the term for processes in the early universe that lead to an asymmetry between baryons and antibaryons.

Renormalization Group

- Leptogenesis occurs at high energy, that is why it is important to take in account the renormalization group effect.
- The renormalization Group Equations are different than those for the SM due to the three Higgs doublets.

$$16\pi^2 \frac{dY_i}{dt} = \Sigma_{k=1}^{n_h} (T_{ik} Y_k + Y_k Y_k^\dagger Y_i + \frac{1}{2} Y_i Y_k^\dagger Y_k) - \frac{9g^2 + 15g'}{4} Y_i$$

where T_{ij} is

$$T_{ij} = tr(Y_i Y_j^\dagger).$$

Leptogenesis

- Is there any way to generate lepton asymmetry?
- The S3 Lagrangian has terms like

$$L = \ldots \quad - Y_1^{\nu} \overline{L_I} (i\sigma_2 H_S^* \nu_{IR}) \quad \ldots \tag{2}$$

- This allow right handed neutrinos to decay in to left handed ones.

$$\nu_R \longrightarrow \nu.$$

- The Lepton and the Baryon Number are not conserved quantities, nevertheless $B - L$ is, so

$$L \longrightarrow B.$$

Leptogenesis

- The first Feynman diagrams of the right handed neutrino decays are

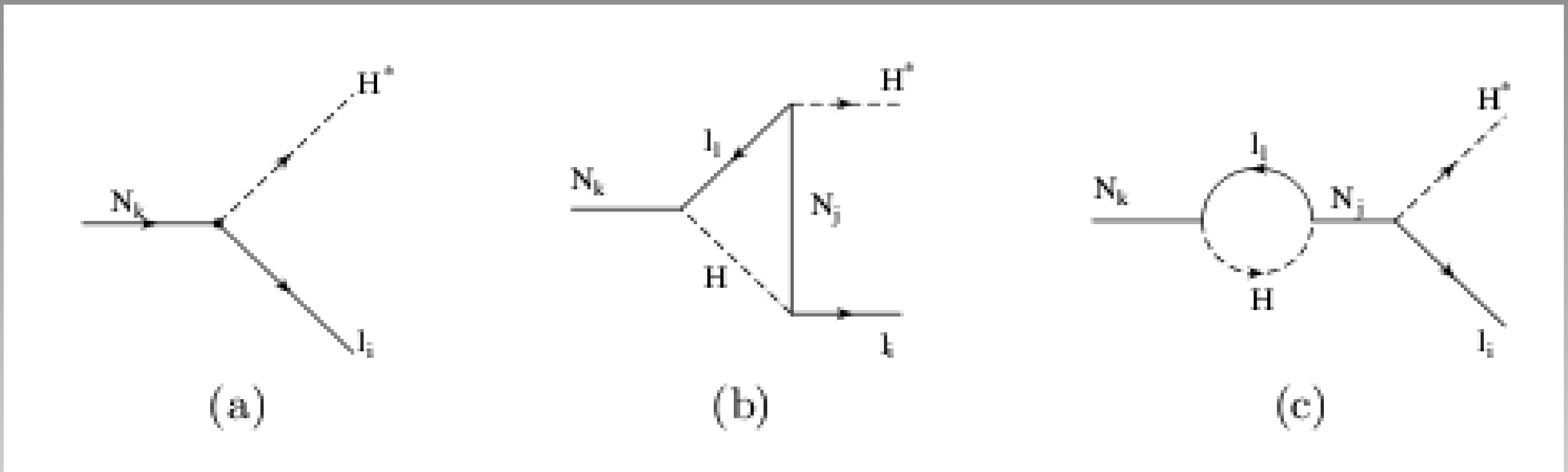


Fig 2.1 a) At tree level. b) One loop diagram. c) Self-interaction diagram.

Leptogenesis

- Replacing

$$-Y_1^{\nu}\overline{L_I}(i\sigma_2 H_S^* \nu_{IR}) \longleftrightarrow h_{ij}\nu_{R_i}\overline{L}_j H.$$

- The decay rate for the neutrinos is

$$\Gamma_{D_i} = \sum_{\alpha}[\Gamma(\nu_i \to H + \ell_\alpha) + \Gamma(\nu_i \to \overline{H} + \overline{\ell}_\alpha)]$$

$$= \frac{1}{8\pi}(hh^\dagger)_{ii} M_i.$$

- The Lepton CP asymmetry is

$$\epsilon_1 = \frac{\sum_\alpha \Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})}{\sum_\alpha \Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})}.$$

Leptogenesis

- We calculate the asymmetry

$$\epsilon \simeq -\frac{3}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)}\sum_{i=2,3} Im\{(h_\nu h_\nu^\dagger)^2_{1i}\}[f(\frac{M_i^2}{M_1^2}) + g(\frac{M_i^2}{M_1^2})],$$

- $f(x)$ is from the loop diagram (Fig 2.1 (a))

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

- $g(x)$ is from the self-interaction diagram (Fig 2.1 (c))

$$g(x) = \frac{\sqrt{x}}{1-x}.$$

Leptogenesis

- The baryon and the lepton asymmetry are related by the Sphalerion process

$$Y_B = a(Y_{B-L}) = \frac{a}{a-1} Y_L,$$

where a is $a = (8N_f + 4N_H)/(22N_f + 13N_H)$ and

$$Y_L = \frac{n_L - n_{\bar{L}}}{s} = \kappa \frac{\epsilon_i}{g*}.$$

Leptogenesis

- g is 110, the relativistic freedom number, κ is obtained from the Boltzman equations, we can reparameterized κ,

$$\kappa \approx \frac{0.3}{K(ln(K))^{0.6}} \quad \text{for} \quad 10 < K < 10^6$$

$$\kappa \approx \frac{1}{2\sqrt{K^2+9}} \quad \text{for} \quad 0 < K < 10,$$

where $k = \Gamma_1/H < 1$ describes off-thermal equilibrium process, $\kappa < 1$ describe the washout effects.

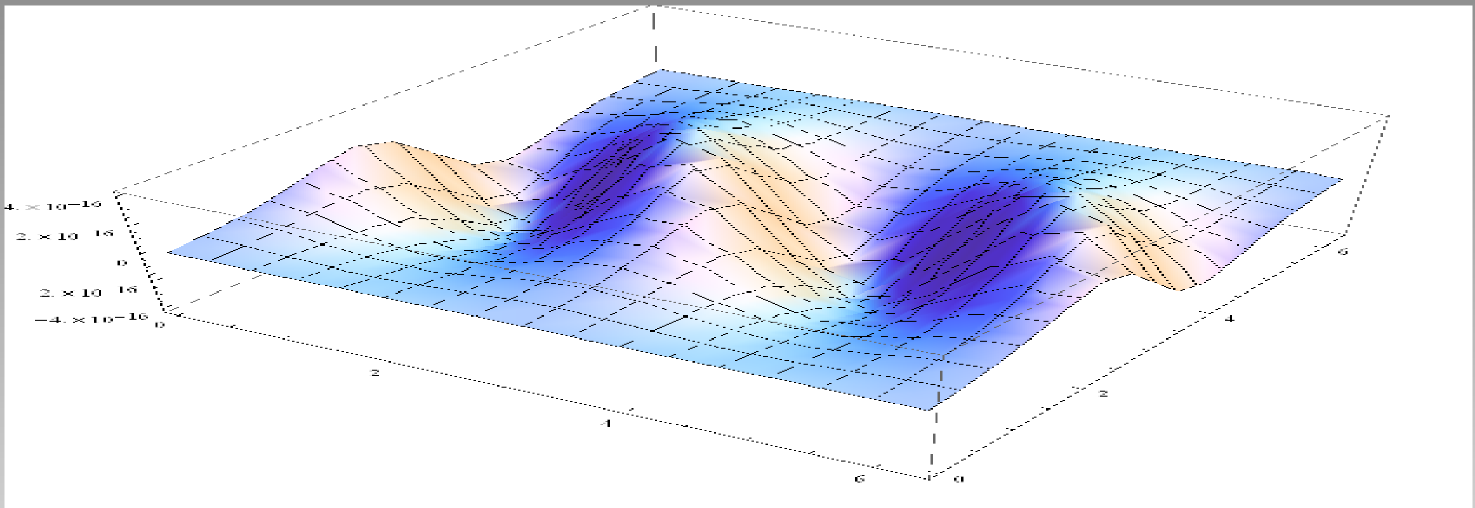
Leptogenesis

with

$$K = \frac{M_{pl}}{1.66\sqrt{g*}(8\pi v^2)} \frac{(m_D^\dagger m_D)_{11}}{M_1}.$$

Results

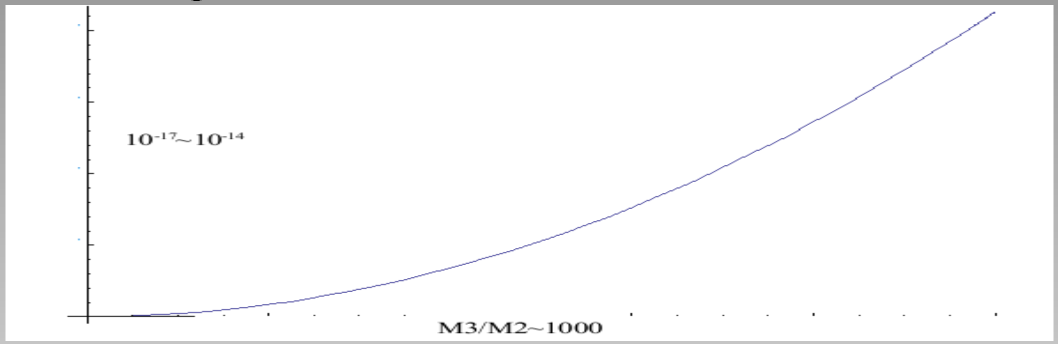
- We can calculate the asymmetry as function of the phases, θ_1 and δ.



- The maximum is reached when $\delta = \frac{3\pi}{4}$ and $\theta_1 = \pi$.

Results

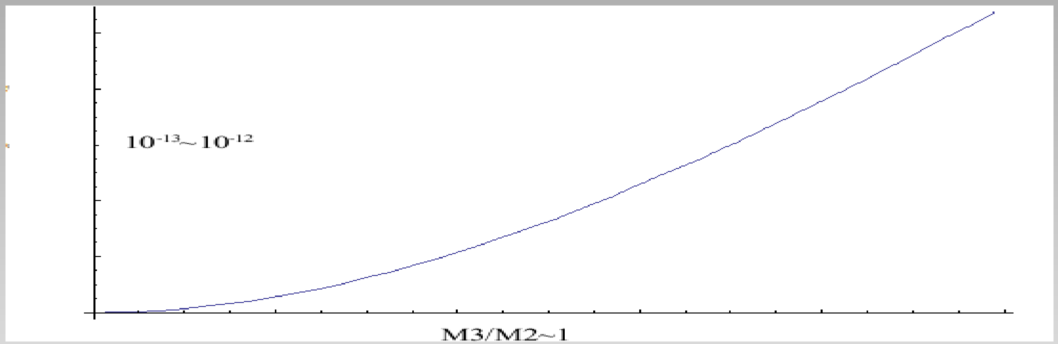
- Baryon asymmetry as function of the difference of masses $M2$ and $M3$.



Results

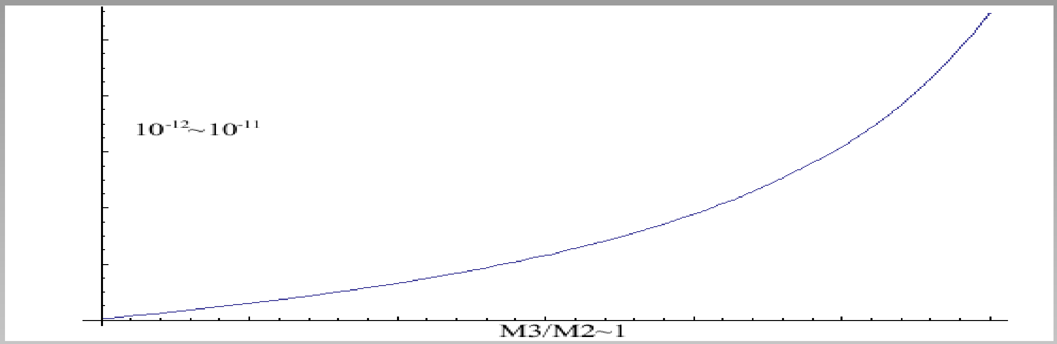
- For close masses we have to take into account the condition $|\Gamma_1 - \Gamma_i| << |M_1 - M_i|$.
- When the masses M_1 and M_2 are of the same order.

If $|\Gamma_1 - \Gamma_i| \sim |M_1 - M_i|$, we can't take into account the self-interaction contribution.



Results

If $|\Gamma_1 - \Gamma_i| << |M_1 - M_i|$.



Conclusions

- The S3 model is a good extension of the SM.
- The texture of the mass matrices and the Yukawa matrices doesn't change in high energies.
- Leptogenesis is very dependent on the phases.
- The S3 model show a contribution to Leptogenesis, this contribution can be considerable with specific values of phases and masses.

Conclusions

Thanks!!!