Research Project: Theoretical astroparticle physics

SAPIENZA
UNIVERSITÀ DI ROMA

IMPRS Recruiting Workshop

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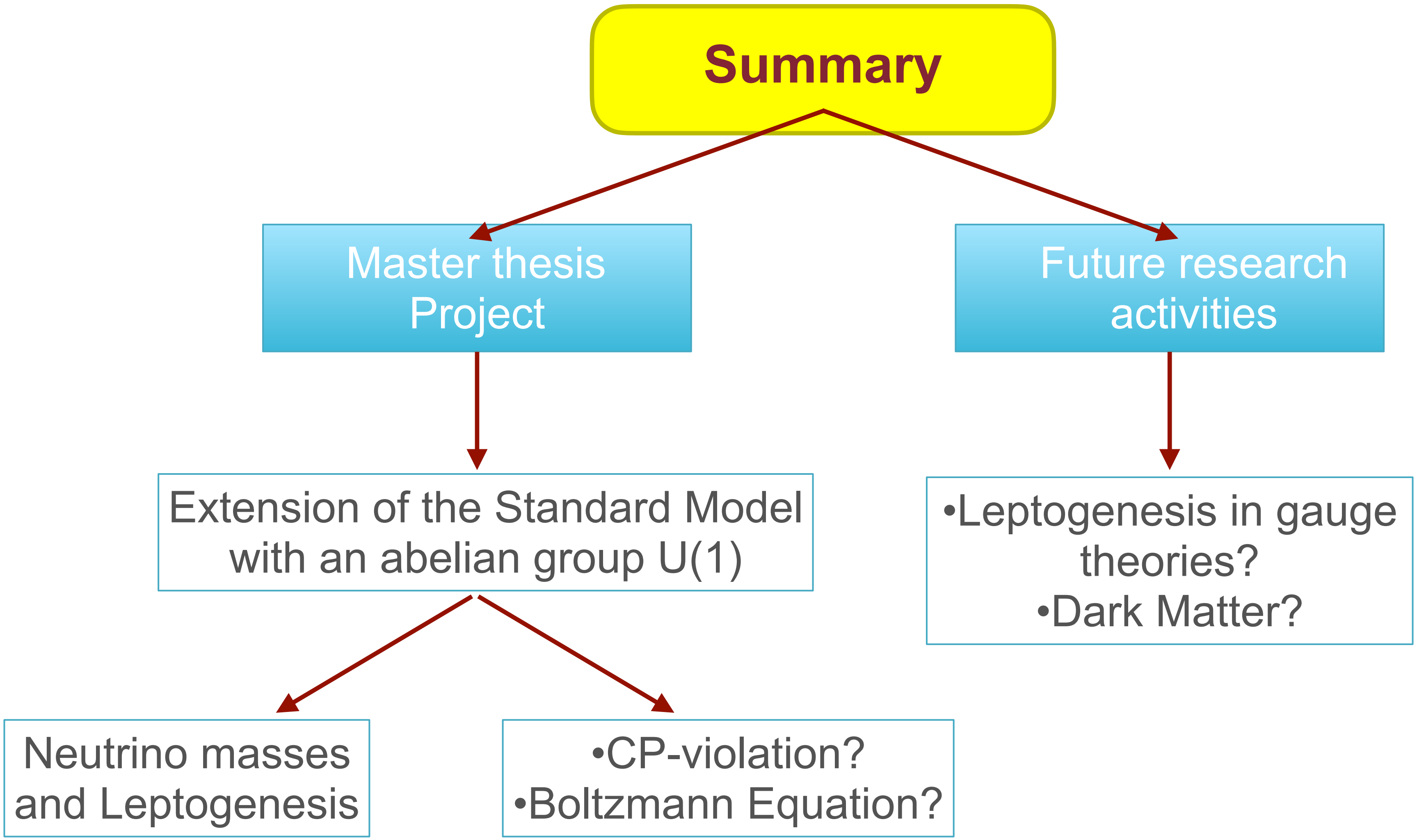

Summary
Master thesis Project
Future research activities
Extension of the Standard Model with an abelian group U(1)
•Leptogenesis in gauge theories?
•Dark Matter?
Neutrino masses and Leptogenesis
•CP-violation?
•Boltzmann Equation?

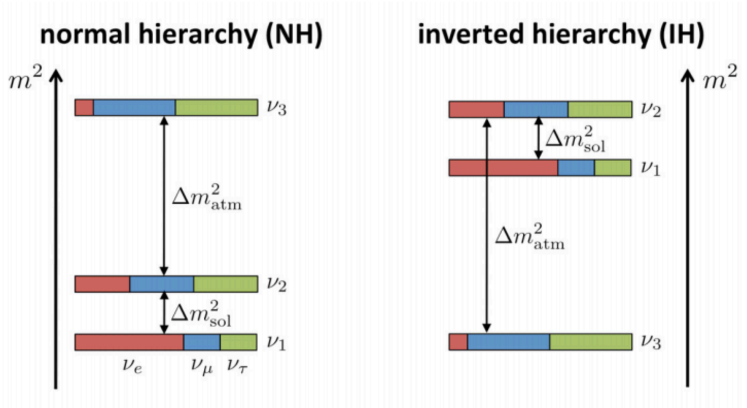
Pontecorvo-Maki-Nakagawa-Sakata Matrix

Leptonic sector defined by 9 parameters + 1 phase:

- 6 masses: $\{m_e, m_\mu, m_\tau, m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau}\}$
- 3 angles: $\{\theta_{12}, \theta_{23}, \theta_{13}\}$
- 1 phase: $\{\delta_{cp}\}$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \sim 7.4 \times 10^{-5} eV^2$$

$$|\Delta m_{32}|^2 = |m^2_3 - m^2_2| \sim 2.4 \times 10^{-3} eV^2$$



$R(\theta_{23})$ $R(\theta_{13}, \delta_{\mathrm{cp}})$ $R(\theta_{12})$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{23}c_{13} \end{bmatrix}$$

$$\Delta m^2_{21} << \Delta m^2_{32}$$

Abelian $U(1)_{L_e - L_\mu - L_\tau}$ flavor symmetry

Majorana Neutrinos

$l_i \sim (+1, -1, -1)$

Dim-5 Weinberg Operator

$$\mathscr{L}^{lo} = \frac{1}{M}\left(x_{12} l_e l_\mu + x_{13} l_e l_\tau\right) H_u H_u + \text{h.c}$$

$$m_\nu = m_0 \begin{pmatrix} 0 & 1 & x \\ 1 & 0 & 0 \\ x & 0 & 0 \end{pmatrix}$$

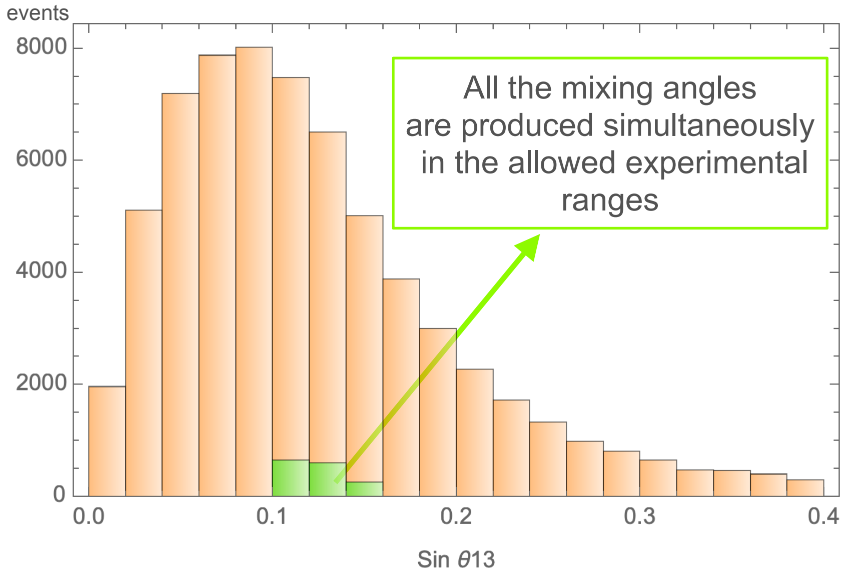
Inverted mass spectrum
$m_1 = -m_2, \quad m_3 = 0$

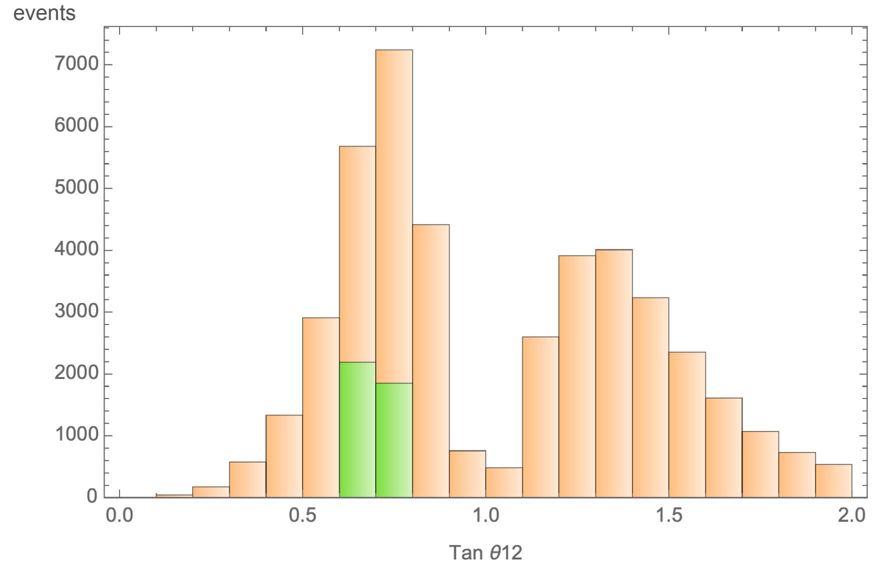
$\theta_{12} = \pi/4, \quad \tan\theta_{23} = x, \quad \theta_{13} = 0$

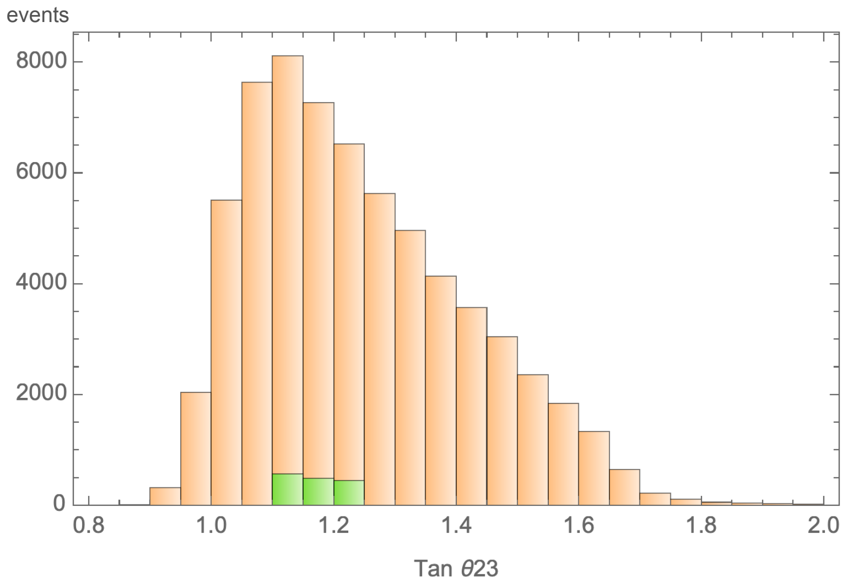
Experimental values:
- $\theta_{13} = 8.64^{\circ}{}^{+0.12^{\circ}}_{-0.13^{\circ}}$
- $\theta_{12} = 33.45^{\circ}{}^{+0.75^{\circ}}_{-0.78^{\circ}} \equiv \theta$sol
- $\theta_{23} = 49.3^{\circ}{}^{+0.9^{\circ}}_{-1.1^{\circ}} \equiv \theta$atm
- $r = \dfrac{\Delta m^2_{sun}}{\Delta m^2_{atm}} \sim 0.03$

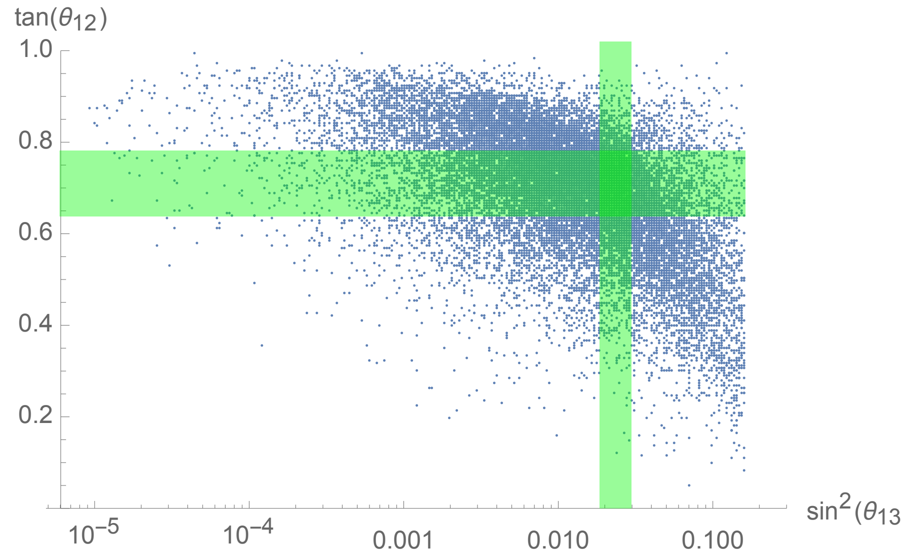
corrections are needed

Introducing two flavons the additional U(1) symmetry is broken

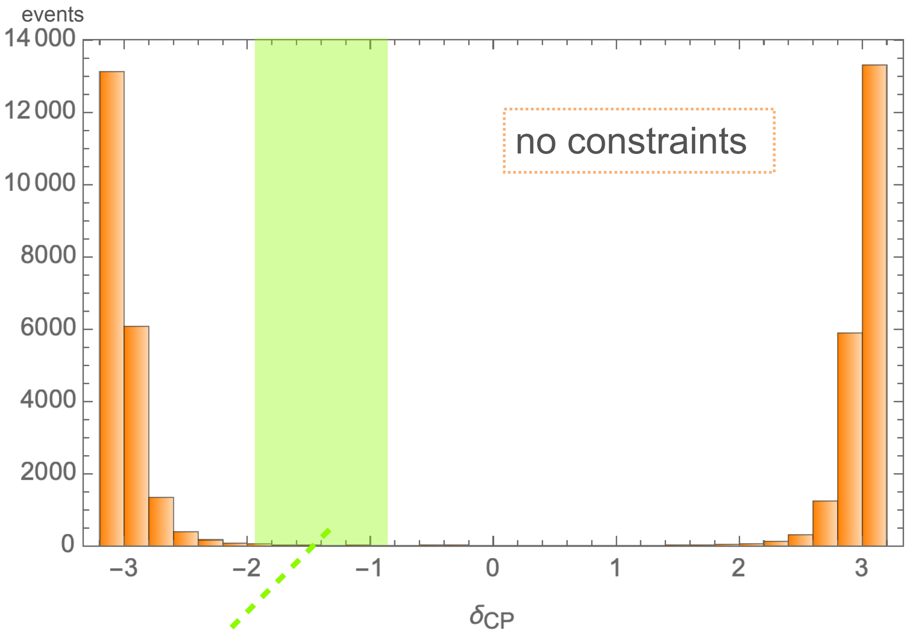

events
8000
6000
4000
2000
0
0.0
0.1
0.2
0.3
0.4
Sin θ13
All the mixing angles
are produced simultaneously
in the allowed experimental
ranges


events
7000
6000
5000
4000
3000
2000
1000
0
0.0
0.5
1.0
1.5
2.0
Tan θ12


events
8000
6000
4000
2000
0
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Tan θ23

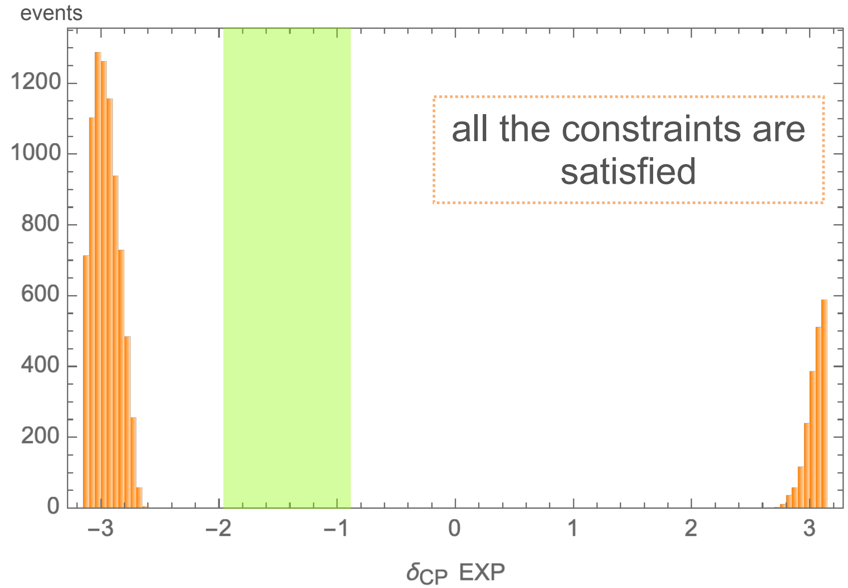

tan(θ12)
1.0
0.8
0.6
0.4
0.2
10^-5
10^-4
0.001
0.010
0.100
sin^2(θ13)

Numerical evaluation of δ_{cp}



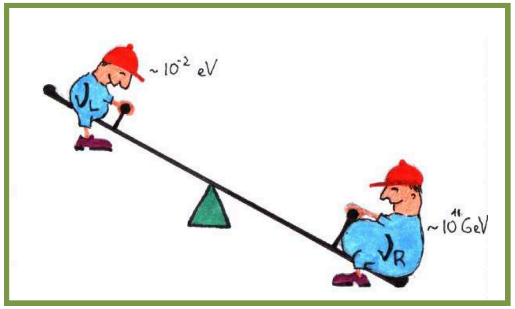
1σ C.L. expected range

If we impose to reproduce simultaneously all the three mixing angles, the parameter r and the charged leptons mass hierarchy in the right allowed experimental ranges, in the distribution of δ_{cp} there is hardly any point falling within the expected ranges.



The model is CP-conserving

Baryogenesis through leptogenesis



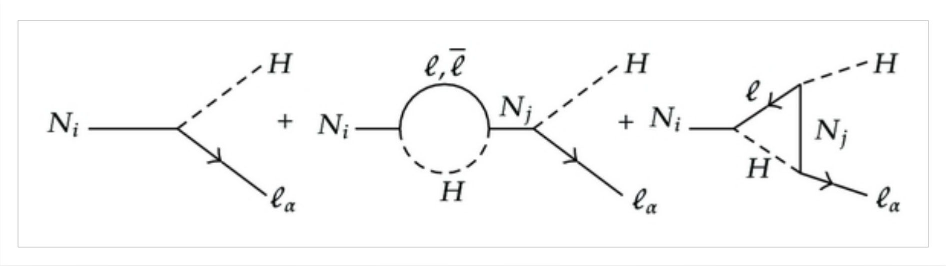
3 right-handed neutrinos $N_R(1,0)$ are introduced via a type-I seesaw

$$m_\nu = -\, m_D^T M_R^{-1} m_D$$

Heavy neutrino mass spectrum:

$$M_1 \sim M_2 \sim 10^{15}\ \text{GeV}$$

$$M_3 \sim 10^{13}\ \text{GeV} \ll M_{1,2}$$



$M_3 \leq T_{\text{reh}} \ll M_{1,2}$

Single flavored regime

SIMPLIFIED FORM

$$Y_{\Delta B} \simeq \frac{135\zeta(3)}{4\pi^4 g_*} \sum_\alpha \varepsilon_{3\alpha} \times \eta_\alpha \times C$$

- $\varepsilon_{3\alpha}$: CP asymmetry parameter
- η_α : efficiency factor
- C : Lepton and B+L violation coefficient

Evaluation of the CP-violation parameter ε_3

The *hat* matrices are the Dirac mass matrices evaluated in the basis in which the Majorana mass matrix is diagonal

$$\hat{m}_D = \begin{pmatrix} \frac{e^{i\alpha}(c-d\lambda^2)}{\sqrt{2}} & \frac{(-a+d\lambda^2)}{\sqrt{2}} & \frac{-b+d\lambda^2}{\sqrt{2}} \\ \frac{e^{i\alpha}(c+d\lambda^2)}{\sqrt{2}} & \frac{(+a+d\lambda^2)}{\sqrt{2}} & \frac{+b+d\lambda^2}{\sqrt{2}} \\ \left(d+\frac{\sqrt{2}cme^{i\alpha}}{W-Z}\right)\lambda^2 & d\lambda^2 & d\lambda^2 \end{pmatrix}.$$

$$\varepsilon_3 = \frac{1}{8\pi v^2}\frac{1}{(\hat{m}_D\hat{m}_D^\dagger)_{33}}\sum_{i=1,2}\mathrm{Im}\left[(\hat{m}_D\hat{m}_D^\dagger)_{3i}\right]^2 f\left(\frac{M_i^2}{M_3^2}\right)$$

$$\varepsilon_3 \simeq 3.9\cdot 10^{-4}\cos\alpha\sin\alpha$$

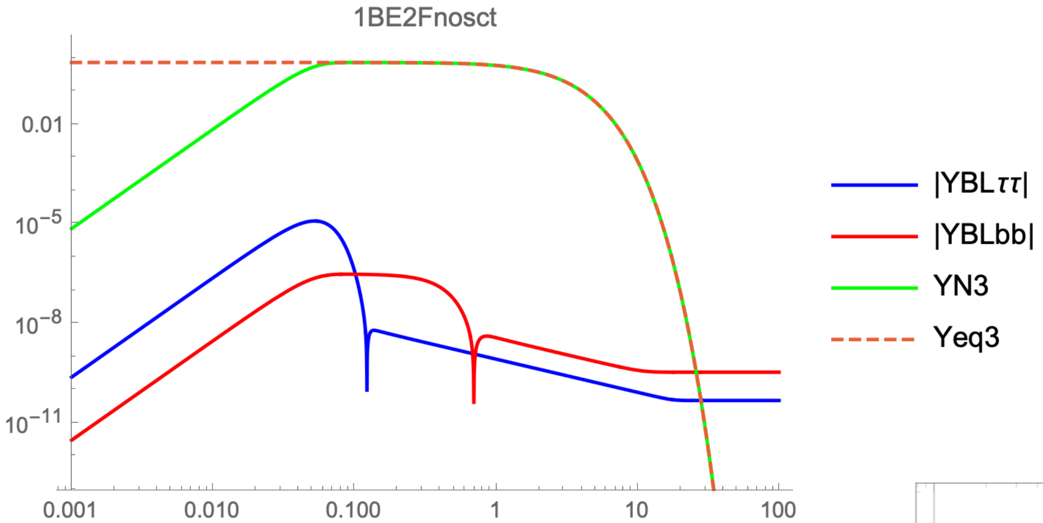
to reproduce the right amount of baryon asymmetry $\varepsilon_3 \sim O(10^{-7}) - O(10^{-5})$ is required

in our model the phase α is a totally free parameter, so that we can assume: $\alpha \sim 10^{-\kappa}$

$$\varepsilon_3 \simeq 3.9\cdot 10^{-4-\kappa}$$

Considering $1 \le \kappa \le 3$ we obtain a value of ε_3 compatible, with some ambiguities, with the requirement needed in order to reproduce the right amount of baryon asymmetry in the Universe

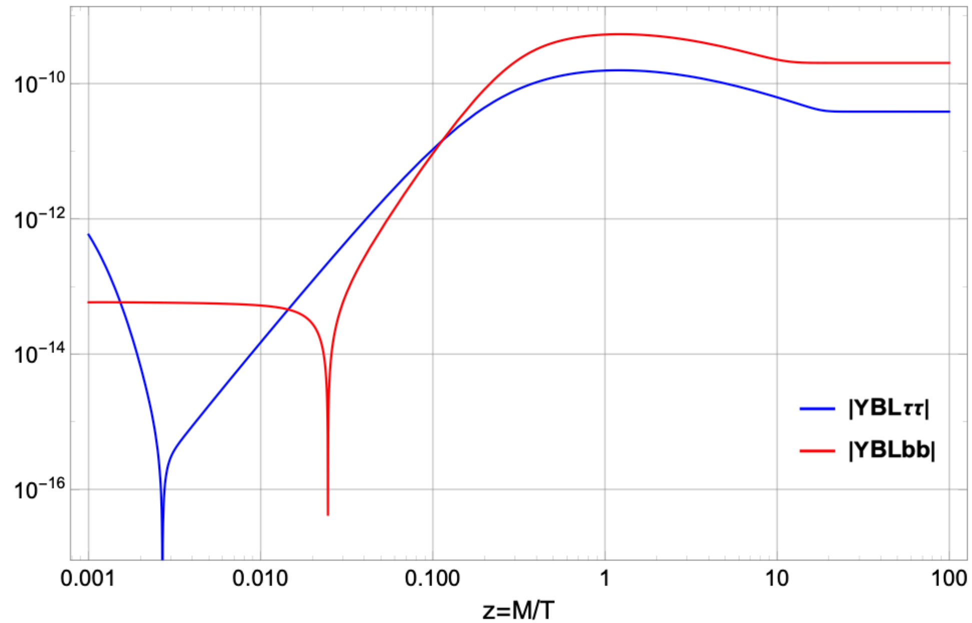
… and now?



$$\frac{d\Upsilon_3}{dz} = -(D(z) - S(z))(\Upsilon_3 - \Upsilon_3^{eq})$$

$$\frac{d\Upsilon_{\tau\tau}^{B-L}}{dz} = \epsilon_{\tau\tau}^{(3)} D(z)(\Upsilon_3 - \Upsilon_3^{eq}) - p_{3\tau}^{(0)}(W(z) + \Delta W)\Upsilon_{\tau\tau}^{B-L}$$

$$\frac{d\Upsilon_{bb}^{B-L}}{dz} = \epsilon_{bb}^{(3)} D(z)(\Upsilon_3 - \Upsilon_3^{eq}) - p_{3b}^{(0)}(W(z) + \Delta W)\Upsilon_{bb}^{B-L}$$



$$Y_{\Delta B} = 8.5 \times 10^{-11}$$

$$Y_{\Delta B}^{BBN} = (8.10 \pm 0.85) \times 10^{-11}$$

$$Y_{\Delta B}^{CMB} = (8.79 \pm 0.445) \times 10^{-11}$$

Future research projects

- Many models based on the same theory show a strong suppression of the CP-violation. Is it only a model dependent feature?
- Leptogenesis in gauge symmetry group like SO(10) or SU(5)?
- Sterile neutrinos as Dark Matter candidates?

I'm always up to working on new projects and subjects related to the neutrino and astroparticle physics!

THANK YOU!