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Leptogenesis in SO(10) with minimal Yukawa sector

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Based on arXiv:2409.03840 [Babu, Di Bari, CSF, Saad, JHEP10(2024)190]

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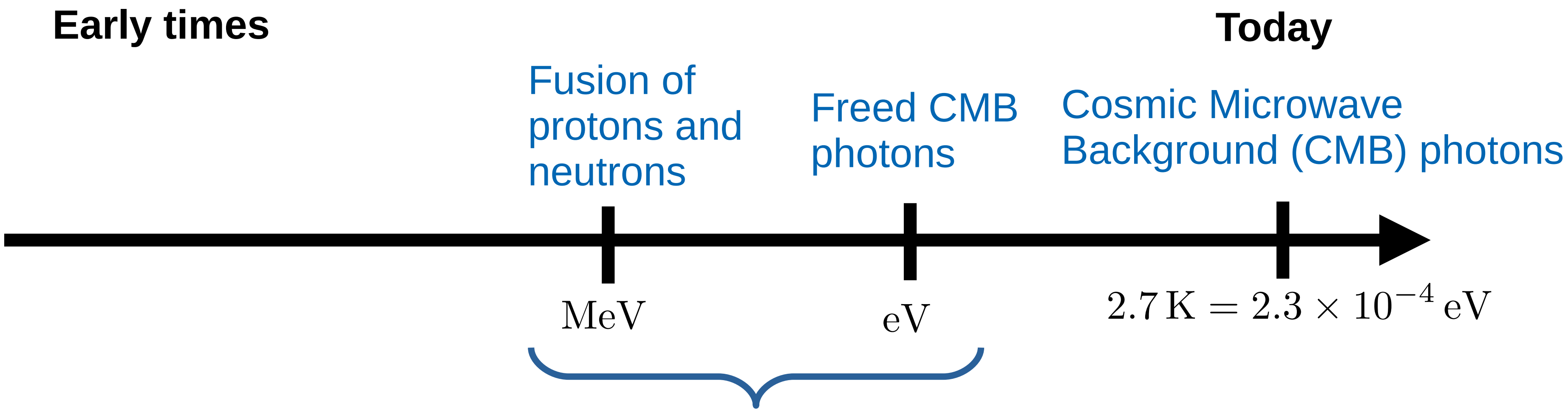
CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

FAPESP SÃO PAULO RESEARCH FOUNDATION

A brief history of the Universe



Ratio of **baryons** (protons + neutrons) density to photon density

$$\frac{n_{b,0}}{n_{\gamma,0}} = 6.1 \times 10^{-10}$$

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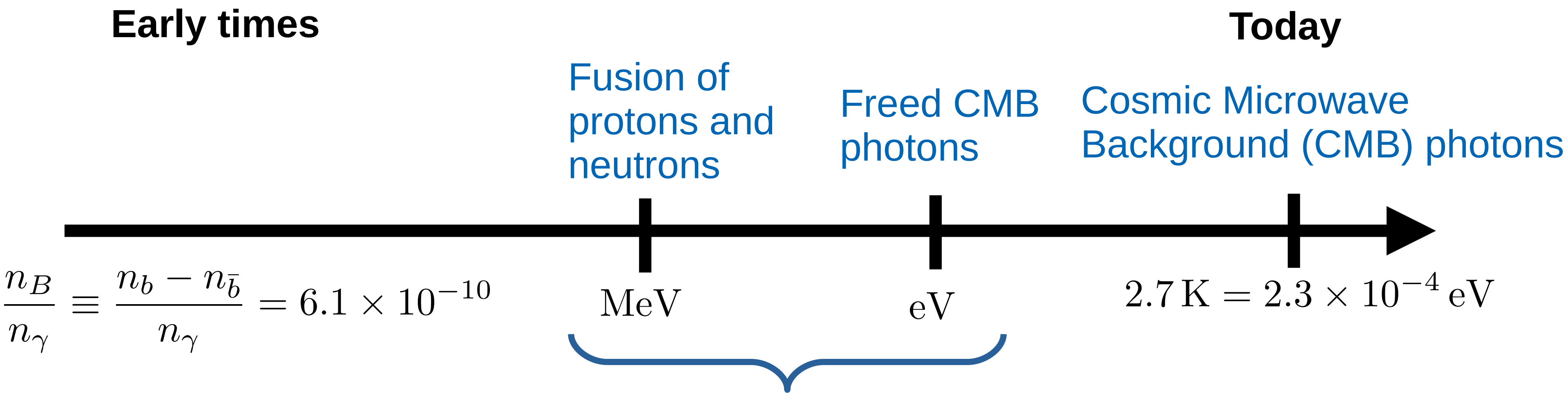

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A brief history of the Universe

Early times

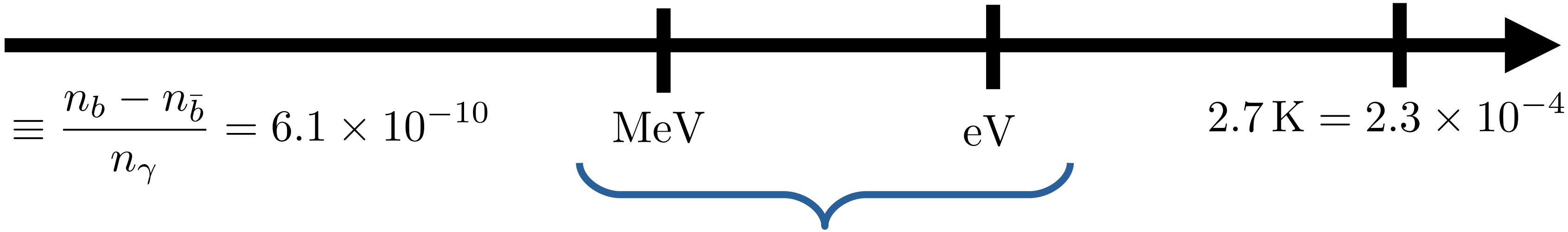
Today

Baryogenesis

Fusion of protons and neutrons

Freed CMB photons

Cosmic Microwave Background (CMB) photons



$$\frac{n_B}{n_\gamma} \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

MeV

eV

$2.7\,\mathrm{K} = 2.3 \times 10^{-4}\,\mathrm{eV}$

Ratio of **baryons** (protons + neutrons) density to photon density

$$\frac{n_{b,0}}{n_{\gamma,0}} = 6.1 \times 10^{-10}$$

SO(10) GUTs contain all the ingredients

Sakharov's conditions (1967)

- **Baryon number violation**

Standard Model $\prod_{\alpha}(QQQ\ell)_{\alpha}$ [t' Hooft (1976)]

Efficient at temperature above 132 GeV [Kuzmin, Rubakov & Shaposhnikov (1985)]
[D'Onofrio, Rummukainen & Tranberg, 1404.3565]

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- **C and CP violation**

New CP-violating and (B-L)-violating processes

Fermion singlet $N \leftrightarrow \ell H$ Higgs triplet $T \leftrightarrow \ell\ell$

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Fermion singlet $N \leftrightarrow \ell H$ Higgs triplet $T \leftrightarrow \ell\ell$

- **Out of thermal equilibrium**

Interaction rates comparable to cosmic expansion rate

$\Gamma \sim \mathcal{H}$

Outline

- SO(10) GUT with minimal Yukawa sector
- Precision baryogenesis calculation
- Predictions
- Remarks

SO(10) GUT with minimal Yukawa sector

Matter is unified $16_\alpha = \{U_a, D_a, U^c_a, D^c_a, E, E^c, \nu, N\}_\alpha$

Predict three right-handed neutrinos

SO(10) GUT with minimal Yukawa sector

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Yukawa Higgs sector $16 \times 16 = 10_s + 120_a + 126_s$

$$\mathcal{L}_{yuk} = 16_F (y_{10}^p 10_H^p + y_{120}^q 120_H^q + y_{126}^r \overline{126}_H^r) 16_F$$

$$p = 1, 2, ..., n_{10}, \quad q = 1, 2, ..., n_{120}, \quad r = 1, 2, ..., n_{126}$$

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Minimal $(n_{10}, n_{120}, n_{126}) = (1, 1, 1)$ [Babu, Bajc & Saad, 1805.10631]

(real, real, complex)

y_{10}, y_{120}, y_{126} (6+3+3) moduli + (6+3+0) phases = 12 moduli + 9 phases

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$$SO(10) \to ... \xrightarrow[126_H]{M_{\rm int}} SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow[10_H + 120_H + 126_H]{M_{EW}} SU(3)_C \times U(1)_{\rm em}$$

A triplet T

SO(10) GUT with minimal Yukawa sector

Fermion masses

$$M_U = D + S + A,$$
$$M_D = D + r_1 S + e^{i\phi} A \equiv v y_D,$$
$$M_E = D - 3 r_1 S + r_2 A \equiv v y_E,$$
$$M_{\nu_D} = D - 3S + r_2^* e^{i\phi} A \equiv v y_{\nu_D},$$
$$M_{\nu_R} = c_R S,$$
$$M_{\nu_L} = c_L S.$$

Type-I seesaw dominance

$$\left|-M_{\nu_D}^T M_{\nu_R} M_{\nu_D}\right| \gg |M_{\nu_L}|$$

Including the vevs and phases:

15 moduli + 12 phases

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Type-I seesaw dominance

$$\left| -M_{\nu_D}^T M_{\nu_R} M_{\nu_D} \right| \gg |M_{\nu_L}|$$

Including the vevs and phases:

15 moduli + 12 phases

Observables: 17 moduli + 2 phases

[(6+3) U, D, E masses; 2 ν mass differences; (3+3) quark and lepton mixing; CKM phase, PMNS phase]

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Predictions: baryon asymmetry, N masses, absolute ν scale, 2 Majorana phases

Precision baryogenesis calculation [CSF, 2109.04478]

- Density matrix formalism: lepton flavor effects + basis independence
- Flavor + spectator effects in the SM

$$-\mathcal{L}_Y = (y_U)_{\alpha\beta}\,\overline{U_\alpha}\epsilon H Q_\beta + (y_D)_{\alpha\beta}\,\overline{D_\alpha}H^* Q_\beta + (y_E)_{\alpha\beta}\,\overline{E_\alpha}H^*\ell_\beta + \mathrm{H.c.}$$

- Focusing the following charges

$$(Y_{\Delta\ell})_{\alpha\beta} \equiv \frac{(n_{\Delta\ell})_{\alpha\beta}}{s} \qquad (Y_{\Delta E})_{\alpha\beta} \equiv \frac{(n_{\Delta E})_{\alpha\beta}}{s}$$

Entropy density today

$$s_0 = 7.04 n_{\gamma,0}$$

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Entropy density today

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Conserved in the SM

$$\boxed{Y_{\widetilde{\Delta}} \equiv \frac{1}{3}Y_B I_{3\times 3} - Y_{\Delta\ell}}$$

Precision baryogenesis calculation [CSF, 2109.04478]

- Density matrix equations

$$s\frac{dY_{\widetilde{\Delta}}}{dt} = \frac{\gamma_E}{2Y^{\text{nor}}}\left\{y_E^\dagger y_E, \frac{Y_{\Delta\ell}}{g_\ell\zeta_\ell}\right\} - \frac{\gamma_E}{Y^{\text{nor}}} y_E^\dagger y_E \frac{Y_{\Delta H}}{g_H\zeta_H} - \frac{\gamma_E}{Y^{\text{nor}}} y_E^\dagger \frac{Y_{\Delta E}}{g_E\zeta_E} y_E$$

$$s\frac{dY_{\Delta E}}{dt} = -\frac{\gamma_E}{2Y^{\text{nor}}}\left\{y_E y_E^\dagger, \frac{Y_{\Delta E}}{g_E\zeta_E}\right\} - \frac{\gamma_E}{Y^{\text{nor}}} y_E y_E^\dagger \frac{Y_{\Delta H}}{g_H\zeta_H} + \frac{\gamma_E}{Y^{\text{nor}}} y_E \frac{Y_{\Delta\ell}}{g_\ell\zeta_\ell} y_E^\dagger$$

Under flavor rotations: $E \to UE, \quad \ell \to V\ell, \quad y_E \to U y_E V^\dagger$

Covariance: $Y_{\Delta\ell} \to V Y_{\Delta\ell} V^\dagger, \quad Y_{\Delta E} \to U Y_{\Delta E} U^\dagger$

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Under flavor rotations: $E \to UE, \quad \ell \to V\ell, \quad y_E \to U y_E V^\dagger$

Covariance: $Y_{\Delta\ell} \to V Y_{\Delta\ell} V^\dagger, \quad Y_{\Delta E} \to U Y_{\Delta E} U^\dagger$

Observable is invariant! $Y_B = 0.315({\rm Tr}Y_{\widetilde{\Delta}} - {\rm Tr}Y_{\Delta E})$

Precision baryogenesis calculation [CSF, 2109.04478]

- Including source *S* and washout *W* terms

$$s\frac{dY_{\widetilde{\Delta}}}{dt} \supset S + W$$

$$S \equiv -\sum_i \epsilon_i \gamma_{N_i} \left(\frac{Y_{N_i}}{Y_{N_i}^{\rm eq}} - 1 \right) \qquad W \equiv \frac{1}{2} \sum_i \frac{\gamma_{N_i}}{Y^{\rm nor}} \left(\frac{1}{2} \left\{ P_i, \frac{Y_{\Delta\ell}}{g_\ell \zeta_\ell} \right\} + P_i \frac{Y_{\Delta H}}{g_H \zeta_H} \right)$$

- Evolutions of N_i

$$s\frac{dY_{N_i}}{dt} = -\gamma_{N_i} \left(\frac{Y_{N_i}}{Y_{N_i}^{\rm eq}} - 1 \right)$$

Precision baryogenesis calculation [CSF, 2109.04478]

- Spectator coefficients

$$(Y_{\Delta\ell})_{\alpha\alpha} = \frac{2}{15} c_B \mathrm{Tr} Y_{\widetilde{\Delta}} - (\mathrm{Tr} Y_{\widetilde{\Delta}})_{\alpha\alpha} \qquad Y_{\Delta H} = -c_H (\mathrm{Tr} Y_{\widetilde{\Delta}} - 2\mathrm{Tr} Y_{\Delta E})$$

$$c_B(T) = 1 - e^{-T_B/T} \qquad T_B = 2.3 \times 10^{12}\,\mathrm{GeV}$$

$$\begin{aligned} c_H(T) \;=\; & \left(\frac{2}{3} + \frac{1}{3} e^{-\frac{T_t}{T}}\right) - \left(\frac{2}{3} - \frac{14}{23}\right)\left(1 - e^{-\frac{T_u}{T}}\right) - \left(\frac{14}{23} - \frac{2}{5}\right)\left(1 - e^{-\frac{T_{u-b}}{T}}\right) \\ & - \left(\frac{2}{5} - \frac{4}{13}\right)\left(1 - e^{-\frac{T_{u-c}}{T}}\right) - \left(\frac{4}{13} - \frac{3}{10}\right)\left(1 - e^{-\frac{T_{B_3-B_2}}{T}}\right) \\ & - \left(\frac{3}{10} - \frac{1}{4}\right)\left(1 - e^{-\frac{T_{u-s}}{T}}\right) - \left(\frac{1}{4} - \frac{2}{11}\right)\left(1 - e^{-\frac{T_{u-d}}{T}}\right) \end{aligned}$$

$T_t = 10^{15}\,\mathrm{GeV},\ T_u = 2 \times 10^{13}\,\mathrm{GeV}, \mathrm{etc.}$ [CSF, 2012.03973]

Predictions

Observables (Δm^2_{ij} in eV^2)	Values at M_Z scale		
	Input	Benchmark Fit: NO	Benchmark Fit: IO
$y_u/10^{-6}$	6.65±2.25	7.30	10.0
$y_c/10^{-3}$	3.60±0.11	3.59	3.57
y_t	0.986±0.0086	0.986	0.986
$y_d/10^{-5}$	1.645±0.165	1.636	1.635
$y_s/10^{-4}$	3.125±0.165	3.122	3.148
$y_b/10^{-2}$	1.639±0.015	1.639	1.637
$y_e/10^{-6}$	2.7947±0.02794	2.7945	2.7906
$y_\mu/10^{-4}$	5.8998±0.05899	5.9011	5.9080
$y_\tau/10^{-2}$	1.0029±0.01002	1.0022	1.0023
$\theta_{12}^{\rm CKM}/10^{-2}$	22.735±0.072	22.729 ($\theta_{12}^{\rm CKM}$ =13.023°)	22.730 ($\theta_{12}^{\rm CKM}$ =13.023°)
$\theta_{23}^{\rm CKM}/10^{-2}$	4.208±0.064	4.206 ($\theta_{23}^{\rm CKM}$ =2.401°)	4.204 ($\theta_{23}^{\rm CKM}$ =2.408°)
$\theta_{13}^{\rm CKM}/10^{-3}$	3.64±0.13	3.64 ($\theta_{13}^{\rm CKM}$ =0.208°)	3.64 ($\theta_{13}^{\rm CKM}$ =0.208°)
$\delta_{\rm CKM}$	1.208±0.054	1.209 ($\delta_{\rm CKM}$ =69.322°)	1.212 ($\delta_{\rm CKM}$ =69.457°)
$\Delta m^2_{21}/10^{-5}$	7.425±0.205	7.413	7.506
$\Delta m^2_{31}/10^{-3}$ (NO)	2.515±0.028	2.514	-
$\Delta m^2_{32}/10^{-3}$ (IO)	-2.498±0.028	-	-2.499
$\sin^2\theta_{12}$	0.3045±0.0125	0.3041 ($\theta_{12} = 33.46°$)	0.3067 ($\theta_{12} = 33.63°$)
$\sin^2\theta_{23}$ (NO)*	0.5705±0.0205	0.4473 ($\theta_{23} = 41.98°$)	-
$\sin^2\theta_{23}$ (IO)*	0.576±0.019	-	0.5784 ($\theta_{23} = 49.51°$)
$\sin^2\theta_{13}$ (NO)	0.02223±0.00065	0.02223 ($\theta_{13} = 8.57°$)	-
$\sin^2\theta_{13}$ (IO)	0.02239±0.00063	-	0.02238 ($\theta_{13} = 8.60°$)
$\delta^\circ_{\rm CP}$ (NO)	207.5±38.5	240.49	-
$\delta^\circ_{\rm CP}$ (IO)	284.5±29.5	-	263.49
$\eta_B/10^{-10}$	6.12±0.04‡	7.6 (7.6)	9.6 (51)
χ^2	-	1.45	5.76†

$$(m_1, m_2, m_3, m_{\beta\beta})$$

$$\text{NO} : (0.038, 8.6, 50, 3.7)\ \text{meV}$$

$$\text{IO} : (49, 50, 0.19, 34)\ \text{meV}$$

[KAMLAND-ZEN, 2203.02139] $m_{\beta\beta} < 36 - 156\,\text{meV}$

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$$(M_1, M_2, M_3)$$

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$$\text{IO} : (1.1 \times 10^4, 1.7 \times 10^{12}, 5.9 \times 10^{14})\ \text{GeV}$$

N_2 leptogenesis + N_1 washout

[Di Bari & Riotto, 0809.2285]

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$$\text{IO} : (49, 50, 0.19, 34)\ \text{meV}$$

[KAMLAND-ZEN, 2203.02139] $m_{\beta\beta} < 36 - 156\,\text{meV}$

$$(M_1, M_2, M_3)$$

$$\text{NO} : (6.6\times10^4, 2.1\times10^{12}, 8.1\times10^{14})\ \text{GeV}$$

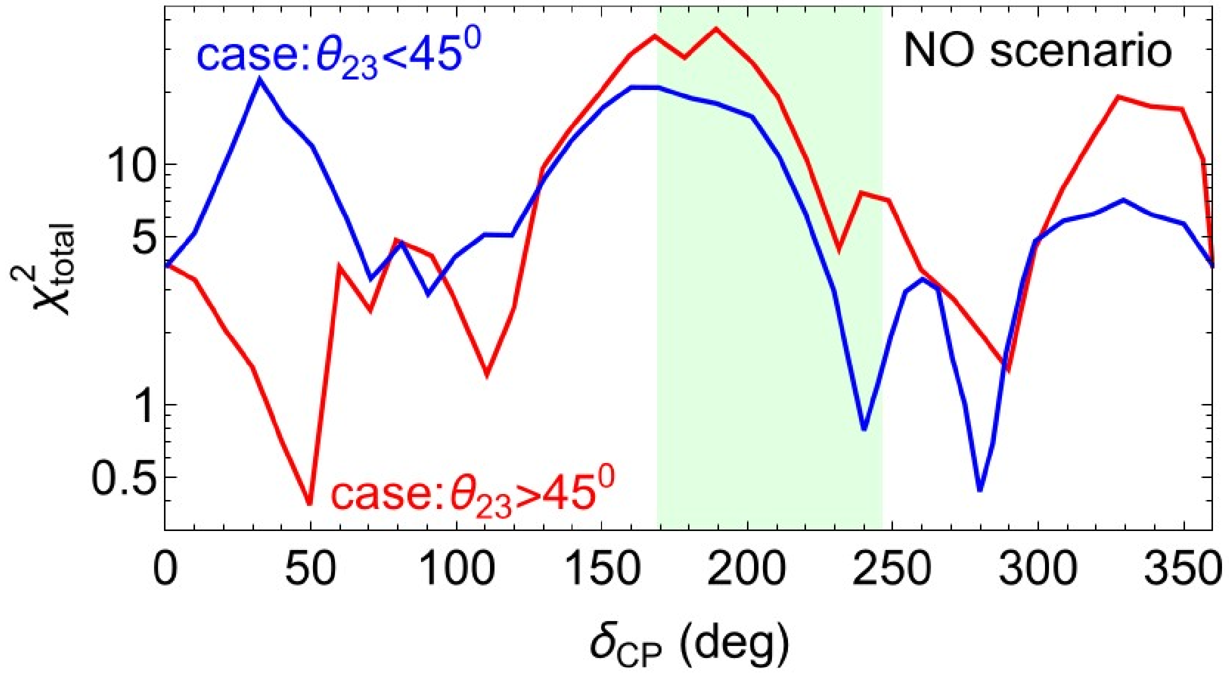
$$\text{IO} : (1.1\times10^4, 1.7\times10^{12}, 5.9\times10^{14})\ \text{GeV}$$

N_2 leptogenesis + N_1 washout

[Di Bari & Riotto, 0809.2285]

Slight preference for NO

Predictions



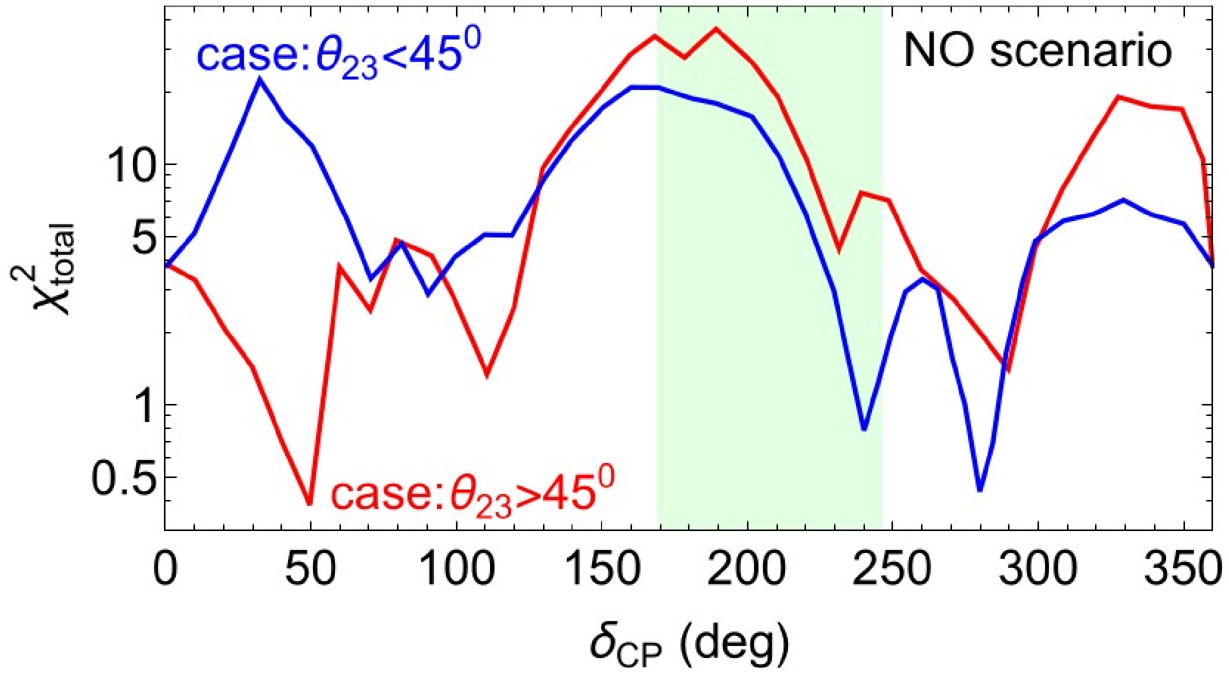
The green band is from

[October 2021 data: www.nu-fit.org]

[Esteban et al., 2007.14792]

Impose (with approximated solutions) $\eta_B/10^{-10} \in (5, 50)$

Predictions



The green band is from

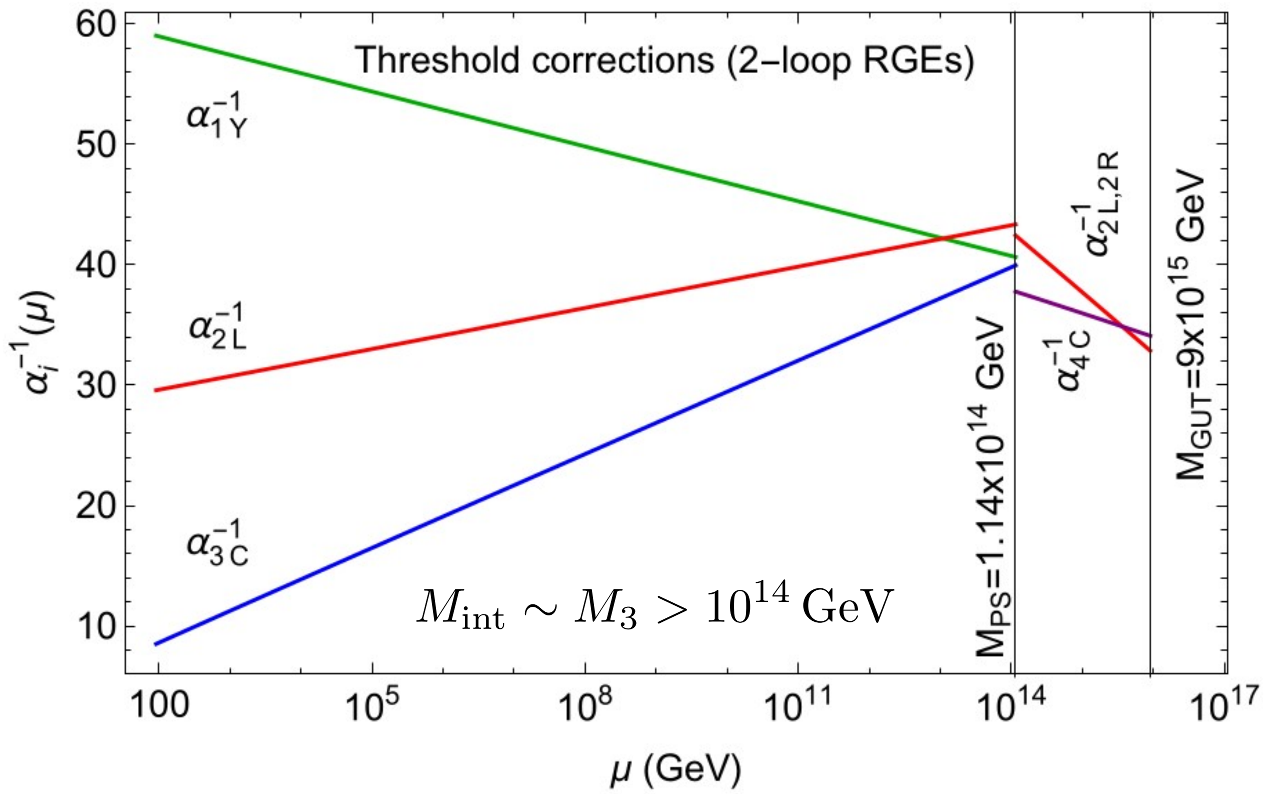
[October 2021 data: www.nu-fit.org]

[Esteban et al., 2007.14792]

Slight preference for $\theta_{23} < 45^\circ$

Impose (with approximated solutions) $\eta_B/10^{-10} \in (5, 50)$

Predictions



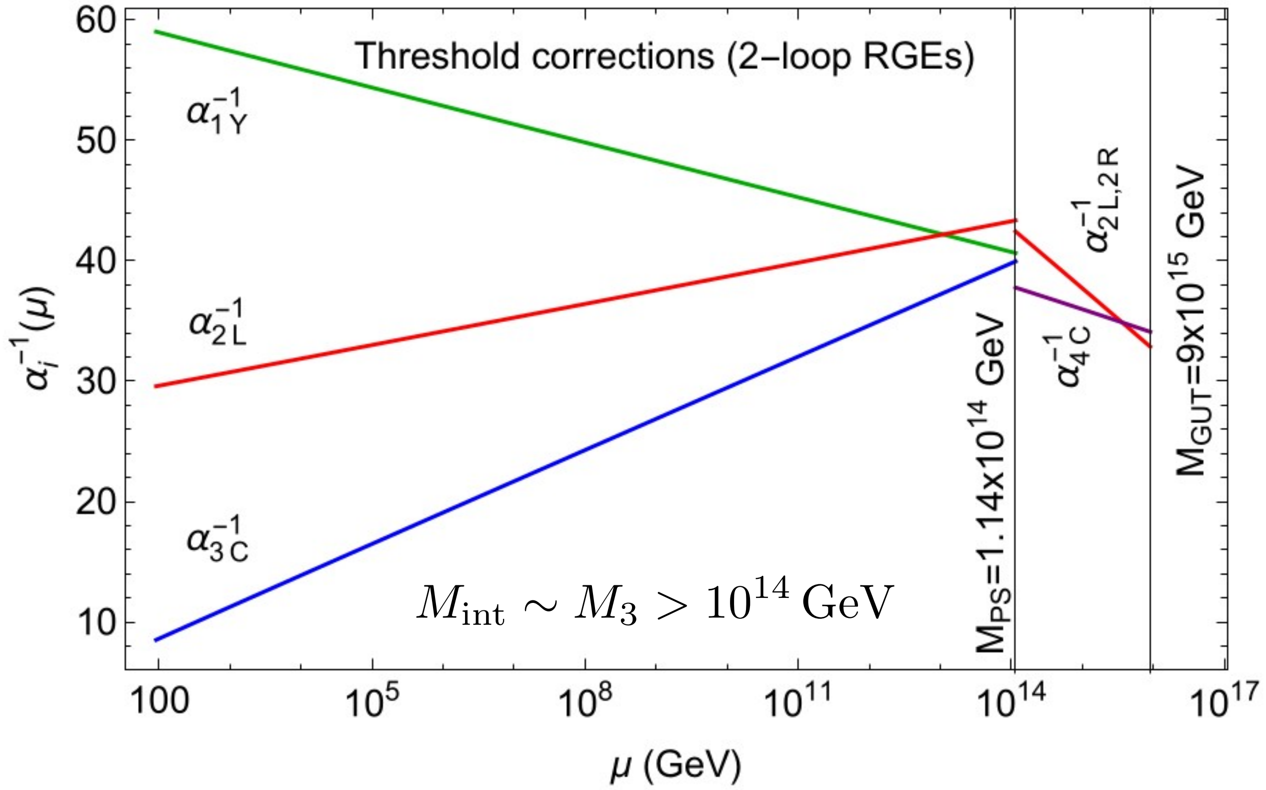
[SuperK, 2010.16098]

$$\tau_p(p \to e^+\pi^0) > 2.4 \times 10^{34}$$

$$\Longrightarrow \; M_{\rm GUT} \gtrsim 5 \times 10^{15}\,\mathrm{GeV}$$

$$SO(10) \xrightarrow[54_H]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2 \xrightarrow[126_H]{M_{\rm int}} SU(3)_C \times SU(2)_L \times U(1)_Y$$

Predictions



[SuperK, 2010.16098]

$$\tau_p(p \to e^+\pi^0) > 2.4 \times 10^{34}$$

$$\implies \; M_{\rm GUT} \gtrsim 5 \times 10^{15}\,{\rm GeV}$$

SO(10) is broken through 54_H instead of 45_H or 210_H

$$SO(10) \xrightarrow[54_H]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2 \xrightarrow[126_H]{M_{\rm int}} SU(3)_C \times SU(2)_L \times U(1)_Y$$

Remarks

- Verify high scale baryogenesis through **consistency check** of fundamental models
- SO(10) with minimal Yukawa sector
  - Neutrinoless double beta decay $m_{\beta\beta} = 3.7\,(34)\,\mathrm{meV}$
  - Slight preference for NO
  - CP phase for NO $\delta_{\mathrm{CP}} \simeq 230^\circ - 300^\circ$
  - Right-handed mass spectrum $(M_1, M_2, M_3) \sim \left(10^{4-5}, 10^{11-12}, 10^{14-15}\right)\ \mathrm{GeV}$
  - N_2 leptogenesis + N_1 washout
  - Break SO(1O) with 54_H to Pati-Salam with Z_2 (consistent w/ proton decay limit)
- High $M_{\mathrm{int}} \rightarrow$ nanoHz gravitational waves from metastable cosmic strings

e.g. [Antusch, Hinze, Saad & Steiner, 2307.04595] [Buchmüller, Domcke & Schmitz, 2307.04691]

Backup

Transition temperatures

- In an expanding Universe, if some interaction rates become slower than Hubble rate $\mathcal{H}$ some effective U(1) symmetries arise. [CSF, 1508.03648] [CSF, 2012.03973]

For a radiation-dominated Universe above T_x, we gain the corresponding $U(1)_x$

$$T_t \sim 10^{15}\,\text{GeV},\qquad T_u \sim 2\times 10^{13}\,\text{GeV},\qquad T_B \sim 2\times 10^{12}\,\text{GeV},$$
$$T_\tau \sim 4\times 10^{11}\,\text{GeV},\qquad T_{u-b} \sim 3\times 10^{11}\,\text{GeV},\qquad T_{u-c} \sim 2\times 10^{10}\,\text{GeV},$$
$$T_\mu \sim 10^{9}\,\text{GeV},\qquad T_{B_3-B_2} \sim 9\times 10^{8}\,\text{GeV}\qquad T_{u-s} \sim 3\times 10^{8}\,\text{GeV},$$
$$T_{B_3+B_2-2B_1} \sim 10^{7}\,\text{GeV},\qquad T_{u-d} \sim 2\times 10^{6}\,\text{GeV},\qquad T_e \sim 3\times 10^{4}\,\text{GeV}.$$

Backup

SO(1O) branching rules

- Branching rules for SO(1O) [Slansky, 1981]

$SU(4) \times SU(2)_L \times SU(2)_R$

$$10 = (1,2,2) + (6,1,1)$$
$$16 = (4,2,1) + (\bar{4},1,2)$$
$$120 = (1,2,2) + (10,1,1) + (\bar{1}0,1,1) + (6,3,1) + (6,1,3) + (15,2,2)$$
$$126 = (6,1,1) + (10,1,1) + (\bar{1}0,1,1) + (6,3,1) + (6,1,3) + (15,2,2)$$

$SU(5) \times U(1)$

$$10 = 5(2) + \bar{5}(-2)$$
$$16 = 1(-5) + \bar{5}(3) + 10(-1)$$
$$120 = 5(2) + \bar{5}(-2) + 10(-6) + \overline{10}(6) + 45(2) + \overline{45}(-2)$$
$$126 = 1(10) + \bar{5}(-2) + 10(-6) + \overline{15}(6) + 45(2) + \overline{50}(-2)$$

Backup

SO(10) branching rules

- Fermion masses in Minimal SO(10) [Babu, Bajc & Saad, 1805.10631]

$$
\begin{aligned}
M_U &= \underbrace{v_{10} y_{10}}_{\equiv D} + \underbrace{v^u_{126} y_{126}}_{\equiv S} + \underbrace{(v^{(1)}_{120} + v^{(15)}_{120}) y_{120}}_{\equiv A}, \\
M_D &= v^*_{10} y_{10} + v^d_{126} y_{126} + (v^{(1)*}_{120} + v^{(15)*}_{120}) y_{120}, \\
M_E &= v^*_{10} y_{10} - 3 v^d_{126} y_{126} + (v^{(1)*}_{120} - 3 v^{(15)*}_{120}) y_{120}, \\
M_{\nu_D} &= v_{10} y_{10} - 3 v^u_{126} y_{126} + (v^{(1)}_{120} - 3 v^{(15)}_{120}) y_{120}, \\
M_{\nu_{L,R}} &= v_{L,R} y_{126}
\end{aligned}
$$

Light neutrino mass matrix $m_\nu = M_{\nu_L} - M^T_{\nu_D} M_{\nu_R} M_{\nu_D}$