Fermion masses, leptogenesis and gravitational waves in SO(10)

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Based on the work with S. Pascoli, J. Turner, S. King, Y. Zhou and B. Fu

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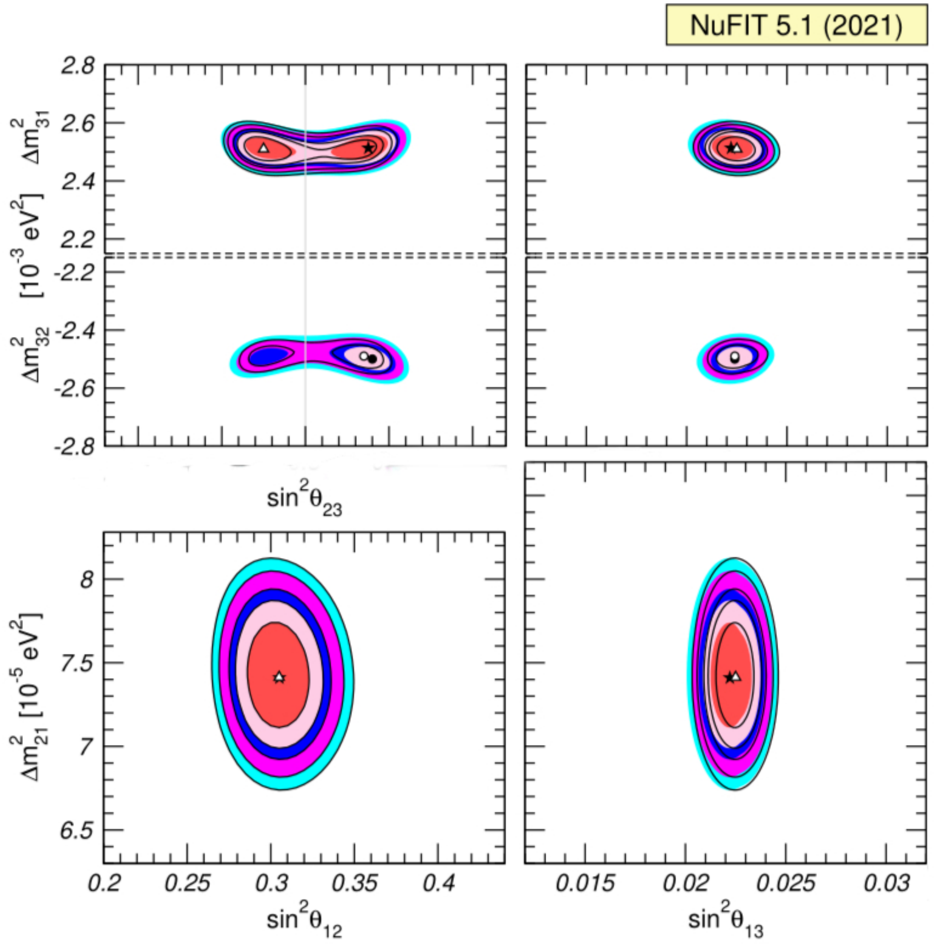
The Standard Model: current issues

- Neutrino Masses and Mixing
- Baryogenesis
- The Standard Model gauge group is arbitrary
- The fermion masses and the mixing angles are free parameters
- Dark matter, …



We need an extension of the Standard Model!

See talk by Yeling Zhou, Shaikh Saad etc...

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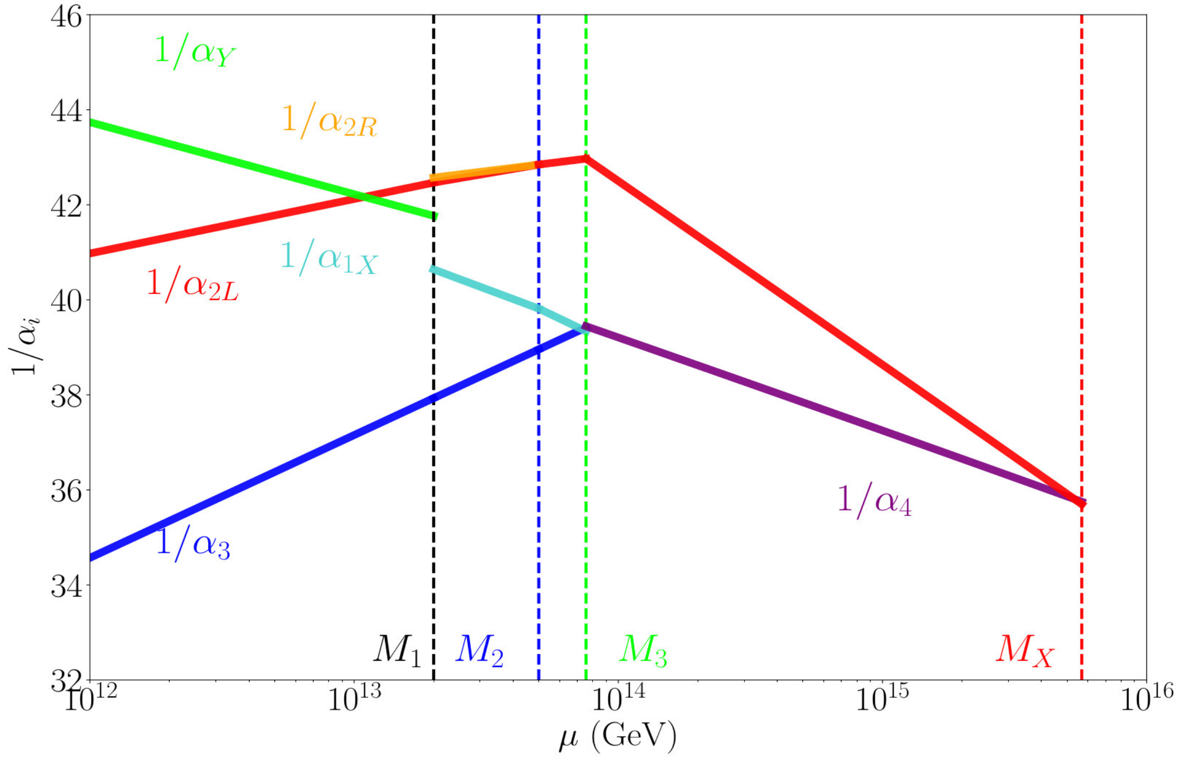
Grand Unification Theory ⇒ SO(10)

Gauge coupling unification

- If we study the running of the couplings of the Standard Model they almost approach the same value
- Assuming an UV complexion after a certain scale all the couplings exactly match at a certain scale
- Strong, weak and electromagnetic interactions are unified into a single fundamental force at high energies



Why SO(10)?

It embeds all fermions plus an extra Standard Model singlet in one representation

$$\psi_+ = \begin{pmatrix} u & d & \nu & e & u^c & d^c & \nu^c & e^c \end{pmatrix}_L$$

Reduces SM degrees of freedom and predicts fermion masses

The extra singlet can be indentified with the right-handed neutrino

Why SO(10)?

Reduces SM degrees of freedom and predicts fermion masses

$$\mathcal{L} = Y_{10}\overline{\mathbf{16}}_F \mathbf{10}_H \mathbf{16}_F + Y_{120}\overline{\mathbf{16}}_F \mathbf{120}_H \mathbf{16}_F + Y_{\overline{126}}\overline{\mathbf{16}}_F \overline{\mathbf{126}}_H \mathbf{16}_F$$

$$\downarrow$$

$$\mathcal{L}_Y = Y_u \bar{Q}\tilde{\Phi} u_R + Y_d \bar{Q}\Phi d_R + Y_e \bar{L}\Phi e_R + Y_\nu \bar{L}\tilde{\Phi}\nu_R + \mathrm{h.c}$$

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Why SO(10)?

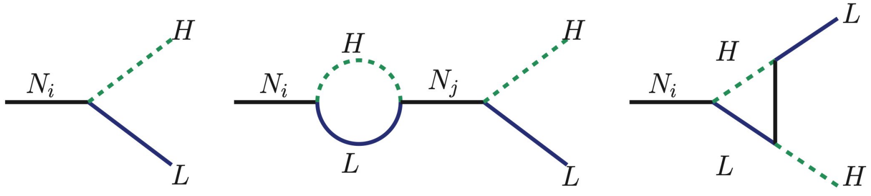
- The Yukawa couplings at low energies are now related
- The goal is to find a fixed parameterization which is dependent on the Higgs sector
- The Yukawa couplings are not anymore free parameters

$$Y_\nu = f(Y_u, Y_d)$$
$$Y_e = g(Y_u, Y_d)$$

Why SO(10)?

The extra singlet can be identified with the right-handed neutrino

- It is possible to predict neutrino masses and mixing angles
- The presence of the right-handed neutrino allows for predicting baryogenesis via leptogenesis



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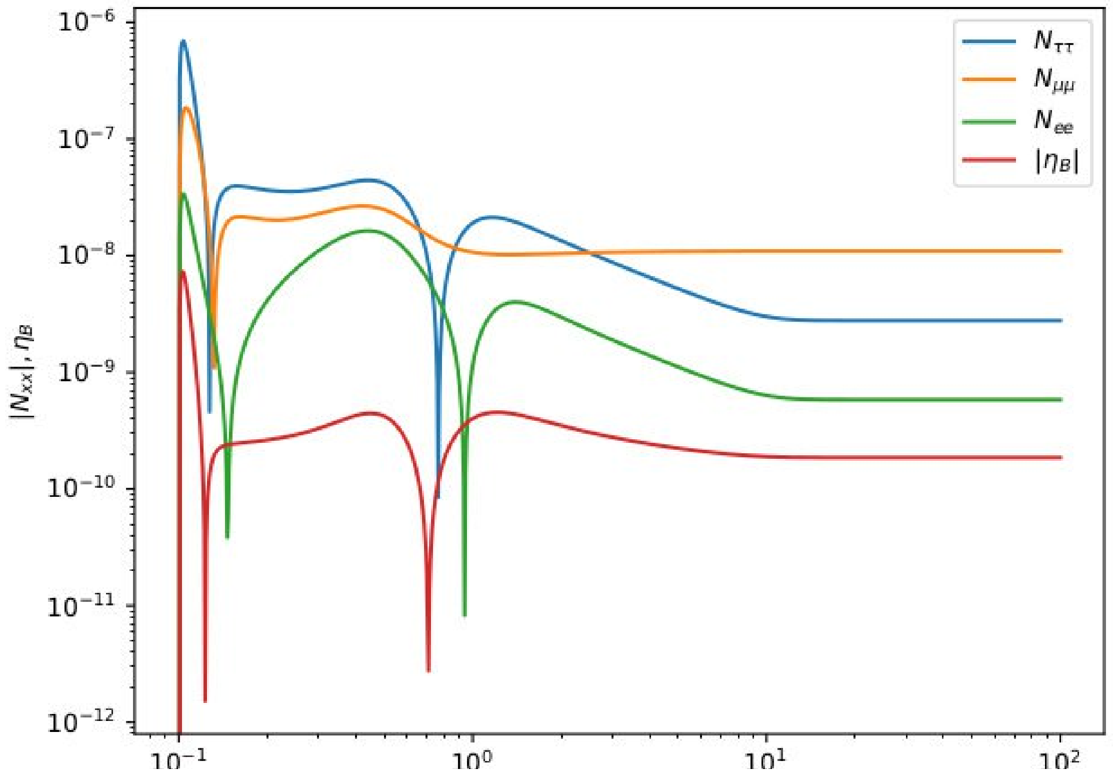
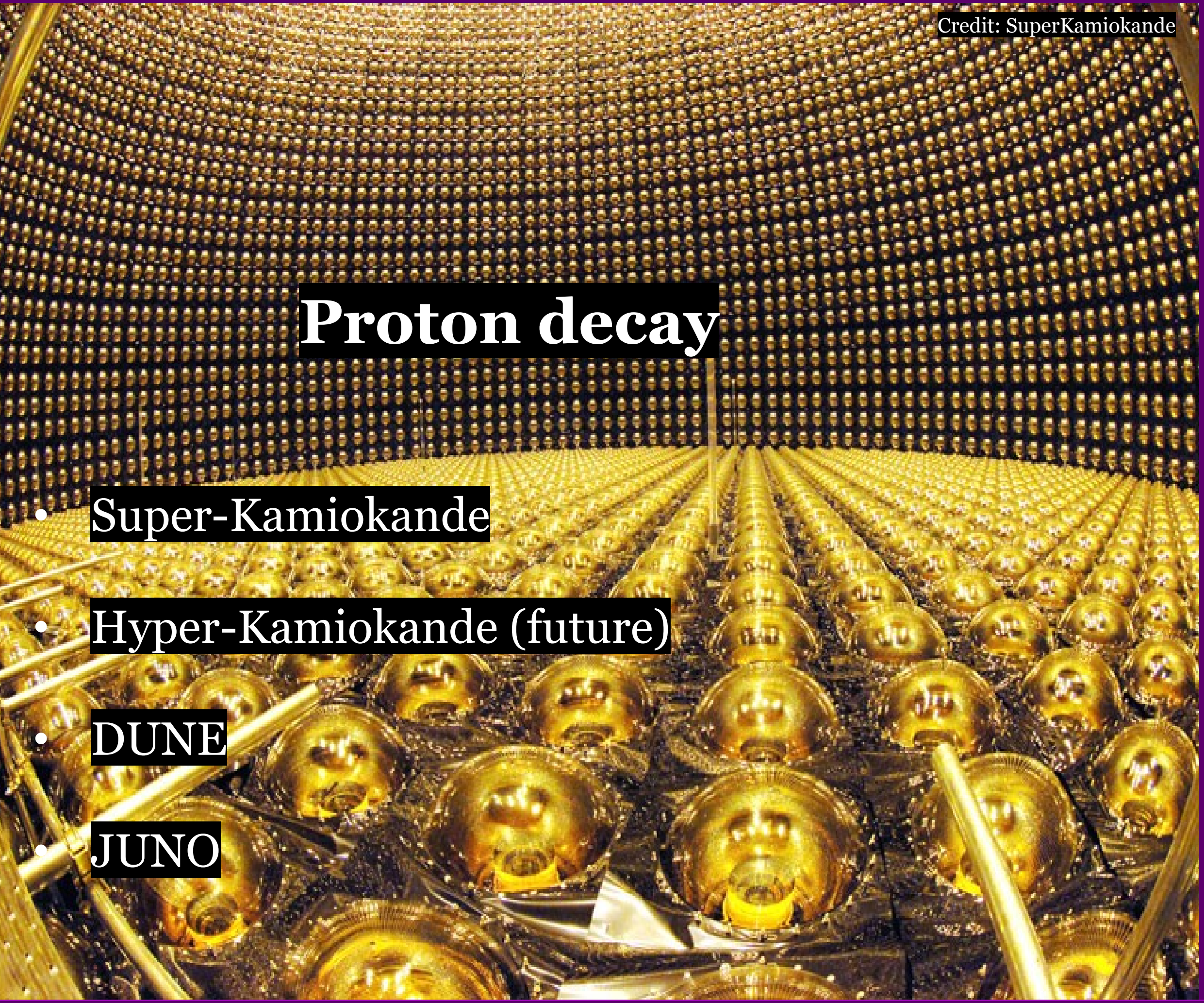
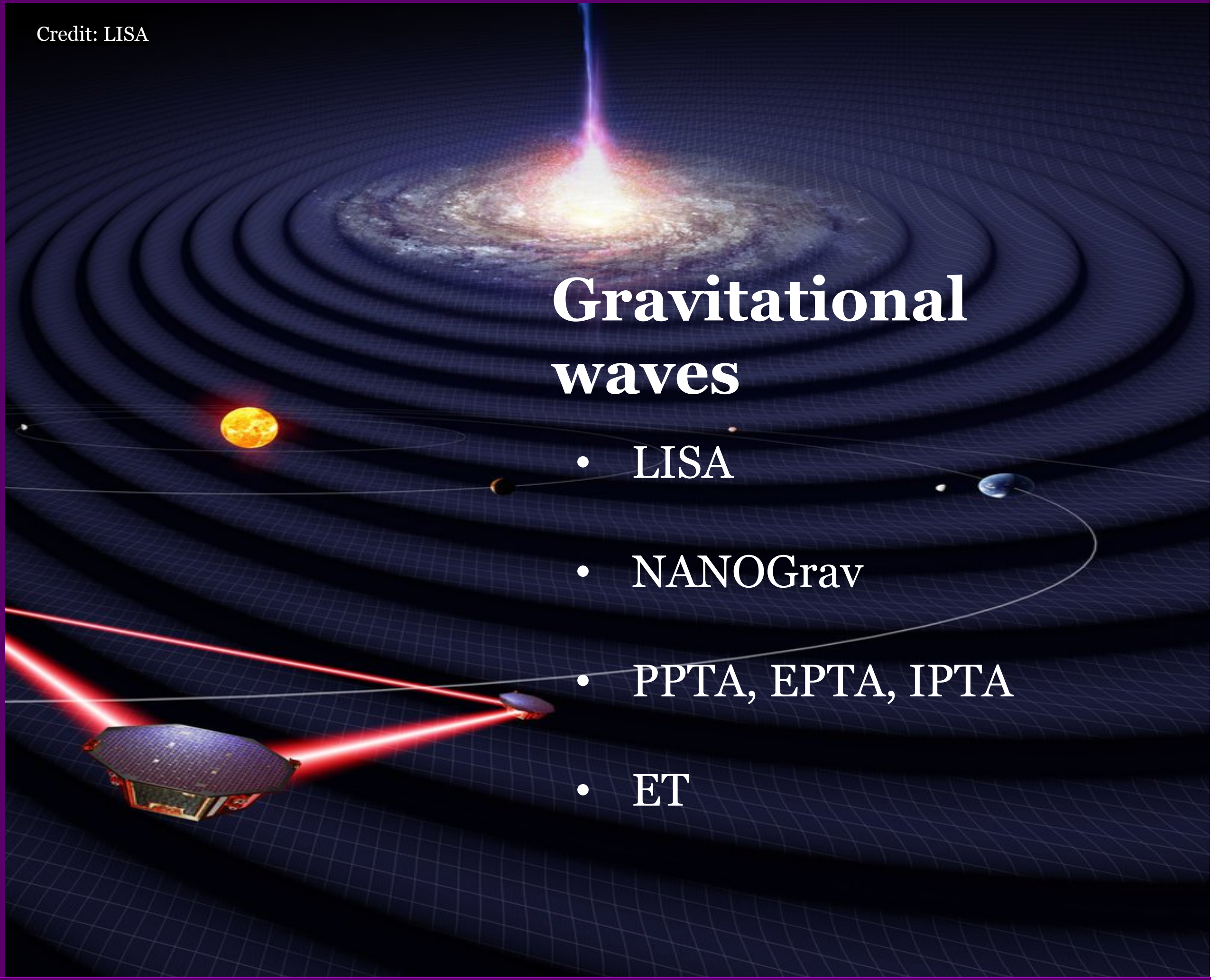


How to test SO(10)



Proton decay

- Super-Kamiokande
- Hyper-Kamiokande (future)
- DUNE
- JUNO



Gravitational waves

- LISA
- NANOGrav
- PPTA, EPTA, IPTA
- ET

The model

Fu, King, LM, Pascoli, Turner, Zhou
2209.00021

Type IIIc breaking chain

$$
\begin{aligned}
& SO(10) \\
& \quad \mathbf{54} \downarrow \text{ broken at } M_X \\
& G_3^c \equiv SU(4) \times SU(2)_L \times SU(2)_R \times Z_2^C \\
& \quad \mathbf{210} \downarrow \text{ broken at } M_3 \\
& G_2^c \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times Z_2^C \\
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& G_1 \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \\
& \quad \overline{\mathbf{126}} \downarrow \text{ broken at } M_1 \\
& G_{\text{SM}} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y
\end{aligned}
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String tension

$$G\mu \simeq \frac{1}{2\left(\alpha_{2R}\left(M_1\right) + \alpha_{1X}\left(M_1\right)\right)} \frac{M_1^2}{M_{\rm pl}^2}$$

The model

Fu, King, LM, Pascoli, Turner, Zhou
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Proton lifetime

$$\tau \simeq 6.9 \times 10^{35} \times \left(\frac{M_U}{10^{16}\text{GeV}}\right)^4 \text{yr}$$

Type IIIc breaking chain

$$SO(10)$$
$$\mathbf{54} \downarrow \text{broken at } M_X$$
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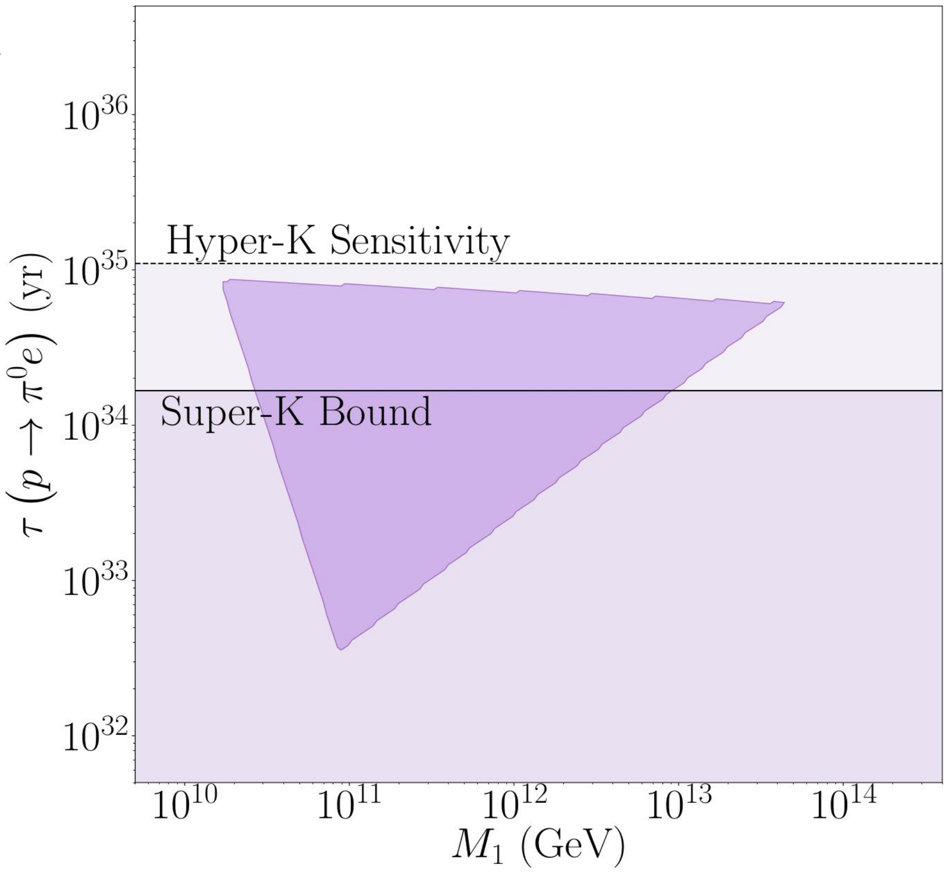
The two scales are linked by gauge unification constraint



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\end{array}
$$

Set RHN neutrino mass up to Yukawa couplings

$$M_{\nu_R} \simeq Y_{\overline{\mathbf{126}}} M_1$$

Fermion masses and leptogenesis

$$Y_{10}, Y_{120}, Y_{\overline{126}}$$

↓

$$Y_e, Y_{\nu_R}, Y_\nu, Y_u, Y_d$$ → Fermion masses

↓

Boltzmann equations

↓

$$\eta_B$$

$$\mathcal{L}_\mathcal{I} = -Y_\nu \overline{L_\alpha} \tilde{\Phi} N - \frac{1}{2} M_N N^c \mathcal{C}^\dagger N_i$$

$$Y_u = h + r_2 f + i\, r_3 h' \,, \qquad Y_d = r_1 (h + f + i\, h') \,, \qquad Y_\nu = h - 3 r_2 f + i\, c_\nu h' \,,$$

$$Y_e = r_1 (h - 3f + i\, c_e h') \,, \qquad M_{\nu_R} = f \, \frac{\sqrt{3}\, r_1}{V_{16}} v_S \,,$$

Fermion masses and leptogenesis

$$Y_{10}, Y_{120}, Y_{\overline{126}}$$

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$$Y_e, Y_{\nu_R}, Y_\nu, Y_u, Y_d$$ → Fermion masses

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$$\mathcal{L}_{\mathcal{I}} = -Y_\nu \overline{L_\alpha} \tilde{\Phi} N - \frac{1}{2} M_N N^c \mathcal{C}^\dagger N_i$$

$$Y_\nu = -\frac{3r_2+1}{r_2-1} Y_u + \frac{4r_2}{r_1(r_2-1)} \operatorname{Re} Y_d + i\frac{c_\nu}{r_1} \operatorname{Im} Y_d,$$

$$Y_e = -\frac{4r_1}{r_2-1} Y_u + \frac{r_2+3}{r_2-1} \operatorname{Re} Y_d + ic_e \operatorname{Im} Y_d.$$

Fermion masses and leptogenesis

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We solved **Density Matrix Equations** using ULYSSES

$$\varepsilon^{(i)}_{\alpha\beta} = \frac{3}{32\pi \left(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu\right)_{ii}} \sum_{j\neq i} \left\{ i \left[\tilde{Y}_{\nu\alpha i} \tilde{Y}^\star_{\nu\beta j} \left(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu\right)_{ji} - \tilde{Y}^\star_{\nu\beta i} \tilde{Y}_{\nu\alpha j} \left(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu\right)_{ij} \right] \frac{\xi\left(x_j/x_i\right)}{\sqrt{x_j/x_i}} + i \frac{2}{3\left(x_j/x_i - 1\right)} \left[\tilde{Y}_{\nu\alpha i} \tilde{Y}^\star_{\nu\beta j} \left(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu\right)_{ij} - \tilde{Y}^\star_{\nu\beta i} \tilde{Y}_{\nu\alpha j} \left(\tilde{Y}_\nu^\dagger \tilde{Y}_\nu\right)_{ji} \right] \right\},$$

$$K_i \equiv \frac{\tilde{\Gamma} i}{H\left(T = MN_i\right)}, \qquad \tilde{\Gamma} i = \frac{MN_i \left(\tilde{Y}\nu^\dagger \tilde{Y}\nu^\dagger\right)_{ii}}{8\pi}$$

Fermion masses and leptogenesis

$$Y_{10}, Y_{120}, Y_{\overline{126}}$$

↓

$$Y_e, Y_{\nu_R}, Y_\nu, Y_u, Y_d$$ → Fermion masses

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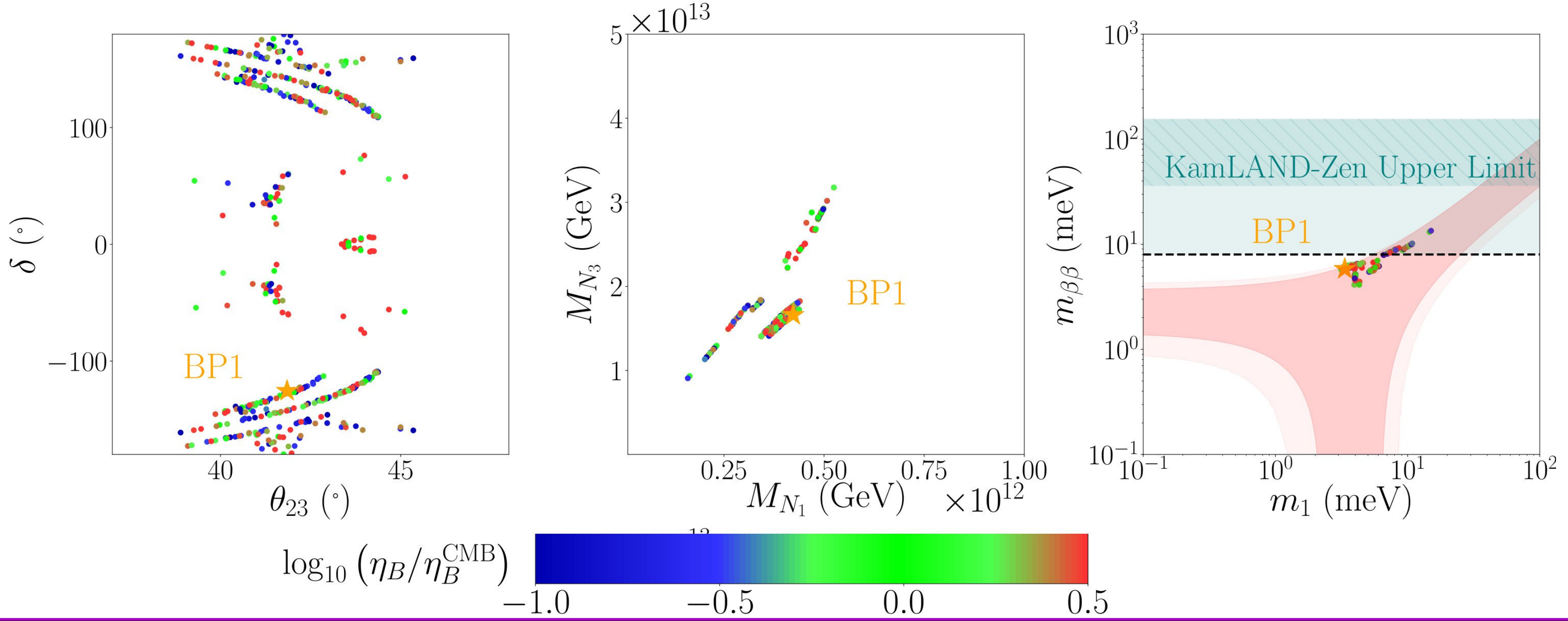
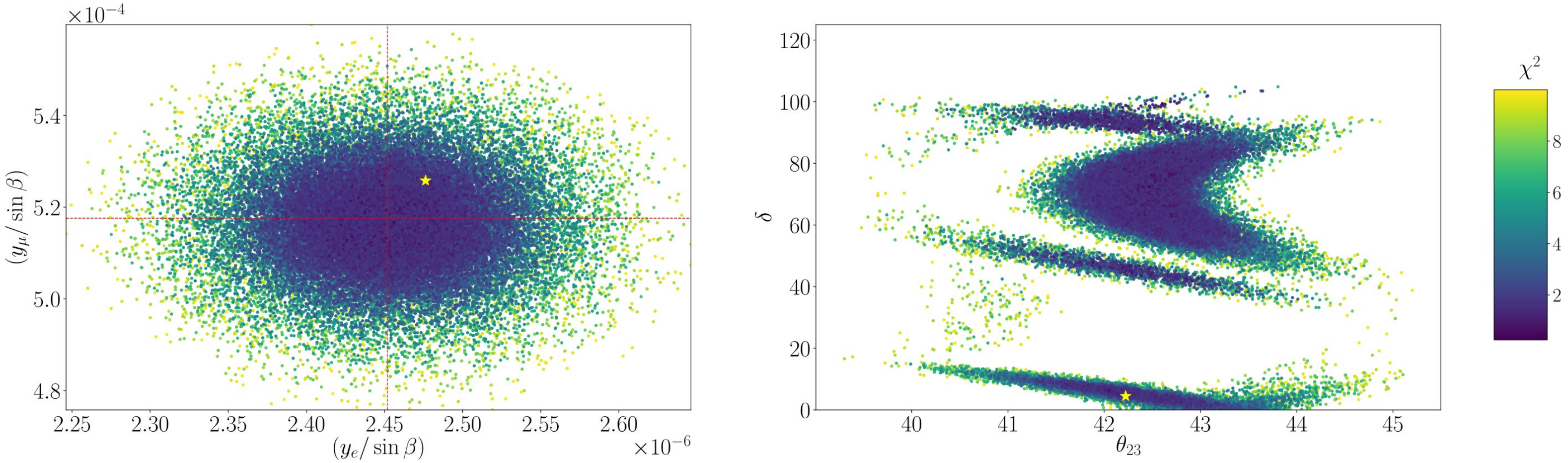


GUTFIT

$$\mathcal{P}_m \in \{a_1, a_2, r_1, r_2, c_e, c_\nu, m_0, \eta_q\}$$

$$\mathcal{O}_n \in \{m_e, m_\mu, m_\tau, \theta_{12}, \theta_{13}, \theta_{23}, \Delta m^2_{21}, \Delta m^2_{31}\}$$

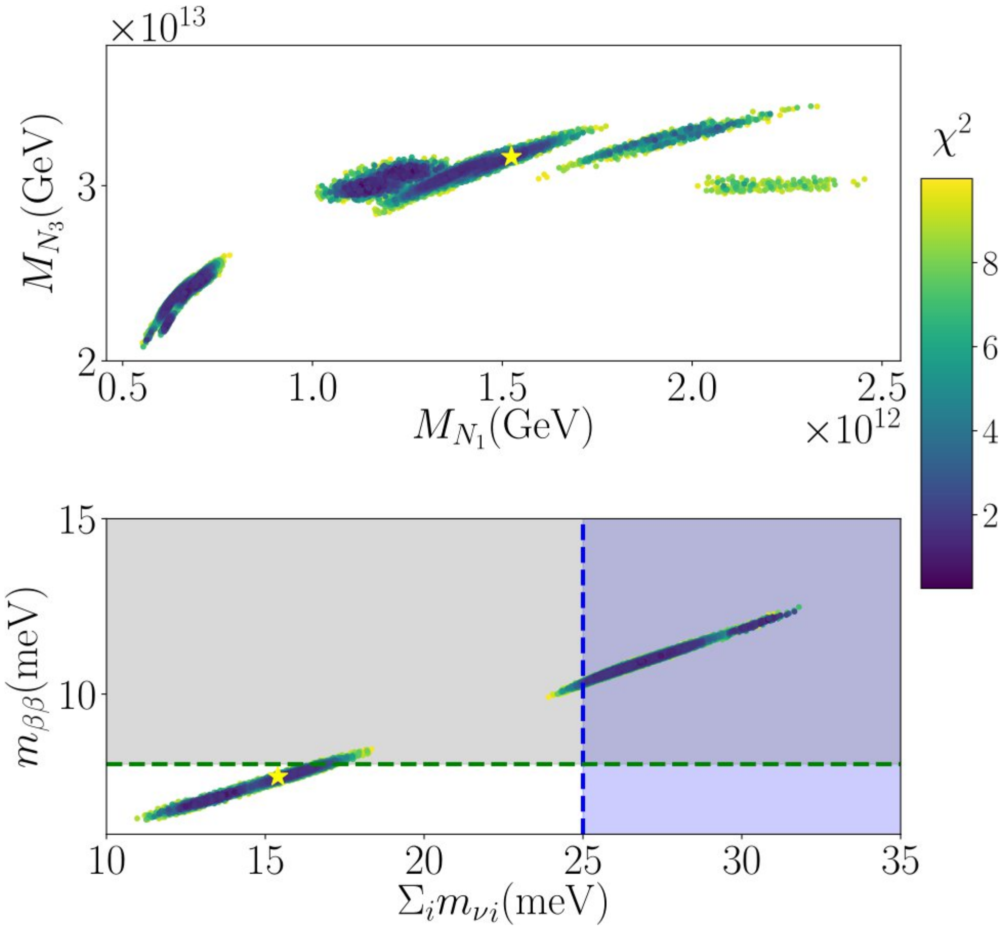


- We considered a different models
- GUTFIT used for scanning the parameter space in the next works
- Scan the parameter space using the MultiNest algorithm (nested sampling)
- It minimize the chi squared.

$$\chi^2 = \sum_n \left[\frac{\mathcal{O}_n(\mathcal{P}_m) - \mathcal{O}_n^{\mathrm{bf}}}{\sigma_{\mathcal{O}_n}} \right]^2 ,$$

Preliminary 23xx.xxxx

Neutrinoless double beta decay and cosmology tests



- SUSY SO(10) model
- Partially testable by neutrinoless double beta decay and cosmological surveys
- It achieve leptogenesis, predict fermion masses and mixing angles

Preliminary 23xx.xxxx

Conclusions

- Succesful gauge coupling unification
- Prediction of fermion masses and mixing angles
- Testable with next-gen GW and proton decay experiments
- Predict both neutrinoless double beta decay and neutrino masses in reach of the next-generation experimens

Thank you