

Testable Leptogenesis

Jacobo López-Pavón

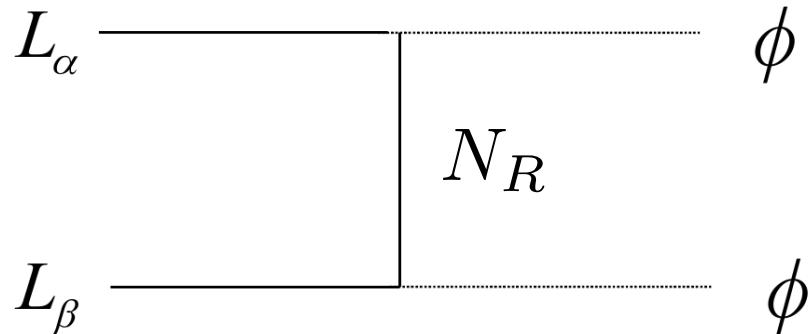


TeVPA 16
CERN, 12-16 Sept 2016

Motivation

- The LHC results indicate that the Higgs mechanism is the responsible for the mass generation of the SM particles.
- The origin of light neutrino masses, which existence is supported by neutrino oscillation experiments, still remains unknown.

Minimal Model: Seesaw Model

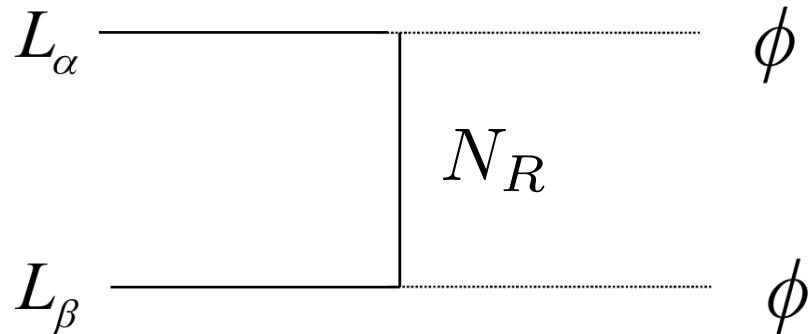


Heavy fermion singlet: ν_R . Type I seesaw.
Minkowski 77; Gell-Mann, Ramond, Slansky
79; Yanagida 79; Mohapatra, Senjanovic 80.

We will focus on the simplest extension of SM able to account for neutrino masses:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_K - \frac{1}{2} \overline{N}_i M_{ij} N_j - Y_{i\alpha} \overline{N}_i \tilde{\phi}^\dagger L_\alpha + h.c.$$

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New Physics Scale ($m_\nu \sim Y^2 v^2 / M$)

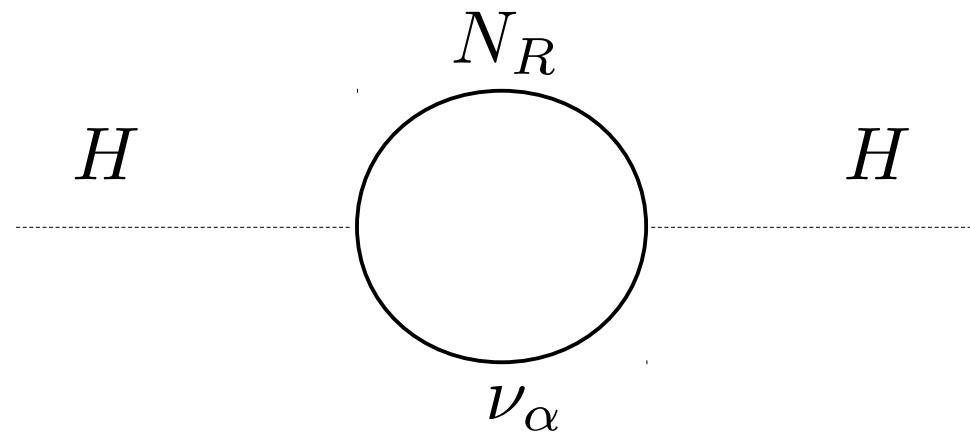
Heavy New Physics scale

$$m_\nu = \frac{v^2}{2} Y \textcolor{red}{M^{-1}} Y^T \lesssim \mathcal{O}(1 \text{ eV})$$

- $Y \sim 1$ suggests M close to the GUT scale.
- Drawback: New Physics effects at low energies very suppressed by the NP scale M .

Light New Physics scale

- Contrary to the high scale models, a low Majorana scale **does not worsen the Higgs mass hierarchy problem.**

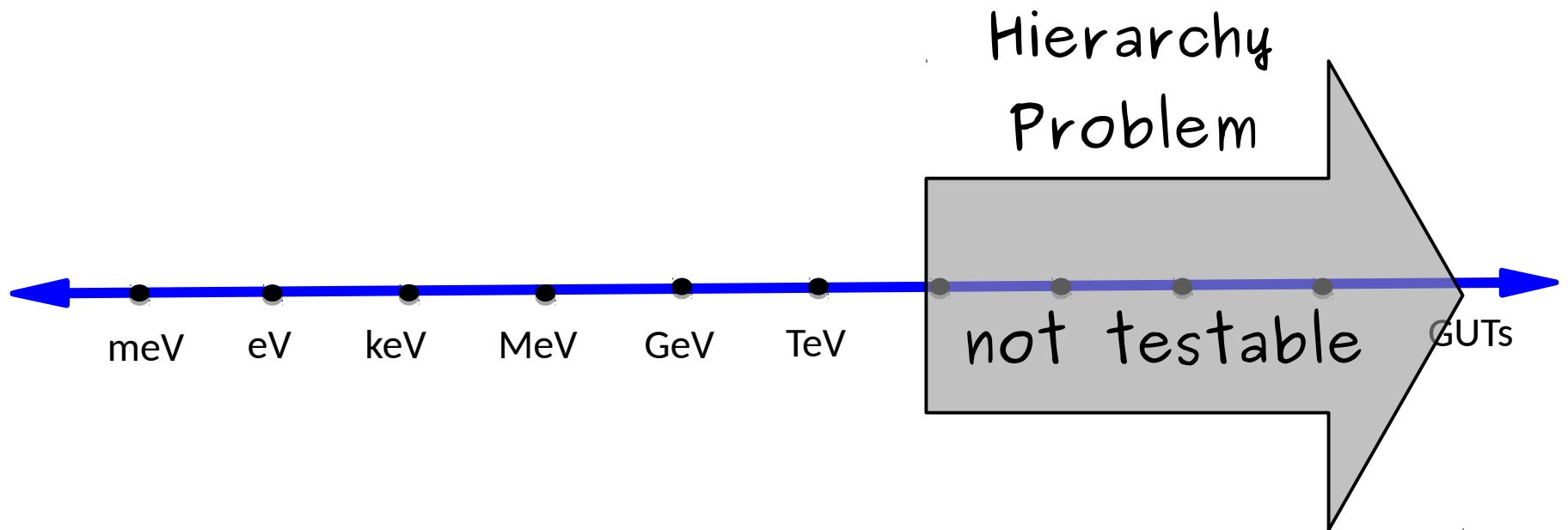


$$[\delta M_H^2]_{N_R} \propto M^2$$

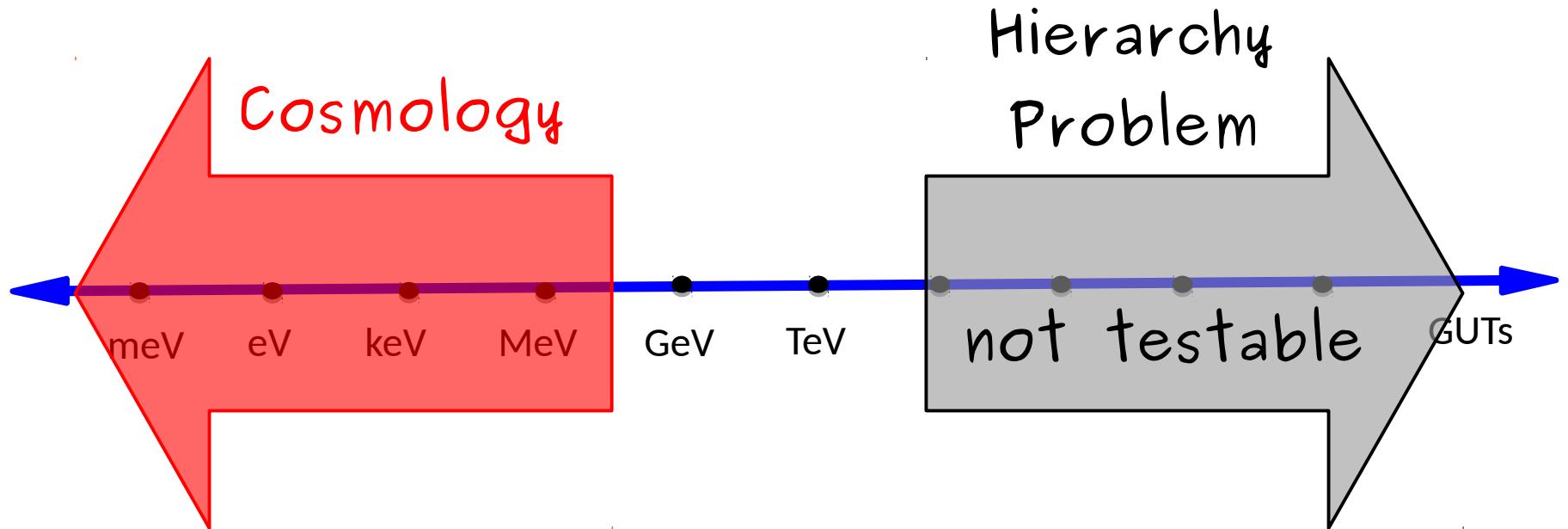
Vissani 1998

- Drawback: small Yukawa couplings required.

The New Physics Scale



The New Physics Scale



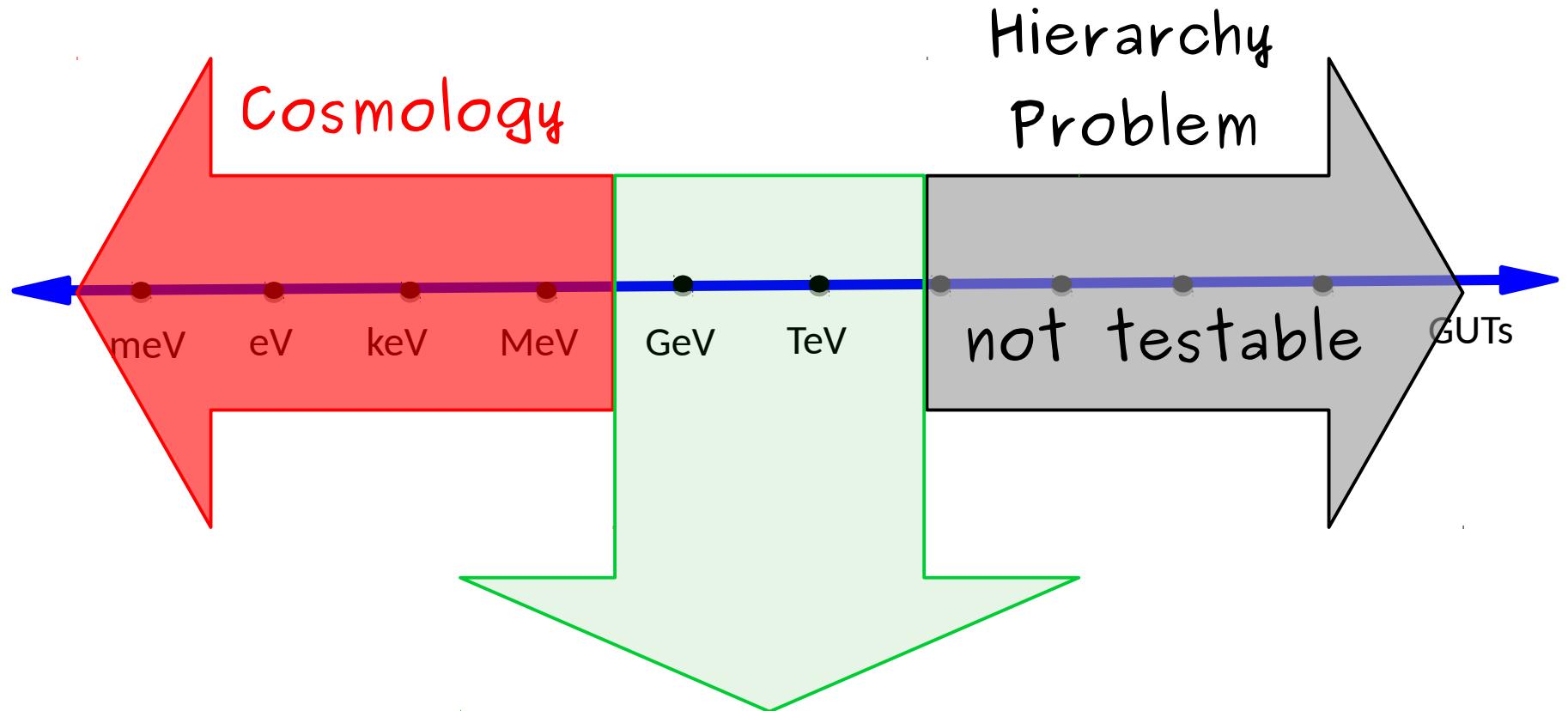
- Minimal Type-I seesaw with $N_R=2$

(or Type-I seesaw with $N_R=3$
& $m_{lightest} \gtrsim 10^{-3} eV$)

CMB+BBN data $\rightarrow M_R > 100 \text{ MeV}$

- Type-I seesaw with $N_R=3$ & $m_{lightest} \lesssim 10^{-3} eV$ $\left\{ \begin{array}{l} M_2, M_3 > 100 \text{ MeV} \\ M_1 \text{ unbounded} \end{array} \right.$

The New Physics Scale



- Resonant Leptogenesis $M > 100\text{GeV}$
Pilaftsis
- Leptogenesis via Oscillations $M = 0.1 - 100\text{GeV}$
Akhmedov, Rubakov, Smirnov (ARS); Asaka, Shaposhnikov (AS)

GeV Scale Leptogenesis

Hernandez, Kekic, JLP, Racker, Rius 1508.03676;
Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Asaka, Shaposhnikov;Shaposhnikov; Asaka, Eijima, Ishida; Canetti, Drewes, Frossard, Shaposhnikov;Drewes, Garbrecht; Shuve, Yavin; Abada, Arcadi, Domcke, Lucente...(see also Klaric's talk)

Kinematic Equations

We have solved the equations for the density matrix in the Raffelt-Sigl formalism

$$\frac{d\rho_N(k)}{dt} = -i[H, \rho_N(k)] - \frac{1}{2} \{\Gamma_N^a, \rho_N\} + \frac{1}{2} \{\Gamma_N^p, 1 - \rho_N\}$$

- Fermi-Dirac or Bose-Einstein statistics is kept throughout
- Collision terms include $2 \leftrightarrow 2$ scatterings at tree level with top quarks and gauge bosons, as well as $1 \leftrightarrow 2$ scatterings, including the resummation of scatterings mediated by soft gauge bosons
- Leptonic chemical potentials are kept in all collision terms to linear order
- Include spectator processes

Kinematic Equations

We have solved the equations for the density matrix in the Raffelt-Sigl formalism using the code **SQuIDS**

Arguelles Delgado, Salvado, Weaver 2015

<https://github.com/jsalvado/SQuIDS>

$$\begin{aligned}
 xH_u \frac{dr_+}{dx} &= -i[\langle H_{\text{re}} \rangle, r_+] + [\langle H_{\text{im}} \rangle, r_-] - \frac{\langle \gamma_N^{(0)} \rangle}{2} \{ \text{Re}[Y^\dagger Y], r_+ - 1 \} \\
 &\quad + i\langle \gamma_N^{(1)} \rangle \text{Im}[Y^\dagger \mu Y] - i\frac{\langle \gamma_N^{(2)} \rangle}{2} \{ \text{Im}[Y^\dagger \mu Y], r_+ \} - i\frac{\langle \gamma_N^{(0)} \rangle}{2} \{ \text{Im}[Y^\dagger Y], r_- \}, \\
 xH_u \frac{dr_-}{dx} &= -i[\langle H_{\text{re}} \rangle, r_-] + [\langle H_{\text{im}} \rangle, r_+] - \frac{\langle \gamma_N^{(0)} \rangle}{2} \{ \text{Re}[Y^\dagger Y], r_- \} \\
 &\quad + \langle \gamma_N^{(1)} \rangle \text{Re}[Y^\dagger \mu Y] - \frac{\langle \gamma_N^{(2)} \rangle}{2} \{ \text{Re}[Y^\dagger \mu Y], r_+ \} - i\frac{\langle \gamma_N^{(0)} \rangle}{2} \{ \text{Im}[Y^\dagger Y], r_+ - 1 \}, \\
 \frac{d\mu_{B/3-L_\alpha}}{dx} &= \frac{\int_k \rho_F}{\int_k \rho'_F} \left\{ \langle \gamma_N^{(0)} \rangle \text{Tr}[r_- \text{Re}(Y^\dagger I_\alpha Y) + ir_+ \text{Im}(Y^\dagger I_\alpha Y)] \right. \\
 &\quad \left. + \mu_\alpha \left(\langle \gamma_N^{(2)} \rangle \text{Tr}[r_+ \text{Re}(Y^\dagger I_\alpha Y)] - \langle \gamma_N^{(1)} \rangle \text{Tr}[YY^\dagger I_\alpha] \right) \right\}, \\
 \mu_\alpha &= - \sum_\beta C_{\alpha\beta} \mu_{B/3-L_\beta},
 \end{aligned}$$

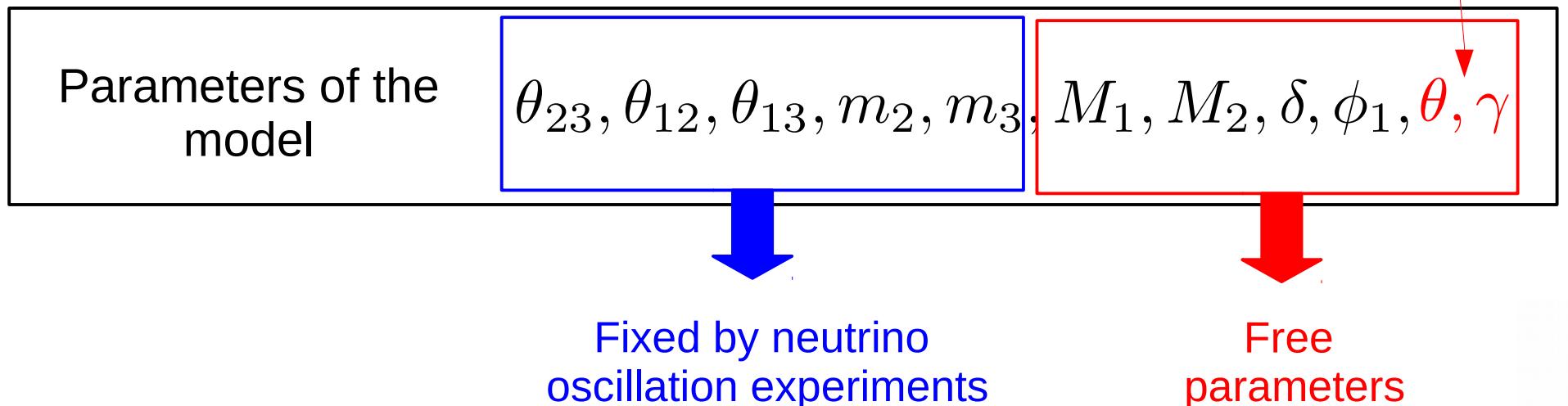
Full parameter space exploration $N_R=2$

$$Y_B^{\text{exp}} \simeq 8.65(8) \times 10^{-11}$$

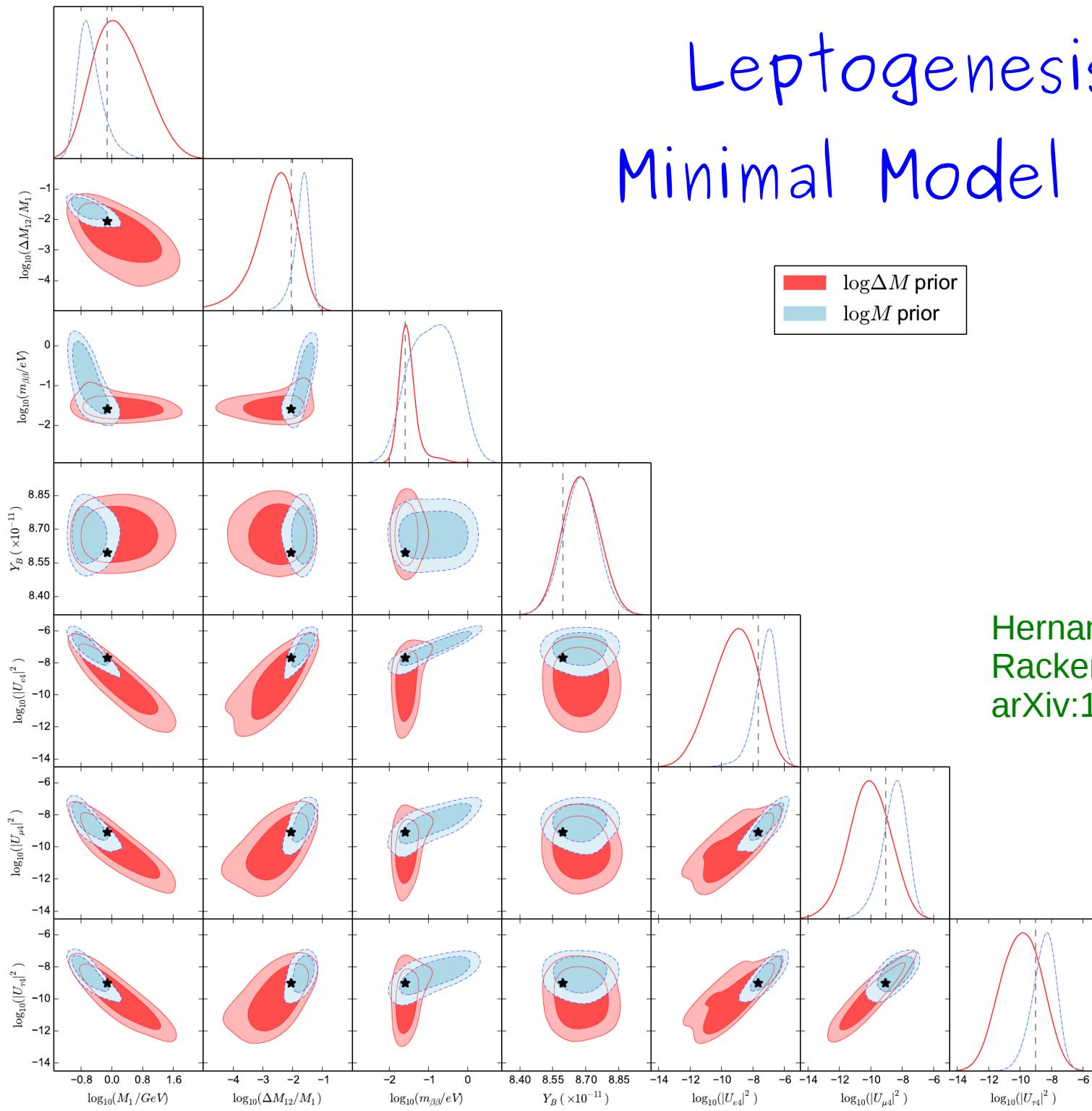
Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

$$\log \mathcal{L} = -\frac{1}{2} \left(\frac{Y_B(t_{\text{EW}}) - Y_B^{\text{exp}}}{\sigma_{Y_B}} \right)^2.$$

Casas-Ibarra
 $R(\theta + i\gamma)$



Leptogenesis in Minimal Model NR=2

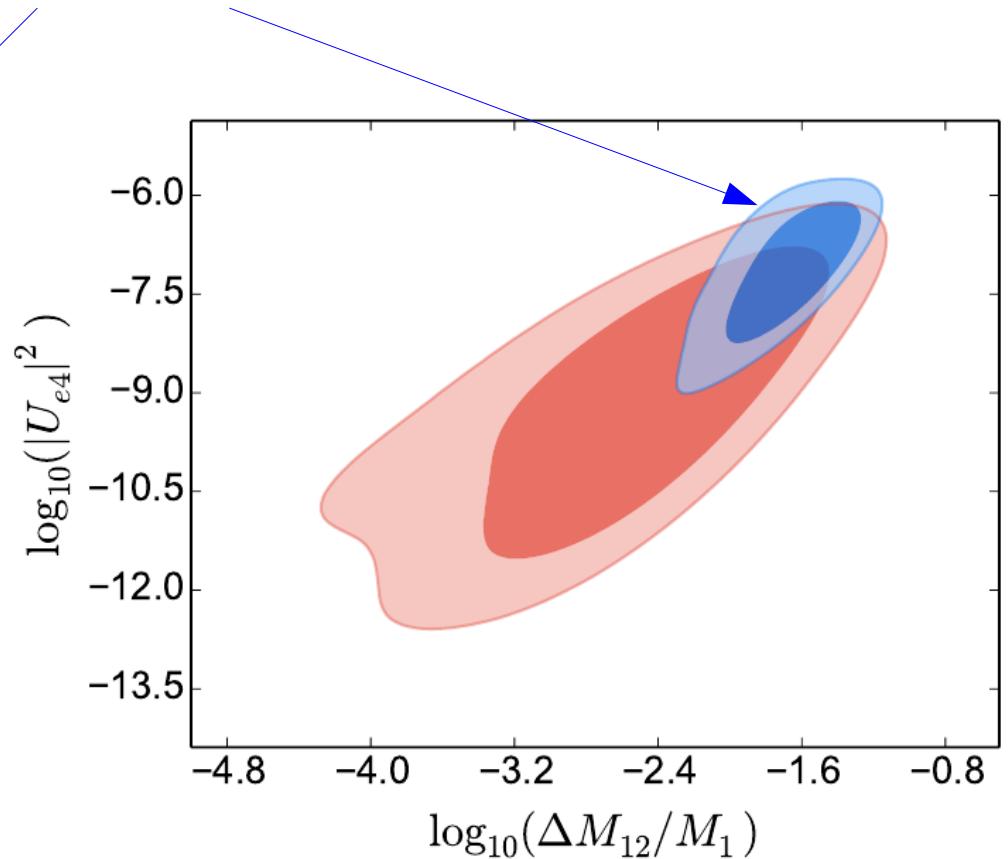
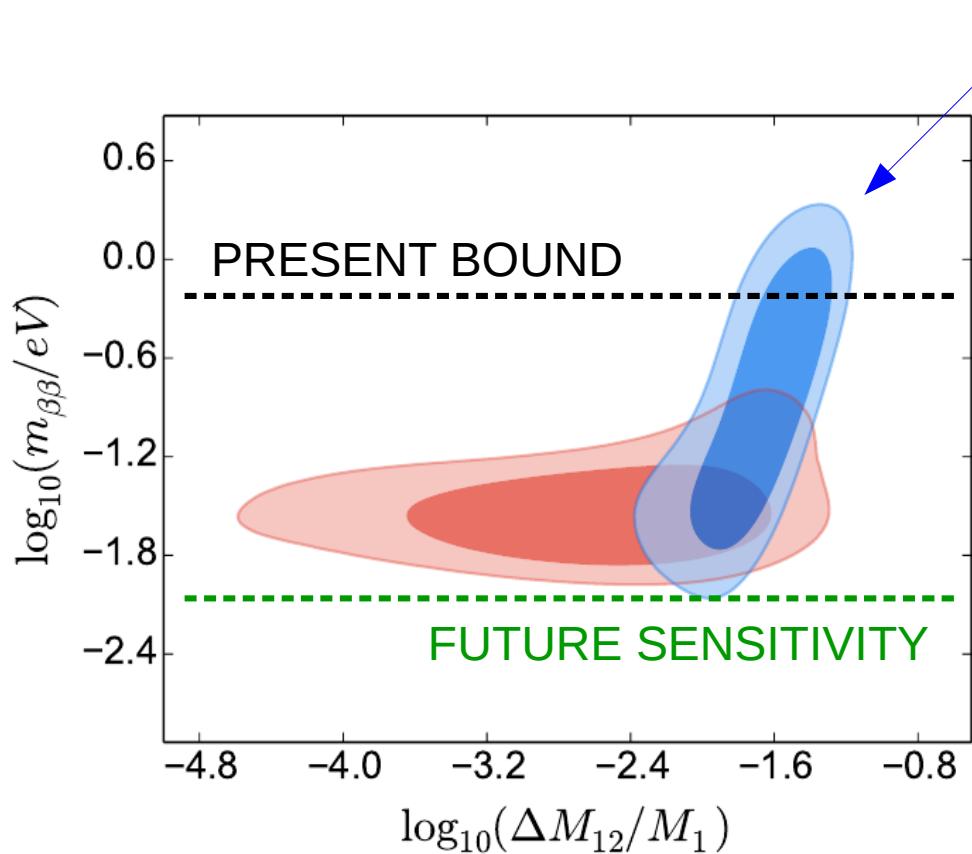


Hernandez, Kekic, JLP,
Racker, Salvado 2016
arXiv:1606.06719

IH

Leptogenesis in Minimal Model NR=2

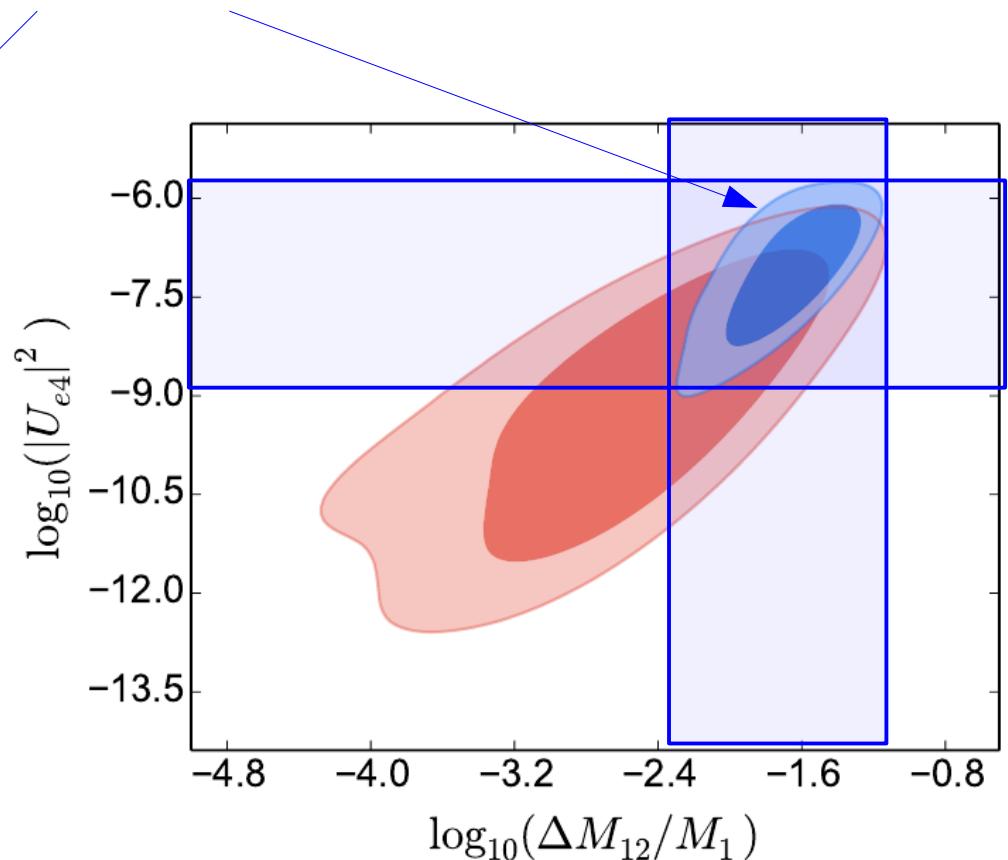
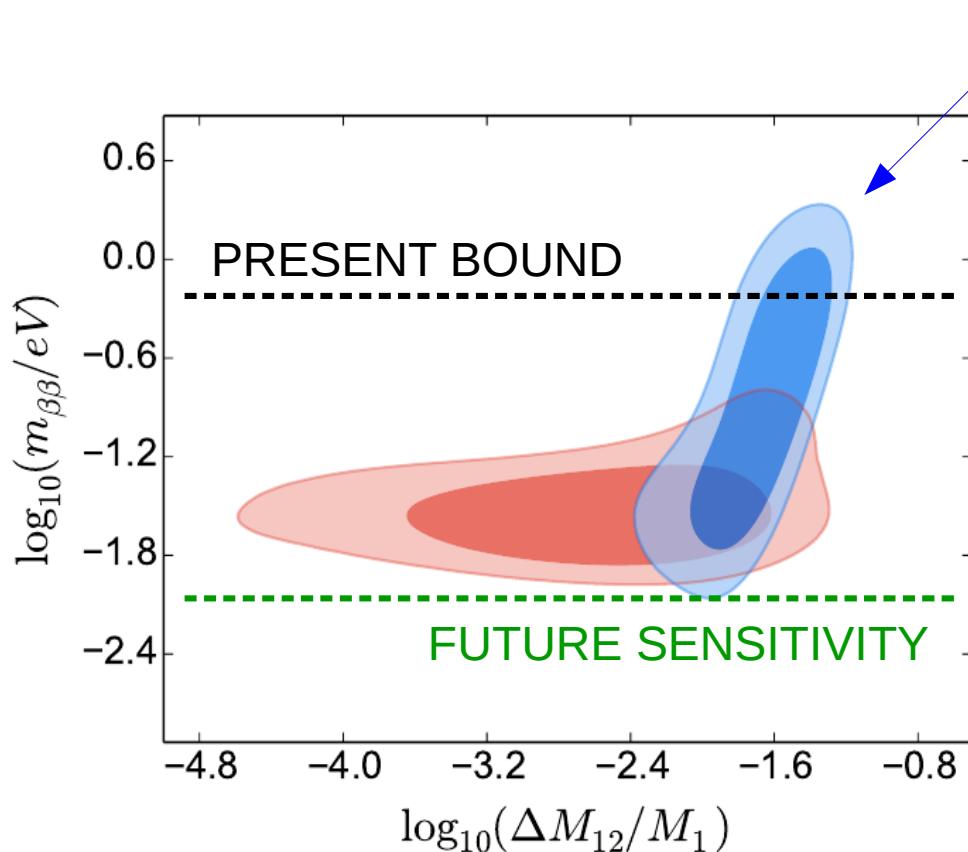
Non very degenerated solutions



Inverted light neutrino ordering (IH)

Leptogenesis in Minimal Model NR=2

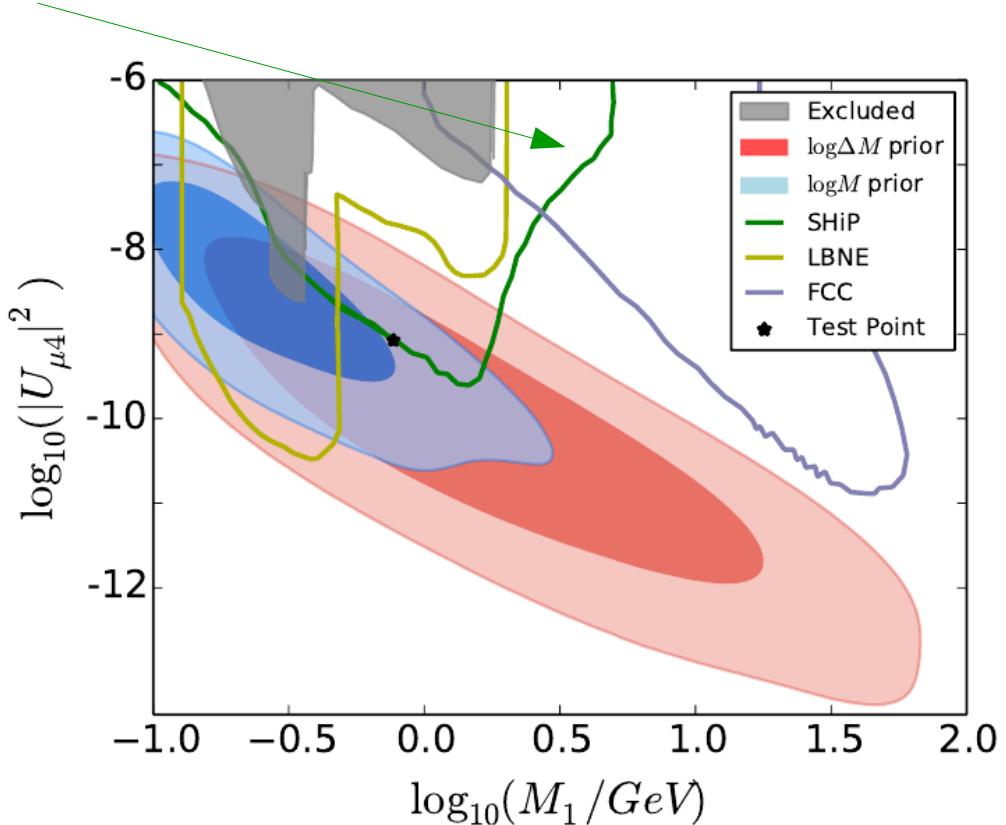
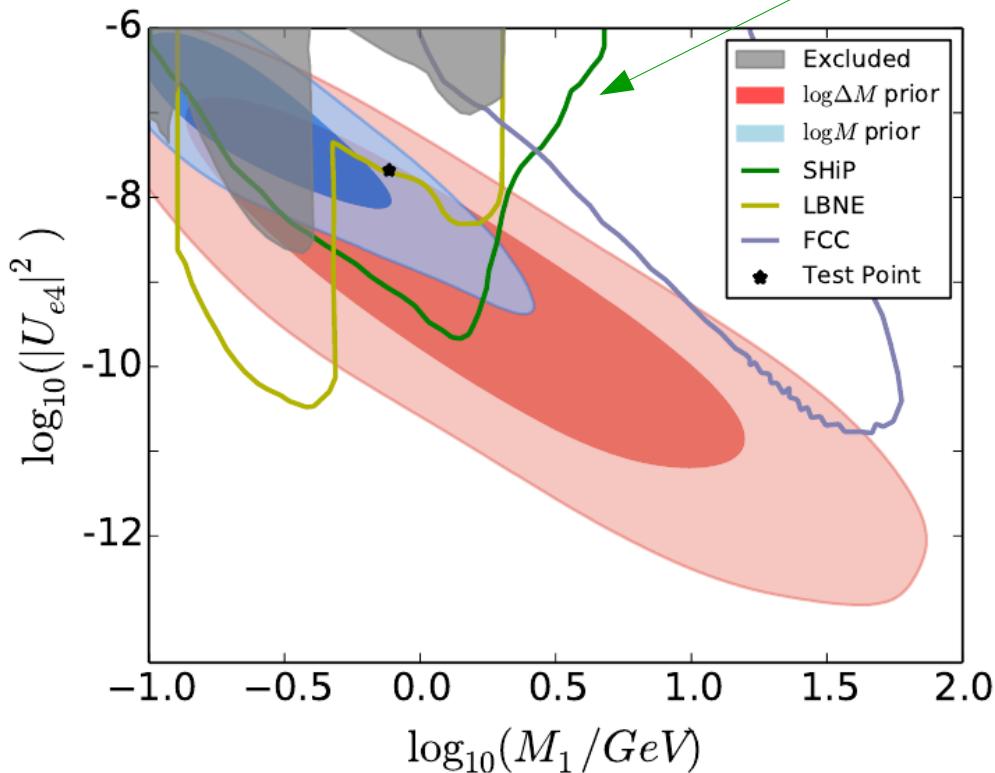
Non very degenerate solutions



Inverted light neutrino ordering (IH)

Leptogenesis in Minimal Model NR=2

SHIP



Inverted light neutrino ordering

What if the sterile ν are
within reach of ShiP?

Can we estimate Y_B
from the experiments?

Predicting Y_B in minimal model $N_R=2$

- **SHIP** sensitive to sterile neutrinos $\longleftrightarrow \left\{ \begin{array}{l} |U_{\alpha j}^2| \gg m_\nu/M \\ (\text{large } R_{ij} \leftrightarrow e^\gamma \gg 1) \end{array} \right.$
- **Baryon asymmetry** for IH and in the weak wash out regime:

$$[Y_B]_{IH} \propto e^{4\gamma} \frac{(\Delta m_{atm}^2)^{3/2}}{4v^6} M_1 M_2 (M_1 + M_2)$$
$$\left[(\sin 2\theta \cos 2\theta_{12} - \cos \phi_1 \cos 2\theta \sin 2\theta_{12}) (\sin^2 2\theta_{23} + (4 + \cos 4\theta_{23}) \sin \phi_1 \sin 2\theta_{12}) \right. \\ \left. + \mathcal{O}(\epsilon) \right]$$

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circled terms: $e^{4\gamma}$, $(\Delta m_{atm}^2)^{3/2}$, $4v^6$, $\sin 2\theta$, $\cos 2\theta_{12}$, $\cos \phi_1$, $\sin 2\theta_{12}$, $\sin^2 2\theta_{23}$, $4 + \cos 4\theta_{23}$, $\sin \phi_1$, $\sin 2\theta_{12}$

Predicting Y_B in minimal model $N_R=2$

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- Baryon asymmetry depends on all the unknown parameters (also on δ at $\mathcal{O}(\epsilon)$)

Predicting Y_B in minimal model $N_R=2$

- **SHIP** can measure (if sterile states not too degenerate)

$$M_1, M_2, |U_{e4}|, |U_{e5}|, |U_{\mu 4}|, |U_{\mu 5}|$$

Predicting Y_B in minimal model $N_R=2$

- SHIP can measure (if sterile states not too degenerate):

$$M_1, M_2, |U_{e4}|, |U_{e5}|, |U_{\mu 4}|, |U_{\mu 5}|$$

SHIP sensitive to
PMNS CP-phases!

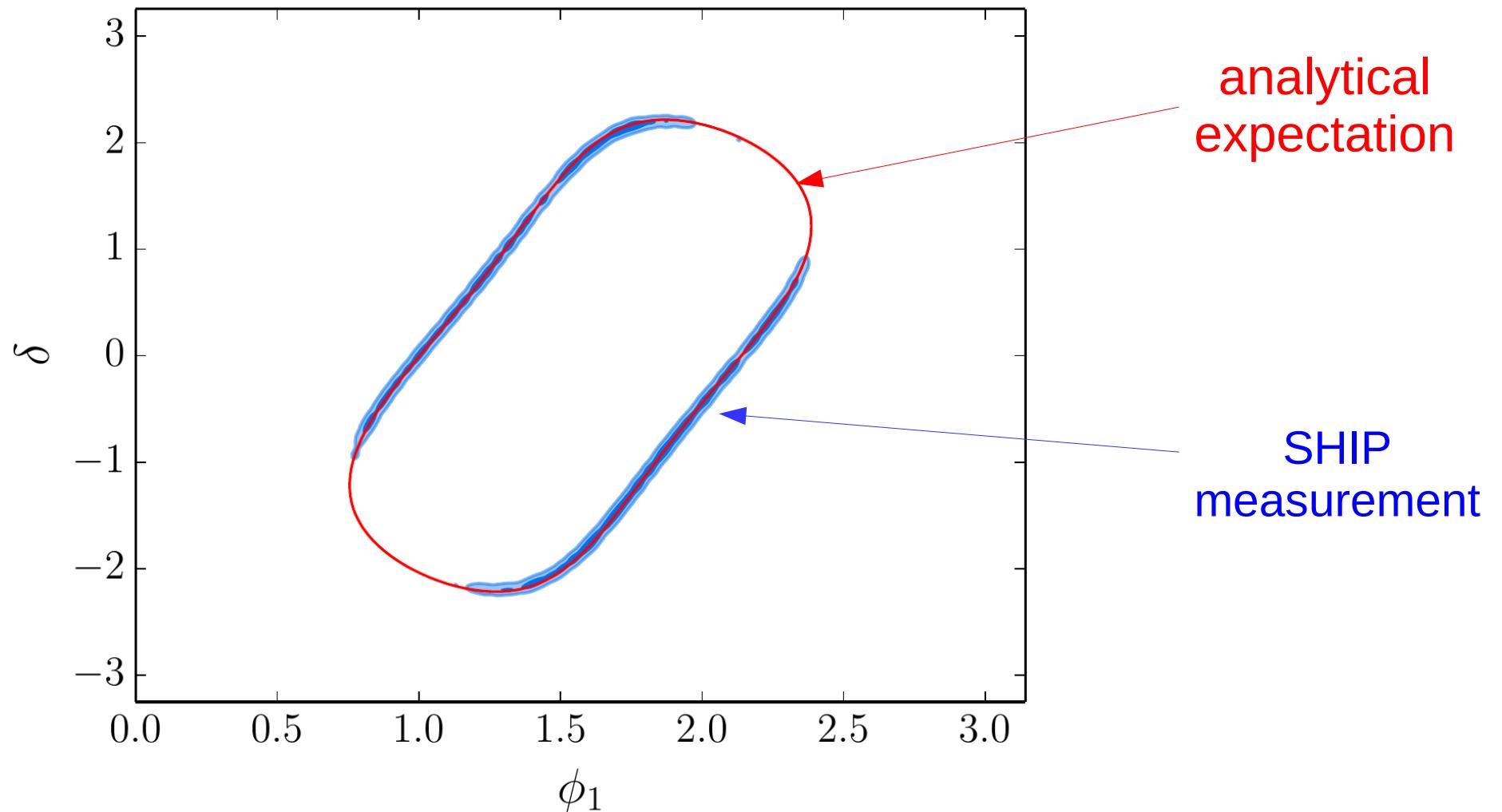
$$\bullet |U_{e4}|^2/|U_{\mu 4}|^2 \simeq |U_{e5}|^2/|U_{\mu 5}|^2 \simeq$$

$$\delta, \phi_1$$

$$(1 + s_{\phi_1} \sin 2\theta_{12})(1 - \theta_{13}^2) + \frac{1}{2}r^2 s_{12}(c_{12}s_{\phi_1} + s_{12})$$

$$\frac{(1 - \sin 2\theta_{12}s_{\phi_1} \left(1 + \frac{r^2}{4}\right) + \frac{r^2 c_{12}^2}{2}) c_{23}^2 + \theta_{13}(c_{\phi_1} s_{\delta} - \cos 2\theta_{12} s_{\phi_1} c_{\delta}) \sin 2\theta_{23} + \theta_{13}^2 (1 + \sin 2\theta_{12}) s_{23}^2 s_{\phi_1}}{(1 - \sin 2\theta_{12}s_{\phi_1} \left(1 + \frac{r^2}{4}\right) + \frac{r^2 c_{12}^2}{2}) c_{23}^2 + \theta_{13}(c_{\phi_1} s_{\delta} - \cos 2\theta_{12} s_{\phi_1} c_{\delta}) \sin 2\theta_{23} + \theta_{13}^2 (1 + \sin 2\theta_{12}) s_{23}^2 s_{\phi_1}}$$

SHIP sensitive to PMNS CP phases



Recall, neutrino oscillation experiments sensitive to δ

Predicting Y_B in minimal model $N_R=2$

- SHIP can measure (if sterile states not too degenerate):

$$M_1, M_2, |U_{e4}|, |U_{e5}|, |U_{\mu 4}|, |U_{\mu 5}|$$

SHIP sensitive to
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- $|U_{e4}|^2/|U_{\mu 4}|^2 \simeq |U_{e5}|^2/|U_{\mu 5}|^2 \simeq$

δ, ϕ_1

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- $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{e5}|^2, |U_{\mu 5}|^2 \propto e^{2\gamma}$

γ

Predicting Y_B in minimal model $N_R=2$

- SHIP sensitive to $M_1, M_2, \phi_1, \delta, \gamma$



- Great but...

...how about θ which is essential to predict Y_B ?

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

$$\begin{aligned} |m_{\beta\beta}|_{IH} &\simeq \\ &\simeq \sqrt{\Delta m_{atm}^2} \left| c_{13}^2 \left(c_{12}^2 + e^{2i\phi_1} s_{12}^2 \left(1 + \frac{r^2}{2} \right) \right) \right. \\ &\quad \left. - f(A) e^{2i\theta} e^{2\gamma} (c_{12} - ie^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23} \theta_{13}) \frac{(0.9 \text{ GeV})^2}{4M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}} \right)^2 \right) \right| \end{aligned}$$

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

$$|m_{\beta\beta}|_{IH} \simeq \text{LIGHT NEUTRINO contribution}$$

$$\simeq \sqrt{\Delta m_{atm}^2} \left[c_{13}^2 \left(c_{12}^2 + e^{2i\phi_1} s_{12}^2 \left(1 + \frac{r^2}{2} \right) \right) - f(A) e^{2i\theta} e^{2\gamma} (c_{12} - ie^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23} \theta_{13}) \frac{(0.9 \text{ GeV})^2}{4M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}} \right)^2 \right) \right]$$

Predicting γ_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

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LIGHT NEUTRINO contribution

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HEAVY NEUTRINO contribution

- Heavy neutrino contribution can be sizable for $M \sim O(GeV)$

Mitra, Senjanovic, Vissani 2011
 JLP, Pascoli, Wong 2012

Predicting γ_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

$$|m_{\beta\beta}|_{IH} \simeq$$

LIGHT NEUTRINO contribution

$$\simeq \sqrt{\Delta m_{atm}^2} \left[c_{13}^2 \left(c_{12}^2 + e^{2i\phi_1} s_{12}^2 \left(1 + \frac{r^2}{2} \right) \right) \right]$$

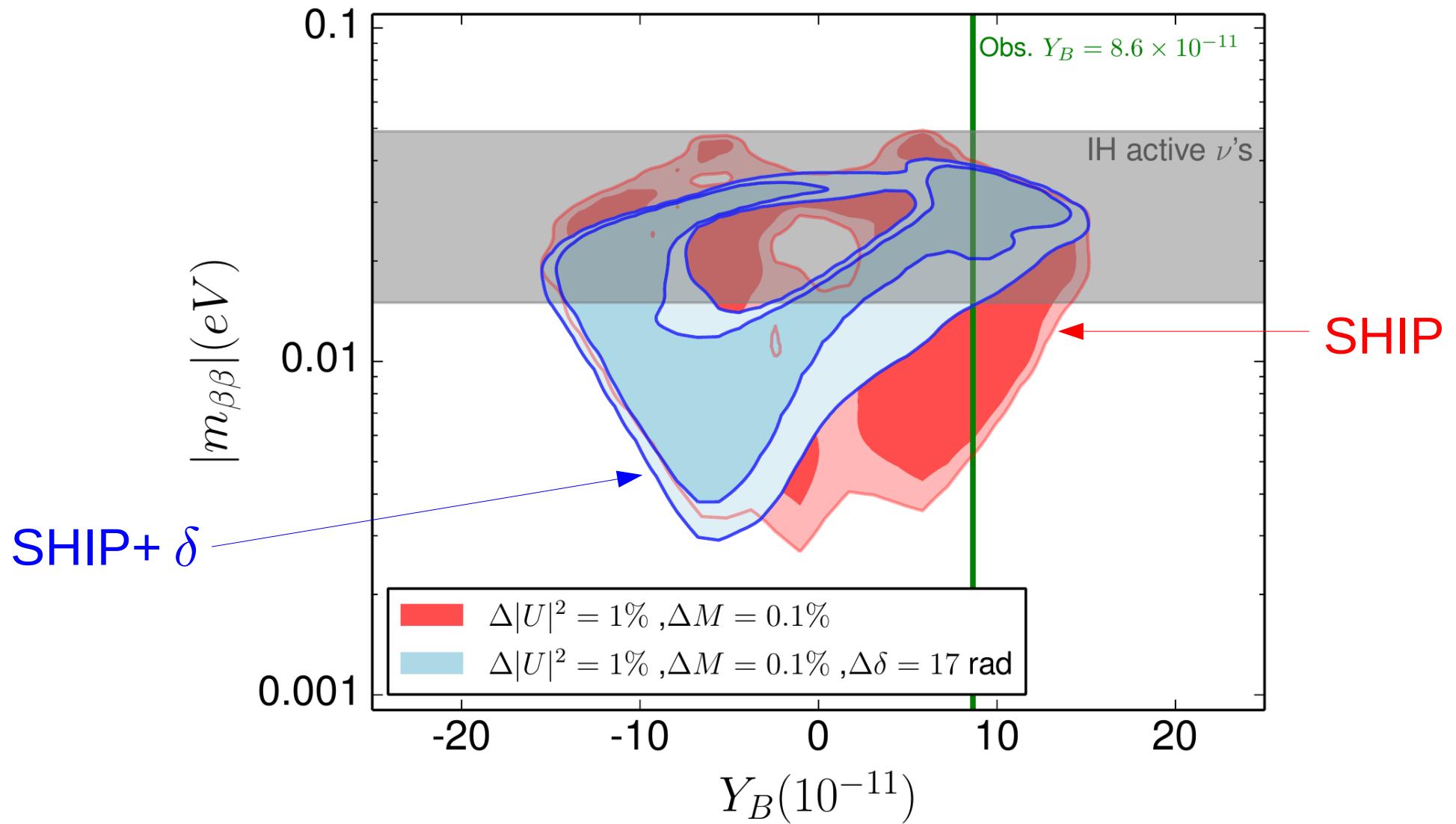
$$- f(A) e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2 e^{i\delta} s_{23} \theta_{13}) \frac{(0.9 \text{ GeV})^2}{4 M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}} \right)^2 \right)$$

θ

HEAVY NEUTRINO contribution

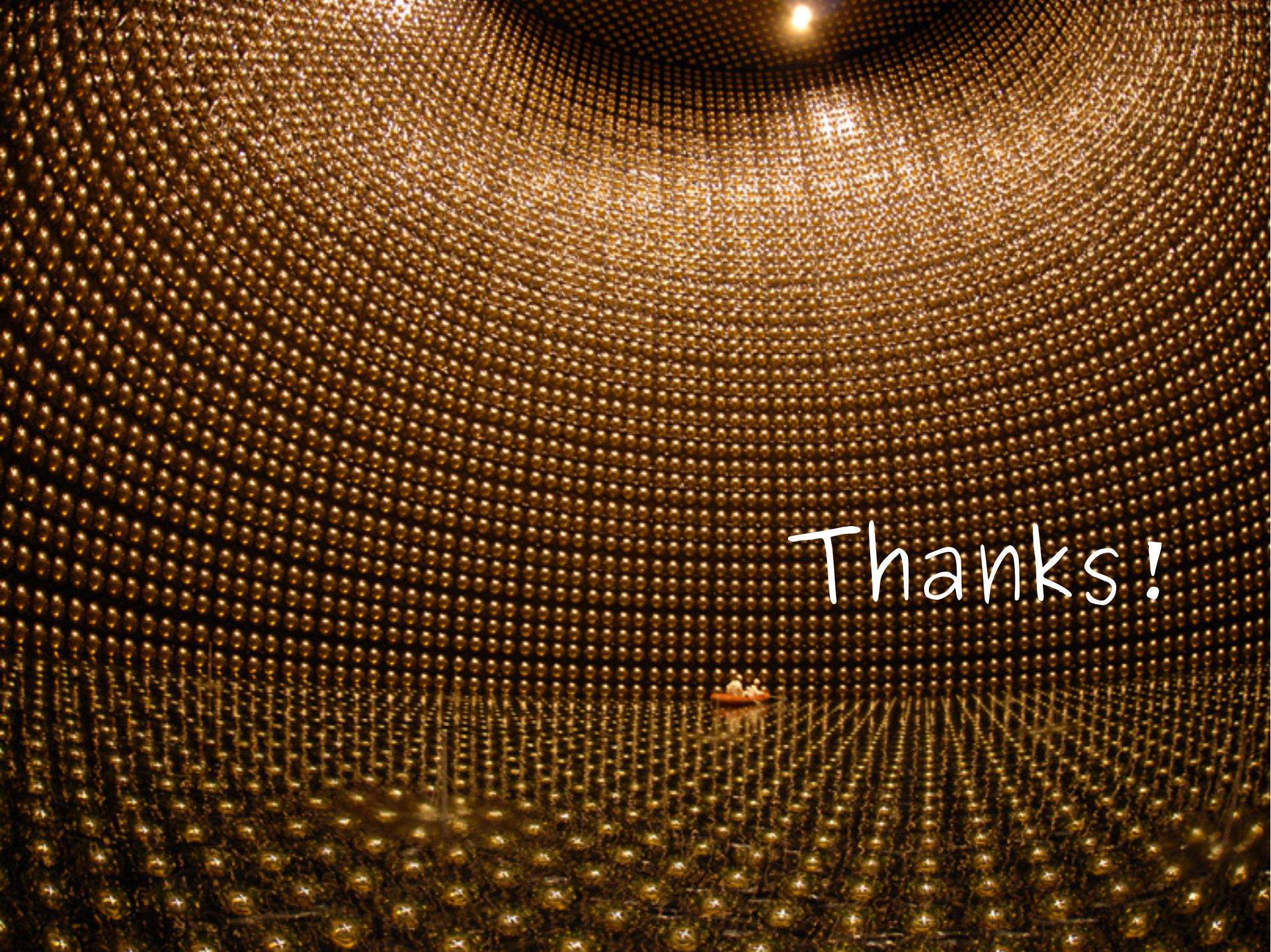
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Predicting Y_B in minimal model $N_R=2$



Summary and Conclusions

- Successful baryogenesis is possible with a mild heavy neutrino degeneracy in the minimal model ($N=2$)
- These less fine-tuned solutions prefer smaller masses $M \leq 1\text{GeV}$ (target region of SHiP) and significant non-standard contributions to neutrinoless double beta decay.
- SHiP, neutrinoless double beta decay and searches for leptonic CP violation in neutrino oscillations are complementary searches regarding the baryon asymmetry prediction.
- If $O(\text{GeV})$ heavy neutrinos would be discovered in SHiP and the neutrino ordering is inverted, predicting the baryon asymmetry looks in principle viable, in contrast with previous beliefs.
- SHIP could precisely determine a combination of the two phases of the U_{PMNS} matrix (regardless the baryon asymmetry generation).



Thanks!

CP invariants

- The lepton asymmetry should be proportional to a combination of the following 4 independent CP-invariants

$$I_1^{(2)} = -\text{Im}[W_{12}^* V_{11} V_{21}^* W_{22}]$$

$$I_1^{(3)} = \text{Im}[W_{12}^* V_{13} V_{23}^* W_{22}]$$

$$I_2^{(3)} = \text{Im}[W_{13}^* V_{12} V_{22}^* W_{23}]$$

$$J_W = -\text{Im}[W_{23}^* W_{22} W_{32}^* W_{33}]$$

}

CP phases from V & W
(U_{PMNS} & R)

}

CP phases from W
(only R)

$$Y = \textcolor{blue}{V}^\dagger \text{Diag } \{y_1, y_2, y_3\} \textcolor{red}{W}$$

CP invariants

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$$I_2^{(3)} = \text{Im}[W_{13}^* V_{12} V_{22}^* W_{23}]$$

$$J_W = -\text{Im}[W_{23}^* W_{22} W_{32}^* W_{33}]$$

$$Y = V^\dagger \text{Diag} \{y_1, y_2, y_3\} W$$

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$$Y = V^\dagger \text{Diag} \{y_1, y_2, y_3\} W$$

CP invariants

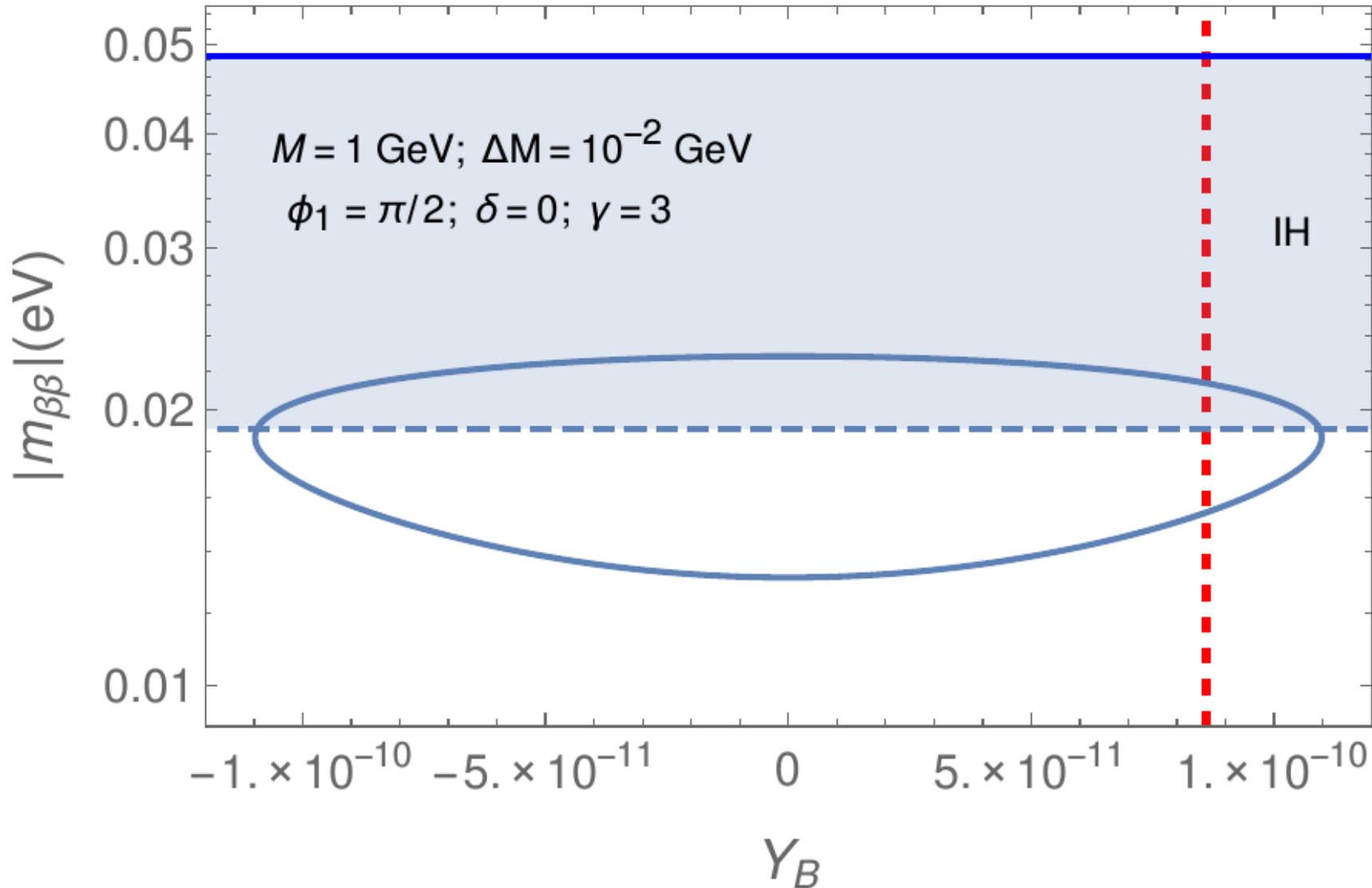
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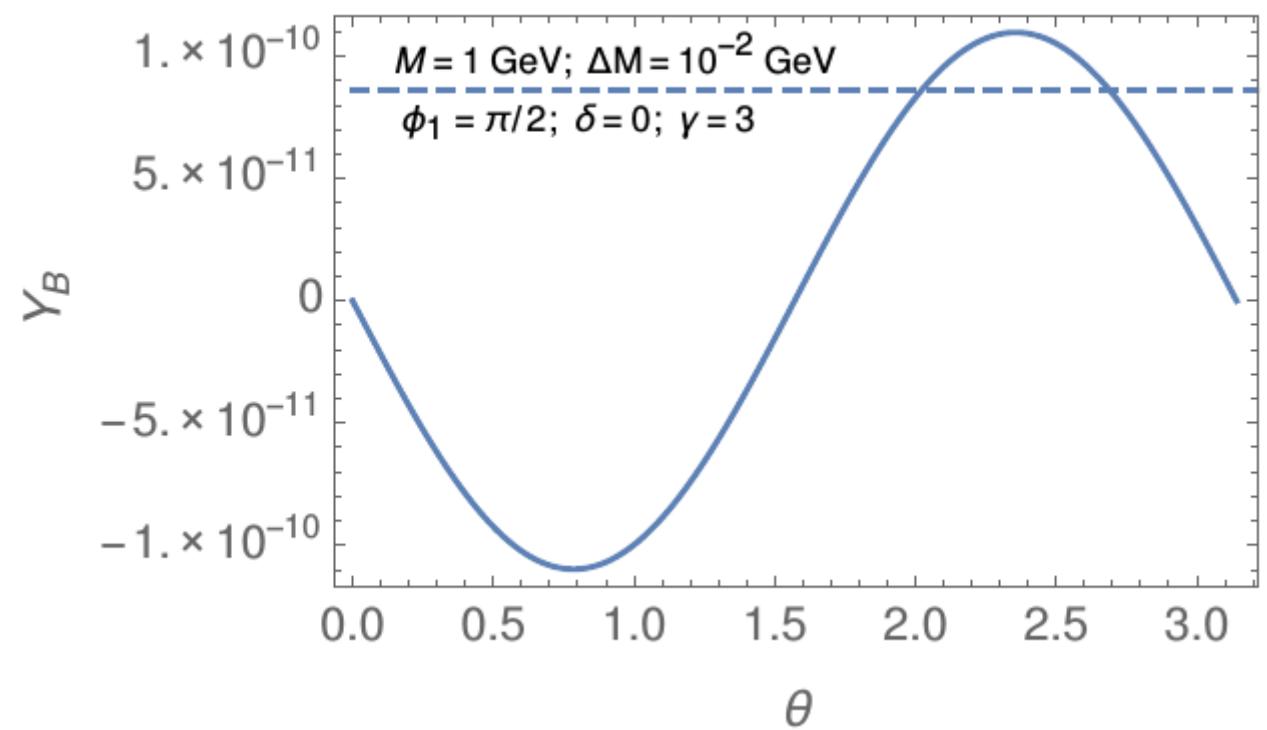
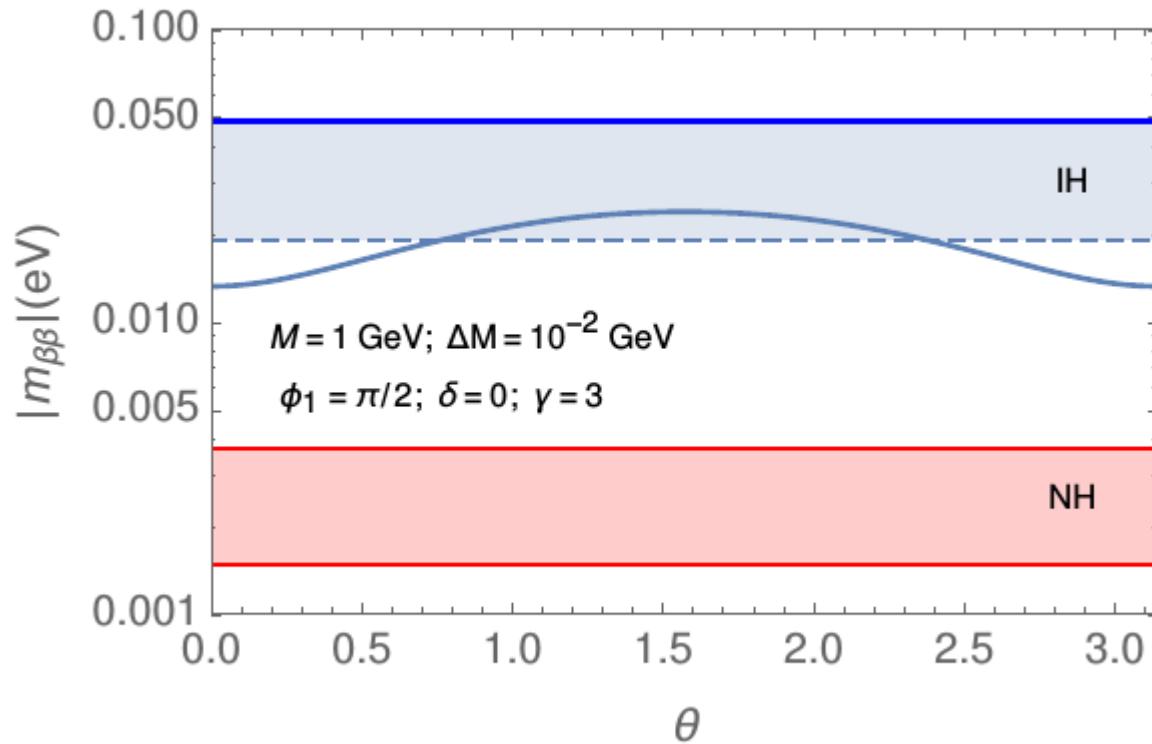
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$$J_W = -\text{Im}[W_{23}^* W_{22} W_{32}^* W_{33}] \quad \left. \right\} ARS$$

$$Y = V^\dagger \text{Diag} \{y_1, y_2, y_3\} W$$

Predicting Y_B in minimal model $N_R=2$



Leptogenesis in Minimal Model



Hernandez, Kekic, JLP,
Racker, Salvadò 2016
ArXiv:1606.06719

CP invariants

- The lepton assymetry should be proportional to a combination of the following 4 independent CP-invariants

$$I_1^{(2)} = -\text{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \simeq \theta_{12} \bar{\theta}_{12} \sin \psi_1$$

$$I_1^{(3)} = \text{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \simeq \theta_{12} \bar{\theta}_{13} \bar{\theta}_{23} \sin(\bar{\delta} + \psi_1)$$

$$I_2^{(3)} = \text{Im}[W_{13}^* V_{12} V_{22}^* W_{23}] \simeq \bar{\theta}_{12} \theta_{13} \theta_{23} \sin(\delta - \psi_1)$$

$$J_W = -\text{Im}[W_{23}^* W_{22} W_{32}^* W_{33}] \simeq \theta_{12} \theta_{13} \theta_{23} \sin \delta$$

$$Y = V^\dagger \text{Diag} \{y_1, y_2, y_3\} W$$

$$Y_B \simeq 1.3 \times 10^{-3} \sum_{\alpha} \mu_{B/3-L_{\alpha}}$$

Sakharov Conditions

(1) C and CP violation. *New CP-phases in the lepton sector.*

(2) Out of equilibrium: *at least one of the states should not reach equilibrium before T_{EW} .*

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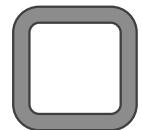


$$Y = -i \mathbf{U}_{PMNS} \sqrt{m_\nu} \mathbf{R}^T \sqrt{M} \frac{\sqrt{2}}{v}$$

Casas-Ibarra

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