Testable Leptogenesis & CP violation

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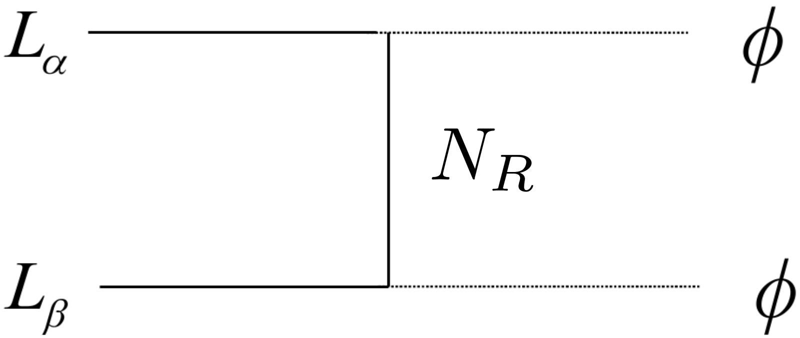
Motivation

- 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:

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

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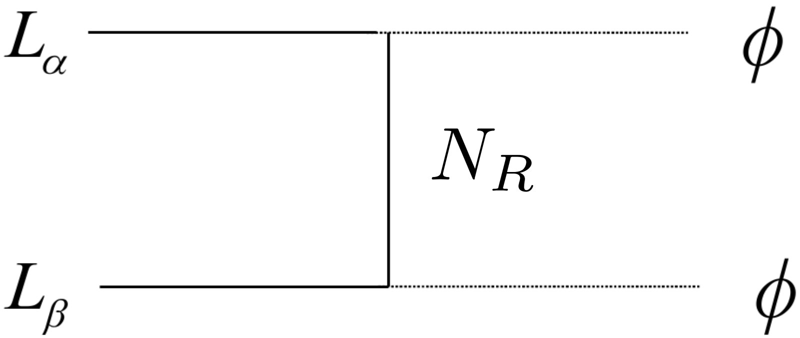

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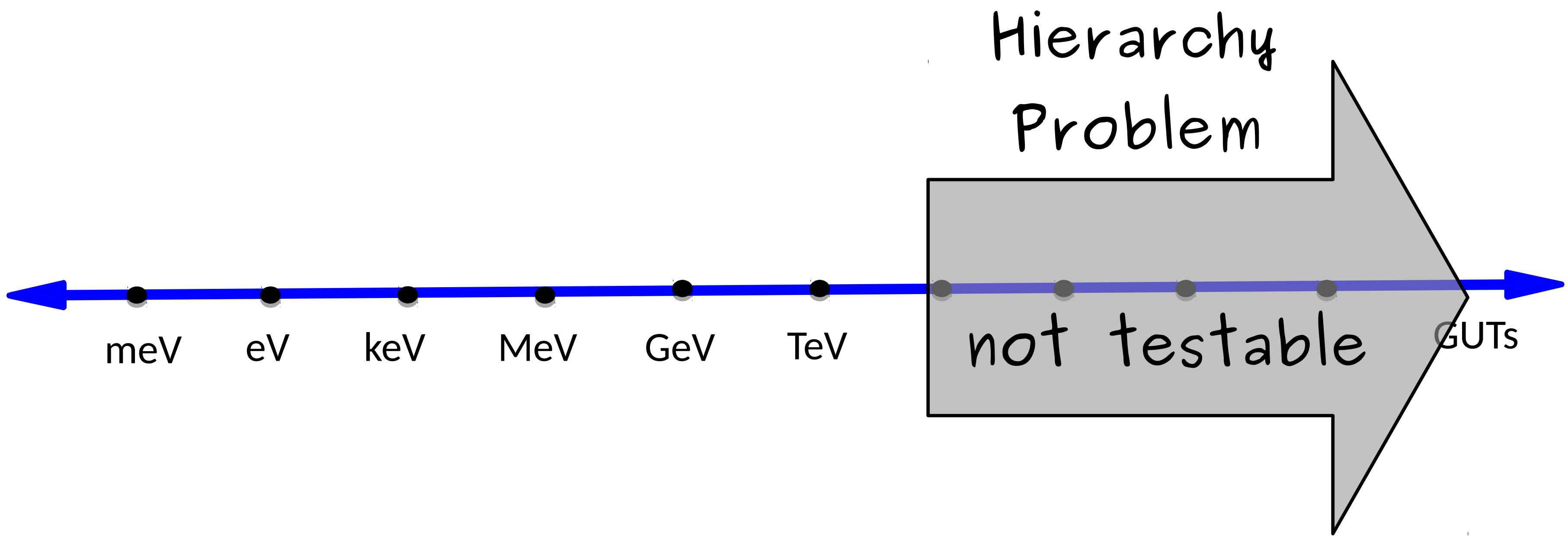
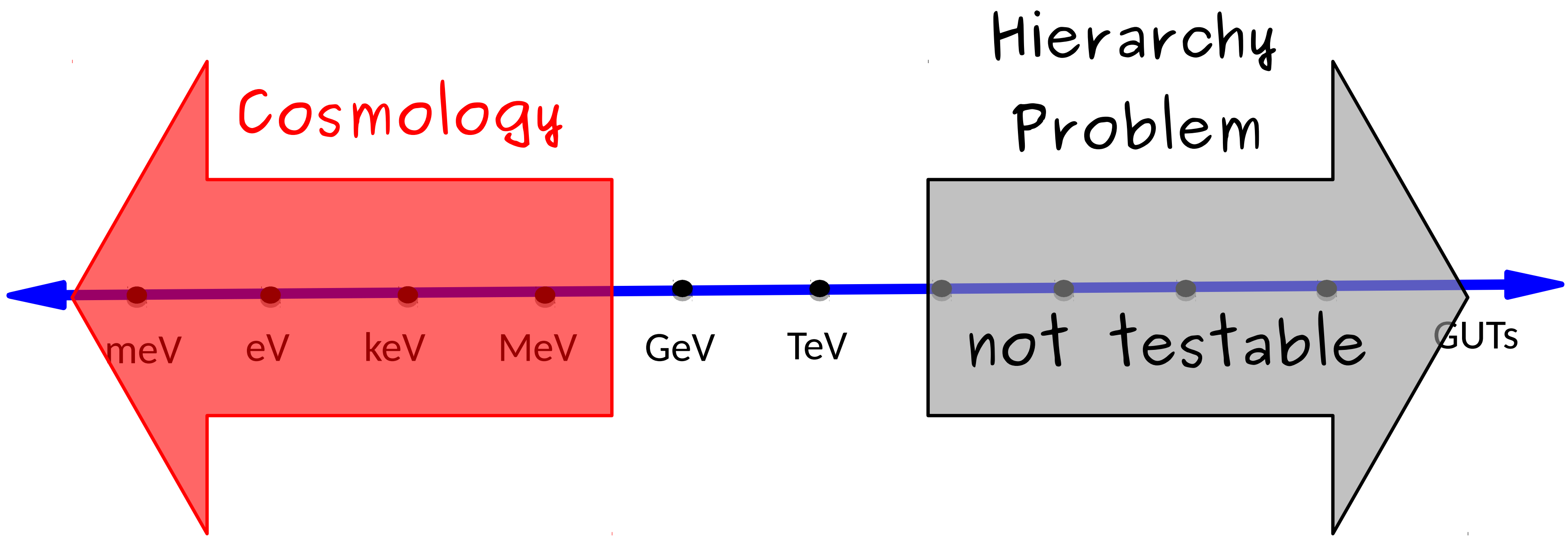
New Physics Scale $(m_\nu \sim Y^2 v^2 / M)$

The New Physics Scale



The New Physics Scale



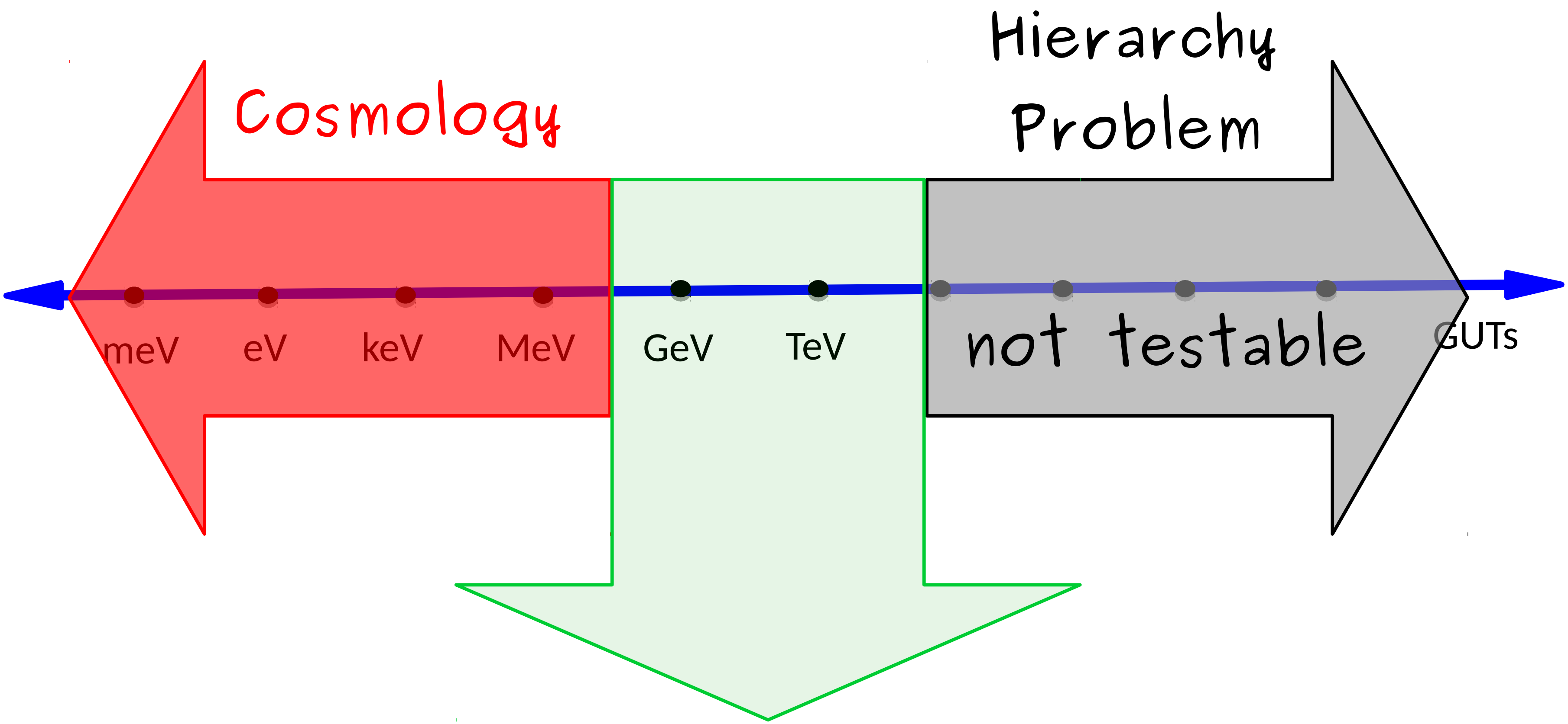
- Minimal Type-I seesaw with **N_R=2** (or Type-I seesaw with **N_R=3** & $m_{lightest} \gtrsim 10^{-3} eV$)

CMB+BBN data ➡ M_R >100 MeV

- Type-I seesaw with **N_R=3** & $m_{lightest} \lesssim 10^{-3} eV$ { M_2, M_3>100 MeV ; M_1 unbounded

P. Hernandez, M. Kekic, JLP 1311.2614;1406.2961

The New Physics Scale



- Resonant Leptogenesis M>100GeV
  Pilaftsis
- Leptogenesis via Oscillations M=0.1–100GeV
  Akhmedov, Rubakov, Smirnov (ARS); Asaka, Shaposnikov (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...

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 ↔ 2 scatterings at tree level with top quarks and gauge bosons, as well as 1 ↔ 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

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

Full parameter space exploration $N_R=2$

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

Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

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

Casas-Ibarra

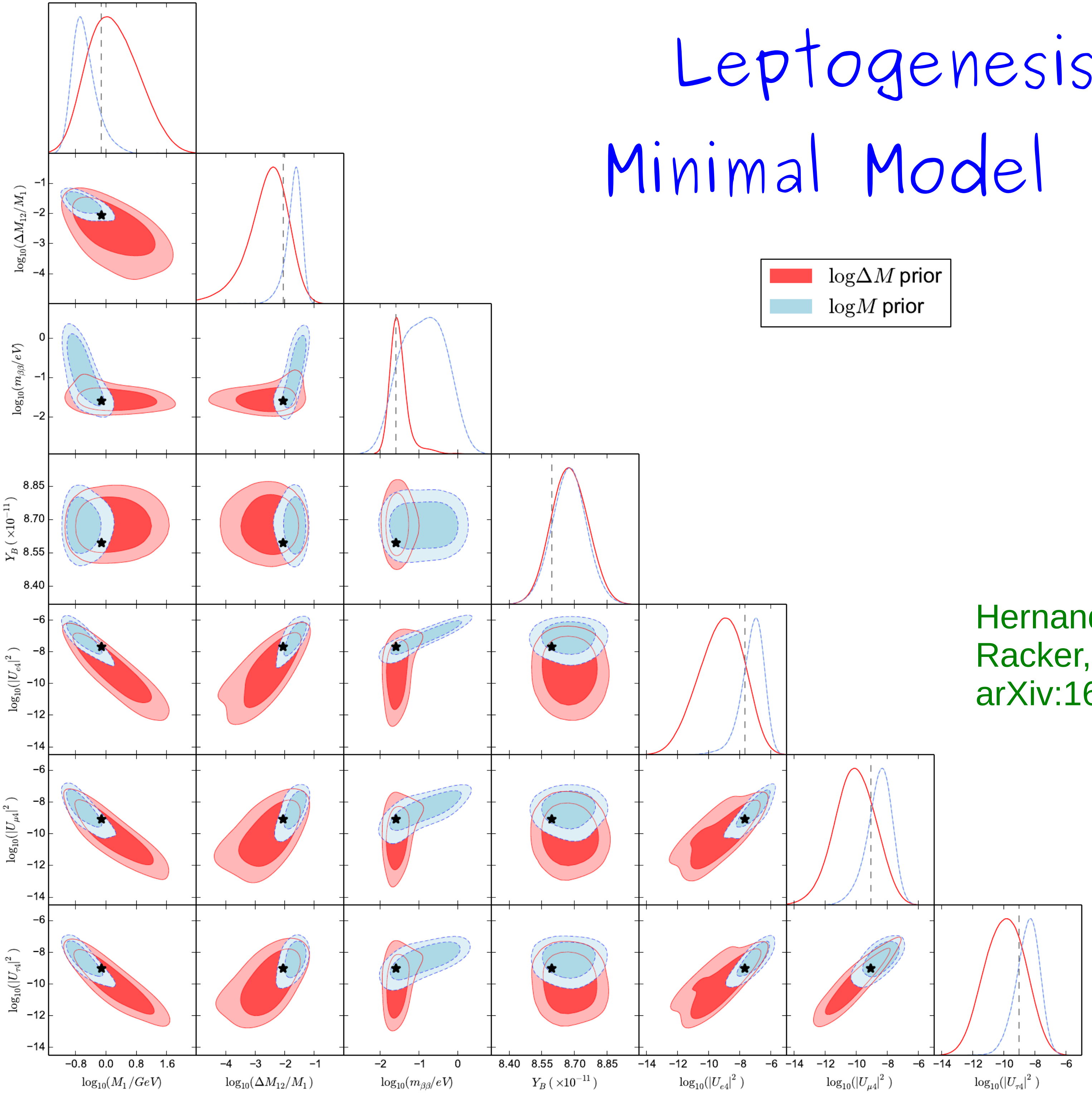
$R\,(\theta + i\gamma)$

Parameters of the model	$\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3$,	$M_1, M_2, \delta, \phi_1, \theta, \gamma$

Fixed by neutrino oscillation experiments

Free parameters

Leptogenesis in Minimal Model $N_R=2$

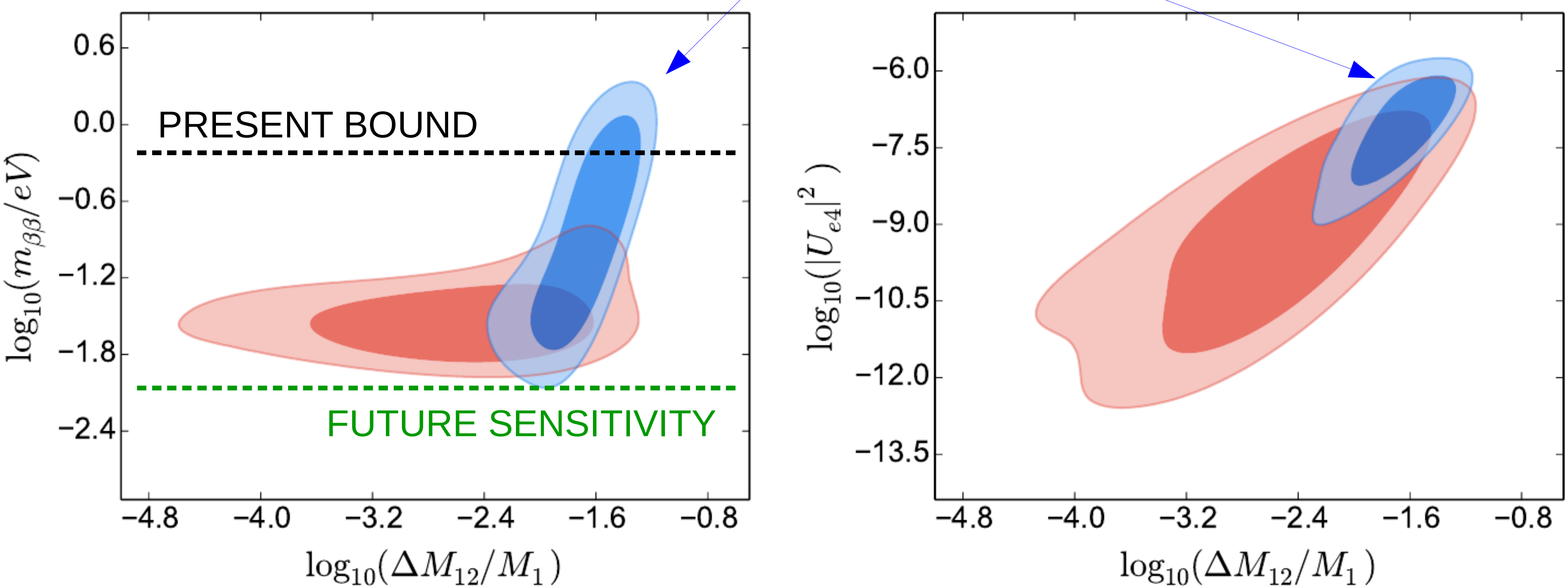


Hernandez, Kekic, JLP, Racker, Salvado 2016
arXiv:1606.06719

IH

Leptogenesis in Minimal Model $N_R=2$

Non degenerated solutions



Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 2016
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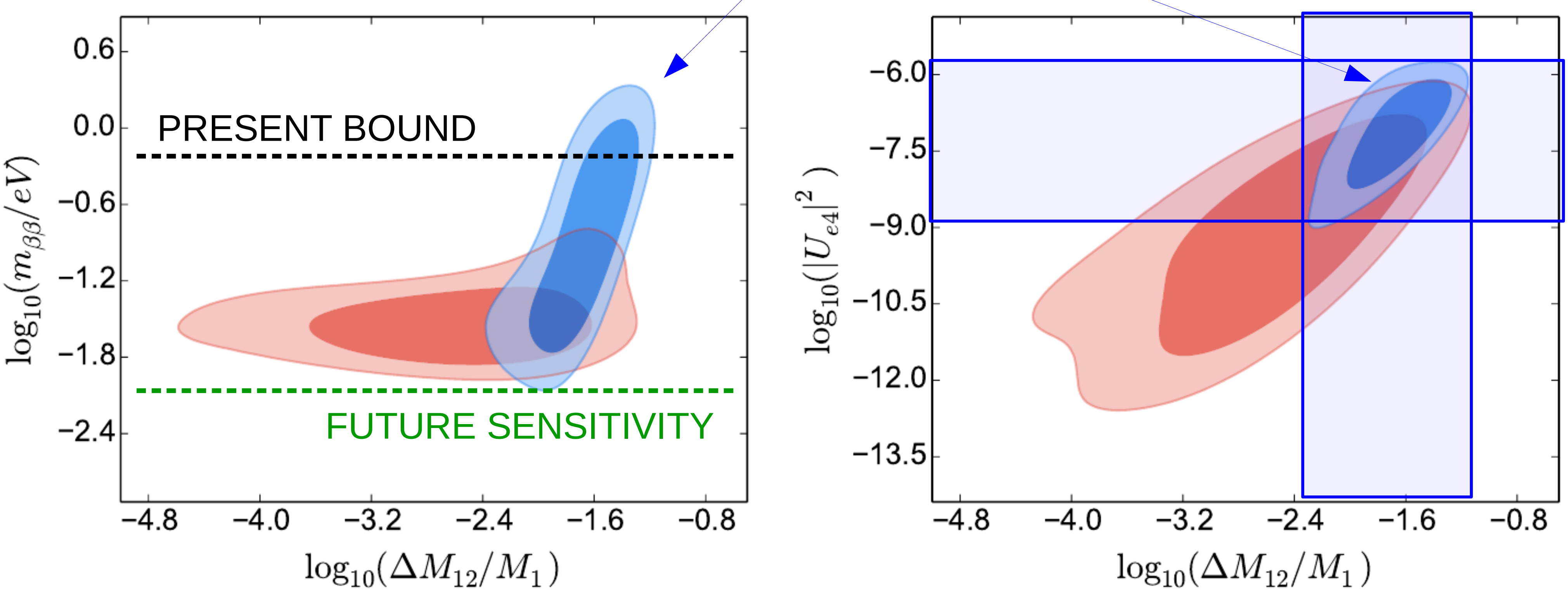

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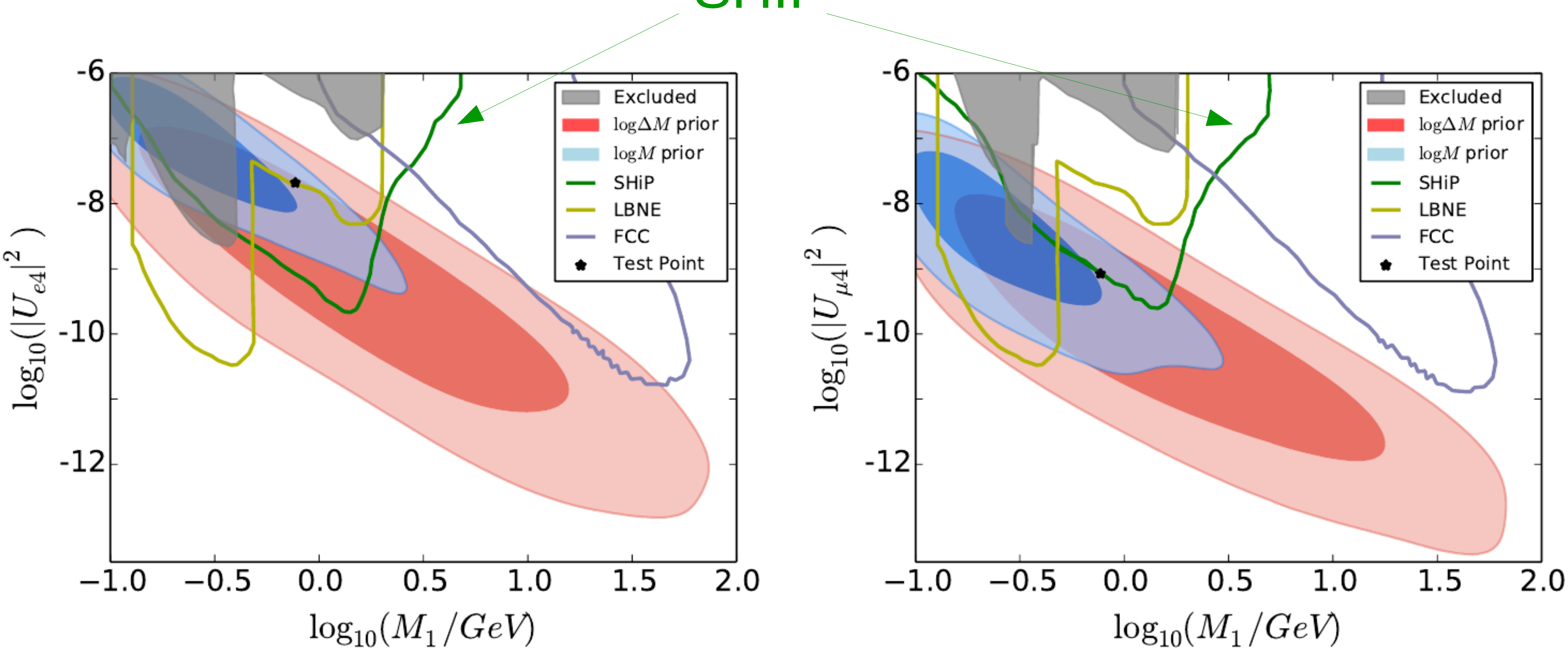
Leptogenesis in Minimal Model $N_R=2$

SHIP



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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 $\Longleftrightarrow$ $\begin{cases} |U^2_{\alpha j}| \gg m_\nu/M \\ \text{(large } R_{ij} \leftrightarrow e^\gamma \gg 1 \text{)} \end{cases}$

- **Baryon asymmetry** for IH and in the weak wash out regime:

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

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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 $N_R=2$

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SHIP sensitive to PMNS CP-phases! δ, ϕ_1

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

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

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- $|U_{e4}|^2, |U_{\mu4}|^2, |U_{e5}|^2, |U_{\mu5}|^2 \propto e^{2\gamma}$

γ

Predicting Y_B in minimal model $N_R=2$

- SHIP sensitive to M_1, M_2, ϕ_1, δ, γ

- 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

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

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

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

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

LIGHT NEUTRINO
contribution

$$\simeq \sqrt{\Delta m^2_{atm}} \left| c^2_{13}\left(c^2_{12} + e^{2i\phi_1} s^2_{12}\left(1 + \frac{r^2}{2}\right)\right) \right.$$

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

Predicting Y_B in minimal model $N_R=2$

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

$$\simeq \sqrt{\Delta m^2_{atm}} \left| c_{13}^2 \left(c_{12}^2 + e^{2i\phi_1} s_{12}^2 \left(1 + \frac{r^2}{2} \right) \right) - f(A)\, e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23}\theta_{13}) \frac{(0.9\,\mathrm{GeV})^2}{4M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}} \right)^2 \right) \right|$$

HEAVY NEUTRINO contribution

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

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

Predicting Y_B in minimal model $N_R=2$

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θ

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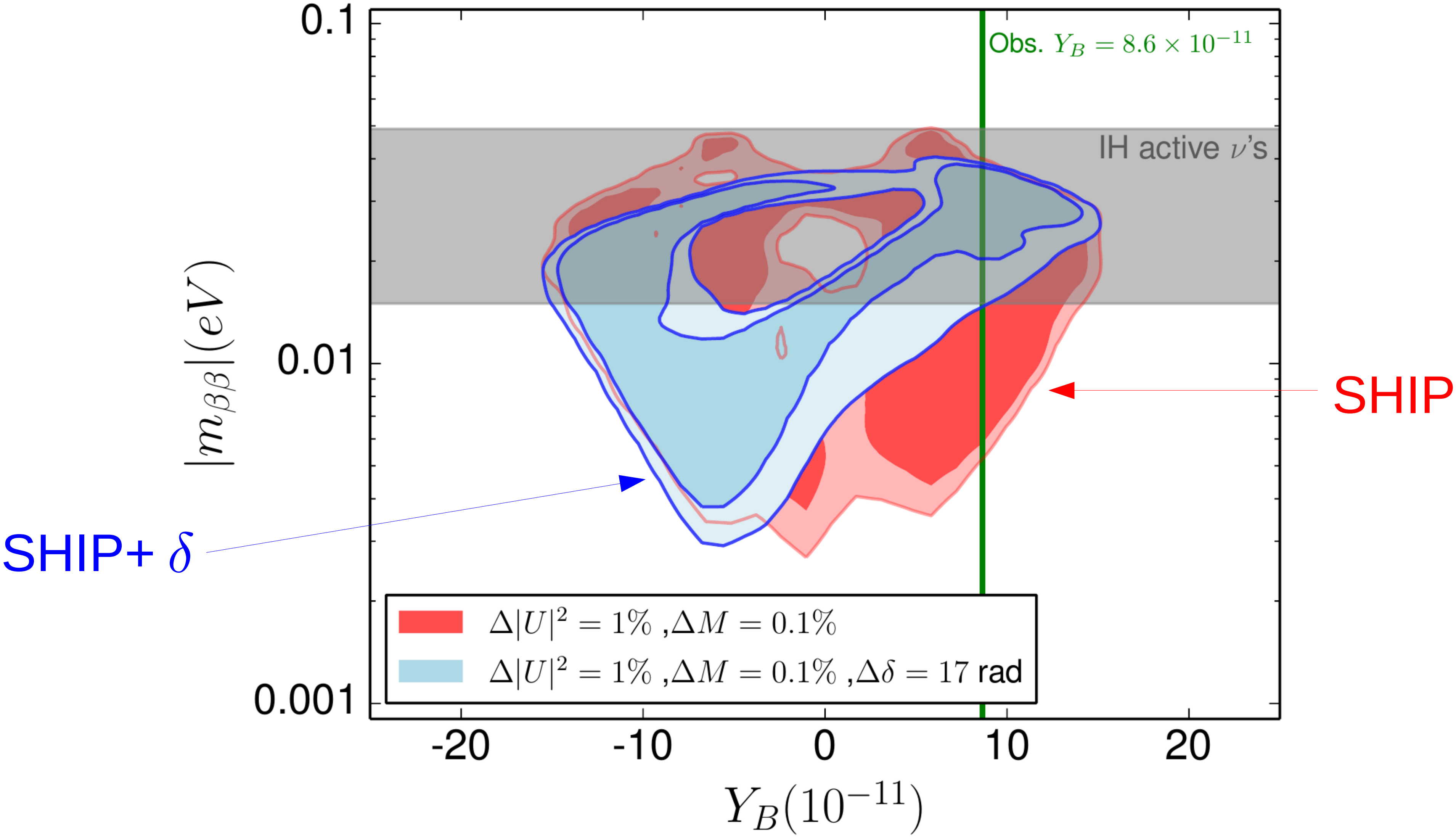
Predicting Y_B in minimal model $N_R=2$



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

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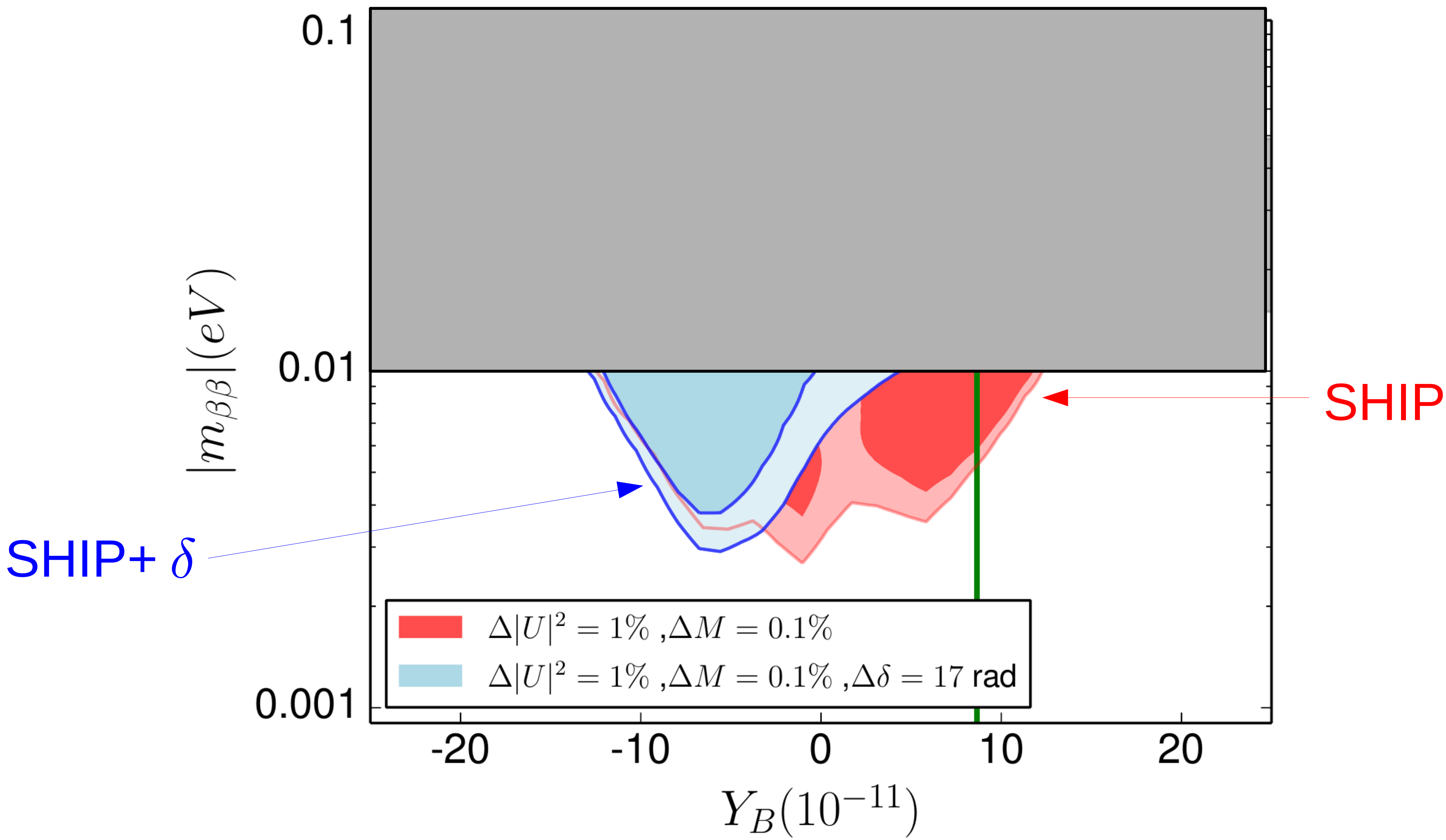

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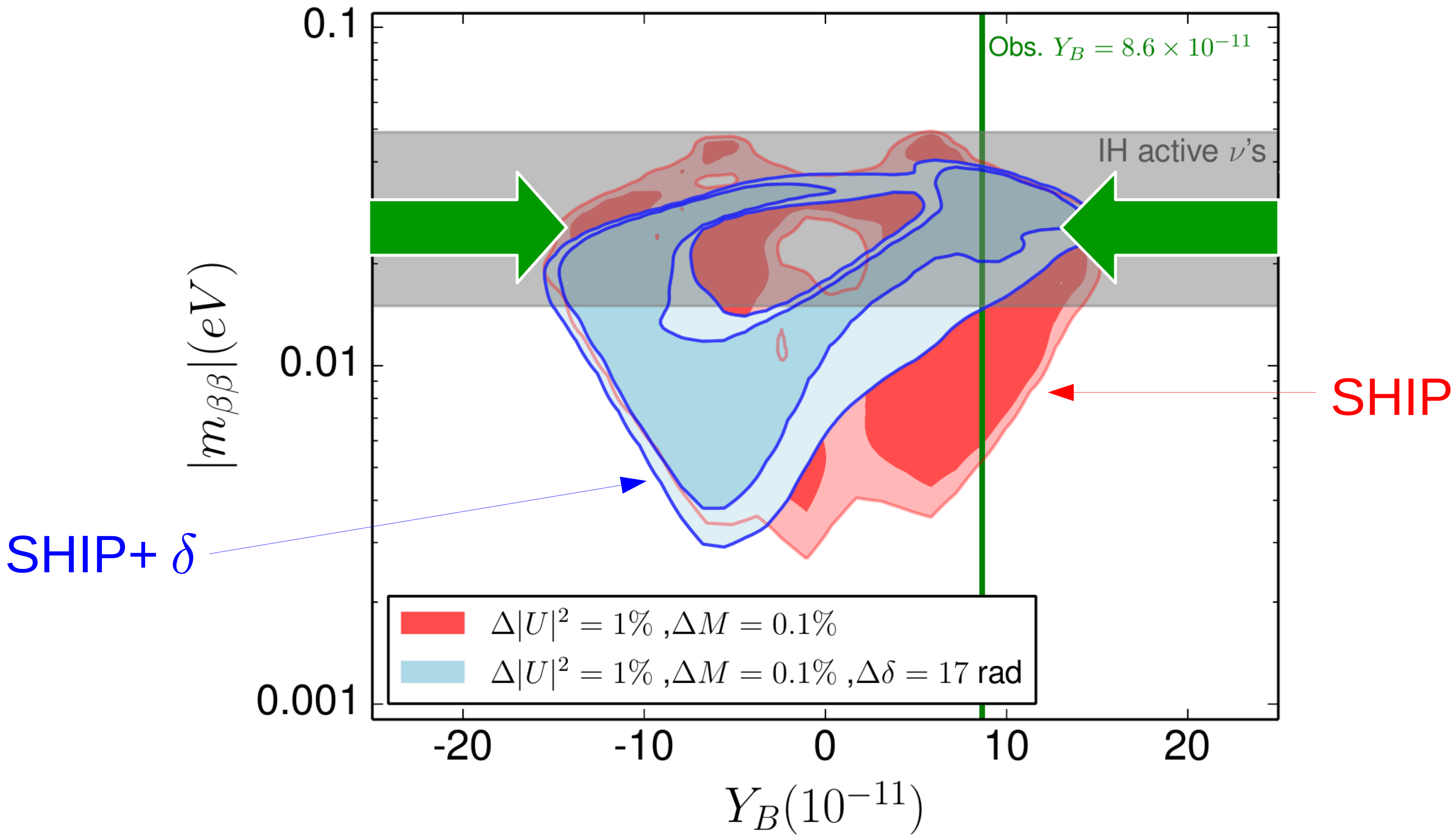


Hernandez, Kekic, JLP, Racker, Salvadò 2016 arXiv:1606.06719

CP-violation in Minimal Model

Measurment of PMNS phases from FCC and ShiP?

Caputo, Hernandez, Kekic, JLP, Salvado
arXiv:1611.05000

CP-violation in minimal model

- **SHIP and FCC** can measure:

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

Sensitivity to PMNS CP-phases! δ, ϕ_1

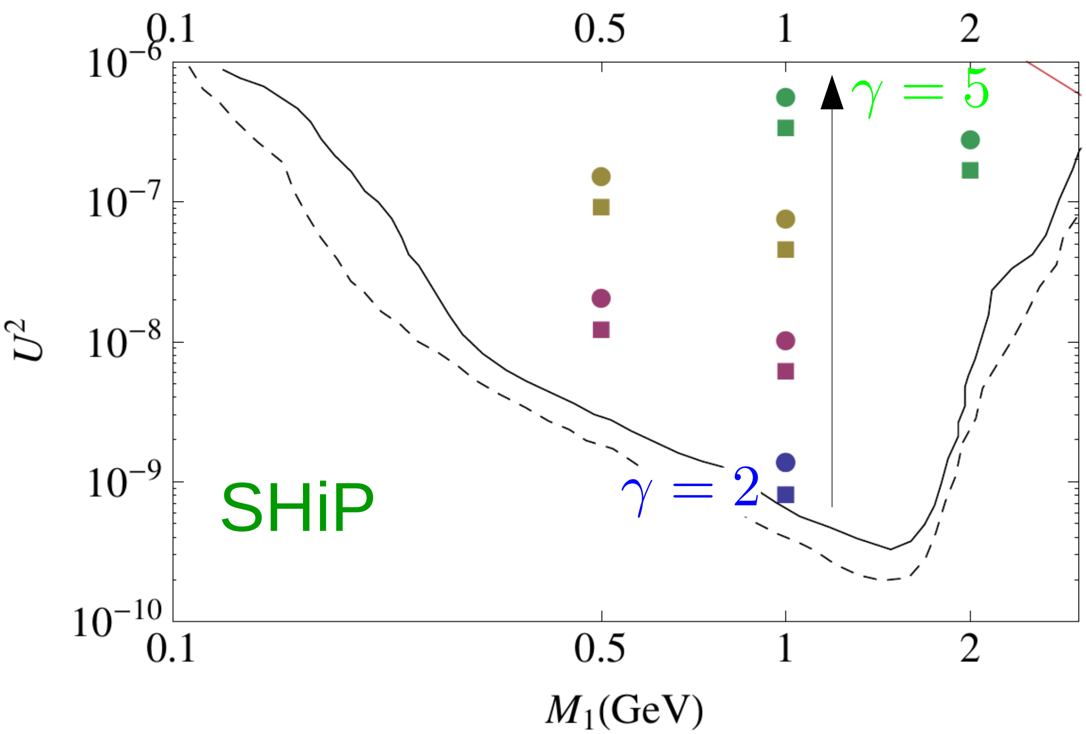
- $|U_{e4}|^2/|U_{\mu 4}|^2 \simeq |U_{e5}|^2/|U_{\mu 5}|^2 \simeq$

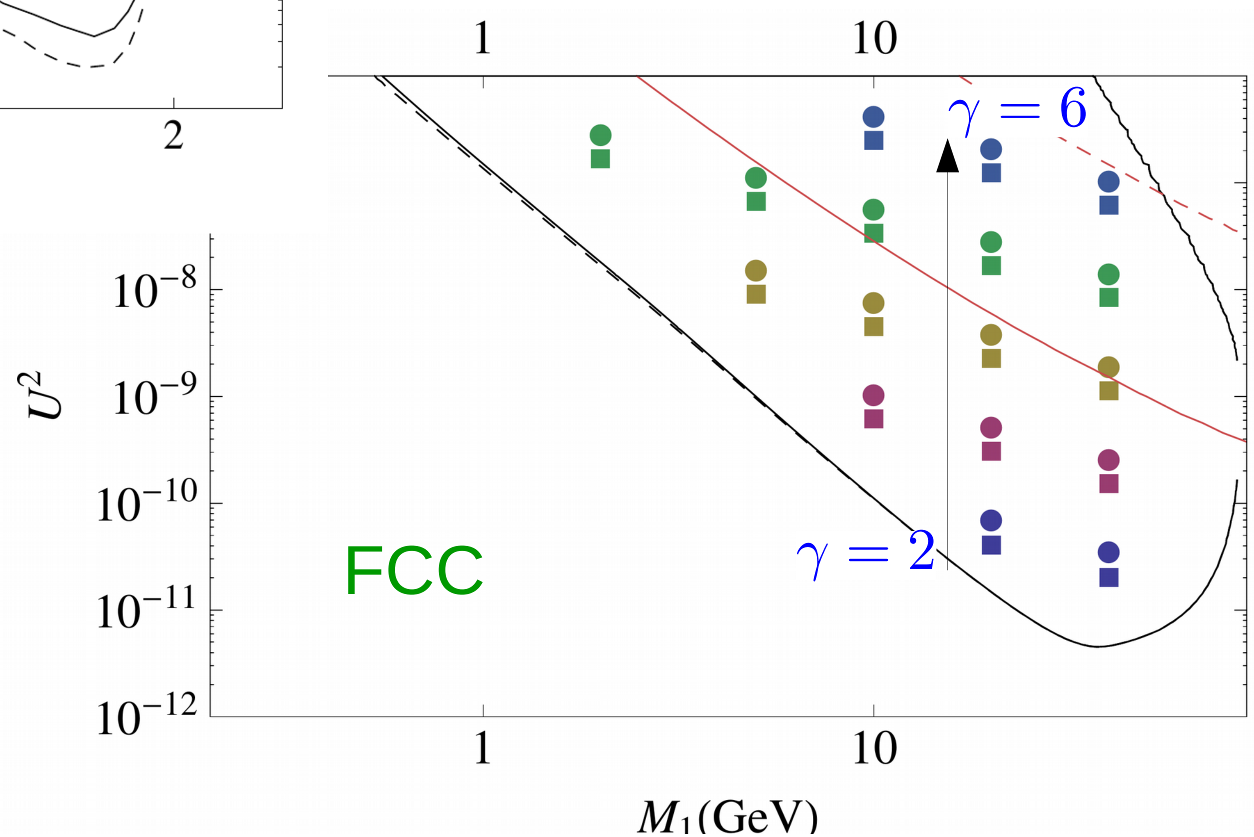
$$\frac{(1 + s_{\phi_1} \sin 2\theta_{12})(1 - \theta_{13}^2) + \frac{1}{2} r^2 s_{12}(c_{12} s_{\phi_1} + s_{12})}{\left(1 - \sin 2\theta_{12} s_{\phi_1} \left(1 + \frac{r^2}{4}\right) + \frac{r^2 c_{12}^2}{2}\right) c_{23}^2 + \theta_{13}(c_{\phi_1} s_\delta - \cos 2\theta_{12} s_{\phi_1} c_\delta)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

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

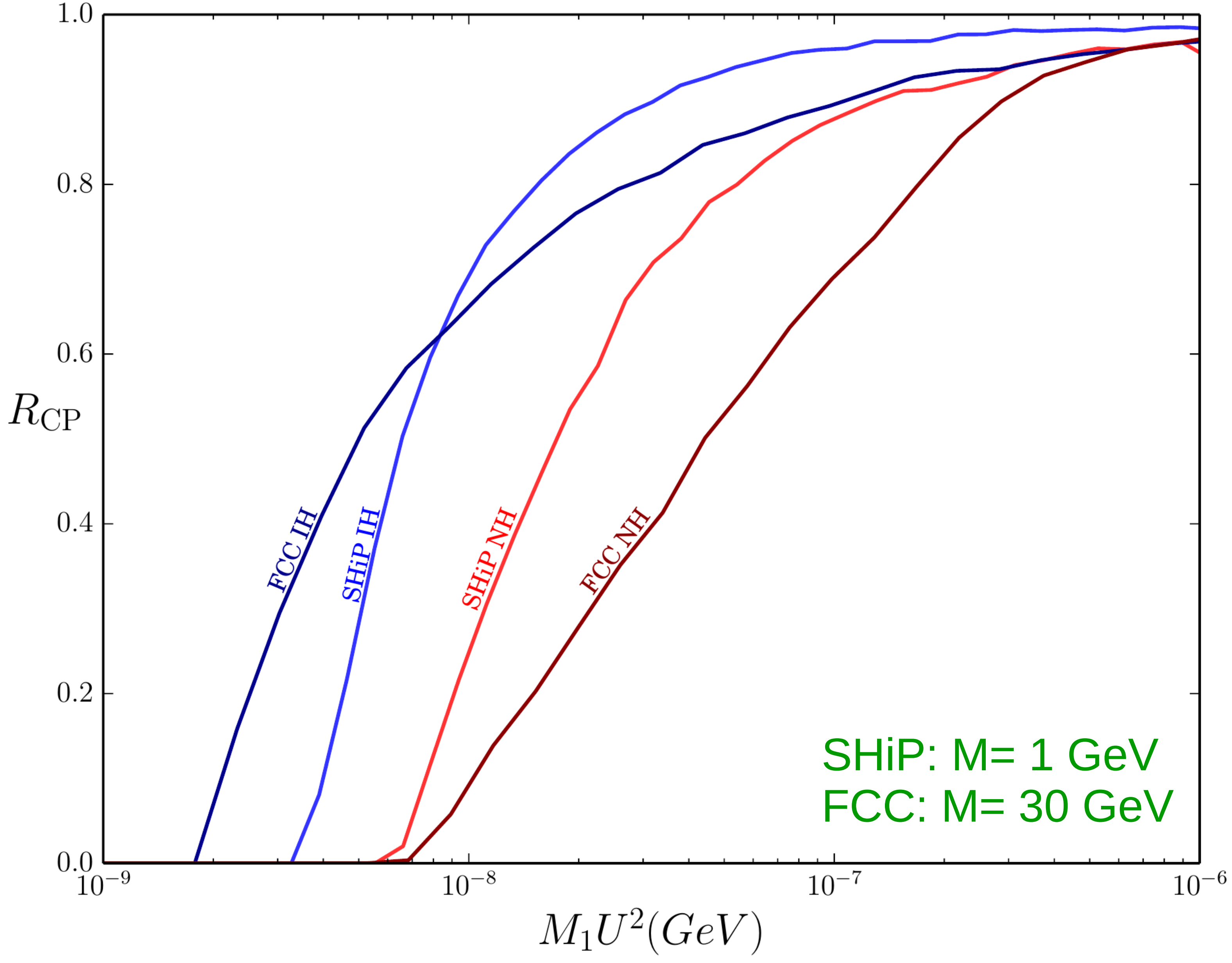
γ

CP-violation in minimal model





5σ discovery CP-violation



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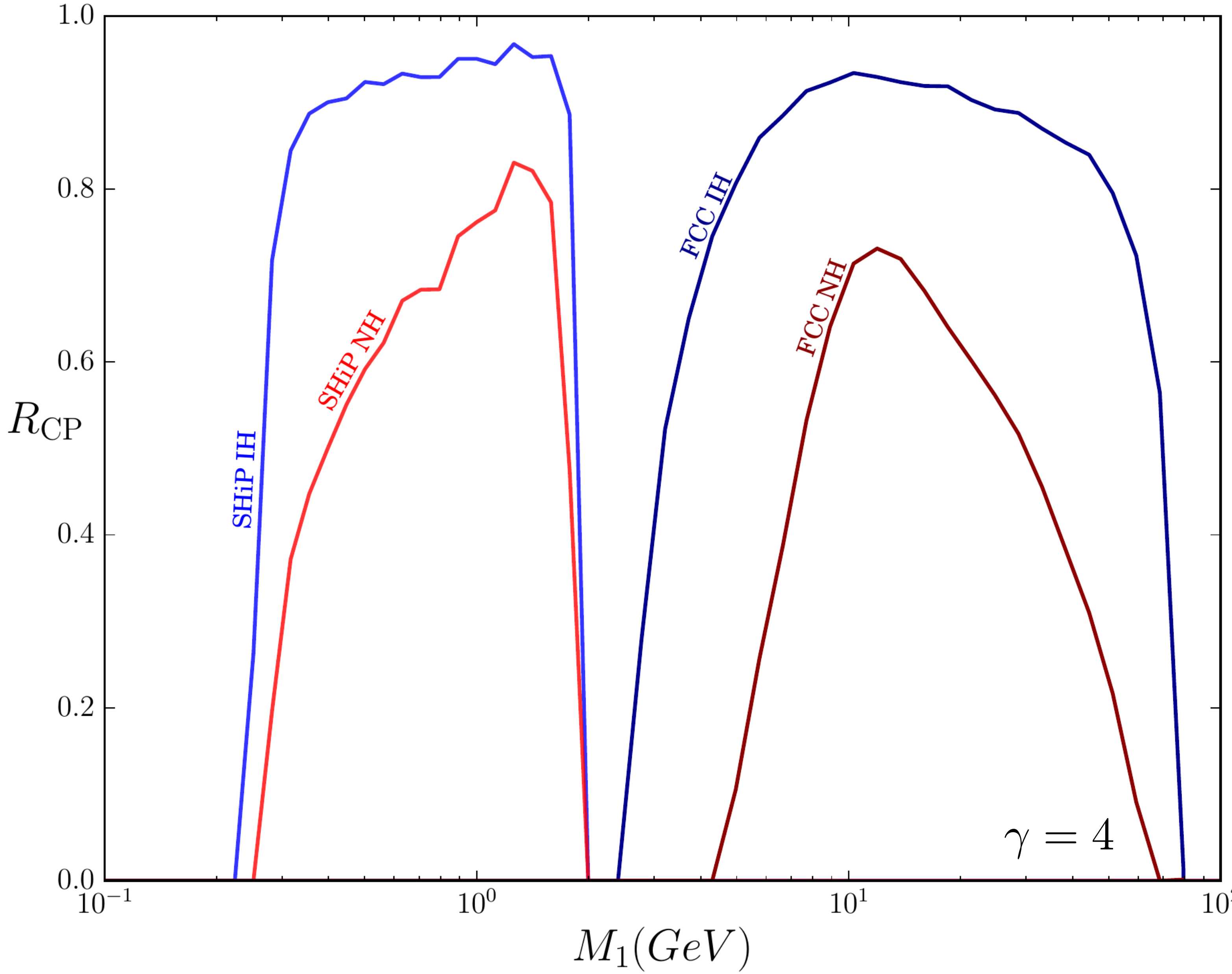


Summary and Conclusions

- Successful baryogenesis is possible with a mild heavy neutrino degeneracy in the minimal model (N=2)

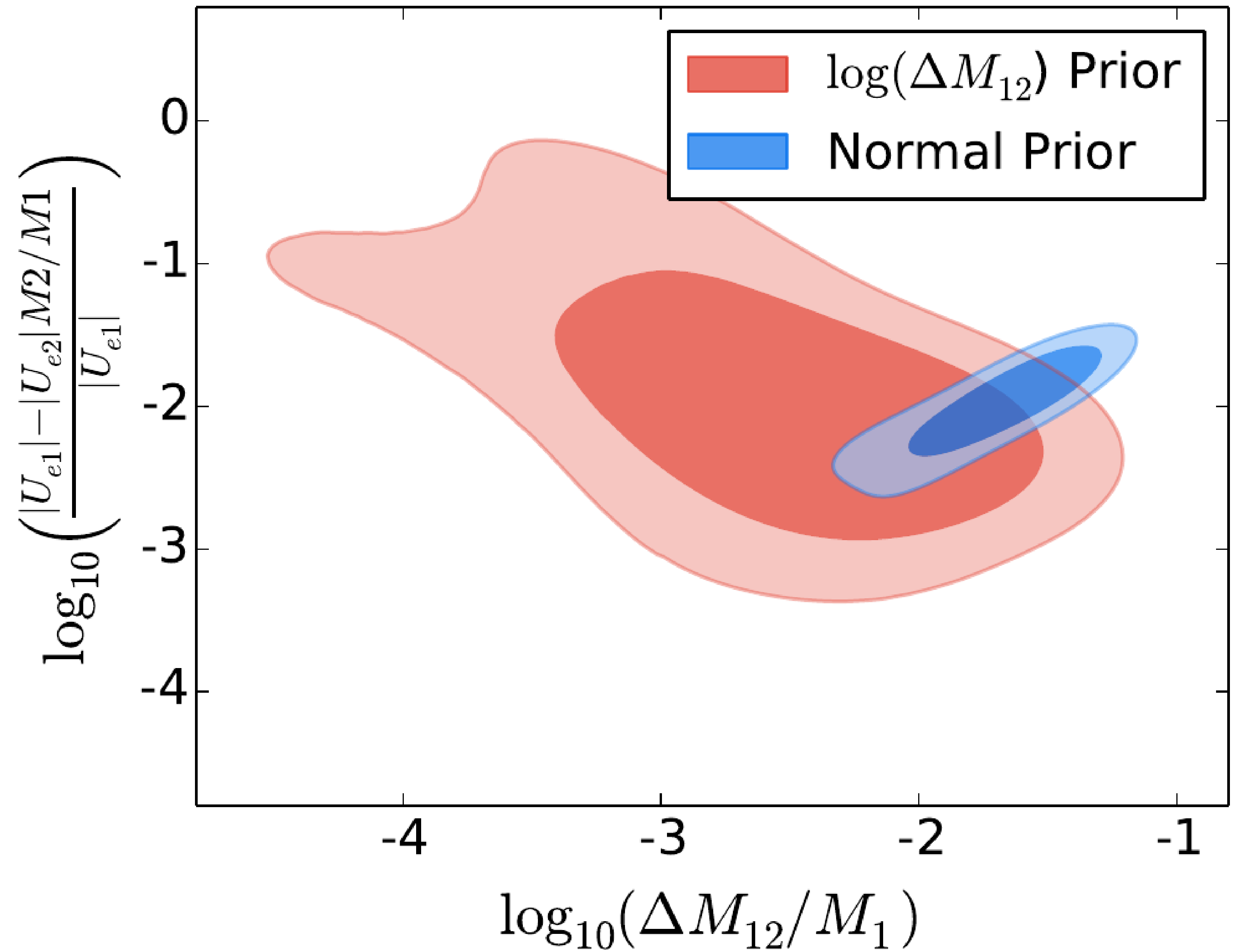
- These less fine-tuned solutions prefer smaller masses M ≤ 1GeV (target region of SHiP) and significant non-standard contributions to neutrinoless double beta decay.

- SHiP, neutrinoless double beta decay and searches for leptonic CP violation in neutrino oscillations are complementary searches regarding the baryon asymmetry prediction.

- If O(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.

- 5σ measurement of leptonic CP violation from ShiP and FCC would be possible in a very significant fraction of parameter space!! (regardless the baryon asymmetry generation).


Thanks!



$\log(\Delta M_{12})$ Prior
Normal Prior
0
-1
-2
-3
-4
-4
-3
-2
-1
$\log_{10}\left(\frac{|U_{e1}|-|U_{e2}|M2/M1}{|U_{e1}|}\right)$
$\log_{10}(\Delta M_{12}/M_1)$

In order to quantify the discovery CP potential we consider that SHiP or FCC-ee will measure the number of electron and muon events in the decay of one of the heavy neutrino states (without loss of generality we assume to be that with mass M_1), estimated as explained in the previous section. We will only consider statistical errors.

The test statistics (TS) for leptonic CP violation is then defined as follows:

$$\Delta\chi^2 \equiv -2 \sum_{\alpha=\text{channel}} N_\alpha^{\text{true}} - N_\alpha^{CP} + N_\alpha^{\text{true}} \log\left(\frac{N_\alpha^{\text{CP}}}{N_\alpha^{\text{true}}}\right) + \left(\frac{M_1 - M_1^{\min}}{\Delta M_1}\right)^2. \tag{10}$$

where $N_\alpha^{\text{true}} = N_\alpha(\delta, \phi_1, M_1, \gamma, \theta)$ is the number of events for the true model parameters, and $N_\alpha^{CP} = N_\alpha(CP, \gamma^{\min}, \theta^{\min}, M_1^{\min})$ is the number of events for the CP-conserving test hypothesis that minimizes $\Delta\chi^2$ among the four CP conserving phase choices $CP = (0/\pi, 0/\pi)$ and over the unknown test parameters. ΔM_1 is the uncertainty in the mass, which is assumed to be 1%.

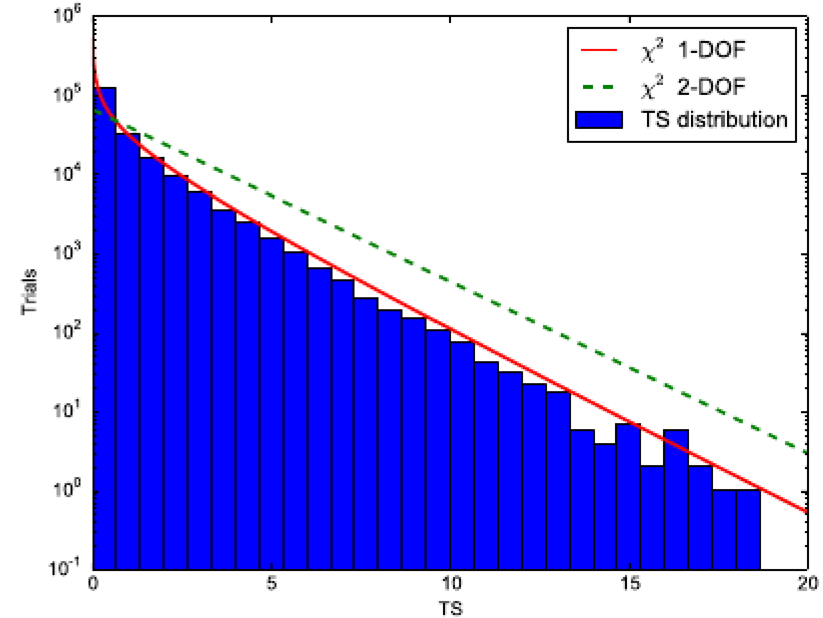
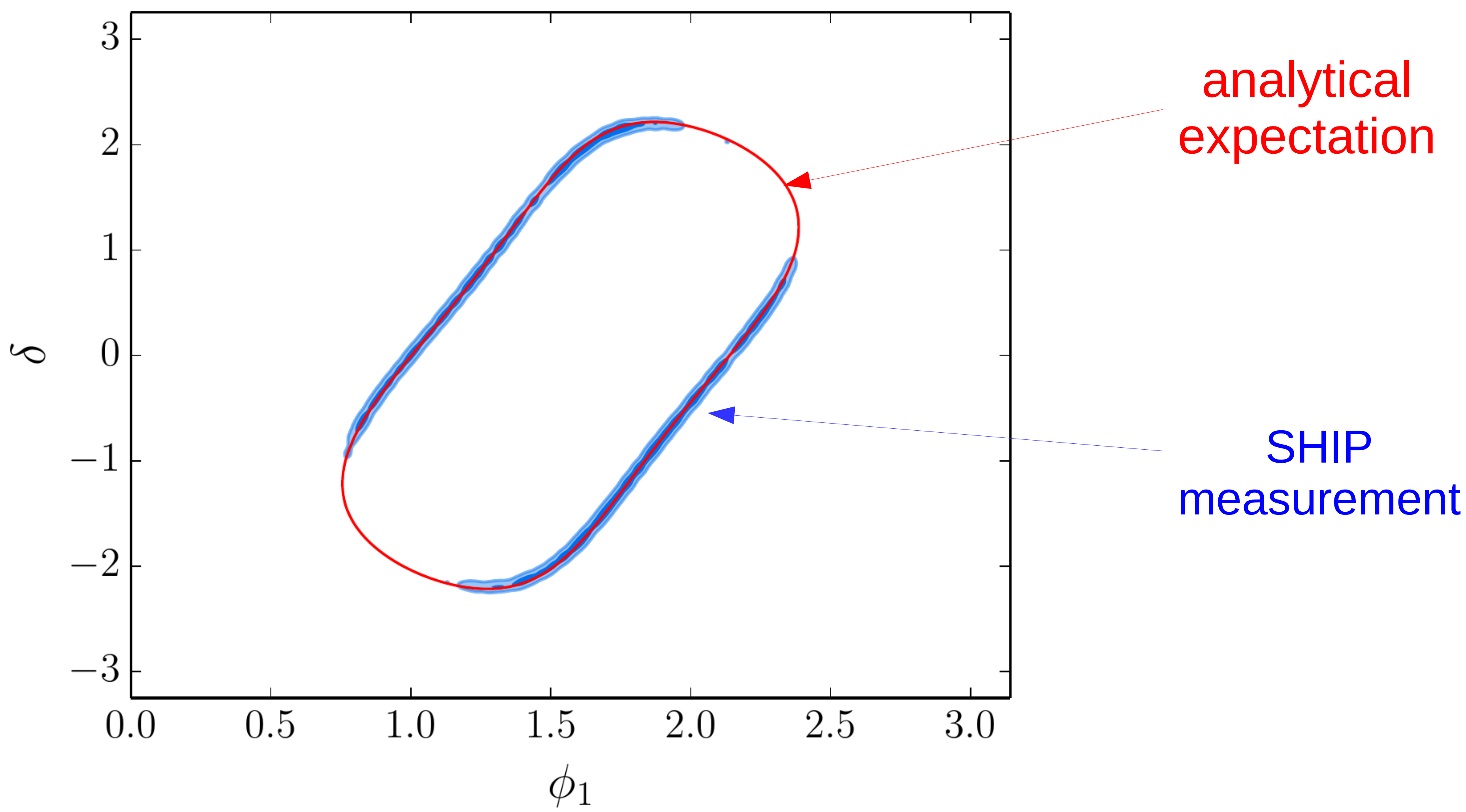


Fig. 4 Distribution of the test statistics for $\mathcal{O}(10^7)$ number of experimental measurements of the number of events for true values of the phases $(\delta, \phi_1) = (0,0)$ for IH and $(\gamma, \theta, M_1) = (3.5, 0, 1)$ GeV, compared to the χ^2 distribution for 1 or 2 degrees-of-freedom.

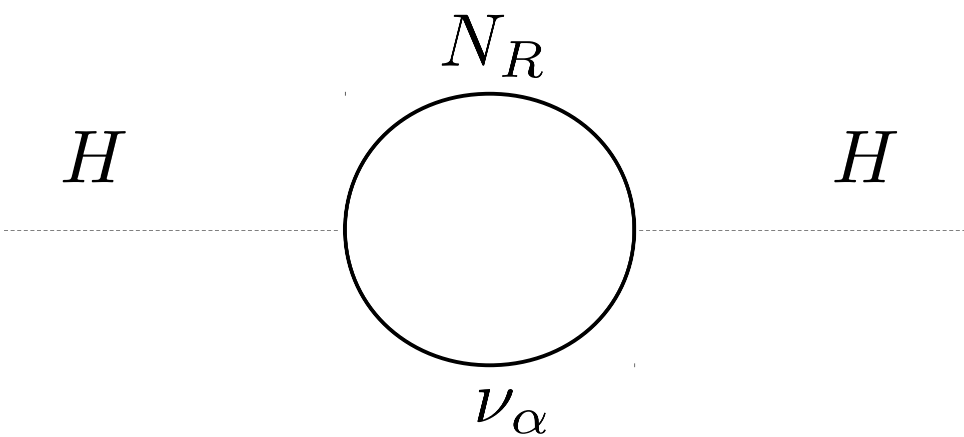
SHIP sensitive to PMNS CP phases



Recall, neutrino oscillation experiments sensitive to δ

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.

CP invariants

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

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

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

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

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

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

} CP phases from W (only R)

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

CP invariants

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

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

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

$$N_R \geqslant 2$$

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

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

$$N_R \geqslant 3$$

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

CP invariants

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

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

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

$AS \;\; \nu MSM$

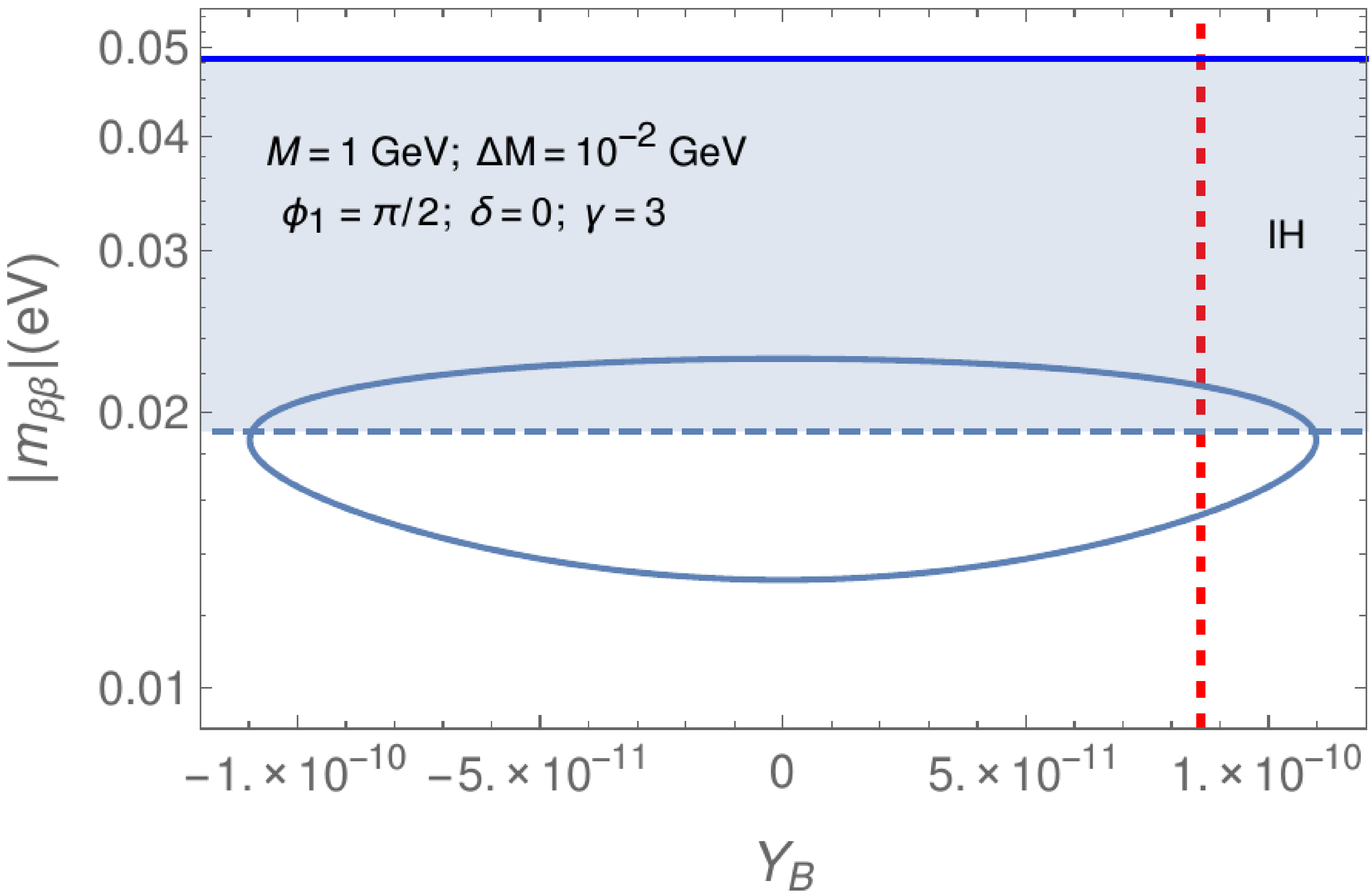
$$I_2^{(3)} = \mathrm{Im}[W_{13}^* V_{12} V_{22}^* W_{23}]$$

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

ARS

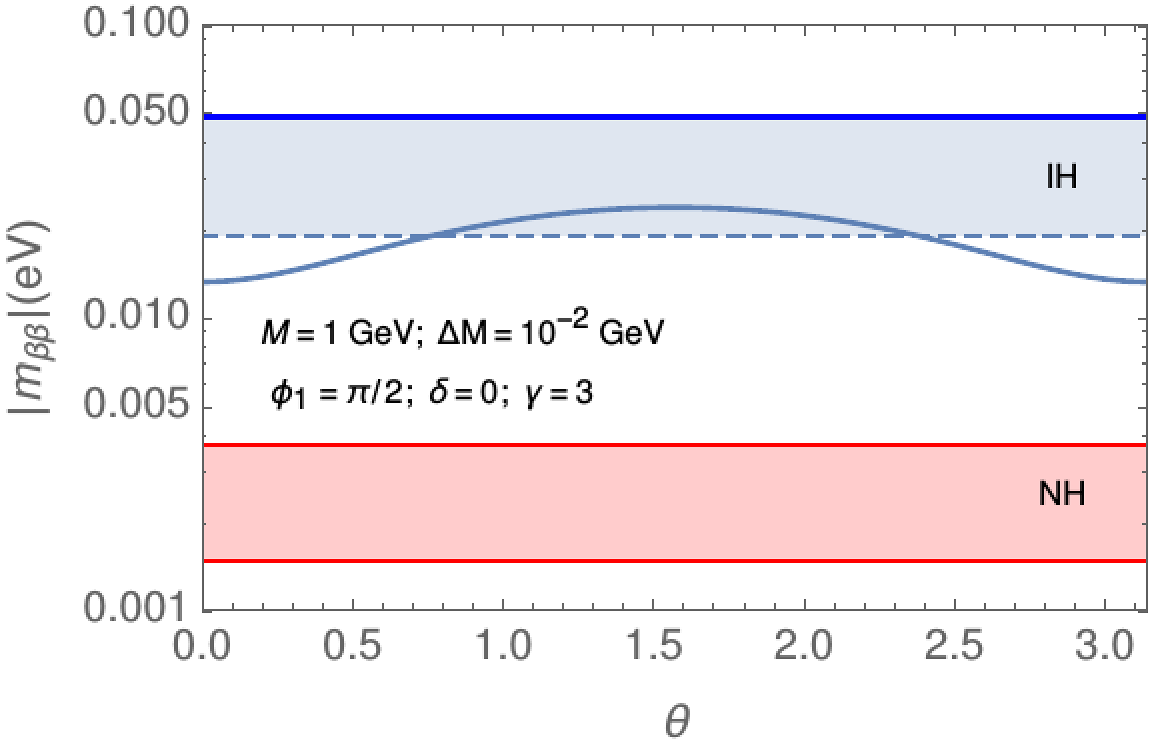
$$Y = V^\dagger \mathrm{Diag}\{y_1, y_2, y_3\} W$$

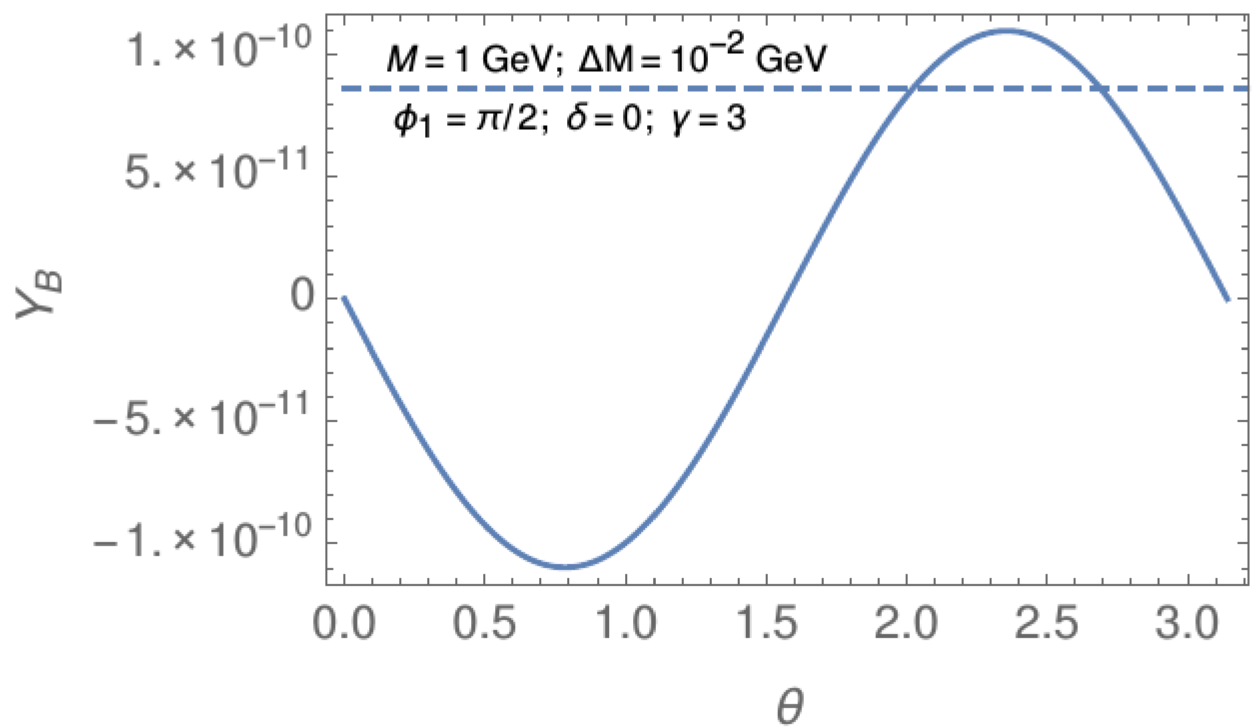
Predicting Y_B in minimal model $N_R=2$



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

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

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

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

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

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

$$Y = V^\dagger \mathrm{Diag}\left\{y_1, y_2, y_3\right\} W$$

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

Heavy New Physics scale

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

- $Y \sim 1$ suggests M close to the GUT scale.

- Drawback: New Physics effects at low energies very suppressed by the NP scale M.