Jacobo López-Pavón

CERN TH Retreat

CERN, 3-4 November 2016

Jacobo López-Pavón

- 2006 – 2010 } PhD
- 2010 – 2012
- 2012 – 2015
- 2015 – 2016

} PD

Sezione di Genova

Research Interests

- Origin of neutrino masses still unknown!

- BSM and Neutrino Physics

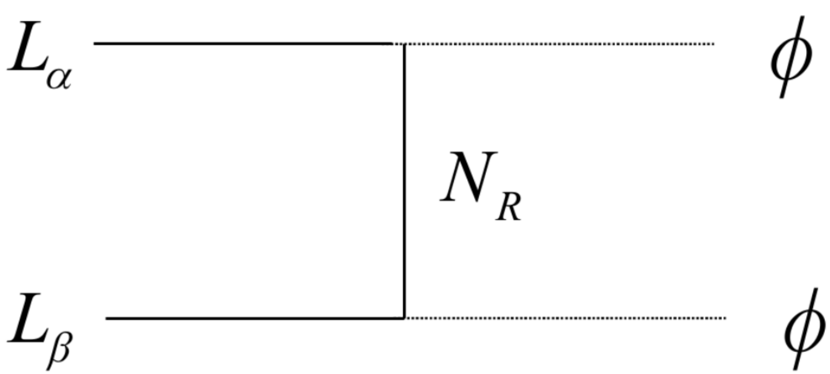
- Neutrino Theory and Phenomenology
mass mechanisms, seesaws, neutrino oscillations, neutrinoless double beta decay, colliders, LFV processes, EW precision tests...

- Particle Physics and Cosmology interplay
leptogenesis, early universe...

Minimal Model: Seesaw Model

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

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



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

Minimal Model: Seesaw Model

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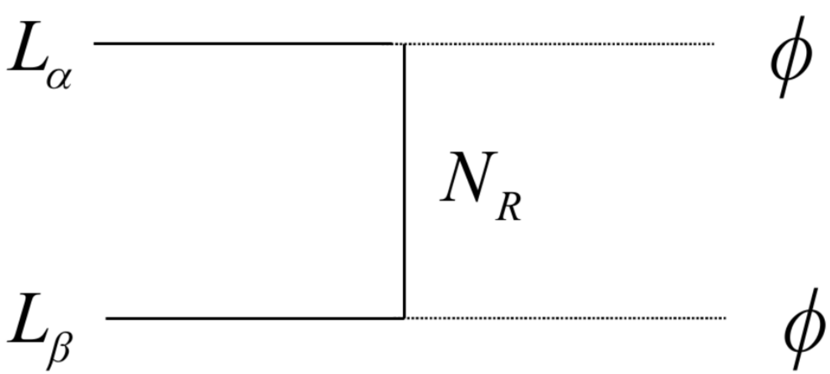
New Physics Scale $\left(m_\nu \sim Y^2 v^2 / M\right)$



Heavy fermion singlet: N_R Type I *seesaw.*
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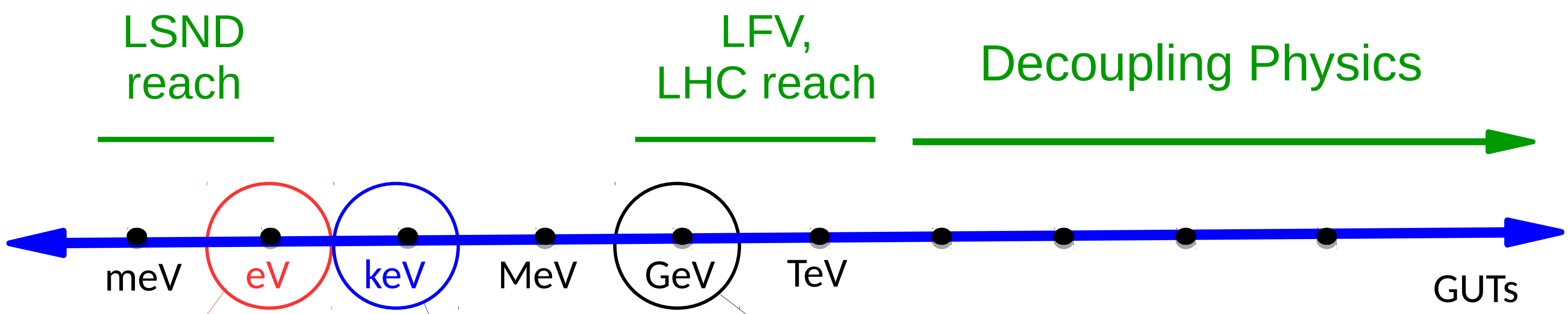
The New Physics Scale is Unbounded



Explanation to neutrino anomalies pointed out mainly by LSND and reactor experiments.

de Gouvea 2005
de Gouvea, Jenkins, Vasudevan 2007
Donini, Hernandez, JLP, Maltoni, Shwetz 2012

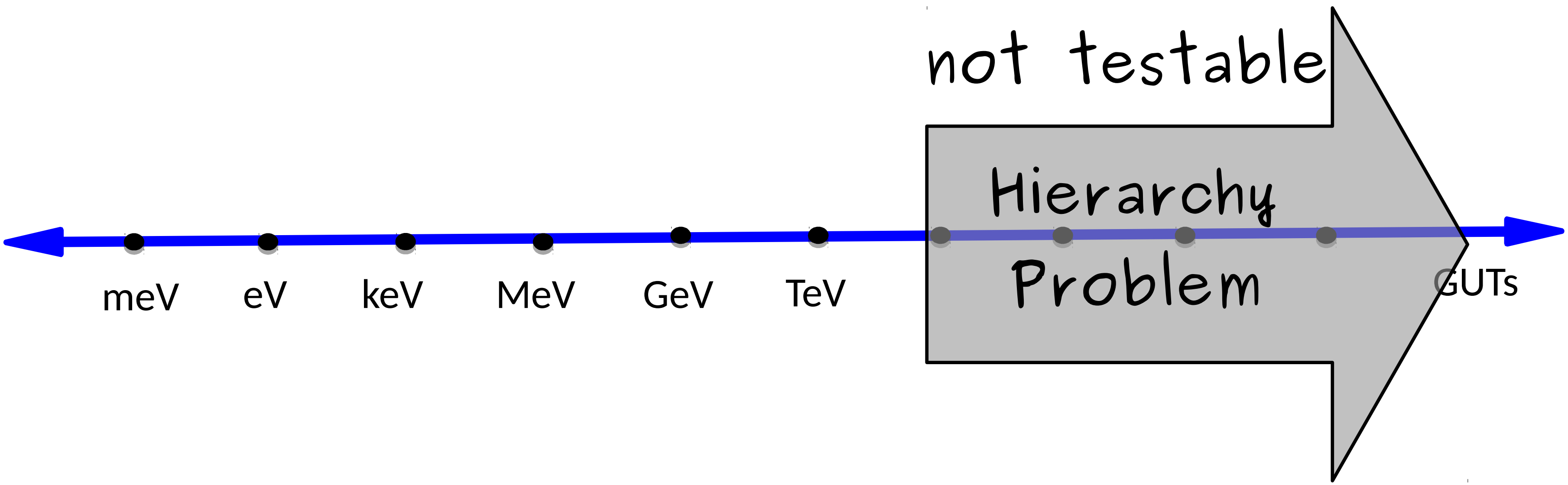
Warm DM candidate. Moreover, after the recent X-ray hint.

Asaka, Blanchet, Shaposhnikov 2005
Bulbul et al.(arXiv:1402.2301)
Boyarsky et al.(arXiv:1402.4119)

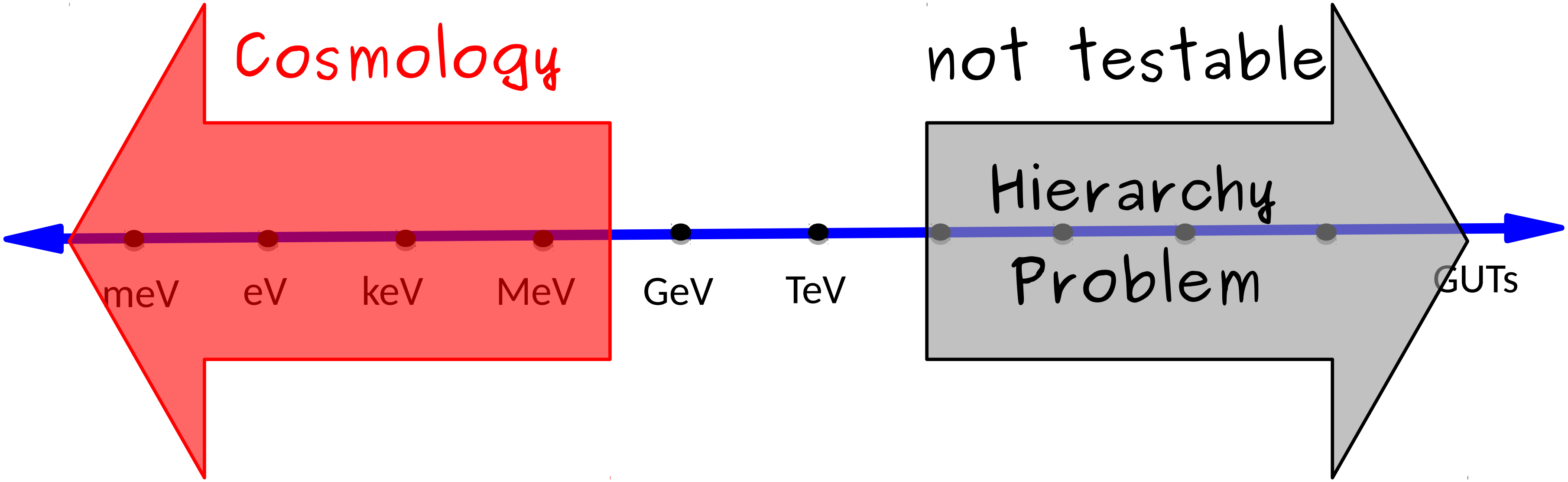
Account for baryon asymmetry in the Universe.

Akhmedov, Rubakov, Smirnov 1998
Asaka, Blanchet, Shaposhnikov 2005
Hernández, Kekic, JLP, Racker, Rius 2015
Hernández, Kekic, JLP, Racker, Salvadò 2016

The New Physics Scale



The New Physics Scale



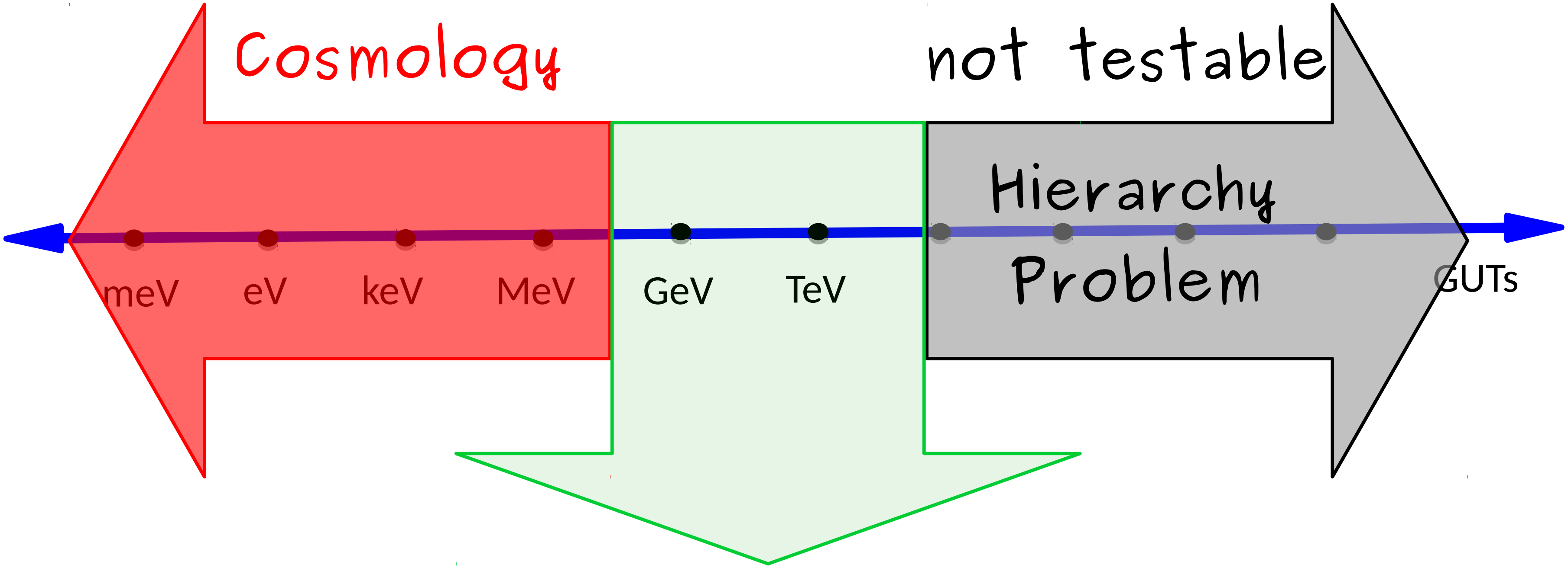
- Minimal Type-I seesaw with **N_R=2** (or Type-I seesaw with **N_R=3** & $m_{lightest} \gtrsim 10^{-3} eV$)

CMB+BBN data ➡ M_R >100 MeV

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

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

The New Physics Scale



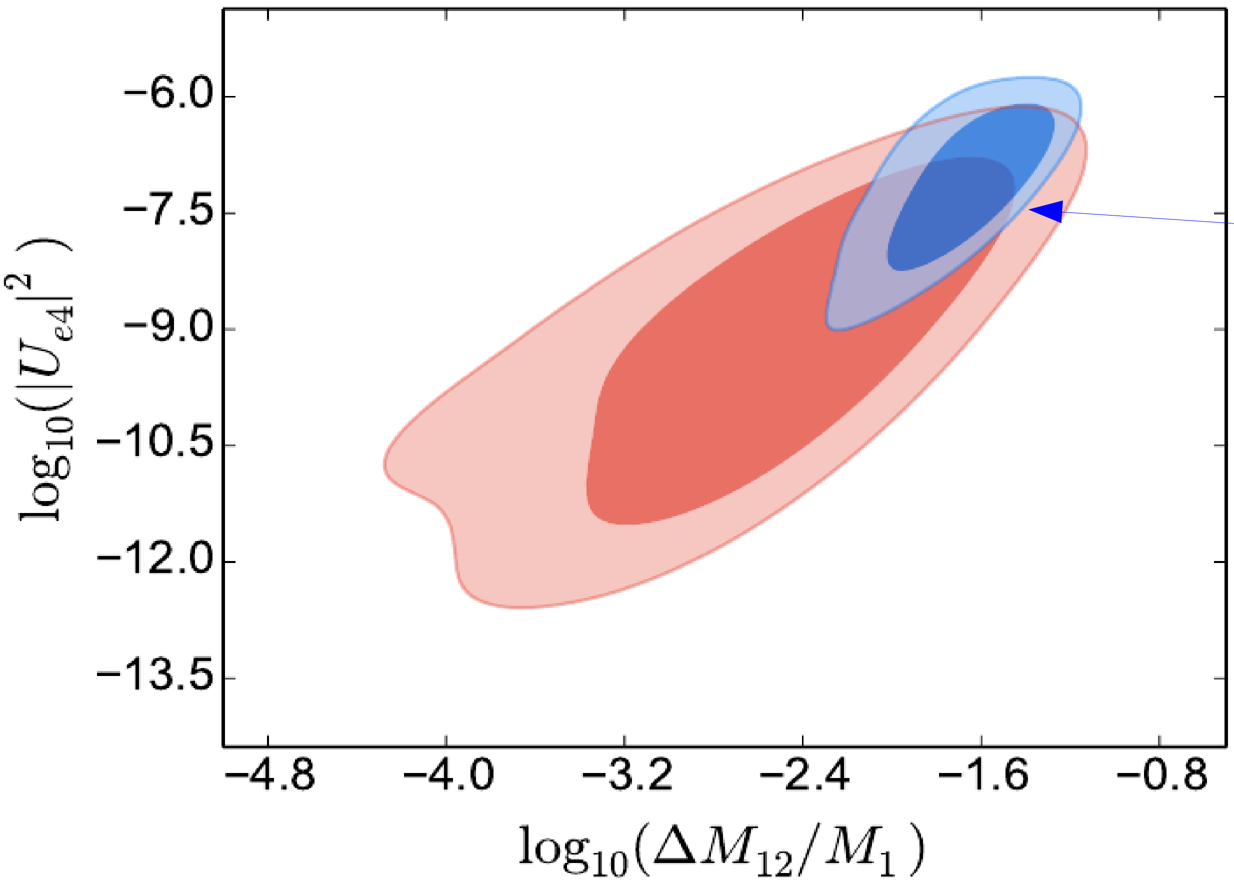
- Leptogenesis via Oscillations M=0.1–100GeV

  Akhmedov, Rubakov, Smirnov (ARS); Asaka, Shaposnikov (AS)

- Resonant Leptogenesis M>100GeV

  Pilaftsis

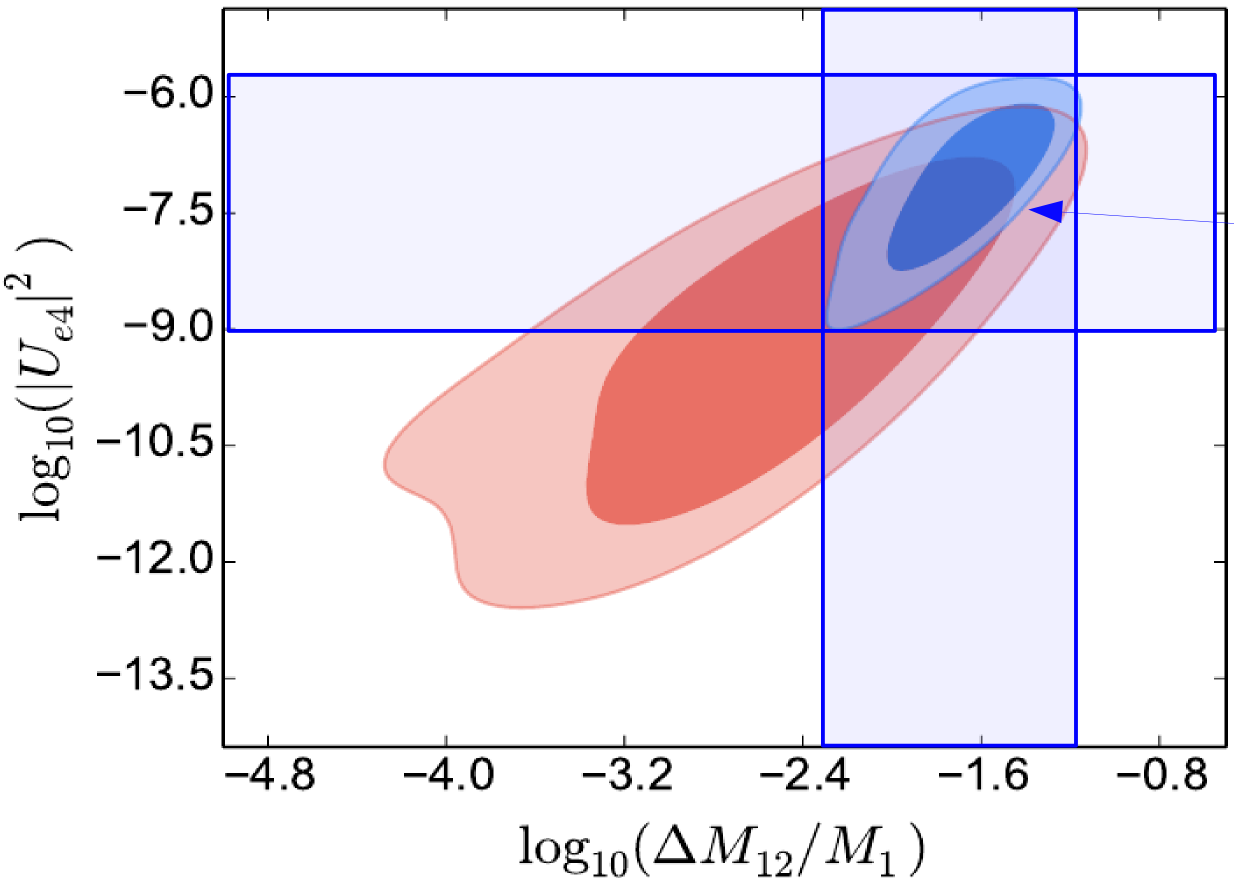
Leptogenesis in Minimal Model $N_R=2$



Not very degenerate solutions

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

Leptogenesis in Minimal Model $N_R=2$



Not very degenerate solutions

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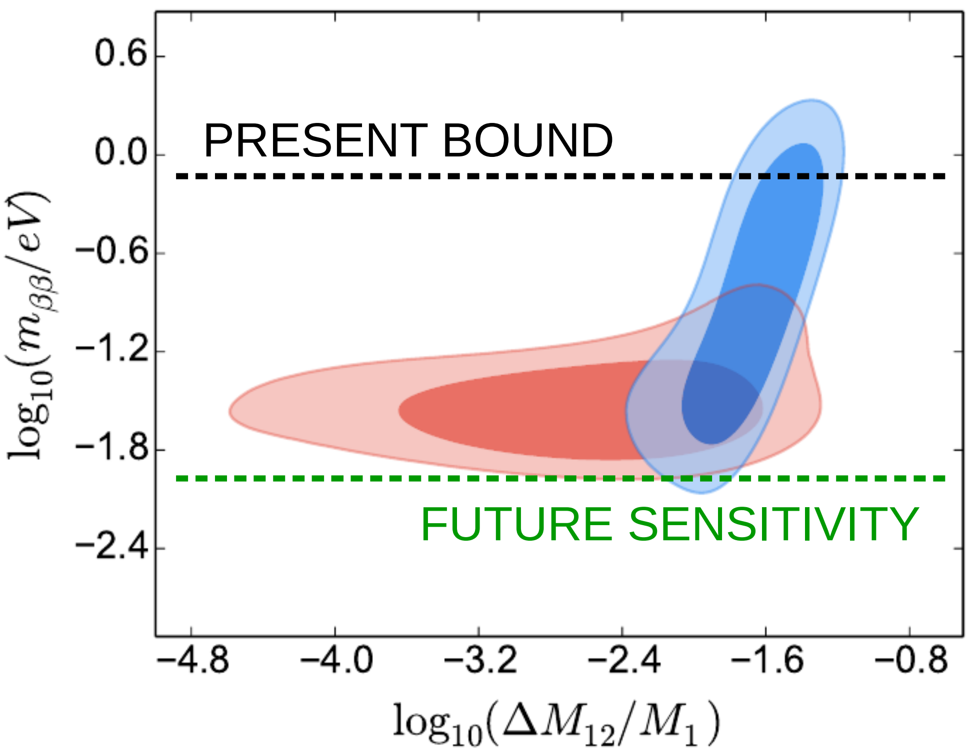
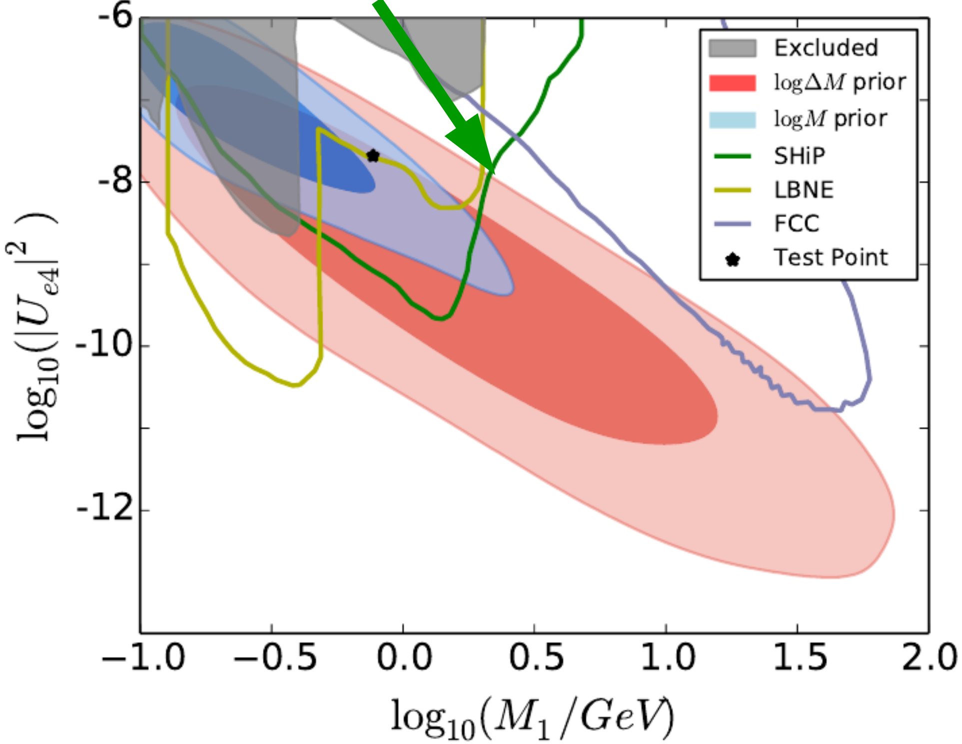
arXiv:1606.06719

Leptogenesis in Minimal Model $N_R=2$

Neutrinoless double beta decay



SHiP



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

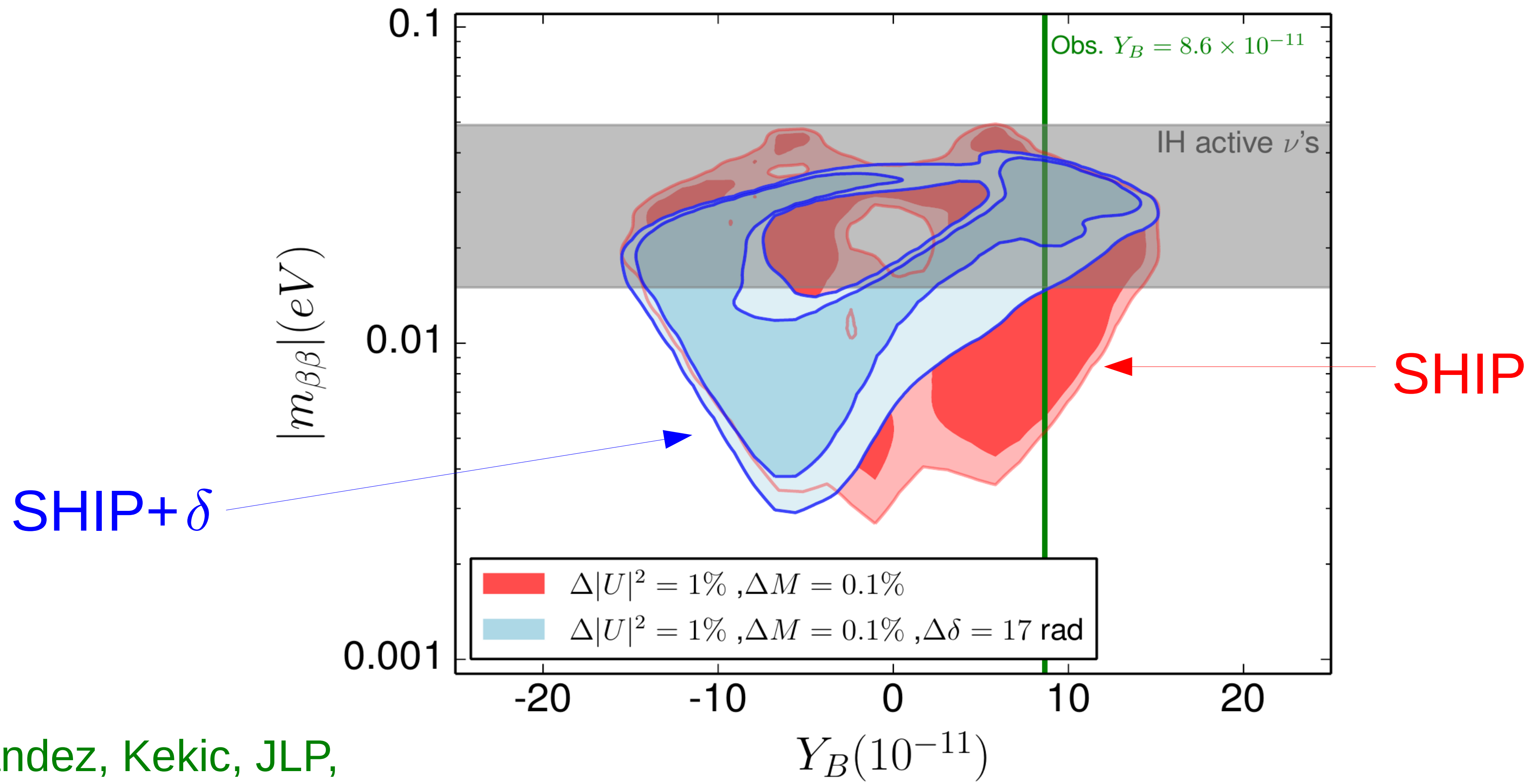
Mitra, Senjanovic, Vissani 2011
JLP, Pascoli, Wong 2012

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

What if the sterile ν are within reach of SHiP?

Can we predict Y_B from the experiments?

Predicting Y_B in minimal model $N_R=2$



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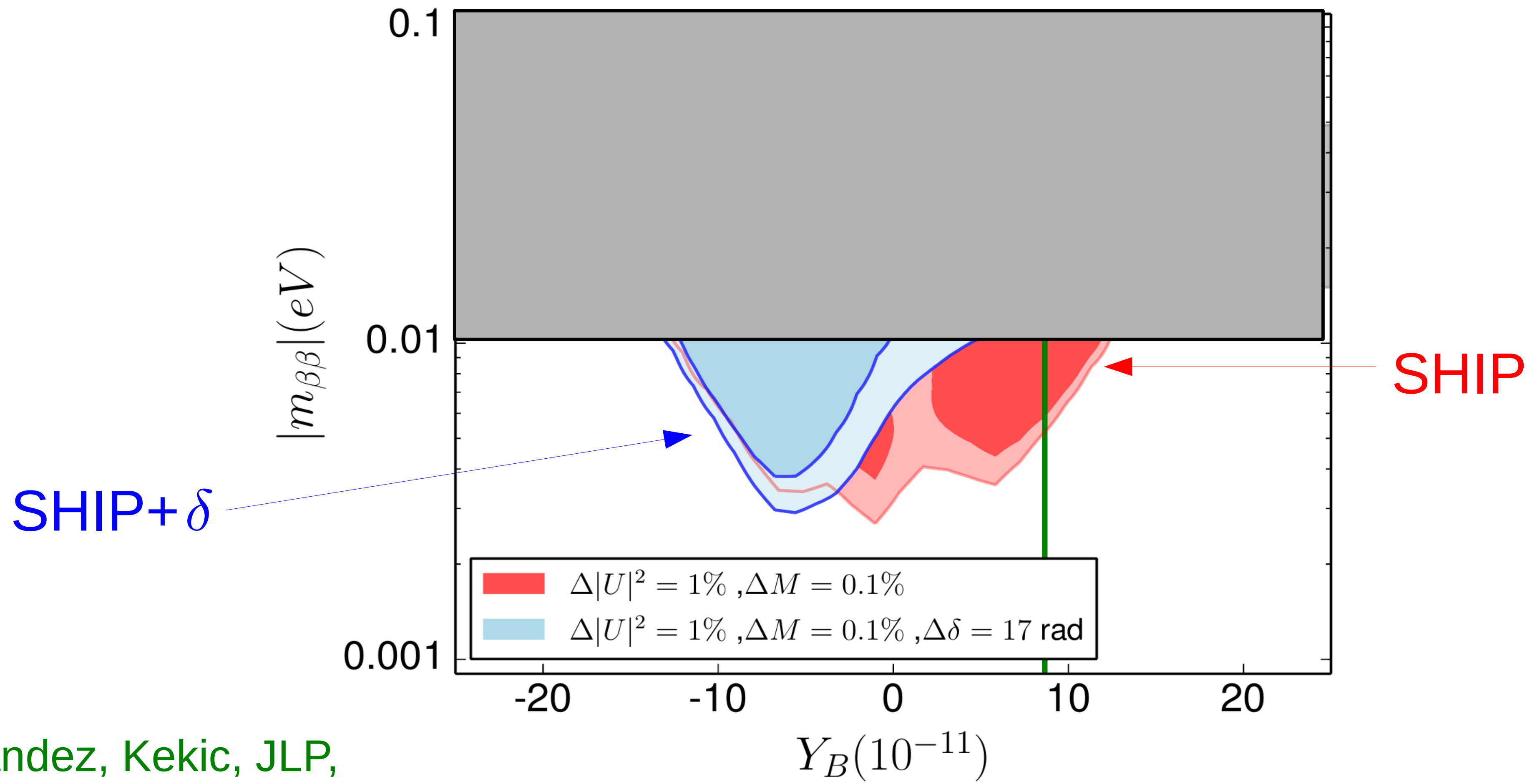

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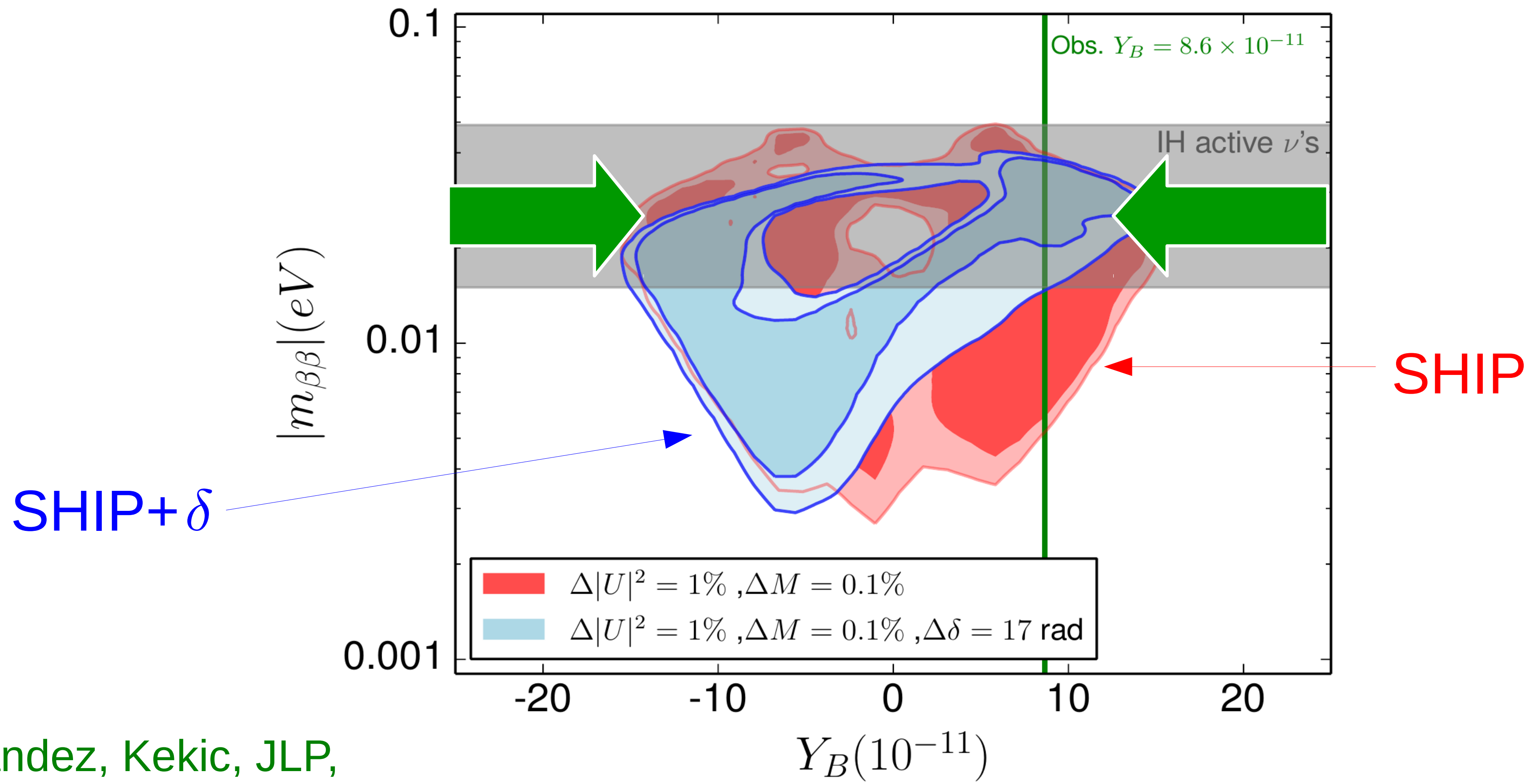


Hernandez, Kekic, JLP, Racker, Salvado 2016
arXiv:1606.06719

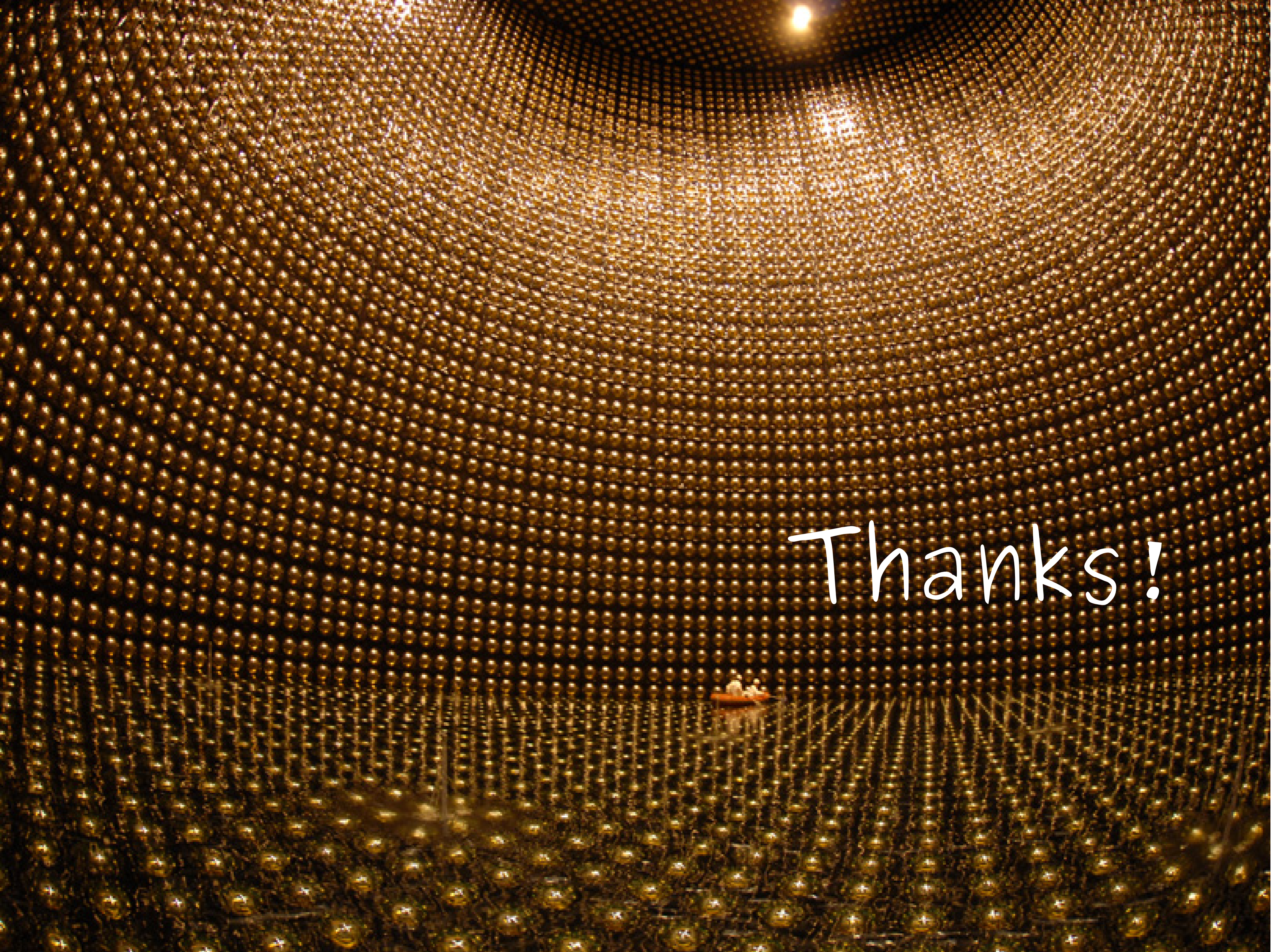
Summary and Conclusions

- I am particularly interested in BSM extensions which can account for the origin of neutrino masses and their phenomenological implications.

- I study different aspects of the neutrino phenomenology: neutrino oscillations, neutrinoless double beta decay, LFV, leptogenesis, colliders, EW precission data, early universe…

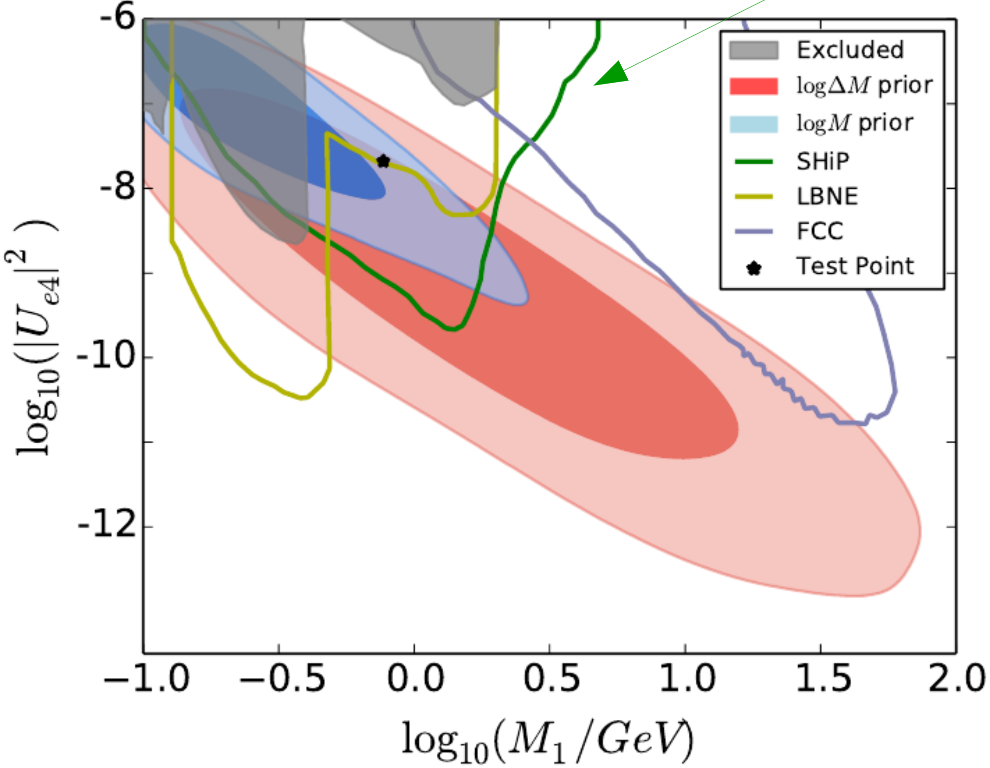
- The combination of all this information will shed light on the origin and nature of neutrino masses.

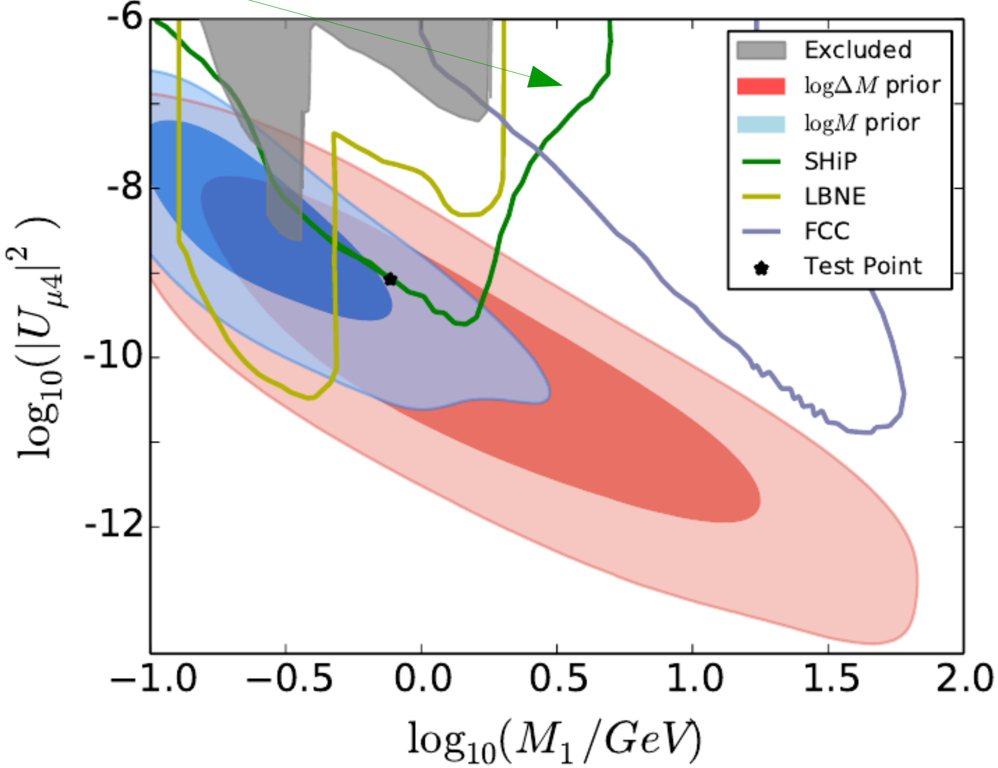
- For instance, we have recently found that the simplest model of neutrino masses able to explain the baryon asymmetry with an O(GeV) new physics scale is indeed testable!


Thanks!

Leptogenesis in Minimal Model N_R=2

SHiP

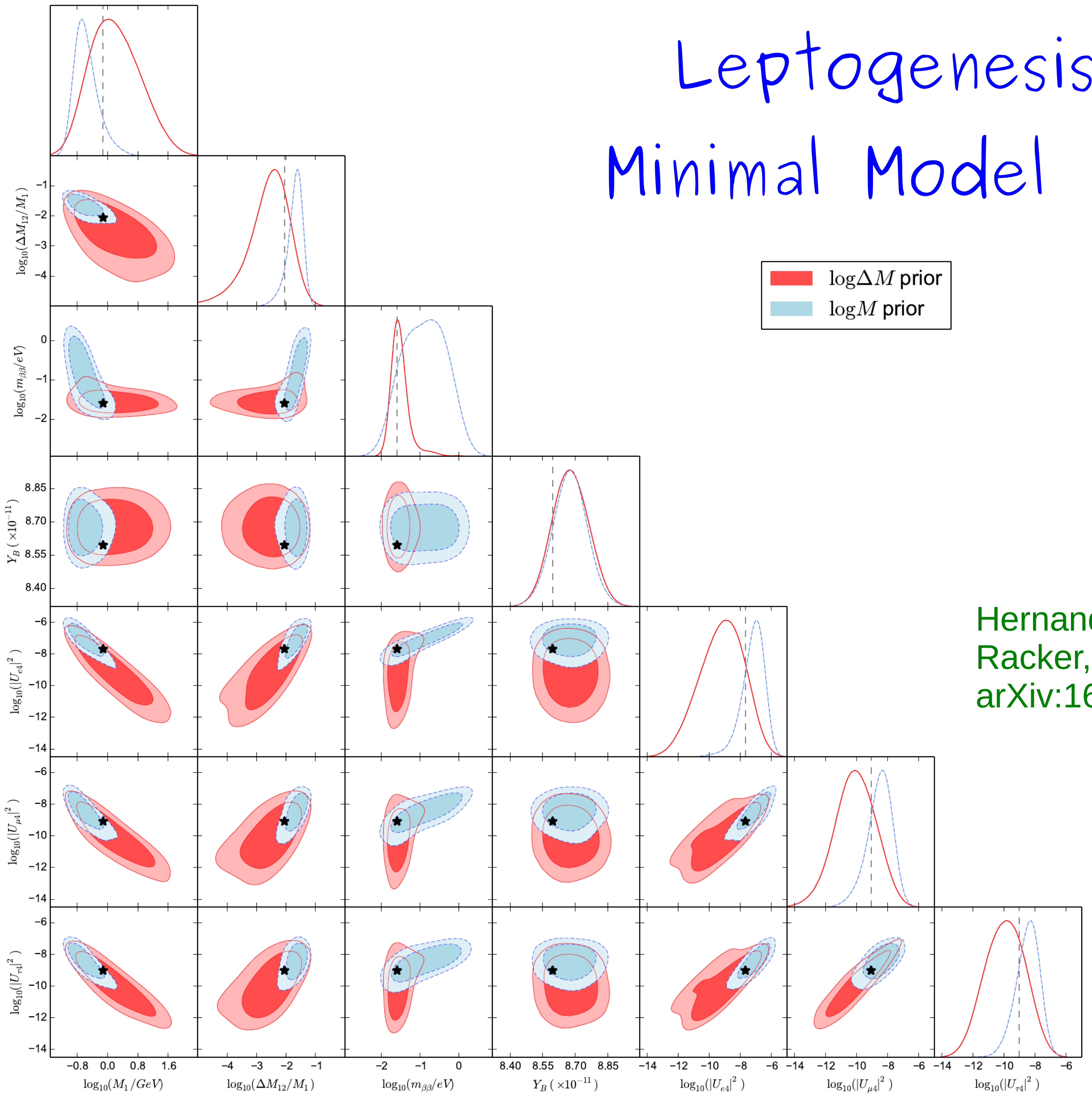




Inverted light neutrino ordering

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

Leptogenesis in Minimal Model $N_R=2$



Hernandez, Kekic, JLP, Racker, Salvado 2016
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IH

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

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

Predicting Y_B in minimal model $N_R=2$

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

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

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

Predicting Y_B in minimal model $N_R=2$

Casas-Ibarra

$R\left(\theta + i\gamma\right)$

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

- Baryon asymmetry strongly depends on all the unknown parameters

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):

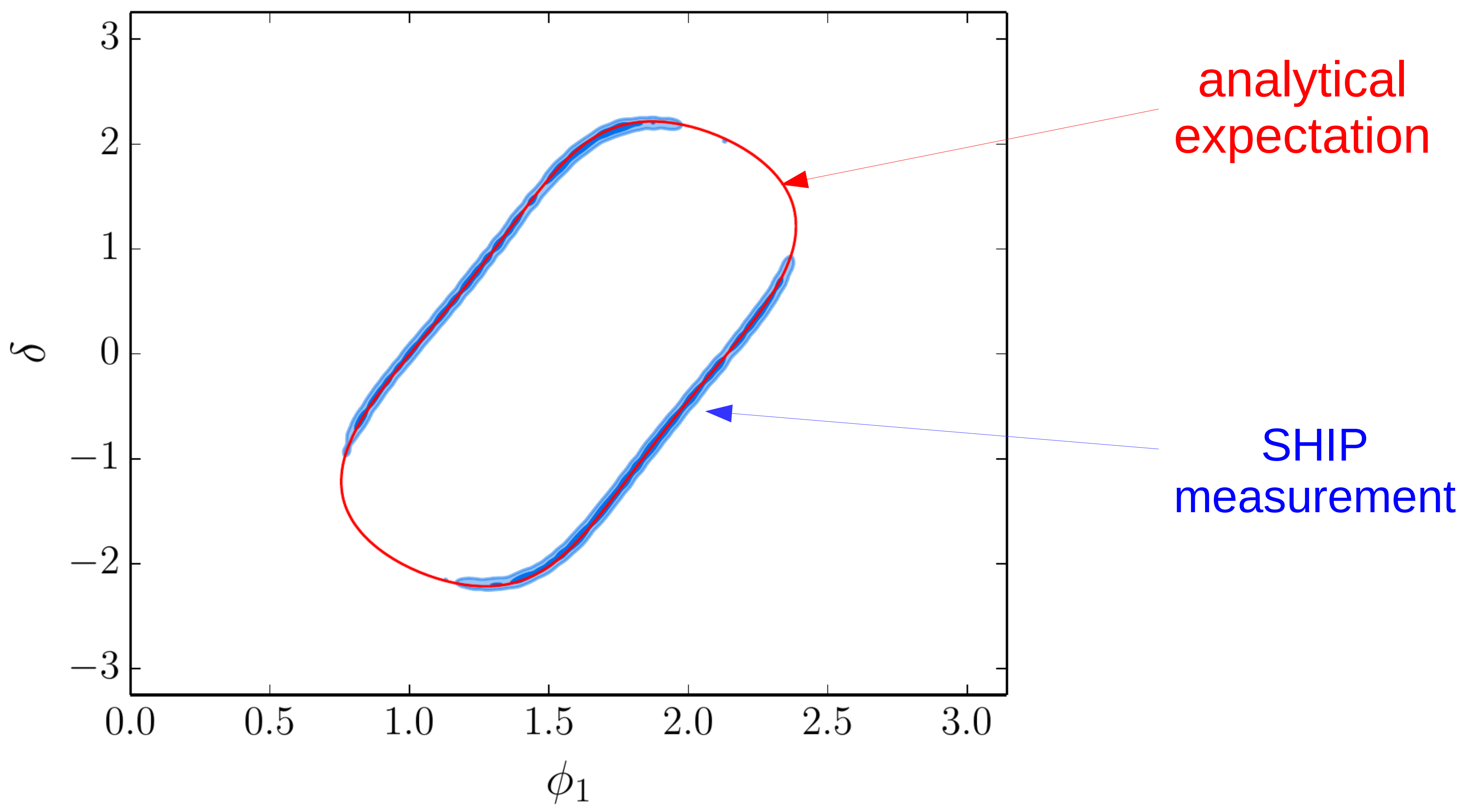
$$M_1, M_2, |U_{e4}|, |U_{e5}|, |U_{\mu 4}|, |U_{\mu 5}|$$

SHIP sensitive to PMNS CP-phases! δ, ϕ_1

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

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

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 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

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

LIGHT NEUTRINO
contribution

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

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

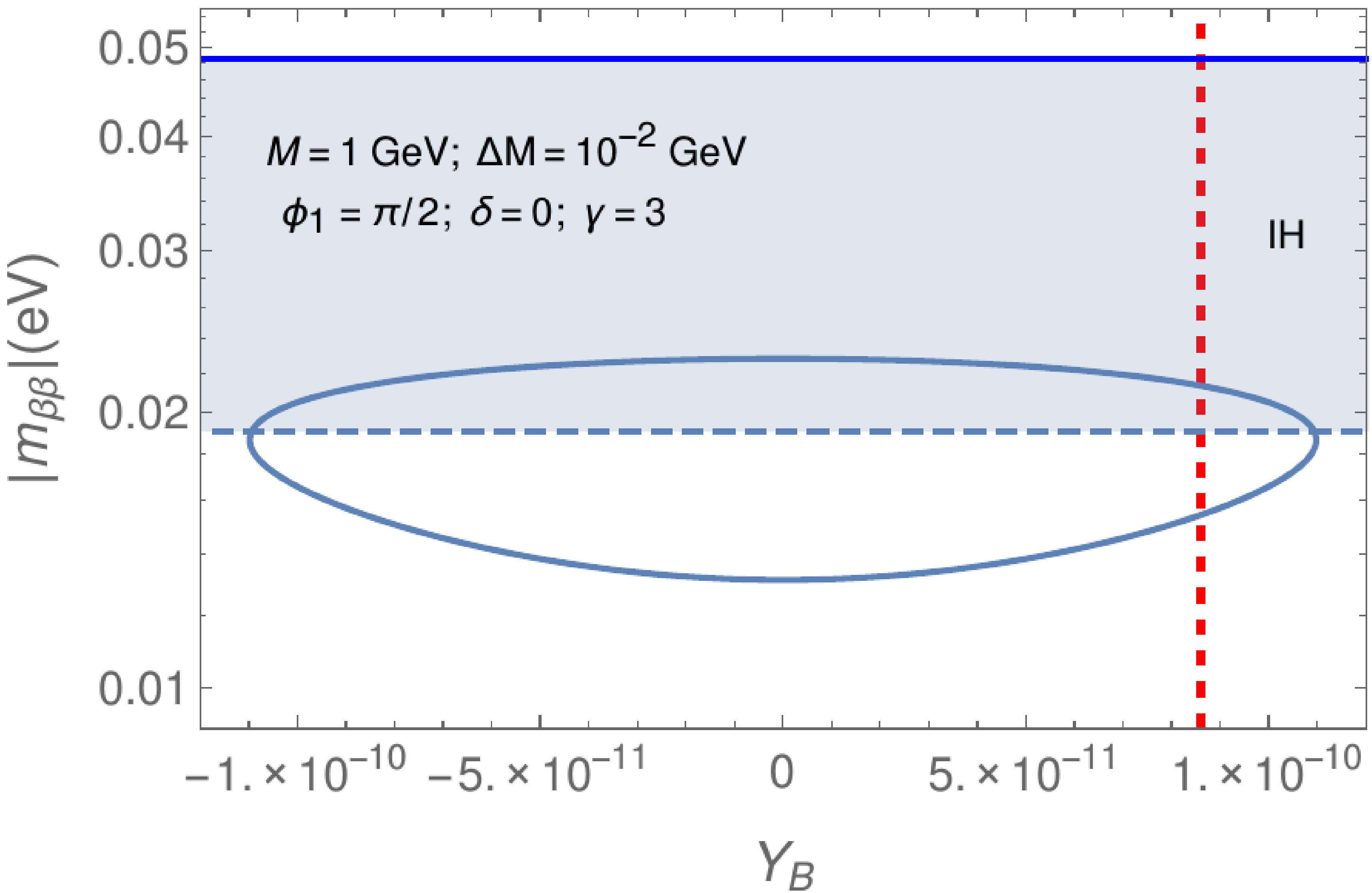
$$\left. - \boxed{f(A)\, e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 (1 - 2e^{i\delta} s_{23}\theta_{13}) \frac{(0.9\,\mathrm{GeV})^2}{4M_1^2} \left(1 - \left(\frac{M_1}{M_1 + \Delta M_{12}}\right)^2\right)} \right|$$

HEAVY NEUTRINO
contribution

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

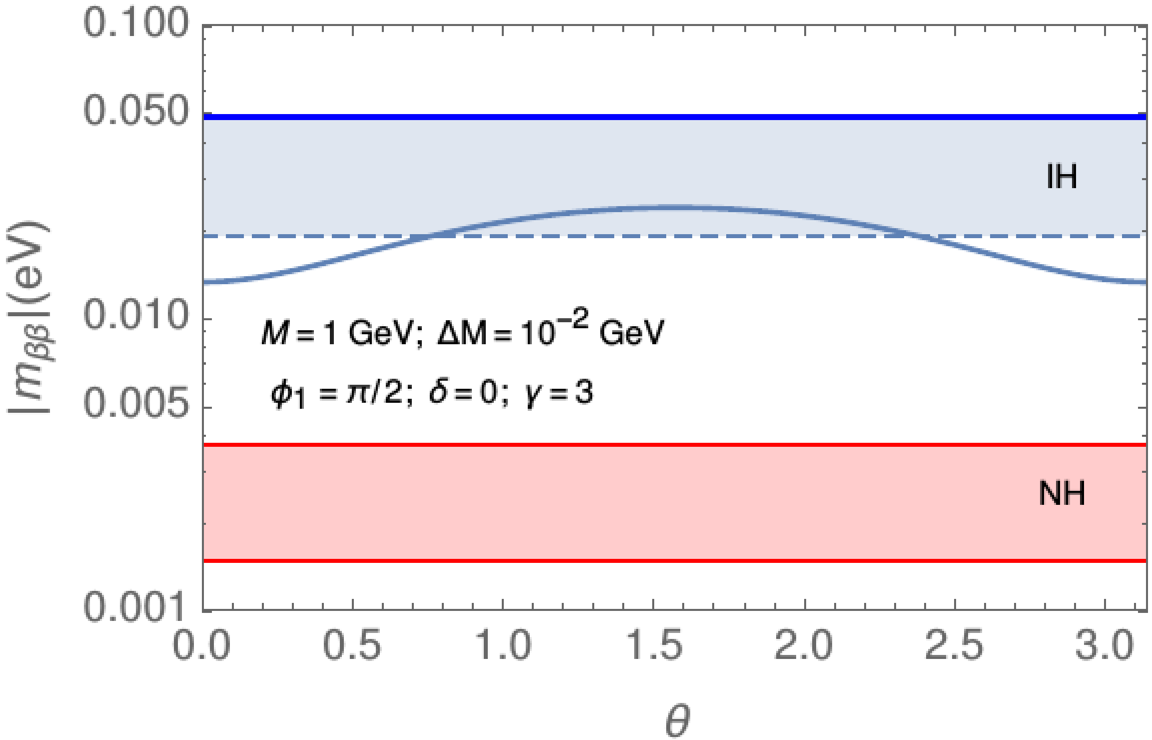
Mitra, Senjanovic, Vissani 2011
JLP, Pascoli, Wong 2012

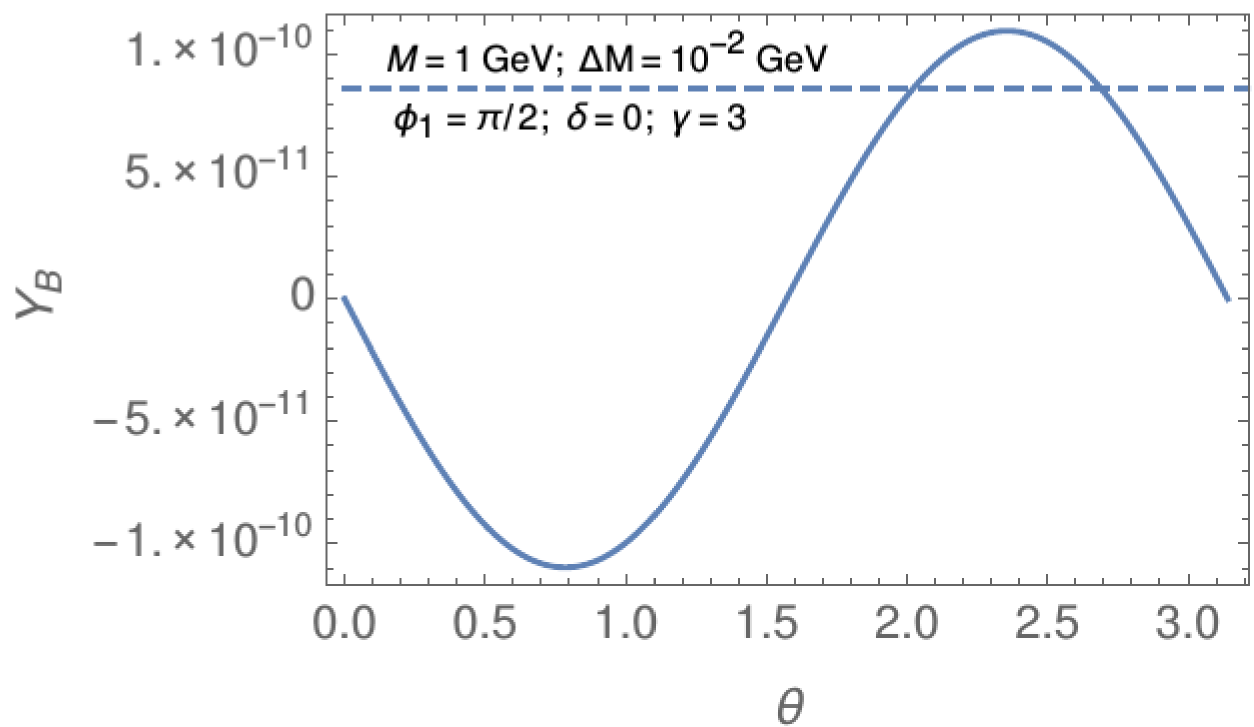
Predicting Y_B in minimal model $N_R=2$



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

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

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

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

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

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

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

CP invariants

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

$$\left.\begin{aligned} I_1^{(2)} &= -\mathrm{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \\ I_1^{(3)} &= \mathrm{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \\ I_2^{(3)} &= \mathrm{Im}[W_{13}^* V_{12} V_{22}^* W_{23}] \end{aligned}\right\}$$

CP phases from V & W
(UPMNS & R)

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

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

$$\left.\begin{aligned} I_1^{(2)} &= -\mathrm{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \\ I_1^{(3)} &= \mathrm{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \end{aligned}\right\} \quad N_R \geqslant 2$$

$$\left.\begin{aligned} I_2^{(3)} &= \mathrm{Im}[W_{13}^* V_{12} V_{22}^* W_{23}] \\ J_W &= -\mathrm{Im}[W_{23}^* W_{22} W_{32}^* W_{33}] \end{aligned}\right\} \quad N_R \geqslant 3$$

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

CP invariants

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

$$\left.\begin{aligned} I_1^{(2)} &= -\mathrm{Im}[W_{12}^* V_{11} V_{21}^* W_{22}] \\ I_1^{(3)} &= \mathrm{Im}[W_{12}^* V_{13} V_{23}^* W_{22}] \end{aligned}\right\} \quad AS \ \ \nu MSM$$

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

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

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

Sakharov Conditions

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

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

Casas-Ibarra

N_R=2: 2 + 1 = 3 phases

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

(3) B+L violation: *SM sphalerons efficientely transfer* ΔL *into* ΔB

Heavy New Physics scale

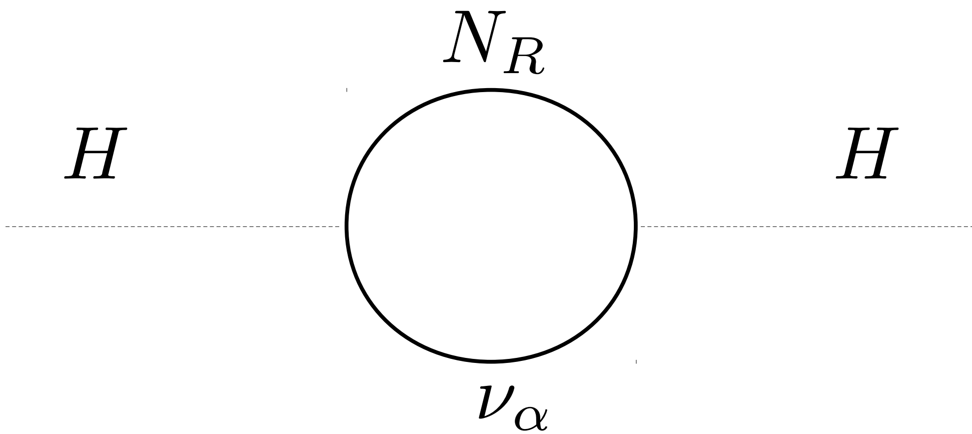
$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T \lesssim \mathcal{O}\,(1\,\mathrm{eV})$$

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

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

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.