HNLs and their relation to the Active Neutrino Sector

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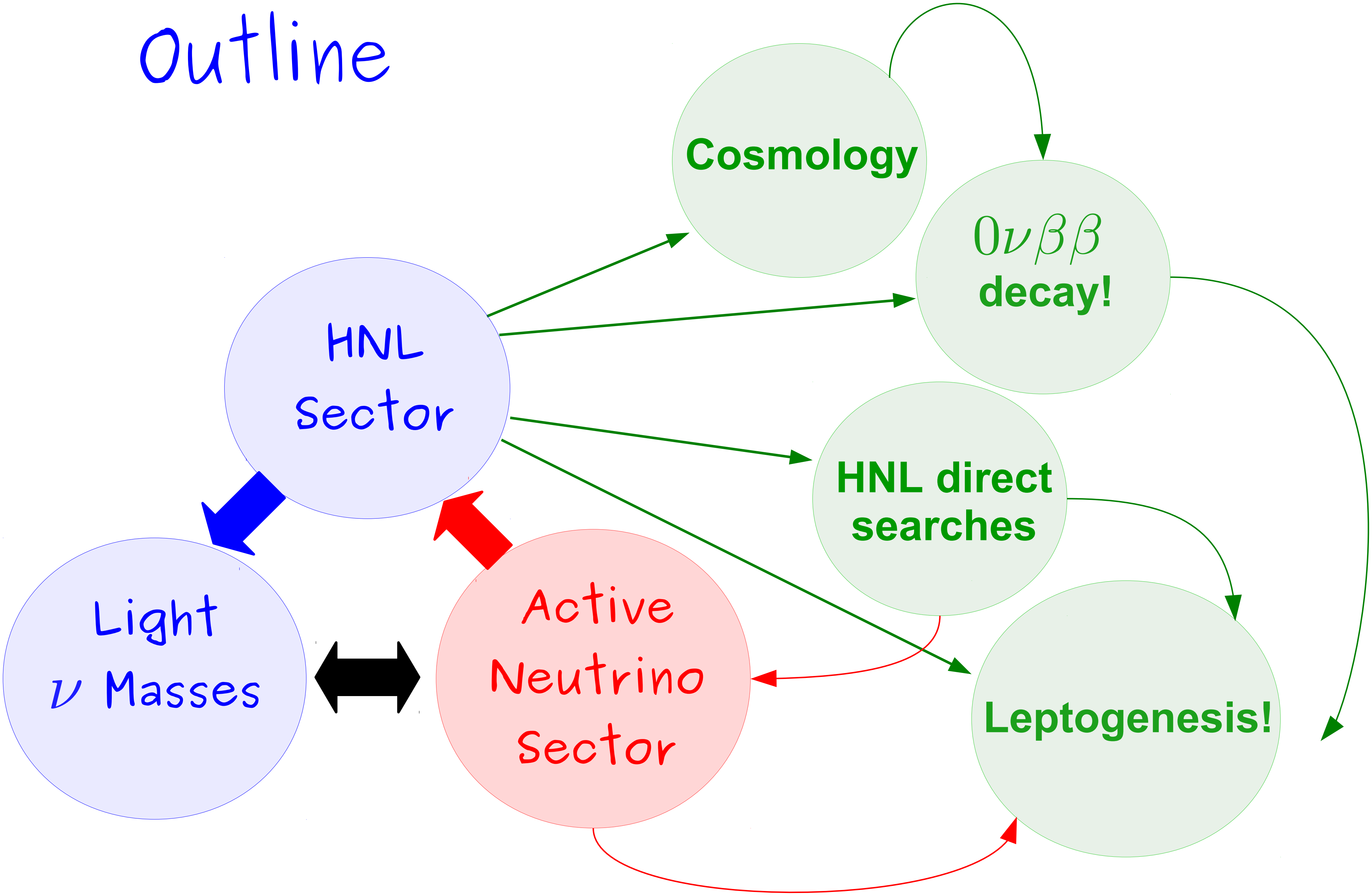
Outline



Cosmology
$0\nu\beta\beta$
decay!
HNL
Sector
HNL direct
searches
Light
ν Masses
Active
Neutrino
Sector
Leptogenesis!

Introducing HNLs

- If we add heavy fermion singlets (HNL or N_R) to the SM field content, the most general lagrangian compatible with the SM gauge symmetries is

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

Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80.

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New Physics Scale

Lepton Number Violation

Introducing HNLs

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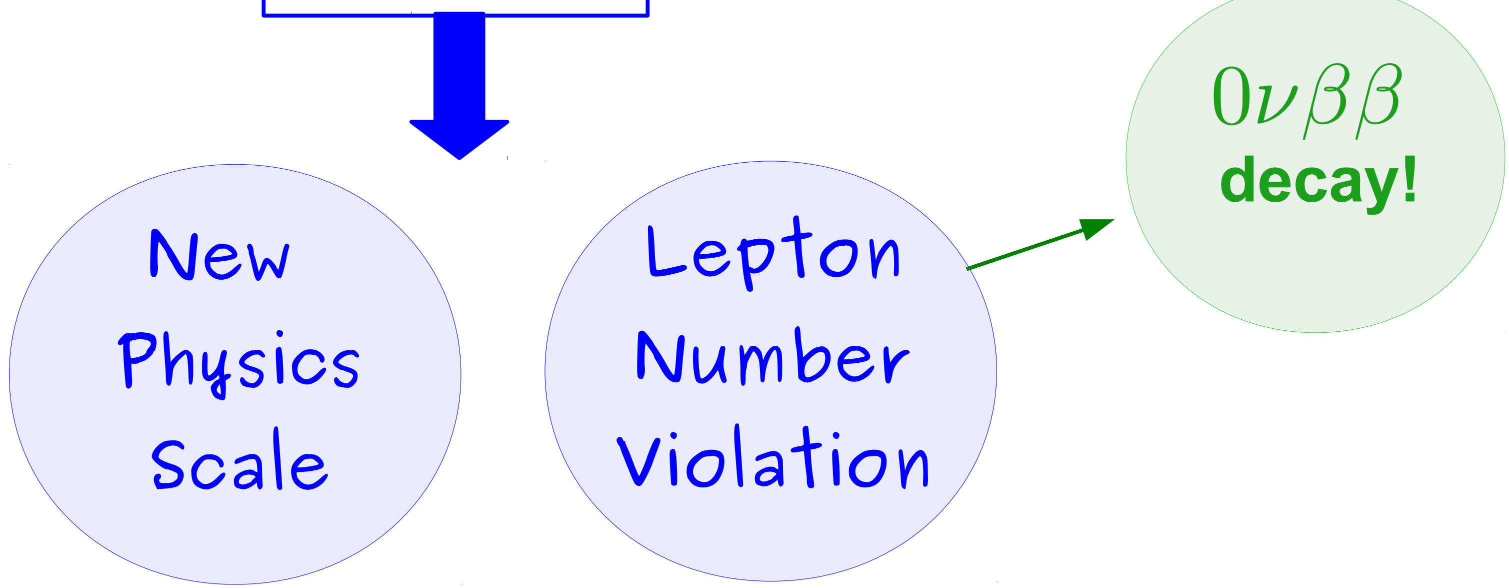

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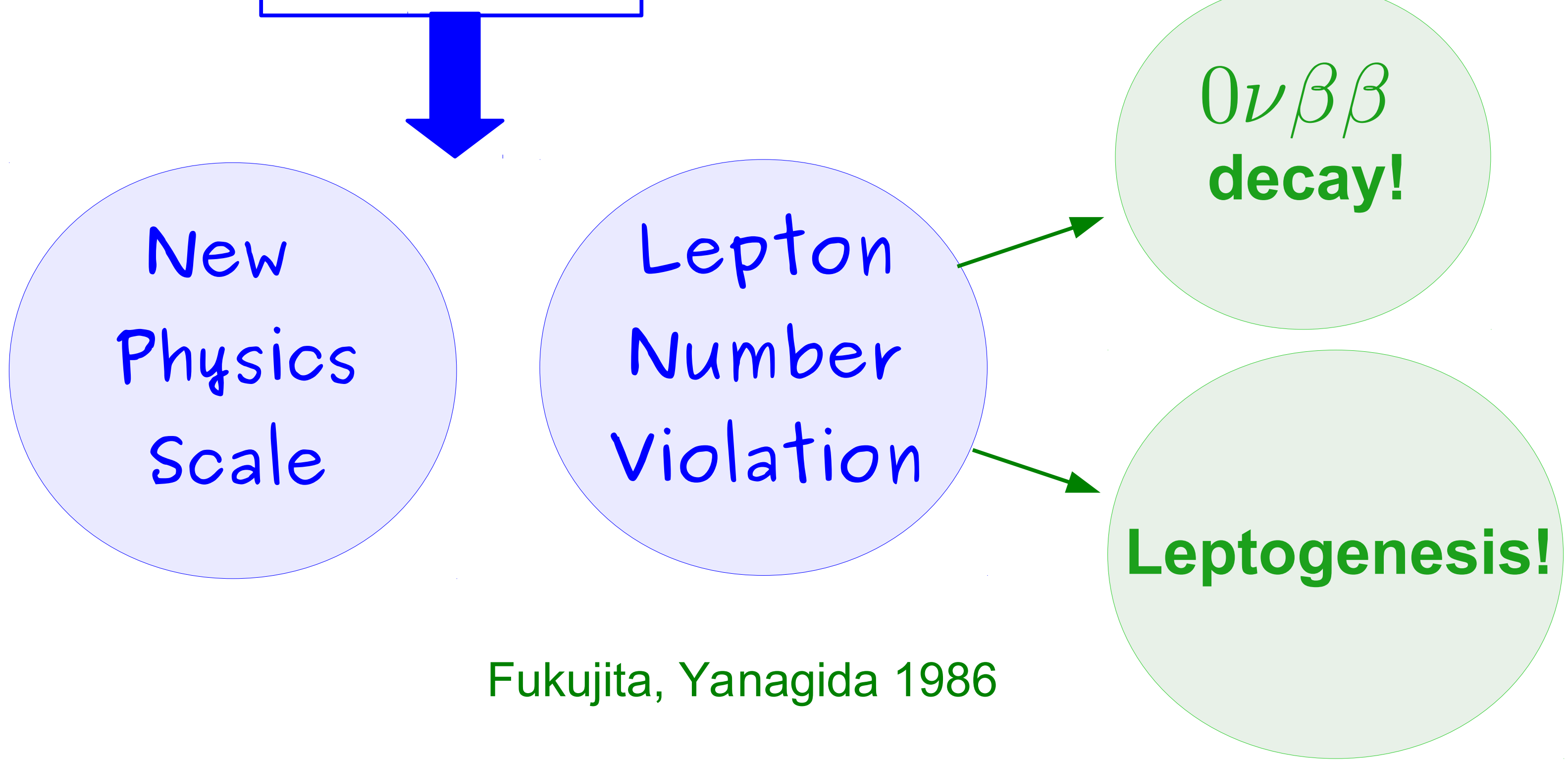


Light neutrino mass generation

- If we add heavy fermion singlets (HNL or N_R) to the SM field content, the most general lagrangian compatible with the SM gauge symmetries is

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

- Introducing HNL automatically generates a contribution to light neutrino masses

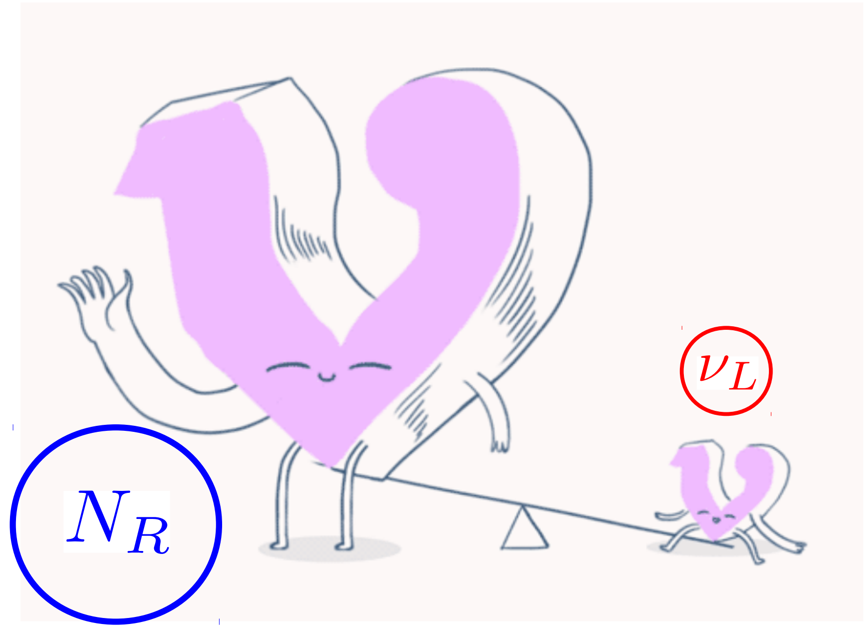
$$m_\nu = -\frac{v^2}{2} Y^T M^{-1} Y$$

Type-I Seesaw Model

Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80.

Relation betwen HNLs and active sector

- **Generation of light neutrino masses imposes constraints on HNL mixing**

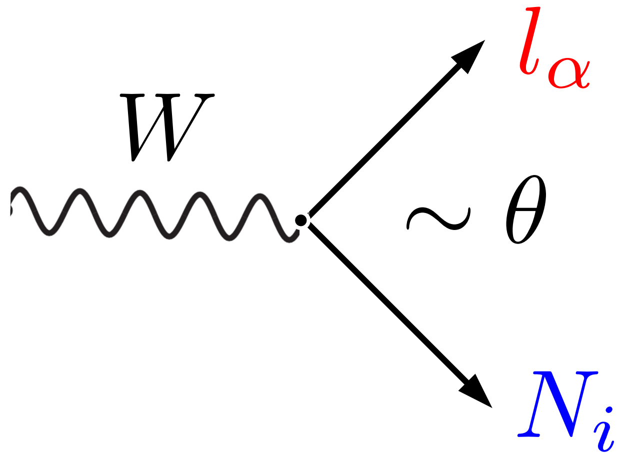


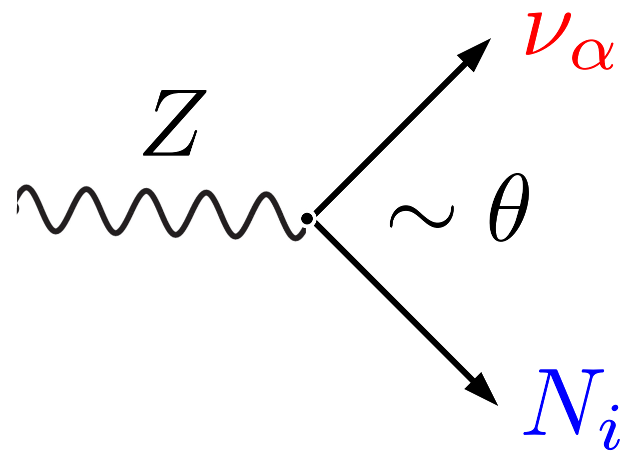
$$m_\nu = -\frac{v^2}{2} Y^T M^{-1} Y = -\theta\, M\, \theta^T = U\, m\, U^T$$

HNL sector

Light-active neutrino sector

Constraint on HNL mixing from active sector





Casas-Ibarra

$$\theta = i U\, m^{1/2} R^{\dagger} M^{-1/2}$$

Active Sector

- 3x3 PMNS mixing matrix
- light neutrino masses

HNL Sector

- Complex $3 \times N_R$ orthogonal matrix
- HNL masses

Light-active Sector

What we know...

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric sector | Interference/Reactor | Solar sector

$$\sin^2\theta_{23} = \begin{matrix} 0.570^{+0.018}_{-0.024} \\ 0.575^{+0.017}_{-0.021} \end{matrix}$$

$$\Delta m^2_{3l} = \begin{matrix} +2.514^{+0.028}_{-0.027} \\ -2.497^{+0.028}_{-0.028} \end{matrix} \times 10^{-3}\mathrm{eV}$$

$$\sin^2\theta_{12} = 0.304^{+0.013}_{-0.012}$$

$$\Delta m^2_{21} = \left(7.42^{+0.21}_{-0.20}\right) \times 10^{-5}\mathrm{eV}$$

$$\sin^2\theta_{13} = \begin{matrix} 0.02221^{+0.00068}_{-0.00062} \\ 0.02240^{+0.00062}_{-0.00062} \end{matrix}$$

(1σ)

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou 2007.14792
http://www.nu-fit.org/

[See talk by Albert Zhou]

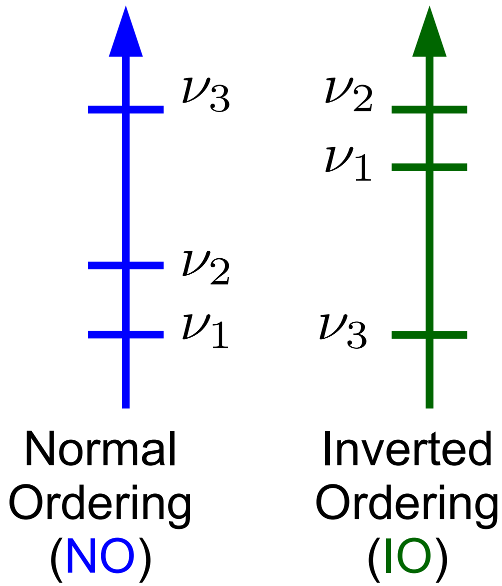
What we don't know...

See for instance: King et al 1402.4271
Altarelli et al 1205.5133, 1002.0211

1. The Octant: $\theta_{23} \gtrless 45^\circ$. *Very relevant for the flavour puzzle.*

2. Neutrino ordering (sign of Δm^2_{31})

Extremely relevant input for other observables as $0\nu\beta\beta$ decay



3. CP violation in the lepton sector

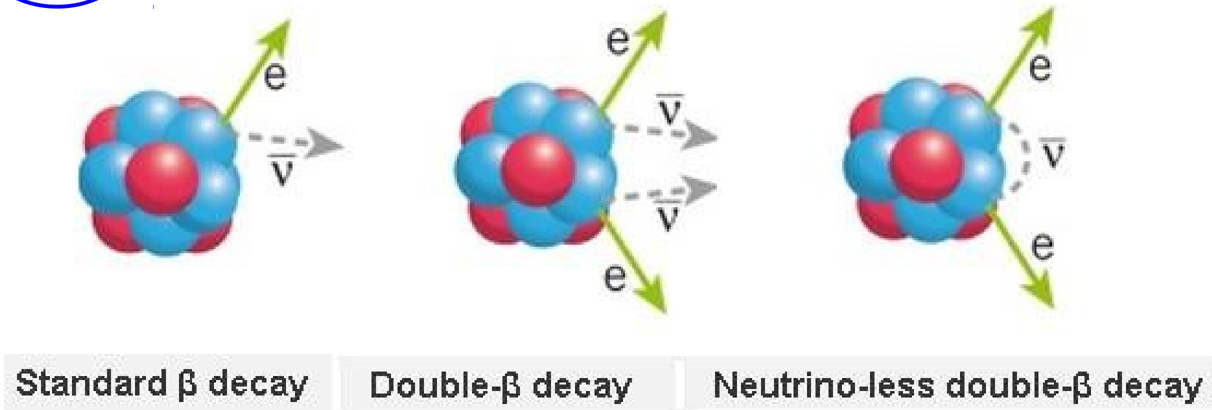
Essential in order to explain the Baryon asymmetry of the universe via Leptogenesis.

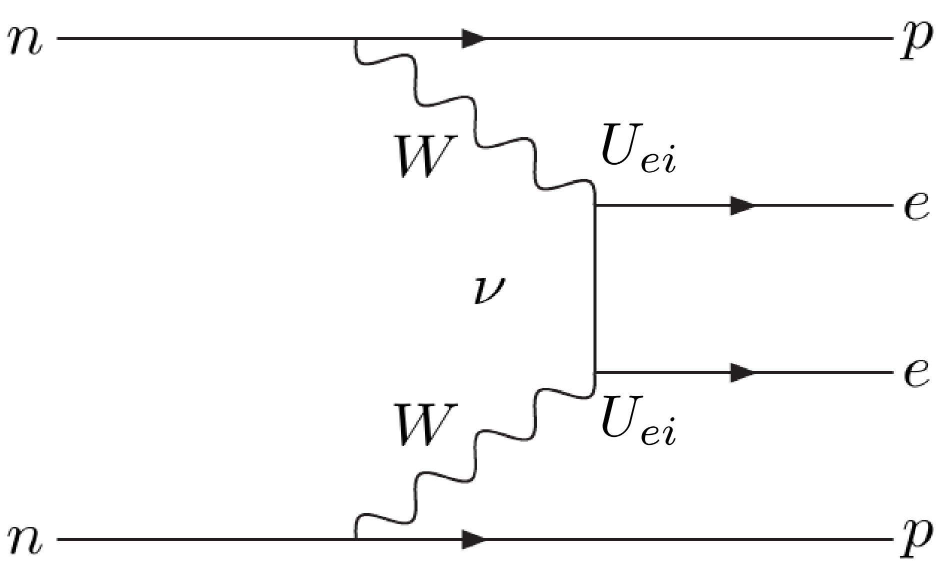
Fukugita, Yanagida 1986

4. Absolute neutrino mass scale

Cosmological probes, Tritium beta decay (KATRIN)

5 Dirac vs Majorana





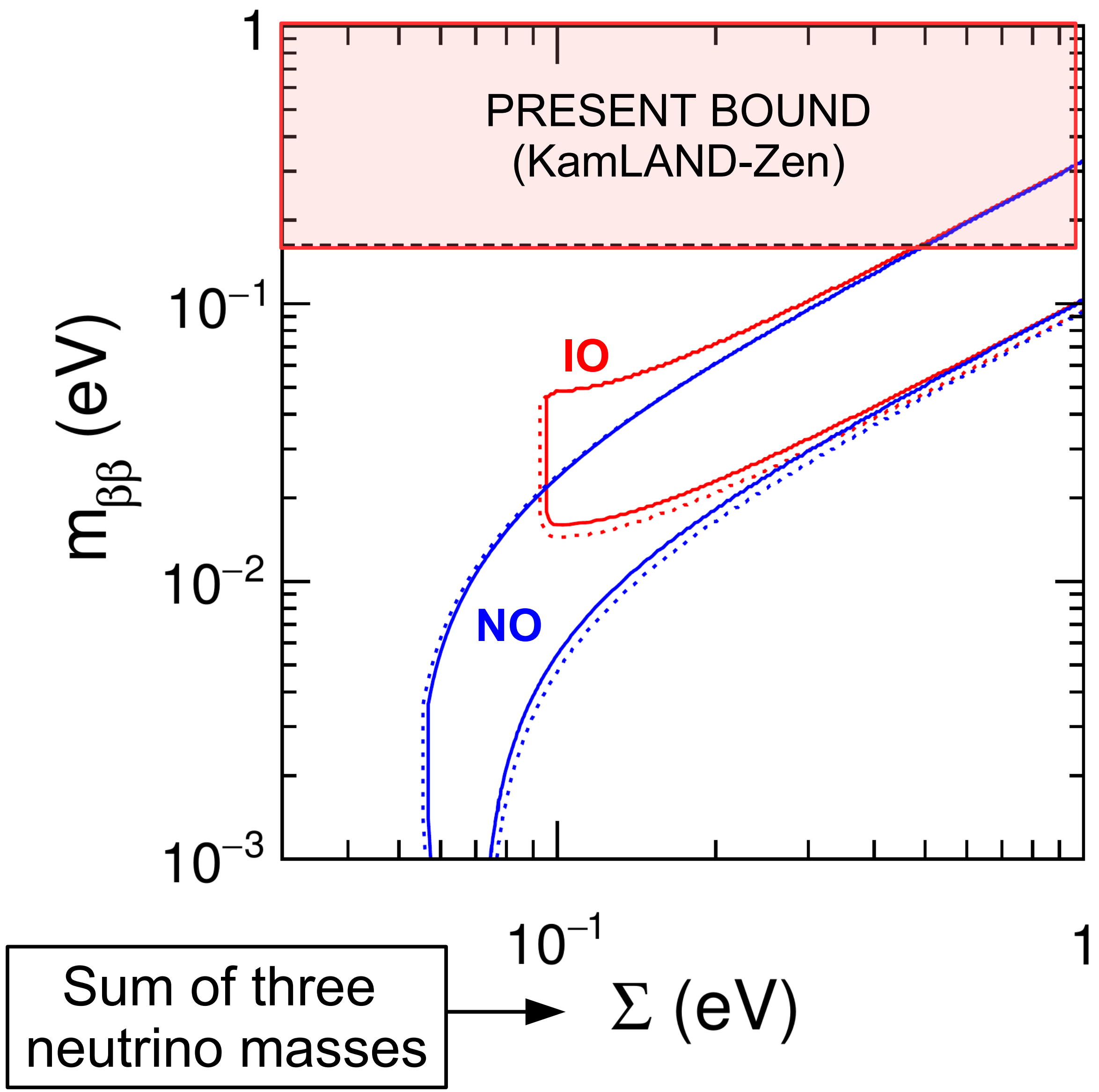
$$\sim m_{\beta\beta} = \sum_i m_i U_{ei}^2$$

mixing

mass of propagating neutrino

[See talks by Ruben Saakyan, Denys Poda & Christophe Wiesinger]

Neutrinoless double beta decay

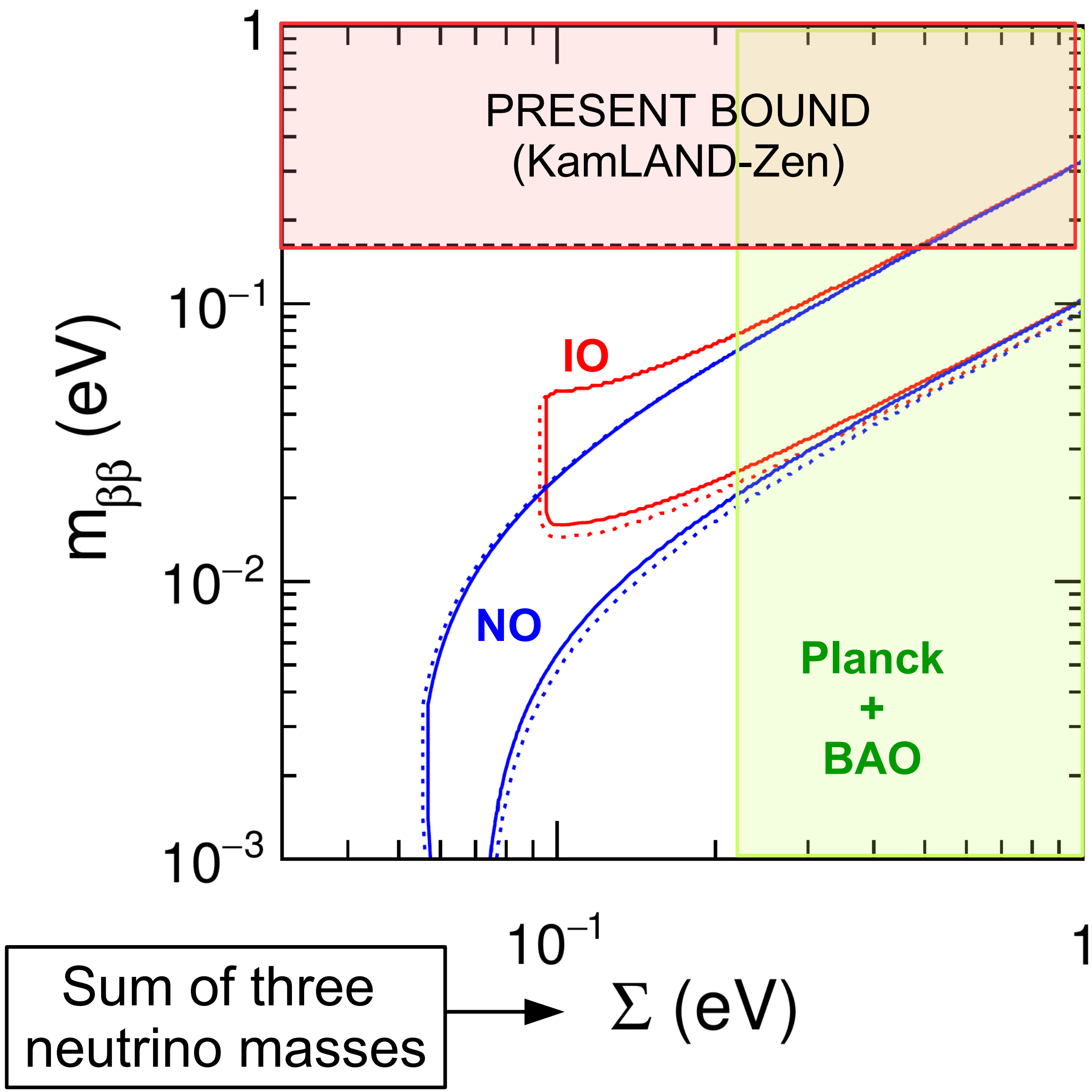


- Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.

- *Extremely relevant input in order to probe New Physics models responsible for ν mass generation.*

Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo 1703.0447

Neutrinoless double beta decay



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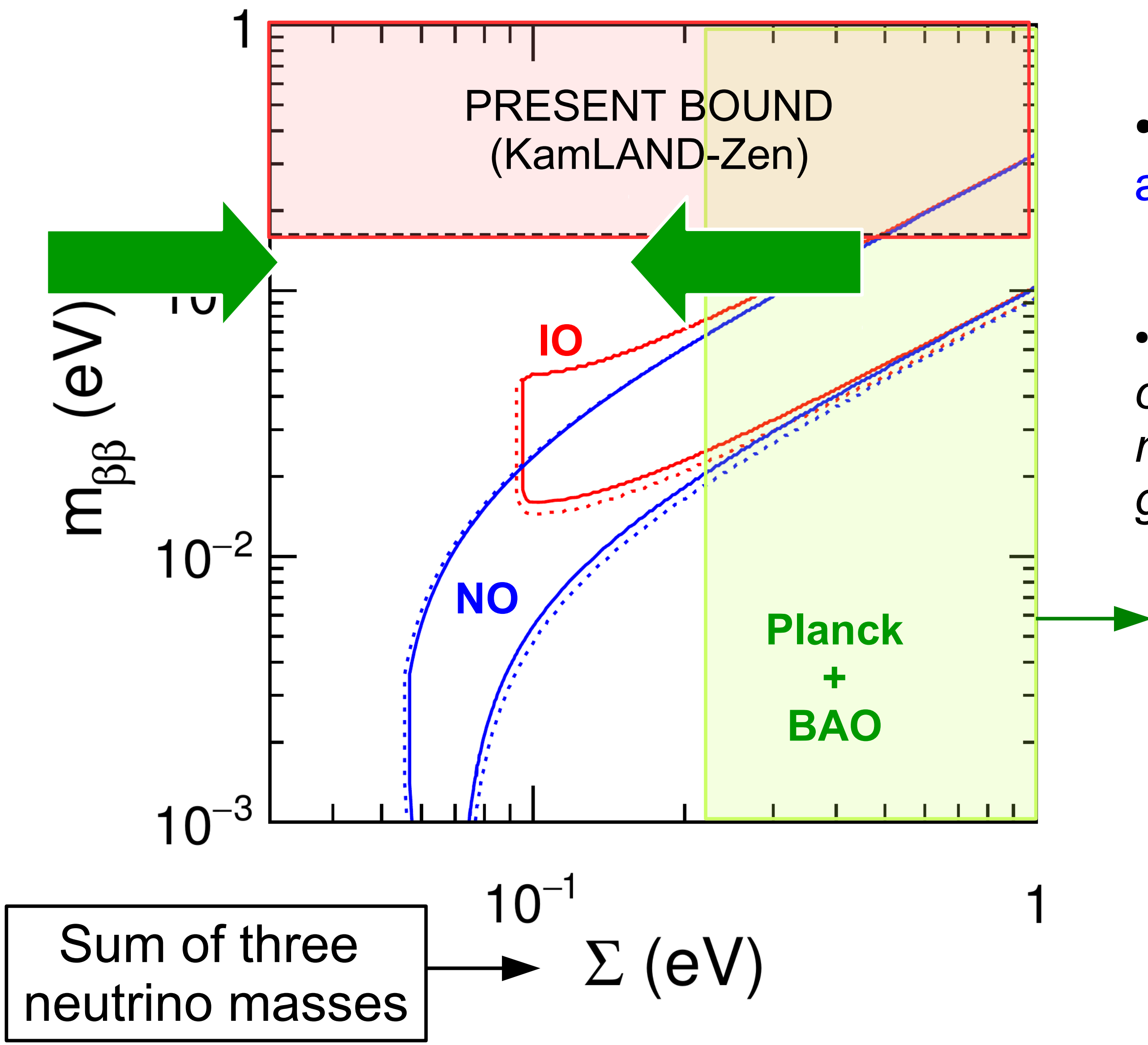
Neutrinoless double beta decay signal?



- Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.

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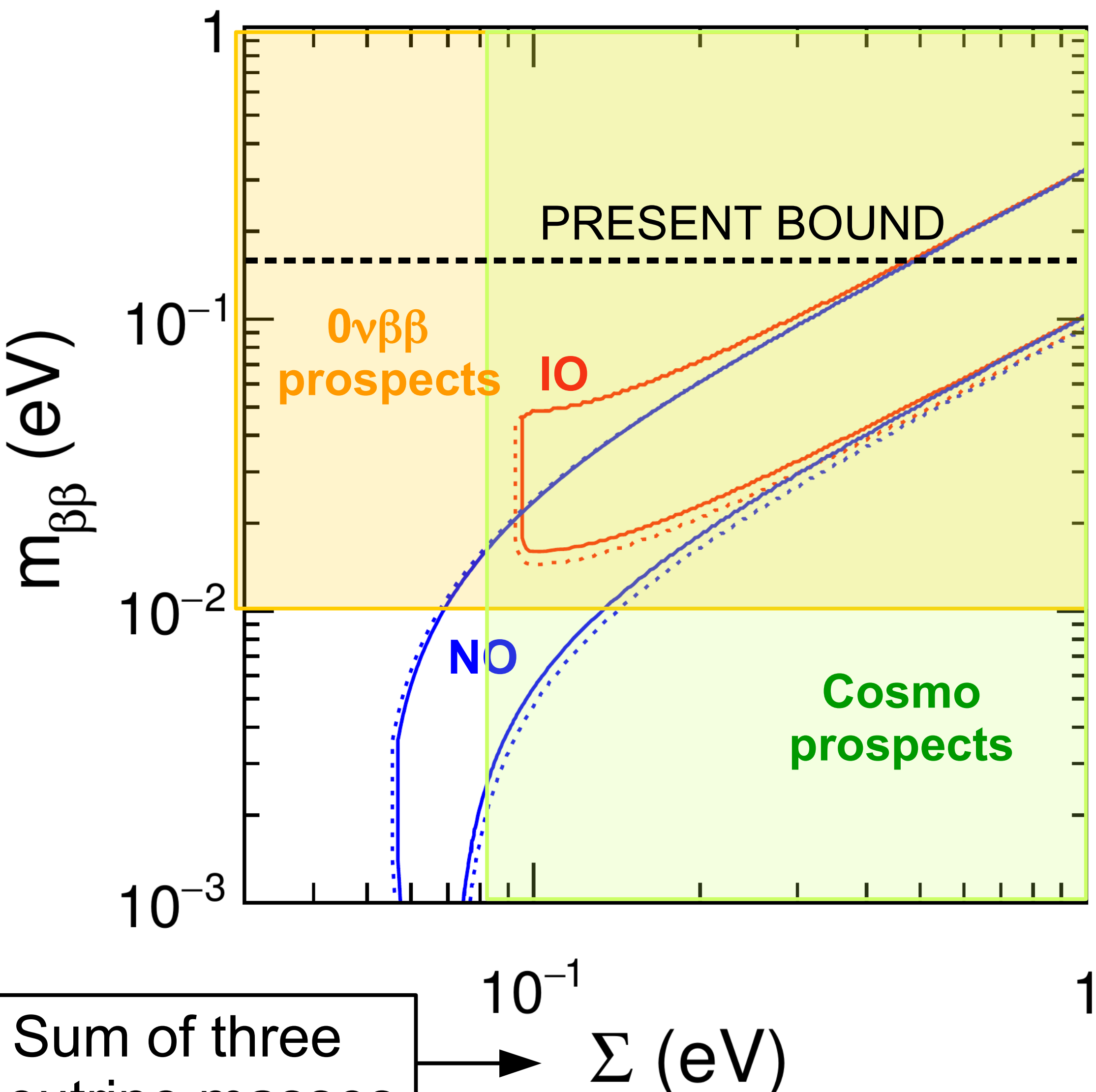
Posibilities:

- **Dominated by New Physics** as HNL contribution

- **Cosmological bound could be relaxed**. For instance, if neutrinos decay (new interactions required) Escudero, JLP, Rius, Sandner 2007.04994

Neutrinoless double beta decay

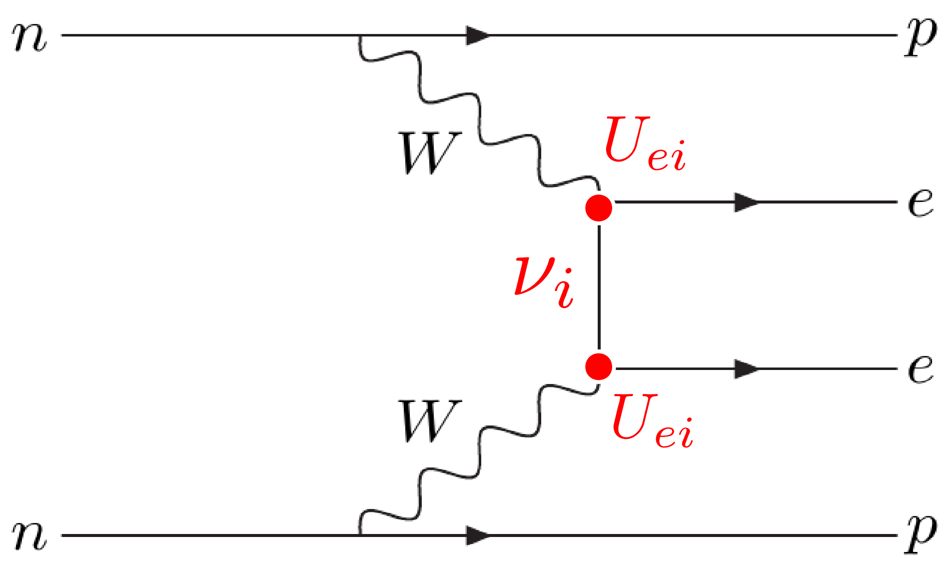


Sum of three neutrino masses

- Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.
- *Extremely relevant input in order to probe New Physics models responsible for ν mass generation.*

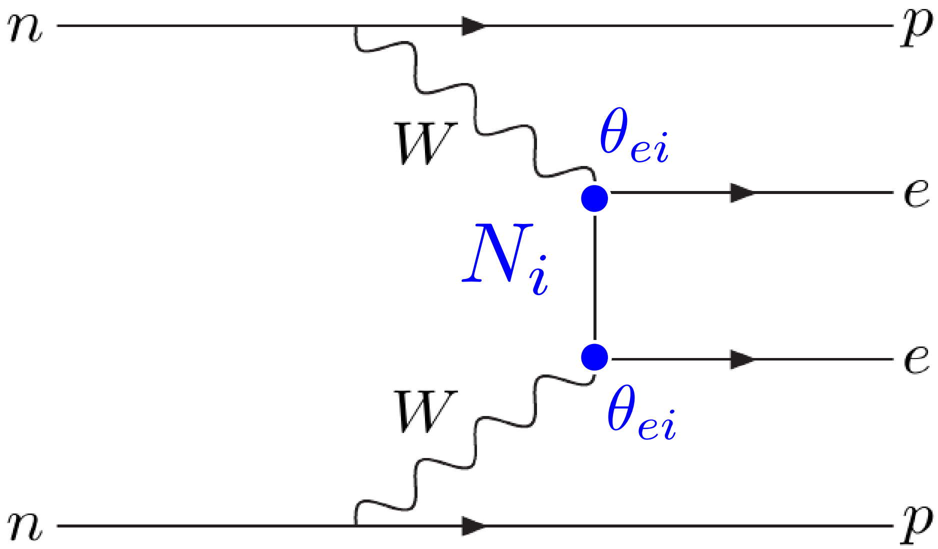
Connection to HNL sector

Neutrinoless double beta decay



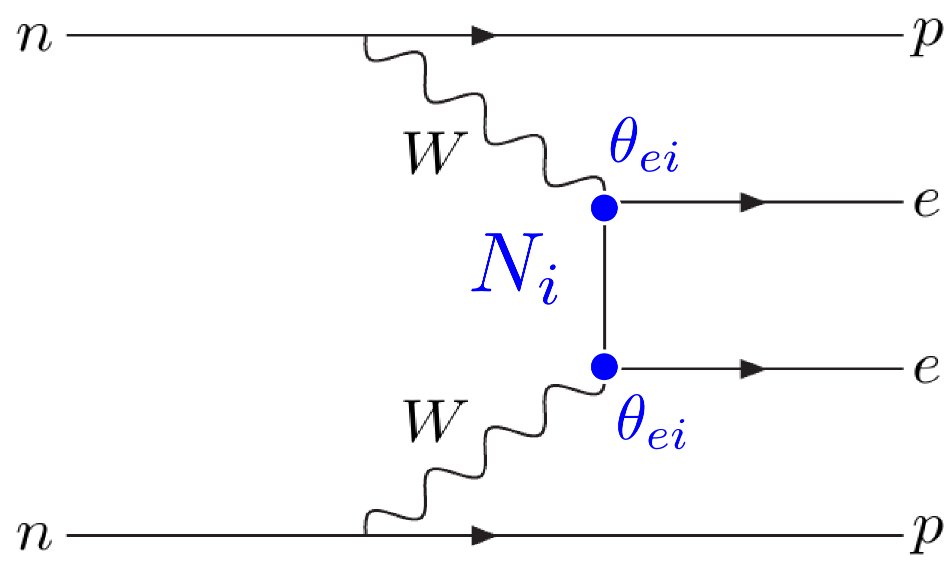
$$m_{\beta\beta} = \sum_{i=light} U_{ei}^2 m_i$$

Neutrinoless double beta decay



$$m_{\beta\beta} = \sum_{i=light} U_{ei}^2 m_i + \sum_{i=heavy} \frac{\mathcal{M}^{0\nu\beta\beta}(M_i)}{\mathcal{M}^{0\nu\beta\beta}(0)} \theta_{ei}^2 M_i$$

Neutrinoless double beta decay



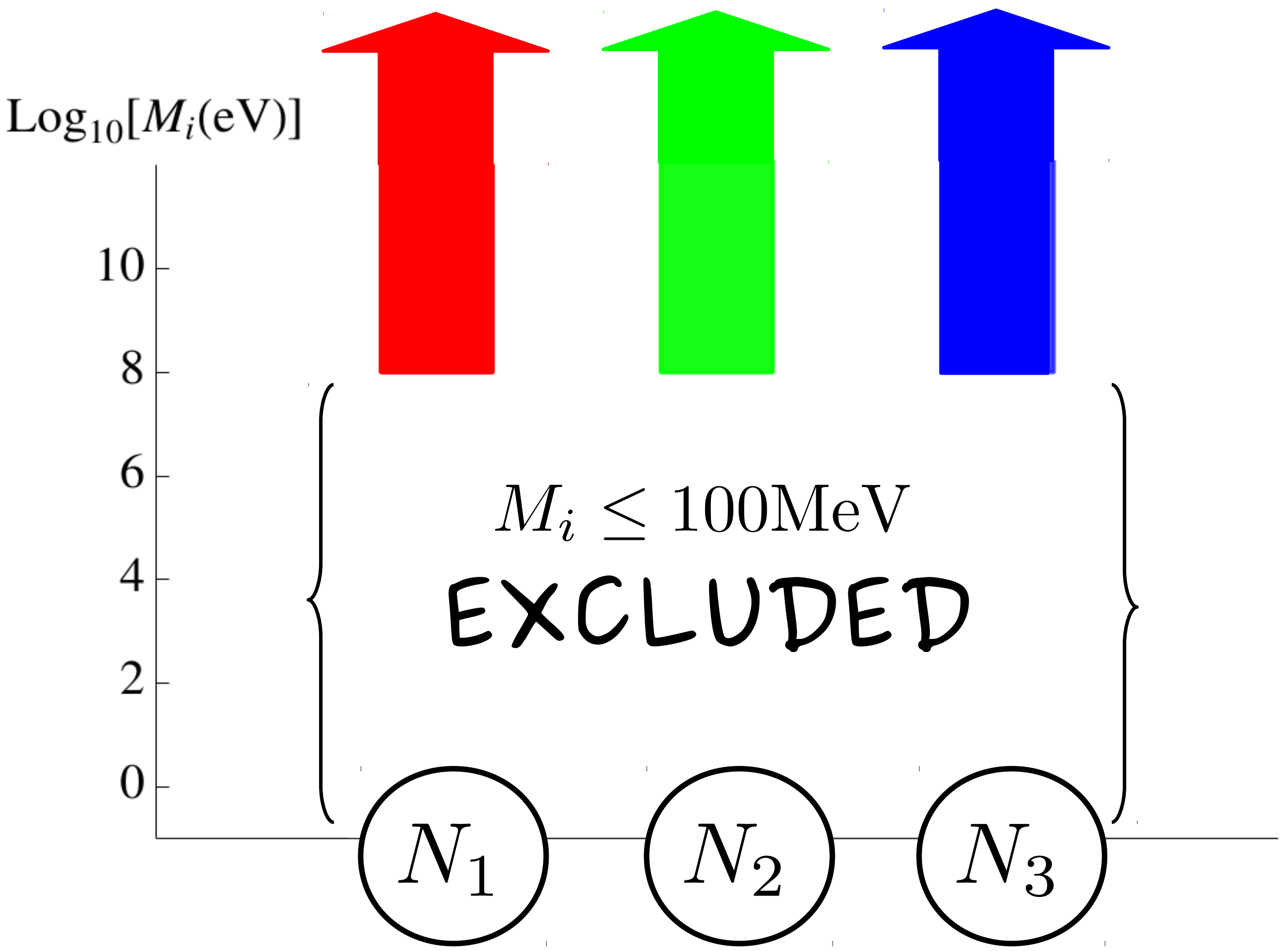
$$m_{\beta\beta} = \sum_{i=light} U_{ei}^2 m_i + \sum_{i=heavy} \overbrace{\underbrace{\frac{\mathcal{M}^{0\nu\beta\beta}(M_i)}{\mathcal{M}^{0\nu\beta\beta}(0)}}}^{\text{NMEs}} \theta_{ei}^2 M_i$$

$$M_i \gg 100\, MeV : \quad \sim 1/M_i^2$$

$$M_i \ll 100\, MeV : \quad \sim 1$$

Cosmology: HNLs scale vs $m_{lightest}$

- $m_{lightest} \geq \mathcal{O}\left(10^{-3} eV\right)$: the three HNLs thermalize.

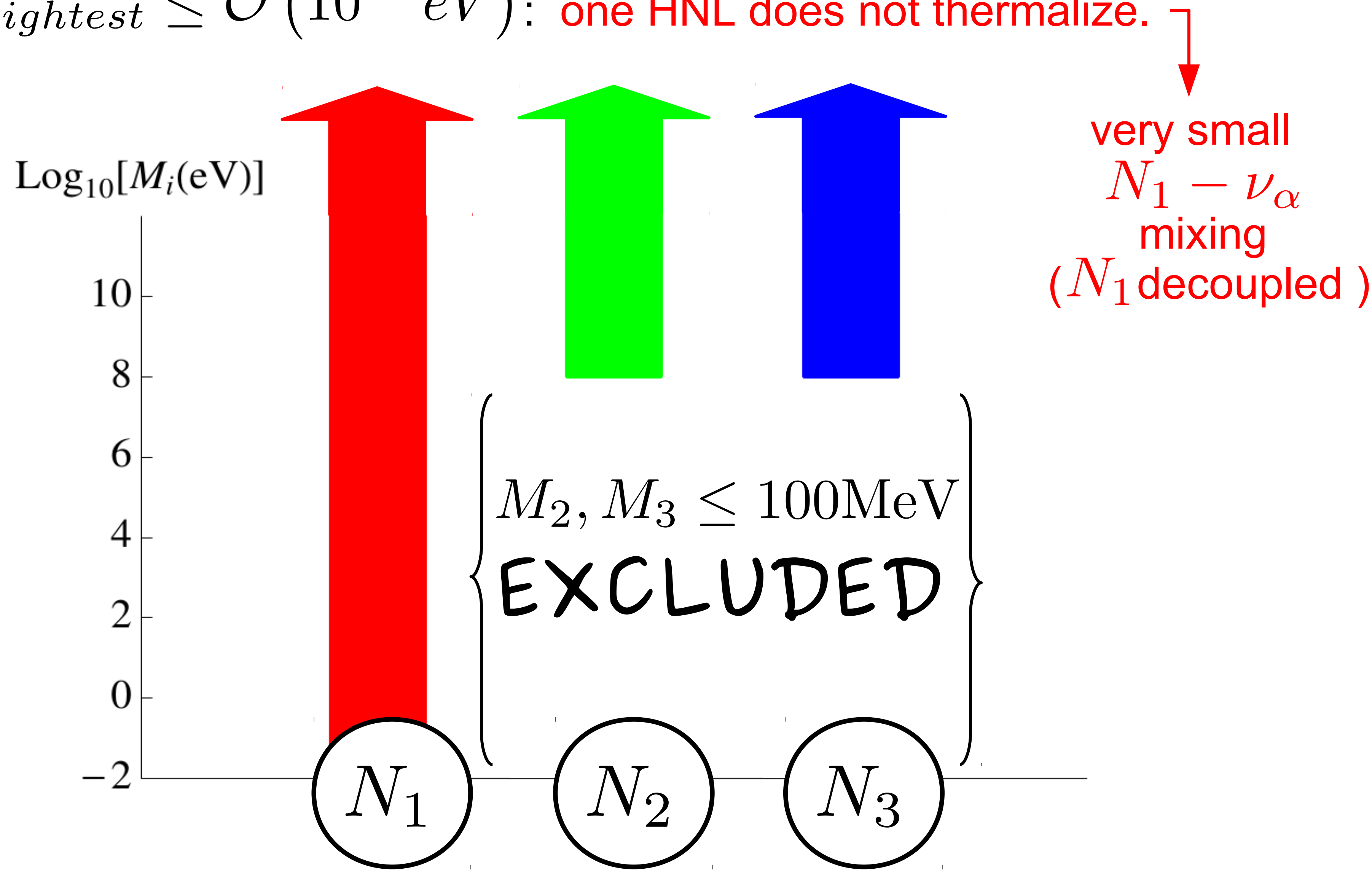


Allowed HNL spectra

Hernandez, Kekic, JLP 2014

Cosmology: HNLs scale vs $m_{lightest}$

- $m_{lightest} \leq \mathcal{O}\left(10^{-3} eV\right)$: one HNL does not thermalize.



Allowed HNL spectra

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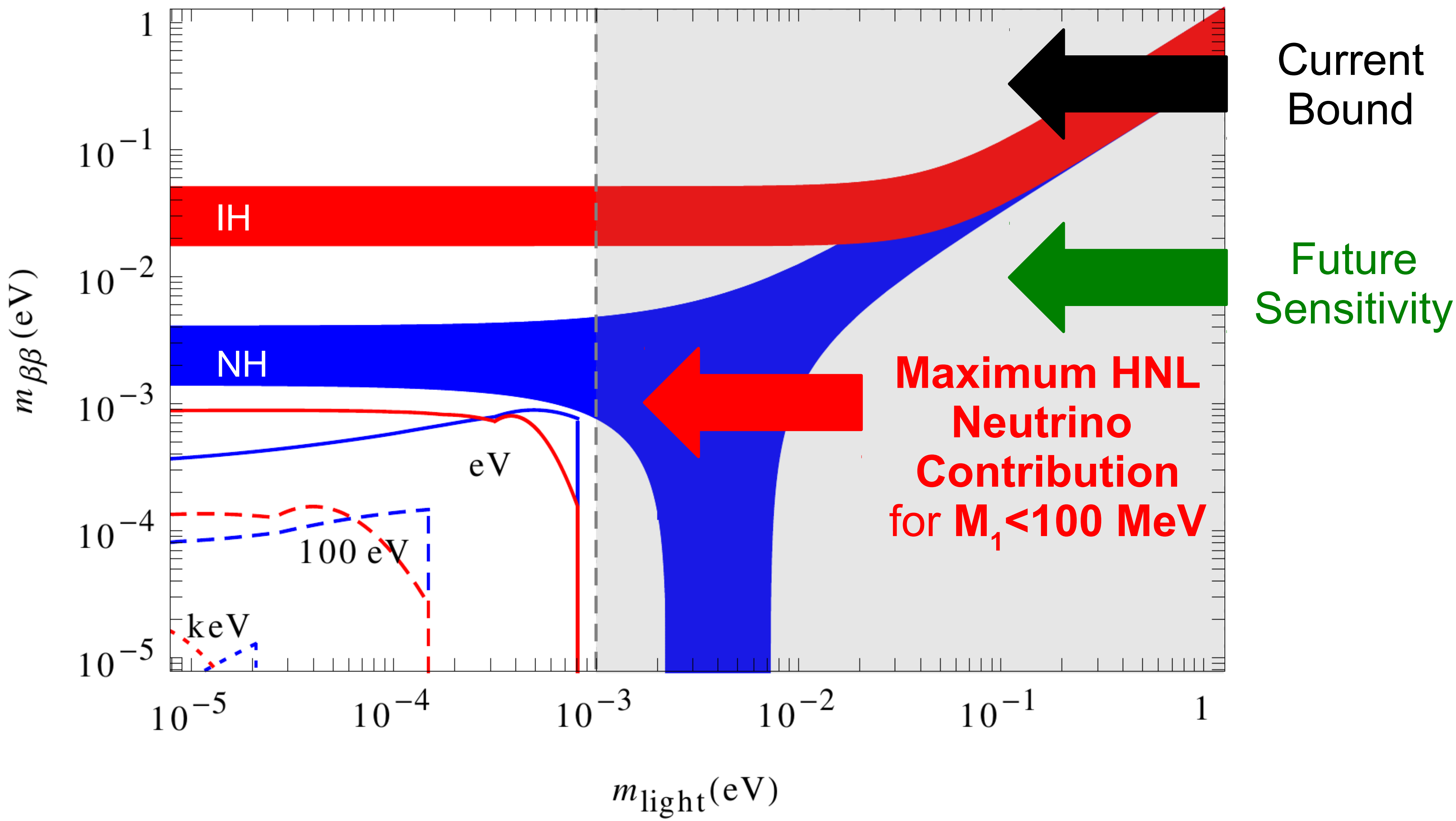
Interplay with neutrinoless double beta decay



Hernandez, Kekic, JLP 2014

Interplay with neutrinoless double beta decay

Good News:

Ibarra, Molinaro, Petcov 2010
Mitra, Senjanovic, Vissani 2011

- Sizable HNL contribution posible for $100\, MeV \lesssim M \lesssim 1\, TeV$

Not so Good News: **Constraint from active sector**

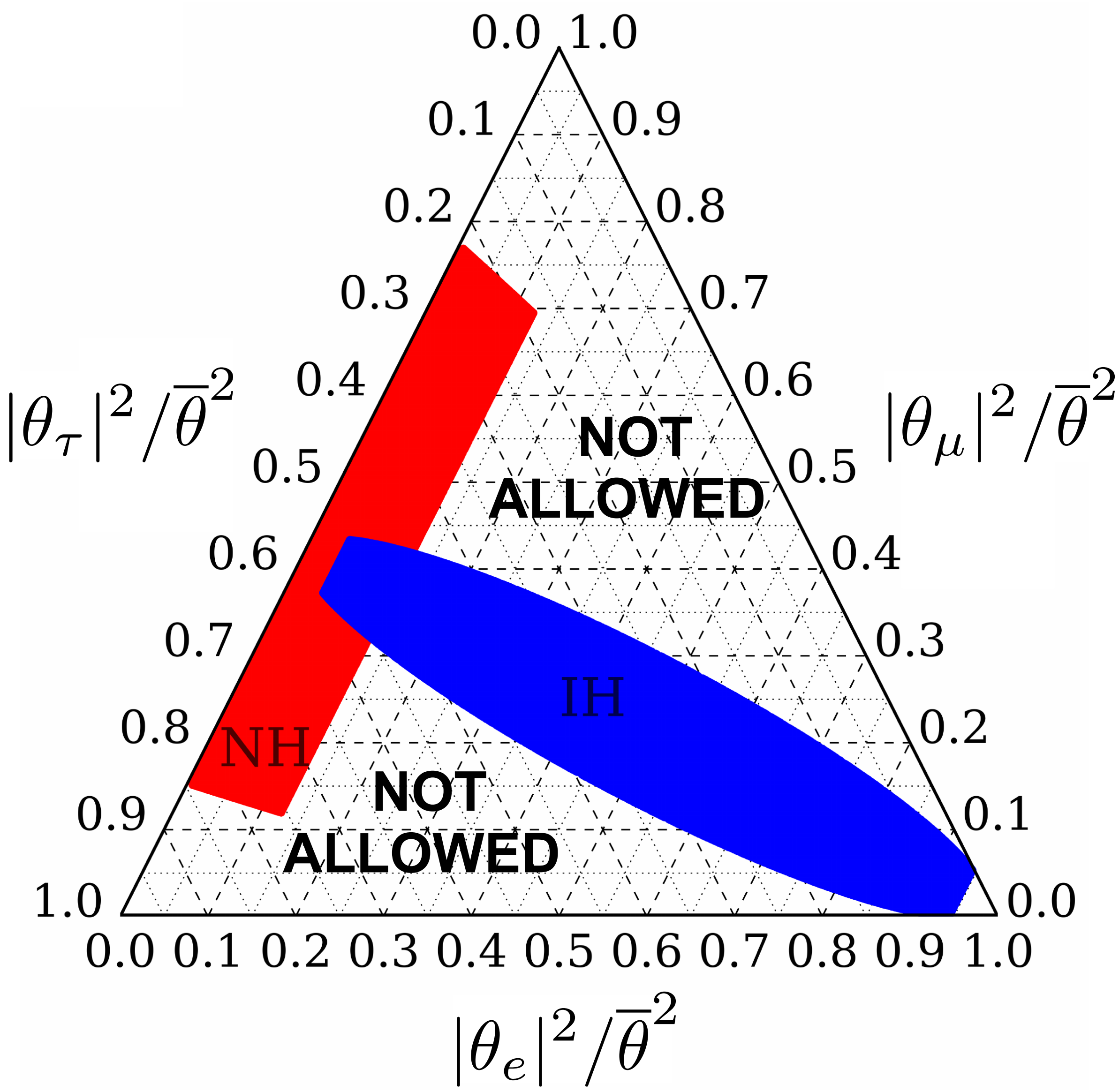
- For $M \gtrsim 5\, GeV$ one-loop corrections to the light neutrino masses become very large.

- Fine tuned cancellation between the tree level and 1-loop correction required.

JLP, Pascoli, Wang 2012
JLP, Molinaro, Petcov 2015
Bolton, Deppisch, Dev 2020

Direct searches of HNLs

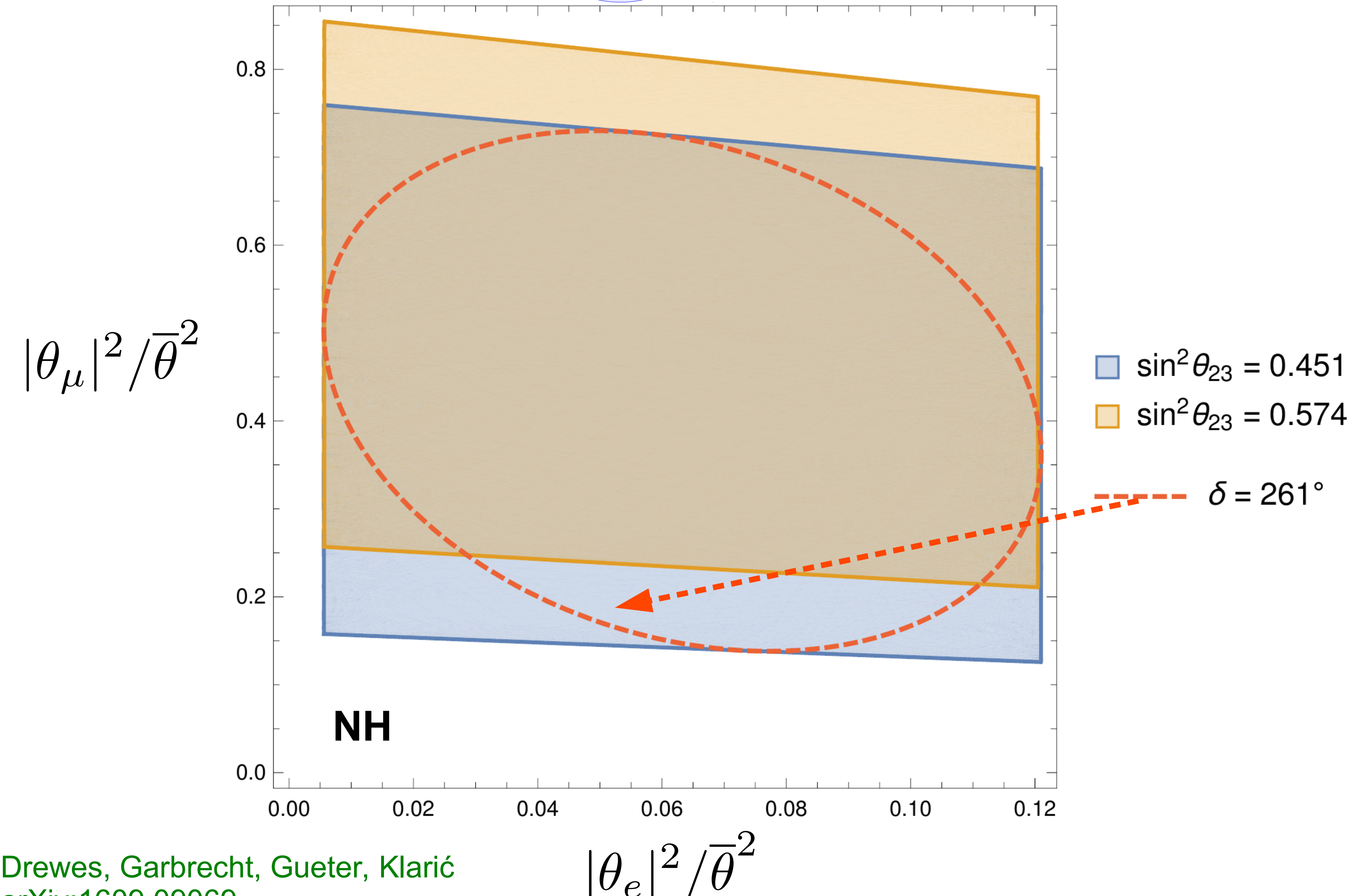
Minimal model $N_R=2$: Flavor Structure



$$\theta = iU\, m^{1/2}\, R^\dagger M^{-1/2}$$

Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

Minimal model $N_R = 2$: Flavor Structure



Drewes, Garbrecht, Gueter, Klarić
arXiv:1609.09069

PMNS CP-phases from HNLs searches

- For instance, **SHiP and FCC-ee** can measure HNLs parameters:

$$M_1, M_2, |\theta_{ei}|, |\theta_{\mu i}|$$

Sensitivity to PMNS CP-phases! δ, ϕ_1

- $|\theta_{e1}|^2/|\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2/|\theta_{\mu 2}|^2 \simeq$

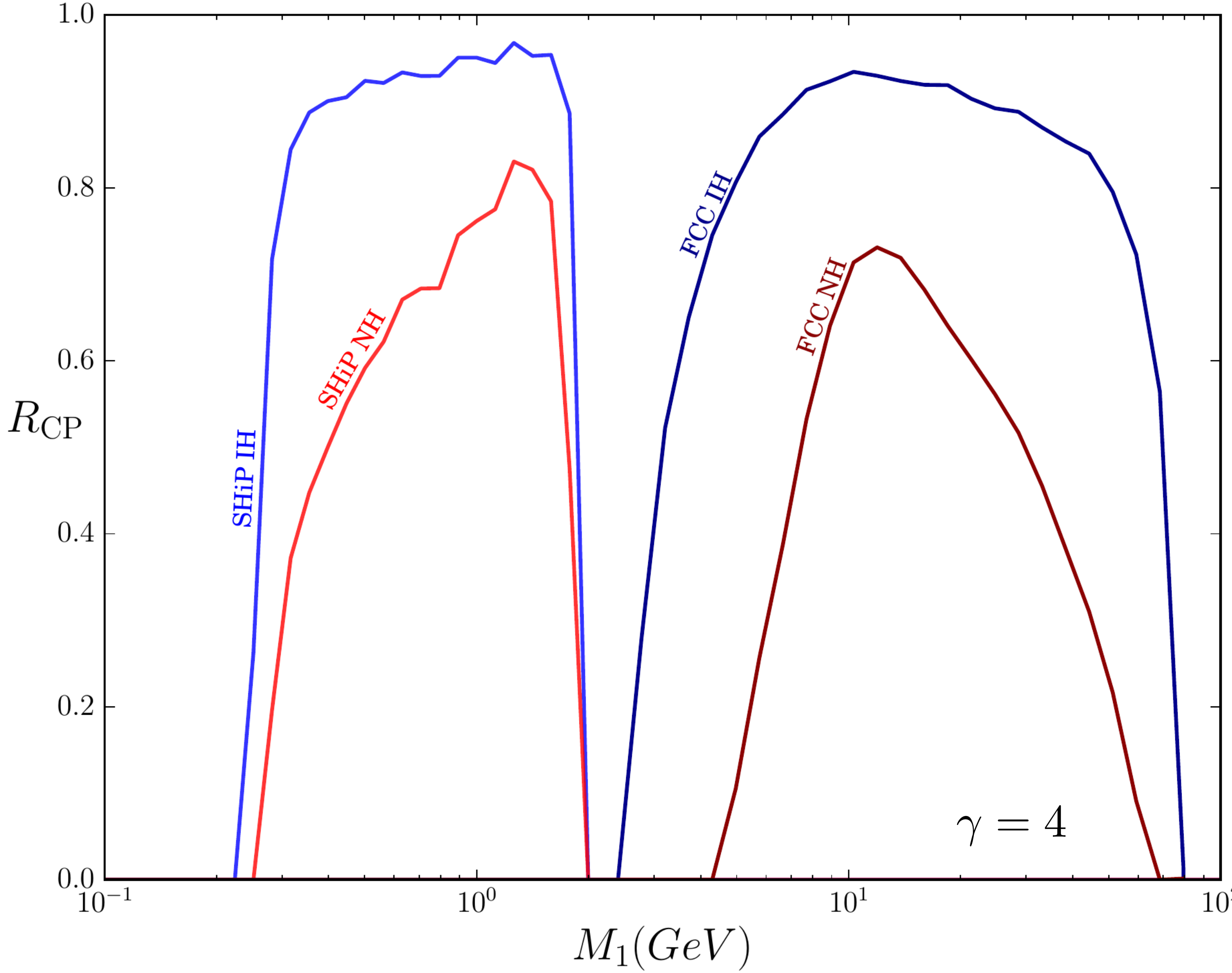
$$\frac{(1 + s_{\phi_1}\sin 2\theta_{12})(1-\theta_{13}^2) + \frac{1}{2}r^2 s_{12}(c_{12}s_{\phi_1} + s_{12})}{\left(1 - \sin 2\theta_{12}s_{\phi_1}\,(1+\frac{r^2}{4}) + \frac{r^2 c_{12}^2}{2}\right)c_{23}^2 + \theta_{13}(c_{\phi_1}s_\delta - \cos 2\theta_{12}s_{\phi_1}c_\delta)\sin 2\theta_{23} + \theta_{13}^2(1+\sin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

- $|\theta_{ei}|^2, |\theta_{\mu i}|^2 \propto e^{2\gamma}$

γ parametrizes size of R_{ij} (and thus heavy mixing)

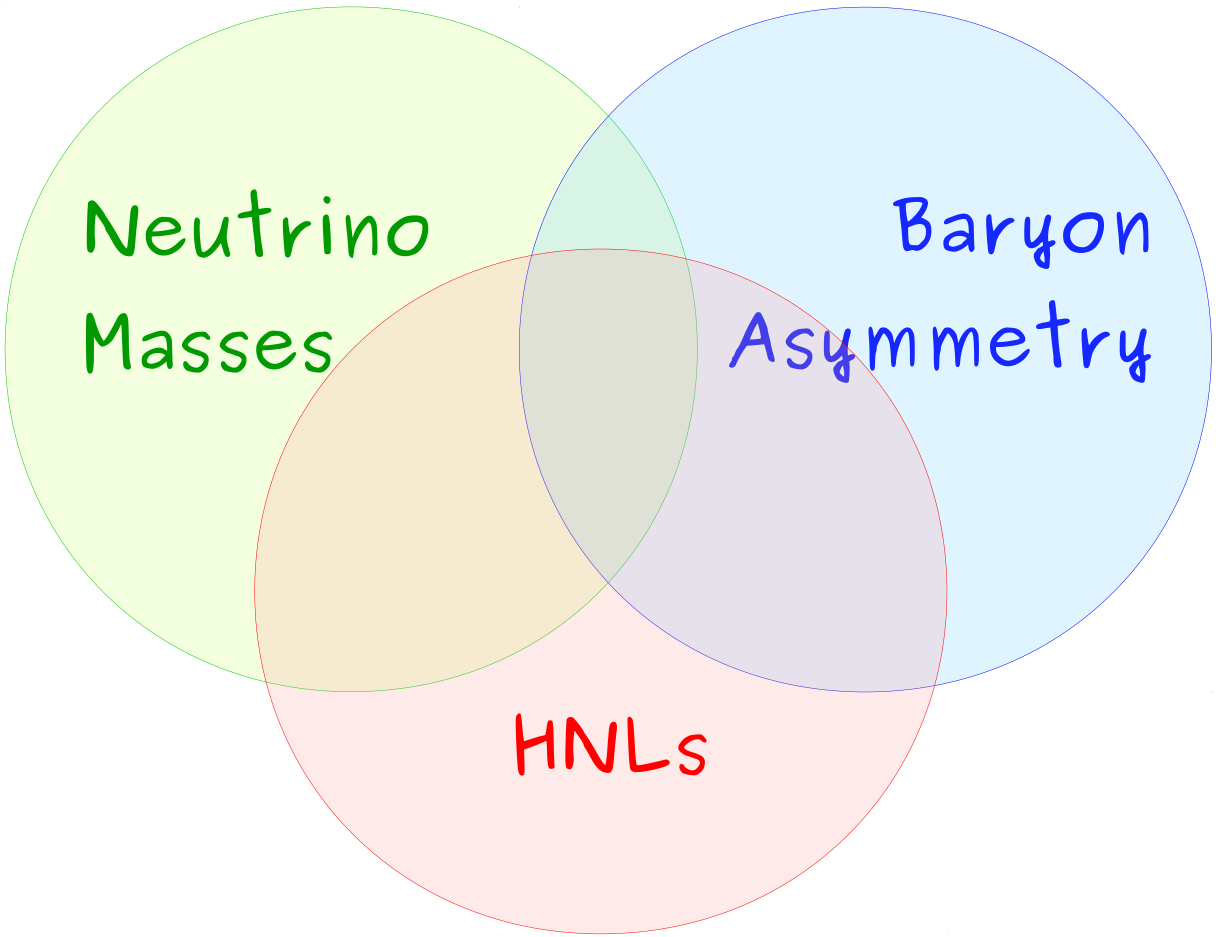
$N_R = 2$

5σ discovery PMNS CP-violation



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

Input from active sector to leptogenesis



How relevant are the PMNS CP phases?

- The Baryon asymmetry generated depends on both light and heavy CP phases.

Light Sector   Heavy Sector

$$Y = U_{PMNS}\sqrt{m}\,R^{\dagger}\sqrt{M}\,\frac{\sqrt{2}}{v}$$

Casas-Ibarra

- **The Dirac CP phase becomes particularly relevant** mainly in two cases:

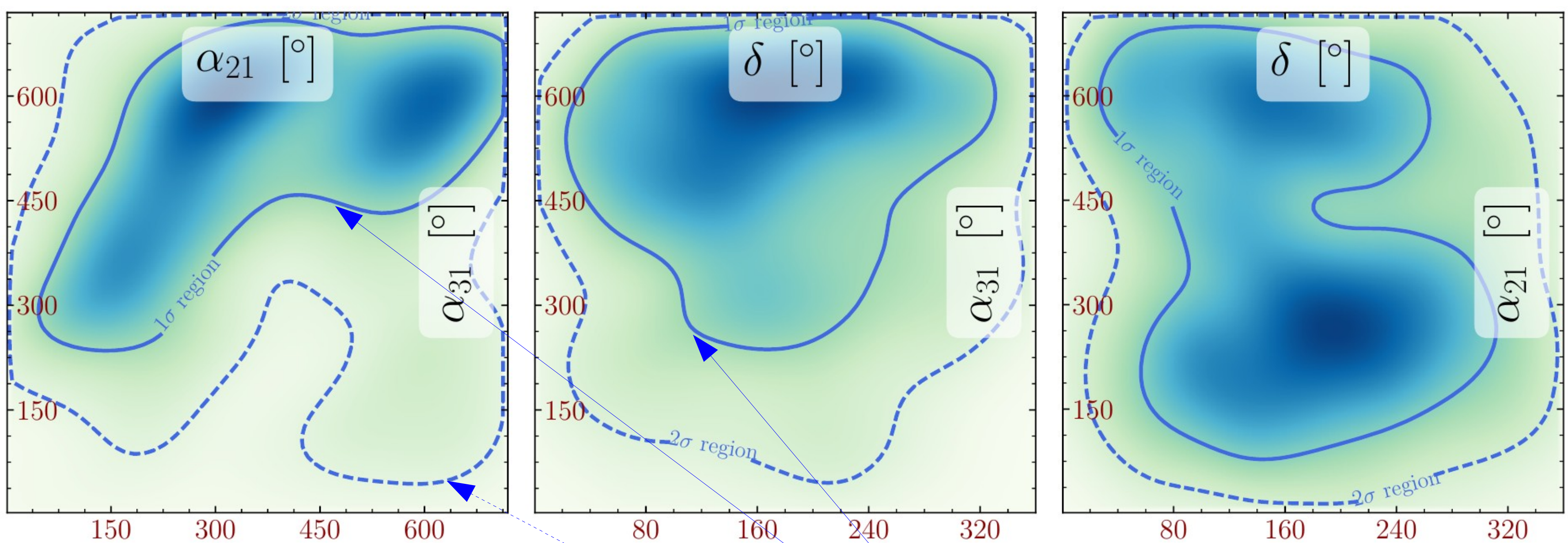
See for instance: Merlo, Rosauro-Alcaraz 1801.03937
Hagedorn, Mohapatra Molinaro Nishi, Petcov 1711.02866

① Flavor Models
Yukawa structure (R matrix) is constrained by flavor symmetries

② Minimal model with 2 N_R
Small number of phases: *1 Dirac + 1 Majorana + 1 Heavy*

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

High Scale (vanilla) Leptogeneis $N_R = 3$



Baryon asymmetry generated in agreement with observed value at:

1σ

2σ

NH

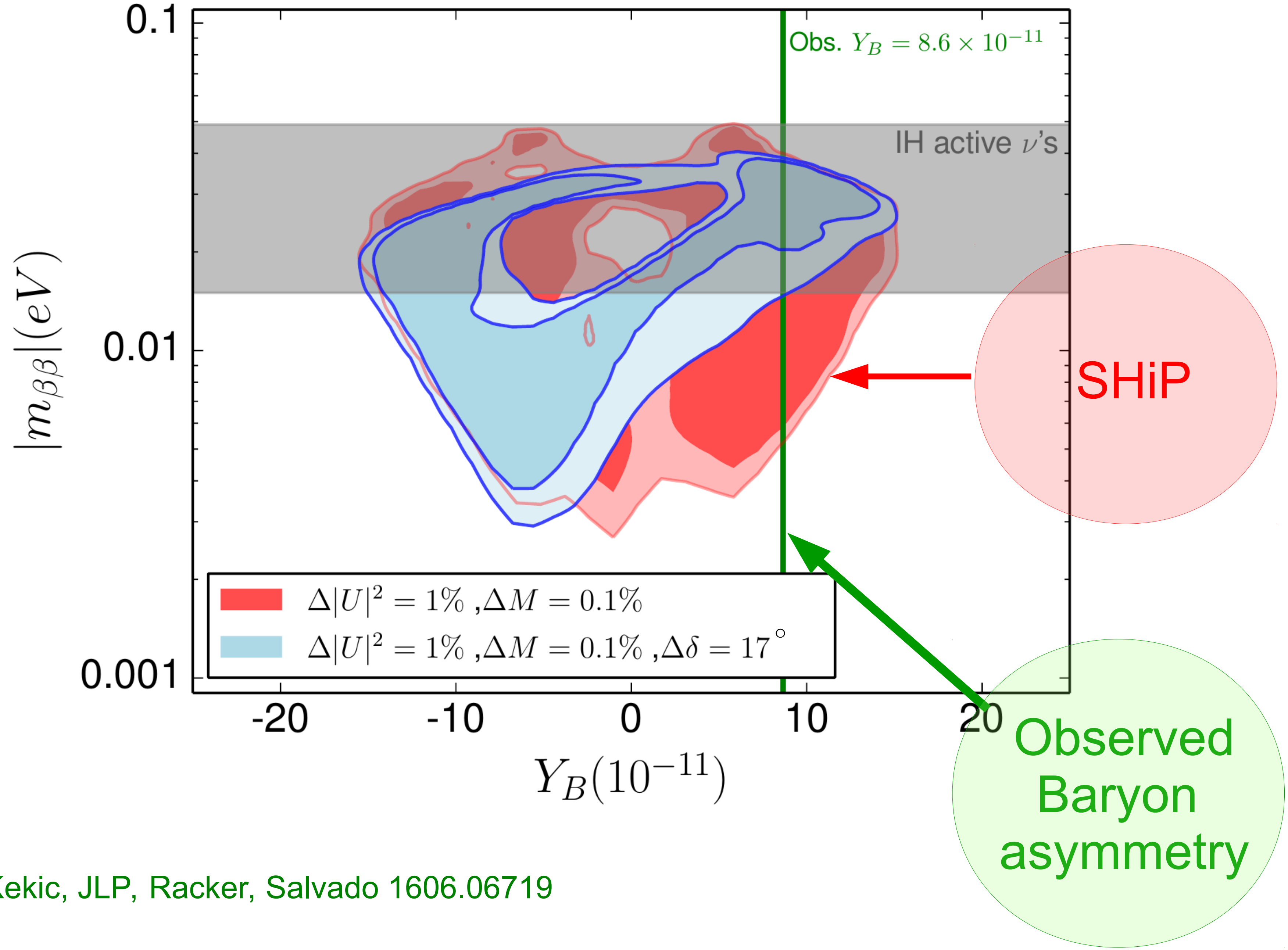
$$M_1 = 10^{13}\, GeV$$

$$M_3 > 3M_2 > 9M_1$$

Moffat, Pascoli, Petcov, Turner 1809.08251

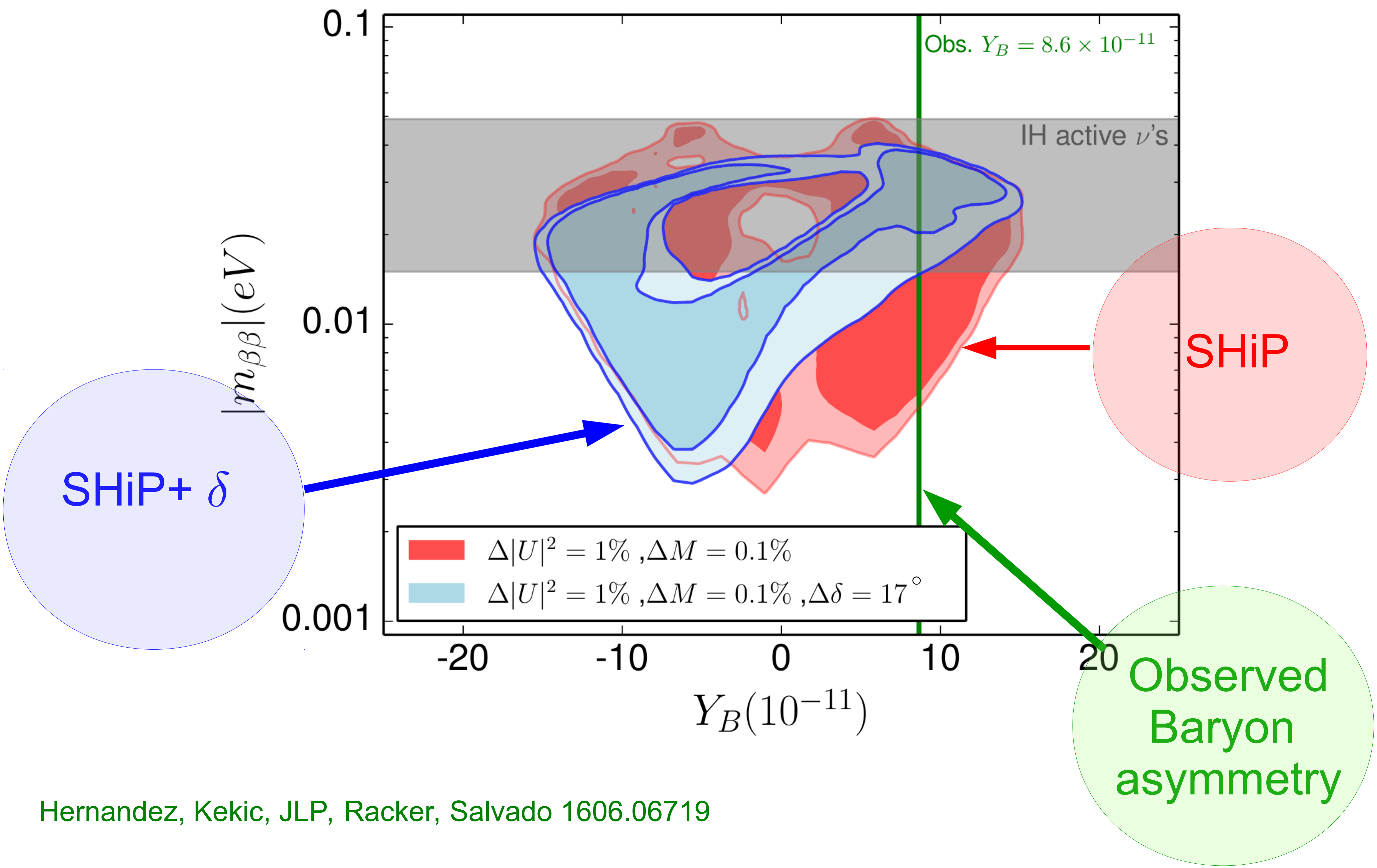
Assuming
No CP-violation from HNL sector

GeV Scale Leptogeneis $N_R = 2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

GeV Scale Leptogeneis $N_R = 2$



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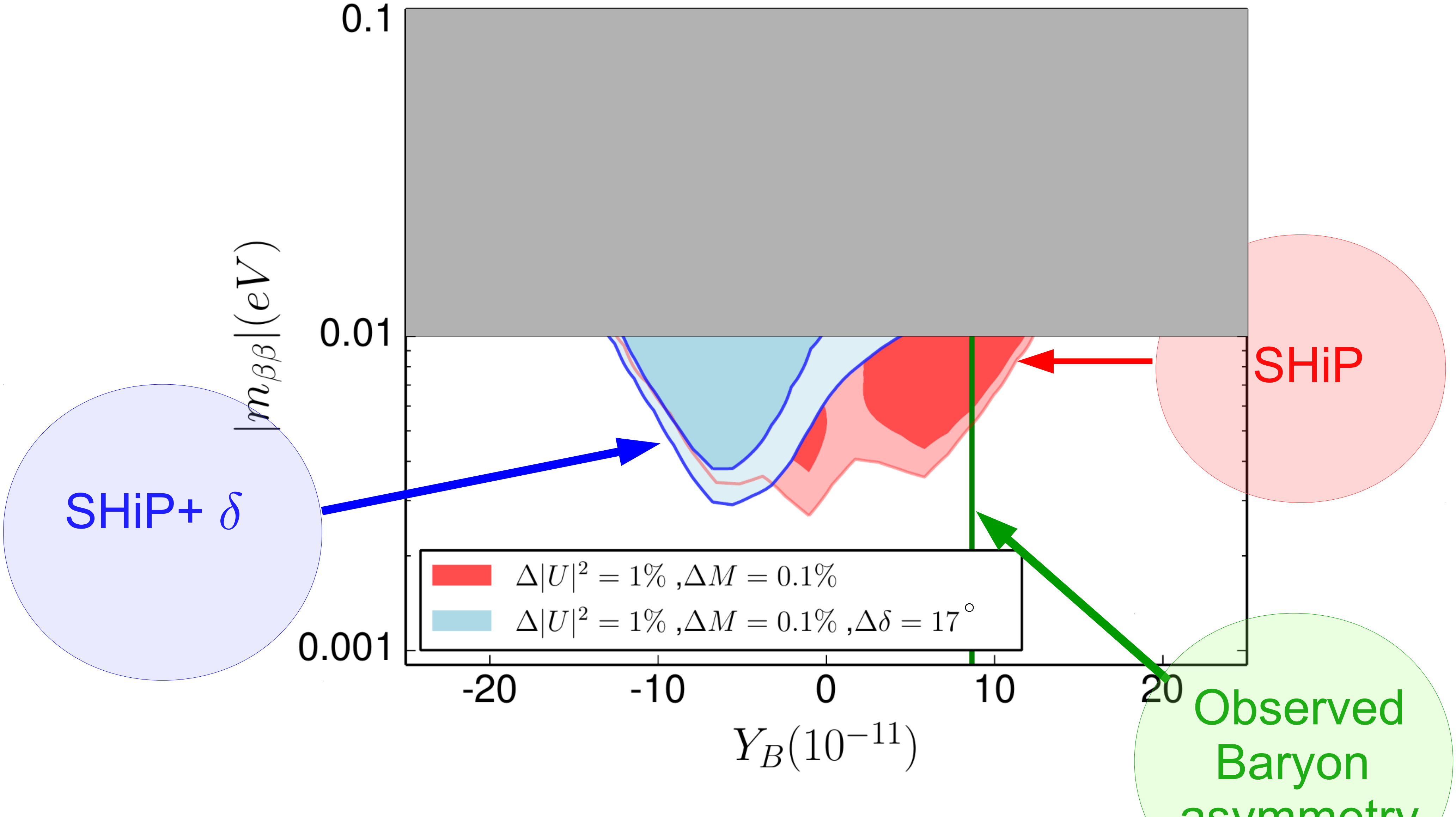
GeV Scale Leptogeneis $N_R = 2$



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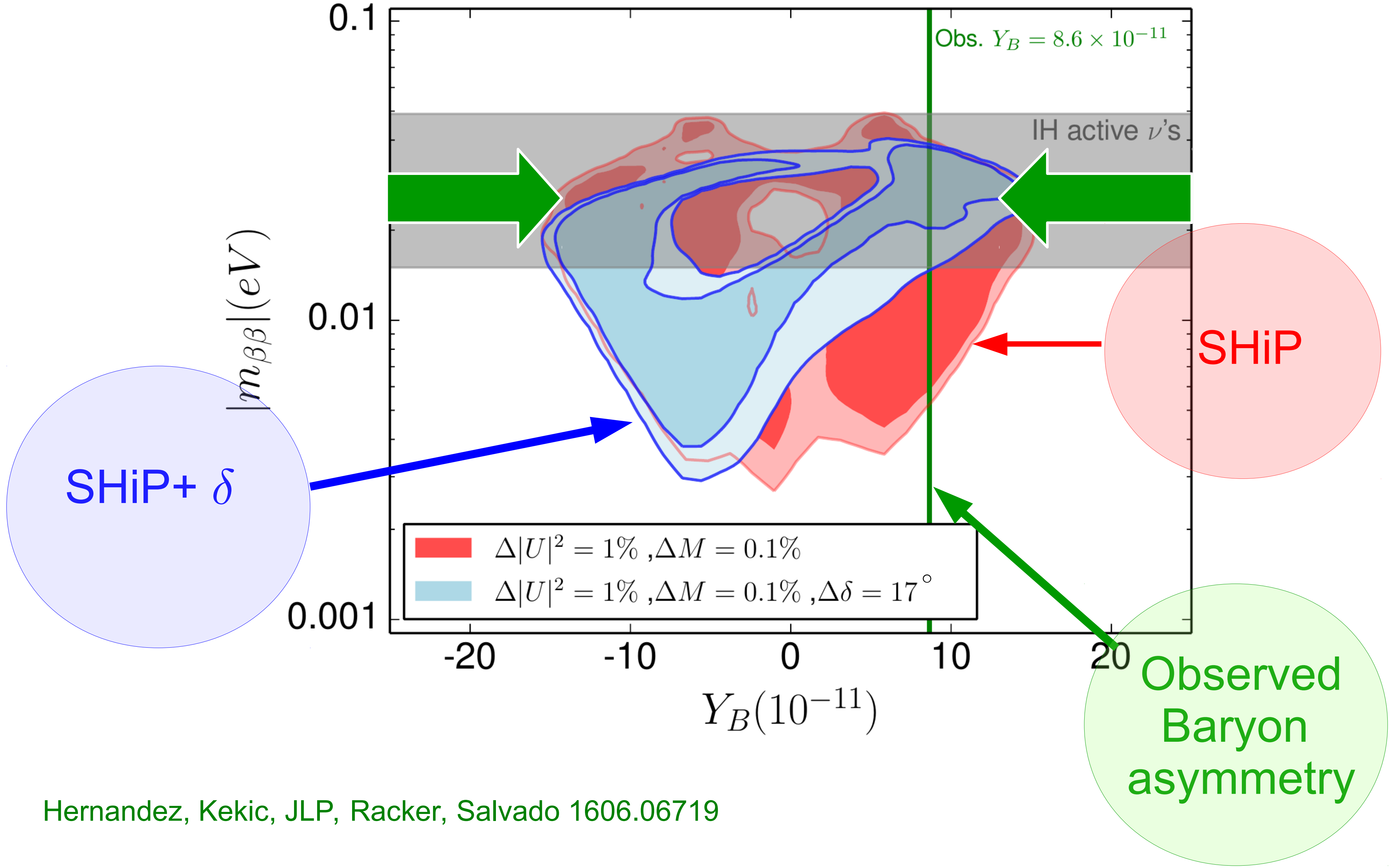


Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Conclusions

HNL relation to active neutrino sector present

if HNL account for light neutrino massess

(as in seesaw models)

- Complementarity among different observables as neutrino oscillations, cosmology, neutrinoless double beta decay and HNLs direct searches.

- Strongest constraints from active neutrino sector in minimal models.

- Constraints still present but can change when introducing new interactions.

  See for instance: Nemevsek, Senjanovic,Tello 1211.2837 [Minimal Left-Right model]
  Ballett, Hostert, Pascoli 1903.07590 [U(1)' extension]

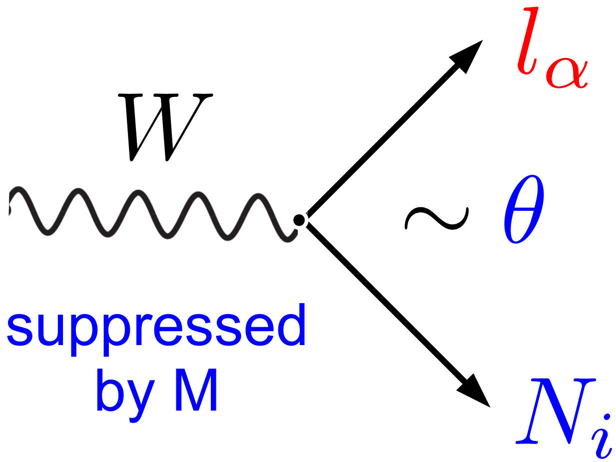
- Low scale Minimal (Type-I) Seesaw Model is strongly constrained by active neutrino sector:

  - *Very constrained flavor structure with strong correlation to PMNS CP phases.*

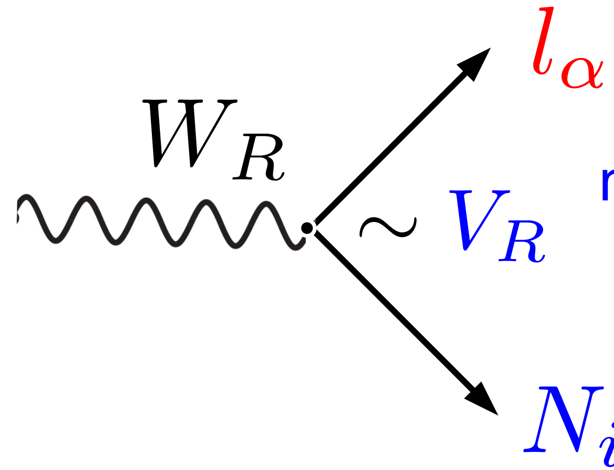
  - *Mechanisms generating neutrino masses and Baryon asymmetry can be potentially tested. Very relevant input from active neutrino sector required.*

Thank you!

Minimal Left-Right Symmetric model



suppressed by M



not suppressed by M but $M_{W_R} \geq 4\,TeV$ (ATLAS)

Nemevsek, Senjanovic, Tello 1211.2837

$$\theta = \left[\frac{v_L}{v_R} - U\, m U^T\, V_R^* M^{-1} V_R^\dagger\right]^{1/2}$$

$\frac{v_L}{v_R}$: vev ratio

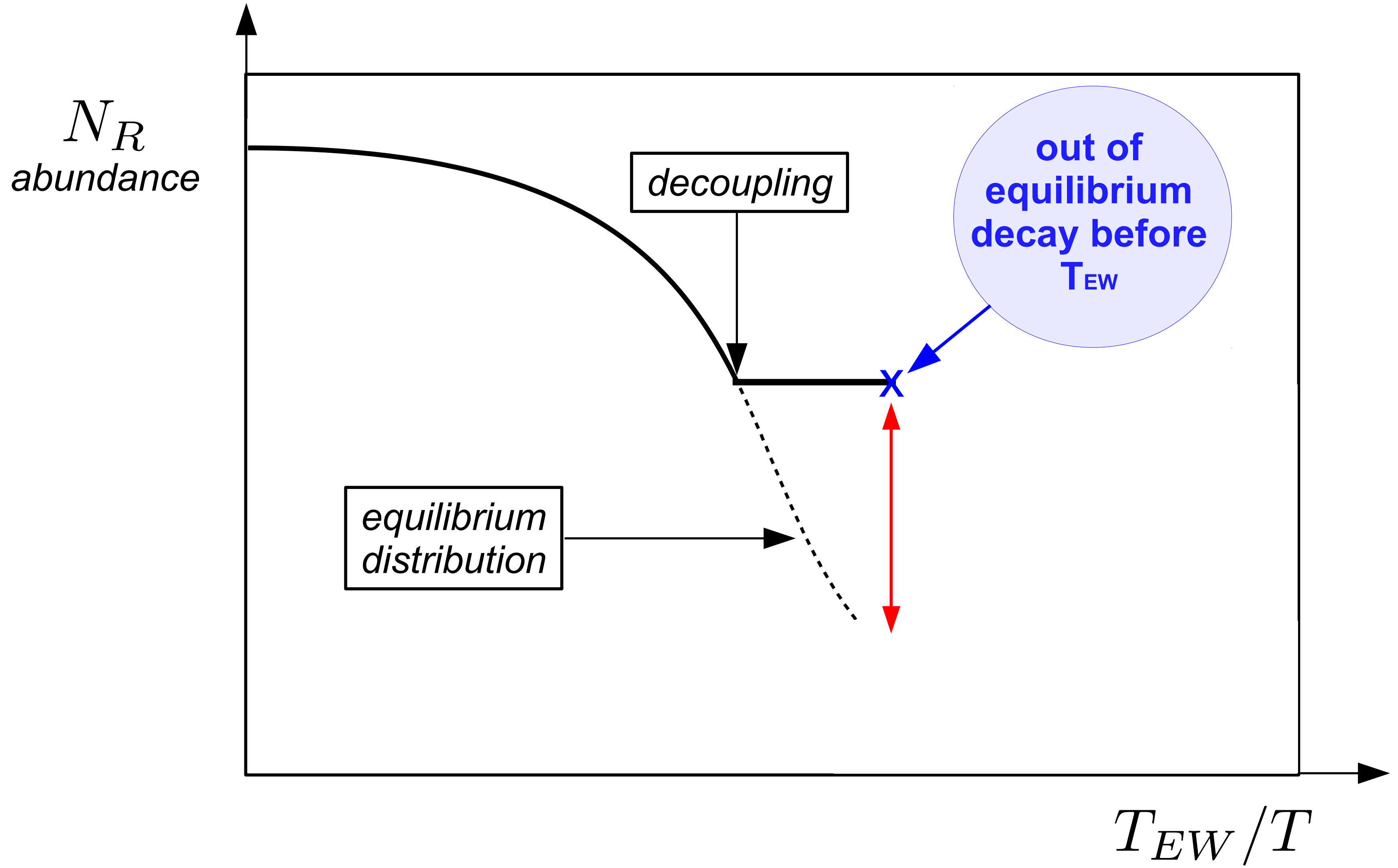
Light Sector

- 3x3 PMNS mixing matrix
- light neutrino masses

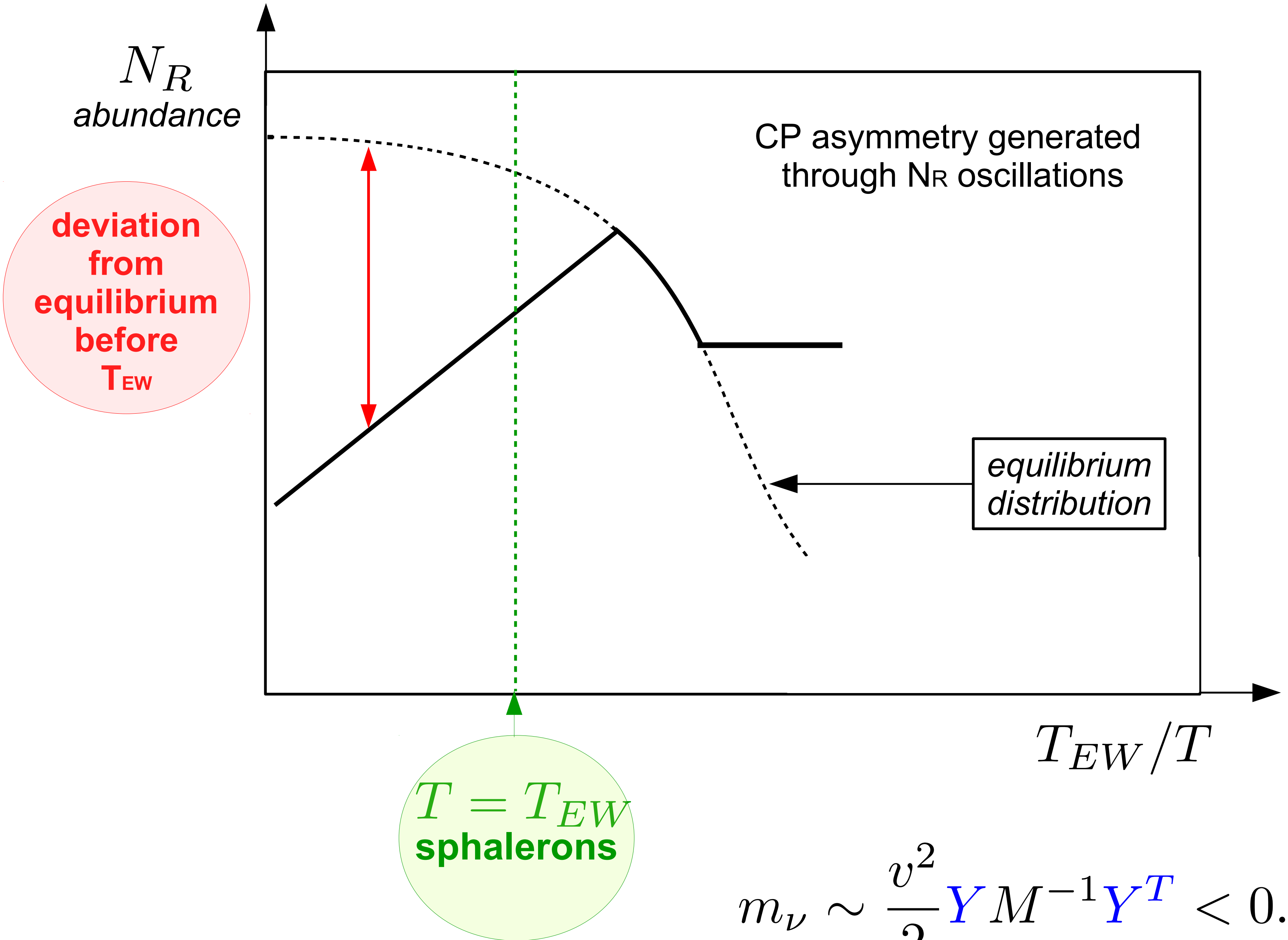
Heavy Sector

- 3×3 unitary matrix
- HNL masses

Standard Leptogenesis



Low Scale Leptogenesis (ARS)



$$m_\nu \sim \frac{v^2}{2} Y M^{-1} Y^T < 0.16\,\mathrm{eV}$$

Are the PMNS CP phases relevant?

- Dependence on CP phases encoded in the Yukawa couplings:

$$Y = U_{PMNS}\sqrt{m}\,R^{\dagger}\sqrt{M}\,\frac{\sqrt{2}}{v}$$

Casas-Ibarra

Light Sector

- Majorana phases
  (experimentally challenging)

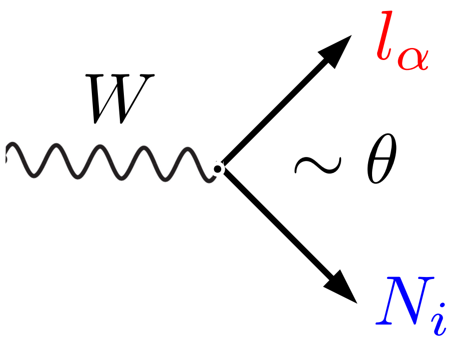
- **Dirac CP phase δ**
  (accessible via neutrino oscillations)

Heavy Sector

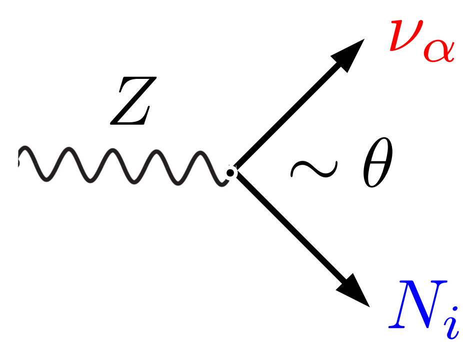
- Complex $3 \times n_R$ orthogonal matrix

	# of extra CP phases
$n_R = 3$	3
$n_R = 2$	1

Direct searches of HNLs



$$\theta = i U_{PMNS}\, m^{1/2}\, \boldsymbol{R}^{\dagger} M^{-1/2}$$



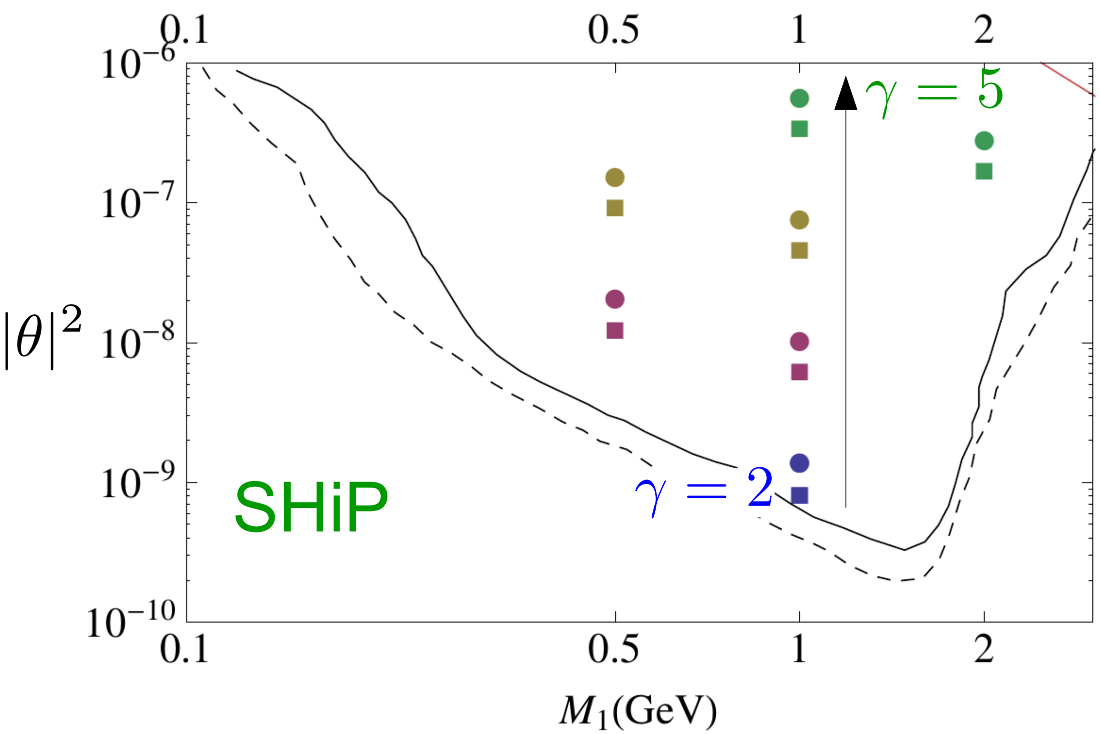
- Direct detection requires:

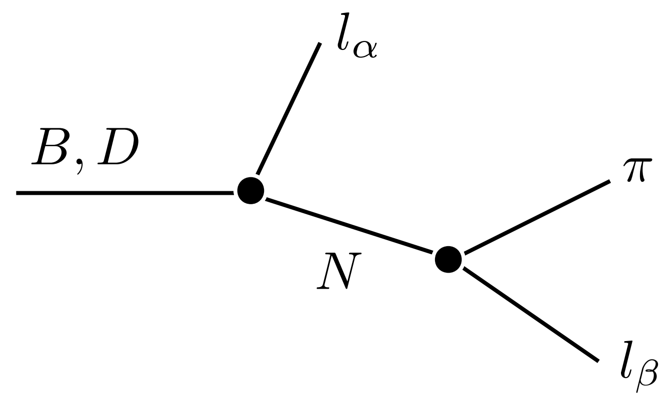
$$\theta \gg \sqrt{m/M} \quad \Longleftrightarrow \quad \boldsymbol{R_{ij}} \gg \boldsymbol{1}$$

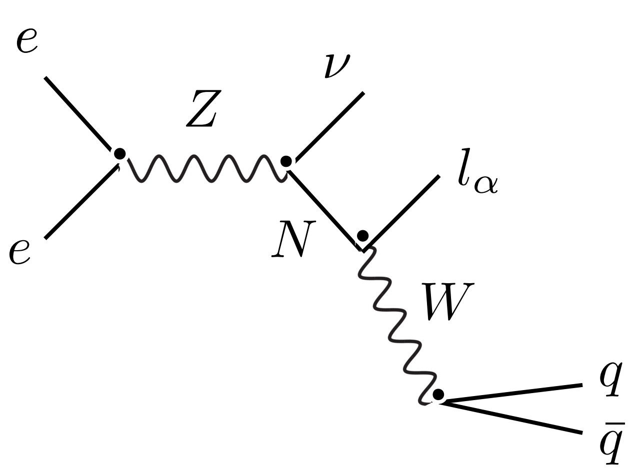
- Phenomenological constraint automatically satisfied in inverse and direct seesaw realizations based on a symmetry protected scenario.

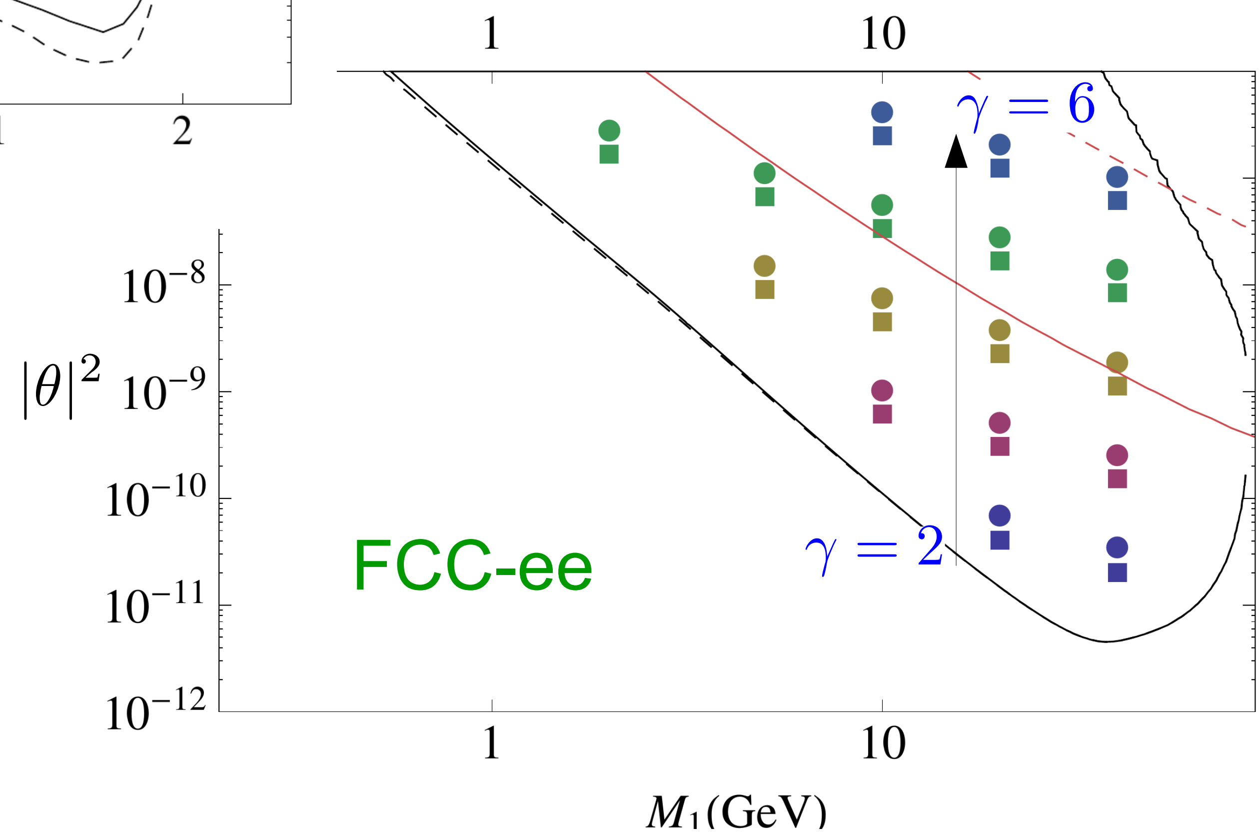
Mohapatra 1986; Mohapatra, Valle 1986; Bernabeu, Santamaria, Vidal, Mendez, Valle 1987; Malinsky, Romao, Valle 2005...

PMNS CP-phases from HNLs searches

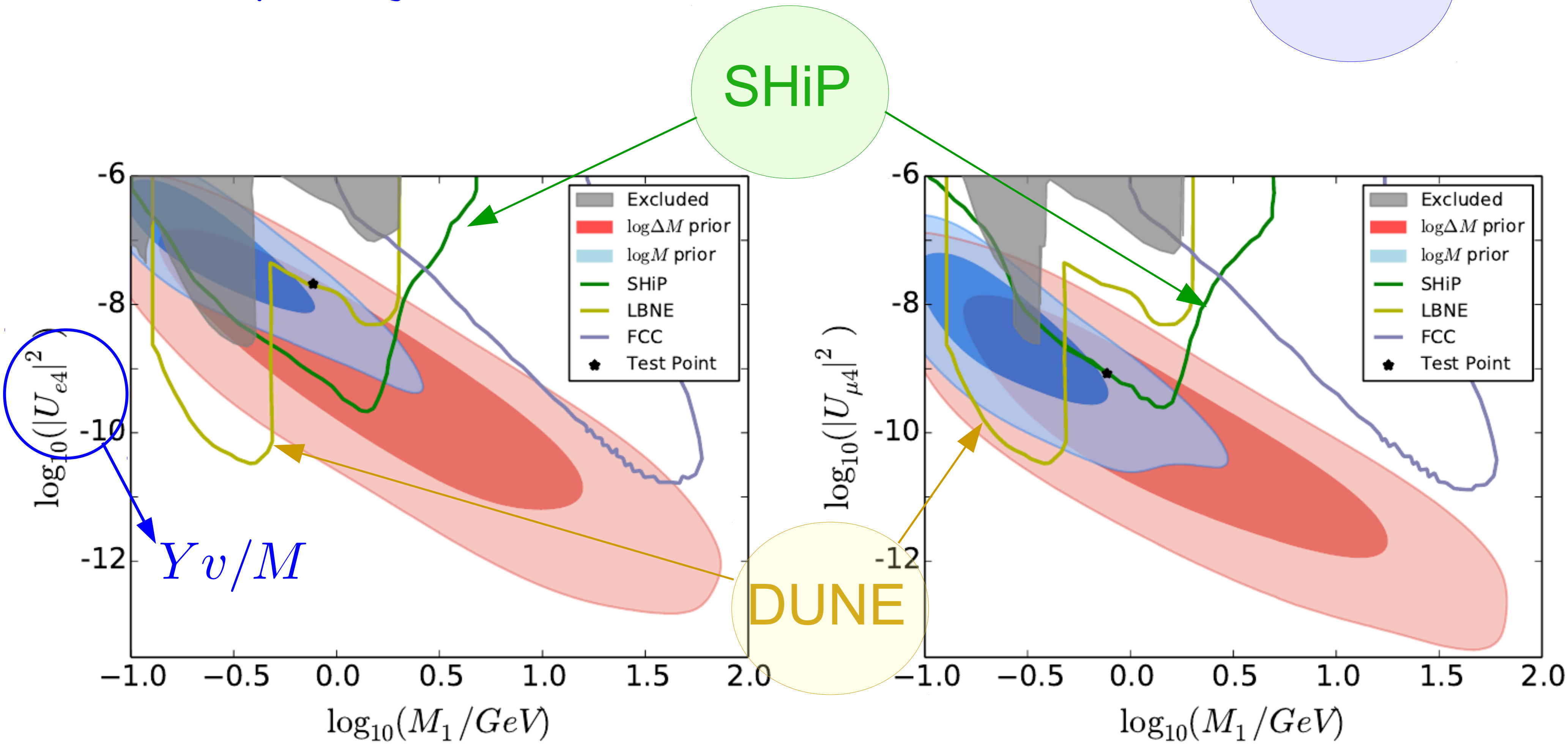








Leptogenesis in Minimal Model $N_R=2$

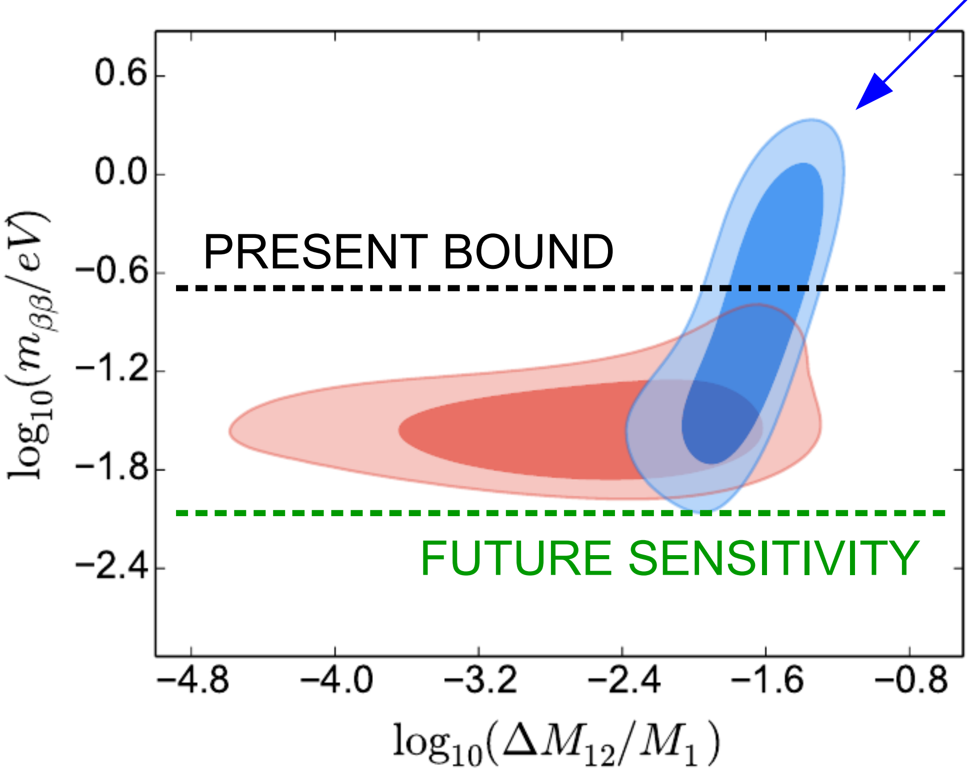


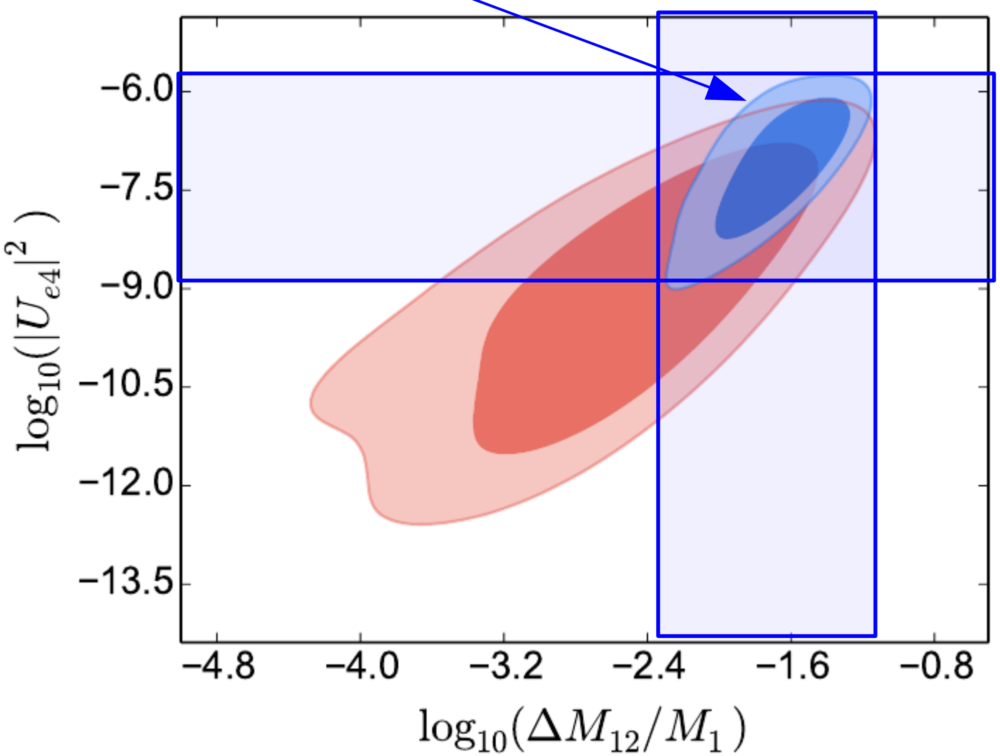
Inverted light neutrino ordering

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Leptogenesis in Minimal Model $N_R=2$

Non very degenerate solutions





Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Approximated LNC

$$M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & \Lambda \\ \epsilon Y_2 v/\sqrt{2} & \Lambda & \mu \end{pmatrix}$$

Mohapatra, Valle 1986; Bernabeu, Santamaria, Vidal, Mendez, Valle 1987; Malinsky, Romao, Valle 2005...

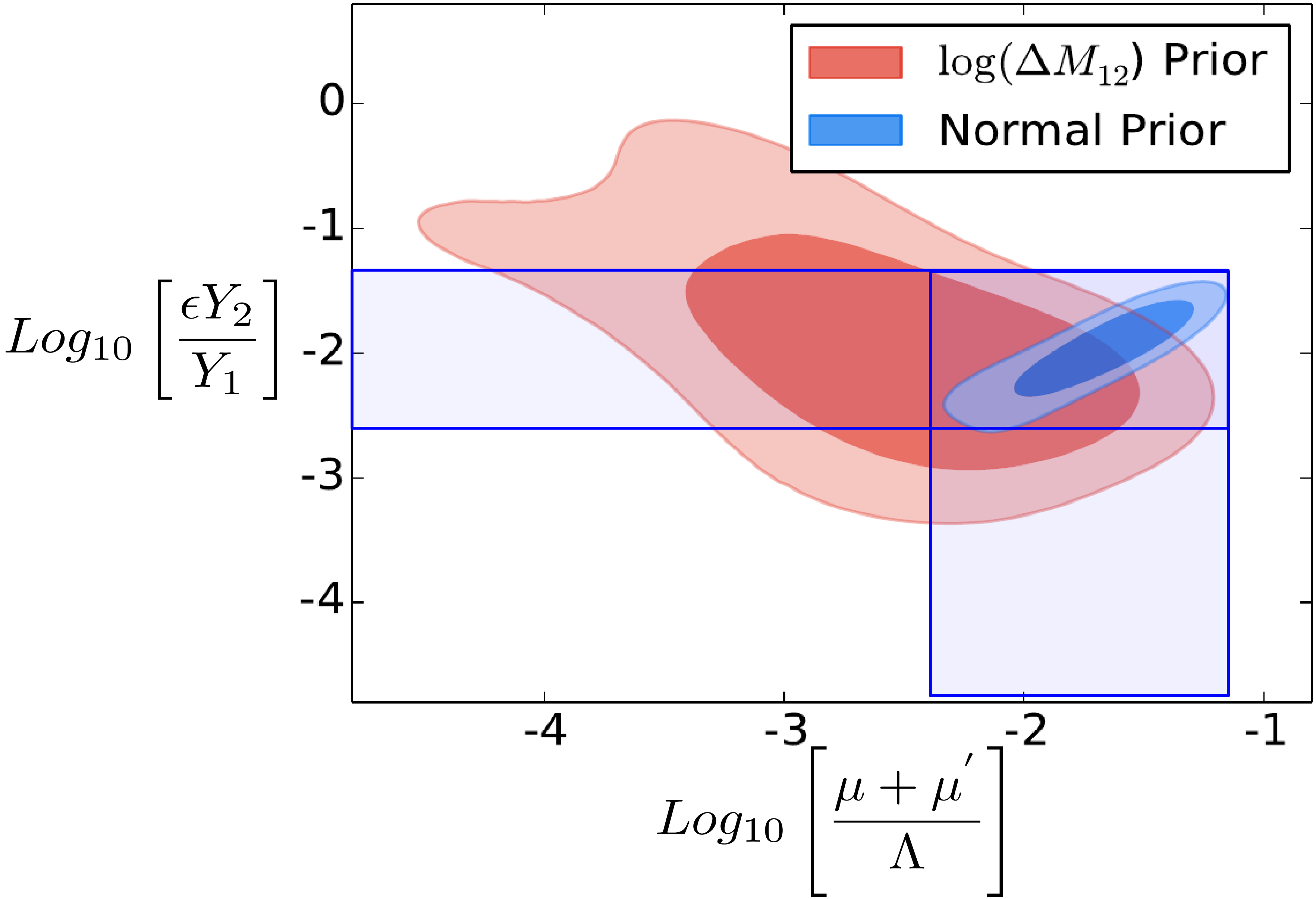
- Light nu masses suppressed with LNV parameters

$$m_\nu = \mu \frac{v^2}{2\Lambda^2} Y_1^T Y_1 + \frac{v^2}{2\Lambda} \epsilon Y_2^T Y_1 + \frac{v^2}{2\Lambda} Y_1^T \epsilon Y_2$$

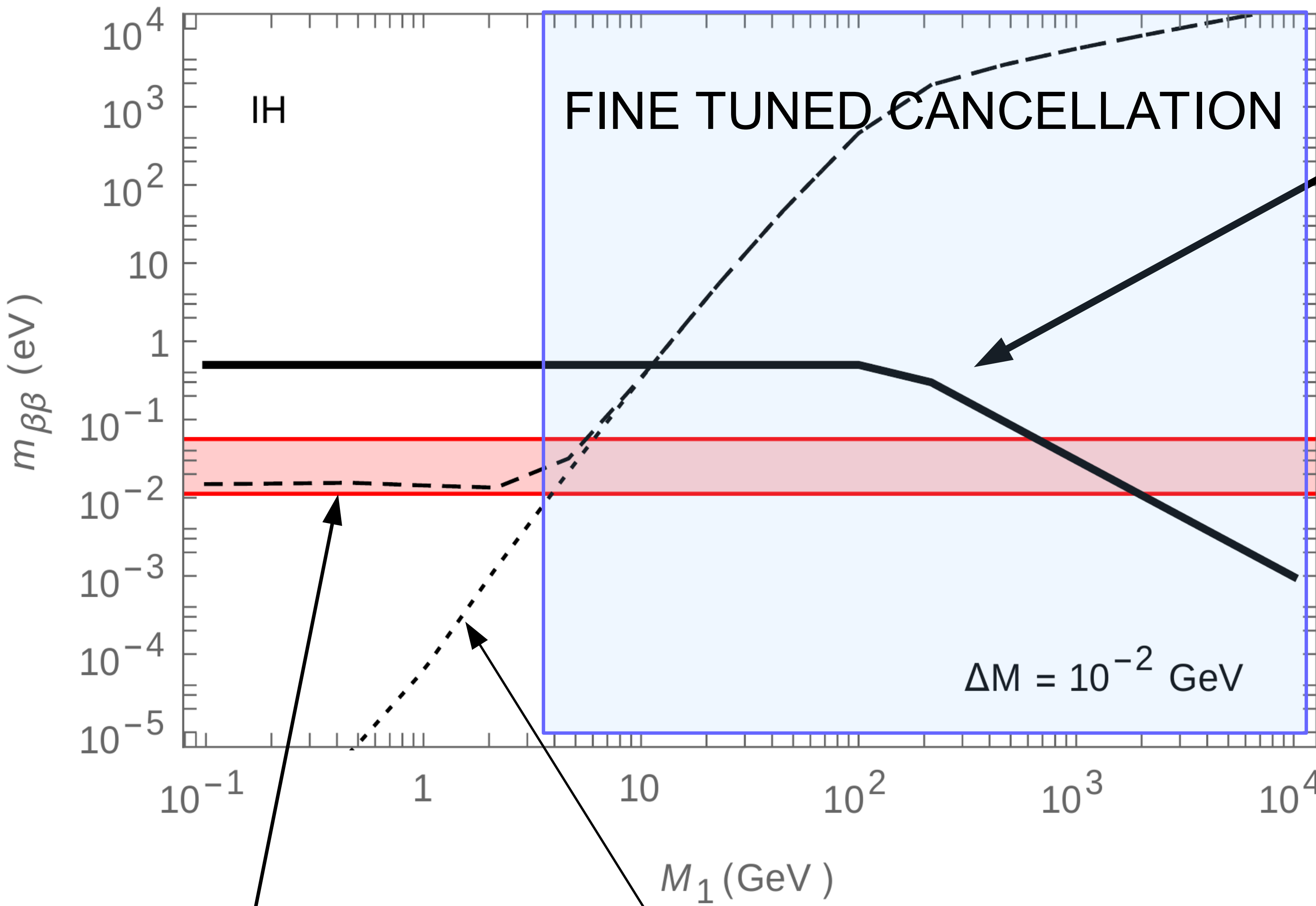
- Quasi-Dirac heavy neutrinos:

$$M_2 \approx M_1 \approx \Lambda \qquad \Delta M \approx \mu' + \mu$$

Approximated LNC



Neutrinoless Double Beta Decay



Maximum heavy neutrino Contribution (sizable!!)

Total light neutrino contribution (tree+loop)

TREE LEVEL light neutrino contribution

1-LOOP correction to light neutrino contribution

JLP, Molinaro, S. Petcov 2015

Model Independent Approach: EFT

• The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

$$\mathcal{O}_W = \sum_{\alpha,\beta} \frac{(\alpha_W)_{\alpha\beta}}{\Lambda} \overline{L}_\alpha \tilde{\Phi} \Phi^\dagger L^c_\beta + h.c.,$$

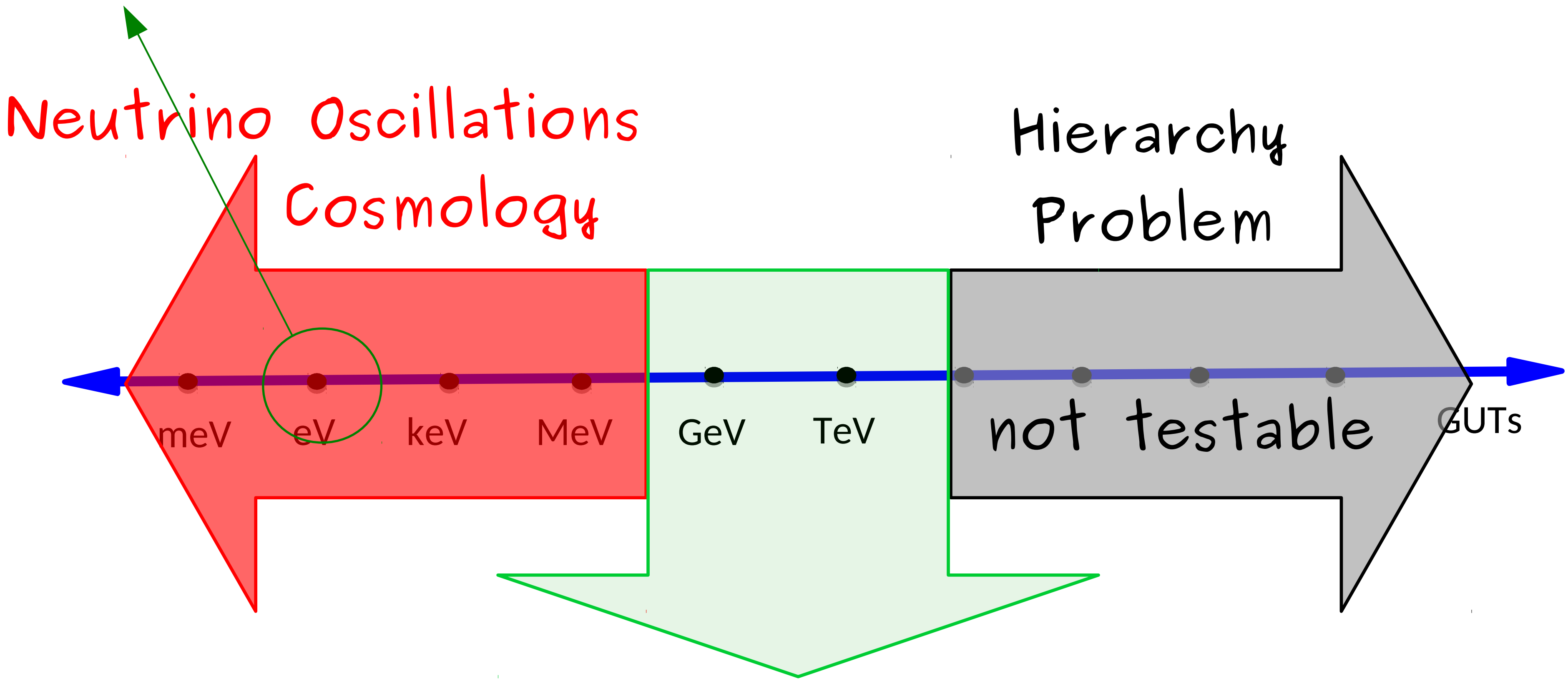
$$\mathcal{O}_{N\Phi} = \sum_{i,j} \frac{(\alpha_{N\Phi})_{ij}}{\Lambda} \overline{N}_i N^c_j \Phi^\dagger \Phi + h.c.,$$

$$\mathcal{O}_{NB} = \sum_{i\neq j} \frac{(\alpha_{NB})_{ij}}{\Lambda} \overline{N}_i \sigma_{\mu\nu} N^c_j B_{\mu\nu} + h.c.$$

Graesser 2007; del Aguila, Bar-Shalom, Soni, Wudka 2009;
Aparici, Kim, Santamaria, Wudka 2009.

[See talks by Seon-Hee Seo, Schwetz-Mangold, Thierry Lasserre & David Henaff]

The HNLs Scale



- $0\nu\beta\beta$ decay
LFV, Beam dump experiments, Colliders…

- Leptogenesis via Oscillations
M=0.1–100GeV
Akhmedov, Rubakov, Smirnov (ARS)
Asaka, Shaposnikov (AS)

- Resonant Leptogenesis
M>100GeV
Pilaftsis