Testable Leptogenesis Scenarios and Phenomenological Implications

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Jornadas Científicas del IFIC, L4: Baryogenesis, dark matter and cosmic messengers

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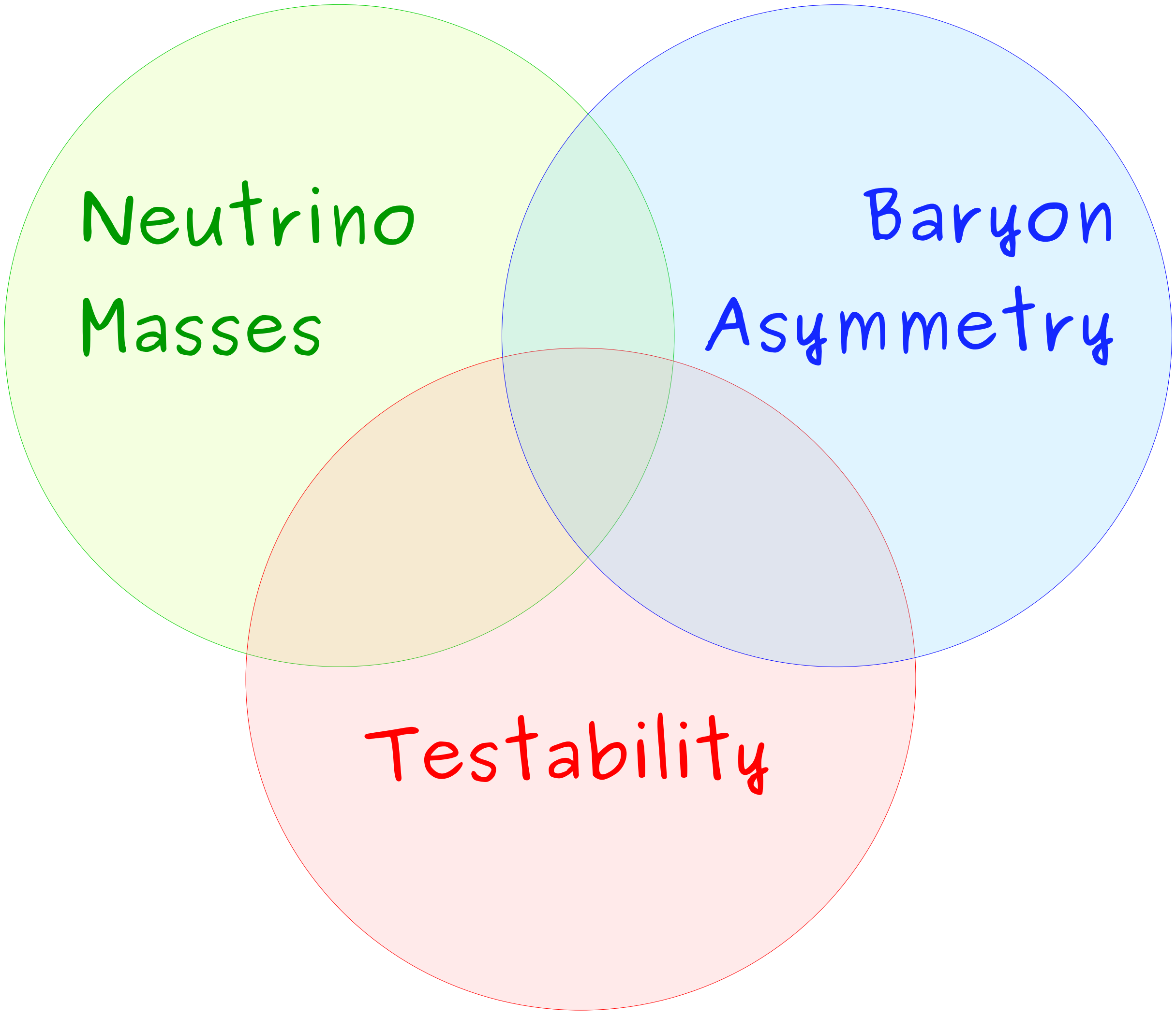


*Based on work in collaboration with **P. Hernandez, N. Rius and S. Sandner***

Other IFIC members study this following different approaches as G. Barenboim,C. Hagedorn, J. Herrero, M. Hirsch, J. W. F. Valle, A. Vicente, O. Vives, J. Zurita, to name a few...

(1) Baryon asymmetry

Baryon asymmetry

- **After the Big-Bang same amount of matter and antimatter generated, but observed universe mainly made out of matter only!**

- The observed baryon asymmetry is quoted in terms of the abundance (number-density asymmetry of baryons normalized to the entropy density):

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

How can the matter asymmetry of our Universe be generated?

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

1. Baryon number violation

If baryon number is conserved, no baryon asymmetry can be generated

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

① **Baryon number violation**

If baryon number is conserved, no baryon asymmetry can be generated

OK in the SM ⇔ Sphalerons @ $T \approx 140$ Gev

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

2 C and CP violation

If C or CP are conserved:

$$\Gamma\left(A \rightarrow B + C\right) = \Gamma\left(\overline{A} \rightarrow \overline{B} + \overline{C}\right)$$

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

② C and CP violation ☐

Exist in the SM

$$Y_B \propto \Delta_{\rm CP}^{\rm quarks} = Im\left[det\left(\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]\right)\right]$$

$$\propto J \prod_{i<j} \propto (m^2_{d_i} - (m^2_{d_j}) \prod_{i<j} (m^2_{u_i} - (m^2_{u_j})$$

There is CP violation in the quark sector

$$J = Im\left[V_ij^* V_{ii} V^*_{ji} V_{jj}\right] \propto \sin \delta_{\rm CKM}$$

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

② C and CP violation

Jarlskog invariant too small

$$Y_B \propto \Delta_{\rm CP}^{\rm quarks} = Im\left[det\left(\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]\right)\right]$$

$$\propto J \prod_{i<j} \propto (m_{d_i}^2 - (m_{d_j}^2) \prod_{i<j} (m_{u_i}^2 - (m_{u_j}^2)$$

Not enough CP violation in the SM

$$J = Im\left[V_ij^* V_{ii} V_{ji}^* V_{jj}\right] \propto \sin \delta_{\rm CKM}$$

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

3 Departure from thermal equilibrium

Production/destruction rates of Baryons are equal in thermal equilibrium: $\Gamma\left(A \to B + C\right) = \Gamma\left(B + C \to A\right)$

Exist in the SM

Due to Hubble expansion of the universe

Baryon asymmetry: Sakharov conditions

- In order to generate the baryon asymmetry the following conditions should be satisfied:

3 Departure from thermal equilibrium

Production/destruction rates of Baryons are equal in thermal equilibrium: $\Gamma\left(A \to B + C\right) = \Gamma\left(B + C \to A\right)$

Exist in the SM ⟺ Deviation too small

Due to Hubble expansion of the universe

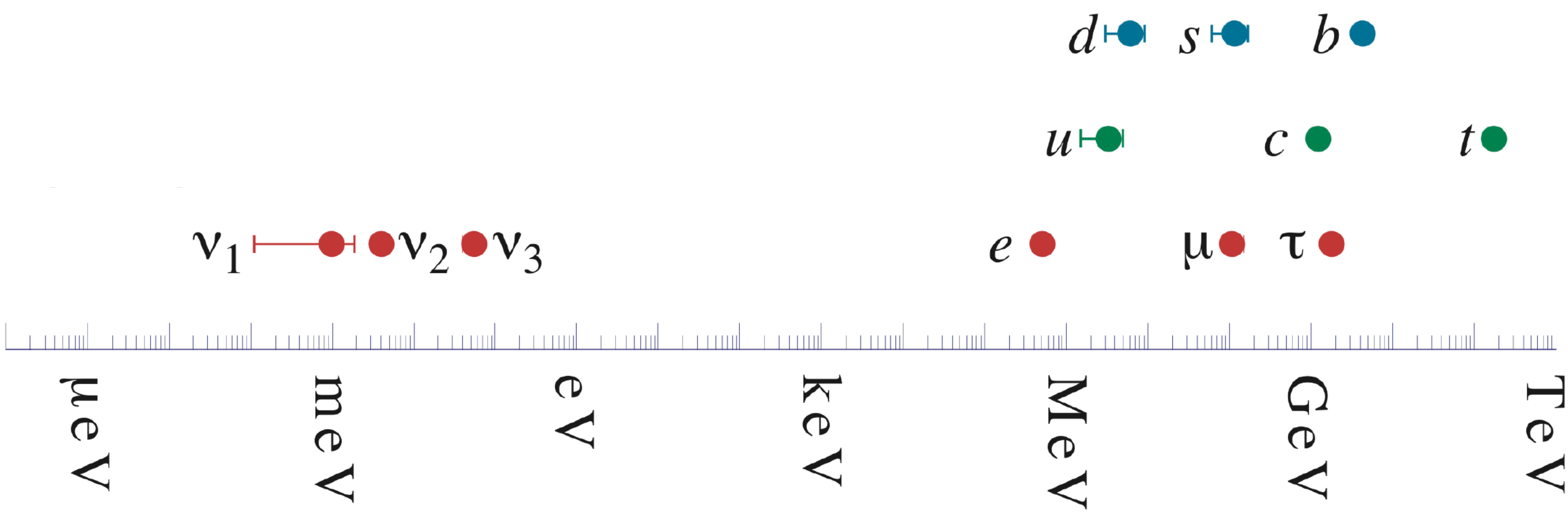
Not enough deviation from thermal equilibrium in the SM!!

Kajantie, Laine, Rummukainen, Shaposhnikov, 1996

②

Origin of neutrino masses

Why are neutrinos so light?



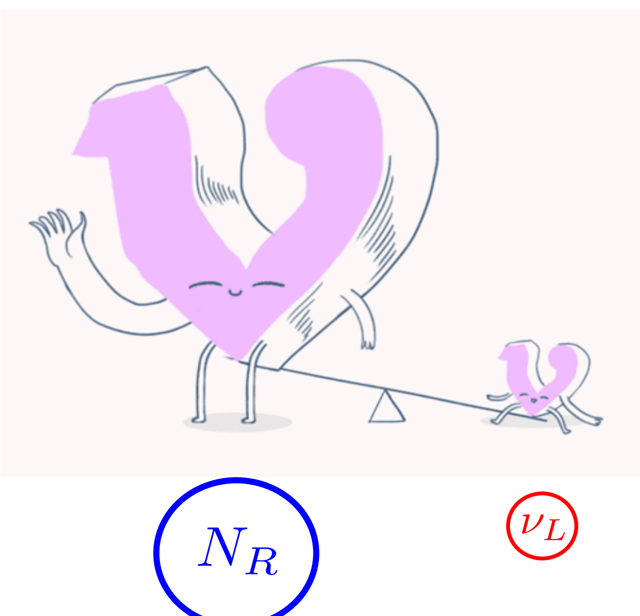
Type-I Seesaw Model

Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_R) to the SM field content:

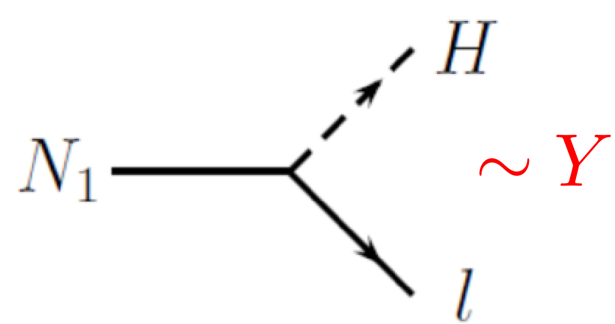
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \boxed{\frac{1}{2}\overline{N_i^c} M_{ij} N_j} - \boxed{Y_{i\alpha}\overline{N_i}\widetilde{H}^\dagger L_\alpha} + h.c.$$

Majorana mass term

Interaction with SM particles via Yukawa coupling



Lepton Number Violation



Minimal Model with approximated LNC

$$
\begin{array}{cccc}
\overline{\nu^c} & \overline{N}_1 & \overline{N}_2 & \\
1 & -1 & 1 & L
\end{array}
$$

$$
M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & M \\ \epsilon Y_2 v/\sqrt{2} & M & \mu \end{pmatrix} \begin{array}{cc} 1 & \nu \\ -1 & N_1^c \\ 1 & N_2^c \end{array}
$$

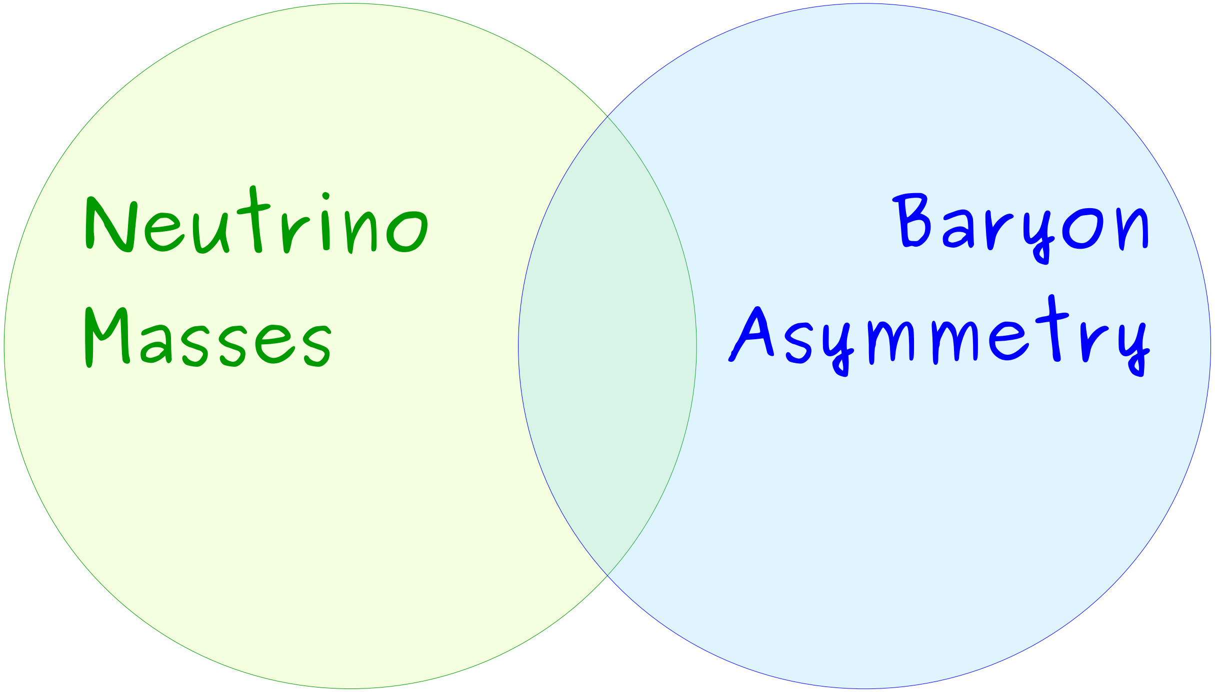
- Light nu masses suppressed with LNV parameters

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

- Quasi-Dirac heavy neutrinos with large mixing:

$$
M_2 \approx M_1 \approx M \qquad \Delta M \approx \mu' + \mu \qquad U_{\nu N} \sim Y_1 v/M
$$

Leptogenesis



See also alternative mechanism: ν Baryogenesis (Hernandez, Rius 97; Fernandez-Martinez, JLP, Ota, Rosauro-Alcaraz 2007.11008; Fernandez-Martinez, JLP, No, Ota, Rosauro-Alcaraz 2210.16279)

Leptogenesis: Sakharov conditions

1 Baryon number violation

If baryon number is conserved, no baryon asymmetry can be generated

OK in the SM $\Longleftrightarrow$ Sphalerons @$T \approx 140$ GeV

Leptogenesis: Sakharov conditions

2 C and CP violation

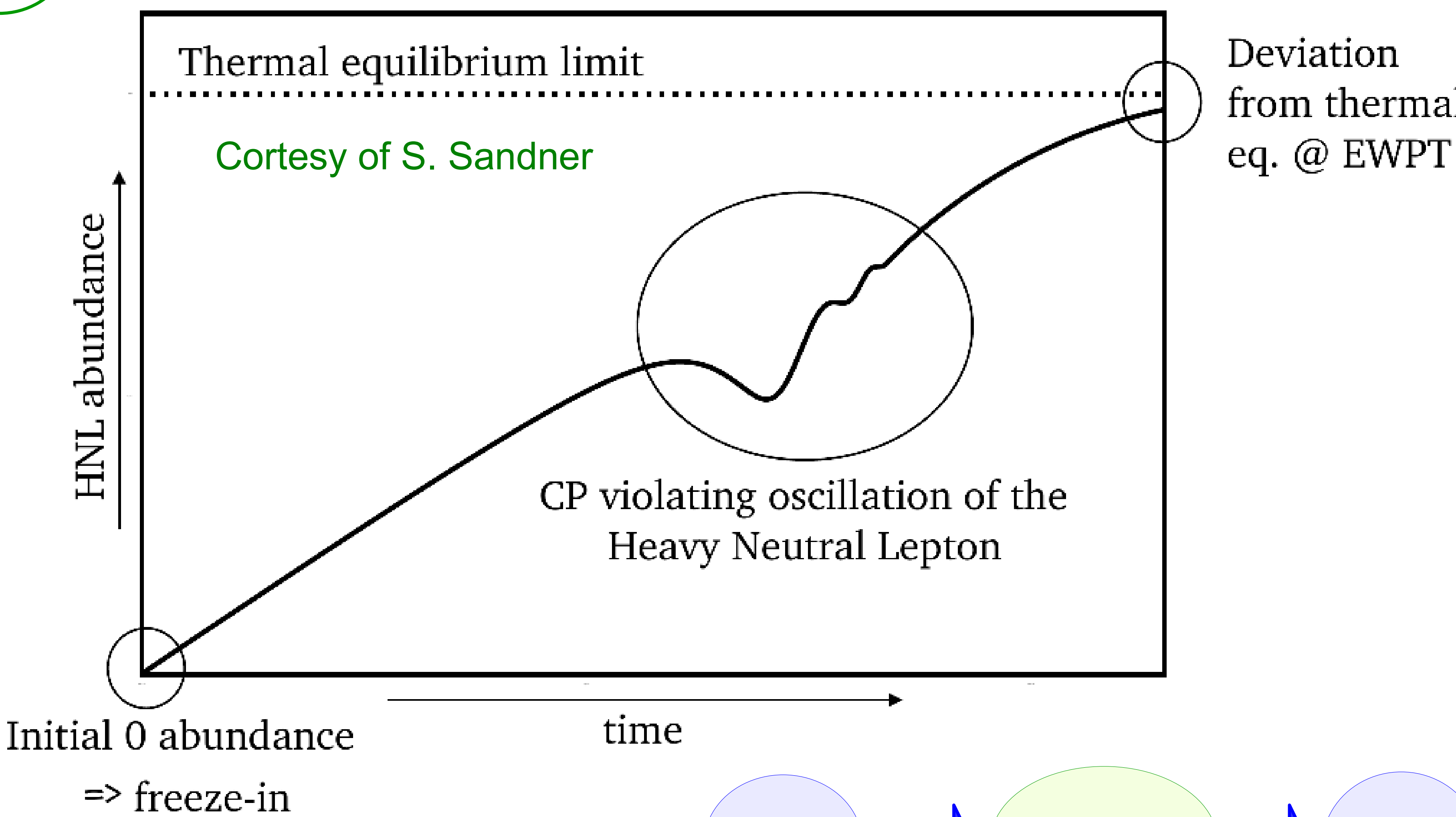
There is CP violation in the SM quark sector

Not enough CP violation in SM !!

if it also exists in lepton sector ⟺ New CP invariants

Low Scale Leptogenesis (ARS)

3 Departure from thermal equilibrium



$L \neq 0$ → $B-L=0$ → $B \neq 0$

Dependence on leptonic CP phases

- It is encoded in the neutrino Yukawa couplings:

- Generation of light neutrino masses imposes constraints on Yukawa couplings from neutrino oscillation data

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

Dependence on leptonic CP phases

- It is encoded in the neutrino Yukawa couplings:

$$Y = f\left(U_{\rm PMNS}, m\,\theta, U^2, M\right)$$

Casas-Ibarra 01
Gavela, Hambye,
Hernandez, Hernadez 09

Light Sector

- Majorana phase ϕ
(experimentally challenging)

- Dirac CP phase δ
(accessible via neutrino oscillations)

Heavy Sector

- **In minimal model with 2 right handed neutrinos**:

1 extra CP phase θ

Leptogenesis: Kinetic Equations

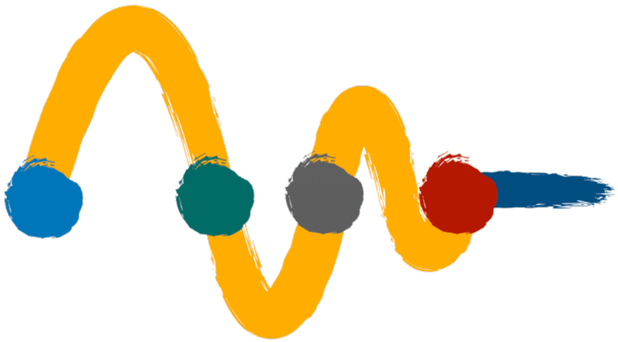
$$
\begin{aligned}
xH_u\frac{\mathrm{d}r_N}{\mathrm{d}x} &= -i[\langle H\rangle, r_N] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^\dagger Y, r_N - 1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^TY^*M, r_N - 1\} \\
&+ \langle\gamma_N^{(1)}\rangle Y^\dagger\mu Y - x^2\langle s_N^{(1)}\rangle MY^T\mu Y^*M \\
&- \frac{\langle\gamma_N^{(2)}\rangle}{2}\{Y^\dagger\mu Y, r_N\} + x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^T\mu Y^*M, r_N\}\,, \\
xH_u\frac{\mathrm{d}r_{\bar N}}{\mathrm{d}x} &= -i[\langle H^*\rangle, r_{\bar N}] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^TY^*, r_{\bar N} - 1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^\dagger YM \\
&- \langle\gamma_N^{(1)}\rangle Y^T\mu Y^* + x^2\langle s_N^{(1)}\rangle MY^\dagger\mu YM \\
&+ \frac{\langle\gamma_N^{(2)}\rangle}{2}\{Y^T\mu Y^*, r_{\bar N}\} - x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^\dagger\mu YM, r_{\bar N}\}\,, \\
xH_u\frac{\mathrm{d}\mu_{B/3-L_\alpha}}{\mathrm{d}x} &= \frac{\int_k \rho_F}{\int_k \rho_F'}\left[\frac{\langle\gamma_N^{(0)}\rangle}{2}(Yr_NY^\dagger - Y^*r_{\bar N}Y^T) - x^2\frac{\langle s_N^{(0)}\rangle}{2}(Y^*Mr_NMY^{\dagger}\right. \\
&- \mu_\alpha\left(\langle\gamma_N^{(1)}\rangle YY^\dagger + x^2\langle s_N^{(1)}\rangle YM^2Y^\dagger\right) + \frac{\langle\gamma_N^{(2)}\rangle}{2}\mu_\alpha(Yr_NY^\dagger + Y \\
&\left.+\, x^2\frac{\langle s_N^{(2)}\rangle}{2}\mu_\alpha\left(YMr_{\bar N}MY^\dagger + Y^*Mr_NMY^T\right)\right]_{\alpha\alpha}\,,
\end{aligned}
$$

- *Stiff non-linear system with several relevant time scales: very hard to numerically explore parameter space.*

Leptogenesis: Kinetic Equations

Hernandez, JLP, Rius, **Sandner**; arXiv:2207.01651

- AMIQS: publicly available software developed by **Stefan Sandner** introduced relevant optimizations that allows a faster scan.



https://github.com/stefanmarinus/amiqs
10.5281/zenodo.6866454

- Dependence on the parameters of the model and correlation between the baryon asymmetry and other observables not easy to understand just from a numerical scan.

- Our ultimate goal is to study this connection with future experimental measurements in order to be able to test leptogenesis.

Analytical understanding required

Towards analytical understanding

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

- Identify the different non-thermal regimes and characteristic time-scales
- Set up a perturbative approximation of the equations $(\epsilon \ll 1, \, \mu/M \ll 1)$
- Identify the CP invariants that control the flavour parameter dependencie,

$$I_0 = \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y \, M^\dagger M Y^\dagger Y_l^\dagger Y\right]\right)$$

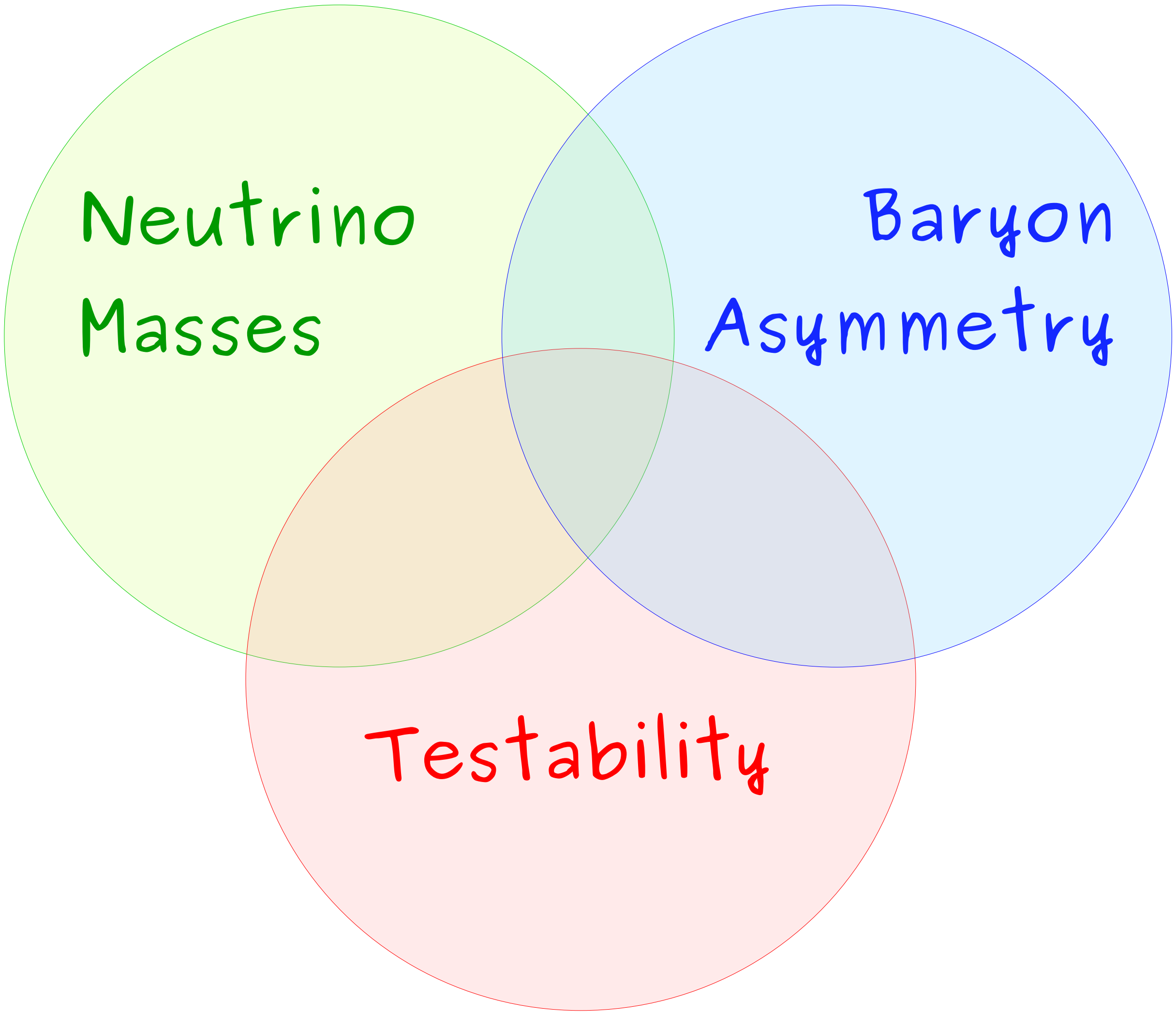
$$\equiv \sum_\alpha y_{l_\alpha}^2 \, \Delta_\alpha\left(\delta, \phi, \Delta m^2_{\rm atm}, \Delta m^2_{\rm sol}, U^2, M, \theta\right)$$

$$I_1 = \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y \, M^\dagger M M^* (Y^\dagger Y)^* M\right]\right)$$

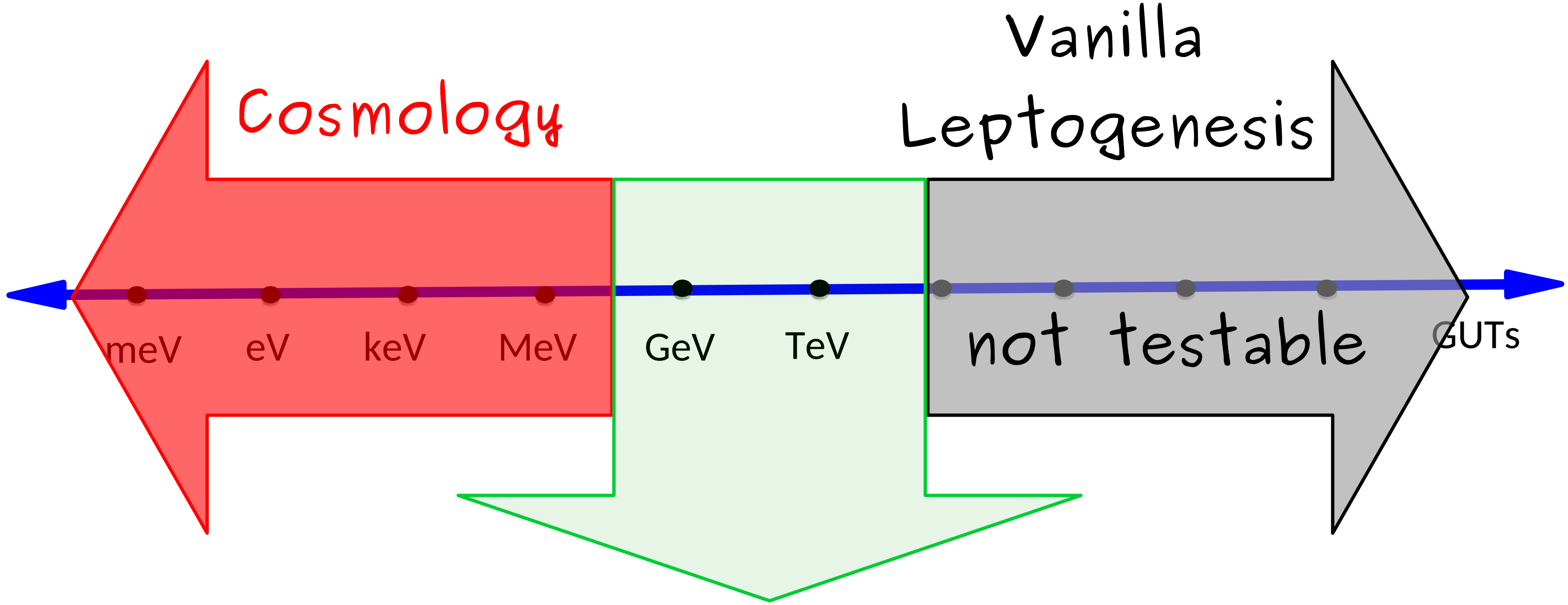
$$\equiv \sum_\alpha \Delta_\alpha^M\left(\delta, \phi, \Delta m^2_{\rm atm}, \Delta m^2_{\rm sol}, U^2, M, \theta\right)$$

- Write the CP invariants in terms of observable parameters: find bounds and correlations implied by the matter-antimatter asymmetry

③ Testability



The New Physics Scale



- $0\nu\beta\beta$ decay, LFV & EW precision data, beam-dump experiments, colliders...

- Leptogenesis via Oscillations
  M=0.1−100GeV

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

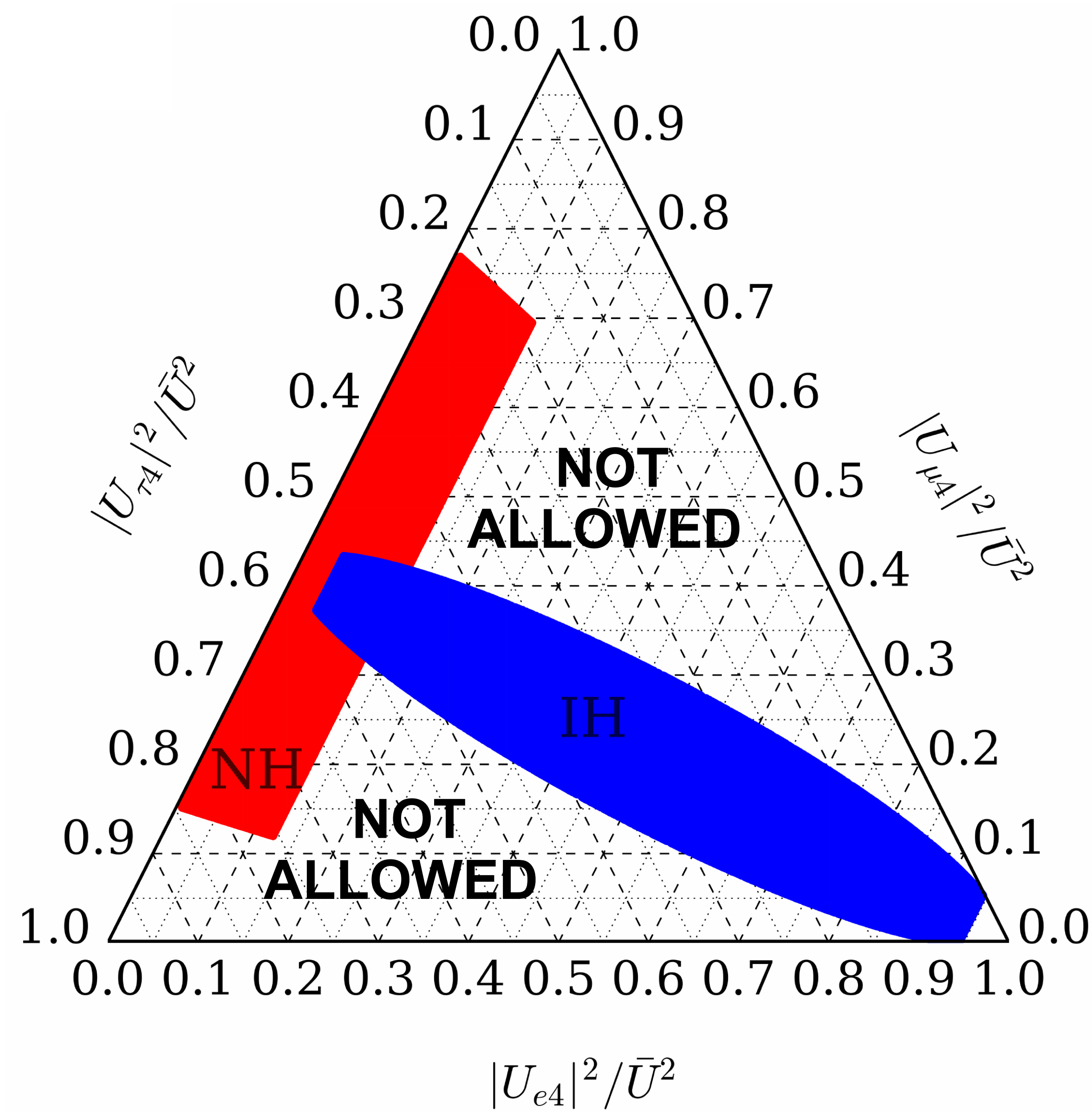
- Resonant Leptogenesis
  M>100GeV

  Pilaftsis

Minimal Model: Flavor Structure

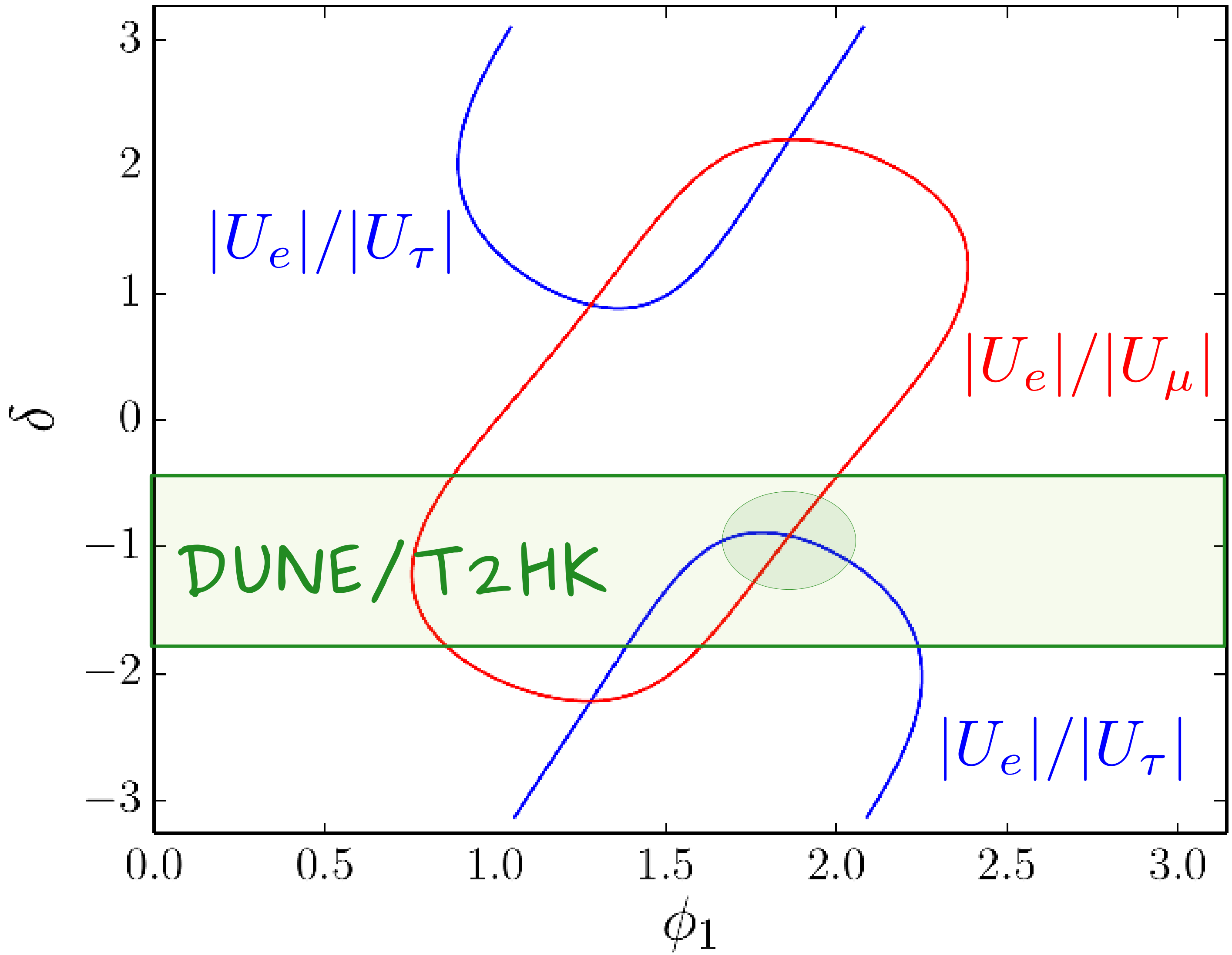
Direct HNL searches sensitive to

$|U_\alpha|(\delta, \phi, U^2),\ M_j$



Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

PMNS CP phases from HNLs searches



- **Potential determination of the PMNS Majorana phase!**

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

"Heavy" CP phase θ from $0\nu\beta\beta$ decay

- **Baryon asymmetry depends on all the unknown parameters**

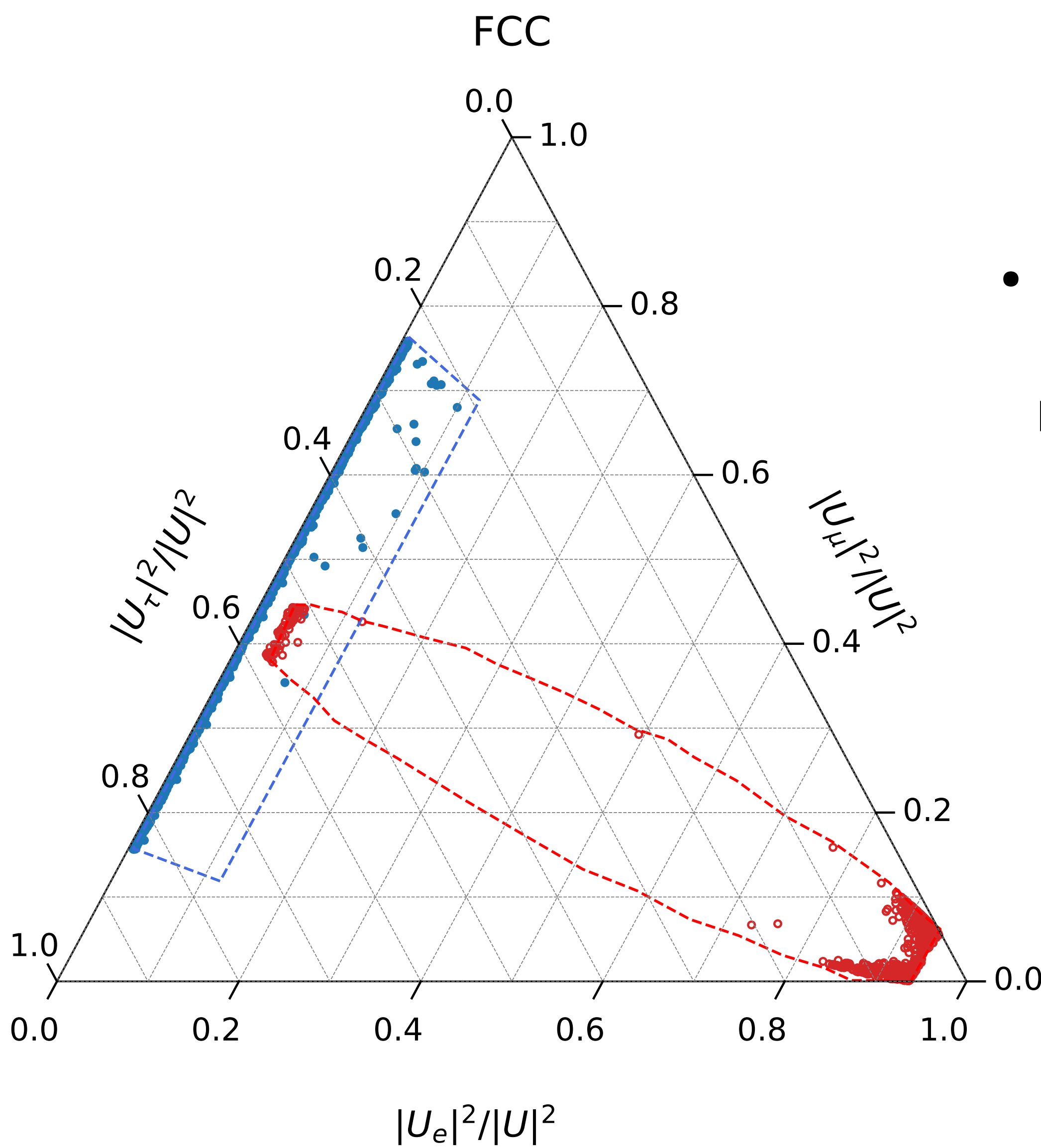
Direct searches sensitive to $|U_\alpha|(\delta, \phi, U^2),\ M_j$

$$(U_\alpha)^2 \propto e^{-2\theta i}\, U^2 f\left(\delta, \phi, M_j\right)$$

Neutrinoless double beta decay sensitive to θ through interference between light and heavy contribution for some regions of parameter space

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Baryon asymmetry: flavor structure

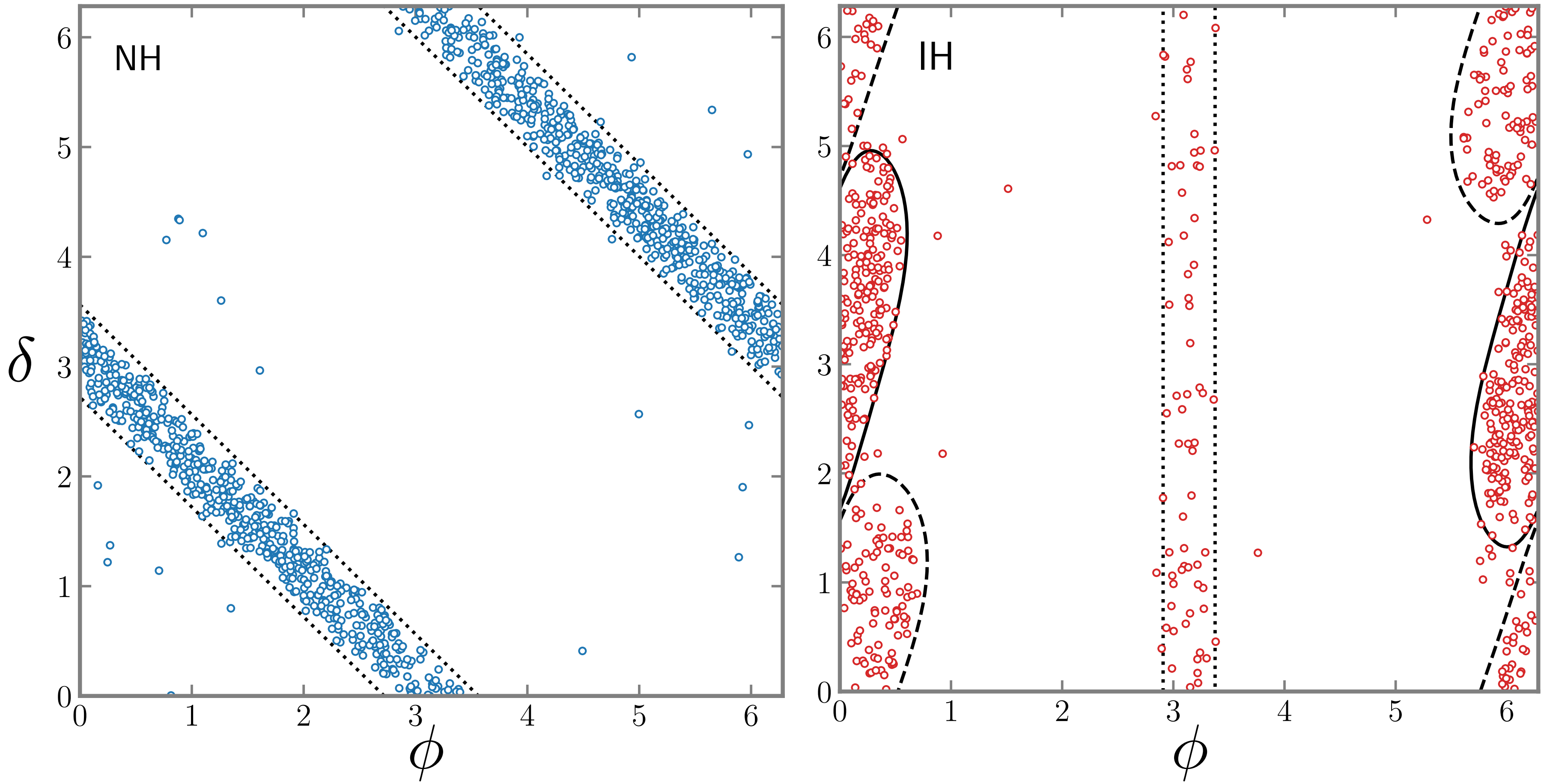


- Flavor correlations implied by reproducing observed matter-antimatter asymmetry in the region of parameter space that can be covered by FCC-ee for

$$\Delta M/M = 10^{-2}$$

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

Baryon asymmetry: PMNS CP phases

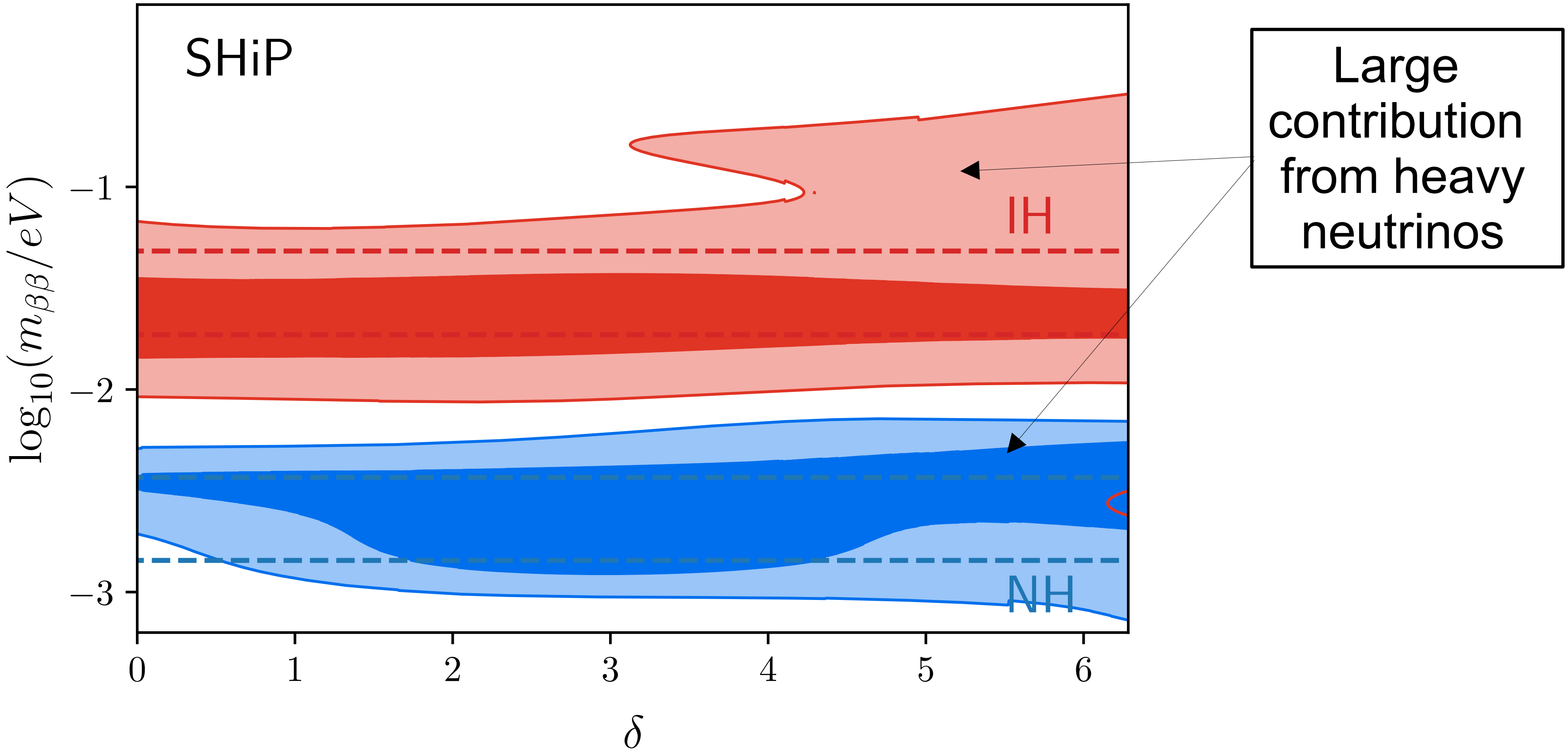


• PMNS CP-phase correlations implied by reproducing observed baryon asymmetry in region of parameter space that can be covered by FCC-ee for

$$\Delta M/M = 10^{-2}$$

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

Baryon asymmetry: 0νββ decay

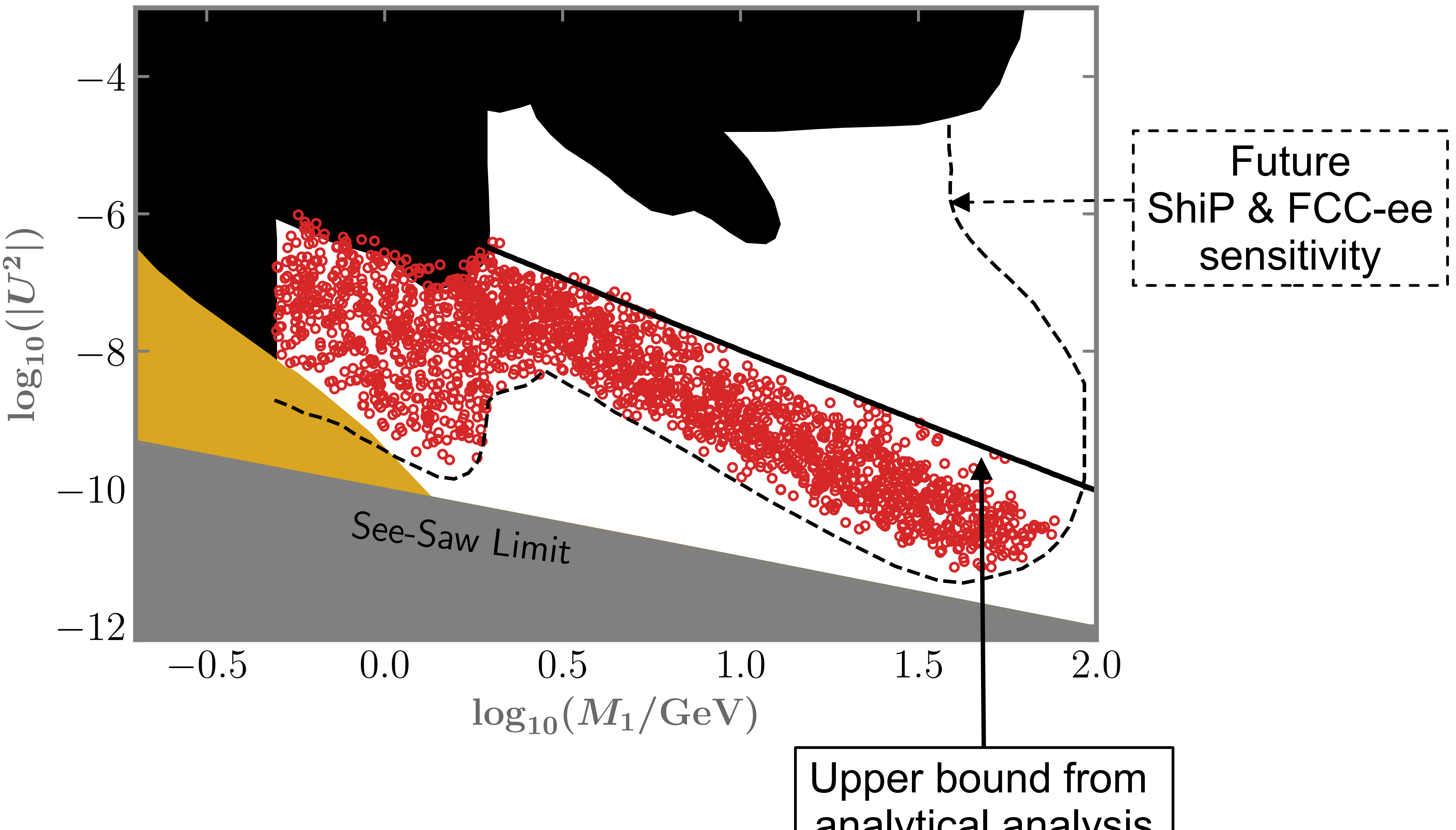


• Correlation with neutrinoless decay rate implied by reproducing observed baryon asymmetry in region of parameter space that can be probed by SHiP for

$$\Delta M/M = 10^{-2}$$

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

Baryon asymmetry: Upper Bound



Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

Conclusions

- Simplest extension of SM able to account for neutrino masses

can explain matter asymmetry of our universe via Leptogenesis even at accessible scales

- We have identified the CP invariants involved in low-scale leptogenesis

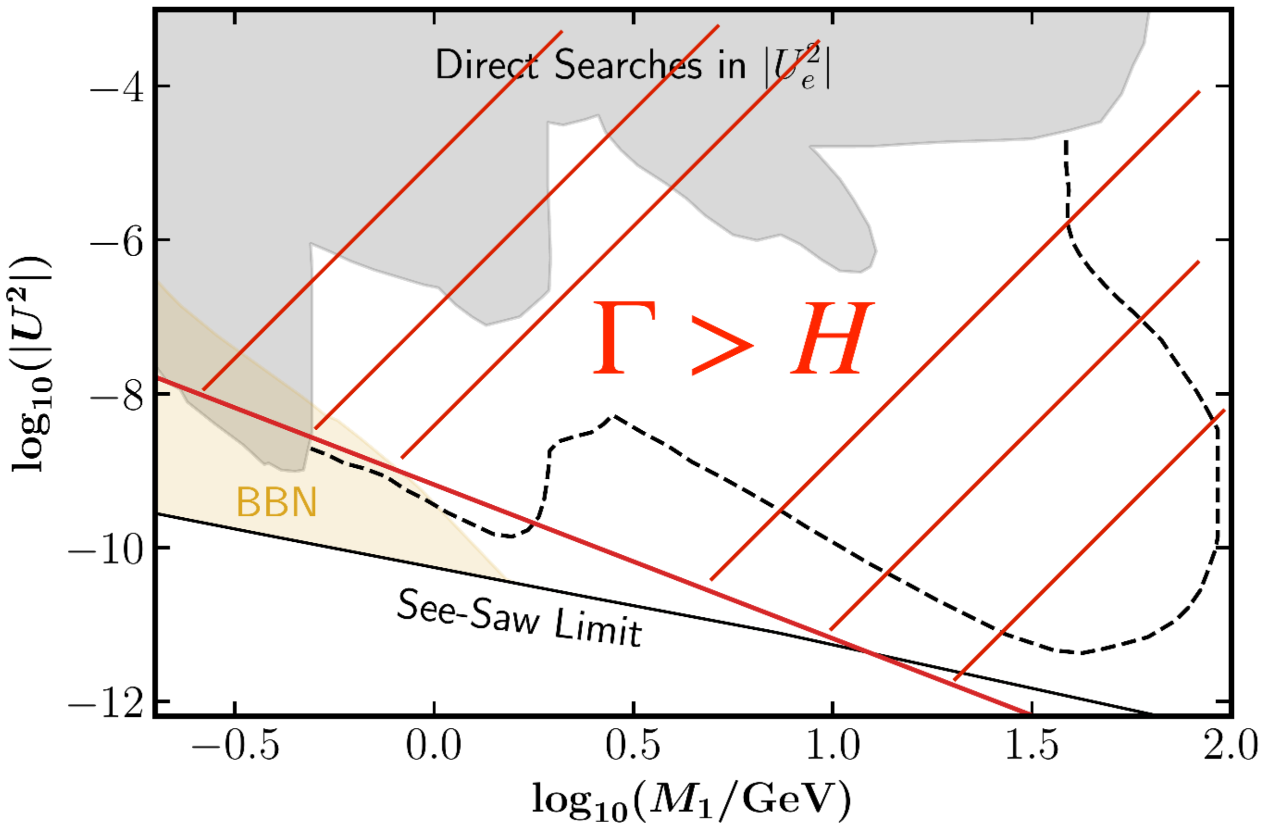
- Analytical treatment shows dependence on the CP invariants, allowing to connect $\mathbf{Y_B}$ to other observables: neutrino masses, CP violation in neutrino oscillations, $0\nu\beta\beta$ decay rate and HNL masses and mixing.

- Searches for the neutrino mass mediators (HNLs) could provide essential info about CP violation, the non-thermal condition and Y_B

- Methods developed can be applied to less minimal scenarios: understanding how Y_B constrains the more complex parameter space.

Non thermal equilibrition

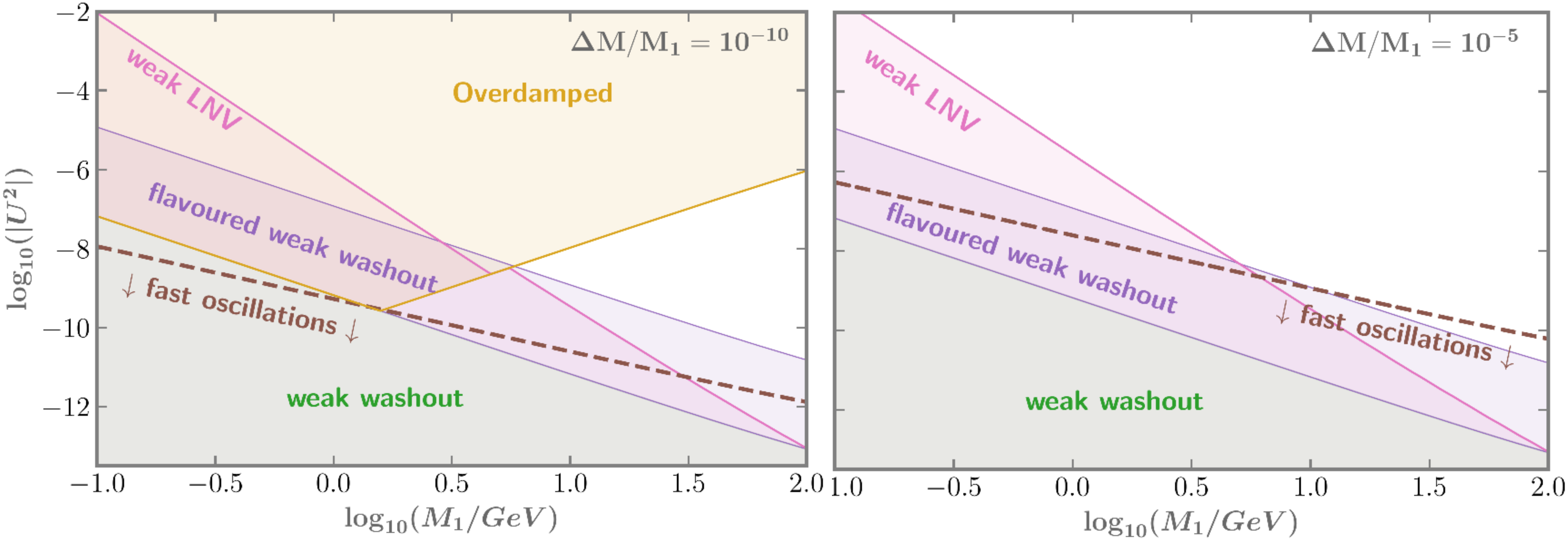
In principle, $\Gamma(T_{\rm EW}) < H(T_{\rm EW})$ is required $\quad (\Gamma \propto Tr\left[Y^\dagger Y\right] T)$



BUT *approximate L symmetry and flavour effects can lead to* **slow modes**.

Non thermal equilibrium regimes

Higly degenerate N_R's — Less degenerate N_R's



Overdamped regime: $\Gamma_{osc}^{slow} = \epsilon^2 \Gamma$ $\quad \epsilon \equiv \frac{\Gamma_{osc}}{\Gamma}$ $\quad \Gamma_{osc}(T) \propto \frac{M_2^2 - M_1^2}{T}$

Flavoured: $y_\alpha \ll y_\beta$ $\quad \Gamma_\alpha \propto (YY^\dagger)_{\alpha\alpha} T$

wLNV: $M \ll T$ $\quad \Gamma_M^{slow} \propto \left(\frac{M_i}{T}\right)^2 \Gamma$

Example: overdamped regime (NH)

$$\left(\sum_\alpha \mu_{B/3-L_\alpha}\right)^{\rm ov-wLNV} \simeq \frac{\kappa x^2}{6\gamma_0+\kappa\gamma_1}\frac{\gamma_0^2}{\gamma_0^2+4\omega^2}\frac{c_H M_P^*}{T_{EW}^3}\left(\Delta^{\rm ov}_{\rm LNC}-\frac{24}{5}\frac{s_0 x^3}{T_{\rm EW}^2}\Delta^{\rm ov}_{\rm LNV}\right)$$

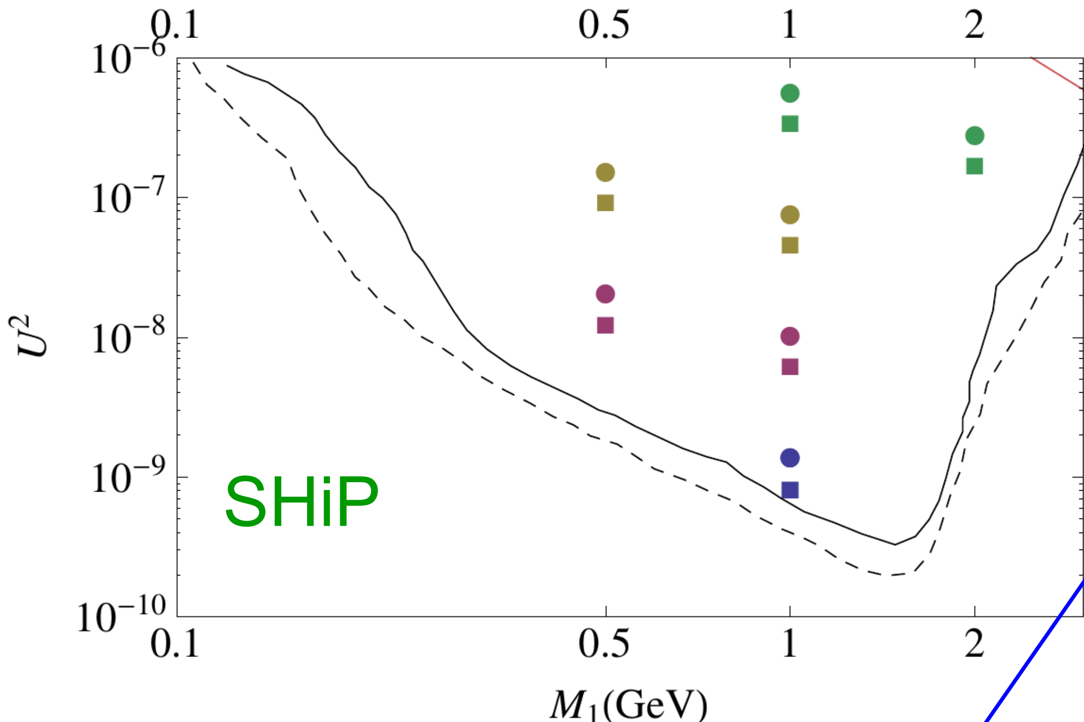
$$\Delta^{\rm ov}_{\rm LNC} = \frac{1}{\left[{\rm Tr}\,(Y^\dagger Y)\right]^2}\sum_\alpha \frac{\Delta_\alpha}{(YY^\dagger)_{\alpha\alpha}} \approx -(M_2^2-M_1^2)\frac{v^2\sqrt{\Delta m^2_{\rm atm}}}{8M^3U^4}s_\theta$$

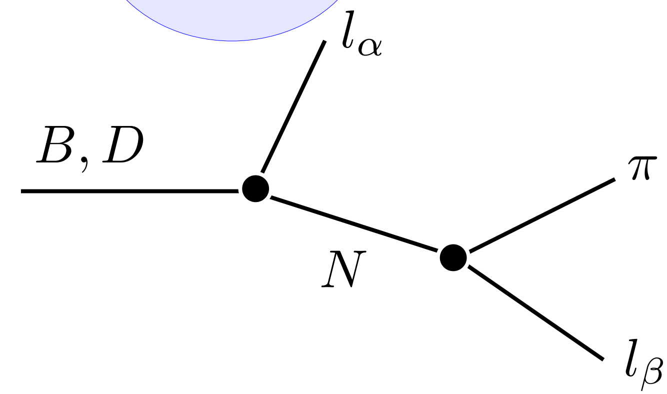
$$\left(\sum_\alpha \Delta_\alpha = 0,\ \Delta^{\rm ov}_{\rm LNC} \propto \sum_\alpha \frac{\Delta_\alpha}{\Gamma_\alpha}\right)$$

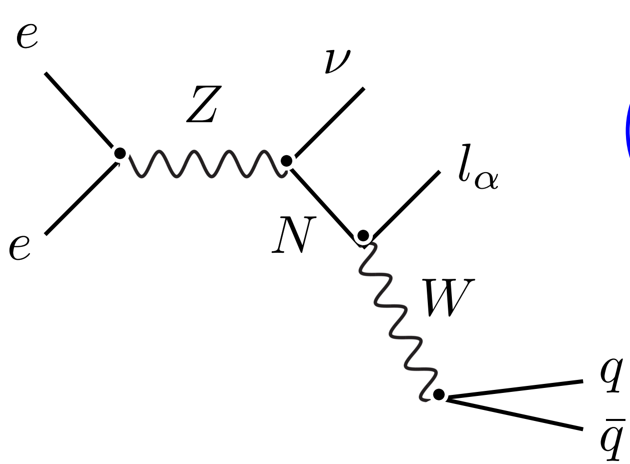
$$\Delta^{\rm ov}_{\rm LNV} = \frac{1}{\left[{\rm Tr}\,(Y^\dagger Y)\right]^2}\sum_\alpha \Delta_\alpha^M \approx -M_1M_2(M_2^2-M_1^2)\frac{\sqrt{\Delta m^2_{\rm atm}}}{4MU^2}s_\theta$$

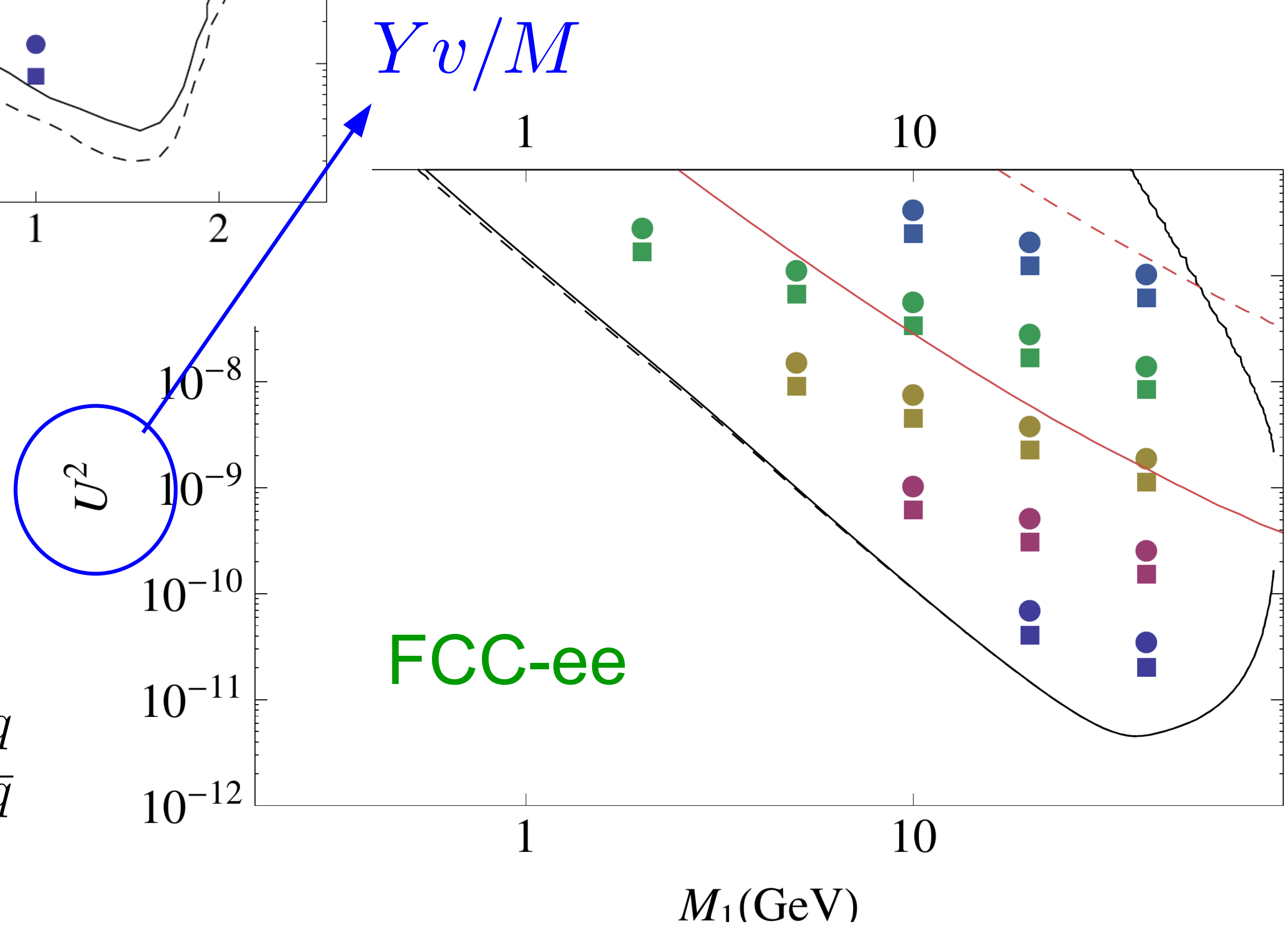
$$\left(\sum_\alpha \Delta_\alpha^M \neq 0\right)$$

Minimal model $N_R = 2$

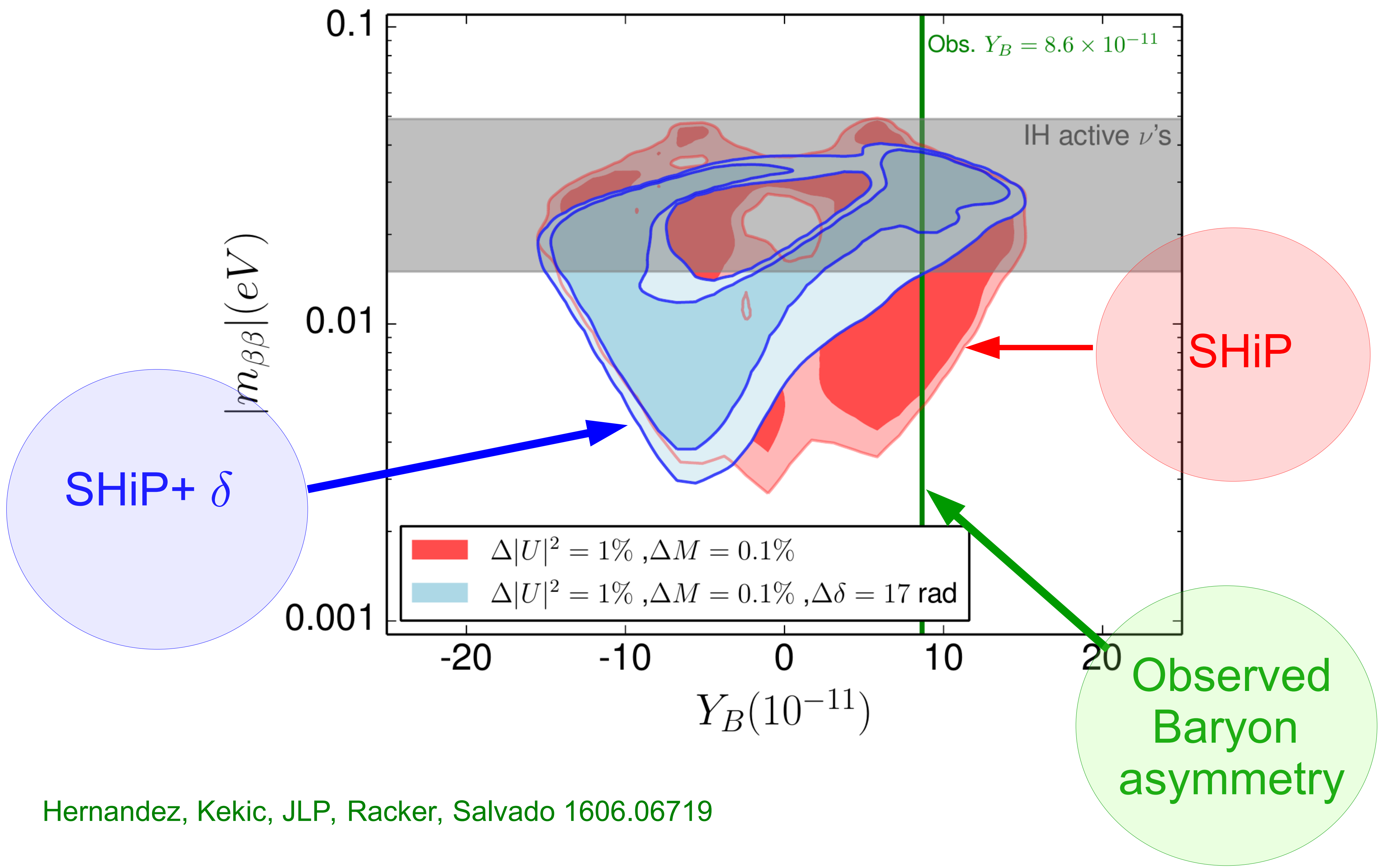






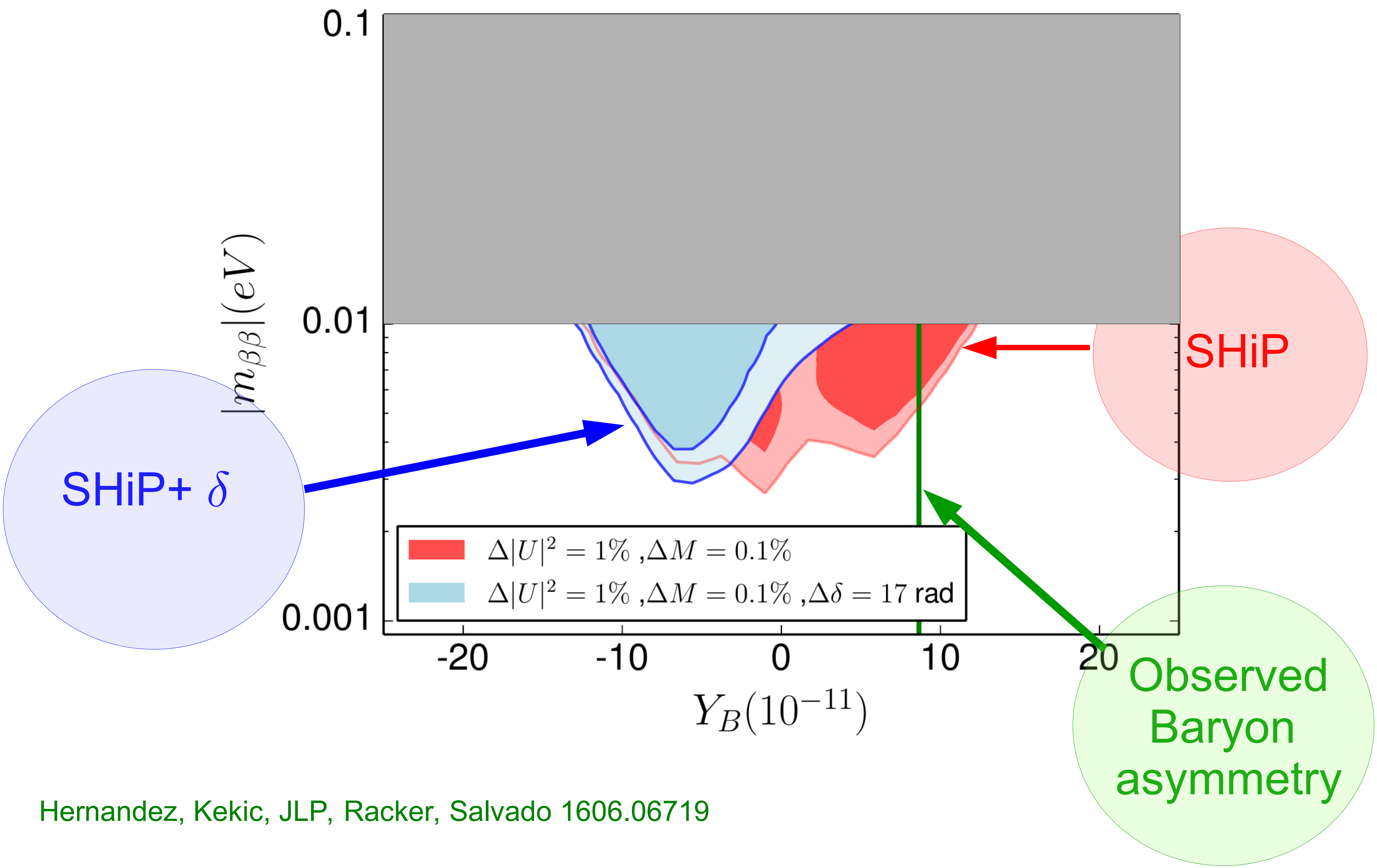


Determining Y_B in minimal model $N_R=2$



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Determining Y_B in minimal model $N_R=2$



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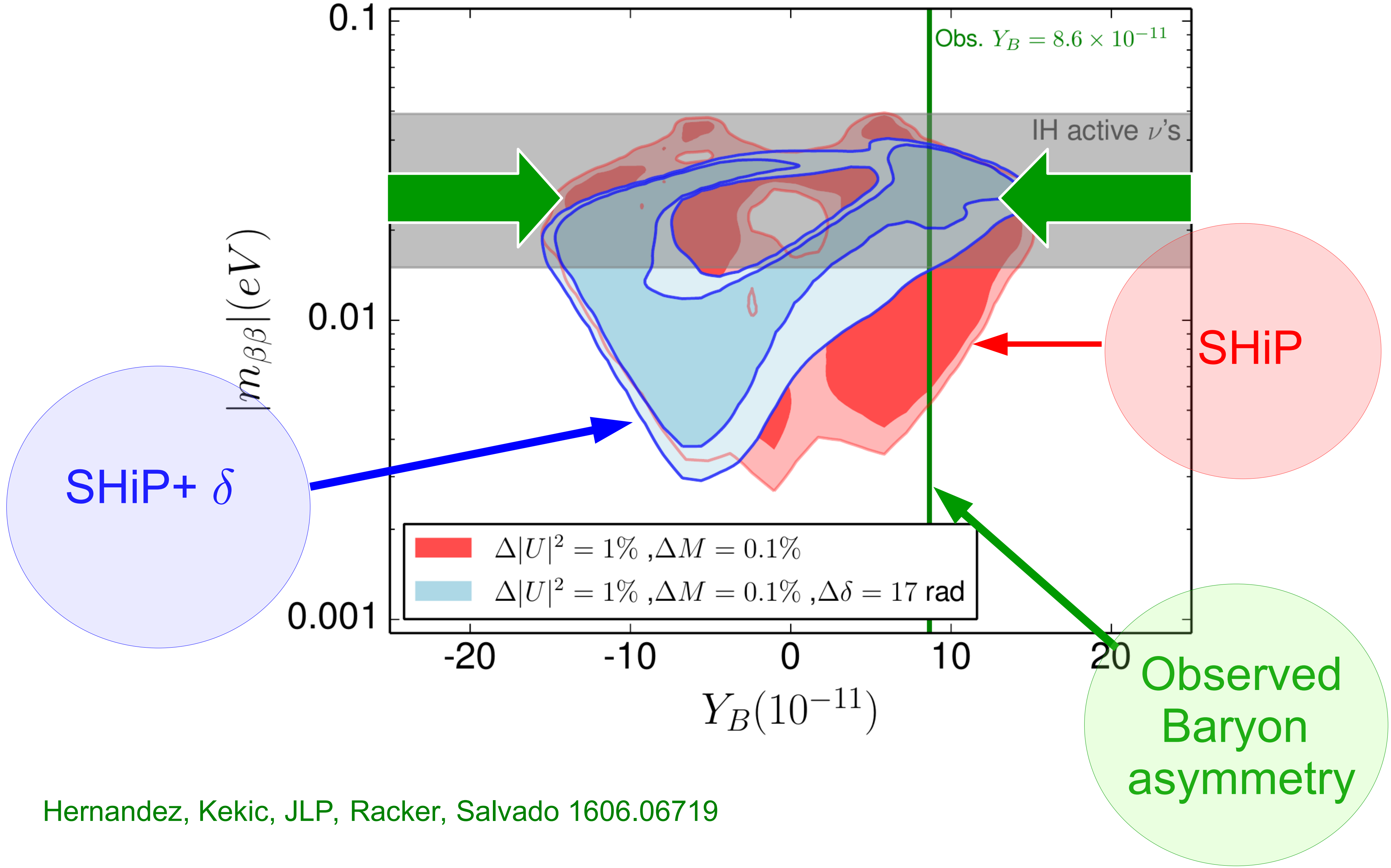
Determining Y_B in minimal model $N_R=2$



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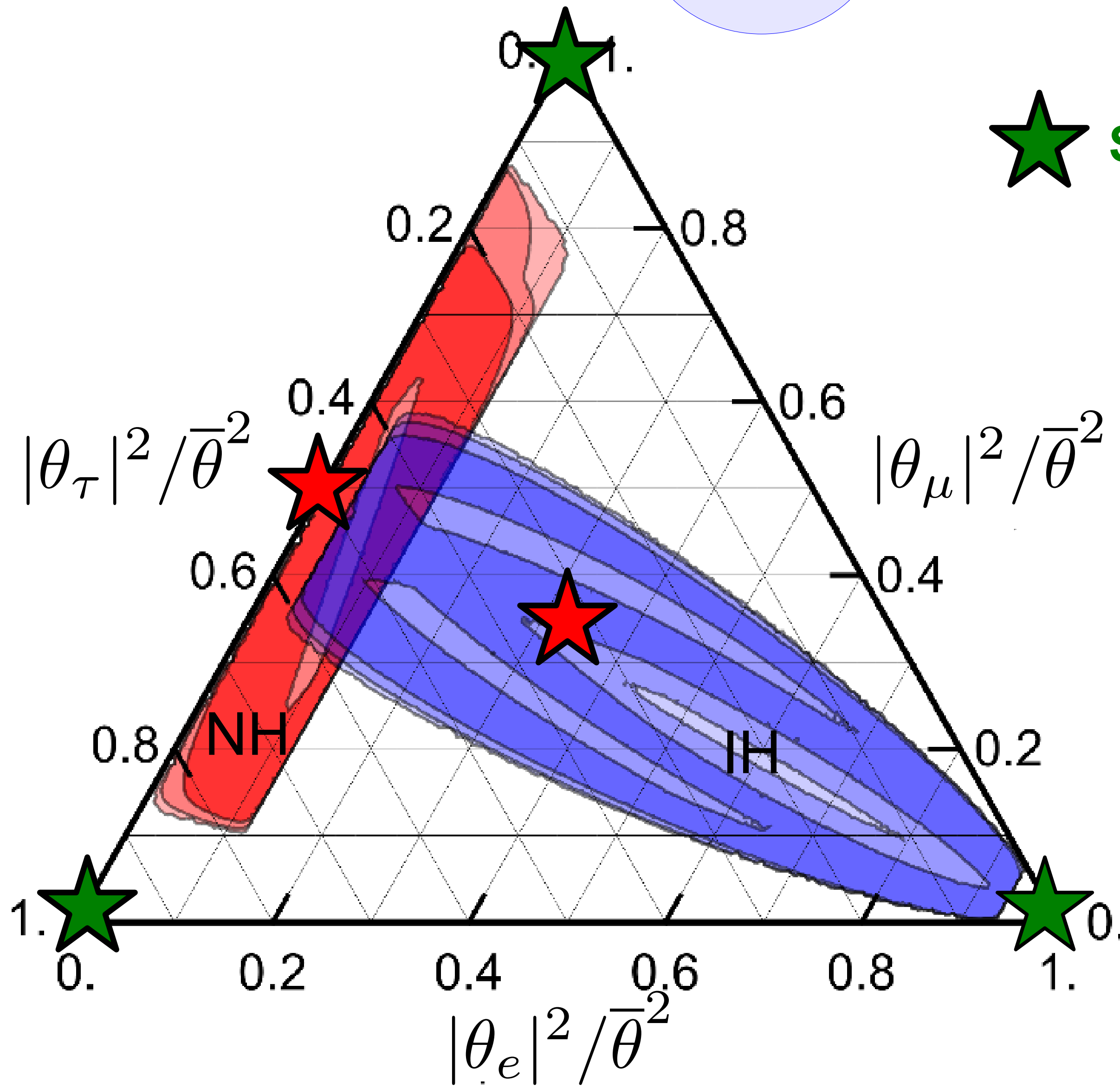
Minimal model $N_R=2$: Flavor Structure



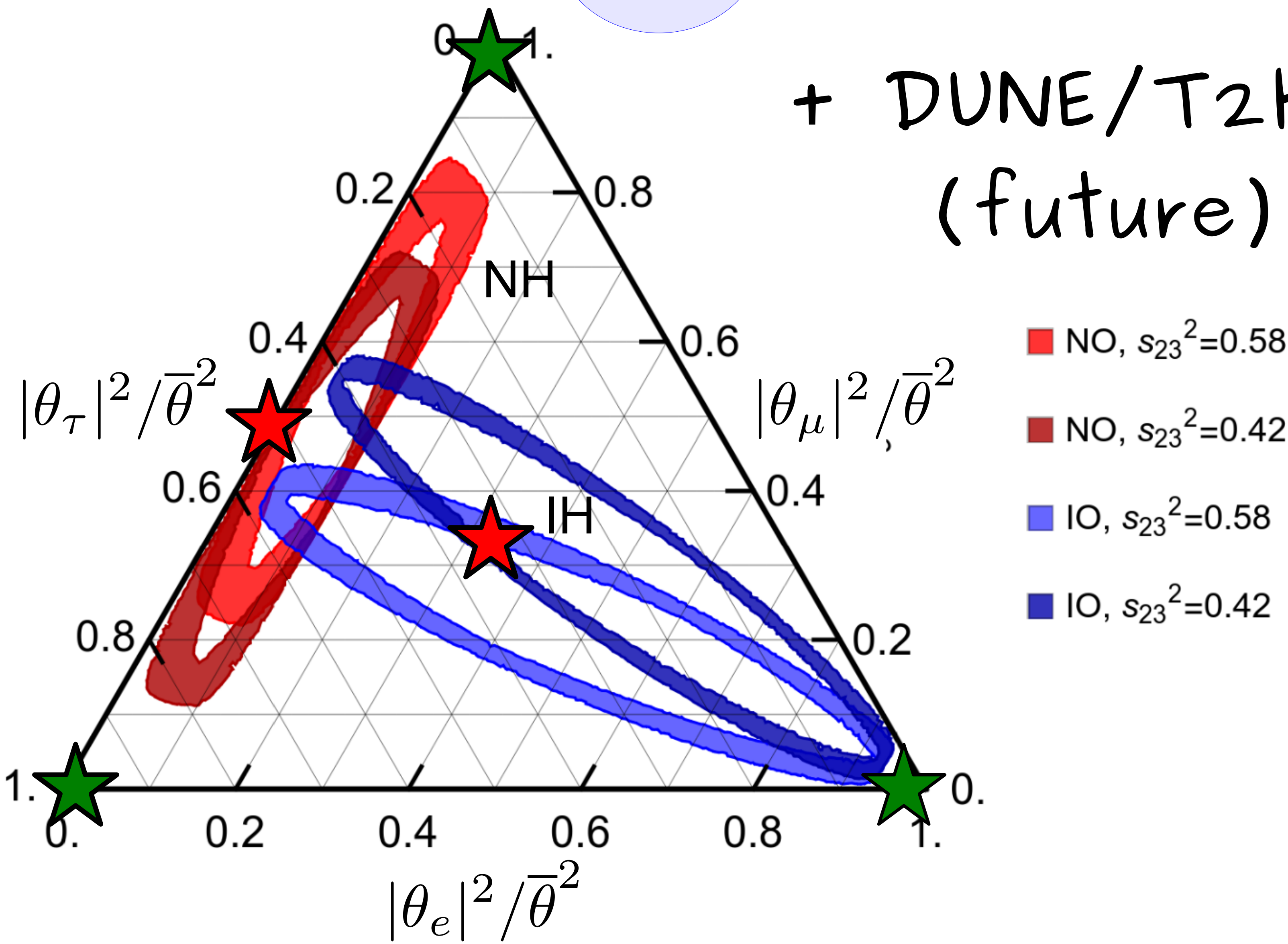
Single flavored benchmarks
(1,0,0), (0,1,0), (0,0,1)

NEW 2021
(0, 1/2, 1/2)
(1/3, 1/3, 1/3)

Abdullahi et al arXiv:2203.08039

Caputo, Hernandez, JLP, Salvado arXiv:1704.08721
Drewes, Klaric, JLP arXiv:2207.02742

Minimal model $N_R=2$: Flavor Structure



+ DUNE/T2HK…
(future)

DUNE forecast assuming $\delta = -\pi/2$

Abdullahi et al arXiv:2203.08039
Drewes, Klaric, JLP arXiv:2207.02742

CP-violation in minimal model

- **SHiP and FCC-ee** can measure:

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

Sensitivity to PMNS CP-phases! δ, ϕ_1

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

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

- $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{e5}|^2, |U_{\mu 5}|^2 \propto \frac{U^2}{M}$

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

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

- Modification of flavor structure controlled by the lightest neutrino mass generated by Weinberg operator. Predictions kept if

$$\frac{v^2 \alpha_w}{\Lambda} \leq 0.1 \sqrt{\Delta m^2_{sol}} \sim 10^{-3} eV$$

Caputo, Hernandez, JLP, Salvado 2017

Model Independent Approach: EFT

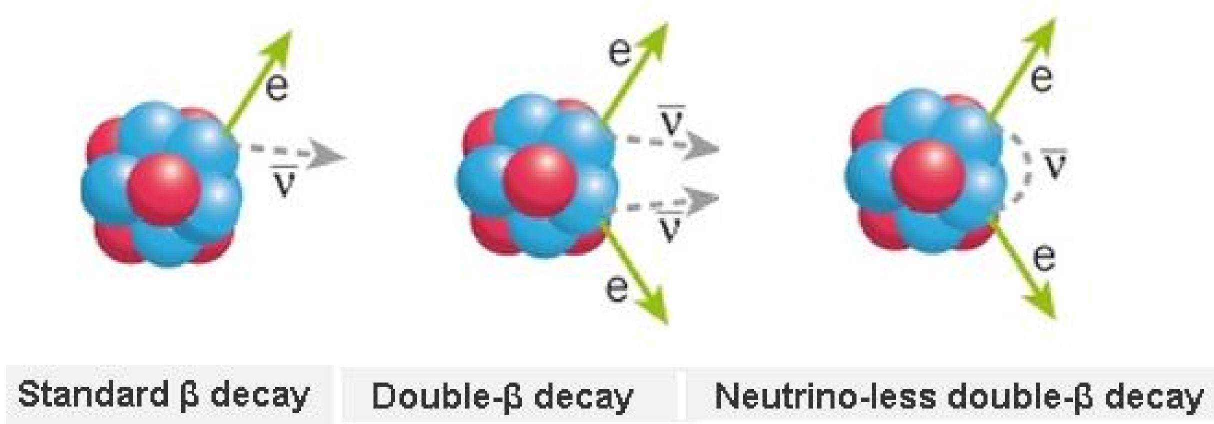
• The leading NP effects are encoded in effective d=5 operators that can be constructed in a gauge invariant way with the SM fields and the N_j

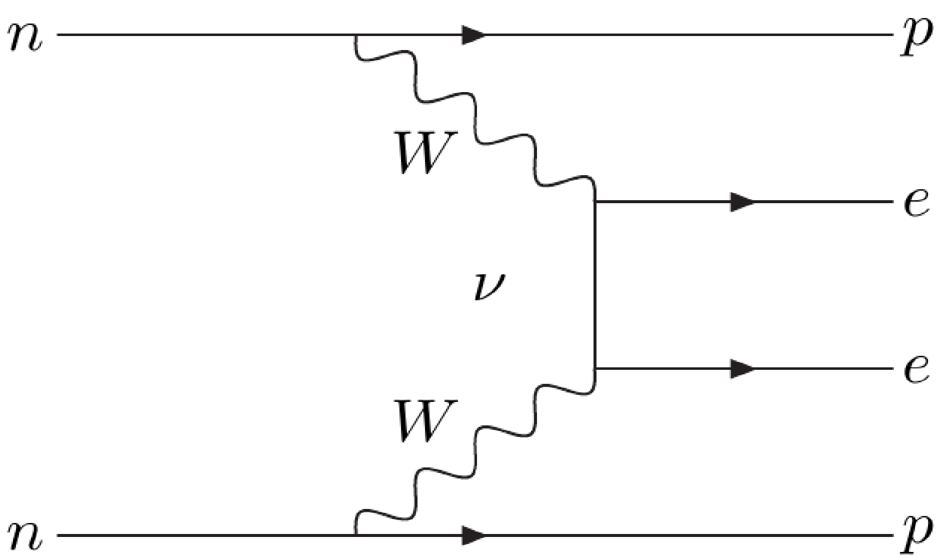
- The higgs can decay to a pair of long-lived heavy neutrinos!
(**powerful signal of two displaced vertices**)

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

Accomando, Delle Rose, Moretti, Olaiya, Shepherd-Themistocleous 2017
Caputo, Hernandez, JLP, Salvado 2017

Neutrinoless double beta decay





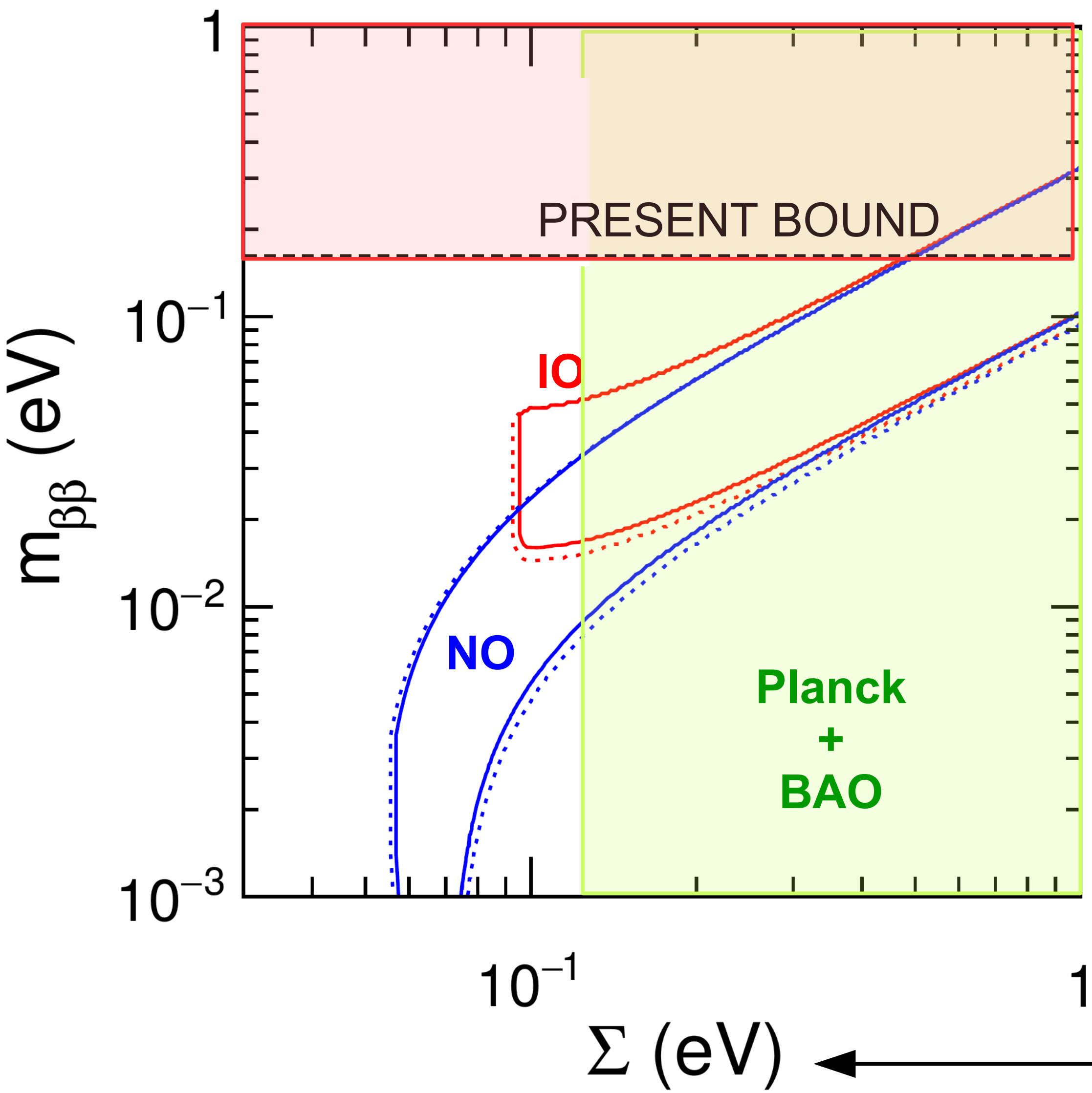
mixing

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

mass of propagating neutrino

$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp}$$

Neutrinoless double beta decay

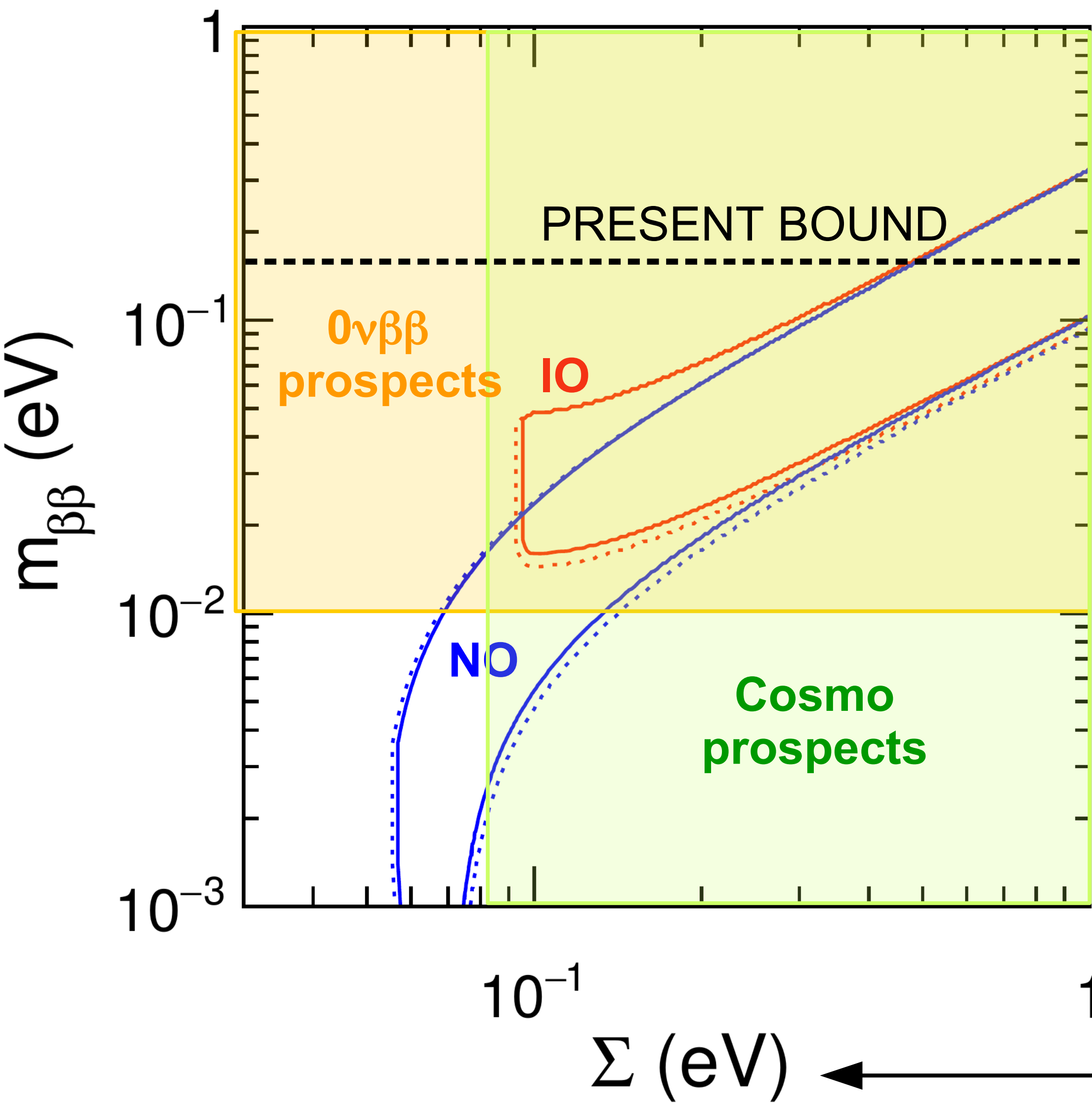


Sum of three neutrino masses

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

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

Neutrinoless double beta decay



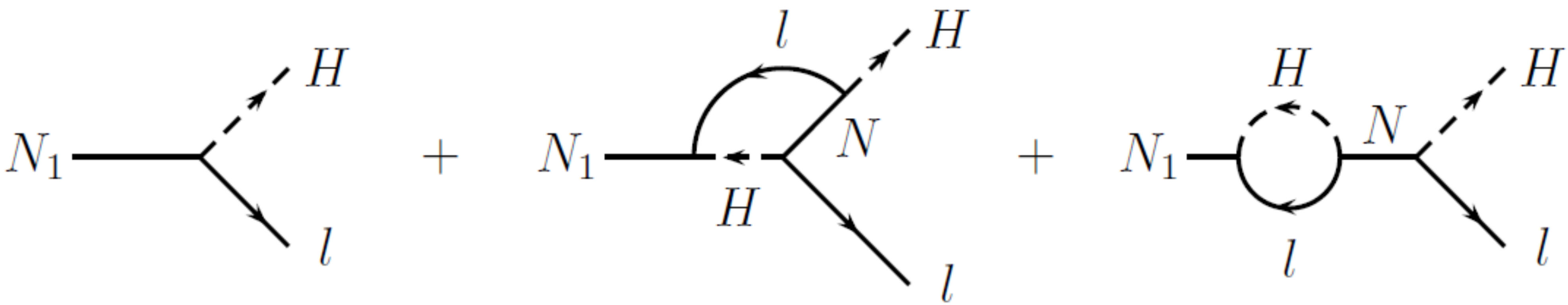
EXO, KamLAND-Zen, CUORE, NEXT, GERDA, SNO+, nEXO, KamLAND2-Zen, AMoRE, PANDA III, Super Nemo…

Sum of three neutrino masses

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

Leptogenesis: Vanilla Scenario

(2) C and CP violation



At one loop: CP asymmetry generated via interference effects

$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to l^c H^c)}{\Gamma(N \to lH) + \Gamma(N \to l^c H^c)} \propto Im(Y^\dagger Y)^2_{ij}$$

Leptogenesis: Vanilla Scenario

3 Departure from thermal equilibrium