Leptogenesis from low energy CP violation in minimal left-right symmetric model

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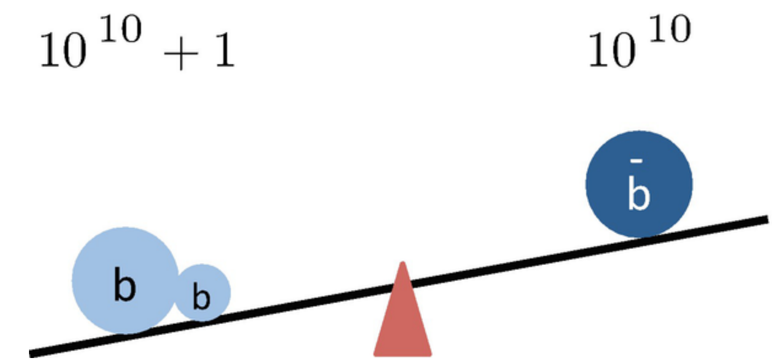
Baryon-antibaryon Asymmetry of the Universe (BAU)

The observed baryon-antibaryon asymmetry (Planck 2018)

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.72 \pm 0.08) \times 10^{-11}$$



K. Fuyuto, Electroweak Baryogenesis and Its Phenomenology, Springer Theses, 2018

To generate the BAU dynamically (**baryogenesis**), Sakharov (1967) proposes three conditions:

- **Baryon number violation**
- **C and CP violation**
- **Deviation from equilibrium**

Standard model confronts the Sakharov conditions

- **Sphaleron process**
- **KM mechanism**
- **Electroweak phase transition (EWPT)**

Existing baryongenesis mechanisms:

- **GUT baryogenesis**: heavy boson out-of-equilibrium decay

A.Y. Ignatiev et al, 1978; M. Yoshimura, 1978; D. Toussaint et al, 1979; S.Dimopoulos, L. Susskind, 1978…

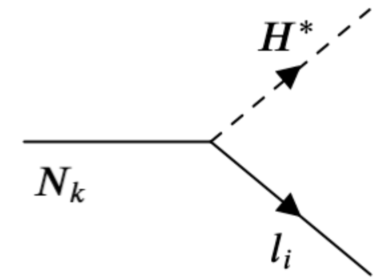
- **Leptogenesis:** heavy neutrino out-of-equilibrium decay

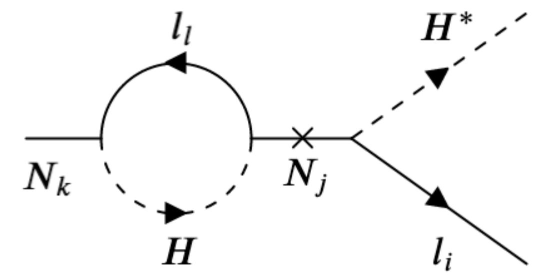
P. Minkowski 1977; T. Yanagida, 1979; S.L. Glashow, 1980; M. Gell-Mann et al, 1979; R. N. Mohapatra, G. Senjanovic, 1981…

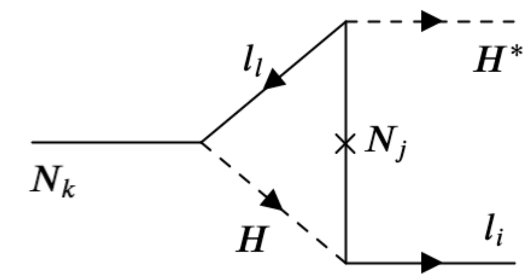
- **Electroweak baryogengesis**: EWPT V. A. Rubakov and M. E. Shaposhnikov, 1996; A. Riotto and M. Trodden, 1999; J. M. Cline, 2006…
- **The Affleck-Dine mechanism**: I. Affleck and M. Dine, 1985; M. Dine, L. Randall, and S. D. Thomas, 1996…

Leptogenesis

Origin of neutrino mass
Origin of BAU







Heavy neutrino out-of-equilibrium decay

generates a CP asymmetry (also a L asymmetry)

$$\epsilon_{N_K} = \sum_i \frac{\Gamma(N_k \to l_i H^*) - \Gamma(N_k \to \bar{l}_i H)}{\Gamma(N_k \to l_i H^*) + \Gamma(N_k \to \bar{l}_i H)},$$

Sphaleron processes convert L to B

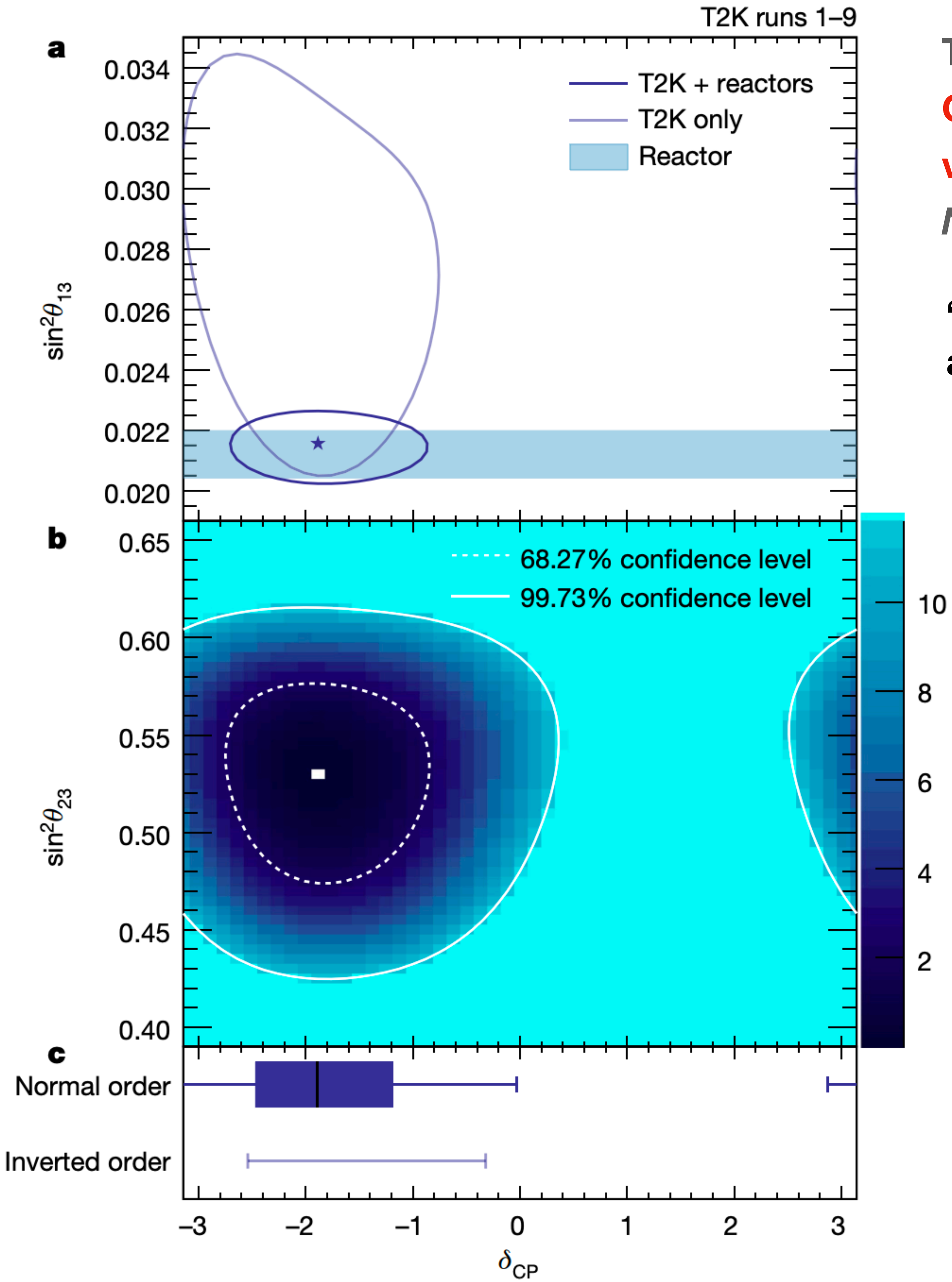
All three Sakharov conditions are naturally fulfilled

N2 leptogenesis
Resonant leptogenesis
Soft leptogenesis
Dirac leptogenesis
Triplet scalar leptogenesis
Triplet fermion leptogenesis

Potential drawbacks:
1. **Associated with high scales -> Hard to probe**
2. **A lower bound on the heavy neutrino mass**
-> a lower bound on the reheat temperature (too high)
-> gravitino overproduction problem

Thermal effects, spectator effects, flavor effects…

For reviews, see, e.g.,
S. Davidson, E. Nardi, and Y. Nir, 0802.2962;
Z.Z. Xing and Z. Zhao, 2008.12090



The T2K Collaboration., Abe, K., Akutsu, R. *et al.* **Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations**. *Nature* 580, 339–344 (2020).

"Both CP conserving points, $\delta_{CP} = 0$ and $\delta_{CP} = \pi$, are ruled out at the 95% confidence level."

If Dirac CP phase is observed, what can we say about BAU?

Can it be the only source of CPV needed in leptogenesis?

Is there a direct connection of the low energy CPV & BAU?

S. Pascoli, S. T. Petcov, and A. Riotto, PRD 2007; NPB 2007

The R matrix ambiguity

Casas-Ibarra parameterization

Casas & Ibarra, NPB 2001

$$\epsilon_N \leftarrow M_D = vY_N$$

$$\tilde{M}_D = iD_N^{1/2} R D_\nu^{-1/2} V_L^\dagger,$$

V_L: neutrino mixing matrix, Low energy CPV

vital to leptogenesis

R matrix: arbitrary orthogonal

Probed by oscillation experiments

Free parameters in R hinders a direct connection of low energy CPV to BAU

R matrix contains information of M_D other than light & heavy masses & mixing? Certainly not. As M_D should contain nothing other than light & heavy masses & mixing.

Existing solutions

Assume CP-conserving R matrix

Moffat, et al, JHEP 2019

Real R + One-loop RGEs

Xing & Zhang, JHEP 2020; Zhao, 2003.00654

Use flavor symmetries to constrain M_D

Apologies for the incomplete list:
Hagedorn, Molinaro, Petcov, JHEP 2009;
Meroni, Molinaro & Petcov, PLB 2012;
Karmakar & Sil, PRD 2015;
Gehrlein et al, NPB 2015;
Ishihara, et al, JHEP 2016;
…

minimal left-right symmetric model (MLRSM)

GUT-inspired Dirac mass hierarchy + type II dominance

Rink, Rodejohann & Schmitz, 2006.03021

Unbroken discrete LR symmetry -> neutrino Dirac coupling fully expressed in light & heavy neutrino masses & mixings

Nemevsek, Senjanovic & Tello, PRL 2013,
Senjanovic & Tello: PRL 2017; PRD 2019; IJMPA 2020. This work

Minimal left-right symmetric model (MLRSM)

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Spontaneous breaking -> parity violation in SM

+ discrete left-right symmetry

Generalized parity P
Generalized charge conjugation C

$$g_L = g_R = g.$$

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
l_L	2	1	-1
l_R	1	2	-1
Δ_L	3	1	2
Δ_R	1	3	2
Φ_1	2	2	0
Φ_2	2	2	0

$$\mathcal{L} \supset -\bar{l}_L(Y_1\Phi_1 - Y_2\Phi_2^*)l_R - \frac{1}{2}(l_L^T C Y_L i\sigma_2 \Delta_L l_L + l_R^T C Y_R i\sigma_2 \Delta_R l_R) - \lambda_{ij}\mathrm{Tr}\left(\Delta_R^\dagger \Phi_i \Delta_L \Phi_j^\dagger\right) + h.c.,$$

$$l_{L,R} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L,R}, \quad \Delta_{L,R} = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}_{L,R}, \quad \Phi_1 = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & -\phi_2^0 \end{pmatrix}, \quad \Phi_2 = \sigma_2\Phi_1^*\sigma_2.$$

Effective trilinear scalar coupling

$$\mu = \frac{(\lambda_{11}+\lambda_{22})v_1 v_2 + \lambda_{12}v_2^2 + \lambda_{21}v_1^2}{v_1^2+v_2^2} v_R.$$

$$\mu = \frac{v_L m_\Delta^2}{v^2}$$

Pati & Salam, PRD 1974;
Mohapatra & Pati, PRD 1975;
Senjanovic & Mohapatra, PRD 1975;
Senjanovic, NPB 1979.

“Disentangle the seesaw”

Charge conjugation as the left-right symmetry

Nemevsek, Senjanovic & Tello, PRL 2013

Under charge conjugation,

$$l_L \leftrightarrow l_R^c, \;\; \Delta_L \leftrightarrow \Delta_R^*, \;\; \Phi \leftrightarrow \Phi^T,$$

$$Y_{1,2} = Y_{1,2}^T, \;\; Y_L = Y_R^* \equiv Y_T,$$

$$M_D = M_D^T.$$

$$M_D = M_N \sqrt{\frac{v_L}{v_R} - \frac{1}{M_N} M_\nu}.$$

In type I seesaw limit,

$$\tilde{M}_D = i D_N^{1/2} R D_\nu^{-1/2} V_L^\dagger,$$

$$R = V_L^* D_\nu.$$

The R matrix is determined, no more ambiguity

Parity as the left-right symmetry

Senjanovic & Tello: PRL 2017; PRD 2019; IJMPA 2020.

Under the generalized parity,

$$l_L \leftrightarrow l_R, \;\; \Delta_L \leftrightarrow \Delta_R, \;\; \Phi \leftrightarrow \Phi^\dagger,$$

$$Y_{1,2} = Y_{1,2}^\dagger, \;\; Y_L = Y_R \equiv Y_T,$$

$$M_D = M_D^\dagger \qquad U_e = \mathbb{I}$$

$$H H^T = \frac{v_L^*}{v_R} - \frac{1}{\sqrt{M_N}} M_\nu^* \frac{1}{\sqrt{M_N}}, \qquad M_D = \sqrt{M_N} H \sqrt{M_N^*}$$

In type I seesaw limit,

$$\tilde{M}_D = D_N^{1/2} H D_N^{1/2} = i V_L D_\nu^{1/2} D_N^{1/2}$$

$$R = D_N^{-1/2} V_L D_\nu^{1/2} D_N^{1/2} V_L D_\nu^{1/2},$$

Input: light & heavy neutrino masses & mixings

Leptogenesis in minimal left-right symmetric model

Neutrino mass generation:

Heavy neutrino -> type I seesaw
Triplets -> type II seesaw

Simultaneous presence of both
-> Mixed type I + II

CP asymmetry generation:

The decaying particle can be

Heavy neutrino
Triplet scalar

Hambye & Senjanovic, PLB 2004

Classification of the models

Model markers

1	Heavy neutrino decay	Type I seesaw
2	Heavy neutrino decay	Mixed type I + II seesaw
3	Triplet scalar decay	Type I seesaw
4	Triplet scalar decay	Mixed type I + II seesaw

We also consider either Parity (P) or Charge conjugation (C) as the LR symmetry,
and both light neutrino mass orderings: Normal ordering (NO) and Inverted ordering (IO)
16 models in all

Note that we work with disentangled seesaw.
Only type I or mixed I+II seesaw need to be disentangled.
MLRSM with discrete LR gives no further constraints on pure type II mass

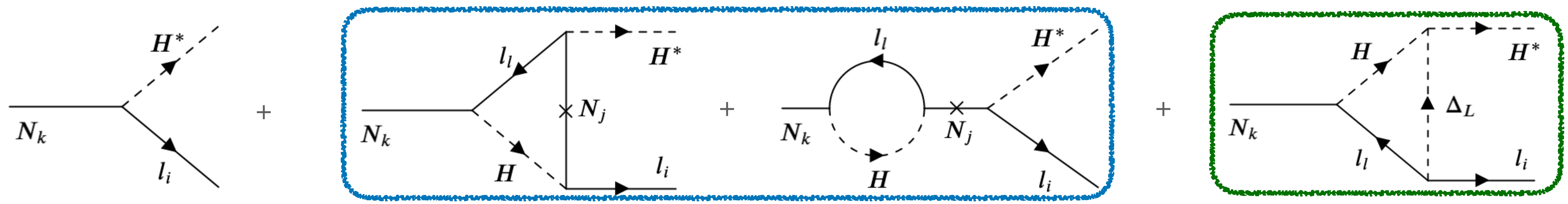
CP asymmetries

Assume leptogenesis happens at $T \geqslant 10^{12}\ \text{GeV}$

$$M_N = v_R Y_R,\ \ M_D = v Y_N$$
$$Y_T \equiv Y_L = Y_R^*\ \text{(C as LR sym)}$$
$$Y_T \equiv Y_L = Y_R\ \text{(P as LR sym)}$$
$$\mu = v_L m_\Delta^2 / v^2$$

Heavy neutrino decay

$$\epsilon_{N_K} = \sum_i \frac{\Gamma(N_k \to l_i H^*) - \Gamma(N_k \to \bar{l}_i H)}{\Gamma(N_k \to l_i H^*) + \Gamma(N_k \to \bar{l}_i H)},$$

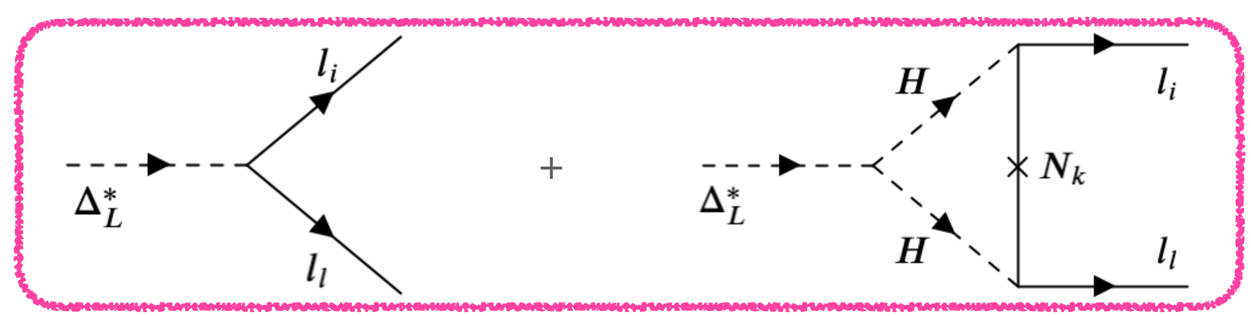


$\epsilon_{N_k}\,(Y_N)$

$\epsilon_{N_k}^{\Delta}\,(Y_N, Y_T, \mu)$

Triplet scalar decay

$$\epsilon_\Delta = 2 \sum_{i,l} \frac{\Gamma(\Delta_L^* \to l_i l_l) - \Gamma(\Delta_L \to \bar{l}_i \bar{l}_l)}{\Gamma(\Delta_L^* \to l_i l_l) + \Gamma(\Delta_L \to \bar{l}_i \bar{l}_l)}$$



$\epsilon_\Delta\,(Y_T, \mu, Y_N)$

All the asymmetries are non-zero & dependent on lepton mixing
-> single flavor regime works

Model parameters & inputs

Light neutrino sector: masses & mixing

Low energy CPV

Input global fit: NuFIT 5.0 (2020), www.nu-fit.org.

Heavy neutrino sector: masses & mixing

Fixed heavy neutrino mass spectrum:
Neither degenerate nor hierarchical

$$m_{N_2} = 2m_{N_1}\,,\;\; m_{N_3} = 3m_{N_1}\,,\;\; m_{N_1} \geqslant 10^{12}\text{GeV}$$

C is the LR symmetry $V_R = V_L^*$
P is the LR symmetry $V_R = V_L$

In analog with the quark sector
All CPV reside in low energy sector

Triplet related: vevs (v_L, v_R), triplet masses

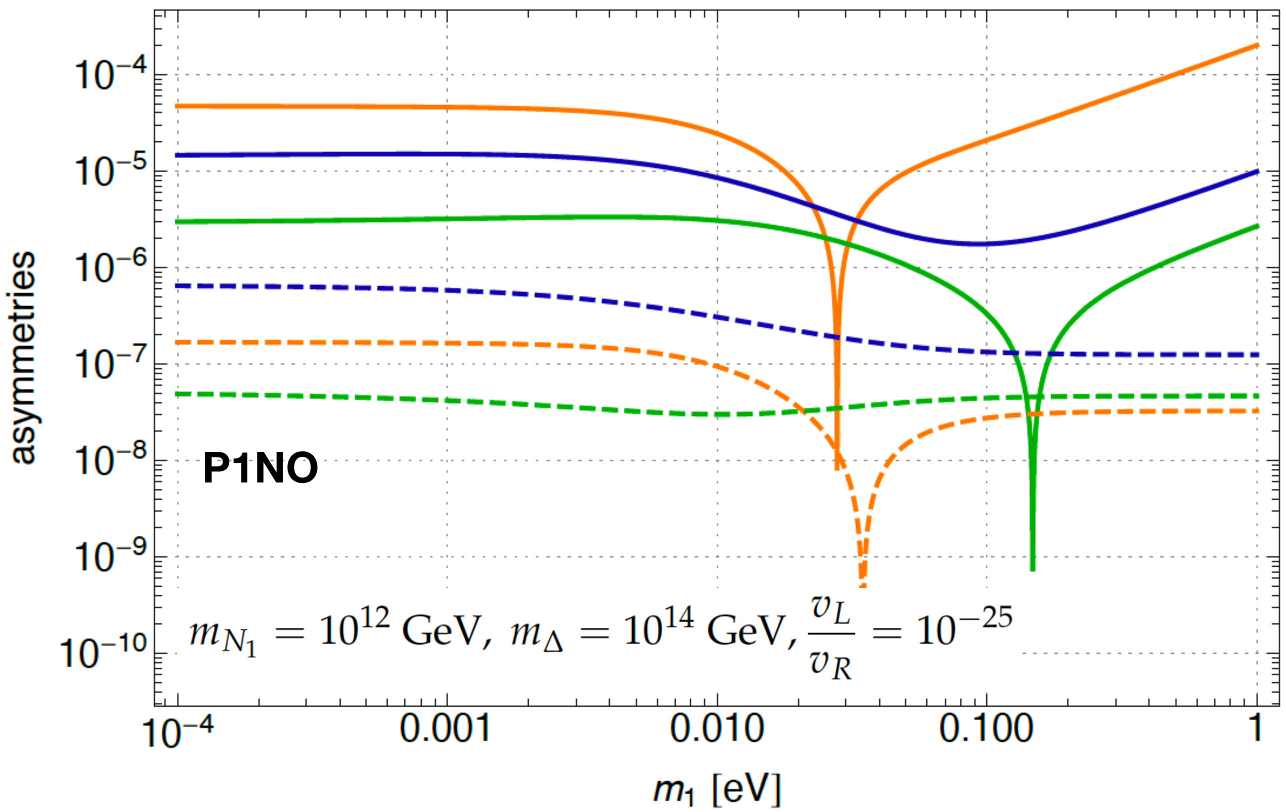
v_L/v_R gets constrained once the mass generation mechanism is chosen

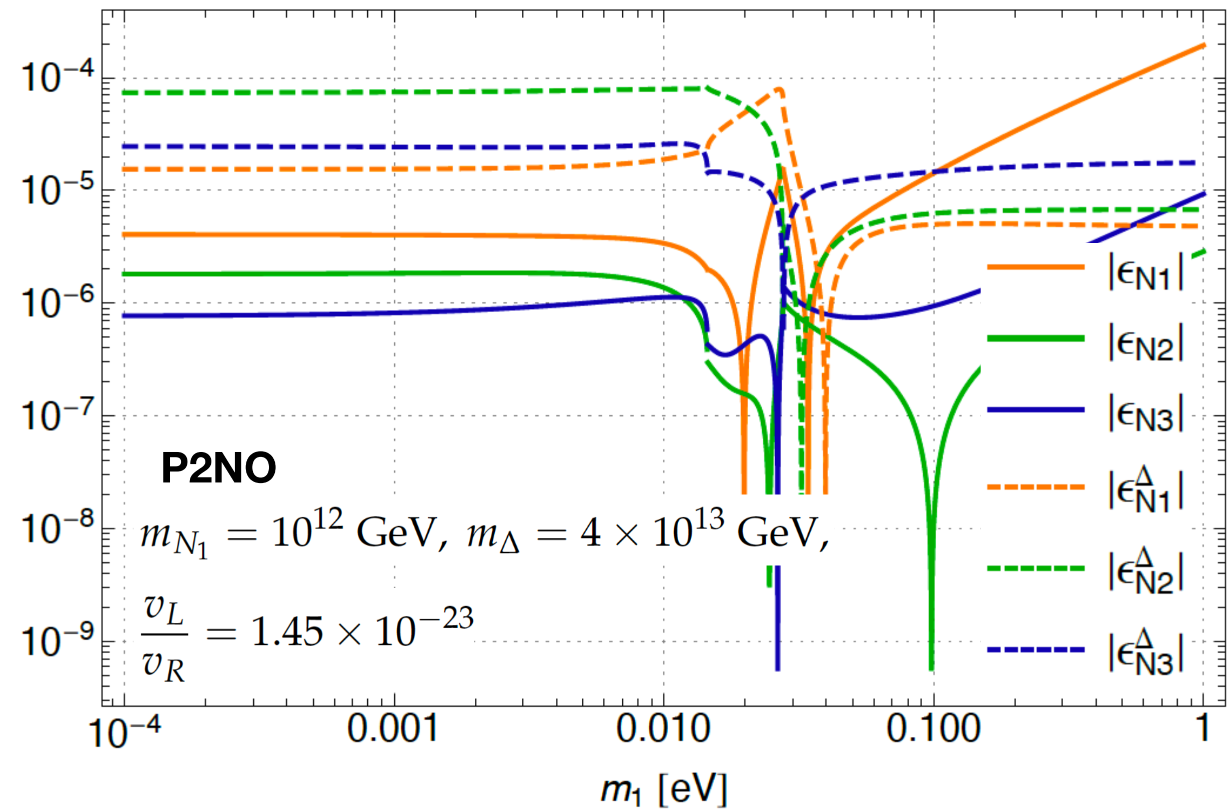
$$m_\Delta \geqslant 10^{12}\text{GeV}$$

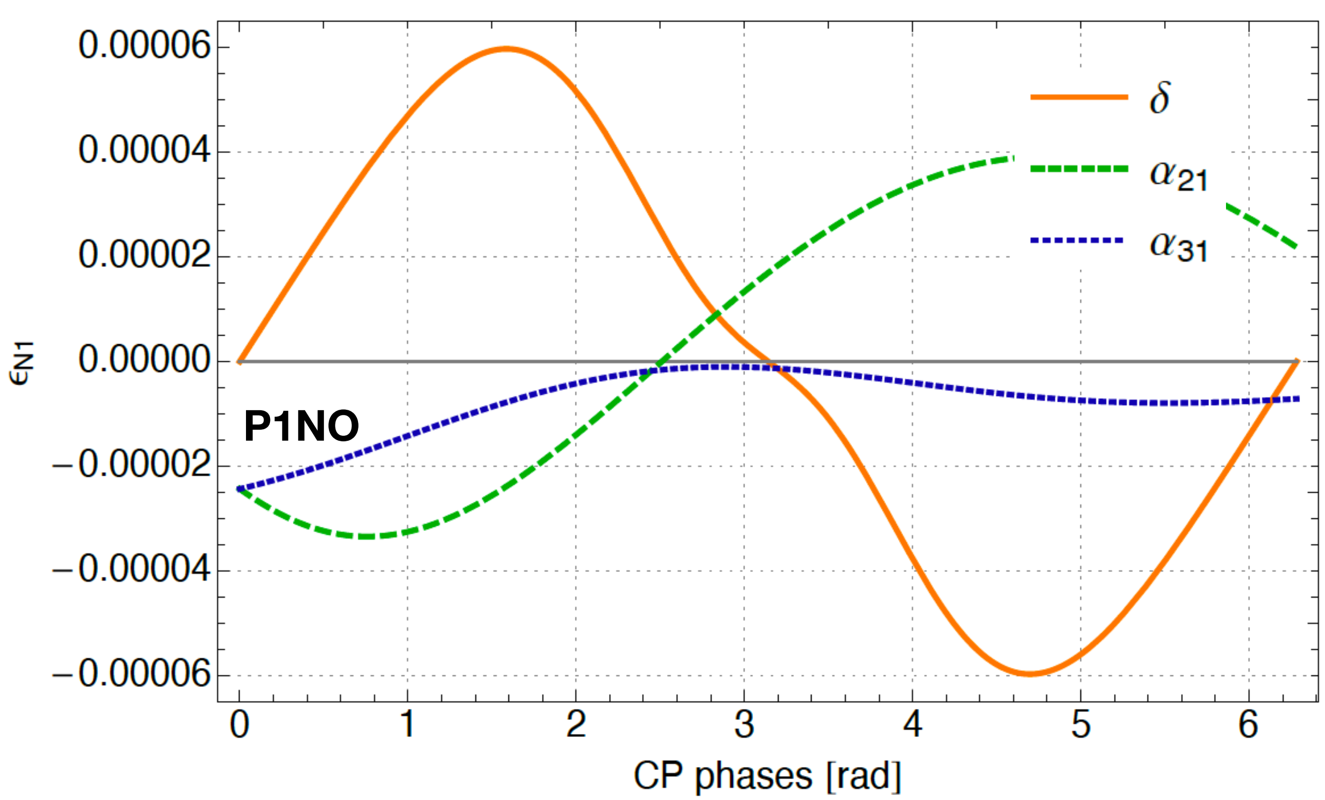
$$M_{W_R} > (2\times 10^5\text{GeV})\left(\frac{M_{N_1}}{10^2\text{GeV}}\right)^{3/4} \qquad v_R > 10^{13}\ \text{GeV}$$

E. Ma, S. Sarkar and U. Sarkar, 1998

Numerical results: CP asymmetries







$$\epsilon_{N_1} = \frac{3}{16\pi}\frac{m_{N_1}}{v^2}\frac{\sum_{i,l} Im[(Y_N)_{1i}(Y_N)_{1l}(M_\nu^{I*})_{il}]}{\sum_i |(Y_N)_{1i}|^2},$$

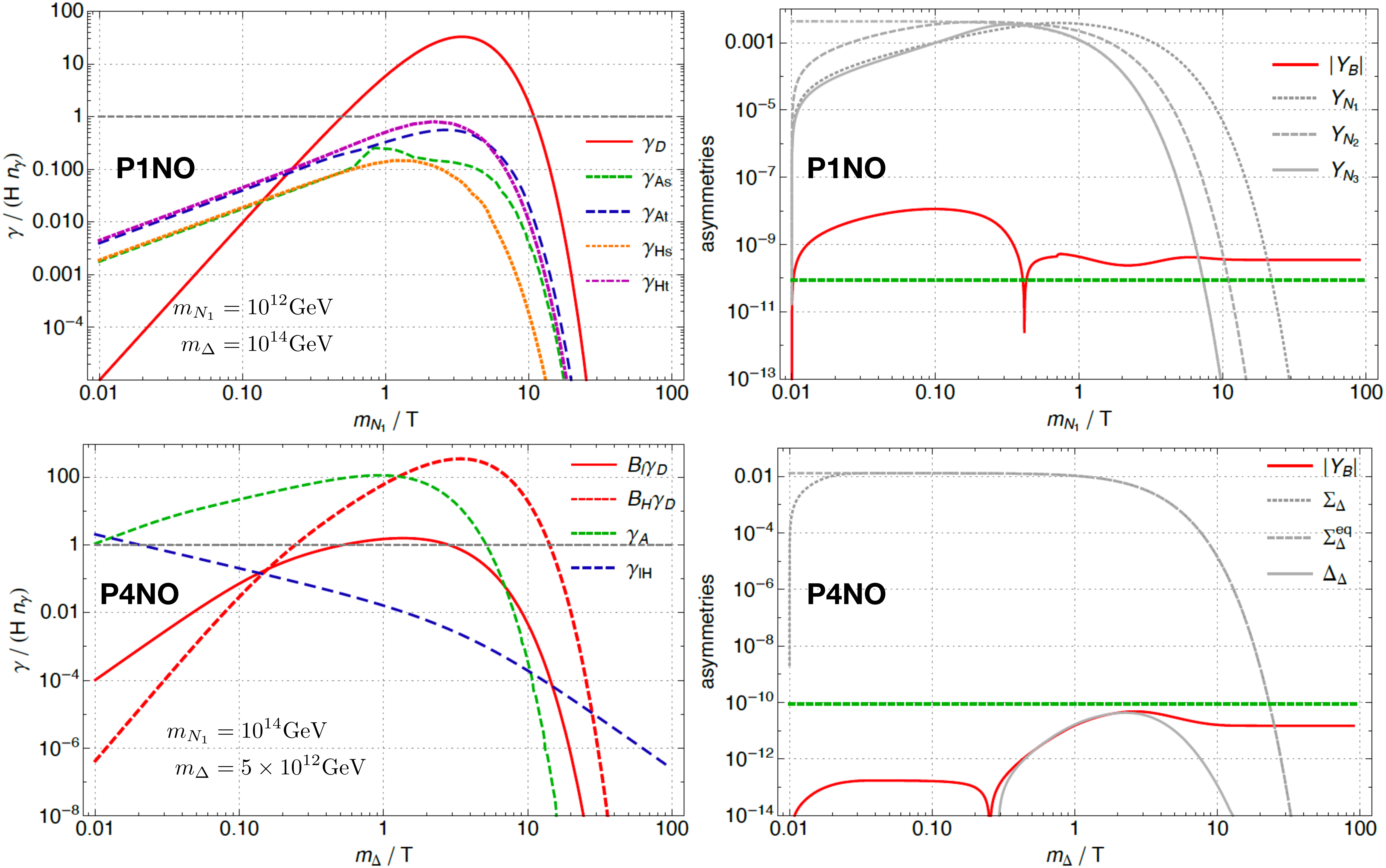
$$\epsilon^\Delta_{N_1} = -\frac{1}{8\pi}\frac{m_{N_1}}{v^2}\frac{\sum_{i,l} Im[(Y_N)_{1i}(Y_N)_{1l}(M_\nu^{II*})_{il}]}{\sum_i |(Y_N)_{1i}|^2}.$$

Hambye & Senjanovic, PLB 2004

Large enough CP asymmetries

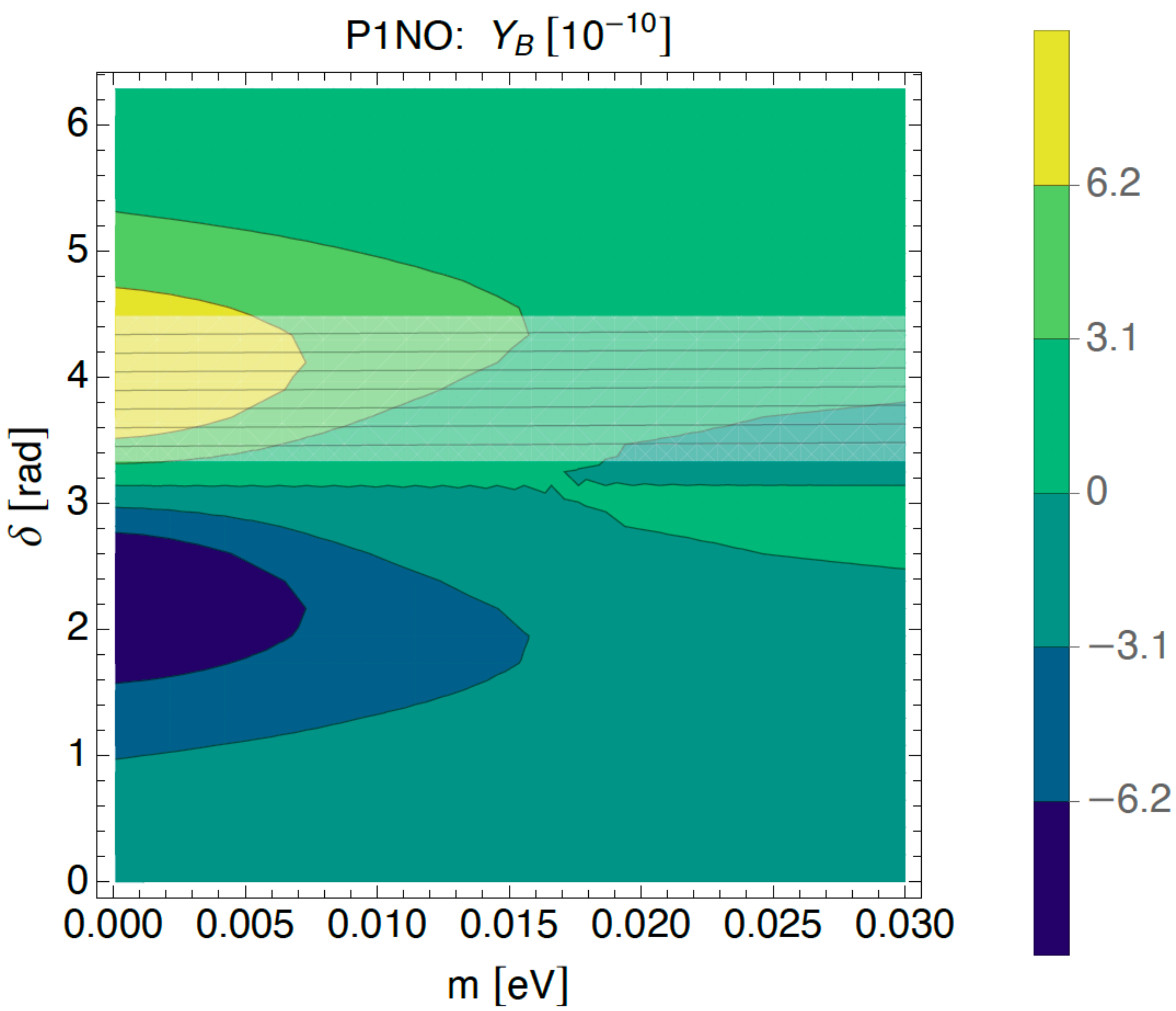
Reaction density, baryon number density & RHN number density evolution

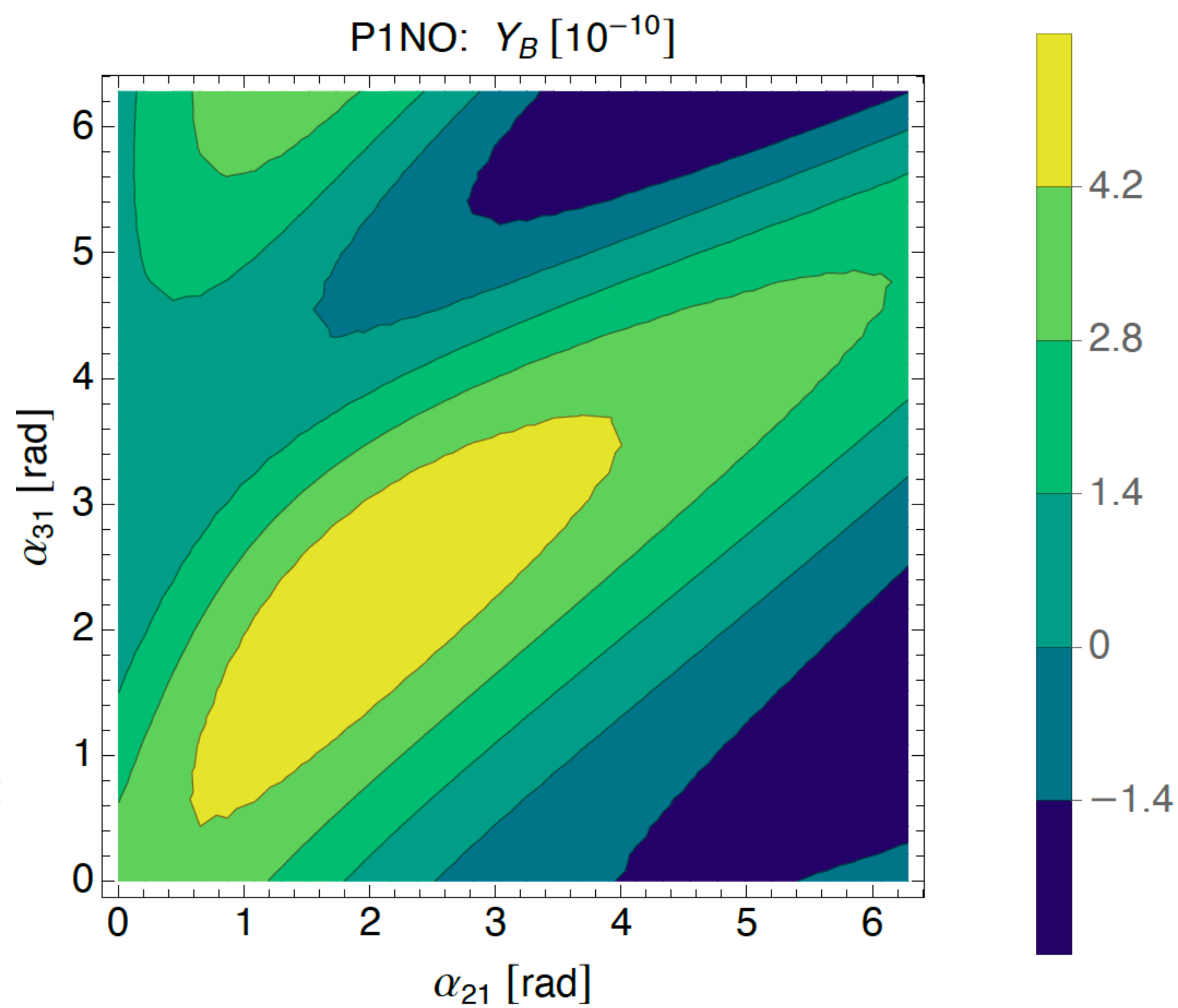
The oscillation parameters are fixed at their best fit values and the Majorana phases are set to zeros. m1=0.01 eV



$B_l \simeq 0.024,\ B_H \simeq 0.976$ **Maximal efficiency** Hambye, Raidal, Strumia, PLB 2006

Numerical results: Baryon asymmetry





$$\alpha_{21} = \alpha_{31} = 0$$

$$m_{\min} = 0.01\text{eV}, \;\; \delta = \delta_{\text{bft}}$$

$$m_{N_1} = 10^{12}\text{ GeV}, \; m_\Delta = 10^{14}\text{ GeV}, \frac{v_L}{v_R} = 10^{-25}$$

Interplay with neutrinoless double beta decay

Effective neutrino mass

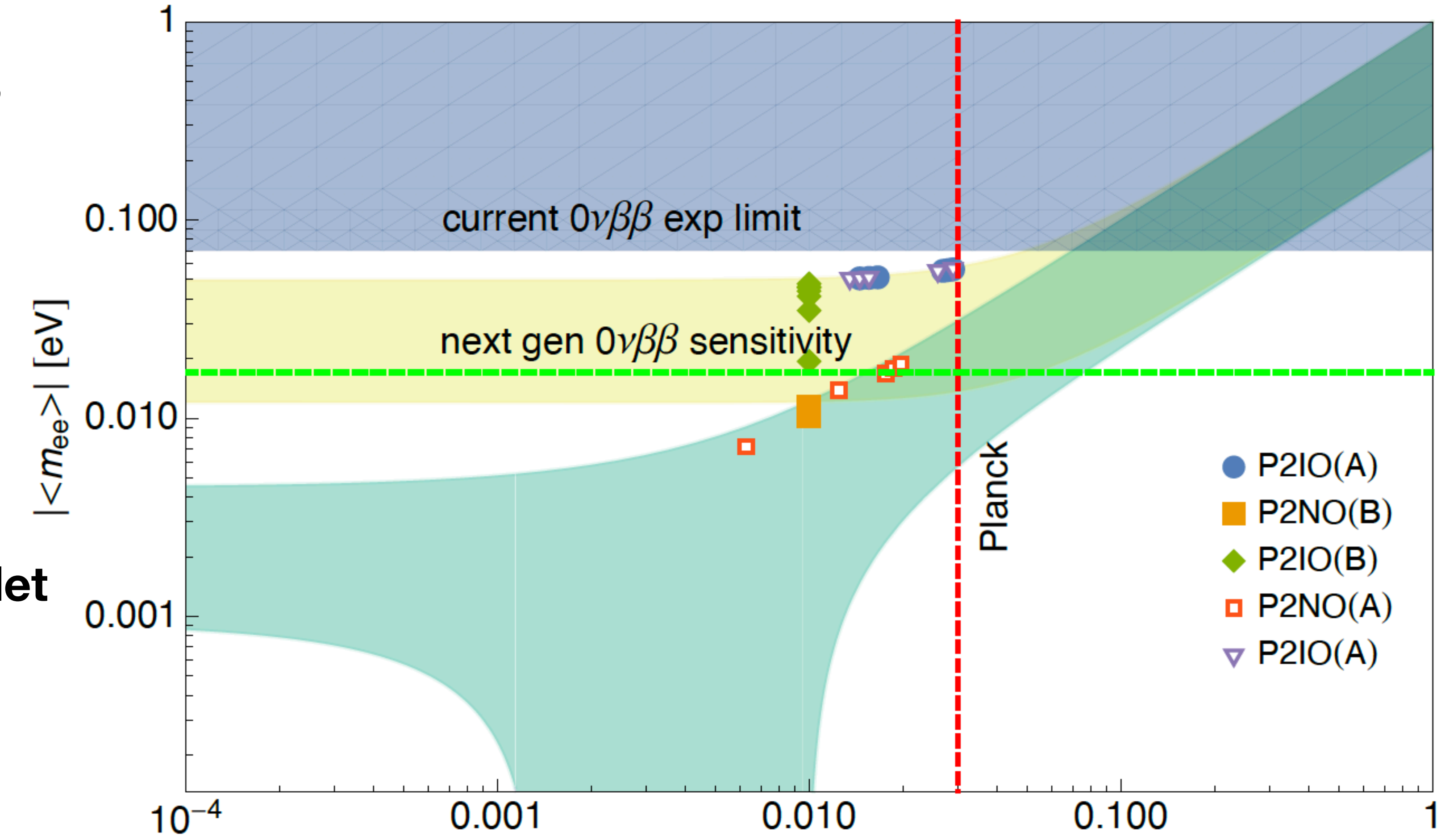
$$|\langle m_{ee}\rangle| = |\sum_{i=1}^{3} U_{ei}^2 m_i|.$$

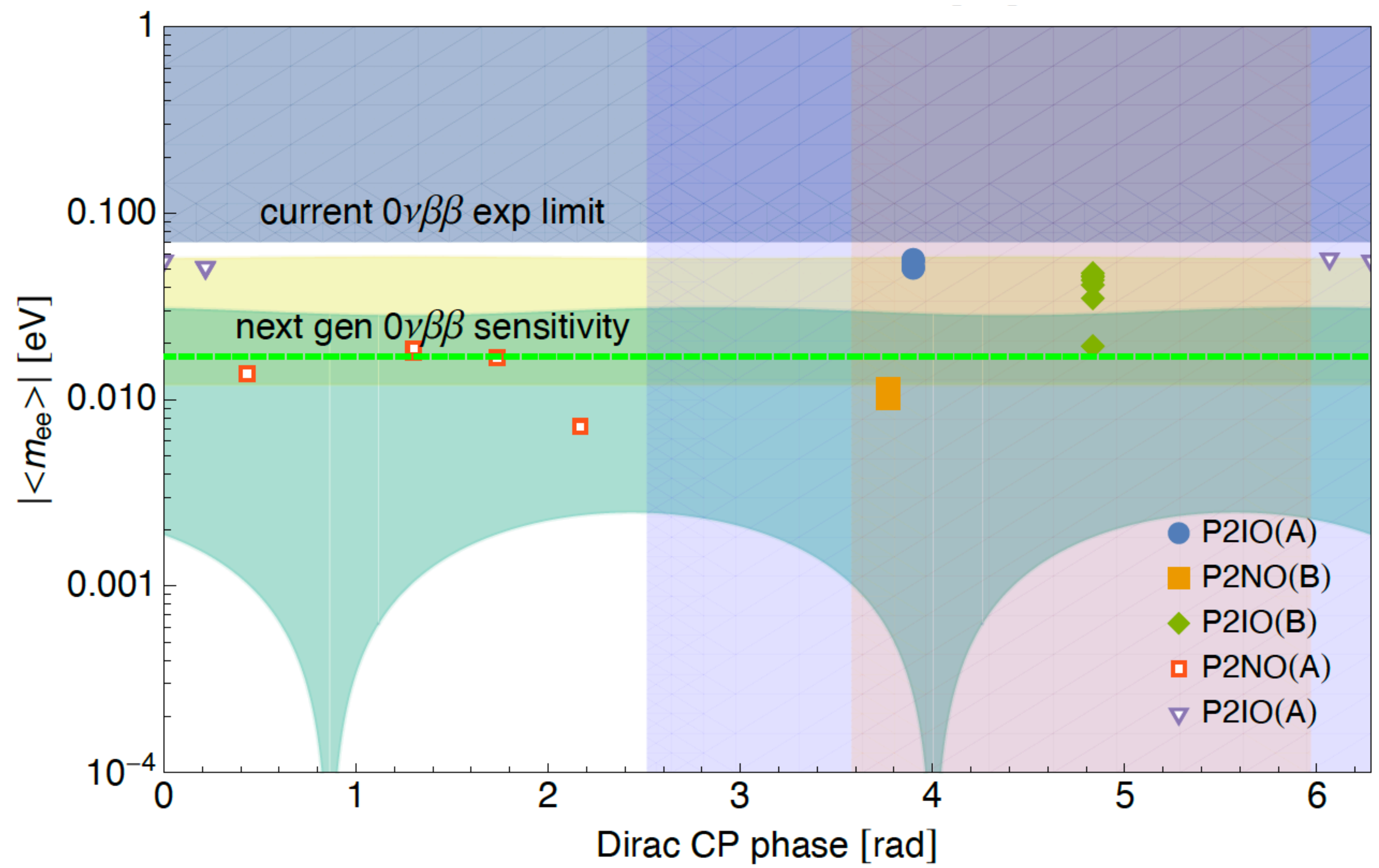
All channels involving W_R and other mediators like heavy neutrinos or triplet scalars in MLRSM are highly suppressed and safely neglected

Predicted phases are within reach of next generation experiments

Some points are excluded by current oscillation experiments

For reviews, see e.g.,
J.D. Vergados, H. Ejiri, F. Simkovic, 2012;
S. Dell'Oro, S. Marcocci, M. Viel and F. Vissani, 2015;
H. Pas and W. Rodejohann, 2015;
J.J. Gomez-Cadenas, J.Martin-Albo, M. Mezzetto, F. Monrabal and M. Sorel, 2012;
S. M. Bilenky and C. Giunti, 2012.





Summary

Disentangling the neutrino Yukawa matrix into light & heavy neutrino masses & mixings:

- **resolves the R matrix ambiguity (Nemevsek, Senjanovic & Tello, 2013; Senjanovic & Tello, 2017, 2019, 2020)**
- **allows to establish a direct connection of low energy CPV & BAU**

Our investigation of the simplest cases shows that:

- **Low energy CPV (esp. the Dirac CP phase) can be the only source of CPV needed in leptogenesis**
- **Predicted CP phases can be probed in next generation neutrinoless double beta decay & oscillation experiments**

Motivate further studies along this track:

- **The flavored regime with lower/varying heavy scales;**
- **A general heavy neutrino mixing**

Thank you for your attention!