Leptonic CP Violation and neutrinoless double beta decay

15 July 2020

Mini-workshop: Particle theory of neutrinoless double beta decay

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Leptonic CP violation

In the lepton sector, CP violation appears in the PMNS matrix in the CC interaction term.

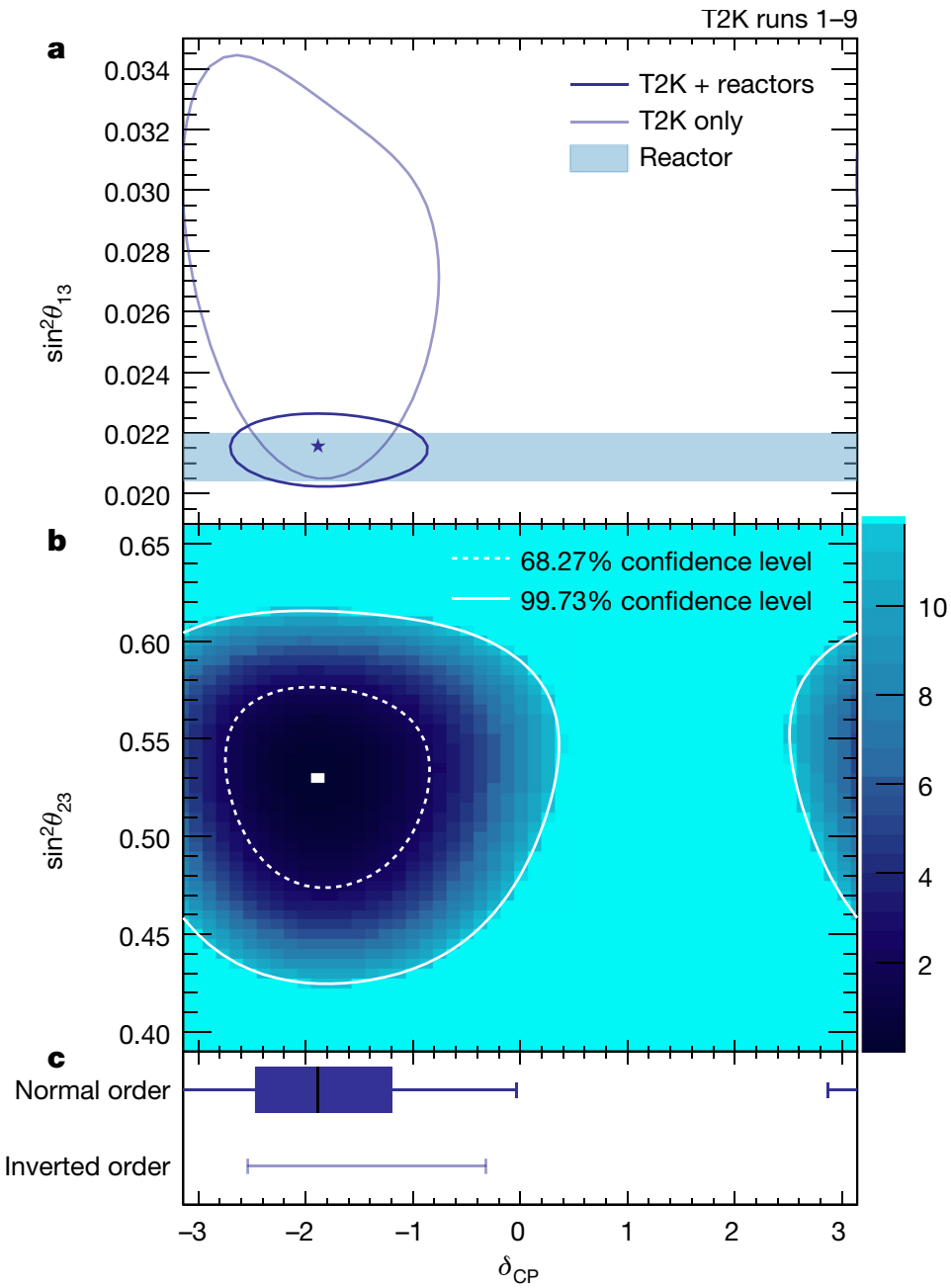
For Dirac neutrinos, one phase is present.

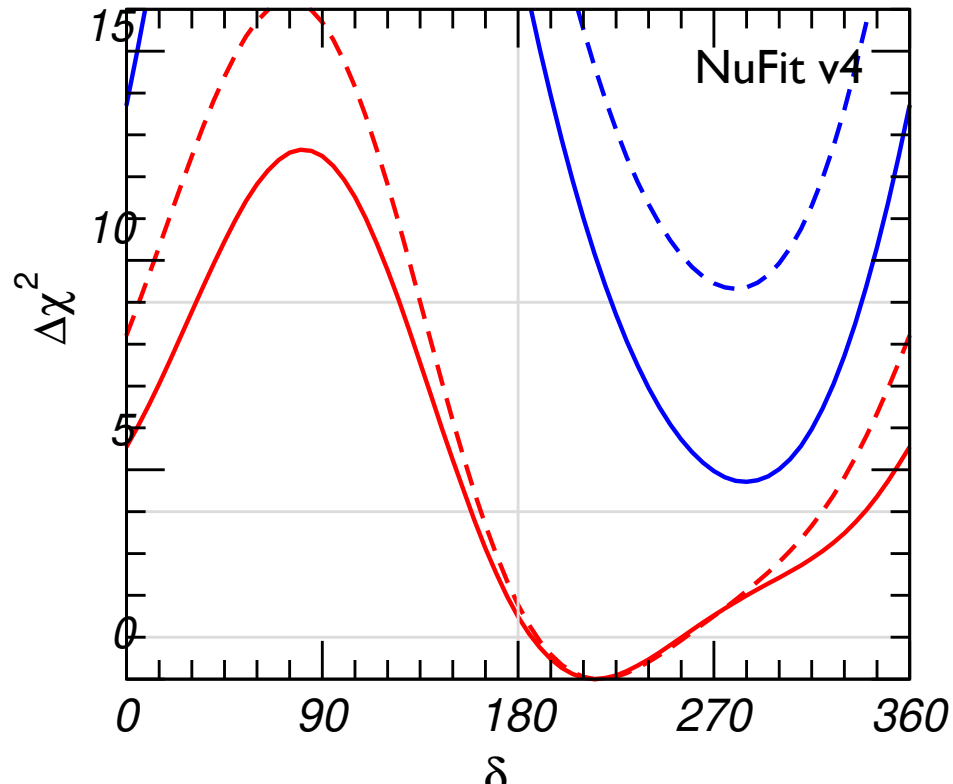
For Majorana neutrinos, the Majorana condition forbids neutrino rephasing: 2 additional CP-violating phases.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\bar{e}^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix}$$
$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

For antineutrinos, $U \rightarrow U^*$

Are we already seeing leptonic CPV?



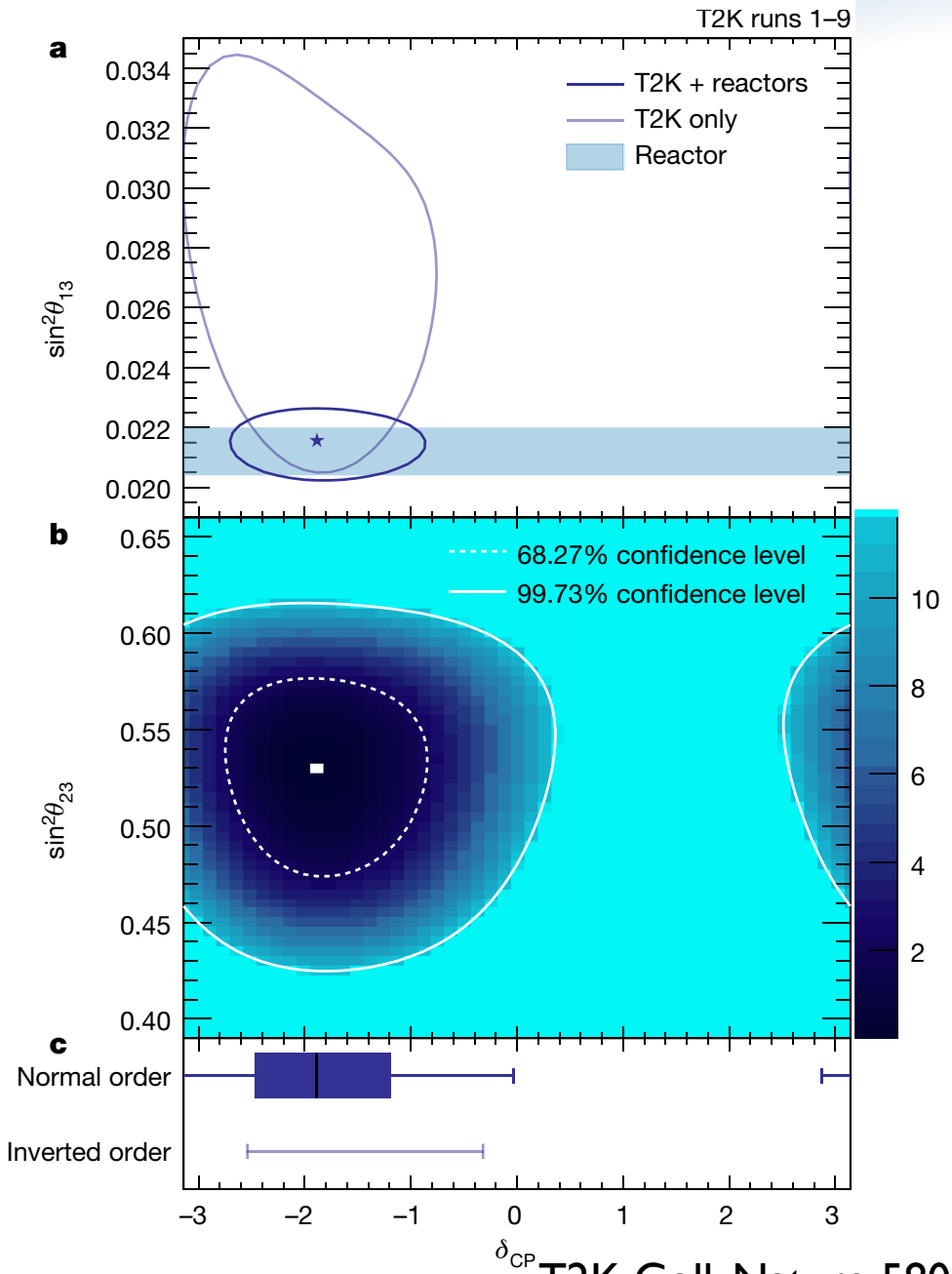


NuFit Coll., 1811.05487

T2K Coll. Nature 580 (2020)

There is a preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.

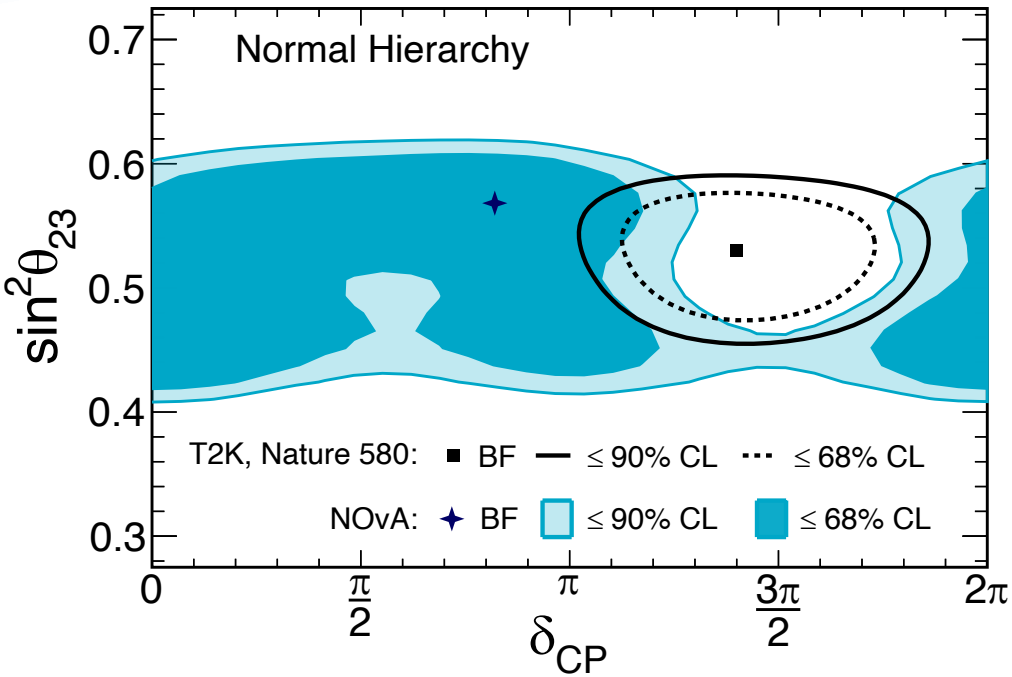
Are we already seeing leptonic CPV?



T2K Coll. Nature 580 (2020)

Comparison to T2K

NOvA Preliminary



NOvA Coll., A. Himmel, Neutrino 2020

Is there a preference for CP-violation? A combined analysis by T2K and NOvA is planned.

1. How are we going to discover leptonic CPV?

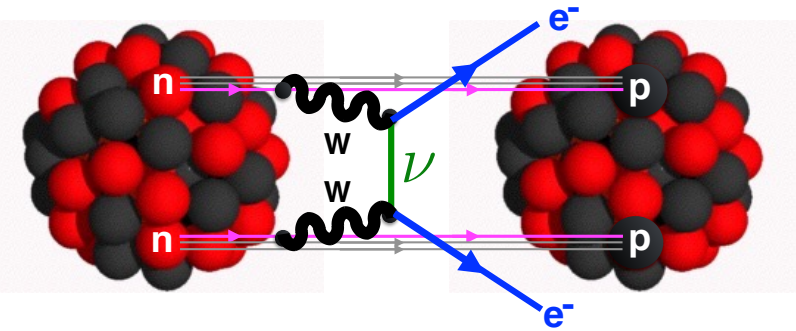
- LBL experiments
- Neutrinoless double beta decay (at least in principle)

2. What can CPV tell us? Implications of CPV

- The origin of leptonic mixing
- Leptogenesis and the baryon asymmetry

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2e, will test the nature of neutrinos.



SP, CERN Courier, Jul 2016

The half-life time depends on neutrino properties

$$T_{1/2}^{-1} \simeq \frac{G_{0\nu}}{m_e} |m_{\beta\beta}|^2 \, M_{\rm NUCL}^2$$

- The effective Majorana mass parameter:

$$|m_{\beta\beta}| \equiv \left| m_1 |U_{\rm e1}|^2 + m_2 |U_{\rm e2}|^2 \, e^{i\alpha_{21}} + m_3 |U_{\rm e3}|^2 \, e^{i(\alpha_{31} - 2\delta)} \right|$$

Mixing angles (known)

CPV phases (unknown)

- M_{NUCL} are the nuclear matrix elements

Predictions for betabeta decay

The predictions for |<m>| depend on the neutrino mass spectrum

- NH (m1<<m2<<m3): |<m>| ~ 1-5 meV

$$|\langle m\rangle| \simeq \left|\sqrt{\Delta m^2_{21}}\cos^2\theta_{13}\sin^2\theta_{12} + \sqrt{\Delta m^2_{31}}\sin^2\theta_{13}e^{i(\alpha_{32}-2\delta)}\right|$$

- IH (m3<<m1~m2): 15 meV < |<m>| < 50 meV

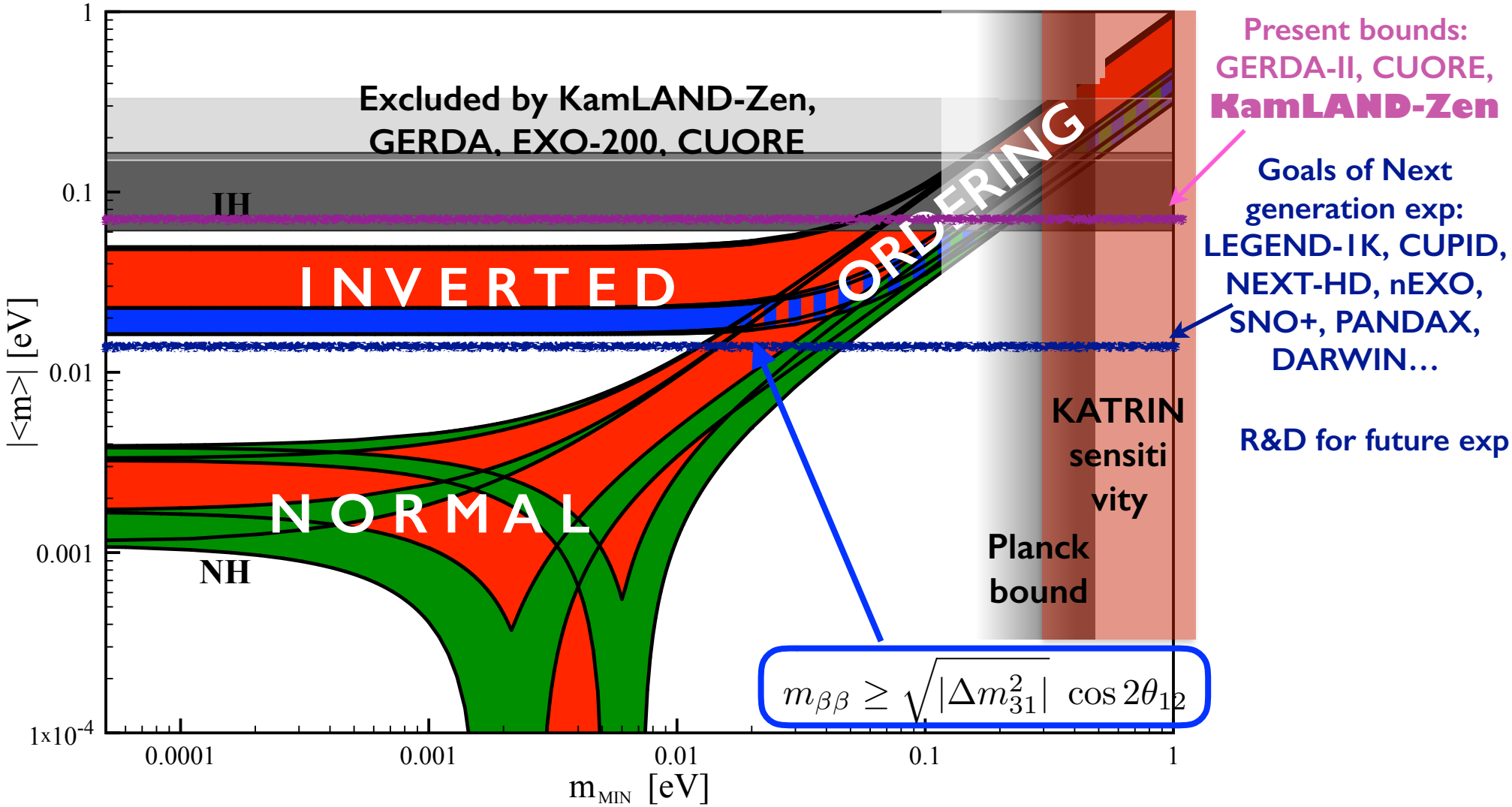
$$\sqrt{\Delta m^2_{31}}\cos 2\theta_{12} \leq |\langle m\rangle| \simeq \sqrt{(1-\sin^2 2\theta_{12}\sin^2\frac{\alpha_{21}}{2})\Delta m^2_{31}} \leq \sqrt{\Delta m^2_{31}}$$

- QD (m1~m2~m3): 44 meV < |<m>| < m1

$$|\langle m\rangle| \simeq m_0\left|(\cos^2\theta_{12}+\sin^2\theta_{12}e^{i\alpha_{21}})\cos^2\theta_{13}+\sin^2\theta_{13}e^{i(\alpha_{31}-2\delta)}\right|$$

Predictions for betabeta decay

The predictions for m_{bb} depend on the neutrino masses:



Wide experimental program ongoing and future.

A positive signal would indicate L violation!

Predictions for betabeta decay

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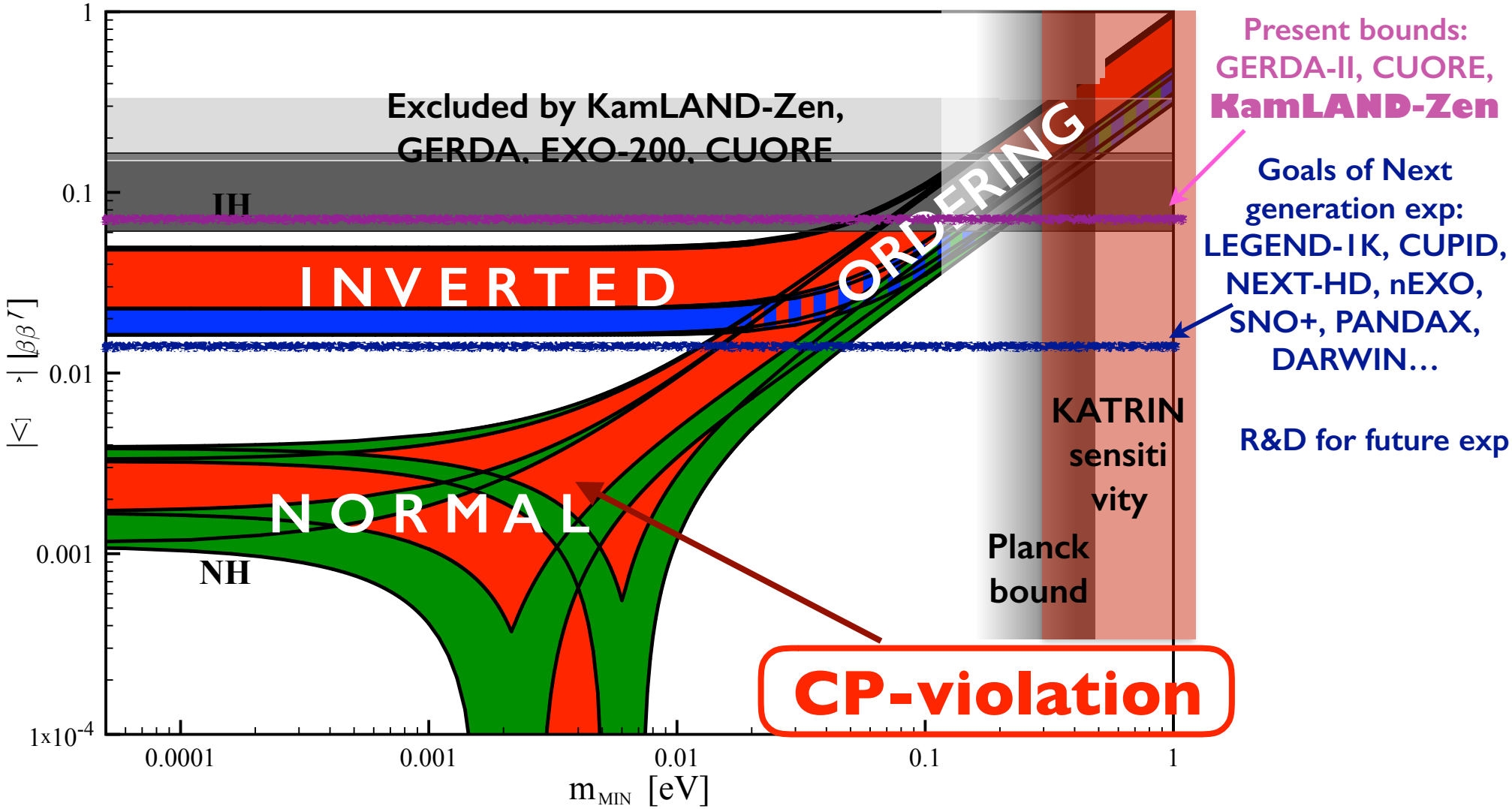

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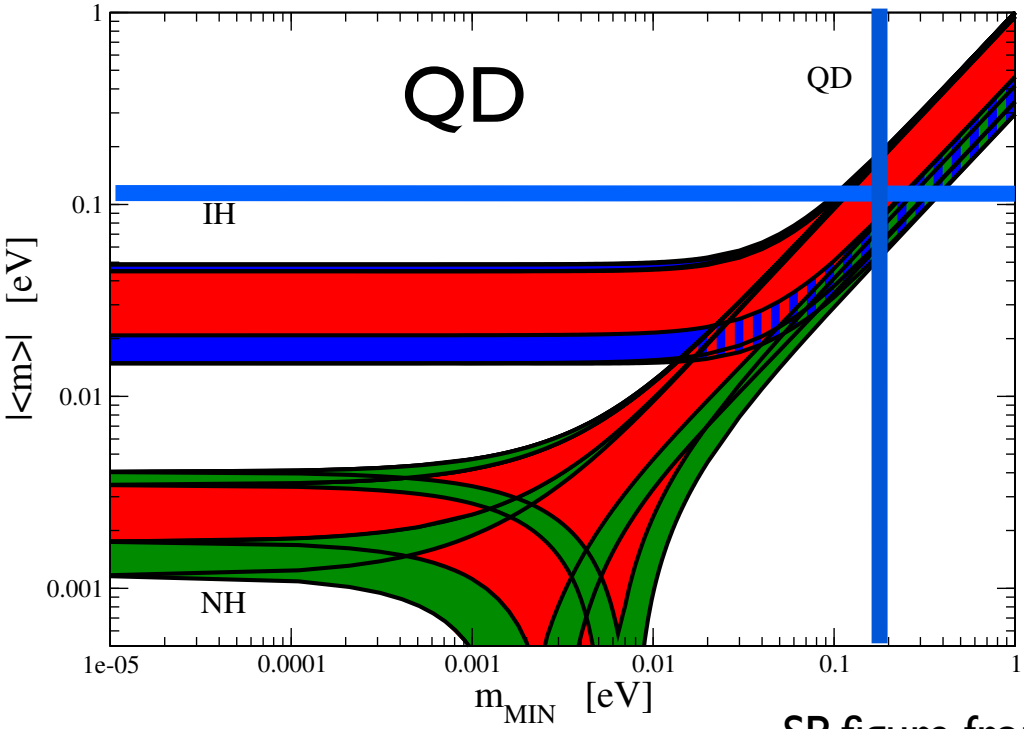
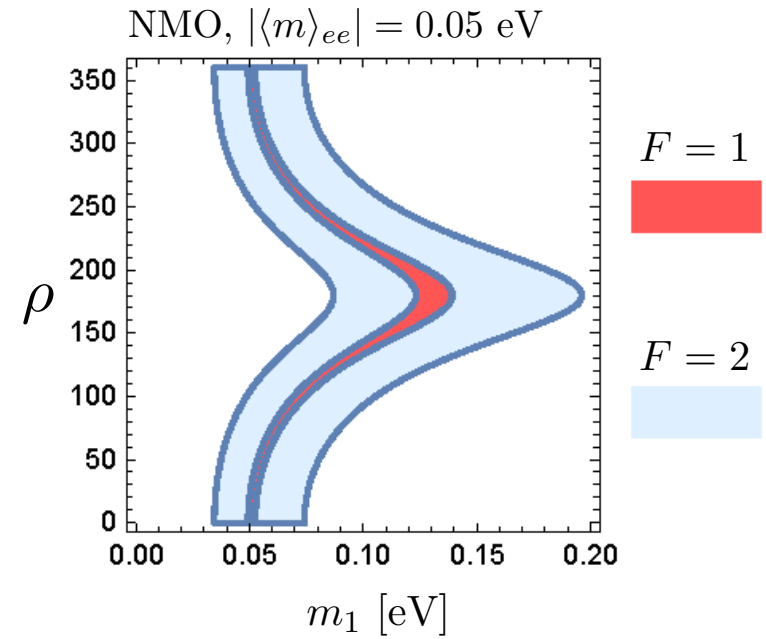
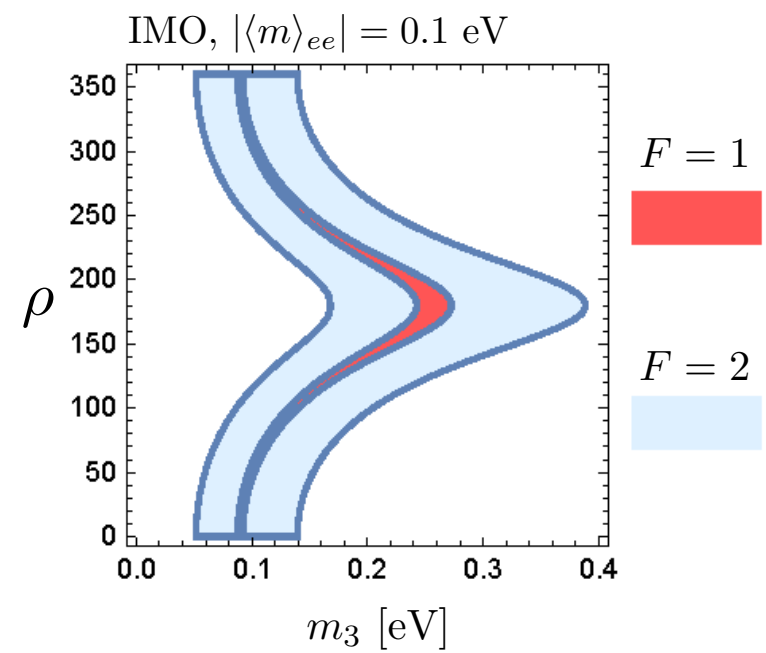
A positive signal would indicate L violation!

Determining CPV with nuless 2beta decay



SP, figure from PDG

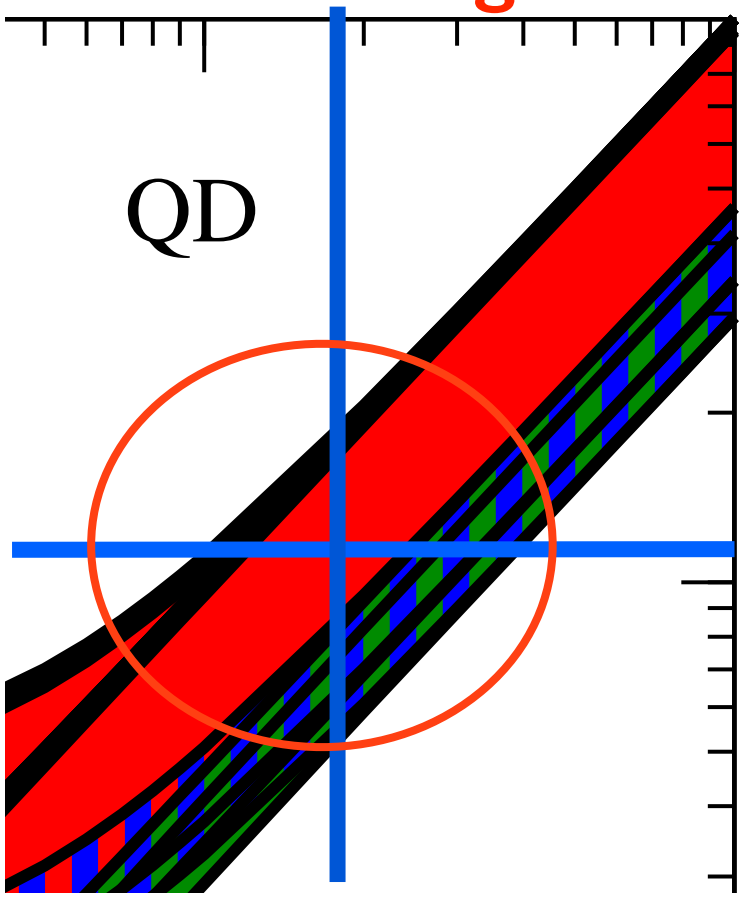


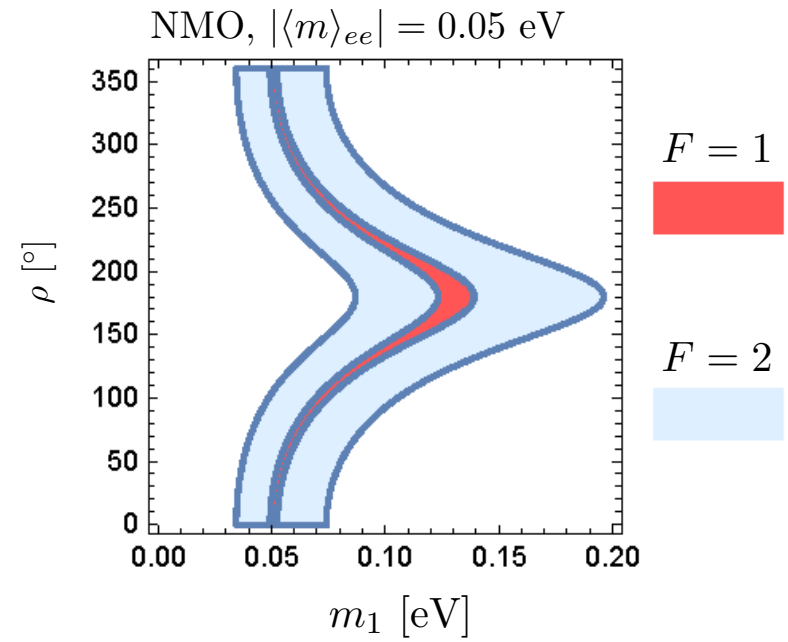


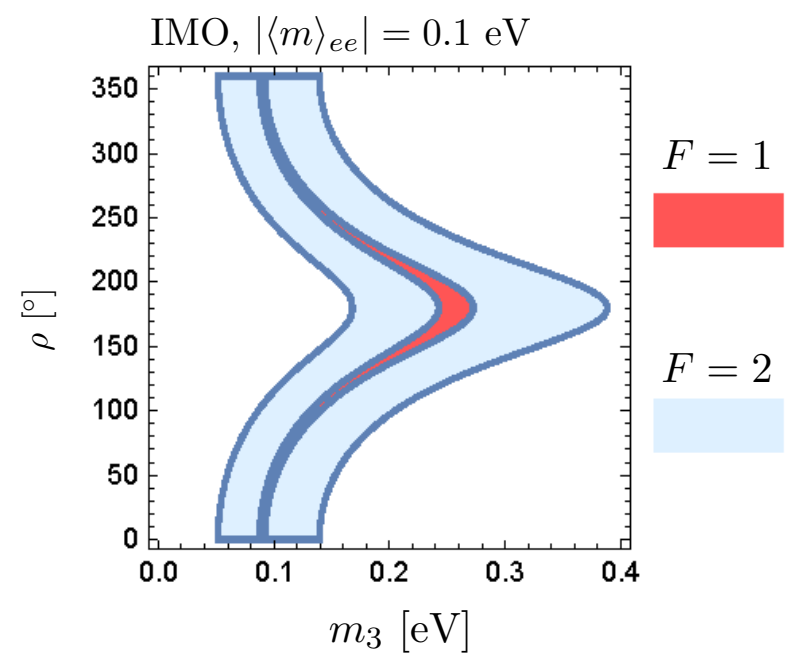
If m_{ee} and neutrino masses are measured with sufficient precision, then it may be possible to establish CPV due to Majorana phases.

Z.-z. Xing, Z.-h. Zhao, Y.-L. Zhou, EPJC75

Determining CPV with nuless 2beta decay







However, this requires also a very precise determination of NME.

See also, SP, Petcov and Wolfenstein, PLB524.; SP, S. Petcov, T. Schwetz, NPB734; F. Simkovic, et al., PRD 87; Joniec, Zralek, PRD73; Deppisch et al, PRD72; Bahcall et al., PRD70; de Gouvea et al, PRD67; SP, et al., PLB579; Nunokawa et al., PRD66; Barger et al., PLB540, Maroni et al, PRD90; Samanta et al., NPB904; Ge et al., PRD95.

Z.-z. Xing, Z.-h. Zhao, Y.-L. Zhou, EPJC75

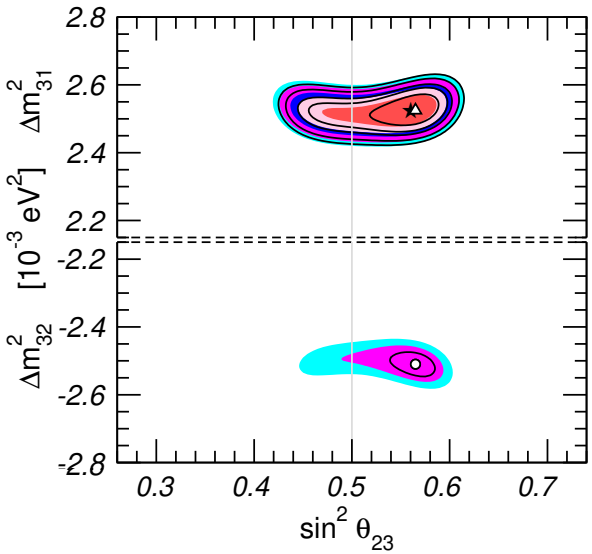
What can leptonic "CPV" tell us?

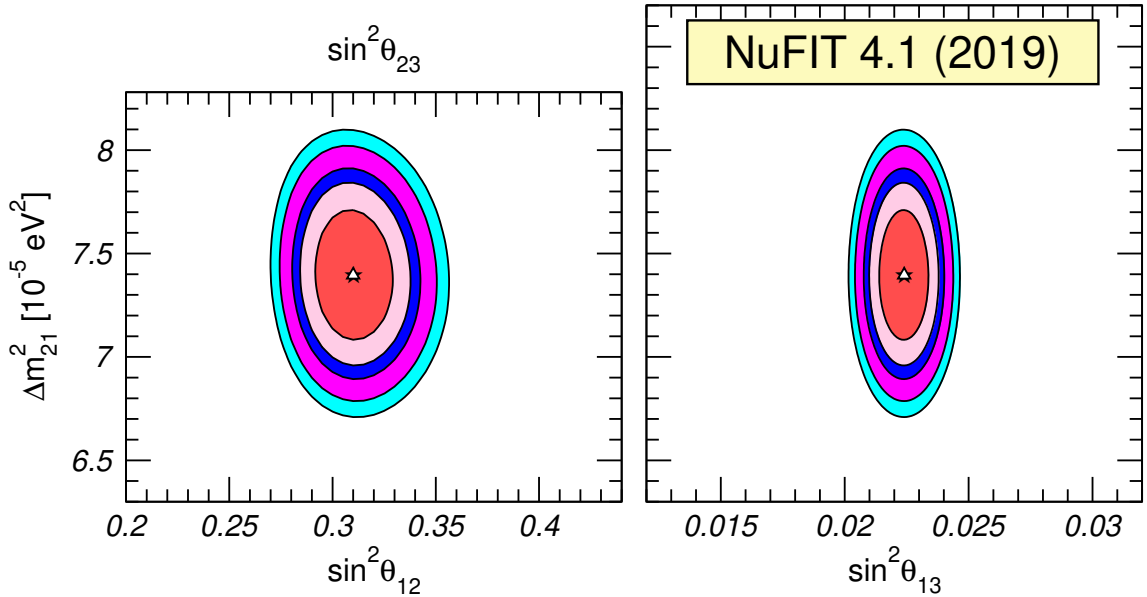
Two main aspects:

- Model predictions for leptonic CPV phases

- the origin of the baryon asymmetry (Leptogenesis)

Hunting for the origin of leptonic mixing





M. C. Gonzalez-Garcia et al., NuFit v4, 1811.05487

Important aspects:

- θ_{23} maximal or close to maximal
- θ_{12} significantly different from maximal
- θ_{13} quite large. This poses some challenges for understanding the origin of the flavour structure
- Mixings very different from quark sector

Masses and mixing from the mass matrix

Neutrino masses and the mixing matrix arises from the diagonalisation of the mass matrix

$$M_M = (U^\dagger)^T m_{\rm diag} U^\dagger \quad \Longrightarrow \quad n_L = U^\dagger \nu_L$$

Theory

Experiments

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U_{\rm osc} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} W_\mu$$

with $U_{PMNS} = U_e^\dagger U_\nu$

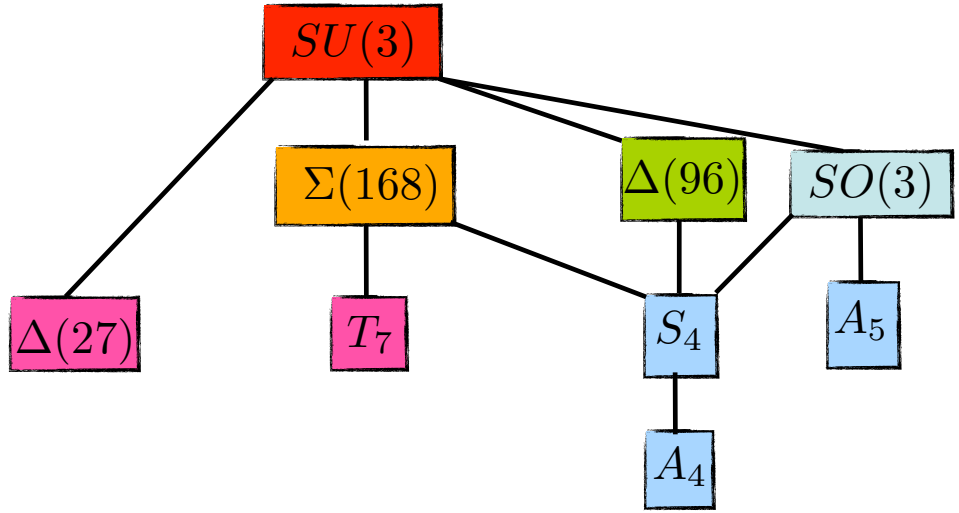
Example. In the diagonal basis for the leptons

$$\mathcal{M}_\nu = \begin{pmatrix} a & b \\ b & c \end{pmatrix}$$

the angle is $\tan 2\theta = \dfrac{2b}{a-c} \gg 1 \quad \text{for} \quad a \sim c \text{ and, or } a, c \ll b$

Symmetry approach

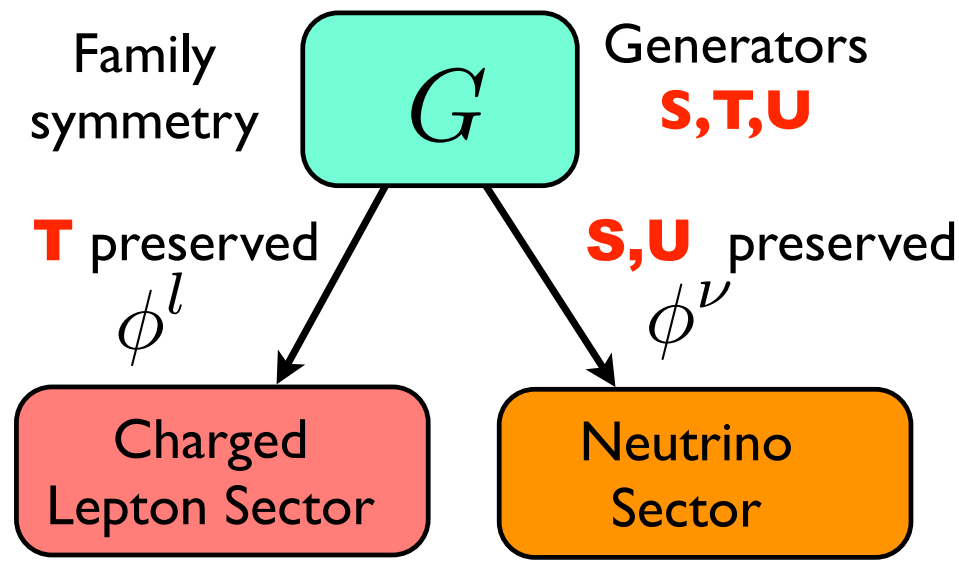
- Choose a leptonic symmetry (e.g. A4, S4, $\mu - \tau$)



- Obtain the mixing matrix (possibly invoking corrections to the first order predictions).

$$U_{PMNS} = U_e^\dagger U_\nu$$

For recent reviews see, e.g. S. King, 1701.04413; Z.-z. Xing, 1909.09610; F. Feruglio, A. Romanino, 1912.06028



Flavour symmetries lead to relations between the masses and/or mixing angles. Examples are the so-called sumrules, e.g.:

$$\sin\theta_{23} - \frac{1}{\sqrt{2}} = \sin\theta_{13}\cos\delta$$

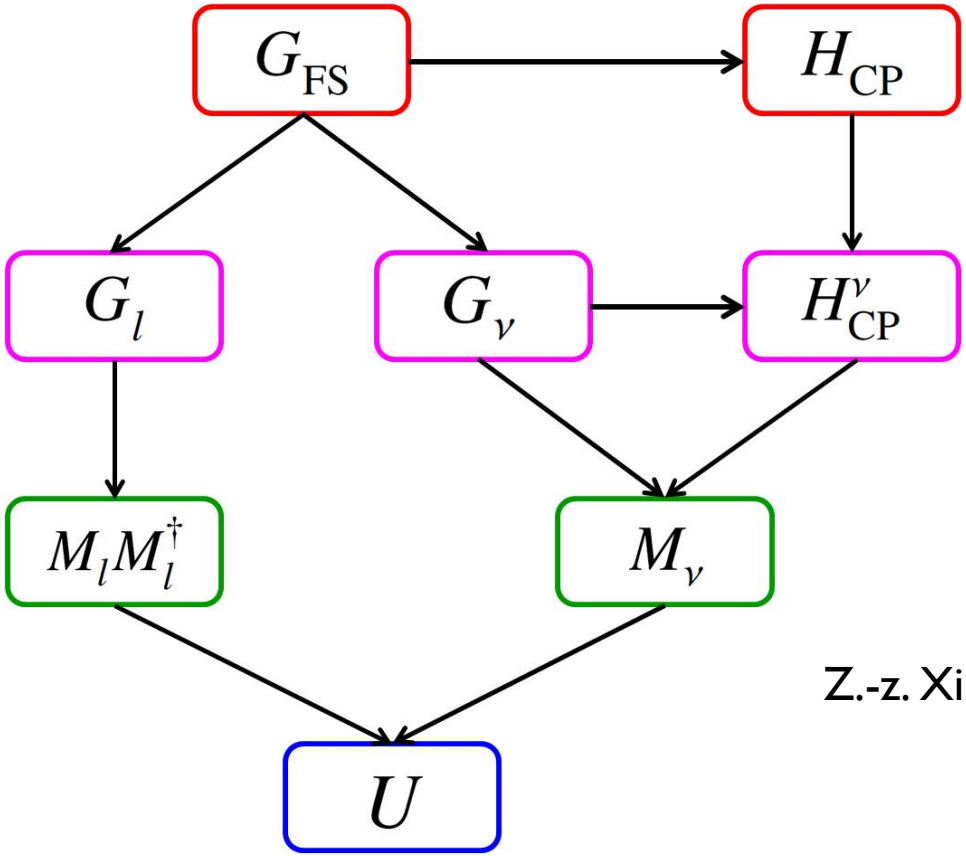
$$\cos\delta = \frac{t_{23}s_{12}^2 + s_{13}^2 c_{12}^2/t_{23} - s_{12}^{\nu 2}(t_{23} + s_{13}^2/t_{23})}{\sin 2\theta_{12} s_{13}}$$

They do not constrain the values of the Majorana phases. One can introduce Generalised CP symmetry:

$$L(t,\vec{x}) \to X L^*(t,-\vec{x})$$

CP symmetry compatible with the flavour symmetry:

$$X\rho(g)^* X^\dagger = \rho(g')$$



Z.-z. Xing, 1909.09610

Requiring CP to be conserved in the neutrino sector

$$X_i^T \, M_\nu \, X_i = M_\nu^*$$

and allows to predict the phases from Majorana masses.

Generically, invoking specific forms of the charged lepton and neutrino mixing matrices, one can obtain specific predictions for the Majorana phases, e.g…..

Case (O)	TBM	GRA	GRB	HG	BM (LC)
A1 (NO)	$342.3 \vee 17.7$	$341.4 \vee 18.6$	$342.9 \vee 17.1$	$342.1 \vee 17.9$	$359.0 \vee 1.0$
A1 (IO)	$342.1 \vee 17.9$	$341.2 \vee 18.8$	$342.7 \vee 17.3$	$341.9 \vee 18.1$	$357.4 \vee 2.6$
A2 (NO)	$17.7 \vee 342.3$	$18.6 \vee 341.4$	$17.1 \vee 342.9$	$17.9 \vee 342.1$	$1.0 \vee 359.0$
A2 (IO)	$17.9 \vee 342.1$	$18.8 \vee 341.2$	$17.3 \vee 342.7$	$18.1 \vee 341.9$	$2.6 \vee 357.4$
B1 (NO)	$340.3 \vee 19.7$	$339.3 \vee 20.7$	$340.8 \vee 19.2$	$339.9 \vee 20.1$	$351.7 \vee 8.3$
B1 (IO)	$345.0 \vee 15.0$	$344.1 \vee 15.9$	$345.7 \vee 14.3$	$345.0 \vee 15.0$	—
B2 (NO)	$15.1 \vee 344.9$	$16.0 \vee 344.0$	$14.4 \vee 345.6$	$15.0 \vee 345.0$	—
B2 (IO)	$20.2 \vee 339.8$	$21.1 \vee 338.9$	$19.6 \vee 340.4$	$20.6 \vee 339.4$	$9.2 \vee 350.8$
B3 (NO)	$342.5 \vee 17.5$	$341.4 \vee 18.6$	$343.1 \vee 16.9$	$342.0 \vee 18.0$	—
B3 (IO)	$342.3 \vee 17.7$	$341.2 \vee 18.8$	$342.9 \vee 17.1$	$341.8 \vee 18.2$	—

A. $\tilde{U}_\nu = R_{23}(\theta^\nu_{23})R_{12}(\theta^\nu_{12})$ and i) $\tilde{U}_e = R^{-1}_{12}(\theta^e_{12})$, ii) $\tilde{U}_e = R^{-1}_{13}(\theta^e_{13})$, iii) $\tilde{U}_e = R^{-1}_{23}(\theta^e_{23})R^{-1}_{12}(\theta^e_{12})$, iv) $\tilde{U}_e = R^{-1}_{23}(\theta^e_{23})R^{-1}_{13}(\theta^e_{13})$, v) $\tilde{U}_e = R^{-1}_{13}(\theta^e_{13})R^{-1}_{12}(\theta^e_{12})$;

B. $\tilde{U}_\nu = R_{23}(\theta^\nu_{23})R_{13}(\theta^\nu_{13})R_{12}(\theta^\nu_{12})$ and vi) $\tilde{U}_e = R^{-1}_{12}(\theta^e_{12})$, vii) $\tilde{U}_e = R^{-1}_{13}(\theta^e_{13})$.

I. Girardi, S.T. Petcov, A. Titov, 1605.04172; see also S. Petcov, NPB 892 (2015)

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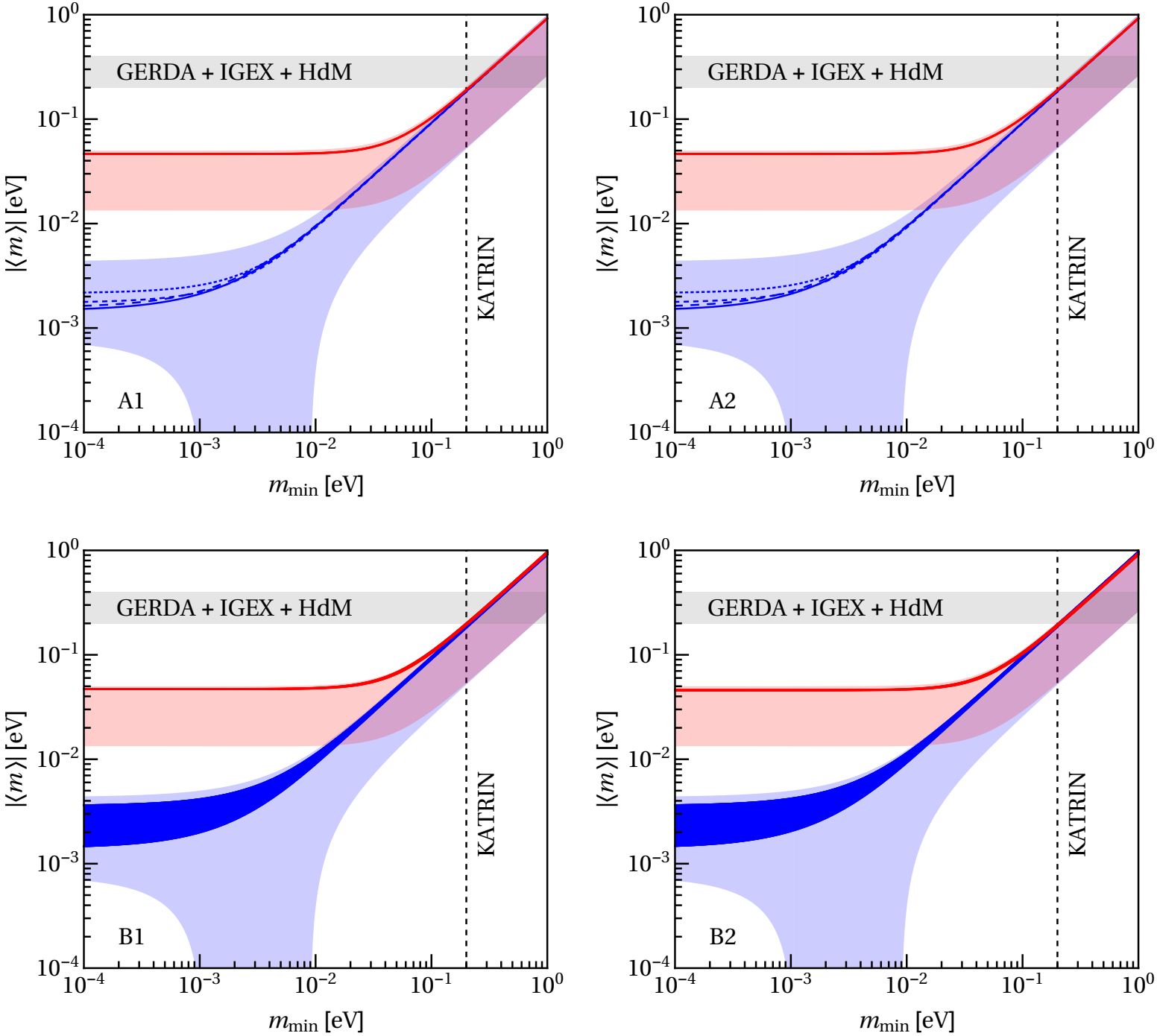
… and for m_{ee} to be confronted with data.



I. Girardi, S. T. Petcov, A. Titov, 1605.04172

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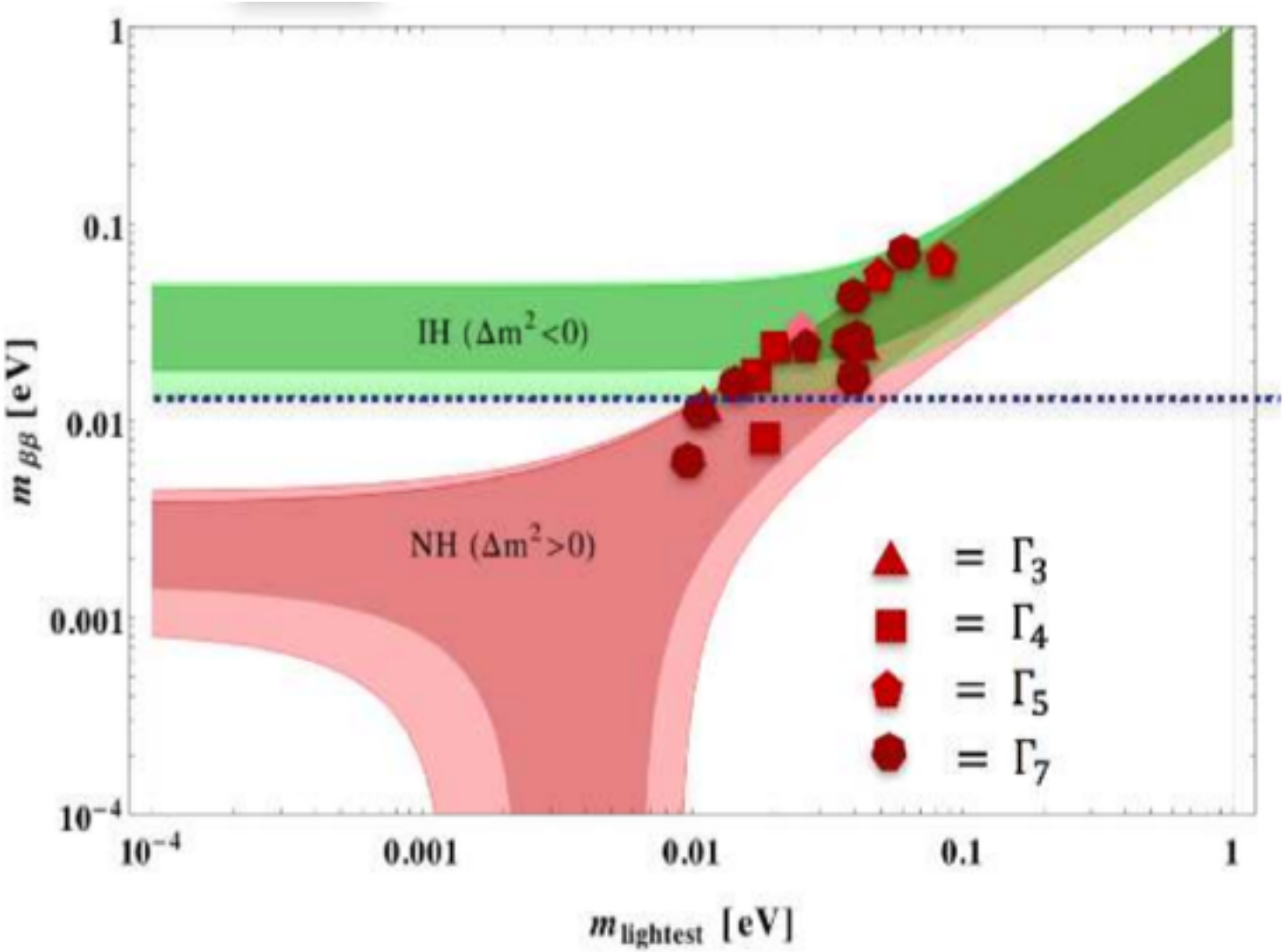
Another example: predictions for modular symmetries.



F. Feruglio, Bethe Colloquium, 18 June 2020, reported in S. Petcov, Neutrino 2020

What can leptonic "CPV" tell us?

- Model predictions for leptonic CPV phases

- the origin of the baryon asymmetry (Leptogenesis in models of neutrino masses)

Neutrino masses BSM: see saw type I

Symmetry magazine

- Introduce a right handed neutrino **N**
- Couple it to the Higgs

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

See-saw type I models can be embedded in GUT theories and explain the baryon asymmetry via leptogenesis.

The baryon asymmetry. The theory

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.18 \pm 0.06) \times 10^{-10}$$

Planck, 1502.01589

In order to generate it dynamically in the Early Universe, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

$$X^c \to \bar{q}q \qquad X \to \bar{q}q$$

$$X \to \ell q \qquad X^c \to \bar{\ell}\bar{q}$$

- C, CP violation;

$$X \to \bar{q}q \qquad X \to \ell q$$

- departure from thermal equilibrium.

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Neutrinoless double beta decay

- departure from thermal equilibrium.

Leptogenesis

- At T>M, the right-handed neutrinos N are in equilibrium thanks to the processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

- When T<M, N drops out of equilibrium

$$N \to \ell H \qquad\qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- Sphalerons convert it into a baryon asymmetry.

T

T=M

T=100 GeV

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry

$$\epsilon \equiv \frac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$$

2. solve the Boltzmann equations to take into account the wash-out of the asymmetry

$$Y_L = k\epsilon$$

3. convert the lepton asymmetry into the baryon one

$$\boxed{Y_B = \frac{k}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4} \epsilon}$$

For T < 10^{12} GeV, flavour effects are important.

Is there a connection between low E CPV and BAU?

ϵ depends on the CPV phases in Y_ν

$$\epsilon \propto \sum_j \Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

One flavour approximation

and in the U mixing matrix via the see-saw formula.

$$m_\nu = U^* m_i U^\dagger = -Y_\nu^T M_R^{-1} Y_\nu v^2$$

Let's consider see-saw type I with 3 NRs.

High energy		
M_R	3	0
Y_ν	9	6

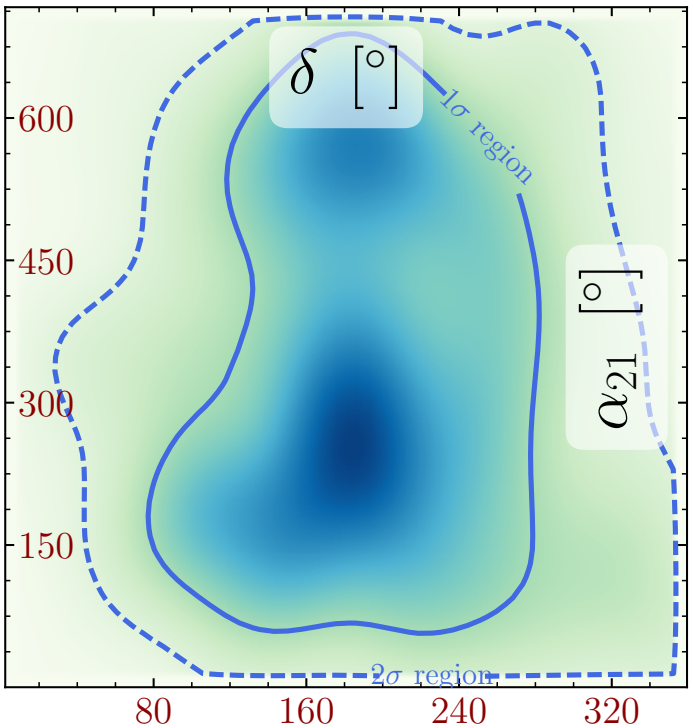
Low energy		
m_i	3	0
U	3	3

3 phases missing!

Does observing low energy CPV imply BAU?

In see-saw type I, let's consider the case of low energy CPV (R real) in presence of flavour effects.

NO, $M_1 = 10^{11}$GeV
$M_2 = 10^{12}$GeV



Intermediate flavour regime:
10^9GeV < M_1 <10^{12}GeV

$$\epsilon_{\tau\tau}^{(1)} = (0.515 - 3.94 c_{13})\, s_{13} \times 10^{-8} \sin\delta$$

$$\epsilon_{\tau\tau}^{(1)} = 2.11 \times 10^{-7} \sin\frac{\alpha_{31}}{2}$$

Moffat, SP, Petcov, Turner, 1804. 05066, 1809.08251
SP, Petcov, Riotto, PRD and NPB 2007; SP 2014

A full study shows that low energy CPV can give an important (even dominant) contribution to the BAU. For Majorana CPV, effects larger by a factor of ~10.

Conclusions

- There are current intriguing hints of CP-violation. Future LBL experiments will hunt for the delta phase and potentially measure it with precision. Neutrinoless double beta decay could point towards Majorana CPV.

- CP violation can related to flavour models.

- CP-violation and L violation, are the key ingredients of leptogenesis.

Neutrinoless double beta decay may give a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.

More details on the low-high energy connection

We try to separate the low energy parameters (measurable in experiments) and the high energy ones on which one cannot get information.

The Casas-Ibarra parameterization is useful:

$$U^* \sqrt{m_i} \sqrt{m_i} U^\dagger = -Y_\nu^T \sqrt{M_R^{-1}} \sqrt{M_R^{-1}} Y_\nu v^2$$

$$U^* \sqrt{m_i} \sqrt{m_i} U^\dagger = -Y_\nu^T \sqrt{M_R^{-1}} \underbrace{RR^T}_{=1} \sqrt{M_R^{-1}} Y_\nu v^2$$

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$$U^* \sqrt{m_i} \boxed{\sqrt{m_i} U^\dagger} = -Y_\nu^T \sqrt{M_R^{-1}} R \boxed{R^T \sqrt{M_R^{-1}} Y_\nu v^2}$$

$$\boxed{Y_\nu v \simeq i \sqrt{M_R} R \sqrt{m_i} U^\dagger_{\rm PMNS}}$$

high energy untestable parameters

low energy parameters

As the simplest example, M1<< M2<<M3.
In the one flavour case (M1≳10^{12} GeV) (pre-2018)

$$\varepsilon_1 = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\alpha\beta\rho} m_\rho^{1/2} m_\beta^{3/2} \cancel{U^*_{\alpha\rho}} U_{\alpha\beta} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2} = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

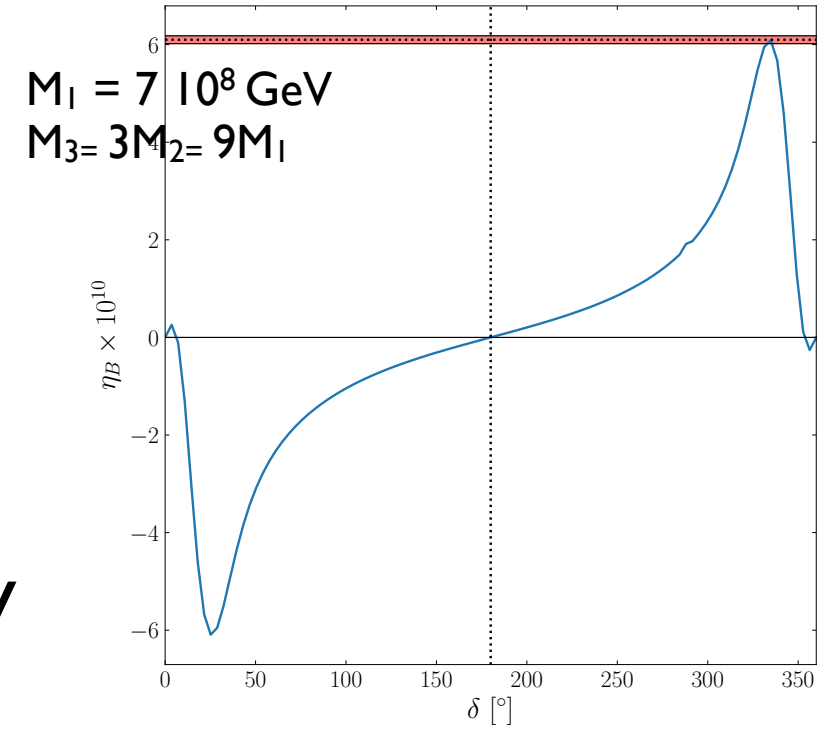
The low energy phases do not enter directly: observing CPV DOES NOT imply a baryon asymmetry.

If flavours can be distinguished, the low energy phases enter directly the baryon asymmetry.

$$\varepsilon_\alpha = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

Low mass flavour regime: $M_1 < 10^9$GeV

$$R \approx \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ \pm i R_{22} & R_{22} & R_{23} \\ -R_{22} & \pm i R_{22} & \pm i R_{23} \end{pmatrix}$$



A special structure of the R matrix is required. R22>>1, enhancing the CP asymmetry without affecting neutrino masses (at three level). Going to lower masses requires finetuning as one-loop mass contributions are important.

High mass (unflavoured) regime: $M_1 > 10^{12}$GeV

Due to washout which is affected by flavour, even at high masses the low energy CPV phases play a role.