Leptonic CP Violation and Matter-Antimatter Asymmetry of the Universe

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There have been remarkable discoveries in neutrino physics in the last ~ 20 years.

Experimental Proofs for $\nu-$Oscillations

$-\nu_{\rm atm}$: SK UP-DOWN ASYMMETRY

θ_Z-, $L/E-$ **dependences of $\mu-$like events**

Dominant $\nu_{\mu} \rightarrow \nu_{\tau}$ K2K, MINOS, T2K; CNGS (OPERA)

$-\nu_{\odot}$: **Homestake, Kamiokande, SAGE, GALLEX/GNO**

Super-Kamiokande, SNO, BOREXINO; KamLAND

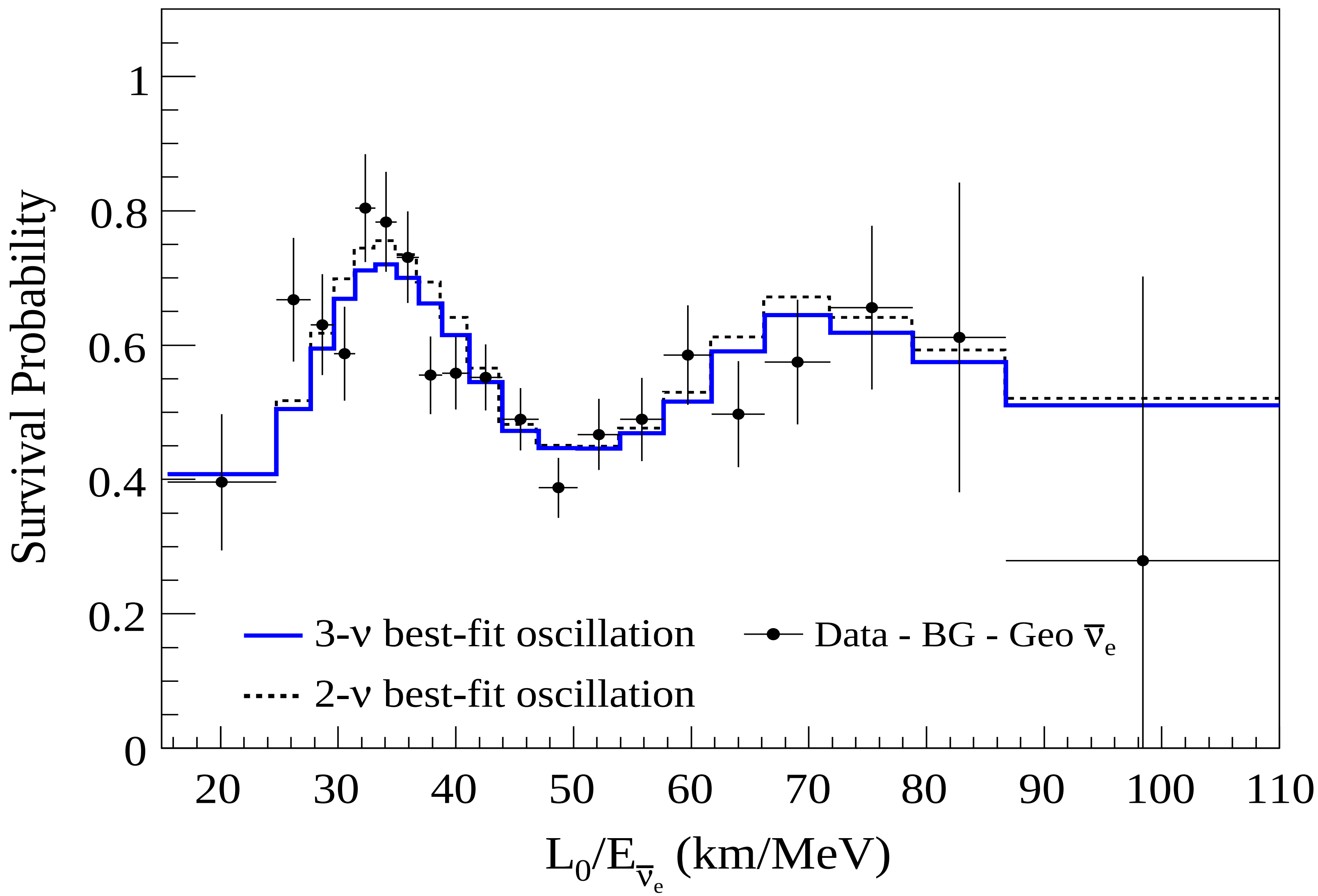
Dominant $\nu_{e} \rightarrow \nu_{\mu,\tau}$ **BOREXINO**

$-\bar{\nu}_e$ (from reactors): **Daya Bay, RENO, Double Chooz**

Dominant $\bar{\nu}_{e} \rightarrow \bar{\nu}_{\mu,\tau}$

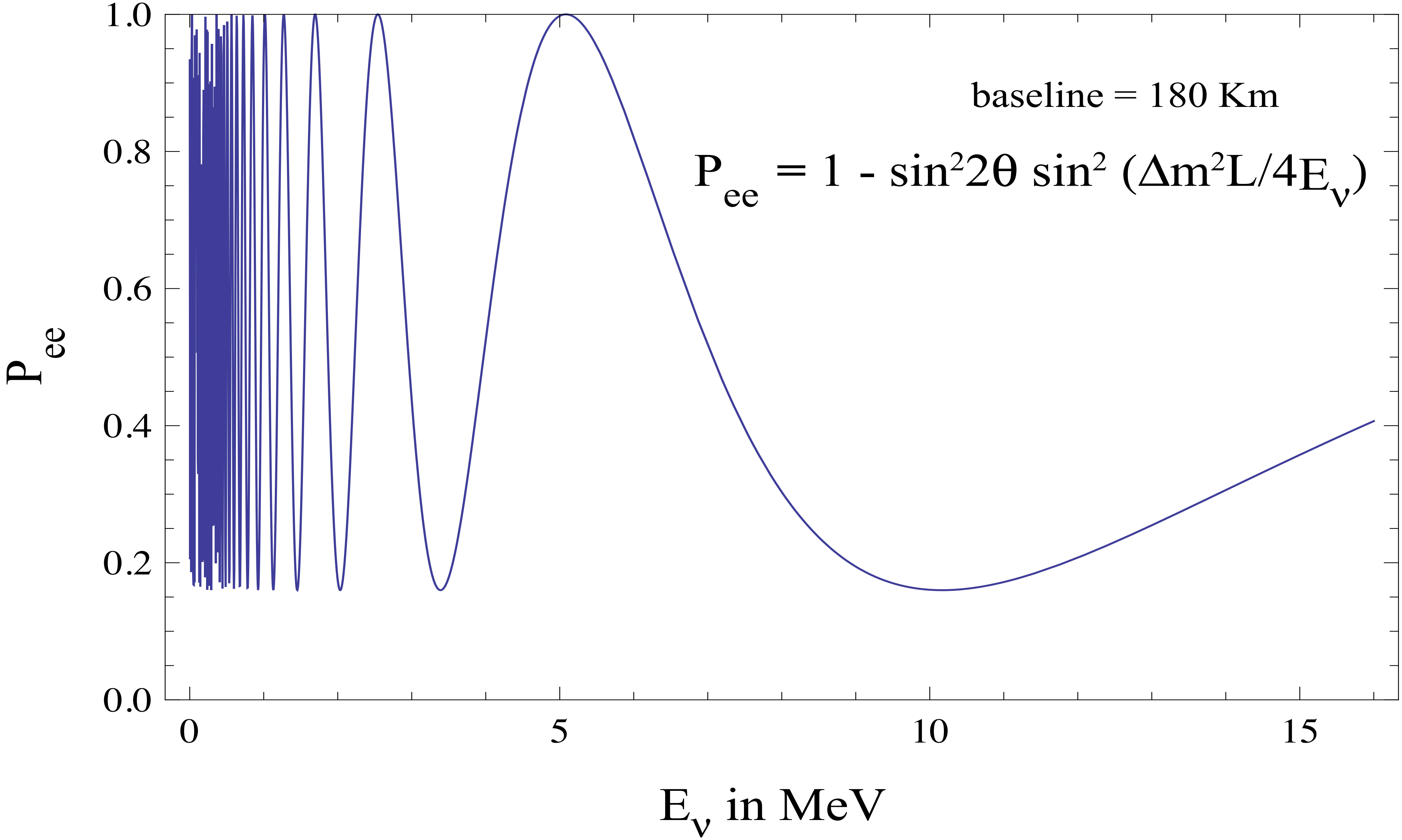
T2K, MINOS, NOνA (ν_{μ} from accelerators): $\nu_{\mu} \rightarrow \nu_{e}$

T2K, NOνA ($\bar{\nu}_{\mu}$ from accelerators): $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$



KamLAND: $L/E-$Dependence (reactor $\bar{\nu}_e$, $\bar{L} = 180$ km, E = (1.8 - 10) MeV)

$\nu_e \rightarrow \nu_e$



Compelling Evidences for $\nu-$Oscillations: ν mixing

$$|\nu_l> = \sum_{j=1}^{n} U^*_{lj}\,|\nu_j>\,, \quad \nu_j:\; m_j \neq 0\,; \quad l = e,\mu,\tau\,; \quad n \geq 3\,;$$

$$\nu_{l\mathrm{L}}(x) = \sum_{j=1}^{n} U_{lj}\,\nu_{j\mathrm{L}}(x)\,, \quad \nu_{j\mathrm{L}}(x):\; m_j \neq 0\,; \quad l = e,\mu,\tau\,.$$

B. Pontecorvo, 1957; 1958; 1967;

Z. Maki, M. Nakagawa, S. Sakata, 1962;

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix.

ν_j, $m_j \neq 0$: Dirac or Majorana particles.

Data: at least 3 νs are light: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 1$ eV.

All compelling data compatible with 3-ν mixing:

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\,\nu_{j\mathrm{L}} \qquad l = e, \mu, \tau.$$

The PMNS matrix U - 3×3 unitary to a good approximation (al least: $|U_{l,n}| \lesssim (<<)0.1$, $l = e, \mu$, $n = 4, 5, ...$).

ν_j, $m_j \neq 0$: Dirac or Majorana particles.

3-ν mixing: 3-flavour neutrino oscillations possible.

ν_μ, E; at distance L: $P(\nu_\mu \to \nu_{\tau(e)}) \neq 0$, $P(\nu_\mu \to \nu_\mu) < 1$

$P(\nu_l \to \nu_{l'}) = P(\nu_l \to \nu_{l'}; E, L; U; m_2^2 - m_1^2, m_3^2 - m_1^2)$

Three Neutrino Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}} \ .$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- U - $n \times n$ unitary:

	n	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6
CP-violating phases:				
• ν_j- Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• ν_j- Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

S.M. Bilenky, J. Hosek, S.T.P., 1980

PMNS Matrix: Standard Parametrization

$$U = V\,P\,, \qquad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix},$$

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

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,

- δ - Dirac CPV phase, $\delta = [0, 2\pi]$; CP inv.: $\delta = 0, \pi, 2\pi$;

- α_{21}, α_{31} - Majorana CPV phases; CP inv.: $\alpha_{21(31)} = k(k')\pi$, $k(k') = 0, 1, 2...$

S.M. Bilenky, J. Hosek, S.T.P., 1980

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.37 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.297$, $\cos 2\theta_{12} \gtrsim 0.29$ (3σ),

- $|\Delta m^2_{31(32)}| \cong 2.53$ (2.43) [2.56 (2.54)] $\times\ 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong$ 0.437 (0.569) [0.425 (0.589)], NO (IO) ,

- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0214$ (0.0218) [0.0215 (0.0216)], NO (IO).

F. Capozzi et al. (Bari Group), arXiv:1601.07777 [arXiv:1703.04471].

• $\text{sgn}(\Delta m^2_{\text{atm}}) = \text{sgn}(\Delta m^2_{31(32)})$ not determined

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} > 0, \quad \text{normal mass ordering (NO)}$$

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{32} < 0, \quad \text{inverted mass ordering (IO)}$$

Convention: $m_1 < m_2 < m_3$ - NO, $m_3 < m_1 < m_2$ - IO

$$\Delta m^2_{31}(NO) = - \Delta m^2_{32}(IO)$$

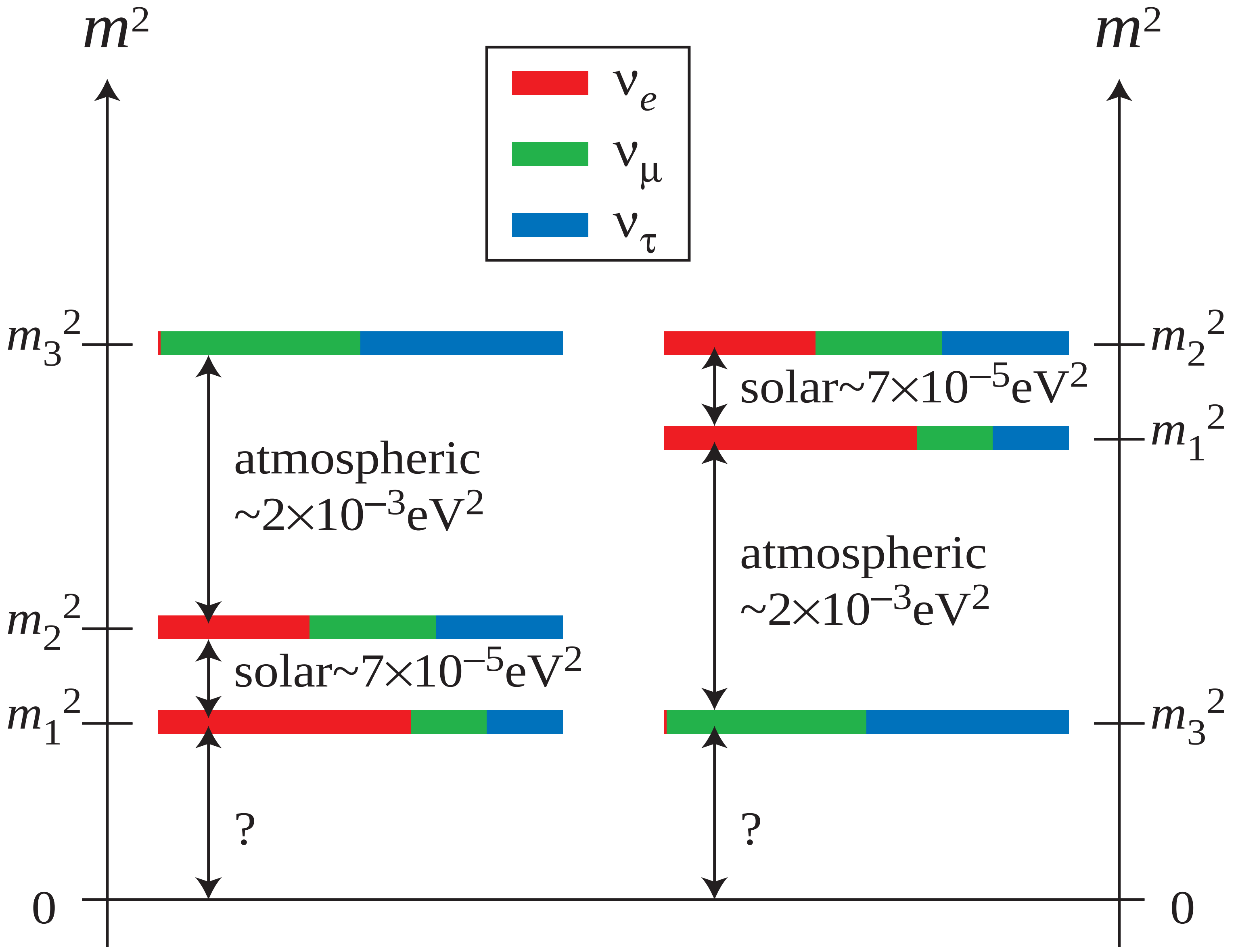
$$m_1 \ll m_2 < m_3, \qquad \text{NH},$$

$$m_3 \ll m_1 < m_2, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3, \ m^2_{1,2,3} >> |\Delta m^2_{31(32)}|, \ \text{QD}; \ m_j \gtrsim 0.10 \text{ eV}.$$

• $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}, \ \ m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$ - NO;

• $m_1 = \sqrt{m_3^2 + \Delta m^2_{23} - \Delta m^2_{21}}, \ \ m_2 = \sqrt{m_3^2 + \Delta m^2_{23}}$ - IO;



m^2
m^2
ν_e
ν_μ
ν_τ
$m_3{}^2$
atmospheric
$\sim 2\times 10^{-3}$eV^2
$m_2{}^2$
solar$\sim 7\times 10^{-5}$eV^2
$m_1{}^2$
?
0
$m_2{}^2$
solar$\sim 7\times 10^{-5}$eV^2
$m_1{}^2$
atmospheric
$\sim 2\times 10^{-3}$eV^2
$m_3{}^2$
?
0

Table 3: Best fit values and allowed ranges at $N\sigma = 1, 2, 3$ for the 3ν oscillation parameters, in either NO or IO. The latter column shows the formal "1σ accuracy" for each parameter, defined as 1/6 of the 3σ range divided by the best-fit value (in percent).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\Delta m^2_{\odot}/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\lvert\Delta m^2_{\rm A}\rvert/10^{-3}$ eV^2	NO	2.49	2.46 – 2.53	2.43 – 2.56	2.39 – 2.59	1.4
	IO	2.48	2.44 – 2.51	2.41 – 2.54	2.38 – 2.58	1.4
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18	2.78 – 3.32	2.65 – 3.46	4.4
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.4
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23	1.98 – 2.31	1.90 – 2.39	3.8
	IO	2.18	2.11 – 2.26	2.02 – 2.35	1.95 – 2.43	3.7
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70	4.48 – 5.88	4.30 – 6.02	5.2
	IO	5.57	5.33 – 5.74	4.86 – 5.89	4.44 – 6.03	4.8
δ/π	NO	1.32	1.14 – 1.55	0.98 – 1.79	0.83 – 1.99	14.6
	IO	1.52	1.37 – 1.66	1.22 – 1.79	1.07 – 1.92	9.3

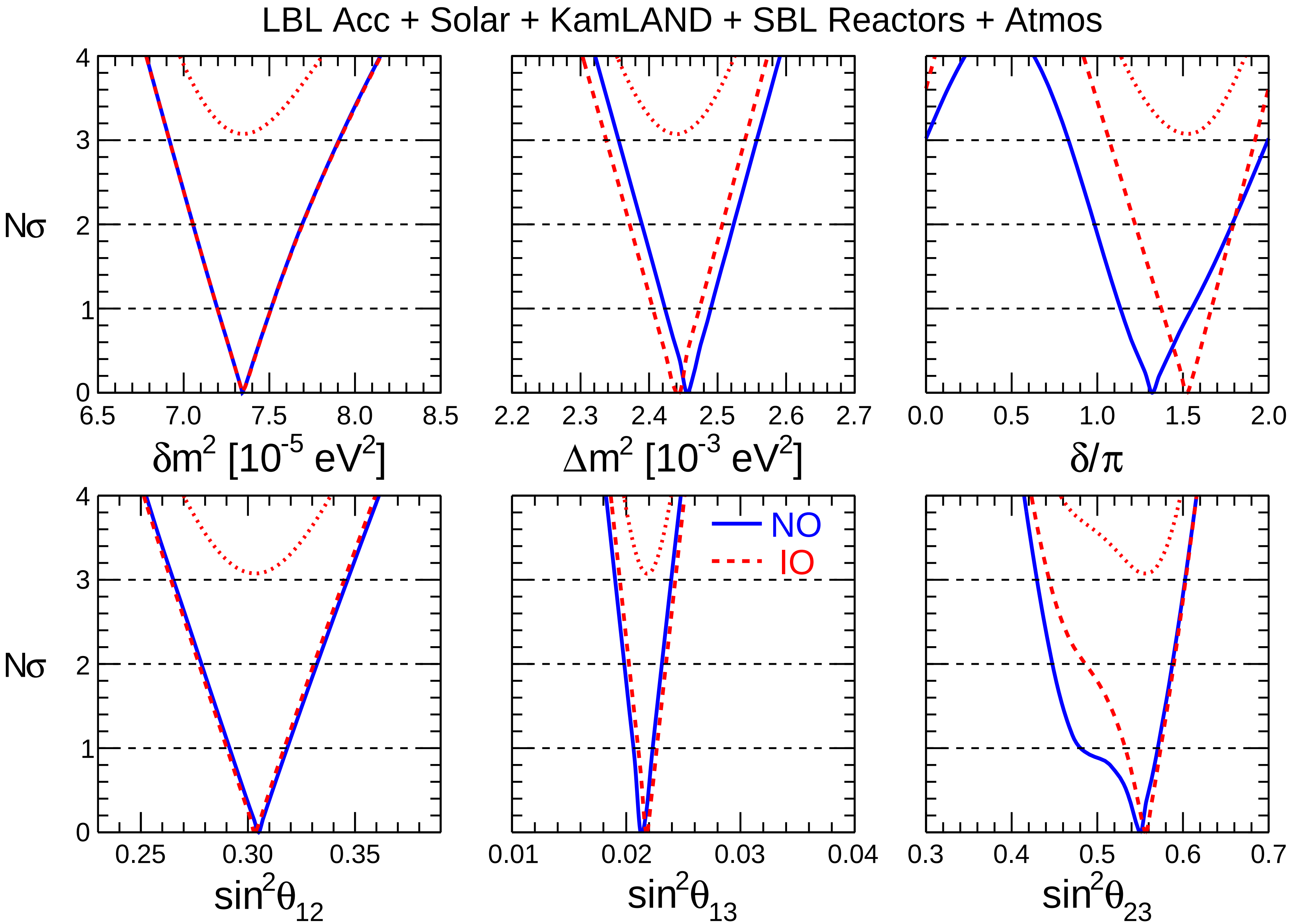
$$\Delta m^2_{\odot} \equiv \Delta m^2_{21}; \quad \Delta m^2_{\rm A} \equiv \Delta m^2_{31(32)},\ \text{NO (IO)}.$$

F. Capozzi et al. (Bari Group), arXiv:1804.09678.

Latest global analysis: data favors NO

IO disfavored at 3.1σ.

F. Capozzi et al., 1804.09678.



F. Capozzi et al. (Bari Group), arXiv:1804.09678.

- Dirac phase δ: $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l \neq l'$; $A^{(l,l')}_{\rm CP} \propto J_{\rm CP} \propto \sin\theta_{13} \sin\delta$:

P.I. Krastev, S.T.P., 1988

$$J_{CP} = {\rm Im}\left\{U_{e1}\, U_{\mu 2}\, U^*_{e2}\, U^*_{\mu 1}\right\} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Current data: $|J_{CP}| \lesssim 0.035$ (can be relatively large!); b.f.v. with $\delta = 3\pi/2$: $J_{CP} \cong -0.035$.

- Majorana phases α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

    S.M. Bilenky, J. Hosek, S.T.P.,1980;
    P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

  - $|< m >|$ in $(\beta\beta)_{0\nu}$−decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \rightarrow e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\delta, \alpha_{21,31}$!

$$\delta \cong 3\pi/2?$$

$$\begin{aligned} J_{CP} &= \text{Im}\left\{U_{e1}\, U_{\mu 2}\, U^*_{e2}\, U^*_{\mu 1}\right\} \\ &= \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta \end{aligned}$$

Data from T2K, Daya Bay, NOνA.

T2K: Tokai - Super Kamiokande

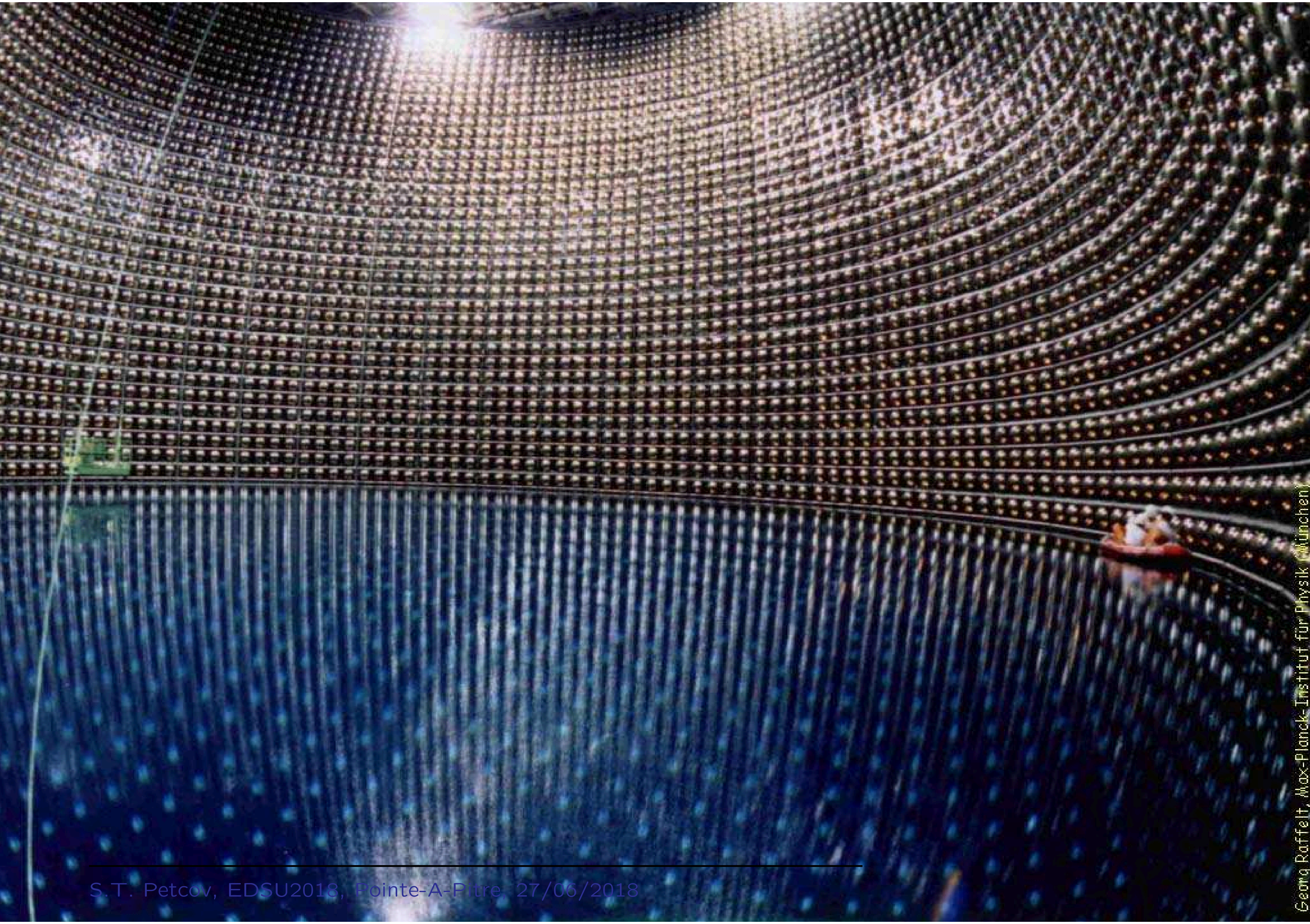
NOνA: Fermilab - site in Minnesota

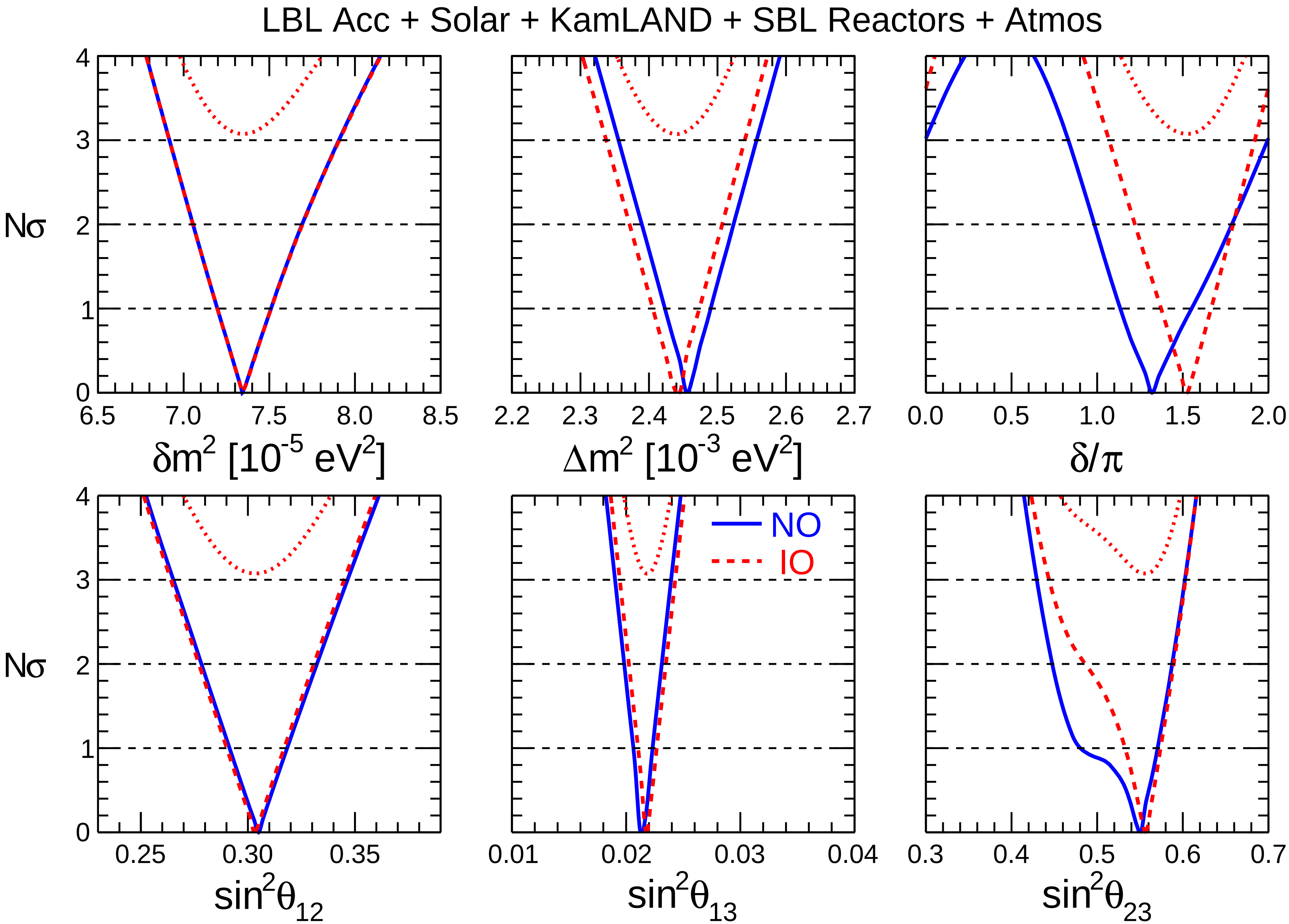
T2K: Tokai - Super Kamiokande; off-axis ν beam, $E = 0.6$ GeV, $L \cong 295$ km, 50 kt water Cherenkov detector.

NOνA: Fermilab - site in Minnesota; off-axis ν beam, $E = 2$ GeV, $L \cong 810$ km, 14 kt liquid scintillator detector.

SK experiment studying atmospheric ν_μ, $\tilde{\nu}_\mu$, ν_e, $\tilde{\nu}_e$ ($E \cong 0.1 \div 100$ GeV), and solar ν_e ($E \cong 5 \div 14$ MeV) oscillations.

Super Kamiokande (SK)


Georg Raffelt, Max-Planck-Institut für Physik (München)



F. Capozzi et al. (Bari Group), arXiv:1804.09678.

- **Best fit value:** $\delta = 1.38\,(1.31)\pi$ **[**$1.30\,(1.54)\pi$**];**
- $\delta = 0$ **or** 2π **are disfavored at** $2.4\,(3.2)\sigma$ **[**$2.6\,(3.0)\sigma$**];**
- $\delta = \pi$ **is disfavored at** $2.0\,(2.5)\sigma$ **[**$1.7\,(3.3)\sigma$**];**
- $\delta = \pi/2$ **is strongly disfavored at** $3.4\,(3.9)\sigma$ **[**$4.3\,(5.0)\sigma$**].**
- **At** 3σ**:** δ/π **is found to lie in** $(0.00 - 0.17(0.16)) \oplus (0.76(0.69) - 2.00))$ **[1.07-1.97 (0.80-2.08)].**

F. Capozzi, E. Lisi *et al.*, arXiv:1703.04471 [E. Esteban *et al.*, NuFit 3.2 (Jan., 2018); F. Capozzi *et al.*, 1804.09678.]

Large $\sin\theta_{13} \cong 0.15 + \delta = 3\pi/2$ - far-reaching implications:

- For the searches for CP violation in ν-oscillations; for the b.f.v. one has $J_{CP} \cong -0.032$;
- Important implications also for the "flavoured" leptogenesis scenario of generation of the baryon asymmetry of the Universe (BAU).

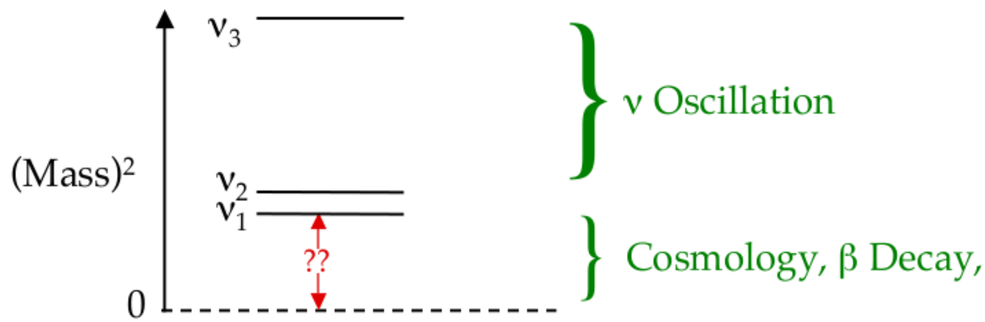
If all CPV, necessary for the generation of BAU is due to δ, a necessary condition for reproducing the observed BAU (in FLG with hierarchical N_j) is

$$|\sin\theta_{13}\sin\delta| \gtrsim 0.09$$

S. Pascoli, S.T.P., A. Riotto, 2006.

Absolute Neutrino Mass Scale

The Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Oscillation Data $\Rightarrow \sqrt{\Delta m^2_{atm}} <$ Mass[Heaviest ν_i]

4

Due to B. Kayser

Absolute Neutrino Mass Measurements

Troitzk, Mainz experiments on $^3\text{H} \to ^3\text{He} + \text{e}^- + \bar{\nu}_\text{e}$:

$$m_{\nu_e} < 2.2 \text{ eV} \qquad (95\% \text{ C.L.})$$

We have $m_{\nu_e} \cong m_{1,2,3}$ in the case of QD spectrum. The KATRIN experiment (11/06/2018) is planned to reach sensitivity

$$\text{KATRIN:} \quad m_{\nu_e} \sim 0.2 \text{ eV}$$

i.e., it will probe the region of the QD spectrum.

Improved β energy resolution requires a ***BIG*** β spectrometer.


KATRIN'S JOURNEY

Mass and Hierarchy from Cosmology

Cosmological and astrophysical data on $\sum_j m_j$: using their latest (2016) data on CMB T power spectrum anisotropies, polarisation, grav. lensing effects, the low l CMB polarisation spectrum data ("low P" data) and adding data on the baryon acoustic oscillations (BAO) and using ΛCDM (6 parameter) model + assuming 3 light massive neutrinos, the Planck collaboration published in 2016 the following limit:

$$\sum_j m_j \equiv \Sigma < 0.170 \text{ eV} \quad (95\% \text{ C.L.})$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP, Planck and future EUCLID experiments might allow to determine

$$\sum_j m_j : \qquad \delta \cong (0.01 - 0.04) \text{ eV}.$$

NH: $\sum_j m_j \leq 0.061$ eV (3σ);

IH: $\sum_j m_j \geq 0.098$ eV (3σ).

Warning: The quoted cosmological bound on $\sum_j m_j$ might not be valid if, e.g., the neutrino masses are generated dynamically at certain relatively late epoch in the evolution of the Universe (see, e.g., S.M. Koksbang, S. Hannestad, arXiv:1707.02579).

Future Progress: of fundamental importance are

- the determination of the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos (which is one of the most challenging and pressing problems in present day elementary particle physics) (GERDA, CUORE, KamLAND-Zen, EXO, LEGEND, nEXO,...);

- determining the status of CP symmetry in the lepton sector (T2K, NOνA; T2HK, DUNE);

- determination of the type of spectrum neutrino masses possess, or neutrino mass ordering (T2K + NOνA; JUNO; PINGU, ORCA; T2HKK, DUNE);

- determination of the absolute neutrino mass scale, or $\min(m_j)$ (KATRIN, new ideas; cosmology).

The program of research extends beyond 2030.

Future Progress

- Determination of the nature - Dirac or Majorana, of ν_j .
- Determination of $\text{sgn}(\Delta m^2_{\text{atm}})$, type of $\nu-$ mass spectrum

$$m_1 \ll m_2 \ll m_3, \qquad \text{NH},$$

$$m_3 \ll m_1 < m_2, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3,\ m^2_{1,2,3} >> \Delta m^2_{\text{atm}},\ \text{QD};\ m_j \gtrsim 0.10\ \text{eV}.$$

- Determining, or obtaining significant constraints on, the absolute scale of ν_j- masses, or $\min(m_j)$.
- Status of the CP-symmetry in the lepton sector: violated due to δ (Dirac), and/or due to α_{21}, α_{31} (Majorana)?
- High precision determination of $\Delta m^2_{\odot}$, θ_{12}, Δm^2_{atm}, θ_{23}, θ_{13}
- Searching for possible manifestations, other than ν_l-oscillations, of the non-conservation of L_l, $l = e, \mu, \tau$, such as $\mu \rightarrow e + \gamma$, $\tau \rightarrow \mu + \gamma$, etc. decays.

• **Understanding at fundamental level the mechanism giving rise to the $\nu-$ masses and mixing and to the L_l-non-conservation. Includes understanding**

– **the origin of the observed patterns of ν-mixing and ν-masses ;**

– **the physical origin of CPV phases in U_{PMNS} ;**

– **Are the observed patterns of ν-mixing and of $\Delta m^2_{21,31}$ related to the existence of a new symmetry?**

– **Is there any relations between $q-$mixing and $\nu-$ mixing?** Is $\theta_{12} + \theta_c = \pi/4$?

– **Is $\theta_{23} = \pi/4$, or $\theta_{23} > \pi/4$ or else $\theta_{23} < \pi/4$?**

– **Is there any correlation between the values of CPV phases and of mixing angles in U_{PMNS}?**

• **Progress in the theory of ν-mixing might lead to a better understanding of the origin of the BAU.**

– **Can the Majorana and/or Dirac CPVP in U_{PMNS} be the leptogenesis CPV parameters at the origin of BAU?**

Leptonic CP Violation

Dirac CP-Nonconservation: δ in U_{PMNS}

Observable manifestations in

$$\nu_l \leftrightarrow \nu_{l'} \; , \quad \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'} \; , \quad l, l' = e, \mu, \tau$$

- not sensitive to Majorana CPVP α_{21}, α_{31}

CP-invariance:

N. Cabibbo, 1978
S.M. Bilenky, J. Hosek, S.T.P.,1980;
V. Barger, S. Pakvasa et al.,1980.

$$P(\nu_l \to \nu_{l'}) = P(\bar{\nu}_l \to \bar{\nu}_{l'}) \; , \quad l \neq l' = e, \mu, \tau$$

CPT-invariance:

$$P(\nu_l \to \nu_{l'}) = P(\bar{\nu}_{l'} \to \bar{\nu}_l)$$

$$l = l' : \quad P(\nu_l \to \nu_l) = P(\bar{\nu}_l \to \bar{\nu}_l)$$

T-invariance:

$$P(\nu_l \to \nu_{l'}) = P(\nu_{l'} \to \nu_l), \; l \neq l'$$

3ν — mixing:

$$A^{(l,l')}_{\text{CP}} \equiv P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'}) \; , \quad l \neq l' = e, \mu, \tau$$

$$A^{(l,l')}_{\text{T}} \equiv P(\nu_l \to \nu_{l'}) - P(\nu_{l'} \to \nu_l), \; l \neq l'$$

$$A^{(e,\mu)}_{\text{T(CP)}} = A^{(\mu,\tau)}_{\text{T(CP)}} = -A^{(e,\tau)}_{\text{T(CP)}}$$

P.I. Krastev, S.T.P., 1988

3-Neutrino Oscillations in Vacuum

$$P(\nu_l \to \nu_{l'}) = \sum_j |U_{l'j}|^2 \, |U_{lj}|^2$$

$$+ 2 \sum_{j>k} |U_{l'j} \, U^*_{lj} \, U_{lk} \, U^*_{l'k}| \, \cos(\frac{\Delta m^2_{jk}}{2p} L - \phi_{l'l;jk}) \, , \;\; l, l' = e, \mu, \tau \, ,$$

$$P(\bar{\nu}_l \to \bar{\nu}_{l'}) = \sum_j |U_{l'j}|^2 \, |U_{lj}|^2$$

$$+ 2 \sum_{j>k} |U_{l'j} \, U^*_{lj} \, U_{lk} \, U^*_{l'k}| \, \cos(\frac{\Delta m^2_{jk}}{2p} L + \phi_{l'l;jk}) \, , \;\; l, l' = e, \mu, \tau \, ,$$

$$\phi_{l'l;jk} = \arg \left(U_{l'j} \, U^*_{lj} \, U_{lk} \, U^*_{l'k} \right) \, .$$

- **Spatial localisation condition**

ΔL - **dimensions of the ν- source (and/or detector):**

$2\pi \Delta L / L^v_{jk} \lesssim 1.$

- **Time localisation condition**

ΔE - **detector's energy resolution:**

$2\pi (L / L^v_{jk})(\Delta E / E) \lesssim 1.$

If $2\pi \Delta L / L^v_{jk} \gg 1$, **and/or** $2\pi (L / L^v_{jk})(\Delta E / E) \gg 1$,

$\bar{P}(\nu_l \to \nu_{l'}) = \bar{P}(\bar{\nu}_l \to \bar{\nu}_{l'}) \cong \sum_j |U_{l'j}|^2 \, |U_{lj}|^2$

In vacuum:

$$A^{(e,\mu)}_{\mathrm{CP(T)}} = 4\, J_{\mathrm{CP}} F^{vac}_{osc}$$

$$J_{CP} = \mathrm{Im}\left\{U_{e2}\, U_{\mu3}\, U^{*}_{e3}\, U^{*}_{\mu2}\right\}$$

$$= \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

$$F^{vac}_{osc} = \sin(\frac{\Delta m^2_{21}}{2E}L) + \sin(\frac{\Delta m^2_{32}}{2E}L) + \sin(\frac{\Delta m^2_{13}}{2E}L)$$

P.I. Krastev, S.T.P., 1988

$$\sin(\frac{\Delta m^2_{21}}{2E}L) \cong 0 : \quad F^{vac}_{osc} \cong 0$$

In matter: **Matter effects violate**

$$\mathrm{CP}: \quad \mathbf{P}(\nu_l \rightarrow \nu_{l'}) \neq \mathbf{P}(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

$$\mathrm{CPT}: \quad \mathbf{P}(\nu_l \rightarrow \nu_{l'}) \neq \mathbf{P}(\bar{\nu}_{l'} \rightarrow \bar{\nu}_l)$$

Can conserve the T-invariance (Earth)

P. Langacker et al., 1987

$$\mathbf{P}(\nu_l \rightarrow \nu_{l'}) = \mathbf{P}(\nu_{l'} \rightarrow \nu_l), \; l \neq l'$$

In matter with constant density (e.g., Earth mantle): $\mathrm{A}_{\mathrm{T}}^{(e,\mu)} = \mathrm{J}^{\mathrm{mat}}\, \mathrm{F}_{\mathrm{osc}}^{\mathrm{mat}}$,

$$J^{\mathrm{mat}} = \frac{1}{8} \sin 2\theta_{12}^{m} \sin 2\theta_{13}^{m} \cos \theta_{13}^{m} \sin 2\theta_{23}^{m} \sin \delta^{m}$$

$$\mathrm{J}^{\mathrm{mat}} = \mathrm{J}_{\mathrm{CP}}^{\mathrm{vac}}\, \mathbf{R}_{\mathbf{CP}}$$

R_{CP} **does not depend on** θ_{23} **and** δ**;**

$\sin 2\theta_{12} \cong 0.92$, $\sin 2\theta_{13} \cong 0.3$: $|R_{CP}| \lesssim 3.0$

P.I. Krastev, S.T.P., 1988

Rephasing Invariants Associated with CPVP

Dirac phase δ:

$$J_{CP} = \text{Im}\left\{U_{e2}\, U_{\mu 3}\, U_{e3}^{*}\, U_{\mu 2}^{*}\right\} \ .$$

C. Jarlskog, 1985 (for quarks)

CP-, T- violation effects in neutrino oscillations

P. Krastev, S.T.P., 1988

Majorana phases α_{21}, α_{31}:

$$S_1 = \text{Im}\,\{U_{e1}U_{e3}^{*}\}\,, \quad S_2 = \text{Im}\,\{U_{e2}U_{e3}^{*}\} \quad \text{(not unique);} \quad \text{or}$$
$$S_1' = \text{Im}\,\{U_{\tau 1}U_{\tau 2}^{*}\}\,, \quad S_2' = \text{Im}\,\{U_{\tau 2}U_{\tau 3}^{*}\}$$

J.F. Nieves and P. Pal, 1987, 2001
G.C. Branco et al., 1986
J.A. Aguilar-Saavedra and G.C. Branco, 2000

CP-violation: both $\text{Im}\,\{U_{e1}U_{e3}^{*}\} \neq 0$ and $\text{Re}\,\{U_{e1}U_{e3}^{*}\} \neq 0$.

S_1, S_2 appear in $|{<}m{>}|$ in $(\beta\beta)_{0\nu}$-decay.

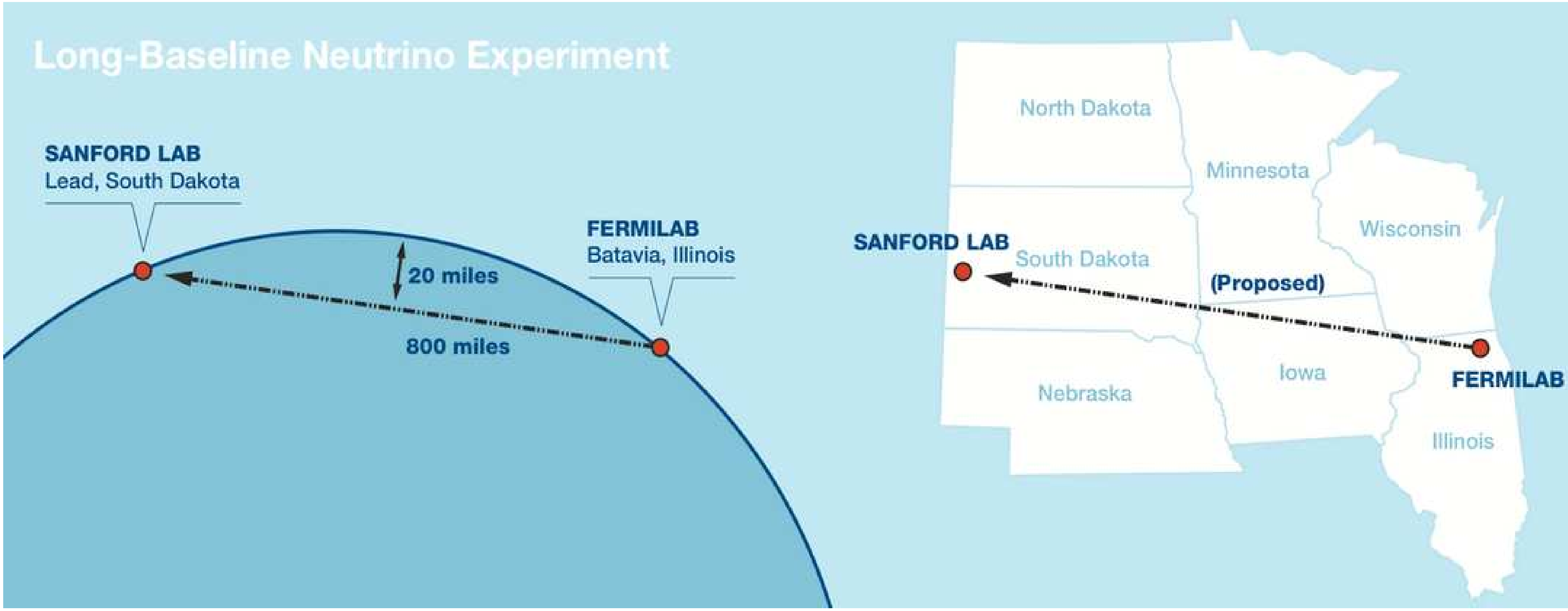
In general, J_{CP}, S_1 and S_2 are independent.

Future LBL Neutrino Oscillation Experiments on CP Violation

T2HK (HK=Hyper-Kamiokande: water-Cherenkov, ~ 0.5 Mton, fiducial $\sim$ 0.2 Mton).

T2HK: $L = 295$ **km,** 2.5° **off-axis (narrow band)** ν_{μ} **beam (from 750 kW proton) beam, maximum at** $E \cong 0.6$ **GeV (the first osc. maximum).**

DUNE: Fermilab-DUSEL, $L = 1290$ **km, 1.2 MW (2.3 MW) proton beam, wide band** ν **beam (first and second osc. maxima at** $E = 2.4$ **GeV and 0.8 GeV); 40 kt fiducial volume LAr detecors; plans to run 5 years with** ν_{μ} **and 5 years with** $\bar{\nu}_{\mu}$**; 2026**



DUNE: Fermilab-DUSEL, 1290 km.

Up to 2nd order in the two small parameters $|\alpha| \equiv |\Delta m^2_{21}|/|\Delta m^2_{31}| \ll 1$ **and** $\sin^2\theta_{13} \ll 1$**:**

$$P_m^{3\nu\ man}(\nu_\mu \to \nu_e) \cong P_0 + P_{\sin\delta} + P_{\cos\delta} + P_3\,,$$

$$P_0 = \sin^2\theta_{23}\,\frac{\sin^2 2\theta_{13}}{(A-1)^2}\,\sin^2[(A-1)\Delta],$$

$$P_3 = \alpha^2\,\cos^2\theta_{23}\,\frac{\sin^2 2\theta_{12}}{A^2}\,\sin^2(A\Delta),$$

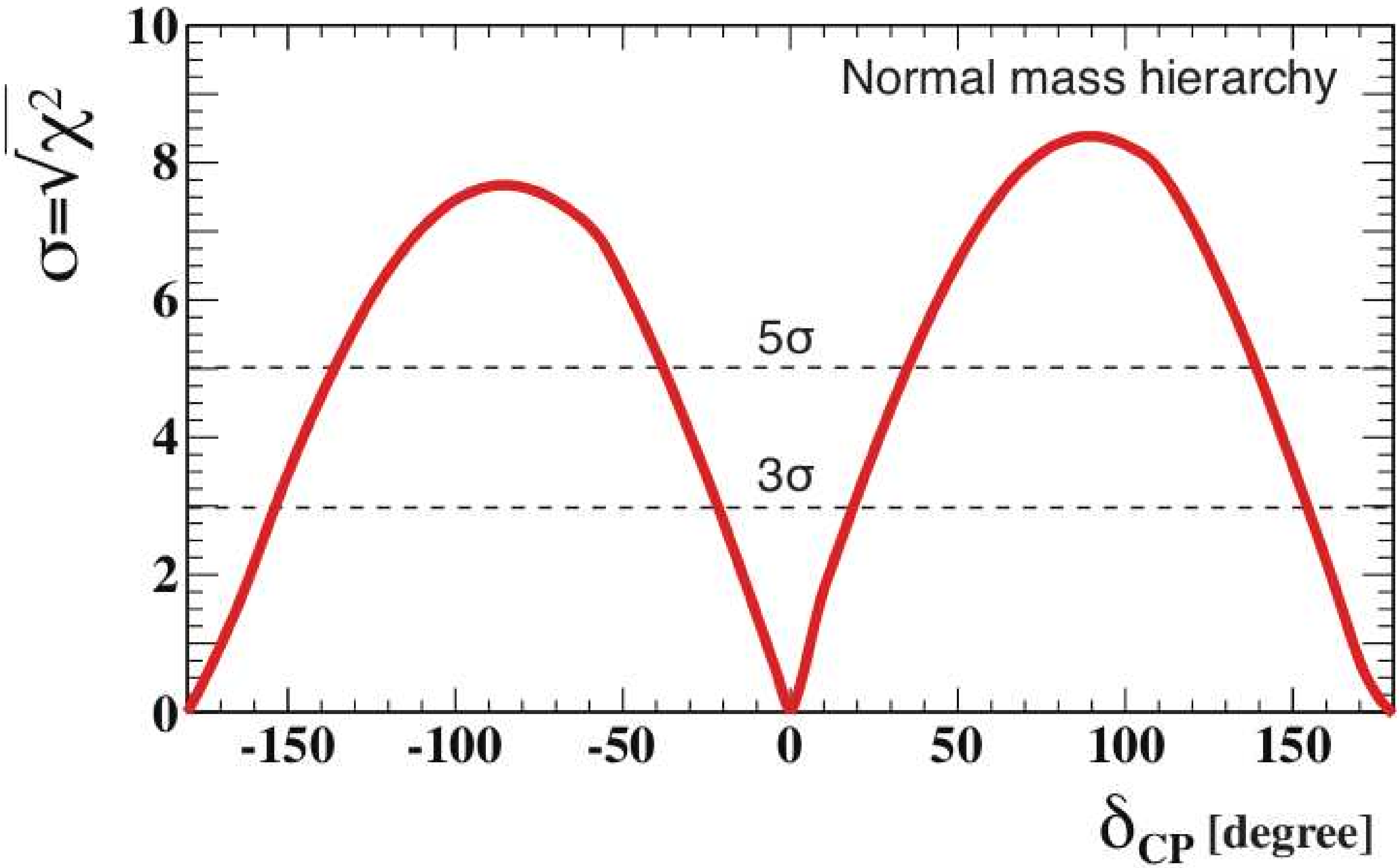
$$P_{\sin\delta} = -\,\alpha\,\frac{8\,J_{CP}}{A(1-A)}(\sin\Delta)(\sin A\Delta)\,(\sin[(1-A)\Delta]),$$

$$P_{\cos\delta} = \alpha\,\frac{8\,J_{CP}\cot\delta}{A(1-A)}(\cos\Delta)(\sin A\Delta)\,\,(\sin[(1-A)\Delta]),$$

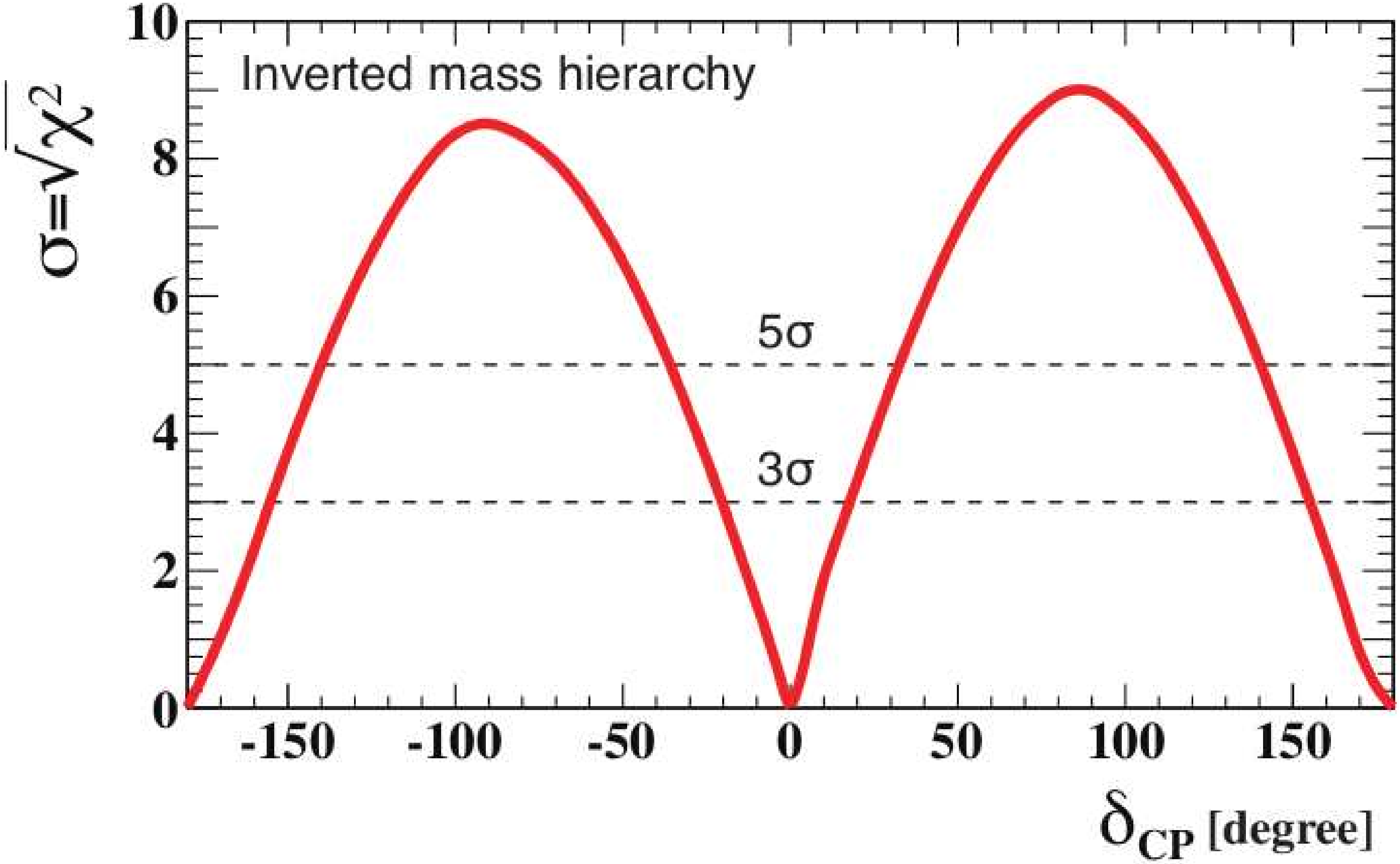
$$\Delta = \frac{\Delta m^2_{31}\,L}{4E}\,,\;\; A = \sqrt{2}G_{\mathrm{F}}N_e^{man}\frac{2E}{\Delta m^2_{31}}.$$

$\bar{\nu}_\mu \to \bar{\nu}_e$: $\delta,\;\; A \to (-\delta),\;\; (-A)$

Expected T2HK sensitivity to CP violation



K. Abe et al., arXiv:1502.05199.



K. Abe et al., arXiv:1502.05199.

The data imply that

$$m_{\nu_j} <<< m_{e,\mu,\tau}, m_q, \ q = u, c, t, d, s, b$$

For $m_{\nu_j} \lesssim 1$ **eV:** $m_{\nu_j}/m_{l,q} \lesssim 10^{-6}$

For a given family: $10^{-2} \lesssim m_{l,q}/m_{q'} \lesssim 10^{2}$

LEPTOGENESIS

M_ν from type I See-Saw Mechanism

P. Minkowski, 1977.
M. Gell-Mann, P. Ramond, R. Slansky, 1979;
T. Yanagida, 1979;
R. Mohapatra, G. Senjanovic, 1980.

• Explains the smallness of $\nu-$masses.

• Through **leptogenesis theory** links the $\nu-$mass generation to the generation of baryon asymmetry of the Universe Y_B.

S. Fukugita, T. Yanagida, 1986; GUT's: M. Yoshimura, 1978.

• In SUSY GUT's with see-saw mechanism of $\nu-$mass generation, the LFV decays

$$\mu \to e + \gamma, \quad \tau \to \mu + \gamma, \quad \tau \to e + \gamma \ , \text{ etc.}$$

are predicted to take place with rates within the reach of present and future experiments.

F. Borzumati, A. Masiero, 1986.

• The ν_j are **Majorana particles**; $(\beta\beta)_{0\nu}-$decay is allowed.

See-Saw: Dirac ν-mass m_D + Majorana mass M_R for N_R

In GUTs, $M_{1,2,3} < M_X$, $M_X \sim 10^{16}$ GeV;

in GUTs, e.g., $M_{1,2,3} = (10^{11}, 10^{12}, 10^{13})$ GeV, $m_D \sim 1$ GeV.

TeV Scale (Resonant) Leptogenesis:

$M_{1,2,3} \sim (10^2 - 10^3)$ GeV (requires fine-tuning (severe)); observation of N_j at LHC - problematic (low production rates); observable LFV processes: $\mu \to e + \gamma$, $\mu \to 3e$, $\mu^- - e^-$ conversion.

Can the CP violation necessary for the generation of the observed value of the Baryon Asymmetry of the Universe (BAU) be provided exclusively by the Dirac and/or Majorana CPV phases in the neutrino PMNS matrix?

Demonstrated in (incomplete list):

S. Pascoli *et al.*, **hep-ph/0609125 and hep-ph/0611338.**
E. Molinaro *et al.*, **arXiv:0808.3534.**
A. Meroni *et al.*, **arXiv:1203.4435.**
C. Hagedorn *et al.*, **arXiv:0908.0240.**
J. Gehrlein *et al.*, **arXiv:1502.00110 and arXiv:1508.07930.**
J. Zhang, Sh. Zhou, arXiv:1505.04858 (FGY 2002 model).
P. Chen *et al.*, **arXiv:1602.03873.**
C. Hegdorn, E. Molinaro, arXiv:1602.04206.
P. Hernandez *et al.*, **arXiv:1606.06719 and 1611.05000.**
M. Drewes *et al.*, **arXiv:1609.09069.**
G. Bambhaniya *et al.*, **arXiv:1611.03827.**

The Seesaw Lagrangian

$$\mathcal{L}^{\text{lep}}(x) \;=\; \mathcal{L}_{\text{CC}}(x) + \mathcal{L}_{\text{Y}}(x) + \mathcal{L}^{\text{N}}_{\text{M}}(x)\,,$$

$$\mathcal{L}_{\text{CC}} \;=\; -\,\frac{g}{\sqrt{2}}\,\overline{l_L}(x)\,\gamma_\alpha\,\nu_{lL}(x)\,W^{\alpha\dagger}(x) + h.c.\,,$$

$$\mathcal{L}_{\text{Y}}(x) \;=\; \lambda_{il}\,\overline{N_{iR}}(x)\,H^\dagger(x)\,\psi_{lL}(x) + Y_l\,H^c(x)\,\overline{l_R}(x)\,\psi_{lL}(x) + \text{h.c.}\,,$$

$$\mathcal{L}^{\text{N}}_{\text{M}}(x) \;=\; -\,\frac{1}{2}\,M_i\,\overline{N_i}(x)\,N_i(x)\,.$$

ψ_{lL} - LH doublet,$\psi^{\text{T}}_{lL} = (\nu_{lL}\ l_L)$, l_R - RH singlet, H - Higgs doublet.
Basis: $M_R = (M_1, M_2, M_3)$; $D_N \equiv \text{diag}(M_1, M_2, M_3)$, $D_\nu \equiv \text{diag}(m_1, m_2, m_3)$.
m_D generated by the Yukawa interaction:

$$-\mathcal{L}^{\nu}_{\text{Y}} = \lambda_{il}\overline{N_{iR}}H^\dagger(x)\psi_{lL}(x),\ v = 174\ \text{GeV},\ v\,\lambda = m_D - \text{complex}$$

For M_R - sufficiently large,

$$m_\nu \simeq v^2\ \lambda^T\,D_N^{-1}\,\lambda = m_{\text{D}}^T\,D_N^{-1}\,m_{\text{D}} = U^*_{\text{PMNS}}\,D_\nu\,U^\dagger_{\text{PMNS}}\ .$$

$$m_\nu \simeq v^2\ \lambda^T\, D_N^{-1}\, \lambda = U^*_{\text{PMNS}}\, D_\nu\, U^\dagger_{\text{PMNS}}\,,$$

$$\lambda \equiv Y_\nu$$

$Y_\nu \equiv \lambda = \sqrt{D_N}\; R\; \sqrt{D_\nu}\; (U_{\text{PMNS}})^\dagger / v_u$, all at M_R;

R-complex, $R^T R = \mathbf{1}$.

J.A. Casas and A. Ibarra, 2001

$D_N \equiv \text{diag}(M_1, M_2, M_3)$, $D_\nu \equiv \text{diag}(m_1, m_2, m_3)$.

Theories, Models:

- R - CP conserving ($SU(5) \times T'$, A. Meroni *et al.*, arxiv:1203.4435; S_4, P. Cheng *et al.*, arXiv:1602.03873; C. Hagedorn, E. Molinaro, arXiv:1602.04206).
- CPV parameters in R determined by the CPV phases in U (e.g., class of A_4 theories).
- Texture zeros in Y_ν: CPV parameters in R determined by the CPV phases in U
(Frampton, Glashow Yanagida (FGY), 2002: $N_{1,2}$, two texture zeros in Y_ν; LG in FGY model: J. Zhang, Sh. Zhou, arXiv:1505.04858).

The CP-Invarinace Constraints

Assume: $C(\overline{\nu}_j)^T = \nu_j$, $C(\overline{N}_k)^T = N_k$, $j,k = 1,2,3.$

The CP-symmetry transformation:

$$U_{\rm CP}\, N_j(x)\, U^{\dagger}_{\rm CP} = \eta^{NCP}_j\, \gamma_0\, N_j(x')\,, \quad \eta^{NCP}_j = i\rho^N_j = \pm i\,,$$
$$U_{\rm CP}\, \nu_k(x)\, U^{\dagger}_{\rm CP} = \eta^{\nu CP}_k\, \gamma_0\, \nu_k(x')\,, \quad \eta^{\nu CP}_k = i\rho^\nu_k = \pm i\,.$$

CP-invariance:

$$\lambda^*_{jl} = \lambda_{jl}\, (\eta^{NCP}_j)^*\, \eta^l\, \eta^{H*}\,, \quad j = 1,2,3,\ l = e,\mu,\tau,$$

Convenient choice: $\eta^l = i$, $\eta^H = 1$ $(\eta^W = 1)$:

$$\lambda^*_{jl} = \lambda_{jl}\, \rho^N_j\,,\ \rho^N_j = \pm 1\,,$$
$$U^*_{lj} = U_{lj}\, \rho^\nu_j\,,\ \rho^\nu_j = \pm 1\,,$$
$$R^*_{jk} = R_{jk}\, \rho^N_j\, \rho^\nu_k, \quad j,k = 1,2,3,\ l = e,\mu,\tau,$$

λ_{jl}, U_{lj}, R_{jk} - either real or purely imaginary.

Relevant quantity:

$$P_{jkml} \equiv R_{jk}\, R_{jm}\, U^*_{lk}\, U_{lm}\,,\ k \neq m\,,$$
$$CP: \quad P^*_{jkml} = P_{jkml}\, (\rho^N_j)^2\, (\rho^\nu_k)^2\, (\rho^\nu_m)^2 = P_{jkml}\,, \quad {\rm Im}(P_{jkml}) = 0\,.$$

$$P_{jkml} \equiv R_{jk}\, R_{jm}\, U^*_{lk}\, U_{lm}\,, \;\; k \neq m\,,$$

$$CP: \quad P^*_{jkml} = P_{jkml}\, (\rho^N_j)^2\, (\rho^\nu_k)^2\, (\rho^\nu_m)^2 = P_{jkml}\,, \quad \mathrm{Im}(P_{jkml}) = 0\,.$$

Consider NH N_j, NH ν_k: $\quad P_{123\tau} = R_{12}\, R_{13}\, U^*_{\tau 2}\, U_{\tau 3}$

Suppose, CP-invrainace holds at low E: $\delta = 0$, $\alpha_{21} = \pi$, $\alpha_{31} = 0$.

Thus, $U^*_{\tau 2}\, U_{\tau 3}$ - purely imaginary.

Then real $R_{12}\, R_{13}$ corresponds to CP-violation at "high" E due to the interplay of R and U: $\mathrm{Im}(P_{123\tau}) \neq 0$ (!)

Baryon Asymmetry

$$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}\,, \quad \text{CMB}$$

Sakharov conditions for a dynamical generation of $Y_B \neq 0$ in the Early Universe

- B **number non-conservation.**
- **Violation of C and CP symmetries.**
- **Deviation from thermal equilibrium.**

Leptogenesis

• **The heavy Majorana neutrinos N_i are in equilibrium in the Early Universe as far as the processes which produce and destroy them are efficient.**

• **When $T < M_1$, N_1 drops out of equilibrium as it cannot be produced efficiently anymore.**

• **If $\Gamma(N_1 \to \Phi^- \, \ell^+) \neq \Gamma(N_1 \to \Phi^+ \, \ell^-)$, a lepton asymmetry will be generated.**

• **Wash-out processes, like $\Phi^+ + \ell^- \to N_1$, $\ell^- + \Phi^+ \to \Phi^- + \ell^+$, etc. tend to erase the asymmetry. Under the condition of non-equilibrium, they are less efficient than the direct processes in which the lepton asymmetry is created. The final resullt is a net (non-zero) lepton asymmetry.**

• **This lepton asymmetry is then converted into a baryon asymmetry by $(B+L)$ violating but $(B-L)$ conserving sphaleron processes which exist within the SM (at $T \gtrsim M_{\mathrm{EWSB}}$).**

S. Fukugita, T. Yanagida, 1986.

In order to compute Y_B:

1. calculate the CP-asymmetry:

$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi^- \ell^+) - \Gamma(N_1 \to \Phi^+ \ell^-)}{\Gamma(N_1 \to \Phi^- \ell^+) + \Gamma(N_1 \to \Phi^+ \ell^-)}$$

2. solve the Boltzmann (or similar) equation to account for the wash-out of the asymmetry:

$$Y_{\mathsf{L}} = \kappa\,\varepsilon$$

where $\kappa = \kappa(\widetilde{m})$ is the "efficiency factor", $\widetilde{m}$ is the "the wash-out mass parameter" - determines the rate of wash-out processes;

3. the lepton asymmetry is converted into a baryon asymmetry:

$$Y_{\mathsf{B}} = -\frac{c_s}{g_*}\kappa\varepsilon, \quad c_s \cong 1/3, \quad g_* = 215/2$$

Baryon number violation in the SM

Instanton and Sphaleron processes

SU(2) instantons lead to (leading order) to effective 12 fermion $(B + L)$ **nonconserving, but** $(B - L)$ **conserving, interactions:**

$O(B + L) = \Pi_i q_{Li} q_{Li} q_{Li} l_{Li}$

These would induce $\Delta B = \Delta L = 3$ **processes:**

$$u_L + d_L + c_L + s_L + t_L + b_L + \nu_{eL} + \nu_{\mu L} + \nu_{\tau L} \rightarrow \bar{d}_R + \bar{b}_R + \bar{s}_R$$

However, at T = 0 the probability of such processes is $\Gamma/V \sim e^{-4\pi/\alpha} \sim 10^{-165}$**.**

't Hooft, 1976

At finite T, the transitions proceed via thermal fluctuations (over the barrier) with an unsuppressed probability (due to sphaleron (static) configurations - saddle "points" of the field energy of the $SU(2)$ gauge - Higgs field system):

$$\Gamma/V \sim \alpha^4 T^4.$$

Kuzmin, Rubakov, Shaposhnikov, 1985;
Arnold et al., 1987 and 1997.

Sphaleron processes are efficient (in the case of interest) at

$$T_{\mathrm{EW}} \sim 140 \text{ GeV} < T < 10^{12} \text{ GeV}$$

Can generate $B \neq 0$, $L \neq 0$ at $T_{\mathrm{EW}} < T (< 10^{12}$ GeV) from $(B-L)_0 \neq 0$ (with $(B-L) = const.$).

Harvey, Turner, 1990

Leptogenesis

$$Y_B = \frac{n_B - n_{\bar{B}}}{S} \sim 8.6 \times 10^{-11} \qquad (n_\gamma{:}\ \sim 6.1 \times 10^{-10})$$

$$Y_B \cong -3 \times 10^{-3}\ \varepsilon\, \kappa$$

W. Buchmüller, M. Plümacher, 1998;
W. Buchmüller, P. Di Bari, M. Plümacher, 2004

$\kappa-$ efficiency factor; $\kappa \sim 10^{-1} - 10^{-3}$: $\varepsilon \gtrsim 10^{-7}$.

ε: $CP-$, $L-$ violating asymmetry generated in out of equilibrium $N_{Rj}-$decays in the early Universe,

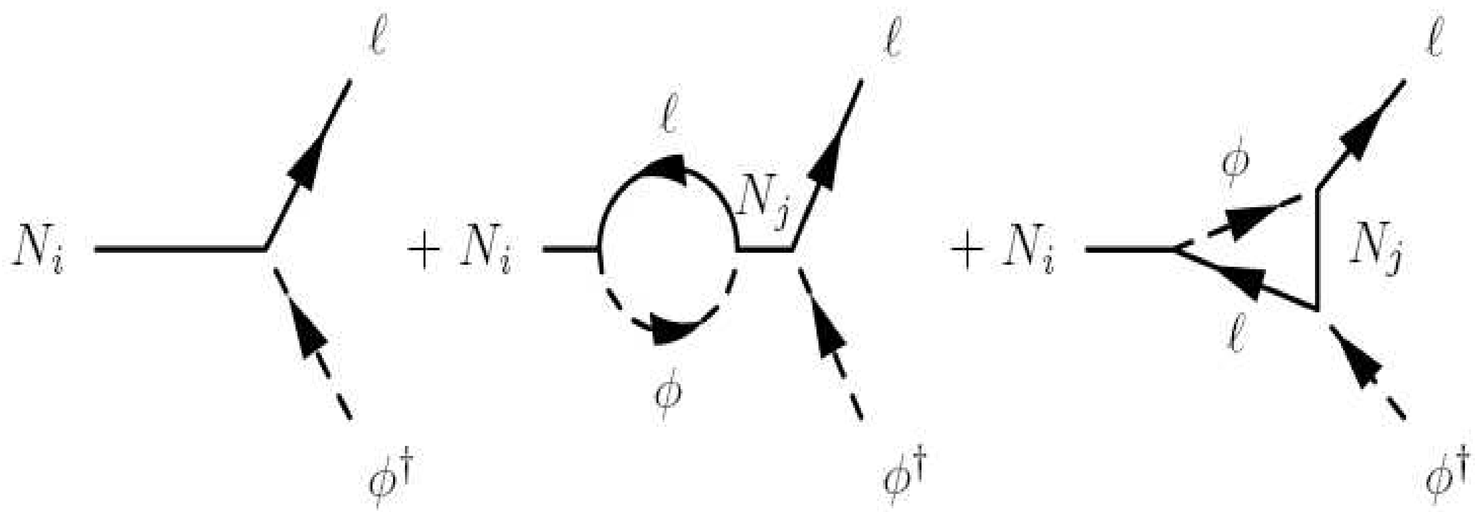
$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi^- \ell^+) - \Gamma(N_1 \to \Phi^+ \ell^-)}{\Gamma(N_1 \to \Phi^- \ell^+) + \Gamma(N_1 \to \Phi^+ \ell^-)}$$

M.A. Luty, 1992;
L. Covi, E. Roulet and F. Vissani, 1996;
M. Flanz *et al.*, 1996;
M. Plümacher, 1997;
A. Pilaftsis, 1997.

$\kappa = \kappa(\widetilde{m})$, $\widetilde{m}$ - determines the rate of wash-out processes:

$\Phi^+ + \ell^- \to N_1$, $\ell^- + \Phi^+ \to \Phi^- + \ell^+$, etc.

W. Buchmuller, P. Di Bari and M. Plumacher, 2002;
G. F. Giudice *et al.*, 2004


N_i
ℓ
$\phi^\dagger$
$+ N_i$
ℓ
ϕ
N_j
ℓ
$\phi^\dagger$
$+ N_i$
ϕ
ℓ
N_j
ℓ
$\phi^\dagger$

Low Energy Leptonic CPV and Leptogenesis

Assume: $M_1 \ll M_2 \ll M_3$

Individual asymmetries:

$$\varepsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im}\left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U_{lj}^* U_{lk} R_{1j} R_{1k}\right)}{\sum_j m_j \left|R_{1j}\right|^2}, \qquad v = 174 \text{ GeV}$$

$$\widetilde{m_l} \equiv \frac{|\lambda_{1l}|^2 v^2}{M_1} = \left|\sum_k R_{1k}\, m_k^{1/2}\, U_{lk}^*\right|^2, \quad l = e, \mu, \tau\,.$$

The "one-flavor" approximation - $\mathbf{Y}_{e,\mu,\tau}$ - "small":

Boltzmann eqn. for $n(N_1)$ and $\Delta L = \Delta(L_e + L_\mu + L_\tau)$.

$Y_l\ H^c(x)\overline{l_R}(x)\psi_{lL}$- out of equilibrium at $T \sim M_1$.

One-flavor approximation: $M_1 \sim T > 10^{12}$ GeV

$$\varepsilon_1 = \sum_l \varepsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im}\left(\sum_{j,k} m_j^2 R_{1j}^2\right)}{\sum_k m_k \left|R_{1k}\right|^2},$$

$$\widetilde{m_1} = \sum_l \widetilde{m_l} = \sum_k m_k \left|R_{1k}\right|^2.$$

Two-Flavour Regime

At $M_1 \sim T \sim 10^{12}$ GeV: Y_τ - in equilibrium, $Y_{e,\mu}$ - not;

wash-out dynamics changes: τ_R^-, τ_L^+

$N_1 \rightarrow (\lambda_{1e}\, e_L^- + \lambda_{1\mu}\, \mu_L^- + \lambda_{1\tau}\, \tau_L^-) + \Phi^+$; $(\lambda_{1e}\, e_L^- + \lambda_{1\mu}\, \mu_L^- + \lambda_{1\tau}\, \tau_L^-) + \Phi^+ \rightarrow N_1$;

$\tau_L^- + \Phi^0 \rightarrow \tau_R^-$, $\quad \tau_L^- + \tau_L^+ \rightarrow N_1 + \nu_L$, etc.

$\varepsilon_{1\tau}$ and $(\varepsilon_{1e} + \varepsilon_{1\mu}) \equiv \varepsilon_2$ evolve independently.

Three-Flavour Regime

At $M_1 \sim T \sim 10^9$ GeV: Y_τ, Y_μ - in equilibrium, Y_e - not.

$\varepsilon_{1\tau}$, ε_{1e} and $\varepsilon_{1\mu}$ evolve independently.

Thus, at $M_1 \sim 10^9 - 10^{12}$ GeV: L_τ, ΔL_τ - distinguishable;

L_e, L_μ, ΔL_e, ΔL_μ - individually not distinguishable;

$L_e + L_\mu$, $\Delta(L_e + L_\mu)$

A. Abada et al., 2006; E. Nardi et al., 2006

A. Abada et al., 2006

Individual asymmetries:

Assume: $M_1 \ll M_2 \ll M_3$, $10^9 \lesssim M_1\ (\sim T) \lesssim 10^{12}$ GeV,

$$\varepsilon_{1l} = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U^*_{lj} U_{lk} R_{1j} R_{1k}\right)}{\sum_j m_j\,|R_{1j}|^2}$$

$$\widetilde{m_l} \equiv \frac{|\lambda_{1l}|^2\, v^2}{M_1} \;=\; \left|\sum_k R_{1k} m_k^{1/2} U^*_{lk}\right|^2, \quad l = e, \mu, \tau\,.$$

The baryon asymmetry is

$$Y_B \;\simeq\; -\frac{12}{37 g_*}\left(\epsilon_2\,\eta\left(\frac{417}{589}\,\widetilde{m_2}\right) + \epsilon_\tau\,\eta\left(\frac{390}{589}\,\widetilde{m_\tau}\right)\right),$$

$$\eta\,(\widetilde{m_l}) \;\simeq\; \left(\left(\frac{\widetilde{m_l}}{8.25\times 10^{-3}\,\mathrm{eV}}\right)^{-1} + \left(\frac{0.2\times 10^{-3}\,\mathrm{eV}}{\widetilde{m_l}}\right)^{-1.16}\right)^{-1}.$$

$Y_{\mathcal{B}} = -(12/37)\,(Y_2 + Y_\tau)$,

$Y_2 = Y_{e+\mu}$, $\varepsilon_2 = \varepsilon_{1e} + \varepsilon_{1\mu}$, $\widetilde{m_2} = \widetilde{m_{1e}} + \widetilde{m_{1\mu}}$

A. Abada et al., 2006; E. Nardi et al., 2006

A. Abada et al., 2006

Real (Purely Imaginary) R: $\varepsilon_{1l} \neq 0$, CPV from U

$\varepsilon_{1e} + \varepsilon_{1\mu} + \varepsilon_{1\tau} = \varepsilon_2 + \varepsilon_{1\tau} = 0$,

$$\begin{aligned}
\varepsilon_{1\tau} &= -\frac{3M_1}{16\pi v^2} \frac{\text{Im}\left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U^*_{\tau j} U_{\tau k} R_{1j} R_{1k}\right)}{\sum_j m_j \, |R_{1j}|^2} \\
&= -\frac{3M_1}{16\pi v^2} \frac{\sum_{j,k>j} m_j^{1/2} m_k^{1/2} (m_k - m_j)\, R_{1j} R_{1k} \text{Im}\left(U^*_{\tau j} U_{\tau k}\right)}{\sum_j m_j \, |R_{1j}|^2}, R_{1j}R_{1k} = \pm\, |R_{1j}R_{1k}|, \\
&= \mp \frac{3M_1}{16\pi v^2} \frac{\sum_{j,k>j} m_j^{1/2} m_k^{1/2} (m_k + m_j)\, |R_{1j} R_{1k}|\, \text{Re}\left(U^*_{\tau j} U_{\tau k}\right)}{\sum_j m_j \, |R_{1j}|^2}, R_{1j}R_{1k} = \pm i |R_{1j}R_{1k}|
\end{aligned}$$

S. Pascoli, S.T.P., A. Riotto, 2006.

CP-Violation: $\text{Im}\left(U^*_{\tau j} U_{\tau k}\right) \neq 0$, $\text{Re}\left(U^*_{\tau j} U_{\tau k}\right) \neq 0$;

$$Y_B = -\frac{12}{37} \frac{\varepsilon_{1\tau}}{g_*} \left(\eta\left(\frac{390}{589}\widetilde{m_\tau}\right) - \eta\left(\frac{417}{589}\widetilde{m_2}\right)\right)$$

$m_1 \ll m_2 \ll m_3$, $M_1 \ll M_{2,3}$; $R_{12}R_{13}$ − real; $m_1 \cong 0$, $R_{11} \cong 0$ (N_3 decoupling)

$$\varepsilon_{1\tau} \;=\; -\,\frac{3M_1\sqrt{\Delta m^2_{31}}}{16\pi v^2}\left(\frac{\Delta m^2_{\odot}}{\Delta m^2_{31}}\right)^{\frac{1}{4}} \frac{|R_{12}R_{13}|}{\left(\frac{\Delta m^2_{\odot}}{\Delta m^2_{31}}\right)^{\frac{1}{2}}|R_{12}|^2 + |R_{13}|^2}$$

$$\times \left(1 - \frac{\sqrt{\Delta m^2_{\odot}}}{\sqrt{\Delta m^2_{31}}}\right) \mathrm{Im}\,(U^*_{\tau 2}U_{\tau 3})$$

$$\mathrm{Im}\,(U^*_{\tau 2}U_{\tau 3}) \;=\; -c_{13}\left[c_{23}s_{23}c_{12}\sin\left(\frac{\alpha_{32}}{2}\right) - c^2_{23}s_{12}s_{13}\sin\left(\delta - \frac{\alpha_{32}}{2}\right)\right]$$

$\alpha_{32} = \pi$, $\delta = 0$: $\mathrm{Re}(U^*_{\tau 2}U_{\tau 3}) = 0$, CPV due to the interplay of R and U.

S. Pascoli, S.T.P., A. Riotto, 2006.

$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$ (NH)

Dirac CP-violation

$\alpha_{32} = 0 \ (2\pi)$, $\beta_{23} = \pi \ (0)$; $\beta_{23} \equiv \beta_{12} + \beta_{13} \equiv \arg(R_{12} R_{13})$.

$|R_{12}| \cong 0.86$, $|R_{13}|^2 = 1 - |R_{12}|^2$, $|R_{13}| \cong 0.51$ - maximise $|Y_B|$:

$$|Y_B| \ \cong 2.1 \times 10^{-13} \, |\sin\delta| \left(\frac{s_{13}}{0.15}\right) \left(\frac{M_1}{10^9 \text{ GeV}}\right) .$$

$|Y_B| \gtrsim 8 \times 10^{-11}$, $M_1 \lesssim 5 \times 10^{11}$ GeV imply

$$|\sin\theta_{13} \sin\delta| \gtrsim 0.11 \,, \qquad \sin\theta_{13} \cong 0.15 \,.$$

The lower limit corresponds to

$$|J_{\rm CP}| \gtrsim 2.4 \times 10^{-2}$$

FOR $\alpha_{32} = 0 \ (2\pi)$, $\beta_{23} = 0 \ (\pi)$:

$$|\sin\theta_{13} \sin\delta| \gtrsim 0.09 \,, \qquad \sin\theta_{13} \cong 0.15 \,; \quad |J_{\rm CP}| \gtrsim 2.0 \times 10^{-2}$$

Realised in a theory based on the S_4 symmetry: P. Cheng *et al.*, arXiv:1602.03873.

The requirement $\sin\theta_{13} \gtrsim 0.09$ (0.11) - compatible with the Daya Bay, RENO, Double Chooz results: $\sin\theta_{13} \cong 0.15$.

$|\sin\theta_{13}\sin\delta| \gtrsim 0.11$ implies $|\sin\delta| \gtrsim 0.7$ - compatible with $\delta \cong 3\pi/2$.

$\sin\theta_{13} \cong 0.15$ and $\delta \cong 3\pi/2$ imply relatively large (observable) CPV effects in neutrino oscillations: $J_{\rm CP} \cong -3.5 \times 10^{-2}$.

$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$ (NH)

Majorana CP-violation

$\delta = 0$, real R_{12}, R_{13} ($\beta_{23} = \pi$ (0));

$\alpha_{32} \cong \pi/2$, $|R_{12}|^2 \cong 0.85$, $|R_{13}|^2 = 1 - |R_{12}|^2 \cong 0.15$ - maximise $|\epsilon_\tau|$ and $|Y_B|$:

$$|Y_B| \cong 2.2 \times 10^{-12} \left(\frac{\sqrt{\Delta m^2_{31}}}{0.05 \text{ eV}}\right) \left(\frac{M_1}{10^9 \text{ GeV}}\right) \frac{|\sin(\alpha_{32}/2)|}{\sin \pi/4}.$$

We get $|Y_B| \gtrsim 8 \times 10^{-11}$, for $M_1 \gtrsim 3.6 \times 10^{10}$ GeV, or $|\sin \alpha_{32}/2| \gtrsim 0.15$

$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$ (IH)

$m_3 \cong 0$, $R_{13} \cong 0$ (N_3 decoupling): impossible to reproduce Y_B^{obs} for real $R_{11}R_{12}$;

$|Y_B|$ suppressed by the additional factor $\Delta m^2_{\odot}/|\Delta_{32}| \cong 0.03$.

Purely imaginary $R_{11}R_{12}$: no (additional) suppression

Dirac CP-violation

$\alpha_{21} = \pi$; $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = 1$;

$|R_{11}| \cong 1.07$, $|R_{12}|^2 = |R_{11}|^2 - 1$, $|R_{12}| \cong 0.38$ - maximise $|\epsilon_\tau|$ and $|Y_B|$:

$$|Y_B| \cong 8.1 \times 10^{-12}\, |s_{13} \sin\delta| \left(\frac{M_1}{10^9 \text{ GeV}}\right) .$$

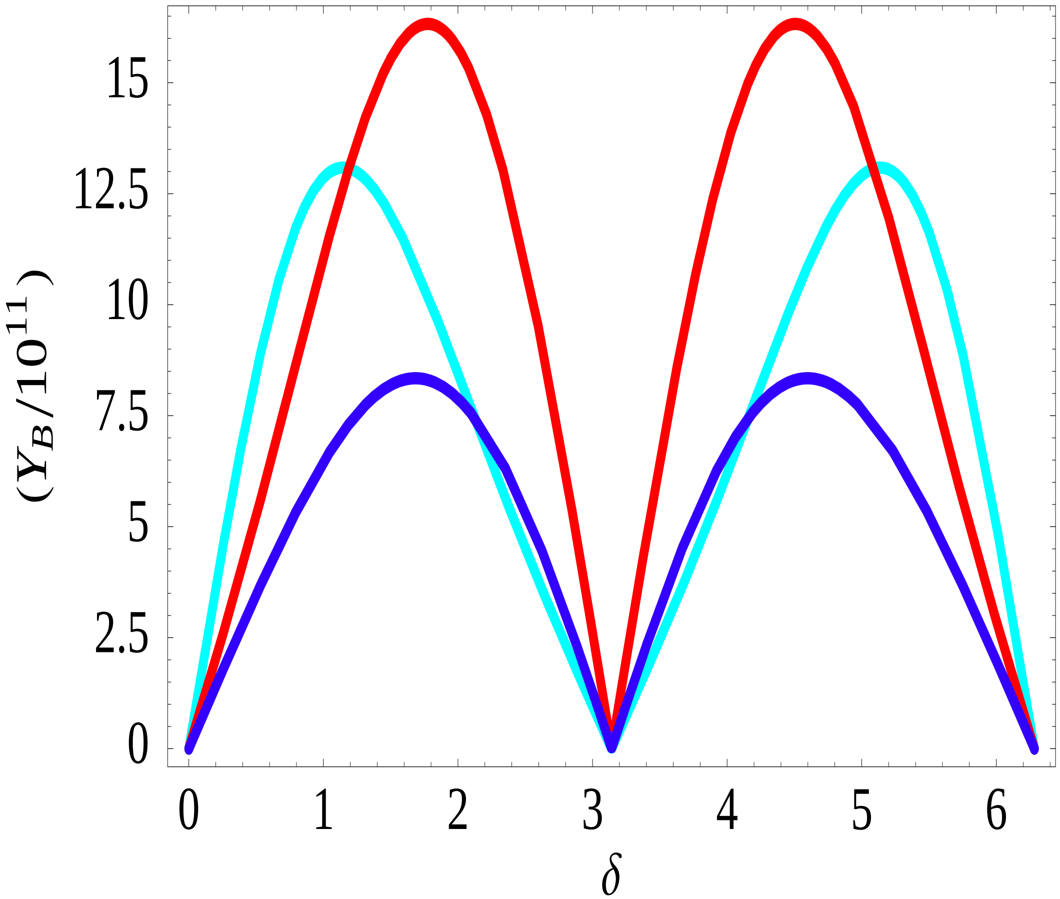
$|Y_B| \gtrsim 8 \times 10^{-11}$, $M_1 \lesssim 5 \times 10^{11}$ GeV imply

$$|\sin\theta_{13} \sin\delta| \gtrsim 0.02 , \qquad \sin\theta_{13} \cong 0.15 .$$

The lower limit corresponds to

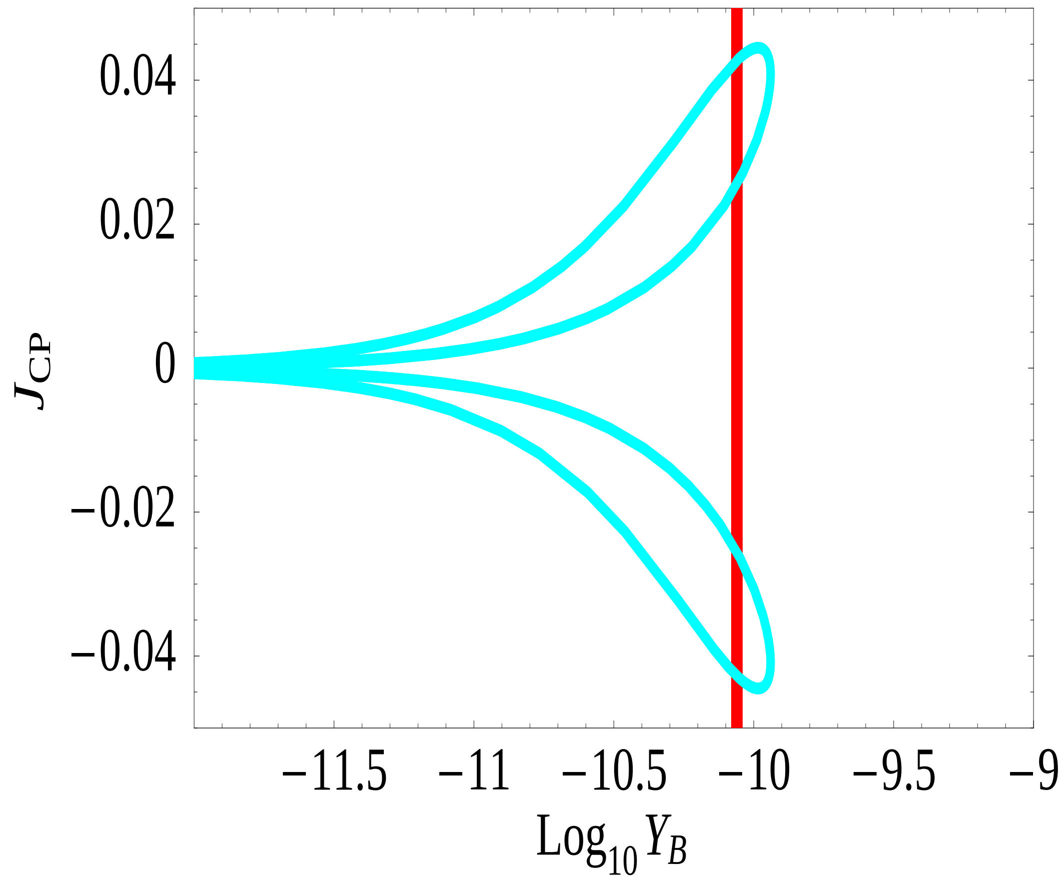
$$|J_{\rm CP}| \gtrsim 4.6 \times 10^{-3}$$

Realised in a theory based on the S_4 symmetry: P. Cheng *et al.*, arXiv:1602.03873.



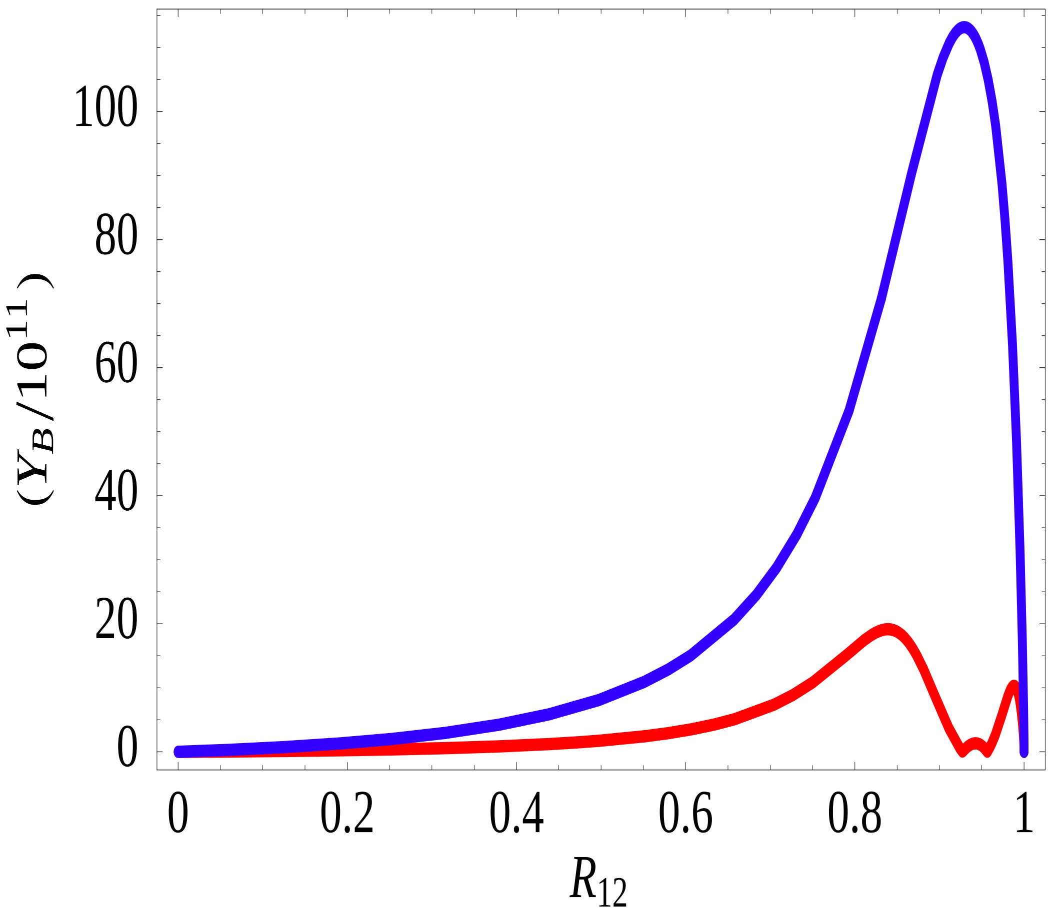
$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; Dirac CP-violation, $\alpha_{32} = 0;\ 2\pi$;
real R_{12}, R_{13}, $|R_{12}|^2 + |R_{13}|^2 = 1$, $|R_{12}| = 0.86$, $|R_{13}| = 0.51$, sign$(R_{12}R_{13}) = +1$;
i) $\alpha_{32} = 0$ $(\kappa' = +1)$, $s_{13} = 0.2$ (red line) and $s_{13} = 0.1$ (dark blue line);
ii) $\alpha_{32} = 2\pi$ $(\kappa' = -1)$, $s_{13} = 0.2$ (light blue line);
$M_1 = 5 \times 10^{11}$ GeV.

S. Pascoli, S.T.P., A. Riotto, 2006.

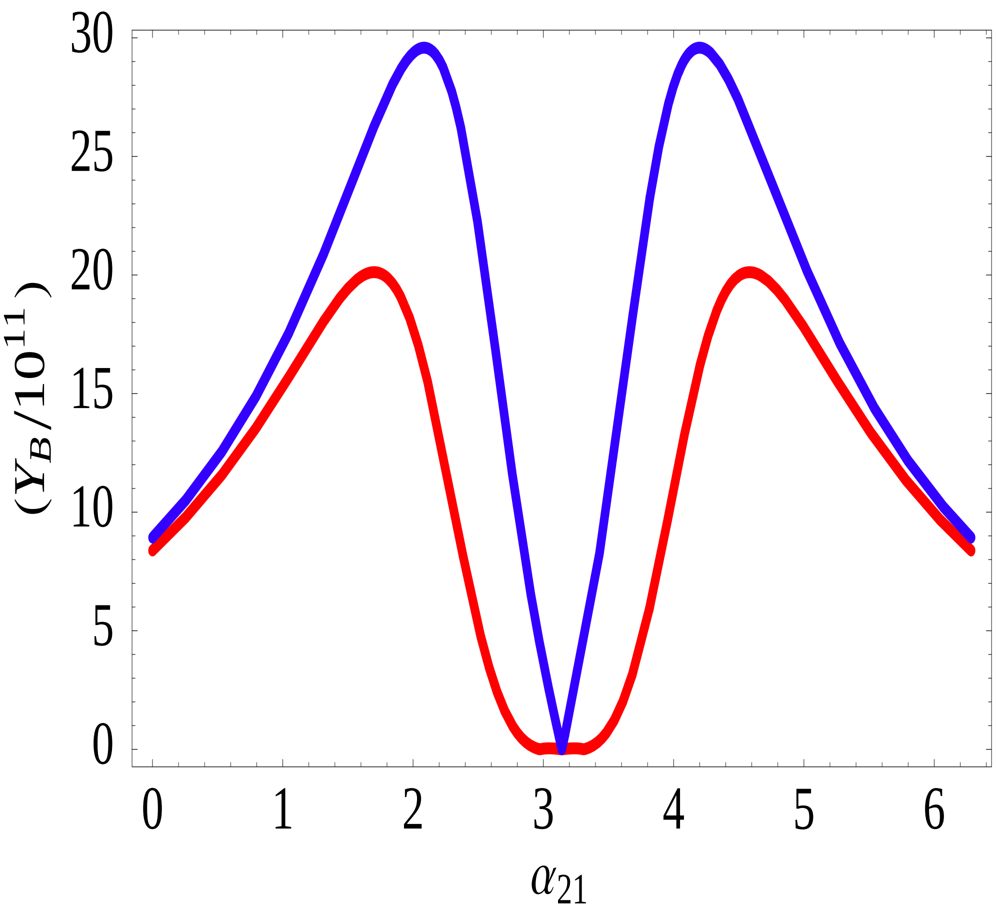


$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; $M_1 = 5 \times 10^{11}$ GeV;
Dirac CP-violation, $\alpha_{32} = 0$ (2π);
$|R_{12}| = 0.86$, $|R_{13}| = 0.51$, sign $(R_{12}R_{13}) = +1$ (-1) $(\beta_{23} = 0$ (π), $\kappa' = +1)$;
The red region denotes the 2σ allowed range of $Y_{\rm B}$.

S. Pascoli, S.T.P., A. Riotto, 2006.

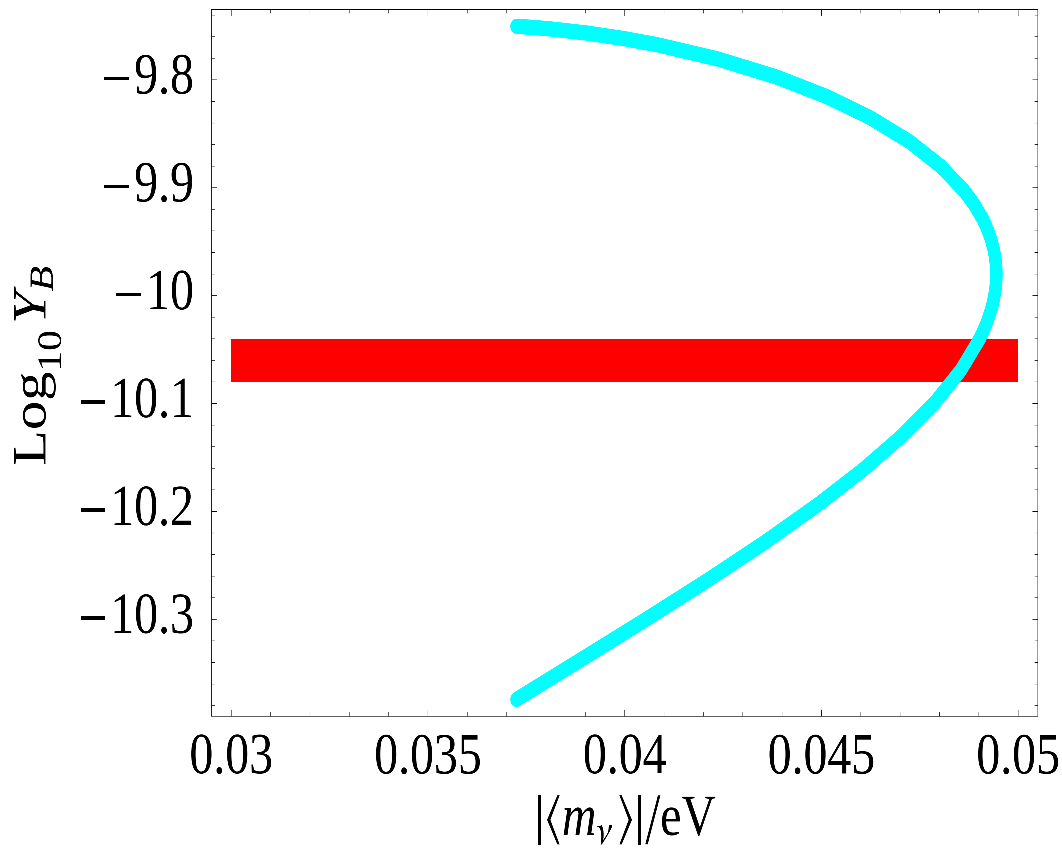


$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; $M_1 = 5 \times 10^{11}$ GeV;
real R_{12}, R_{13}, sign $(R_{12}R_{13}) = +1$, $R_{12}^2 + R_{13}^2 = 1$, $s_{13} = 0.20$;
a) Majorana CP-violation (blue line), $\delta = 0$ and $\alpha_{32} = \pi/2$ ($\kappa = +1$);
b) Dirac CP-violation (red line), $\delta = \pi/2$ and $\alpha_{32} = 0$ ($\kappa' = +1$);
$\Delta m^2_{\odot}$, $\sin^2\theta_{12}$, Δm^2_{31}, $\sin^2 2\theta_{23}$ - fixed at their best fit values.



$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$; $M_1 = 2 \times 10^{11}$ GeV;
Majorana CP-violation, $\delta = 0$;
purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = -1$, $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.2$;
$s_{13} = 0$ (blue line) and 0.2 (red line).

S. Pascoli, S.T.P., A. Riotto, 2006.



$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$; $M_1 = 2 \times 10^{11}$ GeV;
Majorana CP-violation, $\delta = 0$, $s_{13} = 0$;
purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = +1$ $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.05$.
The Majorana phase α_{21} is varied in the interval $[-\pi/2, \pi/2]$.

S. Pascoli, S.T.P., A. Riotto, 2006.

$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$ (IH)

Majorana or Dirac CP-violation

$m_3 \neq 0$, $R_{13} \neq 0$, $R_{11}(R_{12}) = 0$: possible to reproduce Y_B^{obs} for real $R_{12(11)}R_{13} \neq 0$

Requires $m_3 \cong (10^{-5} - 10^{-2})$ eV; non-trivial dependence of $|Y_B|$ on m_3

Majorana CPV, $\delta = 0$ (π): requires $M_1 \gtrsim 3.5 \times 10^{10}$ GeV

Dirac CPV, $\alpha_{32(31)} = 0$: typically requires $M_1 \gtrsim 10^{11}$ GeV

$|Y_B| \gtrsim 8 \times 10^{-11}$, $\quad M_1 \lesssim 5 \times 10^{11}$ GeV imply

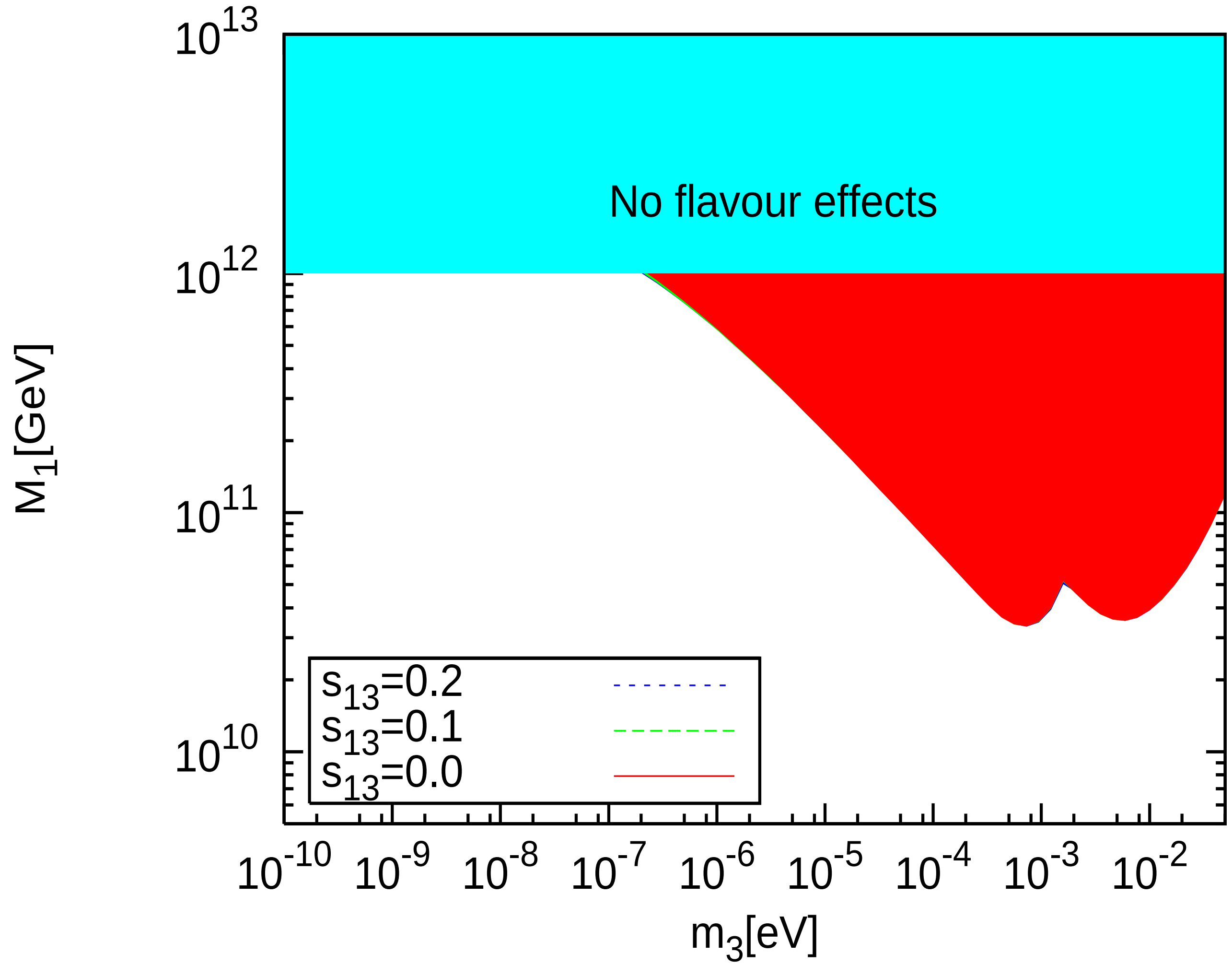
$$|\sin\theta_{13} \sin\delta| \gtrsim (0.04 - 0.09)\,.$$

The lower limit corresponds to

$$|J_{\text{CP}}| \gtrsim (0.009 - 0.02)$$

NO (NH) spectrum, $m_1 <\ (\ll)\ m_2 < m_3$: similar dependence of $|Y_B|$ on m_1 if $R_{12} = 0$, $R_{11}R_{13} \neq 0$; non-trivial effects for $m_1 \cong (10^{-4} - 5 \times 10^{-2})$ eV.

E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007



$m_3 < m_1 < m_2$, $M_1 \ll M_2 \ll M_3$, real R_{1j}; $M_1 = (10^9 - 10^{12})$ GeV, $s_{13} = 0.2; 0.1; 0;$

E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007

Low Energy Leptonic CPV and Leptogenesis: Summary

Leptogenesis: see-saw mechanism; N_j - heavy RH ν's;
N_j, ν_k - Majorana particles

N_j: $M_1 \ll M_2 \ll M_3$

The observed value of the baryon asymmetry of the Universe can be generated

A. CP-violation due to the Dirac phase δ in $U_{\rm PMNS}$, no other sources of CPV (Majorana phases in $U_{\rm PMNS}$ equal to 0, etc.); requires $M_1 \gtrsim 10^{11}$ GeV.

$m_1 \ll m_2 \ll m_3$ (NH):

$$|\sin\theta_{13}\sin\delta| \gtrsim 0.11\,; \qquad |J_{\rm CP}| \gtrsim 2.0 \times 10^{-2}$$

$m_3 \ll m_1 < m_2$ (IH):

$$|\sin\theta_{13}\sin\delta| \gtrsim 0.02\,; \qquad |J_{\rm CP}| \gtrsim 4.6 \times 10^{-3}$$

B. CP-violation due to the Majorana phases in $U_{\rm PMNS}$, no other sources of CPV (Dirac phase in $U_{\rm PMNS}$ equal to 0, etc.); requires $M_1 \gtrsim 3.5 \times 10^{10}$ GeV.

C. CP-violation due to both Dirac and Majorana phases in $U_{\rm PMNS}$.

D. Y_B can depend non-trivially on $\min(m_j) \sim (10^{-5} - 10^{-2})$ eV.

S. Pascoli, S.T.P., A. Riotto, 2006 (A-C);
E. Molinaro, S.T.P., T. Shindou, Y. Takanishi, 2007 (D).

LOW SCALE (TeV,...) LEPTOGENESIS

The CP violation necessary for the generation of the observed value of the Baryon Asymmetry of the Universe (BAU) can be provided exclusively by the Dirac and/or Majorana CPV phases in the neutrino PMNS matrix also in the low scale (TeV, GeV,...) leptogenesis.

P. Hernandez *et al.*, **arXiv:1606.06719 and 1611.05000.**
M. Drewes *et al.*, **arXiv:1609.09069.**
G. Bambhaniya *et al.*, **arXiv:1611.03827.**
R. Volkas *et al.*, **arXiv:1801.03827.**

Conclusions.

- Understanding the status of the CP-symmetry in the lepton sector is of fundamental importance.

- Obtaining information on Dirac and Majorana CPV is a remarkably challenging problem.

- The measurement of the Dirac phase in the PMNS mixing matrix, together with an improvement of the precision on the mixing angles θ_{12}, θ_{13} and θ_{23}, can provide unique information about the possible existence of new fundamental symmetry in the lepton sector.

- The see-saw mechanism provides a link between the ν-mass generation and the baryon asymmetry of the Universe (BAU).

- Any of the CPV phases in $U_{\rm PMNS}$ can be the leptogenesis CPV parameters.

Low energy leptonic CPV can be directly related to the existence of BAU.

- These results underline further the importance of the experimental searches for Dirac and/or Majorana leptonic CP-violation at low energies.