

# Neutrino Theory (Including Leptogenesis)

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Understanding the origin of the pattern of neutrino mixing and of neutrino mass squared differences that emerged from the neutrino oscillation data in the recent years is one of the most challenging problems in neutrino physics. It is part of the more general fundamental problem in particle physics of understanding the origins of flavour in the quark and lepton sectors, i.e., of the patterns of quark masses and mixing, and of the charged lepton and neutrino masses and of neutrino mixing.

“Asked what single mystery, if he could choose, he would like to see solved in his lifetime, Weinberg doesn't have to think for long: he wants to be able to explain the observed pattern of quark and lepton masses.”

From Model Physicist, CERN Courier, 13 October 2017.

Of fundamental importance are also

- . 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, NO $\nu$ A; T2HK, DUNE);
- . determination of the type of spectrum neutrino masses possess, or the “neutrino mass ordering” (T2K + NO $\nu$ A; 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.

# Experimental Proofs for $\nu$ -Oscillations

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

$\theta_Z$ -,  $L/E$ - 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, NO $\nu$ A ( $\nu_\mu$  from accelerators):  $\nu_\mu \rightarrow \nu_e$

T2K, NO $\nu$ A ( $\bar{\nu}_\mu$  from accelerators):  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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

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

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

B. Pontecorvo, 1957; 1958; 1967;

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

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

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

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

These data imply that

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

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

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

**These discoveries suggest the existence of  
New Physics beyond that of the ST.**

## The New Physics can manifest itself (can have a variety of different “flavours”):

- In the existence of more than 3 massive neutrinos:  $n > 3$  ( $n = 4$ , or  $n = 5$ , or  $n = 6, \dots$ ).
- In the observed pattern of neutrino mixing and in the values of the CPV phases in the PMNS matrix.
- In the Majorana nature of massive neutrinos ( $L \neq \text{const.}$ ).
- In the existence of new particles, e.g., at the TeV scale: heavy Majorana neutrinos  $N_j$ , doubly charged scalars, ...
- In the existence of new (FChNC, FCFNSNC) neutrino interactions ( $U(1)_X$ ,  $M_X \lesssim 50$  MeV).
- In the existence of LFV processes:  $\mu \rightarrow e + \gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu - e$  conversion, etc., which proceed with rates close to the existing upper limits.
- In the existence of “unknown unknowns” ...

We can have  $n > 3$  ( $n = 4$ , or  $n = 5$ , or  $n = 6, \dots$ ) if, e.g., **sterile**  $\nu_R$ ,  $\tilde{\nu}_L$  exist and they mix with the active flavour neutrinos  $\nu_l$  ( $\tilde{\nu}_l$ ),  $l = e, \mu, \tau$ .

Two (extreme) possibilities:

i)  $m_{4,5,\dots} \sim 1$  eV;

in this case  $\nu_{e(\mu)} \rightarrow \nu_S$  oscillations are possible (hints from LSND and MiniBooNE experiments, re-analyses of short baseline (SBL) reactor neutrino oscillation data (“reactor neutrino anomaly”), data of radioactive source calibration of the solar neutrino SAGE and GALLEX experiments (“Gallium anomaly”); tests (DANSS, NEOS, PROSPECT, STEREO, ICARUS (at Fermilab), ...).

ii)  $M_{4,5,\dots} \sim (1 - 10^3)$  GeV, low scale seesaw models;

$M_{4,5,\dots} \sim (10^9 - 10^{13})$  GeV, “classical” seesaw models.

## Reference Model: 3- $\nu$ mixing

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} \quad l = e, \mu, \tau.$$

The PMNS matrix  $U$  -  $3 \times 3$  unitary.

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

3- $\nu$  mixing: 3-flavour neutrino oscillations possible.

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

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

# Three Neutrino Mixing

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

$U$  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:

• $\nu_j$ - Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• $\nu_j$ - 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  
J. Schechter, J.W.F. Valle, 1980.  
M. Doi, T. Kotani, E. Takasugi, 1981

# PMNS Matrix: Standard Parametrization

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

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

- $s_{ij} \equiv \sin \theta_{ij}$ ,  $c_{ij} \equiv \cos \theta_{ij}$ ,  $\theta_{ij} = [0, \frac{\pi}{2}]$ ,
- $\delta$  - Dirac CPV phase,  $\delta = [0, 2\pi]$ ; CP inv.:  $\delta = 0, \pi, 2\pi$ ;
- $\alpha_{21}$ ,  $\alpha_{31}$  - Majorana CPV phases; CP inv.:  $\alpha_{21(31)} = k(k')\pi$ ,  $k(k') = 0, 1, 2\dots$   
S.M. Bilenky et al., 1980
- $\Delta m_{\odot}^2 \equiv \Delta m_{21}^2 \cong 7.37 \times 10^{-5}$  eV $^2 > 0$ ,  $\sin^2 \theta_{12} \cong 0.297$ ,  $\cos 2\theta_{12} \gtrsim 0.29$  ( $3\sigma$ ),
- $|\Delta m_{31(32)}^2| \cong 2.53$  (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) ,
- $\theta_{13}$  - 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].

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

Parameter	Ordering	Best fit	$1\sigma$ range	$2\sigma$ range	$3\sigma$ range	“ $1\sigma$ ” (%)
$\Delta m_{\odot}^2 / 10^{-5}$ 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
$ \Delta m_A^2  / 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
$\delta/\pi$	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

$$\Delta m_{\odot}^2 \equiv \Delta m_{21}^2; \quad \Delta m_A^2 \equiv \Delta m_{31(32)}^2, \text{ NO (IO).}$$

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

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

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

$$J_{CP} = \text{Im} \{ U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^* \} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

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  $\alpha_{21}, \alpha_{31}$ :

–  $\nu_l \leftrightarrow \nu_{l'}, \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$  not sensitive;

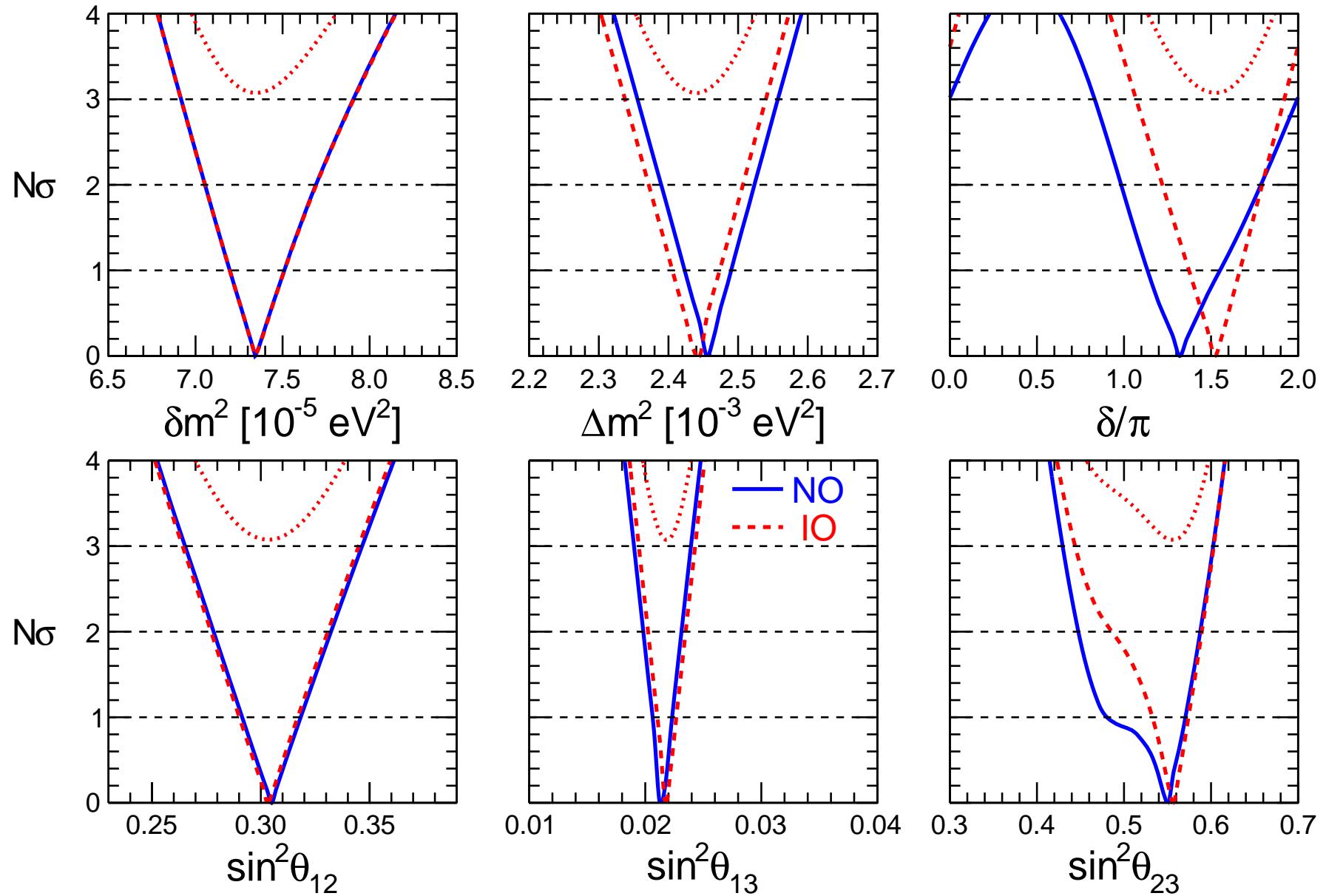
S.M. Bilenky et al., 1980;  
P. Langacker et al., 1987

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

- **Best fit value:**  $\delta = 1.32(1.52)\pi$  [ $1.30(1.54)\pi$ ];
- $\delta = 0$  or  $2\pi$  are disfavored at  $3.0(3.6)\sigma$  [ $2.6(3.0)\sigma$ ];
- $\delta = \pi$  is disfavored at  $1.8(3.6)\sigma$  [ $1.7(3.3)\sigma$ ];
- $\delta = \pi/2$  is strongly disfavored at  $4.4(5.2)\sigma$  [ $4.3(5.0)\sigma$ ].
- **At  $3\sigma$ :**  $\delta/\pi$  is found to lie in **0.83-1.99 (1.07-1.92)** [**1.07-1.97 (0.80-2.08)**].

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

# LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



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

Latest global analysis: data favors NO

IO disfavored at  $3.1\sigma$ .

F. Capozzi et al., 1804.09678.

## Qualitative understanding of $m_{\nu_j} \lll m_{e,\mu,\tau}, m_q$

- **Seesaw mechanisms of neutrino mass generation**

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

W. Konetschny, W. Kummer 1977; M. Magg, C. Wetterich, 1980; T.P. Cheng, L.-F. Li, 1980  
(type II).

R. Foot *et al.*, 1989 (type III).

**Explains the smallness of  $\nu$ -masses (naturalness); connection to grand unification.**

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

S. Fukugita, T. Yanagida, 1986.

- **Radiative generation of  $\nu$  masses and mixing**

A. Zee, 1980; K. Babu, 1985;...; recent review: Y.Cai *et al.*, 1706.08524

## Three Types of Seesaw Mechanisms

Require the existence of new degrees of freedom (particles) beyond those present in the ST

Type I seesaw mechanism:  $\nu_{lR}$  - RH  $\nu s'$  (heavy).

Type II seesaw mechanism:  $H(x)$  - a triplet of  $H^0, H^-, H^{--}$  Higgs fields (HTM).

W. Konetschny, W. Kummer 1977; M. Magg, C. Wetterich, 1980; T.P. Cheng, L.-F. Li, 1980;  
J. Schechter, J.F.W. Valle, 1980 G. Lazarides, Q. Shafi, C. Wetterich, 1981.

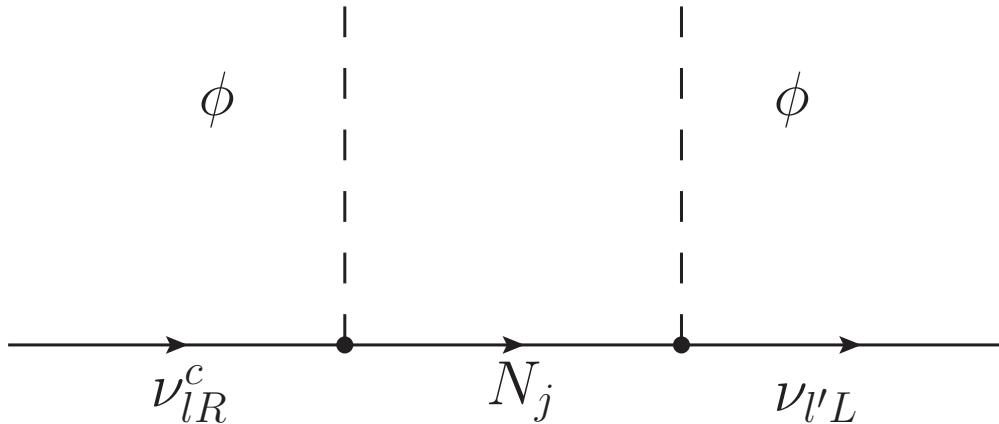
Type III seesaw mechanism:  $T(x)$  - a triplet of fermion fields.

R. Foot *et al.*, 1989

The scale of New Physics determined by the masses of the New Particles.

Massive neutrinos  $\nu_j$  - Majorana particles.

All three types of seesaw mechanisms have TeV scale versions, predicting rich low-energy phenomenology ( $(\beta\beta)_{0\nu}$ -decay, LFV processes, etc.) and New Physics at LHC.



- $\nu_{l'R}(x)$ : Majorana mass term at “high scale” ( $\sim$ TeV; or  $(10^9 - 10^{13})$  GeV in  $SO(10)$  GUT)

$$\mathcal{L}_M^\nu(x) = + \frac{1}{2} \nu_{l'R}^T(x) C^{-1} (M^{RR})_{ll}^\dagger \nu_{lR}(x) + h.c. = - \frac{1}{2} \sum_j \bar{N}_j M_j N_j ,$$

- Yukawa type coupling of  $\nu_{lL}(x)$  and  $\nu_{l'R}(x)$  involving  $\Phi(x)$ :

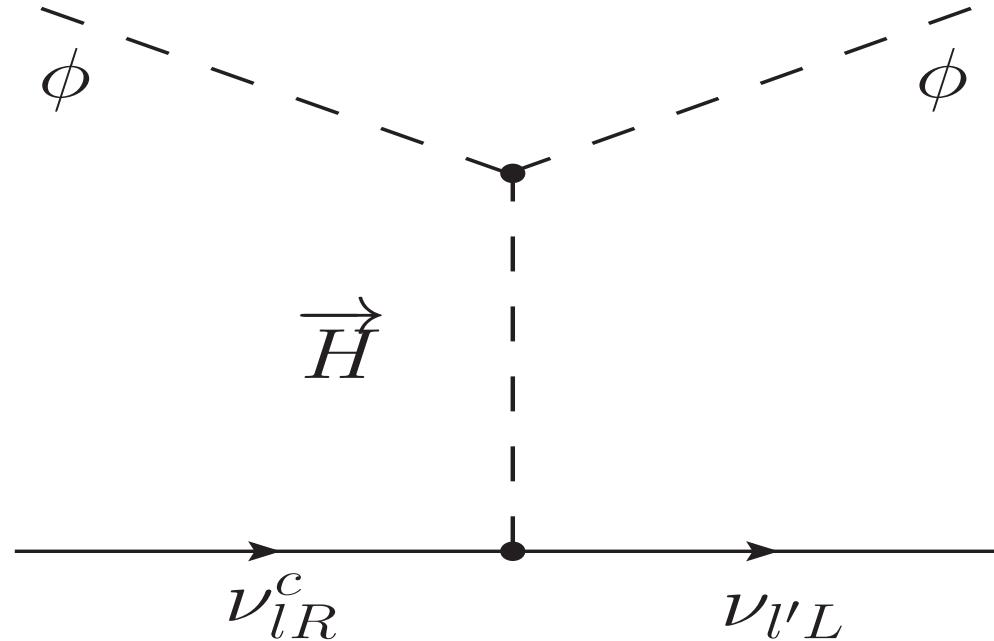
$$\begin{aligned} \mathcal{L}_Y(x) &= \bar{Y}_{l'l}^\nu \overline{\nu_{l'R}}(x) \Phi^T(x) (i\tau_2) \psi_{lL}(x) + \text{h.c.}, \\ &= Y_{jl}^\nu \overline{N_{jR}}(x) \Phi^T(x) (i\tau_2) \psi_{lL}(x) + \text{h.c.}, \\ M_D &= \frac{v}{\sqrt{2}} Y^\nu, \quad v = 246 \text{ GeV}. \end{aligned}$$

For sufficiently large  $M_j$ , Majorana mass term for  $\nu_{lL}(x)$ :

$$M_\nu \cong v_u^2 (Y^\nu)^T M_j^{-1} Y^\nu = U_{\text{PMNS}}^* m_\nu^{\text{diag}} U_{\text{PMNS}}^\dagger .$$

$v_u Y^\nu = M_D$ ,  $M_D \sim 1$  GeV,  $M_j = 10^{10}$  GeV:  $M_\nu \sim 0.1$  eV.

## Type II Seesaw Mechanism

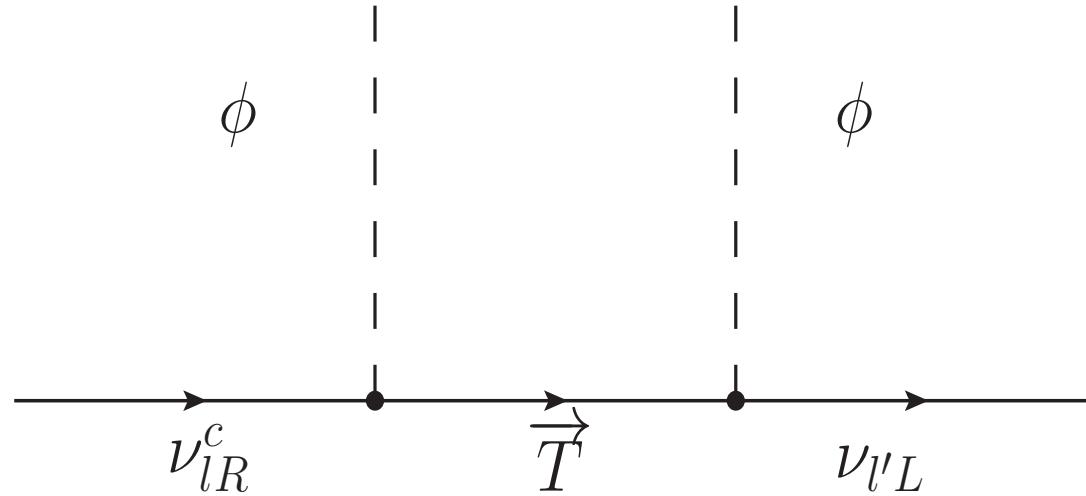


Due to I. Girardi

$$M_\nu \cong h v^2 \mu_H M_H^{-2} = U_{\text{PMNS}}^* m_\nu^{\text{diag}} U_{\text{PMNS}}^\dagger .$$

$h = 10^{-2}$ ,  $\mu_H \sim M_H$ ,  $v = 246$  GeV,  $M_H \sim 6 \times 10^{12}$  GeV:  
 $M_\nu \sim 0.1$  eV.

## Type III Seesaw Mechanism



$$M_\nu \cong v^2 (Y_T)^T M_T^{-1} Y_T = U_{\text{PMNS}}^* m_\nu^{\text{diag}} U_{\text{PMNS}}^\dagger .$$

$v Y_T \sim 1 \text{ GeV}$ ,  $M_T \sim 10^{10} \text{ GeV}$ :  $M_\nu \sim 0.1 \text{ eV}$ .

In EO formalism  $M_\nu$  in all 3 mechanisms - due to the Weinberg dim 5 operator:

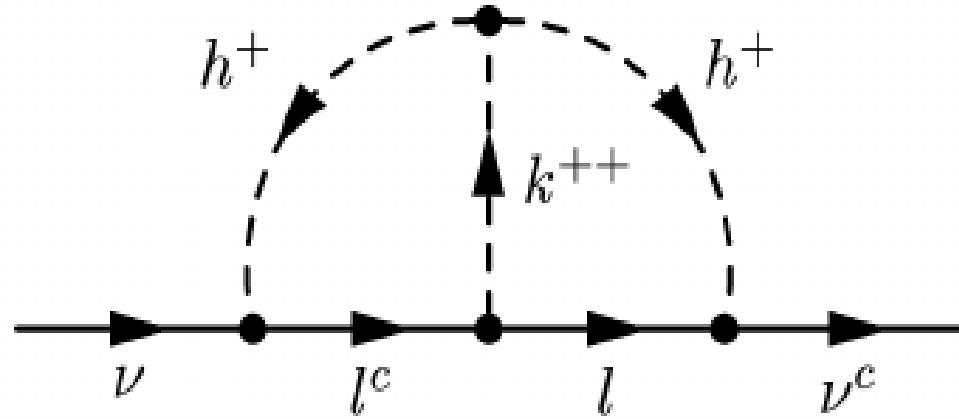
$$\frac{\lambda_{ll'}}{\Lambda} L_l H L_{l'} H$$

# Radiative generation of $\nu$ masses and mixing

A. Zee, 1980; K.S. Babu, 1985;...; Y. Farzan *et al.*, 1208.2732; recent review: Y.Cai *et al.*,  
1706.08524

## Generic features

- Loop suppression helps explaining the smallness of  $\nu$ -masses.
- New particles need not be super heavy - can be at the TeV scale.
- Models at the TeV scale - testable.
- No need to introduce  $\nu_R$ .
- Typically includes extended scalar sector.

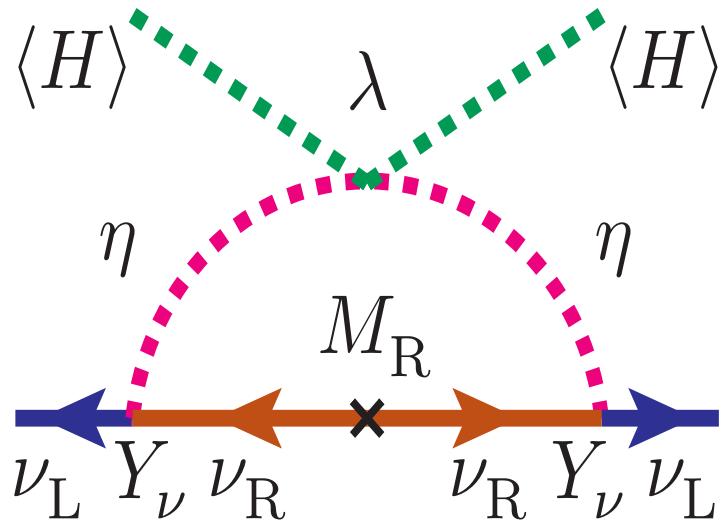


K.S. Babu, 1988

$Y_W(k^{++}) = 4, L(k^{++}) = -2; Y_W(h^+) = 2, L(h^+) = -2;$  no  $\nu_R;$   
 $\nu_j$  – Majorana fermions.

$M(k^{++}) \sim \text{TeV}, M(h^+) \sim \text{TeV}$  – possible.

$k^{++} \rightarrow l^+ + l'^+, l, l' = e, \mu, \tau;$   
 $\mu \rightarrow e + \gamma, \mu \rightarrow 3e, \mu^- + (A, Z) \rightarrow e^- + (A, Z);$   
 $(\beta\beta)_{0\nu}$  – decay.



E. Ma, hep-ph/0601225 (figure from T. Ohlsson, Sh. Zhou, 1311.3846)

$$SU(2)_L \times U(1)_{Y_W} \times Z_2;$$

$\nu_R$  - present,  $M_R$ - Majorana mass of  $\nu_R$ ;

$\eta$  - additional  $SU(2)_L$  doublet;  $\langle \eta^0 \rangle = 0$  (scalar potential);

$Z_2(\eta) = Z_2(\nu_R) = -1$ ;  $Z_2(H) = Z_2(L_l) = Z_2(l_L^c) = +1$ .

$\nu_j$ — Majorana fermions;

DM candidate available: either  $N_1$  ( $N_{1,2,3}$ ,  $M_{1,2,3}$ ,  $\min(M_j) = M_1$ ), or  $\sqrt{2}\text{Re}\eta^0$ .

$M(\eta^\pm) \sim \text{TeV}$ ,  $M_{1,2,3} \sim \text{TeV}$  - possible;

$M(\eta^\pm) > M_{1,2,3}$ :  $\eta^\pm \rightarrow l^\pm N_{1,2,3}$ ,  $N_2 \rightarrow l^\pm l^\mp N_1$ ,  $N_3 \rightarrow l^\pm l^\mp N_{1,2}$

$M(\eta^\pm) < M_{1,2,3}$ :  $N_{1,2,3} \rightarrow l^\pm \eta^\mp$

$\mu \rightarrow e + \gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ ;

$(\beta\beta)_{0\nu}$ — decay.

More cases of  $M_\nu$  generated at 1-loop, 2-loop, 3-loop,..., level are discussed in  
**Y. Farzan et al., 1208.2732.**

Effective operators which generate  $M_\nu$  at 1-loop or 2-loop level are discussed in the recent review:  
**Y.Cai et al., 1706.08524.**

In particular,  $M_\nu$  can be generated at loop level by dim 7 operators:

$$O_3 = L L Q \bar{d} H, \quad O_8 = L \bar{d} \bar{e}^\dagger \bar{u}^\dagger H$$

**UV completion:** LQ with (3,1,-2/3) and (3,3,-2/3) - well known candidates to explain the flavour anomalies (the indications for breaking of lepton universality) B-meson decays.

R. Volkas, talk at  $\nu'2018$

# **Understanding the Pattern of Neutrino Mixing**

## ANARCHY:

A. De Gouvea, H. Murayama, hep-ph/0301050; PLB, 2015.

L. Hall, H. Murayama, N. Weiner, hep-ph/9911341.

$U_{\text{PMNS}}$  from random draw of unbiased distribution of  $3 \times 3$  unitary matrices.

$\theta_{ij}$  random quantities, no correlations whatsoever between the values of  $\theta_{12}$  and/or  $\theta_{13}$  and/or  $\theta_{23}$ . Predicts distributions (not values) of  $\theta_{ij}$ ; values of  $\theta_{ij} \sim \pi/4$  most probable.

Three large mixing angles - most natural for the approach.

However,  $\theta_{13} \cong 0.15\dots$

Values of  $m_j$ ,  $\Delta m_{ij}^2$  - not predicted.

## Family Symmetries (Continuous)

Spontaneously broken  $U(1)_{\text{FN}}$  family symmetry at scale  $M$ :

Frogatt, Nielsen, 1979

$$Y_{ll'}^\ell \overline{\psi_{lL}}(x) \Phi(x) l'_R(x) \rightarrow \left(\frac{\varphi}{M}\right)^{n_{ll'}} \overline{\psi_{lL}}(x) \Phi(x) l'_R(x),$$

$$\varphi - \text{flavon field: } \frac{\langle \varphi \rangle}{M} \sim \lambda = \sin \theta_C = 0.22.$$

Similar generalisation for the two terms in the see-saw Lagrangian:

$$Y_{l'l}^\nu \overline{\nu_{l'R}}(x) \Phi^T(x) (i\tau_2) \psi_{lL}(x), \quad \frac{1}{2} \nu_{l'R}^\top(x) C^{-1} (M_{RR})_{l'l}^\dagger \nu_{lR}(x).$$

Provides an understanding of the hierarchical structure of charged lepton and quark masses. Mixing angles typically related to fermion mass ratios. Large neutrino mixing angles possible for QD neutrino mass spectrum.

# **Understanding the Pattern of Neutrino Mixing**

**With the observed pattern of neutrino mixing Nature is sending us a message. The message is encoded in the values of the neutrino mixing angles, leptonic CP violation phases and neutrino masses. We do not know at present what is the content of Nature's message. However, I believe that it reads**

## **SYMMETRY**

# The Quest for Nature's Message

## Towards Quantitative Understanding of $U_{\text{PMNS}}$ , $m_j$

The observed pattern of 3- $\nu$  mixing, two large and one small mixing angles,

$$\theta_{12} \cong 33^\circ, \theta_{23} \cong 45^\circ \pm 6^\circ \text{ and } \theta_{13} \cong 8.4^\circ,$$

can most naturally be explained by extending the Standard Model (SM) with a flavour symmetry corresponding to a non-Abelian discrete (finite) group  $G_f$ .

$$G_f = A_4, T', S_4, A_5, D_{10}, D_{12}, \dots$$

Vast literature; reviews: G. Altarelli, F. Feruglio, 1002.0211; H. Ishimori et al., 1003.3552; M. Tanimoto, AIP Conf.Proc. 1666 (2015) 120002; S. King and Ch. Luhn, 1301.1340; D. Meloni, 1709.02662; STP, 1711.10806

## Neutrino Mixing: New Symmetry?

- $\theta_{12} = \theta_\odot \cong \frac{\pi}{5.4}$ ,  $\theta_{23} = \theta_{\text{atm}} \cong \frac{\pi}{4} (?)$ ,  $\theta_{13} \cong \frac{\pi}{20}$

$$U_{\text{PMNS}} \cong \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & \epsilon \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}}(?) \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}}(?) \end{pmatrix};$$

Very different from the CKM-matrix!

- $\theta_{12} \cong \sin^{-1} \frac{1}{\sqrt{3}} - 0.020$ ;  $\theta_{12} \cong \pi/4 - 0.20$ ,
- $\theta_{13} \cong 0 + \pi/20$ ,  $\theta_{23} \cong \pi/4 \mp 0.10$ .
- $U_{\text{PMNS}}$  due to new approximate symmetry?

## A Natural Possibility (vast literature):

$$U = U_{\text{lep}}^\dagger(\theta_{ij}^\ell, \delta^\ell) \ Q(\psi, \omega) U_{\text{TBM}, \text{BM}, \text{LC}, \dots} \ \bar{P}(\xi_1, \xi_2),$$

with

$$U_{\text{TBM}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}; \quad U_{\text{BM}} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \pm\frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \pm\frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \mp\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}.$$

- $U_{\text{lep}}^\dagger(\theta_{ij}^\ell, \delta^\ell)$  - from diagonalization of the  $l^-$  mass matrix;
- $U_{\text{TBM}, \text{BM}, \text{LC}, \dots} \bar{P}(\xi_1, \xi_2)$  - from diagonalization of the  $\nu$  mass matrix;
- $Q(\psi, \omega)$ , - from diagonalization of the  $l^-$  and/or  $\nu$  mass matrices.

P. Frampton, STP, W. Rodejohann, 2003

$U_{LC}$ ,  $U_{GRAM}$ ,  $U_{GRBM}$ ,  $U_{HGM}$ :

$$U_{LC} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{c_{23}^\nu}{\sqrt{2}} & \frac{c_{23}^\nu}{\sqrt{2}} & s_{23}^\nu \\ \frac{s_{23}^\nu}{\sqrt{2}} & -\frac{s_{23}^\nu}{\sqrt{2}} & c_{23}^\nu \end{pmatrix}; \quad \mu - \tau \text{ symmetry : } \theta_{23}^\nu = \mp\pi/4;$$

$$U_{GR} = \begin{pmatrix} c_{12}^\nu & s_{12}^\nu & 0 \\ -\frac{s_{12}^\nu}{\sqrt{2}} & \frac{c_{12}^\nu}{\sqrt{2}} & -\sqrt{\frac{1}{2}} \\ -\frac{s_{12}^\nu}{\sqrt{2}} & \frac{c_{12}^\nu}{\sqrt{2}} & \sqrt{\frac{1}{2}} \end{pmatrix}; \quad U_{HGM} = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad \theta_{12}^\nu = \pi/6.$$

$U_{GRAM}$ :  $\sin^2 \theta_{12}^\nu = (2+r)^{-1} \cong 0.276$ ,  $r = (1+\sqrt{5})/2$   
**(GR:**  $r/1$ ;  $a/b = a + b/a$ ,  $a > b$ )

$U_{GRBM}$ :  $\sin^2 \theta_{12}^\nu = (3-r)/4 \cong 0.345$ .

**GRB and HG mixing:** W. Rodejohann et al., 2009.

$U_{\text{TBM(BM)}}$ : Groups  $A_4$ ,  $T'$ ,  $S_4$  ( $S_4$ ),... (vast literature)

(Reviews: G. Altarelli, F. Feruglio, arXiv:1002.0211; M. Tanimoto et al., arXiv:1003.3552;  
S. King and Ch. Luhn, arXiv:1301.1340)

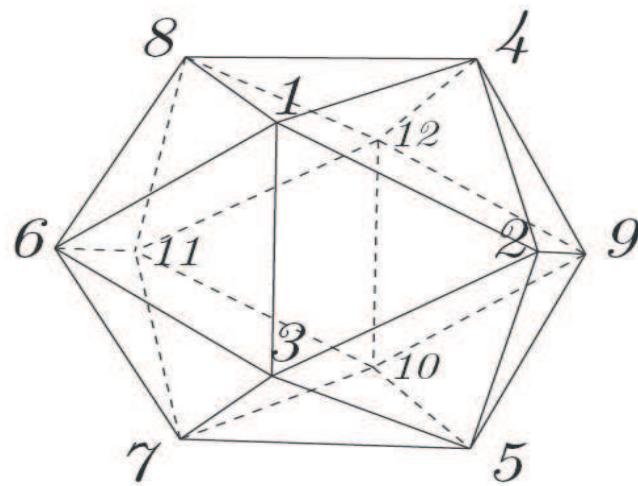
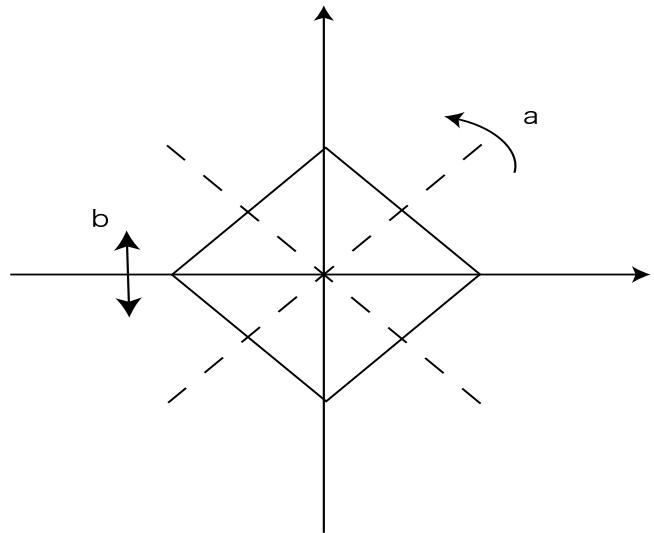
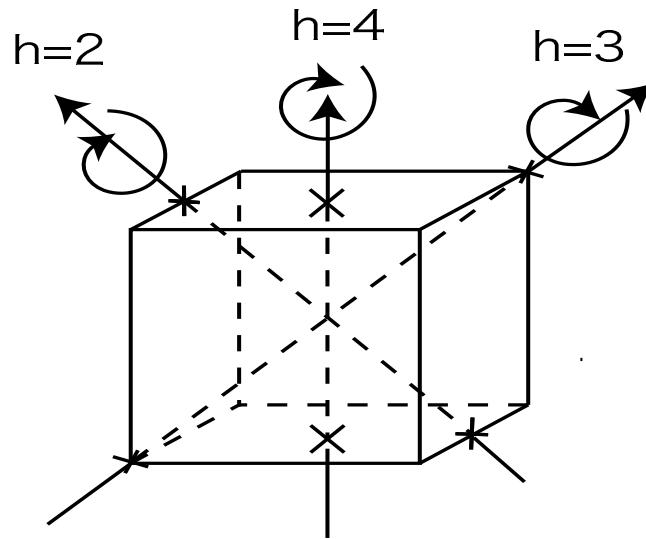
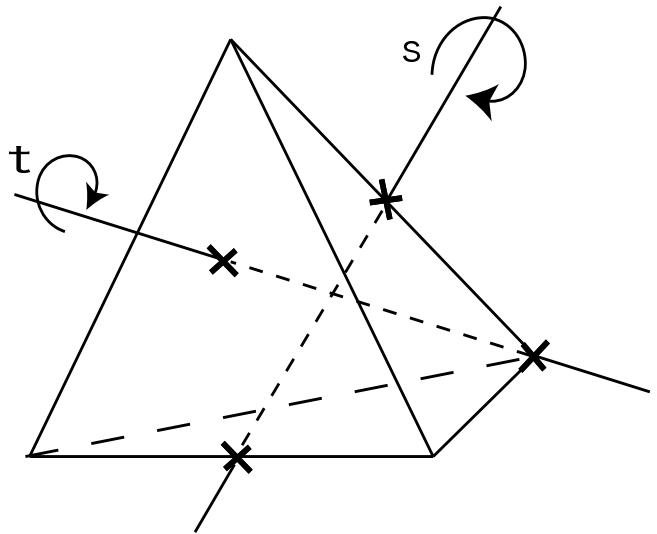
- $U_{\text{GRA}}$ : Group  $A_5, \dots$ ;  $s_{13}^2 = 0$  and possibly  $s_{12}^2 = 0.276$   
and  $s_{23}^2 = 1/2$  must be corrected.  
L. Everett, A. Stuart, arXiv:0812.1057;...
- $U_{\text{LC}}$ : alternatively  $U(1)$ ,  $L' = L_e - L_\mu - L_\tau$   
S.T.P., 1982
- $U_{\text{LC}}$ :  $s_{12}^2 = 1/2$ ,  $s_{13}^2 = 0$ ,  $s_{23}^\nu$  - free parameter;  
 $s_{13}^2 = 0$  and  $s_{12}^2 = 1/2$  must be corrected.

- $U_{\text{GRB}}$ : Group  $D_{10}, \dots$ ;  $s_{13}^2 = 0$  and possibly  $s_{12}^2 = 0.345$  and  $s_{23}^2 = 1/2$  must be corrected.
- $U_{\text{HG}}$ : Group  $D_{12}, \dots$ ;  $s_{13}^2 = 0$ ,  $s_{12}^2 = 0.25$  and possibly  $s_{23}^2 = 1/2$  must be corrected.

For all symmetry forms considered we have:  $\theta_{13}^\nu = 0$ ,  $\theta_{23}^\nu = \mp\pi/4$ .

They differ by the value of  $\theta_{12}^\nu$ :

TBM, BM, GRA, GRB and HG forms correspond to  $\sin^2 \theta_{12}^\nu = 1/3; 0.5; 0.276; 0.345; 0.25$ .



Examples of symmetries:  $A_4$ ,  $S_4$ ,  $D_4$ ,  $A_5$

From M. Tanimoto et al., arXiv:1003.3552

## Predictions and Correlations

$U_\nu = U_{\text{TBM}, \text{BM}, \text{GRA}, \text{GRB}, \text{HG}} \bar{P}(\xi_1, \xi_2); \theta_{12}^\nu;$

$U_\ell^\dagger = R_{12}(\theta_{12}^\ell) Q, Q = \text{diag}(e^{i\varphi}, 1, 1)$

(the “minimal” = simplest case ( $SU(5) \times T'$ , ...))

$U_\ell^\dagger = R_{12}(\theta_{12}^\ell) R_{23}(\theta_{23}^\ell) Q, Q = \text{diag}(1, e^{-i\psi}, e^{-i\omega})$   
(next-to-minimal case)

$\cos \delta = \cos \delta(\theta_{12}, \theta_{23}, \theta_{13}; \theta_{12}^\nu, \dots),$

$J_{CP} = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}, \delta) = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}; \theta_{12}^\nu, \dots),$

$\theta_{12}^\nu, \dots$  - known (fixed) parameters, depend on the underlying symmetry.

For arbitrary fixed  $\theta_{12}^\nu$  and any  $\theta_{23}$   
("minimal" and "next-to-minimal" cases):

$$\cos \delta = \frac{\tan \theta_{23}}{\sin 2\theta_{12} \sin \theta_{13}} [\cos 2\theta_{12}^\nu + (\sin^2 \theta_{12} - \cos^2 \theta_{12}^\nu) (1 - \cot^2 \theta_{23} \sin^2 \theta_{13})].$$

S.T.P., arXiv:1405.6006

This results is exact.

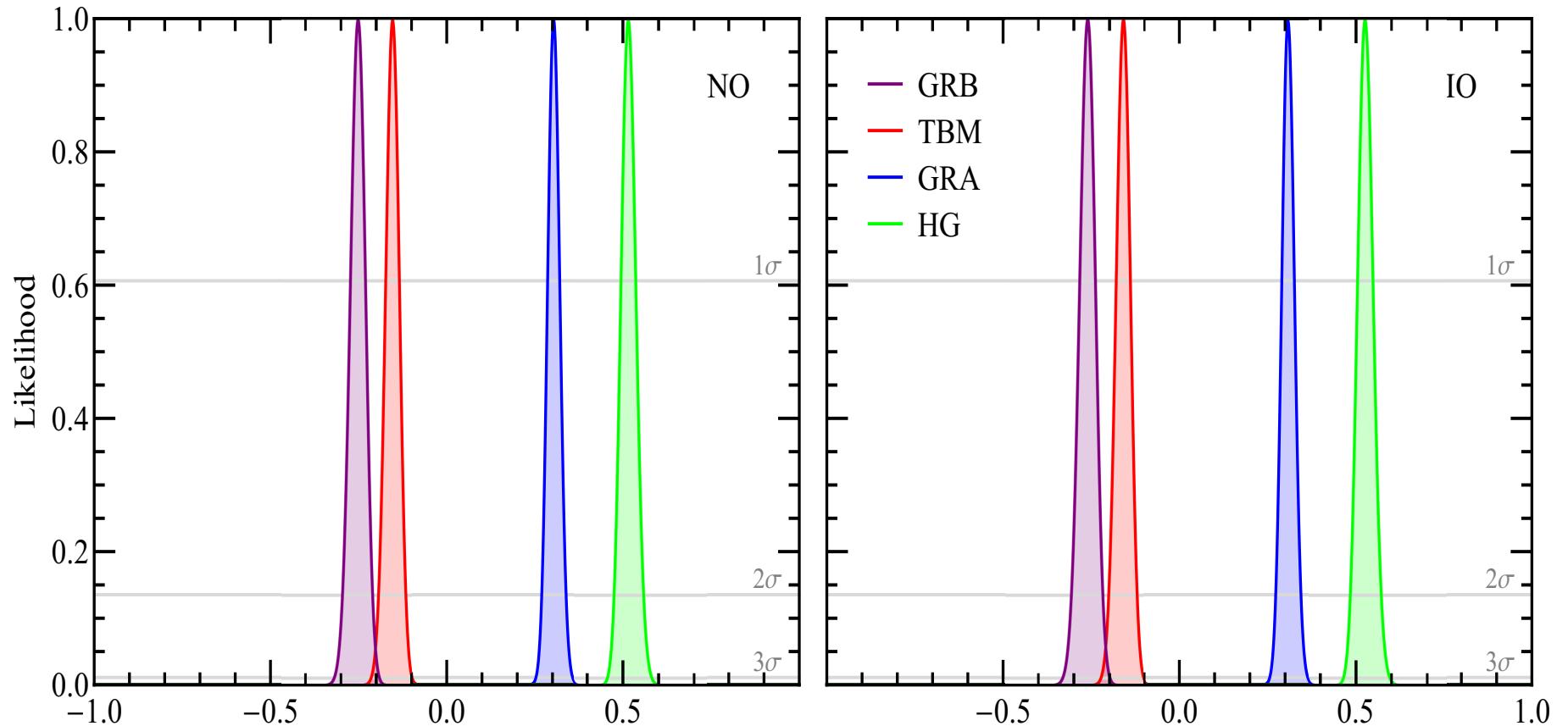
"Minimal" case:  $\sin^2 \theta_{23} = \frac{1}{2} \frac{1 - 2 \sin^2 \theta_{13}}{1 - \sin^2 \theta_{13}}$ .

## Prospective precision:

$\delta(\sin^2 \theta_{12}) = 0.7\% \text{ (JUNO),}$

$\delta(\sin^2 \theta_{13}) = 3\% \text{ (Daya Bay),}$

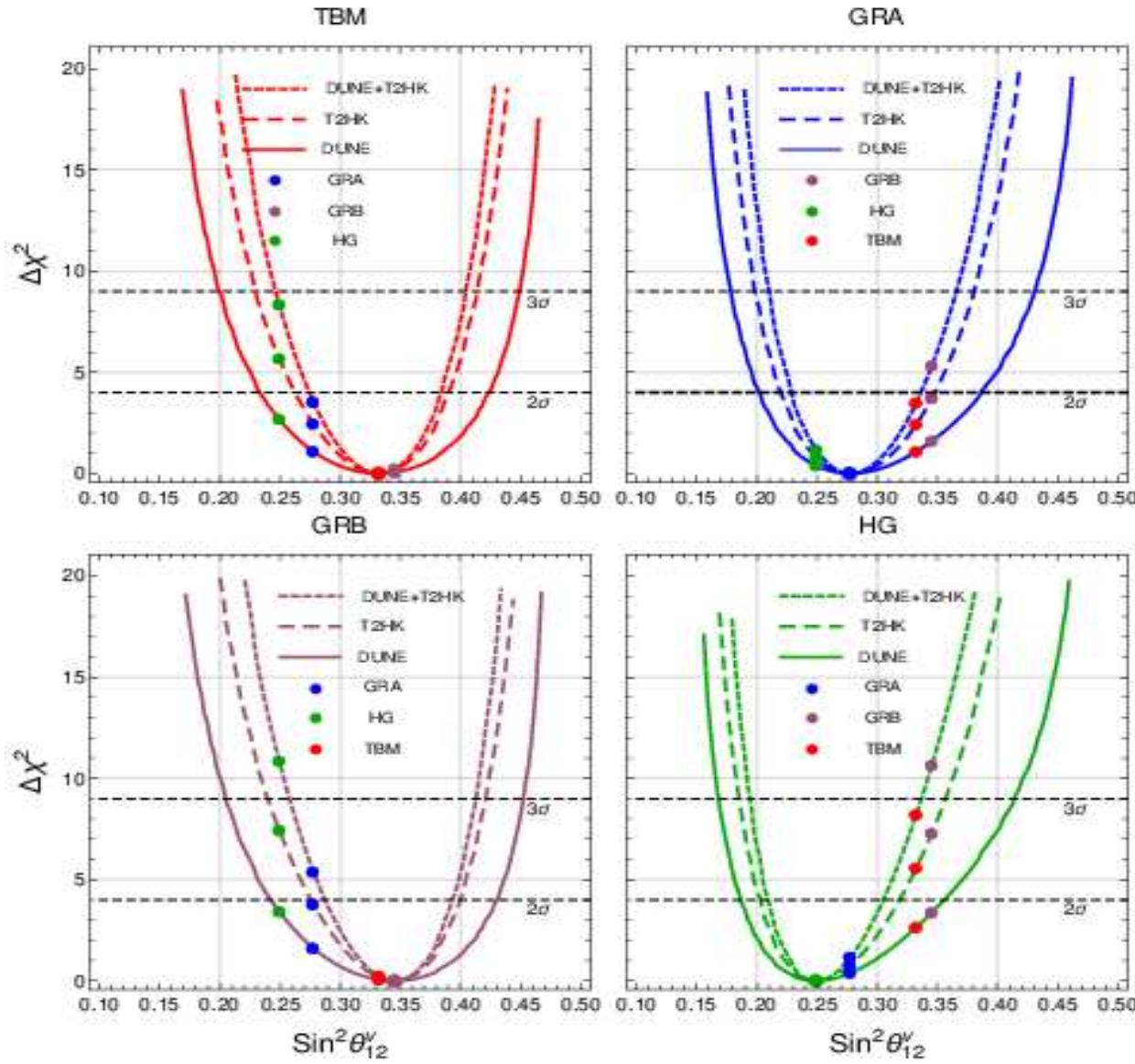
$\delta(\sin^2 \theta_{23}) = 5\% \text{ (T2K, NO}\nu\text{A combined).}$



b.f.v. of  $\sin^2 \theta_{ij}$  ( $\cos^\delta$  Esteban et al., Jan., 2018) + the prospective precision used.

$$\cos \delta = \frac{\tan \theta_{23}}{\sin 2\theta_{12} \sin \theta_{13}} [\cos 2\theta_{12}^\nu + (\sin^2 \theta_{12} - \cos^2 \theta_{12}^\nu) (1 - \cot^2 \theta_{23} \sin^2 \theta_{13})].$$

$\delta(\sin^2 \theta_{23}) = 3\%$  (T2HK, DUNE).



Agarwalla, Chatterjee, STP, Titov, arXiv:1711.02107

**GRB - HG > 3 $\sigma$ ; GRA - GRB  $\geq 2\sigma$ ; TMB - HG  $\cong 3\sigma$ ; TMB - GRA  $\cong 2\sigma$ .**

With T2HKK data - better sensitivity.

## Examples of Predictions and Correlations II.

- $\sin^2 \theta_{23} = \frac{1}{2}$ .
- $\sin^2 \theta_{23} \cong \frac{1}{2} (1 \mp \sin^2 \theta_{13}) + O(\sin^4 \theta_{13}) \cong \frac{1}{2} (1 \mp 0.022)$ .
- $\sin^2 \theta_{23} = 0.455; 0.463; 0.537; 0.545; 0.604$  (**small uncert.**).
- $\sin^2 \theta_{12} \cong \frac{1}{3} (1 + \sin^2 \theta_{13}) + O(\sin^4 \theta_{13}) \cong 0.340$ .
- $\sin^2 \theta_{12} \cong \frac{1}{3} (1 - 2 \sin^2 \theta_{13}) + O(\sin^4 \theta_{13}) \cong 0.319$ .
- **and/or**  $\cos \delta = \cos \delta(\theta_{12}, \theta_{23}, \theta_{13}; \theta_{12}^\nu, \dots)$ ,

$$J_{CP} = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}, \delta) = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}; \theta_{12}^\nu, \dots),$$

$\theta_{12}^\nu, \dots$  - known (fixed) parameters, depend on the underlying symmetry.

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

Prospective (useful/requested) precision:

$\delta(\sin^2 \theta_{12}) = 0.7\%$  (**JUNO**),

$\delta(\sin^2 \theta_{13}) = 3\%$  (**Daya Bay**),

$\delta(\sin^2 \theta_{23}) = 3\%$  (**T2HK, DUNE; T2K+NO $\nu$ A(?)**).

$\delta(\delta) = 10^\circ$  (**THKK?**)

# **LEPTOGENESIS**

# $M_\nu$ from the 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

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

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

F. Borzumati, A. Masiero, 1986.

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

**See-Saw:** Dirac  $\nu$ -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:  $\mu \rightarrow e + \gamma$ ,  $\mu \rightarrow 3e$ ,  
 $\mu^- - e^-$  conversion (?).

### GeV Scale ARS Leptogenesis:

$M_{1,2,3} \sim (1 - 50)$  GeV (requires fine-tuning (severe));  
observation of  $N_j$  at LHC - problematic, signature: displaced vertices,  
requires dedicated experiment(s).

**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.
- M. J. Dolan *et al.*, arXiv:1802.08373.

# The Seesaw Lagrangian

$$\mathcal{L}^{\text{lept}}(x) = \mathcal{L}_{CC}(x) + \mathcal{L}_Y(x) + \mathcal{L}_M^N(x),$$

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

$$\mathcal{L}_Y(x) = \lambda_{il} \overline{N_{iR}}(x) H^\dagger(x) \psi_{lL}(x) + Y_l H^c(x) \overline{l}_R(x) \psi_{lL}(x) + h.c.,$$

$$\mathcal{L}_M^N(x) = -\frac{1}{2} M_i \overline{N_i}(x) N_i(x).$$

$\psi_{lL}$  - LH doublet,  $\psi_{lL}^T = (\nu_{lL} \ l_L)$ ,  $l_R$  - 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:

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

For  $M_R$  - sufficiently large,

$$m_\nu \simeq v^2 \ \lambda^T D_N^{-1} \lambda = U_{\text{PMNS}}^* D_\nu U_{\text{PMNS}}^\dagger.$$

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

$$\lambda \equiv Y_\nu$$

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

*R*-complex,  $R^T R = 1$ .

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  $Y_\nu$ :** CPV parameters in  $R$  determined by the CPV phases in  $U$  (Frampton, Glashow Yanagida (FGY), 2002:  $N_{1,2}$ , two texture zeros in  $Y_\nu$ ; LG in FGY model: J. Zhang, Sh. Zhou, arXiv:1505.04858).

## Baryon Asymmetry

$$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.10 \pm 0.04) \times 10^{-10}, \quad \text{CMB}$$

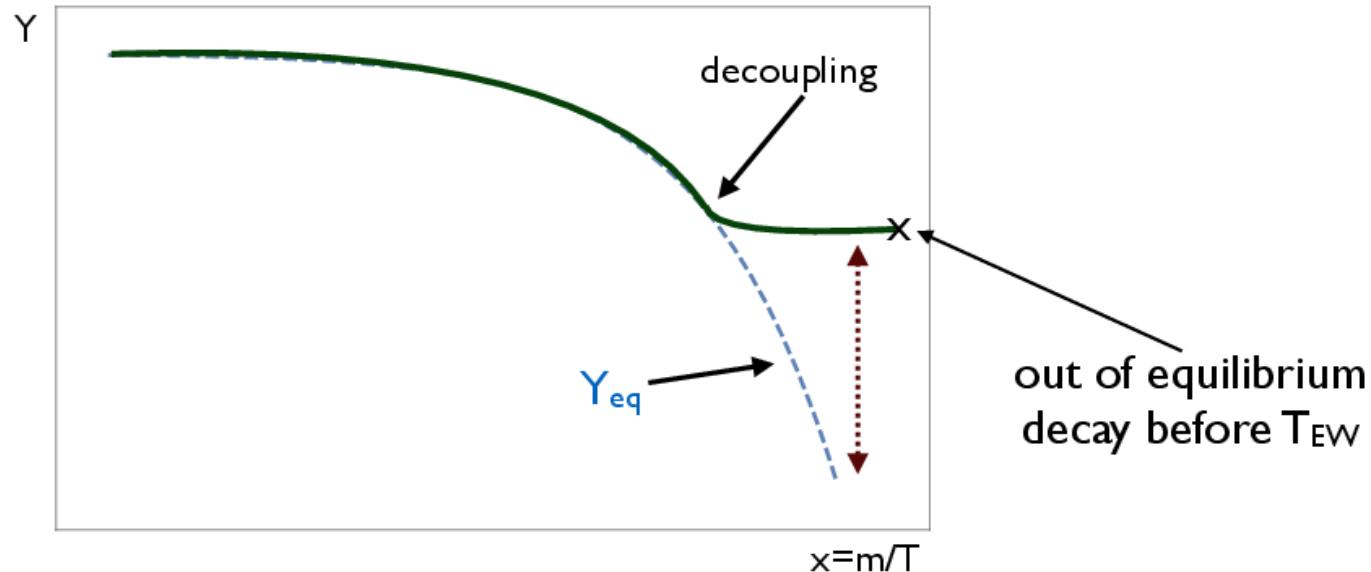
**Sakharov conditions for a dynamical generation of  $Y_B \neq 0$  in the Early Universe**

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

# BAU I: Thermal leptogenesis

Sterile neutrinos in thermal equilibrium if  $|Y| \gtrsim 10^{-7}$

**Thermal leptogenesis:** sterile neutrinos in equilibrium at large temperatures



Generation of a lepton asymmetry due to the Majorana character of the particles

M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45

$M > 10^6$  GeV to reproduce observed BAU  
(relaxed to  $M >$  TeV for degenerate masses)

Difficult to test  
in laboratory

S. Davidson, E. Nardi and Y. Nir, arXiv:0802.2962 [hep-ph]

A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0605281

A. Pilaftsis and T. E. J. Underwood, hep-ph/0309342

K. Moffat, S. Pascoli, S. T. Petcov, H. Schulz and J. Turner, arXiv:1804.05066 [hep-ph]

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M. Lucente, talk at ICHEP 2018

## Leptogenesis (via $N_j$ Decays)

- 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  $\Gamma(N_1 \rightarrow \Phi^- \ell^+) \neq \Gamma(N_1 \rightarrow \Phi^+ \ell^-)$ , a lepton asymmetry will be generated.
- Wash-out processes, like  $\Phi^+ + \ell^- \rightarrow N_1$ ,  $\ell^- + \Phi^+ \rightarrow \Phi^- + \ell^+$ , 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 result 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  $T \gtrsim M_{\text{EWSB}}$ ) and are efficient at  $T_{\text{EW}} \sim 140 \text{ GeV} < T < 10^{12} \text{ GeV}$ .

S. Fukugita, T. Yanagida, 1986.

In order to compute  $Y_B$ :

1. calculate the CP-asymmetry:

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

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

$$Y_L = \kappa \varepsilon$$

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

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

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

# Leptogenesis

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

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

W. Buchmüller, M. Plümacher, 1998;

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

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

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

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

M.A. Luty, 1992;

L. Covi, E. Roulet and F. Vissani, 1996;

M. Flanz *et al.*, 1996;

M. Plümacher, 1997;

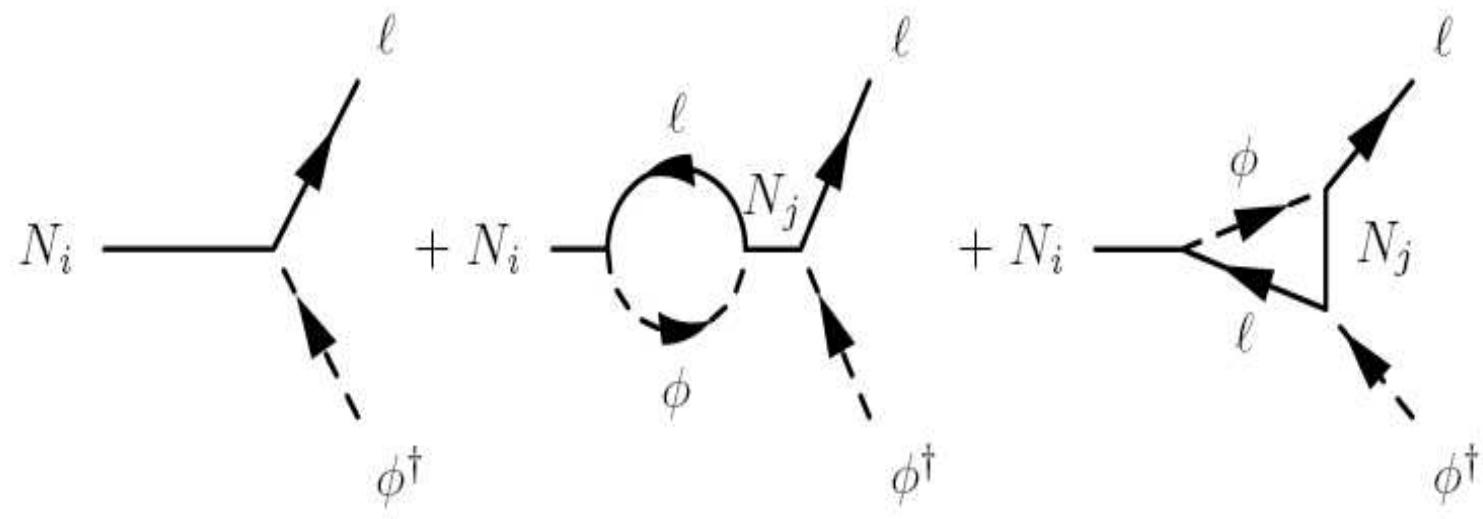
A. Pilaftsis, 1997.

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

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

W. Buchmuller, P. Di Bari and M. Plumacher, 2002;

G. F. Giudice *et al.*, 2004



# Low Energy Leptonic CPV and Leptogenesis

Assume:  $M_1 \ll M_2 \ll M_3$

Individual asymmetries:

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

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

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

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

$$\widetilde{m}_1 = \sum_l \widetilde{m}_l = \sum_k m_k |R_{1k}|^2.$$

## Two-Flavour Regime

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

wash-out dynamics changes:  $\tau_R^-$ ,  $\tau_L^+$

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

$$\tau_L^- + \Phi^0 \tau_R^-, \quad \tau_L^- + \tau_L^+ N_1 + \nu_L, \text{ etc.}$$

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

## Three-Flavour Regime

At  $M_1 \sim T \sim 10^9$  GeV:  $Y_\tau$ ,  $Y_\mu$  - in equilibrium,  $Y_e$  - not.

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

Thus, at  $M_1 \sim 10^9 - 10^{12}$  GeV:  $L_\tau$ ,  $\Delta L_\tau$  - distinguishable;

$L_e$ ,  $L_\mu$ ,  $\Delta L_e$ ,  $\Delta L_\mu$  - individually not distinguishable;

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

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,

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

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

The baryon asymmetry is

$$Y_B \simeq -\frac{12}{37 g_*} \left( \epsilon_2 \eta \left( \frac{417}{589} \widetilde{m}_2 \right) + \epsilon_\tau \eta \left( \frac{390}{589} \widetilde{m}_\tau \right) \right),$$

$$\eta(\widetilde{m}_l) \simeq \left( \left( \frac{\widetilde{m}_l}{8.25 \times 10^{-3} \text{ eV}} \right)^{-1} + \left( \frac{0.2 \times 10^{-3} \text{ eV}}{\widetilde{m}_l} \right)^{-1.16} \right)^{-1}.$$

$$Y_B = -(12/37) (Y_2 + Y_\tau),$$

$$Y_2 = Y_{e+\mu}, \quad \varepsilon_2 = \varepsilon_{1e} + \varepsilon_{1\mu}, \quad \widetilde{m}_2 = \widetilde{m}_{1e} + \widetilde{m}_{1\mu}$$

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  $U$

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

$$Y_B = -\frac{12}{37} \frac{\varepsilon_{1\tau}}{g_*} \left( \eta \left( \frac{390}{589} \widetilde{m}_\tau \right) - \eta \left( \frac{417}{589} \widetilde{m}_2 \right) \right)$$

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

$$\begin{aligned}\varepsilon_{1\tau} &= -\frac{3M_1\sqrt{\Delta m_{31}^2}}{16\pi v^2} \left(\frac{\Delta m_\odot^2}{\Delta m_{31}^2}\right)^{\frac{1}{4}} \frac{|R_{12}R_{13}|}{\left(\frac{\Delta m_\odot^2}{\Delta m_{31}^2}\right)^{\frac{1}{2}} |R_{12}|^2 + |R_{13}|^2} \\ &\quad \times \left(1 - \frac{\sqrt{\Delta m_\odot^2}}{\sqrt{\Delta m_{31}^2}}\right) \text{Im}(U_{\tau 2}^* U_{\tau 3})\end{aligned}$$

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

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

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

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

The lower limit corresponds to

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

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

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

Realised in a theory based on the  $S_4$  symmetry: P. Cheng et al.,  
[arXiv:1602.03873](https://arxiv.org/abs/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:  $J_{CP} \cong -3.5 \times 10^{-2}$ .

$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3$  (**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  $|Y_B|$ :

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

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  $\Delta m_\odot^2/|\Delta_{32}| \cong 0.03$ .

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  $|Y_B|$ :

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

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

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

The lower limit corresponds to

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

Realised in a theory based on the  $S_4$  symmetry: P. Cheng et al.,  
[arXiv:1602.03873](https://arxiv.org/abs/1602.03873).

## 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 ( $\sim$  GeV scale).

M. Drewes *et al.*, arXiv:1609.09069 ( $\sim$ GeV scale).

G. Bambhaniya *et al.*, arXiv:1611.03827 (resonant  $\sim$ TeV scale).

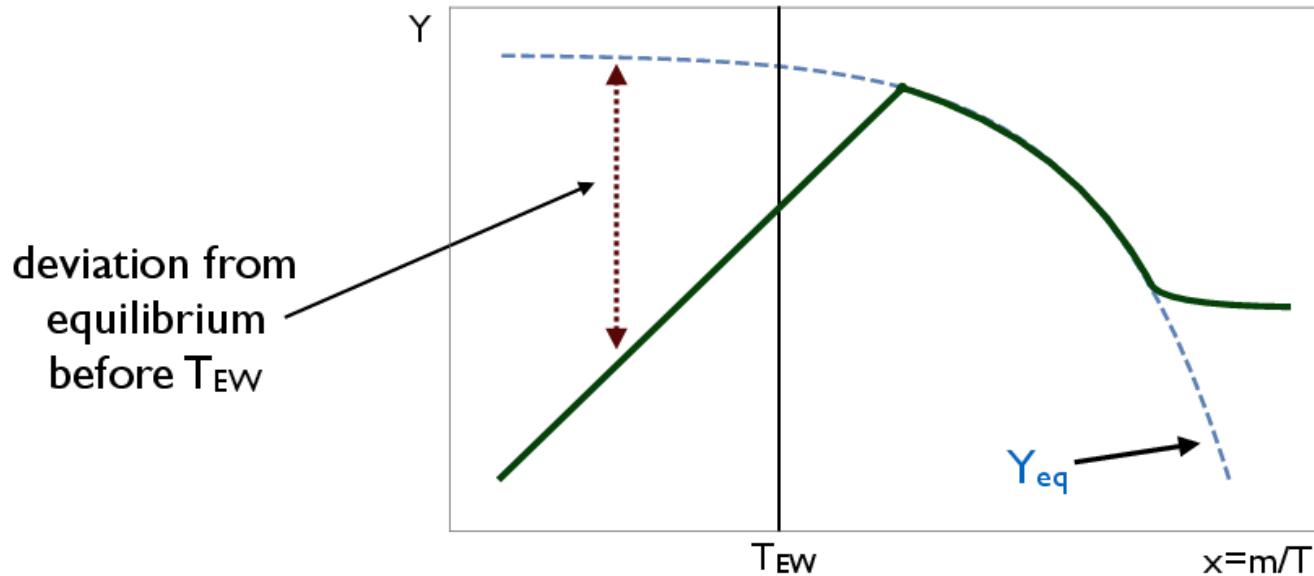
M. J. Dolan *et al.*, arXiv:1802.08373 (resonant  $\sim$ TeV scale).

M. Lucente, talk at ICHEP2018 ( $\sim$ GeV scale).

# BAU II: ARS mechanism

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255

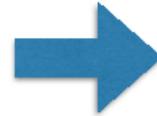
Sterile neutrinos out of equilibrium at large temperatures



From the seesaw relation

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger \simeq 0.3 \left( \frac{\text{GeV}}{M} \right) \left( \frac{Y^2}{10^{-14}} \right) \text{ eV}$$

$M \sim \text{GeV}$  to reproduce  $\nu$  masses



Testable

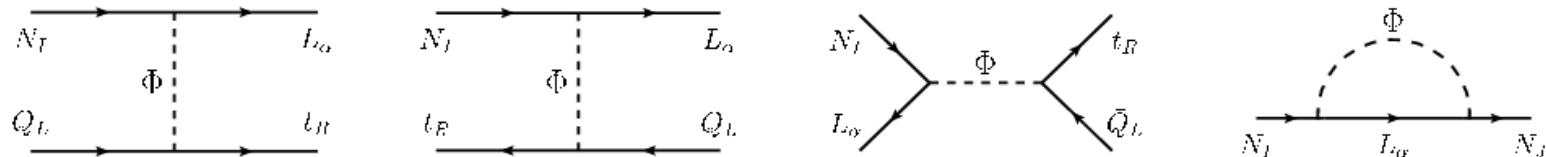
# ARS leptogenesis

How does the mechanism work?

A. Abada, S. Antusch, E. K. Akhmedov, G. Arcadi, T. Asaka, S. Blanchet, L. Canetti, E. Cazzato, V. Domcke, M. Drewes, S. Ejima, O. Fischer, T. Frossard, B. Garbrecht, D. Gueter, T. Hambye, P. Hernández, H. Ishida, M. Kekic, J. Klaric, J. López-Pavón, M.L., J. Racker, N. Rius, V. A. Rubakov, J. Salvado, M. Shaposhnikov, A. Y. Smirnov, D. Teresi...

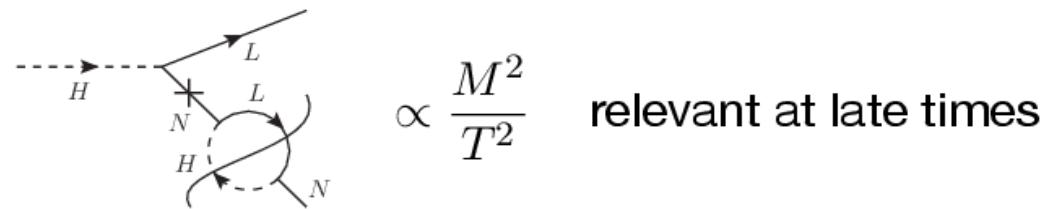
Two kinds of CP processes

**Lepton number conserving**  
(neutrino generation and oscillations)



**Lepton number violating**  
(thermal Higgs decay)

T. Hambye and D. Teresi, arXiv:1606.00017 [hep-ph], arXiv:1705.00016 [hep-ph]



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M. Lucente, talk at ICHEP 2018

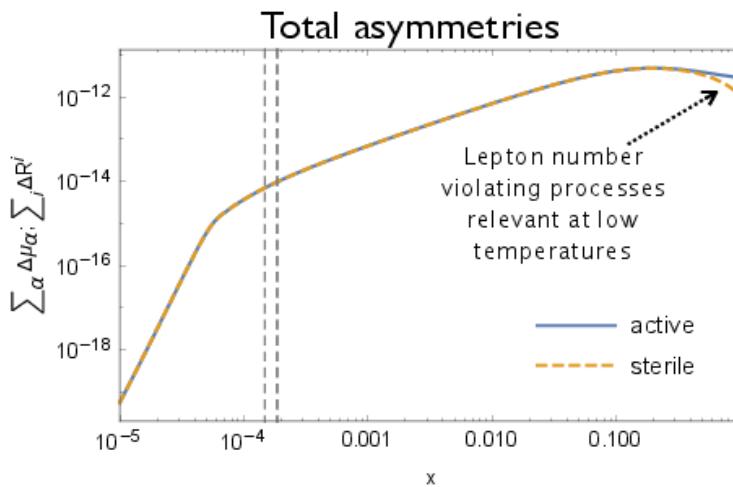
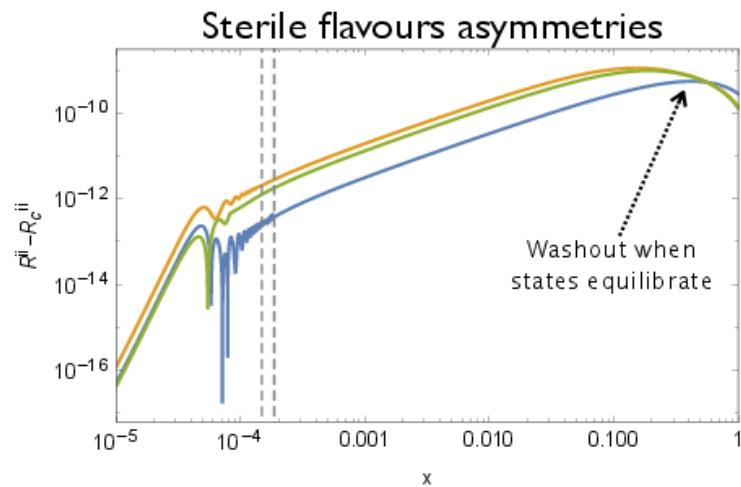
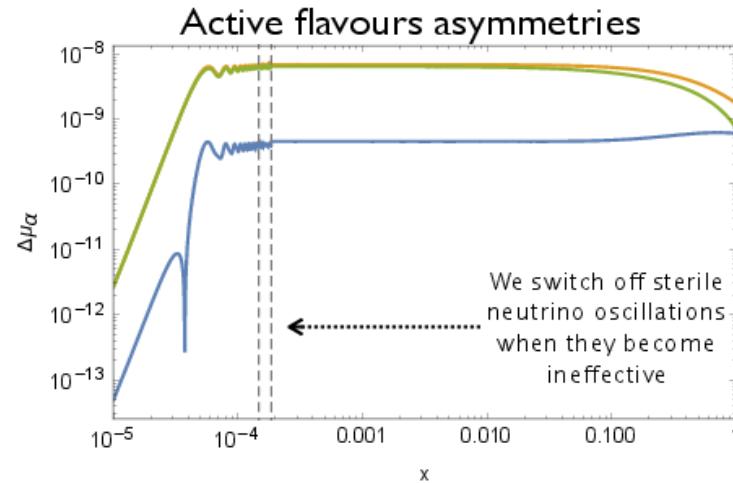
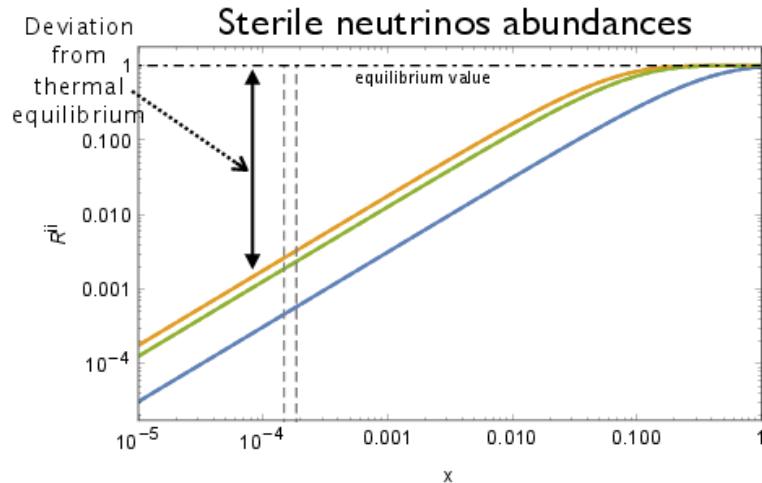
# Asymmetry generation example with 3 RHN

$$x = \frac{T}{T_{EW}}$$

$T_{EW} = 140$  GeV

$R$  : sterile neutrinos density matrix

$\mu_\alpha$  : active flavours chemical potentials



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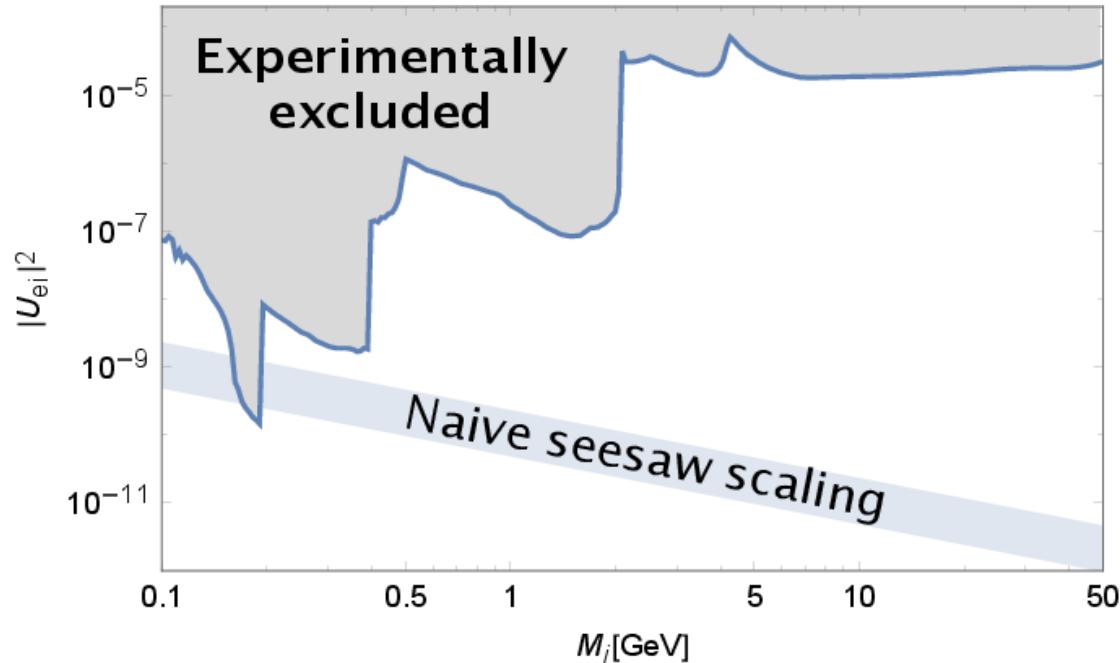
# Testability?

Seesaw scaling

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger$$

In the **absence** of any **structure**  
in the  $F$  and  $M$  matrices

$$|U_{\alpha i}| \lesssim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-5} \sqrt{\frac{\text{GeV}}{M}}$$

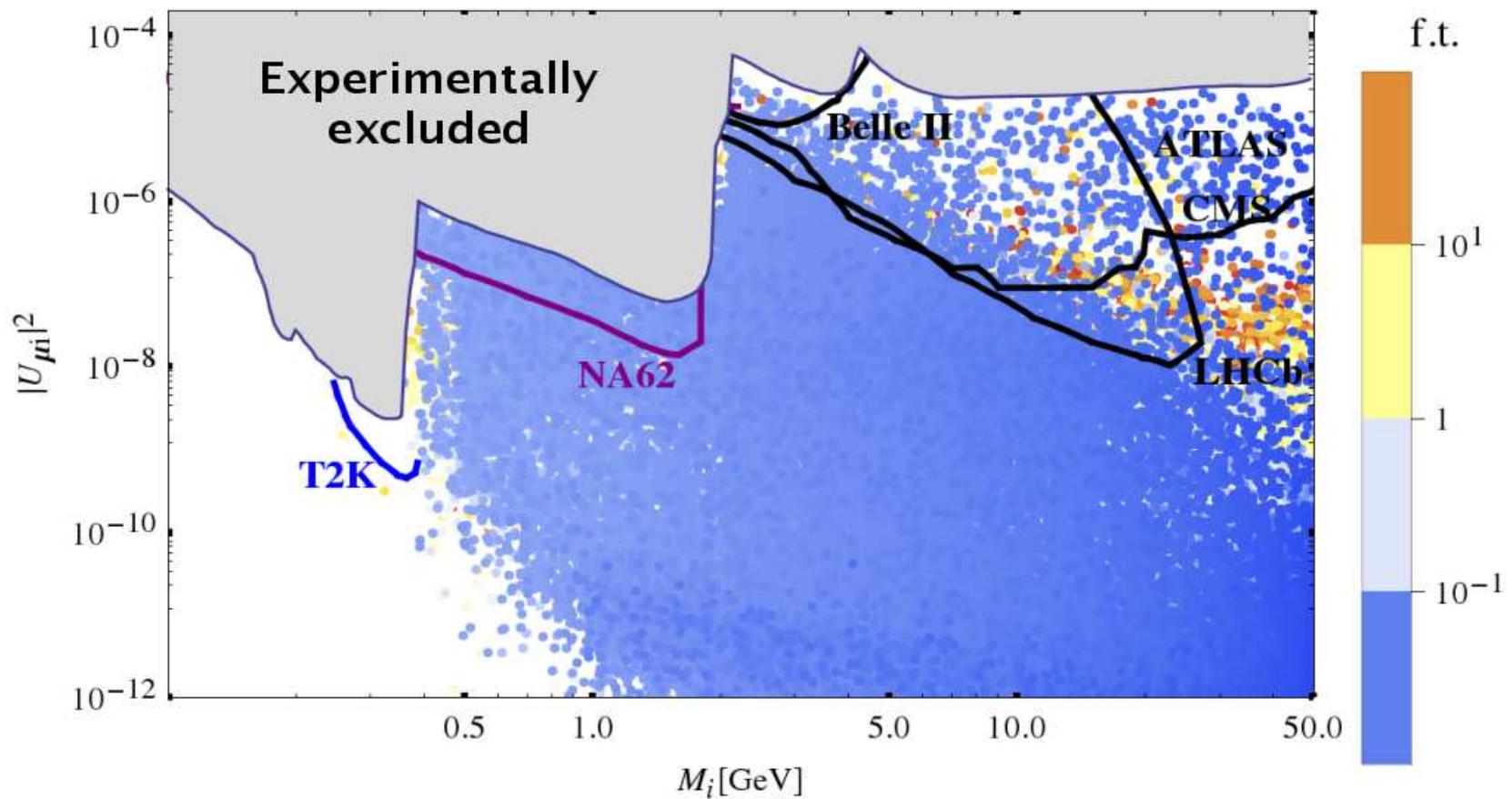


But these are (complex) matrices: cancellations are possible

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# Results



**Solutions with sizeable mixing exhibit a small degree of fine-tuning**

Why?

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## Conclusions.

- Understanding the origin of the pattern of neutrino mixing and of neutrino mass squared differences that emerged from the neutrino oscillation data in the recent years is one of the most challenging problems in neutrino physics.
- The observed pattern of neutrino mixing can be due to a new basic (approximate non-Abelian discrete) symmetry of particle interactions leading to an approximate symmetry form of the PMNS matrix.
- The most important testable consequence of the symmetry approach to understanding the pattern of neutrino mixing is the correlation between the values of some of the neutrino mixing angles and/or the value of  $\cos\delta$  and the values of the neutrino mixing angles:  $\delta = \delta(\theta_{12}, \theta_{13}, \theta_{23}; \theta_{12}^\nu)$ . The second correlation depends on the underlying approximate symmetry form of the  $U_{\text{PMNS}}$ .

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

## Conclusions (contd.)

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

Dirac and Majorana CPV may have the same source.

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

Any of the CPV phases in  $U_{\text{PMNS}}$  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 studies of Dirac (and searches for Majorana) leptonic CP-violation at low energies.