Theory Prospective on $(\beta\beta)_{0\nu}$−Decay
(The Quest for the Nature of Massive Neutrinos)

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Determining the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos is one of the most challenging and pressing problems in present day elementary particle physics.

$\nu_j -$ Dirac or Majorana particles, **fundamental problem**

$\nu_j -$Dirac: **conserved lepton charge exists,**
$L = L_e + L_\mu + L_\tau$, $\nu_j \neq \bar{\nu}_j$

$\nu_j -$Majorana: **no lepton charge is exactly conserved**,
$\nu_j \equiv \bar{\nu}_j$

The observed patterns of $\nu-$mixing and of $\Delta m^2_{\rm atm}$ and $\Delta m^2_\odot$ can be related to Majorana ν_j and a new fundamental (approximate) symmetry.

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

See-saw mechanism: $\nu_j -$ Majorana

Establishing that the total lepton charge $L = L_e + L_\mu + L_\tau$ is not conserved in particle interactions by observing the $(\beta\beta)_{0\nu}-$decay would be a fundamental discovery (similar to establishing baryon number nonconservation (e.g., by observing proton decay)).

Establishing that ν_j are Majorana particles would be of fundamental importance, as important as the discovery of $\nu-$ oscillations, and would have far reaching implications.

Current Challenging Problems:

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

There have been remarkable discoveries in neutrino physics in the last ~ 18 years.

Compellings Evidence for $\nu-$Oscillations

$-\nu_{\text{atm}}$: 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 (ν_μ from accelerators): $\nu_{\mu} \rightarrow \nu_{e}$

Compelling Evidences for ν−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.

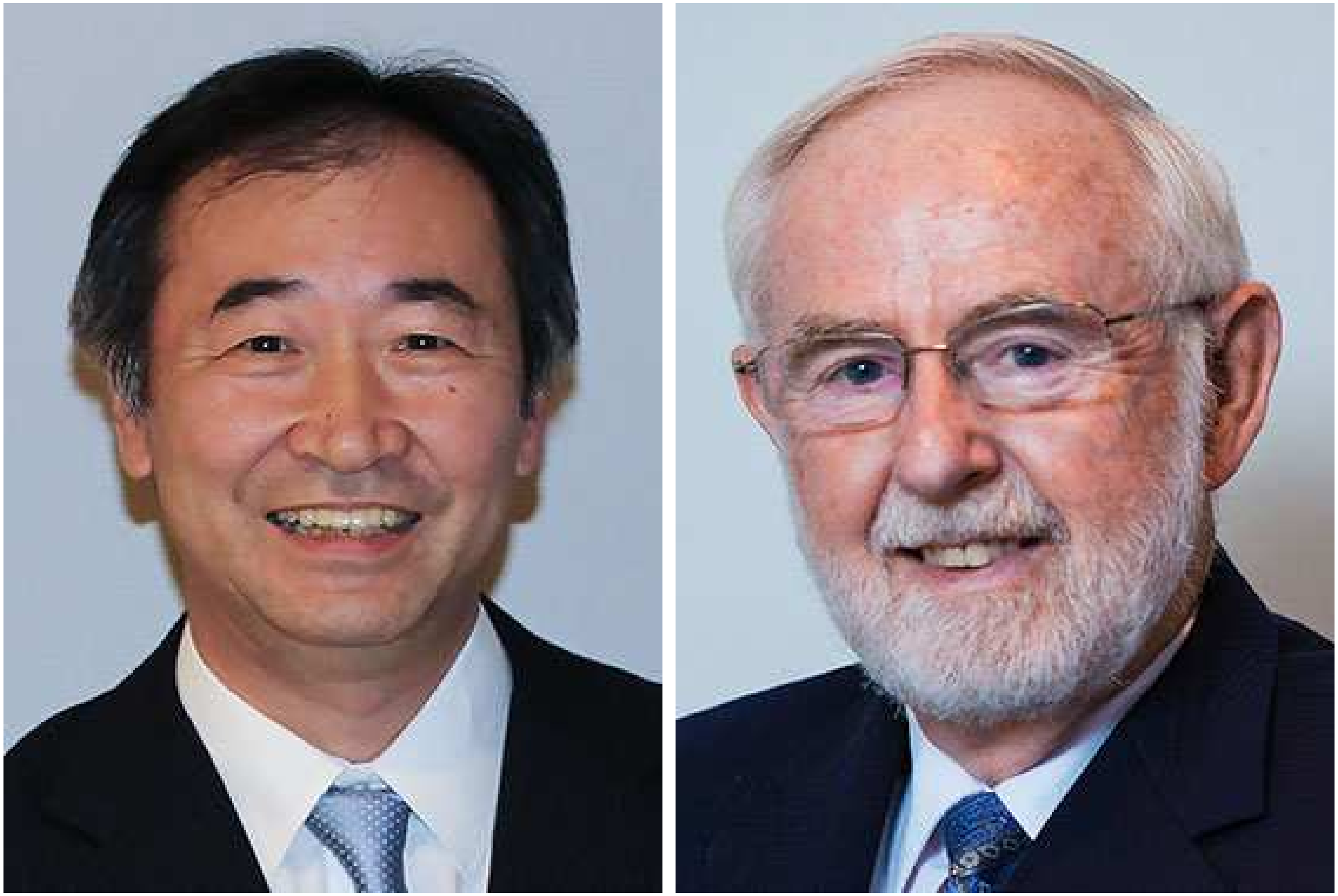
ν_j, $m_j \neq 0$: Dirac or Majorana particles.

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

The Charged Current Weak Interaction Lagrangian:

$$\mathcal{L}^{CC}(x) = -\frac{g}{2\sqrt{2}} \sum_{l=e,\mu,\tau} \bar{l}(x)\gamma_\alpha \,(1-\gamma_5)\, \nu_{l\mathrm{L}}(x)\, W^\alpha(x) + \text{h.c.}\,,$$

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



Dr. T. Kajita, Prof. A. McDonald, Nobel Prize for Physics winners, 2015

LAUREATES

Breakthrough Prize   Special Breakthrough Prize   New Horizons Prize   Physics Frontiers Prize

2016   2015   2014   2013   2012


Kam-Biu Luk and the Daya Bay Collaboration


Yifang Wang and the Daya Bay Collaboration

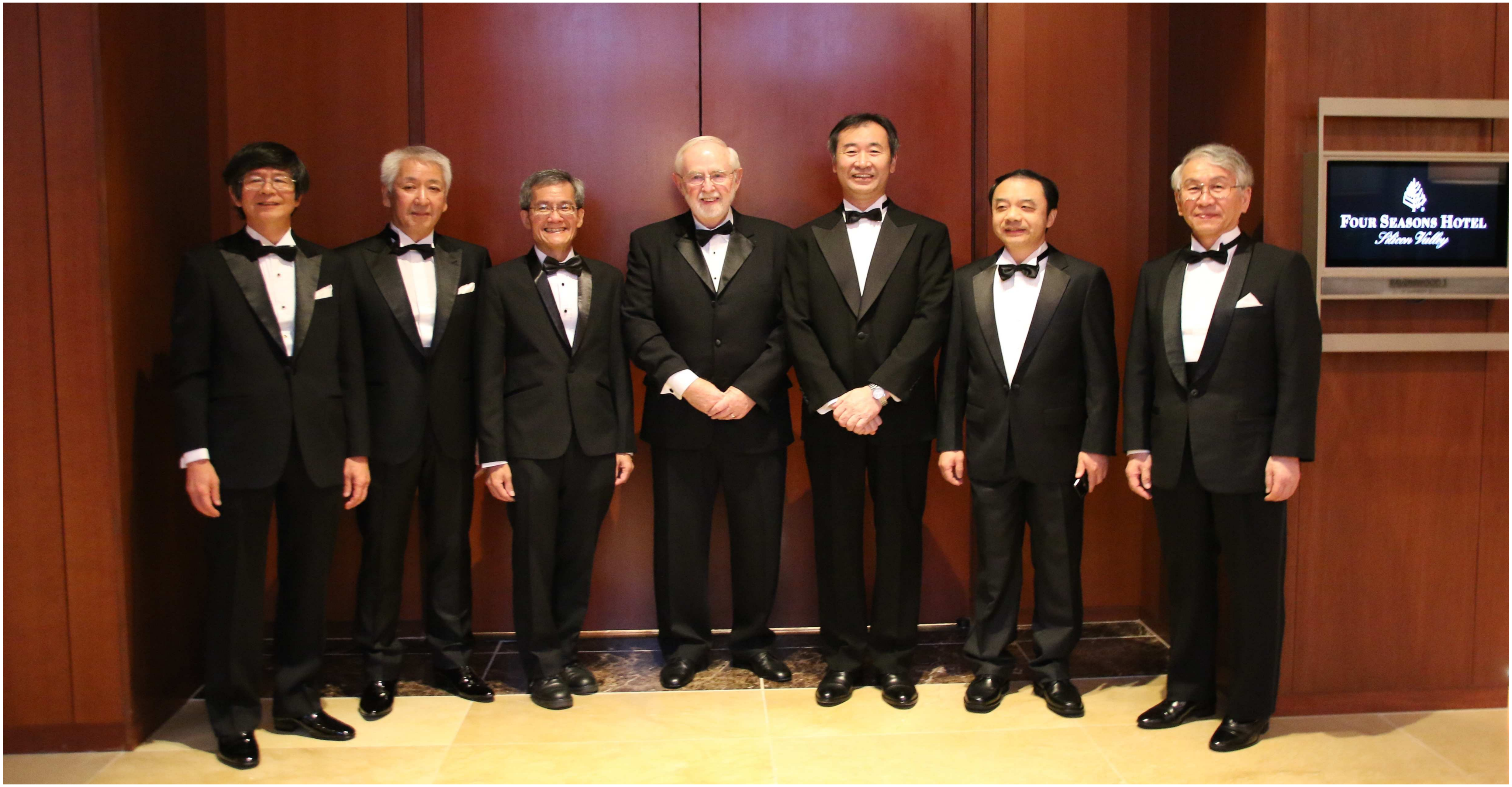

Koichiro Nishikawa and the K2K and T2K Collaboration


Atsuto Suzuki and the KamLAND Collaboration


Arthur B. McDonald and the SNO Collaboration


Takaaki Kajita and the Super K Collaboration


Yoichiro Suzuki and the Super K Collaboration


FOUR SEASONS HOTEL
Silicon Valley

These 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: $10^{-2} \lesssim m_{l,q}/m_{q'} \lesssim 10^2$

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 $n = 6$,...).
- In the Majorana nature of massive neutrinos.
- In the observed pattern of neutrino mixing and in the values of the CPV phases in the PMNS matrix.
- In the existence of new particles, e.g., at the TeV scale: heavy Majorana Neutrinos N_j, doubly charged scalars,...
- In the existence of LFV processes: $\mu \to e + \gamma$, $\mu \to 3e$, $\mu - e$ conversion, etc., which proceed with rates close to the existing upper limits.
- In the existence of new (FChNC, FCFNSNC) neutrino interactions.
- In the existence of "unknown unknowns"...

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

Two (extreme) possibilities:

i) $m_{4,5,...} \sim 1$ eV;
in this case $\nu_{e(\mu)} \rightarrow \nu_S$ oscillations are possible (hints from LSND and MiniBooNE experiments, re-analises of short baseline (SBL) reactor neutrino oscillation data ("reactor neutrino anomaly"), data of radioactive source callibration of the solar neutrino SAGE and GALLEX experiments ("Gallium anomaly"); tests (STEREO, SOX, CeLAND, DANS, ICARUS (at Fermilab), ... under way).

ii) $M_{4,5,...} \sim (10^2 - 10^3)$ GeV, TeV scale seesaw models;
$M_{4,5,...} \sim (10^9 - 10^{13})$ GeV, "classical" seesaw models.

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: $P(\nu_\mu \rightarrow \nu_{\tau(e)}) \neq 0$, $P(\nu_\mu \rightarrow \nu_\mu) < 1$

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

Three Neutrino Mixing

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

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),
- $|\Delta m^2_{31(32)}| \cong 2.53\ (2.43) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong 0.437\ (0.569)$, NO (IO) ,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0214\ (0.0218)$, Capozzi et al. NO (IO).

F. Capozzi et al. (Bari Group), arXiv:1601.07777v1.

- $\Delta m^2_\odot \equiv \Delta m^2_{21} \cong 7.54 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.308$, $\cos 2\theta_{12} \gtrsim 0.28$ (3σ),
- $|\Delta m^2_{31(32)}| \cong 2.47$ (2.42) $\times 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong 0.437$ (0.455), NO (IO) ,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0234$ (0.0240), NH (IH) .
- $1\sigma(\Delta m^2_{21}) = 2.6\%$, $1\sigma(\sin^2\theta_{12}) = 5.4\%$;

$3\sigma(\Delta m^2_{21})$: $(6.93 - 7.97) \times 10^{-5}$ eV^2; $3\sigma(\sin^2\theta_{12})$: $(0.250 - 0.354)$;)

- $3\sigma(|\Delta m^2_{31(23)}|)$: $2.27(2.23) - 2.65(2.60) \times 10^{-3}$ eV^2;

$(2.40(2.30) - 2.66(2.57) \times 10^{-3}$ eV^2;
$3\sigma(\sin^2\theta_{23})$: $0.374(0.380) - 0.628(0.641)$;
$(3\sigma(\sin^2\theta_{23})$: $0.379(0.383) - 0.616(0.637))$

- $3\sigma(\sin^2\theta_{13})$: $0.0176(0.0178) - 0.0296(0.0298)$

$(3\sigma(\sin^2\theta_{13})$: $0.0185(0.0186) - 0.0246(0.0248)$.)

F. Capozzi et al. (Bari Group), arXiv:1312.2878v2 (May 5, 2014)
(F. Capozzi et al. (Bari Group), arXiv:1601.07777v1.)

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

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

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

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

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

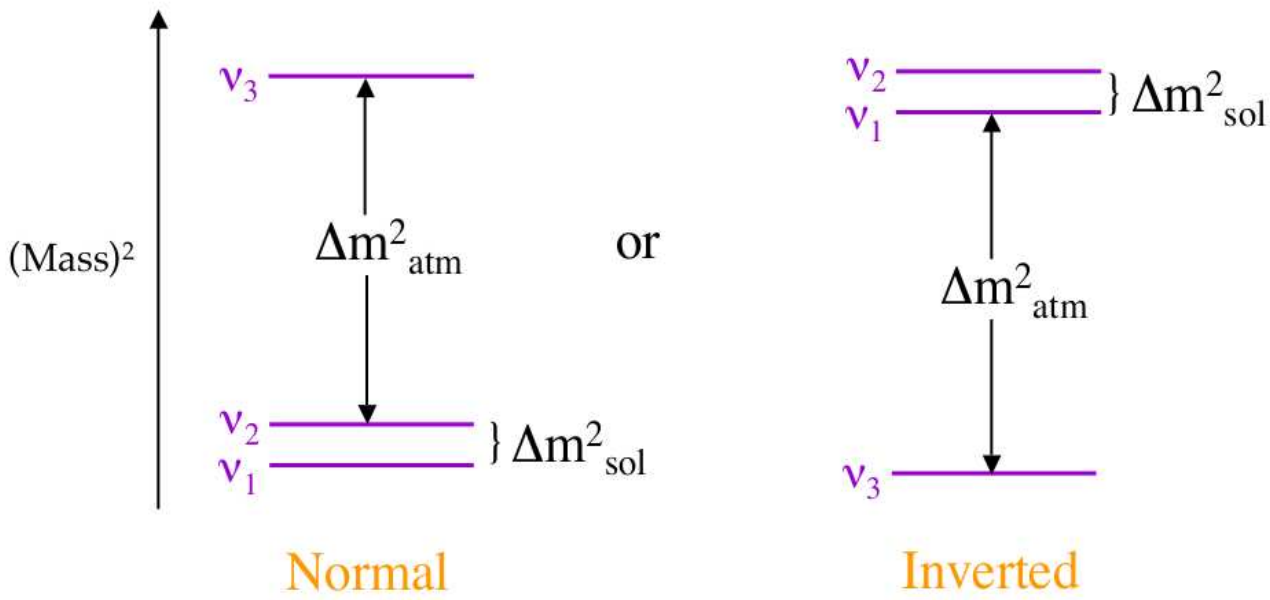
$$m_1 \ll m_2 < m_3, \qquad \text{NH},$$

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

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

• $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$, $m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$ - 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;

The $(\text{Mass})^2$ Spectrum

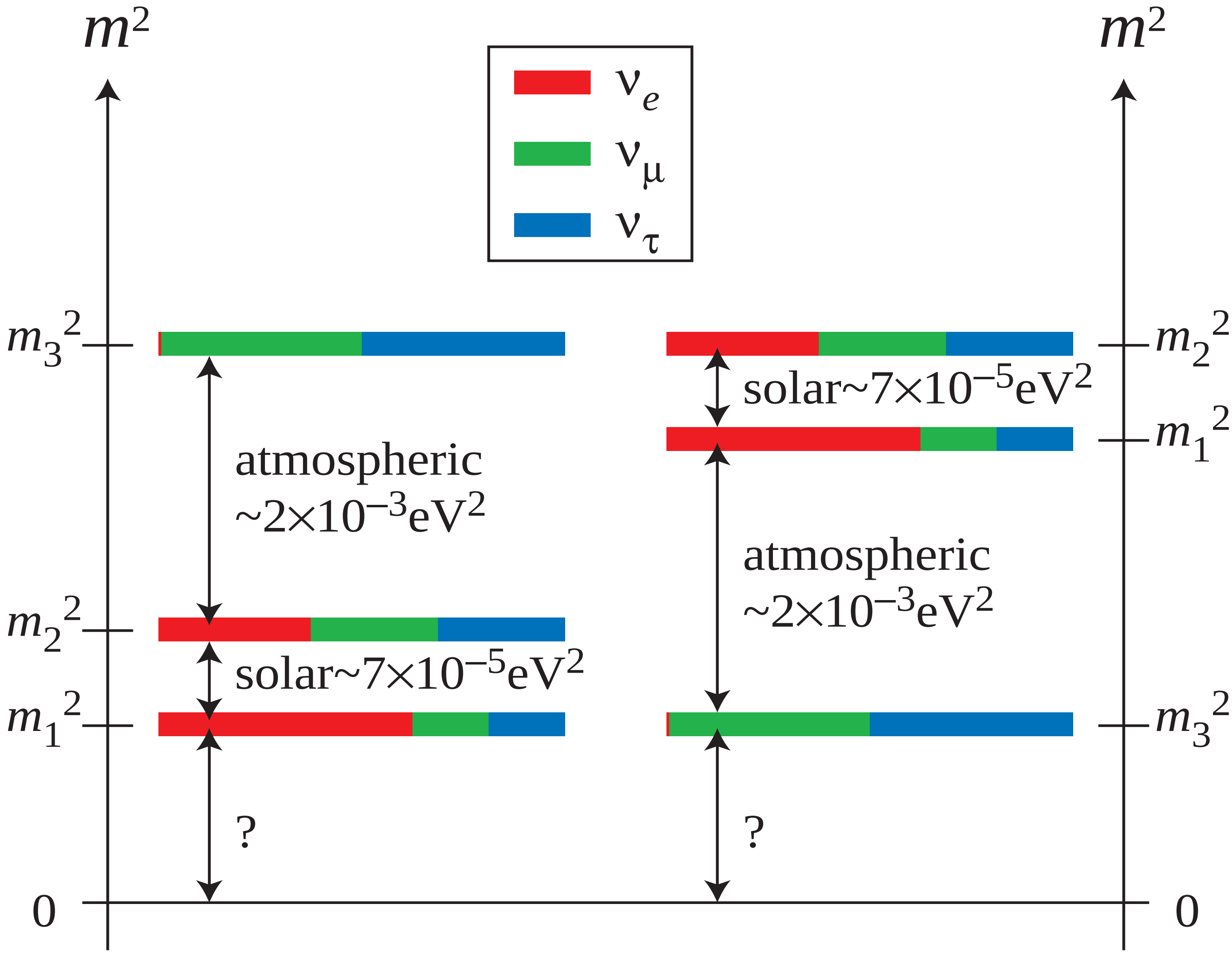


$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ \text{eV}^2$, $\quad \Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ \text{eV}^2$

Are there *more* mass eigenstates, as LSND suggests,
and MiniBooNE recently hints?

3

Due to B. Kayser



S. King, Ch. Luhn, 2013

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

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

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

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

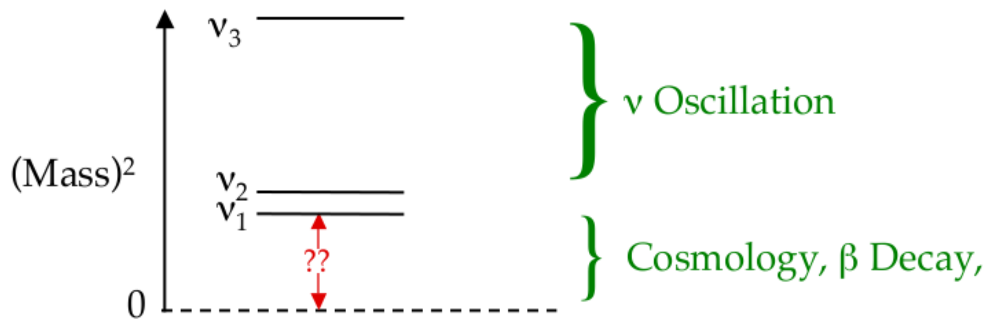
- Majorana phases α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

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

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

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 $^3\text{H} \rightarrow ^3\text{He} + \text{e}^- + \bar{\nu}_\text{e}$:

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

We have $m_{\nu_e} \cong m_{1,2,3}$ in the case of QD spectrum. The upcoming KATRIN experiment 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.

Mass and Hierarchy from Cosmology

Cosmological and astrophysical data on $\sum_j m_j$: the Planck + WMAP (low $l \leq 25$) + ACT (large $l \geq 2500$) CMB data + ΛCDM (6 parameter) model + assuming 3 light massive neutrinos, implies

$$\sum_j m_j \equiv \Sigma < 0.66 \text{ eV} \quad (95\% \text{ C.L.})$$

Adding data on the baryon acoustic oscillations (BAO) leads to:

$$\sum_j m_j \equiv \Sigma < 0.23 \text{ eV} \quad (95\% \text{ C.L.})$$

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

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

NH: $\sum_j m_j \leq 0.05$ eV (3σ);

IH: $\sum_j m_j \geq 0.10$ eV (3σ).

Future Progress

• Determination of the nature - Dirac or Majorana, of ν_j .

• Determination of sgn($\Delta m^2_{\rm atm}$), type of $\nu-$ mass spectrum

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

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

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

• 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}, $\Delta m^2_{\rm atm}$, 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 $U_{\rm PMNS}$;

– 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 $U_{\rm PMNS}$?

• 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 $U_{\rm PMNS}$ be the leptogenesis CPV parameters at the origin of BAU?

The next most important steps are:

• determination of the nature - Dirac or Majorana, of massive neutrinos ($(\beta\beta)_{0\nu}$-decay exps: GERDA, CUORE, EXO, KamLAND-Zen, SNO+, SuperNEMO, MAJORANA, AMORE,...).

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

• determination of the neutrino mass ordering (JUNO, RENO50; ORCA, PINGU (IceCube), HK, INO; T2K + NOνA; DUNE (future); + T2HKK (future)) ;

• determination of the absolute neutrino mass scale, or min(m_j) (KATRIN, new ideas; cosmology);

The program of research extends beyond 2030.

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

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

Neutrino 2016 - XXVII International Conference on Neutrino Physics and Astrophysics

Status and prospects of global analyses of neutrino mass-mixing parameters

A. Marrone
Univ. of Bari & INFN

4-9 July 2016 — London — United Kingdom

Our "pre-London" reference analysis in the standard 3ν mixing scenario:

Bari group, arXiv:1601.07777 (NPB Special Issue on ν Oscillations)

Updated in a preliminary way with some data presented here at Neutrino 2016 (thanks in particular to F. Capozzi):

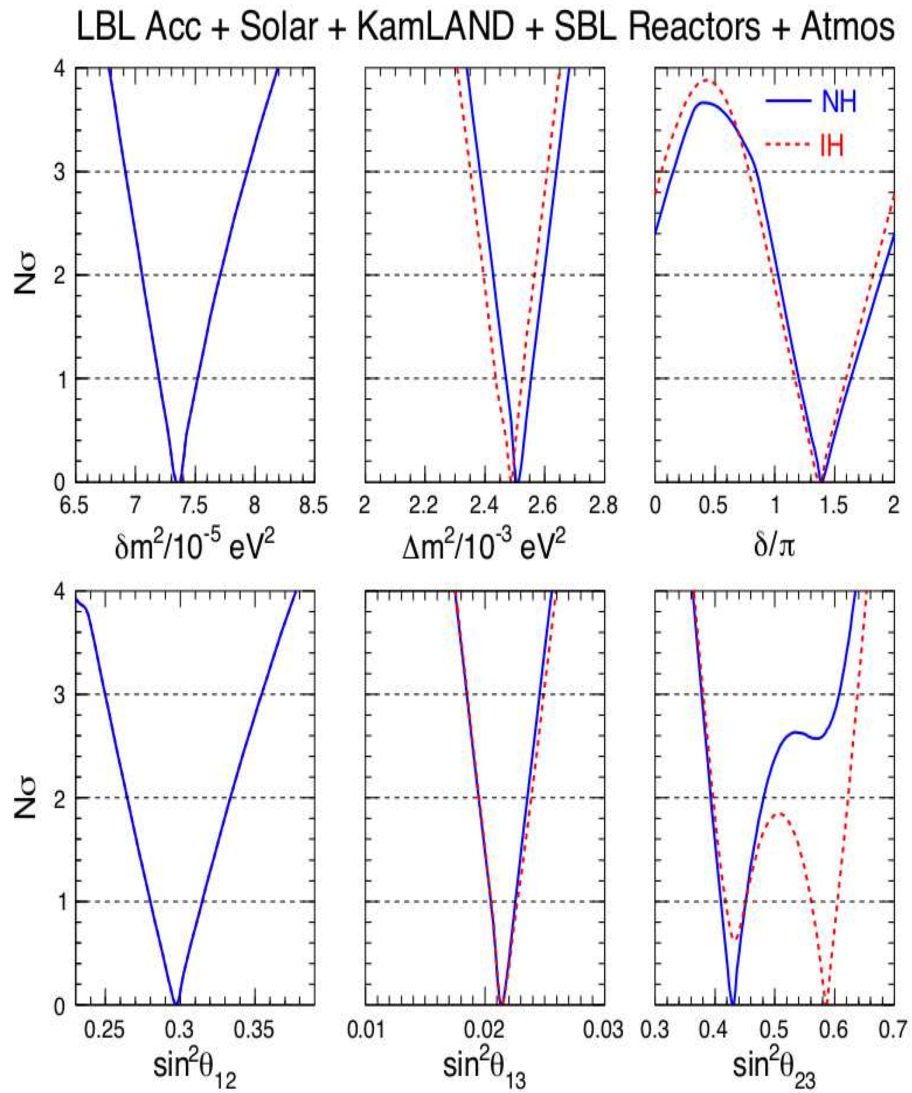
- New NOvA neutrino data in appearance and disappearance channels
- New T2K anti-neutrino data in appearance channel

Other updates not (yet) included

Please focus only on "trends" of the global analysis: numbers may change when a more refined and proper analysis of the new data will be performed in due time

Bounds on single oscillation parameters

(preliminary update)



CP phase trend:

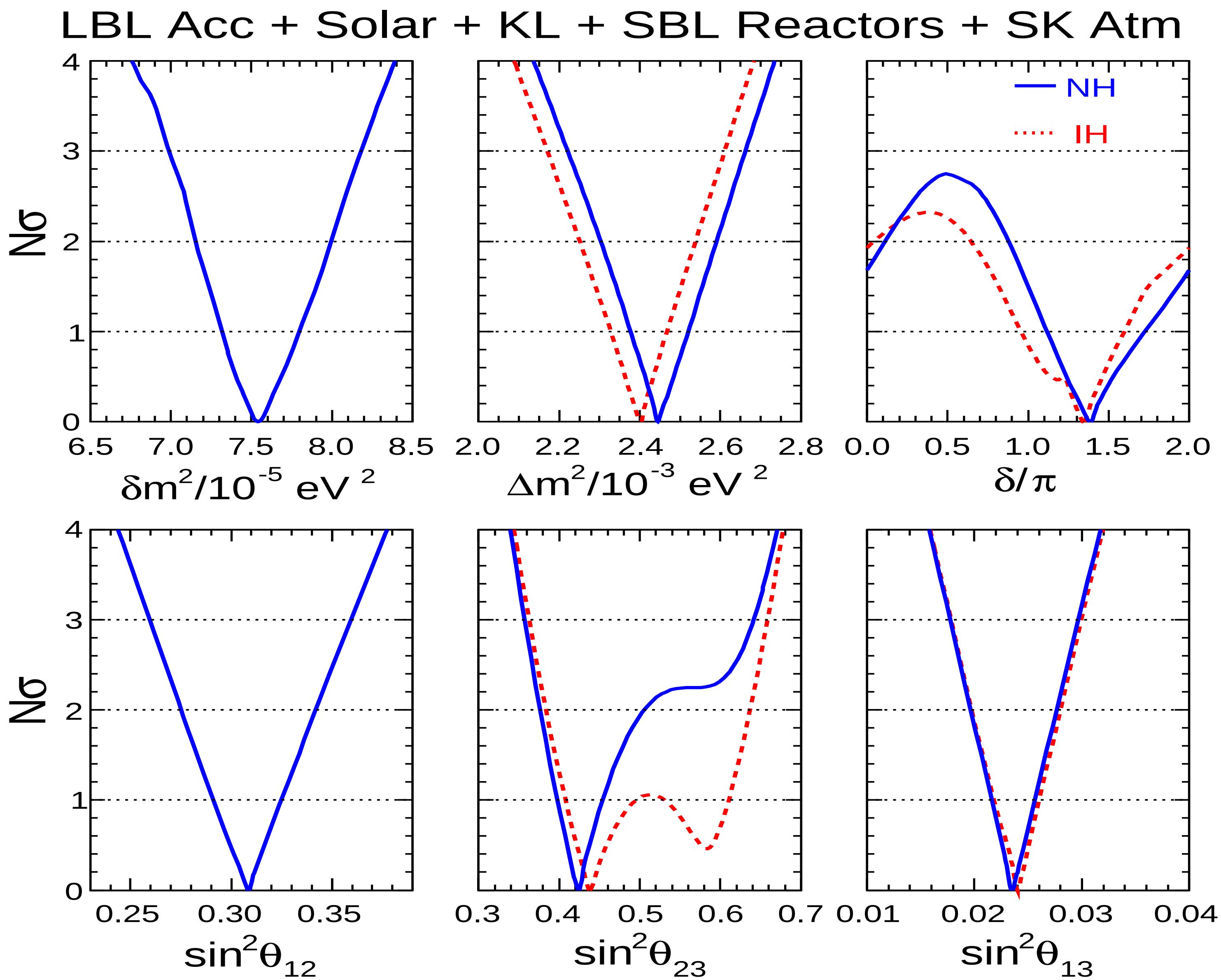
- $\delta \sim 1.4\,\pi$ at best fit
- CP-conserving cases $(\delta = 0, \pi)$ disfavored at $\sim 2\sigma$ level or more
- Significant fraction of the $[0,\pi]$ range disfavored at $>3\sigma$

θ_{23} trend:

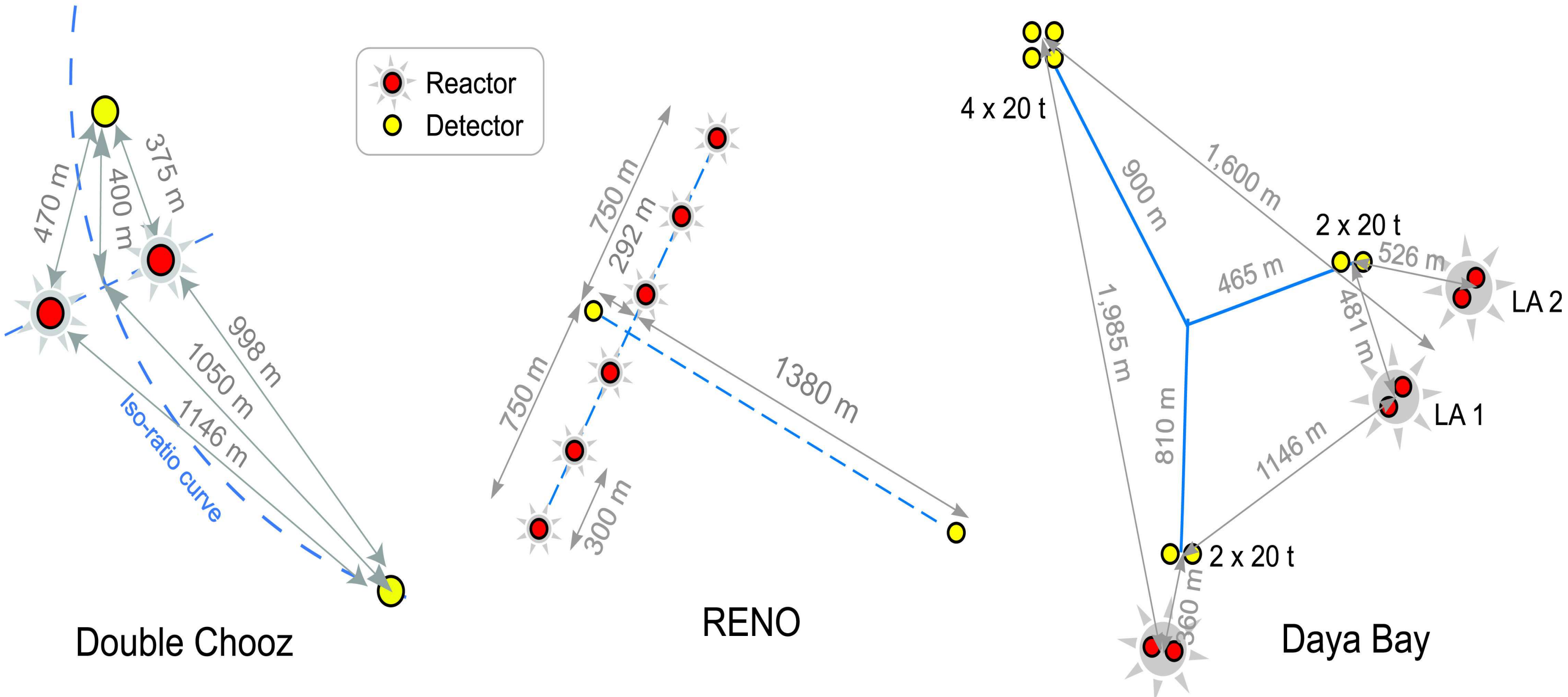
- maximal mixing disfavored at about $\sim 2\sigma$ level
- best-fit octant flips with mass ordering

$$\Delta\chi^2_{\mathrm{IO-NO}} = 3.1$$

inverted ordering slightly disfavored



F. Capozzi, E. Lisi *et al.*, arXiv:1312.2878



M. Mezzetto, T. Schwetz, arXiv:1003.5800[hep-ph]

$P^{3\nu}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = P^{3\nu}(\theta_{13}, \Delta m^2_{31(32)}; \theta_{12}, \Delta m^2_{21}) \cong$

$1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{31(32)}}{4E} L)$, no dependence on θ_{23}, δ.

• Daya Bay, July 2016 (Nu2016):
$\sin^2 2\theta_{13} = 0.0841 \pm 0.0033$.

• RENO, July 2016 (Nu2016):
$\sin^2 2\theta_{13} = 0.087 \pm 0.011$.

• Double Chooz, March 2016:
$\sin^2 2\theta_{13} = 0.111 \pm 0.018$.


Sendai
Super Kamiokande
295km
JAERI
(Tokai)
Japan
KEK
Tokyo
Gifu
Kawasaki
Nagoya
Kyoto
Yokohama
Osaka
(c) 2000 ESRI
~ 420.0 mi / 675.8 km across

T2K: Search for $\nu_\mu \rightarrow \nu_e$ oscillations

T2K: Search for $\nu_\mu \to \nu_e$ oscillations

T2K: first results March 2011 (2 events);
June 14, 2011 (6 events): evidence for $\theta_{13} \neq 0$ at 2.5σ;
July, 2013 (28 events).

For $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$, $\delta = 0$, NO (IO) spectrum:

$\sin^2 2\theta_{13} = 0.14$ (1.7), best fit.

This value is by a factor of ~ 1.6 (1.9) bigger than the value obtained in the Daya Bay and RENO experiments.

$$P^{3\nu}_m(\nu_\mu \to \nu_e) = P^{3\nu}_m(\theta_{13}, \Delta m^2_{31(32)}, \theta_{12}, \Delta m^2_{21}, \theta_{23}, \delta).$$

After 2013 data also on $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations;
July 2016 (Nu2016), 32 $\nu_\mu \to \nu_e$ + 4 $\bar{\nu}_\mu \to \bar{\nu}_e$ events.

The results on $\nu_\mu \rightarrow \nu_e$ oscillations from NOνA (August 6, 2015: 6 (12) events; July 2016 (Nu2016): 33 (34) events) are compatible with, and strengthened, the hint that $\delta \cong 3\pi/2$.

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 $J_{CP} \cong -0.035$;

- 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 is

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

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

Determining the Nature of Massive Neutrinos

Dirac CP-Nonconservation: δ in $U_{\rm PMNS}$

Observable manifestations in

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

- not sensitive to Majorana CPVP $\alpha_{21},\ \alpha_{31}$

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

$$A(\nu_l \leftrightarrow \nu_{l'}) = \sum_j U_{l'j} e^{-i(E_j t - p_j x)} U^{\dagger}_{jl}$$

$$U = VP\ :\ \ P_j e^{-i(E_j t - p_j x)} P^*_j = e^{-i(E_j t - p_j x)}$$

P - diagonal matrix of Majorana phases.

The result is valid also in the case of oscillations in matter: ν_l oscillations are not sensitive to the nature of ν_j.

If ν_j- Majorana particles, U_{PMNS} contains (3-ν mixing)

δ-Dirac, α_{21}, α_{31} - Majorana **physical CPV phases**

ν-oscillations $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$,

- **are not sensitive to the nature of ν_j,**

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

- **provide information on $\Delta m^2_{jk} = m^2_j - m^2_k$, but not on the absolute values of ν_j masses.**

The Majorana nature of ν_j can manifest itself in the existence of $\Delta L = \pm 2$ processes:

$$K^+ \to \pi^- + \mu^+ + \mu^+$$
$$\mu^- + (\text{A}, \text{Z}) \to \mu^+ + (\text{A}, \text{Z} - 2)$$

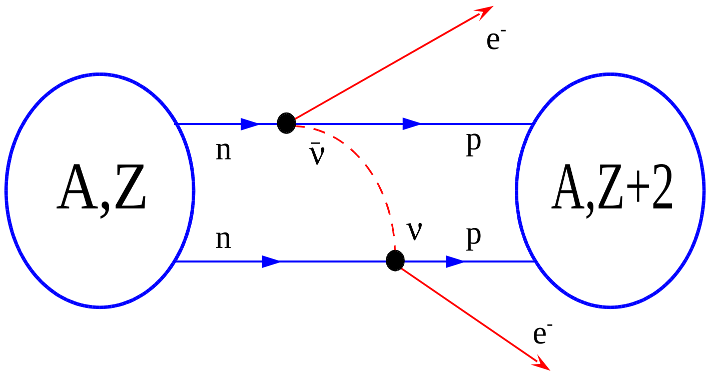
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

$$(\text{A}, \text{Z}) \to (\text{A}, \text{Z} + 2) + e^- + e^-$$

of even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd.

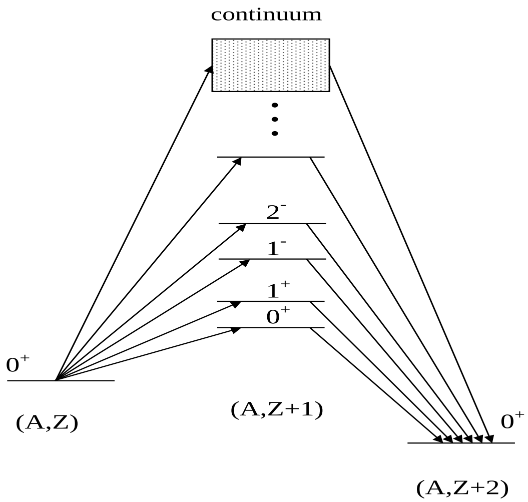
$2n$ from (A,Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of (A,Z+2) and two free e^-.

Nuclear $0\nu\beta\beta$-decay



strong in-medium modification of the basic process

$dd \rightarrow uue^- e^- (\overline{\nu}_e \overline{\nu}_e)$



virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

V. Rodin, talk at Gran Sasso, 2006

$(\beta\beta)_{0\nu}-$Decay Experiments:

- $L-$nonconservation, Majorana nature of ν_j.
- Type of $\nu-$mass spectrum (NH, IH, QD).
- Absolute neutrino mass scale.

^{3}H β-decay , cosmology: m_ν (QD, IH),

- Majorana CPV phases.

$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

$$|<m>| = \left|m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \; e^{i\alpha_{21}} + m_3 |U_{e3}|^2 \; e^{i\alpha_{31}}\right|$$

$$= \left|m_1 \; c_{12}^2 \; c_{13}^2 + m_2 \; s_{12}^2 \; c_{13}^2 \; e^{i\alpha_{21}} + m_3 \; s_{13}^2 \; e^{i\alpha_{31}}\right|, \quad \theta_{12} \equiv \theta_{\odot}, \; \theta_{13}\text{- CHOOZ}$$

α_{21}, α_{31} $((\alpha_{31} - 2\delta) \rightarrow \alpha_{31})$ - the two Majorana CPVP of the PMNS matrix.

CP-invariance: $\alpha_{21} = 0, \pm\pi$, $\alpha_{31} = 0, \pm\pi$;

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of ν_1 and ν_2, and of ν_1 and ν_3 .

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

$$A(\beta\beta)_{0\nu} \sim <m>$$ M(A,Z), M(A,Z) - NME,

$$|<m>| \cong \left|\sqrt{\Delta m^2_{\odot}}\sin^2\theta_{12}e^{i\alpha} + \sqrt{\Delta m^2_{31}}\sin^2\theta_{13}e^{i\beta_M}\right|, \quad m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$|<m>| \cong \sqrt{m_3^2 + \Delta m^2_{13}}\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|, \quad m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$|<m>| \cong m\left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|, \quad m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV} \ \ \text{(QD)},$$

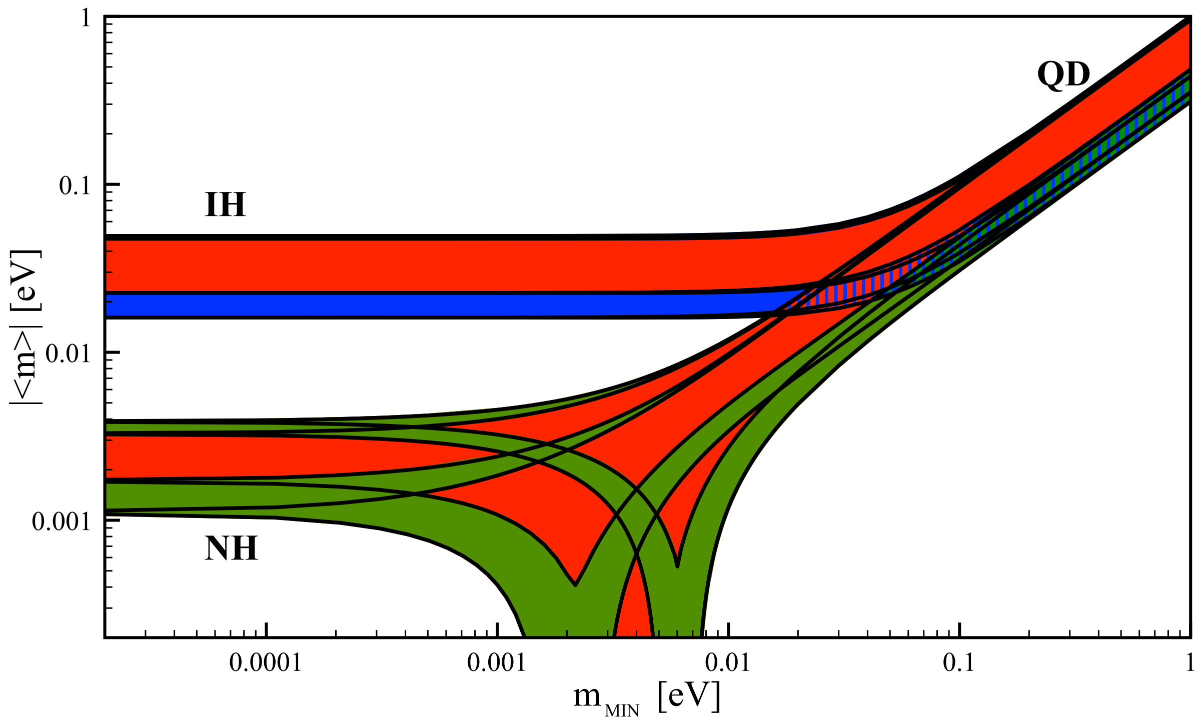
$\theta_{12} \equiv \theta_{\odot}$, θ_{13}-CHOOZ; $\alpha \equiv \alpha_{21}$, $\beta_M \equiv \alpha_{31}$.

CP-invariance: $\alpha = 0, \pm\pi$, $\beta_M = 0, \pm\pi$;

$$|<m>| \lesssim 5 \times 10^{-3} \text{ eV, NH};$$

$$\sqrt{\Delta m^2_{13}}\cos 2\theta_{12} \cong 0.013 \text{ eV} \lesssim |<m>| \lesssim \sqrt{\Delta m^2_{13}} \cong 0.055 \text{ eV}, \quad \text{IH};$$

$$m\cos 2\theta_{12} \lesssim |<m>| \lesssim m,\ m \gtrsim 0.10 \text{ eV}, \quad \text{QD}.$$



S. Pascoli, RPP (PDG), 2016

$\sin^2\theta_{13} = 0.0214 \pm 0.0010$; $\delta = 0$.

$1\sigma(\Delta m^2_{21}) = 2.3\%$, $1\sigma(\sin^2\theta_{12}) = 5.6\%$, $1\sigma(|\Delta m^2_{31(23)}|) = 1.7\%$.

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

$2\sigma(|<m>|\ )$ used.

Results from IGEX (^{76}Ge), NEMO3 (^{100}Mo), CUORICINO+CUORE-0 (^{130}Te):

IGEX ^{76}Ge: $|{<}\, m \,{>}| \; < (0.33 - 1.35)$ eV **(90% C.L.).**

Data from NEMO3 (^{100}Mo), CUORICINO+CUORE-0 (^{130}Te):

$T(^{100}Mo) > 1.1 \times 10^{24}$ **yr,** $|{<}\, m \,{>}| \; <$**(0.3–0.6) eV;**
$T(^{130}Te) > 4.0 \times 10^{24}$ **yr.**

Best Sensitivity Results from 2012-2016:

$$T(^{136}\text{Xe}) > 1.6 \times 10^{25}\text{yr at } 90\% \text{ C.L., EXO}$$

$$T(^{136}\text{Xe}) > 1.07 \times 10^{26}\text{yr at } 90\% \text{ C.L., KamLAND} - \text{Zen}$$

$$|{<}\, m \,{>}| < (0.061 - 0.165)\text{ eV}.$$

$$T(^{76}\text{Ge}) > 5.2 \times 10^{25}\text{yr at } 90\% \text{ C.L., GERDA II}$$

$$|{<}\, m \,{>}| < (0.16 - 0.26)\text{ eV}.$$

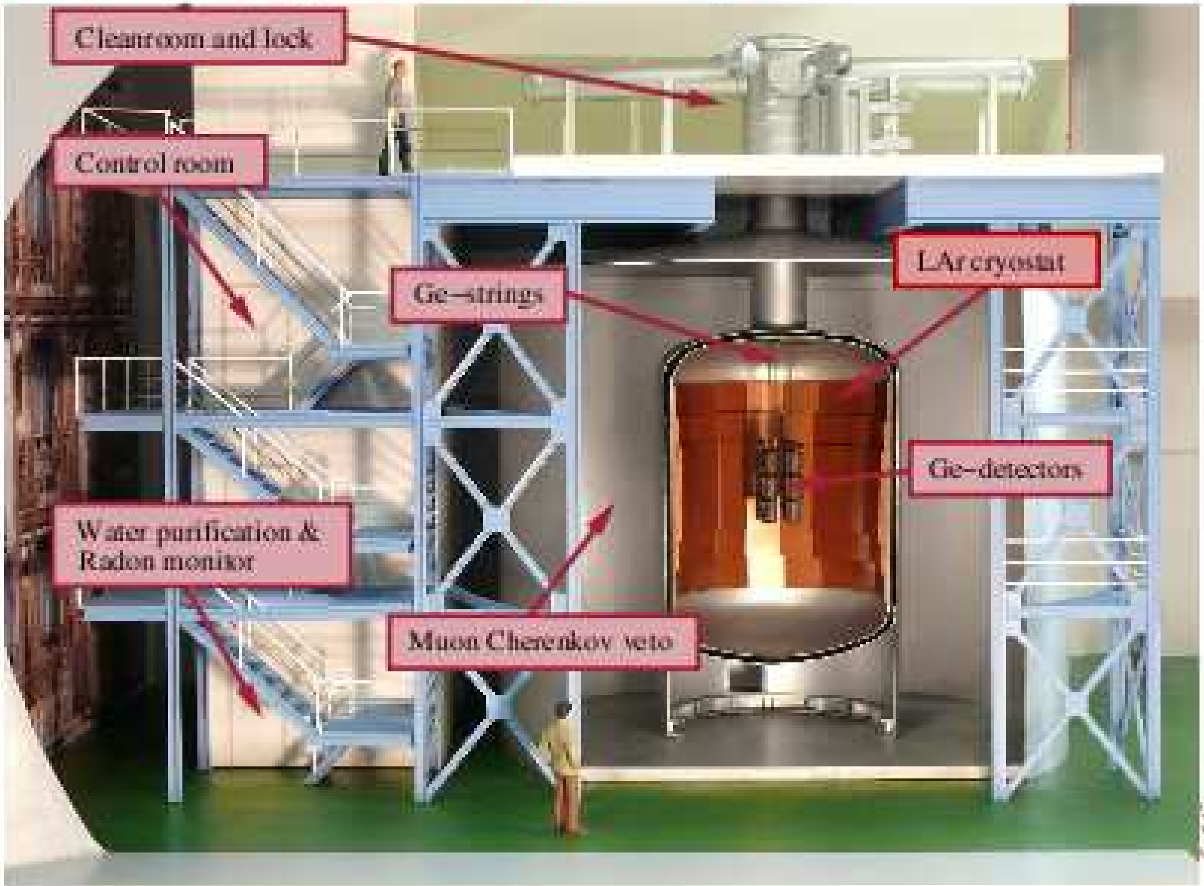
H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$$T(^{76}\text{Ge}) = 2.23^{+0.44}_{0.31} \times 10^{25}\text{ yr at } 90\% \text{ C.L.}$$

Large number of experiments: $|<m>|$ $\sim$ (0.01-0.05) eV

CUORE - ^{130}Te;
GERDA-II - ^{76}Ge;
MAJORANA - ^{76}Ge;
KamLAND-ZEN - ^{136}Xe;
(n)EXO - ^{136}Xe;
SNO+ - ^{130}Te;
AMoRE - ^{100}Mo (S. Korea);
CANDLES - ^{48}Ca;
SuperNEMO - ^{82}Se, ^{150}Nd;
MAJORANA - ^{76}Ge;
NEXT - ^{136}Xe;
DCBA - ^{82}Se, ^{150}Nd;
XMASS - ^{136}Xe;
PANDAX-III - ^{136}Xe;
ZICOS - ^{96}Zr;
MOON - ^{100}Mo;
...

GERDA: Experimental Setup



Majorana CPV Phases and $|{<}m{>}|$

CPV can be established provided

- $|{<}m{>}|$ measured with $\Delta \lesssim 15\%$;

- Δm^2_{atm} (IH) or m_0 (QD) measured with $\delta \lesssim 10\%$;

- $\xi \lesssim 1.5$;

- α_{21} (QD): in the interval $\sim [\frac{\pi}{4} - \frac{3\pi}{4}]$, or $\sim [\frac{5\pi}{4} - \frac{3\pi}{2}]$;

- $\tan^2\theta_{\odot} \gtrsim 0.40$.

S. Pascoli, S.T.P., W. Rodejohann, 2002

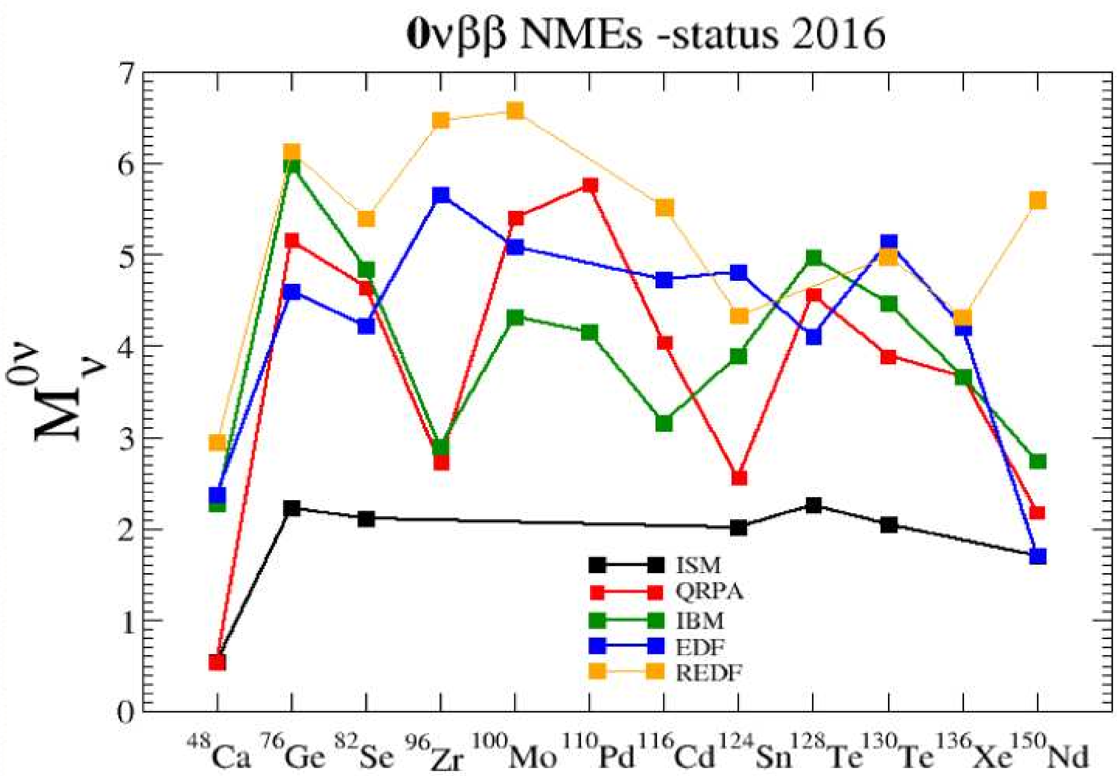
S. Pascoli, S.T.P., L. Wolfenstein, 2002

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

No "No-go for detecting CP-Violation via $(\beta\beta)_{0\nu}$-decay"

V. Barger *et al.*, 2002

NMEs for Light ν Exchange



	mean field meth.	ISM	IBM	QRPA
Large model space	yes	no	yes	yes
Constr. Interm. States	no	yes	no	yes
Nucl. Correlations	limited	all	restricted	restricted

F. Simkovic, September, 2016

The g_A Quenching Problem

g_A: related to the weak charged axial current which is not conserved and therefore can be and is renormalised, i.e., quenched, by the nuclear medium. Effectively, this implies that g_A is reduced from its current standard value $g_A = 1.269$.

The reduction of g_A can have important implications for the $(\beta\beta)_{0\nu}-$decay searches since $T^{0\nu}_{1/2} \propto (g_A^{eff})^{-4}$.

The reduction of g_A necessary in various model NME calculations of $T^{2\nu}_{1/2}$ to reproduce the data; does not imply the same reduction of g_A takes place in the $(\beta\beta)_{0\nu}-$decay NME, there are indications that the reduction is much smaller.

The mechanism of quenching is not understood at present. Thus, the degree of quenching cannot be firmly determined quantitatively and is subject to debates.

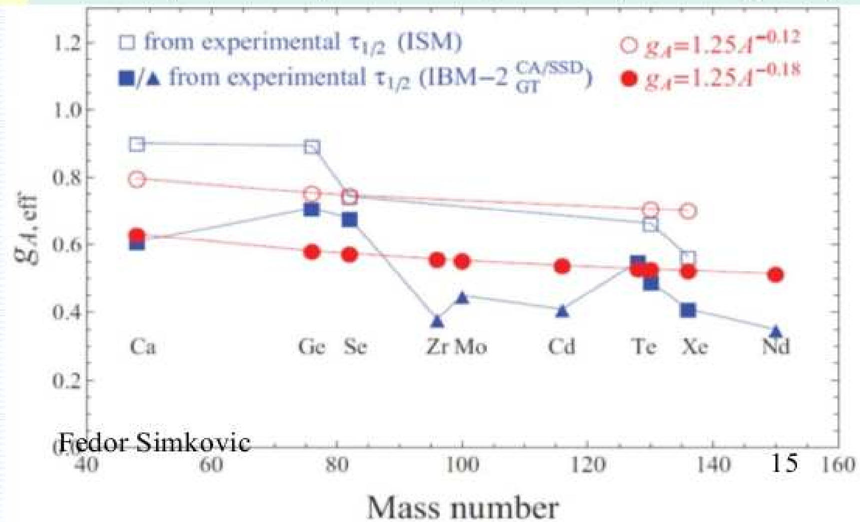
Quenching of g_A *(from theory: $T_{1/2}^{0\nu}$ up 50 x larger)*

$(g^{eff}_A)^4 \simeq 0.66$ (^{48}Ca), 0.66 (^{76}Ge), 0.30 (^{76}Se), 0.20 (^{130}Te) and 0.11 (^{136}Xe)
The Interacting Shell Model (ISM), which describes qualitatively well energy spectra, does reproduce experimental values of $M^{2\nu}$ only by consideration of significant quenching of the Gamow-Teller operator, typically by 0.45 to 70%.

$(g^{eff}_A)^4 \simeq (1.269\, A^{-0.18})4 = 0.063$ (The Interacting Boson Model). This is an incredible result. The quenching of the axial-vector coupling within the IBM-2 is more like 60%.

J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

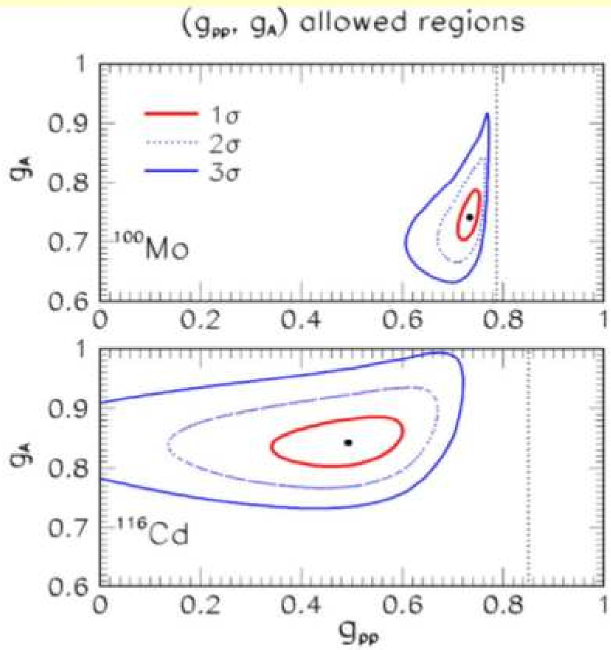
It has been determined by theoretical prediction for the 2νββ-decay half-lives, which were based on within closure approximation calculated corresponding NMEs, with the measured half-lives.

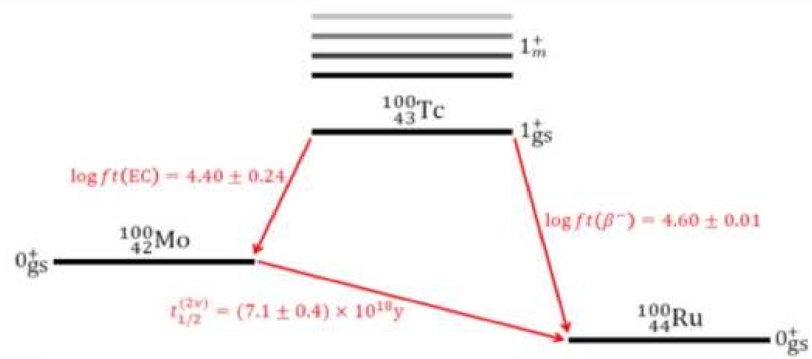


F. Simkovic, September, 2016

Faessler, Fogli, Lisi, Rodin, Rotunno, F. Š, J. Phys. G 35, 075104 (2008).

$(g^{eff}_A)^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd, respectively (The QRPA prediction).
g^{eff}_A was treated as a completely free parameter alongside g_{pp} (used to renormalize particl-particle interaction) by performing calculations within the QRPA and RQRPA. It was found that a least-squares fit of g^{eff}_A and g_{pp}, where possible, to the β-decay rate and β+/EC rate of the $J = 1^+$ ground state in the intermediate nuclei involved in double-beta decay in addition to the 2νββ rates of the initial nuclei, leads to an effective g^{eff}_A of about 0.7 or 0.8.





Extended calculation also for neighbour isotopes performed by

F.F. Depisch and J. Suhonen, arXiv:1606.02908[nucl-th]

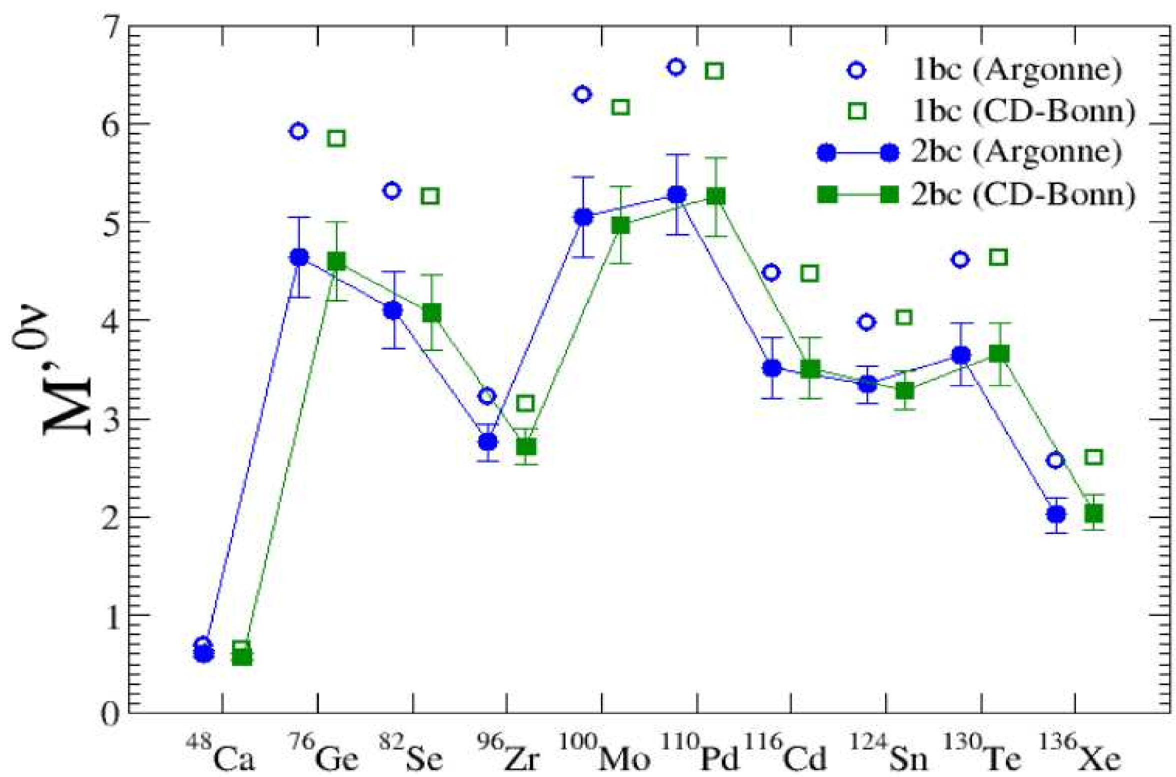
r Simkovic

Dependence of g^{eff}_A on A was not established.

Quenching of g_A, two-body currents and QRPA

(Suppression of the $0\nu\beta\beta$-decay NME of about 20%)

Engel, Vogel, Faessler, F.Š., PRC 89 (2014) 064308



But, a strong suppression of $2\nu\beta\beta$-decay half-life, ($g_A^{eff} = g_A\delta(p=0) = 0.7$-$1.0$)

New Physics and $(\beta\beta)_{0\nu}$-Decay

Light Sterile Neutrinos and $(\beta\beta)_{0\nu}$-Decay

One Sterile Neutrino: the $3+1$ Model

$$|\langle m \rangle| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + m_3 |U_{e3}|^2 e^{i\beta} + m_4 |U_{e4}|^2 e^{i\gamma} \right| .$$

$$U_{e1} = c_{12} c_{13} c_{14}, \quad U_{e2} = e^{i\alpha/2} c_{13} c_{14} s_{12},$$

$$U_{e3} = e^{i\beta/2} c_{14} s_{13}, \quad U_{e4} = e^{i\gamma/2} s_{14} ,$$

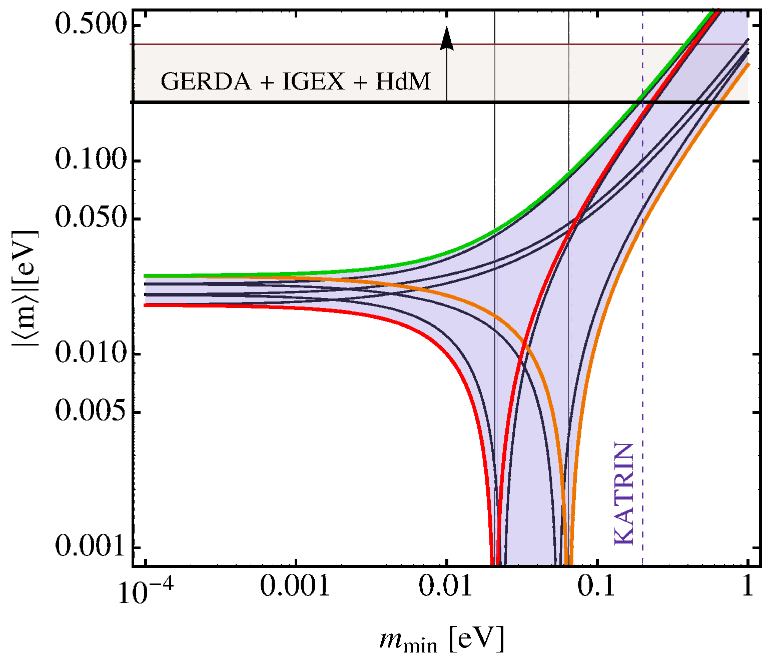
$$\sin^2\theta_{14} = 0.0225 , \quad \Delta m^2_{41(43)} = 0.93 \text{ eV}^2 \quad \text{(A)} ,$$

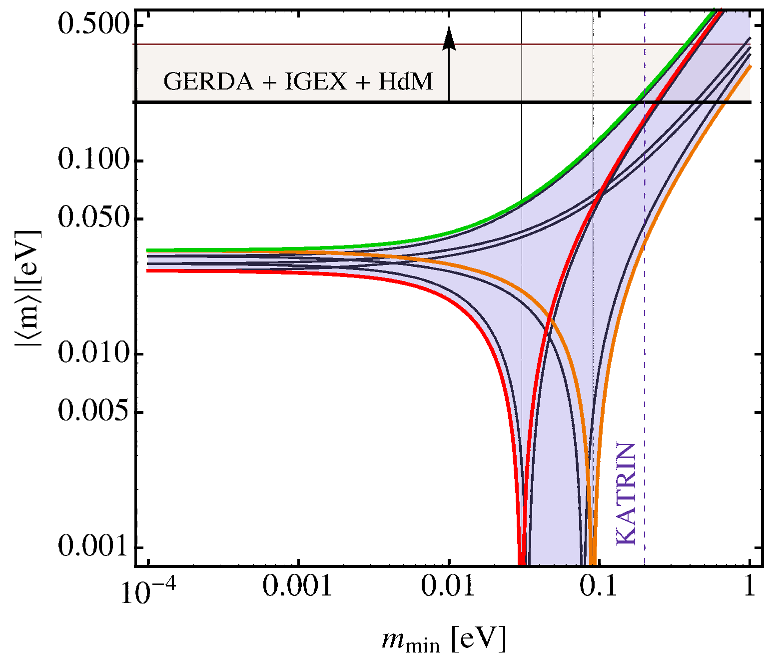
J. Kopp et al., 2013

$$\sin^2\theta_{14} = 0.023 \ (0.028) , \ \Delta m^2_{41(43)} = 1.78 \ (1.60) \text{ eV}^2 \ \text{(B)} .$$

J. Kopp et al., 2013 (ν_e, $\bar{\nu}_e$ disappearnce data);

C. Giunti et al., 2013 (global, except for MiniBooNE results at $E_\nu \leq 0.475$ GeV)



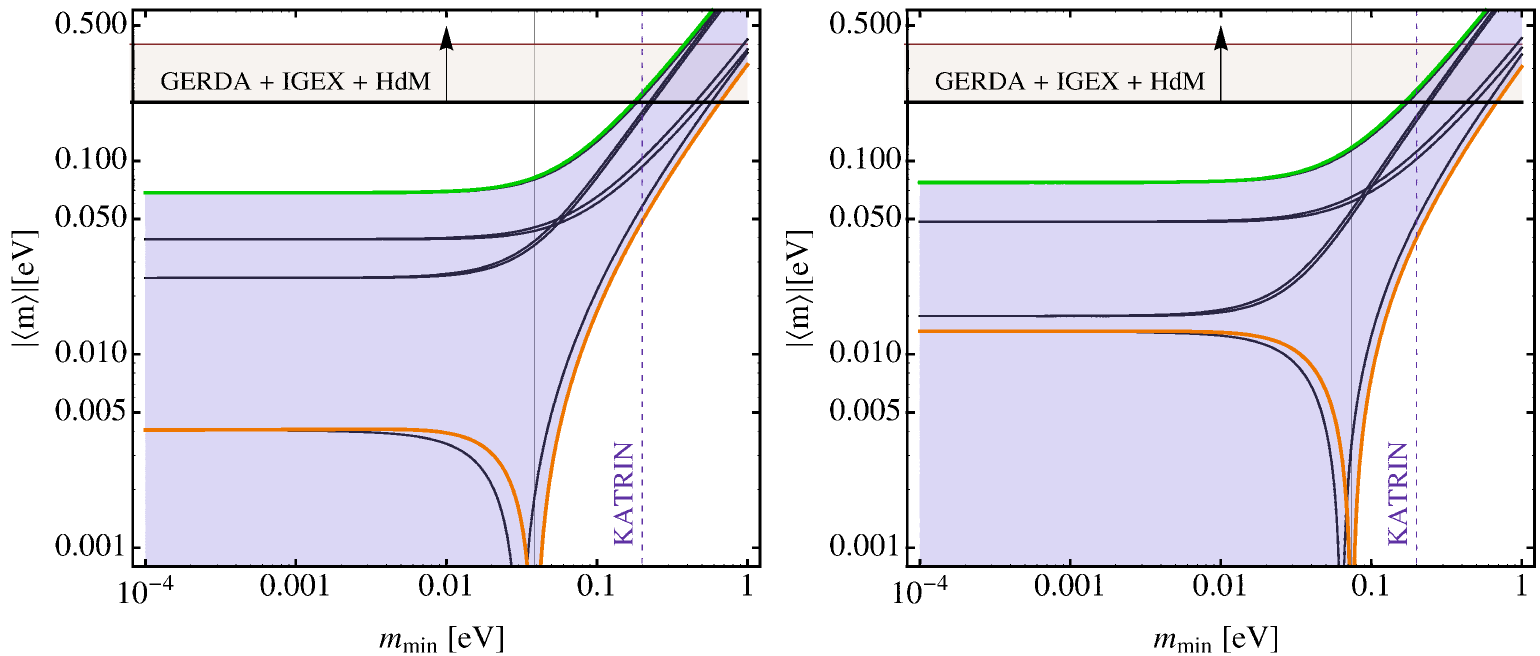


I. Girardi A. Meroni, S.T.P., 2013

NO spectrum; green, red and orange lines: $(\alpha, \beta, \gamma) = (0,0,0), (0,0,\pi), (\pi,\pi,\pi)$; five gray lines: the other five sets of CP conserving values.

Left panel: $\Delta m^2_{41} = 0.93$ eV^2, $\sin\theta_{14} = 0.15$.

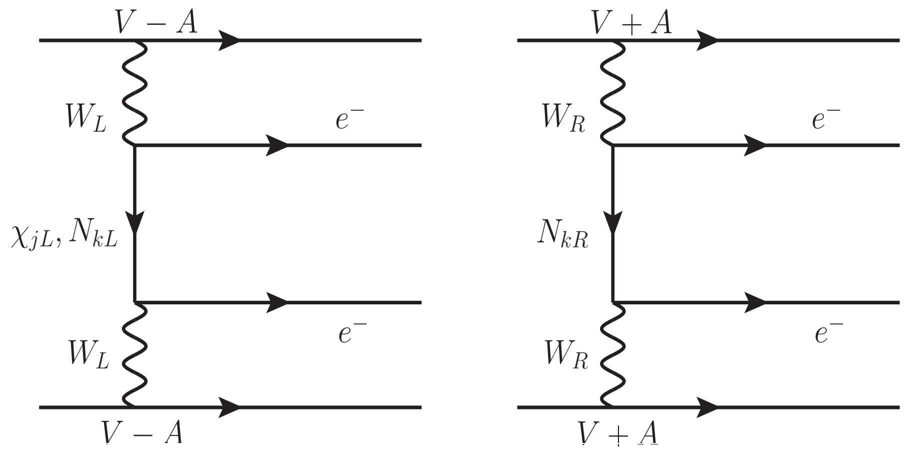
Right panel: $\Delta m^2_{41} = 1.78$ eV^2, $\sin\theta_{14} = 0.15$.



I. Girardi A. Meroni, S.T.P., 2013

IO spectrum; green and orange lines: $(\alpha, \beta, \gamma) = (0, 0, 0), (\pi, \pi, \pi)$; six gray lines: the other six sets of CP conserving values.
Left panel: $\Delta m^2_{43} = 0.93$ eV^2, $\sin\theta_{14} = 0.15$.
Right panel: $\Delta m^2_{43} = 1.78$ eV^2, $\sin\theta_{14} = 0.15$.

Heavy Majorana Neutrino Exchange Mechanisms



Light Majorana Neutrino Exchange

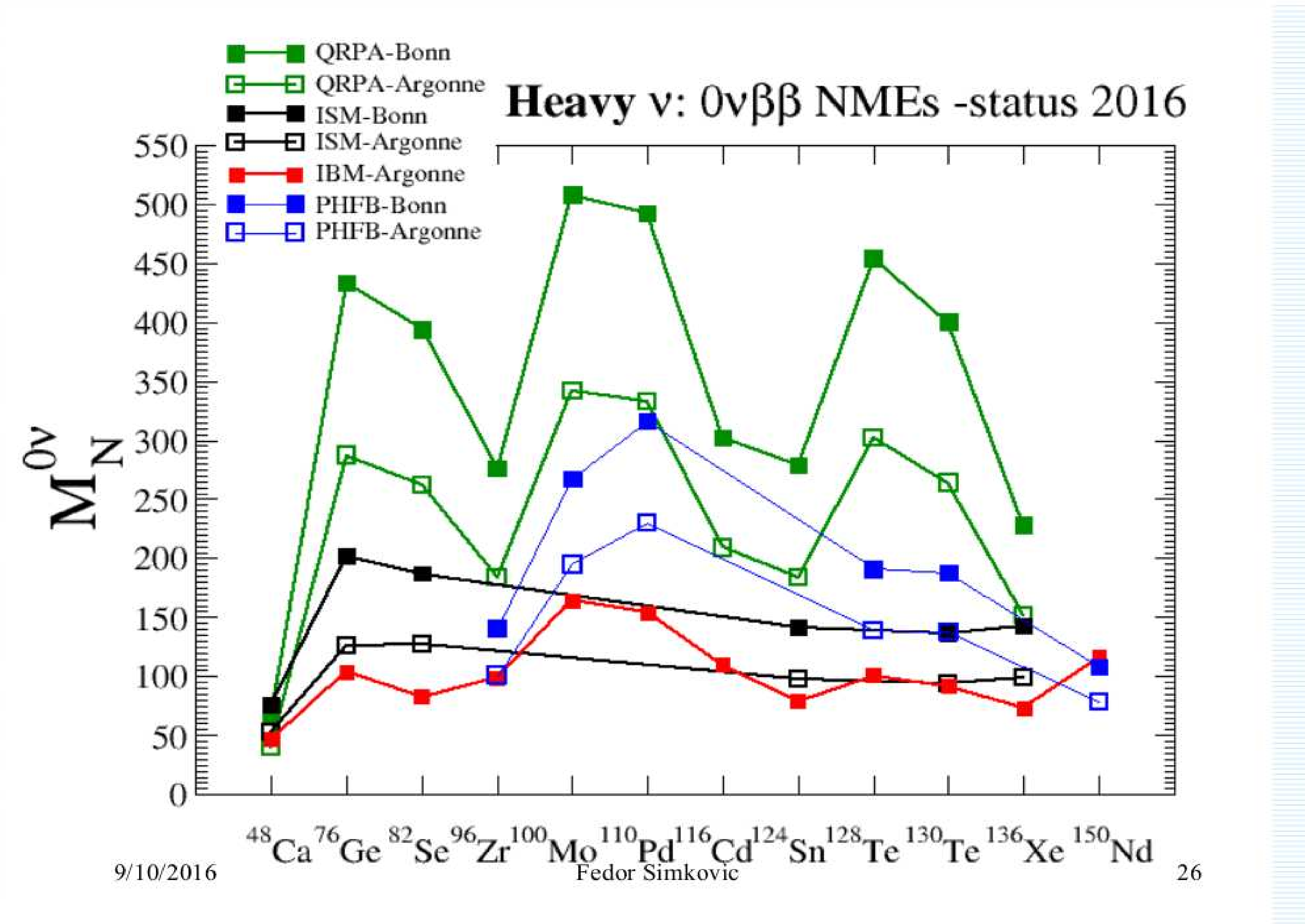
$$\eta_\nu = \frac{<m>}{m_e}\,.$$

Heavy Majorana Neutrino Exchange Mechanisms

(V-A) Weak Interaction, LH N_k, $M_k \gtrsim 10$ GeV:

$\eta_N^L \;=\; \Sigma_k^{heavy}\; U_{ek}^2 \frac{m_p}{M_k}$, m_p - proton mass , U_{ek} - CPV .

NMEs for Heavy Majorana Neutrino Exchange



F. Simkovic, September, 2016

$(\beta\beta)_{0\nu}$-Decay and TeV Scale Type I See-Saw Mechanism

The Seesaw Mechanisms of Neutrino Mass Generation

M_ν **from the See-Saw Mechanism**

P. Minkowski, 1977.

M. Gell-Mann, P. Ramond, R. Slansky, 1979;

T. Yanagida, 1979;

R. Mohapatra, G. Senjanovic, 1980.

- Explain the smallness of $\nu-$masses.

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

S. Fukugita, T. Yanagida, 1986.

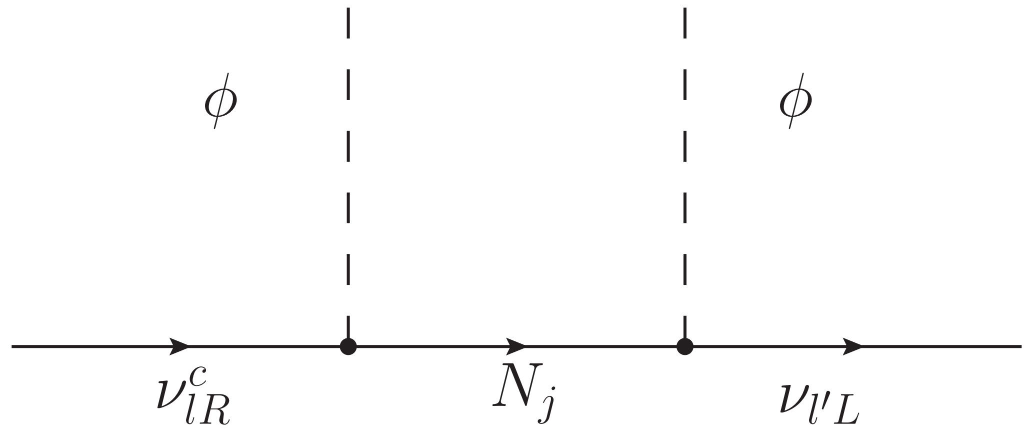
Type I Seesaw Mechanism

- Requires both $\nu_{lL}(x)$ and $\nu_{l'R}(x)$.
- Dirac+Majorana Mass Term: $M^{LL} = 0$, $|M_D = vY^{\nu}/\sqrt{2}| << |M^{RR}|$.
- Diagonalising M^{RR}: N_j - heavy Majorana neutrinos, $M_j \sim$TeV; or $(10^9 - 10^{13})$ GeV in GUTs.

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

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

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



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

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

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

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

TeV Scale Type I See-Saw Mechanism

Type I see-saw mechanism, heavy Majorana neutrinos N_j at the TeV scale:

$m_\nu \simeq -\, M_D \hat{M}_N^{-1} M_D^T$, $\hat{M} = \mathrm{diag}(M_1, M_2, M_3)$, $M_j \sim (100 - 1000)$ GeV.

$$\mathcal{L}_{CC}^N = -\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha + \text{h.c.}\,, \quad (RV)_{\ell k} \equiv U_{\ell 3+k}\,,$$

$$\mathcal{L}_{NC}^N = -\frac{g}{2c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}\,N_{kL}\,Z^\alpha + \text{h.c.}$$

- $|m_{\ell'\ell}| \cong |\sum_k (RV)^*_{\ell' k}\, M_k\,(RV)^\dagger_{k\ell}| \lesssim 1$ eV, $\ell', \ell = e, \mu, \tau$.

One N_1, $M_1 \sim 100$ GeV: $|(RV)_1|^2 \lesssim 10^{-11}$

- **All low-energy constraints can be satisfied in a scheme with two heavy Majorana neutrinos $N_{1,2}$ with $|(RV)_{1,2}|^2 \lesssim 10^{-3}$, if $N_{1,2}$ form a pseudo-Dirac pair:**

$M_2 = M_1(1+z)$, $0 < z \ll 1$.

- **Only NH and IH ν mass spectra possible:** $\min(m_j) = 0$.

• **Requirements:** $|(RV)_{\ell k}|$ **"sizable"**
+ reproducing correctly the neutrino oscillation data:

$$
\begin{aligned}
|(RV)_{\ell 1}|^2 &= \frac{1}{2}\frac{y^2v^2}{M_1^2}\frac{m_3}{m_2+m_3}\left|U_{\ell 3}+i\sqrt{m_2/m_3}U_{\ell 2}\right|^2\,, \quad \text{NH}\,,\\
|(RV)_{\ell 1}|^2 &= \frac{1}{2}\frac{y^2v^2}{M_1^2}\frac{m_2}{m_1+m_2}\left|U_{\ell 2}+i\sqrt{m_1/m_2}U_{\ell 1}\right|^2 \cong \frac{1}{4}\frac{y^2v^2}{M_1^2}\left|U_{\ell 2}+iU_{\ell 1}\right|^2\,, \text{IH}\,,\\
(RV)_{\ell 2} &= \pm i\,(RV)_{\ell 1}\sqrt{\frac{M_1}{M_2}}\,,\ \ \ell = e,\mu,\tau\,,
\end{aligned}
$$

y- **the maximum eigenvalue of** Y^{ν}**,** $v_u \simeq 174$ **GeV.**

4 parameters: M**,** z**,** y **and a phase** ω**.**

A. Ibarra, E. Molinaro, S.T.P., 2010 and 2011

Low energy data:

$$
\begin{aligned}
|(RV)_{e1}|^2 &\lesssim 2\times 10^{-3}\,,\\
|(RV)_{\mu 1}|^2 &\lesssim 0.8\times 10^{-3}\,,\\
|(RV)_{\tau 1}|^2 &\lesssim 2.6\times 10^{-3}\,.
\end{aligned}
$$

S. Antusch et al., 2008

Observation of $N_{1,2}$ at LHC - problematic.

The exchange of virtual N_j contributes to $|<m>|$:

$$|<m>| \cong \left| \Sigma_i (U_{PMNS})^2_{ei}\, m_i - \Sigma_k\, f(A, M_k)\, (RV)^2_{ek}\, \frac{(0.9\ \text{GeV})^2}{M_k} \right|$$

$$f(A, M_k) \cong f(A)\,.$$

For, e.g., ^{48}Ca, ^{76}Ge, ^{82}Se, ^{130}Te and ^{136}Xe, the function $f(A)$ takes the values $f(A) \cong$ 0.035, 0.028, 0.028, 0.033 and 0.032, respectively.

The Predictions for $|<m>|$ can be modified significantly: we can have
$|<m>|^{(NH)}_{\nu+\text{N}} \sim |<m>|^{(IH)}_{\nu}$,
or $|<m>|^{(IH)}_{\nu+\text{N}} \sim |<m>|^{(NH)}_{\nu}$.

$M_{1,2} \sim 1$ TeV, $|<m>|^{heavy} \sim 0.1$ eV.

Uncovering Multiple CP-Nonconserving Mechanisms of $(\beta\beta)_{0\nu}$-Decay

Based on:
1. A. Faessler, A. Meroni, S.T.P., F. Šimkovic, J. Vergados, arXiv:1103.2434 (Phys. Rev. D83 (2011) 113003).
2. A. Meroni, S.T.P. and F. Šimkovic, arXiv:1212.1331 (JHEP **1302** (2013) 025).

If the decay $(A,Z) \to (A,Z+2) + e^- + e^-$ ($(\beta\beta)_{0\nu}$-decay) will be observed, the question will inevitably arise:

Which mechanism is triggering the decay?

How many mechanisms are involved?

"Standard Mechanism": light Majorana ν exchange.

Fundamental parameter - the effective Majorana mass:

$$< m > = \sum_j^{light} \left(U_{ej}\right)^2 m_j \text{ , all } m_j \geq 0 \text{ ,}$$

U - the Pontecorvo, Maki, Nakagawa, Sakata (PMNS) neutrino mixing matrix, m_j - the light Majorana neutrino masses, $m_j \lesssim 1$ eV.

U - CP violating, in general: $(U_{ej})^2 = |U_{ej}|^2 e^{i\alpha_{j1}}$, $j = 2, 3$, α_{21}, α_{31} - Majorana CPV phases.

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

A number of different mechanisms possible.

For a given mechanism κ we have in the case of $(A,Z) \rightarrow (A,Z+2) + e^- + e^-$:

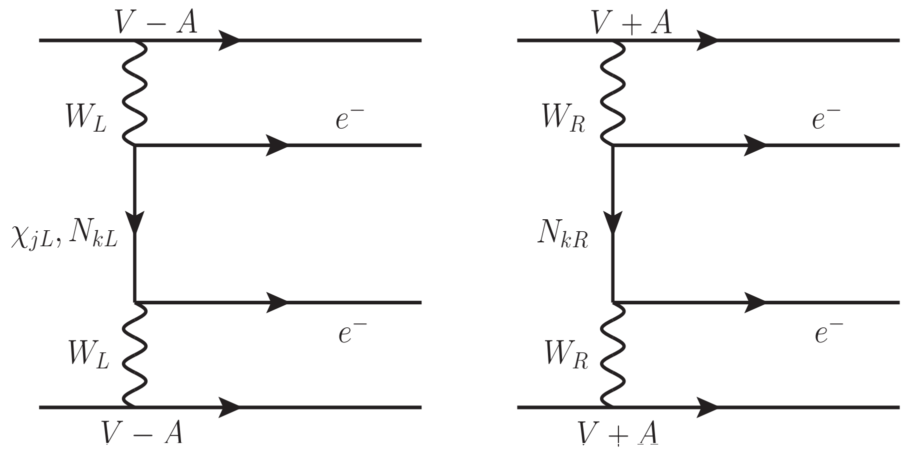
$$\frac{1}{T^{0\nu}_{1/2}} = |\eta^{LNV}_{\kappa}|^2 \; G^{0\nu}(E_0, Z) |M'^{0\nu}_{\kappa}|^2 ,$$

η^{LNV}_{κ} - the fundamental LNV parameter characterising the mechanism κ,

$G^{0\nu}(E_0, Z)$ - phase-space factor (includes $g_A^4 = (1.25)^4$, as well as $R^{-2}(A)$, $R(A) = r_0 A^{1/3}$ with $r_0 = 1.1\ fm$),

$M'^{0\nu}_{\kappa} = (g_A/1.25)^2 M^{0\nu}_{\kappa}$ - NME (includes $R(A)$ as a factor).

Different Mechanisms of $(\beta\beta)_{0\nu}$-Decay



Light Majorana Neutrino Exchange

$$\eta_\nu = \frac{<m>}{m_e}\,.$$

Heavy Majorana Neutrino Exchange Mechanisms

(V-A) Weak Interaction, LH N_k, $M_k \gtrsim 10$ GeV:

$\eta^L_N \;=\; \Sigma_k^{heavy}\; U^2_{ek}\,\frac{m_p}{M_k}$, m_p - proton mass , U_{ek} - CPV .

(V+A) Weak Interaction, RH N_k, $M_k \gtrsim 10$ GeV:

$\eta_N^R = \left(\frac{M_W}{M_{WR}}\right)^4 \sum_k^{heavy} V_{ek}^2 \frac{m_p}{M_k}$; V_{ek}: $N_k - e^-$ in the CC .

$M_W \cong 80$ GeV; $M_{WR} \gtrsim 2.5$ TeV; V_{ek} - CPV, in general.

A comment.

(V-A) CC Weak Interaction:

$\bar{e}(1+\gamma_5)e^c \equiv 2\bar{e_L}\,(e^c)_R$, $e^c = C(\bar{e})^T$,

C - the charge conjugation matrix.

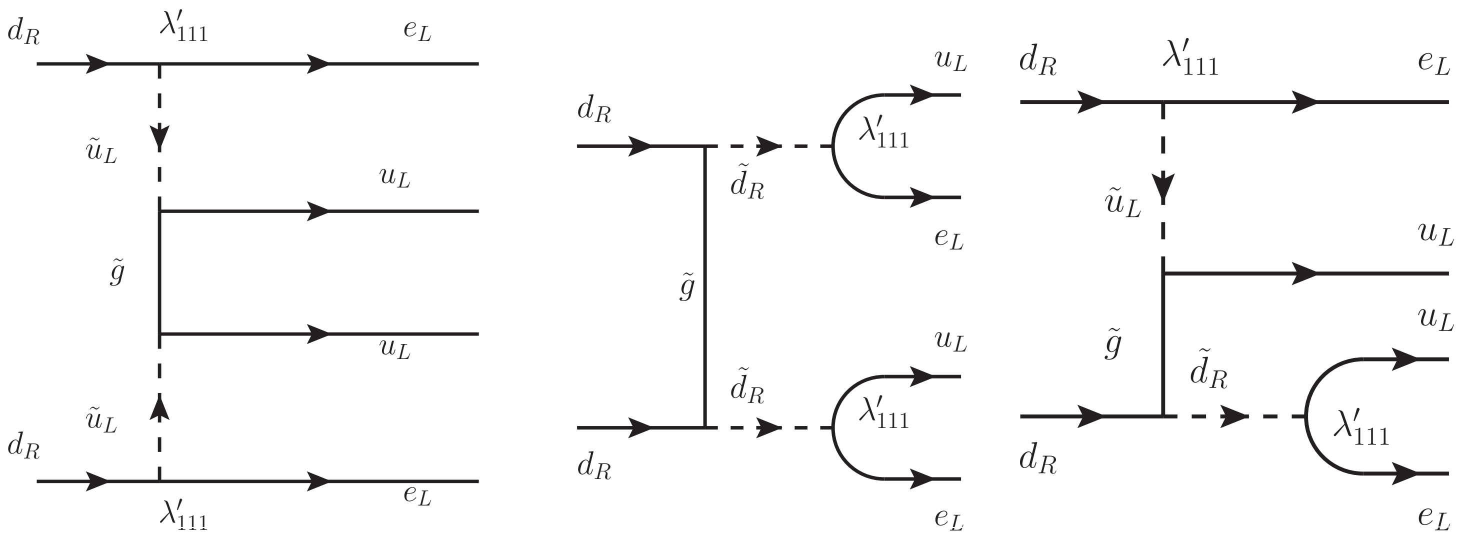
(V+A) CC Weak Interaction:

$\bar{e}(1-\gamma_5)e^c \equiv 2\bar{e_R}\,(e^c)_L$.

The interference term: $\propto m_e$, suppressed.

A. Halprin, S.T.P., S.P. Rosen, 1983

SUSY Models with R-Parity Non-conservation



$$\mathcal{L}_{R_p} = \lambda'_{111}\Big[(\bar{u}_L\ \bar{d}_L)\begin{pmatrix} e^c_R \\ -\nu^c_{eR}\end{pmatrix}\tilde{d}_R + (\bar{e}_L\ \bar{\nu}_{eL})d_R\begin{pmatrix}\tilde{u}^*_L \\ -\tilde{d}^*_L\end{pmatrix}$$

$$+\ (\bar{u}_L\ \bar{d}_L)d_R\begin{pmatrix}\tilde{e}^*_L \\ -\tilde{\nu}^*_{eL}\end{pmatrix}\Big] + h.c.$$

The Gluino Exchange Dominance Mechanism

$$\eta_{\lambda'} = \frac{\pi\alpha_s}{6}\frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}}\frac{m_p}{m_{\tilde{g}}}\left[1 + \left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}}\right)^2\right]^2 ,$$

G_F - the Fermi constant, $\alpha_s = g_3^2/(4\pi)$, g_3 - the SU(3)$_c$ gauge coupling constant, $m_{\tilde{u}_L}$, $m_{\tilde{d}_R}$ and $m_{\tilde{g}}$ - the masses of the LH u-squark, RH d-squark and gluino.

The Squark-Neutrino Mechanism

$$\eta_{\tilde{q}} = \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{2\sqrt{2}G_F} \sin 2\theta^d_{(k)} \left(\frac{1}{m^2_{\tilde{d}_1(k)}} - \frac{1}{m^2_{\tilde{d}_2(k)}}\right) ,$$

$d_{(k)} = d, s, b$; θ^d: $\tilde{d}_{kL} - \tilde{d}_{kR}$ - mixing (3 light Majorana neutrinos assumed).

The $2e^-$ current in both mechanisms:

$\bar{e}(1+\gamma_5)e^c \equiv 2\bar{e_L}\,(e^c)_R$, as in the "standard" mechanism.

Two “Non-Interfering” Mechanisms

Example: light LH and heavy RH Majorana ν exchanges

The corresponding LNV parameters, $|\eta_\nu|$ and $|\eta_R|$ - from “data” on $T^{0\nu}_{1/2}$ of two nuclei:

$$\frac{1}{T_1 G_1} = |\eta_\nu|^2 |{M'}^{0\nu}_{1,\nu}|^2 + |\eta_R|^2 |{M'}^{0\nu}_{1,N}|^2,$$
$$\frac{1}{T_2 G_2} = |\eta_\nu|^2 |{M'}^{0\nu}_{2,\nu}|^2 + |\eta_R|^2 |{M'}^{0\nu}_{2,N}|^2.$$

The solutions read:

$$|\eta_\nu|^2 = \frac{|{M'}^{0\nu}_{2,N}|^2/T_1G_1 - |{M'}^{0\nu}_{1,N}|^2/T_2G_2}{|{M'}^{0\nu}_{1,\nu}|^2|{M'}^{0\nu}_{2,N}|^2 - |{M'}^{0\nu}_{1,N}|^2|{M'}^{0\nu}_{2,\nu}|^2},$$
$$|\eta_R|^2 = \frac{|{M'}^{0\nu}_{1,\nu}|^2/T_2G_2 - |{M'}^{0\nu}_{2,\nu}|^2/T_1G_1}{|{M'}^{0\nu}_{1,\nu}|^2|{M'}^{0\nu}_{2,N}|^2 - |{M'}^{0\nu}_{1,N}|^2|{M'}^{0\nu}_{2,\nu}|^2}.$$

Solutions giving $|\eta_\nu|^2 < 0$ and/or $|\eta_R|^2 < 0$ are unphysical. Given a pair (A_1, Z_1), (A_2, Z_2) of the three ^{76}Ge, ^{100}Mo and ^{130}Te we will be considering, and T_1, and choosing (for convenience) always $A_1 < A_2$, positive solutions for $|\eta_\nu|^2$ and $|\eta_R|^2$ - possible for the following range of values of T_2:

The positivity conditions

$$\frac{T_1 G_1 |M'^{0\nu}_{1,N}|^2}{G_2 |M'^{0\nu}_{2,N}|^2} \leq T_2 \leq \frac{T_1 G_1 |M'^{0\nu}_{1,\nu}|^2}{G_2 |M'^{0\nu}_{2,\nu}|^2}$$

($|M'^{0\nu}_{1,\nu}|^2 / |M'^{0\nu}_{2,\nu}|^2 > |M'^{0\nu}_{1,N}|^2 / |M'^{0\nu}_{2,N}|^2$ (from Table 1) used.)

Using $G_{1,2}$, and QRPA $M'^{0\nu}_{i,\nu}$, $M'^{0\nu}_{i,N}$, $i = 1, 2$, from Table 1 ("CD-Bonn, large, g_A=1.25 (1.0)") in arXiv:1103.2434, we get the positivity conditions for the 3 ratios of pairs of $T^{0\nu}_{1/2}$:

$$0.15 \leq \frac{T^{0\nu}_{1/2}(^{100}Mo)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.18\ (0.17)\,,$$

$$0.17 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.22\ (0.23)\,,$$

$$1.14\ (1.16) \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{100}Mo)} \leq 1.24\ (1.30)\,.$$

Similar results with Argonne, large, g_A=1.25(1.0) NMEs:

$$0.15 \leq \frac{T^{0\nu}_{1/2}(^{100}Mo)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.18\,,$$
$$0.18 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.24~(0.25)\,,$$
$$1.22 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{100}Mo)} \leq 1.36~(1.42)\,.$$

The physical solutions possible only for remarkably narrow intervals of T_2/T_1. If any of the ratios is shown to lie outside the relevant intervals, the case - excluded.

Conditions for only one mechanism being active:

$$|\eta_R|^2 = 0\ :\ \ |M'^{0\nu}_{1,\nu}|^2\, T_1\, G_1 = |M'^{0\nu}_{2,\nu}|^2\, T_2\, G_2\,,$$
$$|\eta_\nu|^2 = 0\ :\ \ |M'^{0\nu}_{1,N}|^2\, T_1\, G_1 = |M'^{0\nu}_{2,N}|^2\, T_2\, G_2\,.$$

Comments.

• The feature discussed above - common to all cases of two "non-interfering" mechanisms considered.

• The indicated specific half-life intervals for the various isotopes, are stable with respect to the change of the NMEs.

• Assuming two "non-interfering" mechnaisms are operative in $(\beta\beta)_{0\nu}-$decay, say light LH and heavy RH Majorana ν exchanges, from the measured half-lives of two nuclei (A_1, Z_1) and (A_2, Z_2), given the corresponding NMEs, one can derive the values of the two relevant LNV constants, $|\eta_\nu|^2$ and $|\eta_R|^2$. Using these as input one can predict the half-life of any third nucleus (A_3, Z_3). If the predicted half-life does not correspond to the measured one, the given pair of mechanisms will be ruled out.

• The intervals of T_2/T_1 depend on the type of the two "non-interfering" mechanisms. However, the differences in the cases of the $(\beta\beta)_{0\nu}$-decays of ^{76}Ge, ^{82}Se, ^{100}Mo and ^{130}Te, triggered by the exchange of heavy Majorana neutrinos coupled to (V+A) currents and i) light Majorana neutrino exchange, or ii) the gluino exchange mechanism, or iii) the squark-neutrino exchange mechanism, are extremely small and cannot be used to distinguish experimentally between the indicated three pairs of $(\beta\beta)_{0\nu}$-decay mechanisms.

For each mechanism κ discussed, the NMEs for the nuclei considered differ relatively little:

$|M'_{\kappa i} - M'_{\kappa j}| << M'_{\kappa i}, M'_{\kappa j}$, typically

$\frac{|M'_{\kappa i} - M'_{\kappa j}|}{0.5(M'_{\kappa i} + M'_{\kappa j})} \sim 0.1$, $i \neq j = {}^{76}Ge, {}^{82}Se, {}^{100}Mo, {}^{130}Te$.

- **One of the consequences - if it will be possible to rule out one pair of these mechanisma as the cause of $(\beta\beta)_{0\nu}$-decay, most likely one will be able to rule out all three of them.**

• **The constraints under discussion will not be valid, in general, if the $(\beta\beta)_{0\nu}$-decay is triggered by two "interfering" mechanisms with a non-negligible (destructive) interference term, or by more than two mechanisms none of which plays a subdominat role in $(\beta\beta)_{0\nu}$-decay.**

The degeneracy between the intervals of allowed values of T_2/T_1 (determined by the positivity conditions) corresponding to different pairs of "non-interfering" mechanisms can be lifted by using in the analysis isotopes with largely different NMEs, e.g., ^{136}Xe, ^{48}Ca, ^{96}Zr, and any of ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te.

A. Meroni, S.T.P. and F. Šimkovic, arXiv:1212.1331.

Constraints from ^3H β-decay data.

Important in the cases of light ν exchange + "nonstandard" mechanisms.

Moscow, Mainz: $m(\bar{\nu}_e) < 2.3$ eV; $|\eta_\nu|^2 \times 10^{10} < 0.21\,.$

KATRIN: $m(\bar{\nu}_e) < 0.2$ eV; $|\eta_\nu|^2 \times 10^{10} < 1.6 \times 10^{-3}\,.$

Theoretical Model Predictions

T' model of lepton flavour: U_{TBM} , $\delta \cong 3\pi/2$ or $\pi/2$.(The pre

I. Girardi, A. Meroni, STP, M. Spinrath, arXiv:1312.1966

- Light neutrino masses: type I seesaw mechanism.

- ν_j - Majorana particles.

- Diagonalisation of M_ν: $U_{\text{TBM}}\Phi$, $\Phi = \text{diag}(1, 1, 1(i))$

- U_{TBM} "corrected" by

$$U^{\dagger}_{\text{lep}} Q = R_{12}(\theta^{\ell}_{12})\, R_{23}(\theta^{\ell}_{23}) Q\,, \quad Q = \text{diag}(1, e^{i\phi}, 1)$$

T' model of lepton flavour: U_{TBM}, $\delta \cong 3\pi/2$ or $\pi/2$.

• T': double covering of A_4 (tetrahedral symmetry group).

• T': $\mathbf{1}$, $1'$, $1''$; $\mathbf{2}$, $2'$, $2''$; $\mathbf{3}$.

• T' model: $\psi_{eL}(x)$,$\psi_{\mu L}(x)$,$\psi_{\tau L}(x)$ - triplet of T';
$e_R(x)$,$\mu_R(x)$ - a doublet, $\tau_R(x)$ - a singlet, of T';
$\nu_{eR}(x)$,$\nu_{\mu R}(x)$,$\nu_{\tau R}(x)$ - a triplet of T';
the Higgs doublets $H_u(x)$, $H_d(x)$ - singlets of T'.

• The discrete symmetries of the model are $T' \times H_{\text{CP}} \times Z_8 \times Z_4^2 \times Z_3^2 \times Z_2$, the Z_n factors being the shaping symmetries of the superpotential required to forbid unwanted operators.

Predictions of the T' Model

- $m_{1,2,3}$ determined by 2 real parameters + Φ^2:

$$\text{NO spectrum A}: \quad (m_1, m_2, m_3) = (4.43, 9.75, 48.73) \cdot 10^{-3}$$

$$\text{NO spectrum B}: \quad (m_1, m_2, m_3) = (5.87, 10.48, 48.88) \cdot 10^{-3}$$

$$\text{IO spectrum}: \quad (m_1, m_2, m_3) = (51.53, 52.26, 17.34) \cdot 10^{-3}$$

$$\text{NO A}: \quad \sum_{j=1}^{3} m_j = 6.29 \times 10^{-2}\ \text{eV}\,,$$

$$\text{NO B}: \quad \sum_{j=1}^{3} m_j = 6.52 \times 10^{-2}\ \text{eV}\,,$$

$$\text{IO}: \quad \sum_{j=1}^{3} m_j = 12.11 \times 10^{-2}\ \text{eV}\,,$$

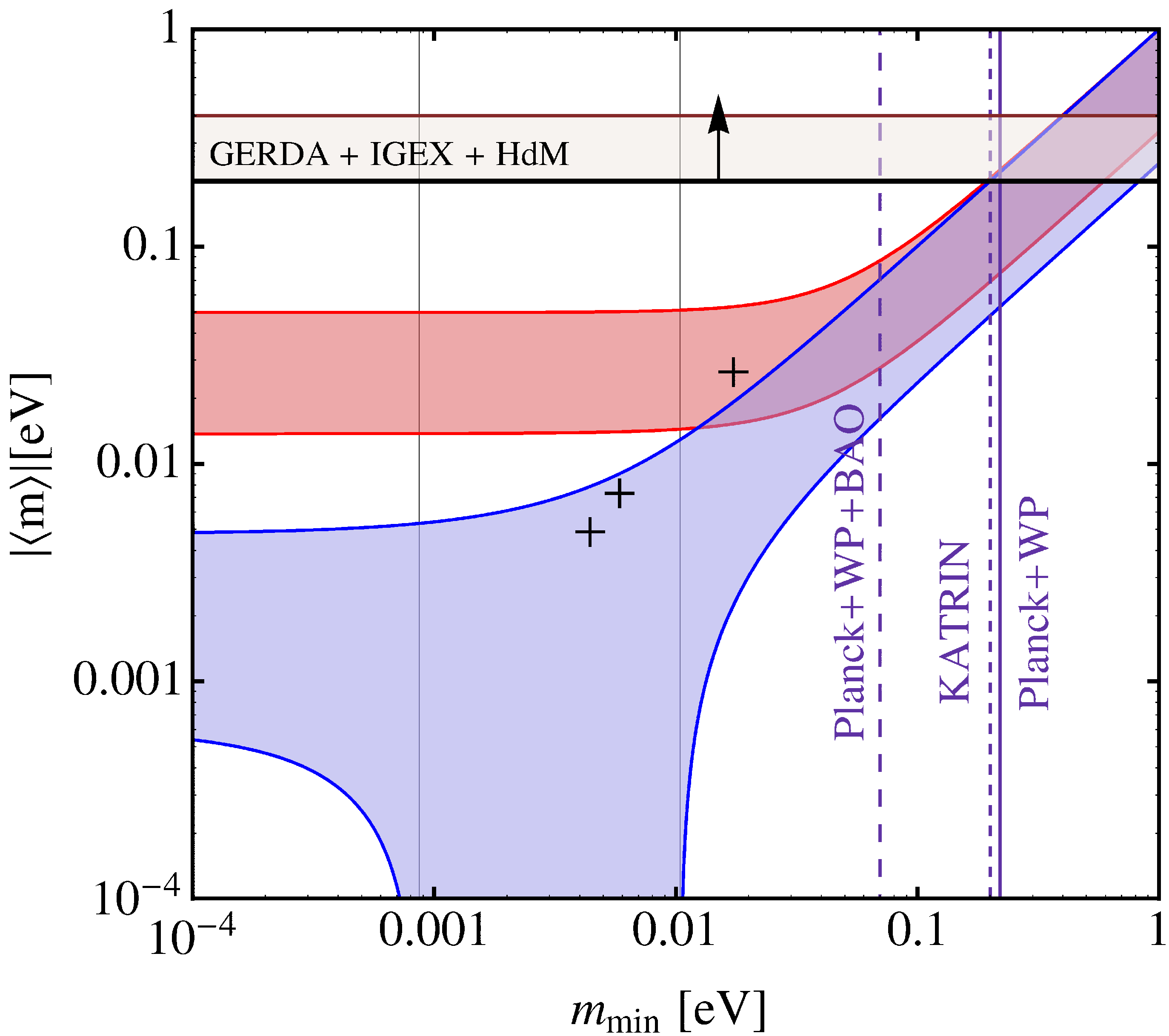
• $\theta_{12}, \theta_{23}, \theta_{13}, \delta, \alpha_{21}, \alpha_{31}$ determined by 3 real parameters.

Given the values of $\theta_{12}, \theta_{23}, \theta_{13}$, $\delta, \alpha_{21}, \alpha_{31}$ are predicted:

$\delta \cong 3\pi/2$ (266°) (or $\pi/2$ (94°));

NO A: $\alpha_{21} \cong +47.0^\circ$ (or -47.0°) $(+2\pi)$,

$\alpha_{31} \cong -23.8^\circ$ (or $+23.8^\circ$) $(+2\pi)$.



1
0.1
0.01
0.001
10^{-4}
$|\langle m \rangle|$[eV]
10^{-4}
0.001
0.01
0.1
1
$m_{\rm min}$ [eV]
GERDA + IGEX + HdM
Planck+WP+BAO
KATRIN
Planck+WP

Conclusions

Determining the nature - Dirac or Majorana, of massive neutrinos is of fundamental importance for understanding the origin of neutrino masses.

The $(\beta\beta)_{0\nu}$-decay experiments:

– **Are testing the status of L conservation, can establish the Majorana nature of ν_j;**

– **Can provide unique information on the ν mass spectrum;**

– **Can provide unique information on the absolute scale of ν masses;**

– **Can provide information on the Majorana CPV phases;**

– **Provide crtitical tests of neutrino-related BSM theoretical ideas.**
$T^{0\nu}_{1/2} = 10^{25}$ **yr probes** $|<m>| \sim 0.1$ **eV;**
$T^{0\nu}_{1/2} = 10^{25}$ **yr probes** $\Lambda_{LNV} \sim 1$ **TeV.**

– **Synergy with searches of BSM physics at LHC.**