Neutrino Masses, Mixing and Leptonic CP Violation: Current Status and Future Prospects

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There have been remarkable discoveries in neutrino physics in the last ~ 16 years.

Compellings Evidence for $\nu-$Oscillations

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

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

Dominant $\nu_\mu \longrightarrow \nu_\tau$ K2K, MINOS, T2K; CNGS (OPERA)

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

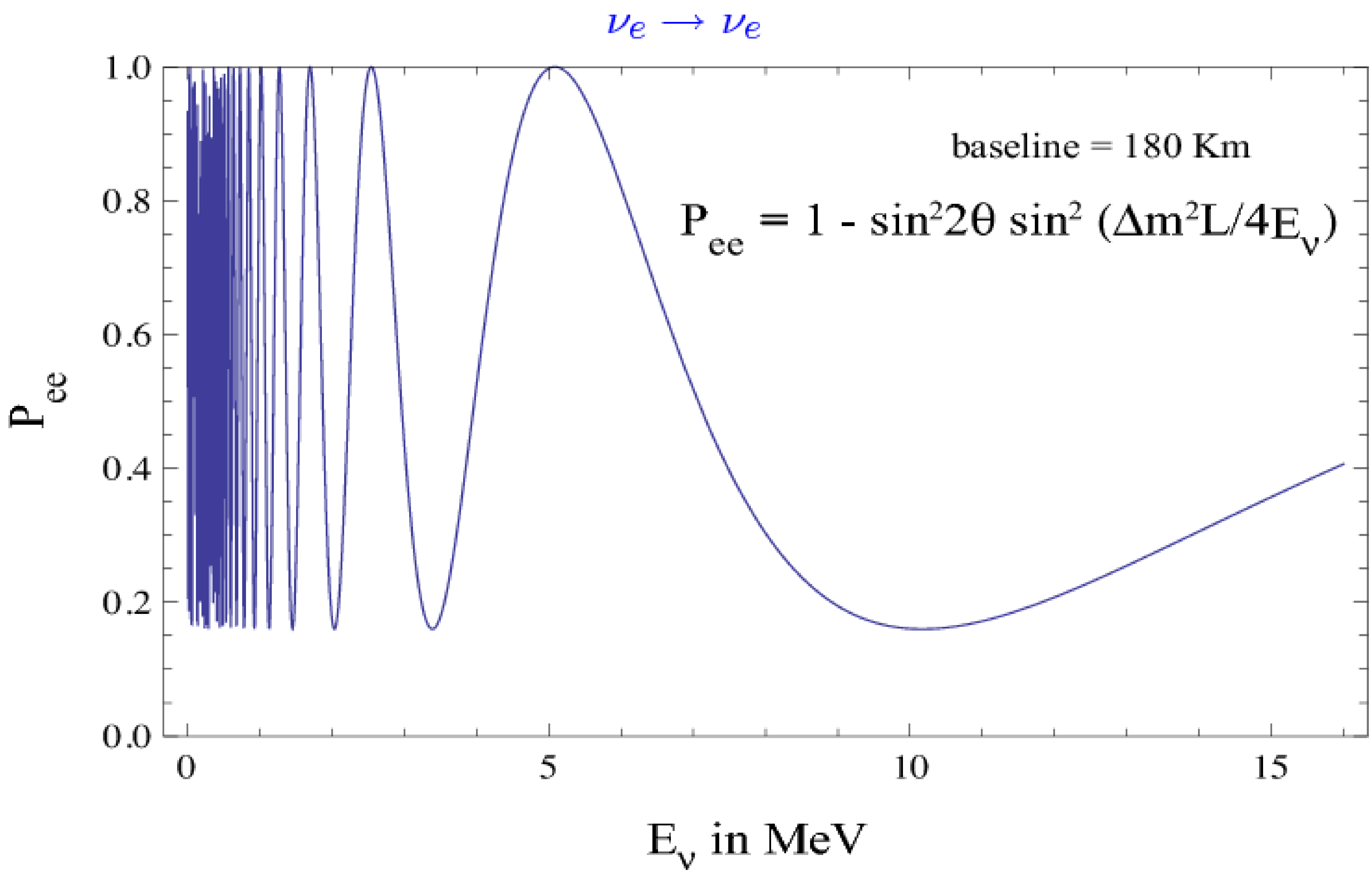
Super-Kamiokande, SNO, BOREXINO; KamLAND

Dominant $\nu_e \longrightarrow \nu_{\mu,\tau}$ **BOREXINO**

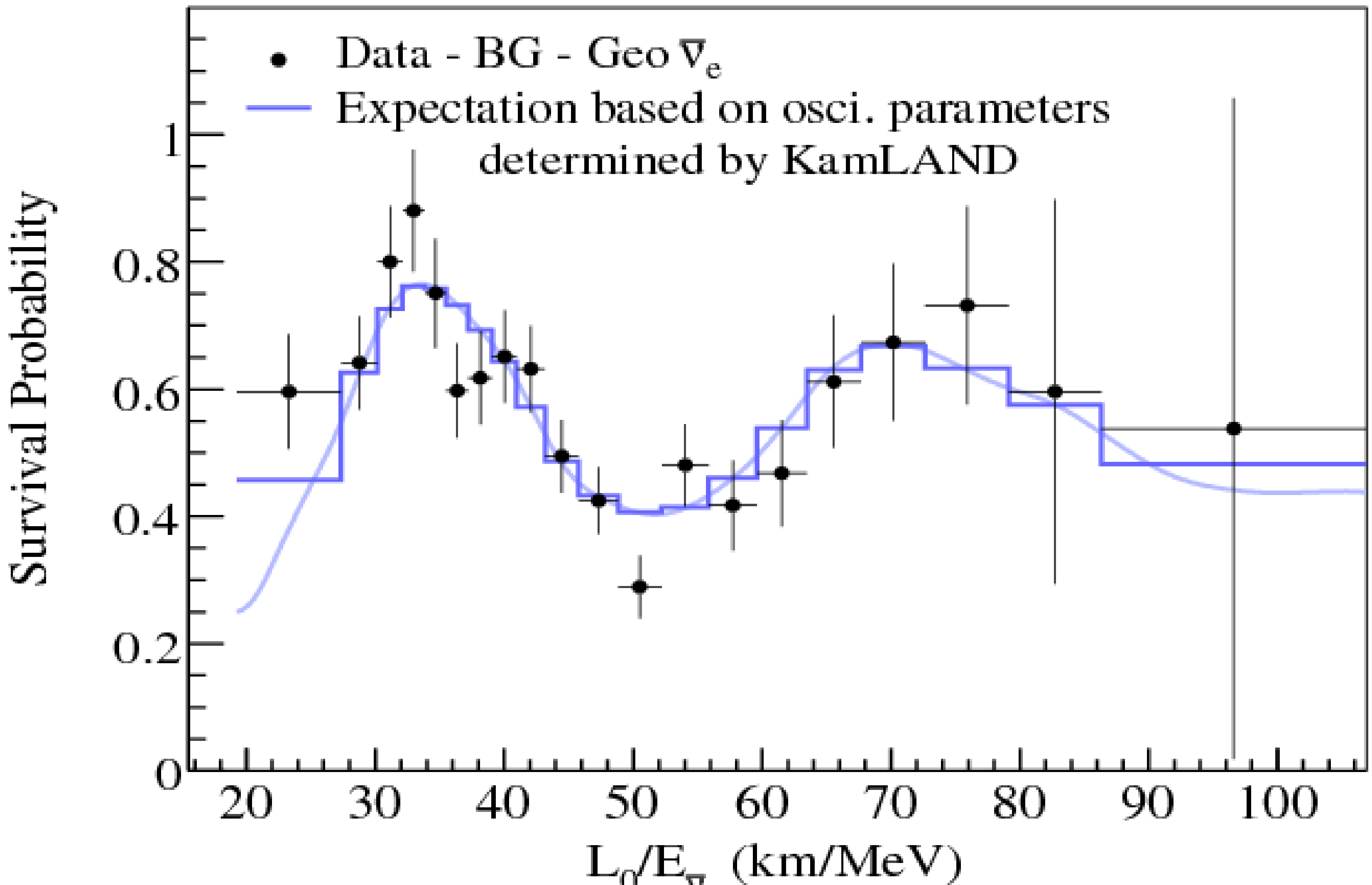
$-\bar{\nu}_e$ (from reactors): **Daya Bay, RENO, Double Chooz**

Dominant $\bar{\nu}_e \longrightarrow \bar{\nu}_{\mu,\tau}$

T2K, MINOS (ν_μ from accelerators): $\nu_\mu \longrightarrow \nu_e$



$\nu_e \longrightarrow \nu_e$
baseline = 180 Km
$P_{ee} = 1 - \sin^2 2\theta \sin^2 (\Delta m^2 L/4E_\nu)$
P_{ee}
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
E_ν in MeV



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

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.

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 $\nu_{e(\mu)} \to \nu_S$ 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"));

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.

We can also have, in principle:

$m_4 \sim 1$ eV ($\nu_{e(\mu)} \to \nu_S$), $m_5 \sim 5$ keV (DM), $M_6 \sim (10 - 10^3)$ GeV (seesaw).

- Data (relativistic ν's): ν_l ($\tilde{\nu}_l$) - predominantly LH (RH).

Standard Theory: ν_l, $\tilde{\nu}_l$ - $\nu_{lL}(x)$;

$\nu_{lL}(x)$ form doublets with $l_L(x)$, $l = e\mu, \tau$:

$$\begin{pmatrix} \nu_{lL}(x) \\ l_L(x) \end{pmatrix} \quad l = e, \mu, \tau\,.$$

- No (compelling) evidence for existence of (relativistic) ν's ($\tilde{\nu}$'s) which are predominantly RH (LH): ν_R ($\tilde{\nu}_L$.)

If ν_R, $\tilde{\nu}_L$ exist, must have much weaker interaction than ν_l, $\tilde{\nu}_l$: ν_R, $\tilde{\nu}_L$ - "sterile", "inert".

B. Pontecorvo, 1967

In the formalism of the ST, ν_R and $\tilde{\nu}_L$ - RH ν fields $\nu_R(x)$; can be introduced in the ST as $SU(2)_L$ singlets.

No experimental indications exist at present whether the SM should be minimally extended to include $\nu_R(x)$, and if it should, how many $\nu_R(x)$ should be introduced.

$\nu_R(x)$ appear in many extensions of the ST, notably in $SO(10)$ GUT's.

The RH ν's can play crucial role
i) in the generation of $m(\nu) \neq 0$,
ii) in understanding why $m(\nu) \ll m_l, m_q$,
iii) in the generation of the observed matter-antimatter asymmetry of the Universe (via leptogenesis).

The simplest hypothesis is that to each $\nu_{lL}(x)$ there corresponds a $\nu_{lR}(x)$, $l = e, \mu, \tau$.

ST + $m(\nu) = 0$: $L_l = const.$, $l = e, \mu, \tau$;
$L \equiv L_e + L_\mu + L_\tau = const.$

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

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

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

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:				
• $\nu_j -$ 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

Majorana Neutrinos

Can be defined in QFT using fields or states.

Fields: $\chi_k(x)$ - 4 component (spin 1/2), complex, m_k

Majorana condition:

$$C\ (\bar{\chi}_k(x))^{\mathrm{T}} = \xi_k \chi_k(x), \quad |\xi_k|^2 = 1$$

– Invariant under proper Lorentz transformations.
– Reduces by 2 the number of components in $\chi_k(x)$.

Implications:

$$U(1): \ \chi_k(x) \rightarrow e^{i\alpha}\chi_k(x) - \ \text{impossible}$$

– $\chi_k(x)$ cannot absorb phases.
– $Q_{U(1)} = 0: \ Q_{\mathrm{el}} = 0, \ L_l = 0, \ L = 0, \ldots$
– $\chi_k(x)$: 2 spin states of a spin 1/2 absolutely neutral particle
– $\chi_k \equiv \bar{\chi}_k$

Propagators: $\Psi(x)$–Dirac, $\chi(x)$–Majorana

$$< 0|T(\Psi_\alpha(x)\bar{\Psi}_\beta(y))|0 >= S^F_{\alpha\beta}(x-y) \ ,$$

$$< 0|T(\Psi_\alpha(x)\Psi_\beta(y))|0 >= 0 \ , \quad < 0|T(\bar{\Psi}_\alpha(x)\bar{\Psi}_\beta(y))|0 >= 0 \ .$$

$$< 0|T(\chi_\alpha(x)\bar{\chi}_\beta(y))|0 >= S^F_{\alpha\beta}(x-y) \ ,$$

$$< 0|T(\chi_\alpha(x)\chi_\beta(y))|0 >= -\xi^* S^F_{\alpha\kappa}(x-y)C_{\kappa\beta} \ ,$$

$$< 0|T(\bar{\chi}_\alpha(x)\bar{\chi}_\beta(y))|0 >= \xi \ C^{-1}_{\alpha\kappa} S^F_{\kappa\beta}(x-y)$$

$$U_{CP} \ \chi(x) \ U^{-1}_{CP} = \eta_{CP} \ \gamma_0 \ \chi(x'), \quad \eta_{CP} = \pm i \ .$$

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

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.54 \times 10^{-5}$ 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), NO (IO).

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

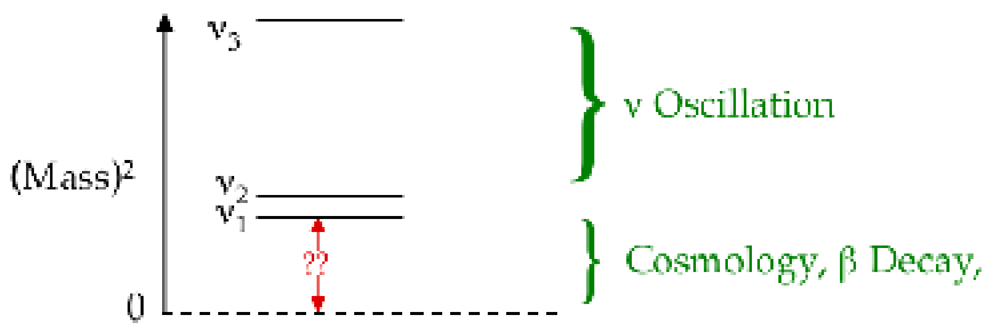
- Fogli et al., Phys. Rev. D86 (2012) 013012, global analysis, b.f.v.: $\sin^2\theta_{13} = 0.0241\ (0.0244)$, NO (IO).

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.54 \times 10^{-5}\ \text{eV}^2 > 0$, $\sin^2\theta_{12} \cong 0.308$, $\cos 2\theta_{12} \gtrsim 0.28\ (3\sigma)$,
- $|\Delta m^2_{31(32)}| \cong 2.47\ (2.42) \times 10^{-3}\ \text{eV}^2$, $\sin^2\theta_{23} \cong 0.437\ (0.455)$, NO (IO),
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0234\ (0.0240)$, NO (IO).
- $1\sigma(\Delta m^2_{21}) = 2.6\%$, $1\sigma(\sin^2\theta_{12}) = 5.4\%$;
- $1\sigma(|\Delta m^2_{31(23)}|) = 2.6\%$, $1\sigma(\sin^2\theta_{23}) = 9.6\%$;
- $1\sigma(\sin^2\theta_{13}) = 8.5\%$;
- $3\sigma(\Delta m^2_{21}):\ (6.99 - 8.18) \times 10^{-5}\ \text{eV}^2$; $3\sigma(\sin^2\theta_{12}):\ (0.259 - 0.359)$;
- $3\sigma(|\Delta m^2_{31(23)}|):\ 2.27(2.23) - 2.65(2.60) \times 10^{-3}\ \text{eV}^2$;
$3\sigma(\sin^2\theta_{23}):\ 0.374(0.380) - 0.628(0.641)$;
- $3\sigma(\sin^2\theta_{13}):\ 0.0176(0.0178) - 0.0295(0.0298)$.

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

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]

Due to B. Kayser

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

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

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

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

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

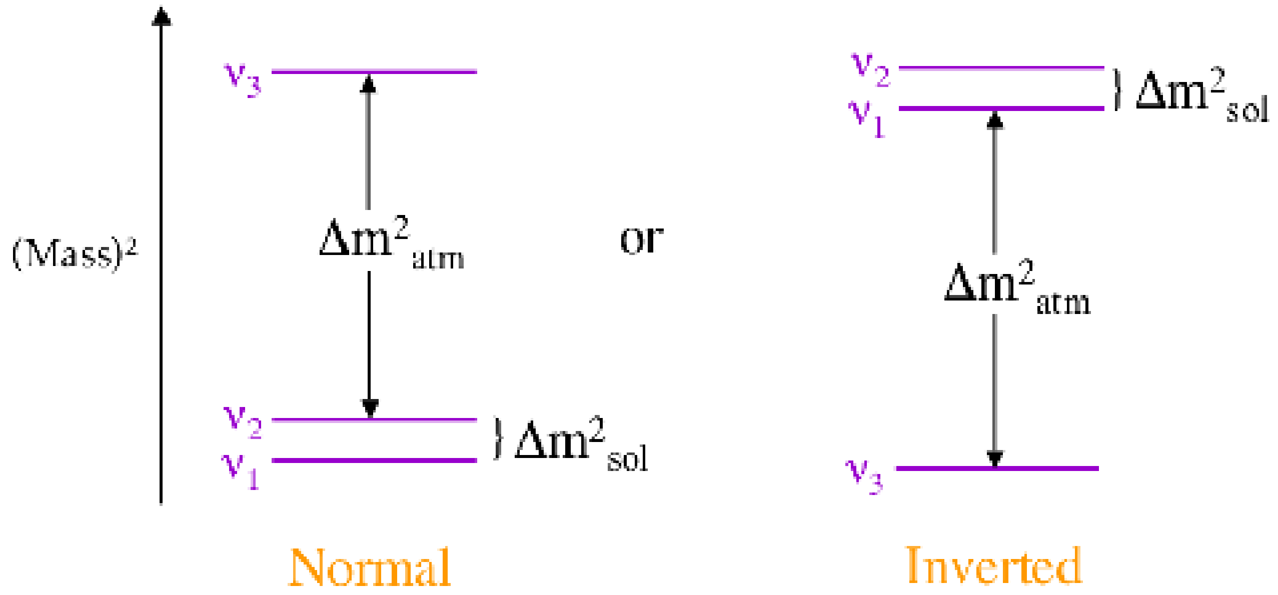
$$m_1 \ll m_2 < m_3, \qquad \text{NH},$$

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

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

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

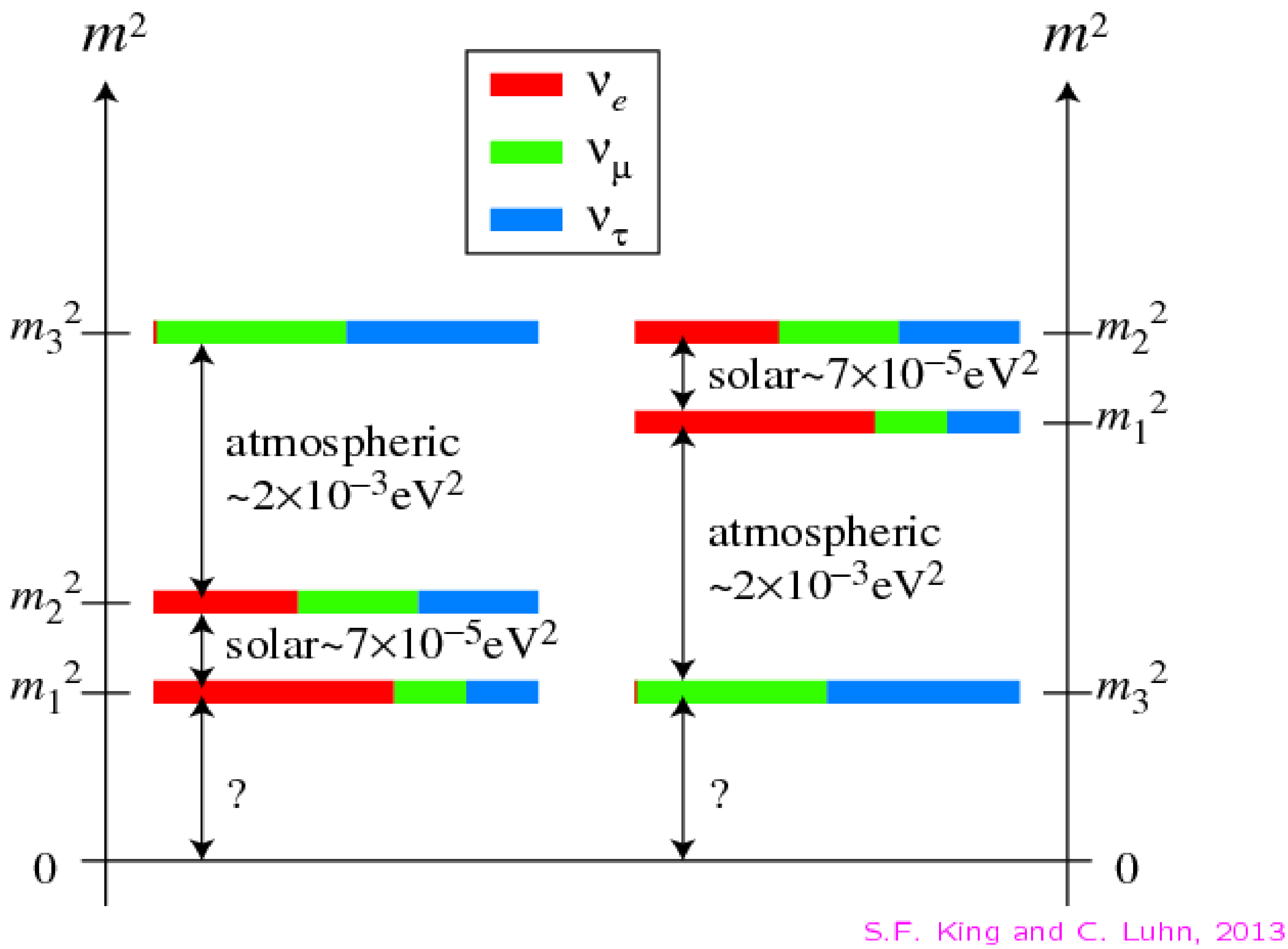
The (Mass)^2 Spectrum



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

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

Due to B. Kayser



m^2
ν_e
ν_μ
ν_τ
m_3^2
m_2^2
m_1^2
0
atmospheric
~2×10^{-3}eV^2
solar~7×10^{-5}eV^2
?
m^2
m_2^2
m_1^2
m_3^2
0
solar~7×10^{-5}eV^2
atmospheric
~2×10^{-3}eV^2
?
S.F. King and C. Luhn, 2013

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

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

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

Current data: $|J_{CP}| \lesssim 0.040$ (can be relatively large!); b.f.v. with $\delta = 3\pi/2$: $J_{CP} \cong -0.030$.

- **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};
  - $\Gamma(\mu \rightarrow e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\delta, \alpha_{21,31}$!

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_{PMNS} ;

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

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

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

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

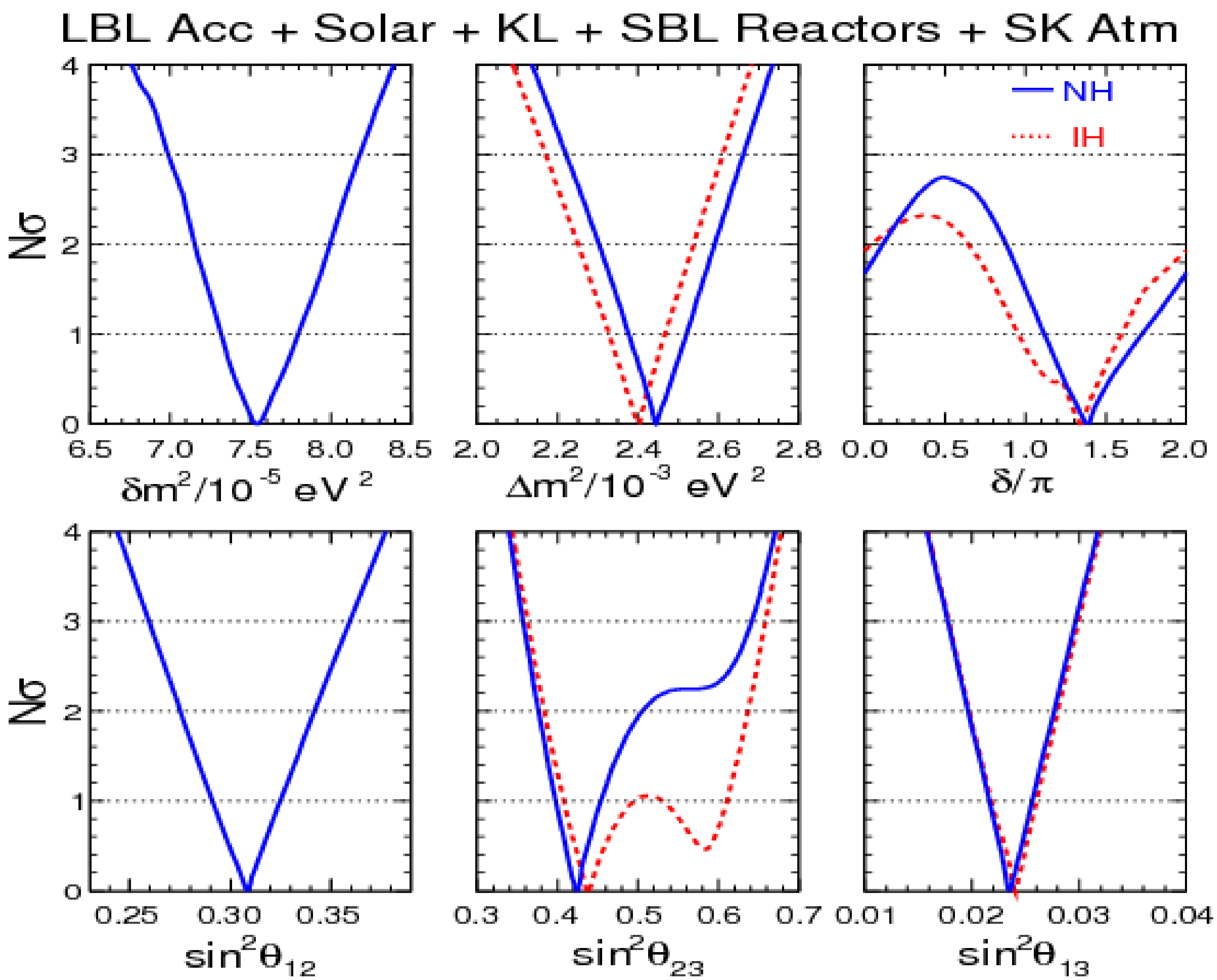
- Progress in the theory of ν-mixing might lead to a better understanding of the origin of the BAU.

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

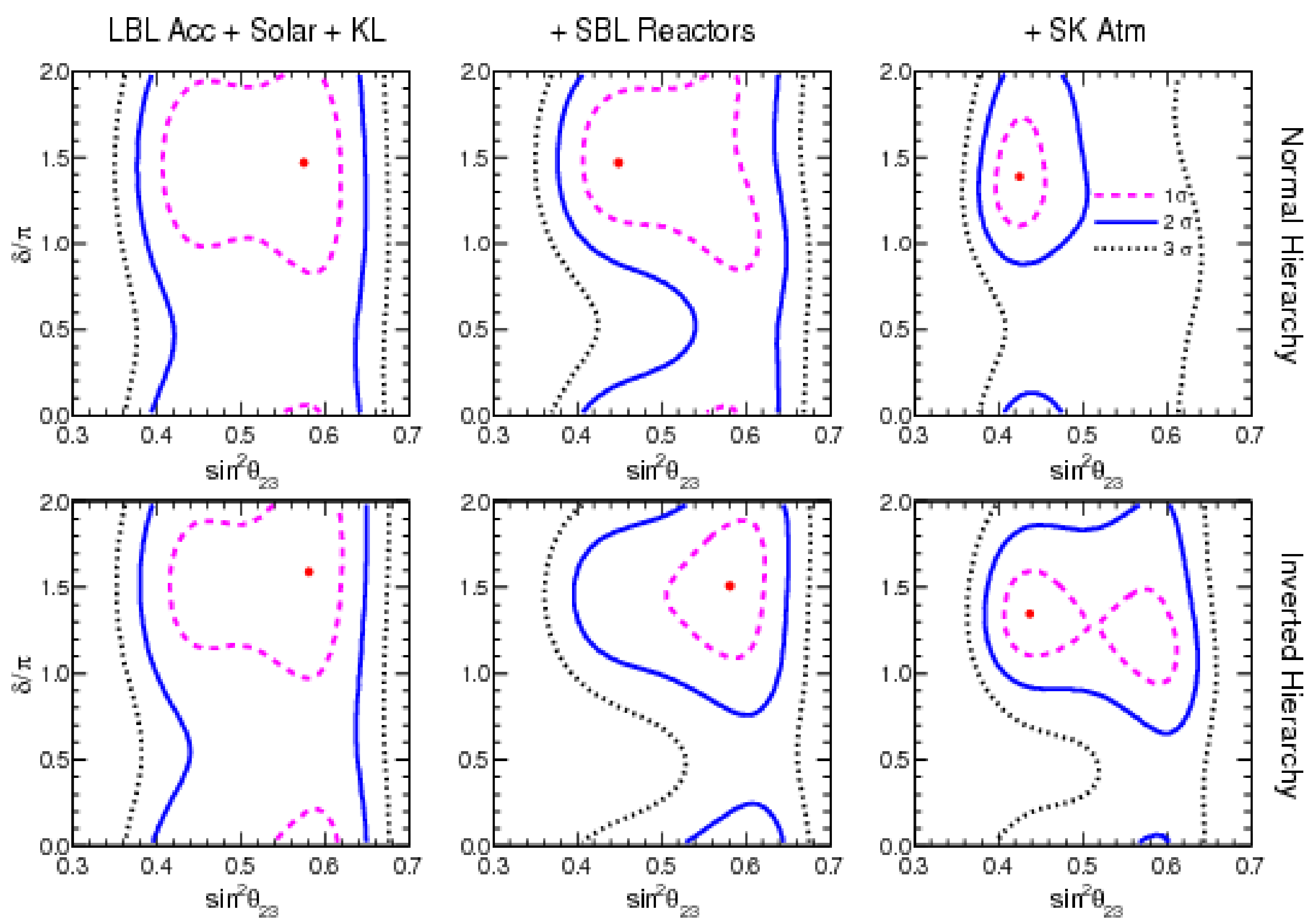
The next most important steps are:

- determination of the nature - Dirac or Majorana, of massive neutrinos.
- determination of the neutrino mass hierarchy;
- determination of the absolute neutrino mass scale (or min(m_j));
- determination of the status of the CP symmetry in the lepton sector.

Hints for Dirac CP Violation: $\delta \cong 3\pi/2$



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



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

Large $\sin\theta_{13} \cong 0.15$ (Daya Bay, RENO) $+\ \delta = 3\pi/2$ - far-reaching implications:

- For the searches for CP violation in ν-oscillations; for the b.f.v. one has $J_{CP} \cong -0.030$;

- 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.

Dirac CP-Nonconservation: δ in U_{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 $\alpha_{21},\ \alpha_{31}$

CP-invariance:

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

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

CPT-invariance:

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

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

T-invariance:

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

3ν—mixing:

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

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

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

P.I. Krastev, S.T.P., 1988; V. Barger, S. Pakvasa *et al.*, 1980

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

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

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

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

In matter: Matter effects violate

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

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

P. Langacker et al., 1987

Can conserve the T-invariance **(Earth)**

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

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

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

R_{CP} does not depend on θ_{23} and δ; $|R_{CP}| \lesssim 2.5$

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

Rephasing Invariants Associated with CPVP

Dirac phase δ:

$$J_{CP} = \text{Im}\left\{U_{e1}\, U_{\mu 2}\, U^*_{e2}\, U^*_{\mu 1}\right\} \ .$$

C. Jarlskog, 1985 (for quarks)

CP-, T- violation effects in neutrino oscillations

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

Majorana phases α_{21}, α_{31}:

$$S_1 = \text{Im}\{U_{e1}U^*_{e3}\}\,, \quad S_2 = \text{Im}\{U_{e2}U^*_{e3}\} \quad \text{(not unique);} \quad \text{or}$$
$$S'_1 = \text{Im}\{U_{\tau 1}U^*_{\tau 2}\}\,, \quad S'_2 = \text{Im}\{U_{\tau 2}U^*_{\tau 3}\}$$

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

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

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

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

- March 8, 2012, Daya Bay: 5.2σ evidence for $\theta_{13} \neq 0$, $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$.

- April 4, 2012, RENO: 4.9σ evidence for $\theta_{13} \neq 0$, $\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$.

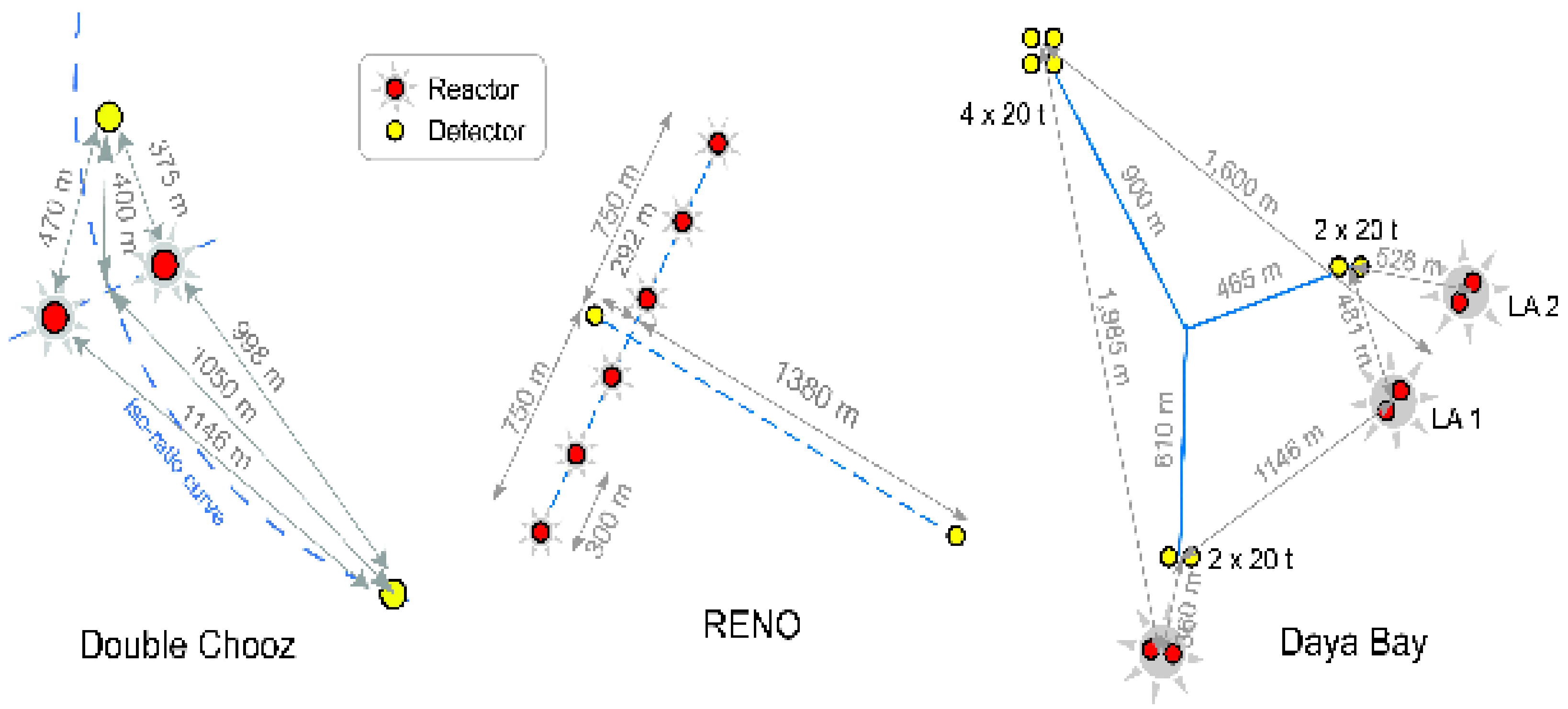
- Nu'2012 (June 4-9, 2012), T2K, Double Chooz: 3.2σ and 2.9σ evidence for $\theta_{13} \neq 0$.

- Daya Bay, 23/08/2013: $\sin^2 2\theta_{13} = 0.090 \pm 0.009$.

- RENO, 12/09/2013 (TAUP 2013): $\sin^2 2\theta_{13} = 0.100 \pm 0.010\ (stat.) \pm 0.012$.

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

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



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


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

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.

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

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

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

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

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

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

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

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

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

Predictions for the CPV Phase δ

Neutrino Mixing: New Symmetry?

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

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

Very different from the CKM-matrix!

- $\theta_{12} \cong \pi/4 - 0.20, \quad \theta_{13} \cong 0 + \pi/20, \quad \theta_{23} \cong \pi/4 - 0.10.$
- U_{PMNS} due to new approximate symmetry?

A Natural Possibility (vast literature):

$$U = U^{\dagger}_{\text{lep}}(\theta^{\ell}_{ij}, \psi)\; Q(\phi, \varphi) U_{\text{TBM,BM,LC}}\; P(\alpha_{21}, \alpha_{31}),$$

with

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

- $U^{\dagger}_{\text{lep}}(\theta^{\ell}_{ij}, \psi)$ - from diagonalization of the l^- mass matrix;
- $U_{\text{TBM,BM,LC}}\; P(\alpha_{21}, \alpha_{31})$ - from diagonalization of the ν mass matrix;
- $Q(\phi, \varphi)$, - from diagonalization of both the l^- and ν mass matrices.

P. Frampton, STP, W. Rodejohann, 2003

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

- $U_{\text{LC(BM)}}$: alternatively $U(1)$, $L' = L_e - L_\mu - L_\tau$

S.T.P., 1982

- U_{TBM}: $s^2_{12} = 1/3$, $s^2_{23} = 1/2$, $s^2_{13} = 0$; $s^2_{13} = 0$ must be corrected; if $\theta_{23} \neq \pi/4$, $s^2_{23} = 0.5$ must be corrected

- U_{BM}: $s^2_{12} = 1/2$, $s^2_{23} = 1/2$, $s^2_{13} = 0$; $s^2_{13} = 0$, $s^2_{12} = 1/2$ and possibly $s^2_{23} = 1/2$ must be corrected.

- U_{LC}: $s^2_{12} = 1/2$, $s^2_{13} = 0$, s^{ν}_{23} - free parameter; $s^2_{13} = 0$ and $s^2_{12} = 1/2$ must be corrected.

None of the symmetries leading to U_{TBM}, U_{BM} or other approximate forms of U_{PMNS} can be exact.

Which is the correct approximate symmetry, i.e., approximate form of U_{PMNS} (if any)?

In the two cases of U_ν given by U_{TBM}, or U_{BM}, the requisite corrections of some of the mixing angles are small and can be considered as perturbations to the corresponding symmetry values.

Depending on the symmetry leading to $U_{\text{TBM,BM}}$ and on the form of U_{lep}, one obtaines diifferent experimentally testable predictions for the sum of the neutrino masses, the neutrino mass spectrum, the nature (Dirac or Majorana) of ν_j and the CP violating phases in the neutrino mixing matrix. Future data will help us understand whether there is some new fundamental symmetry behind the observed patterns of neutrino mixing and Δm^2_{ij}.

Predictions for δ

Assume:

- $U_{PMNS} = U^{\dagger}_{\text{lep}}(\theta^{\ell}_{ij}, \psi)\ Q(\phi, \varphi) U_{\text{TBM,BM}}\ P(\alpha_{21}, \alpha_{31})$,
- $U^{\dagger}_{\text{lep}}$ - minimal, such that

i) $\sin\theta_{13} \cong 0.16$; BM: $\sin^2\theta_{12} \cong 0.31$;
ii) $\sin^2\theta_{23}$ can deviate significantly (by more than $\sin^2\theta_{13}$) from 0.5 (b.f.v. = 0.42-0.43) .

From i), ii) + $m_e << m_\mu << m_\tau$:

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

Leads to $\delta = \delta(\theta_{12}, \theta_{23}, \theta_{13})$ - new sum rules for δ!

D. Marzocca, S.T.P., A. Romanino, M.C. Sevillia, arXiv:1302.

For U_{TBM}:

$$\cos\delta = \frac{\tan\theta_{23}}{3\sin 2\theta_{12}\sin\theta_{13}}\left[1 + \left(3\sin^2\theta_{12} - 2\right)\left(1 - \cot^2\theta_{23}\,\sin^2\theta_{13}\right)\right]$$

For U_{TBM} + b.f.v. of $\theta_{12}, \theta_{23}, \theta_{13}$:

$$\delta \cong 3\pi/2 \text{ or } \pi/2 \qquad (\delta = 266^\circ \text{ or } \delta = 94^\circ)$$

D. Marzocca, S.T.P., A. Romanino, M.C. Sevillia, arXiv:1302.

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

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

For $U_{\rm BM}$:

$$\cos\delta = -\frac{1}{2\sin\theta_{13}}\cot 2\theta_{12}\tan\theta_{23}\left(1-\cot^2\theta_{23}\sin^2\theta_{13}\right).$$

For $U_{\rm BM}$ + b.f.v. of $\theta_{12},\theta_{23},\theta_{13}$:

$$\delta \cong \pi$$

D. Marzocca, S.T.P., A. Romanino, M.C. Sevillia, arXiv:1302.

Determining the $\nu-$Mass Hierarchy (sgn($\Delta m^2_{\rm atm}$))

- **Reactor $\bar{\nu}_e$ Oscillations in vacuum (JUNO, RENO50).**
- **Atmospheric ν experiments: subdominant $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$ and $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ oscillations (matter effects) (HK, ORCA, PINGU (IceCube), INO).**
- **LBL $\nu-$oscillation experiments (T2K, NOνA; LBNO, LBNE, $\nu-$factory); designed to search also for CP violation.**
- ^{3}H **β-decay Experiments (sensitivity to 5×10^{-2} eV) (NH vs IH).**
- $(\beta\beta)_{0\nu}-$**Decay Experiments; ν_j- Majorana particles (NH vs IH).**
- **Cosmology: $\sum_j m_j$ (NH vs IH).**
- **Atomic Physics Experiments: RENP.**

Reactor $\bar{\nu}_e$ Oscillations in vacuum

$$P_{\rm NO}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \cos\frac{\Delta m^2_{\rm A} L}{2E_\nu}\right) - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_\odot\left(1 - \cos\frac{\Delta m^2_\odot L}{2E_\nu}\right)$$
$$+ \sin^2 2\theta_{13}\sin^2\theta_\odot \sin\frac{\Delta m^2_\odot L}{4E_\nu}\sin\left(\frac{\Delta m^2_{\rm A} L}{2E_\nu} - \frac{\Delta m^2_\odot L}{4E_\nu}\right),$$

$$P_{\rm IO}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \cos\frac{\Delta m^2_{\rm A} L}{2E_\nu}\right) - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_\odot\left(1 - \cos\frac{\Delta m^2_\odot L}{2E_\nu}\right)$$
$$+ \sin^2 2\theta_{13}\cos^2\theta_\odot \sin\frac{\Delta m^2_\odot L}{4E_\nu}\sin\left(\frac{\Delta m^2_{\rm A} L}{2E_\nu} - \frac{\Delta m^2_\odot L}{4E_\nu}\right),$$

$\theta_\odot = \theta_{12}, \Delta m^2_\odot = \Delta m^2_{21} > 0$; $\sin^2\theta_{12} \leq 0.36$ at 3σ;

$\Delta m^2_{\rm A} = \Delta m^2_{31} > 0$, NO spectrum,

$\Delta m^2_{\rm A} = \Delta m^2_{23} > 0$, IO spectrum

M. Piai, S.T.P., hep-ph/0112074;

The reactor $\bar{\nu}_e$ detected via

$$\bar{\nu}_e + p \rightarrow e^+ + n\,.$$

The visible energy of the detected e^+:

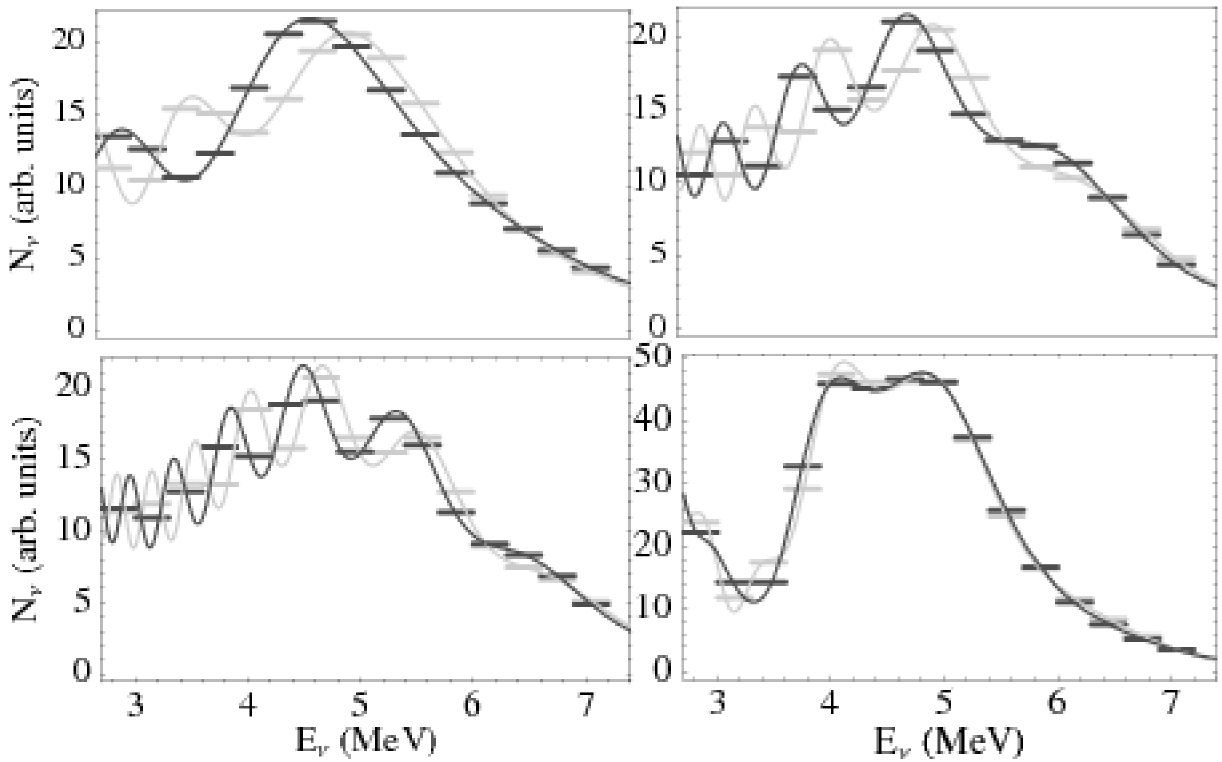
$$E_{vis} = E + m_e - (m_n - m_p) \simeq E - 0.8\ \text{MeV}\,.$$

The measured event rate spectrum vs. L/E_m:

$$N(L/E_m) = \int R(E, E_m)\Phi(E)\sigma(\bar{\nu}_e p \rightarrow e^+ n; E) P_{\bar{e}\bar{e}}^{NO(IO)} dE\,.$$

$$|P_{\text{NO}}(\bar{\nu}_e \rightarrow \bar{\nu}_e) - P_{\text{IO}}(\bar{\nu}_e \rightarrow \bar{\nu}_e)| \propto \sin^2 2\theta_{13} \cos 2\theta_{12}$$

$\cos 2\theta_{12} \cong 0.38$; 3σ: $\cos 2\theta_{12} \geq 0.28$; $\sin^2 2\theta_{13} \cong 0.09$.



M. Piai, S.T.P., 2001

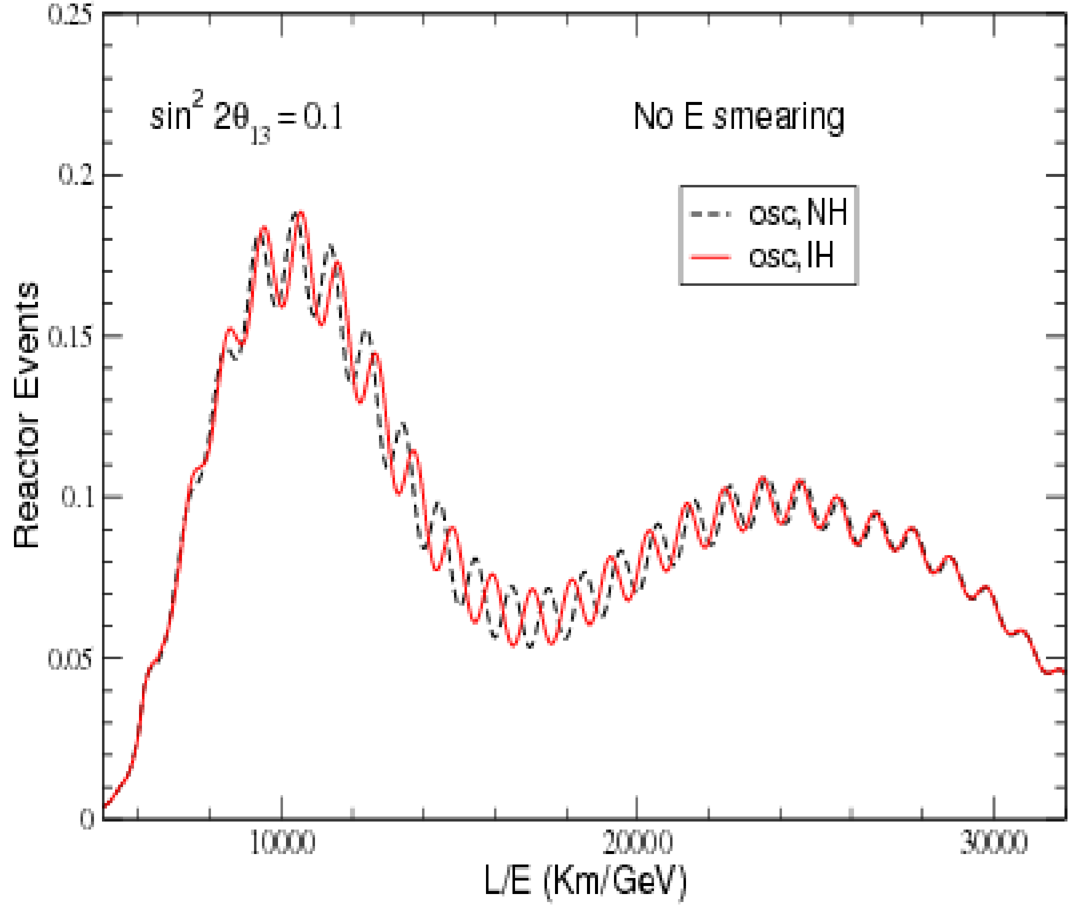
$\sin^2\theta_{13} = 0.05$, $\Delta m^2_{21} = 2 \times 10^{-4}$ eV^2; $\Delta m^2_{A} = 1.3;\ 2.5;\ 3.5 \times 10^{-3}$ eV^2

$L = 20$ km, $\Delta E_\nu = 0.3$ MeV.

$\Delta m^2_{21} = 2 \times 10^{-4}$ eV^2: $L = 20$ km;

$\Delta m^2_{21} = 7.6 \times 10^{-5}$ eV^2: $L \cong 53$ km.

NO – light grey; IO – dark grey



P. Ghoshal, S.T.P., arXiv:1011.1646

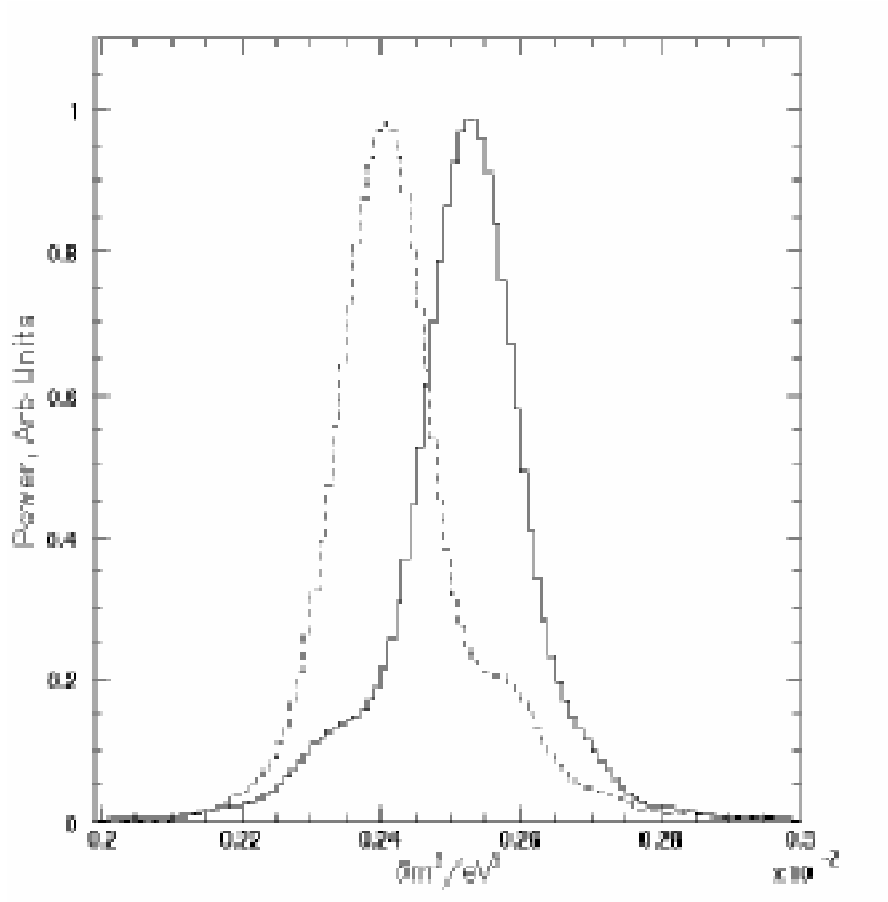
Fourier Analysis:

$$\text{NO}: \quad \cos^2\theta_{12}\,\sin^2\Delta + \sin^2\theta_{12}\,\sin^2(\Delta - \Delta_{21})\,,$$

$$\text{IO}: \quad \sin^2\theta_{12}\,\sin^2\Delta + \cos^2\theta_{12}\,\sin^2(\Delta - \Delta_{21})\,,$$

$$\Delta \equiv \Delta_{31}(NO) = |\Delta_{32}(IO)|\,;$$

$$\sin^2\theta_{12} \cong 0.31\,, \quad \cos^2\theta_{12} \cong 0.69\,.$$



J.Learned et al., 2007

Very challenging; requires:

- energy resolution $\sigma/E_{\text{vis}} \lesssim 3\%/\sqrt{E_{\text{vis}}}$;
- relatively small energy scale uncertainty;
- relatively large statistics ($\sim$ (300 – 1000) kT GW yr);
- relatively small systematic errors;
- subtle optimisations (distance, number of bins, effects of "interfering distant" reactors).

Two experiments planned with $L \cong 50$ km: Juno (20 kT, approved), RENO50 (18 kT). Can measure also $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{31}|$ with remarkably high precision. Can be used for detection of Geo, solar, SN neutrinos as well.

Atmospheric Neutrino Experiments on $\mathrm{sgn}(\Delta m^2_{31})$

Atmospheric ν experiments

Subdominant $\nu_{\mu(e)} \to \nu_{e(\mu)}$ and $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ oscillations in the Earth.

$$P_{3\nu}(\nu_e \to \nu_\mu) \cong P_{3\nu}(\nu_\mu \to \nu_e) \cong s^2_{23}\, P_{2\nu}\,, P_{3\nu}(\nu_e \to \nu_\tau) \cong c^2_{23}\, P_{2\nu}\,,$$

$$P_{3\nu}(\nu_\mu \to \nu_\mu) \cong 1 - s^4_{23}\ P_{2\nu} - 2c^2_{23}s^2_{23}\ \left[1 - Re\ (e^{-i\kappa} A_{2\nu}(\nu_\tau \to \nu_\tau))\right]\ ,$$

$P_{2\nu} \equiv P_{2\nu}(\Delta m^2_{31}, \theta_{13}; E, \theta_n; N_e)$: 2-$\nu$ $\nu_e \to \nu'_\tau$ oscillations in the Earth,
$\nu'_\tau = s_{23}\,\nu_\mu + c_{23}\,\nu_\tau$; $\Delta m^2_{21} \ll |\Delta m^2_{31(32)}|$, $E_\nu \gtrsim 2$ GeV;

κ and $A_{2\nu}(\nu_\tau \to \nu_\tau) \equiv A_{2\nu}$ are known phase and 2-ν amplitude.

NO: $\nu_{\mu(e)} \to \nu_{e(\mu)}$ matter enhanced, $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ - suppressed

IO: $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ matter enhanced, $\nu_{\mu(e)} \to \nu_{e(\mu)}$−suppressed

No charge identification (SK, HK, IceCube-PINGU, ANTARES-ORCA); event rate (DIS regime): $[2\sigma(\nu_l + N \to l^- + X) + \sigma(\bar{\nu}_l + N \to l^+ + X)]/3$

Neutrino Oscillations in Matter

When neutrinos propagate in matter, they interact with the backgrpound of electrons, protons and neutrnos, which generates an effective potential in the neutrino Hamiltonian: $H = H_{vac} + V_{eff}$.

This modifies the neutrino mixing since the eigenstates and the eigenvalues of H_{vac} and of $H = H_{vac} + V_{eff}$ are different, leading to a different oscillation probability w.r.t to that in vacuum.

Typically the matter background is not CP and CPT symmetric, e.g., the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations violate CP and CPT symmetries.

$$P_{3\nu}(\nu_\mu \to \nu_e) \cong \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta M_{31}^2 L}{4E}$$

$\sin^2 2\theta^m_{13}$, ΔM^2_{31} depend on the matter potential
$V_{eff} = \sqrt{2}\, G_F\, N_e$,

For antineutrinos V_{eff} has the opposite sign:
$V_{eff} = -\sqrt{2}\, G_F, N_e$.

$\Delta m^2_{31} > 0$ (NO): $\nu_{\mu(e)} \to \nu_{e(\mu)}$ matter enhanced,
$\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ - suppressed

$\Delta m^2_{31} < 0$ (IO): $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ matter enhanced,
$\nu_{\mu(e)} \to \nu_{e(\mu)}$ −suppressed

$$\sin^2 2\theta_{13}^m = \frac{\tan^2 2\theta_{13}}{(1-\frac{N_e}{N_e^{res}})^2+\tan^2 2\theta_{13}},$$

$$\cos 2\theta_{13}^m = \frac{1-N_e/N_e^{res}}{\sqrt{(1-\frac{N_e}{N_e^{res}})^2+\tan^2 2\theta_{13}}},$$

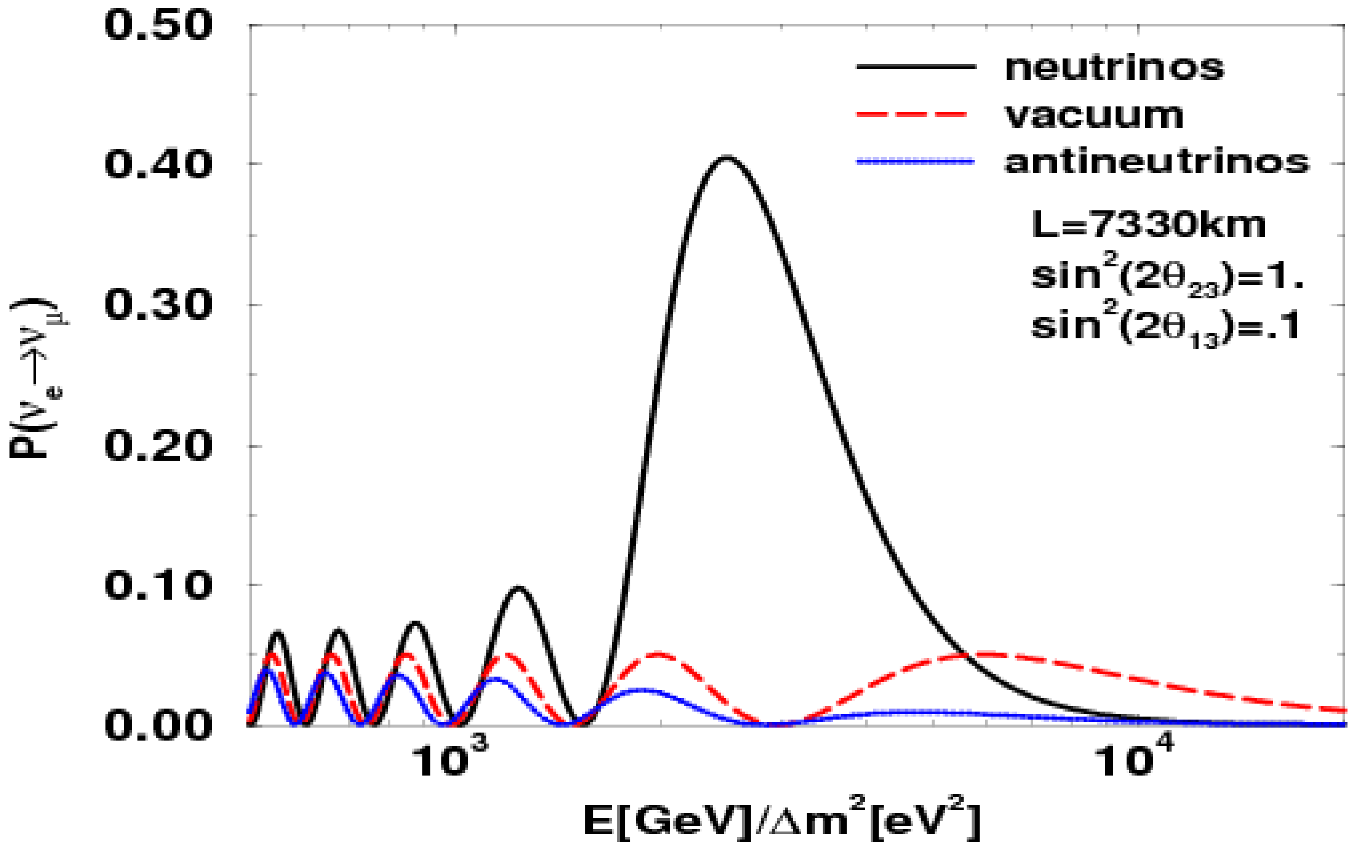
$$N_e^{res} = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2E\sqrt{2}G_F} \cong$$

$$6.56 \times 10^6 \, \frac{\Delta m^2[\mathrm{eV}^2]}{E[\mathrm{MeV}]} \cos 2\theta \, \mathrm{cm}^{-3} \ \mathrm{N_A}\,,$$

$$\frac{\Delta M_{31}^2}{2E} \equiv \frac{\Delta m_{31}^2}{2E} \left((1 - \frac{N_e}{N_e^{res}})^2 \cos^2 2\theta_{13} + \sin^2 2\theta_{13} \right)^{\frac{1}{2}}$$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: $N_e \rightarrow (-N_e)$.

Earth matter effect in $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ (MSW)



$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $E^{res} = 6.25$ GeV; $P^{3\nu} = \sin^2\theta_{23} P_m^{2\nu} = 0.5 P_m^{2\nu}$;
$N_e^{res} \cong 2.3$ cm^{-3} N$_A$; $L_m^{res} = L^v/\sin 2\theta_{13} \cong 6250/0.32$ km; $2\pi L/L_m \cong 0.75\pi (\neq \pi)$.

HyperKamiokande (10SK), IceCube-PINGU, ANTARES-ORCA;

Iron Magnetised detector: INO

INO: 50 or 100 kt (in India); ν_μ and $\bar{\nu}_\mu$ induced events detected (μ^+ and μ^-);
not designed to detect ν_e and $\bar{\nu}_e$ induced events.

IceCube at the South Pole: PINGU

PINGU: 50SK; ν_μ and $\bar{\nu}_\mu$ induced events detected (μ^+ and μ^-, no μ charge identification); Challenge: $E_\nu \gtrsim 2$ GeV (?)

ANTARES in Mediteranian sea: ORCA

Water-Cerenkov detector: Hyper Kamiokande (10SK)

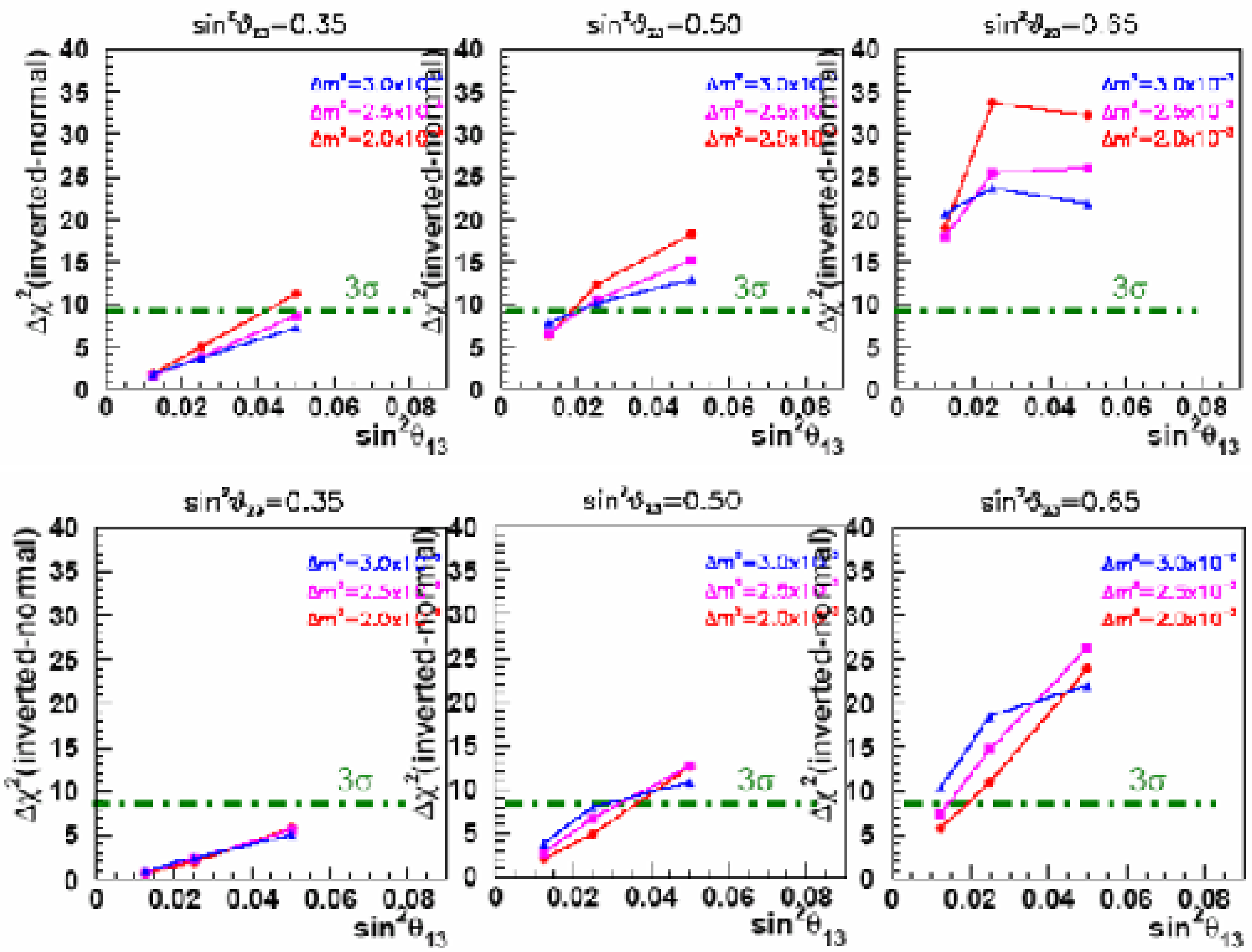
Sensitivity depends critically on θ_{23}, the "true" hierarchy.

J. Bernabeu, S. Palomares-Ruiz, S.T.P., 2003

$$P(\nu_\mu \to \nu_e) \cong \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta M_{31}^2 L}{4E}$$

No charge identification (SK, HK, PINGU, ORCA); event rate (DIS regime):

$$[2\sigma(\nu_l + N \to l^- + X) + \sigma(\bar{\nu}_l + N \to l^+ + X)]/3$$

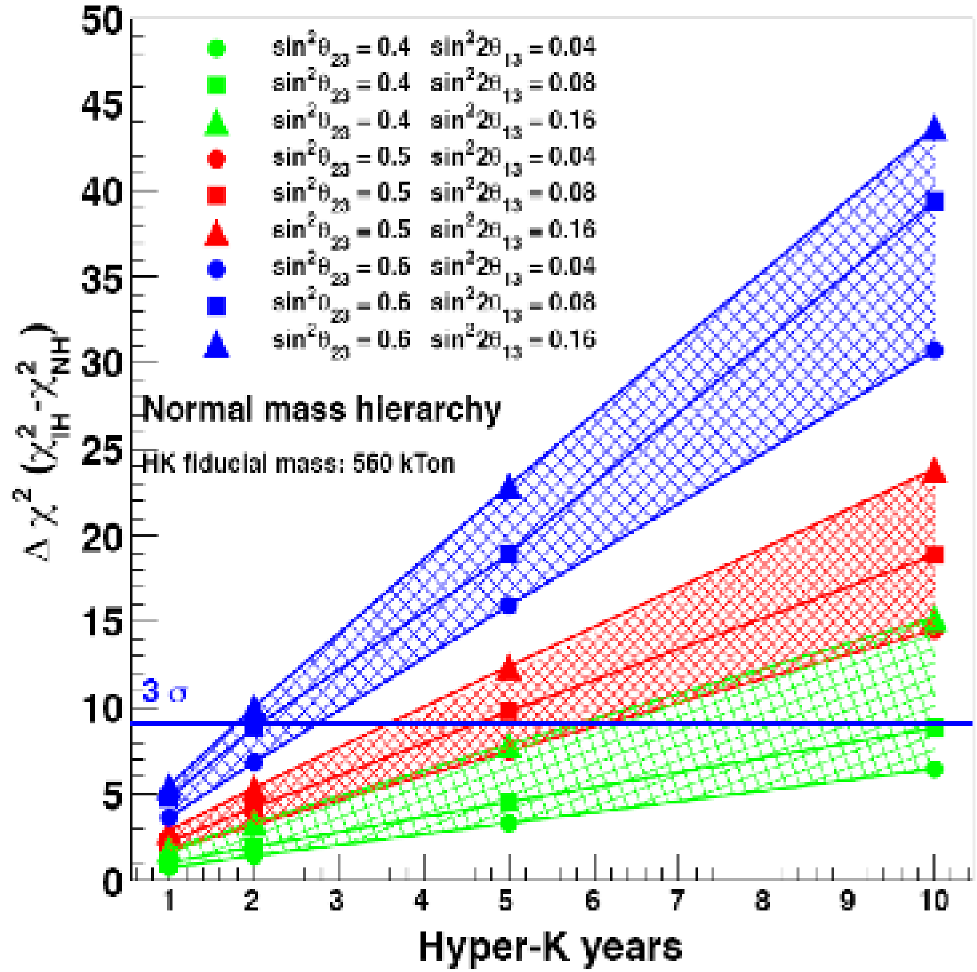


Water-Cerenkov detector, 1.8 MTy (HK = 10SK)

Critical dependence on θ_{23}, "true hierarchy".

T. Kajita et al., 2004

J. Bernabeu, S. Palomares-Ruiz, S.T.P., 2003

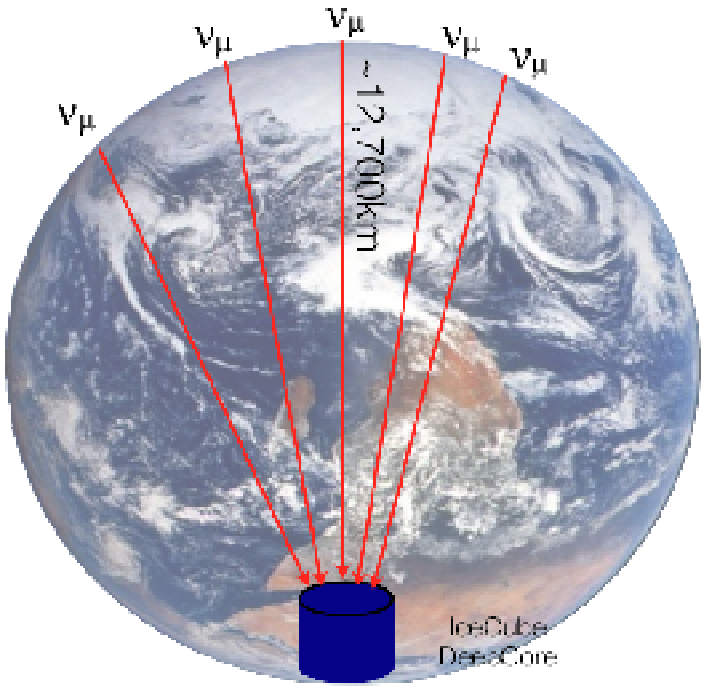


Sensitivity to the neutrino mass hierarchy from HK atmospheric neutrino data. θ_{23} and θ_{13} are assumed to be known as indicated in the figure.

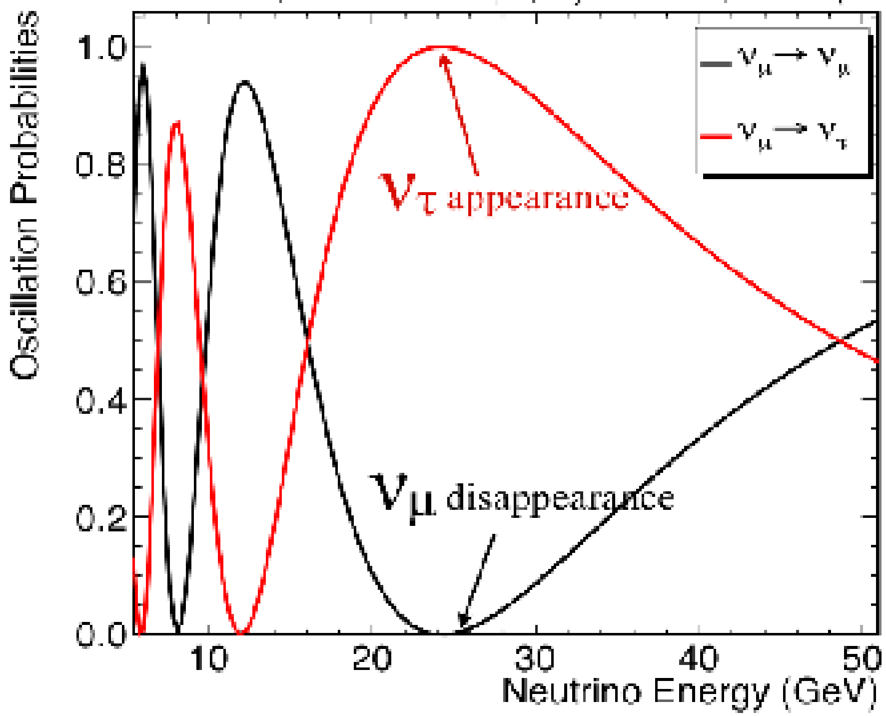
K. Abe et al. [Letter of intent: Hyper-Kamiokande Experiment], arXiv:1109.3262.

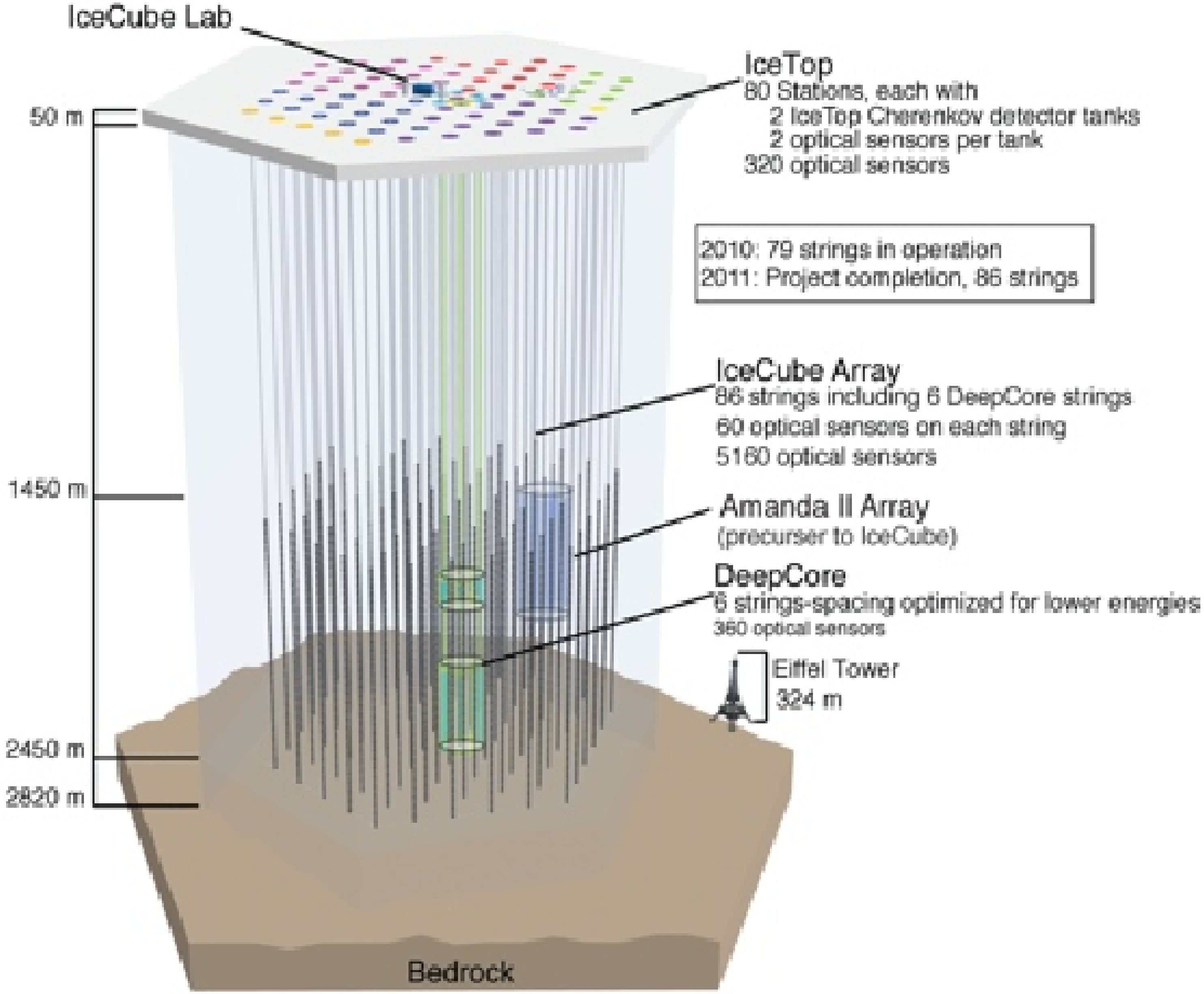
Neutrino Oscillation Source

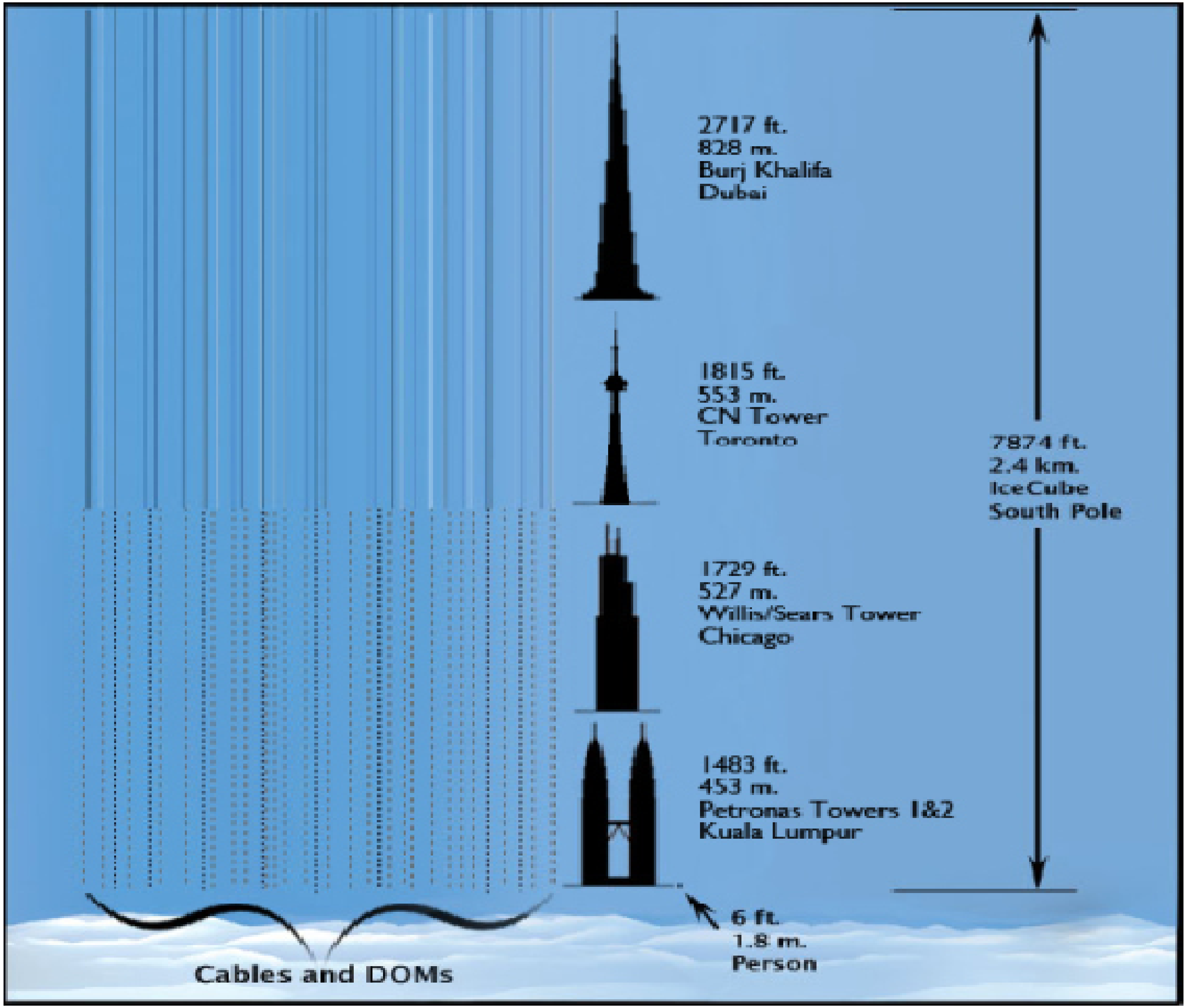
- Northern Hemisphere ν_μ oscillating over one earth radii produces ν_μ (ν_τ) oscillation minimum(maximum) at ~25 GeV
  - Covers all possible terrestrial baselines
  - "Beam" is free and never turns off



Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)

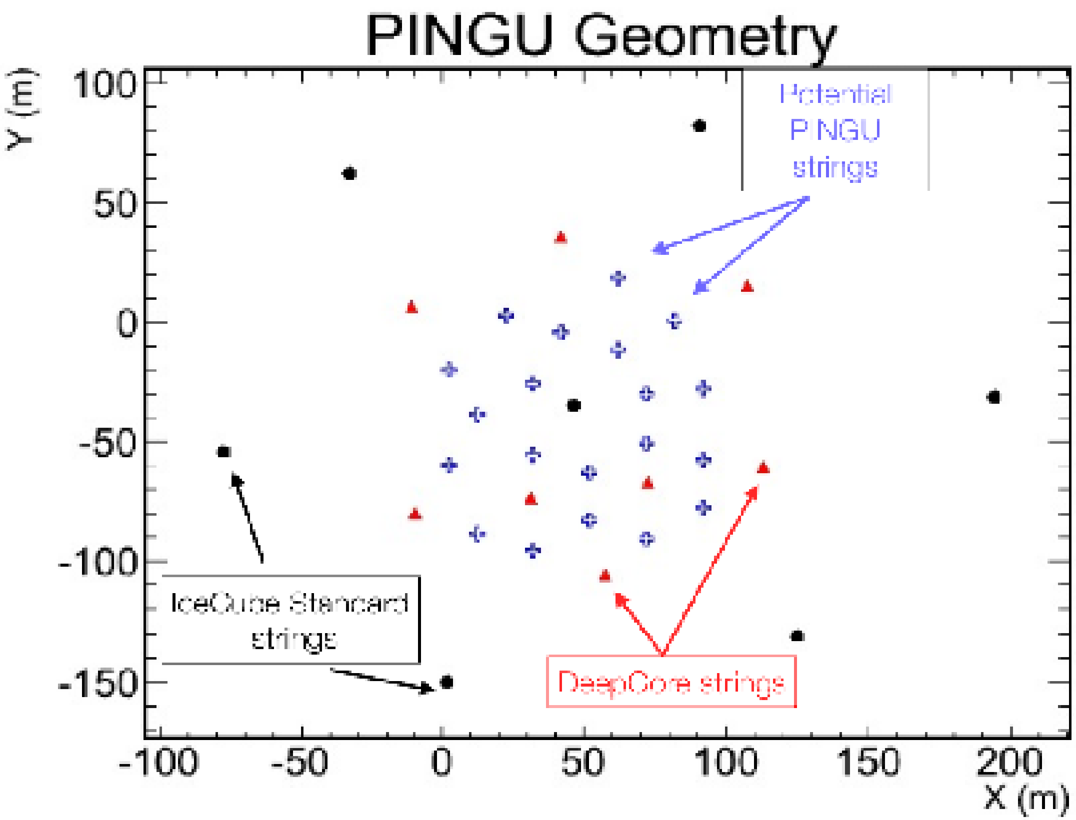



IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors
Amanda II Array
(precurser to IceCube)
DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock


2717 ft.
828 m.
Burj Khalifa
Dubai
1815 ft.
553 m.
CN Tower
Toronto
1729 ft.
527 m.
Willis/Sears Tower
Chicago
1483 ft.
453 m.
Petronas Towers 1&2
Kuala Lumpur
7874 ft.
2.4 km.
IceCube
South Pole
6 ft.
1.8 m.
Person
Cables and DOMs

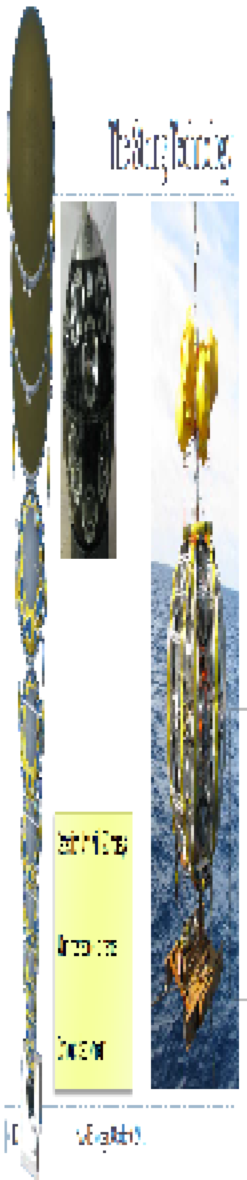
PINGU: Possible Geometry

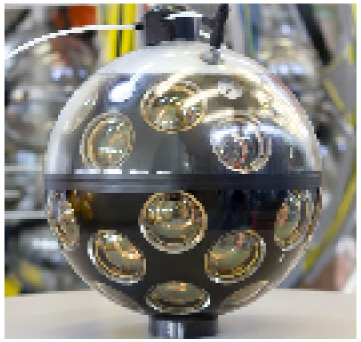
- ~20 strings within DeepCore volume w/ short string-string spacing
  - IC-IC: 125m
  - DC-DC: ~80m
  - PINGU-PINGU: <= 26m
- Shorter DOM-DOM spacing
  - IC-IC: 17m
  - DC-DC: 7m
  - PINGU-PINGU: <= 5m
- R & D for future water/ice cerenkov



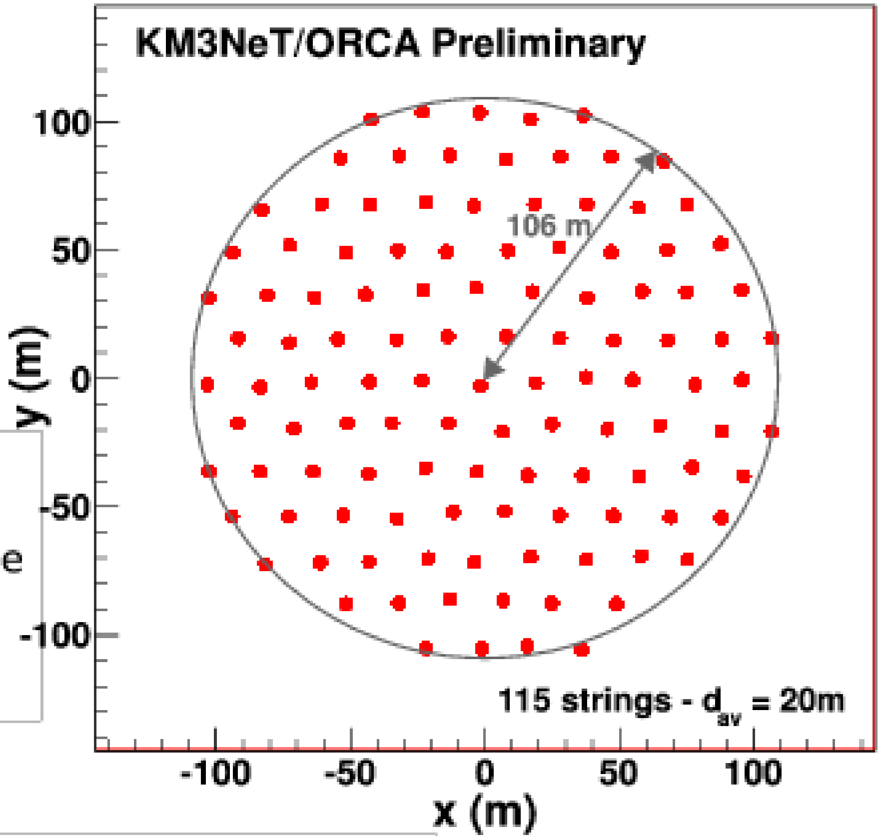
Koskinen, BNL, 2012

he ORCA proposed detector



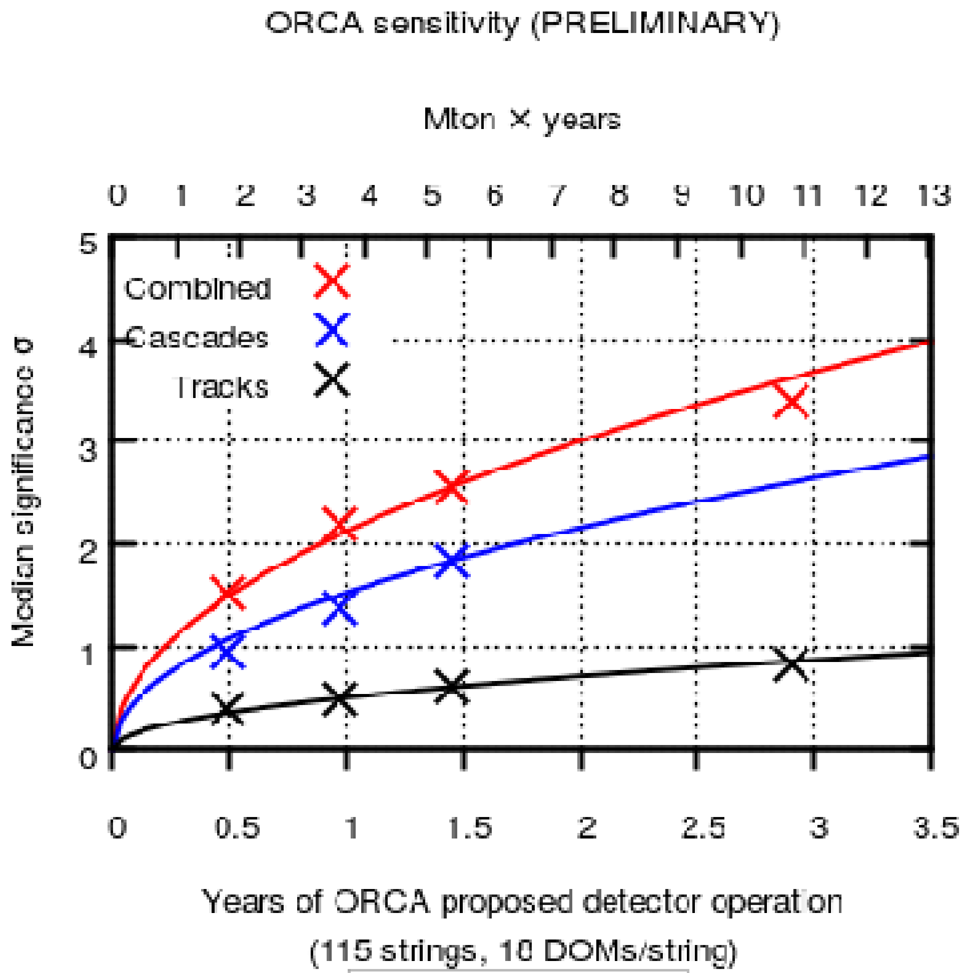


Multi-PMT DOM
31 small PMTs
Almost uniform coverage
Photon counting
Direction of photon
All electronics inside



115 strings (building block) of 18 DOMs each
Estimated cost 40M€

Sensitivity to the NMH



40 M€ investment

Future LBL Neutrino Oscillation Experiments on sgn(Δm^2_{31}) (the Hierarchy) and CP Violation

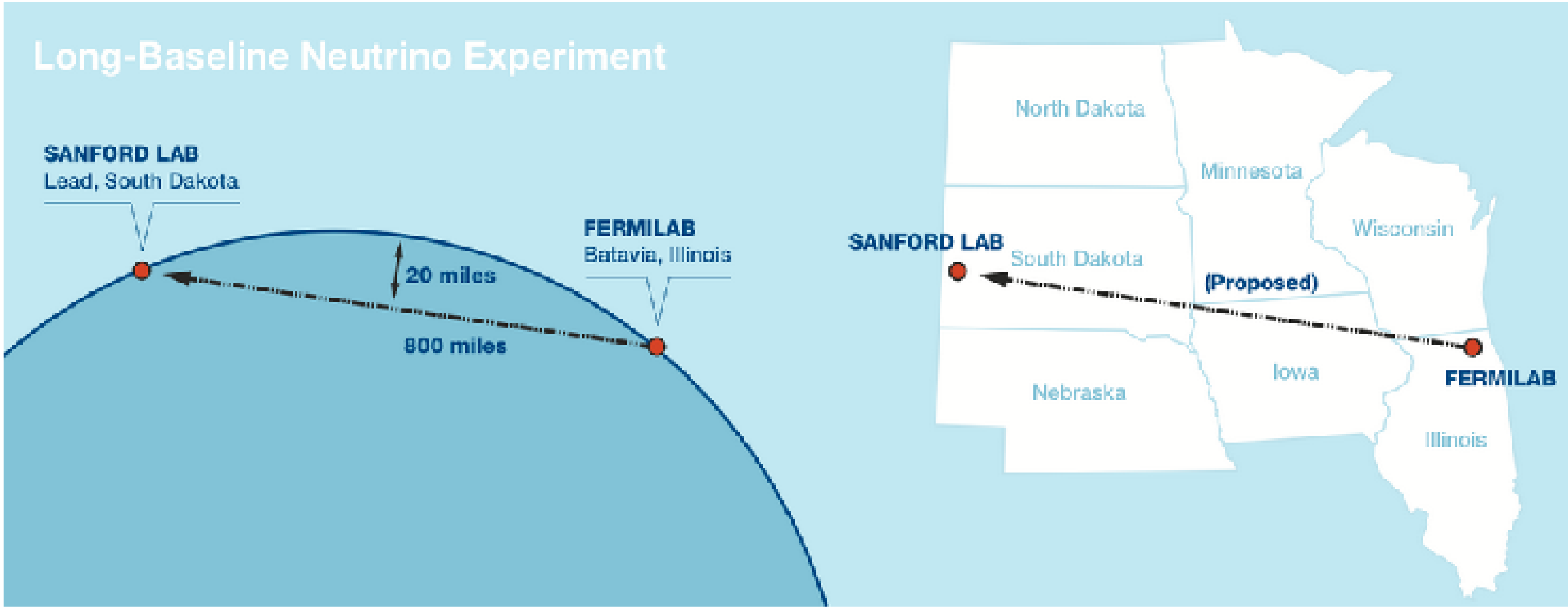
LBL Oscillation Experiments NOνA, LBNE, LBNO

NOνA: Fermilab - site in Minnesota; off-axis ν beam, $E = 2$ GeV, $L \cong 810$ km, 14 kt liquid scintillator; 2014.

LBNE: Fermilab-DUSEL, $L = 1290$ km, 700 KW wide band ν beam (first and second osc. maxima at $E = 2.4$ GeV and 0.8 GeV); 2 or 3 100 kt Water Cherenkov with 15% to 30% PMT covarage, or multiple 17 kt fiducial volume LAr detecors; plans to run 5 years with ν_μ and 5 years with $\bar{\nu}_\mu$; 2025 (?)

LBNO: CERN-Pyhasalmi, $L = 2290$ km, wide band ν_μ 1.6 MW super beam (first and second osc. maxima at $E \cong 4$ GeV and 1.5 GeV); 440 kt Water Cherenkov, or 100 kt LAr, or 50 kt liquid scintillator detector; 2023 (?)


Ontario
NOvA
Soudan
Minnesota
Wisconsin
735 kilometers
Iowa
Fermilab
Illinois


Long-Baseline Neutrino Experiment
SANFORD LAB
Lead, South Dakota
FERMILAB
Batavia, Illinois
20 miles
800 miles
North Dakota
Minnesota
Wisconsin
SANFORD LAB
South Dakota
(Proposed)
Nebraska
Iowa
FERMILAB
Illinois

2100 km from RAL, 1500 km from DESY, and 1160 km from Protvino.

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

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

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

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

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

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

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

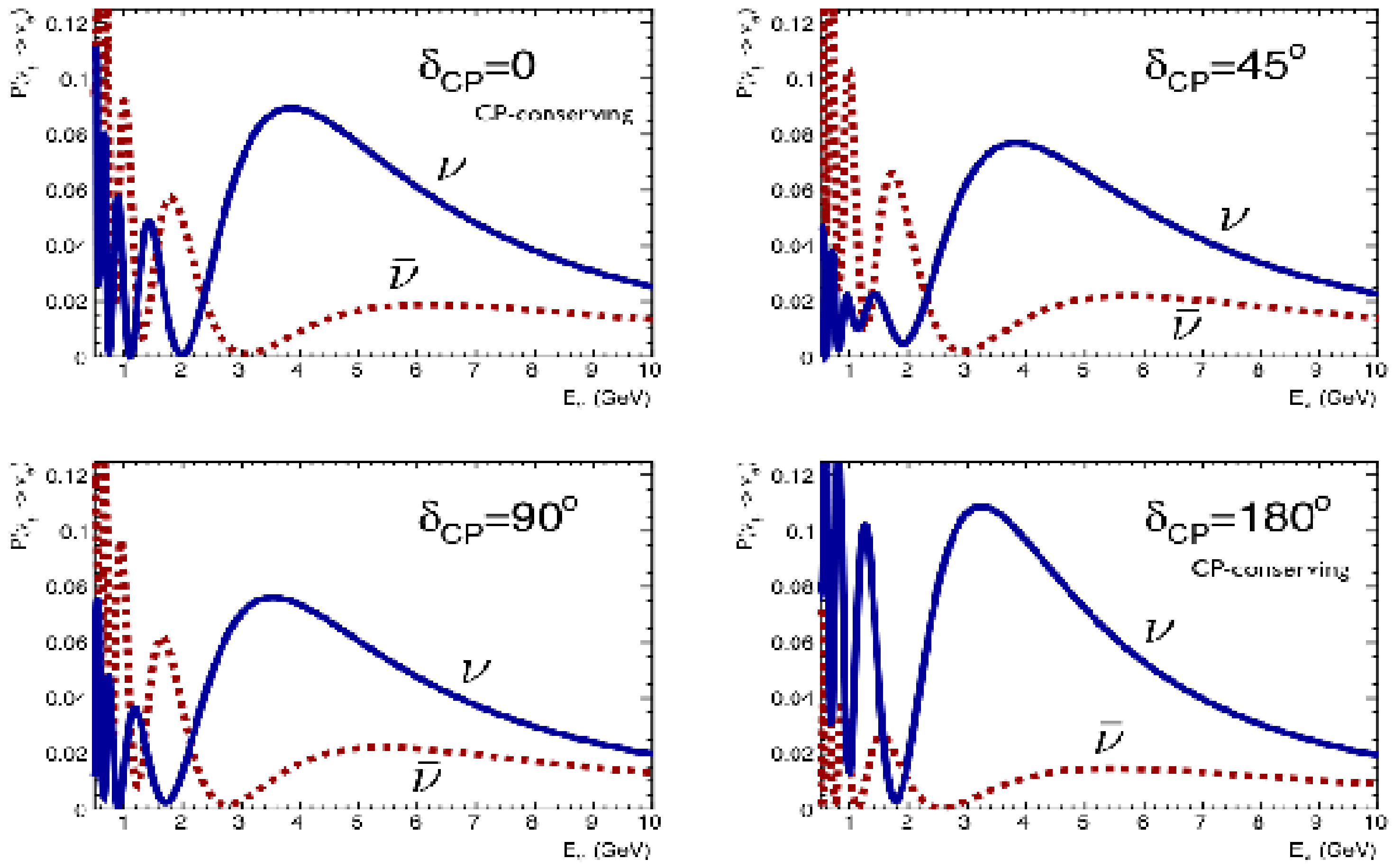
$\bar{\nu}_\mu \to \bar{\nu}_e$: δ, $A \to (-\delta)$, $(-A)$

CERN-Pyhäsalmi: CP-effect $\nu_\mu \rightarrow \nu_e$

★Normal mass hierarchy

L=2300 km

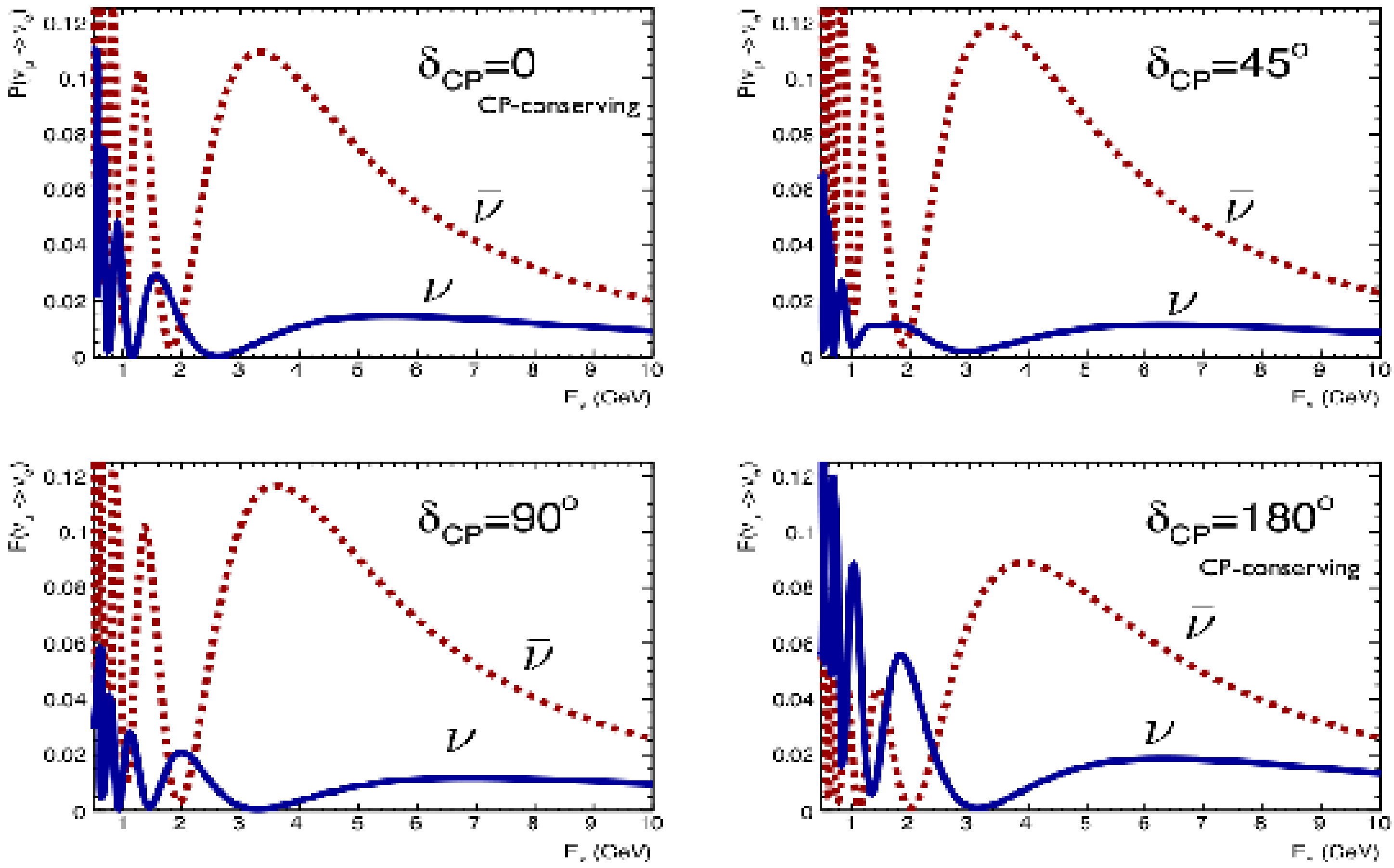
$\sin^2(2\theta_{13}) = 0.09$



CERN-Pyhäsalmi: CP-effect $\nu_\mu \rightarrow \nu_e$

★Inverted mass hierarchy   L=2300 km

$$\sin^2(2\theta_{13}) = 0.09$$



LBNE, for example, could achieve the determination of the mass hierarchy at 3σ in less then a year.

LBNE could also have very good sensitivity to CP-violation with a 60% coverage at 3σ in the allowed range of values of $\sin^2 2\theta_{13}$, for a 200 kton Water Cherenkov or 34 kton LAr detectors (assuming it will run for 5 years in neutrinos and 5 years in antineutrinos).

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.

ν_j- Dirac or Majorana particles, **fundamental problem**

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

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

The observed patterns of $\nu-$mixing and of Δm^2_{atm} and $\Delta m^2_{\odot}$ can be related to Majorana ν_j and an approximate symmetry:

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

S.T.P., 1982

See-saw mechanism: ν_j- Majorana

Establishing that ν_j are Majorana particles would be as important as the discovery of $\nu-$ oscillations.

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:

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

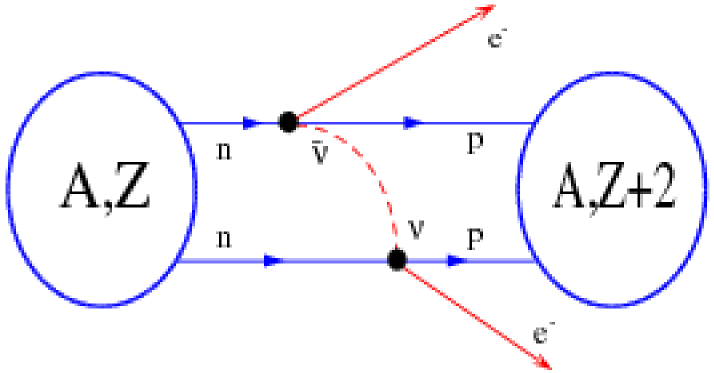
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

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

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

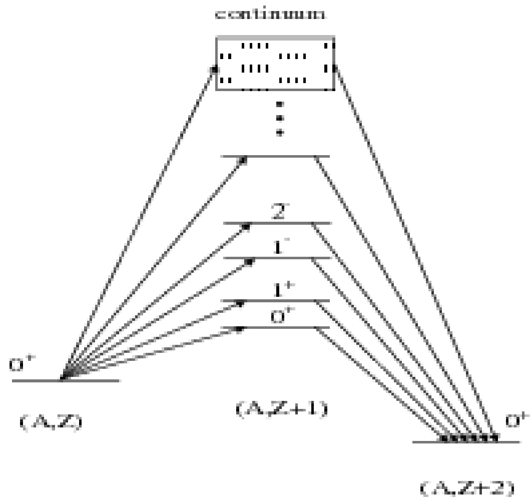
$2n$ from (A,Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of (A,Z+2) and two free e^-.

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



strong in-medium modification of the basic process

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



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:

- 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)

- CPV due to Majorana CPV phases

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

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

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

α_{21}, α_{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,

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

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

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

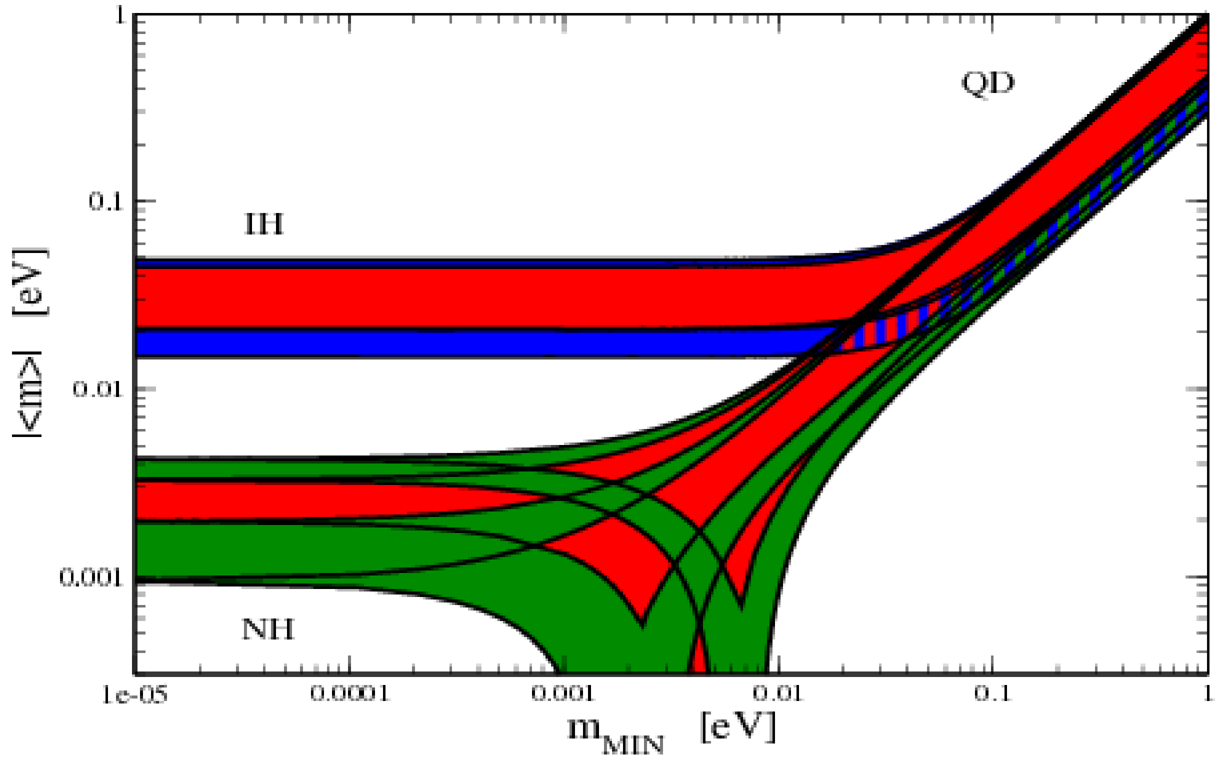
$\theta_{12} \equiv \theta_{\odot}$, θ_{13}-CHOOZ; $\alpha \equiv \alpha_{21}$, $\beta_M \equiv \alpha_{31}$.

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

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

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

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



S. Pascoli, PDG, 2012

$\sin^2\theta_{13} = 0.0236 \pm 0.0042$; $\delta = 0$.

$1\sigma(\Delta m^2_{21}) = 2.6\%$, $1\sigma(\sin^2\theta_{12}) = 5.4\%$, $1\sigma(|\Delta m^2_{31(23)}|) = 3\%$.

From G.L. Fogli *et al.*, arXiv:1205.5254v3

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

Best sensitivity: GERDA (^{76}Ge), EXO (^{136}Xe), KamLAND-ZEN (^{136}Xe).

Claim for a positive signal at $> 3\sigma$:

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

$|<m>| = (0.1 - 0.9)$ eV (99.73% C.L.); b.f.v.: $|<m>| = 0.33$ eV.

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

Recent data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|<m>| <(0.45–0.96)$ eV, $|<m>| <(0.18–0.64)$ eV (90% C.L.).

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

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

Results from 2012-2013:

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

$$T(^{136}\mathrm{Xe}) > 1.9 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.,\ KamLAND - Zen}$$

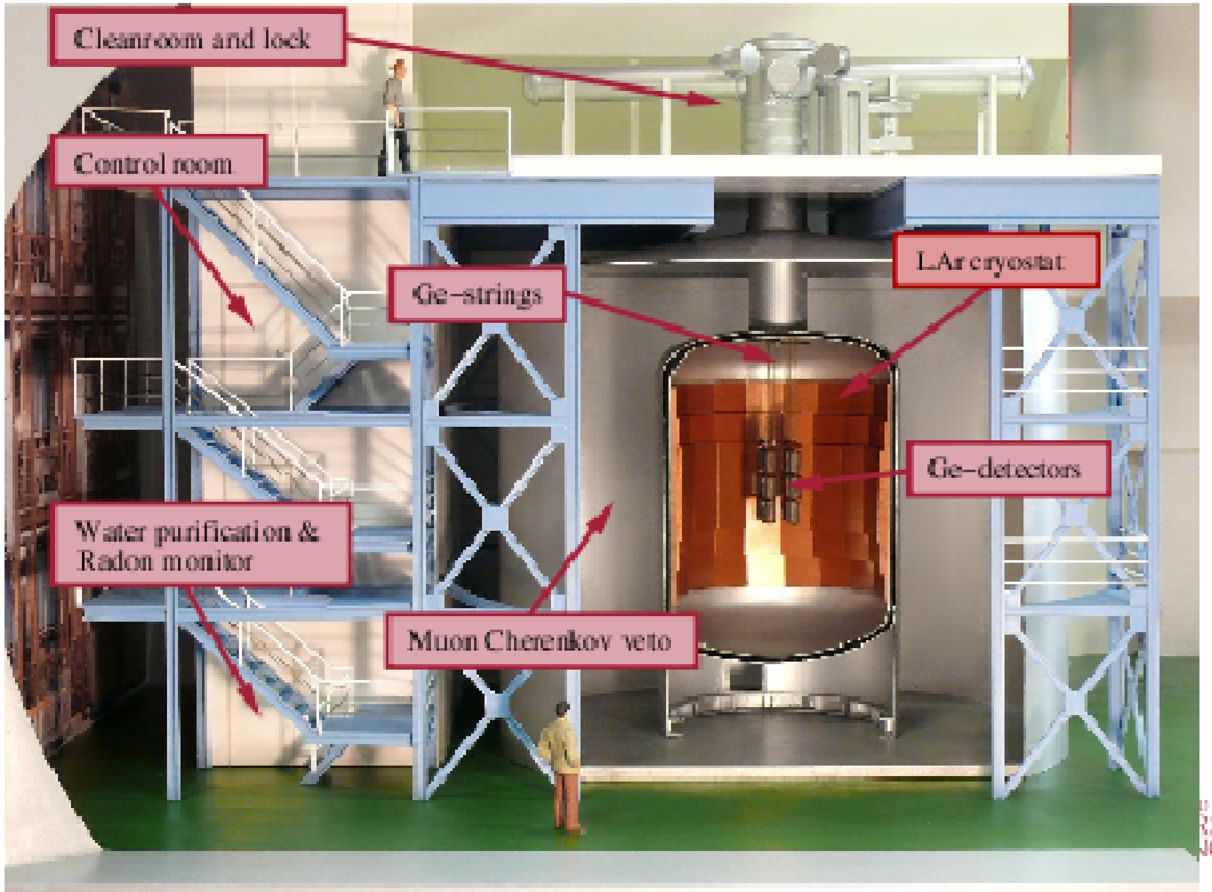
$$T(^{76}\mathrm{Ge}) > 2.1 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.,\ GERDA.}$$

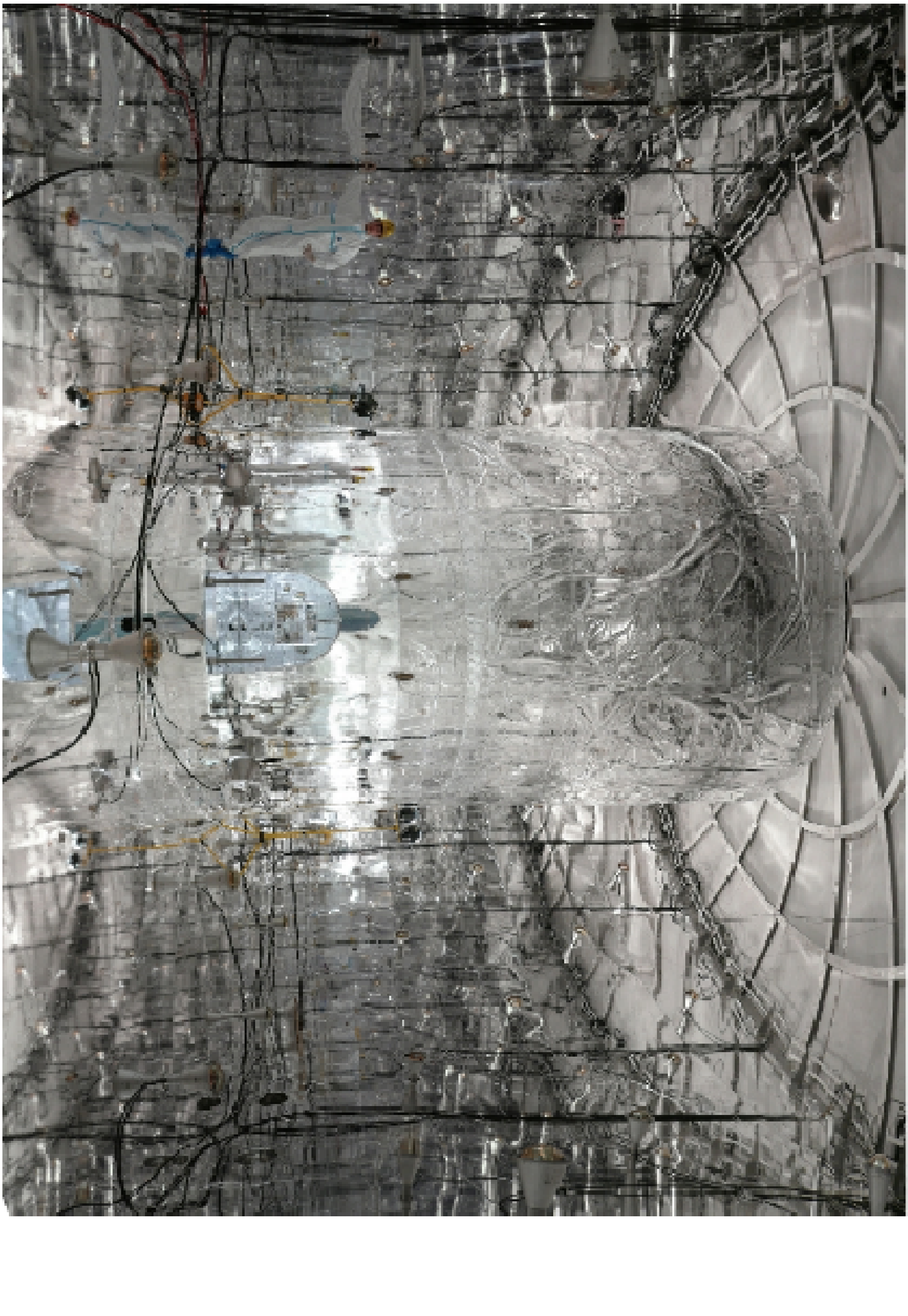
$$T(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.,\ GERDA + IGEX + HdM.}$$

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

CUORE - ^{130}Te,
GERDA - ^{76}Ge,
KamLAND-ZEN - ^{136}Xe;
EXO - ^{136}Xe;
SNO+ - ^{130}Te;
AMoRE - ^{100}Mo (S. Korea);
CANDLES - ^{48}Ca;
SuperNEMO - ^{82}Se,...;
MAJORANA - ^{76}Ge;
COBRA - ^{116}Cd;
MOON - ^{100}Mo.

GERDA: Experimental Setup





Majorana CPV Phases and $|<m>|$

CPV can be established provided

- $|<m>|$ measured with $\Delta \lesssim 15\%$;
- $\Delta m^2_{\rm atm}$ (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

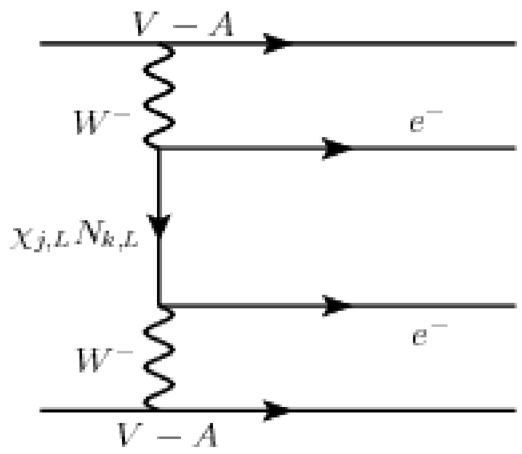
S. Pascoli, S.T.P., L. Wolfenstein, 2002

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

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



Light Majorana Neutrino Exchange

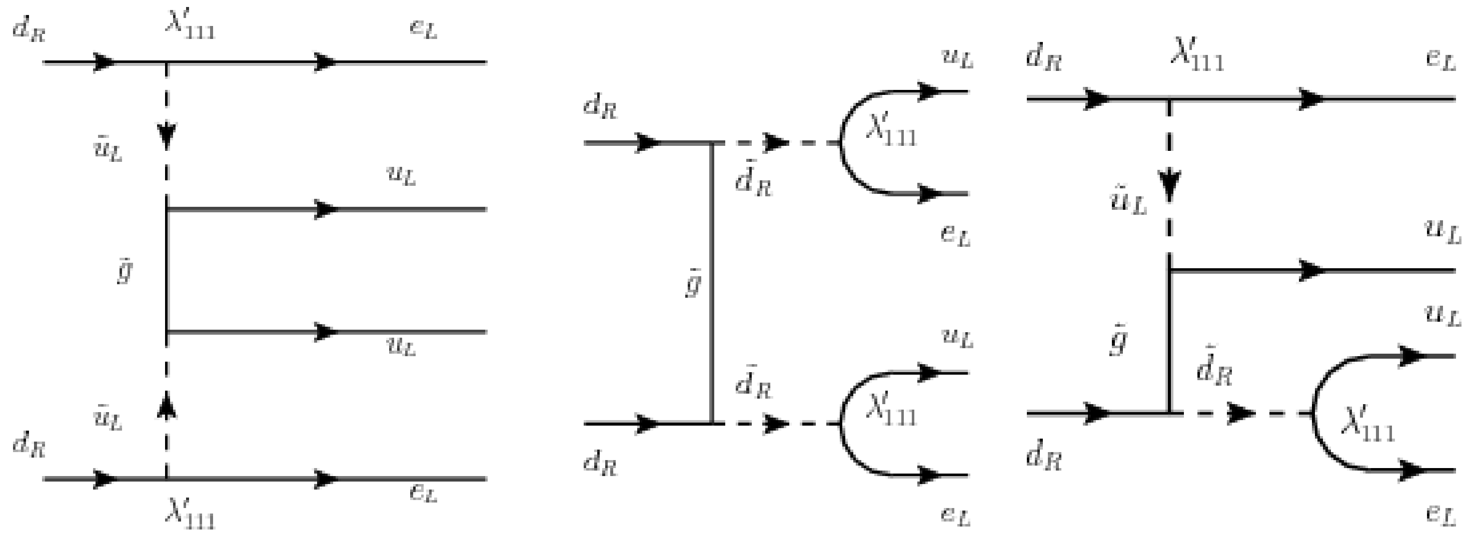
$$\eta_\nu = \frac{<m>}{m_e}.$$

Heavy Majorana Neutrino Exchange Mechanisms

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

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

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 problem of distinguishing between different sets of multiple (e.g., two) mechanisms being operative in $(\beta\beta)_{0\nu}$-decay was studied in

1. A. Faessler, A. Meroni, S.T.P., F. Simkovic and J. Vergados, "Uncovering Multiple CP-Nonconserving Mechanisms of $(\beta\beta)_{0\nu}$-Decay", arXiv:1103.2434, Phys. Rev. D83 (2011) 113003.

2. A. Meroni, S.T.P. and F. Simkovic, "Multiple CP Non-conserving Mechanisms of bb0nu-Decay and Nuclei with Largely Different Nuclear Matrix Elements", (arXiv:1212.1331, JHEP **1302** (2013) 025.

Earlier studies include:
A. Halprin, S.T.P., S.P. Rosen, "Effects of Mixing of Light and Heavy Majorana Neutrinos in Neutrinoless Double Beta Decay", Phys. Lett. 125B (1983) 335).

Absolute Neutrino Mass Measurements

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

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

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.

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


KATRIN'S JOURNEY
UNITED KINGDOM
IRELAND
Dublin
London
Birmingham
Cardiff
Liverpool
Manchester
Celtic Sea
Bay of Biscay
FRANCE
Paris
Nantes
Bordeaux
Lyon
Toulouse
Marseille
Strasbourg
Brussels
Lille
BEL.
Amsterdam
Rotterdam
NETH.
GERMANY
Essen
Cologne
Bonn
Frankfurt am Main
Luxembourg
Stuttgart
Munich
Hamburg
Bremen
Berlin
Leipzig
DENMARK
Copenhagen
Malmö
POLAND
Gdańsk
Poznań
Warsaw
Łódź
Wrocław
Kraków
Kaliningrad
Bornholm
CZECH REPUBLIC
Prague
Brno
SLOVAKIA
Bratislava
AUSTRIA
Vienna
HUNGARY
Budapest
SLOVENIA
Ljubljana
Zagreb
CROATIA
Sarajevo
Belgrade
Serbia
Tirana
Skopje
ROMANIA
Bucharest
Cluj-Napoca
Iaşi
MOLDOVA
Chişinău
UKRAINE
Kiev
L'viv
Rivne
Chernivtsi
Mykolayiv
Odesa
BELARUS
Minsk
Vilnius
Hrodna
Brest
Homyel'
Mahilyow
BULGARIA
Sofia
Varna
Constanța
Black Sea
Istanbul
Bursa
TURKEY
GREECE
Athens
Thessaloniki
Aegean Sea
Rhodes
Crete
Ionian Sea
Tyrrhenian Sea
Naples
Palermo
Sicily
Valletta
MALTA
Sardinia
Cagliari
Genoa
Turin
Milan
Venice
Florence
Zurich
Bern
Geneva
Mediterranean Sea
BALEARIC ISLANDS
Barcelona
Andorra
Bilbao
Madrid
Valencia
SPAIN
Sevilla
Malaga
Gibraltar
Strait of Gibraltar
Alboran Sea
PORTUGAL
Porto
Lisbon
Ceuta
Melilla
Oran
Algiers
ALGERIA
Tunis
TUNISIA
Rabat
Casablanca
MOROCCO
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
300 Kilometers
300 Miles

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:

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

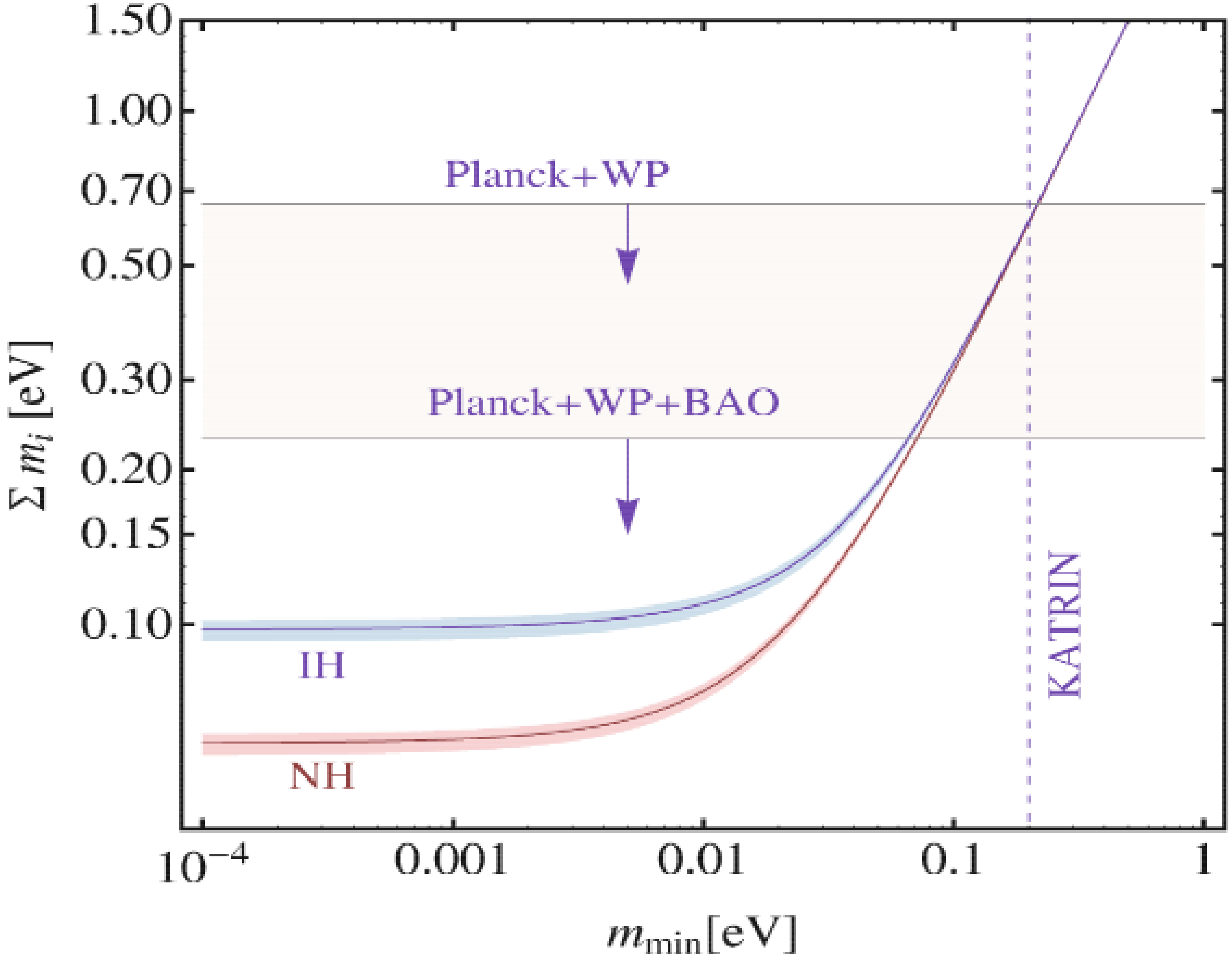
Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP, and Planck experiments, and/or data from future EUCLID experiment, might allow to determine

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

NH: $\sum_j m_j \leq 0.05$ eV (3σ);

IH: $\sum_j m_j \geq 0.10$ eV (3σ).

Mass and Hierarchy from Cosmology



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

Instead of Conclusions

We are at the beginning of the Road...

The future of neutrino physics is bright.

Supporting Slides

The Nature of Massive Neutrinos III:

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.

Three Types of Seesaw Mechanisms

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

Type I seesaw mechanism: ν_{lR} - RH νs' (heavy).

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

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

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

Massive neutrinos ν_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.

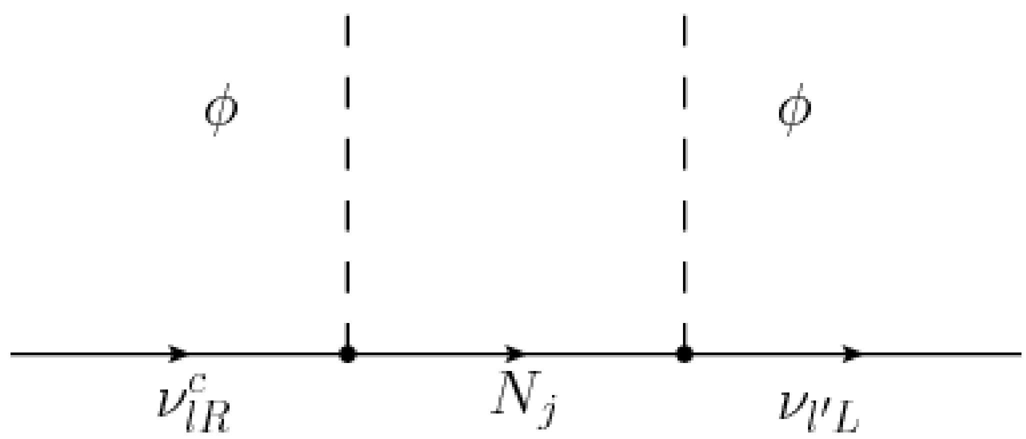
Type I Seesaw Mechanism

- 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.



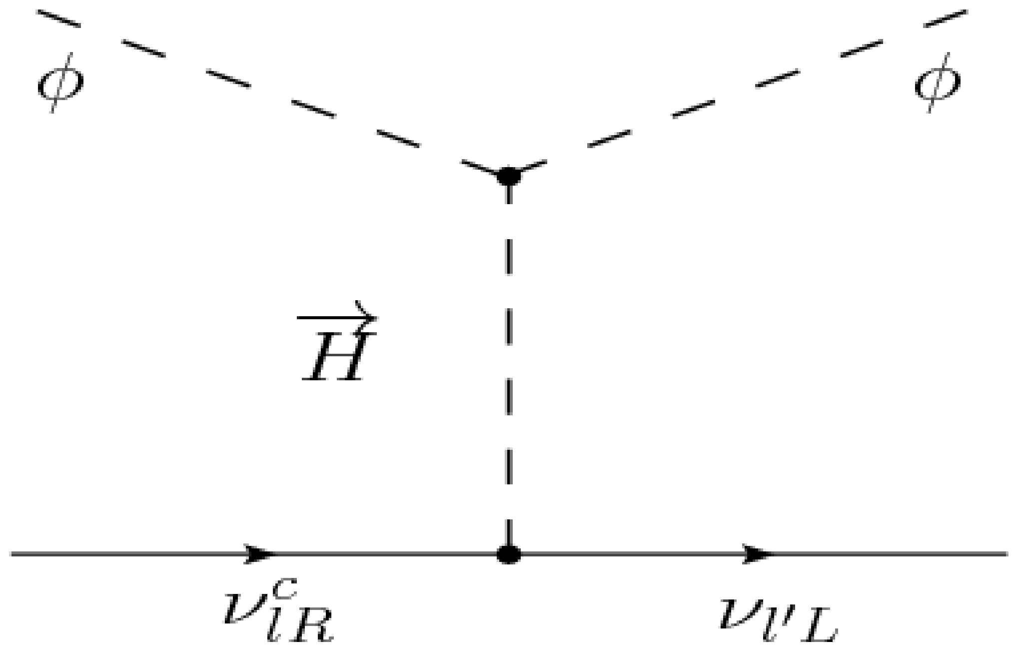
- $\nu_{l'R}(x)$: Majorana mass term at "high scale" (~TeV; or $(10^9 - 10^{13})$ GeV in $SO(10)$ GUT)

$$\mathcal{L}_M^\nu(x) = + \frac{1}{2}\, \nu_{l'R}^{\top}(x)\; C^{-1}\; (M^{RR})^{\dagger}_{l'l}\; \nu_{lR}(x) + h.c. = -\frac{1}{2}\sum_j \bar{N}_j\, M_j\, N_j \;,$$

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

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

Type II Seesaw Mechanism

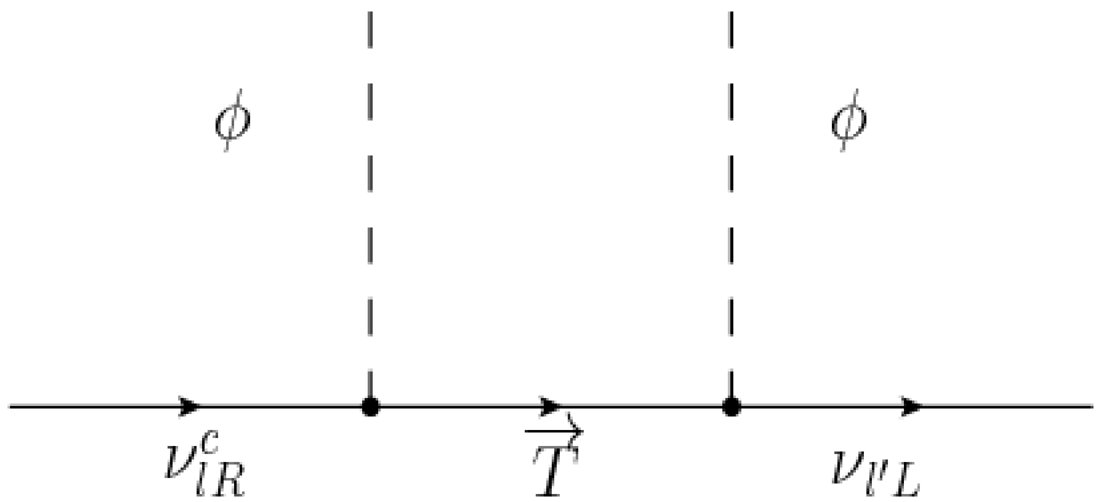


Due to I. Girardi

$$M_\nu \cong h\, v^2\, M_H^{-1} = U^*_{\text{PMNS}}\, m_\nu^{\text{diag}}\, U^\dagger_{\text{PMNS}}\ .$$

$h \sim 10^{-2}$, $v = 246$ GeV, $M_H \sim 10^{12}$ GeV: $M_\nu \sim 0.6$ eV.

Type III Seesaw Mechanism



$$M_\nu \cong v^2 \, (Y_T)^T \, M_T^{-1} \, Y_T = U^*_{\mathrm{PMNS}} \, m_\nu^{\mathrm{diag}} \, U^\dagger_{\mathrm{PMNS}} \, .$$

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

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.

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

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

- **All low-energy constraints can be satisfied in a scheme with two heavy Majorana neutrinos $N_{1,2}$, which 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:

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

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

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

4 parameters: M, z, y and a phase ω.

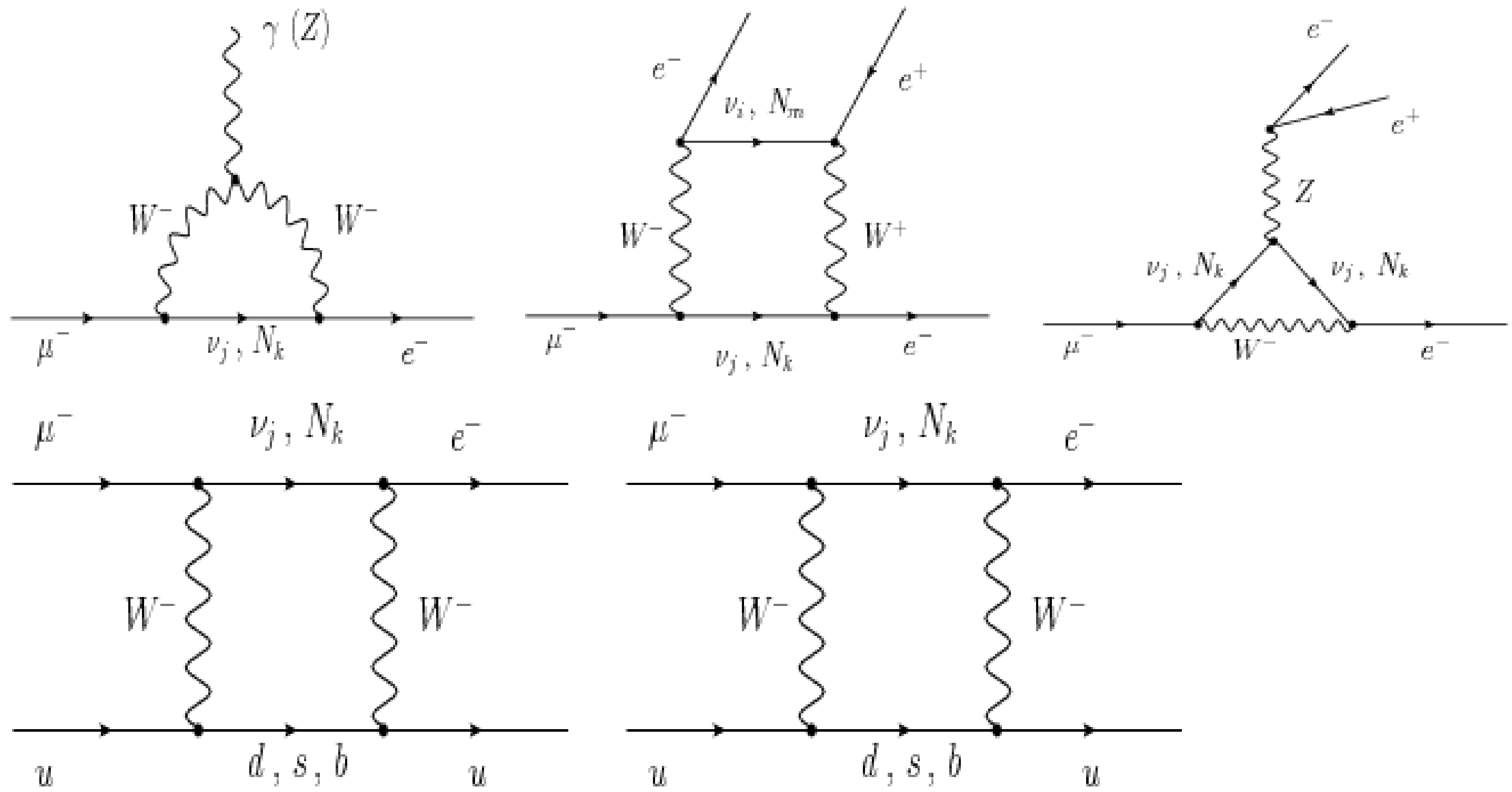
Low energy data:

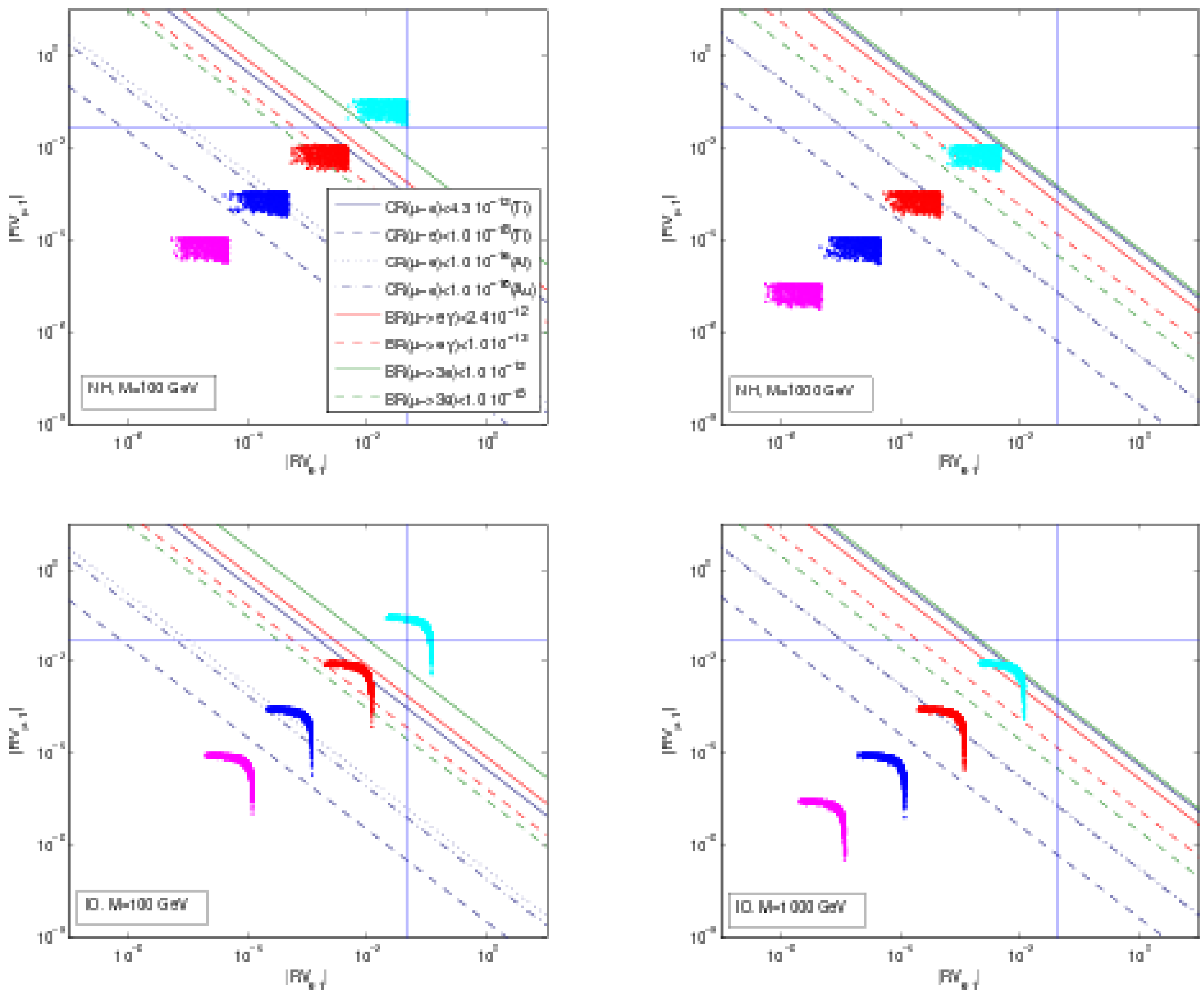
$$
\begin{aligned}
|(RV)_{e1}|^2 &\lesssim 2 \times 10^{-3}, \\
|(RV)_{\mu 1}|^2 &\lesssim 0.8 \times 10^{-3}, \\
|(RV)_{\tau 1}|^2 &\lesssim 2.6 \times 10^{-3}.
\end{aligned}
$$

S. Antusch et al., 2008

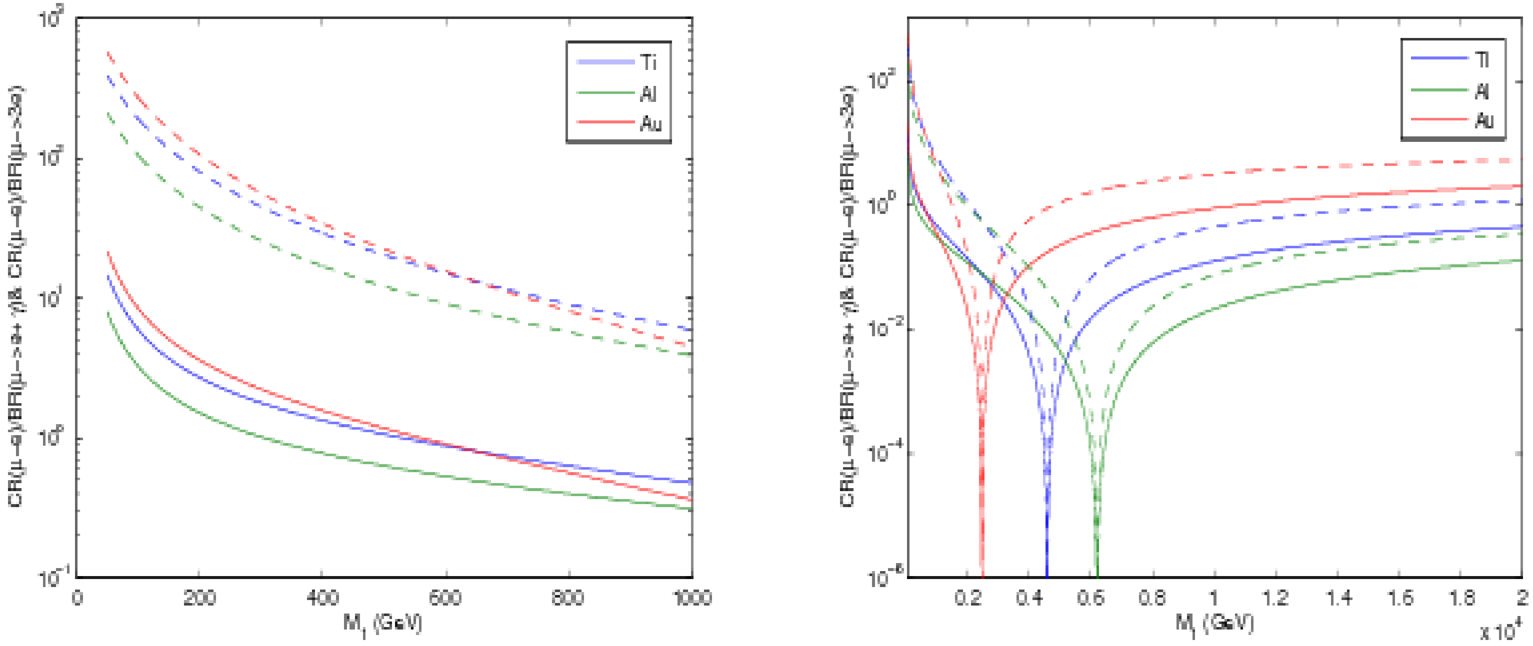
Observation of $N_{1,2}$ at LHC - problematic.

LFV processes: $\mu \to e + \gamma$, $\mu \to 3e$, $\mu^- + \mathcal{N} \to e^- + \mathcal{N}$: can proceed with exchange of virtual N_j:





Current limits and potential sensitivity to $|(RV)_{e1}|$ and $|(RV)_{\mu 1}|$ from data on LFV processes for NH (upper panels) and IH (lower panels) spectra, for $M_1 = 100\,(1000)$ GeV and, $i)$ $y = 0.0001$ (magenta pts), $ii)$ $y = 0.001$ (blue pts), $iii)$ $y = 0.01$ (red pts) and $iv)$ $y = 0.1$ (cyan pts).



The ratio of the $\mu - e$ relative conversion rate and the branching ratio of the i) $\mu \to e\gamma$ decay (solid lines), ii) $\mu \to 3e$ decay (dashed lines), versus the type I see-saw mass scale M_1, for three different nuclei: $^{48}_{22}$Ti (blue lines), $^{27}_{13}$Al (green lines) and $^{197}_{79}$Au (red lines).

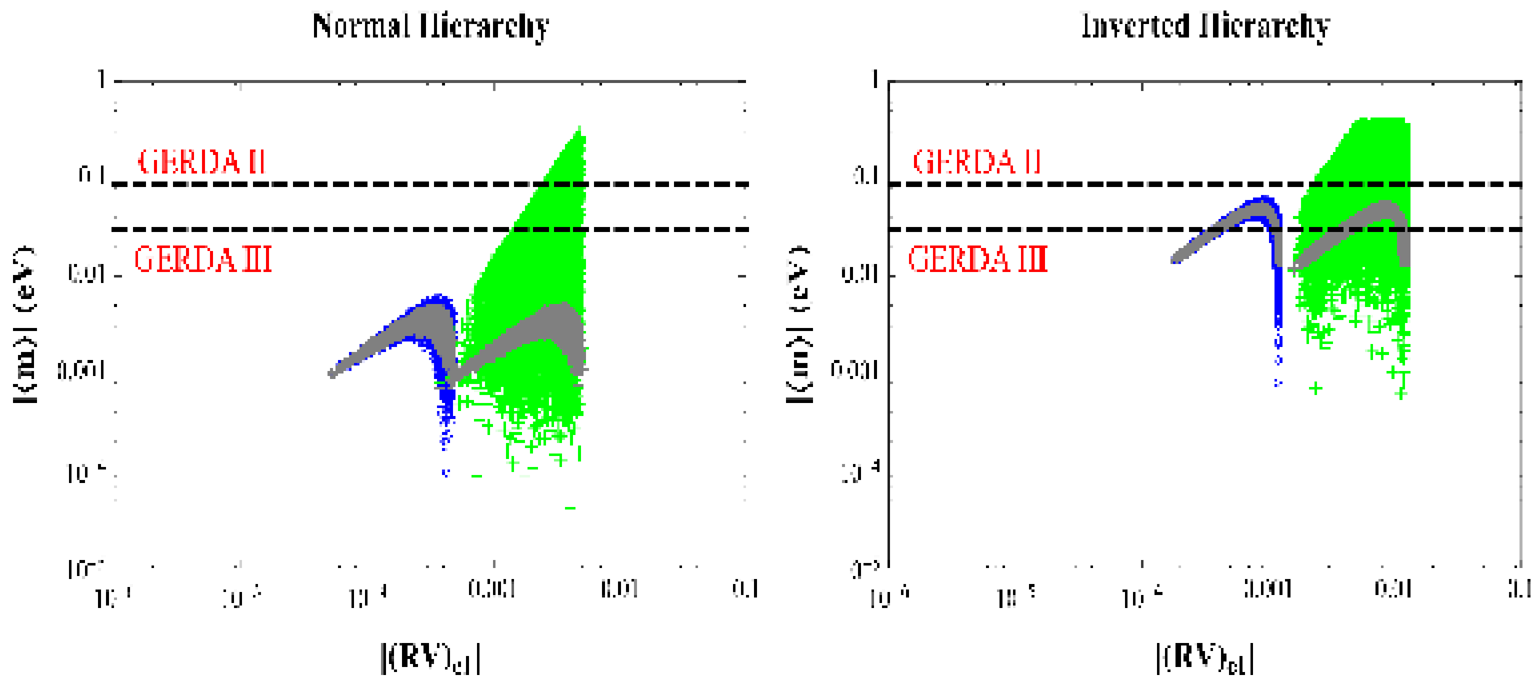
The exchange of virtual N_j gives a contribution to $|<m>|$:

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

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

For, e.g., ^{48}Ca, ^{76}Ge, ^{82}Se, ^{130}Te and ^{136}Xe, the function $f(A)$ takes the values $f(A) \cong$ 0.033, 0.079, 0.073, 0.085 and 0.068, respectively.

- **The Predictions for $|<m>|$ can be modified considerably.**



$|<m>|$ vs $|(RV)_{e1}|$ for ^{76}Ge in the cases of NH (left panel) and IH (right panel) light neutrino mass spectrum, for $M_1 = 100$ GeV and $i)$ $y = 0.001$ (blue), $ii)$ $y = 0.01$ (green). The gray markers correspond to $|<m>^{\rm std}| = |\sum_i (U_{PMNS})^2_{ei} m_i|$.

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