Current Status and Future Prospects of Neutrino Physics

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Kavli IPMU
Tokyo, Japan
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There have been remarkable discoveries in neutrino physics in the last ~ 18 years.

Compellings Evidence for $\nu-$Oscillations

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

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

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

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

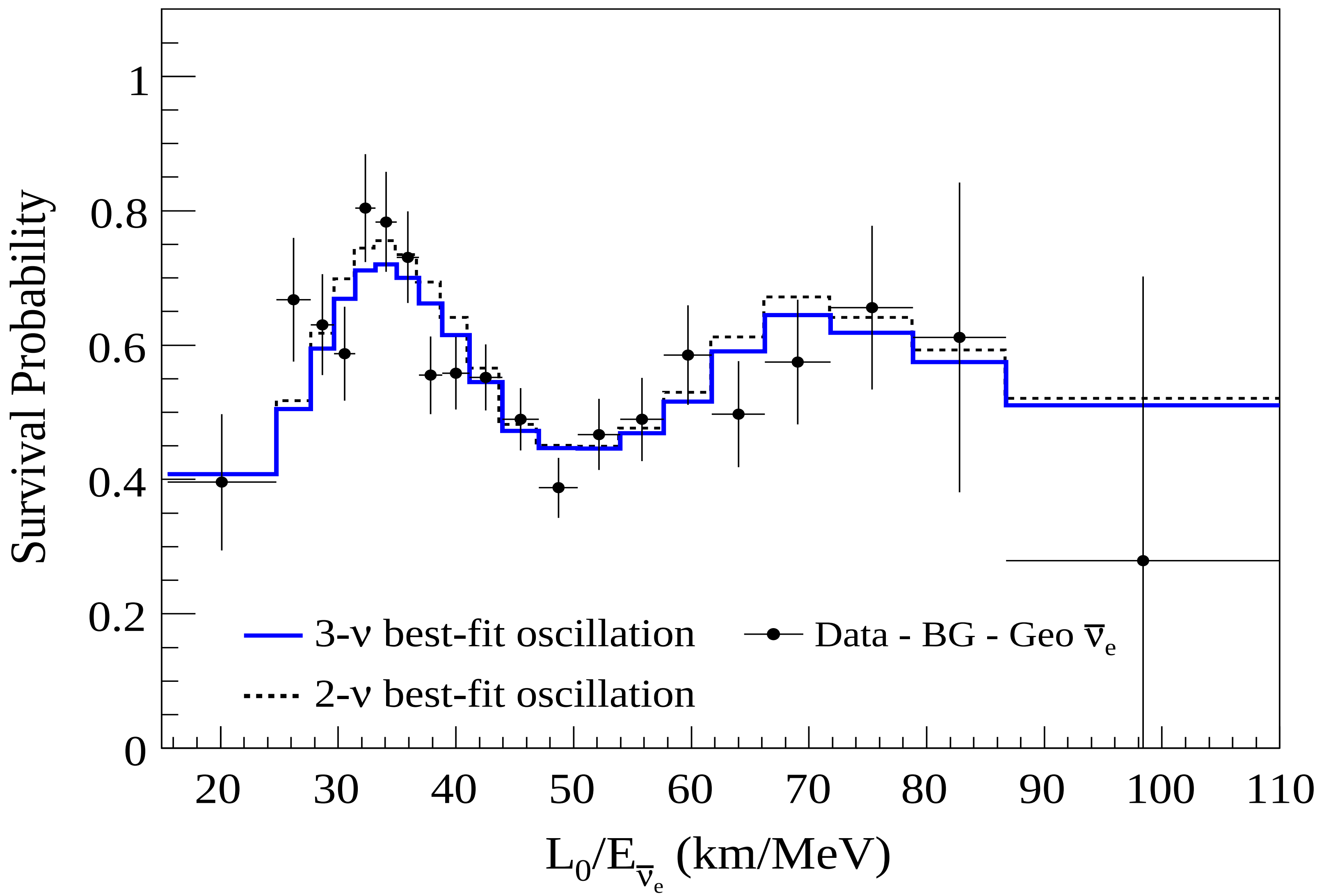
Super-Kamiokande, SNO, BOREXINO; KamLAND

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

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

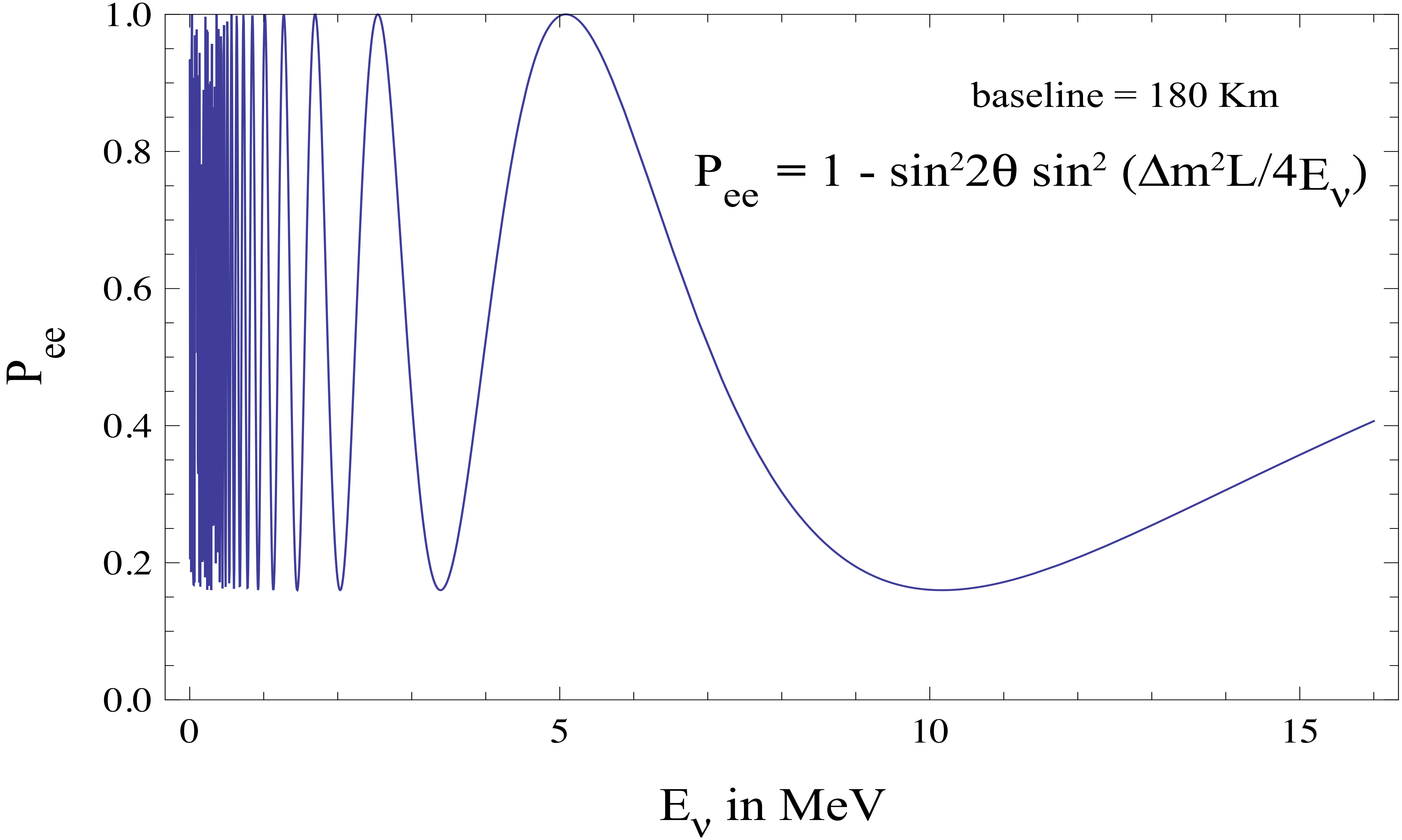
Dominant $\bar{\nu}_e \rightarrow \bar{\nu}_{\mu,\tau}$

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



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

$\nu_e \to \nu_e$



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

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

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

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

B. Pontecorvo, 1957; 1958; 1967;

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

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

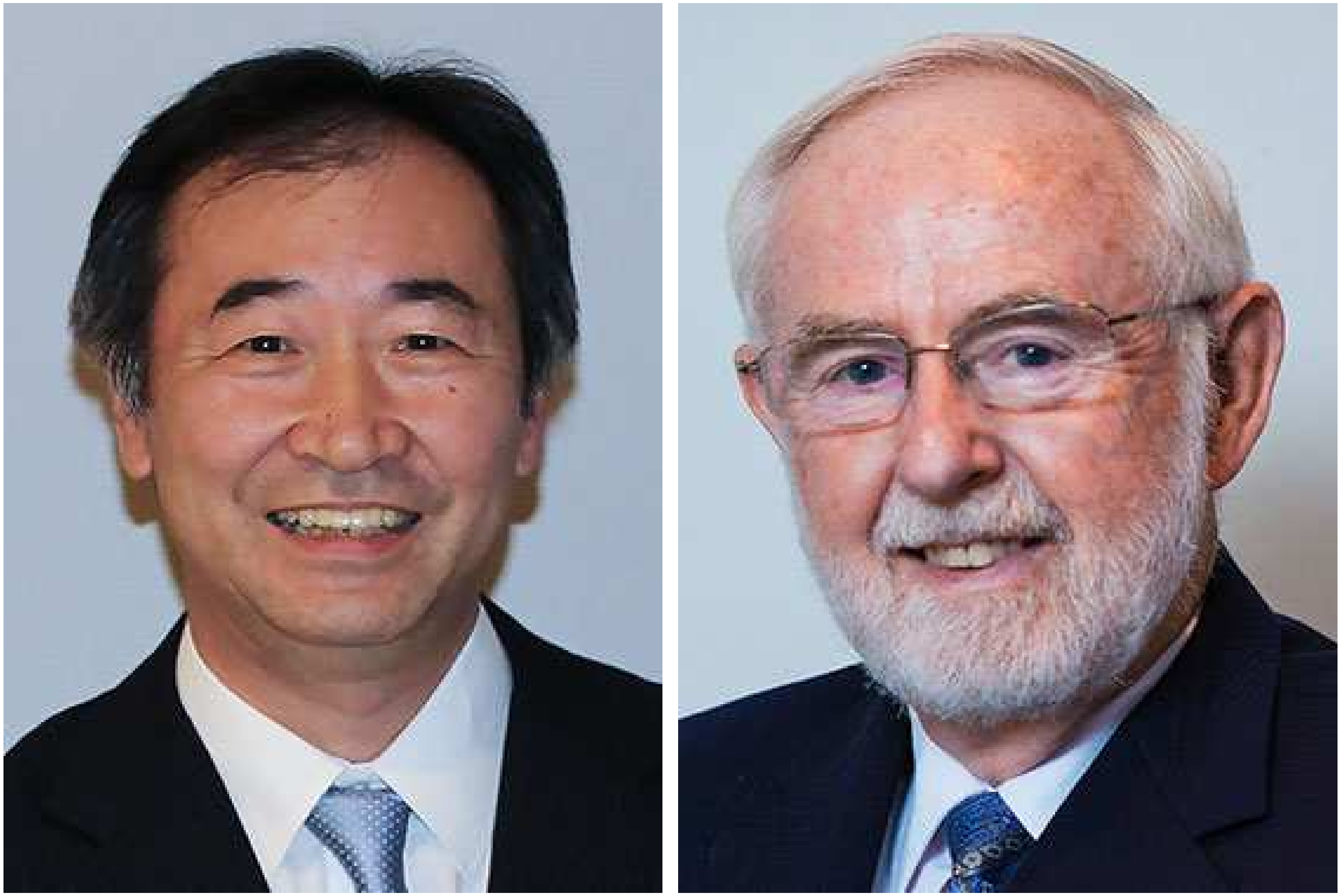
ν_j, $m_j \neq 0$: Dirac or Majorana particles.

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

The Charged Current Weak Interaction Lagrangian:

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

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



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

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2016 | 2015 | 2014 | 2013 | 2012


Kam-Biu Luk and the Daya Bay Collaboration


Yifang Wang and the Daya Bay Collaboration

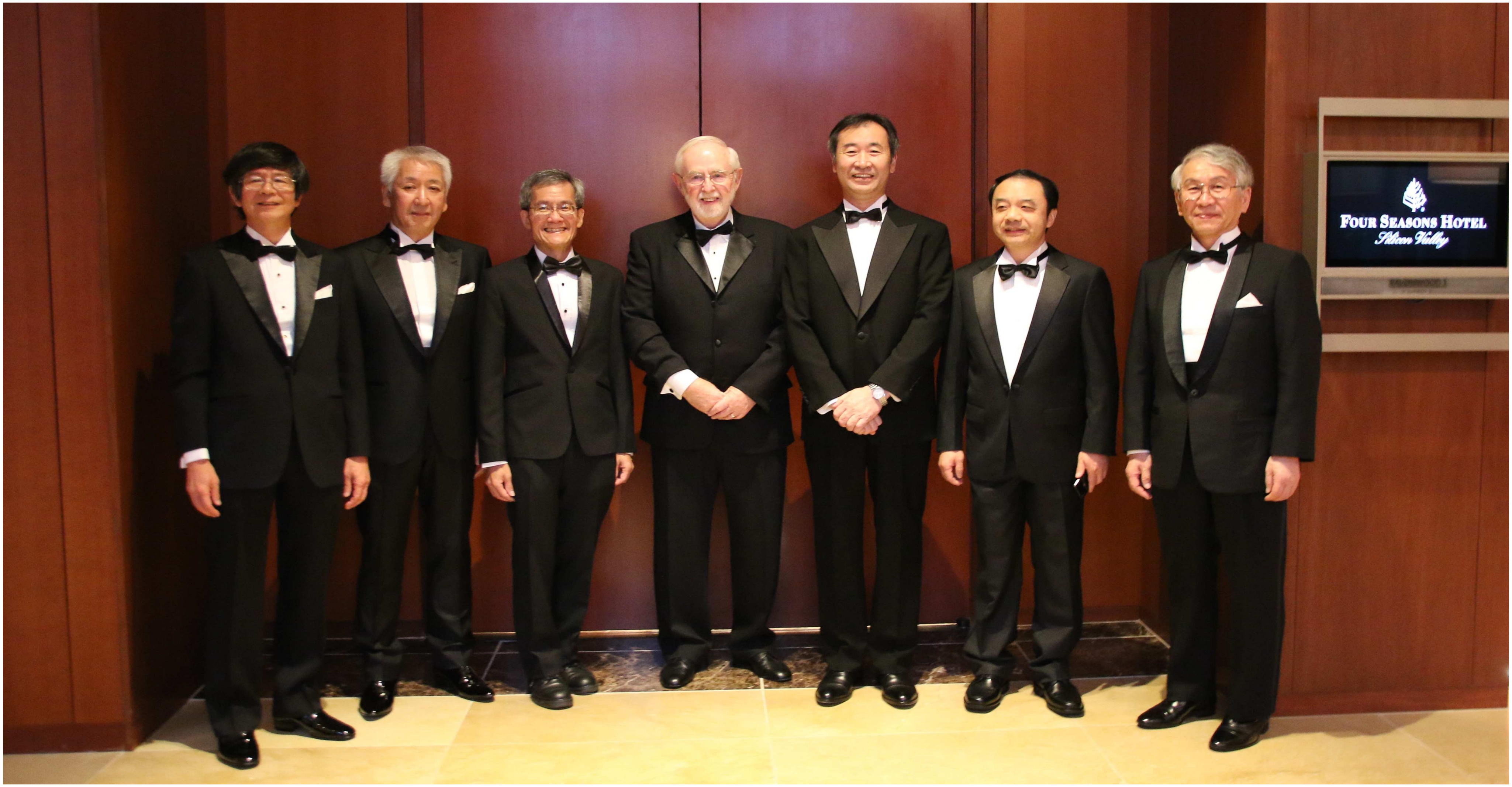

Koichiro Nishikawa and the K2K and T2K Collaboration


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 observed pattern of neutrino mixing and in the values of the CPV phases in the PMNS matrix.

- In the Majorana nature of massive neutrinos.

- 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 particles, e.g., at the TeV scale: heavy Majorana Neutrinos N_j, doubly charged scalars,...

- 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 $\nu_{e(\mu)} \to \nu_S$ 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"); tests (STEREO, BOREXINO,...) 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: $P(\nu_\mu \to \nu_{\tau(e)}) \neq 0$, $P(\nu_\mu \to \nu_\mu) < 1$

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

Three Neutrino Mixing

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

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

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

- U - $n \times n$ unitary:

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

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

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

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:

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

– 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.
– $Q_{U(1)} = 0: \ Q_{\text{el}} = 0,\ L_l = 0,\ L = 0, ...$
– $\chi_k(x)$: 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

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.37 \times 10^{-5}$ 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).
- $1\sigma(\Delta m^2_{21}) = 2.6\%$, $1\sigma(\sin^2\theta_{12}) = 5.4\%$;
- $1\sigma(|\Delta m^2_{31(23)}|) = 2.6\%$, $1\sigma(\sin^2\theta_{23}) = 9.6\%$;
- $1\sigma(\sin^2\theta_{13}) = 8.5\%$;
- $3\sigma(\Delta m^2_{21})$: $(6.99 - 8.18) \times 10^{-5}$ eV^2; $3\sigma(\sin^2\theta_{12})$: $(0.259 - 0.359)$;
($3\sigma(\Delta m^2_{21})$: $(6.93 - 7.97) \times 10^{-5}$ 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

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

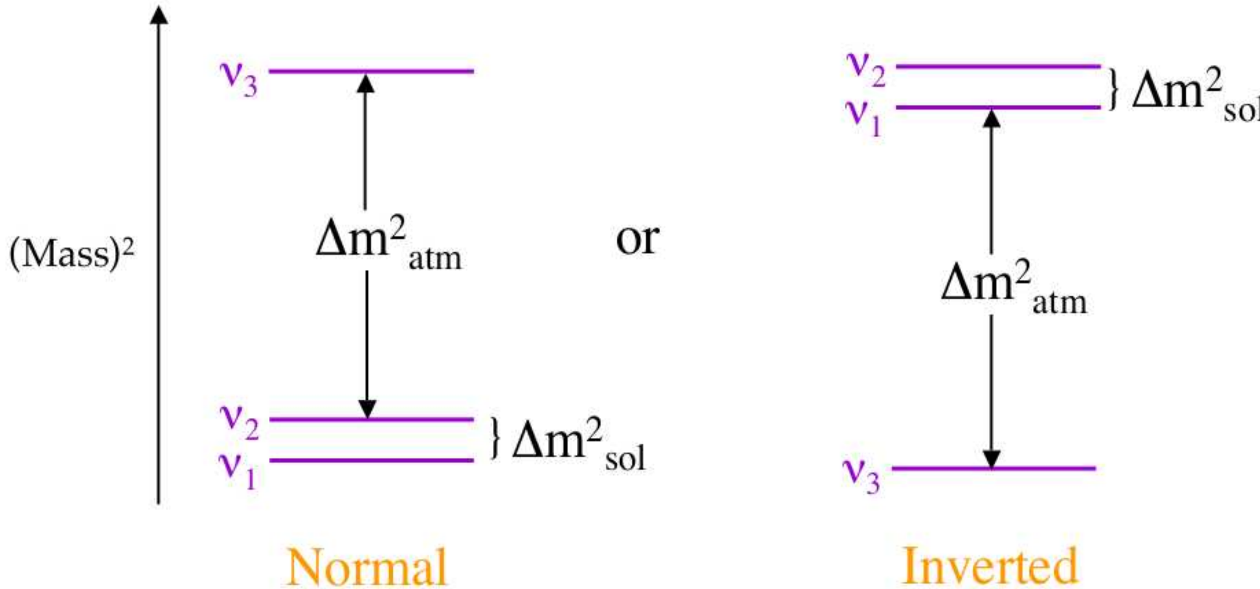
$$m_1 \ll m_2 < m_3, \qquad \text{NH},$$

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

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

- $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$, $m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$ - NO;
- $m_1 = \sqrt{m_3^2 + \Delta m^2_{23} - \Delta m^2_{21}}$, $m_2 = \sqrt{m_3^2 + \Delta m^2_{23}}$ - IO;

The (Mass)^2 Spectrum

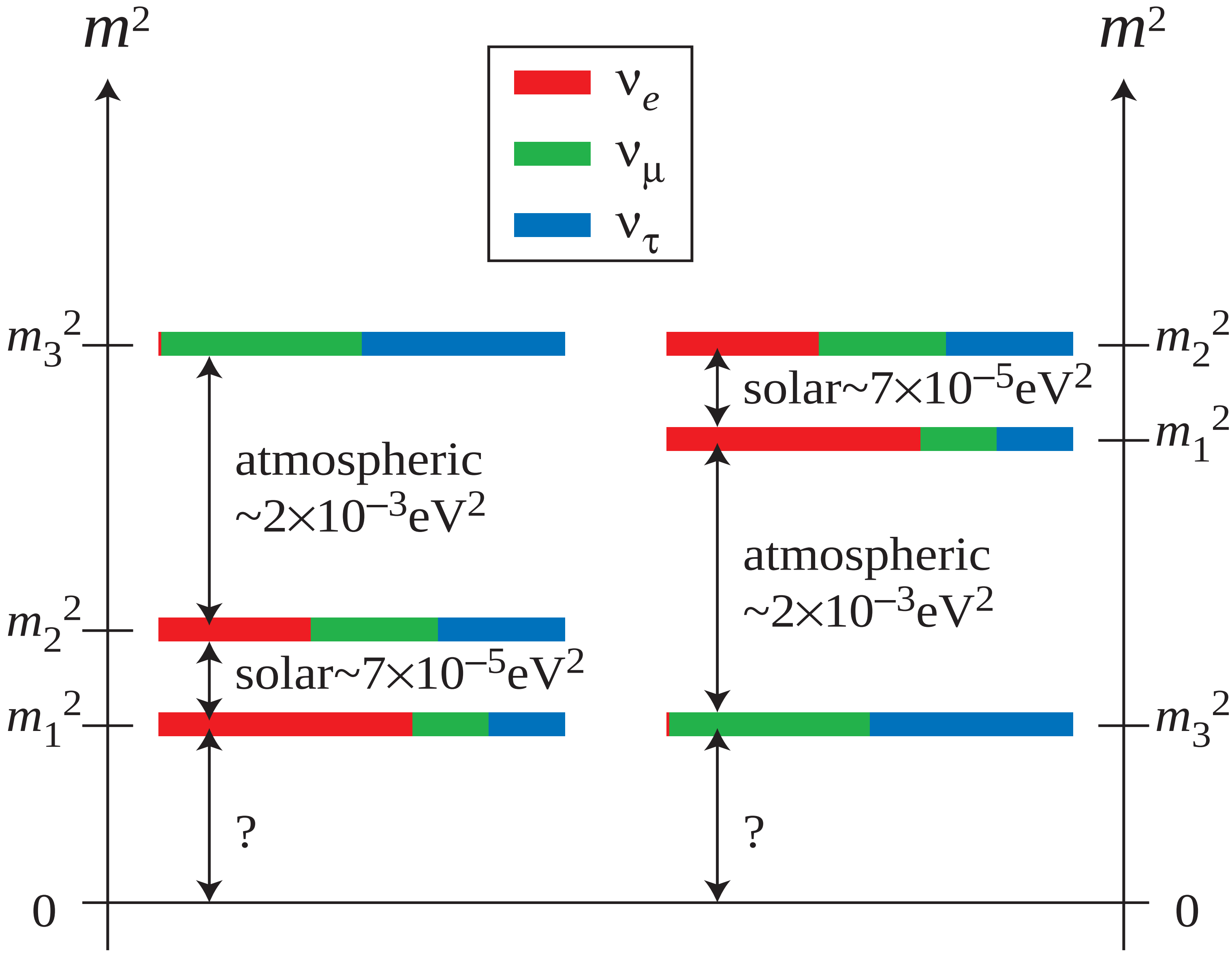


$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ eV^2$, $\quad \Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

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

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;

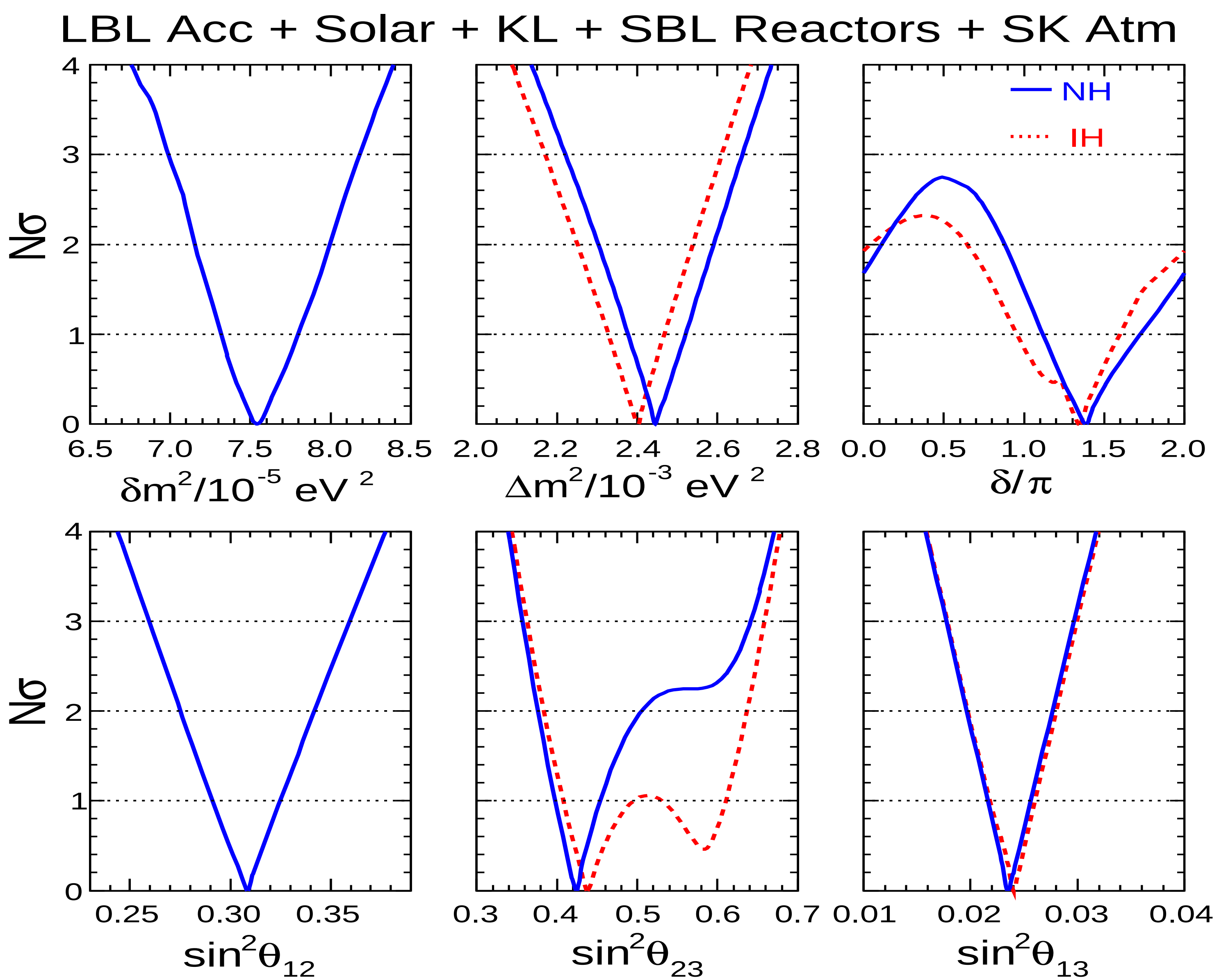
S.M. Bilenky, J. Hosek, S.T.P.,1980;
P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

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

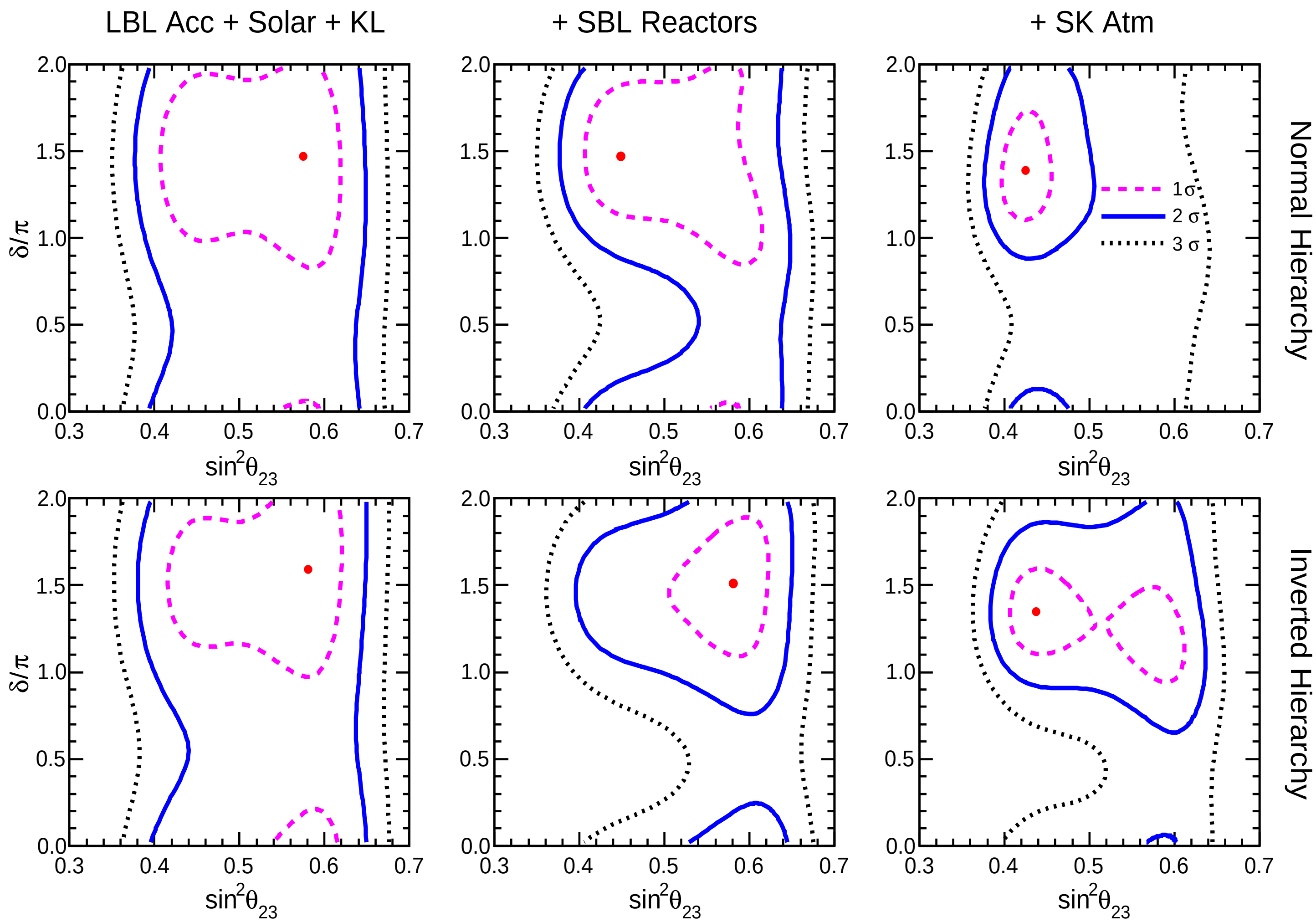
$$\delta \cong 3\pi/2?$$

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

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

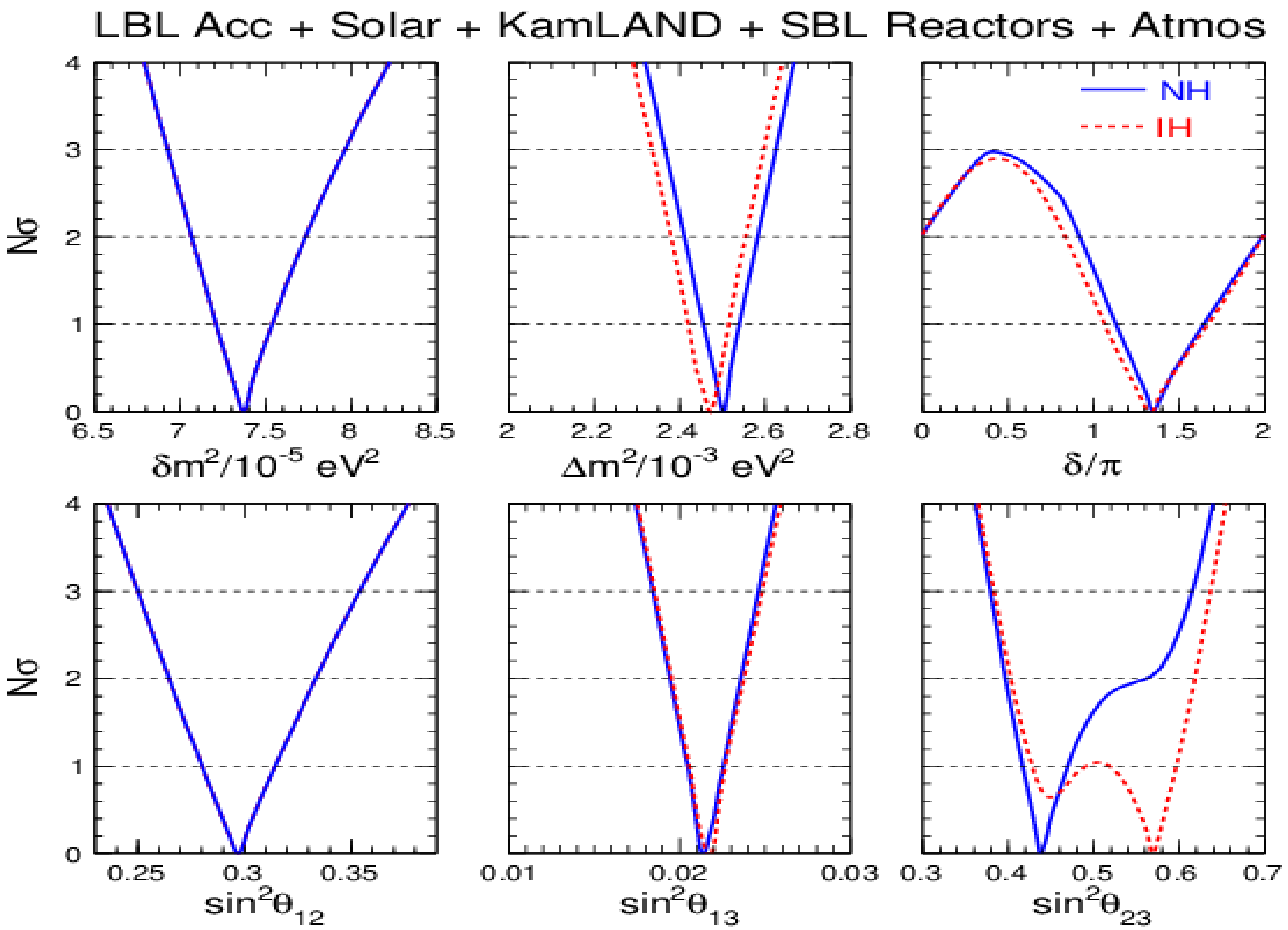


F. Capozzi, E. Lisi *et al.*, arXiv:1312.2878



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

The first results on $\nu_\mu \to \nu_e$ oscillations from NOνA (August 6, 2015; 6 (12) events) are compatible with, and somewhat strengthened, the hint that $\delta \cong 3\pi/2$ (A. Marone, talk at TAUP 2015; F. Capozzi *et al.*, arXiv:1601.01777v1).



F. Capozzi, E. Lisi *et al.*, arXiv:1601.01777v1

• November 11, 2011, Double Chooz: 2σ evidence for $\theta_{13} \neq 0$.

• 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 $\theta_{13} \neq 0$, $\sin^2 2\theta_{13} = 0.113 \pm 0.013 \pm 0.019$.

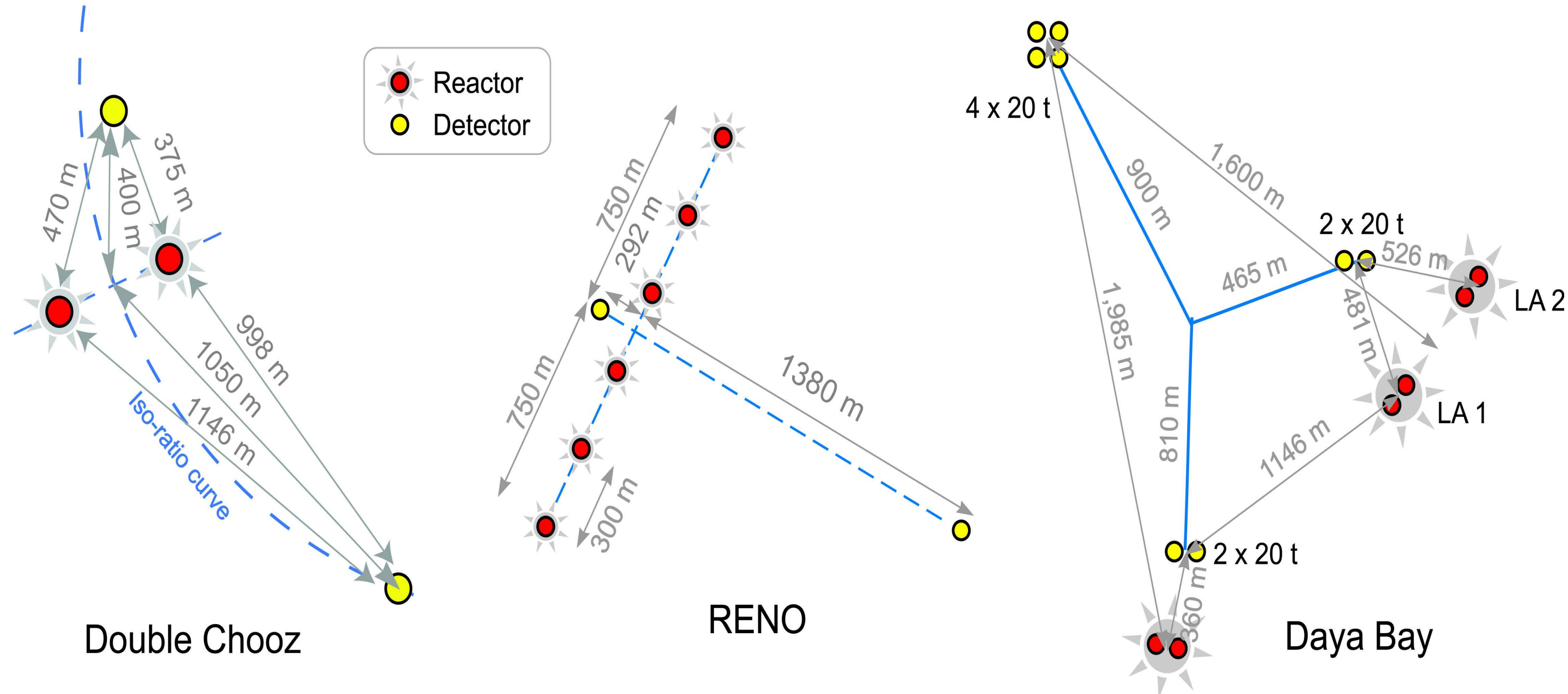
• Daya Bay, May 2015:
$\sin^2 2\theta_{13} = 0.084 \pm 0.005$.

• RENO, April 2015 (WIN 2015):
$\sin^2 2\theta_{13} = 0.087 \pm 0.008\ (stat.) \pm 0.008$.

• Double Chooz, 2014:
$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}\ (0.092^{+0.033}_{-0.029})$.

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

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



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


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: 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.

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

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

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

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

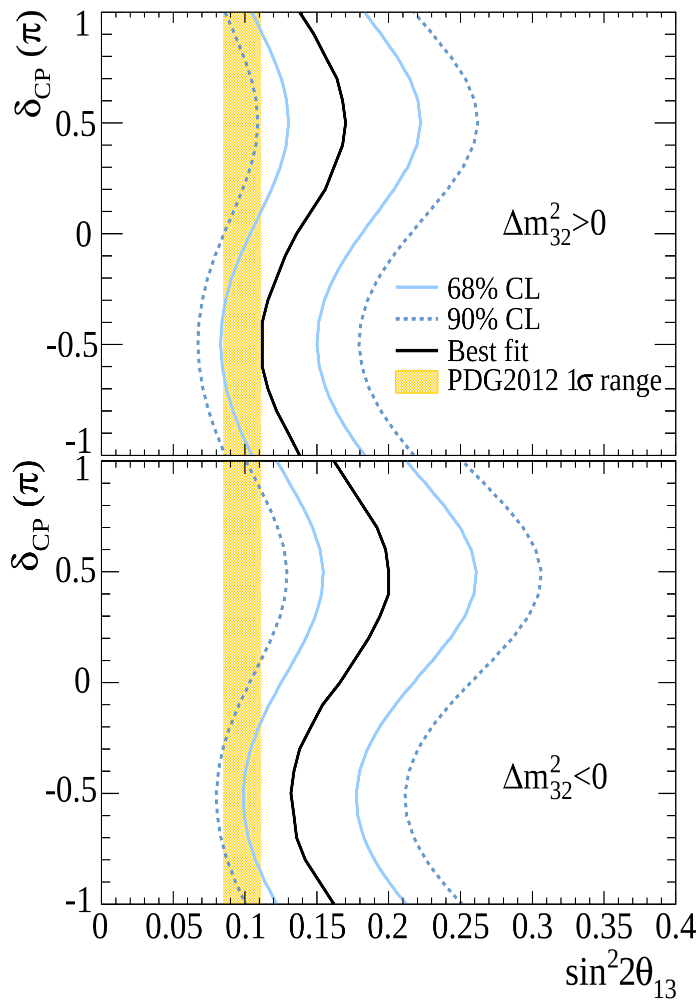
$$P_3 = \alpha^2\cos^2\theta_{23}\,\frac{\sin^2 2\theta_{12}}{A^2}\,\sin^2(A\Delta),$$

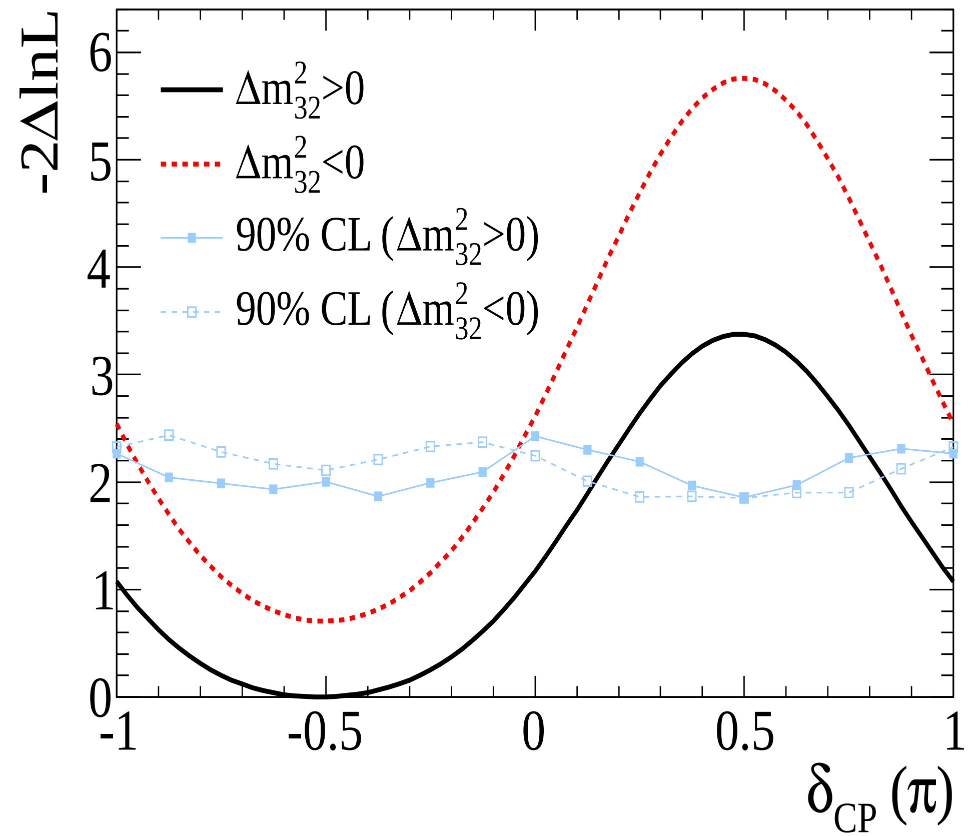
$$P_{\sin\delta} = -\,\alpha\,\frac{8\,J_{CP}}{A(1-A)}(\sin\Delta)(\sin A\Delta)\,(\sin[(1-A)\Delta]),$$

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

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

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





K. Abe *et al.*, T2K Collaboration, arXiv:1311.4750

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).

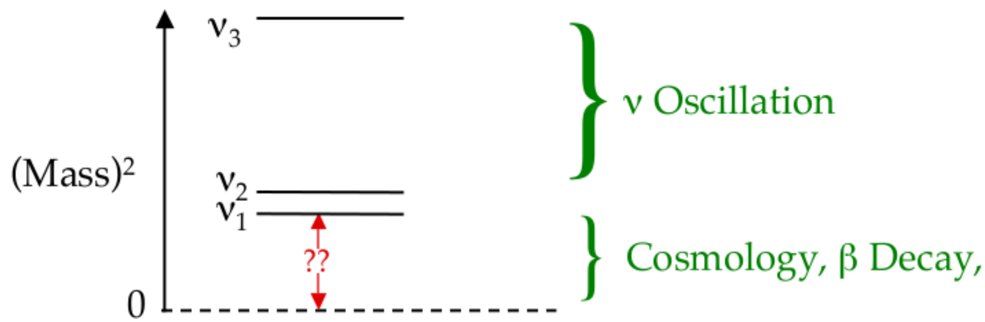
If all CPV, necessary for the generation of BAU is due to δ, a necessary condition for reproducing the observed BAU is

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

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

Absolute Neutrino Mass Scale

The Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

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

4

Due to B. Kayser

Absolute Neutrino Mass Measurements

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

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

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.

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 $\mu \to e + \gamma$, $\tau \to \mu + \gamma$, 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 neutrino mass ordering;

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

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

The program of research extends beyond 2030 (with a total cost exceeding 2.5×10^9 Euro).

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

- **Reactor $\bar{\nu}_e$ Oscillations in vacuum (JUNO, RENO50).**

  S.T.P., M. Piai, hep-ph/0112074 (PL B533 (2002) 94)

- **Atmospheric ν experiments: subdominant $\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$ and $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ oscillations (matter effects) (ORCA, PINGU (IceCube), HK, INO).**

- **LBL $\nu-$oscillation experiments T2K + NOνA; DUNE (future); + T2HK (future), 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

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

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

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

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

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

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

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

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

The visible energy of the detected e^+:

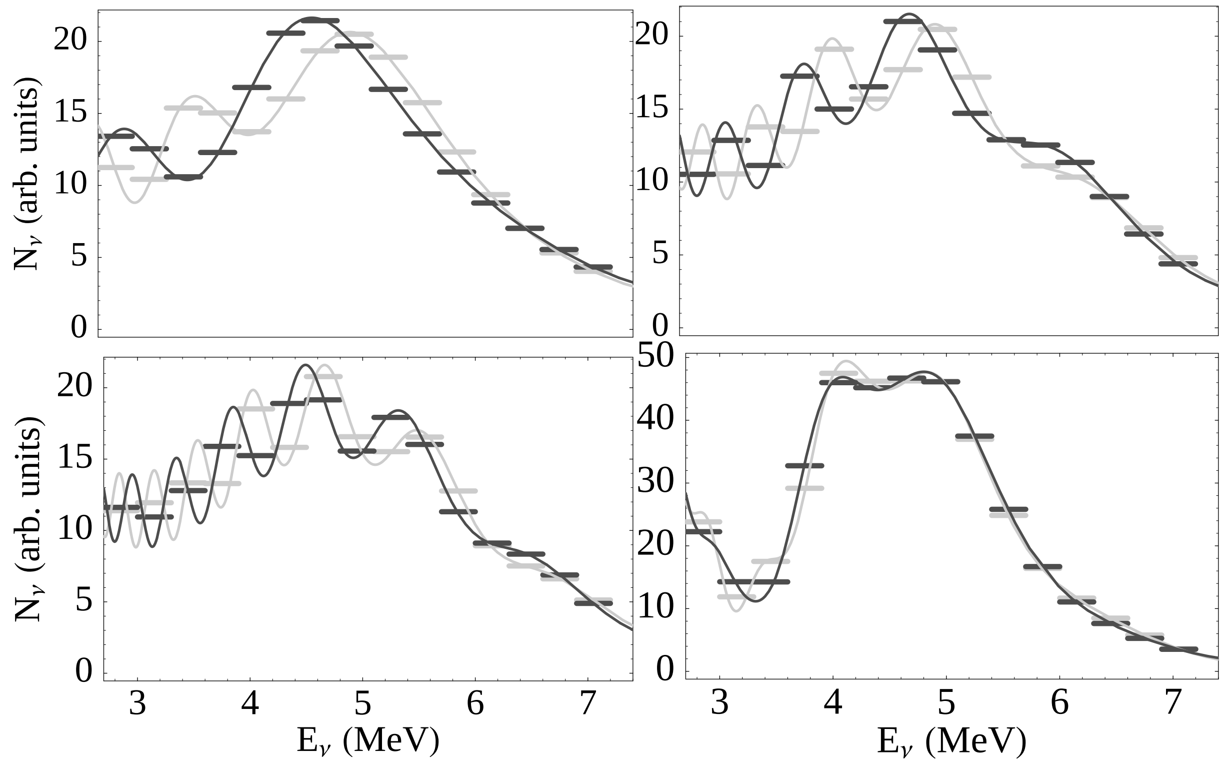
$$E_{vis} = E + m_e - (m_n - m_p) \simeq E - 0.8 \text{ MeV}\,.$$

The measured event rate spectrum vs. L/E_m:

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

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

$\cos 2\theta_{12} \cong 0.40$; 3σ : $\cos 2\theta_{12} \geq 0.29$; $\sin^2 2\theta_{13} \cong 0.084$.



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

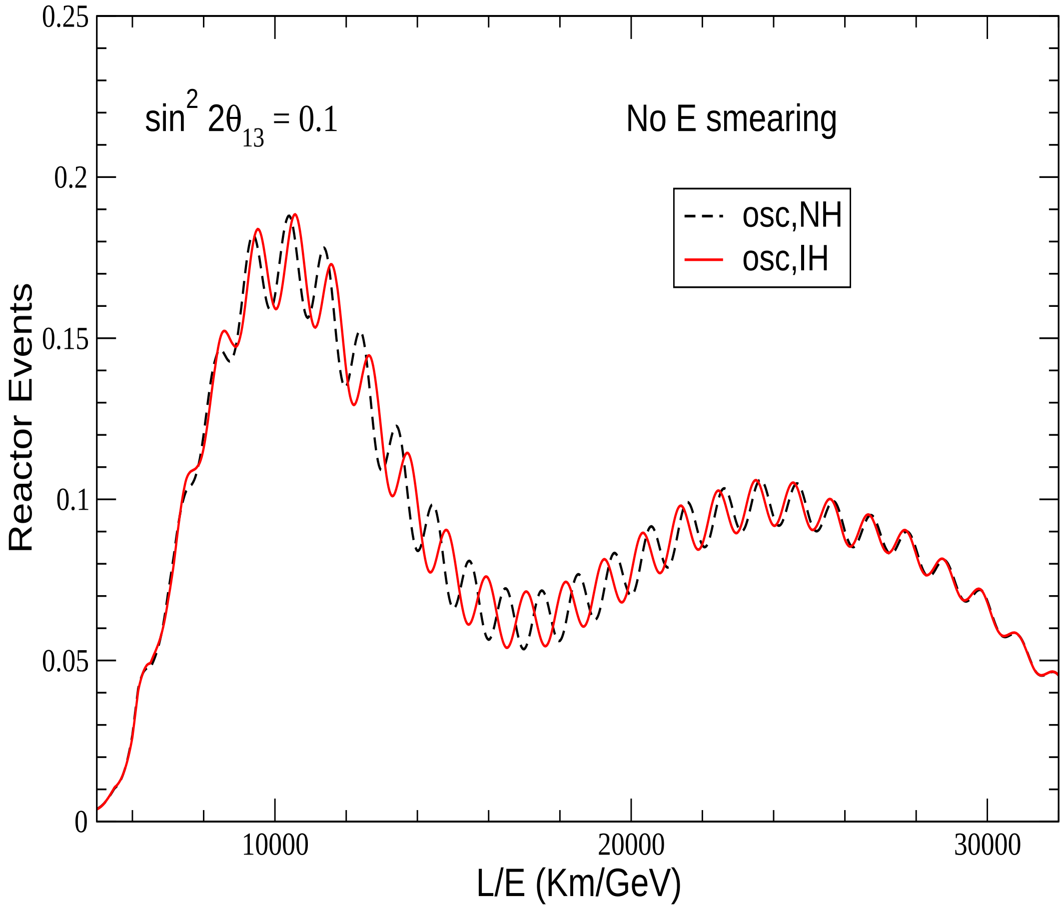
$\sin^2\theta_{13} = 0.05$, $\Delta m^2_{21} = 2\times10^{-4}$ eV^2; $\Delta m^2_{\rm A} = 1.3;\ 2.5;\ 3.5\times10^{-3}$ eV^2

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

$\Delta m^2_{21} = 2\times10^{-4}$ eV^2: $L = 20$ km;

$\Delta m^2_{21} = 7.6\times10^{-5}$ eV^2: $L \cong 53$ km.

NO – light grey; IO – dark grey



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

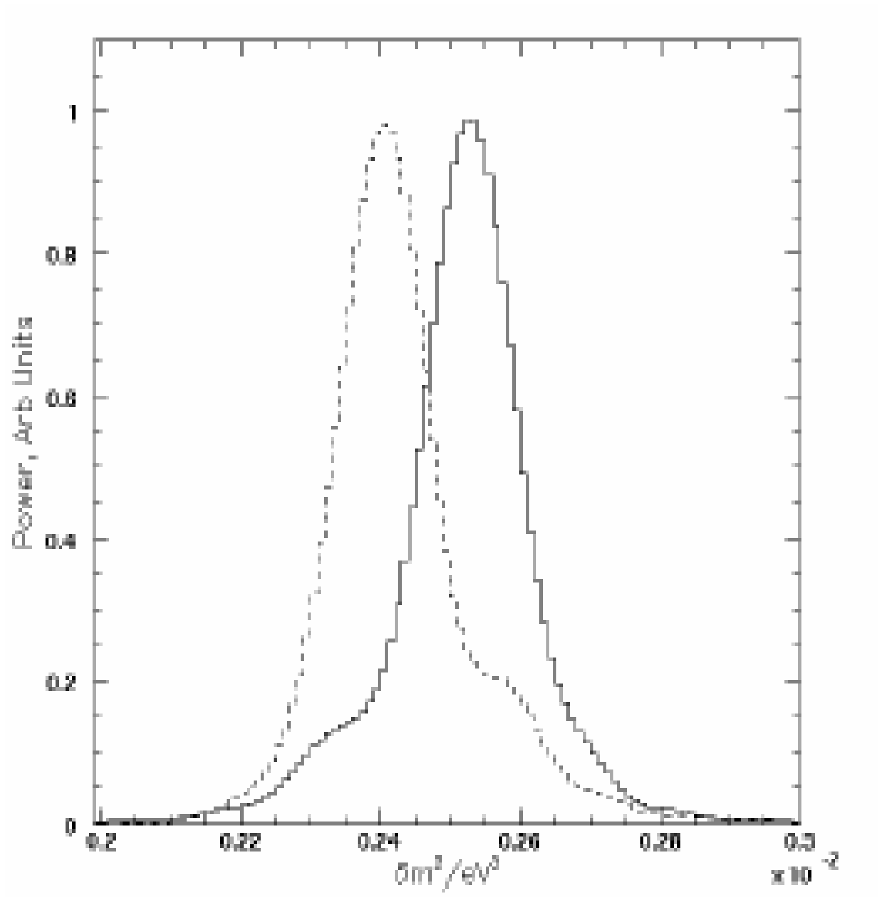
Fourier Analysis:

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

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

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

$$\sin^2\theta_{12} \cong 0.30, \quad \cos^2\theta_{12} \cong 0.70.$$



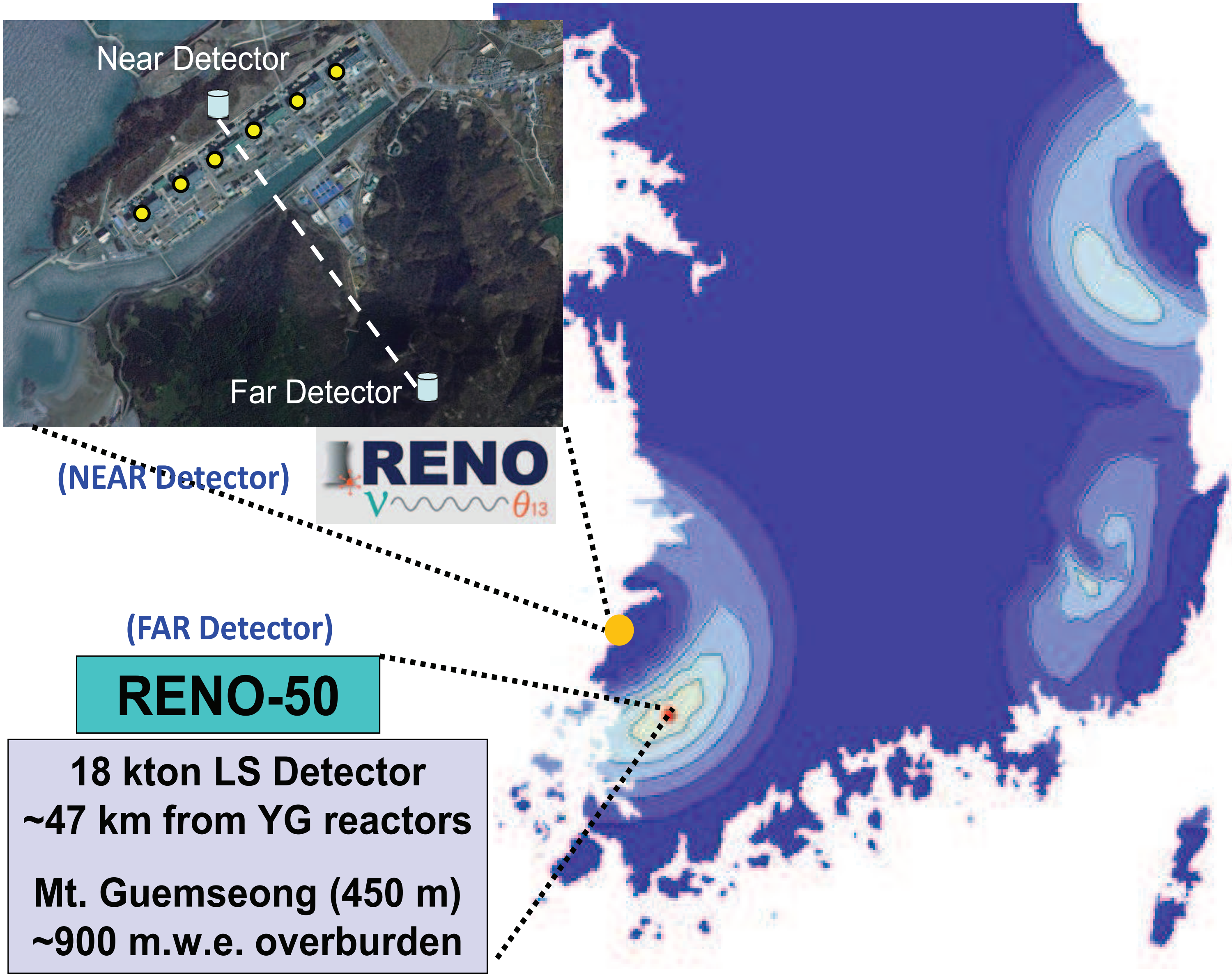
J.Learned et al., 2007

Very challenging; requires:

- energy resolution $\sigma/E_{\rm vis} \lesssim 3\%/\sqrt{E_{\rm vis}}$;
- 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.


Guangzhou
Guang Zhou
Dongguan
Huizhou
Zhaoqing
CNS
2.5 h drive
Shen Zhen
Huizhou NPP
Lufeng NPP
Daya Bay
NPP
Zhongshan
Zhu Hai
Zhujiang River Estuary
Hong Kong
Hong Kong
Macau
Macau
JUNO site
53 km
53 km
Taishan NPP
Yangjiang NPP


Near Detector
Far Detector
RENO
(NEAR Detector)
(FAR Detector)
RENO-50
18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden

Atmospheric Neutrino Experiments on sgn(Δm^2_{31})

Atmospheric ν experiments

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

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

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

$P_{2\nu} \equiv P_{2\nu}(\Delta m^2_{31}, \theta_{13}; E, \theta_n; N_e)$: 2-$\nu$ $\nu_e \rightarrow \nu'_\tau$ 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 $A_{2\nu}(\nu_\tau \rightarrow \nu_\tau) \equiv A_{2\nu}$ are known phase and 2-ν amplitude.

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

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

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

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.

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

$\sin^2 2\theta_{13}^m$, ΔM_{31}^2 depend on the matter potential
$V_{eff} = \sqrt{2}\, G_F\, N_e$,

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

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

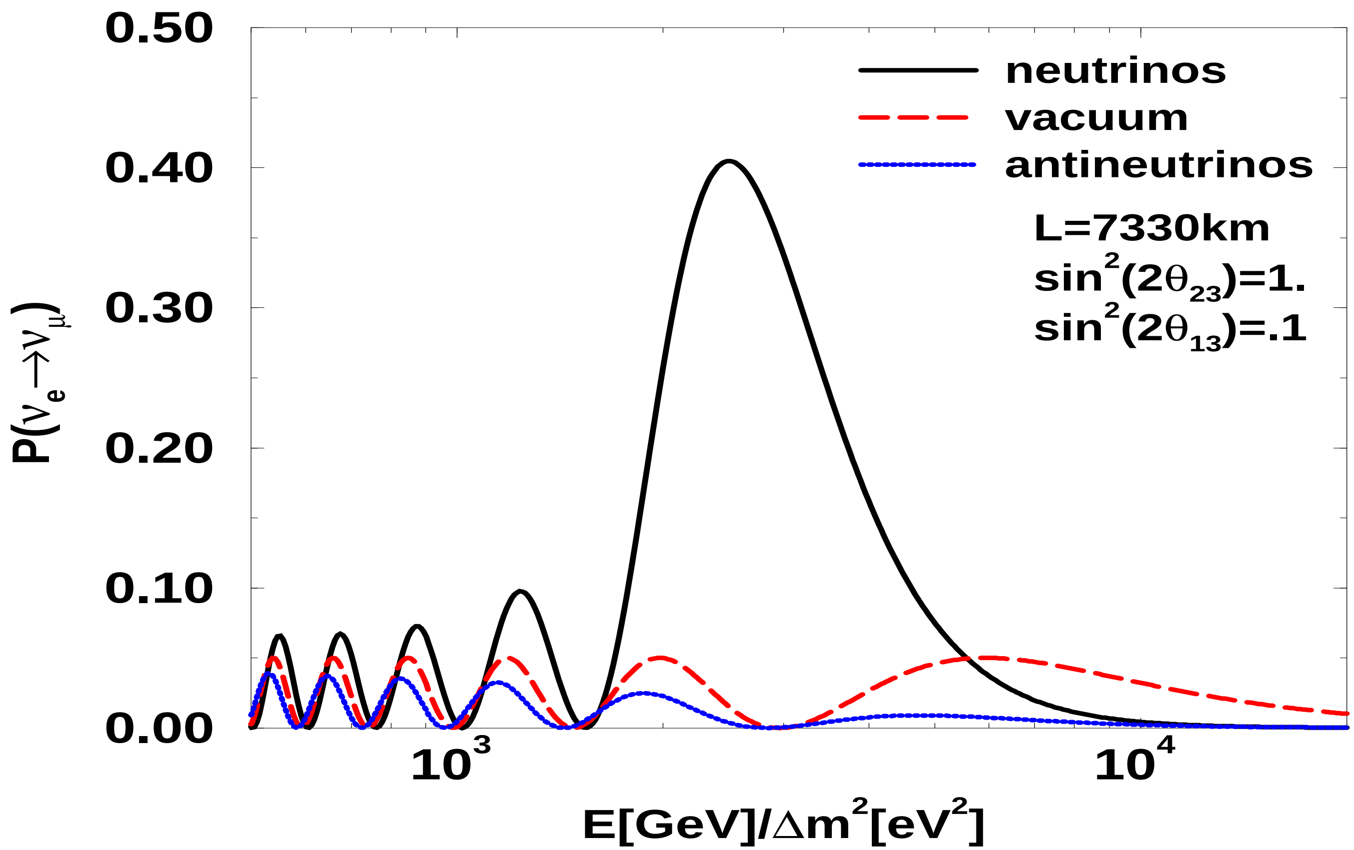
$\Delta m_{31}^2 < 0$ (IO): $\bar{\nu}_{\mu(e)} \rightarrow \bar{\nu}_{e(\mu)}$ matter enhanced,
$\nu_{\mu(e)} \rightarrow \nu_{e(\mu)}$ −suppressed

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

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

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, KM3Net-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 (?)

KM3Net in Mediteranian sea: ORCA

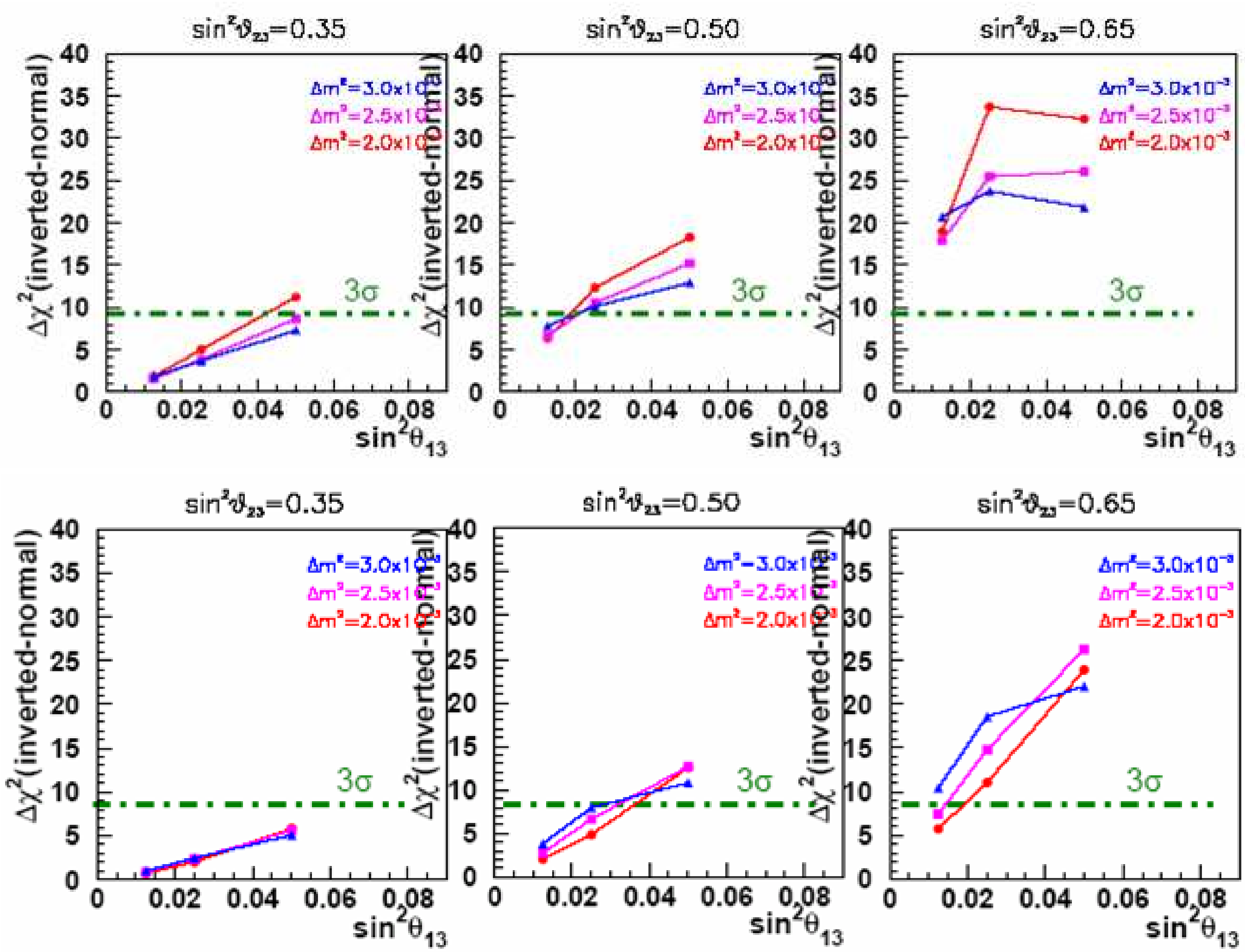
Water-Cerenkov detector: Hyper-Kamiokande (0.99 Mton; fiducial: 0.56 Mton)

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

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

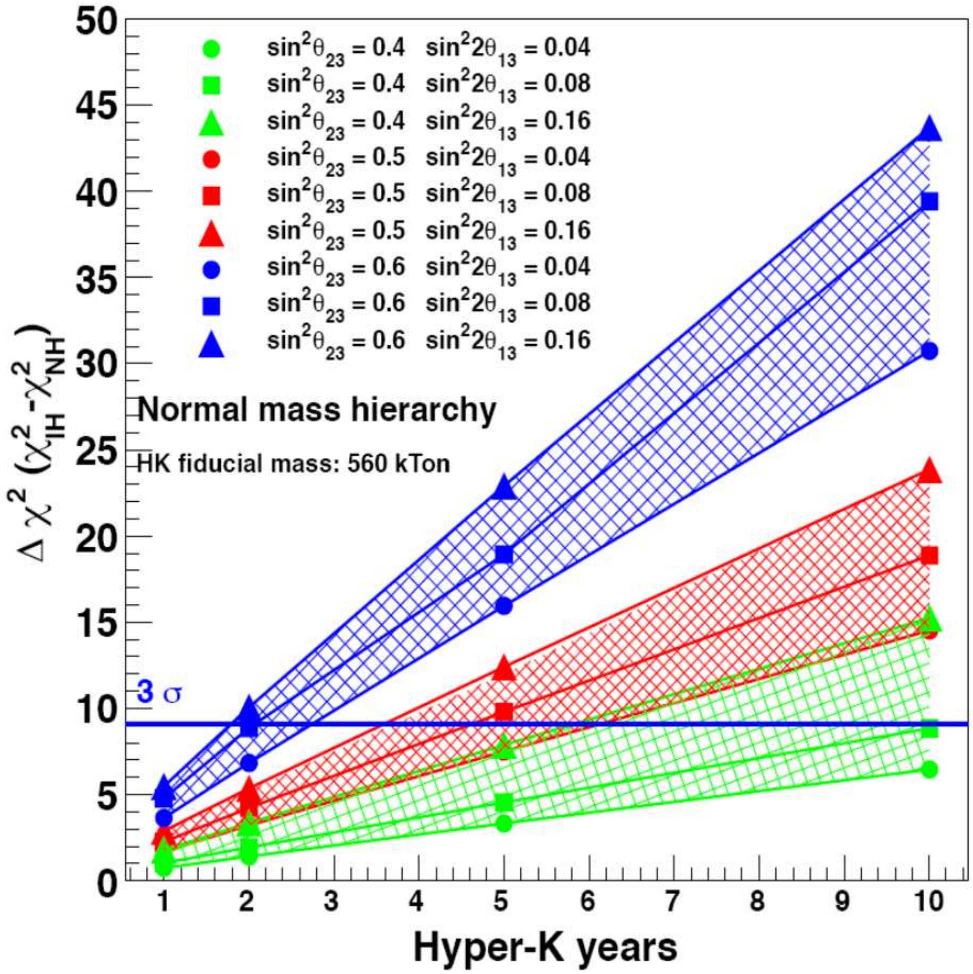


Water-Cerenkov detector, 1.8 MTy (HK)

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.

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

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

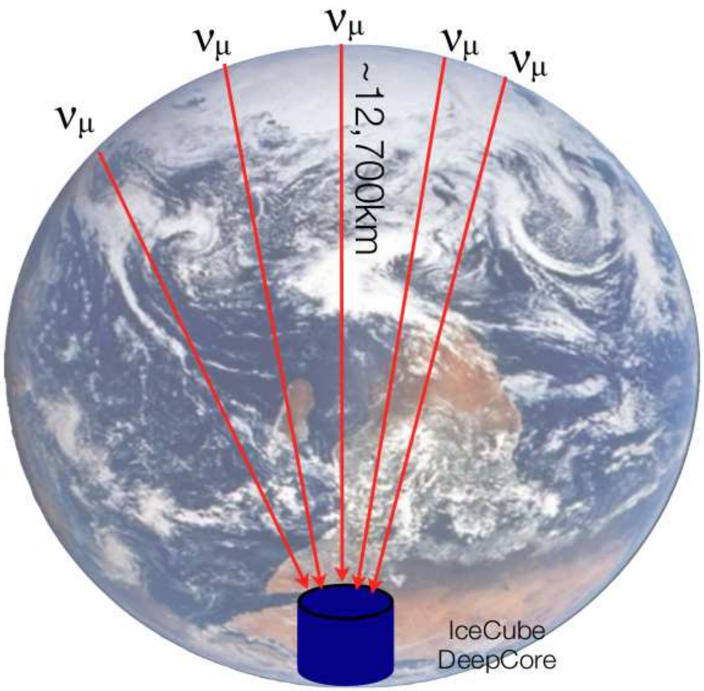
Some physics targets and expected sensitivities of the HK experiment (K. Abe et al., arXiv:1109.3262) and T2HK experiment (K. Abe et al., arXiv:1502.05199) Improvements are expected; only selected values are listed (e.g., other channels will be accessible for nucleon decays).

Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		$7.5\,\text{MW} \times 10^7$ sec
– CP phase precision	$< 19^\circ$	@ $\sin^2 2\theta_{13} = 0.1$, MO known
– CPV discovery coverage	76% ($3\,\sigma$), 58% ($5\,\sigma$)	@ $\sin^2 2\theta_{13} = 0.1$, MO known
– $\sin^2\theta_{23}$	± 0.015	1σ @ $\sin^2\theta_{23} = 0.5$
Atmospheric neutrino study		10 years observation
– MO determination	$> 3\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$> 3\,\sigma$ CL	@ $\sin^2\theta_{23} < 0.46$ or $\sin^2\theta_{23} > 0.56$
Nucleon Decay Searches		10 years data
– $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL UL)	
	5.7×10^{34} yrs ($3\,\sigma$ discovery)	
– $p \to \bar{\nu} + K^+$	3.2×10^{34} yrs (90% CL UL)	
	1.2×10^{34} yrs ($3\,\sigma$ discovery)	
Astrophysical neutrino sources		
– ^{8}B ν from Sun	200 ν's / day	7.0 MeV threshold (total energy)
– Supernova burst ν	170,000$\sim$260,000 ν's	@ Galactic center (10 kpc)
	30$\sim$50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	
– WIMP annihilation at Sun		5 years observation
(σ_{SD}: WIMP-proton spin	$\sigma_{SD} = 10^{-39}\text{cm}^2$	@ $M_{\text{WIMP}} = 10\,\text{GeV}$, $\chi\chi \to b\bar{b}$ dominan
dependent cross section)	$\sigma_{SD} = 10^{-40}\text{cm}^2$	@ $M_{\text{WIMP}} = 100\,\text{GeV}$, $\chi\chi \to W^+W^-$ do

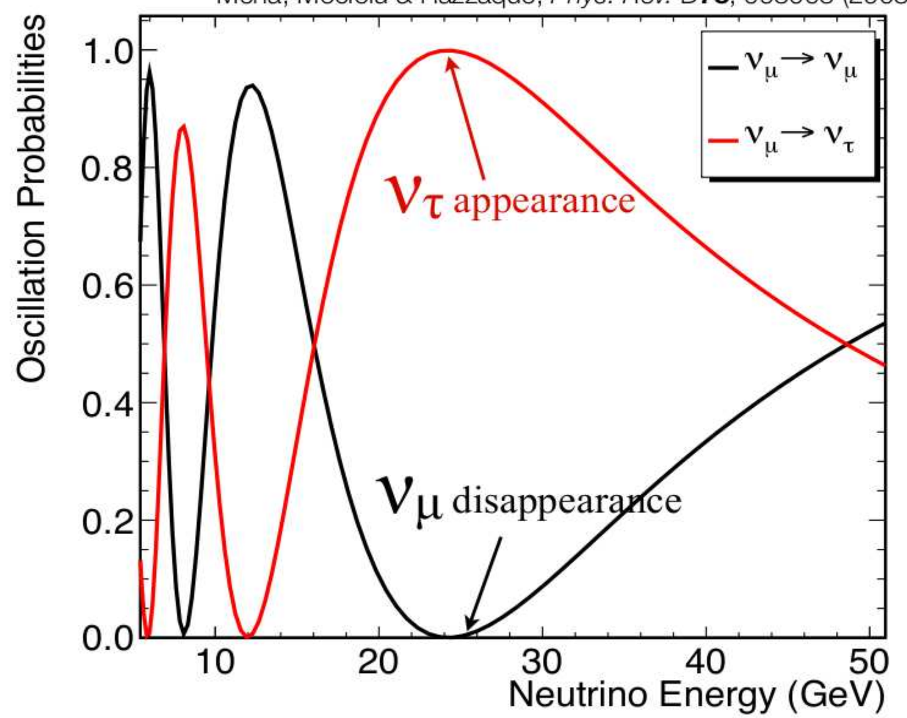
Neutrino Oscillation Source

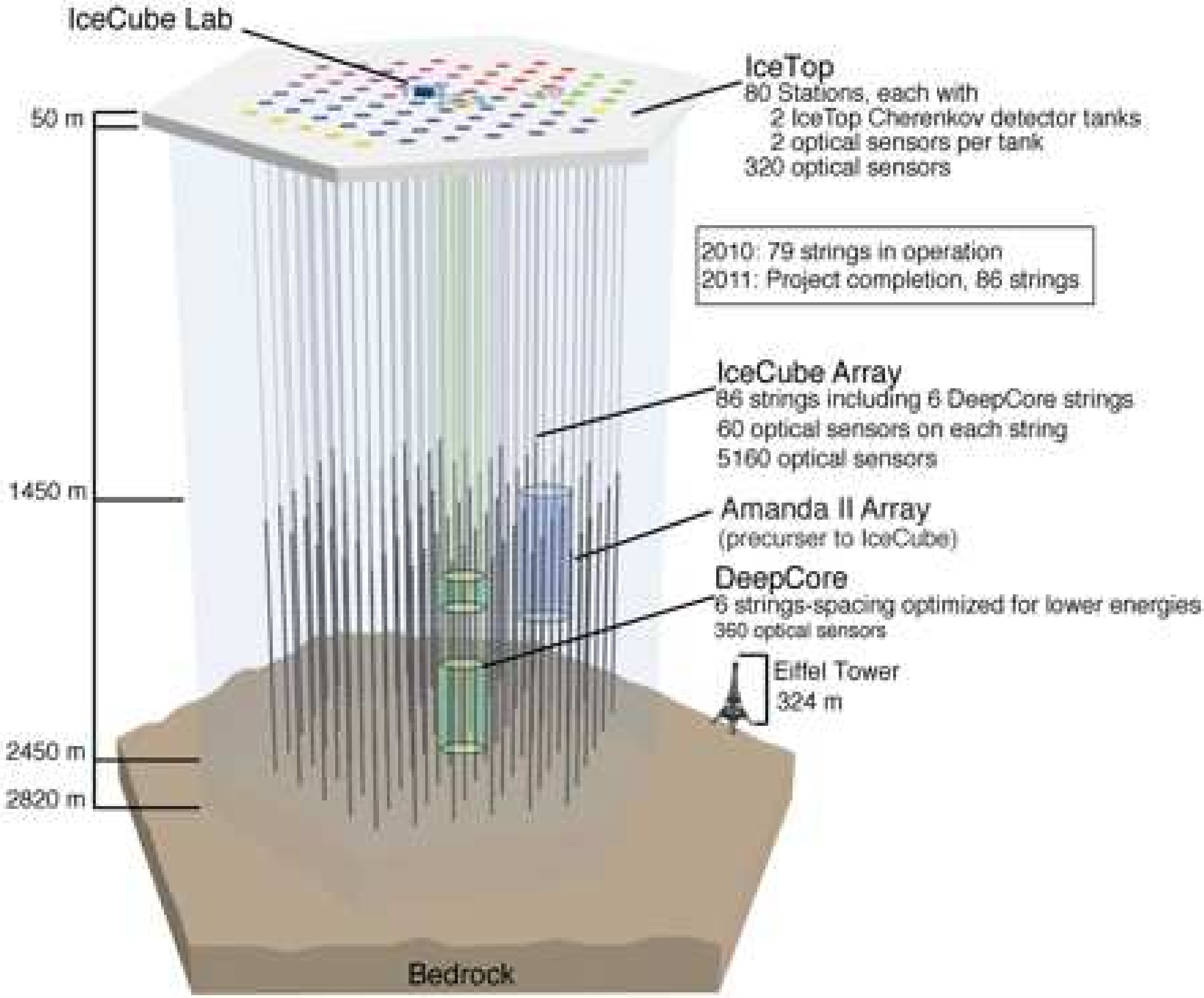
- Oscillation
- IceCube-DeepCore Physics
- PINGU
- Beyond

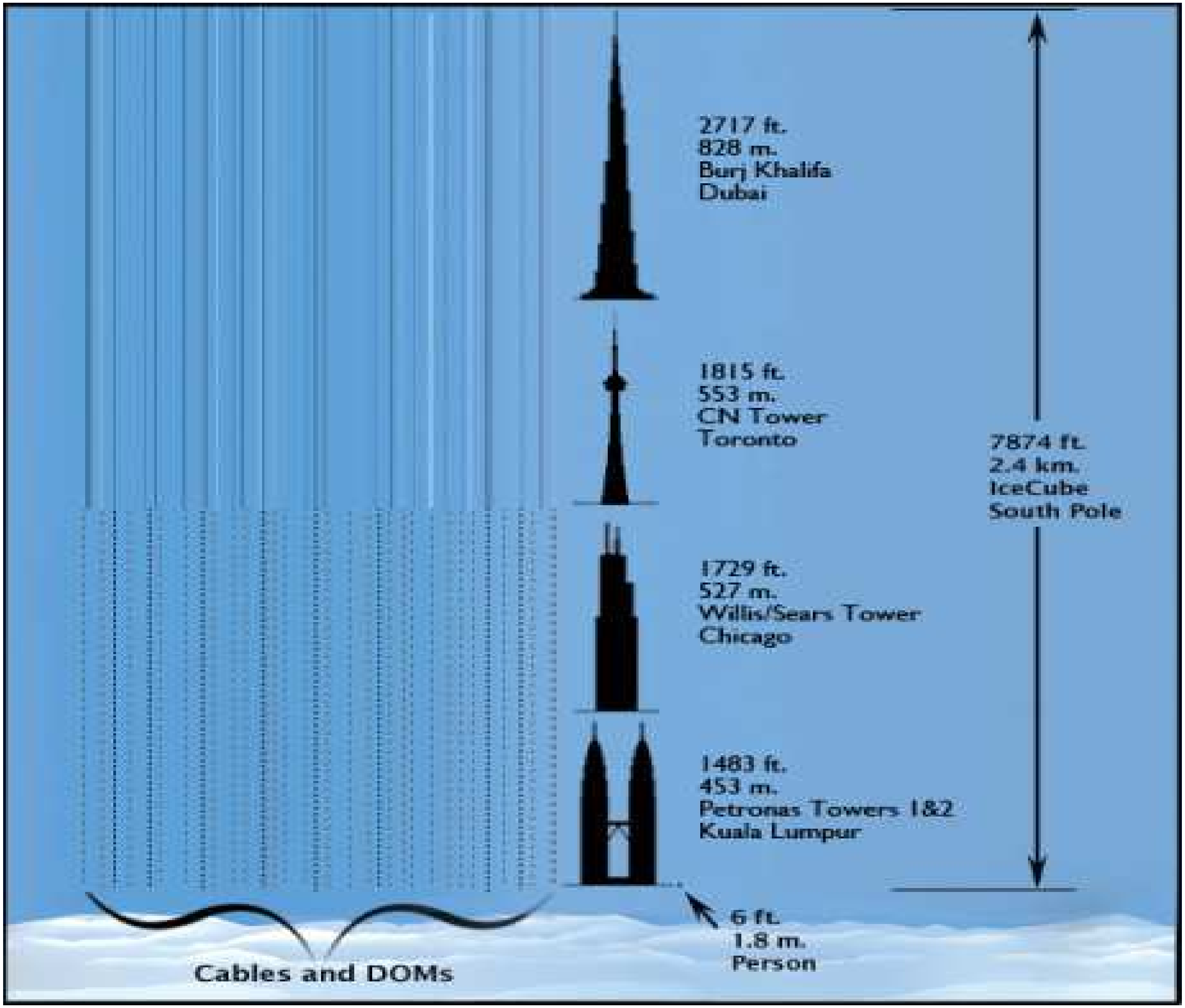
- Northern Hemisphere ν_μ oscillating over one earth radii produces ν_μ (ν_τ) oscillation minimum(maximum) at ~25 GeV
  - Covers all possible terrestrial baselines
  - "Beam" is free and never turns off



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

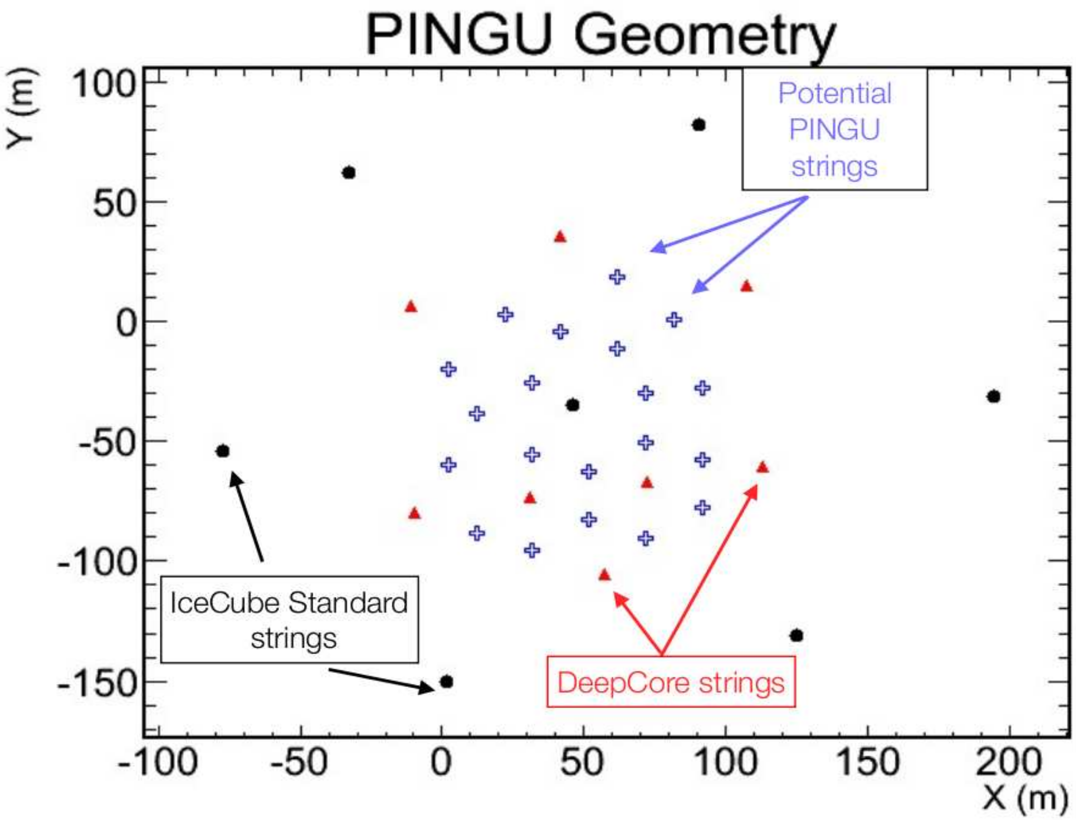



IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
50 m
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors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


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

PINGU: Possible Geometry

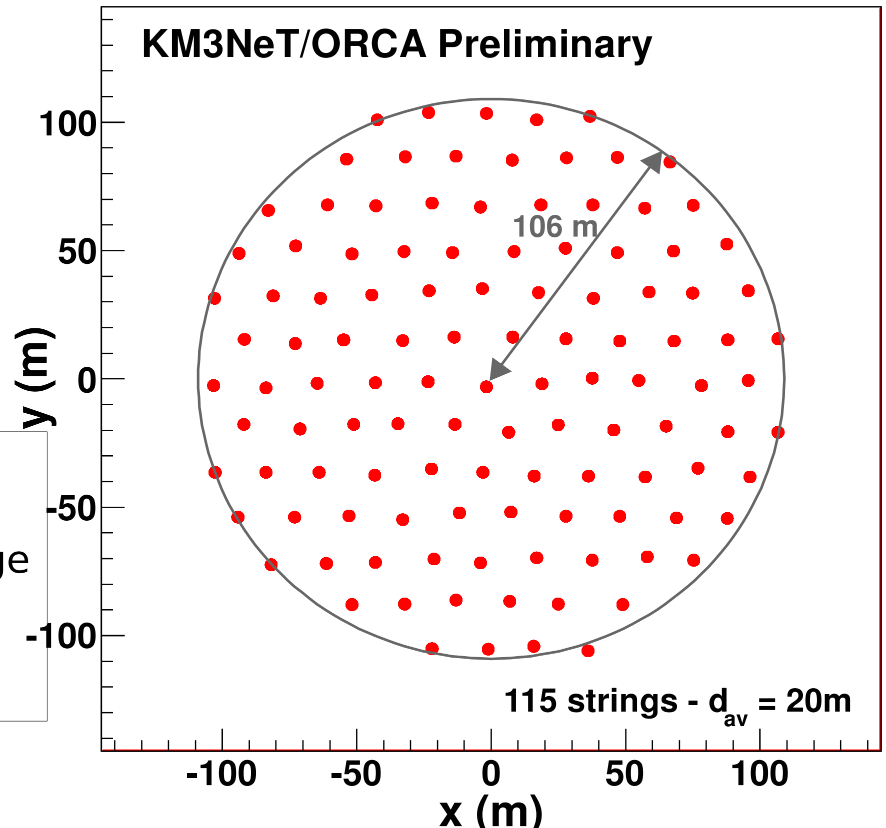
- ~20 strings within DeepCore volume w/ short string-string spacing
  - IC-IC: 125m
  - DC-DC: ~80m
  - PINGU-PINGU: <= 26m
- Shorter DOM-DOM spacing
  - IC-IC: 17m
  - DC-DC: 7m
  - PINGU-PINGU: <= 5m
- R & D for future water/ice cerenkov



Koskinen, BNL, 2012

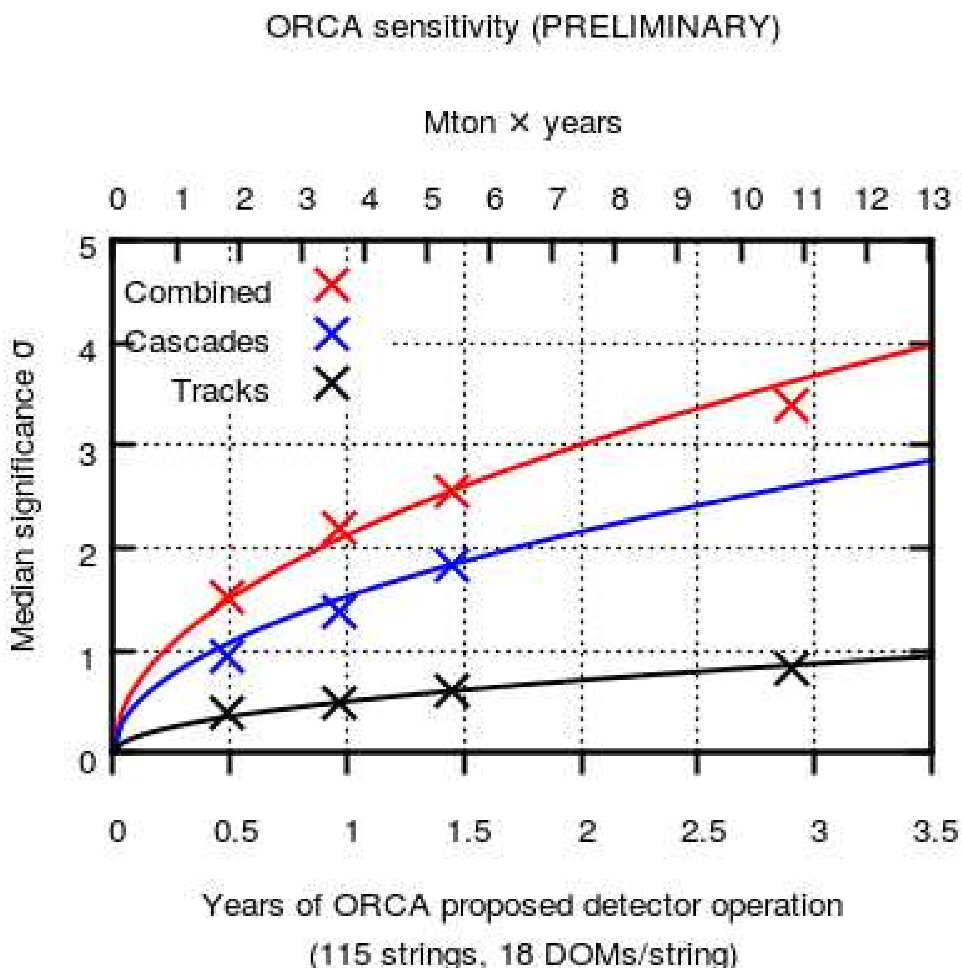
he ORCA proposed detector

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

03/09/2014

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

LBL Oscillation Experiments NOνA, DUNE, T2HK (HK=Hyper-Kamiokande)

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

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

DUNE: Fermilab-DUSEL, $L = 1290$ km, 1.2 MW (2.3 MW) proton beam, wide band ν beam (first and second osc. maxima at $E = 2.4$ GeV and 0.8 GeV); 34 kt fiducial volume LAr detecors; plans to run 5 years with ν_μ and 5 years with $\bar{\nu}_\mu$; 2025 (?)

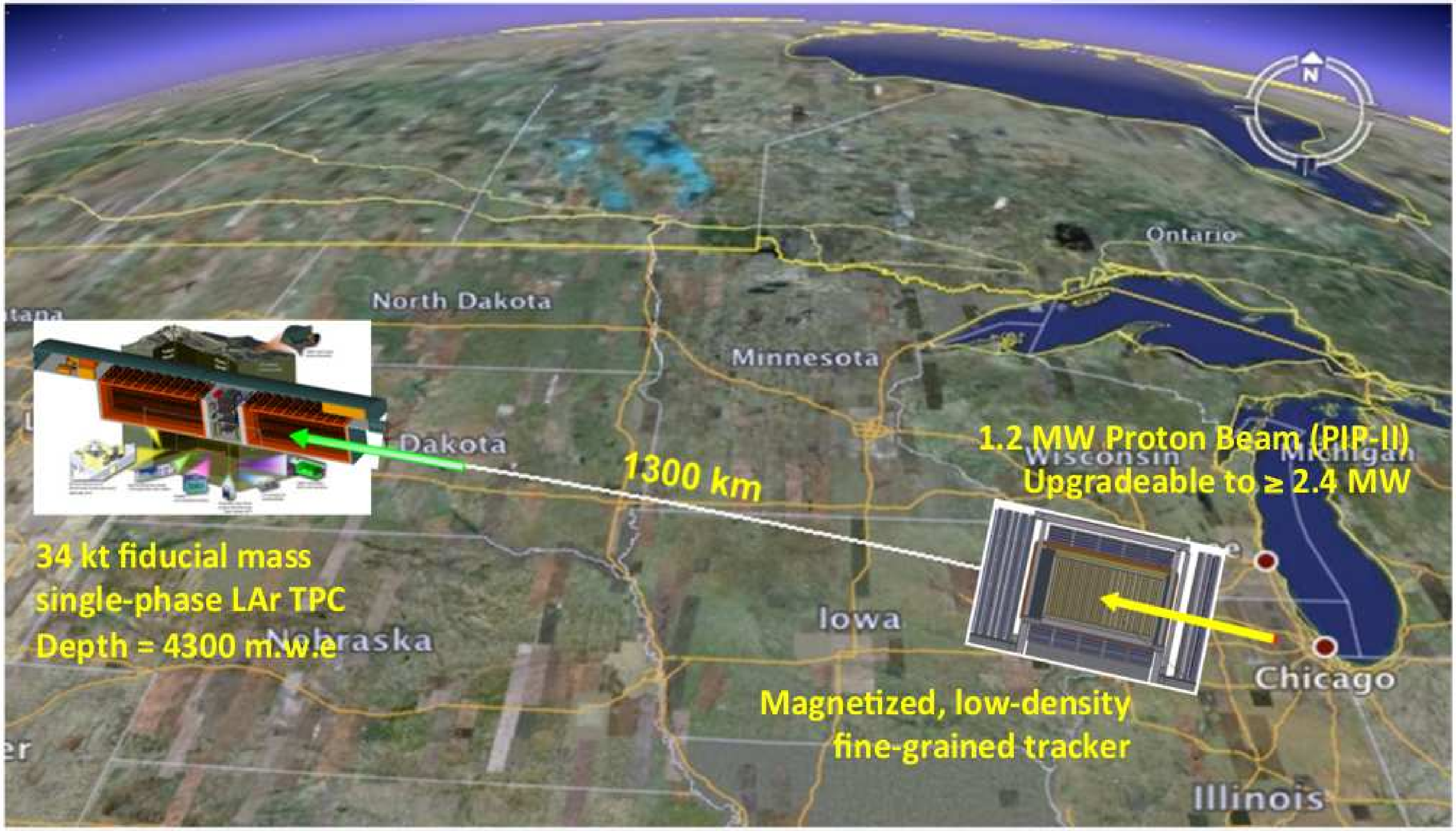

Sendai
Super Kamiokande
295km
JAERI
(Tokai)
Japan
KEK
Tokyo
Gifu
Kawasaki
Nagoya
Kyoto
Yokohama
Osaka
(c) 2000 ESRI
~ 420.0 mi / 675.8 km across

T2SK, T2HK

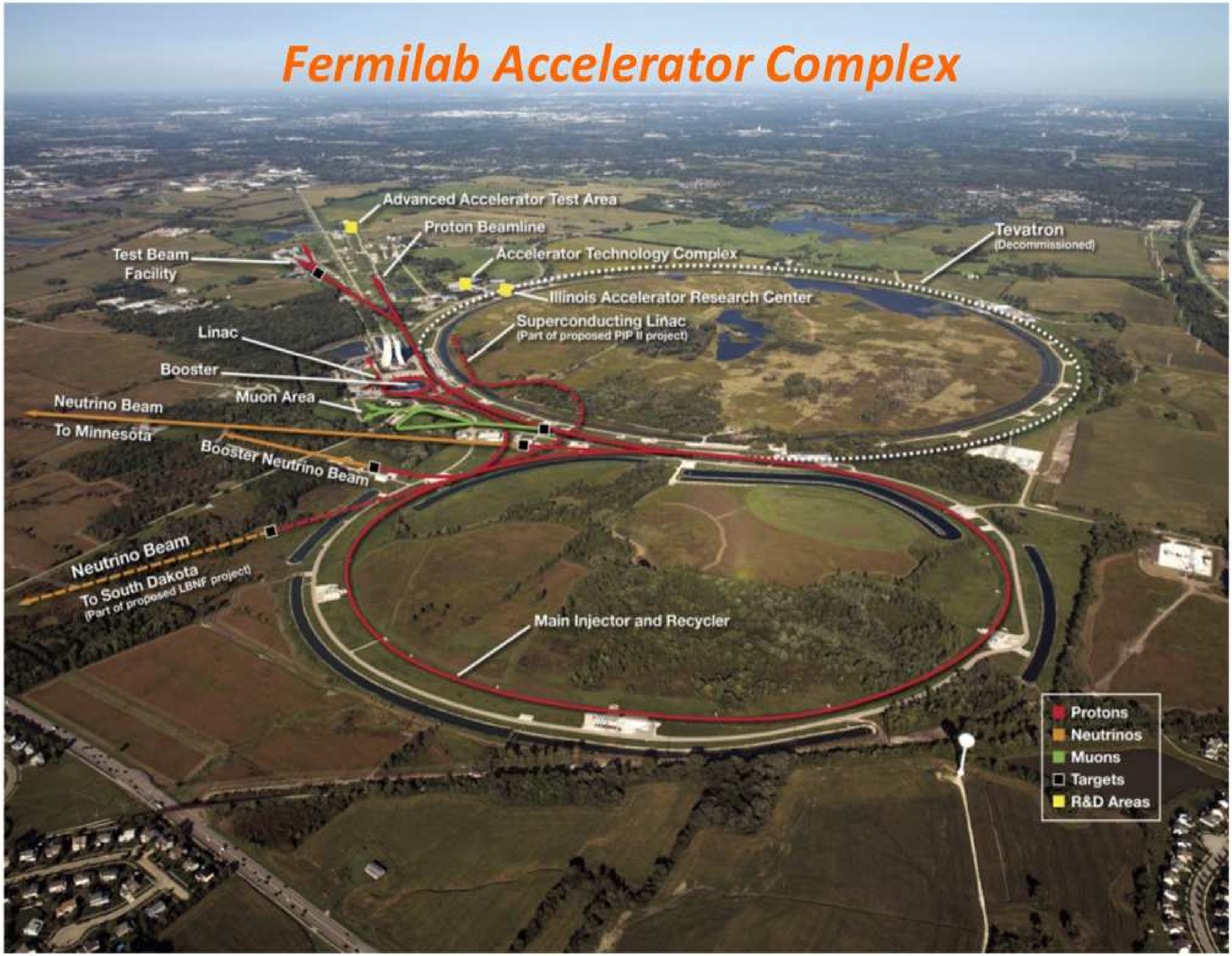

Ontario
NOνA
Soudan
Minnesota
Wisconsin
735 kilometers
Iowa
Fermilab
Illinois

The slides on the LBNE (ELBNF $\rightarrow$ DUNE) project are from the talk by B.C. Choudhary, given at the NuPhys (Prospects in Neutrino Physics) Workshop, December 15 - 17, 2014, London, UK.

LBNE Design



North Dakota
Minnesota
Ontario
Dakota
1300 km
1.2 MW Proton Beam (PIP-II)
Upgradeable to ≥ 2.4 MW
Wisconsin
Michigan
34 kt fiducial mass
single-phase LAr TPC
Depth = 4300 m.w.e
Nebraska
Iowa
Chicago
Magnetized, low-density
fine-grained tracker
Illinois



Fermilab Accelerator Complex
Advanced Accelerator Test Area
Proton Beamline
Test Beam Facility
Accelerator Technology Complex
Tevatron
(Decommissioned)
Illinois Accelerator Research Center
Superconducting Linac
(Part of proposed PIP II project)
Linac
Booster
Muon Area
Neutrino Beam
To Minnesota
Booster Neutrino Beam
Neutrino Beam
To South Dakota
(Part of proposed LBNF project)
Main Injector and Recycler
Protons
Neutrinos
Muons
Targets
R&D Areas

LBNE Parameters

- Wide band neutrino beam from FNAL
  - protons: 60-120 GeV, 1.2 MW; upgradable to 2.3 MW
  - 10 μS pulses every 1.0 to 1.33 sec depending on P energy&power.
  - Neutrinos: sign selected, horn focused, 0.5 - 5 GeV
  - 1300 km thru the Earth to Sanford Underground Research Facility.
- Liquid argon TPC parameters
  - 34 kt fiducial (50kt tot) at 4850 ft level. cosmics ~0.1Hz, beam ~ 9k CC/yr
  - drift ~3.5 m, field: 500 V/cm, 2 mods = (14m(H)X 22m(W)X45m(L))
  - readout: x,u,v, pitch: 5 mm, wrapped wires, 2X108 APAs, 2X(275k ch)
  - Max Yield: ~9000 e/mm/MIP, 10000 ph/mm/MIP
- near detector parameters
  - distance ~450 m, ~3M events/ton/MW/yr
  - Magnetized Fine Grained Tracker (8 ton) with ECAL, and muon id.
  - Supplemented by a small LARTPC (few tons) or gas TPC.

Scale of project is dictated by physics. Beam and ND and FD detectors require high technology. Project can be done in phases with international partners.

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

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

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

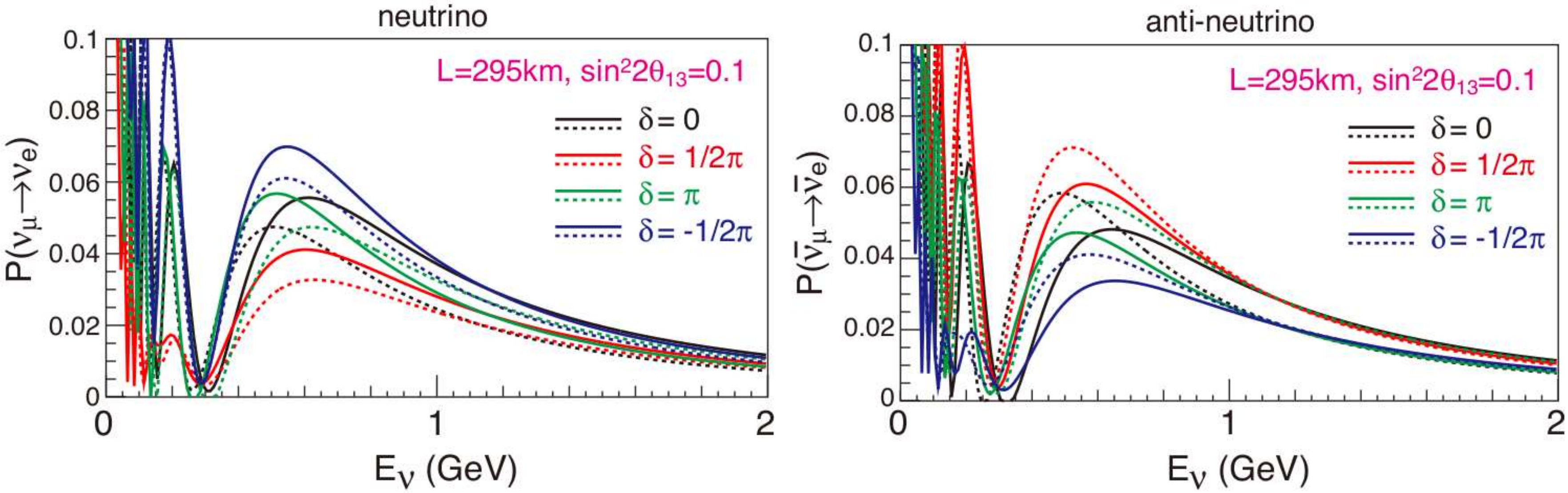
$$P_3 = \alpha^2\cos^2\theta_{23}\,\frac{\sin^2 2\theta_{12}}{A^2}\,\sin^2(A\Delta),$$

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

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

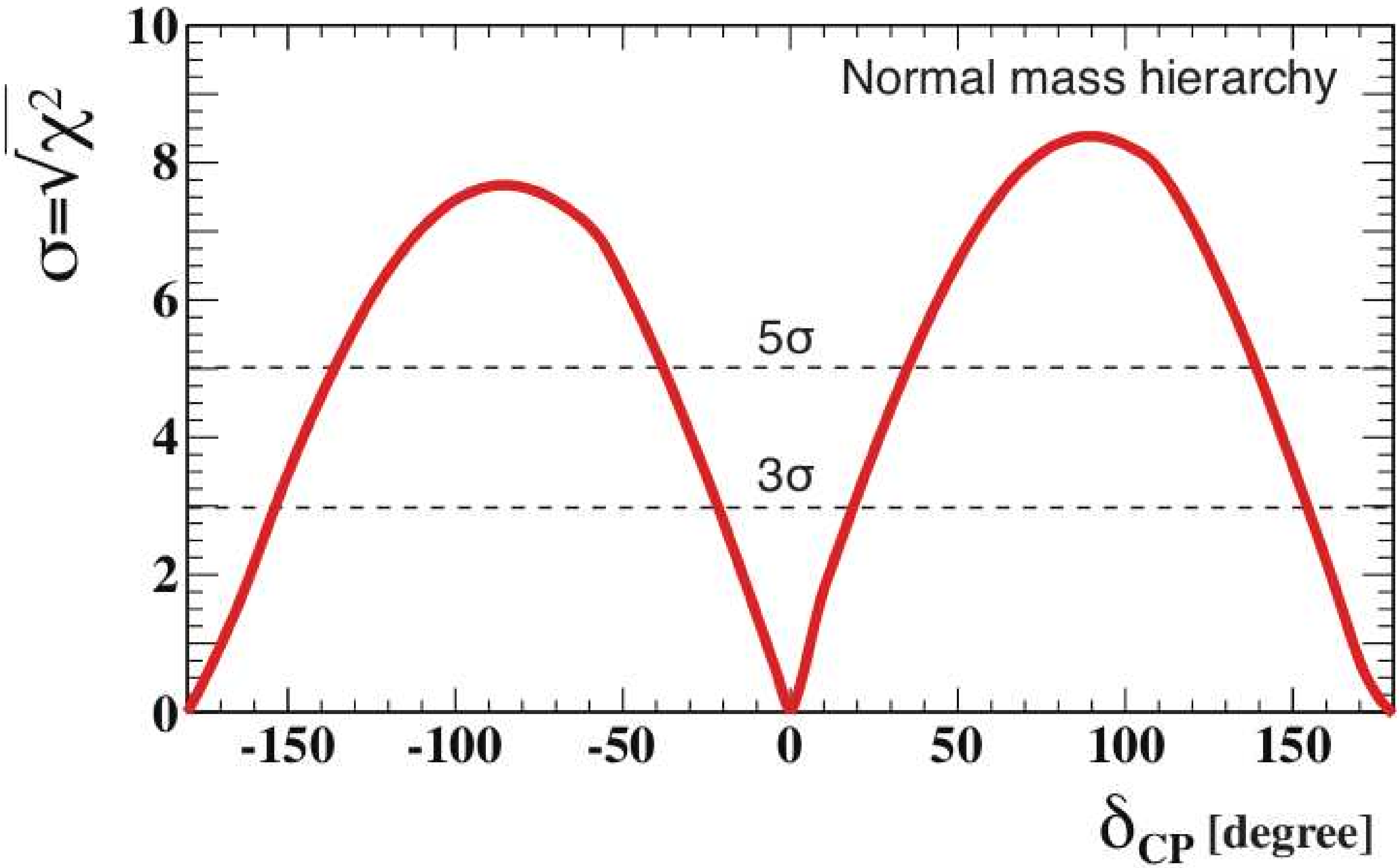
$$\Delta = \frac{\Delta m^2_{31}\,L}{4E},\;\; A = \sqrt{2}G_{\rm F}N_e^{man}\frac{2E}{\Delta m^2_{31}}.$$

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

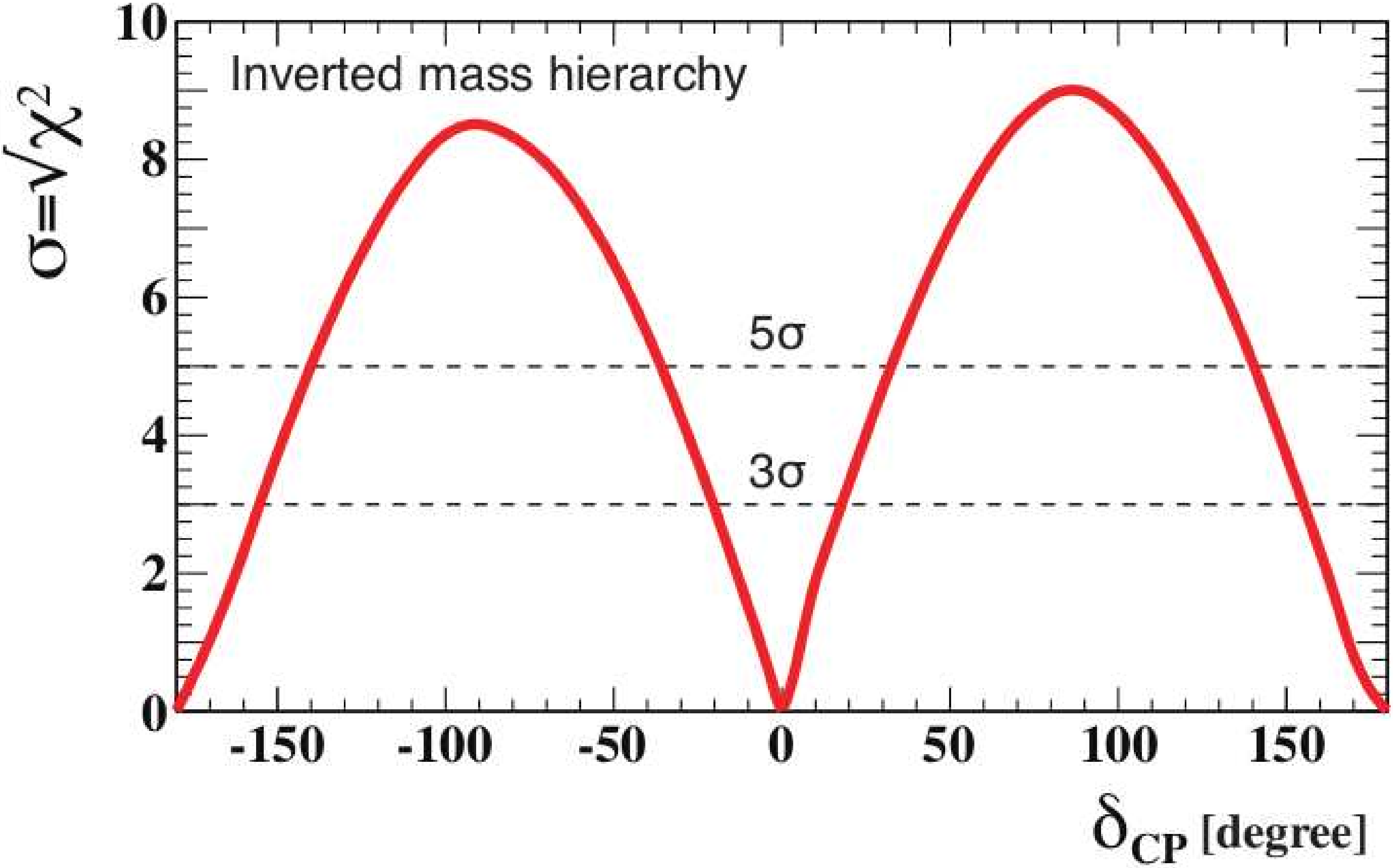


The $\nu_\mu \to \nu_e$ (left) and $\bar{\nu}_\mu \to \bar{\nu}_e$ (right) oscillation probabilities as a function of the neutrino energy for L=295 km (T2SK, T2HK) and $\sin^2 2\theta_{13} = 0.1$. Black, red, green, and blue lines correspond to $\delta = 0, \frac{1}{2}\pi, \pi$, and $-\frac{1}{2}\pi$, respectively. Solid (dashed) line represents the case for a NO (IO) mass spectrum.

Expected T2HK sensitivity to CP violation



K. Abe et al., arXiv:1502.05199.

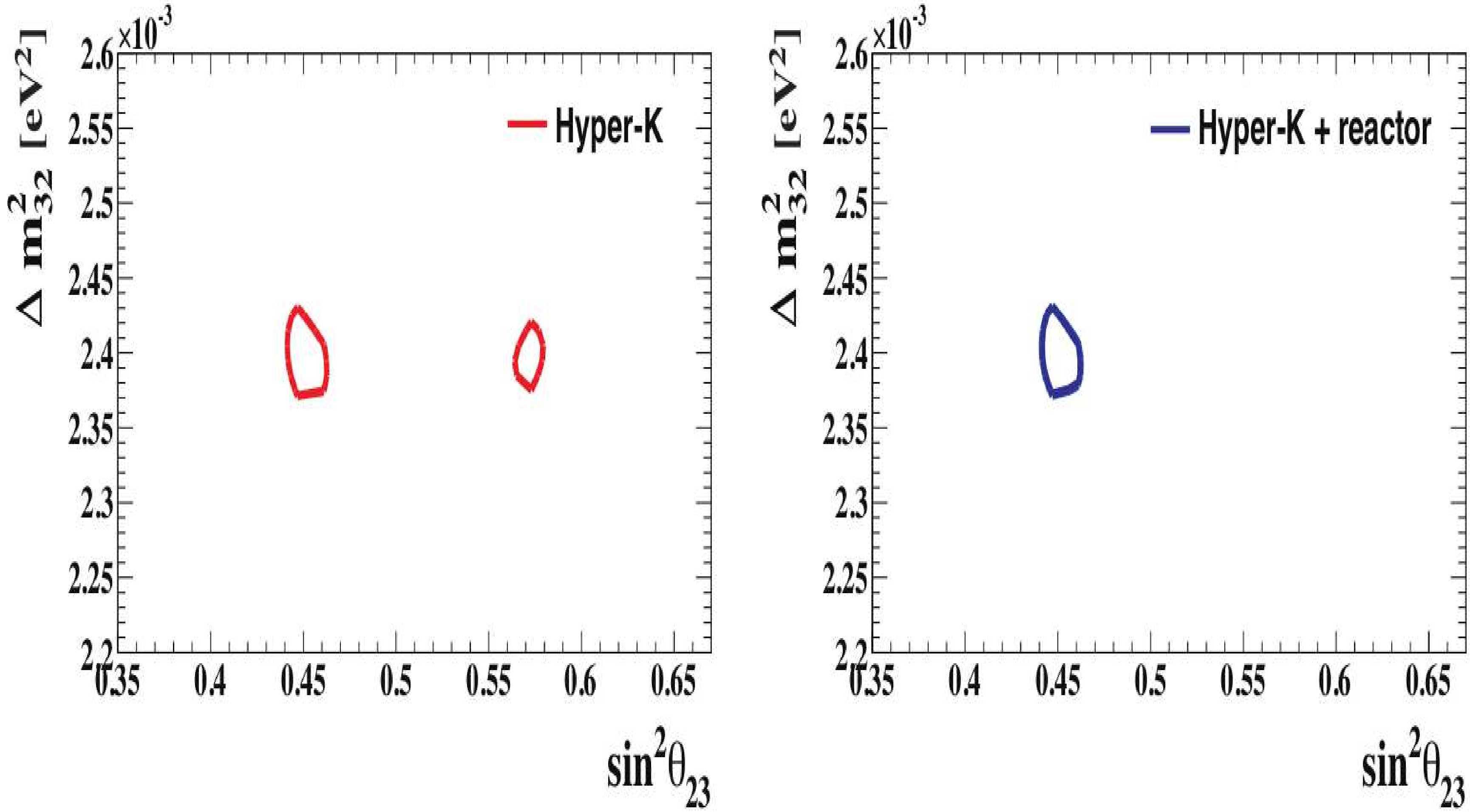


K. Abe et al., arXiv:1502.05199.

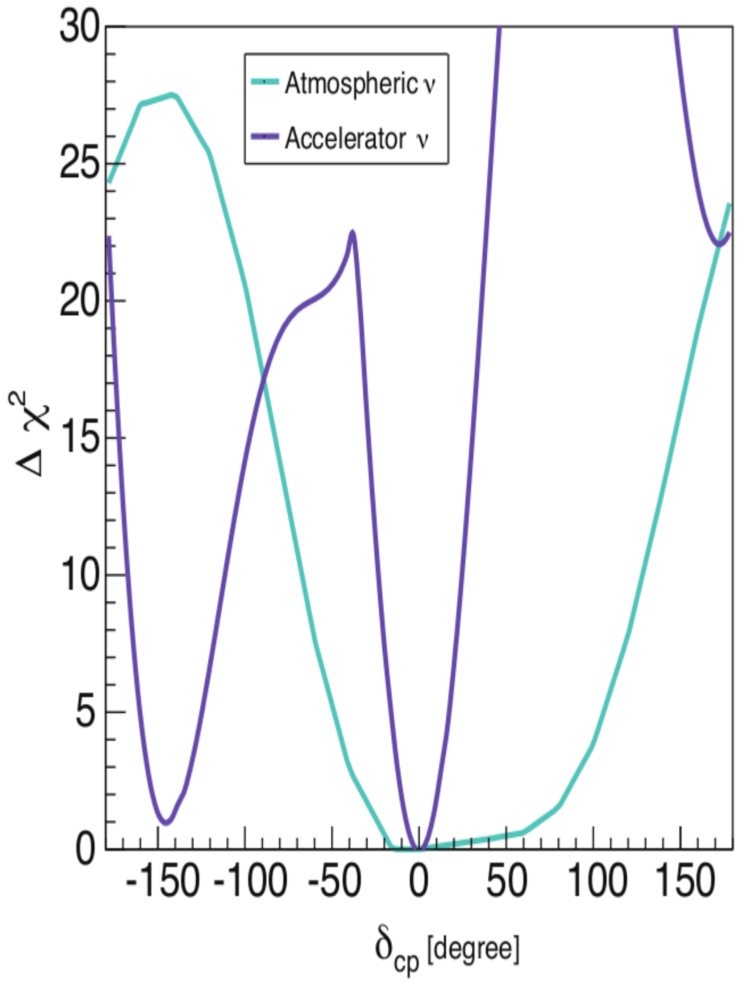
Expected 1σ uncertainty of Δm^2_{32} and $\sin^2\theta_{23}$ for true $\sin^2\theta_{23} = 0.45, 0.50, 0.55$. Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ is imposed.

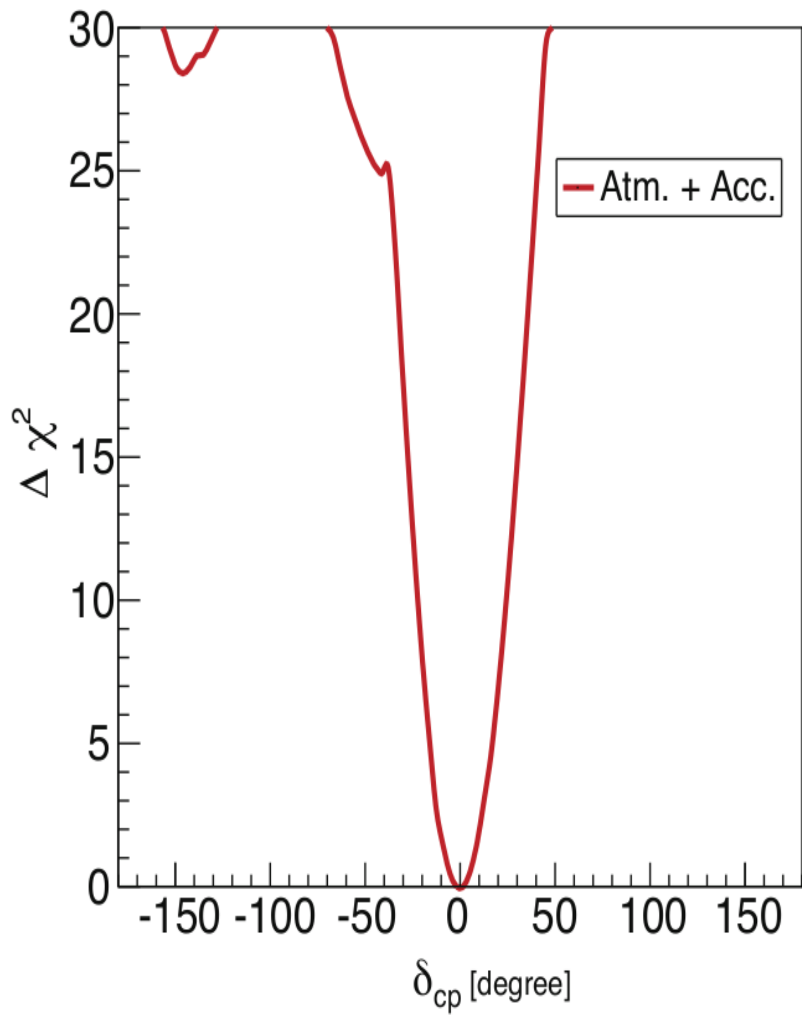
True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$
NO	1.4×10^{-5}	0.006	1.4×10^{-5}	0.015	1.5×10^{-5}	0.009
IO	1.5×10^{-5}	0.006	1.4×10^{-5}	0.015	1.5×10^{-5}	0.009

K. Abe et al., arXiv:1502.05199.



90% CL allowed regions in the $\sin^2\theta_{23}$–Δm^2_{32} plane. The true values are $\sin^2\theta_{23} = 0.45$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2. Effect of systematic uncertainties is included. Left: T2HK only; right: with a reactor constraint.

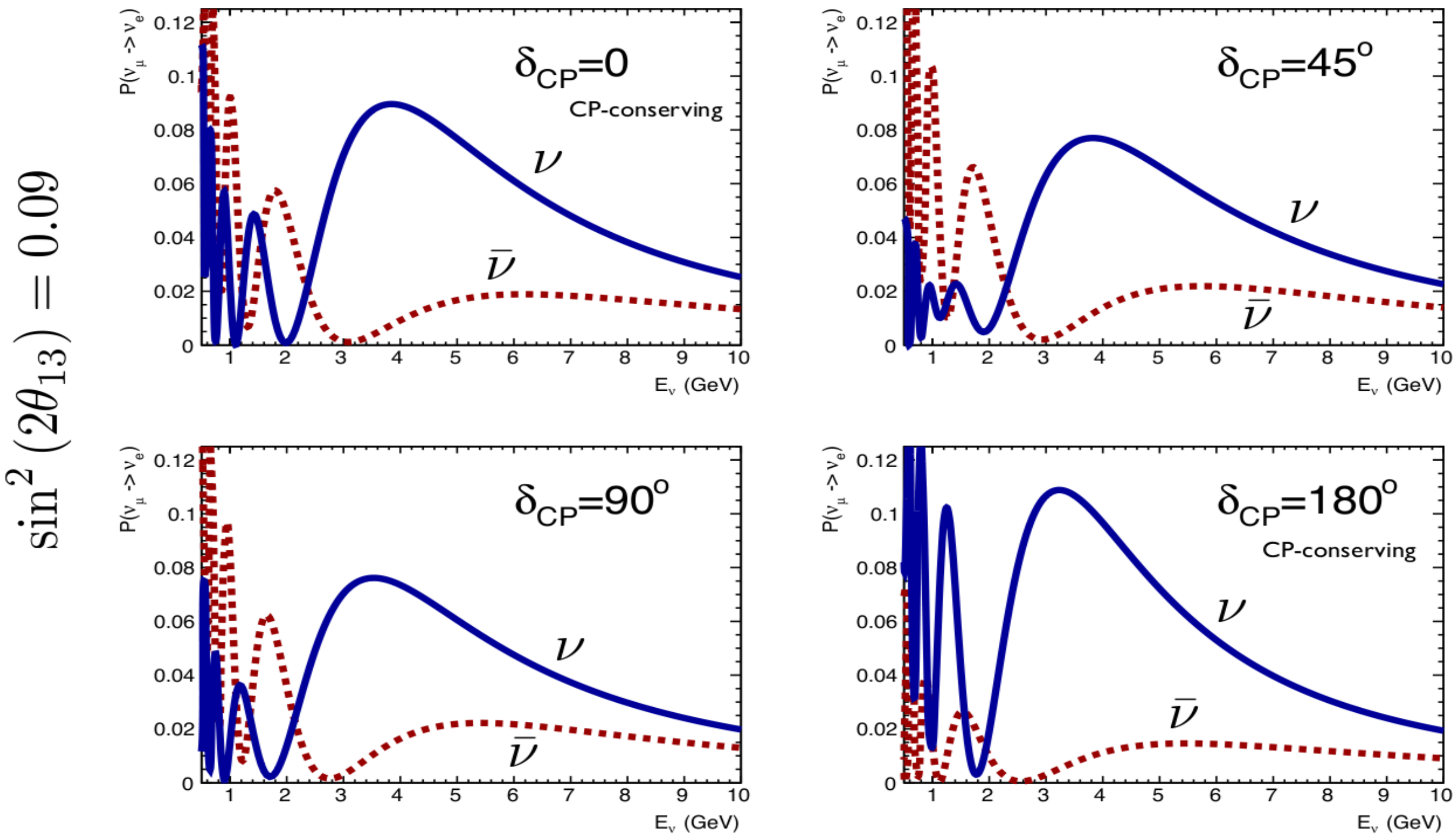




Combination of the T2HK and HK ν_{atm} data. Expected $\Delta\chi^2$ values for a) accelerator and atmospheric neutrino measurements (left), and b) for combining the two measurements (right), assuming that the mass ordering is unknown. The true mass ordering and value of δ are assumed to be NO and $\delta = 0$. In this example study, the $\Delta\chi^2$ is simply added.

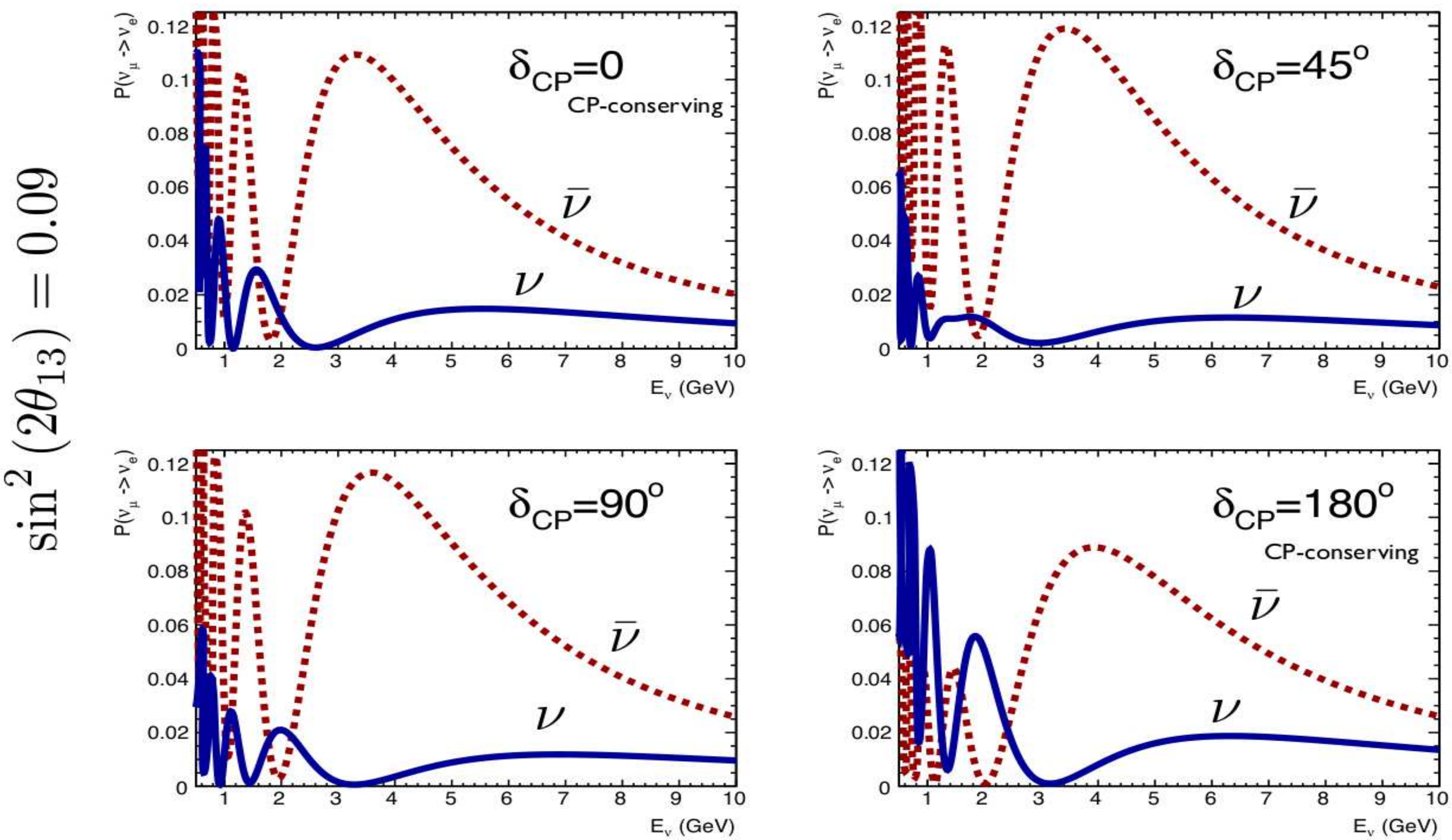
CERN-Pyhäsalmi: CP-effect $\nu_\mu \rightarrow \nu_e$

★Normal mass hierarchy L=2300 km

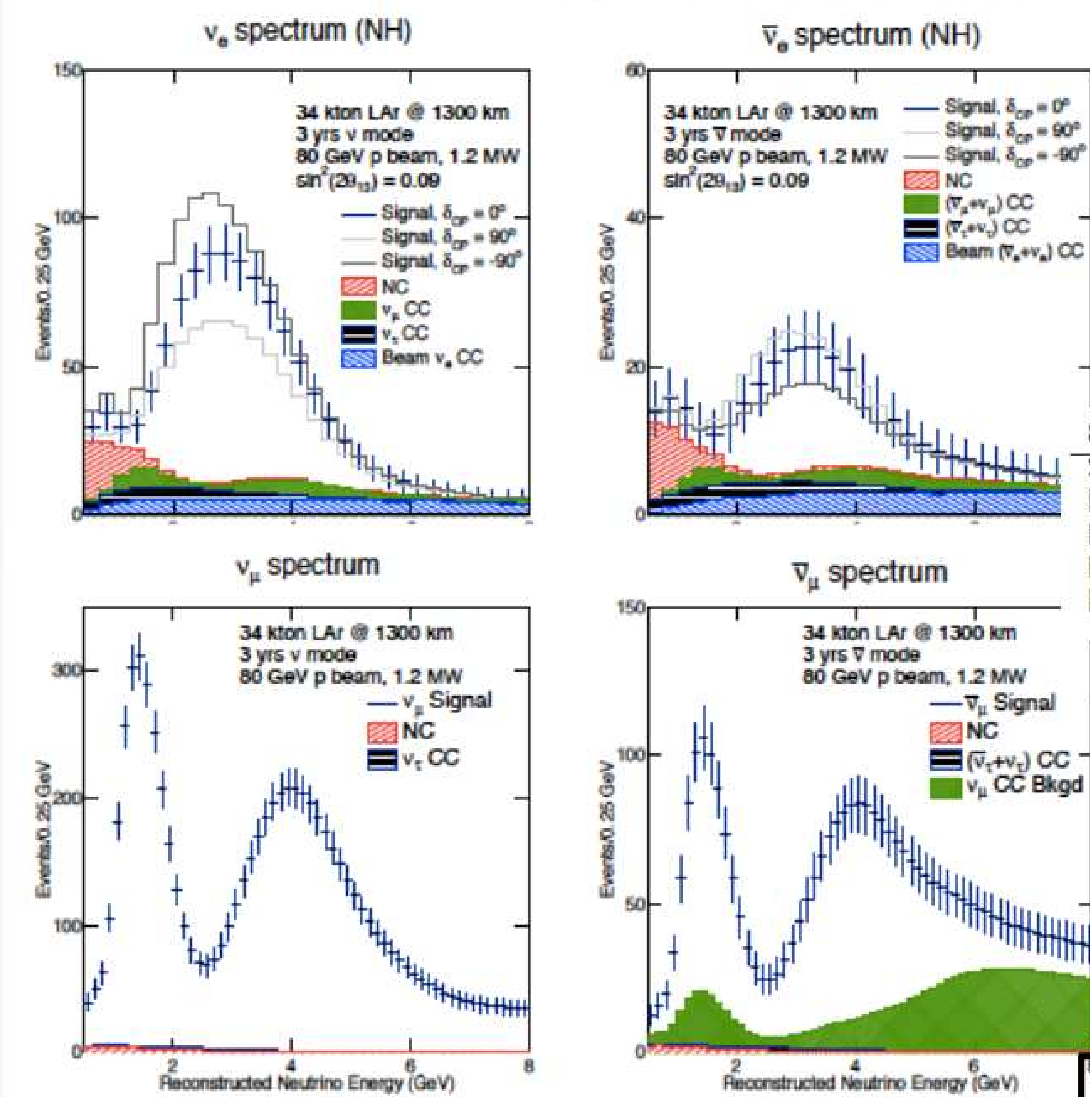


CERN-Pyhäsalmi: CP-effect $\nu_\mu \to \nu_e$

★Inverted mass hierarchy L=2300 km



LBNE Event Rate



34 kton Lar
1.2 MW beam
NH, $\delta_{CP} = 0$
Fit parameters from 2012

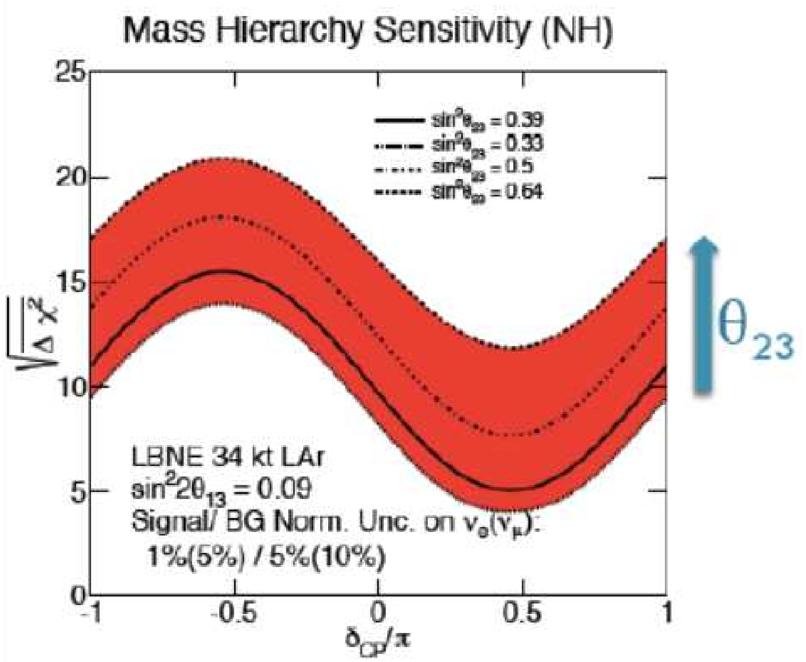
80 GeV Beam	ν mode	$\bar{\nu}$ mode
Signal: $\nu_e + \bar{\nu}_e$	777	189
BG: NC	67	39
BG: $\nu_\mu + \bar{\nu}_\mu$ CC	84	39
BG: Beam $\nu_e + \bar{\nu}_e$	147	81
BG: $\nu_\tau + \bar{\nu}_\tau$ CC	49	32

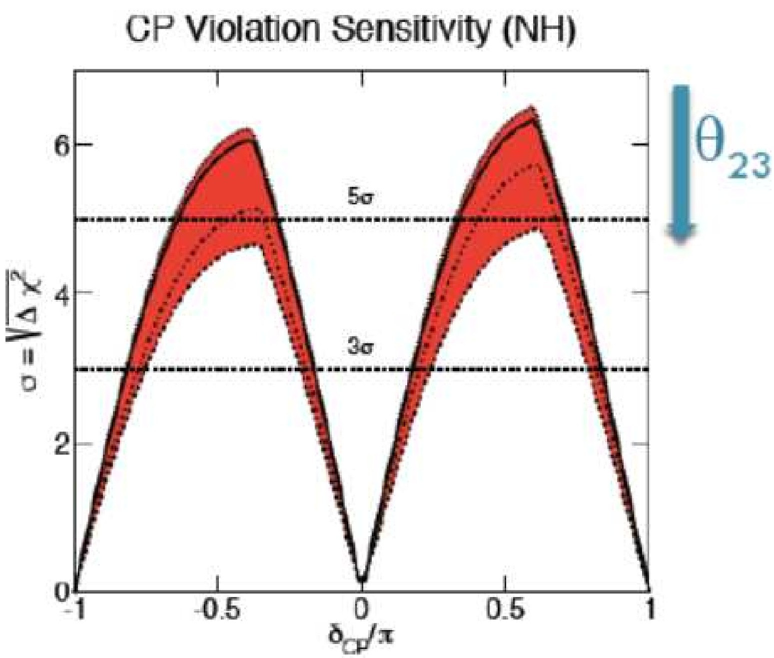
Full oscillation structure visible in energy spectrum. A combined fit to the spectrum to provide unambiguous parameter sensitivity in one experiment

arXiv:1307.7335 – LBNE Document

15-17/12/2014 BCC - NuPhys2014, Queen Mary-University of London, UK 21

LBNE Sensitivity to MH & CPV





Width of the band indicates variation within the 2013 allowed rage for ϑ_{23}.

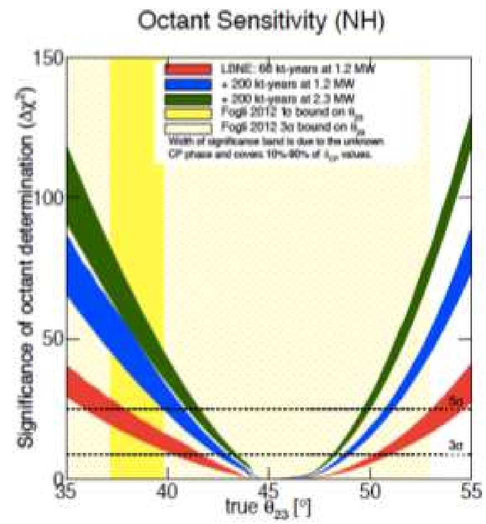
Exposure ~ 245kTon ~ 34 kT X 1.2 MW X (3ν + 3νbar) years

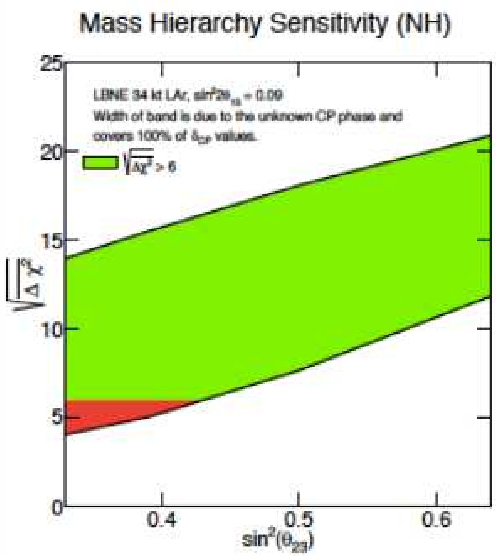
Elizabeth Worchester – NOW 2014

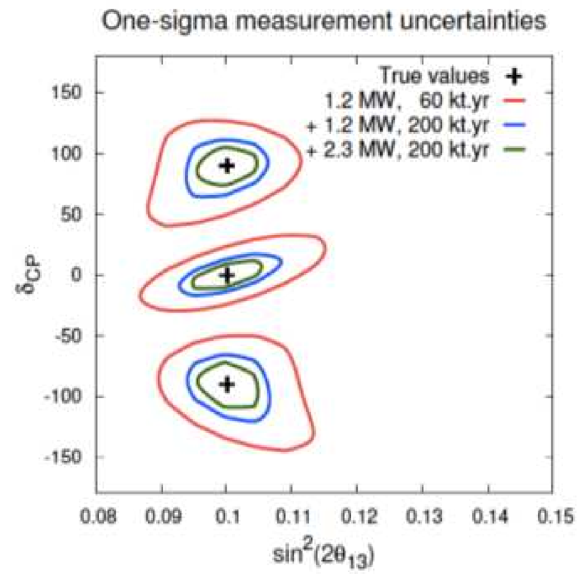
arXiv:1307.7335 – LBNE Document

15-17/12/2014 BCC - NuPhys2014, Queen Mary-University of London, UK 22

Other Measurements for a Comprehensive Program







34kton, 6 yrs, 1.2MW

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

DUNE 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).

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

The Quest for Nature's Message

With the observed pattern of neutrino mixing Nature is sending us a message. The message is encoded in the values of the neutrino mixing angles, leptonic CP violation phases and neutrino masses. The message can have two completely different contents: it can read

ANARCHY or SYMMETRY.

ANARCHY:

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

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

Understanding the Pattern of Neutrino Mixing.

Predictions for the CPV Phase δ.

Neutrino Mixing: New Symmetry?

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

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

Very different from the CKM-matrix!

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

A Natural Possibility (vast literature):

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

with

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

• $U_{\text{lep}}^{\dagger}(\theta_{ij}^{\ell}, \delta^{\ell})$ - from diagonalization of the l^- mass matrix;

• $U_{\text{TBM,BM,LC,...}} \; \bar{P}(\xi_1, \xi_2)$ - from diagonalization of the ν mass matrix;

• $Q(\psi, \omega)$, - from diagonalization of the l^- and/or ν mass matrices.

P. Frampton, STP, W. Rodejohann, 2003

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

$$U_{\rm LC} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{c^{\nu}_{23}}{\sqrt{2}} & \frac{c^{\nu}_{23}}{\sqrt{2}} & s^{\nu}_{23} \\ \frac{s^{\nu}_{23}}{\sqrt{2}} & -\frac{s^{\nu}_{23}}{\sqrt{2}} & c^{\nu}_{23} \end{pmatrix} ; \;\; \mu - \tau \text{ symmetry : } \;\theta^{\nu}_{23} = \mp\pi/4\,;$$

$$U_{\rm GR} = \begin{pmatrix} c^{\nu}_{12} & s^{\nu}_{12} & 0 \\ -\frac{s^{\nu}_{12}}{\sqrt{2}} & \frac{c^{\nu}_{12}}{\sqrt{2}} & -\sqrt{\frac{1}{2}} \\ -\frac{s^{\nu}_{12}}{\sqrt{2}} & \frac{c^{\nu}_{12}}{\sqrt{2}} & \sqrt{\frac{1}{2}} \end{pmatrix} ; \;\; U_{\rm HGM} = \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} , \;\; \theta^{\nu}_{12} = \pi/6\,.$$

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

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

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

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

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

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

• $U_{\rm GRA}$: Group A_5,...; $s^2_{13} = 0$ and possibly $s^2_{12} = 0.276$ and $s^2_{23} = 1/2$ must be corrected.

L. Everett, A. Stuart, arXiv:0812.1057;...

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

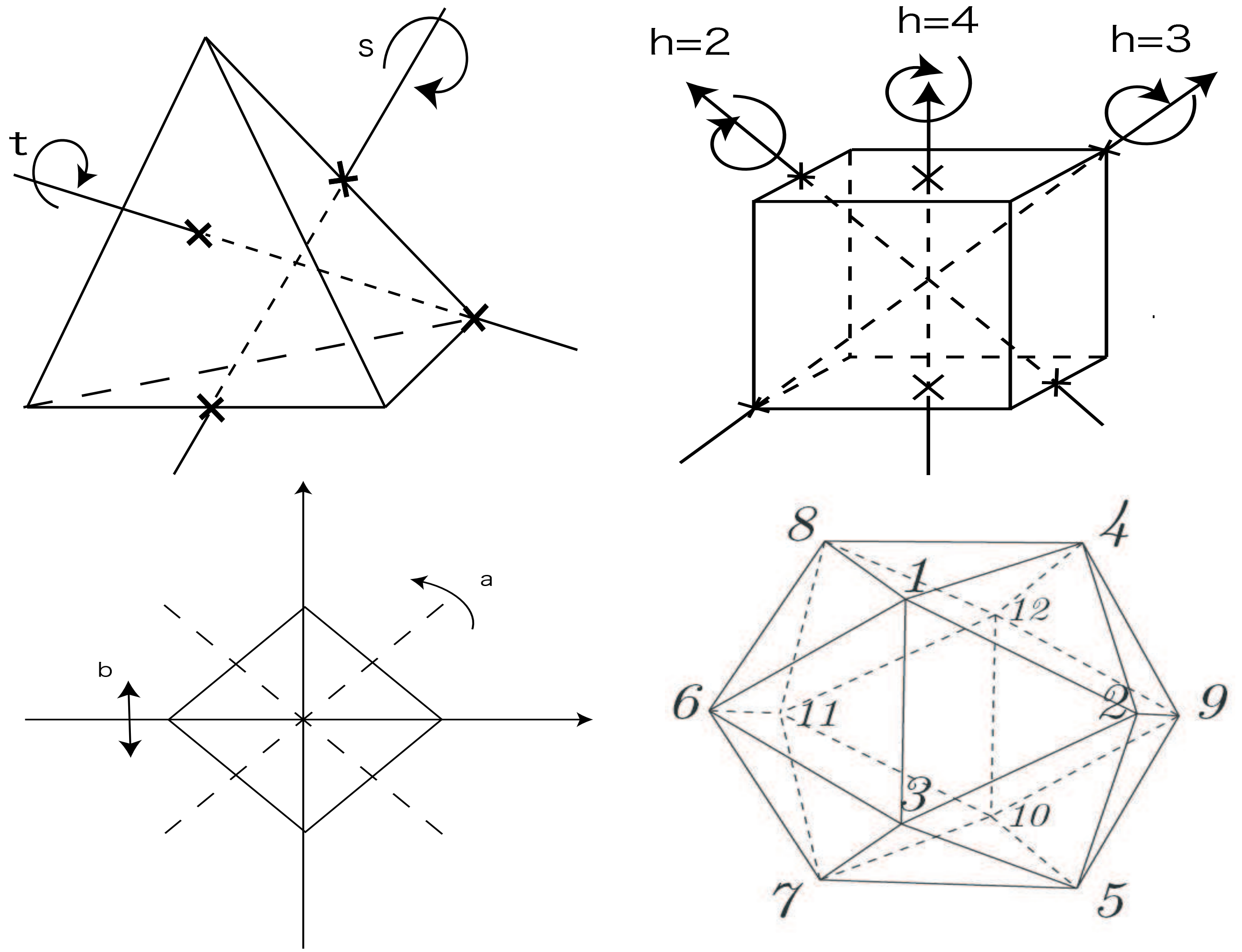
S.T.P., 1982

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

• $U_{\rm GRB}$: Group D_{10},...; $s^2_{13} = 0$ and possibly $s^2_{12} = 0.345$ and $s^2_{23} = 1/2$ must be corrected.

• $U_{\rm HG}$: Group D_{12},...; $s^2_{13} = 0$, $s^2_{12} = 0.25$ and possibly $s^2_{23} = 1/2$ must be corrected.

For all symmetry forms considered we have: $\theta^{\nu}_{13} = 0$, $\theta^{\nu}_{23} = \mp\pi/4$.
They differ by the value of θ^{ν}_{12}:
TBM, BM, GRA, GRB and HG forms correspond to $\sin^2\theta^{\nu}_{12} = 1/3;\ 0.5;\ 0.276;\ 0.345;\ 0.25$.



Examples of symmetries: A_4, S_4, D_4, A_5

From M. Tanimoto et al., arXiv:1003.3552

For arbitrary fixed θ^{ν}_{12} and any θ_{23} ("minimal" and "next-to-minimal" cases):

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

S.T.P., arXiv:1405.6006

This results is exact.

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

In all cases TBM, BM (LC), GRA, GRB, HG:

- New sum rules relating θ_{12},θ_{13}, θ_{23} and δ;
- $J_{CP} = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}, \delta) = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}; \theta^{\nu}_{12})$.

S.T.P., arXiv:1405.6006

• $J_{CP} = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}, \delta) = J_{CP}(\theta_{12}, \theta_{23}, \theta_{13}; \theta^{\nu}_{12})$.

• TBM case: $\delta \cong 3\pi/2$ or $\pi/2$; b.f.v. of θ_{ij}:
$\delta \cong 263.5^\circ$ or 96.5°, $\cos\delta = -0.114$, $J_{CP} \cong \mp 0.034$.

• GRAM case, b.f.v. of θ_{ij}: $\delta \cong 286.8^\circ$ or 73.2°;
$\cos\delta = 0.289$, $J_{CP} \cong \mp 0.0327$.

• GRBM case, b.f.v. of θ_{ij}: $\delta \cong 258.5^\circ$ or 101.5°;
$\cos\delta = -0.200$, $J_{CP} \mp 0.0333$.

• HGM case, b.f.v. of θ_{ij}: $\delta \cong 298.4^\circ$ or 61.6°;
$\cos\delta = 0.476$, $J_{CP} \cong \mp 0.0299$.

• BM, LC cases: $\delta \cong \pi$, $\cos\delta \cong -0.978$, $J_{CP} \cong \mp 0.008$

The results shown - for NO neutrino mass spectrum; the results are practically the same for IO spectrum. (Best fit values of θ_{ij}: F. Capozzi et al., arXiv:1312.2878v1.)

S.T.P., arXiv:1405.6006

By measuring $\cos\delta$ or δ one can distiguish between different symmetry forms of $\tilde{U}_\nu$!

Relatively high precision measurement of δ will be performed at the future planned neutrino oscillation experiments, (DUNE, T2HK) see, e.g., A. de Gouvea *et al.*, arXiv:1310.4340; P. Coloma *et al.*, arXiv:1203.5651; R. Acciarri *et al.* [DUNE Collab.], arXiv:1512.06148, 1601.05471 and 1601.02984.

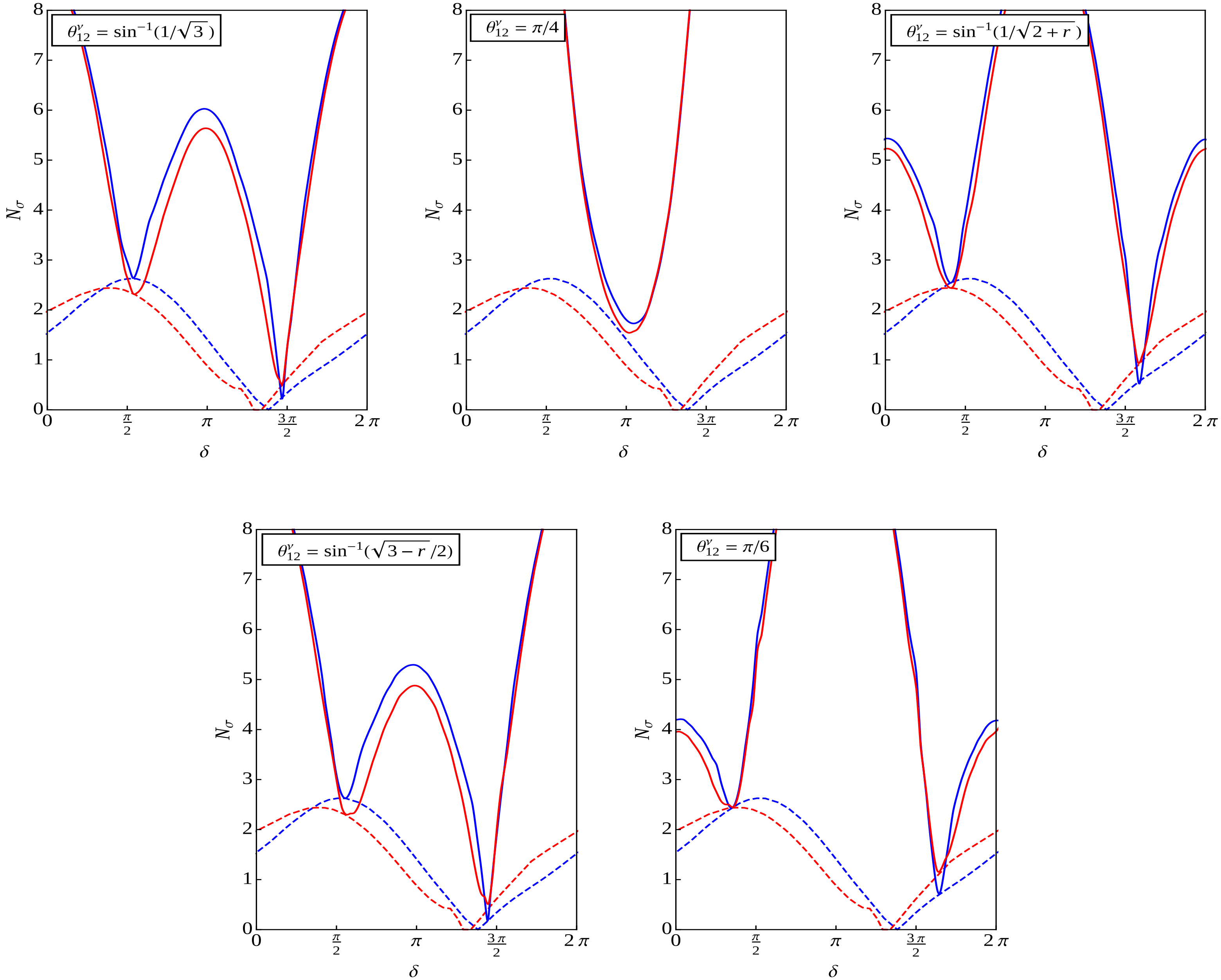
Statistical analysis, likelihood method;
input "data": $\sin^2\theta_{13}$, $\sin^2\theta_{12}$, $\sin^2\theta_{12}$, δ
from F. Capozzi et al., arXiv:1312.2878v2 (May 5, 2014).

$$L(\cos\delta) \propto \exp\left(-\frac{\chi^2(\cos\delta)}{2}\right)$$

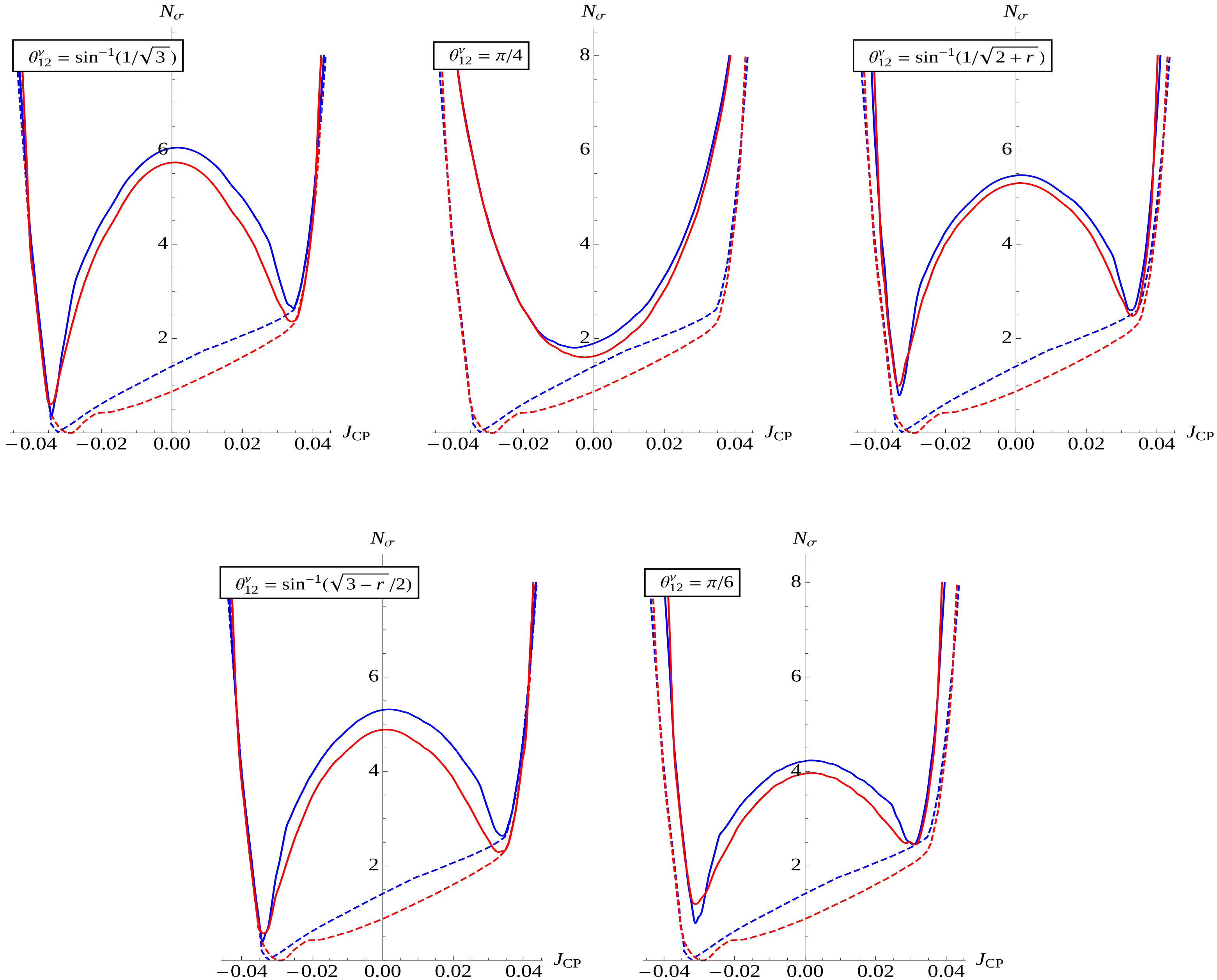
nσ confidence level interval of values of $\cos\delta$:

$$L(\cos\delta) \geq L(\chi^2_{\rm min}) \cdot L(\chi^2 = n^2)$$

I. Girardi, S.T.P., A. Titov, arXiv:1410.8056



I. Girardi, S.T.P., A. Titov, arXiv:1410.8056



I. Girardi, S.T.P., A. Titov, arXiv:1410.8056

TBM, GRA, GRB, HG: $J = 0$ **excluded at** 5σ, 4σ, 4σ, 3σ **confidence level.**

At 3σ: $0.020 \leq |J_{\rm CP}| \leq 0.039$.

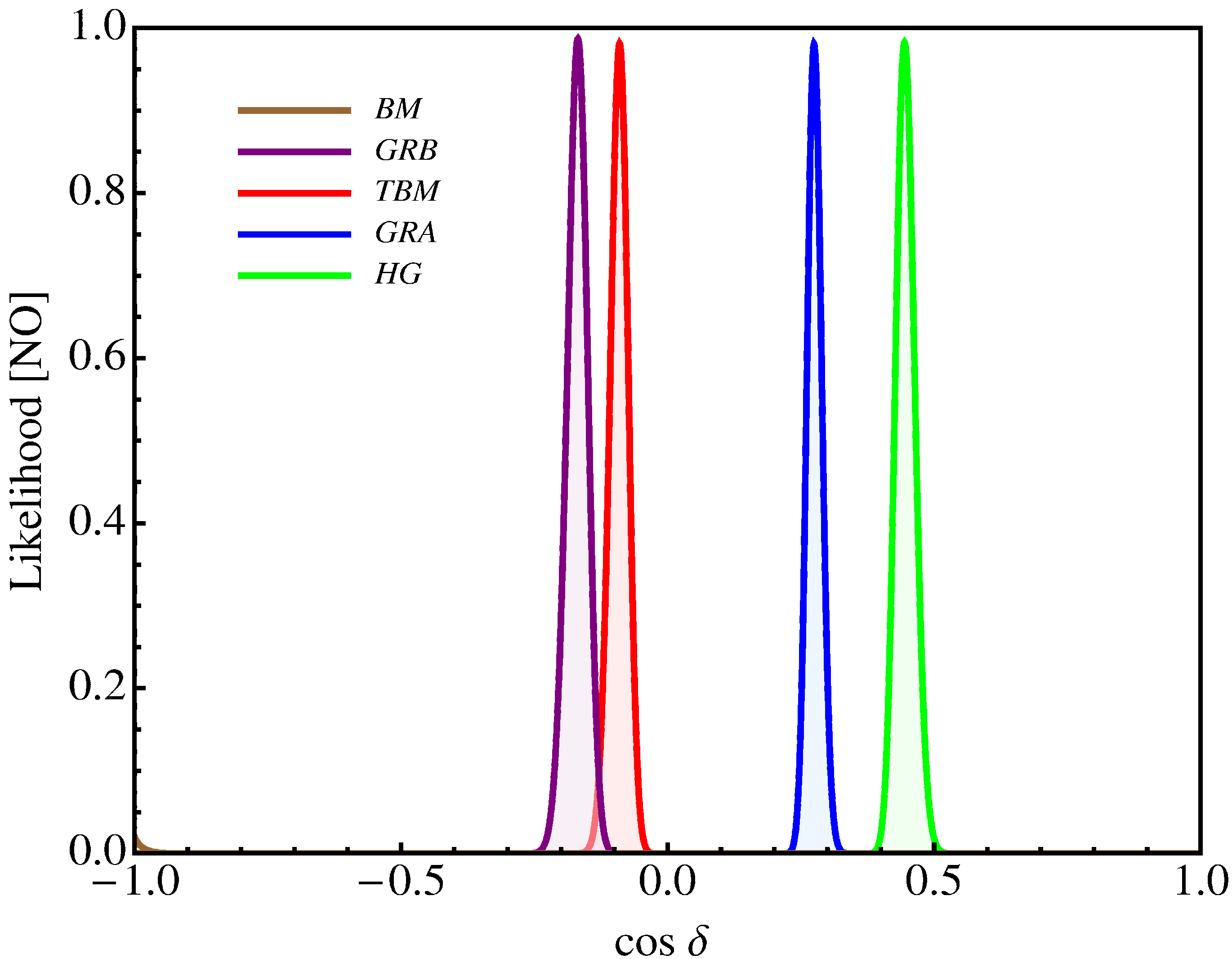
BM (LC), b.f.v.: $J_{\rm CP} = 0$;
at 3σ: -0.026 $(-0.025) \leq J_{\rm CP} \leq 0.021$ (0.023) **for NO (IO) neutrino mass spectrum.**

Prospective precision:

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

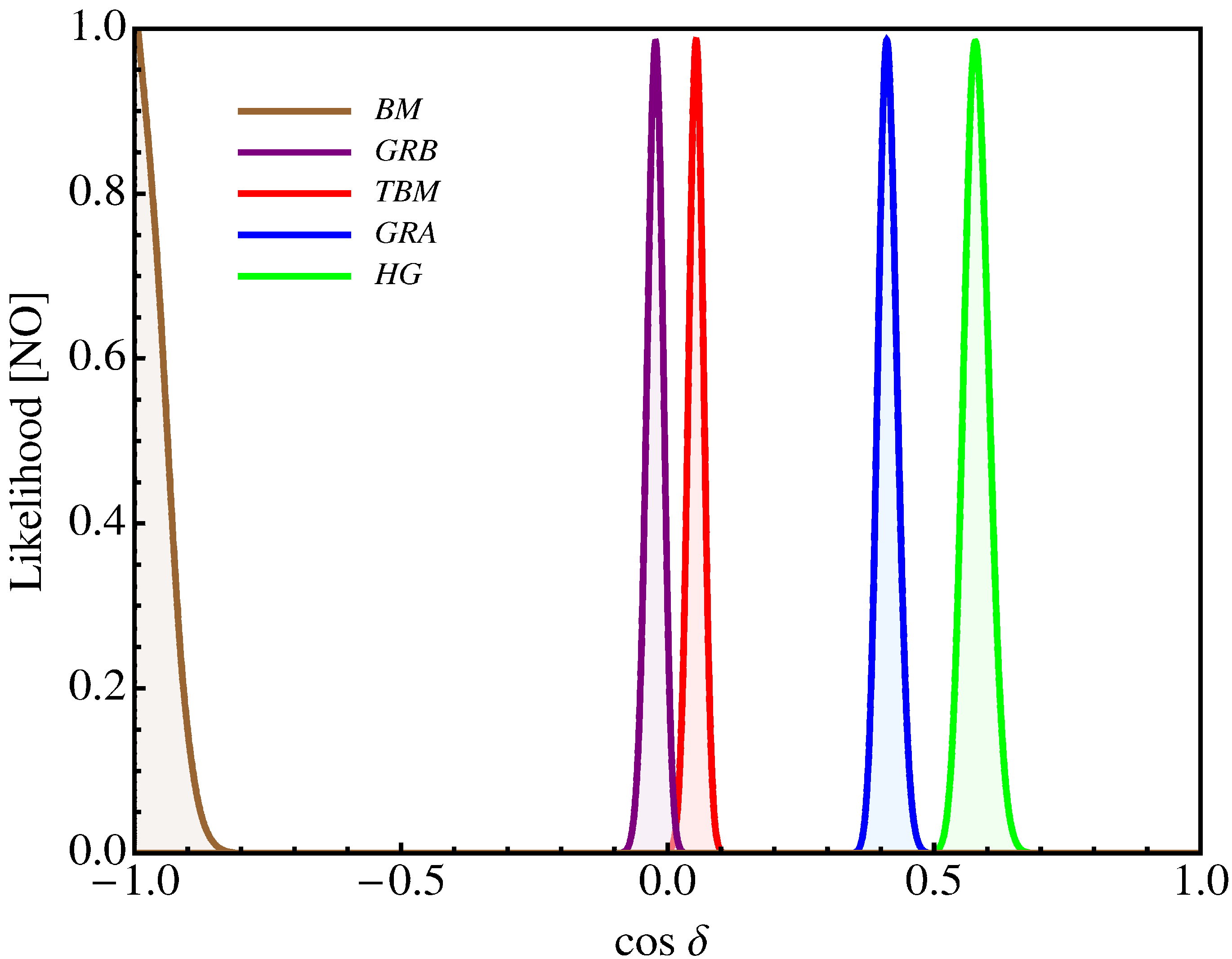
$\delta(\sin^2\theta_{13}) = 3\%$ **(Daya Bay),**

$\delta(\sin^2\theta_{23}) = 5\%$ **(T2K, NOνA combined).**



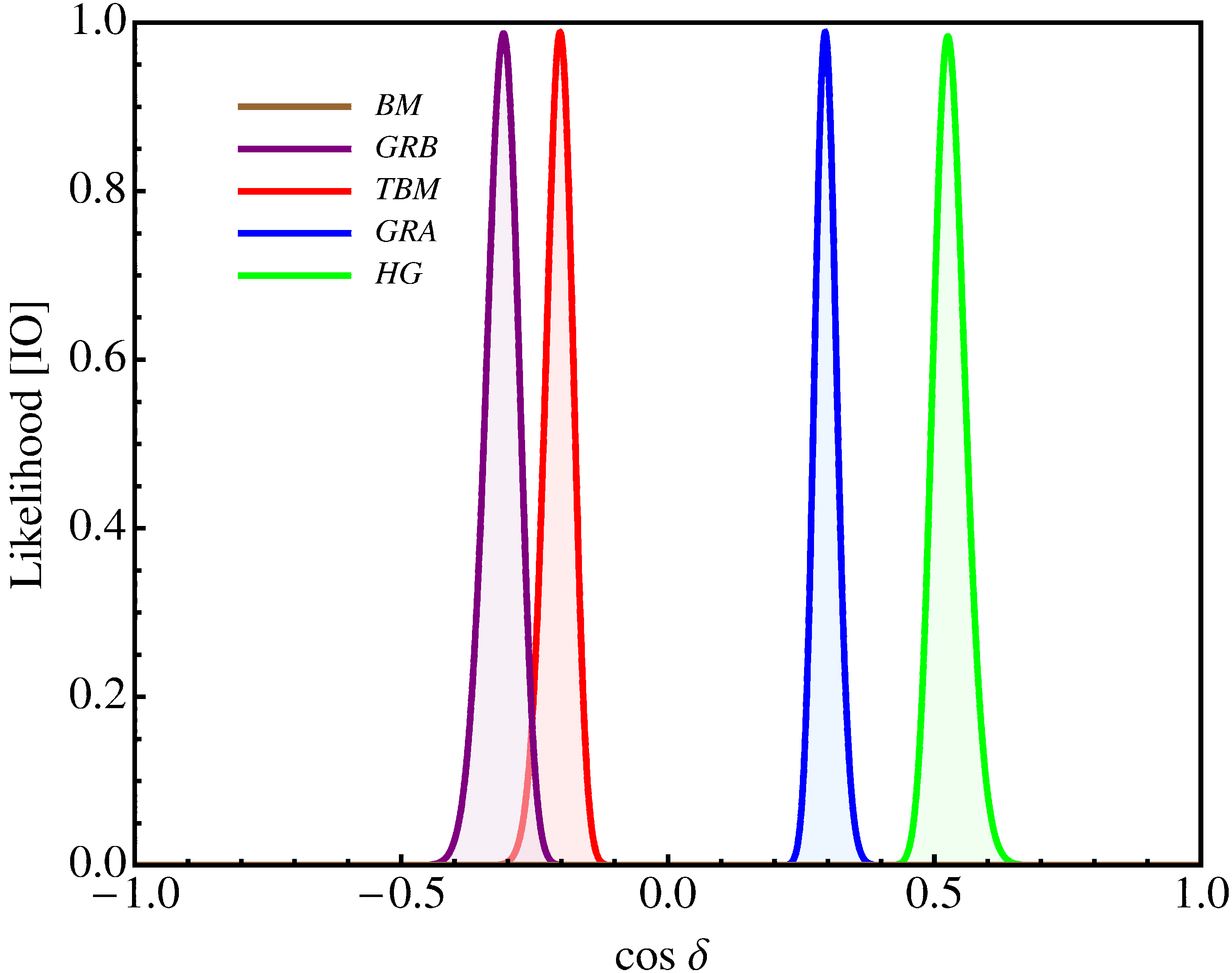
I. Girardi, S.T.P., A. Titov, arXiv:1410.8056

b.f.v. of $\sin^2\theta_{ij}$ (Capozzi et al., 2014) + the prospective precision used.



I. Girardi, S.T.P., A. Titov, arXiv:1410.8056

The same, but for $\sin^2\theta_{12} = 0.33$ **(the BM prediction dependence on** $\sin^2\theta_{12}$**).**



I. Girardi, S.T.P., A. Titov, arXiv:1410.8056

$\sin^2\theta_{23} = 0.557$ **(b.f.v.: C. Gonzales-Garcia et al., 2014, IO case).**

For, e.g., $|\cos\delta| < 0.93$ **(76% of values of δ), and** $\Delta(\cos\delta) = 0.10\,(0.08)$:
$\Delta\delta\Delta(\cos\delta)/\sqrt{1-0.93^2} = 16^\circ\,(12^\circ)$.
Planned to be reached, e.g., in T2HK.
Thus, a measurement of $\cos\delta$ in the quoted range will allow to distinguish between the TBM/GRB, BM (LC) and GRA/HG forms at $\sim 3\sigma$ C.L., if $\sin^2\theta_{12}$, $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$ are measured with the prospective precisions.

Distinguishing between GRA and HG forms at 3σ C.L. requires $1\sigma(\cos\delta) \cong 0.03$ (if b.f.v. of $\cos\delta$ at one of the two maxima).

TBM and GRB cannot be distinguished at 3σ C.L. with the prospective uncertainties on $\sin^\theta_{ij}$;
for zero uncertainties on $\sin^\theta_{ij}$ (infinite precision), can be distinguished if $1\sigma(\cos\delta) \cong 0.03$.

I. Girardi, S.T.P., A. Titov, arXiv:1504

The predictions obtained for $\cos\delta$ are valid in a large class of theoretical models of (lepton) flavour based on discrete symmetries.

J. Gehrlein *et al.*, **"An $SU(5) \times A_5$ Golden Ratio Flavour Model", arXiv:1410.2095;**

I. Girardi *at al.*, **"Generalised Geometrical CP Violation in a T' Lepton Flavour Model", arXiv:1312.1966, JHEP 1402 (2014) 050.**

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

Determining the Nature of Massive Neutrinos

This is one of the most challenging and pressing problems in neutrino physics.

- Massive Dirac Neutrinos: $U(1)$, Conserved (Additive) Charge, e.g., L.

- Massive Majorana Neutrinos: No Conserved (Additive) Charge(s).

The type of massive neutrinos in a given theory is determined by the type of (effective) mass term $\mathcal{L}^{\nu}_{m}(x)$ neutrinos have, more precisely, by the symmetries $\mathcal{L}^{\nu}_{m}(x)$ and the total Lagrangian $\mathcal{L}(x)$ of the theory have.

Mass Term: any by-linear in fermion (neutrino) fields invariant under the proper Lorentz transformations.

Seesaw Mechanisms of Neutrino Mass Generation

- Predict light massive Majorana neutrinos

- 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.

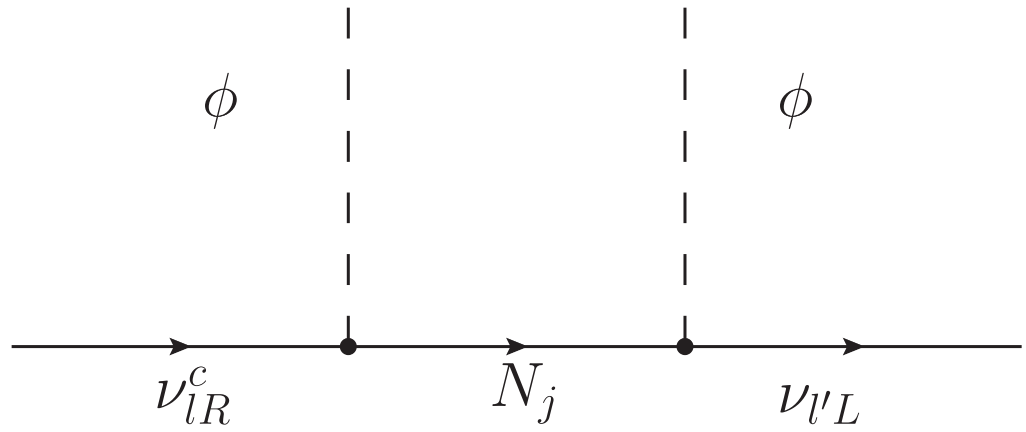
Type I Seesaw Mechanism

- 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" ($\sim$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 $\Phi(x)$:

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

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

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 $\Delta m^2_{\rm atm}$ 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:

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

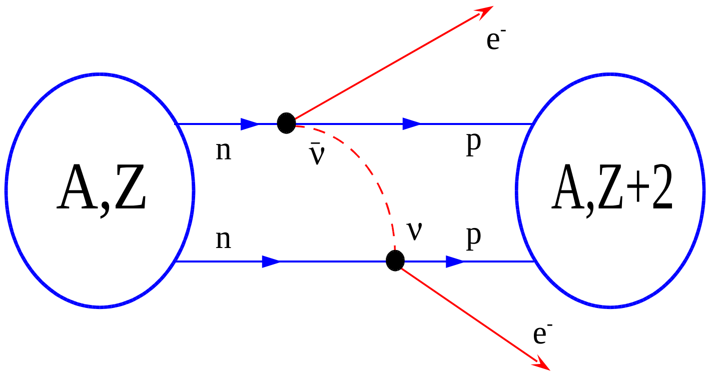
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

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

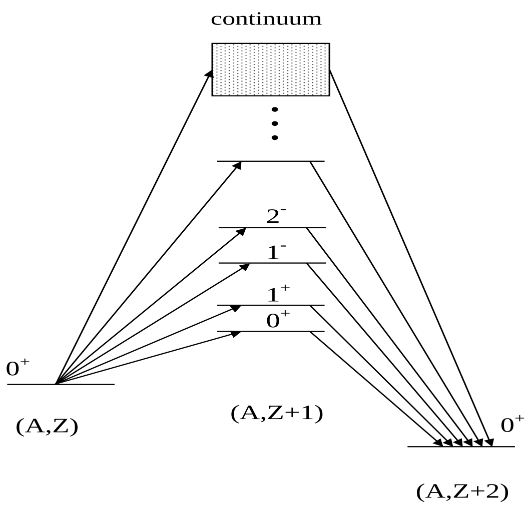
of even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd.

$2n$ 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
$dd \to uue^-e^-(\overline{\nu}_e\overline{\nu}_e)$



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:

- Majorana nature of ν_j
- Type of ν−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,

$$|<m>| = \left| m_1 |U_{\mathrm{e}1}|^2 + m_2 |U_{\mathrm{e}2}|^2 \; e^{i\alpha_{21}} + m_3 |U_{\mathrm{e}3}|^2 \; e^{i\alpha_{31}} \right|$$

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

α_{21}, α_{31} - 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,

$|<m>| \cong \sqrt{m_3^2 + \Delta m_{13}^2} \left|\cos^2\theta_{12} + e^{i\alpha_{21}}\ \sin^2\theta_{12}\right|$, $m_3 < (\ll) m_1 < m_2$ (IH),

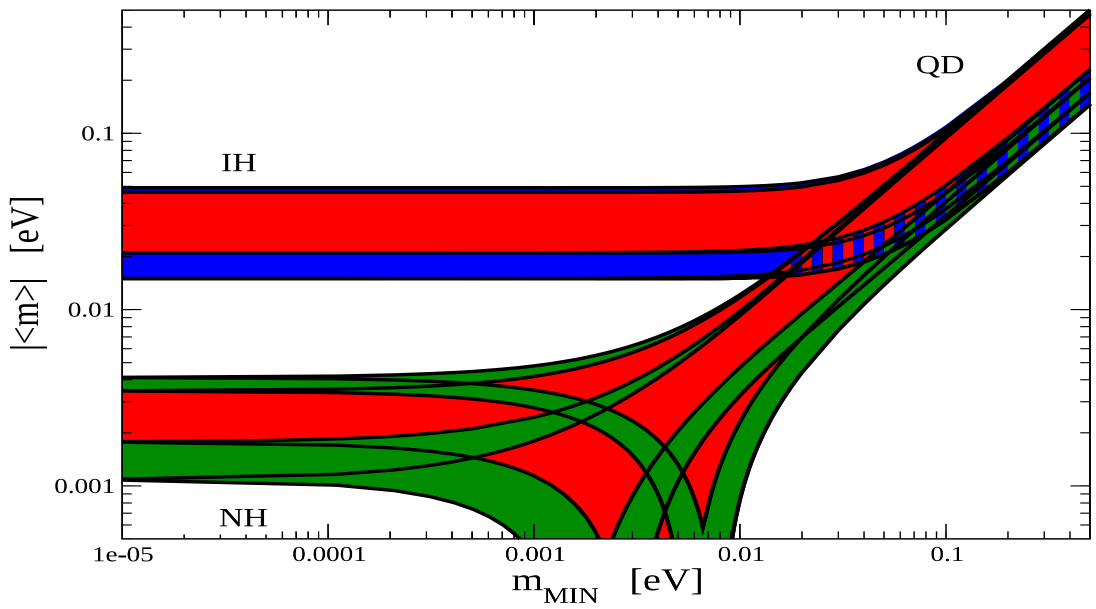
$|<m>| \cong m \left|\cos^2\theta_{12} + e^{i\alpha}\ \sin^2\theta_{12}\right|$, $m_{1,2,3} \cong m \gtrsim 0.10$ eV (QD),

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

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

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

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



S. Pascoli, PDG, 2014

$\sin^2\theta_{13} = 0.0234\ (0.0240) \pm 0.0021;\ \delta = 0.$

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

From F. Capozzi *et al.*, arXiv:1312.5254v2 (May 5, 2014)

$2\sigma(|<m>|\ )$ 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),

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

Results from 2012-2013:

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

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

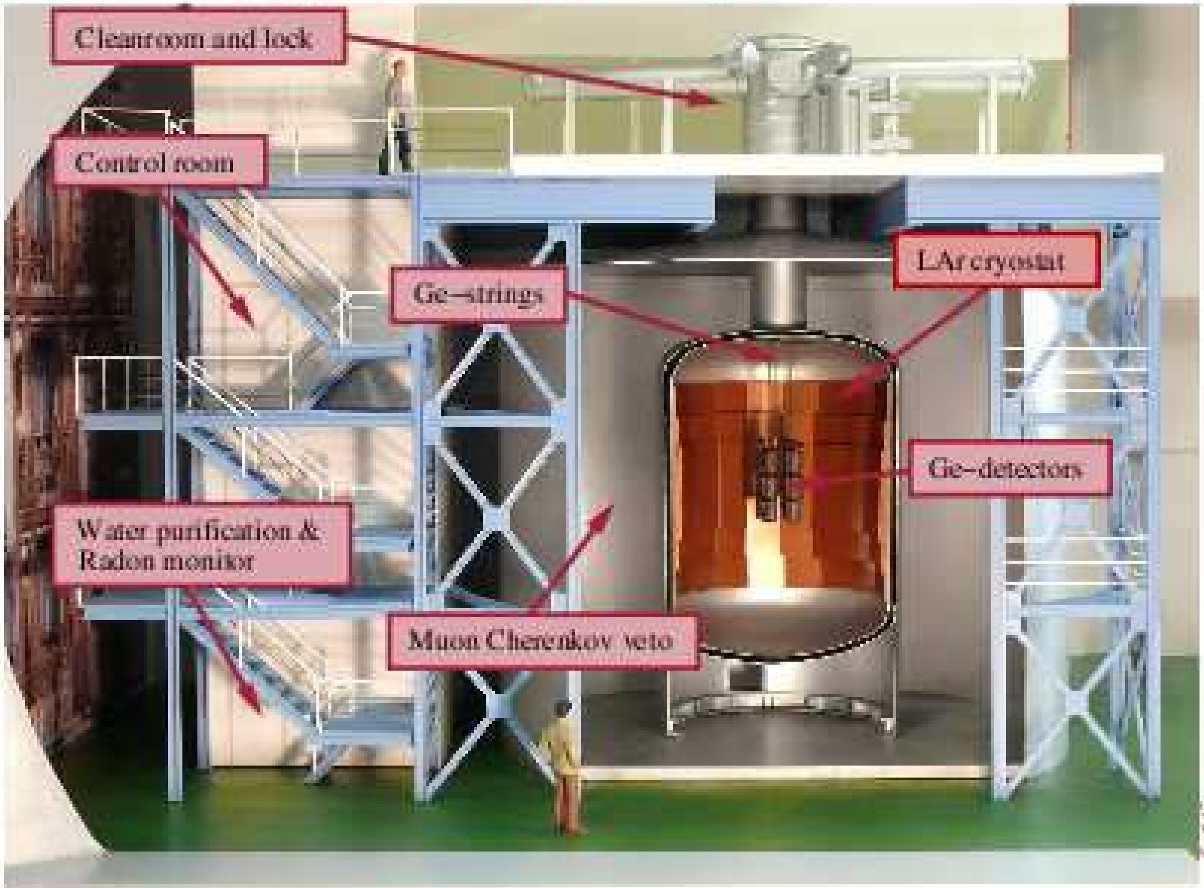
$$T(^{76}Ge) > 2.1 \times 10^{25}\text{yr at}\, 90\%\ \text{C.L.},\ \text{GERDA.}$$

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

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

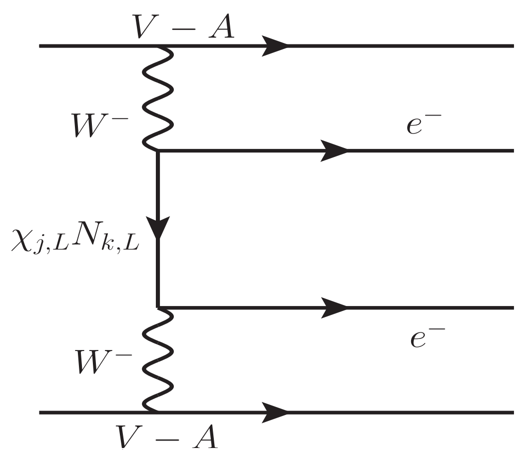
S. Pascoli, S.T.P., L. Wolfenstein, 2002

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

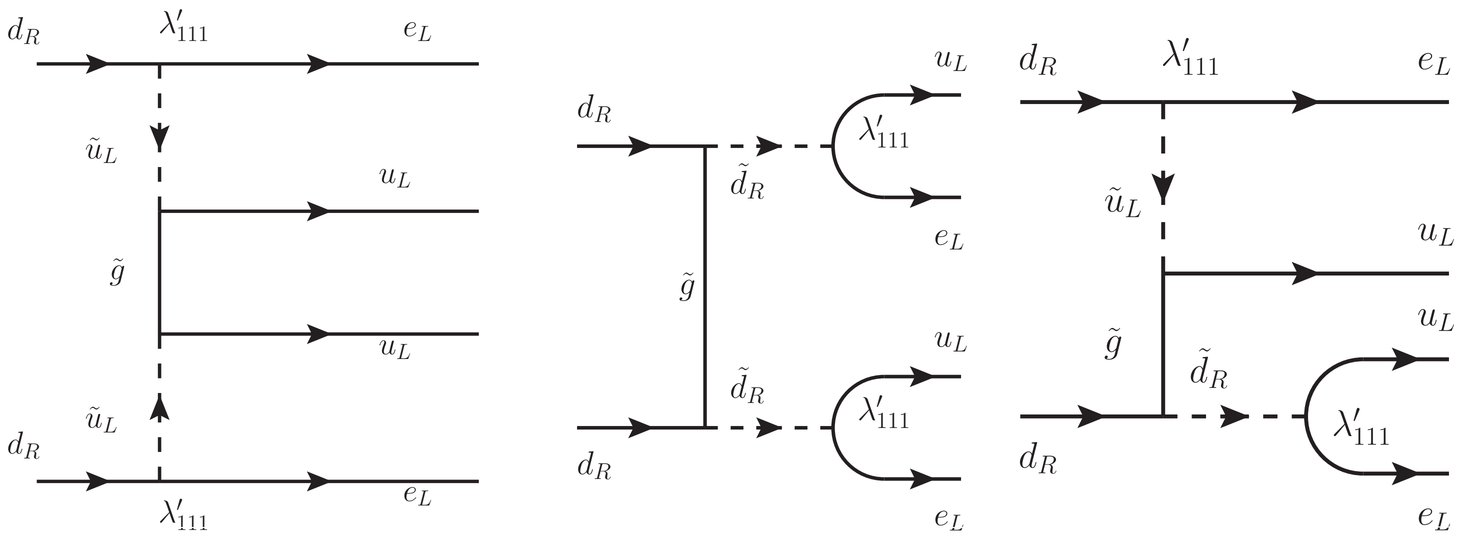
$$\eta_\nu = \frac{<m>}{m_e}\,.$$

Heavy Majorana Neutrino Exchange Mechanisms

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

$\eta^L_N \;=\; \Sigma_k^{heavy}\; U^2_{ek}\frac{m_p}{M_k}$, 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).

Instead of Conclusions

We are at the beginning of the Road...

The next 5, 10, 15,... years will be very exciting in Neutrino (Lepton) Physics!