Present Status in Neutrino Phenomenology

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Research in Neutrino Physics: we strive to understand at deepest level what are the origins of neutrino masses and mixing and what determines the pattern of neutrino mixing and of neutrino mass squared differences that emerged from the neutrino oscillation data in the recent years. And we try to understand what are the implications of the remarkable discovery that neutrinos have mass, mix and oscillate for elementary particle physics, cosmology and for better understanding of the Earth, the Sun, the stars, formation of Galaxies, the Early Universe, i.e., for better deeper understanding of Nature in general.

Of fundamental importance are:

- the determination of the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos (which is one of the most challenging and pressing problems in present day elementary particle physics) (GERDA, CUORE, KamLAND-Zen, EXO, LEGEND, nEXO,...);
- determining the status of CP symmetry in the lepton sector (T2K, NOνA; T2HK, DUNE); leptonic CPV might be at the origin of matter-antimatter (or baryon) asymmetry of the Universe;
- determination of the type of spectrum neutrino masses possess, or the "neutrino mass ordering" (T2K + NOνA; JUNO; PINGU, ORCA; INO, T2HKK, DUNE);
- determination of the absolute neutrino mass scale, or $\min(m_j)$ (KATRIN, new ideas; cosmology).

The program of research extends beyond 2035.

BS3νRM: eV scale sterile ν's; NSI's; ChLFV processes ($\mu \rightarrow e + \gamma$, $\mu \rightarrow 3e$, $\mu^- - e^-$ conversion on (A,Z)); $\nu-$related BSM physics at the TeV scale (N_{jR}, H^{--}, H^-, etc.).

Experimental Proofs for $\nu-$Oscillations

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

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

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

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

Super-Kamiokande, SNO, BOREXINO; KamLAND

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

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

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

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

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

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: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 0.5$ eV.

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 ($L \neq$ const.).
- In the existence of new particles, e.g., at the TeV scale: heavy Majorana Neutrinos N_j, doubly charged scalars,...
- In the existence of new (FChNC, FCFNSNC) neutrino interactions ($U(1)_X$, $M_X \lesssim 50$ MeV).
- In the existence of LFV processes: $\mu \to e + \gamma$, $\mu \to 3e$, $\mu - e$ conversion, etc., which proceed with rates close to the existing upper limits.
- In the existence of "unknown unknowns"...

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

Two (extreme) possibilities:

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

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

We can also have, in principle:

$m_4 \sim 5$ keV (DM), $M_{5,6} \sim (10 - 10^3)$ GeV (seesaw).

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

Data: 3 νs are light: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 0.5$ eV.

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

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

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

Three Neutrino Mixing

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

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

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

- U - $n \times n$ unitary:

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

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

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

PMNS Matrix: Standard Parametrization

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

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

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CPV phase, $\delta = [0, 2\pi]$; CP inv.: $\delta = 0, \pi, 2\pi$;
- α_{21}, α_{31} - Majorana CPV phases; CP inv.: $\alpha_{21(31)} = k(k')\pi$, $k(k') = 0, 1, 2...$

S.M. Bilenky et al., 1980

- $\Delta m^2_\odot \equiv \Delta m^2_{21} \cong 7.34 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.305$, $\cos 2\theta_{12} \gtrsim 0.306$ (3σ),
- $|\Delta m^2_{31(32)}| \cong 2.448$ (2.502) $\times 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong 0.545$ (0.551), NO (IO) ,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0222$ (0.0223)

F. Capozzi et al. (Bari Group), arXiv:2003.08511.

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

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

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

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

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

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

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

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

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

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

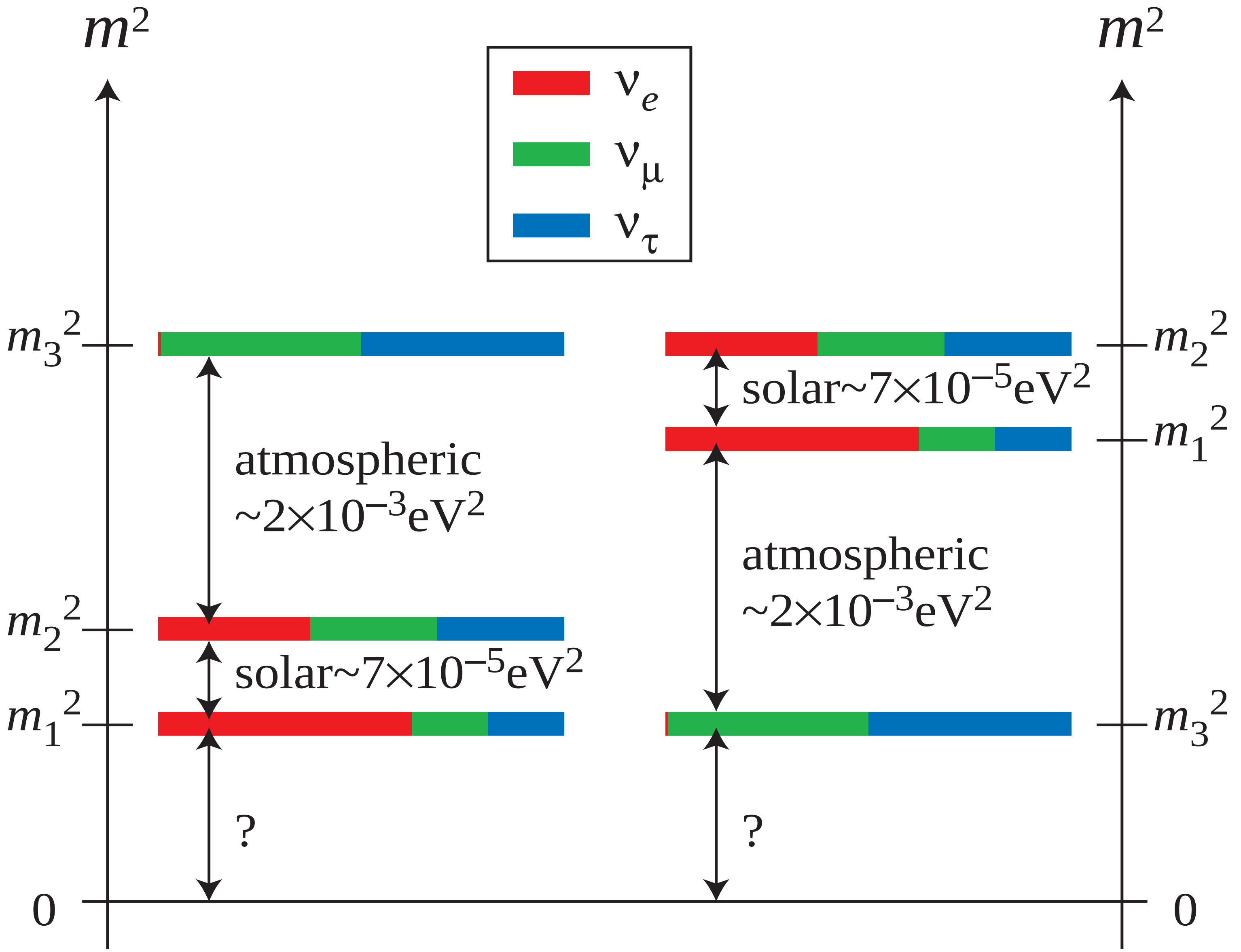

m^2
m^2
ν_e
ν_μ
ν_τ
m_3^2
m_2^2
m_1^2
atmospheric
$\sim 2\times10^{-3}$eV^2
solar$\sim 7\times10^{-5}$eV^2
?
0
m_2^2
m_1^2
m_3^2
solar$\sim 7\times10^{-5}$eV^2
atmospheric
$\sim 2\times10^{-3}$eV^2
?
0

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

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

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

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

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

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

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

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

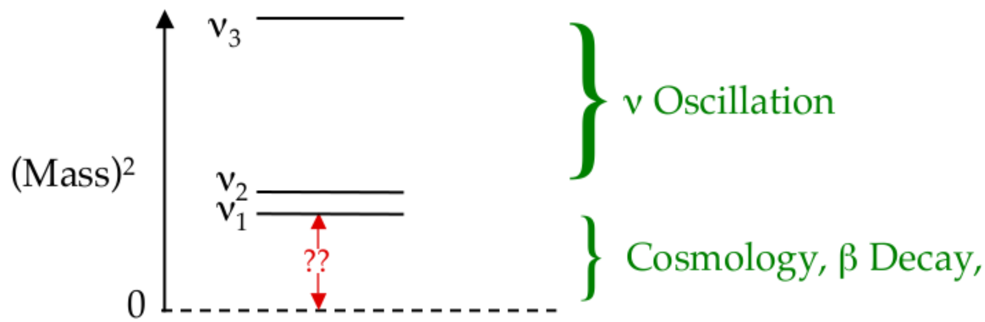
- Majorana phases α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

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

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

Absolute Neutrino Mass Scale

The Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

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

4

Due to B. Kayser

Absolute Neutrino Mass Measurements

Troitzk, Mainz, KATRIN experiments on $^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$**.**

The best limit was reported at the ν 2020 by the KATRIN Collaboration (talk by S. Martens):

$$\text{KATRIN:} \quad m_{\nu_e} < 1.1 \text{ eV (90\% CL)}$$

Troitzk and Mainz experiments have obtained:

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

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

The KATRIN experiment is planned to reach sensitivity

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

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
Belfast
Irish Sea
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
Guernsey (U.K.)
Jersey (U.K.)
Sea
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
RUSSIA
Vilnius
Mahilyow
Minsk
BELARUS
Hrodna
Homyel'
Gdańsk
Hamburg
Bremen
Berlin
Poznań
POLAND
Warsaw
Brest
Łódź
Wrocław
Kiev
Rivne
UKRAINE
L'viv
Amsterdam
NETH.
Rotterdam
Essen
Cologne
Leipzig
Brussels
Lille
BEL.
Bonn
GERMANY
Frankfurt am Main
Prague
CZECH REPUBLIC
Brno
Kraków
Chernivtsi
Mykolayiv
Luxembourg
LUX.
Paris
SLOVAKIA
Bratislava
Chișinău
Iași
MOLDOVA
Odesa
Stuttgart
Strasbourg
Munich
Vienna
Budapest
Cluj-Napoca
Nantes
LIECH.
AUSTRIA
Zürich
Bern
Vaduz
SWITZ.
Geneva
HUNGARY
ROMANIA
FRANCE
Bay of Biscay
Ljubljana
SLOVENIA
Zagreb
Bucharest
Constanța
Black Sea
Lyon
Milan
Venice
Turin
Bordeaux
MASSIF CENTRAL
Genoa
CROATIA
BOSNIA AND HERZEGOVINA
Belgrade
Varna
Serbia
BULGARIA
Bilbao
Toulouse
MONACO
SAN MARINO
Sarajevo
Sofia
Andorra
Marseille
Ligurian Sea
Florence
Istanbul
Porto
Skopje
Bursa
PORTUGAL
Madrid
Barcelona
VATICAN CITY
Tirana
Thessaloniki
TURKEY
Lisbon
SPAIN
Valencia
Balearic Sea
Sardinia
Naples
Tyrrhenian Sea
GREECE
Aegean Sea
İzmir
BALEARIC ISLANDS
Athens
Sevilla
Cagliari
Ionian Sea
Mediterranean Sea
Palermo
Gibraltar
Málaga
Sicily
Rhodes
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Algiers
Melilla (SPAIN)
Oran
Tunis
Crete
Rabat
Valletta
MALTA
Casablanca
MOROCCO
ALGERIA
TUNISIA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
0 300 Kilometers
0 300 Miles

Mass and Hierarchy from Cosmology

Cosmological and astrophysical data on $\sum_j m_j$ (Planck CMB + BAO data + ΛCDM (6 parameter) model + assuming 3 light massive neutrinos, talk by L. Knox at this Conference):

$$\sum_j m_j \equiv \Sigma < 0.150 \text{ eV} \quad (95\% \text{ C.L.})$$

The upper limit depends on the data set and assumptions used. According to F. Capozzi et al., arXiv:2003.08511, it reads:

$$\sum_j m_j \equiv \Sigma < 0.12 - 0.69 \text{ eV} \quad (95\% \text{ C.L.})$$

where 0.69 eV corresponds to the data set used which leads to the most conservative result.

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

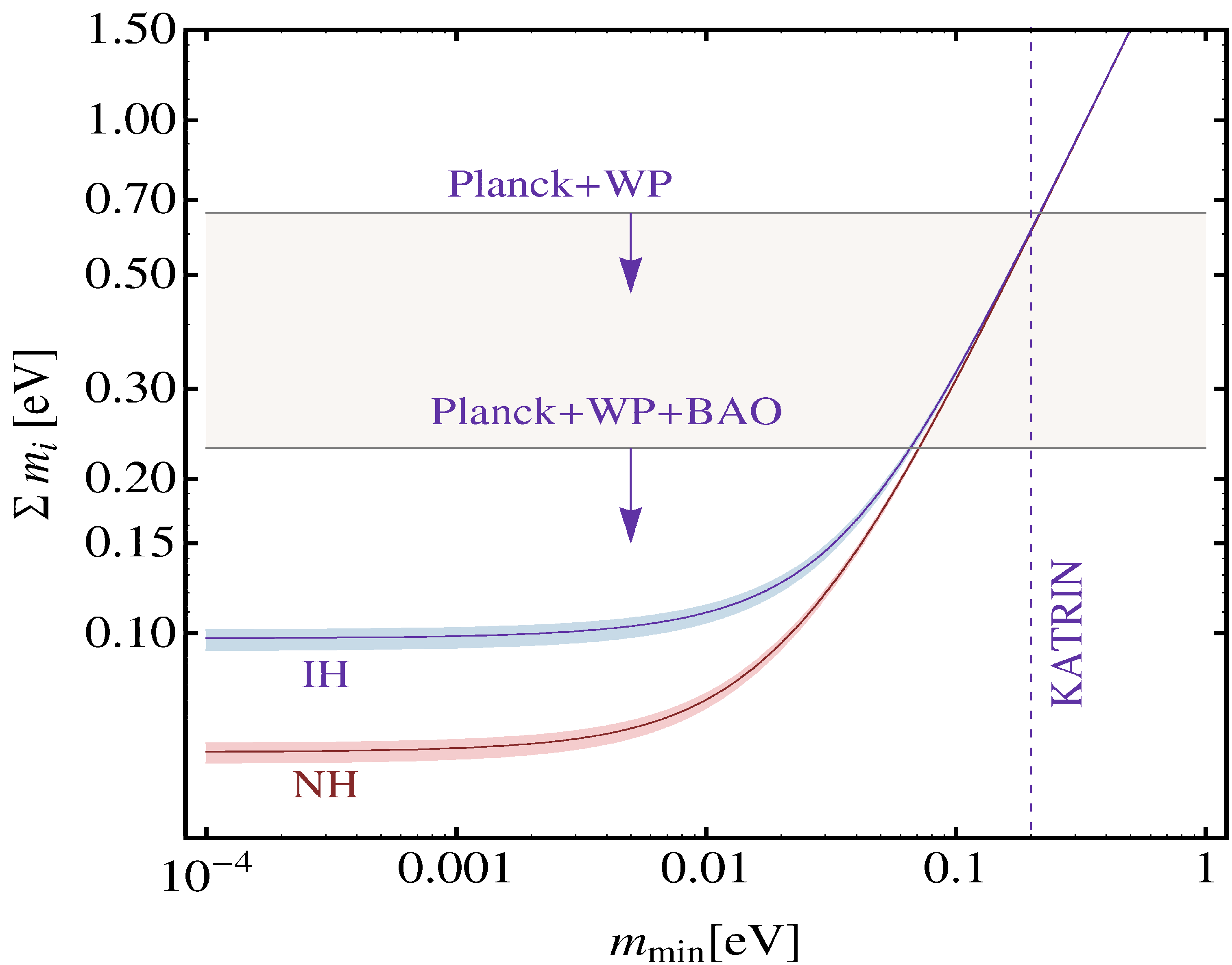
$$\sum_j m_j : \qquad \delta \cong (0.01 - 0.04) \text{ eV}.$$

Similar sensitivity ($\delta \cong 0.03$ eV) is planned to be reached in CMB-S4 experiment, and/or combining data from DESI and CMB-S4 experiments ($\delta \cong 0.012 - 0.020$ eV).

NH: $\sum_j m_j \leq 0.061$ **eV** **(3σ);**

IH: $\sum_j m_j \geq 0.098$ **eV** **(3σ).**

Mass and Hierarchy from Cosmology



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

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

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

First appeared in the global data analysis in F. Capozzi et al., arXiv:1312.2878

Since 2018 up to Neutrino'2020 – strong indications in favor of NO neutrino mass spectrum obtained in the global analyses of F. Capozzi et al. and I. Esteban et al.

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

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

2018 global analysis: data favors NO

IO disfavored at 3.1σ.

F. Capozzi et al., 1804.09678.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.90	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2\theta_{12}/10^{-1}$	NO	3.05	2.92 – 3.19	2.78 – 3.32	2.65 – 3.47	4.5
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.5
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.485	2.453 – 2.514	2.419 – 2.547	2.389 – 2.578	1.3
	IO	2.465	2.434 – 2.495	2.404 – 2.526	2.374 – 2.556	1.2
$\sin^2\theta_{13}/10^{-2}$	NO	2.22	2.14 – 2.28	2.07 – 2.34	2.01 – 2.41	3.0
	IO	2.23	2.17 – 2.30	2.10 – 2.37	2.03 – 2.43	3.0
$\sin^2\theta_{23}/10^{-1}$	NO	5.45	4.98 – 5.65	4.54 – 5.81	4.36 – 5.95	4.9
	IO	5.51	5.17 – 5.67	4.60 – 5.82	4.39 – 5.96	4.7
δ/π	NO	1.28	1.10 – 1.66	0.95 – 1.90	0 – 0.07 $\oplus$ 0.81 – 2	16
	IO	1.52	1.37 – 1.65	1.23 – 1.78	1.09 – 1.90	9

$\delta m^2 \equiv \Delta m^2_{21}$; $\Delta m^2 \equiv \Delta m^2_{31(32)} \overset{-}{(+)} 0.5\Delta m^2_{21}$, **NO (IO).**

F. Capozzi et al. (Bari Group), arXiv:2003.08511.

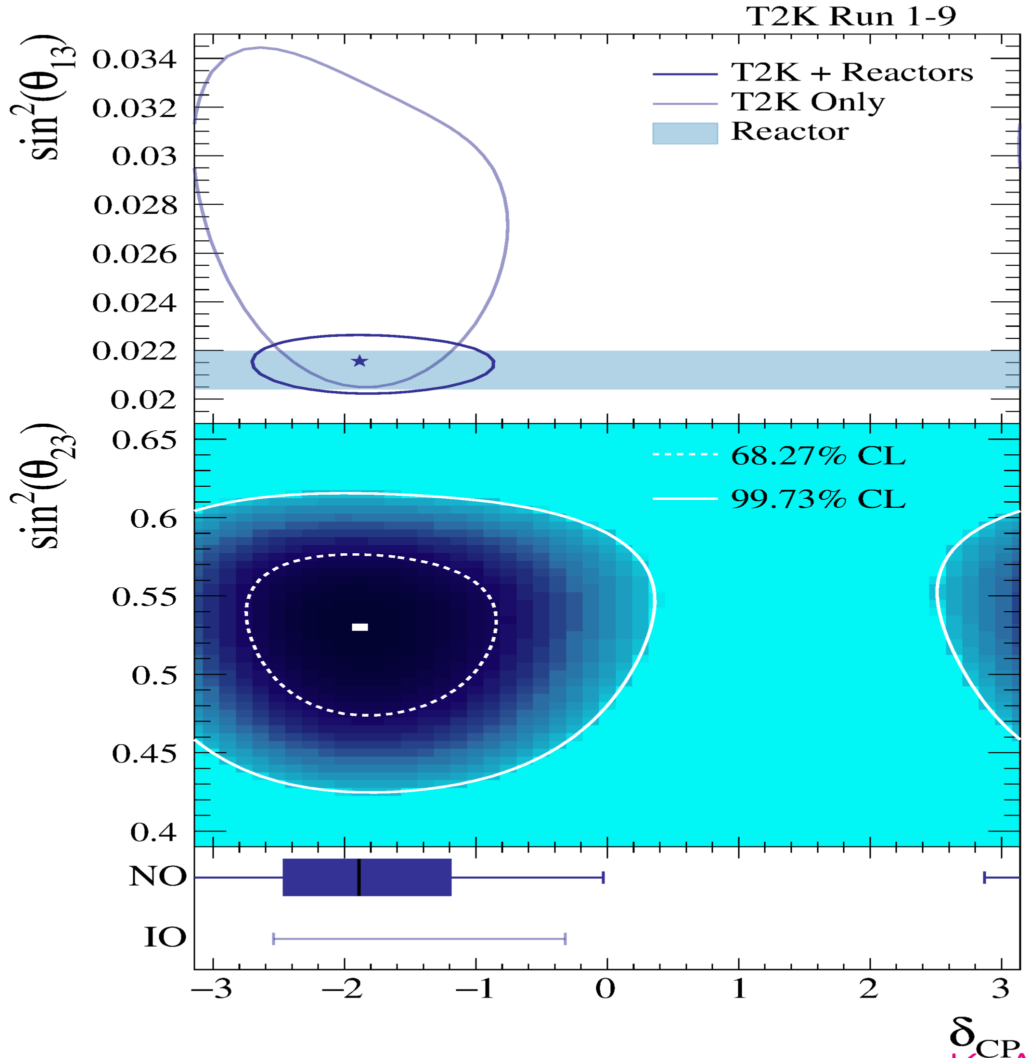
March 2020 global analysis (Bari Group):

- **Best fit value:** $\delta = 1.28\,(1.52)\pi$**;**
- $\delta = 0$ **or** 2π **are disfavored at** $2.6\,(>5)\sigma$**;**
- $\delta = \pi$ **is allowed (disfavored) at** $1.6\,(3.2)\sigma$
- $\delta = \pi/2$ **is strongly disfavored at** $4.2\,(>5)\sigma$
- **At** 3σ**:** δ/π **is found to lie in the intervals** $0.00 - 0.07 \oplus 0.81 - 2.00$ **(1.09-1.90).**

- **Data favors NO: IO disfavored at** 3.2σ**.**

F. Capozzi et al. (Bari Group), arXiv:2003.08511.

Latest results from T2K



K. Abe et al., 1910.03887

Best fit value: $\delta = -1.89\,(-1.38)$, NO (IO).
$\delta = 0, \pi$ disfavored at 95% CL.
At 3σ: δ is found to lie in [-3.41,-0.03] ([-2.54,-0.32]), NO (IO).

2020 global analyses after Nu2020: combine latest T2K and NOνA data.

Results on CPV due to δ and NO vs IO spectrum - inconclusive.

K.J. Kelly, P.A. Machado, S.J. Parke, Y.F. Perez Gonzalez and R. Zukanovich-Funchal,
"Back to (Mass-)Square(d) One: The Neutrino Mass Ordering in Light of Recent Data," arXiv:2007.08526 [hep-ph].

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou,
"The fate of hints: updated global analysis of three-flavor neutrino oscillations," arXiv:2007.14792 [hep-ph].

Result on CPV, b.f.v.: $\delta = 197^{\circ}$, NO; $\delta = 282^{\circ}$, IO.

At 3σ: δ is found to lie in $[120^{\circ}, 369^{\circ}]$ ($[193^{\circ}, 352^{\circ}]$), NO (IO).

IO: CPV due to δ at 3σ.

IO disfavored at 1.6σ with respect to NO (2.7σ including SuperK ν_{atm} data).

Determining the $\nu-$Mass Ordering (sgn($\Delta m^2_{\rm atm(31)}$))

- **LBL $\nu-$oscillation experiments (T2K, NOνA; T2HK, T2HKK, DUNE); designed to search also for CP violation.**
- **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).**
- **Reactor $\bar{\nu}_e$ Oscillations in vacuum (JUNO).**
- ^{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.**

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.

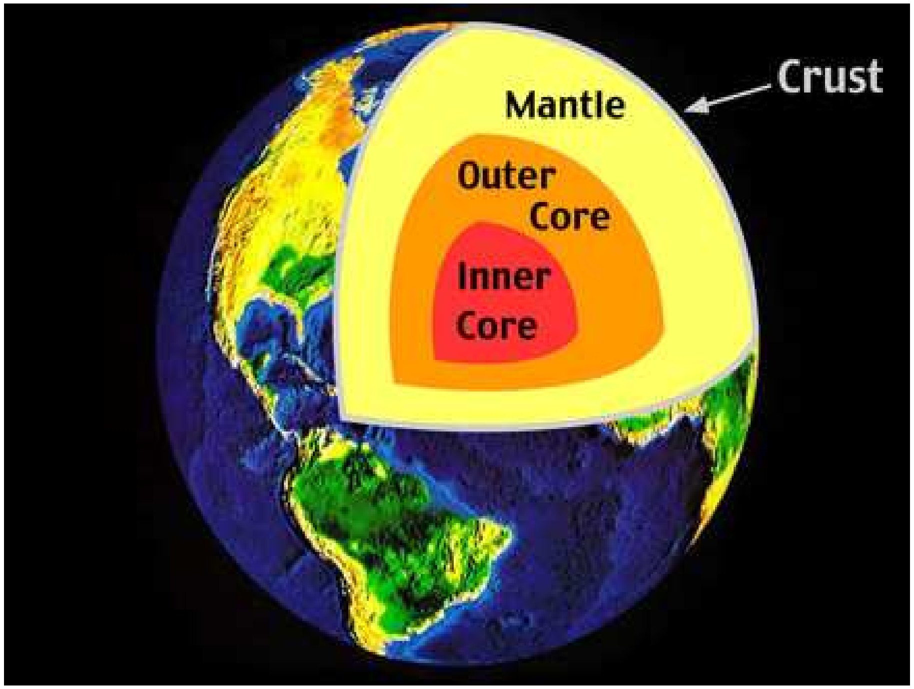
NO: $\nu_{\mu(e)} \to \nu_{e(\mu)}$ **matter enhanced,** $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ **- suppressed**

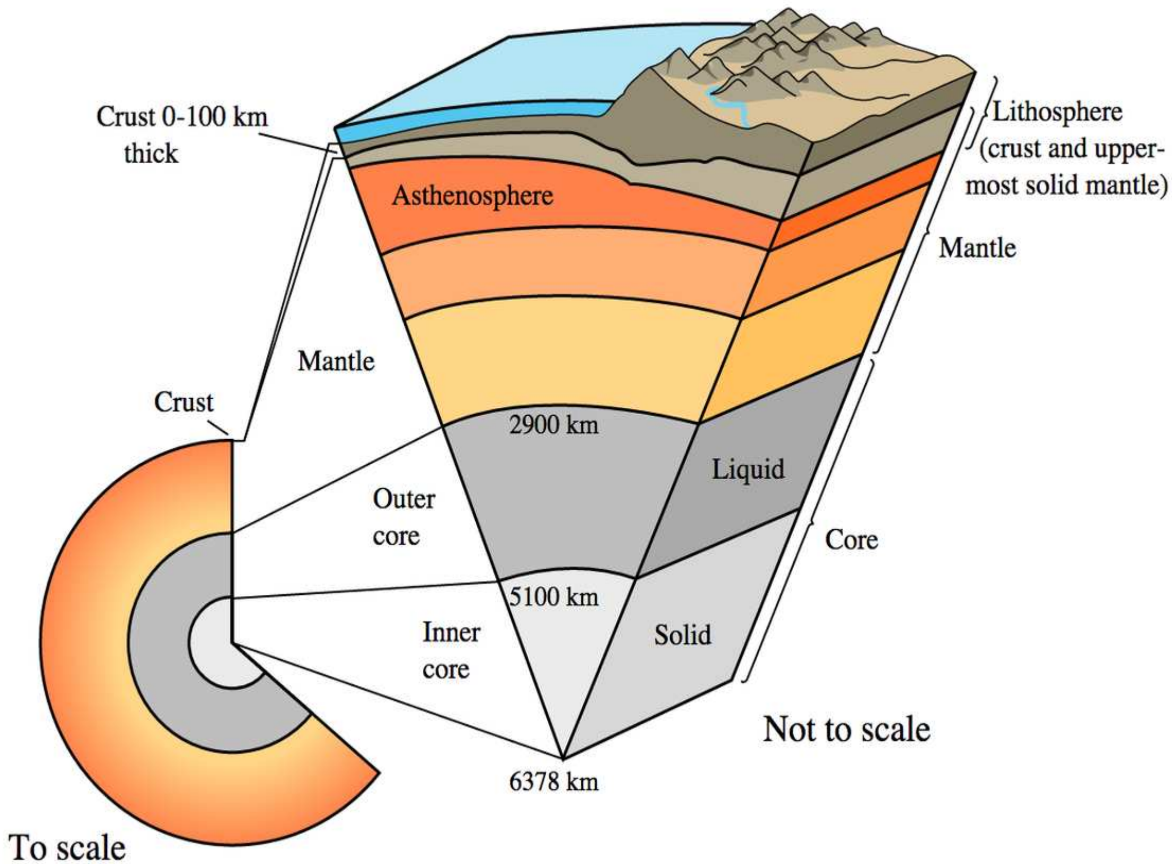
IO: $\bar{\nu}_{\mu(e)} \to \bar{\nu}_{e(\mu)}$ **matter enhanced,** $\nu_{\mu(e)} \to \nu_{e(\mu)}$**−suppressed**

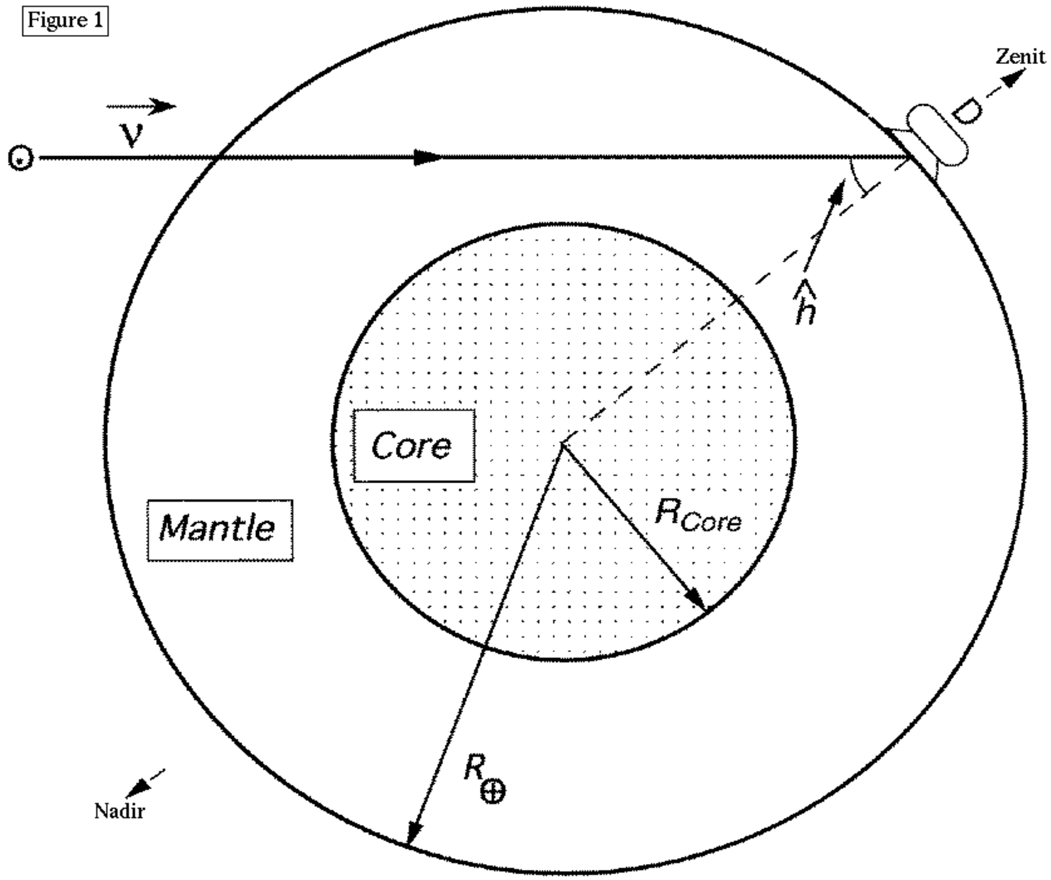
No charge identification (SK, HK, IceCube-PINGU, ANTARES-ORCA);
event rate (DIS regime): $[2\sigma(\nu_l + N \to l^- + X) + \sigma(\bar{\nu}_l + N \to l^+ + X)]/3$

Charge identification: INO; event rate (DIS regime): $\sigma(\nu_l + N \to l^- + X)$,
$\sigma(\bar{\nu}_l + N \to l^+ + X)$

The Earth




Crust 0-100 km
thick
Asthenosphere
Lithosphere
(crust and upper-
most solid mantle)
Mantle
Mantle
Crust
2900 km
Liquid
Outer
core
Core
5100 km
Inner
core
Solid
Not to scale
6378 km
To scale



Earth: $R_{core} = 3446$ km, $R_{mant} = 2885$ km

Earth: $\bar{N}_e^{mant} \sim 2.3\ N_A\ cm^{-3}$, $\bar{N}_e^{core} \sim 5.7\ N_A\ cm^{-3}$

The Earth

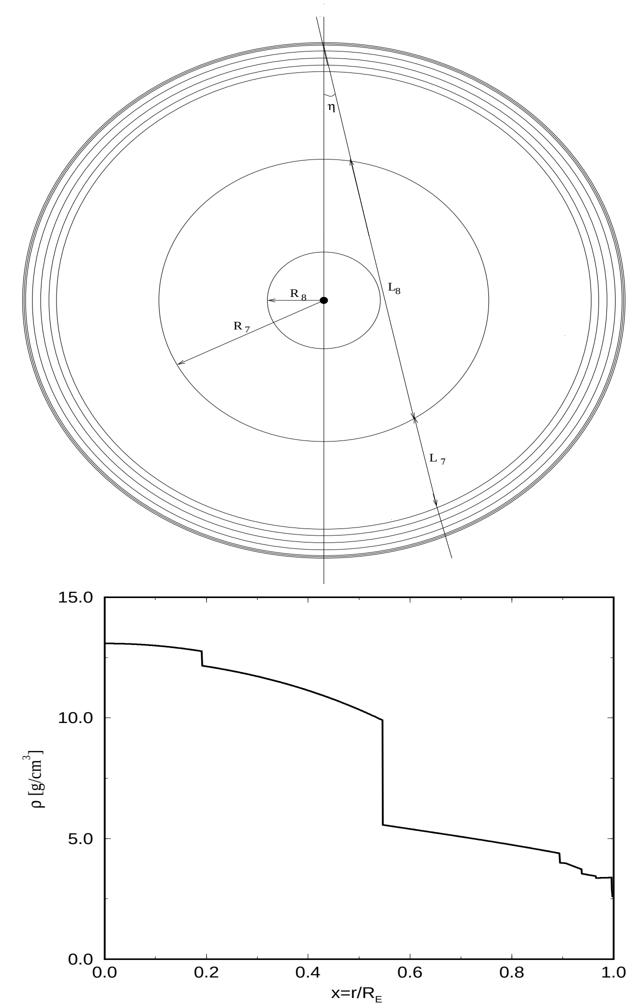


FIG. 1. Density profile of the Earth.

$R_c = 3446$ km, $R_m = 2885$ km; $\bar{N}_e^{mant} \sim 2.3\ N_A\ cm^{-3}$, $\bar{N}_e^{core} \sim 5.7\ N_A\ cm^{-3}$

For $\theta_n \leq 33.17^o$, or path lengths $L \geq 10660$ km, neutrinos cross the Earth core.

The path length for neutrinos which cross only the Earth mantle is given by $L = 2R_\oplus \cos\theta_n$.

If neutrinos cross the Earth core, the lengths of the paths in the mantle, $2L^{\rm man}$, and in the core, $L^{\rm core}$, are determined by: $L^{\rm man} = R_\oplus \cos\theta_n - (R_c^2 - R_\oplus^2 \sin^2\theta_n)^{\frac{1}{2}}$, $L^{\rm core} = 2(R_c^2 - R_\oplus^2 \sin^2\theta_n)^{\frac{1}{2}}$.

The change of N_e from the mantle to the core, according to PREM, can well be approximated by a step function.

N_e changes relatively little around the quoted mean values along the trajectories of neutrinos which cross a substantial part of the Earth mantle, or the mantle and the core, and the two-layer constant density approximation, $N_e^{man} = const. = \tilde{N}_e^{man}$, $N_e^c = const. = \tilde{N}_e^c$, $\tilde{N}_e^{man}$ *and* $\tilde{N}_e^c$ *being the mean densities along the given neutrino path in the Earth*, **was shown to be sufficiently accurate in what concerns the calculation of neutrino oscillation probabilities in a large number of specific cases.**

This is related to the fact that relatively small changes of density along the path of the neutrinos in the mantle (or in the core) take place over path lengths which are typically considerably smaller than the corresponding oscillation length in matter.

Neutrino Oscillations in Matter (Earth mantle)

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

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

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

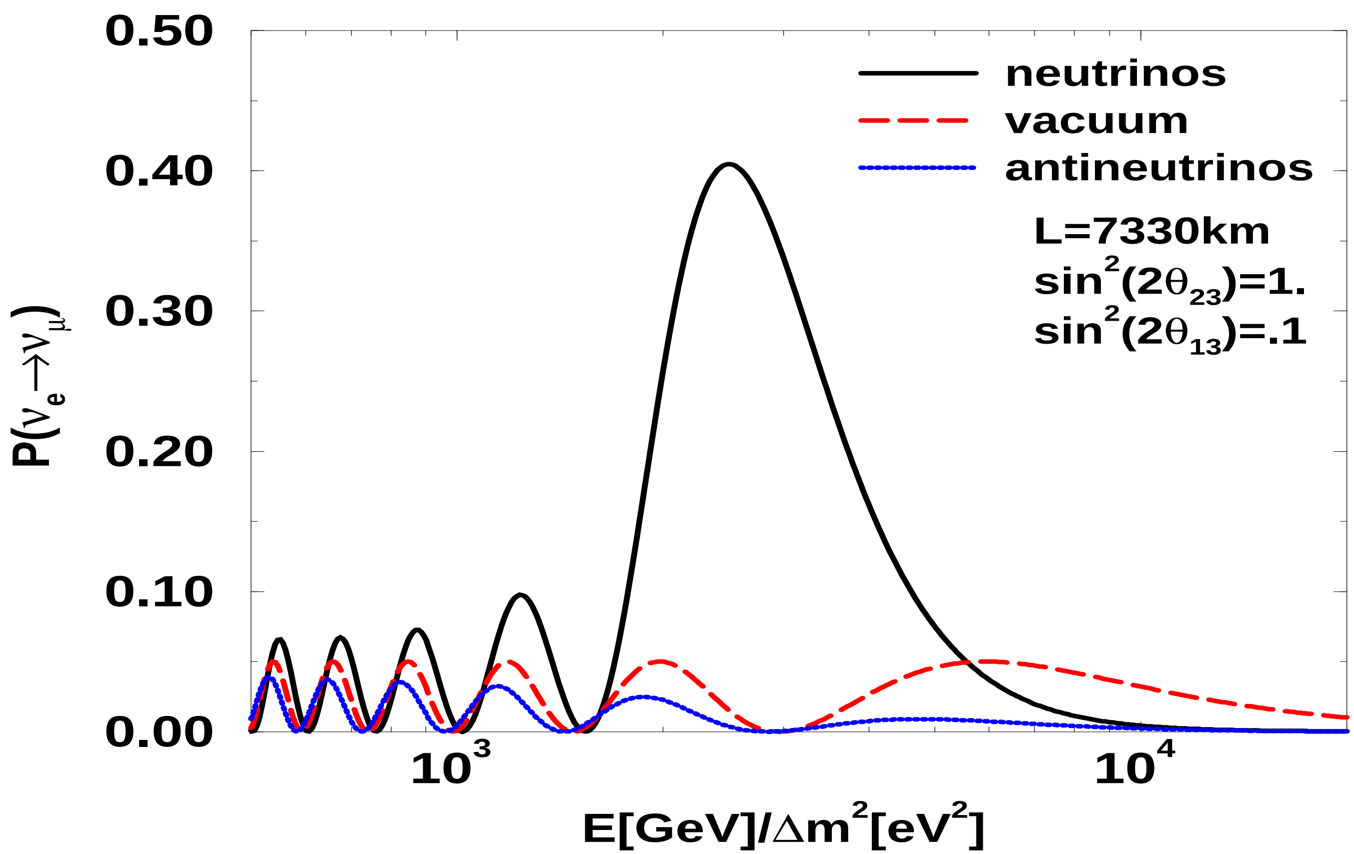
$$\cos 2\theta_{13}^m = \frac{1-N_e/N_e^{res}}{\sqrt{(1-\frac{N_e}{N_e^{res}})^2+\tan^2 2\theta_{13}}},$$

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

$$6.56 \times 10^6 \, \frac{\Delta m^2[\text{eV}^2]}{E[\text{MeV}]} \cos 2\theta \, \text{cm}^{-3} \; \text{N}_\text{A} \, ,$$

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

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

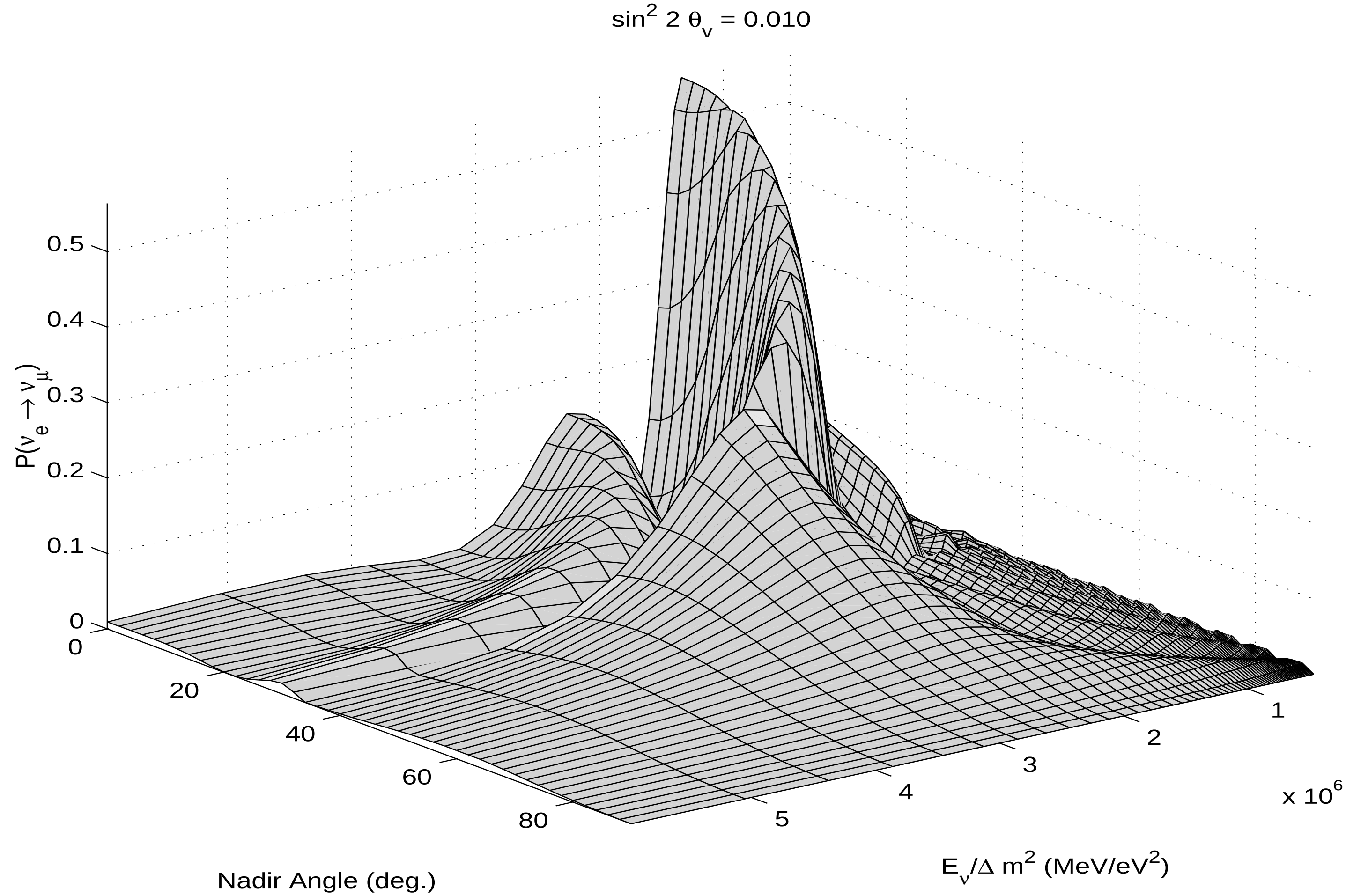


$\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2, $E^{res} = 6.25$ GeV; $P^{3\nu} = \sin^2\theta_{23} P^{2\nu}_m = 0.5 P^{2\nu}_m$;
$N_e^{res} \cong 2.3$ cm^{-3} N$_A$; $L_m^{res} = L^v / \sin 2\theta_{13} \cong 6250/0.32$ km; $2\pi L/L_m \cong 0.75\pi (\neq \pi)$.

I. Mocioiu, R. Shrock, 2000

Oscillations of Neutrinos Crossing the Earth Core

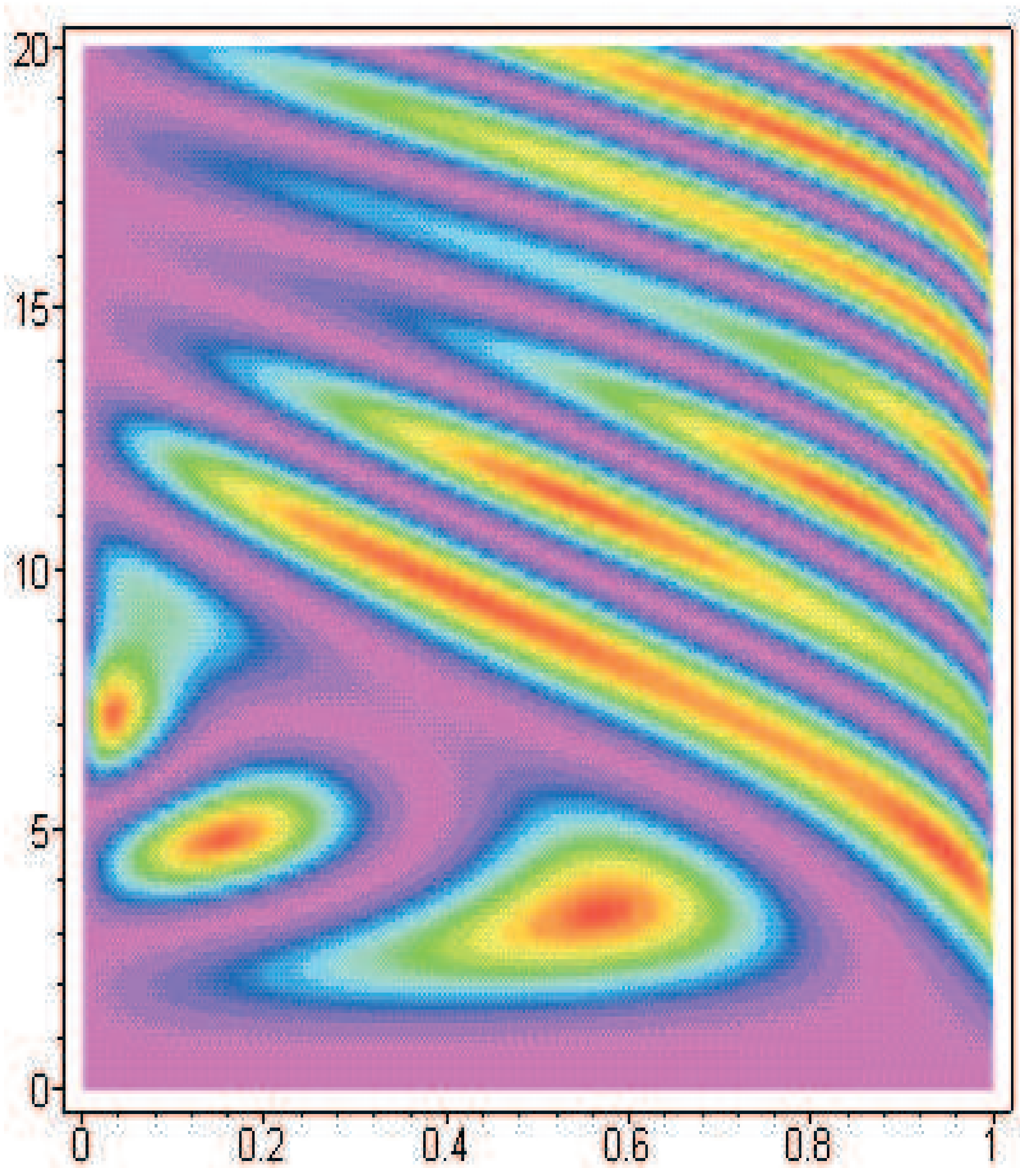
Earth matter effects in $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ (NOLR)



S.T.P., 1998;
M. Chizhov, M. Maris, S.T.P., 1998; M. Chizhov, S.T.P., 1999

$P(\nu_e \to \nu_\mu) \equiv P_{2\nu} \equiv (s_{23})^{-2} P_{3\nu}(\nu_{e(\mu)} \to \nu_{\mu(e)})$, $\theta_\mathrm{v} \equiv \theta_{13}$, $\Delta m^2 \equiv \Delta m^2_{\mathrm{atm}}$;

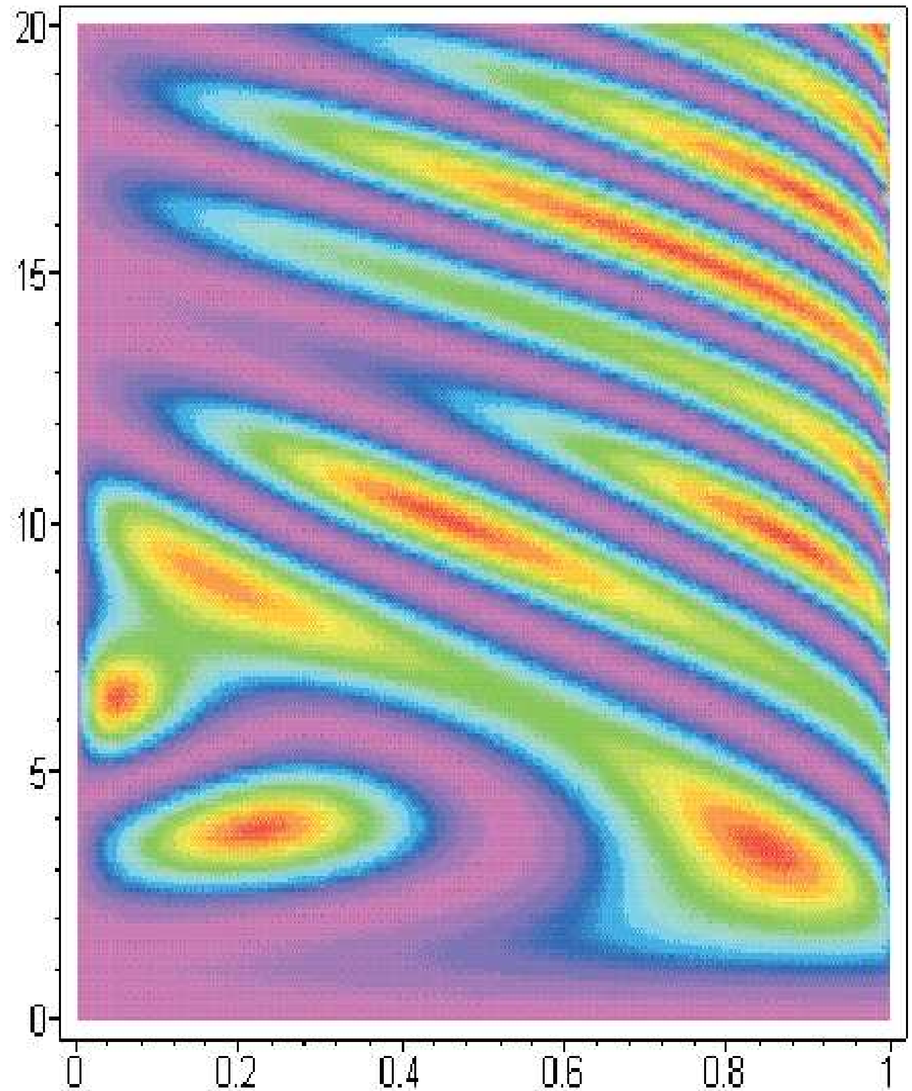
Absolute maximum: Neutrino Oscillation Length Resonance (NOLR);
Local maxima: MSW effect in the Earth mantle or core.



$(s_{23})^{-2} P_{3\nu}(\nu_{e(\mu)} \rightarrow \nu_{\mu(e)}) \equiv P_{2\nu}$; **NOLR: "Dark Red Spots"**, $P_{2\nu} = 1$;

Vertical axis: $\Delta m^2/E$ $[10^{-7} eV^2/MeV]$; **horizontal axis:** $\sin^2 2\theta_{13}$; $\theta_n = 0$

M. Chizhov, S.T.P., 1999 (hep-ph/9903399,9903424)



The same for $\theta_n = 23^\circ$.
Vertical axis: $\Delta m^2/E$ $[10^{-7} eV^2/MeV]$; **horizontal axis:** $\sin^2 2\theta_{13}$; $\theta_n = 0$

M. Chizhov, S.T.P., 1999 (hep-ph/9903399,9903424)

• **For Earth center crossing ν's ($\theta_n = 0$) and, e.g.** $\sin^2 2\theta_{13} = 0.01$, **NOLR occurs at** $E \cong 4$ **GeV** **($\Delta m^2(atm) = 2.5 \times 10^{-3}$ eV^2).**

S.T.P., hep-ph/9805262

• **For the Earth core crossing ν's:** $P_{2\nu} = 1$ **due to NOLR when**

$$\tan \Phi^{\rm man}/2 \equiv \tan \phi' = \pm \sqrt{\frac{-\cos 2\theta''_m}{\cos(2\theta''_m - 4\theta'_m)}},$$

$$\tan \Phi^{\rm core}/2 \equiv \tan \phi'' = \pm \frac{\cos 2\theta'_m}{\sqrt{-\cos(2\theta''_m)\cos(2\theta''_m - 4\theta'_m)}}$$

$\Phi^{\rm man}$ ($\Phi^{\rm core}$) - **phase accumulated in the Earth mantle (core),**
θ'_m (θ''_m) - **the mixing angle in the Earth mantle (core).**

$P_{2\nu} = 1$ **due to NOLR for** $\theta_n = 0$ **(Earth center crossing ν's) at,**
e.g. $\sin^2 2\theta_{13} = 0.034;\ 0.154$, $E \cong 3.5;\ 5.2$ **GeV ($\Delta m^2(atm) = 2.5 \times 10^{-3}$ eV^2).**

At the same time for E =3.47 GeV (5.19 Gev), the probability $P_{2\nu} \gtrsim 0.5$ **for the values of** $\sin^2 2\theta_{13}$ **from the interval** $0.02 \lesssim \sin^2 2\theta_{13} \lesssim 0.10$ **(**$0.04 \lesssim \sin^2 2\theta_{13} \lesssim 0.26$**).**

M. Chizhov, S.T.P., Phys. Rev. Lett. 83 (1999) 1096 (hep-ph/9903399); Phys. Rev. Lett. 85 (2000) 3979 (hep-ph/0504247); Phys. Rev. D63 (2001) 073003 (hep-ph/9903424).

The mantle-core enhancement of $P_m^{2\nu}$ (or $\bar{P}_m^{2\nu}$) is relevant, in particular, for the searches of sub-dominant $\nu_{e(\mu)} \rightarrow \nu_{\mu(e)}$ (or $\bar{\nu}_{e(\mu)} \rightarrow \bar{\nu}_{\mu(e)}$) oscillations of atmospheric neutrinos having energies $E \gtrsim 2$ GeV and crossing the Earth core on the way to the detector.

S.T.P., hep-ph/9805262; M. Chizhov, S.T.P., hep-ph/9903424

The effects of Earth matter on the oscillations of atmospheric (and accelerator) neutrinos have not been observed so far.

The fluxes of atmospheric $\nu_{e,\mu}$ of energy E, which reach the detector after crossing the Earth along a given trajectory specified by the value of θ_n, $\Phi_{\nu_{e,\mu}}(E,\theta_n)$, are given by the following expressions in the case of the 3-neutrino oscillations under discussion:

$$\Phi_{\nu_e}(E,\theta_n) \cong \Phi^0_{\nu_e}\left(1 + [s^2_{23}r - 1]\ P^{2\nu}_m\right),$$

$$\Phi_{\nu_\mu}(E,\theta_n) \cong \Phi^0_{\nu_\mu}\left(1 + s^4_{23}[(s^2_{23}\ r)^{-1} - 1]P^{2\nu}_m - 2c^2_{23}s^2_{23}\left[1 - Re\ (e^{-i\kappa}A^{2\nu}_m(\nu_\tau \rightarrow \nu_\tau))\right]\right),$$

where $\Phi^0_{\nu_{e(\mu)}} = \Phi^0_{\nu_{e(\mu)}}(E,\theta_n)$ is the $\nu_{e(\mu)}$ flux in the absence of neutrino oscillations and

$$r \equiv r(E,\theta_n) \equiv \frac{\Phi^0_{\nu_\mu}(E,\theta_n)}{\Phi^0_{\nu_e}(E,\theta_n)} \quad .$$

s^2_{23}**: b.f.v.** 0.573 (0.575) **NO (IO);** 3σ **CL: (0.415-0.619).**

$r(E,\theta_n) \cong (2.6 \div 4.5)$ **for neutrinos giving the main contribution to the multi-GeV samples,** $E \cong (2 \div 10)$ **GeV.**

M. Honda, 1995.

The effects of Earth matter on the oscillations of atmospheric (and accelerator) neutrinos have not been observed so far.

INO is a suitable (if not perfect) detector that can observe these effects.

We have studied the possibility to observe matter effects (including the NOLR) and to determine the neutrino mass ordering in experiments with iron magnetised detectors (INO) in J. Bernabeu et al., hep-ph/0110071; S. Palomares-Ruiz and S.T.P., hep-ph/0406096; S.T.P. and T. Schwetz, hep-ph/0511277.
Results from the last two studies are discussed in what follows.

The sensitivity of the atmospheric neutrino experiments to the neutrino mass ordering depends strongly on the chosen value of $\sin^2\theta_{23}$ **from its** 3σ **allowed range: it is maximal (minimal) for the maximal (minimal) allowed value of** $\sin^2\theta_{23}$**.**

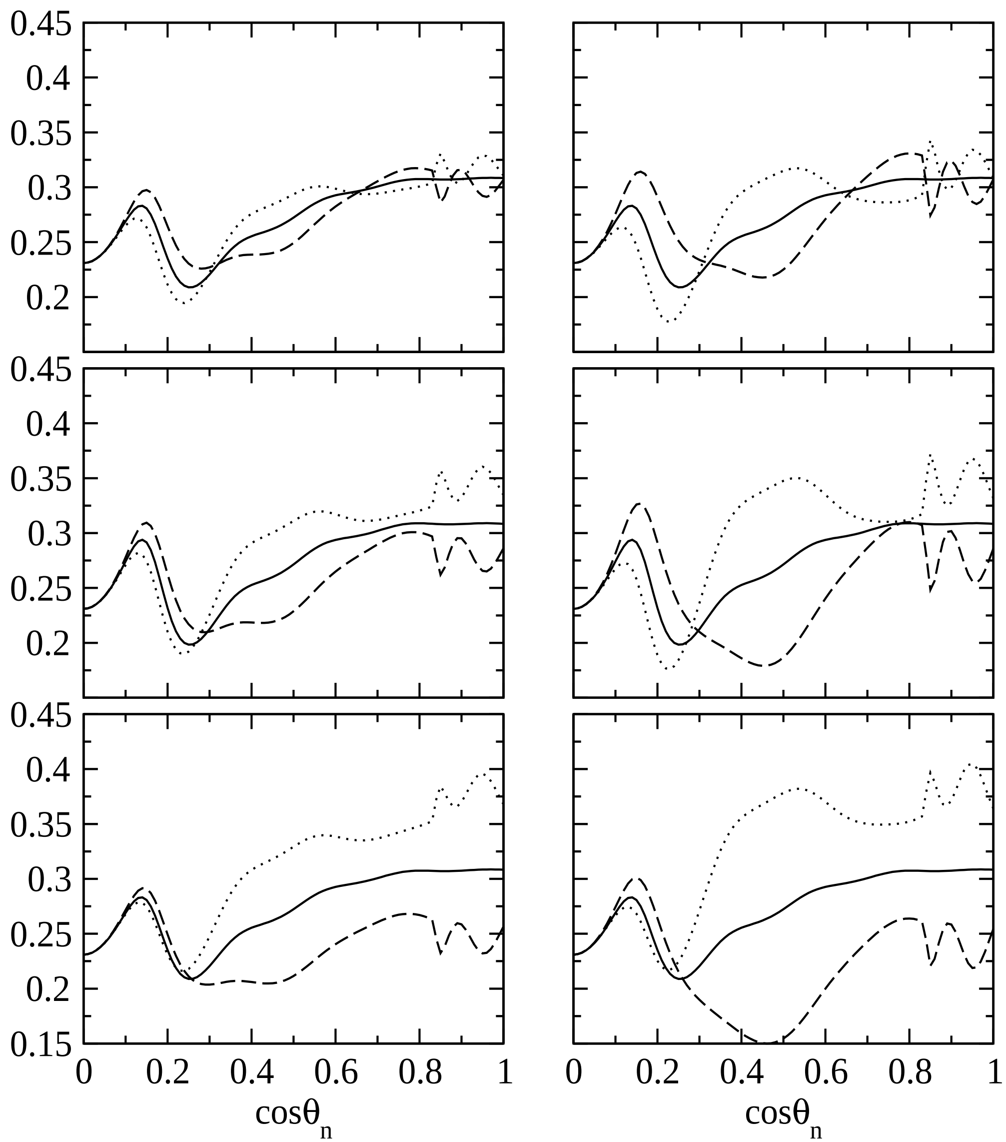
J. Bernabeu, S. Palomares-Ruiz, S.T.P., hep-ph/0305152

In hep-ph/0406096 the observables most sensitive to the Earth matter effects and to the neutrino MO have been considered –
the Nadir-angle (θ_n) distribution of the ratio $N(\mu^-)/N(\mu^+)$ of the multi-GeV μ^- and μ^+ event rates,
or equivalently the Nadir-angle distribution of the $\mu^- - \mu^+$ event rate asymmetry

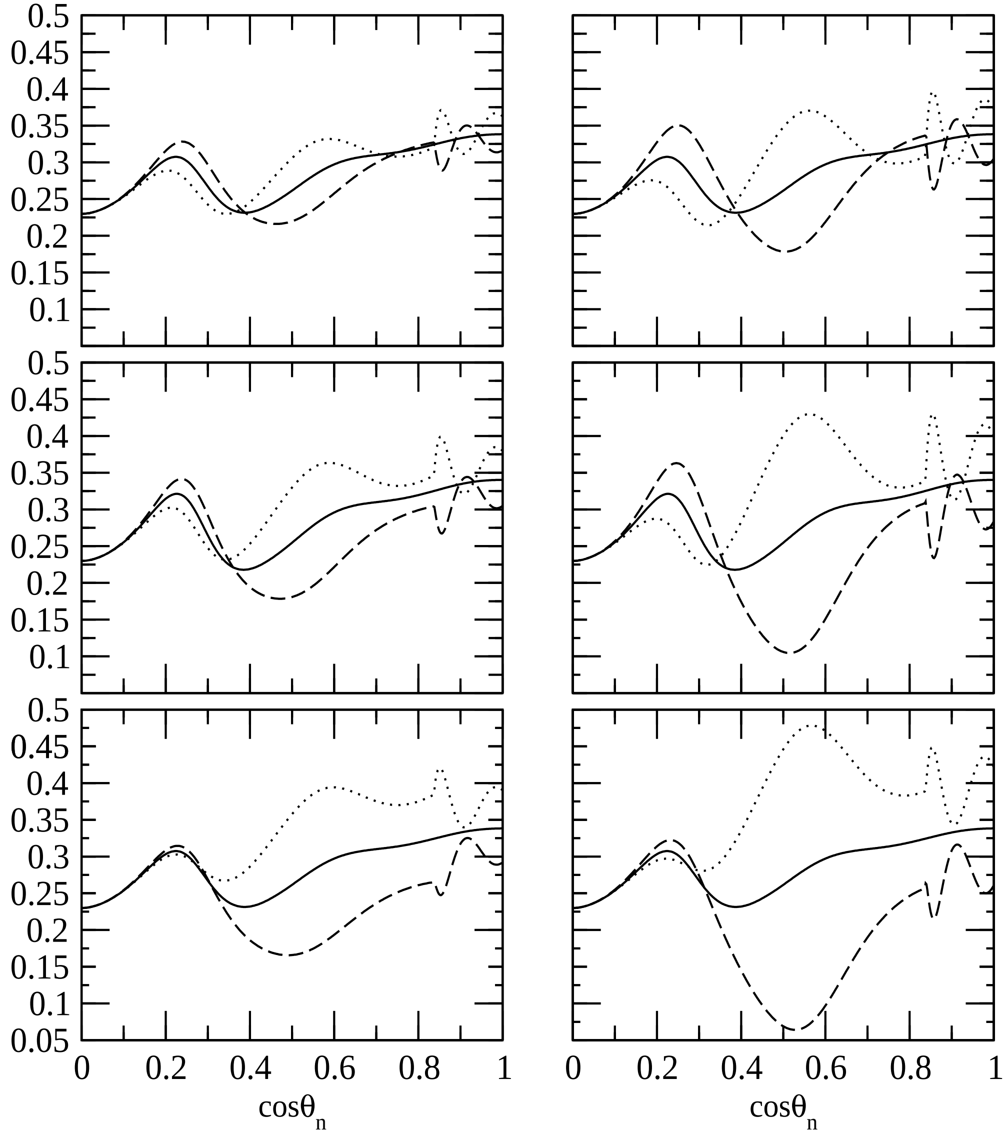
$$A_{\mu^-\mu^+} = \frac{N(\mu^-) - N(\mu^+)}{N(\mu^-) + N(\mu^+)} \ .$$

The following approximate relation holds (within $\sim 20\%$ and typically with much higher precision) for the range of values of the parameters of interest: $N(\mu^-)/N(\mu^+) \cong 6\ A_{\mu^-\mu^+}$.

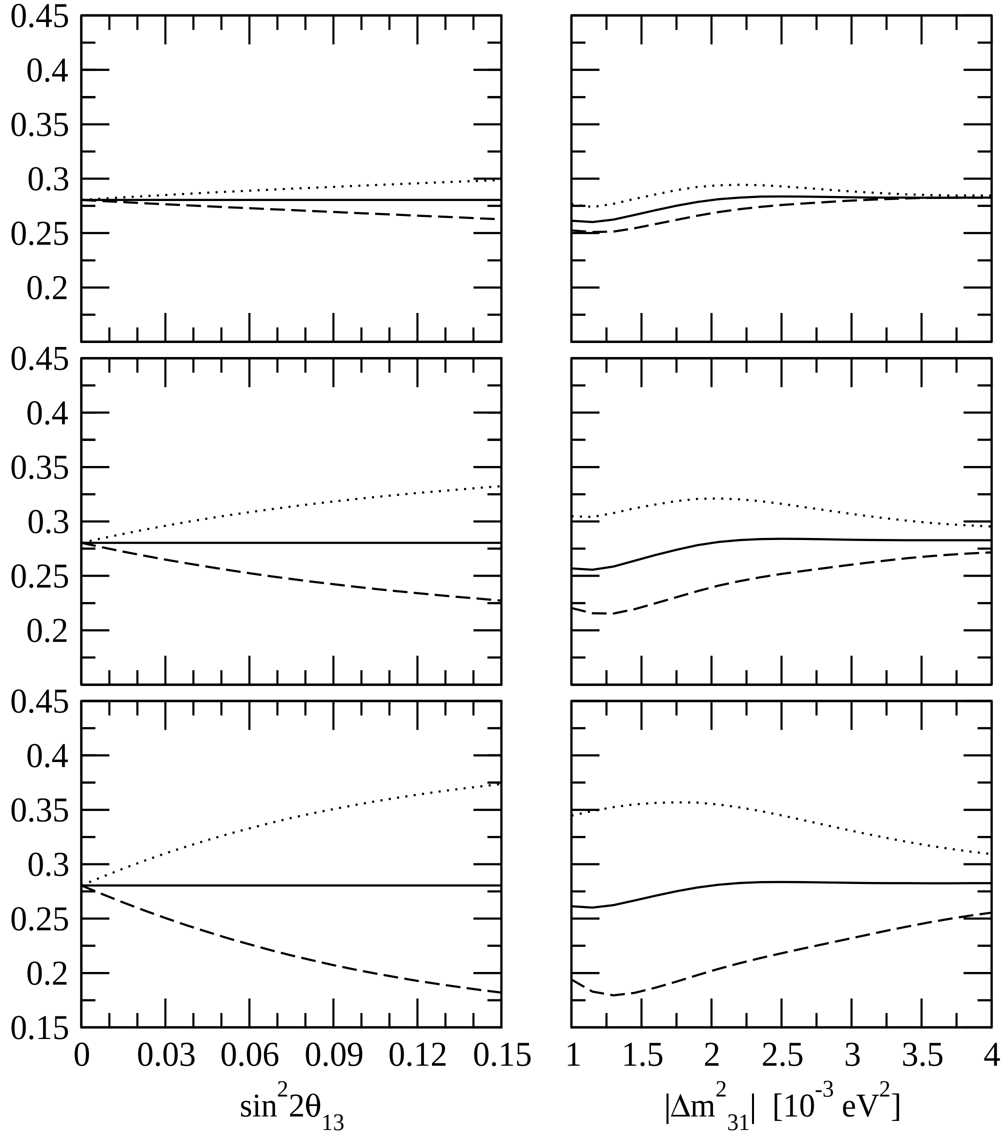
These are compared with the predicted Nadir-angle distributions of the same ratio and asymmetry in the case of 2-neutrino ($\sin^2\theta_{13} = 0$) vacuum $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ oscillations of the atmospheric ν_μ and $\bar{\nu}_\mu$, $A^{2\nu}_{\mu^-\mu^+}$.



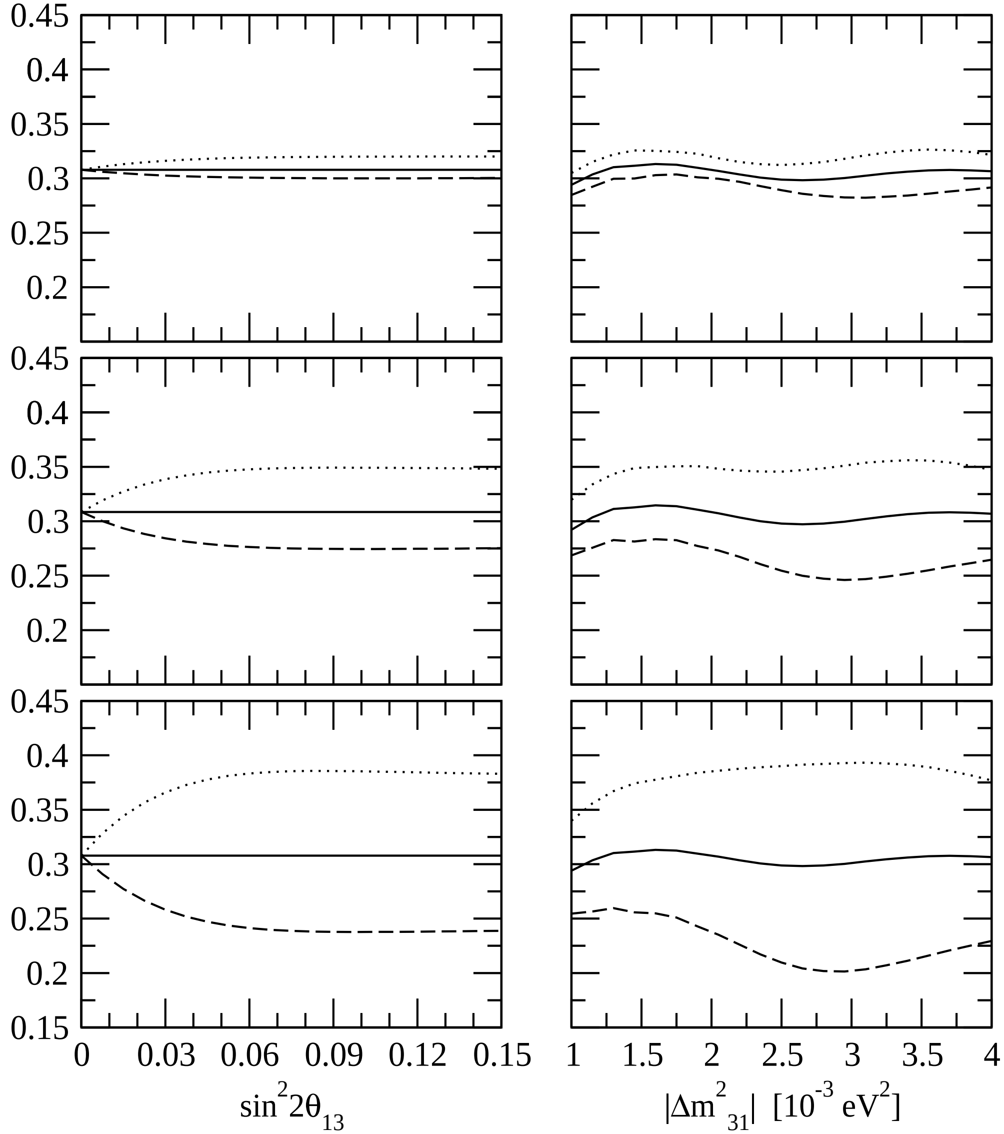
The θ_n **distributions of** $A^{2\nu}_{\mu^-\mu^+}$ **(solid lines),** $(A^{3\nu}_{\mu^-\mu^+})_{\rm NH}$ **(dashed),** $(A^{3\nu}_{\mu^-\mu^+})_{\rm IH}$ **(dotted), integrated over** E_ν **(and** E_μ**) in [2.0-10.0] GeV, for** $|\Delta m^2_{31}| =$ 2×10^{-3} eV^2, $s^2_{23} = 0.36$, **0.50, 0.64; (upper, middle, lower panels), and** $s^2_{13} = 0.05$, **0.10** (left, right panels).



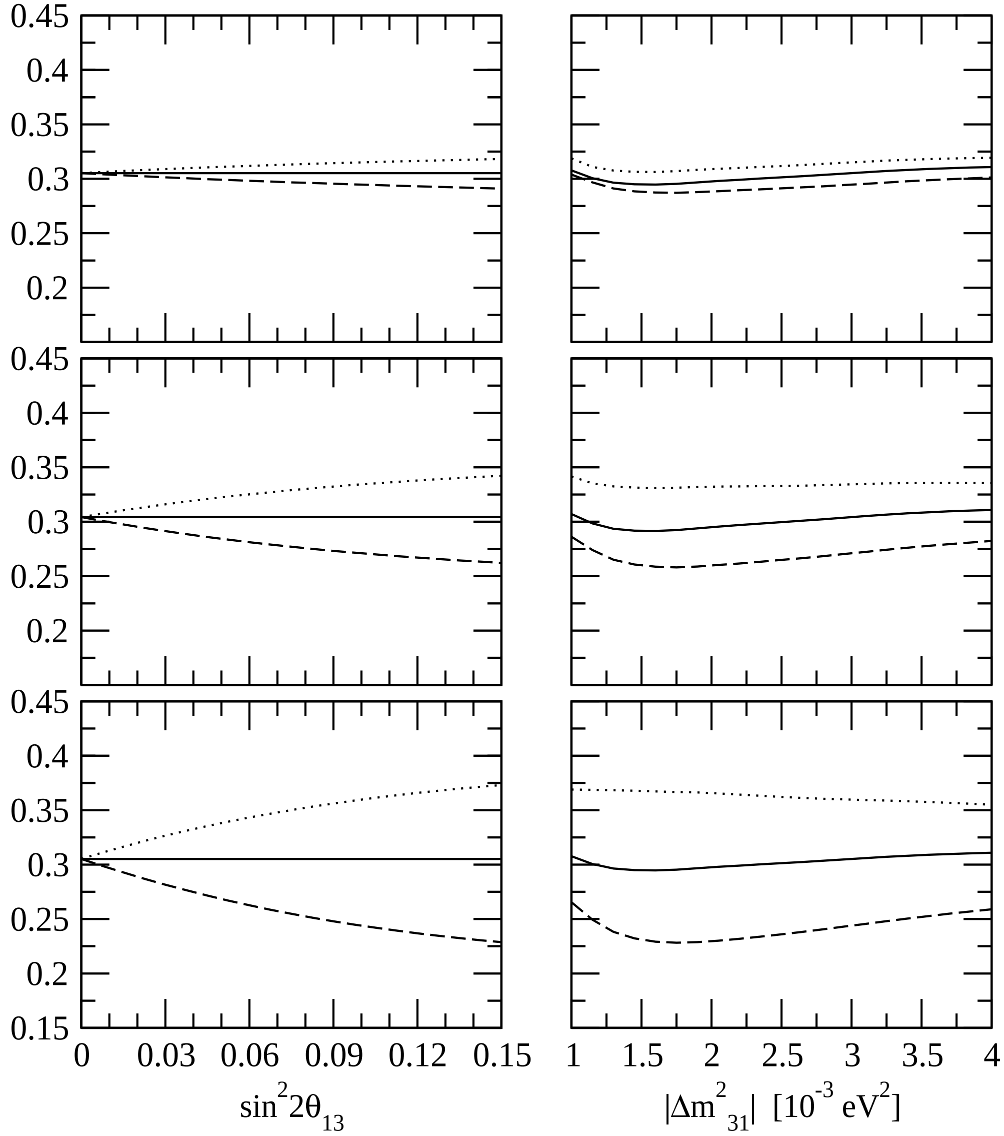
The same as in the previous figure , but for μ^- and μ^+ event rates integrated over the neutrino (and muon) energy in the interval $E = (5.0 - 20.0)$ GeV and for $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2.



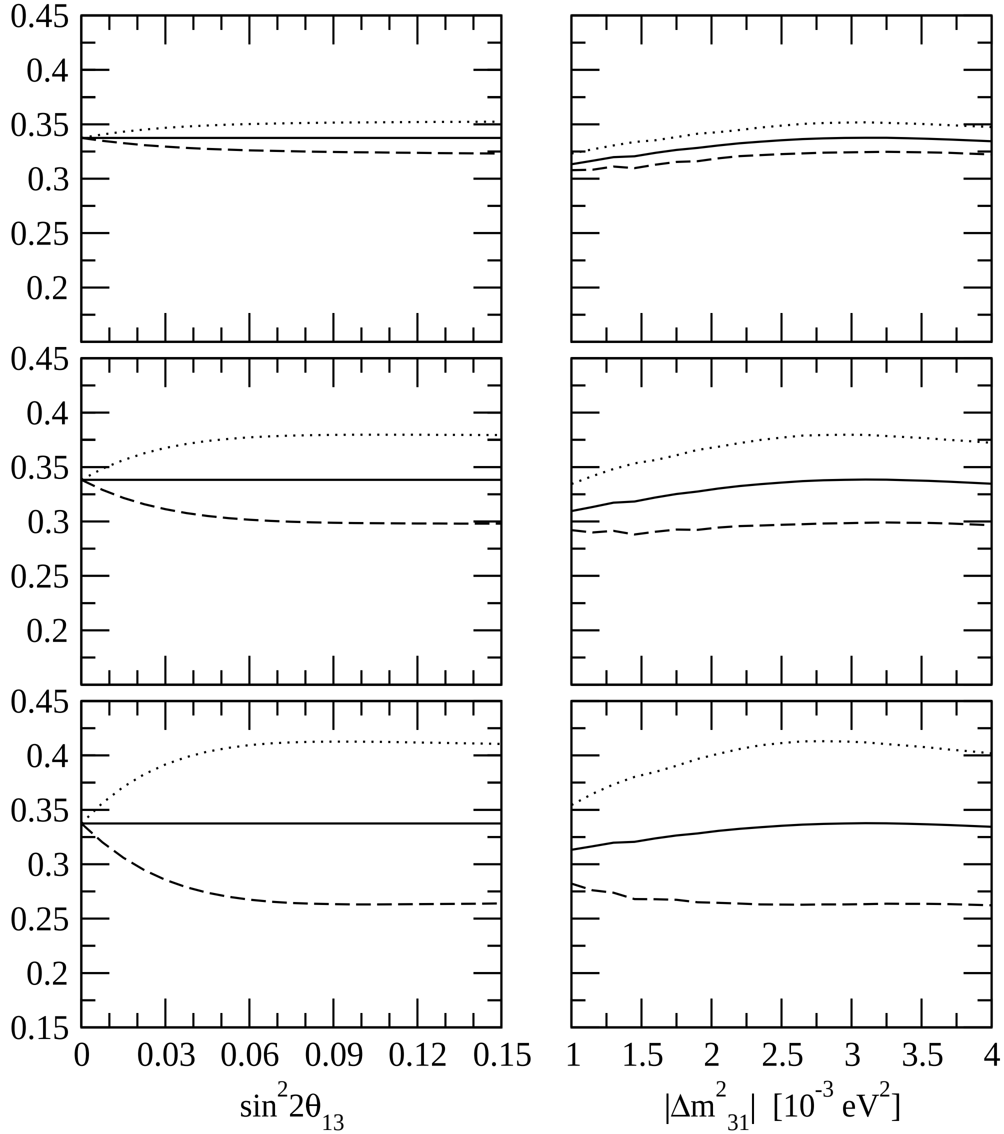
$A^{2\nu}_{\mu^-\mu^+}$ **(solid lines),** $(A^{3\nu}_{\mu^-\mu^+})_{\rm NH}$ **(dashed),** $(A^{3\nu}_{\mu^-\mu^+})_{\rm IH}$ **(dotted), integrated over** θ_n**,** $0.30 \leq \cos\theta_n \leq 0.84$ **(*mantle bin*),** E_ν **(and** E_μ**) in [2.0-10.0] GeV, as function of i)** s^2_{13} **for for** $|\Delta m^2_{31}| = 2 \times 10^{-3}$ eV^2 **(left panels), ii)** $|\Delta m^2_{31}|$ **for** $s^2_{13} = 0.10$ **(right panels), for** $s^2_{23} = 0.36$**, 0.50, 0.64; (upper, middle, lower panels).**



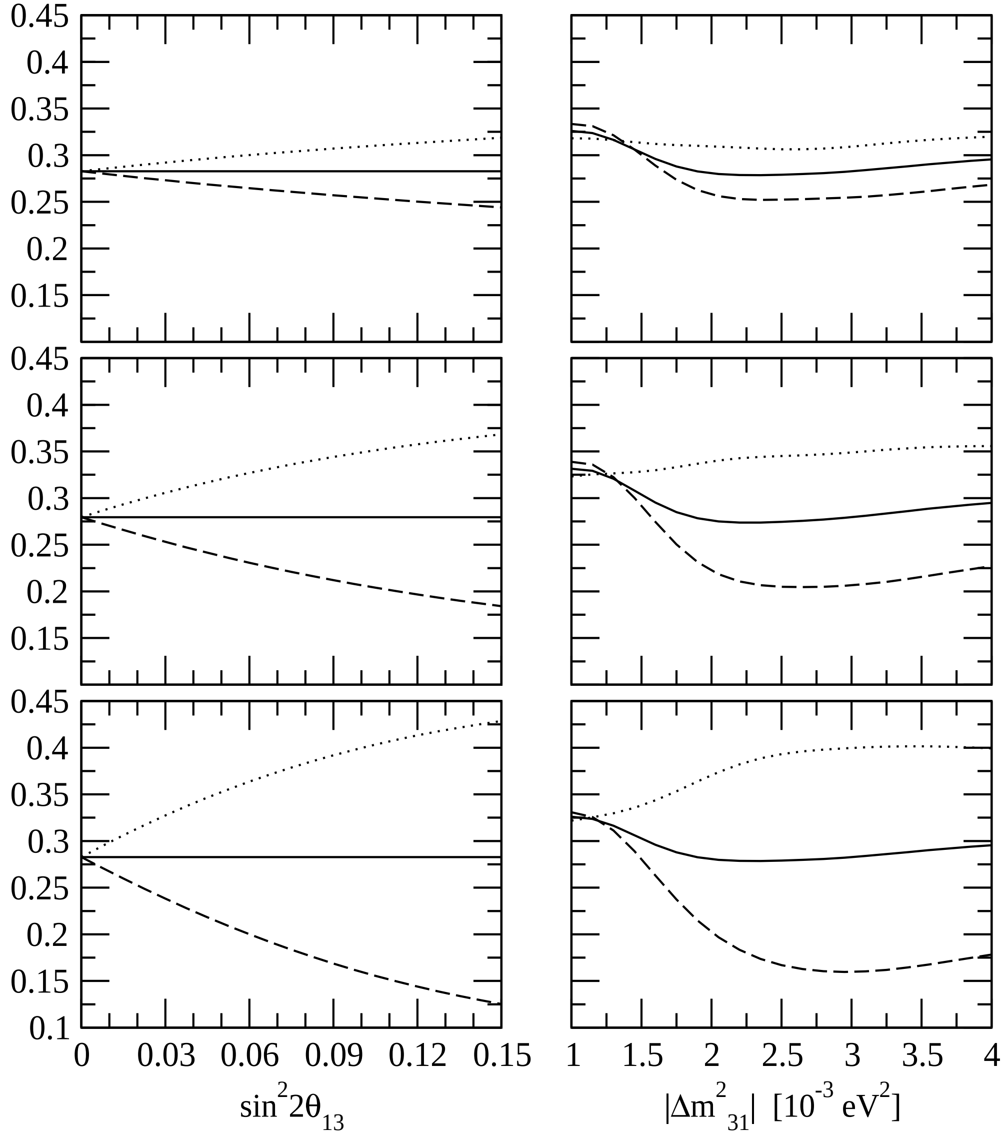
The same but for μ^- and μ^+ event rates integrated over θ_n in the interval corresponding to $0.84 \leq \cos\theta_n \leq 1.00$ (*core bin*).



The same for the "mantle bin", but for $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2 and μ^- and μ^+ event rates, integrated over the neutrino (and muon) energy in the interval $E = (2.0 - 20.0)$ GeV.



The same but for $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2 and μ^- and μ^+ event rates, integrated over E_ν (and E_μ) in the interval $E = (2.0 - 20.0)$ GeV and over θ_n in the interval corresponding to $0.84 \leq \cos\theta_n \leq 1.00$ (*core bin*).



The same for the "mantle bin", but for μ^- and μ^+ event rates integrated over the neutrino (and muon) energy in the interval $E = (5.0 - 20.0)$ GeV, and for $|\Delta m^2_{31}| = 3 \times 10^{-3}$ eV^2.

We concluded that for $\sin^2\theta_{23} \gtrsim 0.50$**,** $\sin^2 2\theta_{13} \gtrsim 0.06$ **and** $|\Delta m^2_{31}| = (2-3)\times 10^{-3}$ eV^2**, the Earth matter effects produce a relative difference between the** *integrated asymmetries* $\bar{A}_{\mu^-\mu^+}$ **and** $\bar{A}^{2\nu}_{\mu^-\mu^+}$ **in the** *mantle* **(**$\cos\theta_n = 0.30 - 0.84$**) and** *core* **(**$\cos\theta_n = 0.84 - 1.0$**) bins, which is bigger in absolute value than approximately** $\sim 15\%$**, can reach the values of** $(30-35)\%$**, and thus can be sufficiently large to be observable.**

A very detailed study of the potential of iron magnetised detectors (INO) for observing the Earth matter effects and determine the neutrino MO (a statistical analysis including the prospective $E-$ and θ_n- resolustions, systematic and statistical erors, dependence on the binning, charge misidentification) was performed in S.T.P. and T. Schwetz, hep-ph/0511277.

The conclusions read:

Having in mind magnetized iron calorimeters like INO, we have performed a χ^2-analysis including realistic neutrino fluxes, detection cross sections, and various systematical uncertainties. We discuss how the performance depends on detector characteristics like energy and direction resolutions or charge miss-identification, and on the systematical uncertainties related to the atmospheric neutrino fluxes. we show how the mass hierarchy determination depends on the true values of θ_{13}, θ_{23}, as well as on the true hierarchy.

Focusing on the detection of muons, one of our main findings is that the ability to reconstruct the energy and direction of the neutrino is crucial for the mass hierarchy determination.

Assuming $\sin^2 2\theta_{13} \simeq 0.1$ and the optimistic values for the neutrino energy and direction reconstruction accuracies of 5% and 5°, respectively, the mass hierarchy can be identified at the 2σ C.L. already with roughly 200 events (sum of neutrino and antineutrino events, including oscillations).

In contrast, for less ambitious resolutions of 15% and 15°, of the order of 5000 events are needed. These numbers are based on the detection of muons with a correct charge identification of 95% and an energy threshold of 2 GeV.

The reason for the relatively high sensitivity which can be achieved using high resolution μ-like events comes from the fact that the difference in the signals for normal and inverted hierarchies shows a characteristic oscillatory behaviour in the neutrino energy, as well as in the Nadir angle. If the energy and direction reconstruction are sufficiently precise to resolve these structures, a statistical analysis using energy as well as directional information (ideally an un-binned likelihood analysis) provides very good sensitivity to the hierarchy. For worse energy and direction reconstruction, these oscillatory structures are averaged out, which leads to a much worse sensitivity.

Our results imply that for resolutions of 15% for the neutrino energy and 15° for the neutrino direction, in a INO-like detector exposures of the order of a few Mton years are required to obtain a reasonable hierarchy sensitivity. However, we stress again that for high quality event samples with more precise reconstruction of the neutrino energy and direction the required exposures are significantly smaller.

Hyper Kamiokande (5SK), 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 (?)

KM3Net in Mediteranian sea: ORCA (near Toulon)

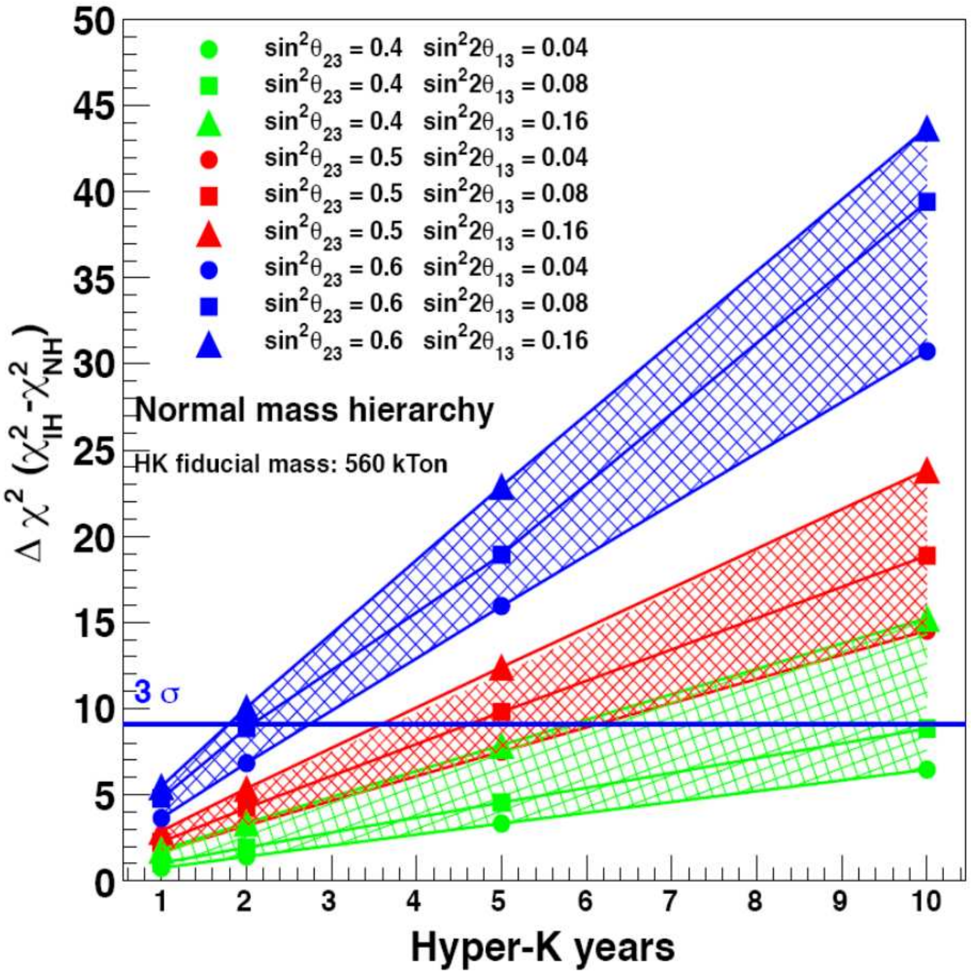
Water-Cerenkov detector: Hyper Kamiokande (5SK)

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



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.

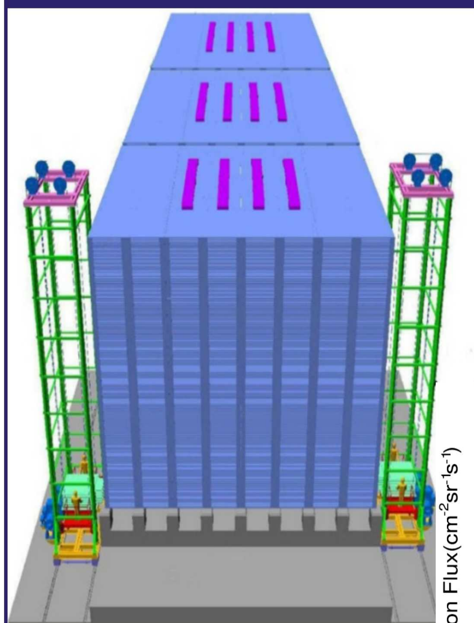
K. Abe et al. [Letter of intent: Hyper-Kamiokande Experiment], arXiv:1109.3262.

INO, ICAL

India-Based Neutrino Observatory (INO)

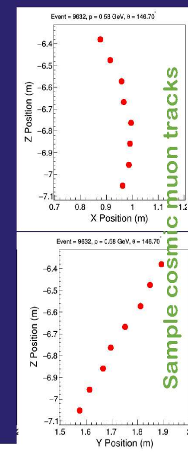
Goal: Precision tests of 3-flavor model with atmospherics

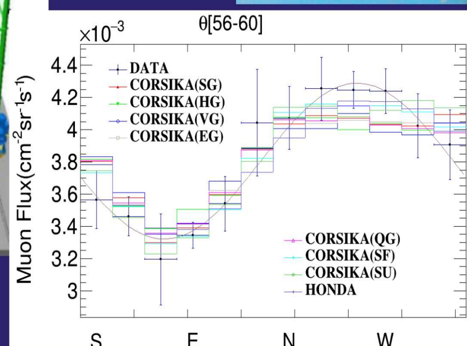
51 kt Magnetized Iron Calorimeter



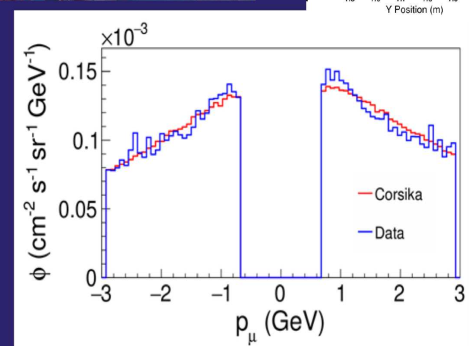
Proposed 51 kton magnetized Iron CALorimeter ($10^5 m^2$ glass RPC, 3.6M electronics channels)

85-ton prototype, 4m×4m×11 layer magnet, with 2mx2m RPCs and ICAL electronics operating for 2 years.





Comparison of azimuthal muon flux with CORSIKA and HONDA simulations



Comparison of the muon momentum spectra with CORSIKA simulations, negative (positive) values correspond to $\mu^+(\mu^-)$

The INO Collaboration

Collaborating Institutions:

- AMU
- American C
- BHU
- BARC
- Calcutta U
- Calicut U
- Delhi U
- HPU
- HNBGU
- HRI
- Hyd. U
- IISER (M)
- IIT (B)
- IIT (G)
- IIT (M)
- IMSc
- IoP
- Jammu U
- JNU
- Karnataka CU
- Kashmir U
- Lucknow U
- N Bengal U
- Panjab U
- PRL
- Sikkim MU
- SINP
- Tezpur U
- TIFR U
- Utkal U
- VECC
- Visva Bharati

• INO Collaborating Institutions

Participation from nearly 100 scientists and engineers from 28 national labs, IITs and universities from all over the country.

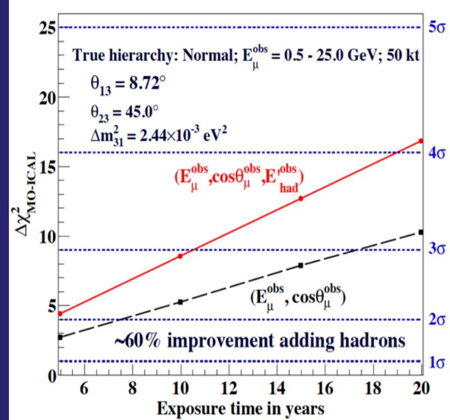
J. Klein, talk at ν 2020

INO

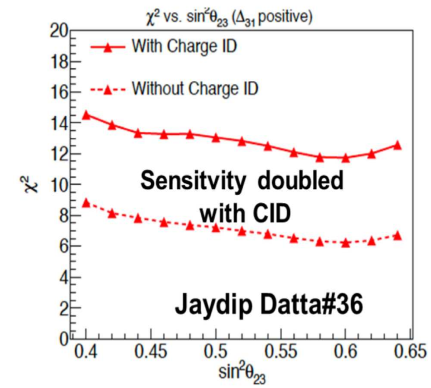
Physics Sensitivities

Combination of high mass, tracking, and charge ID via magnet, provides precision handle on atmospheric direction and energy up to 25 GeV

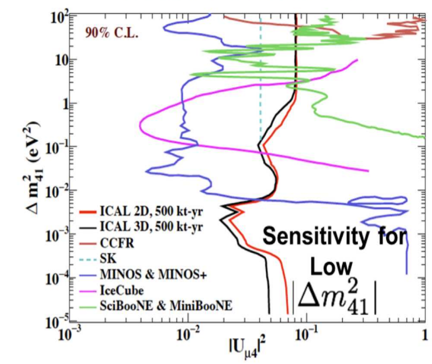
Hierarchy Sensitivity



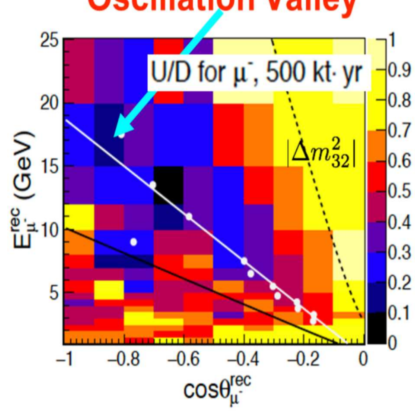
Matter vs. Vacuum



Sterile Neutrino

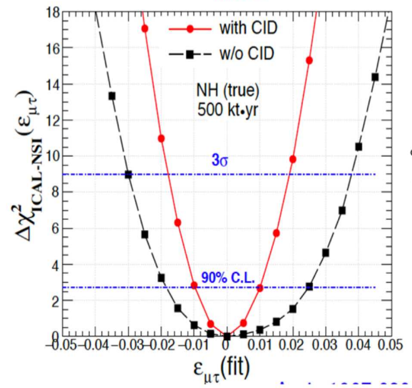


Oscillation Valley



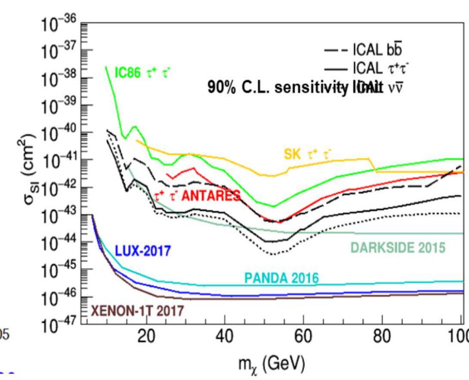
Anil Kumar#573

NSI



Amina Khatun#569

WIMP Annihilation



Deepak Tiwari #288

J. Klein, talk at ν 2020

Instead of Conclusions on INO, ICAL:

Just Build It!