India-Based Neutrino Observatory

INO

Physics and Status Report

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(http://www.imsc.res.in/∼indu)

Outline of talk

- The context: INO and the physics of atmospheric neutrinos

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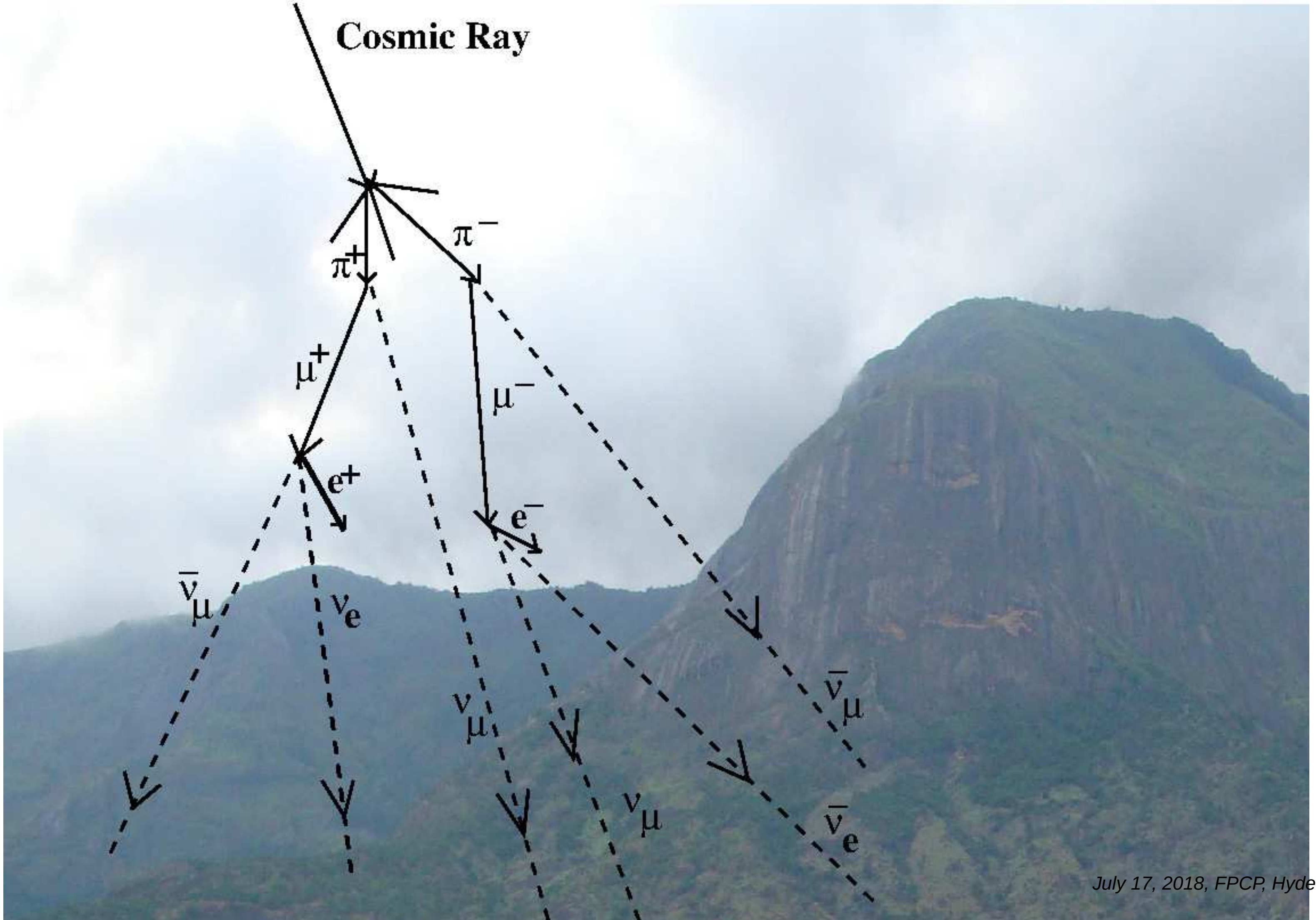
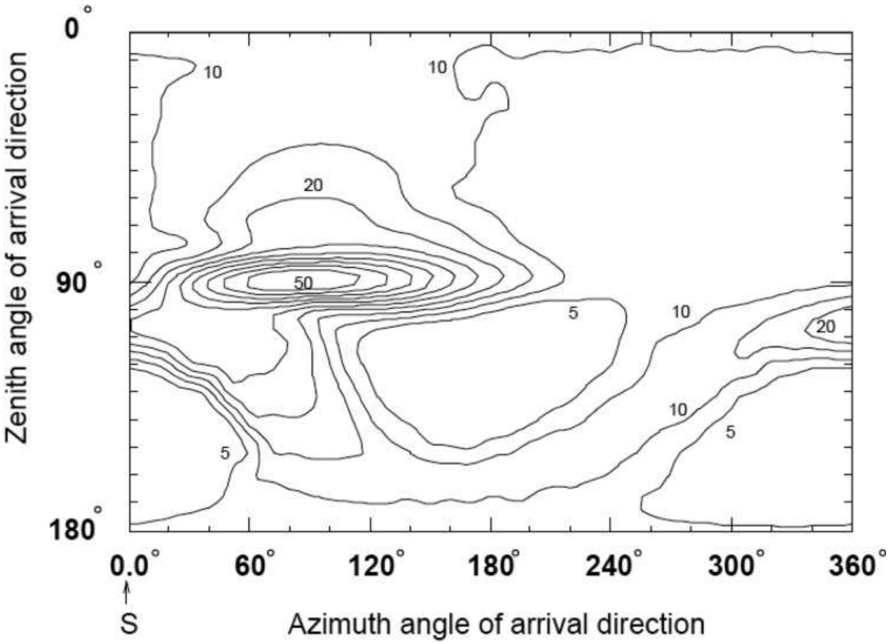
- INO-Status Report

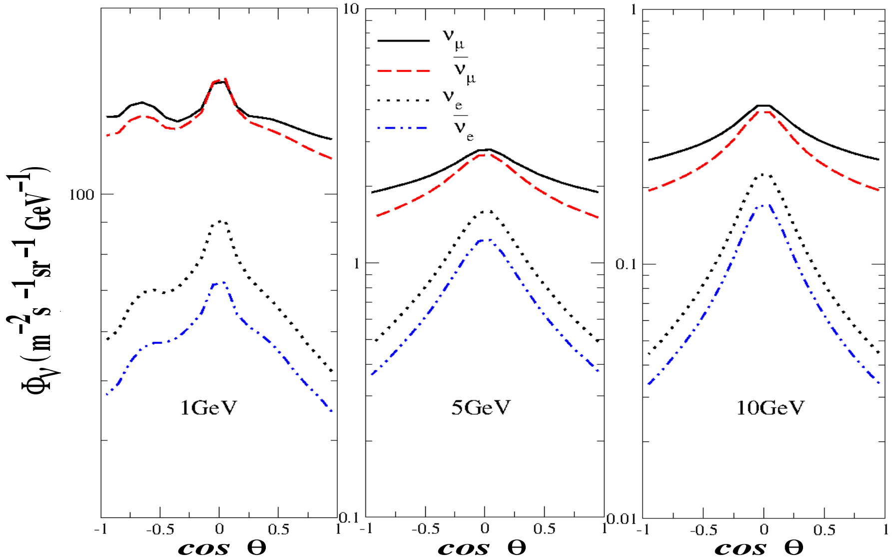
Atmospheric Neutrinos

- Cosmic rays interact with C, O nuclei in Earth's atmosphere to give pions and kaons. These decay to muons and both neutrinos and anti-neutrinos. $\pi^\pm(K) \to \mu^\pm \nu_\mu \,; \quad \mu^\pm \to \nu_\mu \, e^\pm \, \nu_e \,.$



Atmospheric Neutrino Fluxes





Rigidity at SK

$\Phi_{\mu,e}(E_\nu, \cos\theta)$

- Rigidity latitude dependent; actually magnetic latitude
- East-west asymmetry pronounced at low energies.
- Large contribution from up-going neutrinos.

Characteristics of Atm. ν Detectors

Atmospheric neutrinos have large L and E range. So most atmospheric neutrino detectors have:

- Nearly 4π coverage in solid angle;
- Sensitivity to as low/high energies as possible; note that the most interesting region for observing matter effects in the 2–3 sector is 3–15 GeV;
- Sensitivity to direction, actually up/down discrimination;
- Desirable: Good charge resolution to distinguish neutrino and anti-neutrino events.
- Sensitivity to both electrons and muons
- Desirable: sensitivity to hadrons and tau (indirect).

What can these detectors tell us about neutrino oscillations?

Parameters of 3-flavour mixing

Neutrino masses are not well-known. Oscillation studies only determine the mass-squared differences: $\Delta m_{ij}^2 = m_i^2 - m_j^2$ and the mixing angles θ_{ij}.

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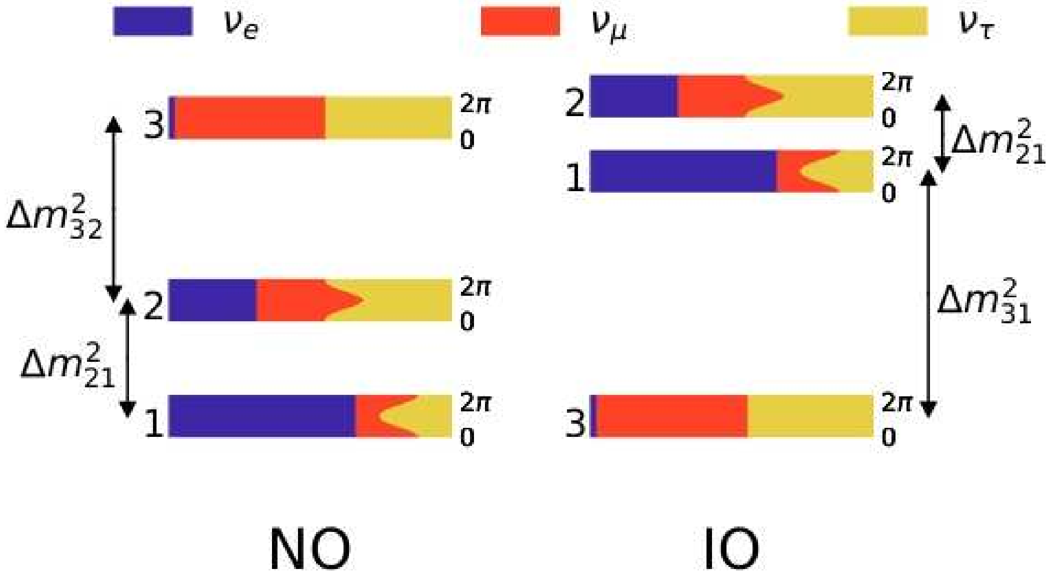

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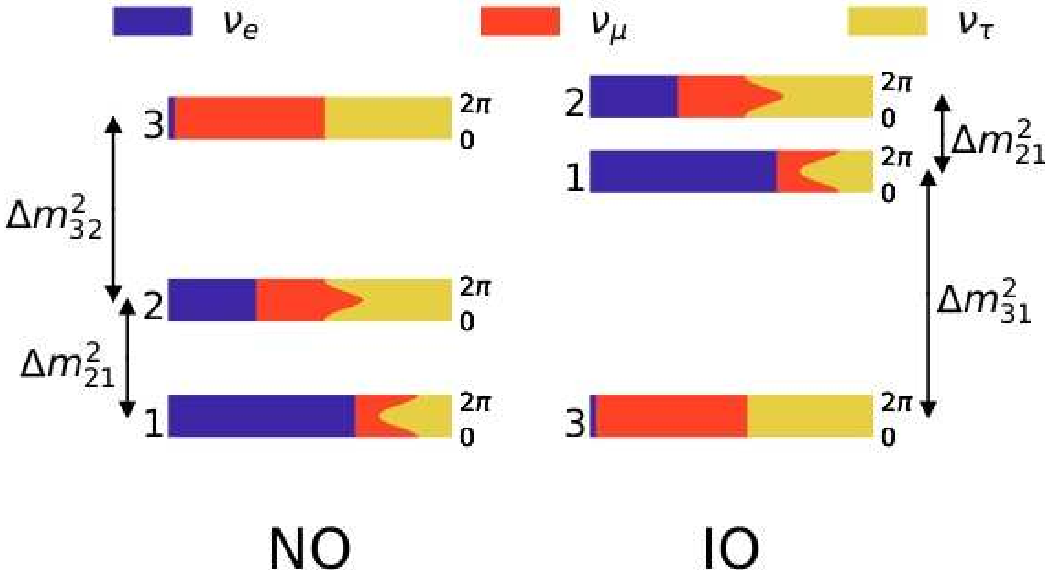
- $\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2 ;
  $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}$ eV^2
  $\Delta m^2_{32} > 0$ (?)
  $\sum_i m_i < 0.7$–2 eV.



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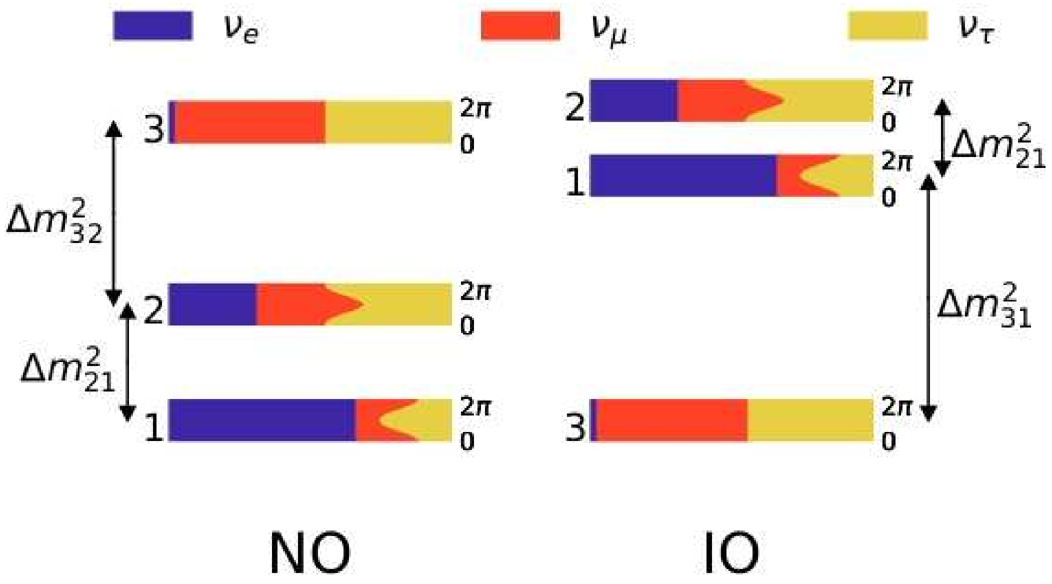
- $\theta_{12} \sim 34°$; $\Delta_{21} > 0$ (Solar)
  $\theta_{23} \sim 45°$: octant?
  $\theta_{13} \sim 8.5°$;

$\Rightarrow$ Possible to detect CP violation

- $\delta_{CP} > \pi$: difference between interaction of $\nu, \overline{\nu}$ with matter



(de Salas et al., hep-ph/1806.11051)

eutrino versus Anti-neutrino Propagation

- The ν_e, ν_μ and ν_τ flavours do not have definite masses:

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i \ .$$

where ν_1, ν_2 and ν_3 have well-defined masses: m_1, m_2 and m_3, some are non-zero. $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$ is the mixing matrix.

- The Earth matter effect mainly occurs in the θ_{13} parameter for atmospheric neutrinos:

$$(\sin\ 2\theta_{13})_m = \frac{(\sin\ 2\theta_{13})}{\sqrt{[\cos 2\theta_{13} - (A/\Delta m^2_{32})]^2 + (\sin 2\theta_{13})^2}} \tag{1}$$

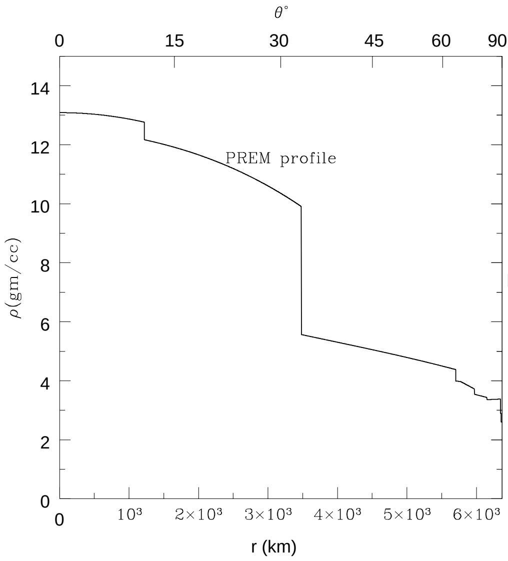
where $A = 7.6 \times 10^{-5}\ \rho\ E\ eV^2\ ; \quad \Delta m^2_{32} = m^2_3 - m^2_2\ ,$

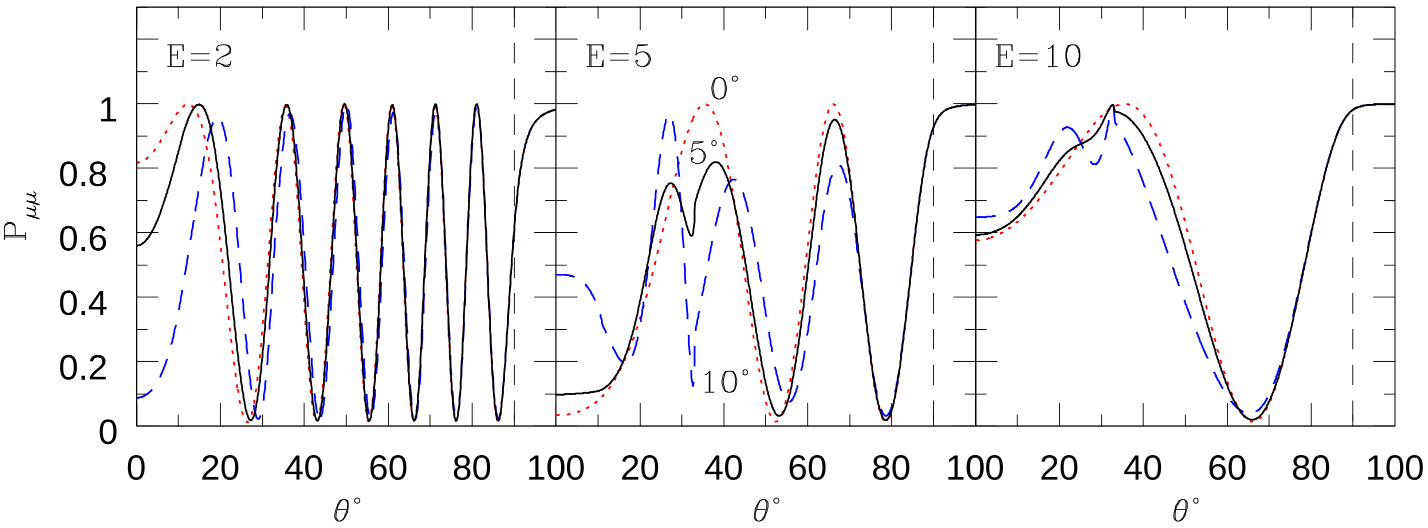
Here ρ = earth density (gms/cc); E = neutrino energy in GeV;

$A \rightarrow -A$ for anti-neutrinos.

Physics of Atmospheric Neutrinos-1

- Sensitivity to Earth Matter Effects; hence hierarchy





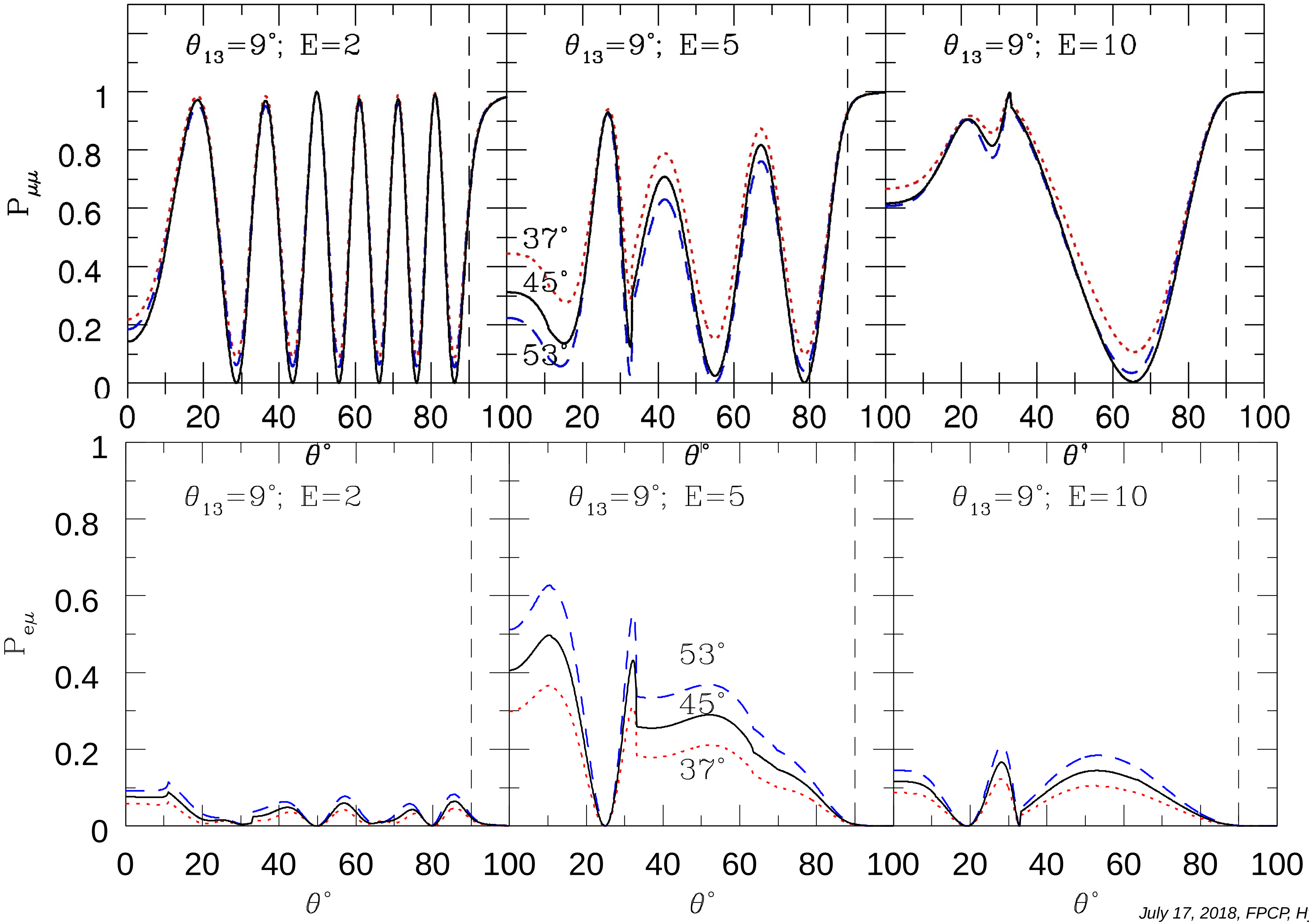
- Sensitivity is hierarchy dependent. Shown here is the sensitivity with the normal hierarchy, $\Delta m^2 > 0$ for different θ_{13}, now known to be $\sim 8.5^\circ$

- Reduced sensitivity in anti-neutrino sector since $A \to -A$

- Probe of PREM profile possible, especially for $\theta < 20^\circ$; not easy to alter Earth density since mass of Earth tightly constrained!

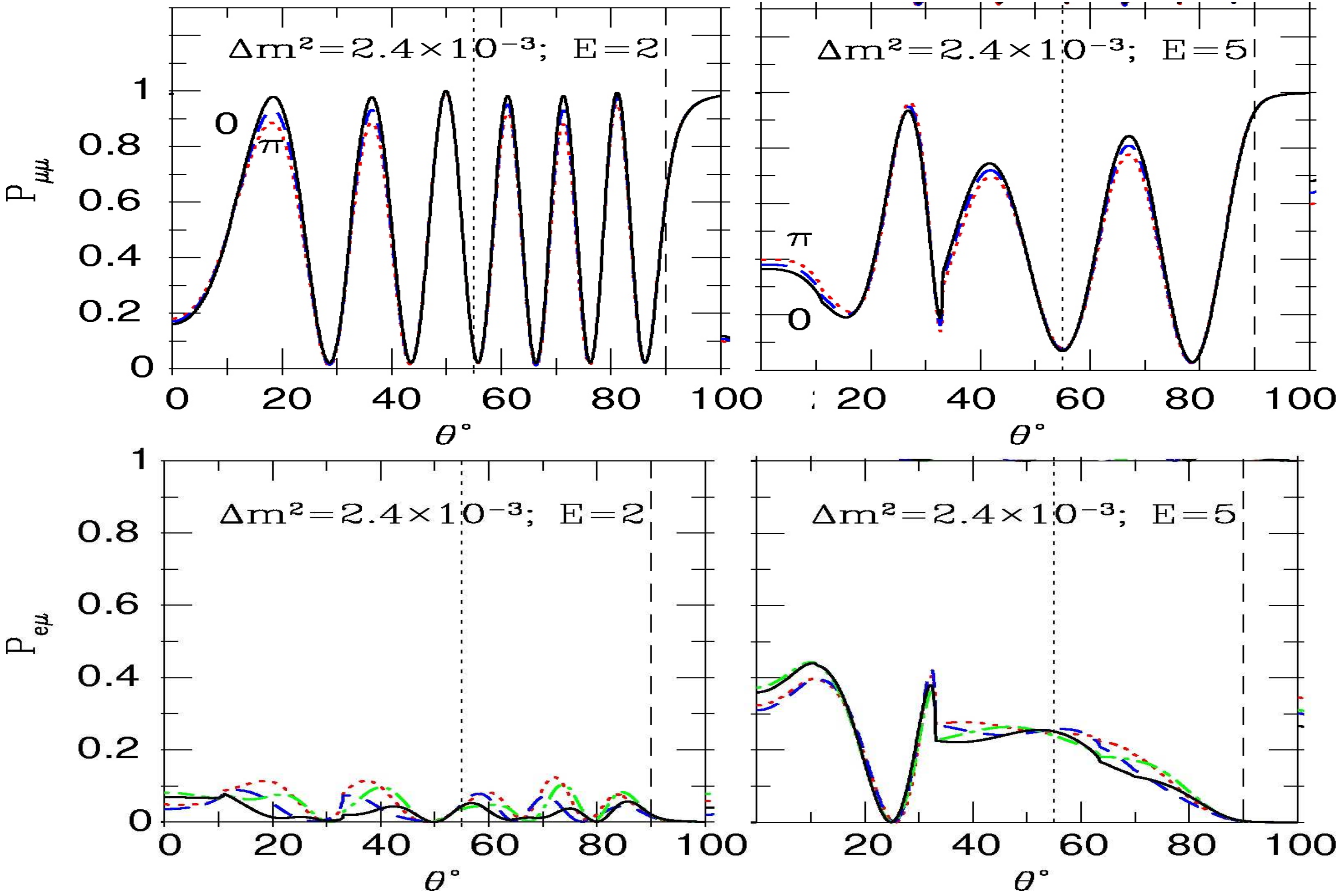
Physics of Atmospheric Neutrinos-2

- Sensitivity to octant of θ_{23}



Physics of Atmospheric Neutrinos-3

- Sensitivity to the CP phase



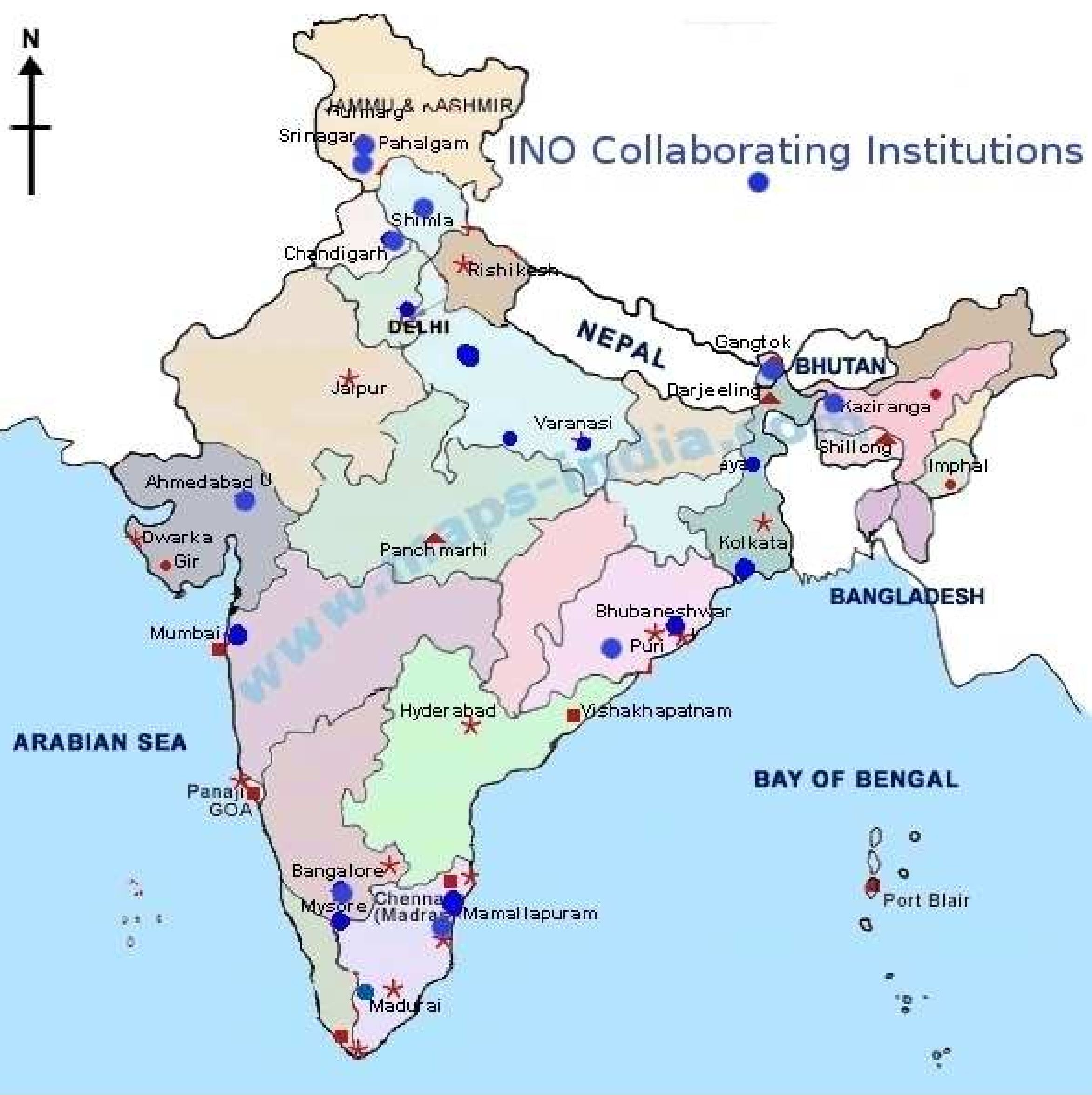
India-based Neutrino Observatory Project

At Pottipuram, Theni

The INO Project

- A mega Science Project funded by the Dept. of Science and Technology and Dept. of Atomic Energy, Govt. of India
- Immediate goal: Creation of an underground laboratory for research in neutrino physics at Pottipuram
- Will develop into a full fledged underground laboratory over the years for other studies in physics, biology and geology
- Main detector proposed is magnetised Iron CALorimeter (ICAL) to study primarily atmospheric neutrinos
- Will incorporate a centre for particle physics and detector technology and its varied applications at Madurai
- The INO graduate training program has already begun

The INO Collaboration*



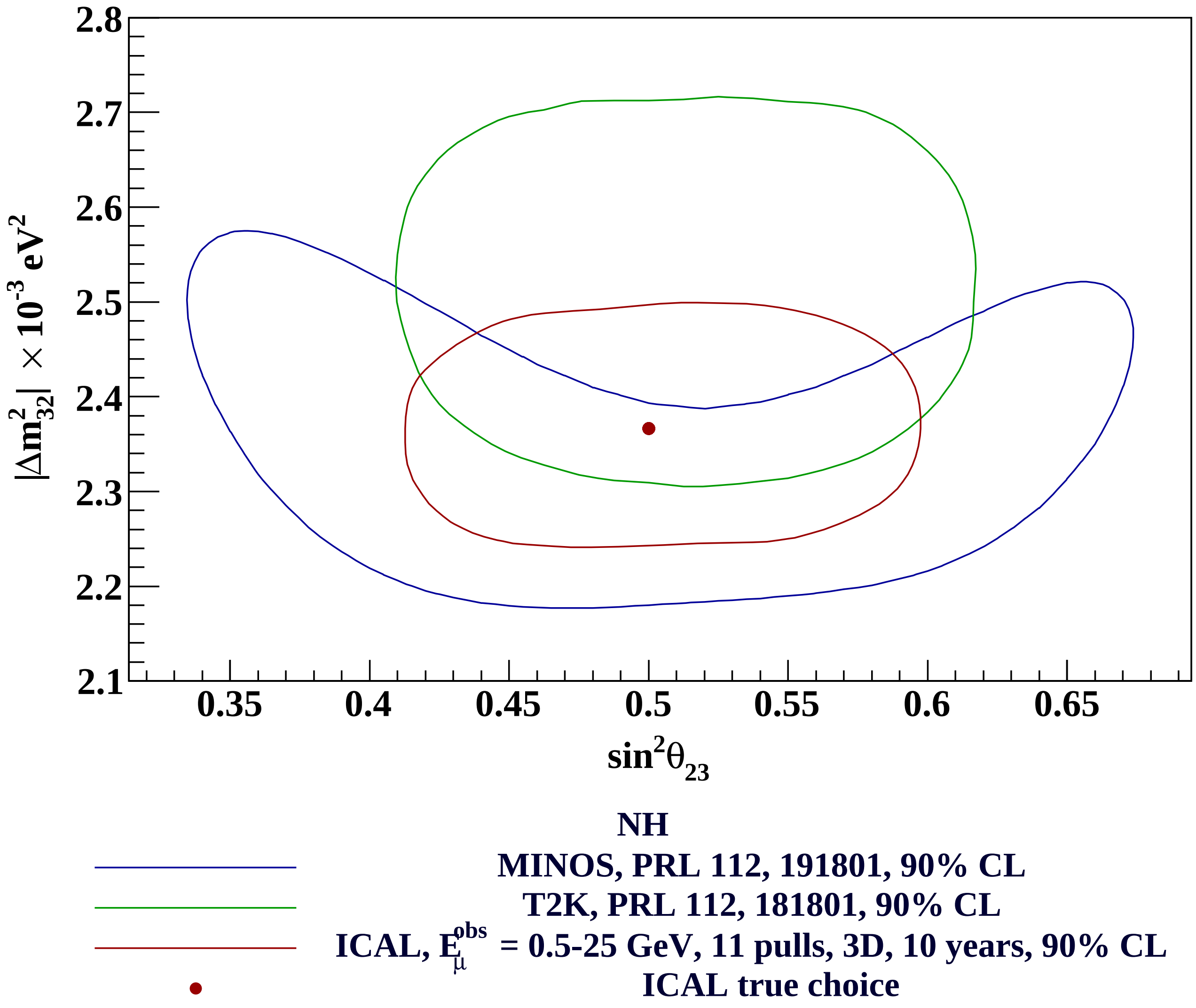
- American College
- AMU
- BHU
- BARC
- CKU
- CU
- DU
- HRI
- UoH
- HPU
- HNBGU
- IITB
- IISER(M)
- IITG
- IGCAR
- IMSc
- IOP
- JU
- KU
- MU
- NBU
- PU
- PRL
- SINP
- SU
- SMIT
- TIFR
- Tezpur U
- VECC

- Project Director: V.M. Datar, TIFR

Physics at ICAL/INO

- Proposed 50 kton magnetised iron calorimeter (ICAL) to be able to *separately* study atmospheric neutrino and anti-neutrino events.
- Hence ICAL will be sensitive to the mass hierarchy through the dominant mode of charged current detection of muon neutrinos: $\nu_\mu N \to \mu^- X; \overline{\nu}_\mu N \to \mu^+ X$
- It will have limited sensitivity to electron neutrinos and hence δ_{CP} through CC channel
- It will have indirect sensitivity to tau neutrinos
- It will have limited sensitivity to steriles due to the poor separation of neutral current NC and CC electron channels
- It has sensitivity to exotic physics such as dark matter annihilation in the Sun, magnetic monopoles, NSI, etc

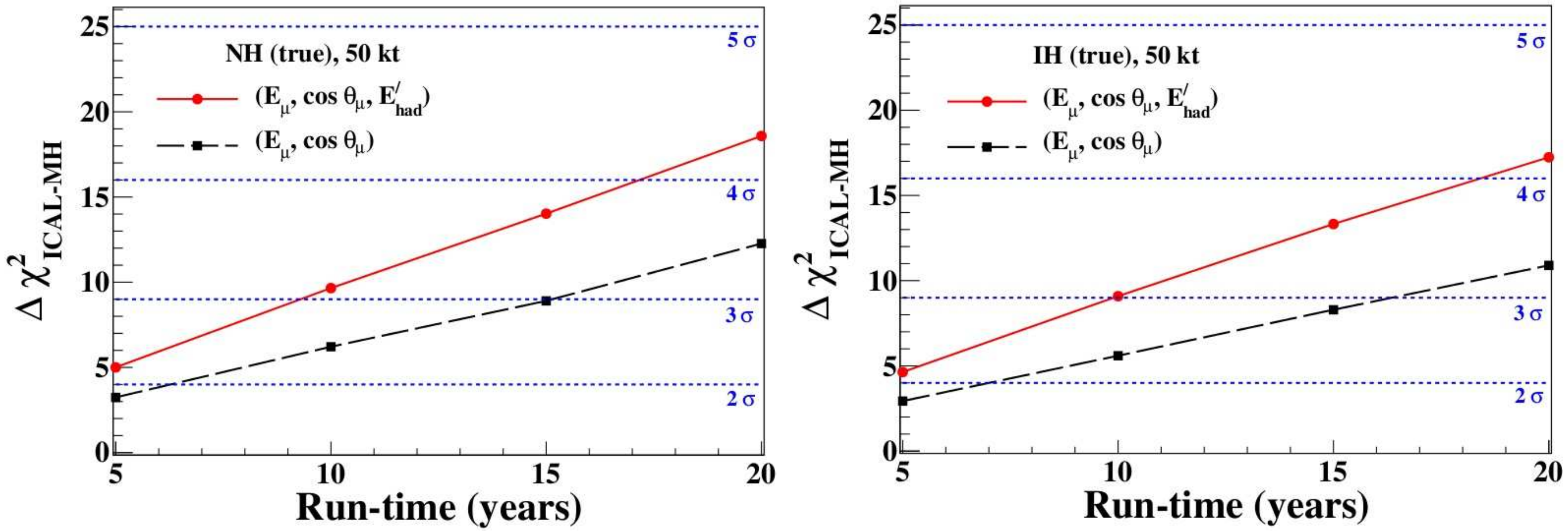
Physics reach of INO: Precision Studies



- Note ICAL yet to be built! S M Lakshmi, 1605.04185
- Result marginalised over magnitude of Δm^2, as well as θ_{23} and θ_{13}.

Physics reach of INO: Mass ordering

- Mass Ordering

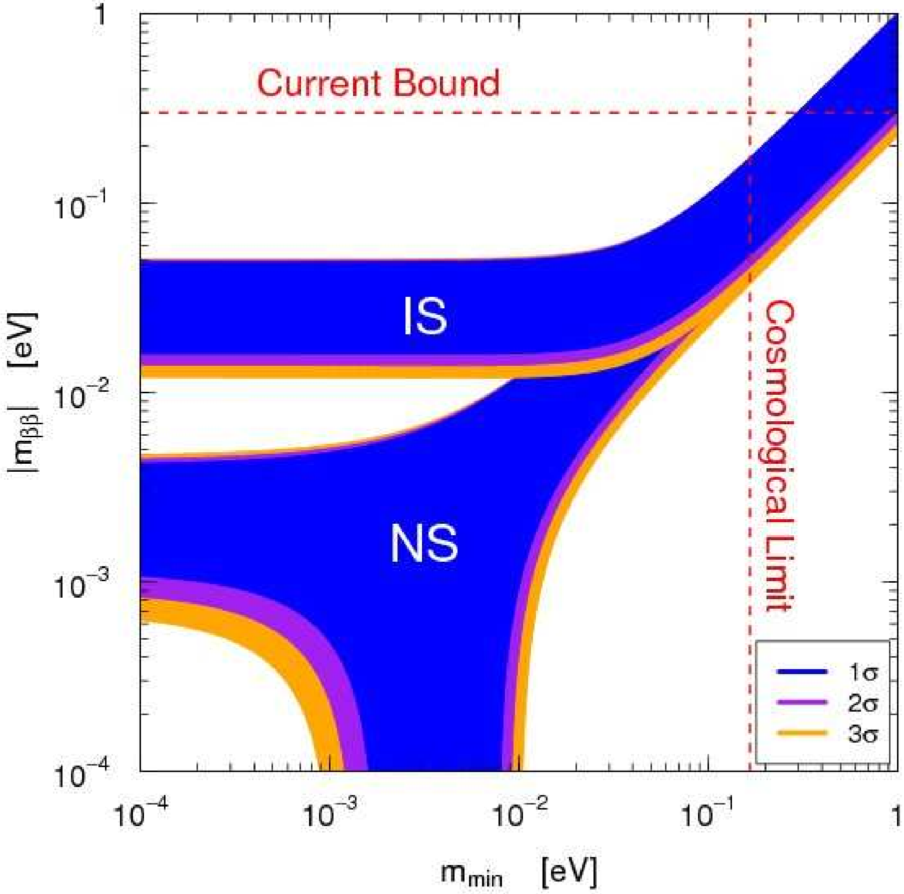


- Note improvement with addition of hadrons; M M Devi, JHEP10, 2014

- Result marginalised over magnitude of Δm^2, as well as θ_{23} and θ_{13}.

Global status: Mass hierarchy

- Matter effect / mass hierarchy is the centrepiece of ICAL physics.
- It has a major role to play in understanding models of neutrino mass and mixing. It also impacts the determination of whether neutrinos are Majorana or Dirac type of fermions.

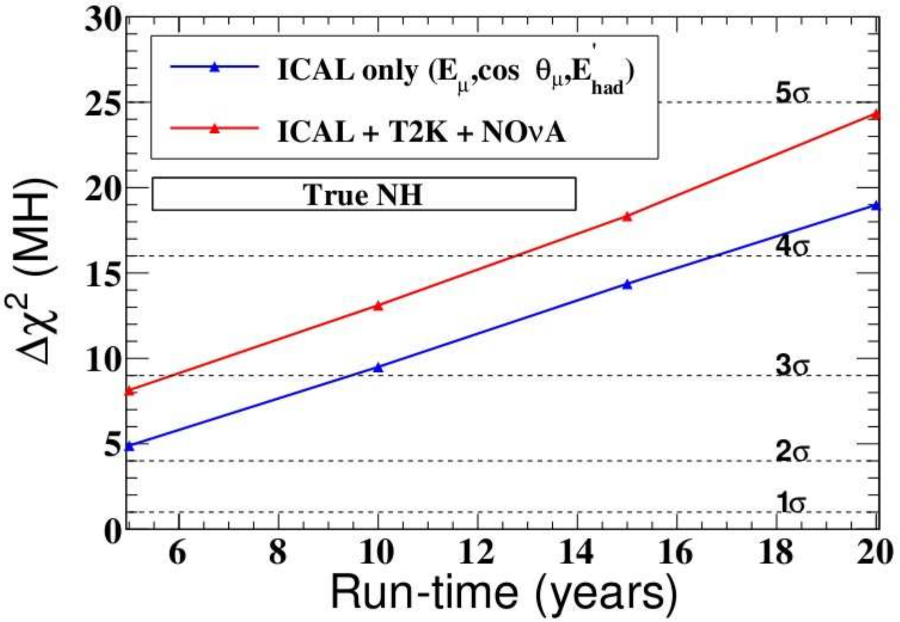


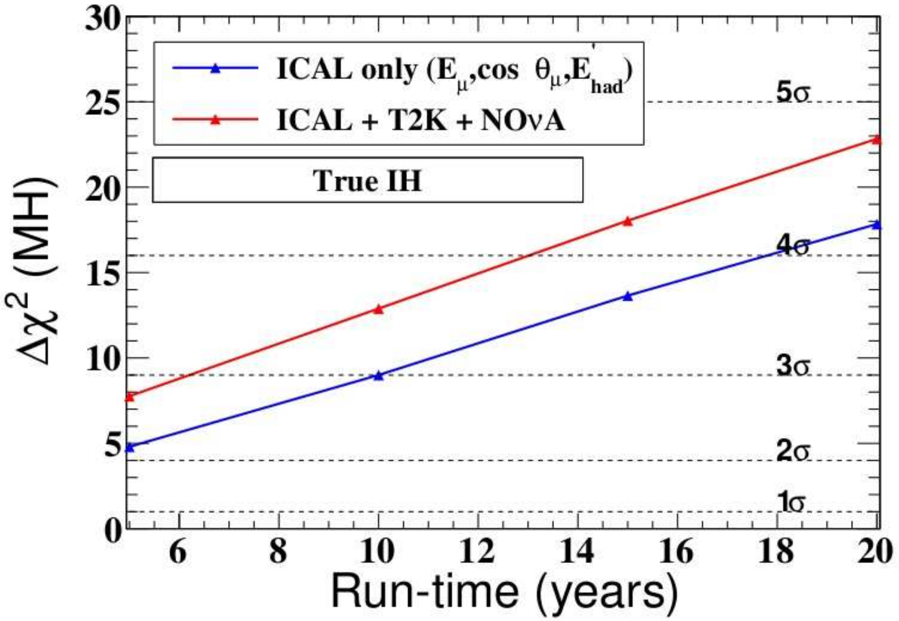
What is the role of other experiments in determining this quantity?

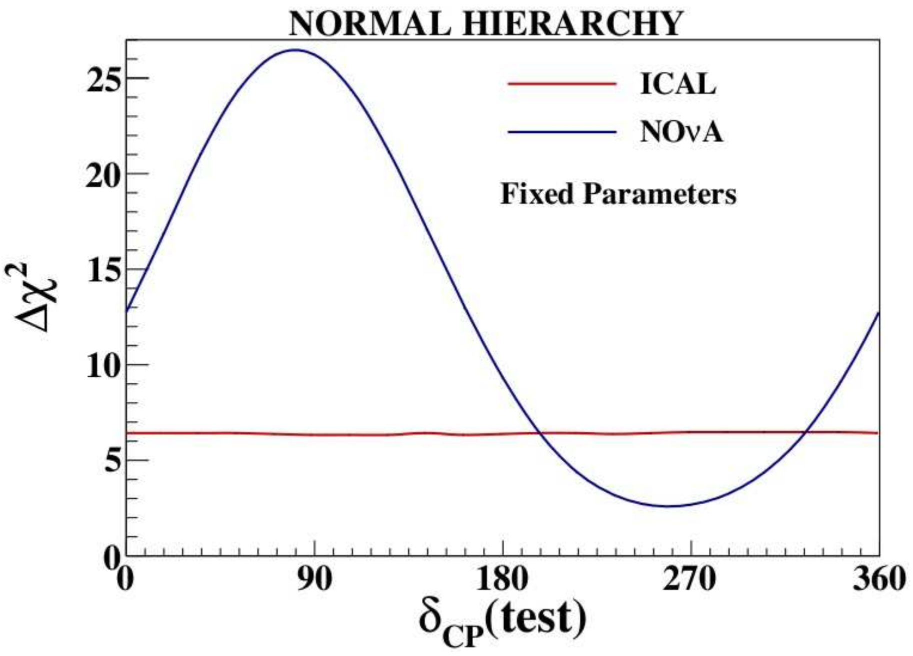
Apart from INO, MINOS, T2K, NOνA, PINGU/Icecube, JUNO, DUNE, Hyper-K, LBNE all will/are probing mass hierarchy. Each is an amazing experiment.

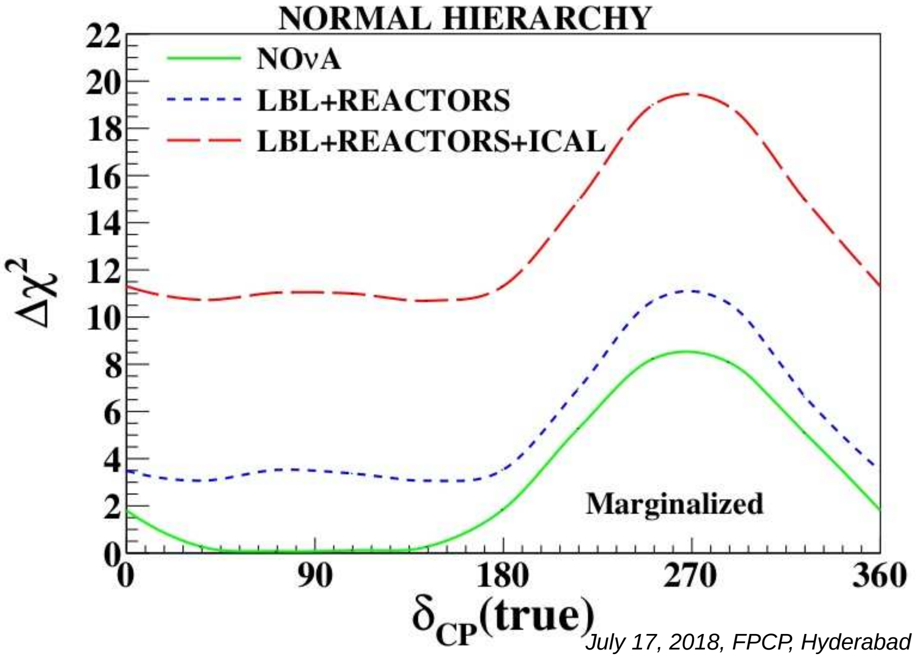
Most have to disentangle effects of CP phase from the hierarchy measurement; can accomplish this only for a fraction of possible δ_{CP} from $-\pi$ to π.

Additional Synergies







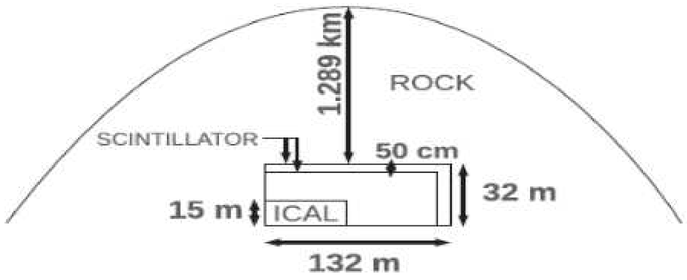


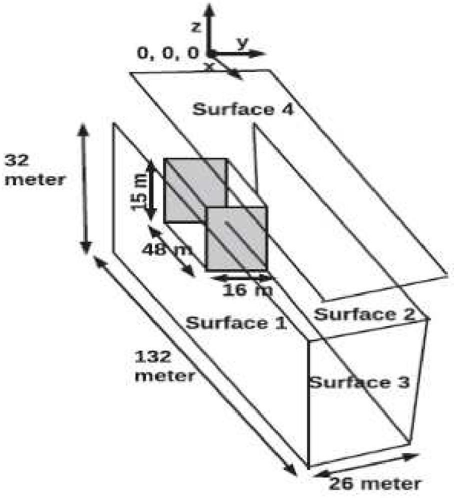
Other Physics

- Sterile neutrinos; hard since need to measure all neutrino flavours.
- Neutrino decay (via Majorons) into steriles; S. Choubey, arXiv:1709.10376: simulations bound $m_3/\tau_3 < 4 \times 10^{-6}$ eV^2 (90CL)
- Non-standard neutrino interactions, such as flavour-dependent long-range forces; Amina Khatun, 1801.00949
- Look for signatures of CP violation, Lorentz invariance violation, etc.
- Can use the detectors to probe non-oscillation, non-neutrino physics: cosmic muons, dark matter, etc.
- Bottom line: lots of exciting possibilities; but must build detector!

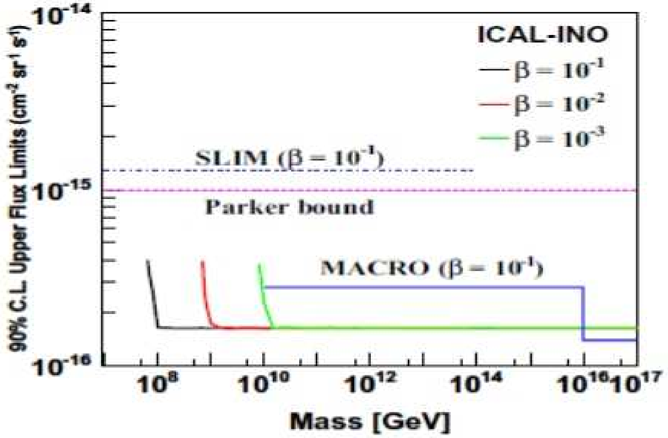
Example, with ICAL+

Searching for Magnetic Monopoles using ICAL

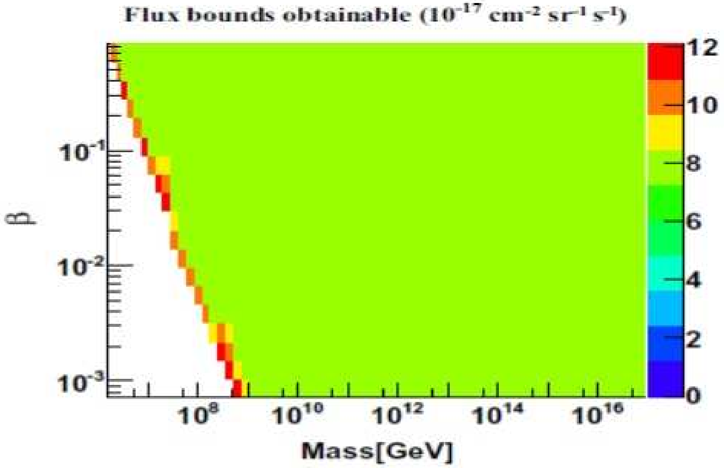




N. Dash et al., Astropart. Phys. ***70****, 33 (2015)*



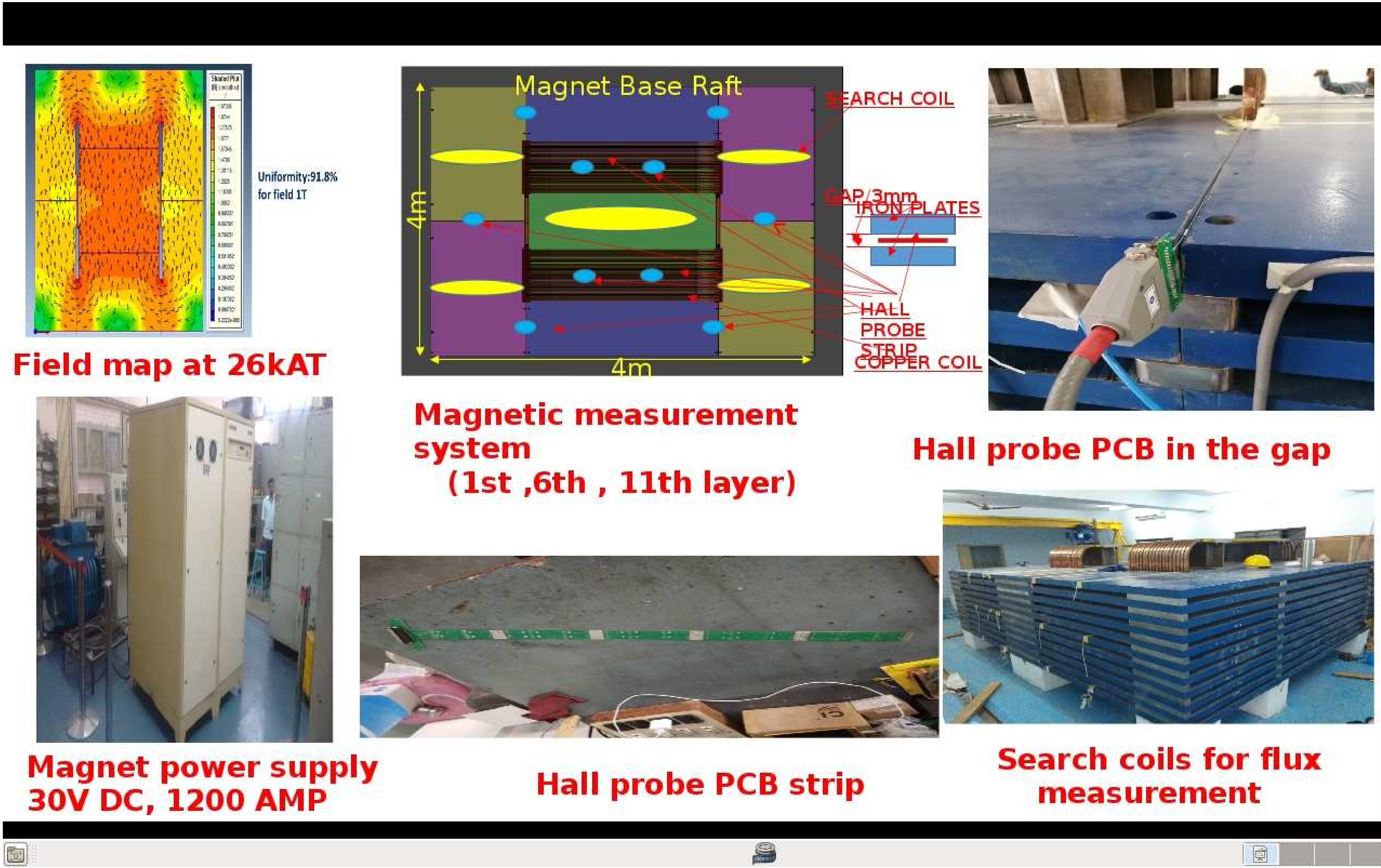
ICAL only



ICAL+

N. Dash, PhD thesis

Status of ICAL Prototype



Field map at 26kAT

Magnetic measurement system
(1st ,6th , 11th layer)

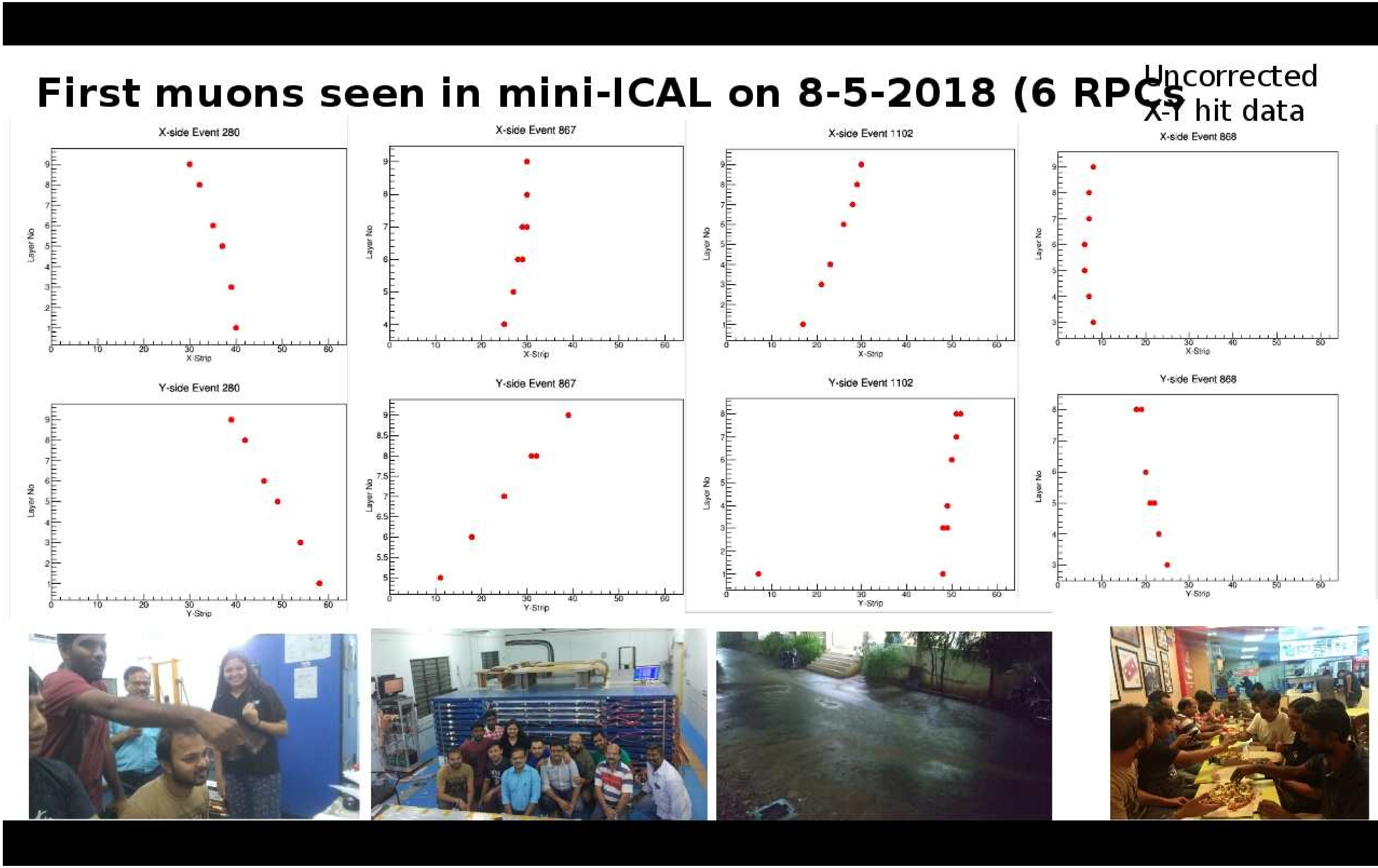
Hall probe PCB in the gap

Magnet power supply
30V DC, 1200 AMP

Hall probe PCB strip

Search coils for flux measurement

Cosmic Muons in 5 layers



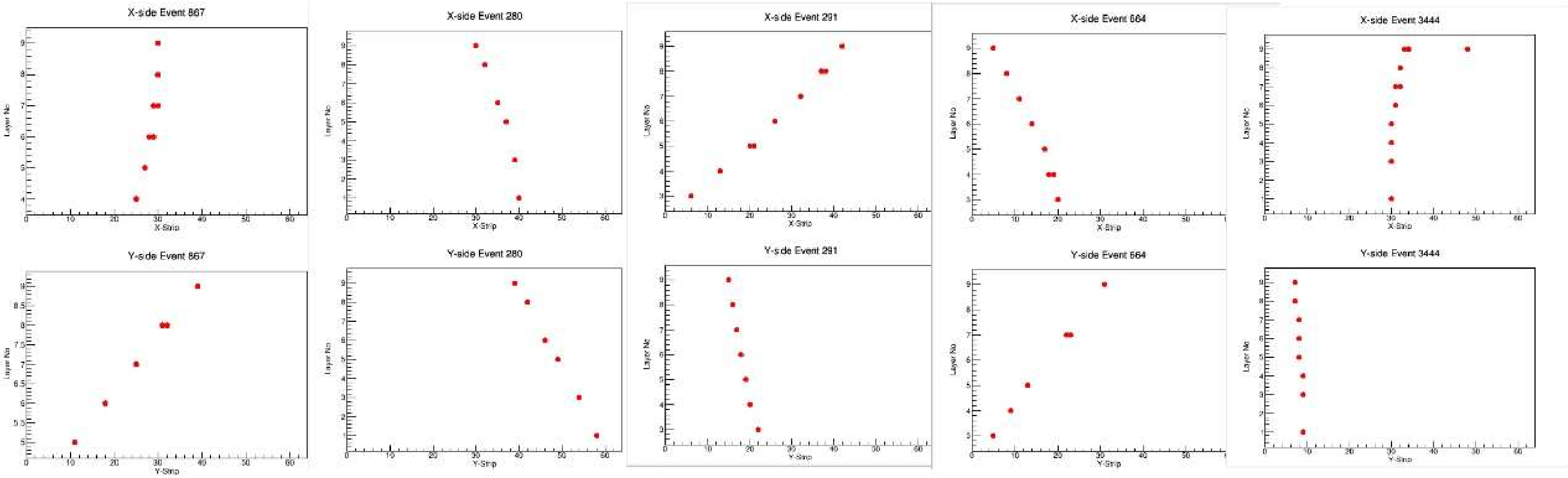
First muons seen in mini-ICAL on 8-5-2018 (6 RPCs

Uncorrected X-Y hit data

Cosmic Muons in 8 layers

8 RPCs at centre of mini-ICAL (23-5-2018)

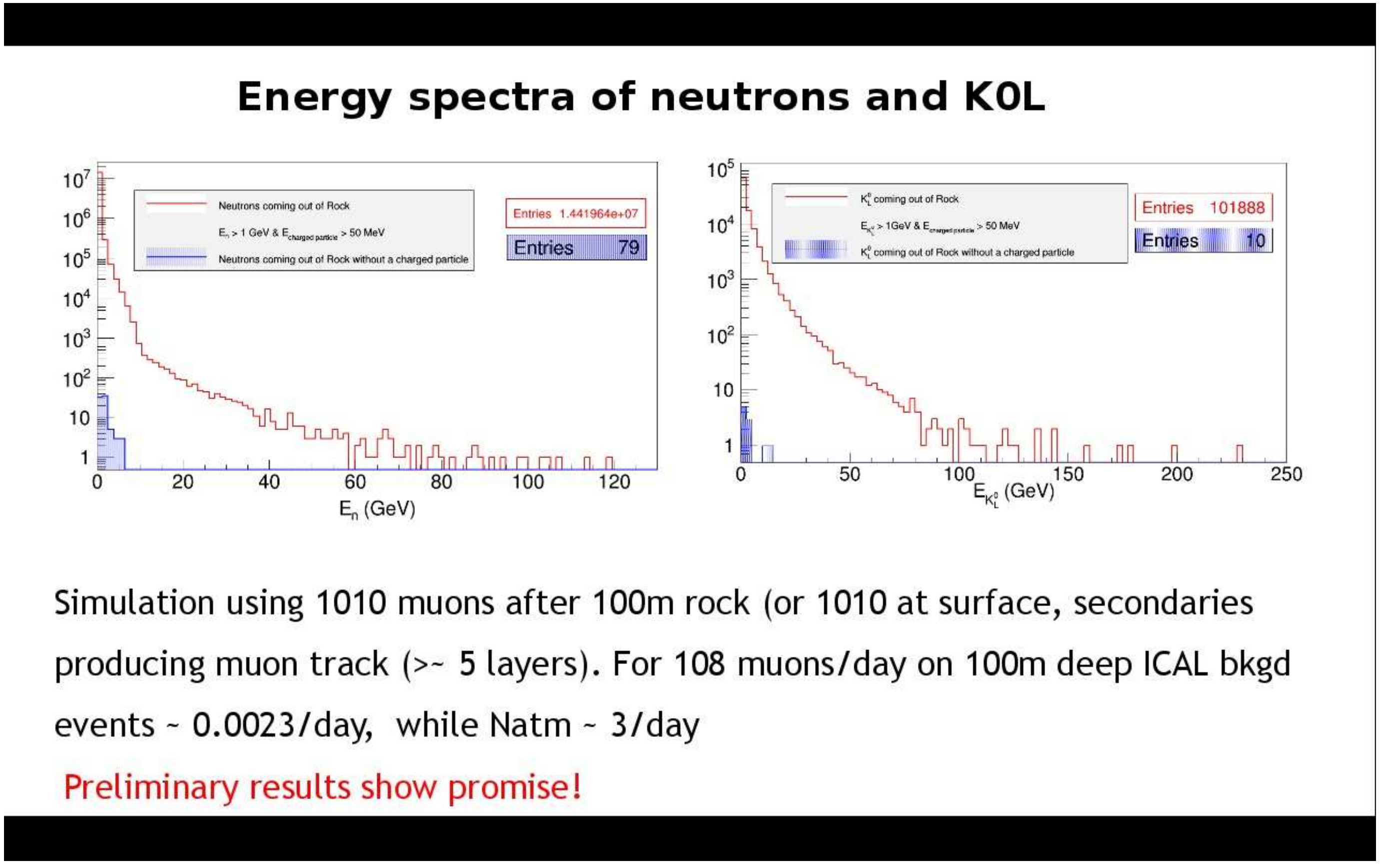
Offset corrected X-Y hit data



I = 900 A ; B = 1.4 Tesla

Proposal for a near-surface detector

- A cosmic muon veto detector (CMV) with efficiency of 99.99% needed
- Results with one CMV (1m $\times$ 1m $\times$ 0.3m) look promising
- Simulations to check background from neutrals



Energy spectra of neutrons and K0L

Simulation using 1010 muons after 100m rock (or 1010 at surface, secondaries producing muon track (>~ 5 layers). For 108 muons/day on 100m deep ICAL bkgd events ~ 0.0023/day, while Natm ~ 3/day

Preliminary results show promise!

INO and Outreach

- Public awareness programmes began in late 2009. After many such outreach meetings, the locals accepted the project.
- A sustained, deliberate mis-information campaign against INO. Warns of danger from neutrinos, dangers from construction, and danger of a hidden “secret” agenda.
- Another round of outreach started last week; hope that can convince locals, environmental activists, and politicians that project poses no danger; will in fact be boon for students in TN and India.
- Look forward to support from entire community. THANK YOU.

Additional Slides

Neutrino Oscillations

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle \ . \tag{2}$$

Here U is the 3×3 unitary matrix which may be parametrised as (ignoring Majorana phases):

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta_{CP}} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{CP}} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} . \tag{3}$$

δ_{CP} is the CP violating (Dirac) phase and M_ν is diagonalised in the charged-lepton mass basis by U:

$$U^\dagger M_\nu U = \mathrm{diag}(m_1, m_2, m_3). \tag{4}$$

Matter Effects

First consider matter of constant density ρ (in gms/cc). Then we can replace the vacuum values by the corresponding matter-modified effective ones obtained by diagonalising the matter dependent matrix (Hamiltonian):

(5)
$$U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

where

(6)
$$A = 2\sqrt{2} G_F n_e E = 7.63 \times 10^{-5}\ \mathrm{eV}^2\ \rho(\mathrm{gm/cc})\ E(\mathrm{GeV})\ \text{eV}^2.$$

Mixing angles in matter

Further simplification arises because $\Delta m^2_{21} \ll \Delta m^2_{31}$ and we can treat the propagation in matter as a one mass-scale problem involving only $\Delta m^2_{32} \approx \Delta m^2_{31}$. The matter dependent mixing angle $\theta_{12,m}$ may be approximately written as

$$\sin 2\theta_{12,m} \approx \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - (A/\Delta m^2_{21})\cos^2\theta_{13})^2 + \sin^2 2\theta_{12}}} \ . \tag{7}$$

The effect of matter on the angle θ_{13} is non-trivial and is given by

$$\sin 2\theta_{13,m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - (A/\Delta m^2_{31}))^2 + (\sin 2\theta_{13})^2}} \ . \tag{8}$$

$$\sin 2\theta_{23,m} \approx \sin 2\theta_{23} \ . \tag{9}$$