India-based Neutrino Observatory (INO)

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Outline of talk

- On particles, their interactions, and neutrinos in particular.

- The status of the India-based Neutrino Observatory.

Some preliminary facts

- Matter is made up of atoms. Atoms have electrons with a central nucleus. The nucleus contains protons and neutrons.

Particle	Charge
Electron	-1
Proton	$+1$
Neutron	0
Atom	0

- Radioactivity was discovered in 1986. It was soon determined that α, β and γ rays were emitted by the nucleus of atoms.
- Beta rays were established to be electrons, and the interactions producing them were called weak interactions.

The Standard Model of Particle Physics

- There are four fundamental forces in nature: gravity, electro-magnetic, strong and weak.
- Leptons are those particles that *do not* experience strong forces (which baryons do).
- Weak forces are like beta decay or the fusion processes that power the Sun. (The fusion in a fusion bomb is a *strong interaction process.*)

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Particle	electro-magnetic	strong	weak
p^+	✔	✔	✔
n^0	✘?!	✔	✔
e^-	✔	✘	✔
ν_e	✘	✘	✔

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- Leptons come in three *flavours* or *types* or *generations*:

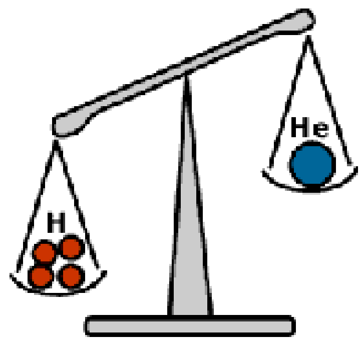
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

μ and τ heavier versions of e. Reason for their existence (and no. of generations) a mystery.

All neutrinos are assumed massless within the Standard Model.

An aside: Solar Neutrinos

Nuclear energy comes from transforming mass to energy, according to Einstein's equation, $E = mc^2$. In the case of nuclear fusion, it comes from Aston's discovery (1920) that 4 hydrogen nuclei are heavier than a helium nucleus.



The difference arises due to nuclear binding.

The key to the old puzzle

In 1920, Eddington used the results of Aston to argue that hydrogen could burn into helium in stars like the Sun, and in principle, that there was enough energy in the Sun for it to shine for 100 billion years.

By 1938, von Weizäcker and then Bethe completed the detailed calculation of the evolution of the Sun. In brief, the result can be expressed as

$$p + p + p + p \rightarrow {}^{4}\mathrm{He}$$

Note: Baryon number conservation, charge conservation, lepton number conservation and Energy-momentum conservation.

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$$p + p + p + p \rightarrow {}^{4}\mathrm{He} + 2\,e^{+} + 2\nu_e + 26.7 \text{ MeV} \,.$$

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The proof of the pudding . . .

The proof of the pudding . . .

. . . is in looking for, and finding the neutrinos!

Since neutrinos interact only weakly with matter, notoriously hard to detect.

First attempts were made as early as 1960's.

Early solar neutrino experiments

Davis and collaborators, first results in 1968.

600 tons of perchloroethylene (drycleaning fluid!) containing Chlorine.

$$\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^- \ .$$

Event rate about 1 in 3 days.

$$R^{CC} = \frac{\text{Number of events observed}}{\text{Number of events expected}} \simeq \frac{1}{3} \ .$$

Here CC means charged current:

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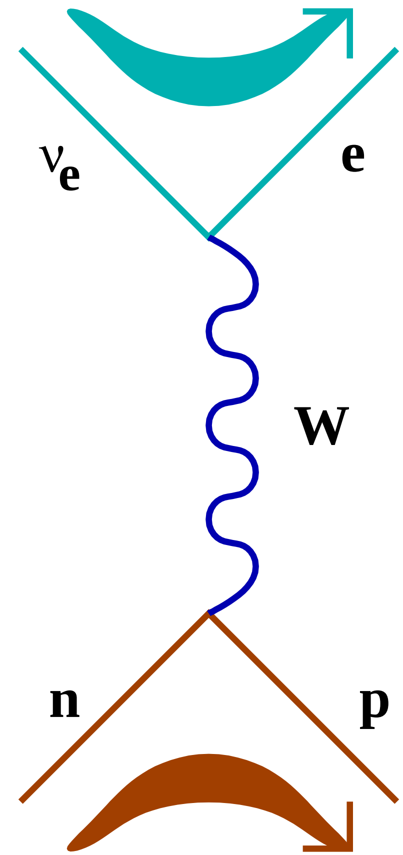

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Solar neutrino experiments: from the Sun

An important criticism of Davis' experiment was that there was no guarantee that the neutrinos he observed were indeed from the Sun.

Koshiba, Totsuka and collaborators, 1986, Kamioka in Japan, followed by Super-Kamioka, used a tank of water to detect neutrinos. The detection is by elastic scattering of neutrinos on water.

$$\nu_X + e \to \nu_X + e \ .$$

All flavours contribute, but mostly (6:1) e-type neutrinos.

The Super-K solar data

Super-K: 22,500 tons of (pure) water. About 3 events per day.

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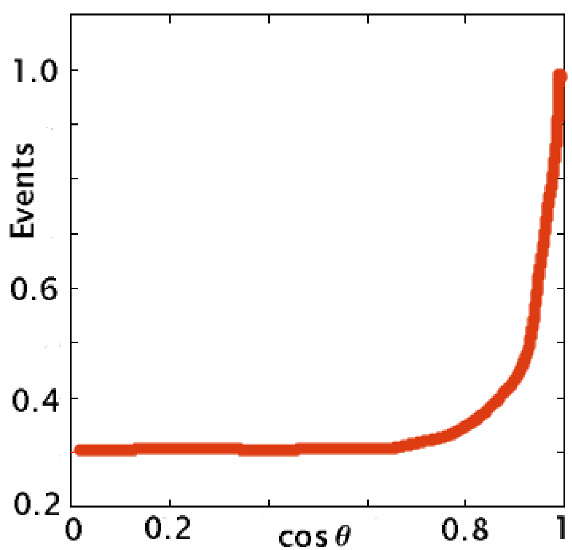


First evidence that the Sun does shine due to nuclear fusion.

Confirmation from GALLEX (GNO) (down to small neutrino energy 0.24 MeV):

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^- \,.$$

New puzzle: Rates lower than expected.

Neutrino oscillations

Neutrinos come in more than one *flavour* or *type*. Consider, for simplicity, two-flavours, ν_e and ν_μ.

If neutrinos are massive (different masses), and, further, show the quantum mechanical phenomenom called *flavour mixing*, then neutrinos can *oscillate* between flavours.

$$\begin{aligned} \nu_e &= \cos\theta\ \nu_1 + \sin\theta\ \nu_2\ , \\ \nu_\mu &= -\sin\theta\ \nu_1 + \cos\theta\ \nu_2\ . \end{aligned}$$

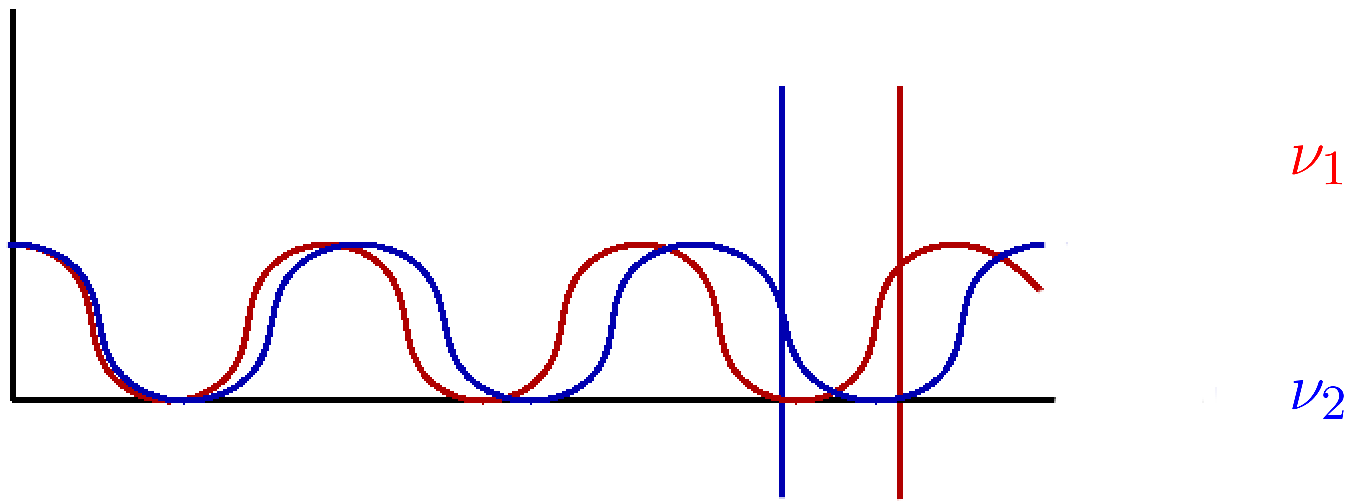
ν_1 and ν_2 are quantum mechanical states with given energy (and momentum) (mass eigenstates). They evolve according to

$$\nu_i(t) = \exp\left[-iE_i t\right] \nu_i(0)\ .$$

Neutrino oscillations

Can then ask what is the probability that a ν_e that is produced at $t = 0$ remains ν_e at a given time $t = t$.

If $E_2 > E_1$, oscillation period of ν_2 greater than that of ν_1.



Real $\nu_e(t) = \cos\theta$ ↻ $+ \sin\theta$ ↻

Hence as the neutrino travels to the Earth it oscillates between different flavours of neutrinos.

Caution: No matter effects: neutrinos get modified as they come out of the super-dense (150 gm/cc) core of the Sun.

The final denouement

An obvious test of the oscillation hypothesis is to look for the other flavours of neutrinos, from the Sun.

The SNO detector, Sudbury, Canada, 1000 tons of heavy water D_2O, announced their first results in 2002, and then in 2003.

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\begin{aligned}
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&\simeq \frac{1}{3}\ (\text{Cl and Ga}). \\
R^{ES} &\simeq \frac{1}{2}\ (\text{Super-K}). \\
R^{NC} &\simeq 1\ .
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Here NC stands for the neutral current process:

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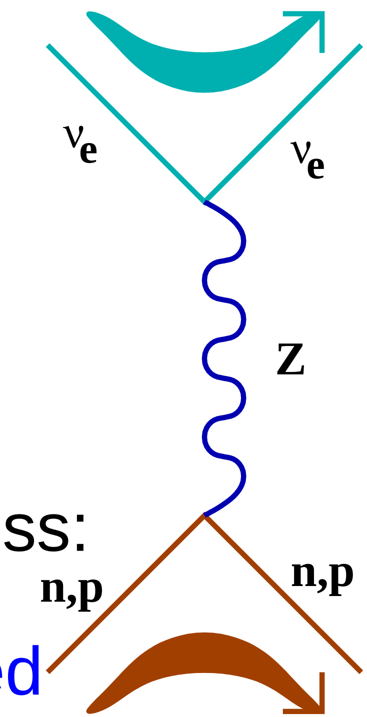


Here NC stands for the neutral current process:

Hence the Standard Solar Model is vindicated in the neutral current sector.

Outlook

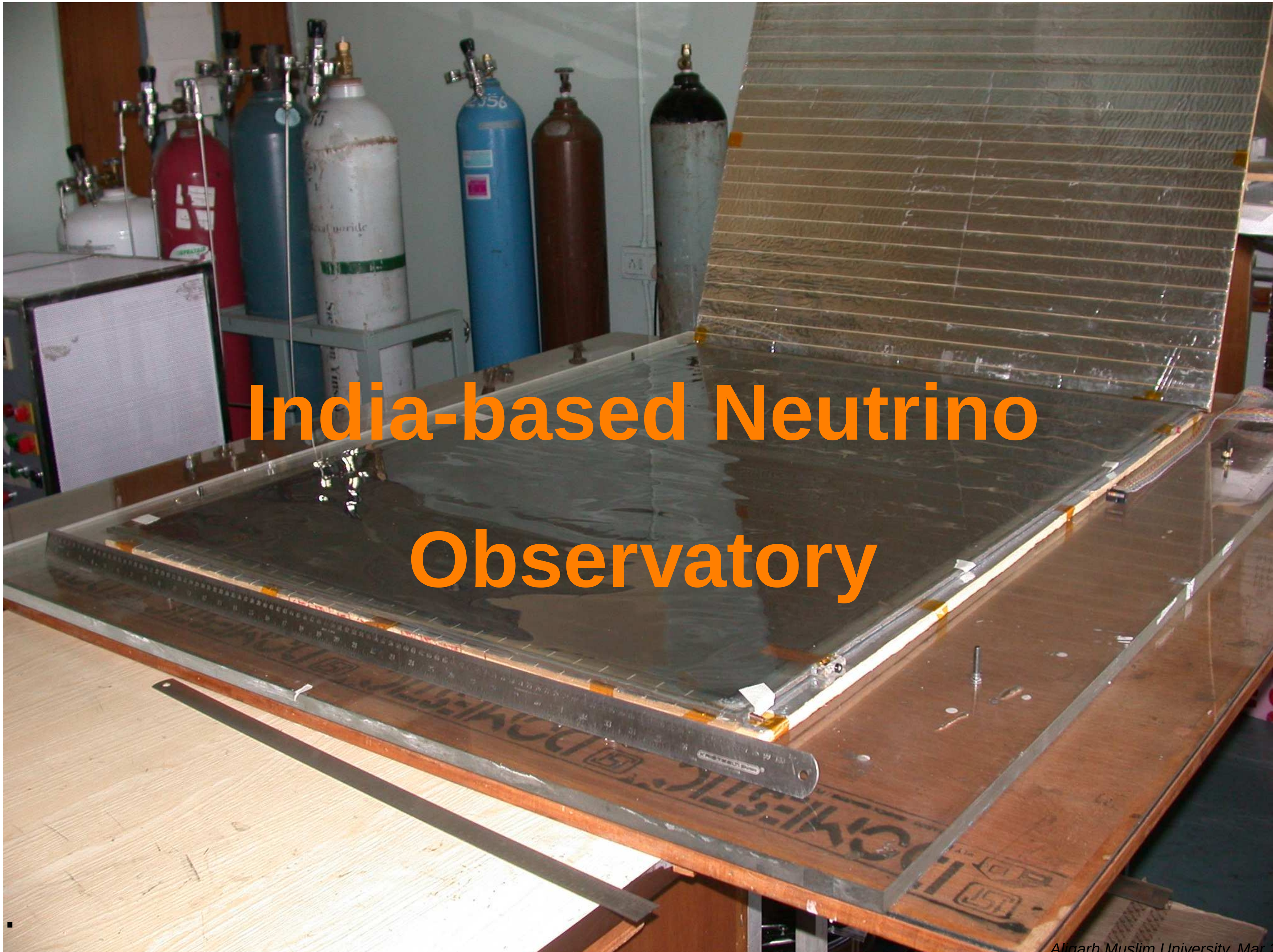
The Sun does shine via weak nuclear fusion. Solar neutrinos have been unambiguously detected.

Solar neutrinos exhibit *oscillation* and hence are massive (at least one neutrino is massive). This is new physics beyond the Standard Model of Particle Physics.

Look for oscillations in other neutrino-related phenomena: atmospheric neutrinos, accelerator neutrinos, reactor (anti)neutrinos, etc.

Very exciting results that relate to fundamental properties of neutrinos and their interactions.

A proposal, the India-based Neutrino Observatory (INO) is exploring the possibility to build an underground neutrino detector in India.



India-based Neutrino Observatory

A Schematic of Neutrino Properties

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

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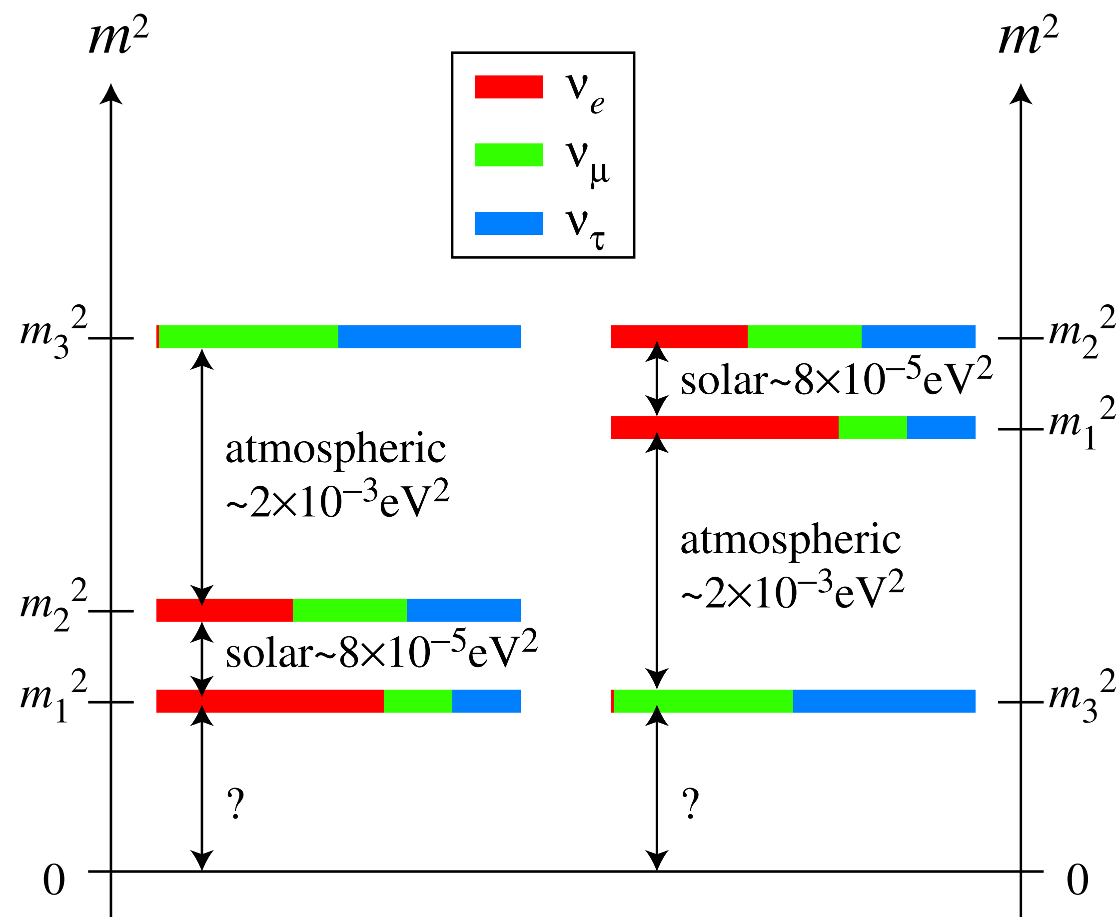

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$\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
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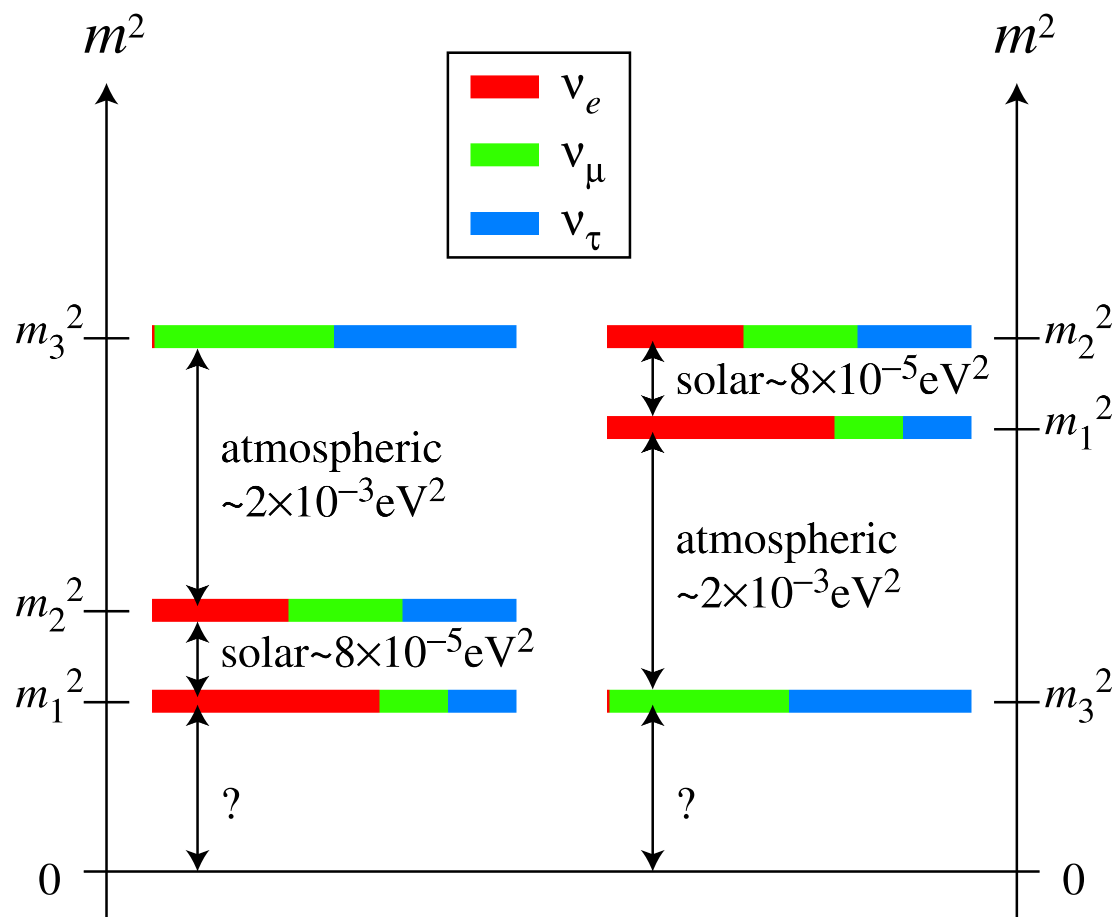
$\sum_i m_i < 0.7$–2 eV.



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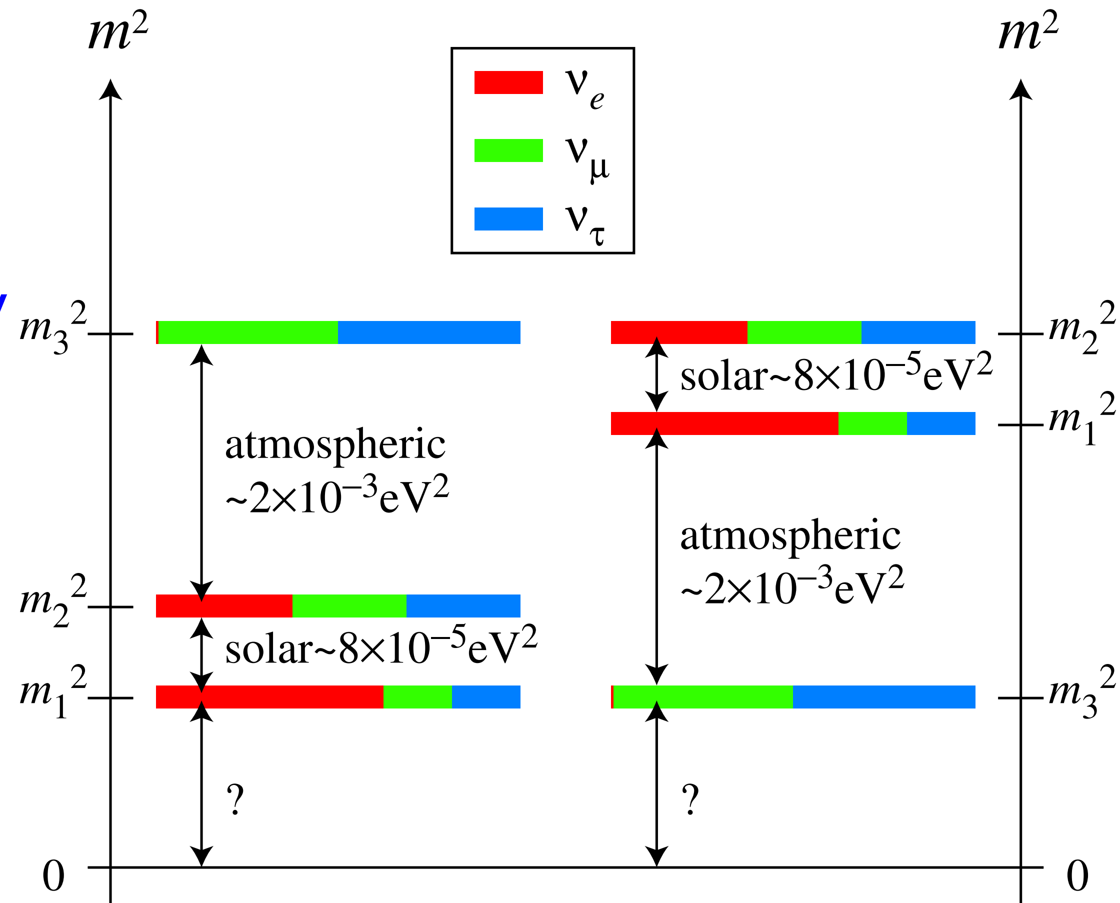
- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV (Degenerate hierarchy)
- $m_1 < m_2 \ll m_3$ (Normal hierarchy)
- $m_3 \ll m_1 < m_2$ Inverted hierarchy)



(APS multi-divisional neutrino study, physics/0411216)

In Summary

- Neutrinos are the least understood particles in nature.
- They have exotic properties: non-zero, distinct masses, and non-trivial mixing among the different flavours: this is because of compelling evidence for neutrino oscillation.
- While the depletion effects of oscillation are well-studied, a complete oscillation (with one minimum and one maximum) has not yet been directly studied in any single experiment and has only been inferred.
- The mass-squared differences as well as the masses are very small; the origin of small masses is a puzzle.

The INO Collaboration

- Stage I : Study of atmospheric neutrinos

  The feasibility study of about 2 years duration for both the laboratory and detector is under-way. Issues under study are

  - Site Survey
  - Detector R & D, including construction of a prototype
  - Physics Studies
  - Human resources development

- After approval is obtained, actual construction of the laboratory and ICAL detector will begin

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- Other detectors/physics like neutrinoless double beta decay?

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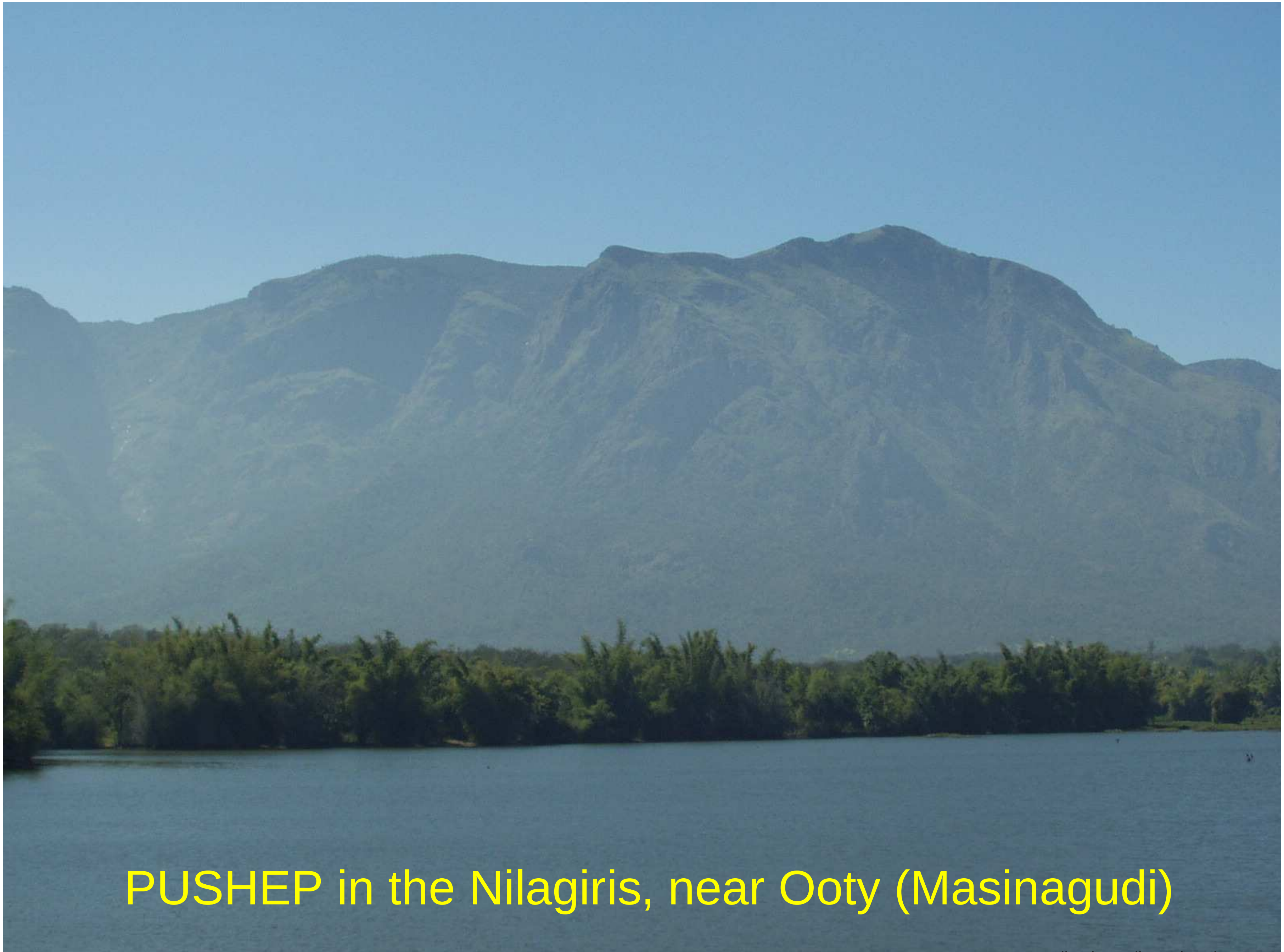
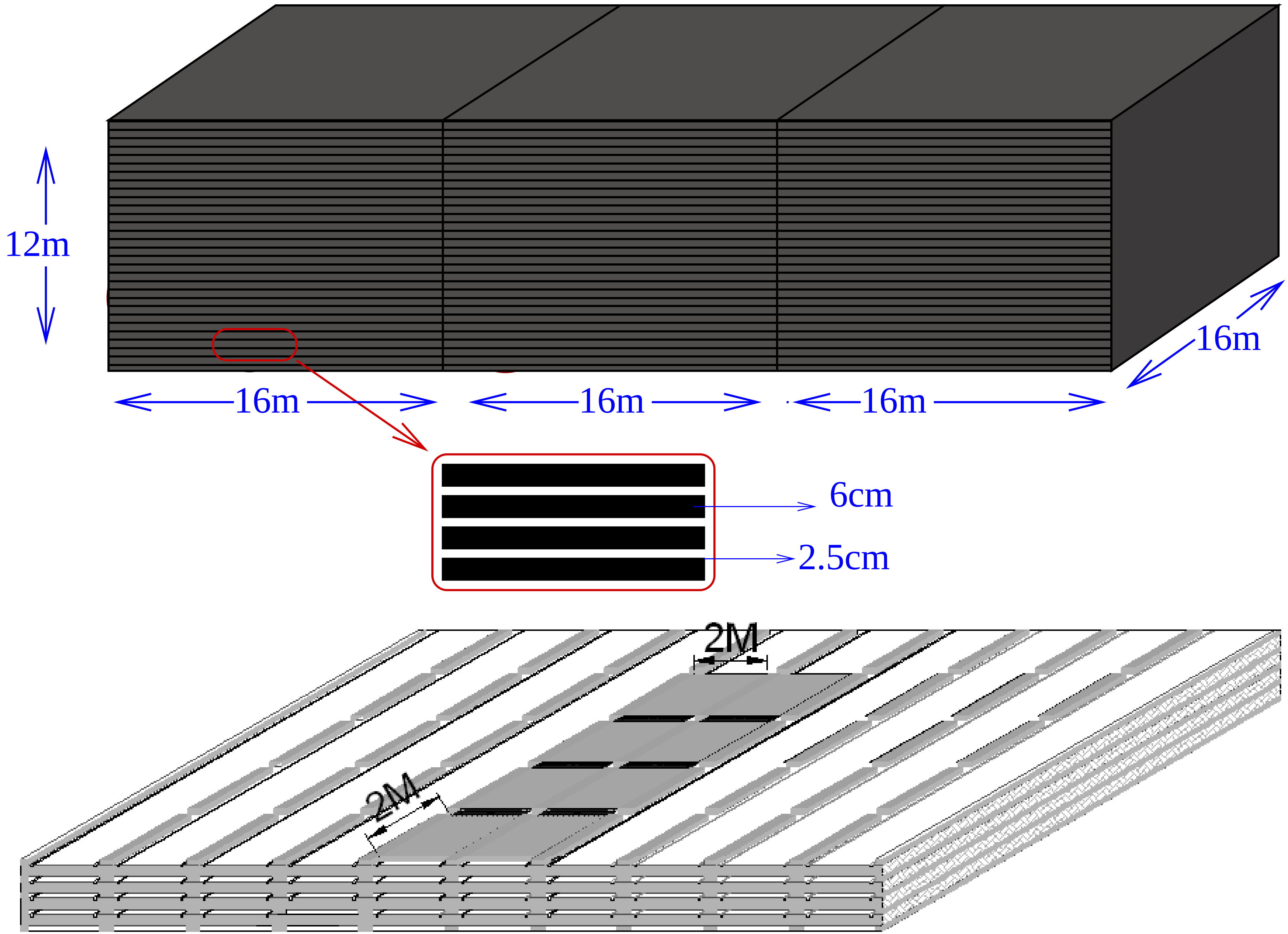
- Other detectors/physics like neutrinoless double beta decay?

- Should be an international facility

Site survey: PUSHEP

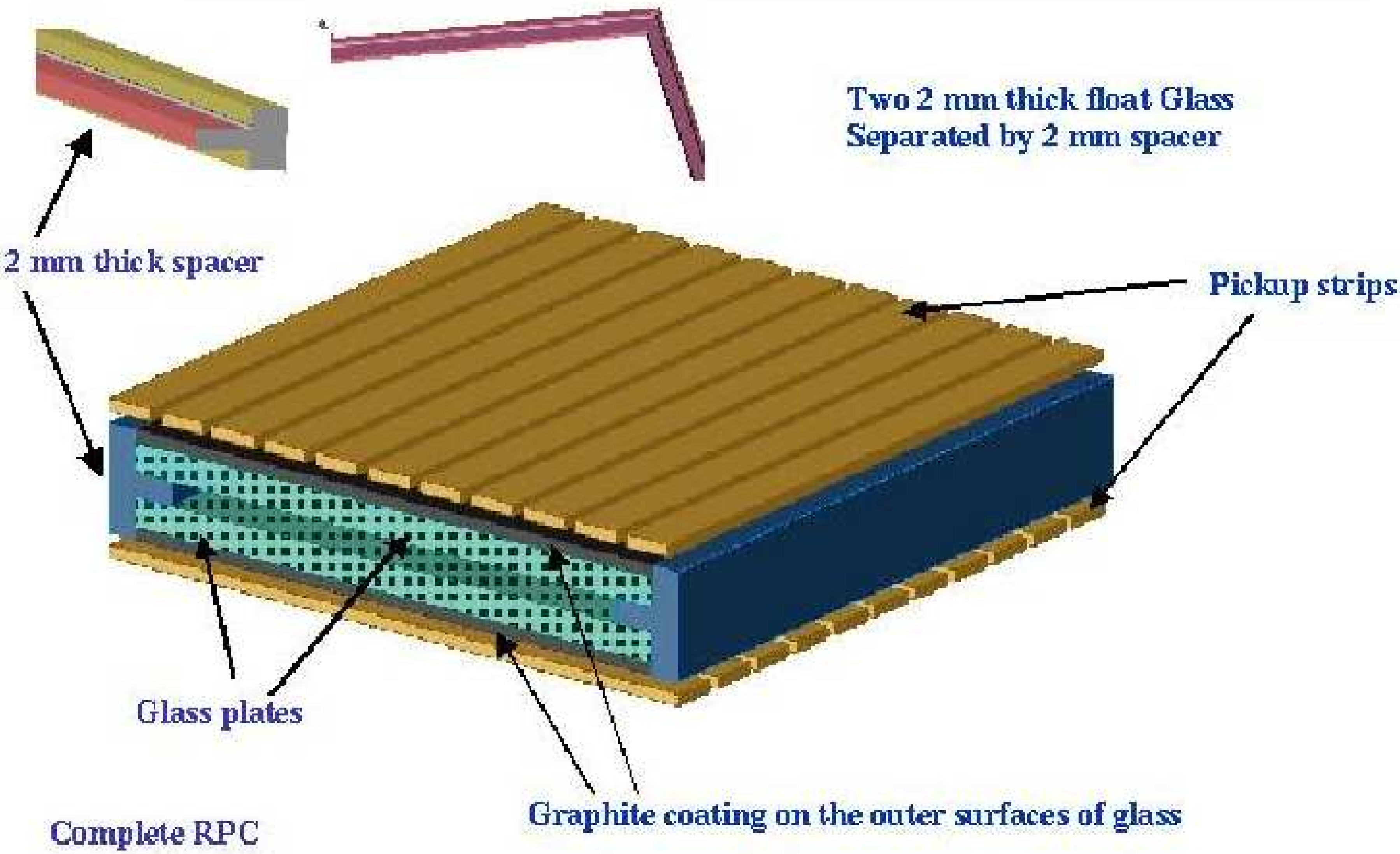


The ICAL detector



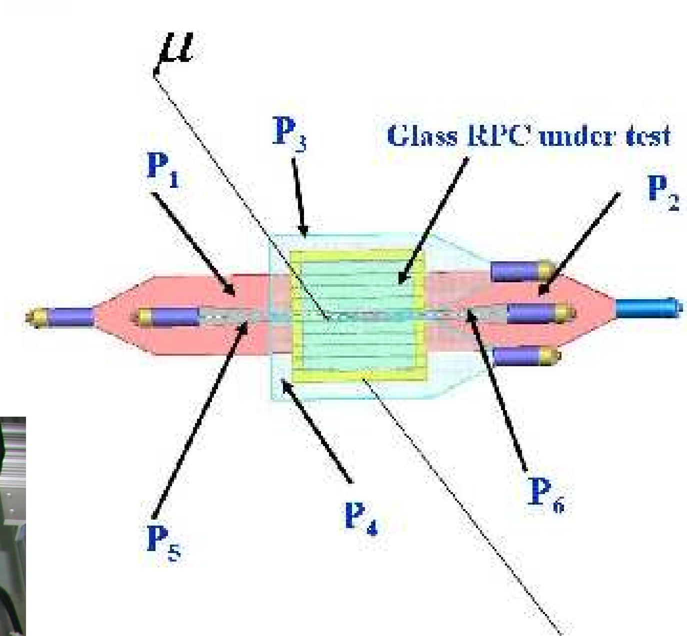
The active detector elements: RPC

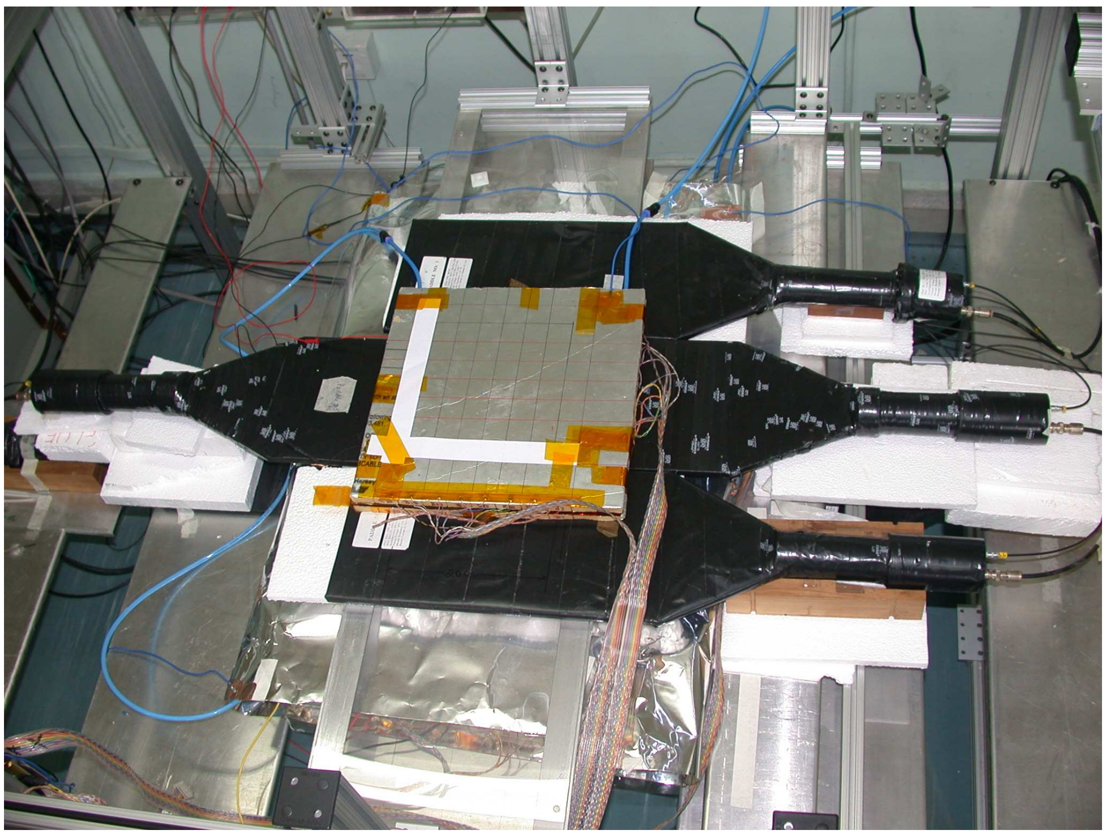
RPC Construction: Float glass, graphite, and spacers



Fabricating RPC's

at TIFR . . .





And of course . . .

Specifications of the ICAL detector

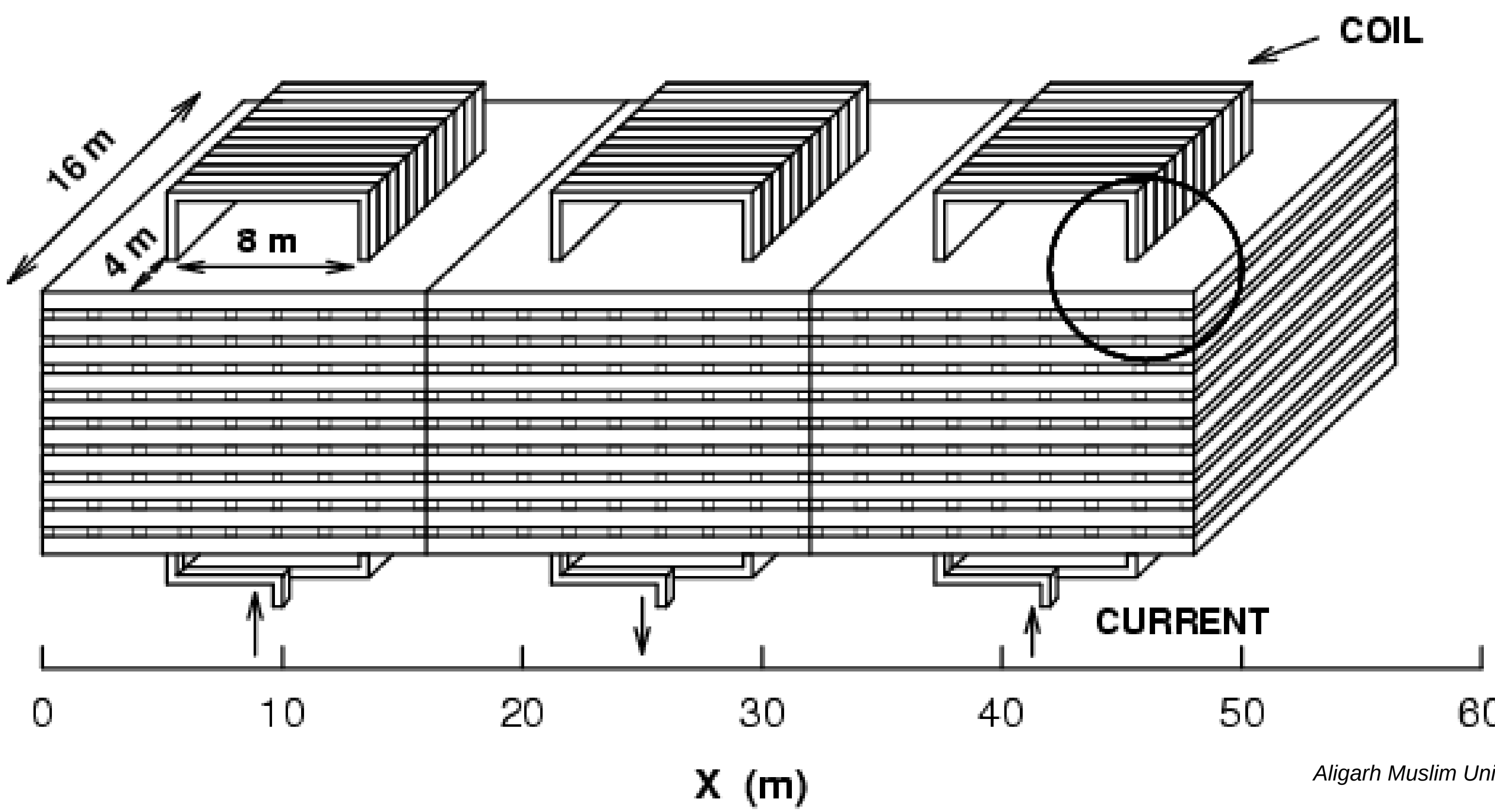
ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 12 m
Detector dimension	48 m $\times$ 16 m $\times$ 12 m
No. of layers	140
Iron plate thickness	$\sim$ 6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.3 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	$\sim$ 27000
No. of electronic readout channels	3.6×10^6

Magnet studies

Design criteria:

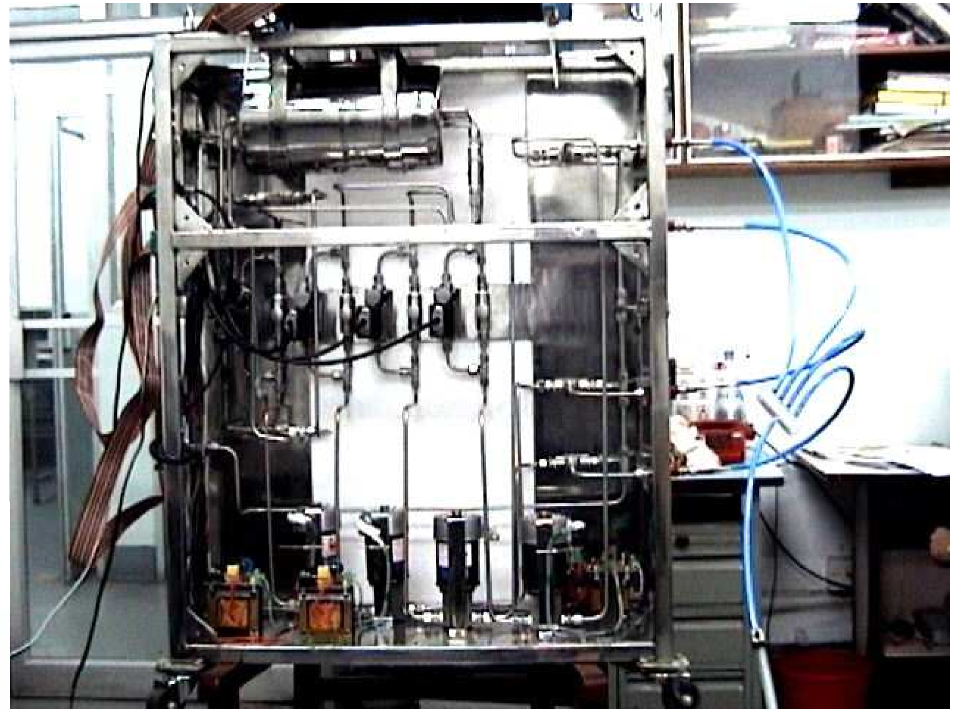
- Field uniformity
- Modularity
- Optimum copper-to-steel ratio
- Access for maintenance

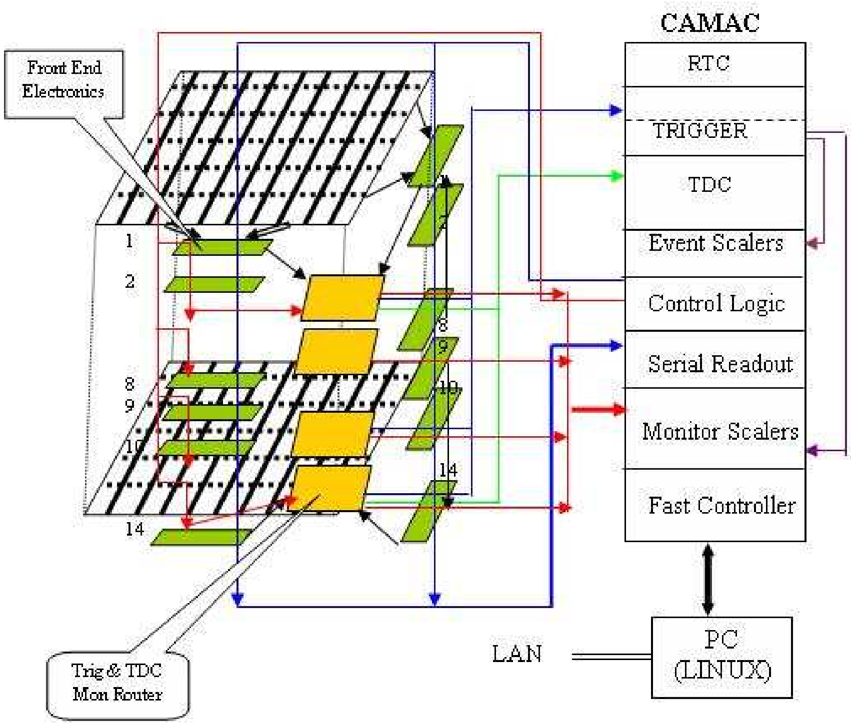
Toroidal Magnet design



For the prototype . . .

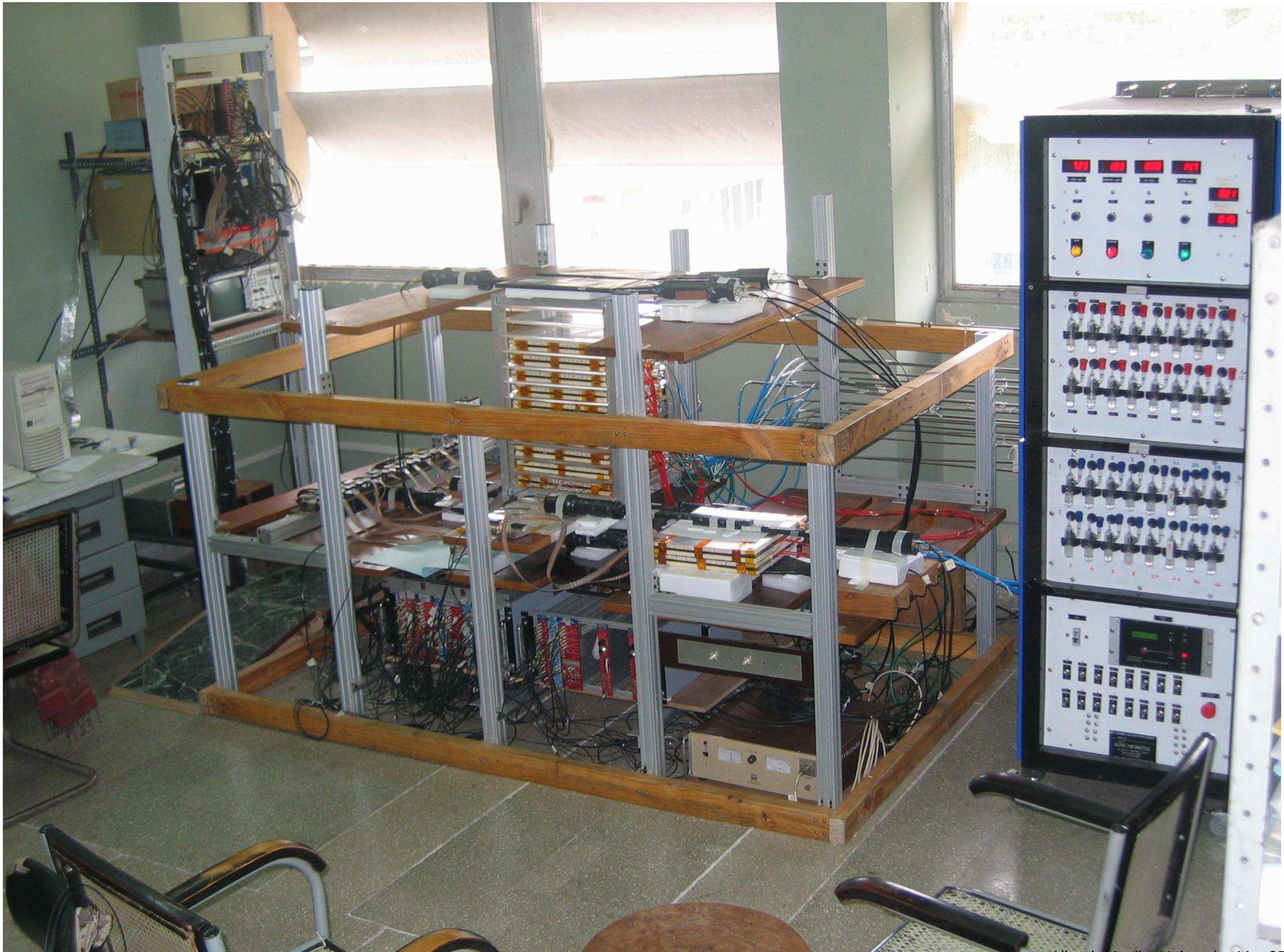
The gas-mixing unit at SINP

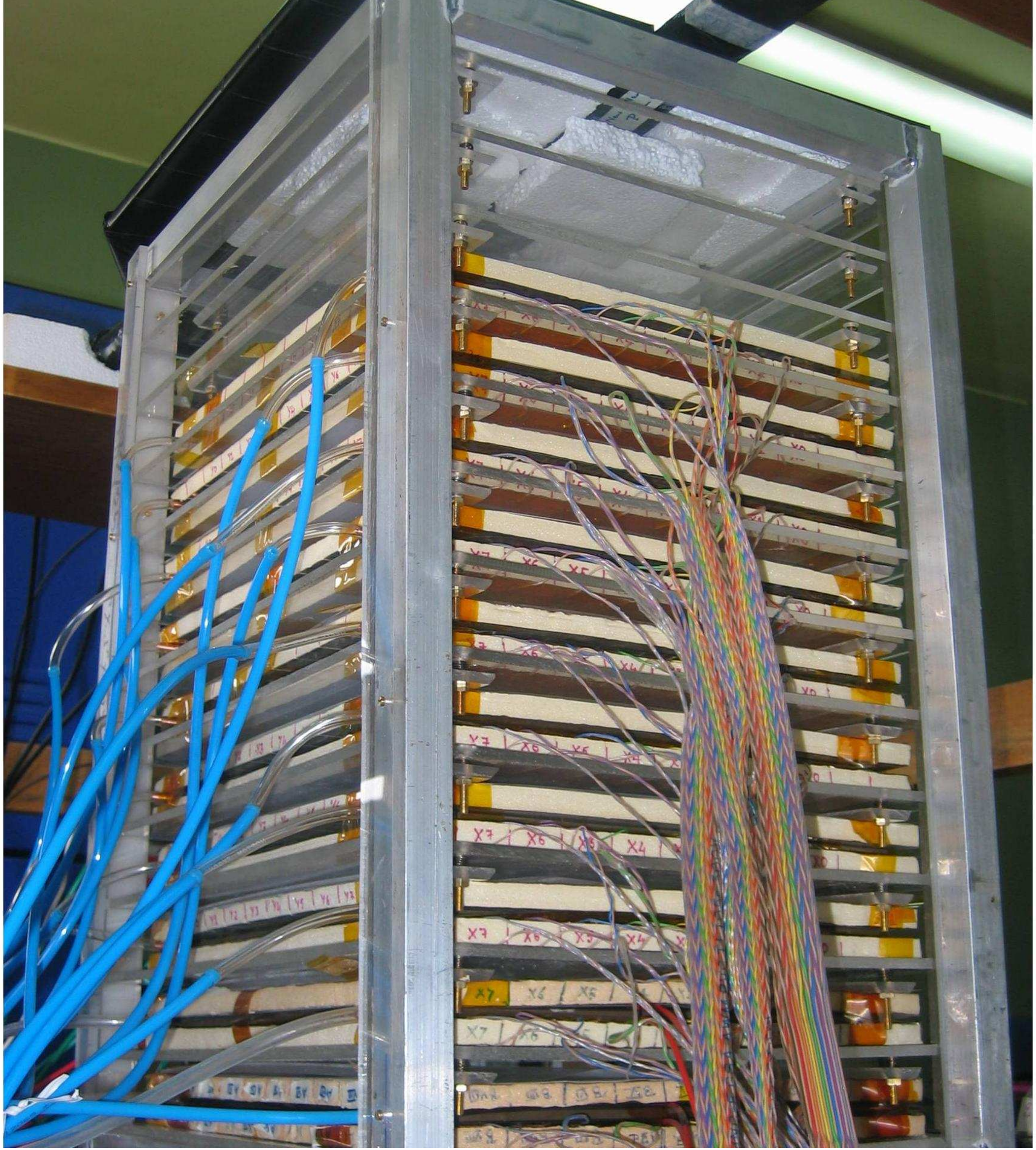




A schematic of the read-out electronics for the prototype

For the prototype, at TIFR . . .

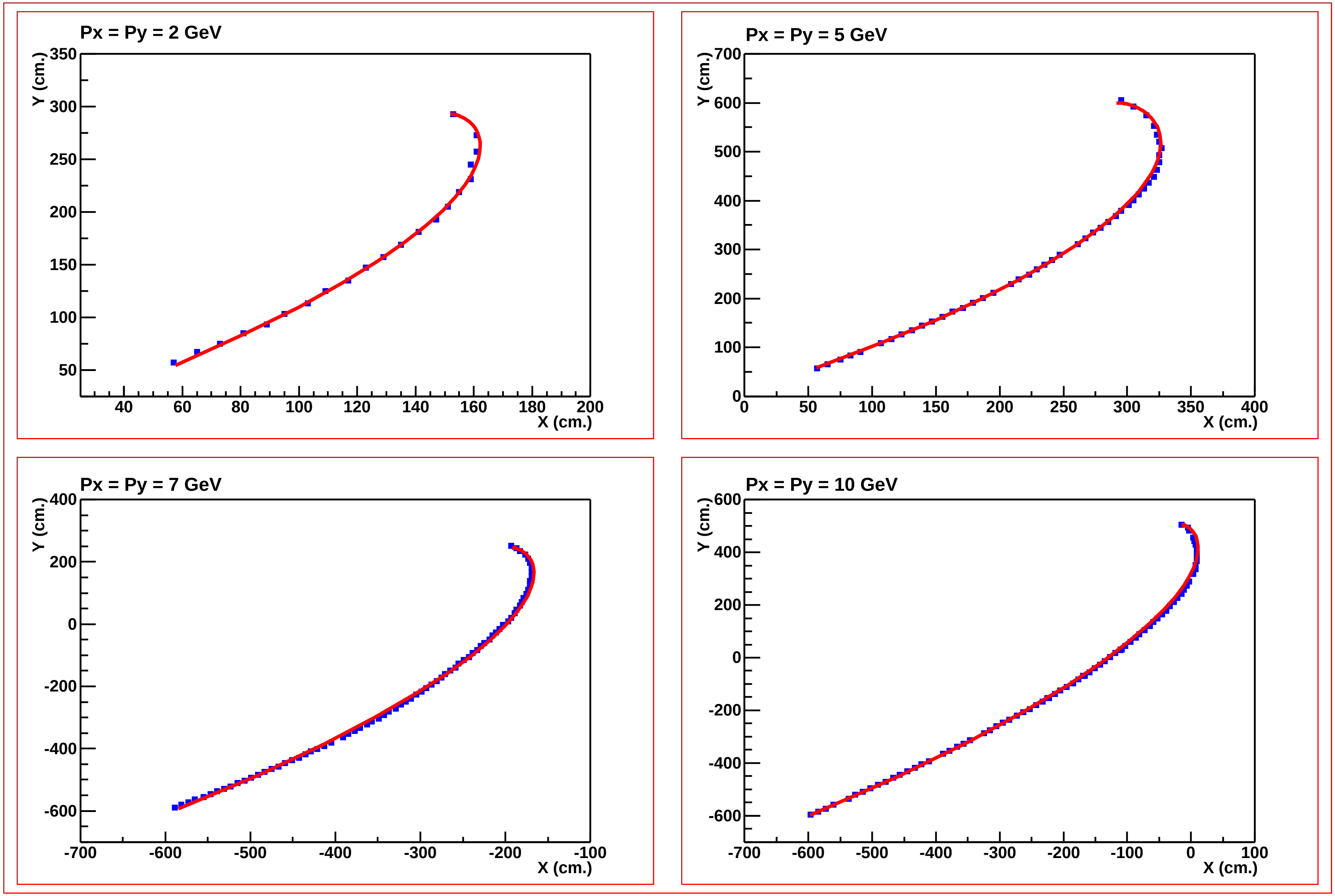




Physics with Atmospheric Neutrinos

- A muon-type neutrino from the atmosphere enters the detector.
- It interacts (mostly with the iron) and produces a muon and (perhaps) some hadrons.
- The muon *bends* in the magnetic field and leaves a curved (helical) track in the detector.
- From the bending/length of the track, the momentum and direction of the track is reconstructed.
- From the number of hits, the hadron energy is found.
- Energy and direction of the parent neutrino is reconstructed.
- The direction of bending allows the charge of the muon (and hence the type of neutrino) to be determined.
- Computer simulations of all this have been achieved.

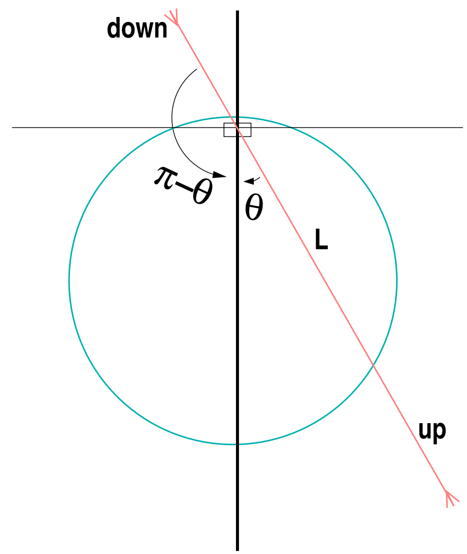
Sample tracks and fits



Physics goals

➢ Main goal: Study oscillation pattern in atmospheric neutrino events. The up/down events ratio is sensitive to oscillation parameters.

(Pietropaolo and Picchi)



$$\frac{\text{up rate}}{\text{down rate}} = P_{\mu\mu} = R \otimes \left\{ 1 - \frac{\sin^2 2\theta_{23}}{2} \left(1 - \cos 2.54\, \Delta m^2_{32} \frac{L}{E} \right) \right\} .$$

R is determined by the L/E resolution of the ICAL detector

So, analysis *needs* a knowledge of this resolution function, which depends on the quality of reconstruction of tracks in the detector.

Physics possibilities

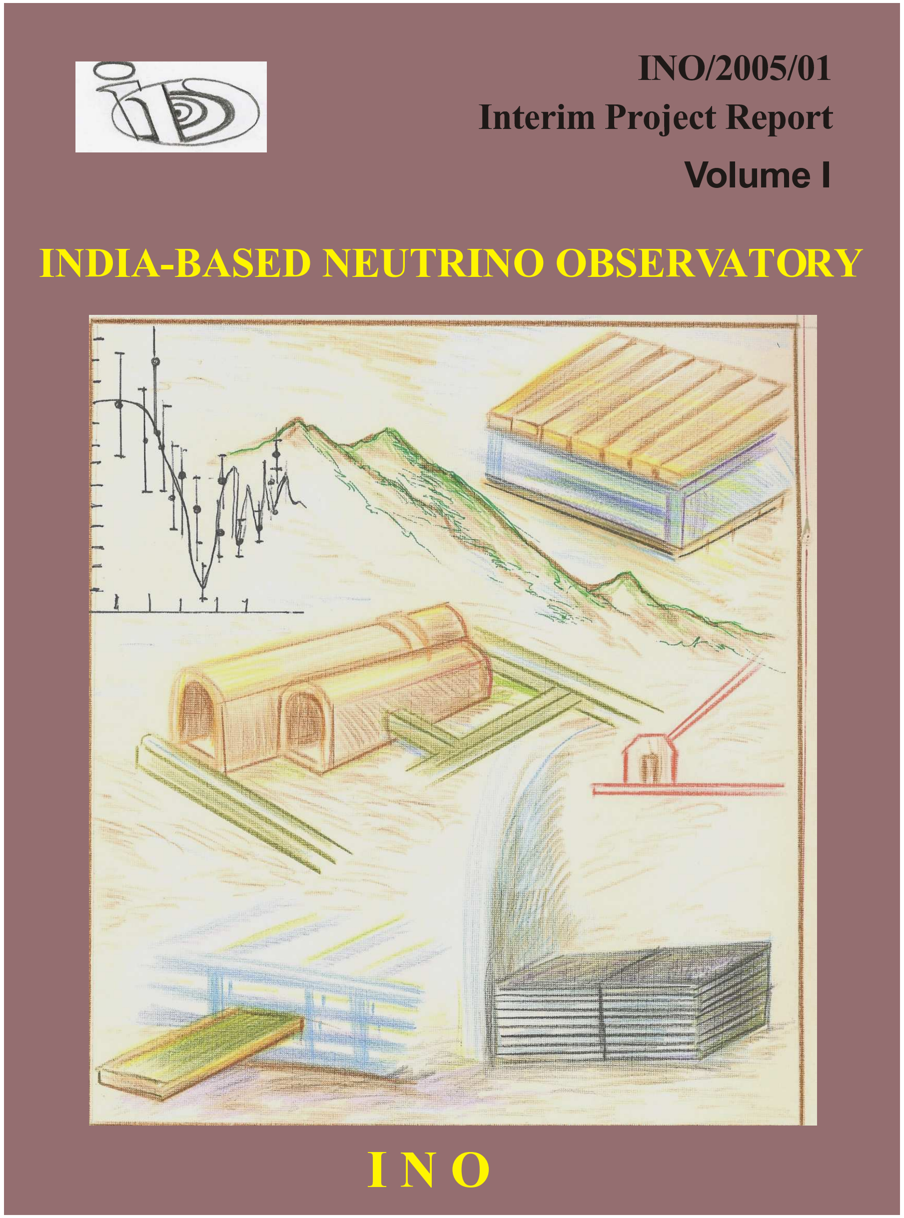
. . . *WITH ATMOSPHERIC NEUTRINOS*

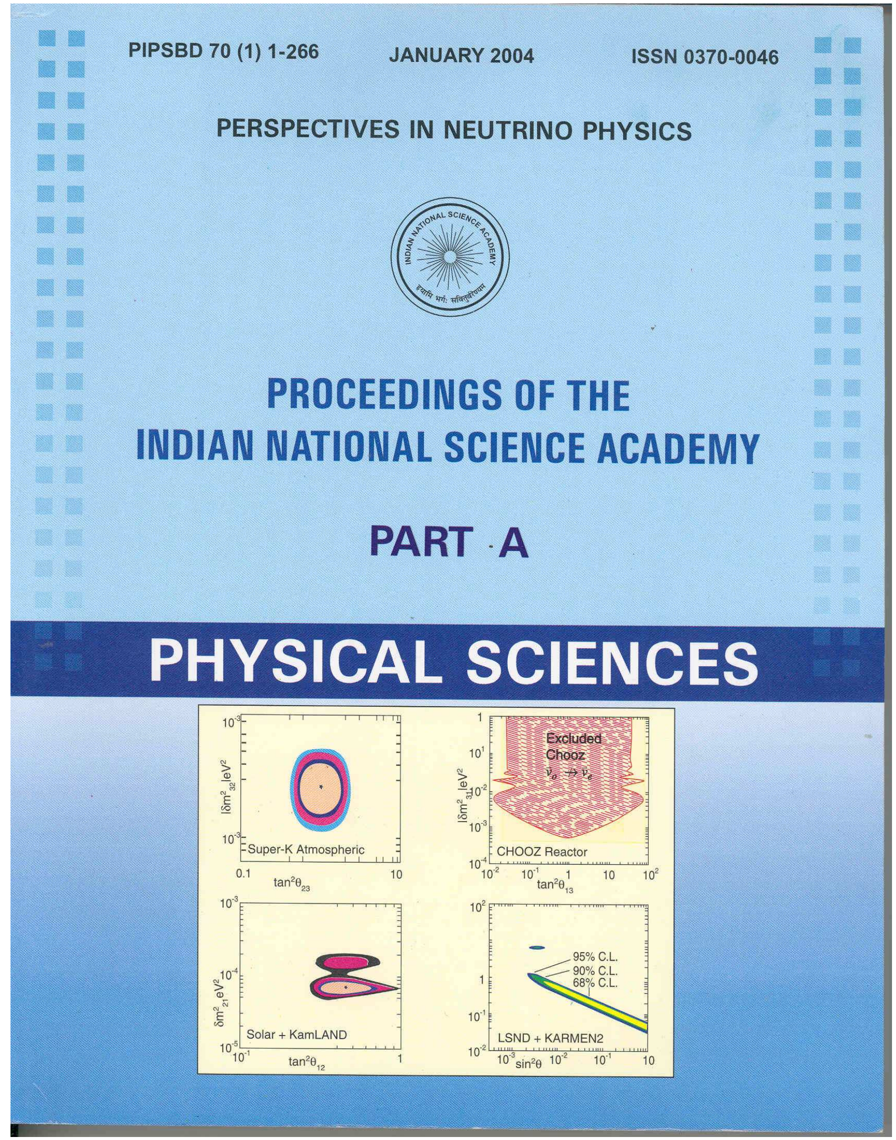
- Determination of mixing parameters, especially in 2–3 sector. Determine mass ordering of the 2–3 states and the octant of θ_{23}.
- Discrimination between oscillation of ν_μ to active ν_τ and sterile ν_s from up/down ratio in "muon-less" events.
- Probing CPT violation from rates of neutrino- to rates of anti-neutrino events in the detector.
- Constraining long-range leptonic forces by . . ..

. . . *WITH LONG BASE-LINE NEUTRINOS*

- Precision neutrino oscillation studies

Status Report





Interim Report, submitted to funding authorities, May 1, 2005

In short . . .

The outlook looks good! This is a massive project:

Looking for active collaboration both within India and abroad

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The INO Collaboration[1]

- **Aligarh Muslim University, Aligarh:**
  M. Sajjad Athar, Rashid Hasan, S. K. Singh
- **Bhabha Atomic Research Centre (BARC), Mumbai:**
  V. Arumugam, Anita Behere, M. S. Bhatia, V. B. Chandratre, V. M. Datar, M. P. Diwakar, M. G. Ghodgaonkar, A. K. Mohanty, P. K. Mukhopadhyay, S. C. Ojha, L. M. Pant, K. Srinivas
- **Calcutta University (CU), Kolkata:**
  Amitava Raychaudhuri
- **Delhi University (DU), Delhi:**
  Brajesh Choudhary, Debajyoti Choudhury, Sukanta Dutta, Ashok Goyal, Kirti Ranjan
- **Harish Chandra Research Institute (HRI), Allahabad:**
  Anindya Datta, Raj Gandhi, Pomita Ghoshal, Srubabati Goswami, Poonam Mehta, S. Rakshit
- **University of Hawaii (UHW), Hawaii:**
  Sandip Pakvasa
- **Himachal Pradesh University (HPU), Shimla:**
  S. D. Sharma
- **Indian Institute of Technology, Bombay (IITB), Mumbai:**
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- **The Institute of Mathematical Sciences (IMSc), Chennai:**
  D. Indumathi, H. S. Mani, M. V. N. Murthy, G. Rajasekaran, Abdul Salam[2]
- **Institute of Physics (IOP), Bhubaneswar:**
  D. P. Mahapatra, S. C. Phatak
- **North Bengal University (NBU), Siliguri:**
  A. Bhadra, B. Ghosh, A. Mukherjee, S. K. Sarkar
- **Panjab University (PU), Chandigarh:**
  Vipin Bhatnagar, M. M. Gupta, J. B. Singh
- **Physical Research Laboratory (PRL), Ahmedabad:**
  A. S. Joshipura, Subhendra Mohanty, S. D. Rindani

[1] This is an open collaboration and experimentalists are especially encouraged to join.
[2] Until March 5, 2005

- **Saha Institute of Nuclear Physics (SINP), Kolkata:**
  Pratap Bhattacharya, Sudeb Bhattacharya, Suvendu Bose, Sukalyan Chattopadhyay, Ambar Ghosal, Asimananda Goswami, Kamales Kar, Debasish Majumdar, Palash B. Pal, Satyajit Saha, Abhijit Samanta, Abhijit Sanyal, Sandip Sarkar, Swapan Sen, Manoj Sharan
- **Sikkim Manipal Institute of Technology, Sikkim:**
  G. C. Mishra
- **Tata Institute of Fundamental Research (TIFR), Mumbai:**
  B. S. Acharya, Sudeshna Banerjee, Sarika Bhide, Amol Dighe, S. R. Dugad, P. Ghosh, K. S. Gothe, S. K. Gupta, S. D. Kalmani, N. Krishnan, Naba K. Mondal, P. Nagaraj, B. K. Nagesh, Biswajit Paul, Shobha K. Rao, A. K. Ray, L. V. Reddy, B. Satyanarayana, S. Upadhya, Piyush Verma
- **Variable Energy Cyclotron Centre (VECC), Kolkata:**
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Scientific Steering Committee

C. V. K. Baba, *Nuclear Science Centre, New Delhi*
Ramnath Cowsik, *Indian Institute of Astrophysics, Bangalore*
H. S. Mani, *The Institute of Mathematical Sciences, Chennai*
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