Neutrino Oscillations in the back-drop of the India-based Neutrino Observatory (INO)

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For the INO Collaboration

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Outline of talk

- On neutrinos, their interactions, and oscillations in particular.
- The status of the India-based Neutrino Observatory.

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^+	✔	✔	✔
e^-	✔	✘	✔
ν_e	✘	✘	✔

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

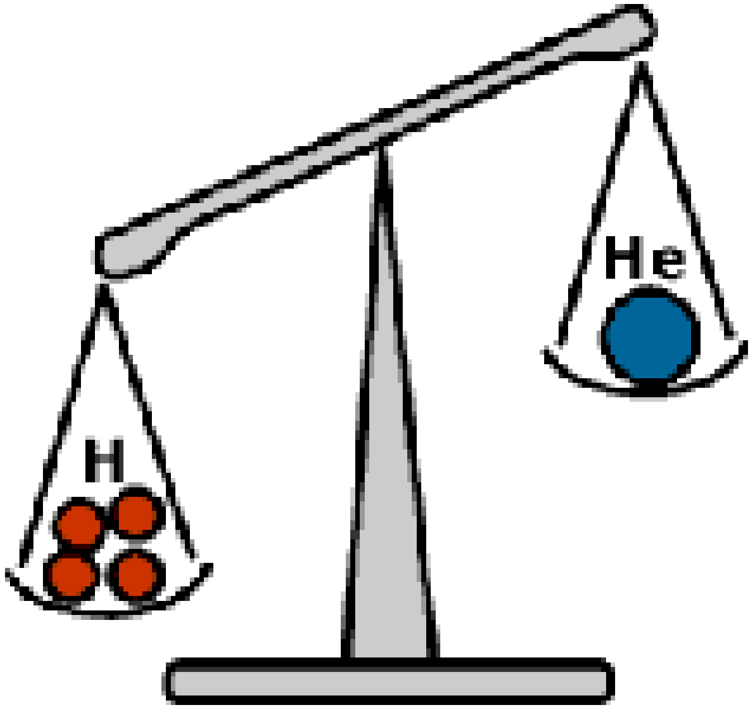
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

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

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

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

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

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The proof of the pudding . . .

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

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

First attempts were made as early as the 1960s.

Early solar neutrino experiments

Davis and collaborators;
first results in 1968.

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

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

Looked for "needle" Argon in Chlorine "haystack". Event rate about 1 in 3 days.

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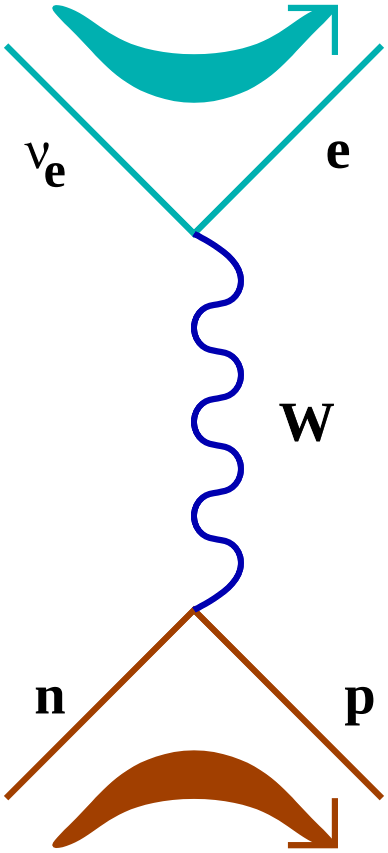

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Question re Davis' expt: Are these solar neutrinos?

Koshiba, Totsuka and collaborators, 1986, Kamioka, Japan.

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

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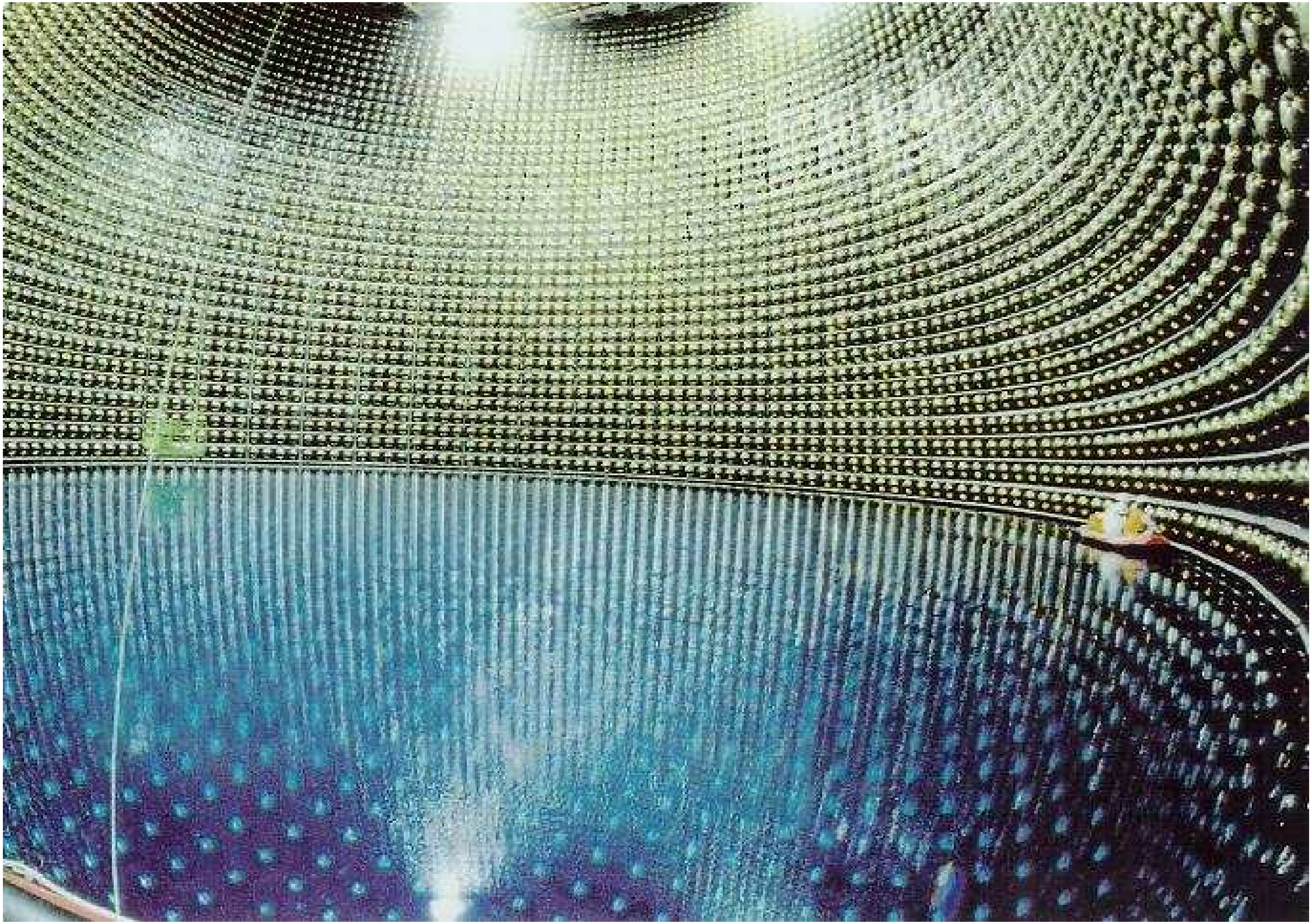
Super-K: 22,500 tons of (pure) water. About 3 events per day.

Solar neutrino experiments: from the Sun



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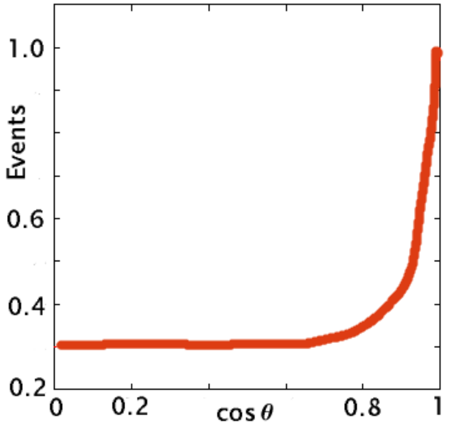


First evidence that the Sun does shine due to nuclear fusion.

Confirmation from GALLEX (GNO) (down to small neutrino energy 0.24 MeV): $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$.

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.

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

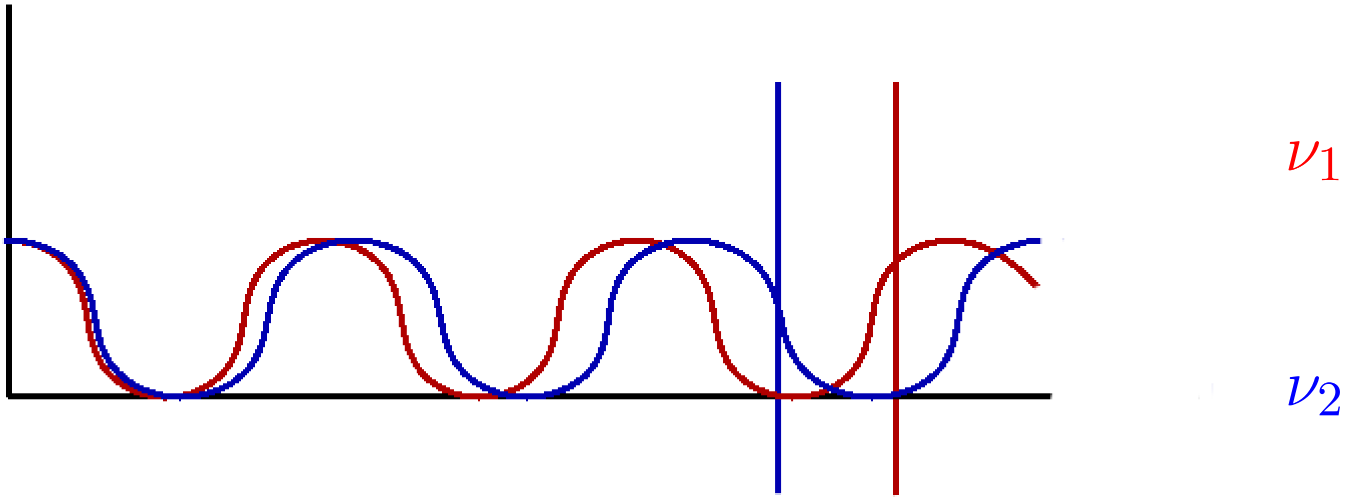
ν_1 and ν_2 are quantum mechanical states with given energy (and momentum) (mass eigenstates). They evolve according to

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

Neutrino oscillations

One 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 $\nu_e(t) = \cos\theta \circlearrowright + \sin\theta \circlearrowright$

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

Caution: matter effects: neutrinos get modified as they come out of the super-dense (150 gm/cc) core of the Sun.

The final denouement

Test of oscillation hypothesis: look for other flavours of neutrinos.

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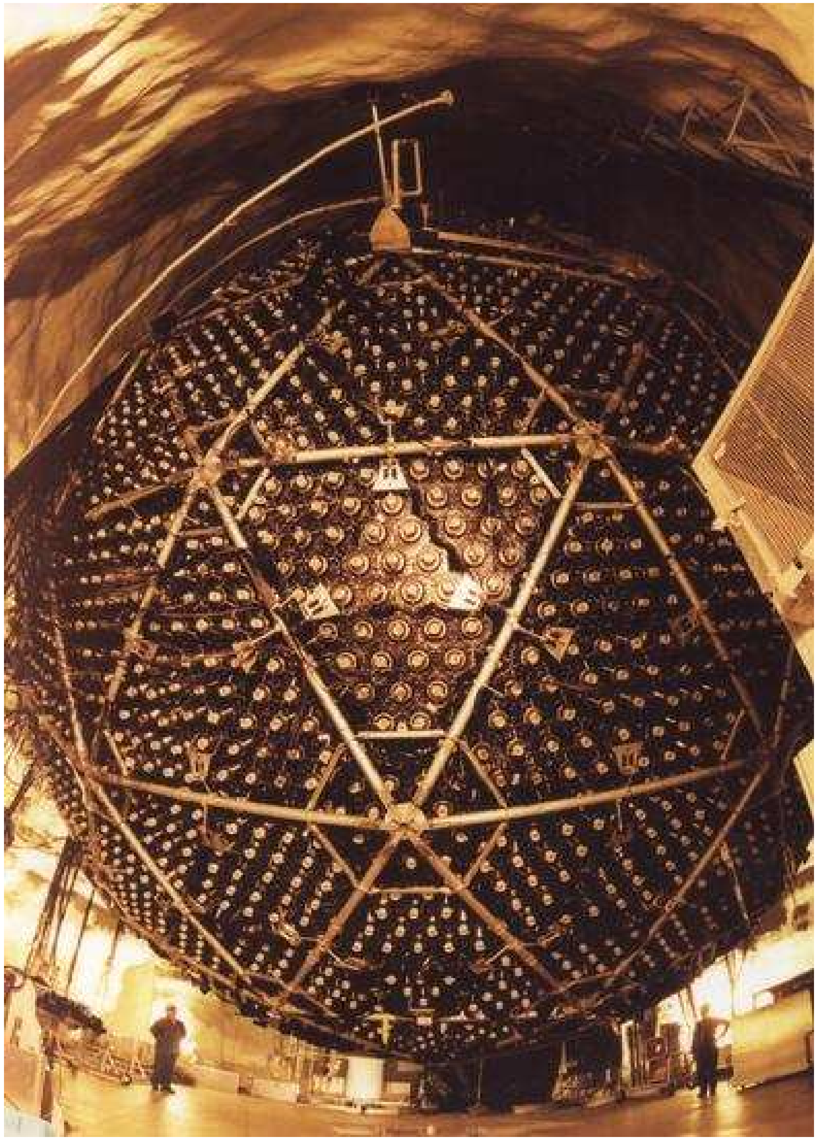

The SNO detector, Sudbury, Canada

1000 tons of heavy water D_2O

First results announced in 2002.

$$\begin{aligned} R^{CC} &= \frac{\text{Number of events observed}}{\text{Number of events expected}} \\ &\simeq \frac{1}{3}\ (\text{Cl and Ga}). \\ R^{ES} &\simeq \frac{1}{2}\ (\text{Super-K}). \\ R^{NC} &\simeq 1\ . \end{aligned}$$

NC stands for the neutral current process:

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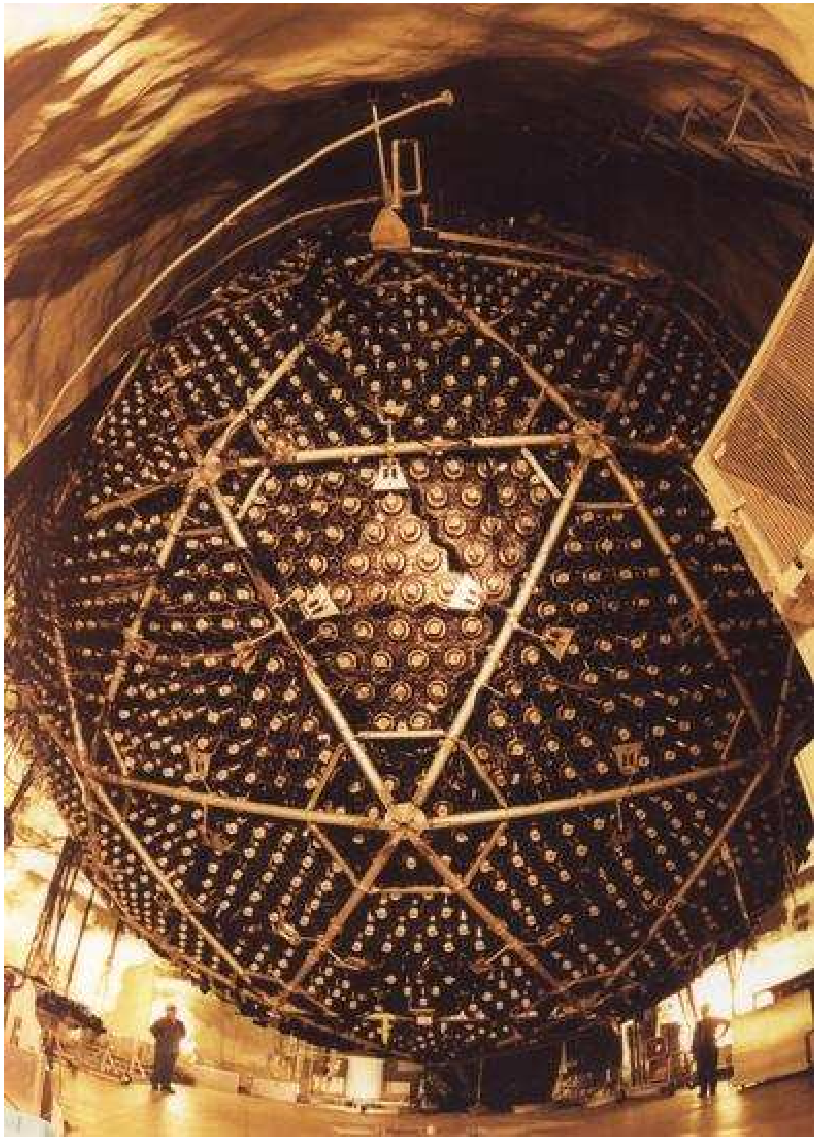

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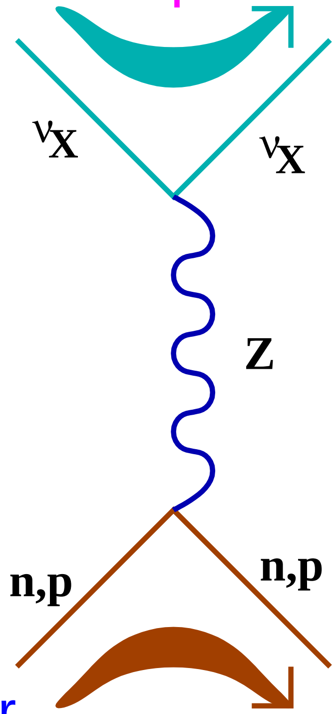

Hence the Standard Solar Model is vindicated in the NC sector.

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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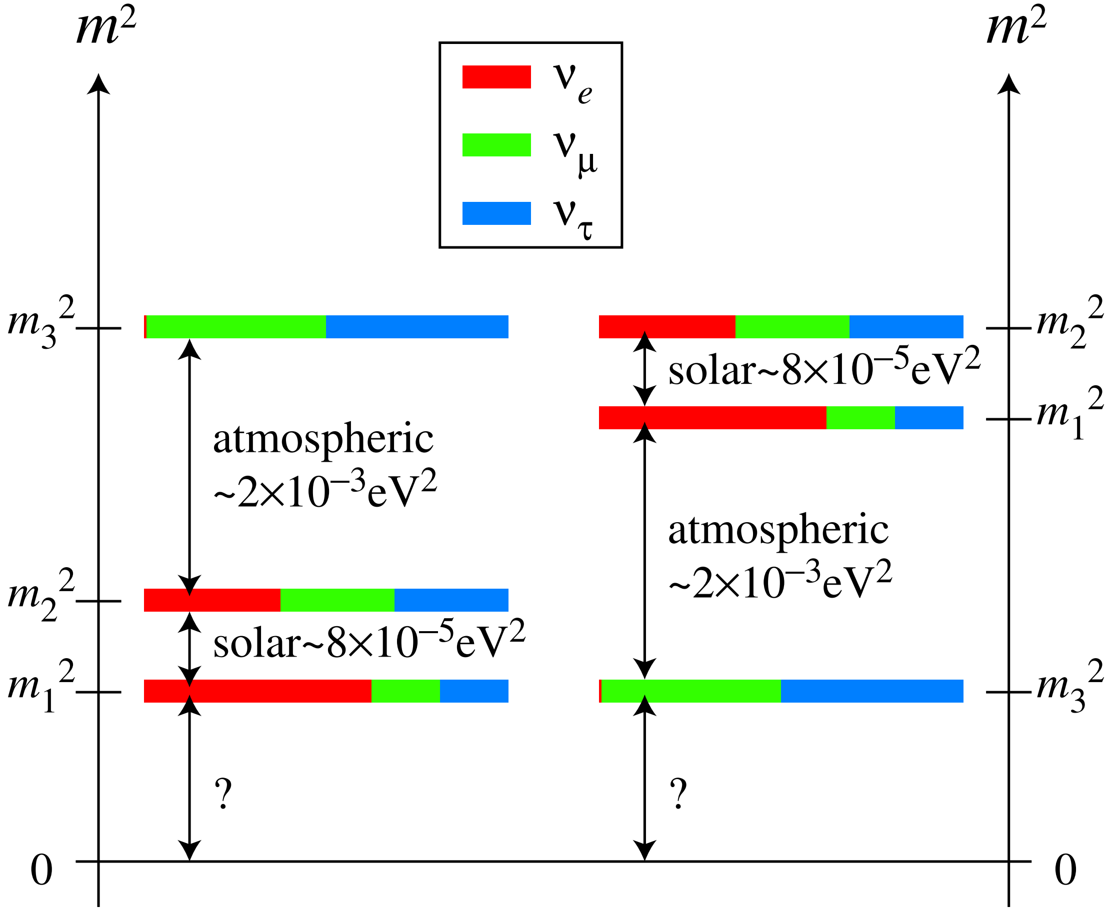

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$\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
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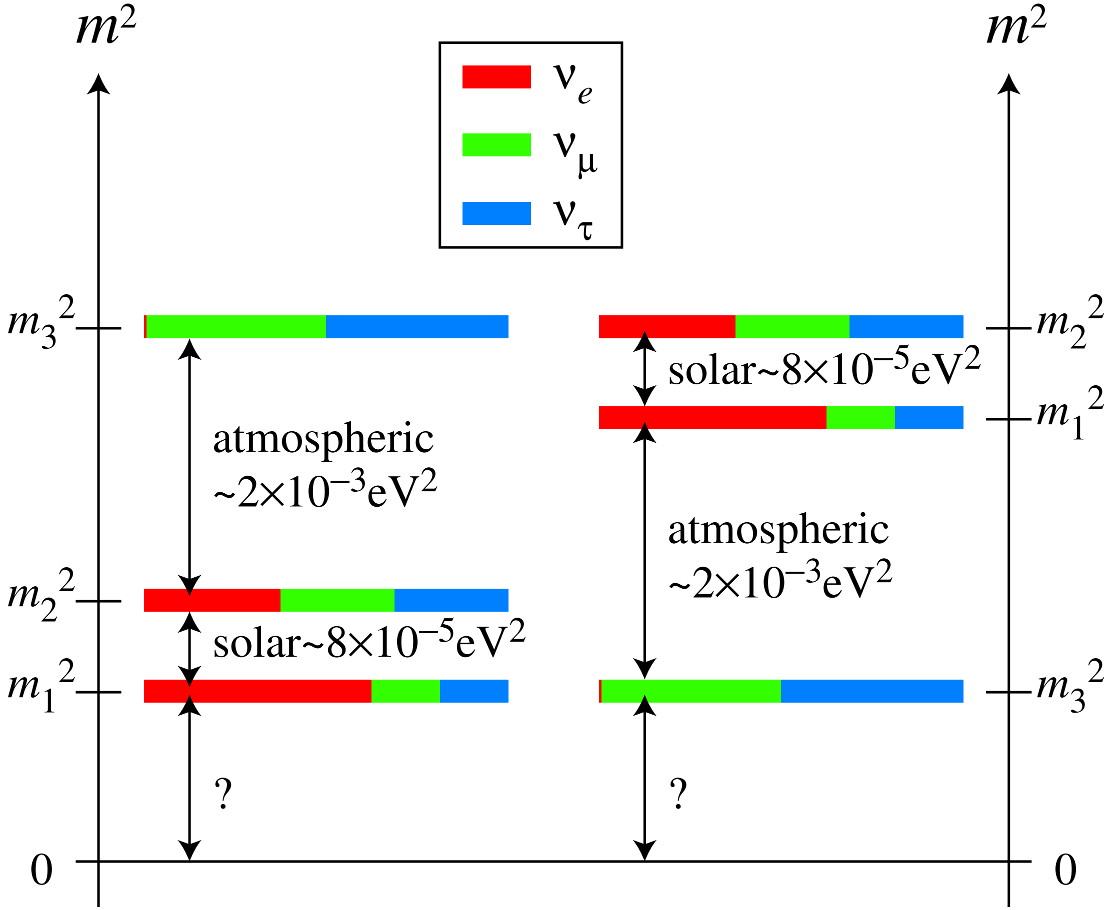

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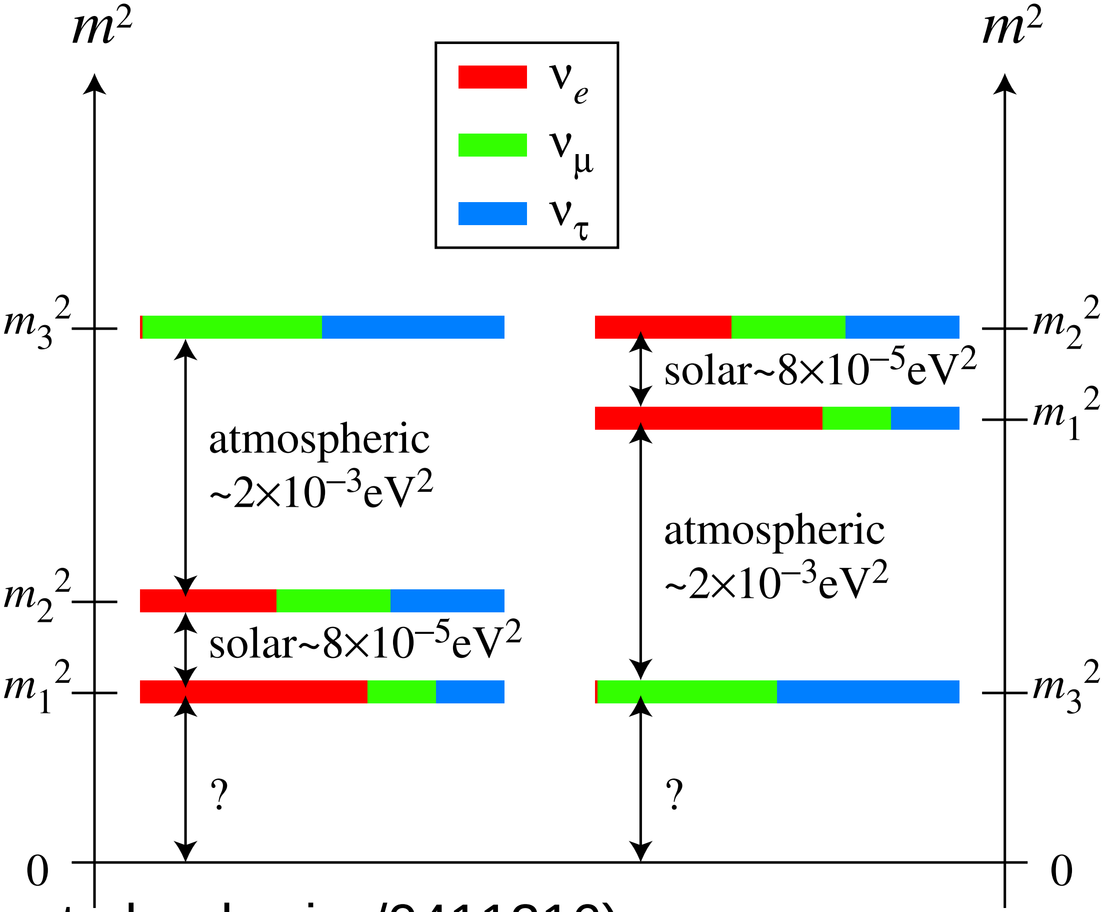
- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV (Degenerate hierarchy)
- $m_1 < m_2 \ll m_3$ (Normal hierarchy)
- $m_3 \ll m_1 < m_2$ Inverted hierarchy)



(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
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- Other detectors/physics like neutrinoless double beta decay?

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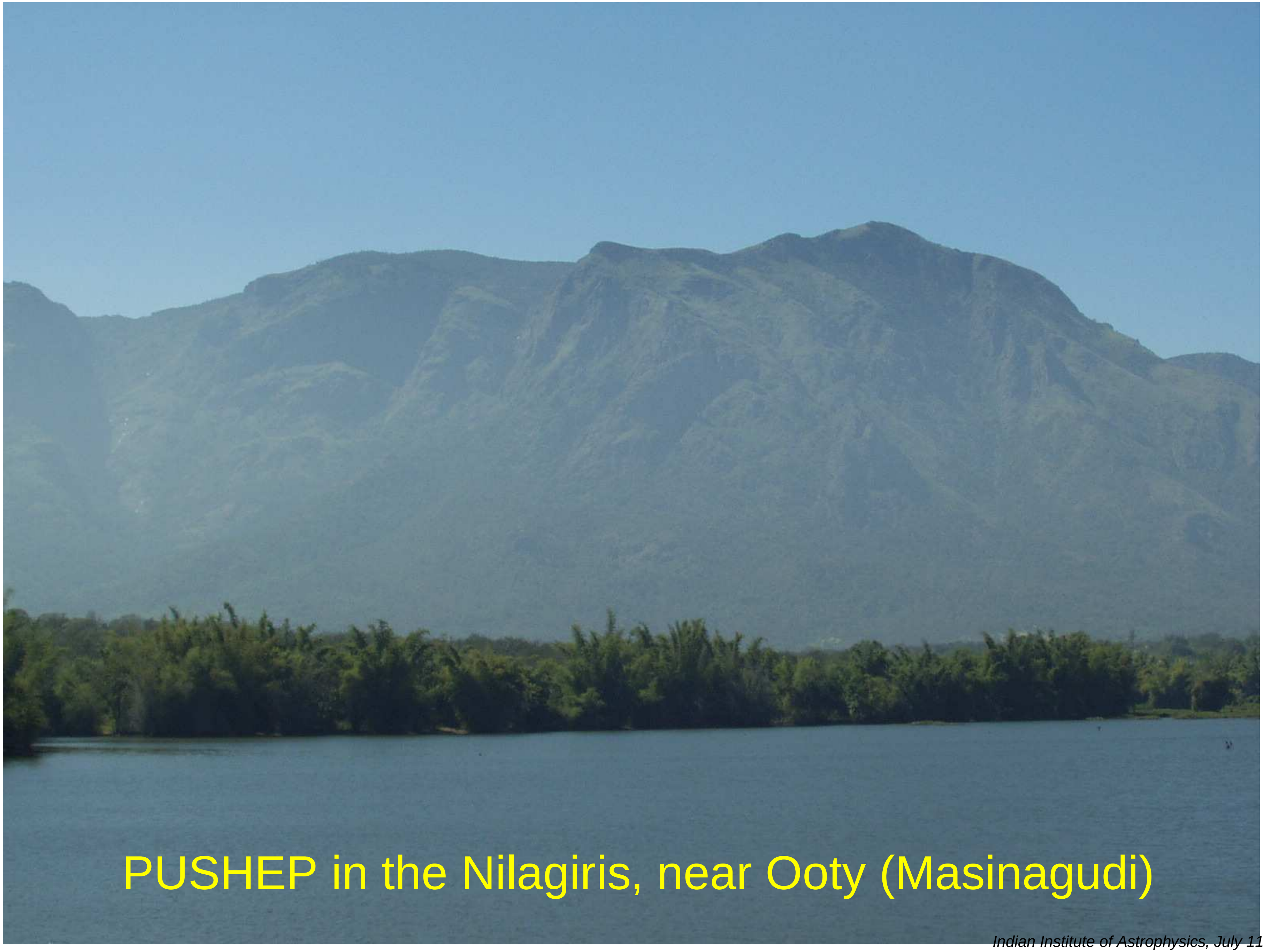
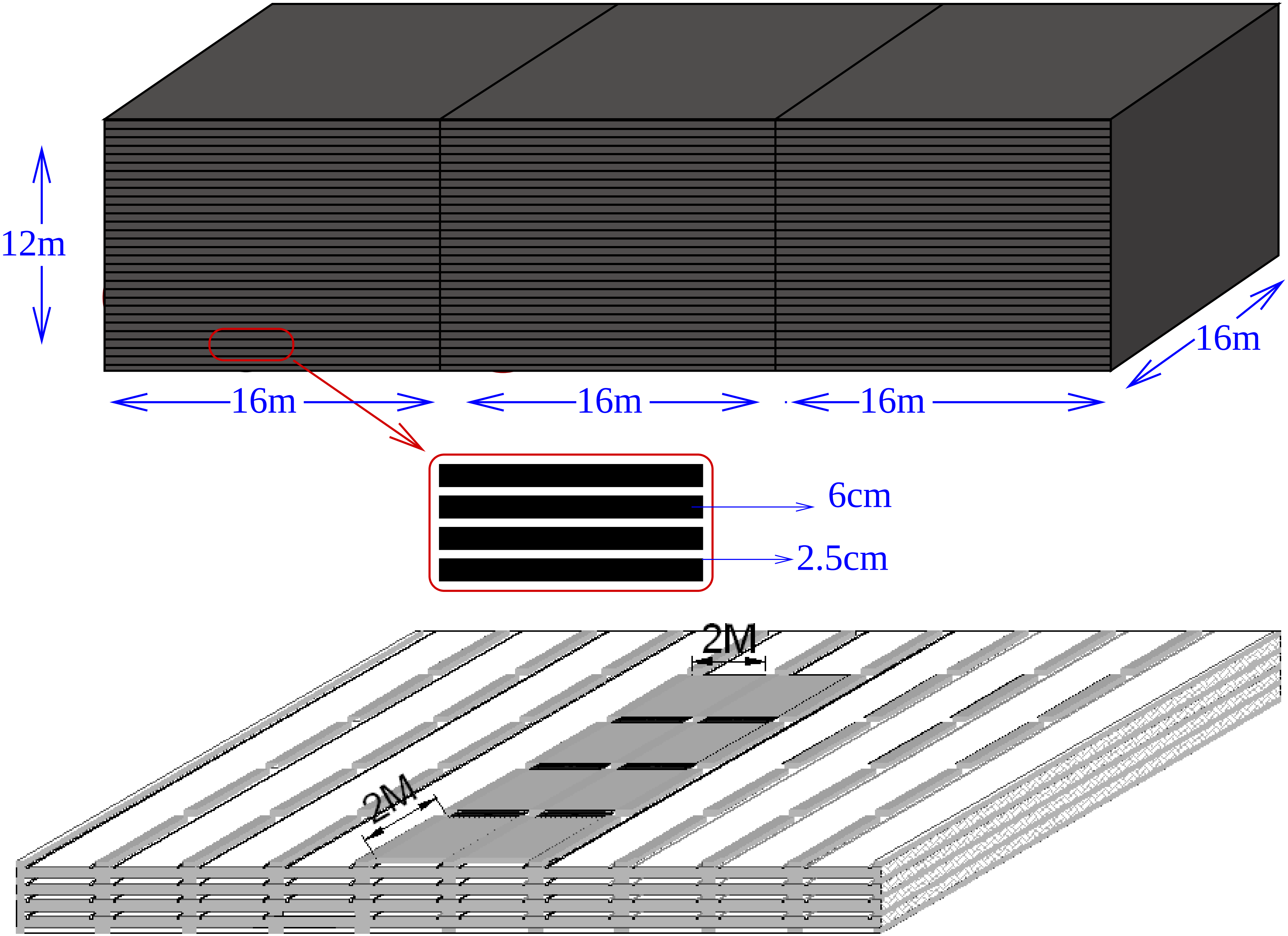
- Should be an international facility

Site survey: PUSHEP



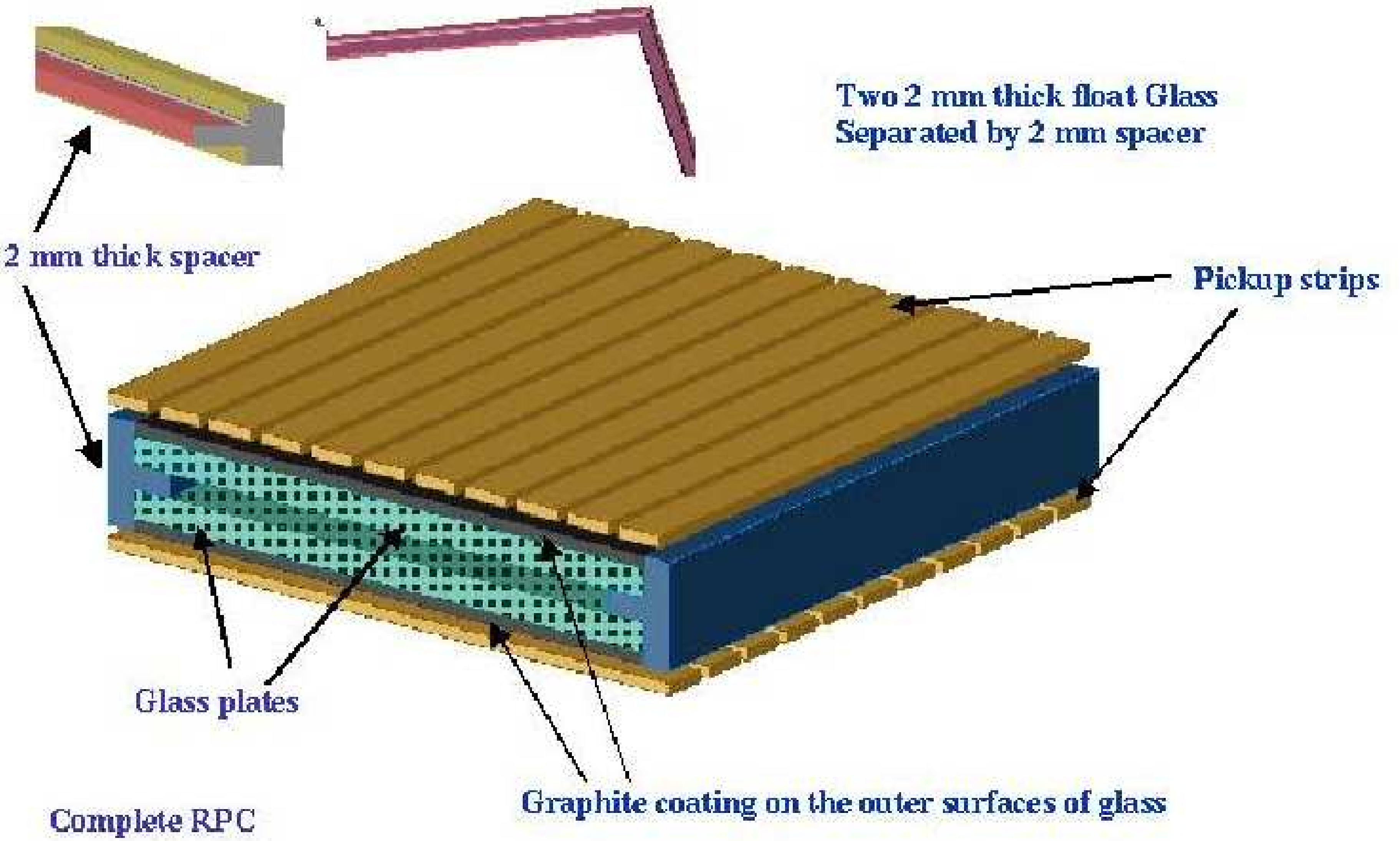
PUSHEP in the Nilagiris, near Ooty (Masinagudi)

The ICAL detector



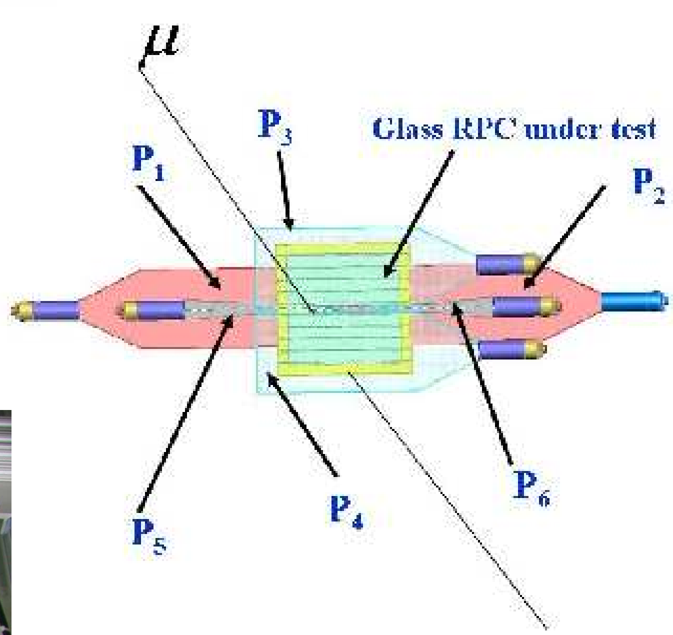
The active detector elements: RPC

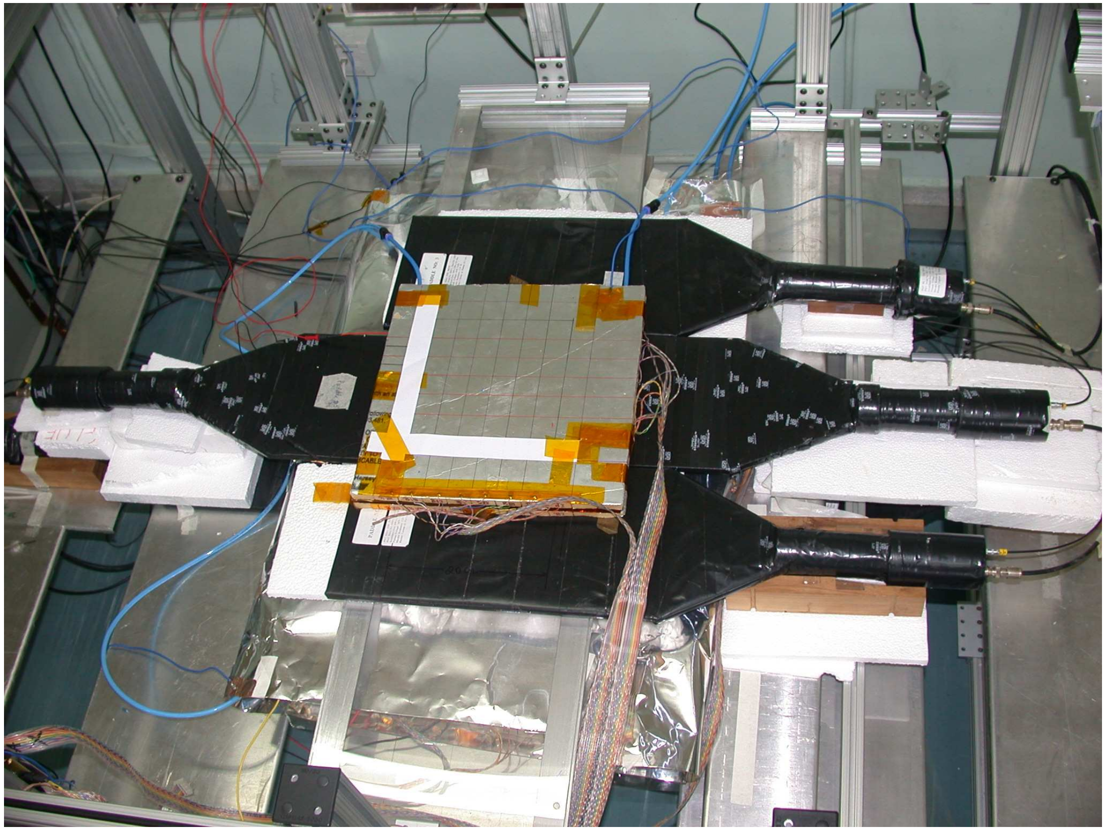
RPC Construction: Float glass, graphite, and spacers



Fabricating and testing RPCs

at TIFR . . .





And of course . . .

Specifications of the ICAL detector

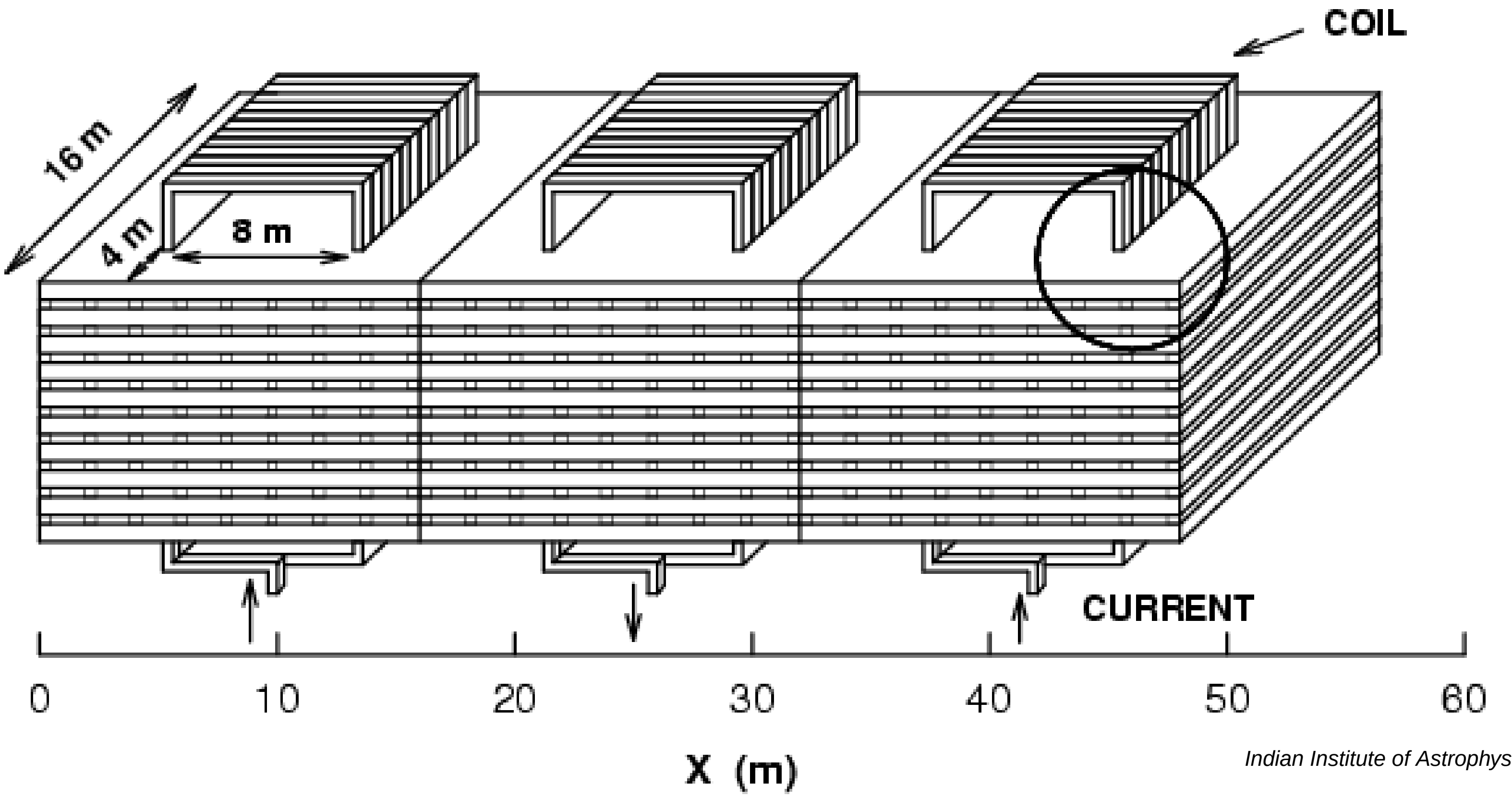
ICAL	
No. of modules	3
Module dimension	16 m × 16 m × 12 m
Detector dimension	48 m × 16 m × 12 m
No. of layers	140
Iron plate thickness	$\sim$ 6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.3 Tesla
RPC	
RPC unit dimension	2 m × 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module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

Magnet studies

Design criteria:

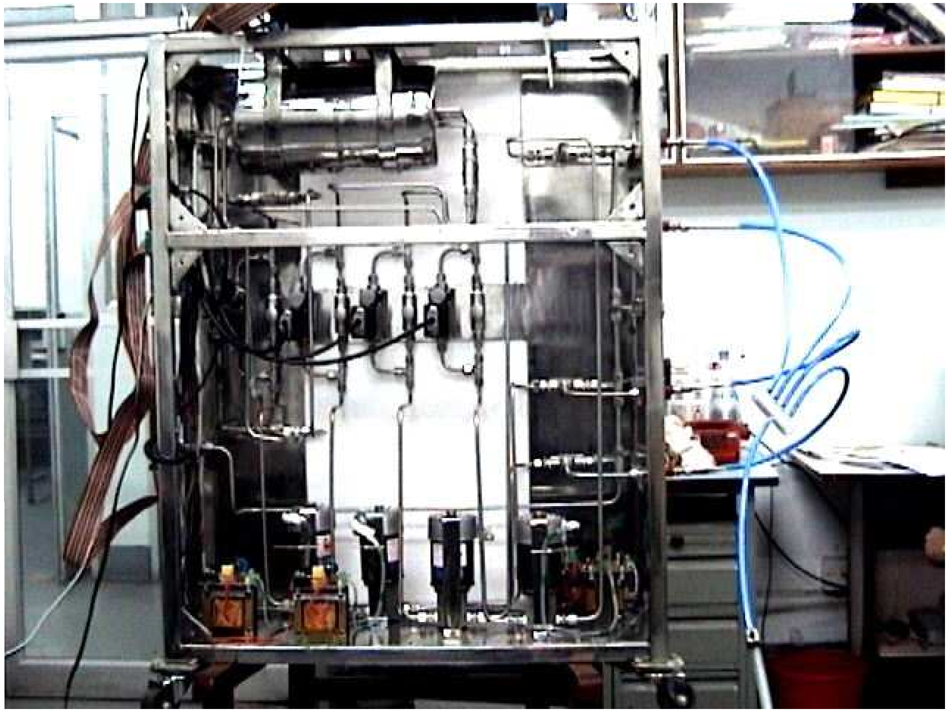
- Field uniformity
- Modularity
- Optimum copper-to-steel ratio
- Access for maintenance

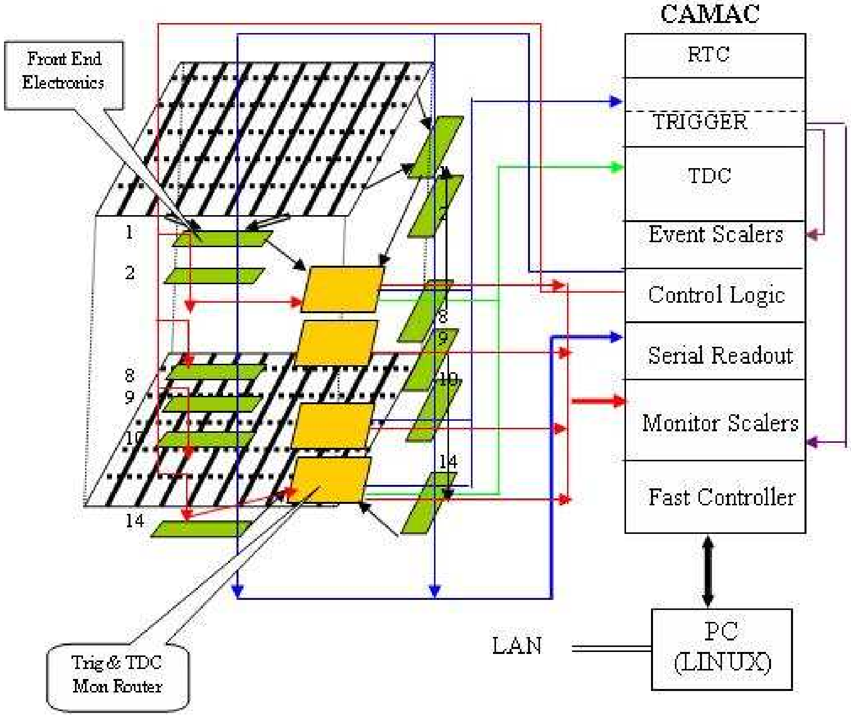
Toroidal Magnet design



For the prototype . . .

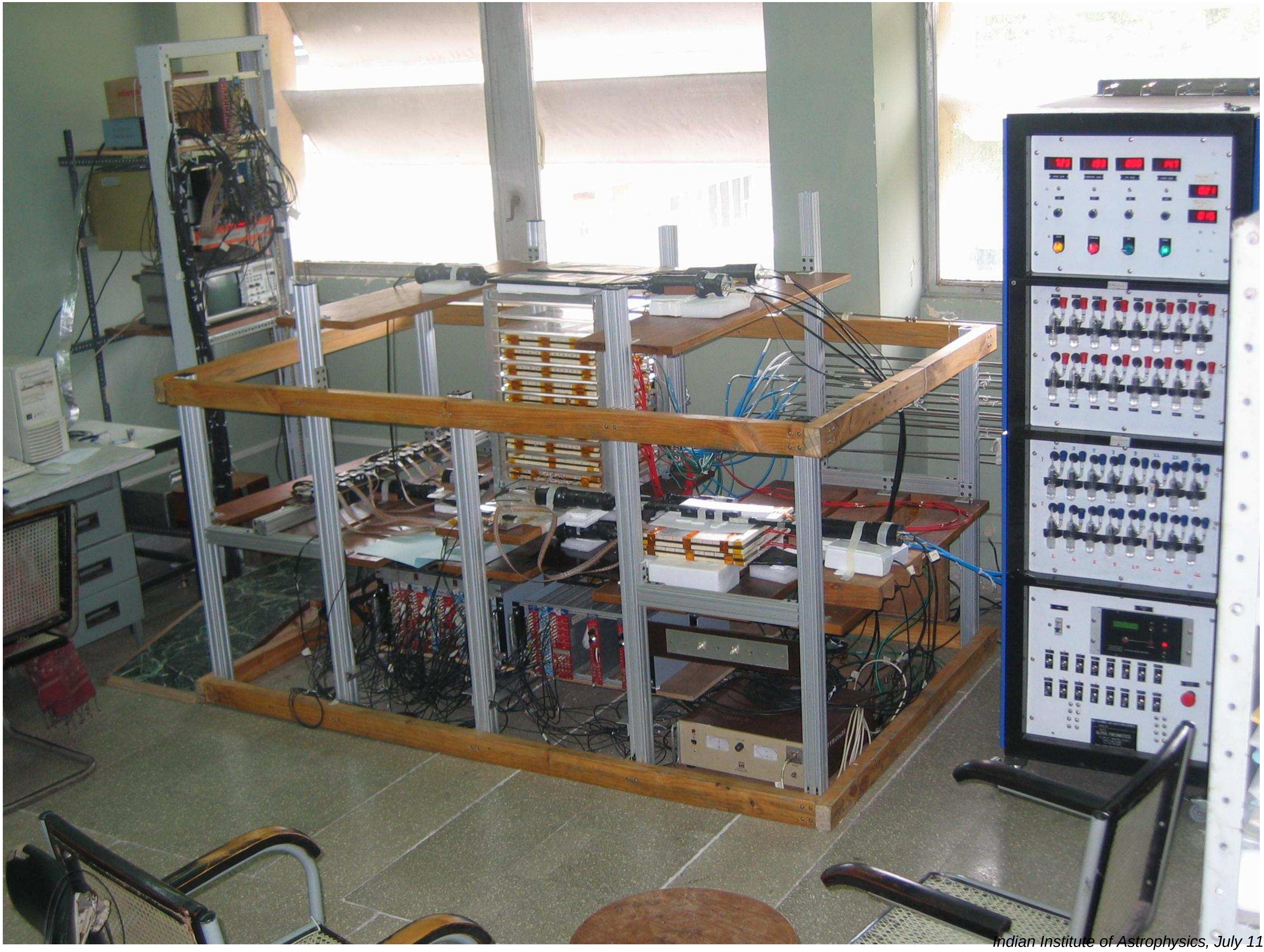
The gas-mixing unit at SINP

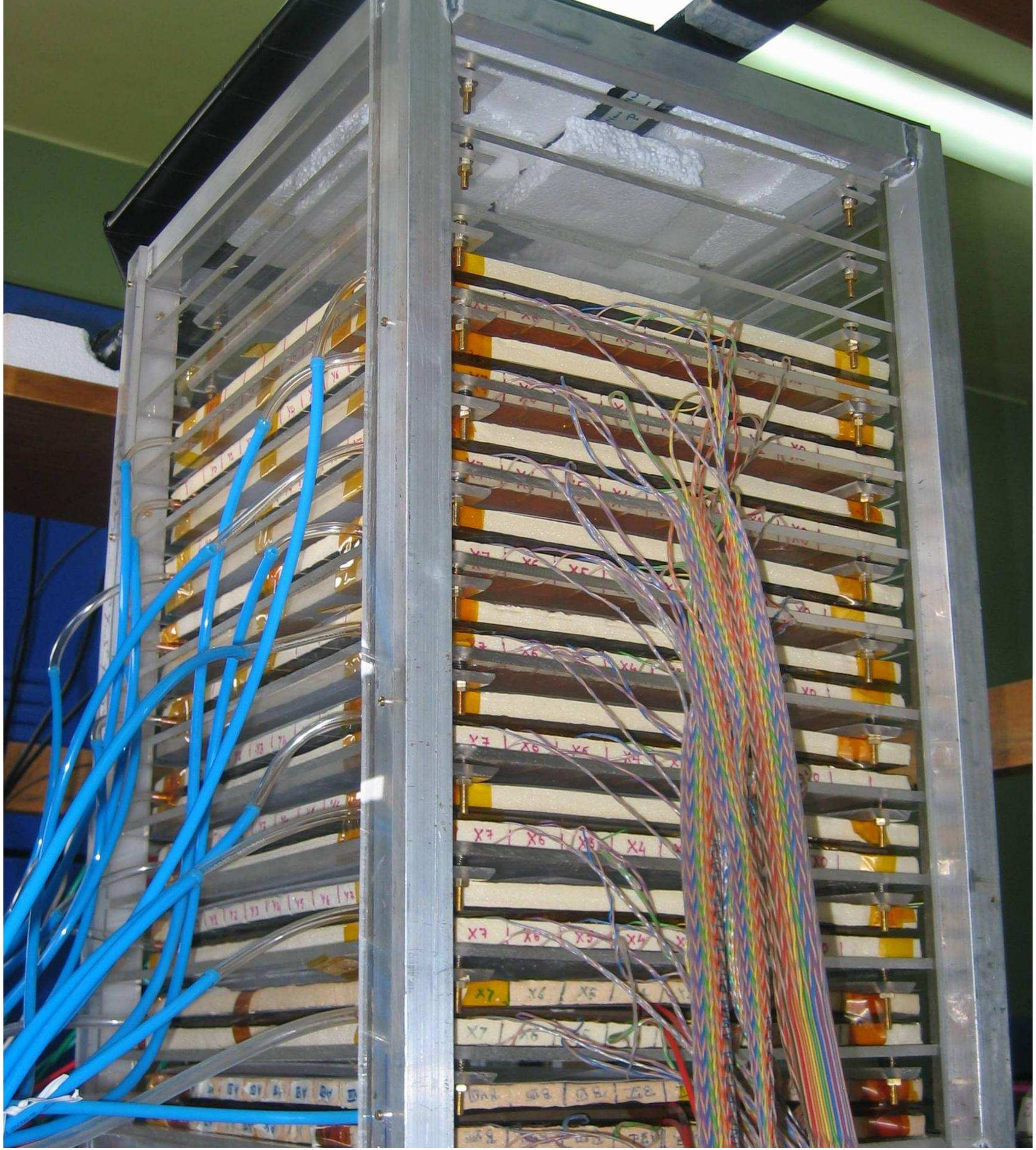




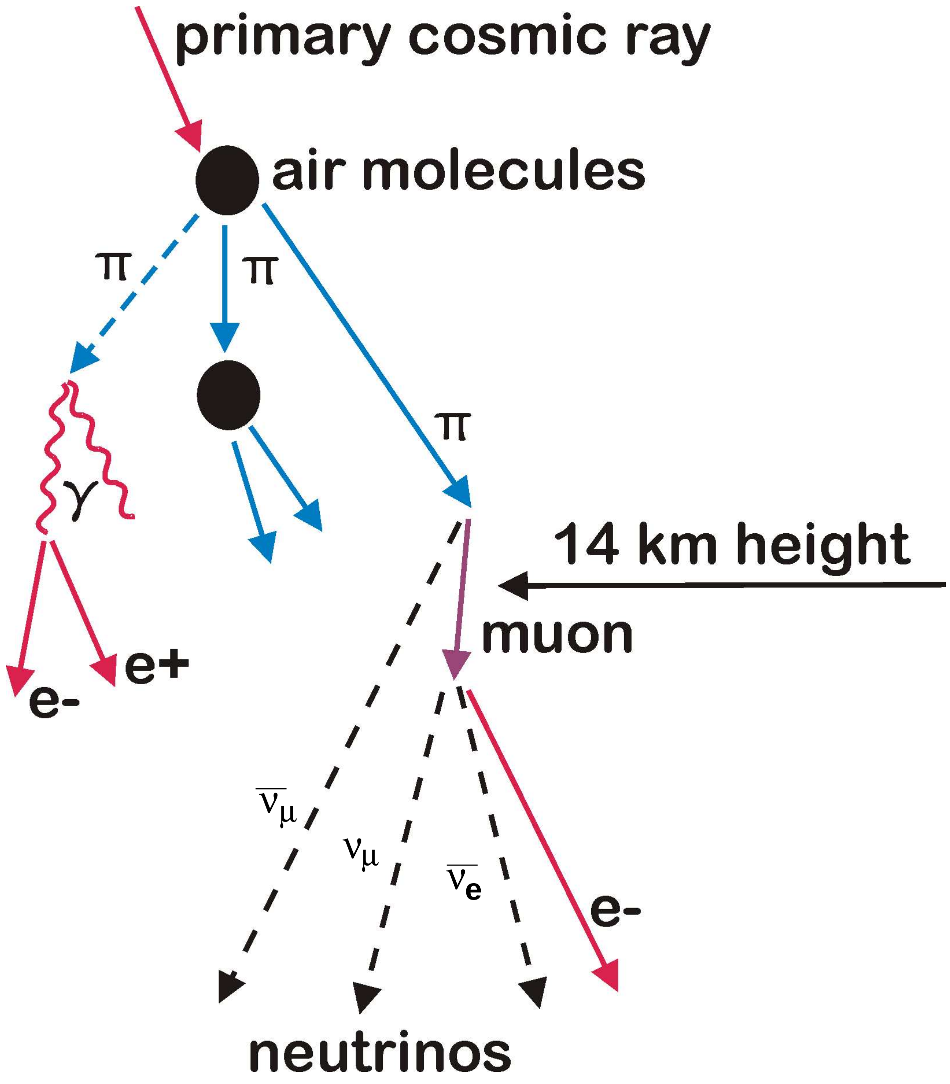
A schematic of the read-out electronics for the prototype

For the prototype, at TIFR . . .




X7 | X6 | X5 | X4
Y5 | Y4 | Y3 | Y2
X0

Physics with Atmospheric Neutrinos



The up-going muon neutrinos are found to be depleted in Super-K detector.

In ICAL, such a neutrino interacts (mostly with the iron) and produces a muon and (perhaps) some hadrons.

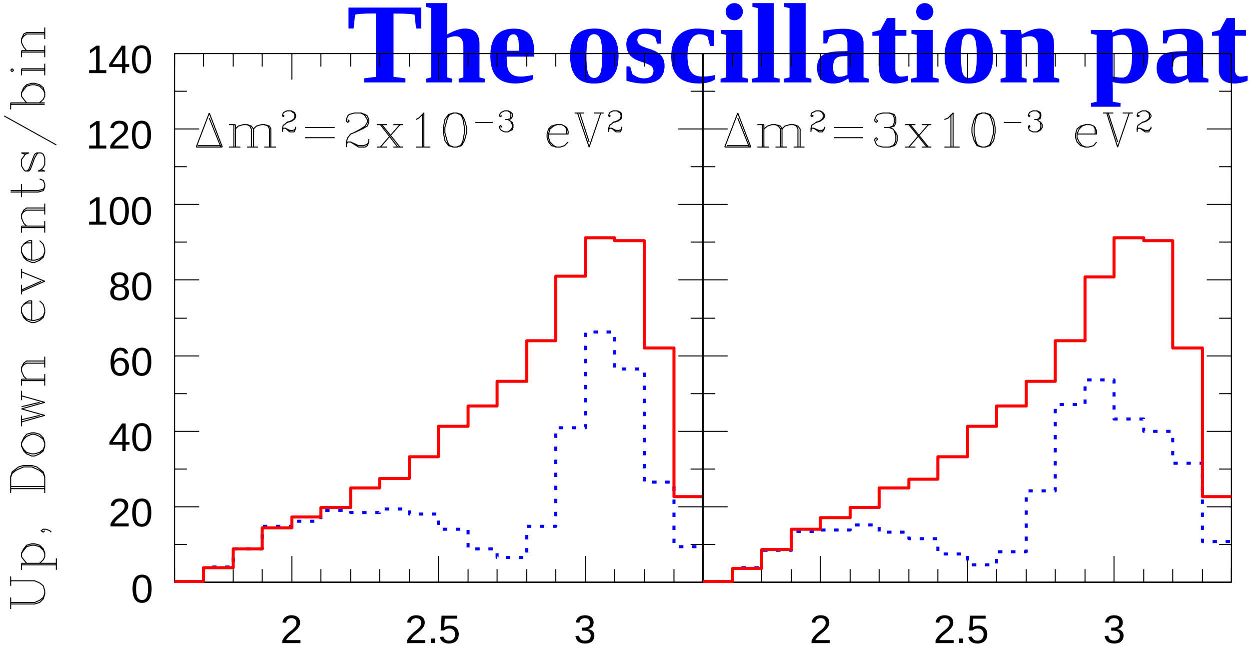
The muon *bends* in the magnetic field and leaves a curved (helical) track in the detector.

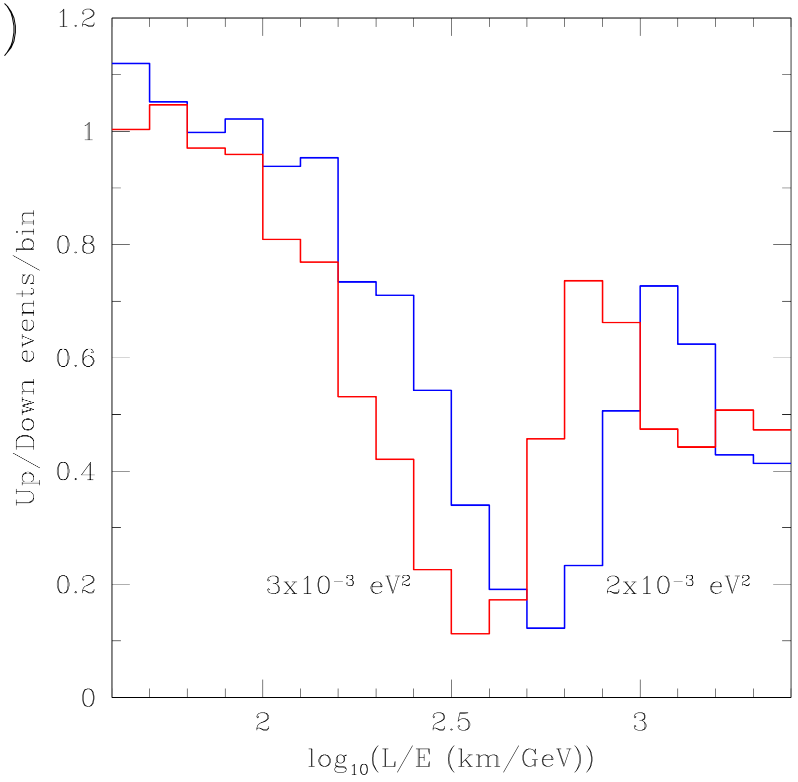
These can be simulated and analysed for sensitivity to neutrino parameters (energy and path length).

➢ Main goal: Study oscillation pattern in atmospheric neutrino events.

The up/down events ratio is sensitive to oscillation parameters.

The oscillation pattern





Physics possibilities

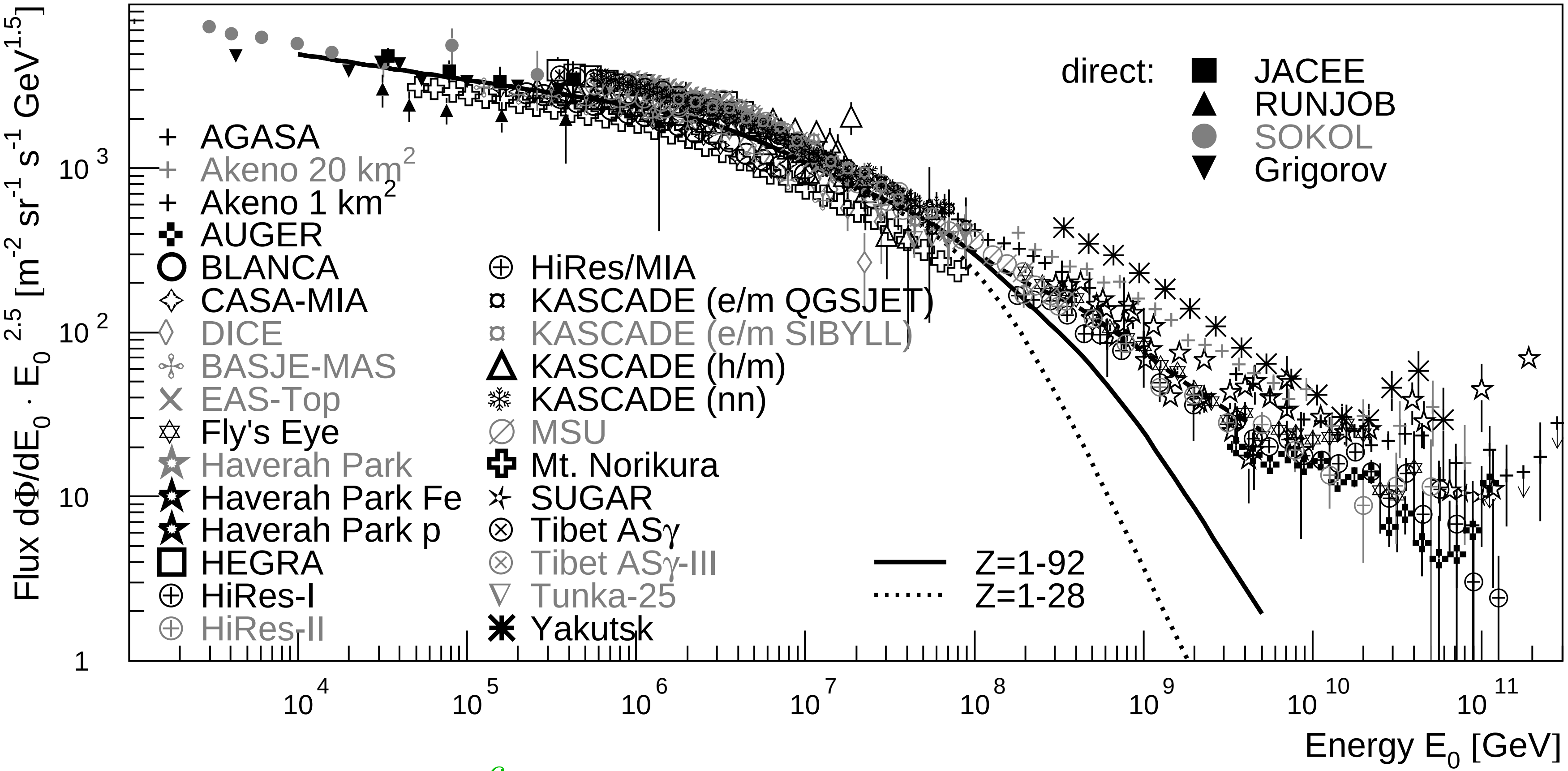
. . . WITH ATMOSPHERIC NEUTRINOS

- 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

High Energy Muons (J.R. Hoerandel, Aspen, astro-ph/0508014).



The knee is at few $\times 10^6$ GeV; physical origin is not fully understood.

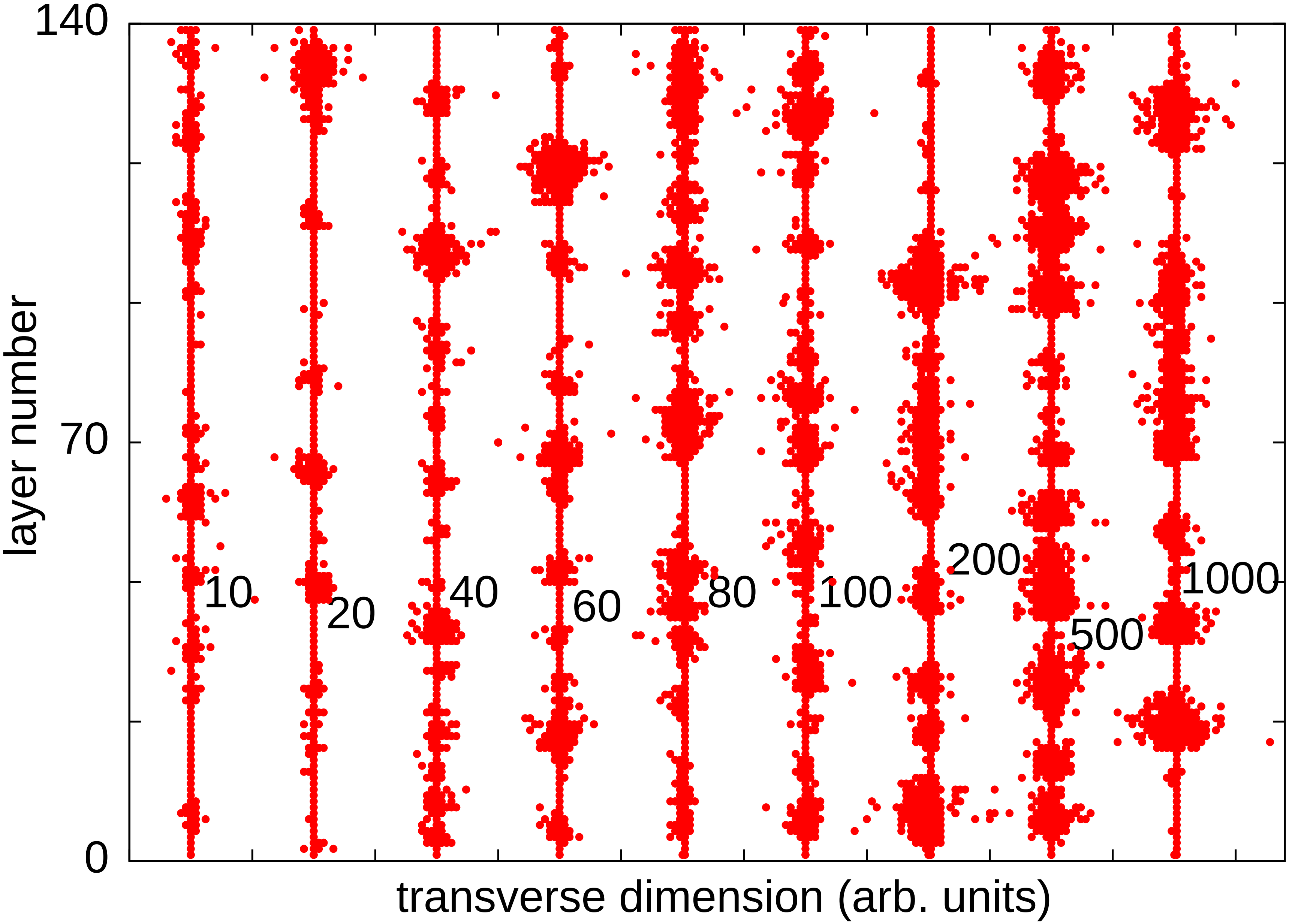
There may be new competing astrophysical processes.

Phenomenological models very uncertain.

Major background to UHE neutrinos from AGN, GRB, etc. (Icecube).

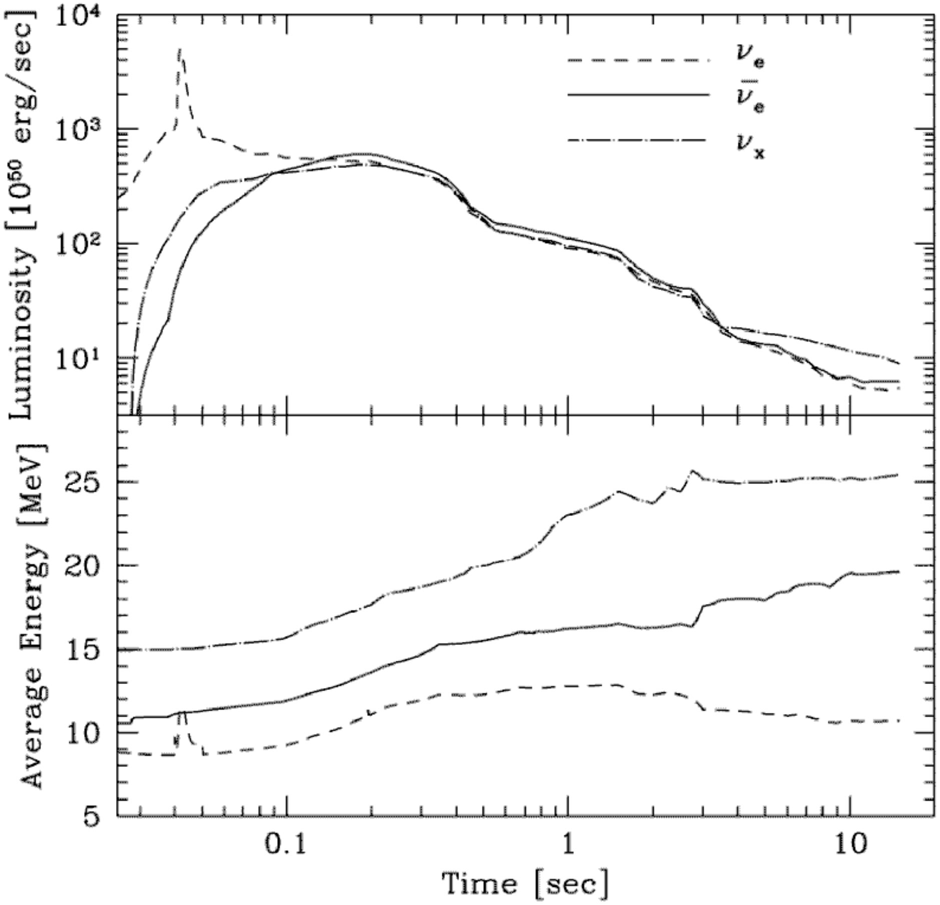
ICAL will complement balloon/air-shower experiments (KASCADE).

ICAL as a pair-meter



Muons with TeVs of energy radiate e^+-e^- pairs which cascade.

An aside I: supernova neutrinos



(A) (Takahashi et al., PRD 64 2001): The luminosities are similar; the average energies are very different.

(B) (Raffelt et al., Astrophys J. 590 2003): The average energies are the same but the luminosities differ.

In either case, these is great sensitivity to neutrino oscillation. Choubey et al., Dutta et al.

Conversely, if the neutrino oscillation parameters are known, information may be got on the shock wave.

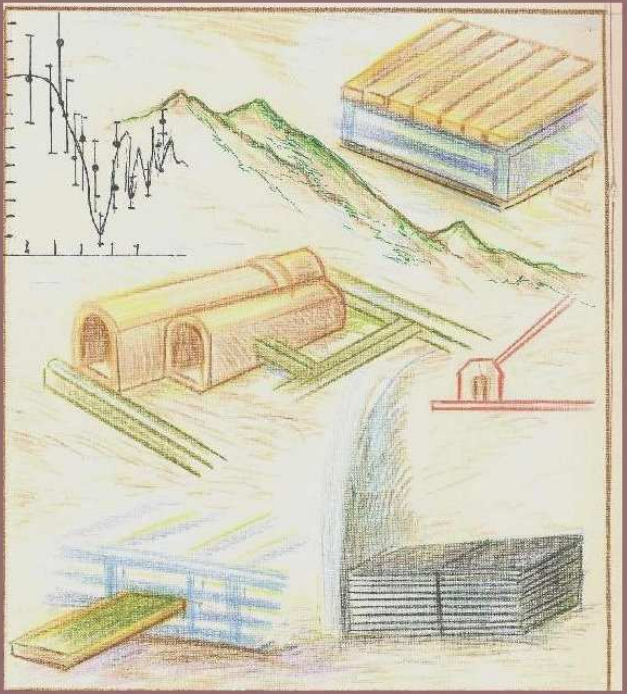
An aside II: more on neutrino properties

- It is still not known whether neutrinos are Majorana or Dirac.
- Can be tested in neutrino-less double beta decay. Prelim. proposal at INO.

  If Majorana, can build see-saw models to explain smallness of neutrino mass.
- Another issue: matter–anti-matter asymmetry in the Universe $\Longrightarrow$ baryogenesis.
- Necessary: $\not{B}$,$\not{C}P$, non-equilibrium at early times.
- $\Delta(B - L) = 0 \Longrightarrow$ baryogenesis via leptogenesis.

INO/2006/01
Project Report
Volume I

INDIA-BASED NEUTRINO OBSERVATORY



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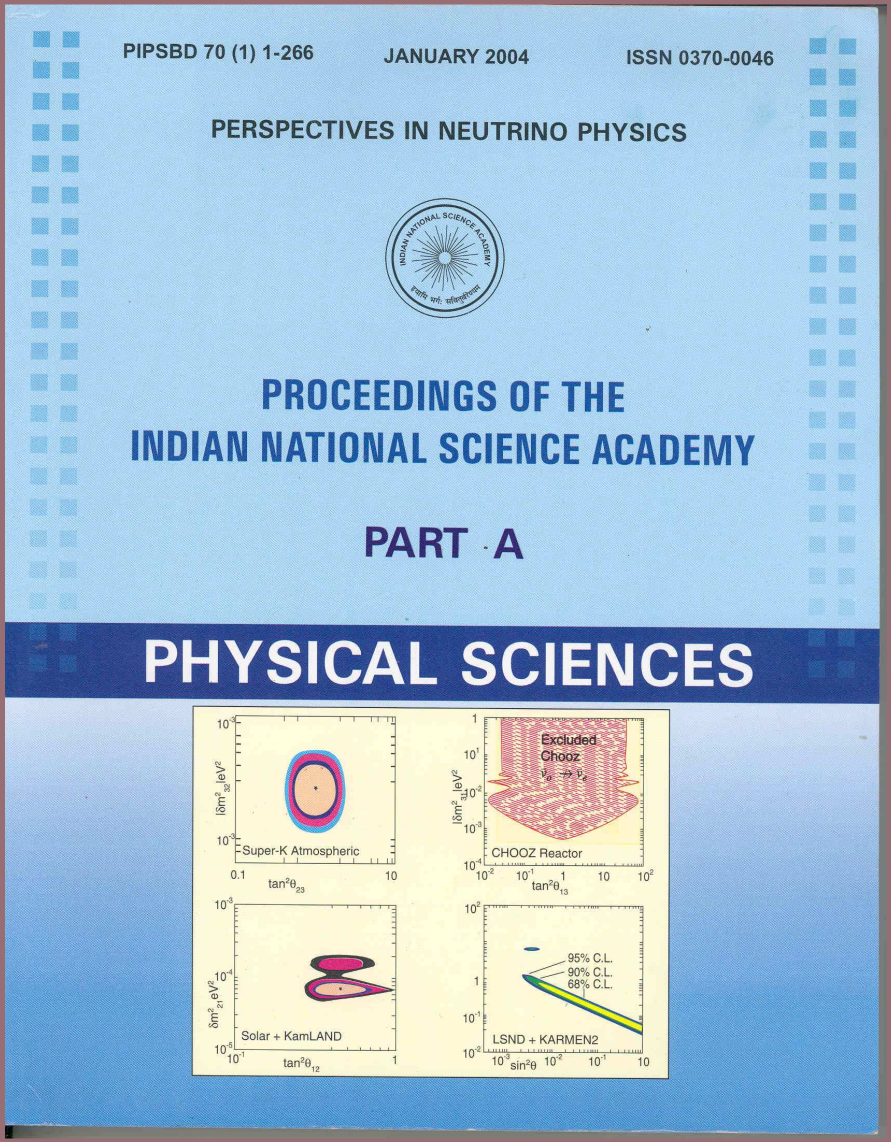

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PERSPECTIVES IN NEUTRINO PHYSICS

PROCEEDINGS OF THE
INDIAN NATIONAL SCIENCE ACADEMY

PART A

PHYSICAL SCIENCES

Interim Report, May 25th, 2006

In short . . .

The outlook looks good! This is a massive project:

Looking for active collaboration both within India and abroad

The INO Collaboration[1]

- **Aligarh Muslim University (AMU), Aligarh:**
  M. Sajjad Athar, Rashid Hasan, S. K. Singh
- **Benares Hindu University (BHU), Varanasi:**
  B.K. Singh, C.P. Singh, V. 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 (since retired), L. M. Pant, K. Srinivas
- **Calcutta University (CU), Kolkata:**
  Amitava Raychaudhuri (presently at HRI, Allahabad)
- **Delhi University (DU), Delhi:**
  Brajesh Choudhary, Debajyoti Choudhury, Sukanta Dutta, Ashok Goyal, Kirti Ranjan
- **Harish Chandra Research Institute (HRI), Allahabad:**
  Sanjib K. Agarwalla, Sandhya Choubey, Anindya Datta, Raj Gandhi, Pomita Ghoshal, Srubabati Goswami, Poonam Mehta, Sukanta Panda, S. Rakshit, Amitava Raychaudhuri
- **University of Hawaii (UHW), Hawaii:**
  Sandip Pakvasa
- **Himachal Pradesh University (HPU), Shimla:**
  S. D. Sharma
- **Indian Institute of Technology, Bombay (IITB), Mumbai:**
  Basanta Nandi, S. Uma Sankar, Raghav Varma
- **Indira Gandhi Centre for Atomic Research, Kalpakkam**:
  J. Jayapandian, C.S. Sundar
- **The Institute of Mathematical Sciences (IMSc), Chennai:**
  D. Indumathi, H. S. Mani, M. V. N. Murthy, G. Rajasekaran, D. V. Ramakrishna, Nita Sinha, Abdul Salam (Till March, 2005)
- **Institute of Physics (IOP), Bhubaneswar:**
  Pankaj Agrawal, 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
- **Saha Institute of Nuclear Physics (SINP), Kolkata:**
  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 (SMI), 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, G.K. Padmashree, Biswajit Paul, Shobha K. Rao, A. K. Ray, L. V. Reddy, B. Satyanarayana, S. Upadhya, Piyush Verma
- **Variable Energy Cyclotron Centre (VECC), Kolkata:**
  R. K. Bhandari, Subhasish Chattopadhyay, Premomay Ghosh, B. Mohanty, G. S. N. Murthy, Tapan Nayak, S. K. Pal, P. R. Sarma, R. N. Singaraju, Y. P. Viyogi

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Amit Roy, *Nuclear Science Centre, New Delhi*
Probir Roy, *Tata Institute of Fundamental Research, Mumbai*
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[1] This is an open collaboration and experimentalists are especially encouraged to join.