Big World of small Neutrinos
An introduction to INO

M.V.N. Murthy

Institute of Mathematical Sciences, Chennai

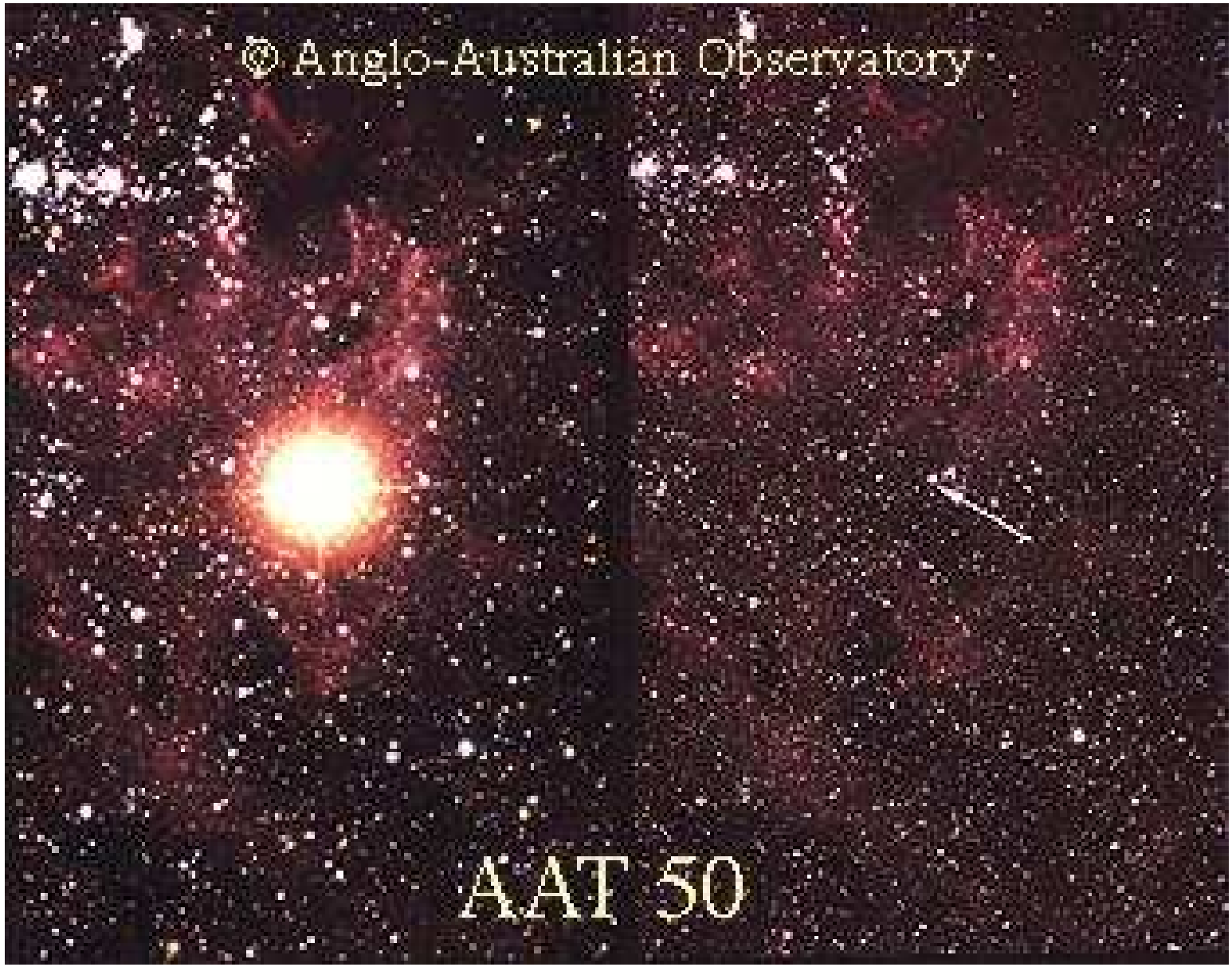
(murthy@imsc.res.in)

INO Collaboration

A Poster from Fermi Lab

- Sources- Natural and Laboratory.
- Introduction and Overview
- Observations and Anomalies.
- Possible Solutions - Neutrino oscillations.
- New generation of precision experiments-
- India-based Neutrino Observatory

Neutrinos are everywhere

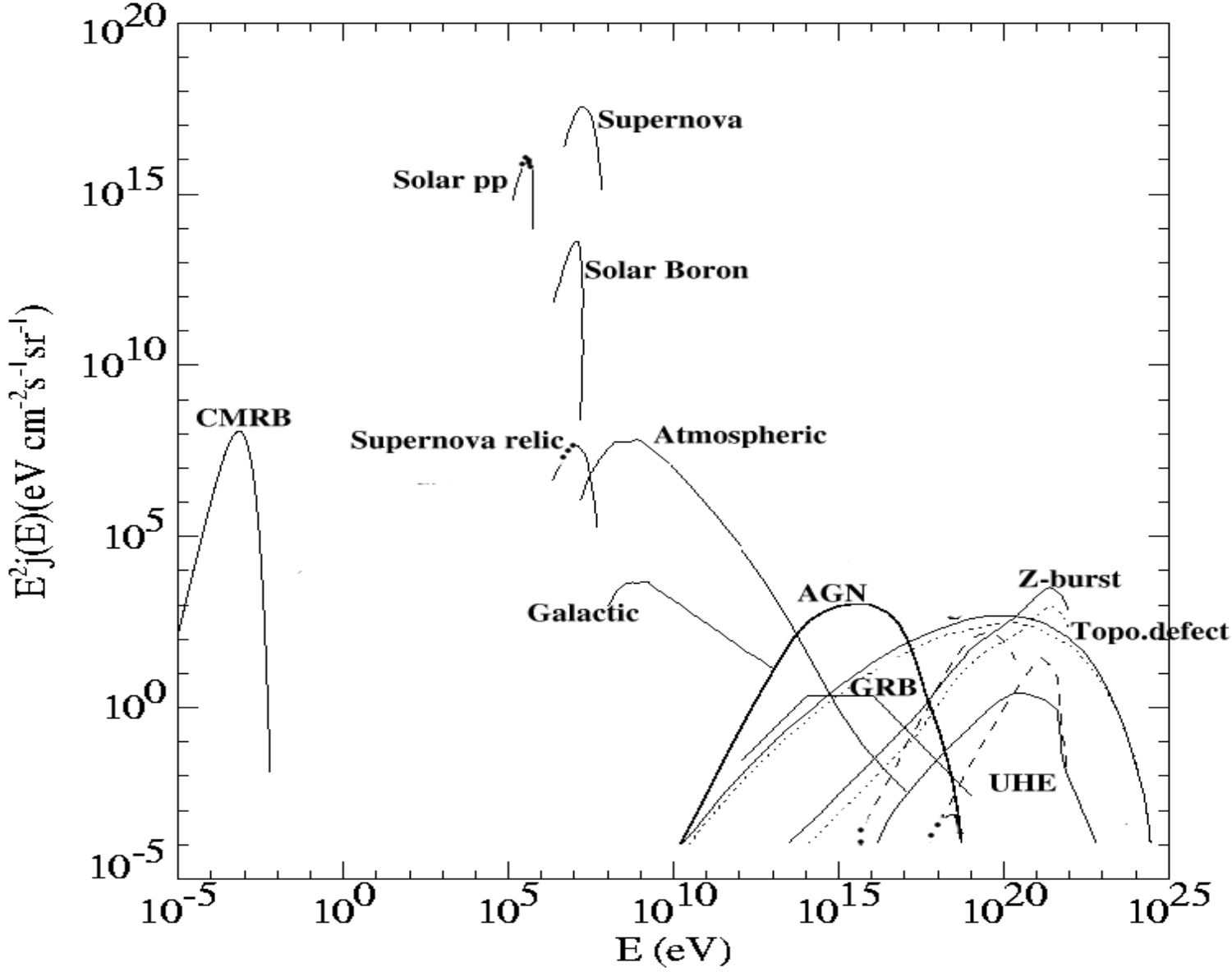


Sources of Neutrinos

- From Big Bang– about 330 neutrinos per cm^3 (0.0004 eV).
- Sun and Stars– Earth receives more than 40 billion ν per sec. per cm^2 (< 20 MeV).
- Cosmic Ray interactions in Earth's atmosphere (MeV –GeV).
- Interior of the Earth–Geoneutrinos.
- Neutrinos from Reactors (MeV).
- Neutrinos from Accelerators (GeV).
- Neutrinos from muon storage rings (10's GeV)?
- Beta beams (100's MeV) ?

Our body contains about 20 mg of K^{40}, which is beta-active. As a consequence, we emit about 340 millions neutrinos per day without knowing that.

Spectrum of Naturally produced ν's



Discovery of the Neutrino

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

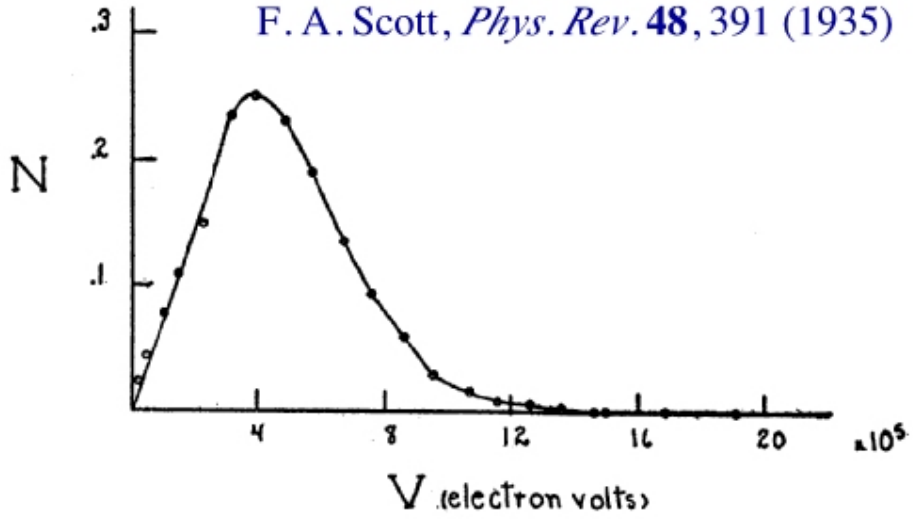


FIG. 5. Energy distribution curve of the beta-rays.

- Radio-active decays: α, β and γ
- Unlike α and γ decays, the emitted electron spectrum in β decay was continuous (1930, James Chadwick).
- Problem with energy conservation principle in Beta disintegration of the nucleus.

Desperate Remedy by Pauli

Pauli's letter of the 4th of December 1930

Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of...the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle ...The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

Your humble servant,
W. Pauli

The Neutrino Time Line

- **1930 Pauli proposes a neutral particle called** neutrino **later by Fermi** $H^3 \rightarrow He^3 + e^- + \bar{\nu}_e$
- **1956 Experimentally discovery** $\bar{\nu}_e + p \rightarrow e^+ + n$ **using neutrinos from fission reactor.**
- **1962 Muon neutrino discovered.**
- **1964 Atmospheric neutrinos observed at KGF.**
- **1967 Beginning of the Solar Neutrino Experiments (Ray Davis at Home Stake mines)**
- **1987 Observation of Neutrinos from SN1987A at Kamioka and IMB.**
- **1998 Evidence of neutrino mass– deficit of muon neutrinos from the atmosphere.** Super K**.**
- **2004 Evidence of Neutrino Oscillations– Confirmation of the Standard Solar Model by SNO.**

Some facts

- Matter is made up of atoms. Atoms have electrons with a central nucleus. The nucleus contains protons and neutrons (nucleons).
- There are four fundamental forces in nature: gravity, electro-magnetic, strong and weak.
- Electro-magnetic interaction between electrons and nuclei is responsible for the formation of atoms.
- Strong interactions between nucleons results in the formation of nuclei.
- Beta decay is caused by the weak interaction which some times renders nuclei unstable (beta-active).
- Gravity is ofcourse important on large scales though it may not important on the scale of atoms and nuclei.

The Standard Model of Particle Physics

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

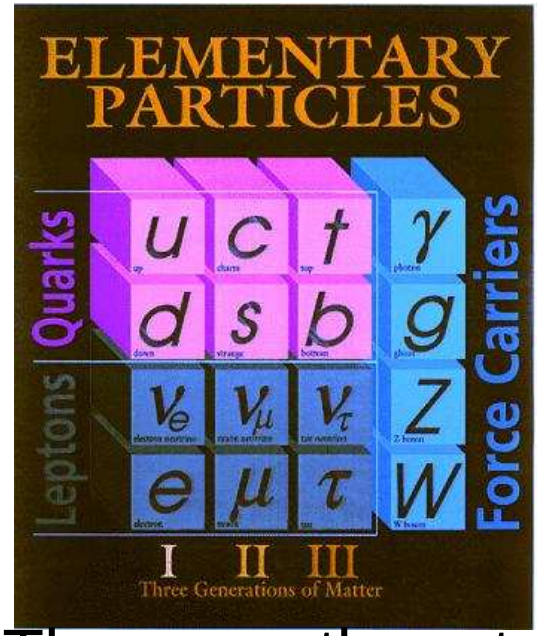
Leptons come in three *flavours* or *types* or *generations*:

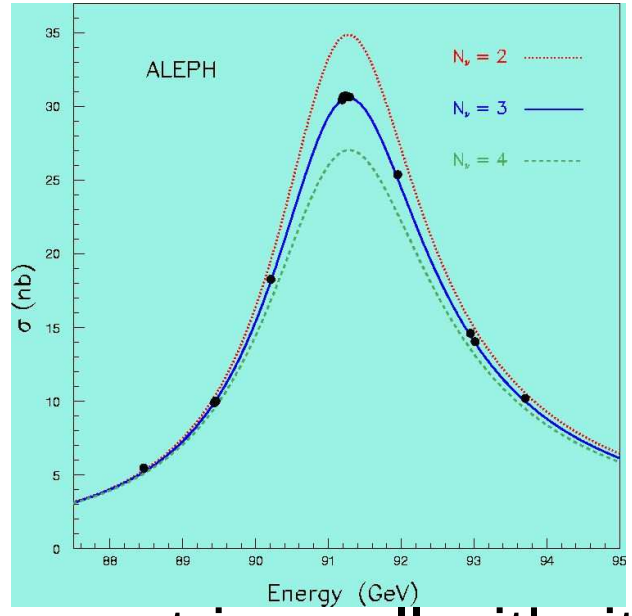
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

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.

Neutrinos in the Standard Model





- There are three types of active neutrinos all with it strictly zero mass in SM along with their anti-neutrinos.

  $\nu_L \quad \overrightarrow{CPT} \quad \bar{\nu}_R$

  Non-zero neutrino mass $\Rightarrow$ SM is incomplete

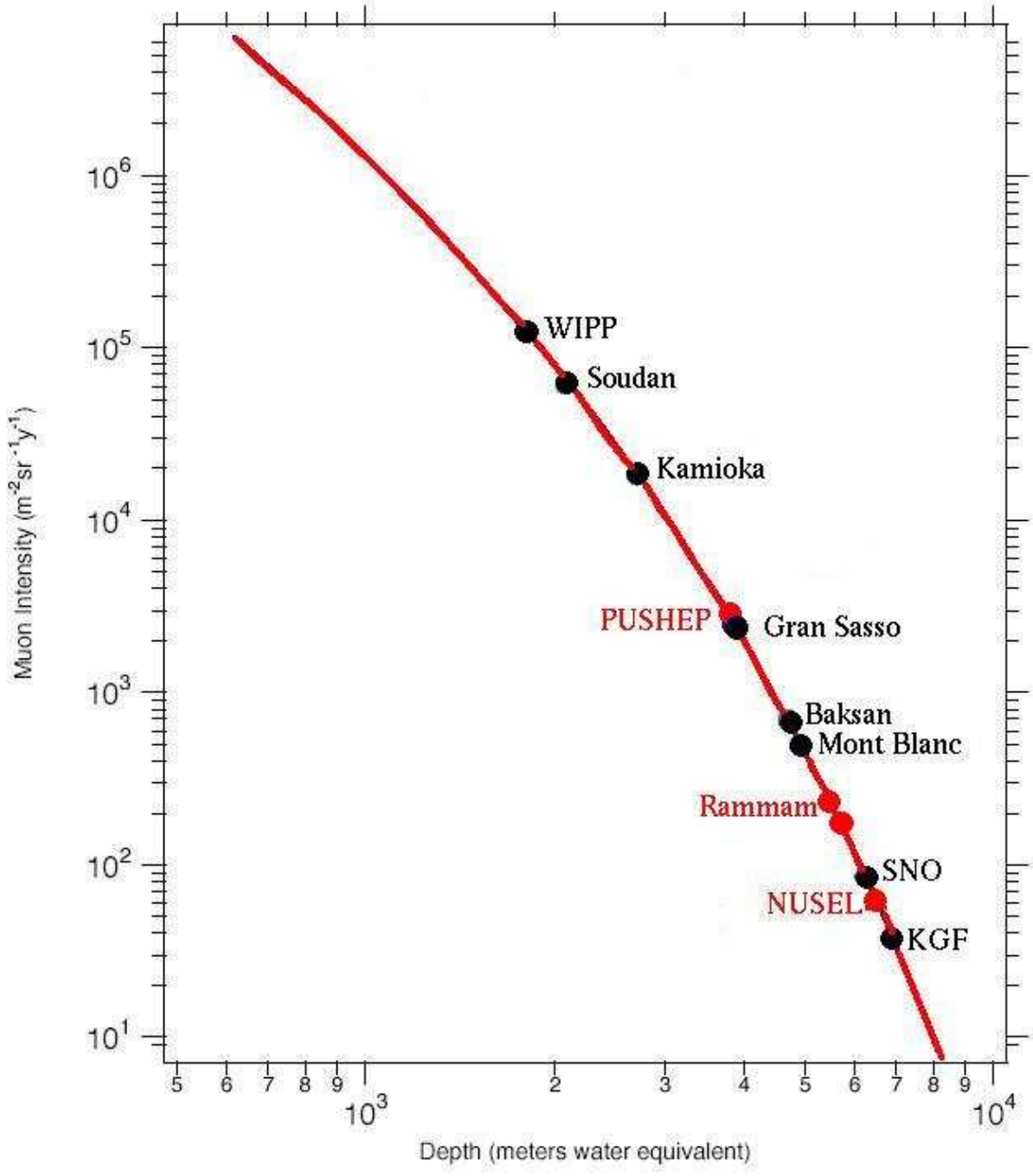
- Interaction strength is extremely weak.

  The detectors have to be huge to catch them.

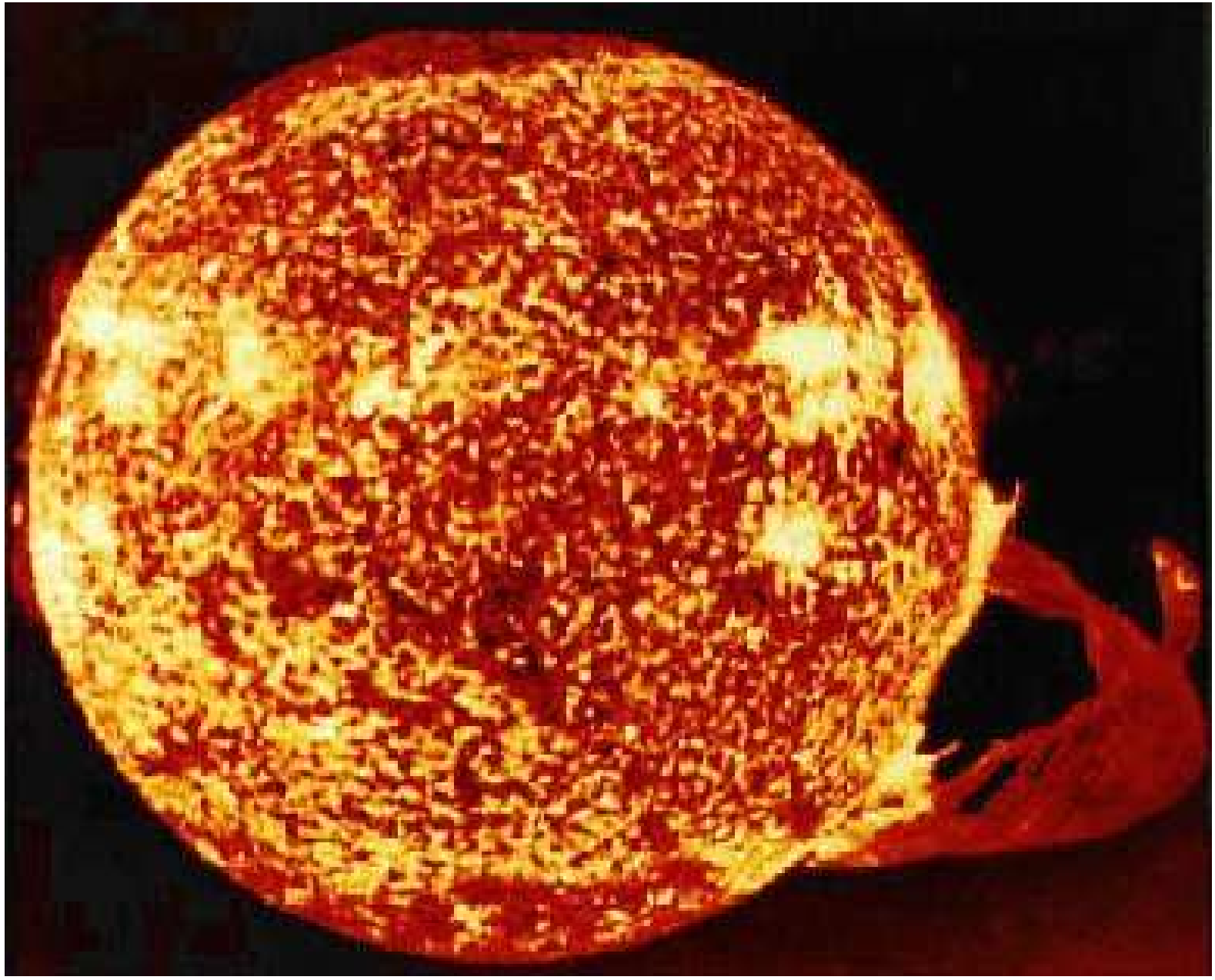
- Background can be enormous-

  Experiments located deep underground.

Underground Laboratories



How the Sun shines?



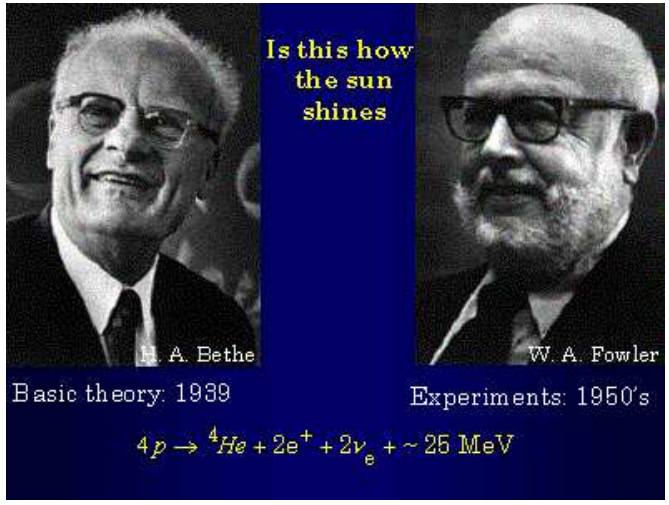
The solar neutrino problem

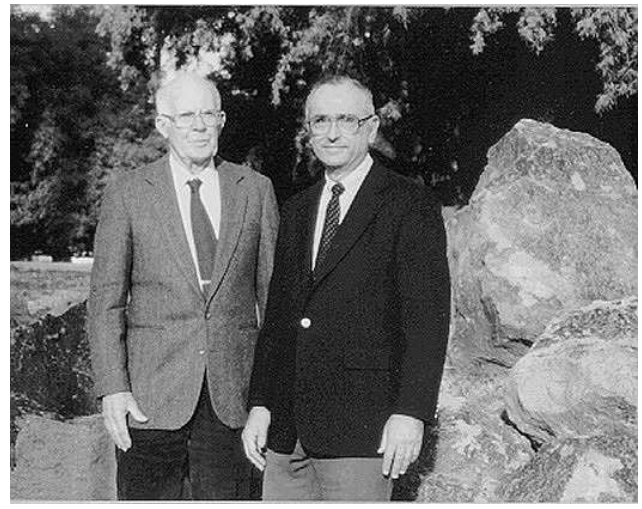
1938 Bethe - Energy produced by Sun (stars) is a result of nuclear fusion of H to He. Quasi-static equilibrium - thermal pressure gravitational contraction.

Sun $\Rightarrow$ The evolutionary sequence of a homogeneous star after 4.6×10^9 years.

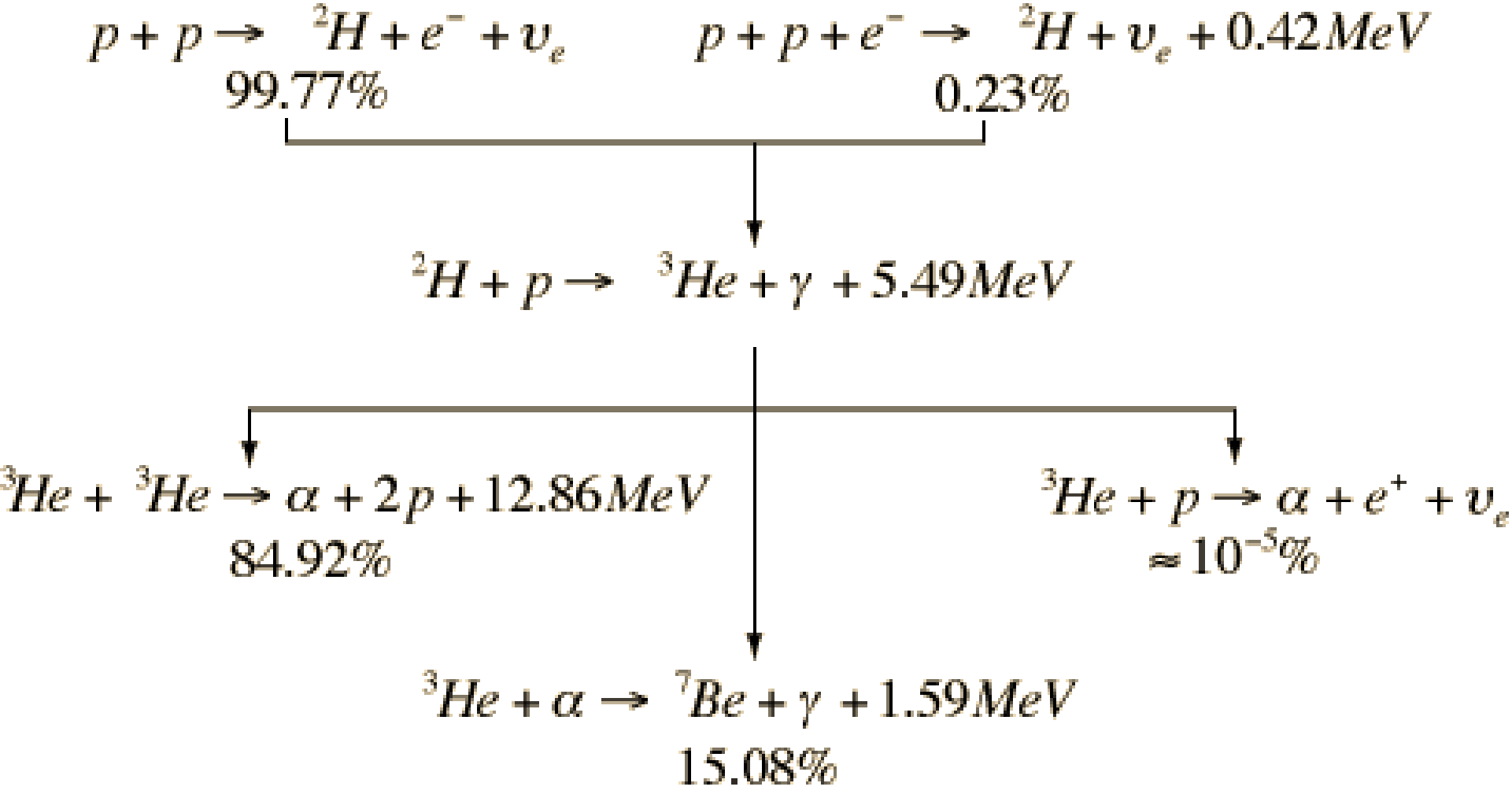
Neutrinos are products of these fusion reactions in the deep interior of the Sun. The main sequence of Hydrogen fusion in to Helium may be summarised as

$$4p \rightarrow He^4 + 2e^+ + 2\nu_e + 26.7MeV$$

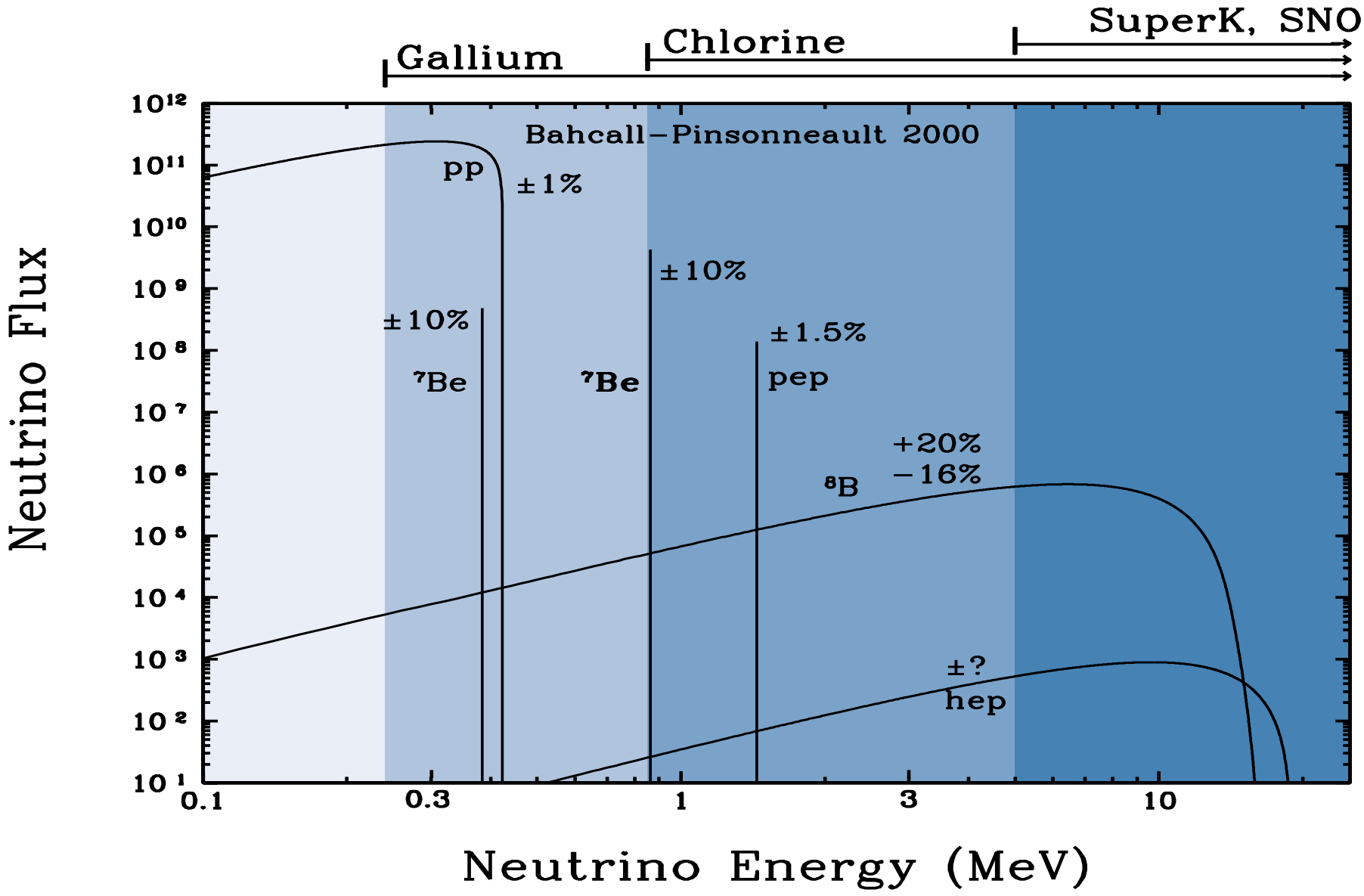




The p–p Chain


$p + p \rightarrow {}^2H + e^- + \upsilon_e$
99.77%
$p + p + e^- \rightarrow {}^2H + \upsilon_e + 0.42\,MeV$
0.23%
${}^2H + p \rightarrow {}^3He + \gamma + 5.49\,MeV$
${}^3He + {}^3He \rightarrow \alpha + 2p + 12.86\,MeV$
84.92%
${}^3He + p \rightarrow \alpha + e^+ + \upsilon_e$
$\approx 10^{-5}\%$
${}^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59\,MeV$
15.08%

Solar Neutrino Spectra



Estimate of the neutrino flux

The

$$4p \rightarrow He^4 + 2e^+ + 2\nu_e + 26.7MeV$$

summarises the main energy production mechanism. Assume the entire luminosity of the sun is due to this process:

$$\phi_\nu = 2\frac{L_\odot(erg/sec)}{26.7(MeV)4\pi D^2}$$

$$D = 1.5 \times 10^{13} cms. \quad L_\odot = 3.8 \times 10^{33} erg/sec.$$

$$\phi_\nu = 6 \times 10^{10} \nu_e \ \ /cm^2/sec$$

The real proof of " How the Sun shines" lies in detecting these neutrinos.

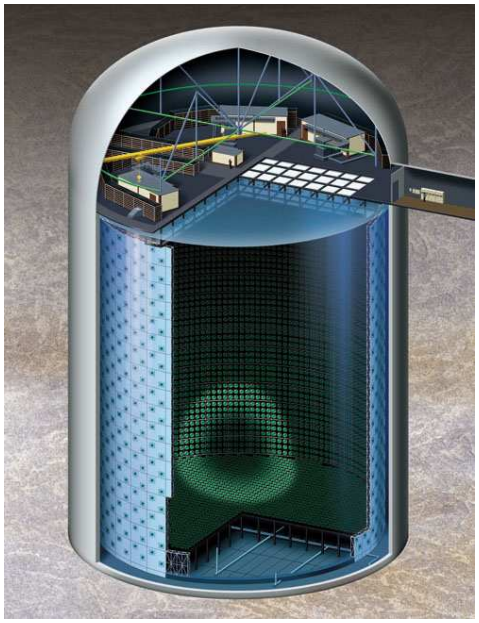
Solar Neutrino Experiments

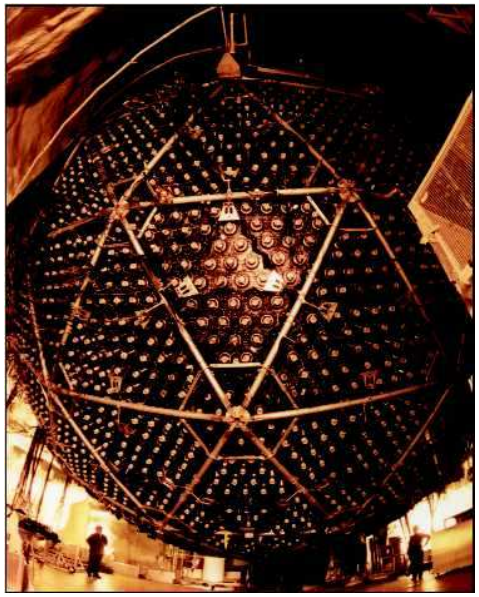
1964 Raymond Davis and Homestake experiment- 600 tons of C_2Cl_4 in a tank in Homestake mine.

$$\nu_e + Cl^{37} \rightarrow e^- + A^{37}$$

is a direct measure of the neutrino flux. Count the argon atoms to get neutrino flux.- Davis gathered data until 1994 and in all gathered 2000 Argon atoms in three decades.

Cerenkov detectors -SK and SNO





Enormous water tank- lined with **Photomultiplier Tubes** placed in a Mine. (32 Kton in Super-K).

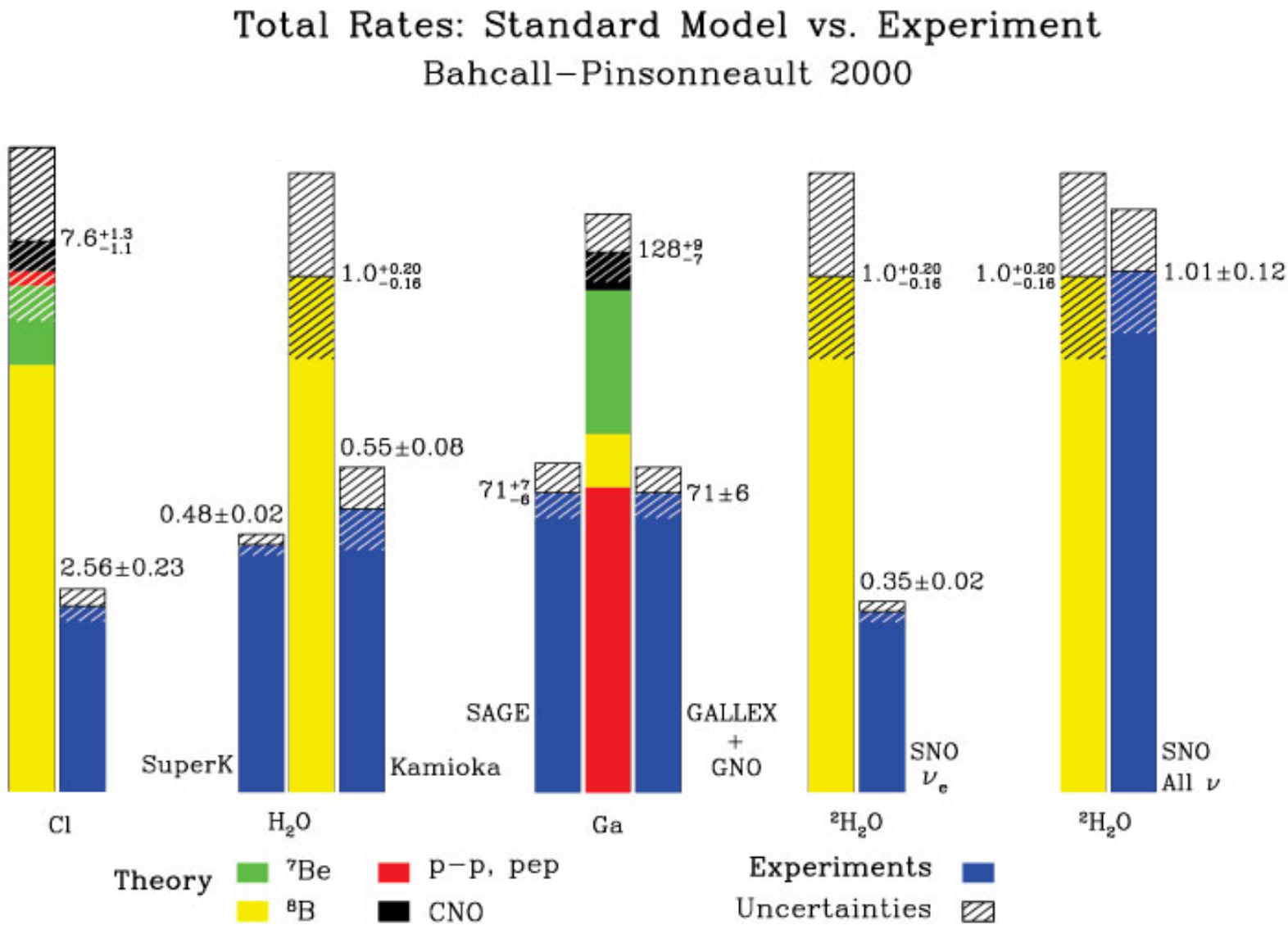
$$\nu_e + e^- \rightarrow e^- + \nu_e$$

Heavy Water detector at SNO

1kton of heavy water stored in an acrylic vessel sorrounded by water. Capable of detecting ES, CC and NC reactions.

The PMT's detect the flashes of light created by charged particles in real time with good direction.

Summary of Solar Neutrino Observations



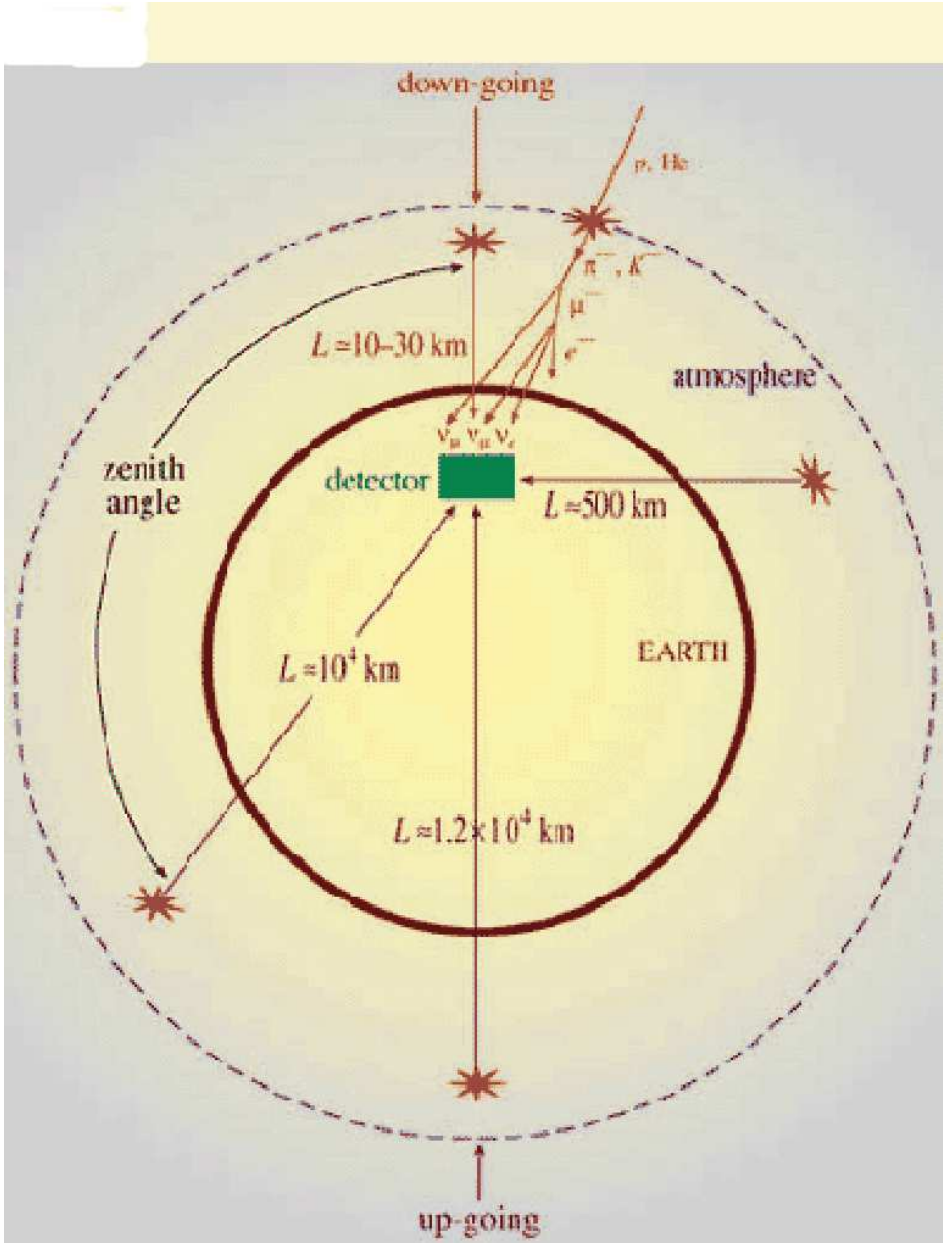
Deficit confirmed–energy dependent–Solar neutrino puzzle

(*SNU=1 neutrino interaction per second for* 10^{38} *target atoms).*

Experiment	Observed/Predicted	Energy
Davis (1964-1994)	$0.33 \pm 0.03 \pm 0.05$	E$>$ 0.814 MeV
K & SK (1986 - 2000)	$0.465 \pm 0.005 \pm 0.015$	E $>$ 6.5 MeV
Ga-SAGE (1988-1996)	$0.60 \pm 0.06 \pm 0.04$	E $>$ 0.233 MeV
SNO (1998-2002)	0.347 ± 0.029(CC)	E $>$ 6.75 MeV

We discuss another puzzle closer home!

The Atmospheric Neutrino Puzzle



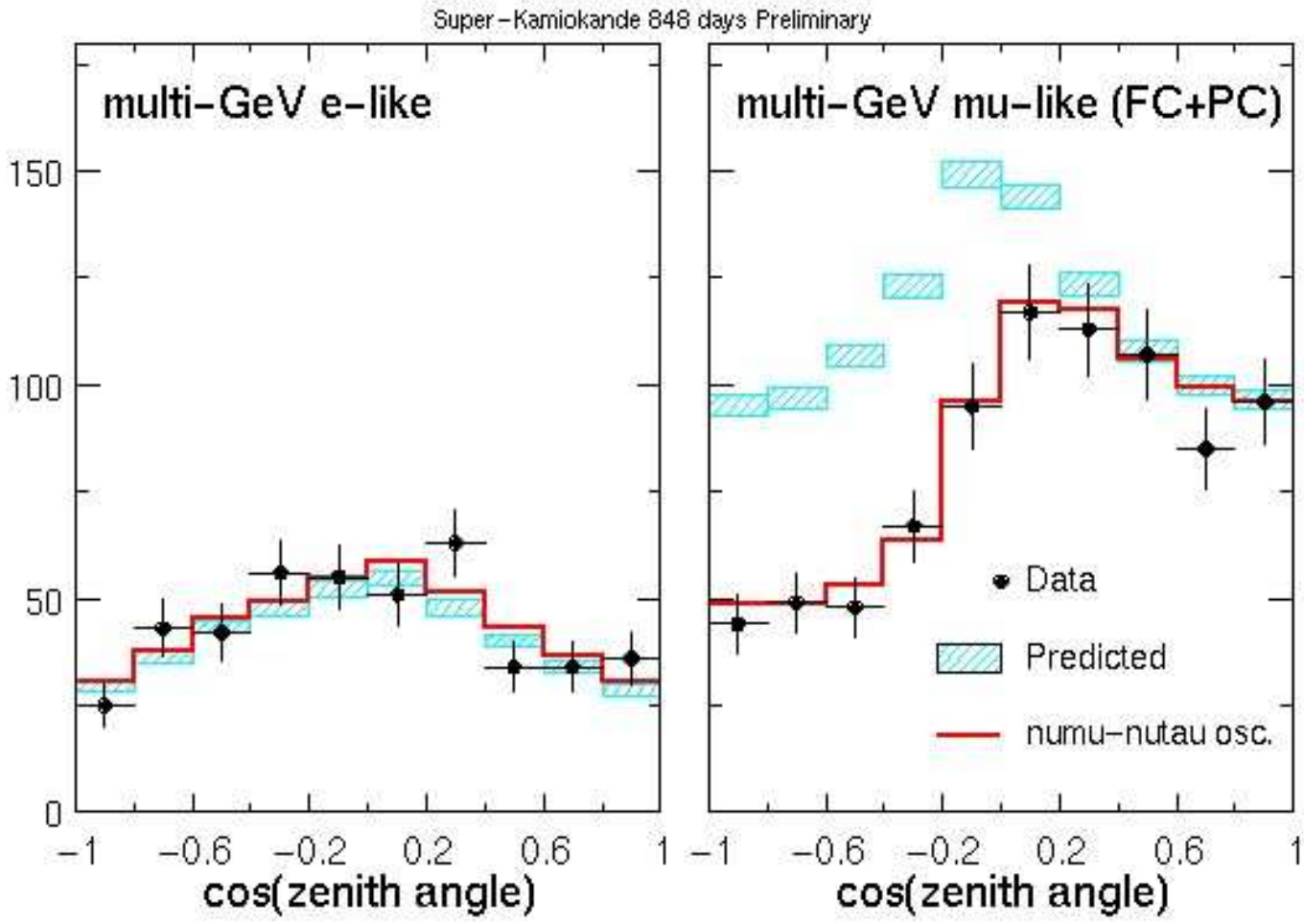
Production of
Atmospheric Neutrinos:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu, \quad \mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

The puzzle

$$R = \frac{R_{obs}}{R_{MC}} = 0.65 \pm 0.02 \pm 0.05$$



Results so far

- Neutrinos from SUN observed - confirmation of fusion as source of energy in stars. But the numbers do not match prediction- an energy dependent deficit.
- Atmospheric neutrinos also show deficit- There is an up-down asymmetry and is also energy dependent.Evidence for Neutrino mass
- Neutrinos from Stellar Collapse observed-SN1987A. Stellar collapse scenario qualitatively confirmed.
- Physics beyond SM needed to account for puzzles above.

Short primer on neutrino oscillations

Simplest and by far the most appealing solution.

For simplicity, consider two neutrinos ν_e, ν_μ different from mass eigenstates: At t_0.

$$\begin{aligned} |\nu_e(t_0)> &= \cos\theta|\nu_1(t_0)> + \sin\theta|\nu_2(t_0)> \\ |\nu_\mu(t_0)> &= -\sin\theta|\nu_1(t_0)> + \cos\theta|\nu_2(t_0)> \end{aligned}$$

At time t, propagated states are:

$$\begin{aligned} |\nu_e(t)> &= \cos\theta|\nu_1(t)> + \sin\theta|\nu_2(t)>, \\ &= [\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t}]|\nu_e(t_0)> \\ &+ \cos\theta\sin\theta[e^{-iE_2 t} - e^{-iE_1 t}]|\nu_\mu(t_0)> \end{aligned}$$

where

$$E_i = (p^2 + m_i^2)^{1/2} \approx p + \frac{m_i^2}{2p}; \quad m_i \ll E_i$$

The Probability of oscillation

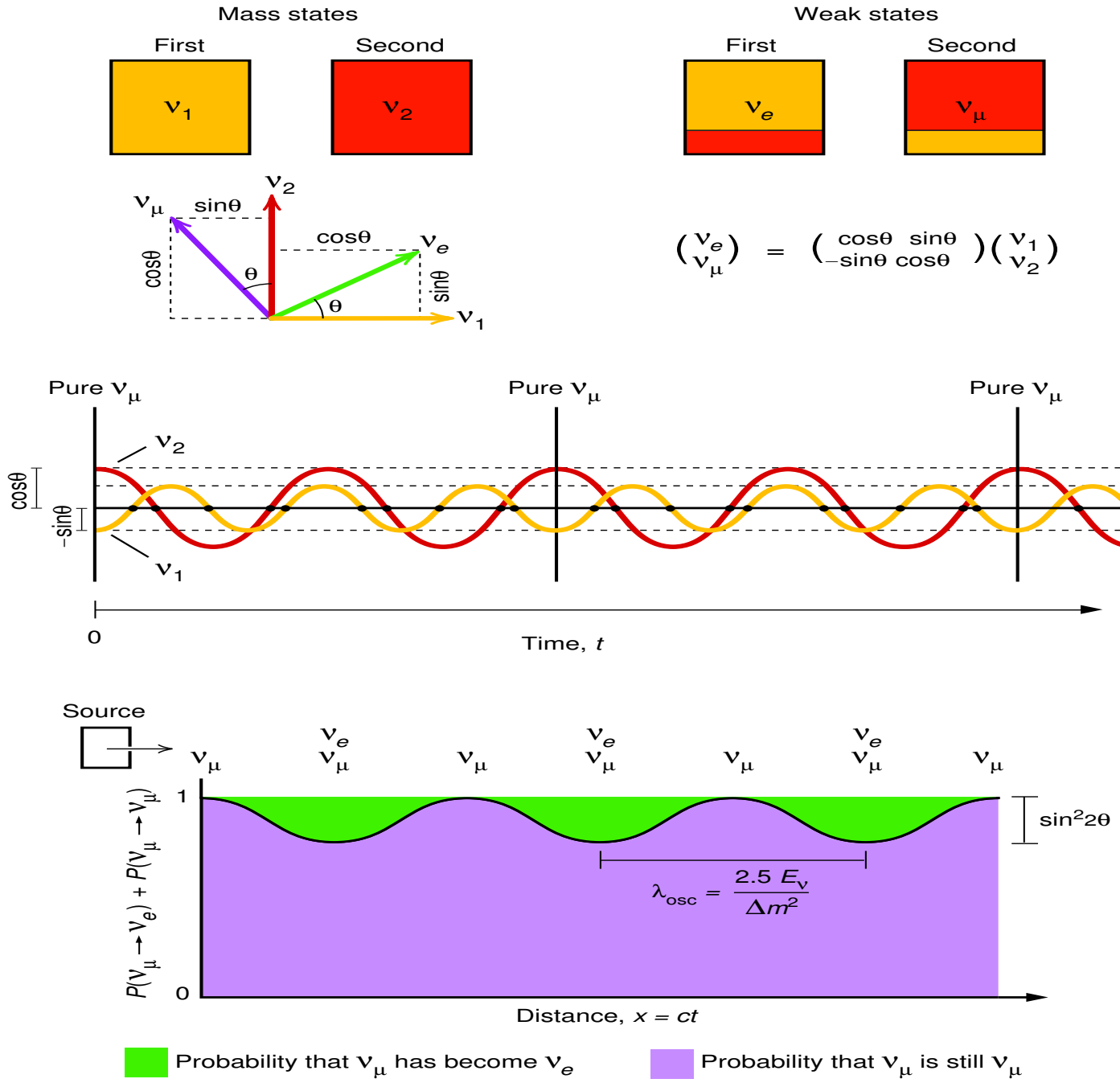
$$P_{\nu_e \to \nu_\mu} = |<\nu_e(t_0)|\nu_\mu(t)>|^2 = \sin^2 2\theta \ \ \sin^2 \frac{\Delta m^2 t}{4p};$$

$$= \sin^2 2\theta \ \ \sin^2 \frac{\Delta m^2 L}{4E}$$

$$\Delta m^2 = m_2^2 - m_1^2.$$

Neutrinos are relativistic, $v \approx c = 1$. Replace time by length of propagation:

Thus neutrinos oscillate IFF mass squared difference and mixing are both non-zero


Mass states
First
Second
ν_1
ν_2
Weak states
First
Second
ν_e
ν_μ
ν_μ sinθ
ν_2
cosθ
ν_e
cosθ
θ
θ
sinθ
ν_1
$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$
Pure ν_μ
Pure ν_μ
Pure ν_μ
ν_2
cosθ
−sinθ
ν_1
0
Time, t
Source
ν_μ
ν_e ν_μ
ν_μ
ν_e ν_μ
ν_μ
ν_e ν_μ
ν_μ
1
0
$P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu)$
$\sin^2 2\theta$
$\lambda_{osc} = \frac{2.5\ E_\nu}{\Delta m^2}$
Distance, $x = ct$
Probability that ν_μ has become ν_e
Probability that ν_μ is still ν_μ

The Final Solution !

- **Solution to Solar Neutrino Puzzle: Part of the ν_e flux oscillated into ν_x which is almost undetected.**
  Relevant L for this to happen is the Sun-Earth distance. Required $\Delta m^2 = 7 \times 10^{-5}$eV^2. Further complicated by matter effects on neutrinos.
- **Is there a way of detecting the oscillated neutrinos ν_x?**
  Precisely what SNO did.

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.

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

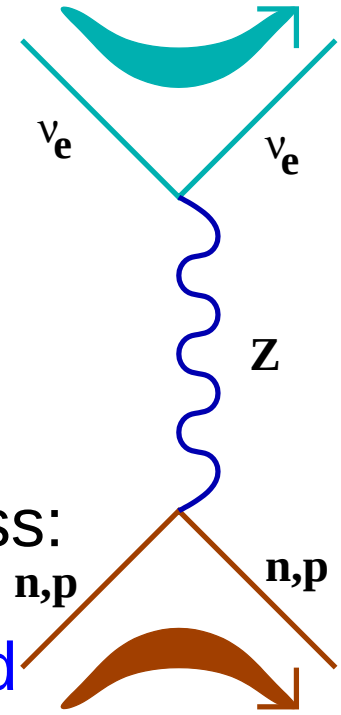
Here NC stands for the neutral current process:

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.

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



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.

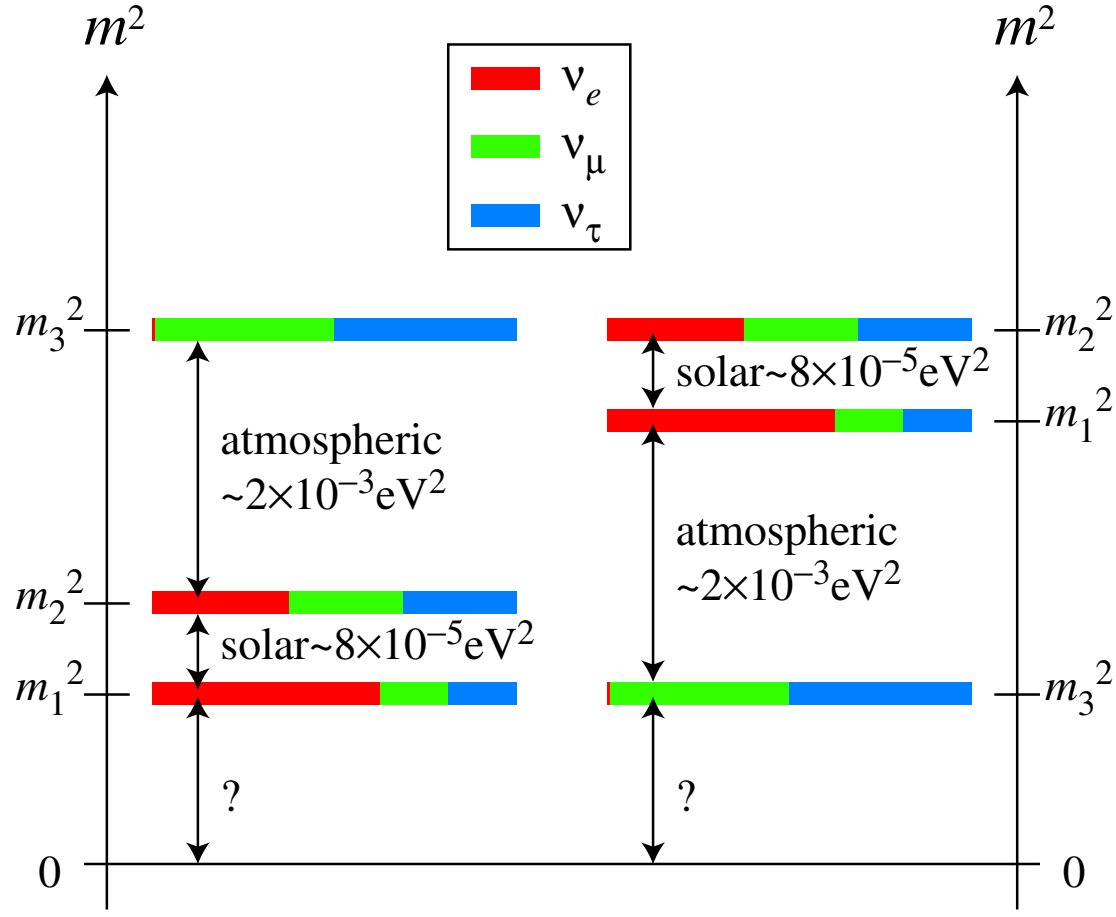

India-based Neutrino
Observatory

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}.

A Schematic of Neutrino Properties

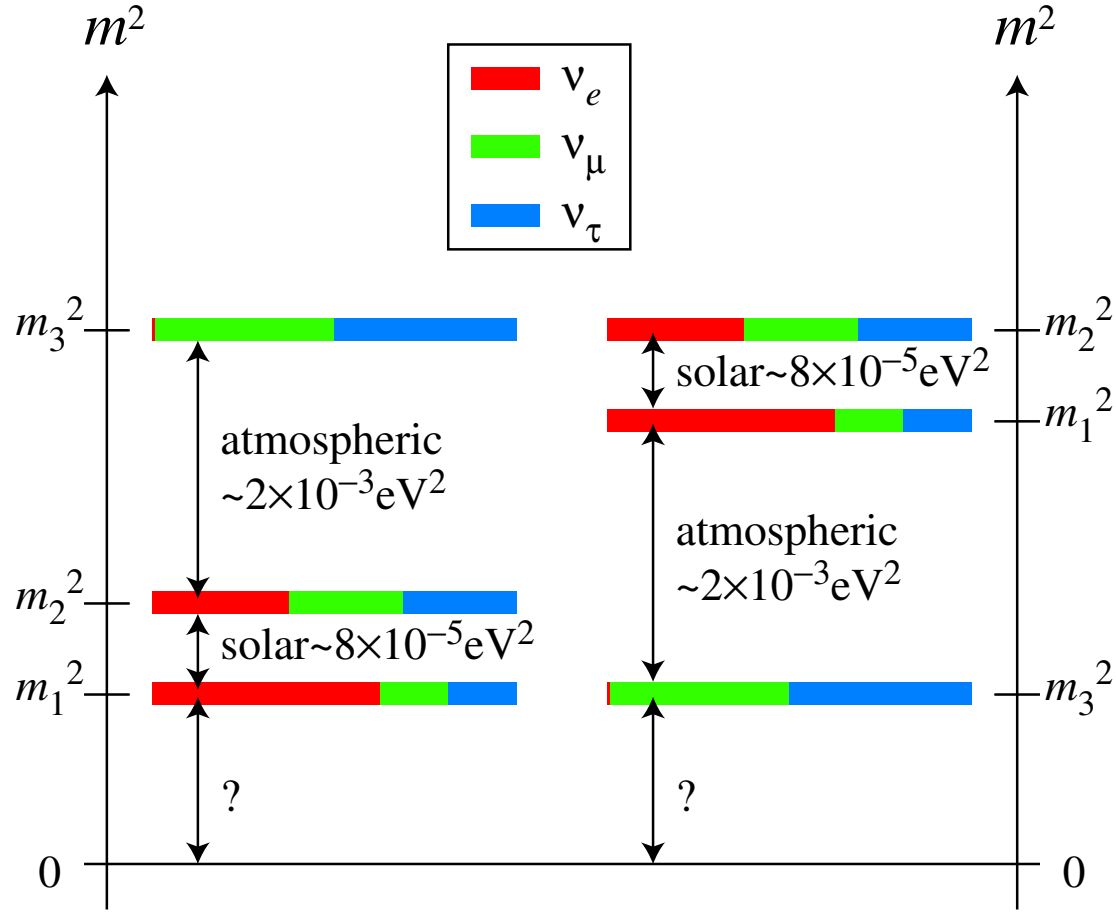
Neutrino masses are not well-known. Oscillation studies only determine the mass-squared differences: $\Delta m^2_{ij} = m^2_i - m^2_j$ and the mixing angles θ_{ij}.



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}.

$\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
$|\Delta m^2_{32}| \sim 2.0 \times 10^{-3}$ eV^2 ;
$\sum_i m_i < 0.7$–2 eV.



A Schematic of Neutrino Properties

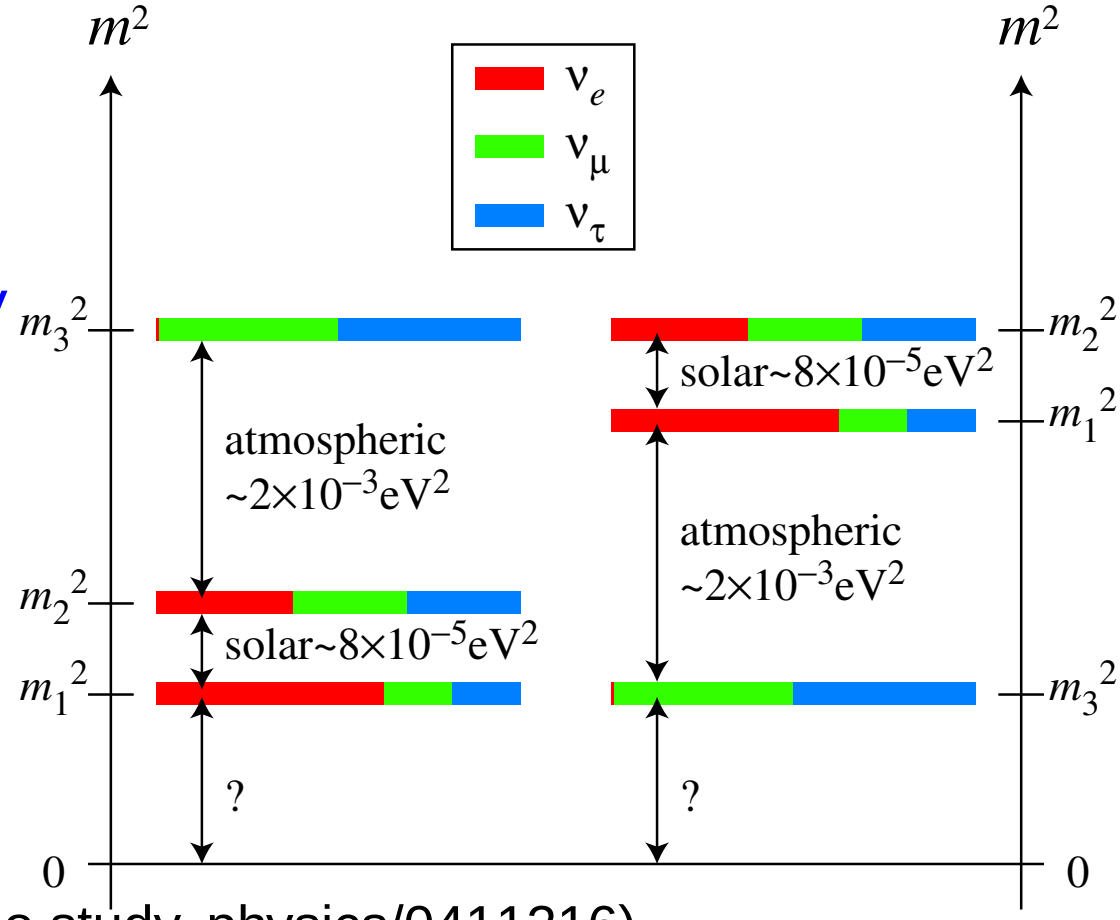
Neutrino masses are not well-known. Oscillation studies only determine the mass-squared differences: $\Delta m^2_{ij} = m^2_i - m^2_j$ and the mixing angles θ_{ij}.

$\Delta m^2_{21} \sim 0.8 \times 10^{-4}$ eV^2 ;
$|\Delta m^2_{32}| \sim 2.0 \times 10^{-3}$ eV^2 ;
$\sum_i m_i < 0.7$–2 eV.

- $m_1 \sim m_2 \sim m_3 \sim 0.2$ 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 has been completed. Issues studied 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

The INO Collaboration

- Stage I : Study of atmospheric neutrinos

  The feasibility study of about 2 years duration for both the laboratory and detector has been completed. Issues studied 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

- Stage II : Study of long-baseline neutrinos, from a neutrino factory?
- Other detectors/physics like neutrinoless double beta decay?

The INO Collaboration

- Stage I : Study of atmospheric neutrinos

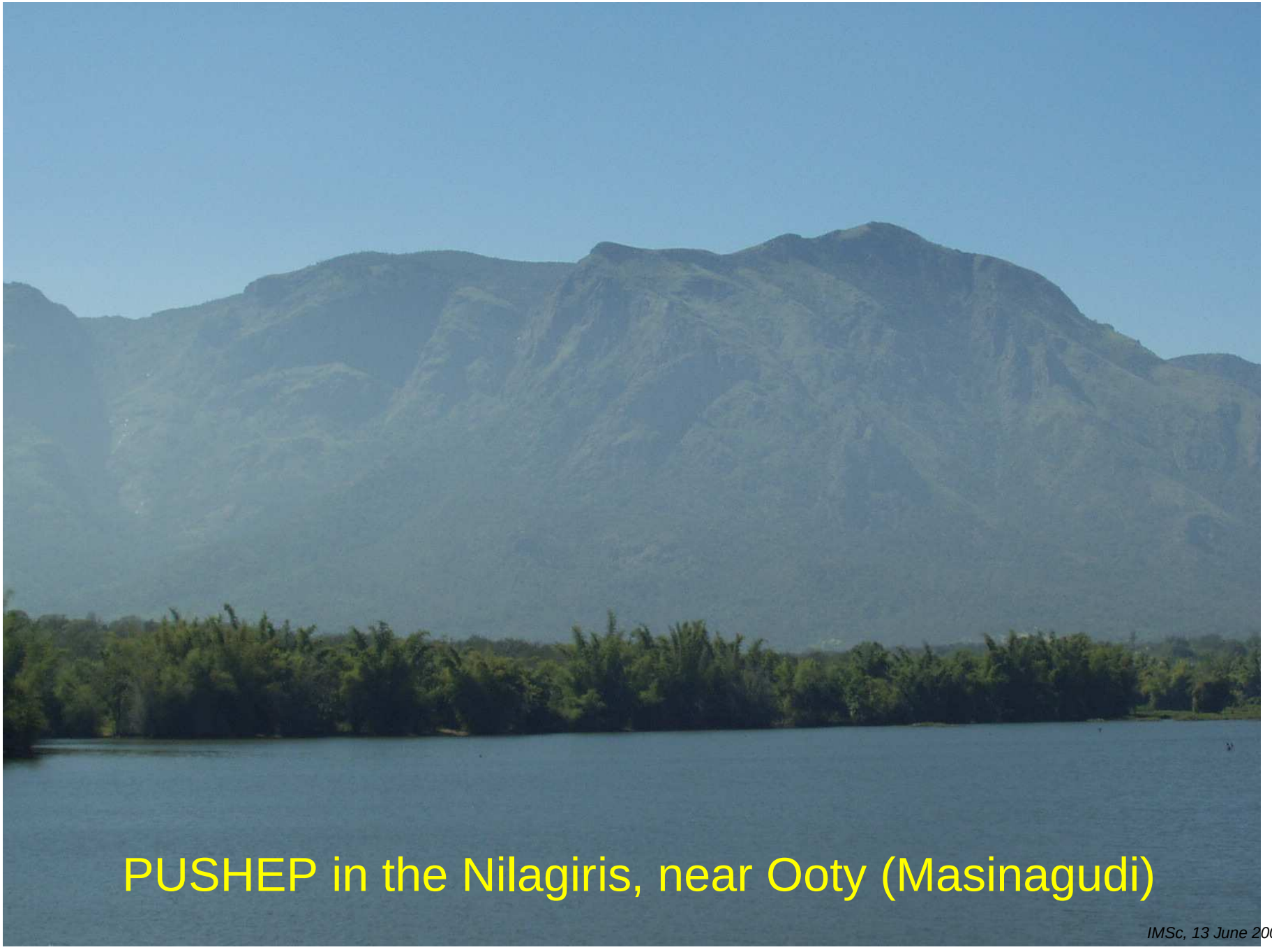
  The feasibility study of about 2 years duration for both the laboratory and detector has been completed. Issues studied are

  - 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

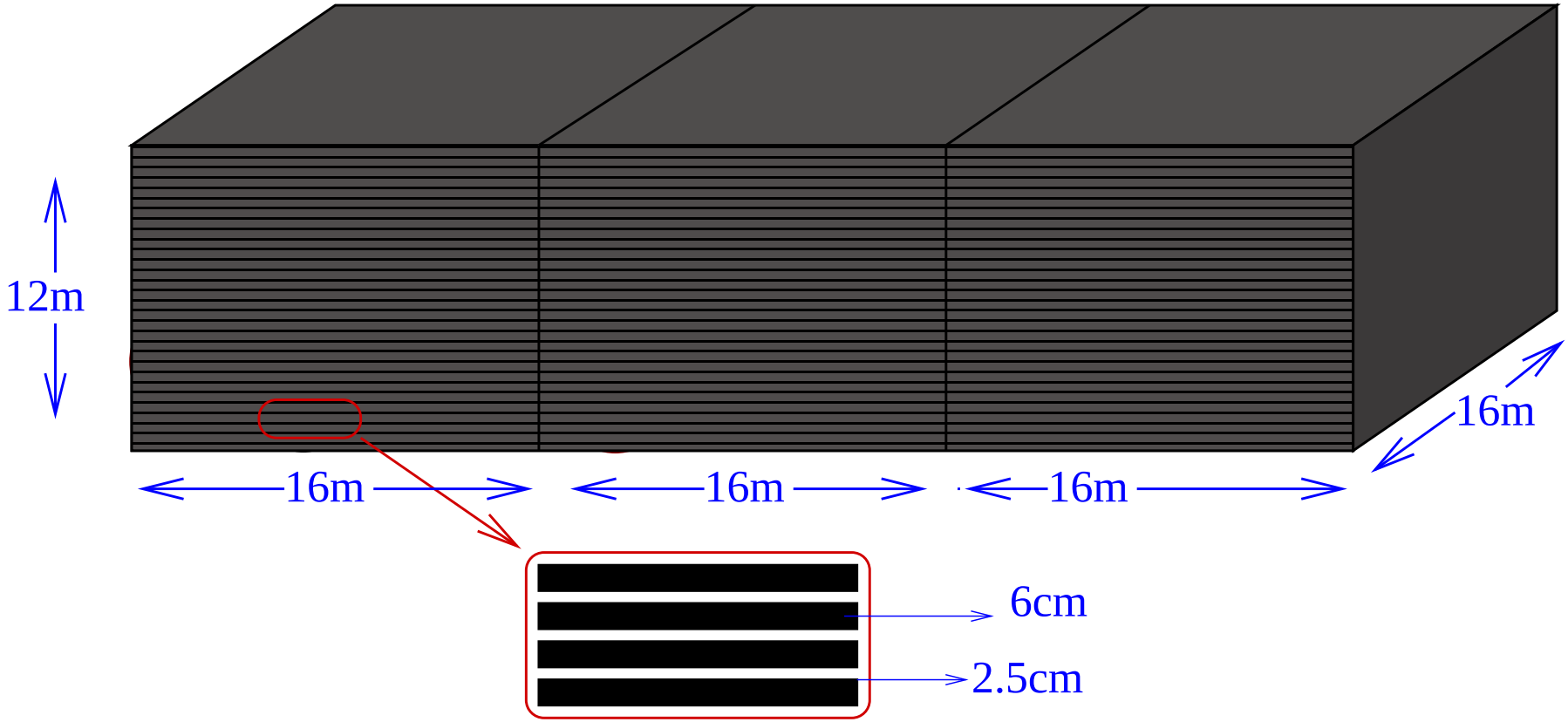
- Stage II : Study of long-baseline neutrinos, from a neutrino factory?
- Other detectors/physics like neutrinoless double beta decay?
- Should be an international facility

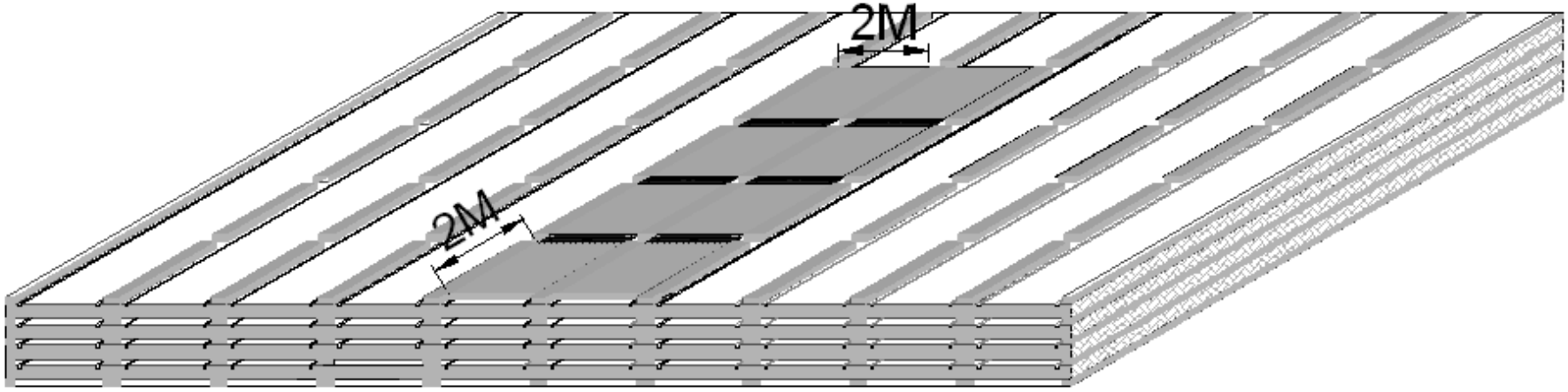
Site survey: PUSHEP



PUSHEP in the Nilagiris, near Ooty (Masinagudi)

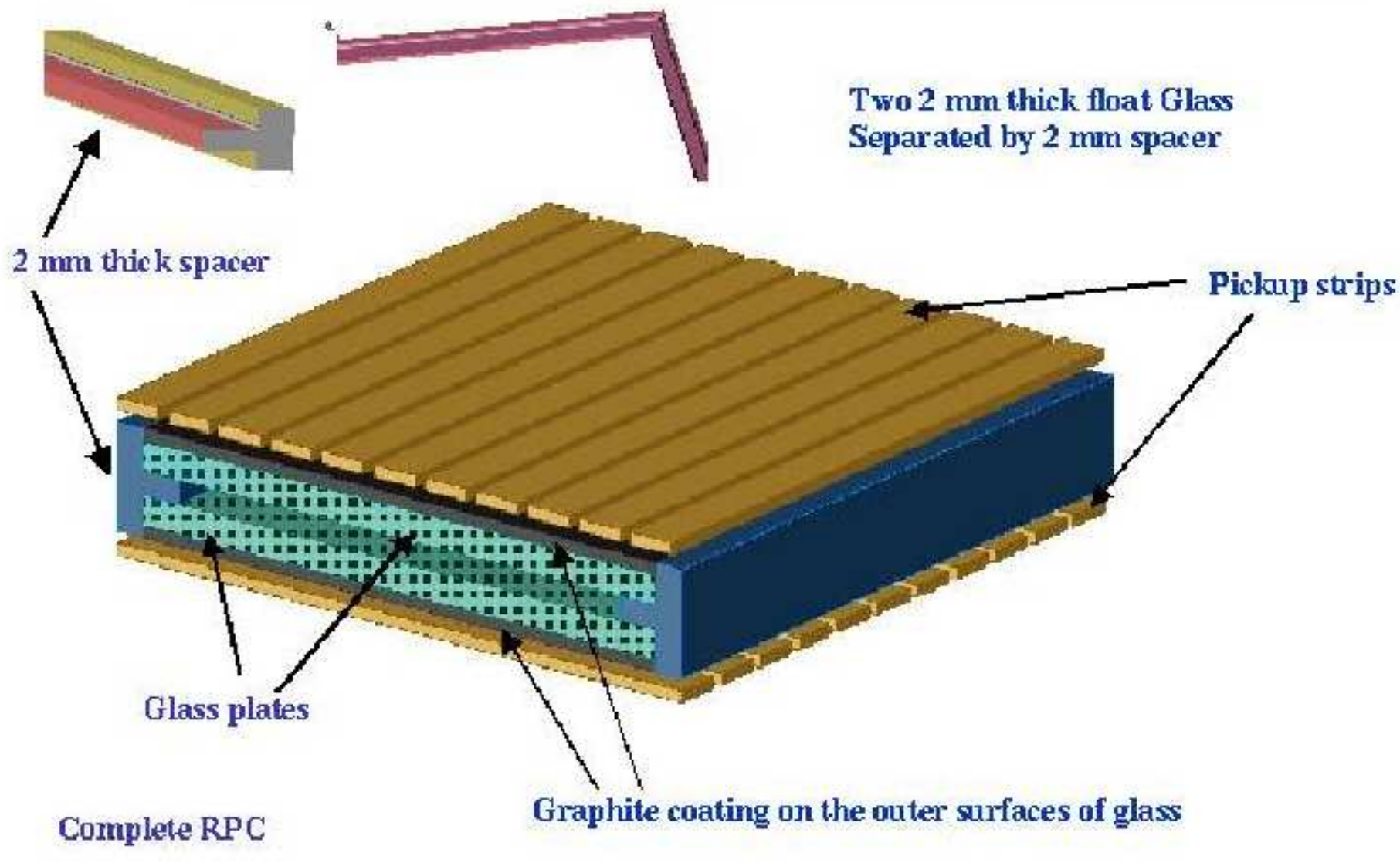
The ICAL detector





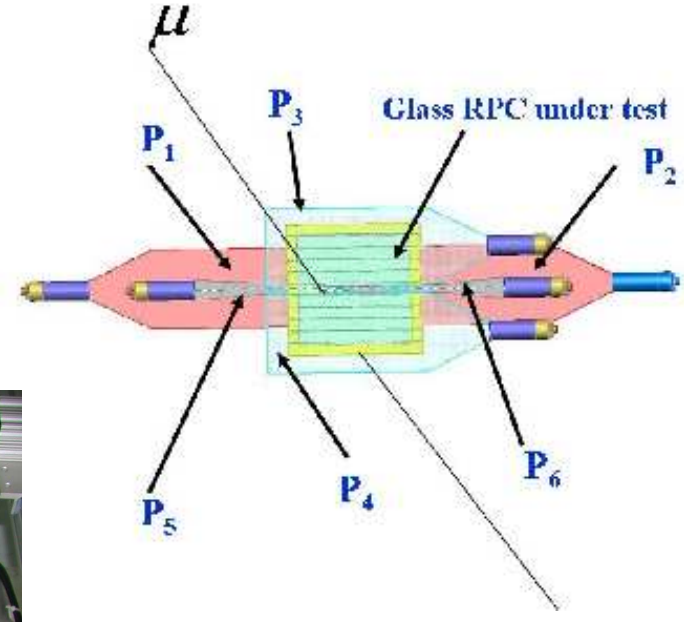
The active detector elements: RPC

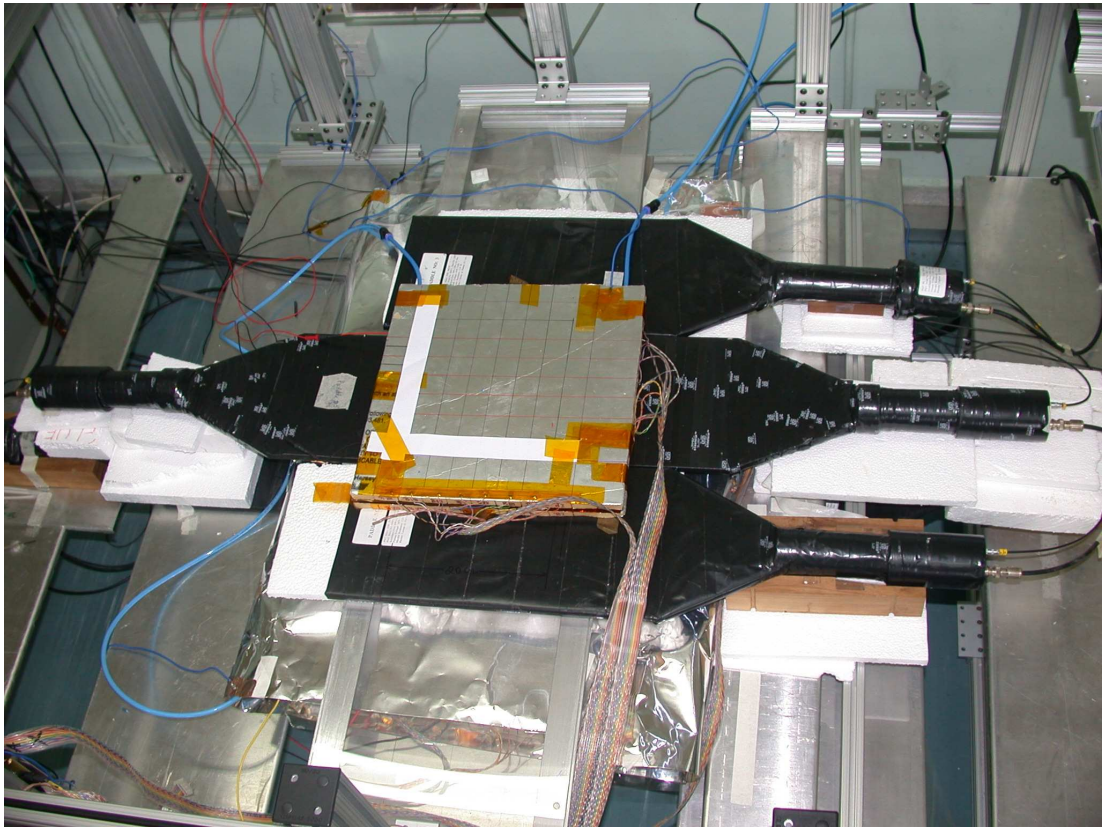
RPC Construction: Float glass, graphite, and spacers



Fabricating RPC's

at TIFR . . .





And of course . . .

Specifications of the ICAL detector

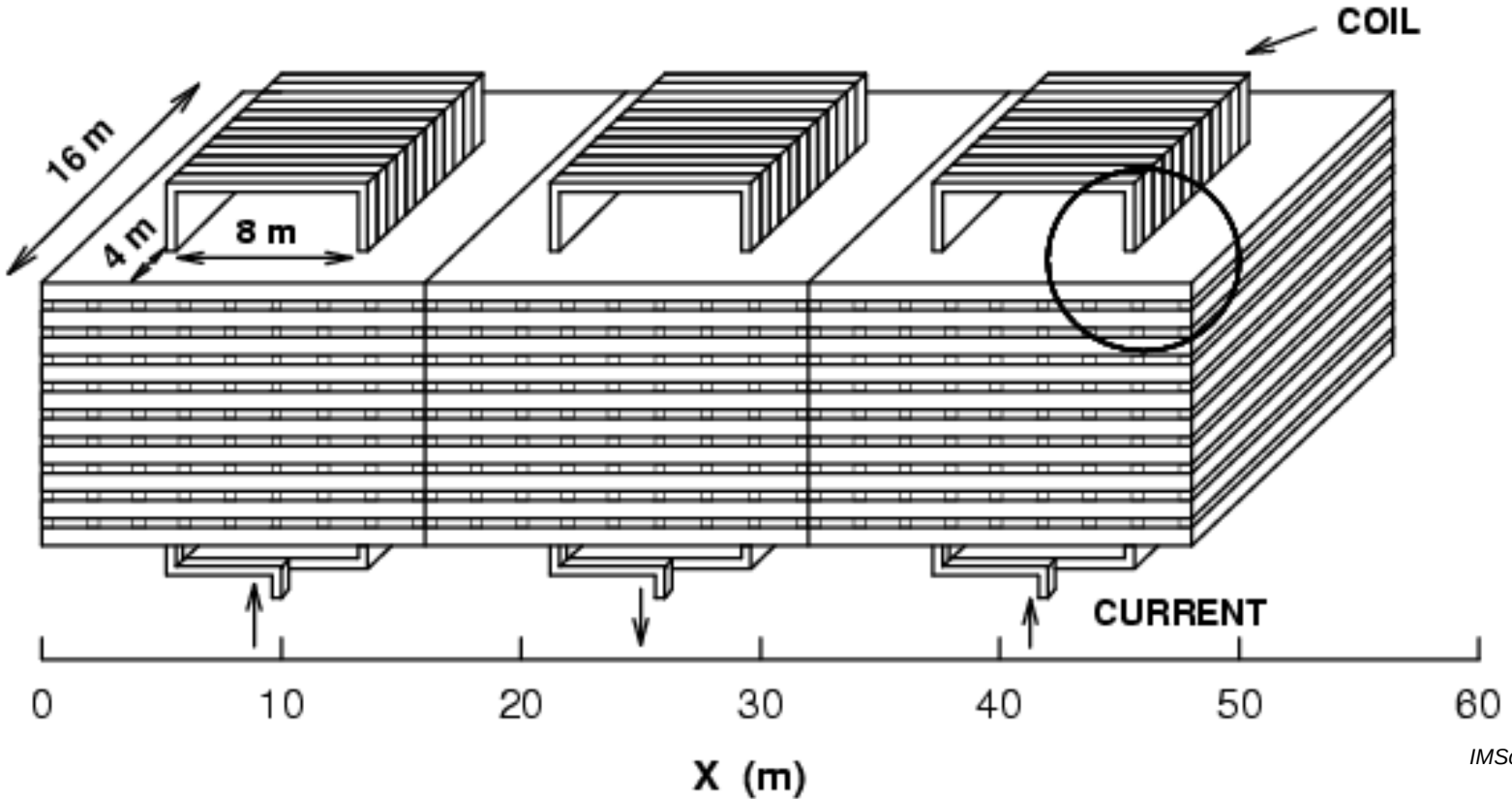
ICAL	
No. of modules	3
Module dimension	16 m $\times$ 16 m $\times$ 12 m
Detector dimension	48 m $\times$ 16 m $\times$ 12 m
No. of layers	140
Iron plate thickness	$\sim$ 6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.3 Tesla
RPC	
RPC unit dimension	2 m $\times$ 2 m
Readout strip width	3 cm
No. of RPC 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 $\times$ 10^6

Magnet studies

Design criteria:

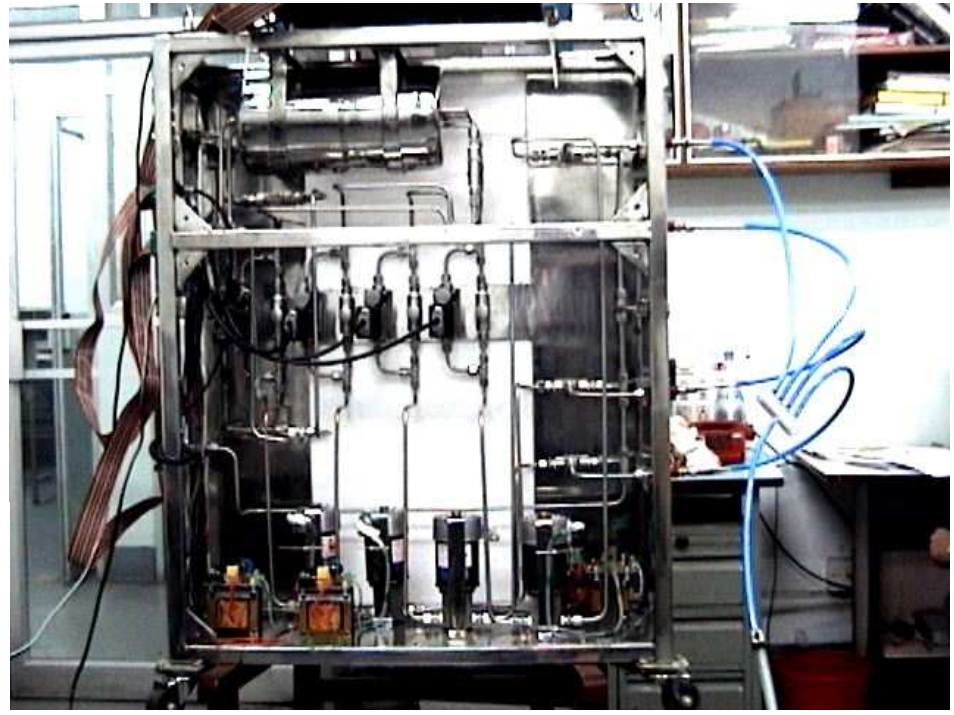
- Field uniformity
- Modularity
- Optimum copper-to-steel ratio
- Access for maintenance

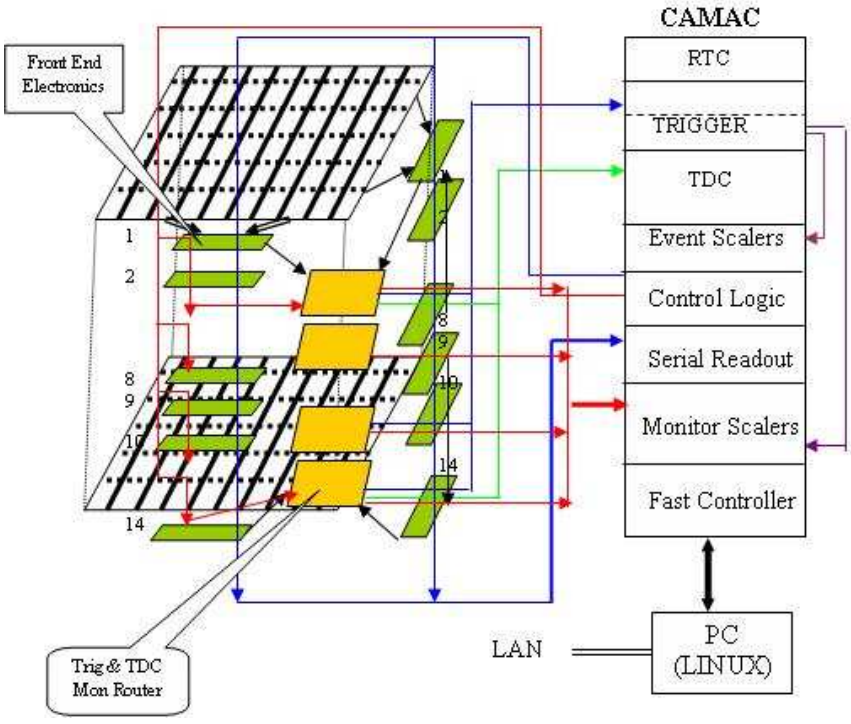
Toroidal Magnet design



For the prototype . . .

The gas-mixing unit at SINP



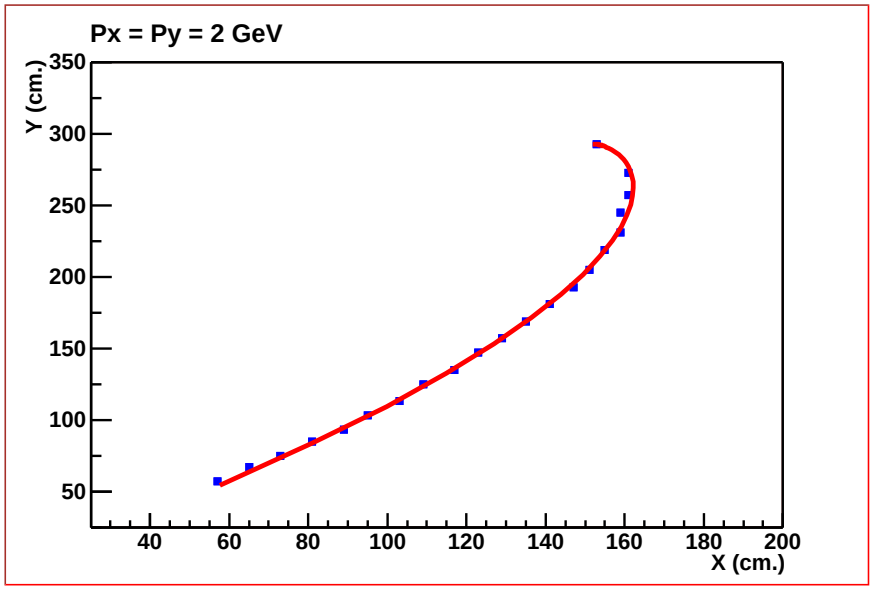


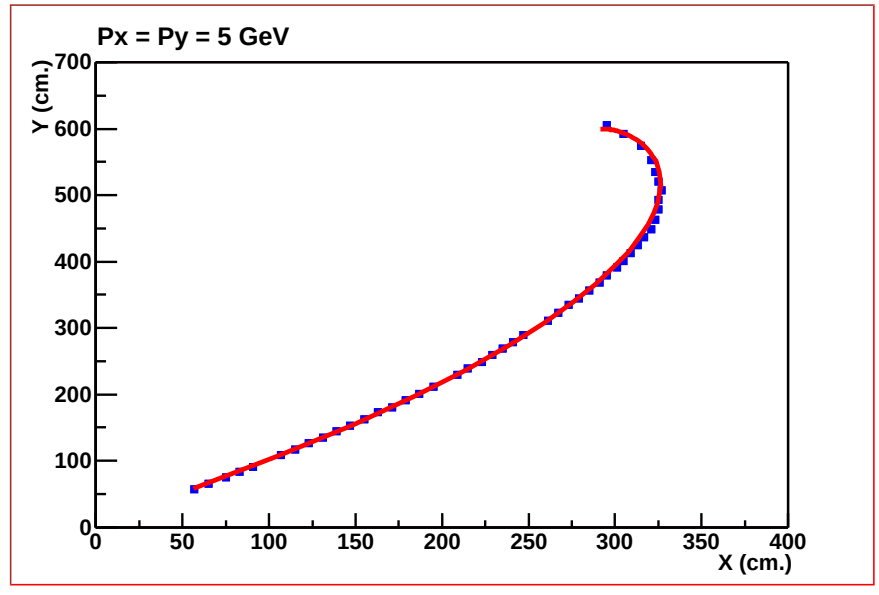
A schematic of the read-out electronics for the prototype

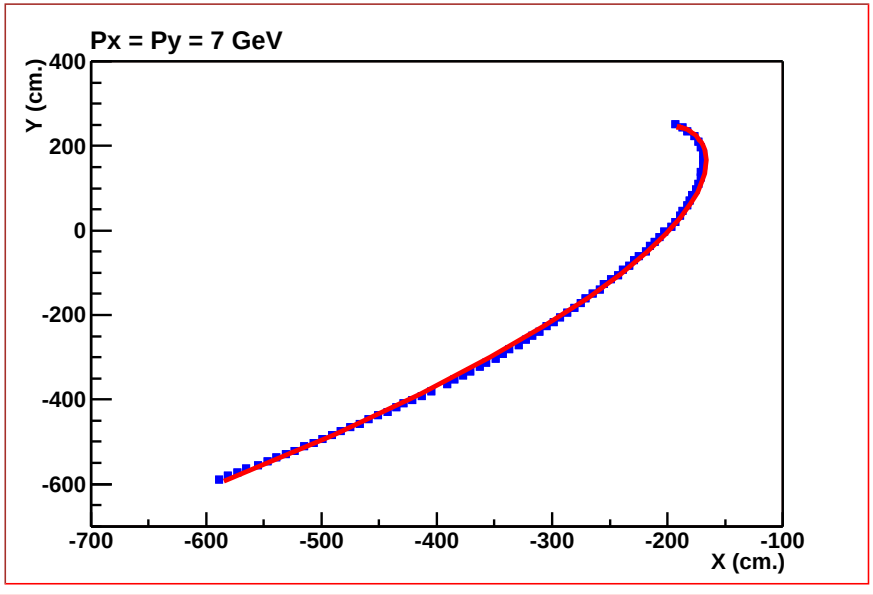
Physics with Atmospheric Neutrinos

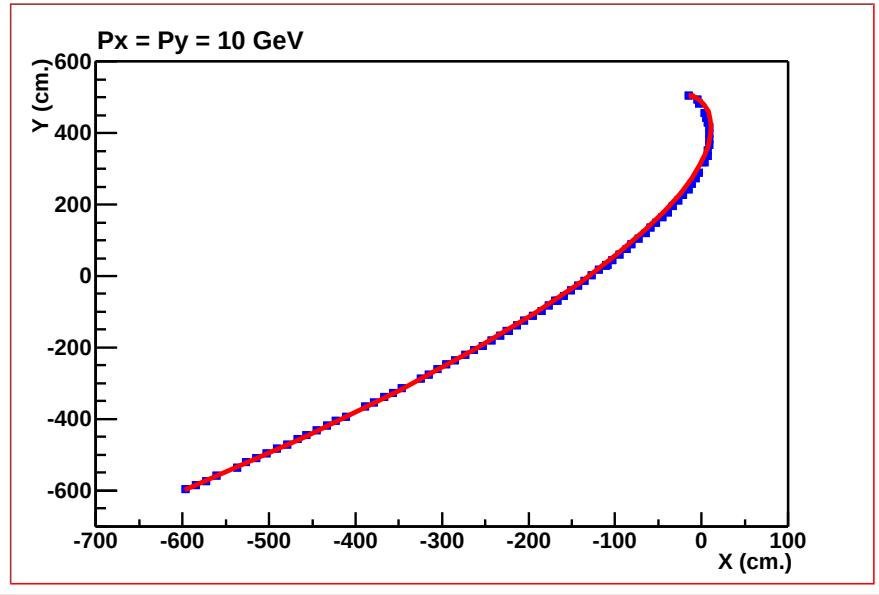
- A muon-type neutrino from the atmosphere enters the detector.
- It interacts (mostly with the iron) and produces a muon and (perhaps) some hadrons.
- The muon *bends* in the magnetic field and leaves a curved (helical) track in the detector.
- From the bending/length of the track, the momentum and 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.

Sample tracks and fits





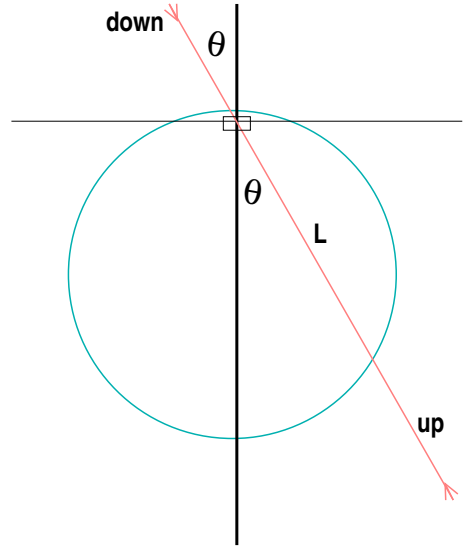




Physics goals

➢ 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 . . ..

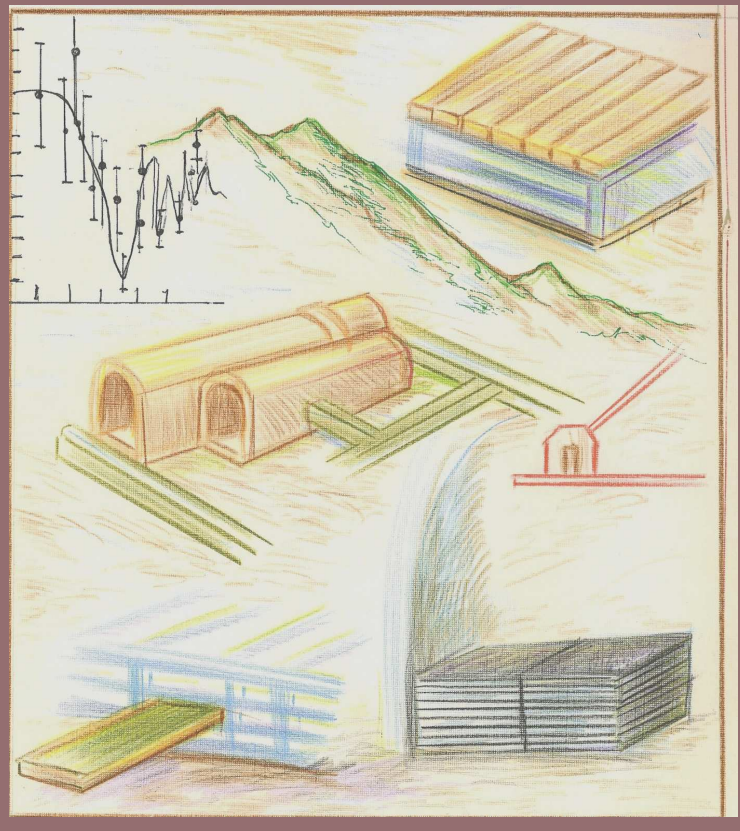
. . . WITH LONG BASE-LINE NEUTRINOS

- Precision neutrino oscillation studies

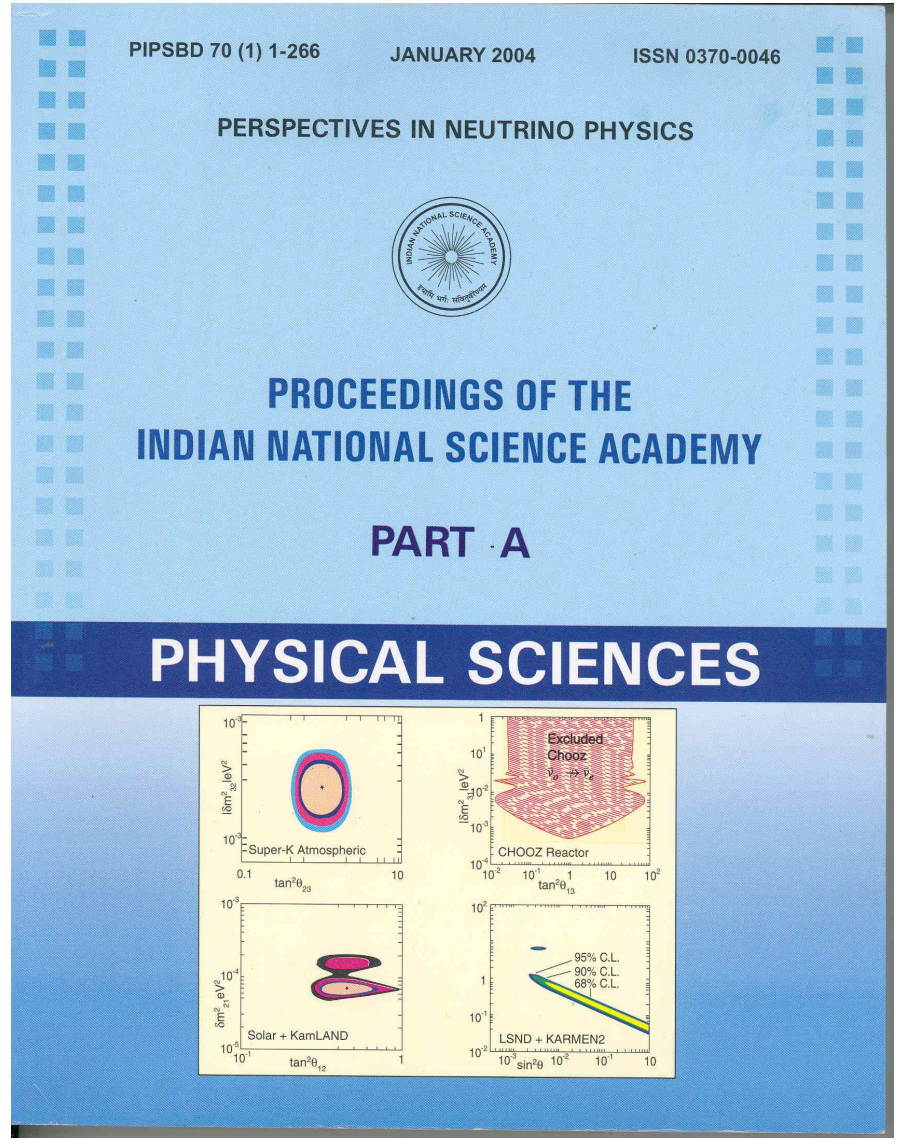
Status Report

INO/2005/01
Interim Project Report
Volume I

INDIA-BASED NEUTRINO OBSERVATORY



I N O



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

---

- **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:**
  Basanta Nandi, S. Uma Sankar, Raghav Varma
- **The Institute of Mathematical Sciences (IMSc), Chennai:**
  D. Indumathi, H. S. Mani, M. V. N. Murthy, G. Rajasekaran, Abdul Salam
- **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
- **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:**
  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

E-mail: ino@tifr.res.in URL: http://www.imsc.res.in/∼ino