THE INO PROPOSAL AND NEUTRINOS IN ASTROPHYSICS

Kamales Kar

Saha Institute of Nuclear Physics

School-cum-Workshop on Low Energy Nuclear Astrophysics

19 January, 2006

- INDIA-BASED NEUTRINO OBSERVATORY (INO) PROPOSAL FOR AN UNDERGROUND FACILITY
- FIRST PROPOSED EXPERIMENT: Study of neutrino oscillation with an Iron Calorimeter (ICAL) Detector using Atmospheric Neutrinos

  1) Observing a full oscillation cycle

  2) Extracting mass squared difference and mixing angle

  3) Throw light on mass hierarchy

  4) Use ICAL Detector for LONG BASELINE EXPERIMENTS
- IMPACT ON NEUTRINOS IN ASTROPHYSICS

  Time Sequence: The ICAL Experiment Followed by a Future Galactic Supernova Explosion
- Possibility of future facility for detecting low energy neutrinos

Super-Kamiokande and Sudbury Experiments

$\Downarrow$

Neutrinos are indeed massive !!!

Three active flavors (Decay width of Z boson saturated by 3 active flavors):

$$\nu_e \quad \nu_\mu \quad \nu_\tau$$

Mass Limits:

- From tritium $\beta-$decay spectrum, $m_{\nu_e} < 2.2$ eV
- From decay of π^-, $m_{\nu_\mu} < 190$ KeV 90% CL
- From decay of τ^-, $m_{\nu_\tau} < 18.2$ MeV 95% CL

However ν oscillation expts give much tighter limits.

Also, from cosmological data $\Sigma_i\, m_{\nu_i} < 0.7$eV WMAP

$\nu-$less double beta decay: ν a Majorana or Dirac particle
and gives $\langle m_\nu^{\rm Maj} \rangle = \Sigma_i\, \lambda_i\, |U|^2_{ei}\, m_i < 0.4$eV

2 active νs:

Mass eigenstates: $|\nu_1\rangle$ $|\nu_2\rangle$ Masses: m_1 m_2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Mass eigenstates evolve in time as e^{iE_it}

$$E_i^2 = m_i^2 + p^2 \tag{1}$$

$$P_{\nu_\mu\nu_e} = sin^2(2\theta)\ \ sin^2(\Delta m^2 X/(4E)) \tag{2}$$

$\Delta m^2 = m_2^2 - m_1^2, \quad X = Distance\ \ Travelled$

OSCILLATION IN PRESENCE OF MATTER

ν_es interact with the electrons in the matter and give rise to an extra potential (proportional to n_e) i the mass matrix. This results in matter-enhanced neutrino oscillation (MSW effect).

THE EFFECT IS IMPORTANT FOR SOLAR, ATMOSPHERIC AND SUPERNOVA NEUTRINOS.

3 active νs:

Mass eigenstates: $|\nu_1\rangle$ $|\nu_2\rangle$ $|\nu_3\rangle$ Masses: m_{ν_1} m_{ν_2} m_{ν_3}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12} & -s_{23}c_{12} - c_{23}s_{13}s_{12} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

δ : CP violating phase=0,

2 mass squared differences: $\Delta m^2_{21}, \Delta m^2_{32}$ $\left(\Delta m^2_{ij} = m^2_i - m^2_j\right)$, and 3 angles $\theta_{12}, \theta_{23}, \theta_{13}$

- Solar (Cl, Ga, SK, SNO) and KamLAND reactor Expt:

$$5.4 \times 10^{-5}\mathrm{eV}^2 < \Delta m^2_{21} < 9.4 \times 10^{-5}\mathrm{eV}^2$$

$$0.30 < \tan^2\theta_{12} < 0.64$$

(Best-fit: $\Delta m^2_{21} = 6.9 \times 10^{-5}\mathrm{eV}^2$ and $\tan^2\theta_{12} = 0.40$) Note: $m^2_2 > m^2_1$.

- Atmospheric (SK) and K2K Expt:

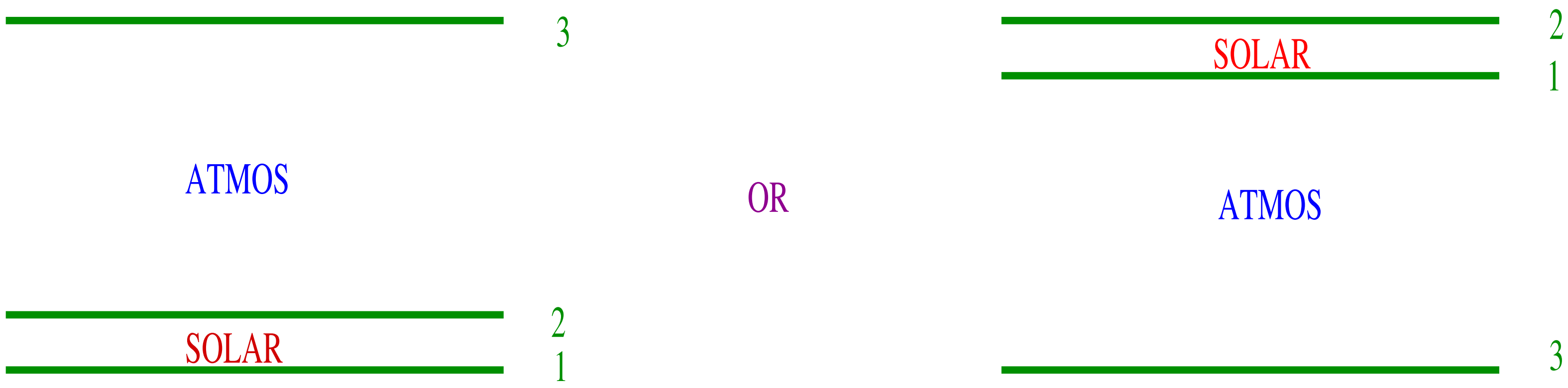
$$1.4 \times 10^{-3}\mathrm{eV}^2 < |\Delta m^2_{32}| < 5.1 \times 10^{-3}\mathrm{eV}^2$$

$$0.86 < \sin^2 2\theta_{23} \leq 1.0$$

(Best-fit: $|\Delta m^2_{23}| = 2.0 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1.0$) Sign of Δm^2_{32} not known.

Outstanding Issues

- Mass Hierarchy ? Δm^2_{32} $+ve$ or $-ve$?



- Across generation mixing angle $\theta_{13} \neq 0$?
  CHOOZ $\rightarrow \sin^2 2\theta_{13} < 0.13$
- More accurate measurements of $\Delta m^2_{21}, \Delta m^2_{32}, \theta_{12}, \theta_{23}$
- CP violation in leptonic sector ?
- $\nu-$ Dirac or Majorana ?

Experiment	Country	Type of detector	Major goals	Time schedule
Super-Kamiokande	Japan	Water Cerenkov	Solar, Supernova Atmospheric Long-baseline(K2K)	1996-
SNO	Canada	D_2O Cerenkov	Solar, Supernova	1999-
GNO	Italy	Gallium	Solar	1998-
ICARUS	Italy	Liquid Argon	Atmospheric Proton Decay Long-baseline	200?
KamLAND	Japan	Scintillator	Reactor	2001-
MiniBooNE	USA	Scintillator	Short baseline Fermilab booster	2003-
MINOS	USA	Iron Calorimeter	Long baseline Fermilab injector	2005
Opera	Gran Sasso	Iron Emulsion	Tau appearance	2005
MONOLITH	?	Iron Calorimeter	Atmospheric Long-baseline	?

India-based Neutrino Observatory - An Iron Calorimeter (ICAL) Experiment

1. Introduction
2. The Detector
3. Simulation with atmospheric neutrinos
4. Sites -
   - PUSHEP (near Singara), T.N. SELECTED SITE.
   - Rammam (near Darjeeling), W.B.
   - (Rohtang Pass)
5. Physics Issues:
   - With atmospheric neutrinos
   - With neutrino factories

Introduction

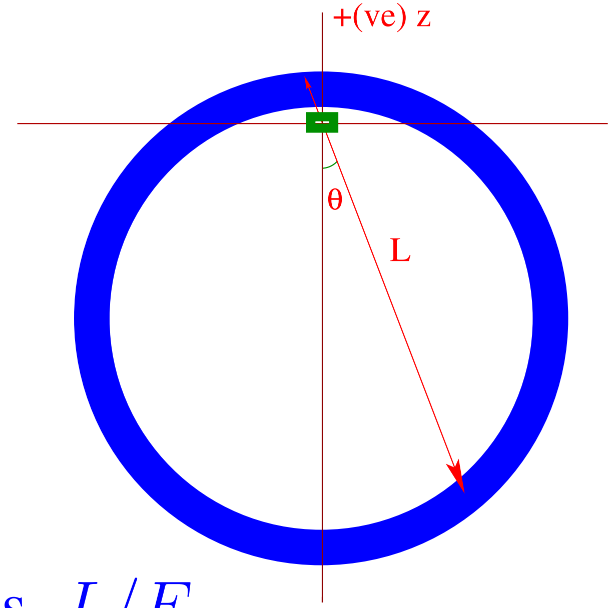
First Goal: With atmospheric νs study of survival prob vs. L/E.

Observe the full oscillation swing and thus establish the Oscillation hypothesis.

$L \longrightarrow$ downgoing νs ~ 10 km
upgoing νs ~ 12000 km

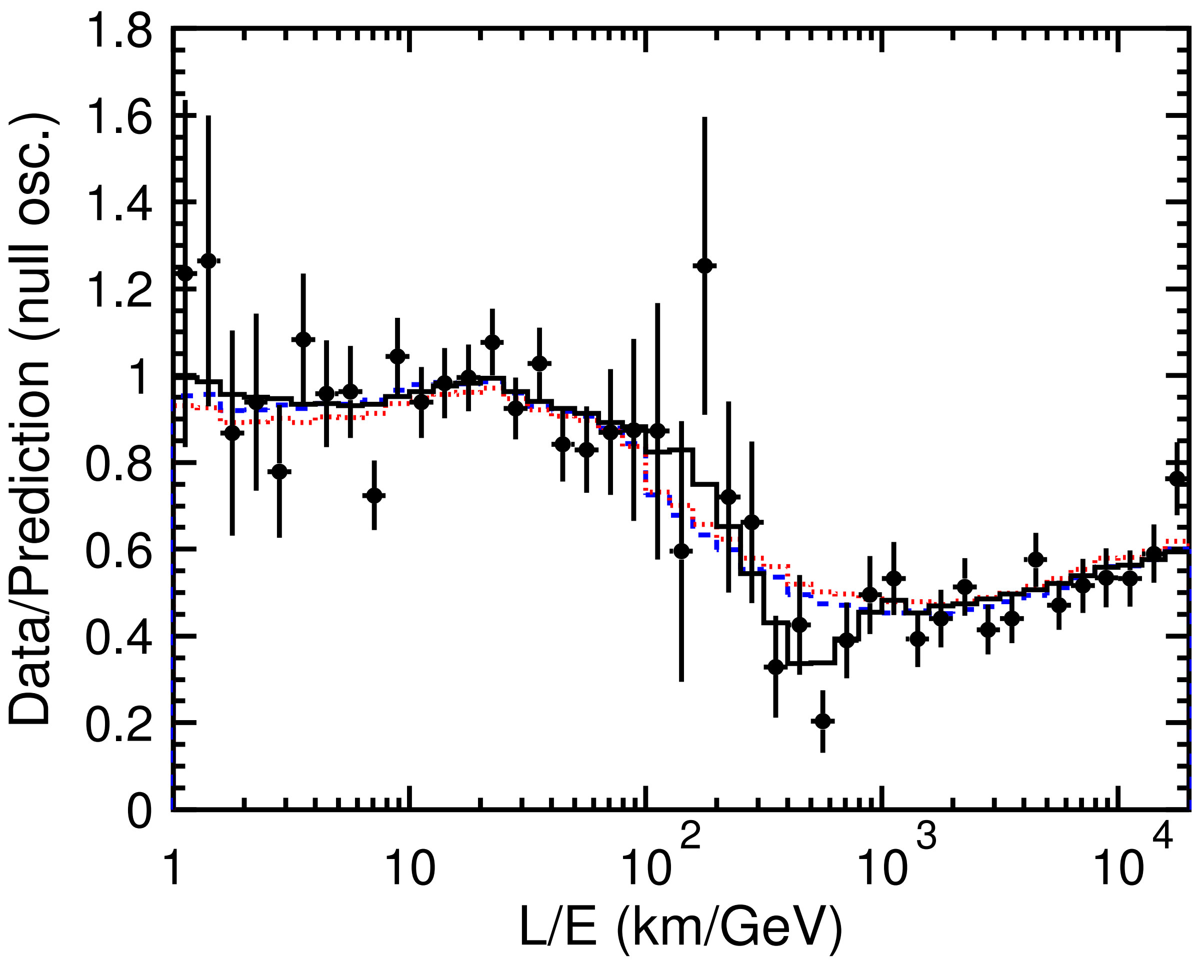
$E \longrightarrow 1 - 50$ GeV

Down $\longrightarrow$ near detector $\longrightarrow$ No oscllation
Up $\longrightarrow$ far detector $\longrightarrow$ Oscillation



$\frac{\text{up}}{\text{down}}$ vs. L/E

SK → recent analysis of old data



Solid line → two flavor oscillation

Points → no oscillation

Detector structure

Magnetised iron calorimeter with large mass (and density) and fast timing

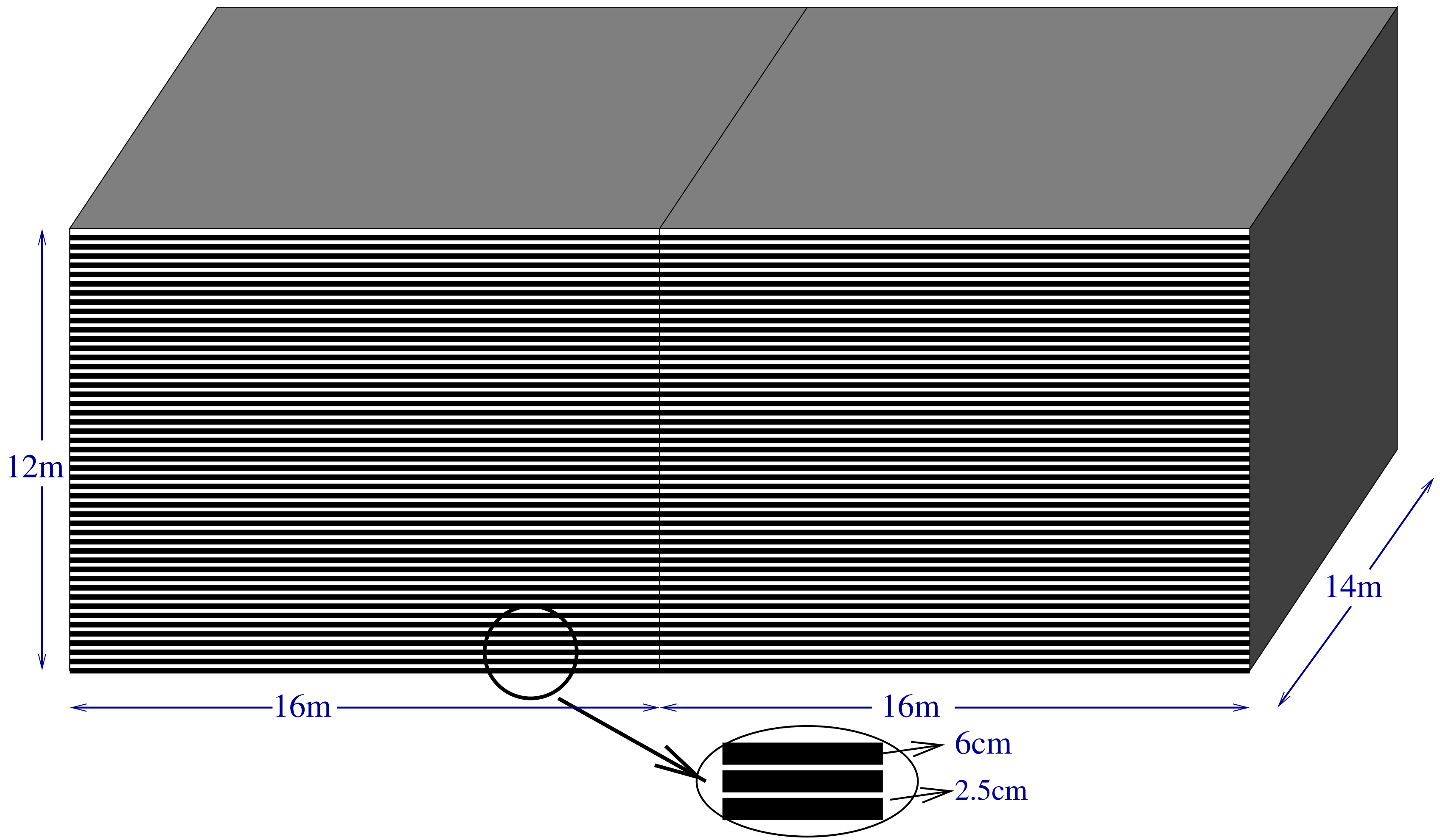
E : Fully confined (FC) events $\rightarrow$ by track length

Partially confined (PC) events $\rightarrow$ by bending in magnetic field

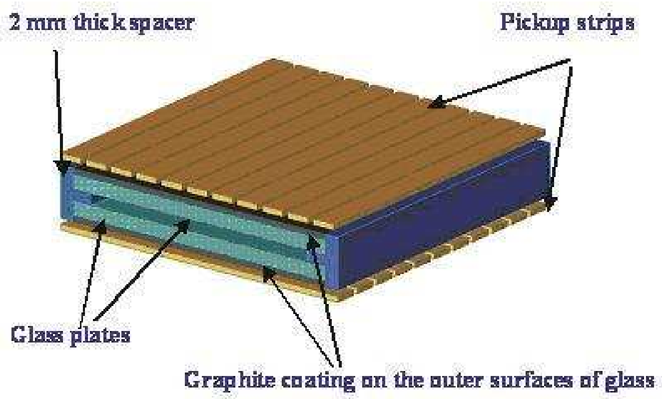
L : Direction measurement

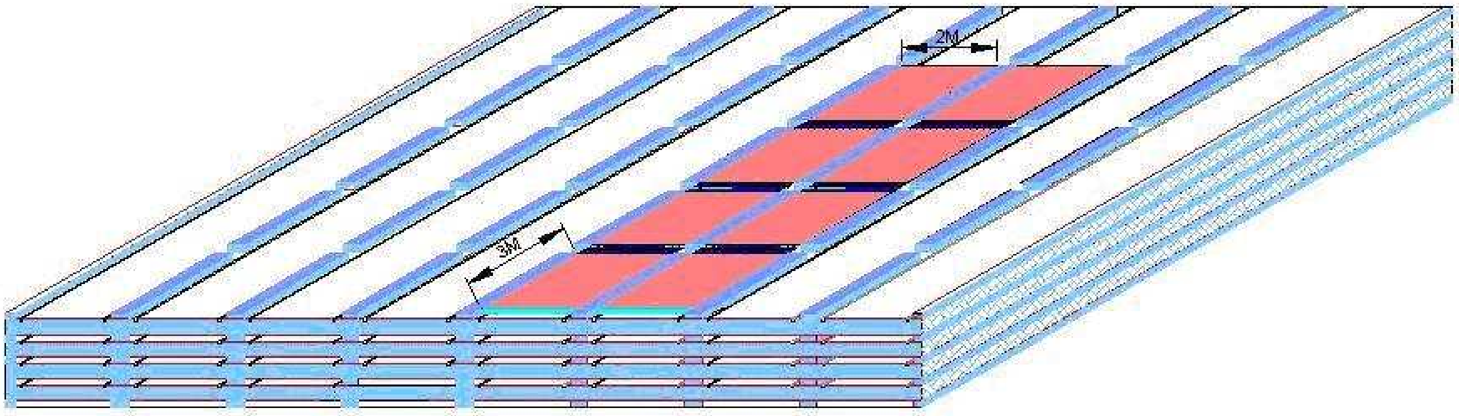
Details:

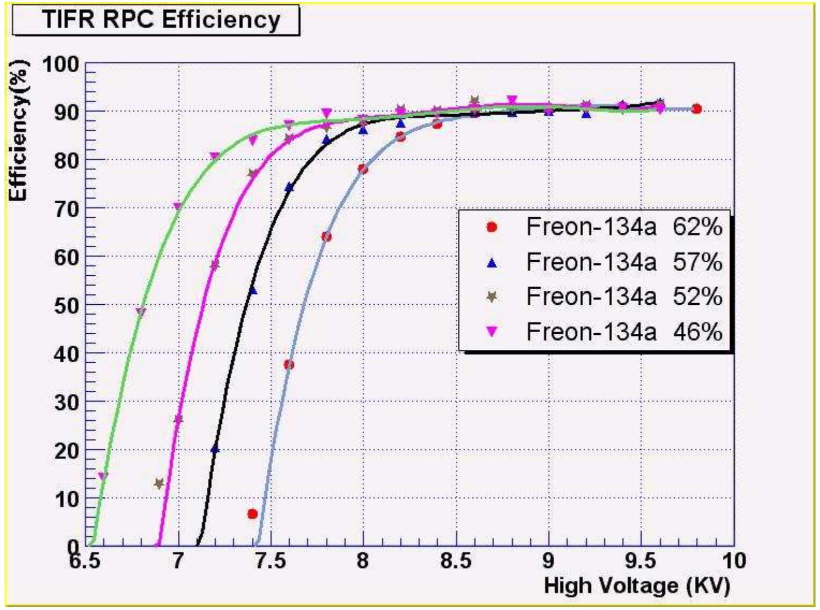
- ♣ Mass 50 kton
- ♣ size 3 module each 16 m $\times$ 16 m $\times$ 12 m (h)
- ♣ 140 layers of iron plates of thickness 6.0 cm
- ♣ Gap between two iron layer 2.5 cm; each detector chamber: $200 \times 200 \times 1$ cm^3
- ♣ Magnetic field 1 - 1.4 Tesla
- ♣ Plates arranged horizontally/vertically
- ♣ Surrounded by external layers of scintillator counter
  Veto layer identify PC events as well as muons coming from outside

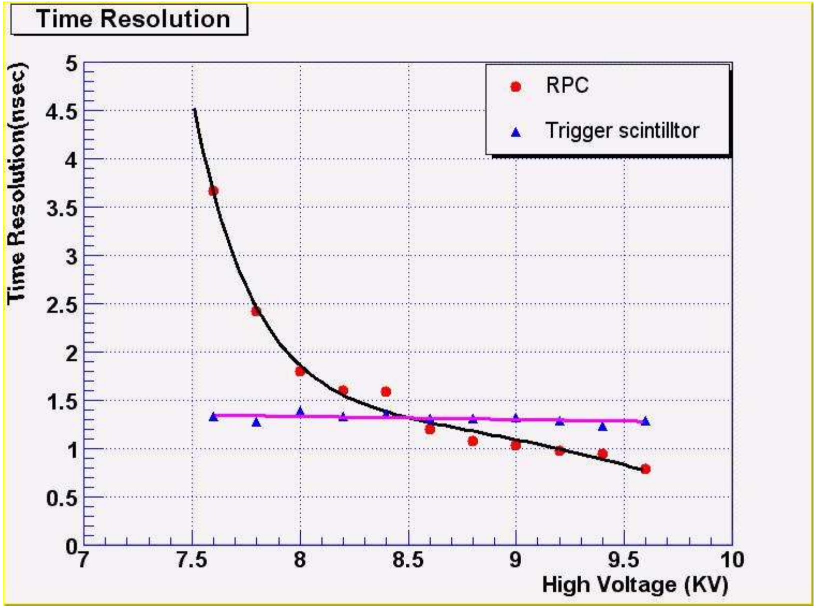


12m
16m
16m
14m
6cm
2.5cm


2 mm thick spacer
Pickup strips
Glass plates
Graphite coating on the outer surfaces of glass


2M
3M


TIFR RPC Efficiency
Efficiency(%)
100
90
80
70
60
50
40
30
20
10
0
6.5
7
7.5
8
8.5
9
9.5
10
High Voltage (KV)
Freon-134a 62%
Freon-134a 57%
Freon-134a 52%
Freon-134a 46%


Time Resolution
Time Resolution(nsec)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
7
7.5
8
8.5
9
9.5
10
High Voltage (KV)
RPC
Trigger scintilltor

Glass spark chambers

- Low cost active detectors with time resolution $\sim 10^{-9}$s
- Gas mixture of Argon, Freon and Isobutane
- 2 mm thick float glass plates with volume resistivity 10^{12} Ohms-cm. kept 2mm apart.
- Operates in spark mode, ensuring containment of spark and fast recovery
- total of 18,000 RPC detector elements.

Present status

- RPCs been built at TIFR, SINP
- Advanced gas mixing unit built in SINP, TIFR
- Efficiency of performance of the prototype at TIFR $> 90\%$ above 8.6 KeV

- Ongoing R & D

  i) RPC timing, charge distribution, noise, cross talk

  ii) Test of linearity of mean charge vs. Voltage

  iii) Performance with different gas composition and mixing

  iv) MAGNET DESIGN: at VECC and BARC

  v). A PROTOTYPE 1 m $\times$ 1 m $\times$ 1m with the magnetic field will soon be built at VECC

Simulation

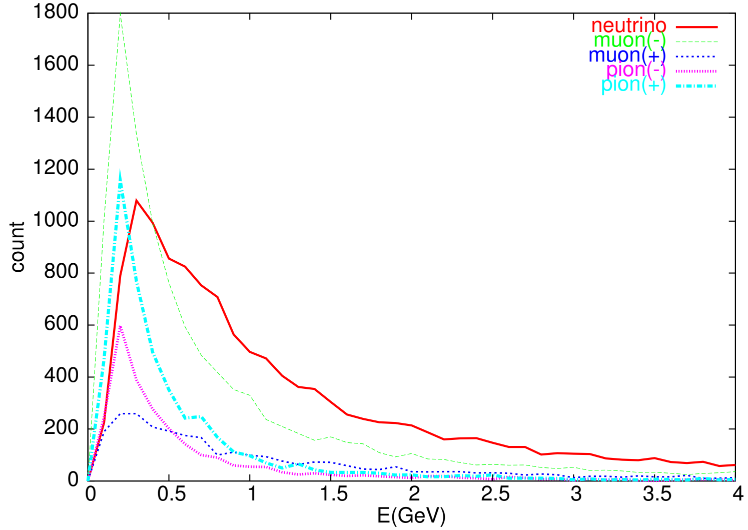
- GEANT3-based ICAL simulation program developed and used
- Atmospheric ν CC events generated using NUANCE package (hep-ph/0208030)
- 32 kton with/without magnetic field
- With horizontal iron layers (ICAL-H)
- With vertical iron layers (ICAL-V)
- A 100 kton detector (ICAL100)
- Use > 7 hits criterion for an event

$$L = (R - d)\cos\theta + \left[R^2 - (R - d)^2 \sin^2\theta\right]^{\frac{1}{2}}$$

$R \rightarrow$ radius of earth $\quad d \rightarrow$ depth of the detector.

Mirror downgoing νs with an angle $\pi - \theta$ and consider them to be the 'no oscillation' standard for upgoing νs with angle θ.

Uniform magnetic field in z-direction used
Also used uniform magnetic field in other directions as well as non-uniform fields



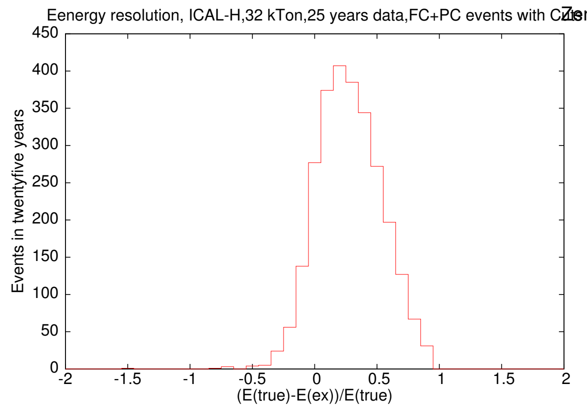
Energy distribution of ν and other particle for simulated 25 yrs data

No. of years	FC			FC + PC		
	No. of selected events	No. with correct charge identification	Charge identification efficiency (%)	No. of selected events	No. with correct charge identification	Charge identification efficiency (%)
5	2613	2451	93.8	3169	2967	93.6
25	13314	12420	93.3	16136	15027	93.1

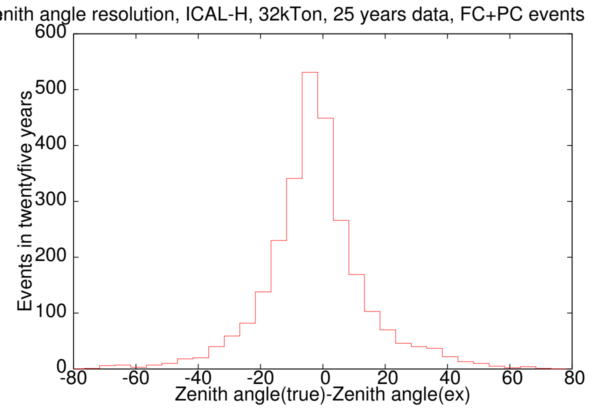
ICAL-H charge identification efficiency for simulated 5-year and 25-year atmospheric neutrino data samples.

(With magnetic field)

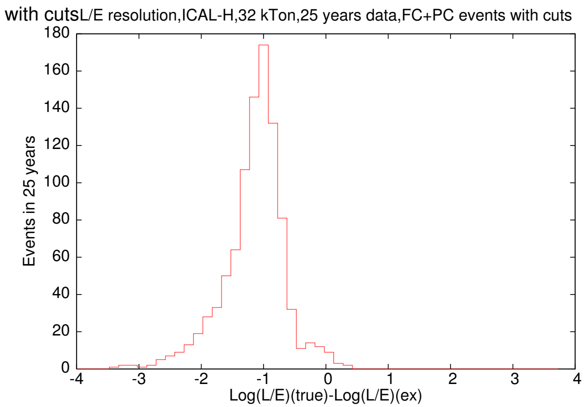
Resolution



Energy

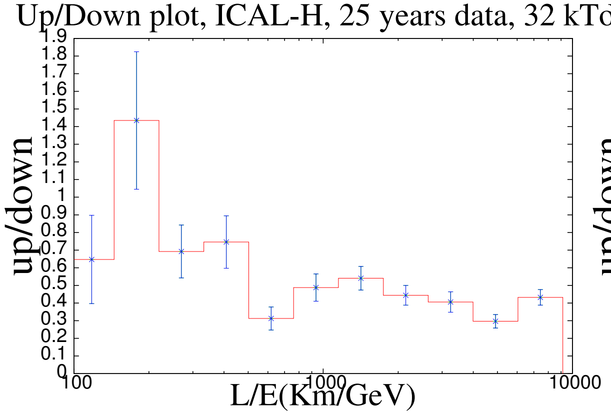


Zenith angle

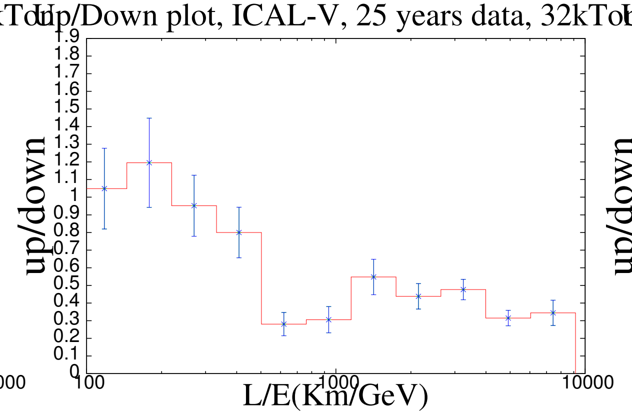


L/E

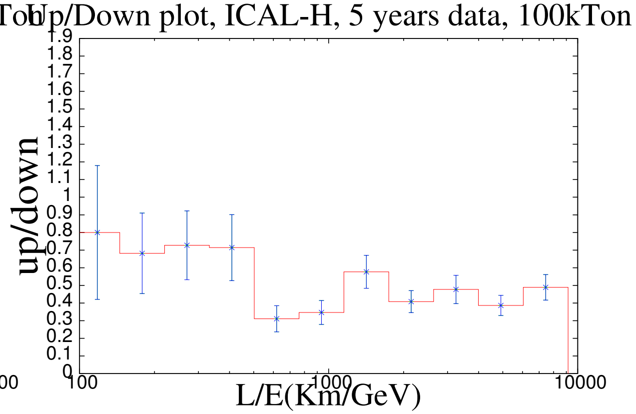
Up/Down Plots



ICAL-H (25yr)



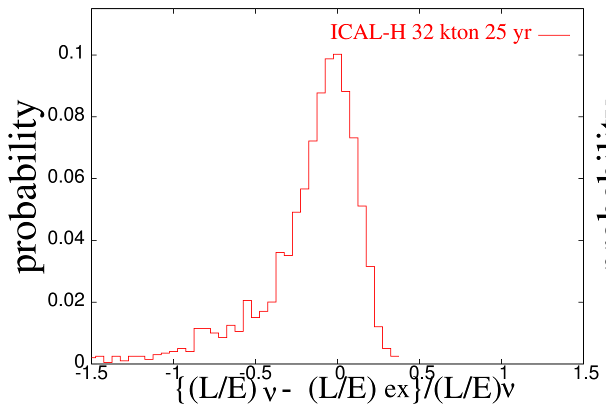
ICAL-V (25 yr)



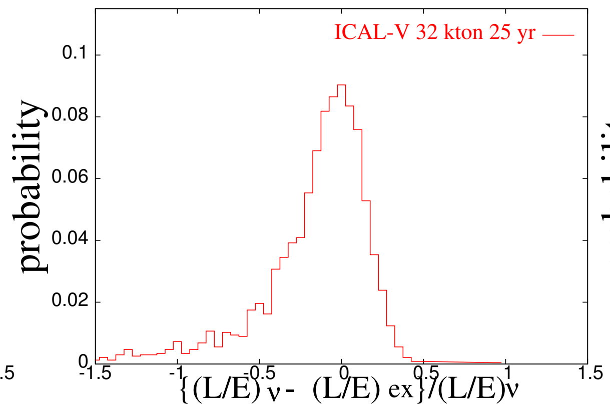
ICAL100 (5 yr)

(Without magnetic field)

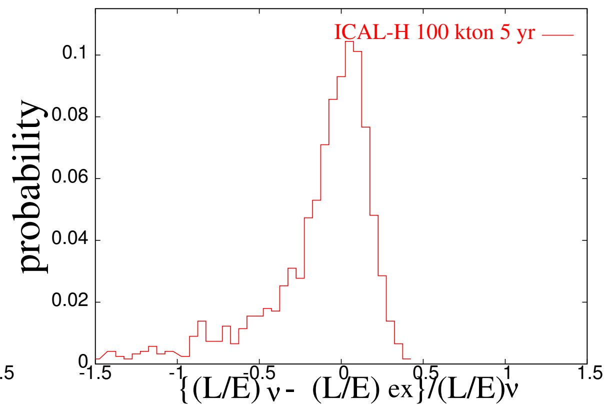
Resolution



ICAL-H (25yr)

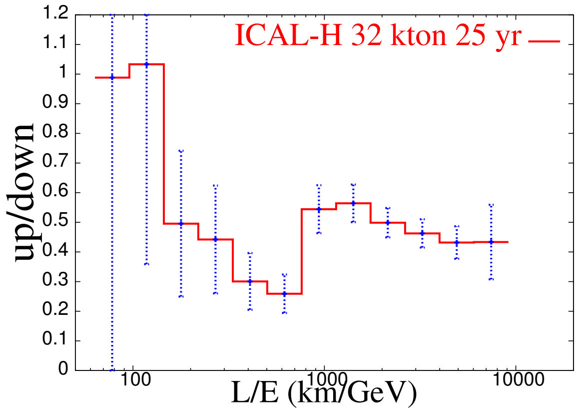


ICAL-V (25 yr)

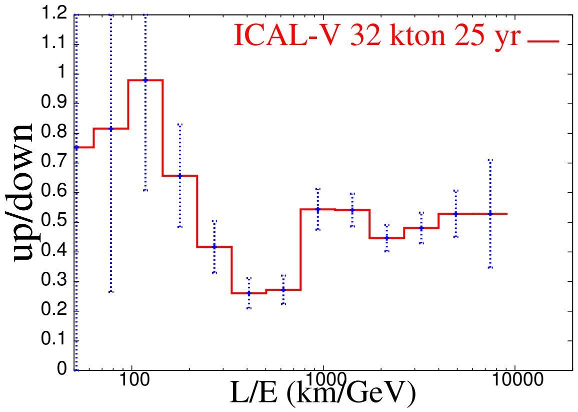


ICAL100 (5 yr)

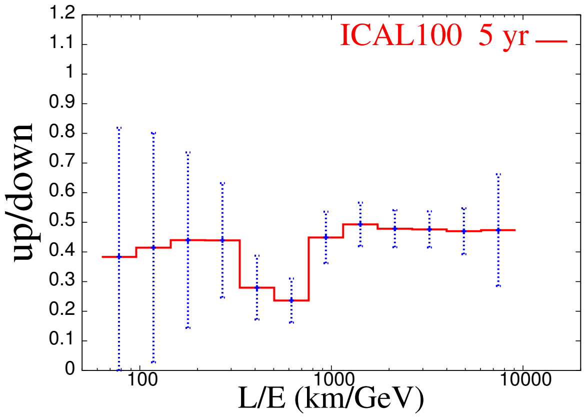
Up/Down Plots



ICAL-H (25yr)



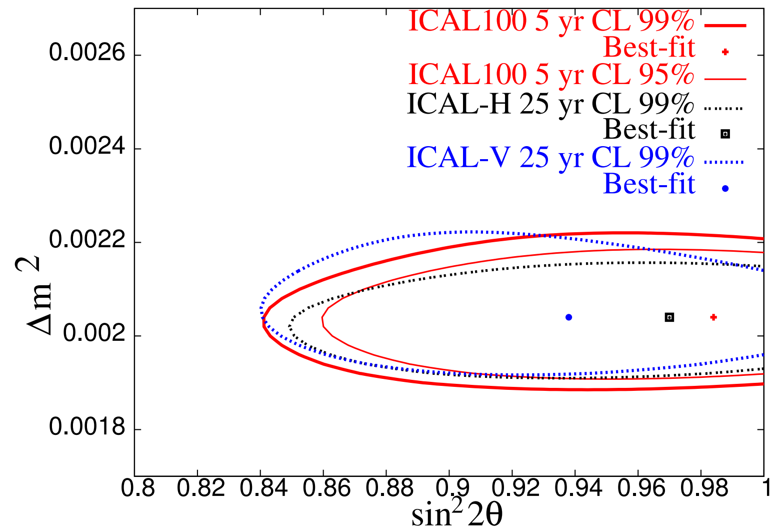
ICAL-V (25 yr)



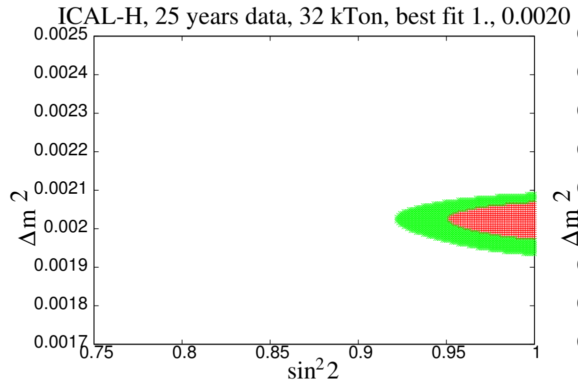
ICAL100 (5 yr)

Contour plots

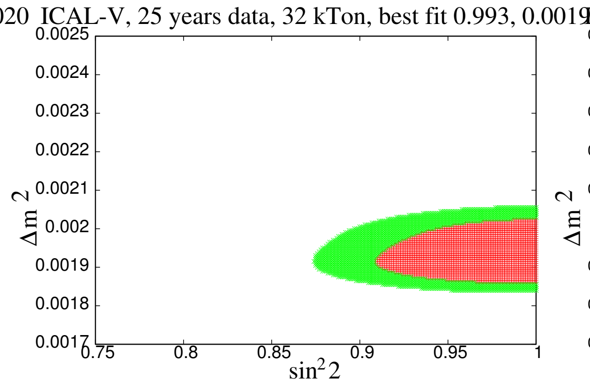
(Without magnetic field)



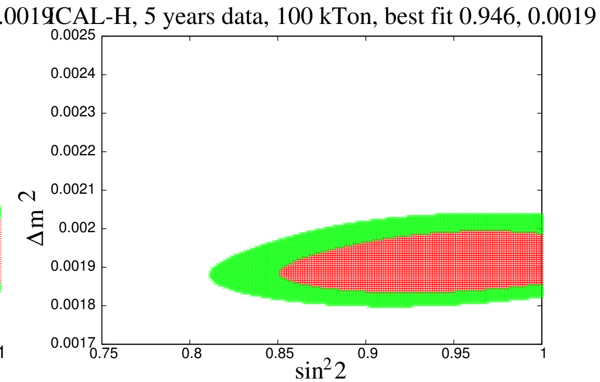
(With magnetic field)



ICAL-H (25yr)

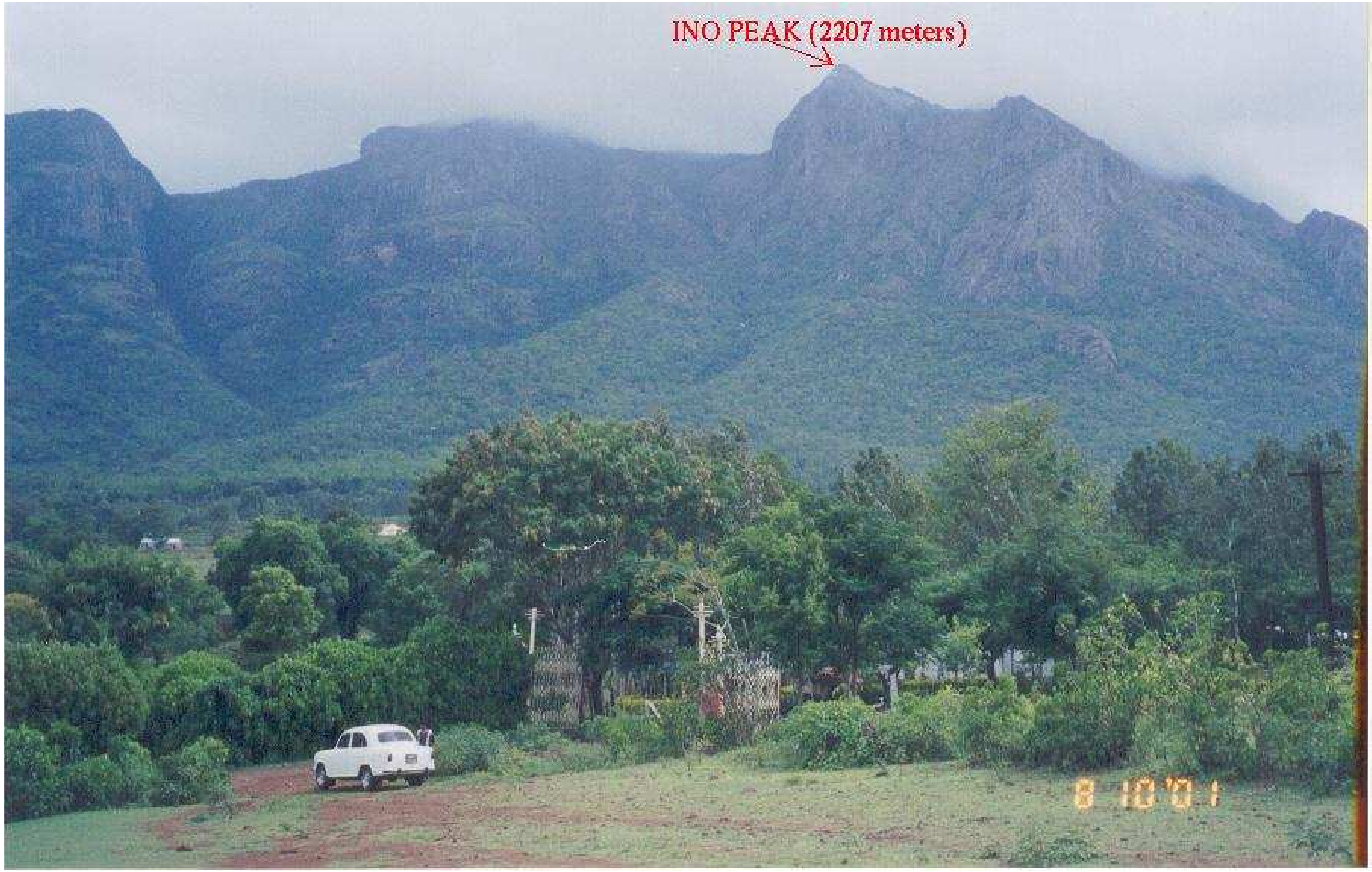


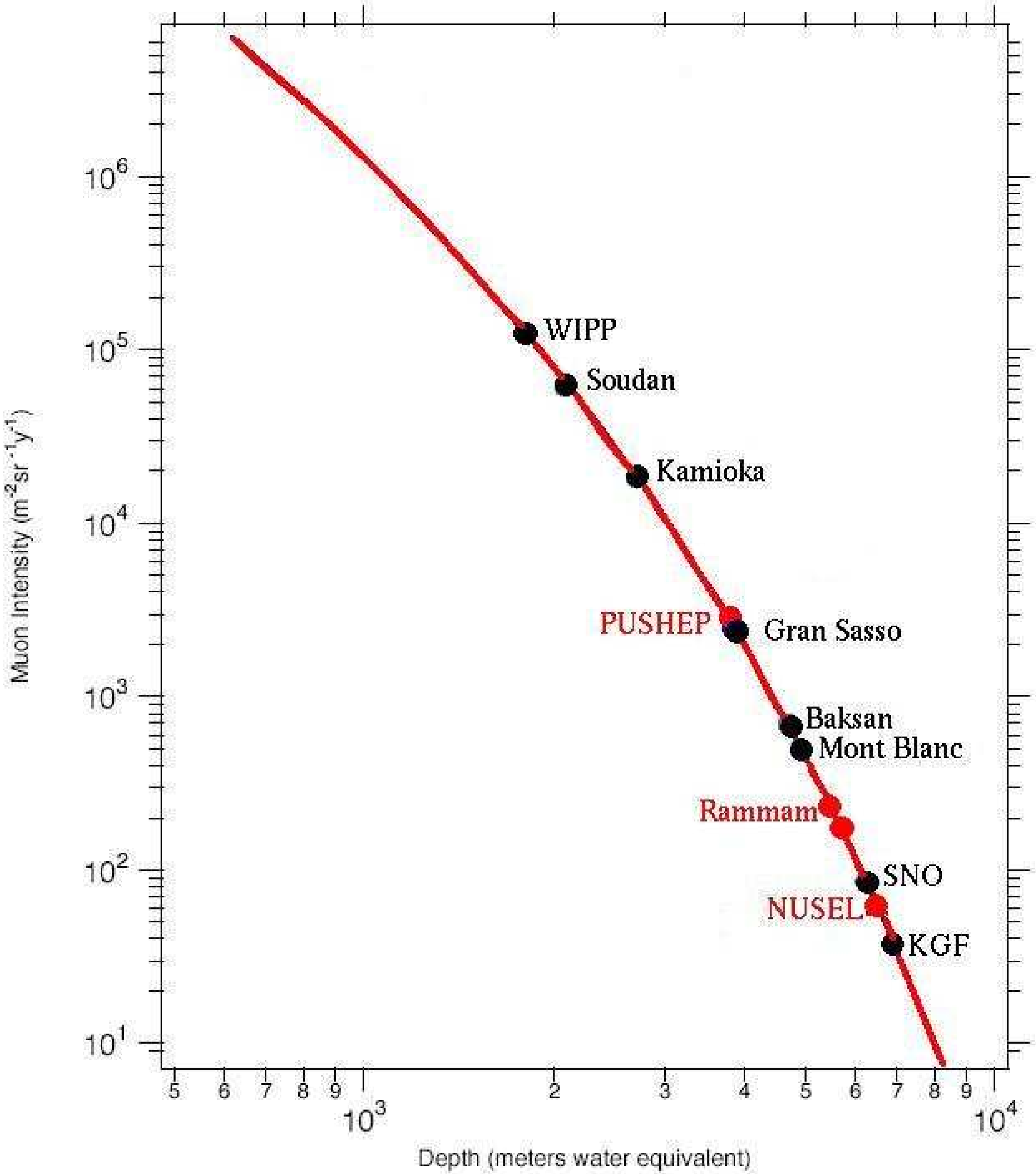
ICAL-V (25 yr)



ICAL100 (5 yr)


Singara Power House
Rock disposal
Ridge


INO PEAK (2207 meters)
8 10'01

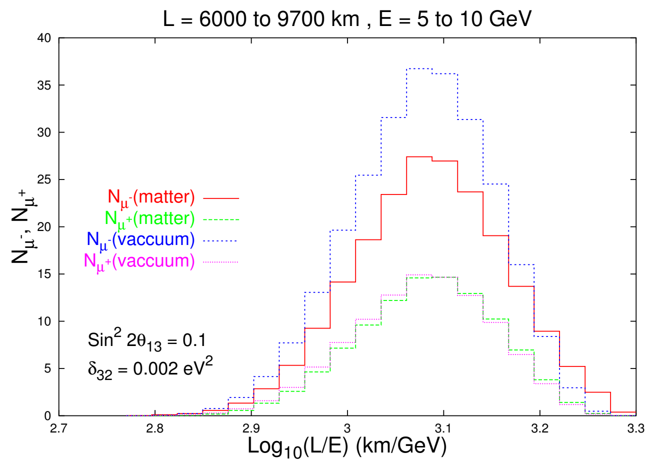

Muon Intensity (m^{-2}sr^{-1}y^{-1})
Depth (meters water equivalent)
WIPP
Soudan
Kamioka
PUSHEP
Gran Sasso
Baksan
Mont Blanc
Rammam
SNO
NUSEL
KGF

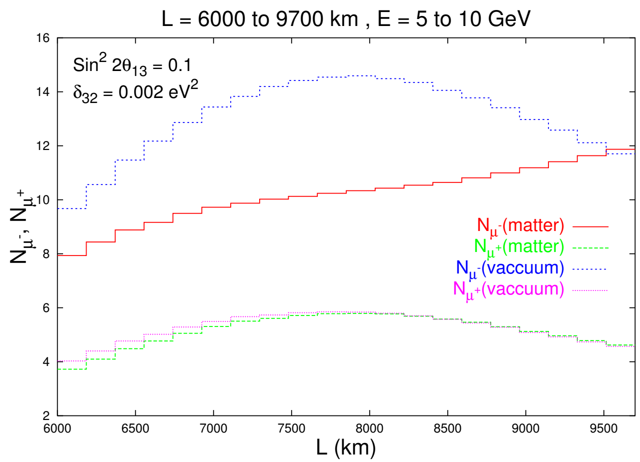
Physics issues

i) With atmospheric neutrinos

Matter effect

- No. of muons depends on $P_{\mu\mu}$ and $P_{e\mu}$
- The effect on ν different from that on $\bar{\nu}$





With $E = 5 - 10$ GeV, $L \sim 6000 - 9700$ km, 50% μ identification, Exposure 1000 kton-yr, Δ_{32}= 0.002 eV^2 and $\sin^2 2\theta_{13} = 0.1$

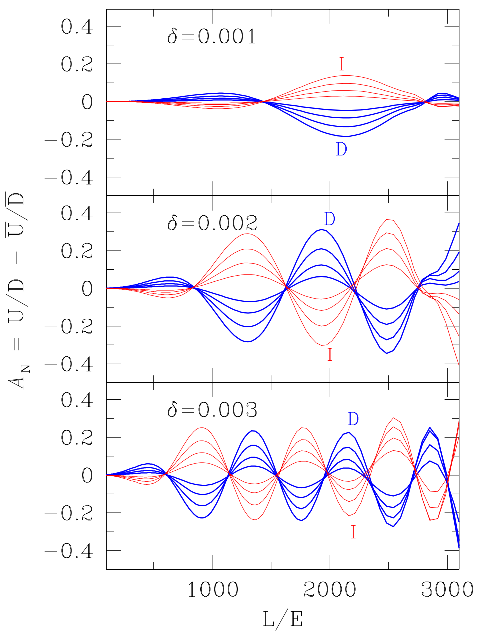
Total μ^+ events: vacuum 105	Matter 103	
Total μ^- events: vacuum 261	Matter 204	A 4σ effect

For $\sin^2 2\theta_{13} = 0.05$ it is a 2σ effect

Normal vs. Inverted mass hiearchy

Define $A_N(x) = \frac{U}{D}(x) - \frac{\bar{U}}{\bar{D}}(x)$

$U(D) \rightarrow$ neutrinos $\bar{U}(\bar{D}) \rightarrow$ antineutrinos, $E_{\rm min} = 4$ GeV and $\delta = \Delta_{32}$=1, 2, 3×10^{-3} eV^2.
Calculated for both normal and inverted with $\theta_{13} = 5°, 7°, 9°, 11°$.

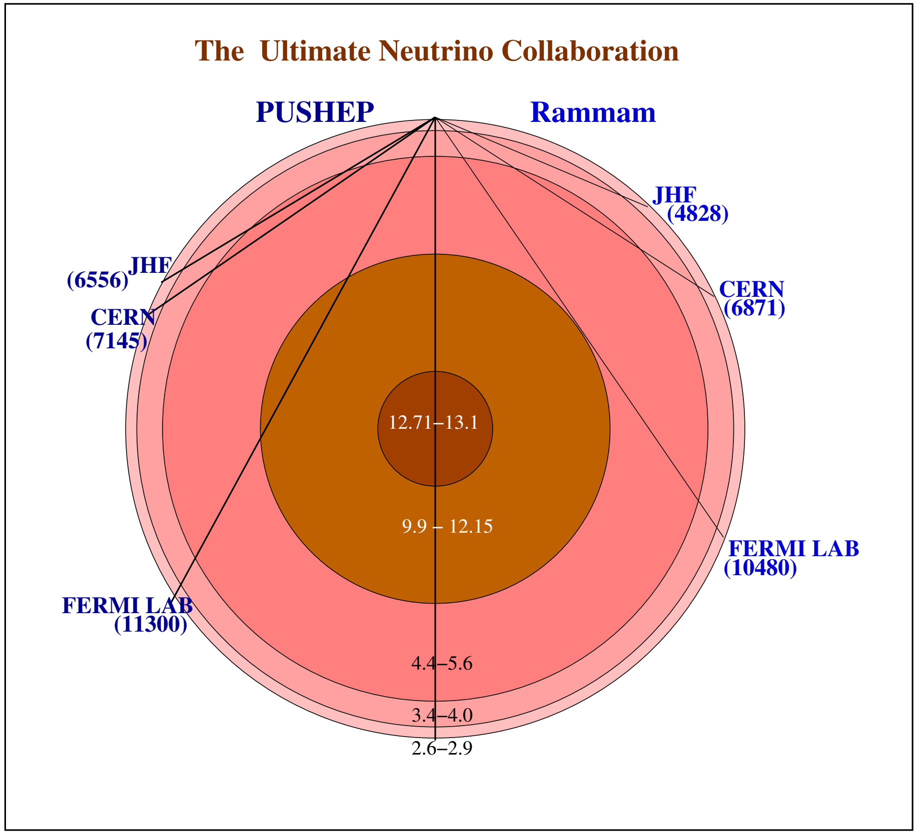


Need about 500-1000 kton-year to resolve the 2 mass hiearchies.

Also $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{\rm sterile}$ can be studied.

ii) With ν factories

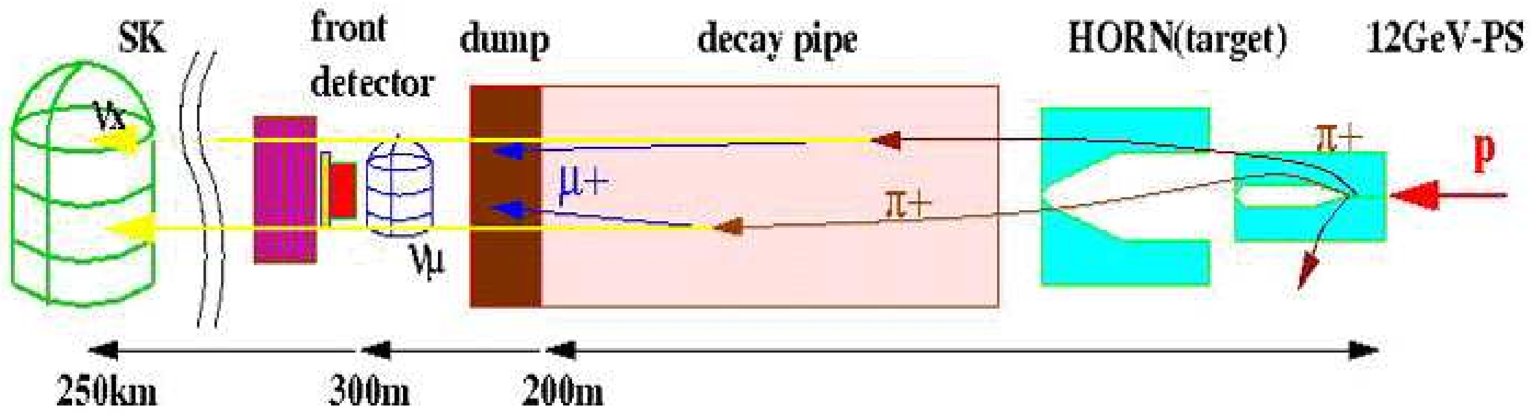
Intense controlled high luminosity ν-beam ($\nu_\mu + \bar{\nu}_e$ or $\nu_e + \bar{\nu}_\mu$) from muon storage rings



Baselength (km) from the proposed νs factories

Long Baseline Neutrino Oscillation Experiment

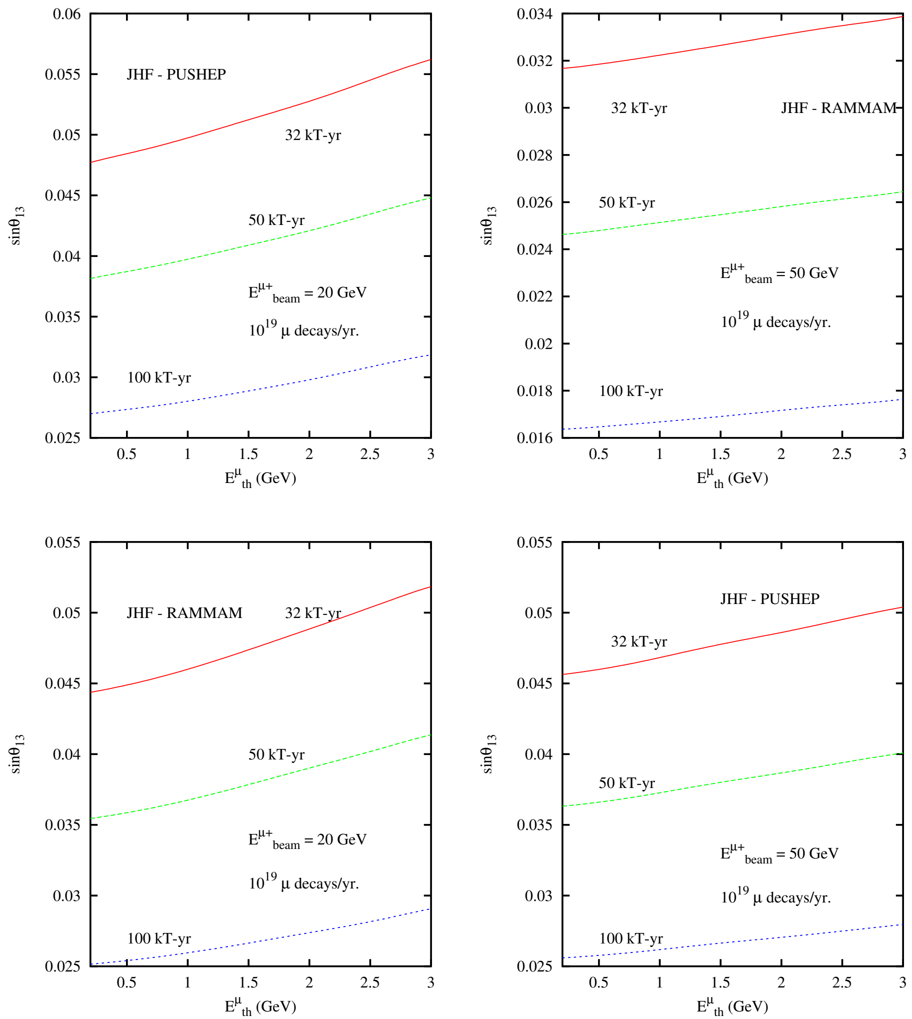
ν_μs from 12 GeV proton synchroton accelerator (KEK)
9with front detector, 1 kton water Cherenkov)
$\Downarrow$ (250km)
Super-Kamiokande (Far Detector)



Determination of θ_{13}

Involve signal of wrong sign muon in $\nu_e \rightarrow \nu_\mu$ oscillation for a given kton-yr expsure.

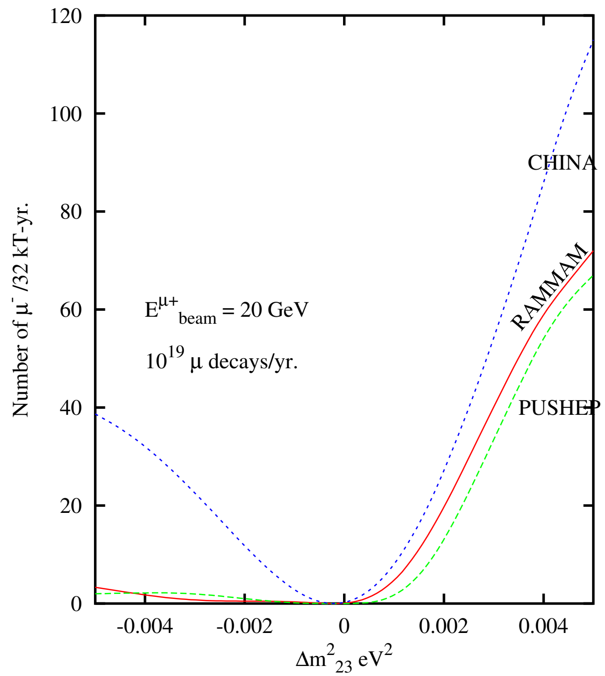
$$E^{\mu^+} = 50/20 \text{ GeV}, \ 10^{19} \text{ decays/yr}$$



Determination of mass hierarchy

For small θ_{13} and if matter pot. $A \sim \frac{E_\nu}{\Delta_{32}} > 0,\ \nu_e \to \nu_\mu$ enhanced and $\bar{\nu}_e \to \bar{\nu}_\mu$ suppressed

Converse if $A \sim \frac{E_\nu}{\Delta_{32}} < 0.$



For 32 kton-yr. exposure E^{μ^+} =20 GeV and 10^{19} decays/yr

Also can probe CP violation in leptonic sector

INTRODUCTION TO SUPERNOVA NEUTRINOS

- Exploding star, brighter than an entire galaxy (i.e. several billion stars)
- EM radiation takes a small fraction of energy : 10^{49-50} ergs
- K.E. of exploding matter : 10^{51} ergs
- ENERGY CARRIED BY THE INVISIBLE NEUTRINOS : 10^{53} ERGS
- In our galaxy seen by the naked eye in last 1000 years:
  1006, 1954 (Crab Nebula), 1572 (Tyco), 1604 (Kepler)
- Baade+Zwicky (1934): Collapse of large stars $\longrightarrow$ explosion w Neutron star/ black hole
- TYPE II - Core Collapse Supernovae - Exact mechanism of Explosion?
- Involves Astrophysics+ Particle Physics + Nuclear Physics....
- NEUTRINO detection beyond the sun : DETECTION OF 1987A (11 + 8 ν's)
- Huge flux of neutrinos emitted over tens of seconds during explosion $\longrightarrow$ cooling to neutron star

DETECTION OF SUPERNOVA NEUTRINOS AT KamLAND DETECTOR

- KamLAND: 1 kton of liquid scintillator (C_nH_{2n}) at the Kamioka mines
- Use this to learn about ν oscillation

  Solar sector : $\Delta m^2_\odot \equiv \Delta m^2_{21} = 8.0 \times 10^{-5} eV^2$;sin^2($\theta_{12}$)=0.28 Cl, Ga, H_2O, D_2O

  Atmospheric sector: $\Delta^2_{atm} \equiv \Delta m^2_{32} = 2.1 \times 10^{-3} eV^2$:sin^2(θ_{23}=1.0 H_2O

  These sectors are coupled by : θ_{13}; (CHOOZ) $sin^2_{13} \leq 0.03$
- OUTSTANDING ISSUES:

  a). Sign of $\Delta_{31} = m_3^2 - m_1^2$

  $\Delta_{31} > 0$ Normal Mass Hierarchy (NH)

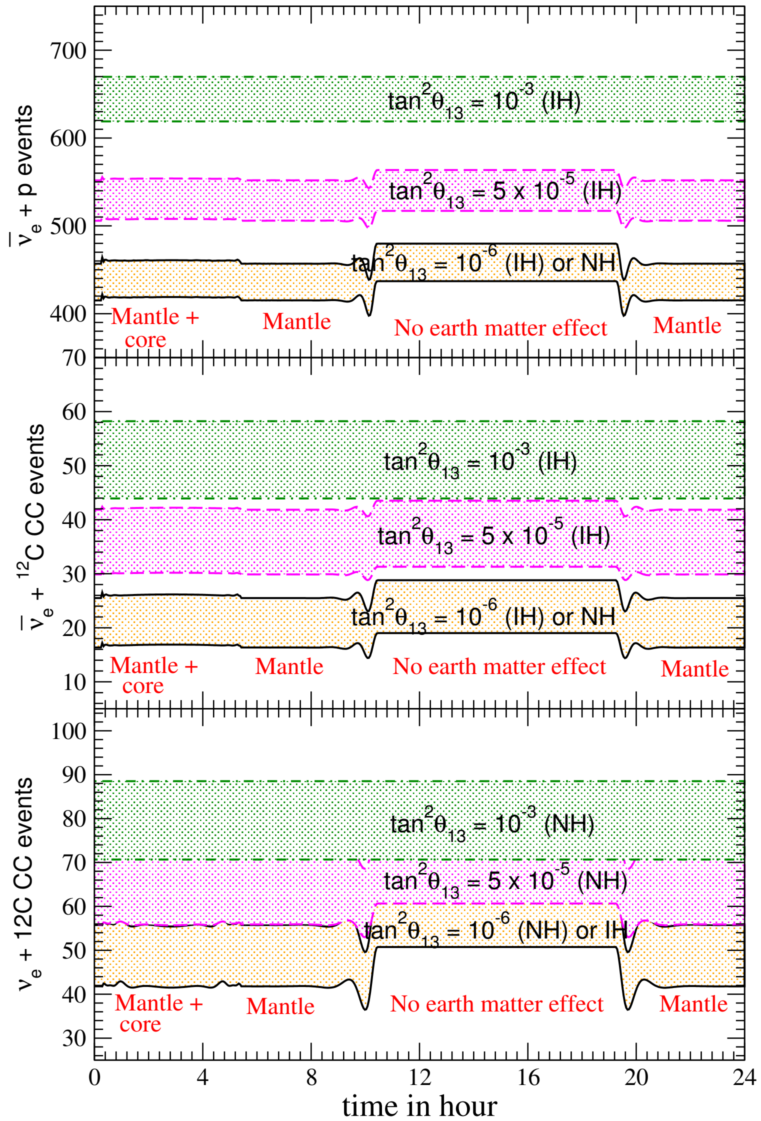
  $\Delta_{31} < 0$ Inverted Mass Hierarchy (IH)

  b). How small is θ_{13}?
- Assume a SN event at the Galactic Centre (declination $\delta_s = -28.9^o$) The distance is 10 kpc. Also T_{ν_e}=3.5 MeV, $T_{\bar{\nu}_e}$=5.0 MeV and T_x=8.0 MeV
- Reactions at the detector:

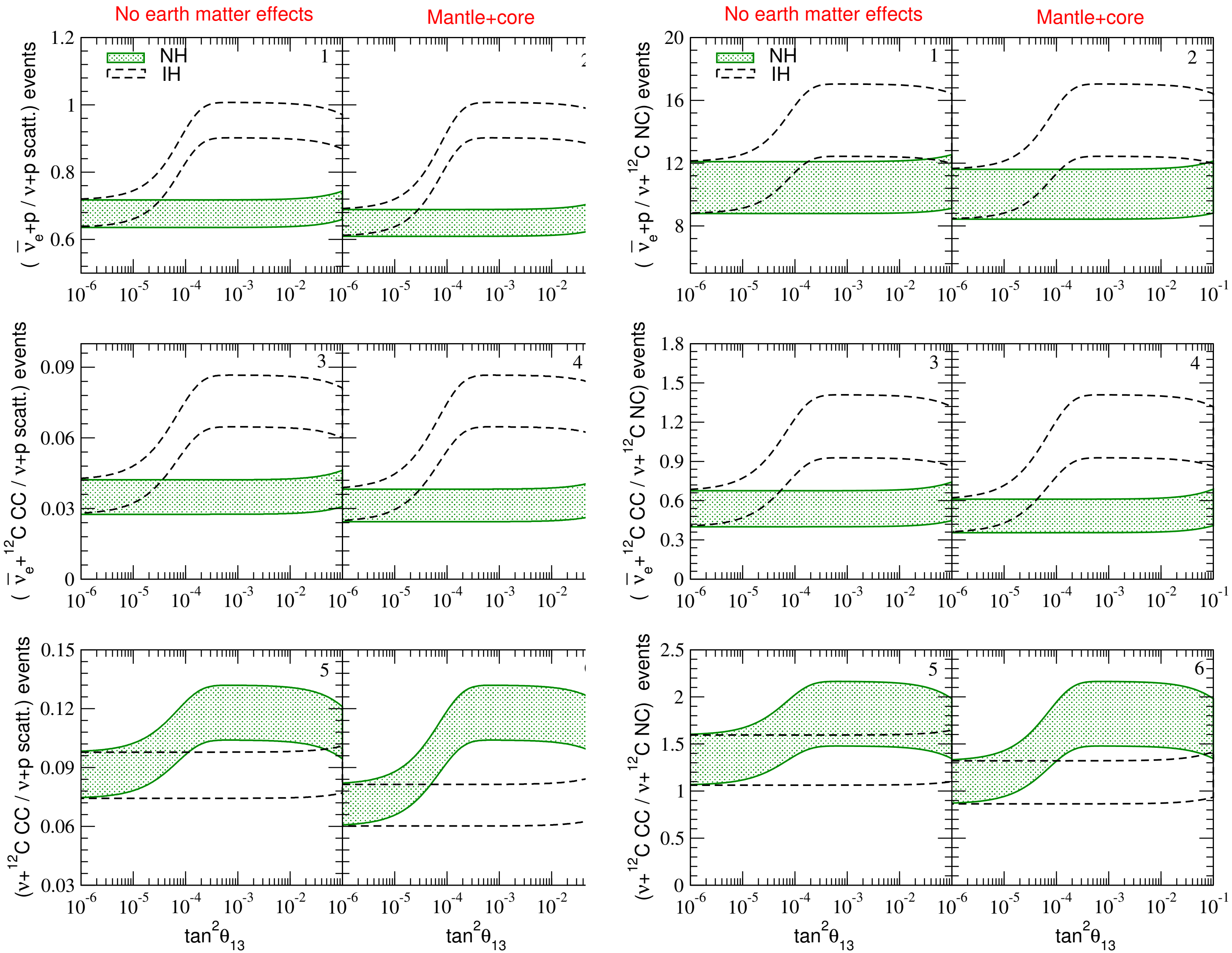
  CC capture of $\bar{\nu}_e$ on p: $\bar{\nu}_e + p \rightarrow e^+ + n$; Elastic Scatterng on p: $\nu + p \rightarrow \nu + p$

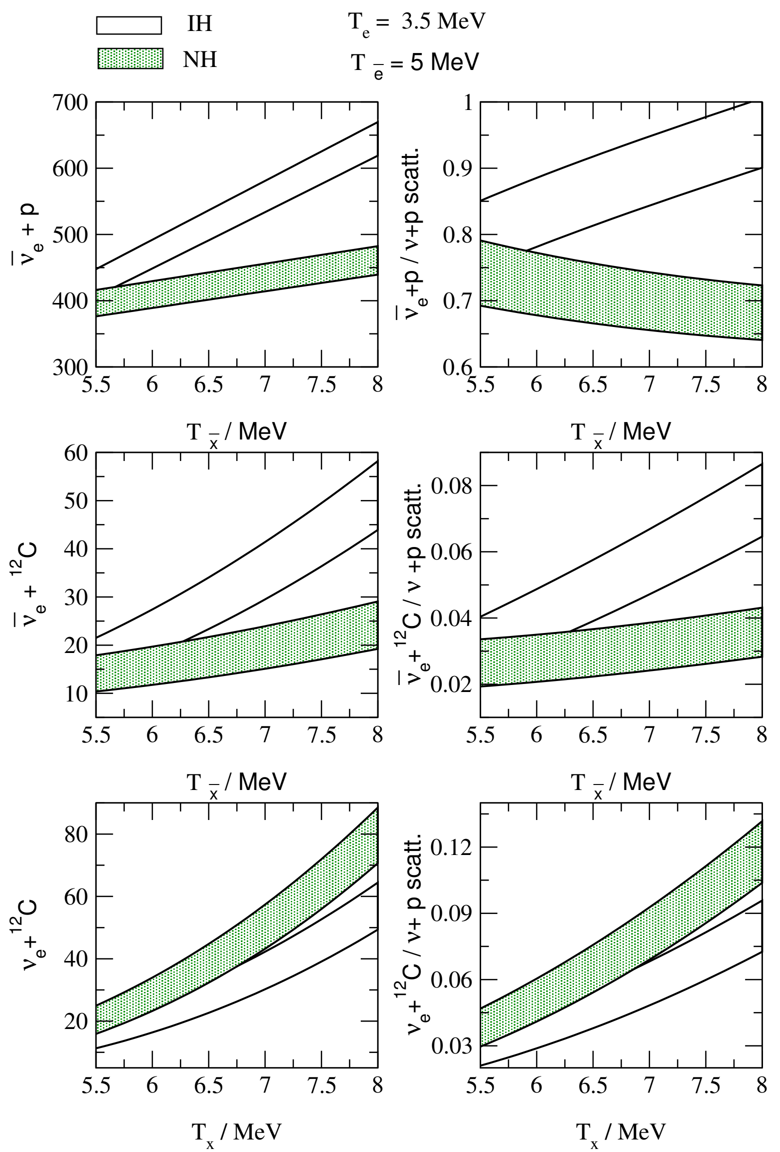
  CC capture of $\bar{\nu}_e$ on ^{12}C : $\bar{\nu}_e +^{12} C + e^-$; NC excitation on ^{12}C : $\nu(\bar{\nu}) +^{12} C \rightarrow^{12} C^* + \nu(\bar{\nu})$

FOR KNOWN VALUES OF θ_{13} AND IDENTIFIED MASS HIERARCHY ONE CAN FIND THE LUMINOSITY MORE ACCURATELY



A. Bandyopadhyay, S. Choubey, S. Goswami an K. Kar (2004)





IH
NH
T_e = 3.5 MeV
$T_{\bar{e}}$ = 5 MeV
$\bar{\nu}_e + p$
$\bar{\nu}_e$+p / ν+p scatt.
$T_{\bar{x}}$ / MeV
$\bar{\nu}_e$ + ^{12}C
$\bar{\nu}_e$+^{12}C / ν +p scatt.
ν_e+^{12}C
ν_e+^{12}C / ν+ p scatt.
T_x / MeV

OTHER AREAS IN ASTROPHYSICS: hep-ph/0512179

Probing the Cosmic Ray 'Knee' and Very High Energy Prompt Muon and Neutrino fluxes via Underground Muons, by Raj Gandhi and Sudhakar Panda

Very High E (1TeV to 1000 TeV) using 100 kTon iron calorimeter

India-based Neutrino Observatory wants to :

- Verify oscillation hypothesis and find Δm^2_{32} and θ_{23}
- Find the mass hierarchy
- Stronger limit on 13 mixing angle
- INO Detector R & D, Simulation, Site preparation all progressing well.

THESE FINDING WILL HAVE IMPORTANT EFFECTS ON PREDICTION FOR DETECTION OF FUTURE SUPERNOVA NEUTRINOS AND OTHER AREAS OF ASTROPHYSICS WITH NEUTRINOS

ALSO A NUMBER OF IMPORTANT EXPERIMENTS FOR NUCLEAR ASTROPHYSICS IN THE UNDERGROUND FACILITY IN FUTURE

ACKNOWLEDGEMENT: INO Collaboration