Future Atmospheric Neutrino Experiments

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Need for new Atmospheric Neutrino Detectors

- *Experimental field of Neutrino Physics has moved to the phase of decisive and precision measurement of oscillation parameters.*
- *New and planned long base line experiments will provide bulk of the data necessary to achieve this.*
- *Is there still need for new atmospheric neutrino experiments?*

Physics with Atmospheric Neutrinos

- *It span a large range of L/E .*
- *Oscillation can be seen as a function of L/E.*
- *Possibility of observing matter effect .*
- *Sensitivity to the sign of Δm^2_{23}.*
- *Measuring θ_{13}.*
- *CP Phase measurement.*

Magnetised Iron Tracking Calorimeter

India-based Neutrino Observatory (INO) initiative

Goal: *A large mass detector with charge identification capability*

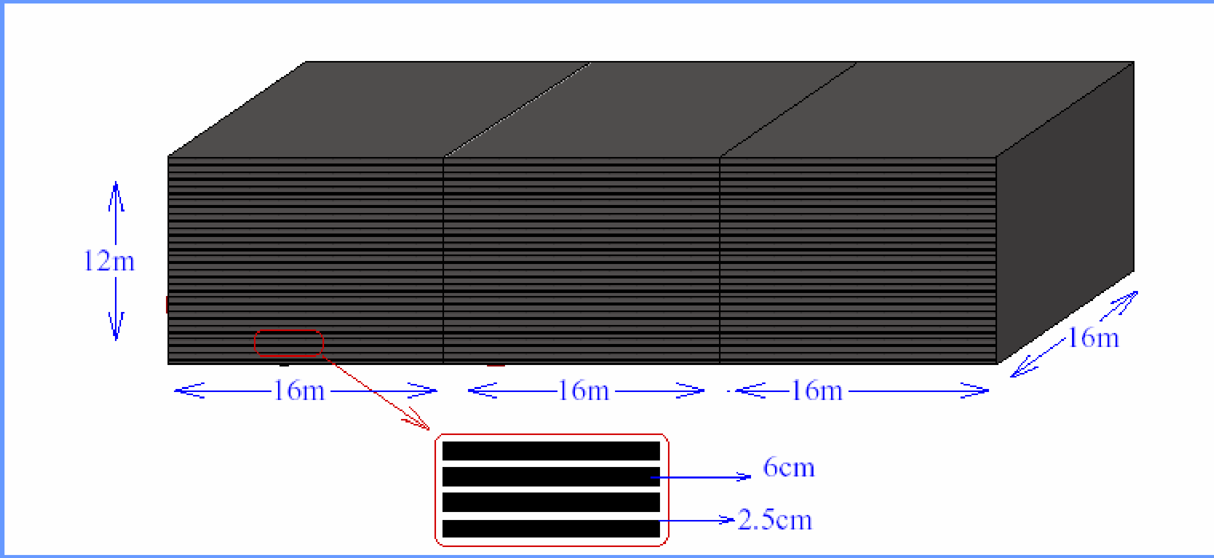
- *Two phase approach:*

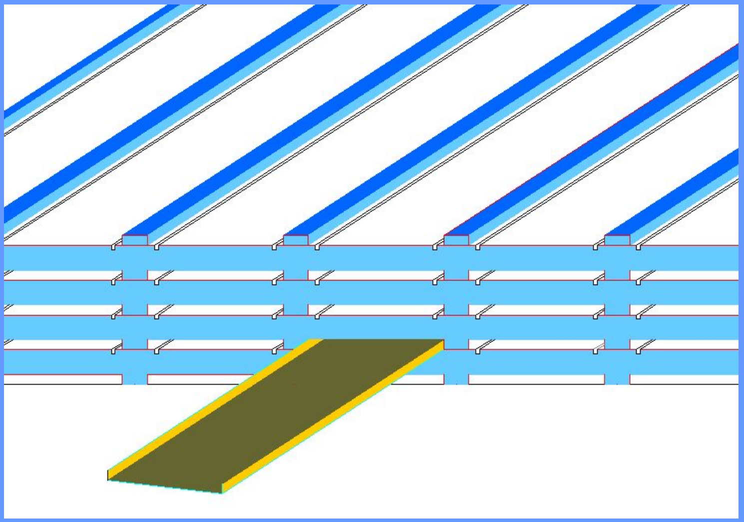
R & D and Construction	Operation of the Detector
Phase I Physics studies, Detector R & D, Site survey, Human resource development **Phase II** Construction of the detector	**Phase I** Physics with Atmospheric Neutrinos **Phase II** Physics with Neutrino beam from a factory

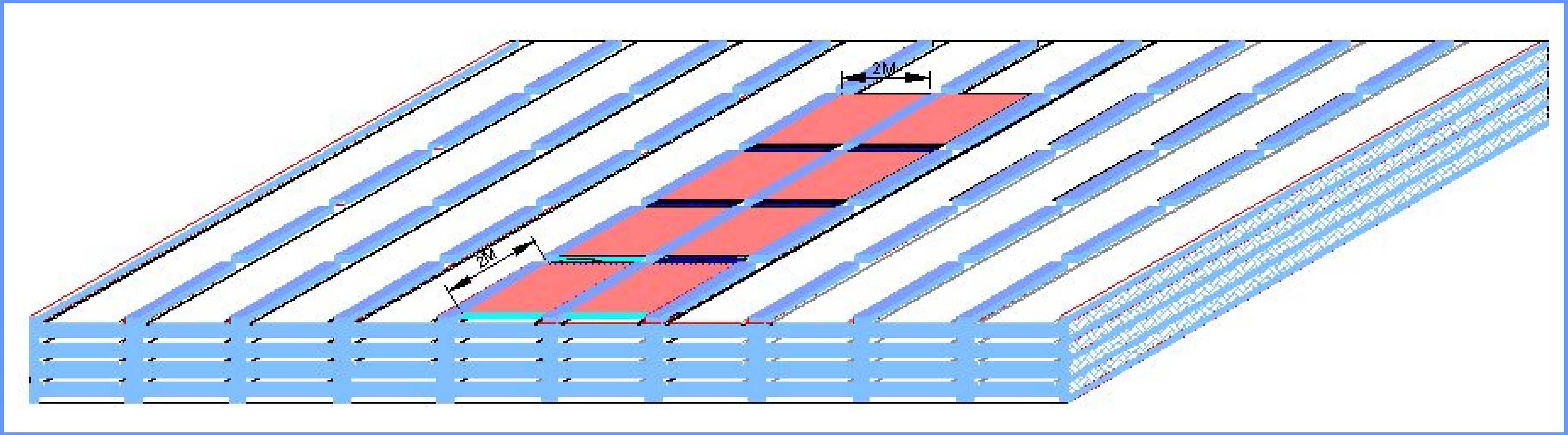
Choice of Neutrino Source and Detector

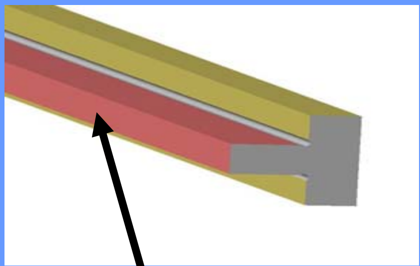
- ***Neutrino Source***
  - ***Need to cover a large L/E range.***
    - ***Large L range***
    - ***Large E_ν range***
  - ***Use Atmospheric neutrinos as source.***
- ***Detector Choice***
    - ***Should have large target mass (50-100 KT)***
    - ***Good tracking and Energy resolution (tracking calorimeter)***
    - ***Good directionality (<= 1 nsec time resolution)***
    - ***Ease of construction***
    - ***Modularity***
    - ***Complimentarity with other existing and proposed detectors***
  - ***Use magnetised iron as target mass and RPC as active detector medium.***

INO Detector Concept







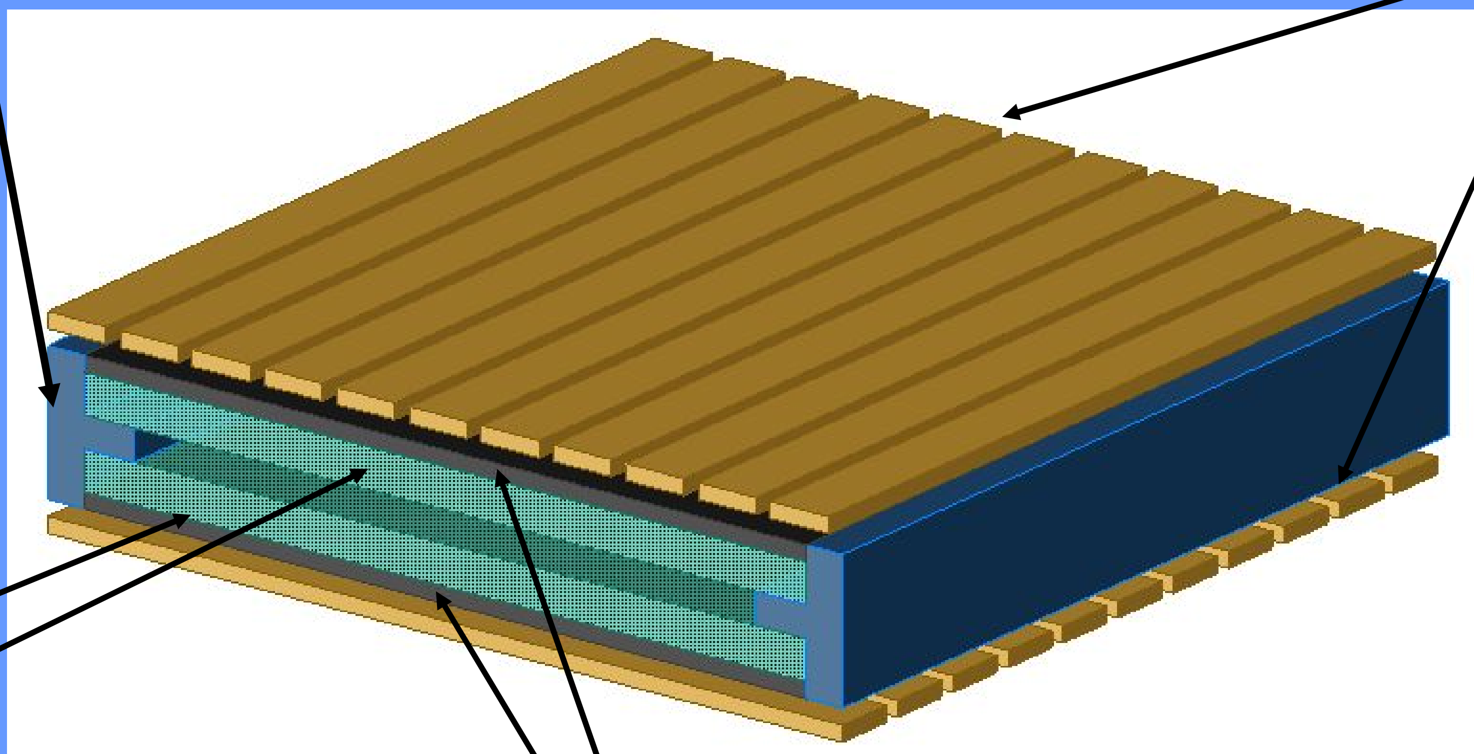


Construction of RPC

Two 2 mm thick float Glass
Separated by 2 mm spacer

2 mm thick spacer

Pickup strips



Glass plates

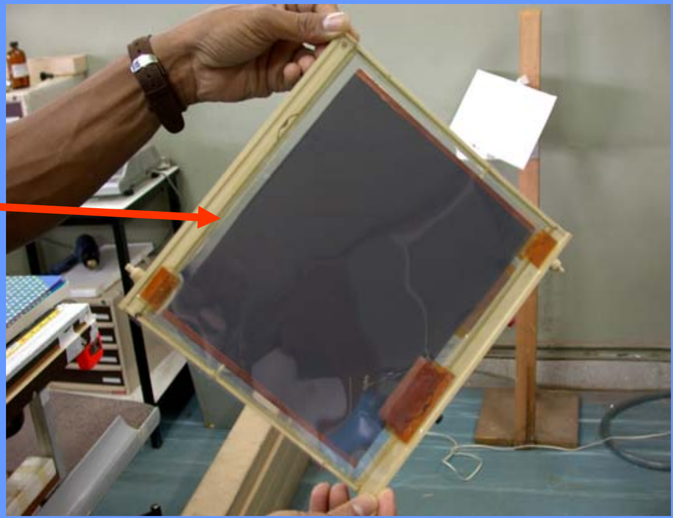
Resistive coating on the outer surfaces of glass

ICAL Detector Specifications

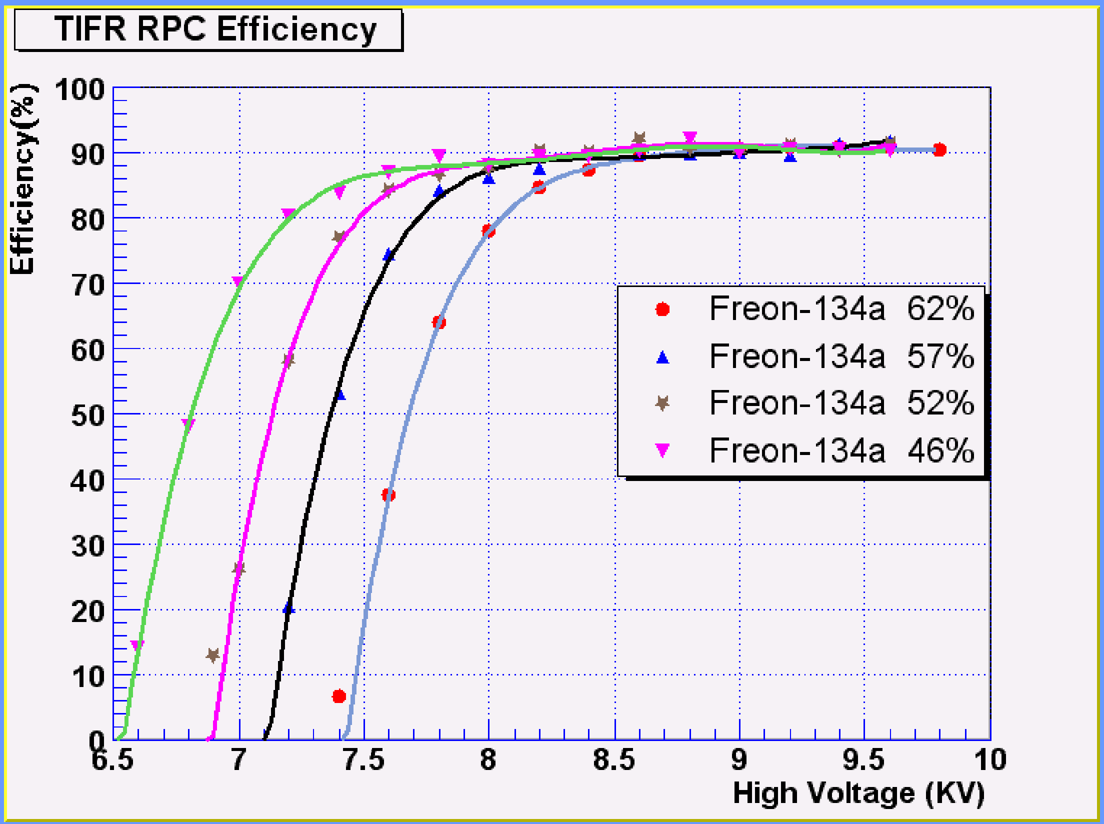
No of modules	3
Module dimension	16 m X 16 m X 12 m
Detector dimension	48 m X 16 m X 12 m
No of layers	140
Iron plate thickness	6 cm
Gap for RPC trays	2.5 cm
Magnetic field	1.3 Tesla
RPC unit dimension	2 m X 2 m
Readout strip width	3 cm
No. of RPCs/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC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

RPC R & D

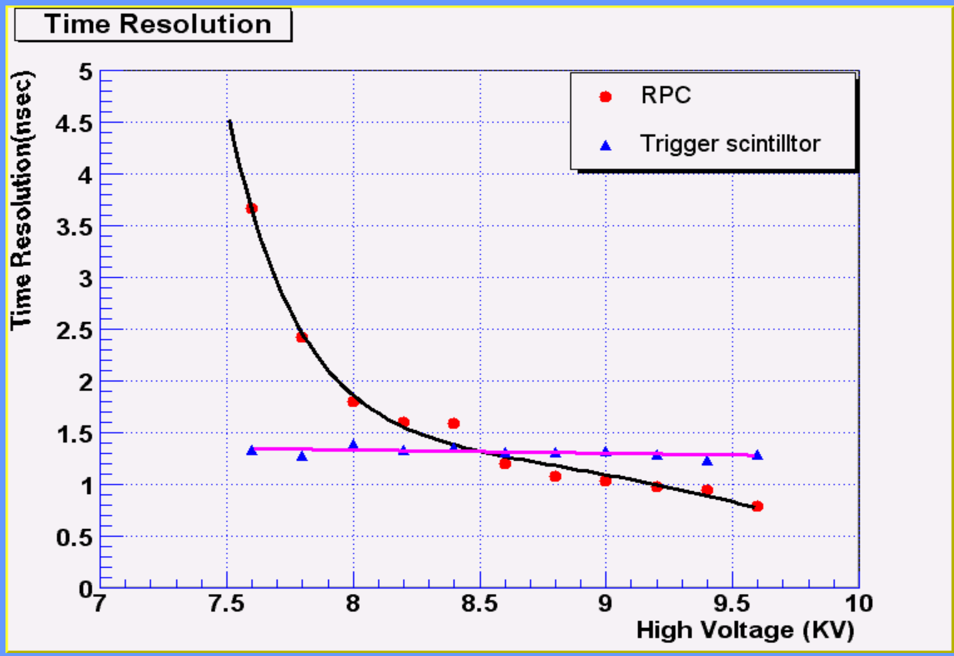
- ***Built RPCs of different sizes***
  - ***30 cm X 30 cm***
  - ***120 cm X 90 cm***



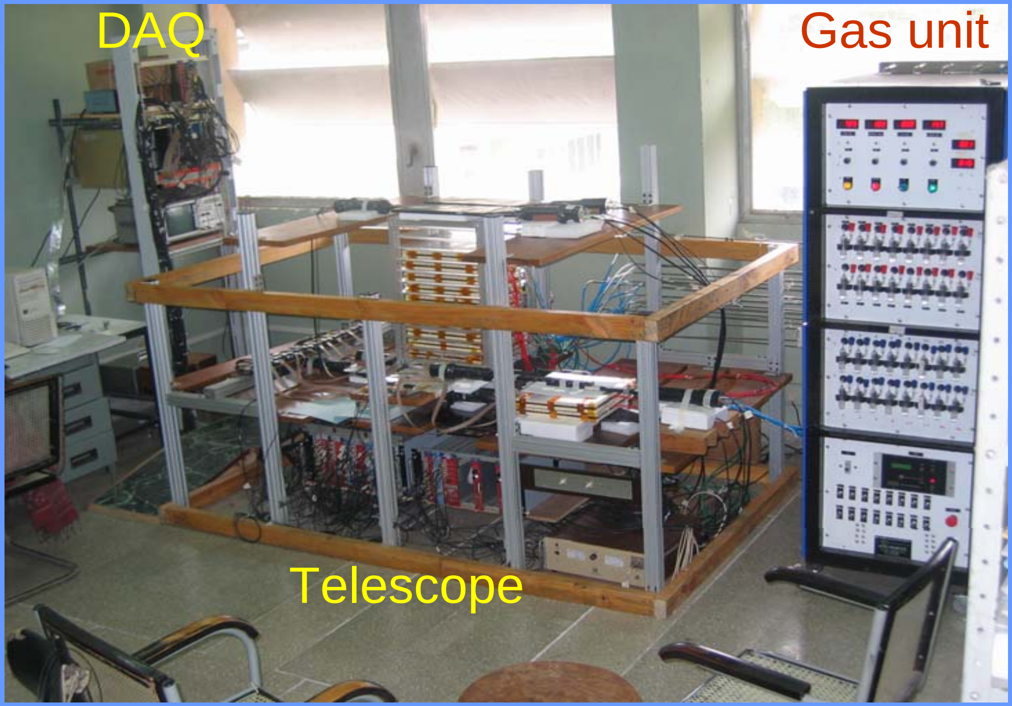
RPC Efficiencies and Timing



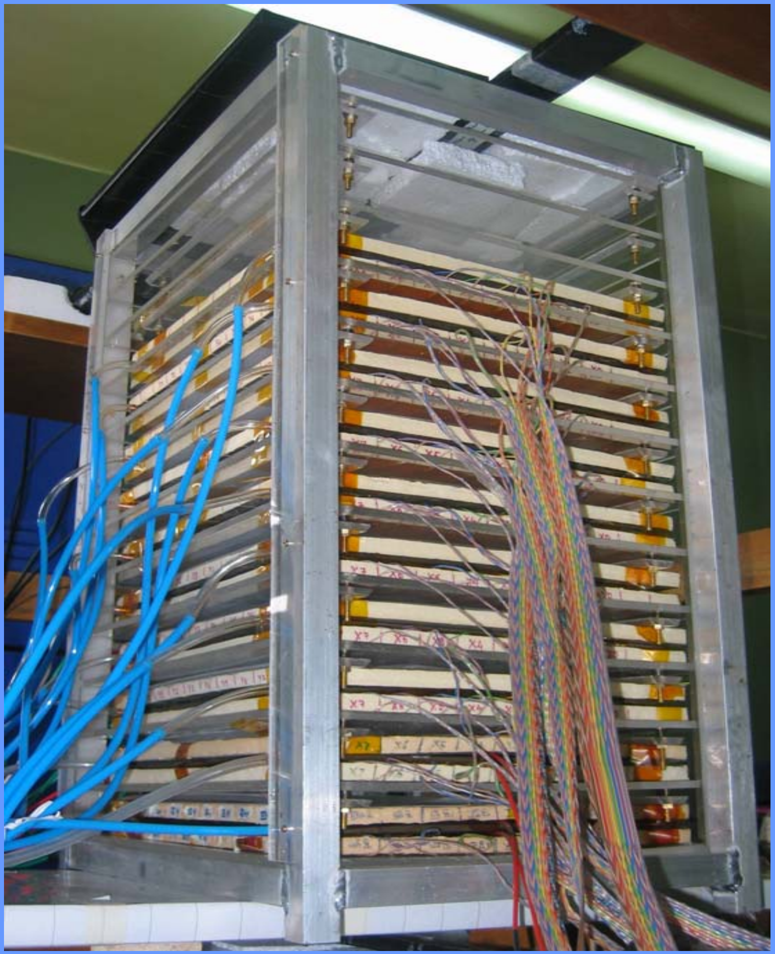
RPC working in Streamer mode



Cosmic Muon Test



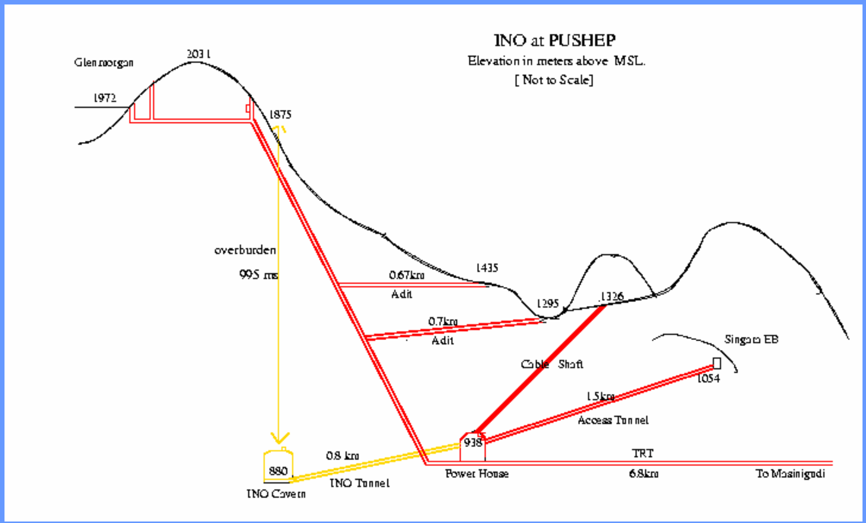
- Streamer mode (R134a=62%, Argon=30% and the rest Iso-Butane)
- Recording hits, timing, noise rates etc



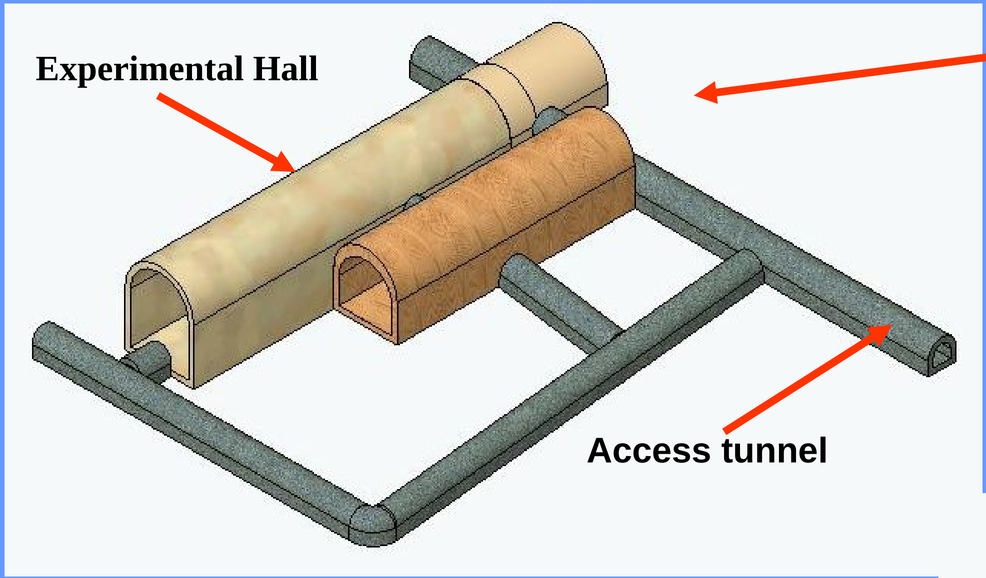
Stack of 10 RPCs

Location of the Underground Laboratory

- ***Studies were performed on two potential sites.***
  - ***Pykara Ultimate Stage Hydro Electric Project (PUSHEP) at Masinagudi, Tamilnadu***
  - ***Rammam Hydro Electric Project Site at Darjeeling District in West Bengal***
- ***INO Site Selection Committee after thorough evaluation have now recommended PUSHEP at Tamilnadu as the preferred site for the underground lab.***

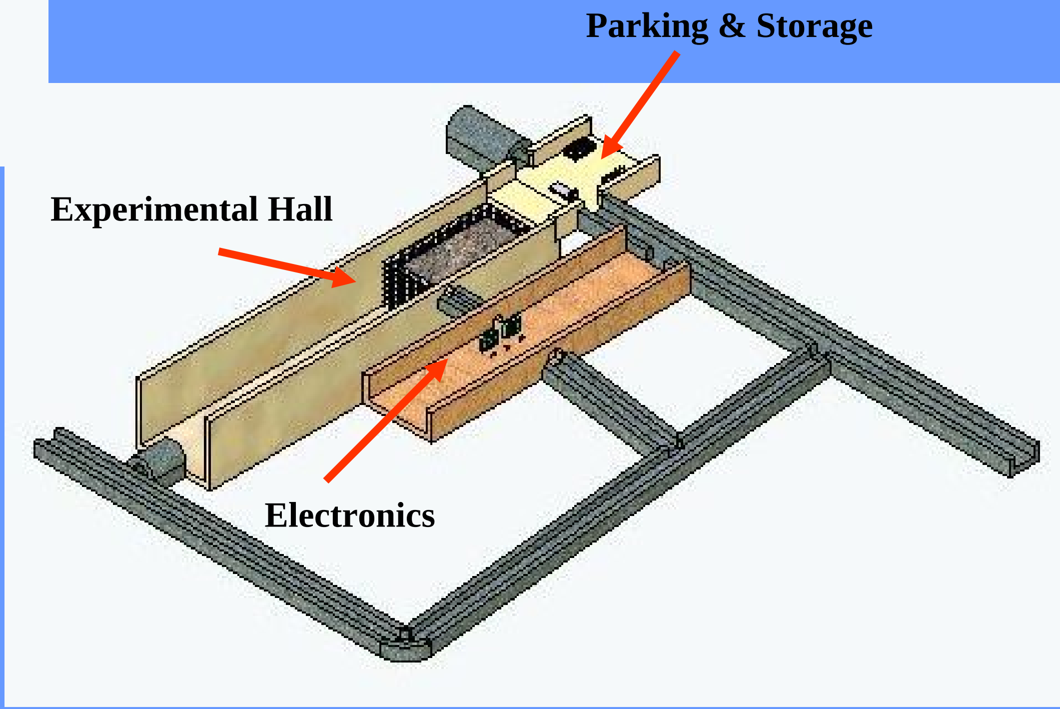


Underground Cavern



Layout of the Underground Cavern

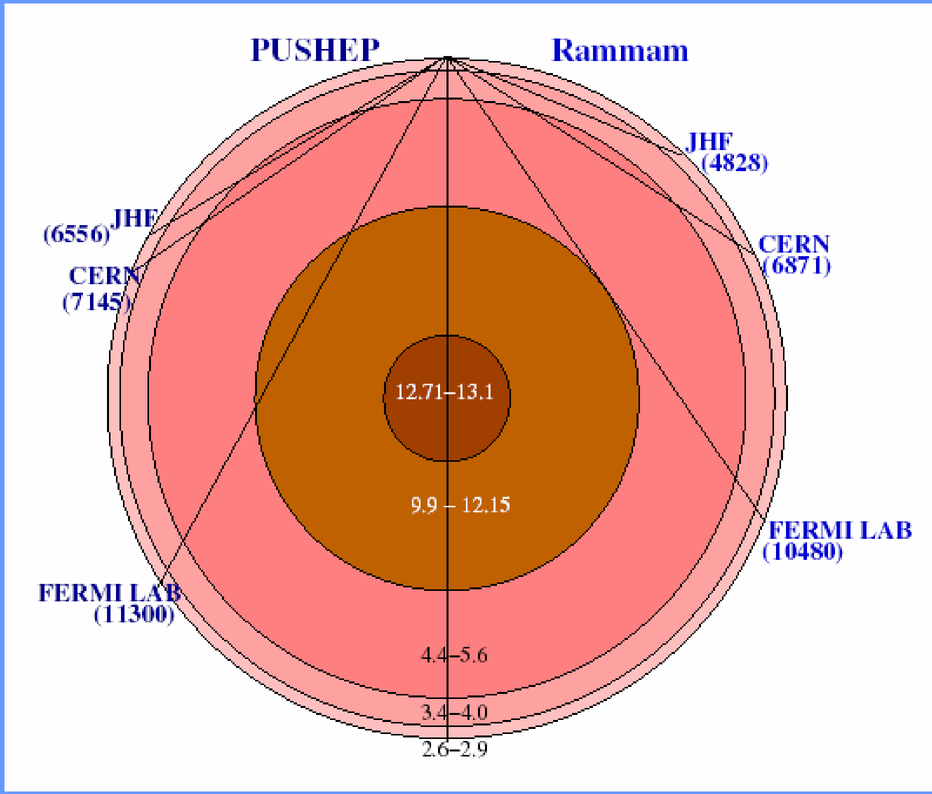
Size of the experimental hall
150 m X 22 m X 30 m



Physics using atmospheric neutrinos during Phase I

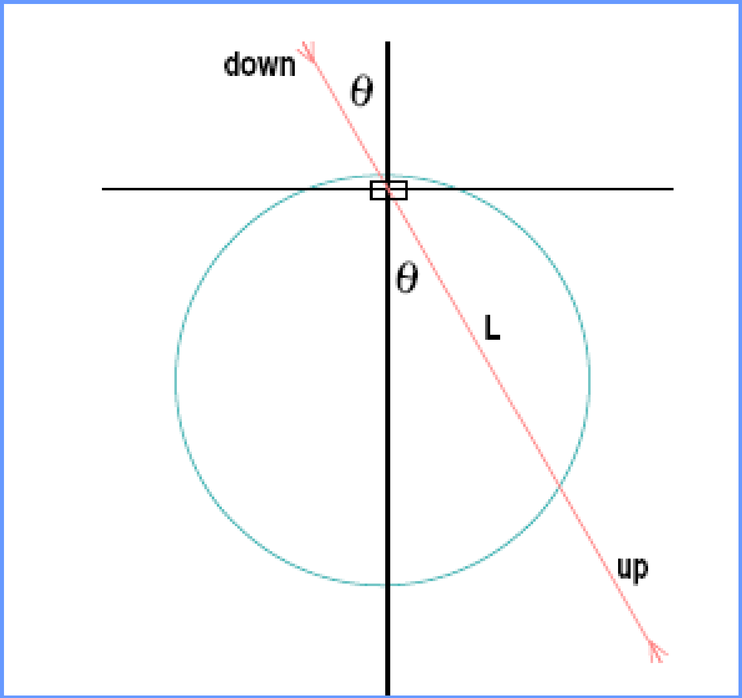
- *Improved measurement of oscillation parameters.*
- *Search for potential matter effect in neutrino oscillation.*
- *Determining the sign of Δm^2_{23} using matter effect.*
- *Is θ_{23} maximal ? If not $\theta_{23} < \pi/4$ or $> \pi/4$?*
- *Probing CPT violation in neutrino sector.*
- *Ultra high energy muons in cosmic rays.*

Physics with Neutrino beam from NUFACT – Phase II



- *Determination of θ_{13}.*
- *Determining the sign of Δm^2_{23}.*
- *Matter effect in $\nu_\mu \rightarrow \nu_\tau$ oscillation.*
- *Probing CP violation in leptonic sector.*

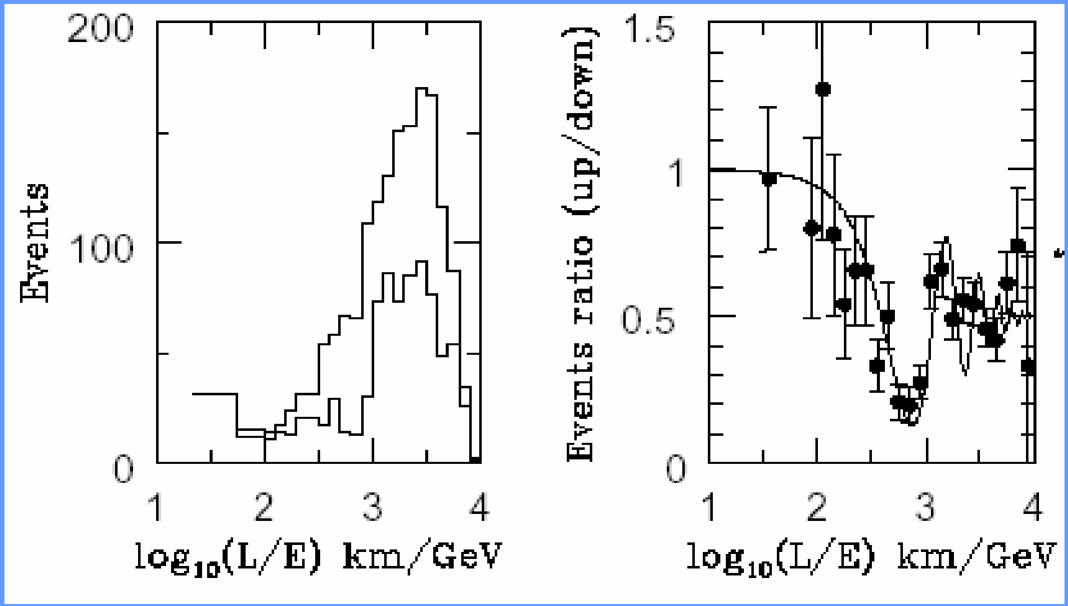
Disappearance of ν_μ vs. L/E



The disappearance probability can be measured with a single detector and two equal sources:

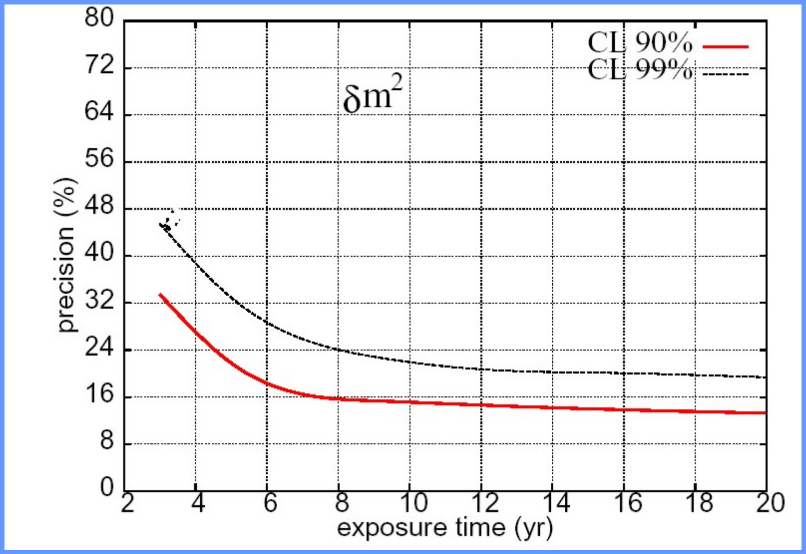
$$\frac{N_{up}(L/E)}{N_{down}(L'/E)} = P(\nu_\mu \rightarrow \nu_\mu; L/E)$$

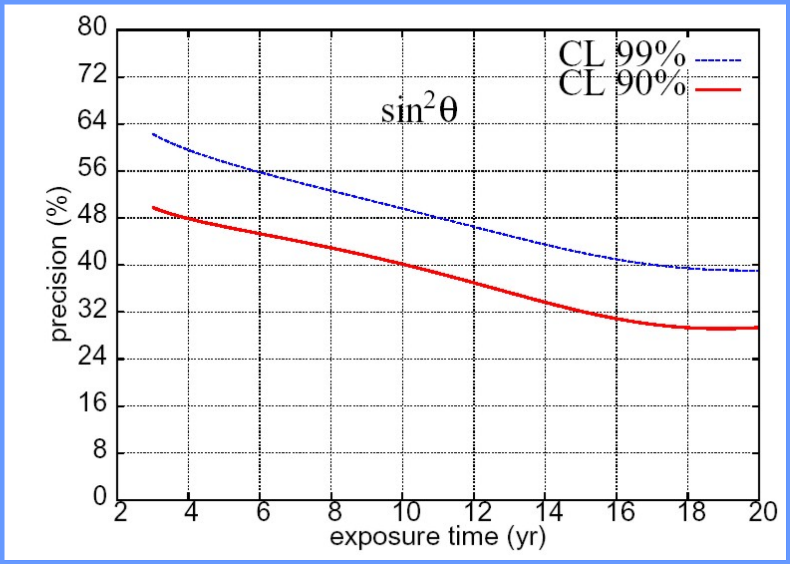
$$= 1 - \sin^2(2\Theta)\,\sin^2(1.27\,\Delta m^2\,L/E)$$

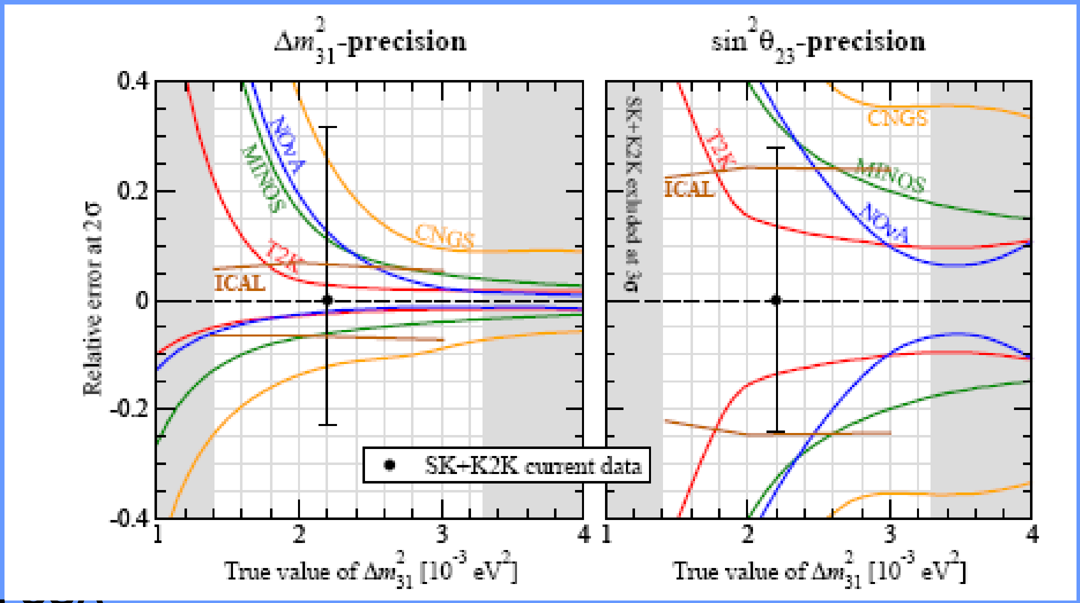


Neutrino 2006, Santa Fe, USA

Precision Measurement of Oscillation Parameters







Neutrino 2006, Santa Fe, USA

Matter Effect

R. Gandhi et al PRL 94, 051801, 2005

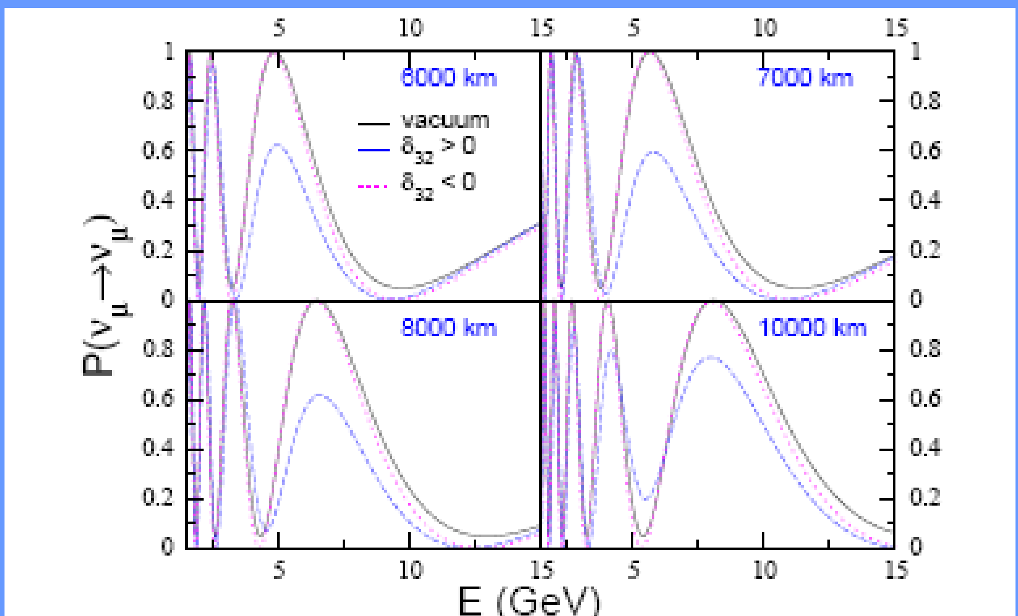
Total no. of ν_μ charge current events:

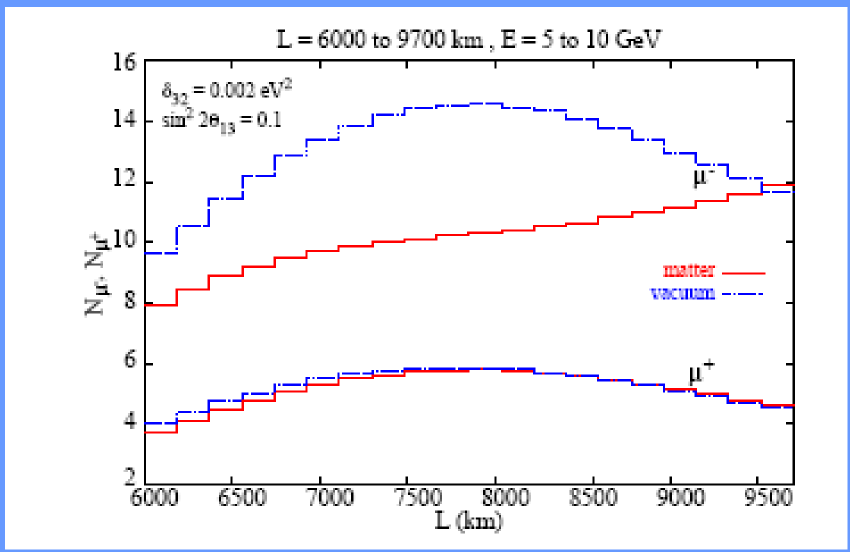
$$N_\mu = N_n \times M_Y \int dE \int d\cos\theta_z \left[\frac{d^2\phi_\mu}{dE d\cos\theta_z} P_{\mu\mu}(E,L) + \frac{d^2\phi_e}{dE d\cos\theta_z} P_{e\mu}(E,L) \right] \sigma_\mu(E)$$

Neglecting Δ_{21}

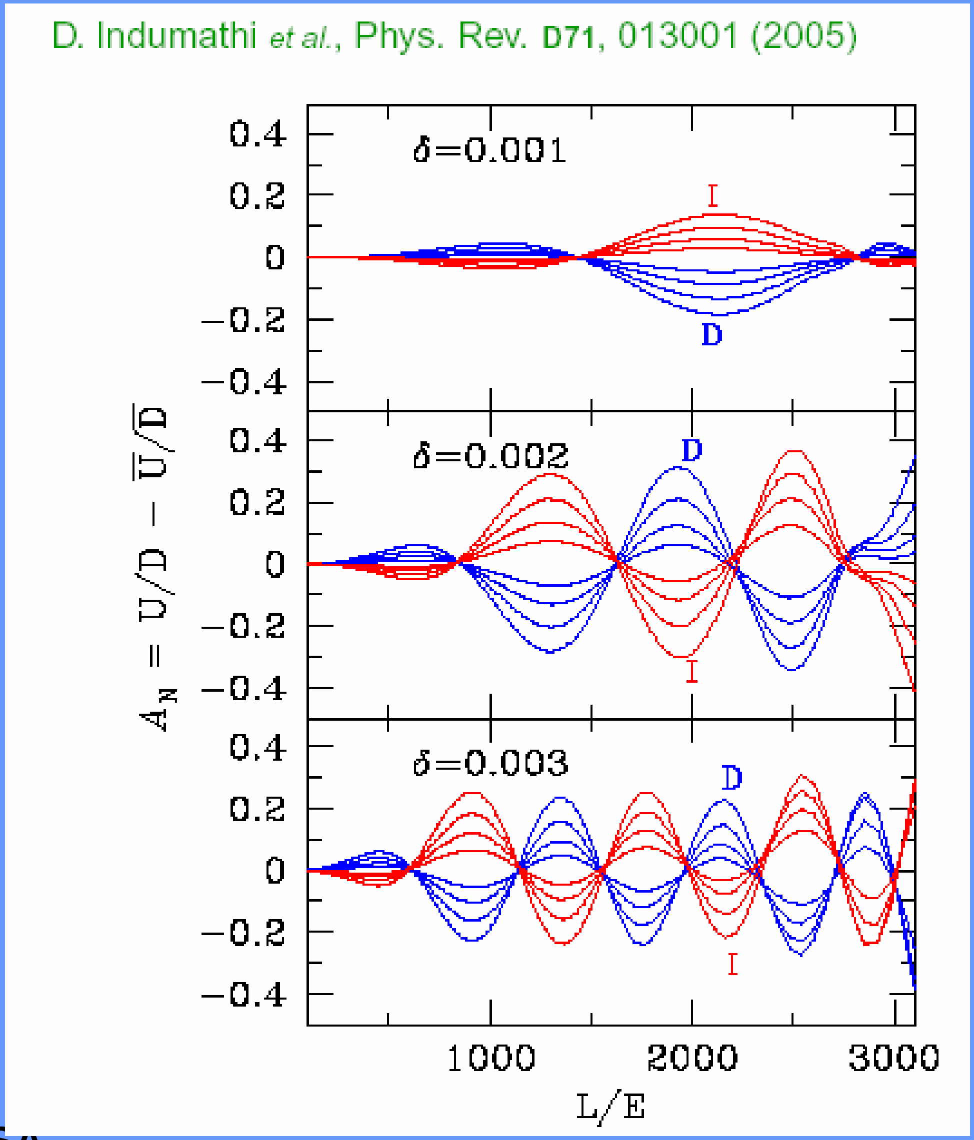
$$P^{vac}(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta_{31} L/E)$$

$$P^{mat}(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta^m{}_{13} \sin^2(1.27\Delta^m{}_{31} L/E)$$

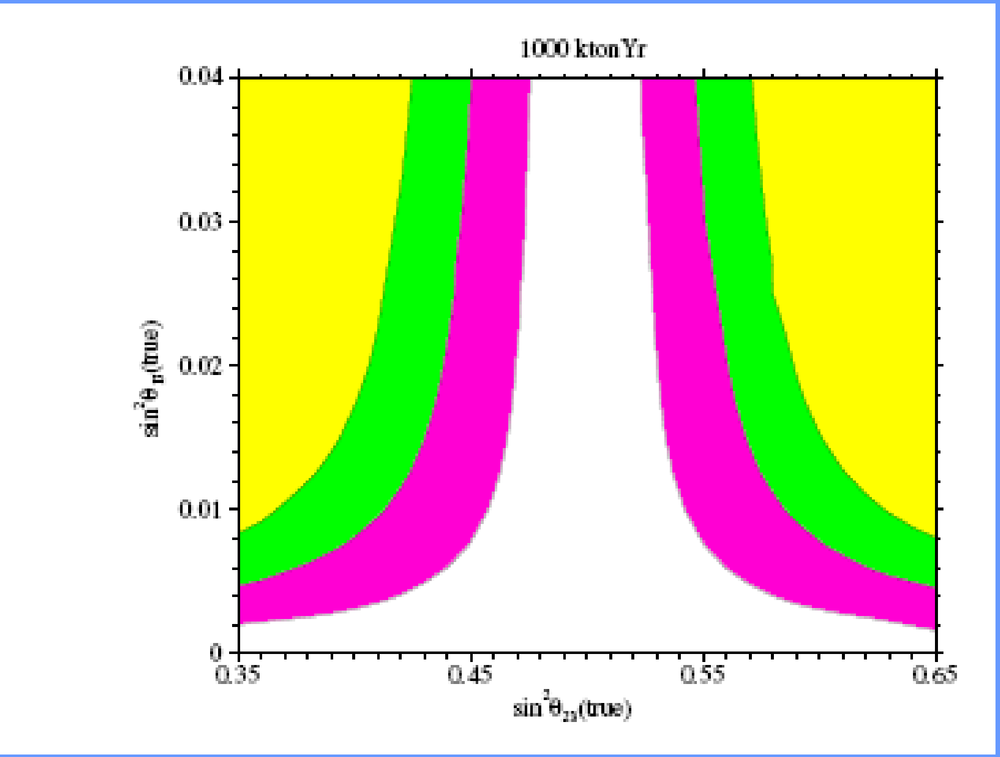


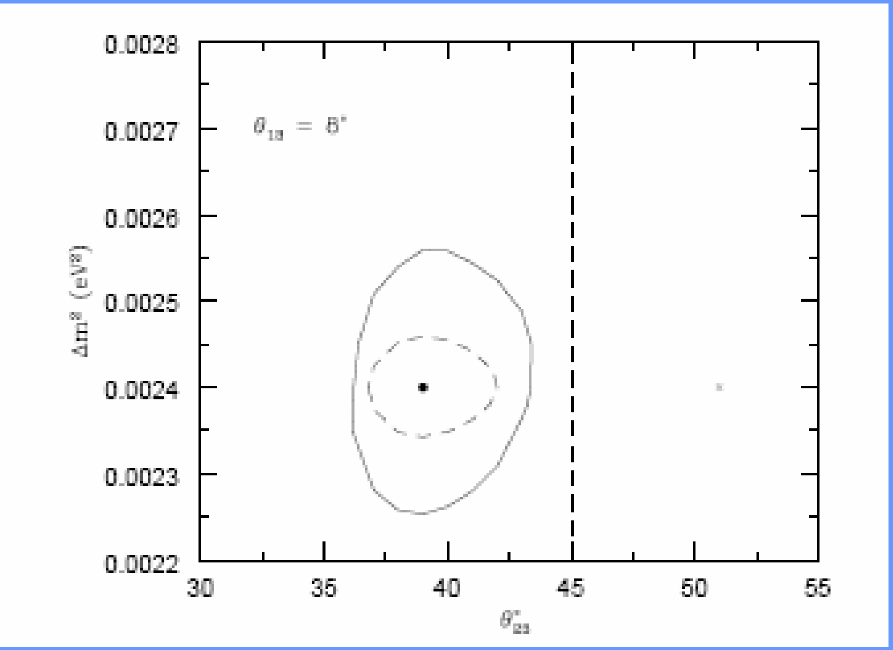


Mass Hierarchy from matter induced asymmetry



Deviation from maximality of θ_{23}





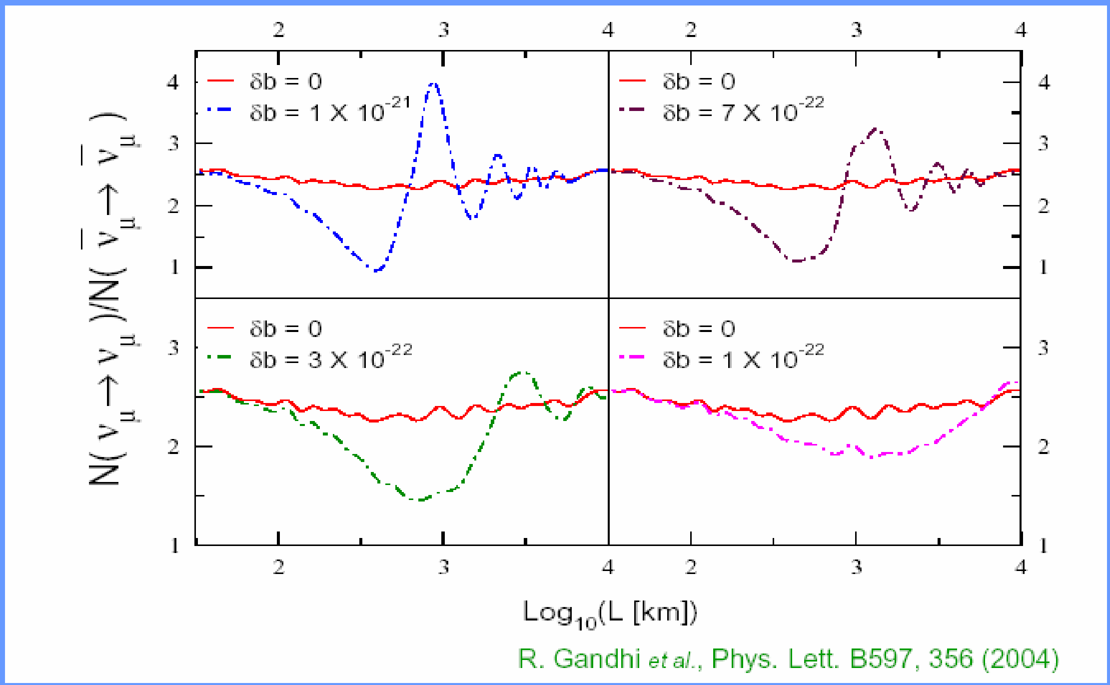
CPT Violation

The expression for survival probability for the case of CPTV 2-flavour oscillations

$$P_{\mu\mu}(L) = 1 - \sin^2 2\theta \sin^2\left[\left(\frac{\delta_{32}}{4E} + \frac{\delta b}{2}\right)L\right]$$

and

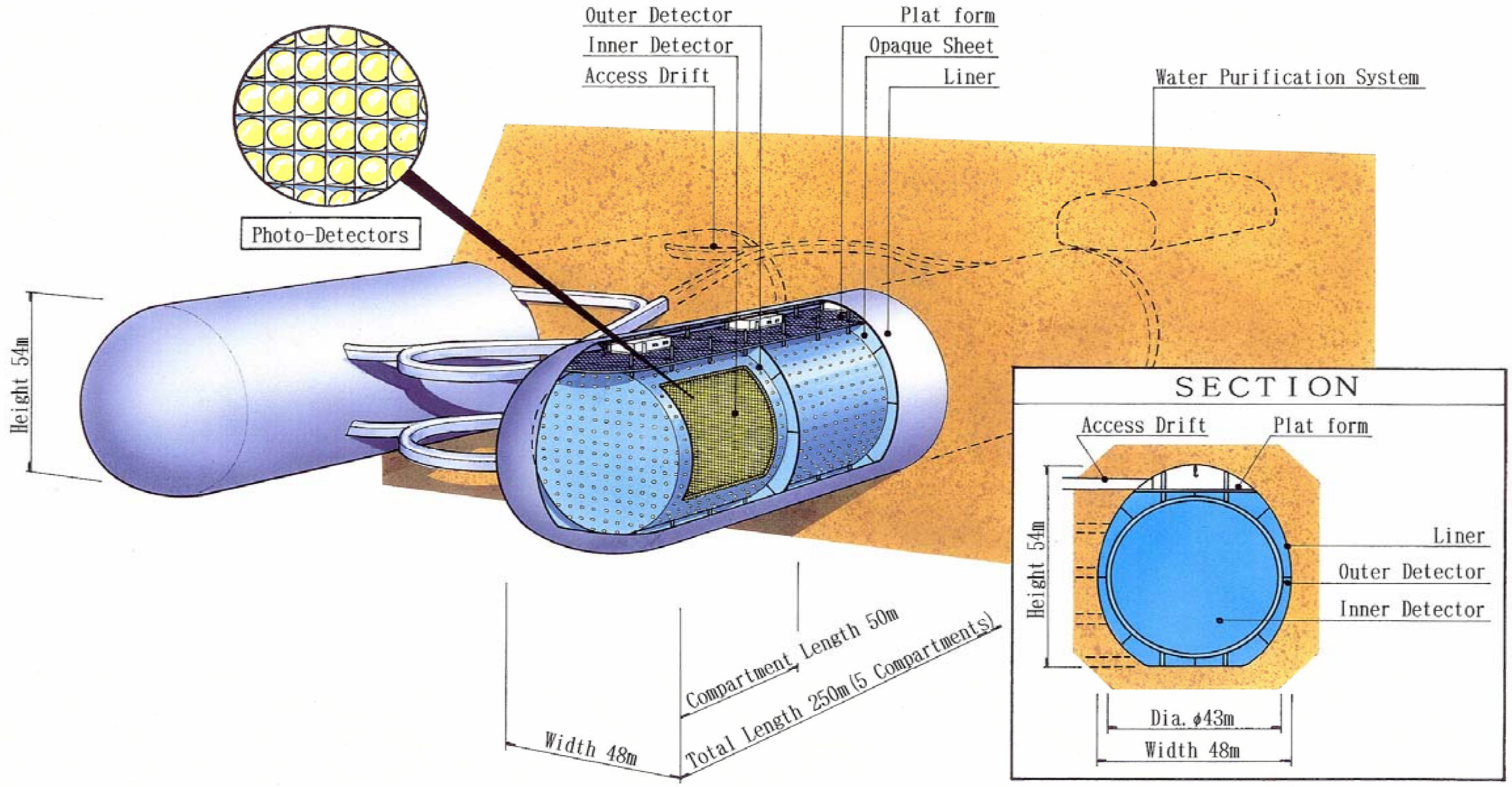
$$\Delta P^{CPT}_{\mu\mu} = P_{\mu\mu} - P_{\overline{\mu\mu}} = -\sin^2 2\theta \sin\left(\frac{\delta_{32}L}{2E}\right)\sin(\delta b L)$$



Future water Cherenkov detectors

Hyper-Kamiokande

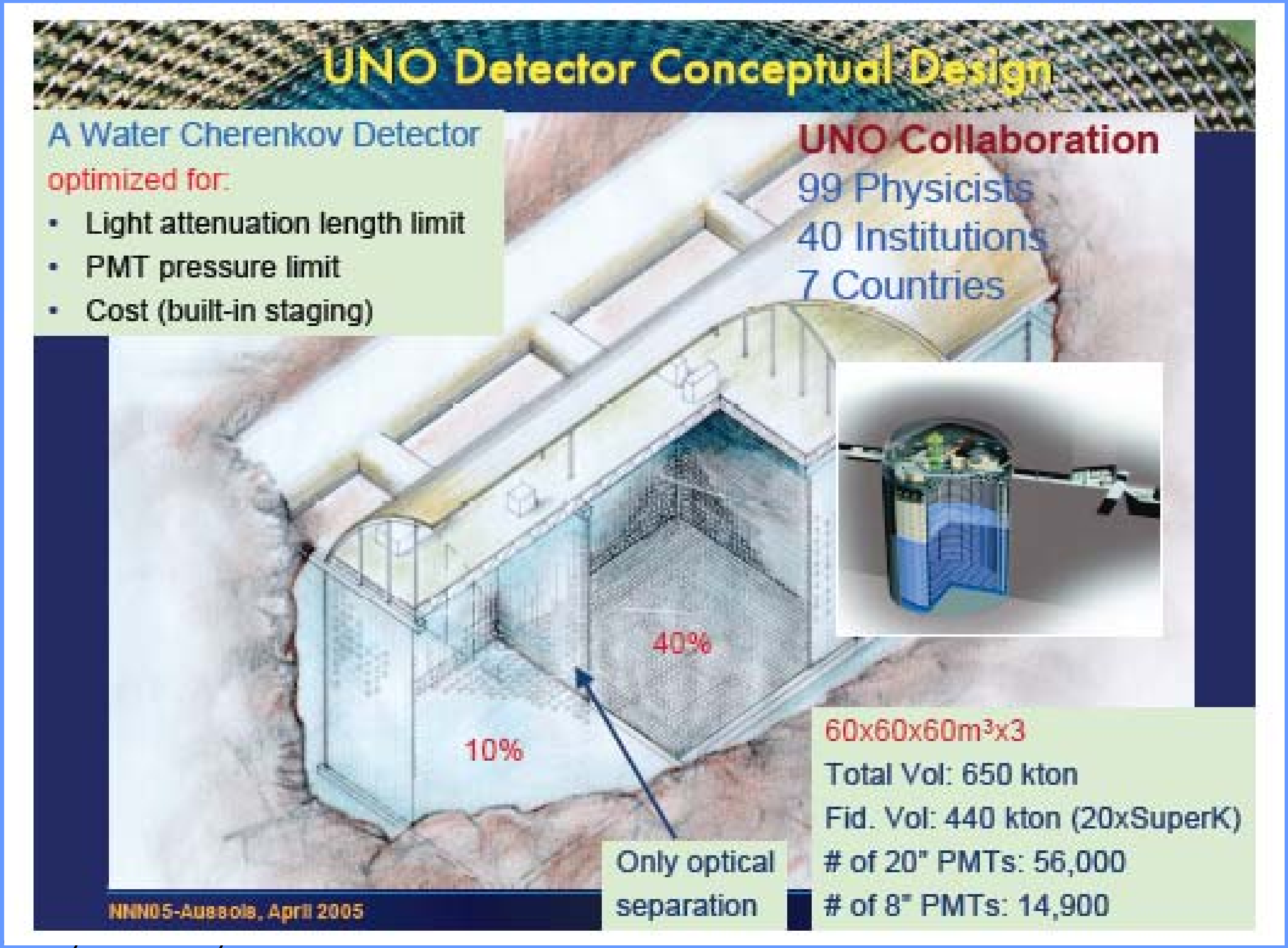
~1 Mton water Cherenkov detector at Kamioka



Why this design has been chosen ?

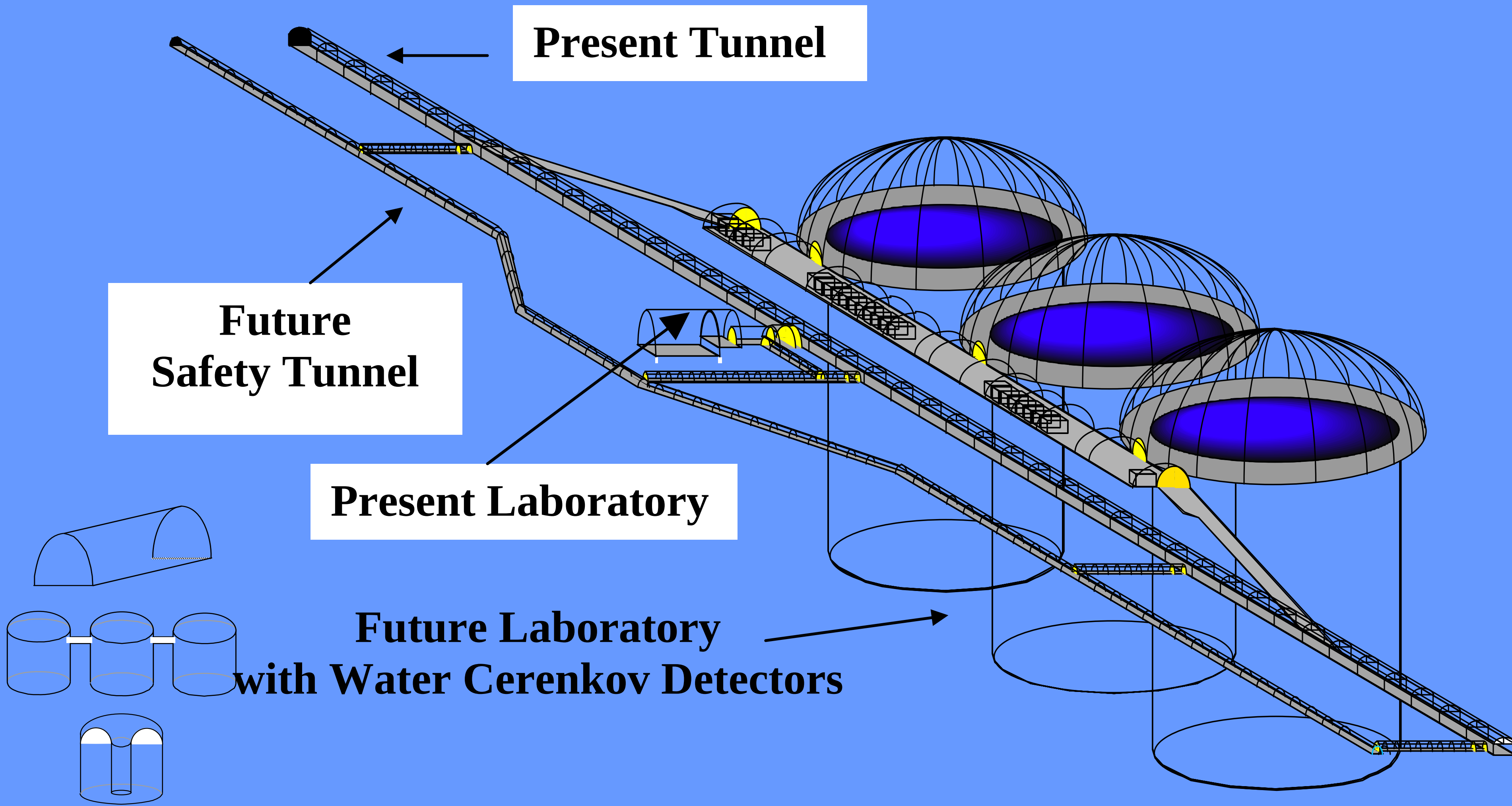
- *Water depth < 50 m*
  (If the present 20-inch PMT or similar one will be used.)
- *Linear dimensions for light path < 100 m*
- *Optimization of M_{FID}/M_{TOTAL}*
- *Rock stability*
  - *Avoid sharp edges. Spherical shape is the best.*
- *solution: Tunnel-shaped cavity*
- *Single Cavity or Twin Cavities?*
  - *Single Cavity*
    - *M_{FID}/M_{TOTAL} is better*
    - *Cost is lower*
    - *Larger area of stable rock mass needed.*
  - *Twin Cavities*
    - *Two detectors are independent. One detector is alive when the other is calibrated or maintained.*
    - *Both cavities should be excavated at the same time. But staging scenario is possible for the later phase of the detector construction.*
- *solution: Twin cavities*

UNO


UNO Detector Conceptual Design
A Water Cherenkov Detector
optimized for:
• Light attenuation length limit
• PMT pressure limit
• Cost (built-in staging)
UNO Collaboration
99 Physicists
40 Institutions
7 Countries
40%
10%
Only optical separation
60x60x60m³x3
Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuperK)
# of 20" PMTs: 56,000
# of 8" PMTs: 14,900
NNN05-Aussois, April 2005

MEMPHYS

-> a **very large Laboratory** to allow the installation of a **Megaton**-scale **Cerenkov** Detector ($\approx 10^6$ m^3)



Physics reach
of
Megaton scale Water Cherenkov Detectors

Octant of θ_{23}

Nonzero θ_{13}

δCP

oscillation effects in ν_e

Pares and Smirnov hep-ph/0309312 (at Sub-GeV range)

$$\frac{\Psi(\nu e)}{\Psi_0(\nu e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1)$$ ← LMA

$$- r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23} (\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$ ← interference

$$+ 2\tilde{s}_{13}^2 (r \cdot s_{23}^2 - 1)$$ ← ϑ_{13} resonance

r : μ/e flux ratio (~2 at low energy)

$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

$R_2 = \mathrm{Re}(A^*_{ee} A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee} A_{e\mu})$

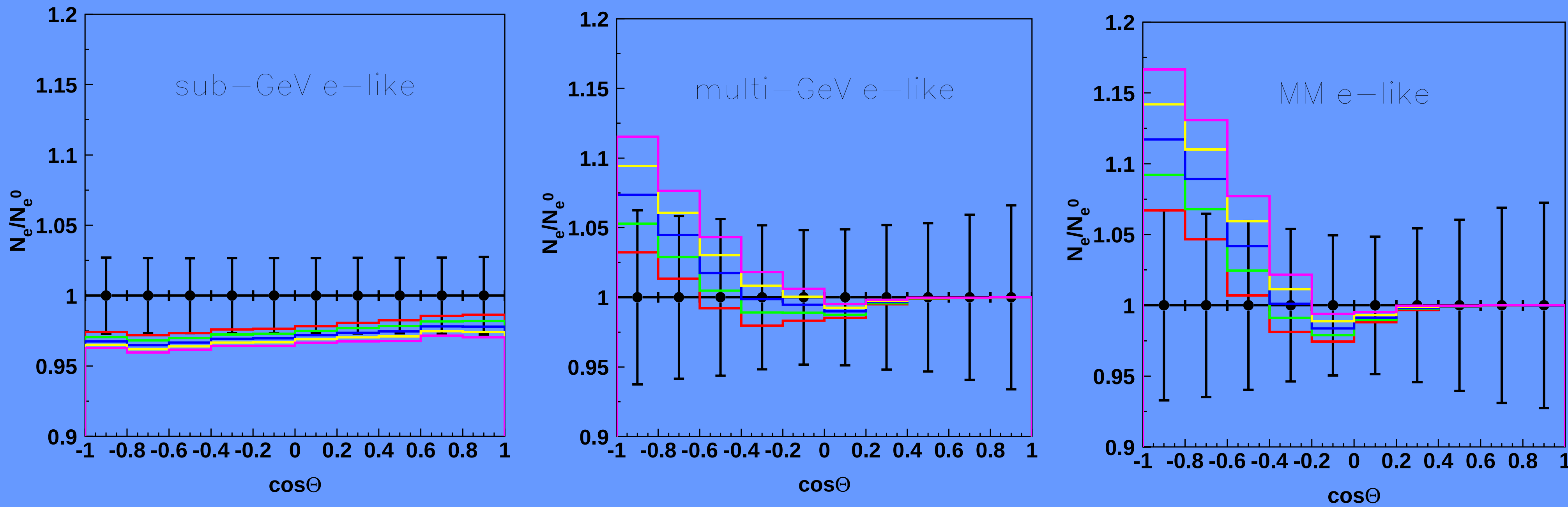
A_{ee} : survival amplitude of the 2ν system

$A_{e\mu}$: transition amplitude of the 2ν system

Effect of θ_{23} after ν interactions

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4 ~ 0.6
$s^2\theta_{13}$=0.04
δcp=45^o
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

no osc. with 20yrs stat.error
s^2_{23}=0.40
0.45
0.50
0.55
0.60



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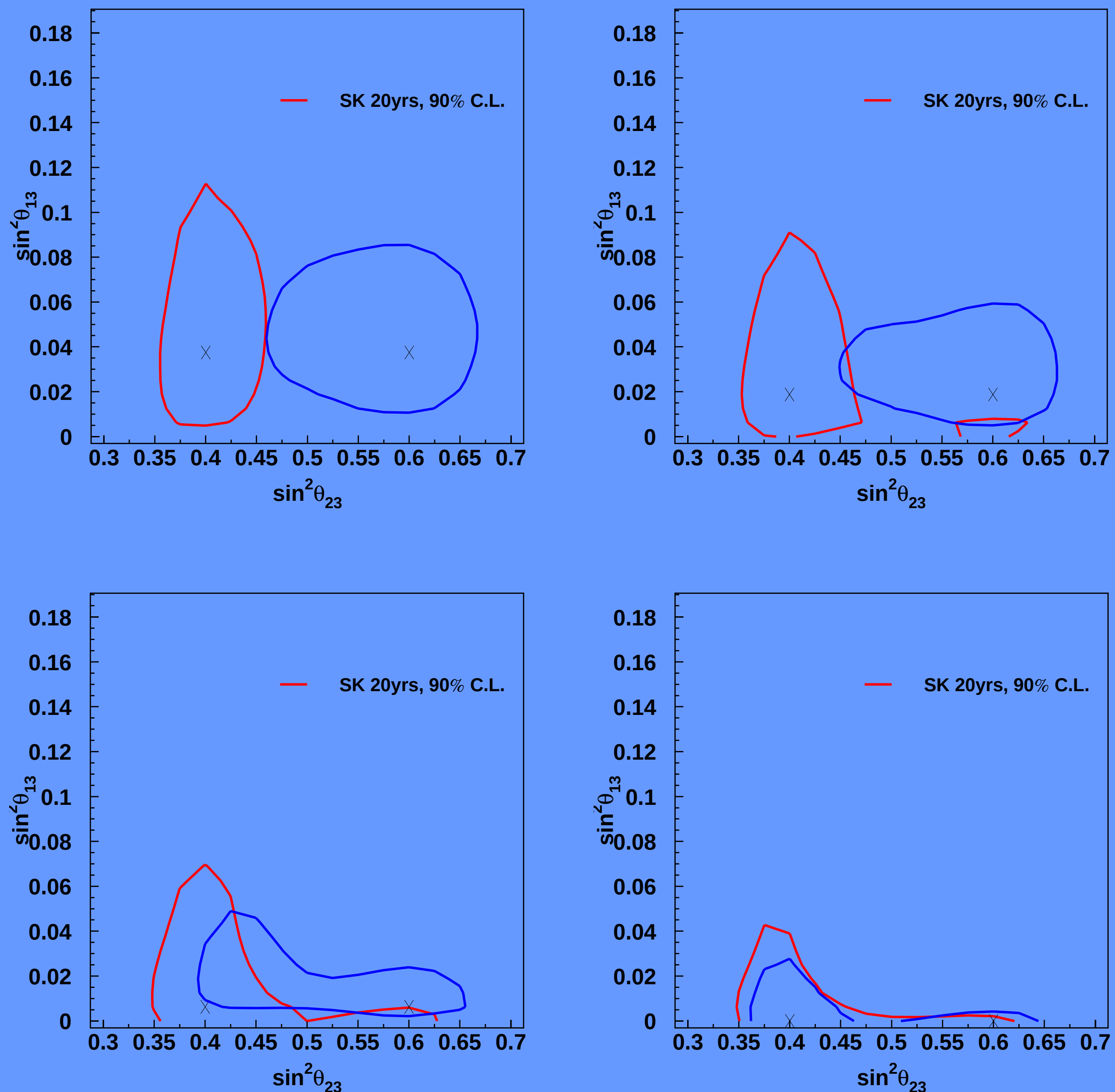
Discrimination of θ_{23} octant

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4 or 0.6
$s^2\theta_{13}$=0.00~0.04
δcp=45^o
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

$s^2\theta_{23}$ = 0.40 or 0.60
$\leftarrow\rightarrow$ $s^2 2\theta_{23}$=0.96

With 20yrs SK, discrimination is possible for large θ_{13}.



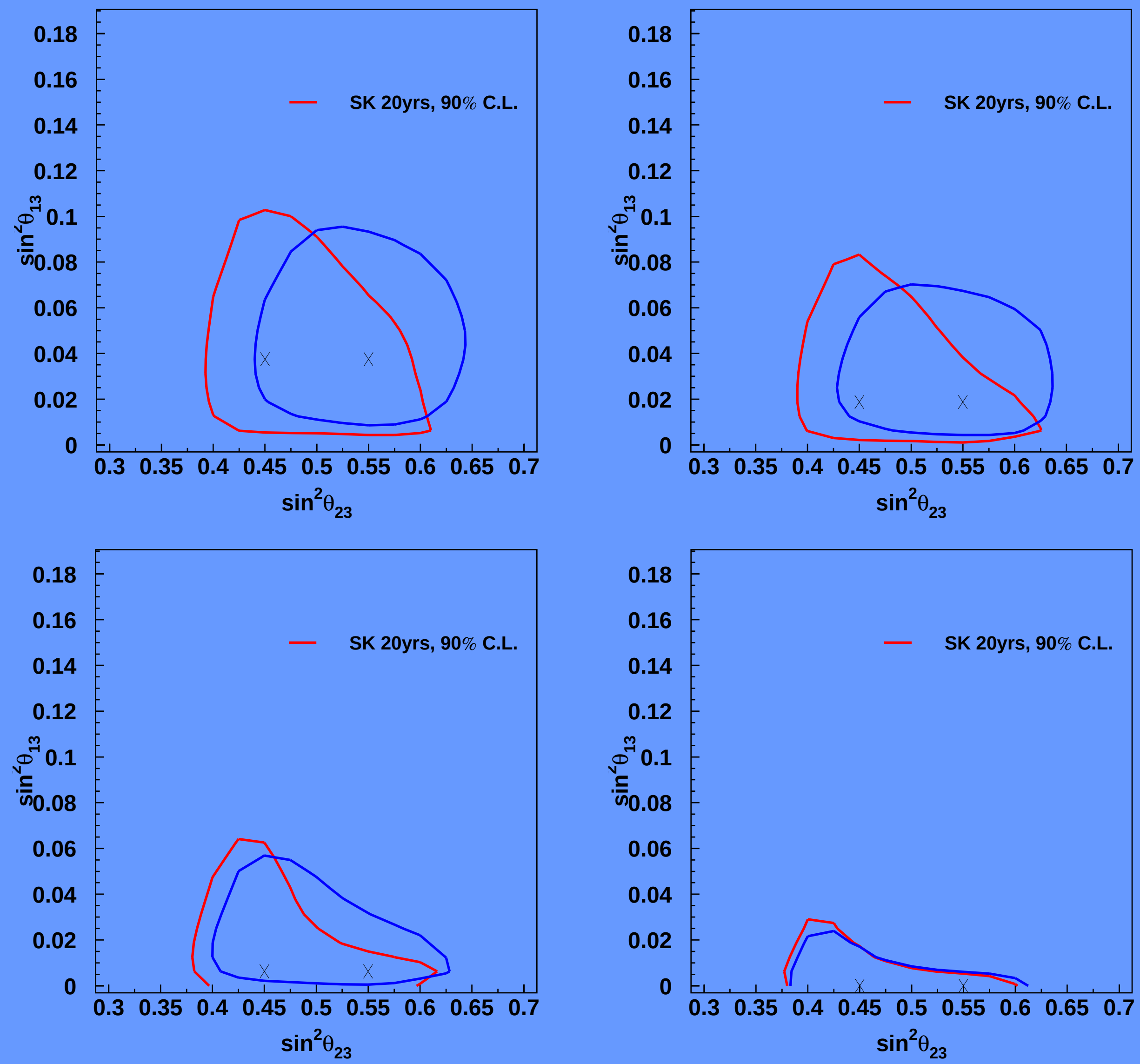
Neutrino 2006, Santa Fe, USA

Discrimination of θ_{23} octant

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.45 or 0.55
$s^2\theta_{13}$=0.00~0.04
δcp=45°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

$s^2\theta_{23}$ = 0.45 or 0.55
←→ $s^2 2\theta_{23}$=0.99

With 20yrs SK, discrimination is very hard.



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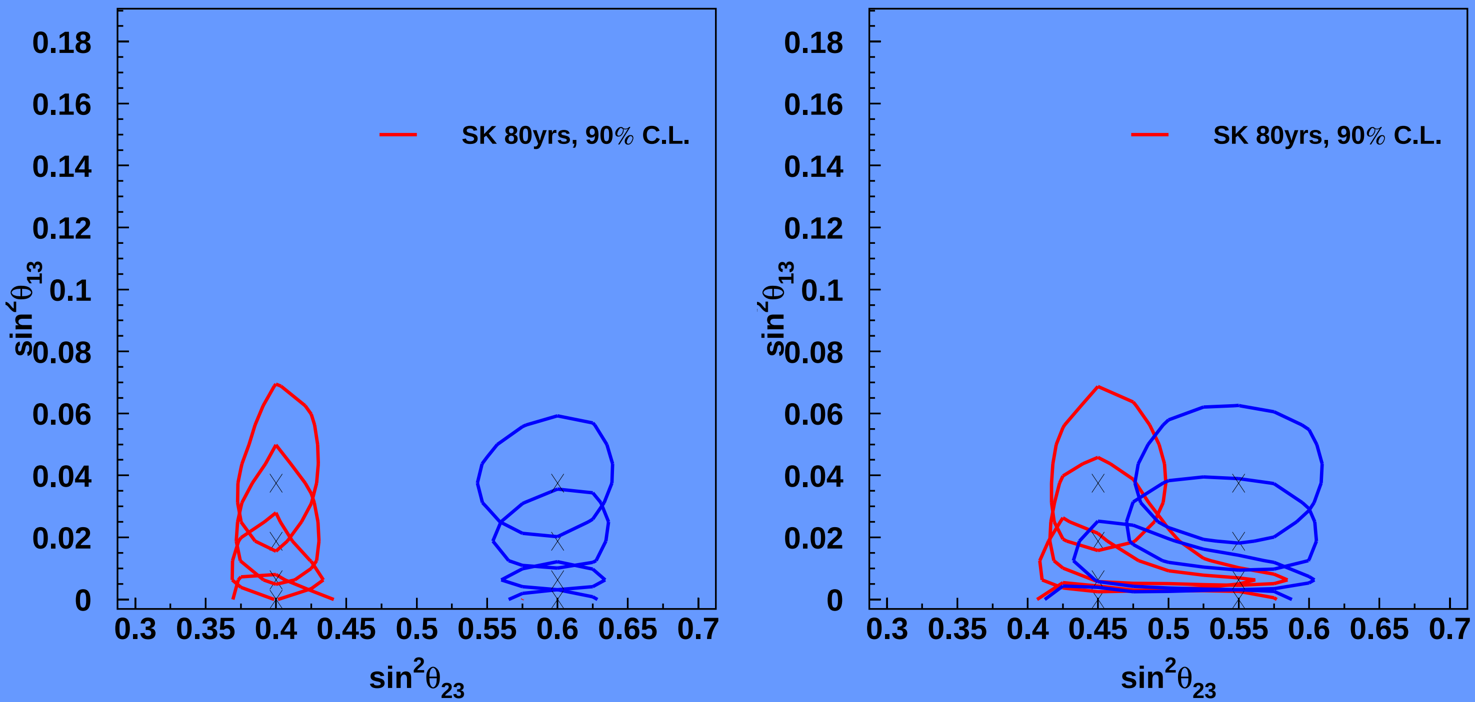
Discrimination of θ_{23} octant, SKx80yrs

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.40 ~ 0.60
$s^2\theta_{13}$=0.00~0.04
δcp=45^o
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

80yrs SK ~ 4yrs HK

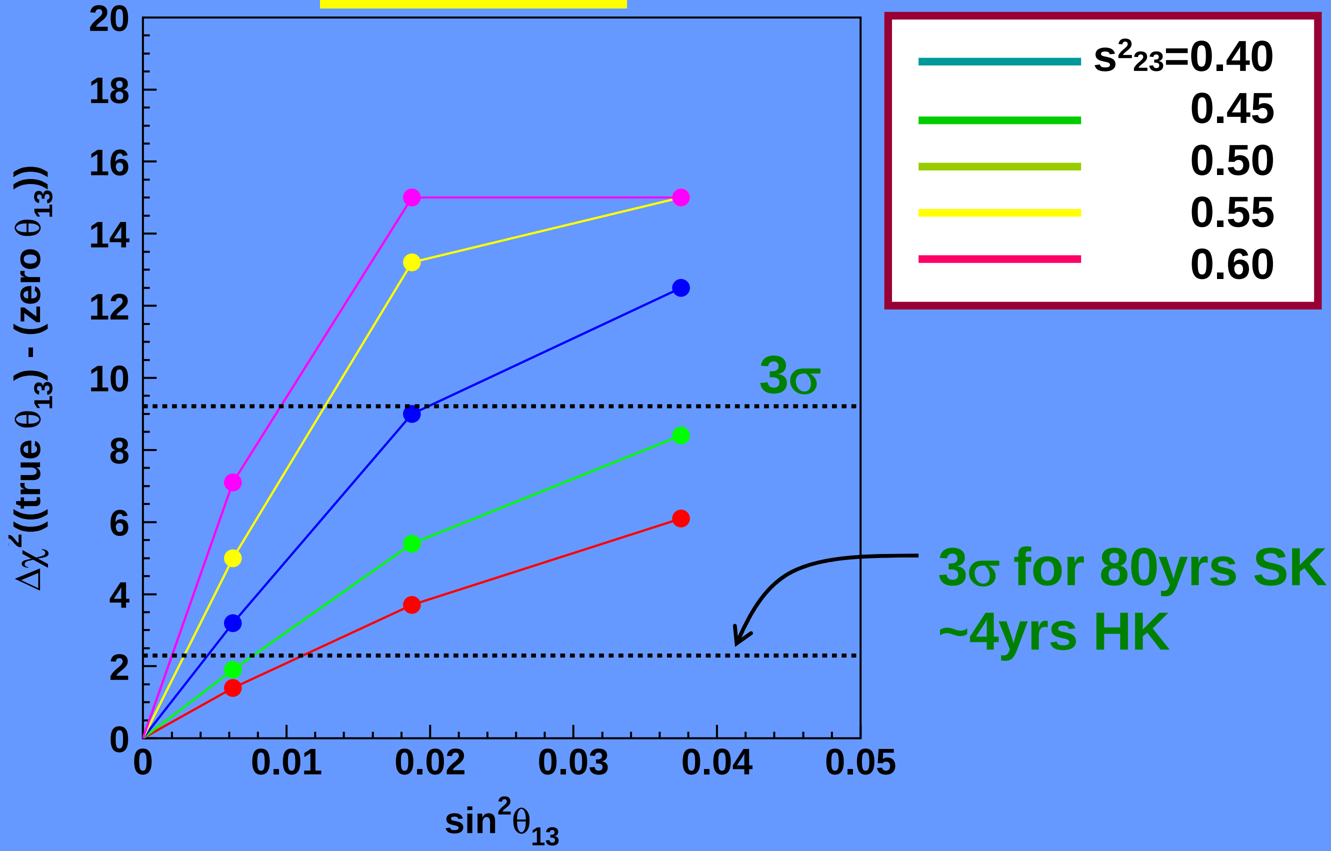


With 80yrs SK, discrimination is better and possible for many test points.

Significance for nonzero θ_{13}

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00\sim0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3e\text{-}5$
$\Delta m^2_{23}=2.5e\text{-}3$

20yrs SK

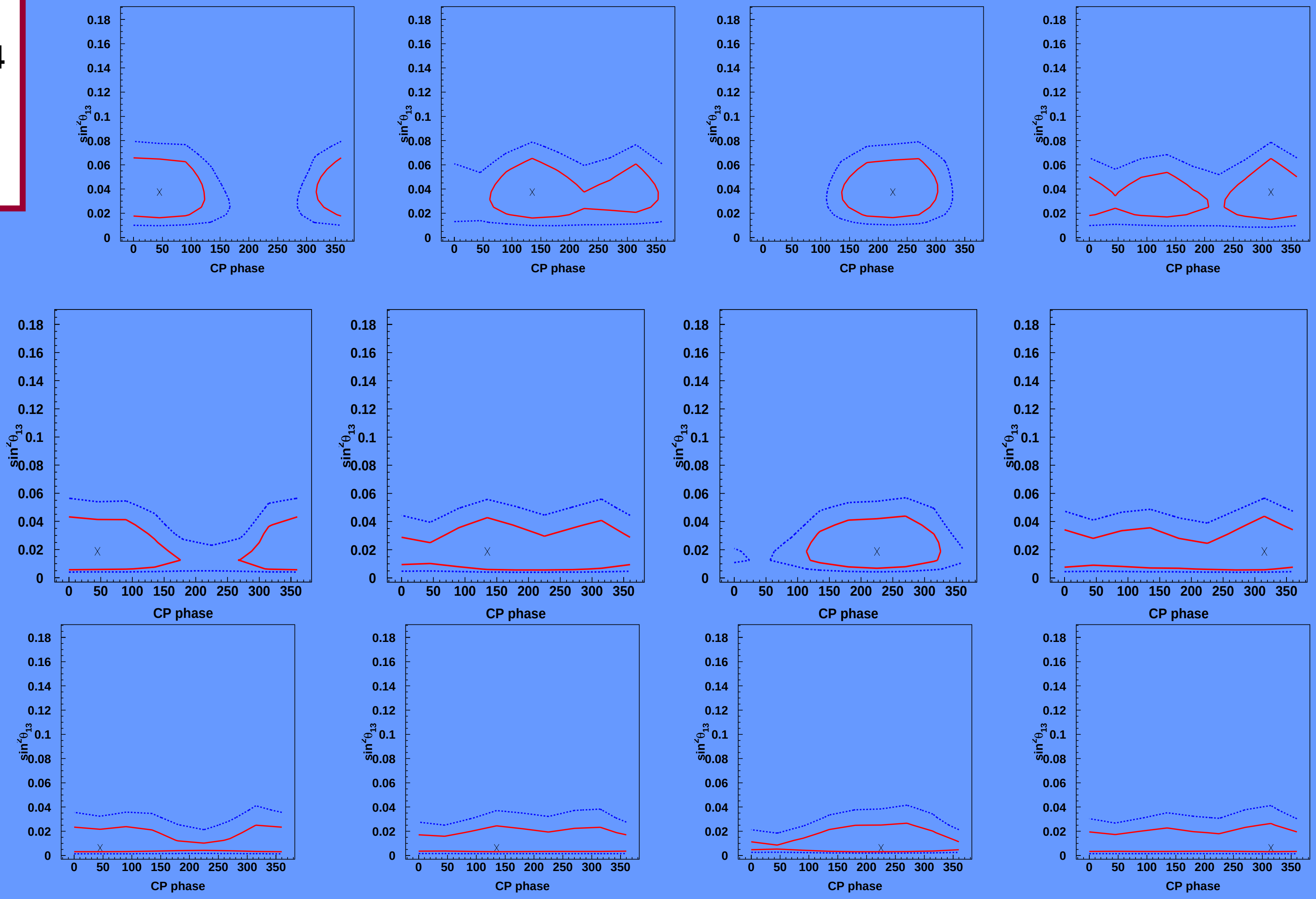


Positive signal for nonzero θ_{13} can be seen if θ_{13} is near the CHOOZ limit and $s^2\theta_{23} > 0.5$

δ_{CP} sensitivity

80yrs SK ~ 4yrs HK

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.5
$s^2\theta_{13}$=0.00~0.04
δcp=0°~360°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3



CP phase could be seen if θ13 is close to the CHOOZ limit.

Neutrino 2006, Santa

Summary

- **A large magnetised detector of 50-100 Kton like INO is needed to achieve some of the very exciting physics goals using atmospheric neutrinos.**
- **It will complement the existing and planned water cherenkov detectors.**
- **Can be used as a far detector during neutrino factory era.**
- **R & D for setting up such a detector in India is in progress.**

- **If θ_{13} is close to the CHOOZ limit, then next generation water Cherenkov detectors could give us precious information on;**
  - **octant of θ_{23}**
  - **nonzero θ_{13}**
  - **δCP**