Atmospheric Neutrinos

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Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (IPMU),

The University of Tokyo

2012, September-13,14
@ V International Pontecorvo Neutrino Physics School
in Alushta, Crimea, Ukraine

Prolog

This year: A turning point of neutrino oscillations

- 2011: T2K has first shown the evidence of non-zero θ_{13}
- 2012: Reactor experiments have detemined the value of θ_{13} at ~10% level.
- Current Value of the mixing angles and the mass differences:

Best parameter value from a single experiment (except solar ν)

${\Delta m_{12}}^2$	$= 7.58^{+0.21}_{-0.20} \times 10^{-5} eV^2$	$(\sim 2.8\%\ @\Delta\chi^2 = 1)$	$[KamLAND]$
$\sin^2\theta_{12}$	$= 0.310^{+0.014}_{-0.014}$	$(\sim 4.5\%\ @\Delta\chi^2 = 1)$	[all solar experiments]
${\Delta m_{23}}^2$	$= 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$	$(\sim 4.2\%\ @\Delta\chi^2 = 1)$	$[MINOS]$
$\sin^2\theta_{23}$	$= 0.575^{+0.038}_{-0.075}$	$(\sim 13\%\ @\Delta\chi^2 = 1)$	[Super-Kamiokande 3ν for Inv.MH]
$\sin^2\theta_{13}$	$= 0.0223 \pm 0.0028$	$(\sim 13\%\ @\Delta\chi^2 = 1)$	[Daya Bay]

➔ **Missing: Mass hierarchy, CP phase, Majorana phase.**

- Discovery of Neutrino Oscillation has come from the study of the Atmospheric Neutrinos in 1998.

Idea to use atmospheric neutrinos to study neutrino oscillations

- **S. M. Bilenky and B. Pontecorvo**
  Physics Report 41(1978)225-261

LEPTON MIXING AND NEUTRINO OSCILLATIONS

S.M. BILENKY and B. PONTECORVO

Joint Institute for Nuclear Research, Dubna, USSR "survival" of the cosine term is that the effective source dimension r must be smaller than the oscillation length

$$r \lesssim L. \tag{81}$$

Since $r \simeq 10^{-3} R$, the inequality (81) is comparable, in essence, with the inequality (80). Thus we conclude that the condition of coherence (79) does not impose any conditions supplementary to the condition (81).

5.8. *Oscillations and cosmic neutrinos*

The phenomena of neutrino oscillations, if it does take place, could be of importance in cosmic ray neutrino* experiments. Let us give a few examples.

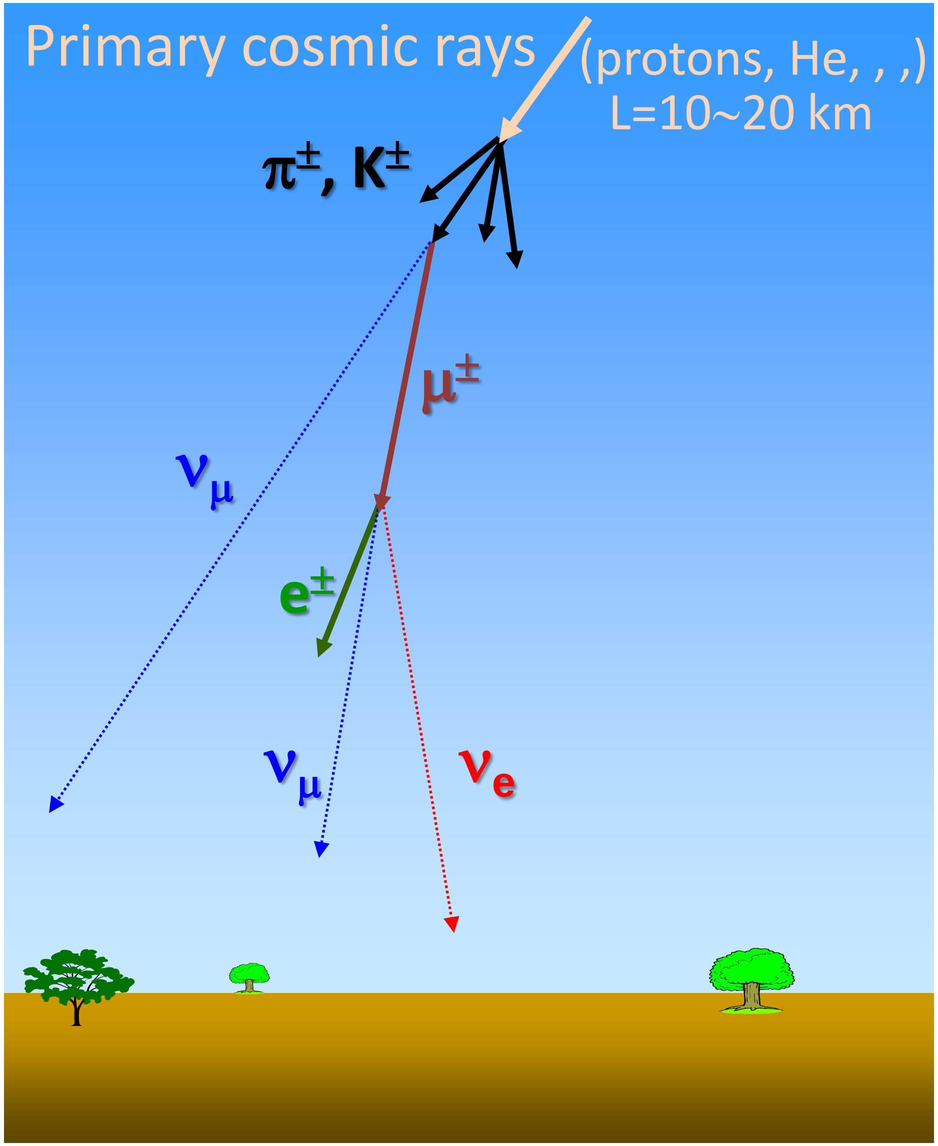
1) At the underground Neutrino Observatory of the Institute for Nuclear Research Academy of Sciences of the USSR an experiment is being prepared [43], in which there will be detected high energy muon neutrinos emitted by mesons, which are produced in collisions of cosmic ray protons with nitrogen and oxygen nuclei in the atmosphere. The energy spectra and other properties of those neutrinos have been calculated and the results are given in ref. [44]. High energy muons produced by ν_μ's interacting with nuclei in the Earth will be detected by 8 hodoscope plane systems (every one of which has an area of 1500 m^2) of organic scintillators. The scintillator systems are in coincidence, the logic giving information on the muon trajectory and also establishing whether the detected muon has come either from "above" or from "below" (in the last case it is produced by a muon neutrino impinging upon the Earth opposite face and passing through the Earth). The average neutrino momentum in such experiments is 5–10 GeV, and the distance from the neutrino source to the detector is $R \simeq 10^4$ km for neutrinos coming from the Earth opposite face. Making use of formula (66) it is possible to test the neutrino mixing hypothesis by comparing the measured and "expected" ν_μ intensities. The sensitivity of those experiments for testing neutrino mixing is, in principle, quite high [43], the value of M^2_{min} (see the definition (60)) being $M^2_{min} \simeq 10^{-3}$ $(eV)^2$. Thus, these experiments have a sensitivity intermediate between that of the experiments wherein artificial (reactor, accelerator) neutrinos are used and that of the investigations wherein solar neutrinos are used. However, the statistical accuracy which can

Contents of my lecture

- Almost same as two years ago.
  - Usefull only for new studuents
- Today
  - Introduction (flux…..)
  - Historical issues
  - Kamiokande indication and other experiments
  - Super-K overview and oscillation measurements
- Tomorrow
  - Atmospheric 3 flavor oscillations
  - Future atmospheric neutrinos by new generation detectors
    - MH, Octant of theta23, CP phase measurement
  - Beyond

Introduction: Atmospheric Neutrinos

Atmospheric Neutrinos



$p/He + N \rightarrow \pi/K + X$

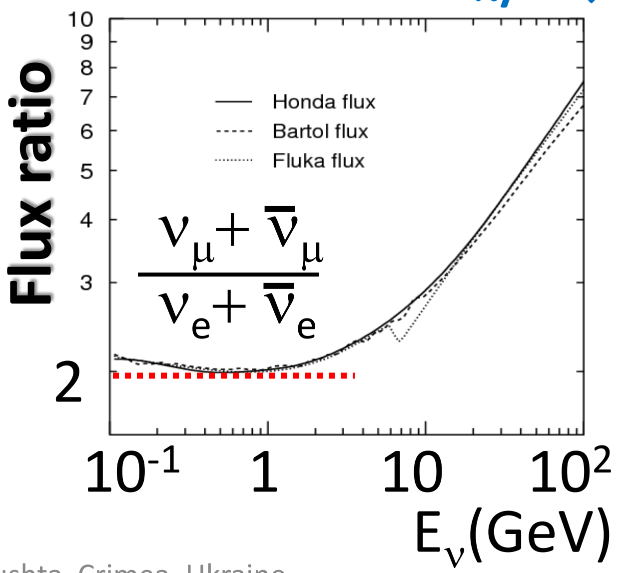
$\pi/K \rightarrow \mu + \nu_\mu$

$\mu \rightarrow e + \nu_e + \nu_\mu$

For the low energy limit

- μ's decay before reaching the ground
- $\nu_\mu : \nu_e = 2 : 1$

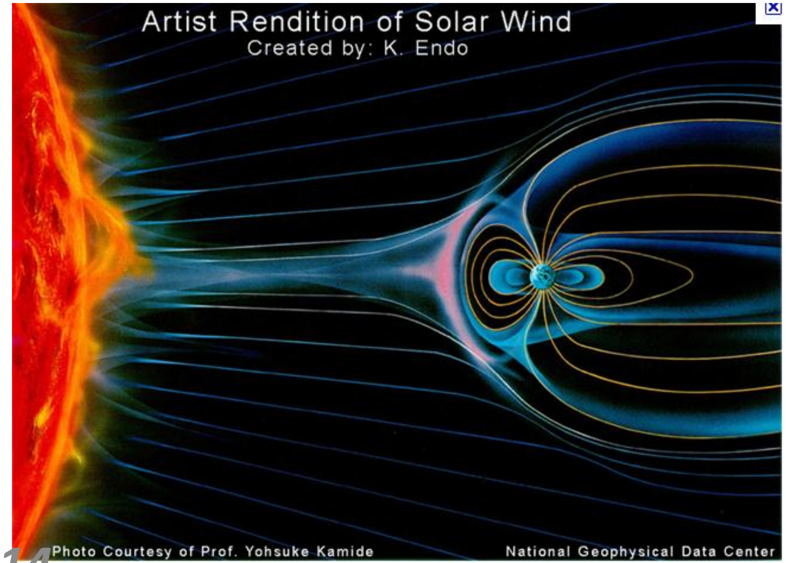
For higher energy:
$\pi/K \rightarrow \mu+\nu_\mu$
~~$e+\nu_\mu+\nu_e$~~



Atmospheric Neutrino Flux Calculation

Need knowledge of

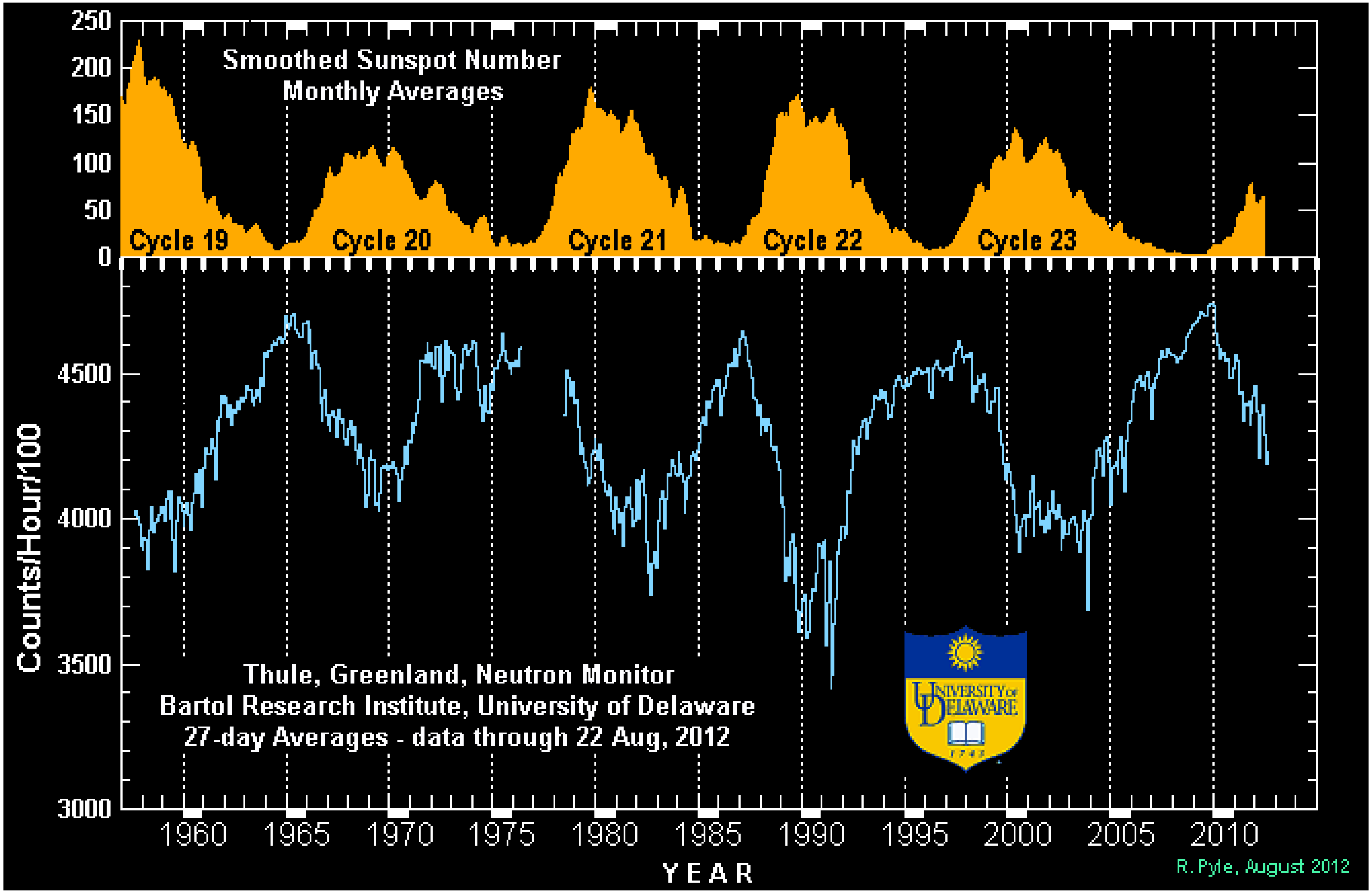
- Primary Cosmic Ray Flux (p, He,…)
  - Modulation by Solar Activity (Solar wind)
    - Solar wind drives back the low energy cosmic ray entering into the solar sphere
    - Solar wind varies with solar activity (solar minimum and maximum)
    - Effect: factor 5 at 1GeV; ~10% for 10GeV



Solar wind

- Stream of charged particles
- Mostly electrons and protons
- 10~100keV

Solar Cycle



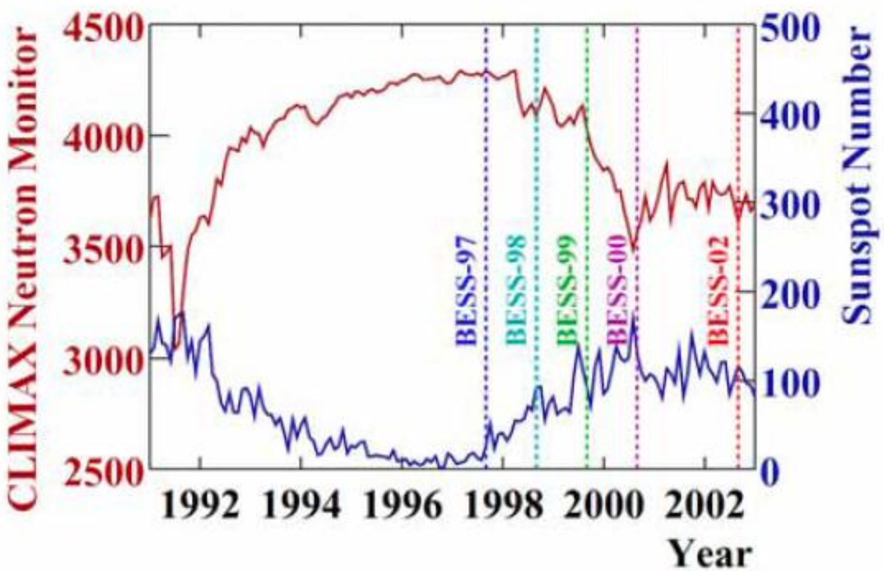
http://neutronm.bartol.udel.edu

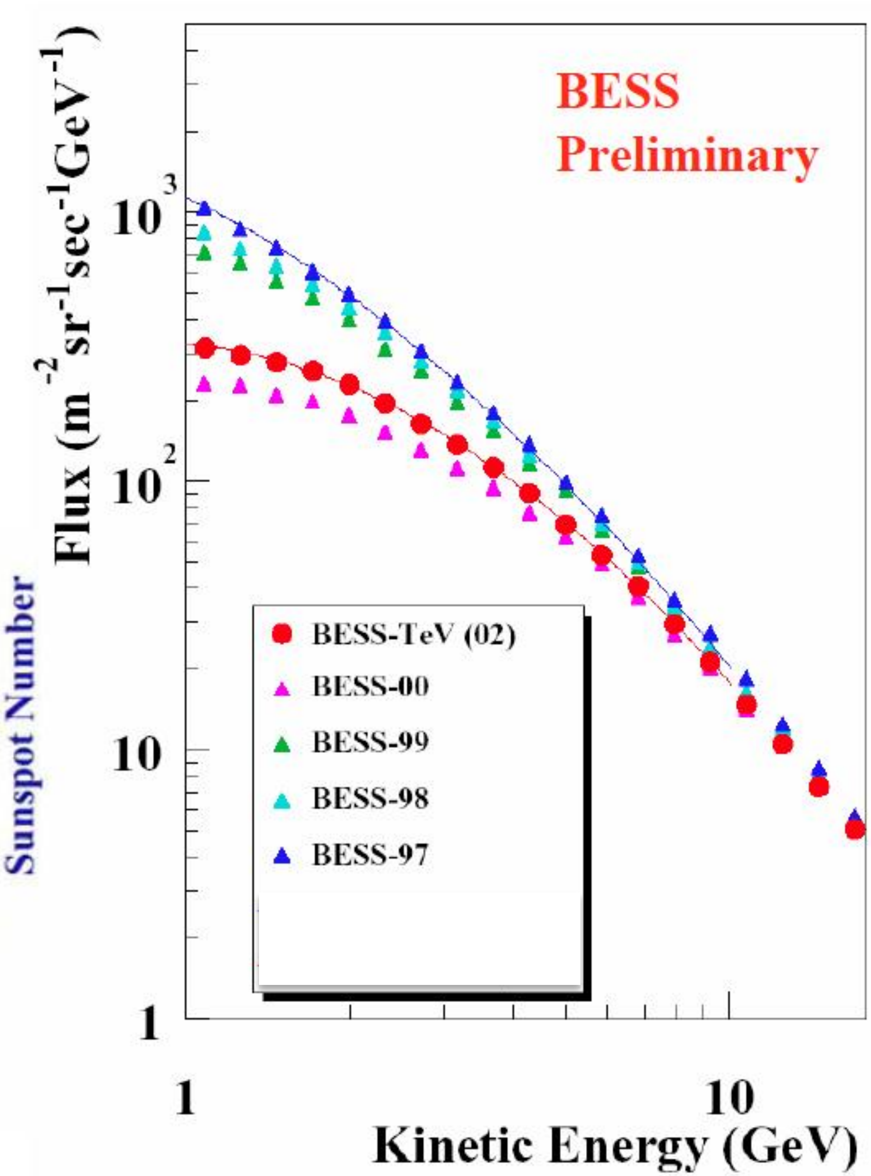
Solar Modulation

Proton flux

S. Hisano, BESS collaboration

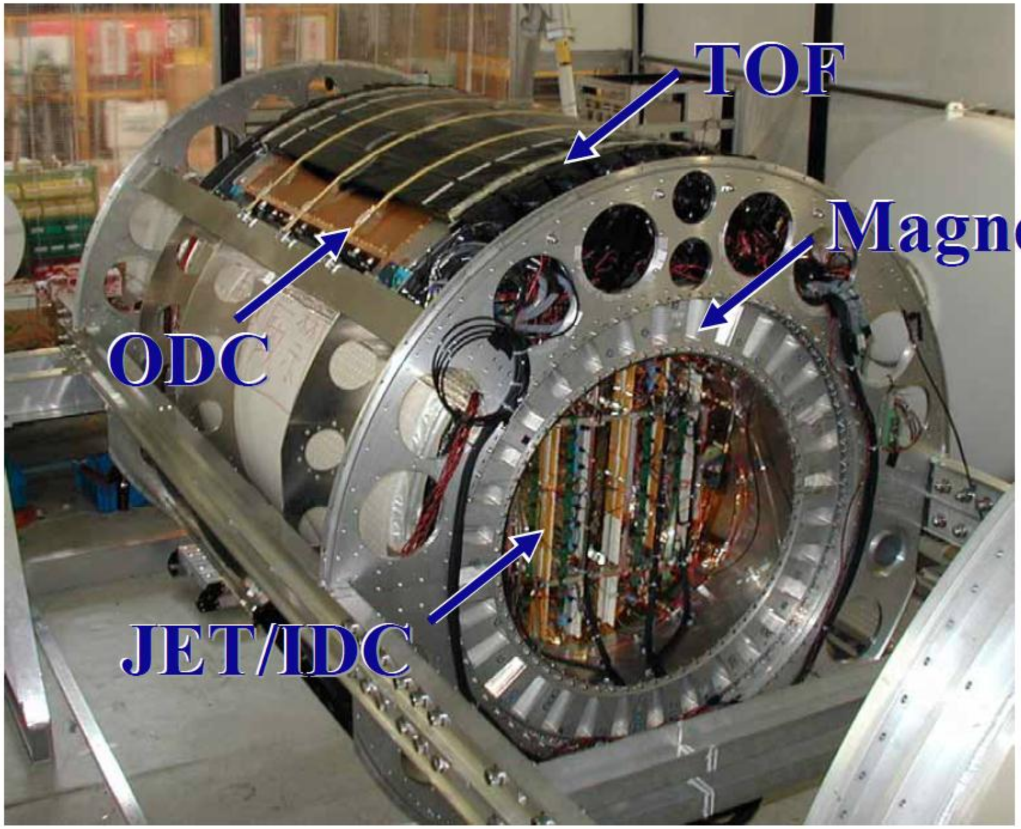
Solar modulation effect clearly identified

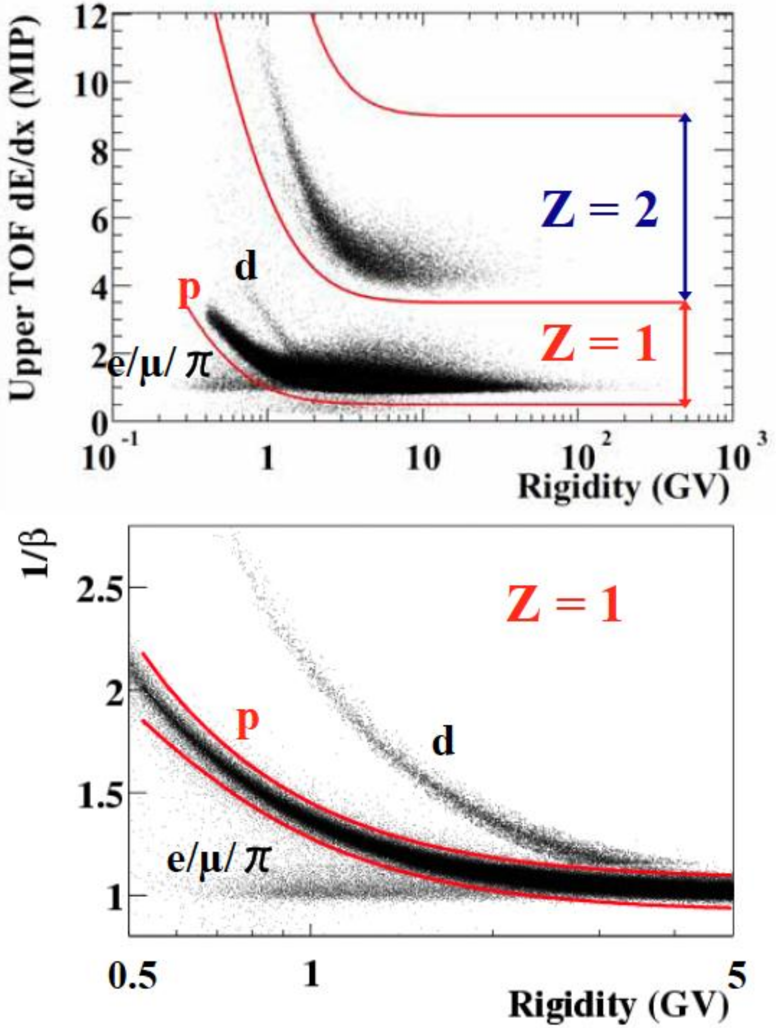




BESS

BESS-TeV spectrometer

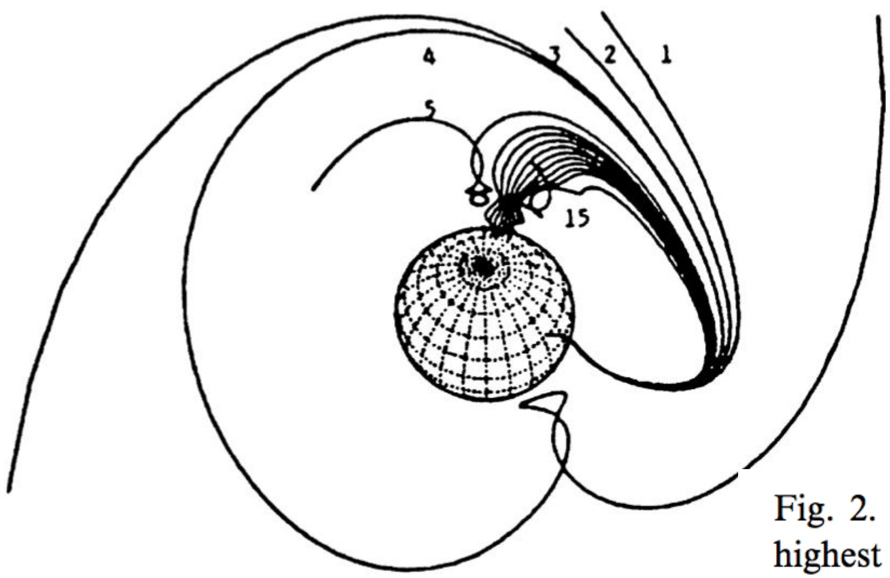




Atmospheric Neutrino Flux Calculation

Need knowledge of

- Primary Cosmic Ray Flux (p, He,…)
  - Modulation by Solar Activity
  - Geomagnetic cut-off
    - Affect on low energy CR
    - A function of the location on the earth and arriving direction

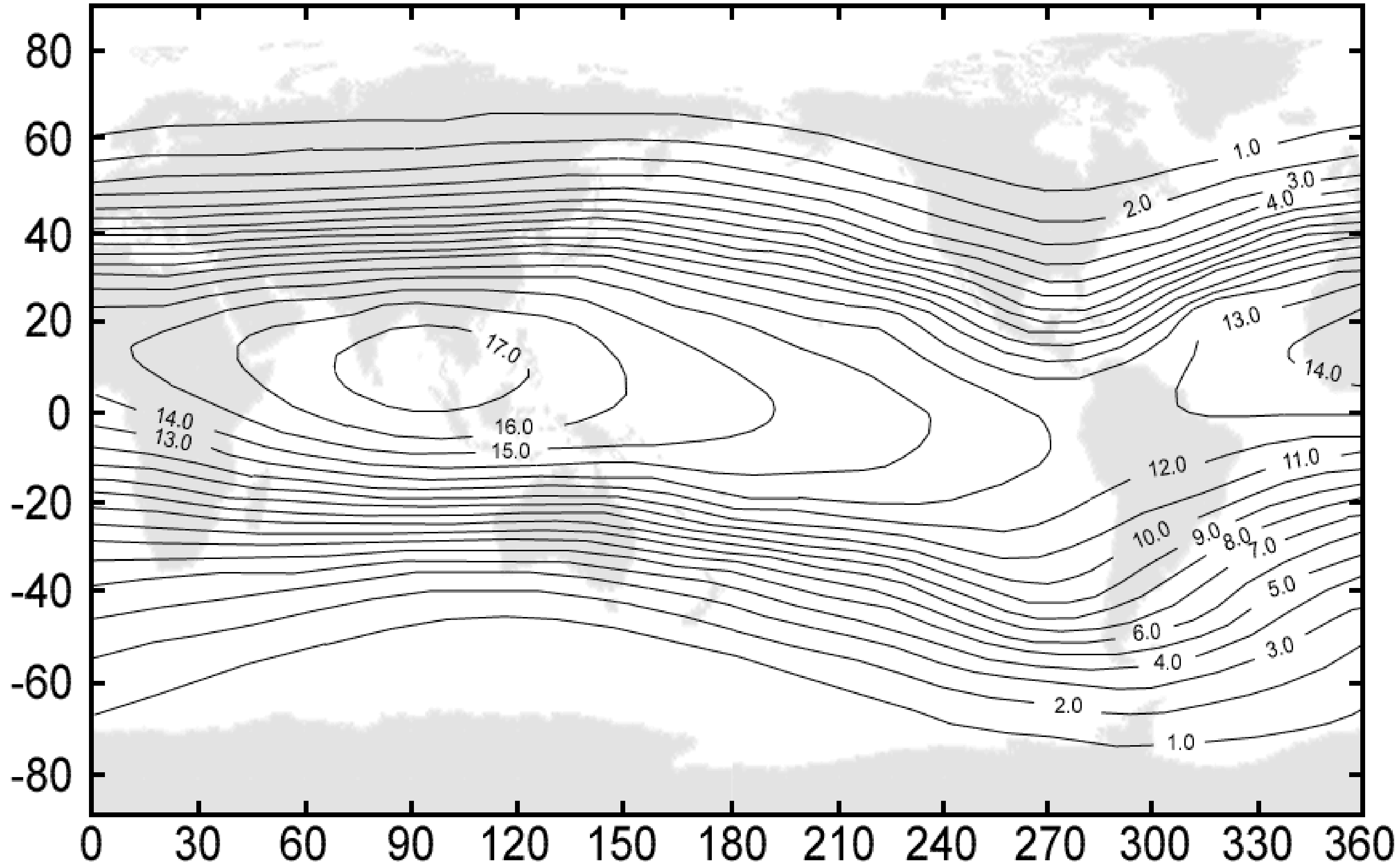


- Shielding effect of the magnetic field of the earth

D.F. Smart and M.A.Shea,
Advances in Space Research 36 (2005) 2012

Fig. 2. Illustration of the cosmic ray trajectory-tracing process. The highest rigidity (most resistant to geomagnetic bending) is labeled 1 and the lowest rigidity is labeled 15.

Geomagnetic cut-off



- Lowest regidity (GV) of primary cosmic ray particles which enter the atmosphere

➔ Atmospheric neutrinos ➔ 'Position' and time dependent

Atmospheric Neutrino Flux Calculation

Need knowledge of

- Primary Cosmic Ray Flux (p, He,…)
  - Modulation by Solar Activity
  - Geomagnetic cut-off
- Hadron Interactions (production of π, K)
- Decay of Secondary Particles (π, K, μ)
  - Technical problem
  - 3D calculation (influence in low energy, horizontal direction)

$$
\begin{aligned}
A_{\mathrm{cr}} + A_{\mathrm{air}} \rightarrow\ & \pi^{\pm}, K^{\pm}, K^{0}, \ldots \\
& \pi^{+} \rightarrow \quad \mu^{+} + \nu_{\mu} \\
& \qquad\qquad \mu^{+} \rightarrow \quad e^{+} + \nu_{e} + \bar{\nu}_{\mu} \\
& \pi^{-} \rightarrow \quad \mu^{-} + \bar{\nu}_{\mu} \\
& \qquad\qquad \mu^{-} \rightarrow \quad e^{-} + \bar{\nu}_{e} + \nu_{\mu}
\end{aligned}
$$

Many Improvements of the flux calculation for the last 10 years!

Comment on Primary Cosmic Ray

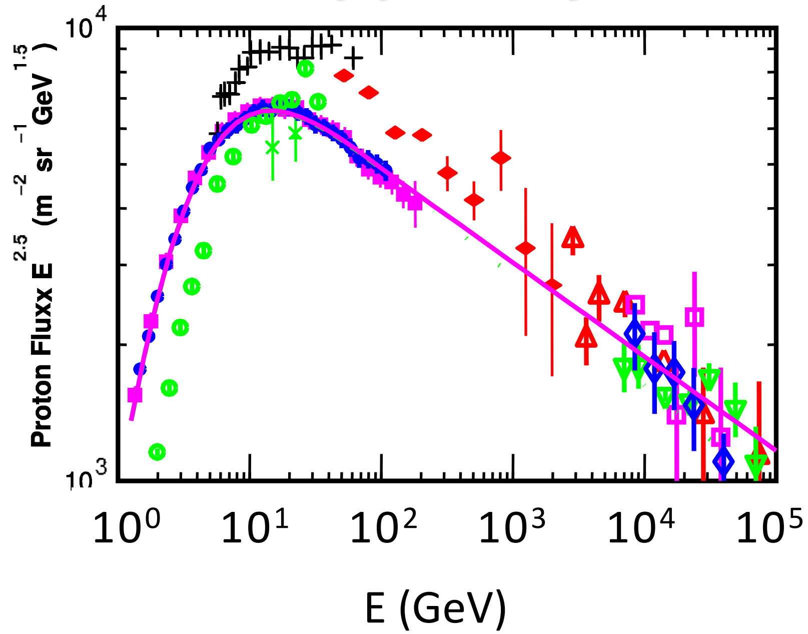
- **$\langle E_\nu \rangle \leftarrow \sim 1/10 \times \langle E_p \rangle$**

  1 GeV $\nu \leftarrow \sim$ 10 GeV proton

  10 GeV $\nu \leftarrow \sim$100 GeV proton

- **Improvement**
  – Precise measurement by BESS (<500 GeV) and AMS (<200 GeV)
  – Uncertainty was significantly reduced

cosmic-ray proton flux



solid circle (blue): AMS
solid square (purple): BESS
line: fit used for Honda flux

Flux uncertainty

- **Uncertainty of absolute ν-Flux**
  - **10% @ <10GeV 🡐 25%**
  - **~30% @~100GeV**
- **In order to overcome those uncertainties,**

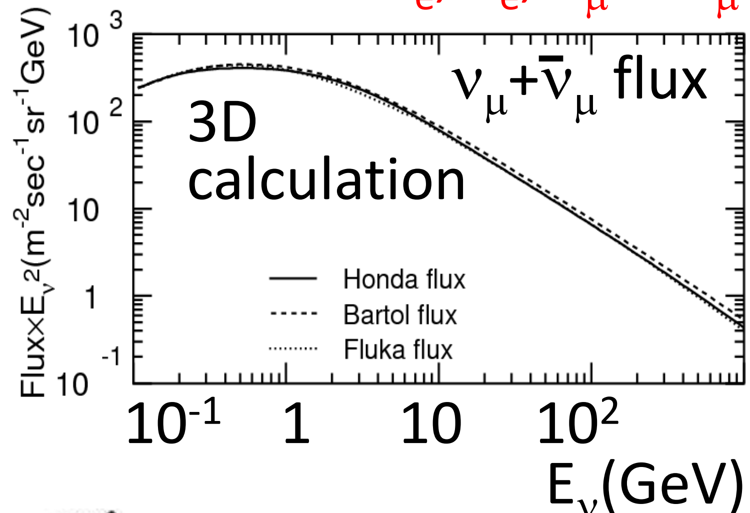
➔ use double ratio for the study of neutrino oscillation

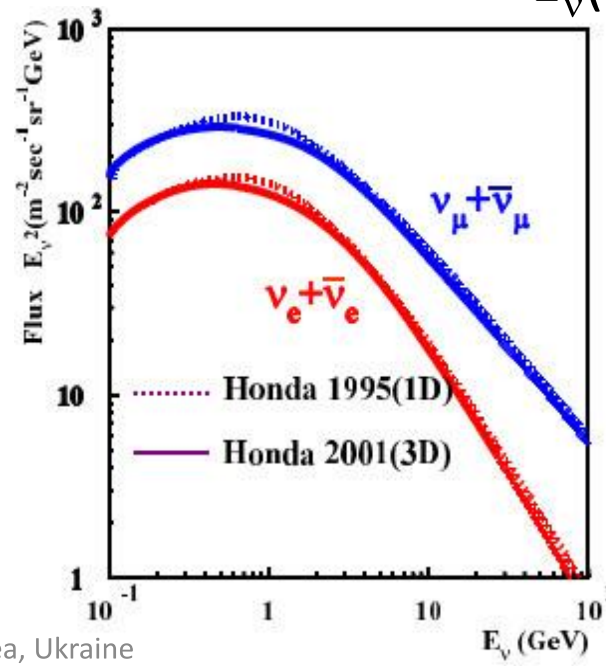
- **Uncertainty in R (flux)**
  - **3% @ <5GeV**
  - **15% @~100GeV**

$$R = \left(\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}\right)_{data} \Big/ \left(\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}}\right)_{MC}$$

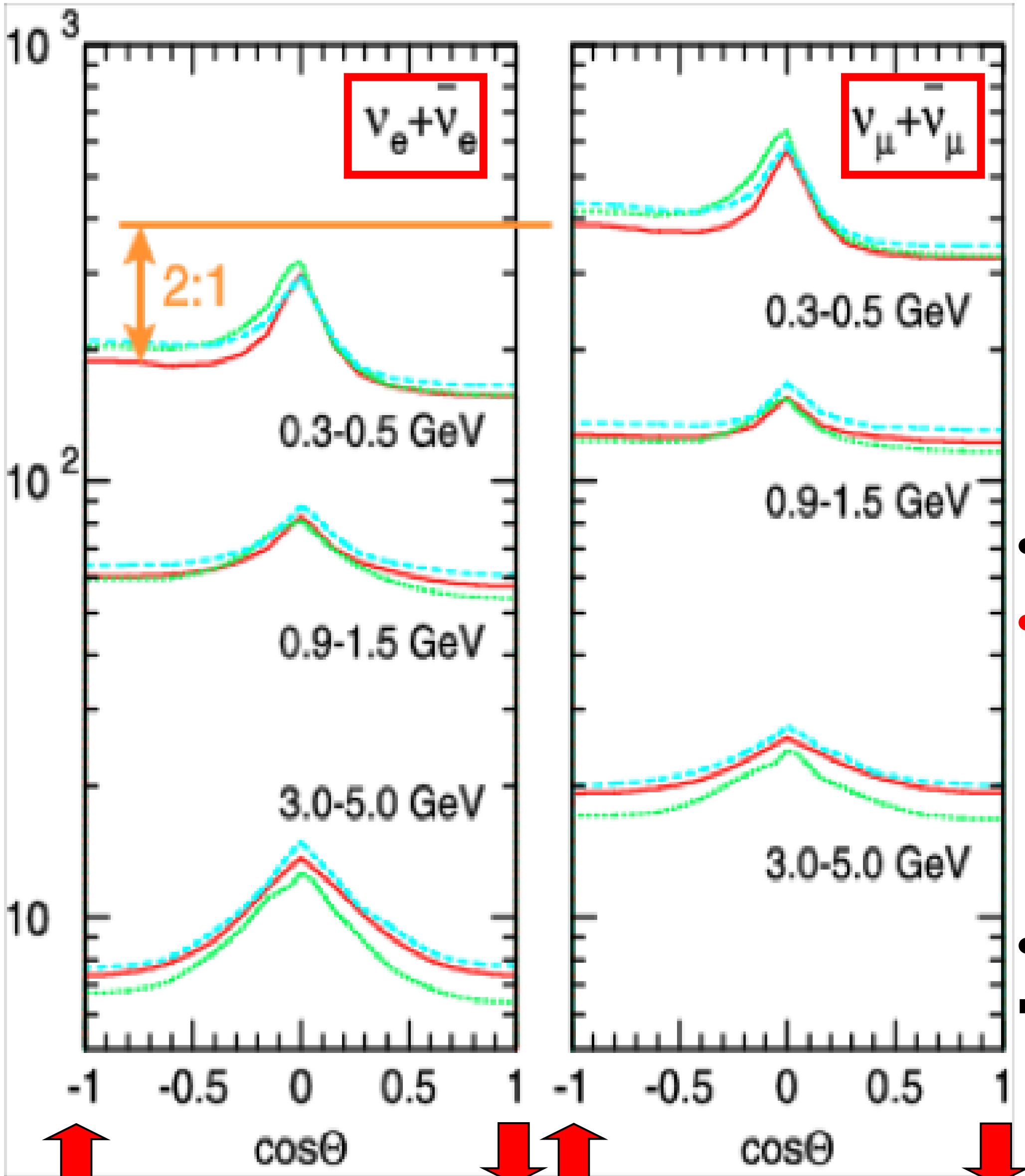
≠1 ➔ *Evidence for neutrino oscillation*

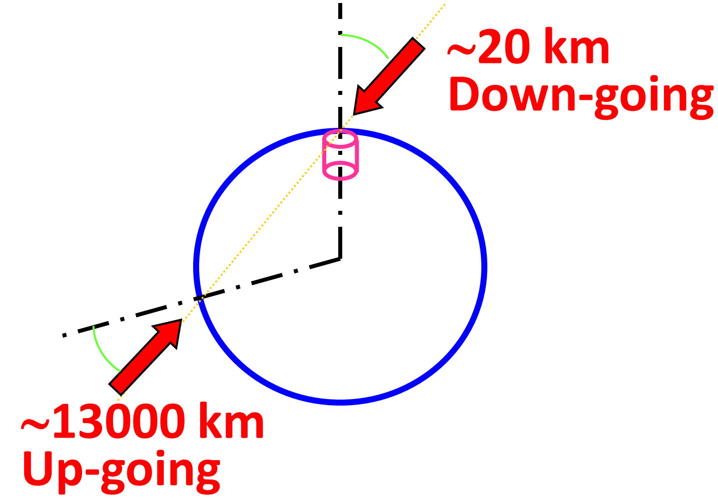
Mixture of ν_e, $\bar{\nu}_e$, ν_μ & $\bar{\nu}_\mu$





Zenith angle distribution





- Key to the oscillation analysis
- Up-Down Symmetry

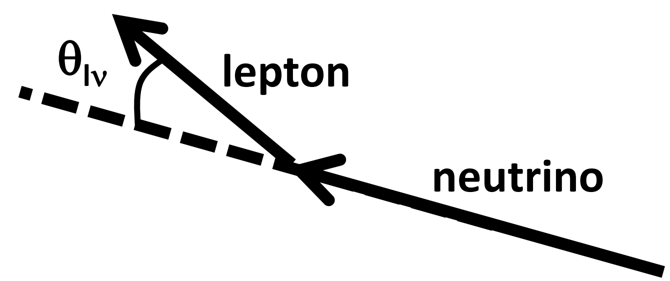
🡐 uniformity of Pr. CR for the energy above the geomagnetic cut off

- Asymmetry

➔ flux independent evidence of neutrino oscillation

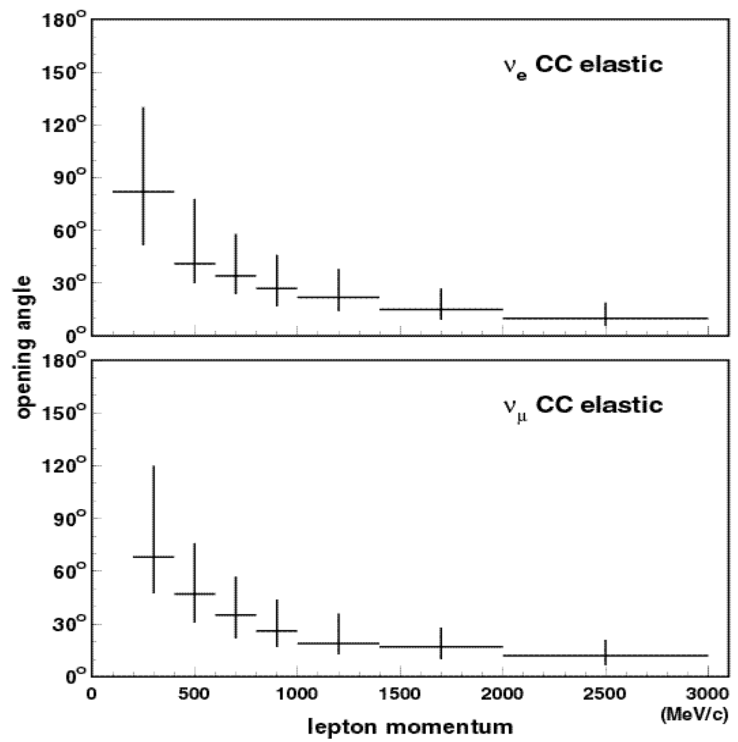
Zenith angle distribution

- **Uncertainty in Up/Down**
  ➔1~2% E_ν <1GeV
  ~1% in a few GeV region
- **Uncer. of Hol./Ver. (up-μ)**
  ➔~2% (from π/K ratio)



Angular Correlation ($\theta_{lepton-\nu}$)

- No good correlation below ~500 MeV (>30 deg)
- Good correlation in high energy region (>500 MeV)



Oscillation Study

- **Ratio**
- **Zenith Angle**

- **Need improvements for the parameter determination**

  ➔ Need precise and absolute value of neutrino flux

Atmospheric neutrino Experiments History

Back to 1960

Experimental idea to detect Atmospheric Neutrinos

- ***First indication of a possibility to detect atmospheric neutrinos:***

ON HIGH ENERGY NEUTRINO PHYSICS

M. A. Markov

Joint Institute for Nuclear Research, Dubna, USSR

Proc. 1960 Annual Int. Conf. on High Energy Physics at Rochester

I will report on investigations in the field of high and intermediate energy neutrino physics carried on at the Joint Institute for Nuclear Research in 1958-60. The full texts of the papers on which I will comment can be found in the pamphlet entitled " On High Energy Neutrino Physics " (Dubna 1960).

Various possibilities of neutrino experiments using accelerators or cosmic rays are discussed in this report. The analyses show that it is possible to carry on neutrino experiments with existing accelerators and underground, with cosmic ray neutrinos. In fact, Ponte-

This (experimentally dictated) cut-off is at a momentum smaller than that at which non-applicability of perturbation theory could be suspected. The decay $\mu \rightarrow e+\gamma$ gives the more stringent restriction on the cut-off. In accordance with the experimental upper limit; $\frac{W(e+\gamma)}{W(e+\nu+\bar{\nu})} < 1.2 \times 10^{-6}$ the critical momentum must be chosen, $k_{max} < 50$ BeV.

One natural cut-off mechanism would be an intermediate vector boson. Another possibility is that the neutrino associated with the μ-meson is different from

In 1960, M.A.Markov suggested: upward and horizontal muons are signature of high energy neutrinos

Experimental idea to detect Atmospheric Neutrinos

- ***First idea for water detectors***

Ann. Rev. Nucl. Sci. 10, 63(1960)

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y.

I. SIGNIFICANCE OF EXTENSIVE AIR SHOWERS

1. Exploration of Space by Analysis of Received Radiation

Although bound to earth and its immediate vicinity, man has acquired a wealth of knowledge about a volume of space 10^{58} times that of the earth, almost entirely by interpretation of incoming radiation. The richest and clearest information has been conveyed by visible light. Recent years have witnessed a rapid advance in the detection and interpretation of radio signals. Rockets and satellites have opened up the fields of ultraviolet and x-ray astronomy. Gamma-ray astronomy is on the horizon. Each of these bands of radiation has its own peculiar potentialities for telling the story of special processes occurring in different parts of the universe, and about the conditions of matter and fields that make these processes possible.

K. Greisen described:

water detector for atmospheric ν detection

Experimental measurements of the Atmospheric Neutrinos

- ***First detection***

Kolar gold mine in India
S. Miyake *et al*.
<u>July 12</u>, 1965 (Received)
Phys. Lett. <u>18</u>(1965) 196

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Following the early work [1] carried out at great depths underground in the Kolar Gold Mines in South India, we have specifically designed an experiment for the detection of muons produced

- ***Second detection (2 weeks later)***

South African gold mine
F. Reines *et al*.
<u>July 26</u>, 1965 (Received)
Phys. Rev. Lett. <u>15</u>, 429 (1965)

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

The flux of high-energy neutrinos from the decay of K, π, and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.[1] In addition, there has been some con-

each. Each detector element, Fig. 2, is a rectangular box of Lucite of wall area 3.07 m^2 containing 380 liters of a mineral-oil based liquid scintillator,[4] and is viewed at each end by two 5-in. photomultiplier tubes. The array

Detectors for those experiments

- Both detected horizontal and upgoing muons

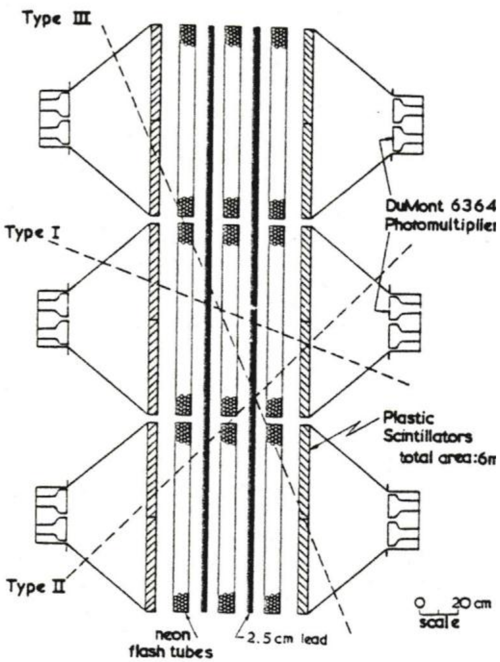
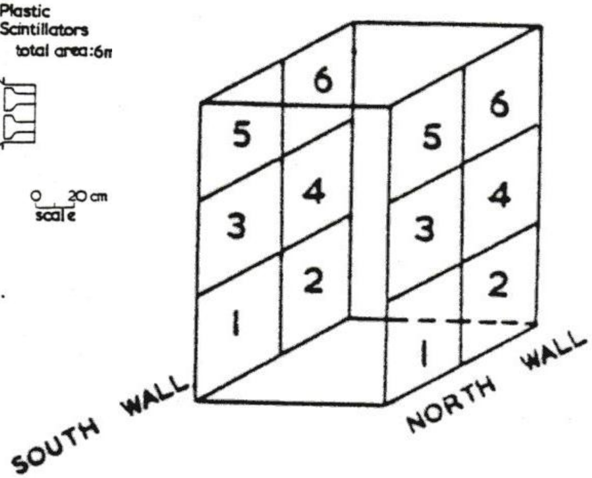
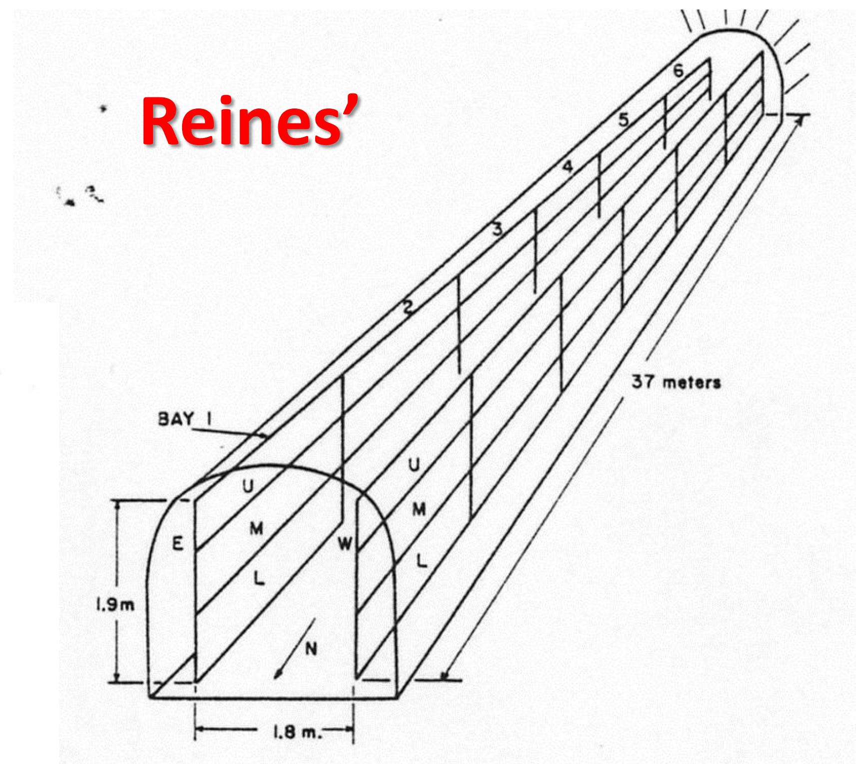


Fig. 1. Neutrino telescope.

Miyake's

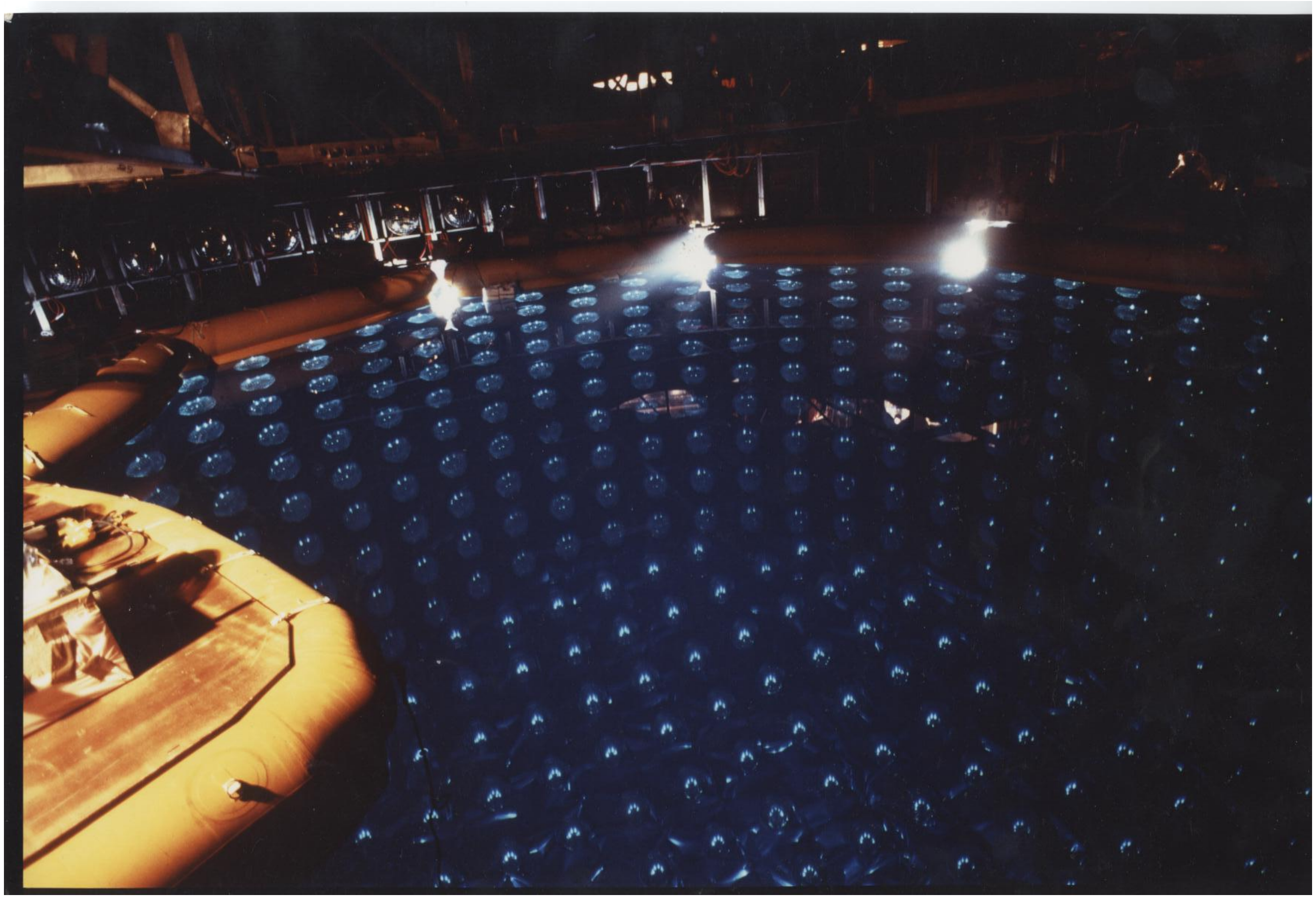


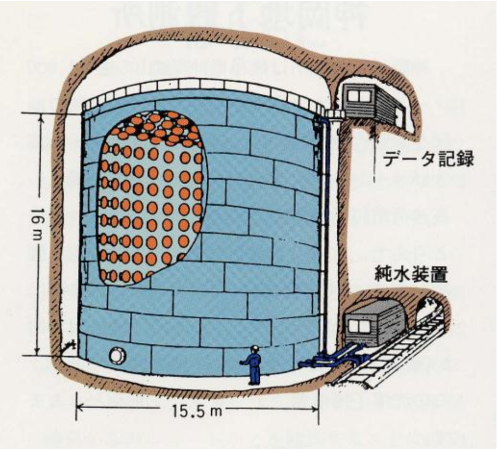
Reines'



20 years later
Early indications

The First Problem





1983~1996
Started as a proton decay search experiment

3000 ton total mass
1000 ton fidutial mass for atmospheric neutrino study

The First Problem

Volume 205, number 2,3 PHYSICS LETTERS B 28 April 1988

EXPERIMENTAL STUDY OF THE ATMOSPHERIC NEUTRINO FLUX

K.S. HIRATA, T. KAJITA, M. KOSHIBA, M. NAKAHATA, S. OHARA, Y. OYAMA, N. SATO, A. SUZUKI, M. TAKITA, Y. TOTSUKA
ICEPP, Department of Physics, Department of Astronomy, Faculty of Science, University of Tokyo, Tokyo 113, Japan

T. KIFUNE, T. SUDA
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan

K. NAKAMURA, K. TAKAHASHI, T. TANIMORI
National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

K. MIYANO, M. YAMADA
Department of Physics, University of Niigata, Niigata 950-21, Japan

E.W. BEIER, L.R. FELDSCHER, E.D. FRANK, W. FRATI, S.B. KIM, A.K. MANN, F.M. NEWCOMER, R. VAN BERG, W. ZHANG
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

and

B.G. CORTEZ
AT&T Bell Laboratories, Holmdel, NJ 07922, USA

Received 25 January 1988

We have observed 277 fully contained events in the KAMIOKANDE detector. The number of electron-like single-prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single-prong events is 59 ± 7% (statistical error) of the predicted number of the Monte Carlo calculation. We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.

Primary cosmic rays striking the atmosphere produce pions and kaons which subsequently decay into muons and muon-neutrinos, and much less abundantly, electrons and electron-neutrinos. The muons further decay into electron-neutrinos and muon-neu-

We have made a detailed study of the atmospheric neutrino spectrum in the large underground detector KAMIOKANDE, in which we find an apparent discrepancy in the ratio of the observed number of atmospheric electron-neutrino-induced events to the

Atmospheric Neutrinos are the backgrounds for proton decay in large water Cherenkov Detectors in 80's:

Kamiokande: observed atmospheric-ν interactions happed inside of the detector and found fewer μ-like events

The first problem:

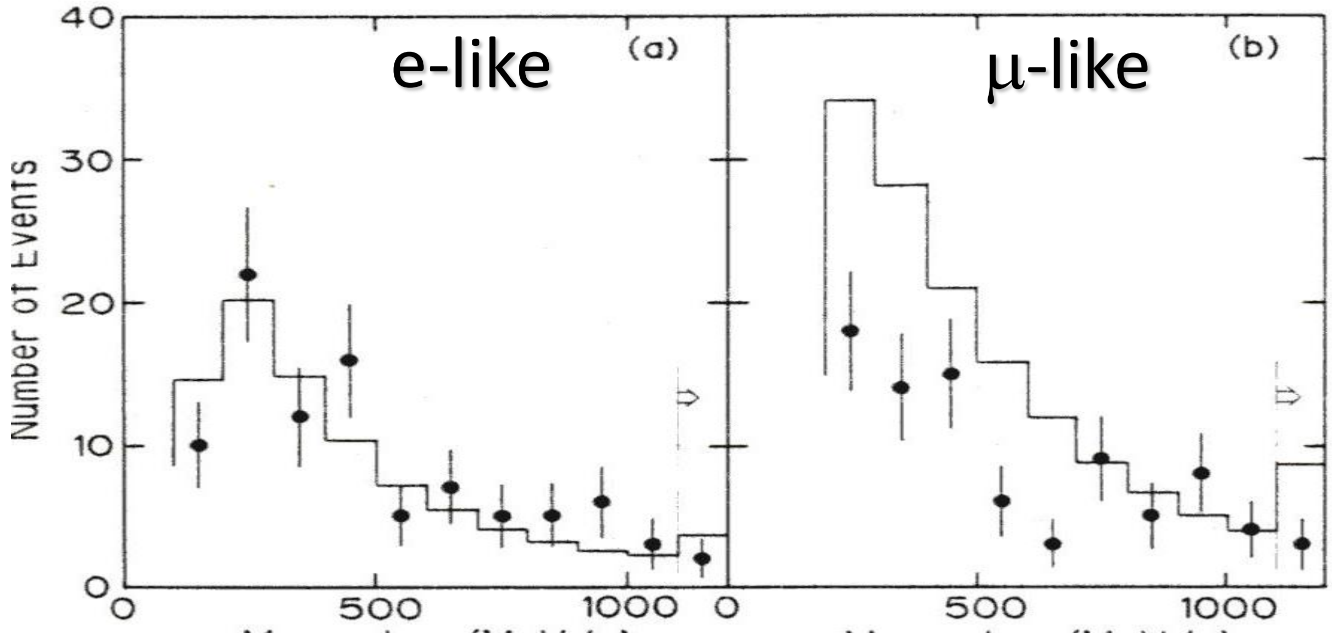
PLB, 205, 416 (1988)

By Kamiokande

Kamiokande Data

In 1988, Kamiokande saw few μ

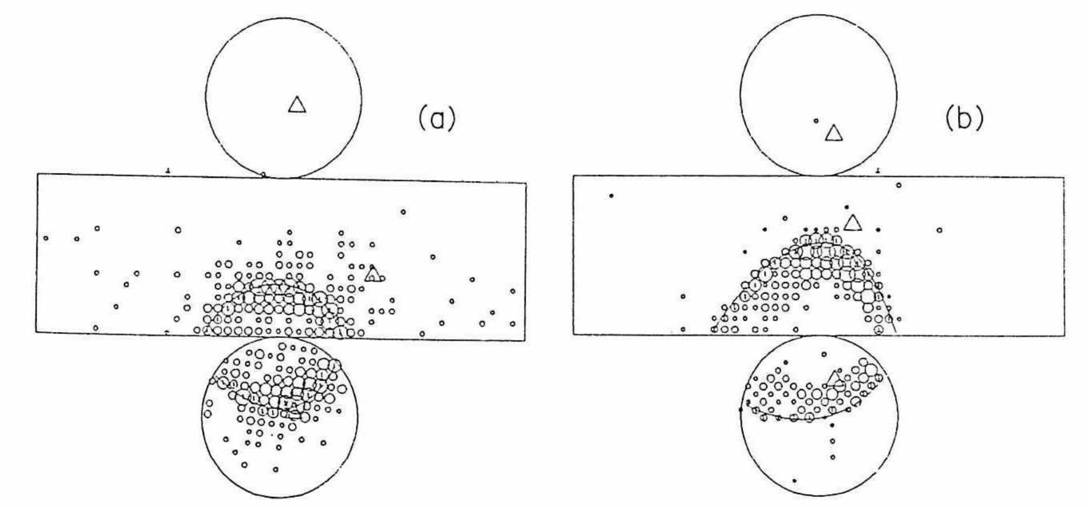
R= (Obs./MC)μ-like = 0.59±7% (stat.)

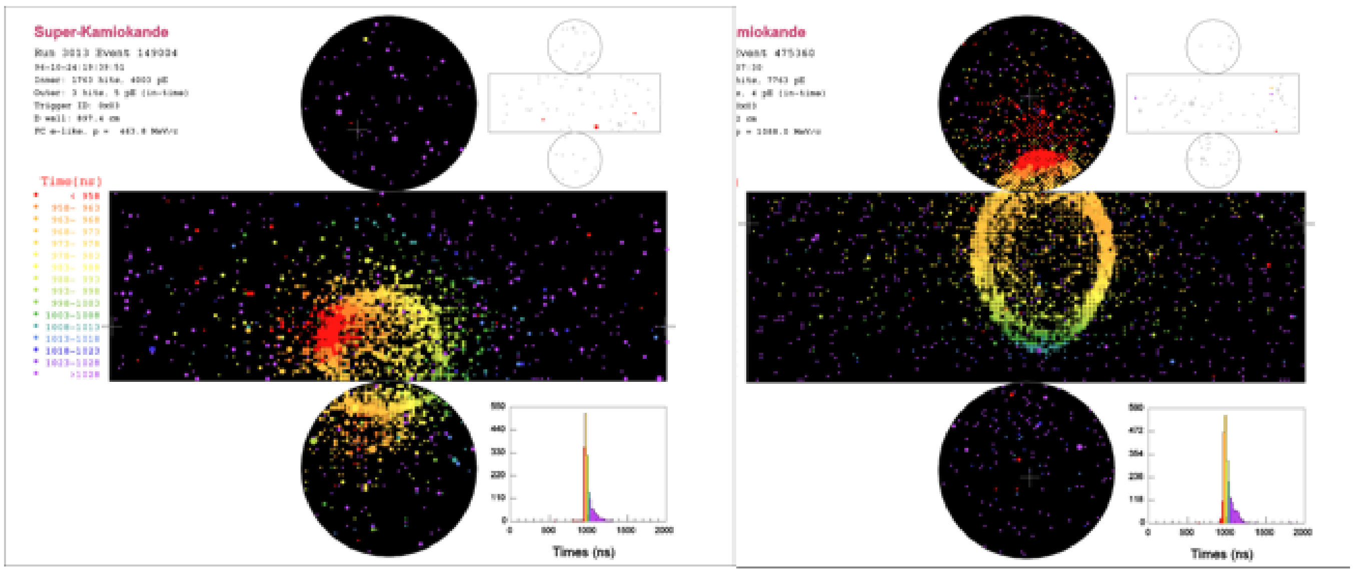


Momentum (MeV/c)

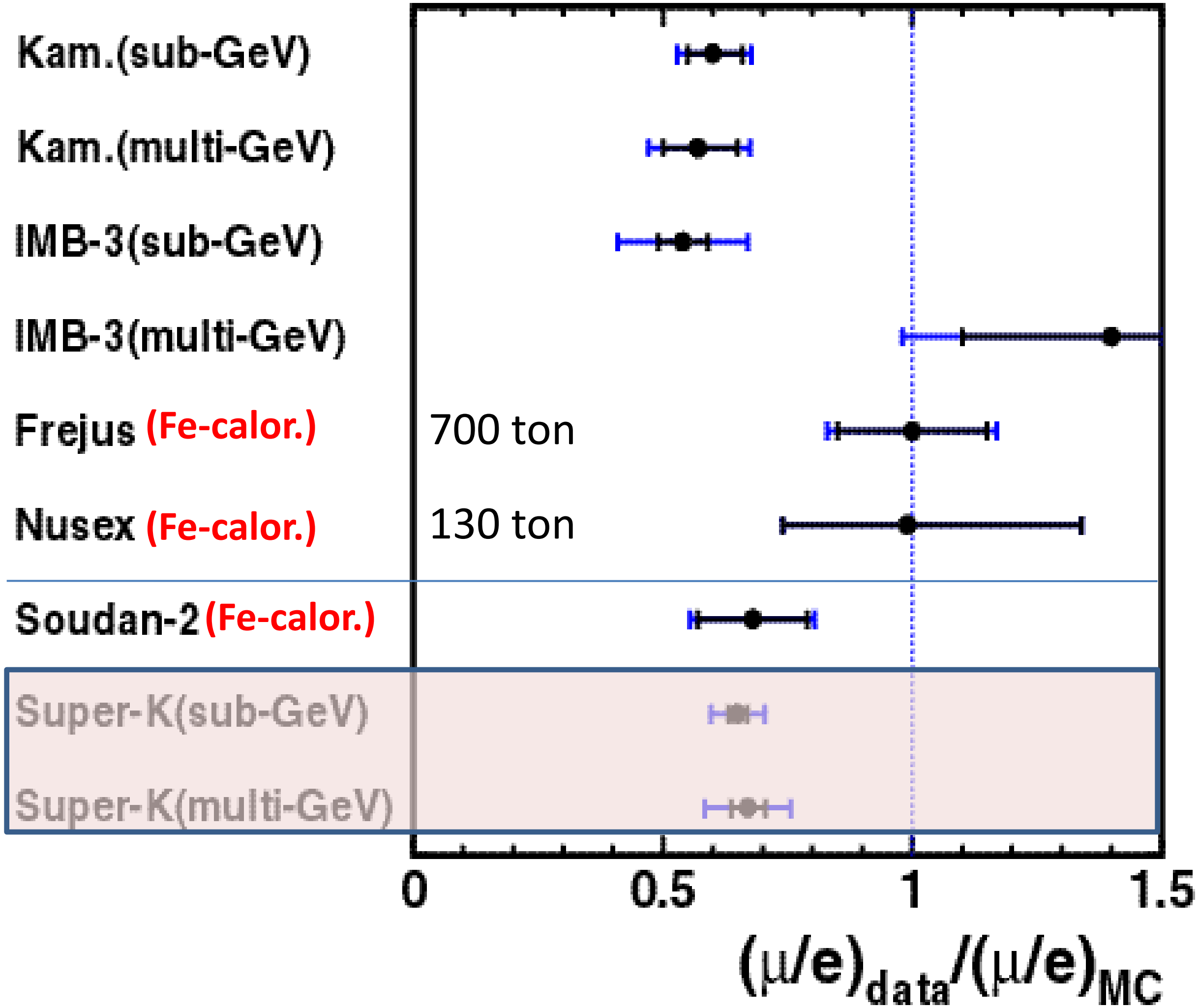
- **Problems:**
  - **Large uncertainty of the flux calculation**
  - **Theorists did not believe large mixing**

μ/e separation





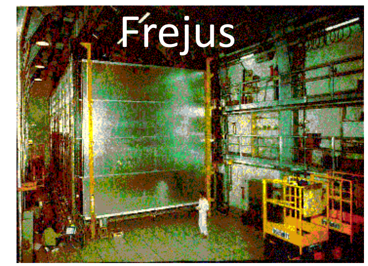
R measurement in 90's



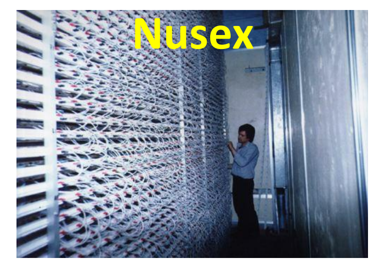
1988

1992

1997



In early 90's, there are some confusion of the data



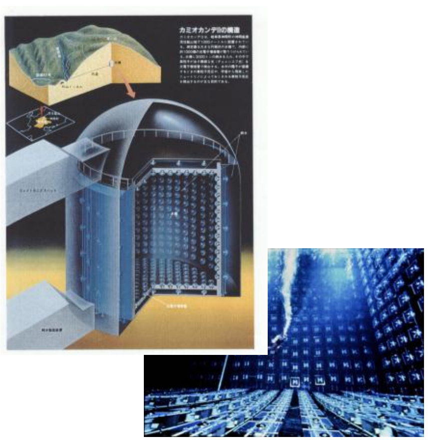
IMB-3

- Observed small μ/e ratio in 1992
- 8000 ton Water Cherenkov Detector
- 3300 ton fiducial mass

Water Cherenkov detectors have played a major role in low energy neutrino physics

80’s	90’s	00’s	10’s	20’s	30’s	40’s

Kamiokande, IMB
(a few thousand tons)

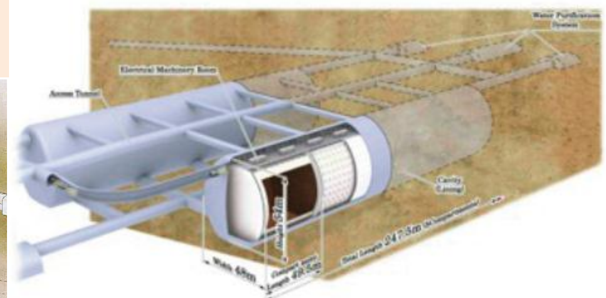


Supernova-ν: SN1987A
Solar ν problem
Atm ν anomaly

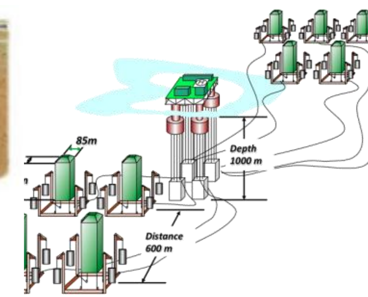
Super-Kamiokande
(50, 000 tons)
SNO (D_2O)
(1000 tons)

Atm ν oscillation
Solar ν oscillation
Supernova-ν ??

Hyper-Kamiokande
(~1Mton)



Multi-Megaton



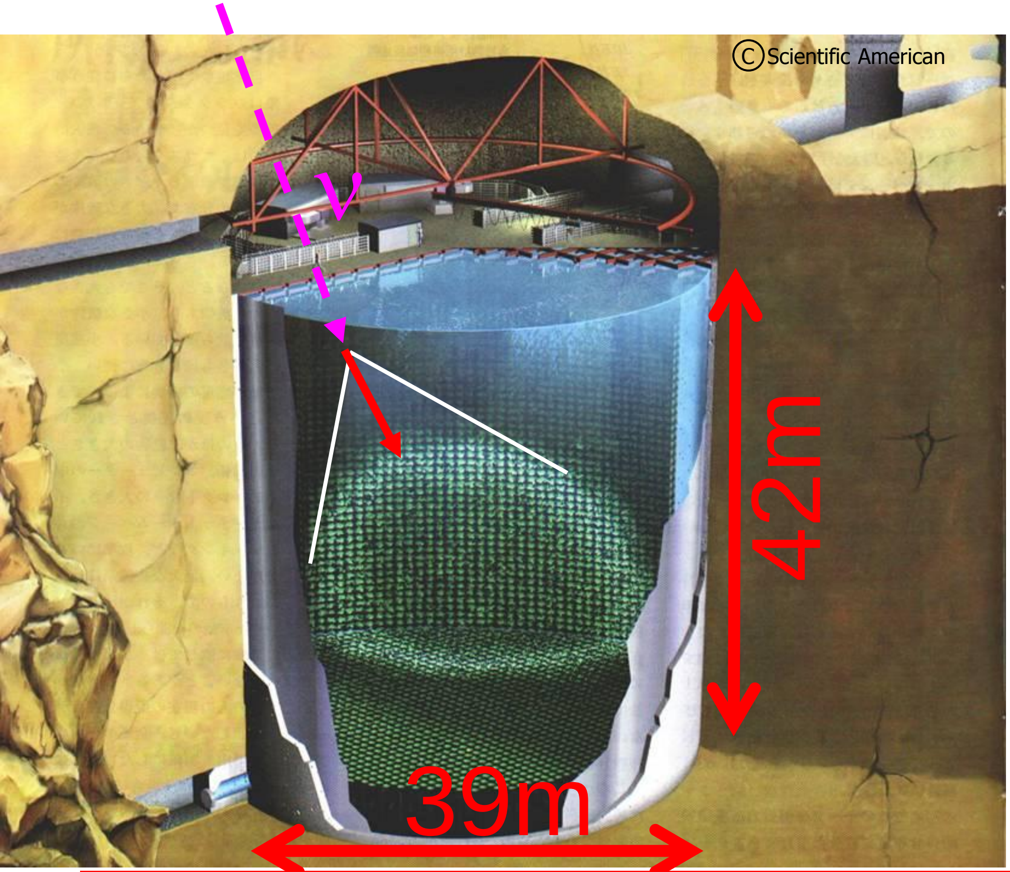
Mass hierarchy, CPV
Supernova ν
Supernova Relic ν
Proton decay
New physics ?

Breakthrough

Super-Kamiokande

Super-Kamiokande

50,000 tons of Imaging Water Cherenkov Detector



- Inner: 32,000 tons
  (Outer Vol: ~2.5 m thick)
- Fid. Vol: 22,500 tons

- 11,146 PMTs (ID)
  - 50 cm in diameter
  - 40% coverage
- 1,885 PMTs (OD)
  - 20 cm in diameter
- 1,000 m underground

~130 Collaborators from 36 inst. (5 countries)

Super-K Collaboration

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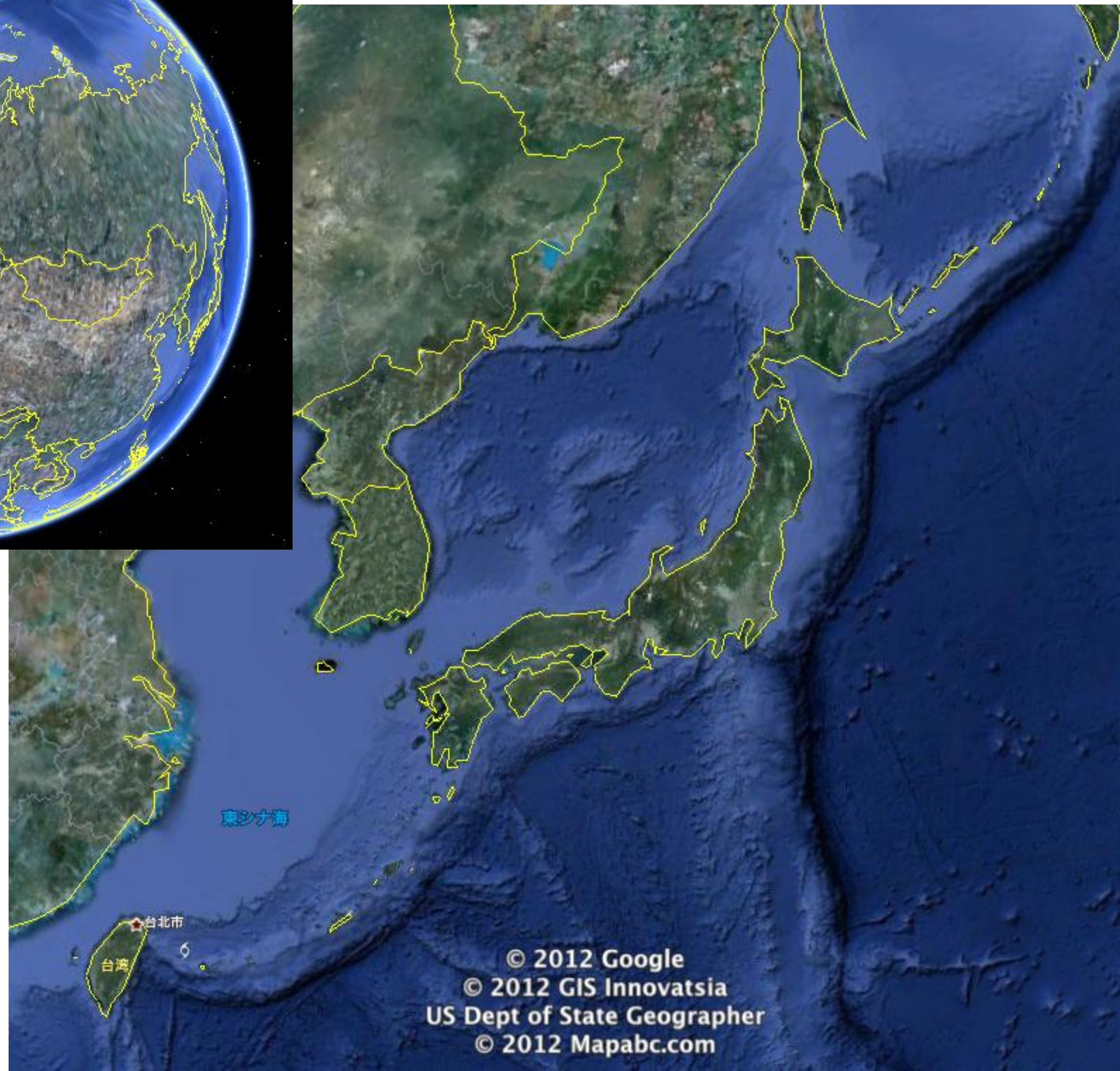
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台湾
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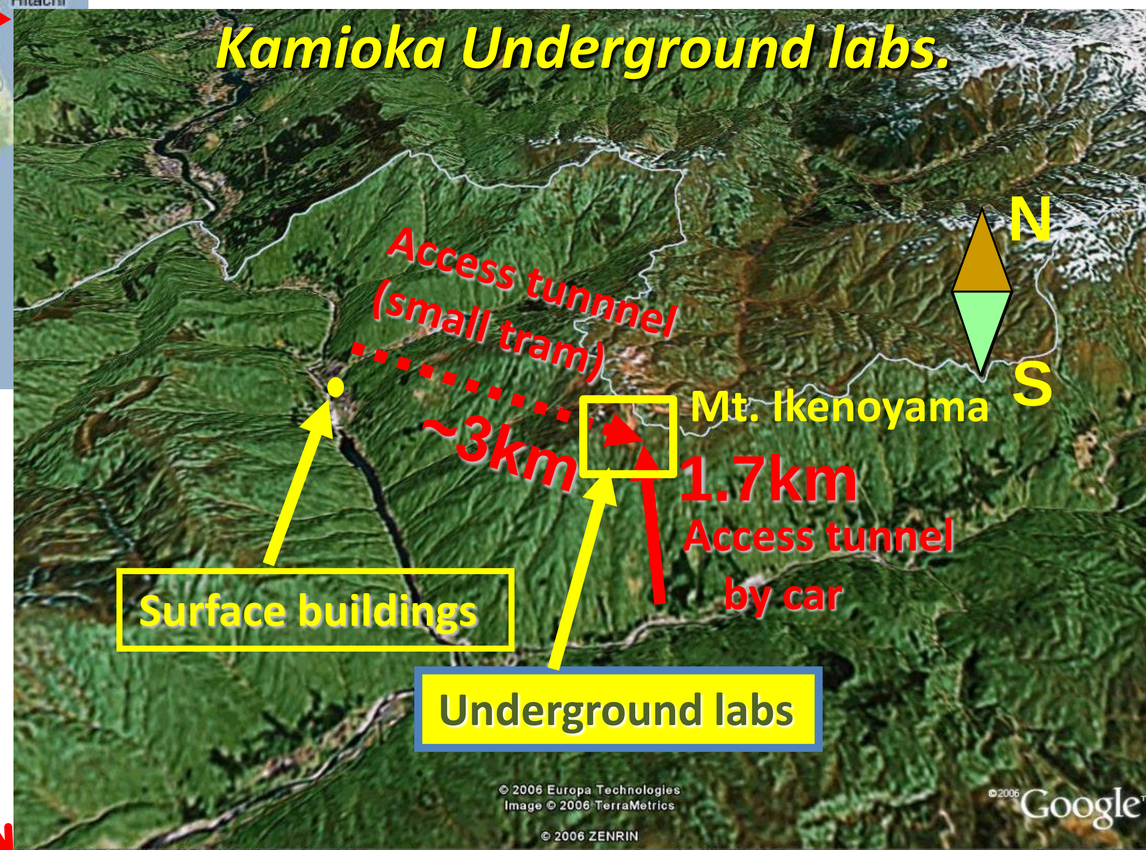
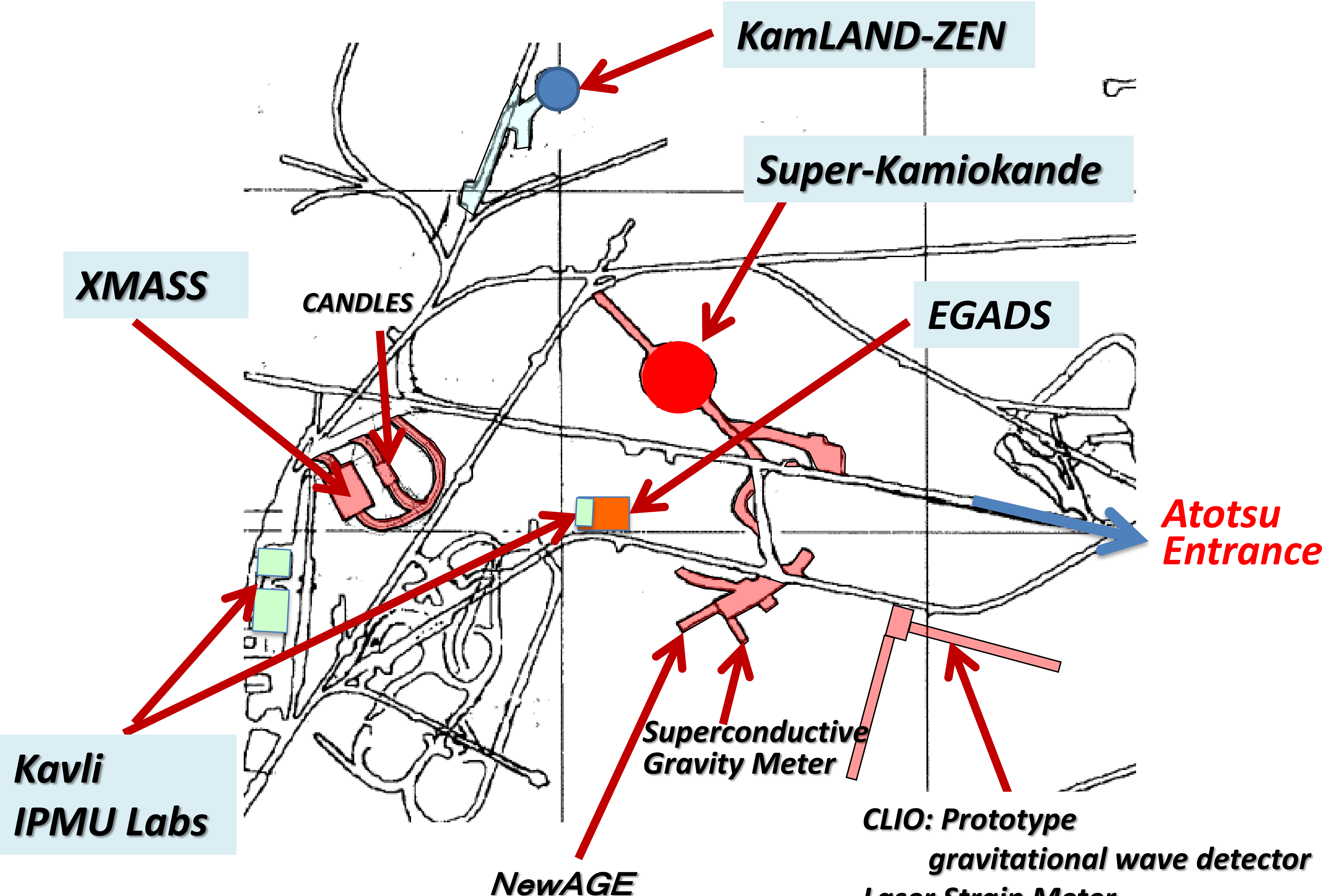
12/09/13~14

Kamioka Underground laboratories

- 1000 m underground
- 24 hours access by car



- **40 min drive from the Toyama airport**
- **Office buildings : 10 minutes drive fromthe mine entrance:**


KamLAND-ZEN
Super-Kamiokande
XMASS
CANDLES
EGADS
Atotsu
Entrance
Kavli
IPMU Labs
Superconductive
Gravity Meter
CLIO: Prototype
gravitational wave detector
Laser Strain Meter
NewAGE

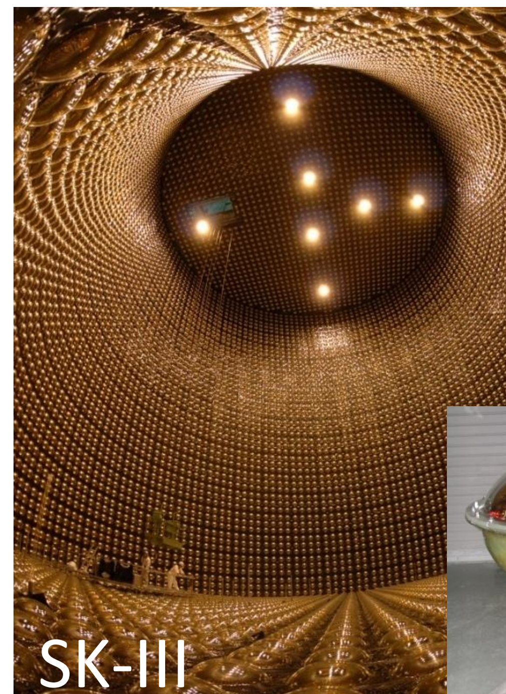
Brief history of Super-K

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12

SK-I | SK-II | SK-III | SK-IV

K2K | T2K

- **SK started on April, 1996 (SK-I)**
  - **12th Anniversary**
- **4 phases: SK-I, SK-II, SK-III, SK-IV**
  - **Accident (lost more than half of PMTs)**
    - **Nov-12, 2001**
  - **SK-II (5,182 PMTs (19% cov.))**
    - **Dec-2002 → Nov-2005**
  - **SK-III (11,129 PMTs (40% cov.))**
    - **July-2006 →**
  - **SK-IV w/new front end electronics**
    - **Sept-6, 2008 →**
- **K2K: March-1999 → Nov-2004**
- **T2K: 2009 →**

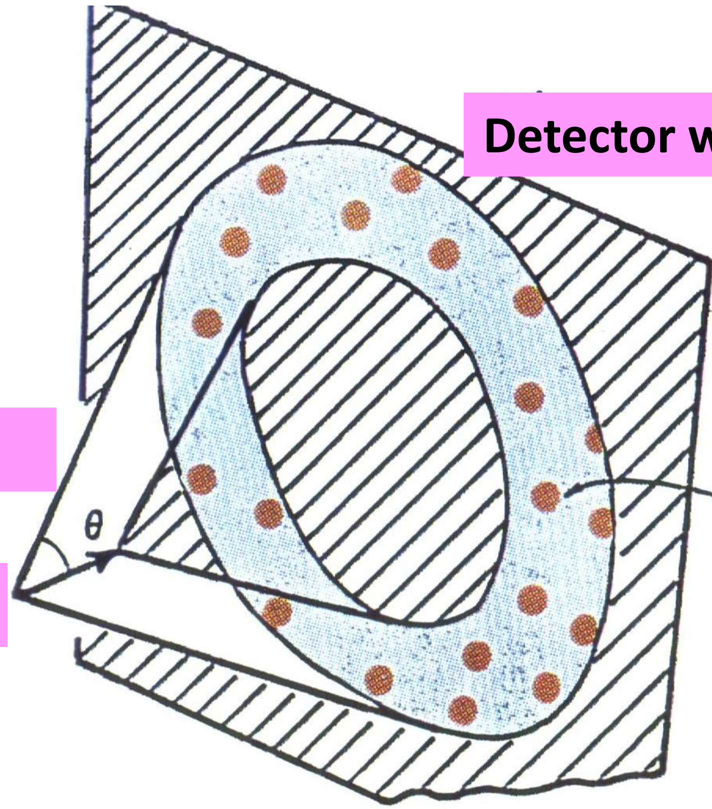


Protection case

Detection Principle - Cherenkov light

Cherenkov Angle:
$\cos\theta_c = 1/n\beta$
n=1.33 for water

$\Theta = 42$*deg for* $\beta=1$



The Cherenkov Ring on the detector wall

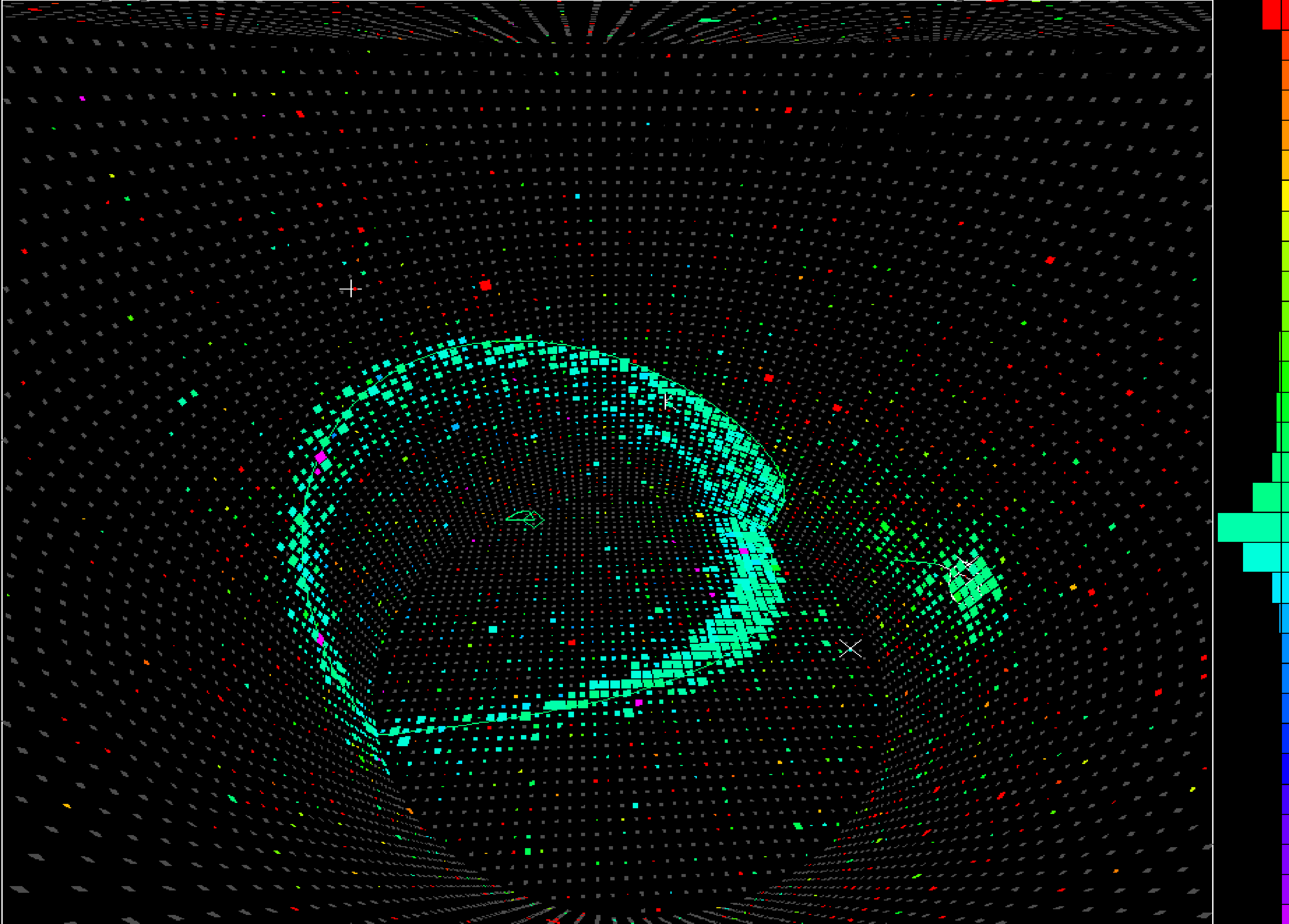
Cherenkov radiation

- Cherenkov threshold for a particle, m.

$$p_c = \frac{m}{\sqrt{n^2 - 1}}$$

- Threshold momentum
  - $e^{\pm}$ (0.511 MeV/c^2) 0.569 MeV/c
  - $\mu^{\pm}$ (105.7 MeV/c^2) 115.7 MeV/c
  - $\pi^{\pm}$ (139.6 MeV/c^2) 155.5 MeV/c
  - $p^{\pm}$ (938.3 MeV/c^2) 1044.9 MeV/c
- Number of Cherenkov photons:

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha Z^2}{\lambda^2}(1 - \frac{1}{n^2\beta^2}) = \frac{2\pi\alpha Z^2 \sin^2\theta_c}{\lambda^2}$$


Super-Kamiokande

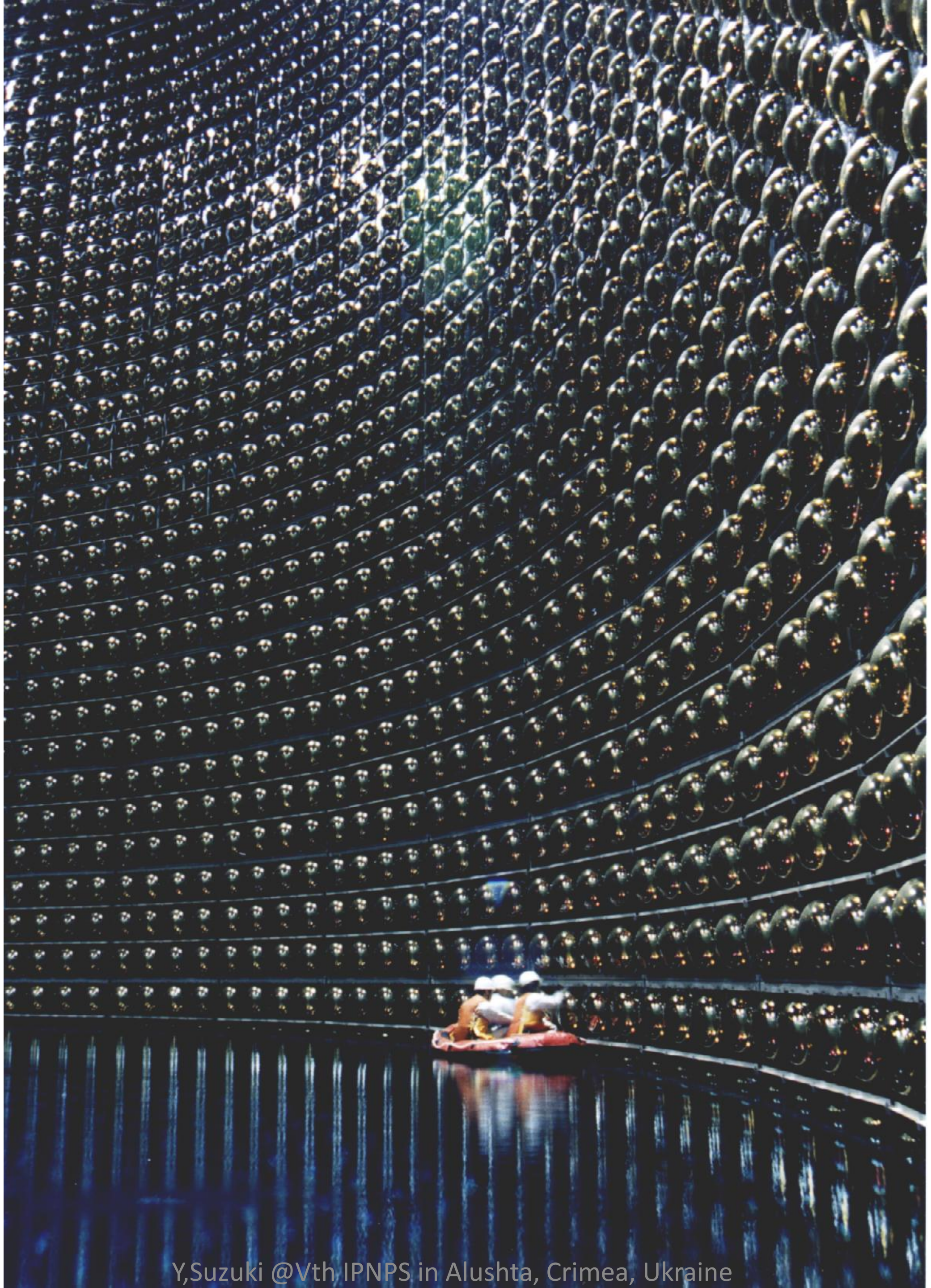
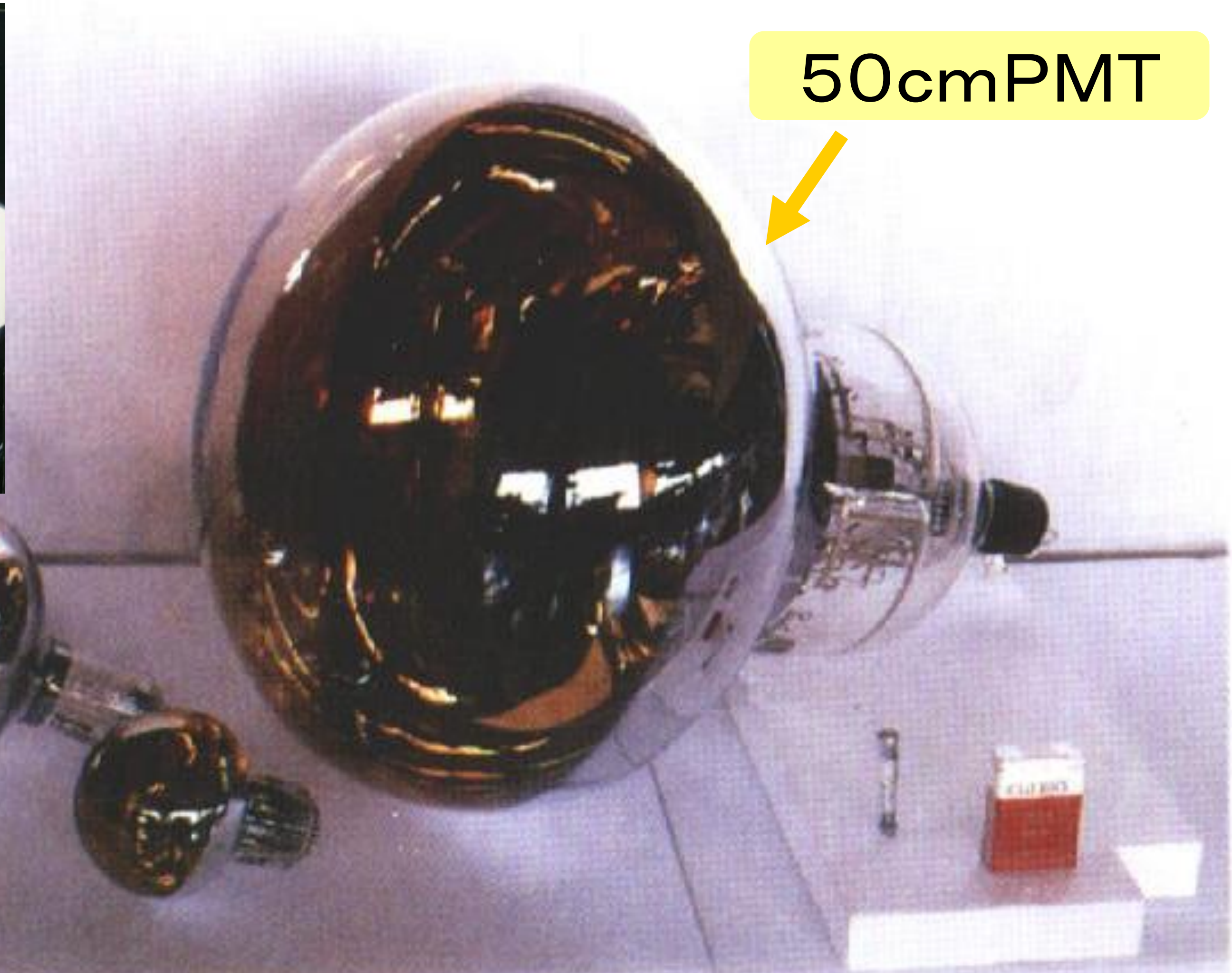
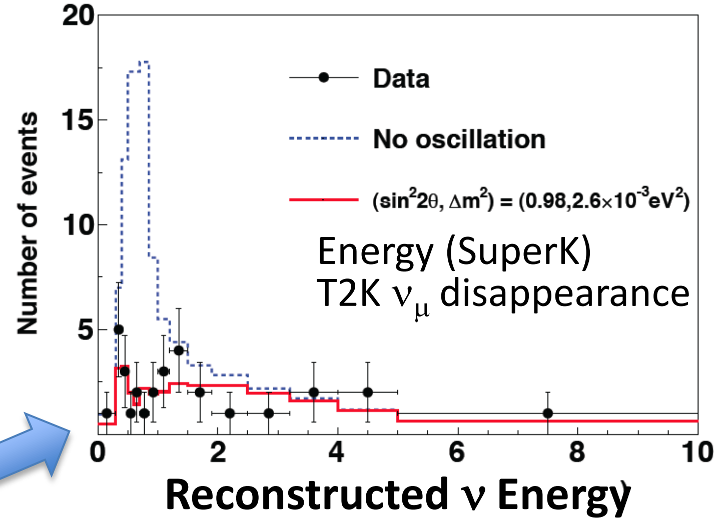


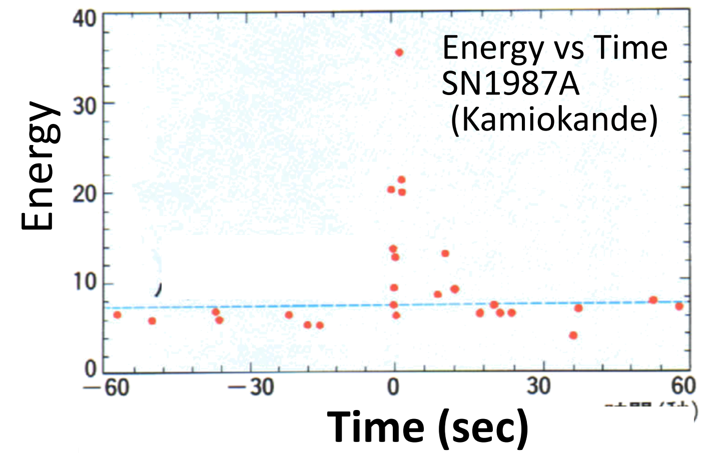
Photo-multiplier tube

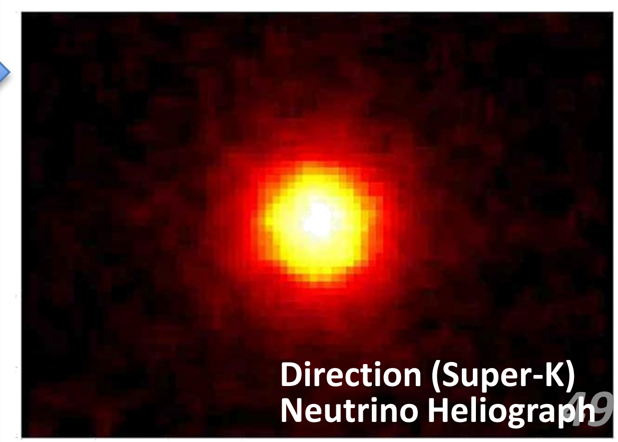


Water Cherenkov

- Water Cherenkov can do astrophysics
  - **Energy**
    - Number of observed photons ⇔ energy of recoil charged particles
  - **Time**
    - $\Delta t \sim$ nsec
  - **Direction**
    - Low energy (< 10 MeV) ν_x:
      $\nu_x + e \rightarrow \nu_x + e$, $\Delta\theta$ ← multiple scatt.
    - High energy (GeV<) ν_μ:
      $\nu_\mu + X \rightarrow \mu + X'$, 30 deg (GeV)~2deg



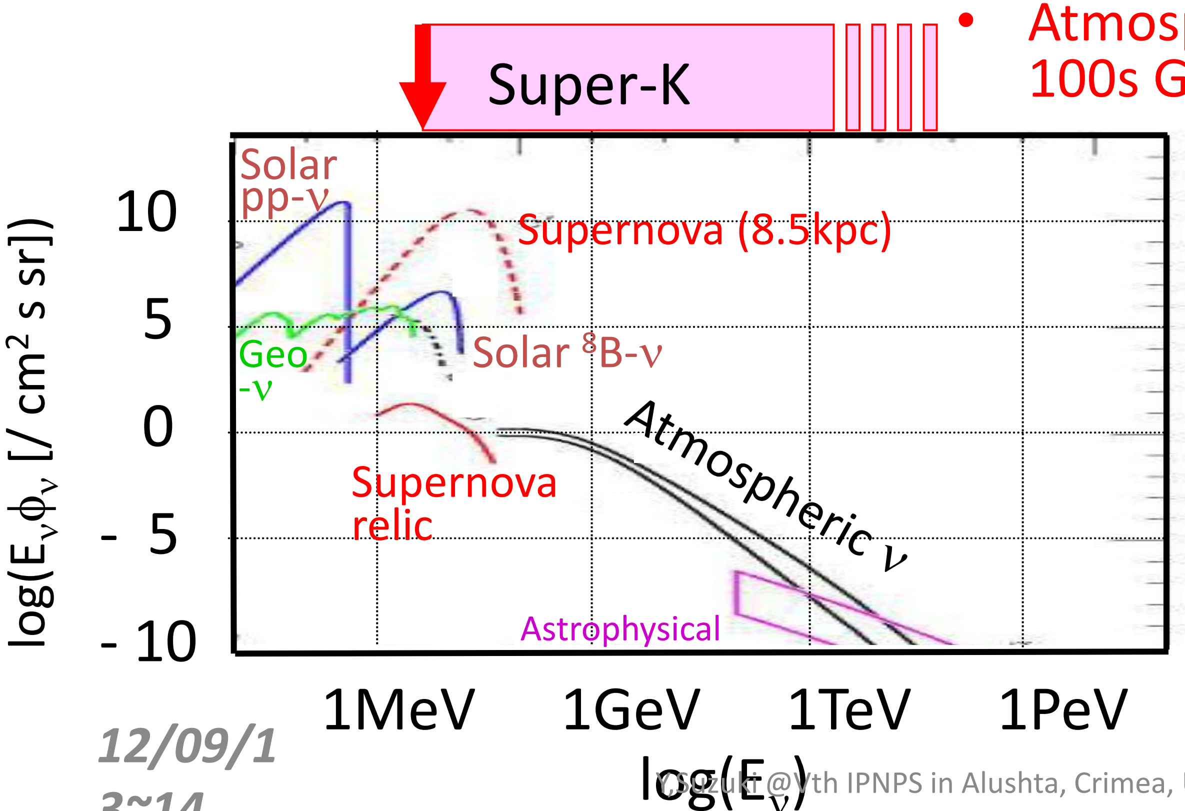




Energy Range *(data from SK-I)*

- Trigger:
  - 100% eff. for E_{kin} > **3.5 MeV**
    (50% efficiency @ 3.0MeV)
- Trigger Rate:
  - 1,700Hz → 15 Hz (recorded)

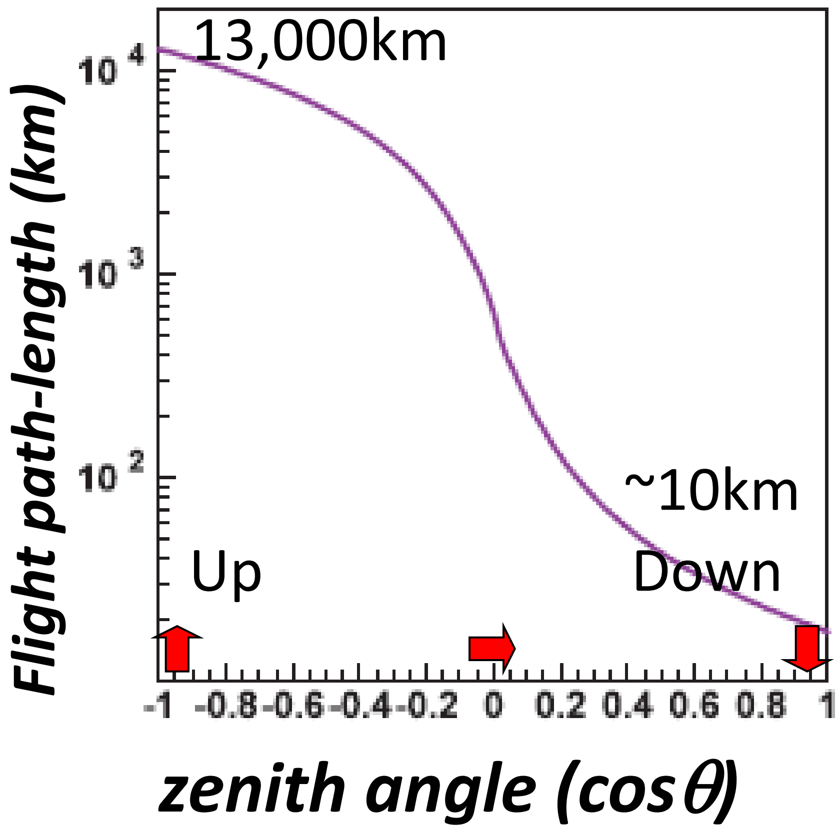
- Solar neutrinos (< 15 MeV): neutrino osc, inside of the sun
- Supernova ν's (10~20 MeV):
  Burst: Explosion mech., ν osc in SN
  Relic (not found yet): His. heavy elem. Syn., Total SN energy
- Atmospheric Neutrinos (< a few 100s GeV): neutrino osc



- 6 p.e. / MeV
- Resolution
  (solar/supernova ν)
  14.2% @10MeV
  (atmospheric ν)
  $1.7+0.7/\sqrt{E(GeV)}$ %
  (single ring μ)

Atmospheric Neutrino Measurements in Super-K

Atmospheric Neutrino Events in Super-K



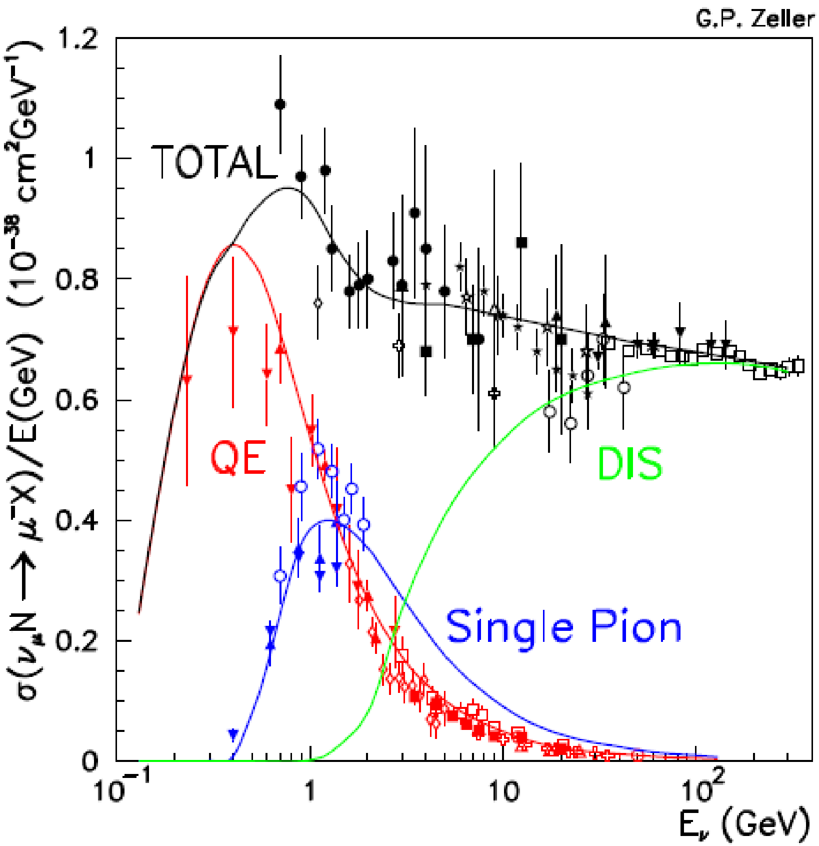
L = ~10~13,000 km

- Wide range of path-length
  (3 orders)

E = ~0.1~10,000 GeV

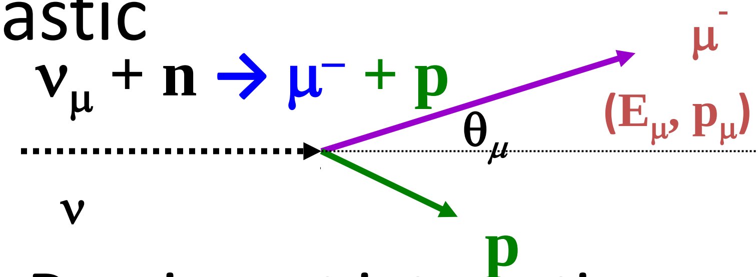
- Wide range of the energy
  (5 orders)

νA cross sections above 0.1 GeV



- Charged Current Quasi-Elastic

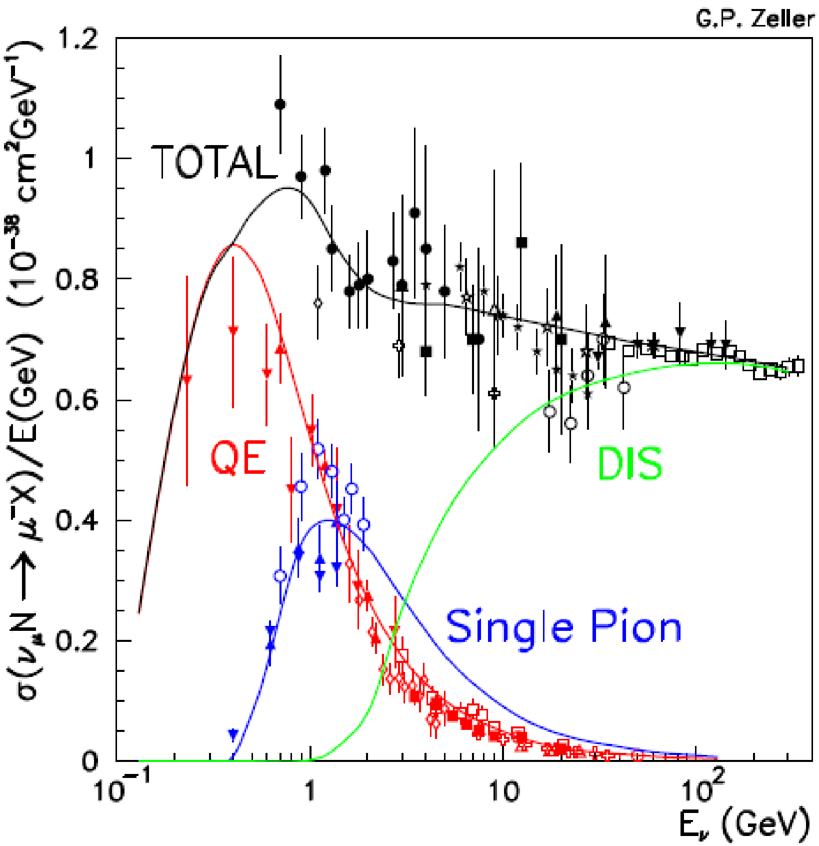
$$\nu_\mu + n \rightarrow \mu^- + p$$



  - Dominaent interaction below 1 GeV
  - 100 % efficiency at SK
  - 1 Ring
  - E_ν can be reconstructed ← (p_μ, θ_μ)

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

νA cross sections above 0.1 GeV



- Charged Current non- Quasi-Elastic

  $\nu_\mu + N \rightarrow \mu + N' + \pi's + X$

  - Single π (resonanct, non-resonant)
  - Multi-π
  - DIS

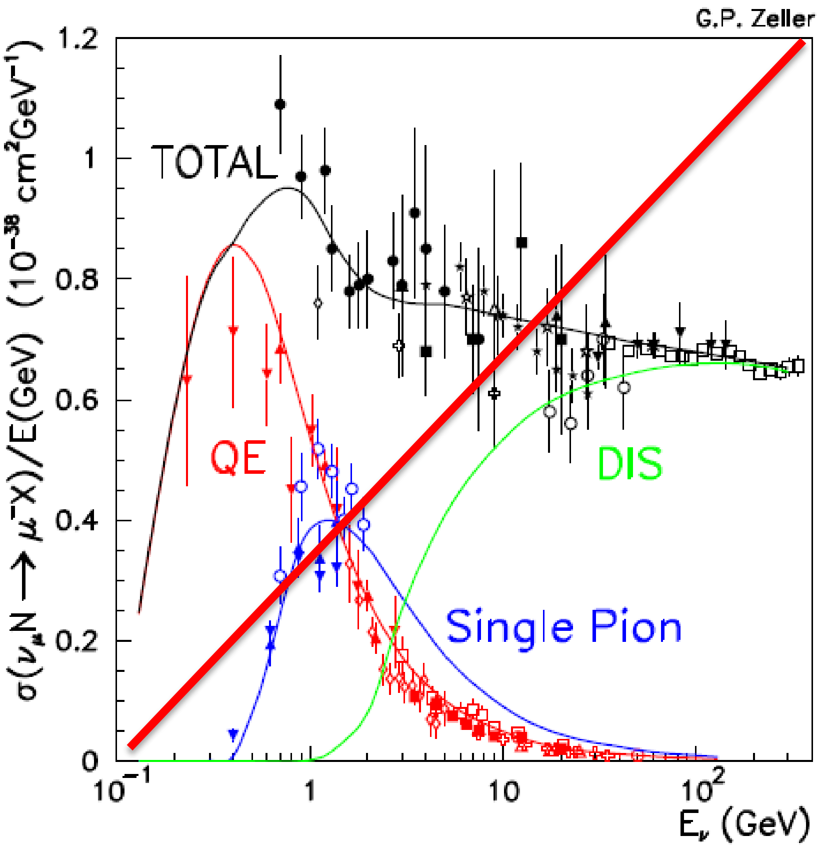
  – Dominaent interaction above 1GeV

  – 100 % efficiency at SK

  – 1 Ring, multi-RIngs

  – BG for E_ν determination

νA cross sections above 0.1 GeV



- Neutral Current

  $\nu_\mu + N \rightarrow \nu + N + \pi\text{'s}$

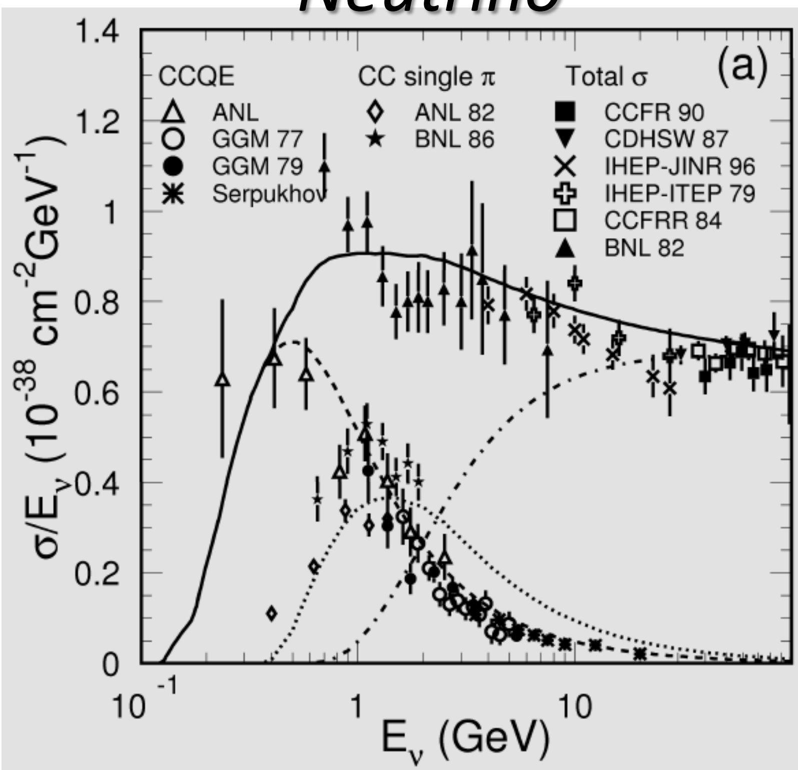
  - Coherent π^0
  - Elastic (not obserbable in Water Cherenkov detector)
  - Single π (resonanct, non-resonant)
  - Multi-π
  - DIS

  – 1/3 of CC

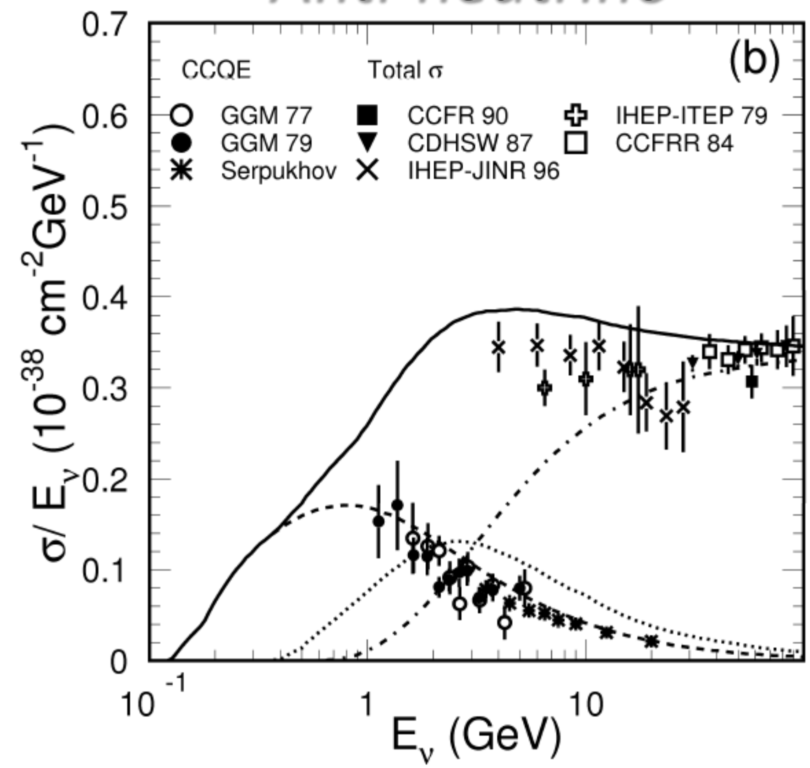
  – 40 % efficiency at SK

Anti-neutrinos

Neutrino



Anti-neutrino



Parameters used in our simulation program:

M_A(QE) = 1.11GeV/c^2

M_A(1π) = 1.21 GeV/c^2

others….

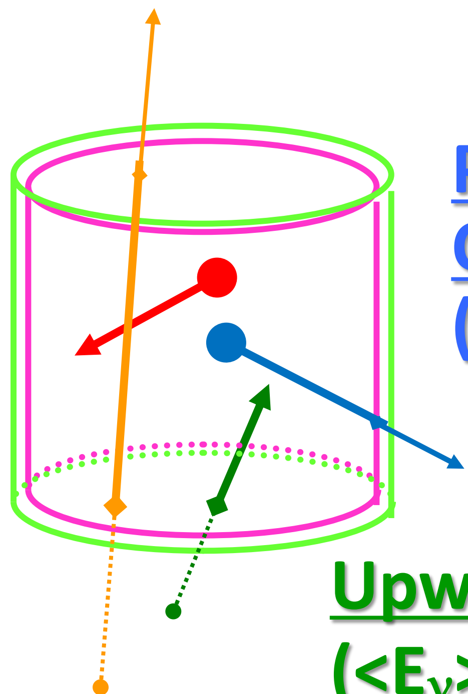
Checked parameter dependence:

Very small effect on the oscillation analysis

Atmospheric Neutrino Events in Super-K

- ***Event category***

Fully Contained (FC)
($\langle E_\nu \rangle$ ~ 1GeV)
subGeV: Evis<1.33GeV
Multi-GeV: >1.33GeV



Partially Contained (PC)
($\langle E_\nu \rangle$ ~ 10GeV)

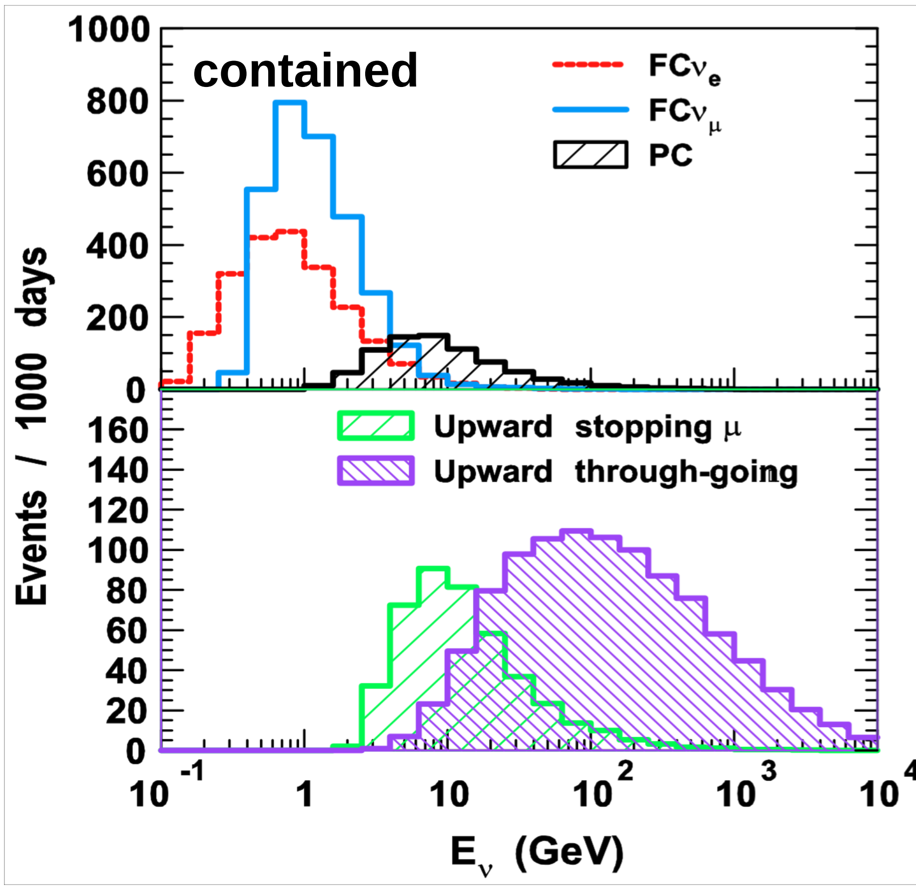
Upward Through-going μ
($\langle E_\nu \rangle$ ~ 100GeV)

Upward Stopping μ
($\langle E_\nu \rangle$ ~ 10GeV)

Interaction in the rocks under the detector

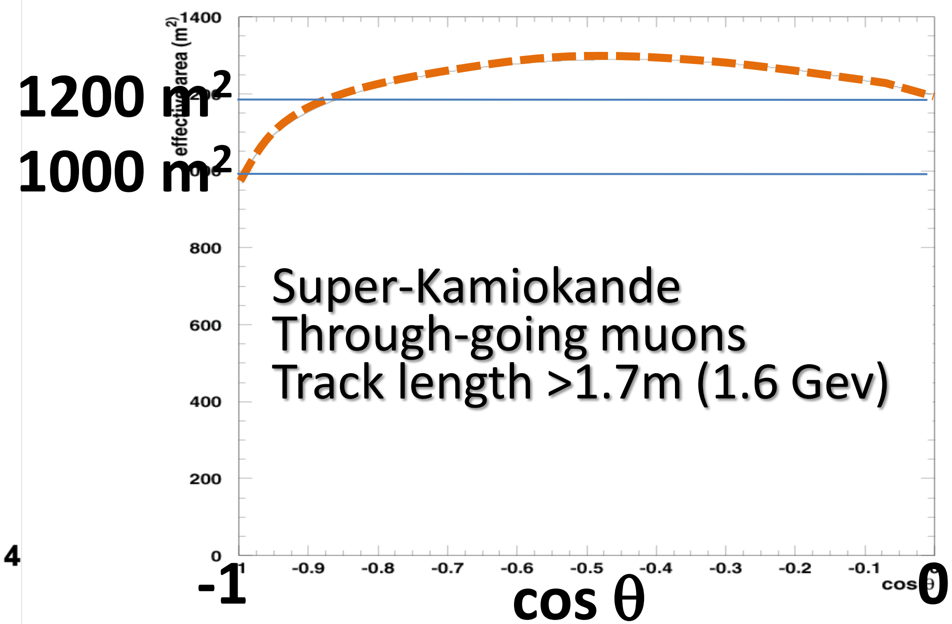
Atmospheric Neutrino Events in Super-K

Parent neutrino Energy



- **Fiducial volume: 22.5 kton**
- **Effective area: ~1,200m²**

Effective Area



Analysis

1. Ring Count (1R, 2R,,,,)
2. Particle ID (e/γ, μ , (π), (p))
3. Vertex and Energy Momentum Reconstruction
4. Fiducial Volume cut

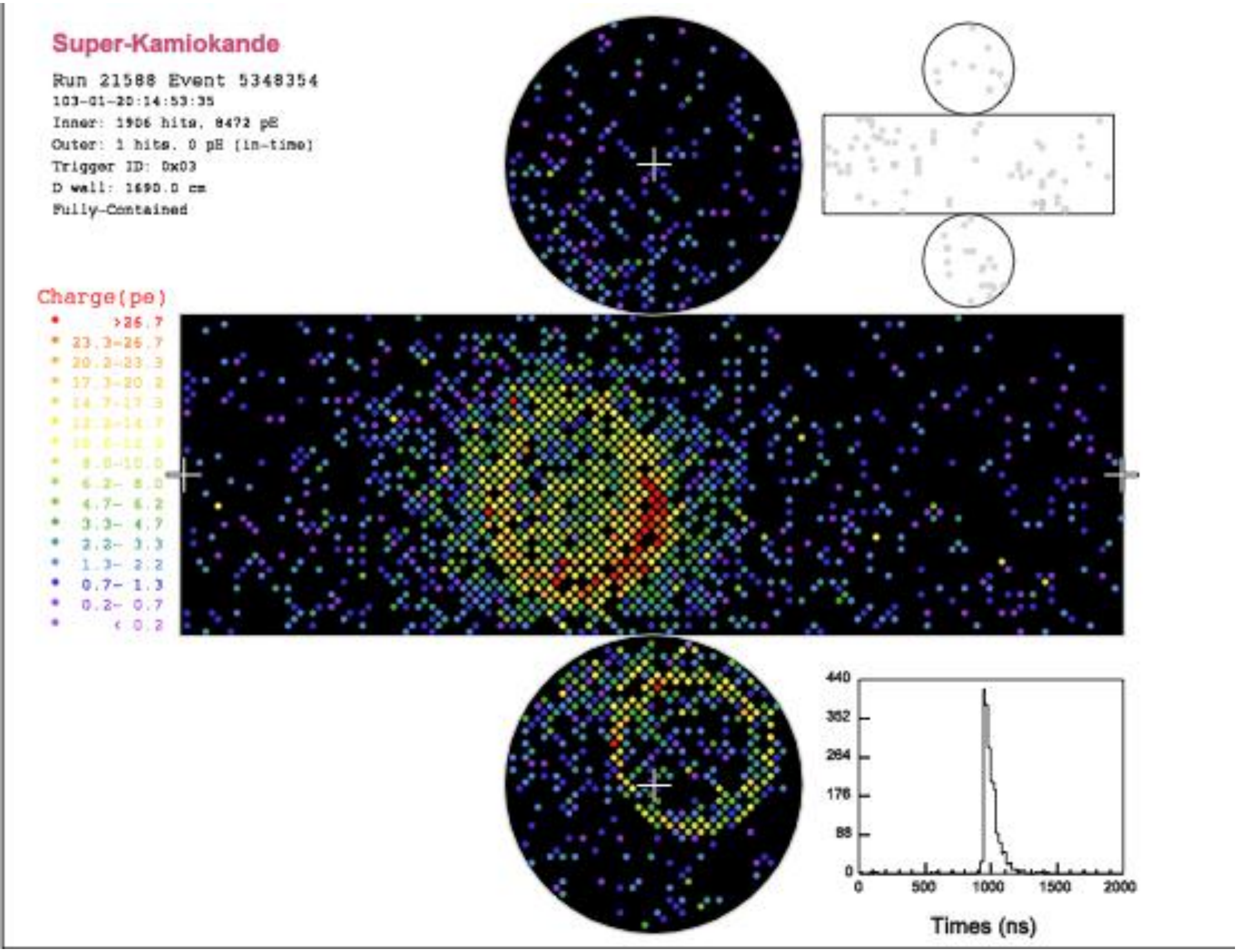
   (>2m from the wall; 22.5kton)
5. Minimum energy cut: > 30 MeV (FC),

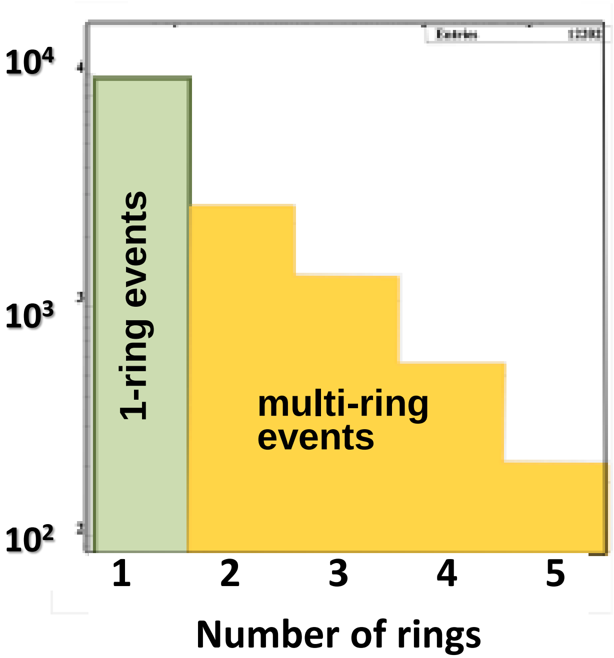
   > ~ 350 MeV (PC)

➔ Final Sample:

◎ *FC: 8.2 ev./day and PC: 0.58 ev./day*

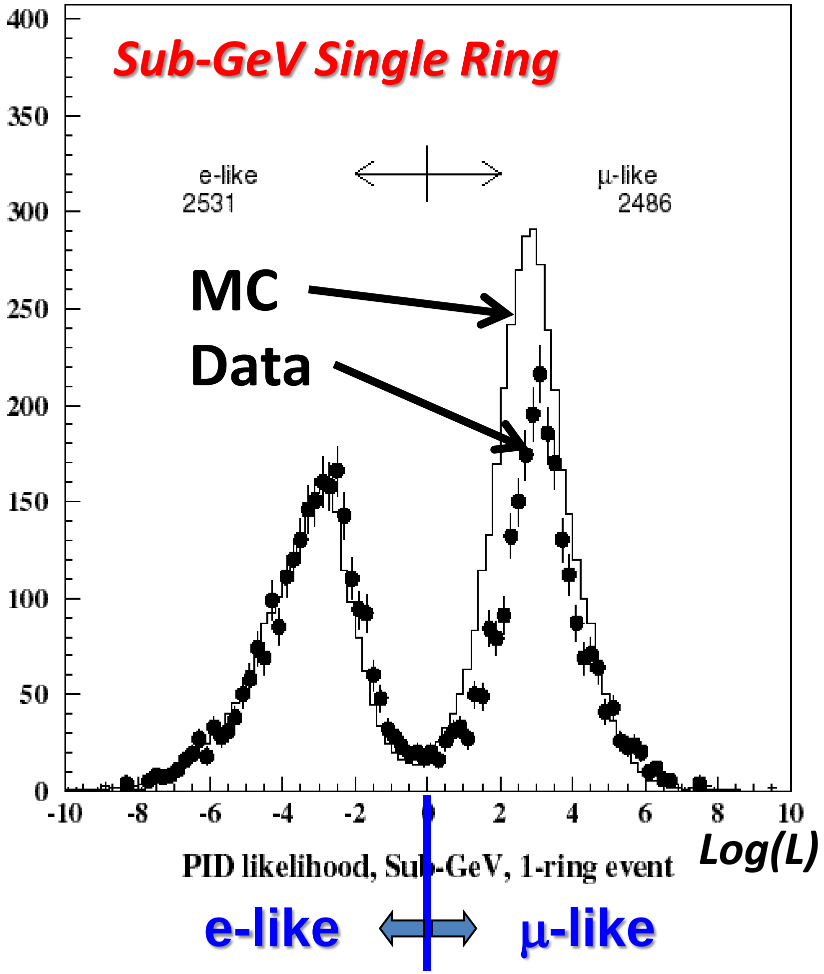
Ring Counts:
Fully Contained(FC) events

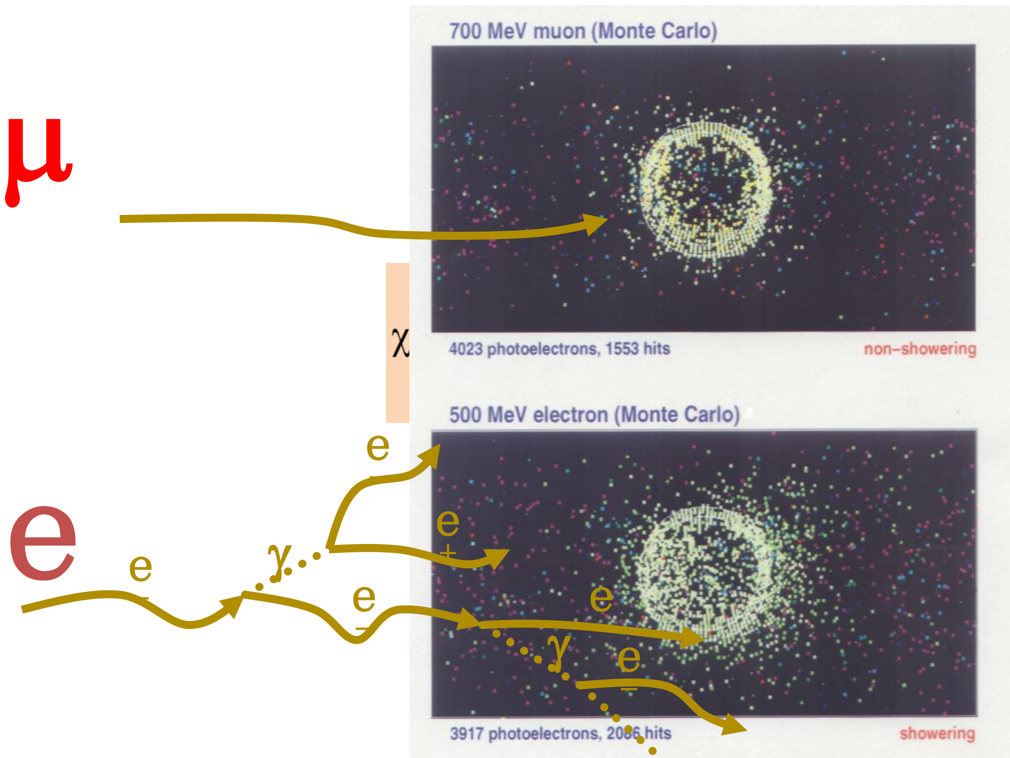




μ / e separation

Likelihood for particle identification



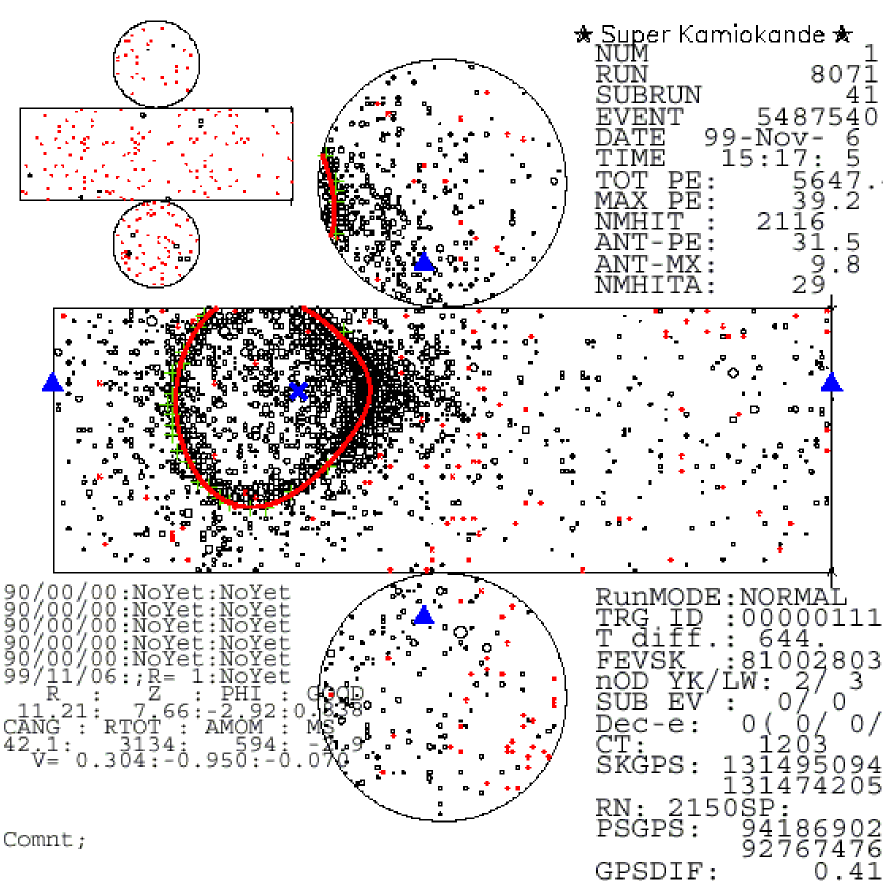


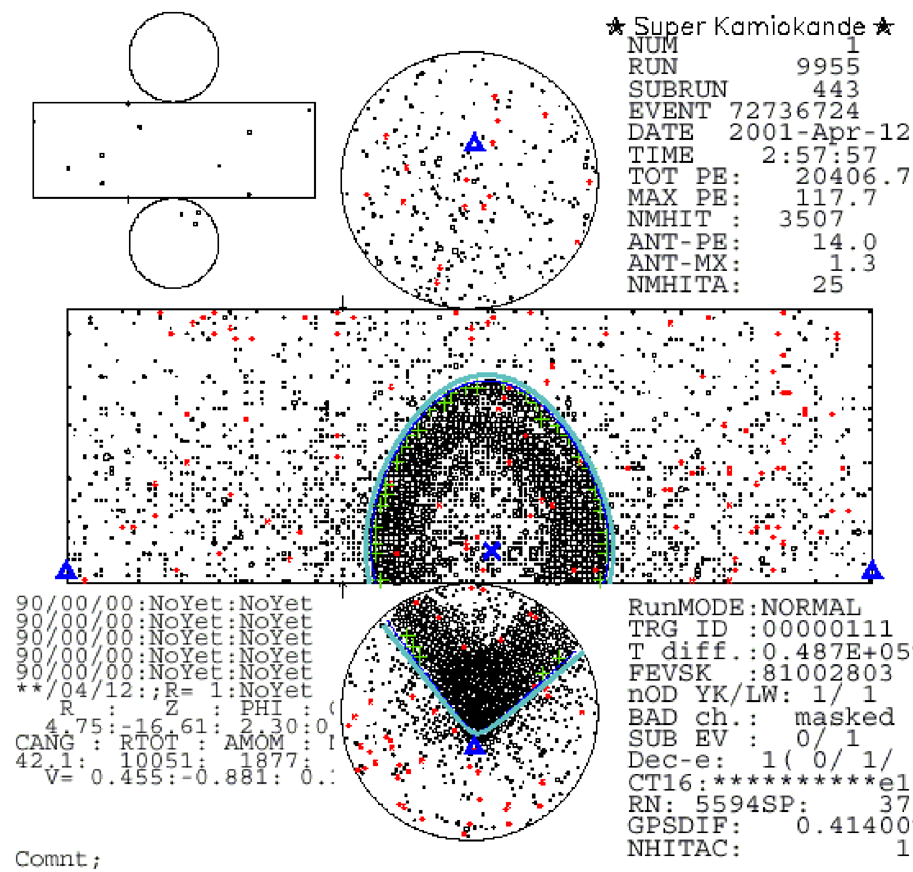
Mis-identification:

0.6 ± 0.1 %	**for sub-GeV**
~ 2 %	**for multi-GeV**

Checked by cosmic ray μ (decay electrons), e/μ beam at KEK (E261A)

e-like and μ-like events in Super-Kamiokande





Number of Events (SK-I)

FC+PC
1489days

Sub-GeV:(Evis<1.33GeV)

	Data	MC(Honda)
1ring	6447	7784.9
e-like	3266	3081.0
m-like	3181	4703.9
Multi ring	2457	2985.6
Total	8906	10770.5

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.638 \pm 0.016 \pm 0.050$$

Multi-GeV:(1.33GeV<Evis)

	Data	MC(Honda)
1ring	1436	1675.9
e-like	772	707.8
m-like	664	968.2
Multi ring	1532	1903.5
Total	2968	3579.4
Total PC	913	1230.0

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.648 \, {}^{+0.030}_{-0.028} \pm 0.078$$

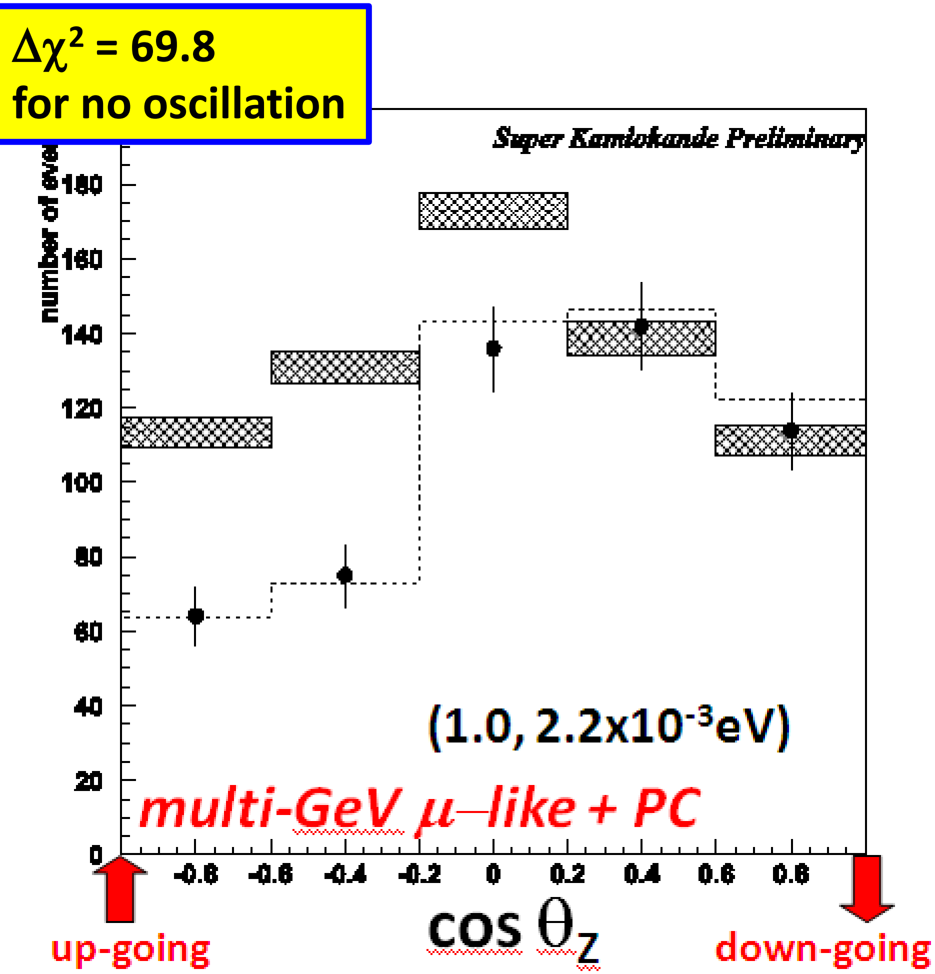
Up stopping μ
1657days

Observed 0.41 ± 0.02(stat.) ± 0.02(syst.) ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
Expected (Honda) 0.68 ± 0.15(theo.)

Up through going μ
1678days

Observed 1.70 ± 0.04(stat.) ± 0.02(syst.) ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
Expected (Honda) 1.84 ± 0.41(theo.)

Discovery of Atmospheric ν Oscillation



- **June 1998: Atmospheric Neutrino Oscillation (*Super-Kamiokande*)**
  - Asymmetry in zenith angle distribution; ν_μ deficits (up-going)
  - Independent of the flux calculations
  - Definitive eveidence
- Atmospheric neutrino anomaly came later than solar neutrino problem but resolved earlier
- **K2K and MINOS** confirmed the oscillation by accelerator neutrinos

Recent Results (Super-K)

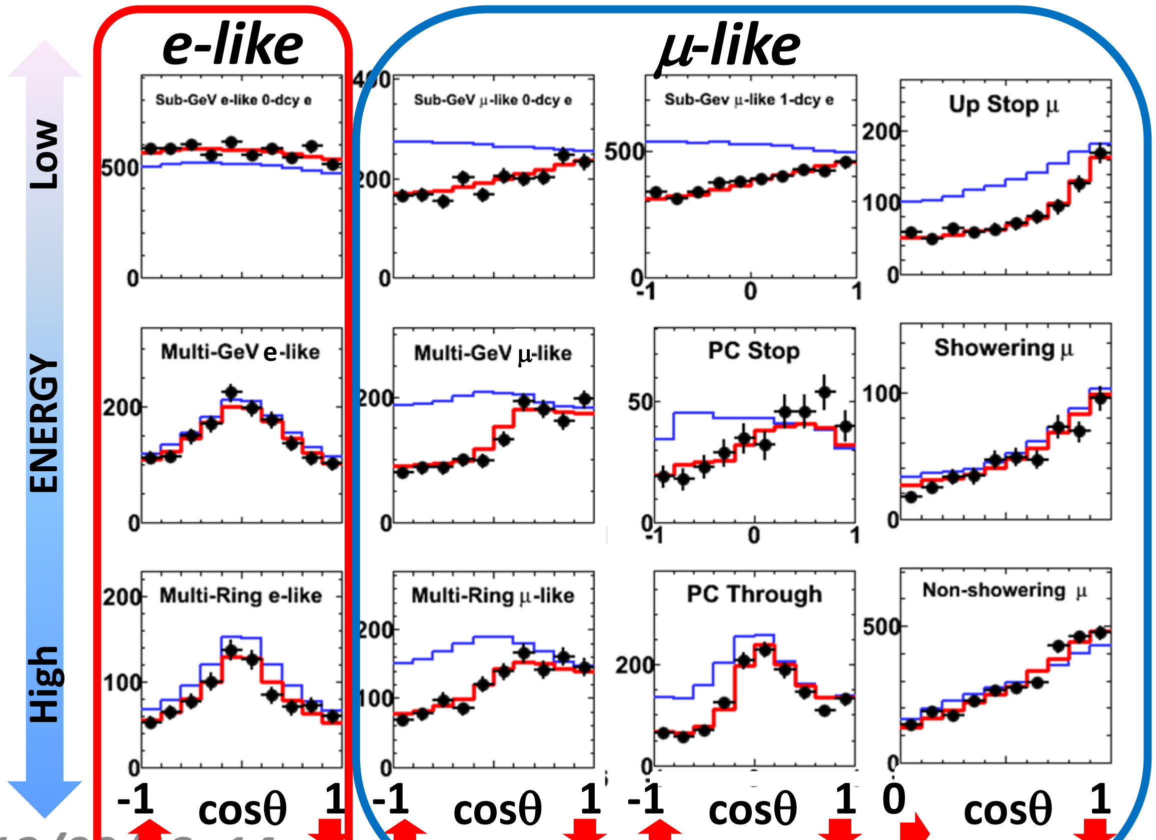
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11

4 **SK-I** (11,146 PMTs) 6

12 **SK-II** (5,182 PMTs) 11

6 **SK-III** (11,129 PMTs) 9

SK-IV (11,129 PMTs)

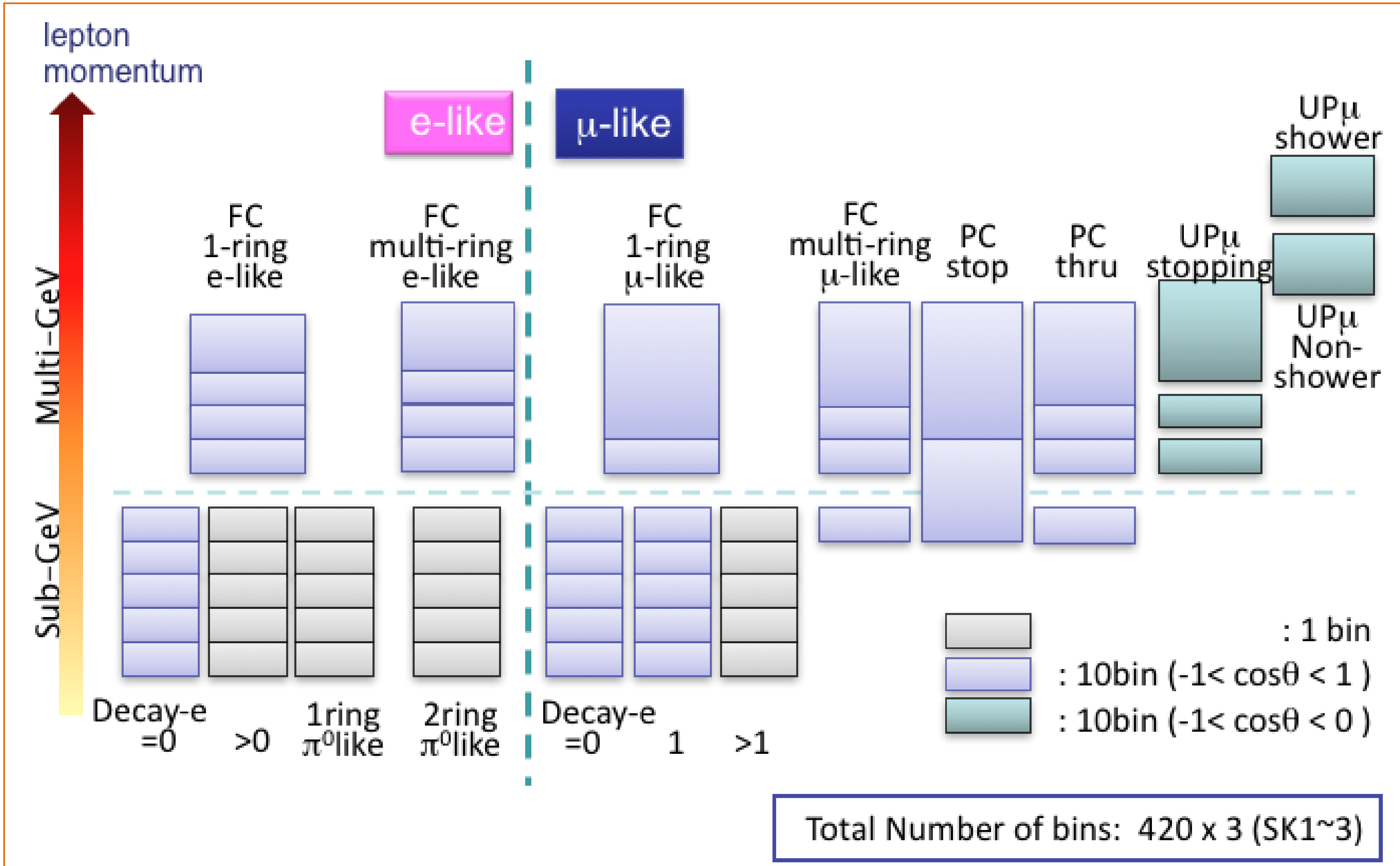


- Latest SK results
  - **SK-I,II,III combined**
  - 2806days (173ktyr) for FC+PC
    - 24841 events
  - 3109days for up-μ
    - 4238 events

Up/Down ~ 1-(1/2)sin²2θ

Transition region ← Δm²

Fitting for oscillation parameters (SKI+SKII+SKIII)



Systematic Errors

Neutrino flux related
Neutrino interaction related
Reconstruction related
Others

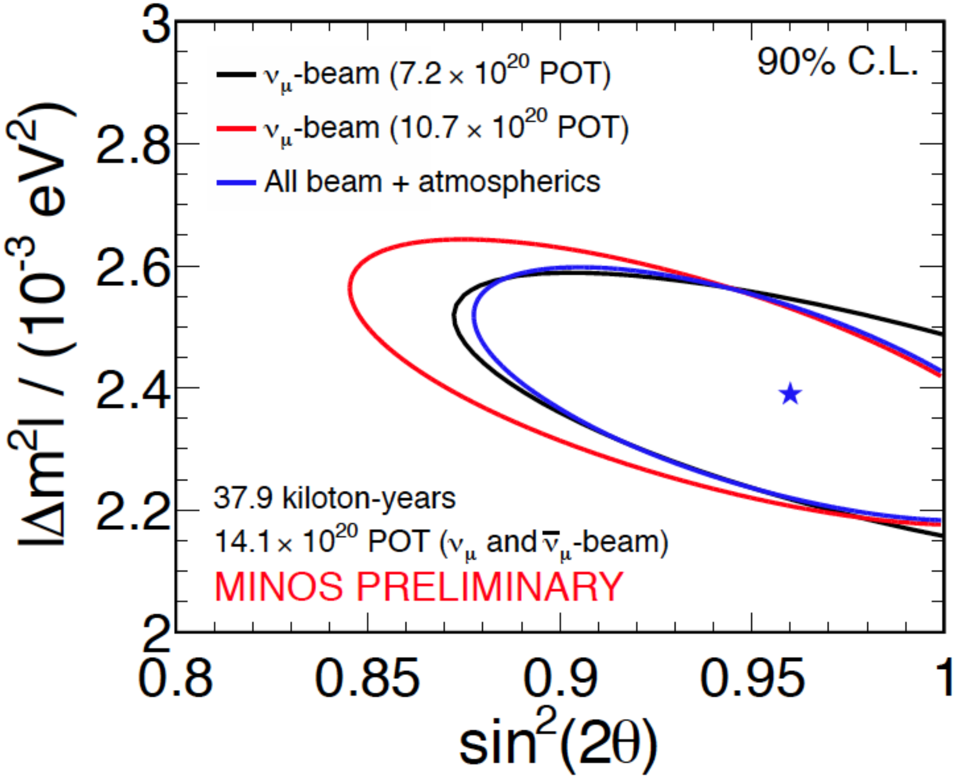
33~59 parameters are evaluated for each SK period.

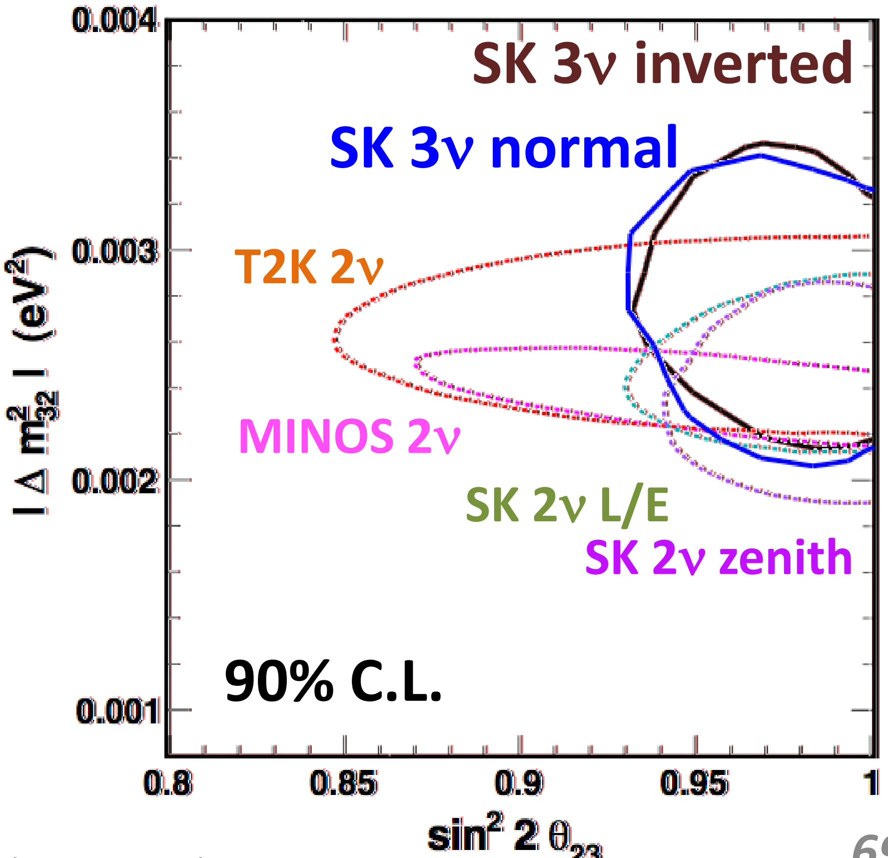
Total = 123 terms

1. absolute normalization (<1GeV)
2. absolute normalization (>1GeV)
3. $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ $(E_\nu<1GeV)$
4. $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ $(1<E_\nu<10GeV)$
5. $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ $(E_\nu>10GeV)$
6. $\bar{\nu}_e/\nu_e$ $(E_\nu<1GeV)$
7. $\bar{\nu}_e/\nu_e$ $(1<E_\nu<10GeV)$
8. $\bar{\nu}_e/\nu_e$ $(E_\nu>10GeV)$
9. $\bar{\nu}_\mu/\nu_\mu$ $(E_\nu<1GeV)$
10. $\bar{\nu}_\mu/\nu_\mu$ $(1<E_\nu<10GeV)$
11. $\bar{\nu}_\mu/\nu_\mu$ $(E_\nu>10GeV)$
12. up/down
13. horizontal/vertical
14. K/π
15. L_ν (production height)
16. sample-by-sample FC Multi-GeV
17. sample-by-sample PC + UPstop μ
18. M_A in CCQE, single-π
19. CCQE (model dependence)
20. CCQE (anti-ν/ν)
21. CCQE (μ/e)
22. single-π (cross section)
23. single-π (anti-ν/ν)
24. single-π (π0/π+-)
25. DIS(model dependence)
26. DIS (cross section)
27. coherent π (cross section)
28. NC/CC
29. nuclear effect in ^{16}O
30. nuclear effect (pion spectrum)
31. $CC\nu_\tau$ interaction cross section
32. hadron sim. (NC contami. in FCμ)
33. Solar activity
34. FC reduction
35. PC reduction
36. UPμ reduction
37. FC/PC separation
38. Normalization of PC stop/thru (top)
39. Normalization of PC stop/thru (barrel)
40. Normalization of PC stop/thru (bottom)
41. non-ν BG (flasher)
42. non-ν BG (cosmic-ray μ)
43. BG subtraction of Upthru (shower) μ
44. BG subtraction of Upthru (non-shower) μ
45. BG subtraction of UPstop μ
46. UPμ stop/thru separation
47. UPμ non-shower/shower separation
48. ring separation
49. PID for single-ring
50. PID for multi-ring
51. energy calibration
52. energy cut for UPstop μ
53. up/down symmetry of energy calib.
54. non-ν_e BG in Multi-GeV 1-ring electron
55. non-ν_e BG in Multi-GeV m-ring electron
56. Likelihood of Multi-GeV m-ring e-like
57. Efficiency for 2-ring π^0
58. number of event for 1-ring π^0
59. Decay electron tagging
60. Fiducial volume
61. Up thru μ length cut
62. Decay electron tagging from pi+
63. Matter effect
64. Low-q2 for DIS W<2GeV
65. Low-q2 for DIS W>2GeV

$\Delta m_{23}{}^2, \theta_{23}$

- Best: $\sin^2 2\theta_{23}$=1.00 > 0.96 (1 par. 90%) [SKI+II+II+IV Atm ν, zenith]
- Best: $\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$ [MINOS beam]



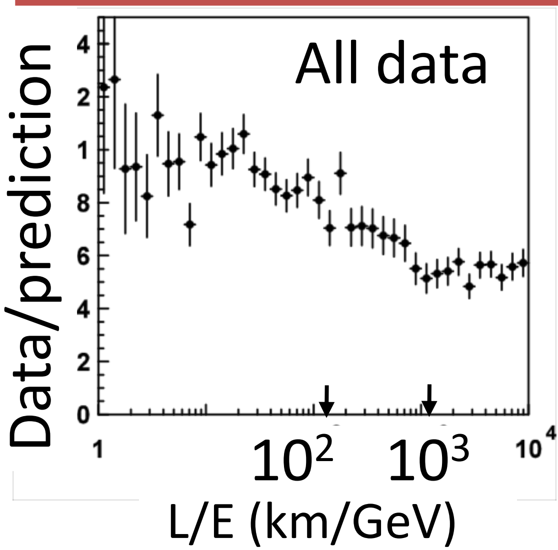


L/E analysis

- **Can observe oscillation pattern in L/E plot ← $\lambda \sim E$**
  - **→ direct oscillatory evidence**
  - **→ distinguish other exotic hypotheses**
  - **→ strong constraint on Δm^2**

($\lambda/E=4\pi/\Delta m^2$: Position of Dip)

Difficult to see the pattern for all the data



Select events : $\Delta(E/L) < 70\%$

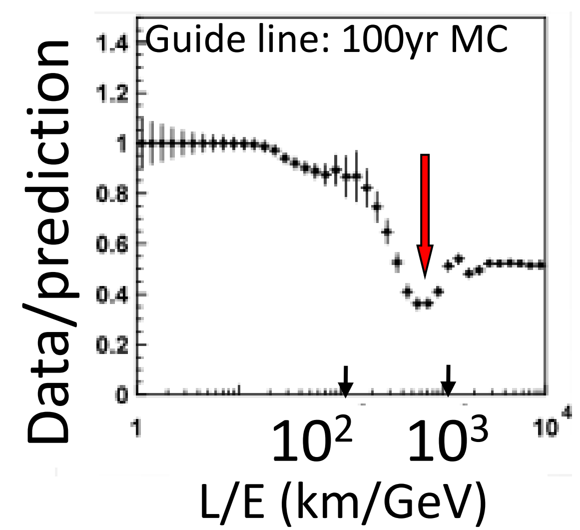
~1 /5 of total data

Rejected events

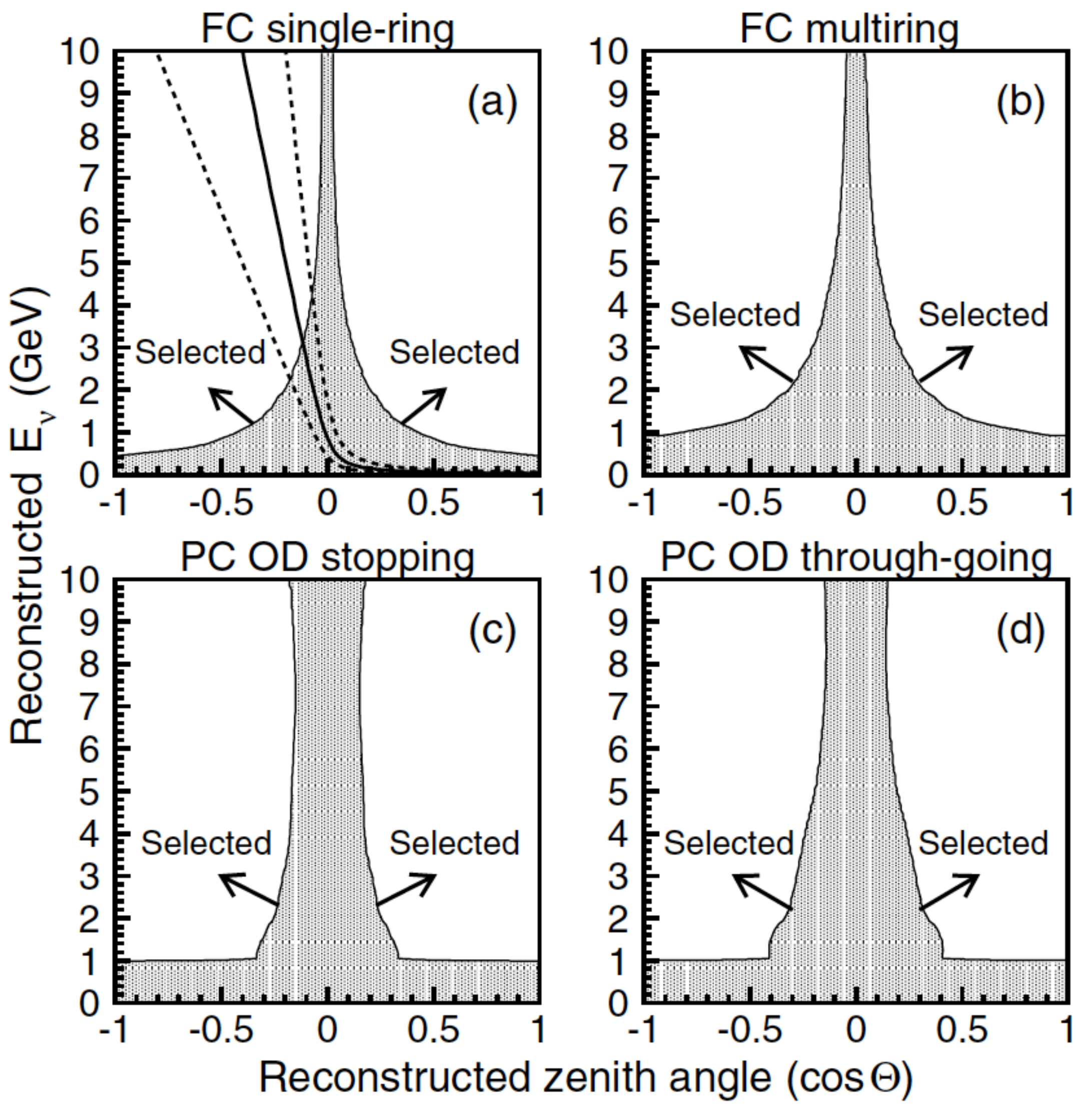
horizontally going events:

low energy events:

→ poor ΔL, $\Delta\theta$ determination



L/E analysis

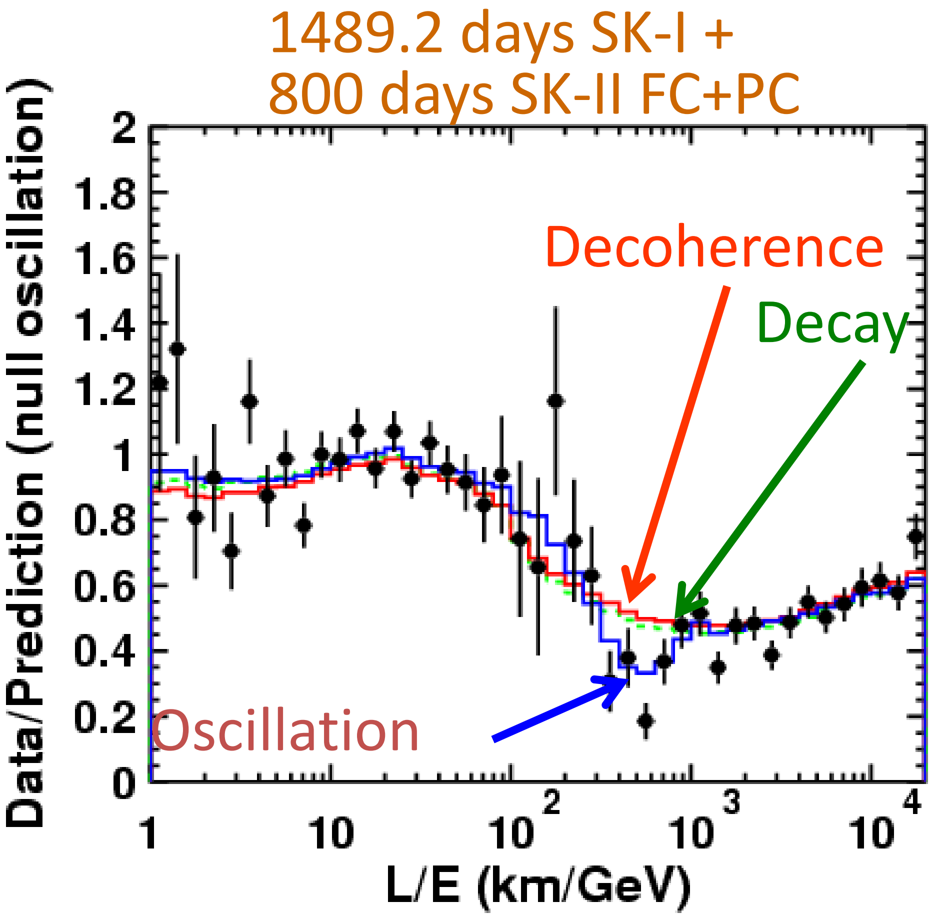


- Contour plots of 70% L/E resolution

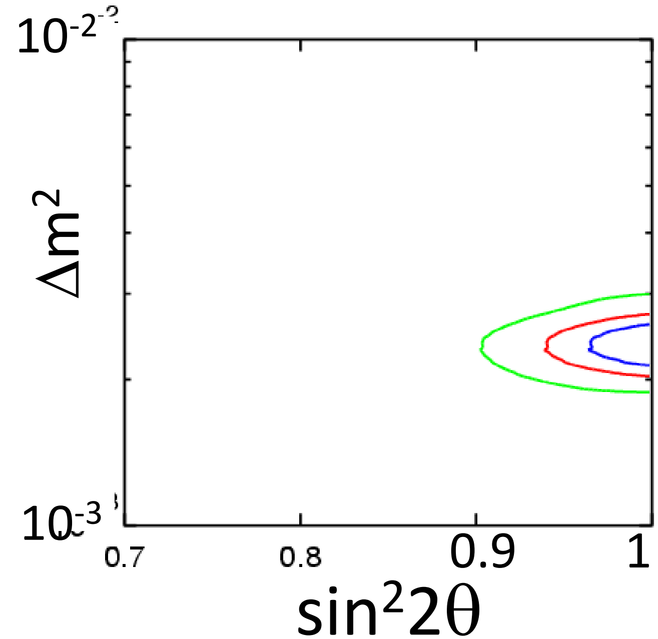
Guide line in FC plot

- Solid line: full oscillation
- Dashed line: half oscillation

Result of L/E analysis (SK-I + SK-II)



- The first dip has been observed at ~500km/GeV
- This provides a strong confirmation of neutrino oscillation
- The first dip observed cannot be explained by other hypotheses



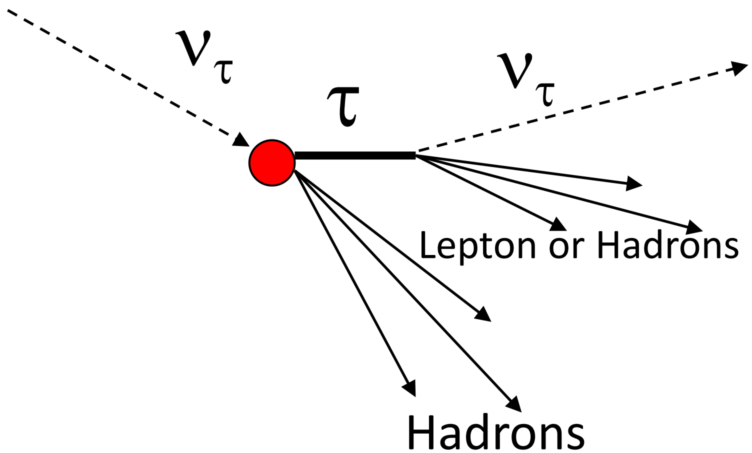
4.8 σ to decay
5.3 σ to decoherence

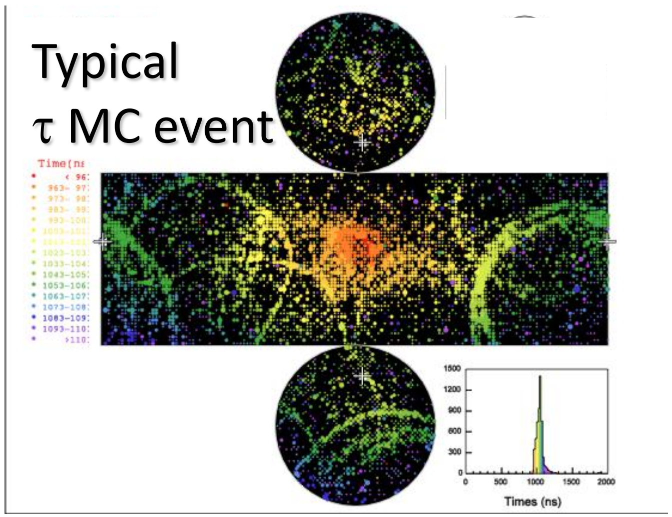
ν_τ appearance

- How we can test it?
- Do we have evidence for ν_τ appearance?

Yes

Search for τ appearance in atmospheric ν





- τ events cannot be identified by event by event basis

$$\nu_\tau + N \rightarrow \tau + N' + \pi + \pi \;.....$$

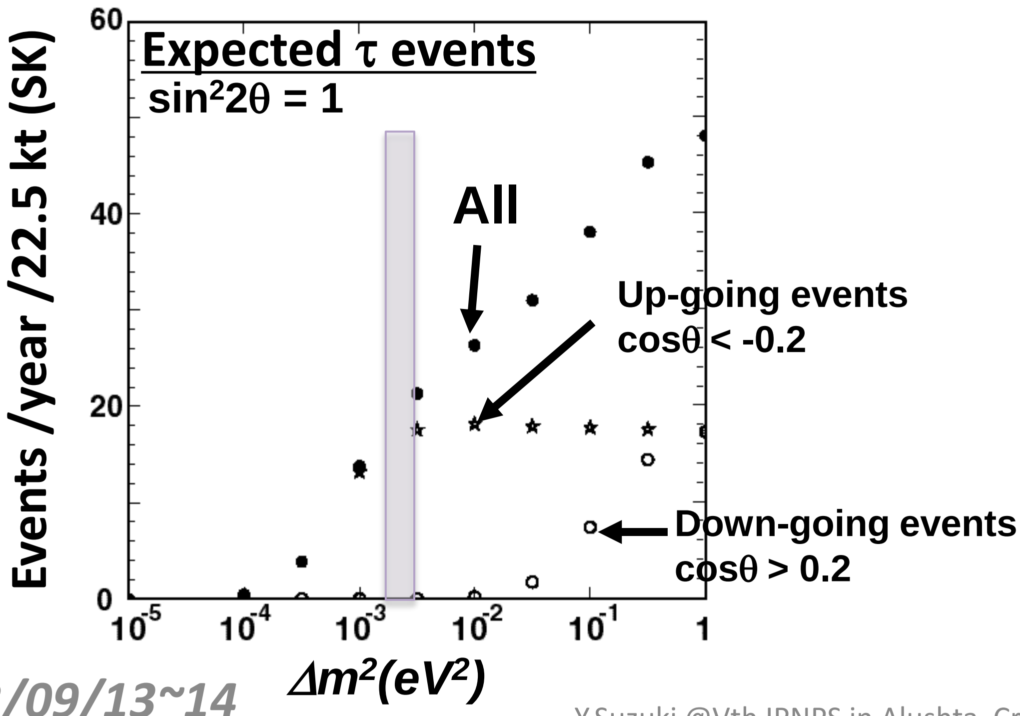
→ $\mu\nu\nu$, $e\nu\nu$,

→ ν+hadrons

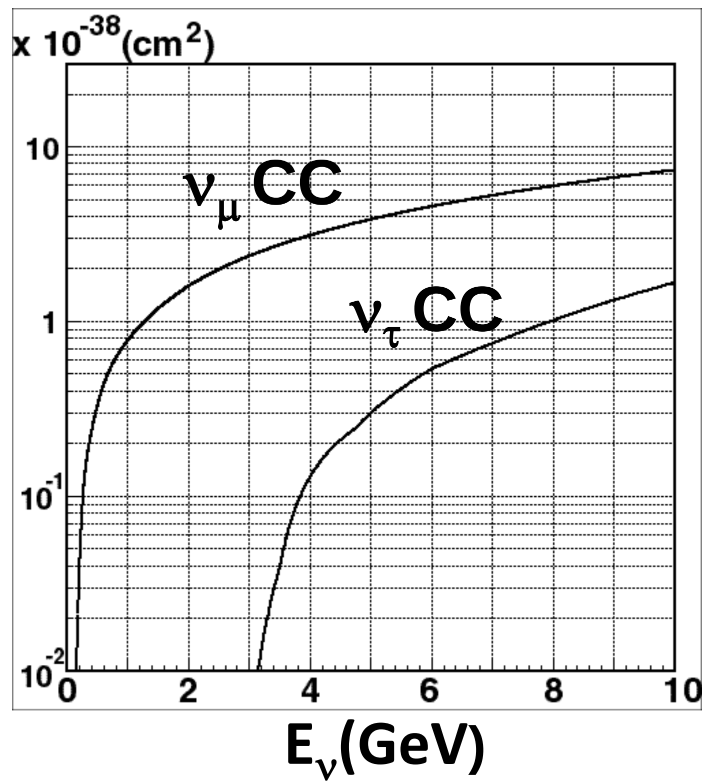
  - Many Hadrons
  - Rather spherical
  - Complicatd
- Make statistical analysis by using the characteristicw of τ production

Search for τ appearance in atmospheric ν

- But not easy
  - E_{th} >3.5 GeV
  - Low rate
    - ~ 1 CC ν_τ FC ev /kt/yr
    - BG ~ 130 ev /kt/yr



Neutrino CC cross sections

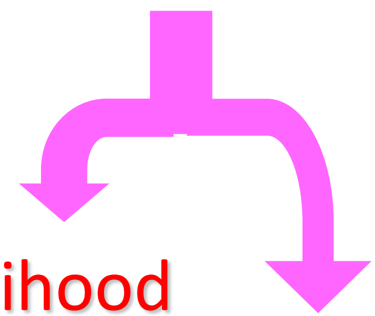


Selection of τ enriched sample

- Pre-selection

1. Multi-GeV, multi-ring contained events
   - High energy
   - Many particles
2. Fiducial cut
   - 2m from the ID PMTs
3. Most energetic ring
   - electron

Efficiency:
- 81% for the ν_τ CC events
- 23% for the backgrounds

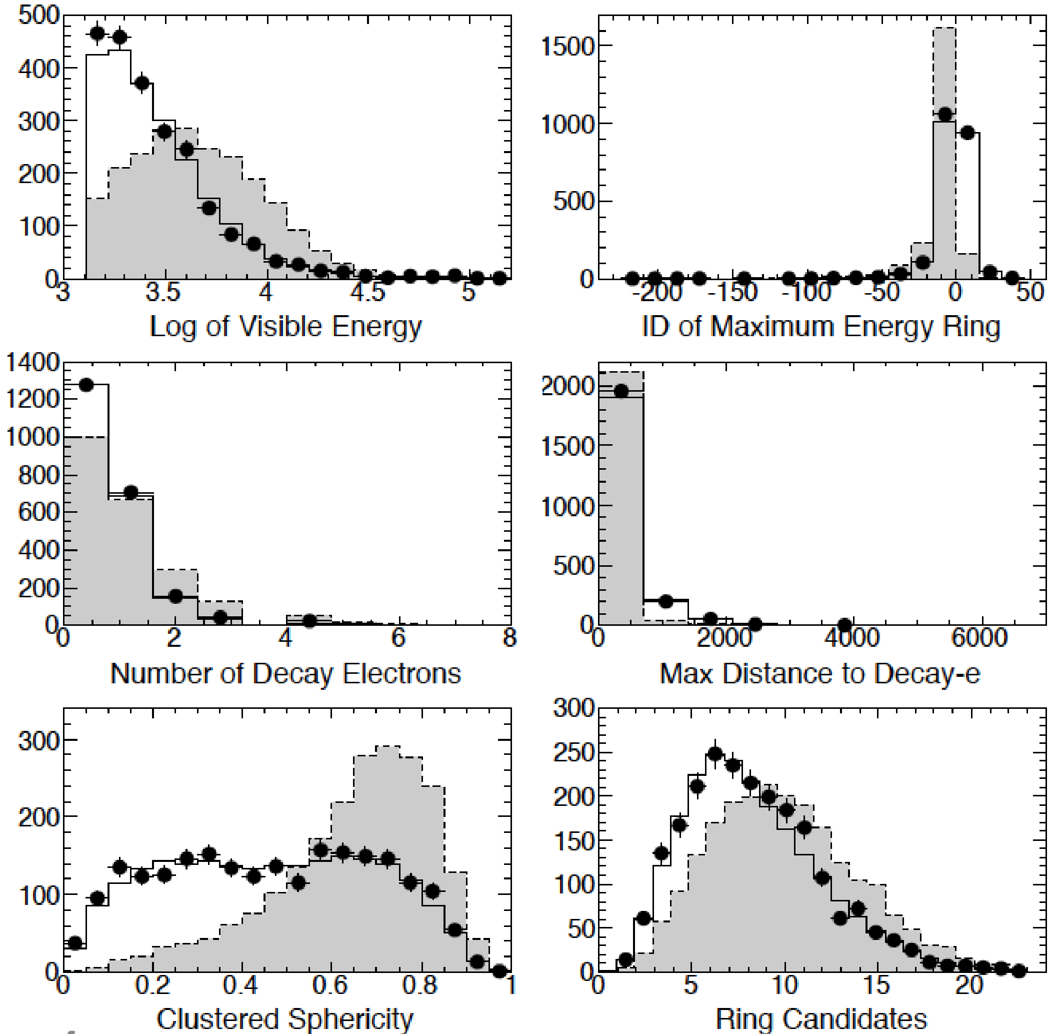


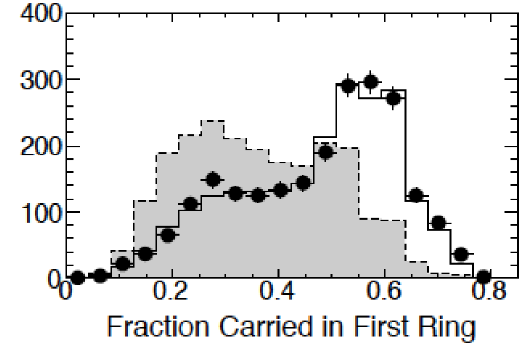
Likelihood

<u>**Neural Network**</u>

(2 independent analyses)

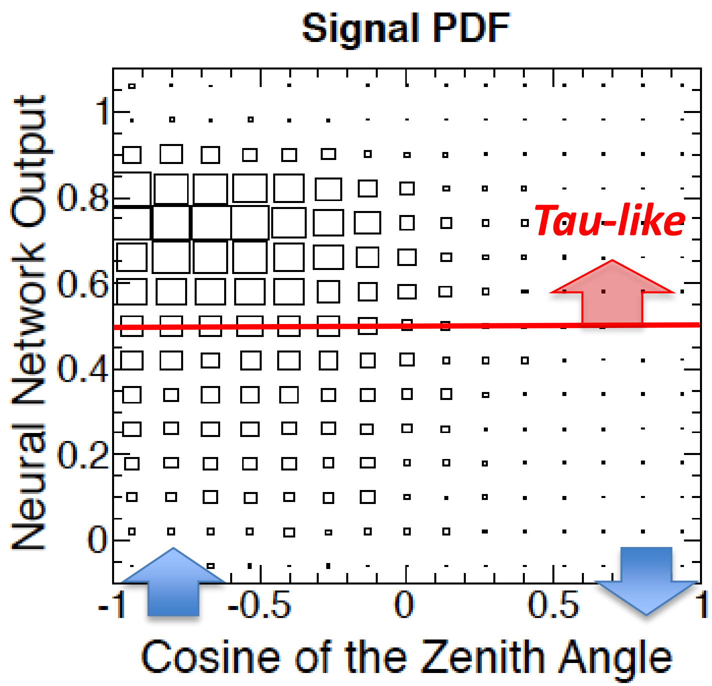
Seven input variables to the neural network or likelihood

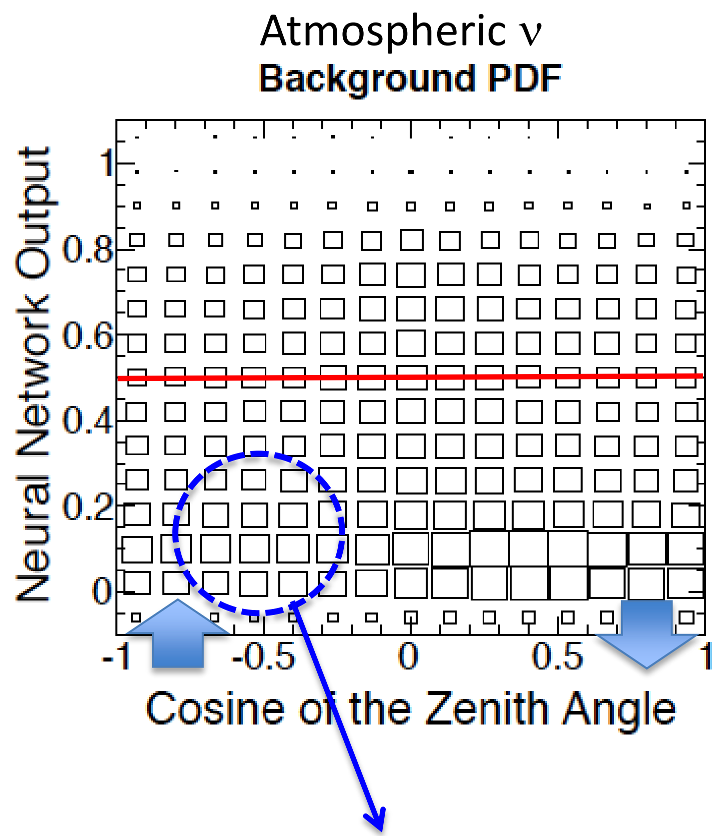




- Points: downward going data
- Solid line: downward going atmospheric MC
- Shaded: Tau signal MC
  - Tau normalization: arbitrary

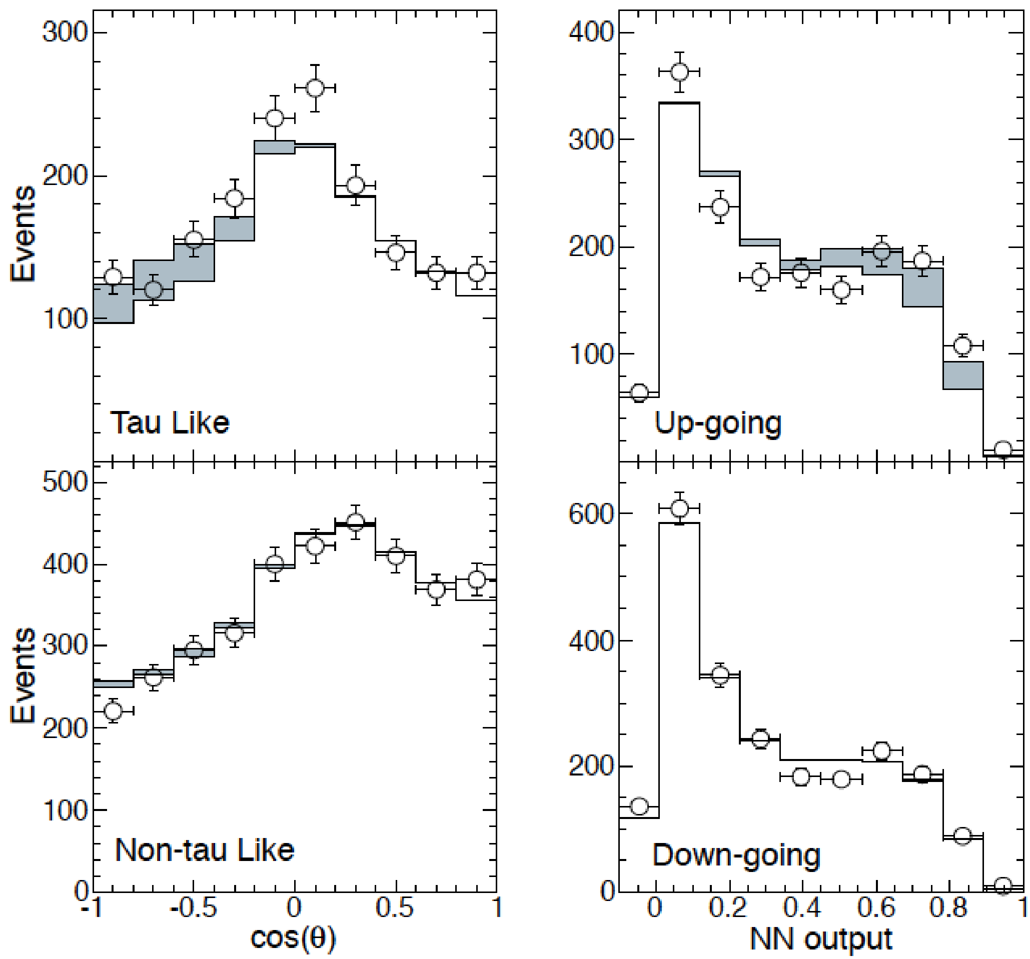
Histgram of PDF after the learning





Oscillated to tau neutrinos
(mostly non-interactiing)

Maximum likelihood fit results



- Tau like: NN > 0.5
- Non-tau like: NN < 0.5
- Up-going: cosθ <-0.1
- Down-going: cosθ > 0.1
- Gray: fitted tau signal
  - $N_{total}(\cos\theta) = \alpha N_{tau} + \beta N_{bkg}$

Tau Appearance

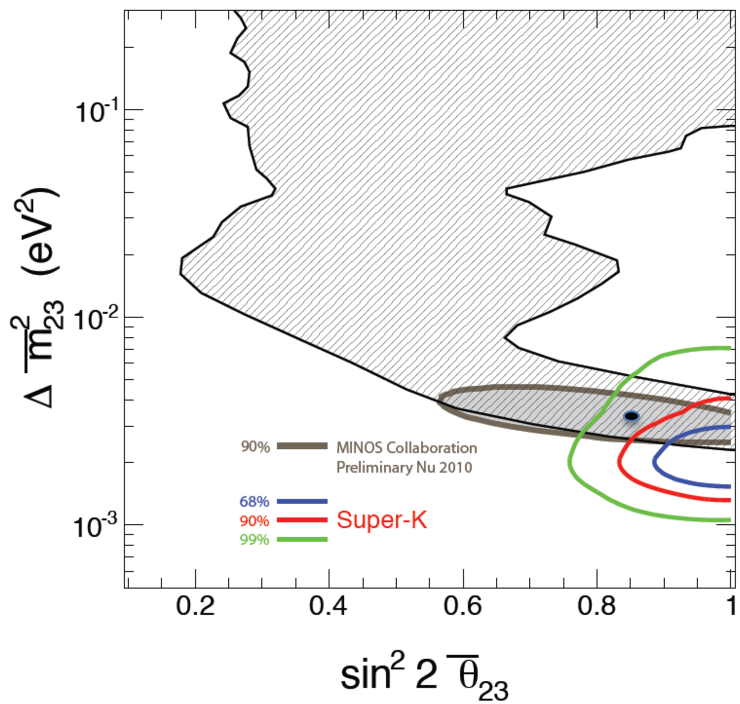
- SK results:
  - 2806 days of data
  - Relotive to the expectation of unity
    - τ: $1.42 \pm 0.35(stat)^{+0.14}_{-0.12}(syst)$
    - BG: $0.94 \pm 0.02(syst)$
  - # of events (found) $180.1 \pm 44.3(stat)^{+17.8}_{-15.2}(syst)$
  - # of events (expected) $120.2^{+34.2}_{-34.8}(syst)$
  - Excluded no tau production at **3.8σ**

Tau appearance

- OPERA results:
  - Found 1 more candidate of ν_τ (total 2 ν_τ events)
    - expected events 2.1
    - with 0.2 backgrounds

CPT Violation ?

Motivation : MINOS anti-ν data @Nu2010 suggested oscillation parameter may be differet in anti-ν oscillation.



- Test of CPT
  - Produce MC for ν (Δm_{23}^2, θ_{23}) and $\overline{\nu}$ ($\Delta\overline{m}_{23}^2$, $\overline{\theta}_{23}$) separately, and look for best parameter set

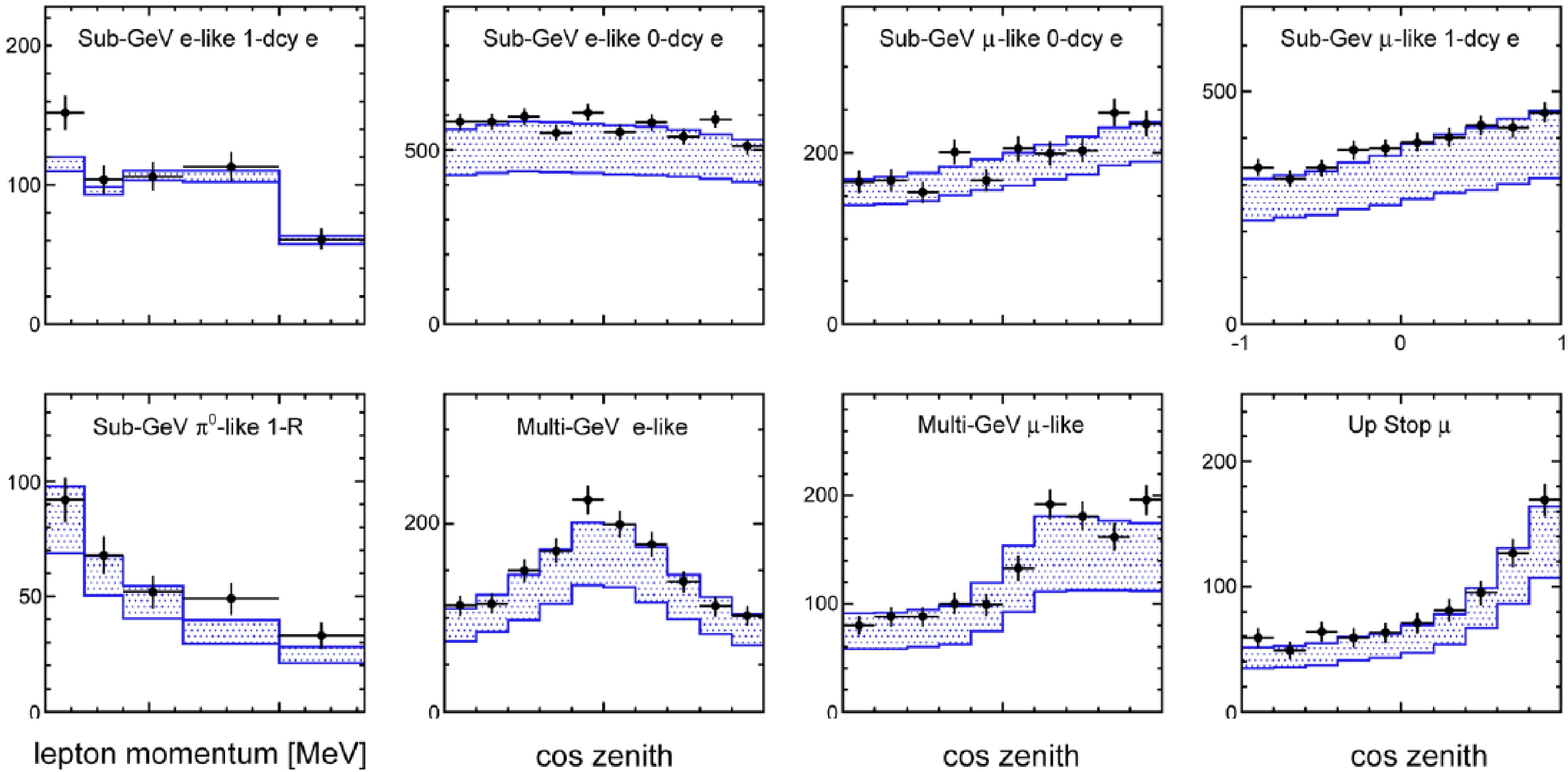
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2 2\bar{\theta} \sin\left(\frac{\Delta \bar{m}^2 L}{4E}\right),$$

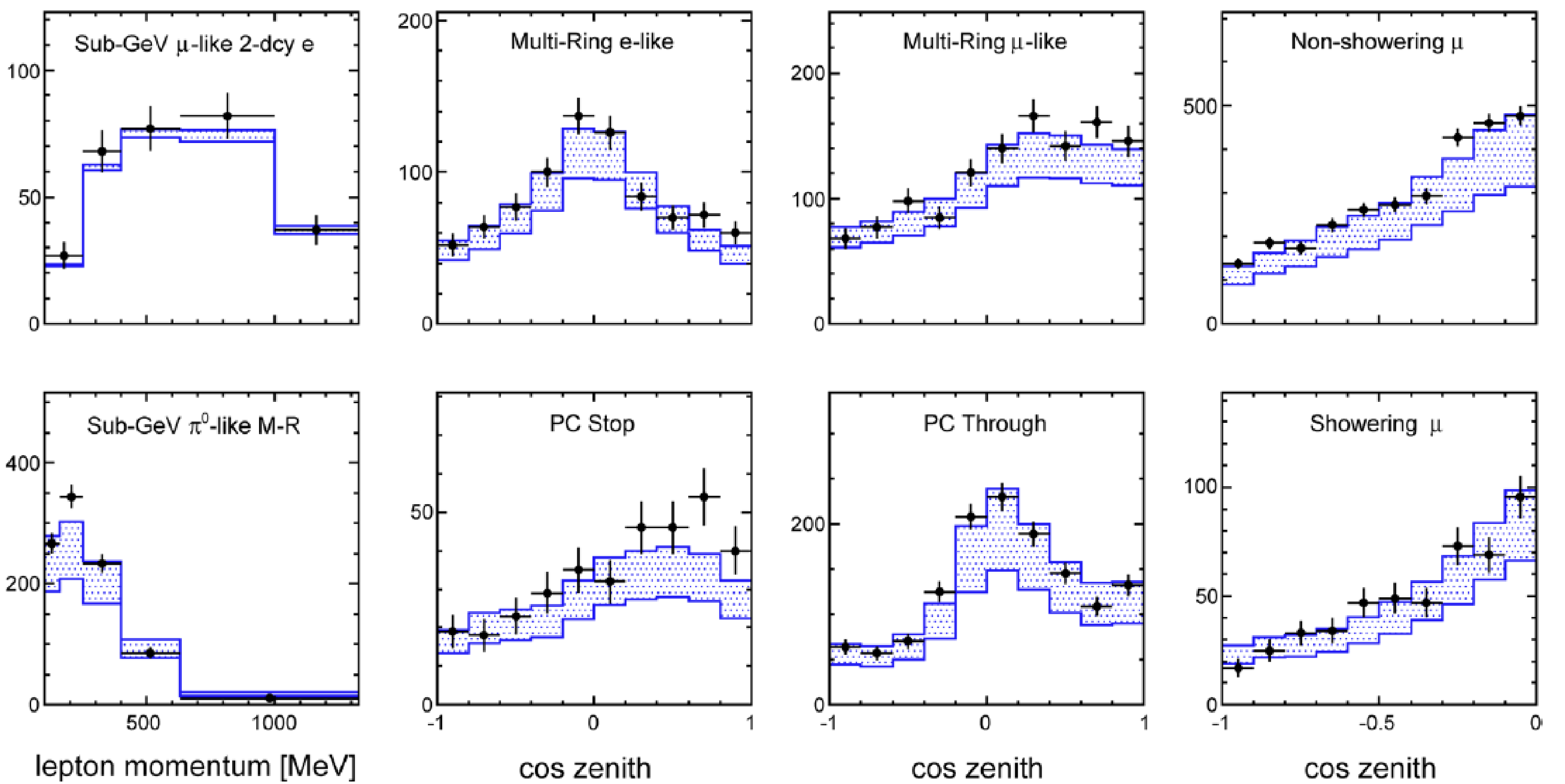
where L is the neutrino path length and E is the neutrino energy

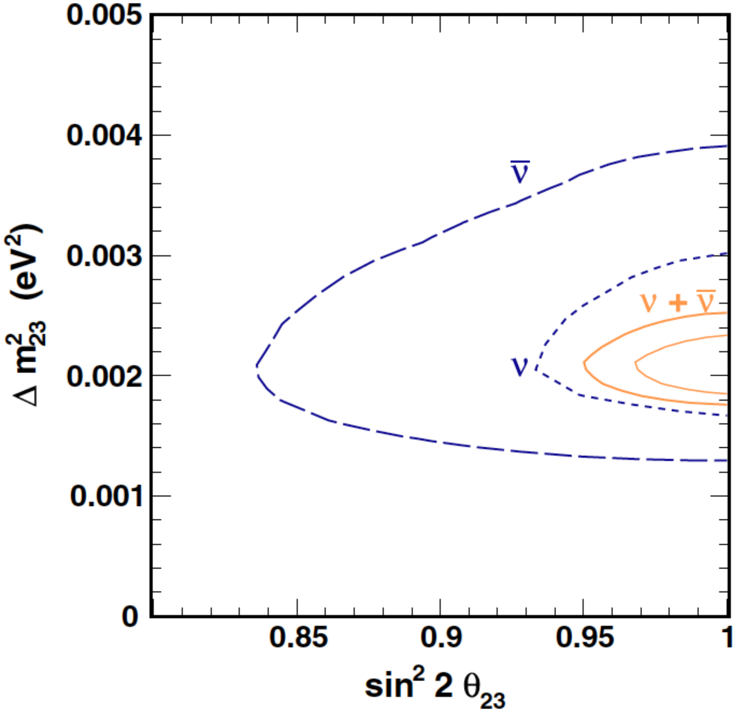
Result of fit

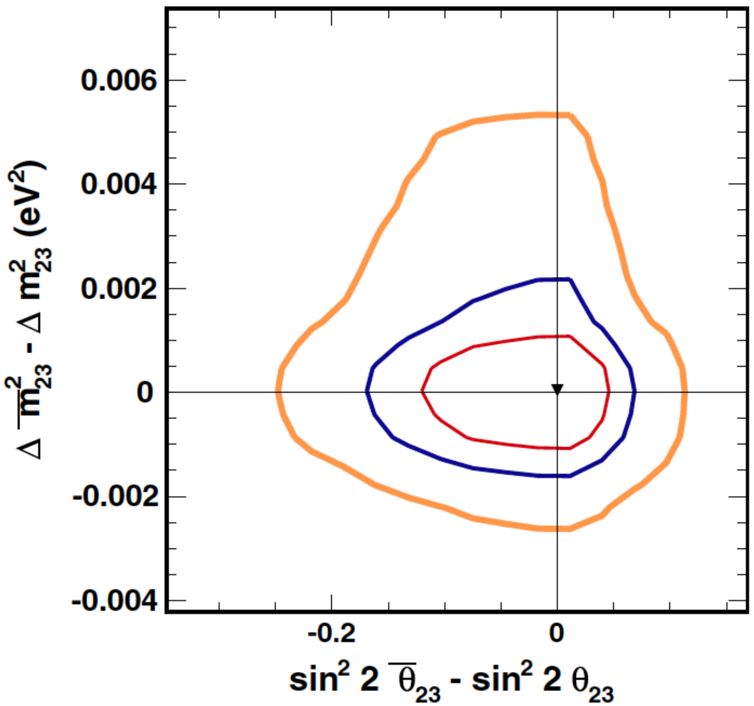
- Shaded resion shows the anti-neutrino composition



Result of fit







SK results

- Neutrino

  $\Delta m_{23}{}^2 = 2.2\text{x}10^{-3} eV^2$

  $\sin^2 2\theta_{23} = 1.0$

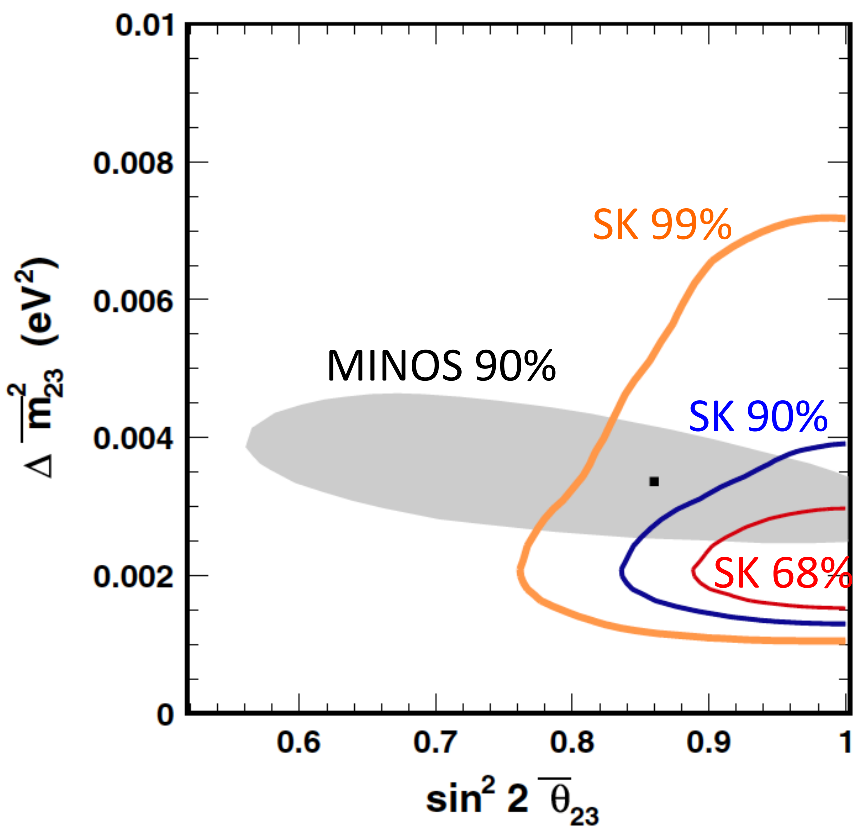
- Anti-neutrino

  $\Delta \overline{m}_{23}{}^2 = 2.0\text{x}10^{-3} eV^2$

  $\sin^2 2\overline{\theta}_{23} = 1.0$

- No evidence for CPT violating oscillations (SK) was found

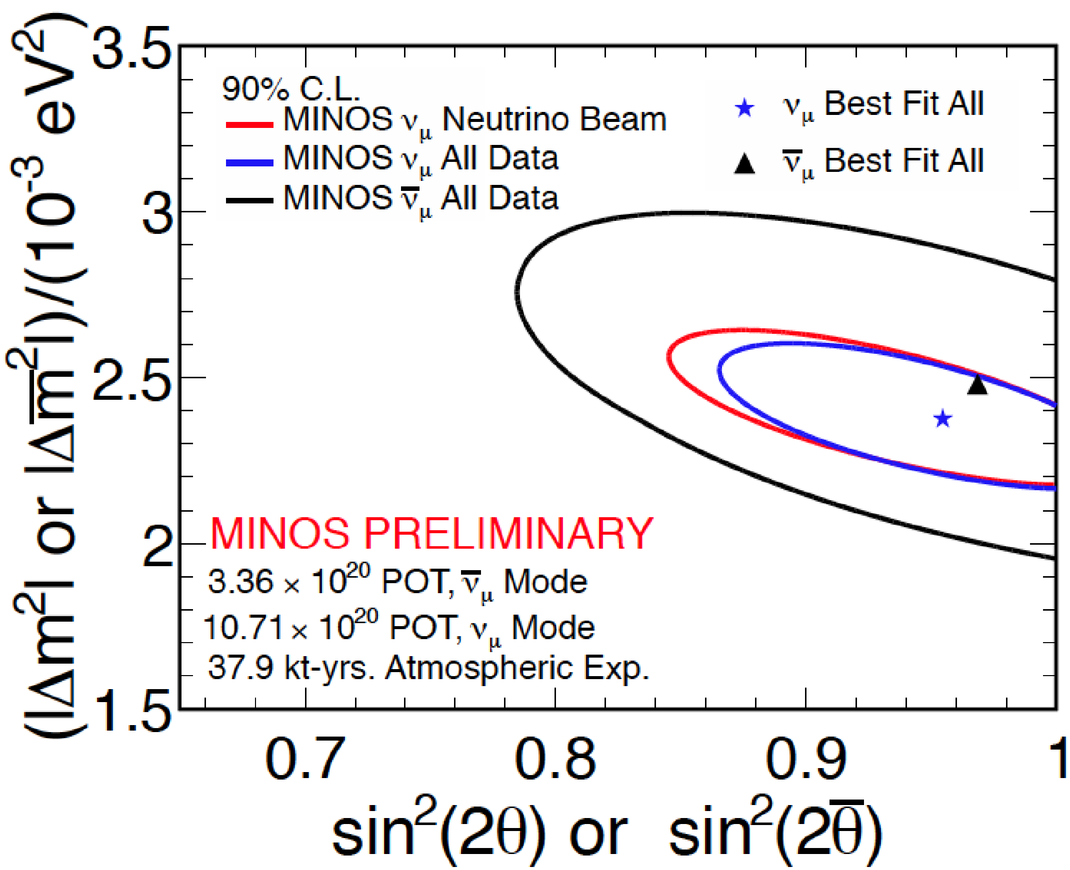
Anti-neutrino comparison



- Allowe regions for the anti-nutrino mixing parameters
- SK-I+II+III
- Shaded region: MINOS2011 allowed region for anti-neutrino dispappeance in an anti-neutrino beam.

Recent MINOS result

- MINOS: more data → no difference



Part II

3 flavor atmospheric ν oscillation

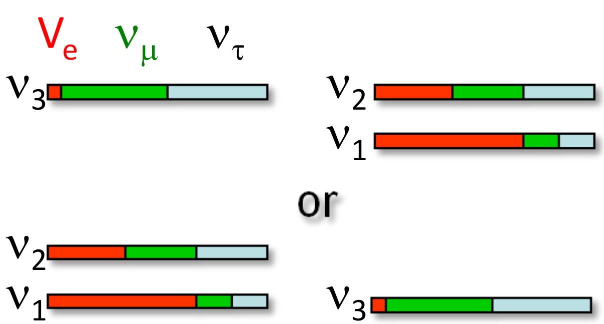
3 flavor mixing

$$\text{mixing: } \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates — mass eigenstates

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric ν Long baseline Acc (θ_{23}: maximal?)	Reactor ShortBL ($\sin^2\theta_{13}$~0.025, δ_{CP} ?)	Solar ν Reactor LBL (θ_{12}: large)



Remaining Problems

- **CPV**
- **Mass hierarchy: sign of Δm_{13}^2**
- **Octant of θ_{23} : if $\theta_{23} \neq \pi/4$**

- Atmospheric neutrino oscillation is mainly through θ_{23}, but small effects from θ_{13} and θ_{12} may be seen: sub-dominant effects
- Mass hierarchy may also be untangled

ν_e appearance in 3 flavor oscillation

The ν_e flux after oscillations

$$\Phi(\nu_e) = \Phi_0(\nu_e)P_{ee} + \Phi_0(\nu_\mu)P_{\mu e} = \Phi_0(\nu_e)(P_{ee} + rP_{\mu e})$$

- $\Phi_0(\nu_e)$, $\Phi_0(\nu_\mu)$: fluxes at the detector without oscillation
- $r(E, \Theta_z) = \Phi_0(\nu_\mu)/\Phi_0(\nu_e)$: ratio of the orininal fluxes

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$

Solar term

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin^2\theta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$

Interfarence term. δCP

$$-2\sin^2\tilde{\theta}_{13}(1 - r \cdot \sin^2\theta_{23})$$

Ue3 term, matter enhance

$$-\sin^2\tilde{\theta}_{13}P_2(r-2) + \sin^4\tilde{\theta}_{13}(1 - r\sin^2\theta_{23})(2 - P_2)$$

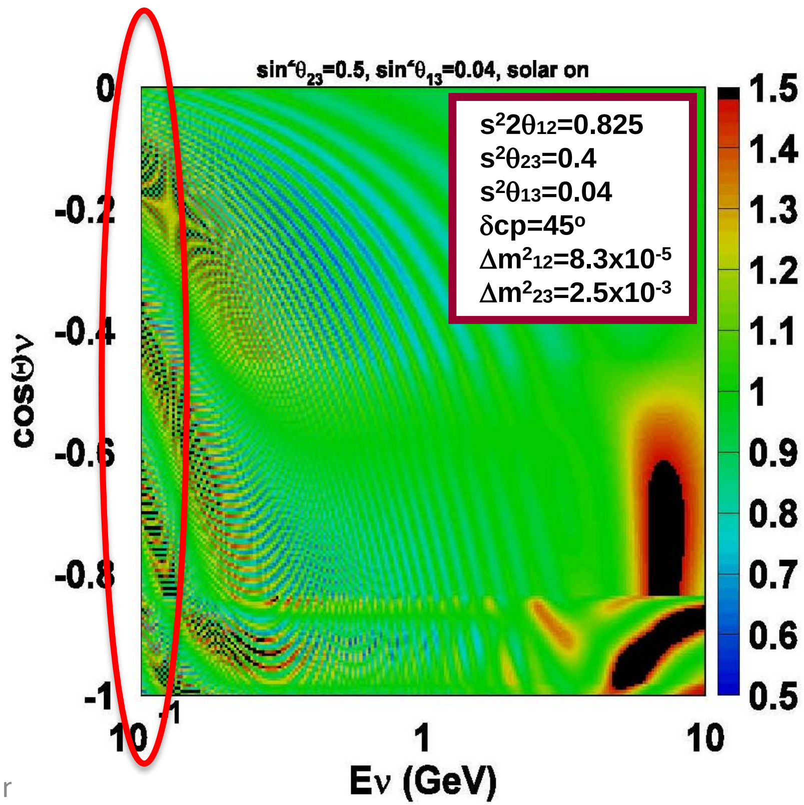
Negligible Ue3 term

- ~ : mixing angle in matter
- $P_2 = |A_{e\mu}|^2$: $\nu_\mu \rightarrow \nu_e$ in matter
- $R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$, $I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

Solar term

- Proportional to P_2
  - Matter effect → maximum @ the resonance energy
    $E_{res} \sim (\Delta m_{21}{}^2 \cos 2\theta_{12})/(2V\cos^2\theta_{13})$
  - For $\Delta m_{12}{}^2 = 7.6 \times 10^{-5}$ eV^2
    → E_{res} δ 0.1 GeV
  - Large matter effect at the low energy end of sub-GeV samples
- r → depend on energy,
  - r=2.04~2.06 (close to 2 in sub-GeV), larger (in high energy region)
- Screening effect ($r\cos^2\theta_{23}$-1):
  - θ_{23} = 45 deg → 0.02-0.03
  - excess for θ_{23} < 45 deg
  - deficiency for θ_{23} > 45 deg
- No θ_{13} dependence

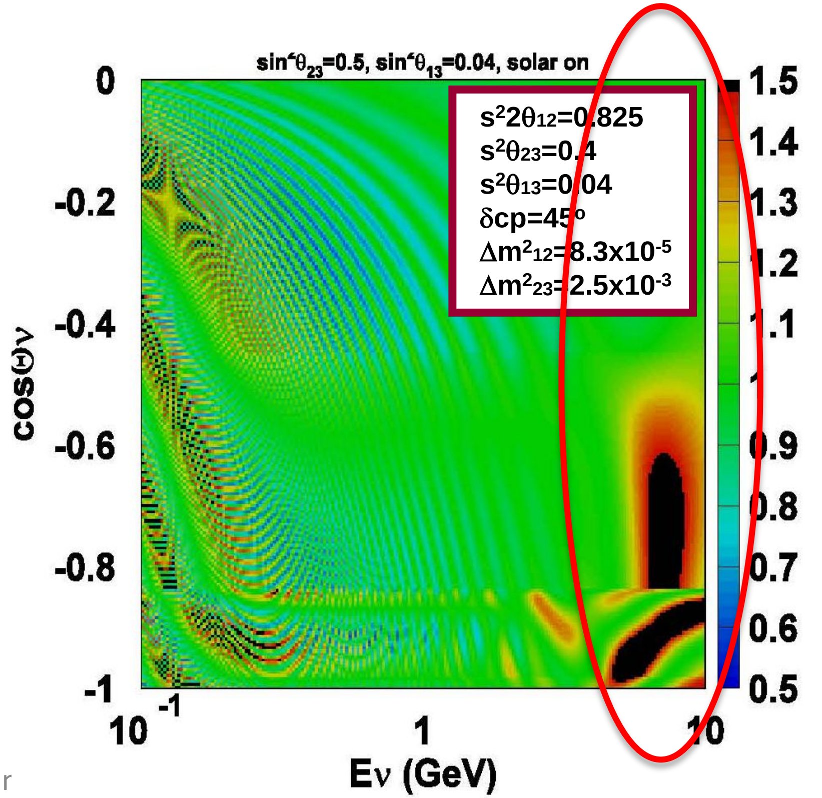
$$; \; P_2(r \cdot \cos^2\theta_{23} - 1)$$



U_{e3} oscillation

$$-2\sin^2\tilde{\theta}_{13}(1 - r\cdot\sin^2\theta_{23})$$

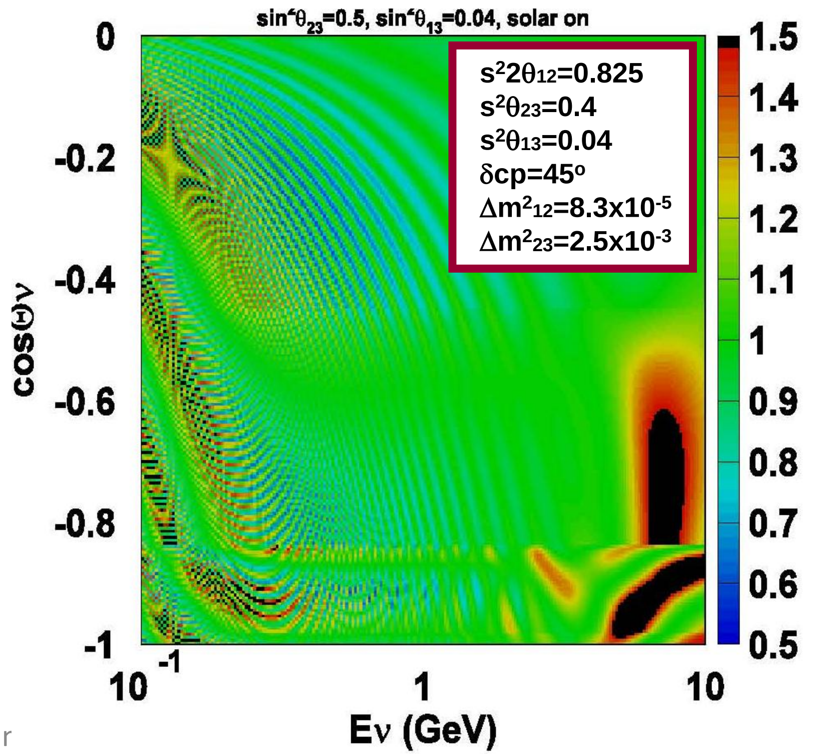
- Matter enhancement for $\Delta m_{13}{}^2$=2.4x10^{-3} eV^2
  ➔ ~ 10 GeV
- ~ 10% effect
- No screening effect in high energy (r > 2)



Interefarene

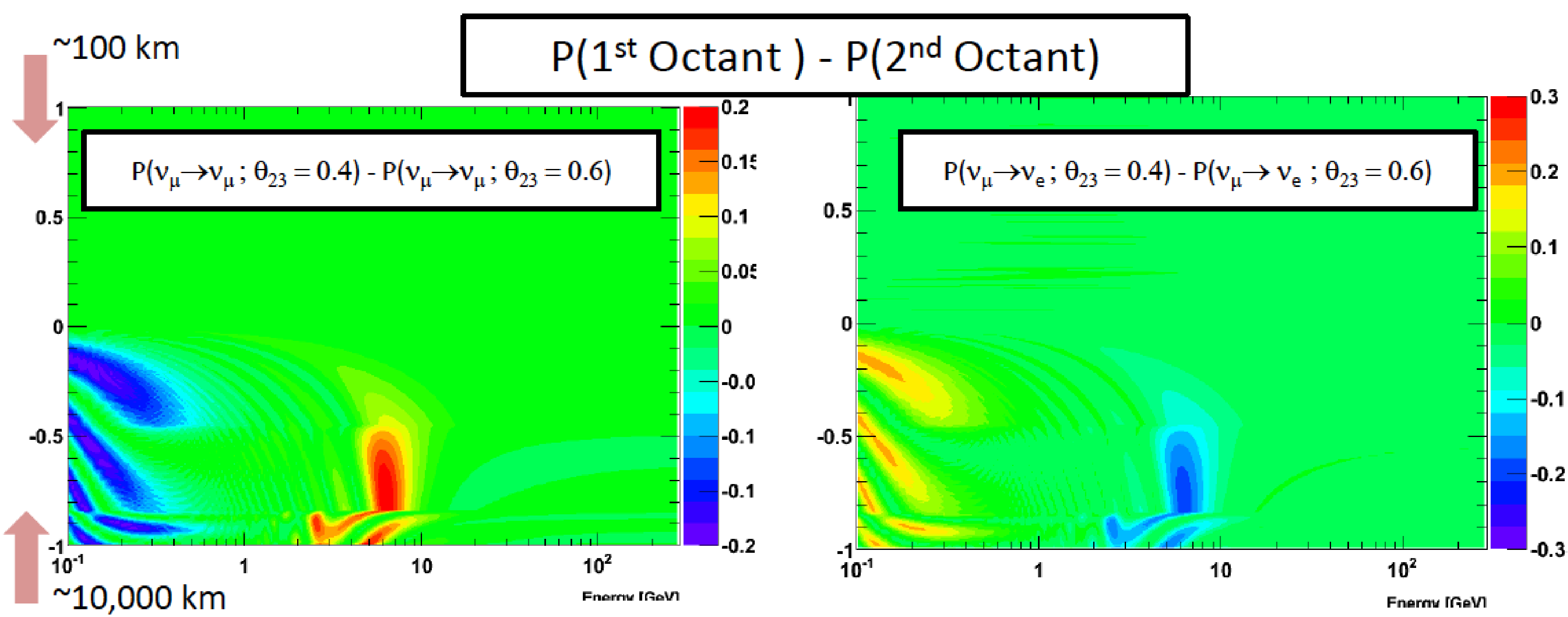
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin^2\theta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$

- Depend on $\sin\tilde{\theta}_{13}$ linearly
  - ➔ not strongly suppressed
- Interference depend on
  - ➔ sign of $\sin\tilde{\theta}_{13}$
- No screaning effect.
- Proportional to $\sin^2\theta_{23}$ sensitive to the octant of θ_{23}.
- smallness :
  - 🡐 from $\sin\theta_{13}$, R_2 and I_2
- Size of δ_{CP}
  - ⬄ Magnitude of resonance effect



Octant

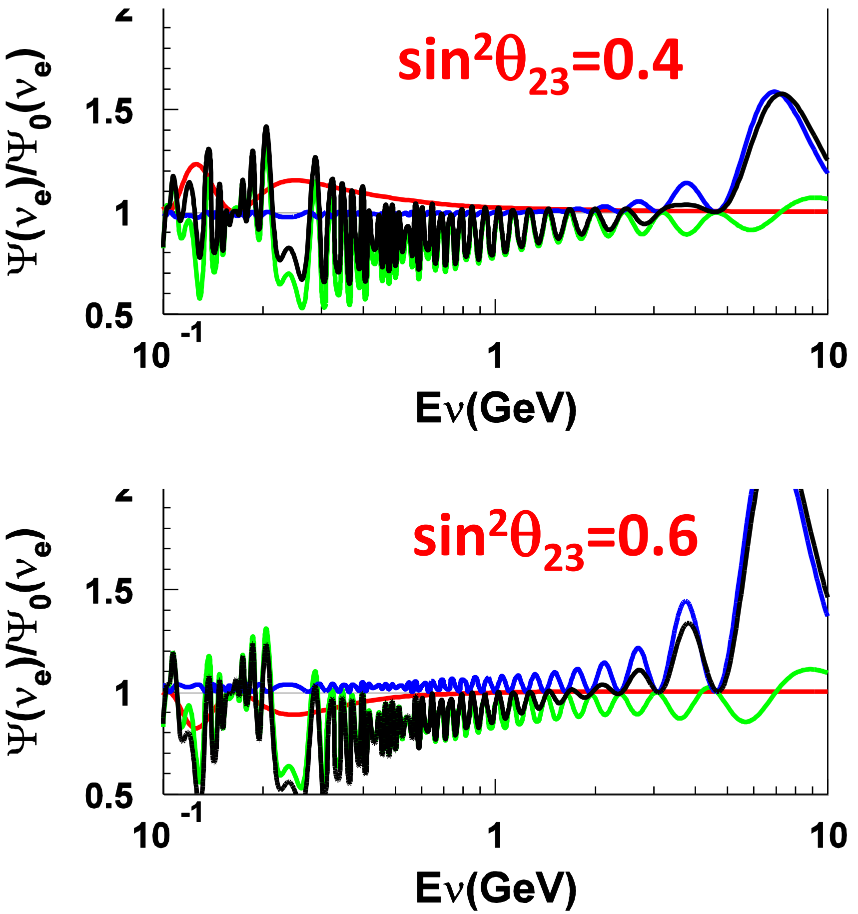
- octant of θ_{23}: appearance and disappearance interplay.

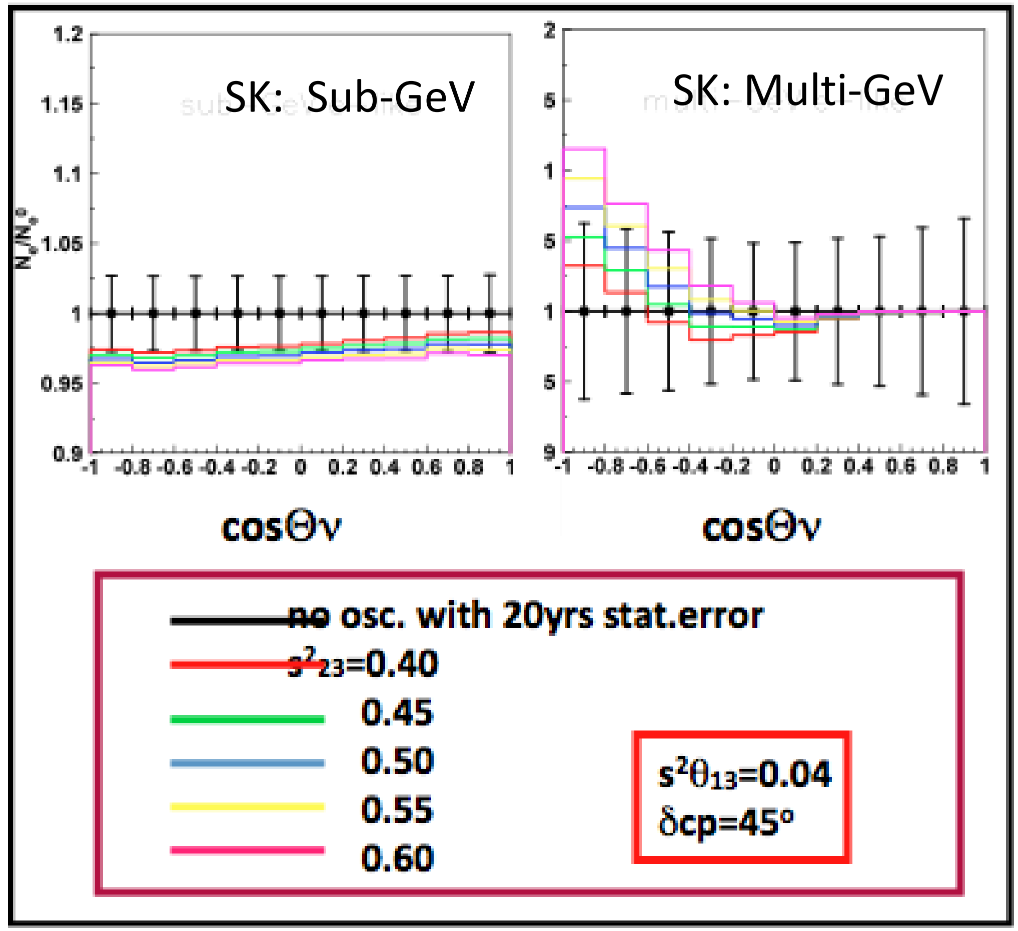


Anti-neutrinos

- $\nu \Leftrightarrow \bar{\nu}$:
  ➔ V ⇔ -V
- Mass hierarchy
  ← asymmetry of ν and $\bar{\nu}$
  – Resonance condition: $V \sim \Delta m^2$
  – Resonance
    ➔ ν + NMH or $\bar{\nu}$ + IMH

Example





- Total
- Solar term
- θ_{13} term
- Interference

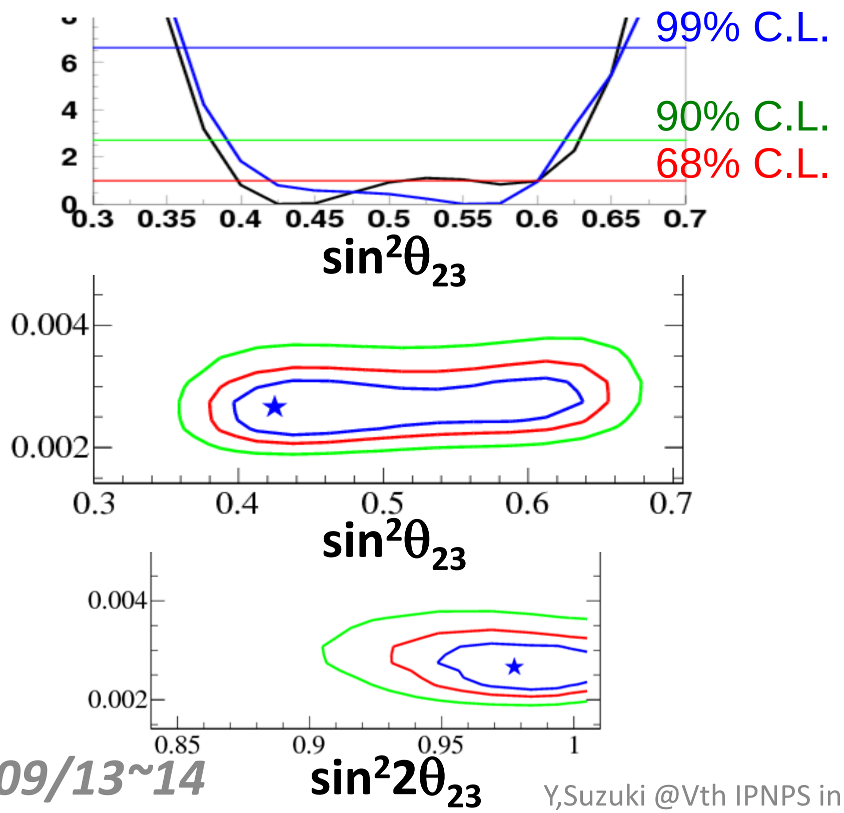
Fixed: $\cos \Phi\nu = -0.8$
$\Delta m^2_{23} = 2.5\times10^{-3}\,eV^2$ (positive)
$\Delta m^2_{12} = 8.3\times10^{-5}\,eV^2$
$\sin^2 2\theta_{12} = 0.825$
$\sin^2\theta_{13} = 0.04$, $\delta_{CP} = 45$ deg

Current situation of atmospheric ν θ_{23} Octant (SK data)

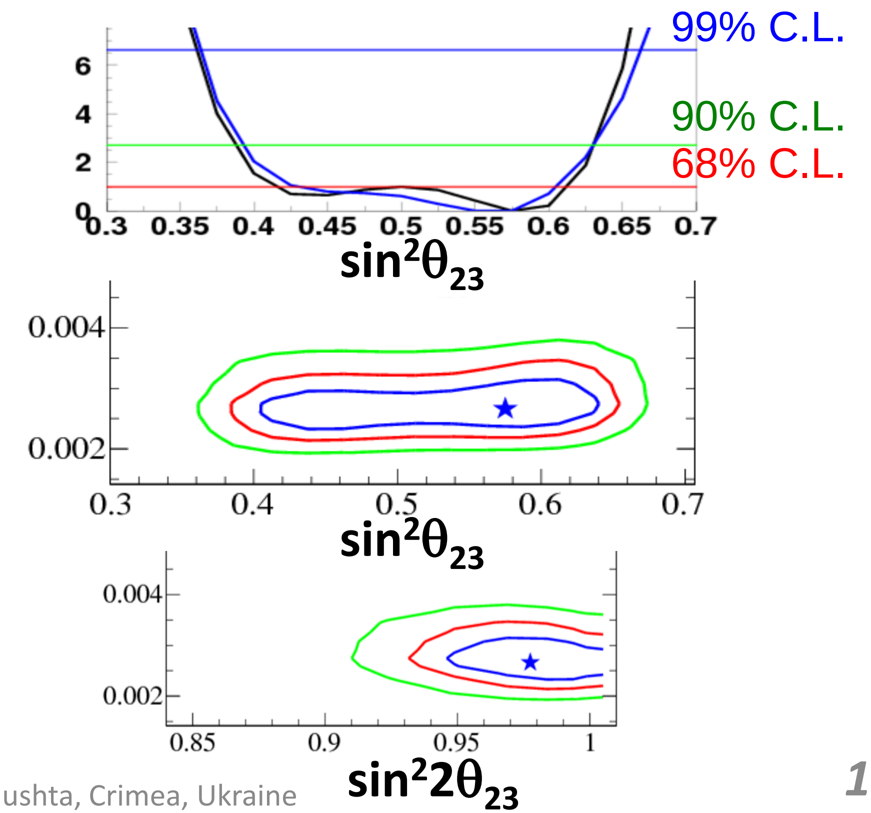
Super-Kamiokande atmospheric neutrino 3 flavor analysis
--- θ_{13} free in the fitting
--- θ_{13} fixed at the best value

We may start to see 1 σ level effect ??

- Normal Mass Hierarchy
- Best fit value: 0.425



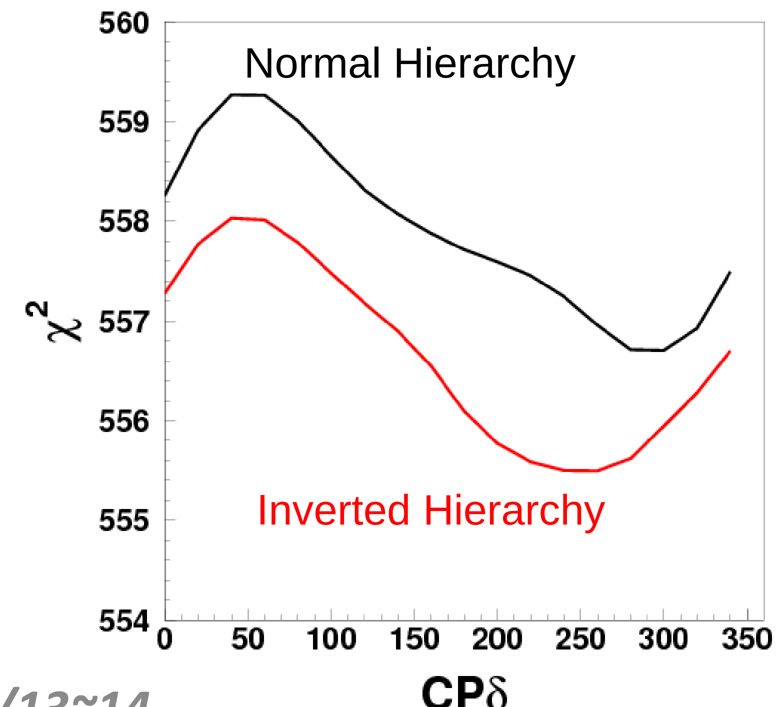
- Inverted Mass Hierarchy
- Best fit value: 0.575



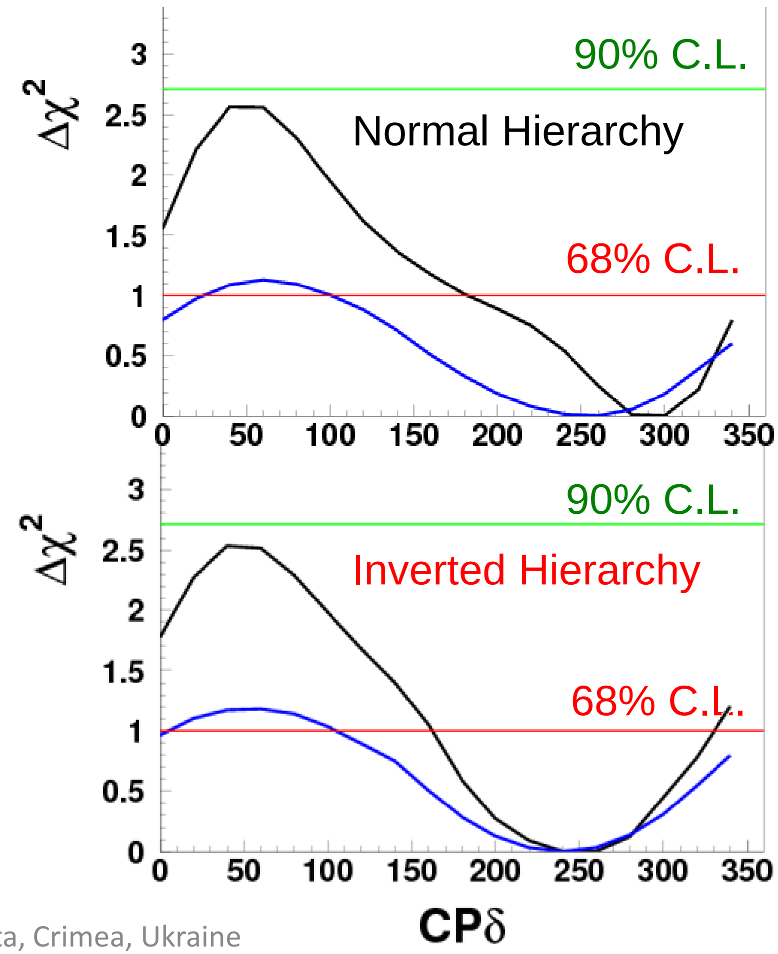
Current situation of atmospheric ν
Mass Hierarchy and CP phase

- There may be a hit in Atm ν (SK)
  - NH: χ^2_{min} = 556.7 / 477 dof
  - IH : χ^2_{min} = 555.5 / 477 dof

χ^2_{min} (NH) – χ^2_{min} (IH)= 1.2



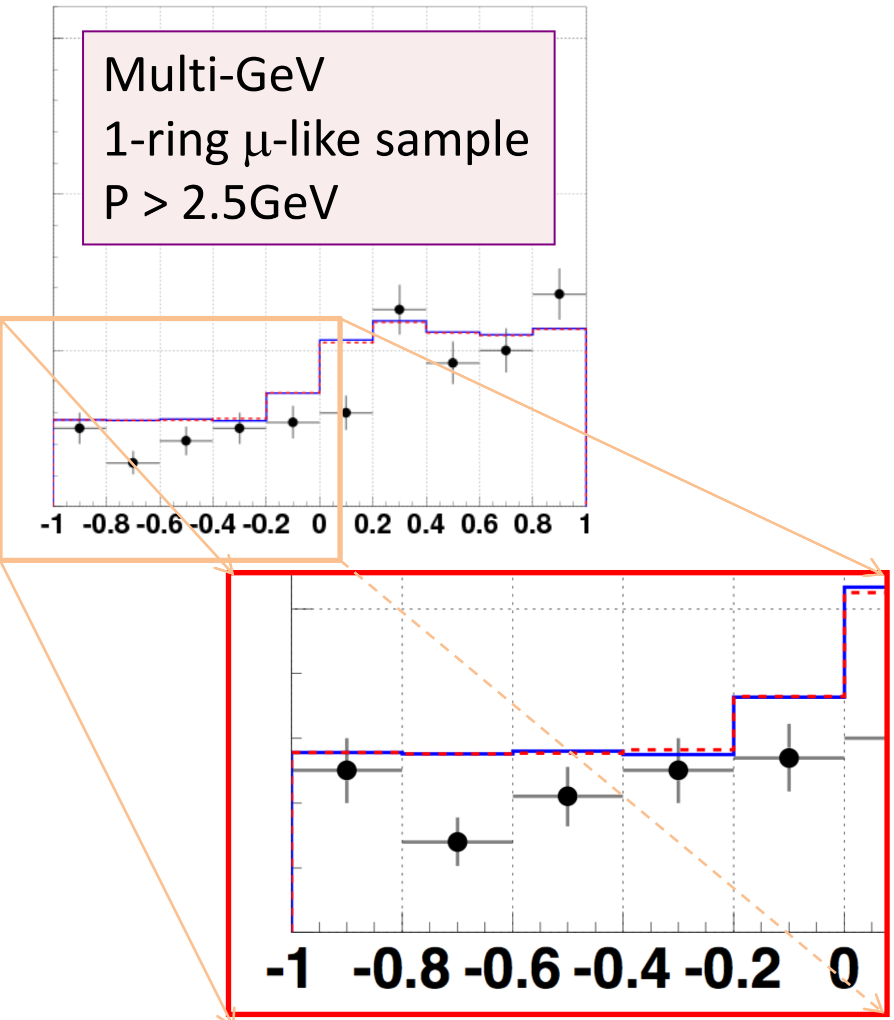
--- θ_{13} free in the fitting
--- θ_{13} fixed at the best value

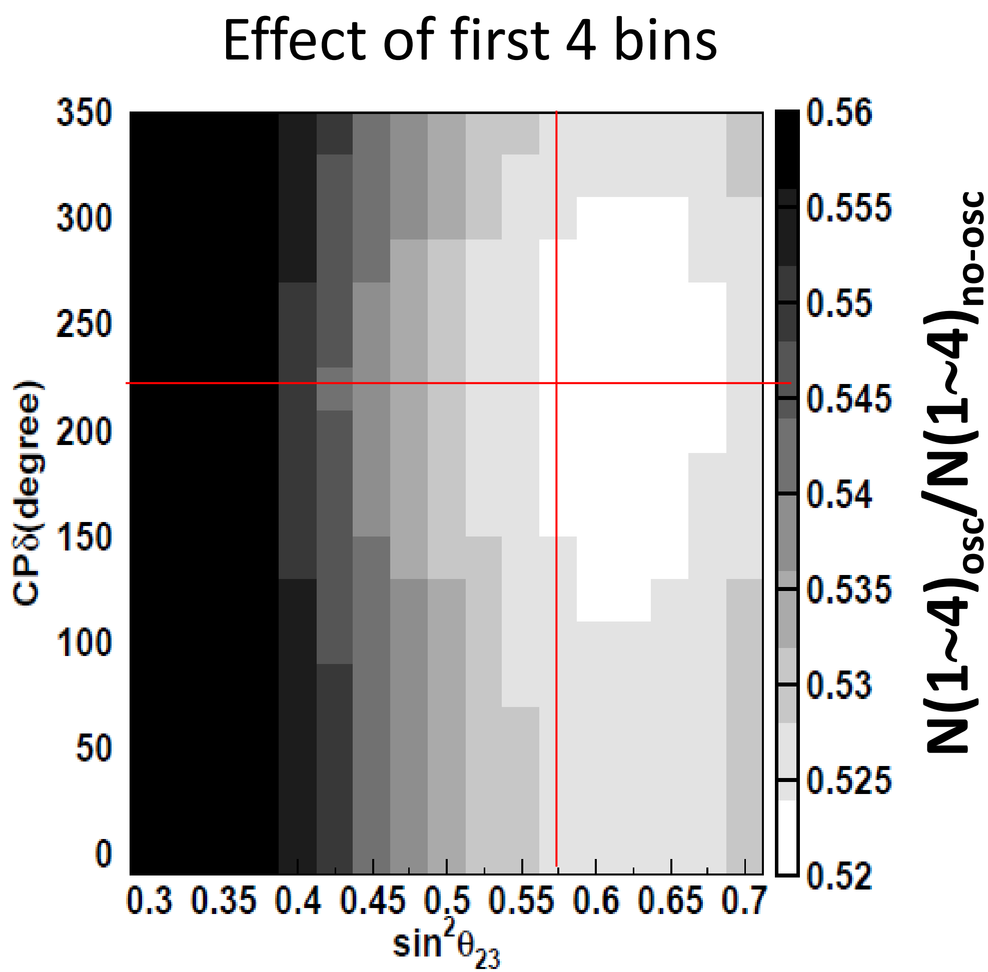


101

CP phase

- Why 220°





Future

We need to complete the neutrino oscillation study

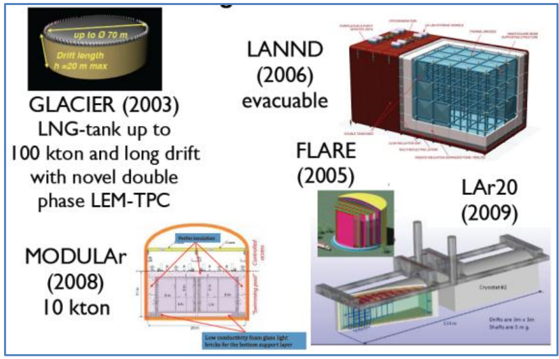
  – Mass hierarchy, CP-phase

- Need **Mega-ton (or more) or sophisticated detector** as a far detector of long baseline experiments and also as a stand alone detector

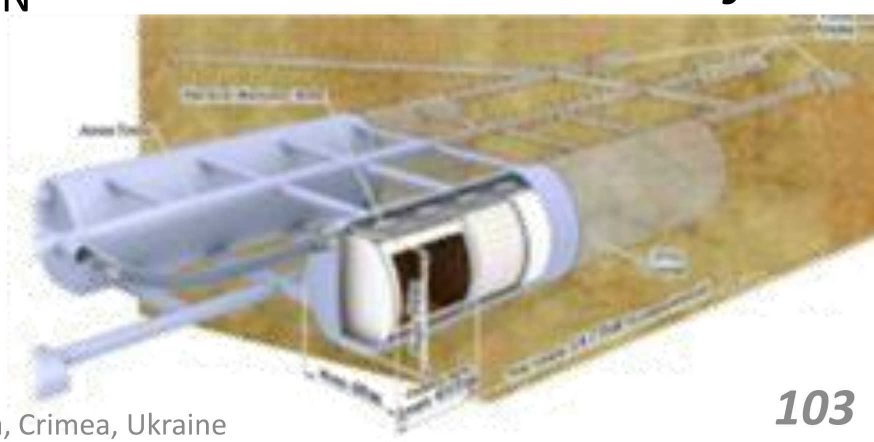
    ← Atmospheric Neutrino may play again important roles

  – liq. Ar.
    - US. Homestake w/ ν–beam from Fermilab
    - Europe: example, Pyhäsalmi ← CERN
  – Water
    - Japan: 0.5 Mton water Cherenkov
    - w/ν–beam from JPARC
  – Liq. Scint.
    - Europe: many options

Liq. Ar
Several Concepts, A. Rubia
@NEUTRINO2012



Hyper-Kammiokande
0.56 Mton fid.

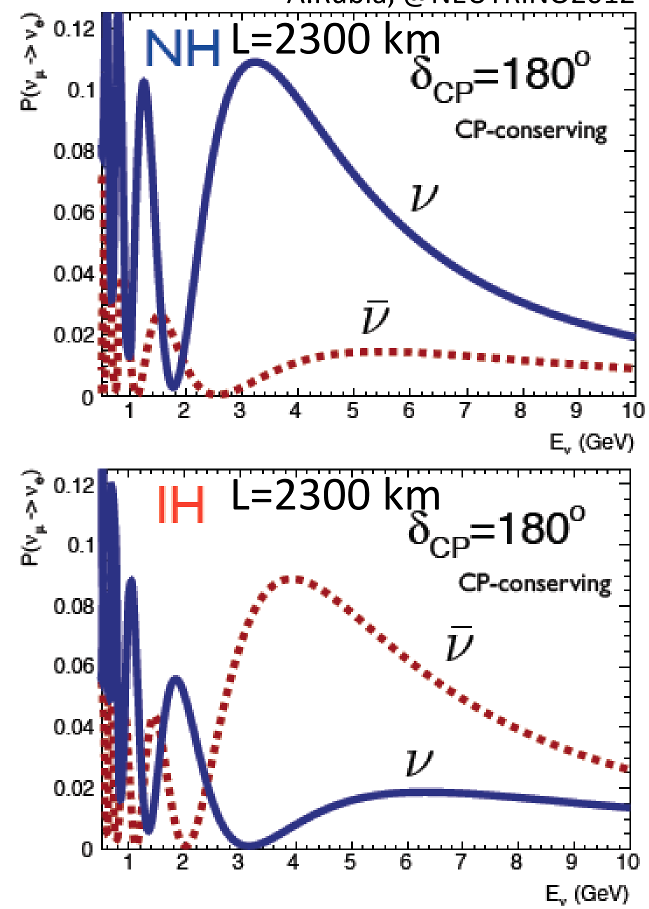


LENA

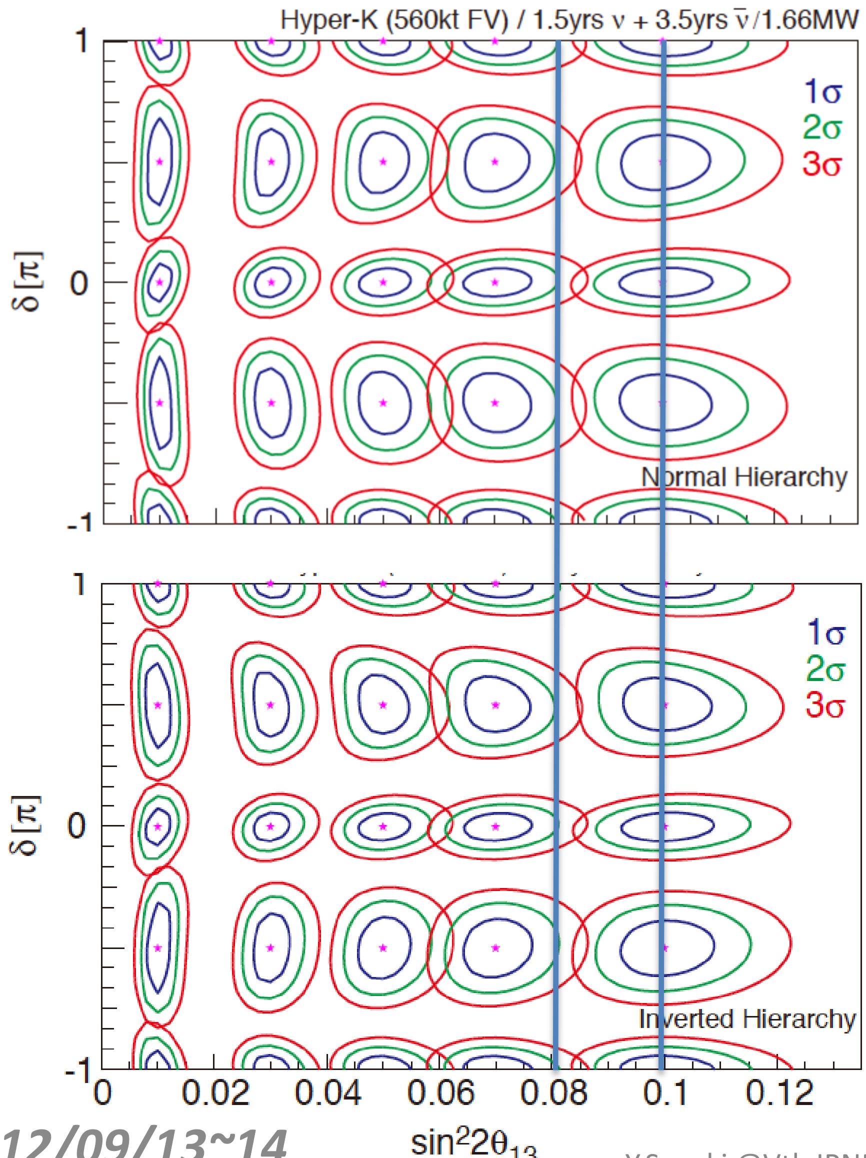
Sensitivity

- Mass hierarchy (MH)
  - ➔ MH is an exclusive OR (On/Off) problem
  - ➔ 2~3σ effect is enough to judge.
  - – Find a place no obstacles from other parameters
  - – Very long baseline (ex): Clear difference Normal MH ⇔ Inverted MH
    - But there may be a dark horse !
- CP phase
  - – We hope that MH will be resolved before the CPV experiments.
  - – Shorter distance may be justified for a good CPV experiment

A.Rubia, @NEUTRINO2012



CP phase

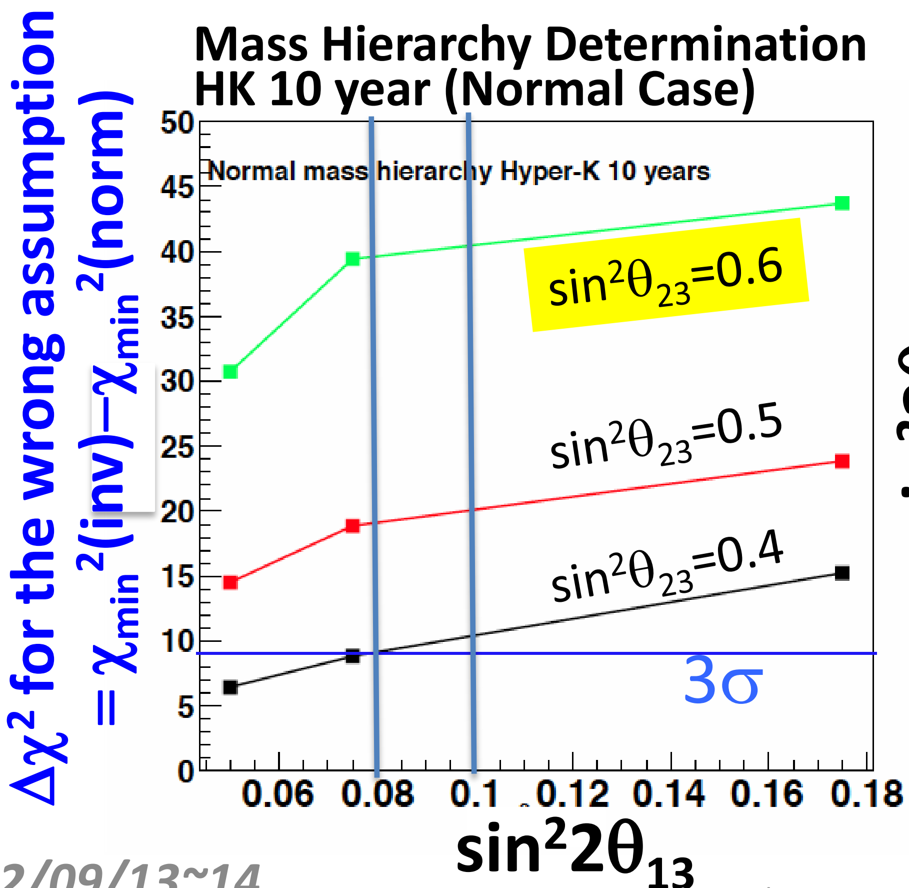


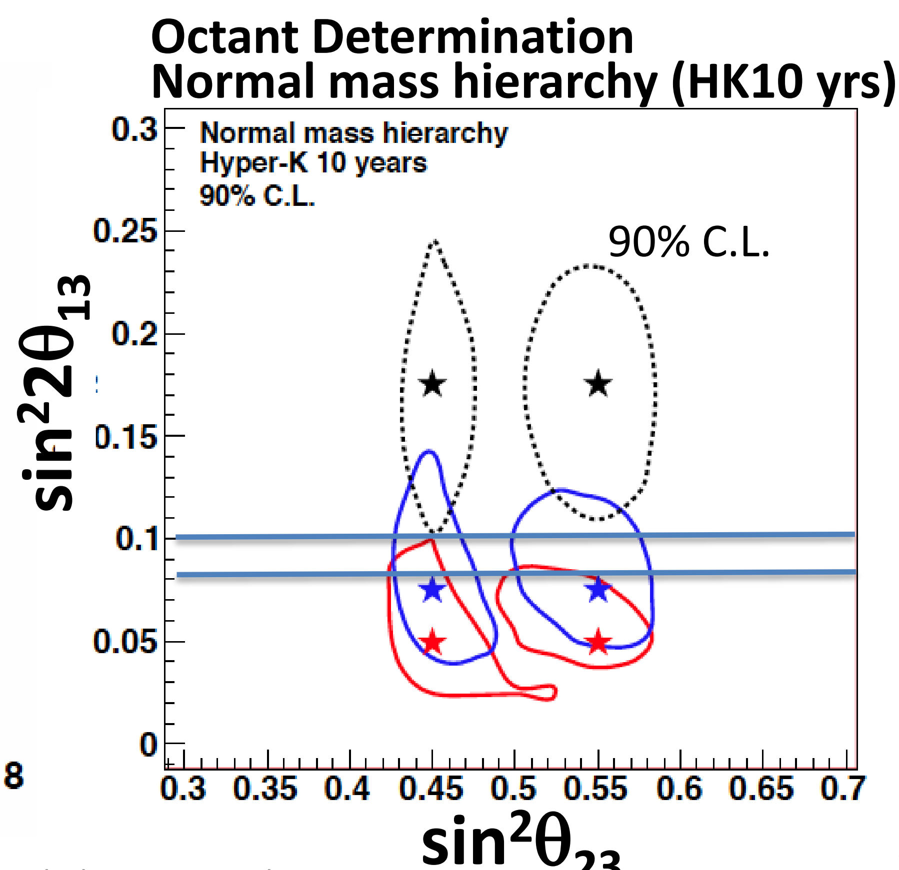
- HK (0.56 Mt)+JPARC
  - 295 km baseline
  - 0.75 MW x10 (3+7) yrs
  - 5% systematics

➔ 74% of δ can be covered and determined with 3σ effect (for known MH)

Role of the atmospheric neutrinos
(Complementary or Short Cut for MH & Octant)

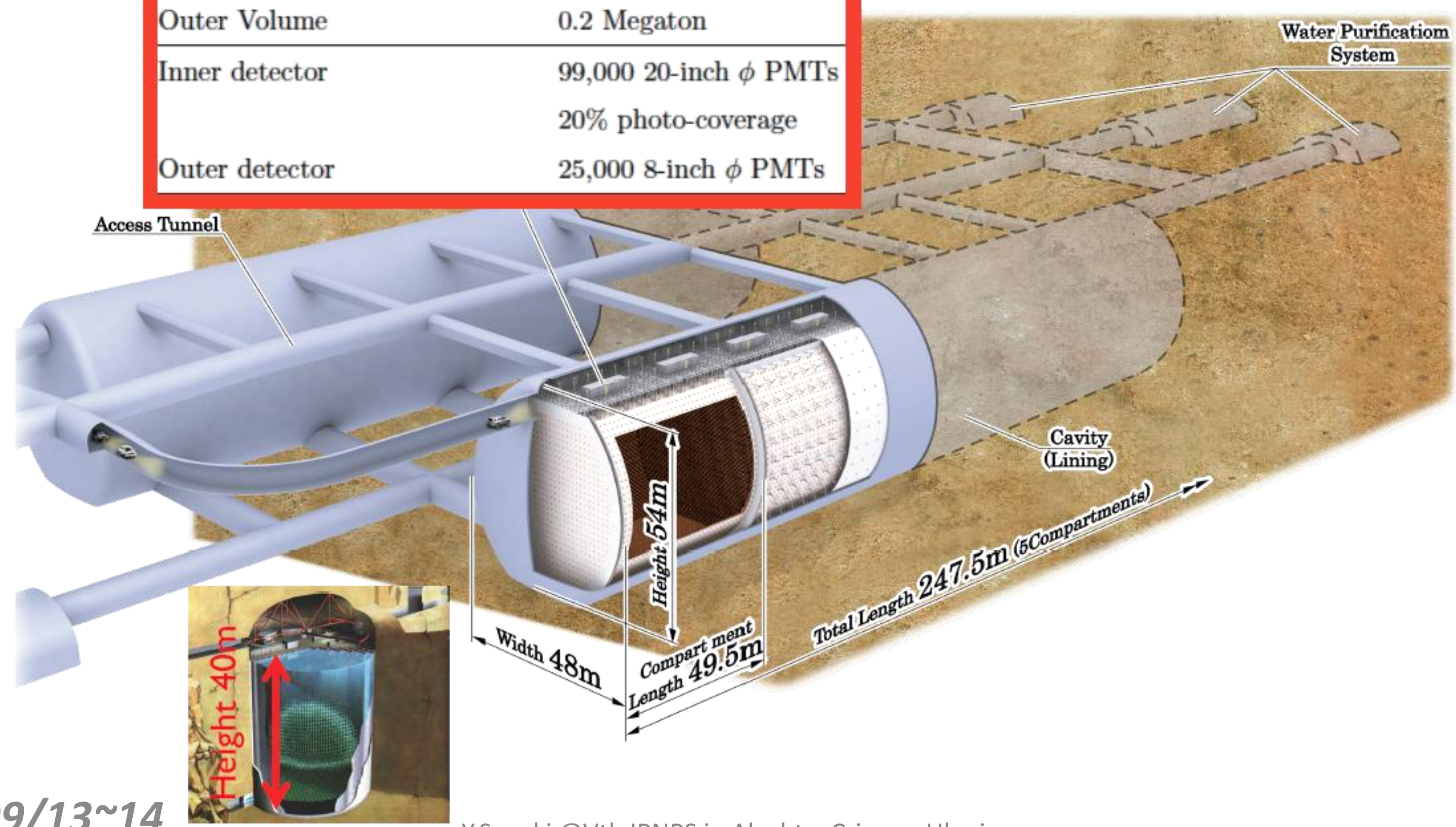
- Atmospheric ν: larger θ_{13} is a good news for atmospheric neutrinos





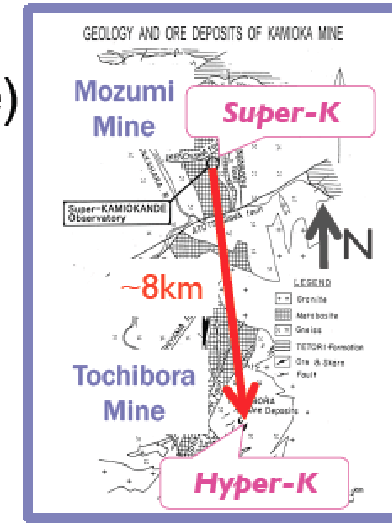
Hyper-Kamiokande

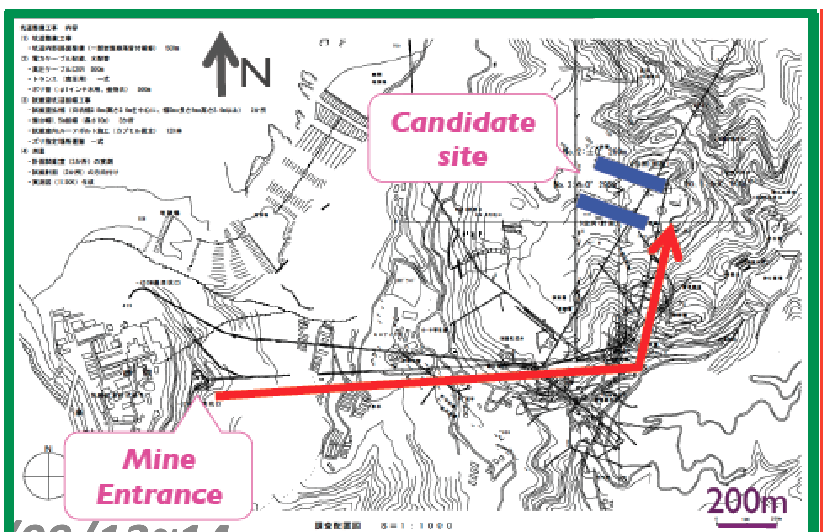
Total Volume	0.99 Megaton
Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
Outer Volume	0.2 Megaton
Inner detector	99,000 20-inch ϕ PMTs
	20% photo-coverage
Outer detector	25,000 8-inch ϕ PMTs

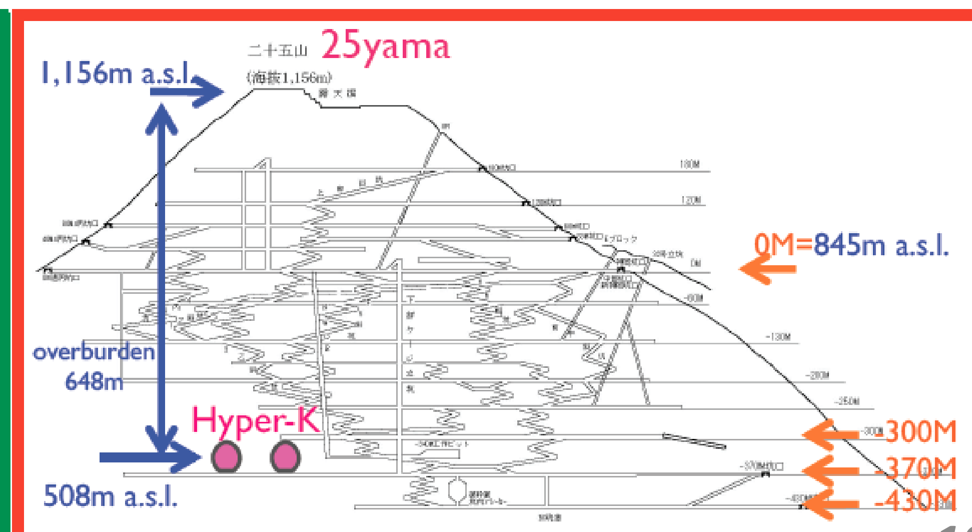


Hyper-K candidate site

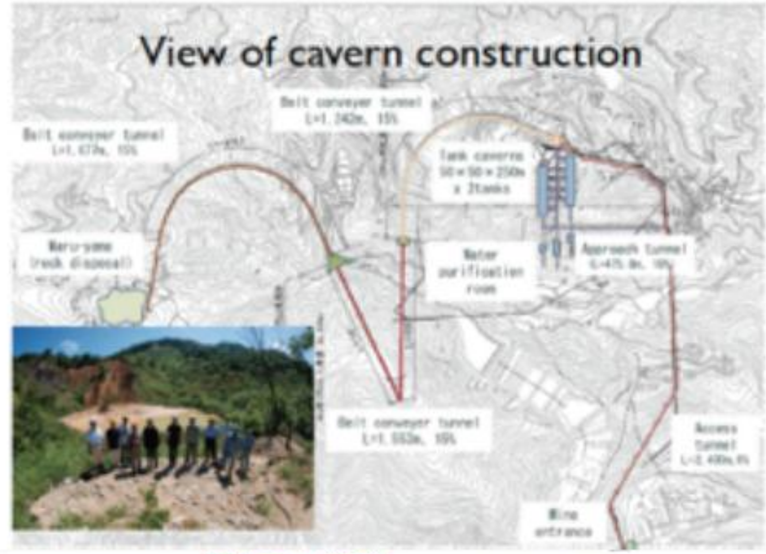
- 8km south from Super-K
  - same T2K beam off-axis angle (2.5 degree)
  - same baseline length (295km)
- 2.6km horizontal drive from entrance
- under the peak of Nijuugo-yama
  - 648m of rock or 1,750 m.w.e. overburden
- 13,000 m^3/day or 1megaton/80days natural water



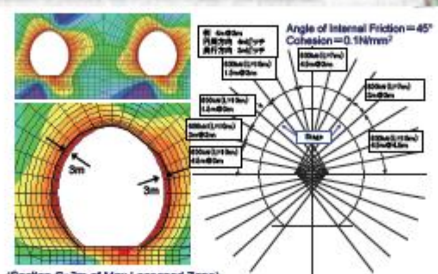


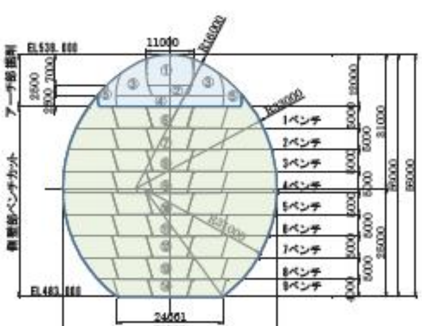


Cavern excavation



- geological survey, in-situ rock stress tests
- scheduling & costing ongoing





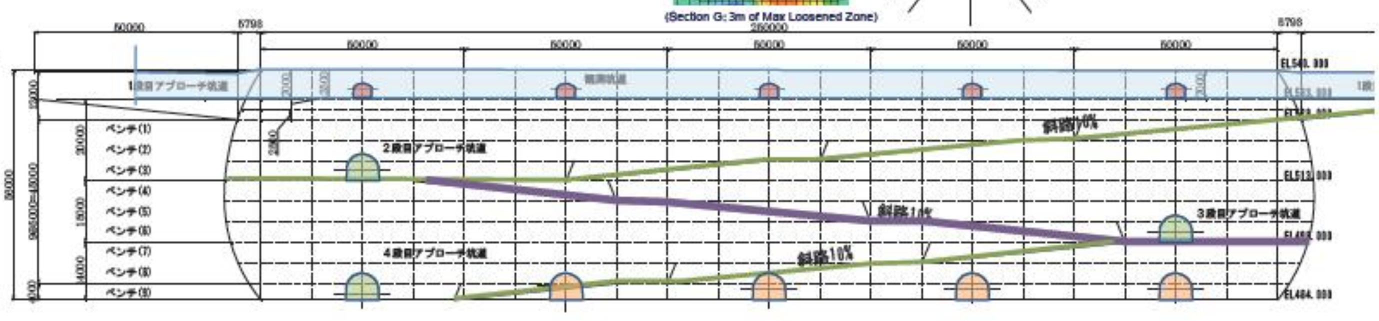
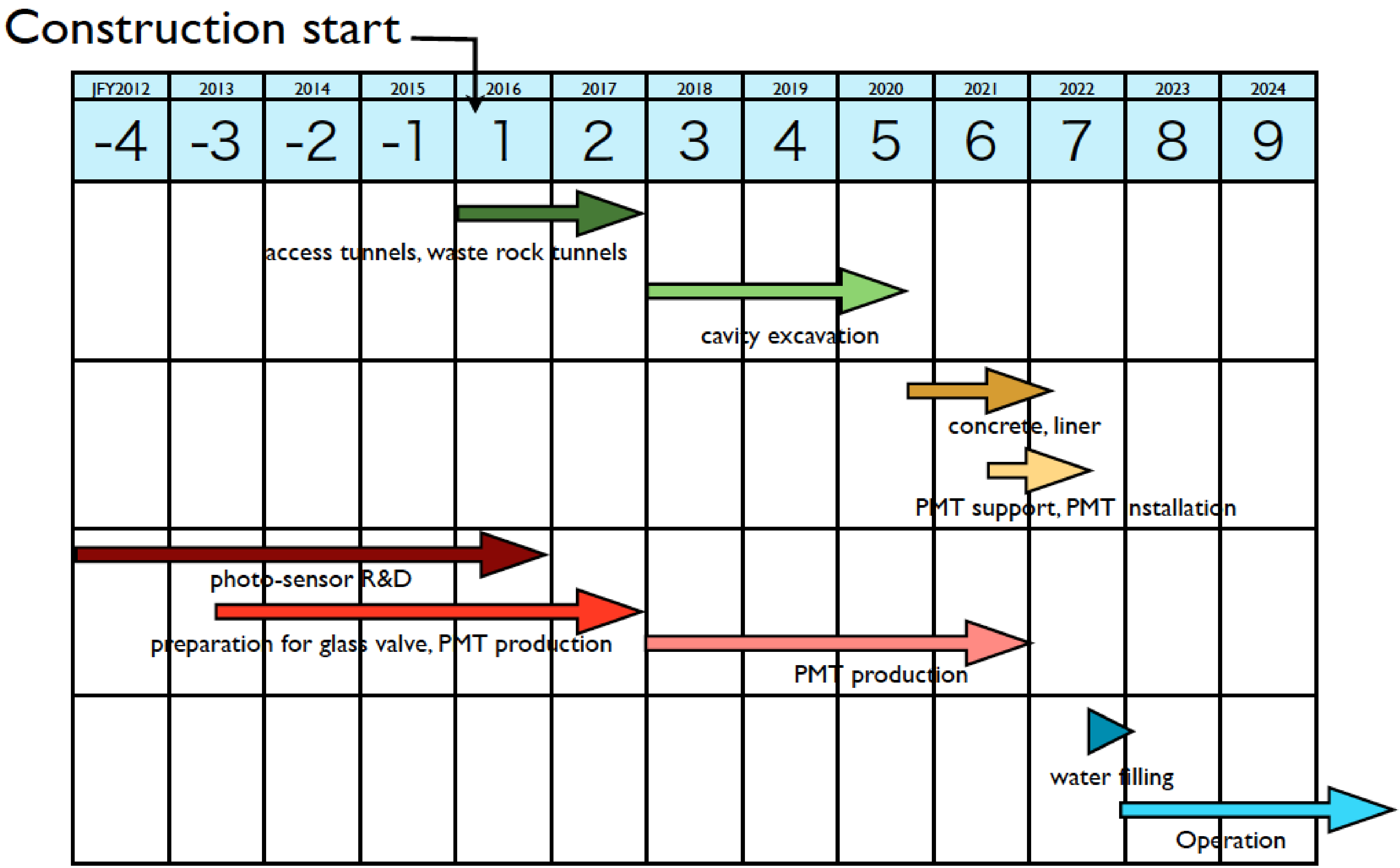


Photo-sensor

- Candidates for ID sensor
  - 20" Hybrid Photo Detector (HPD)
  - Improved 20" PMT
- Proof test of 8" HPD in water tank from this winter
- 20" HPD prototype expected in ~a year

Preparation @ Kamioka

Schedule



assuming budget being approved from JPY2016

Hyper-K WG,
arXiv:1109.3262 [hep-ex]

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

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A. K. Ichikawa,[4] M. Ikeda,[4] K. Inoue,[8,14] H. Ishino,[7] Y. Itow,[6] T. Kajita,[13,14] J. Kameda,[12,14]
Y. Kishimoto,[12,14] M. Koga,[8,14] Y. Koshio,[12,14] K. P. Lee,[13] A. Minamino,[4] M. Miura,[12,14]
S. Moriyama,[12,14] M. Nakahata,[12,14] K. Nakamura,[2,14] T. Nakaya,[4,14] S. Nakayama,[12,14]
K. Nishijima,[9] Y. Nishimura,[12] Y. Obayashi,[12,14] K. Okumura,[13] M. Sakuda,[7] H. Sekiya,[12,14]
M. Shiozawa,[12,14,*] A. T. Suzuki,[3] Y. Suzuki,[12,14] A. Takeda,[12,14] Y. Takeuchi,[3,14]
H. K. M. Tanaka,[11] S. Tasaka,[1] T. Tomura,[12] M. R. Vagins,[14] J. Wang,[10] and M. Yokoyama[10,14]

(Hyper-Kamiokande working group)

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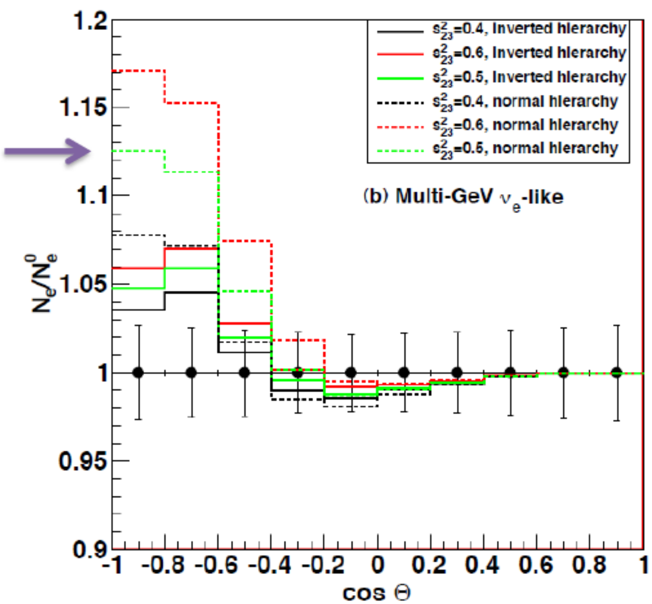
3262v1 [hep-ex] 15 Sep 2011

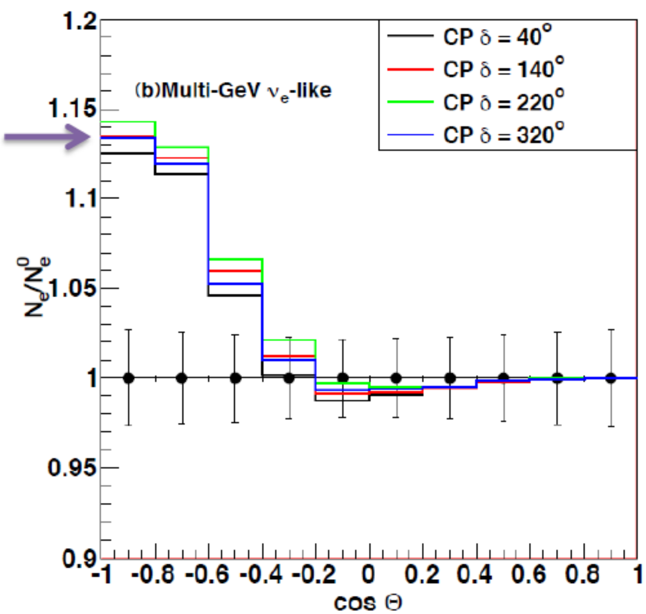
Sensitivity of the atmospheric neutrinos in Hyper-Kamiokande

- HK: 10 yrs MC➔ ~584,000 FC events (~160 FC events/day)

Electron like samples (expected effects)

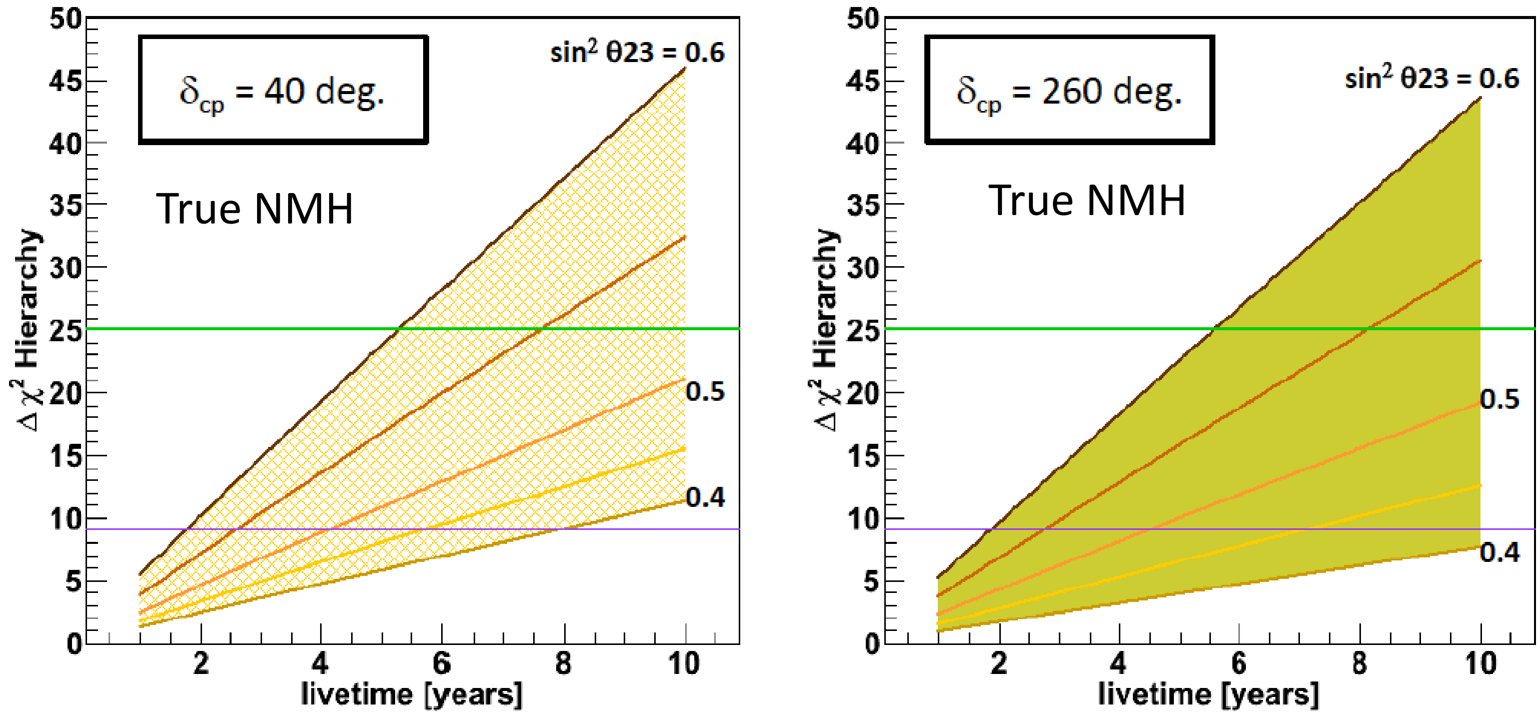
Equivalent MC →





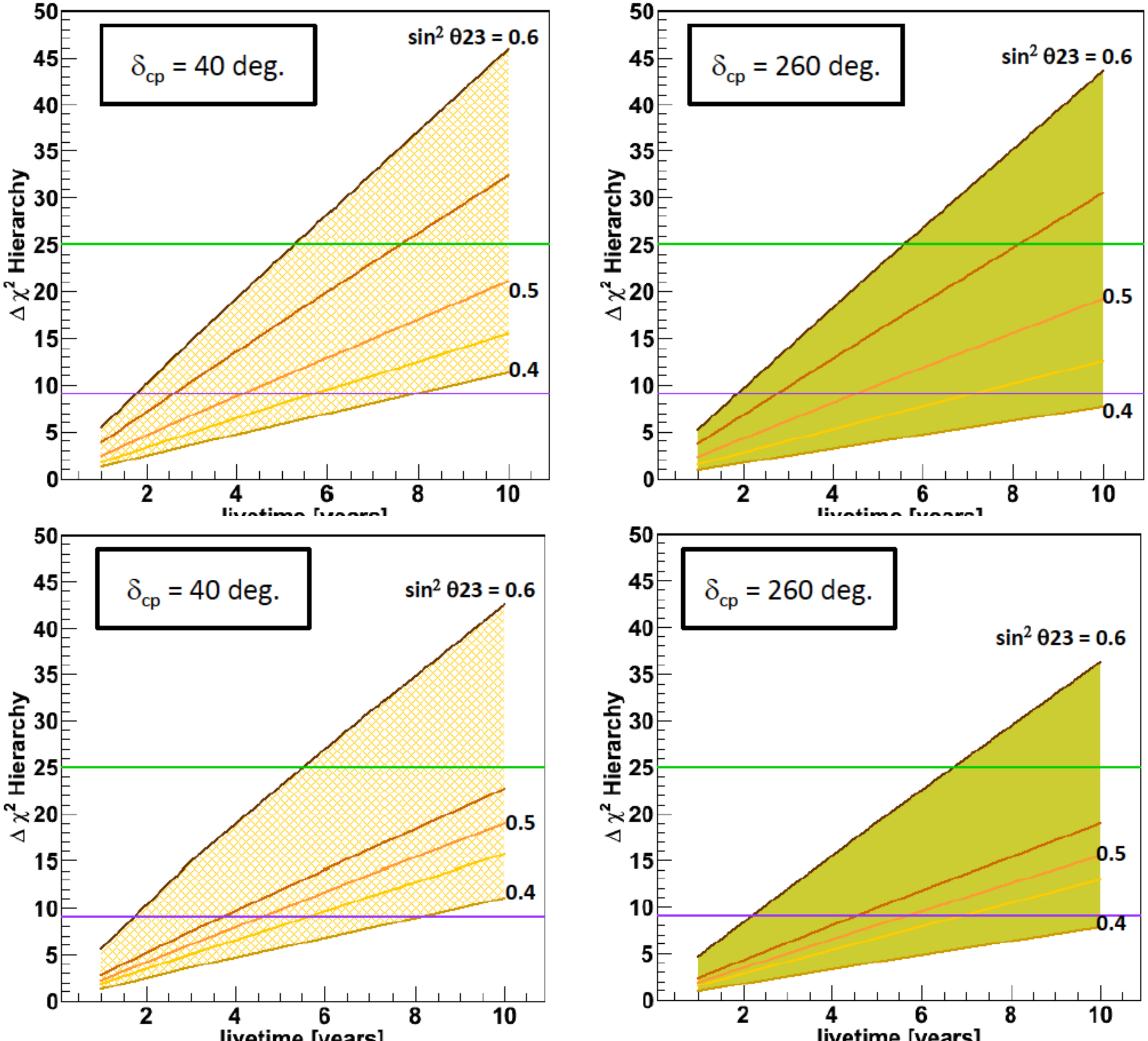
- Effect of the θ_{23} is large
- Effect of δ_{CP} is small (statistics is crucial)

Mass Hierarchy



- **$\Delta\chi^2$ for the wrong assumption ($\Delta\chi^2$(IMH)-$\Delta\chi^2$ (NMH))**
- **$\sin^2 2\theta_{13}$ = 0.10 : fixed (large θ_{13} → enhance matter effect and hence the electron appeance)**
- **HK: 1yr to 10 yr operation**
- **If $\sin^2\theta_{23}$ is large (~0.6), then it is easier to determine the MH.**
  - **Even 1 yr of data of HK (~ 20 yr of SK) → $\Delta\chi^2$ > 5**
- **Some dependence on CP phase, but not large (see also other slide)**

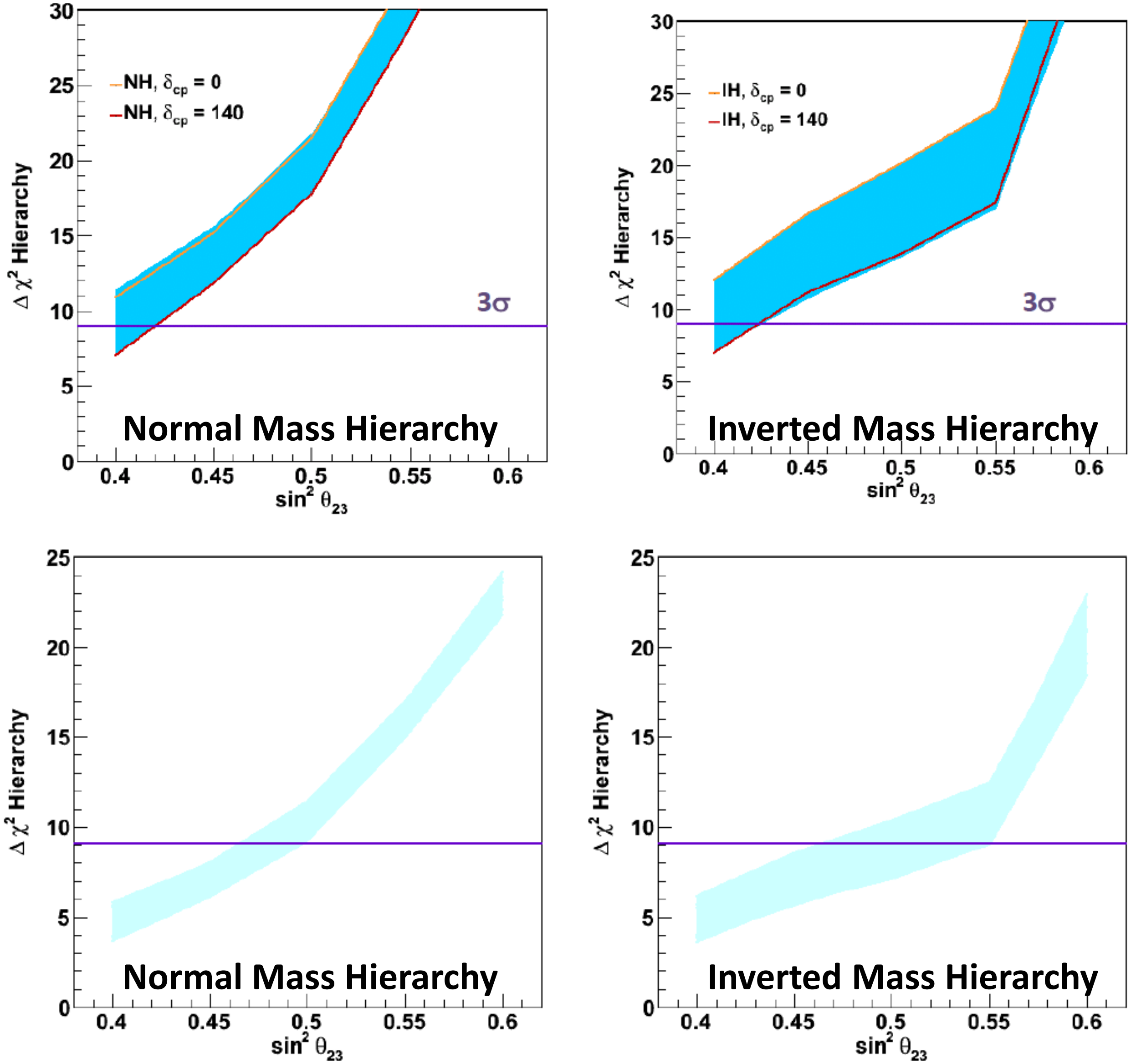
Mass Hierarchy



True:
Normal Mass Hierarchy

True:
Inverted Mass Hierarchy

Mass Hierarchy



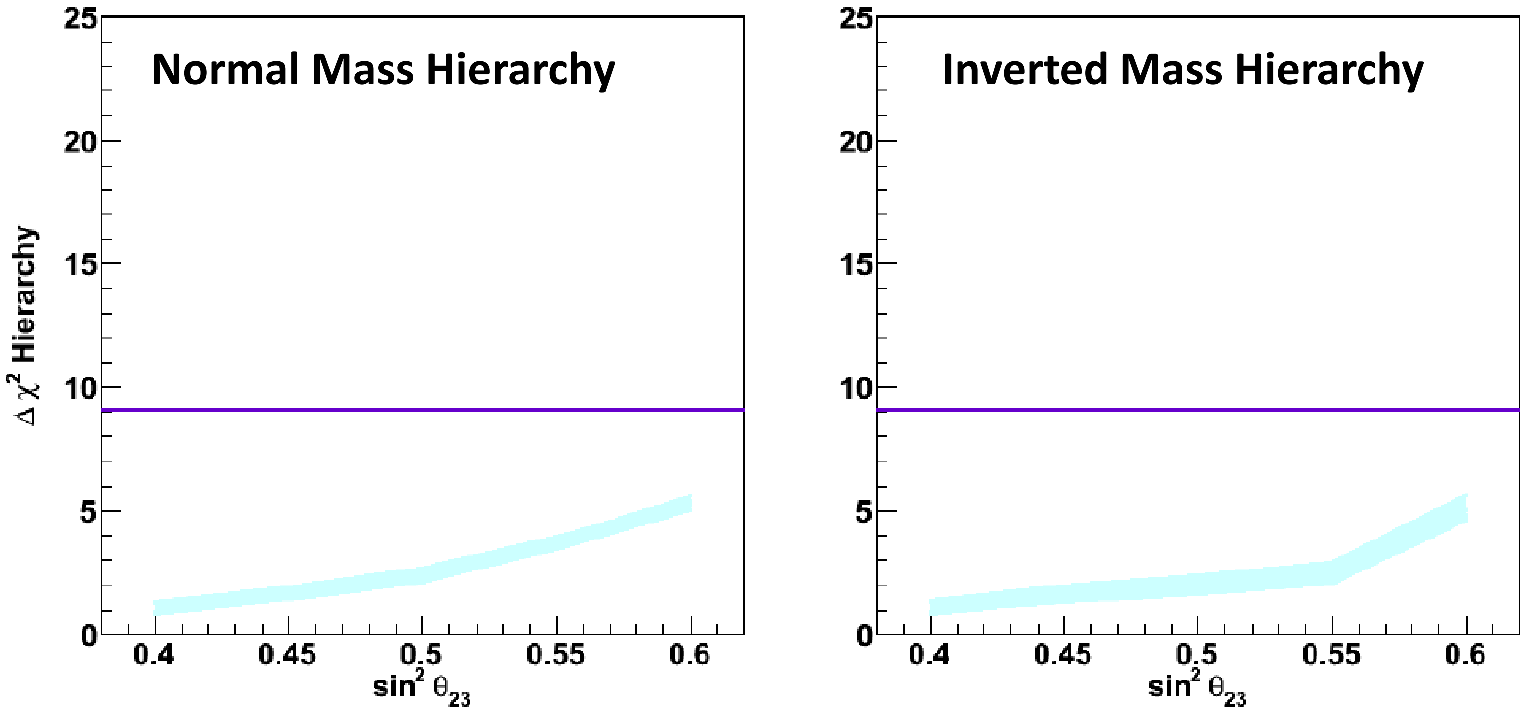
HK: 10 yrs

- $\sin^2 2\theta_{13}$=0.1: fixed
- Thickness of band ➔ range of CP phase

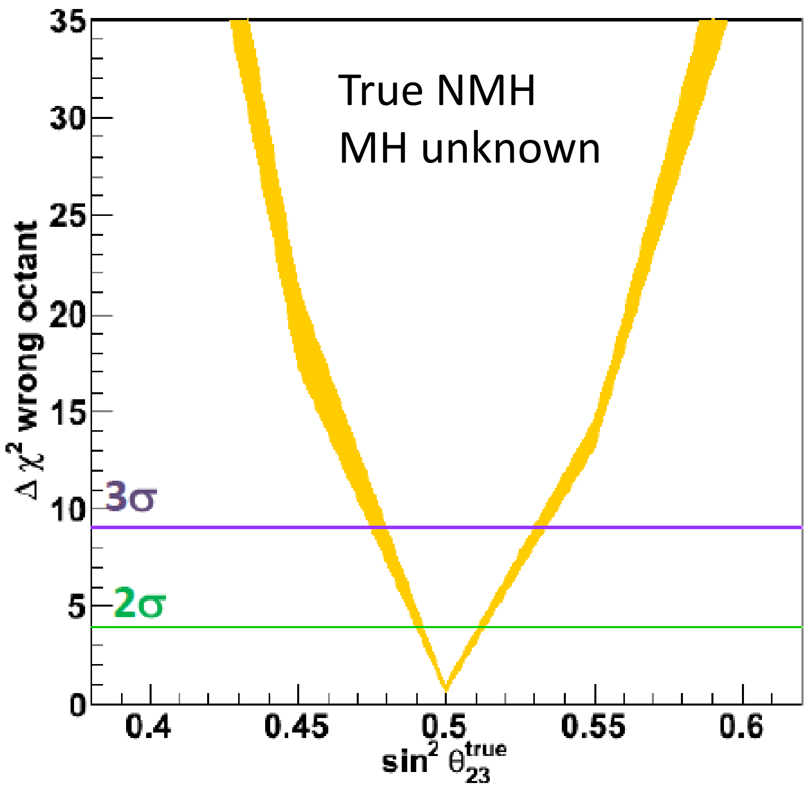
HK: 5 yrs

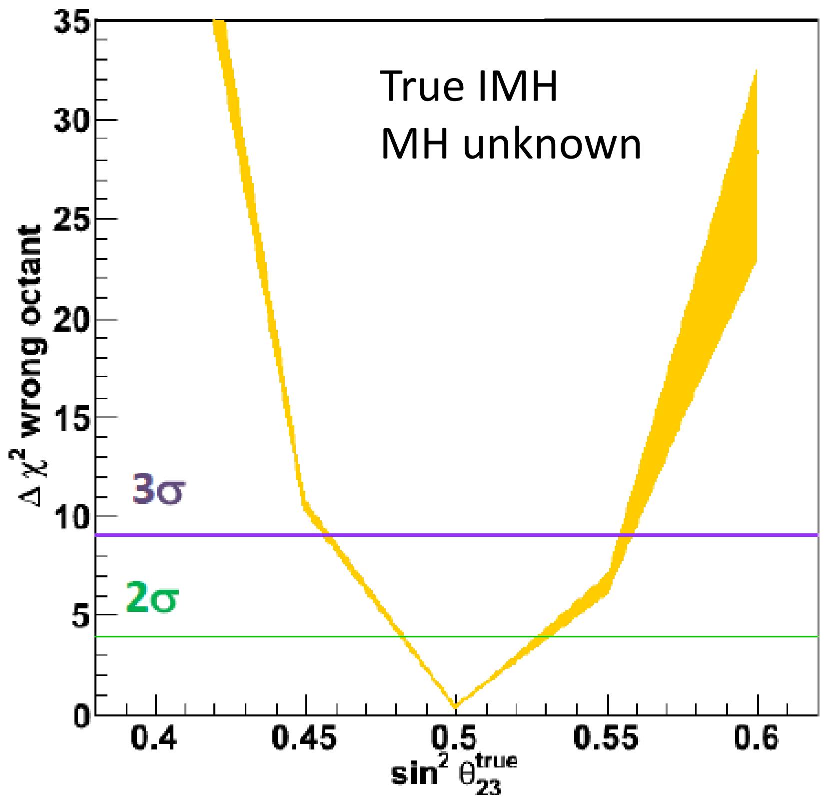
Mass Hierarchy

HK 1 yr = SK 20 yrs



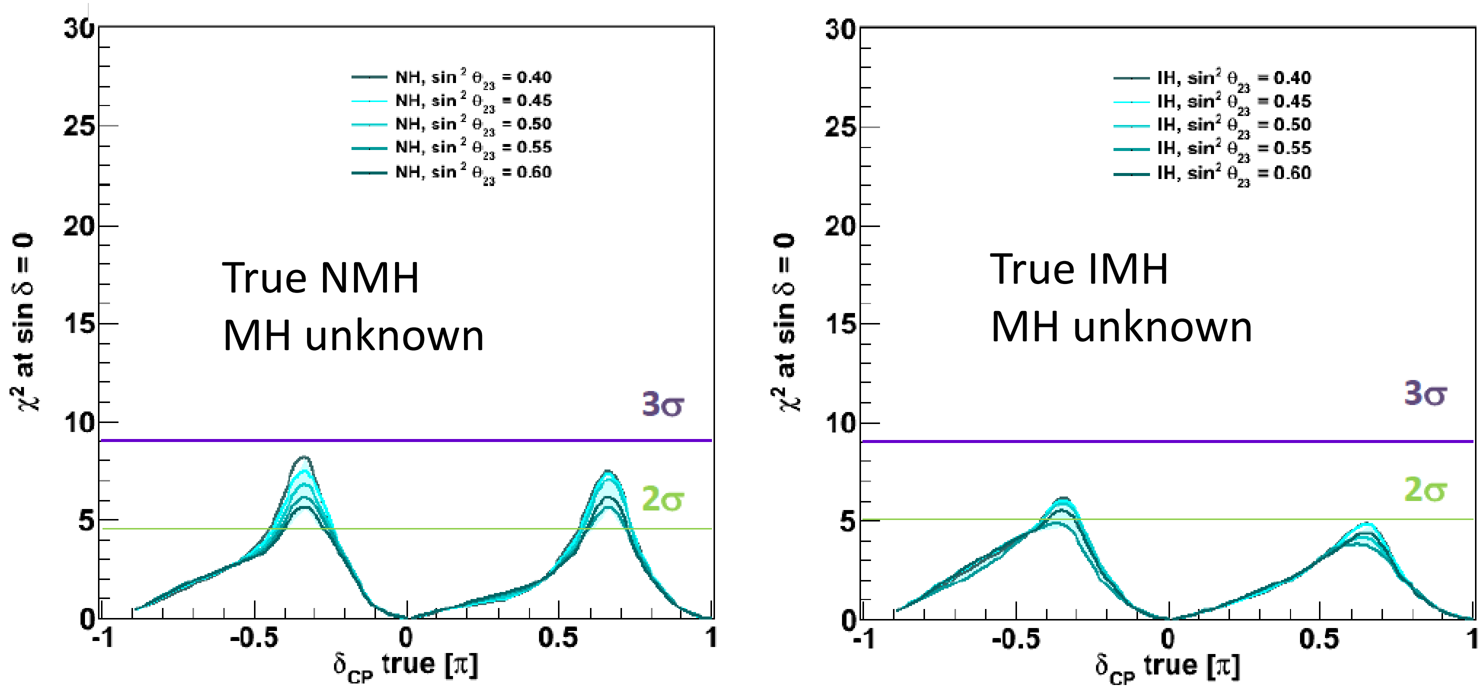
θ_{23} Octant





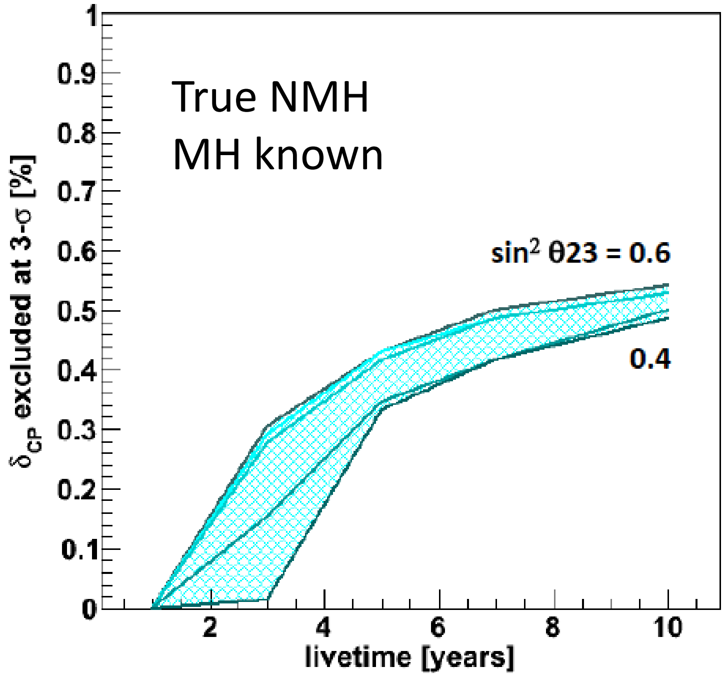
- **HK 10 yrs**
- **$\sin^2 2\theta_{13}$=0.1 (fixed)**
- **Thickness of band ➔ the uncertainty of CP phase**

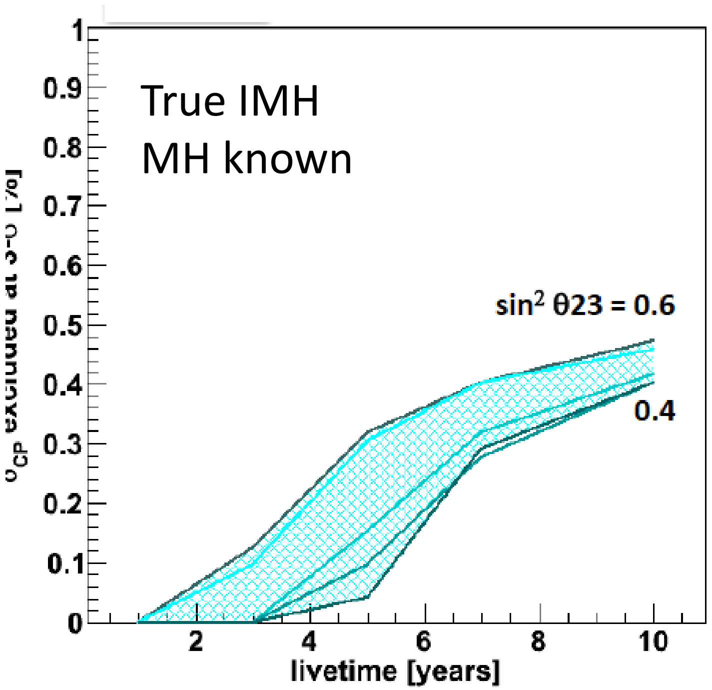
CP Vioration ?



- HK: 10 yrs
- $\Delta\chi^2$ to δ_{cp}=0 and π
- $\sin^2 2\theta_{13}$=0.1: fixed
- Assume MH unknown

CP phase





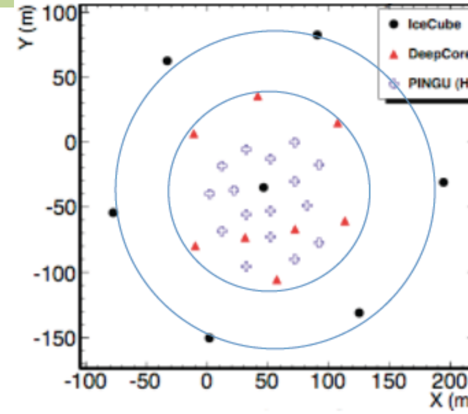
- Fraction of δ_{CP} excluded at 3σ for a fixed vlue of δ_{CP}
- MH is known

IceCUBE: PINGU

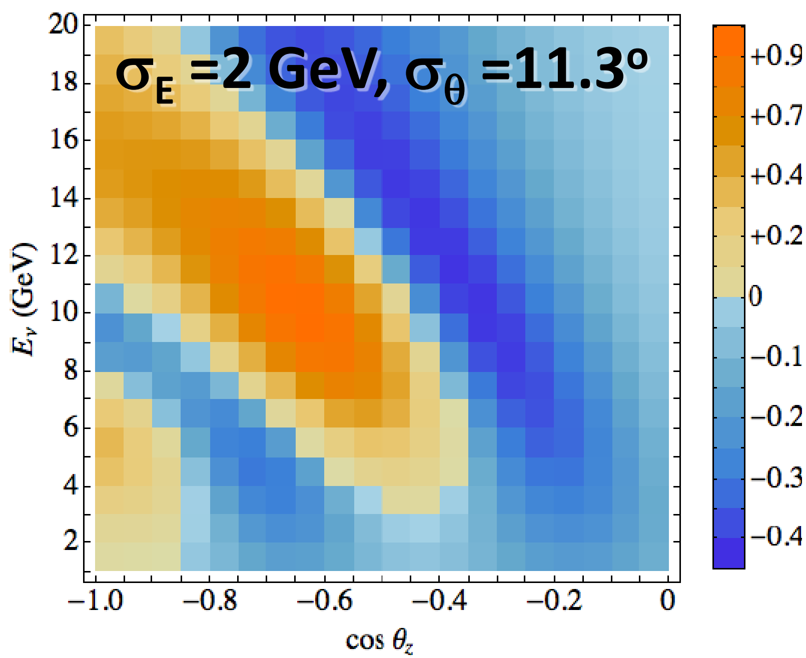
Quick MH ?

- PINGU ?
  - Add 20 strings with ~1000 optical modules inside the IceCUBE Deep Core region
  - Expected energy threshold of 1 GeV
  - Multi-Megaton effective mass
  - Shorter path to the MH
    - E. Akhmedov, S. Razzaque, A. Smirnov: arXiv: 1205.7071v2

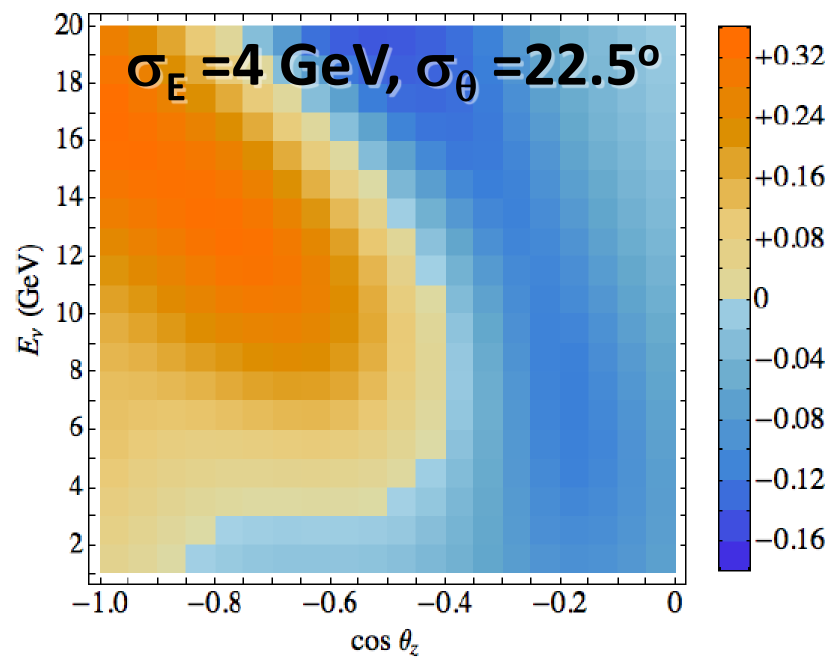
PINGU geometry
(more compact version also studied)



S^{tot} = 7.2σ for 10% systematics



S^{tot} = 3.0σ for 10% systematics



Is future bright?

- Yes ….Mass Hierarchy, CPV ➔ Origin of Matter..
- but may be difficult…..(by other reason than science)

Is future bright?

- Yes ….Mass Hierarchy, CPV ➔ Origin of Matter..
- but may be difficult…..(by other reason than science)

Debt and politics in America and Europe

Turning Japanese

The absence of leadership in the West is frightening—and also rather familiar

Jul 30th 2011 | from the print edition

The Economist

http://www.economist.com/node/21524874

How we justify FUTURE under such serious environments

- For our funding agencies and general public
  - One number δ_{cp} may not justify spending a few hundred million Euros/dollars and a few 10s billion yen for the large detectors
- Need Neutrino Oscillation + alpha……
  - Multi-purpose is really important and essential
    - Must have a big chance of a discovery
    - Measurements (bread and butter)

  ➔ Proton decay and Astrophysics….

More ingredients

- Proton decay and astrophysics can justify even larger detectors.
- Multi-Megaton
  - PINGU (but need much lower threshols and much higher resolution): alrady discussed.→ MICA (IceCUBE) ?

➔Multi-Megaton a la SK/HK (TITAND)

Discovery potential

- Proton Decay: 10^{36} years
- Supernova Neutrinos: Burst detection every year (5 events for 5 Mton @5Mpc (1SN/yr))

Measurements

- Armospheric neutrinos (CP, …)
- Solar neutrinos

- More money to the detector !

Multi-Megaton
TITAND

Detector

Requirements for the detector

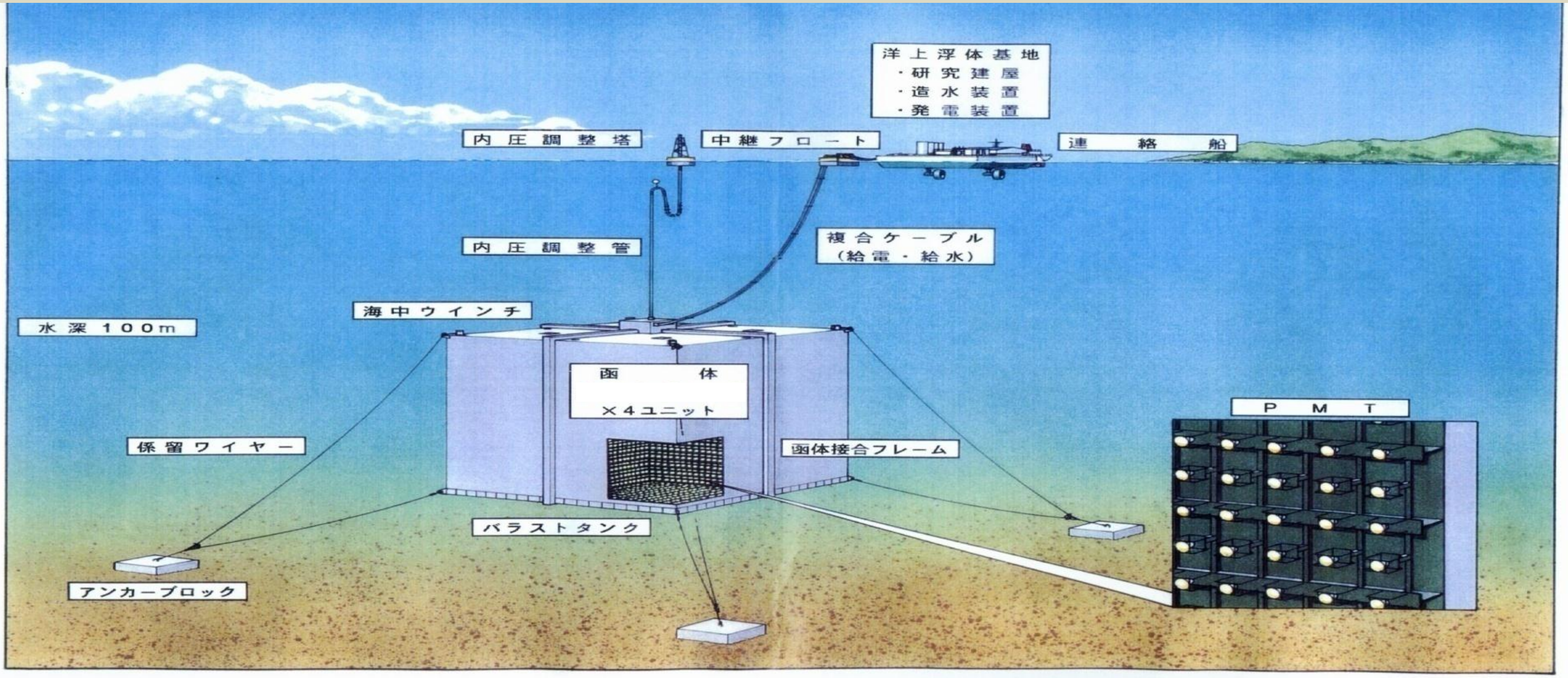
1) Scalability: may start with 1 Mt

   but can be expandable to 8 Mt and beyond

2) Inexpensive

3) Short construction time

TITAND



浮沈式陽子崩壊実験装置イメージ図

TITAND-I

85m x 85m x 105m x 4 units = 3.03 Mt

(2.22 Mt fiducial : ~ SK x 100)

TITAND-II

4 module ➔ 8.8 Mt f.v. (SK x 400)

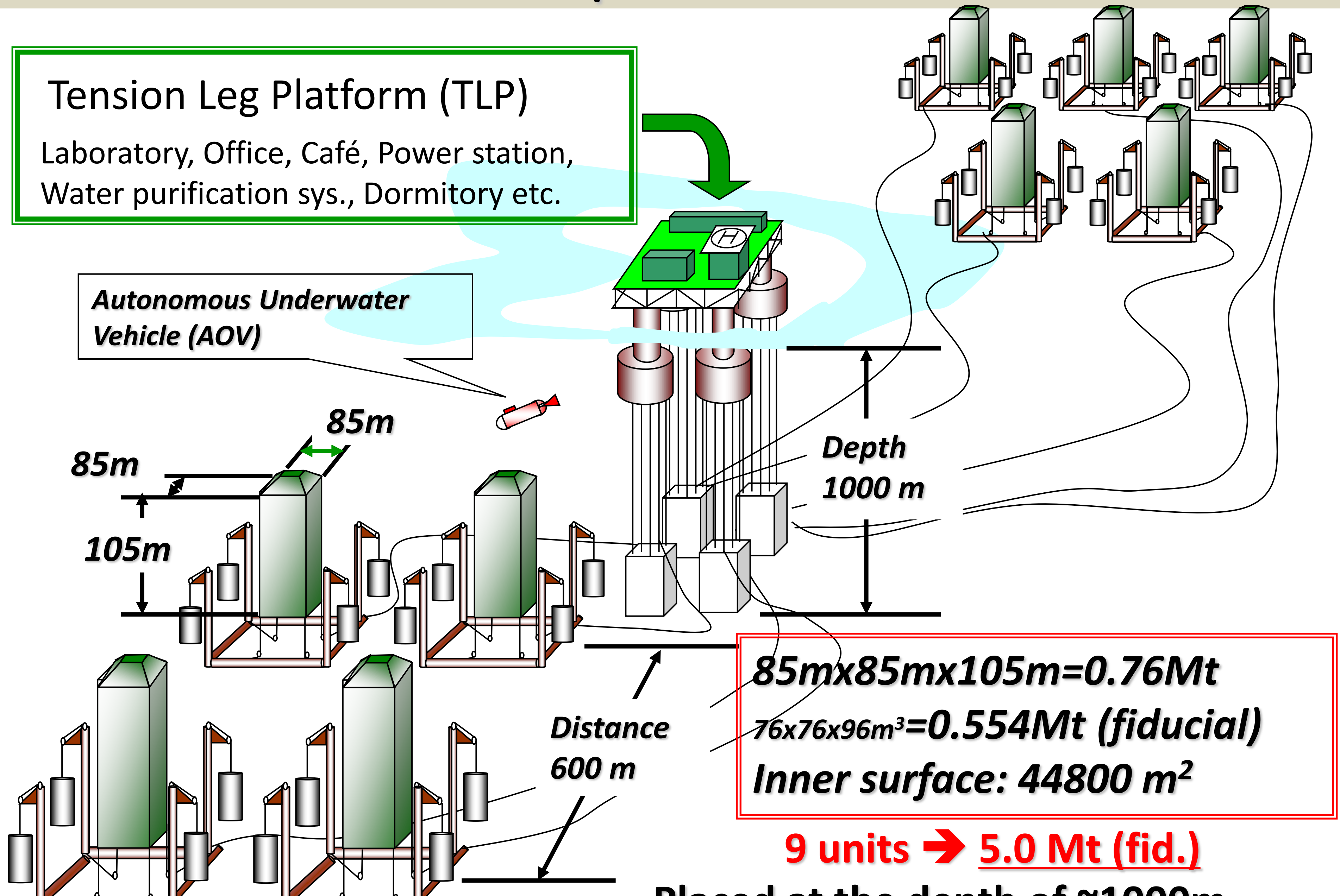
Ref:1) Y. Suzuki, hep-ex/0110005 (in 2001)
2) Y. Suzuki, in Proc. of Neutrino Oscillation in Venice, Feb, 2006

But this is shallow @100 m depth

Deep-TITAND

Tension Leg Platform (TLP)

Laboratory, Office, Café, Power station, Water purification sys., Dormitory etc.



85mx85mx105m=0.76Mt

$76x76x96m^3$=0.554Mt (fiducial)

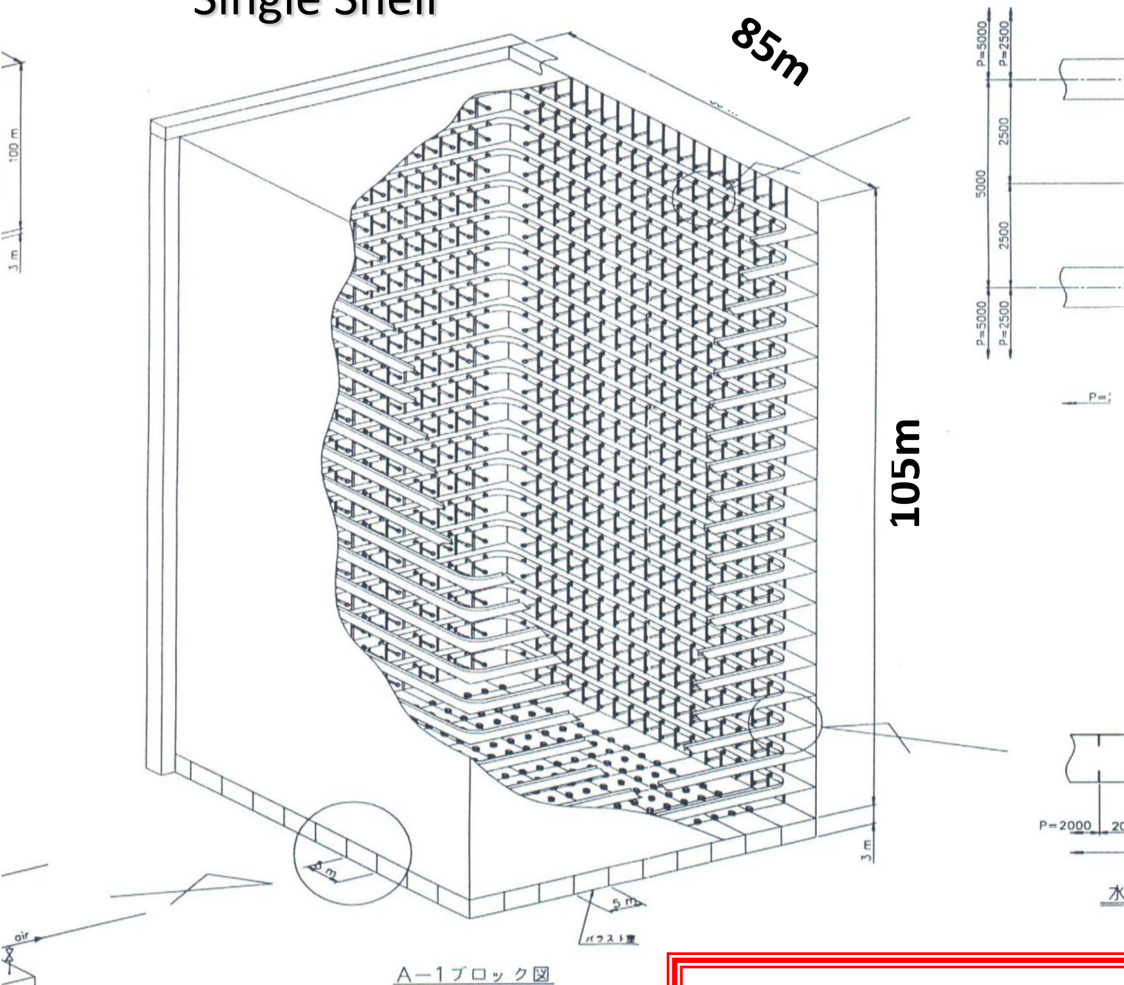
Inner surface: 44800 m^2

9 units → 5.0 Mt (fid.)

Placed at the depth of ~1000m

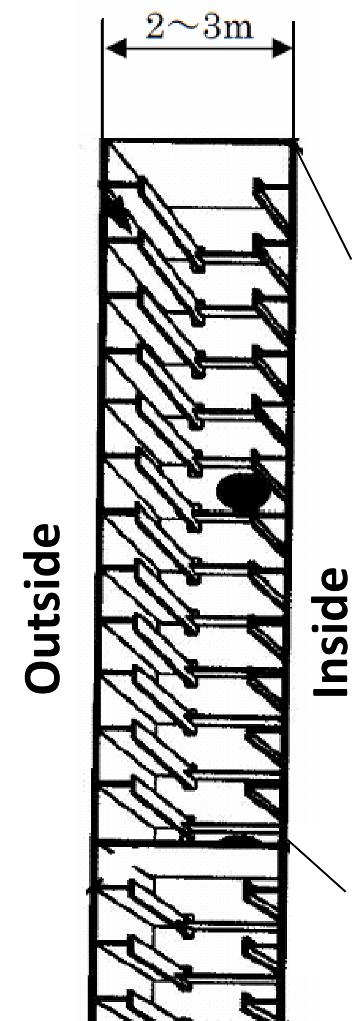
Structure

Single Shell



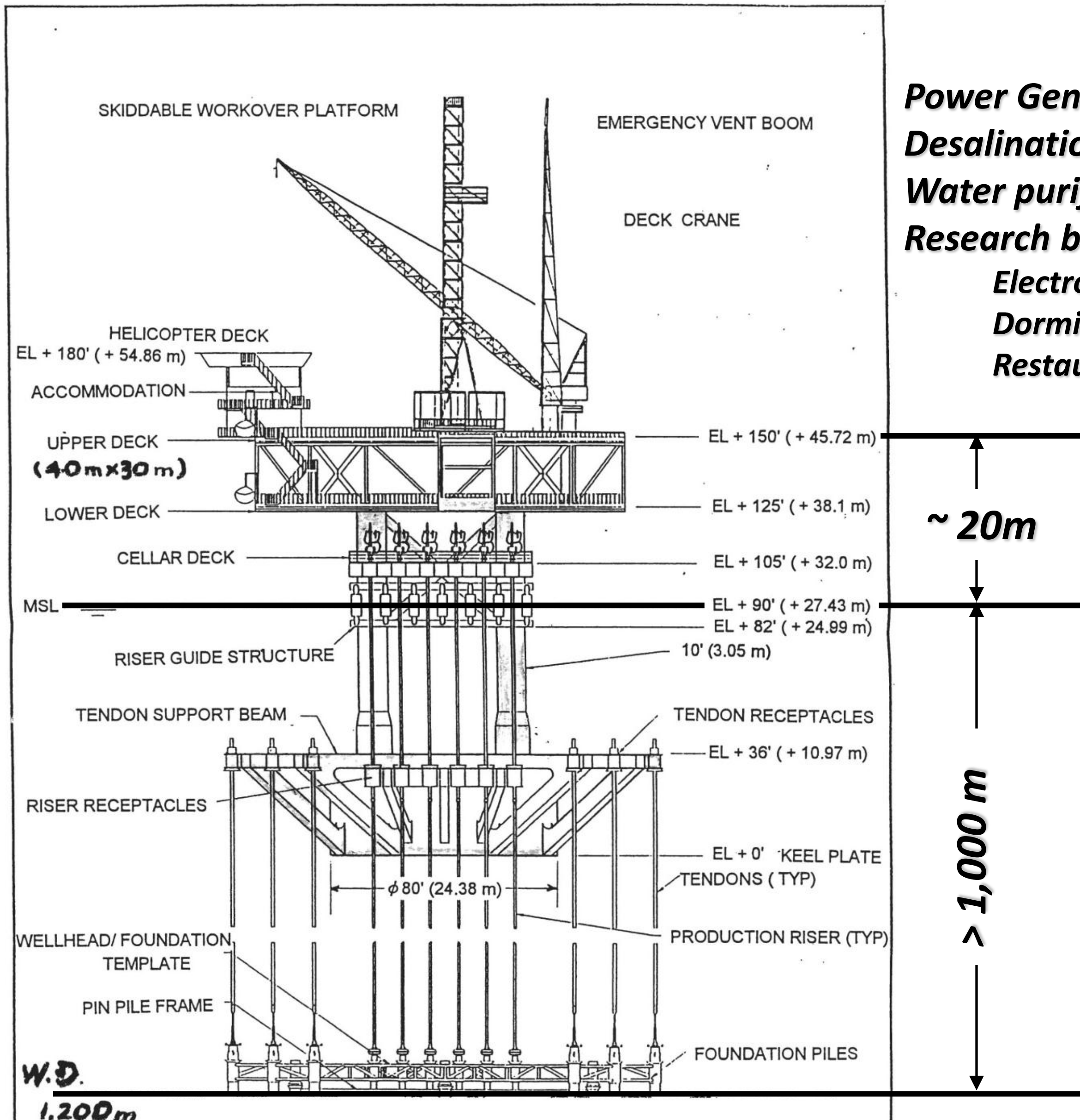
OR

Double Shell
Structure



Semi-pressure vessel
upto >0.3 atm (in/out)

Tension Leg Platform doe utilities



Power Generator
Desalination system
Water purification system
Research buildings
- ***Electronics & computer***
- ***Dormitory***
- ***Restaurant & Cafe***

Upper Deck

~ 20m

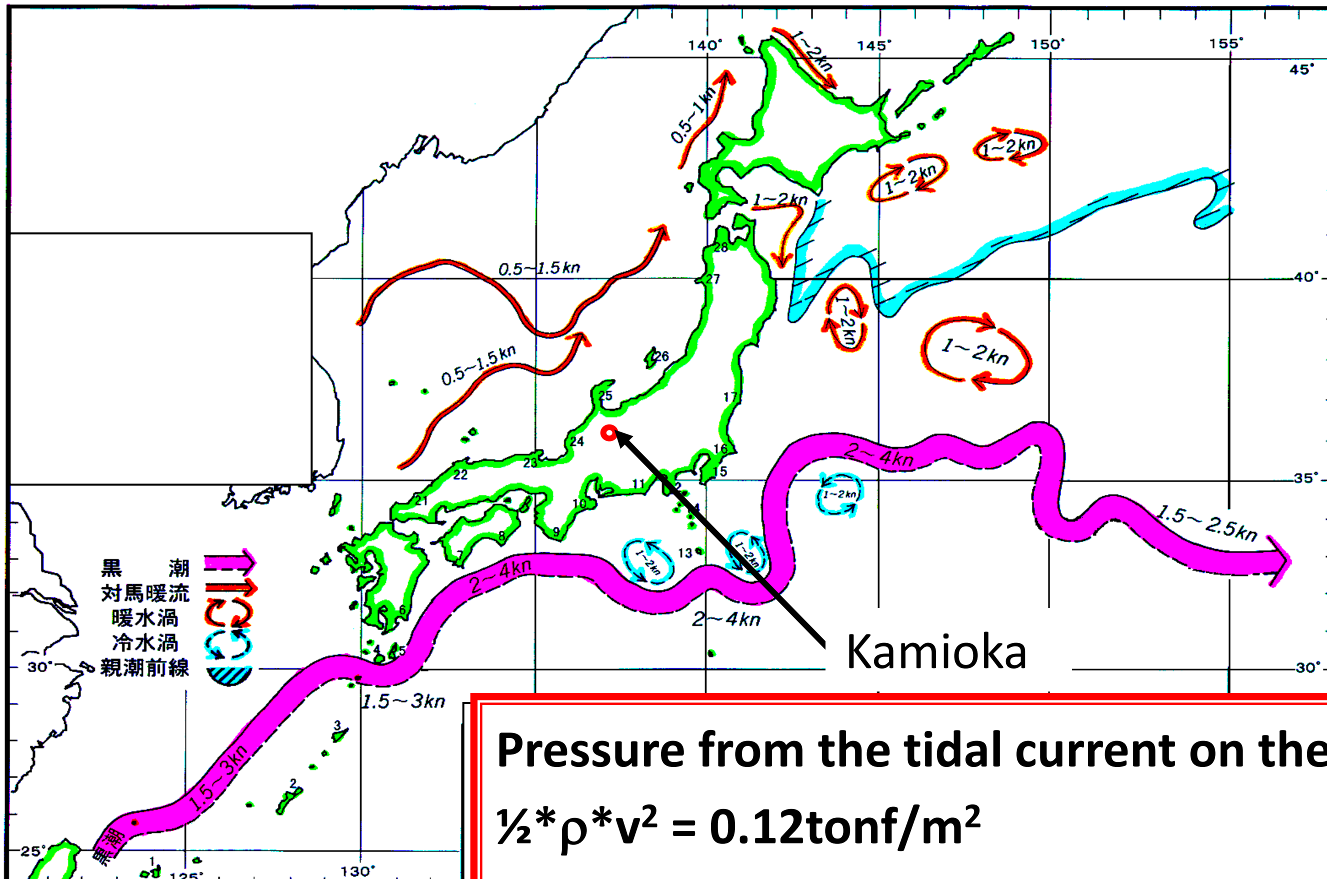
Sea level

> 1,000 m

Bottom of The sea

Where we can place the detector?

Tidal current < 3 knot
~ 5.6km/hour (1.5m/s)



Pressure from the tidal current on the wall:

$\frac{1}{2} * \rho * v^2$ = 0.12tonf/m^2

0.12x85x105 = *1071 ton per one wall*

Construction periods

		1st yr	2nd yr	3rd yr
	Design			
	Preparation			
	Construction			
	Installation			

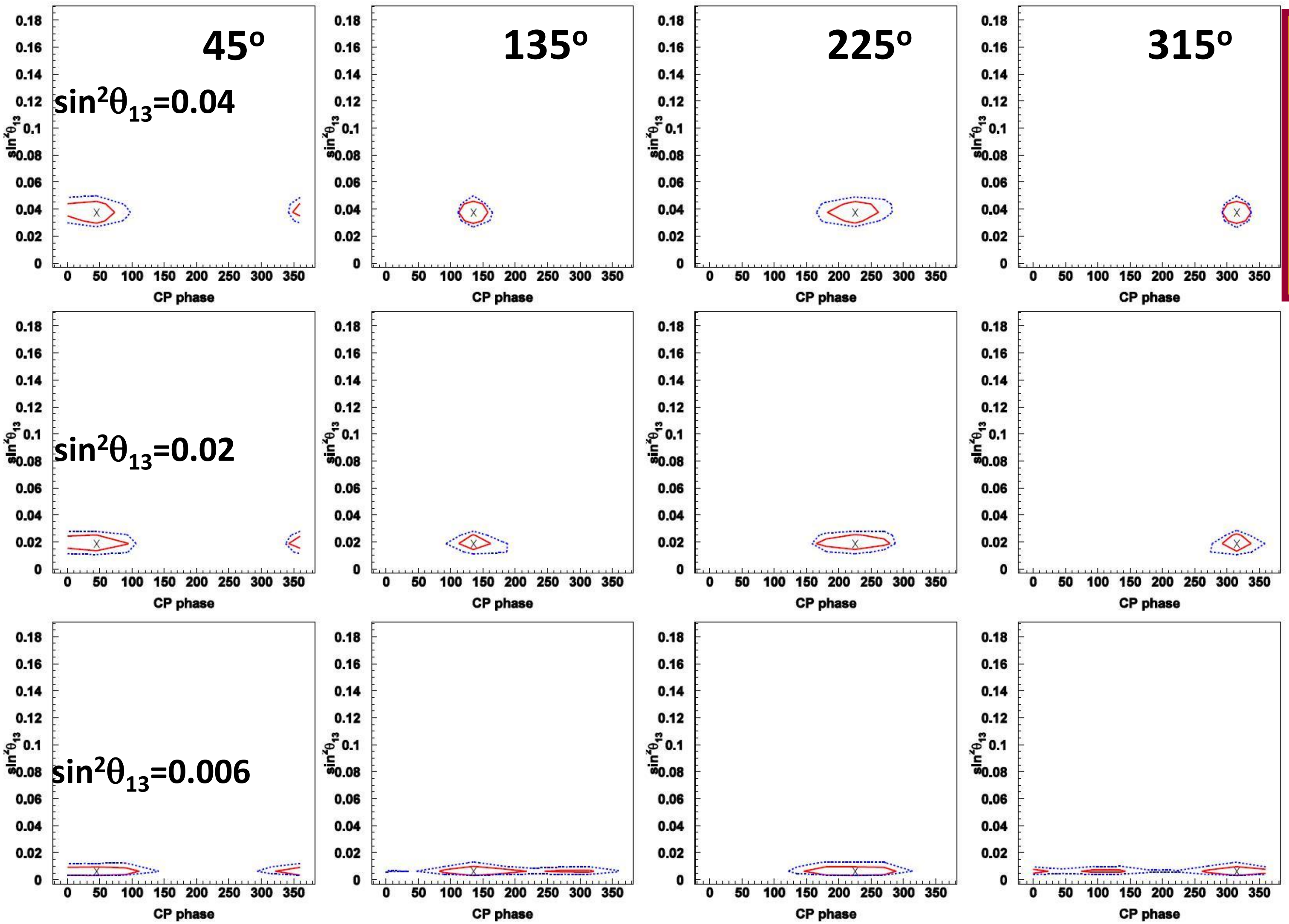
Total 3 years construction time:

very short

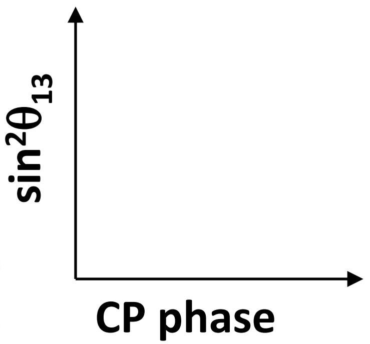
But the manufacturing time for the light sensors is not included.

Sensitivity

CP phase (800yrs SK = 4 yrs of **5Mton detector**)



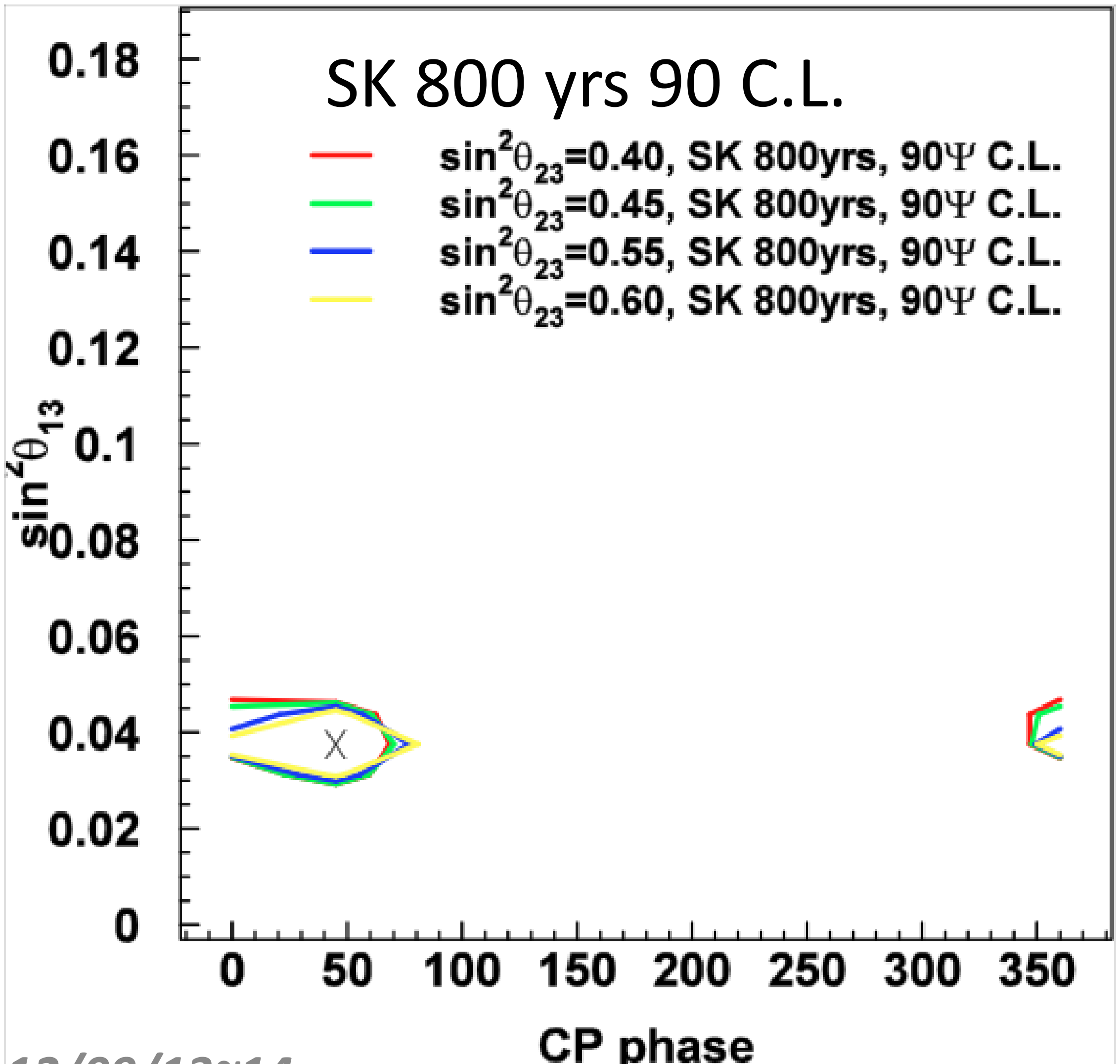
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.006\sim0.04$
$\delta cp=0^o\sim360^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$



No degeneracy

For 5 Mton detector, CP phase could be determined, since we now know that θ_{13} is large: $\sin^2\theta_{13}$ ~ 0.025

No strong θ_{23} dependence for CP phase search



We can also assume that the mass hierarchy will be determined by some other experiments before the time of the multi-megaton detector.

Other science for 5 Mt detector

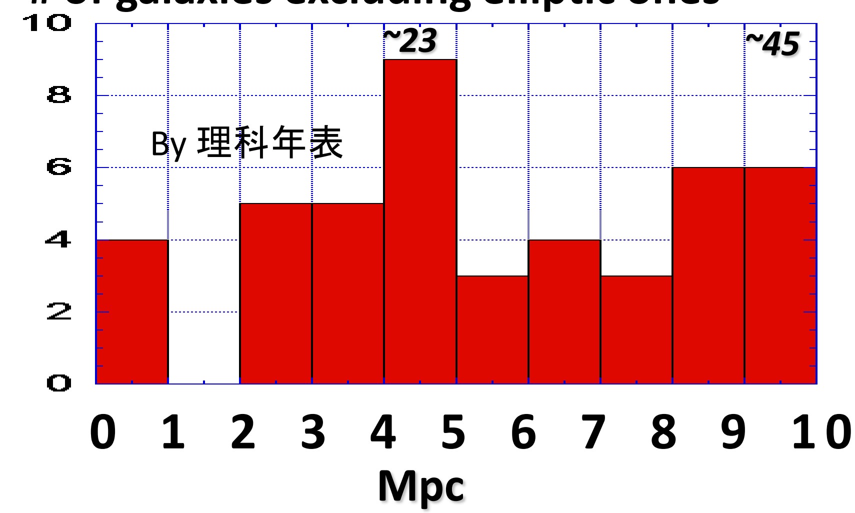
Supernova Rate

- **Galactic SN rate**
  - **Every 30 ~50 years in our Galaxy**
    - ← SN rate external Gal., Galactic ^{26}Al abundance, Historical Gal. SN, ……..,
- **Number of Galaxies**
  - ***23 within 5 Mpc***
  - ***45 within 10 Mpc***

➔ 1 SN every 1~2 years (5~10Mpc)

- **There are Galaxies beyond 2 Mpc where SNe have frequently happened**

➔ 1 SN every year (within 5 Mpc) is not bad estimate



- **NGC6946 (5.9 Mpc)** ***10 in 90yr***

1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et

- **M83 (4.3Mpc)** ***6 in 60yr***

1923A, 1945B, 1950B, 1957D, 1968L, 1983N

- **NGC2403 (3.3Mpc)** ***3 in 50yr***

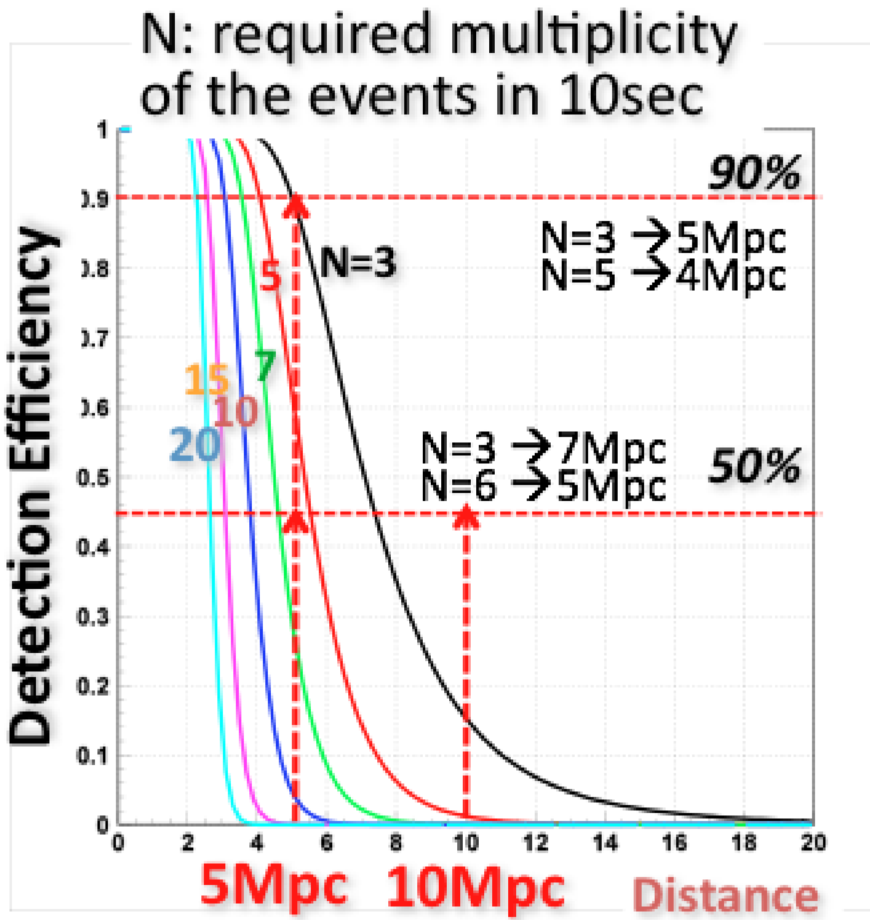
1954J, 2002kg, 2004dj

Is it possible to detect SN neutrinos from the distance of 5Mpc

- Yes!
- SN1987A(50kpc): Extrapolation to 5Mpc & 5Mt
  - ➔ Kamiokande: 2.7 events
  - ➔ IMB: 6.0 events
- Typical Simulation 5.2 events

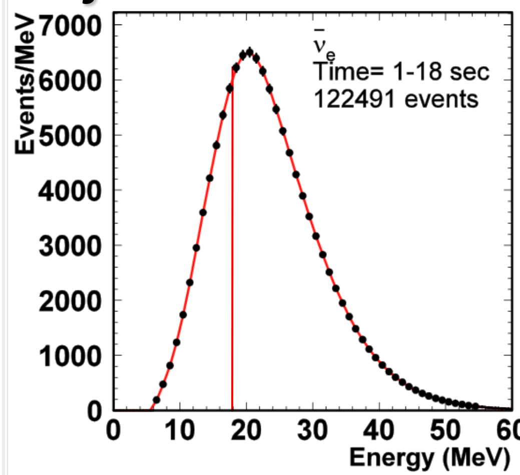
Expect ~5 events for 5Mt and 5Mpc distance

Trigger sensitivity to distant SNe



Background:

Most BG from single spallation ev.
➔ accidental coincidence
Select Eth > 18 MeV to remove spallation events
BG free measurement



signal loss:
~20% at most

No significance influence

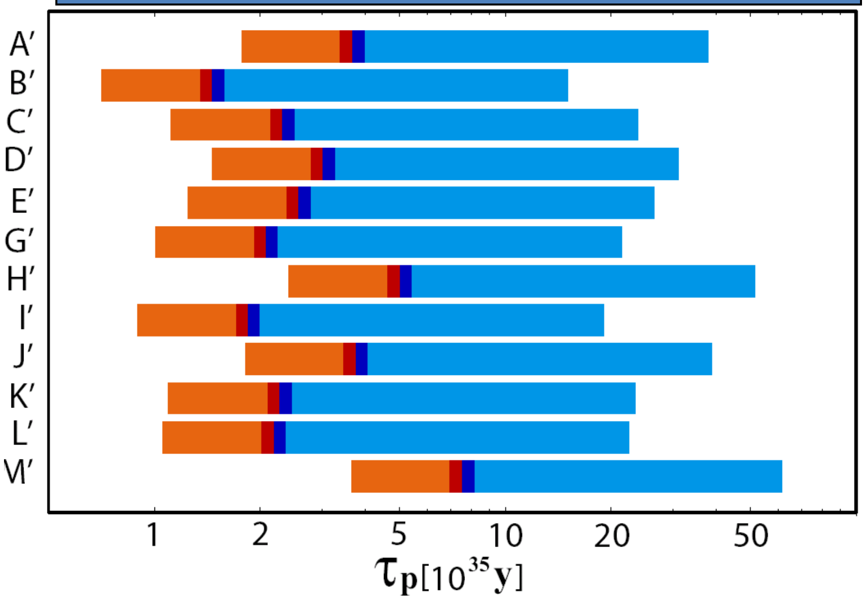
Could detect SN almost every year

Galactic SN (10kpc)	***1.3M events***
Neutronization B	***2500 events***

Proton Decay

J. Ellis, NNN05, April 7th, 2005

Lifetime in benchmark scenarios (Flipped SU(5)xU(1))



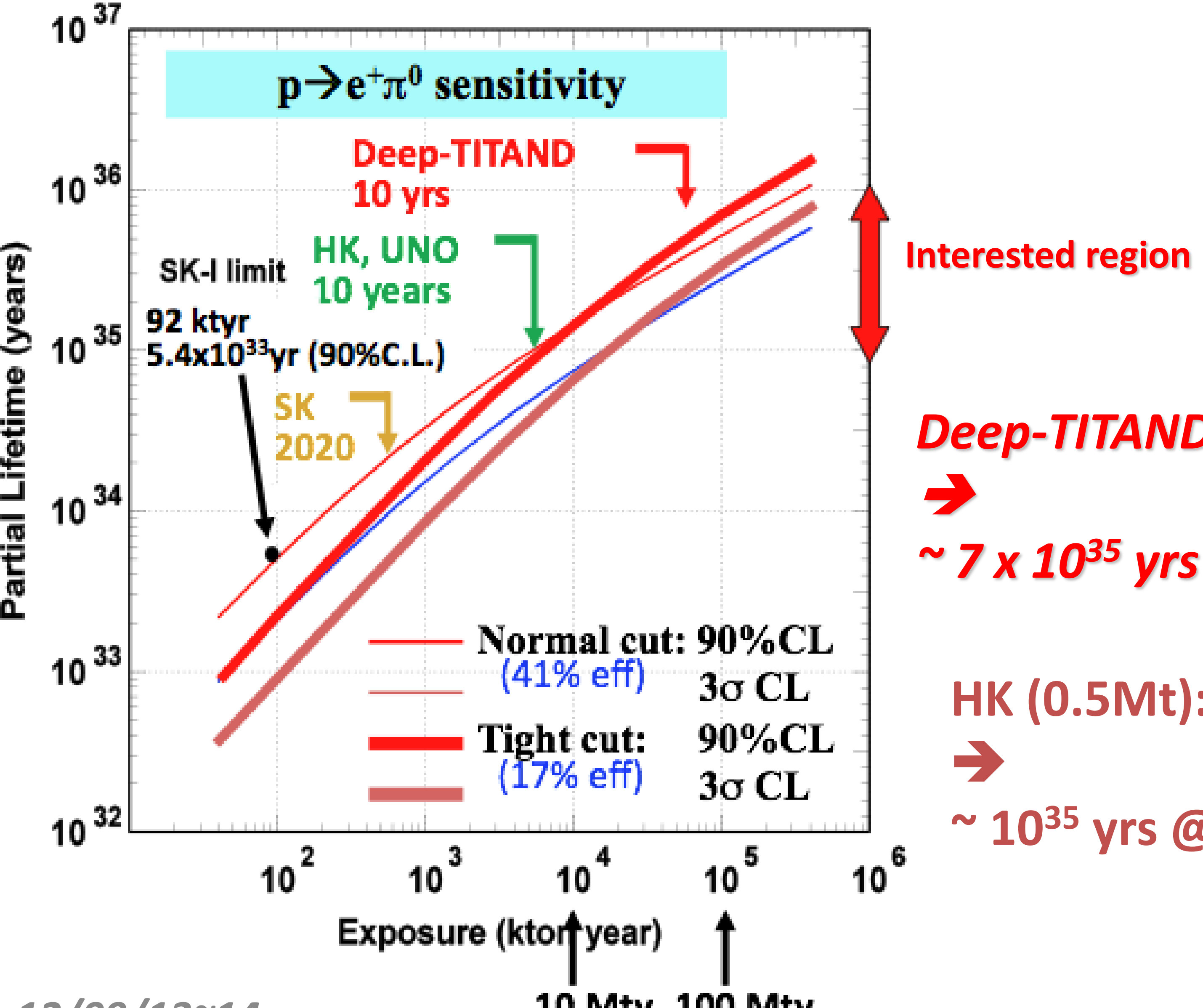
Prediction ?

- ***νK, μK*** : strong model dependence
- Prediction from Dimension 6 in SUSY GUT
  - Less model dependent
  - Reasonable range: ***10^{35} ~10^{36} yr for $e\pi^0$***

    ← From coupling unification

  → Search up to ~10^{36} yr is quite important and add significant value to the multi-megaton detector
- ***Sensitivity for $e\pi^0$ will guide the size of the experiment***

Sensitivity for $p \rightarrow e^{+}\pi^{0}$



Deep-TITAND(5 Mt):10 yrs

➔

~ 7 x 10^{35} yrs @90% C.L.

HK (0.5Mt): 10yrs

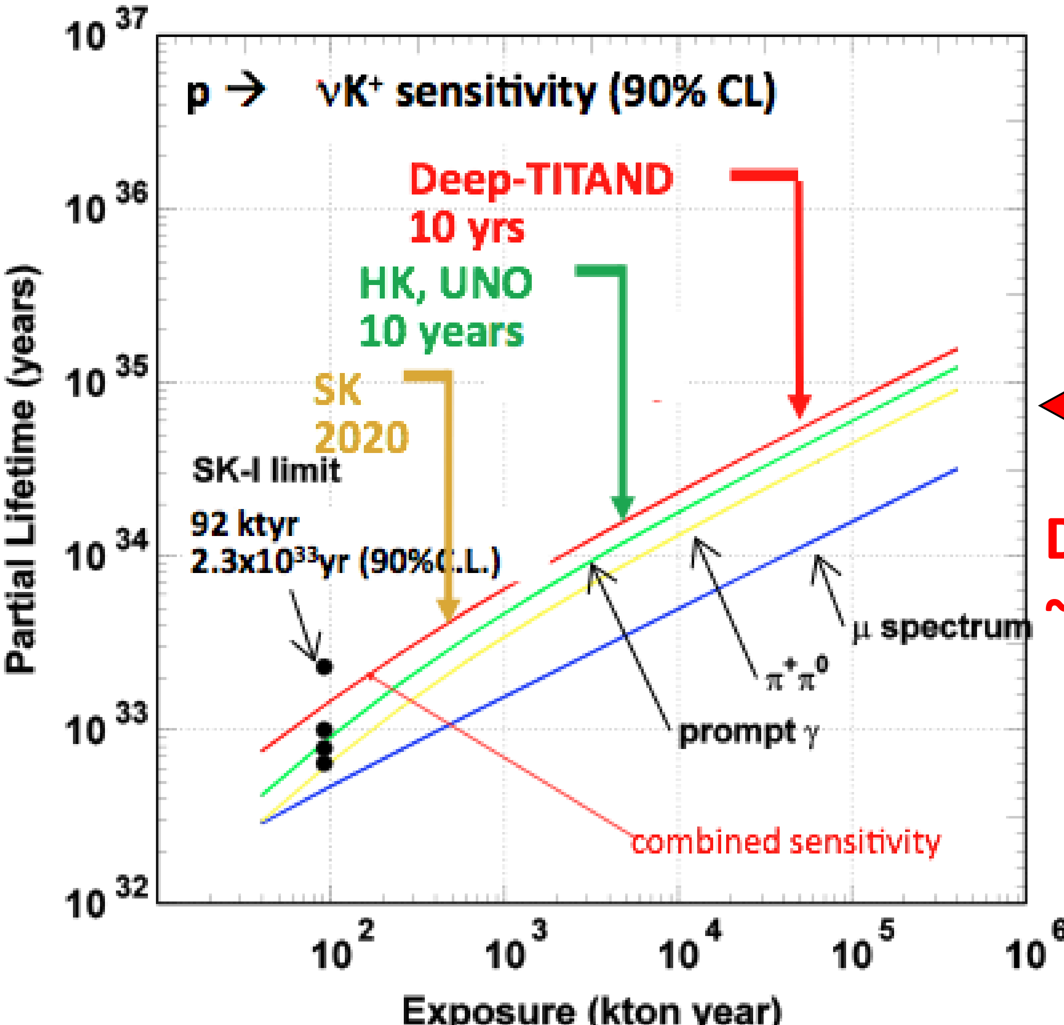
➔

~ 10^{35} yrs @90% C.L.

Sensitivity for p→νK⁺

- Assume; 40% coverage:

  Need more study for the 20% coverage

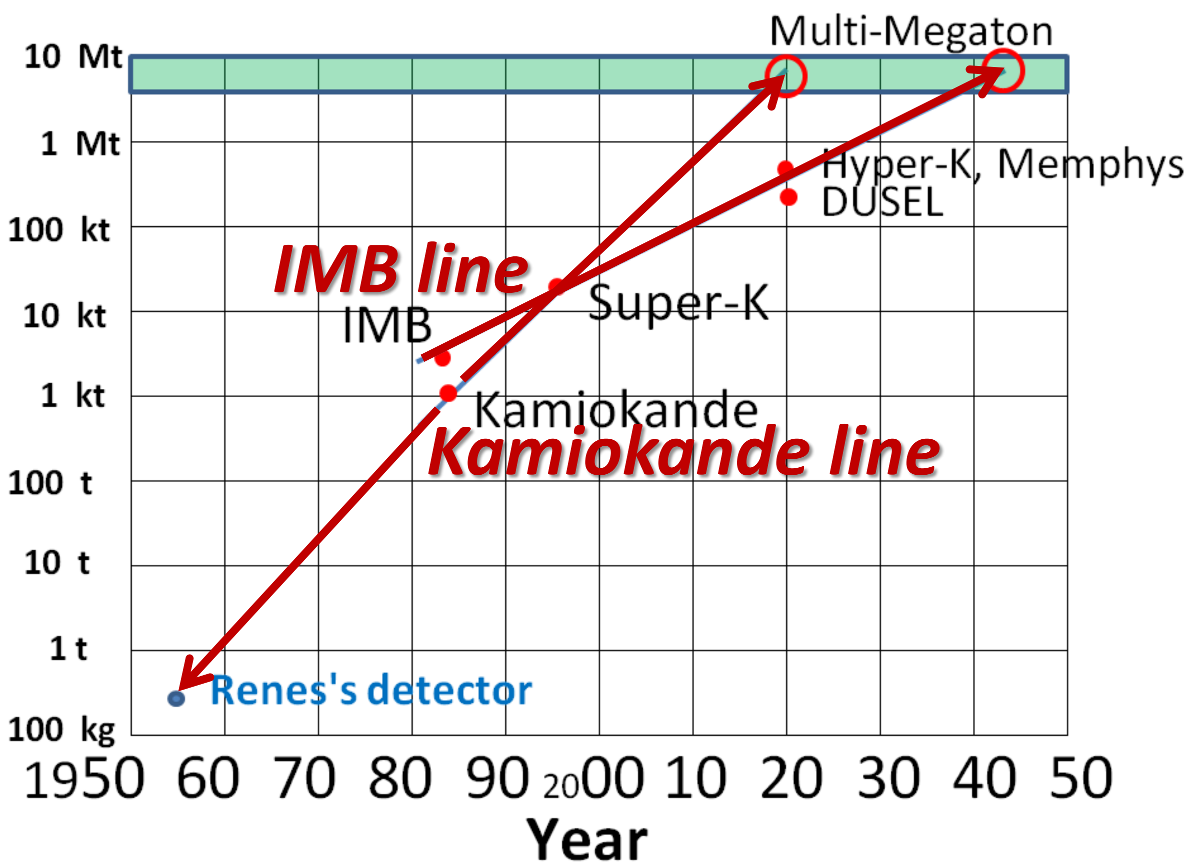


Interested point

Deep-TITAND (5 Mt): 10 yrs
~ 8 x 10^{34} yrs @90% C.L.

HK (0.5Mt): 10yrs
~ 2 x 10^{34} yrs @90% C.L.

A multi-megaton detector

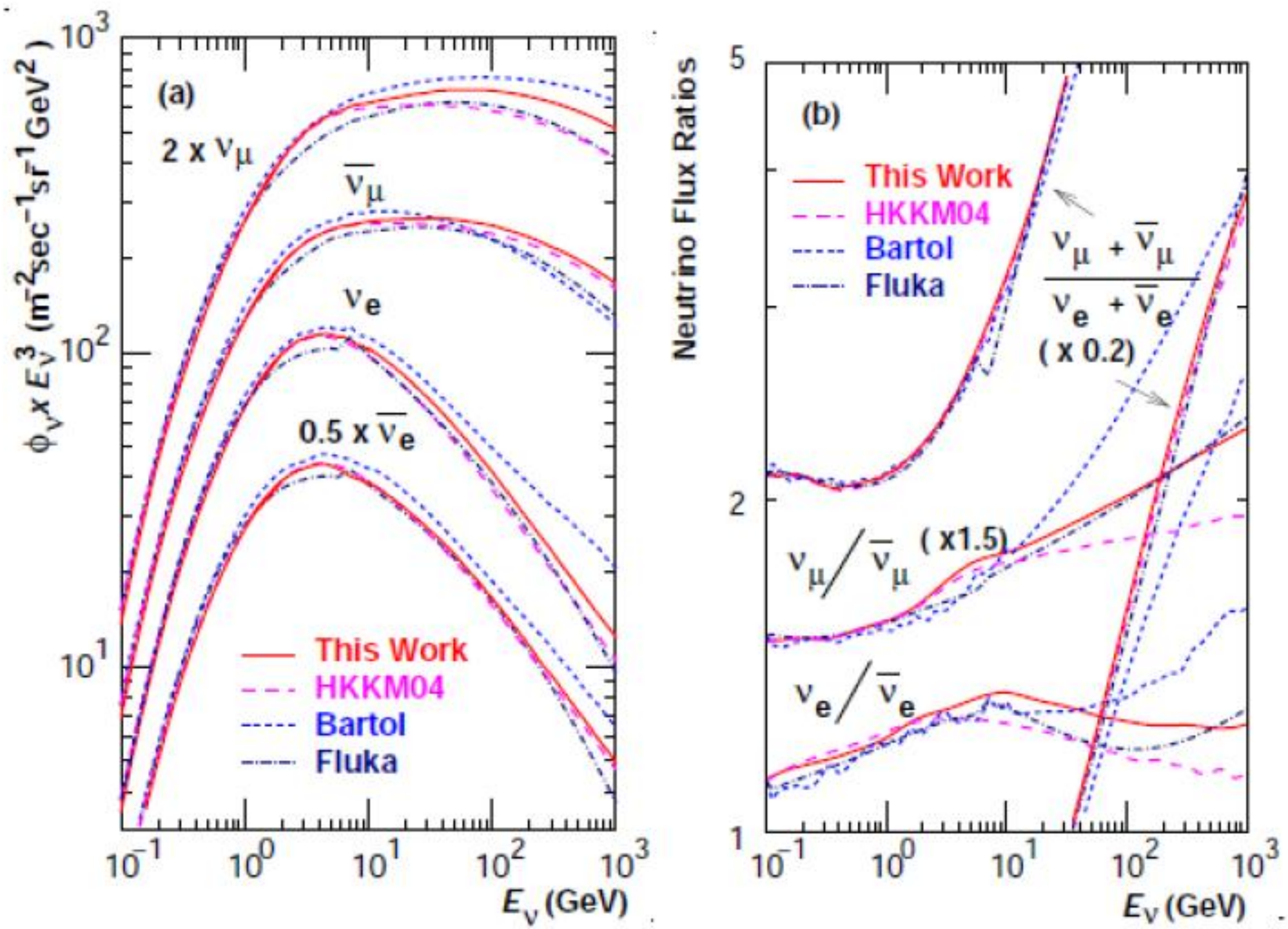


If we scale the development of the size of the past Water Cherenkov detectors, we may realize a multi-megaton detector around 2040.

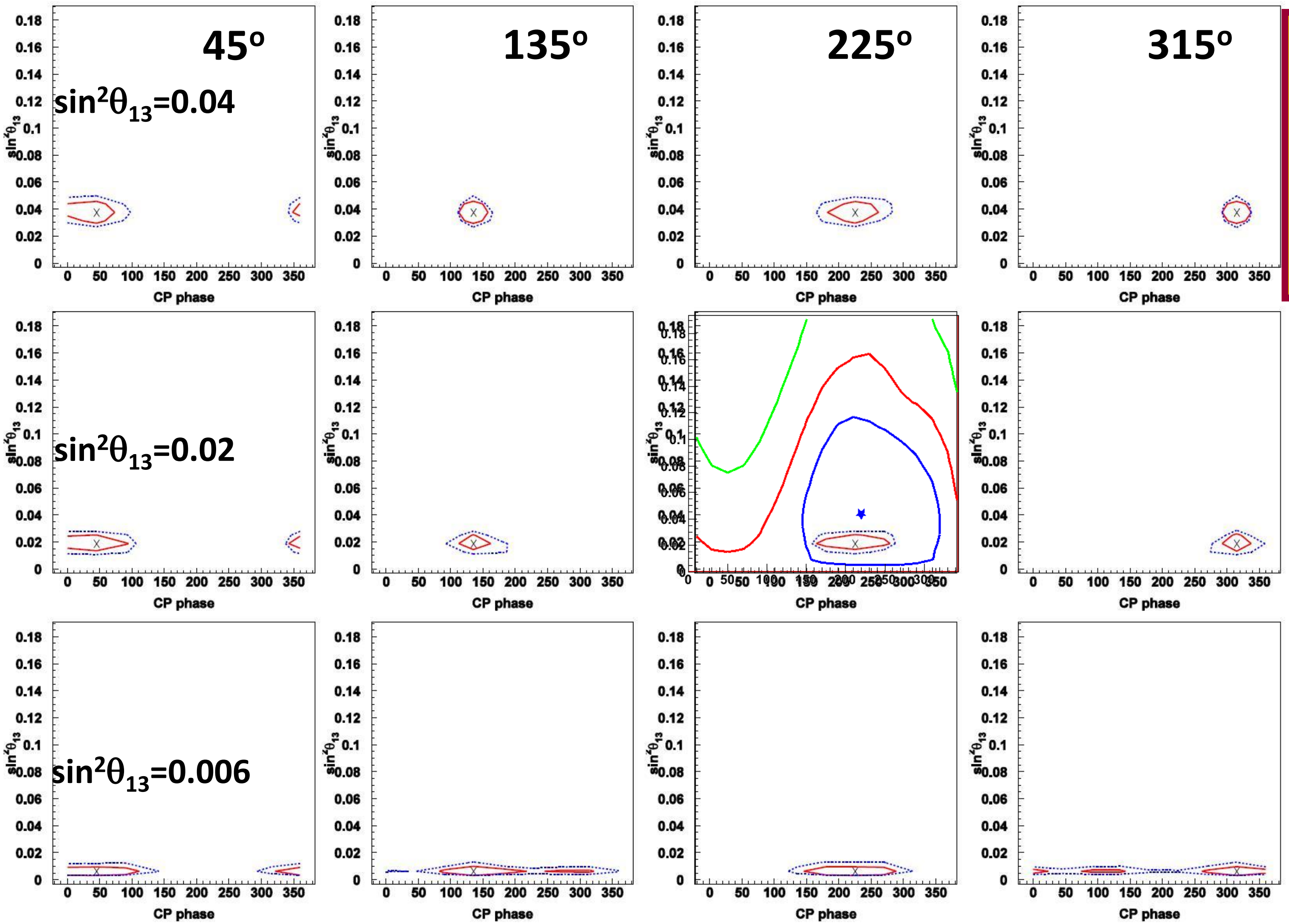
END

Atmospheric ν flux

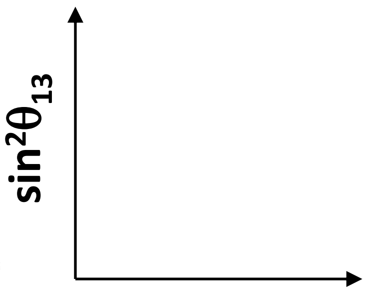
PHYSICAL REVIEW D **75, 043006 (2007)**



CP phase (800yrs SK = 4 yrs of **5Mton detector**)



$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.006\sim0.04$
$\delta cp=0^o\sim360^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$



No degeneracy

For 5 Mton detector, CP phase could be determined, since we now know that θ_{13} is large: $\sin^2\theta_{13} \sim 0.025$

How do we realize the next-next generation detectors

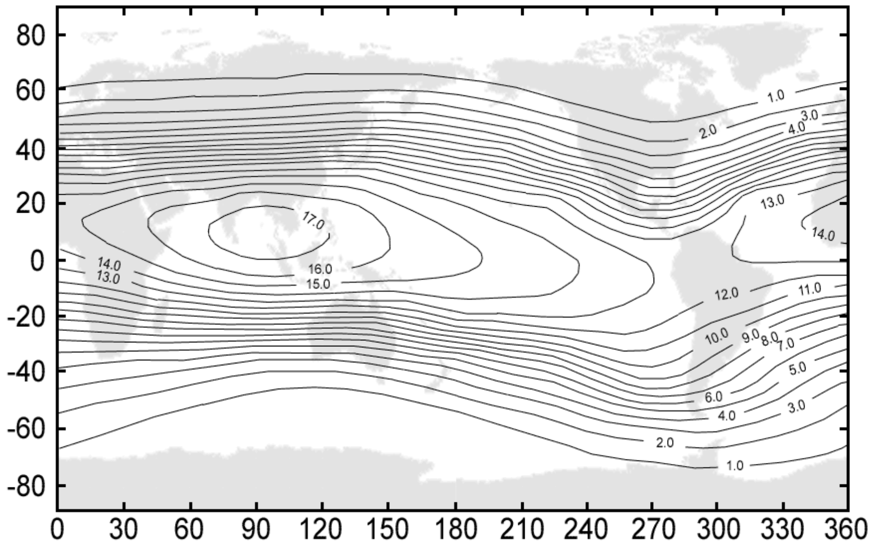
'Maybe' expensive

- Need Good bread-and-butter science
  - Atmospheric Neutrinos
  - Serve as a movable far detector for LBLE at any distance, and can be added magnetic detector for neutrino factory
  - **Supernova burst !**
- Must have a Big Chance for a Discovery
  - **Proton decay !**

Atmospheric Neutrino Flux Calculation

Need knowledge of

- Primary Cosmic Ray Flux (p, He,…)
  - Modulation by Solar Activity
  - Geomagnetic cut-off
    - Affect on low energy CR
    - A function of the location on the earth and arriving direction

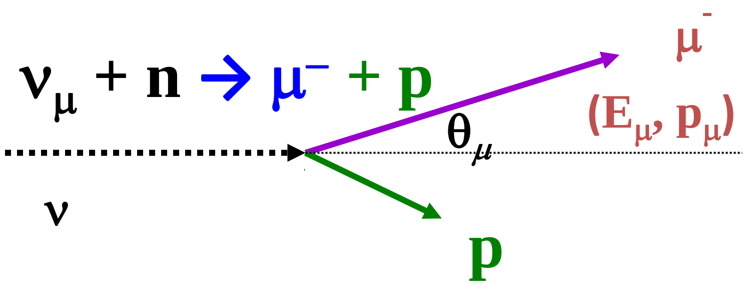


- Shielding effect of the magnetic field of the earth
- Lowest energy of primary cosmic ray particles which enter the atmosphere.

➔ Atmospheric neutrinos ➔ 'Position' and time dependent

Neutrino Interaction @~1 GeV and E_ν reconstruction

$\nu_\mu + n \rightarrow \mu^- + p$



- ✧ Charged Current Quasi-Elastic
  - ✧ ~100% efficiency for SK
  - ✧ $E_\nu \leftarrow (\theta_\mu, p_\mu)$

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

$\nu_\mu + N \rightarrow \mu + N' + \pi\text{'s} + X$

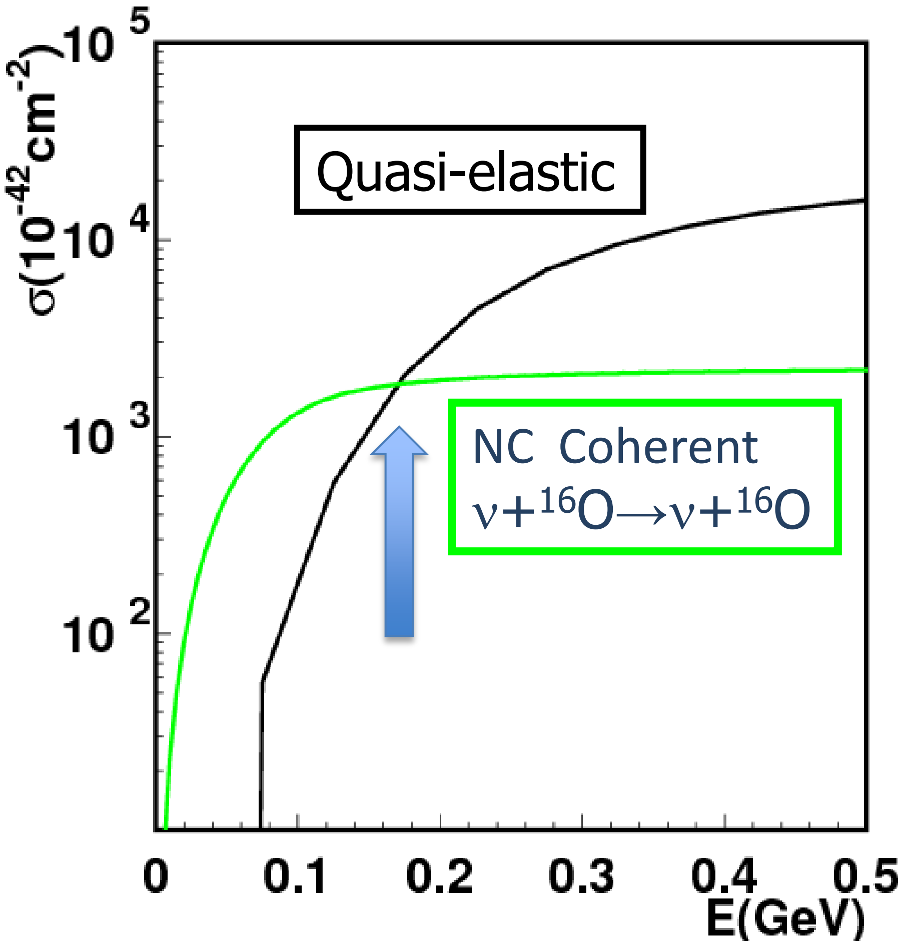
Single π,
Multi-π, Deep Inelastic

$\nu_\mu + N \rightarrow \nu + N + \pi\text{'s}$

Coherent π^0
Neutral Current sigle π

- ✧ CC non-QE
  - ✧ ~100% efficiency for SK
  - ✧ Bkg. for E_ν measurement
- ✧ NC
  - ✧ ~40% efficiency for SK

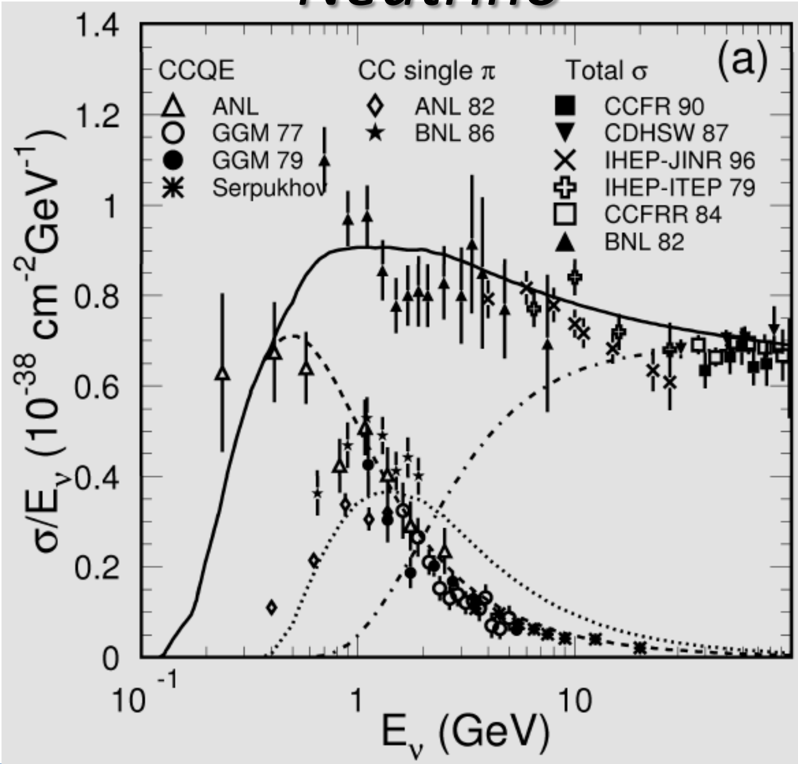
Coherent Scattering



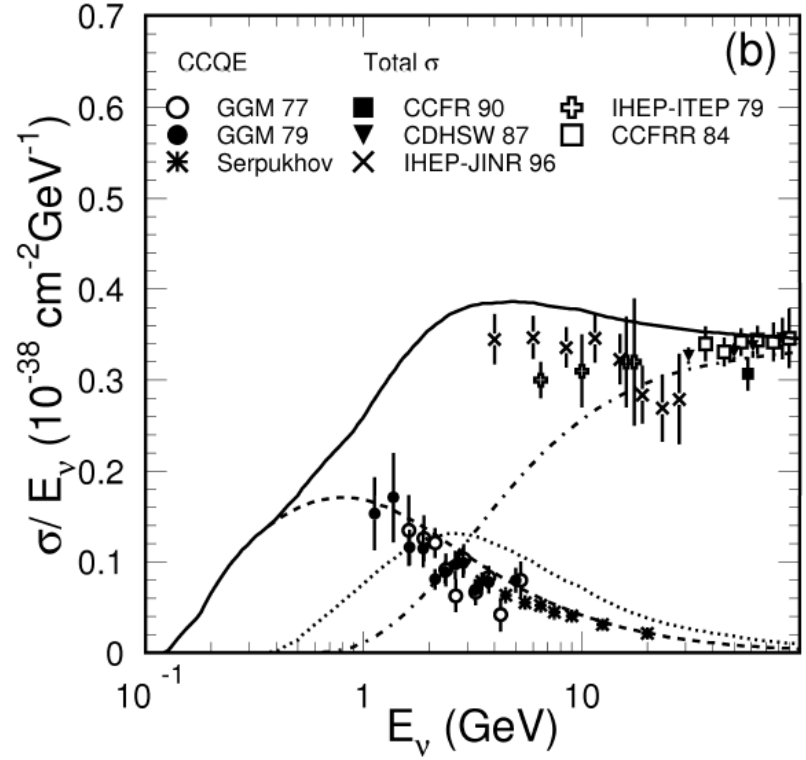
- At 0.2 GeV coherent scattering saturates and QE interactions start to dominate

Anti-neutrinos

Neutrino



Anti-neutrino



Parameters used in our simulation program:

- $M_A(QE) = 1.11 GeV/c^2$
- $M_A(1\pi) = 1.21 GeV/c^2$
- **Coherent π : Marteau et.al.**
- **Multi-π: hep-ex/0203009**

Checked parameter dependence:
Very small effect on the oscillation analysis