Atmospheric and Solar Neutrino Experiments

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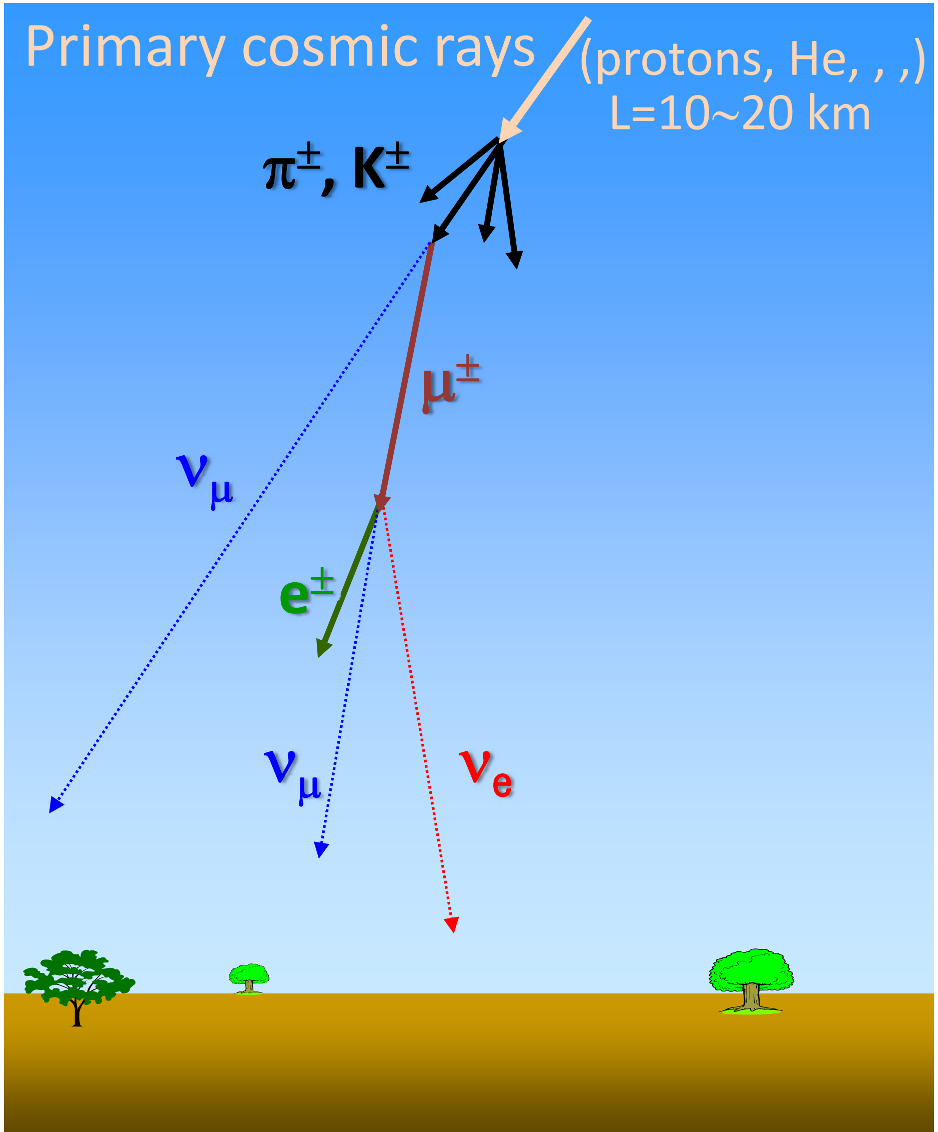
Preface

- Discovery of Neutrino Oscillation has come from the study of the Atmospheric and Solar Neutrinos

- My talk includes a historical review and future experiments
- I do not intend to update the data

Atmospheric Neutrino Experiments

Atmospheric Neutrinos



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

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

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

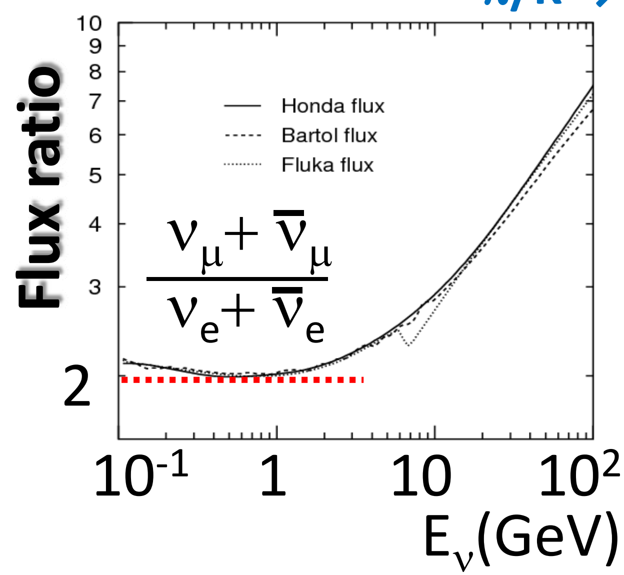
For the low energy limit

- 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 drives back the low energy cosmic ray entering into the solar sphere
    - Solar wind varies with solar activity (solar minimum and maximum)
    - Effect: factor 2 for 1GeV; ~10% for 10GeV
  - Geomagnetic cut-off
    - Affect on low energy CR
    - A function of the location on the earth and arriving direction

  ➔ **Atmospheric neutrinos → 'Position' and time dependent**
- Hadron Interactions (production of π, K)
- Decay of Secondary Particles (π, K, μ)
  - 3D calculation (influence in low energy, horizontal direction)

Many Improvements for the last 10 years!

Comment on Primary Cosmic Ray

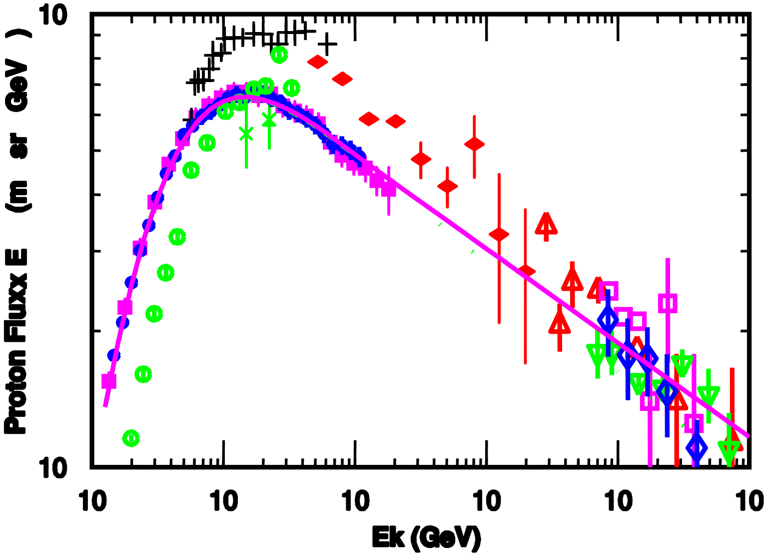
- **$<E_\nu>$ ← ~1/10 x $<E_p>$**

  1 GeV ν ← ~ 10 GeV proton

  10 GeV ν ← ~100 GeV proton

- **Improvement in the last 10 years:**
  - 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

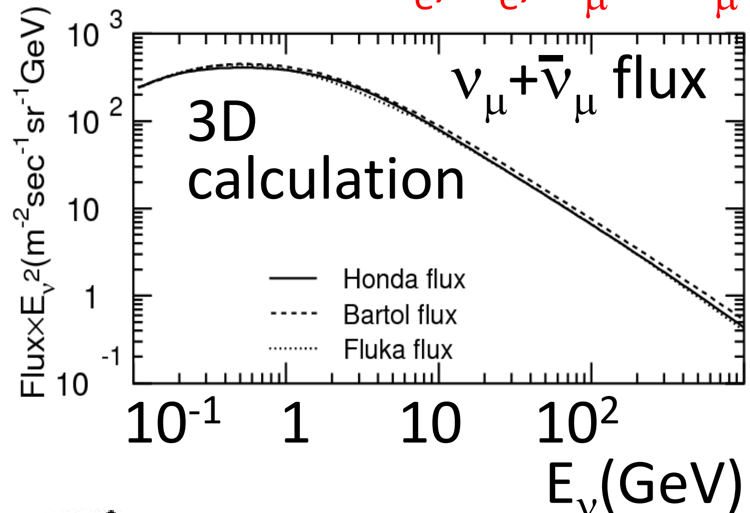
Flux uncertainty

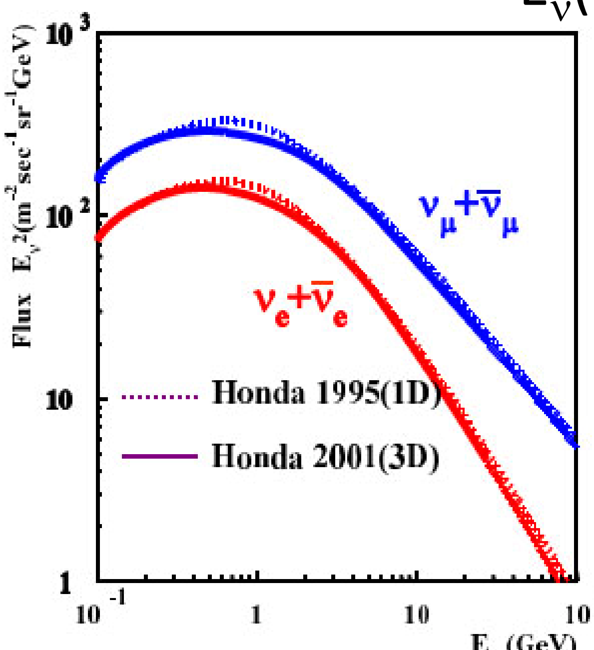
- **Uncertainty of absolute ν-Flux**
  - **10% @ <10GeV ← 25%**
  - **~30% @~100GeV**
- **Uncertainty in R (flux)**
  - **3% @ <5GeV**
  - **15% @~100GeV**
  - **Use double ratio for the study of neutrino oscillation**

$$R = \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{data} \Bigg/ \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{MC}$$

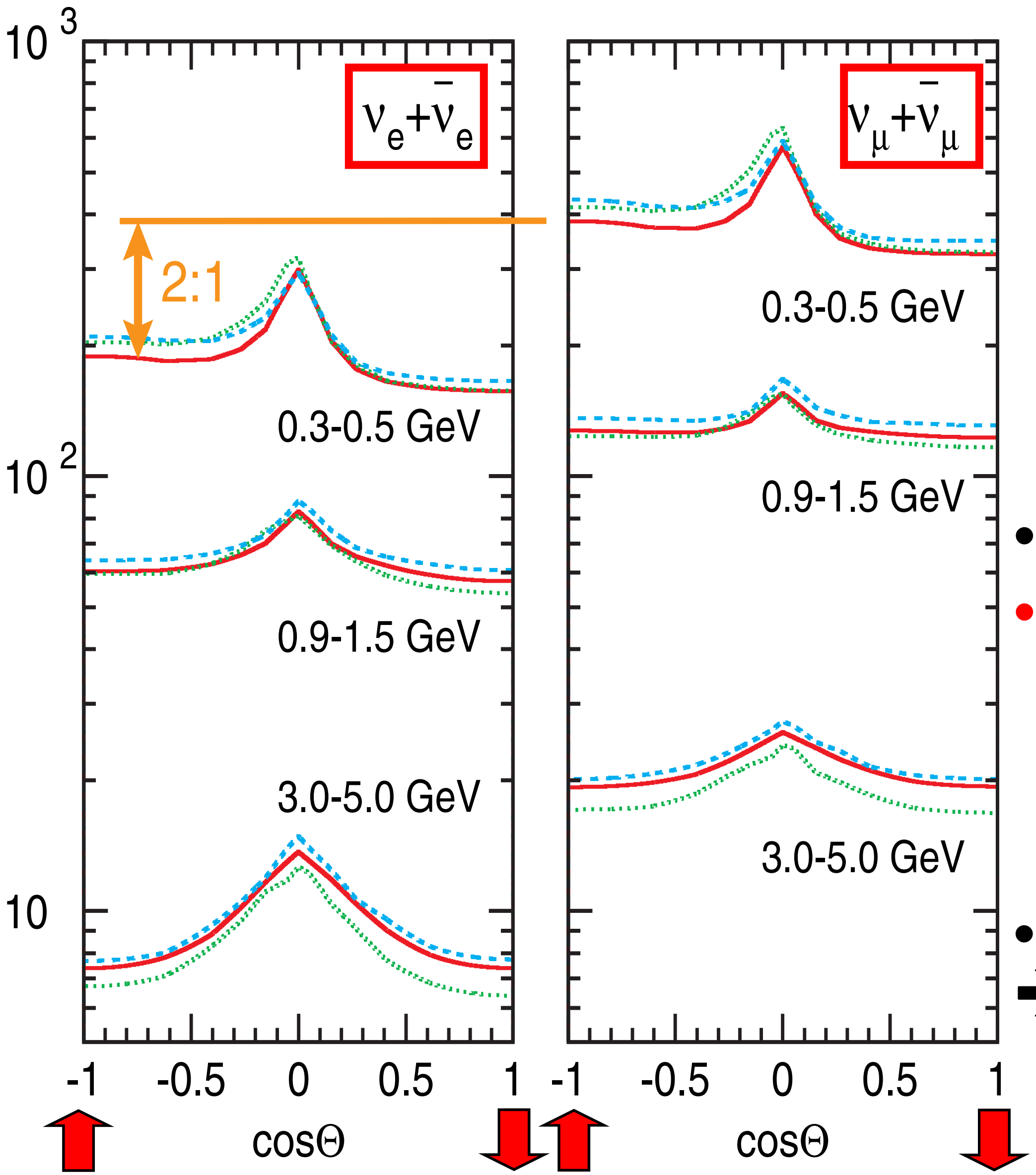
≠1 → *Evidence for neutrino oscillation*

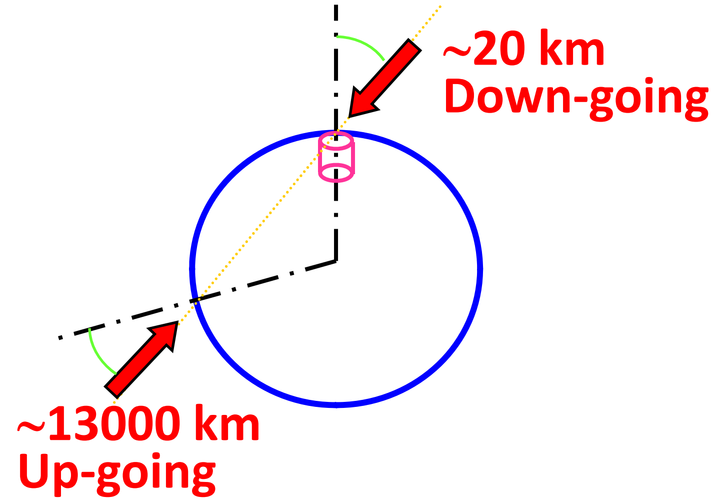
Mixture of ν_e, $\bar{\nu}_e$, ν_μ & $\bar{\nu}_\mu$





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

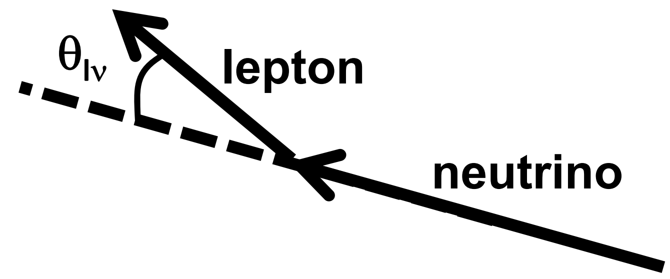
- **Uncertainty in Up/Down**

  ➔1~2% E_ν <1GeV

  ~1% in a few GeV region

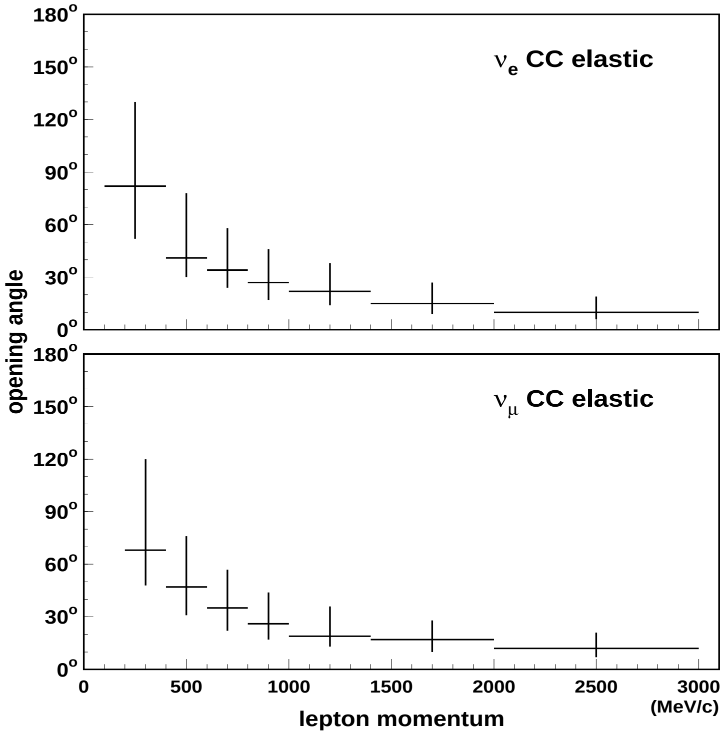
- **Uncer. of Hol./Ver. (up-μ)**

  ➔~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**

- **Improvements for the parameter determination**

  ➔ **Need precise and absolute value of neutrino flux**

Experiments

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 neutri-

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 inter-

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*.
July 12, 1965 (Received)
Phys. Lett. 18(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*.
July 26, 1965 (Received)
Phys. Rev. Lett. 15, 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

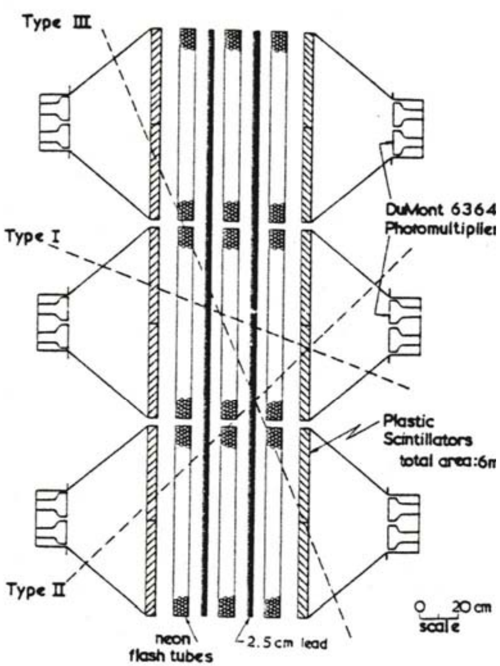
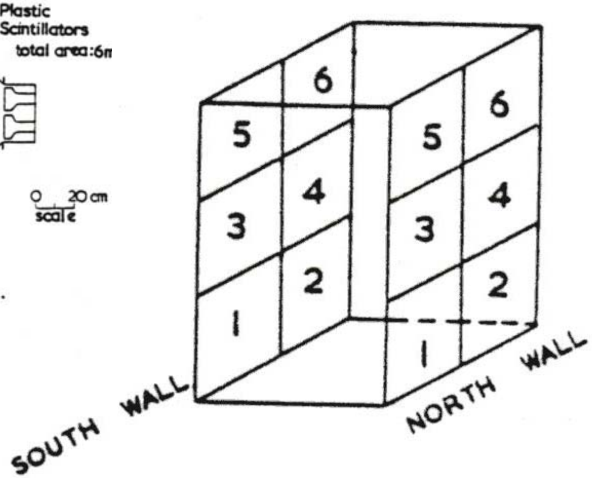
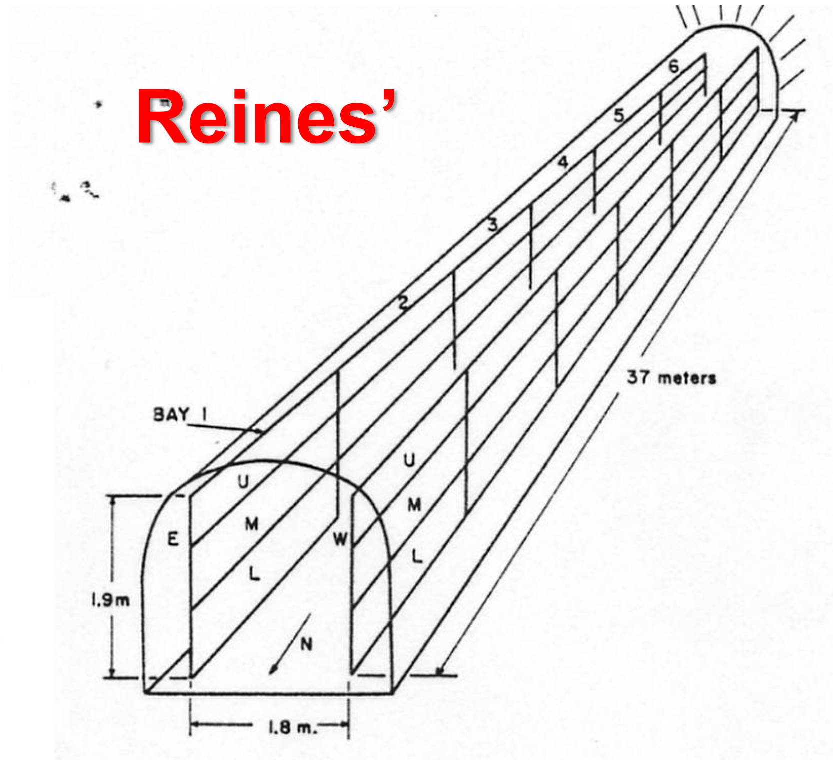


Fig. 1. Neutrino telescope.

Miyake's



Reines'



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
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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 $59 \pm 7\%$ (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: saw atm-ν interactions happed inside of the detector

The first problem

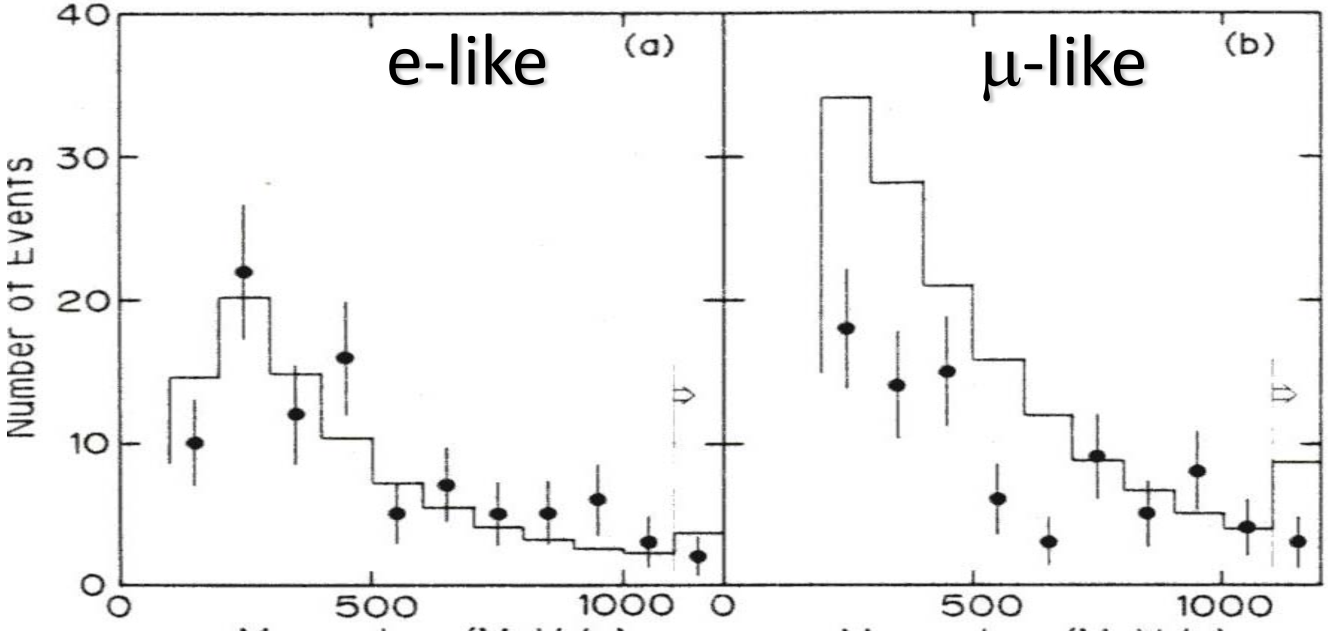
PLB, 205, 416 (1988)

By Kamiokande

Kamiokande Data

In 1988, Kamiokande saw few μ

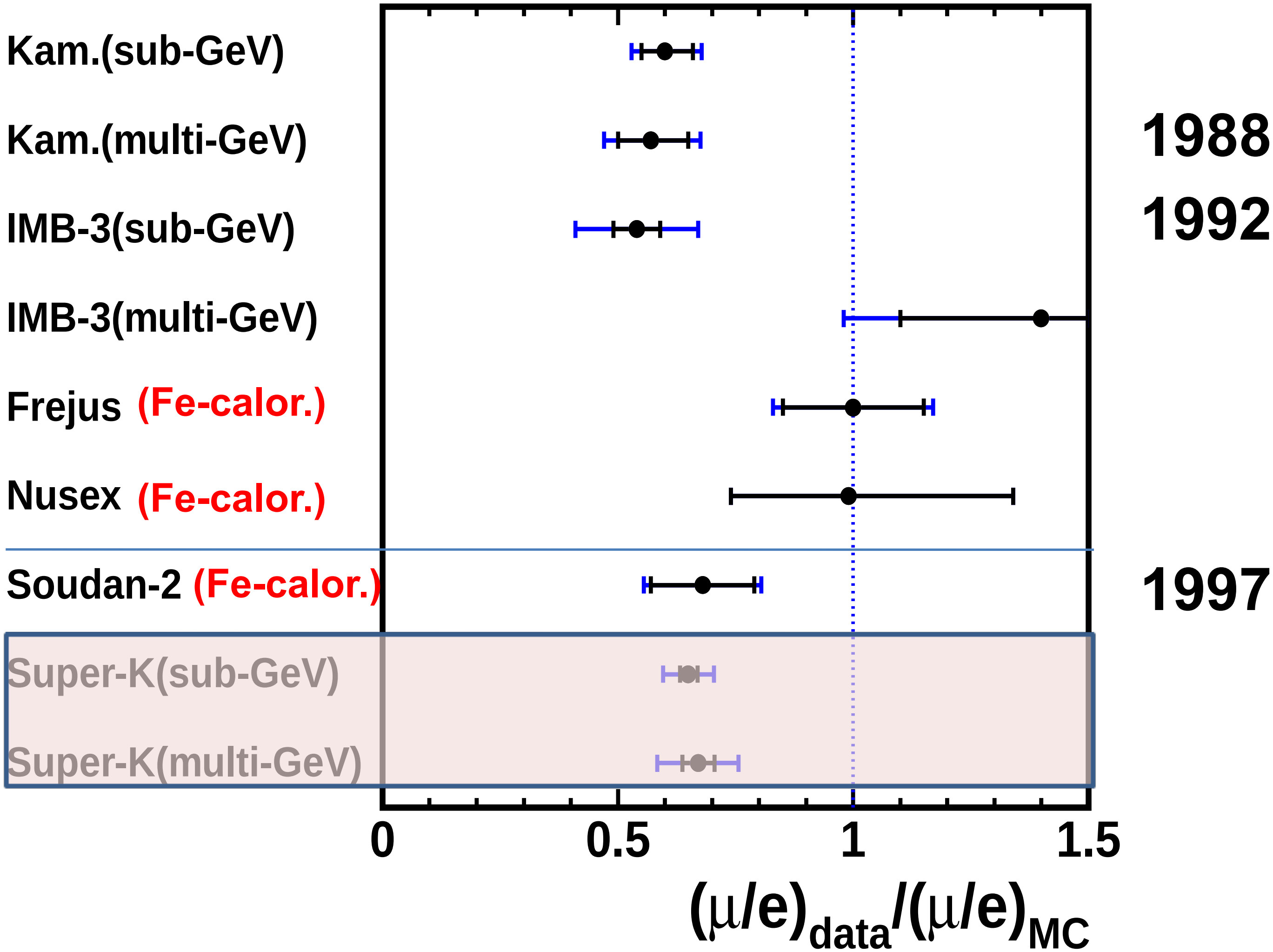
$R = (Obs./MC)_{\mu\text{-like}} = 0.59 \pm 7\%$ (stat.)



Momentum (MeV/c)

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

R measurement in 90's

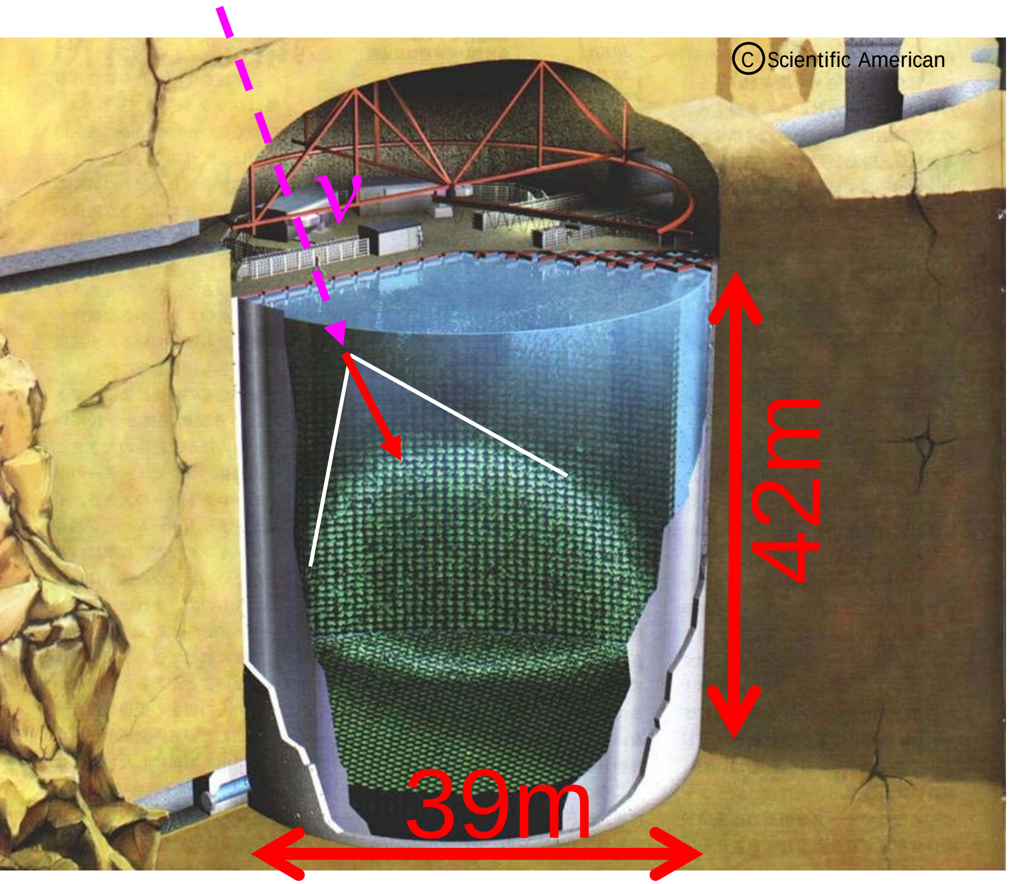


Breakthrough

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

Boston University
S. Desai, M. Earl, E. Kearns, M.D. Messier, K. Scholberg, J.L. Stone, L.R. Sulak, C.W. Walter

Brookhaven National Laboratory
M. Goldhaber

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University of Washington
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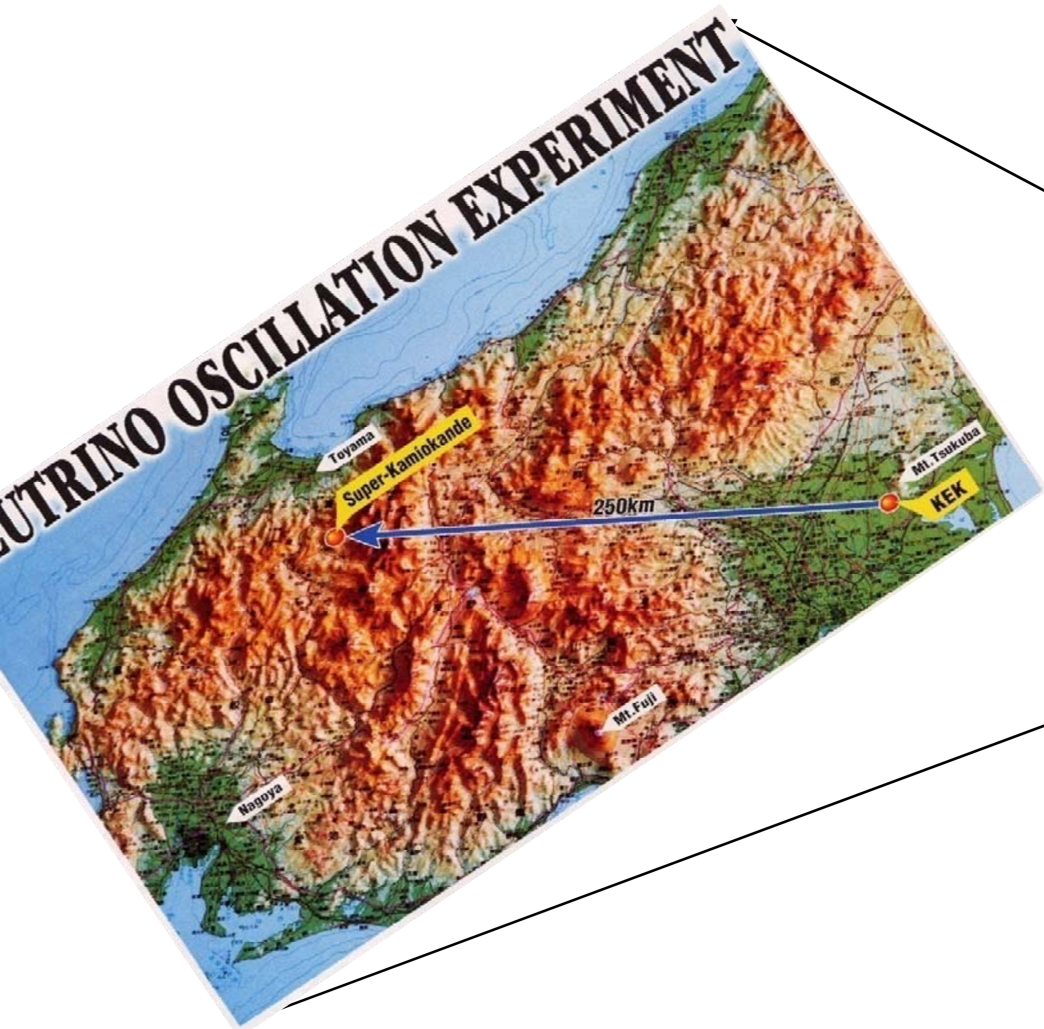
S. Tasaka

Department of Physics, Kobe University
M. Kohama, A.T. Suzuki

Department of Physics, Kyoto University
T. Inagaki, T. Nakaya, K. Nishikawa

Shizuoka Seika College, Shizuoka University
H. Okazawa, T. Ishizuka

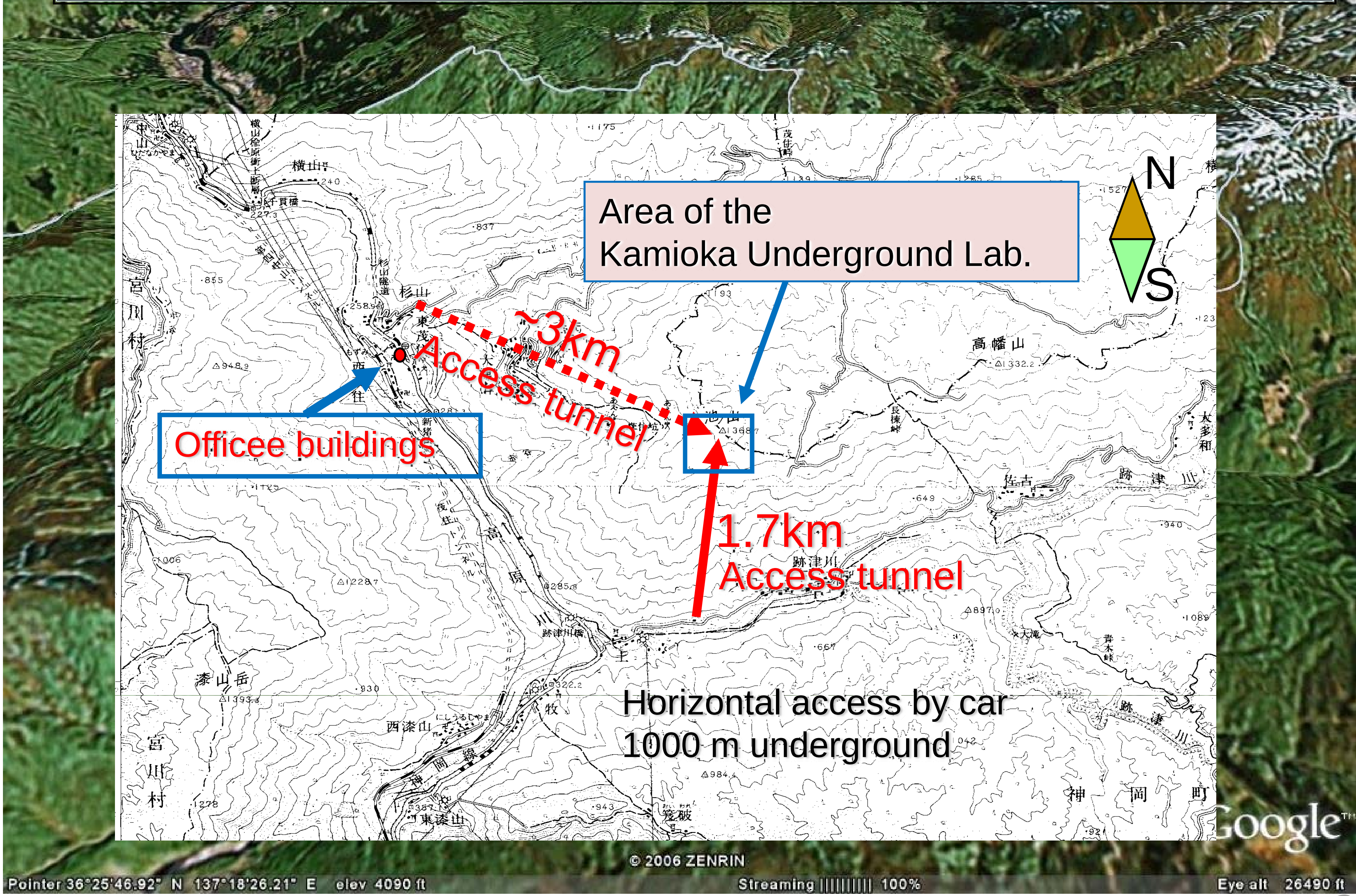
Department of Physics, Seoul National University
H.I. Kim, S.B. Kim, J. Yoo


UTRINO OSCILLATION EXPERIMENT
Toyama
Super-Kamiokande
250km
Mt.Tsukuba
KEK
Mt.Fuji
Nagoya

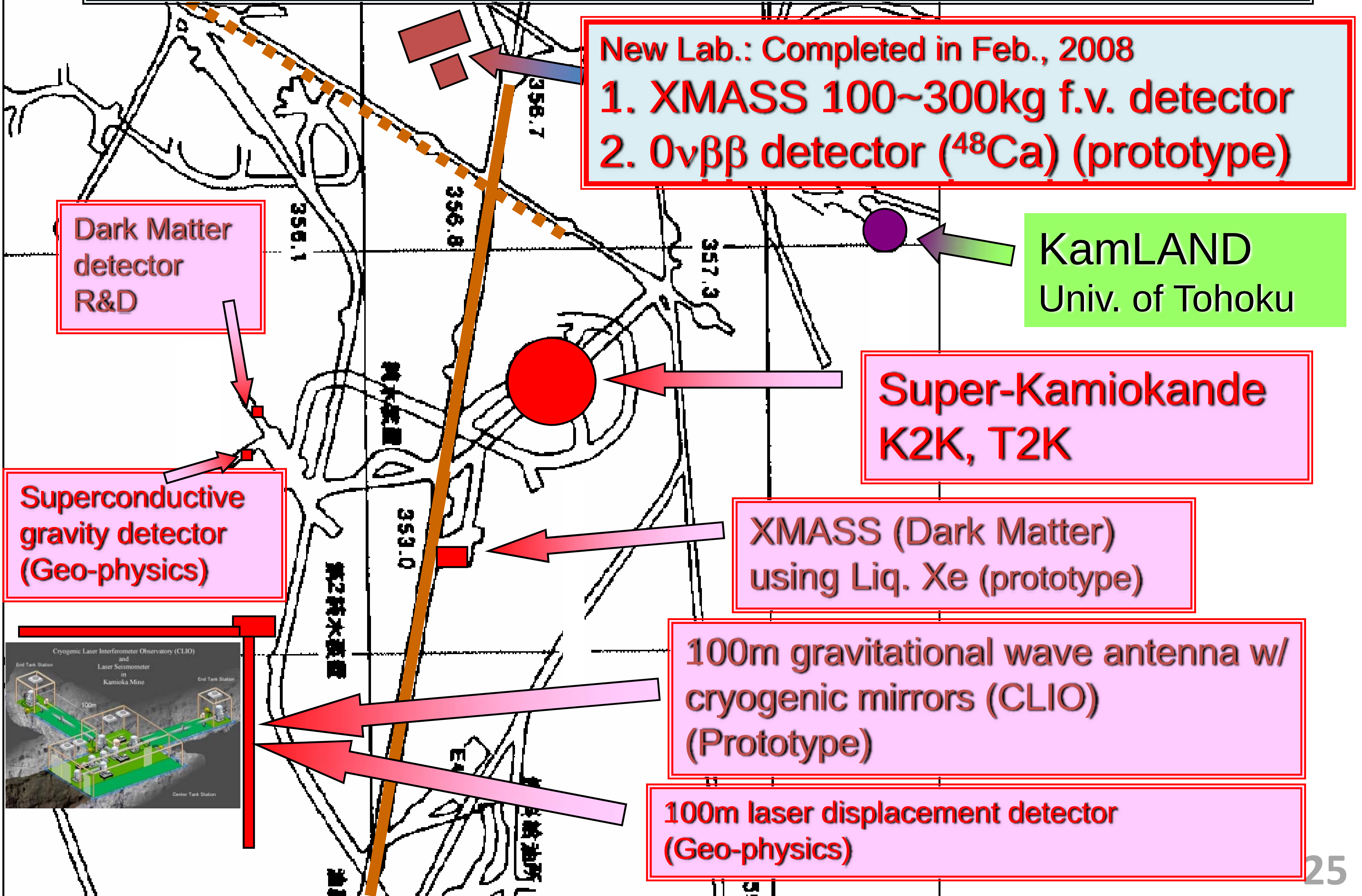

RUSSIA
Microsoft MapPoint
Yichun
Harbin
GOBI
Jixi
CHINA
Jilin
Sapporo
110°
Beijing
40°
P'yŏngyang
Taiyuan
Sendai
Seoul
160°
Tengxian
JAPAN
Taegu
Kyōto
Nanjing
Ōita
30°
Kagoshima
Nanchang
Taipei
PACIFIC OCEAN
25°
Tropic of Cancer
T'ainan
20°
©2003 Microsoft Corp.
130° 135° 140° 145° 150°

Kamioka Observatory

Kamioka Observatory



Kamioka Observatory



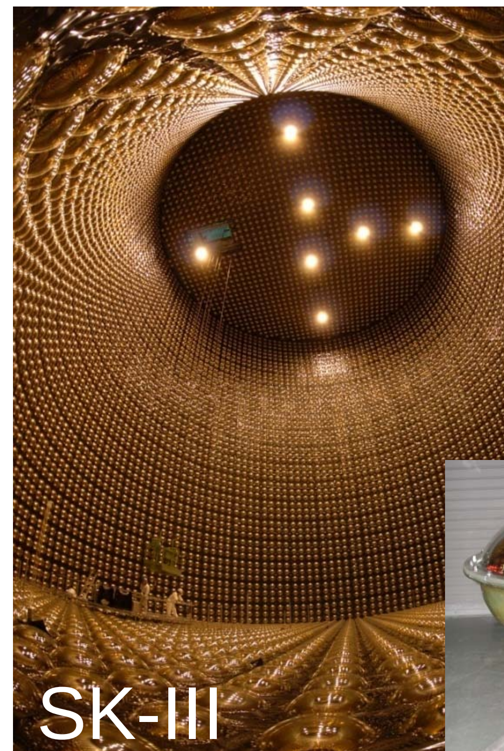
Brief history of Super-K

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

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

K2K | T2K

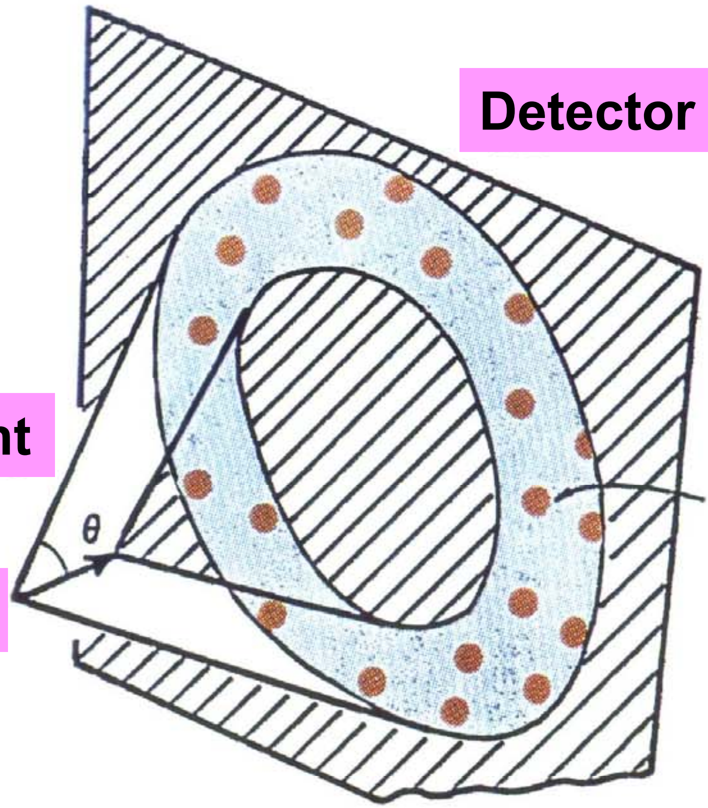
- **SK started on April, 1996 (SK-I)**
  - **12th Anniversary**
- **4 phases: SK-I, SK-II, SK-III, SK-IV**
  - **Accident (lost more than half of PMTs)**
    - **Nov-12, 2001**
  - **SK-II (5,182 PMTs (19% cov.))**
    - **Dec-2002 → Nov-2005**
  - **SK-III (11,129 PMTs (40% cov.))**
    - **July-2006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



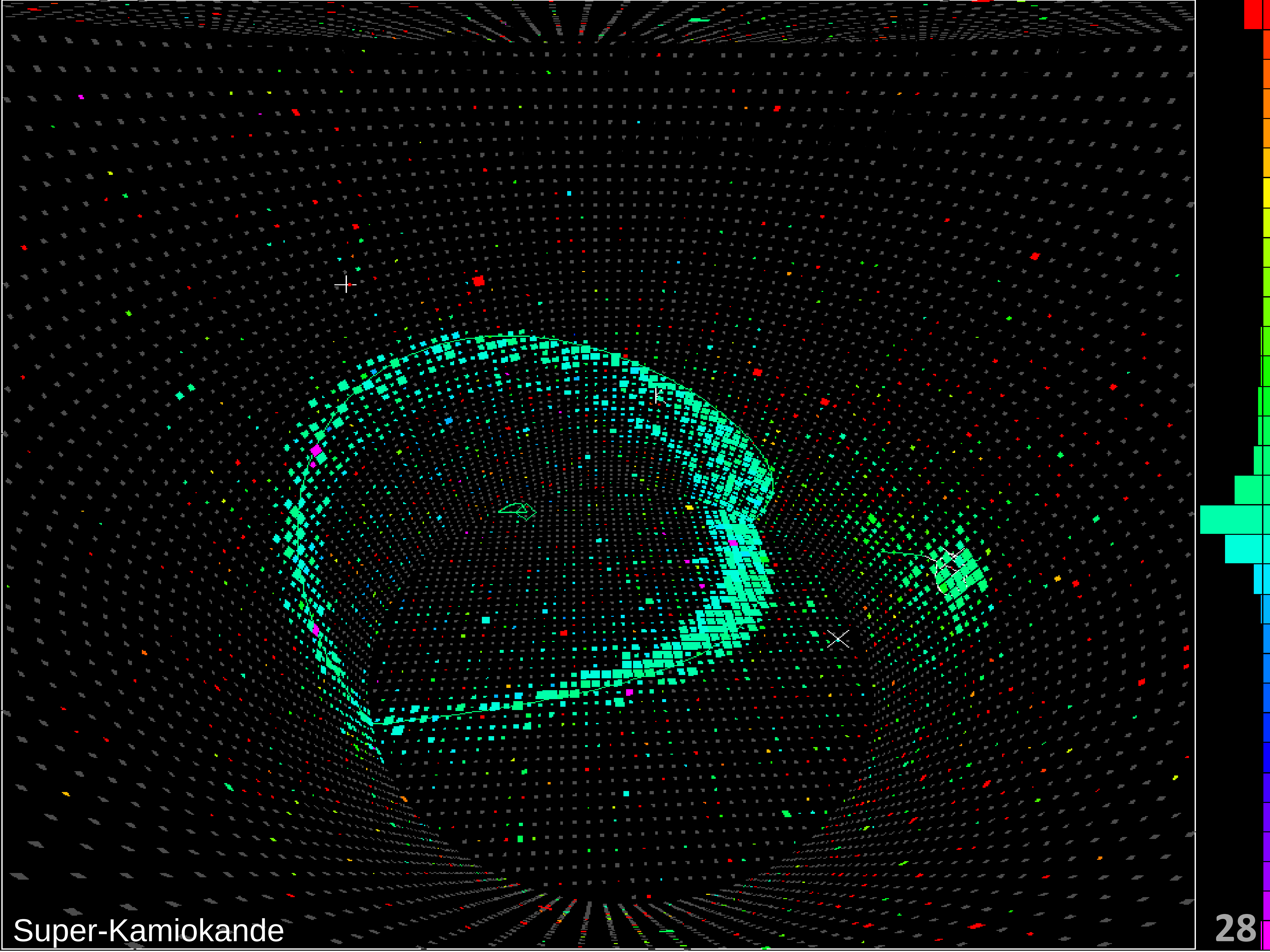
Protection case

Detection Principle -- Cherenkov light

Cherenkov Angle:
$\cos\theta = 1/n\beta$
n=1.33 for water
➔
Θ = 42deg for β=1



The Cherenkov Ring on the detector wall


Super-Kamiokande

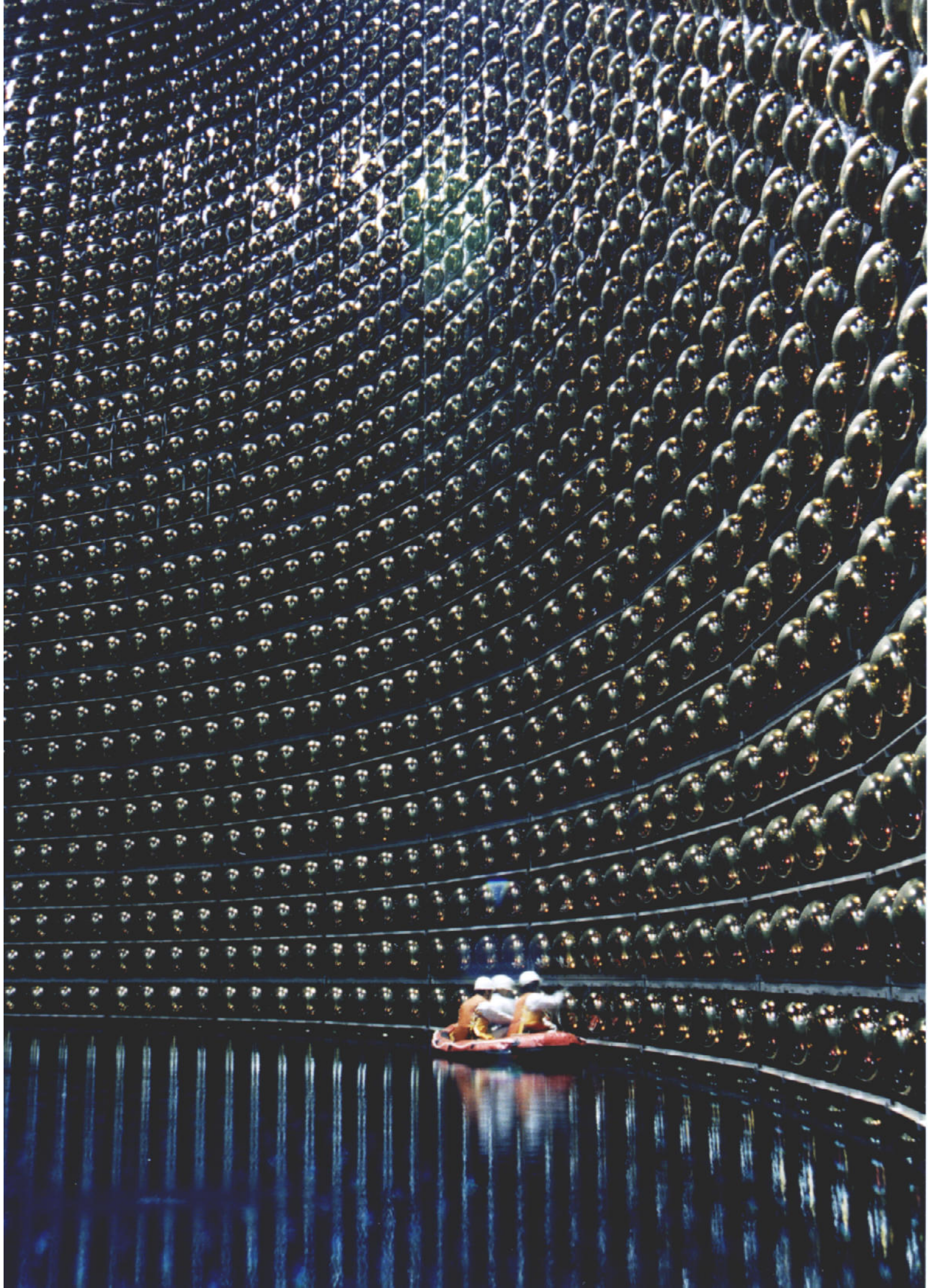
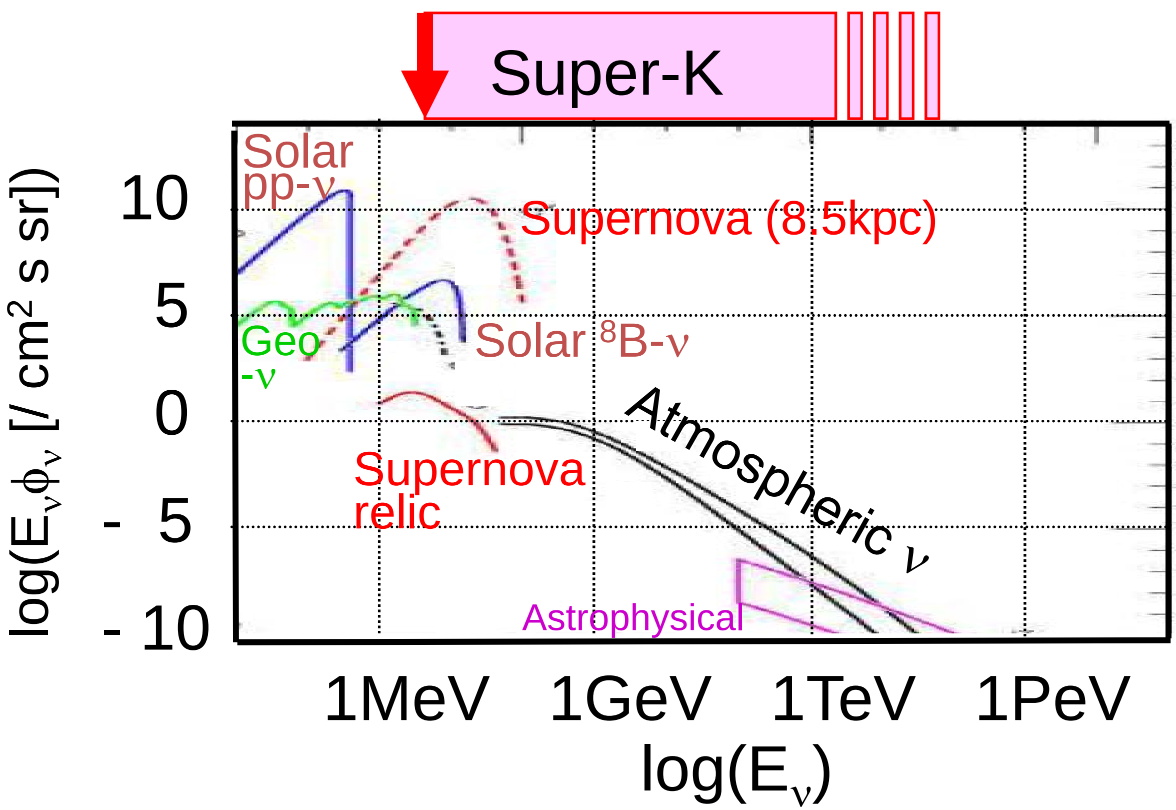


Photo-multiplier tube

Energy Range (data from SK-I)

- Trigger: 100% eff. for E_{obs} > **4.5 MeV**
  (50% efficiency @ 3.7MeV)
- Trigger Rate: 1,700Hz → 15 Hz (recorded)



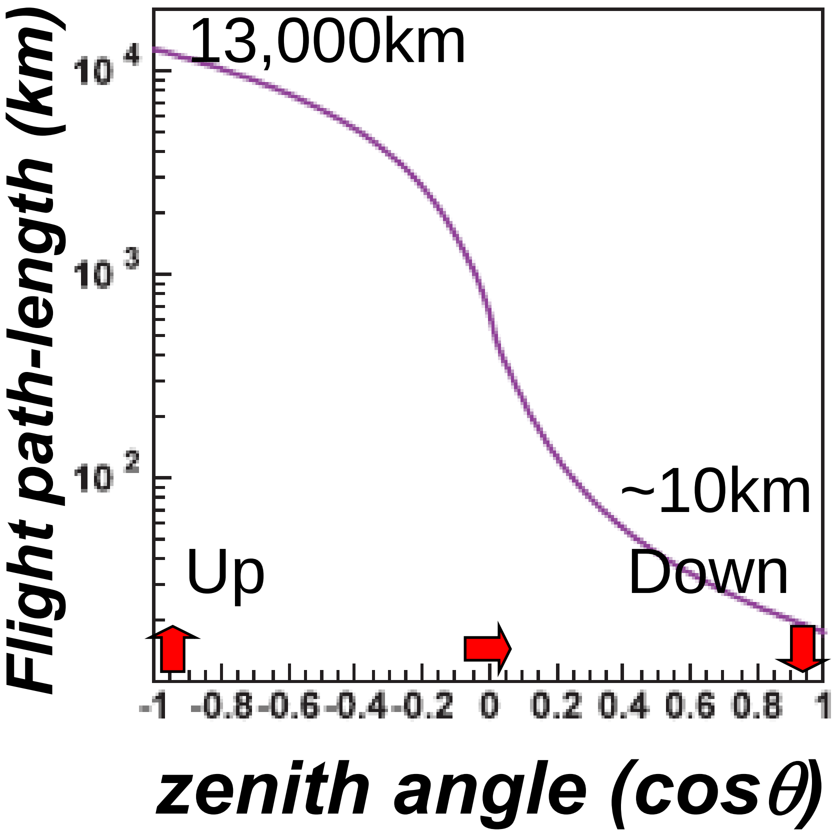
- 6 p.e. / MeV
- Resolution

(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



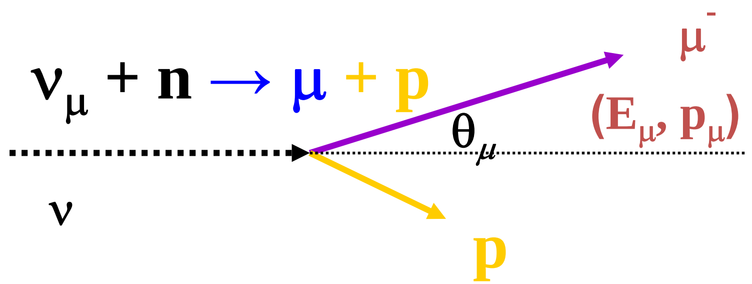
Wide range of path-length **(3 orders)**

L: ~10~13,000 km

Wide range of the energy **(5 orders)**

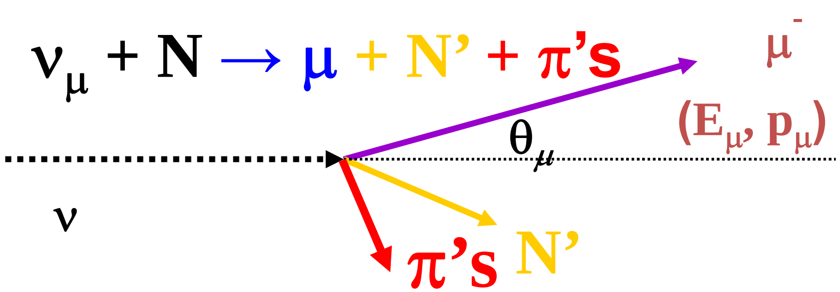
E: ~0.1~10,000 GeV

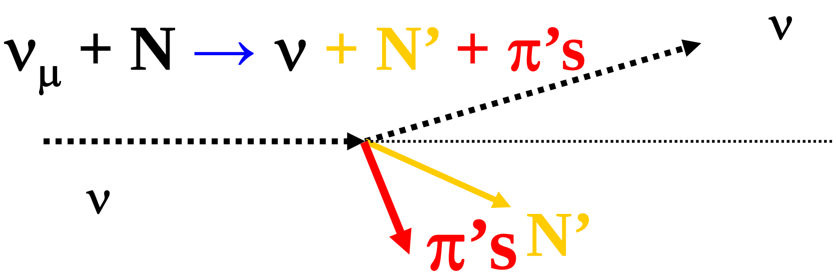
Neutrino Interaction @~1 GeV and E_ν reconstruction



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

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

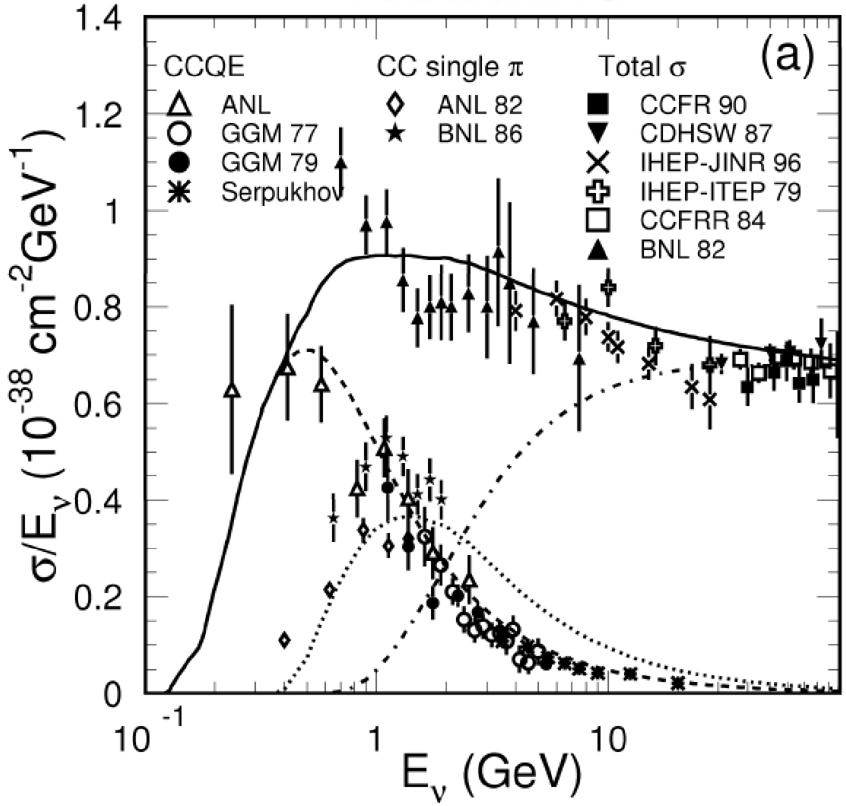




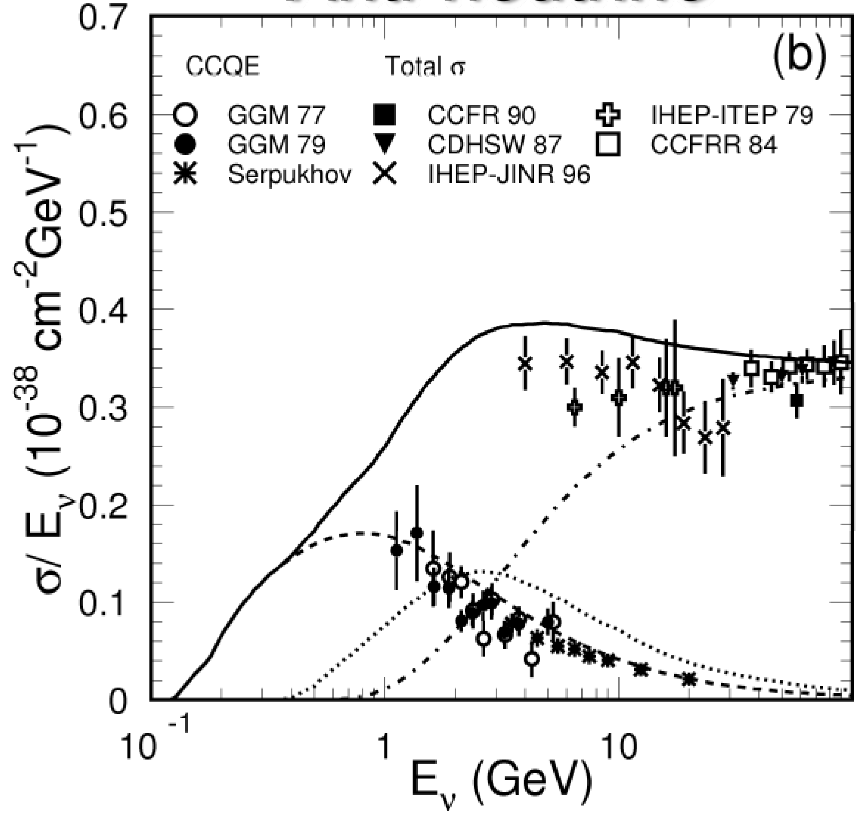
- ✧ CC non-QE
  - ✧ ~100% efficiency for SK
  - ✧ Bkg. for E_ν measurement
- ✧ NC
  - ✧ ~40% efficiency for SK

cross sections

Neutrino



Anti-neutrino



Parameters used in our simulation program:

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

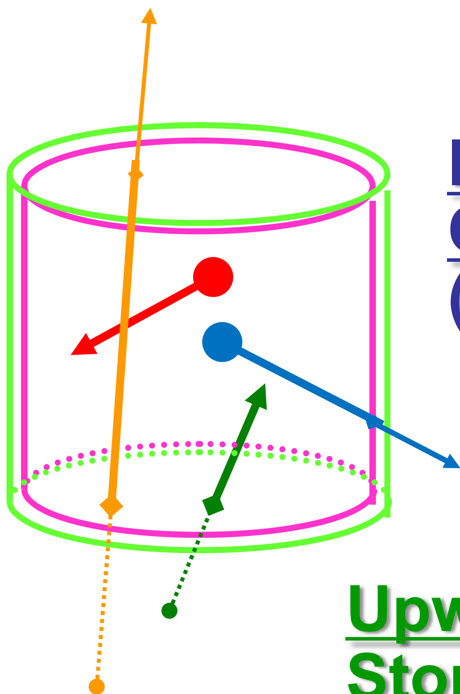
Checked parameter dependence: Very small effect on oscillation analysis

Atmospheric Neutrino Events in Super-K

- *Event category*

Fully Contained (FC)
(<E_{ν}> ~ 1GeV)
subGeV: Evis<1.33GeV
Multi-GeV: >1.33GeV

Partially Contained (PC)
(<E_{ν}> ~ 10GeV)

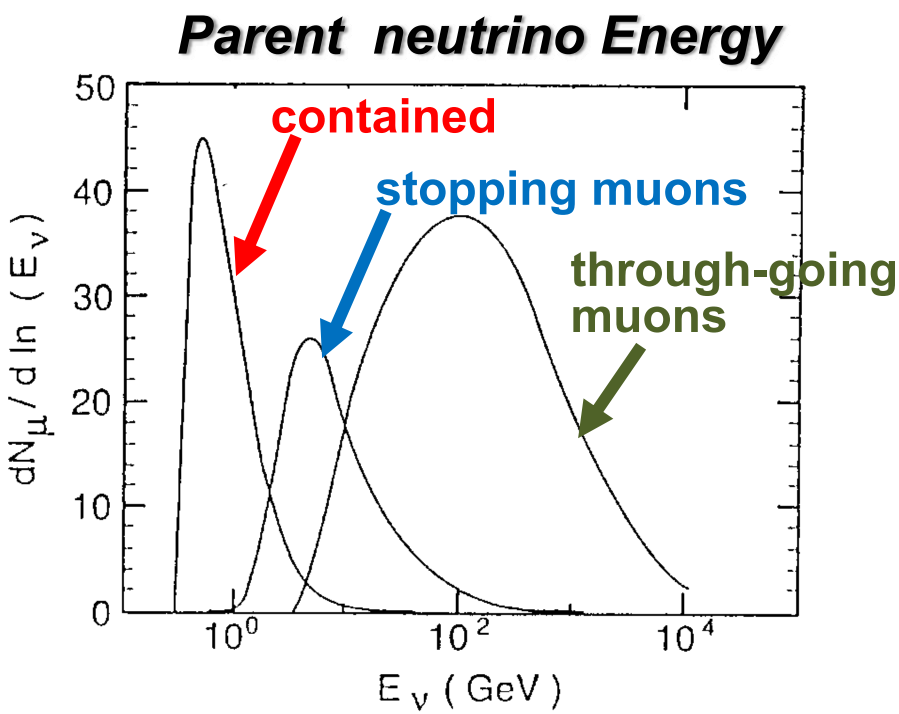


Upward Through-going μ
(<E_{ν}> ~ 100GeV)

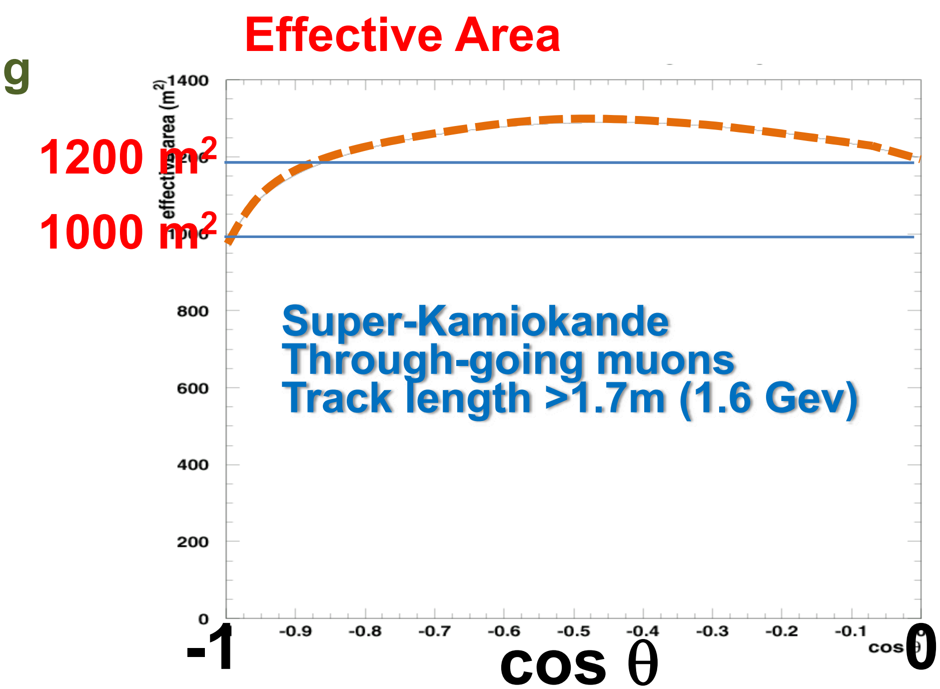
Interaction in the rock

Upward Stopping μ
(<E_{ν}> ~ 10GeV)

Atmospheric Neutrino Events in Super-K



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



Analysis

1. Ring Count (1R, 2R,,,,)
2. Particle ID (e/γ, μ , (π), (p))
3. Energy Momentum Reconstruction

➔

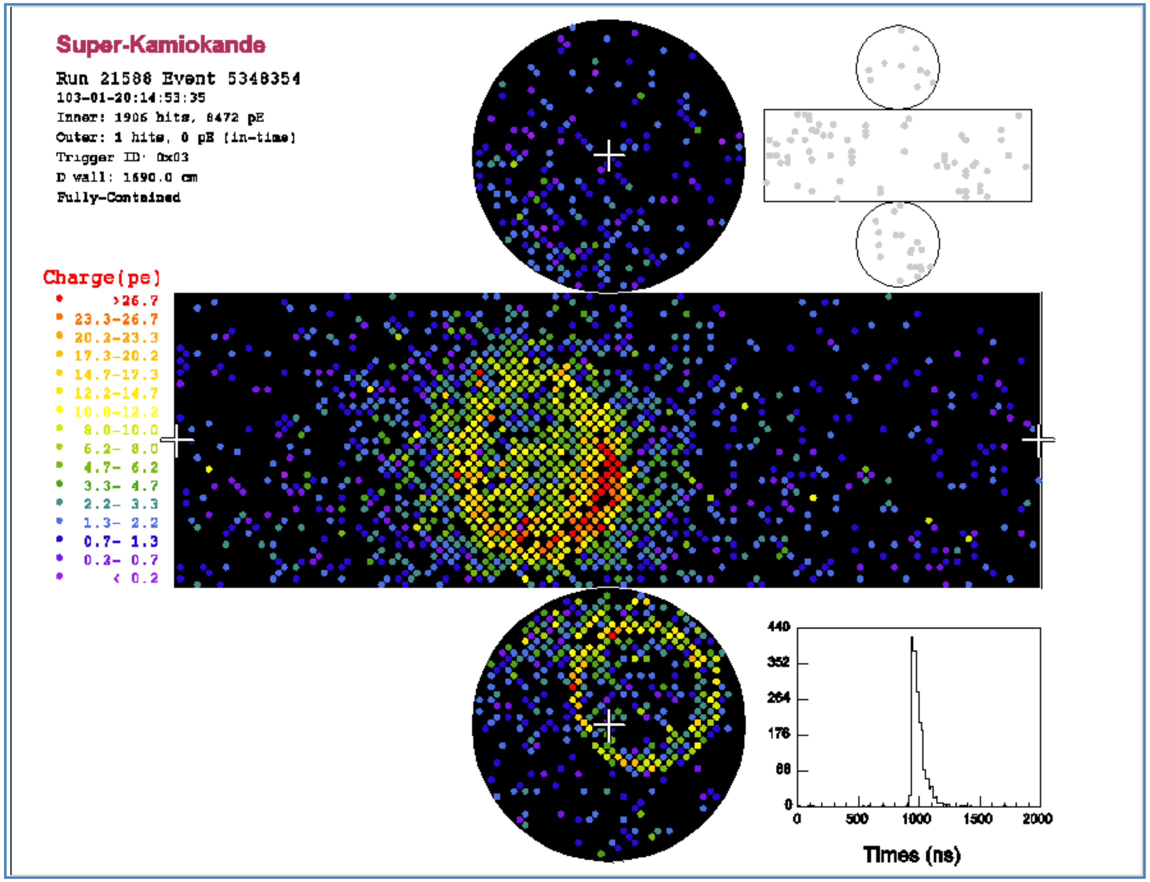
4. Fiducial Volume cut (>2m from the wall; 22.5kton)
5. Minimum energy cut: > 30 MeV (FC),
   >~ 350MeV (PC)

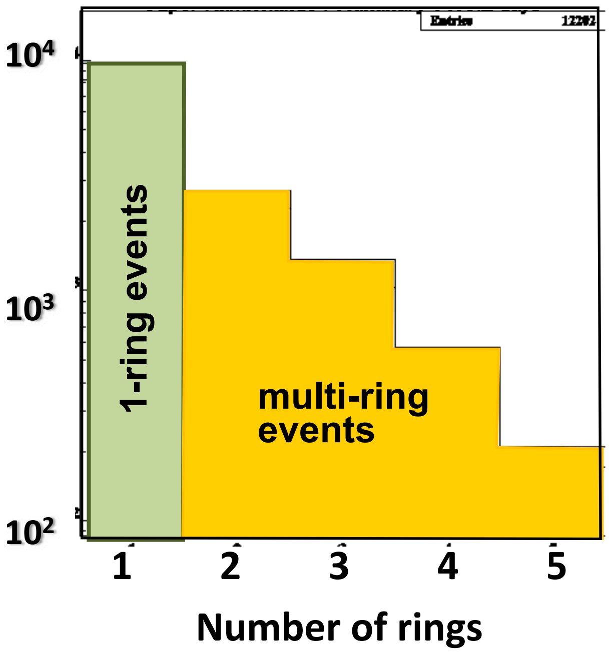
➔ Final Sample:

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

Ring Counts:

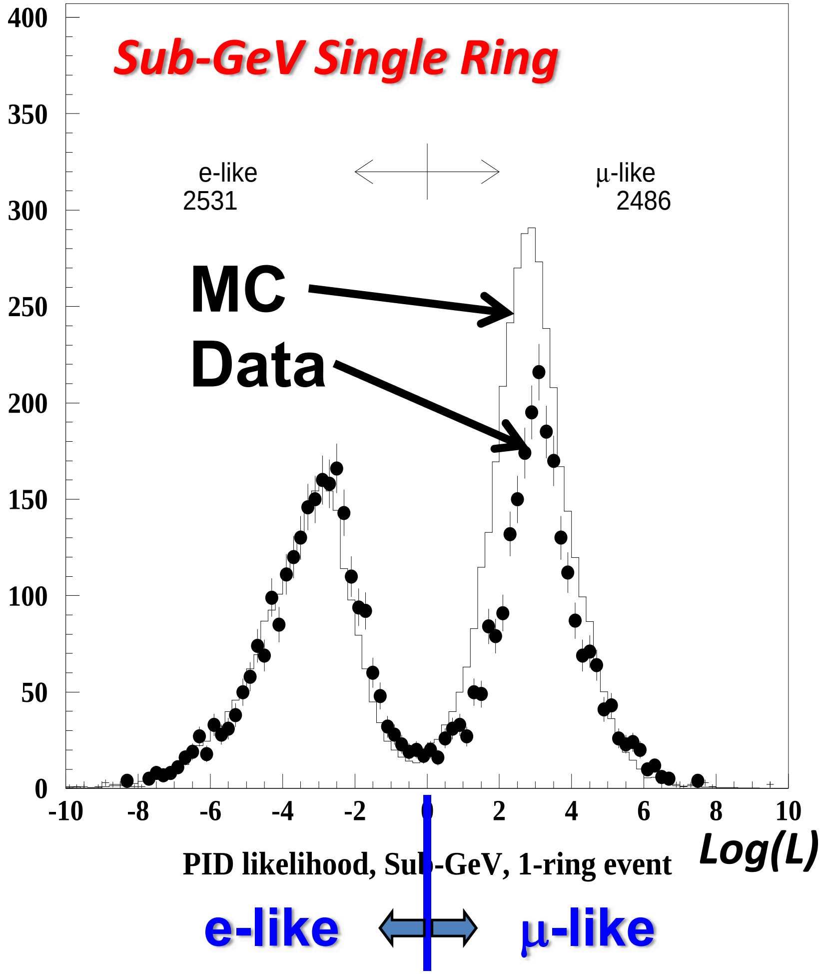
Fully Contained(FC) events

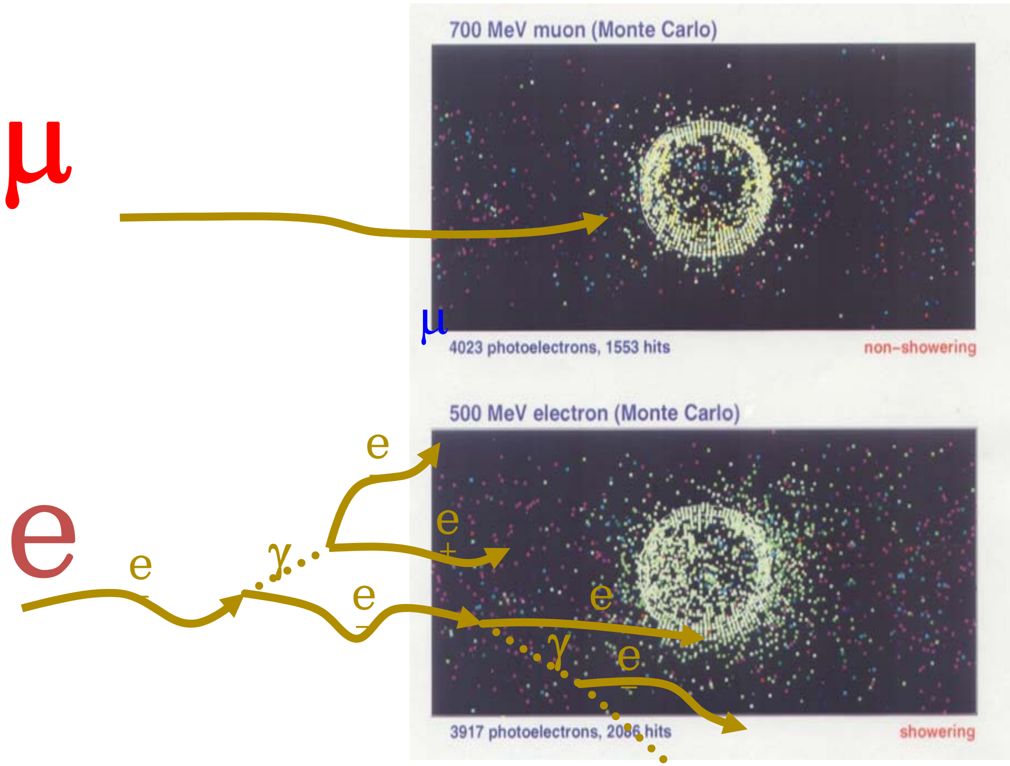




μ / e separation

Likelihood for particle identification



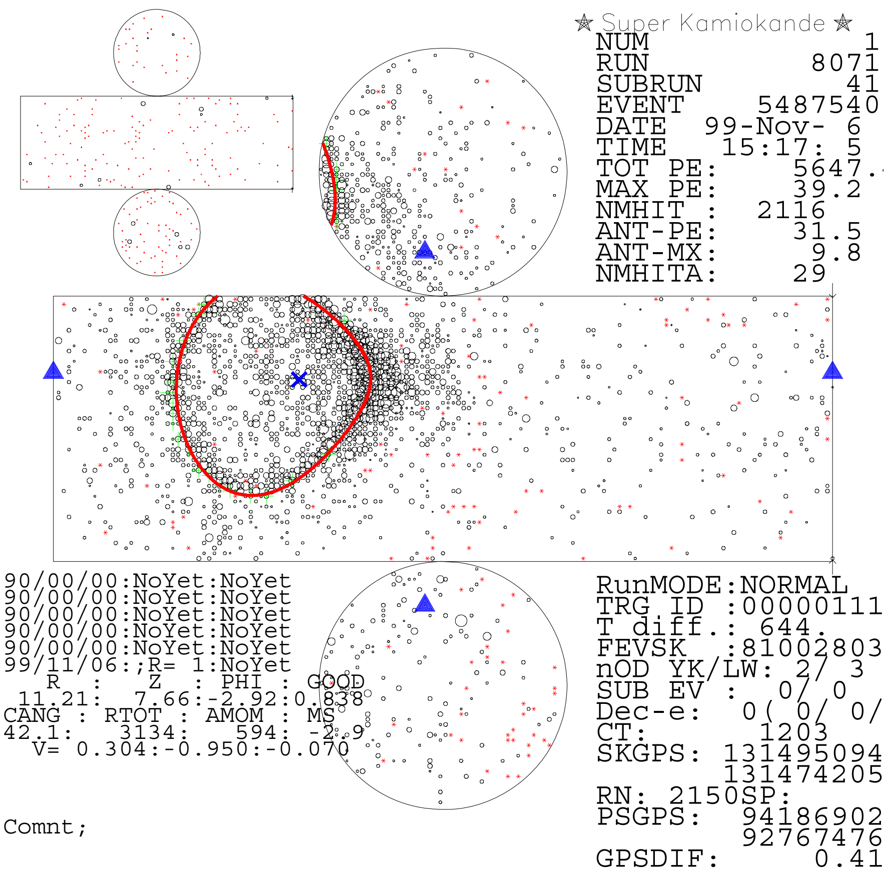


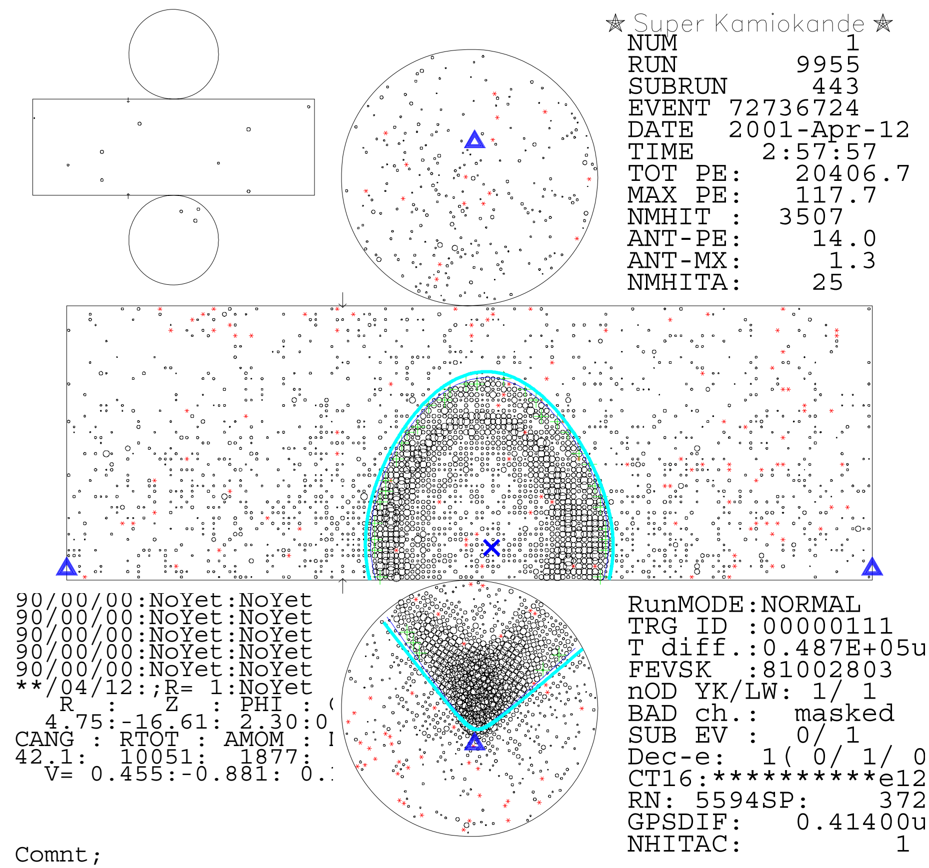
Mis-identification:

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 (SKI)

FC+PC
1489days

Sub-GeV:(Evis<1.33GeV)

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

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

Multi-GeV:(1.33GeV<Evis)

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

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.658 \, ^{+0.030}_{-0.028} \pm 0.078$$

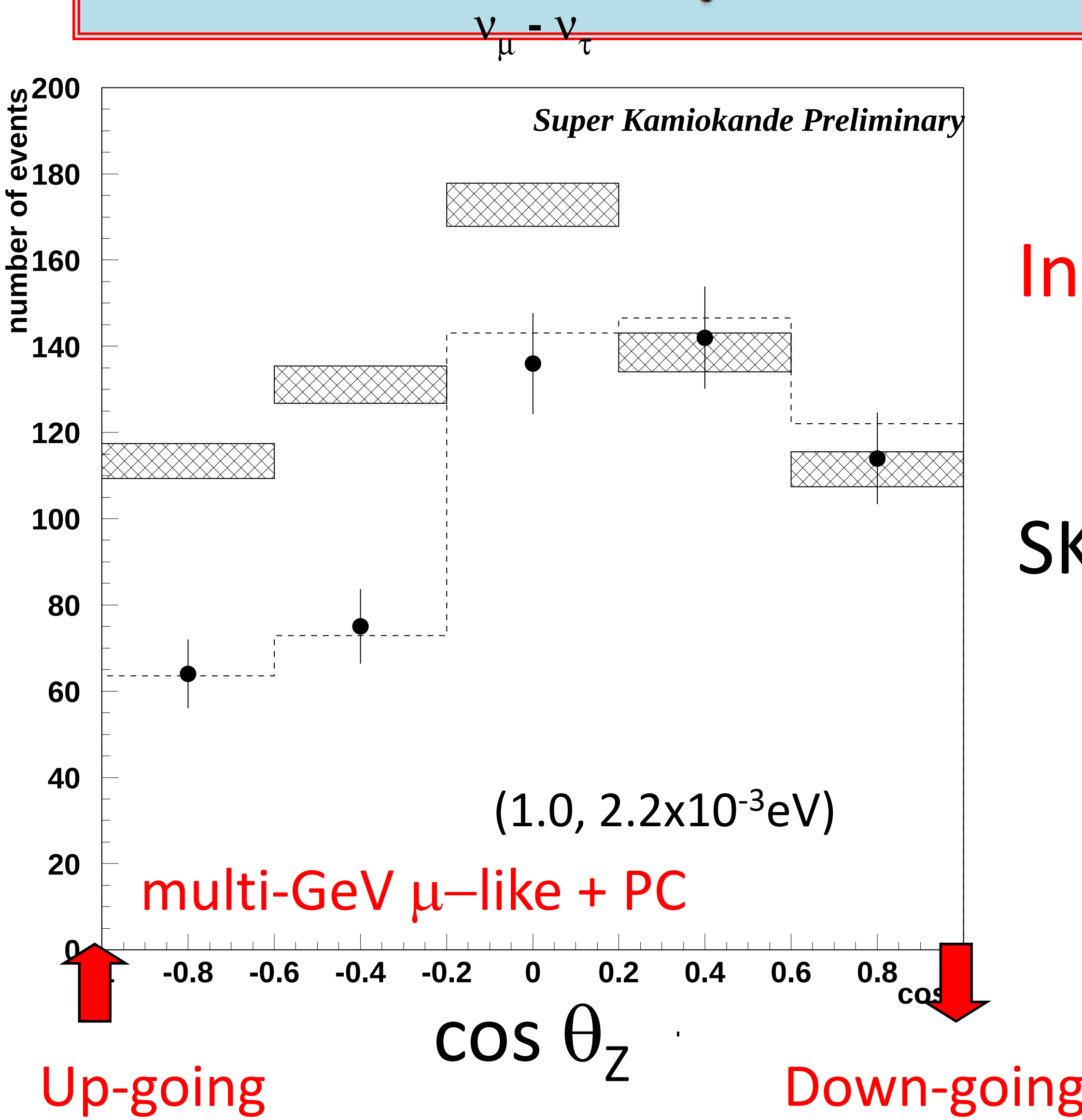
Up stopping μ 1657days

Observed	0.41 +/-0.02(stat.) +/-0.02(syst.) ($x10^{-13}cm^{-2}s^{-1}sr^{-1}$)
Expected (Honda)	0.68 +/-0.15(theo.)

Up through going μ 1678days

Observed	1.70 +/-0.04(stat.) +/-0.02(syst.) ($x10^{-13}cm^{-2}s^{-1}sr^{-1}$)
Expected (Honda)	1.84 +/-0.41(theo.)

Discovery of Atmospheric Neutrino Oscillation by Super-Kamiokande



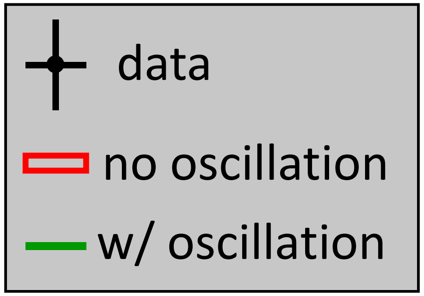
In 1998

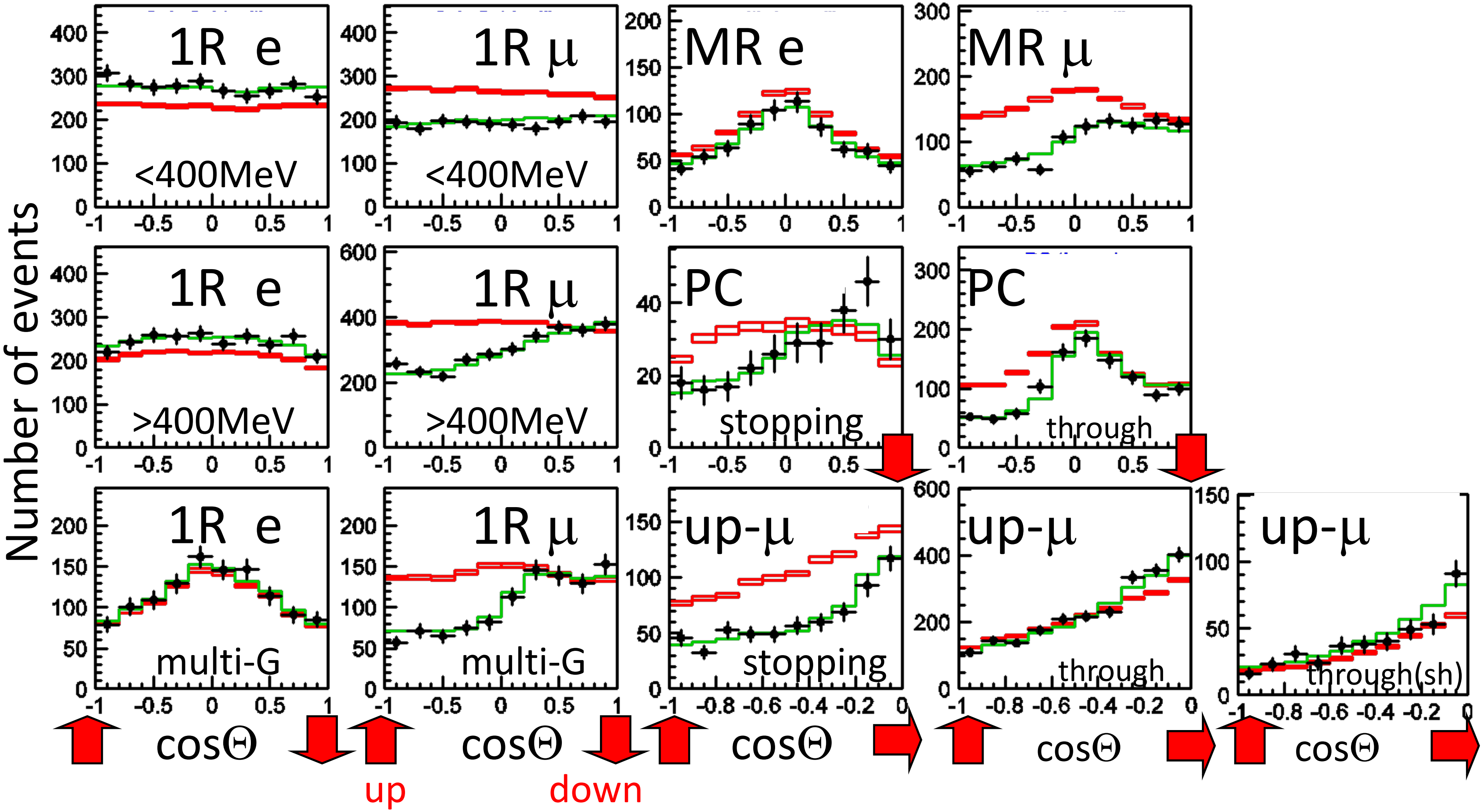
(10 yrs after the KM indication)

SK provided

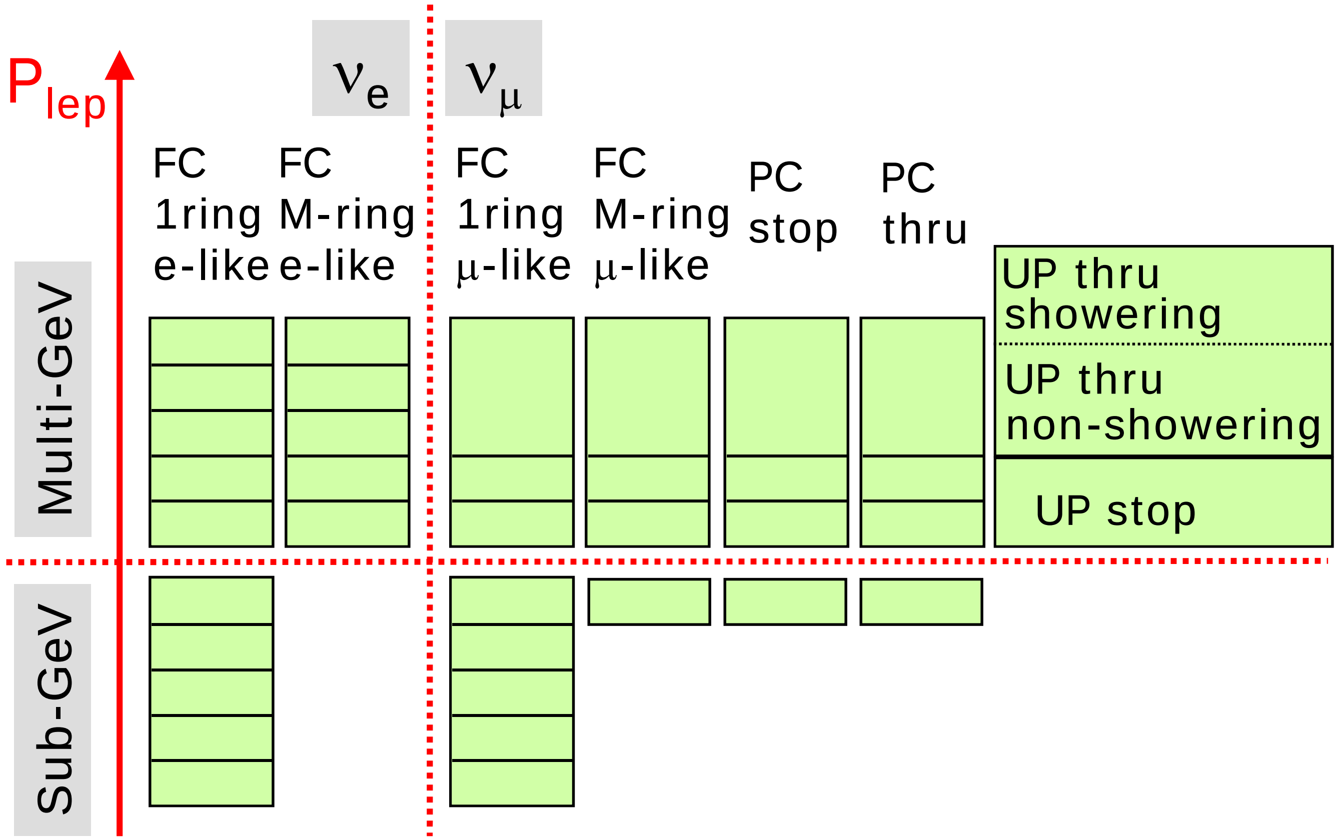
- definitive evidence
- in zenith angle distributions
- independent of the flux calculations

Zenith angle Distribution (SK-I + SK-II)





SK-I + SK-II combined analysis



38 event type and momentum bins
x
10 zenith bins

→ 380 bins

we did not combine the SK-I and SK-II data
← Detector related systematic errors are different

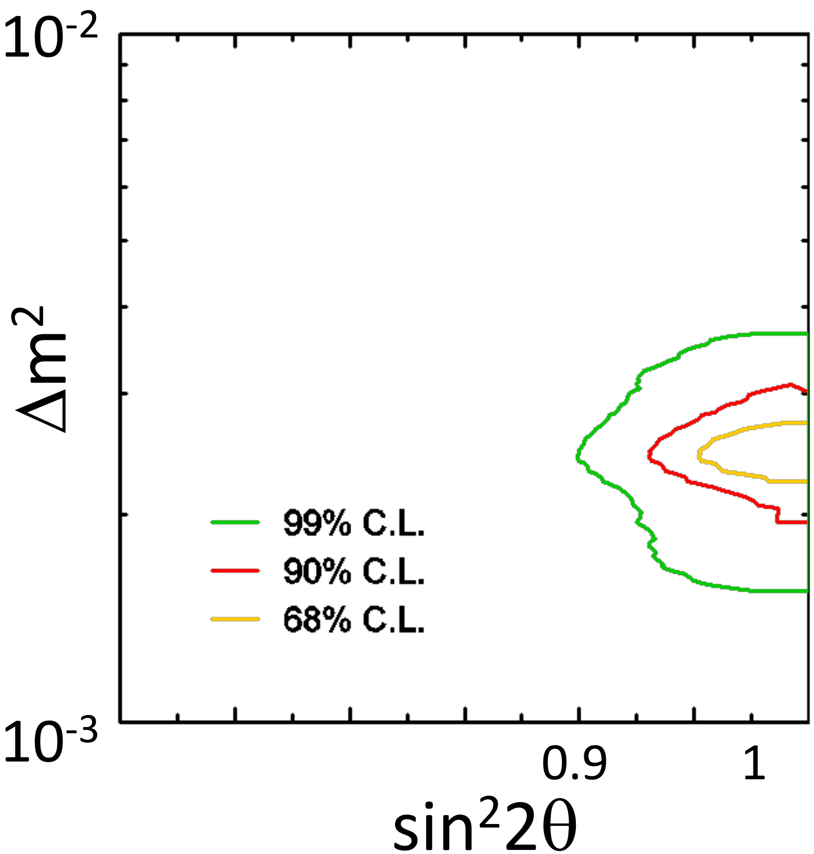
380 bins for SK-I + 380 bins for SK-II → 760 bins in total

Oscillation Parameters (SK-I + SK-II)

Assume 2 neutrino oscillation: $\nu_\mu \rightarrow \nu_\tau$

$$\chi^2 \equiv \sum^{\#\text{ of bins}} \left(2(N_i^{\text{exp}} - N_i^{\text{obs}}) + 2N_i^{\text{obs}} \ln \frac{N_i^{\text{obs}}}{N_i^{\text{exp}}} \right) + \sum_{j=1} \left(\frac{\varepsilon_j}{\sigma_j} \right)^2$$

$$N_i^{\text{exp}} = N_i^0 \cdot P(\nu_\alpha \rightarrow \nu_\beta) \cdot (1 + \sum_{j=1} f_j^i \cdot \varepsilon_j)$$



Best fit (Physical Region)

$\sin^2 2\theta = 1.00$

$\Delta m^2 = 2.5 \times 10^{-3}\ \text{eV}^2$

$\chi^2_{min} = 839.6/755\text{dof}$

$\Delta\chi^2 = 555.8$ (for no osc.)

$1.9 \times 10^{-3}\ \text{eV}^2 < \Delta m^2 < 3.1 \times 10^{-3}\ \text{eV}^2$

$\sin^2 2\theta > 0.93$ (@90%C.L.)

$\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{sterile}$?

- Experimental Strategy
  1) Use enriched NC sample and 2) matter effect
- Neutrino oscillation in Matter
  - $\nu_\mu \rightarrow \nu_\tau$: **No matter effect**
  - $\nu_\mu \rightarrow \nu_s$: **matter effect**

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\zeta - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\zeta = \sqrt{2}\, G_F n_n E_\nu / \Delta m^2$$

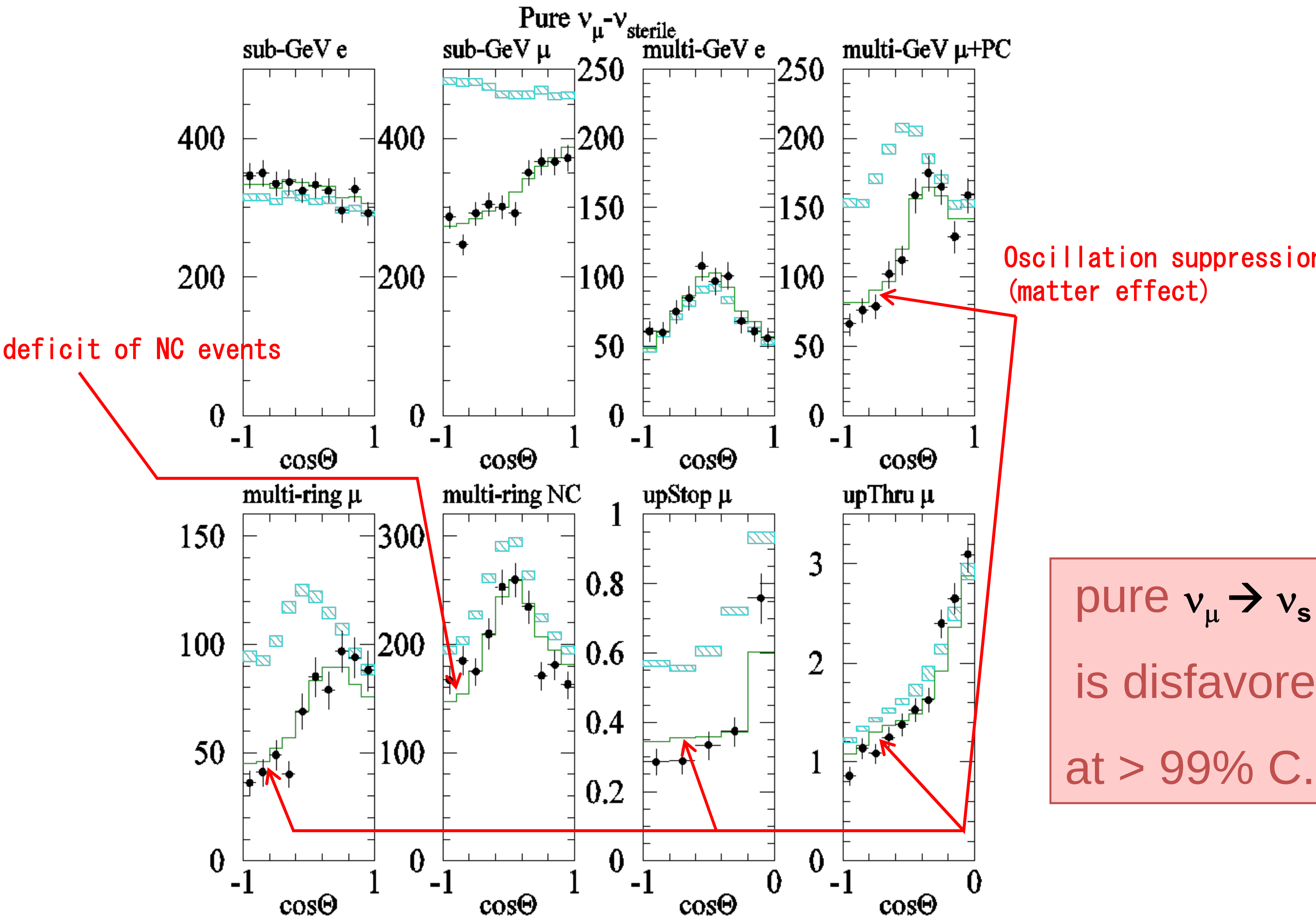
$$\begin{pmatrix} \nu_\mu \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

For $\sin^2 2\theta \sim 1$: $\quad \sin^2 2\theta_m \sim \dfrac{1}{\zeta^2 + 1}$

And for E_ν = 30 ~ 100 GeV

➔ $\zeta \gg 1$ ⇒ **$\sin^2 2\theta_m \ll 1$: Suppression of the oscillation effect**

$\nu_\mu \leftrightarrow \nu_s$ zenith angle distribution



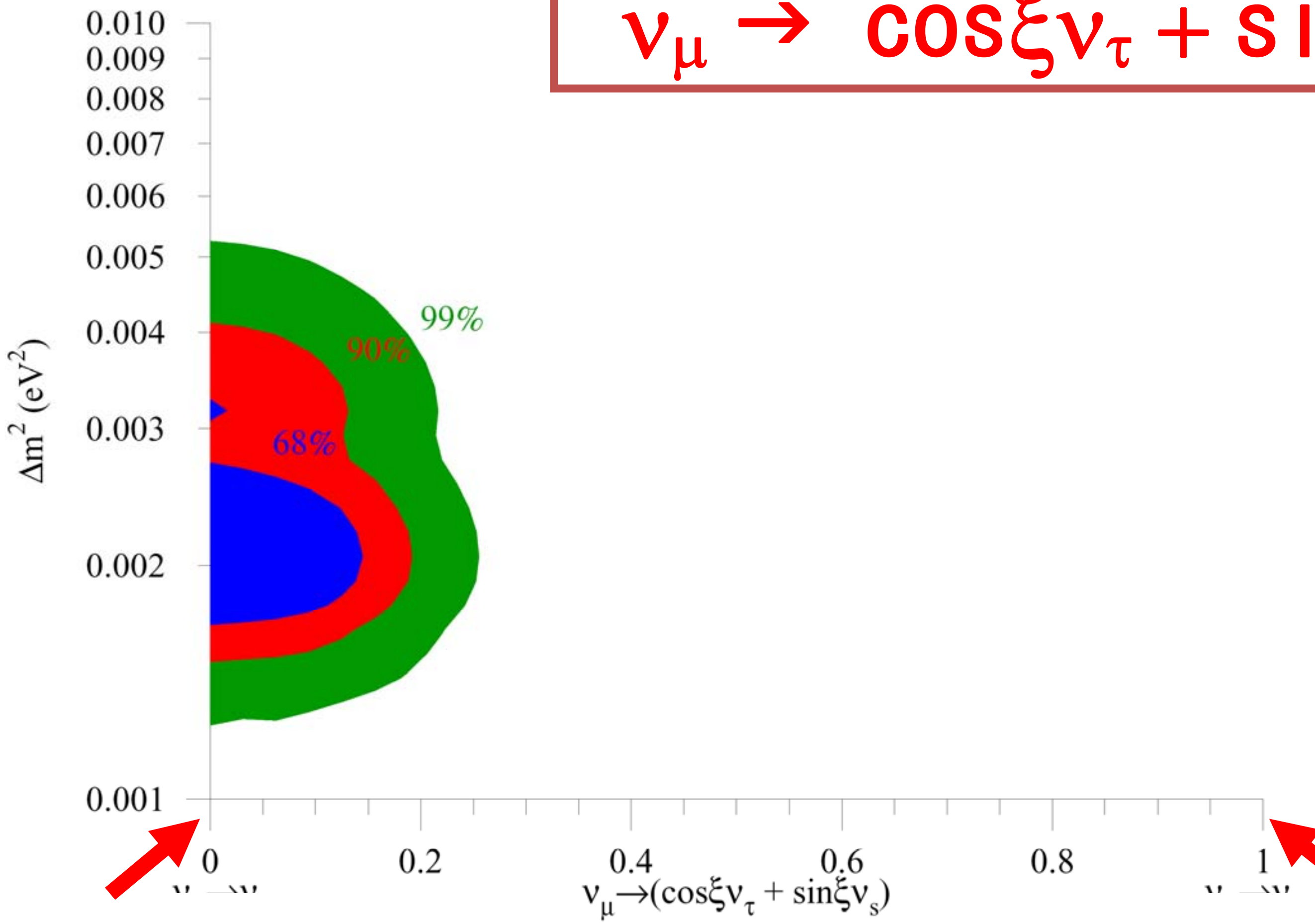
pure $\nu_\mu \rightarrow \nu_s$

is disfavored

at > 99% C.L.

Limit on sterile mixture

$\nu_\mu \rightarrow \cos\xi\nu_\tau + \sin\xi\nu_s$



pure $\nu_\mu \rightarrow \nu_\tau$

$\sin^2\xi$

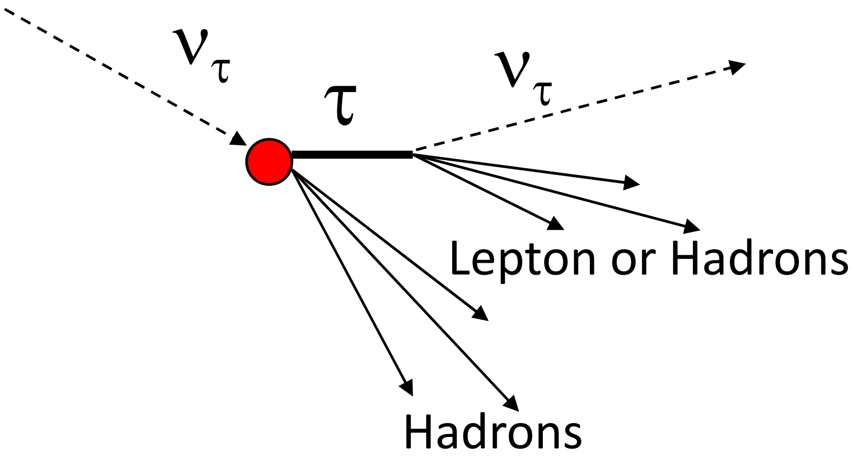
pure $\nu_\mu \rightarrow \nu_s$

ν_τ appearance

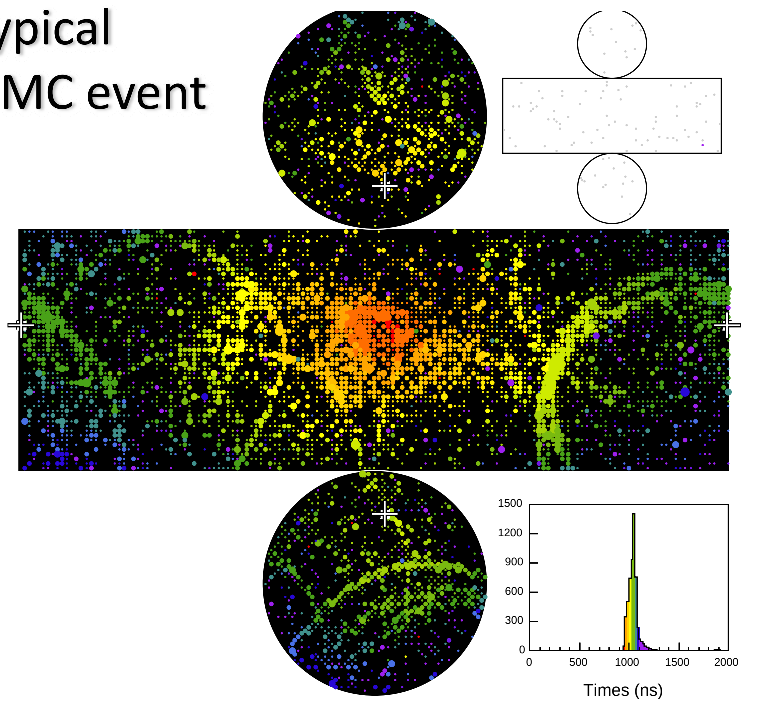
- How we can test it?
- Do we have evidence for ν_τ appearance?

Yes

Search for τ appearance in atmospheric ν



Typical
τ MC event



- τ events cannot be identified by event-by-event basis

  $\nu_\tau + N \rightarrow \tau + N' + \pi + \pi \ldots\ldots$

  (τ →) $\mu\nu\nu$, $e\nu\nu$,

  (τ →) ν+hadrons $(\pi,\pi,\ldots.)$

  → Many Hadrons

  → Rather Spherical

  → Complicated events

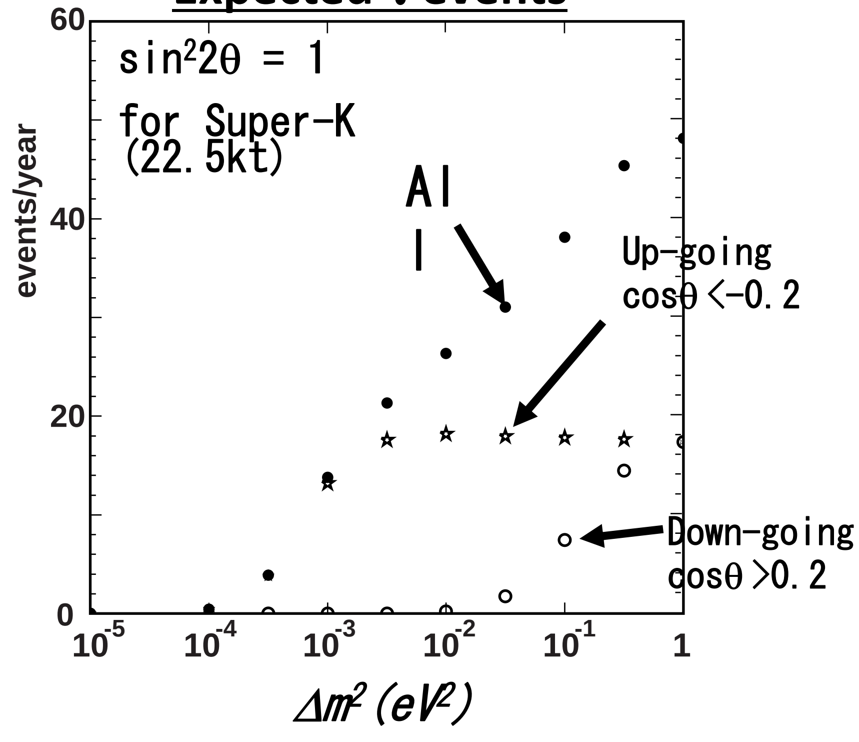
- Make statistical analysis

  ← using characteristics of τ production

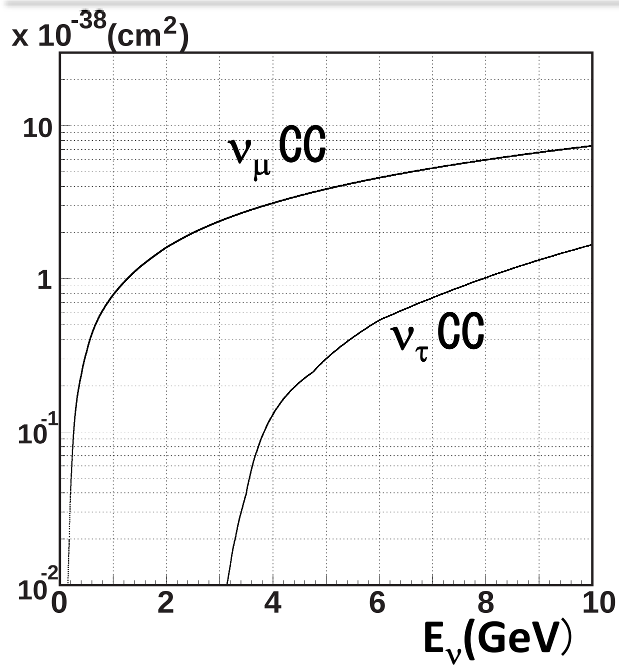
Search for τ appearance in atmospheric ν

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

Expected τ events



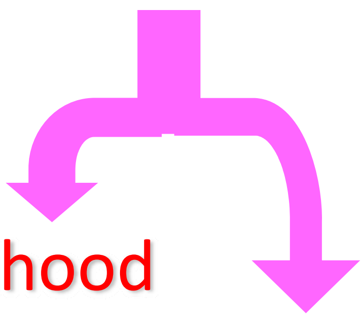
Neutrino CC cross sections



Selection of τ enriched sample

Pre-selection

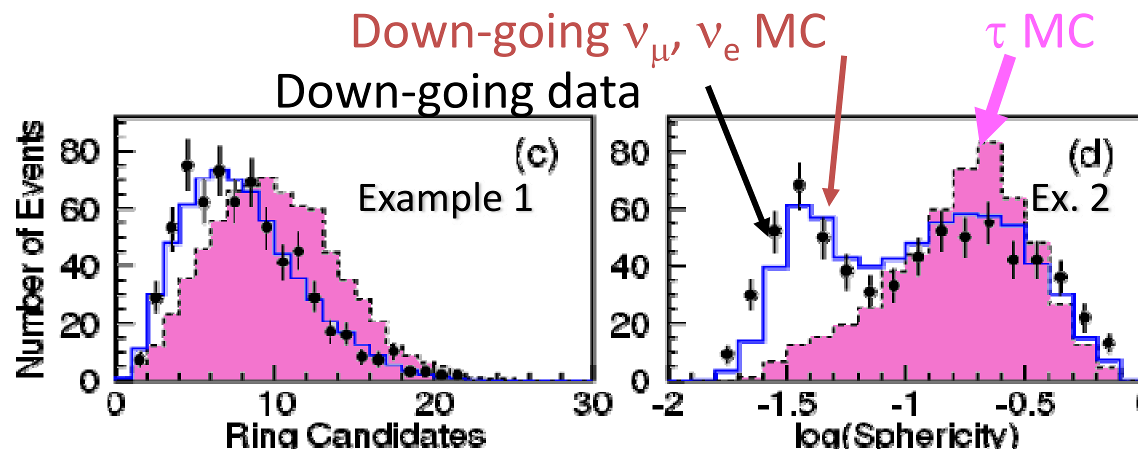
1) multi-GeV, multi-ring
   ➔ High Energy
   many particles
2) Fiducial volume:
   2m from the ID PMTs
3) Most energetic ring:
   e-like



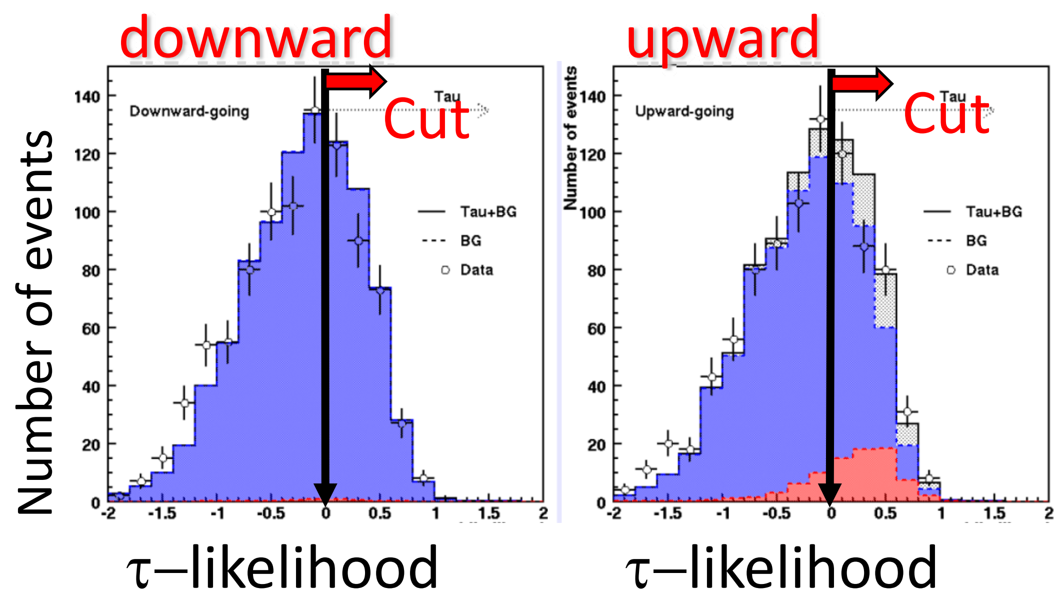
Likelihood

Neural Network

(2 independent analyses)



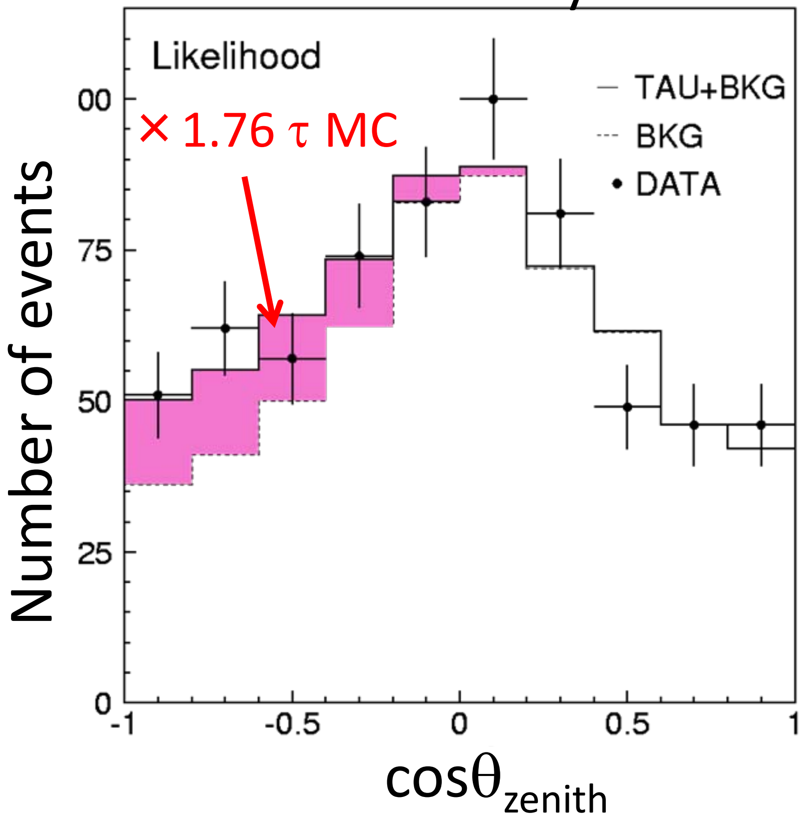
Use 6 distributions to make likelihood



➔ Select τ-like events

Zenith angle dist. and results

Likelihood analysis



Fit in zenith angle distribution to evaluate τ contribution:

$$N_{total}(\cos\theta) = \alpha N_{tau} + \beta N_{bkg}$$

$\alpha = 1.76$ and $\beta = 0.9$

Fitted # of τ events (corr. for 43% efficiency)	138 ±48(stat.) +14.8 /-31.6
Expected # of τ events	78.4±26(syst.)

Tau appearance : 2.4 σ

	Observed.	Expected
Neutral Network:	134±48(stat.) +16 /-27.2	78.4±27(syst)

Both analysis:
consistent with expected excess of upgoing τ's

L/E analysis

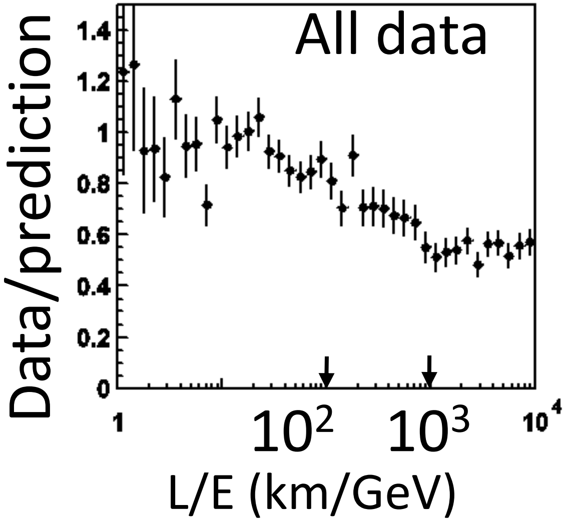
- **Can observe oscillation pattern in L/E plot ← $\lambda \sim E$**
  → direct oscillatory evidence
  → distinguish other exotic hypotheses
  → strong constraint on Δm^2

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

Difficult to see the pattern for all the data

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

~1 /5 of total data

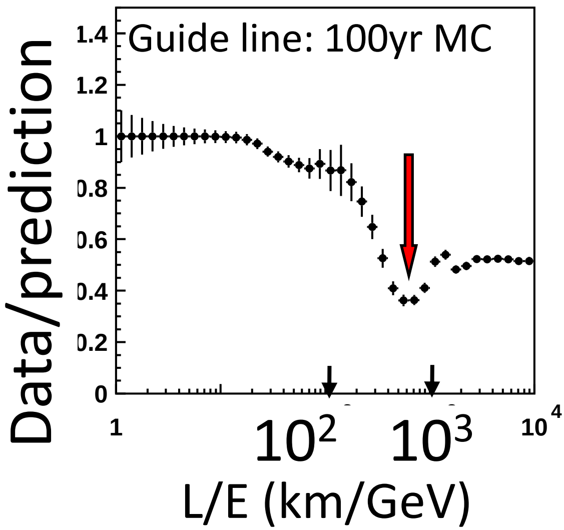


Rejected events

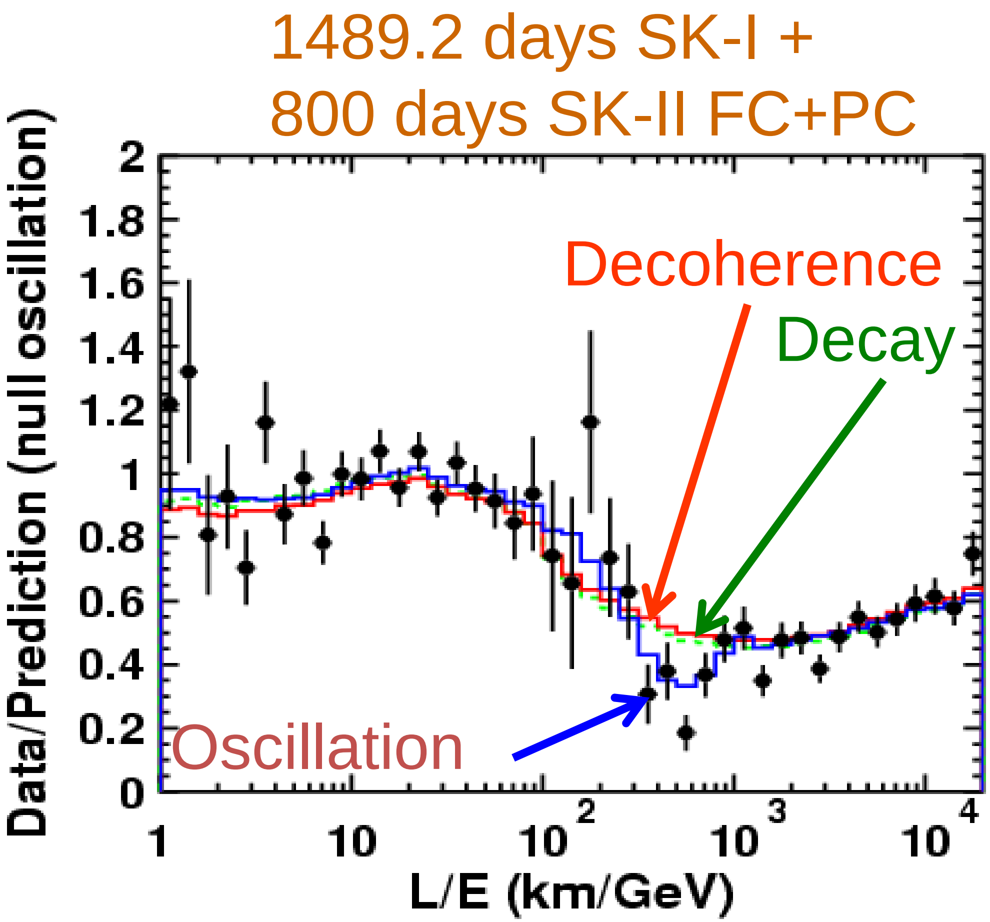
horizontally going events:

low energy events:

→ poor ΔL, $\Delta\theta$ determination

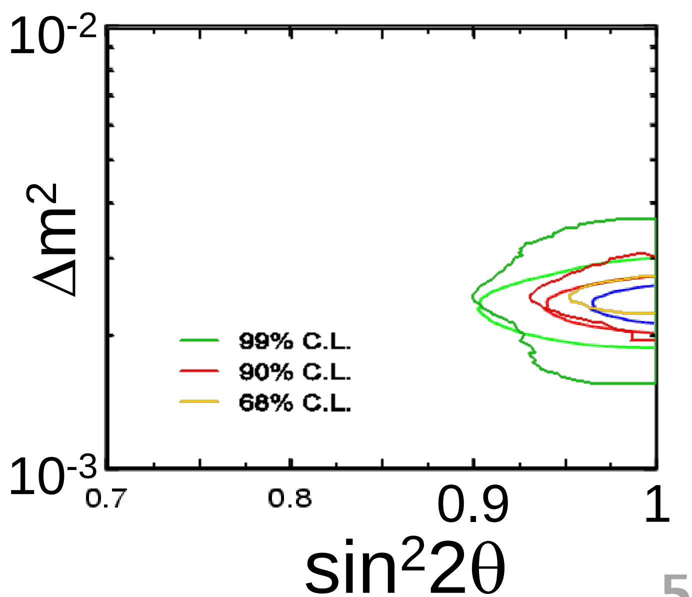


Result of L/E analysis (SK-I + SK-II)



- 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

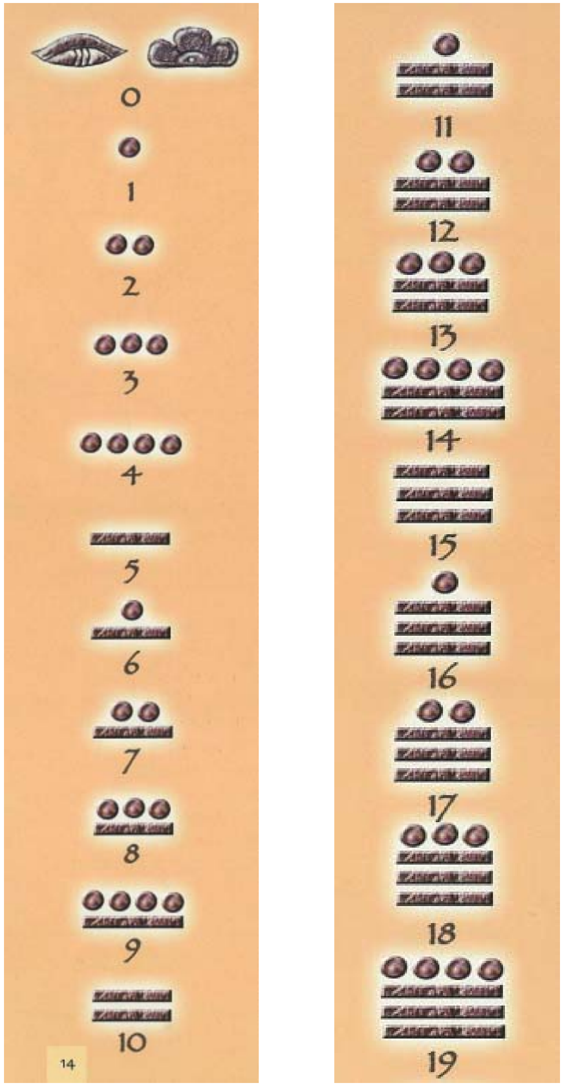


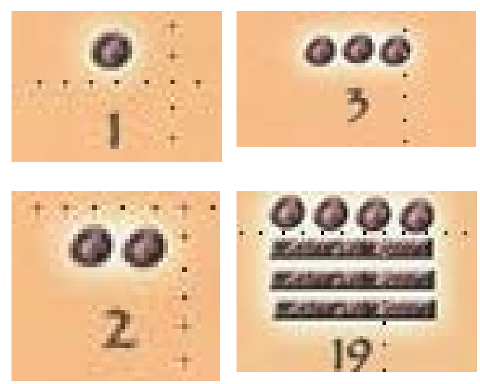
Break !?

Quiz !?

1, 20, 400, ? , ・・・

Mayas Calculus



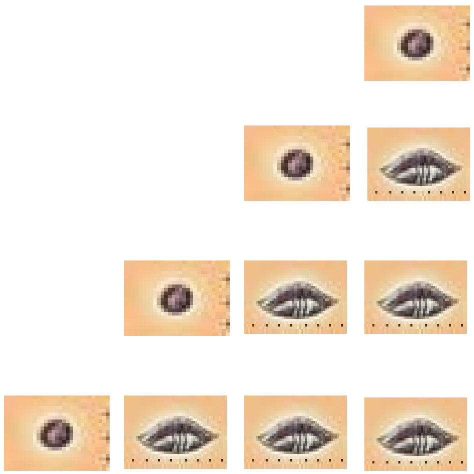


→ 23

→ 59

Vigesimal: base-20 numerical system
They have zero!

The size of Water Cherenkov Detector



1 Kt: Kamiokande

20 Kt: Super-Kamiokande

400 Kt: *HK, UNO, Memphis*
(next generation detectors)

8000 Kt:

Mayas Prediction for the size of
<u>next-next generation</u> Water Cherenkov Detectors
(30 years from now ??)

8 Mega ton detector !?

Sub-dominant effects
and
future atmospheric neutrino experiments

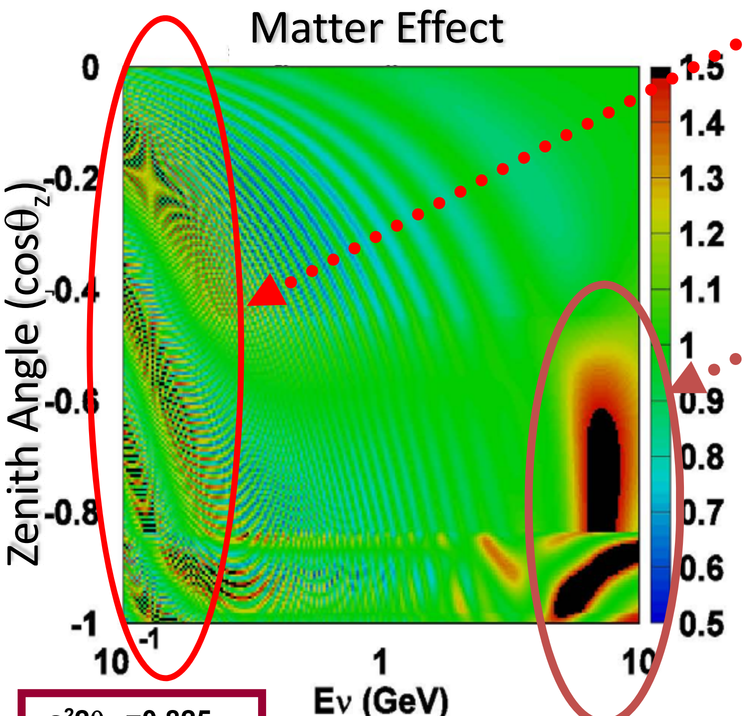
Sub-dominant effects

- We will summarize SK results and sensitivity of future experiments.
- We treat 0.5 Mton (fiducial mass) detectors like HK, UNO, Memphis as next generation experiments and a 5 Mton (fiducial mass) detector like deep-TITAND as a next-next generation experiment.
- For the evaluation of the future sensitivity, we have used full SK simulation to scale to Mton detectors.

3 flavor oscillation and ν_e-appearance

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1) - r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2) + 2\tilde{s}_{13}^2(r \cdot s_{23}^2 - 1)$$

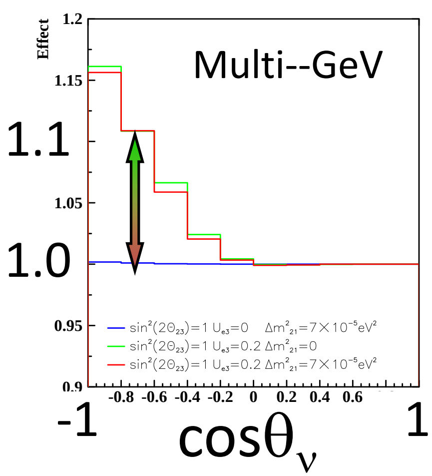
~ : mixing angle in matter
$P_2 = |A_{e\mu}|^2$: $\nu_e \rightarrow \nu_{\mu\tau}$ in matter
$R_2 = Re(A^*_{ee}A_{e\mu})$
$I_2 = Im(A^*_{ee}A_{e\mu})$



1^{st} term: solar term (θ_{12}, Δm_{12})
mostly in low energy
cancellation effect (c^2_{23}=0.5, $r=\nu_\mu/\nu_e$=2@LE)
1~2% effect

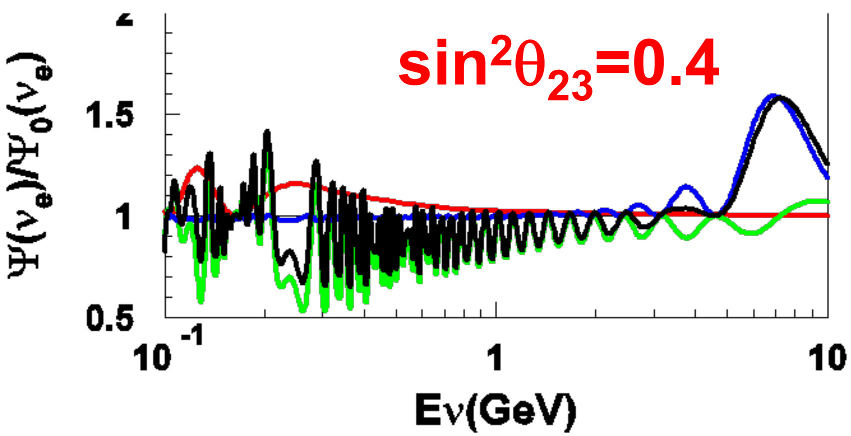
3^{rd} term: θ_{13} term
> a few GeV
in multi-GeV
10~15% effect

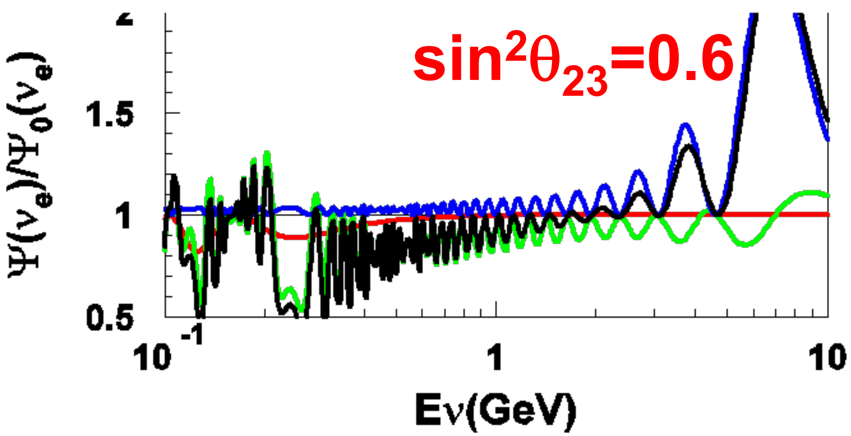
2^{nd} term: Interference
CP-phase

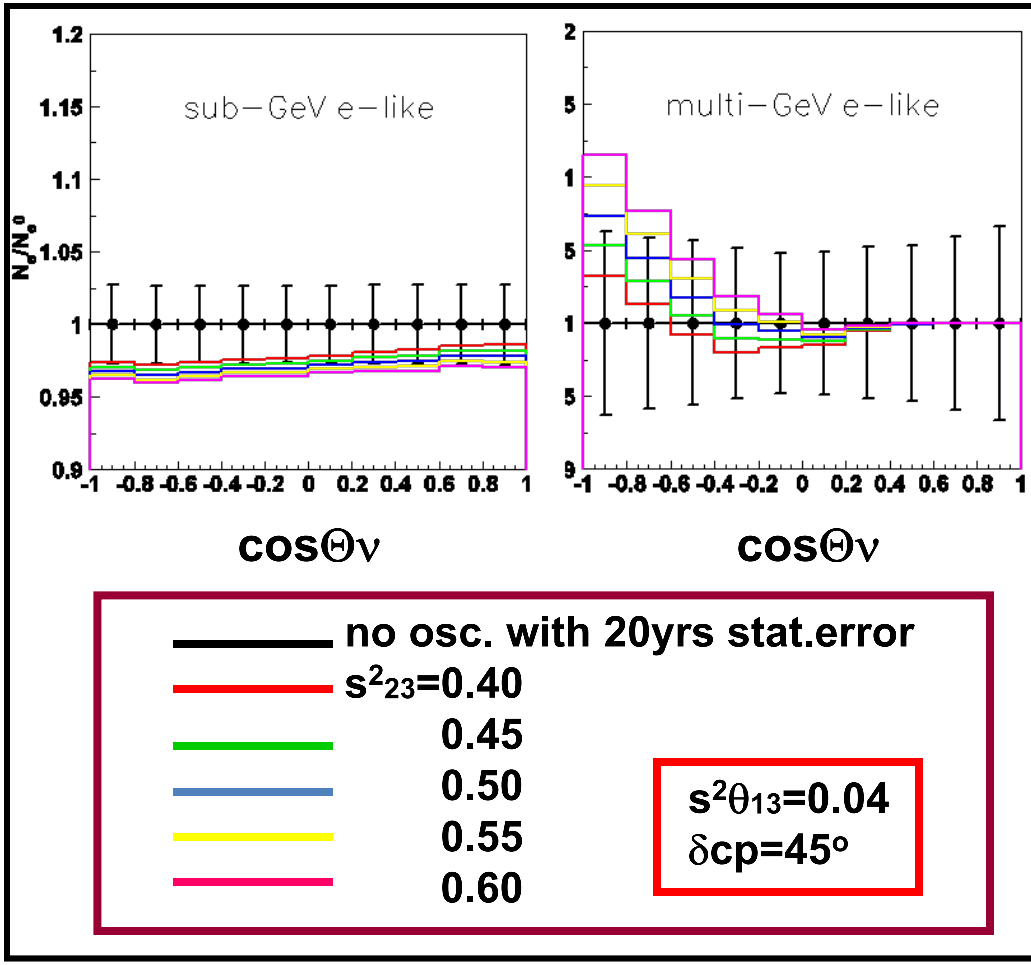


$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4
$s^2\theta_{13}$=0.04
δ_{cp}=45°
Δm^2_{12}=8.3x10^{-5}
Δm^2_{23}=2.5x10^{-3}

θ_{23} and Octant







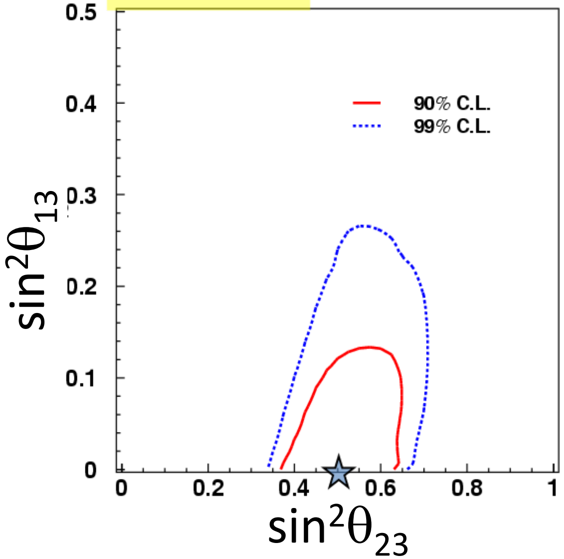
$s^2\theta_{13}=0.04$
$\delta cp=45^o$
$\cos\Theta\nu=-0.8$

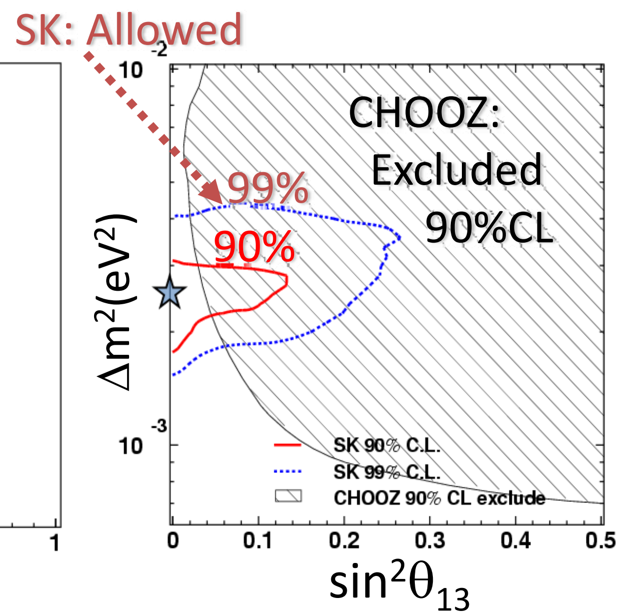
- Total
- Solar term
- θ_{13} term
- Interference

Fixed
Δm^2_{23} = 2.5x10^{-3}eV^2 (positive)
Δm^2_{12} = 8.3x10^{-5}eV^2
$\sin^2 2\theta_{12}$ = 0.825

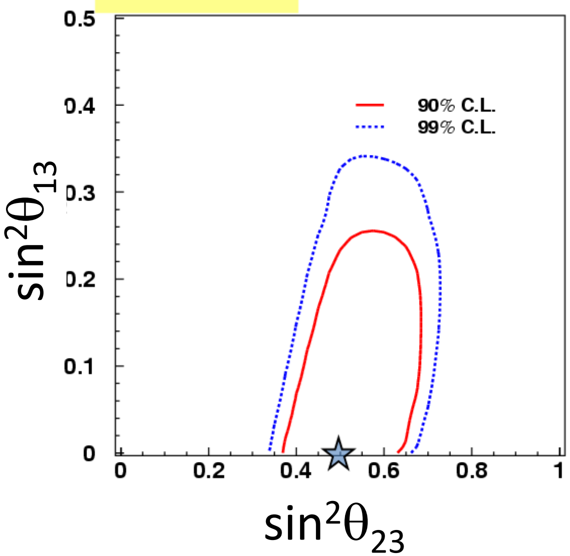
SK 3 flavor analysis (θ_{13}; without solar term)

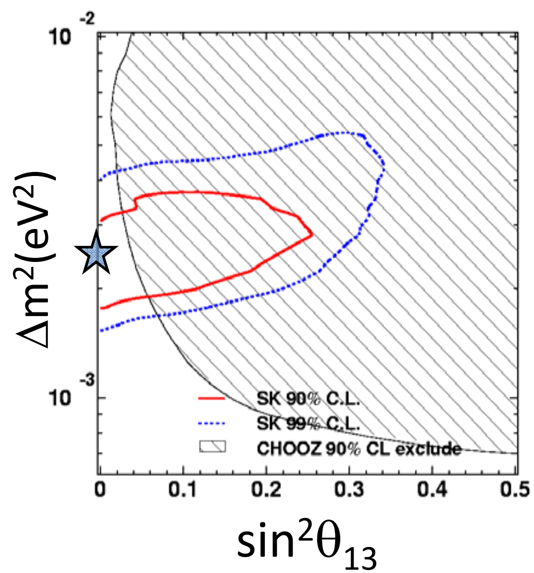
Normal





Inverse





The effect of θ_{13} was looked for

- could not find a positive signal
- set upper limit for both
  - normal hierarchy and
  - inverted hierarchy

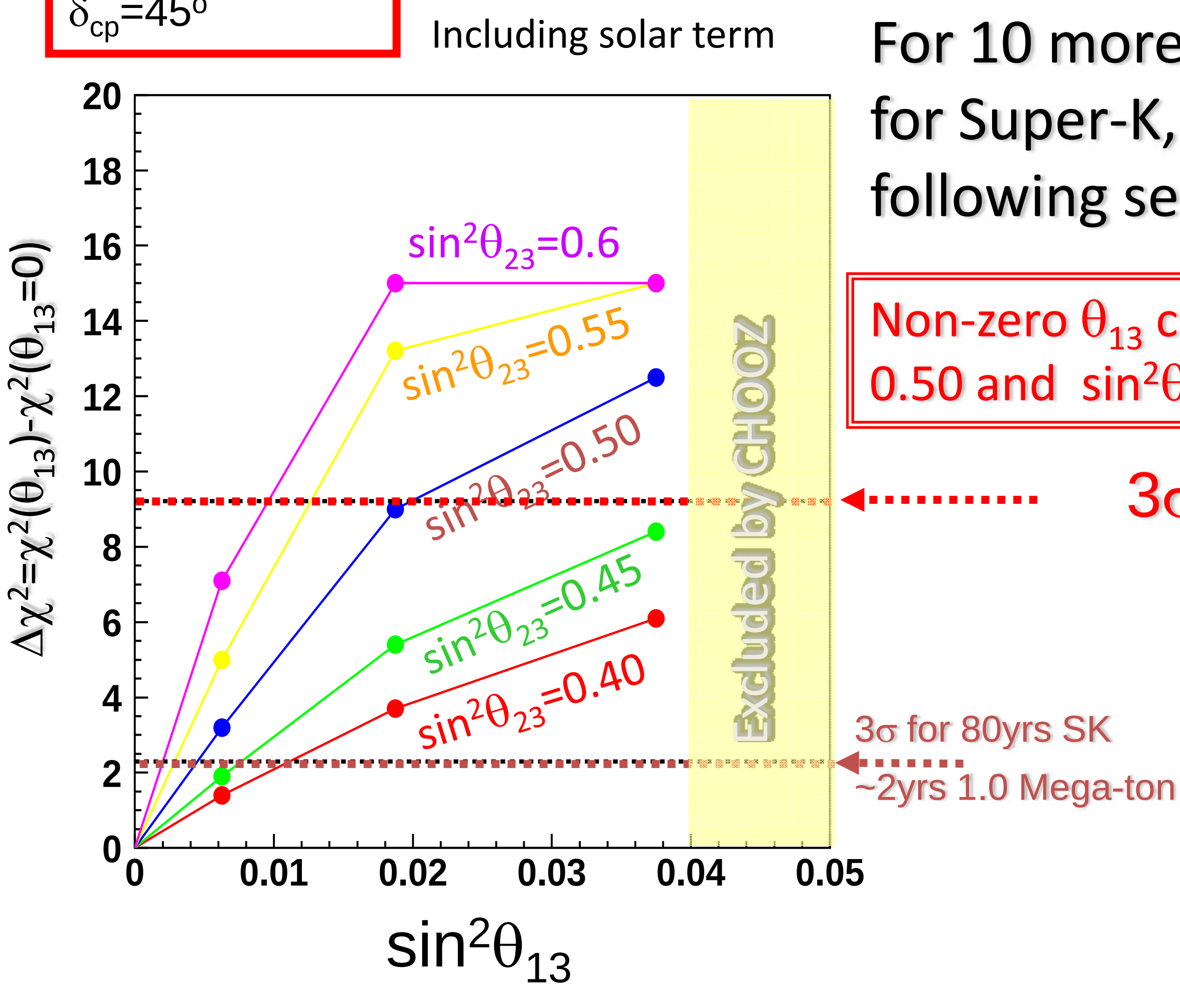
For the normal hierarchy case,
χ^2_{min}/dof= 376.82/368
@(2.5×10^{-3}, 0.5, $\sin^2\theta_{13}$=0.0)

Parameter Range (90% C.L.)
$\sin^2\theta_{13} < 0.14$
$0.36 < \sin^2\theta_{23} < 0.65$

For the inverted hierarchy case,
χ^2_{min}/dof= 376.76/368
@(2.5×10^{-3}, 0.525,
$\sin^2\theta_{13}$=0.000625)

Future sensitivity for non-zero θ_{13}

$s^2 2\theta_{12}=0.825$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$
$\delta_{cp}=45^o$



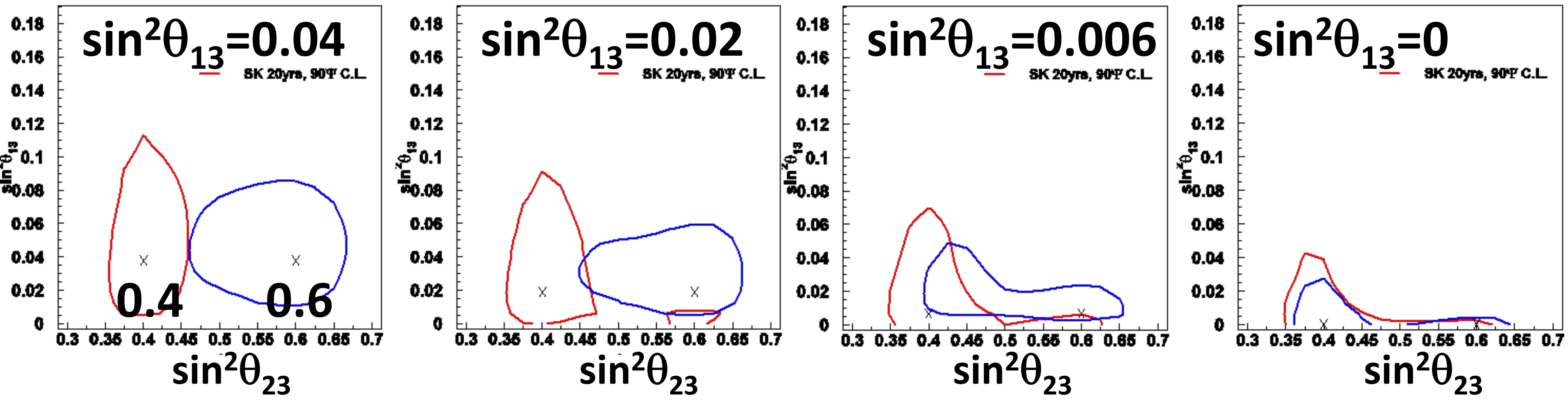
For 10 more years (20yrs) of data for Super-K, we can reach the following sensitivity.

Non-zero θ_{13} can be observed for $\sin^2\theta_{23} > 0.50$ and $\sin^2\theta_{13} > 0.01\sim0.02$

3σ for 20 yrs SK

For 80yr of SK, ~2yrs of 1 Mt detector
➔ $\sin^2\theta_{13} < 0.01$ for most of the value of $\sin^2\theta_{23}$

Discrimination of the θ_{23} octant for SK-20 yrs



Reconstructed 90%CL contours

for the evens produced at the test points,

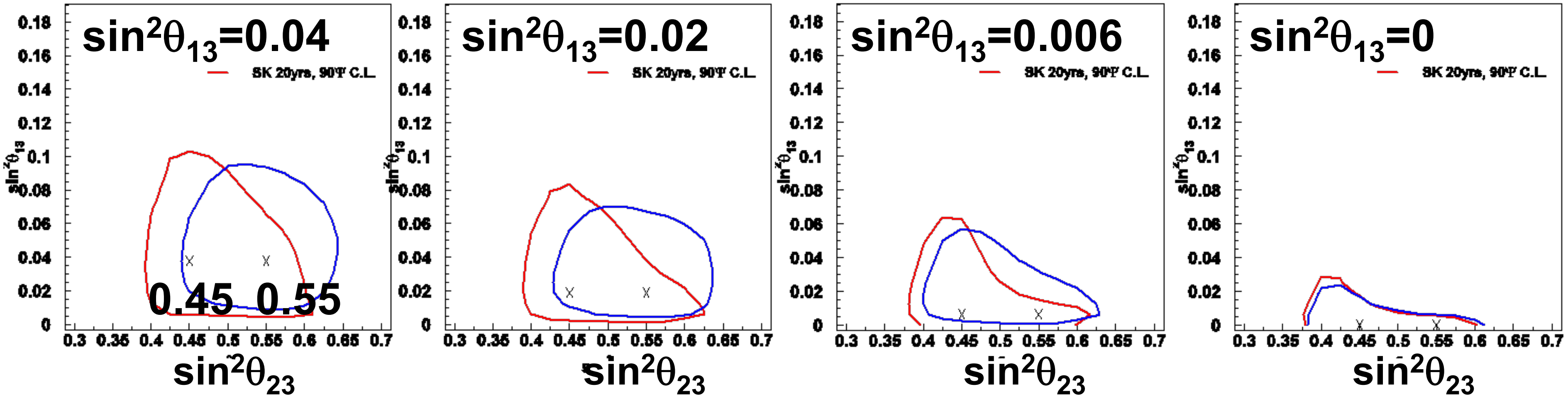
($\sin^2\theta_{23}$= 0.4 and 0.6 ($\sin^2 2\theta_{23}$=0.96)

with various value of $\sin^2\theta_{13}$)

See whether the separation is possible or not

Possible for larger $\sin^2\theta_{13}$ for SK 20 yrs

Discrimination of the θ_{23} octant for SK-20 yrs

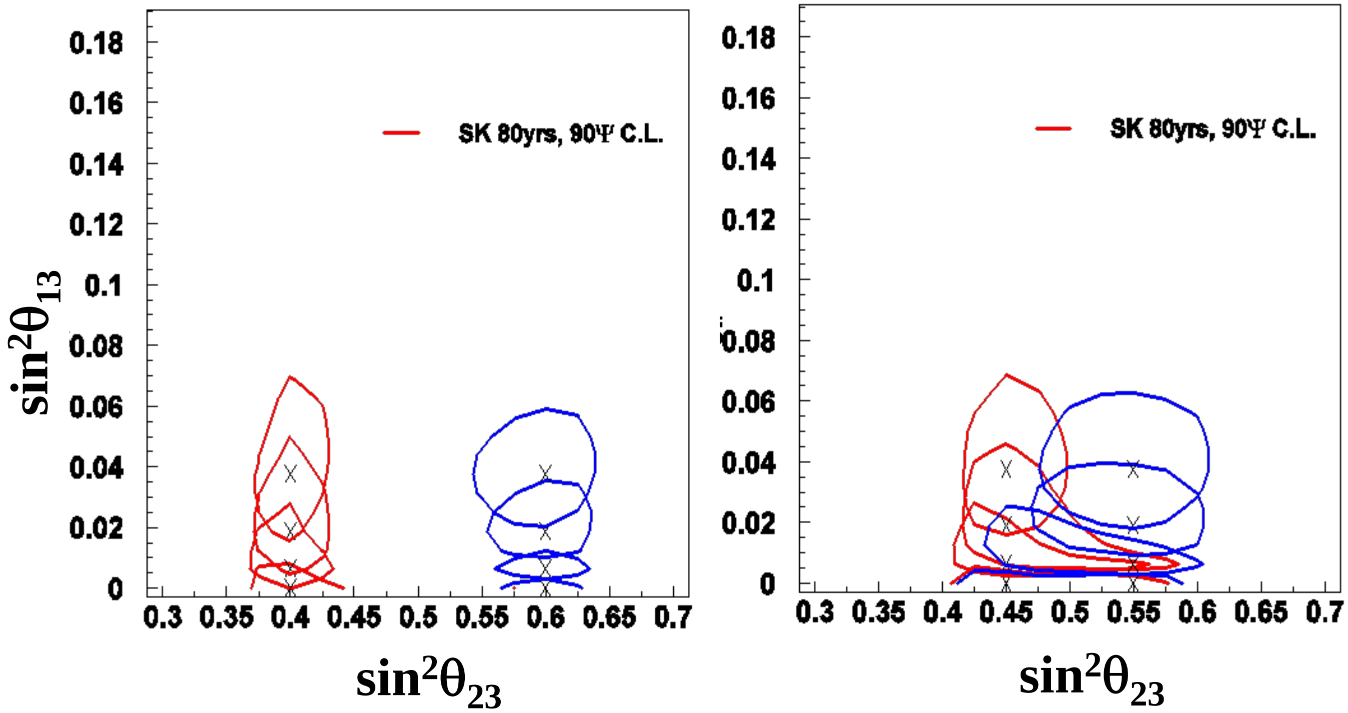


For $\sin^2\theta_{23}$= 0.45 and 0.55

Difficult for SK 20 yrs

80yrs SK ~ 3.6yrs of UNO or HK

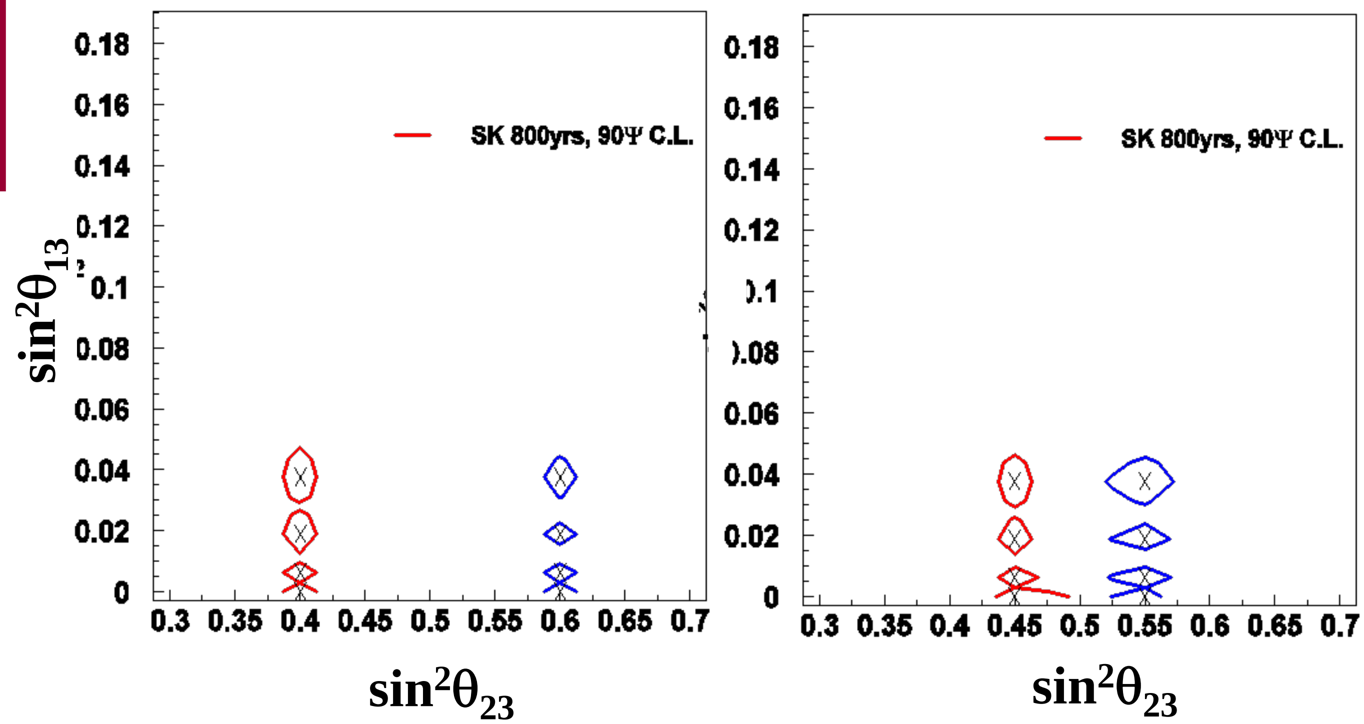
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3x10^{-5}$
$\Delta m^2_{23}=2.5x10^{-3}$



For UNO or HK, discrimination is possible for $\sin^2\theta_{23}$ = 0.40 or 0.60 ($\sin^2 2\theta_{23}$=0.96)

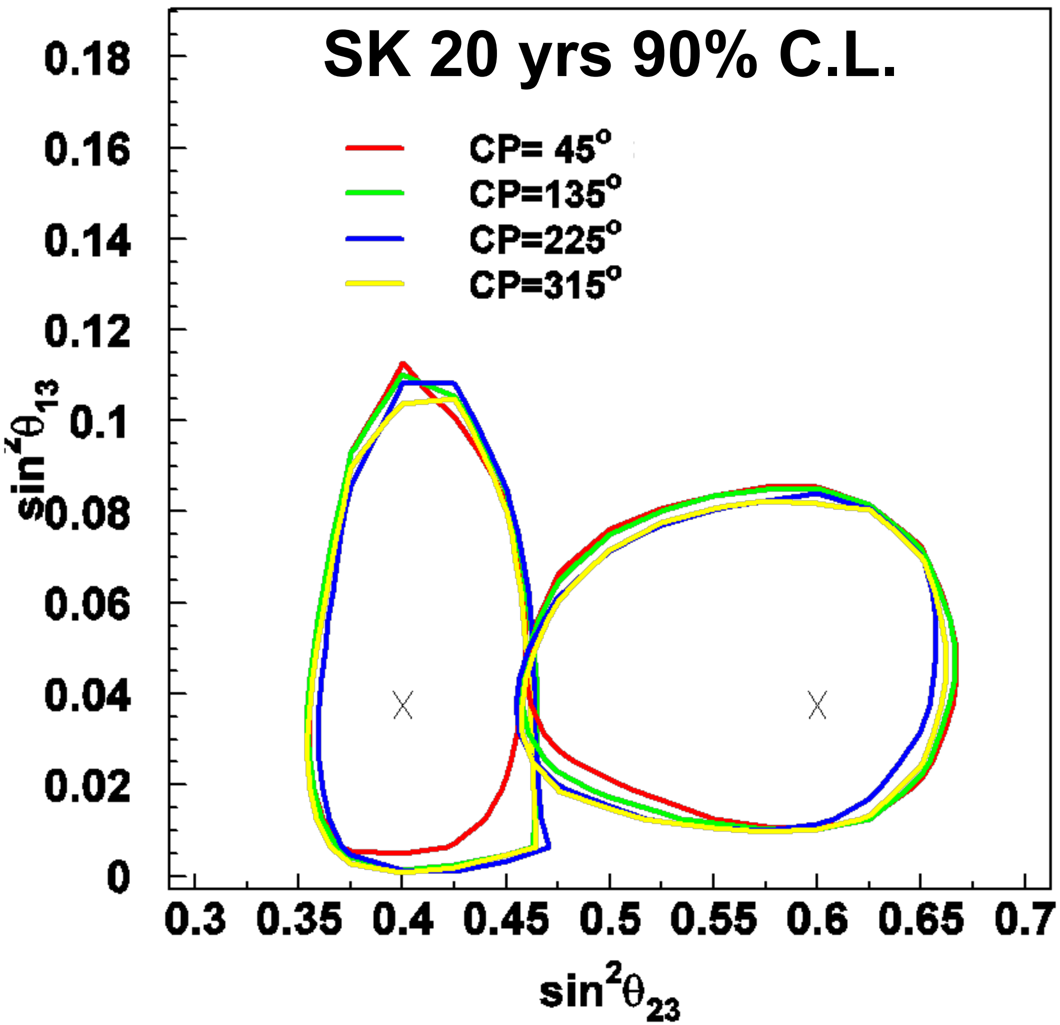
800yrs SK ~ 4yrs of Deep-TITAND

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00 \sim 0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$

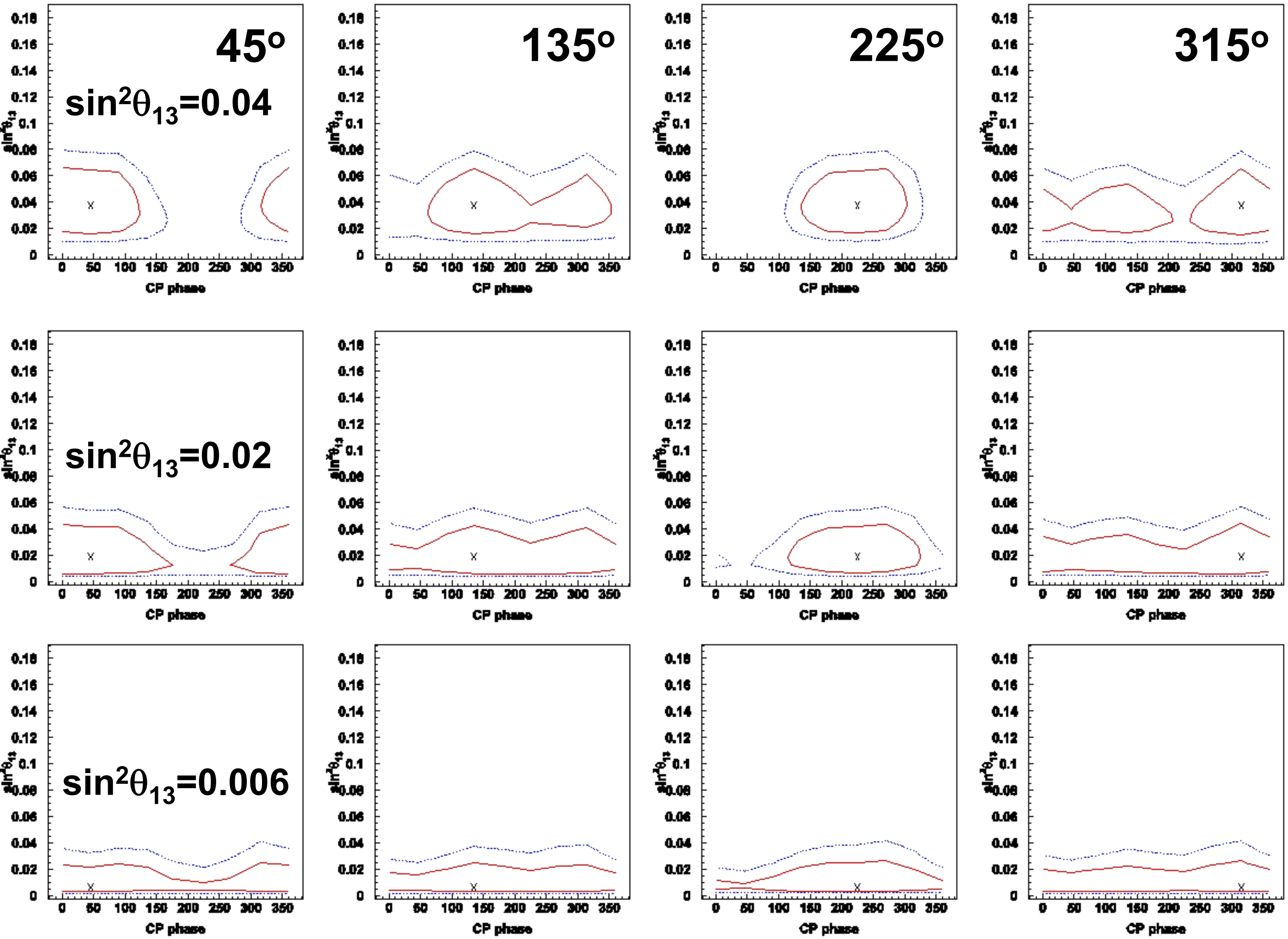


For Deep-TITAND, octant can be resolved for $\sin^2\theta_{23} > 0.45$ or < 0.55 ($\sin^2 2\theta_{23} > 0.99$)

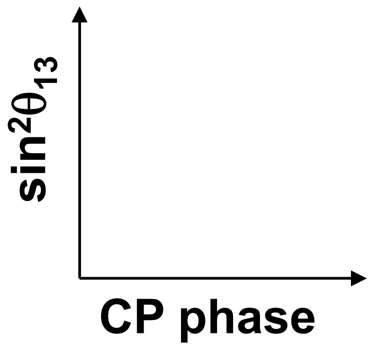
No strong CP phase dependence for Octant search



CP phase (80yrs SK = 3.6yrs of UNO or HK)

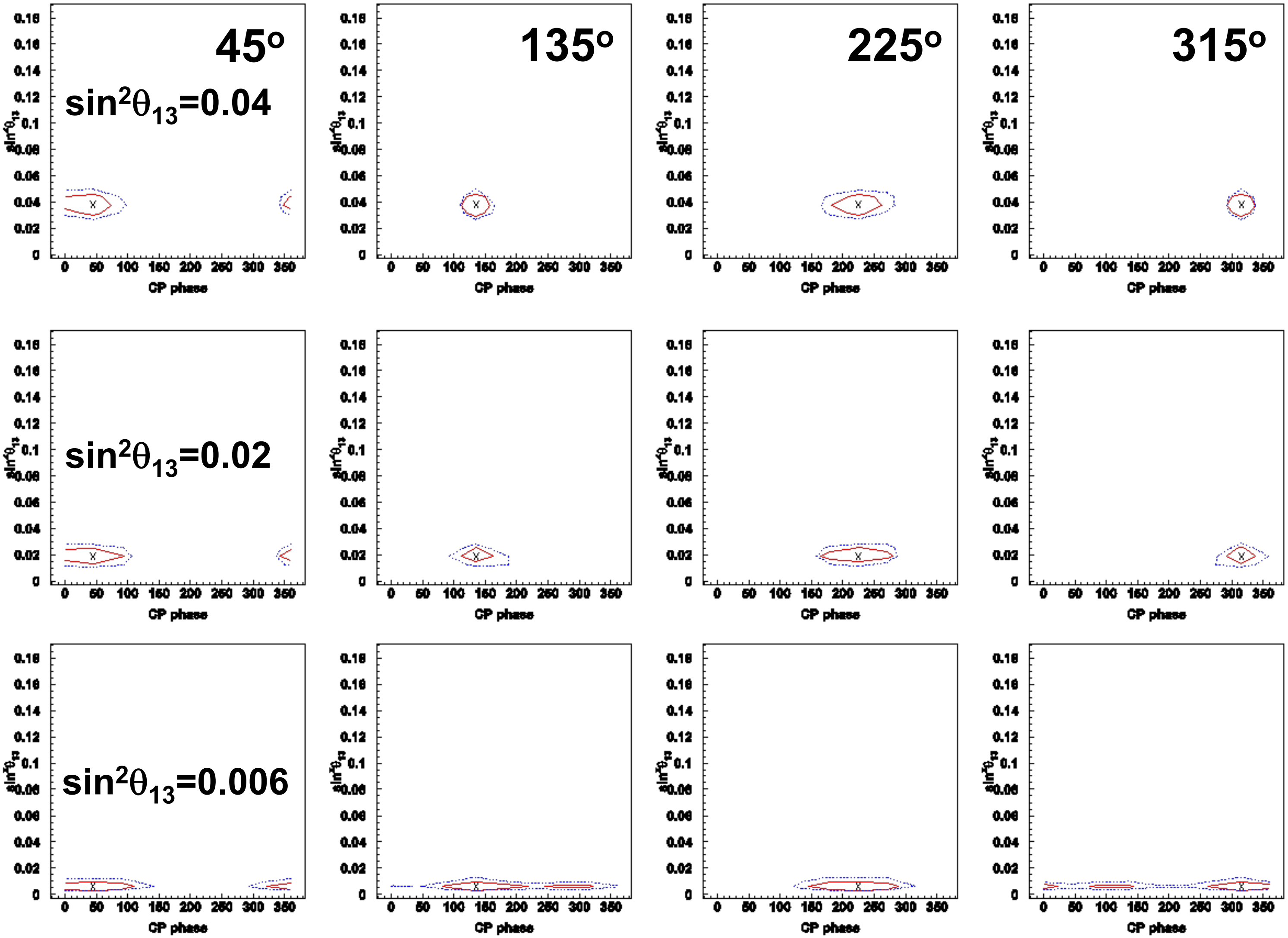


$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.006\sim0.04$
$\delta cp=0^o\sim360^o$
$\Delta m^2_{12}=8.3\text{x}10^{-5}$
$\Delta m^2_{23}=2.5\text{x}10^{-3}$

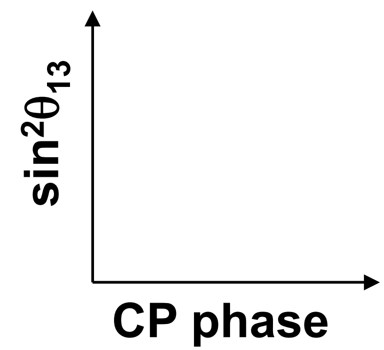


For UNO or HK, CP phase may be seen if θ_{13} is close to the CHOOZ limit

CP phase (800yrs SK = 4 yrs of Deep-TINTAND)



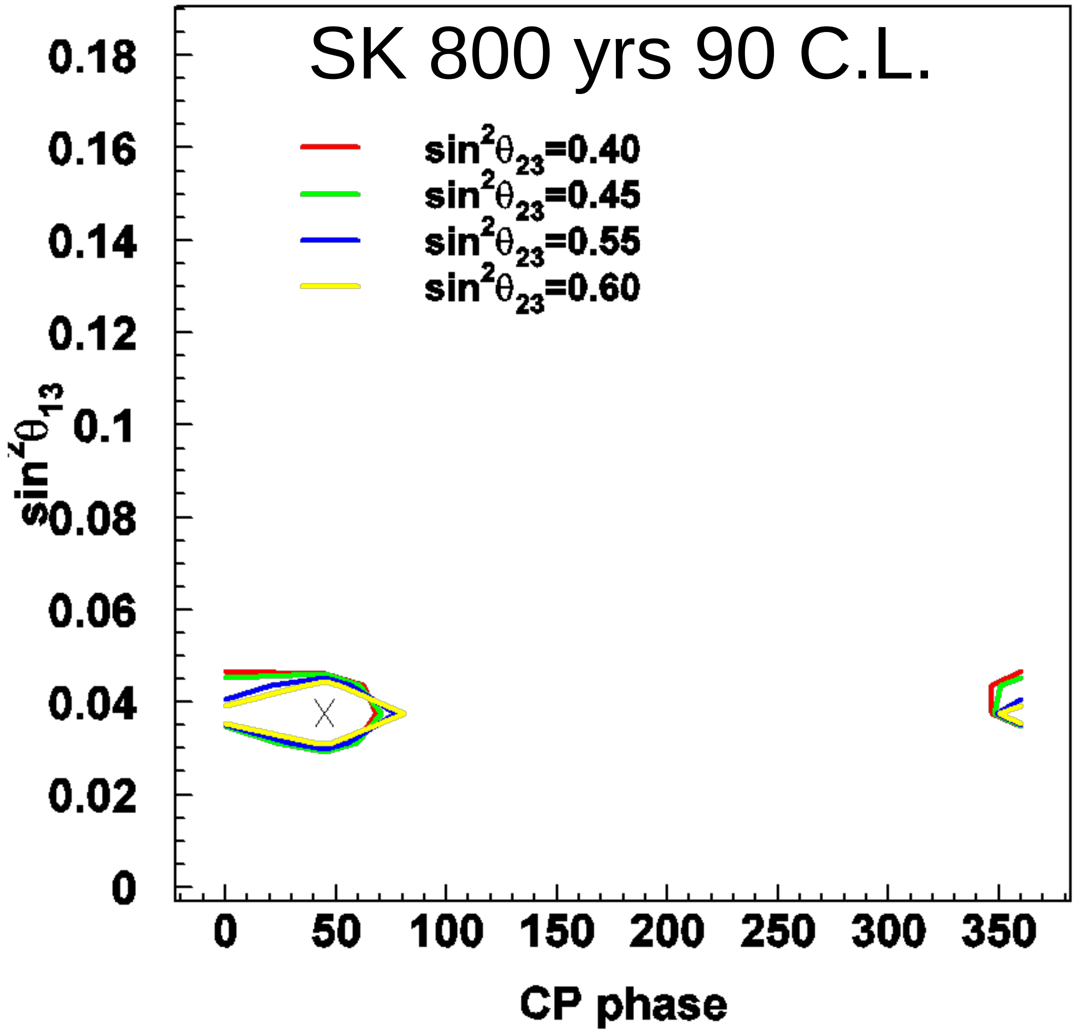
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.006\sim0.04$
$\delta cp=0^o\sim360^o$
$\Delta m^2_{12}=8.3\text{x}10^{-5}$
$\Delta m^2_{23}=2.5\text{x}10^{-3}$



No degeneracy

For Deep-TITAND, CP phase could be determined if θ_{13} is larger than $\sin^2\theta_{13}\sim 0.006$

No strong θ_{23} dependence for CP phase search

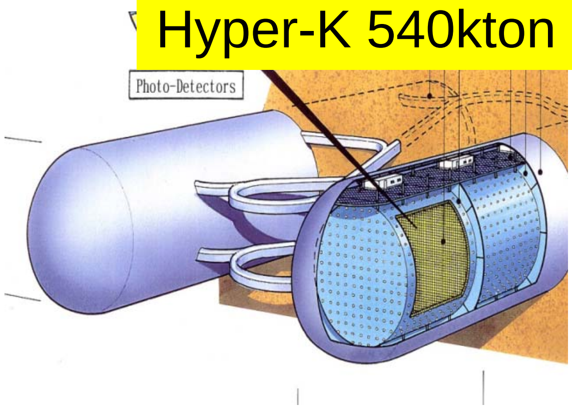


Future Detectors

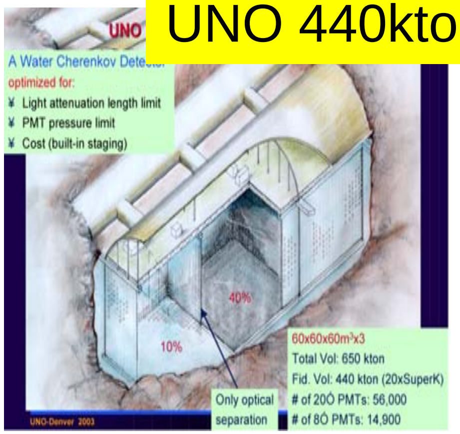
‘Standard’ <u>Next</u> Generation Experiments

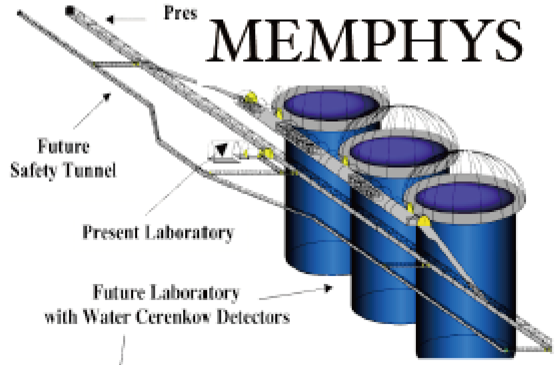
- Typical → Detector 0.5 Mton (fiducial Volume)

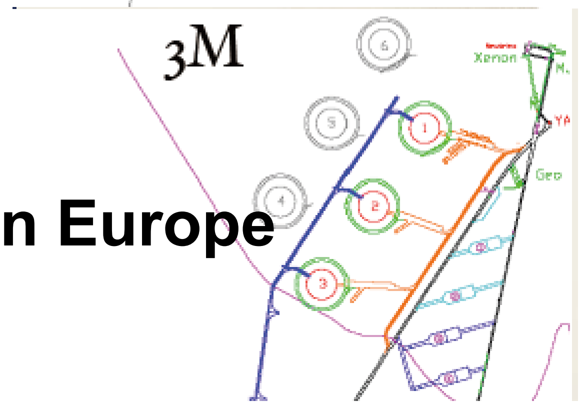
Hyper-K 540kton



UNO 440kton







In Japan

In US

In Europe

- ***Underground detectors***

Next-next generation detector (Multi-Megaton Detector) What kind?

Requirements for the detector

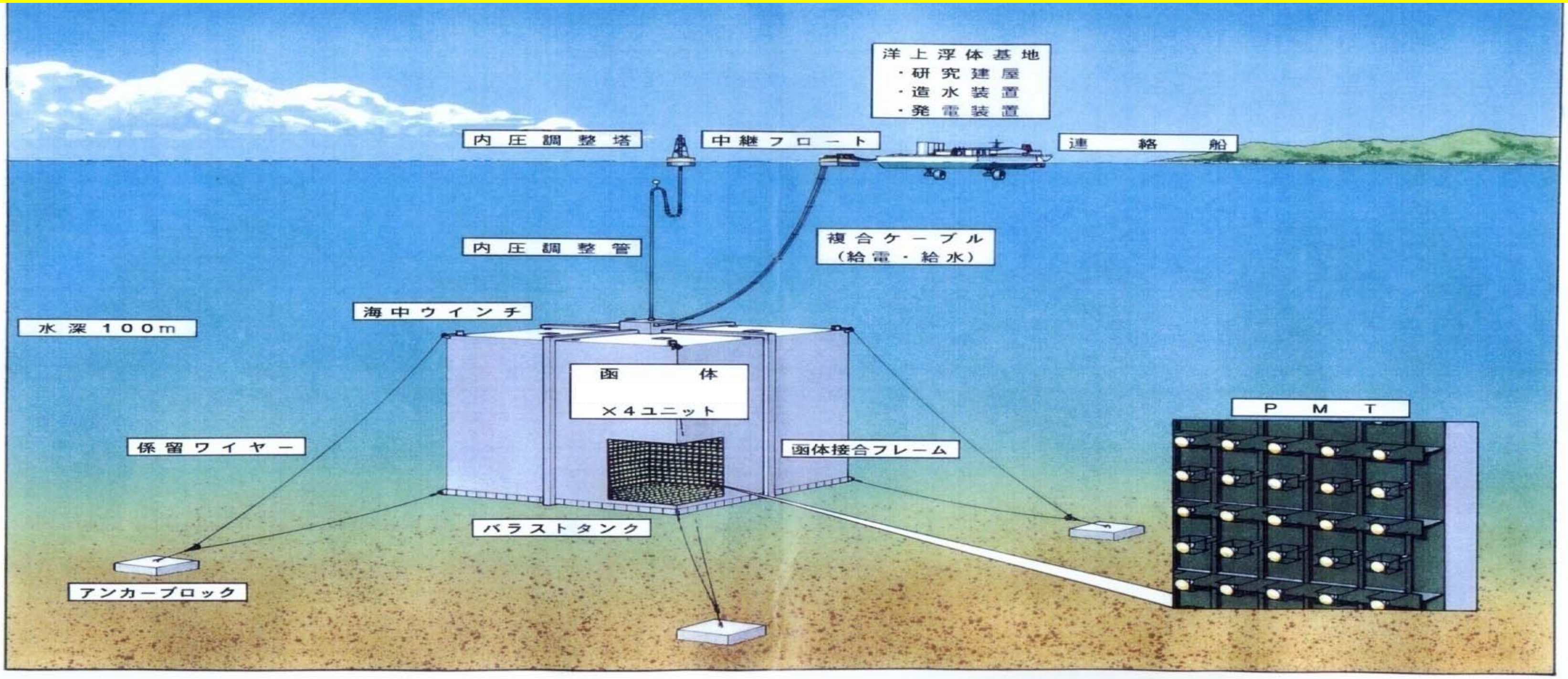
1) Scalability: may start with 1 Mt

   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)

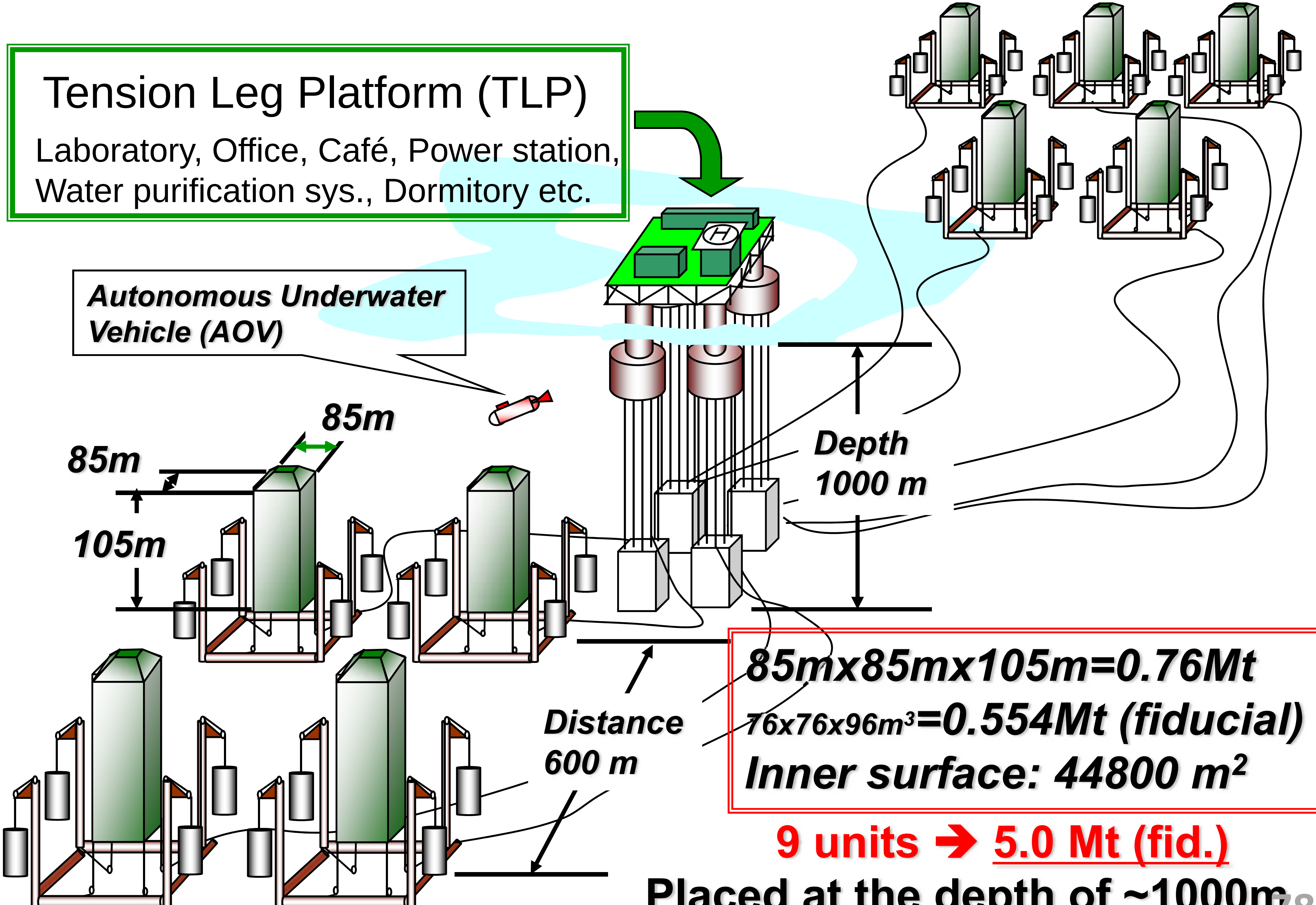
Ref:1) Y. Suzuki, hep-ex/0110005 (in 2001)
2) Y. Suzuki, in Proc. of Neutrino Oscillation in Venice, Feb, 2006

But this is shallow @100 m depth

Deep-TITAND

Tension Leg Platform (TLP)

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



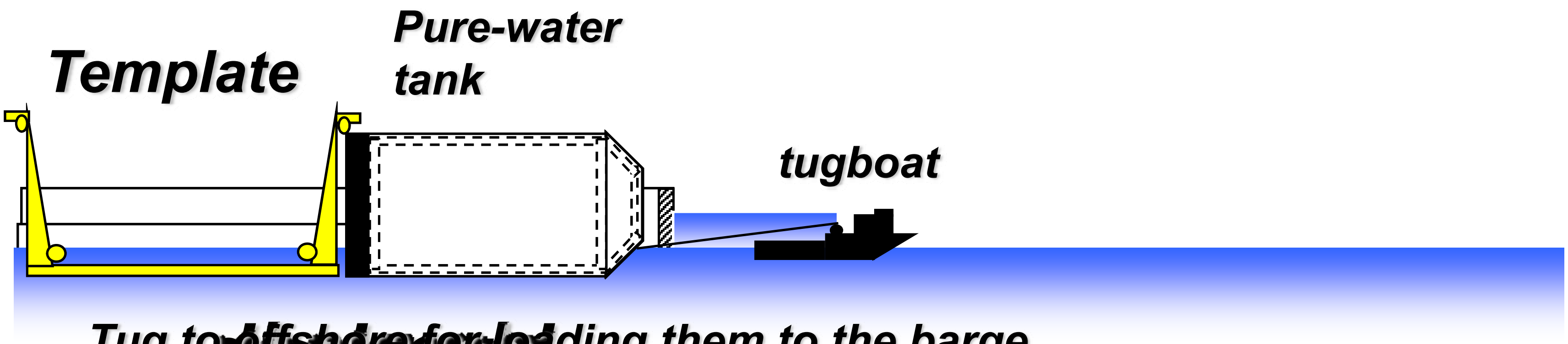
85mx85mx105m=0.76Mt

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

Inner surface: 44800 m^2

9 units ➔ <u>5.0 Mt (fid.)</u>

Placed at the depth of ~1000m



Tug to offshore for loading them to the barge

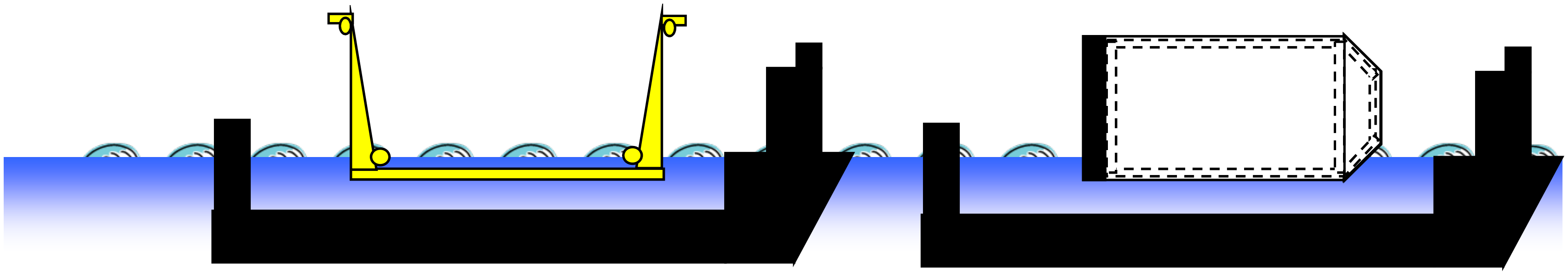
How to construct

Construct steel container (unit) at the DOCK

- **85m x 85m x 105m**
- **Maximum size of DOCK in the world**
  - **➔ width:108m x length: 480m**

Install PMTs(or equivalent)

- **Number of PMTs**
- **44,800 PMTs for one unit**
  - **(for 1/2 SK density)**

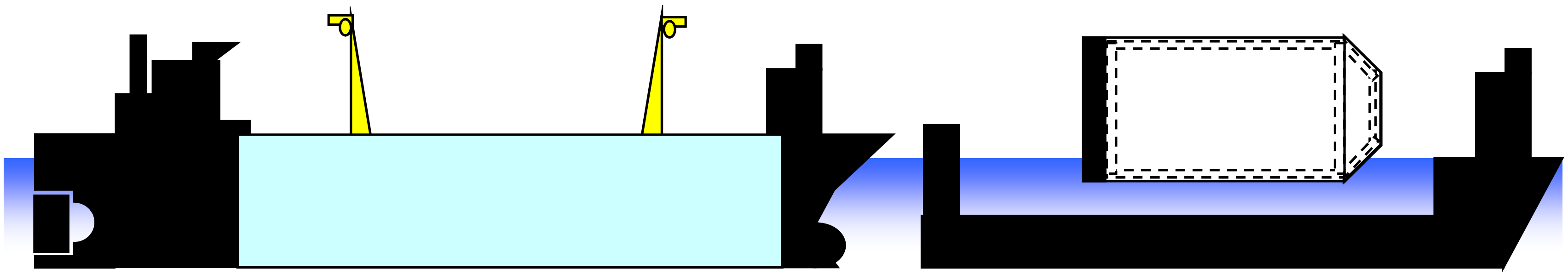


Sinking barge
(loading capacity:
20,00[illegible])

Move to the installation site

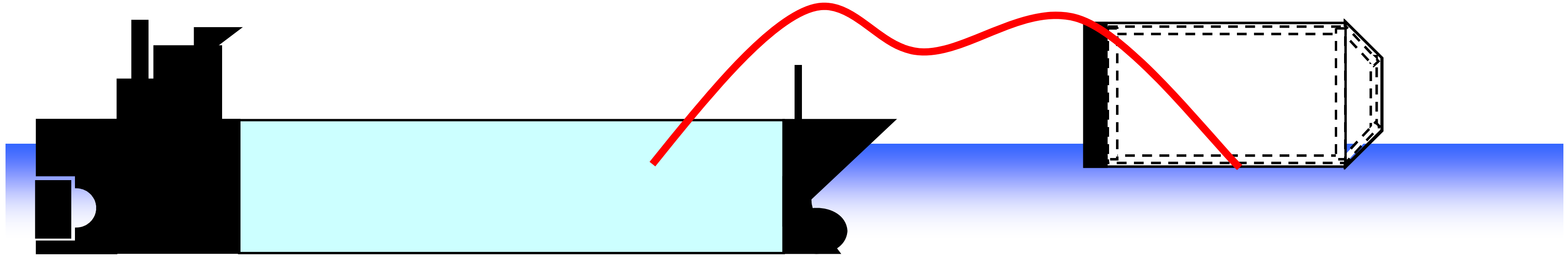
Sinking barge

The installation site



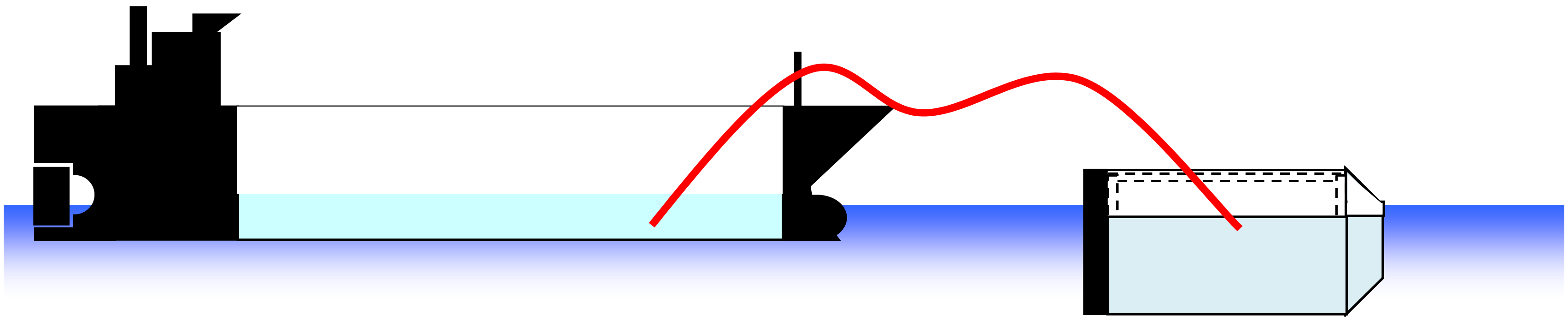
Unload the template and the water tank

Bring a Ultra Large Crude Oil Carrier (ULCC)
which containes pure water

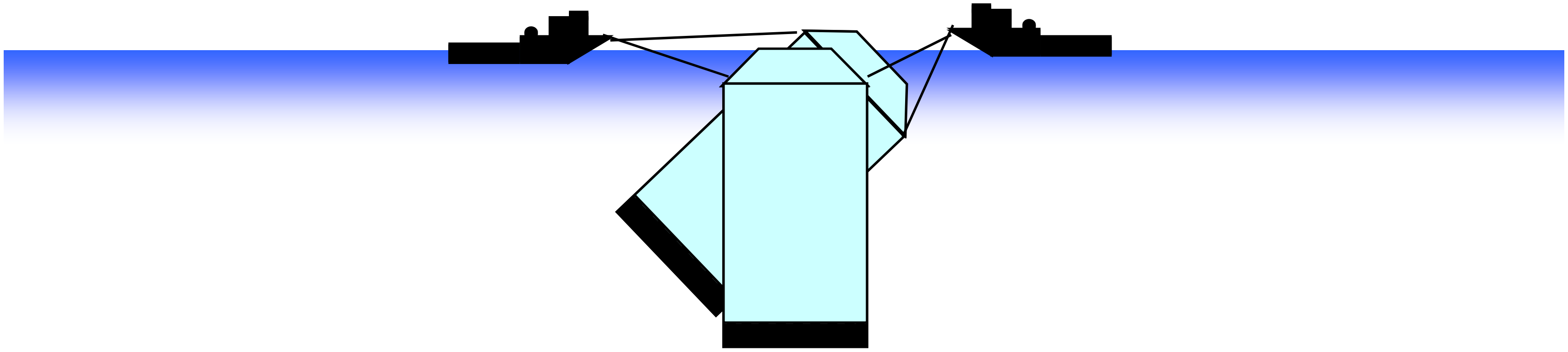


Bring a Ultra Large Crude Oil Carrier (ULCC)
which contains pure water

ULCC: 300ktons x 3 ➔ 760ktons for one unit
Transfer speed 10ktons /hour (30 hours /ship)

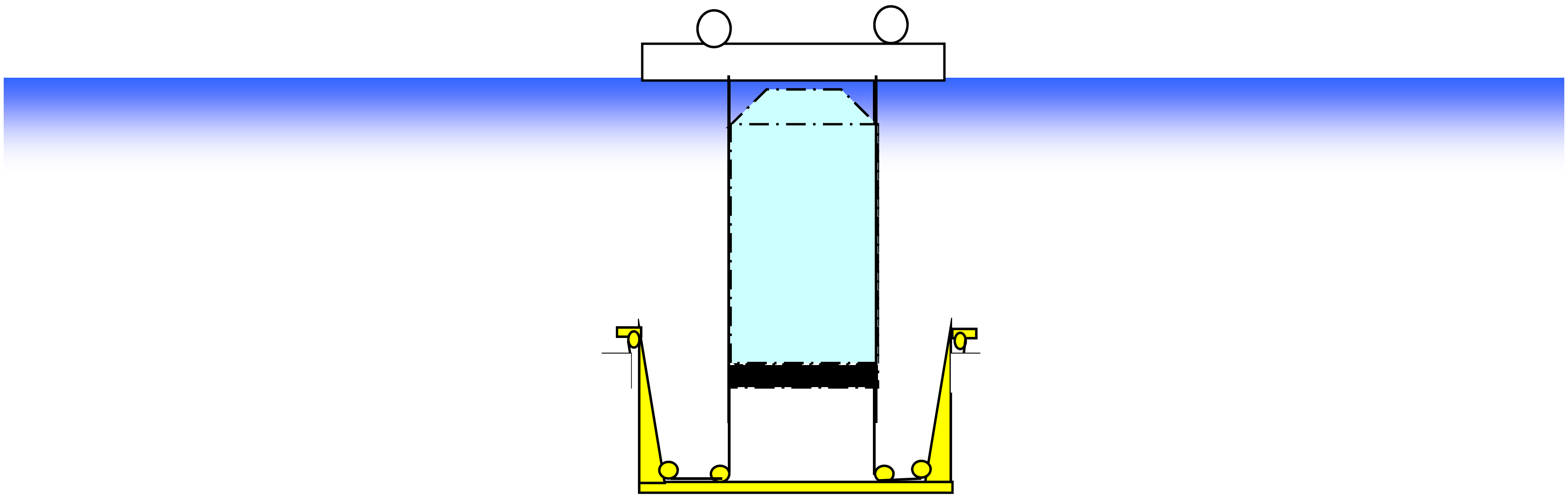


Water is poured into a tank



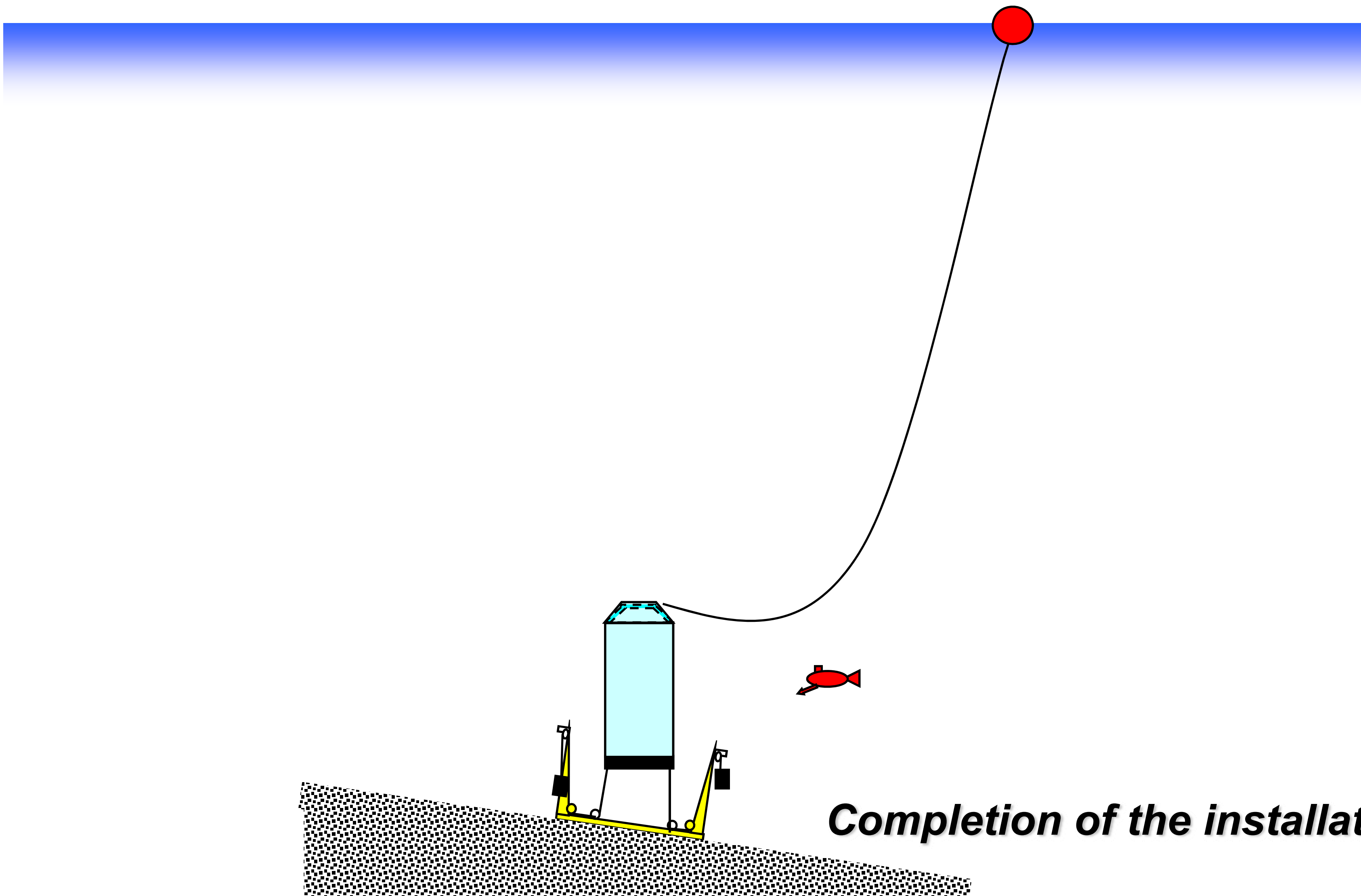
The water tank is rotated

Winch



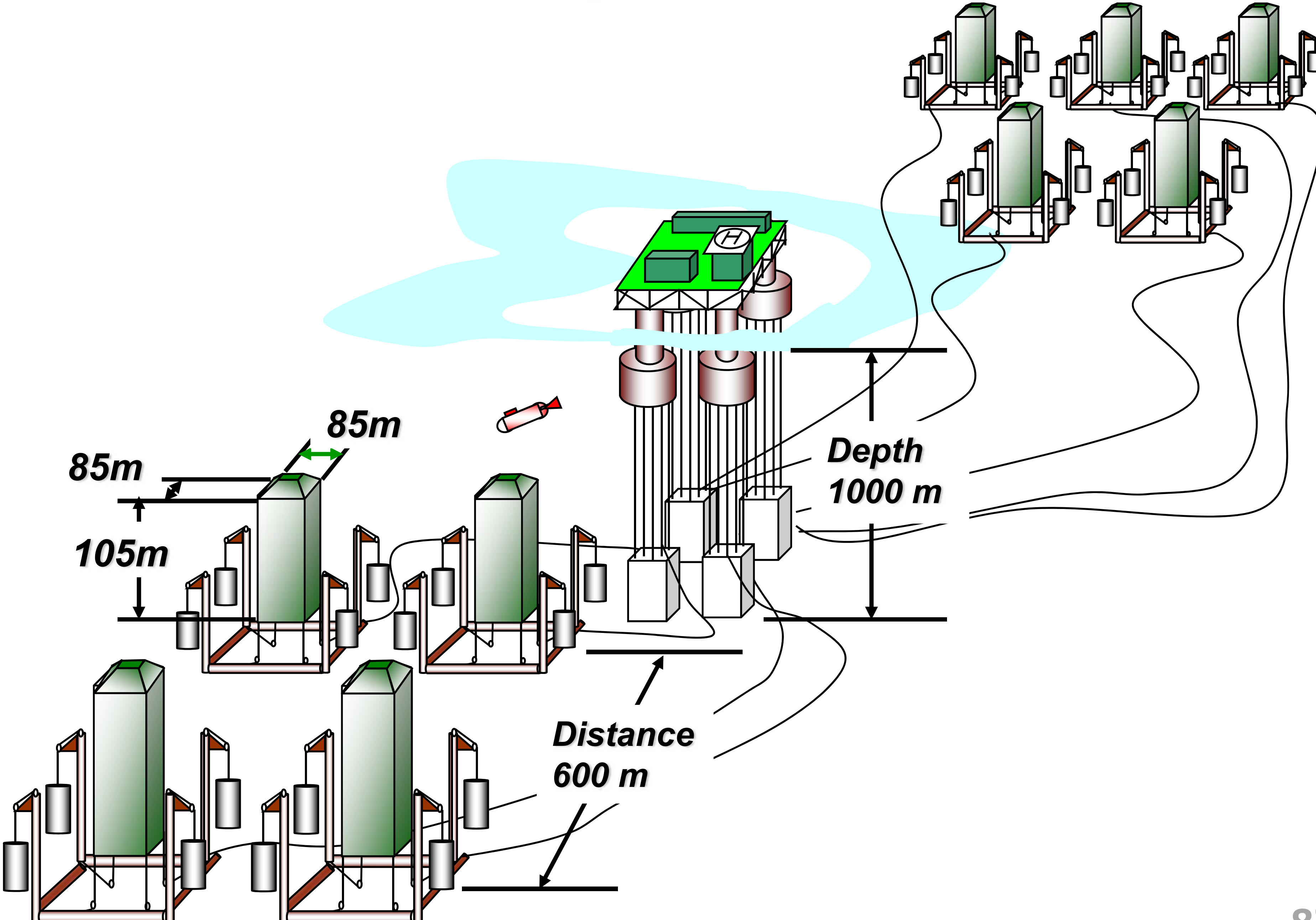
The template and the water tank is joint together

Bring the template and the water tank to the bottom of the sea

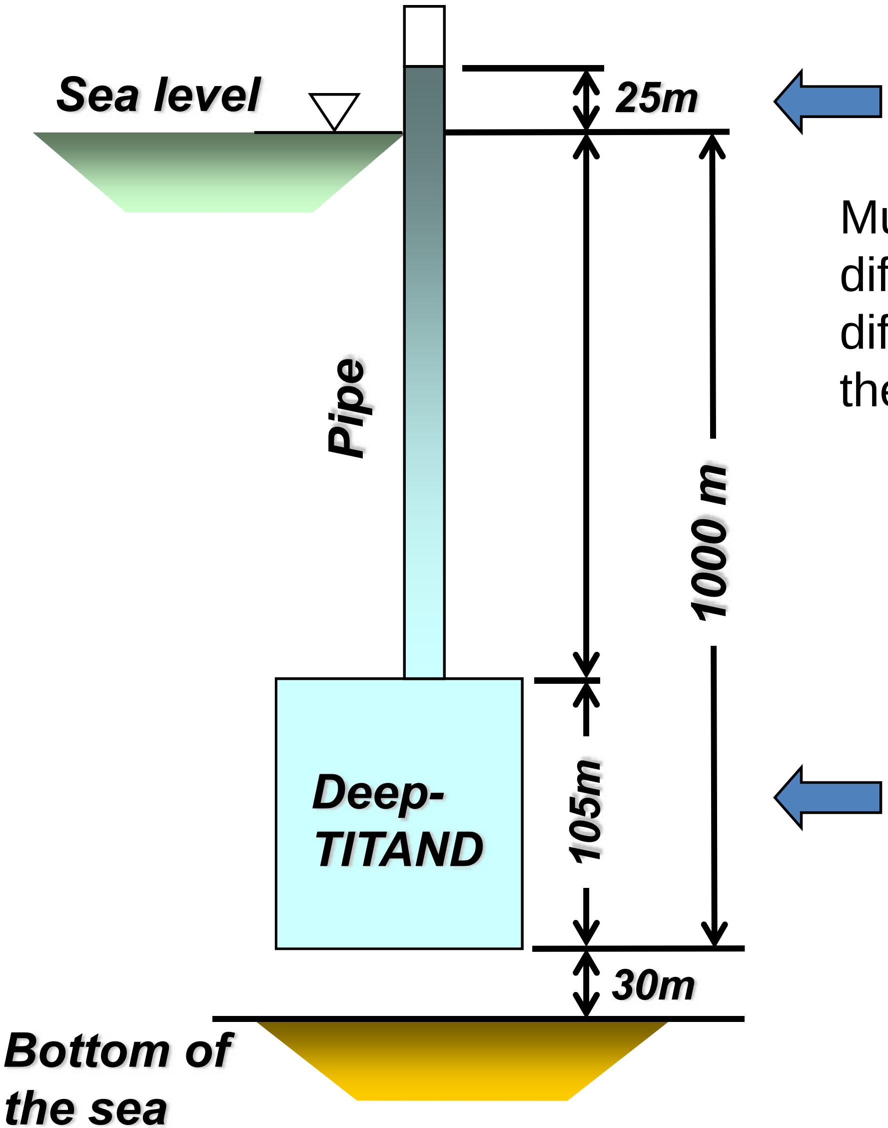


Completion of the installation

Deep-TITAND



Pressure Head



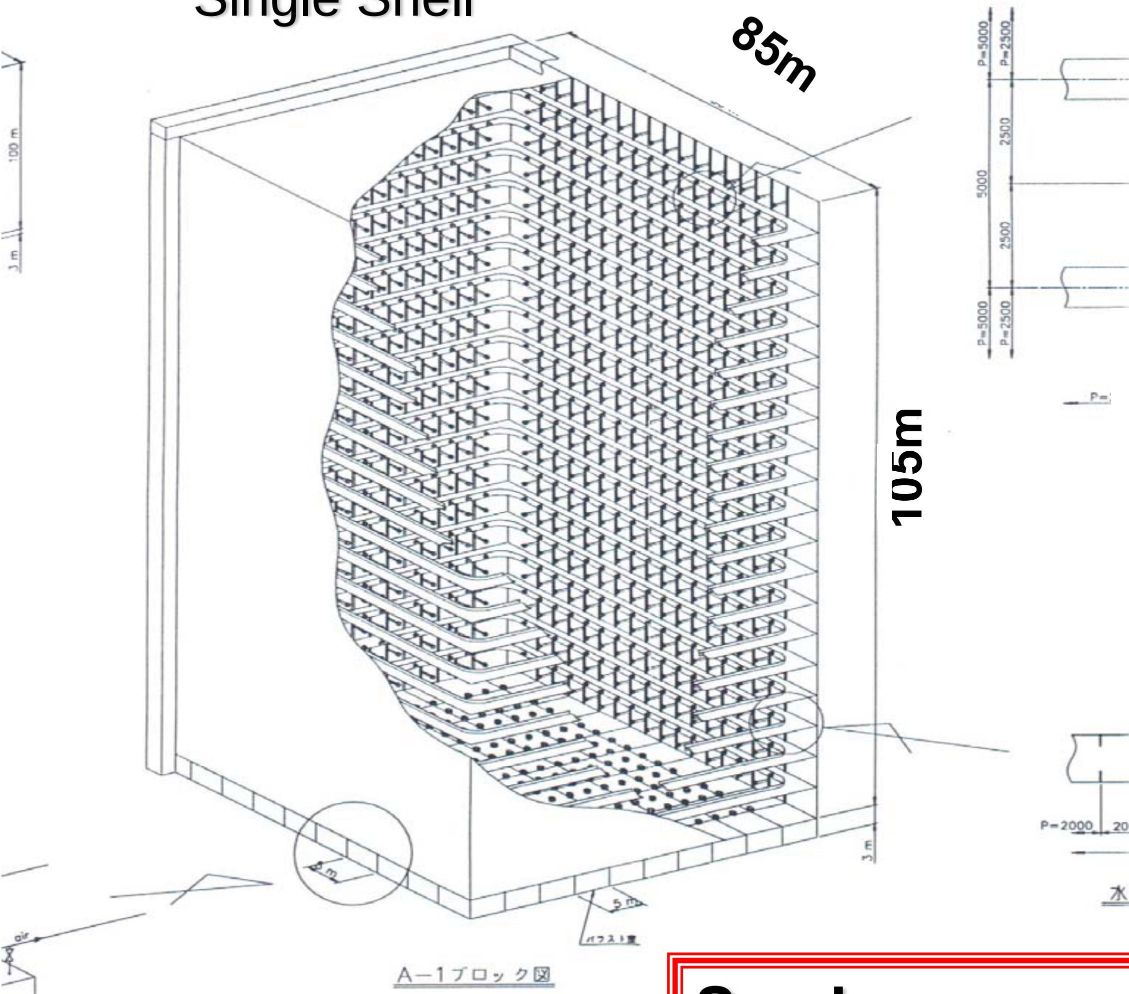
+ 2.5 atm

Must compensate the pressure difference due to the density difference between the salt water and the pure water by 2.5%

Pressure balance between Inside and outside

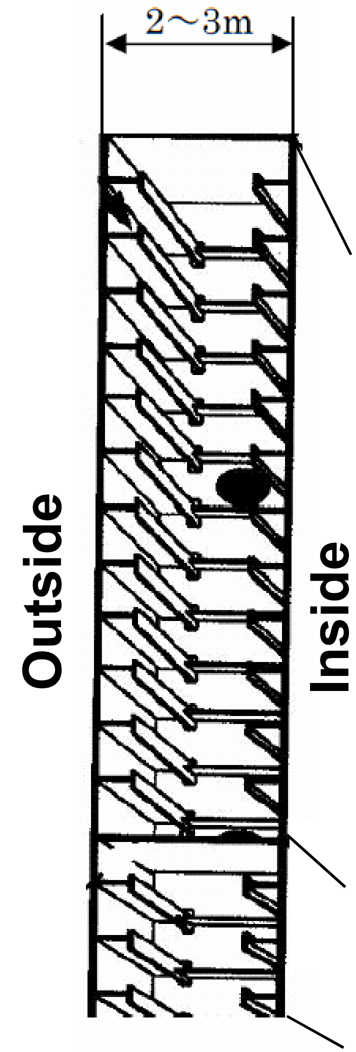
Structure

Single Shell



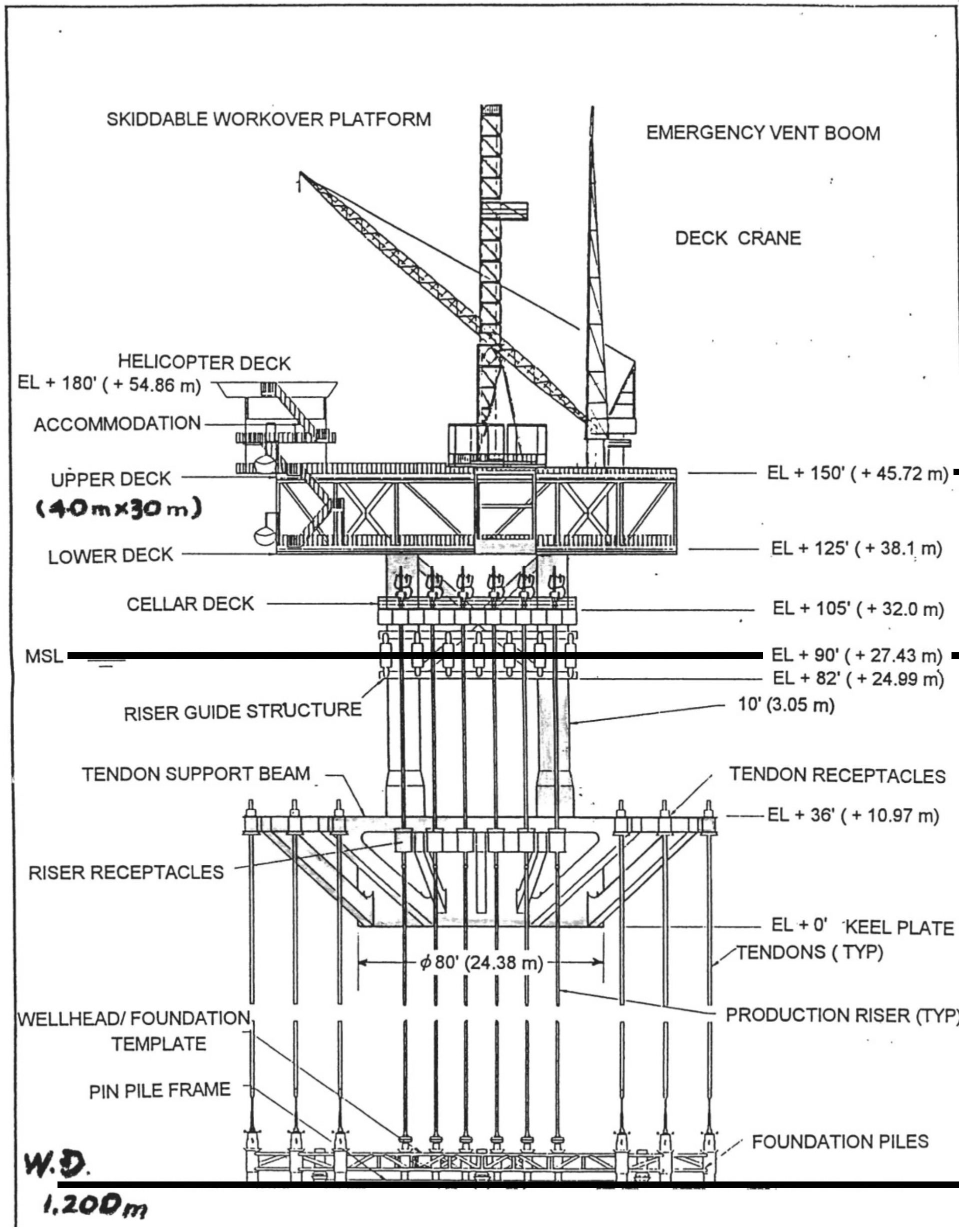
OR

Double Shell Structure



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

Tension Leg Platform



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

Upper Deck

~ 20m

Sea level

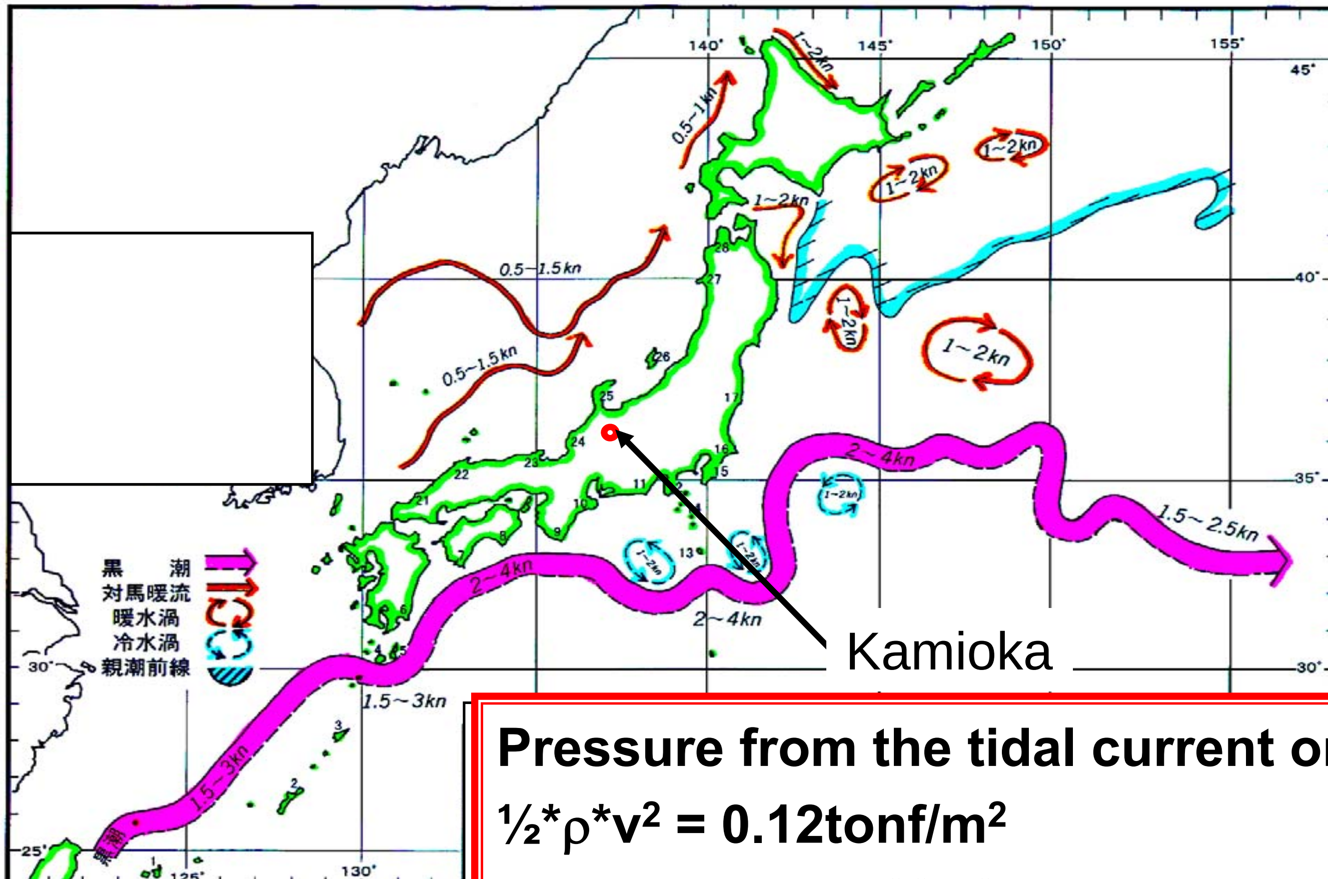
> 1,000 m

Bottom of The sea

Where we can place the detector?

Tidal current < 3 knot

~ 5.6km/hour (1.5m/s)

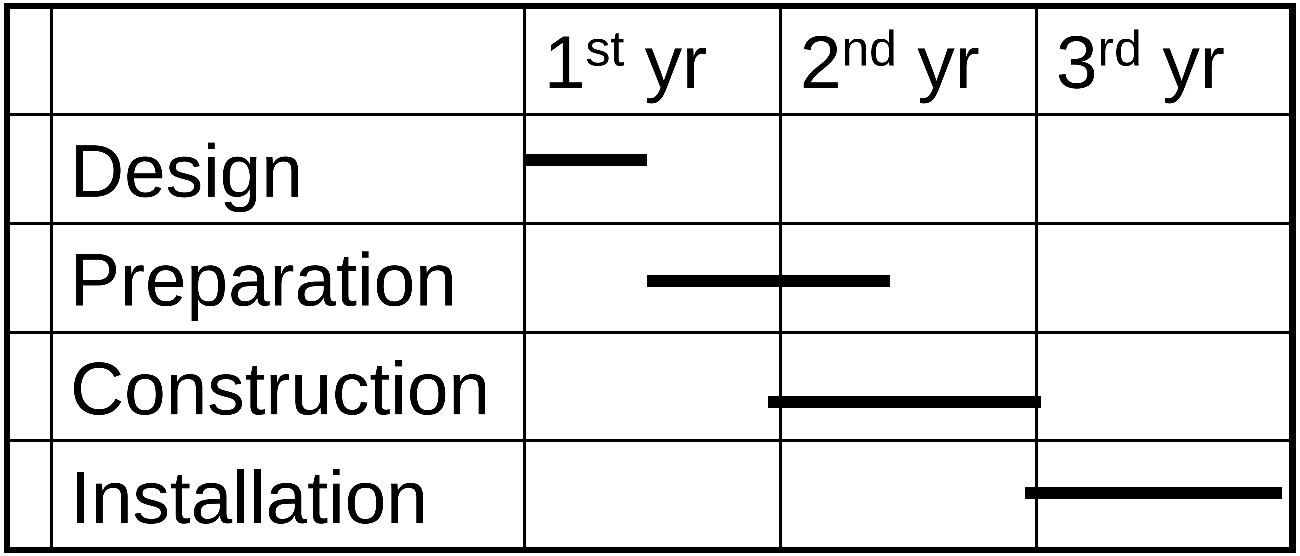


Pressure from the tidal current on the wall:

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

0.12x85x105 = *1071 ton per one wall*

Construction periods



Total 3 years construction time:

very short

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

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 !**

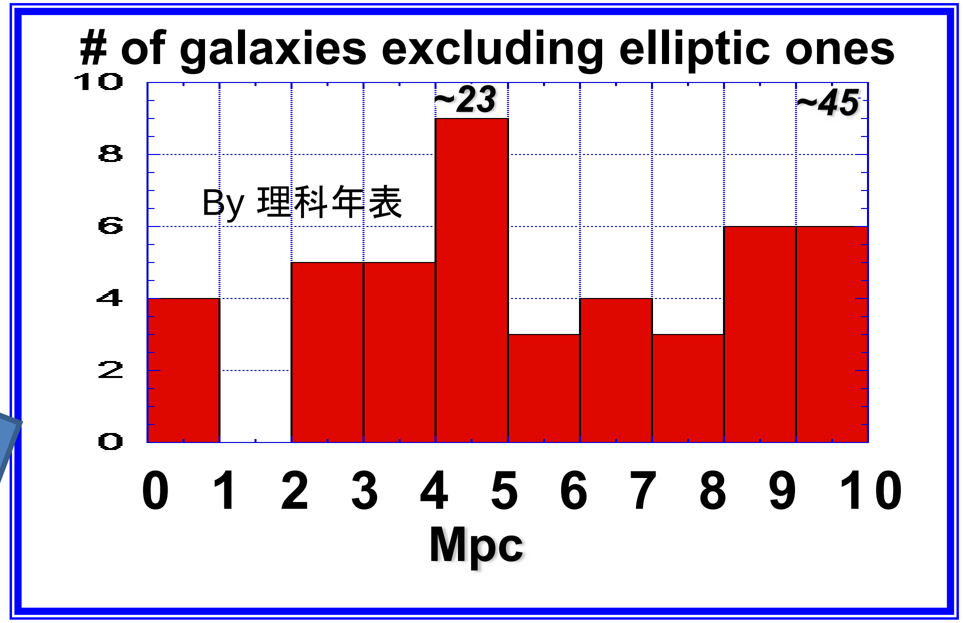
Supernova Rate

- **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

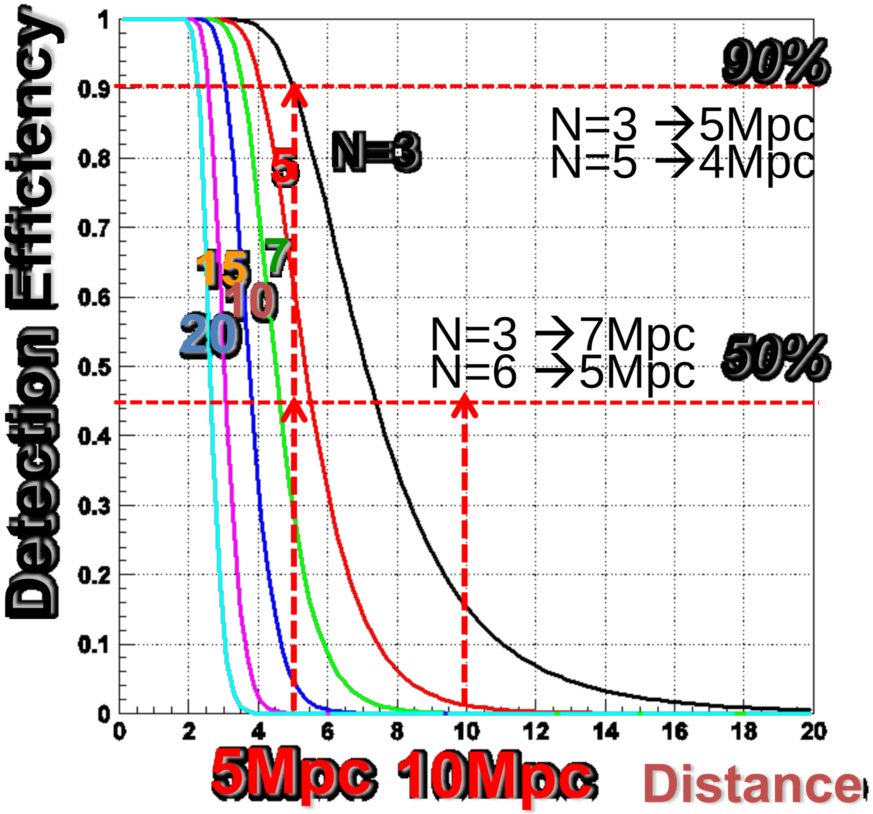
Is it possible to detect SN neutrinos from the distance of 5Mpc

- 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

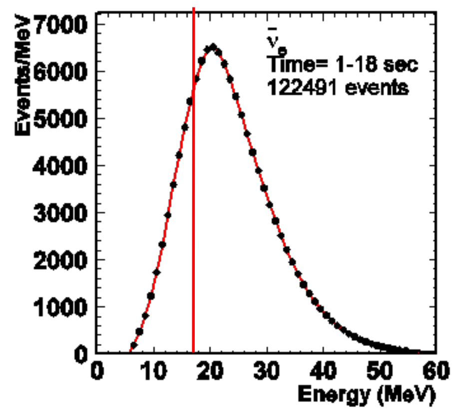
Trigger sensitivity to distant SNe

N: required multiplicity of the events in 10sec



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

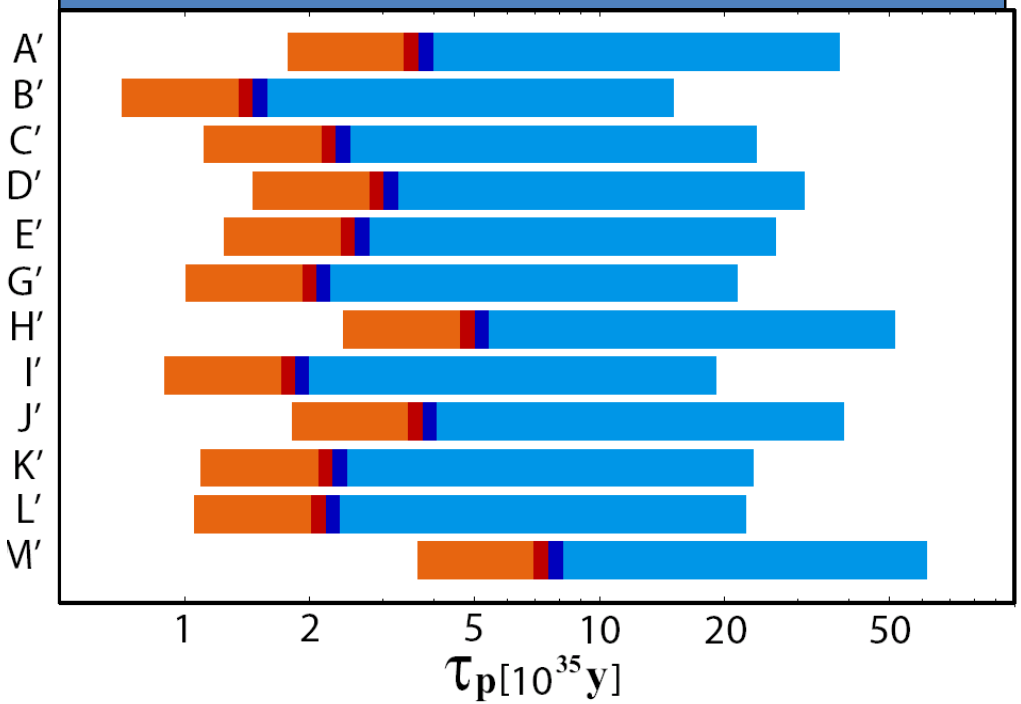
Galactic SN (10kpc)		***1.3M events***
	Neutronization B	***2500 events***

Proton Decay

What is the required sensitivity

J. Ellis, NNN05, April 7th, 2005

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



Theorists do not give us any guarantee, but

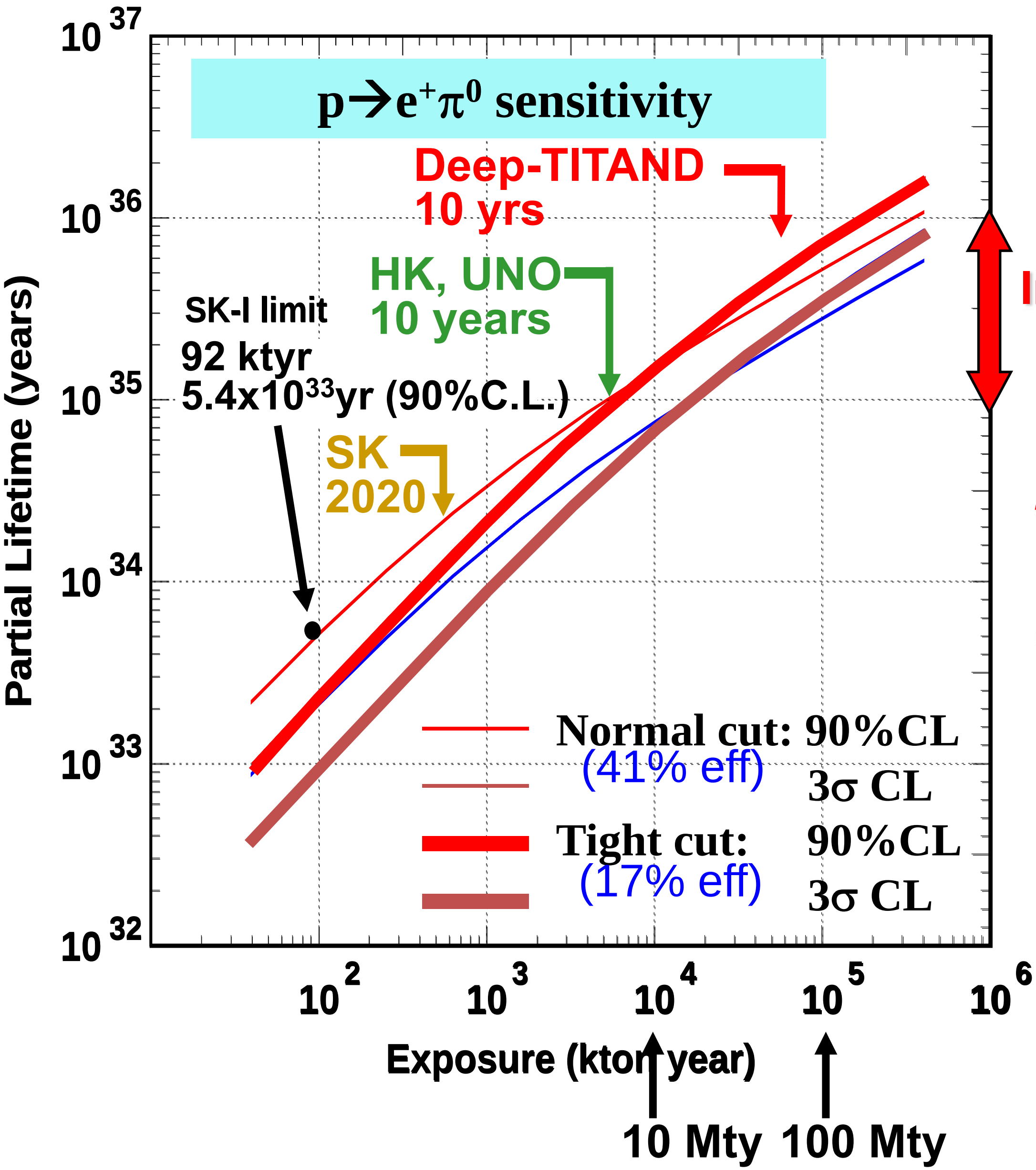
Theorists' best bets ???

~ 10^{35} ~ 10^{36} yr for $e\pi^0$

< 10^{35} yr for νK, μK

Detector Size ➔ The larger, the better

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



Deep-TITAND(5 Mt):10 yrs

➔

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

HK, UNO (0.5Mt): 10yrs

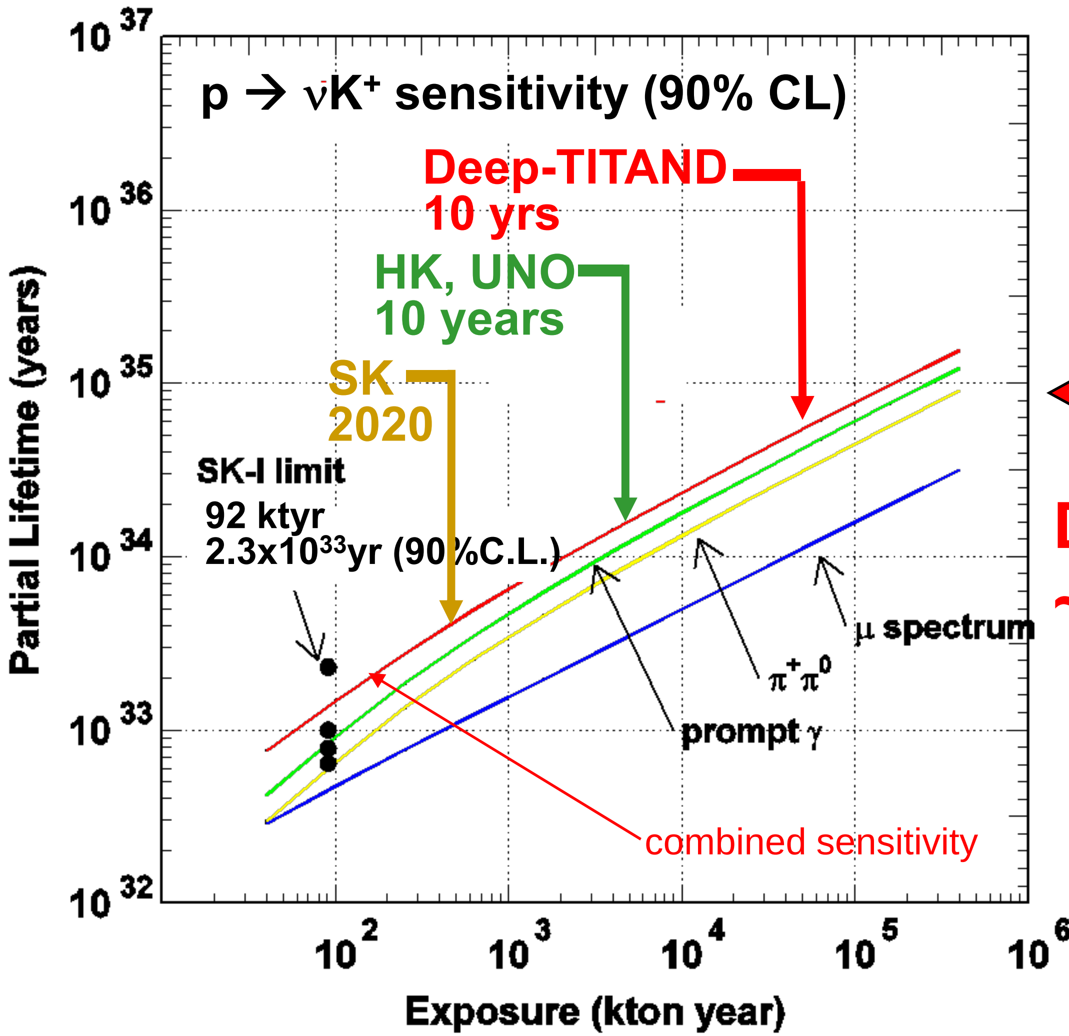
➔

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

Summary

1 kt Kamiokande was built for proton decay,
but, found the neutrino burst from SN1987A

20kt Super-Kamiokande has extended
the study on neutrinos
and discovered neutrino oscillations

8000 kt detector will be built for neutrino studies,
but, may find proton decay

To be continued