Atmospheric Neutrinos

Y. Suzuki

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September-29, 2010
@ IV International Pontecorvo Neutrino Physics School
in Alushta, Crimea, Ukraine

First idea to use atmospheric neutrinos to study neutrino oscillations

- **S. M. Bilenky and B. Pontecorvo**
  Physics Report 42(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*

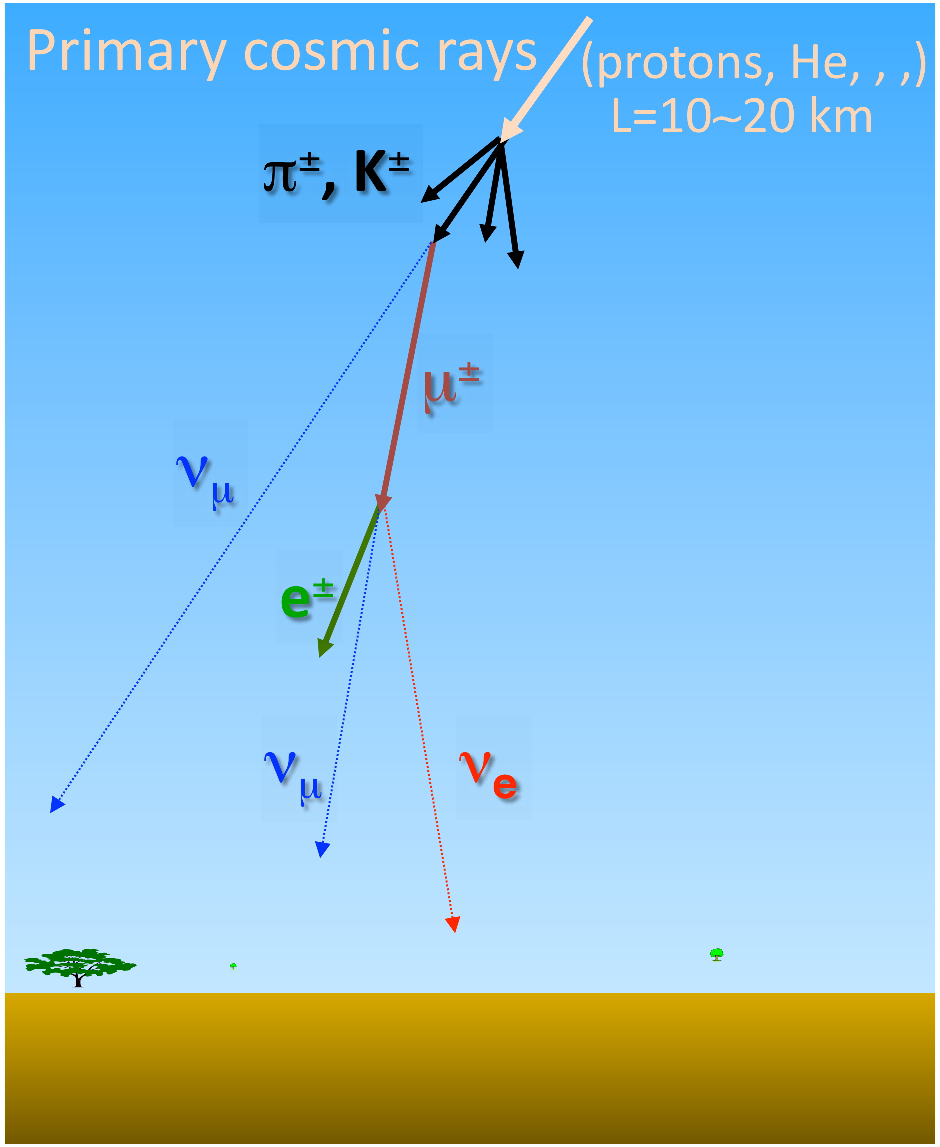
The phenomena of neutrino oscillations, if it does take place, could be of importance in cosmic ray neutrino* experiments. Let us give a few examples.

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 $M^2_{\min} \simeq 10^{-3}$ $(\mathrm{eV})^2$. 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

Preface

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

Atmospheric Neutrinos



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

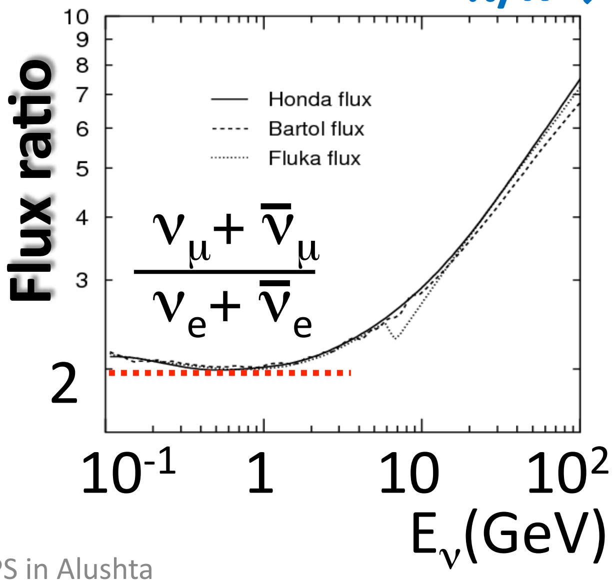
$\pi/K \rightarrow \mu + \nu_\mu$

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

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

Solar wind

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

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

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)

Many Improvements for the last 10 years!

Comment on Primary Cosmic Ray

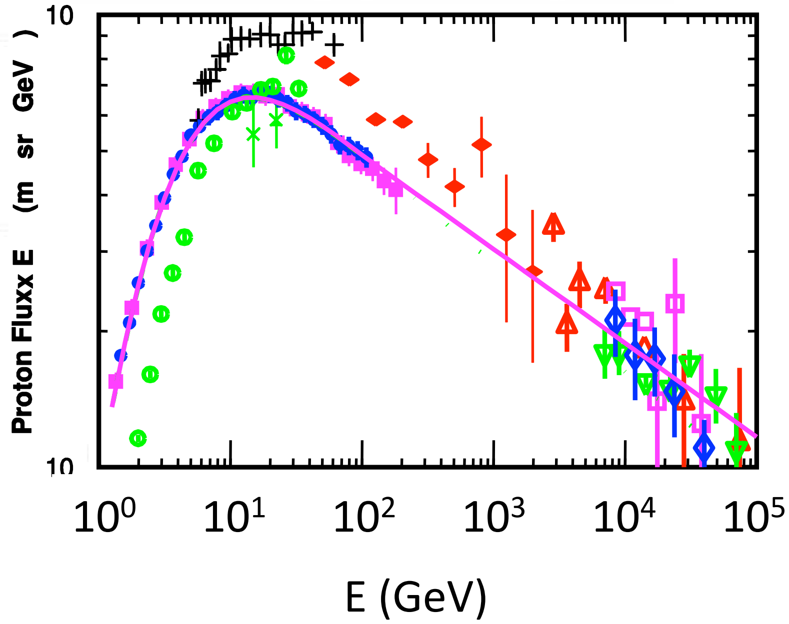
- **$\langle E_\nu \rangle \leftarrow \sim 1/10 \times \langle E_p \rangle$**

  1 GeV ν ← ~ 10 GeV proton

  10 GeV ν ← ~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

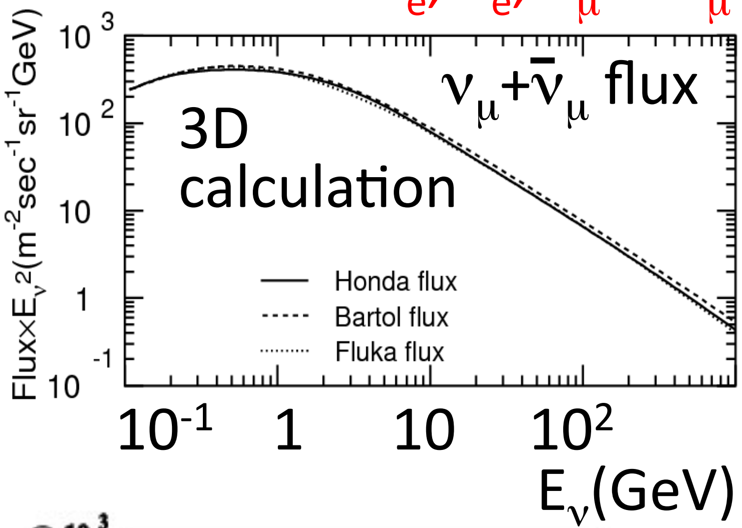
Flux uncertainty

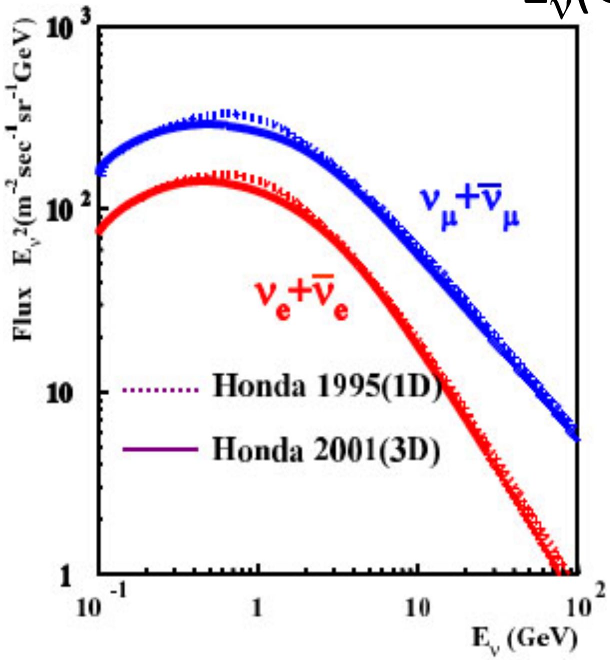
- **Uncertainty of absolute ν-Flux**
  - **10% @ <10GeV ← 25%**
  - **~30% @~100GeV**
- **Uncertainty in R (flux)**
  - **3% @ <5GeV**
  - **15% @~100GeV**
  - **Use double ratio for the study of neutrino oscillation**

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

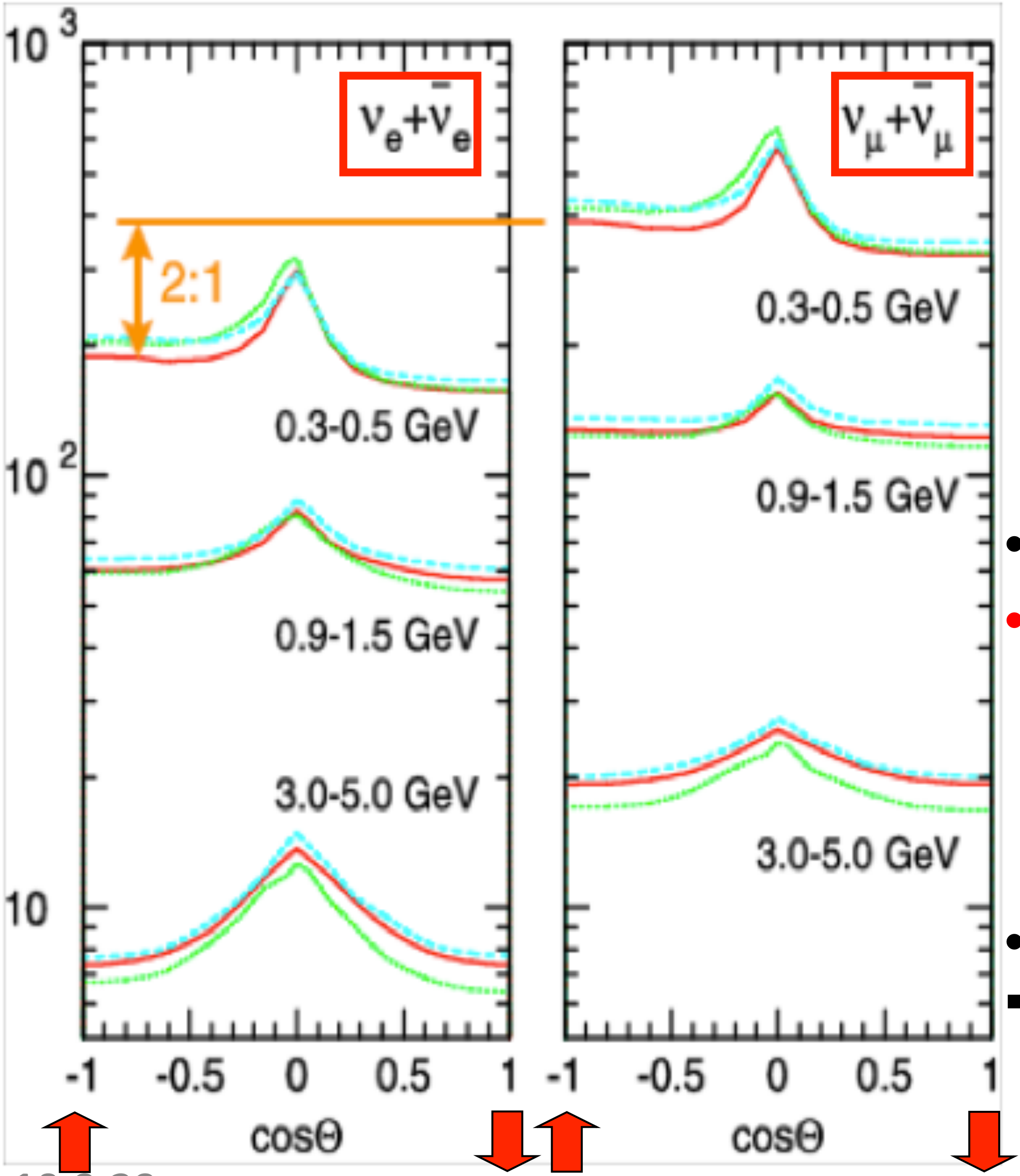
≠1 → *Evidence for neutrino oscillation*

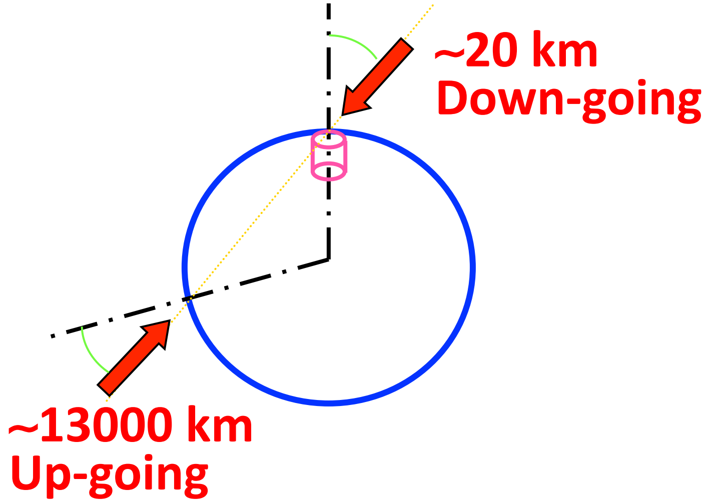
Mixture of ν_e, $\overline{\nu}_e$, ν_μ & $\overline{\nu}_\mu$





Zenith angle distribution





- Key to the oscillation analysis
- Up-Down Symmetry

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

- Asymmetry

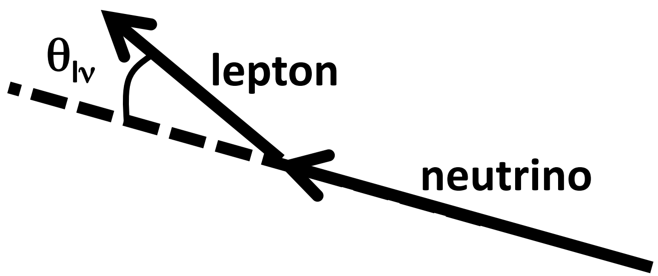
➔ flux independent evidence of neutrino oscillation

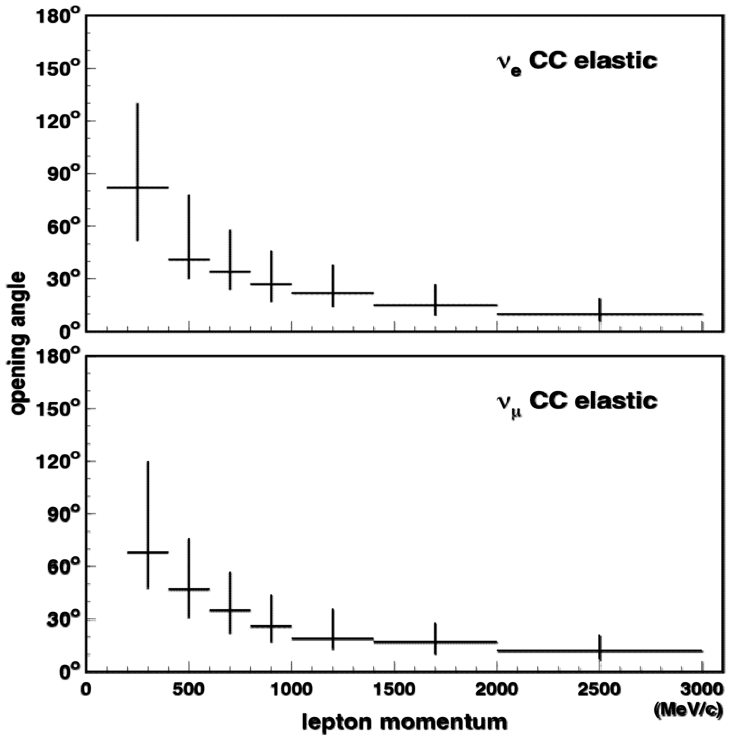
Zenith angle distribution

- **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 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

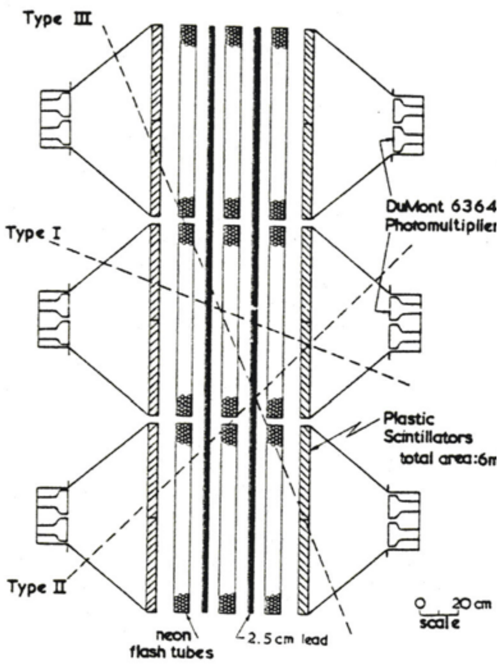
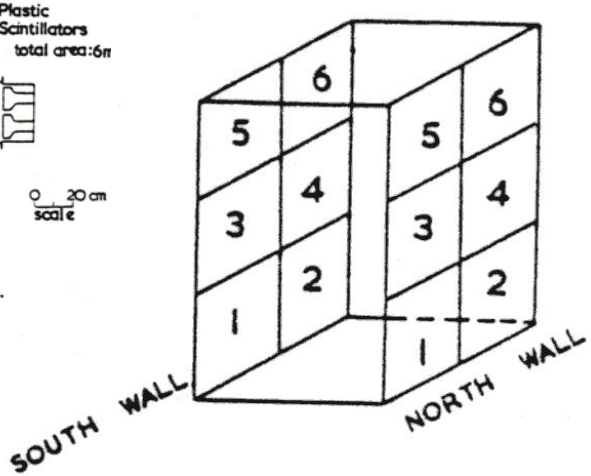
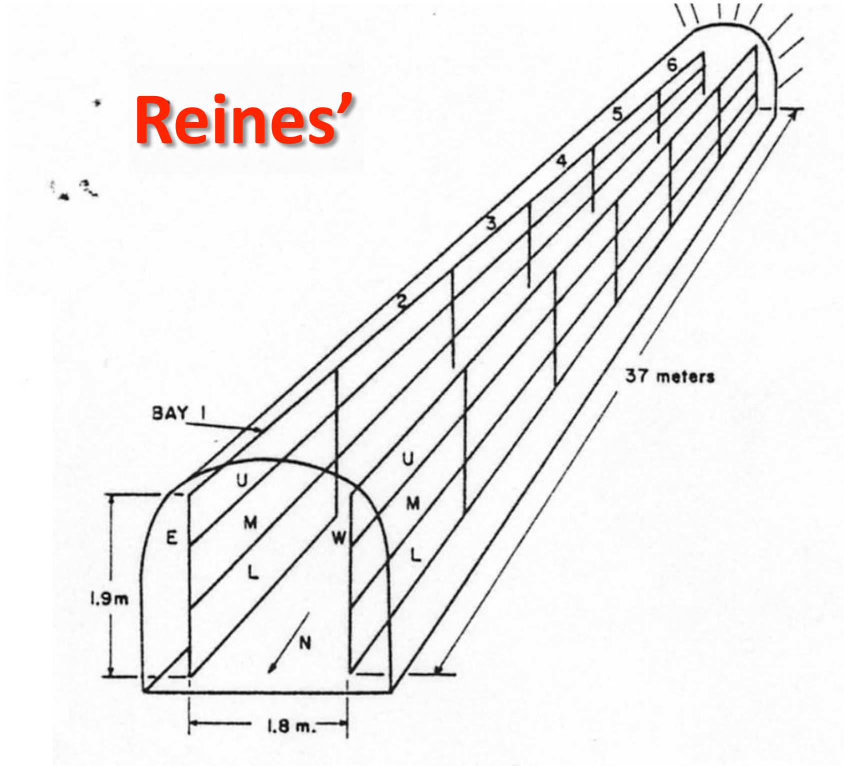


Fig. 1. Neutrino telescope.

Miyake's



Reines'



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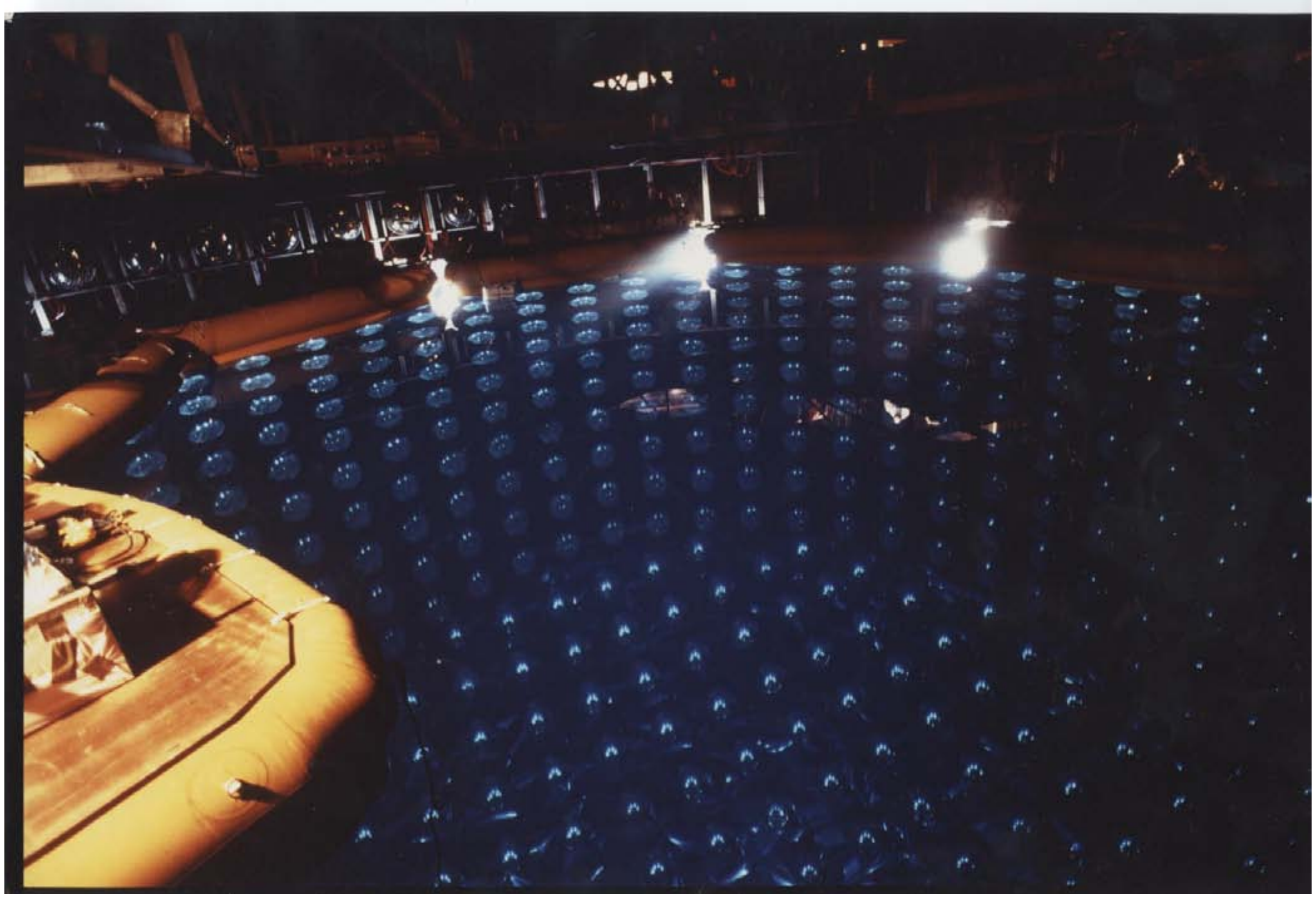
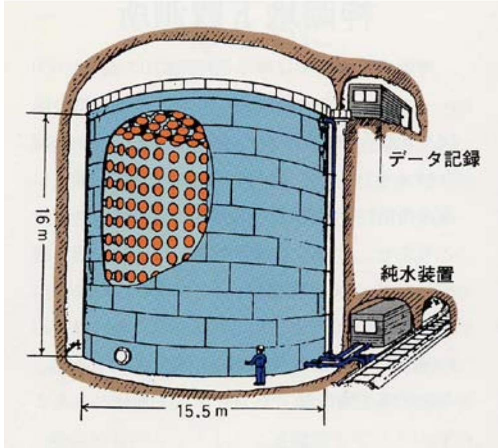
The First Problem





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

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National Laboratory for High Energy Physics (KEK), Ibaraki 305, Japan

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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 $59 \pm 7\%$ (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

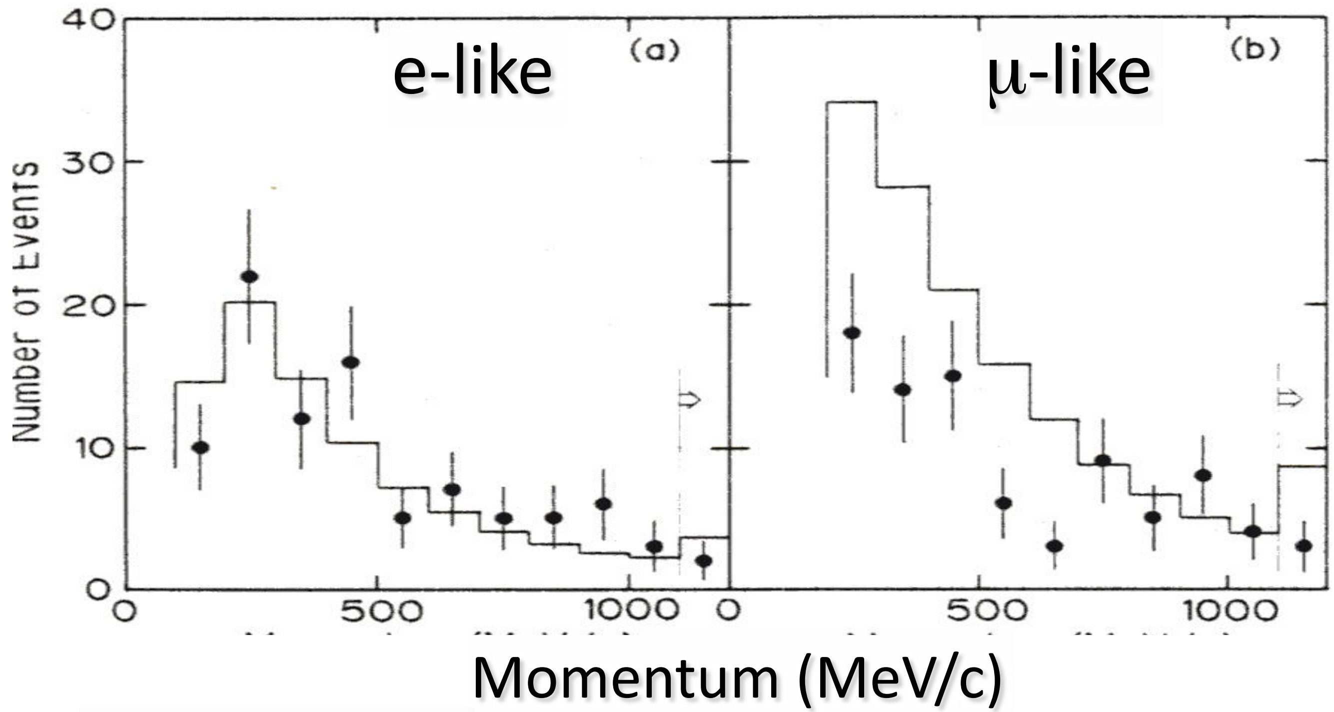
PLB, 205, 416 (1988)

By Kamiokande

Kamiokande Data

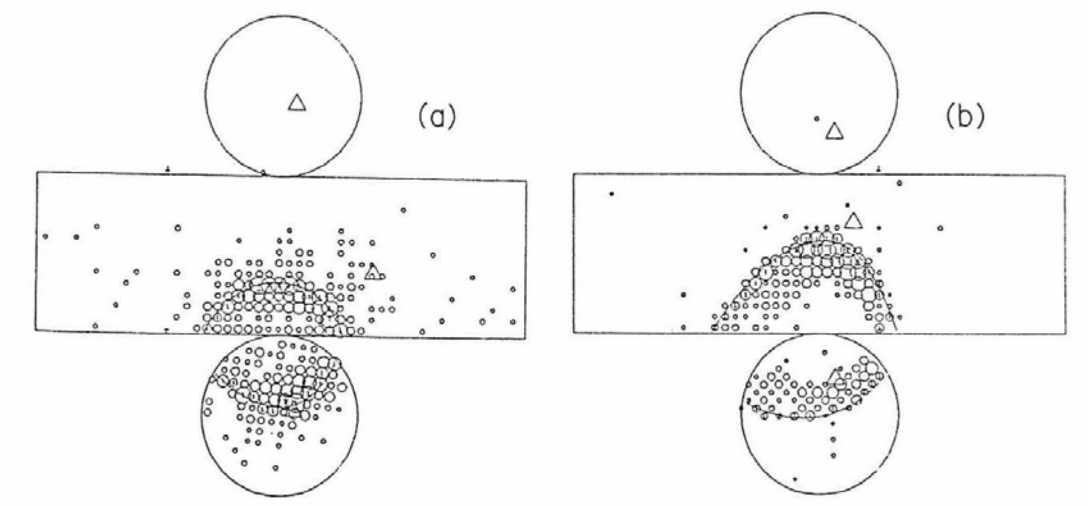
In 1988, Kamiokande saw few μ

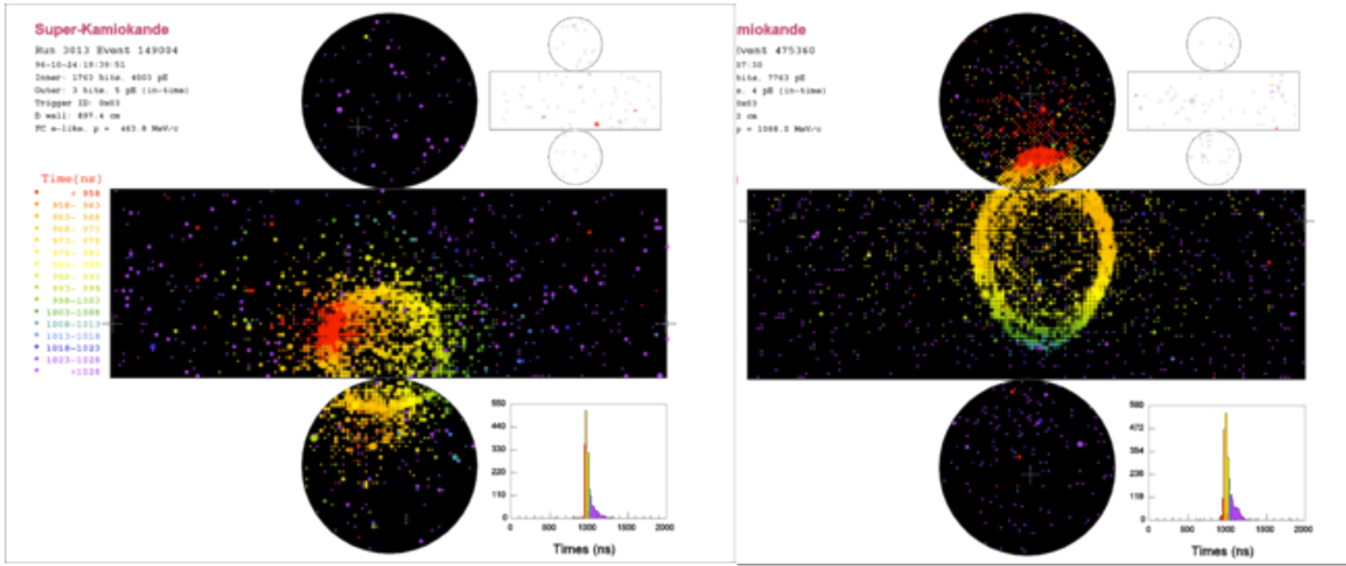
R= (Obs./MC)μ-like = 0.59±7% (stat.)



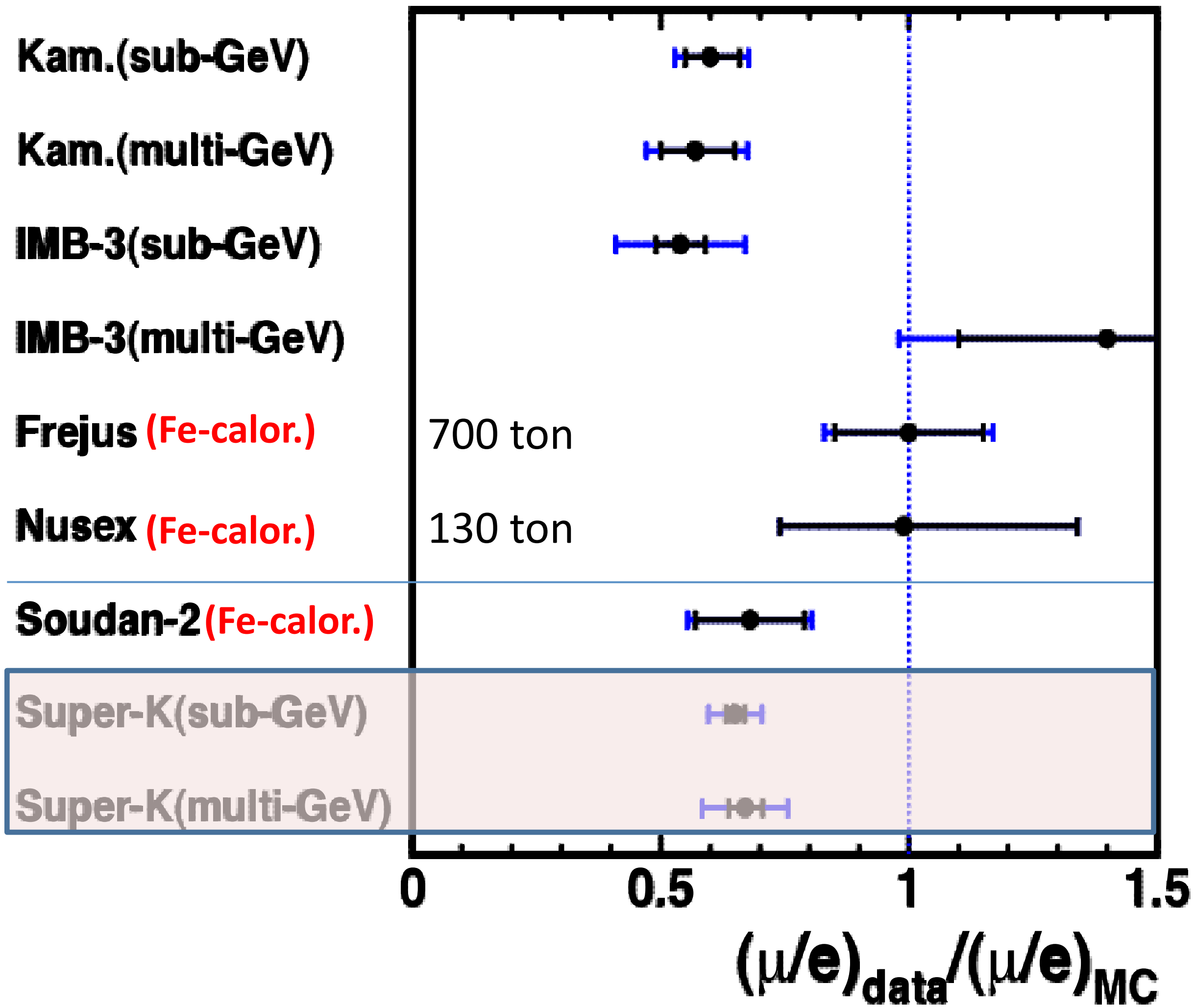
- **Problems:**
  - **Large uncertainty of the flux calculation**
  - **Theorists did not believe large mixing**

μ/e separation





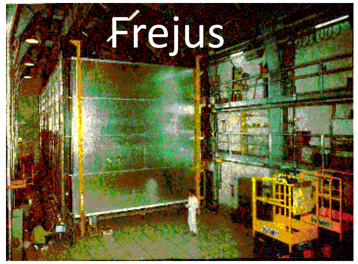
R measurement in 90's



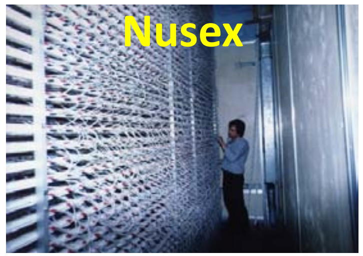
1988

1992

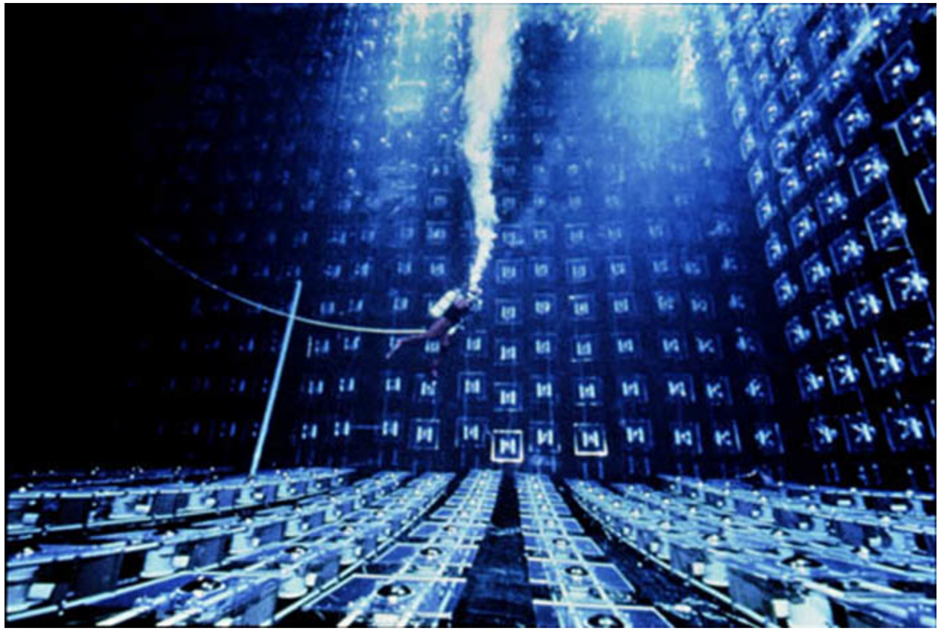
1997



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



IMB-3



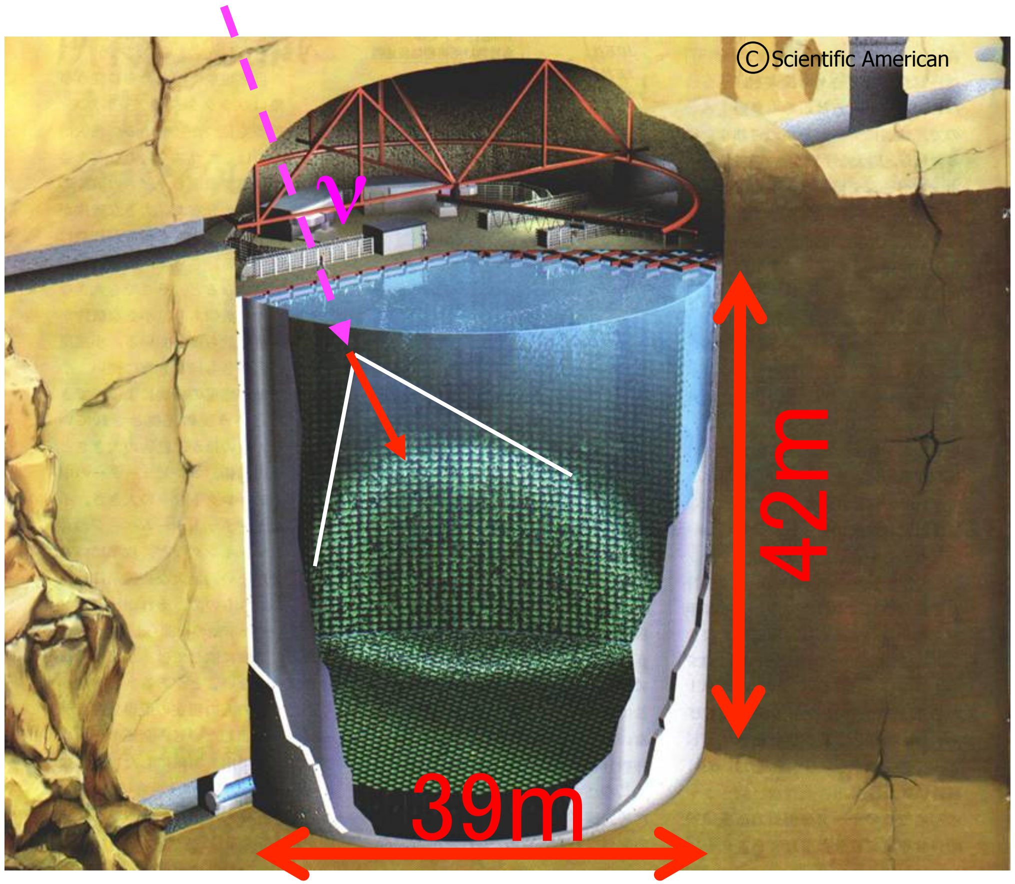
- Observed small μ/e ratio in 1992
- 8000 ton Water Cherenkov Detector
- 3300 ton fiducial mass

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

University of California, Irvine
T. Barszczak, D. Casper, W. Gajewski, W.R. Kropp, S. Mine, D.W. Liu, M.B. Smy, H.W. Sobel, M.R. Vagins

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George Mason University
R.W. Ellsworth

University of Hawaii
A. Kibayashi, J.G. Learned, S. Matsuno, D. Takemori

Los Alamos National Laboratory
T.J. Haines

Louisiana State University
S. Dazeley, K.B. Lee, R. Svoboda

University of Maryland
E. Blaufuss, J.A. Goodman, G. Guillian, G.W. Sullivan, D. Turcan

University of Minnesota
A. Habig

State University of New York, Stony Brook
J. Hill, C.K. Jung, K. Martens, M. Malek, C. Mauger, C. McGrew, E. Sharkey B. Viren, C. Yanagisawa

University of Warsaw
U. Golebiewska, D. Kielczewska

University of Washington
S.C. Boyd, A.L. Stachyra, R.J. Wilkes, K.K. Young

Institute for Cosmic Ray Research, University of Tokyo
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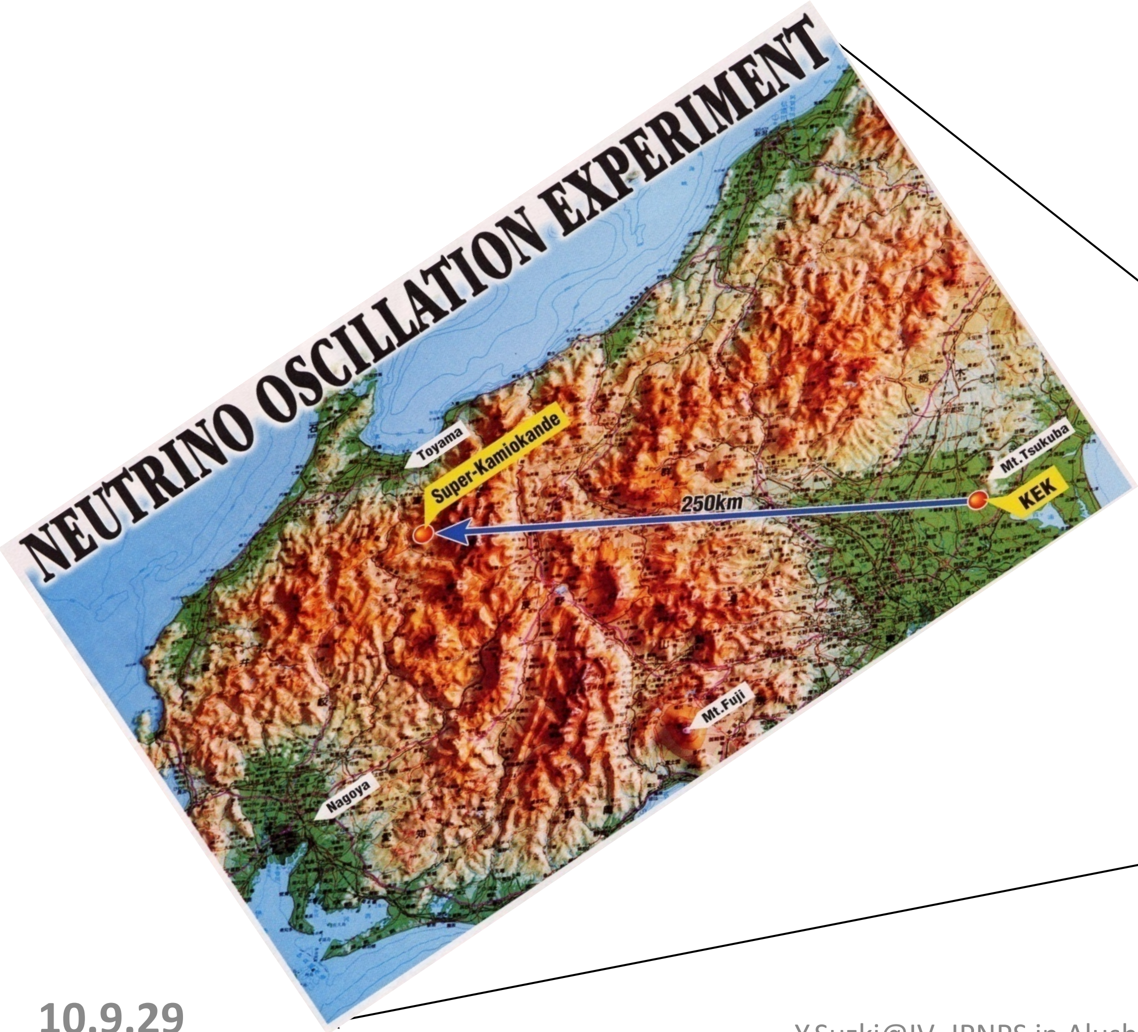
Gifu University
S. Tasaka

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


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


RUSSIA
Microsoft® MapPoint®
GOBI
Harbin
Jixi
CHINA
Jilin
Sapporo
Beijing
P'yŏngyang
Taiyuan
Seoul
Sendai
Tengxian
JAPAN
Taegu
Kyoto
Nanjing
Ōita
Kagoshima
Nanchang
Taipei
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40°
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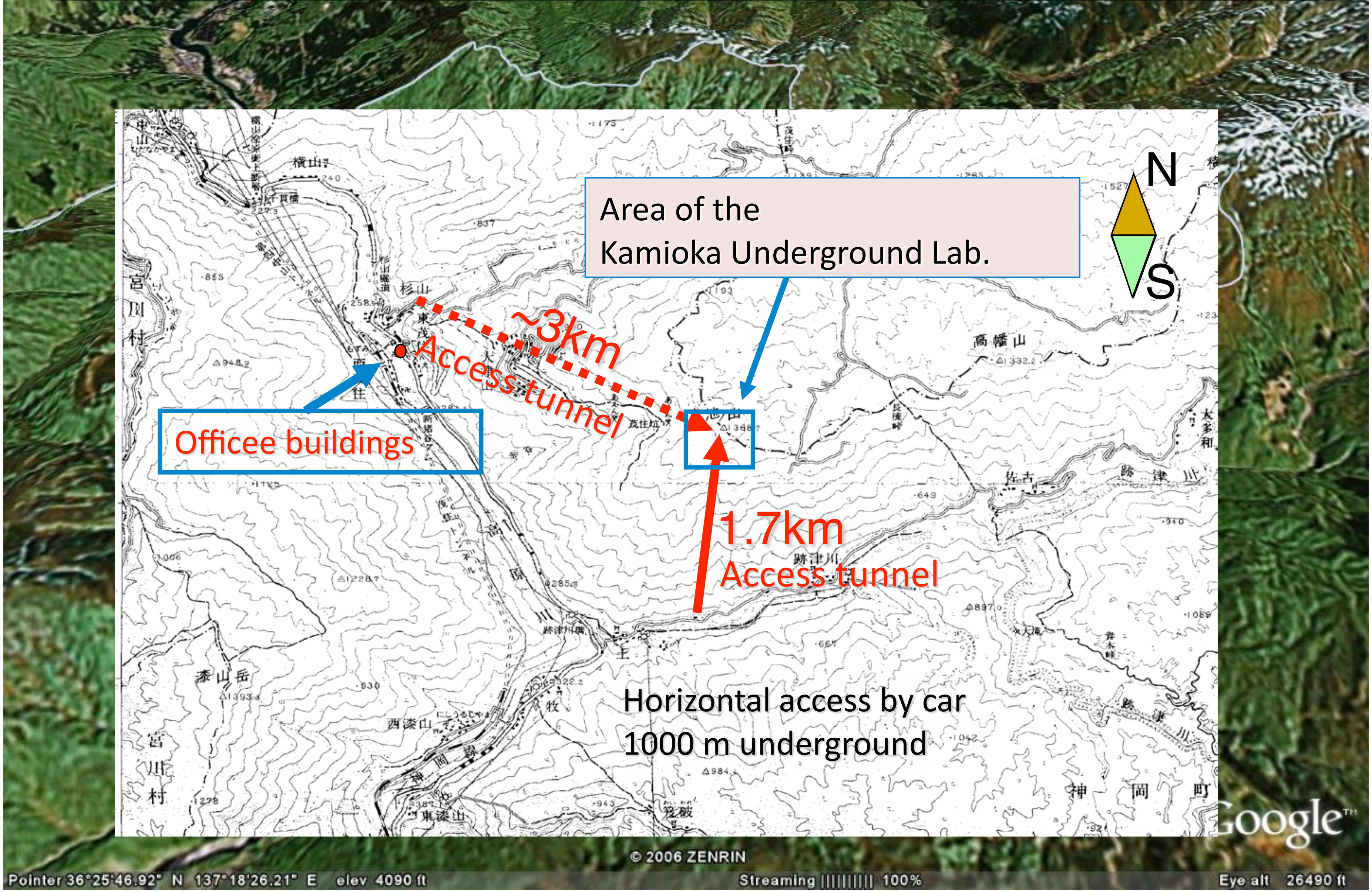
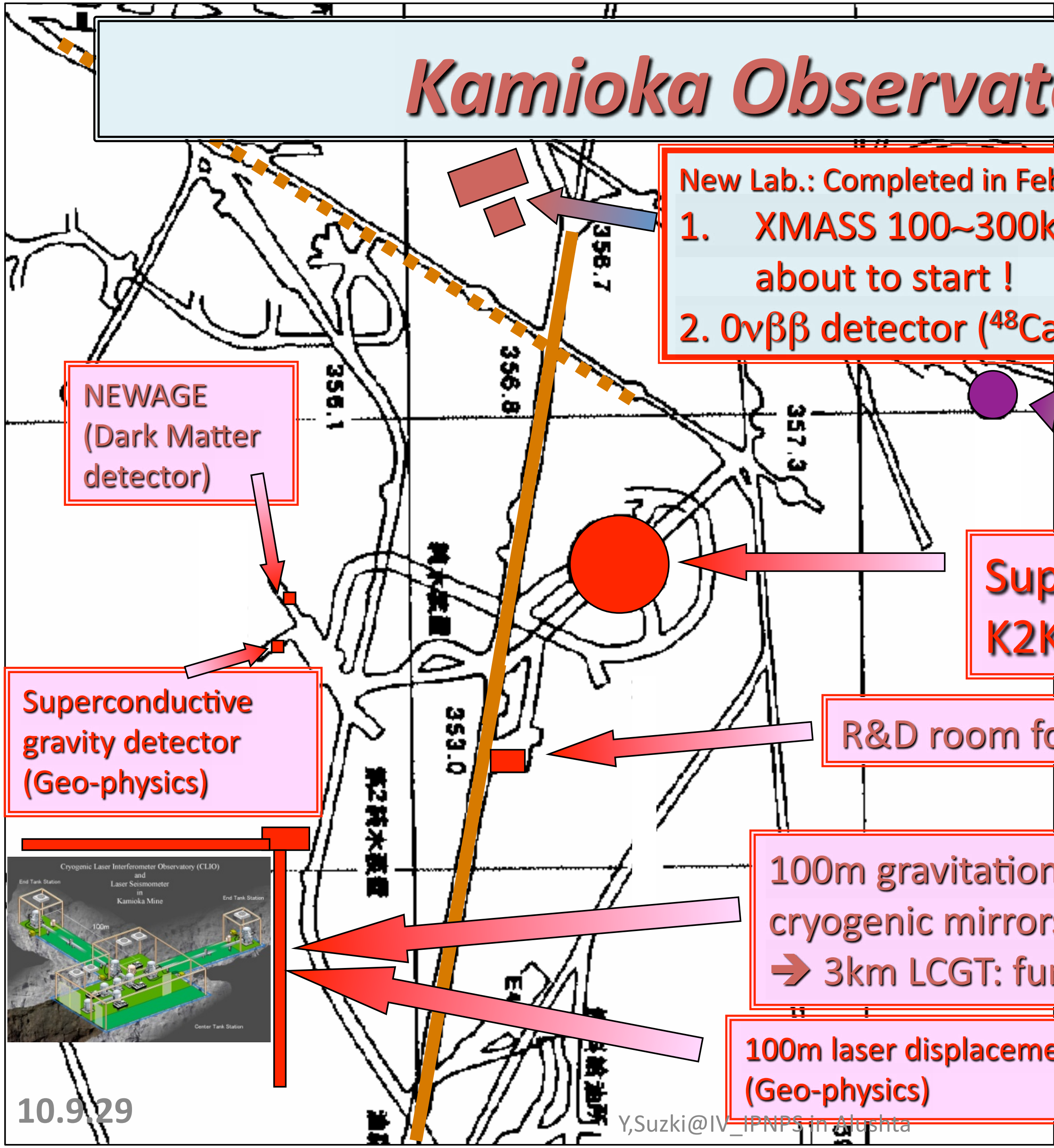
20°

Kamioka Observatory

Kamioka Observatory



Kamioka Observatory



New Lab.: Completed in Feb., 2008

1. XMASS 100~300kg f.v. detector (Liq. Xenon) about to start !
2. 0νββ detector (^{48}Ca) (prototype)

NEWAGE (Dark Matter detector)

KamLAND
Univ. of Tohoku

Super-Kamiokande
K2K, T2K

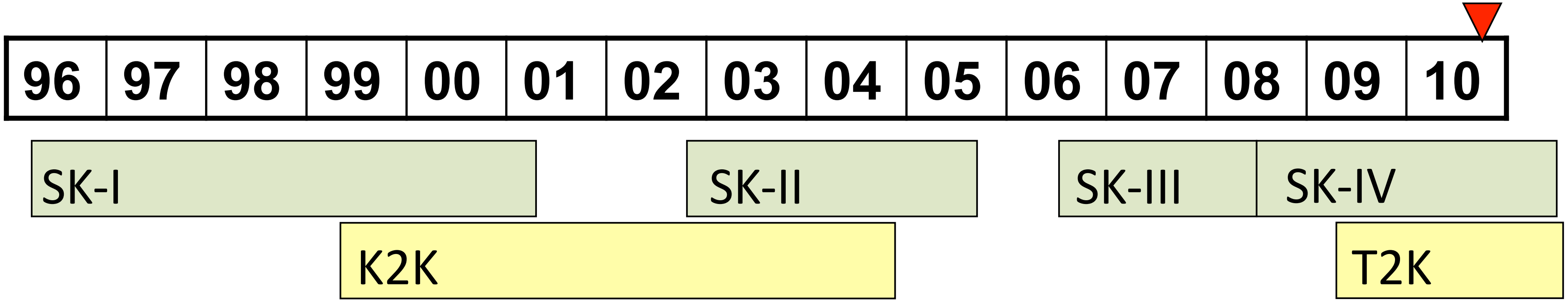
Superconductive gravity detector (Geo-physics)

R&D room for XMASS

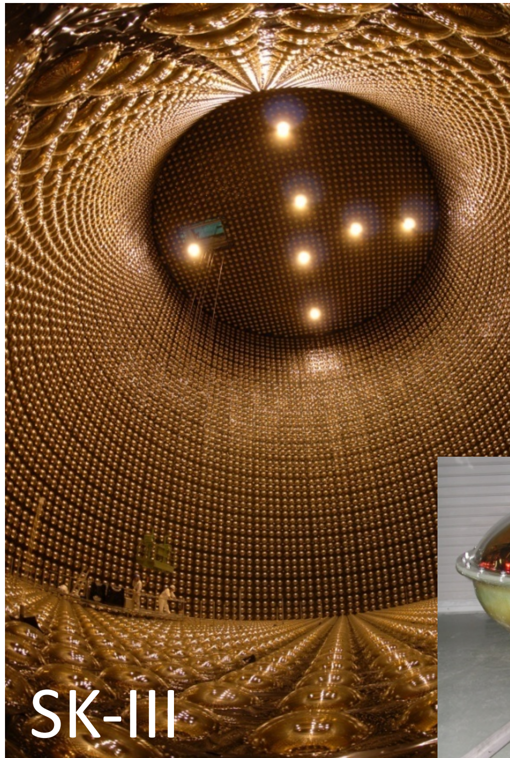
100m gravitational wave antenna w/ cryogenic mirrors (CLIO) (Prototype)
➔ 3km LCGT: funded this yr ($120M)

100m laser displacement detector (Geo-physics)

Brief history of Super-K



- **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 →**

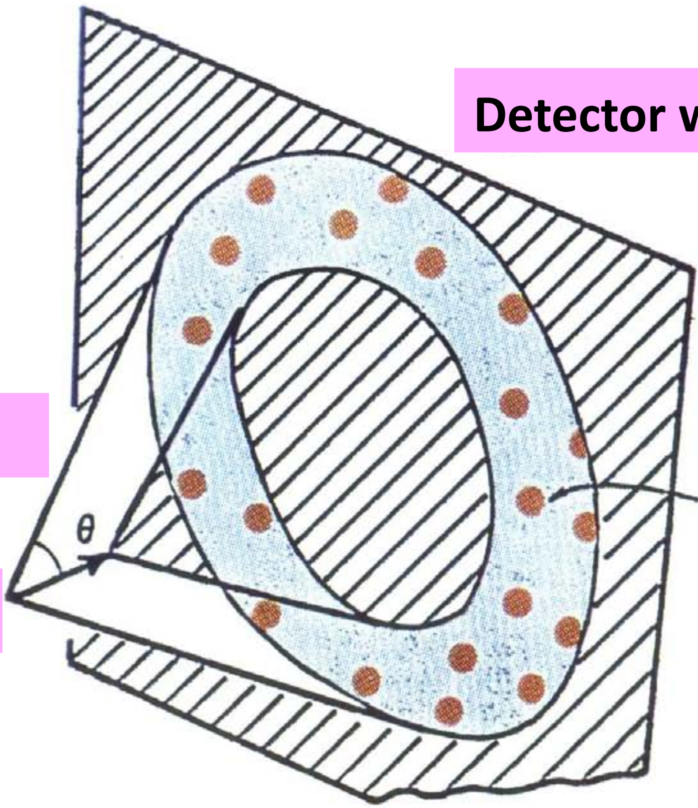


Protection case

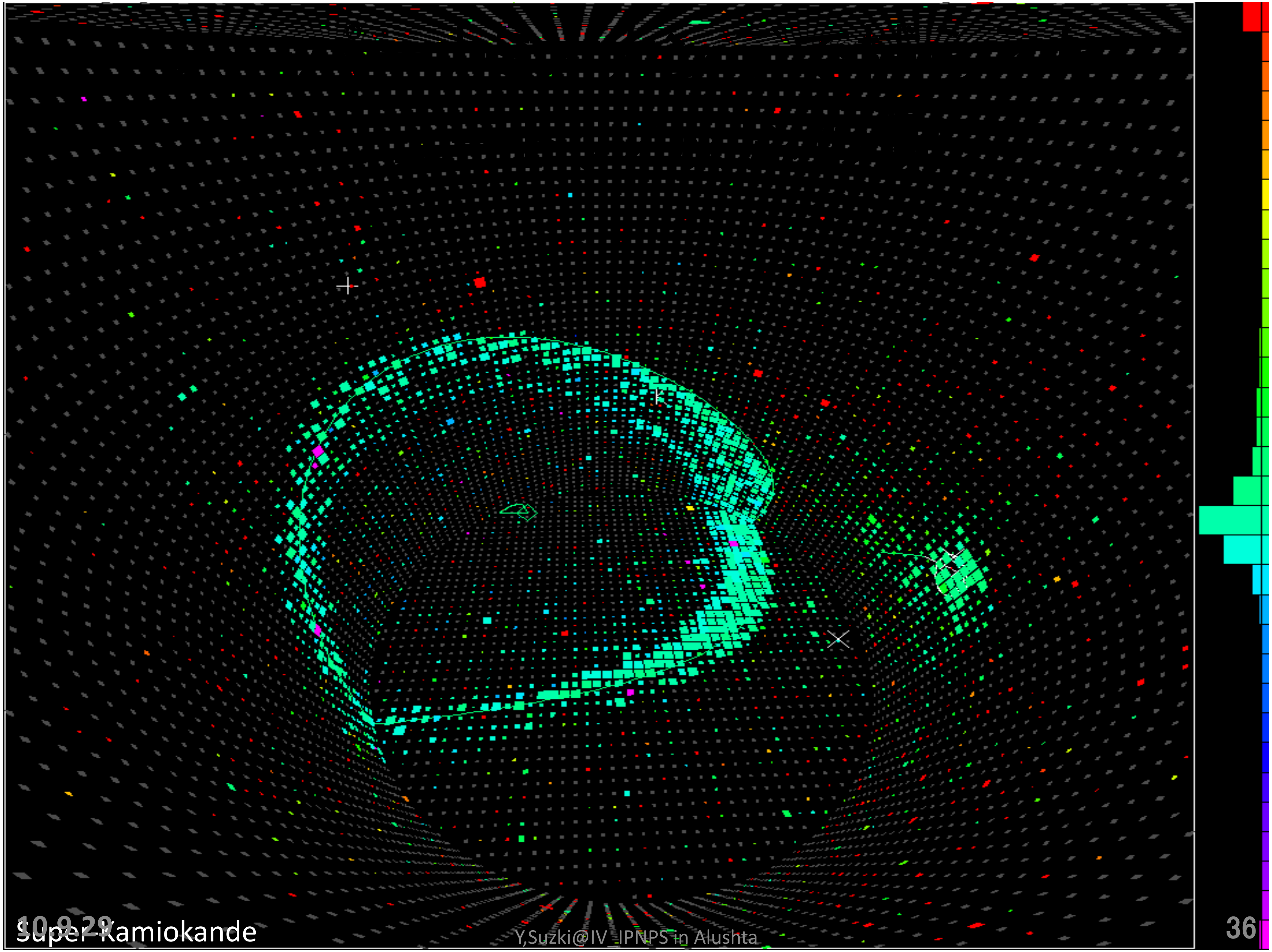
Detection Principle -- Cherenkov light

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

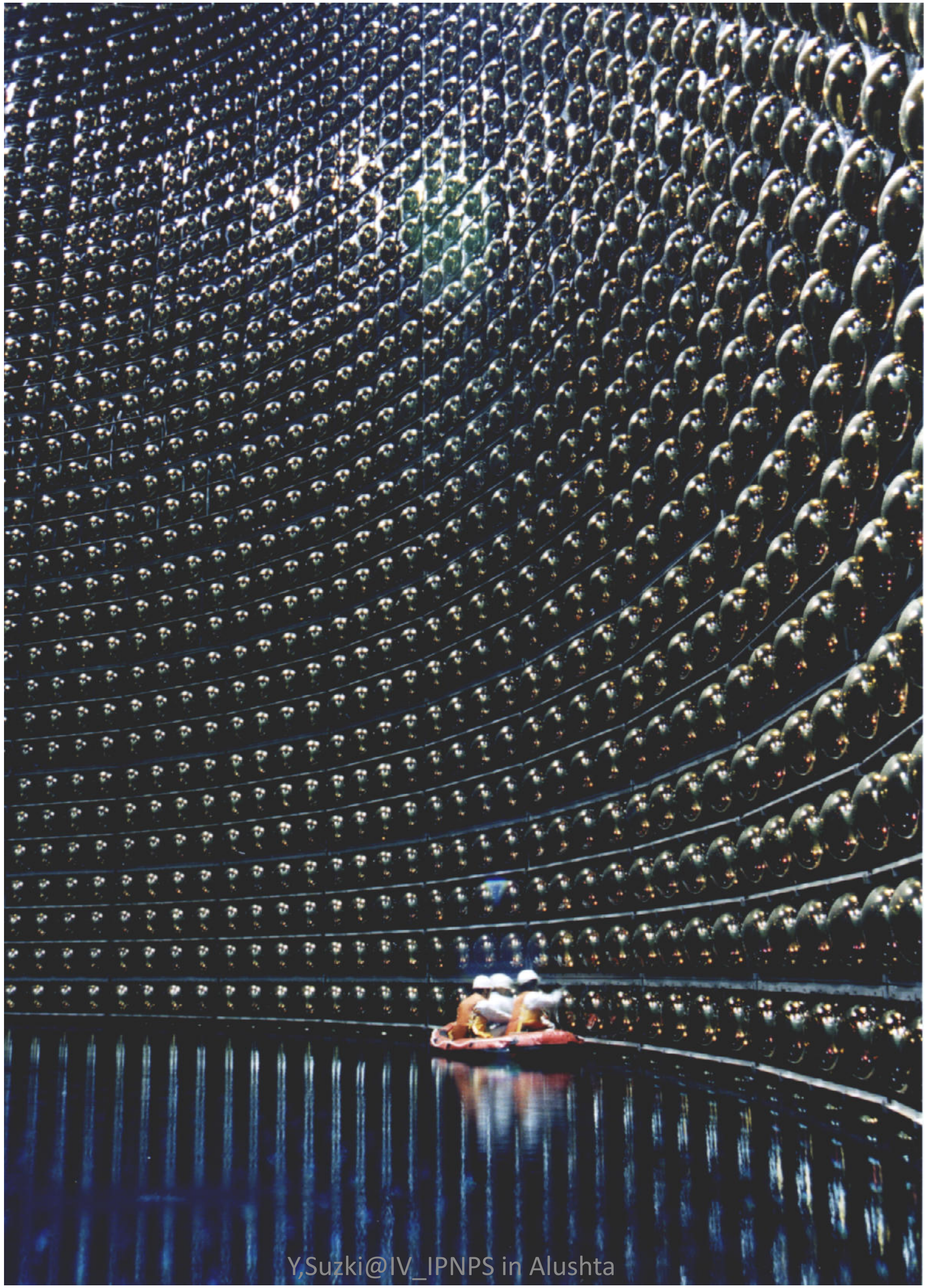
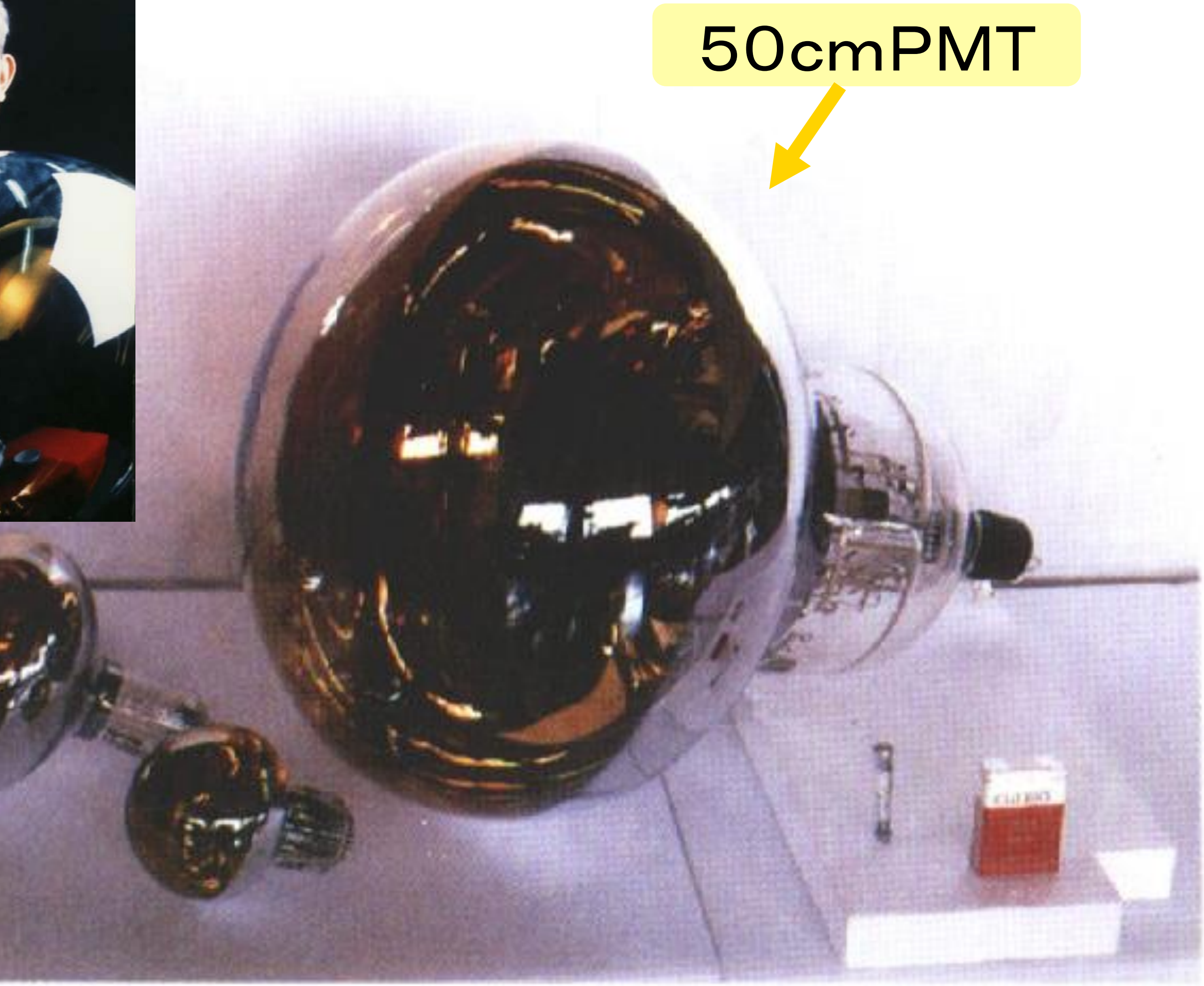
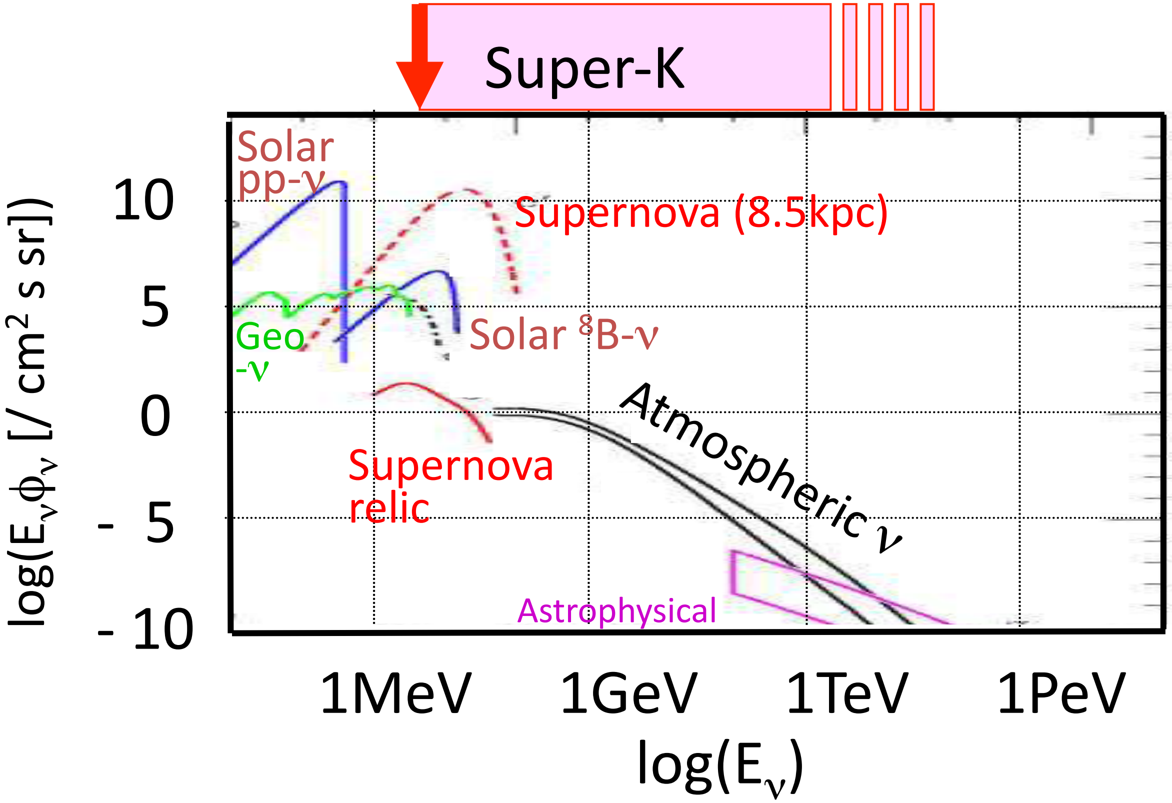


Photo-multiplier tube



Energy Range *(data from SK-I)*

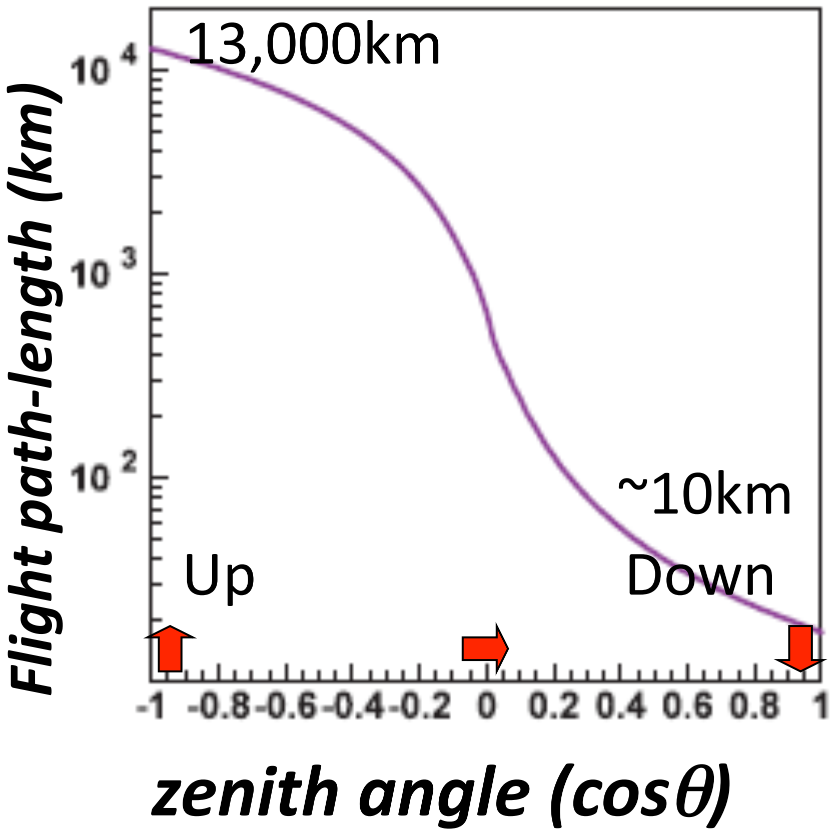
- Trigger: 100% eff. for E_{obs} > **4.5 MeV**
  (50% efficiency @ 3.7MeV)
- Trigger Rate: 1,700Hz → 15 Hz (recorded)



- 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

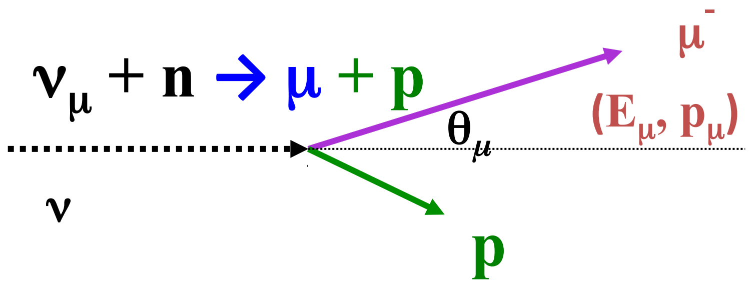


Wide range of path-length
(3 orders)
L: ~10~13,000 km

Wide range of the energy
(5 orders)
E: ~0.1~10,000 GeV

Neutrino Interaction @~1 GeV and E_ν reconstruction

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



- 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

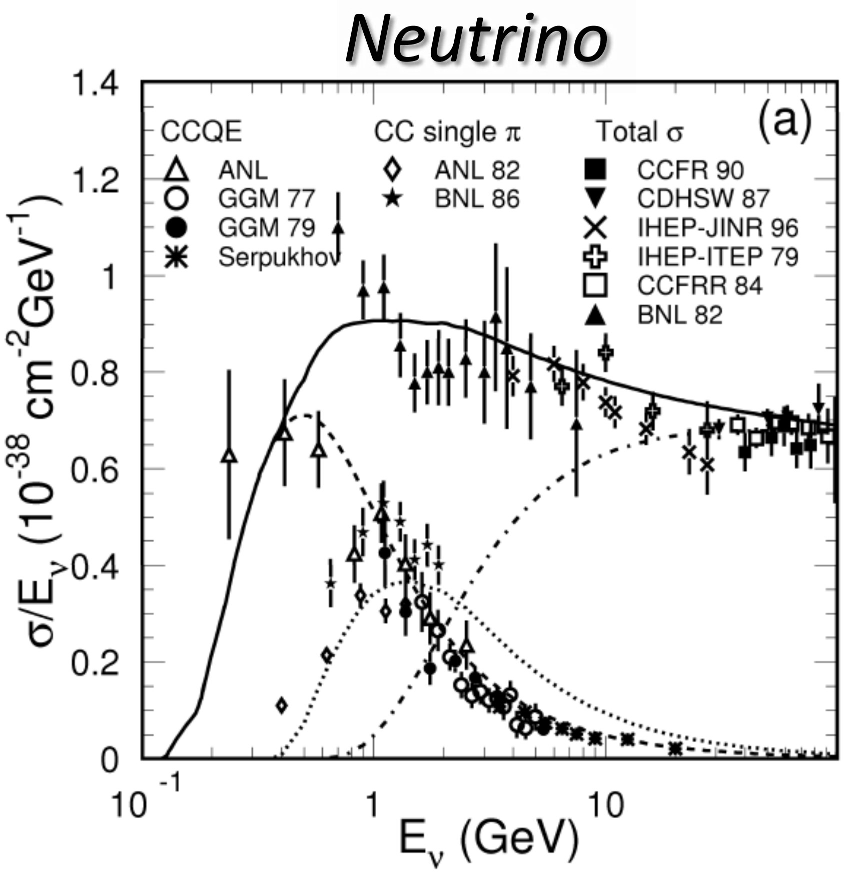
- CC non-QE
  - ~100% efficiency for SK
  - Bkg. for E_ν measurement

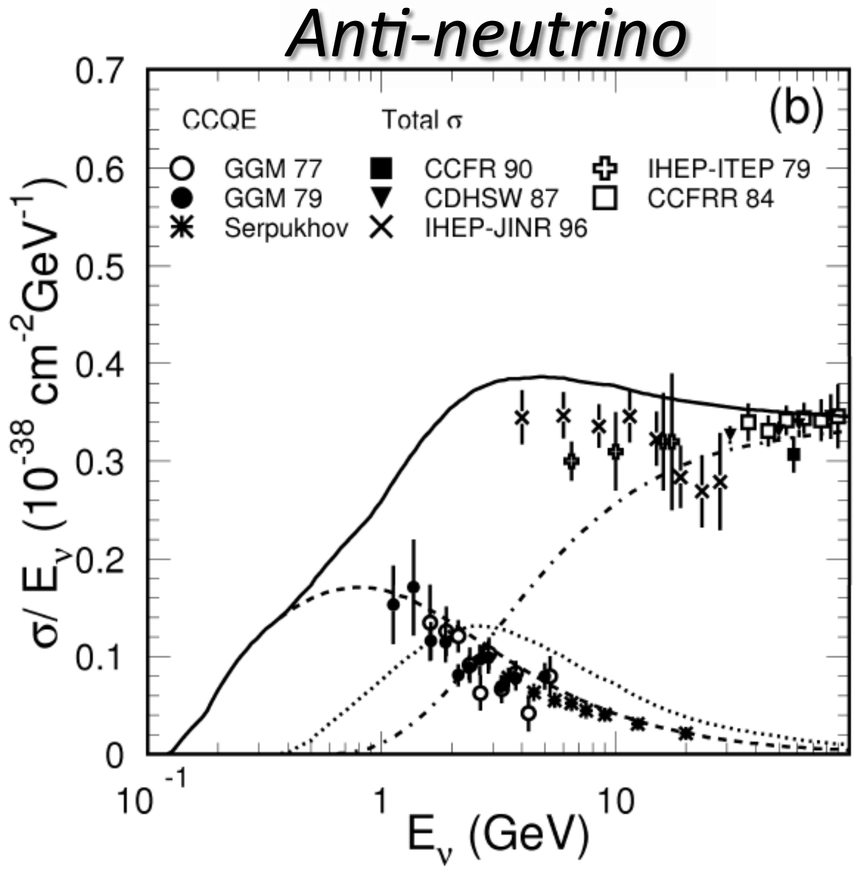
$\nu_\mu + N \rightarrow \nu + N + \pi\text{'s}$

Neutral Current

- NC
  - ~40% efficiency for SK

cross sections





Parameters used in our simulation program:

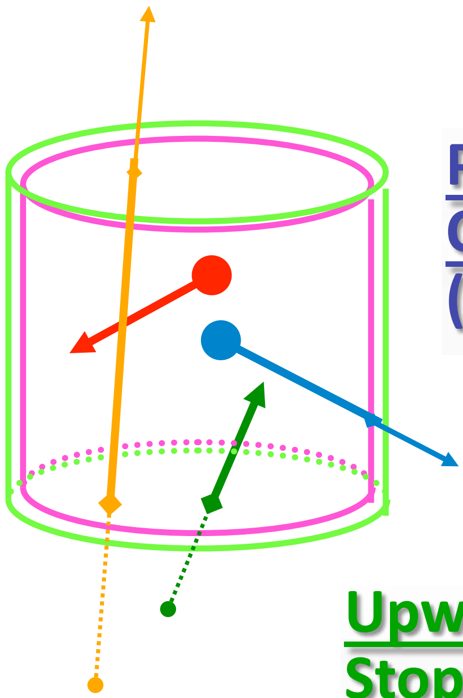
- M_A(QE) =1.11GeV/c^2
- $M_A(1\pi)$ =1.21 GeV/c^2
- Coherent π : Marteau et.al.
- Multi-π: hep-ex/0203009

Checked parameter dependence: Very small effect on oscillation analysis

Atmospheric Neutrino Events in Super-K

- *Event category*

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



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

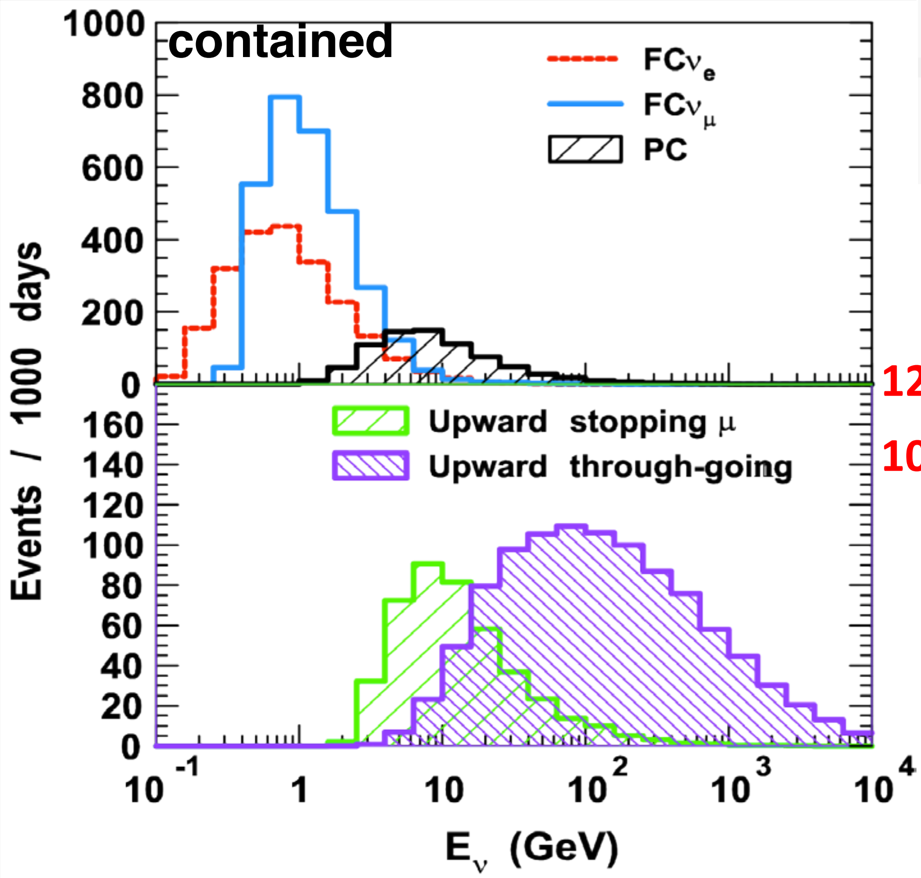
Upward Through-going μ
($\langle E_\nu \rangle$ ~ 100GeV)

Interaction in the rock

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

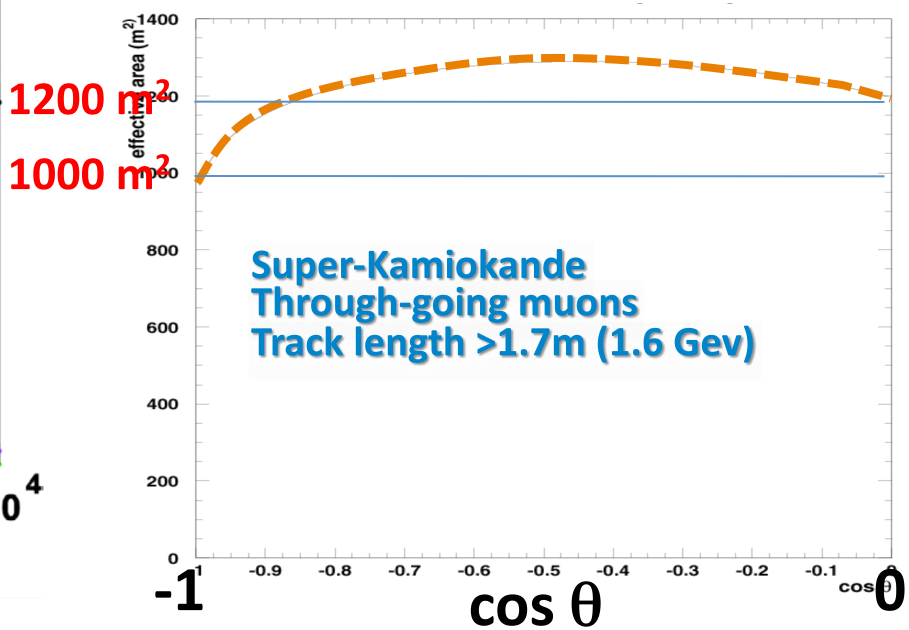
Atmospheric Neutrino Events in Super-K

Parent neutrino Energy

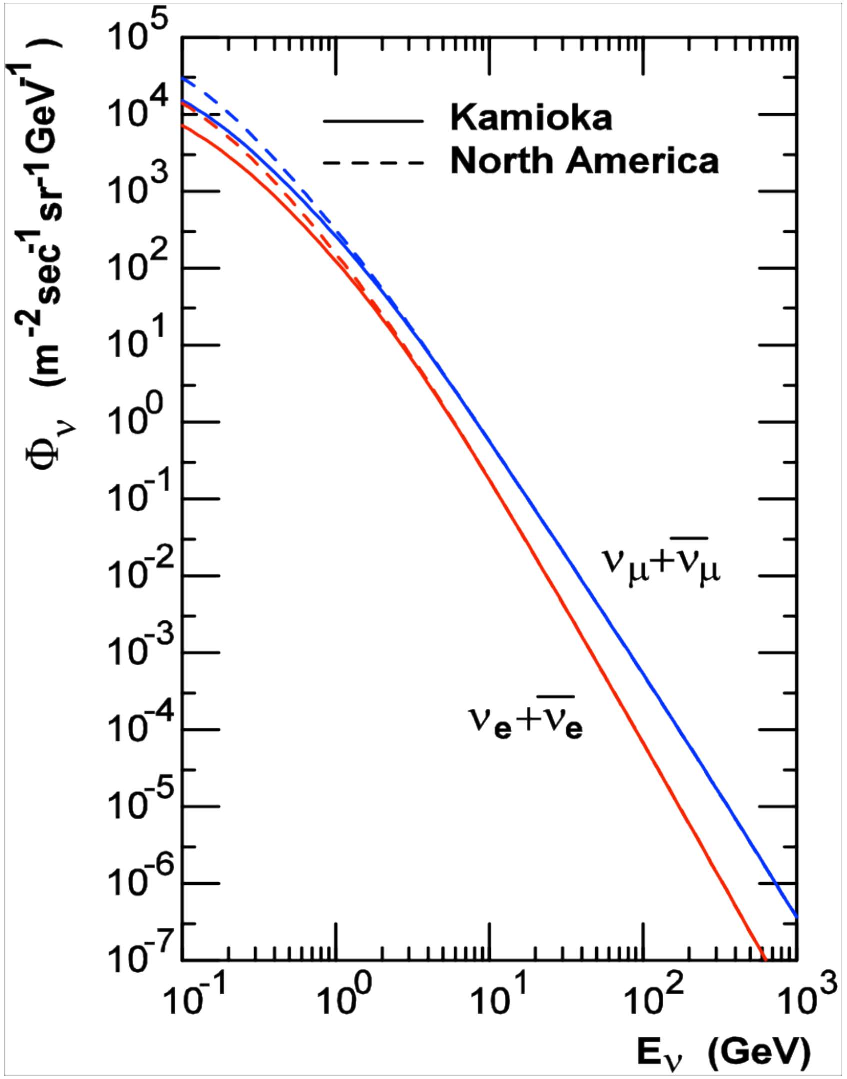


- **Fiducial volume: 22.5 kton**
- **Effective area: ~1,200m²**

Effective Area



Upward going muons



- Sensitivity towards high energy neutrinos
- Cross sections
  - $\sigma(\nu N) \sim E_\nu$
- Muon Range
  - ~Proportional to Ev

Analysis

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

➔

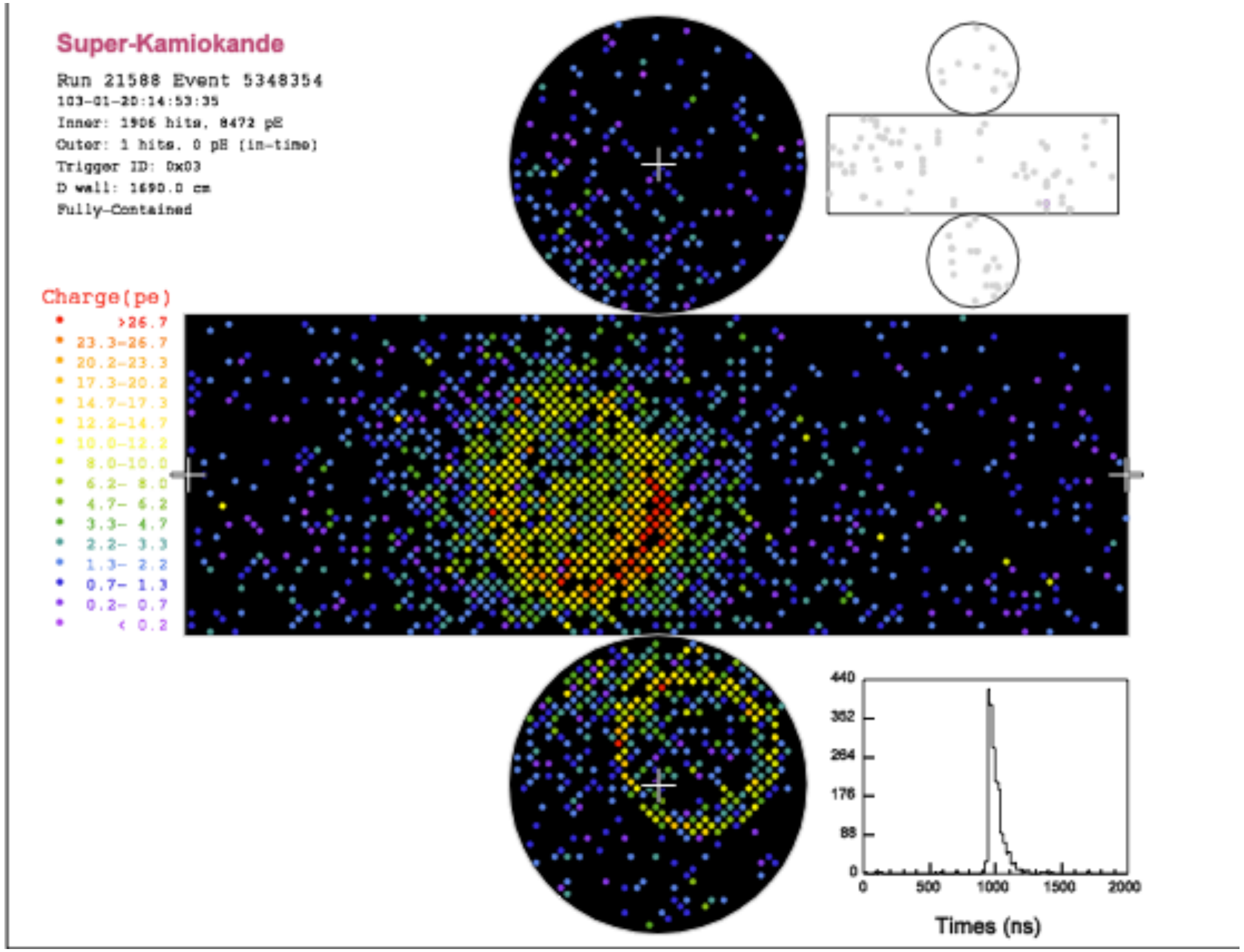
4. **Fiducial Volume cut (>2m from the wall; 22.5kton)**
5. **Minimum energy cut: > 30 MeV (FC),**
   >~ 350MeV (PC)

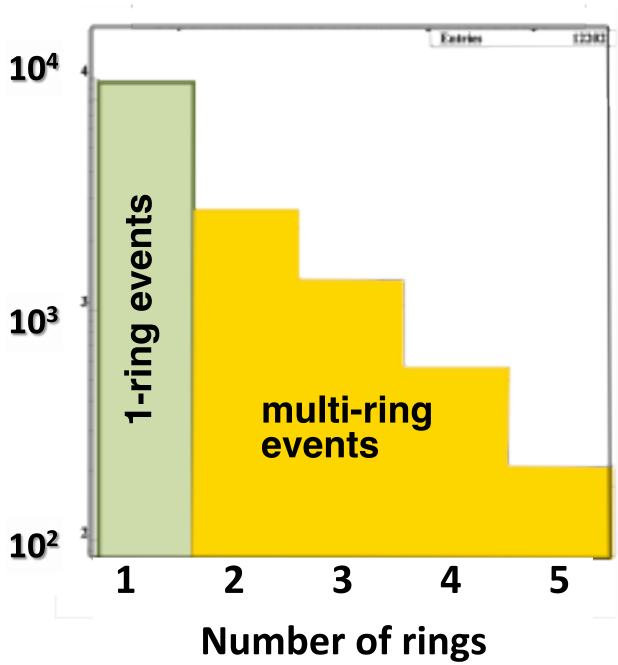
➔ Final Sample:

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

Ring Counts:

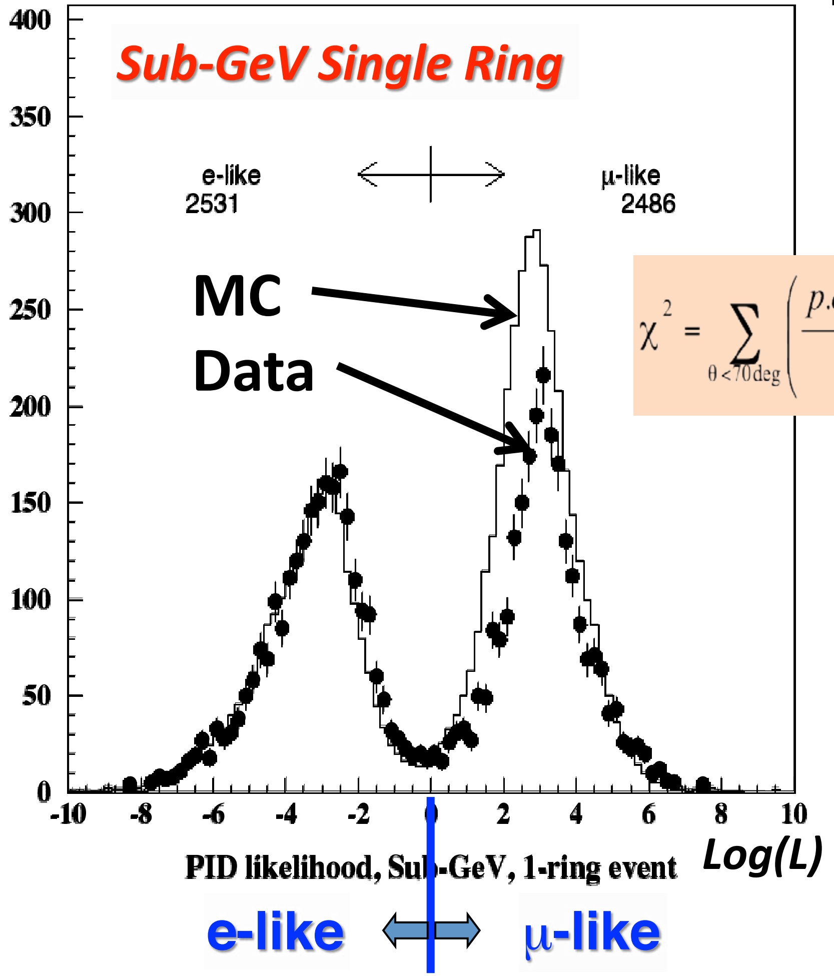
Fully Contained(FC) events



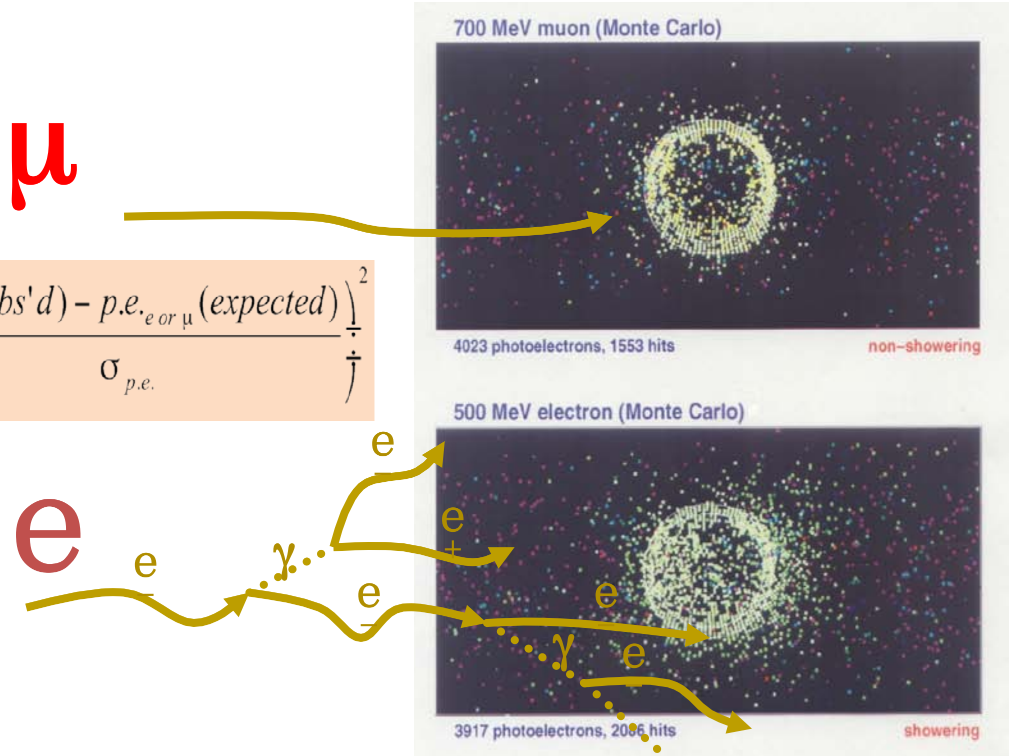


μ / e separation

Likelihood for particle identification



$$\chi^2 = \sum_{\theta < 70\deg} \left(\frac{p.e.(obs'd) - p.e._{e\ or\ \mu}(expected)}{\sigma_{p.e.}} \right)^2$$

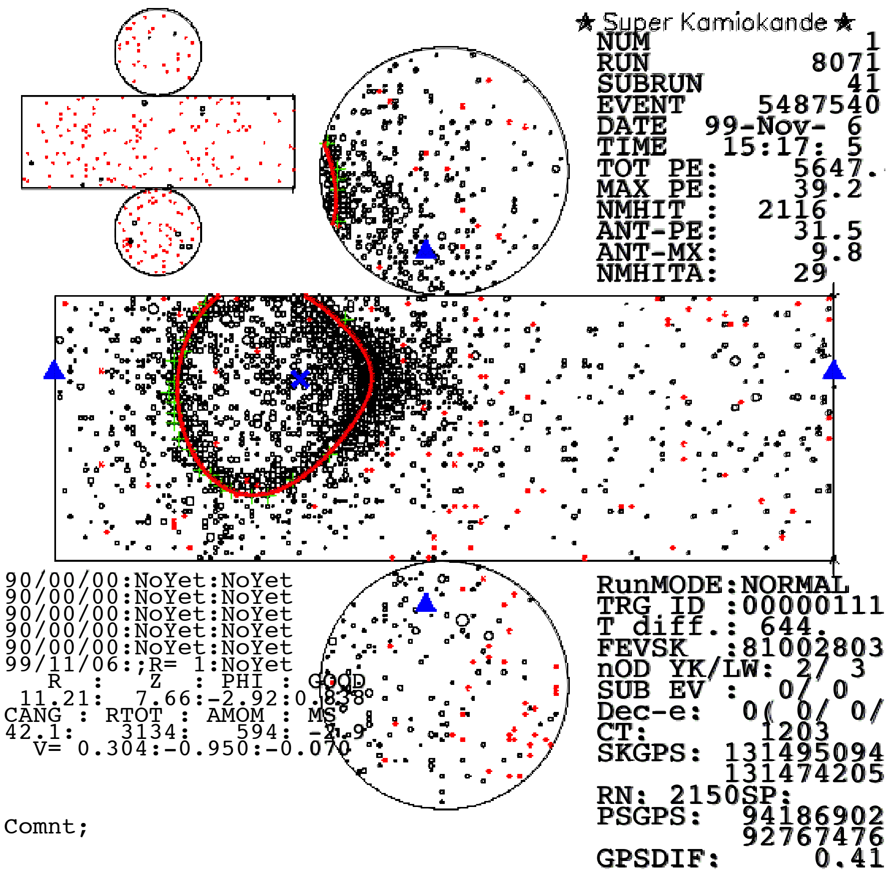


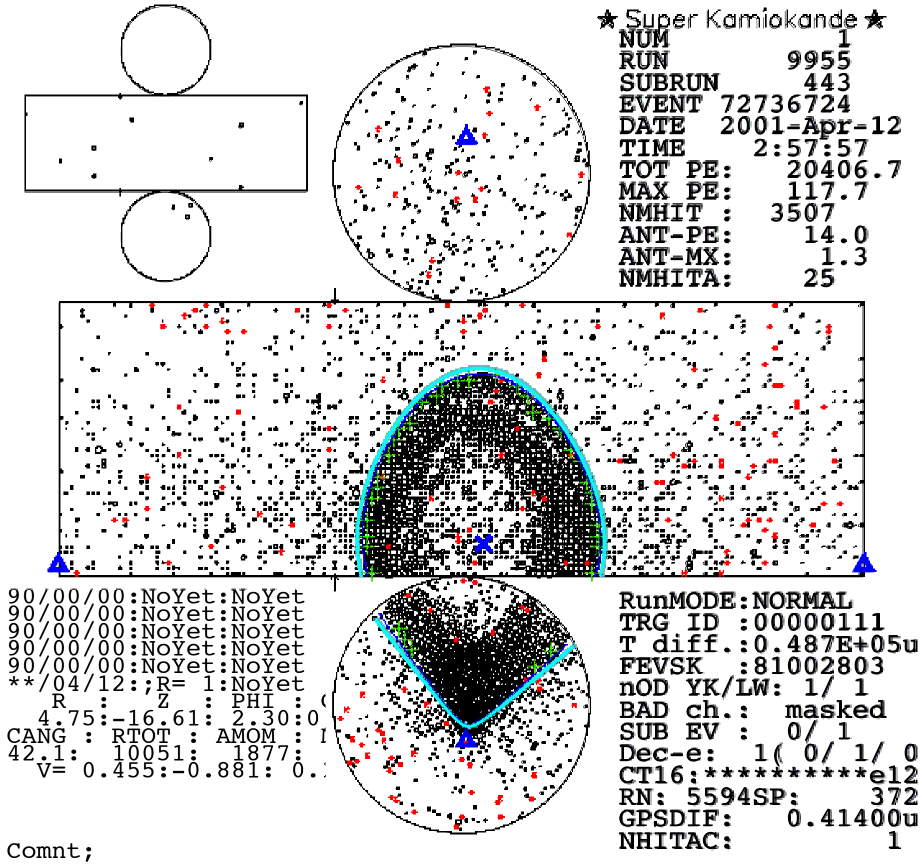
Mis-identification:

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

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

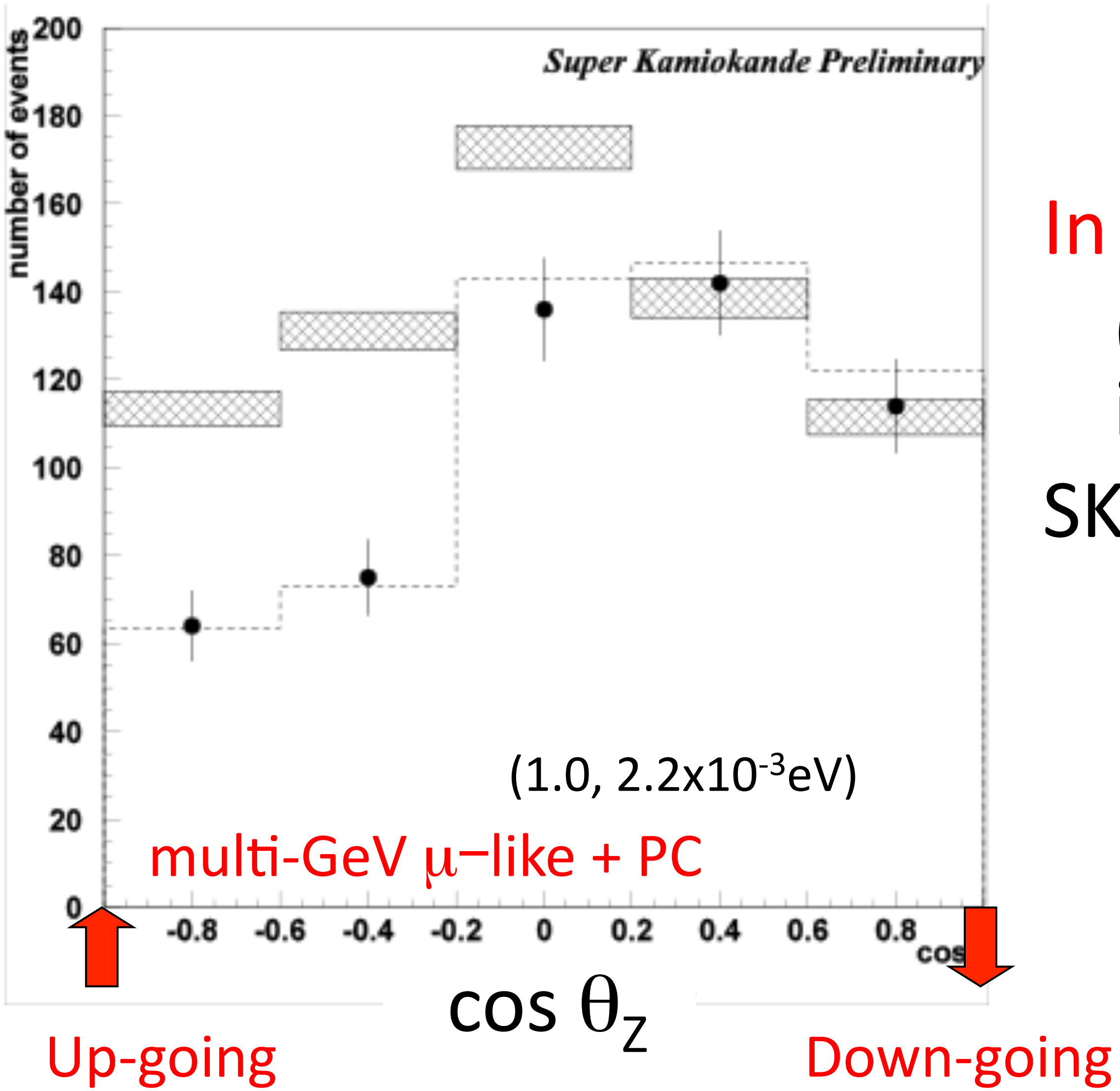
Up stopping μ 1657days

Observed	0.41 +/-0.02(stat.) +/-0.02(syst.) ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
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 Neutrino Oscillation by Super-Kamiokande



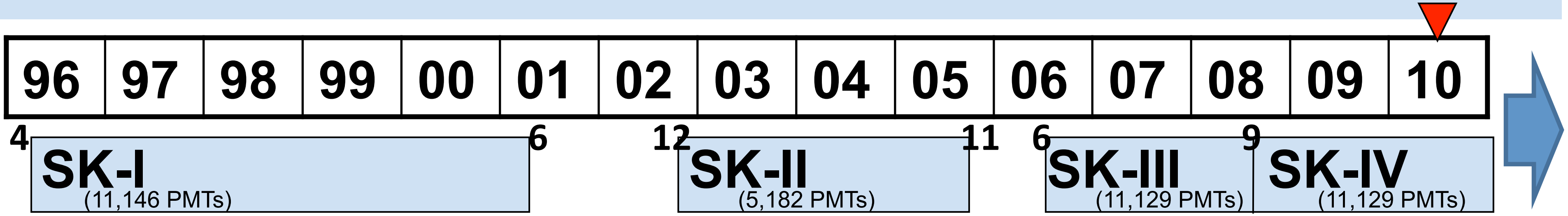
In 1998

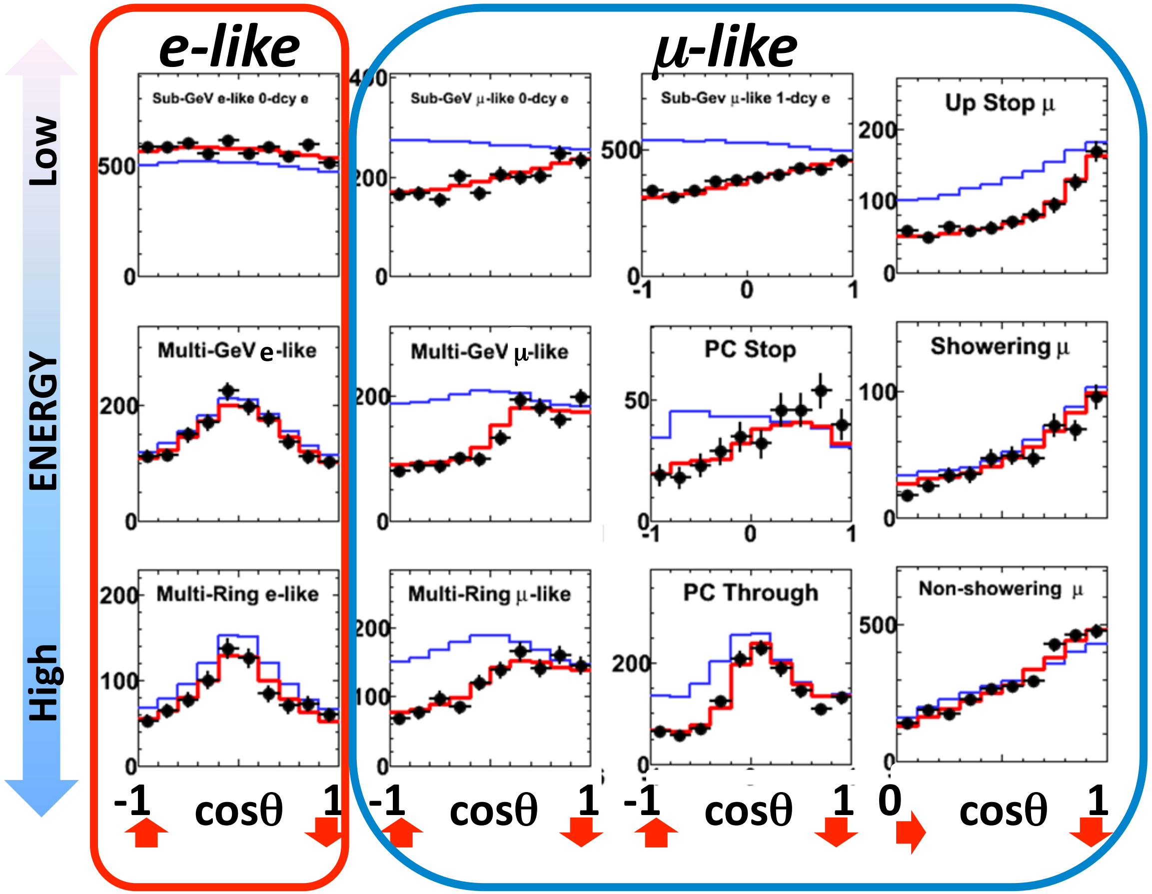
(10 yrs after the KM indication)

SK provided

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

Experimental Results (Super-K)

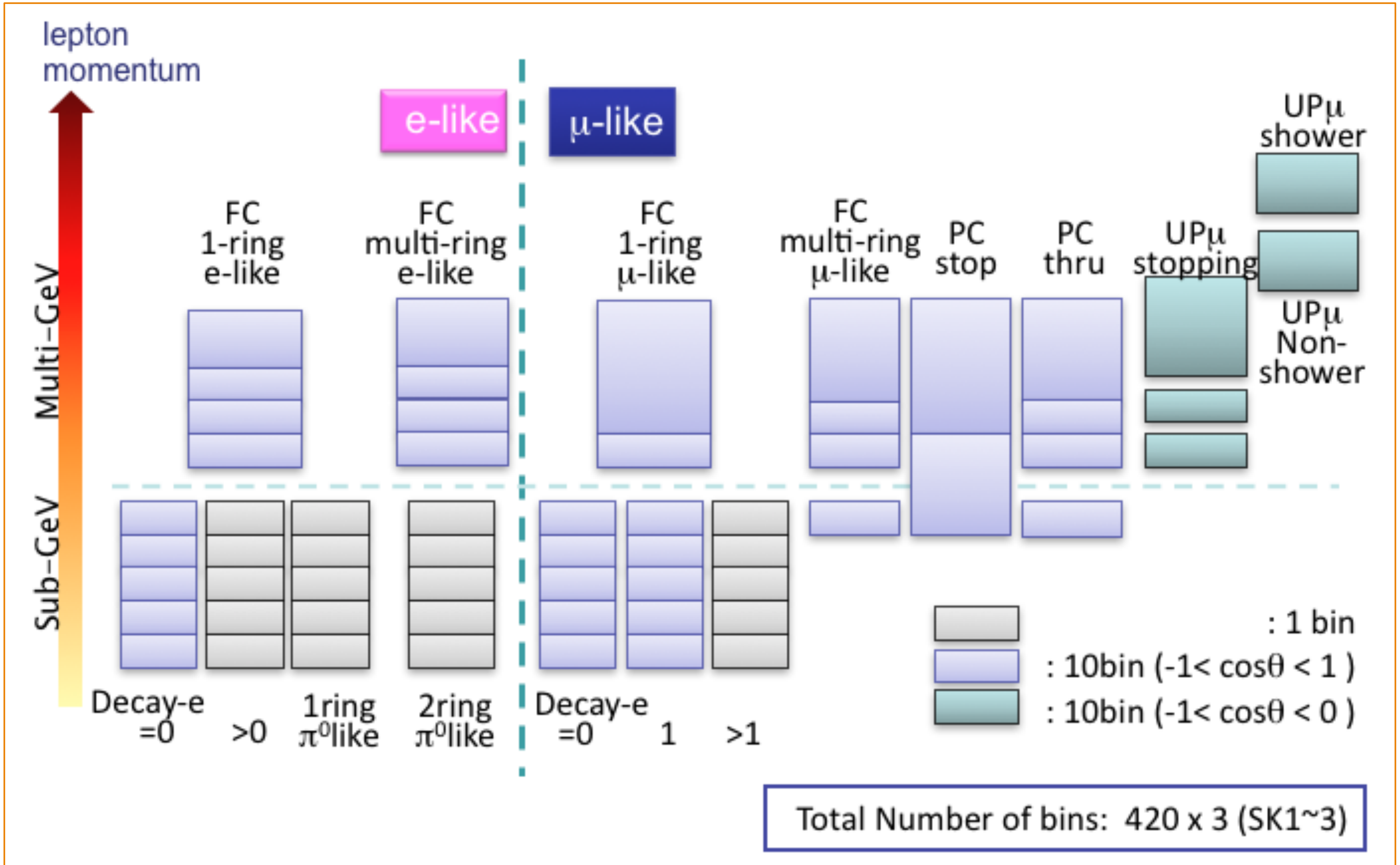




- Latest SK results
  - **SK-I,II,III combined**
  - 2806days (173ktyr) for FC+PC
    - 24841 events
  - 3109days for up-μ
    - 4238 events

Up/Down ~ 1-(1/2)sin²2θ
Transition region ← Δm²

Fitting for oscillation parameters (SKI+SKII+SKIII)



Systematic Errors

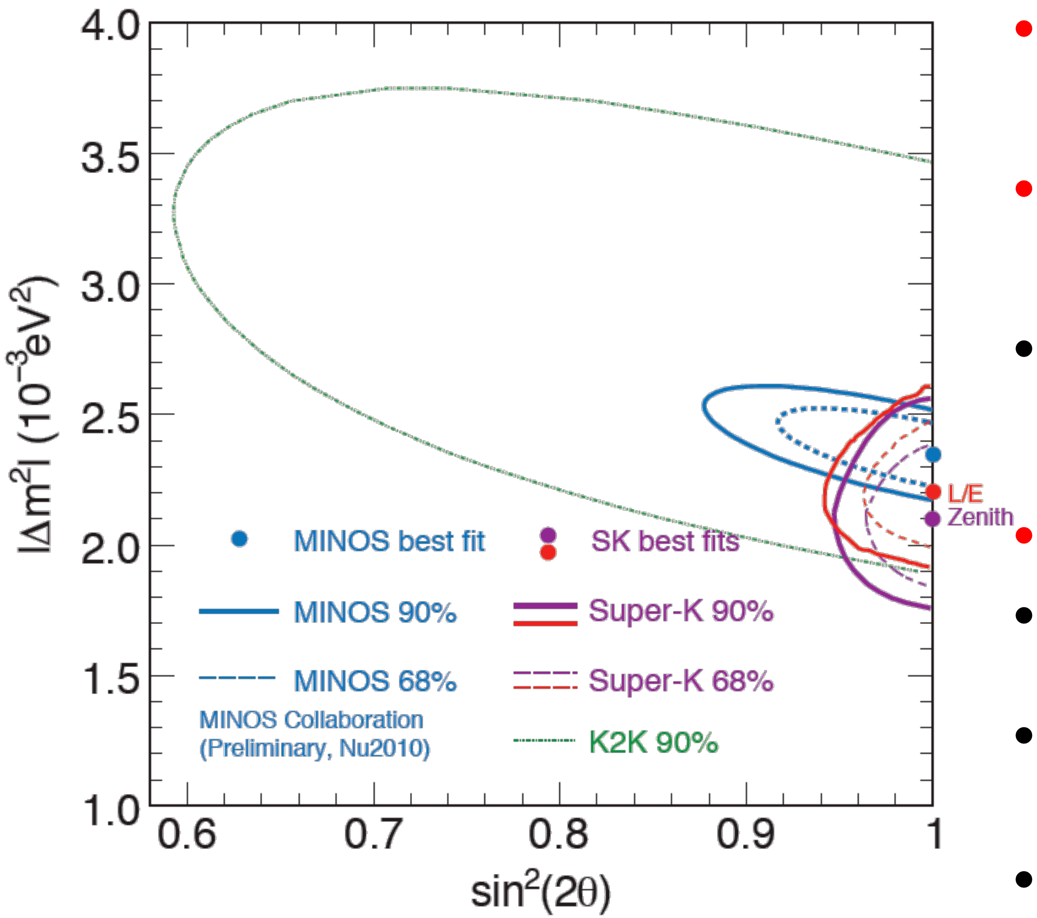
Neutrino flux related
Neutrino interaction related
Reconstruction related
Others

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_ν<1GeV)
4. $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ (1<E_ν<10GeV)
5. $(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ (E_ν>10GeV)
6. $\bar{\nu}_e/\nu_e$ (E_ν<1GeV)
7. $\bar{\nu}_e/\nu_e$ (1<E_ν<10GeV)
8. $\bar{\nu}_e/\nu_e$ (E_ν>10GeV)
9. $\bar{\nu}_\mu/\nu_\mu$ (E_ν<1GeV)
10. $\bar{\nu}_\mu/\nu_\mu$ (1<E_ν<10GeV)
11. $\bar{\nu}_\mu/\nu_\mu$ (E_ν>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

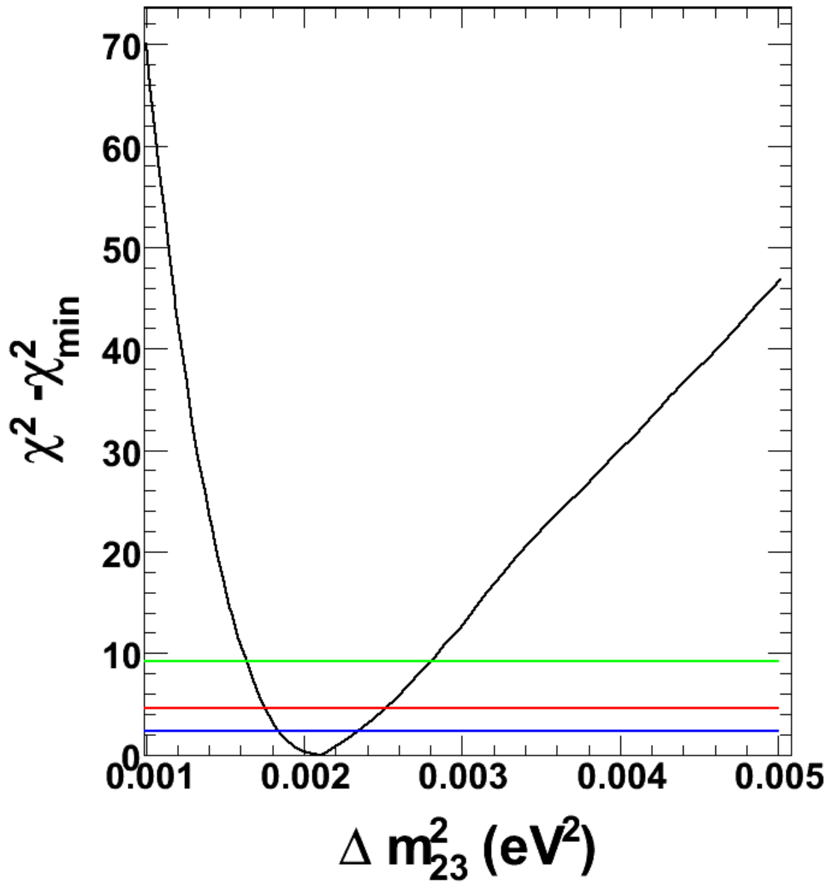
Oscillation Parameters

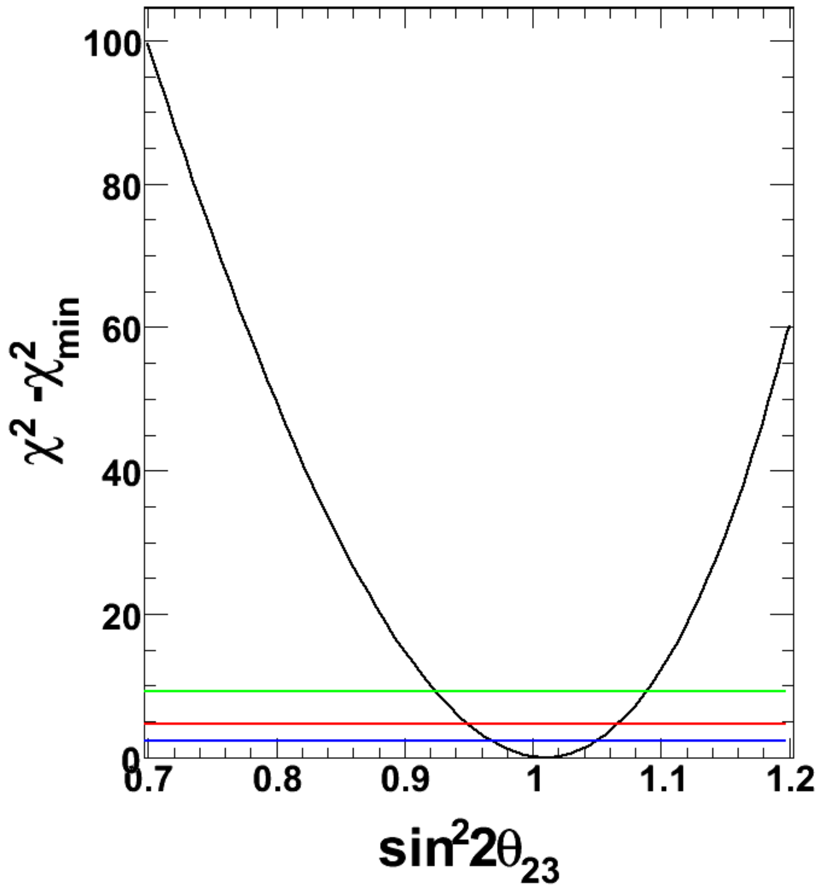


- **$\Delta m_{23}^2 = 2.11^{+0.11}_{-0.19} \times 10^{-3}\ eV^2$ (Atm-ν: Zenith)**
- **$\Delta m_{23}^2 = 2.19^{+0.14}_{-0.13} \times 10^{-3}\ eV^2$ (Atm-ν: L/E)**
- $\Delta m_{23}^2 = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ eV^2$ (MINOS@Neutrino2010)
- **$\sin^2 2\theta > 0.96$ (90%) (Atm-ν)**
- $\sin^2 2\theta > 0.91$ (90%) (MINOS)
- Δm^2: LBL experiment getting better sensitivity
- $\sin^2 2\theta$: atm-ν is better

χ^2 distribution

Consistent with maximal mixing

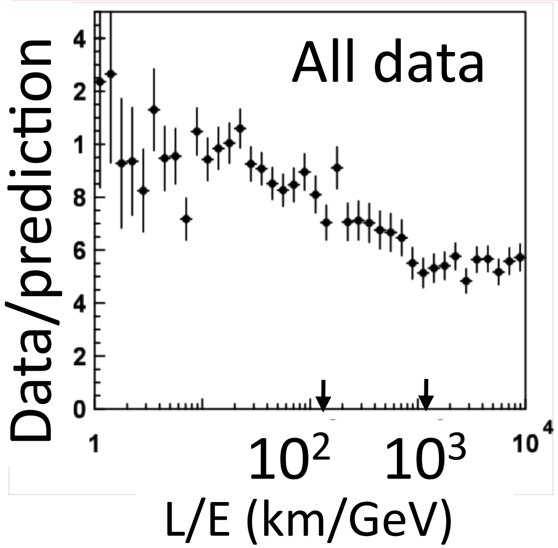




L/E analysis

- Can observe oscillation pattern in L/E plot ← λ ~ 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 : $\Delta(E/L) < 70\%$

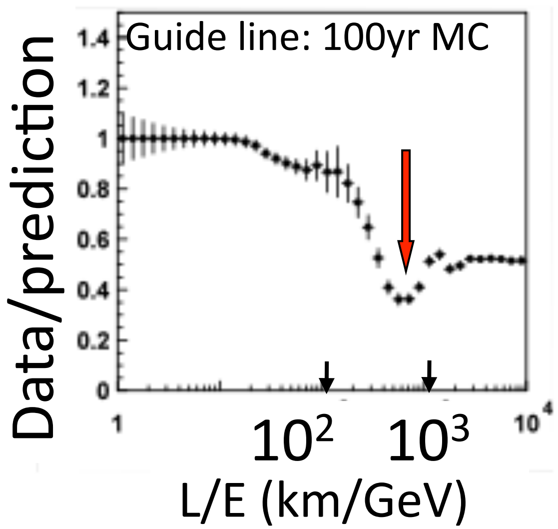
Rejected events

horizontally going events:

low energy events:

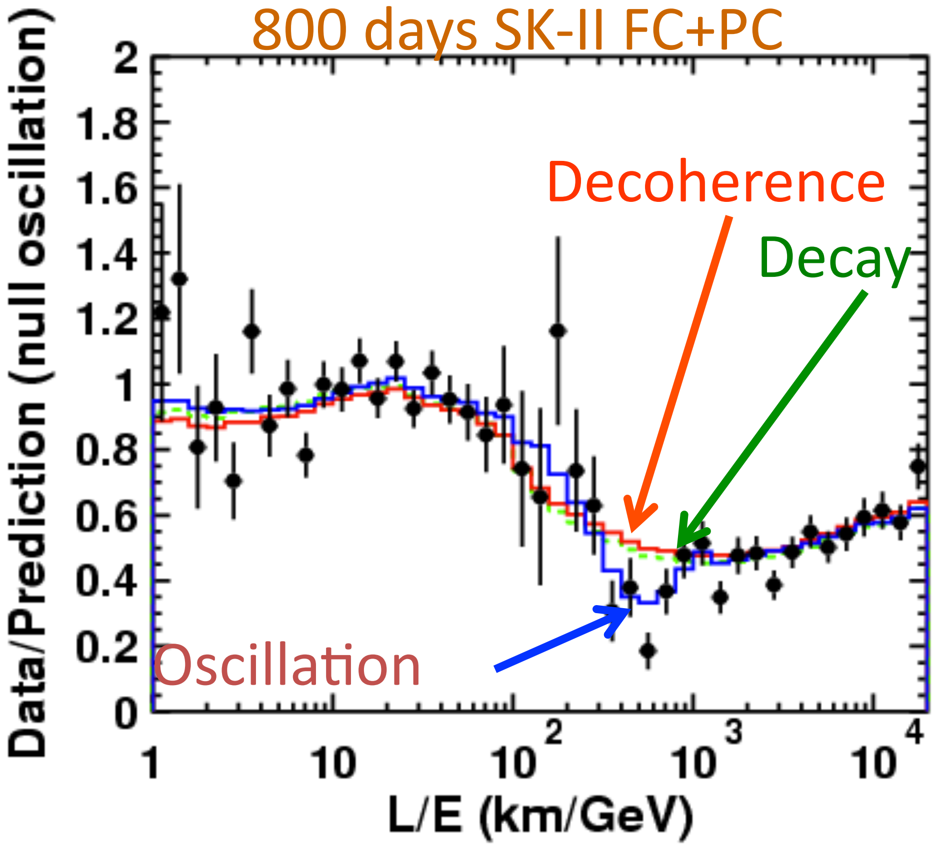
→ poor ΔL, Δθ determination

~1 /5 of total data



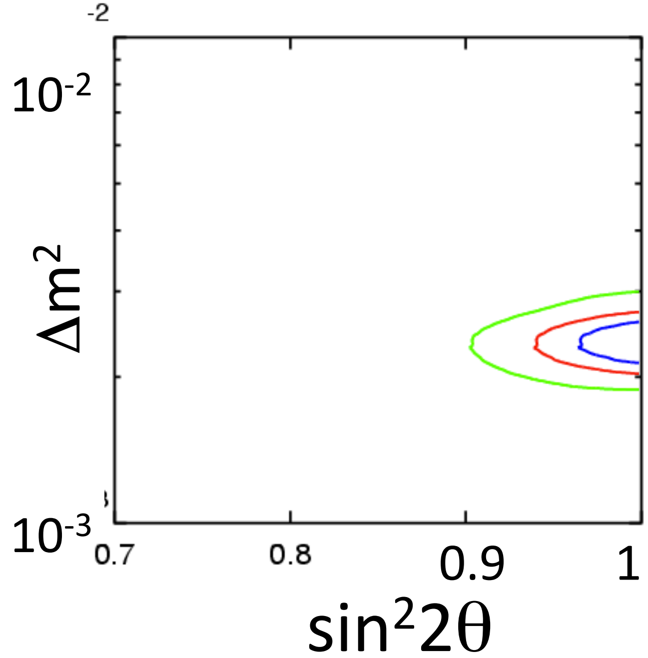
Result of L/E analysis (SK-I + SK-II)

1489.2 days SK-I +
800 days SK-II FC+PC



4.8 σ to decay
5.3 σ to decoherence

- 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

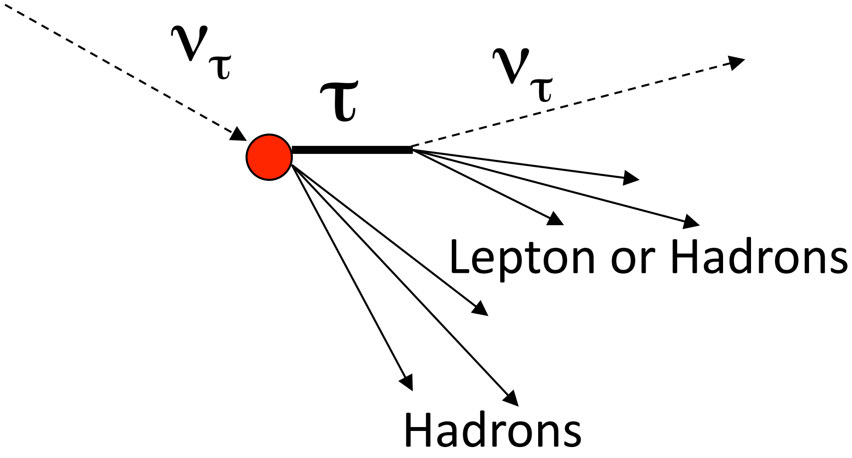


ν_τ appearance

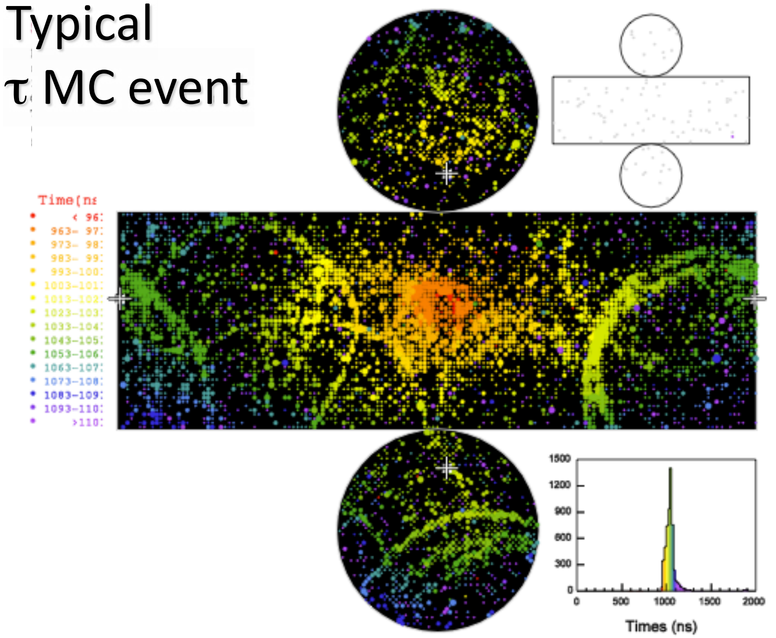
- How we can test it?
- Do we have evidence for ν_τ appearance?

Yes

Search for τ appearance in atmospheric ν



Typical
τ MC event



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

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

  ↳ $\mu\nu\nu$, $e\nu\nu$,

  ↳ ν+hadrons(π,π,....)

  →Many Hadrons

  →Rather Spherical

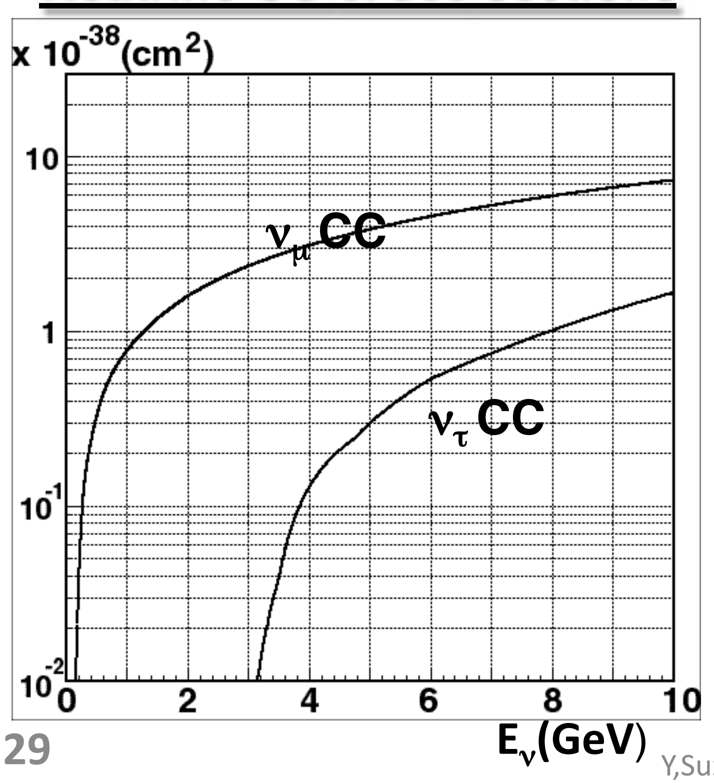
  →Complicated events
- Make statistical analysis

  ← using characteristics of τ production

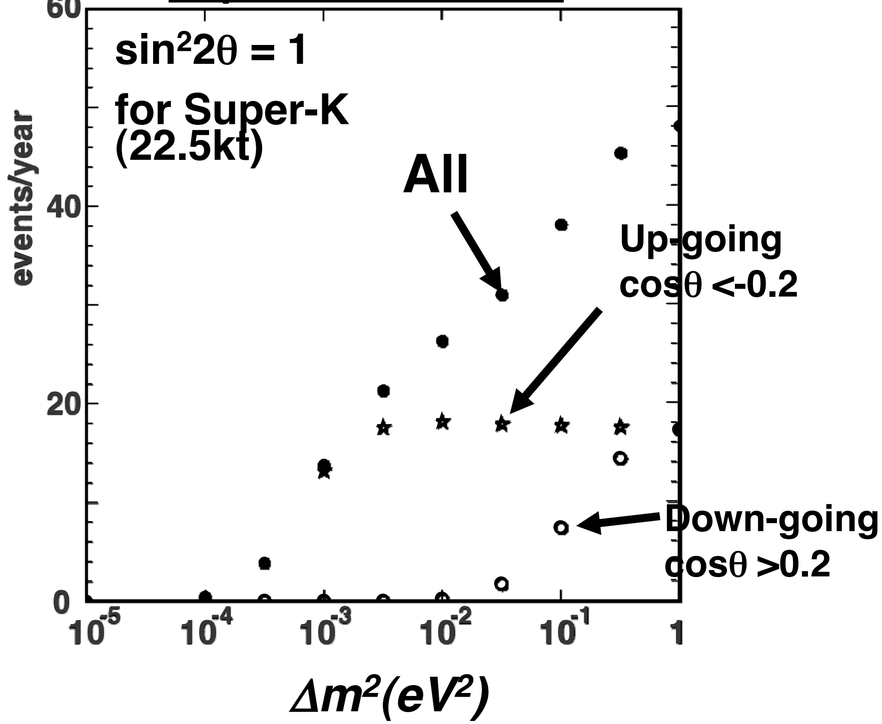
Search for τ appearance in atmospheric ν

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

Neutrino CC cross sections



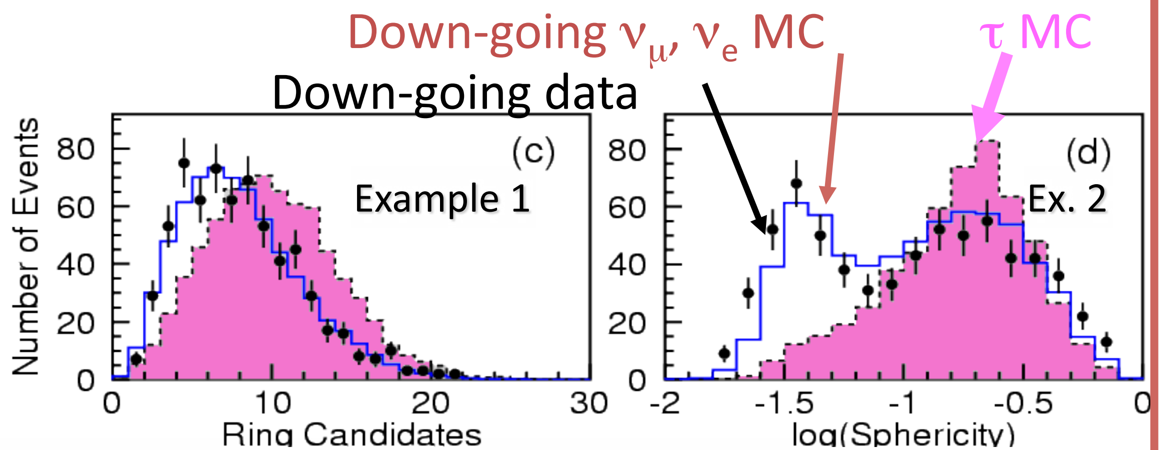
Expected τ events



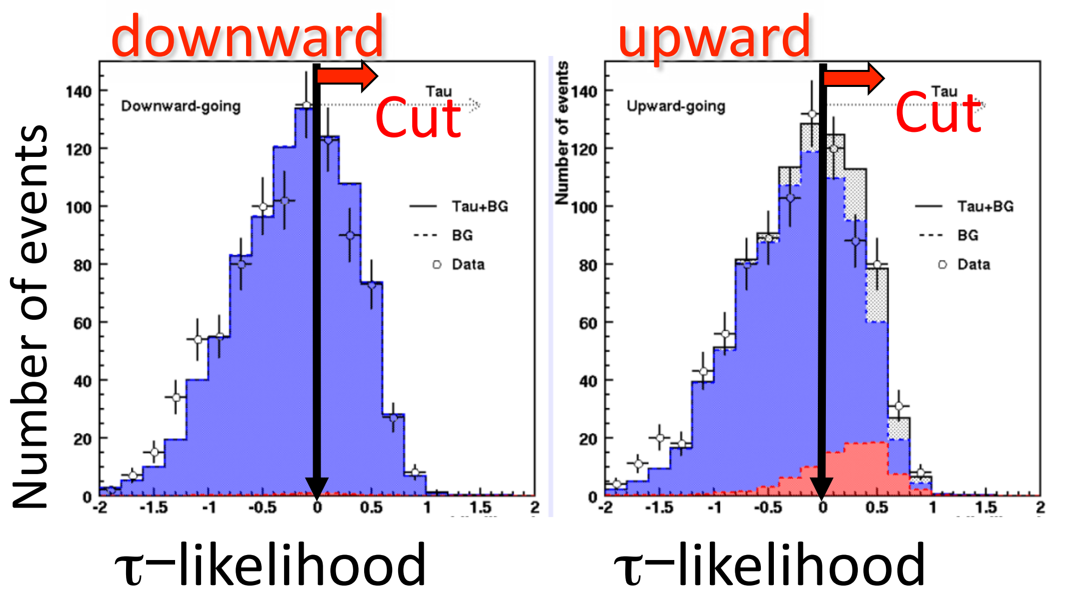
Selection of τ enriched sample

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



Use 6 distributions to make likelihood



Likelihood

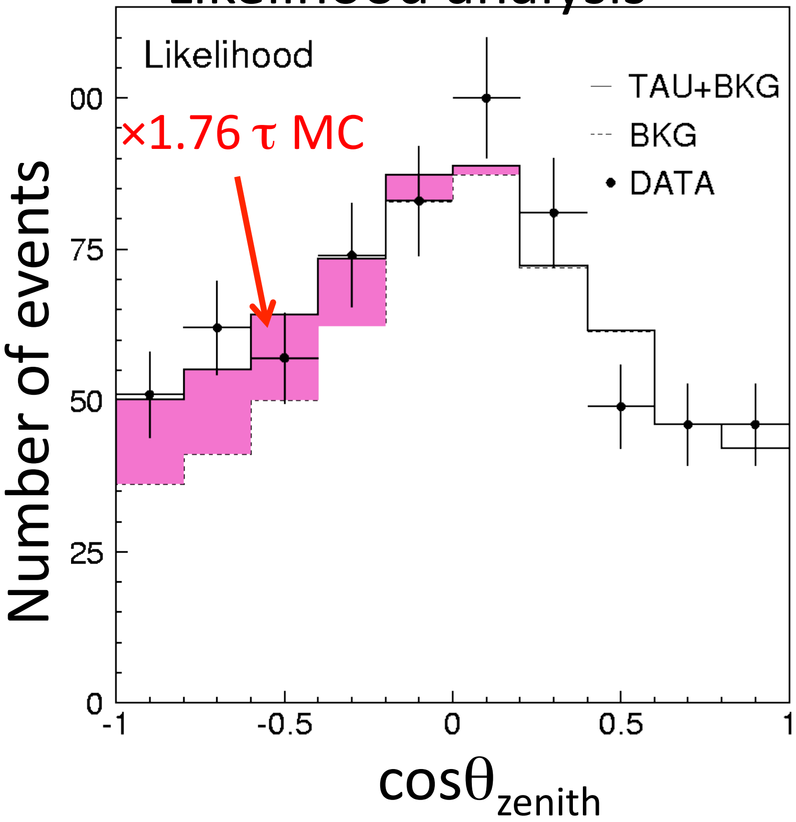
Neural Network

(2 independent analyses)

➔ 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

Atmospheric Neutrinos

30-Sept-2010

- Small but important effect
- future

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

- Experimental Strategy
  1) Use enriched NC sample and
  2) matter effect

$\nu_\mu \rightarrow \nu_\tau$: A=0

$\nu_\mu \rightarrow \nu_s$: $A = -\sqrt{2}G_F E_\nu n_n$

$\nu_e \rightarrow \nu_{\mu,\tau}$: $A = 2\sqrt{2}G_F E_\nu n_e$

Matter potential for $\nu_\alpha \rightarrow \nu_\beta$

$$A = 2\sqrt{2}G_F E_\nu (N(\nu_\alpha) - N(\nu_\beta))$$

$N(\nu_e) = n_e - (1/2)n_n$

$N(\nu_{\mu,\tau}) = -(1/2)n_n$

$N(\nu_s) = 0$

$\nu_\mu \rightarrow \nu_\tau$: No matter effect

$\nu_\mu \rightarrow \nu_s$: matter effect

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

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

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

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

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

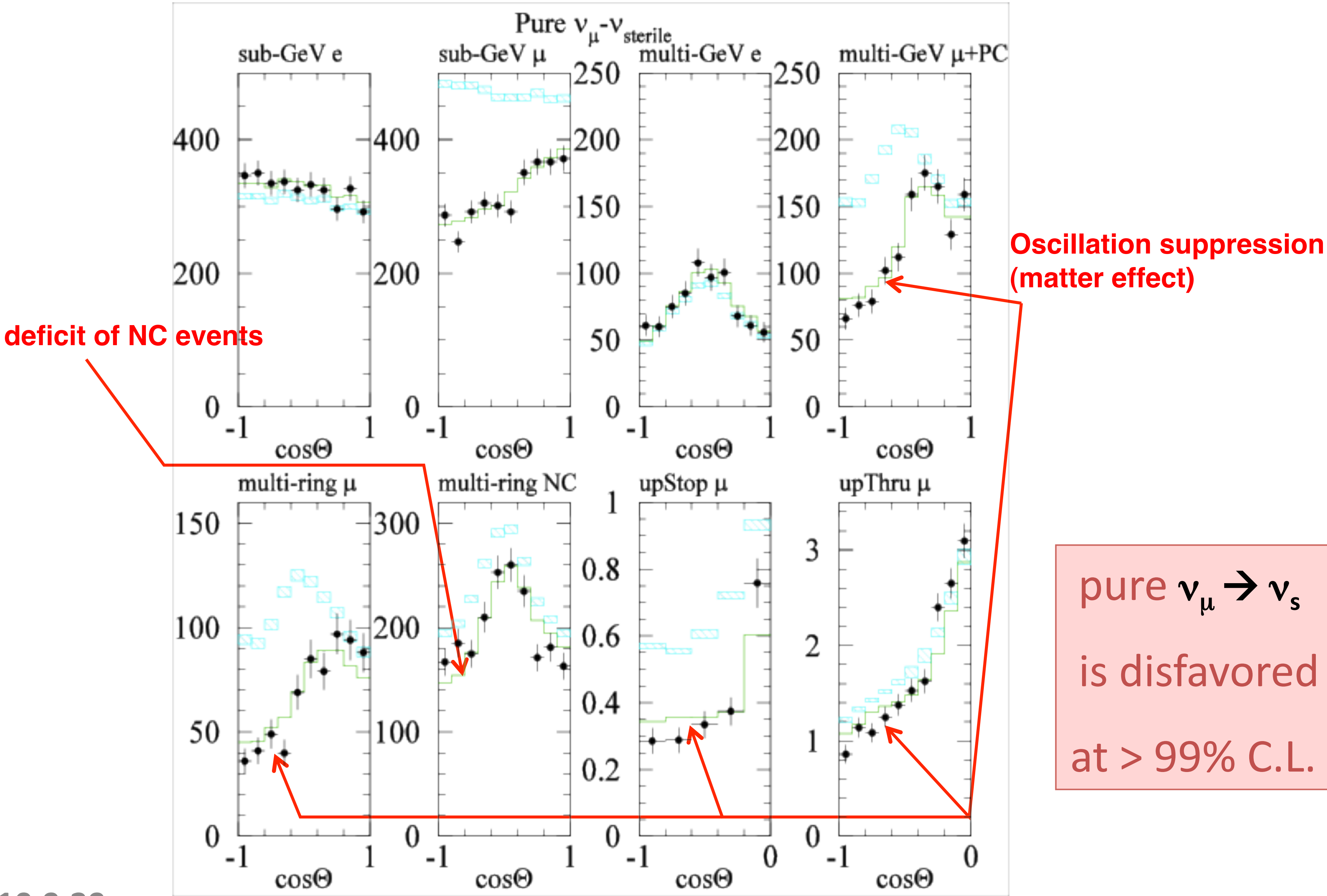
And for E_ν = 30 ~ 100 GeV

➔ $A \gg 1$

$\sin^2 2\theta_m < 1$:

Suppression of the oscillation effect

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



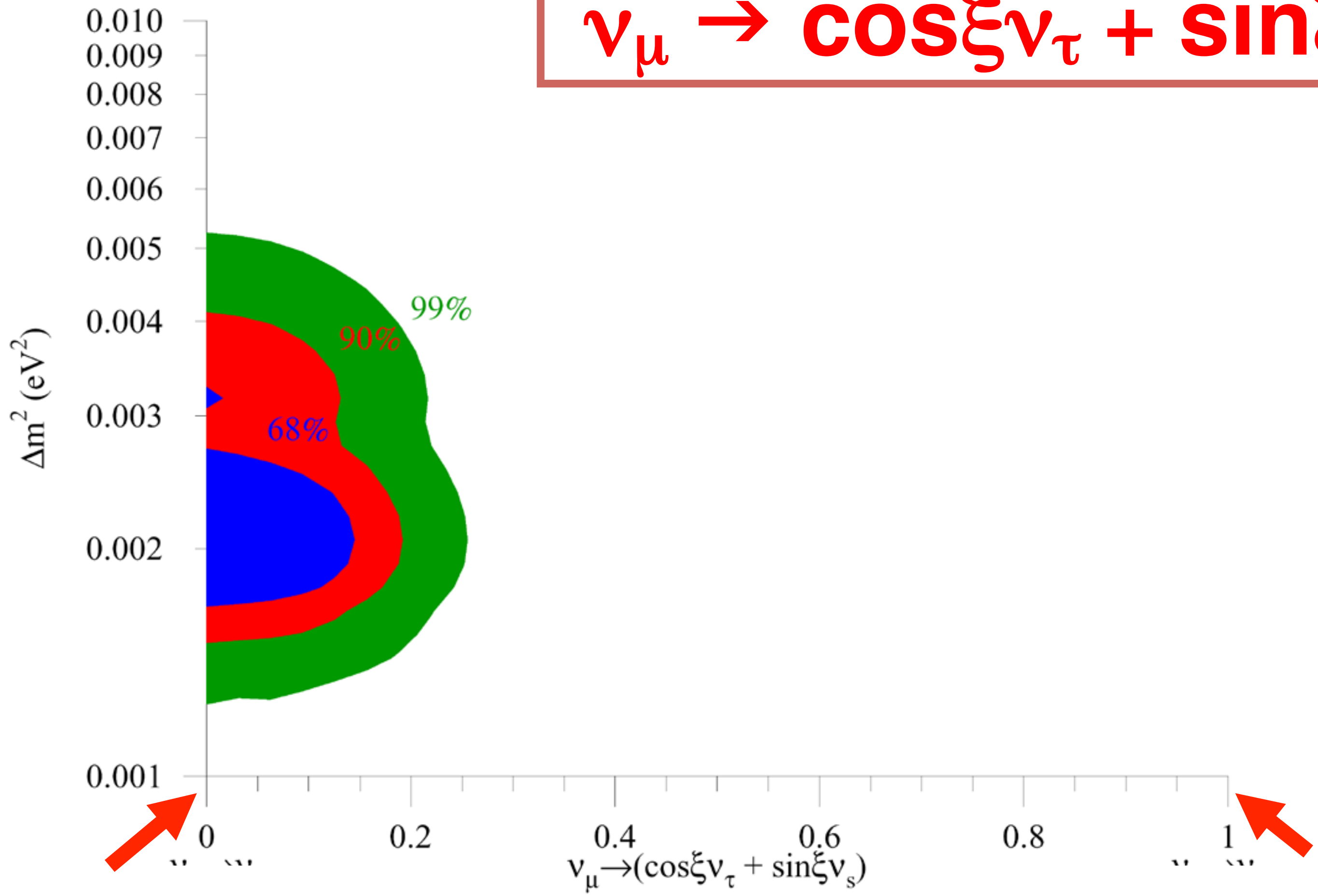
pure $\nu_\mu \rightarrow \nu_s$

is disfavored

at > 99% C.L.

Limit on sterile mixture

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

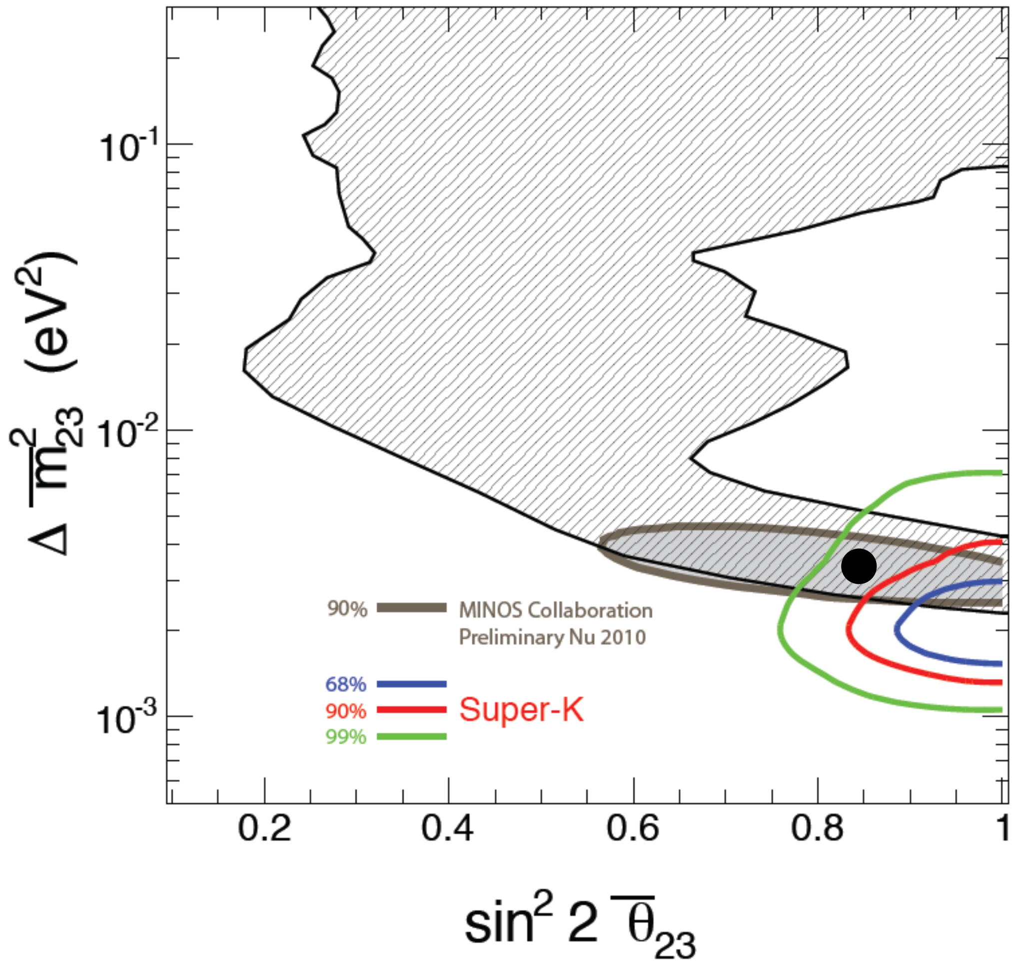


pure $\nu_\mu \rightarrow \nu_\tau$

$\sin^2\xi$

pure $\nu_\mu \rightarrow \nu_s$

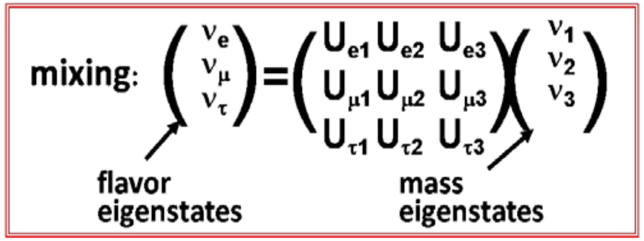
CPT test by atmospheric ν



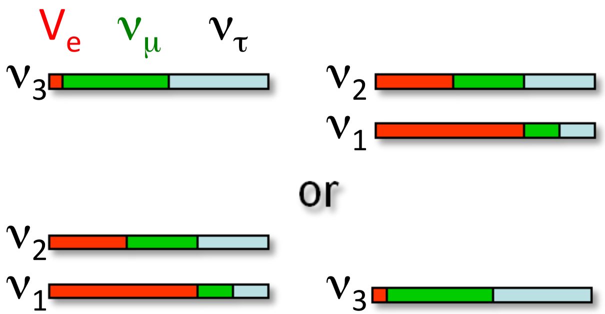
- Produce MC for ν (Δm_{23}^2, θ_{23}) and $\overline{\nu}$ ($\Delta \overline{m}_{23}^2$, $\overline{\theta}_{23}$) separately, and look for best parameter set
- Neutrino
  Δm_{23}^2=2.2x$10^{-3}$$eV^2$
  $\sin^2 2\theta_{23}$=1.0
- Anti-neutrino
  $\Delta \overline{m}_{23}^2$=2.0x$10^{-3}$$eV^2$
  $\sin^2 2\overline{\theta}_{23}$=1.0
- **No evidence for CPT violating oscillations (SK) was found**

3 flavor analysis and future atmospheric neutrino experiments

Remaining Problems



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



Atmospheric ν
Long baseline
(θ_{23}: maximal?)

Reactor, LongBL
(θ_{13}: upper limit)
Not determined yet

Solar ν
Reactor LBL
(θ_{12}: large)

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

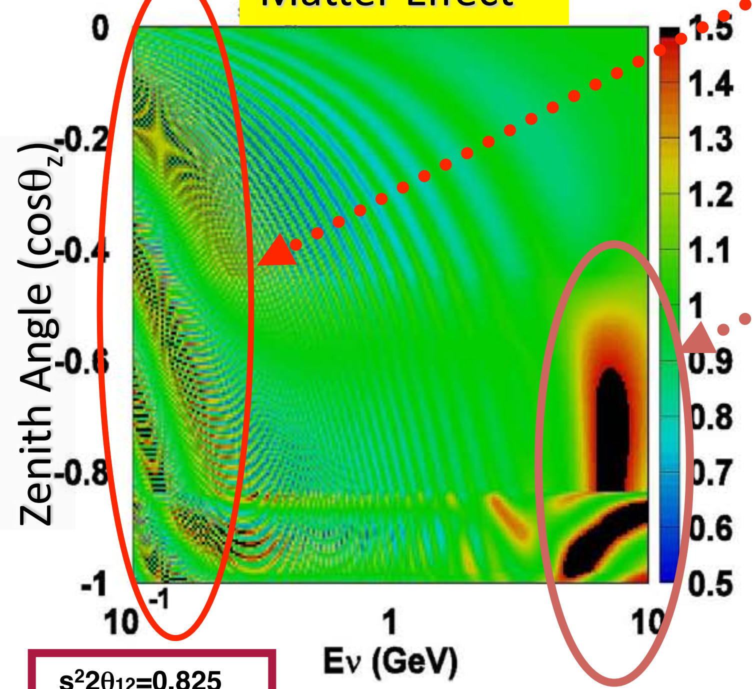
- Atmospheric neutrino oscillation is mainly due to through θ_{23}, but small effects from θ_{13} and θ_{12} may be seen: sub-dominant effects
- Mass hierarchy may also be untangled

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
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$
$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

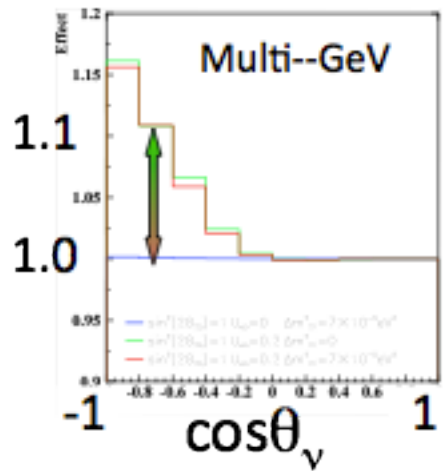
Matter Effect



$s^2 2\theta_{12}$=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}

1^{st} term: solar term (θ_{12}, Δm_{12})
mostly in low energy
cancellation effect (if c^2_{23}=0.5,r=ν_μ/ν_e=2@LE)
1~2% effect (may determine c^2_{23}<0.5,>0.5)

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



2^{nd} term: Interference
CP-phase

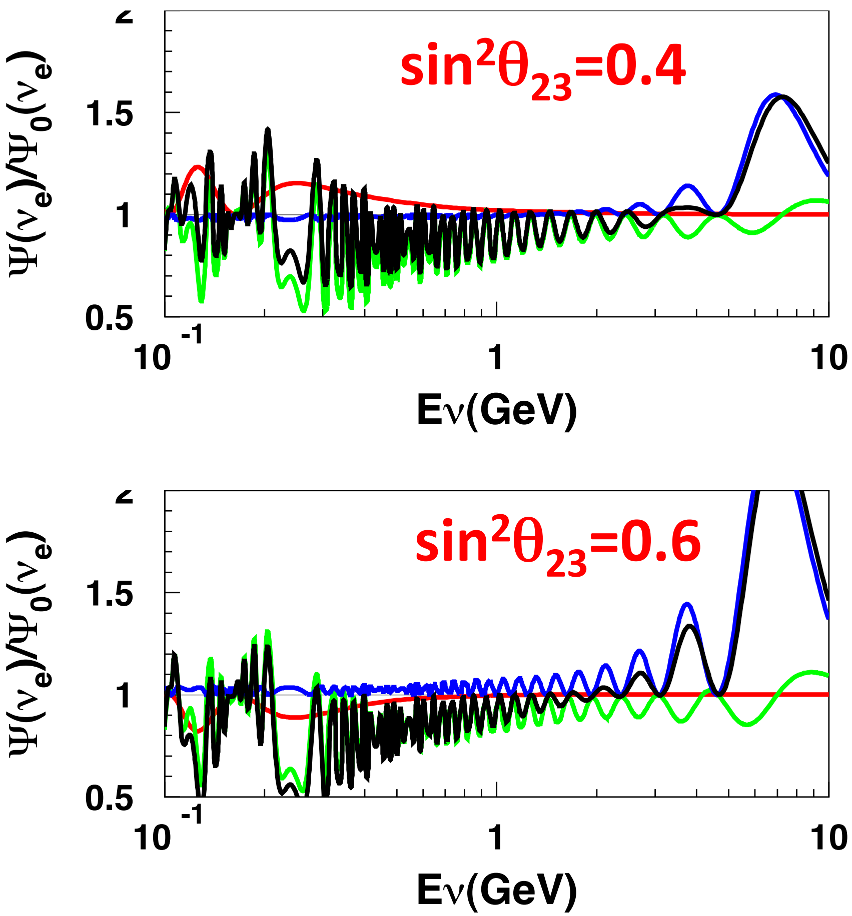
Comment on solar term

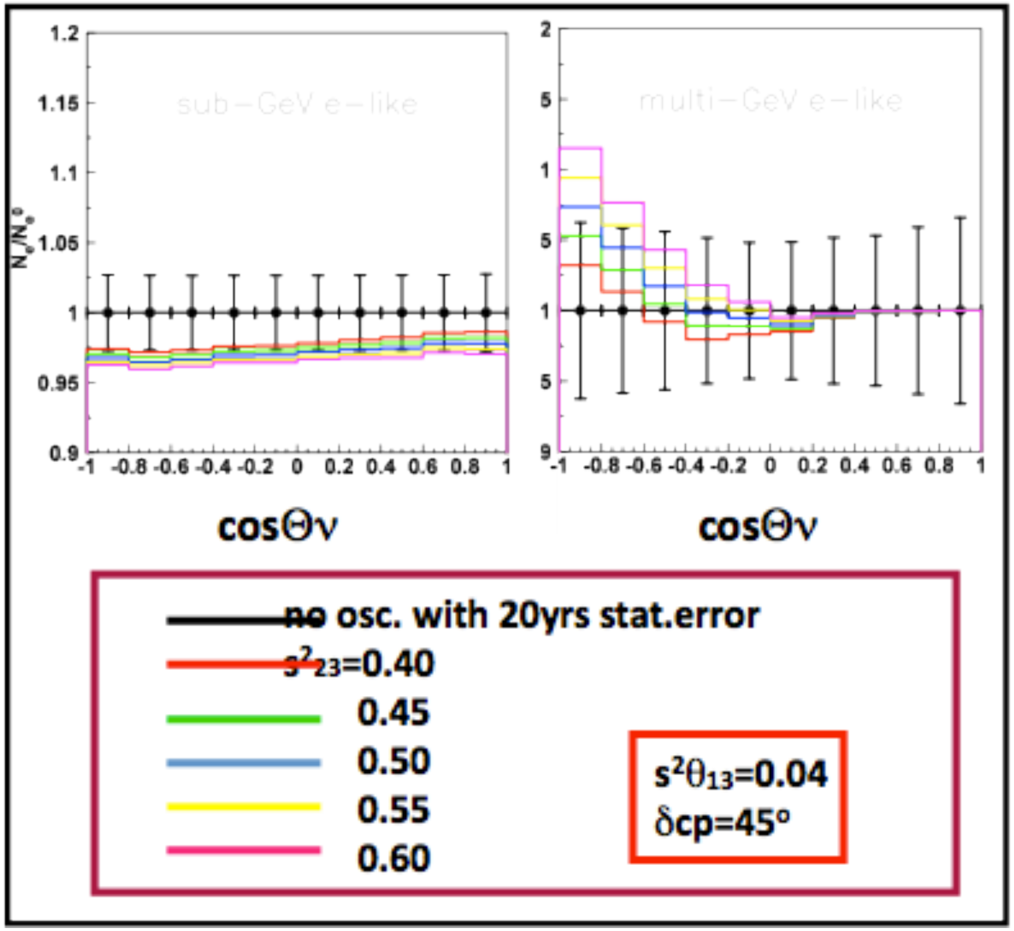
- Δm_{12}^2: 8×10^{-5} eV^2
- Δm_{23}^2: 2.5×10^{-3} eV^2
- Crossing the diameter of the earth (up-going)
  - L ~ 13,000 km
  - E ~ 1 GeV

  ➔E/L ~ 8x 10^{-5} (GeV/km) ≈solar Δm^2

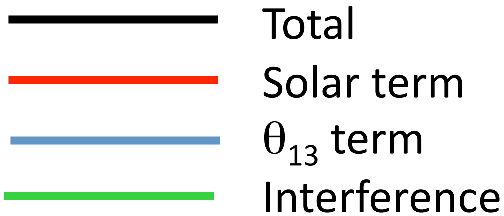
  $(\lambda/E = 4\pi/\Delta m^2)$

Example





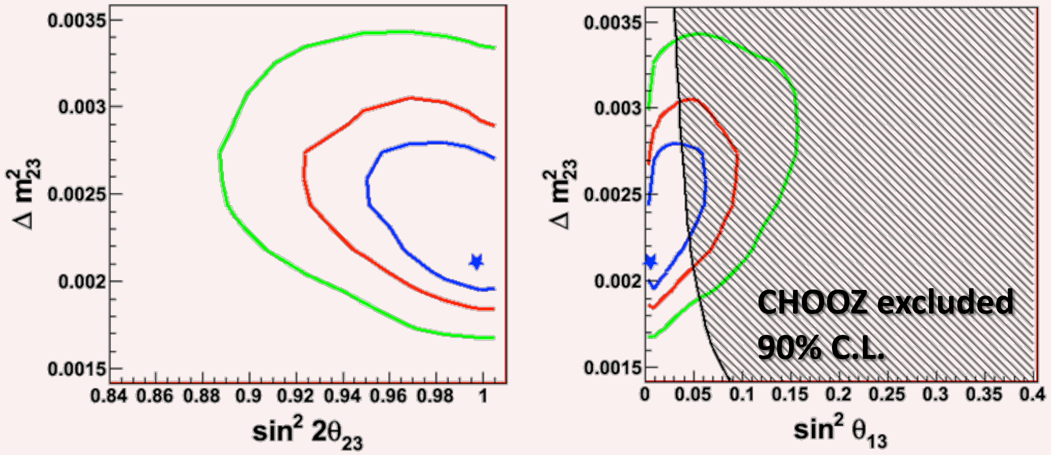
s²θ13=0.04
δcp=45º
cosΘν=-0.8



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

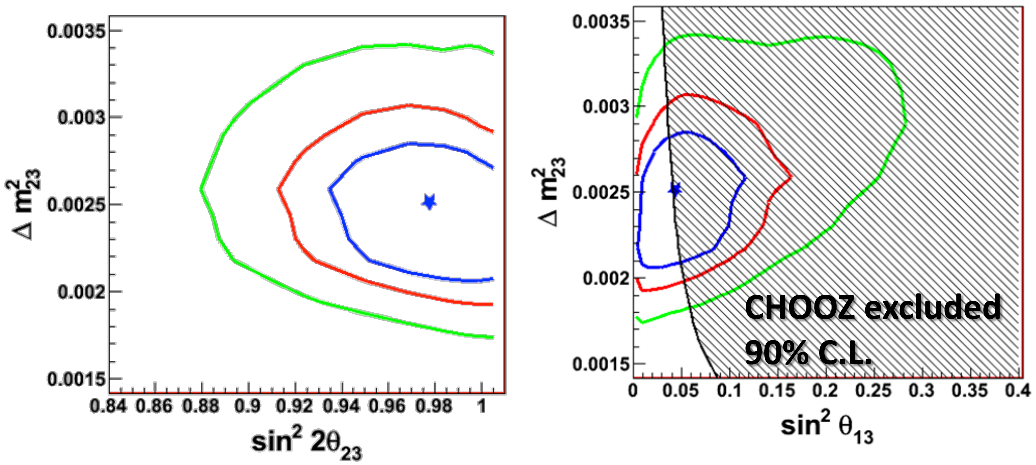
Oscillation Parameters (3 flavor)

Normal Mass Hierarchy



$$\Delta m^2_{23} = 2.11^{+0.43}_{-0.12}\ eV^2$$
$$\sin^2\theta_{23} = 0.525^{+0.072}_{-0.084}$$
$$\sin^2\theta_{13} < 0.066\ (90\%\ C.L.)$$

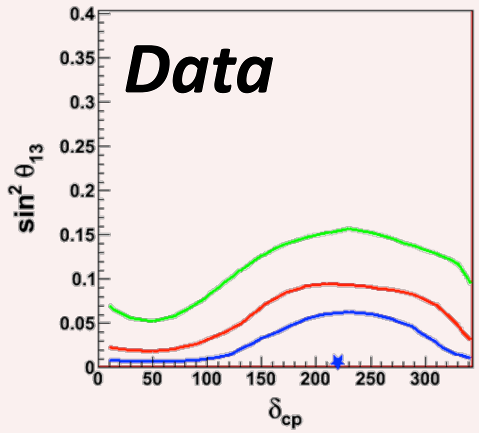
Inverted Mass Hierarchy

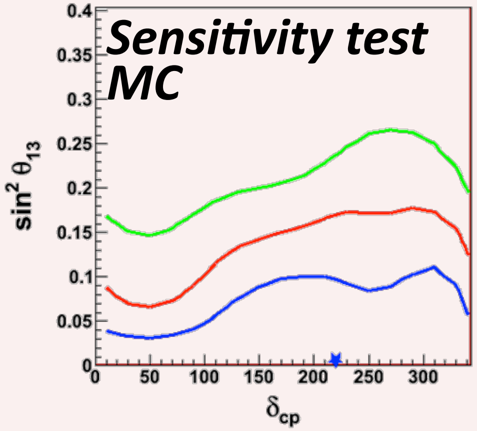


$$\Delta m^2_{23} = 2.51^{+0.13}_{-0.42}\ eV^2$$
$$\sin^2\theta_{23} = 0.575^{+0.048}_{-0.074}$$
$$\sin^2\theta_{13} < 0.122\ (90\%\ C.L.)$$

CP phase

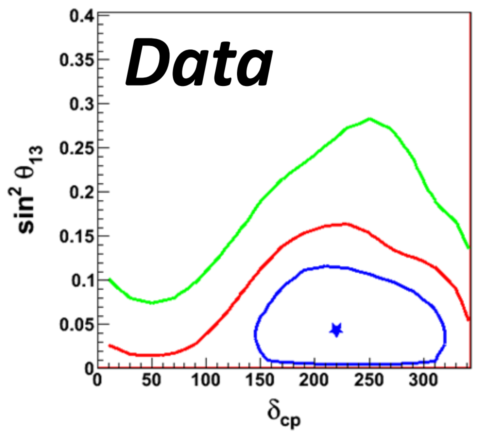
Normal Mass Hierarchy

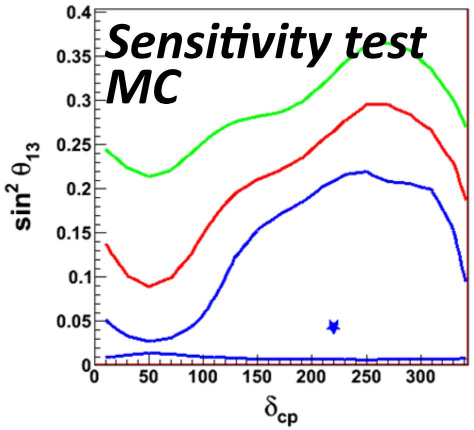




- **Best fit (NMH)**
  - **CP phase: 220°**
  - **$\sin^2\theta_{13}$: 0.006**
    < 0.066 (90% C.L.)

Inverted Mass Hierarchy

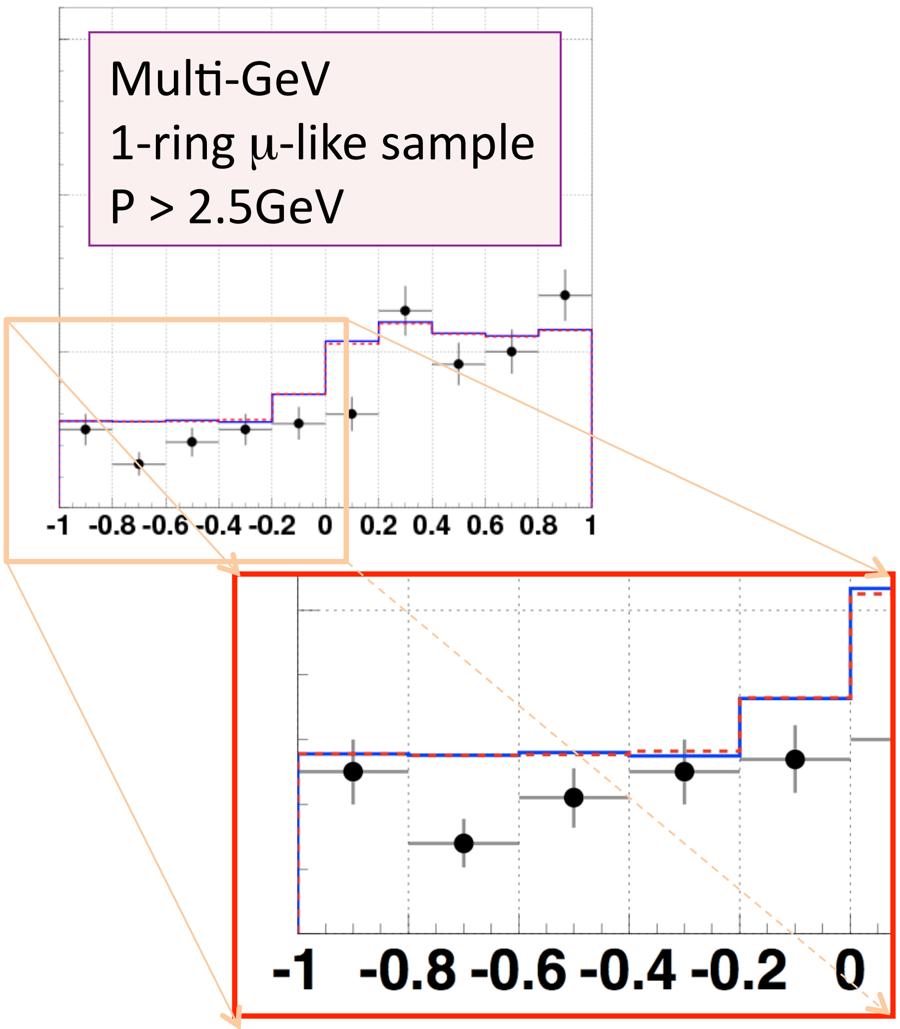




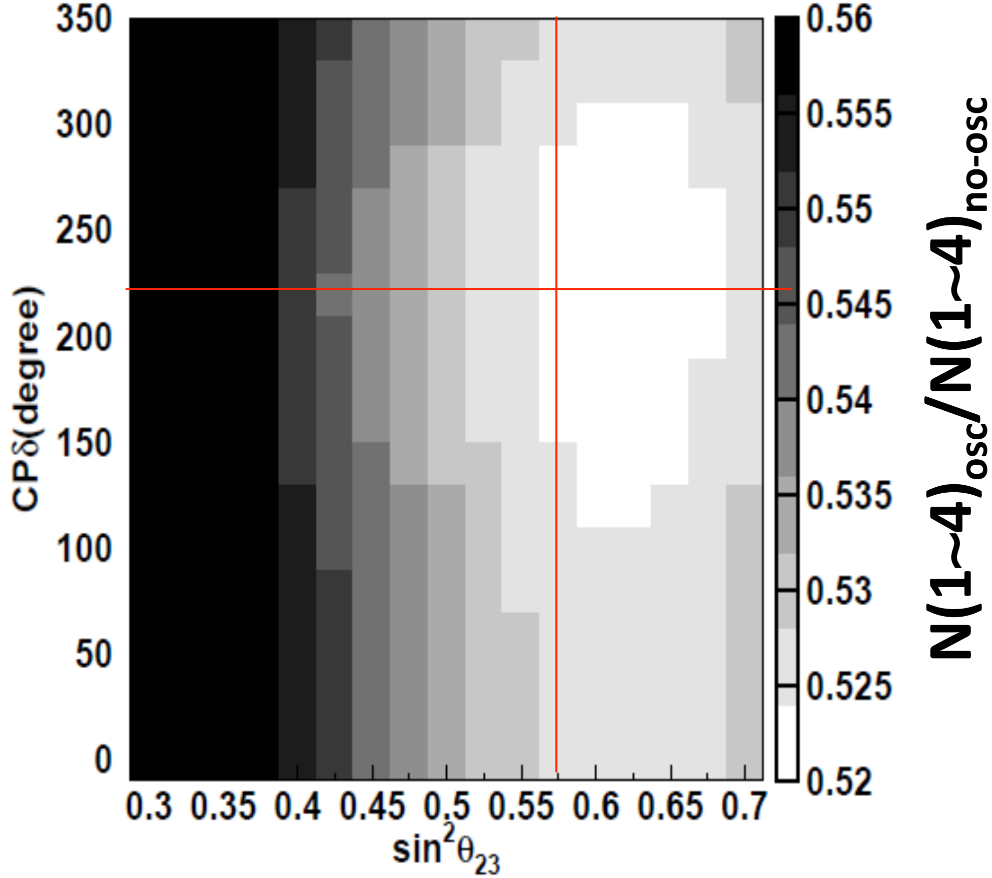
- **Best fit (IMH)**
  - **CP phase: 220°**
  - **$\sin^2\theta_{13}$: 0.044**
- **No significance @90% C. L.**
- **Statistical fluctuation or may be something**

CP phase

- Why 220°

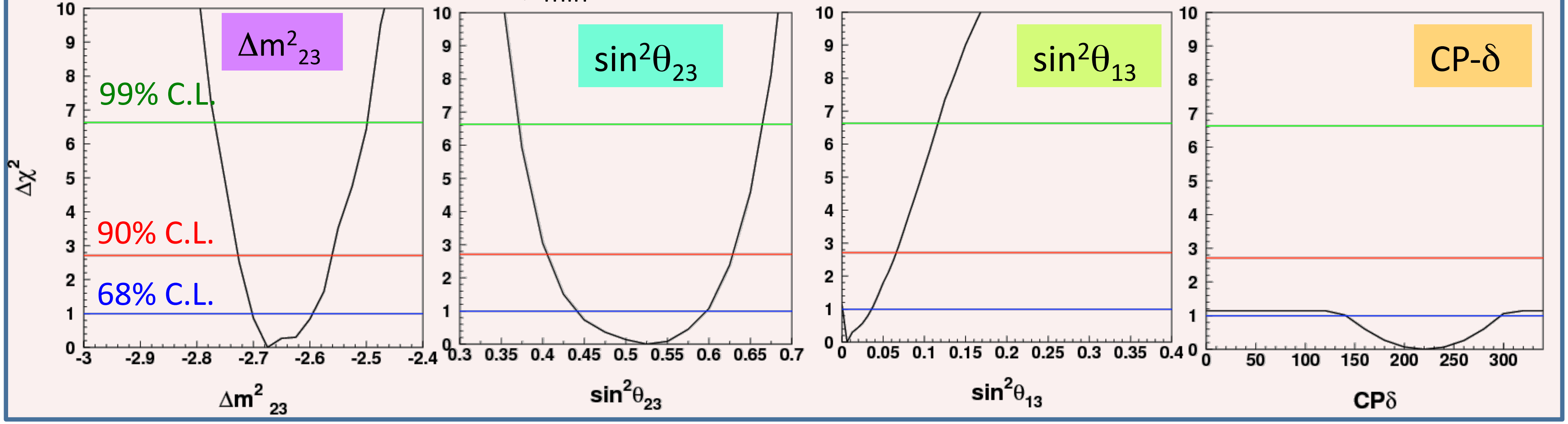


Effect of first 4 bins

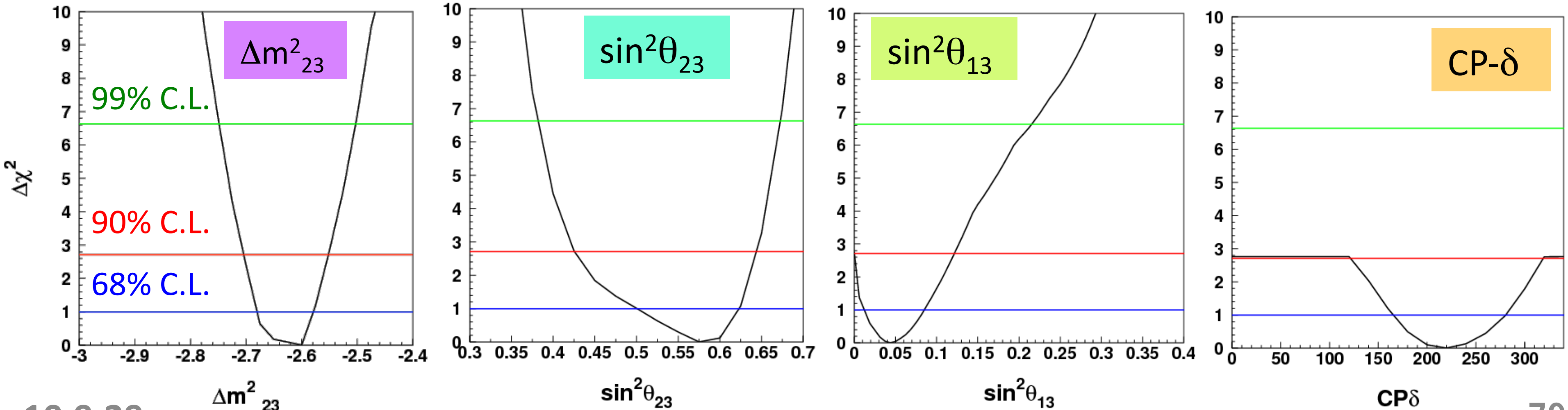


$\Delta\chi^2$

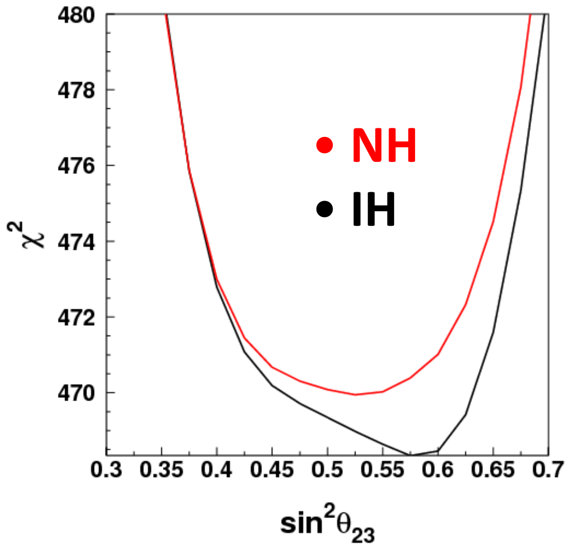
Normal Mass Hierarchy: χ^2_{min} = 469.94/416dof

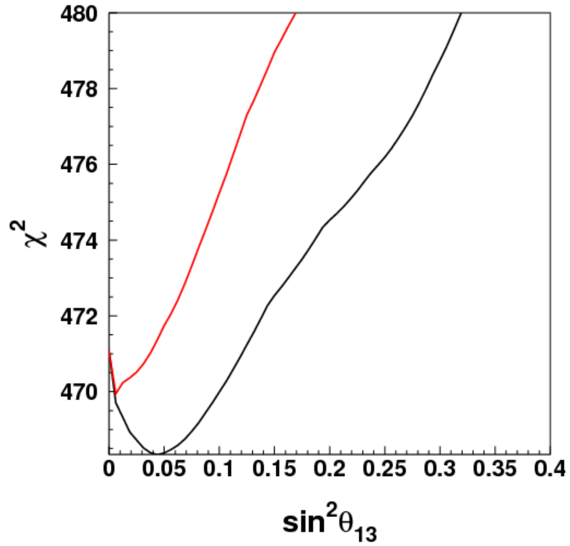


Inverted Mass Hierarchy: χ^2_{min} = 468.34/416dof



Hierarchy



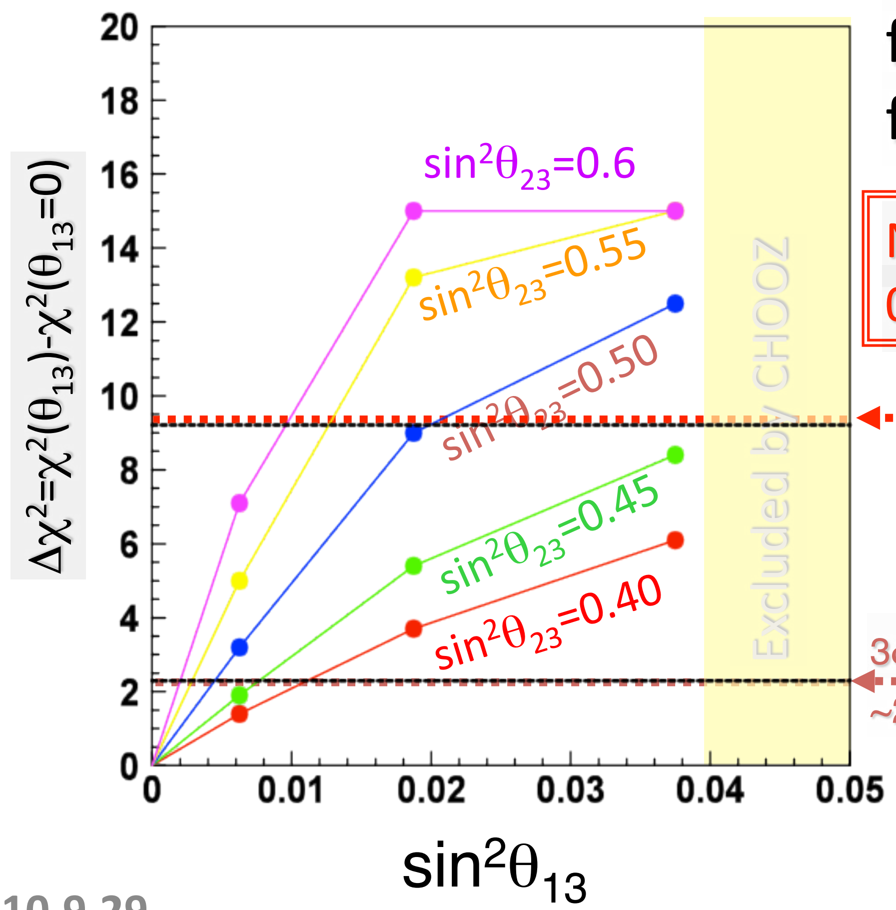


- Normal hierarchy (NH):χ^2_{min}= 469.94/416dof
- Inverted hierarchy (IH):χ^2_{min}= 468.34/416dof
  ➔ $\Delta\chi^2$ = 1.6
- No significant difference

Future sensitivity for non-zero θ_{13}

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

Including solar term



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

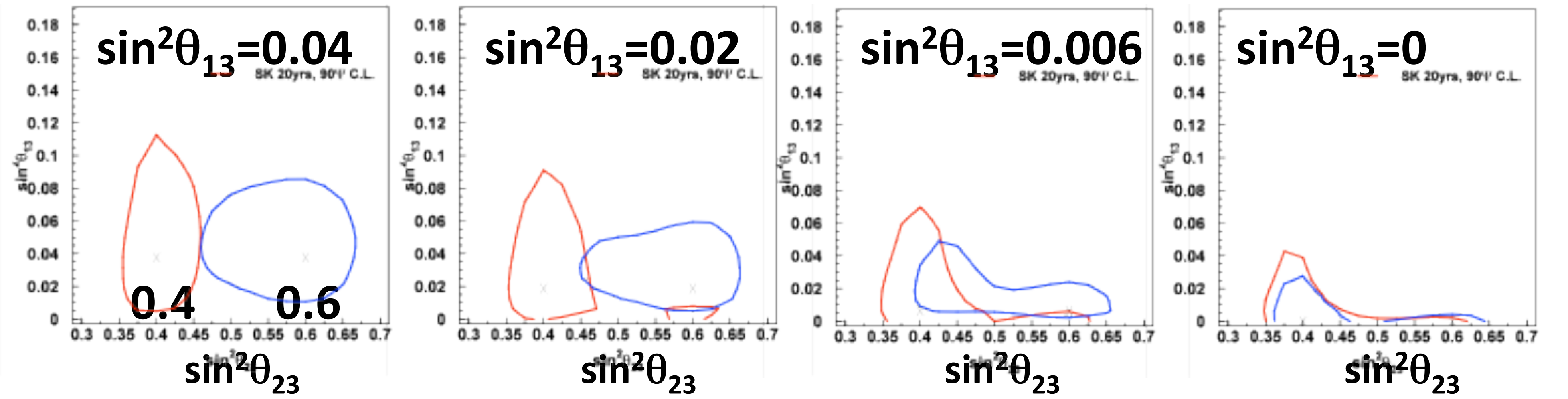
Non-zero θ_{13} can be observed for $\sin^2\theta_{23}$ > 0.50 and $\sin^2\theta_{13}$ > 0.01~0.02

3σ for 20 yrs SK

3σ for 80yrs SK
~2yrs 1.0 Mega-ton

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,

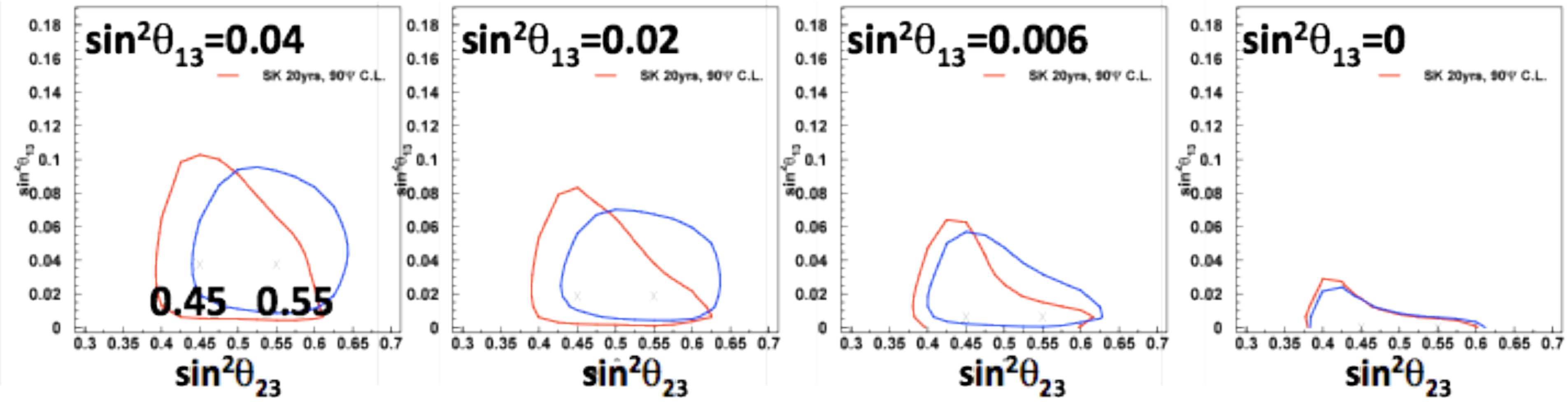
($\sin^2\theta_{23}$= 0.4 and 0.6 ($\sin^2 2\theta_{23}$=0.96)

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

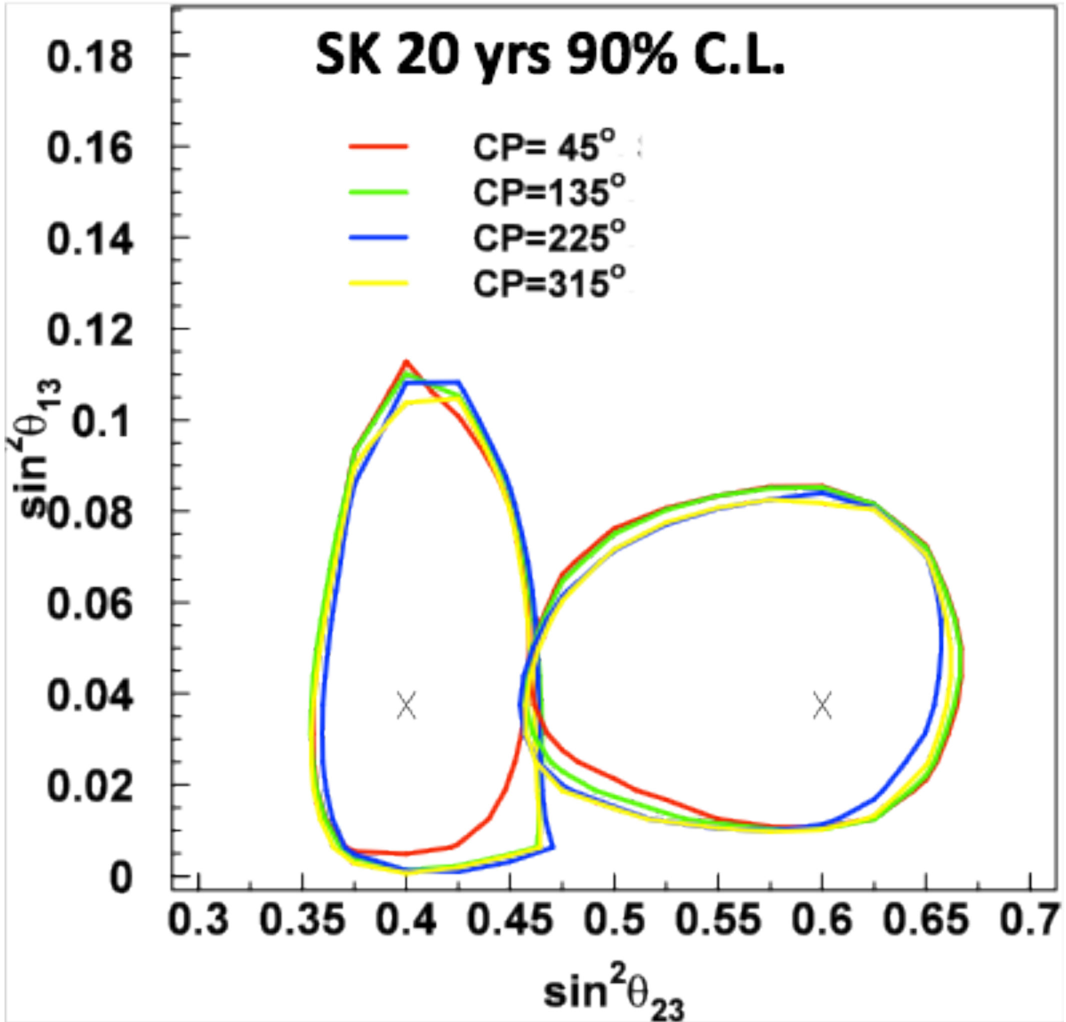
Discrimination of the θ_{23} octant for SK-20 yrs



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

Difficult for SK 20 yrs

No strong CP phase dependence for Octant search

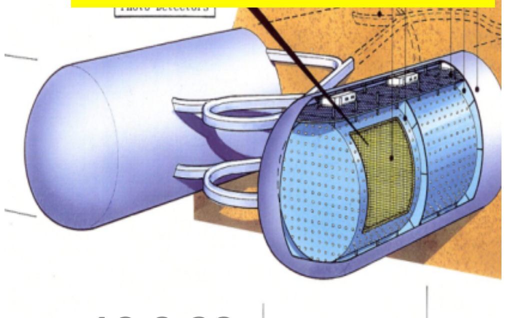


Megaton class detectors
Next Generation

- Near future: Mega Watt Accelerator + Megaton class detector (H_2O, L.Ar, L.Scint)
  - Standard and strong approach to study neutrino oscillations
- Megaton detectors themselves: important tool to study atmospheric neutrinos, supernova neutrinos, proton decay and so on

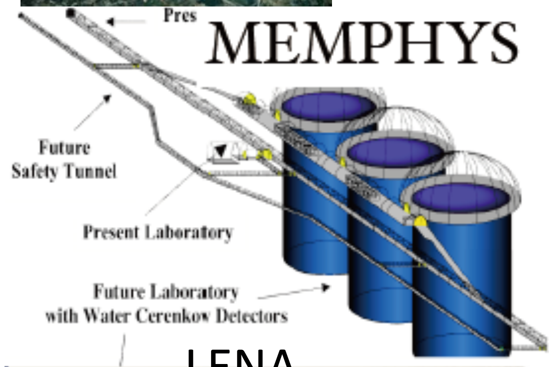
L. Ar. (? kton)

Hyper-K 540kton



DUSEL

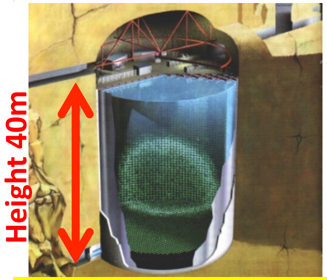
Water or L. Ar.



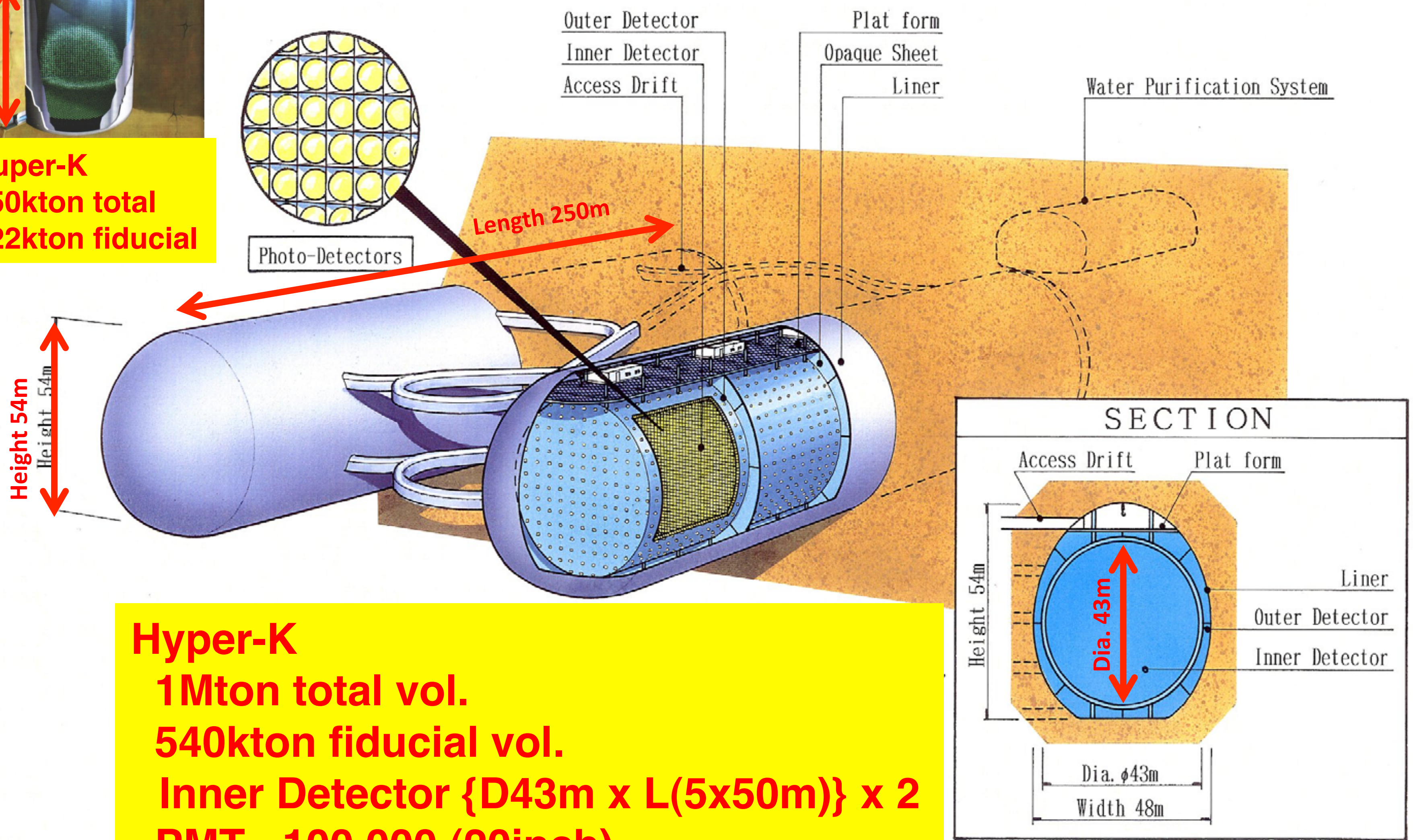
LENA
GLACIER

Hyper-Kamiokande

Ring-imaging water Cherenkov detector

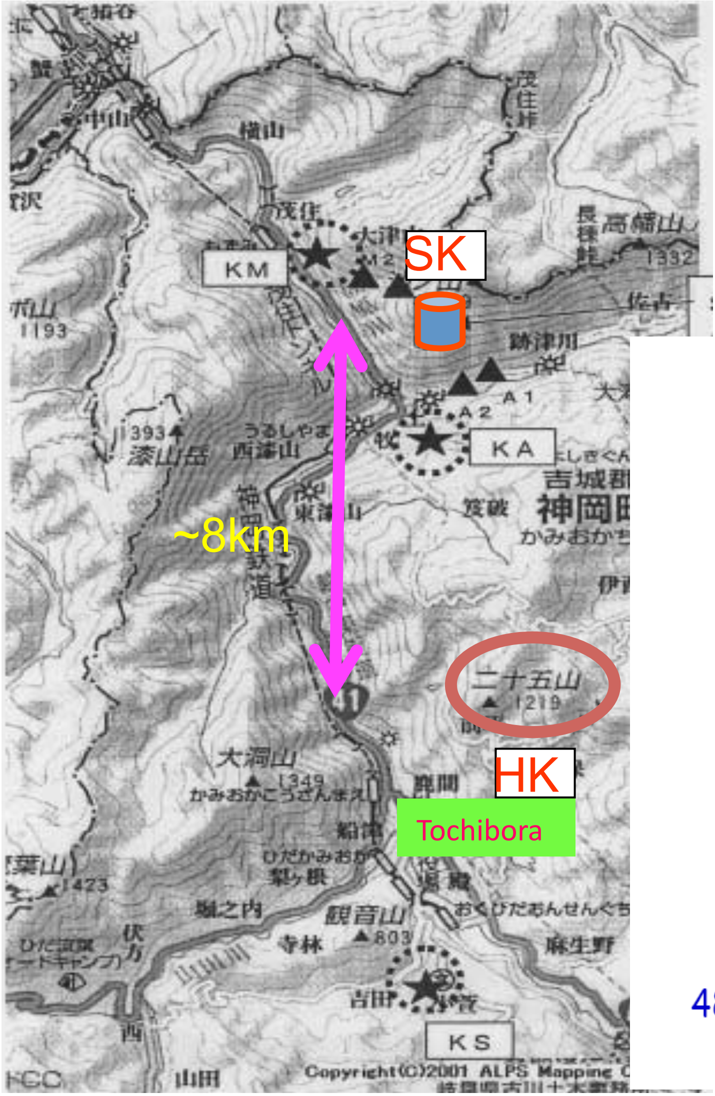


Super-K
50kton total
22kton fiducial

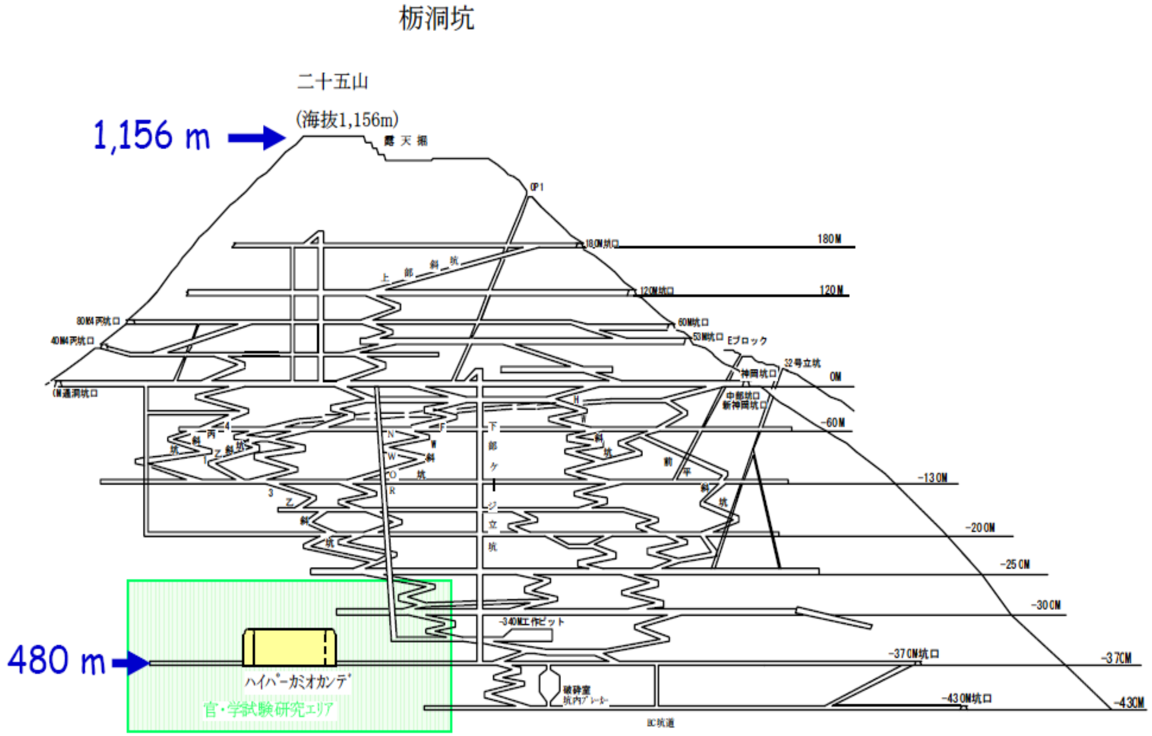


Hyper-K
1Mton total vol.
540kton fiducial vol.
Inner Detector {D43m x L(5x50m)} x 2
PMT ~100,000 (20inch)
(Photo-coverage 20%)

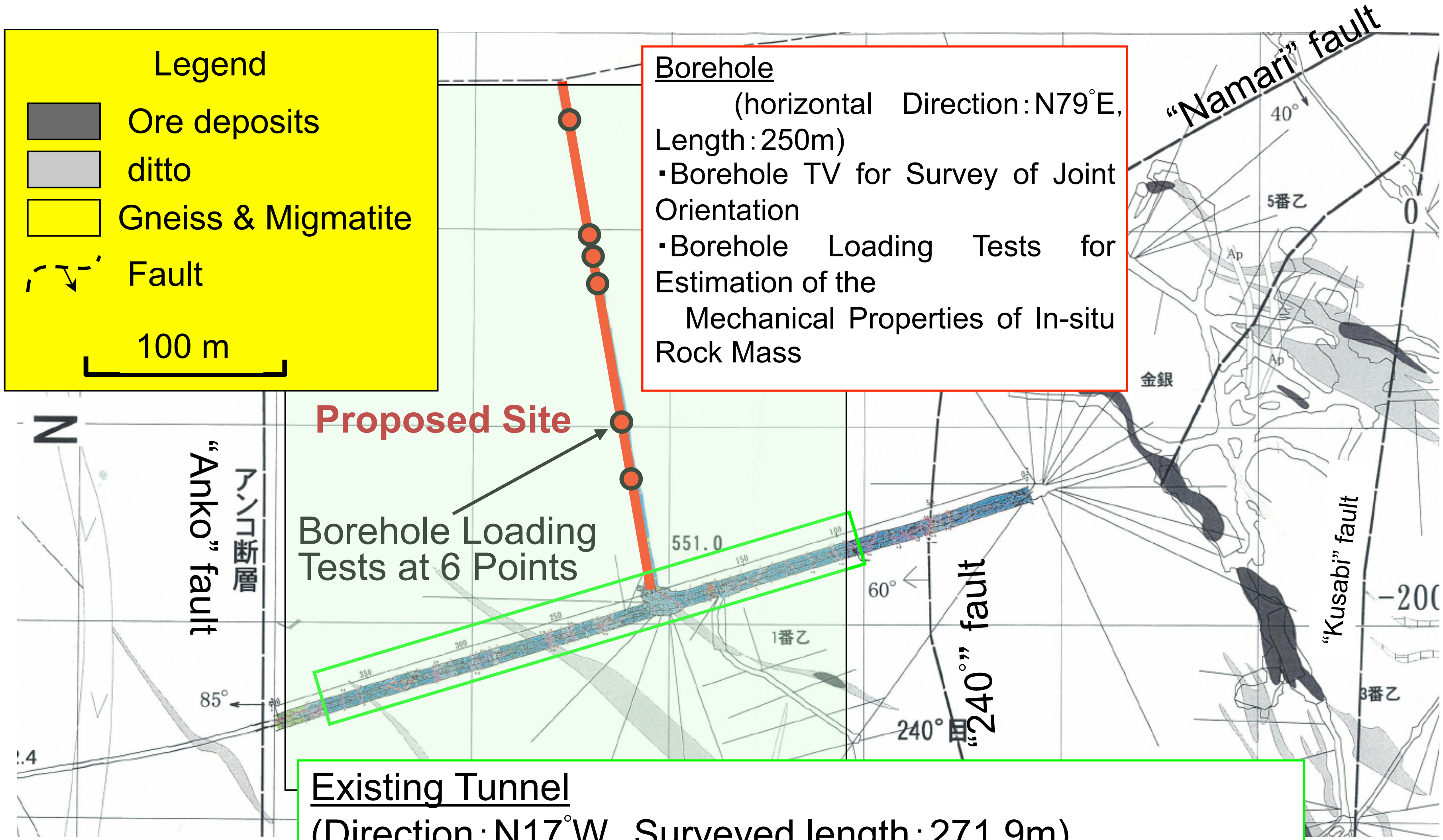
Candidate site



Beam bend: 3.45°
Beam axis: 2.3° off-axis



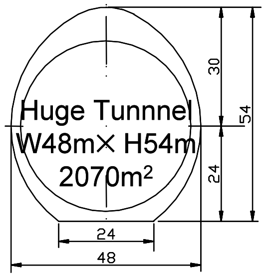
Site Study



Borehole
(horizontal Direction : N79°E, Length : 250m)
- Borehole TV for Survey of Joint Orientation
- Borehole Loading Tests for Estimation of the Mechanical Properties of In-situ Rock Mass

Existing Tunnel
(Direction : N17°W, Surveyed length : 271.9m)
- Joint Orientation survey
- Rock samples (Measurement of Mechanical Properties)

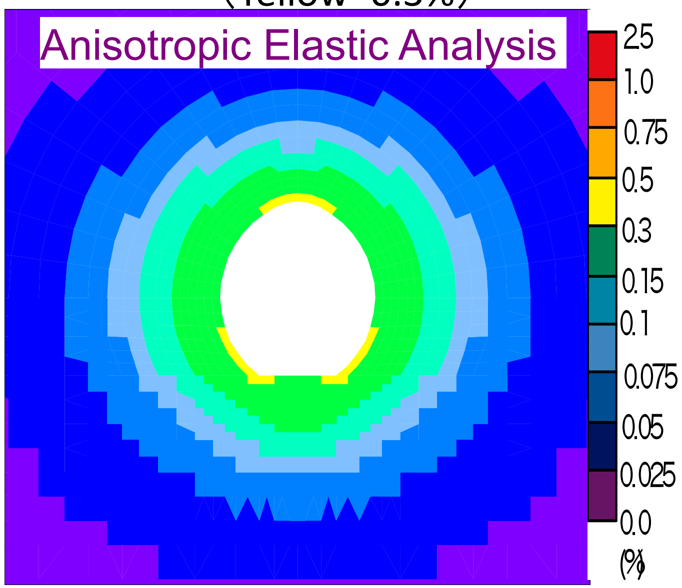
FEM analyses



Crack-tensor analysis

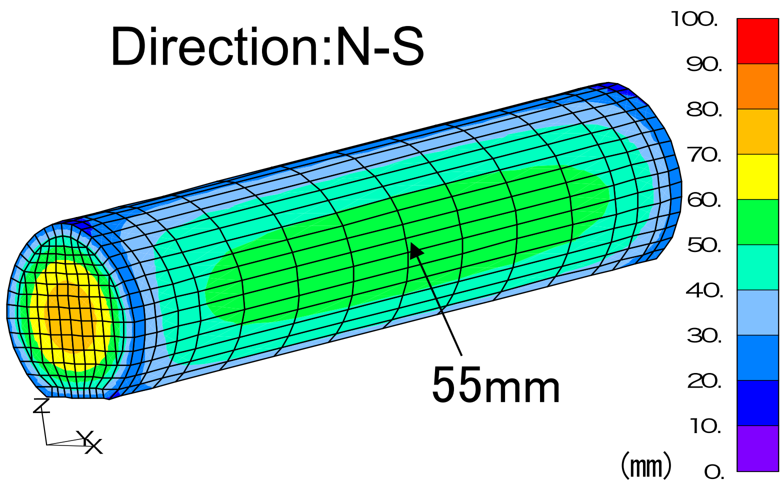
- Anisotropic Young's Modulus considering joint distributions and Rock properties
- In-situ stress; isotropic (overburden=500m)
- cavern direction; North-South

Maximum shear strain (central section)
（Yellow=0.3%）



Share stran＞0.3% in 2.5m

Displacement of cavern wall
（Red~100mm）



55mm displacement at central section

N-S cavern direction is better (due to E-W joint directions)
Feasibility of the cavern with our best knowledge of the site

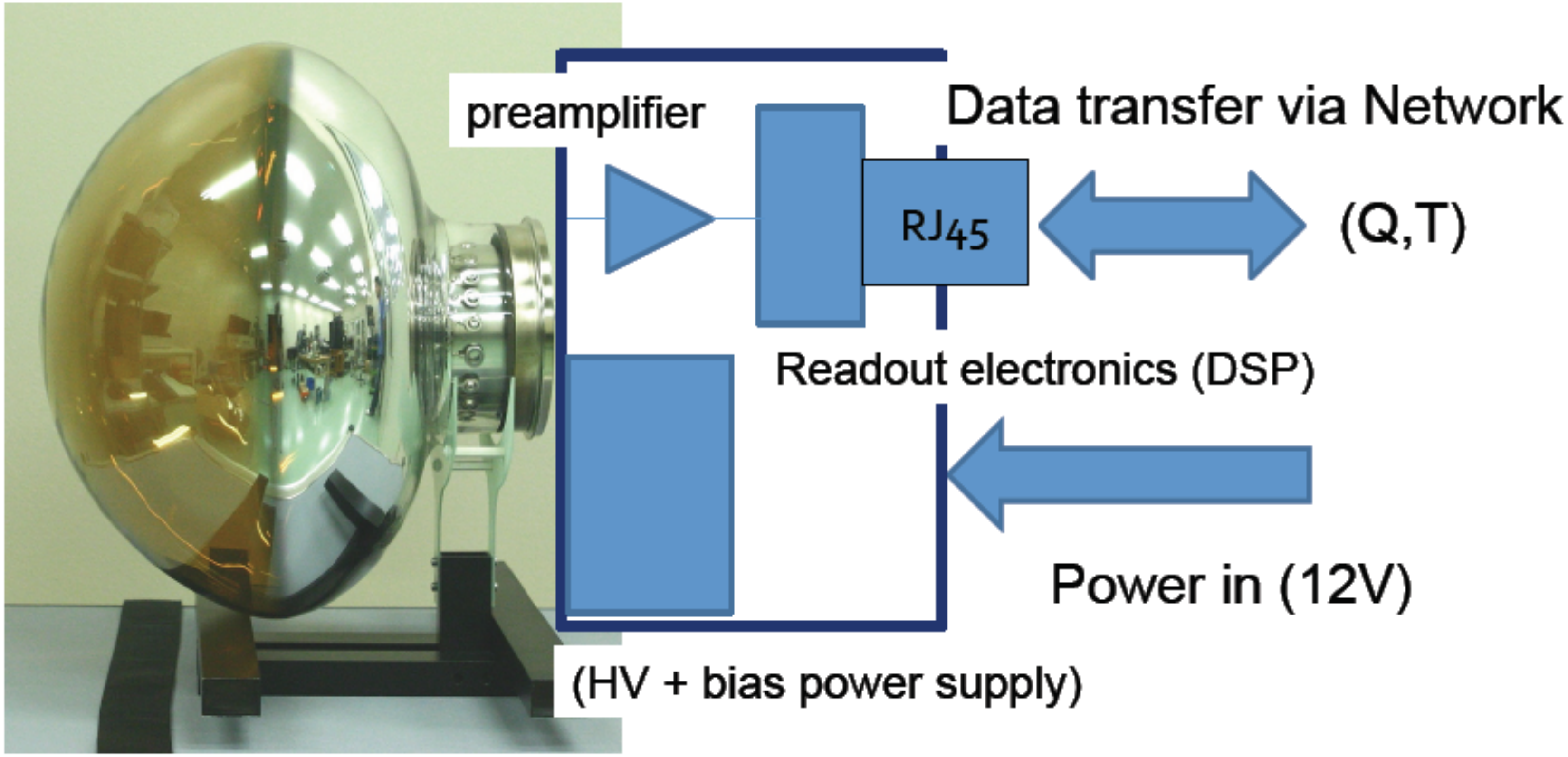
HPD vs PMT

	13inch HPD	13inch PMT (R8055)	20inch PMT (for SK)
Single Photon Time Resolution	190ps	1400ps	2300ps
Single Photon Energy Resolution	24%	70%	150%
Quantum efficiency	20%	20%	20%
Collection efficiency	97%	70%	70%
Power consumption	<<700mW	~700mW	~700mW
Gain	10^5	10^7	10^7

20

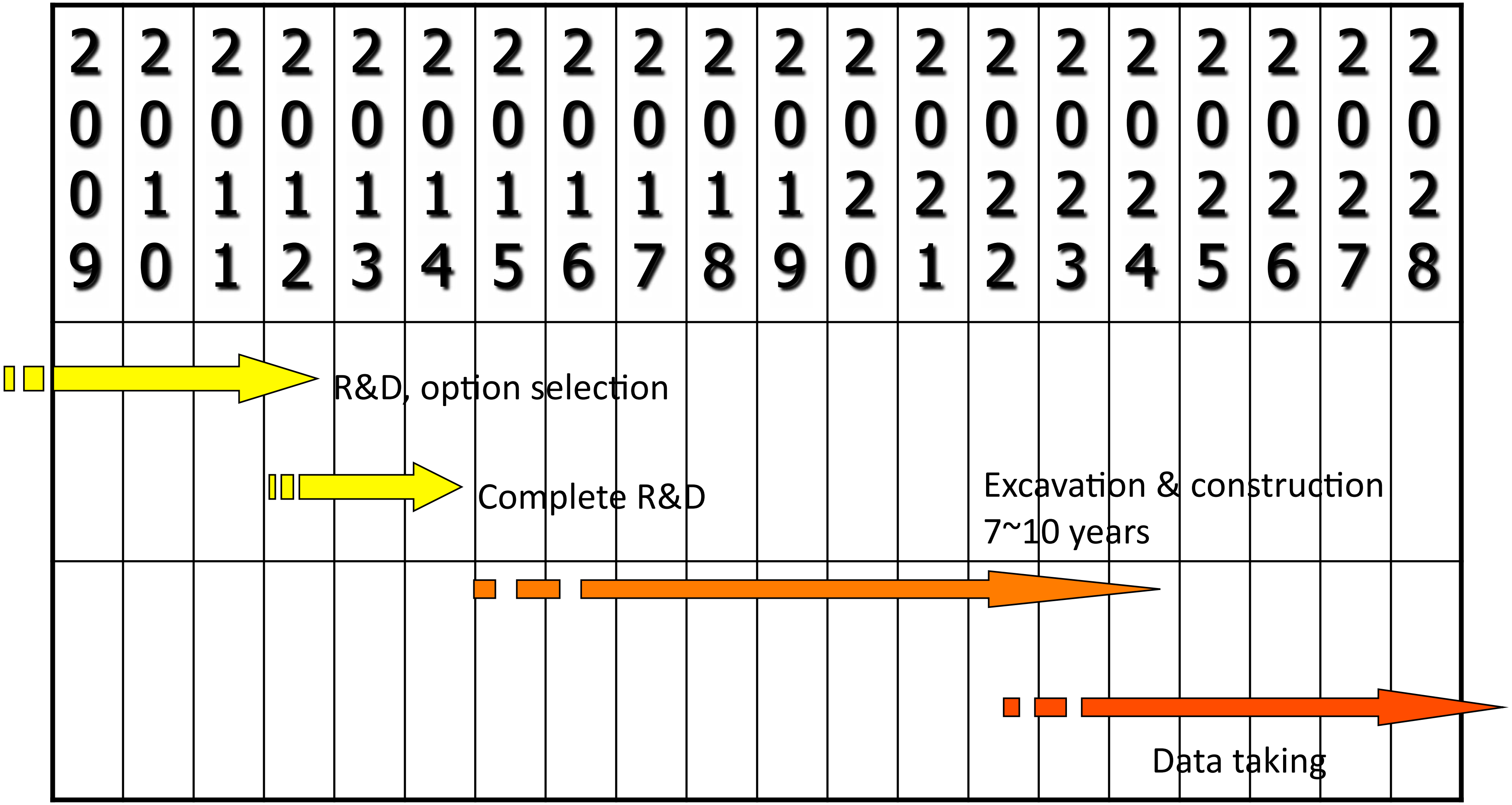
Digital HPD

Compact detector with Network + Power supply



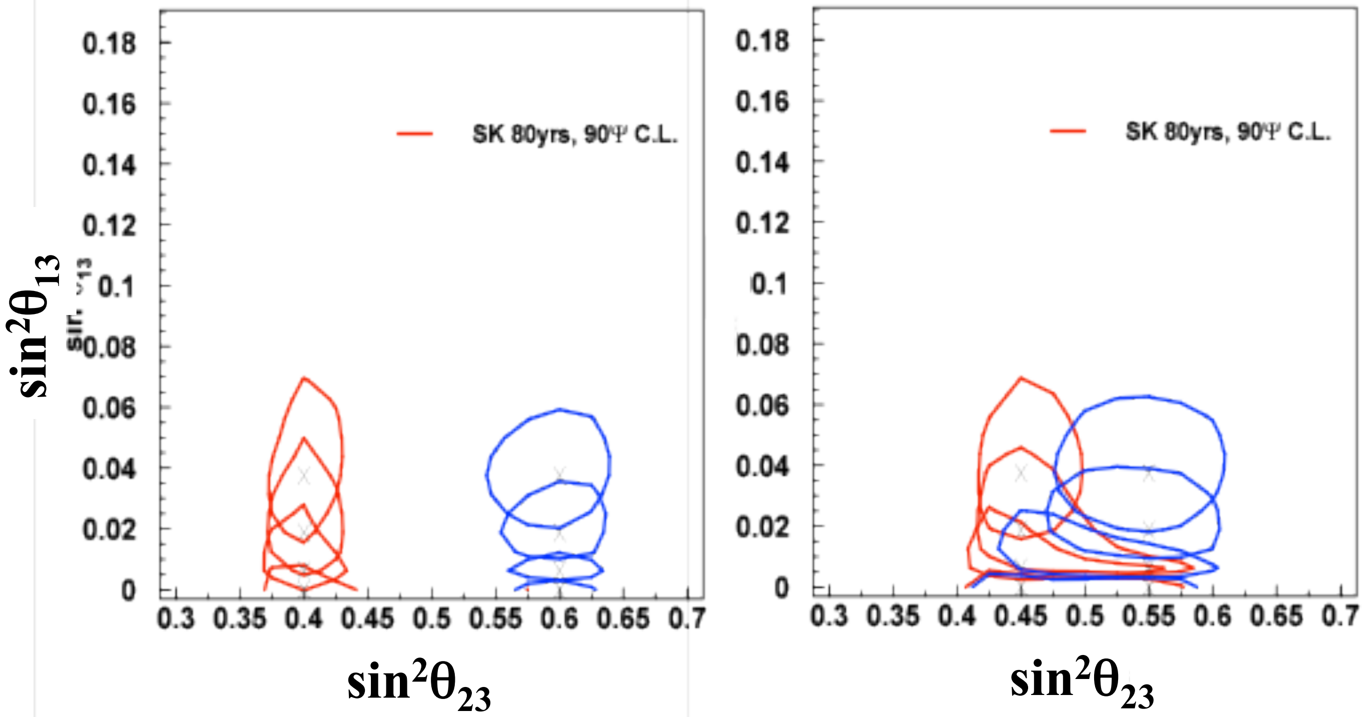
21

Time table of R&D and construction



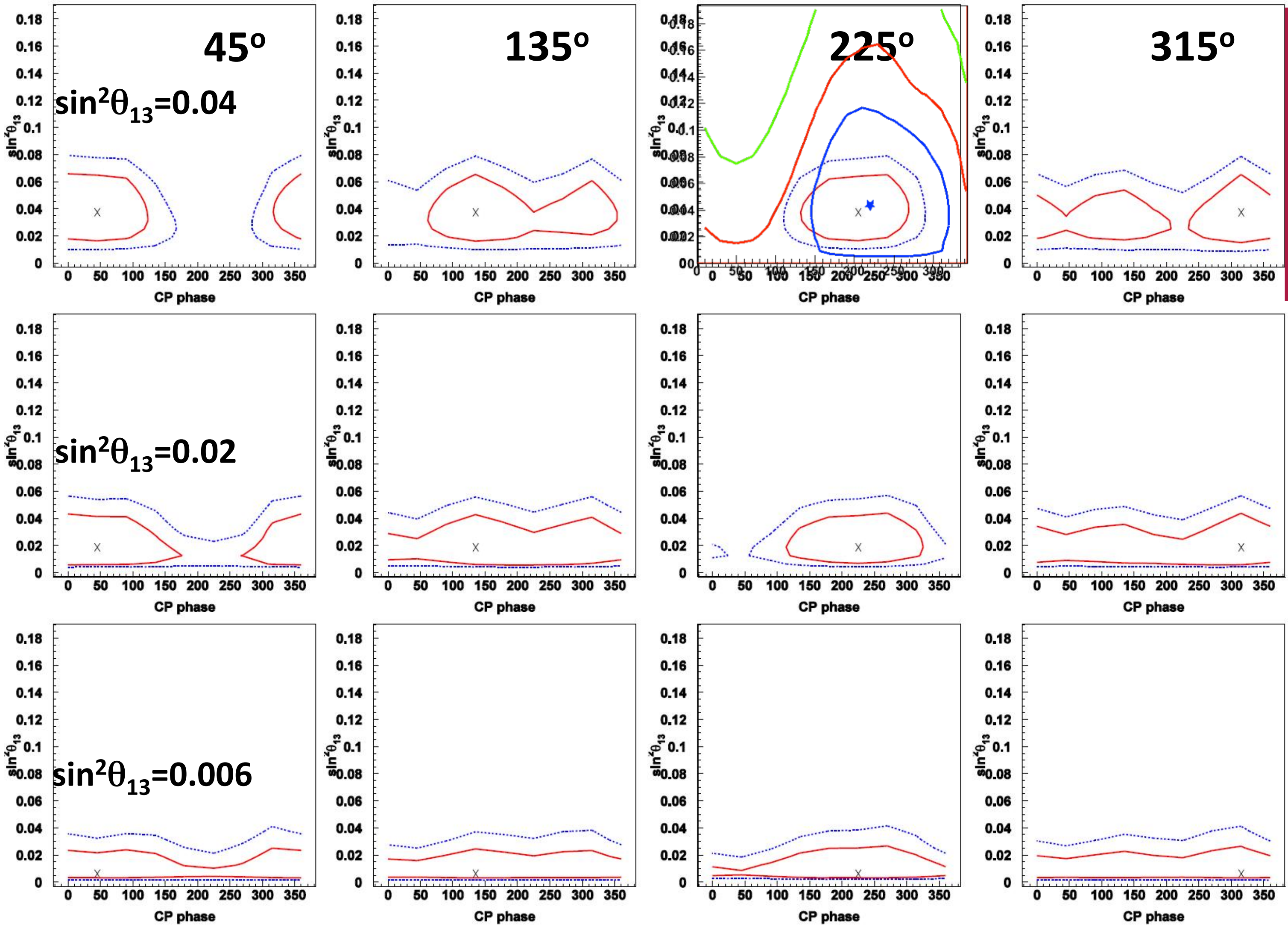
80yrs SK ~ 3.6yrs of HK

$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.40 \sim 0.60$
$s^2\theta_{13}=0.00\sim0.04$
$\delta cp=45^o$
$\Delta m^2_{12}=8.3\text{x}10^{-5}$
$\Delta m^2_{23}=2.5\text{x}10^{-3}$

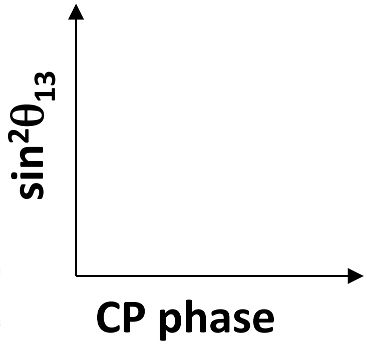


For HK, discrimination is possible for $\sin^2\theta_{23}$ = 0.40 or 0.60 ($\sin^2 2\theta_{23}$=0.96)

CP phase (80yrs SK = 3.6yrs of 0.5 Mt detector (HK, Memphys, DUSEL…)



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

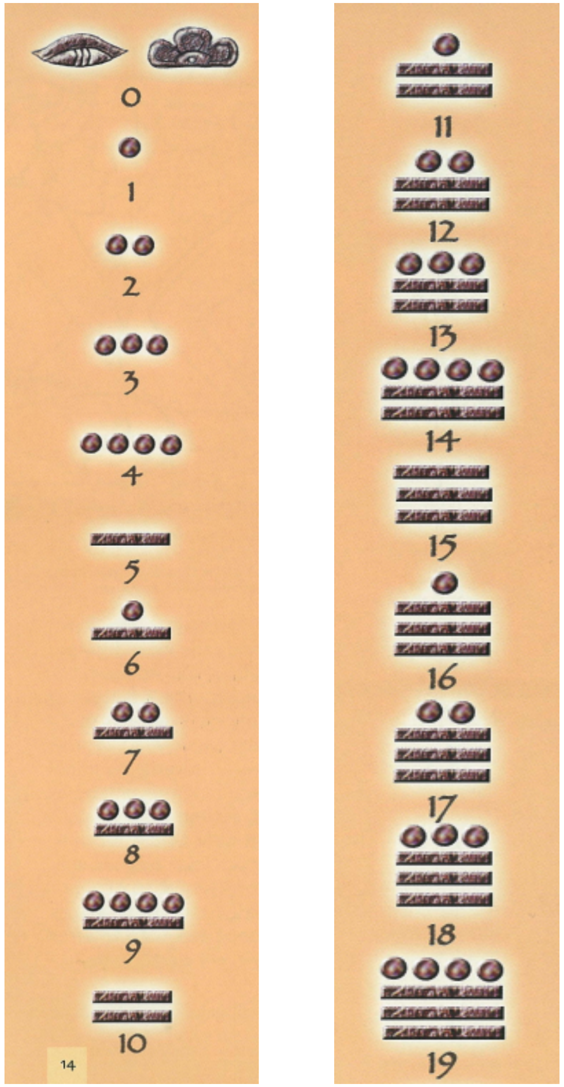


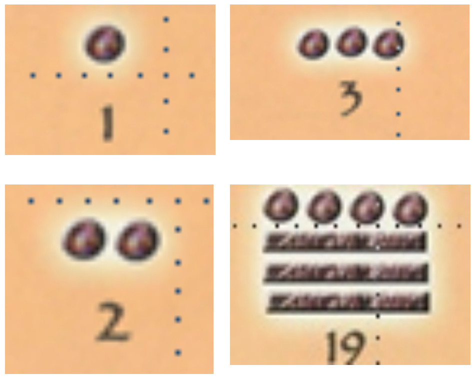
For HK…., CP phase may be seen
if θ_{13} is close to the CHOOZ limit

Quiz !?

1, 20, 400, [?], ・・・

Mayas Calculus





→ **23**

→ **59**

Vigesimal: base-20 numerical system

They have zero!

1 Kt: Kamiokande

20 Kt: Super-Kamiokande

400 Kt: *HK, DUSEL, Memphis*

(next generation detectors)

8000 Kt:

Mayas Prediction for the size of

next-next generation Water Cherenkov Detectors

(30 years from now ??)

8 Mega ton detector !?

Next-next generation detector
(Multi-Megaton Detector)

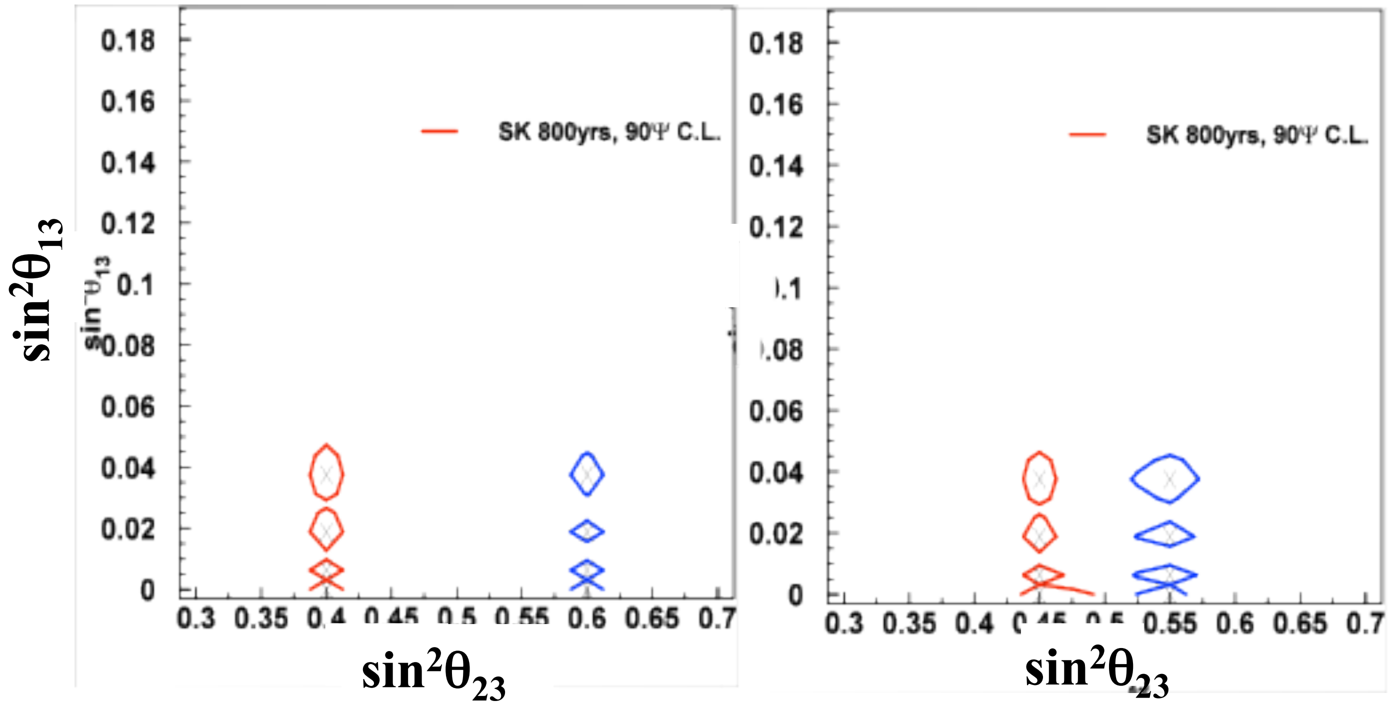
1) Follow Maya's prediction ?
2) Precise atmospheric neutrino measurement

But not only that

3) Supernova burst detection : every year
4) Proton Decay up to 10^{36} yrs

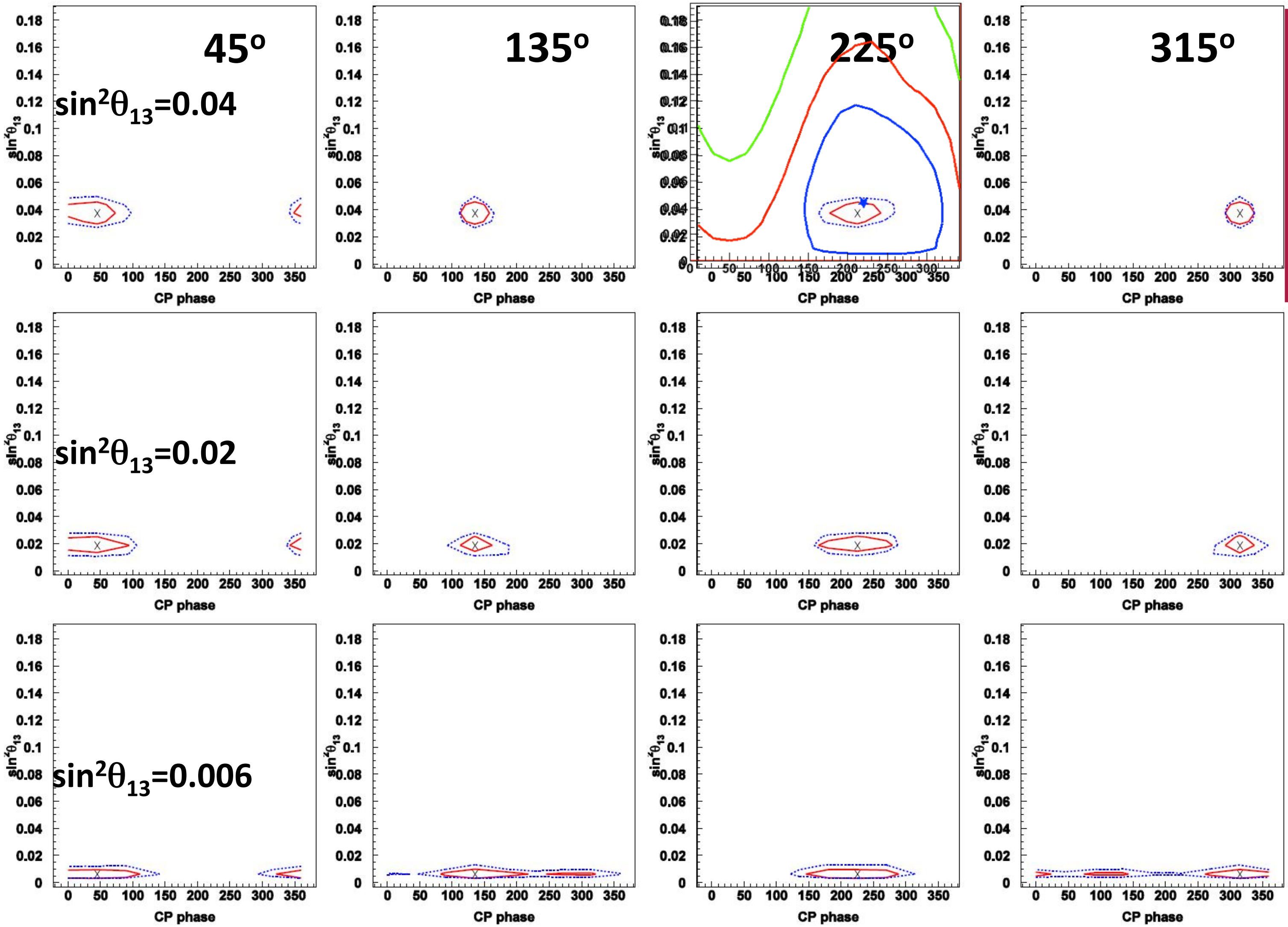
800yrs SK ~ 4yrs of 5 Mt detector

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.40 ~ 0.60
$s^2\theta_{13}$=0.00~0.04
δcp=45°
Δm^2_{12}=8.3x10^{-5}
Δm^2_{23}=2.5x10^{-3}

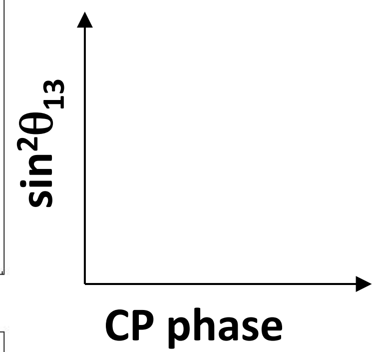


For 5 Megaton, octant can be resolved for $\sin^2\theta_{23}$ > 0.45 or < 0.55 ($\sin^2 2\theta_{23}$ > 0.99)

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



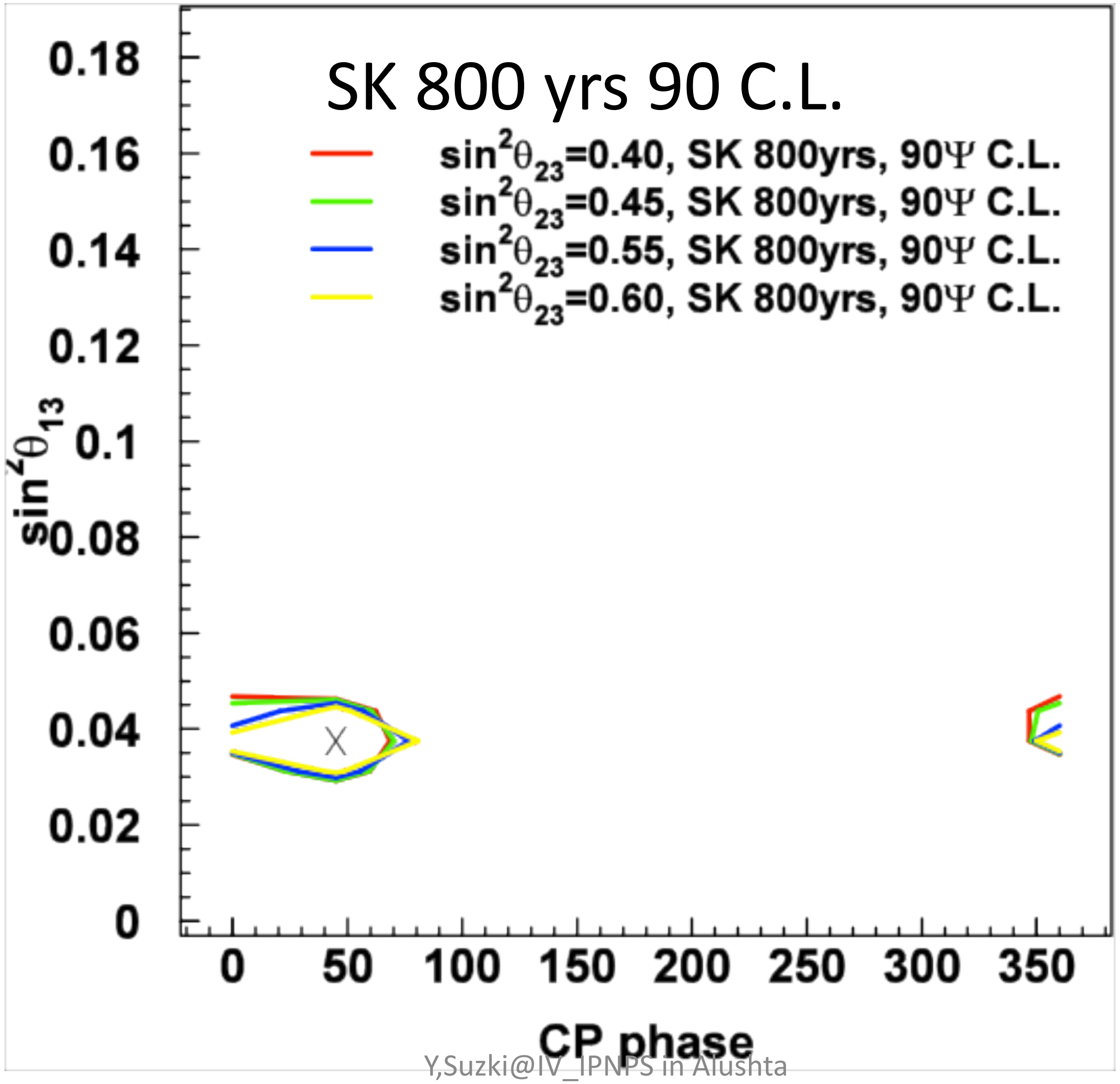
$s^2 2\theta_{12}=0.825$
$s^2\theta_{23}=0.5$
$s^2\theta_{13}=0.006\sim0.04$
$\delta cp=0^o\sim360^o$
$\Delta m^2_{12}=8.3\times10^{-5}$
$\Delta m^2_{23}=2.5\times10^{-3}$



No degeneracy

For 5 Mton detector, CP phase could be determined if θ_{13} is larger than $\sin^2\theta_{13}\sim 0.006$

No strong θ_{23} dependence for CP phase search



Other science for 5 Mt detector

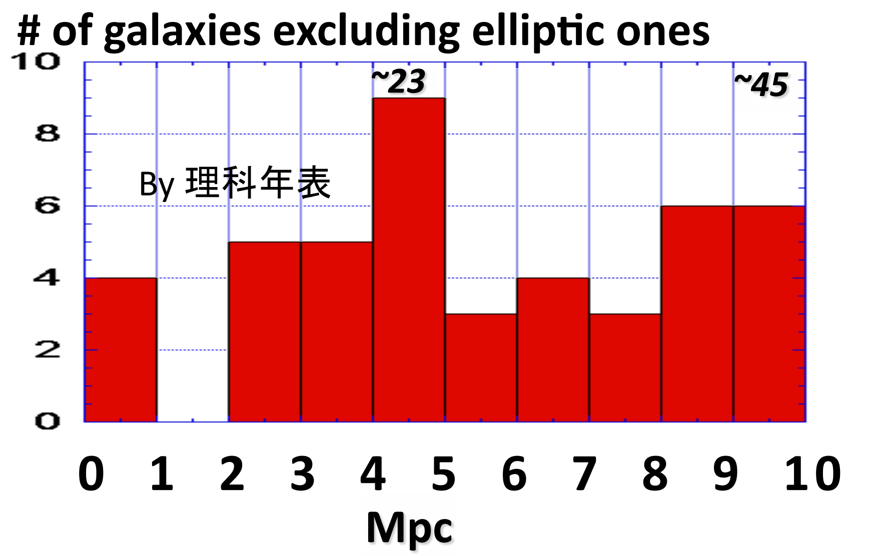
Supernova Rate

- **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***

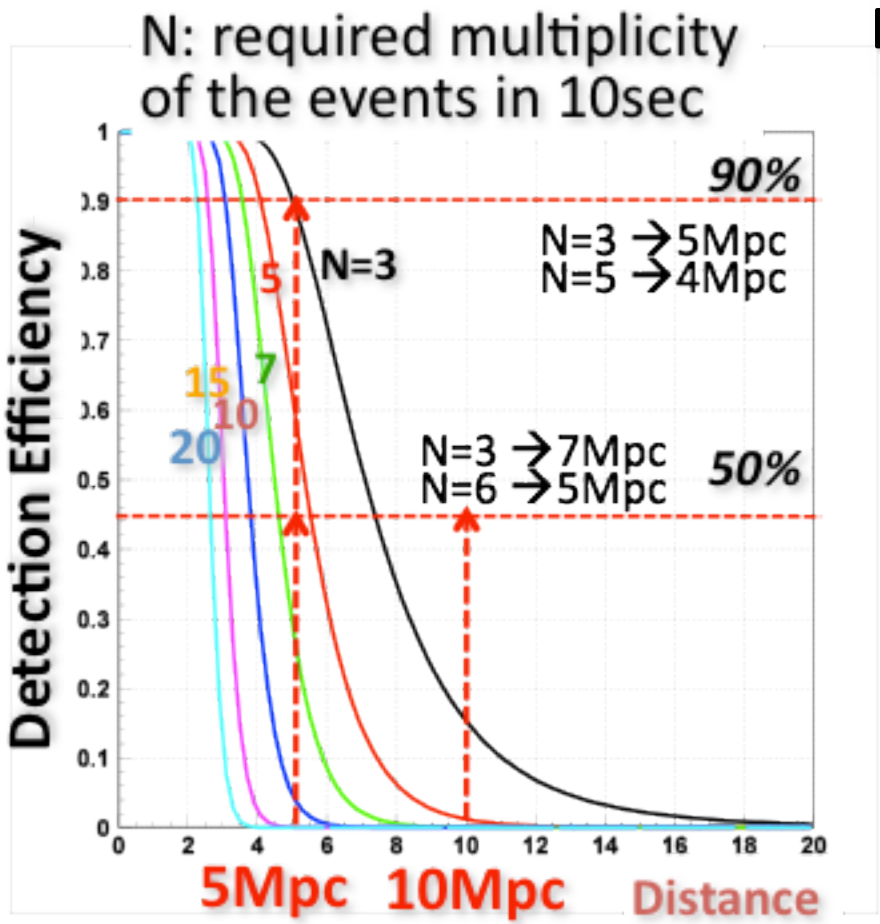
1954J, 2002kg, 2004dj

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

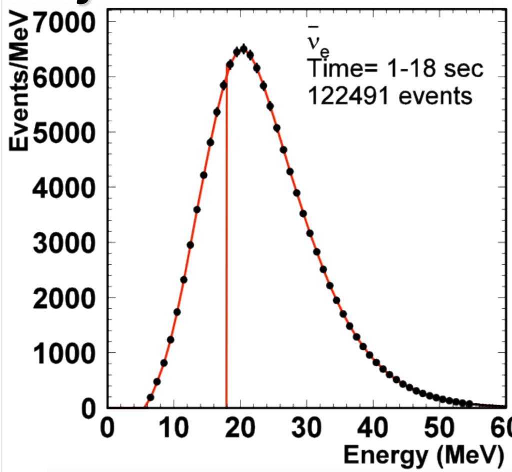
Expect ~5 events for 5Mt and 5Mpc distance

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

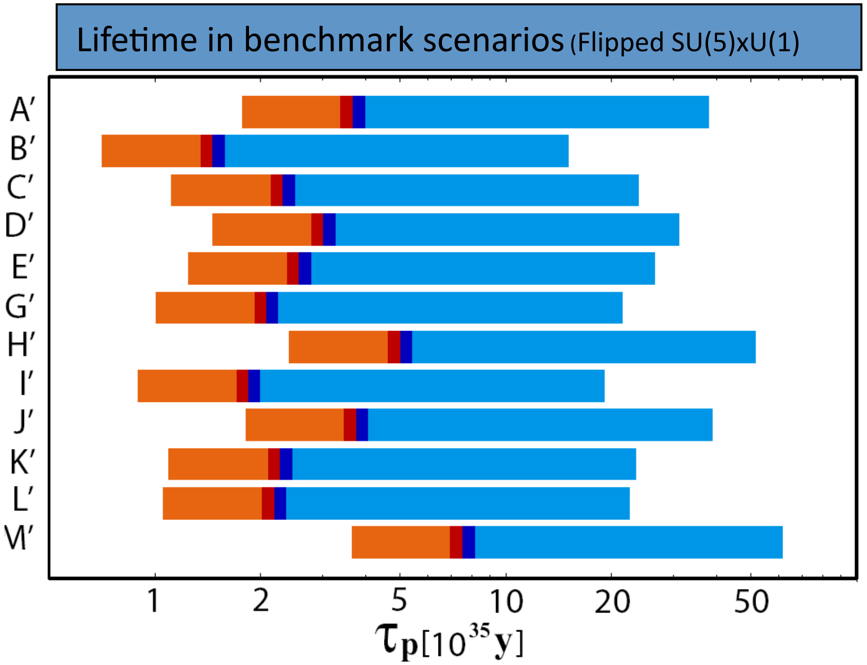
No significance influence

Could detect SN almost every year

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

Proton Decay

J. Ellis, NNN05, April 7th, 2005



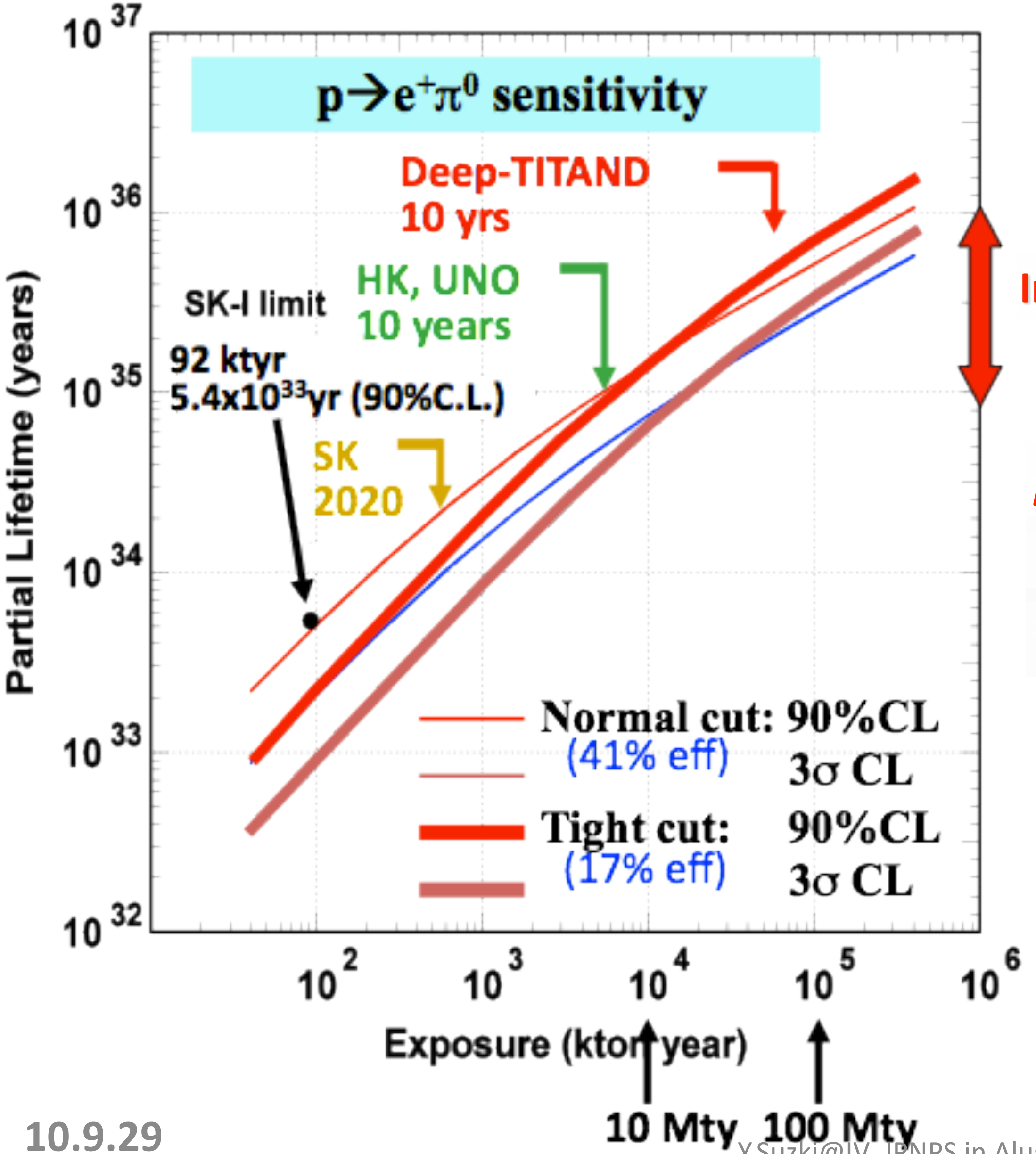
Prediction ?

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

    ← From coupling unification

    → Search up to ~10^{36} yr is quite important and add significant value to the multi-megaton detector
- ***Sensitivity for eπ^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, UNO (0.5Mt): 10yrs

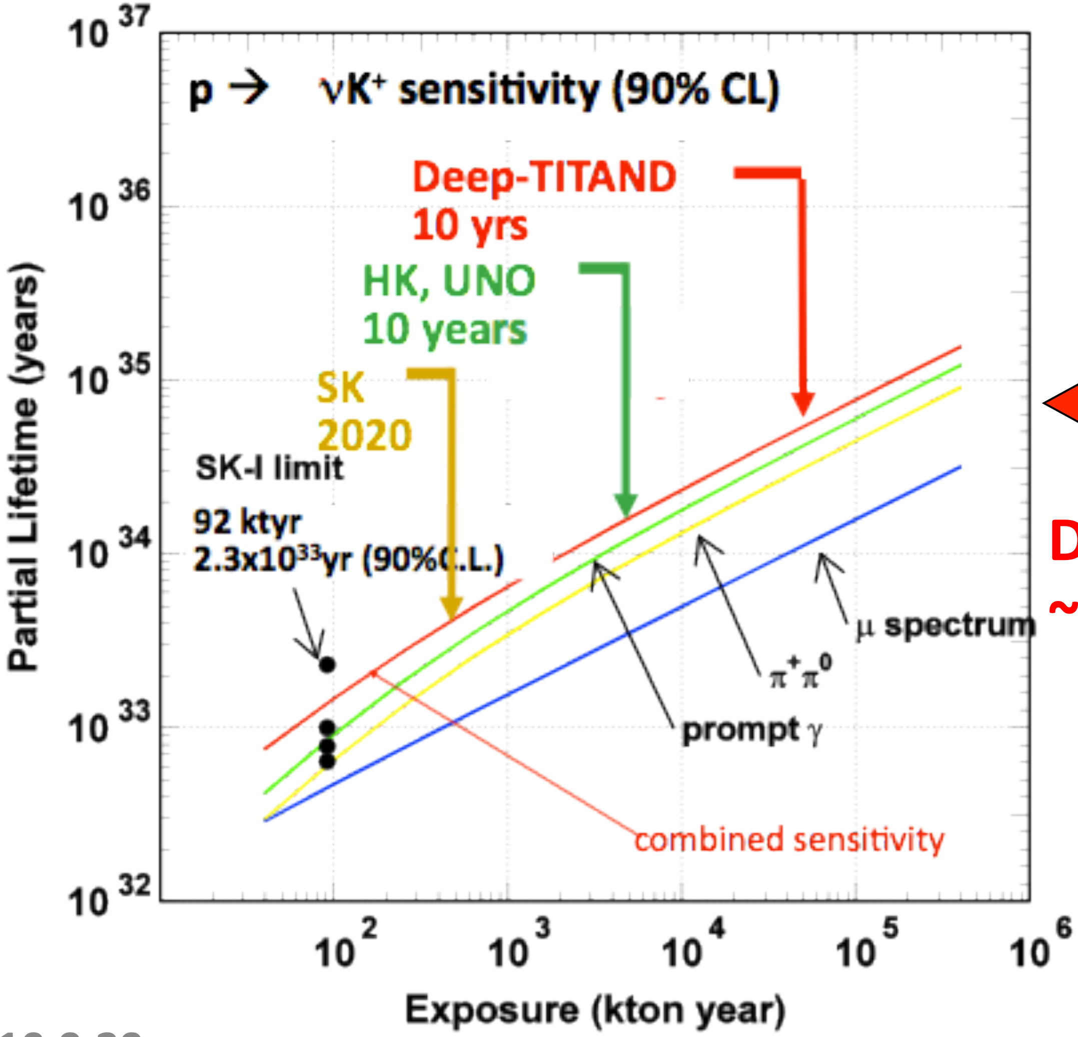
➔

~ 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.

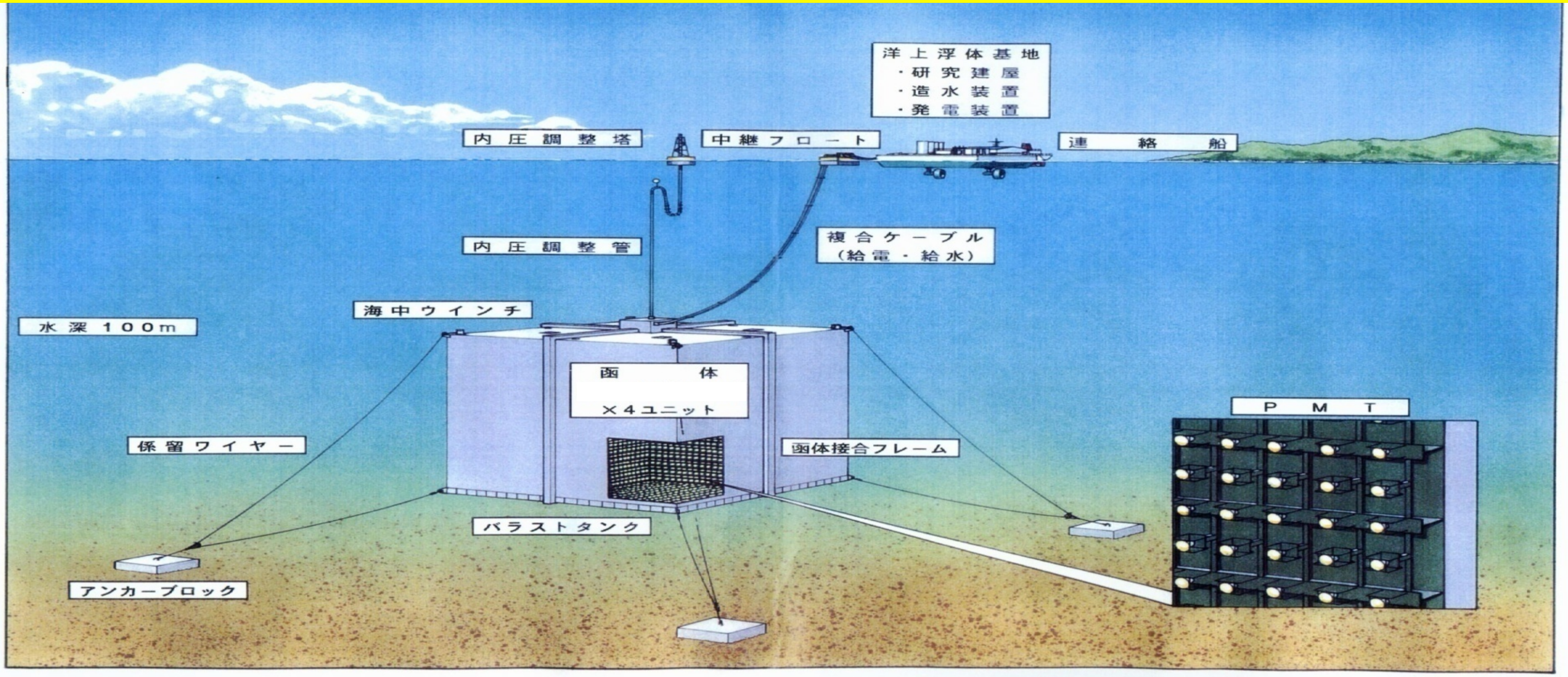
HK, UNO (0.5Mt): 10yrs
~ 2 x 10^{34} yrs @90% C.L.

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)

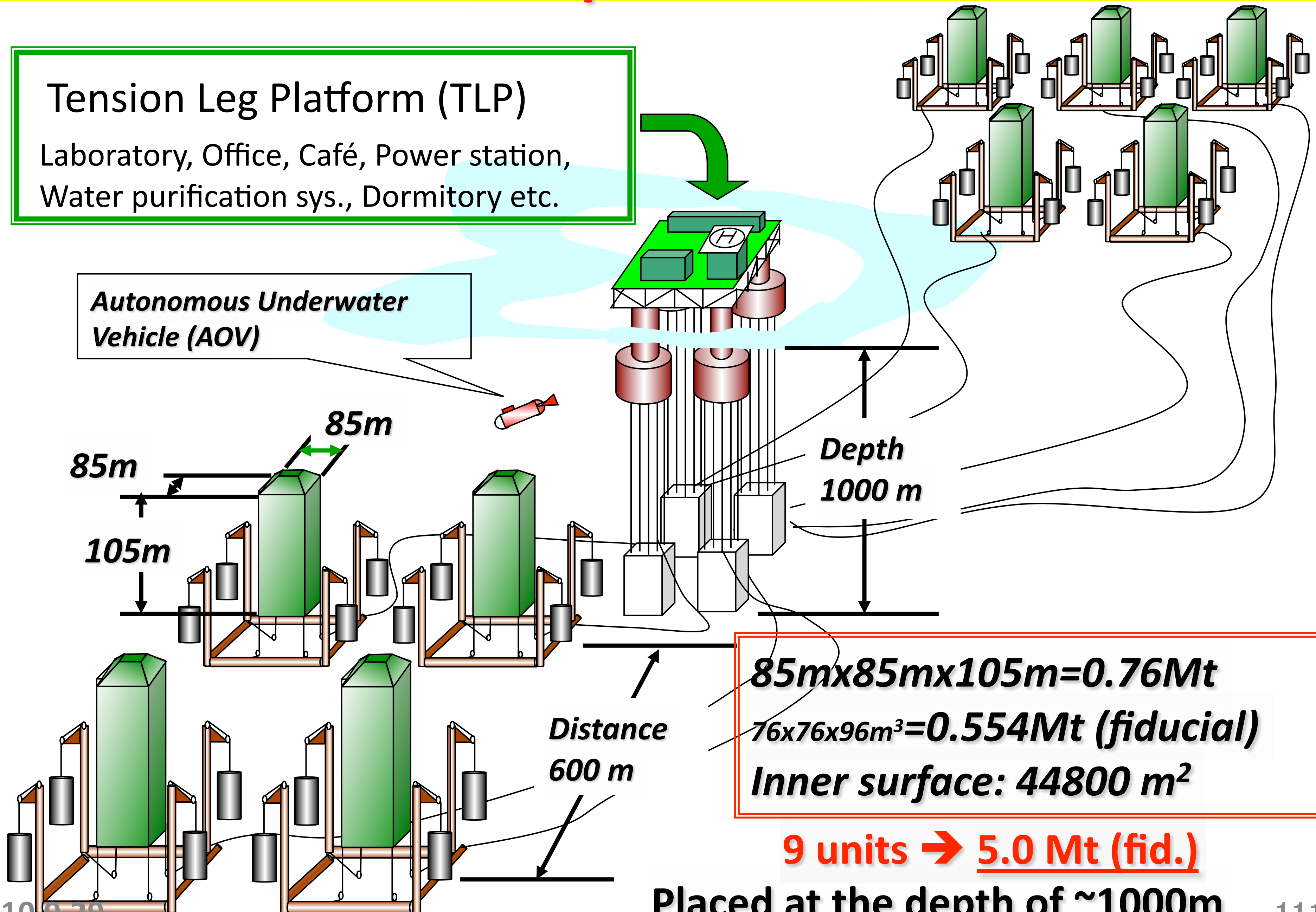
Ref:1) Y. Suzuki, hep-ex/0110005 (in 2001)
2) Y. Suzuki, in Proc. of Neutrino Oscillation in Venice, Feb, 2006

But this is shallow @100 m depth

Deep-TITAND

Tension Leg Platform (TLP)

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



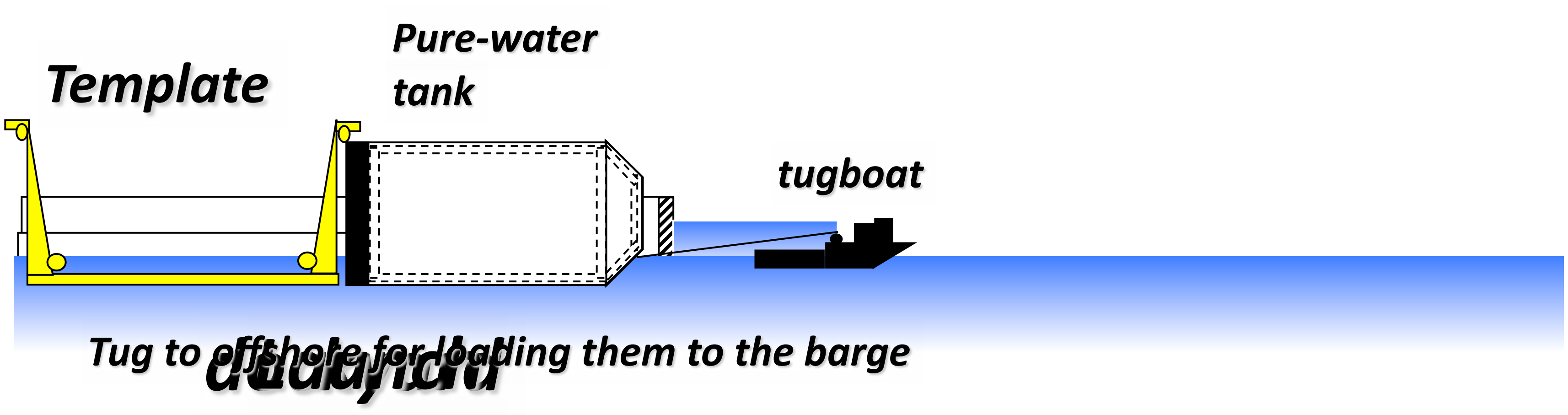
85mx85mx105m=0.76Mt

76x76x96m³=0.554Mt (fiducial)

Inner surface: 44800 m²

9 units → 5.0 Mt (fid.)

Placed at the depth of ~1000m



How to construct

Construct steel container (unit) at the DOCK

85m x 85m x 105m

Maximum size of DOCK in the world

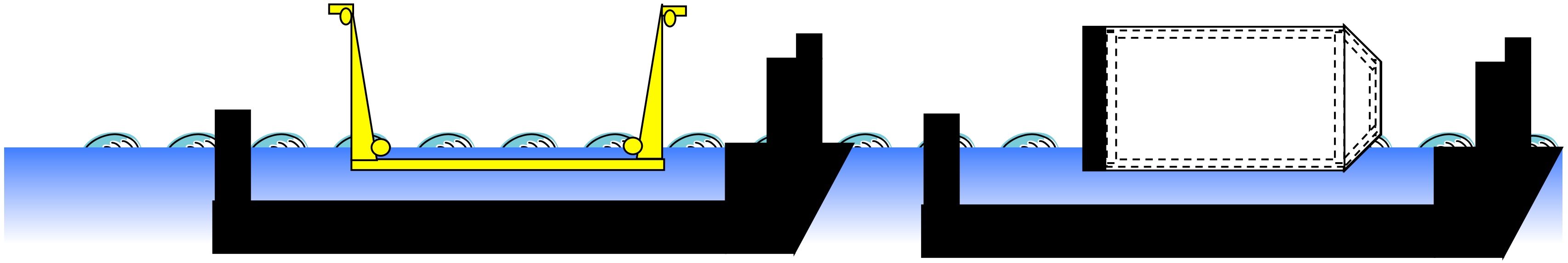
➔ width:108m x length: 480m

Install PMTs(or equivalent)

Number of PMTs

44,800 PMTs for one unit

(for 1/2 SK density)

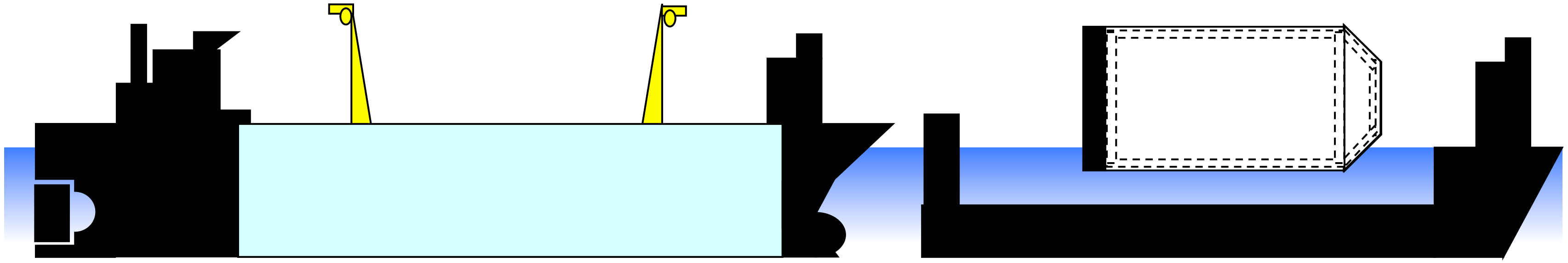


Sinking barge
(loading capacity:
20,000～30,000 tons)

Move to the installation site

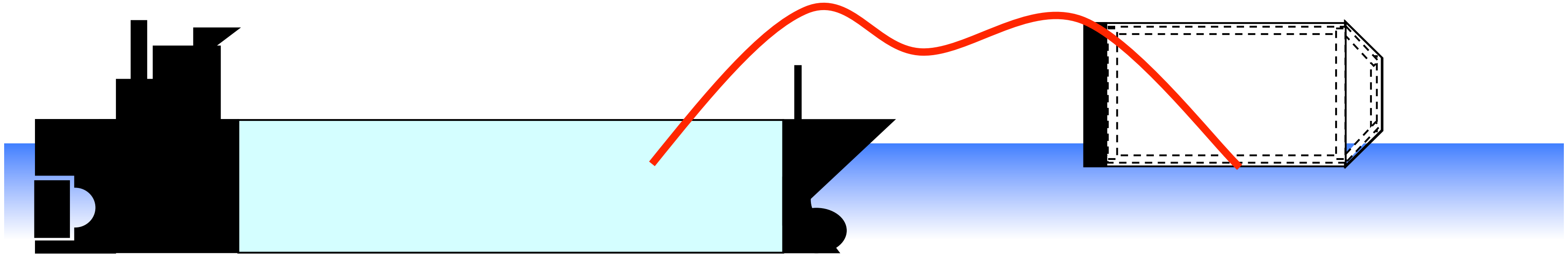
Sinking barge

The installation site



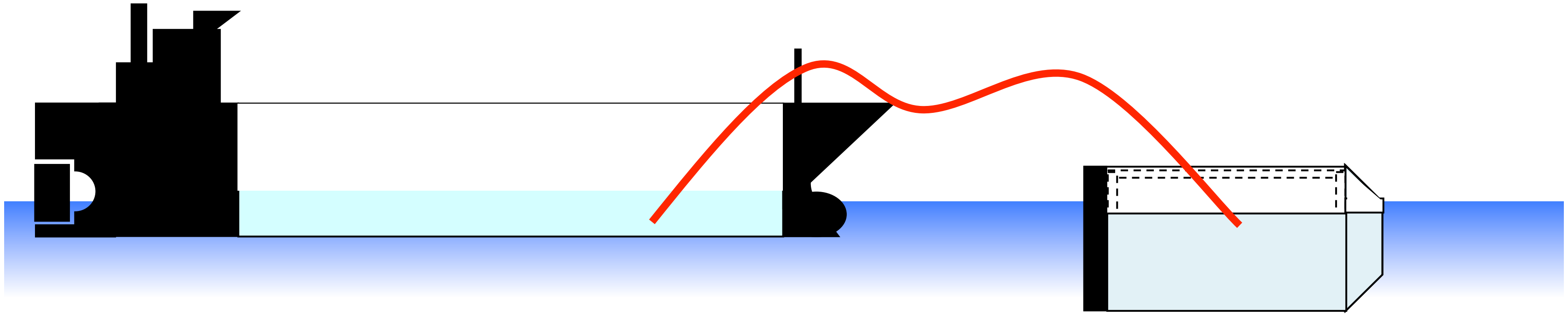
Unload the template and the water tank

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

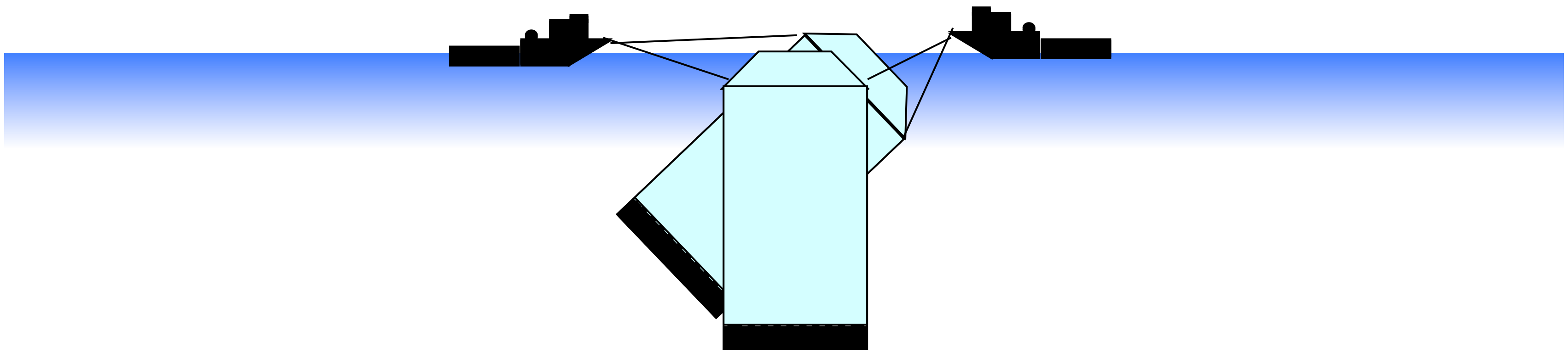


Bring a Ultra Large Crude Oil Carrier (ULCC) which contains pure water

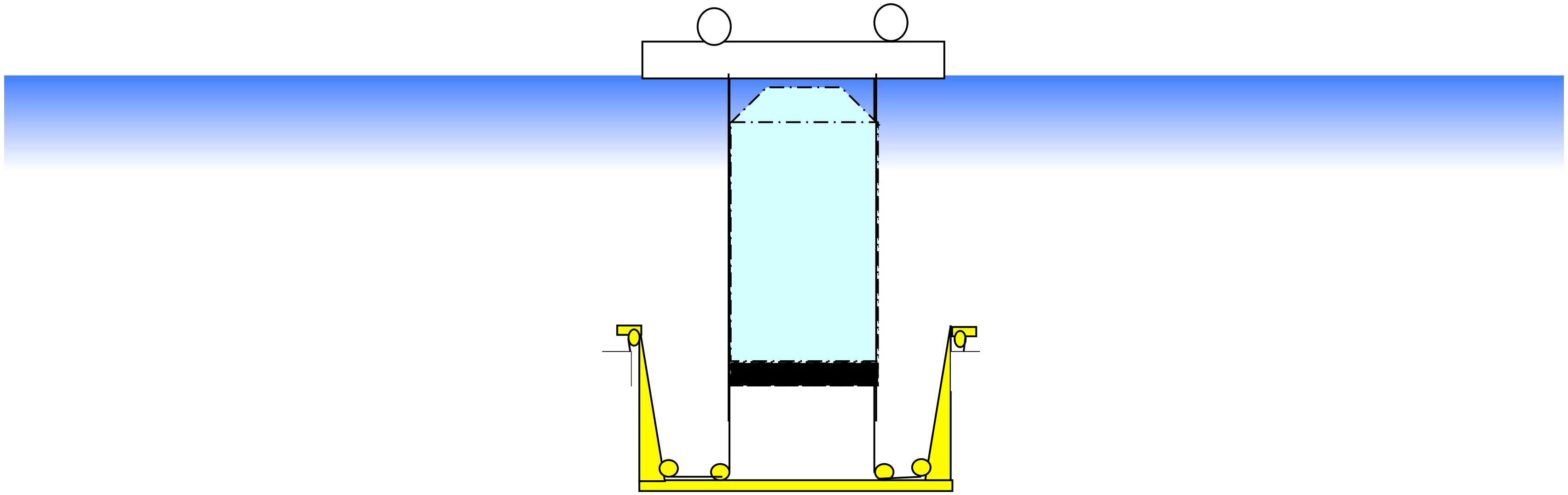
ULCC: 300ktons x 3 → 760ktons for one unit
Transfer speed 10ktons /hour (30 hours /ship)



Water is poured into a tank

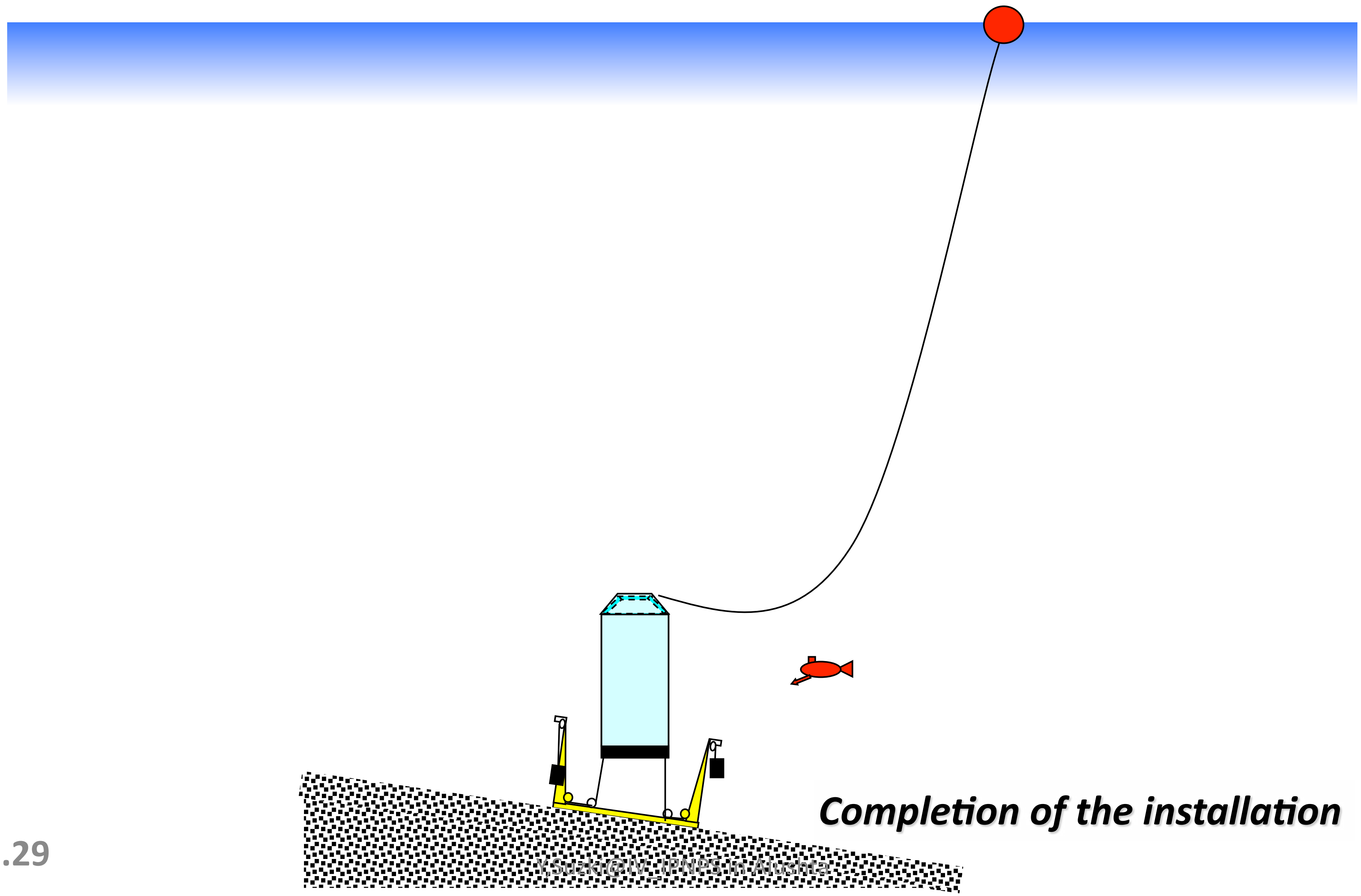


The water tank is rotated



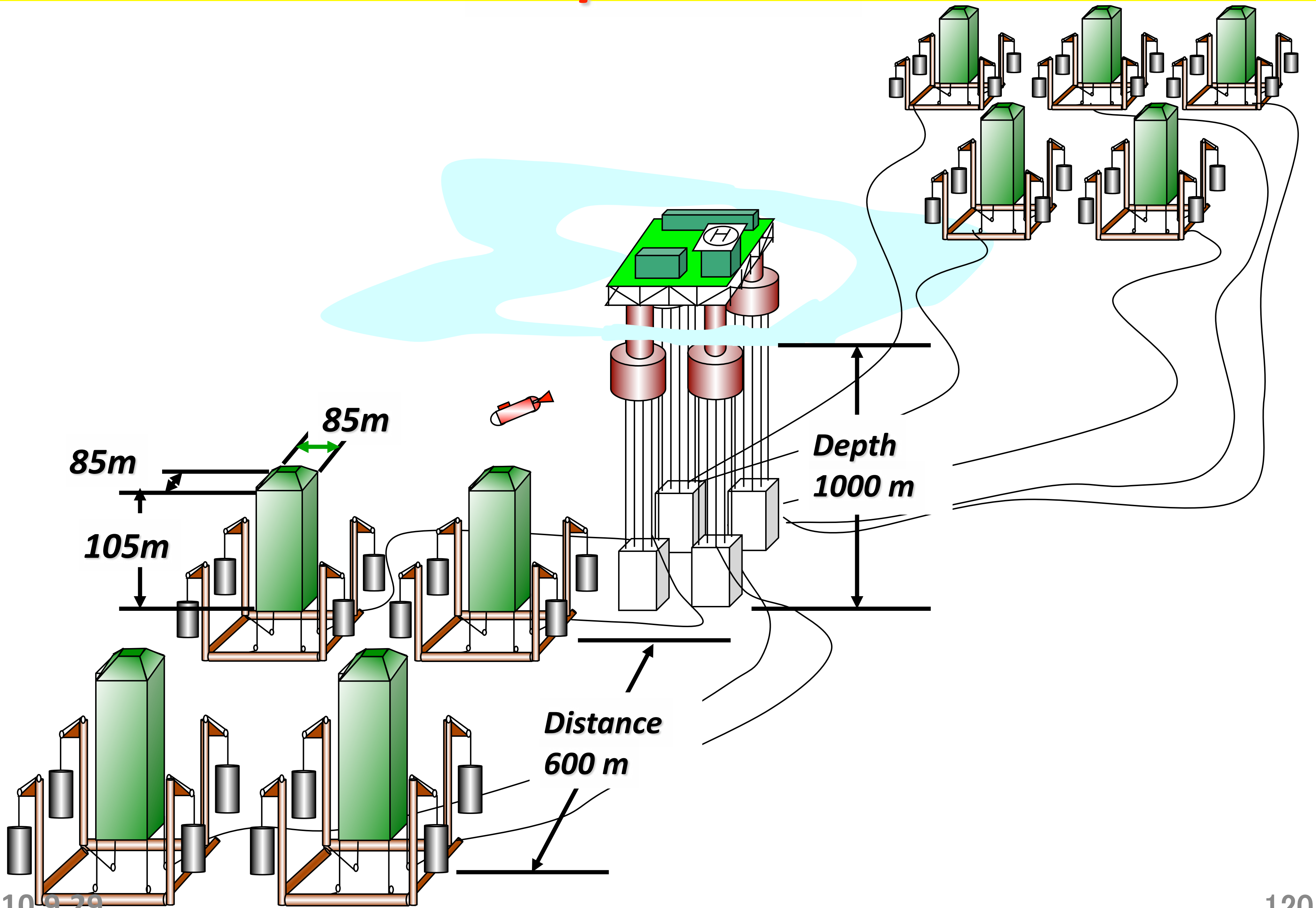
The template and the water tank is joint together

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

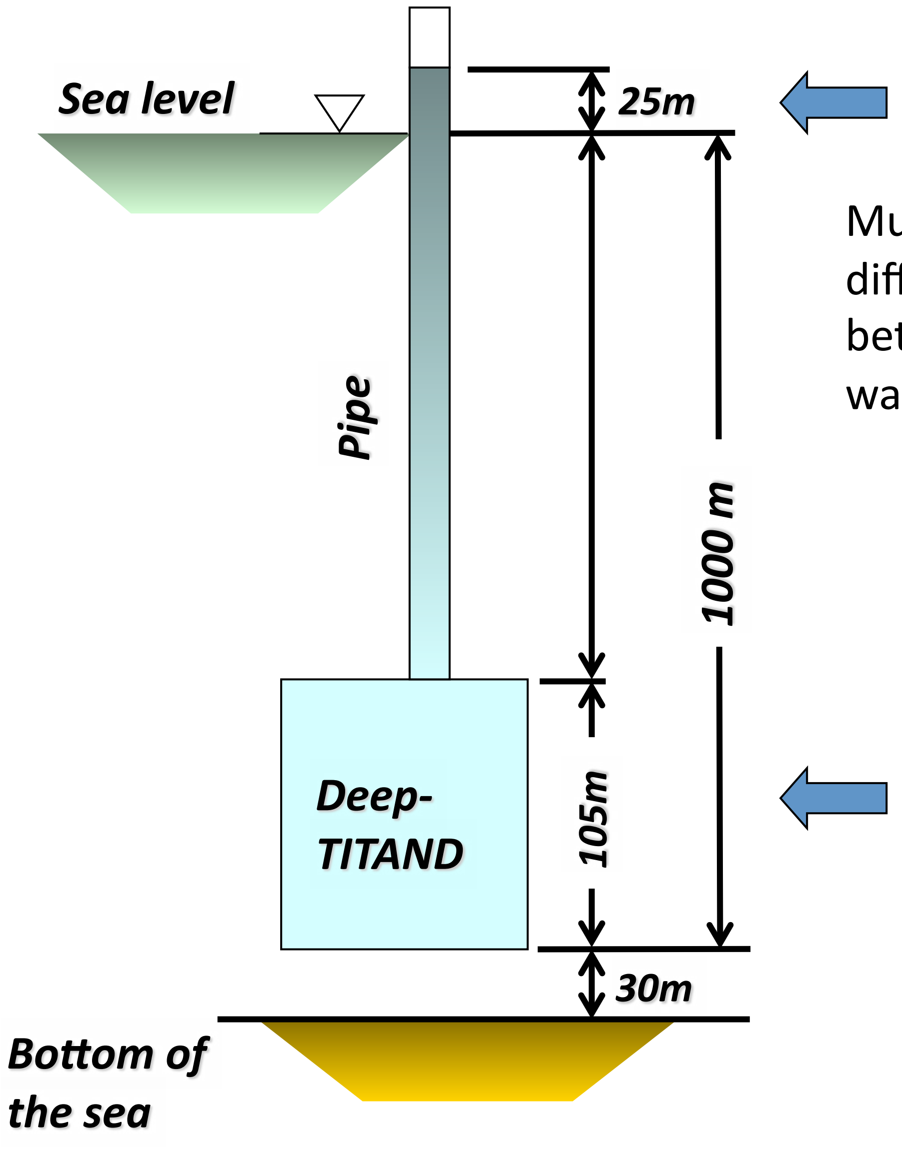


Completion of the installation

Deep-TITAND



Pressure Head



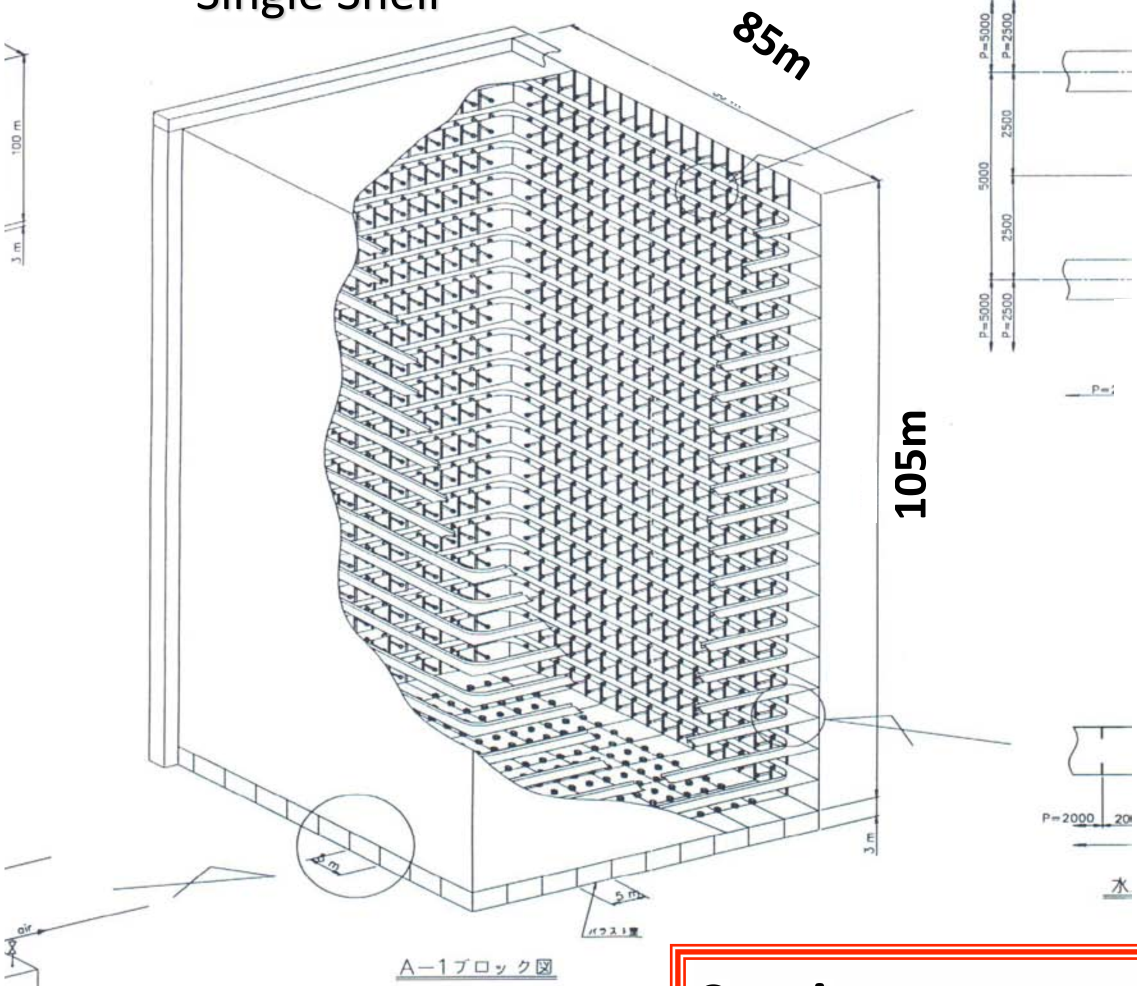
+ 2.5 atm

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

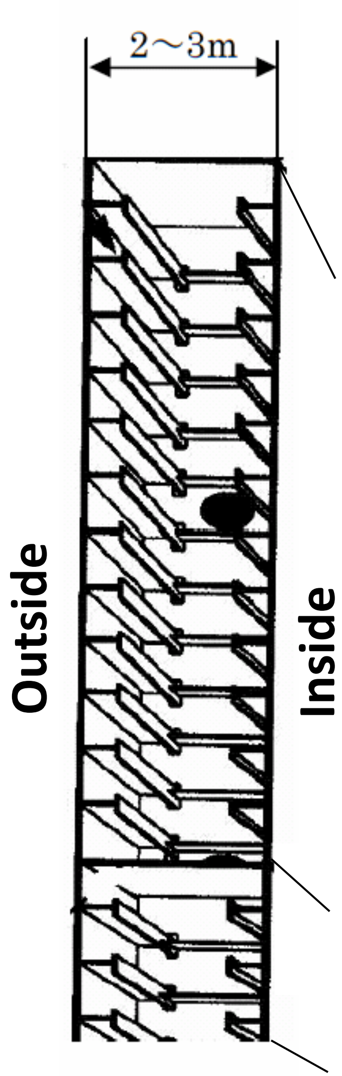
Structure

Single Shell



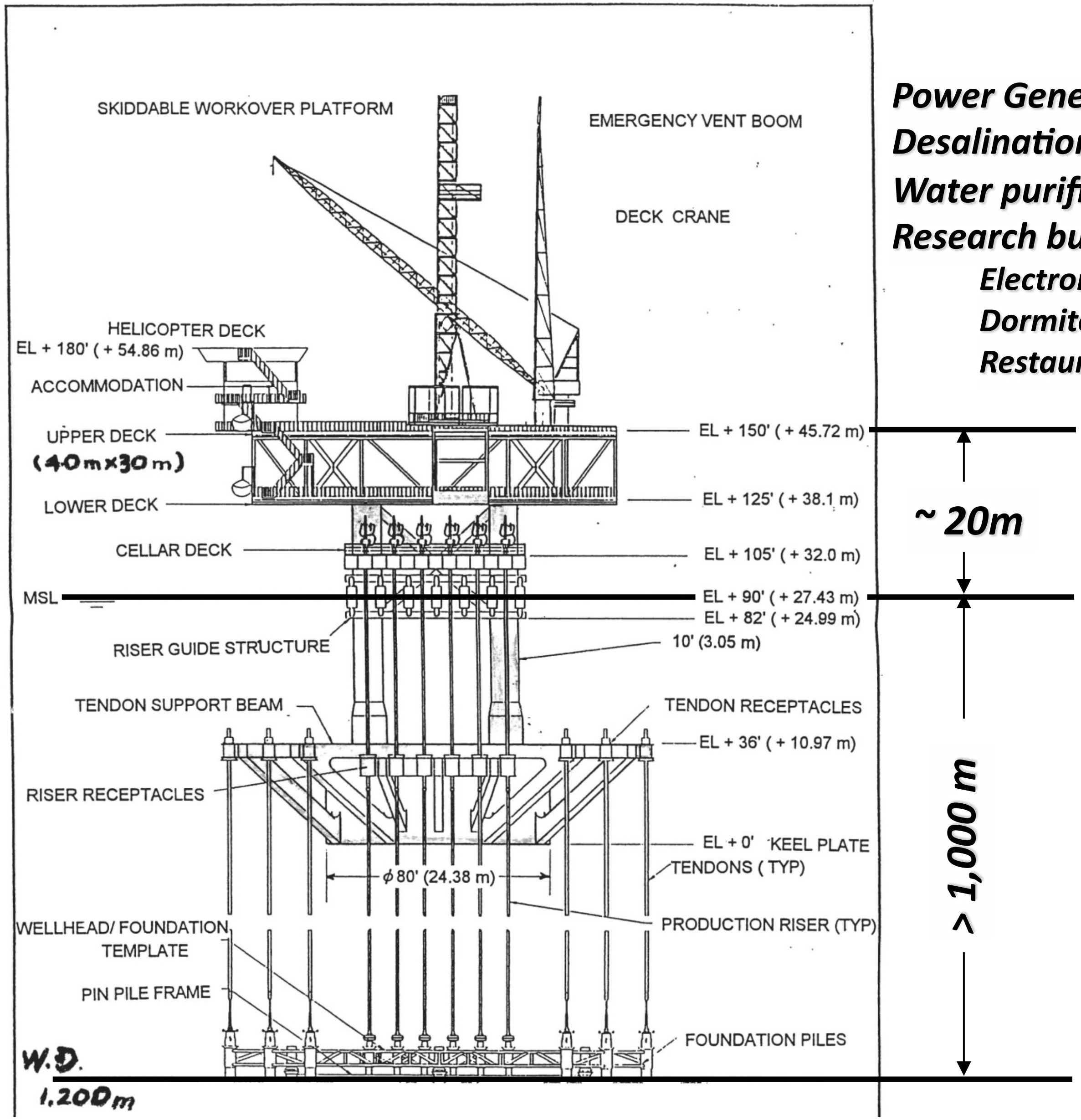
OR

Double Shell Structure



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

Tension Leg Platform

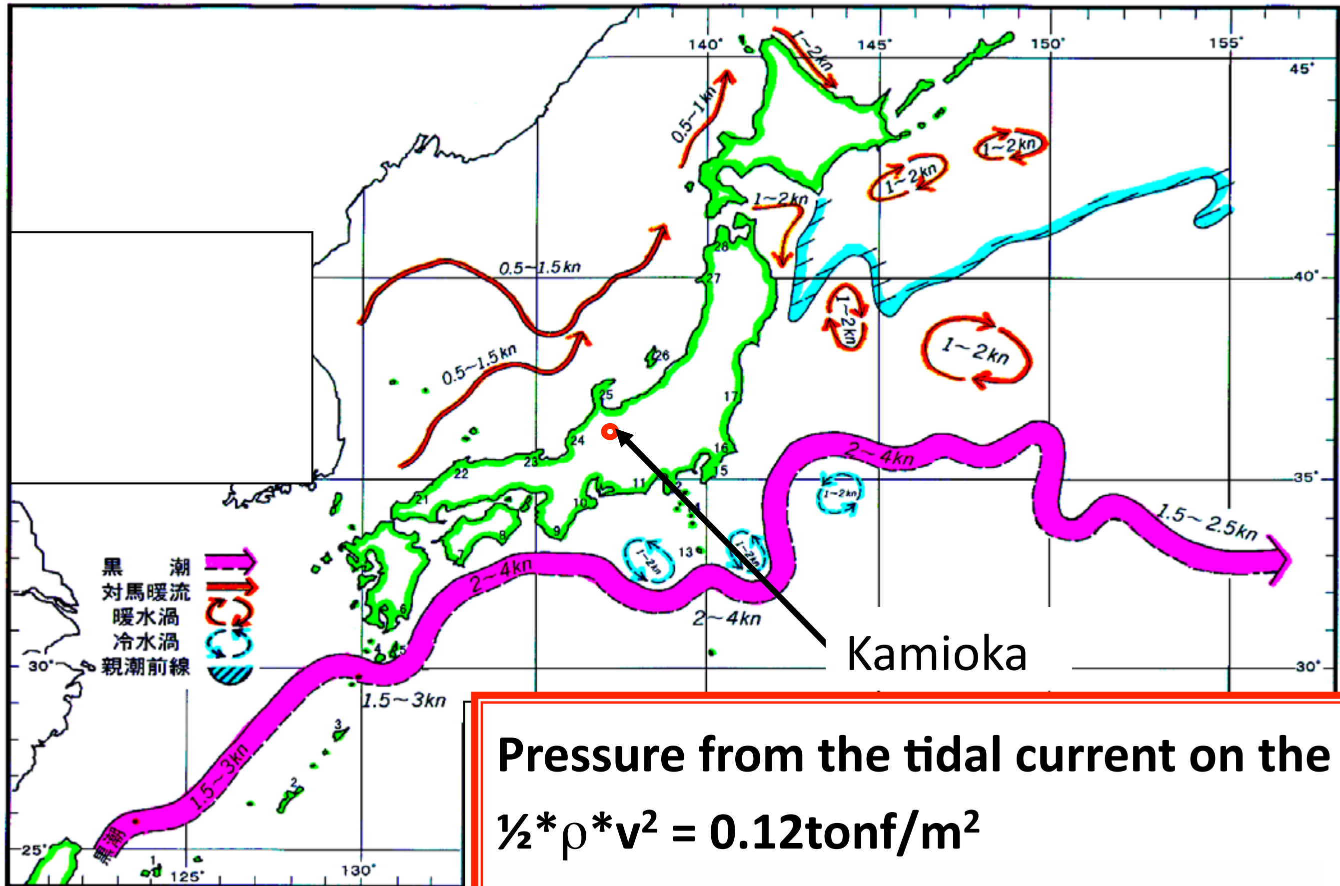


Power Generator
Desalination system
Water purification system
Research buildings
- ***Electronics & computer***
- ***Dormitory***
- ***Restaurant & Cafe***

Where we can place the detector?

Tidal current < 3 knot

~ 5.6km/hour (1.5m/s)

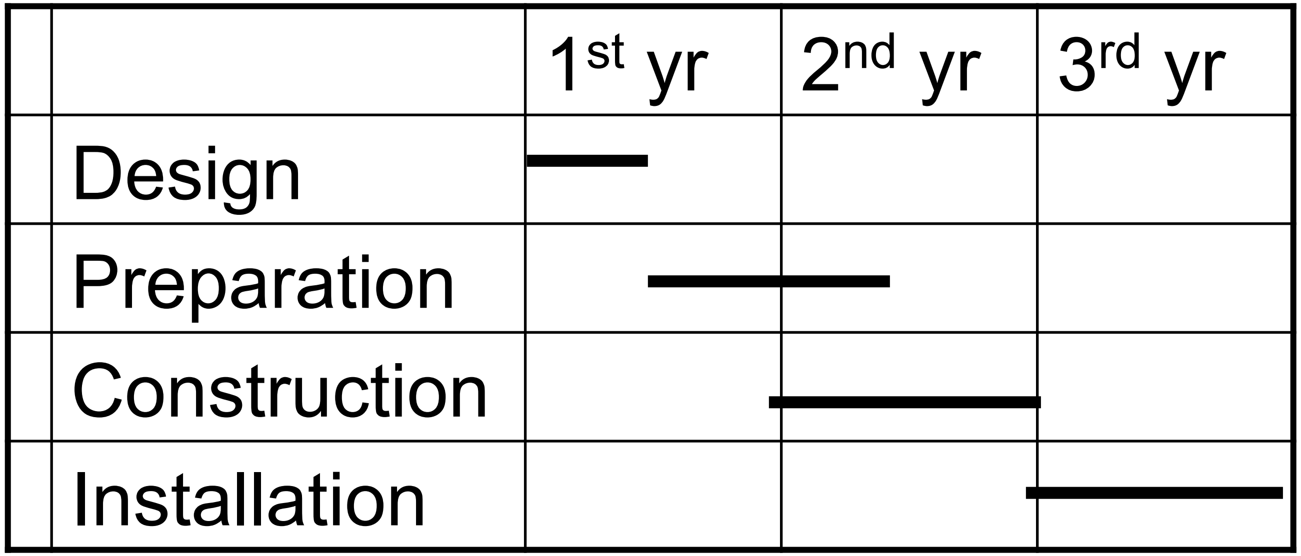


Pressure from the tidal current on the wall:

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

0.12x85x105 = *1071 ton per one wall*

Construction periods



Total 3 years construction time:

very short

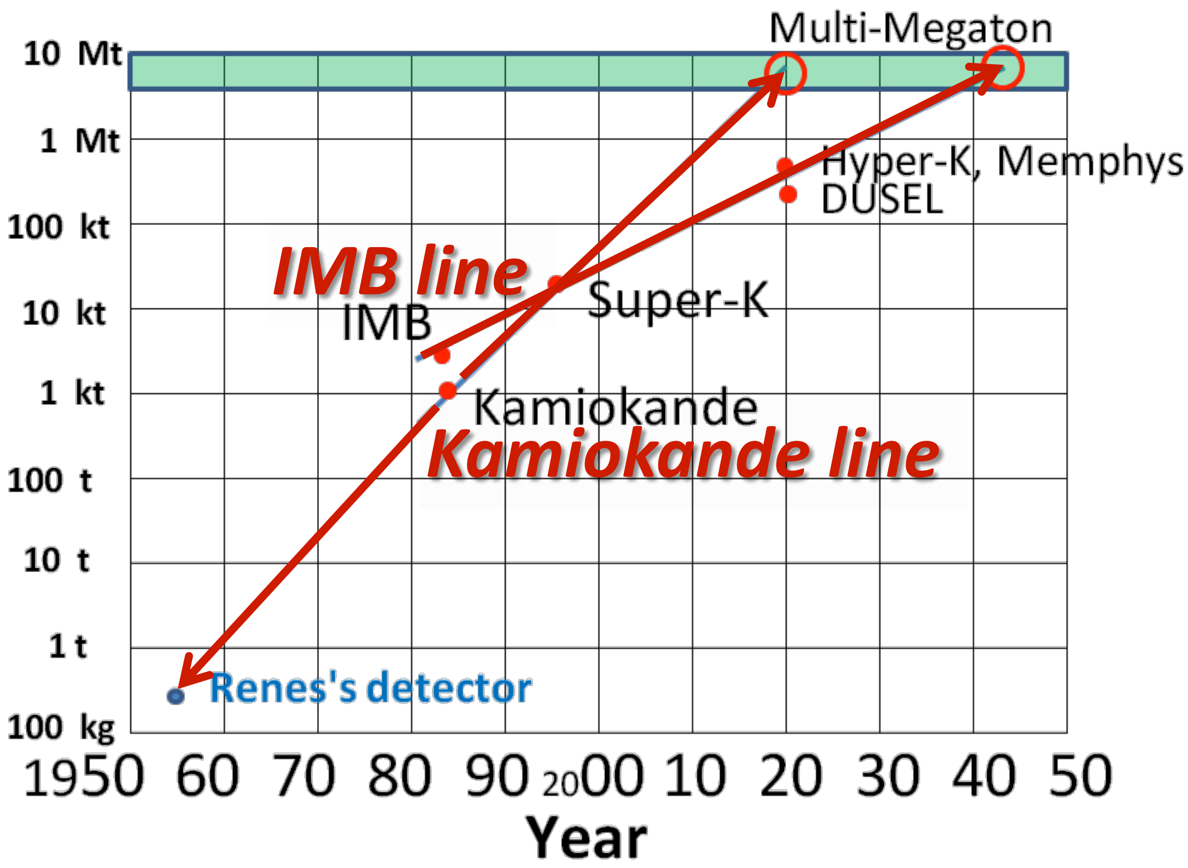
But the manufacturing time for the light sensors is not included.

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 !**

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.