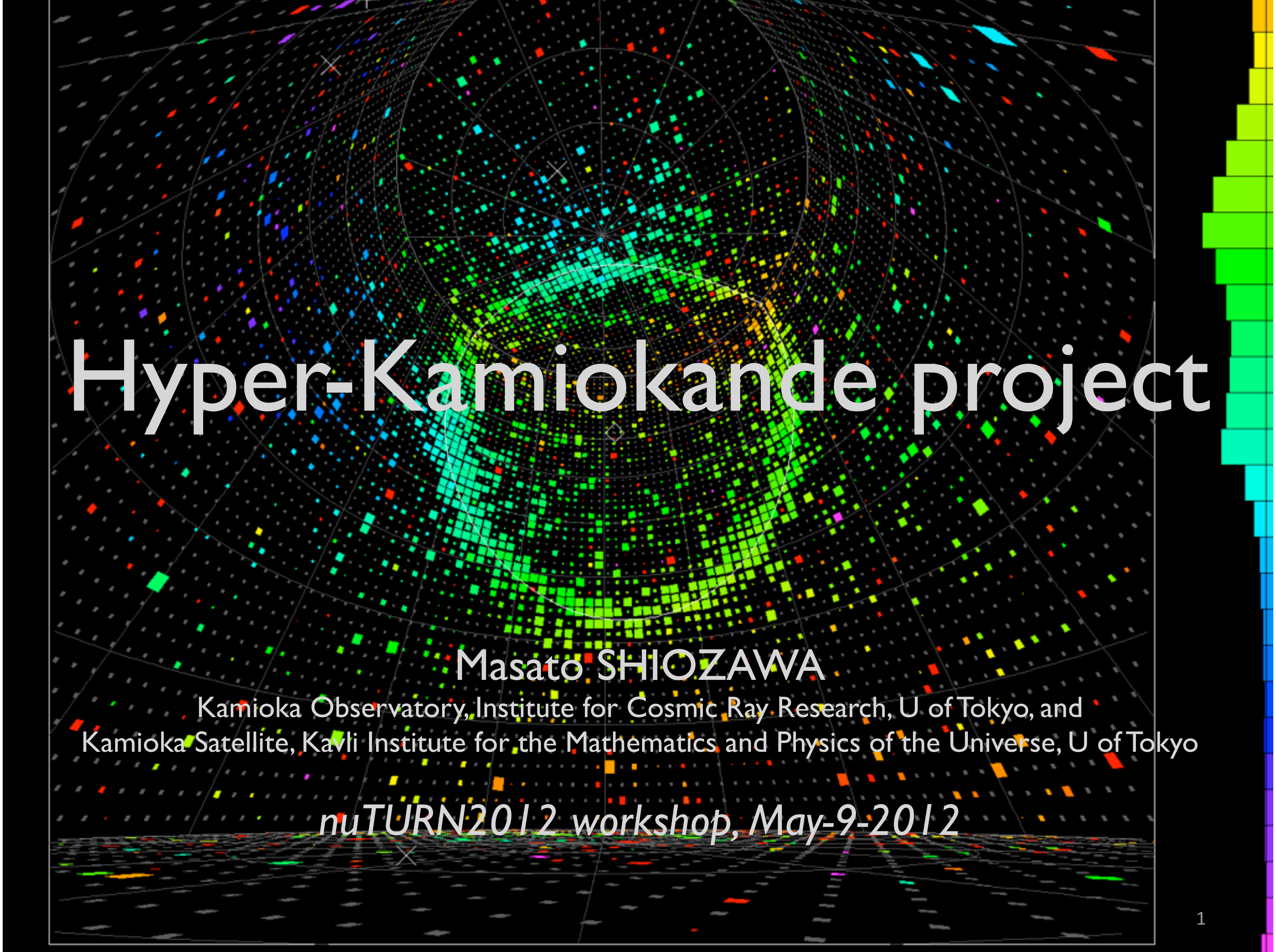


Hyper-Kamiokande project

Masato SHIOZAWA

Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
Kamioka Satellite, Kavli Institute for the Mathematics and Physics of the Universe, U of Tokyo

nuTURN2012 workshop, May-9-2012

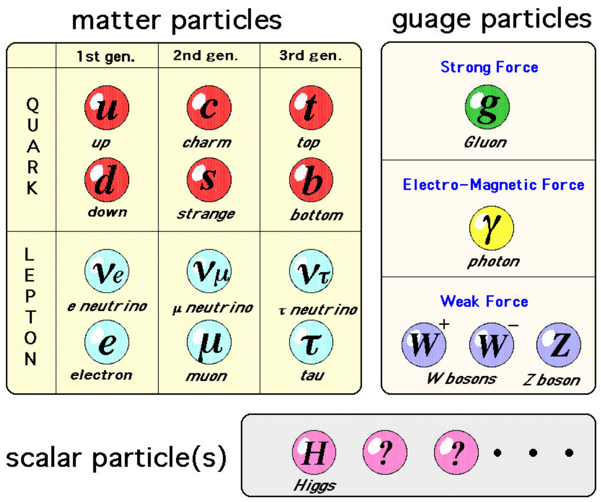
Outline

- Introduction
  - physics motivation for Hyper-K
- Hyper-K detector design
- Physics potentials of Hyper-K
  - impact of large θ_{13}
- Summary

Introduction

Standard Model

- The paradigm of elementary particles and interactions -



Questions on the SM structure

- why the gauge structure of $SU(3) \otimes SU(2) \otimes U(1)$?
- why the structure of 3 generations of quarks and leptons?

Questions on the neutrinos

- why the mass so tiny?
  - an evidence of new physics (suggesting high E scale physics)
- why the family mixing so large? different from quarks?
- Did CP violation in neutrinos play an important role in creating the observed matter-antimatter asymmetry in the universe?

→Physics beyond standard model is required.

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

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

K. Abe,[12,14] T. Abe,[10] H. Aihara,[10,14] Y. Fukuda,[5] Y. Hayato,[12,14] K. Huang,[4] A. K. Ichikawa,[4] M. Ikeda,[4] K. Inoue,[8,14] H. Ishino,[7] Y. Itow,[6] T. Kajita,[13,14] J. Kameda,[12,14] Y. Kishimoto,[12,14] M. Koga,[8,14] Y. Koshio,[12,14] K. P. Lee,[13] A. Minamino,[4] M. Miura,[12,14] S. Moriyama,[12,14] M. Nakahata,[12,14] K. Nakamura,[2,14] T. Nakaya,[4,14] S. Nakayama,[12,14] K. Nishijima,[9] Y. Nishimura,[12] Y. Obayashi,[12,14] K. Okumura,[13] M. Sakuda,[7] H. Sekiya,[12,14] M. Shiozawa,[12,14,*] A. T. Suzuki,[3] Y. Suzuki,[12,14] A. Takeda,[12,14] Y. Takeuchi,[3,14] H. K. M. Tanaka,[11] S. Tasaka,[1] T. Tomura,[12] M. R. Vagins,[14] J. Wang,[10] and M. Yokoyama[10,14]

(Hyper-Kamiokande working group)

[1] *Gifu University, Department of Physics, Gifu, Gifu 501-1193, Japan*

[2] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan*

[3] *Kobe University, Department of Physics, Kobe, Hyogo 657-8501, Japan*

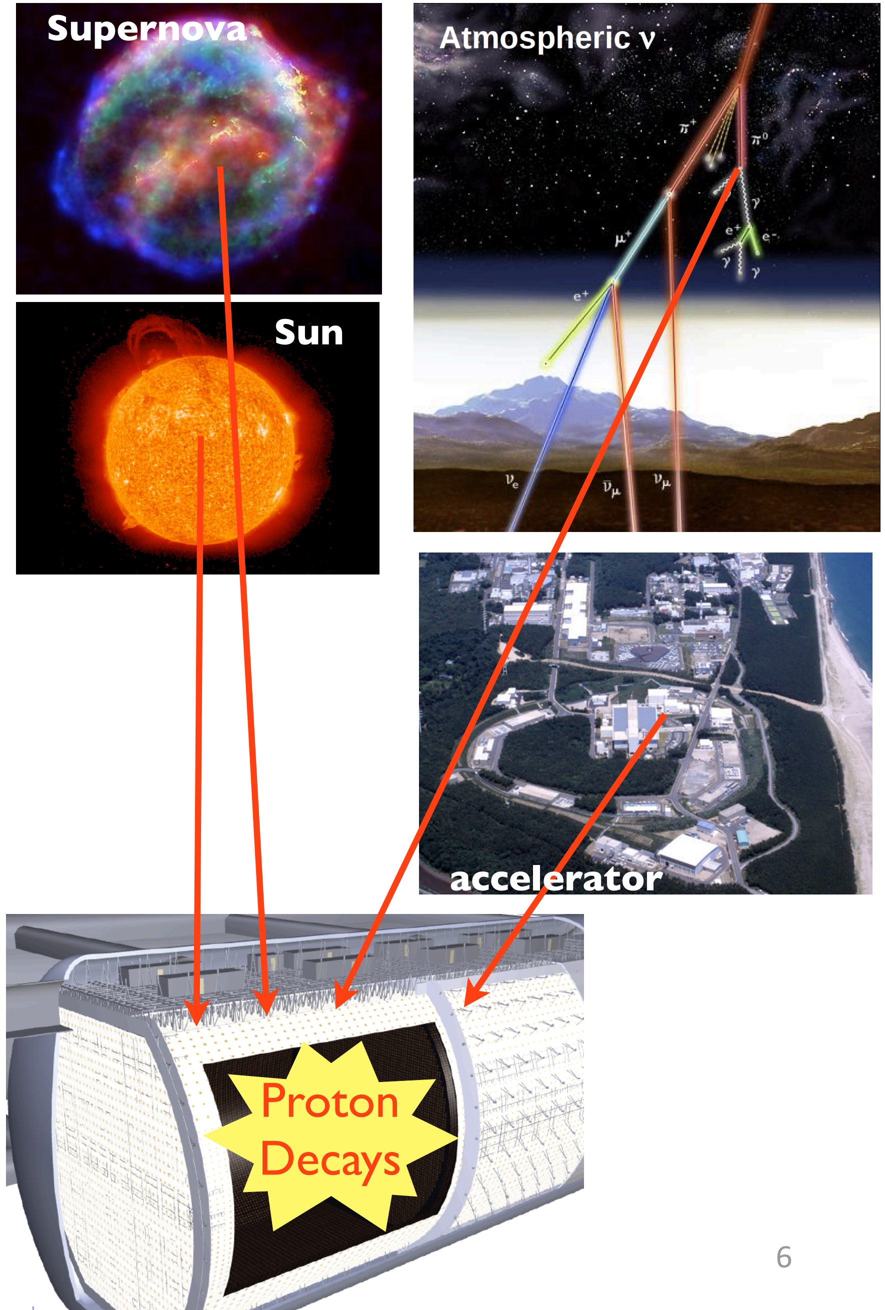
[4] *Kyoto University, Department of Physics, Kyoto, Kyoto 606-8502, Japan*

[5] *Miyagi University of Education, Department of Physics, Sendai, Miyagi 980-0845, Japan*

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

Multi-purpose detector, Hyper-K

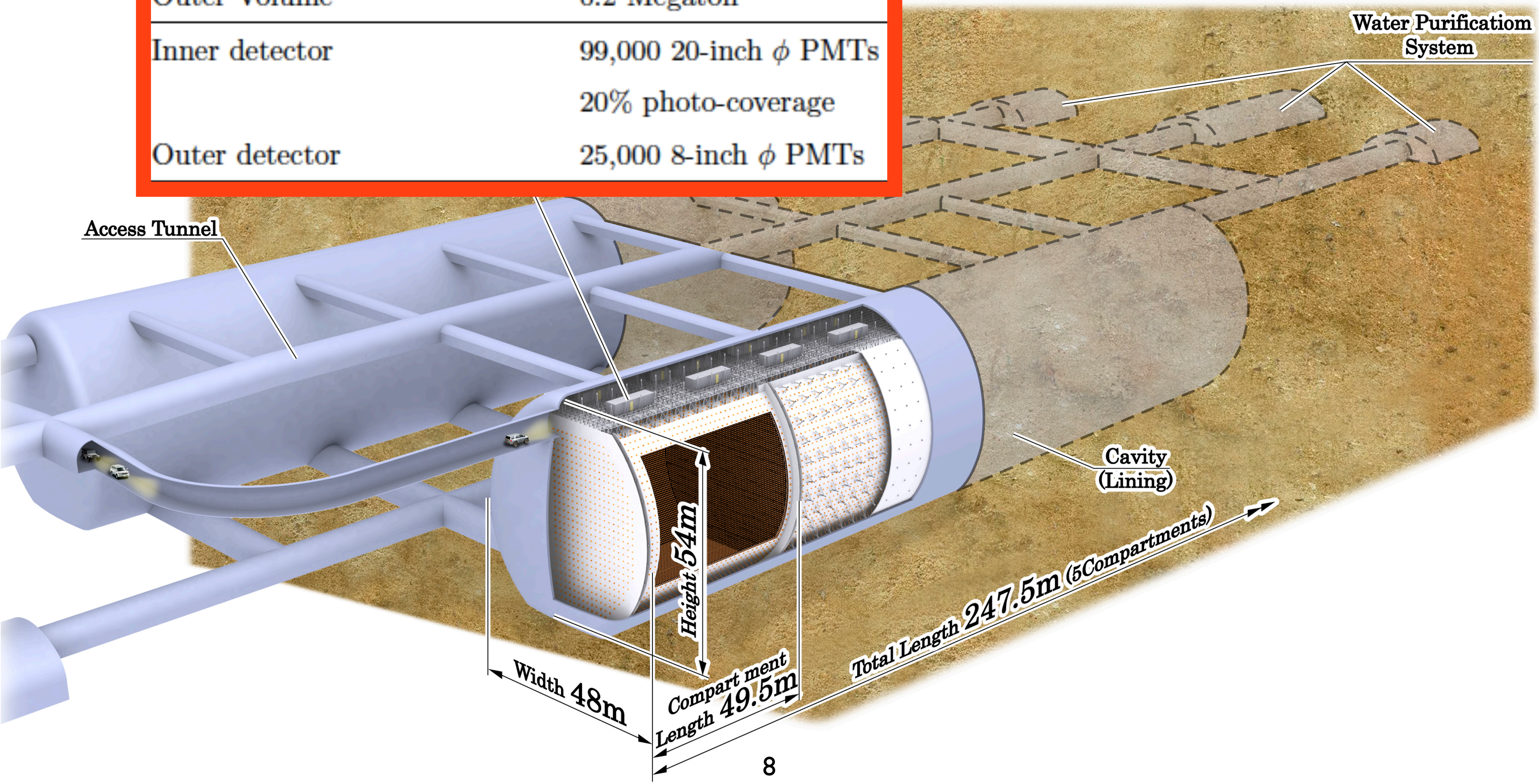
- Total (fiducial) volume is 1 (0.56) million ton
  - 25 × Super-K
- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac δ)
  - ν mass hierarchy determination($\Delta m^2_{32}>0$ or <0)
  - θ_{23} octant determination ($\theta_{23}<\pi/4$ or $>\pi/4$)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years
- Neutrinos from astrophysical objects
  - 200 ν's / day from Sun
  - 250,000 (50) ν's from Supernova @Galactic-center (Andromeda)
  - 830 ν's / 10 years Supernova relic ν
  - WIMP ν, solar flare ν, etc



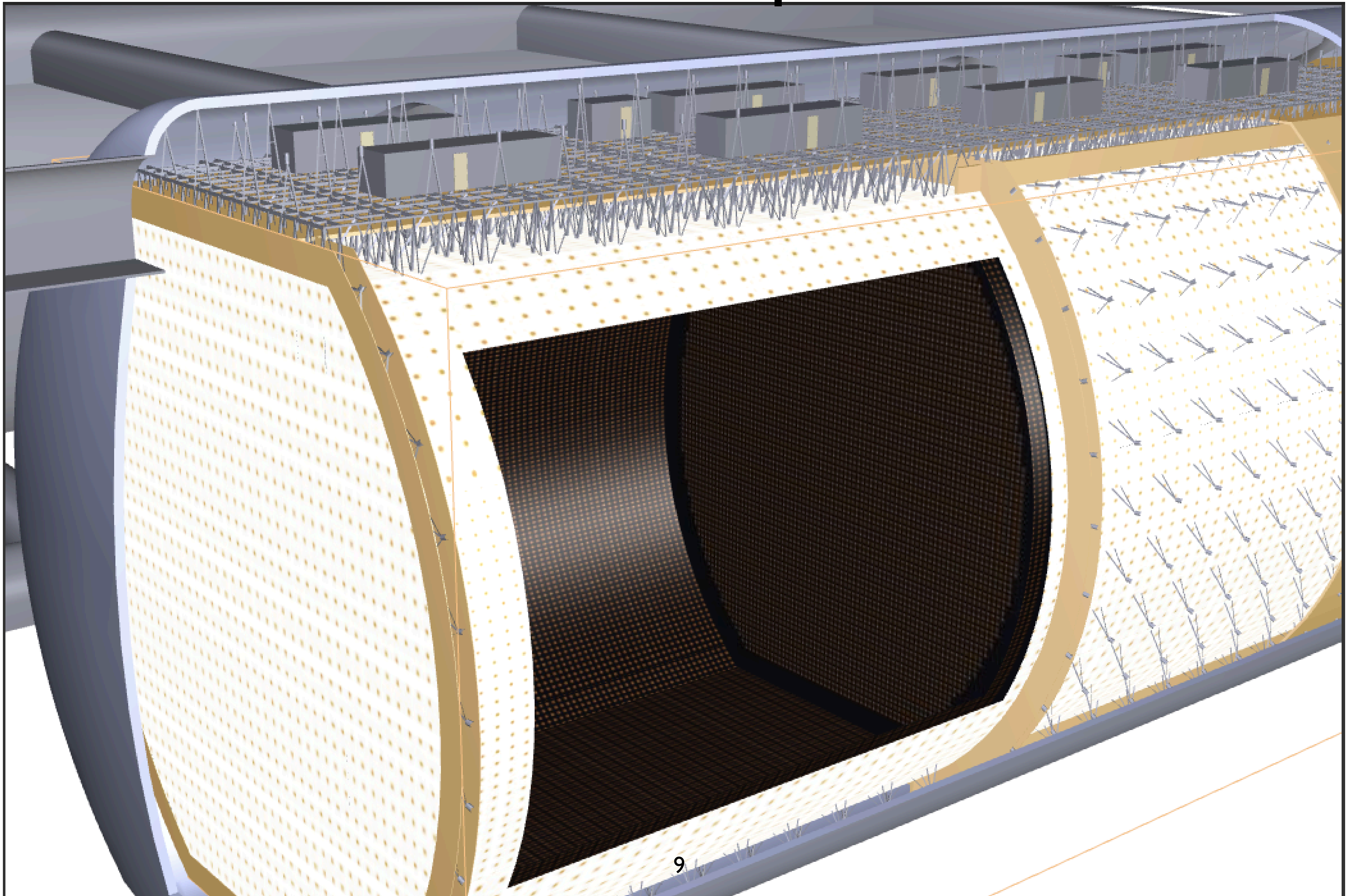
Hyper-K detector

Schematic view of Hyper-K

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

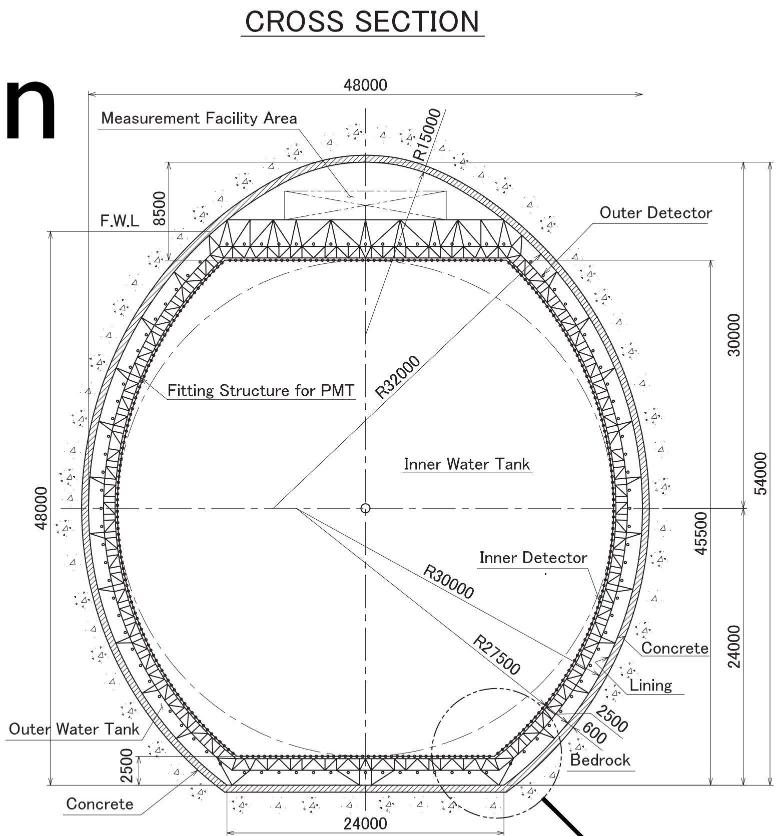


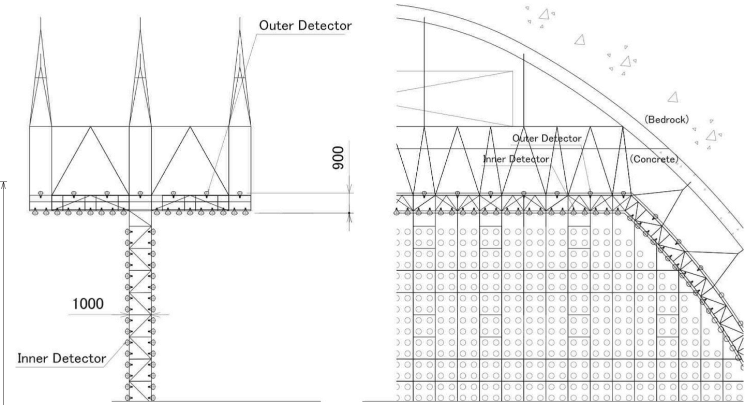
One of 10 compartments

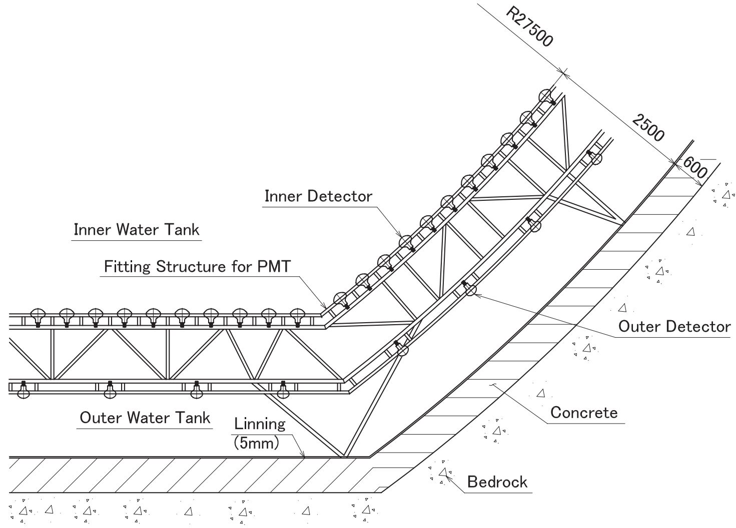


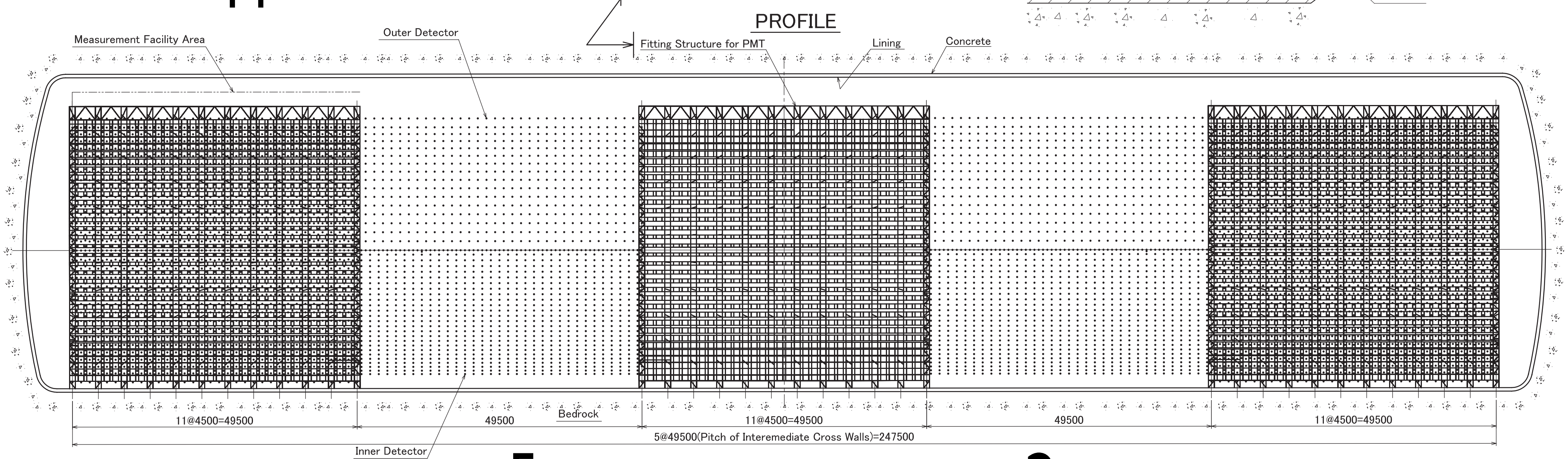
Tank Design

- liner
- PMT support structure





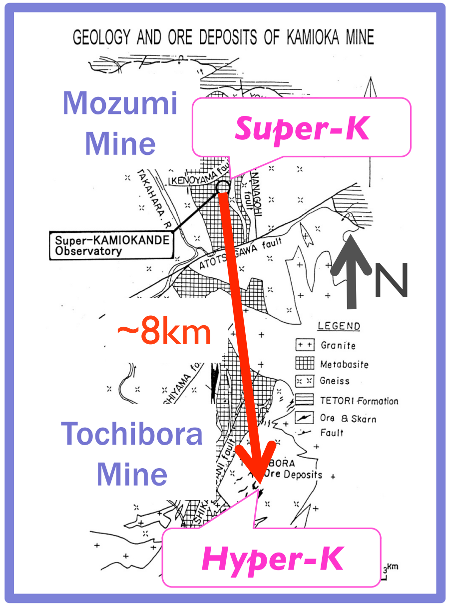


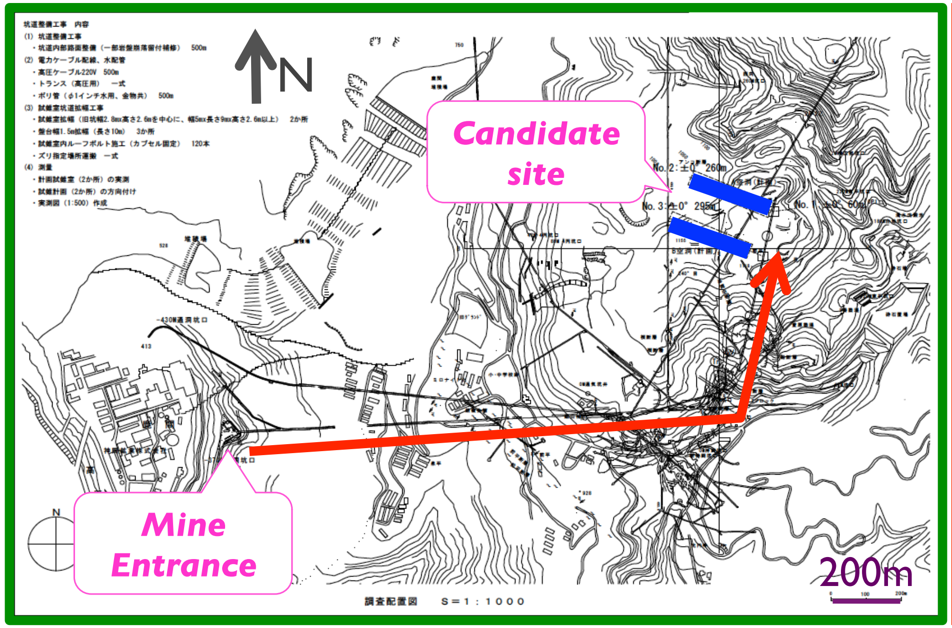


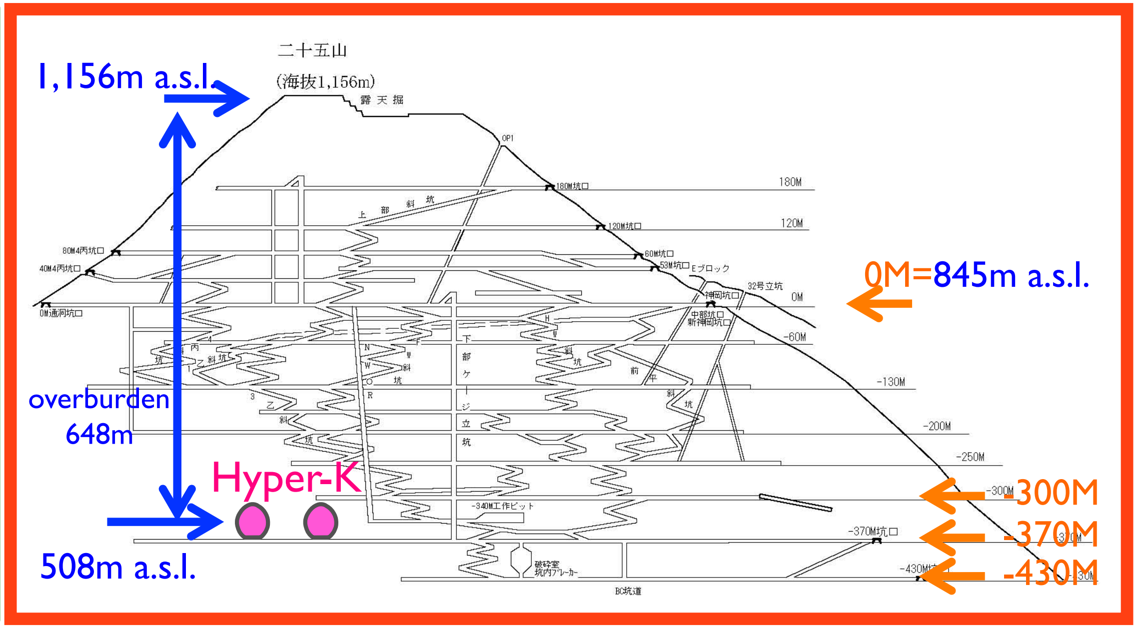
5 compartments × 2

Hyper-Kamiokande candidate site

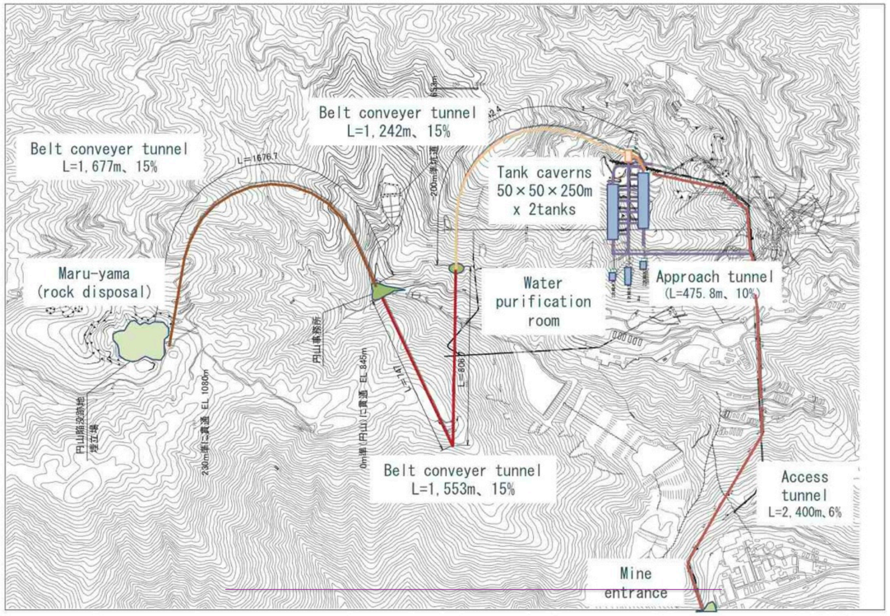
- ✦ 8km south from Super-K
  - ✦ same T2K beam off-axis angle (2.5 degree)
  - ✦ same baseline length (295km)
- ✦ 2.6km horizontal drive from entrance
- ✦ under the peak of Nijuugo-yama
  - ✦ 648m of rock or 1,750 m.w.e. overburden
- ✦ 13,000 m^3/day or 1megaton/80days natural water



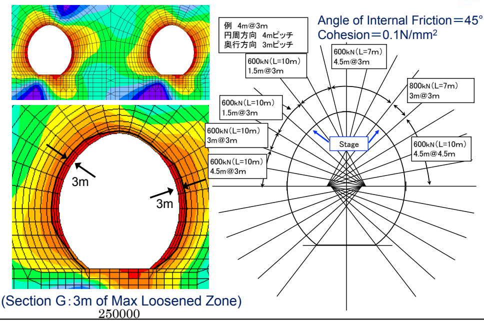




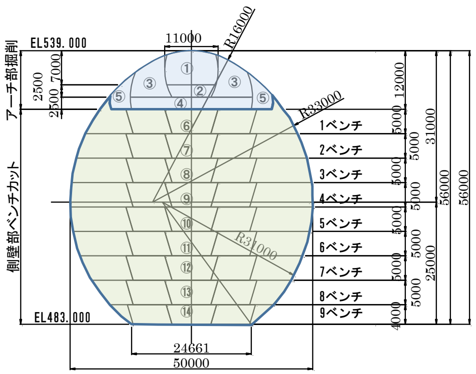
Cavern excavation

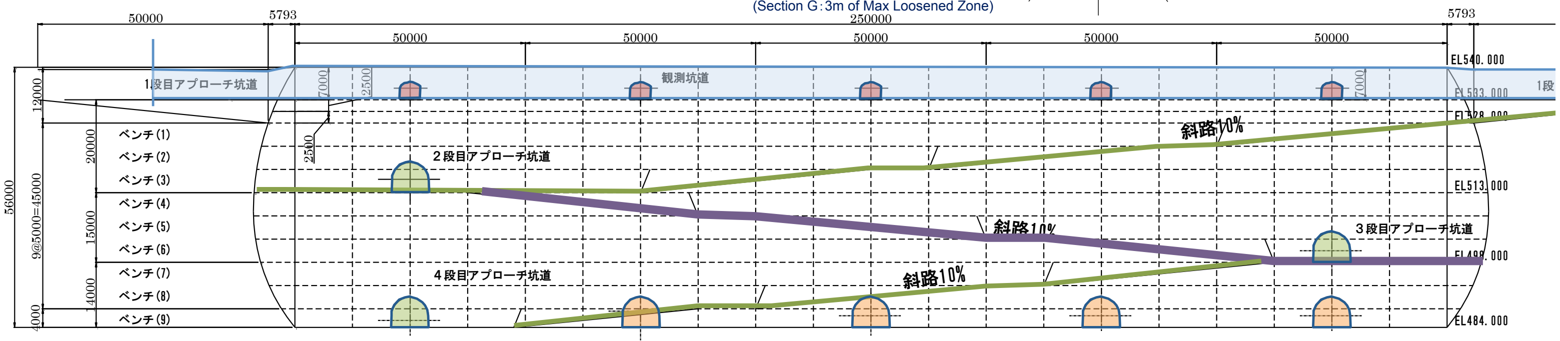


- geological survey, in-situ rock stress tests
- scheduling & costing ongoing



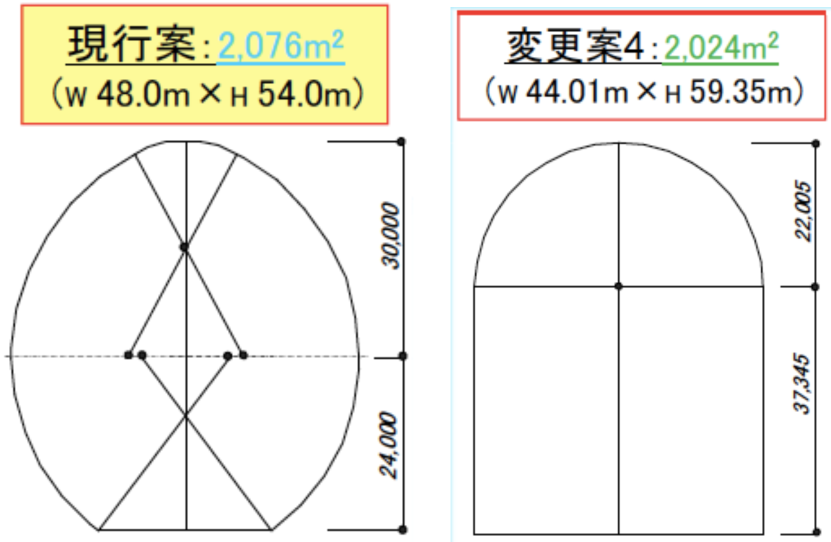
(Section G : 3m of Max Loosened Zone)

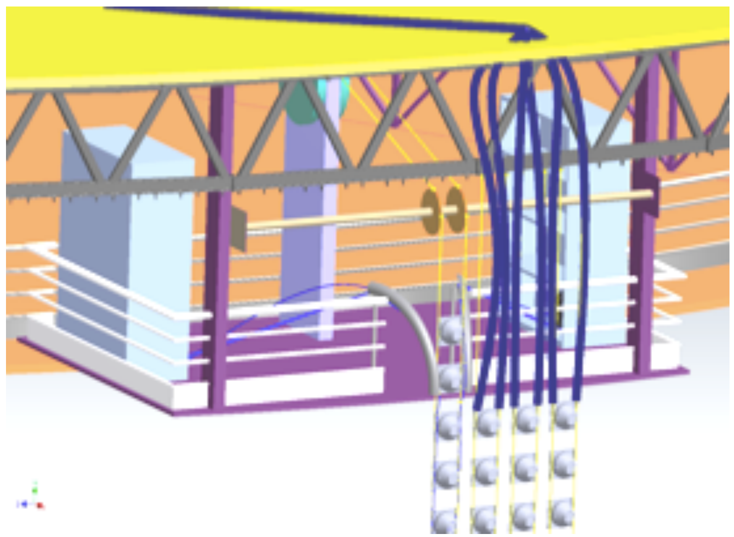




On-going studies

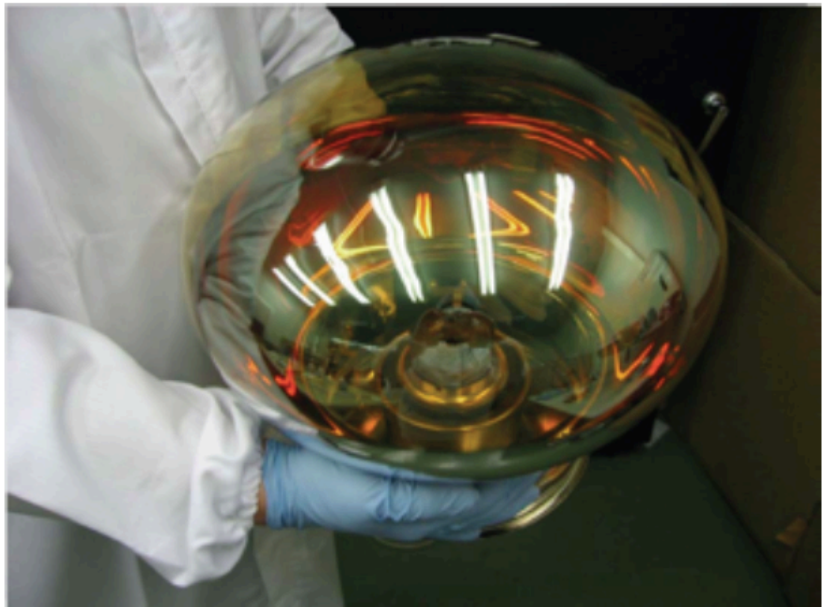
- design optimization is going on to achieve concrete proposal, lower cost, shorter construction period.
  - vertical straight wall possible? expecting cost &period reduction for liner construction
  - further reduction by wire support of PMTs
- need to secure waste rock disposal. (feasibility, cost estimation)
- water purification system design, water quality control strategy underway.



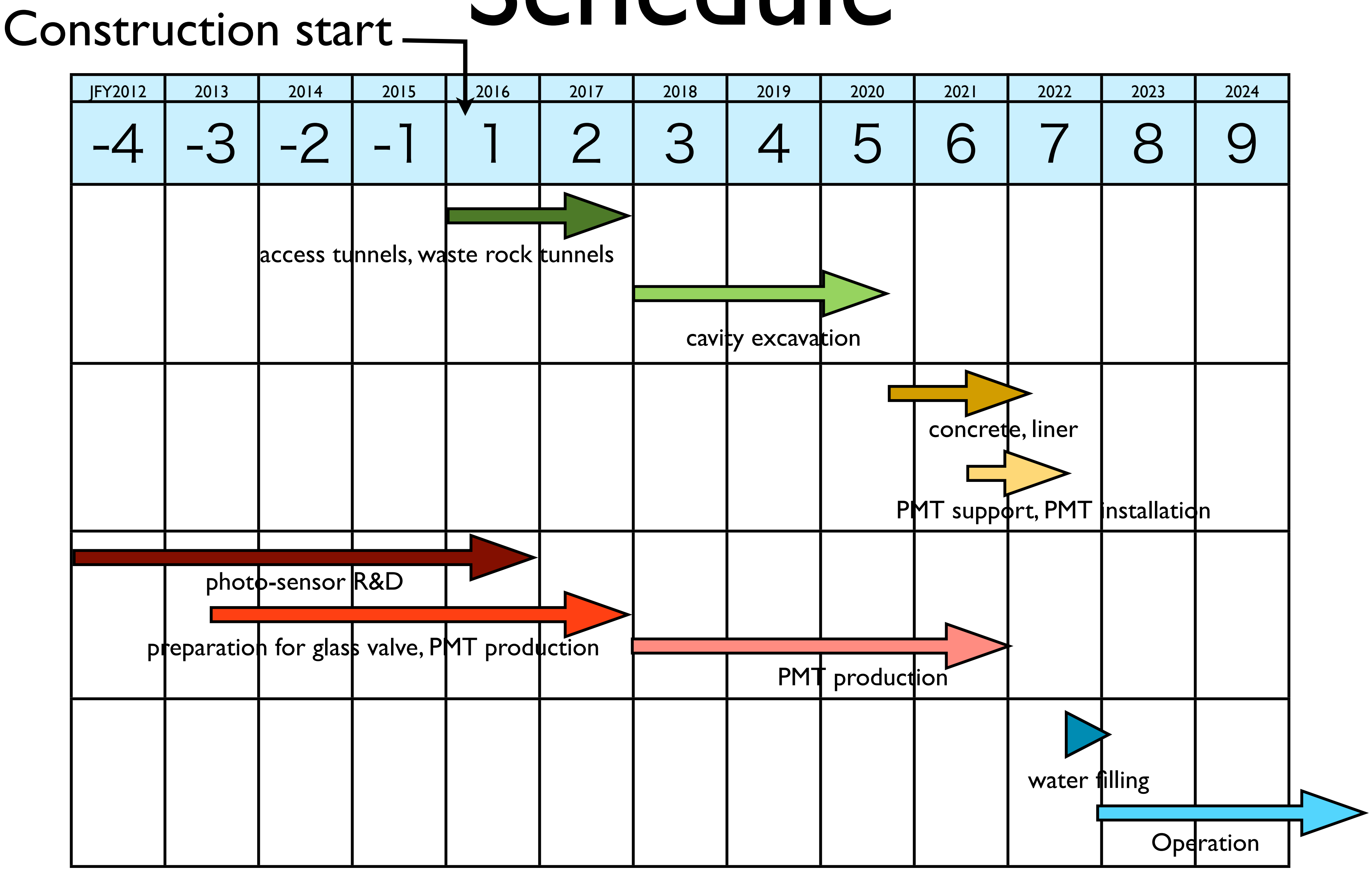


More on developments

- sensors
  - 20 inch Hybrid PD
  - New 20inch PMT
  - prototype in a year
- proof test by 8inch HPD from this summer
- water-proof system for DAQ electronics
- detector calibration method
  - quick, easy way
- software
  - HK simulation & reconstruction
  - Physics sensitivity studies



Schedule



assuming budget being approved from JPY2016

Physics Potentials

ν physics targets of Hyper-K

Given $\sin^2\theta_{13}$~a few %

Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$)

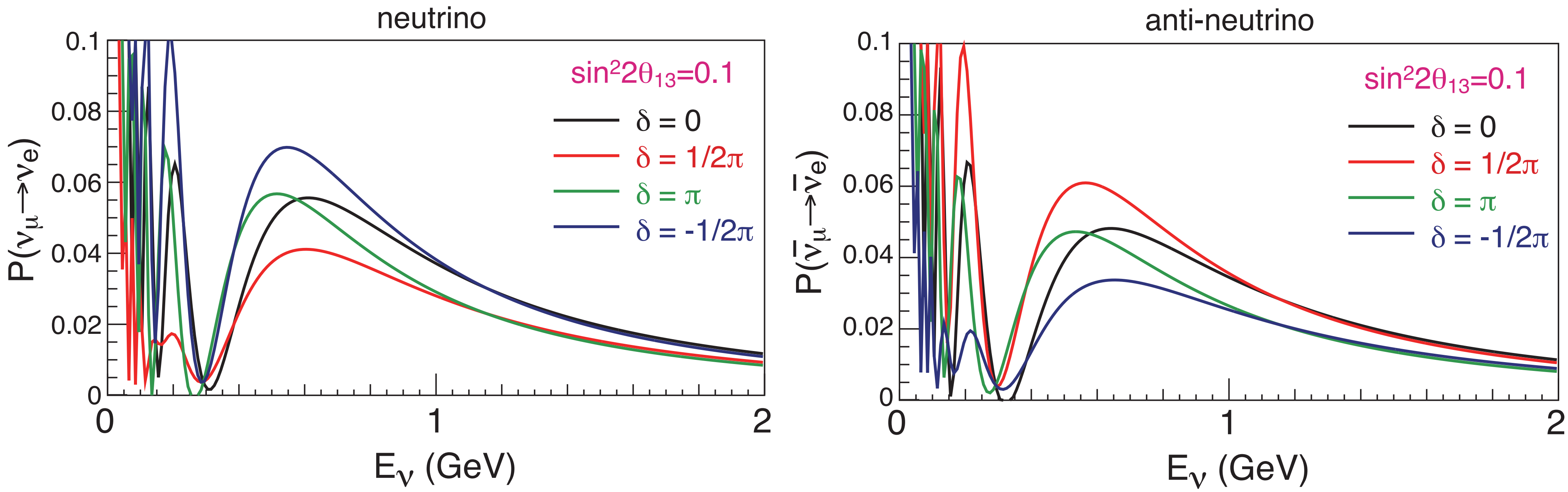
- Leptonic CP violation, Dirac phase δ
- ν mass hierarchy, $\Delta m^2_{32}>0$ or $\Delta m^2_{32}<0$
- θ_{23} octant, $\theta_{23}<\pi/4$ or $\theta_{23}>\pi/4$

Aiming to explore full picture of neutrino oscillation parameters.

Electrical Machinery Room
Access Tunnel
Cavity (Lining)
Height 54m
Width 48m
Compart ment Length 49.5m
Total Length 247.5m (5Compartments)
Hyper-K
Super-K
x25 Larger ν Target
~0.6GeV νμ
295km
Quest for CP Violation in lepton sector
higher intensity ν by upgraded J-PARC
JPARC
© 2010 ZENRIN
Data © 2010 MIRC/JHA
© 2010 Cnes/Spot Image
© 2010 Mapabc.com
©2009 Google
36°24'46.66" N 139°18'01.27" E 標高 214 メートル
高度 188.55 キロメートル

$\nu_\mu \rightarrow \nu_e$ probability

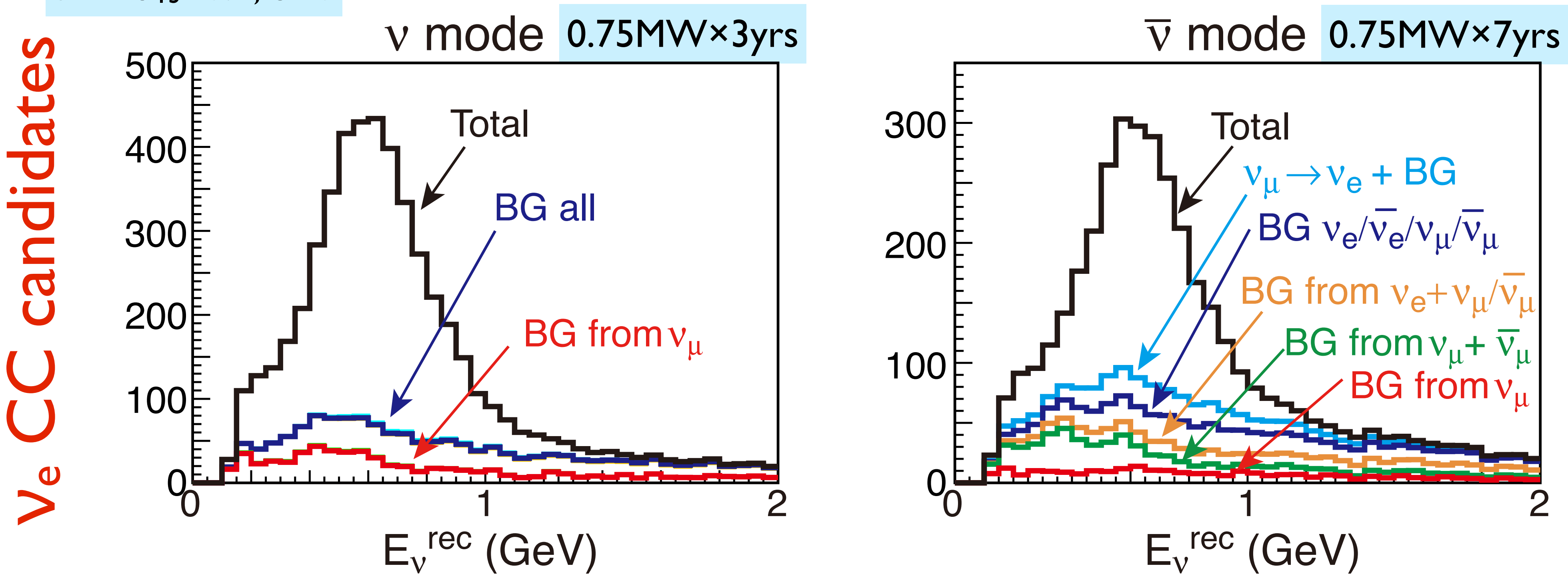
Normal hierarchy



- CPV test by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- sensitive to exotic CPV (non MNS matrix origin)

Selected ν_e CC candidates

$\sin^2 2\theta_{13}=0.1, \delta=0$



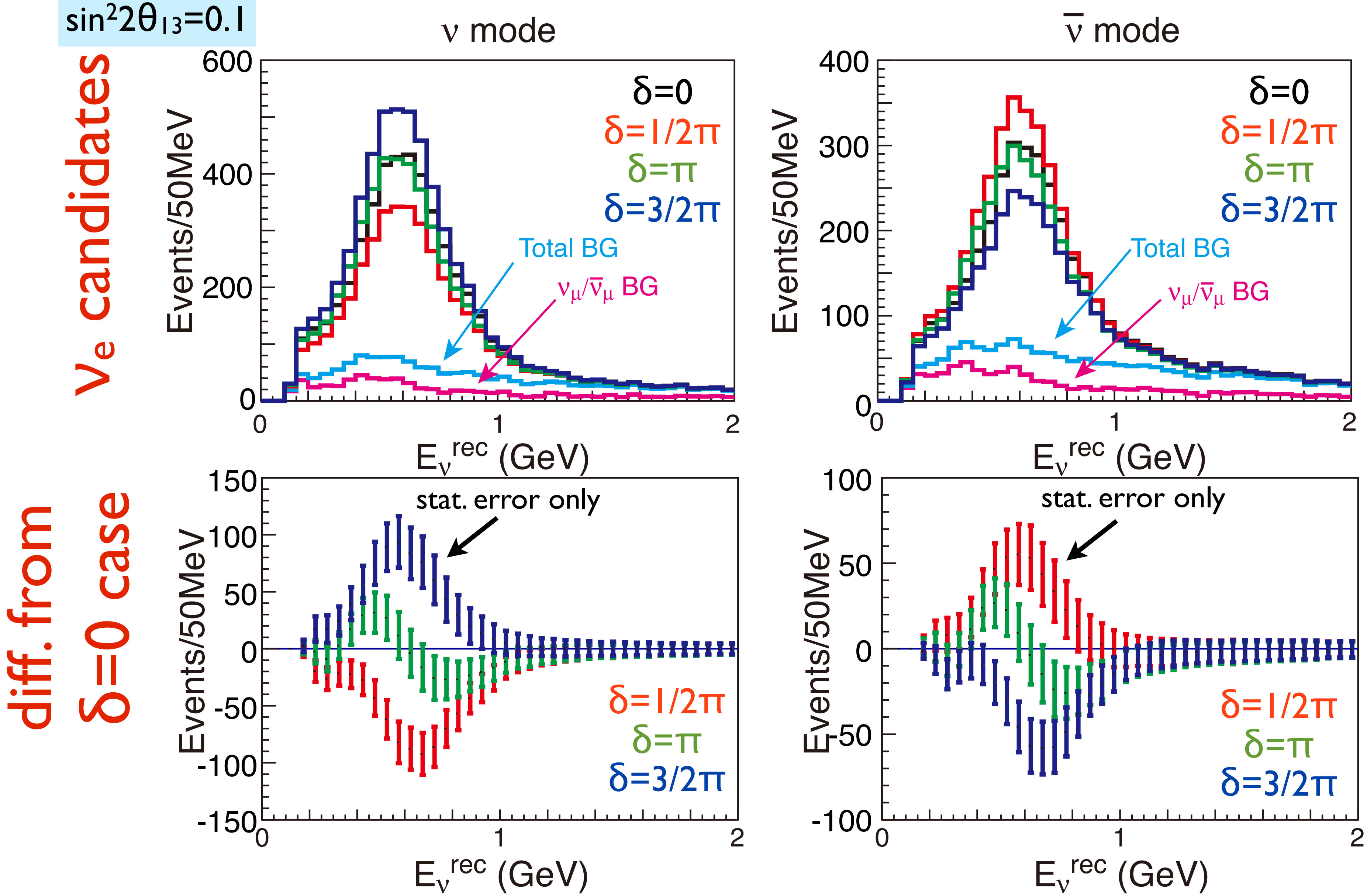
$\nu_\mu \rightarrow \nu_e$CC: 3,606 ev
$\nu_\mu + \bar{\nu}_\mu$CC : 35
$\nu_e + \bar{\nu}_e$CC :880
NC :649

$\nu_\mu \rightarrow \nu_e$CC: 2,339 ev
$\nu_\mu + \bar{\nu}_\mu$CC : 23
$\nu_e + \bar{\nu}_e$CC :878
NC :678

ν_e signal efficiency ⇔ remaining BG
64% ν_μ+antiν_μCC <0.1%, NCπ^0 <5%
($0.1 < E^{rec}_\nu < 1.25$ GeV)

Expected ν_e CC candidates

$\sin^2 2\theta_{13}=0.1$



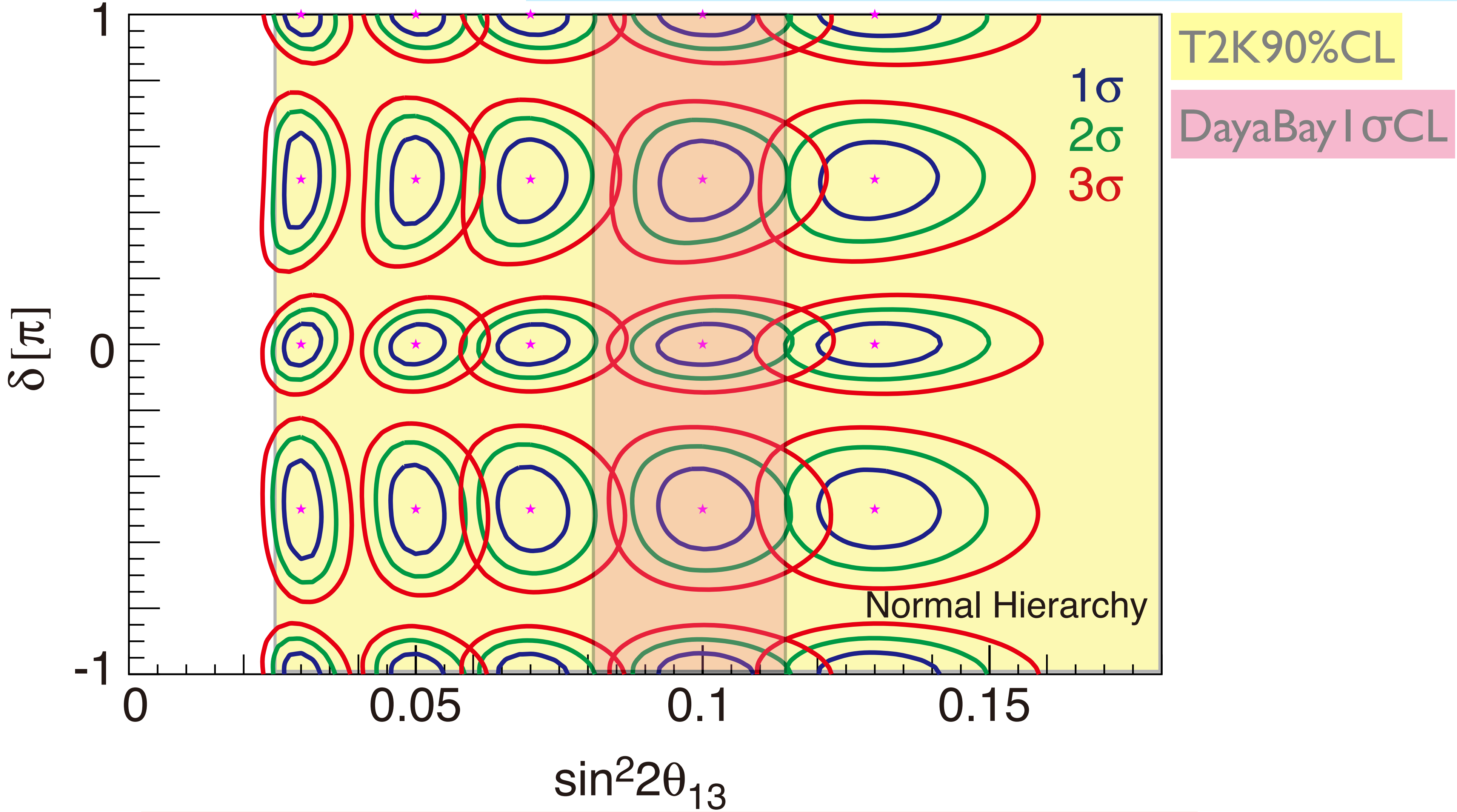
Numbers and shape for CP measurement

Contours

7.5MW ・ years

Normal mass hierarchy (known)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

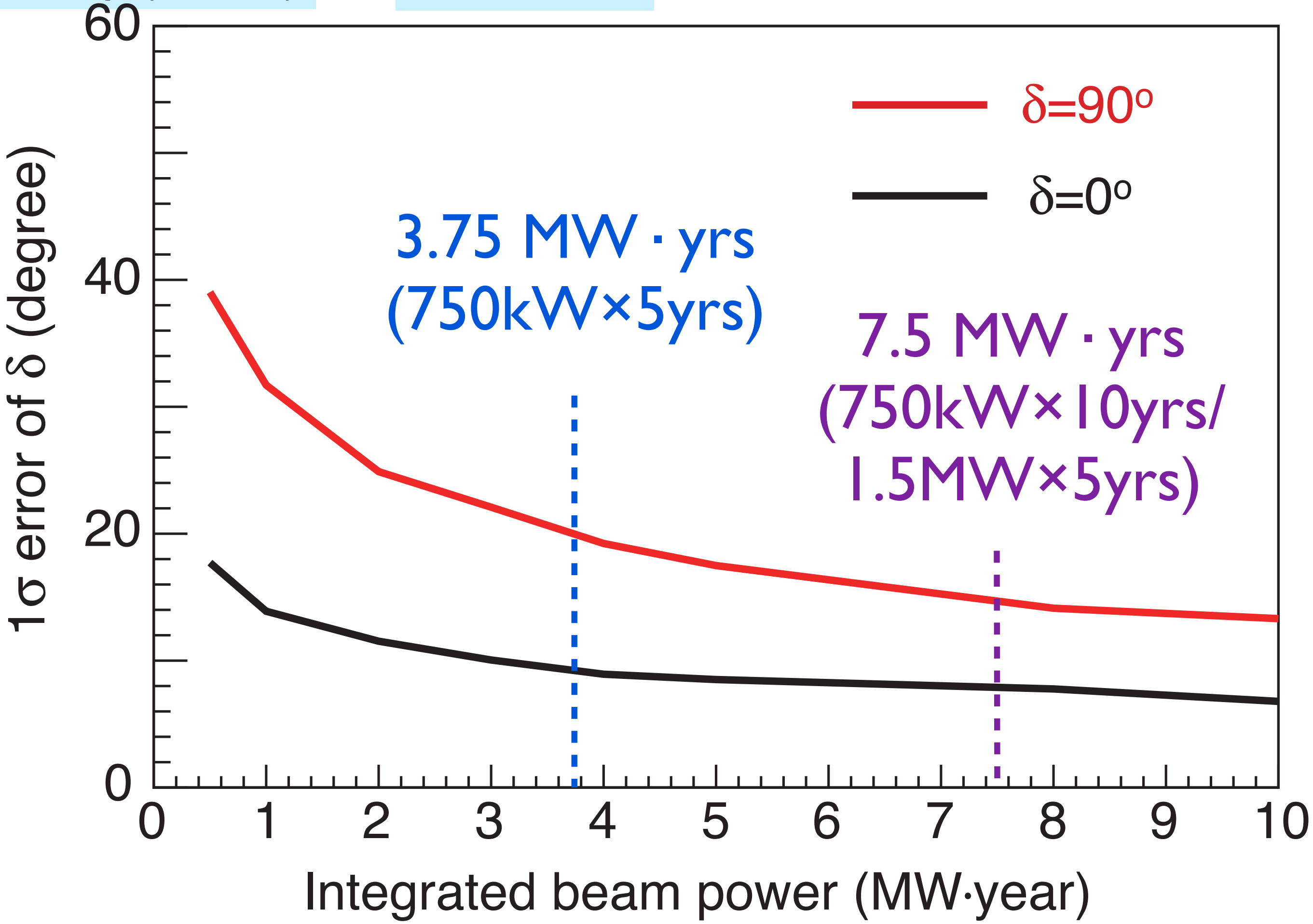


Good sensitivity in whole θ_{13} allowed region!

δ resolution

Normal mass hierarchy (known)

$\sin^2 2\theta_{13}=0.1$



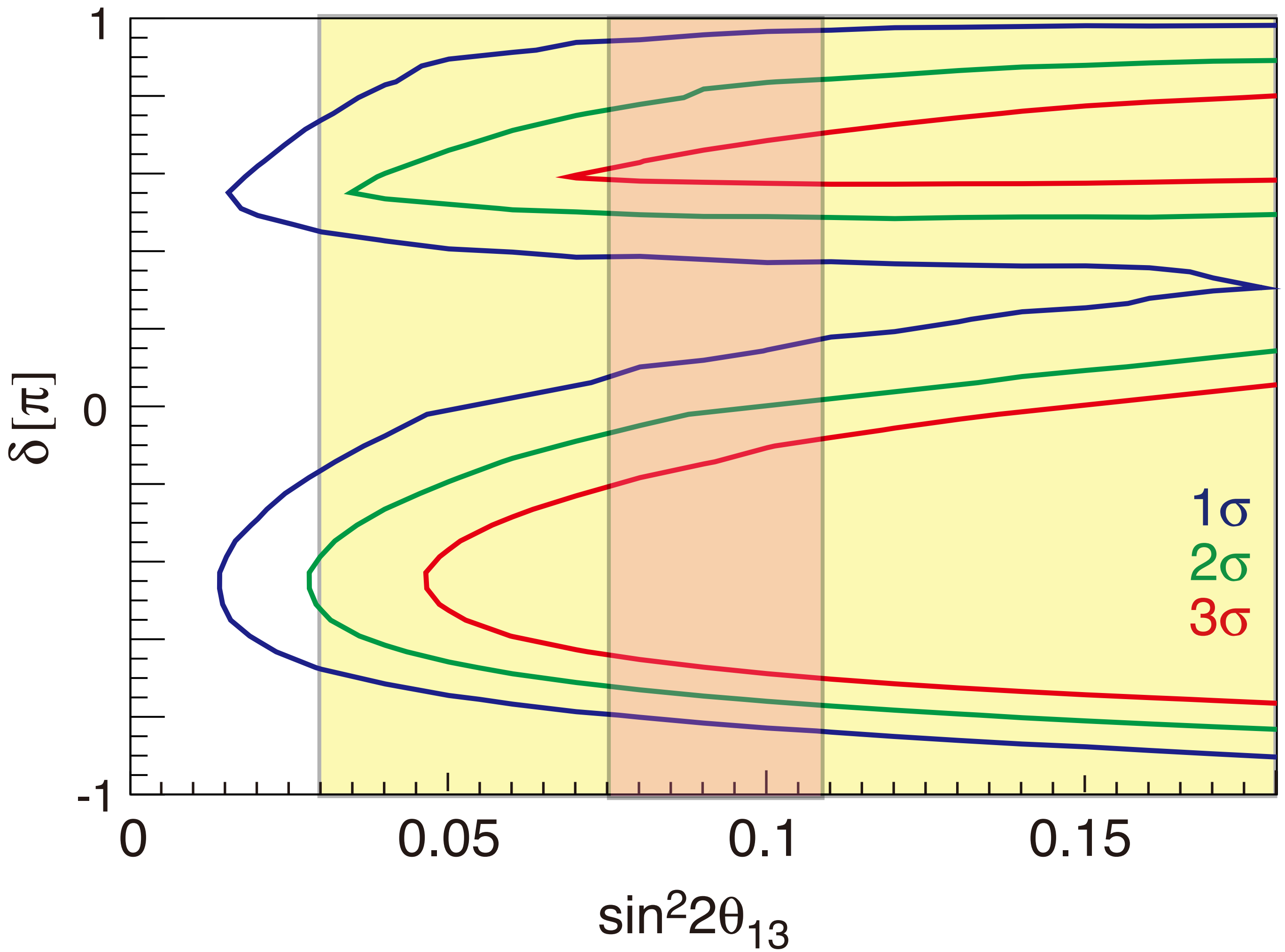
- δ precision < 20° (δ=90°)
  < 10° (δ= 0°)
- modest dependence on θ_{13} value

mass hierarchy determination

discrimination power of mass hierarchy

T2K90%CL

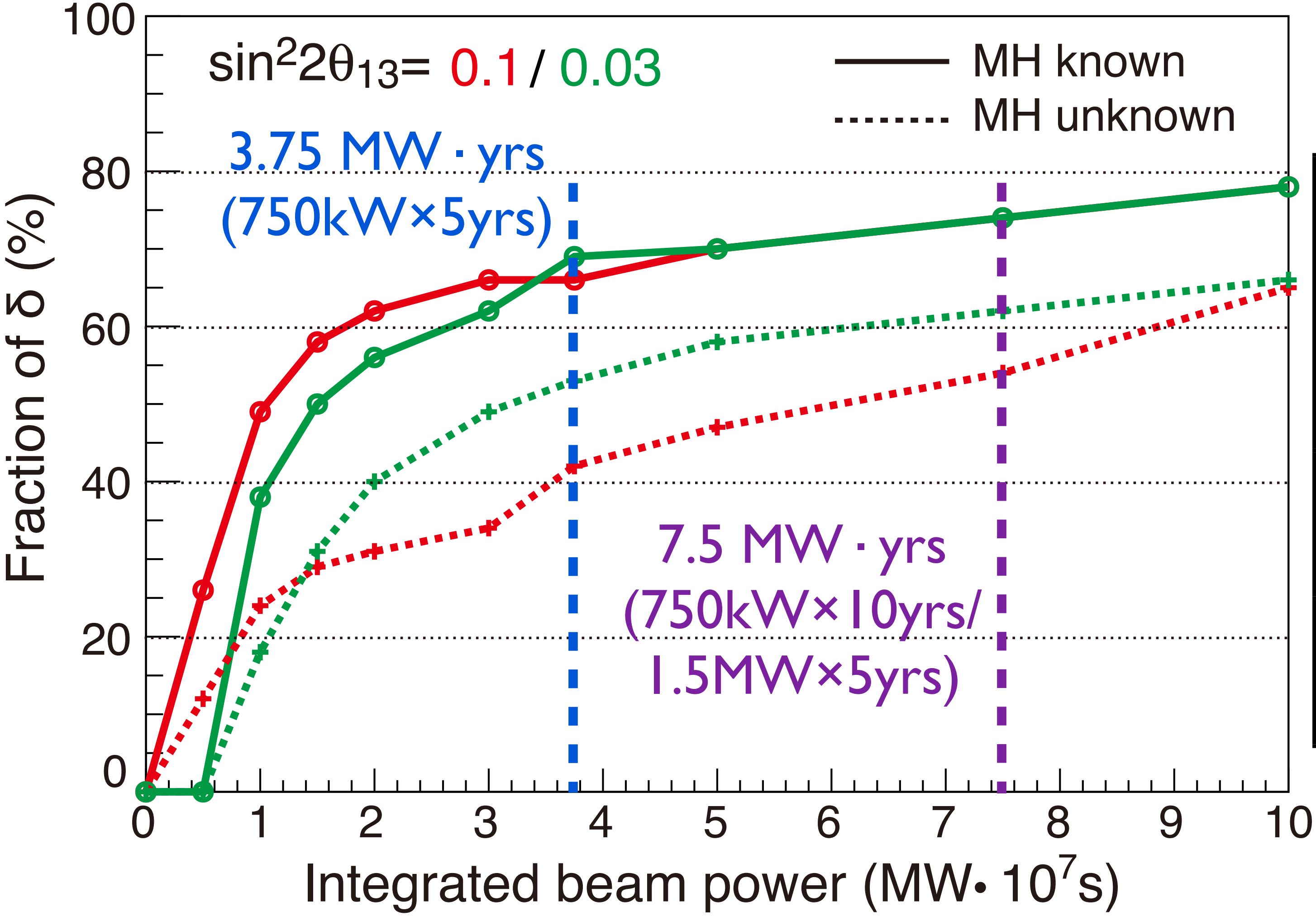
DayaBay1σ



Chance to determine MH by HK-JPARC experiment !

Fraction of δ (%) for CPV discovery

Fraction of δ in % for which expected CPV ($\sin\delta \neq 0$) significance is $>3\sigma$

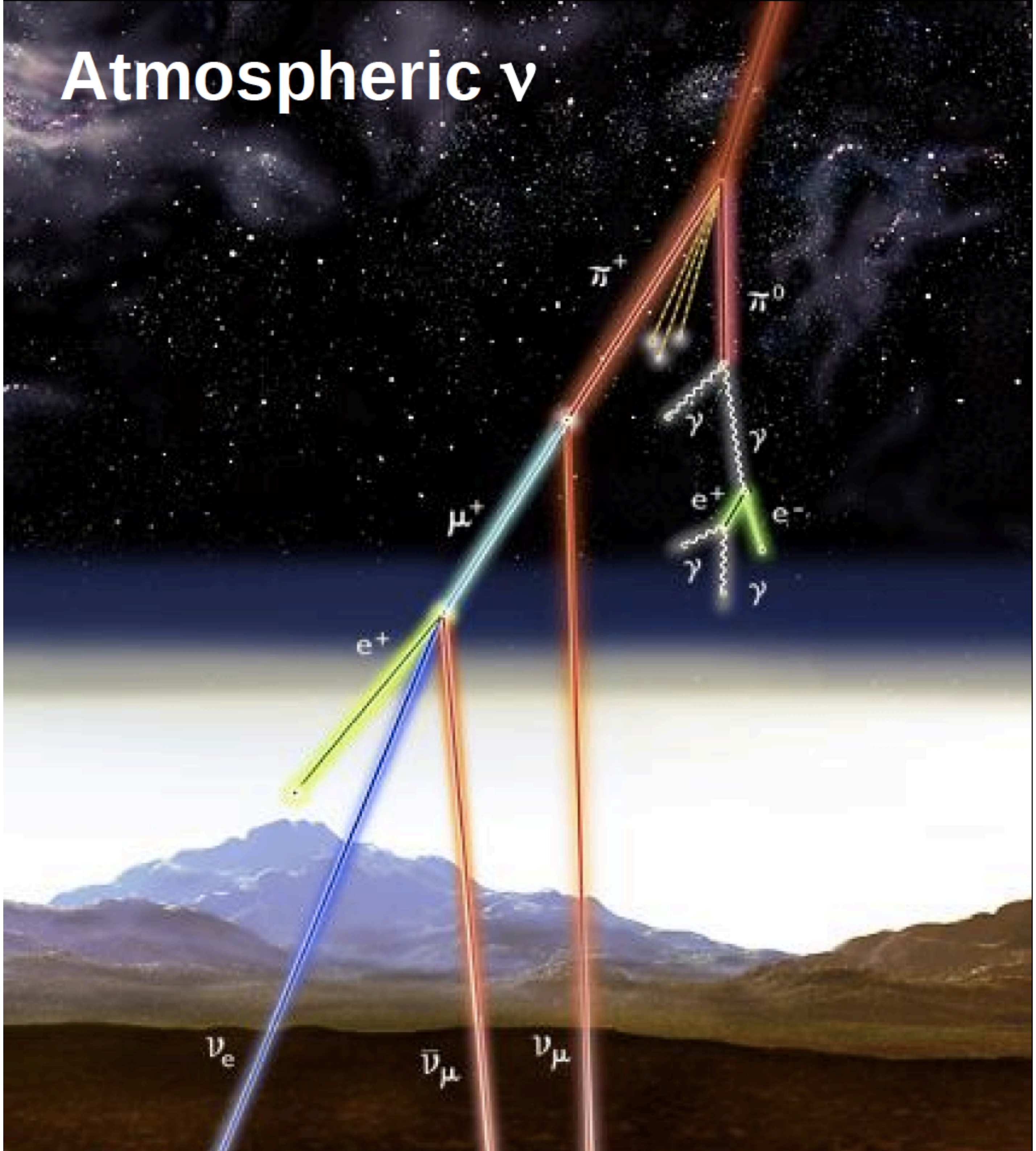


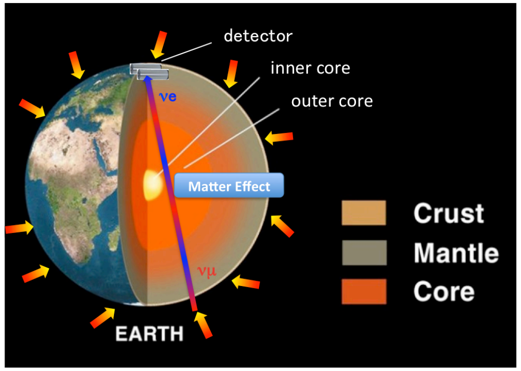
$\sin^2 2\theta_{13}=0.1$

(MW× yrs)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

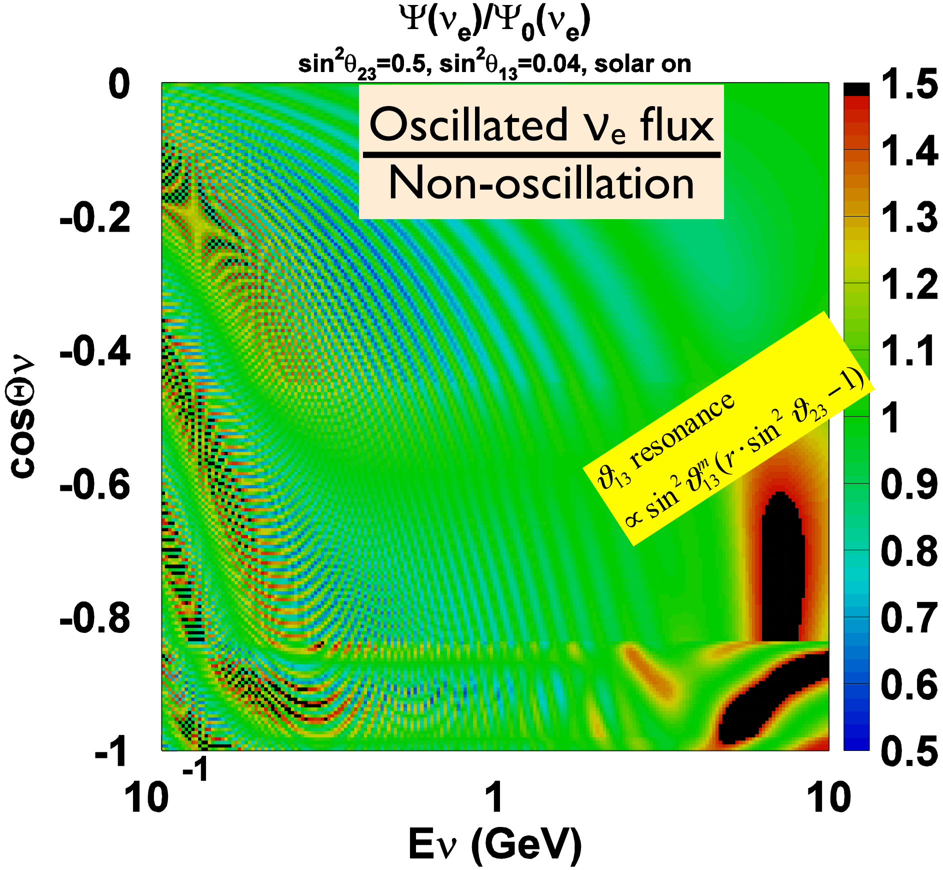
- Effect of unknown mass hierarchy is limited
  - Input from atm ν and other experiments also expected for MH

Atmospheric ν





Atmospheric ν_e flux



NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

r : μ/e flux ratio (~2 at low energy)

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

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

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

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

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

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

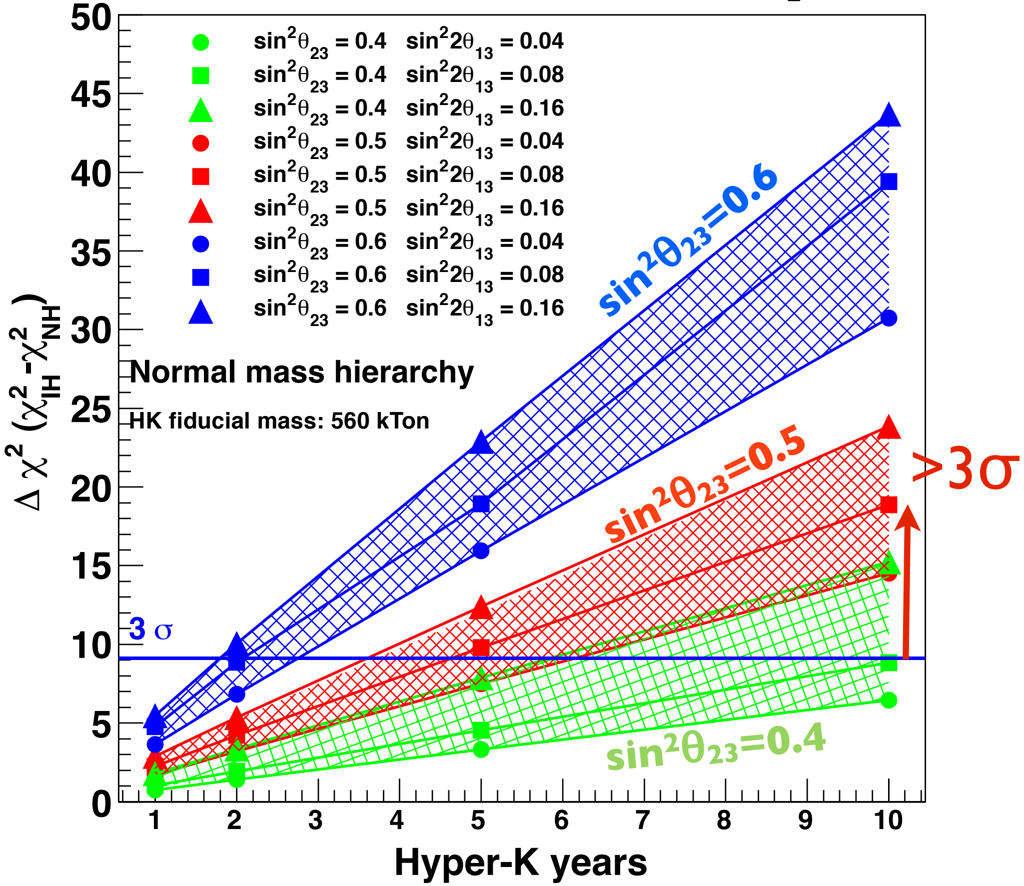
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$ Interference term

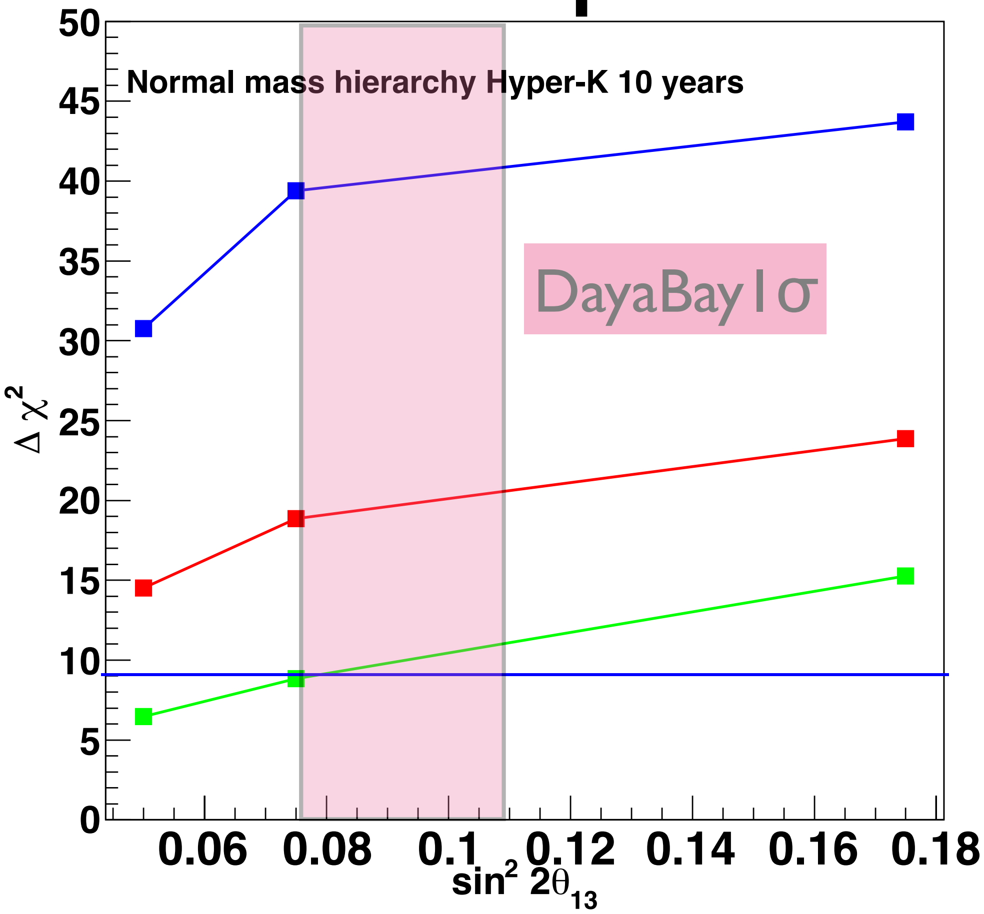
$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1)$$ θ_{13} resonance term

ν_e appearance is expected due to Earth's matter potential
- happens in ν in the case of normal mass hierarchy
- in anti-ν in inverted mass hierarchy

Large θ_{13} value gives us a good chance to discriminate mass hierarchy.

Mass hierarchy discrimination power

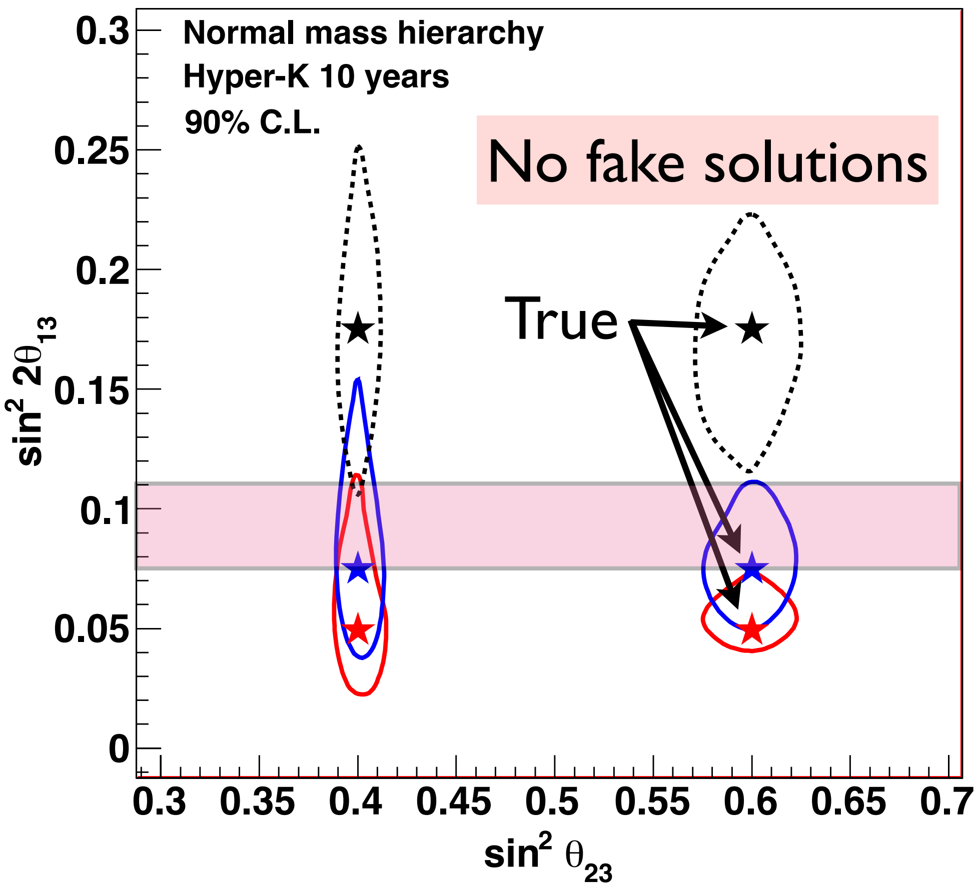




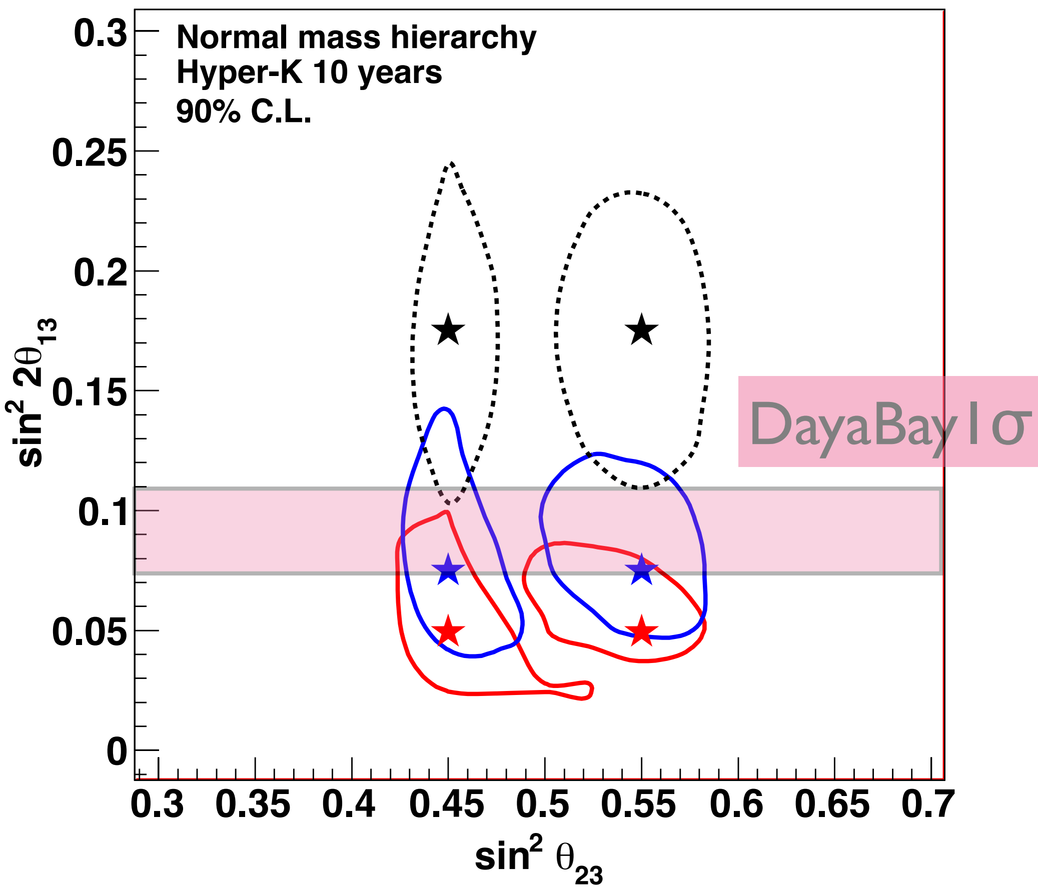
- expect to discriminate normal from inverted hierarchy w/ 3σ significance by ~5years data.
- Large θ_{13} values are encouraging.

θ_{23} octant

$\sin^2 2\theta_{23} = 0.96$
↓
$\sin^2\theta_{23} = 0.4$ or 0.6

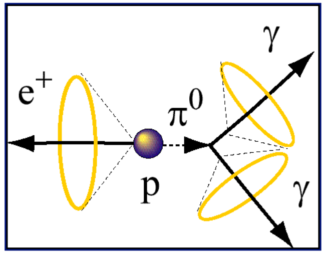


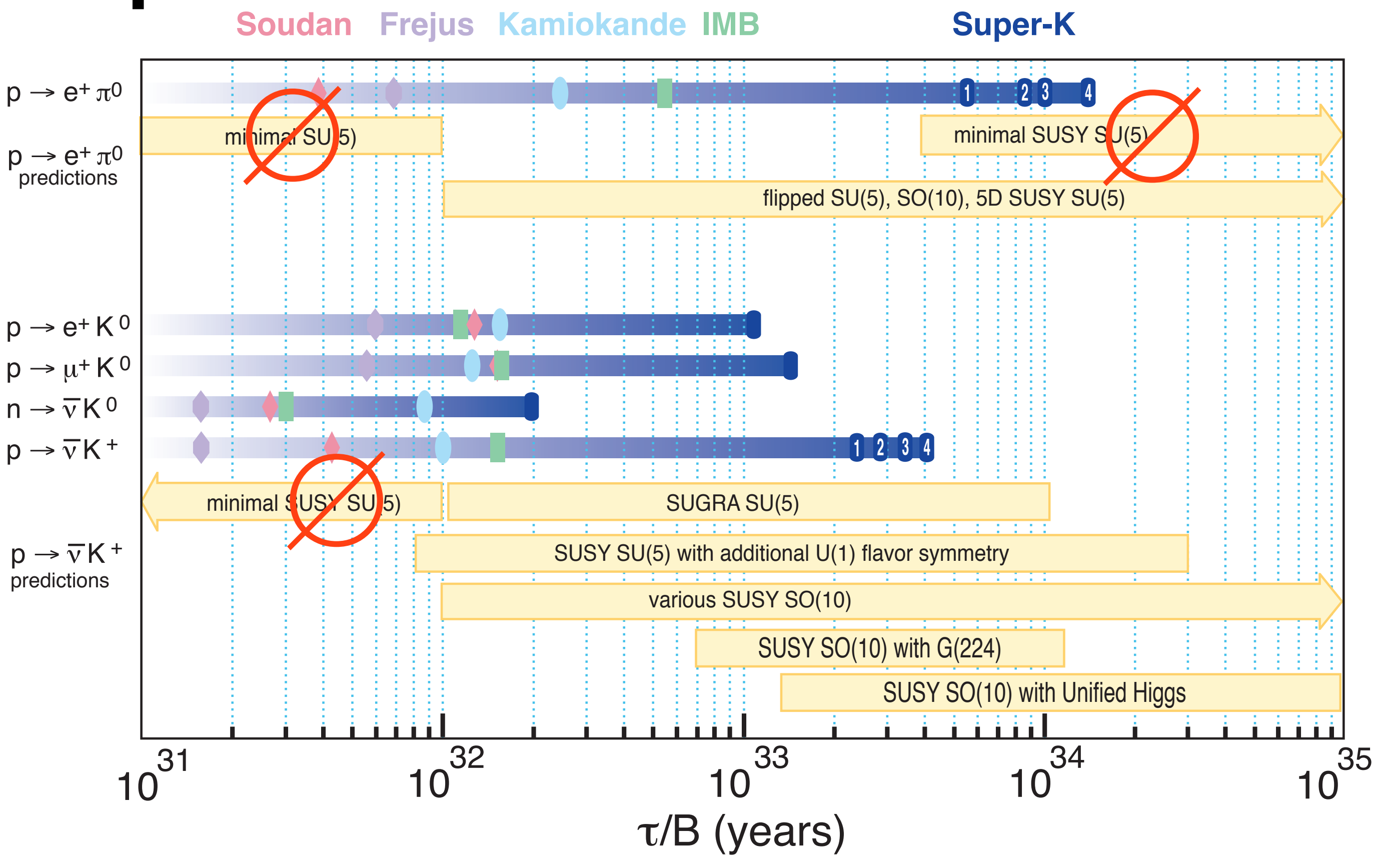
$\sin^2 2\theta_{23} = 0.99$
↓
$\sin^2\theta_{23} = 0.45$ or 0.55

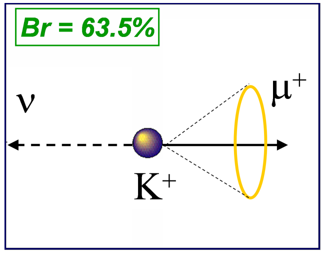


If $\sin^2 2\theta_{23} < 0.99$, θ_{23} octant can be determined.

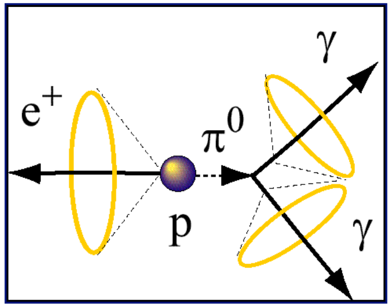
Experimental Limits







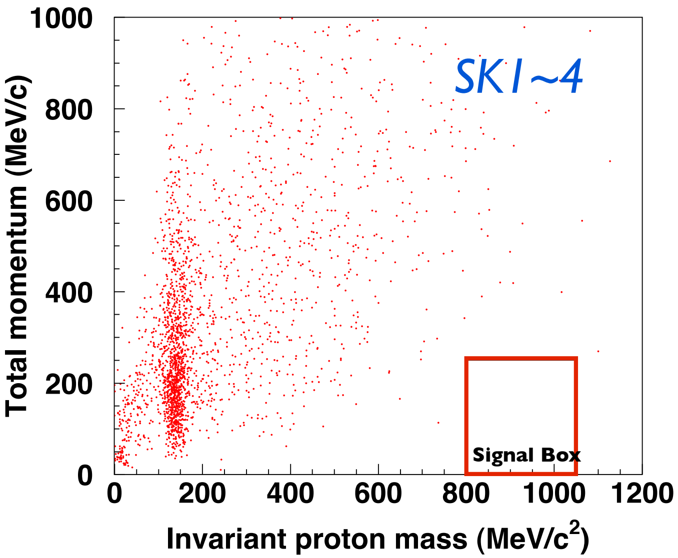
- Super-K gives most stringent limits for many decay modes.
  - $\tau(p \rightarrow e^+\pi^0) > 1.3\times10^{34}$ years (90%C.L. by 220kton・yrs data)
  - $\tau(p \rightarrow \nu K^+) > 4.0\times10^{33}$ years (90%C.L. by 220kton・yrs)
- No signal evidence has been found ➡ giving constraints on models (GUTs)
  - Constraints on SUSY models (ex: R-parity conservation)
  - Exclude minimal *SU(5)* and minimal SUSY *SU(5) models.*

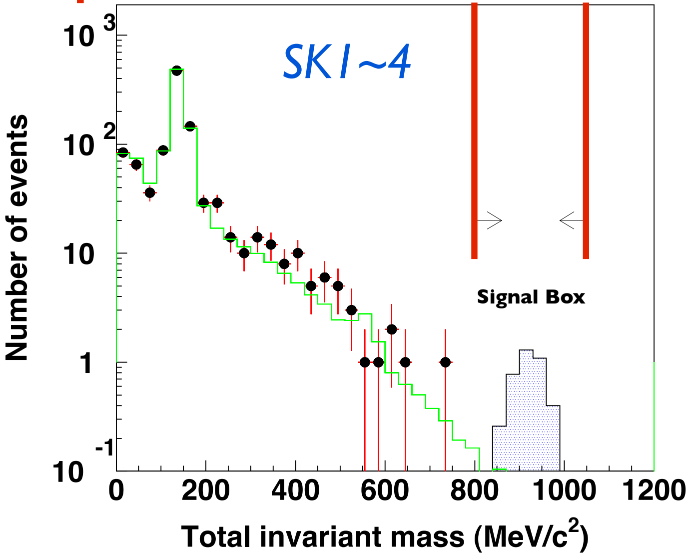


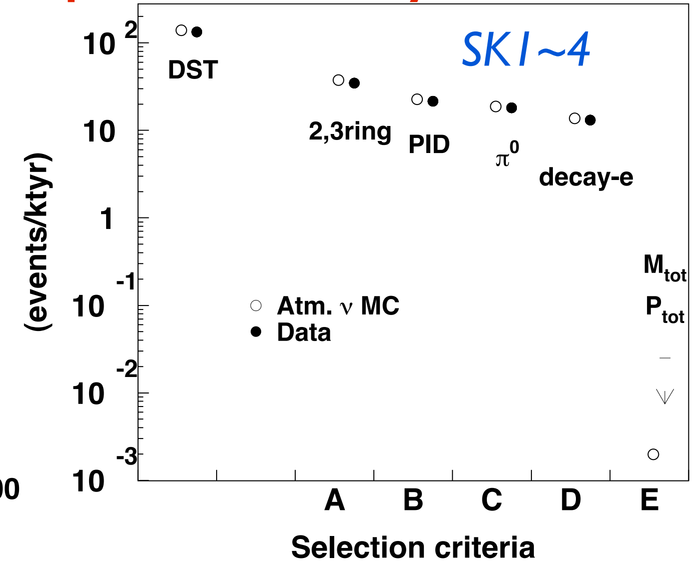
$p \rightarrow e^+ + \pi^0$ searches

Super-K cut
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c^2
  $P_{total} < 250$ MeV/c

Super-K data are well reproduced by BG MC.

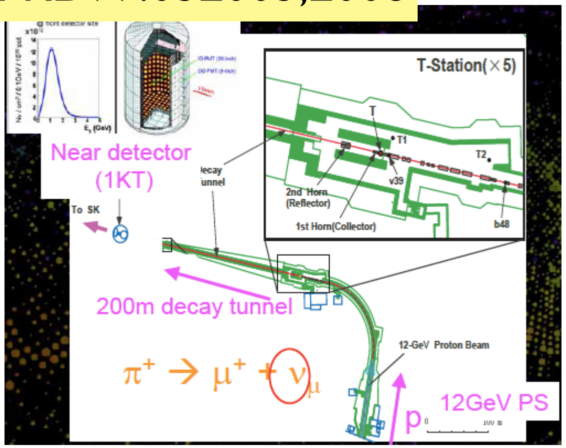






- detection efficiency = 45%
- atmospheric ν BG = 2.1±0.3(stat.)±0.8(syst.) $(\text{Mton}\times\text{years})^{-1}$
- $\tau_{proton}/Br > 1.3 \times 10^{34}$ years @ 90%CL

PRD77:032003,2008

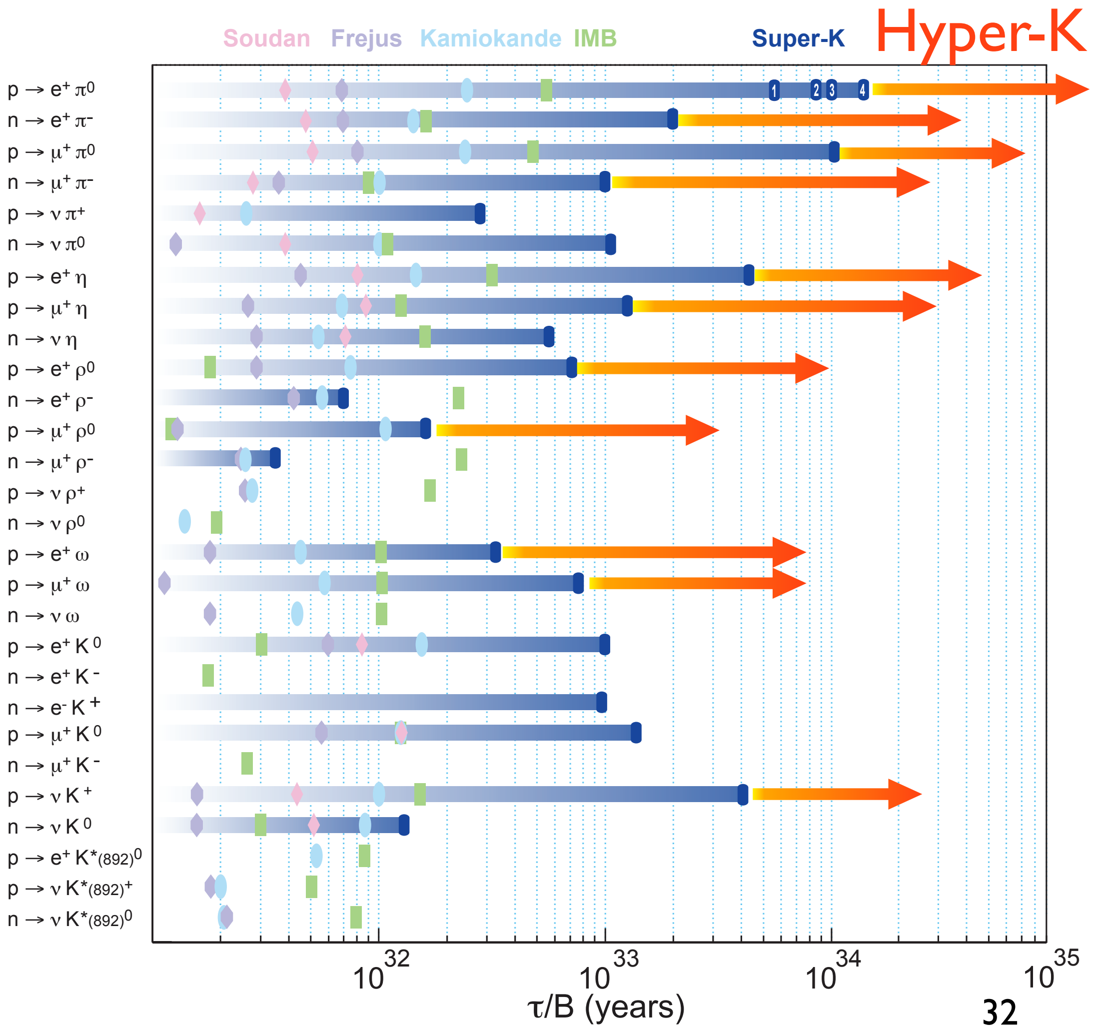


- BG measurement by accelerator ν (K2K)
  - $BG = 1.63^{+0.42}_{-0.33}$(stat.)$^{+0.45}_{-0.51}$(syst.) $(\text{Mt}\times\text{yrs})^{-1}$ (E_ν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

Quality of next generation search is guaranteed.

Search for nucleon decays

- many models predicts branching ratio of $p \to e^+\eta$, $e^+\rho$, $e^+\omega$ are 10~20%
- Flipped SU(5) (Ellis) predicts $Br(p \to e^+\pi^0) \sim Br(p \to \mu^+\pi^0)$
- (B-L) violated mode, e.g. $|\Delta B|=2$.

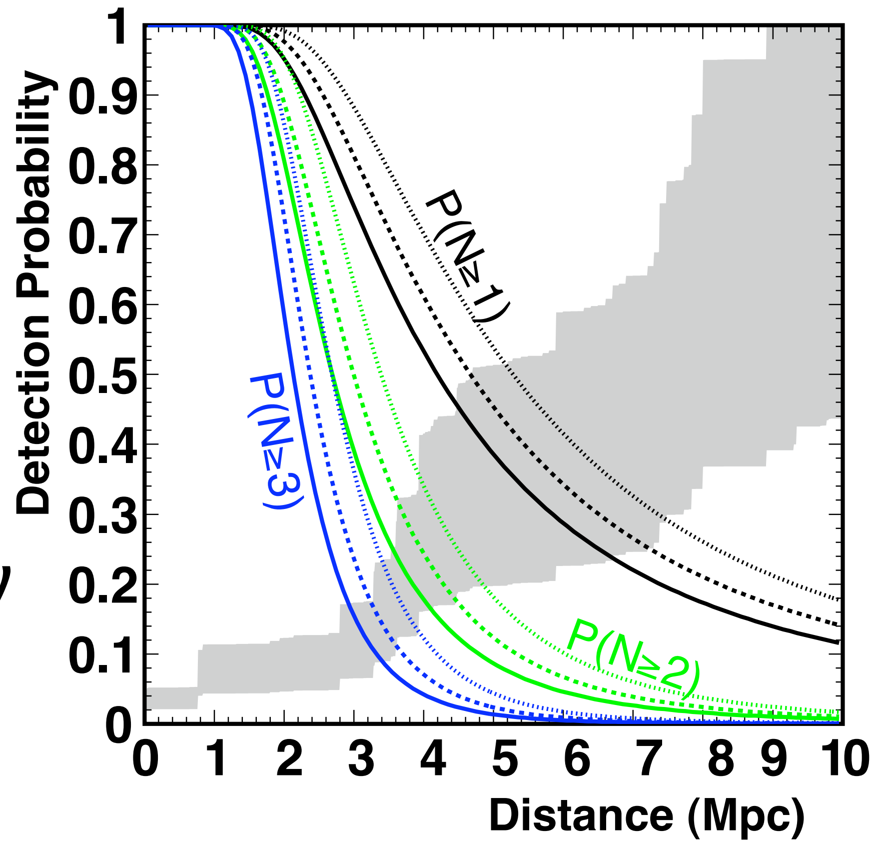


<u>*Hyper-K sensitivities*</u>

- *$p \to e^+ + \pi^0$*
  - τ_{proton}/Br > 1.3×10^{35} years @90%CL
  - 5.6Mton×years (10 Hyper-K years)
- *$p,n \to (e^+,\mu^+)+(\pi,\rho,\omega,\eta)$*
  - $O(10^{34\sim35})$years
- *SUSY favored $p \to \nu + K^+$*
  - 2.5×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Other various decay modes.
  - (B-L) violated modes
  - radiative decays $p \to e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron振動 ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - pp→XX..., nn→XX...

Other topics

- ν burst from Supernova
  - up to distance of ~Mpc
- relic SN ν (with Gd?)
- precise measurement of solar ν
- ν from WIMP, GRB, solar flare..
- Geophysics (ν tomography of Earth)



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

Summary

- Hyper-Kamiokande will cover rich physics topics.
  - discovery reach for leptonic CP violation.
  - good chance to discriminate hierarchy and θ_{23} octant.
  - ~10 times better sensitivity for nucleon decays.
  - various astrophysical objects.

- Effect of large $\sin^2 2\theta_{13}$ (~0.1)
  - JPARC-HK
    - small effect on CPV test if mass hierarchy is known.
    - (δ, sign(Δm^2_{23})) degeneracy may happen.
    - Chance to determine the mass hierarchy.
  - Atmospheric ν
    - Good chance to determine the mass hierarchy and θ_{23} octant