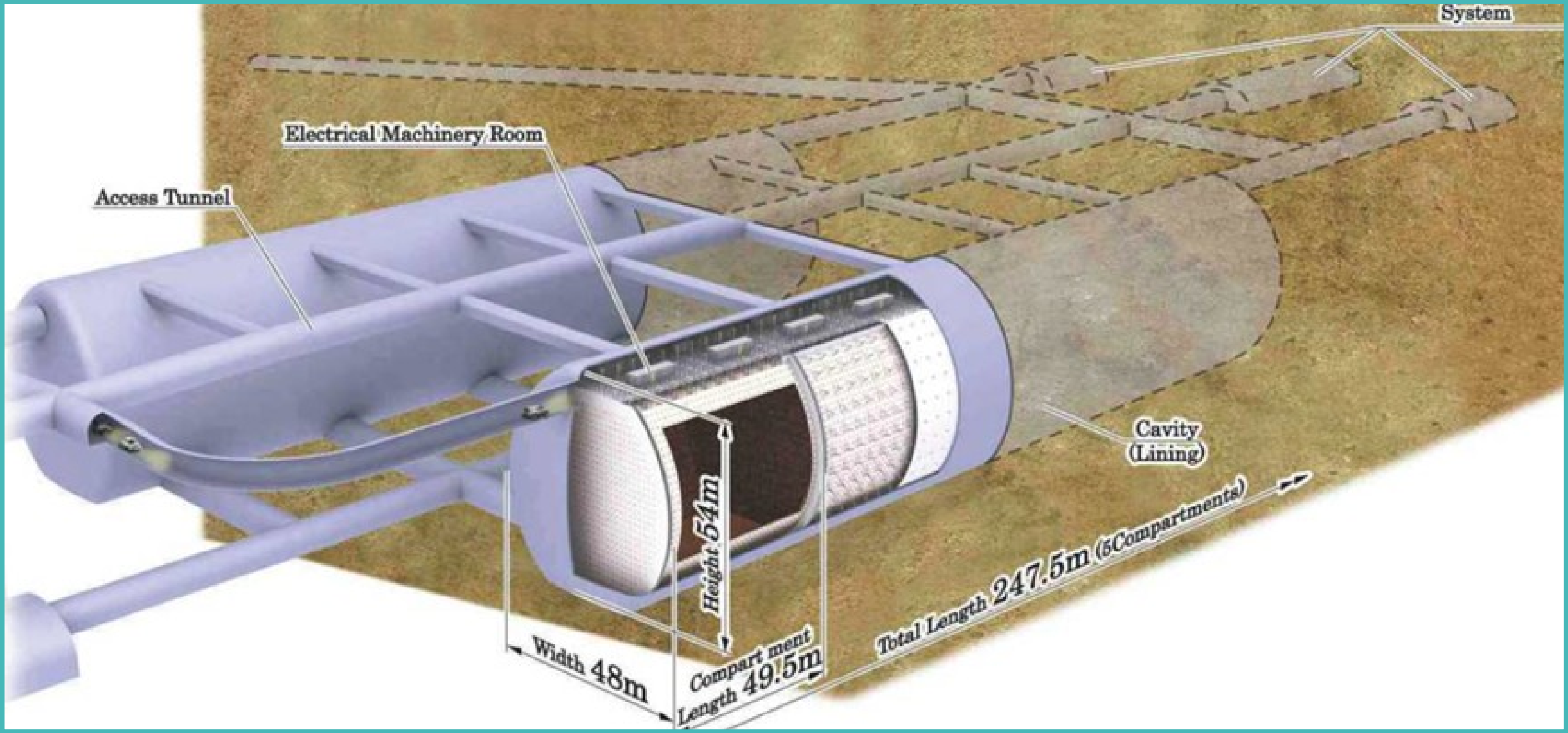


Hyper-Kamiokande R&D

Francesca Di Lodovico (QMUL)
on behalf of the Hyper-Kamiokande working groups

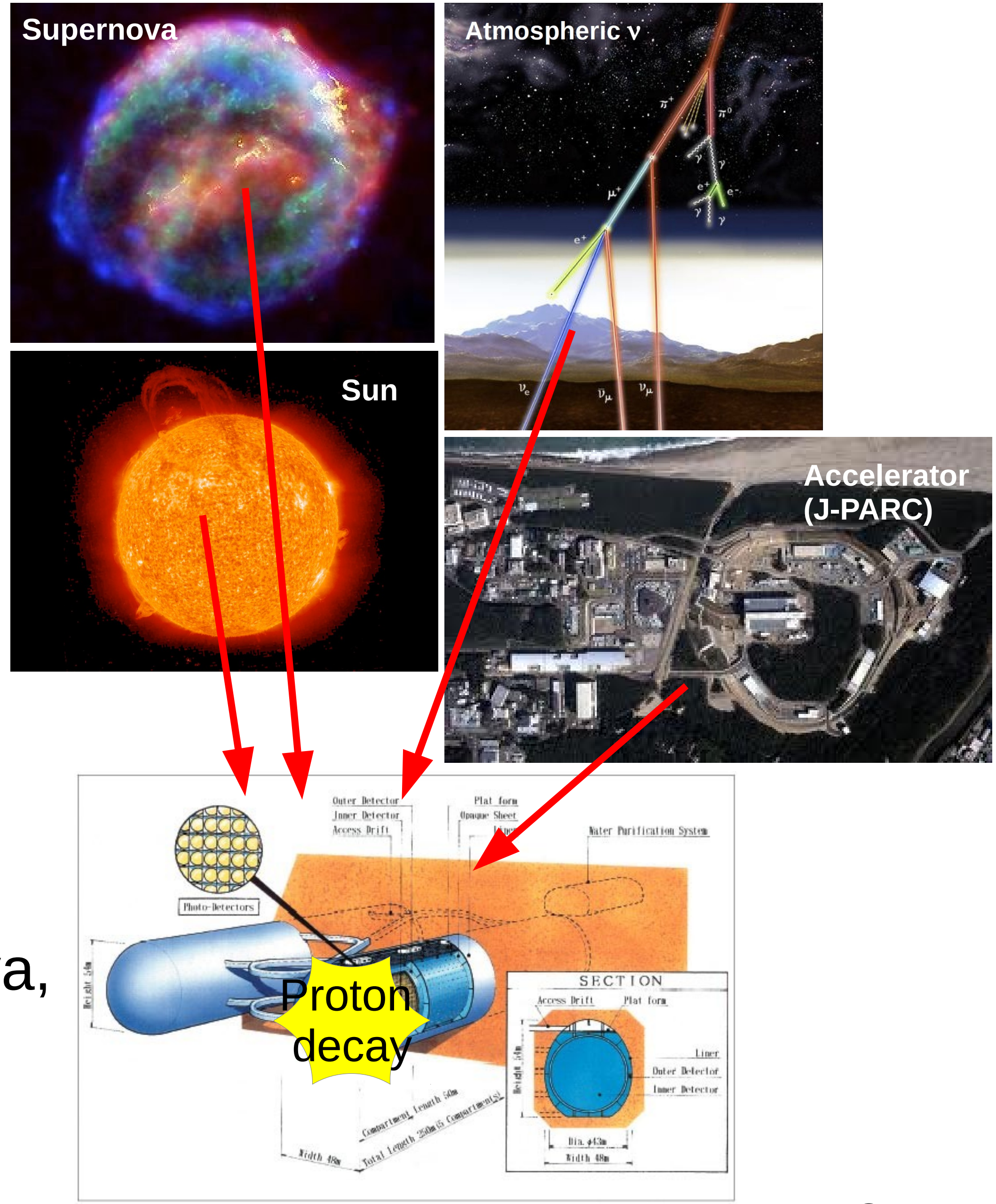
NNN13, Kavli, IPMU
11-13 November 2013

The Hyper-Kamiokande Project

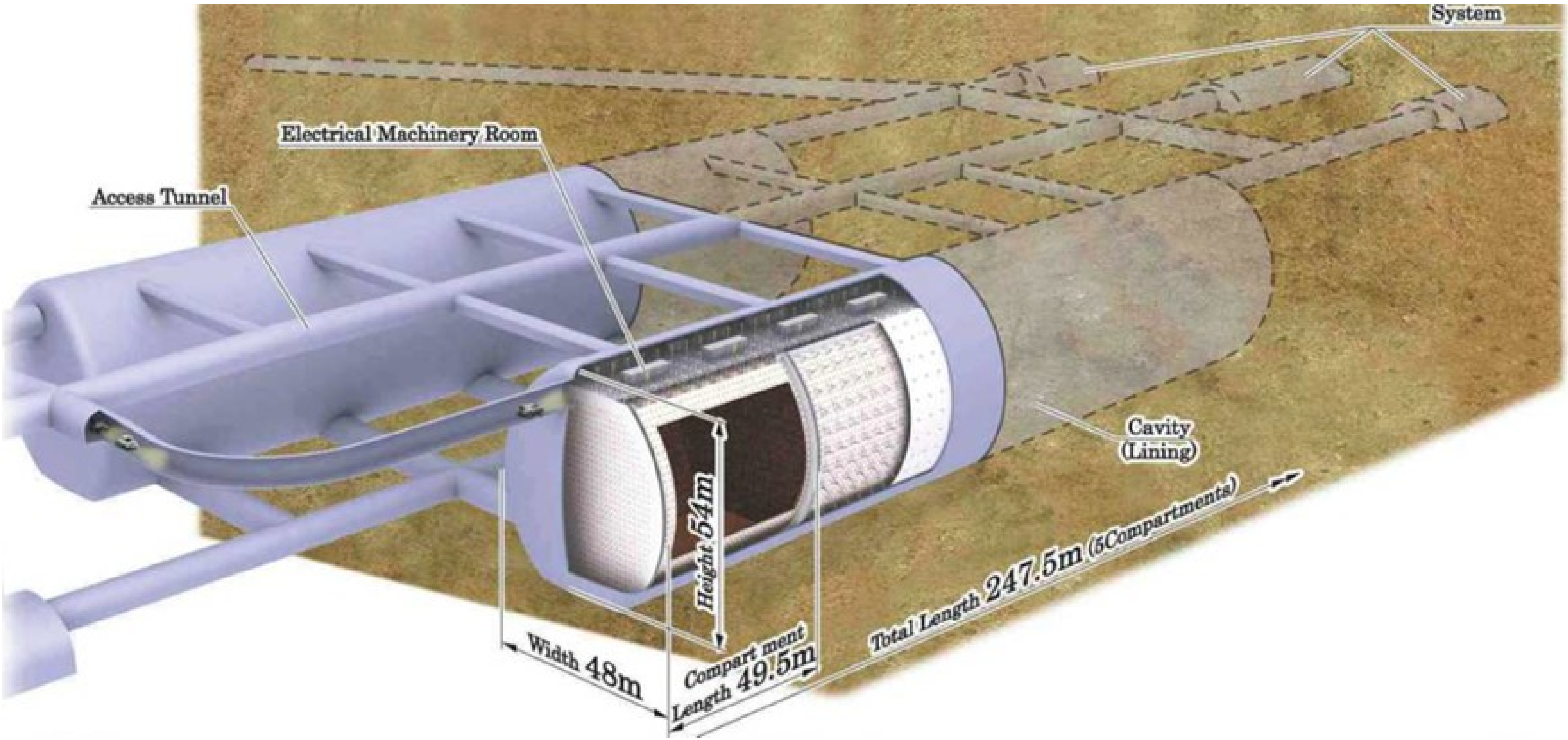
Multi-purpose neutrino experiment.

→ Main goal: CP violation

- Neutrino oscillations, using both:
  - Neutrino beam from J-PARC (expected beam > 1MW)
  - Atmospheric neutrinos
- Search for proton decay
- Solar neutrinos
- Astrophysical neutrinos (supernova, dark matter, solar flare, ...)
- Neutrino geophysics

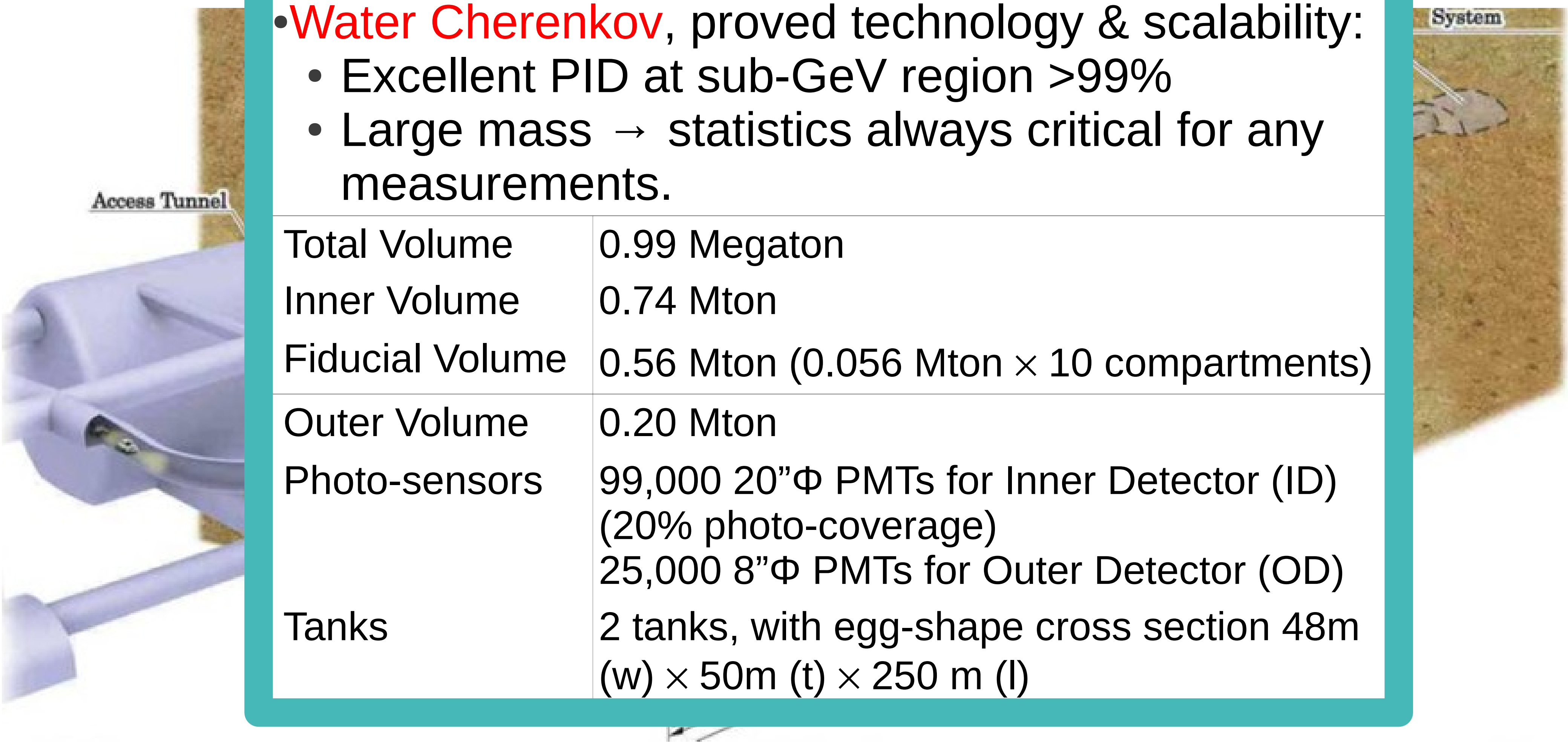


Hyper-Kamiokande Overview



25 x Super-Kamiokande

Hyper-Kamiokande Overview



- Water Cherenkov, proved technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.20 Mton
Photo-sensors	99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage) 25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	2 tanks, with egg-shape cross section 48m (w) × 50m (t) × 250 m (l)

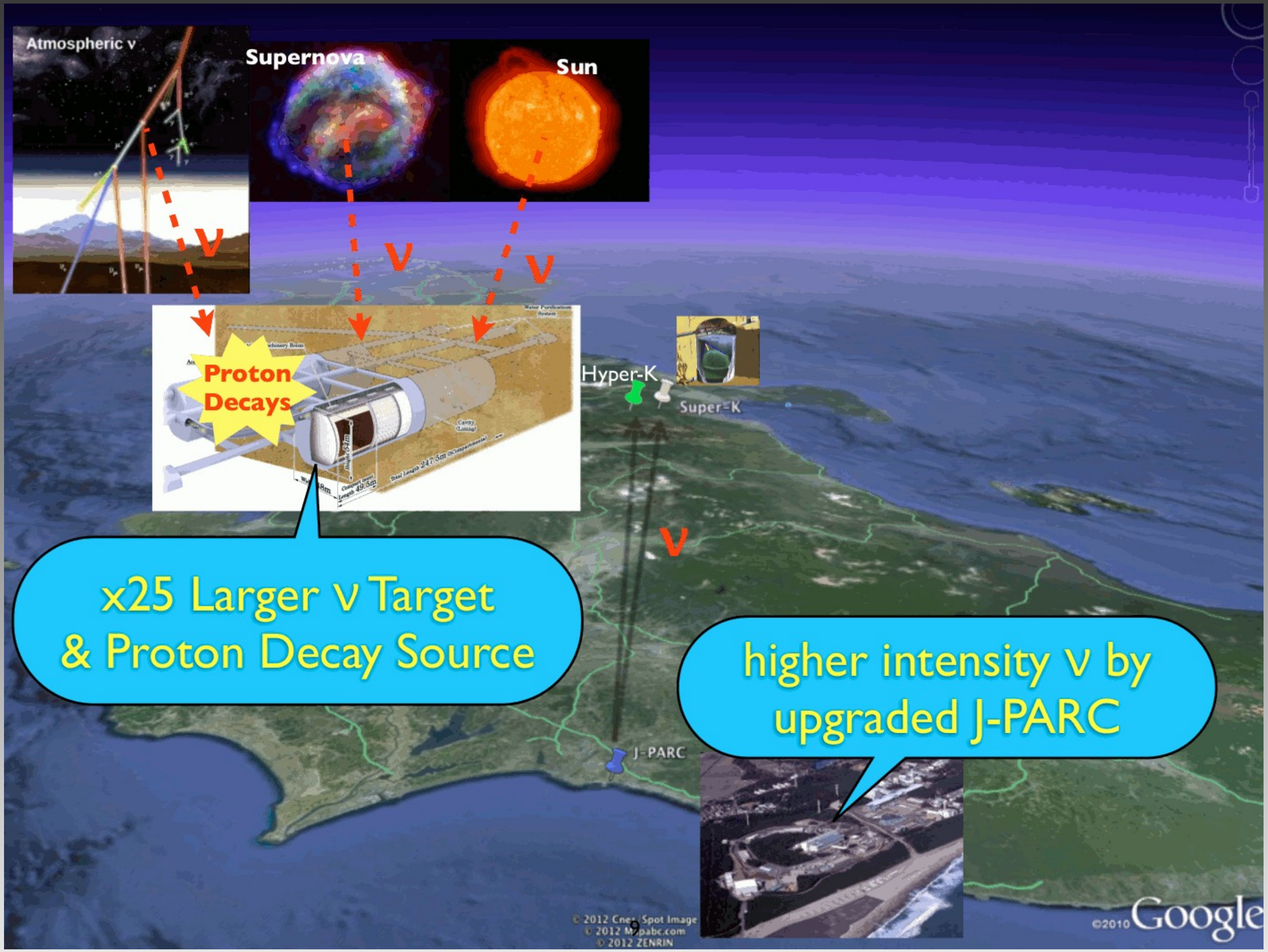
25 x Super-Kamiokande

Outline

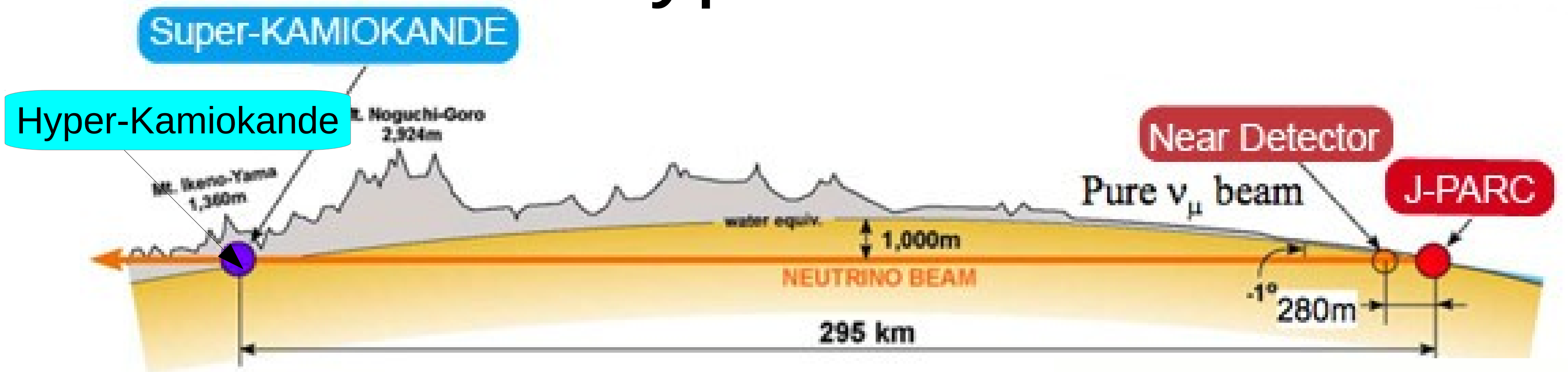
Letter of Intent, Hyper-K WG
arXiv:1109.3262 [hep-ex]
and updates

- Physics in a nutshell
- R&D
  - Software
  - (Beam &) Near Detectors
  - Cavern Construction
  - Detector Design
  - PMTs
  - Others
- Schedule and Summary

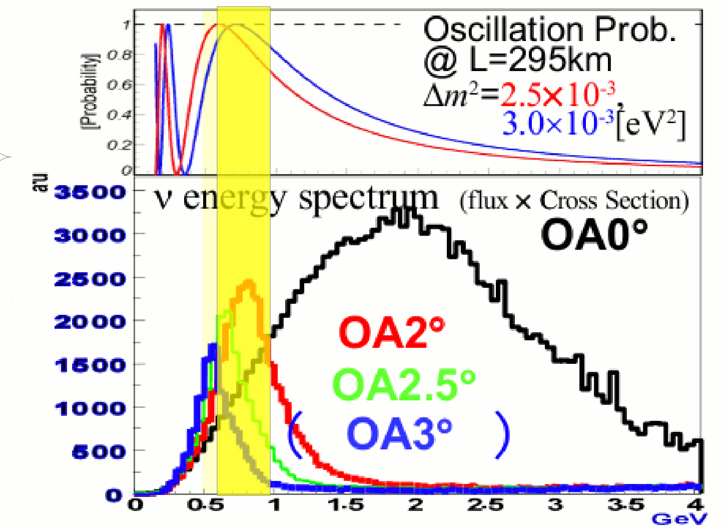
Physics in a Nutshell

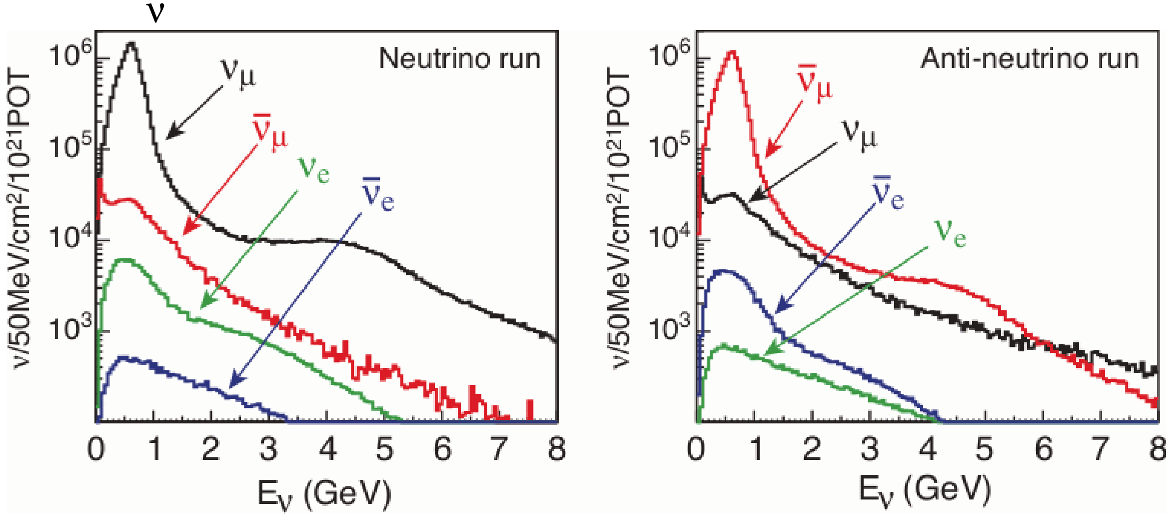


Tokai-2-Hyper-Kamiokande



- Natural extension of the technique being proven by the success of T2K:
  - Use J-PARC beam
  - Hyper-K at 295km as Super-K
  - Off-axis narrow-band beam
  - E_ν~0.6 GeV

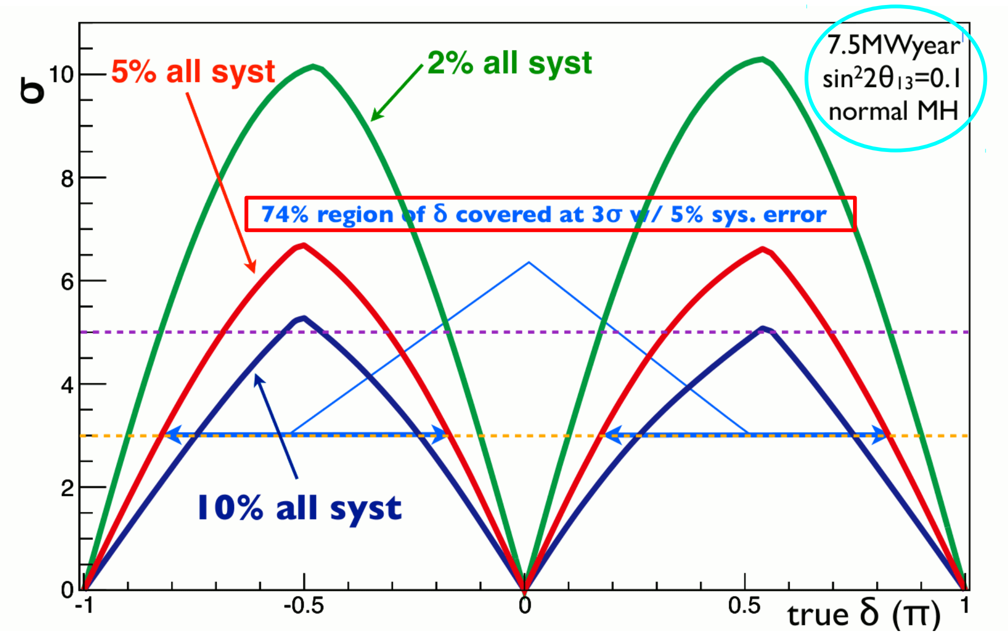




Expected Unoscillated Neutrino Flux at Hyper-K

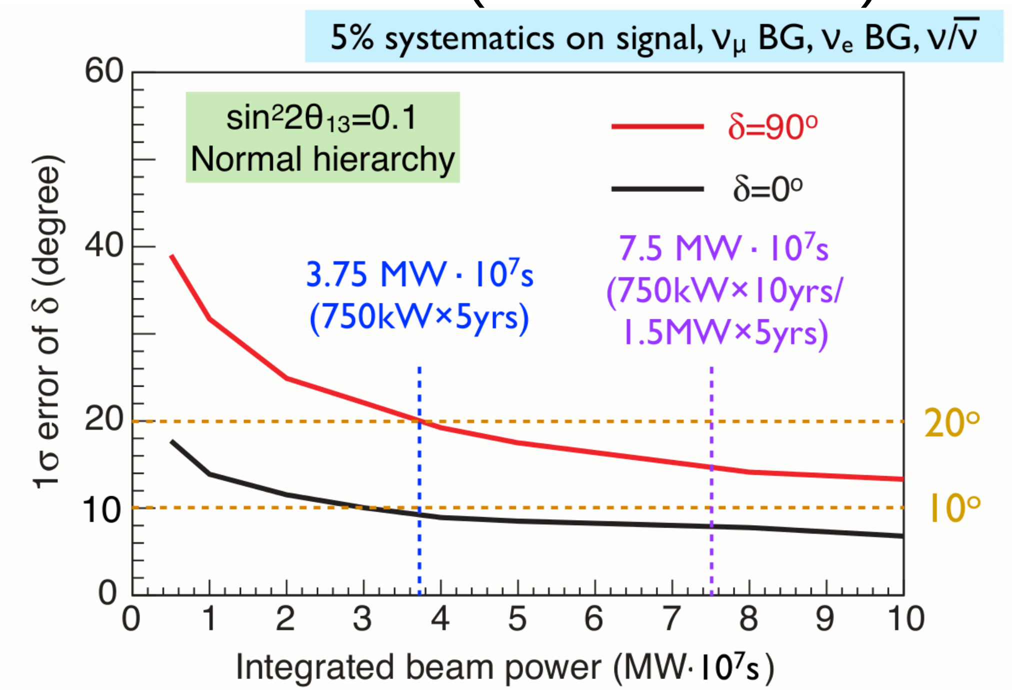
Expected Sensitivity to CP Violation

CPV discovery sensitivity w/ mass hierarchy known.



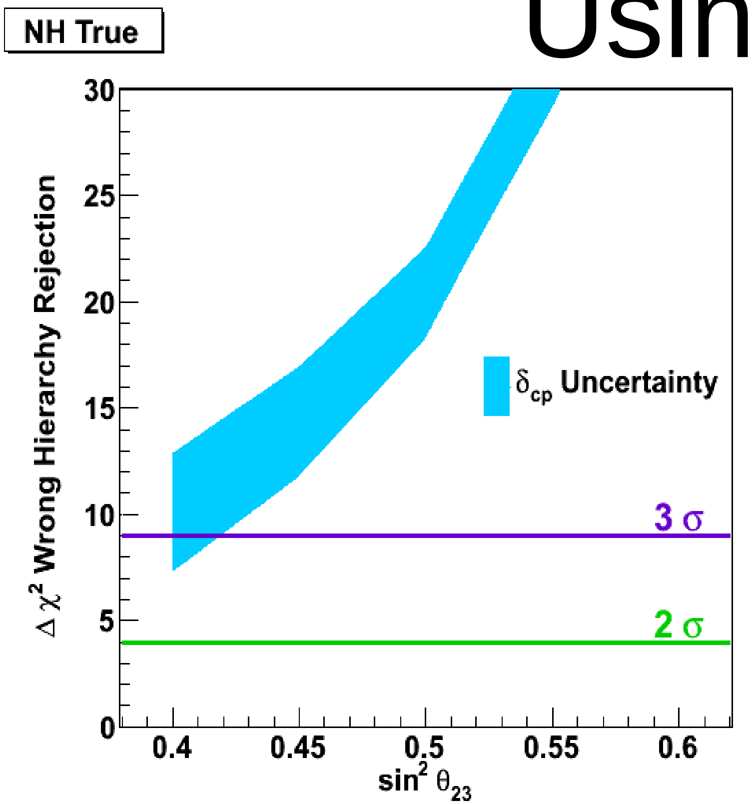
δ precision:

< 10°for δ=0° (< 20°for δ=90°)

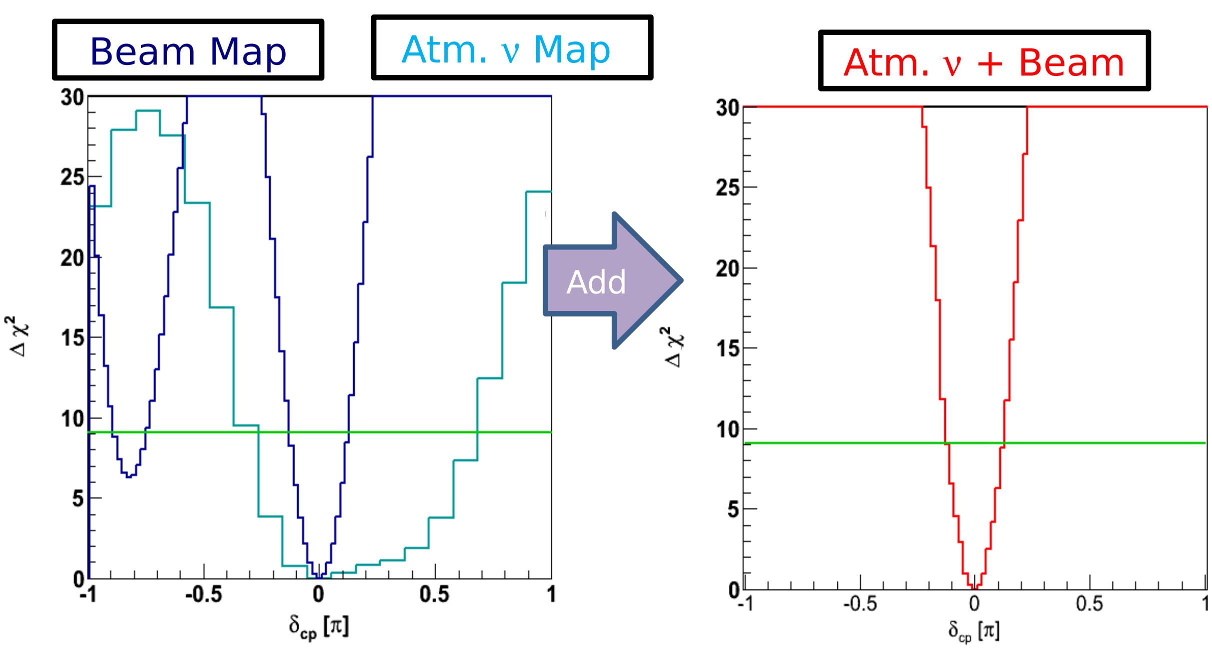


- Assuming 5% nominal systematics and 0.750MW/y (3y ν-beam and 7y $\bar{\nu}$-beam), 74% region of δ can be covered at 3σ.
- It corresponds to a precision of < 10° for δ=0°.

Using Atmospherics



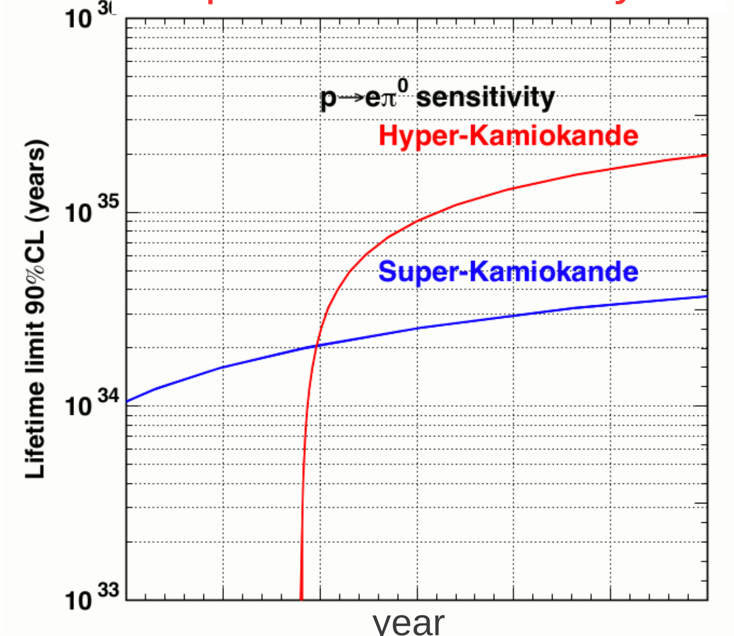
- Sensitivity mainly depends on θ_{23}, δ, and MH.
- 3σ mass hierarchy determination for $\sin^2\theta_{23} >$ 0.42 (0.43) for normal (inverted) hierarchy (10y).
- Caveat: the $\Delta\chi^2$ method to determine σ is used. Ongoing work to use Qian et al., PRD 86, 113011 (2012).

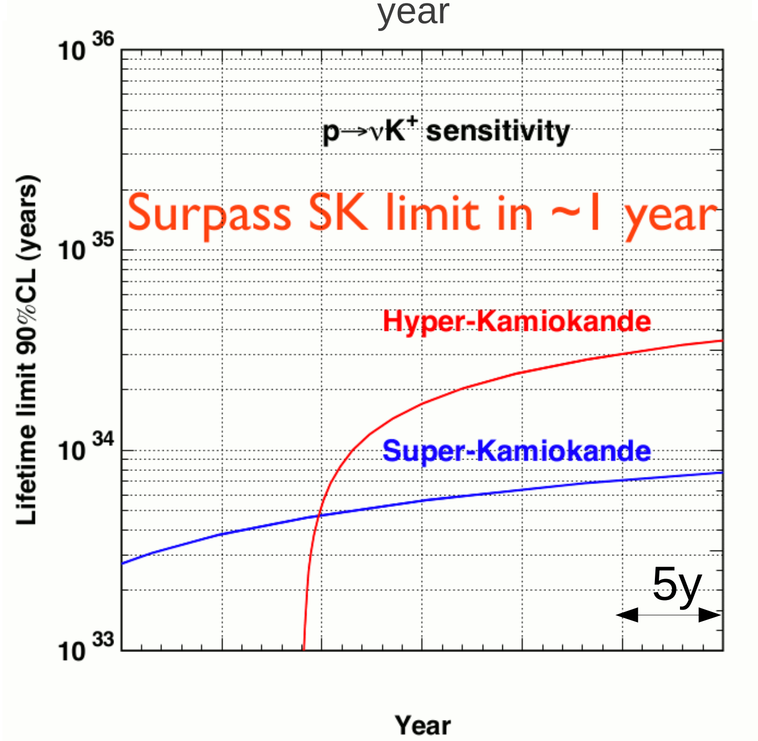


- Hierarchy is unknown, but NH is true.
- True $\delta_{CP} = 0.0$; $\sin^2 2\theta_{13} = 0.10$; $\sin^2 2\theta_{23} = 1.0$
- Degenerate solution exists at 3σ for the beam-only case.

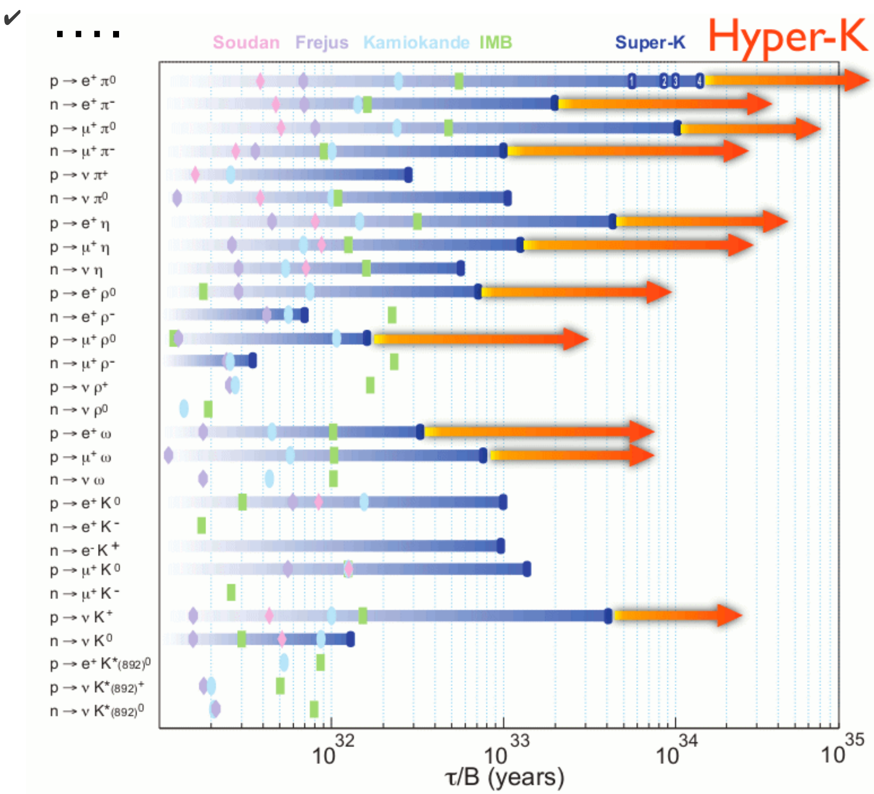
Proton Decay Sensitivities

Surpass SK limit in ~1 year





- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
  - $p \to e\pi^0$: 1.3×10^{35} y at 90%CL
  - $p \to \nu K^+$: 2.5×10^{34} y at 90%CL
  - Many other modes:
    - $(p,n) \to (e,\mu) + (\pi,\rho,\omega,\eta)$
    - K^0 modes
    - $\nu\pi^0$, $\nu\pi^+$
    - ....



“Other” Physics Topics at Hyper-K

- Solar Neutrinos: 200 ν’s / day from Sun → study of day/night asymmetry of the solar neutrinos flux.

- Astrophysical neutrinos:
  - ~200k ν’s from Supernova at Galactic center (10kpc)
    → time variation & energy can be measured with high statistics
  - For supernova explosions outside our galaxy, we expect ~30-50 events from M31 (Andromeda Galaxy)
  - We expect ~310 SRN in the energy range ~30-50 MeV for 10y.

- Solar flare neutrinos can be detected by Hyper-K and will be a strong test of neutrino emission models.

- Indirect dark matter search.

- Geophysical neutrinos → measurement of Earth's density.

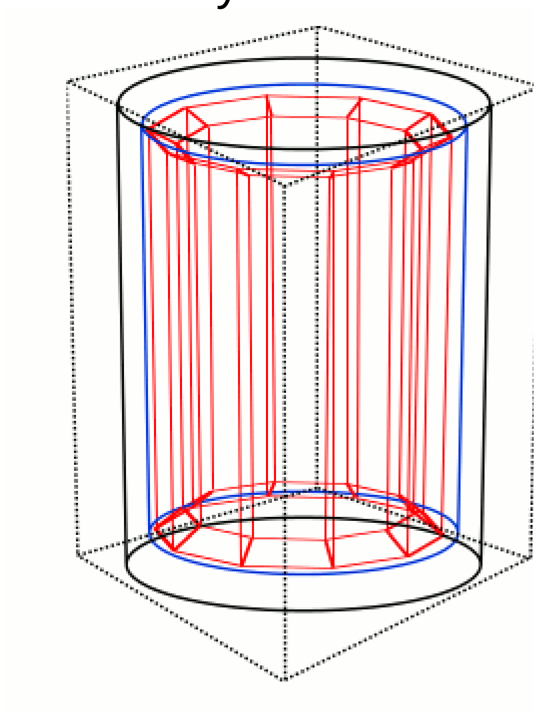
R&D

- Software
- (Beam &) Near Detectors
- Cavern Construction
- Detector Design
- PMTs
- Others

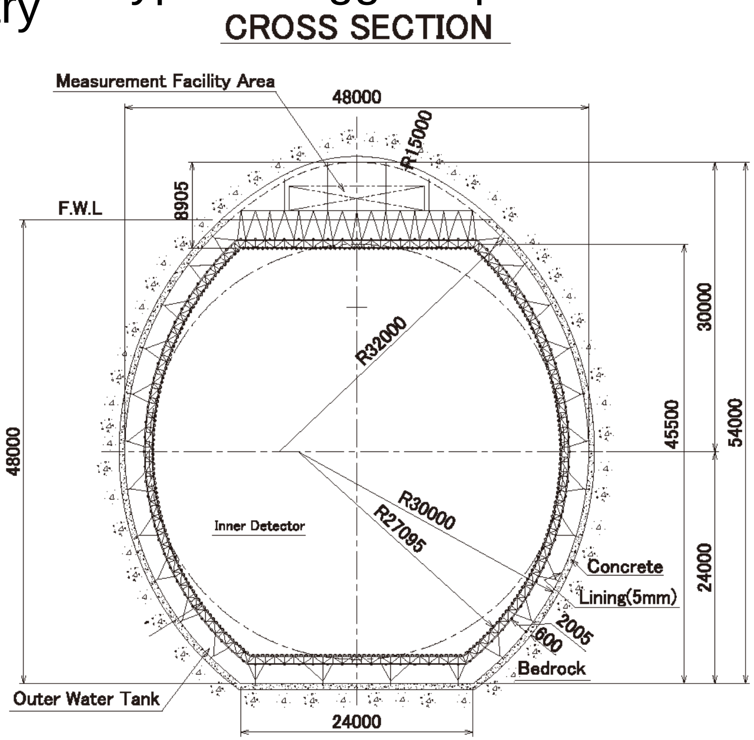
WCSim

- WCSim is a flexibile Geant4-based simulation of a water-Cherenkov detector with top and side photo-multiplier tubes.
- Developed by Duke University: https://wiki.bnl.gov/dusel/index.php/WCSim
- Implemented Hyper-Kamiokande "egg-shape" geometry (WCSim default: cylinder shape).

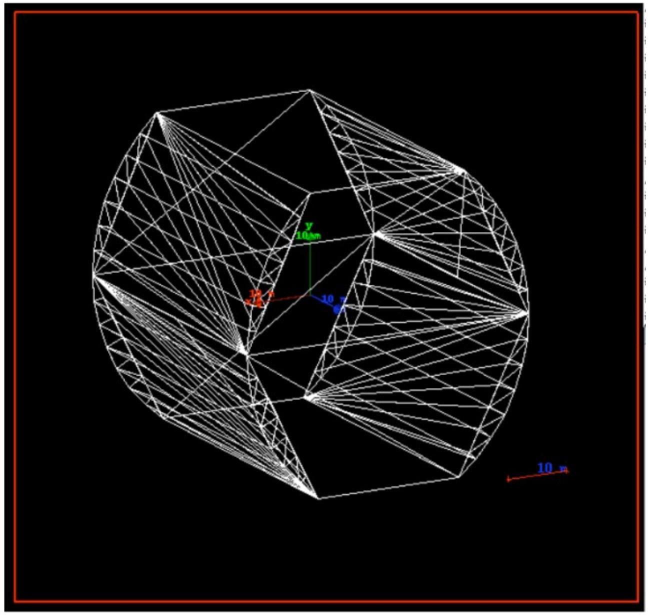
Nominal Cylindrical Geometry



Hyper-K "egg-shape"



Implementation of Hyper-K "egg-shape"



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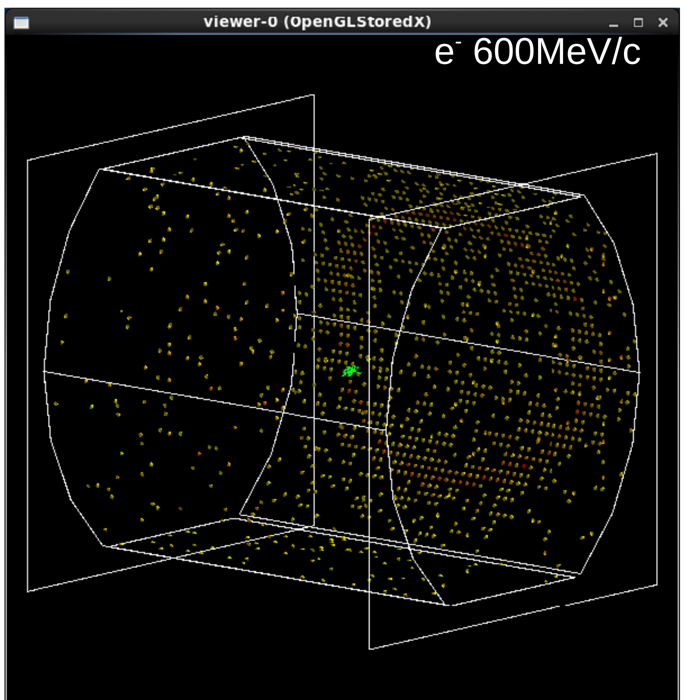
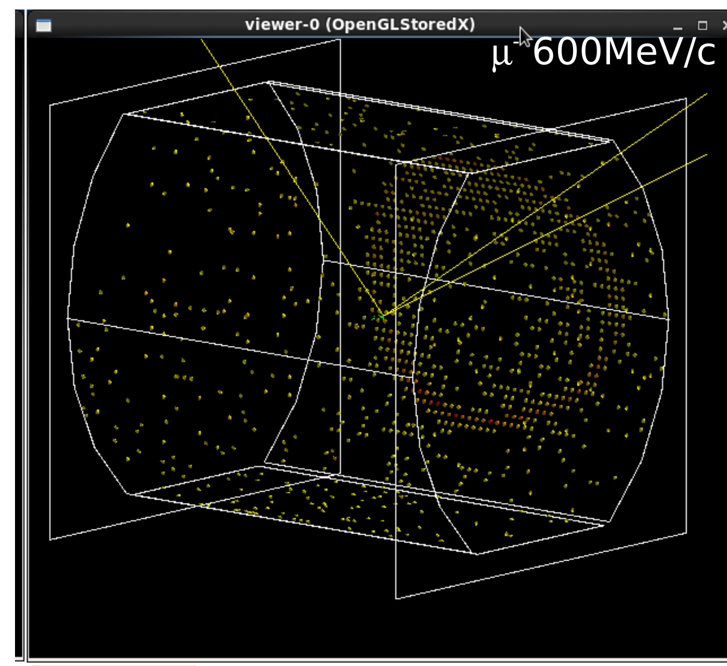


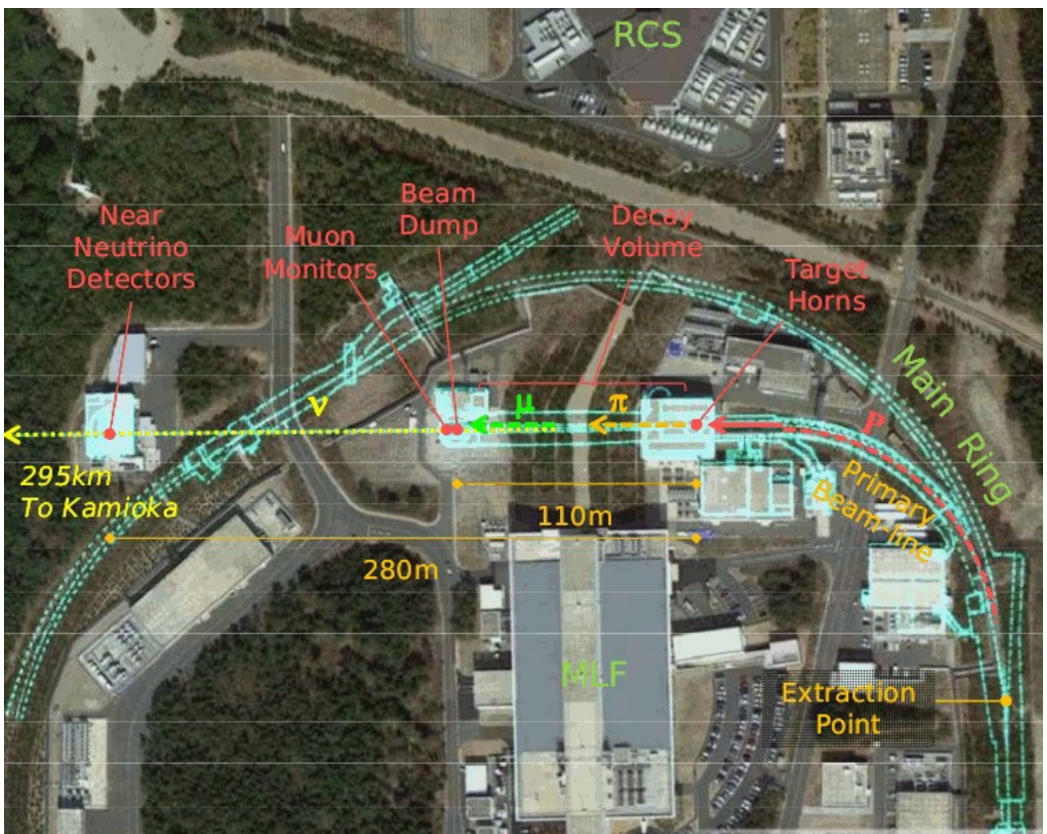


Ongoing work to develop software and more in general computing model for Hyper-K to be used in future physics studies.

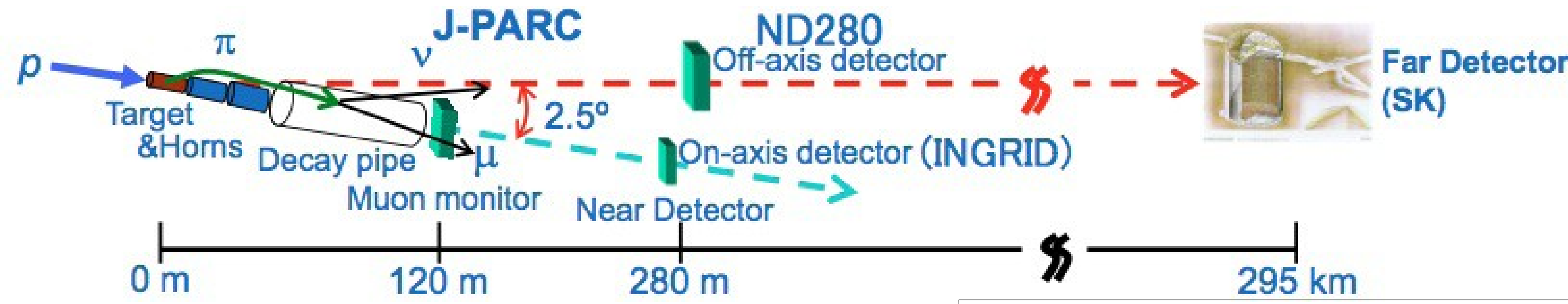
(Beam &) Near Detectors

Beam for Tokai-2-Hyper-Kamiokande

- Next upgrade (intermediate plan) towards a 750kW operation.
- See T. Sekigushi's talk for details on the upgrade.
- It will concern:
  - Upgrade plan for J-PARC accelerators.
  - Upgrade plan for the neutrino beam-line to accept a 750MW beam.



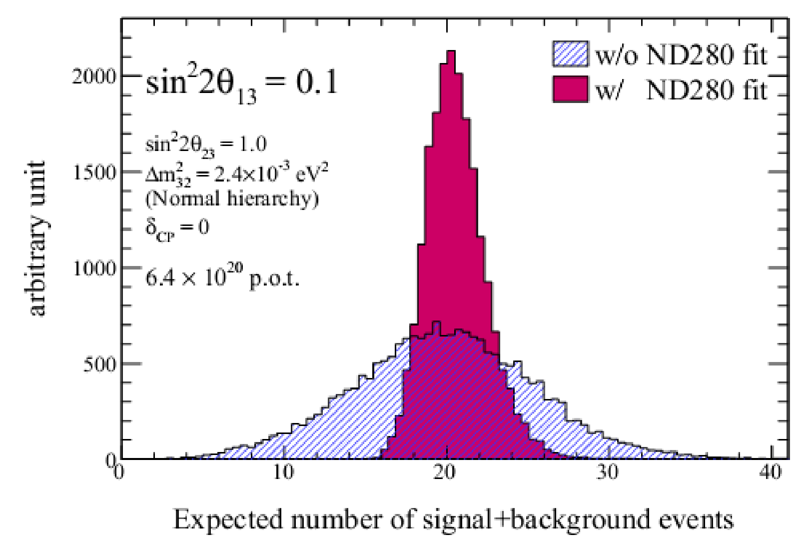
Near Detectors



- Currently two near detectors:
  - INGRID, on-axis, for neutrino beam direction.
  - ND280, off-axis, for spectrum measurement.

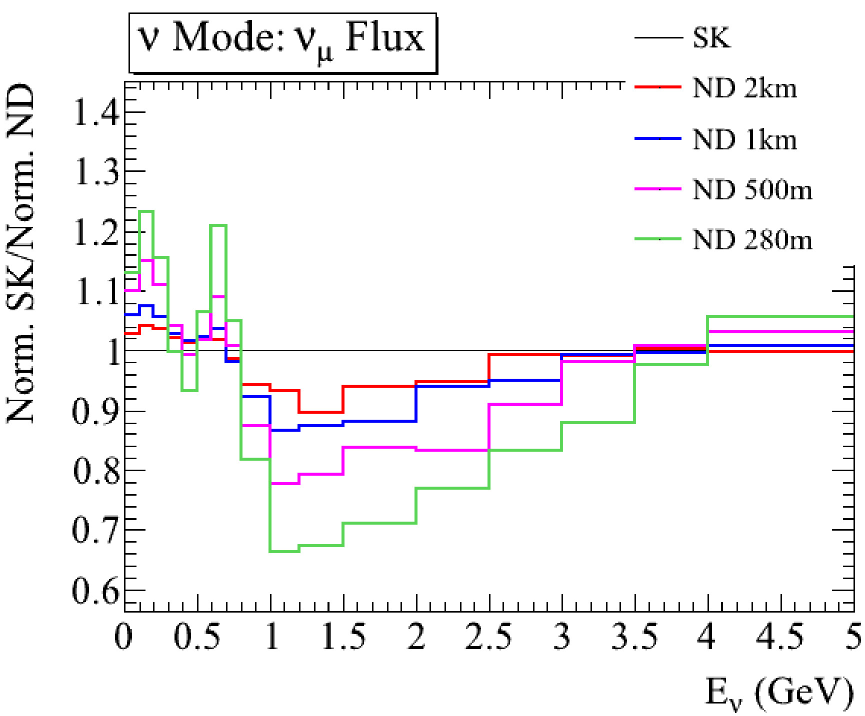
- Ongoing discussion on ND280 possible upgrade for Hyper-Kamiokande (T2HK).

- T2K Summer 2013 ν_e appearance measurement.
- Predicted number of events error reduction due to ND280:

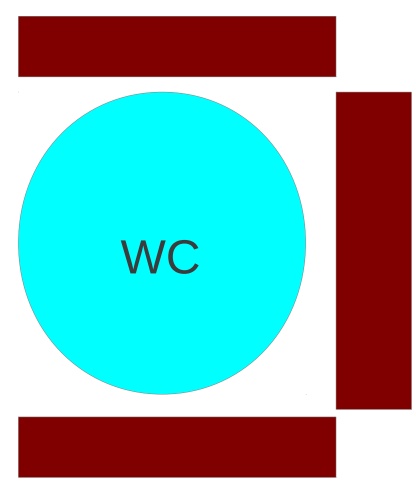


Near Detector(s)

- New Near Detector(s) current under-investigation. Several options.
- Reduce the current systematic errors at Hyper-Kamiokande using:
  - ND beam spectrum similar to HK spectrum
  - same WC detector as Hyper-K
  - ν_e xsection measurement, good ν_e - π^0 separation,..
  - energy spectrometer



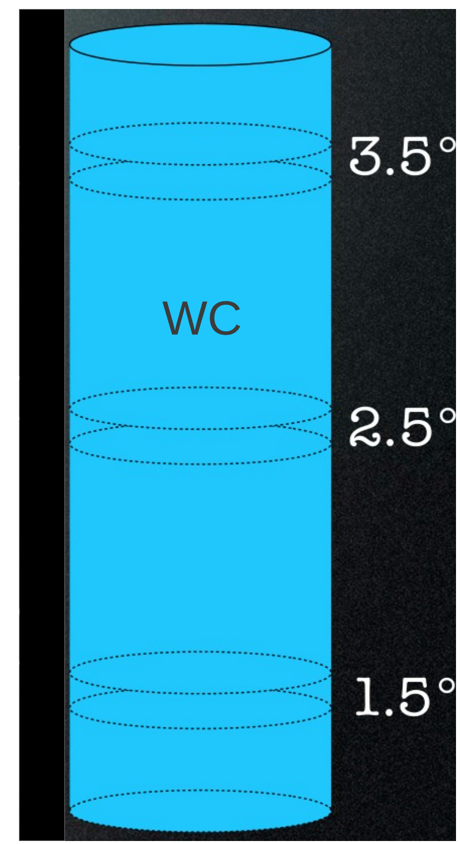
~1kton WC @ 2km
Xsection view



Muon Range Detector

Inspired by 2007
2km T2K proposal

Energy spectrometer

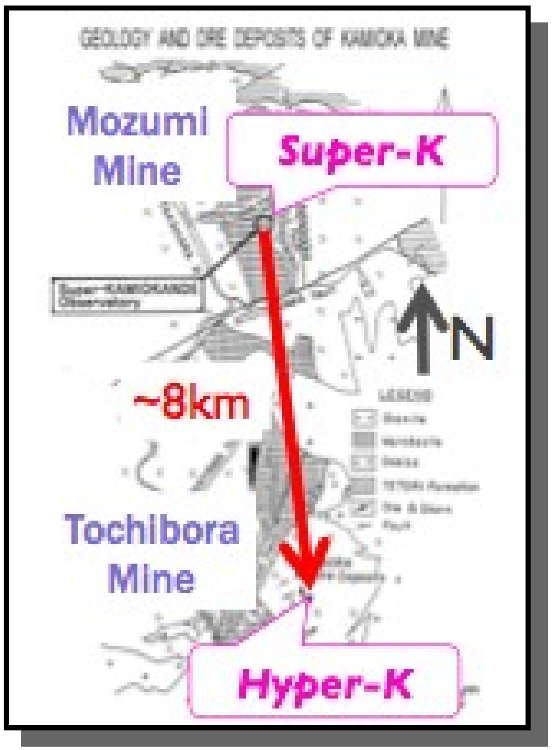


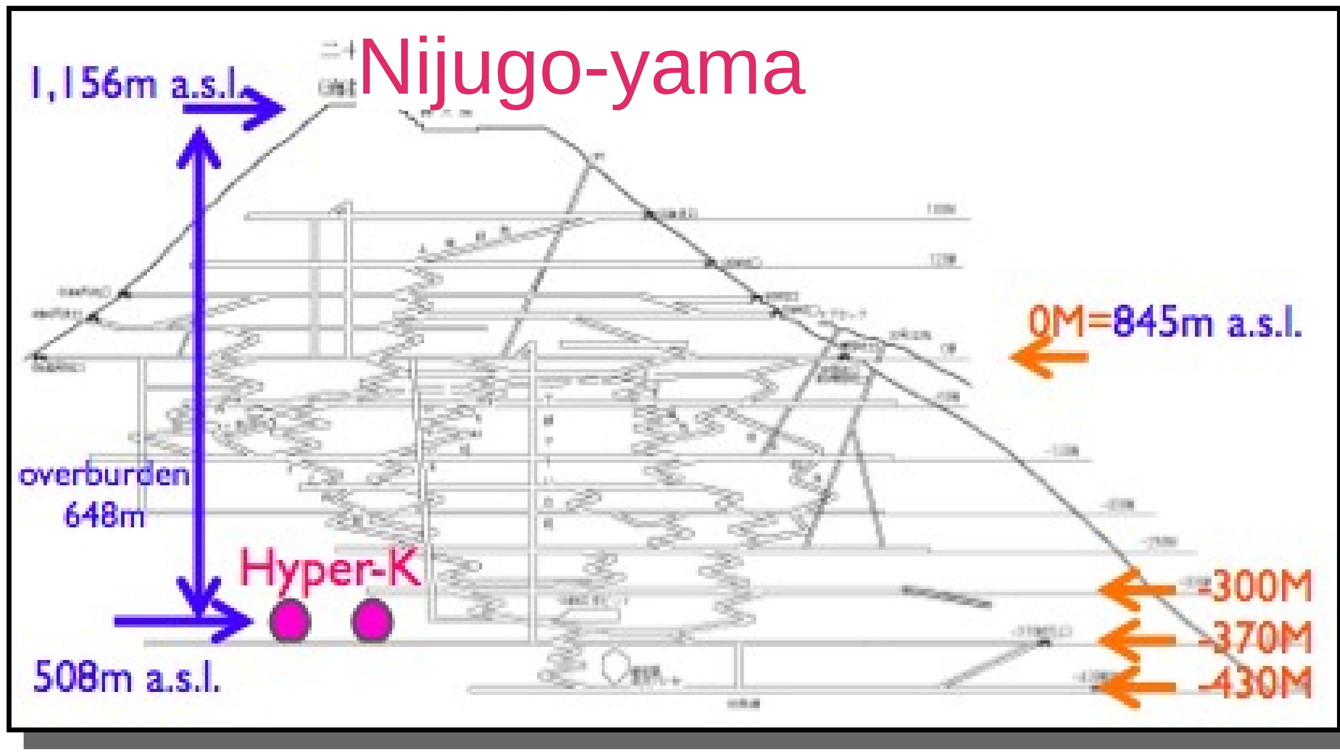
Poster #20, M. Hartz, M. Wilking

Cavern Construction

Candidate Site: Tochibora Mine

- Located under “Nijugo-yama” (Mt. 25), ~8km south from Super-K.
- Identical baseline (295km) and off-axis angle (2.5º) to T2K.
- Overburden ~650m (~1755 m.w.e.).



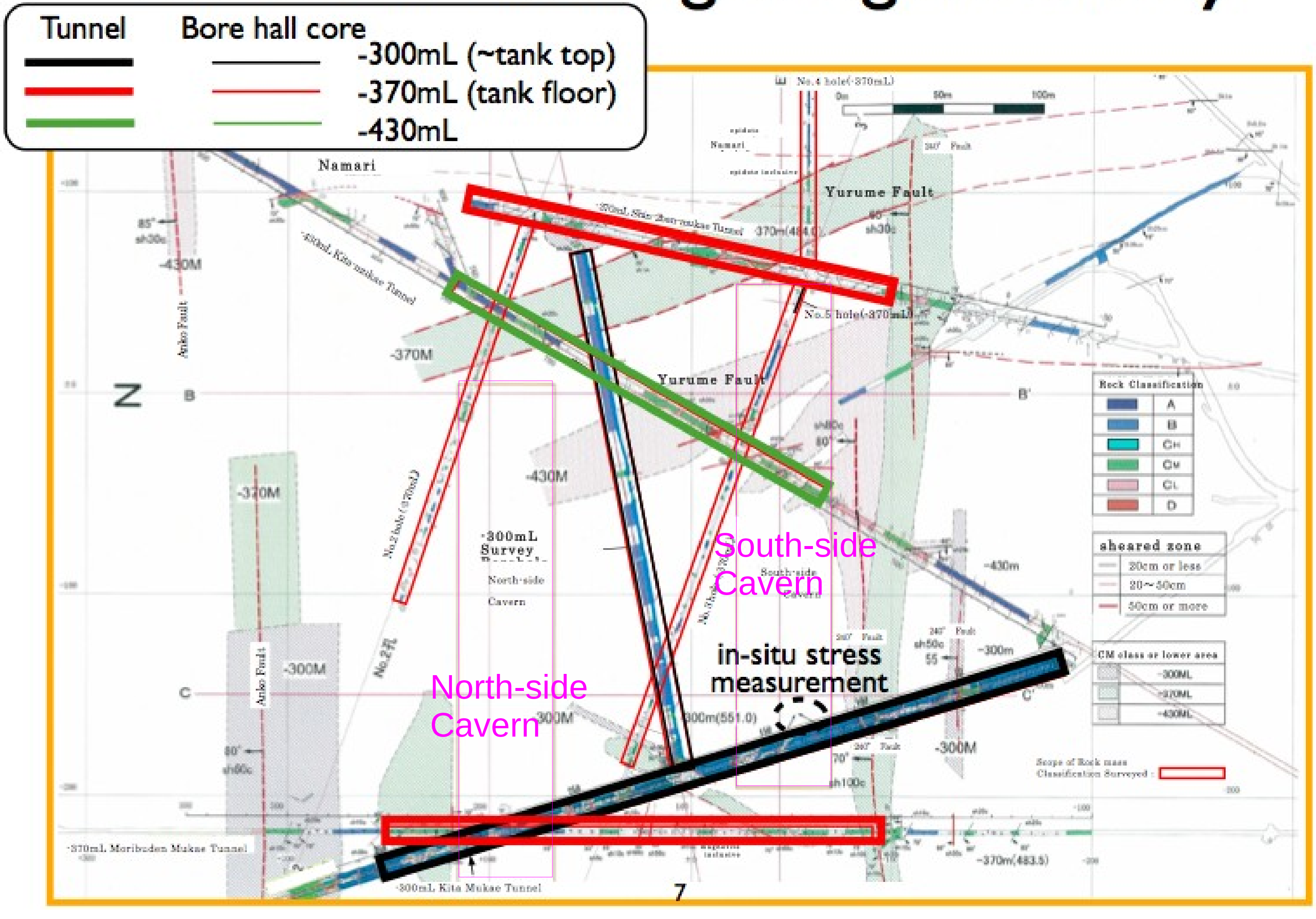


- The candidate site vicinity was used for mining.
- Historically many surveys have been done in wide area and at several levels/depths, ex. mapping the location of faults.
- Many existing tunnels and shafts already escavated.

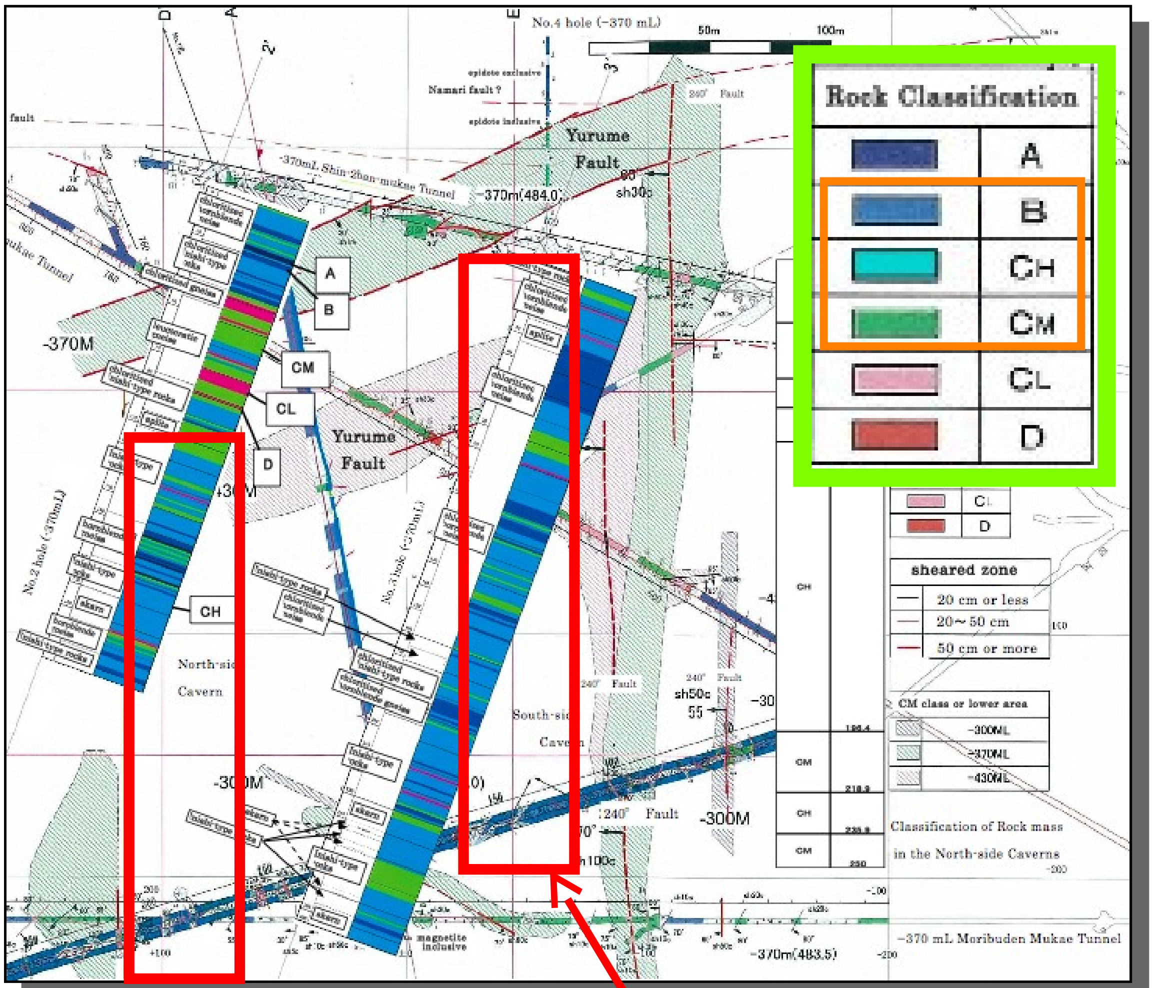
Geological Survey

- The rock mass characterization has been done by mapping the existing tunnels and geological logging of rock core samples.

Overview of the geological survey



Rock Mass Characterization



HK tank location

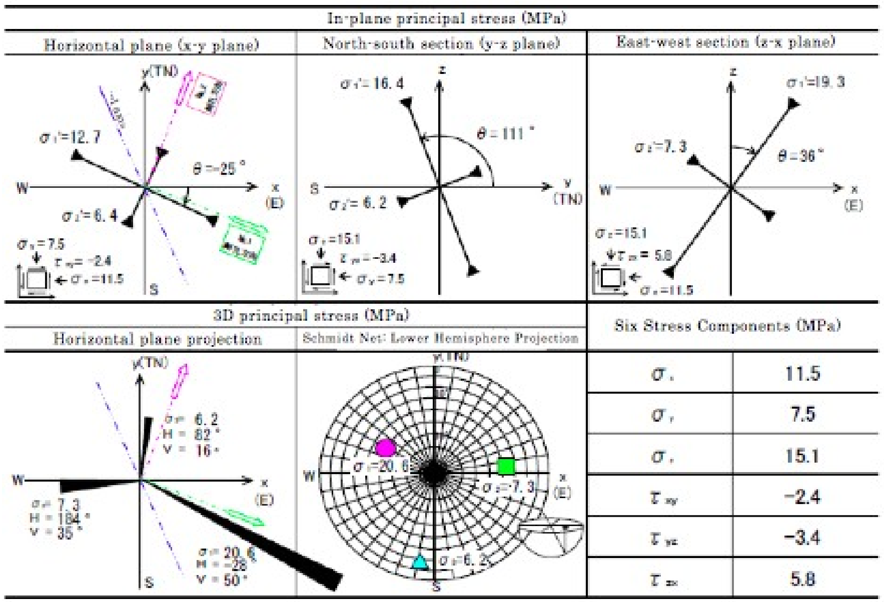
- From the survey results, rock mass characteristics are classified into 6 categories:
- A, B, CH, CM, CL and D (defined by CRIEPI).
- ‘A’ (blue) is the highest grade rock and ‘D’ (red) is lowest.
- Based on these results, HK tank location decided.

(CRIEPI: The Central Research Institute of Electric Power Industry)

- For both caverns for the tank locations, 90% of bedrock is CH or higher grade.

Cavern Stability

Initial stress measurements

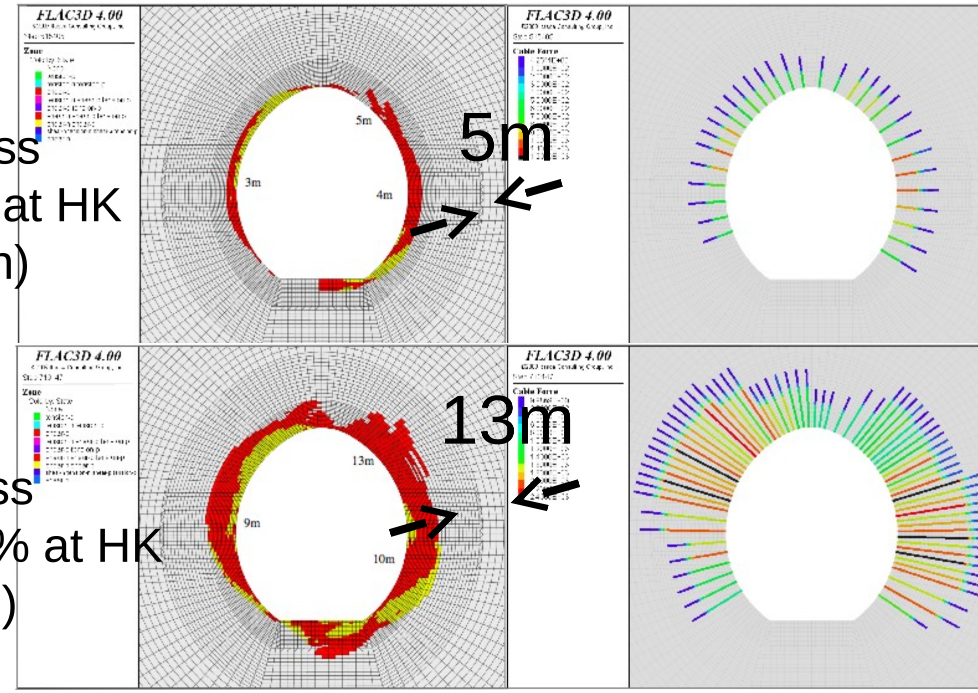


σ_x	11.5
σ_y	7.5
σ_z	15.1
τ_{xy}	-2.4
τ_{yz}	-3.4
τ_{zx}	5.8

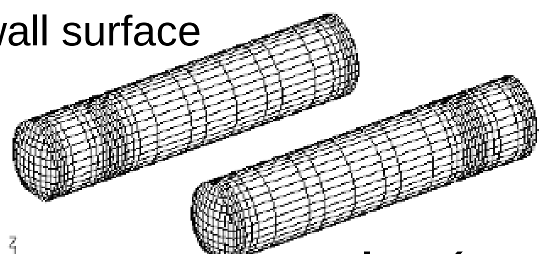
Plasticity region depth PS-anchor tension

CH class (>70% at HK location)

CM class (20~30% at HK location)

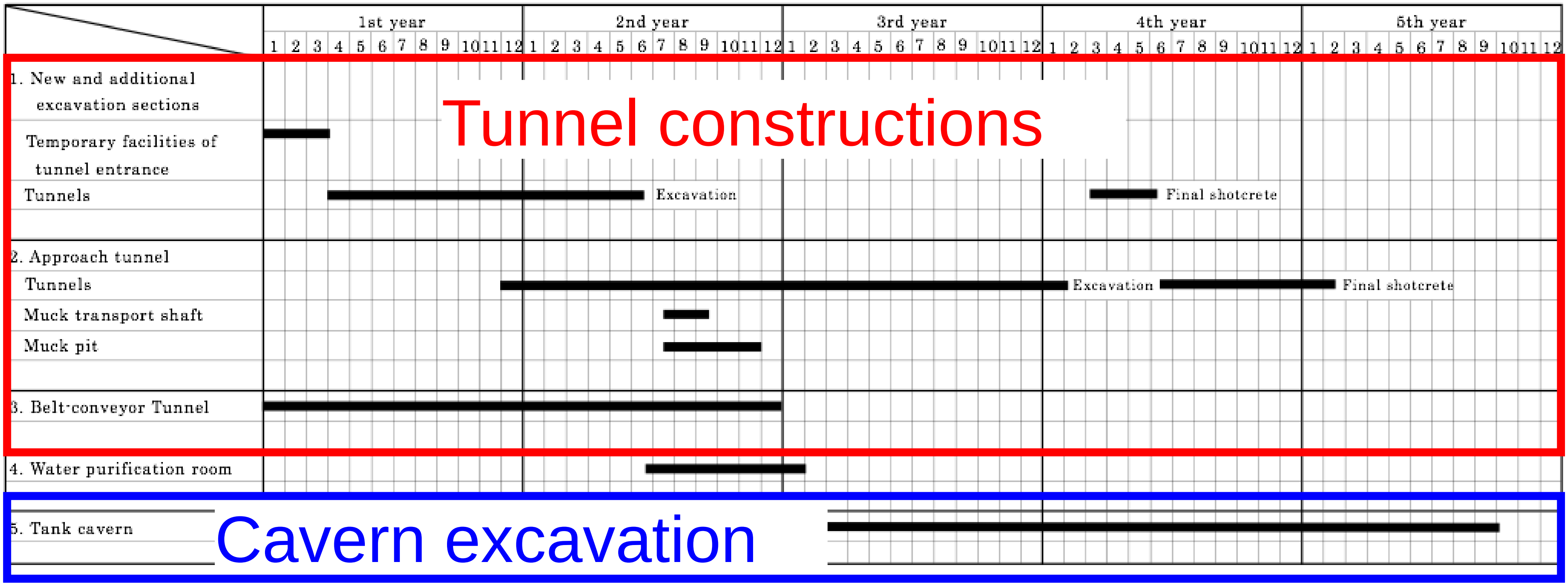


Segmented wall surface of caverns



- Based on the survey results (rock mass characteristics and initial stresses), the structural stability of caverns was studied
- The excavation-steps were taken into account in the studies, including the cavern supporting material.
- For all rock mass classes (B, CH, CM), HK caverns can be constructed by existing excavation/support techniques.

Excavation Schedule

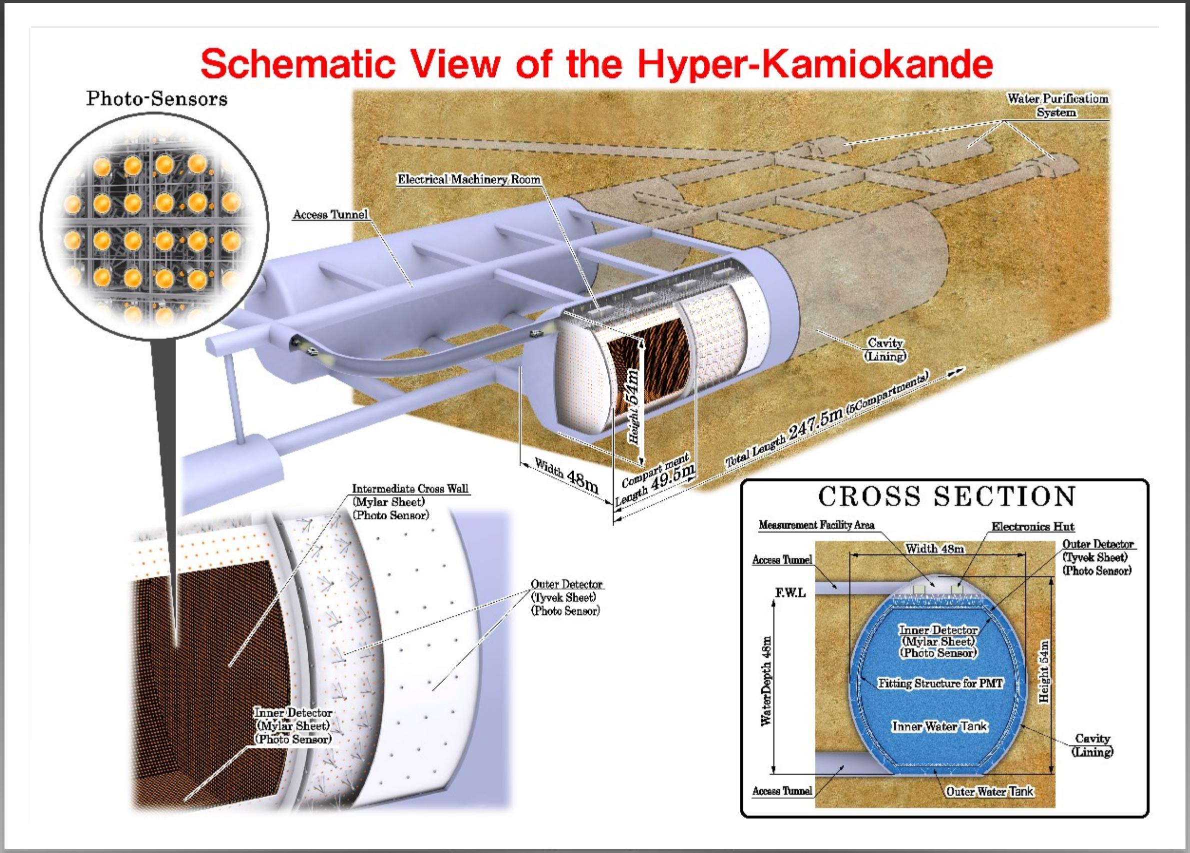


- Cavern construction period: ~5 years
- Transport / approach tunnels: ~3 years
- Excavation of caverns: ~3 years

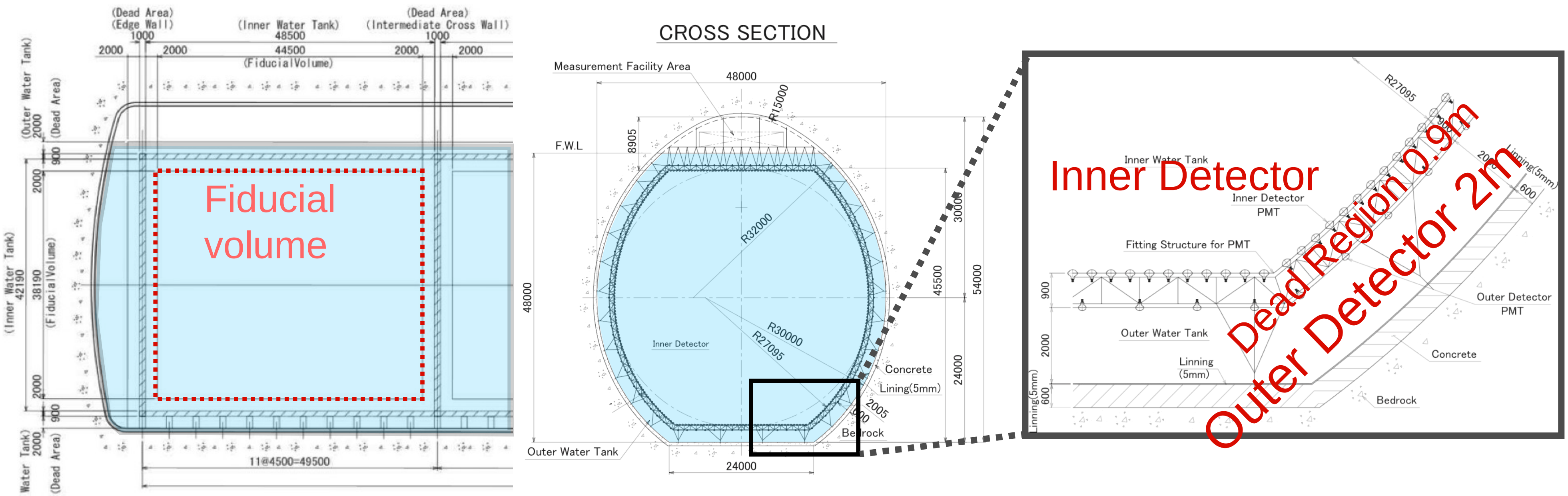
Geological Survey at Mozumi Mine

- Geological survey at the Mozumi mine, already used for Super-K, recently started.
- It should allow to have deeper caverns (> 700m overburden).
- First rock mass characterization has been done: rock quality at Mozumi-site is comparable with Tochibora-site
- More tests under way to complete the geological survey.

Detector Design

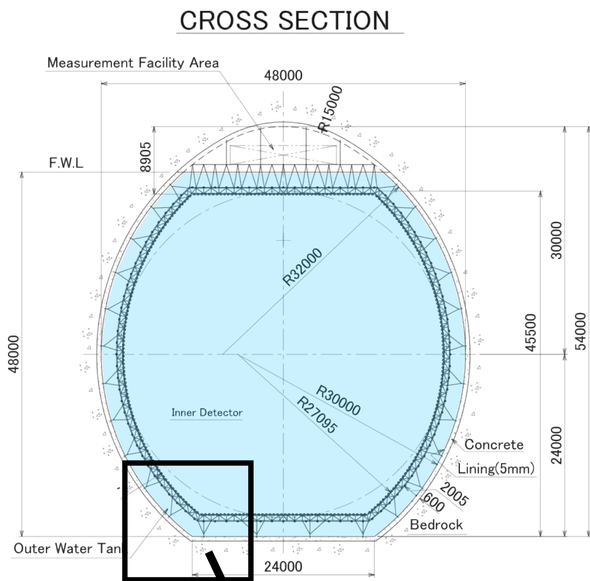


Hyper-K Tanks



- Two water tanks: 54m(H) x 48m(W) x 250m(L) / tank
- Water tanks are segmented into 10 compartments
  - 5 compartments / tank
  - Each compartment optically separated and consists of Inner Detector (ID) and Outer Detector (OD)

Water Containment System



- Tank lining consists of concrete (60cm) and Polyethylene (5mm) linings

Polyethylene sheet

- Drain lines are separated for sump water and leak-water from tank.

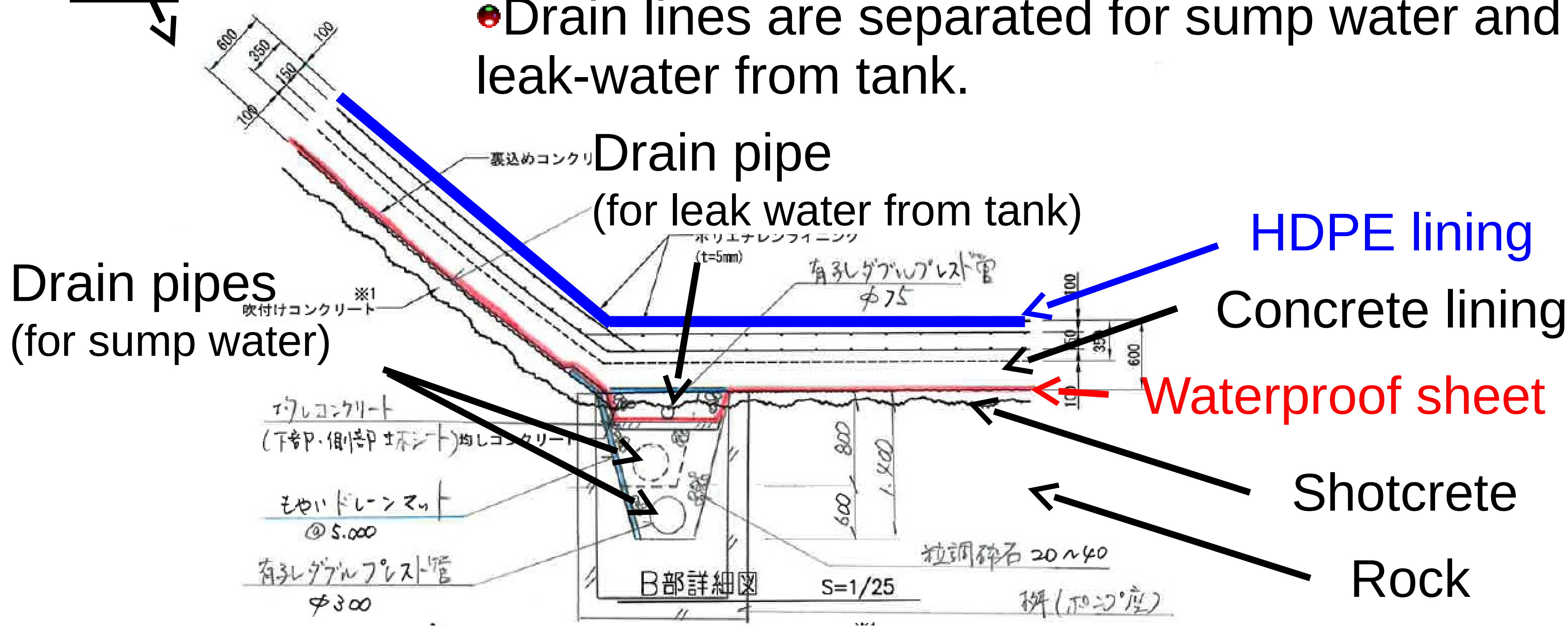
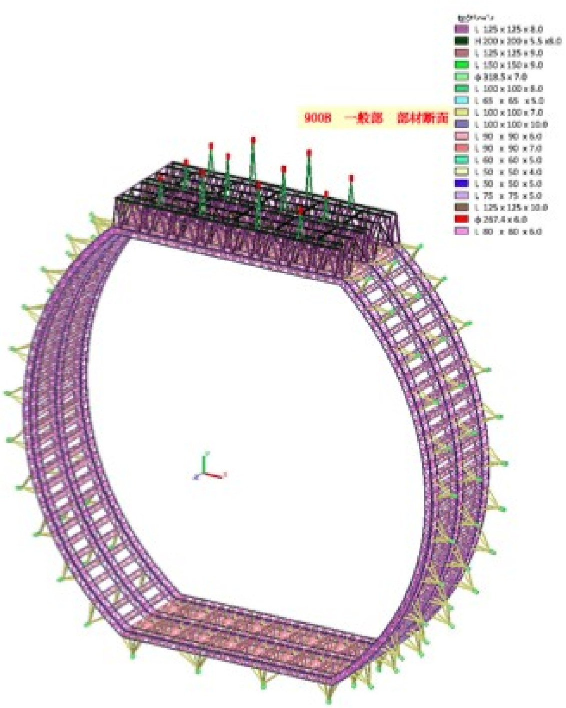


Photo-sensor Support

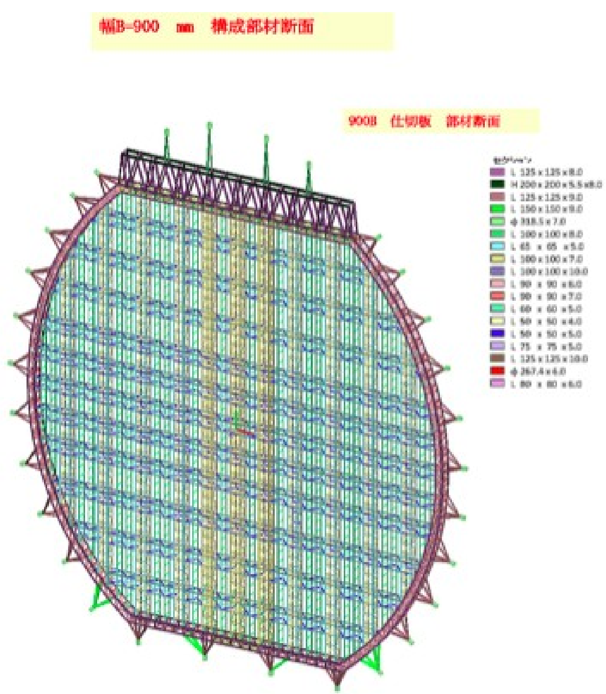
- Number of photo-sensors:
  - Inner Detector (ID): ~99,000 of 20” (20% photo coverage)
  - Outer Detector (OD): ~25,000 of 8” (identical coverage to SK)
- Stainless-steel supporting structure holds photo-sensors

Inner PMT (20”)

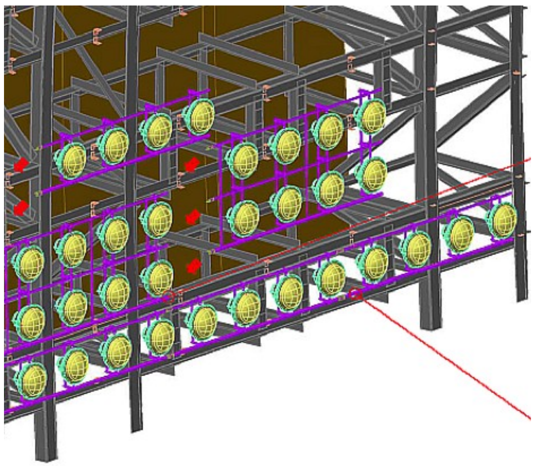
Barrel part



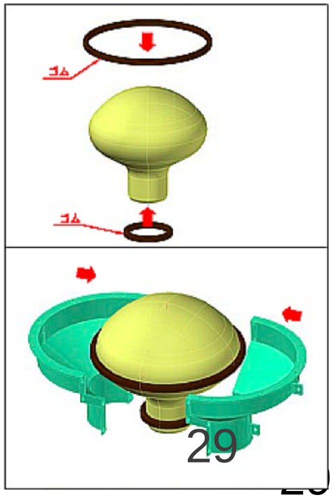
Segmentation wall



Mounting Photo-sensor



Housing



Designing work...

- The major part of HK tank has been designed.
- Include layout of water pipes, front-end electronics, cables, calibration holes, plug manholes, ... etc.

Electronics & cable layout

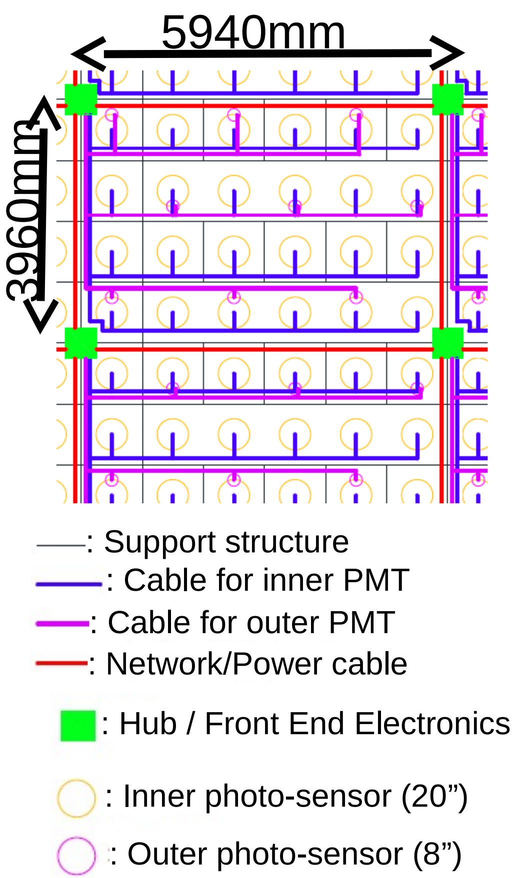
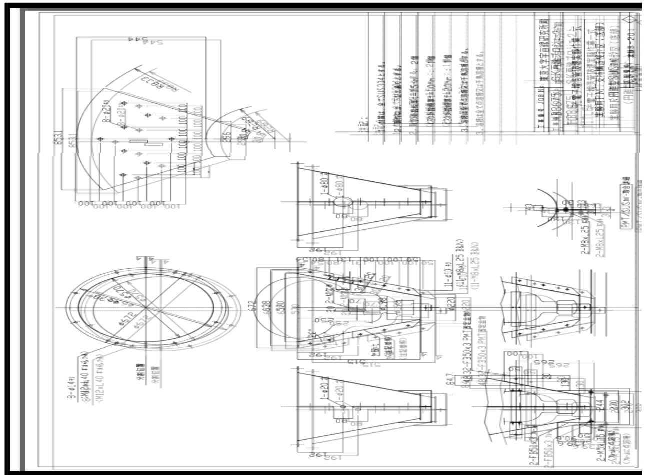
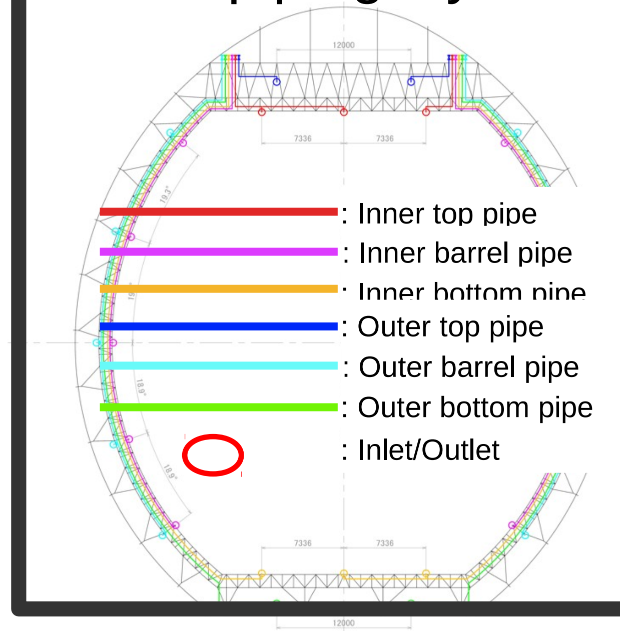


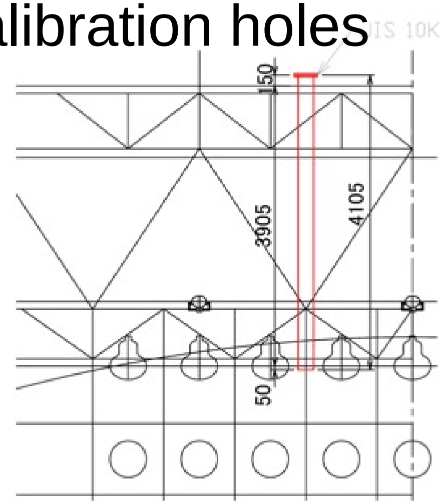
Photo-sensor housing



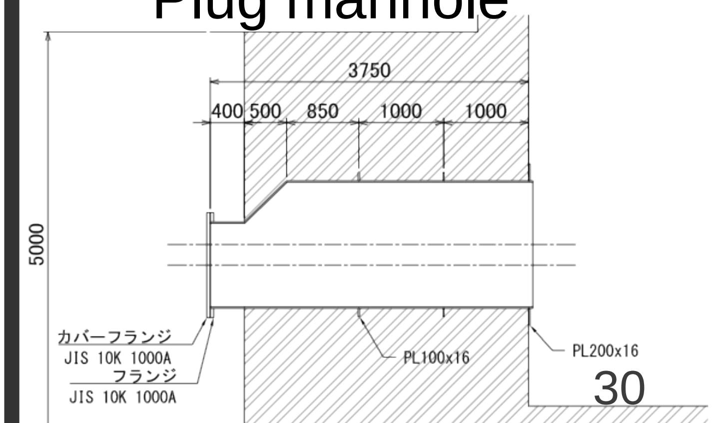
Water piping layout



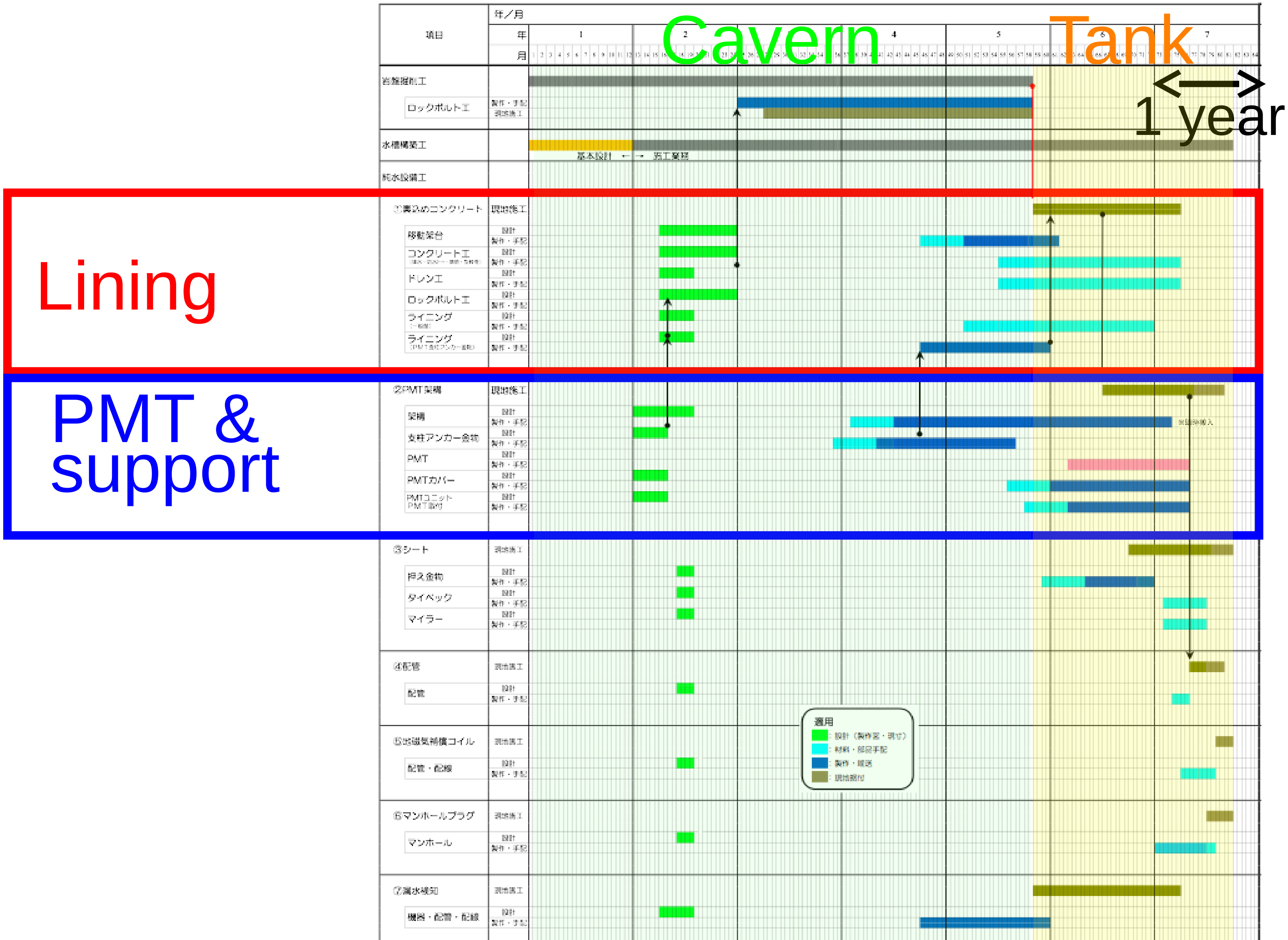
Calibration holes



Plug manhole



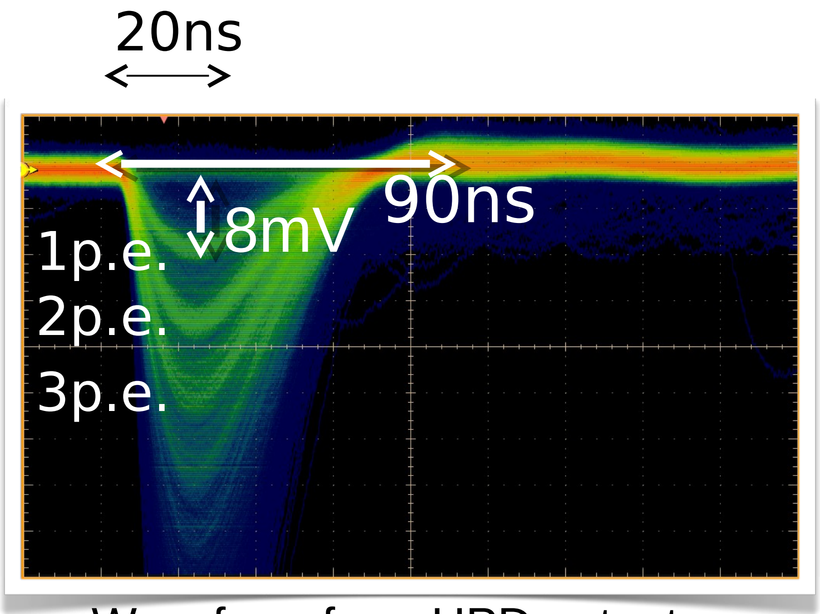
Tank construction schedule



- Tank construction: ~2 years
- Lining: 1+ years, PMT installation: ~1 year

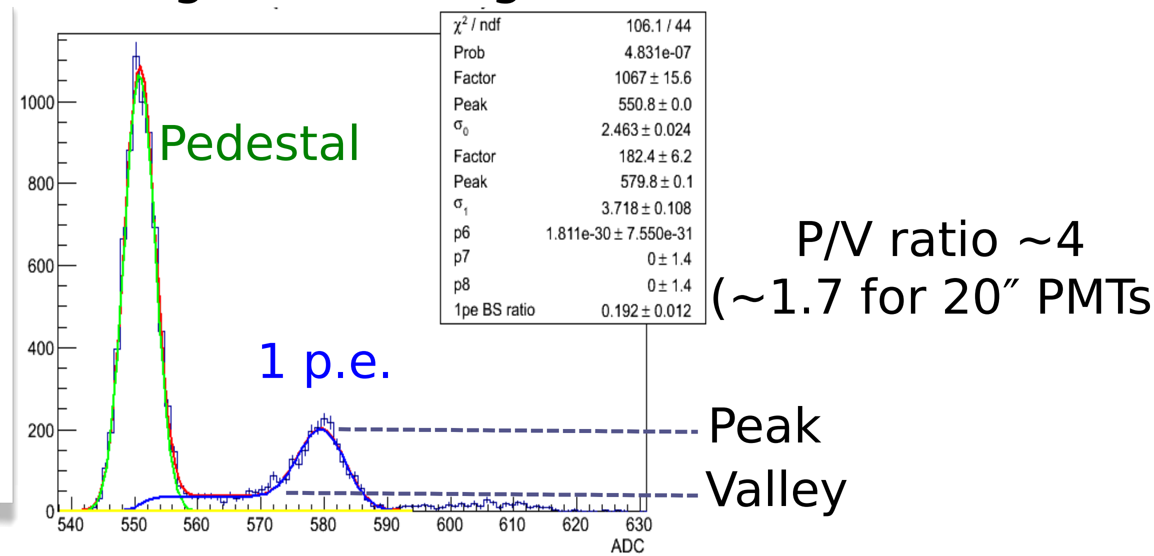
See F. Retiere's talk for details on types of HK photosensors

8" HPD Testing



Waveform from HPD output

Integrated Charge Distribution

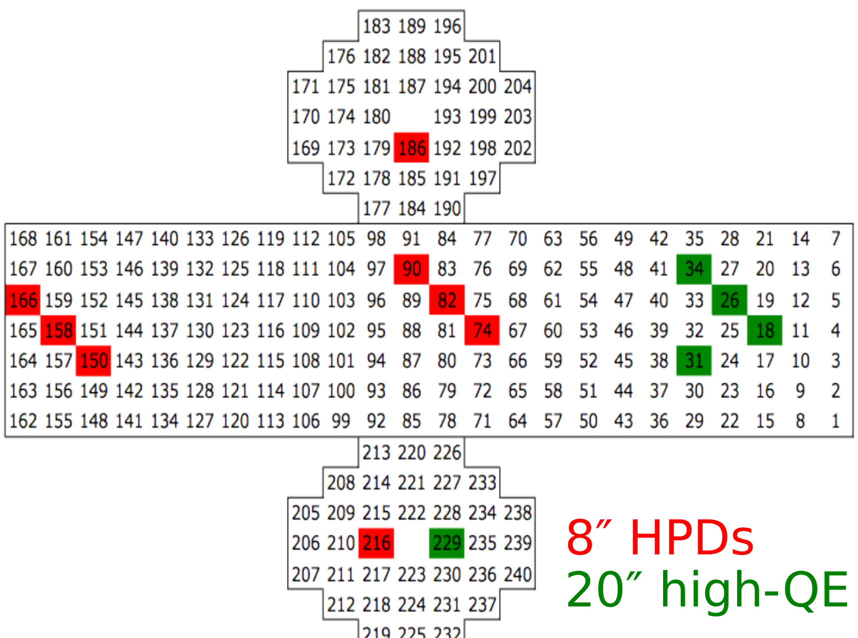


- Pre-test performed before installation in a 200ton tank.
- Confirmed that the basic performance was good
  - P/V: ~4, TTS: ~1ns, Dark rate: comparable to 20″ PMTs, …

Tests in a Water Cherenkov Detector

- EGADS detector : a 200 ton scale model of Super-K
  - To demonstrate the safety and effectiveness of "SK + Gadolinium"
  - 240 inward-facing photodetectors
  - Electronics : ATMs (used in SK-1,2,3), to be upgraded to QBEEs (SK4)

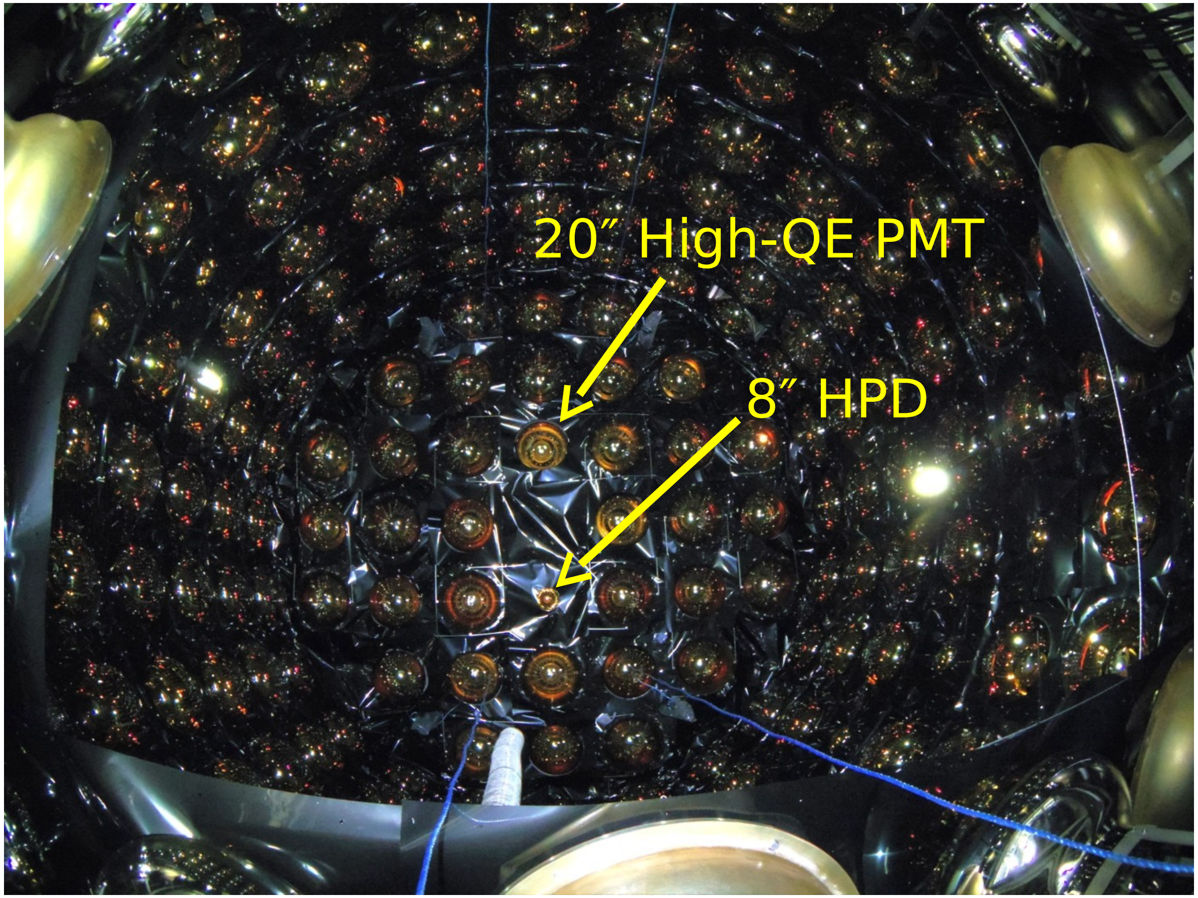
- Eight 8″ HPDs and five 20″ high-QE PMTs were mounted
  - Other 227 photodetectors are R3600, and can be used as references for the new photodetector evaluation



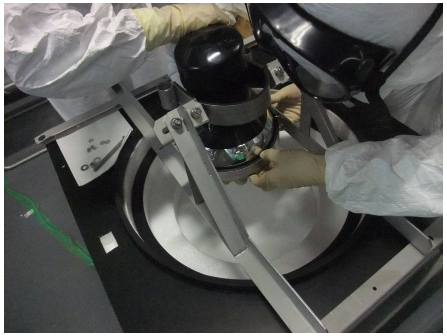
8″ HPDs
20″ high-QE PMTs

Photodector Installation in EGADS

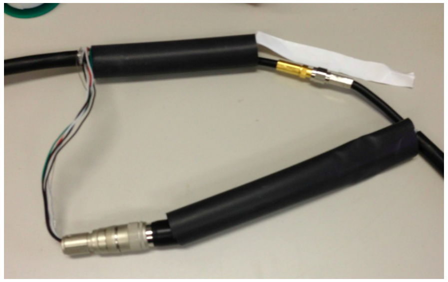
All 240 photodetectors were installed in July-August



HPD with supporting frame



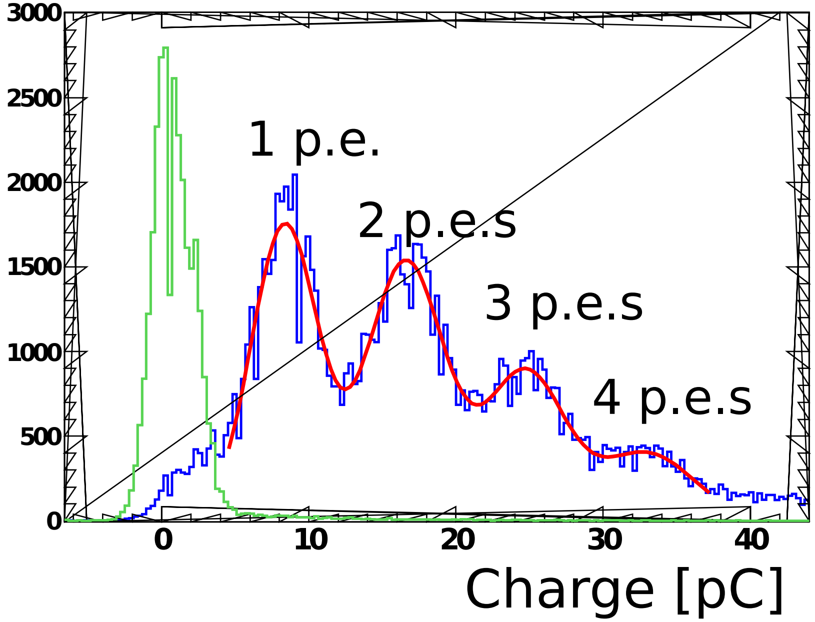
Water-proof cable connection

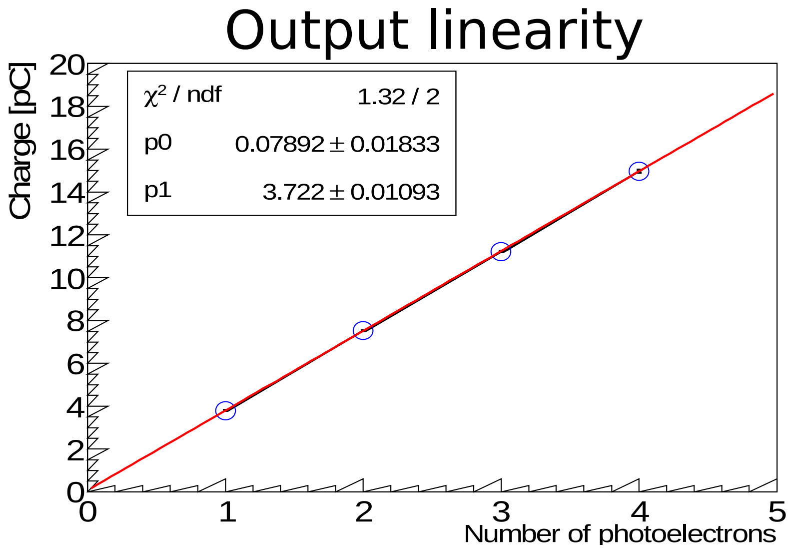


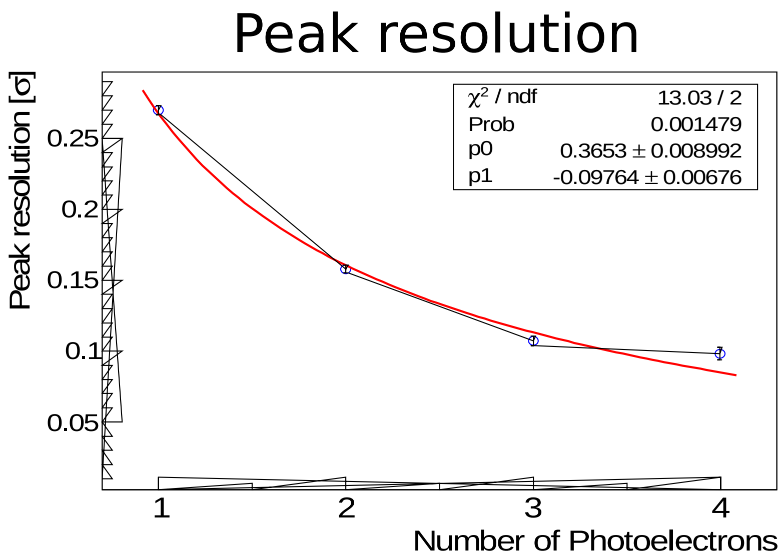
Cable connection in the tank

Testing in EGADS: Multi p.e.s peaks by HPDs

- EGADS is in the commissioning phase
- Initial tests with new photosensors started.



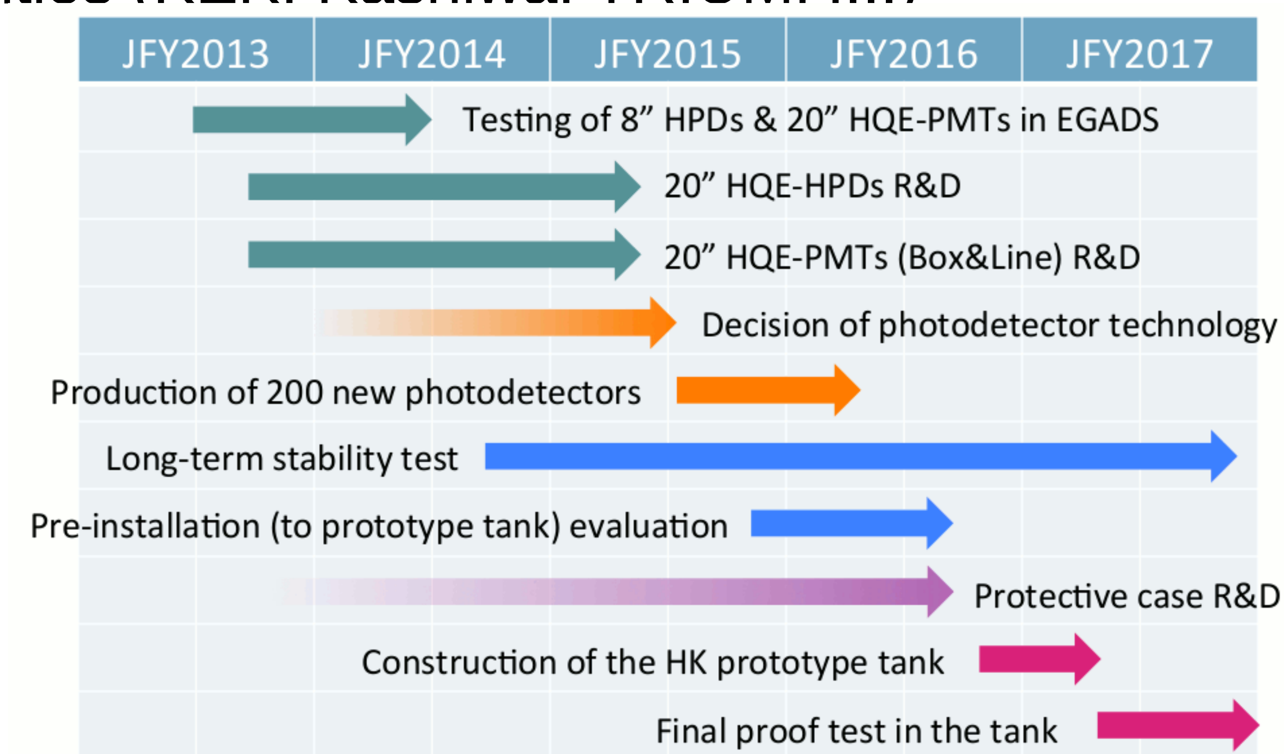




- Multi photoelectron peaks are clearly visible.
- About 30% σ at 1 p.e. peak

Future Tests

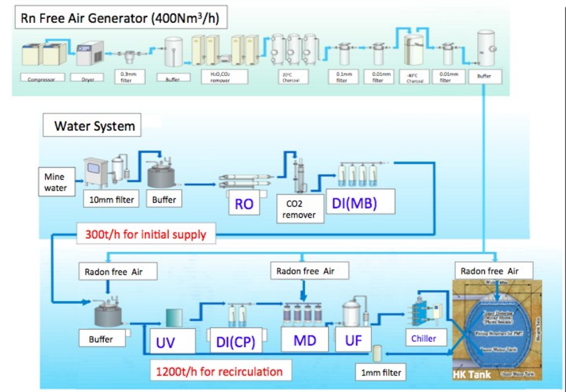
- Hamamatsu Photonics K.K. is making prototypes of
  - New 20″ PMT (Box&Line dynode)
  - 20″ HPD
- Planning to start tests in this year
- Future: continue tests at different facilities:
  - EGADS
  - 1kton WC prototype (construction 2016-17)
  - Other facilities (KEK, Kashiwa, TRIUMF,...)

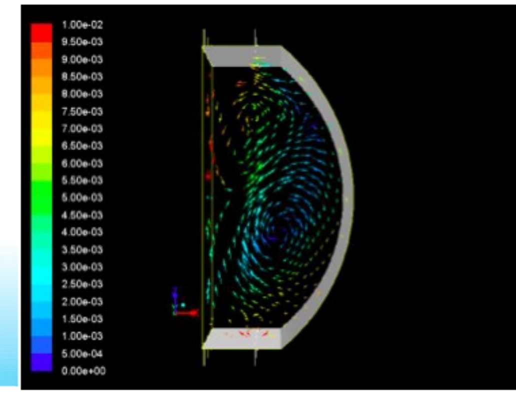


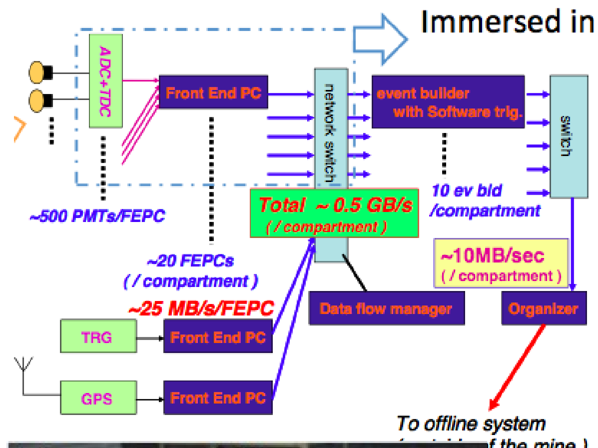
Other R&D

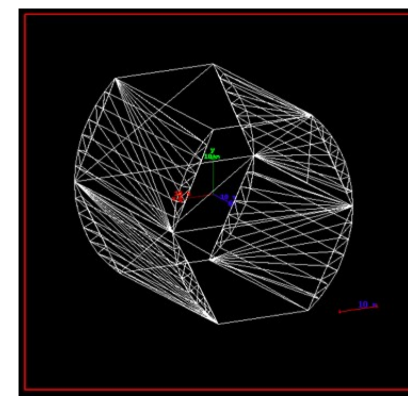
- Water system
- Readout electronics
- Calibration system
- DAQ
- ...

- Progress within the international working group

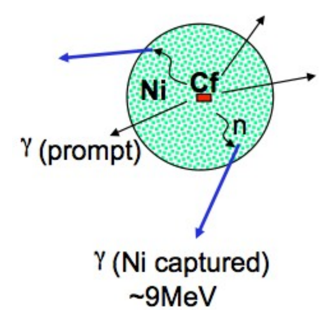




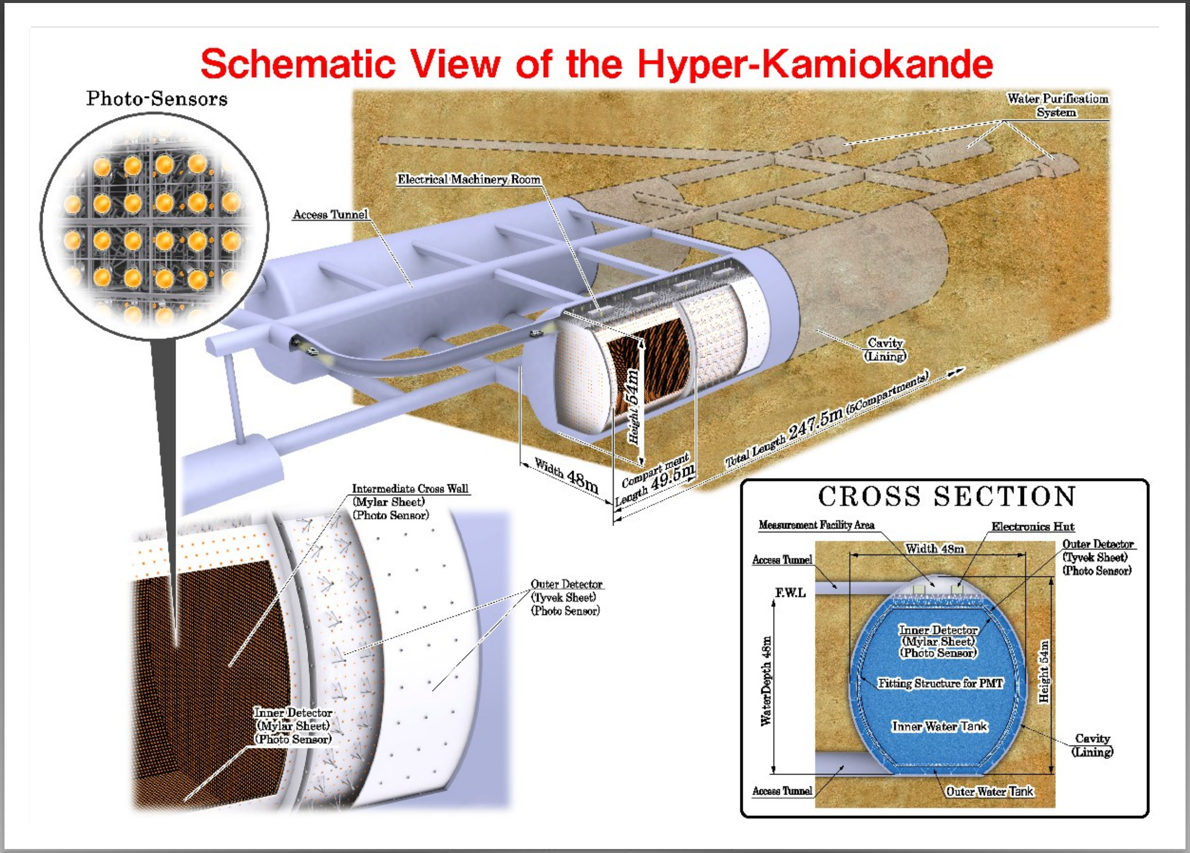




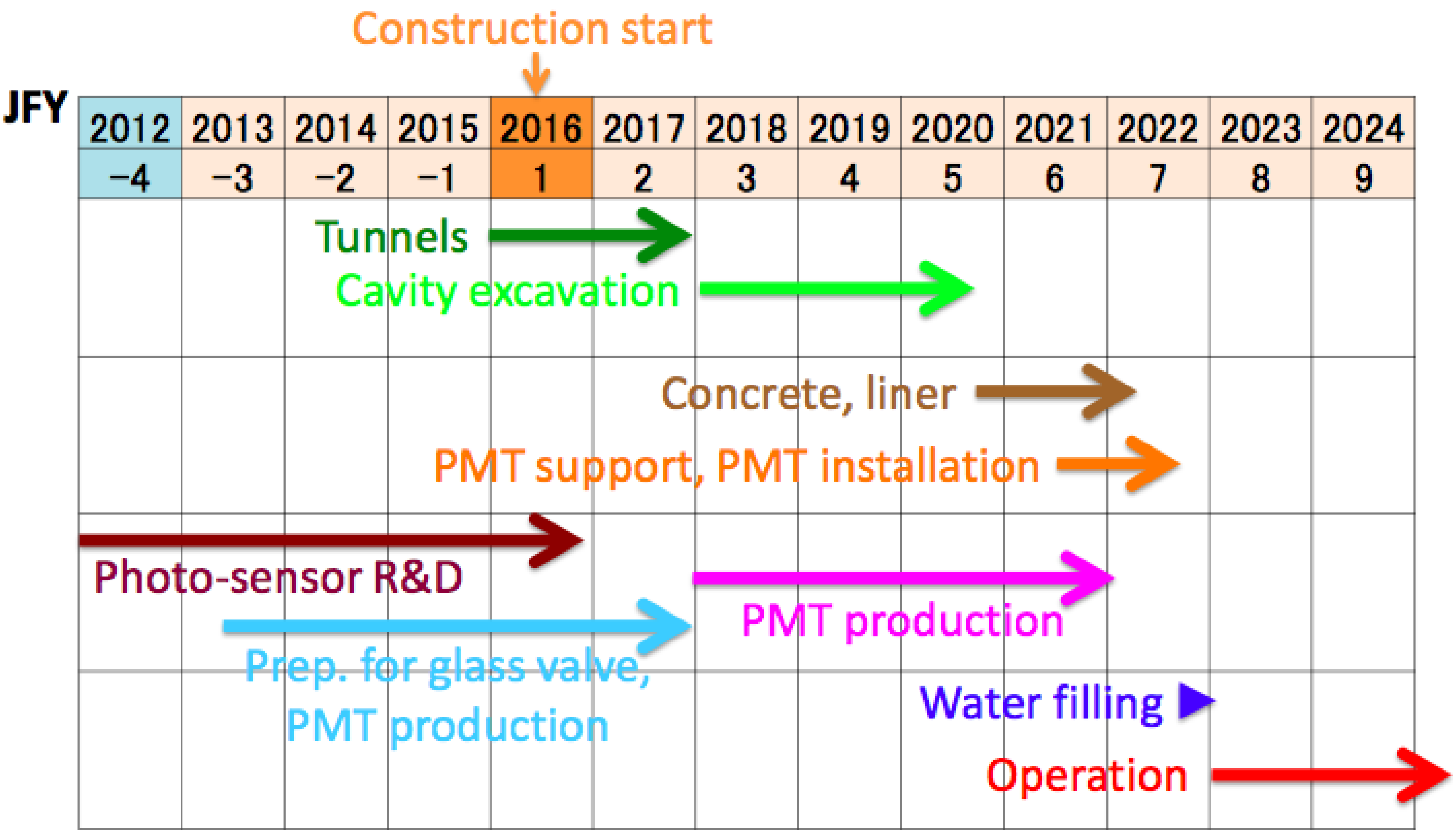
SK Nickel source



Schedule & Summary



Overall Project Schedule

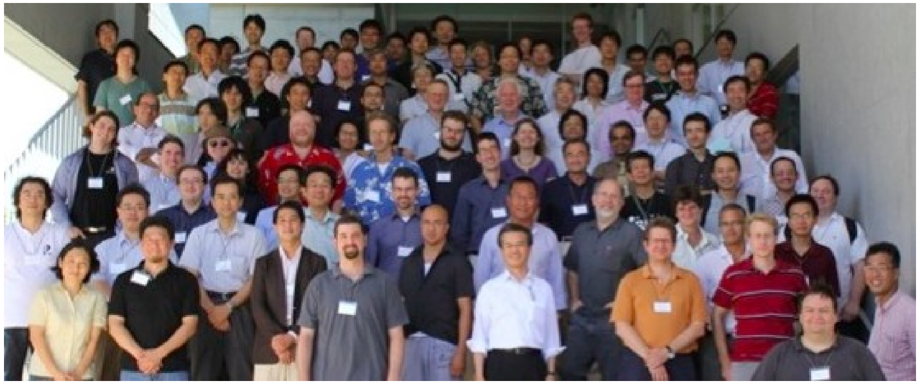


Overall Hyper-K construction: ~7 years

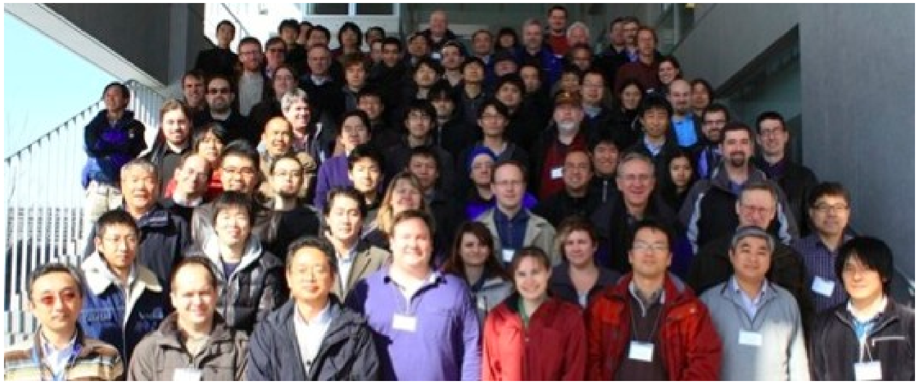
The Hyper-Kamiokande Project

- Three International Open Meetings (2012-2013) so far.
- Formed international working groups.

August 21-23, 2012
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=7



January 14-15, 2013
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=10



June 21-22, 2013
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=23

Next meeting:
27-28 January 2014,
Kavli, IPMU.

First EU Open Meeting
18 December 2013, London
http://indico.cern.ch/e/HKEUOpenMeeting

Summary

- Hyper-K covers wide range of physics:
  - Neutrino oscillation with beam-ν & atmospheric-ν
    - → Main goal: CP violation
  - Nucleon decay search and astrophysical neutrinos

- R&D started in all areas and progressing:
  - Software
  - (Beam &) Near Detectors
  - Cavern Construction (technical design document ready)
  - Detector Design
  - PMTs
  - Others (electronics, DAQ, water system, calibration, etc.)

- Japan HEP community: HK at highest priority.
- Strongly growing international community.
- Next Hyper-K Open Meeting: January 27-28, Kavli, IPMU.

Backup Slides

$\nu_\mu \rightarrow \nu_e$ Probability

$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$

$\Phi = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

$$P(\nu_\mu \rightarrow \nu e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}$$ **Leading term** — θ_{13}

$$+8C_{13}^2 S_{12} S_{13} (C_{12} C_{13} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{32} \sin\Phi_{21}$$ CPC

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CPV

$\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

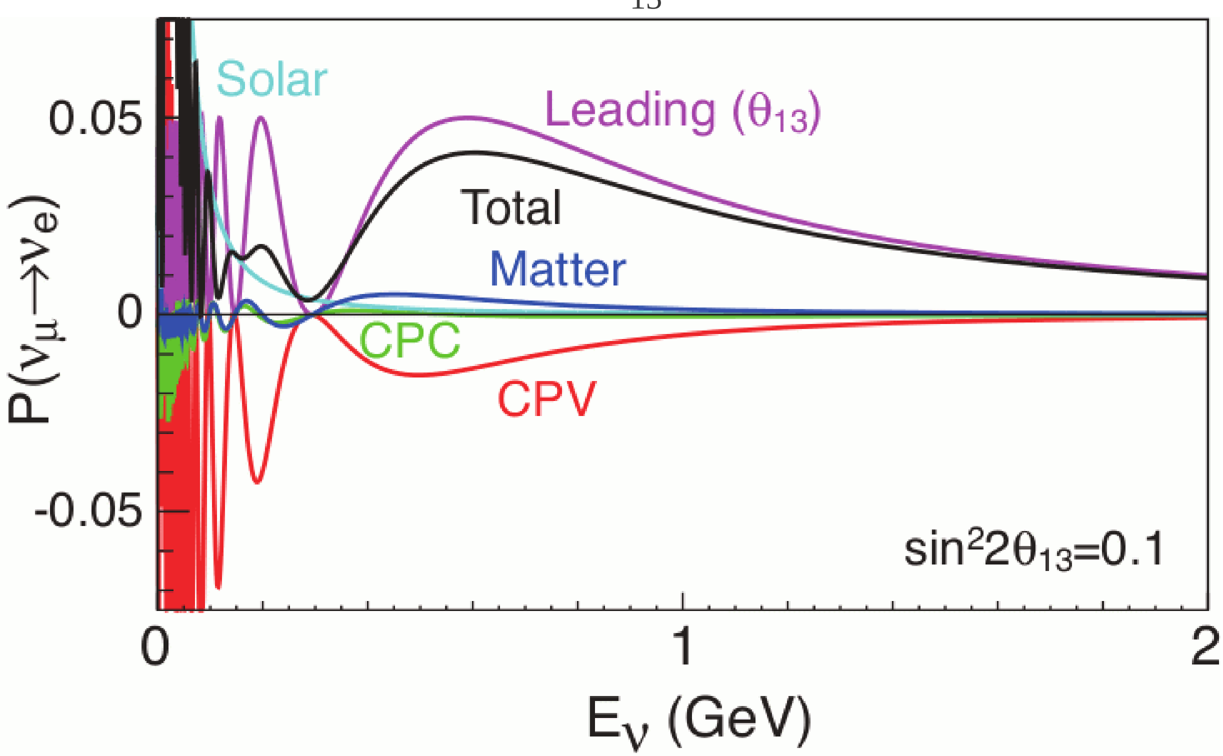
$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$ Solar

$$-8C_{13}^2 S_{12} S_{23}^2 \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cos\Phi_{32} \sin\Phi_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2\Phi_{31}$$

Matter Effect

$$a = 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} eV^2 \frac{\rho}{gcm^{-3}} \frac{E}{GeV}$$



Leading Term μ $\sin^2 2\theta_{13}$

CPV Term μ $\sin 2\theta_{13}$

Matter Effect μ $\sin^2 2\theta_{13}$

For large $\sin^2 2\theta_{13}$:

Signal ↑, CP Asymmetry ↓,

Matter/CP ↑

$\nu_\mu \rightarrow \nu_e$ Probability

$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$

$\Phi = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

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$$+8C_{13}^2 S_{12} S_{13} (C_{12} C_{13} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{32} \sin\Phi_{21}$$ CPC

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CPV

$\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$ Solar

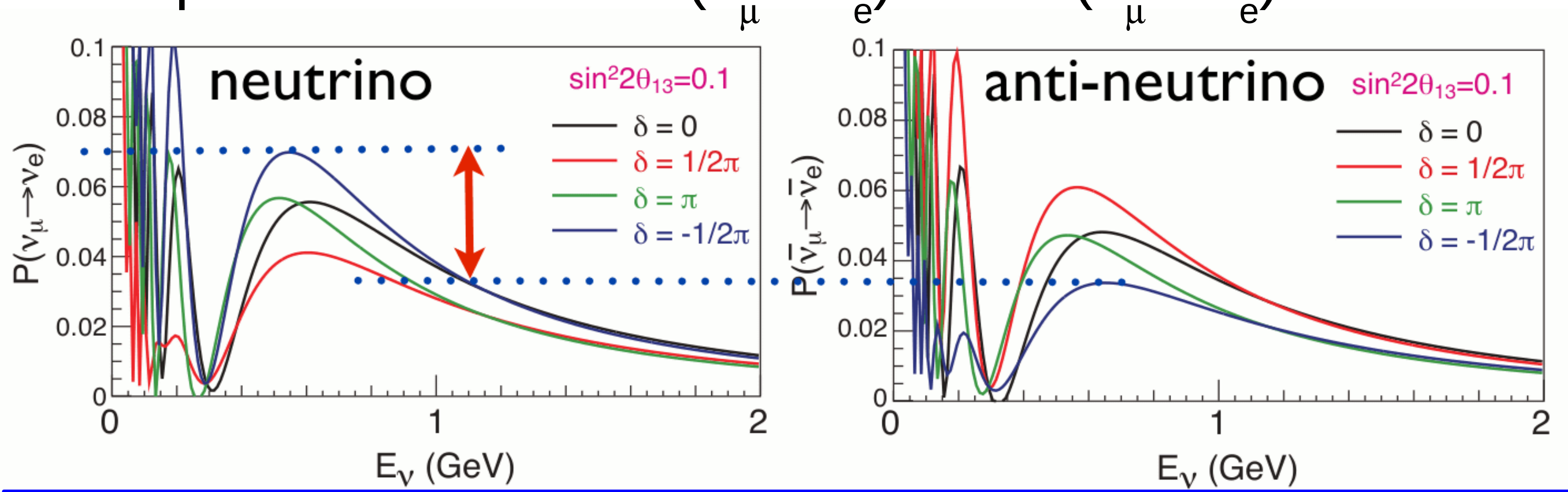
$$-8C_{13}^2 S_{12} S_{23}^2 \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cos\Phi_{32} \sin\Phi_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2\Phi_{31}$$

Matter Effect

$a = 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} eV^2 \frac{\rho}{gcm^{-3}} \frac{E}{GeV}$

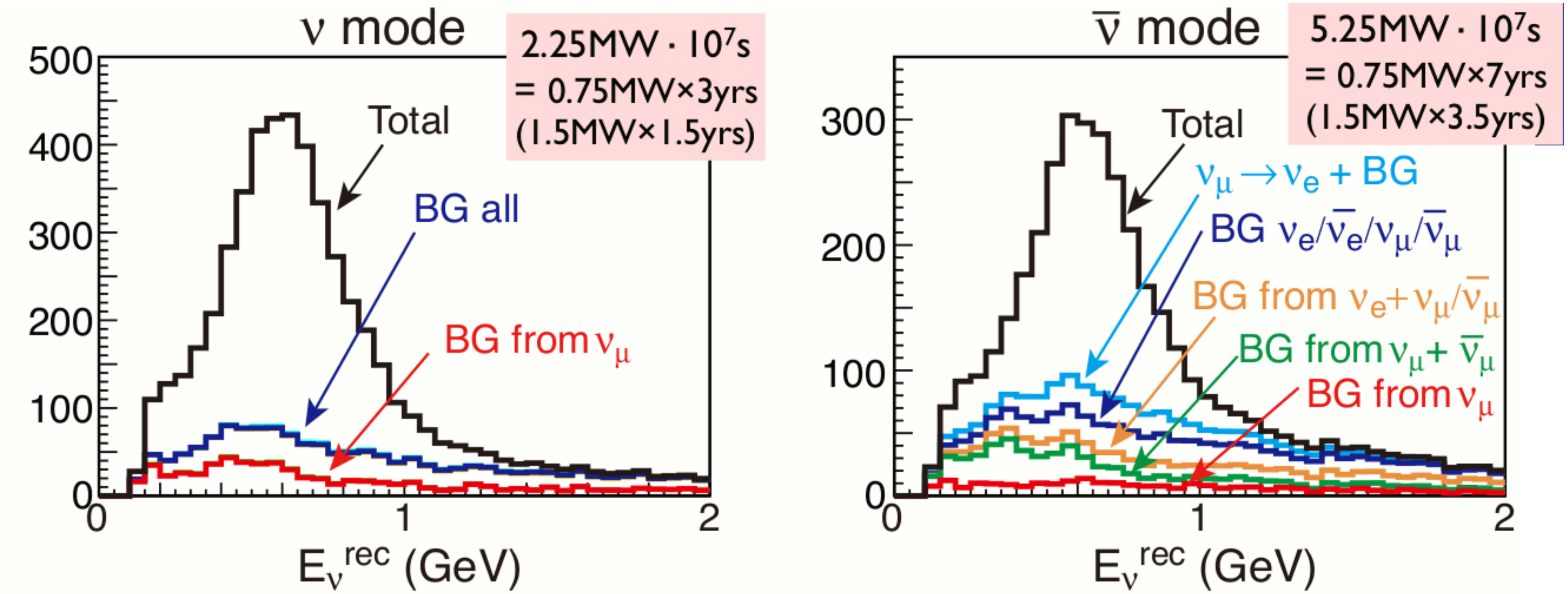
- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$:



Difference $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ as large as ~±25% at nominal (δ=0)

Simulated ν_e Candidates after Selection

- Full simulation of ν beam, detector response and reconstruction
- PMT Coverage: ~20%

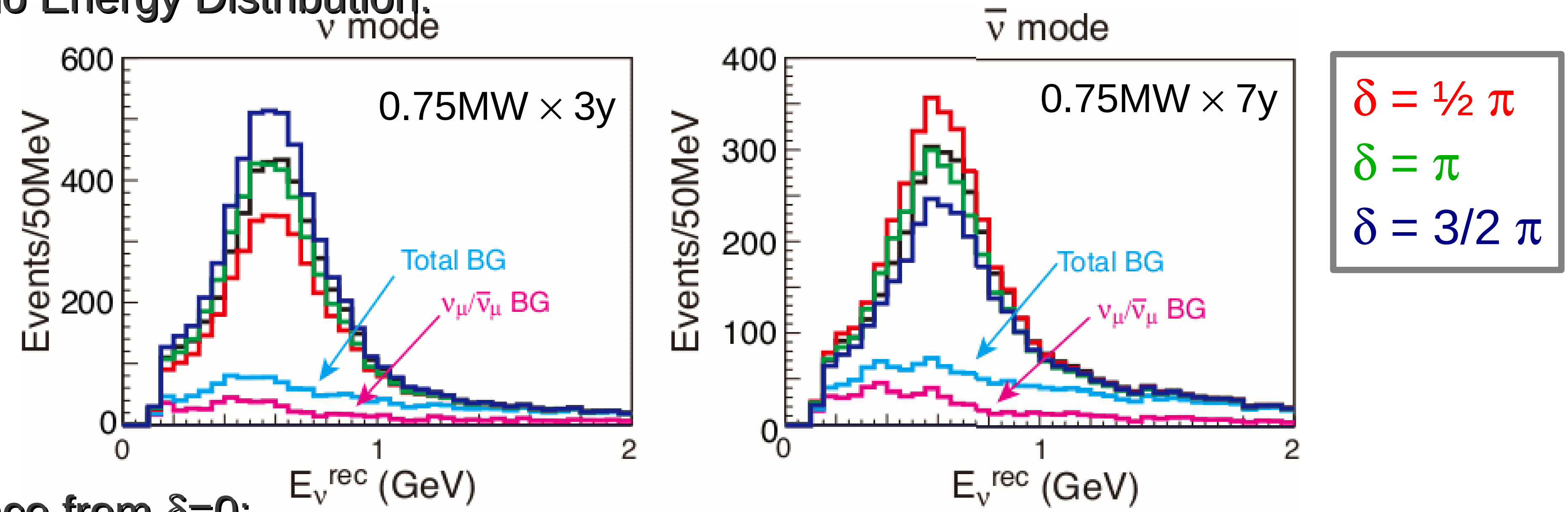


	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

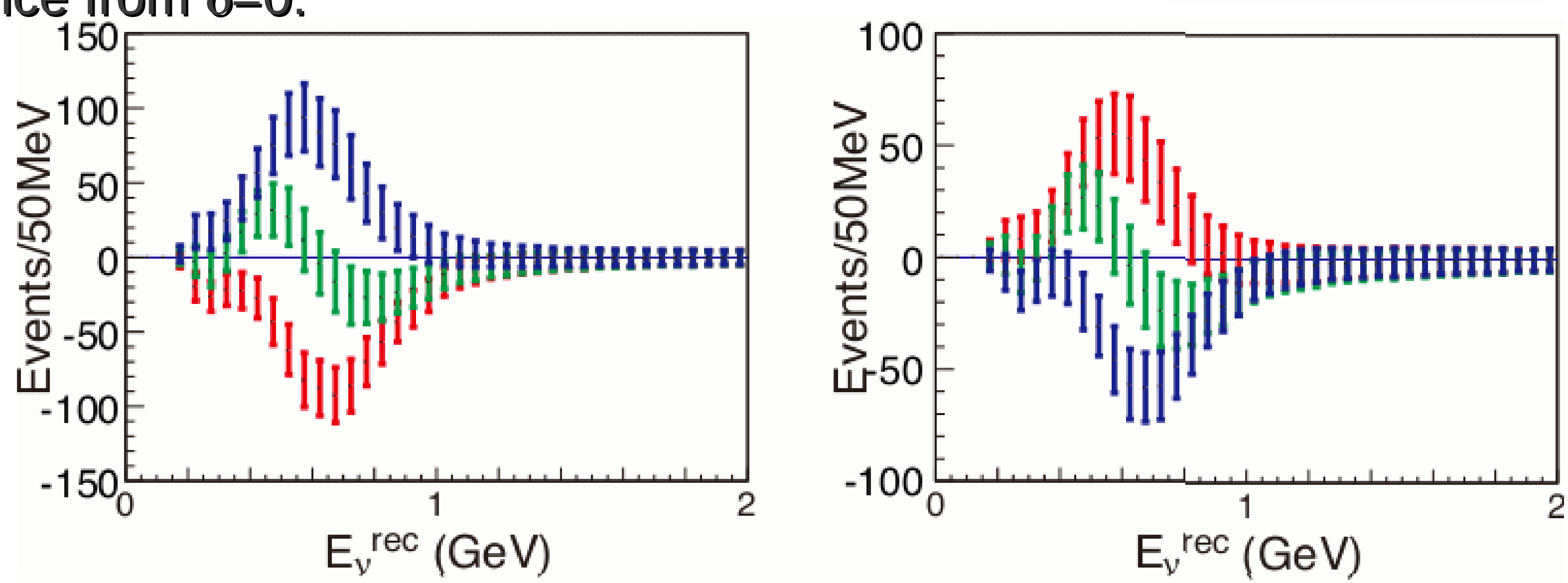
- ~2000 ~ 3600 events in $\bar{\nu}$ and ν beams, respectively
- Major backgrounds: beam $\nu_e/\bar{\nu}_e$ and NC-π^0

Effect of δ

Neutrino Energy Distribution:



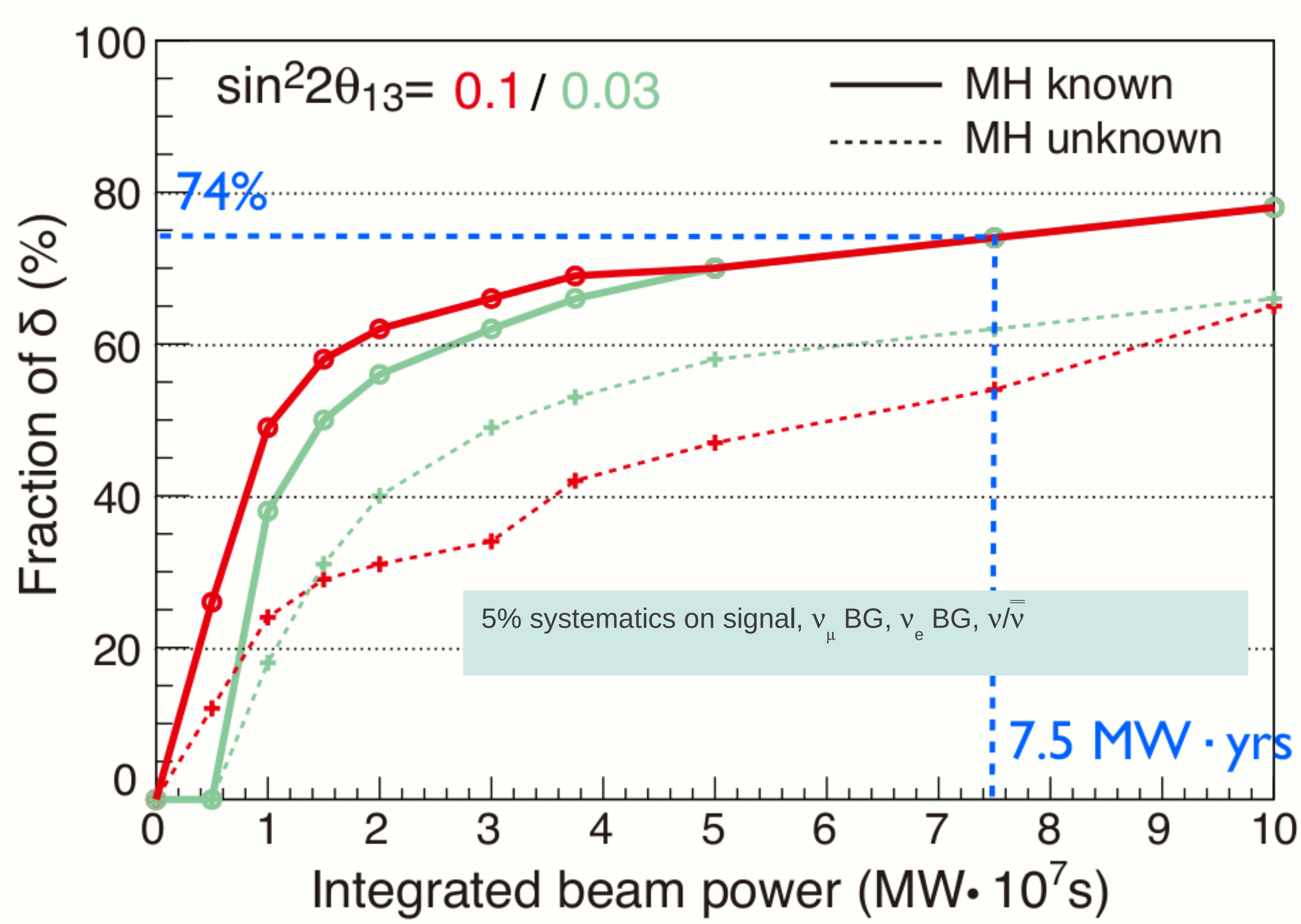
Difference from δ=0:



- Number + shape sensitive to all values of δ

Expected Sensitivity to CP Violation

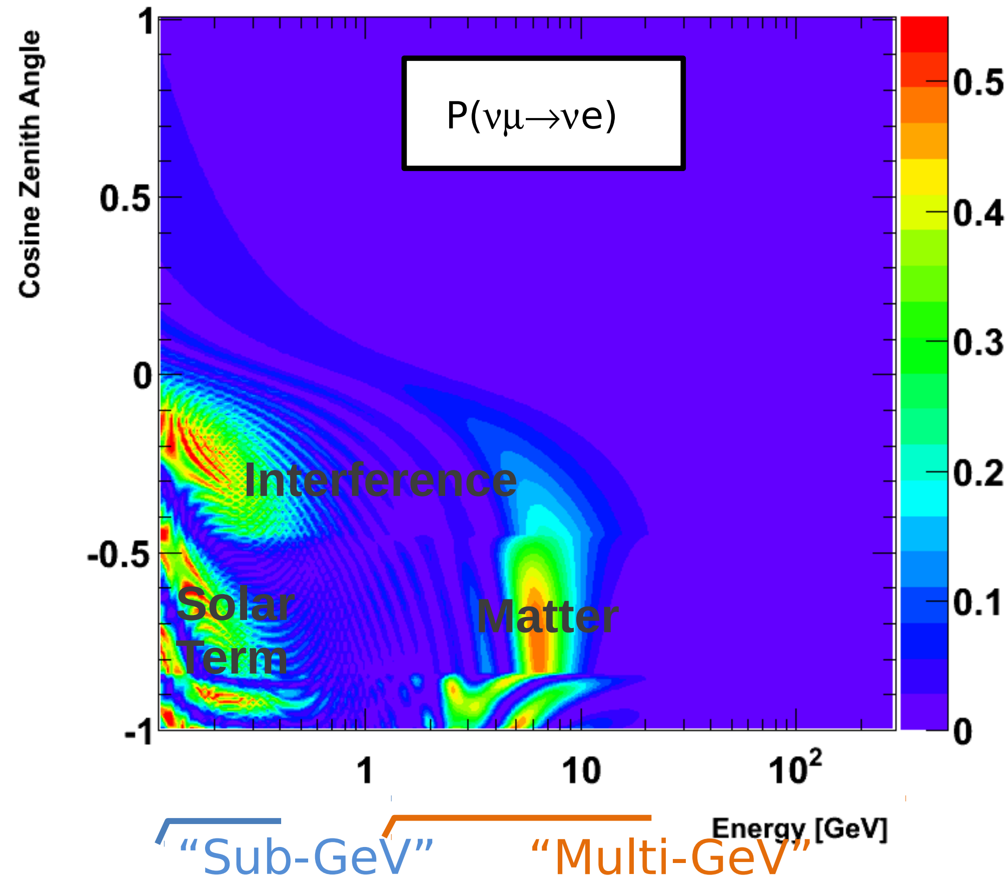
Fractional region of δ(%) for which the CPV ($\sin\delta \neq 0$) significance is $> 3\sigma$



Atmospheric Neutrinos

ν_e appearance and ν_μ distortion are expected due to the MSW effect in the Earth's matter:

- Mass hierarchy: asymmetry between neutrinos and antineutrinos
- Octant of oscillation: appearance (and $\nu_\mu \to \nu_\mu$ disappearance) interpl
- CP phase δ (and θ_{13}):magnitude o resonance effect.



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

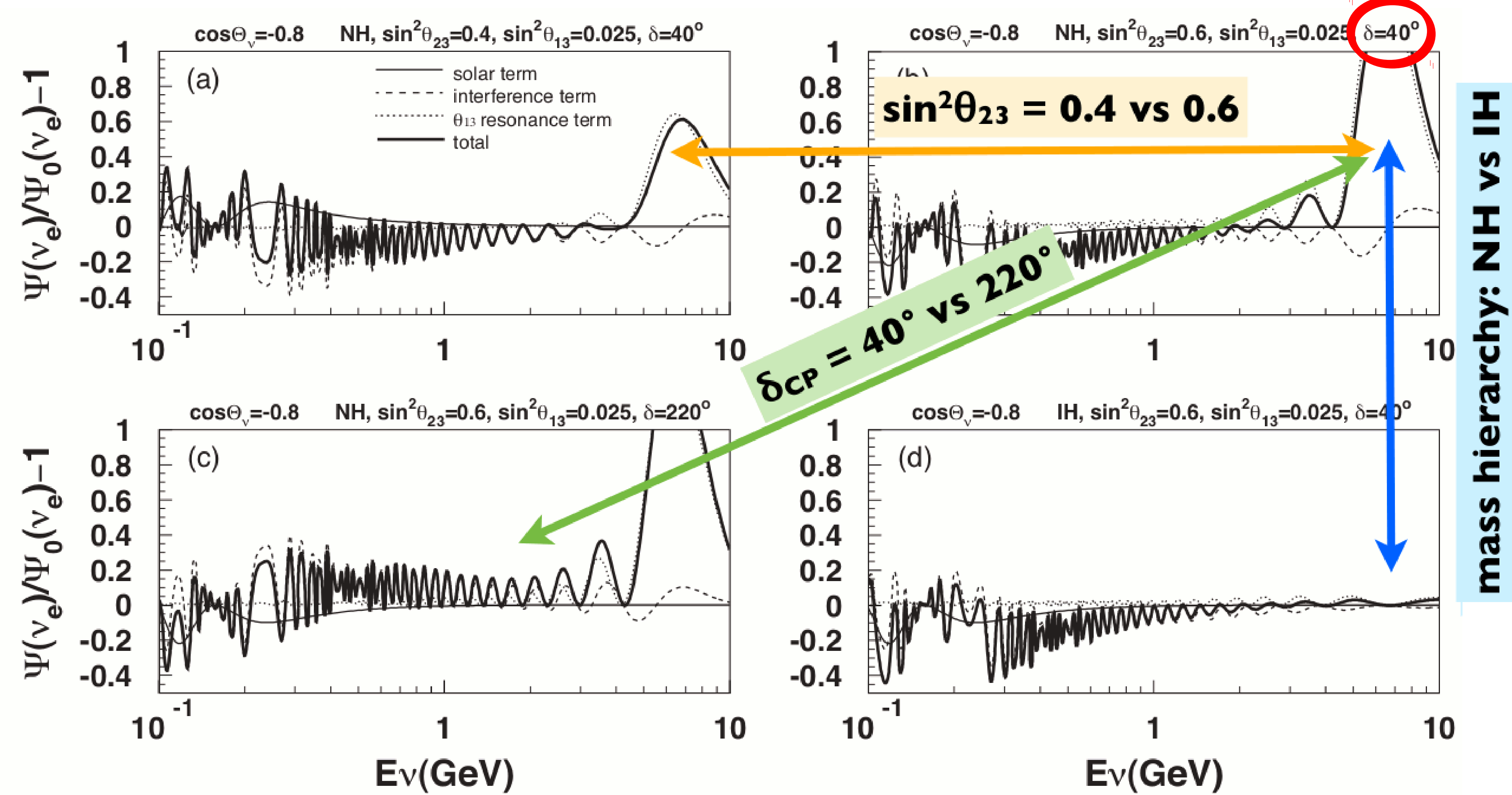
$$-r\sin\tilde{\theta}_{13}\cos^2\tilde{\theta}_{13}\sin 2\theta_{23}(\cos\delta R_2 - \sin\delta I_2)$$ Interference

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

$P_2 = P(\nu_e \to \nu_{\mu,\tau})$

R_2 and I_2 are the oscillation amplitudes for CP even and odd terms

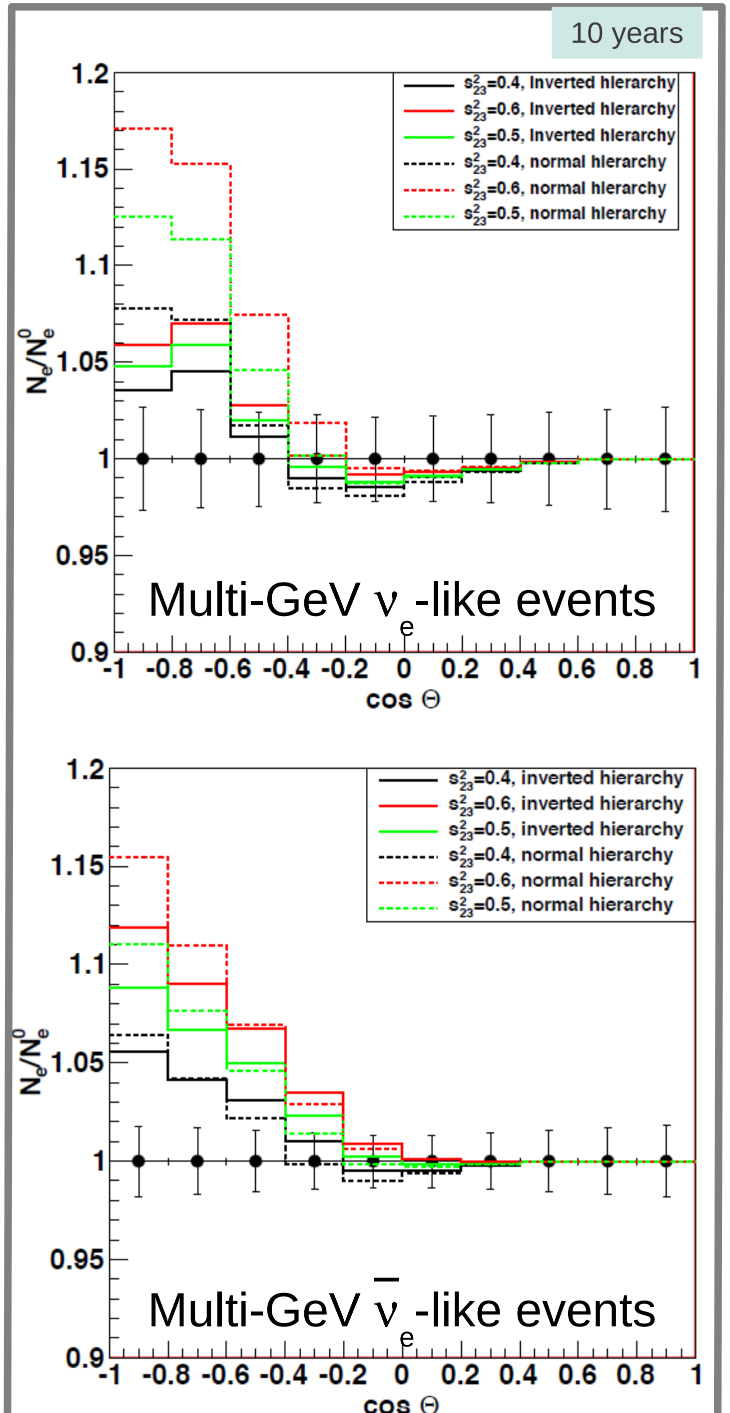
Oscillated ν_e flux relative to the non-oscillated flux as a function of the neutrino energy for the up-ward going neutrinos with zenith angle 0.8

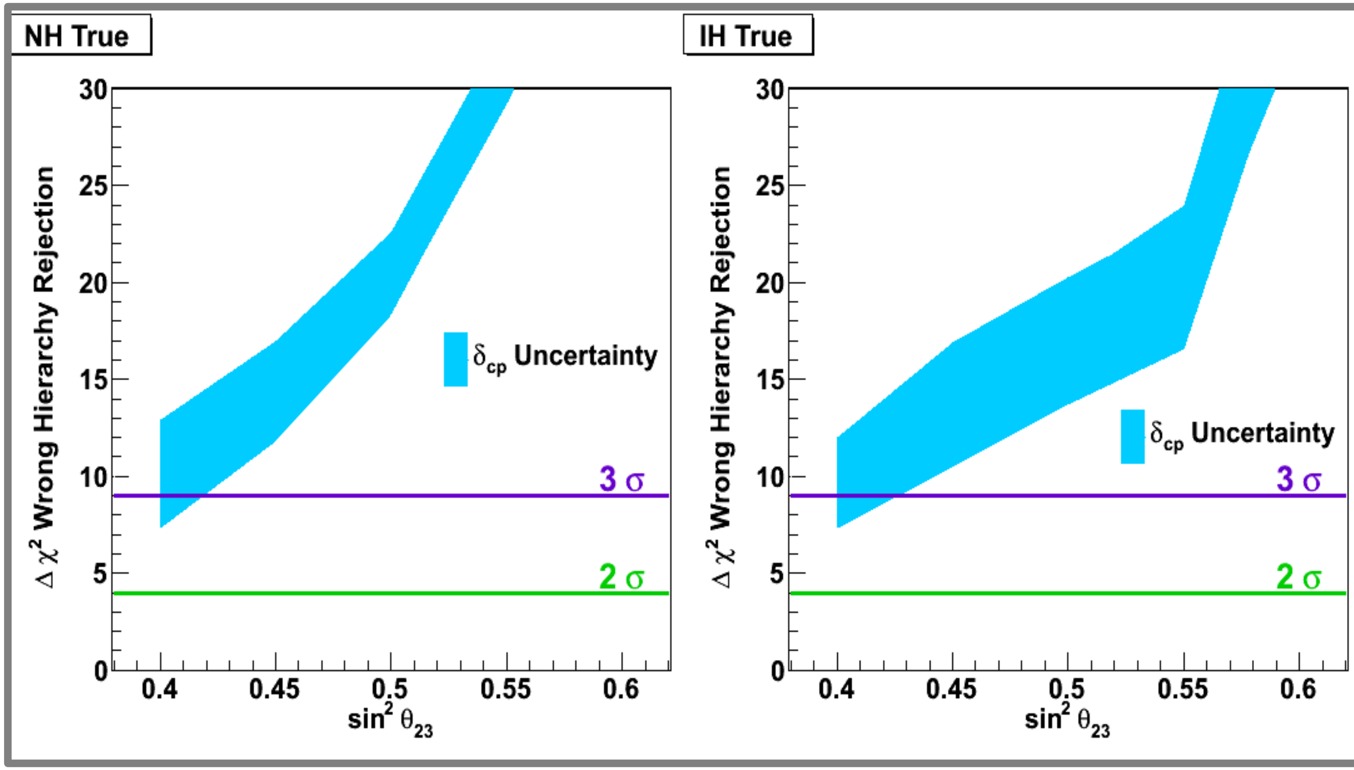


Through matter effect (MSW), we study:

- Mass Hierarchy: asymmetry between ν and $\bar{\nu}$
- Octant of θ_{23}: ν_e appearance and ν_μ disappearance interplay
- δ_{CP} (and θ_{13}): magnitude of resonance effect

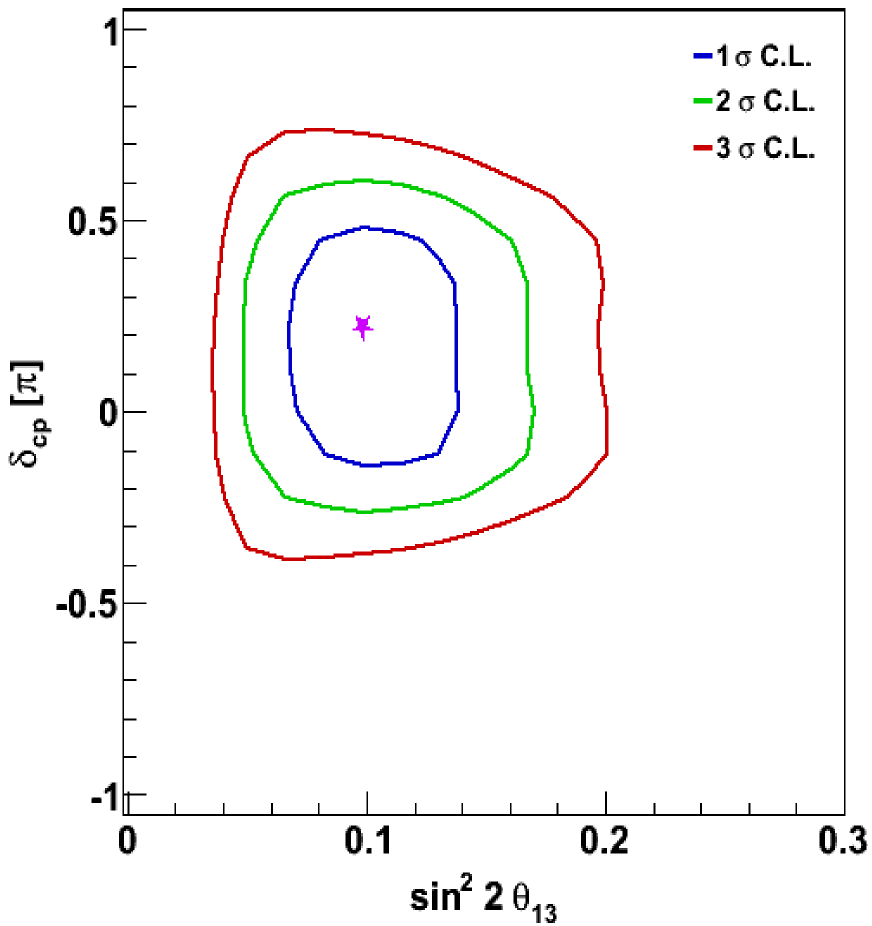
Mass Hierarchy Sensitivity



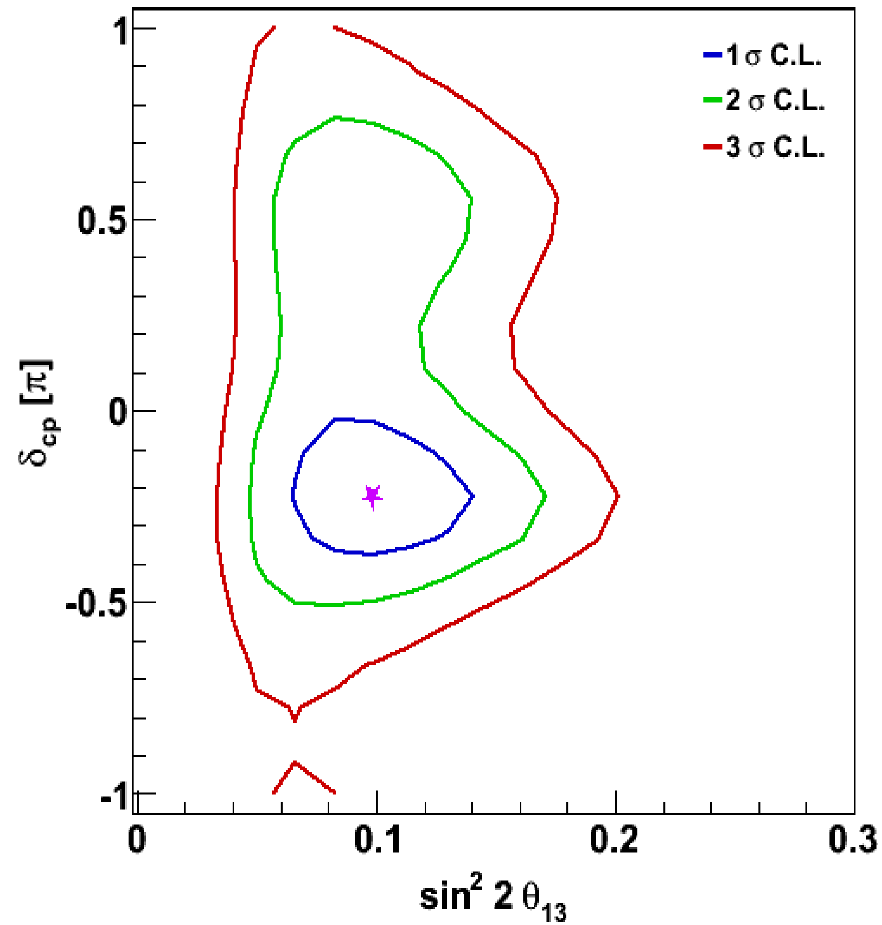


- Sensitivity mainly depends on θ_{23}, δ. Also some dependence on the mass hierarchy.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- <u>Caveat</u>: the $\Delta\chi^2$ method to determine the number of σ's is used.

Sensitivity to δ_{cp} and θ_{13} (No Reactor Constraint, NH)

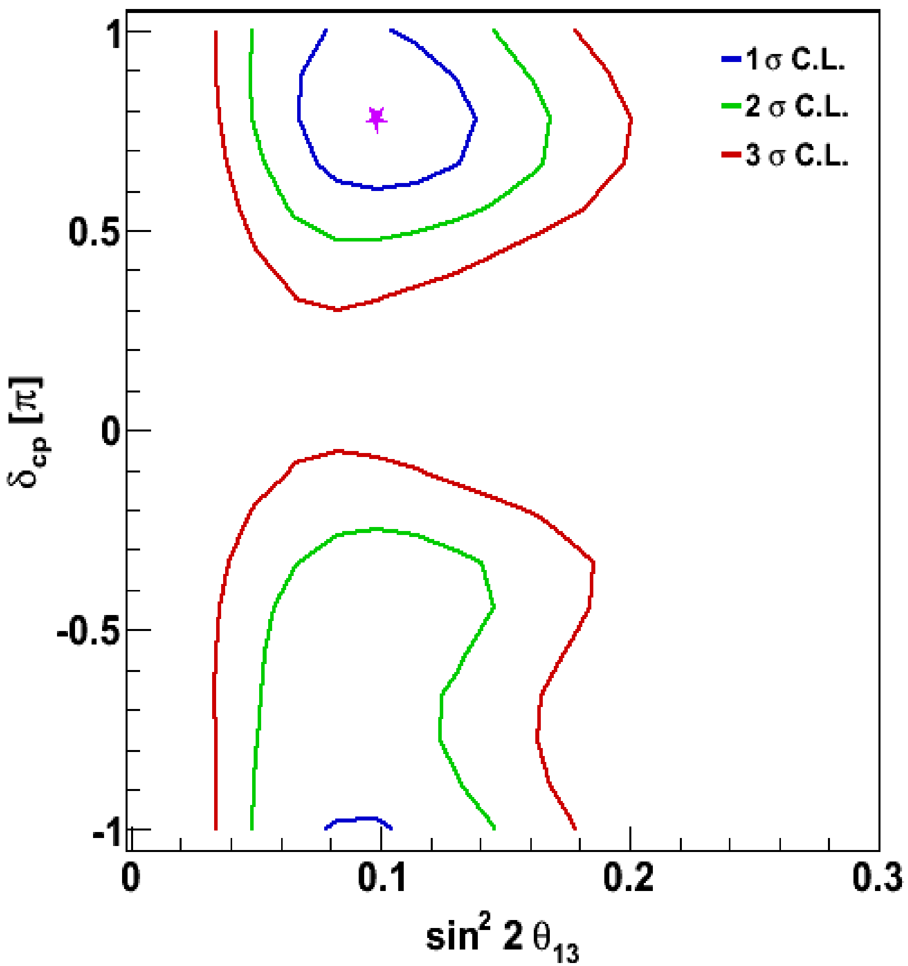


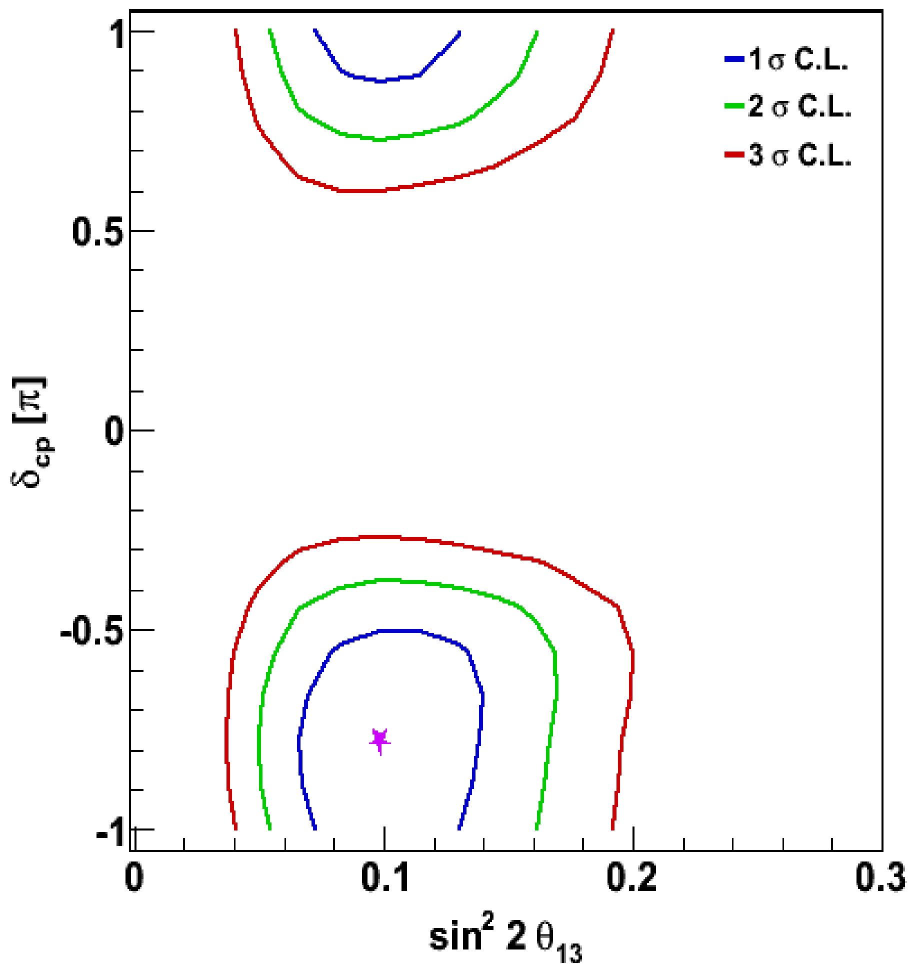
sin22θ13 = 0.10
σιν2θ23 = 0.50
Δμ232 = 2.4ξ10−3 ες2
δχπ = 0.698 (40 δεγ)



sin22θ13 = 0.10
σιν2θ23 = 0.50
Δμ232 = 2.4ξ10−3 ες2
δχπ = −0.698 (−40 δεγ)

Sensitivity to δ_{CP} and θ_{13} (No Reactor Constraint, NH)





$\sin^2 2\theta_{13} = 0.10$
$\sin^2\theta_{23} = 0.50$
$\Delta m^2_{32} = 2.4\text{x}10^{-3}\ \text{eV}^2$
$\delta cp = 2.443\ (140\ \text{deg})$

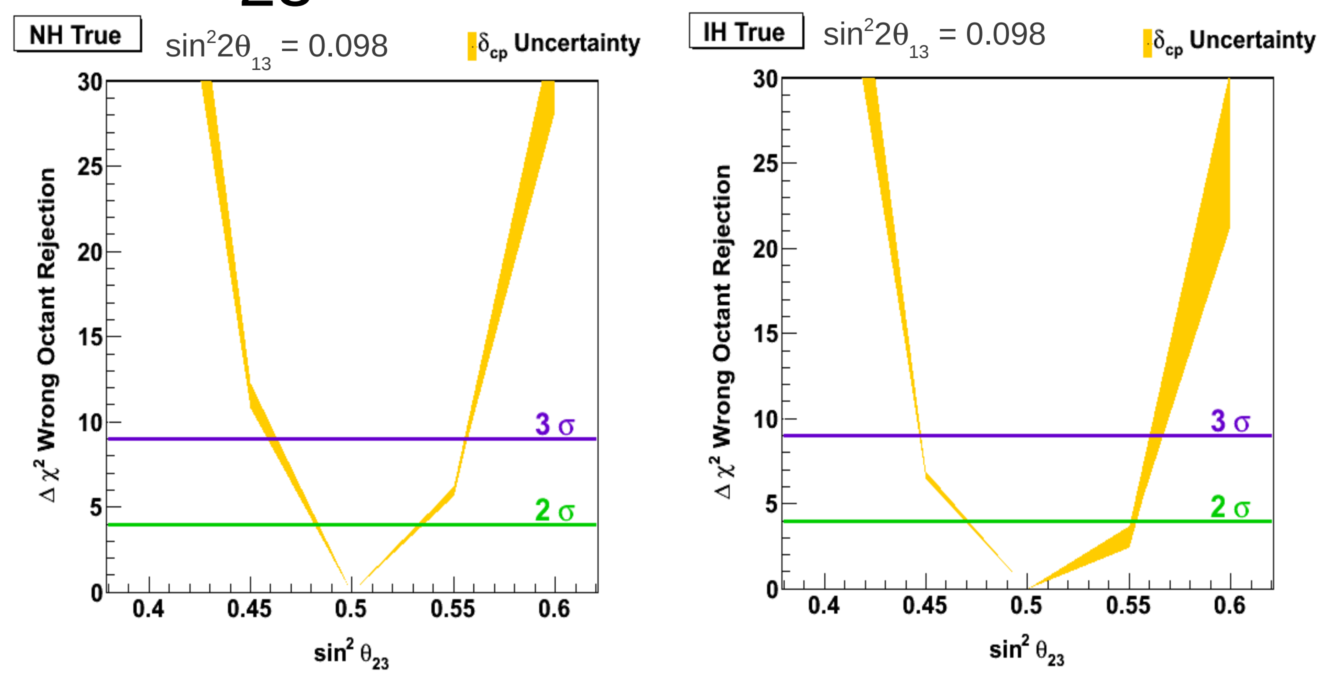
$\sin^2 2\theta_{13} = 0.10$
$\sin^2\theta_{23} = 0.50$
$\Delta m^2_{32} = 2.4\text{x}10^{-3}\ \text{eV}^2$
$\delta cp = -2.443\ (-140\ \text{deg})$

Atmospheric Neutrino Sensitivity Summary

Objective		Normal	Inverted	Comment
Hierarchy	2σ	$\sin^2 2\theta_{23} > 0.96$	$\sin^2 2\theta_{23} > 0.96$	5 years
	3σ	$\sin^2 \theta_{23} > 0.4$	$\sin^2 \theta_{23} > 0.4$	10 years
Octant	2σ	$\sin^2 2\theta_{23} > 0.997$	$\sin^2 2\theta_{23} > 0.99$	5 years
	3σ	$\sin^2 2\theta_{23} > 0.99$	$\sin^2 2\theta_{23} > 0.97$	5 years

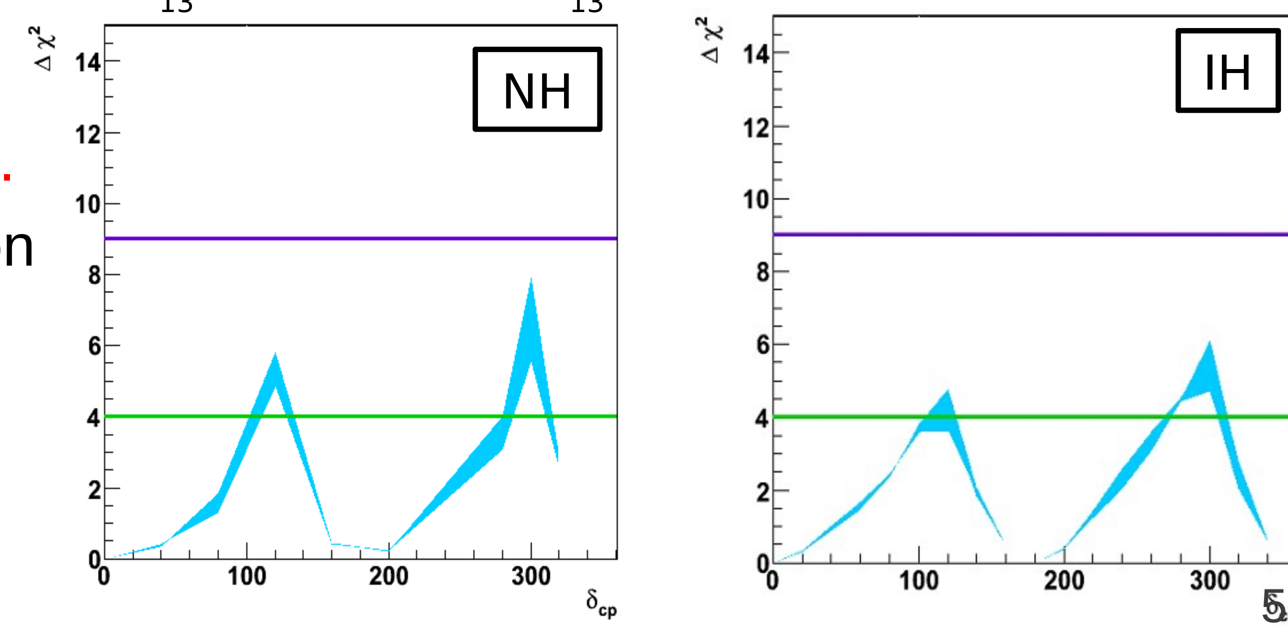
Sensitivity for θ_{23} Octant and CPV

- θ_{23} octant sensitivity.
- Thickness of the band corresponds to the uncertainty from δ_{CP}.



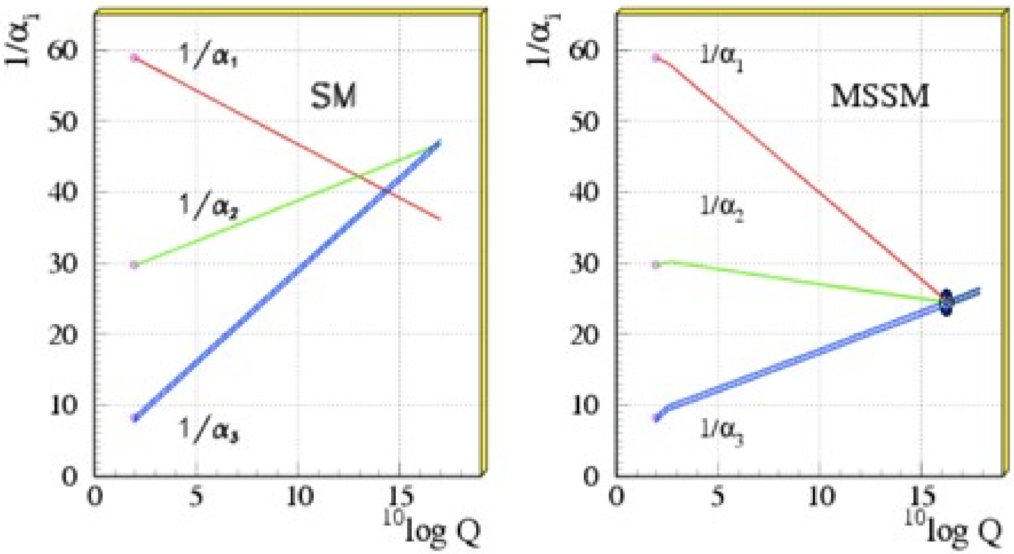
θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.099$

- Excluded 3σ δ_{CP} fraction.
- Sensitivity to CP-violation is limited under both hierarchy assumptions.



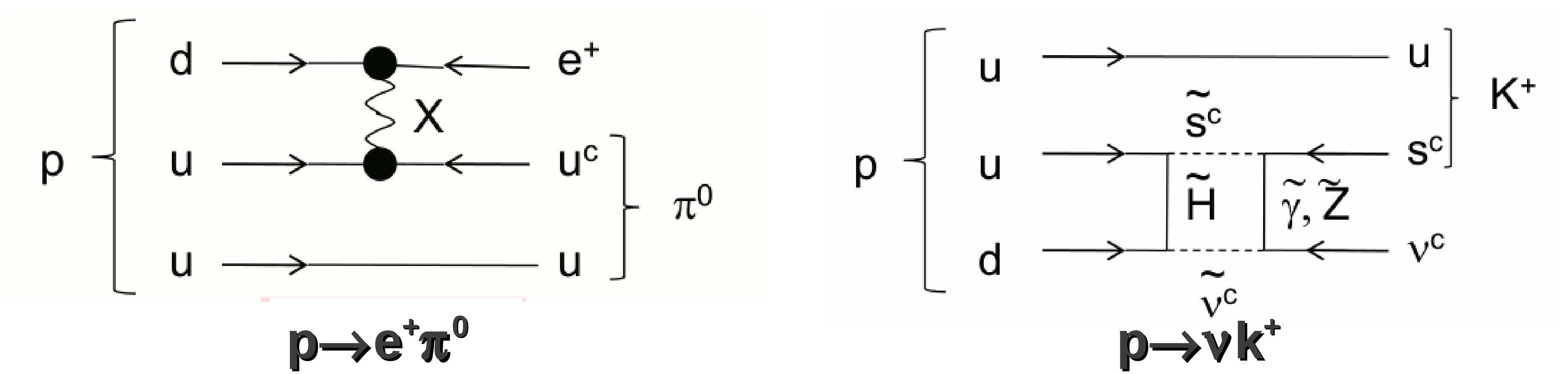
Nucleon Decays

- Only direct probe of Grand Unified Theories



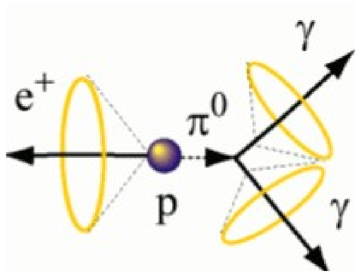
- Many GUT models predict decays of protons and bound neutrons with $\tau = O(10^{34\text{-}35})$ years.

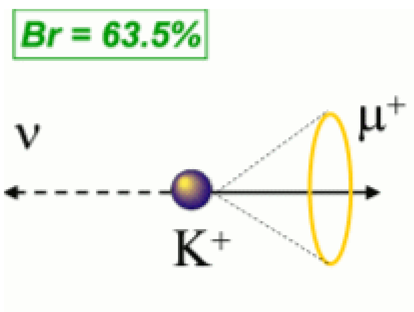
- Two modes favoured by many models:

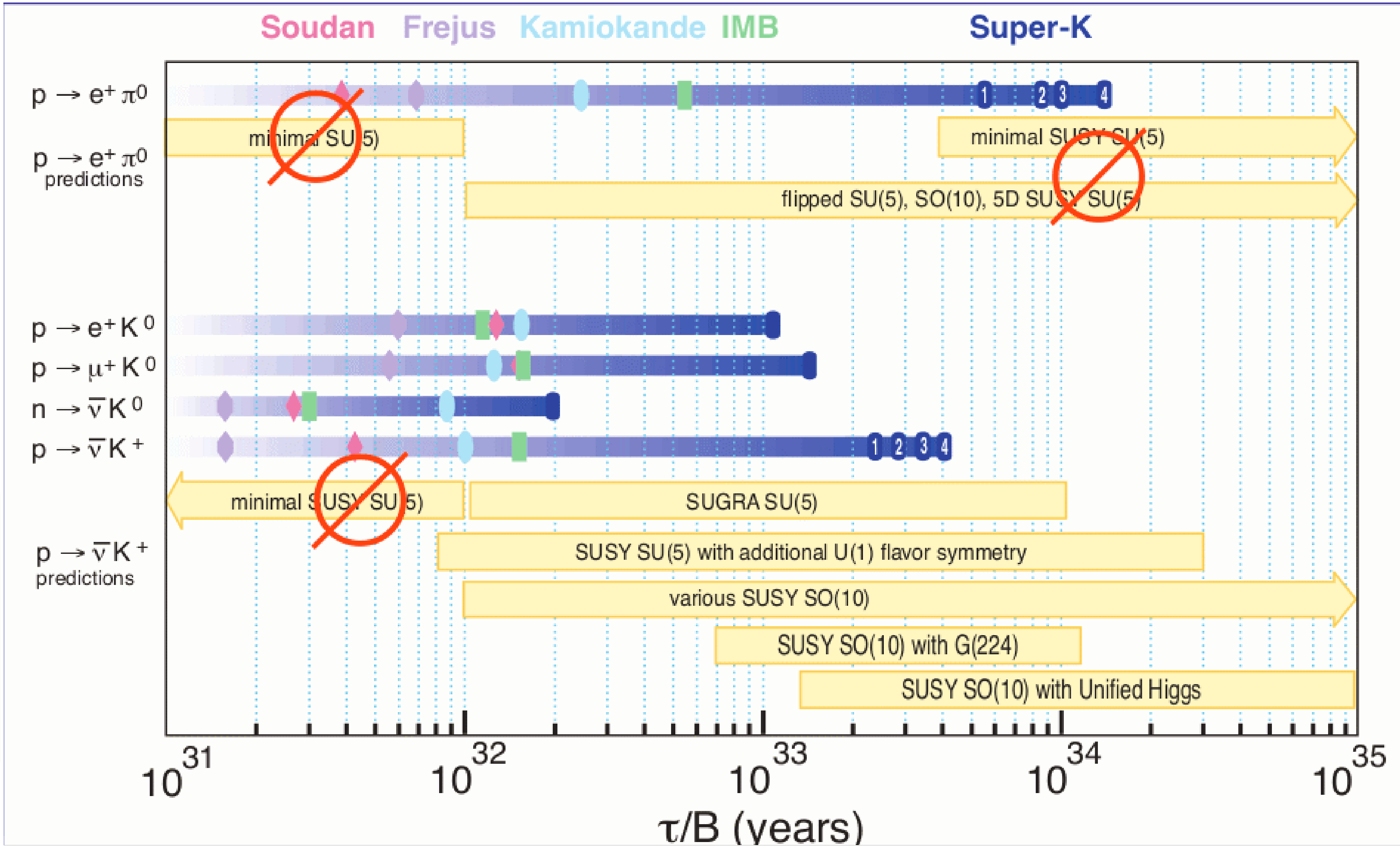


- Other modes are also important.

Experimental Limits







- Most stringent limits from Super-K for many decay modes.
- No signal evidence has been found → give constraints on models.
- After 15y Super-K running (220kton years):

  $\tau(p \to e^+\pi^0) > 1.3\times10^{34}$ y $\tau(p \to \nu k^+) > 4.0\times10^{33}$ y @90%CL
- Order of magnitude necessary to be significant.