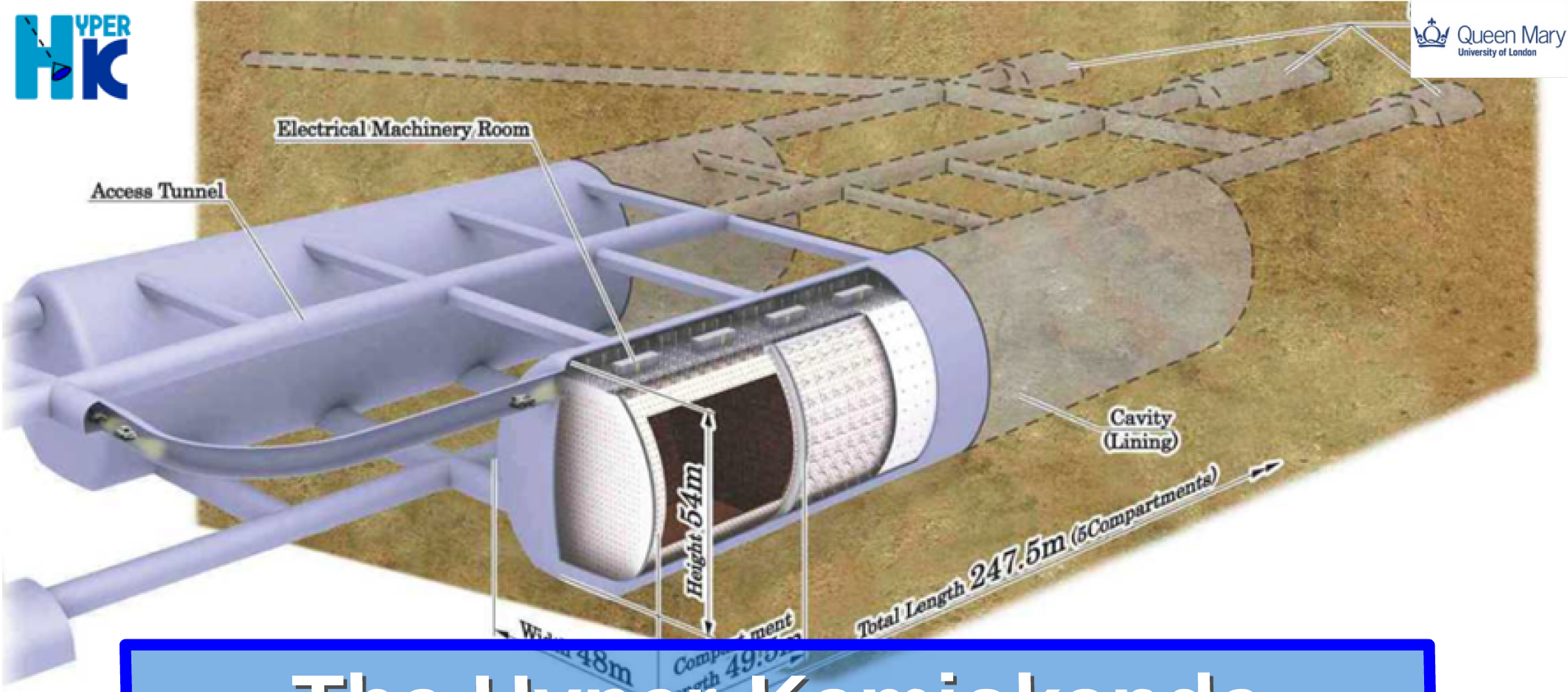


The Hyper-Kamiokande Project

Ryan Terri (QMUL)

ESSνSB Meeting
Lund, Sweden, 13-14 March 2014

Neutrino Oscillation: Open Questions

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

θ_{23} : "atm." mixing angle θ_{13} θ_{12} : "solar" mixing angle

$$\left(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}\right)$$

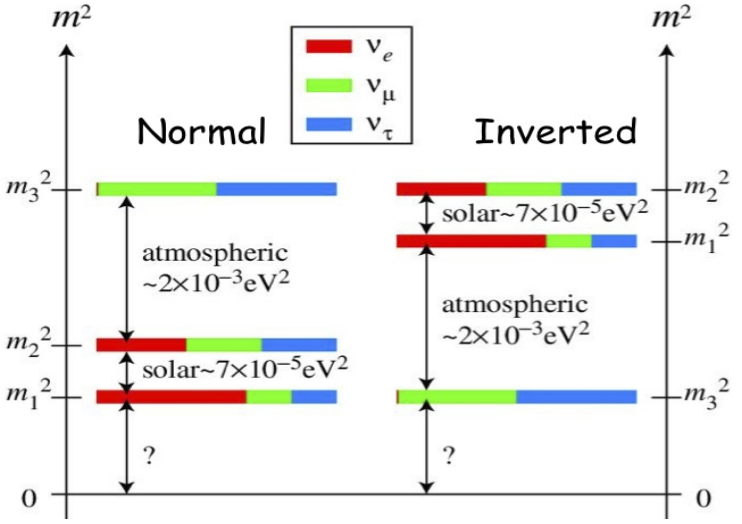
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i}U_{\alpha i}^{*}U_{\beta j}^{*}U_{\alpha j}\right]\sin^{2}\left(\frac{\Delta m_{ij}^{2}L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i}U_{\alpha i}^{*}U_{\beta j}^{*}U_{\alpha j}\right]\sin\left(\frac{\Delta m_{ij}^{2}L}{2E}\right)$$

Unknown which mass eigenstate is lightest

Unknown what δ_{CP} value is

Unknown is θ_{23} is 45° (40° +5°/-2°)

Unknown if U_{PMNS} is unitary or not

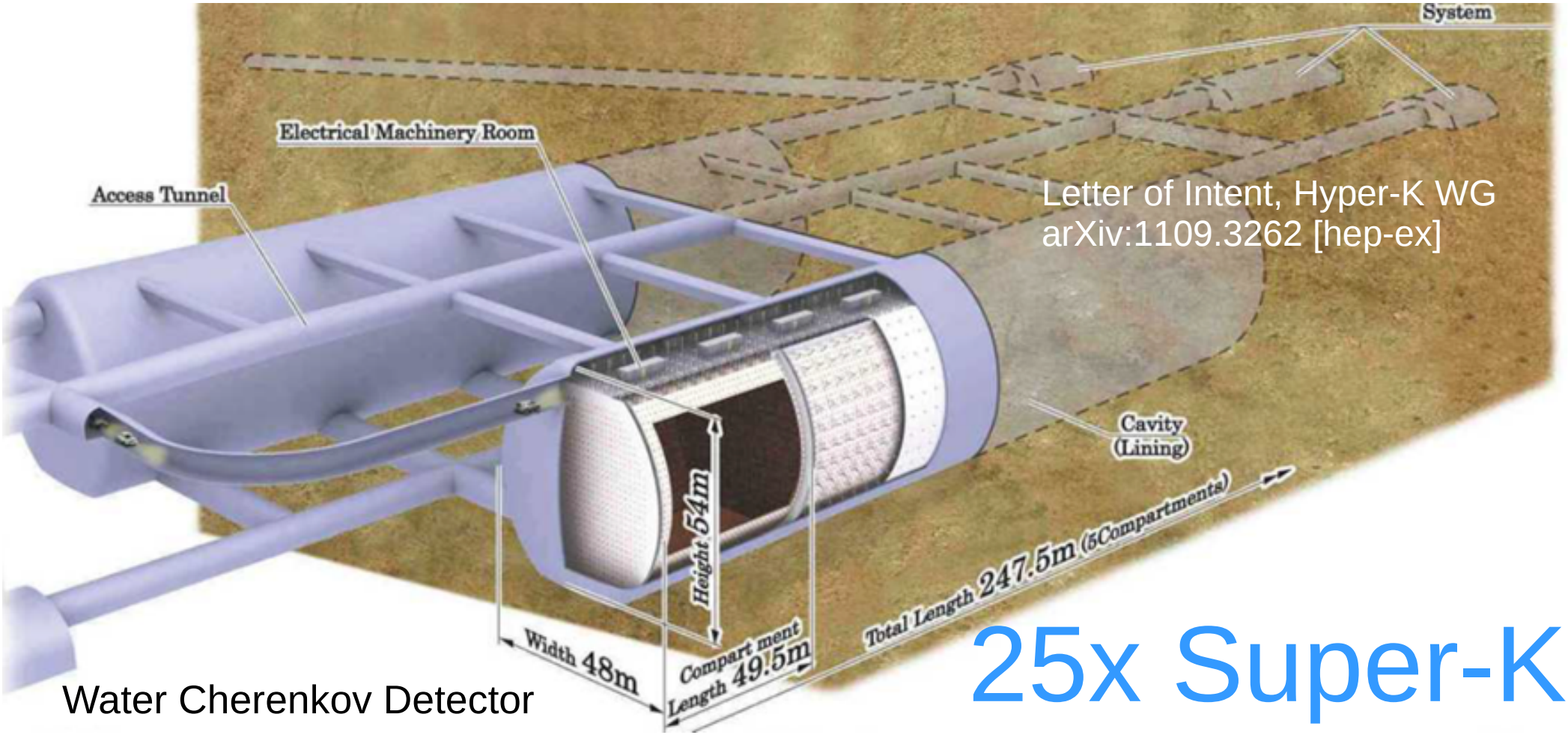


$\Delta m^2_{ij} = m_i^2 - m_j^2$

L = distance travelled (km)

E = neutrino energy (GeV)

Hyper-Kamiokande



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

25x Super-K

Water Cherenkov Detector

Total Volume: 0.99 Mton
Inner Volume: 0.74 Mton
Fiducial Volume: 0.56 Mton (10 compartments*)
Outer Volume: 0.2 Mton

99000 20” PMTs (20% photo-coverage) in Inner Detector (ID)
25000 8” PMTs for Outer Detector (OD)
*still being optimized

Also includes neutrino beam from J-PARC in experimental definition

The Hyper-Kamiokande Project

- Four International Open Meetings (2012-2014) @ IPMU, Japan.
- Formed international working groups.

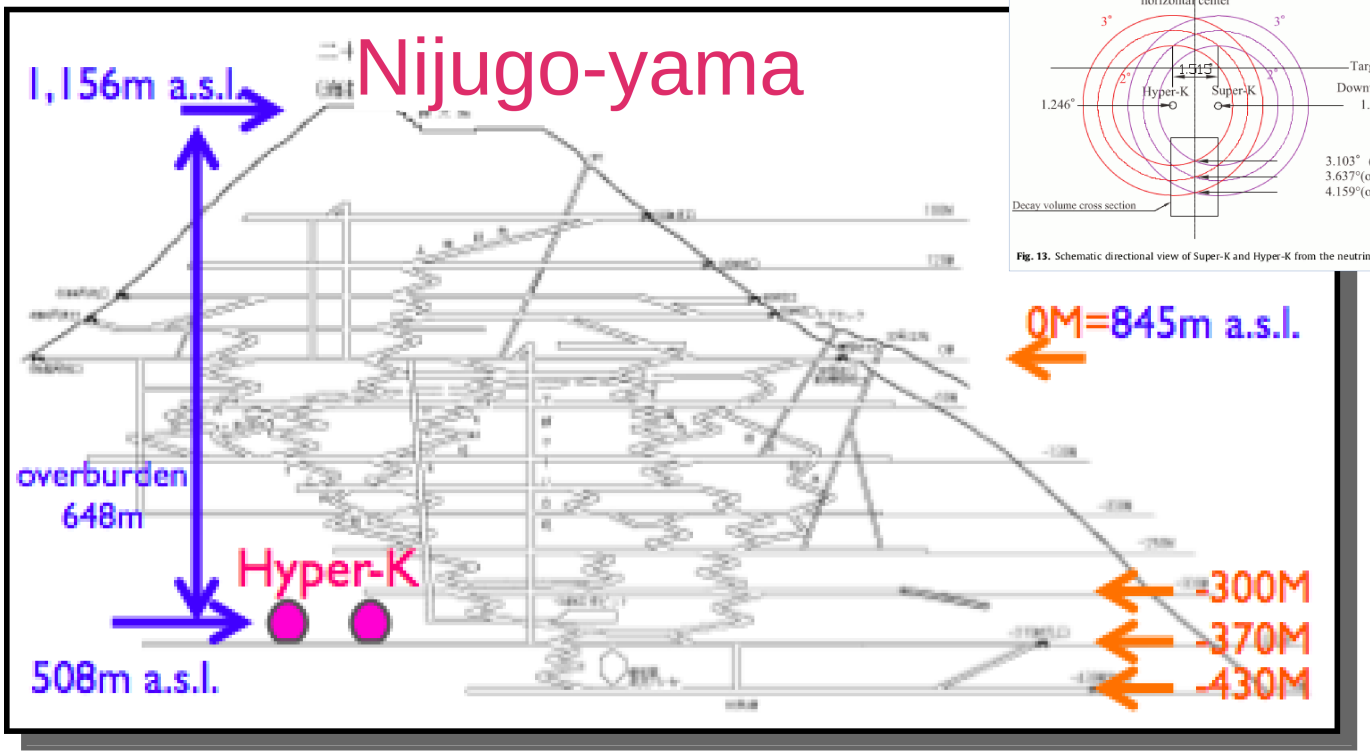
August 21-23, 2012
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=7
January 14-15, 2013
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=10
June 21-22, 2013
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=23
January 27-28, 2014
http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=29

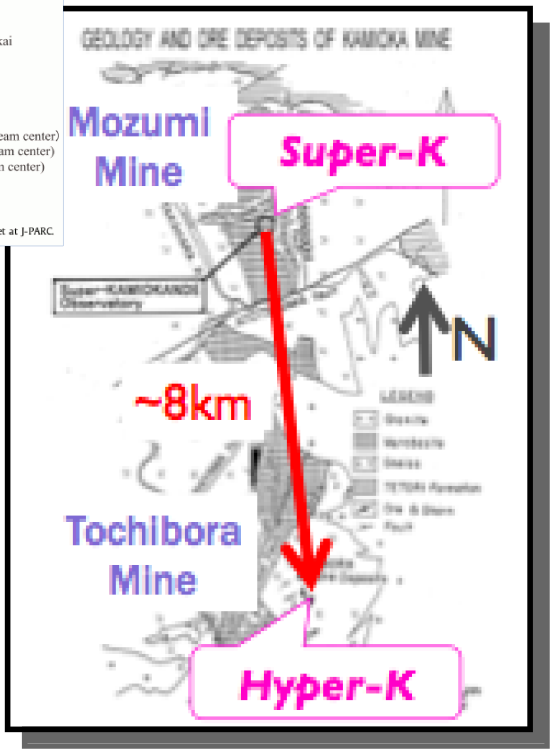
Please look at the slides from the meetings for detailed information on topics

Possible Locations

2 possible locations: Tochibora & Mozumi (current site of SK)

Both sites are 2.5° off-axis & 295km from beam target at J-PARC





Tochibora: ~650 m rock, 1755 mwe; HK can be built there with current techniques

Mozumi: deeper cavern than SK (~800 m)

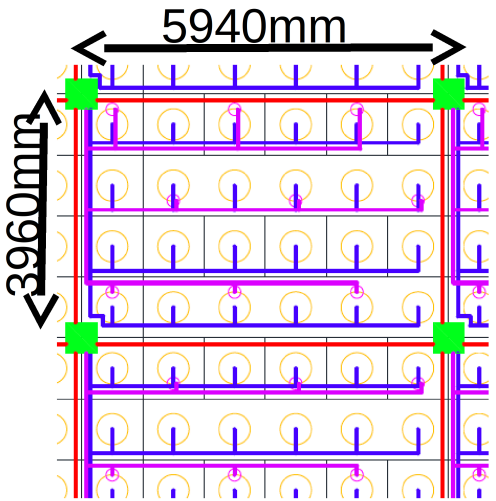
Rock quality comparable w/ Tochibura

More geologic tests underway

Tank Design

All major parts of the HK tank has been designed

Electronics



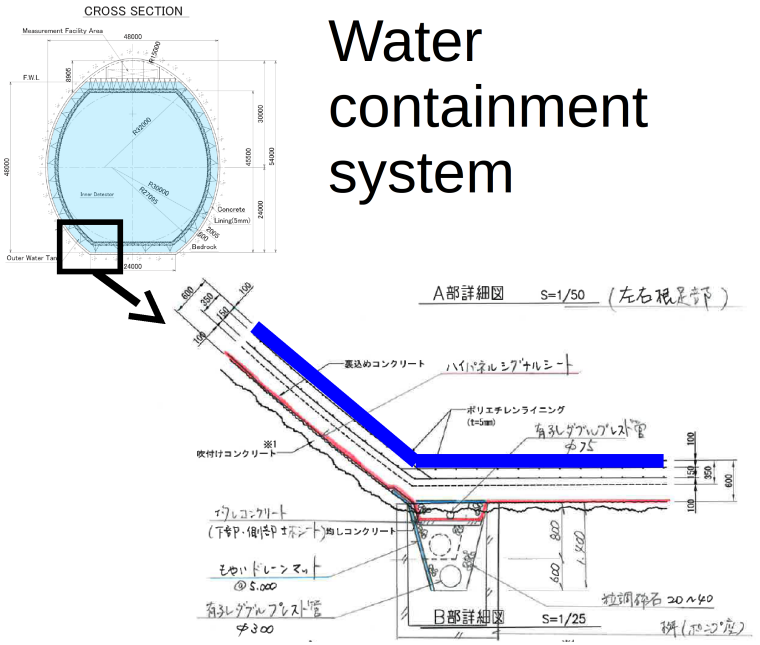
—: Support structure
—: Cable for inner PMT
—: Cable for outer PMT
—: Network/Power cable

■ : Hub / Front End Electronics

○ : Inner photo-sensor (20”)

○ : Outer photo-sensor (8”)

Water containment system



Water piping layout

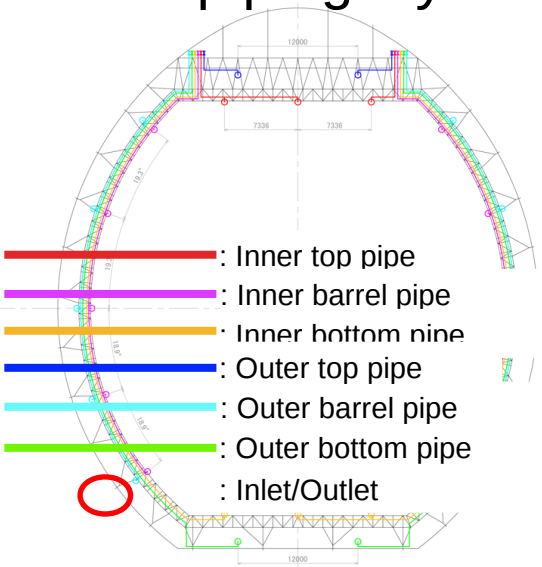
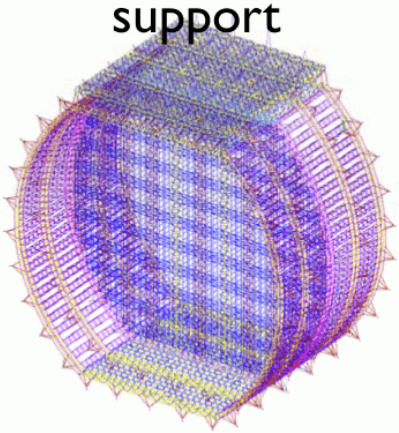
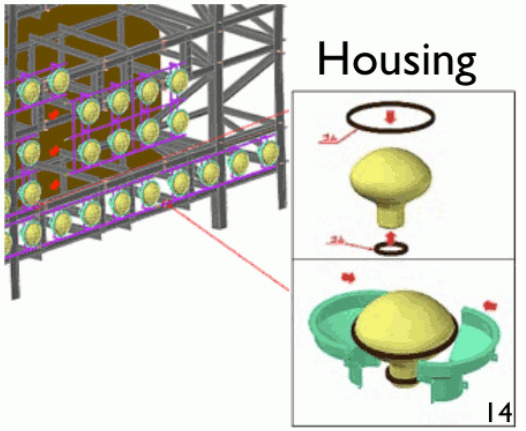


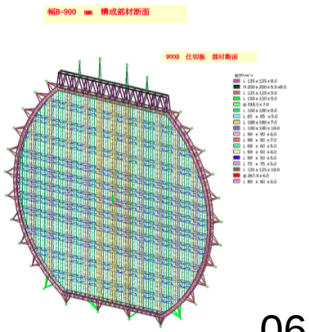
Photo-sensor support



Mounting Photo-sensor



Separation wall



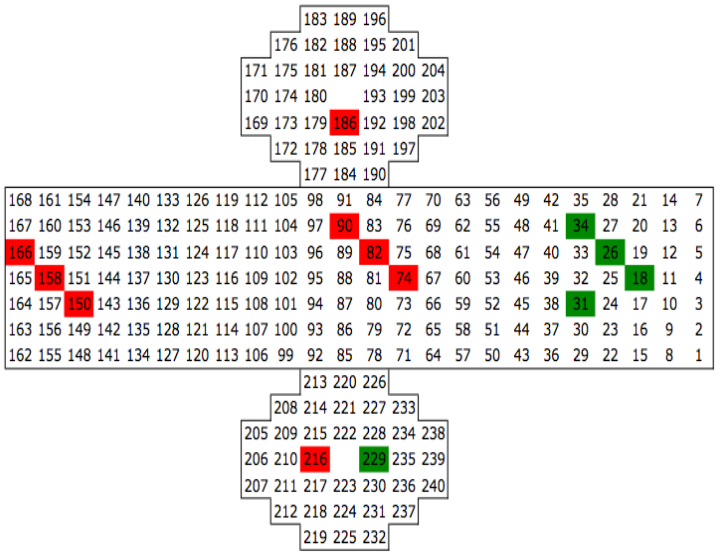
PMT Development & Testing

Photo-detectors

R&D going on to get better performance and lower cost.

established | *R&D* | *R&D*

quantum eff. (QE)	22%	30%	30%
collection eff. (CE)	80%	93%	95%
timing resolution (FWHM)	5.5 nsec	2.7 nsec	1 nsec



8″ HPDs
20″ high-QE PMTs

EGADS: demonstrating safety & effectiveness of Gd-doped water
240 inward-facing PMTs

EGADS used to test high-QE PMTs

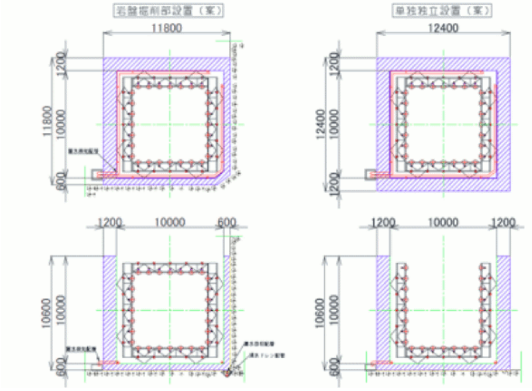
Has 227 PMTs (R3600; currently in SK) for reference for photo-detector evaluation

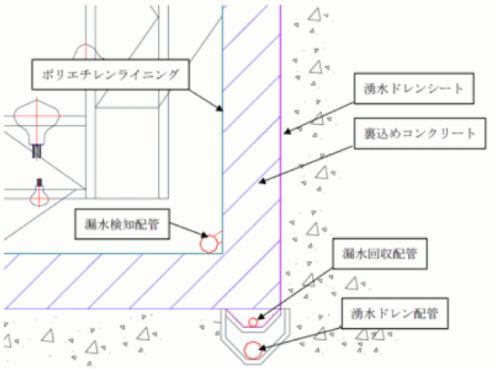
1kton WC Prototype

•Prototype (1kton, ~10×10×10 m^3) for R&D test approved in Japan as Grant-in-Aid: ~ USD 1.7M/5 years (2013-17).

- It's one of the 20 proposals selected each year from all areas in science.

- Main feasibility studies:
  - Photosensor and corresponding support structure
  - Liners
  - Leak water collection detection
  - DAQ
  - Electronics
  - Calibration system
  - ….

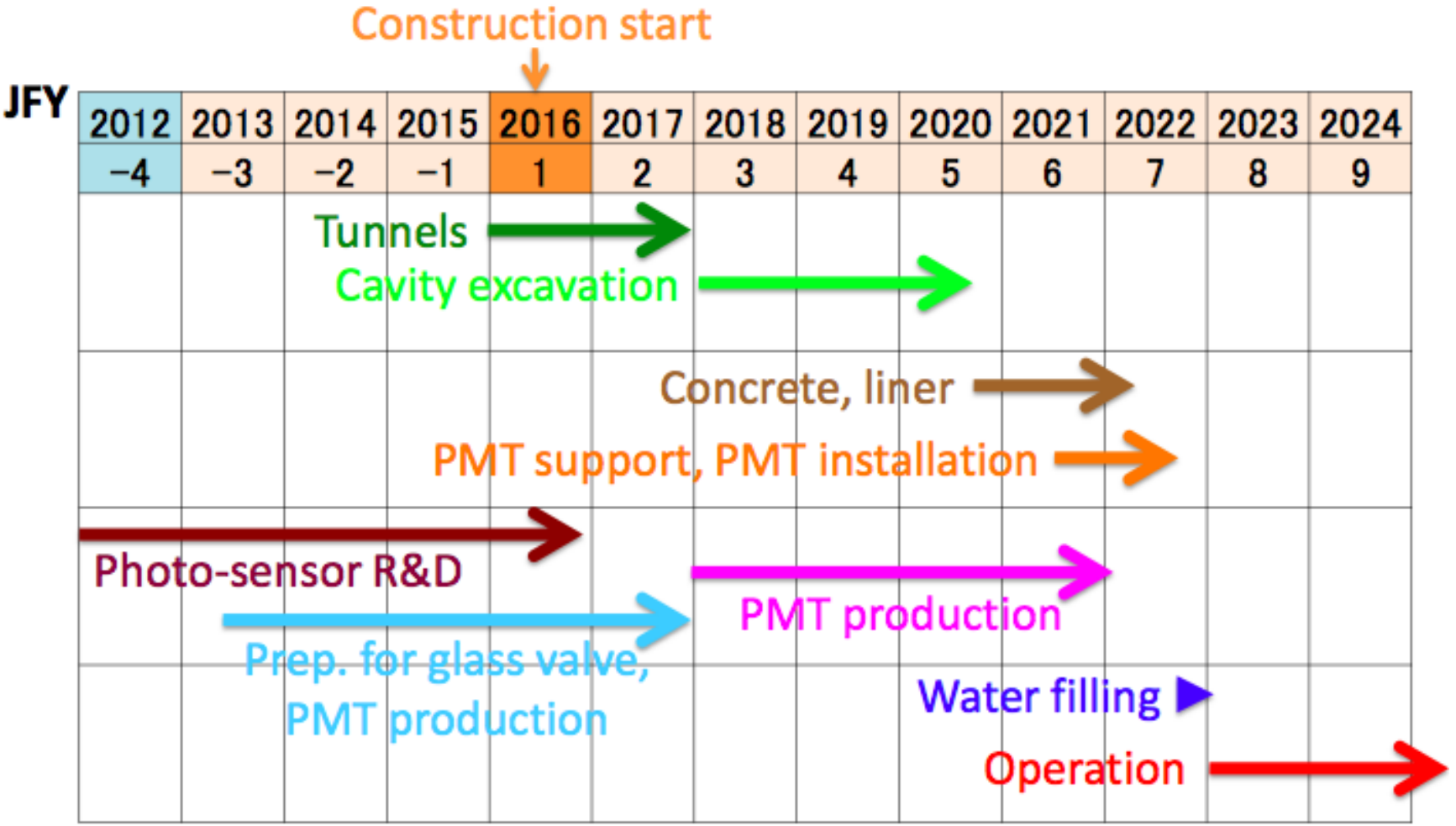




- Location site (J-PARC, KEK, Kamioka) being discussed.

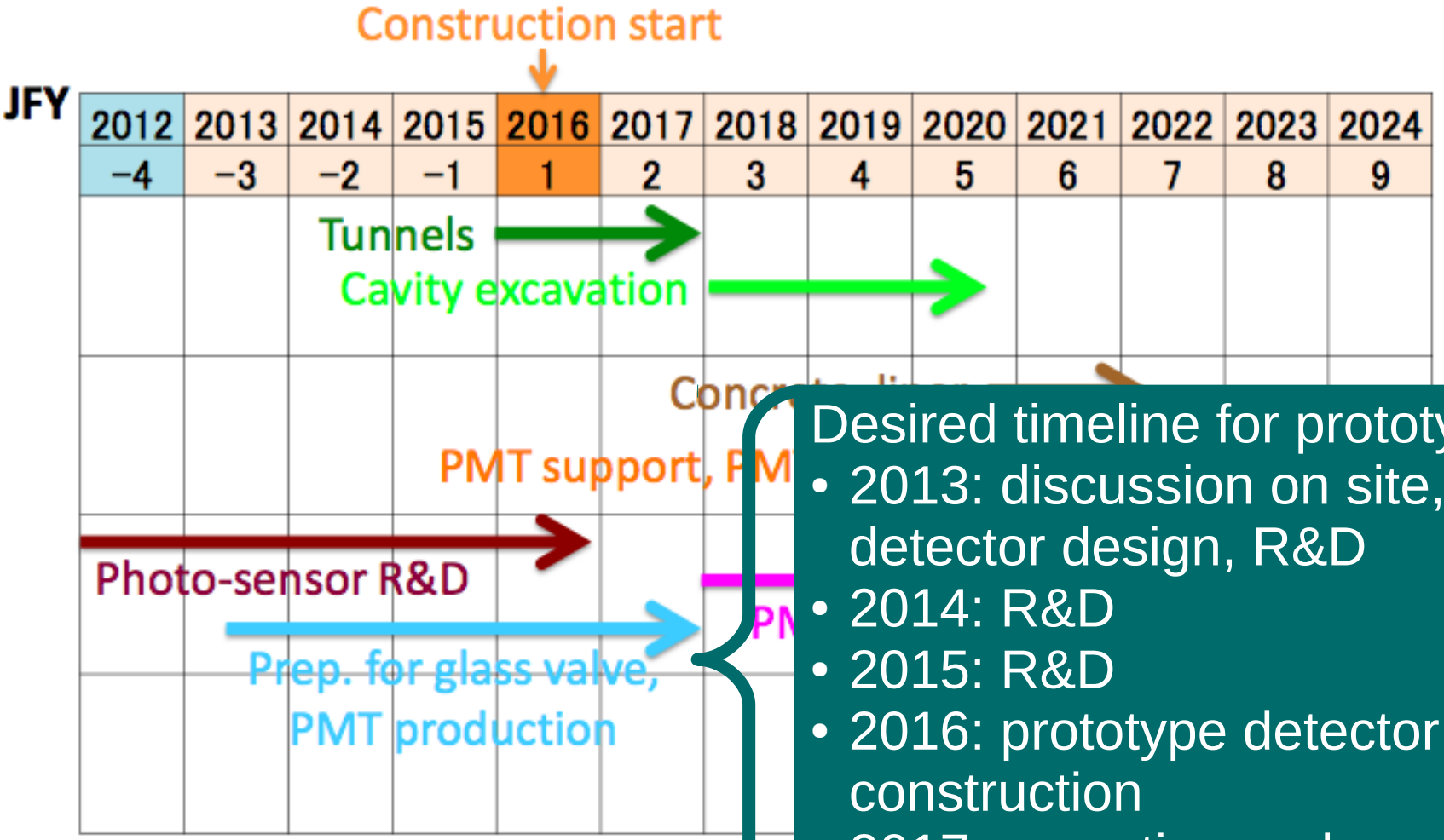
Overall Project Schedule

- Overall HK construction: ~7 years
- Assuming full funding starting in 2016.



Overall Project Schedule

- Overall HK construction: ~7 years
- Assuming full funding starting in 2016.

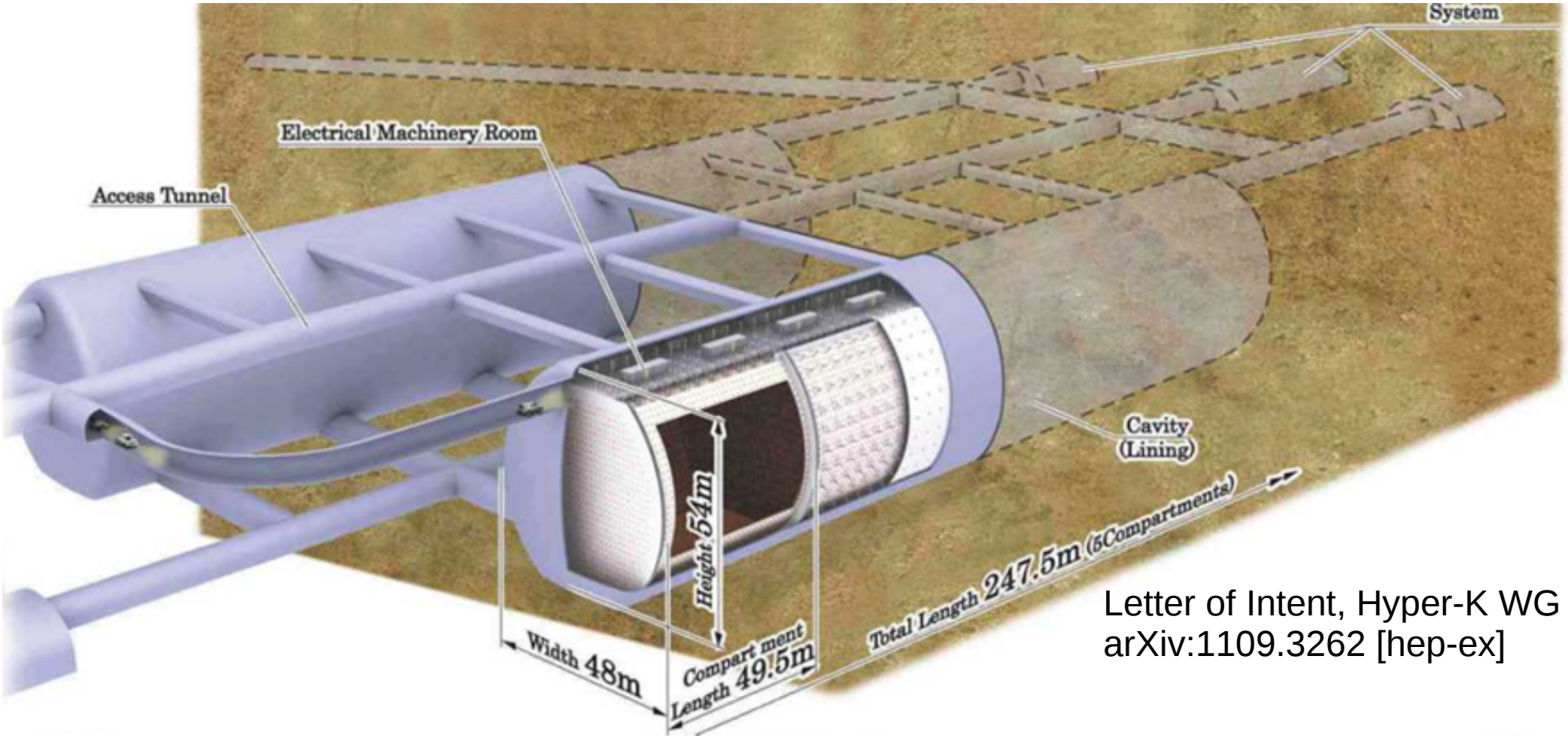


Desired timeline for prototype
- 2013: discussion on site, detector design, R&D
- 2014: R&D
- 2015: R&D
- 2016: prototype detector construction
- 2017: operation and conclusion on components

J-PARC Upgrades

- Plan for upgrade to the J-PARC beam line pointed at HK is in development
  - Goal to increase power for running a 1.5MW*yr through various improvements in J-PARC accelerators and neutrino beam line
  - Please see proceeding from T. Ishida from NuFact2013 (arXiv:1311.5287 [hep-ex])
- LoI to J-PARC being developed for this plan as well as new near detectors in an intermediate location
  - 1-2 km from neutrino target
  - Complementary designs to constrain flux & cross section uncertainties
    - Both have water targets
  - Submit April 2014

Hyper-Kamiokande Physics



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

Multi-purpose detector

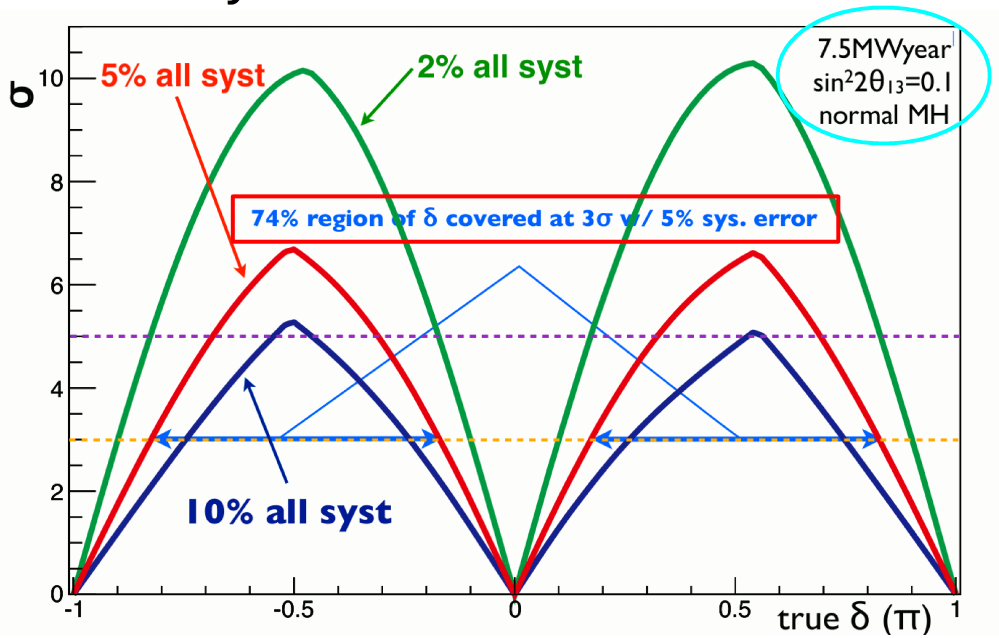
Atmospheric Neutrino Oscillations
Beam Neutrino Oscillations
Solar Neutrino Oscillations

Proton Decay Searches
Relic Supernova Neutrinos
Other Astrophysical Neutrinos

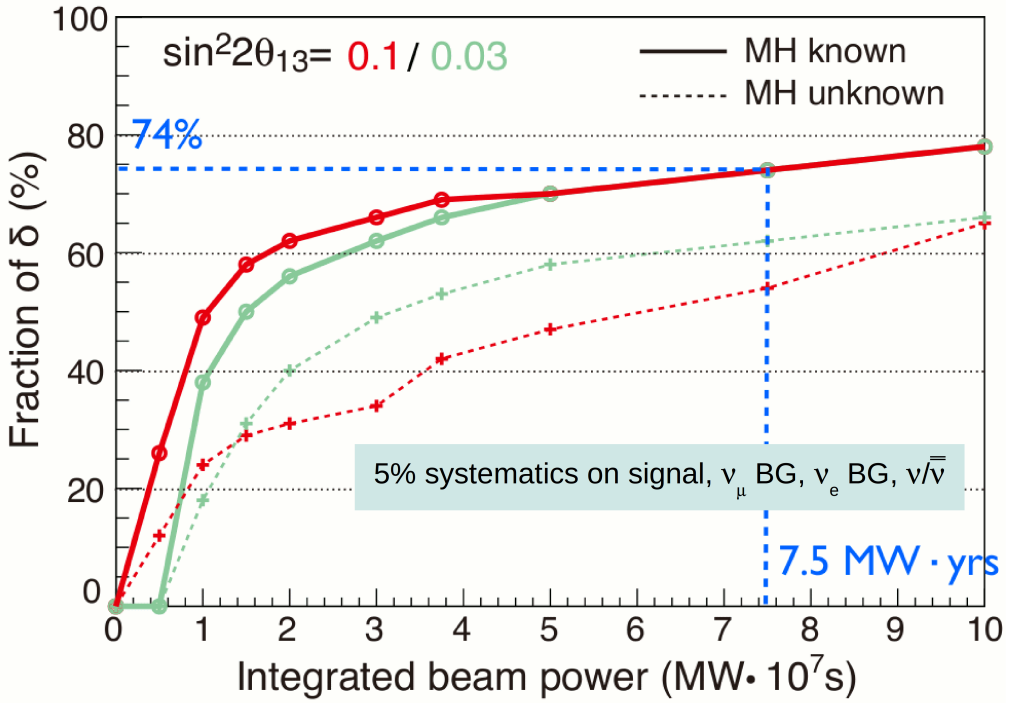
Neutrino geophysics
Exotic Searches
Etc.

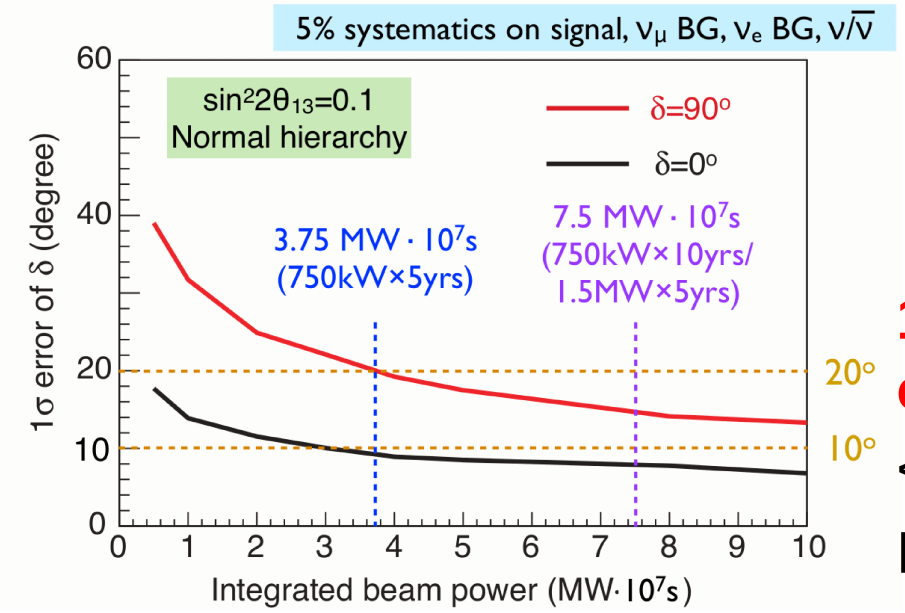
Expected Sensitivity to CP Violation

CPV discovery sensitivity w/ mass hierarchy known.



Fractional region of δ(%) for which the CPV (sin δ ≠0) significance is > 3σ





δ coverage:

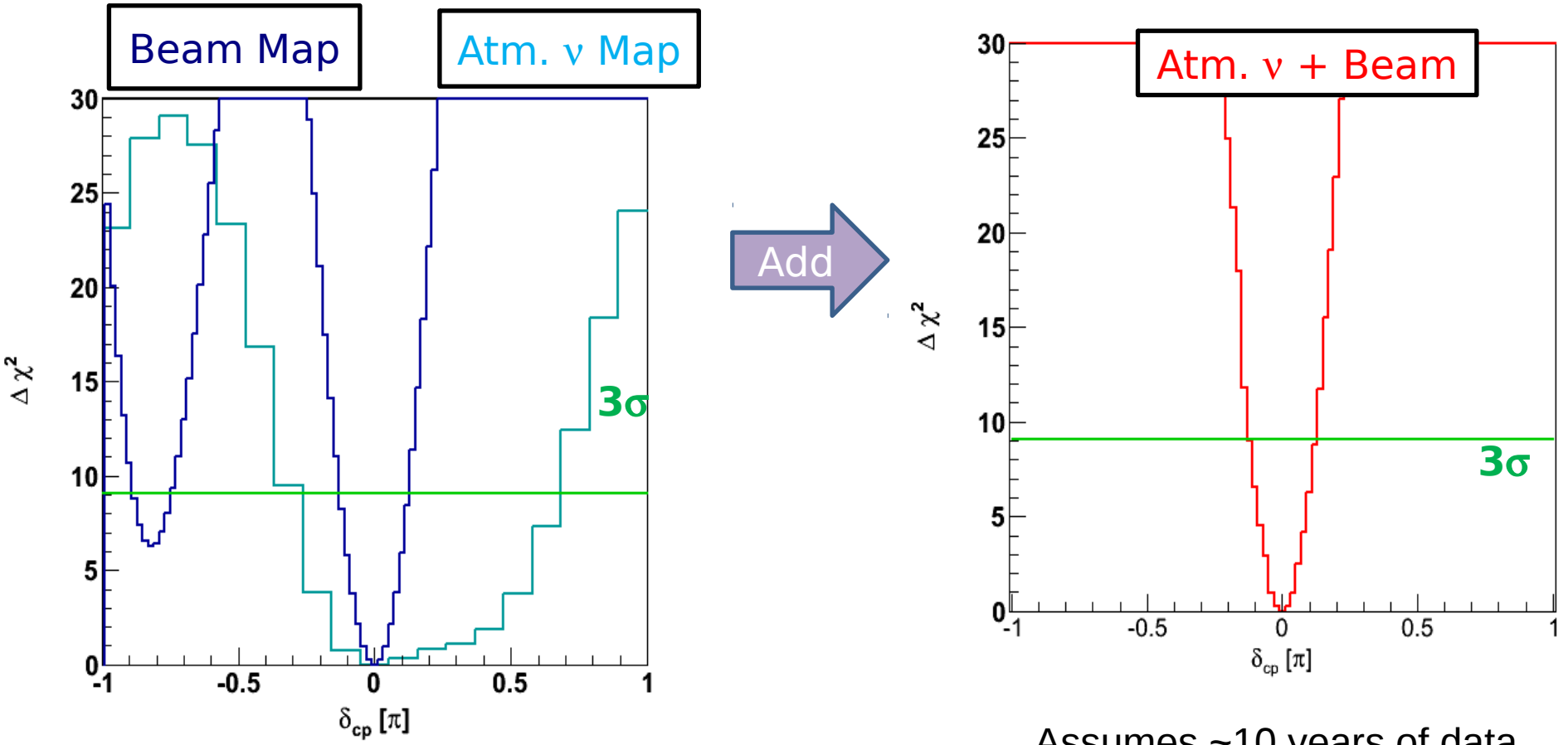
CPV > 3σ (5σ) for 74%(55%) of δ

1σ uncertainty of δ as a function of the beam power:

< 20°(10°) for δ = 90°(0°)

Modest dependence on θ_{13}

Beam + Atmospheric ν: Allowed δ_{CP}

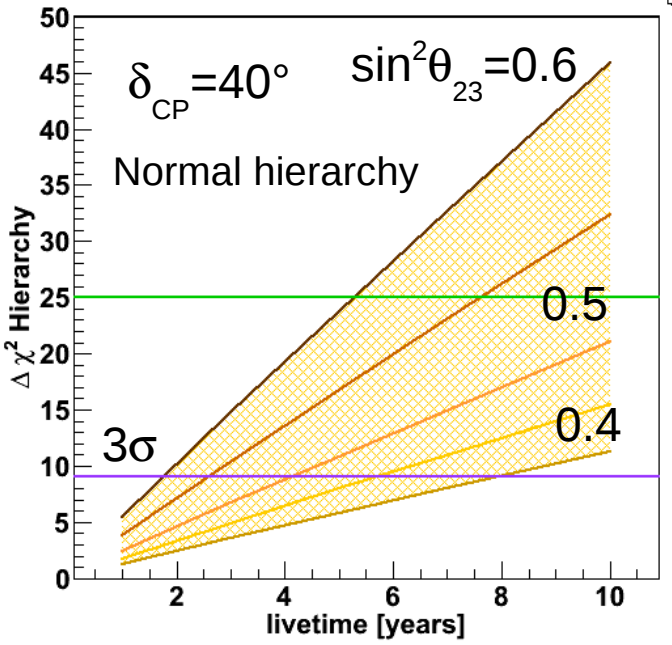


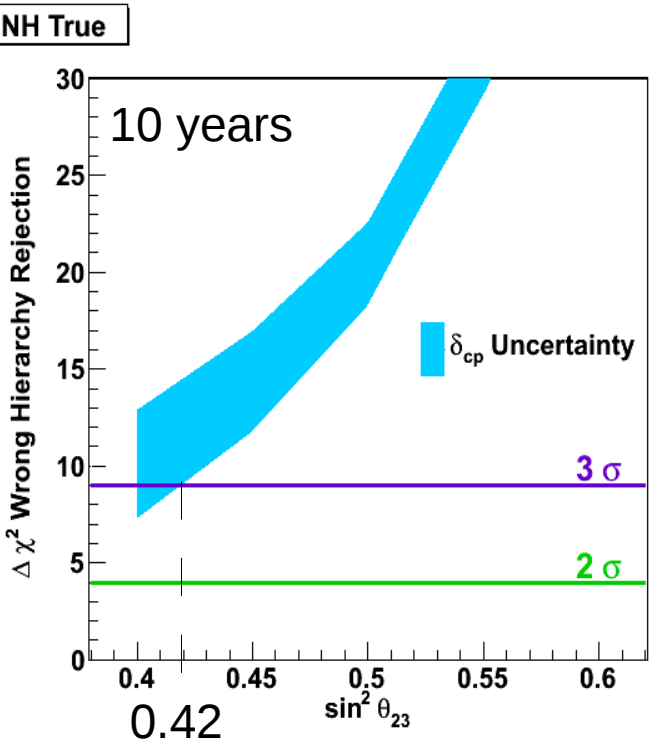
Assumes ~10 years of data
3ν:7$\bar{\nu}$ for beam neutrinos

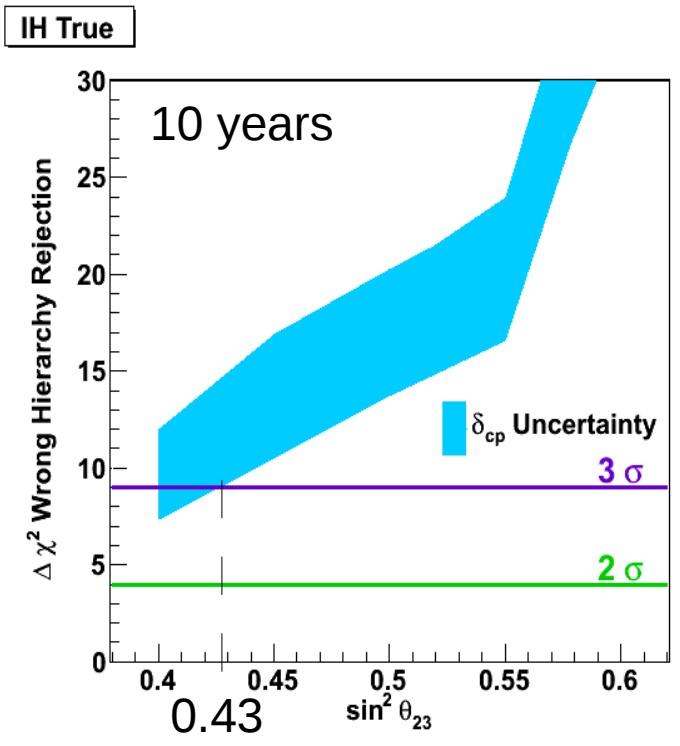
- Hierarchy is unknown, but NH is true.
- True δ_{CP} = 0.0; $\sin^2 2\theta_{13}$ = 0.10; Maximal mixing $\sin^2 2\theta_{23}$ = 1.0
- Degenerate solution exists at 3σ in the beam only case.

Mass Hierarchy Sensitivity

Significance for MH determination
as a function of HK lifetime

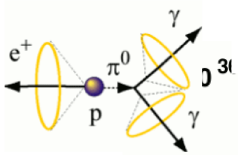




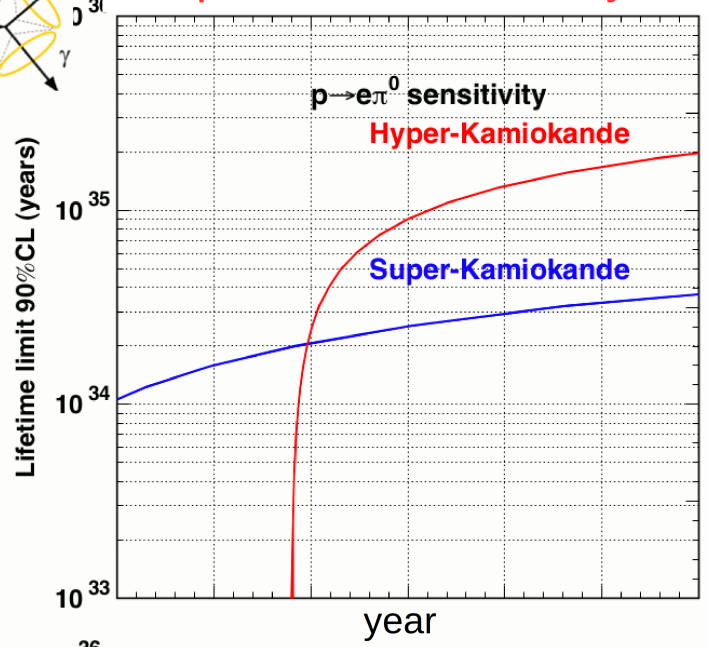


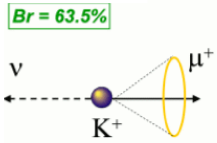
- Sensitivity mainly depends on θ_{23}, δ and slightly on the MH itself.
- 3σ mass hierarchy determination for $\sin^2\theta_{23} > 0.42$ (0.43) for normal (inverted) hierarchy for 10yr data taking.
- Caveat: the $\Delta\chi^2$ method to determine the number of σ's is used.

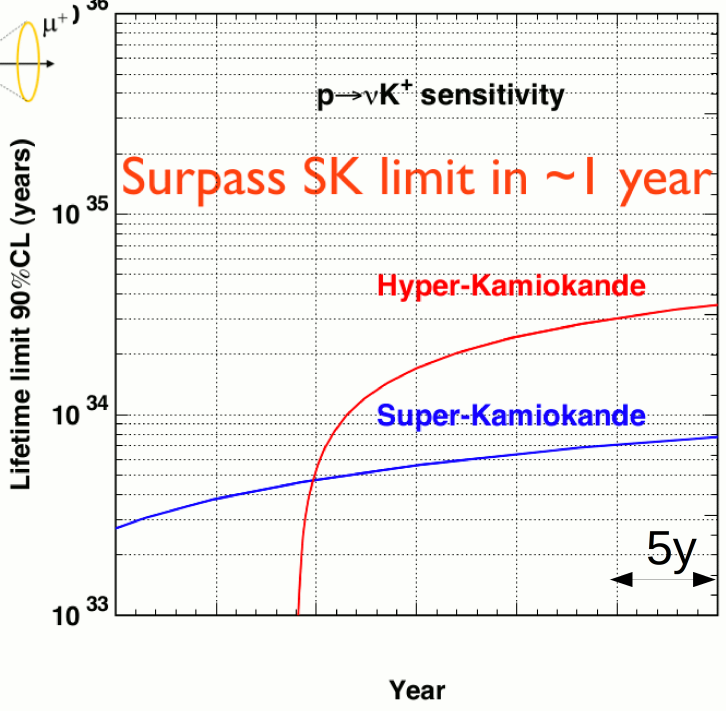
Proton Decay Sensitivities



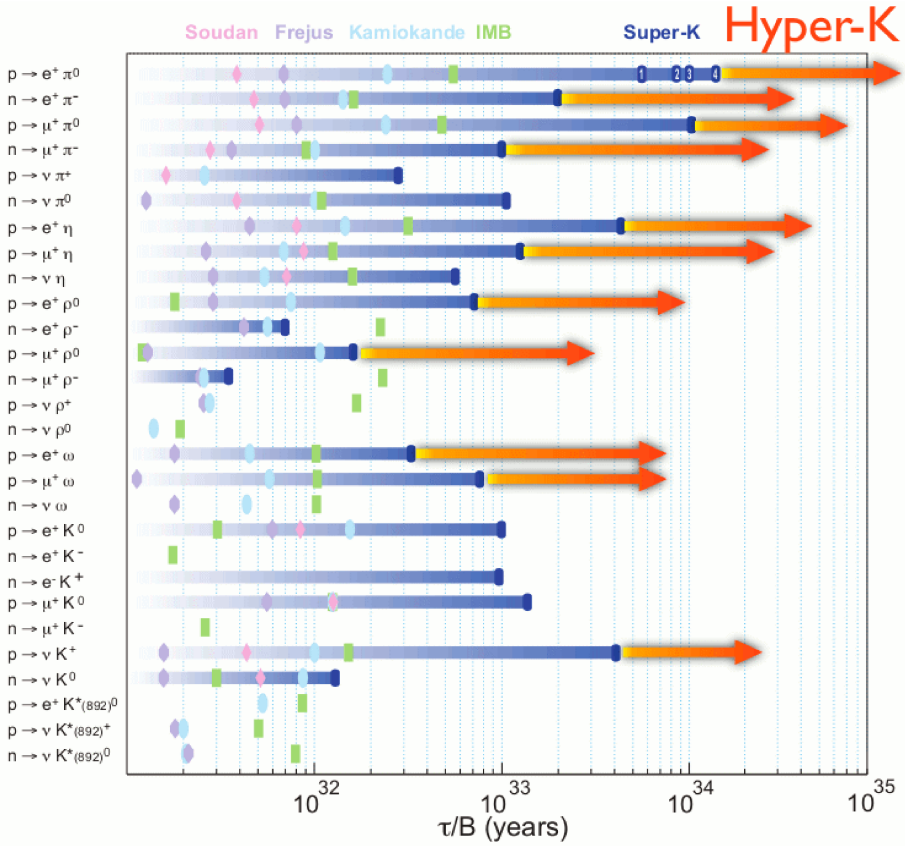
Surpass SK limit in ~1 year







- 10 times better sensitivity than SK
- HK surpasses limits in ~1 yr
  - $p \rightarrow e^+\pi^0$: 1.3×10^{35} yr
  - $p \rightarrow \bar{\nu}K^+$: 2.5×10^{34} yr
  - Many other modes:
    - e.g.: $n \rightarrow (e,\mu)(\pi,\rho,\omega,\eta)$: $10^{14\text{-}35}$ yr



Approval Status

- R&D budget (w/ WC proto-type) for Hyper-K approved in 2013.
- Recommended by HEP community as one of the two major large scale projects: http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
- KEK Roadmap includes Hyper-K:

  http://kds.kek.jp/getFile.py/access?sessionId=1&resId=0&materialId=0&confId=11728
- Cosmic Ray community endorses HK as large scale project.
- Just received outcome from Science Council of Japan
  - HK one of 27 projects selected as most important

    (In Japanese): http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-22-t188-1.pdf
  - Prepare report for MEXT for road map of big projects this year (2014)
- Proposals from other countries are currently being written
  - Includes EU (UK has bridging funds) and Canada
    - US waiting on results of P5 before proposals can be considered

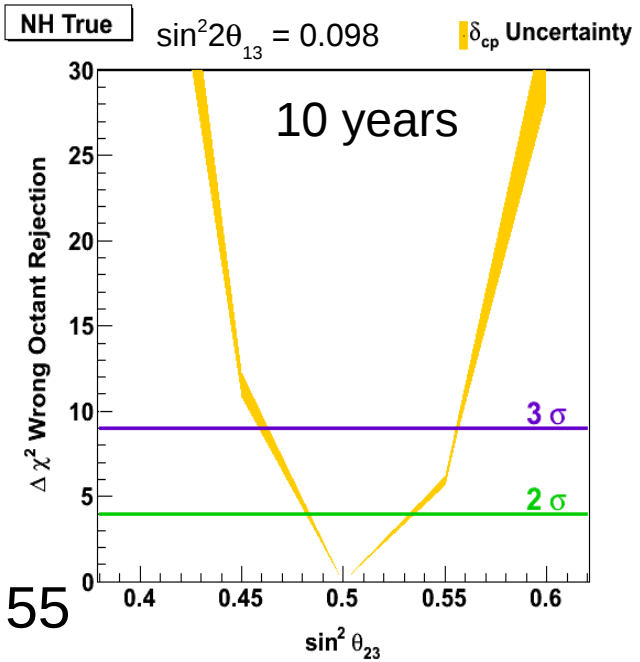
Summary

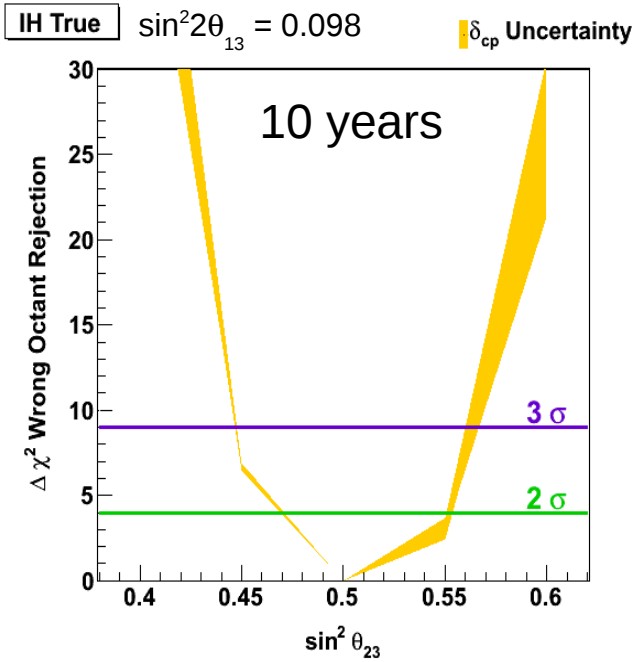
- Hyper-Kamiokande's physics program is well suited to address remaining issues in neutrino oscillations
  - Part of a larger physics program including BSM searches and astro(particle) physics
- Base detector design is understood
  - Still lots of R&D to be done to optimize physics and costs for HK tank
  - Beam upgrade and new near detectors at J-PARC proposed
- Should have clearer picture of Hyper-Kamiokande's funding status in the next year or so

BACKUPS

Sensitivity for θ_{23} Octant and CPV

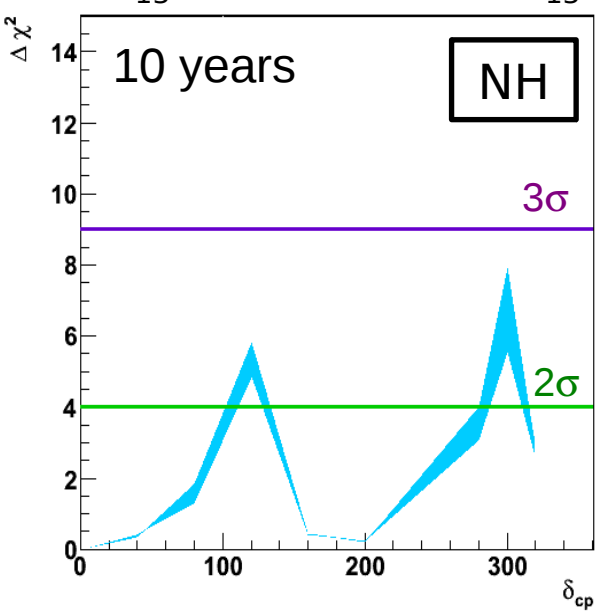
- θ_{23} octant sensitivity.
- Thickness of the band corresponds to the uncertainty from δ_{CP}.
- We can expect discrimination between $\sin^2\theta_{23}$ 0.4-0.6, w/ limited discrimination b/w 0.45-0.55

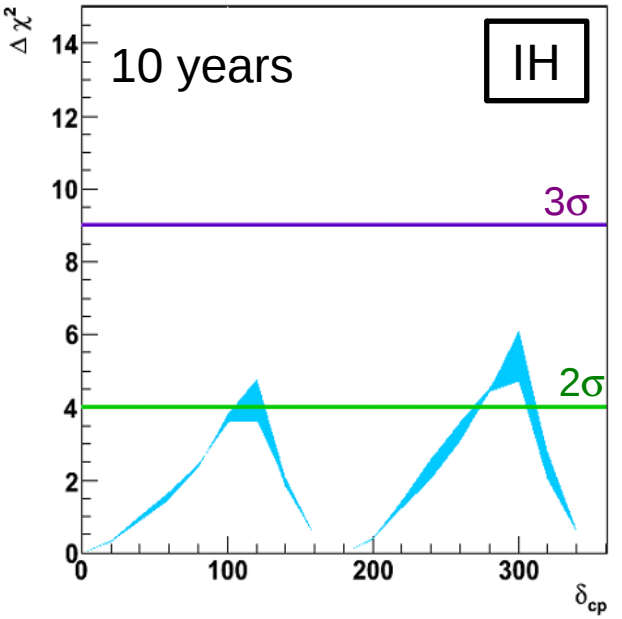




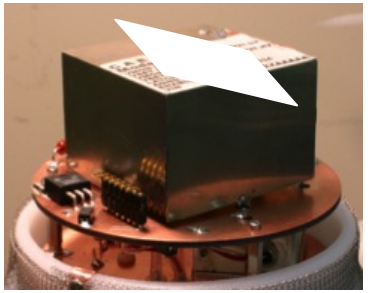
θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.099$

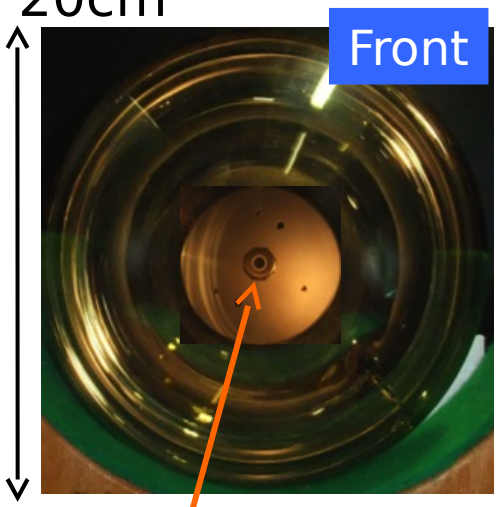
- Excluded 3σ δ_{CP} fraction.
- Thickness of the band corresponds to the uncertainty from $\sin^2 2\theta_{23}$
- Sensitivity to CP-violation is limited under both hierarchy assumptions.

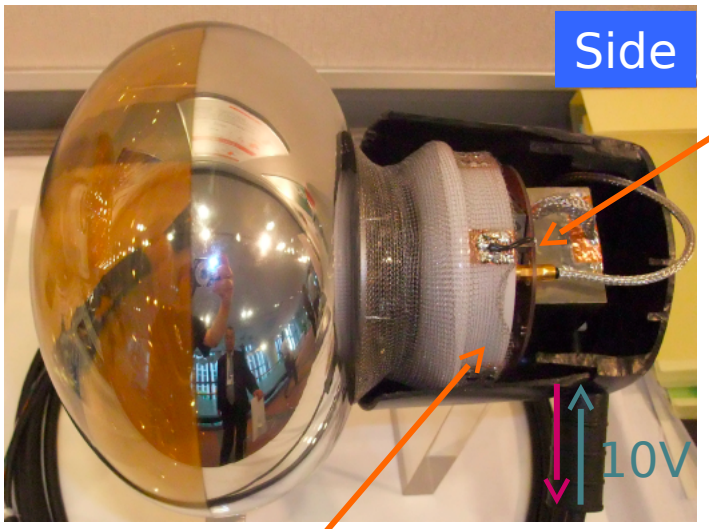




8" HPD Prototype







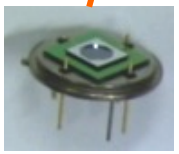
High voltage module
(2ch 10kV/500V Max.)

HV module and preamplifier are packed and waterproofed

→ No HV line in water

Signal

Preamp board

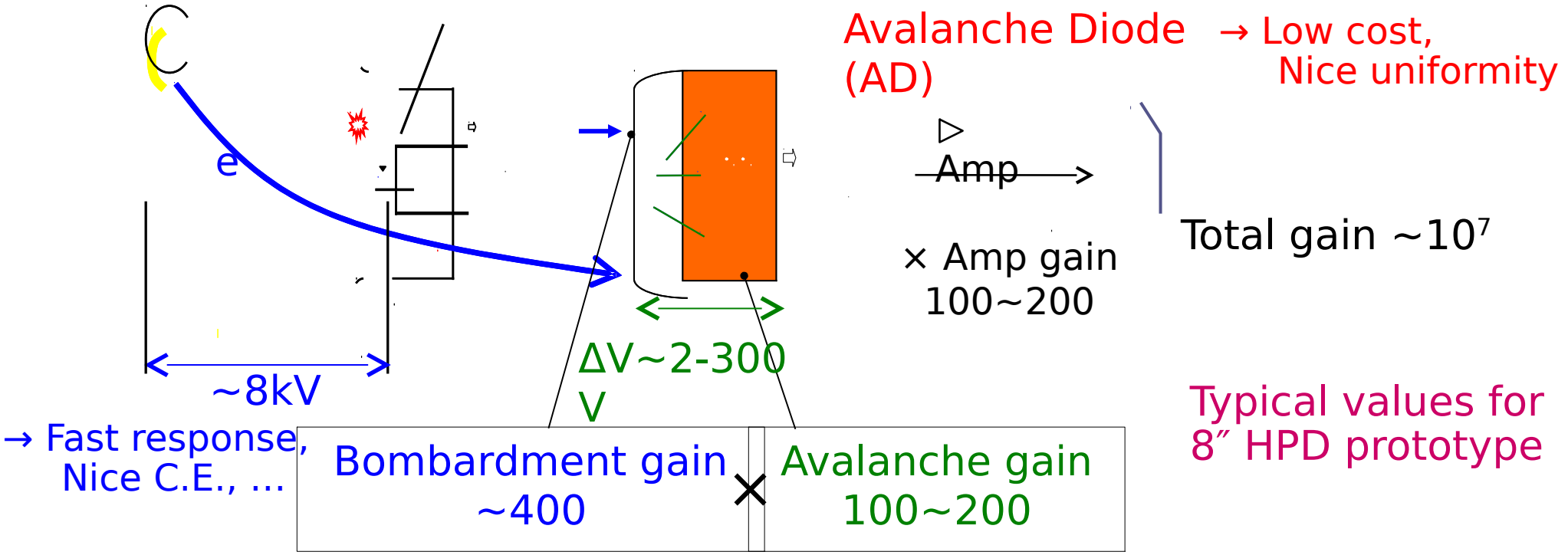


5mmφ AD

Spectral response		300 - 650 (420 max.) nm
Photocathode		Bialkali
Window material		Borosilicate glass
Gain		4 - 9 x 10^4
Time	Rise	1.7 ns
	Fall	2.7 ns
	T.T.S.	0.62 ns (σ)
Dynamic range		100 pC (1.5 x 104 p.e.)

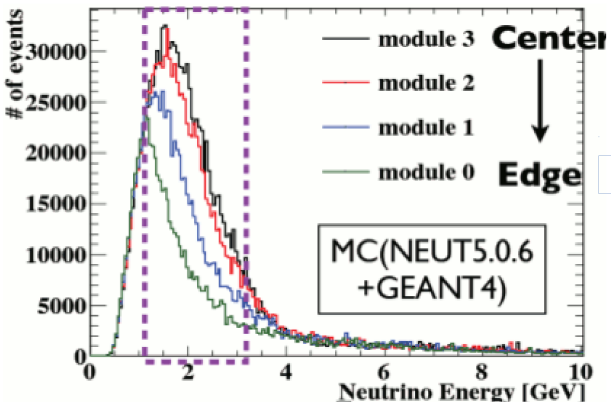
Ten 8″ HPDs were made for long-term testing

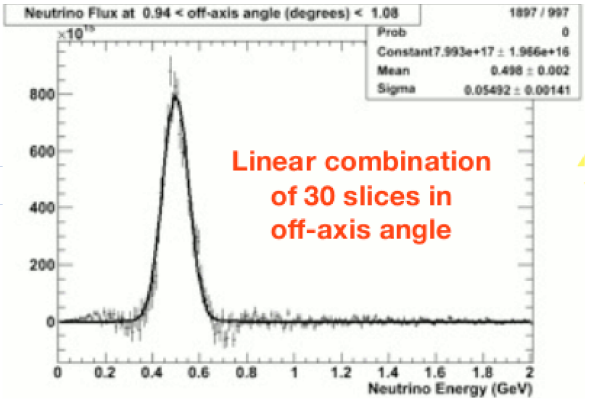
Hybrid Photodetector (HPD)



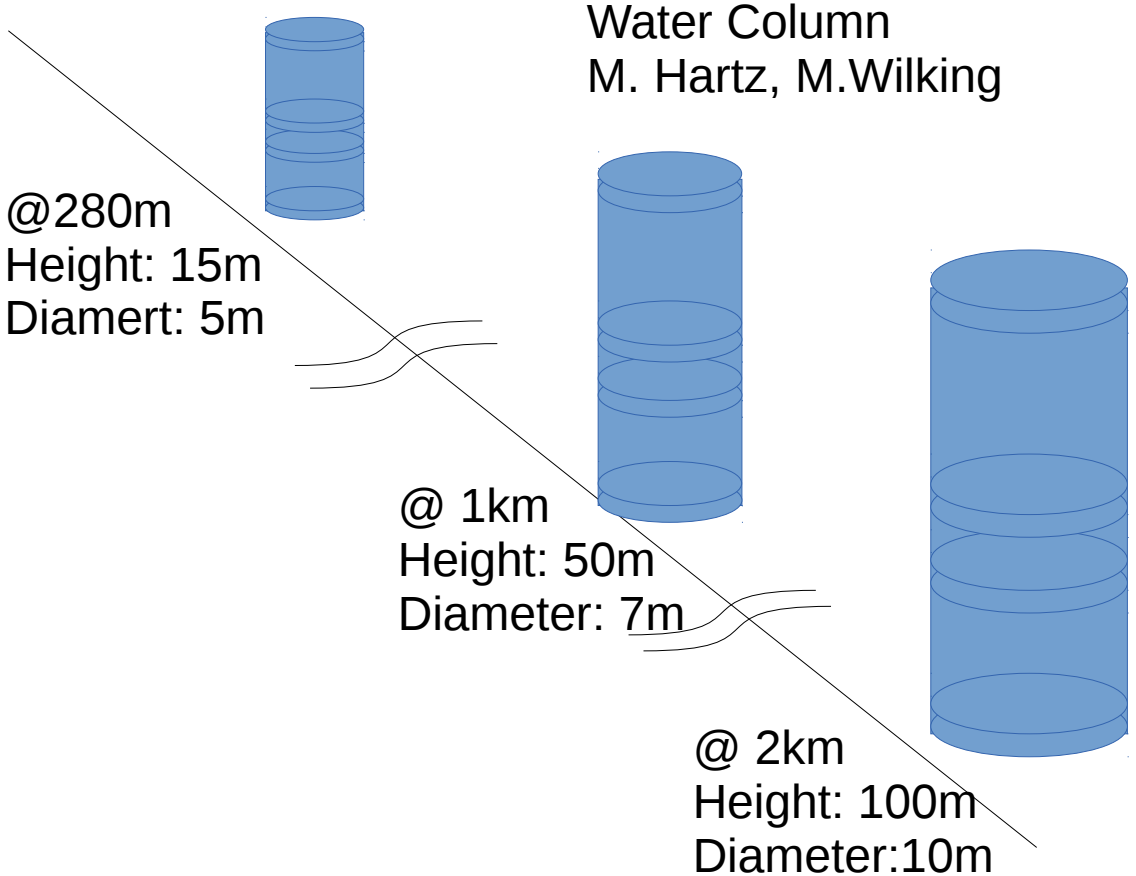
- ~8kV supply voltage + Avalanche diode multiplication
  - High voltage to focus photoelectrons into the small AD (5-20mmφ)
  - Better 1p.e. measurement capability
  - Better timing resolution, faster response
- Simple mechanical structure
  - Axial symmetric response
  - Lower production cost, shorter production period

Water Column





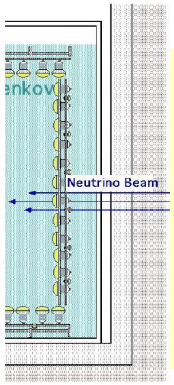
Water Column
M. Hartz, M.Wilking



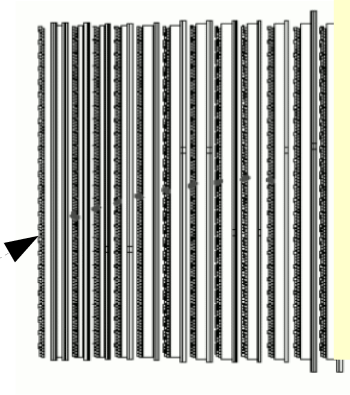
- Minimize dependence on neutrino interaction sampling the beam at several off-axis angles.
- Favoured <1km baseline from engineering point of view.
- Possibly add brine (Konaka) around detector to stop muons.

Tokai Intermediate Tank for Unoscillated Spectrum

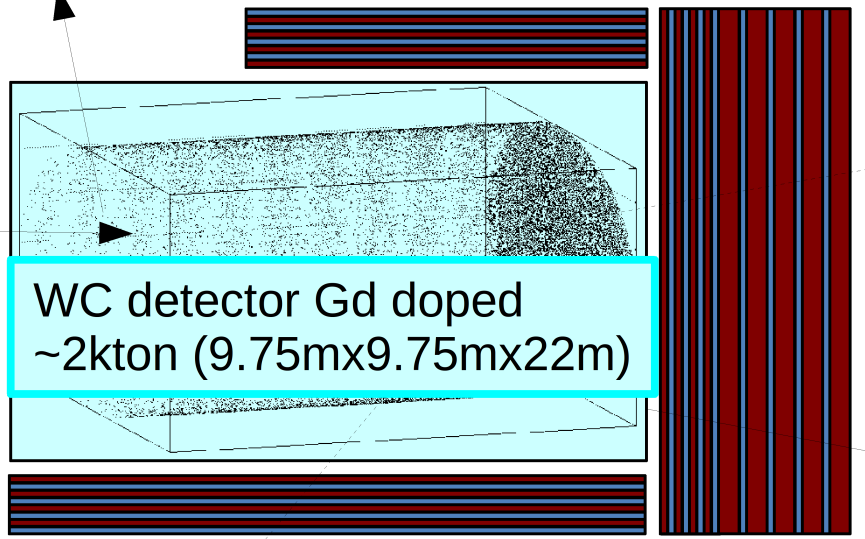
- TITUS -



PMTs facing outwards in the veto region to reject particles that enter or are produced outside the detector



To measure energy, angle and production point of muon. Currently optimizing thickness& length&magnetization

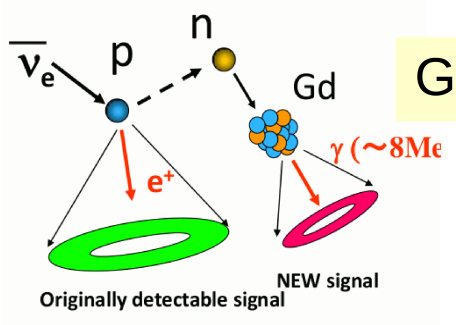


ν beam

WC detector Gd doped ~2kton (9.75mx9.75mx22m)

Water-Cherenkov target. Currently optimizing shape (cylinder vs cuboid) w/ engineers.

Aim to use LAPPDs (hybrid configuration w/ PMTs)



Gd doped water.