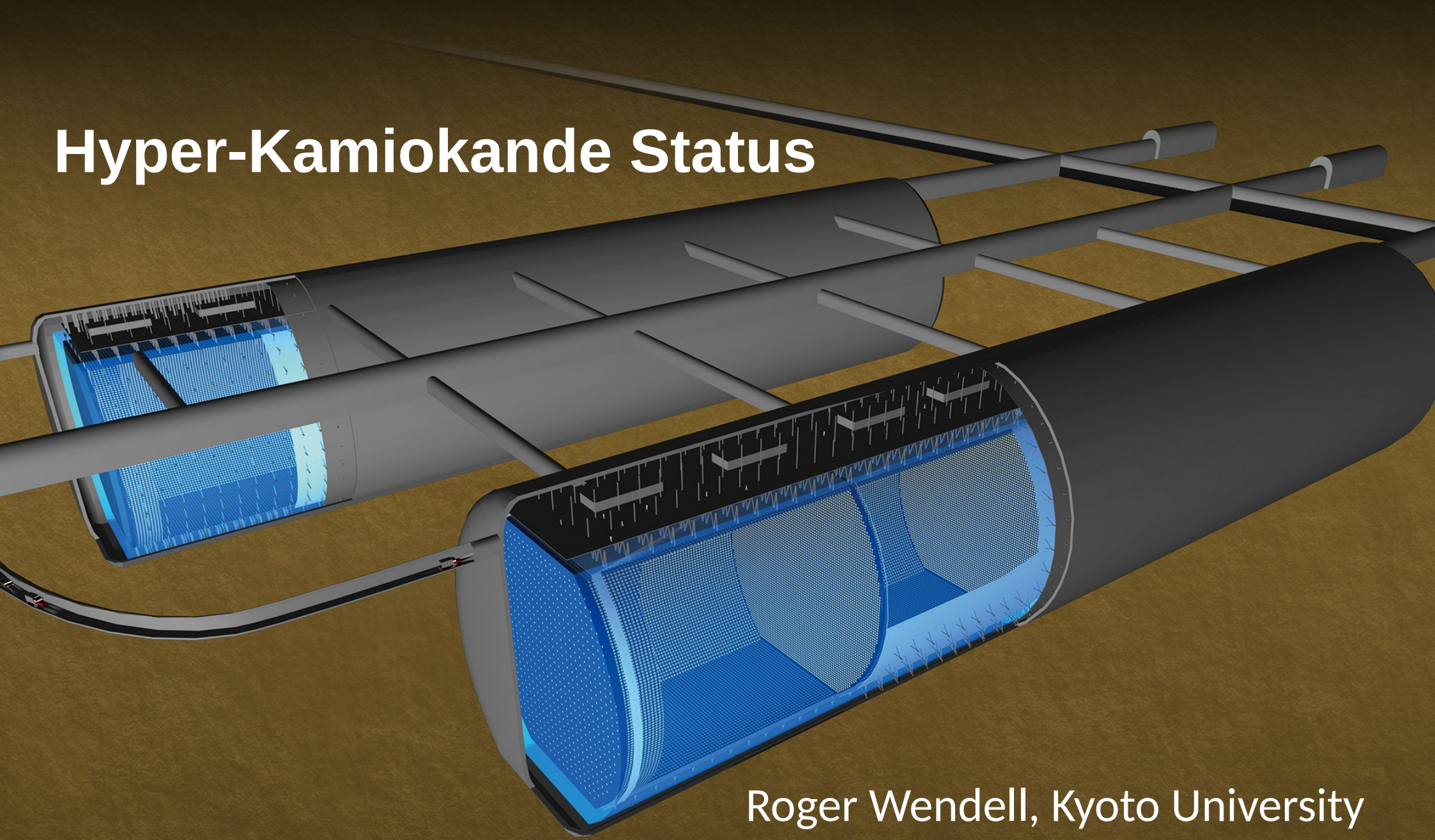
Hyper-Kamiokande Status



Roger Wendell, Kyoto University

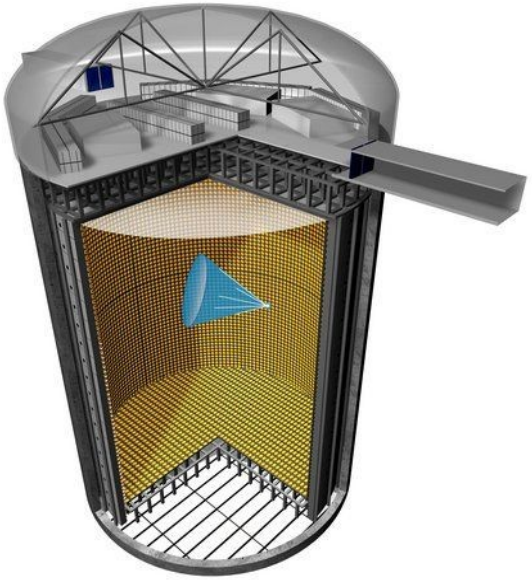
1st Neutrino Oscillation Tomography Workshop

2016.01.08

ERI, Tokyo, Japan

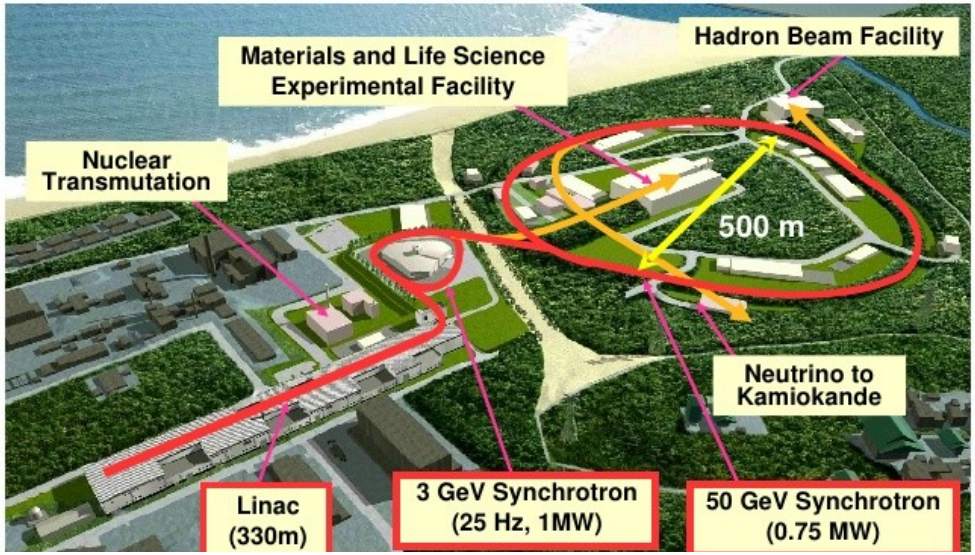
A Tale of Two experiments

スーパーカミオカンデ
Super-Kamiokande



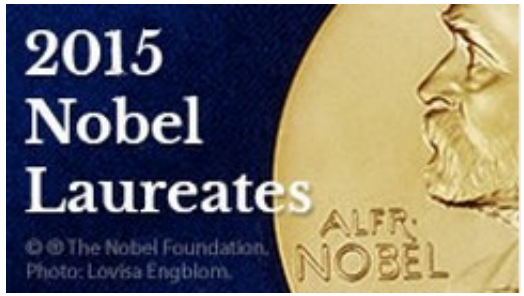
- 50 Kiloton Water Cherenkov Detector
  - Inner Detector 11,146 20” PMTs
  - Outer Detector 1885 8” PMTs
- Multipurpose machine
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos
  - Nucleon Decay
  - Far detector for T2K

T2K



- Nearly pure $\nu\mu$ beam, peak at ~650 MeV
  - Directed at Super-K, 295km away
- Precision oscillation measurements using off-axis technique
- Cross section measurements on a variety of targets using a complex of near detectors at 280m from the beam target

A Big Year for Neutrinos And Their Oscillations



Takaaki Kajita (SK)

Art McDonald (SNO)

Ko Nishikawa (T2K)

Yoichiro Suzuki (SK)

Takaaki Kajita (SK)

- Neutrino Oscillation Discovery at Super-Kamiokande recognized with 2015 Nobel Prize
- Both the Super-Kamiokande and T2K collaborations have been awarded the Breakthrough Prize in Fundamental Physics, 2016 … time to take <u>the next step!</u>

Hyper-Kamiokande

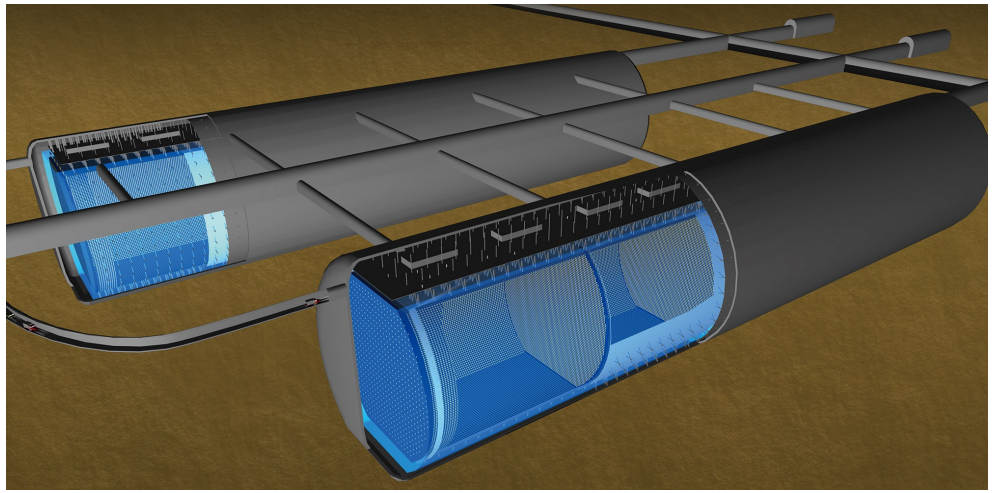
スーパーカミオカンデ
Super-Kamiokande

T2K

Detector × 25

POT × 2
(× 12 cur.)

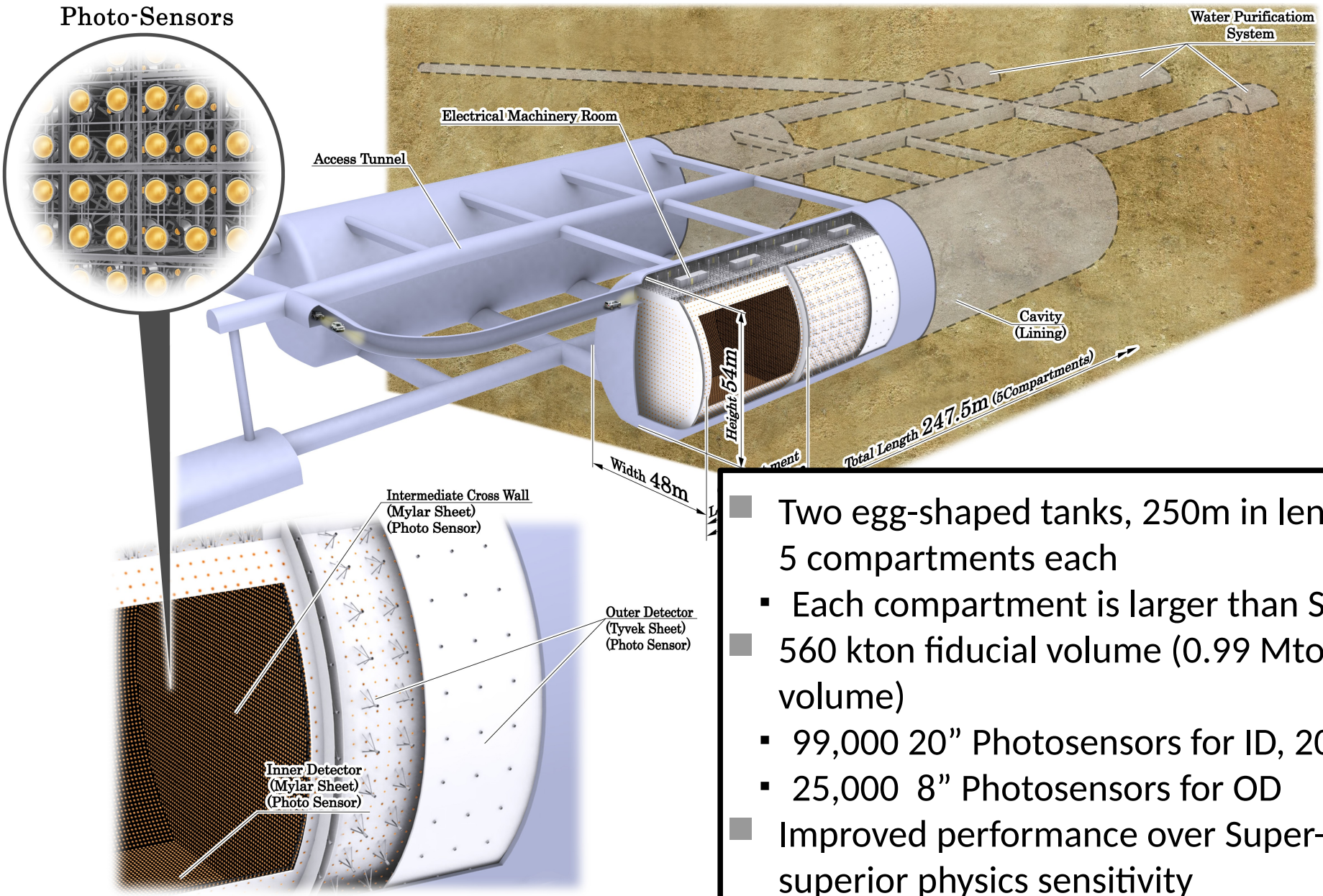
Hyper-Kamiokande



- 560 Kiloton Water Cherenkov Detector with a high intensity beam from J-PARC
- Multipurpose machine with all of the physics topics of Super-K and T2K, plus a few more
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos
  - Nucleon Decay
  - Far detector for T2K
  - Neutrino Geochemistry

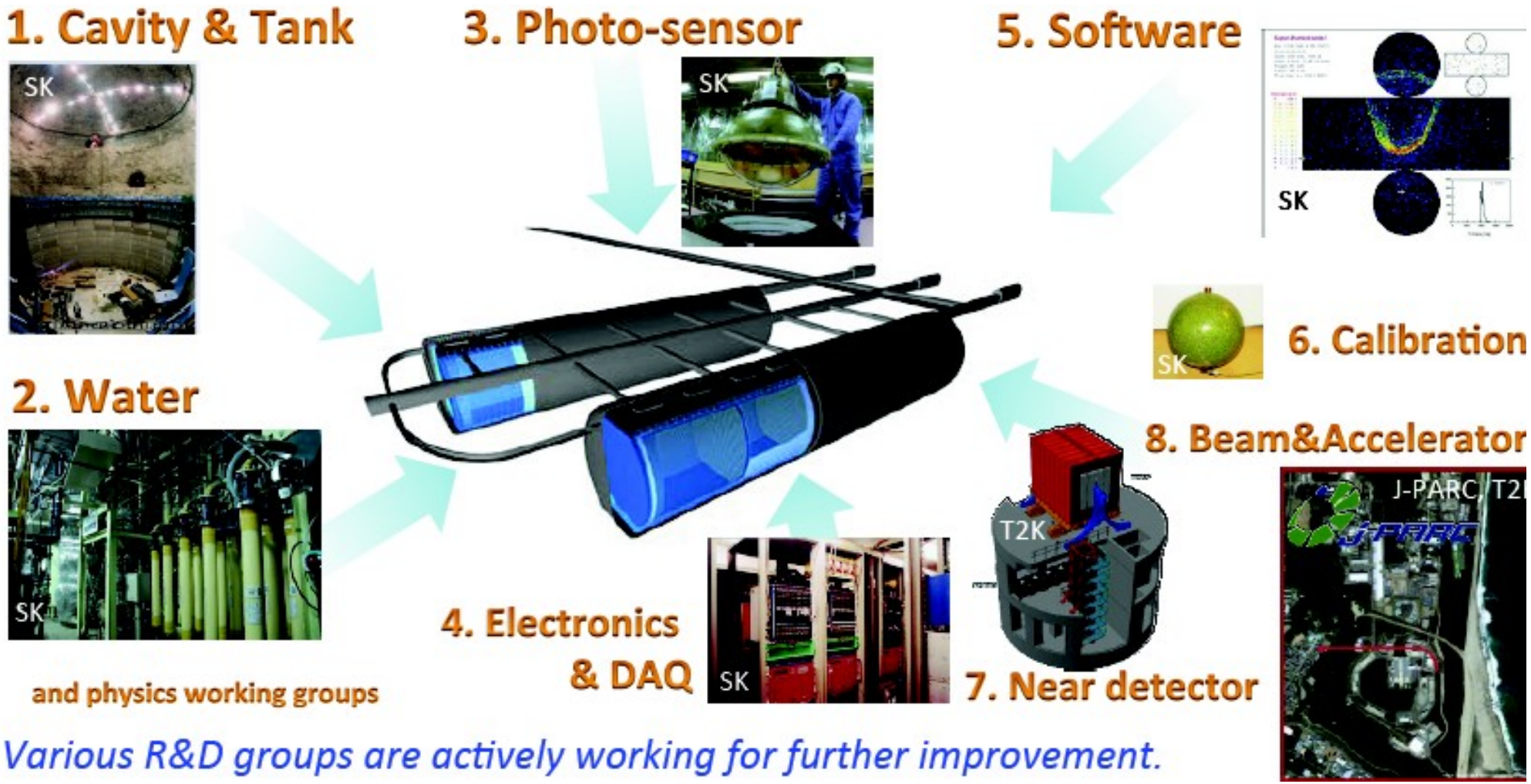
Hyper-Kamiokande : Detector and R&D

Hyper-Kamiokande: The Detector



- Two egg-shaped tanks, 250m in length, with 5 compartments each
  - Each compartment is larger than Super-K
- 560 kton fiducial volume (0.99 Mton total volume)
  - 99,000 20” Photosensors for ID, 20%
  - 25,000 8” Photosensors for OD
- Improved performance over Super-K for superior physics sensitivity

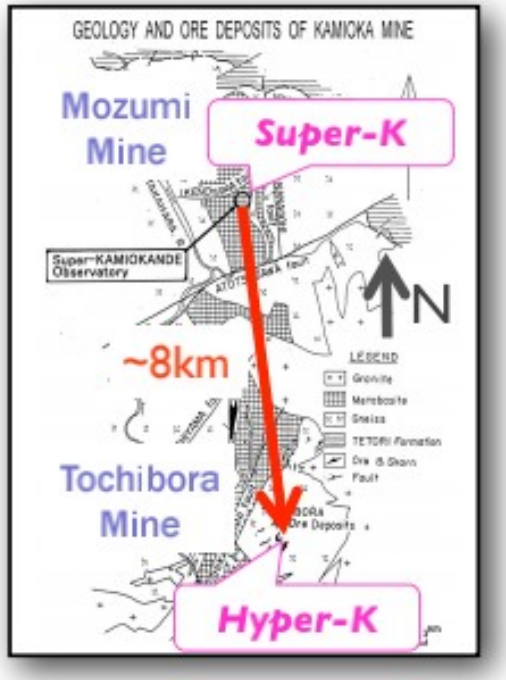
Hyper-Kamiokande: Development Efforts

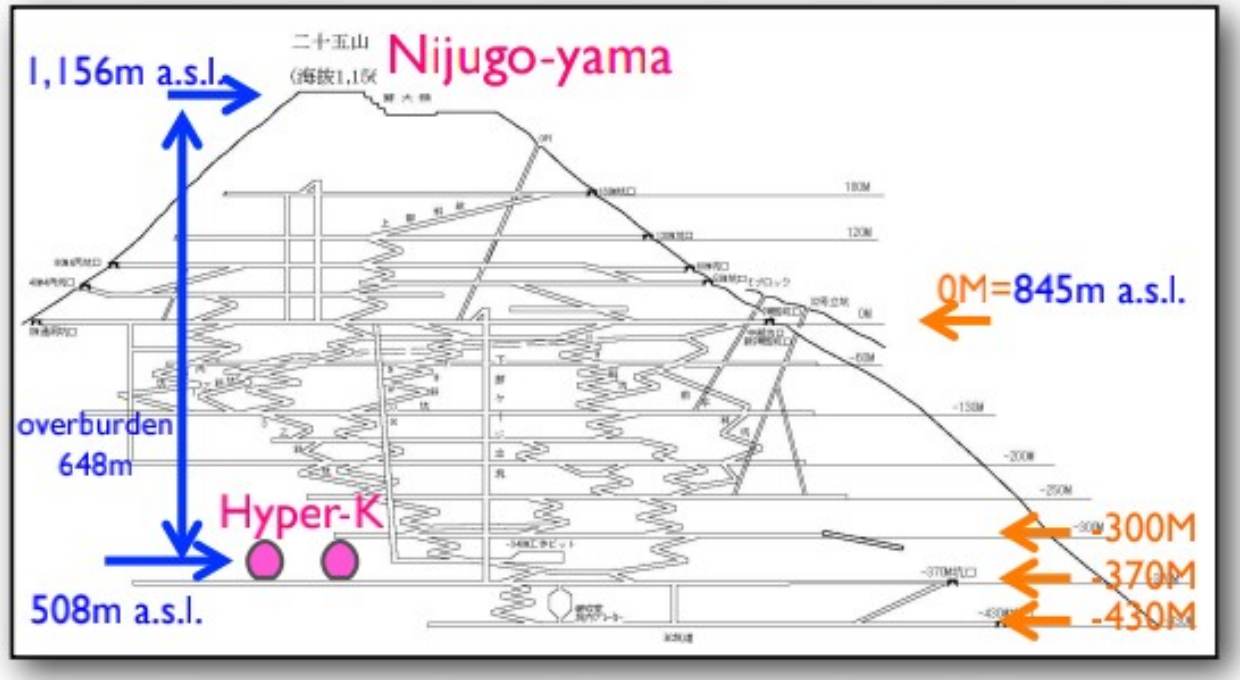


Various R&D groups are actively working for further improvement.

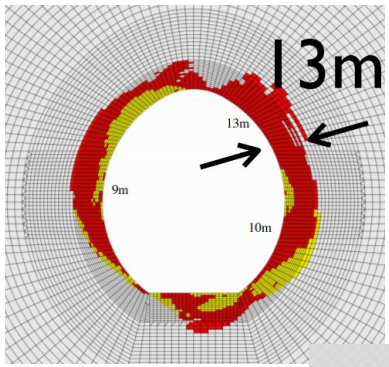
- Aiming to build a *better* detector than predecessors
  - Not just something bigger!
- Build from Super-K / T2K experiences while developing independent tools for Hyper-K
- Development efforts across the board (too many to discuss today!)

Hyper-Kamiokande: Location

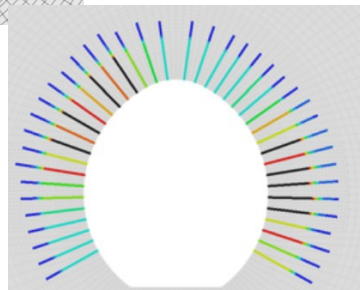




- Candidate detector site: "Nijuugo-yama," roughly 8 km south of Super-K in Gifu Prefecture
  - Same off axis angle from J-PARC = same beam neutrino energy spectrum
  - Slightly shallower overburden, 648 m (compared to 1,000m)
- Several detailed geological studies have been performed
  - Hyper-K can be built with existing technology

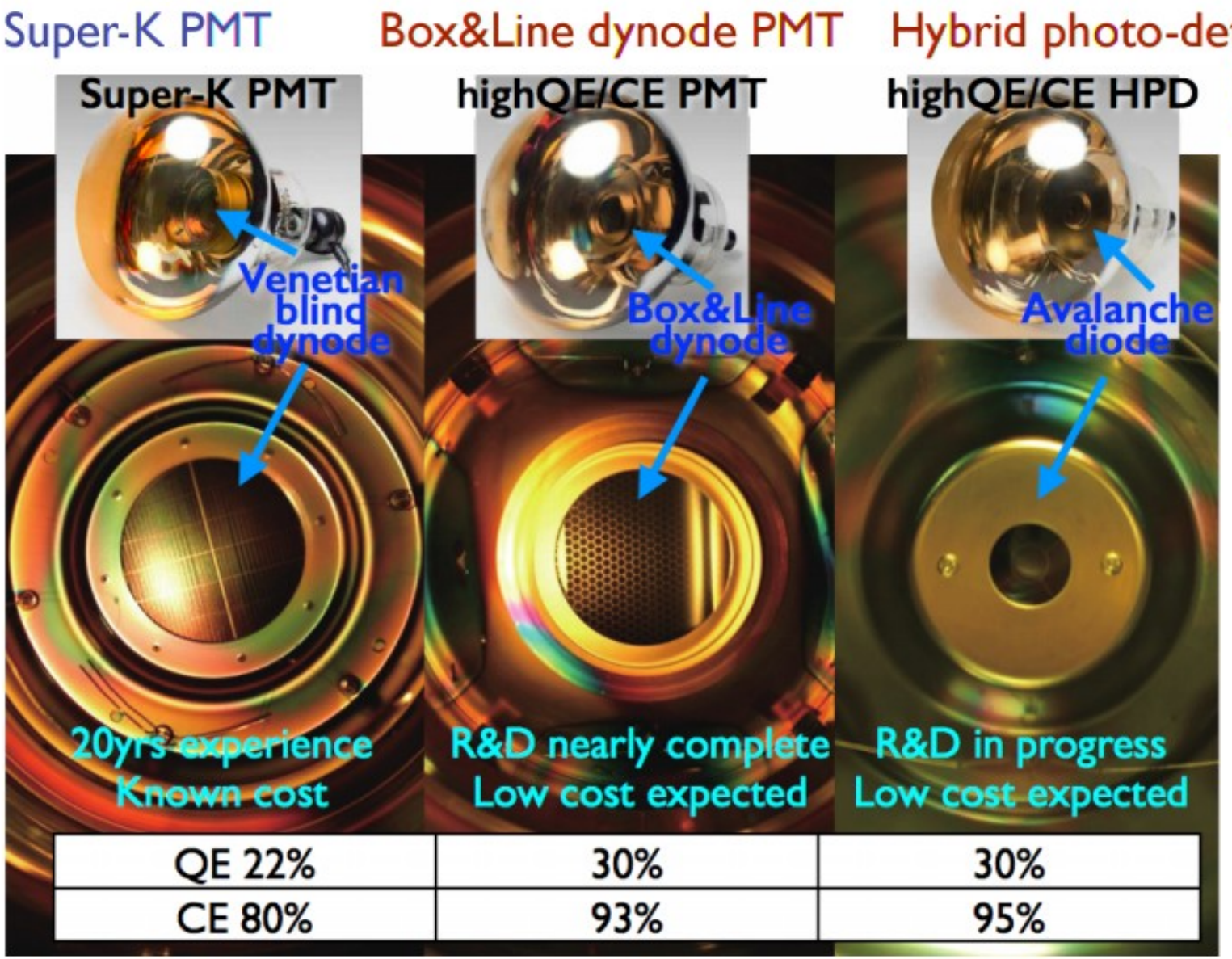


Plasticity model



Rock bolt depolyment

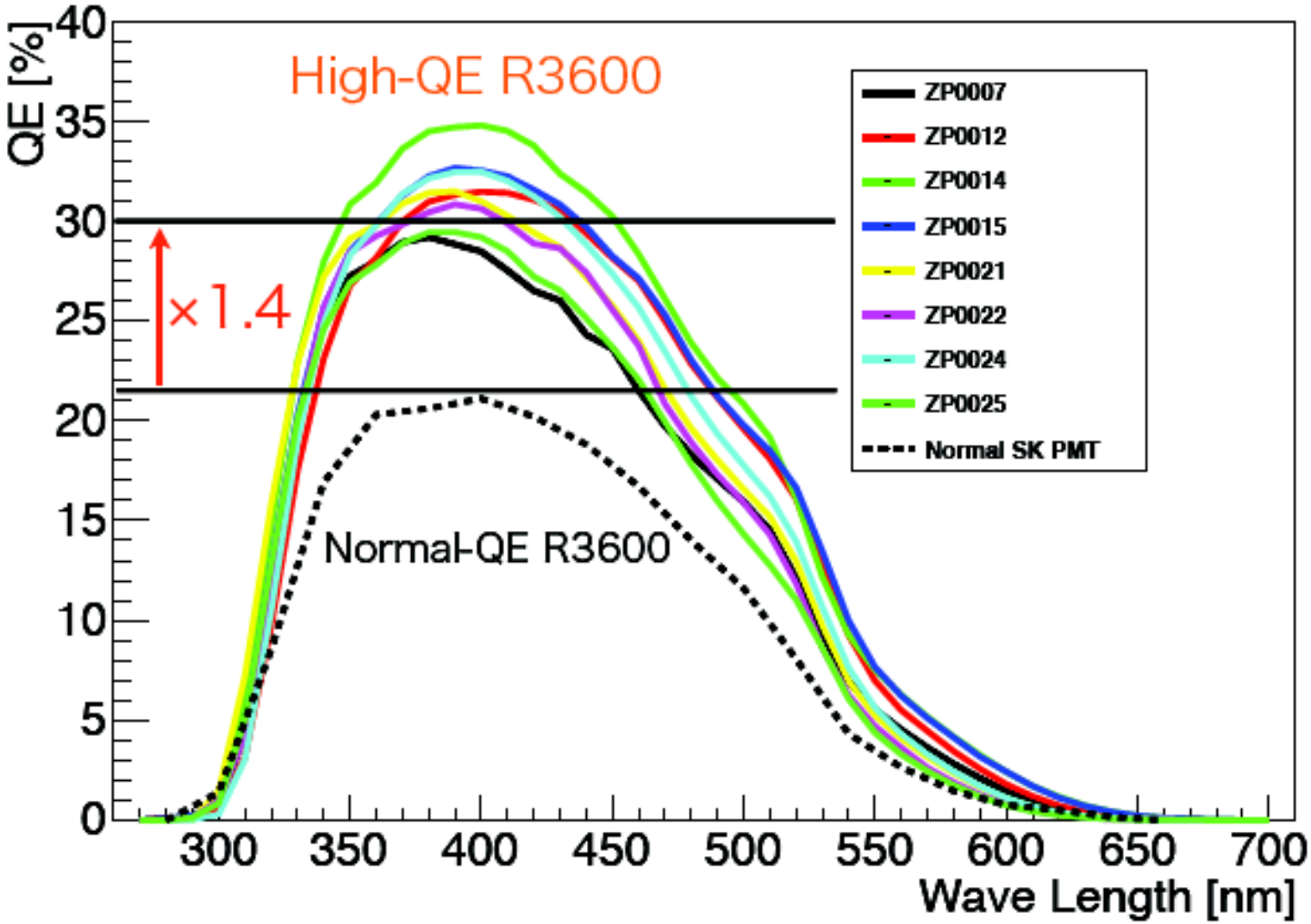
Photosensor R&D, in collaboration with Hamamatsu



QE 22%	30%	30%
CE 80%	93%	95%

- Many studies on-going, some in-situ (EGADs 200 t tank)
  - Time and charge response
  - Stability in and out of water
  - Temperature dependence
  - Pressure tolerance
  - Amplifier design
  - Photon detection efficiency
  - Gain and dark rate stability tests
  - Glass properties
  - Photodiode obtimization

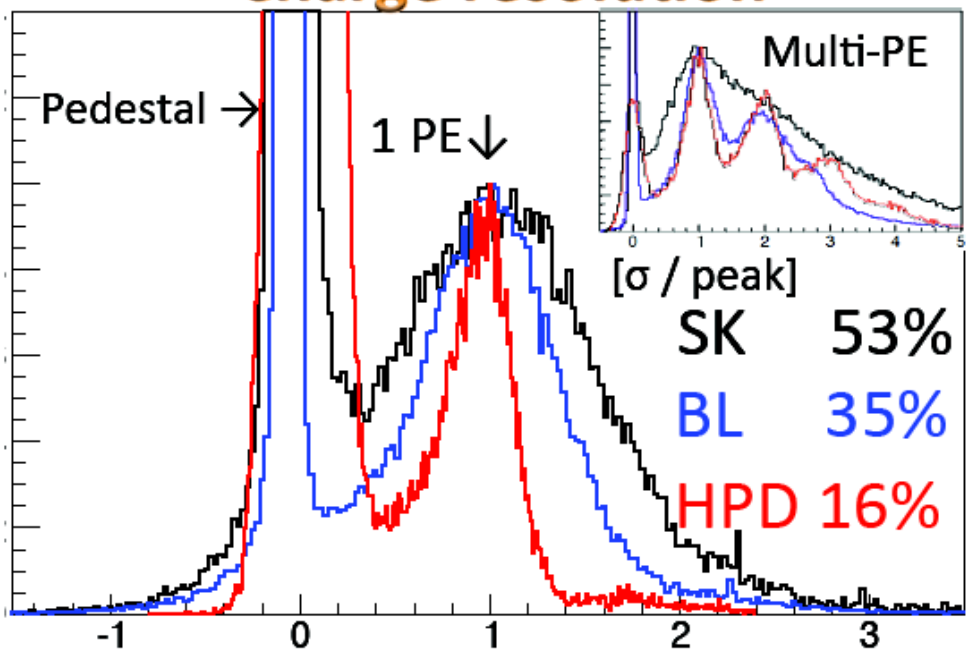
Photosensor R&D, in partnership with Hamamatsu



- Improved photocathode designs have boosted the quantum efficiency at ~400 nm from 22% (SK PMT) to **30%**

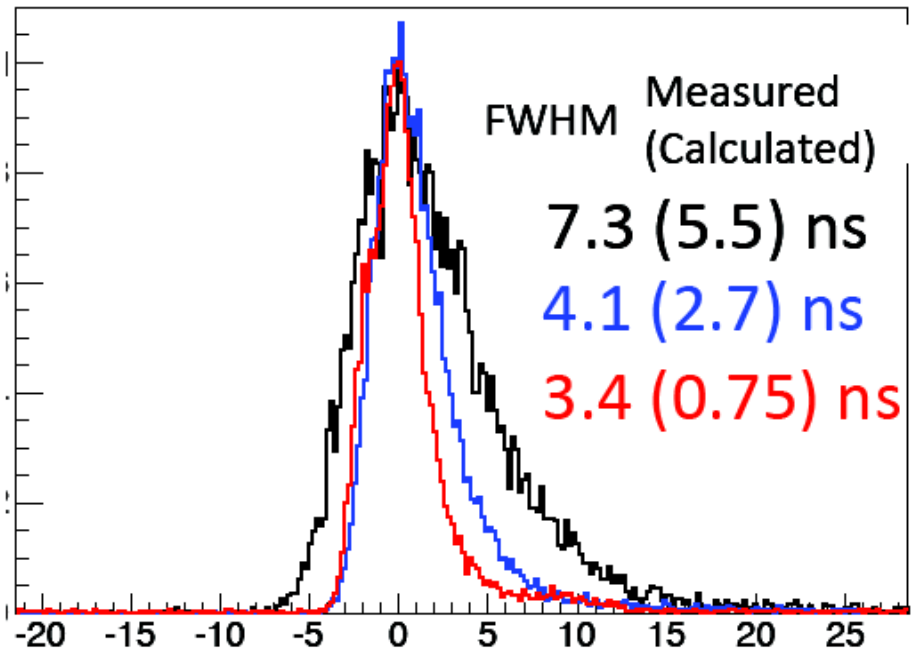
Photosensor R&D

Charge resolution



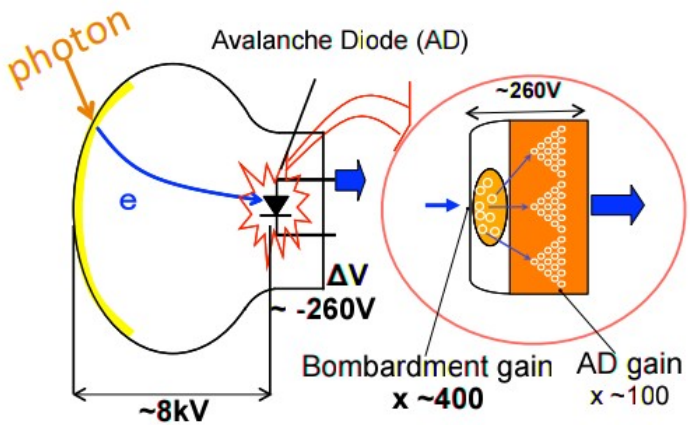
Photoelectrons

Time resolution



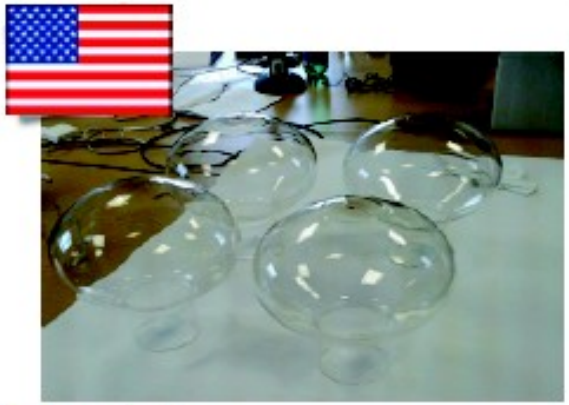
Time (ns)

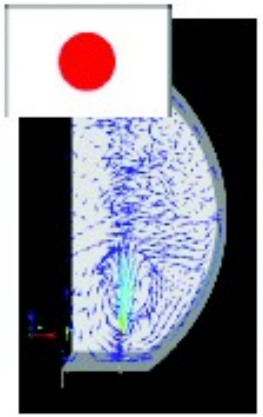
	SK PMT	B&L PMT	HPD
1p.e. Δt (ns)	2.1	1.1	1.4
1p.e. ΔQ/Q (%) Peak/Valley ratio	53 2.2	35 4.3	16 3.9

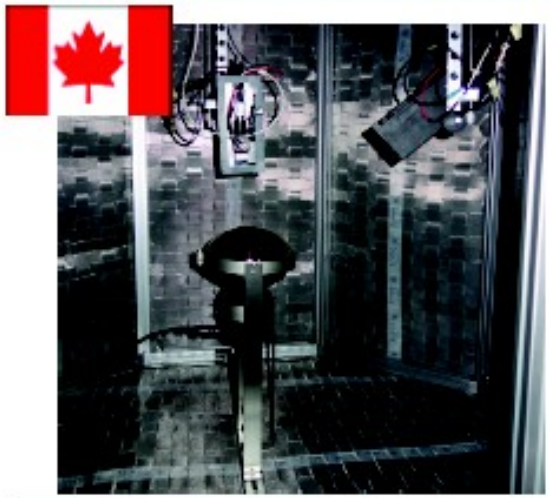


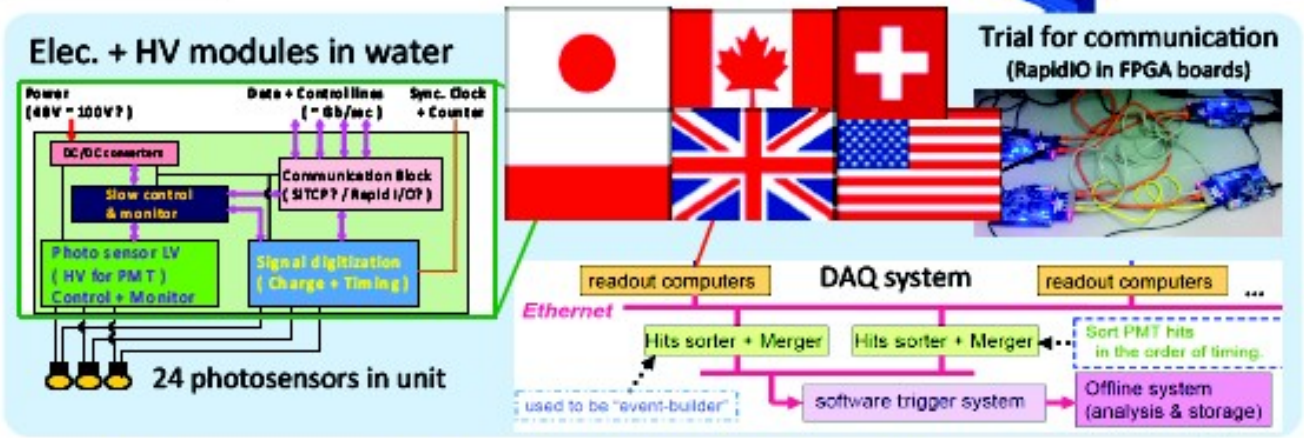
- New photosensor designs show improved charge and timing response over SK PMT

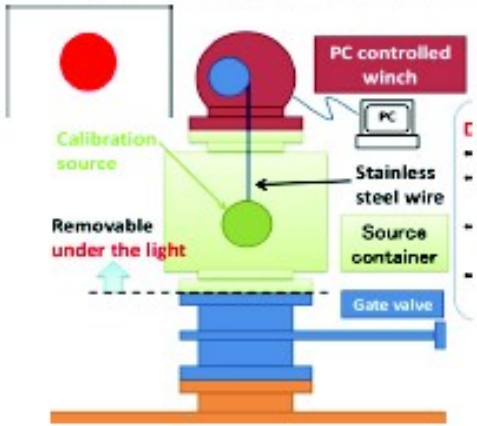
Worldwide R&D





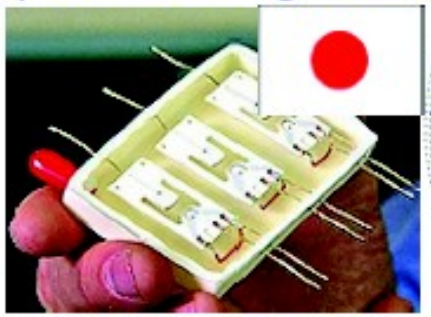


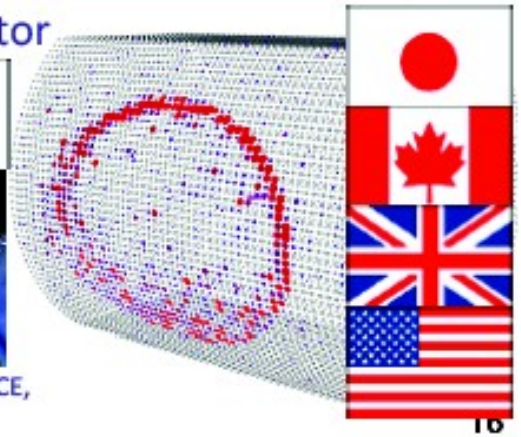




LED

Compact neutron generator



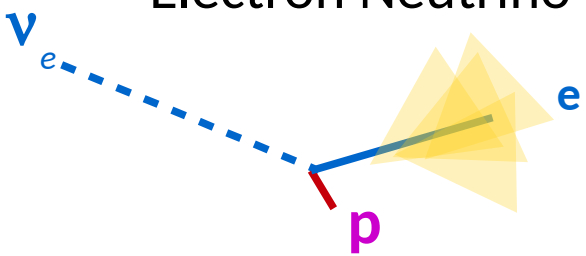


IEEE TRANSACTIONS ON PLASMA SCIENCE,
VOL. 40, NO. 9, SEPTEMBER 2012

Hyper-Kamiokande : (Geo) Physics

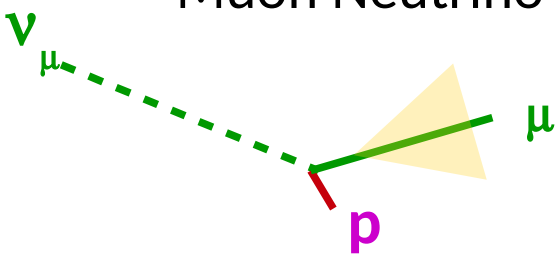
Neutrino Interaction's in Hyper-Kamiokande: Introduction

Electron Neutrino

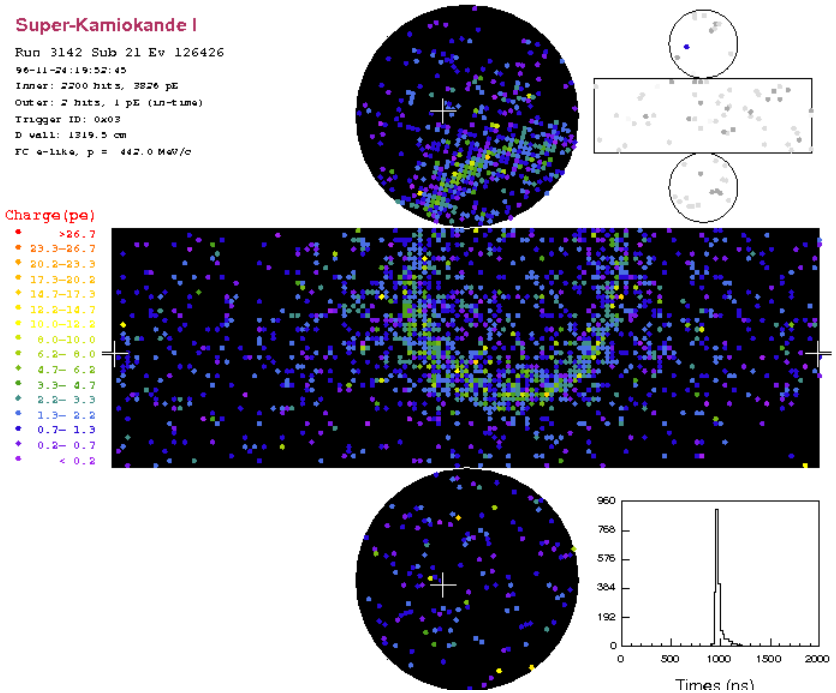


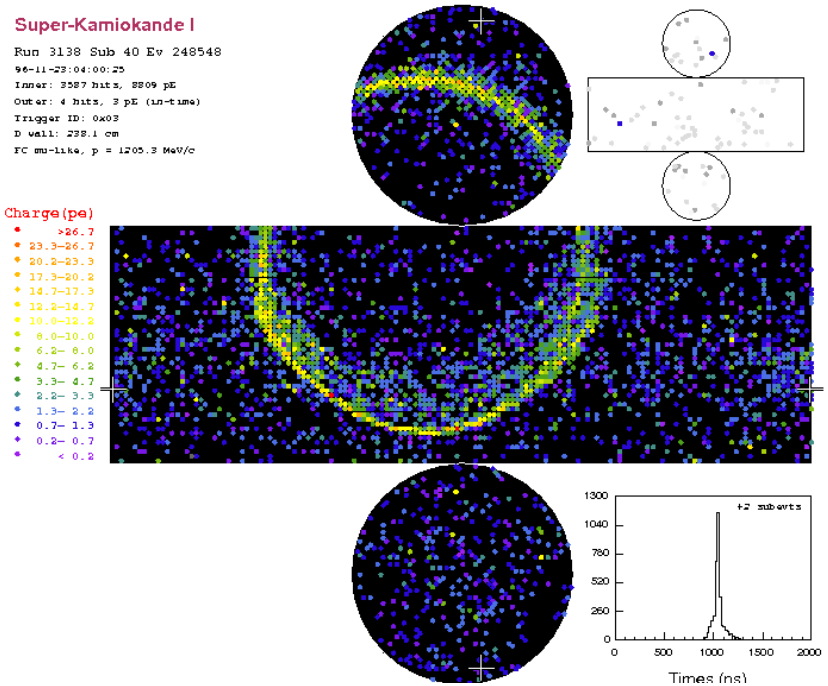
Electron-like(e-like)

Muon Neutrino



Muon-like (μ-like)



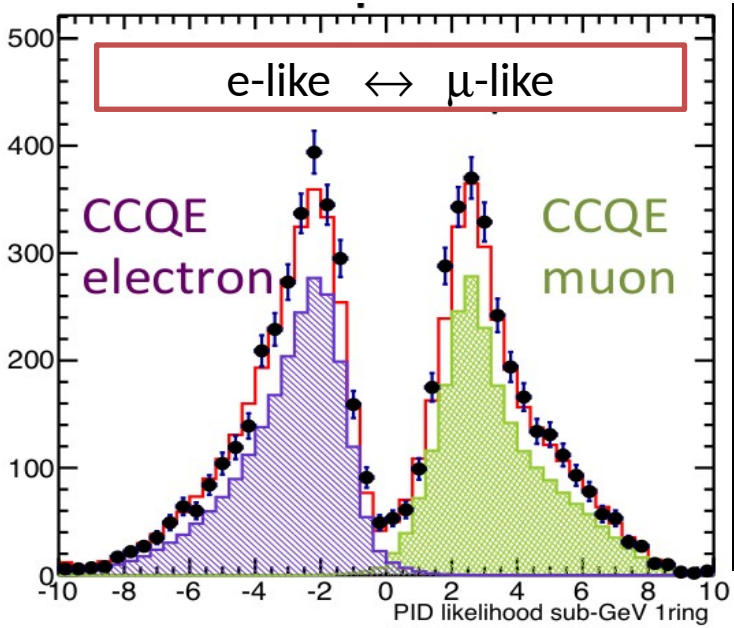


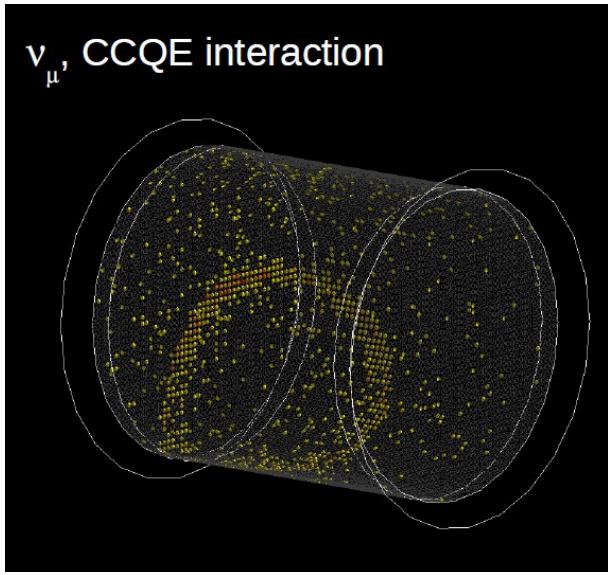
Analysis samples are separated based upon: the number of visible rings, the PID of the leading ring, and the total energy, whether or not particles are entering/exiting the detector

A Word About Performance

Resolution	Hyper-K
σ_{mom} e / μ	5.6% /3.6%
σ_{dir} e / μ	3.0° / 1.8°
Atmospheric	ν CC Purity
FC e-like	94.2 %
FC μ-like	95.7 %
PC μ-like	98.7 %
MIS PID	<1%, 1 GeV

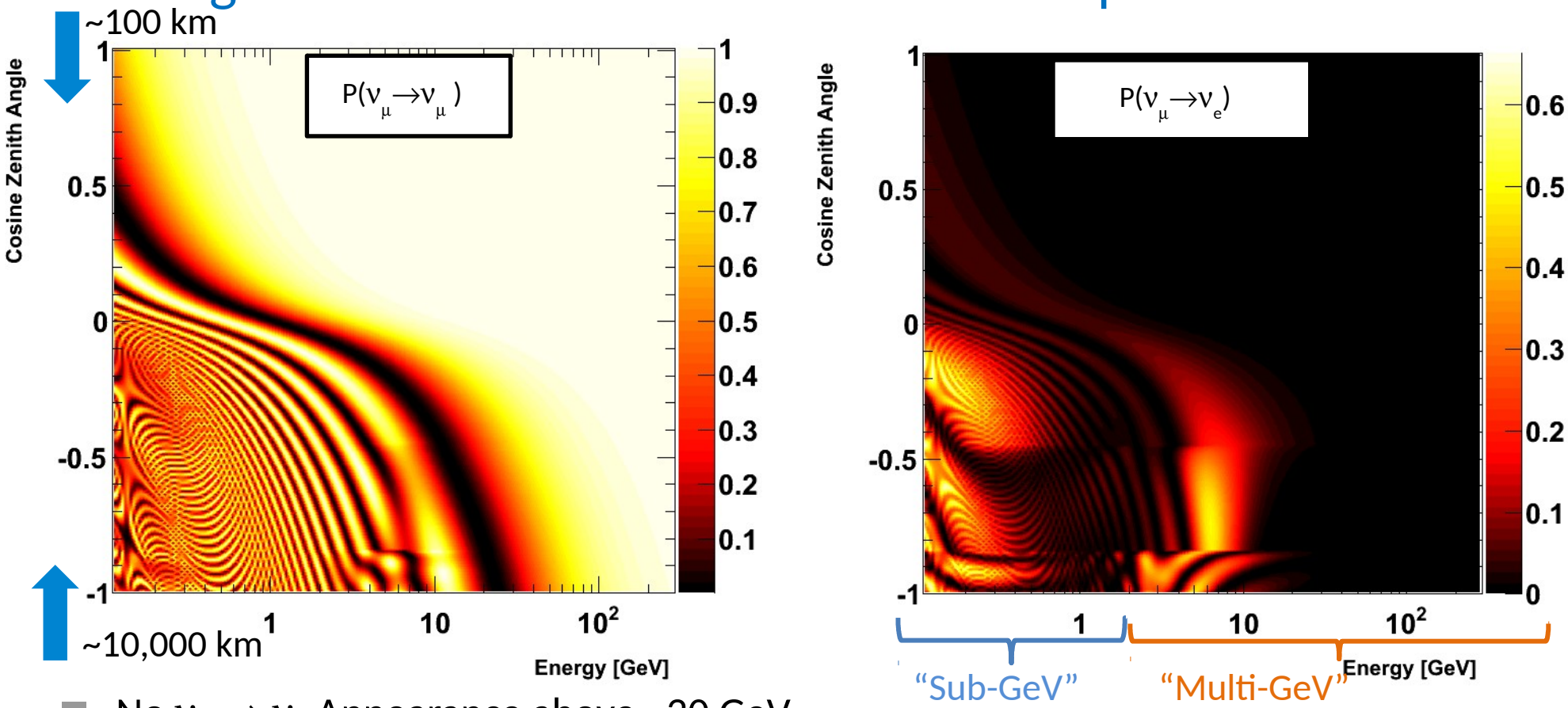
SK-IV Atmospheric ν





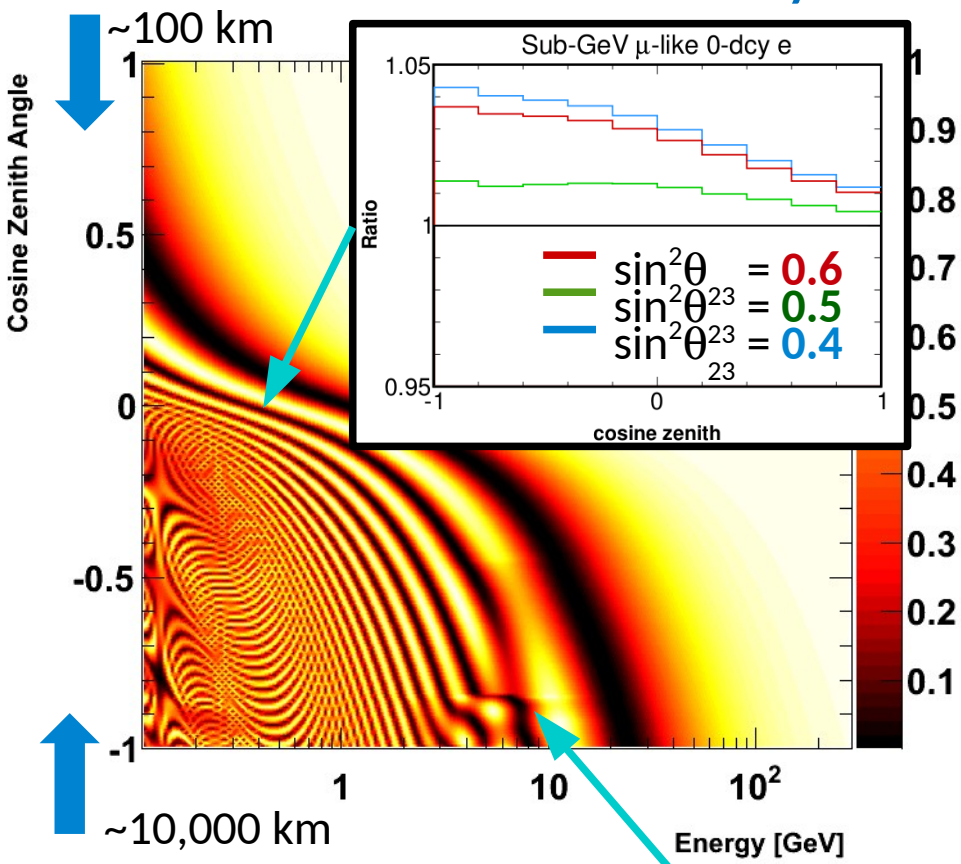
- Hyper-K's performance is expected to exceed that of Super-K
- Simulations we realistic estimates of reconstruction performance and systematic errors (including flux and cross section sources)
  - Based on Super-K and T2K technology, lots of synergy
  - However, **no improvements** beyond what has been proven in SK **assumed** for atmospheric neutrino studies

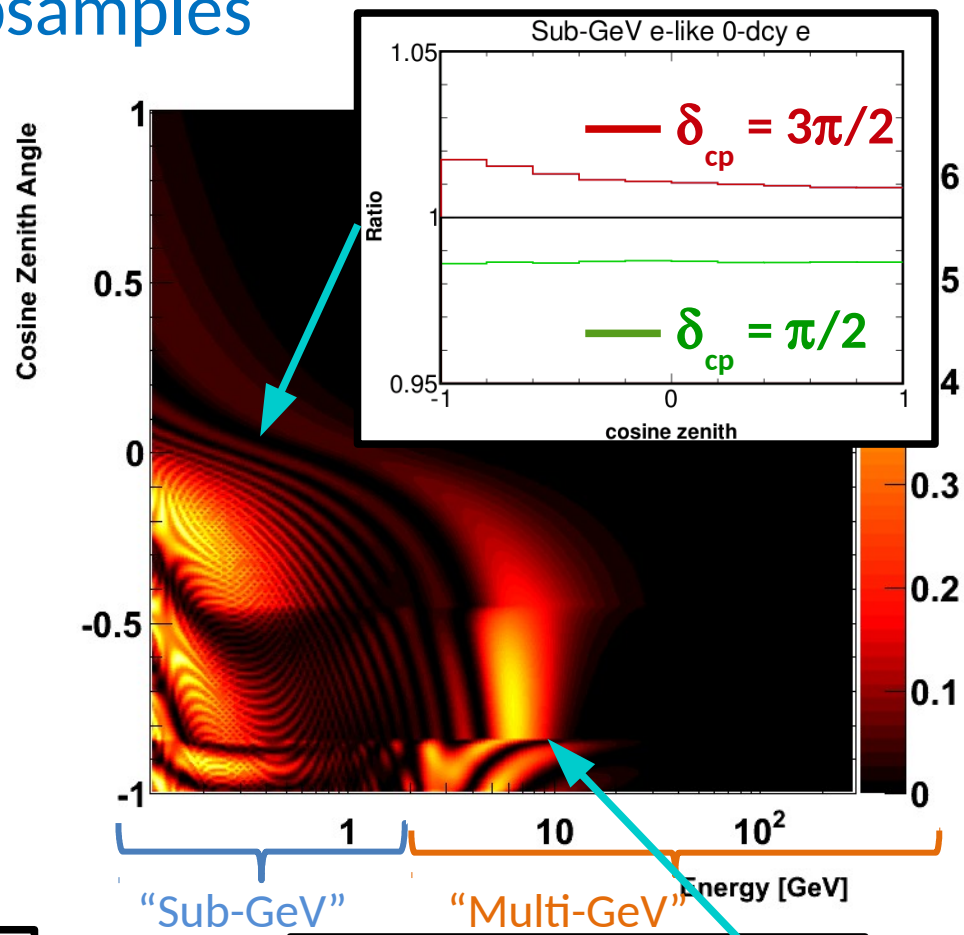
Searching for Three-Flavor Effects: Oscillation probabilities



- No $\nu_\mu \rightarrow \nu_e$ Appearance above ~20 GeV,
- Effect of matter during flight is important
  - Resonant oscillations between 2-10 GeV (for ν or $\bar{\nu}$ depending upon MH)
  - Size of the effect depends upon the electron density of the matter
  - Rate of upward-going electron neutrino-like events can be used to study the chemical composition of the Earth's matter
  - (Effects also expected in muon samples)

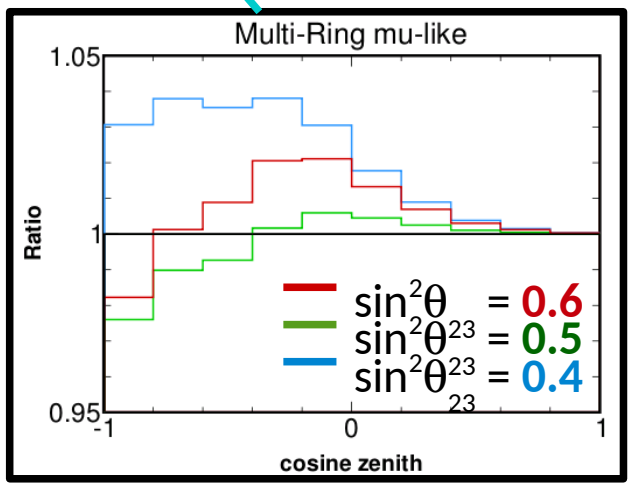
Oscillation Effects on Analysis Subsamples

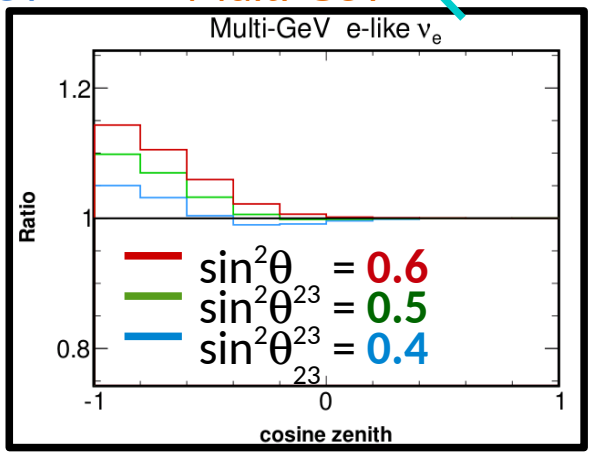




Ratio to two-flavor oscillations

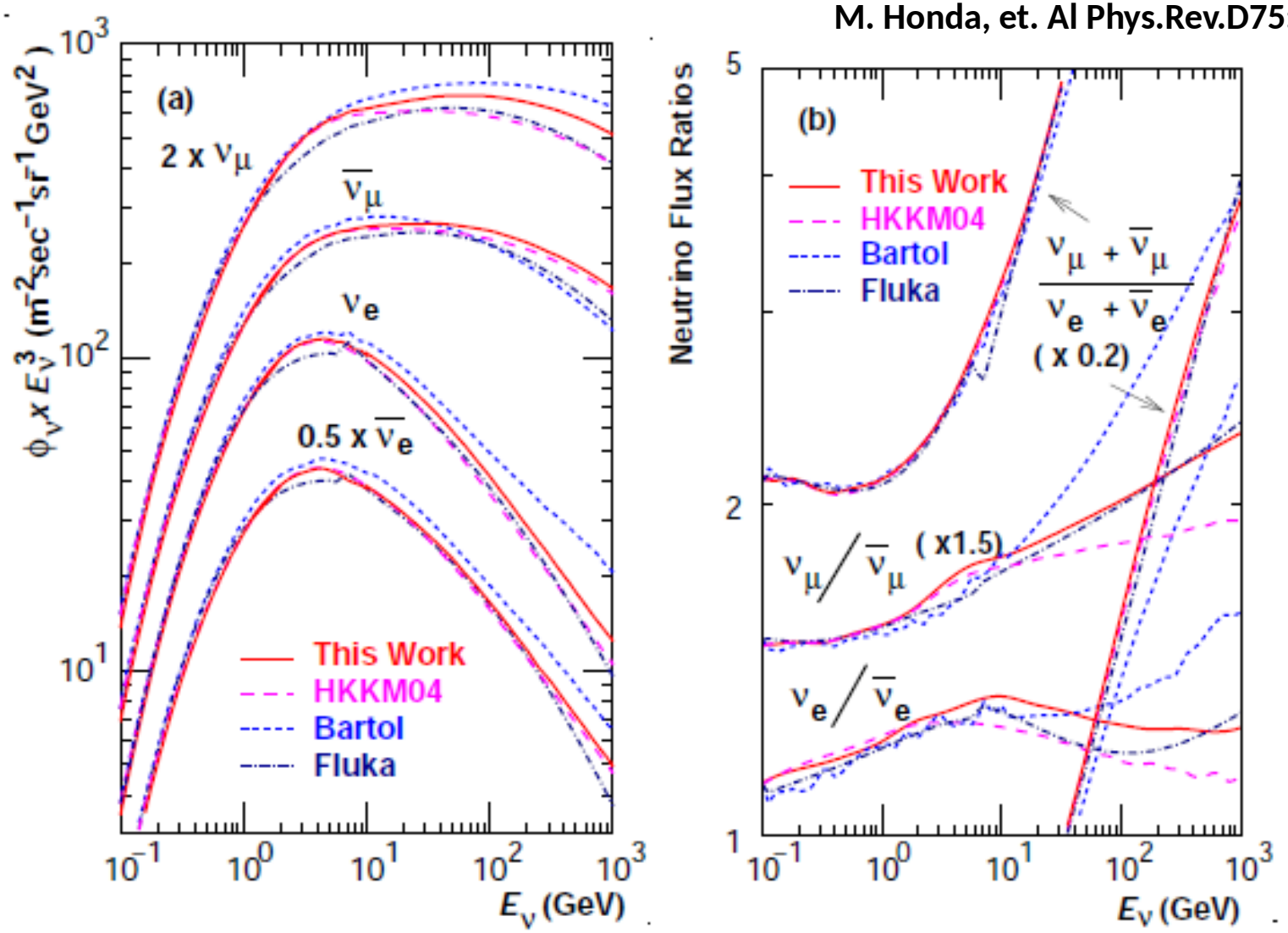
Appearance effects are halved in the IH





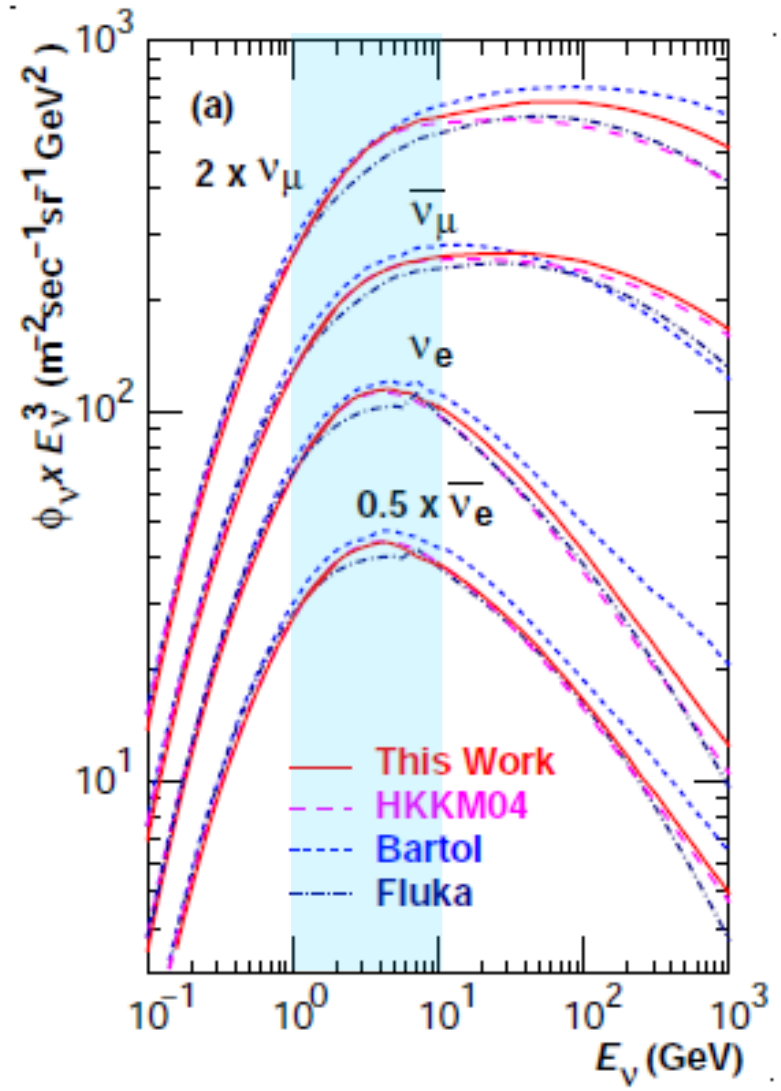
The Complication : Atmospheric Neutrino Flux

M. Honda, et. Al Phys.Rev.D75:043006,2007

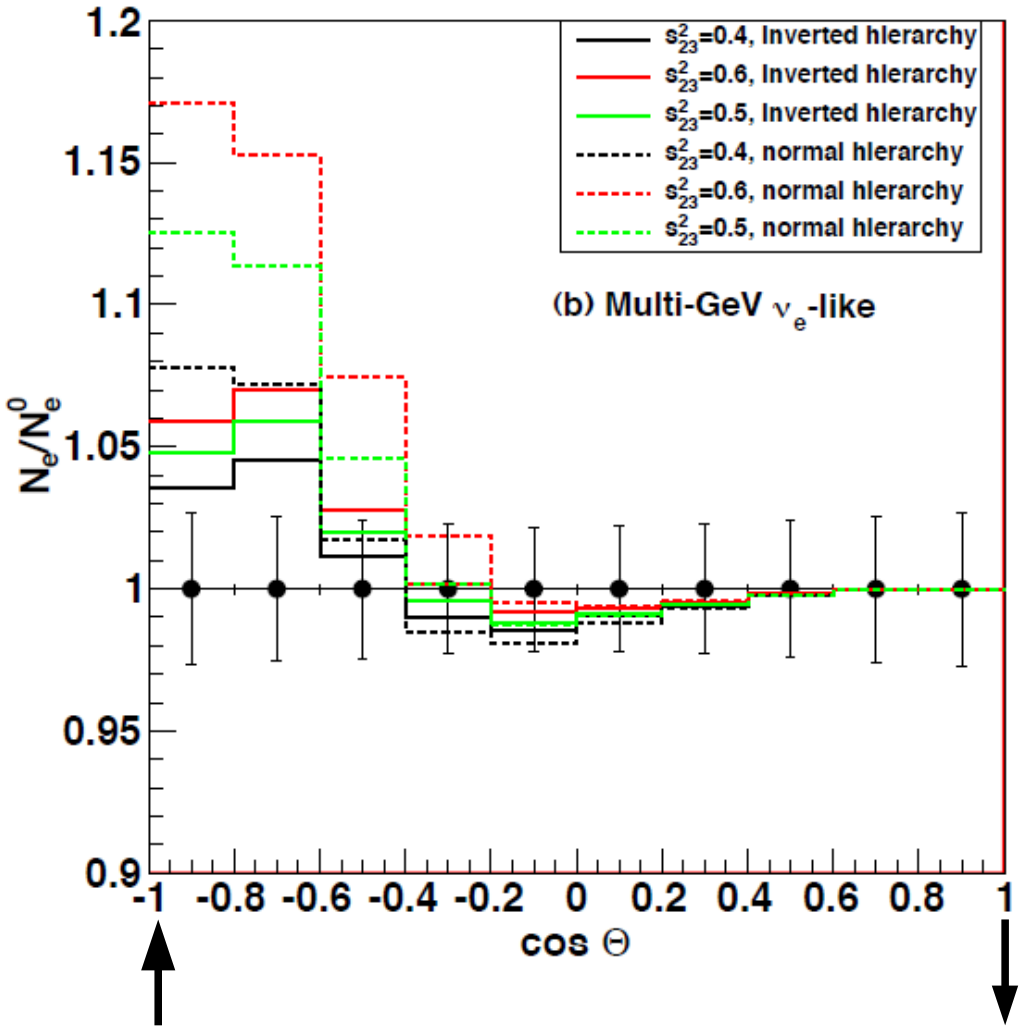


- Neutrino flux at 10 GeV is about 1000 times smaller than that at 1 GeV
  - Very massive detectors are needed!

The Complication : Atmospheric Neutrino Flux



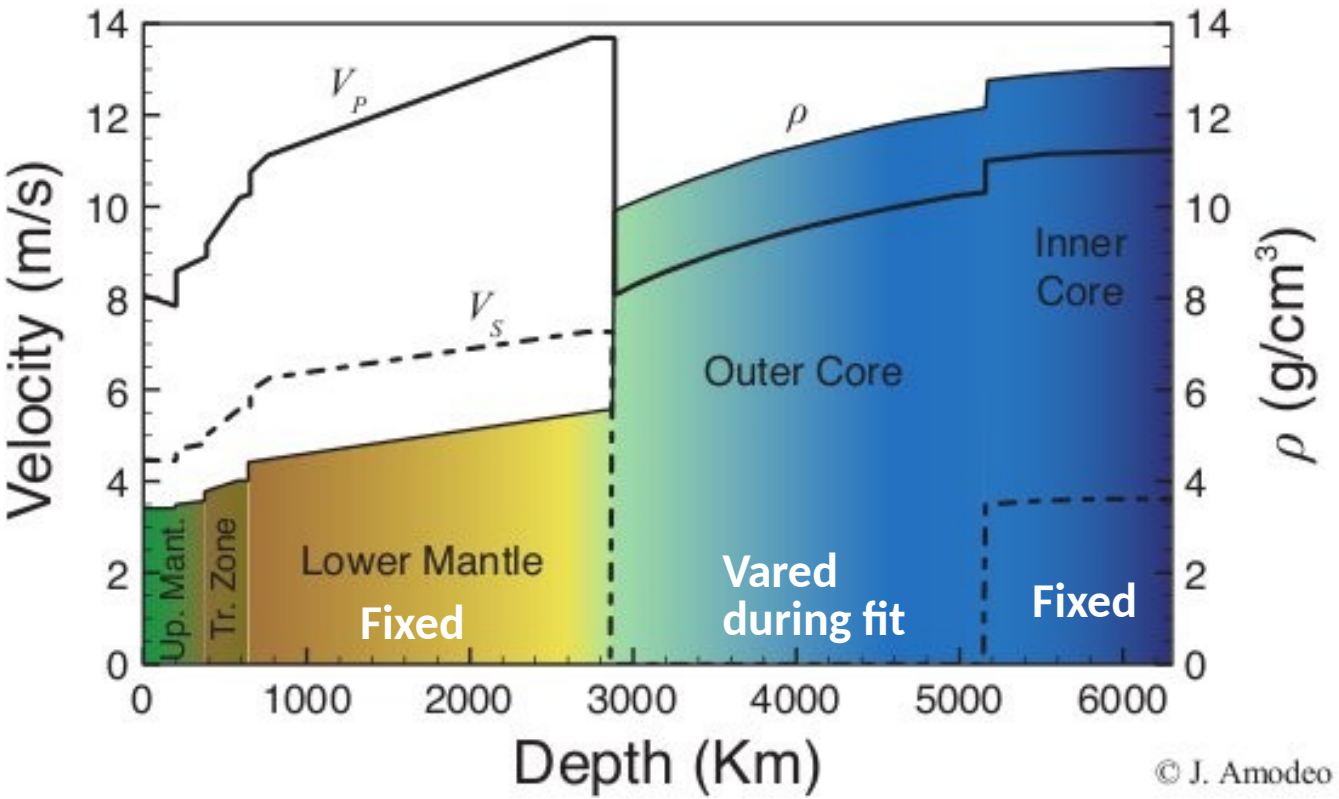
M. Honda, et. Al Phys.Rev.D75:043006,2007

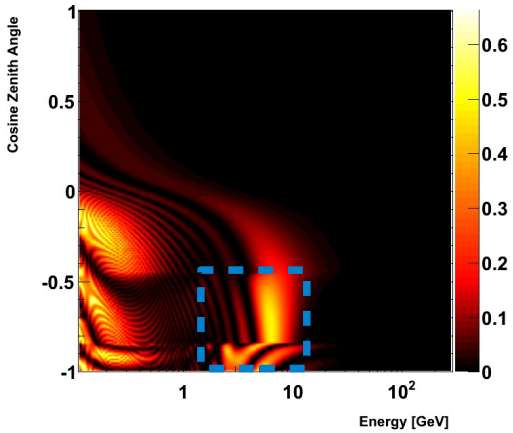


- Neutrino flux at 10 GeV is about 1000 times smaller than that at 1 GeV
  - Very massive detectors are needed!

Geophysics: Chemical Composition of Earth's Outer Core

A. Taketa

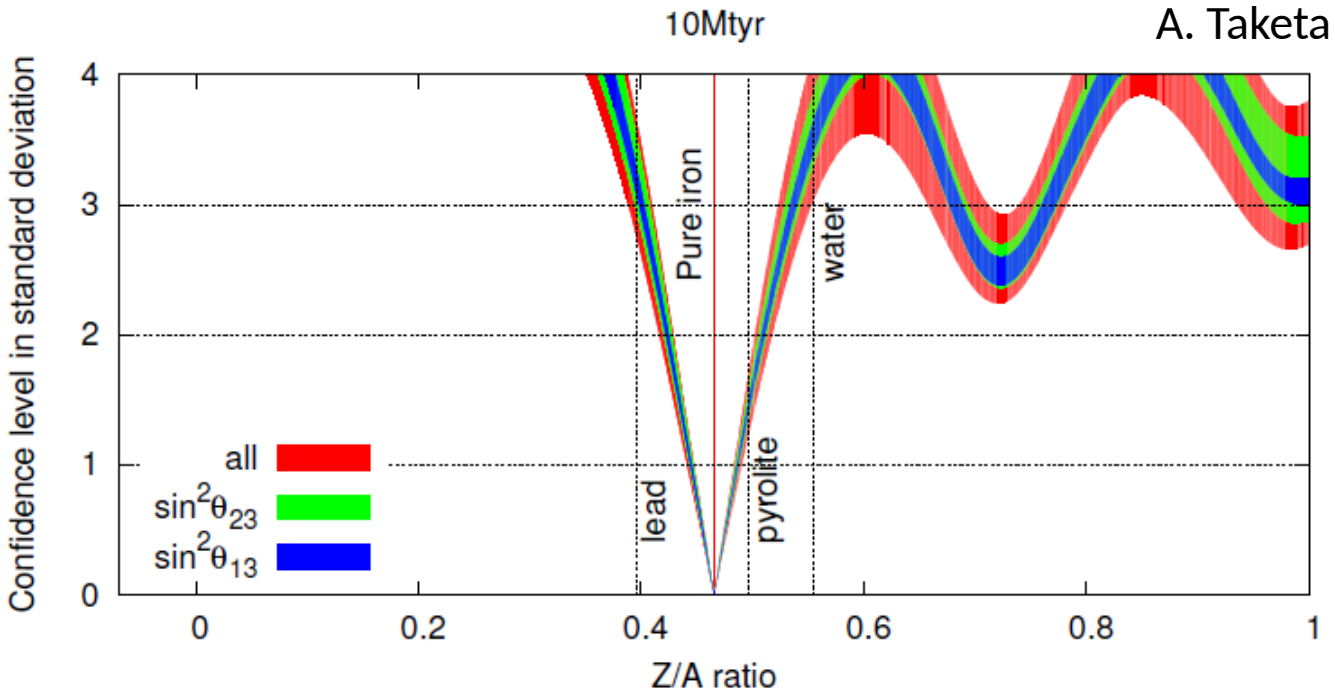


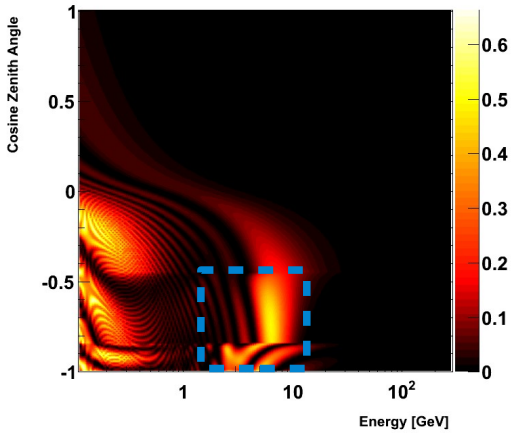


- Density profile of the Earth is well known from seismic measurements
  - Outer core is thought to be liquid iron+Ni and another light element (Unmeasured!)
- With 10 years of data Hyper-K can begin Earth Spectroscopy
  - First Z/A measurement, can exclude lead-based and water-based outer core
  - Longer exposures more useful (want to discriminate iron from pyrolite)

Geophysics: Chemical Composition of Earth's Outer Core

A. Taketa





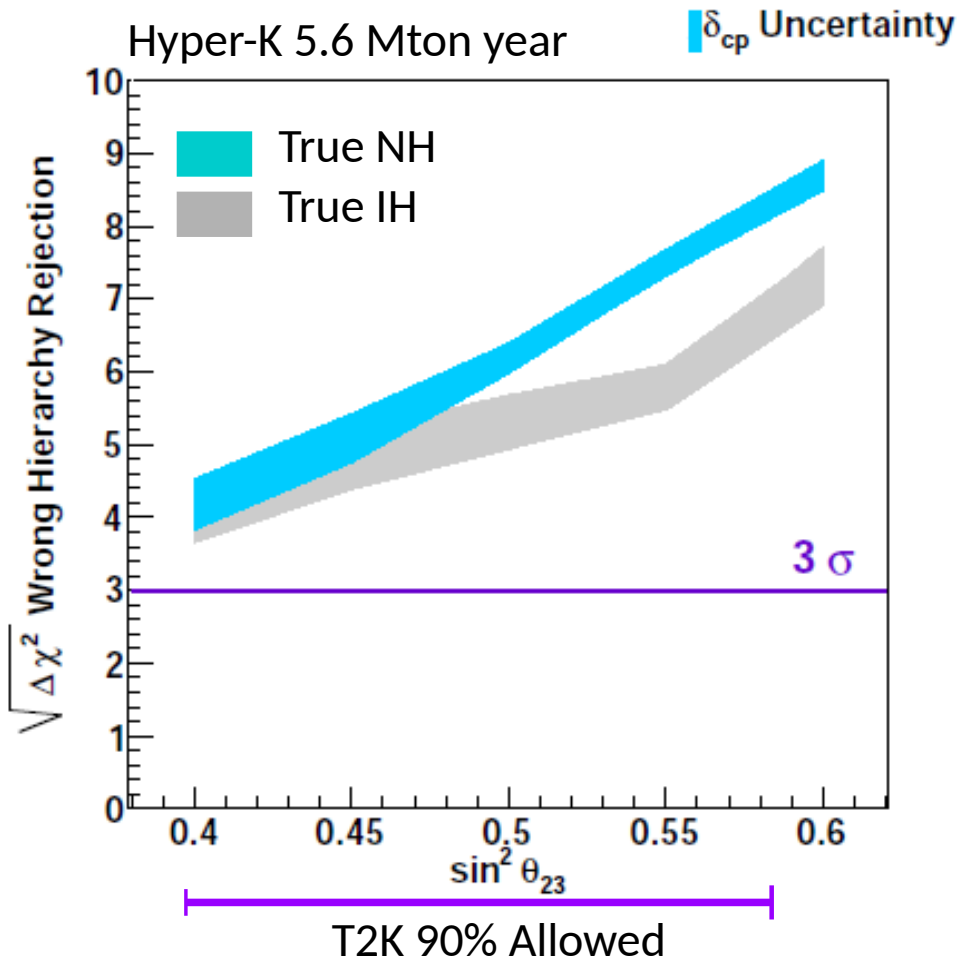
$\sin^2\theta_{23}$ = 0.43 , NH

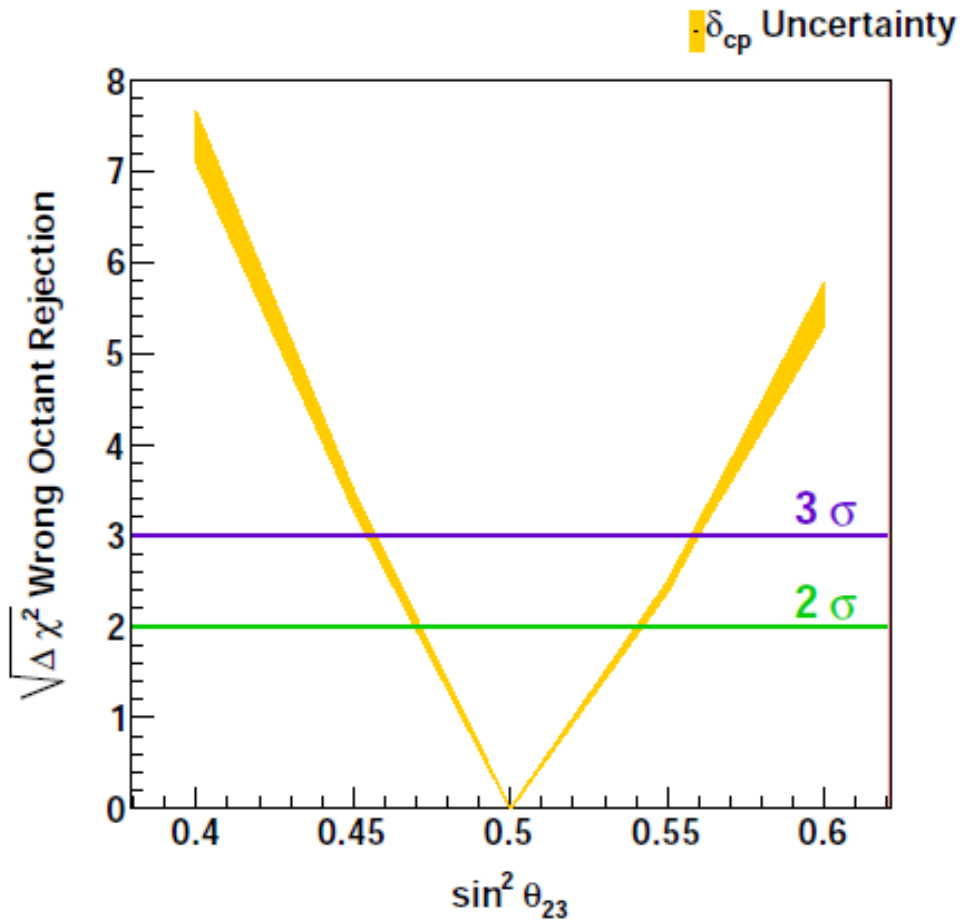
Hydrogen content [wt%] 0 20 40 60 80 100

Oxygen content [wt%] 0 100

- Density profile of the Earth is well known from seismic measurements
  - Outer core is thought to be liquid iron+Ni and another light element (Unmeasured!)
- With 10 years of data Hyper-K can begin Earth Spectroscopy
  - First Z/A measurement, can exclude lead-based and water-based outer core
  - Longer exposures more useful (want to discriminate iron from pyrolite)

Hyper-K Sensitivity 10 Years: Atmospheric Neutrinos

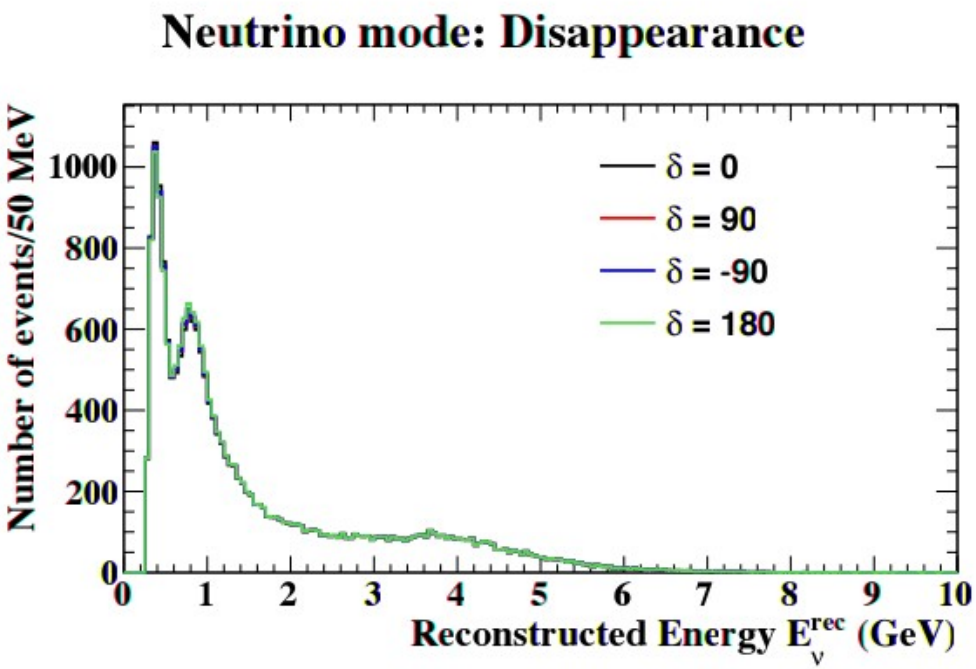


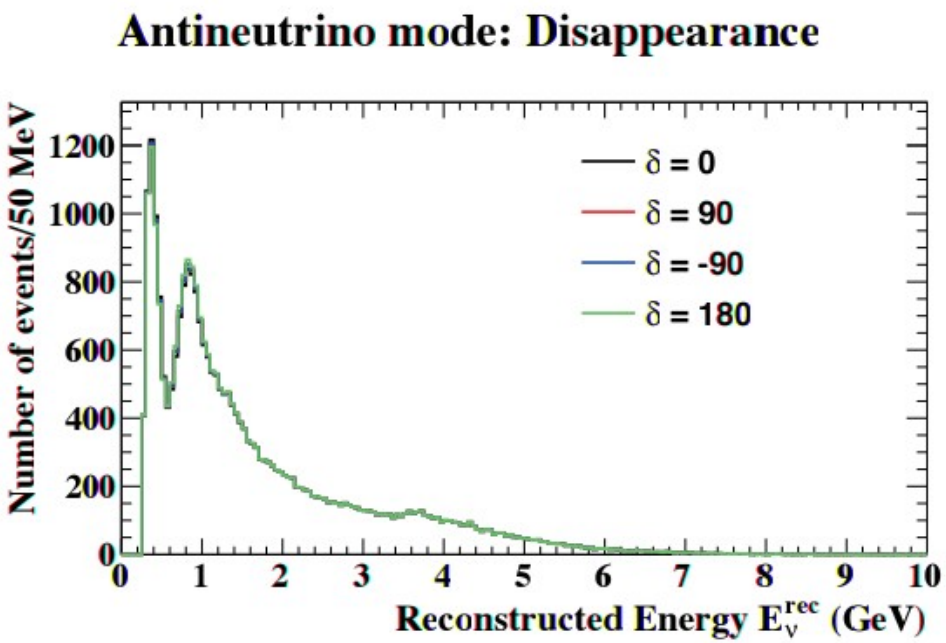


- Geochemical measurement depends on mass hiearrchy – but HK can measure it! Expect better than ~4σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $\sin^2 2\theta_{23} < 0.99$

What do the beam neutrinos buy you?

- Answer: Precision oscillation parameter measurements

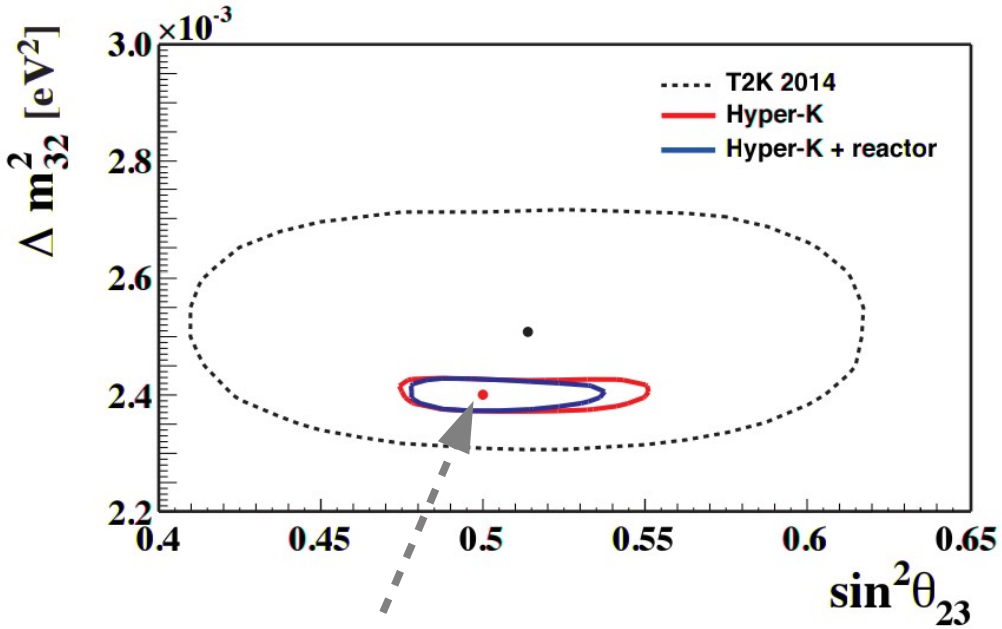




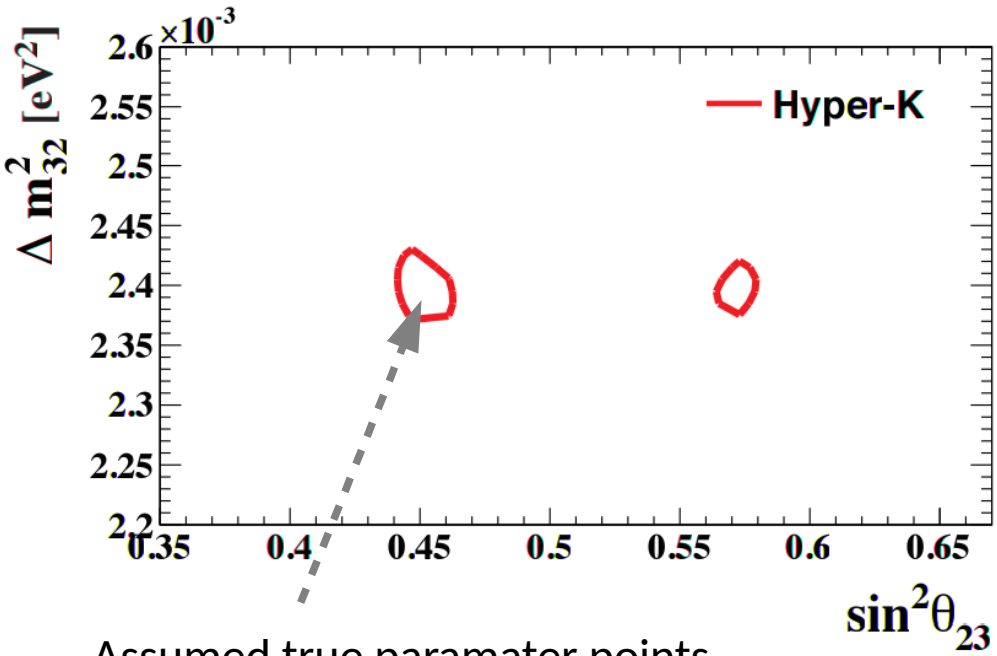
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

- Low background rates can be reduced with reconstruction (in development)
- For comparison, T2K currently has 120 (34) numu (numubar) candidates

What do the beam neutrinos buy you?



Assumed true paramater points

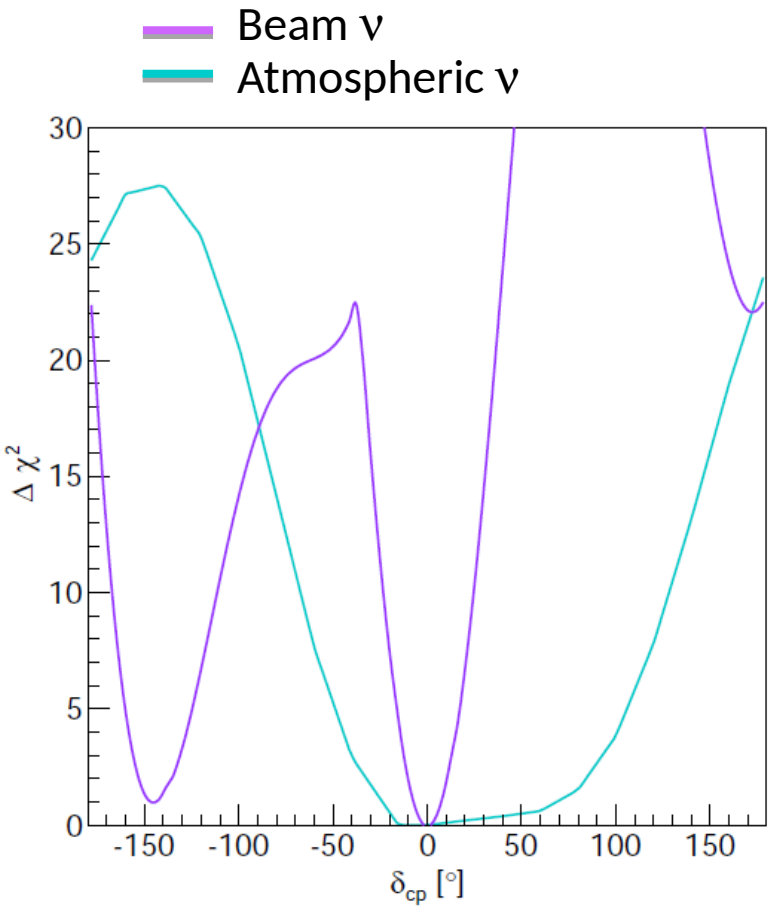


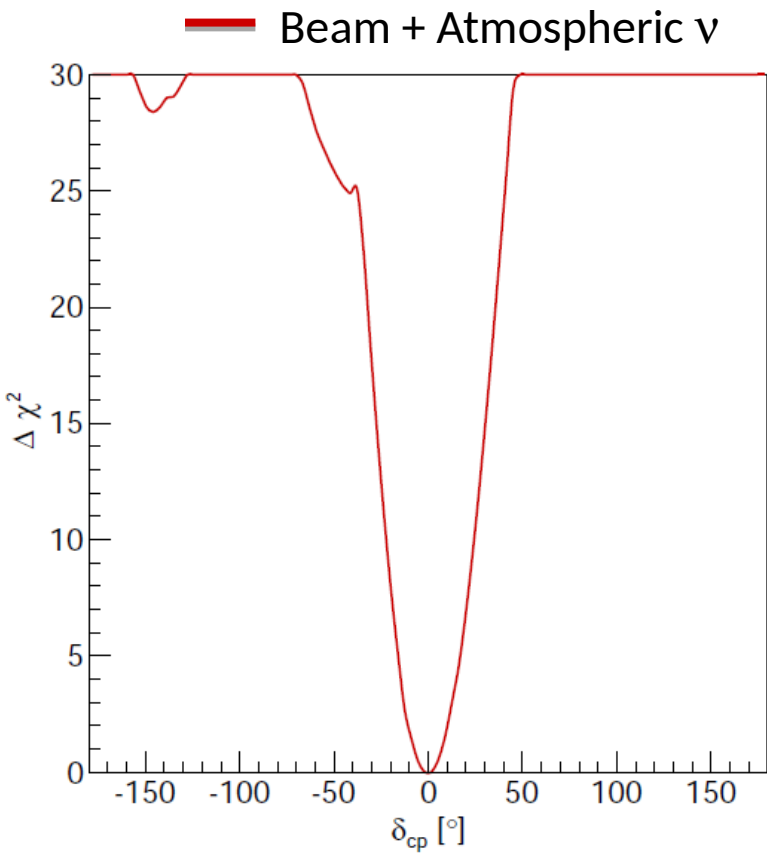
Assumed true paramater points

- Hyper-K will make measurements of atmospheric mixing parameters with unparalleled precision
  - Reduce uncertainties for earth core geochemistry measurements

- These plots are for beam neutrinos only
  - In combination with atmospheric neutrinos the octant ambiguity (right) is resolved!

Combination With Beam Neutrinos





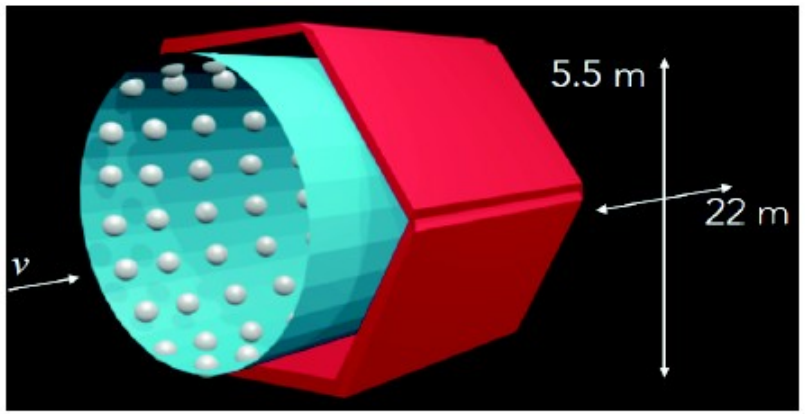
- Addition of atmospheric neutrino data to the beam measurement can improve the δ_{cp} measurement, particularly in regions of limited sensitivity for the beam
- Similarly the beam measurement gives an improved prediction of the upward-going electron rate, meaning faster determination of the mass hierarchy

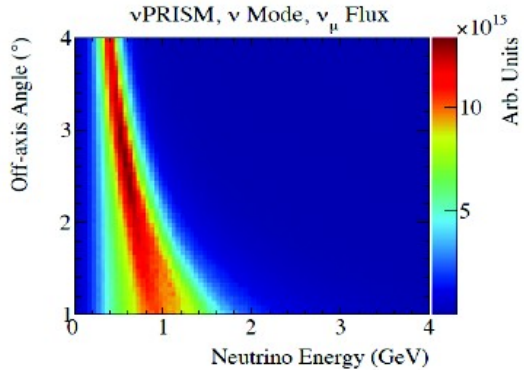
The Bottom Line

- Even if Hyper-K itself does not make the most precise measurement of the Earth's chemical composition its oscillation parameter measurement precision and cross section measurements will reduce uncertainties that affect other sensitive experiments

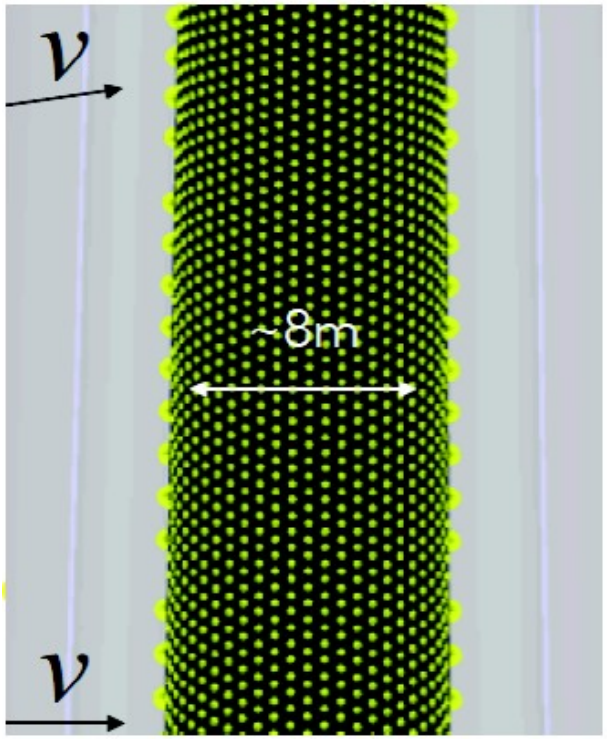
- Neutrino cross section measurements at HK near detectors
  - ν_μ and ν_e
  - Water and other targets

TITUS
WČ+MRD





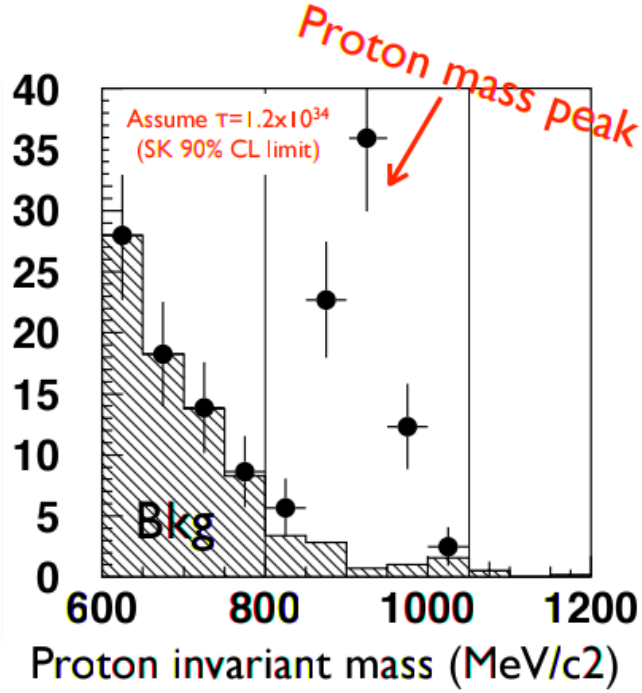
νPRISM
50m tall WČ



Other Physics: The Tip of the Iceberg

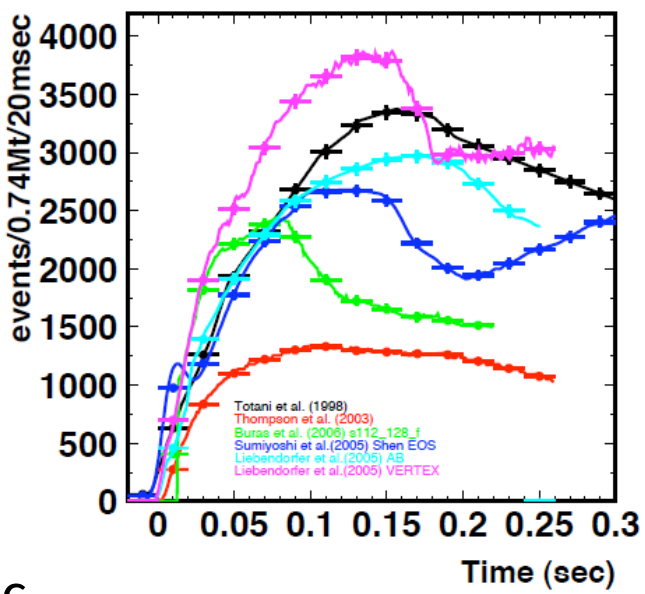
Nucleon Decay Potential

- 3σ discovery of $p \rightarrow e^+\pi^0$ if $\tau < 5 \times 10^{34}$ years
- 3σ discovery of $p \rightarrow \nu K^+$ if $\tau < 1 \times 10^{34}$ years
- Sensitivity to several other decays:
  - $p \rightarrow l^+M^0$, $n \rightarrow l^+\pi^-$, $p \rightarrow l^+X$, $p \rightarrow l^+\nu\nu$, $nn \rightarrow N\pi$, etc.
  - See the design report for the full list!
- In the case of a null observation push SK limits by an order of magnitude +



Astrophysical Neutrinos

- Supernova bust neutrinos up to 2 Mpc (10/century)
- Relic supernova neutrinos ~ 20 neutrinos / year
- High statistics solar neutrino observation ~ 200 / day
- x5 – 10 improvement in sensitivity to neutrinos from dark matter annihilation in the Sun, Earth, and Galactic center



Other Oscillation Physics

- 8-19° $\Delta(\delta cp)$, CP-violation at 3σ for 76% of values
- Sterile, Lorentz-invariance violating, and other exotic osc.

Other Physics: The Tip of the Iceberg

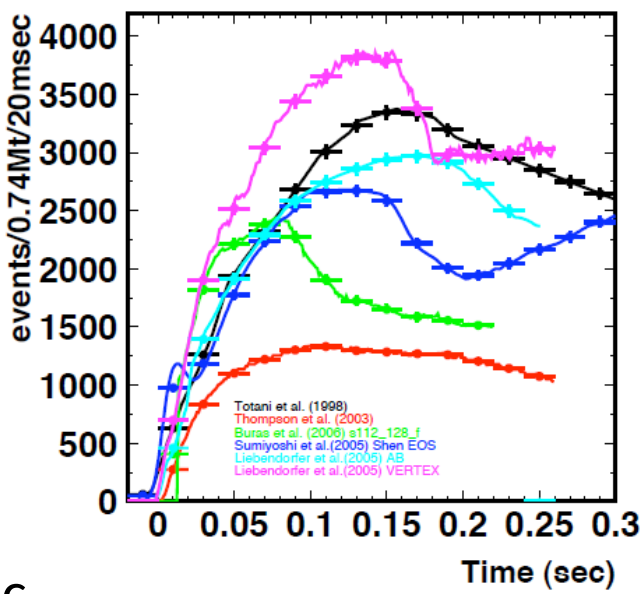
Nucleon Decay Potential

- 3σ discovery of $p \rightarrow e^+\pi^0$ if $\tau < 5 \times 10^{34}$ years
- 3σ discovery of $p \rightarrow \nu K^+$ if $\tau < 1 \times 10^{34}$ years
- Sensitivity to several other decays:
  - $p \rightarrow l^+M^0$, $n \rightarrow l^+\pi^-$, $p \rightarrow l^+X$, $p \rightarrow l^+\nu\nu$, $nn \rightarrow N\pi$, etc.
  - See the design report for the full list!
- In the case of a null observation push SK limits by an order of magnitude +

- Recently Super-K has found two candidates in the mode
  - $p \rightarrow \mu^+\pi^0$ (BG = 0.87)
- Excellent motivation
  - Reduce backgrounds!
  - Build a larger detector!

Astrophysical Neutrinos

- Supernova bust neutrinos up to 2 Mpc (10/century)
- Relic supernova neutrinos ~ 20 neutrinos / year
- High statistics solar neutrino observation ~ 200 / day
- x5 – 10 improvement in sensitivity to neutrinos from dark matter annihilation in the Sun, Earth, and Galactic center



Other Oscillation Physics

- 8-19° $\Delta(\delta cp)$, CP-violation at 3σ for 76% of values
- Sterile, Lorentz-invariance violating, and other exotic osc.

Hyper-Kamiokande : Status and Road Map

Forming the Proto-Collaboration

Inaugural Symposium, Kashiwa, January 31, 2015

- Memorandum of understanding for cooperation on the development of the Hyper-K project signed by KEK-IPNS and ICRR
  - These are the lead institutions on T2K and Super-K, and are major players in J-HEP community
- Kicked off the Hyper-K proto-collaboration

What is Happening Now?

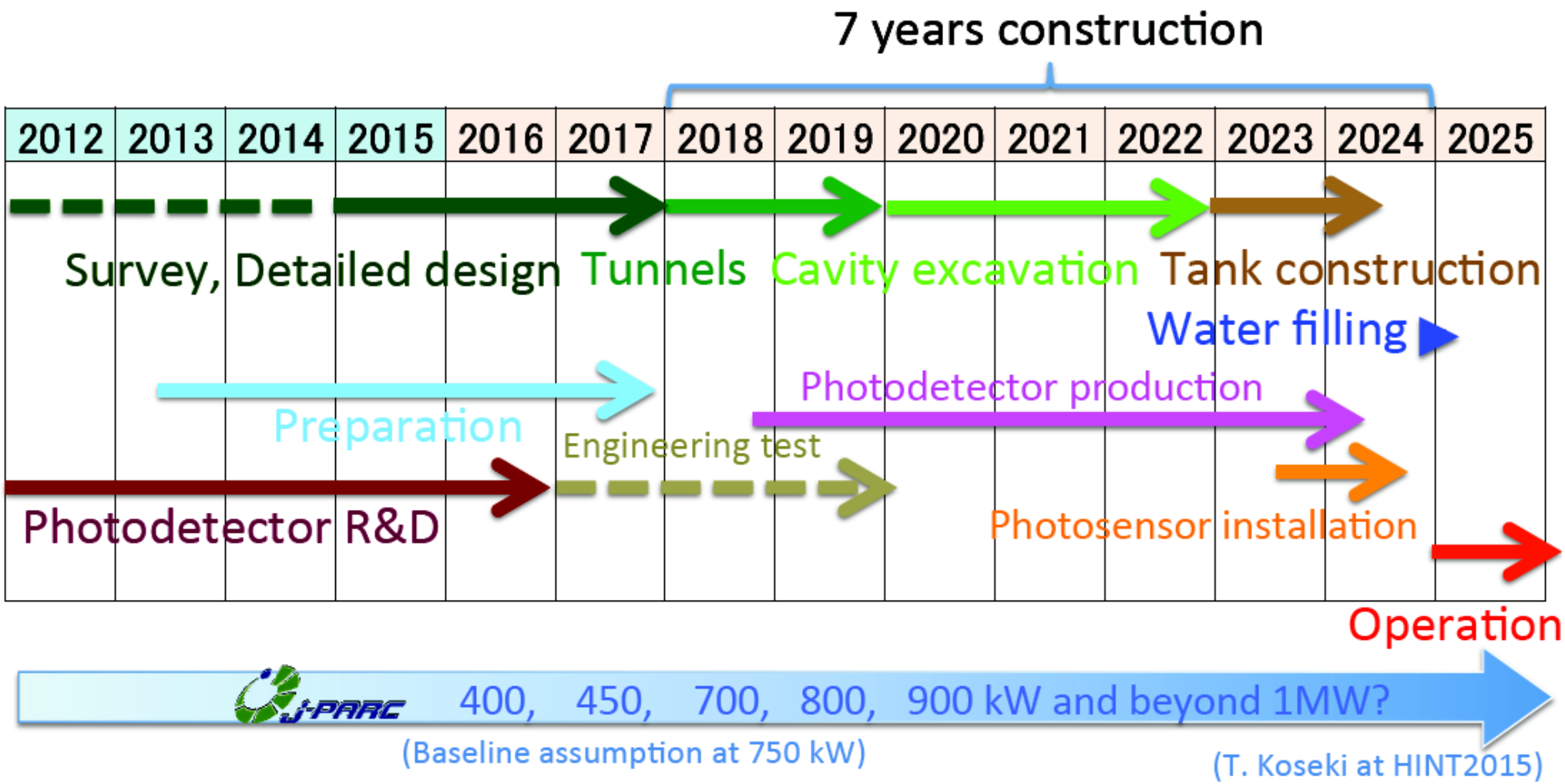
- **Design Report** for release in 2016
  - Comprehensive summary of the entire project
  - Optimum detector design, including excavation, water system, etc.
  - Construction cost and timescale
  - Design of near detectors for beam neutrino measurement
  - Role of international institutions
  - Physics potential

- Design report will be reviewed by **ICRR** and **KEK-IPNS**
  - Promote and improve the project

- Aim for submission to the **Science Council of Japan** and the next **MEXT road map** in 2016-17
  - Start budget request in the same time period

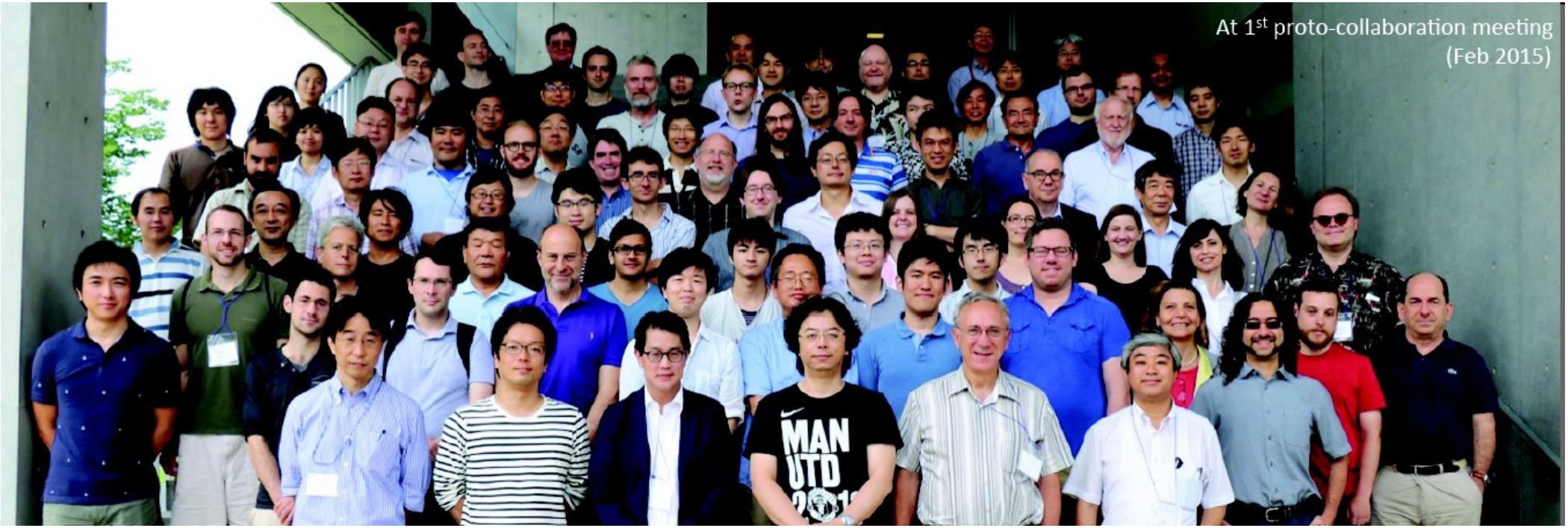
- Very active period for the project, additional participation is always welcome!

Hyper-Kamiokande Notional Timeline



- If the budget proposal is approved, **construction** can start in **2018**
- **Physics** running would then start in **2025**
- J-PARC has already achieved 360 kW operation and is expected 750 kW by 2019
  - Opens the possibility for >= MW operation after 2020

Hyper-Kamiokande Proto-Collaboration



(1st) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=7#all.detailed
(2nd) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=10#all.detailed
(3rd) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=23#all.detailed
(4th) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=29#all.detailed
(5th) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=34#all.detailed
(6th) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=52#all.detailed
(1st ProtoCollab) http://indico.ipmu.jp/indico/conferenceTimeTable.py?confId=67#all.detailed

Still open to new collaborators!

23 countries, 261 people (Oct.2015)

Hyper-Kamiokande: Summary

- The time to realize the next generation of neutrino detectors is at hand
- Hyper-Kamiokande will offer unprecedented access to a wide variety of physics
  - Join the emerging field of Earth neutrino spectroscopy
- Proto-collaboration has been formed and promotion of the project is being supported by KEK-IPNS and ICRR
- Preparation of a comprehensive summary of the project in the form of a Design Report is underway now
  - Detector optimization and full physics sensitivity studies are included
- Start budget request process in this year, with plenty of work to be done
  - Open to new collaborators!

Thank You!