The Hyper-Kamiokande Experiment

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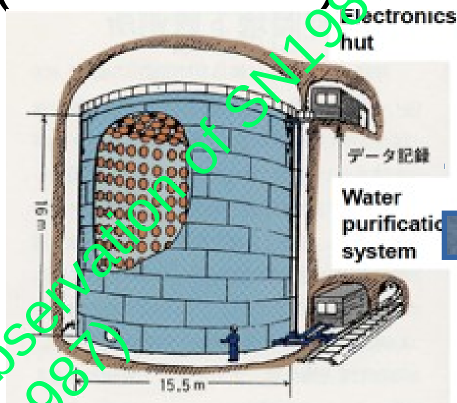
GDR Meeting
Saclay - Nov 4-5, 2015

Kamiokande Evolution

Three generations of large Water Cherenkov in Kamioka

Kamiokande
(1983-1996)

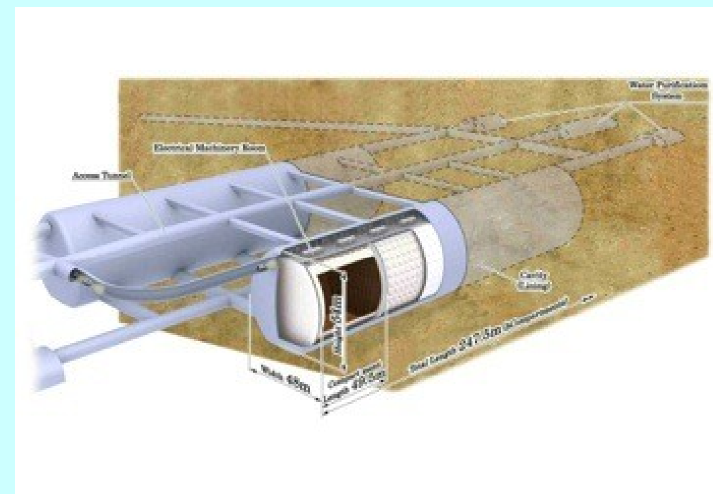


3kton

Super-Kamiokande
(1996-)

50kton

Hyper-Kamiokande
(202?-)



1Mton=1000kton

(560kton fiducial)

Observation of SN1987A
(1987)

Discovery of neutrino oscillation (1998)

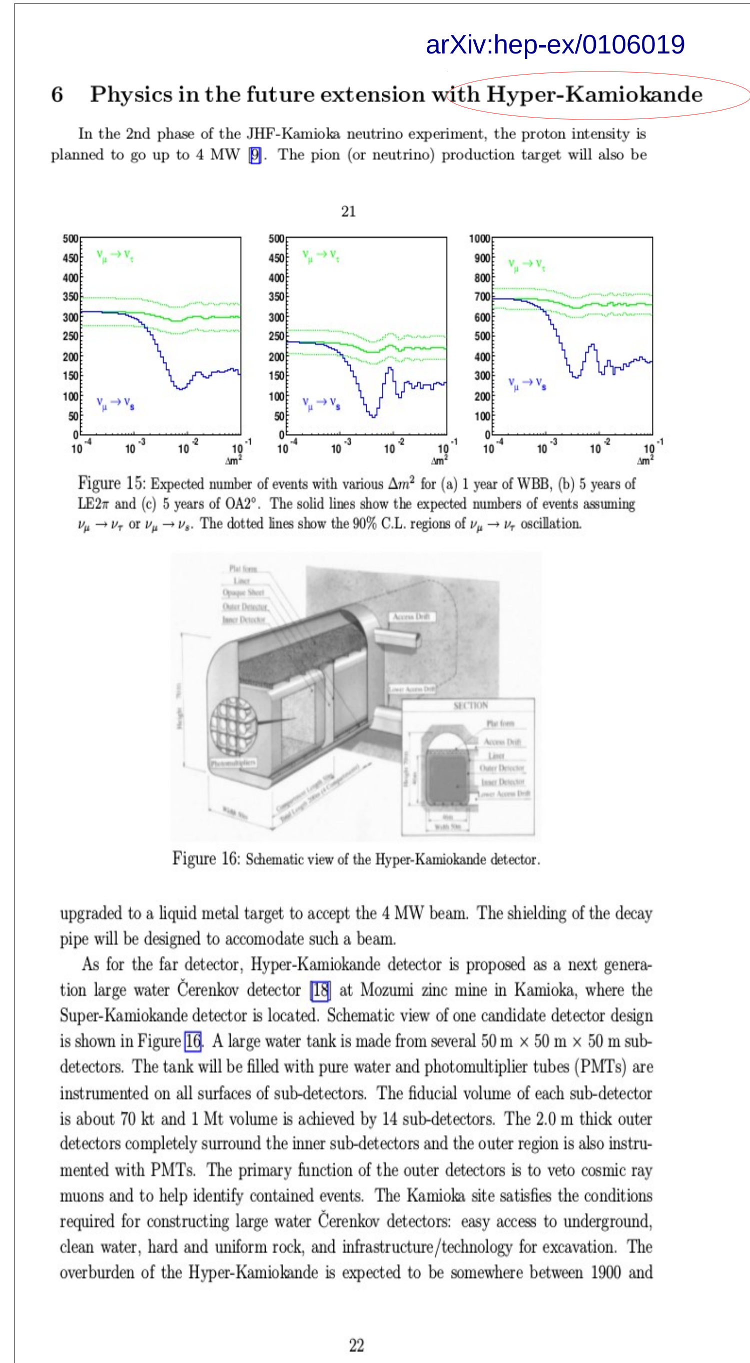
Observation of electron neutrino appearance
(w/ beam, T2K, 2013)

x17

x20
(x25 fiducial mass)

Hyper-Kamiokande in 2001

- In 2001, Letter of Intent for T2K.
- Hyper-Kamiokande introduced as a future extension of T2K.
- Second phase assumed to happen if T2K would have observed muon-into-electron neutrino oscillations.
- We are now in a position to plan this second phase of the Long Baseline Neutrino Experiment called Hyper-Kamiokande.



arXiv:hep-ex/0106019

6 Physics in the future extension with Hyper-Kamiokande

In the 2nd phase of the JHF-Kamioka neutrino experiment, the proton intensity is planned to go up to 4 MW [9]. The pion (or neutrino) production target will also be

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Figure 15: Expected number of events with various Δm^2 for (a) 1 year of WBB, (b) 5 years of LE2π and (c) 5 years of OA2°. The solid lines show the expected numbers of events assuming $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$. The dotted lines show the 90% C.L. regions of $\nu_\mu \to \nu_\tau$ oscillation.

Figure 16: Schematic view of the Hyper-Kamiokande detector.

upgraded to a liquid metal target to accept the 4 MW beam. The shielding of the decay pipe will be designed to accomodate such a beam.

As for the far detector, Hyper-Kamiokande detector is proposed as a next generation large water Čerenkov detector [18] at Mozumi zinc mine in Kamioka, where the Super-Kamiokande detector is located. Schematic view of one candidate detector design is shown in Figure 16. A large water tank is made from several 50 m × 50 m × 50 m sub-detectors. The tank will be filled with pure water and photomultiplier tubes (PMTs) are instrumented on all surfaces of sub-detectors. The fiducial volume of each sub-detector is about 70 kt and 1 Mt volume is achieved by 14 sub-detectors. The 2.0 m thick outer detectors completely surround the inner sub-detectors and the outer region is also instrumented with PMTs. The primary function of the outer detectors is to veto cosmic ray muons and to help identify contained events. The Kamioka site satisfies the conditions required for constructing large water Čerenkov detectors: easy access to underground, clean water, hard and uniform rock, and infrastructure/technology for excavation. The overburden of the Hyper-Kamiokande is expected to be somewhere between 1900 and

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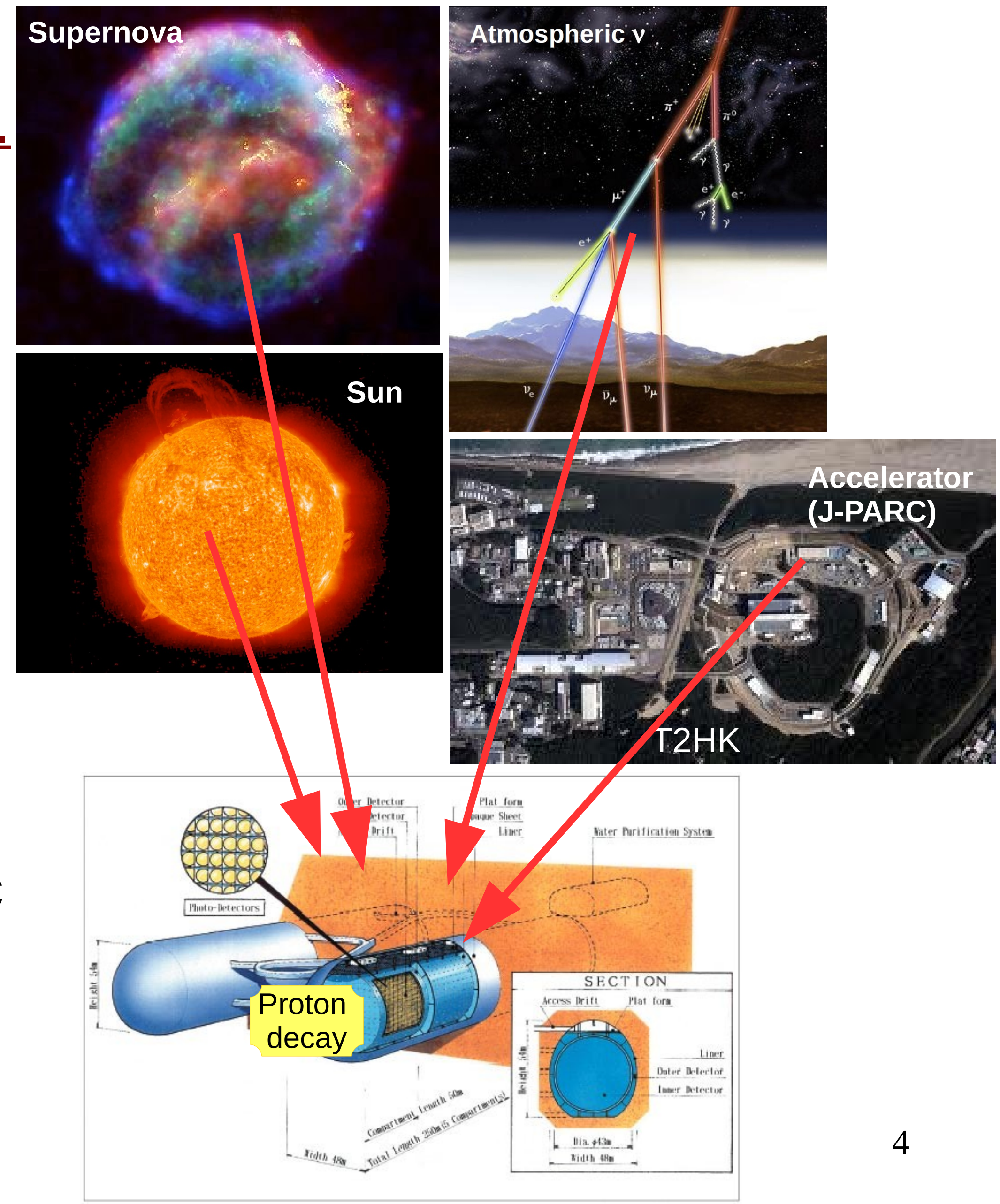
The Hyper-K Project

Multi-purpose neutrino experiment.
Wide-variety of scientific goals:

- Neutrino oscillations:
  - Neutrino beam from J-PARC
  - Atmospheric neutrinos
  - Solar neutrinos

- Search for proton decay

- Astrophysical neutrinos
(supernova bursts, supernova relic neutrinos, dark matter, solar flare, …)



Outline

- Overview
  - Status of the Project
- Experimental Design
- Physics:
  - Beam
  - Atmospherics
  - Proton Decay
  - Astro

Current Status

Hyper-K Proto-Collaboration

Inaugural Symposium, Kashiwa, January 31, 2015

KEK-IPNS and UTokyo-ICRR
signed a MoU for cooperation
on the Hyper-Kamiokande project.

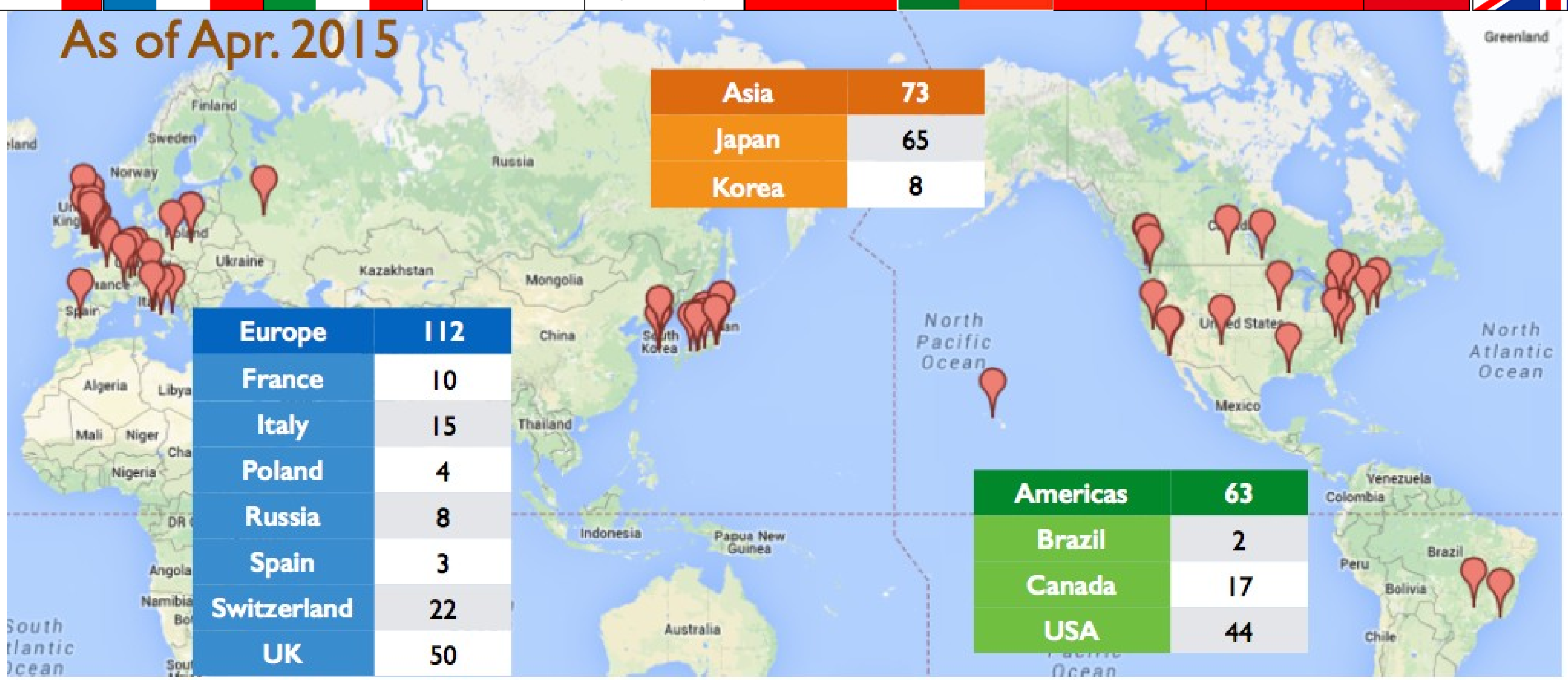
Important moment.
The proto-collaboration is born.

First Meeting of the proto-collaboration: June 29-July 1, @Kashiwa

Hyper-K in the World

(http://www.hyperk.org
http://www.hyper-k.org)

- 13 countries, ~250 members and growing
- Governance structure has been defined
  - International Steering Committee, International Board Representatives, and Working Groups, Conveners Board
  - R&D fund and travel budget already secured in some Countries, and more in securing processes.



Asia	73
Japan	65
Korea	8

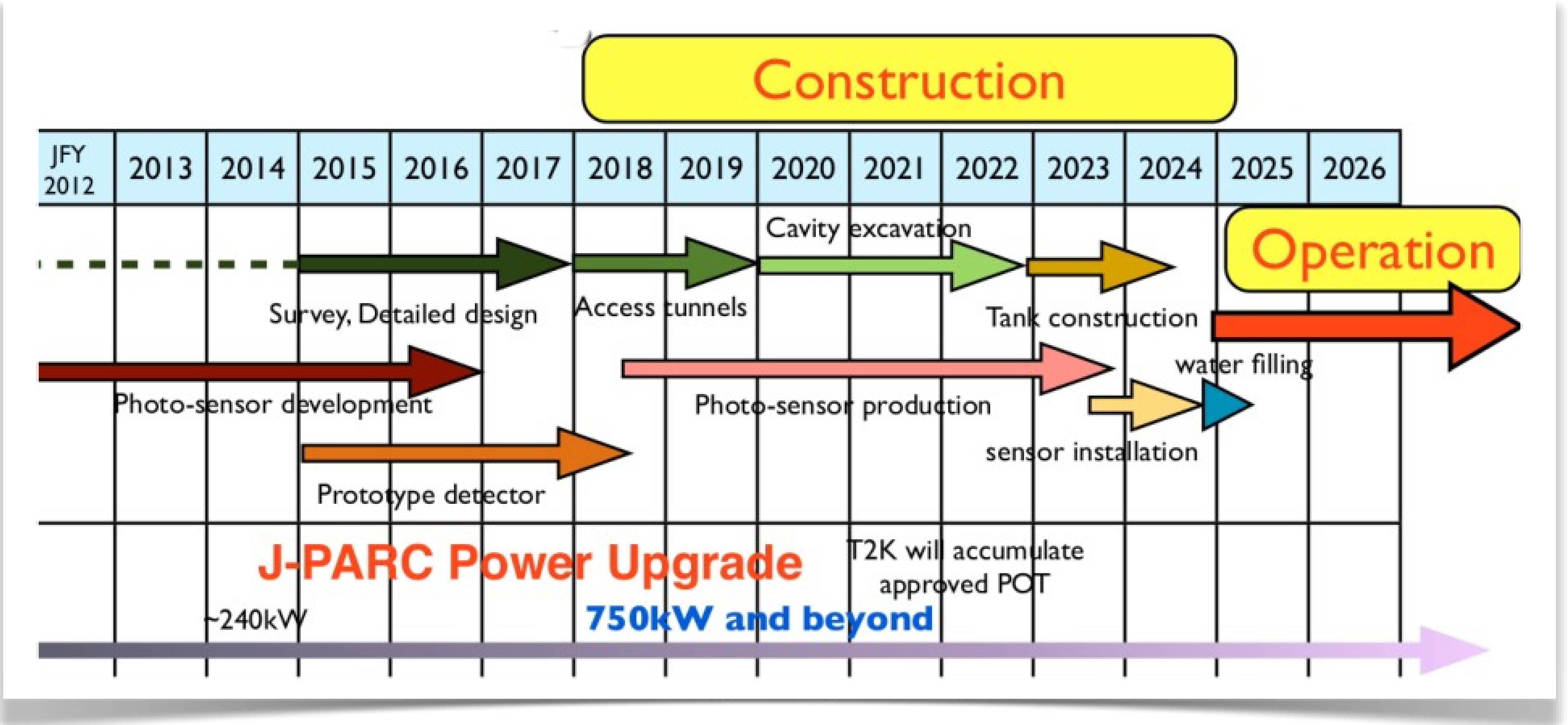
Europe	112
France	10
Italy	15
Poland	4
Russia	8
Spain	3
Switzerland	22
UK	50

Americas	63
Brazil	2
Canada	17
USA	44

Future Steps for the proto-collaboration

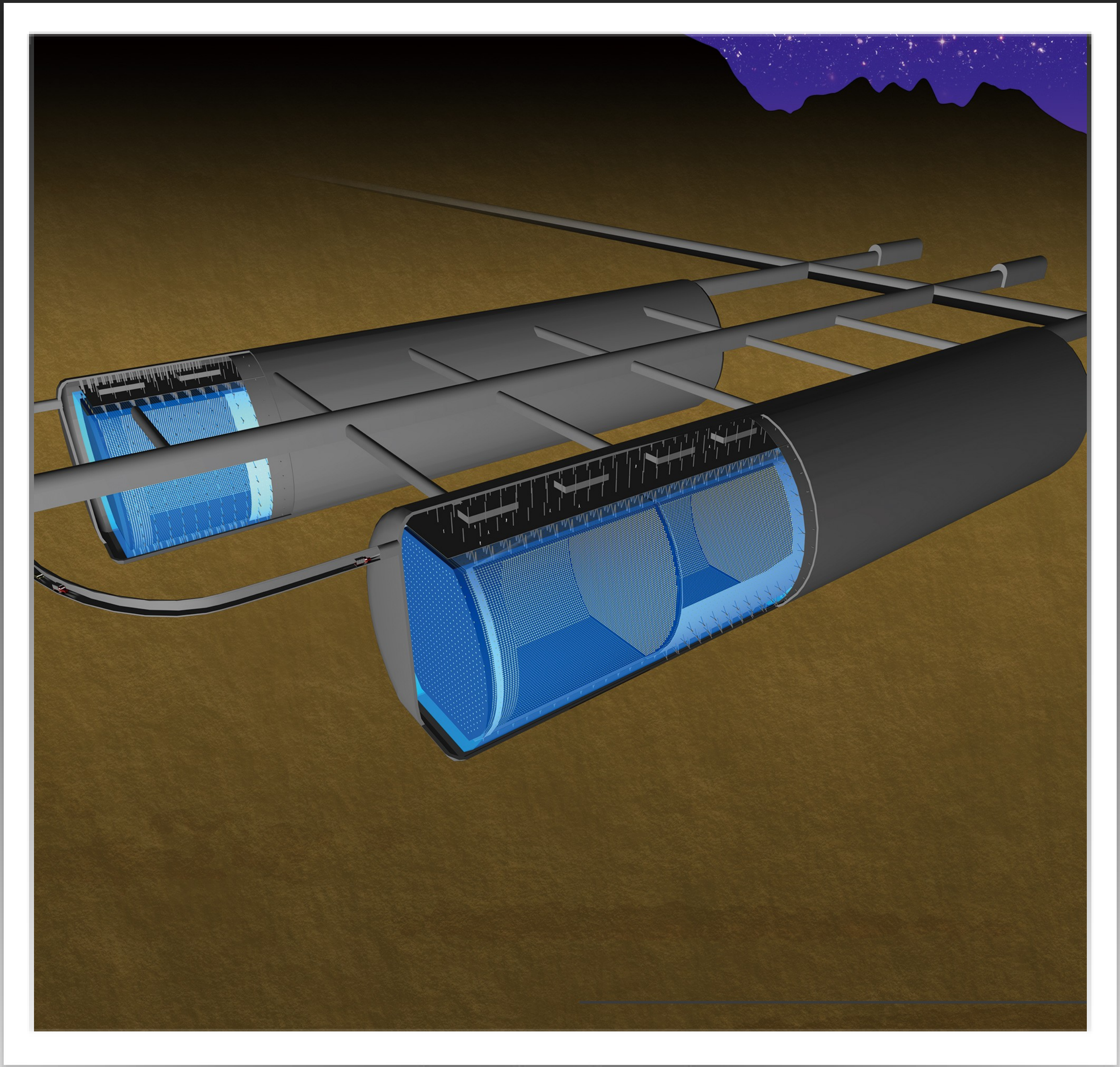
- Design Report (DR)
  - Currently being finalized. It will serve as input to Japanese science roadmap (2016-2017).
  - Advisory committee formed by Directors (Hyper-K Advisory Committee, HKAC).
  - Current ongoing work:
    - R&D for far detector
    - Design optimization
    - Construction cost & period
    - Beam & near detector suite
    - International responsibilities
- Once the budget is approved:
  - Construction can start in 2018, w/ data taking in ~2025
- DR studies still ongoing, non-beam studies presented in this talk.

The Hyper-Kamiokande Timeline

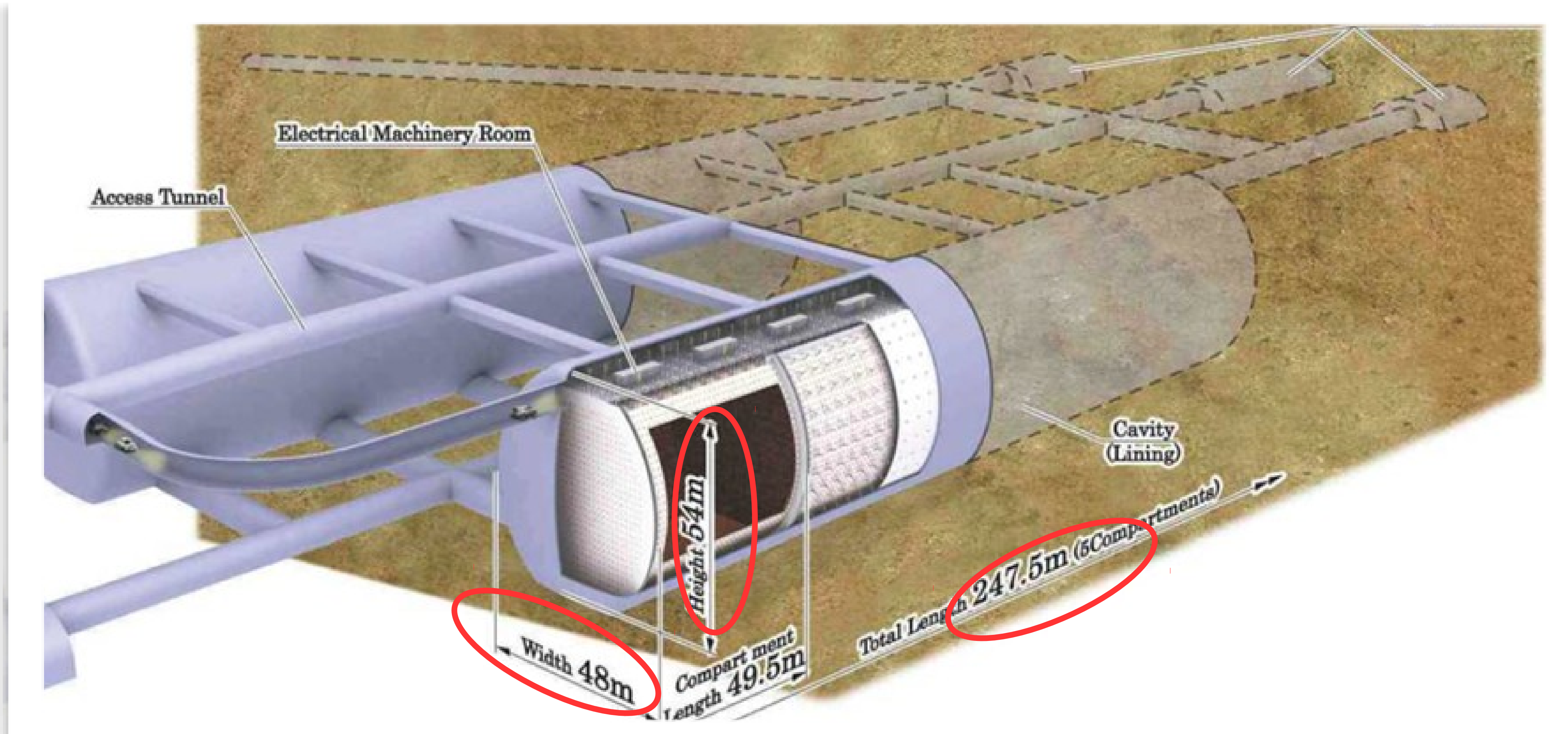


~2017 Major design decisions finalized
~2018 Construction starts
~2025 Data taking start
> 2025 Discoveries!

The Experiment



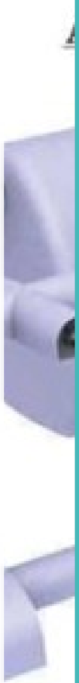
The Hyper-Kamiokande Detector

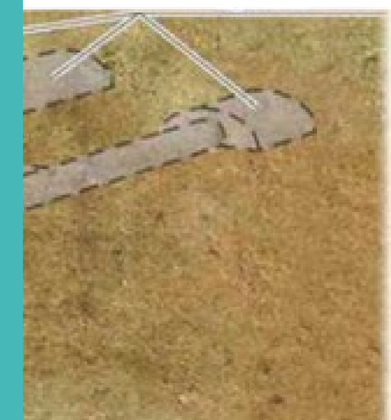


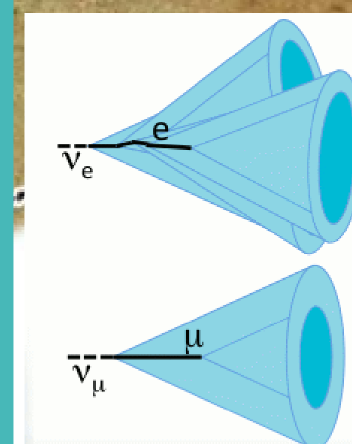
The Hyper-Kamiokande Detector

- Water Cherenkov, proven 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	0.2 Megaton
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) •5 optically separated compartments per tank



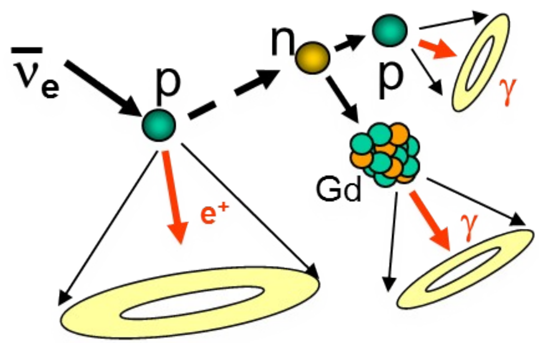




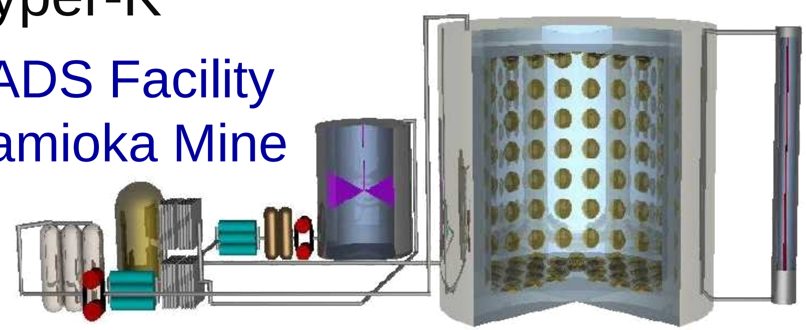
Gadolinium Option

Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004

- Gd-doping proposed in 2004 mainly to greatly enhance relic supernova neutrino detection.
- It can help also other physics
  - Beam physics → distinguish ν and $\bar{\nu}$; CCQE and other ν-interactions
  - Proton decays → reduce background
- R&D programme started with EGADS (200ton scale model of Super-K)
- Now finishing → Super-K will run with the Gd-doping
- Considered as possible option for Hyper-K

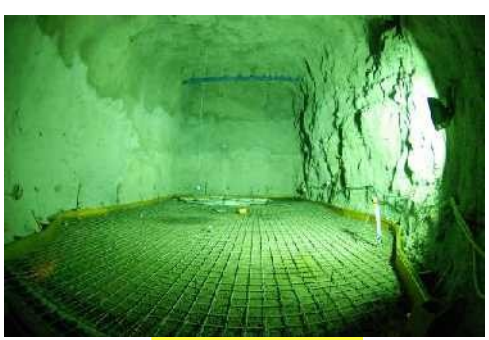


EGADS Facility
in Kamioka Mine



April 2015: fully loaded (0.2%) with Gd sulfate, and functioning perfectly.

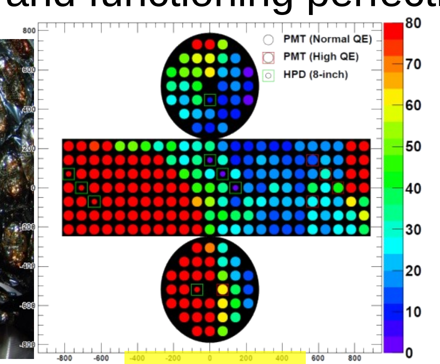
EGADS:



12/2009

11/2011

8/2013

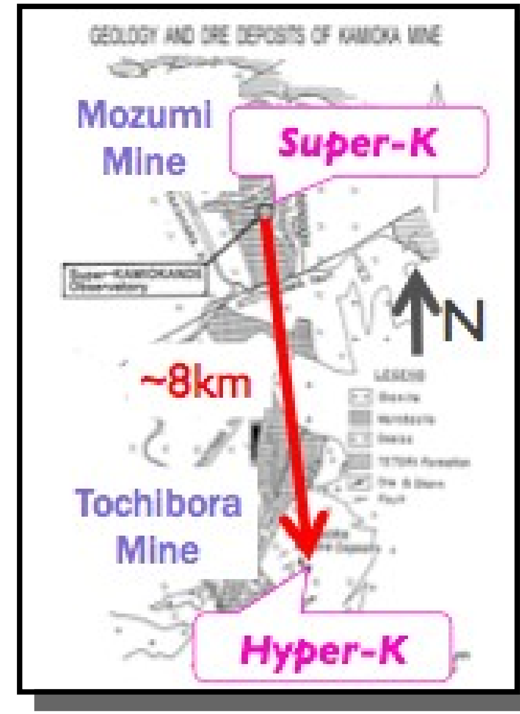


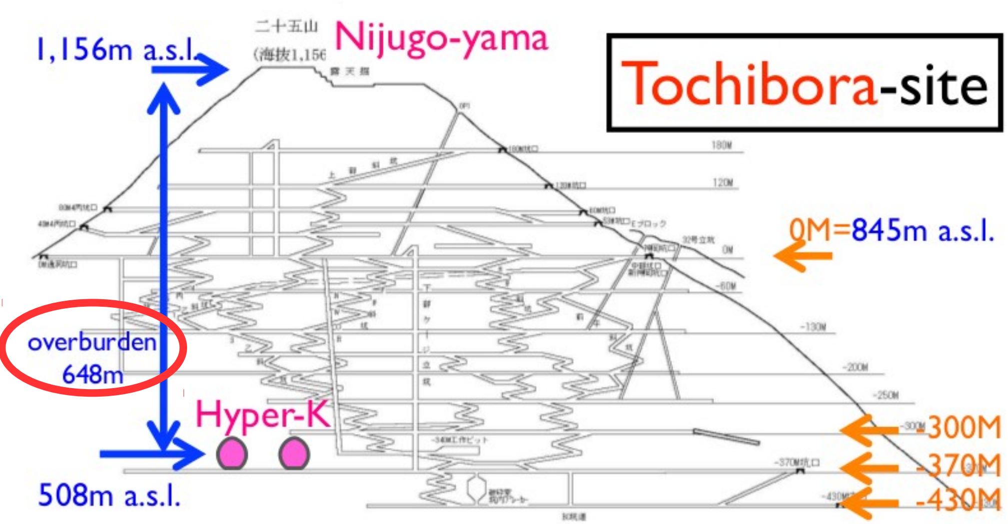
6/2015

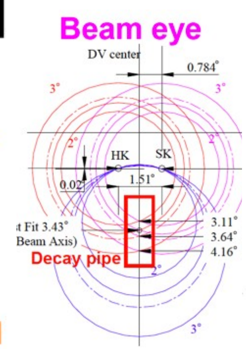
Site(s) and Cavern(s)

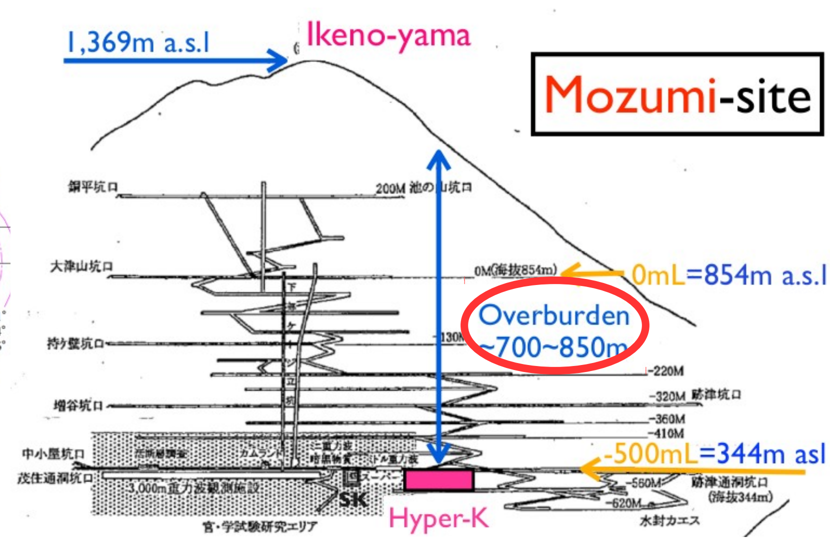
Two sites are being investigated:

- Tochibora mine:
  - ~8km South from Super-K
  - Identical baseline (295km) and off-axis angle (2.5º) to Super-Kamiokande
- Mozumi mine (same as Super-K)
  - Deeper than Tochibora
- Rock quality in the two sites similar
- Confirmed HK cavern can be built w/ existing techniques





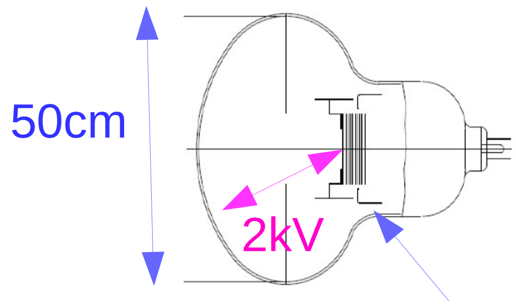




Photosensors Candidates

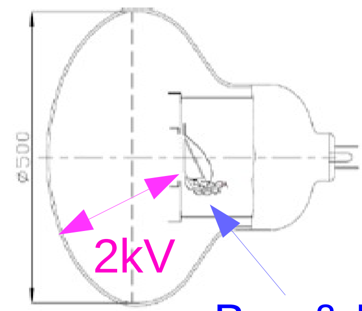
R&D going to get better performance and lower costs

Established (**SK PMT**)



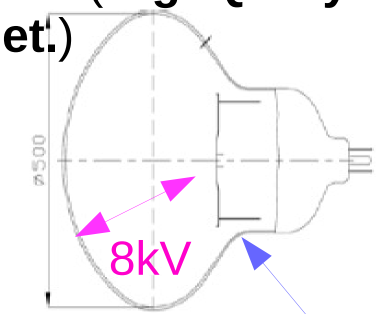
Venetian blind dynod

R&D (**HighQE/CE PMT**)



Box & Line dynod (unique drift path)

R&D (**HighQE hybrid det.**)



Avalance diode

	Established (SK PMT)	R&D (HighQE/CE PMT)	R&D (HighQE hybrid det.)
Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

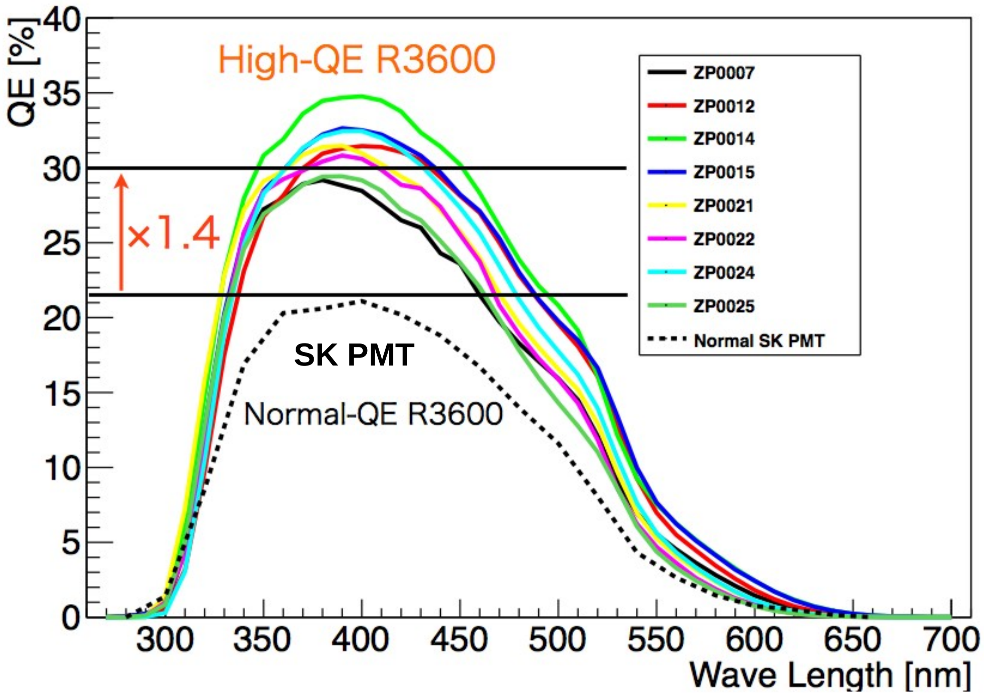
SK PMT:
- Super-K ID PMTs
- Used for ~20 years →Guaranteed
- Complex production → Expensive

HighQE/CE PMT:
- Under development
- Better performance
- Same technology → Lower risk

HighQE hybrid det.:
- Under development
- Far better performance
- Simple structure →Lower cost
- New technology →Higher risk

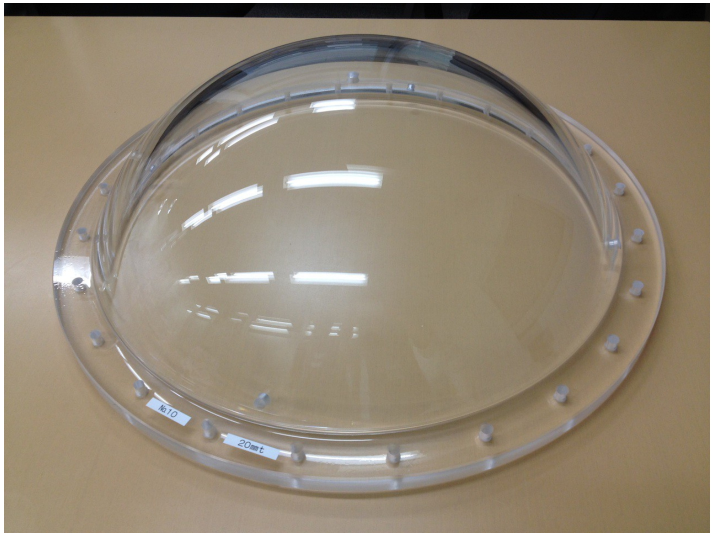
Lower Risk ← → Higher Performance

Photosensors con't



- High Quantum Efficiency (QE) of ~30% has been achieved for 50cm B&L PMT and HPD.
- Current studies open to other photo-sensor options as well to achieve a better performance and/or reduced cost.

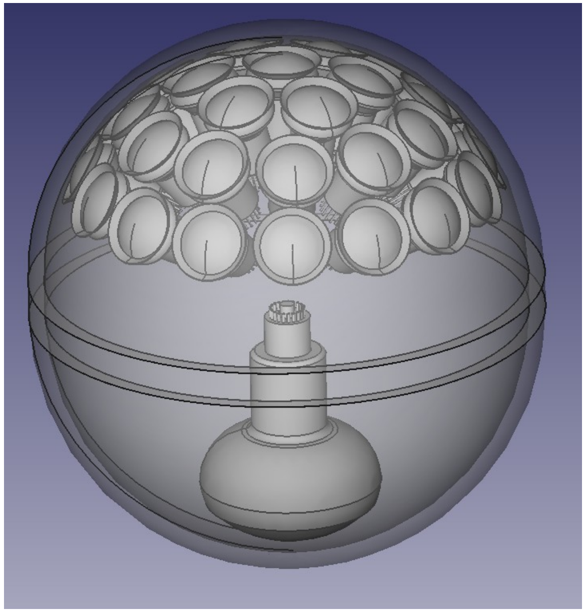
The HQE B&L 1 PMT bulb has been improved for a test and its specification allows the bulb.
A protective cover is needed to avoid any cascade implosion of the photosensors, making up for the difficult control of the glass quality in the production.



Schedule

Items		Remaining issues
ID photosensor	**HQE 50 cm B&L PMT (Hamamatsu R12860-HQE)**	Confirmation of pressure resistance
(Alternative)	HQE 50 cm HPD (Hamamatsu R12850-HQE)	Electronics development, Test in water, Confirmation of pressure resistance
OD photosensor	**20 cm B&L PMT (Hamamatsu R5912)**	Implosion test
(Alternative)	HQE 20 cm HPD	Confirmation of pressure resistance, Cost estimation
(Alternative)	HQE 20-30 cm PMT	HQE study, Trial manufacture and necessary test
(ID and OD photosensor alternative)	Multi-channel optical module	Performance simulation in Hyper-K, Cost estimation, Selection of 7.7 cm photosensor, Trial manufacture and necessary test
ID cover	**Acrylic and stainless steel**	Implosion test, Photosensor evaluation with attached
(Alternative)	Full acrylic (or acrylic and other resin)	Design and simulation, Implosion test

Alternative Options

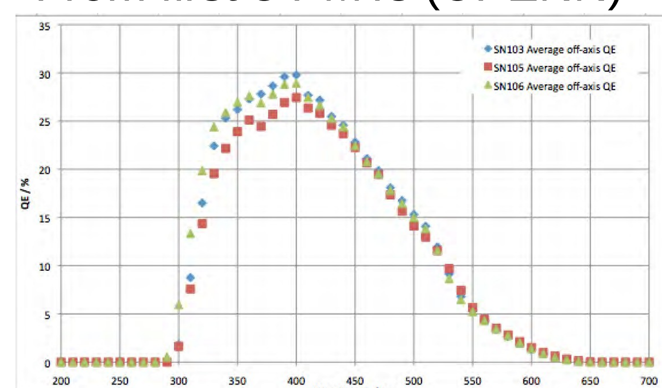


- MultiPMTs with 3inch PMTs based on KM3Net design seems to be promising and affordable alternative.
- MultiPMTs automically solve problems with pressure, in-water electronics, magnetic field cancellation and provide options for an integrated OD.
- Current 3inch PMTs are sufficient for Hyper-K.

ETEL/ADIT 11" HQE PMTs

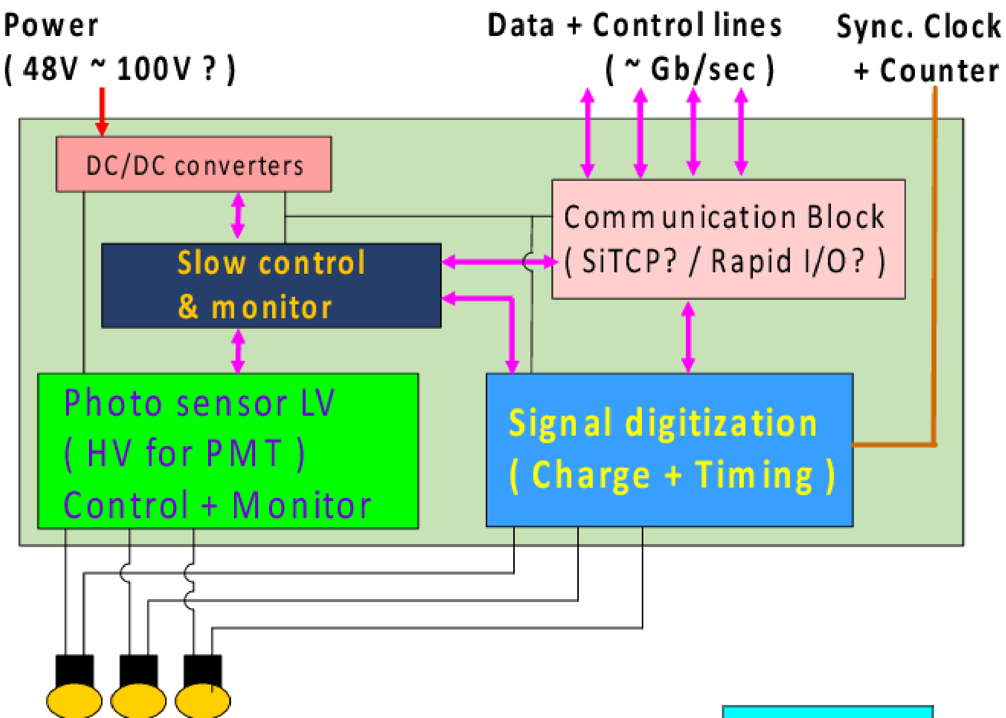
- An NSF award under the S4 program was granted to develop PMTs for the WC option of LBNE.
- This award funds production of 20 11-inch HQE PMTs.
- Ongoing tests at UPENN/UCD.
- Funding obtained to move to second generation "fully functional" and water sealed PMTs.

From first 3 PMTs (UPENN)



Electronics/DAQ

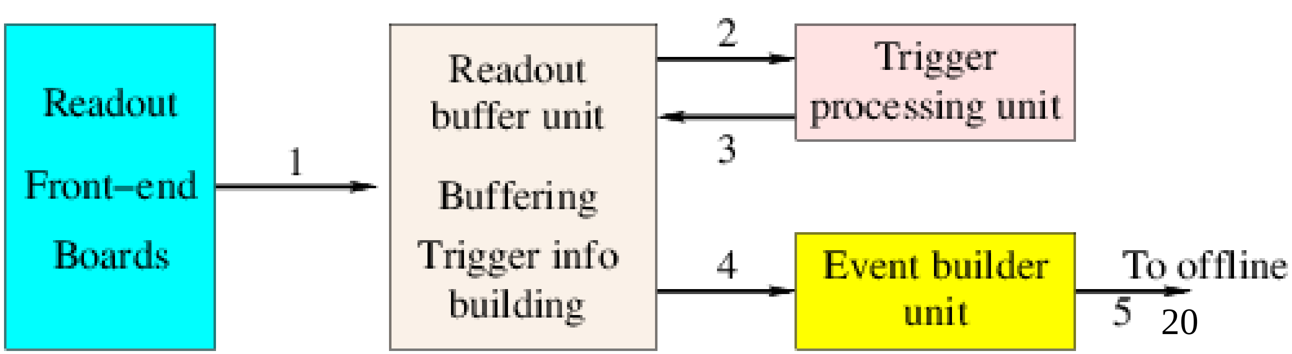
- Front-end electronics module with the power supply for the photo-sensor in the detector water, close to the photo-sensor.
- Schematic diagram of the front end module:



The signal digitization block accept the signals from the photo sensors and convert them to the digital timing and charge data. Two options:

- Charge to time conversion (QTC) chips
- Flash ADC (FADC) chips

DAQ & triggering simplified block diagram:



Calibrations

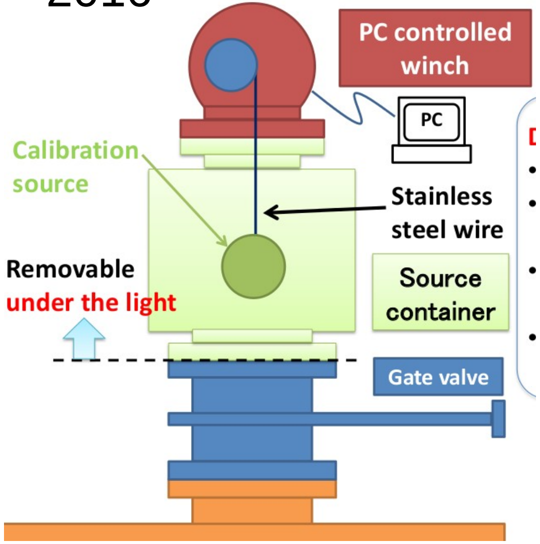
Nominal methods as in Super-K, but with 3D automated deployment systems. Further additions: external PMT calibration, integrated light injection system.

Calibration items	Calibration sources used in SK
Photosensor & electronics calibrations	
High-voltage tuning	Xe flash lamp
Single photo-electron charge (gain)	Nickel source
Electronics threshold effect	Nickel source
Photo-detection efficiency	Nickel source
Non-linearity (photosensor and electronics)	Nitrogen-dye laser
Overall charge scale	Cosmic-ray muons
'Time-walk' correction (TQ map)	Nitrogen-dye laser
Timing resolution	Nitrogen-dye laser
Dark noise	Off-timing hits
Optical properties of detector material	
Light transparency of water (absorption, scattering)	Nitrogen laser, laser diodes
Optical properties of PMT glass & housing material	(Nitrogen laser, laser diodes, Xe lamp)
Calibrations dedicated for physics analyses	
Solar and supernova ν etc.: energy scale and vertex	LINAC, DT generator, Nickel source
Beam and atmospheric ν etc.: energy/momentum scale and PID	Cosmic-ray muons, decay-e's, π^0

Calibrations

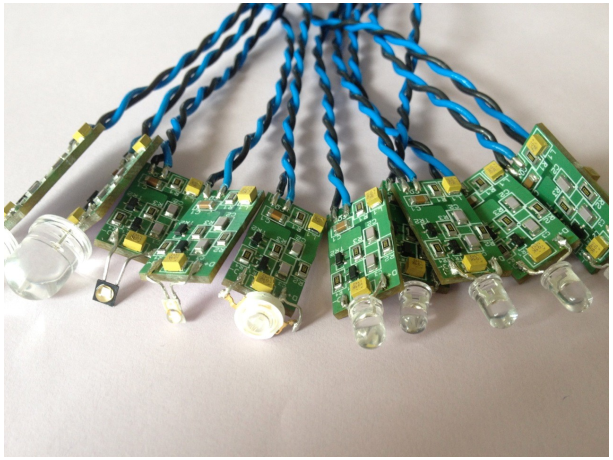
Nominal methods as in Super-K, but with 3D automated deployment systems. Further additions: external PMT calibration, integrated light injection system.

- Simple semi-automated calibration system (to be deployed in SK)
- Computed controlled.
- Compact and light-shielded.
- R&D (3D) for HK in 2015-2016



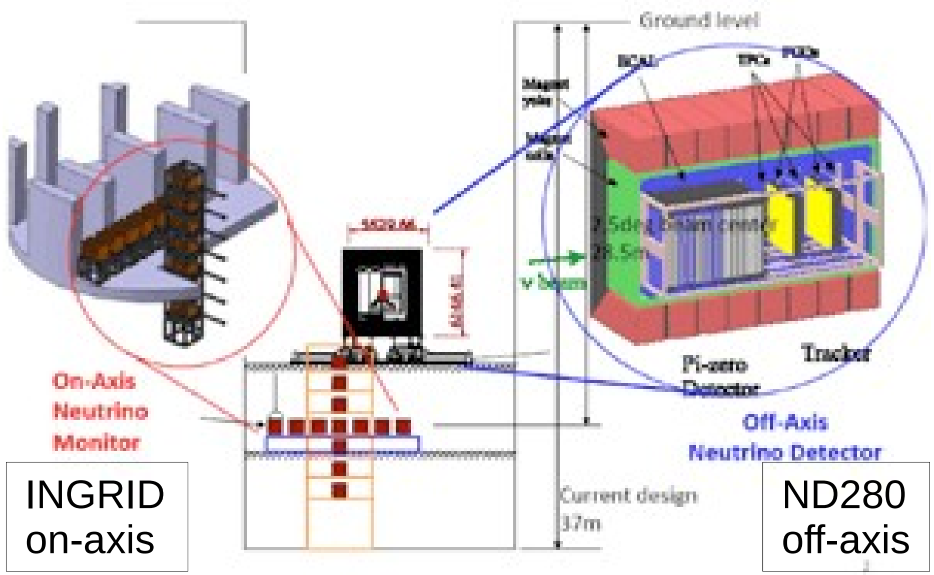
- Study response & reflection of large photosensors in water (Photosensor Testing Facility at TRIUMF)
- Optical system with laser, monitor and receiver PMTs in place and tested.

- Use LED as a light source for optical calibration.
- Can build an automated system that can illuminate each PMT with known sources
- Tests of LEDs underway



Near Detectors

T2K: suit of near detectors at 280m from the target



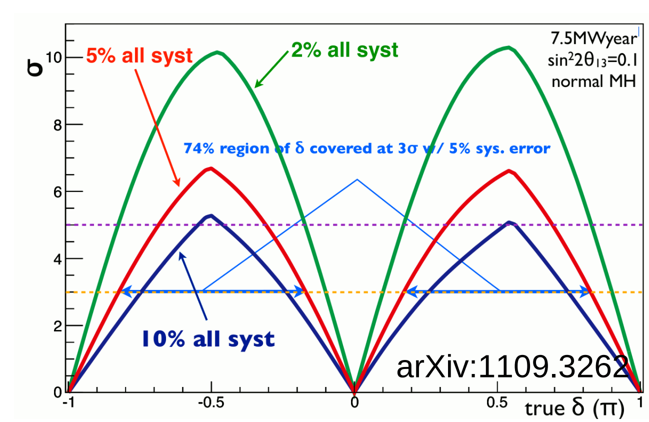
Under investigation three complementary options:

- Refurbished ND280/INGRID detectors
- New detectors in the 280m pit
- New "intermediate" WC detector at ~1-2km

Optimization criteria based on reducing systematic errors for oscillations.

Current T2K systematic errors for oscillations

ν_e	Systematic sources(%)	ν_μ
3.1	Flux & Combined Cross-Sections	2.7
4.7	Independent Cross Sections	5.0
2.4	Pi Hadronic Interactions (FSI)	3.0
2.7	SK Detector Efficiencies	4.0
6.8	**TOTAL**	**7.6**



Detectors at 280m

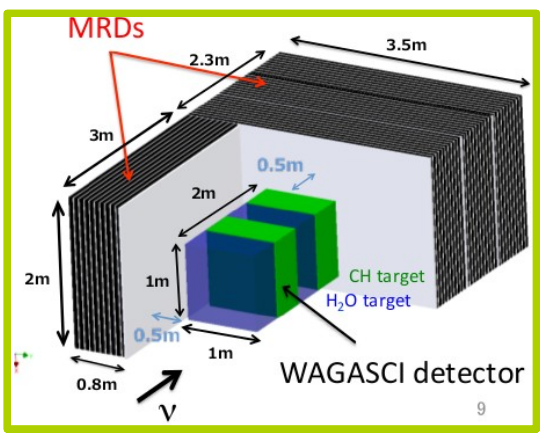
Three options currently envisages for Hyper-K. No final decision made yet on any of the projects. Some options may happen earlier for the T2K upgrade.

1) ND280 improvements:

- Replace with D_2O to the FGD2 and P0D water layers. Quasi-free neutron target.
- Replace scintillator with WbLS to measure deposited charge from water/D_2O layers.

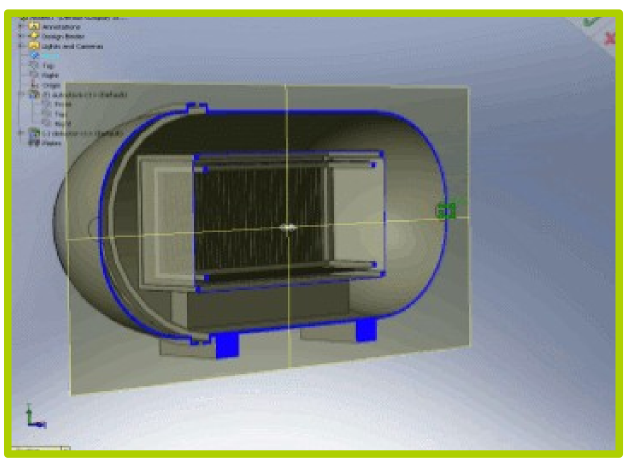
2) Add new detectors in the 280m pit:

Water-grid scintillator detector



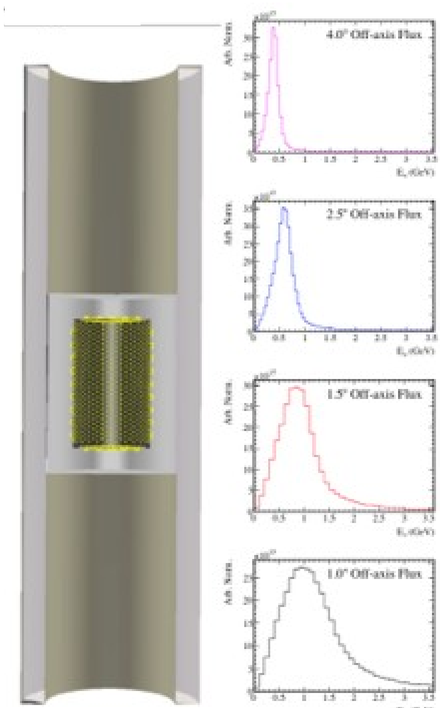
Most advanced

High pressure TPC



Intermediate Detector

Ongoing studies for a combined intermediate detector.

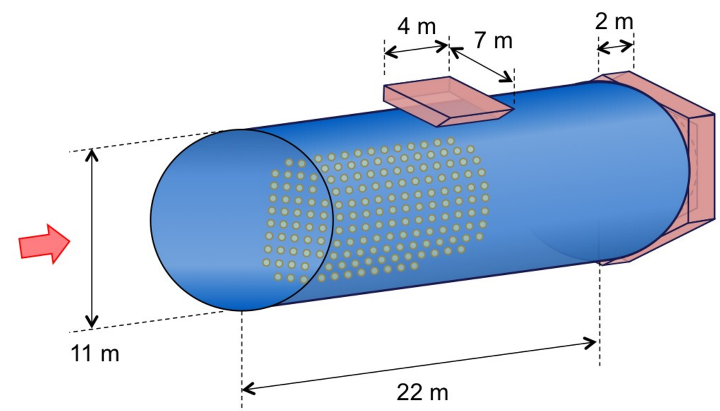


"ν-PRISM" (~1km)

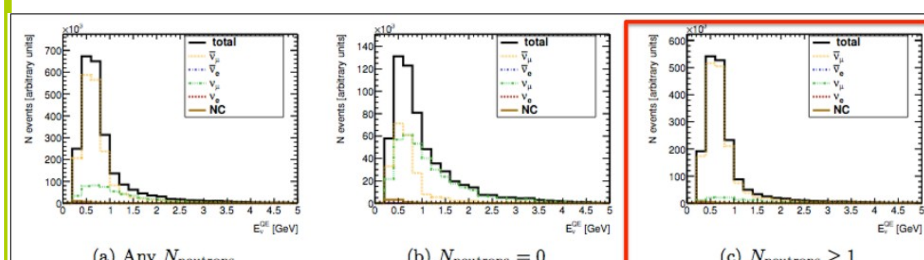
- tall (~50 m) WC detector spanning wide range of off-axis angles
- effectively isolate response in narrow band of energy by comparing interactions at different off-axis angles

"TITUS" (~2 km)

- 2 kt Gadolinium-doped WC detector with magnetized MRD



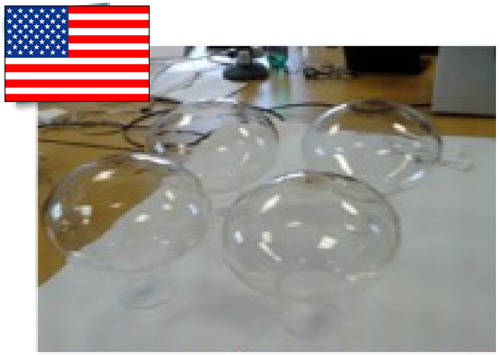
- Use G_d for neutrino interaction separation in particular, G_d for $\bar{\nu}/\nu$ separation.

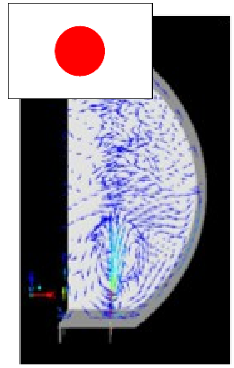


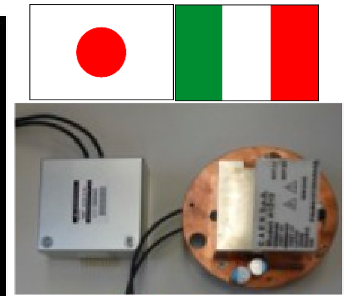
(a) Any $N_{neutrons}$ (b) $N_{neutrons} = 0$ (c) $N_{neutrons} \geq 1$

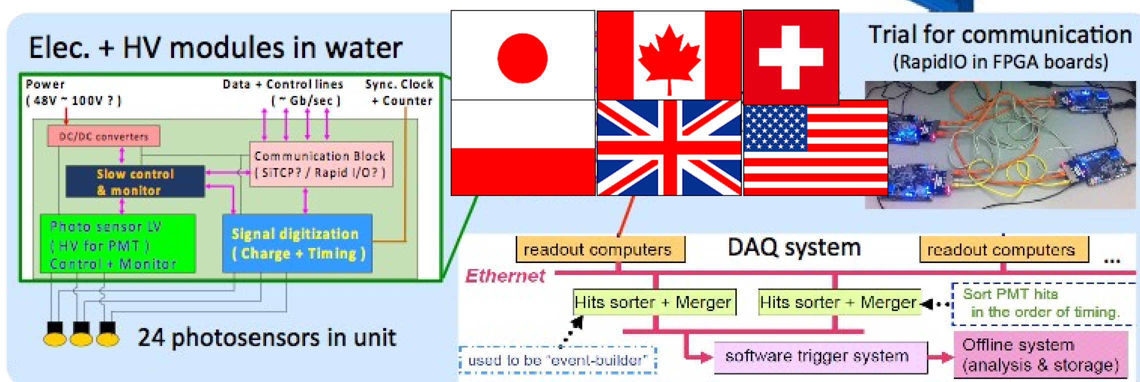
Anti-neutrino Mode

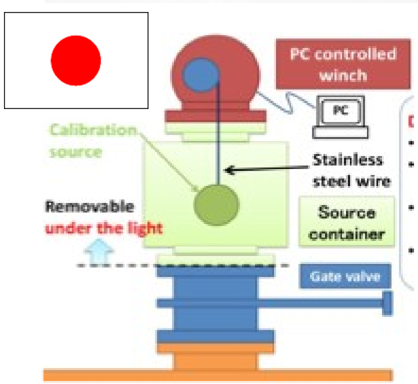
World-wide R&D





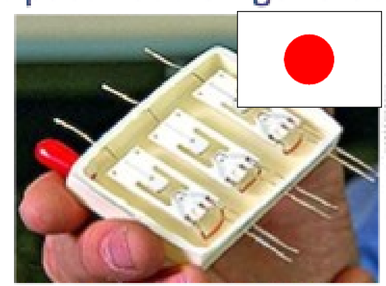




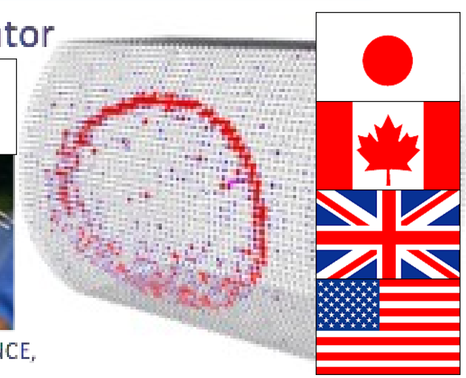


LED

Compact neutron generator

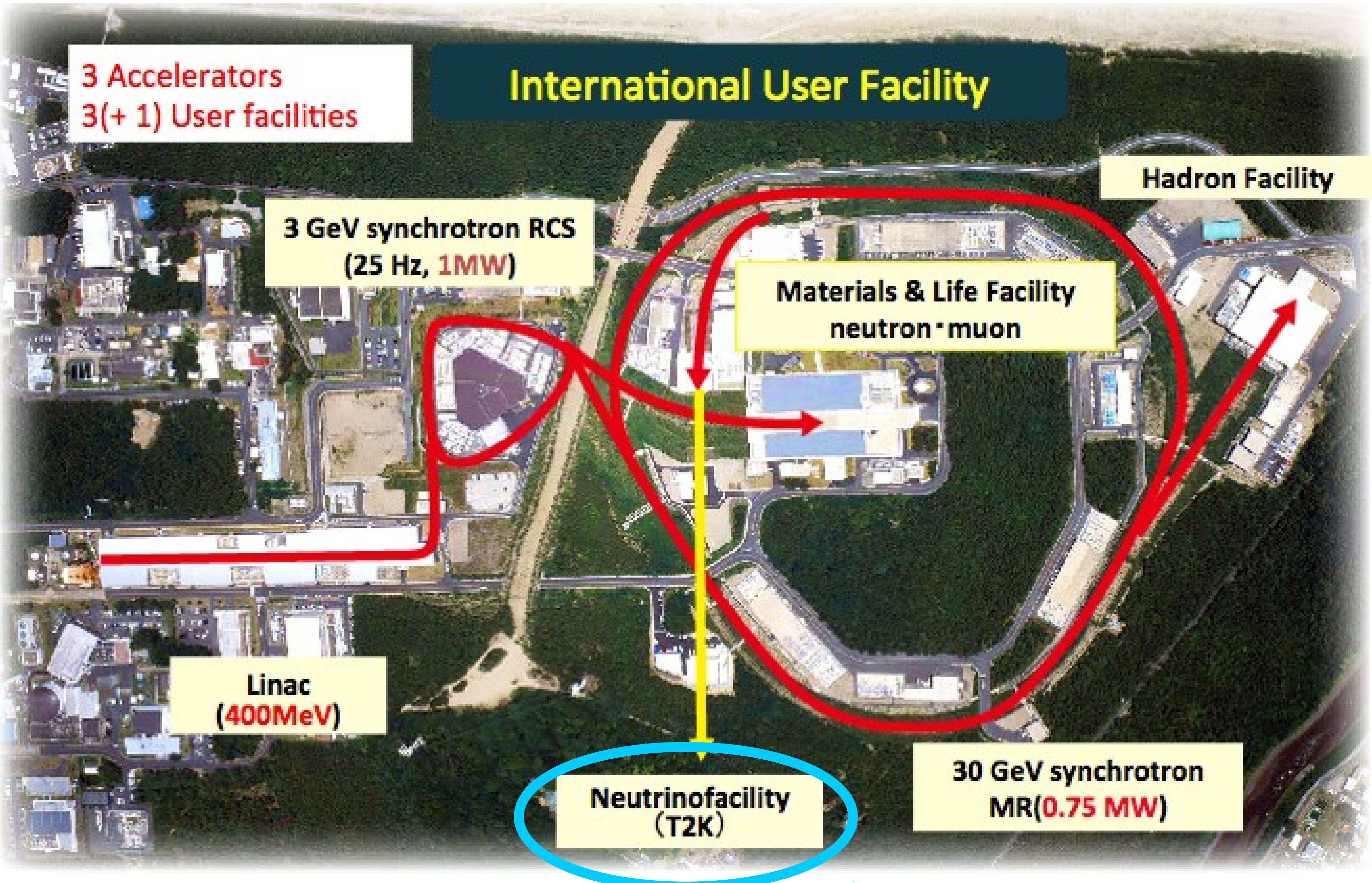


IEEE TRANSACTIONS ON PLASMA SCIENCE,
VOL. 40, NO. 9, SEPTEMBER 2012



- Intense R&D world wide, but large number of things to do.
- Open to new collaborators.

Hyper-Kamiokande Beam

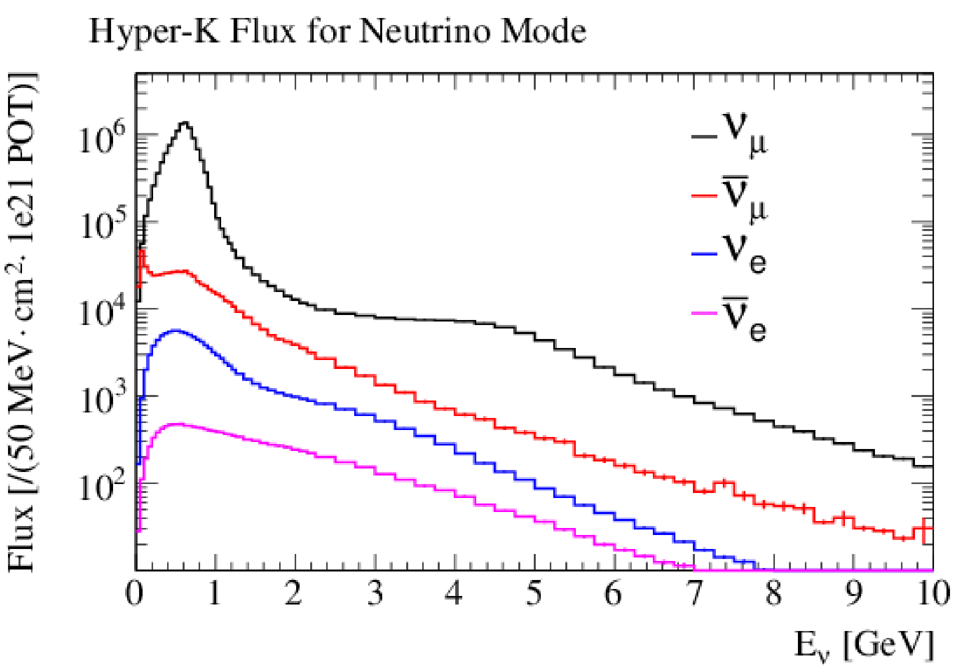


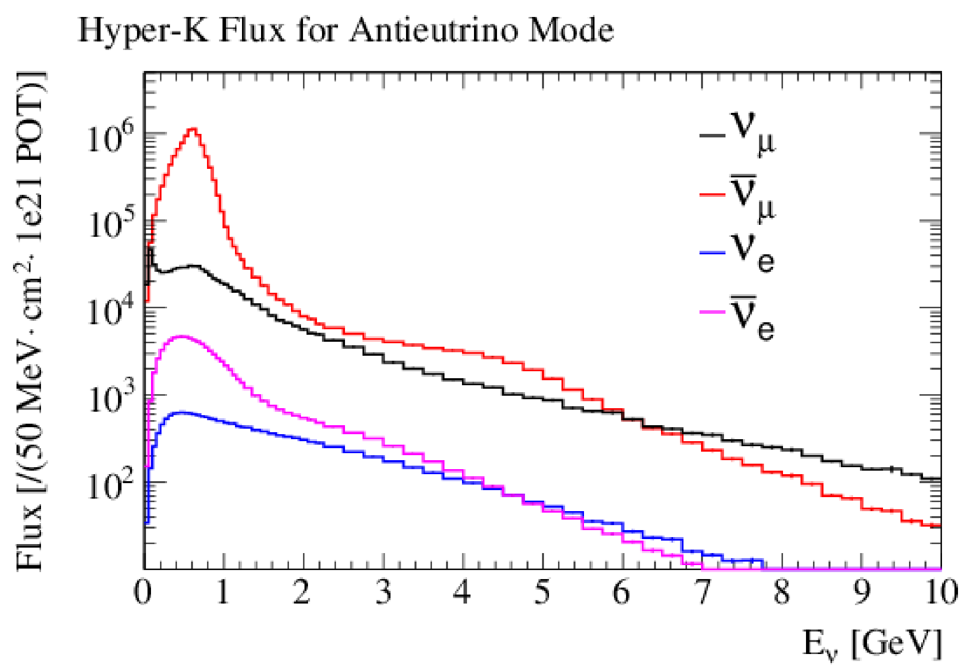
Neutrino Flux for Hyper-Kamiokande

- At least 750kW expected at the starting of the experiment.
- Assumed **7.5MW × $\mathbf{10^7}$ s** (1.56×10^{22} POT) for the following sensitivity studies
  - 10 years are needed if 750kW per 10^7s/year
  - 5 years assuming 1.5MW per 10^7s/year
  - Nominal beam sharing between ν and $\bar{\nu}$-mode beams

    ν-mode: $\bar{\nu}$-mode => 1 : 3

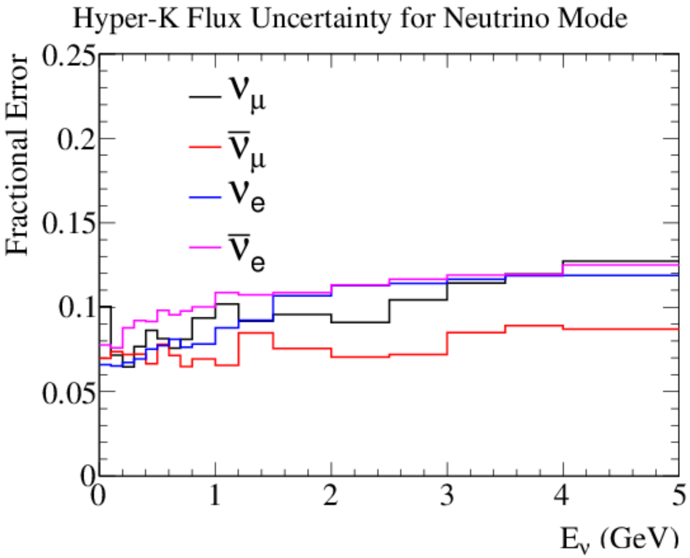
Expected unoscillated neutrino flux at Hyper-K

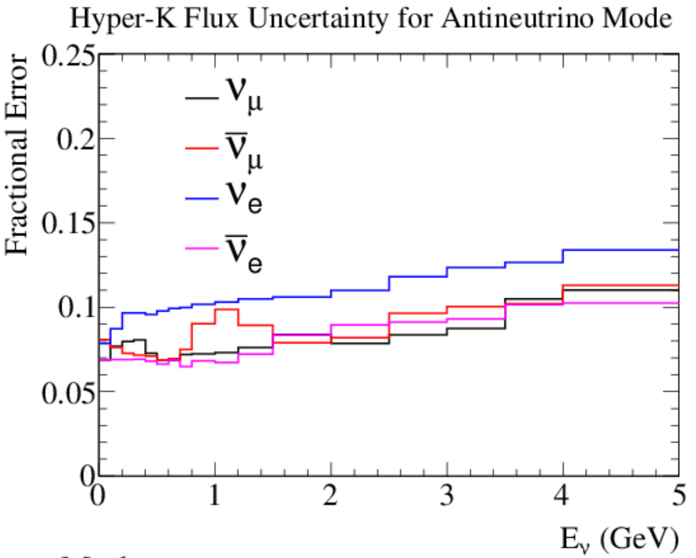




Flux Calculation

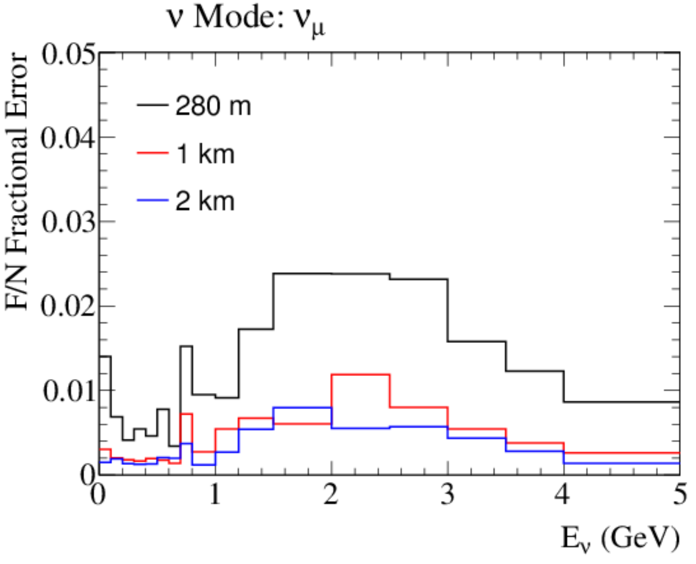
- Several uncertainties (primary production of pions and kaons, secondary interactions, properties of proton beam, alignment of beam components, modeling of horn fields)
- Dominant hadronic interaction modeling → use hadron production data w/ replica of T2K target at NA61/SHINE

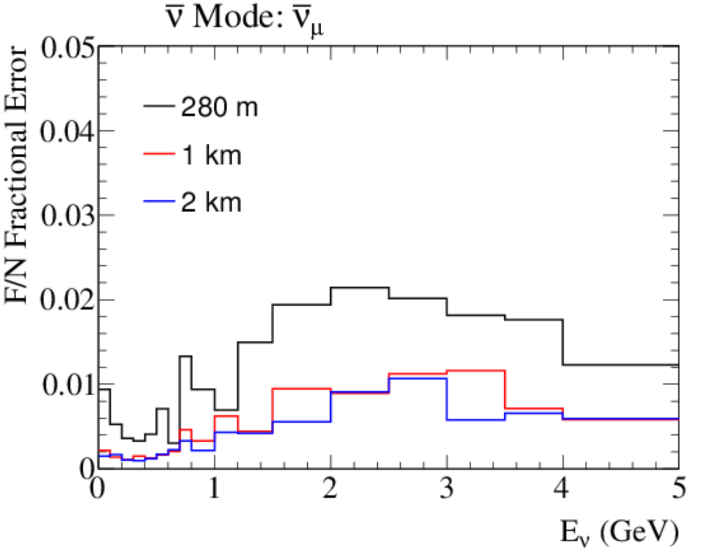




Predicted uncertainty in the neutrino flux calculation assuming replica target hadrn production data

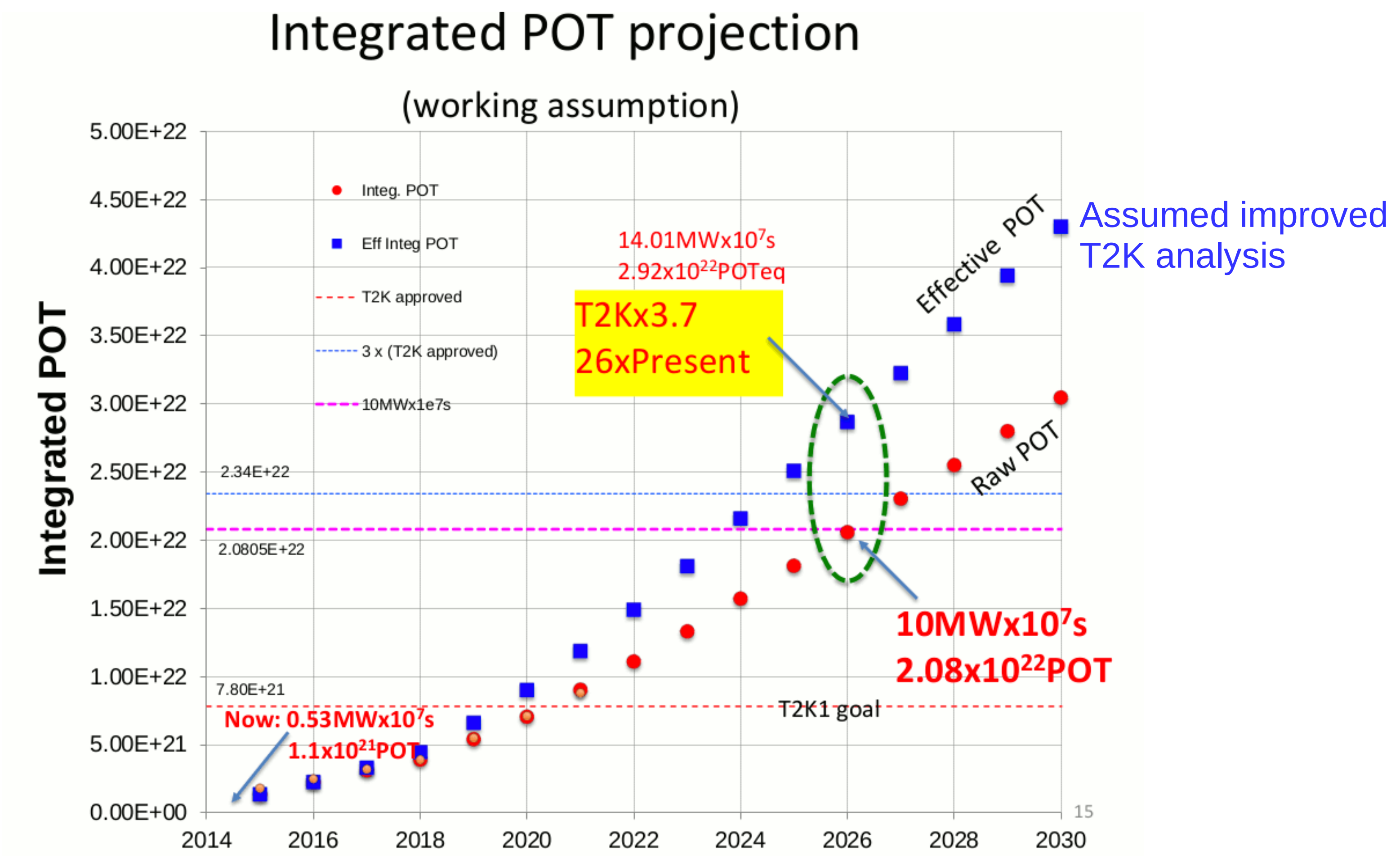
The uncertainty on the near-to-far flux ratio for near detectors at 280m/1km/2km



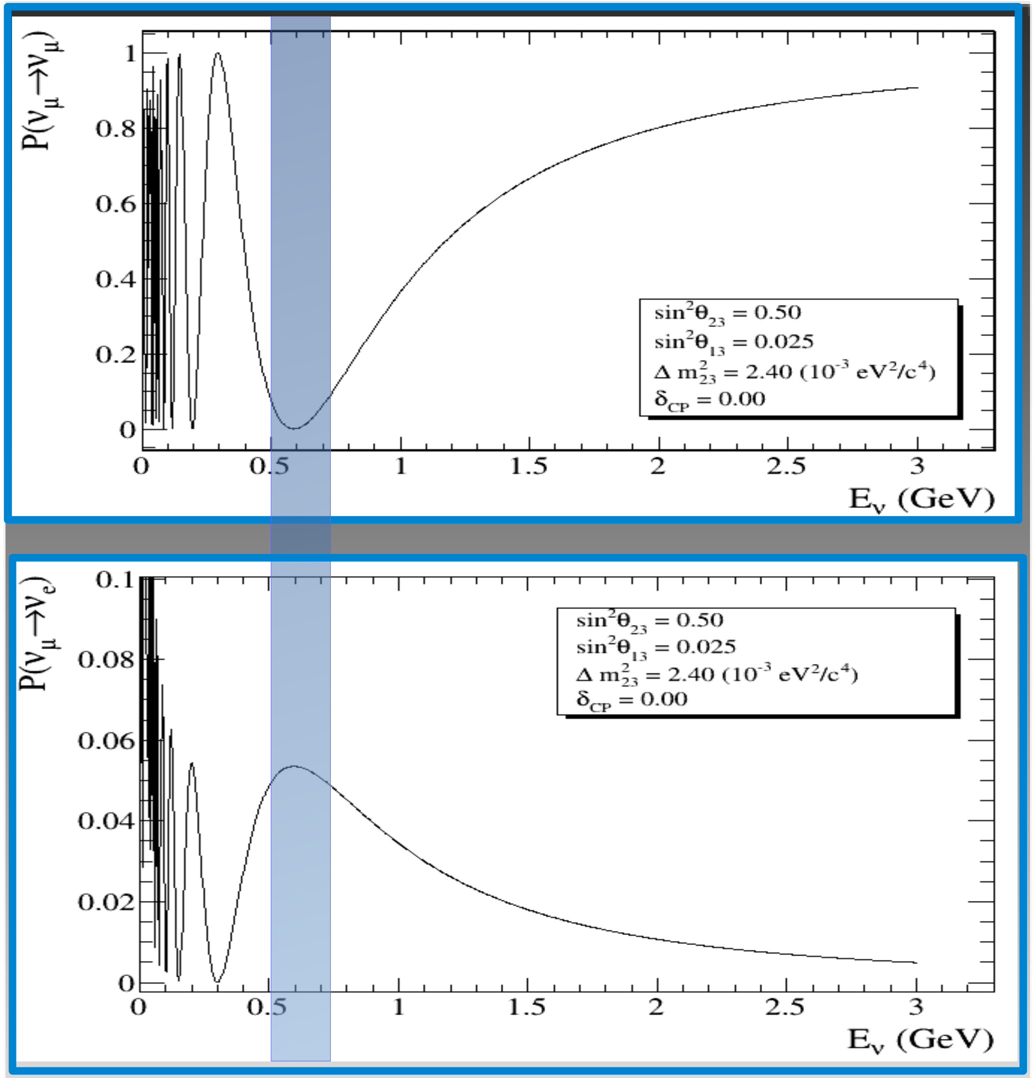


Further J-PARC Potential

- Ongoing studies for a running of J-PARC up to 2026.
- T*. Kobayashi, Potential J-PARC beam power improvement and beam delivery before 2026," (2015), Talk presented at the Workshop for Neutrino Programs with Facilities in Japan, August 4, 2015 Tokai,Japan*



The Physics Potential

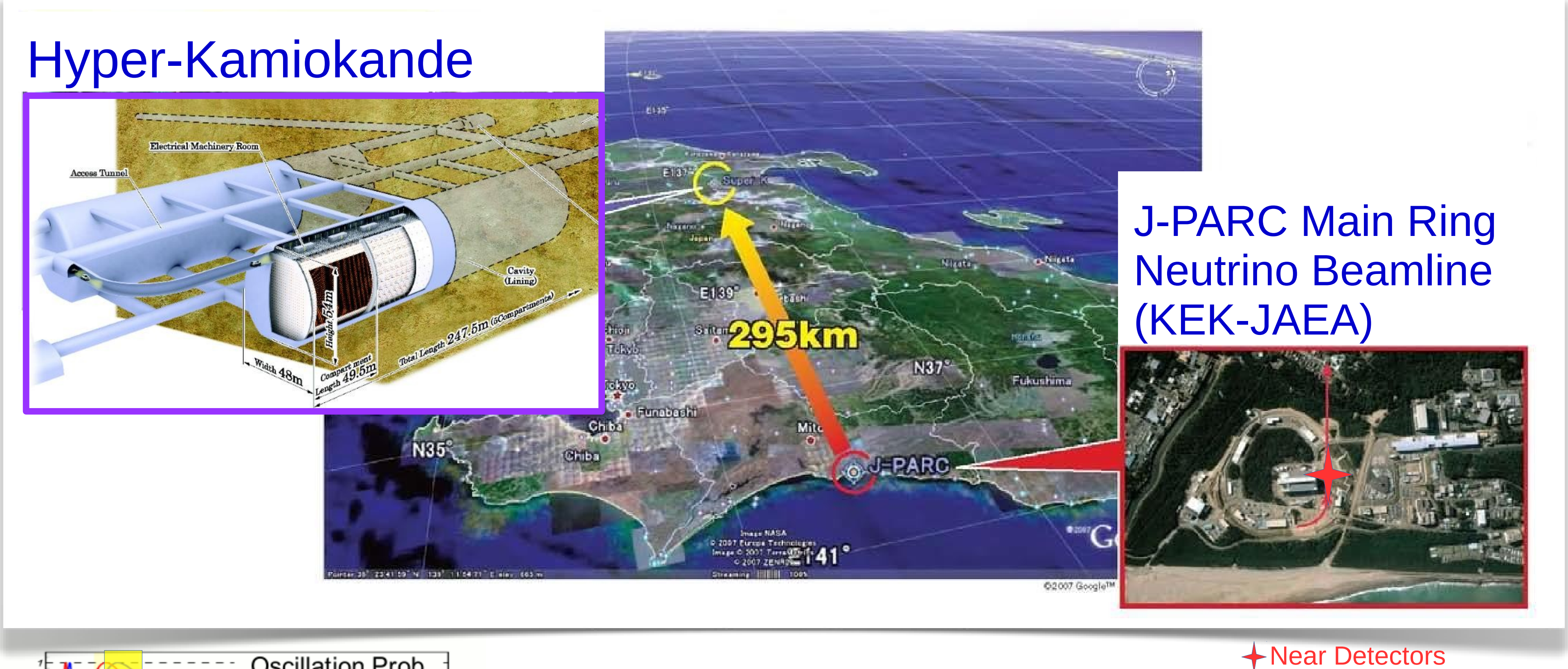


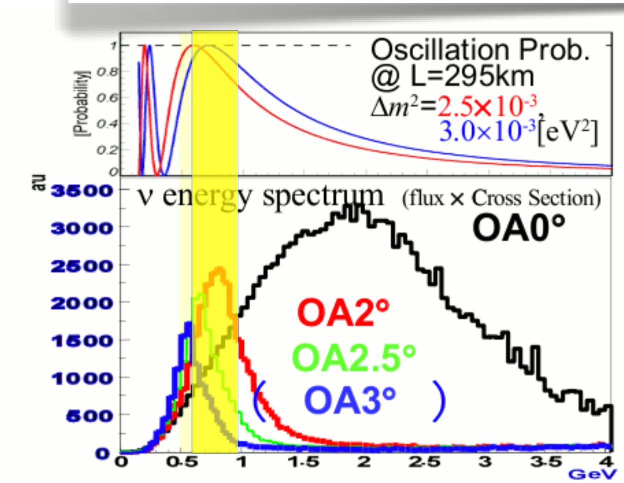
ν beam energy peak

PTEP 2015 053C02

Tokai to Hyper-Kamiokande

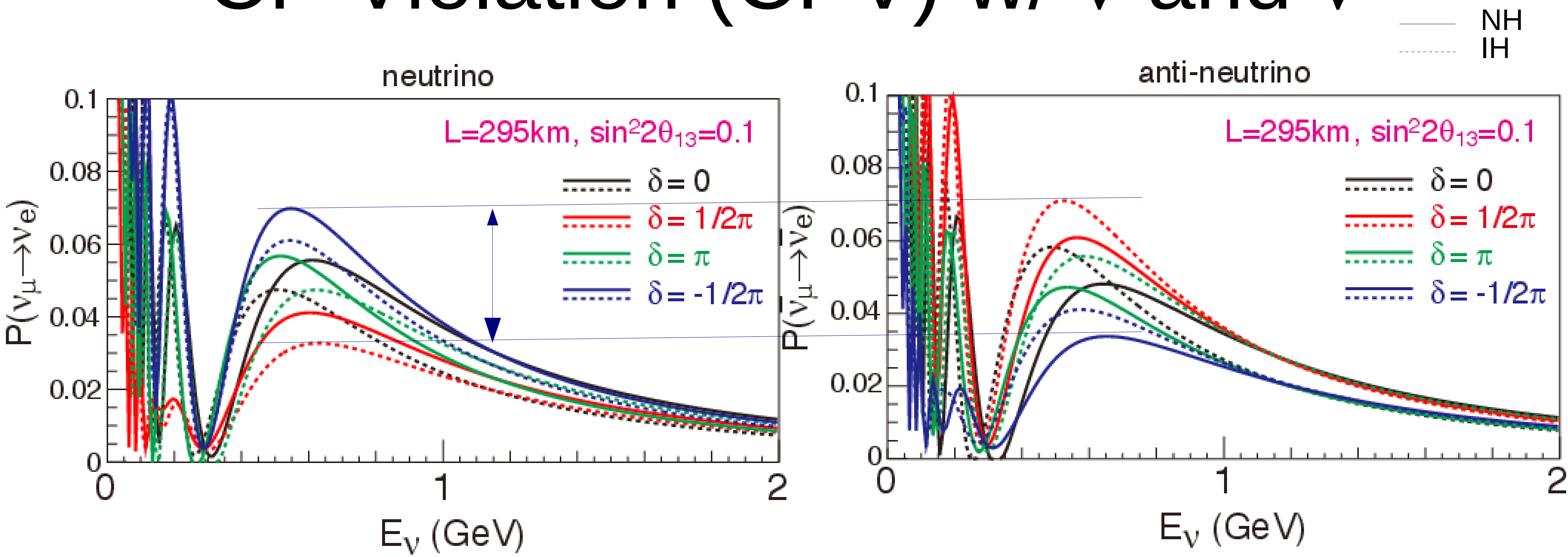
Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power 750kW, 2.5° off-axis angle.





- Narrow-band beam at ~600MeV at 2.5° off-axis
- Take advantage of Lorentz Boost and 2-body kinematics in $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Pure ν_μ beam with ~1% ν_e contamination

CP Violation (CPV) w/ ν and $\bar{\nu}$



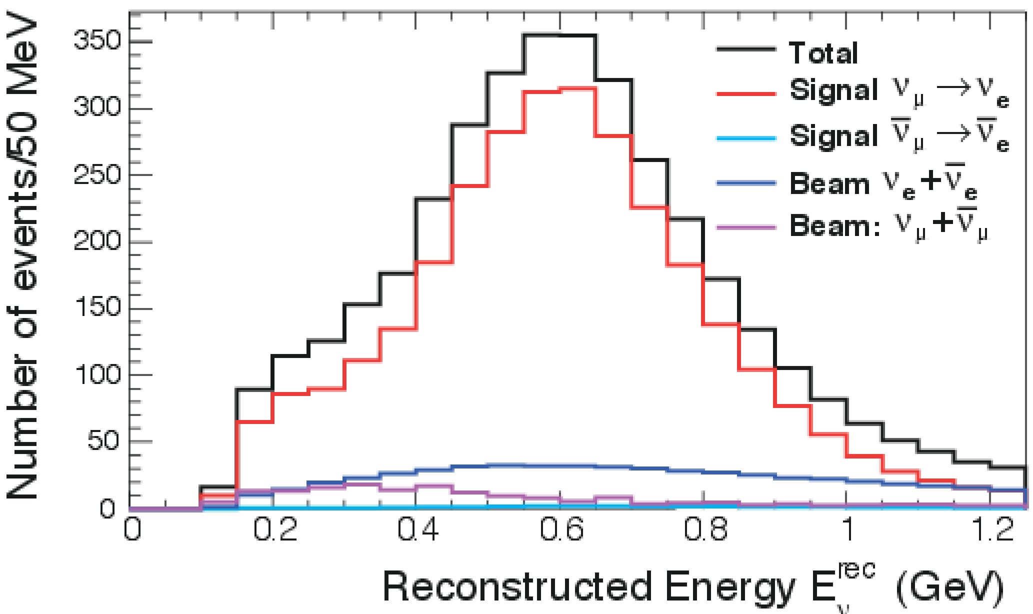
- CP Violation will manifest itself in neutrino oscillations:

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$

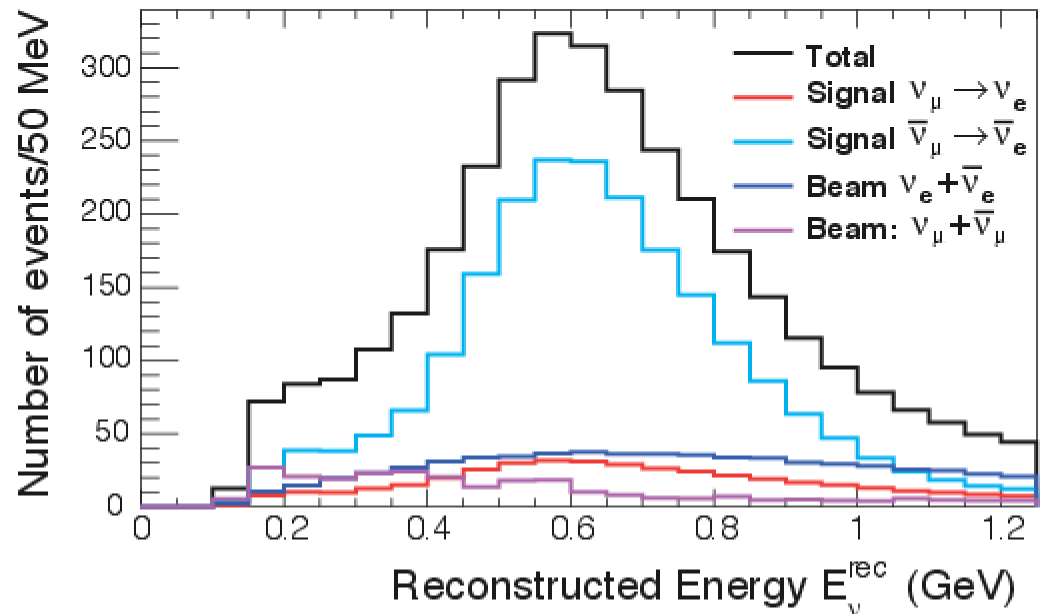
- CPV cannot show up in the disappearance oscillations ($\alpha = \beta$).
- CPV requires all mixing angles to be non zero.
- For Hyper-K: max. ~±25% change from δ=0 case.
- Sensitive to exotic (non-PMNS) CPV source

Expected Events

Appearance ν mode



Appearance $\bar{\nu}$ mode

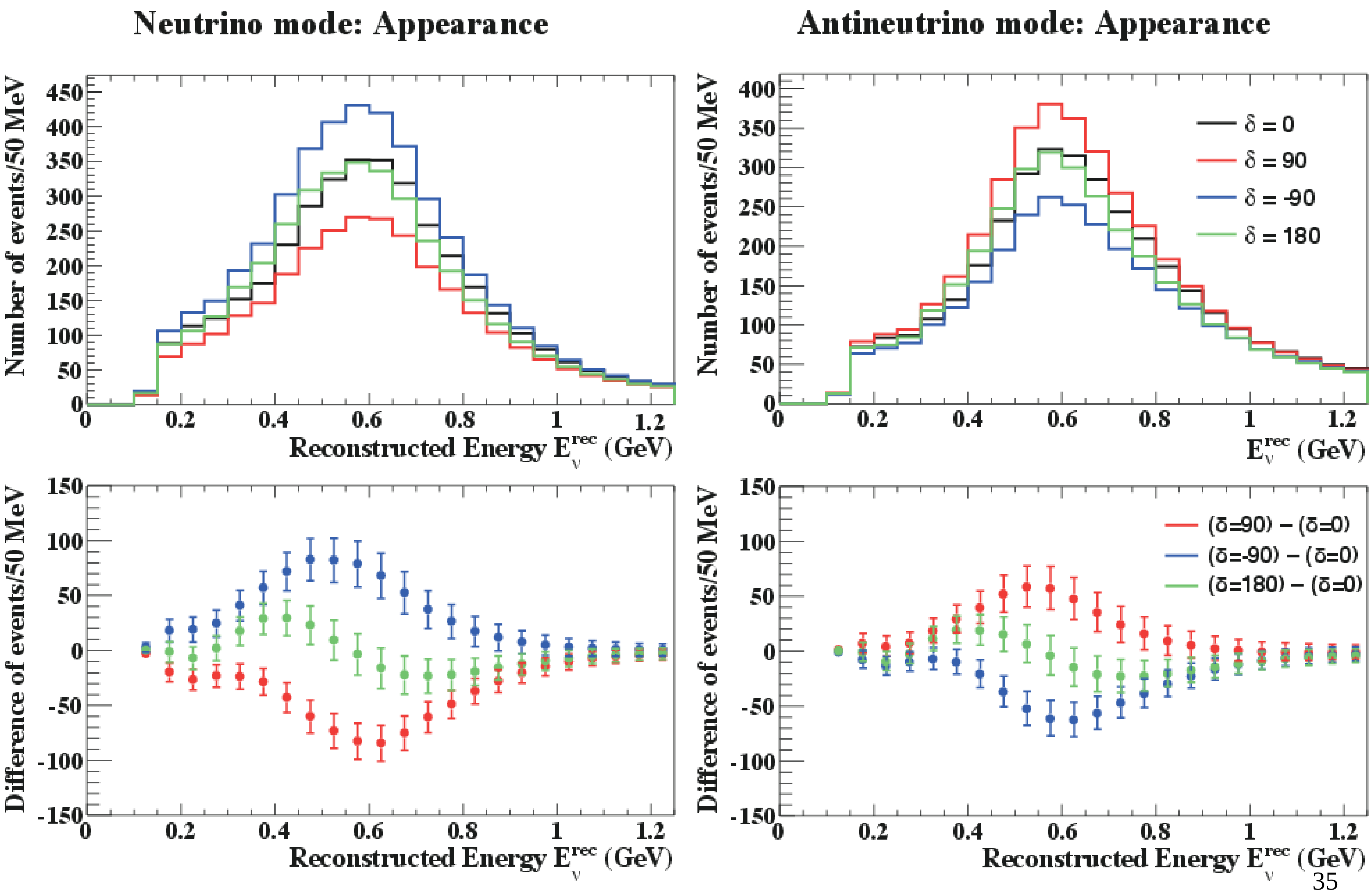


Appearance	Signal		Background					Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	265	265	3397

Disappearance	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	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

Large expected number of events. NH, $\sin^2 2\theta_{13} = 0{,}1$ and $\delta_{CP} = 0$

Expected Events



Hyper-K Sensitivity to δ_{CP}

- Based on experience and prospects of T2K.
- Three main categories of systematic uncertainties:
  - Flux and cross section uncertainties constrained by the fit to current ND.
  - Cross section uncertainties not constrained by the fit to current ND data: errors reduced as more categories of samples are added to ND fit.
  - Uncertainties on the far detector reduced as most of them are estimated by using atmospheric neutrinos as a control sample (larger stat at Hyper-K).

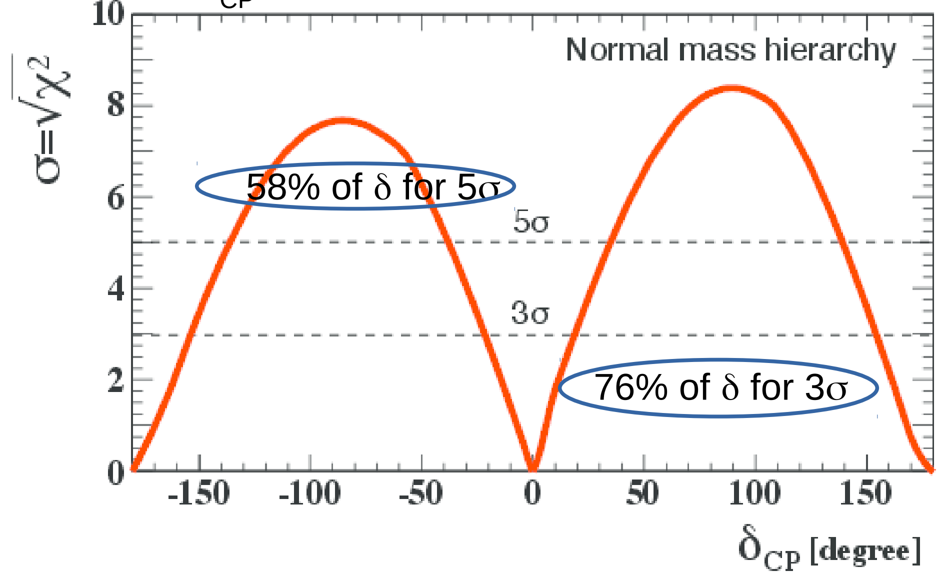
Errors (%) on the expected number of events				
	ν mode		$\bar{\nu}$ mode	
	ν_e	ν_μ	ν_e	ν_μ
Flux & Near Detector (ND)	3.0	2.8	5.6	4.2
ND-independ. xsect	1.2	1.5	2.0	1.4
Far Detector	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

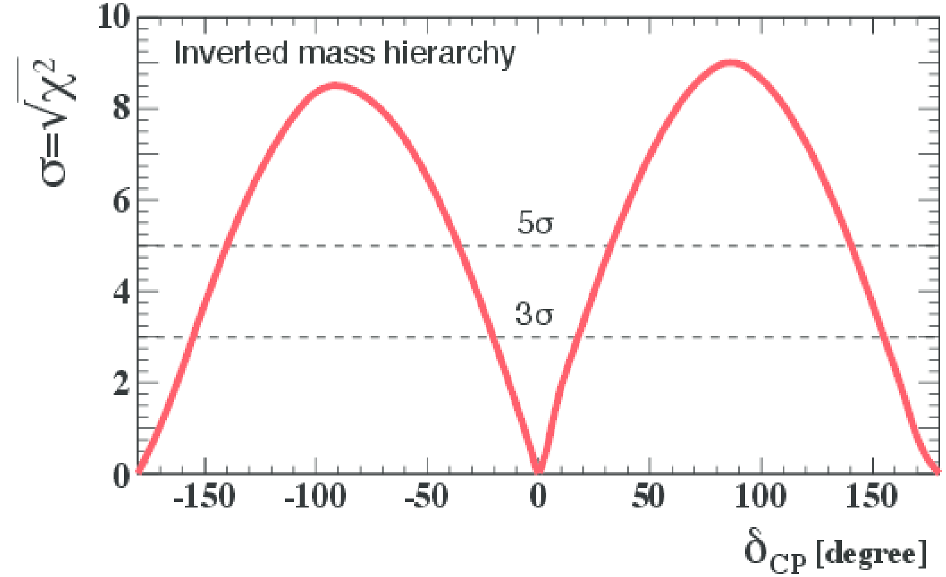
- Planning to update errors and thus sensitivities based on the discussions on the T2K upgrade.

Hyper-K Sensitivity to δ_{CP}

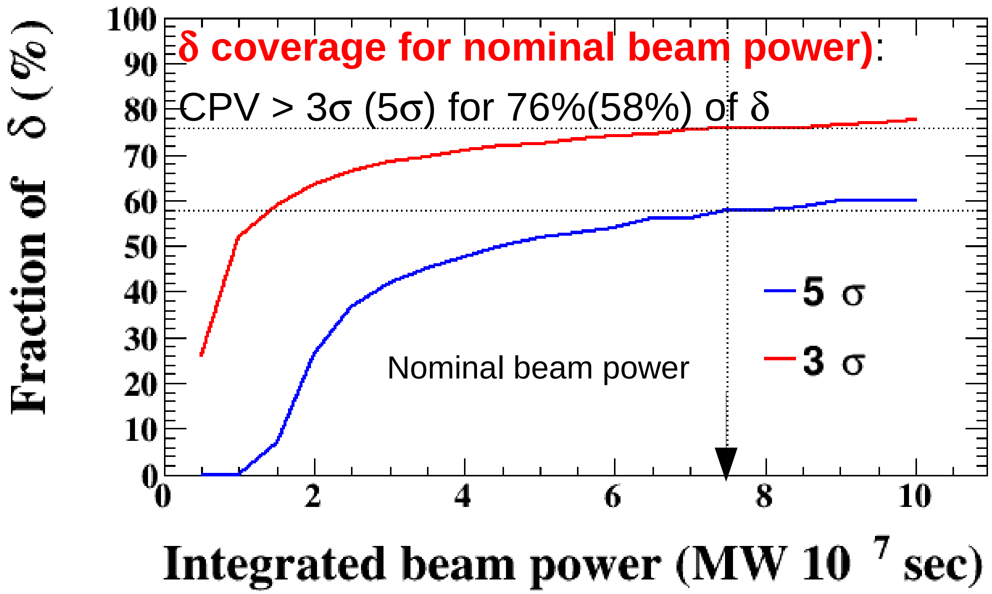
CPV discovery sensitivity

to $\delta_{CP}=0,\pi$ w/ MH known

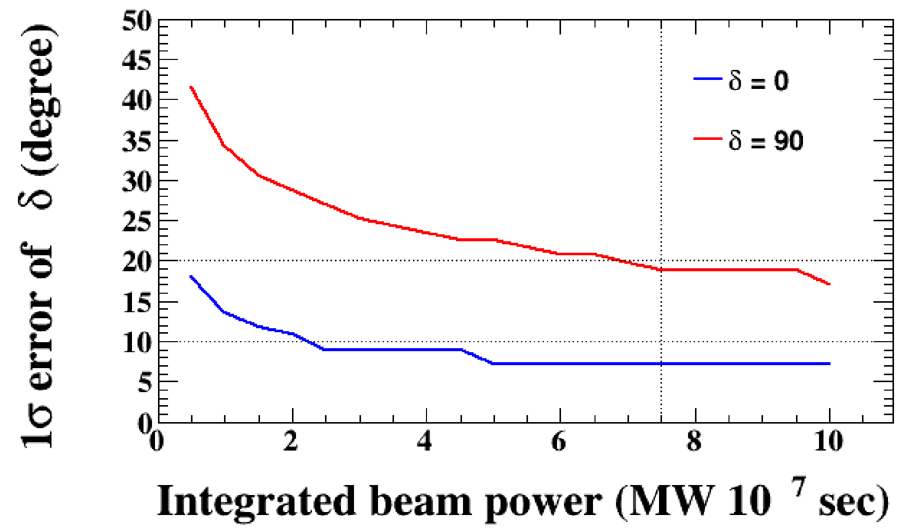




Fractional region of δ(%) for CPV (sin δ ≠0) > 3,5 σ

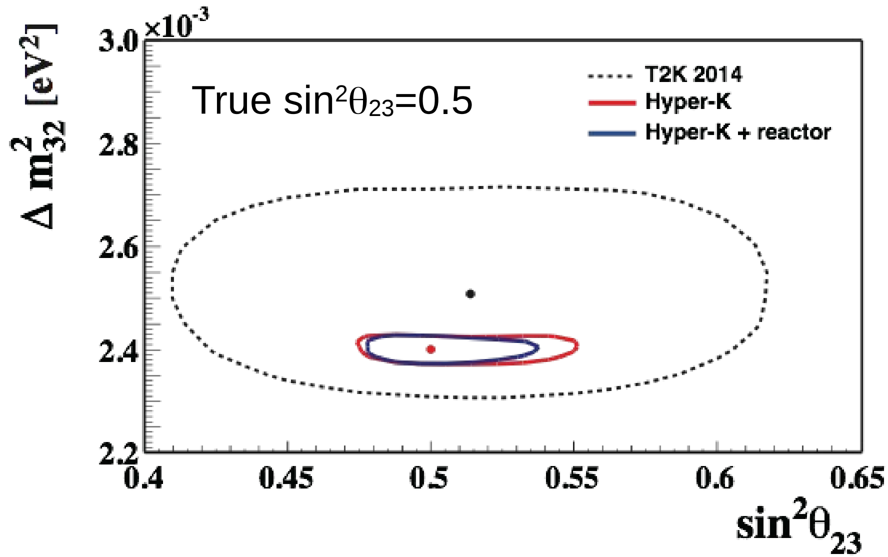


1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)

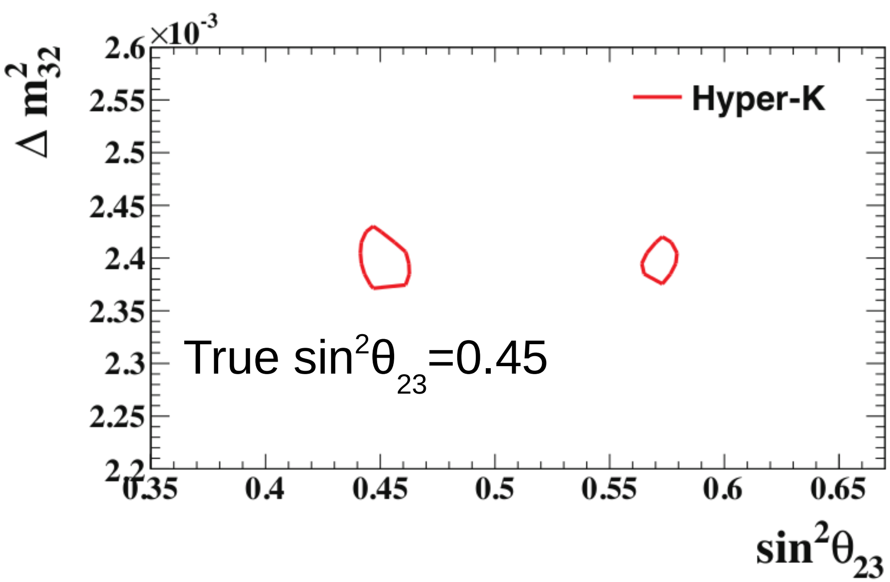


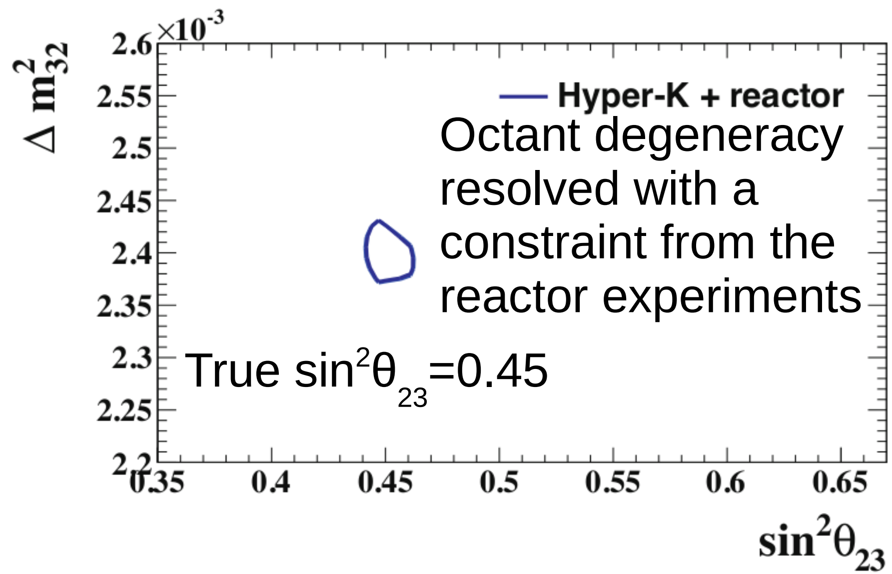
Sensitivity to θ_{23} and Δm^2_{23}

- $\sin^2 2\theta_{23}$ and Δm^2_{23} free parameters as well as $\sin^2 2\theta_{13}$ and δ_{CP} in the fit.
- Octant resolution w/ reactor θ_{13}: ~3σ wrong octact rejection for $\sin^2\theta_{23}$<0.46 or >0.56



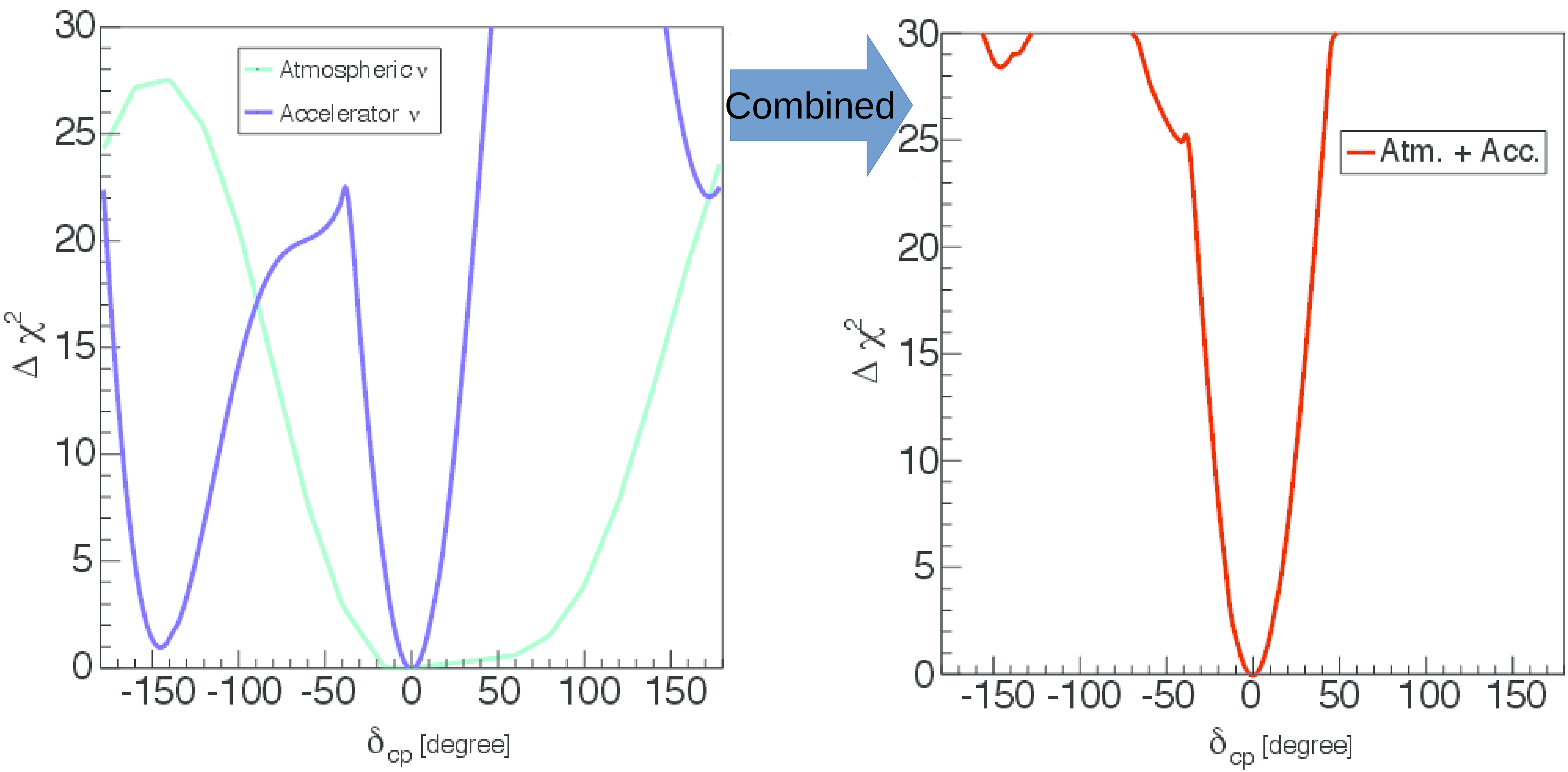
True $\sin^2\theta_{23}$	1σ err $\sin^2\theta_{23}$	1σ err Δm^2_{23} (10^{-5}eV^2)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5





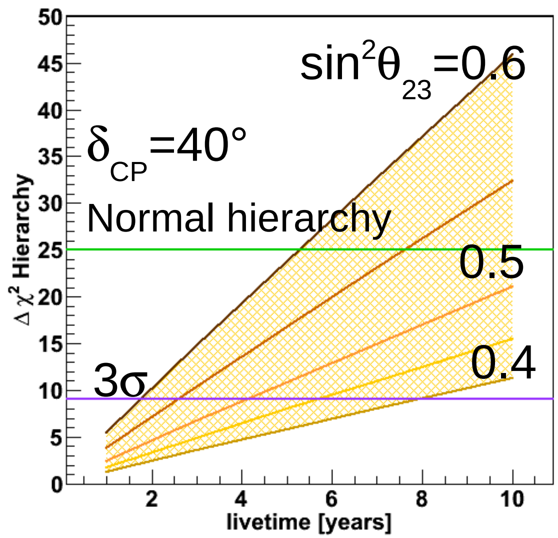
HK ATMP Sensitivity to CPV

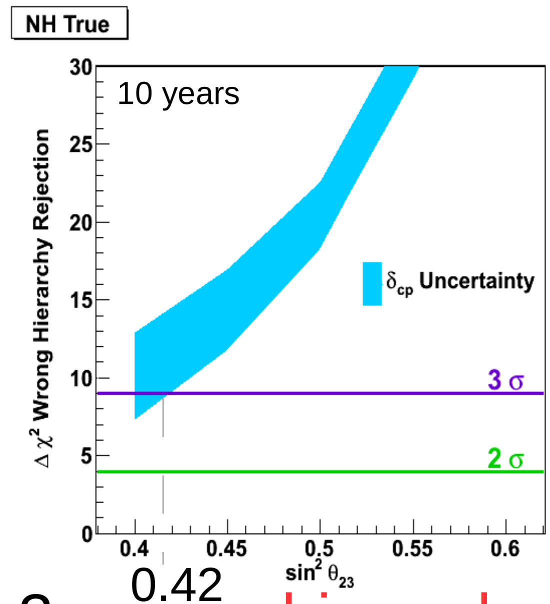
- Hyper-K will observe both accelerator and atmospheric neutrinos.
- Physics capability can be enhanced by combining the two analyses.
- Second minimum for beam analysis if MH not known.
- ATMP can discriminate MH, but worse measurement of CP.
- Both measurements can resolve fake solution and provice a precise measurement of CP.

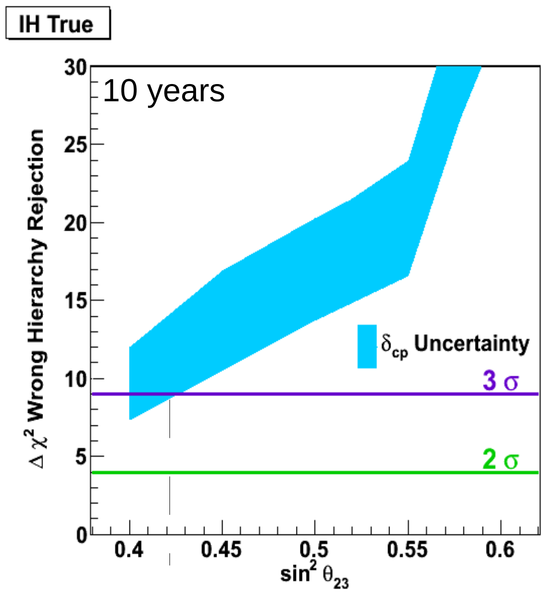


Hyper-K ATMP Sensitivity to MH

Significance for MH determination
as a function of Hyper-K lifetime

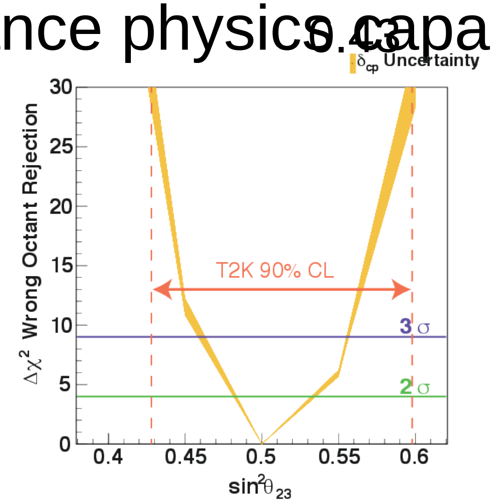






- Use atmospherics for 3σ mass hierarchy determination.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.

- Using ATMP neutrino events the θ_{23} octant can be determined.
- Discrimination between the wrong octant per each value of $\sin^2\theta_{23}$:

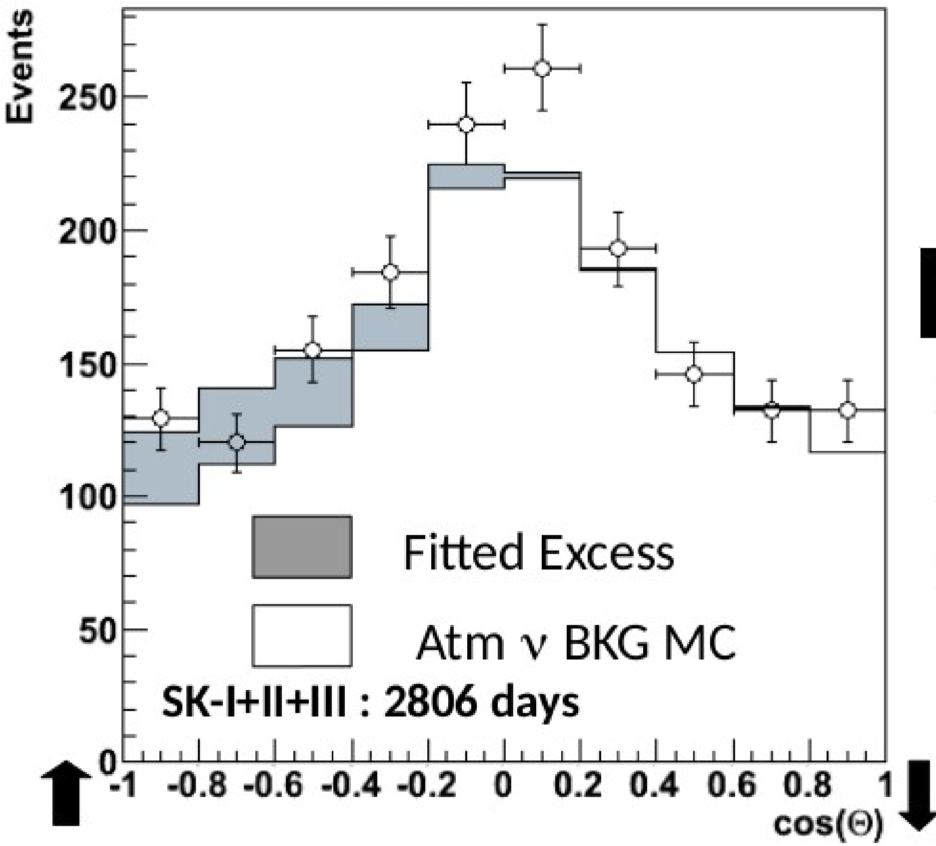


Tau Neutrinos

Super-Kamiokande

- Observed 180.1±44.3 (stat)+/- 17.8/15.2 (syst) tau leptons.
- Excluded the no-tau-appearance hypothesis at the 3.8σ level.

Phys. Rev. Lett. **110**, 181802 (2013)



Pre-cuts + NN

- Total selection efficiency of 60%

per/ 100 kton yr.	Hyper-K	LBNE
Signal CC $\nu\tau$	40.2	28.5
Background	448.7	44.8
S /$\sqrt{B}$, 10 years	~14	~8

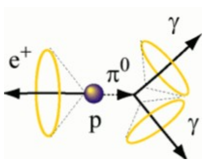
- HK Numbers are upward-going event rate
- LBNE based on PRD82, 093012

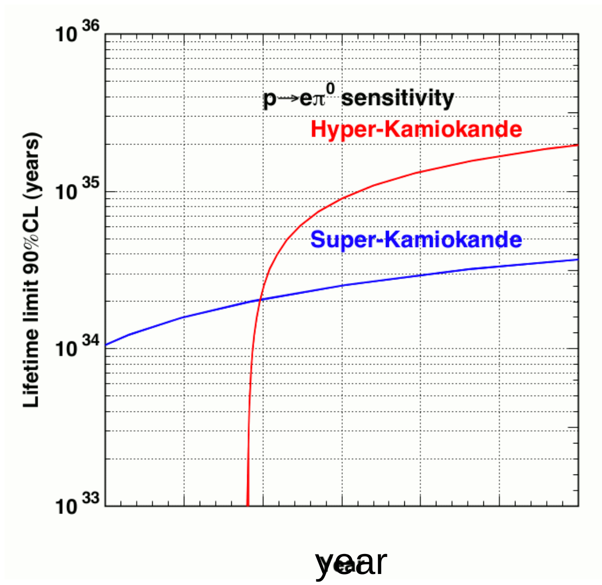
- After 10 years Hyper-K will have O(2,000) ν_τ events that can be used to study CC ν_τ cross sec on, leptonic universality, etc.

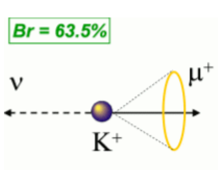
arXiv:1109.3262

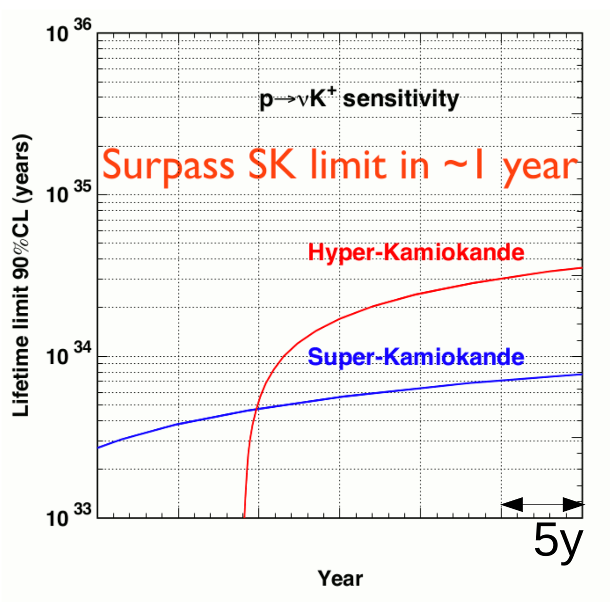
Proton Decay Sensitivity

Surpass SK limit in ~1 year

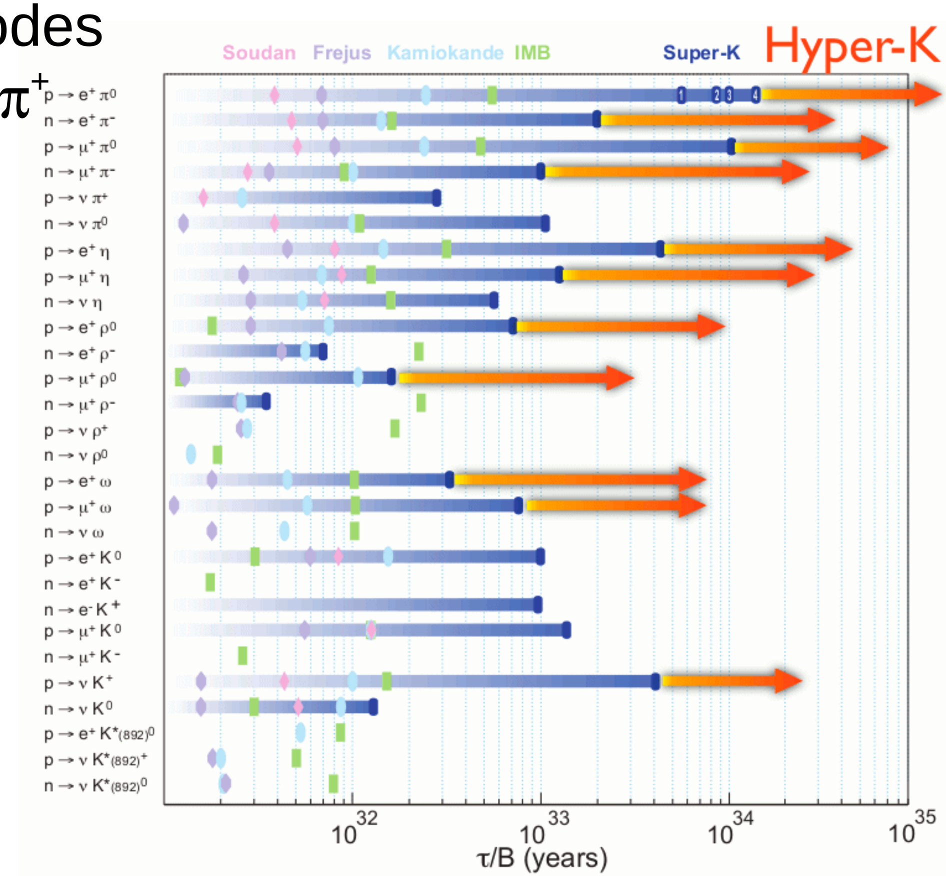




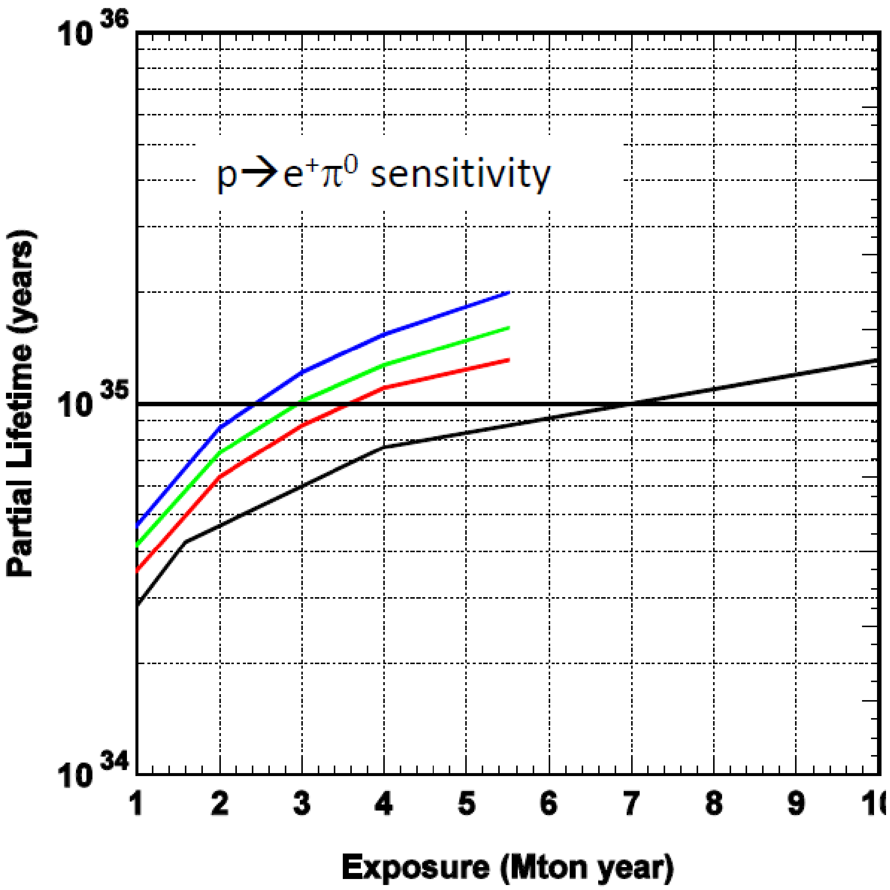




- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
- Hyper-K is sensitive in every single mode
  - $p \to e^+\pi^0$: 1.3×10^{35} y at 90% CL
  - $p \to \bar{\nu}K^+$: 3×10^{34} y at 90% CL
  - Many other modes:
    - p,n → $(e^+,\mu^+) + (\pi,\rho,\omega,\eta)$; $10^{34\text{-}35}$y
    - K^0 modes
    - $\nu\pi^0$, $\nu\pi^+$
    - ….



Improved Hyper-K sensitivity to $e^+\pi^0$

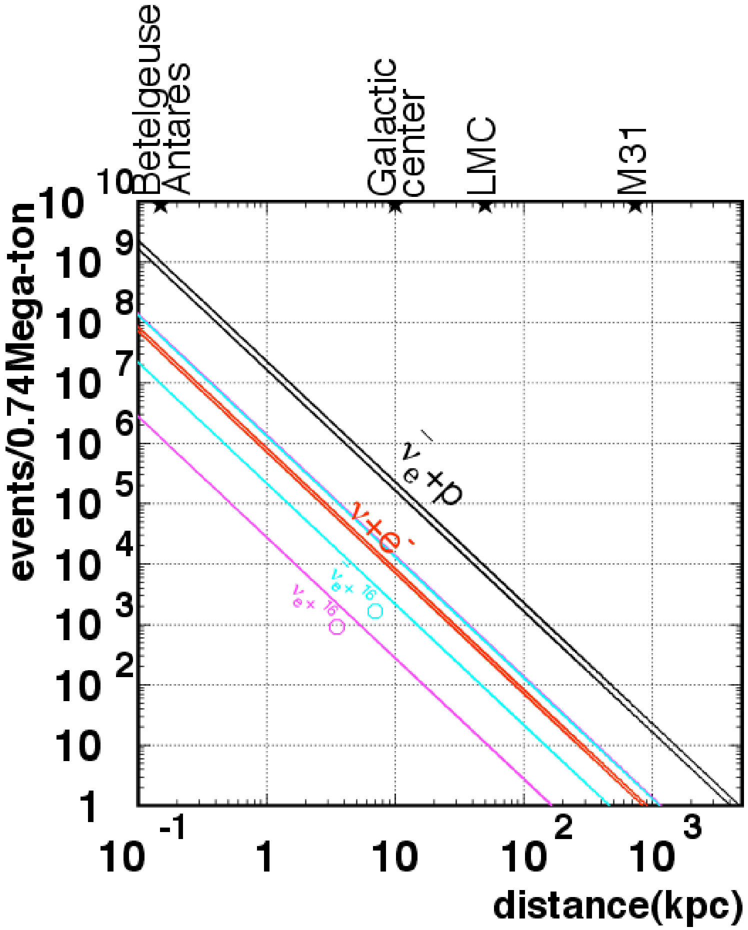


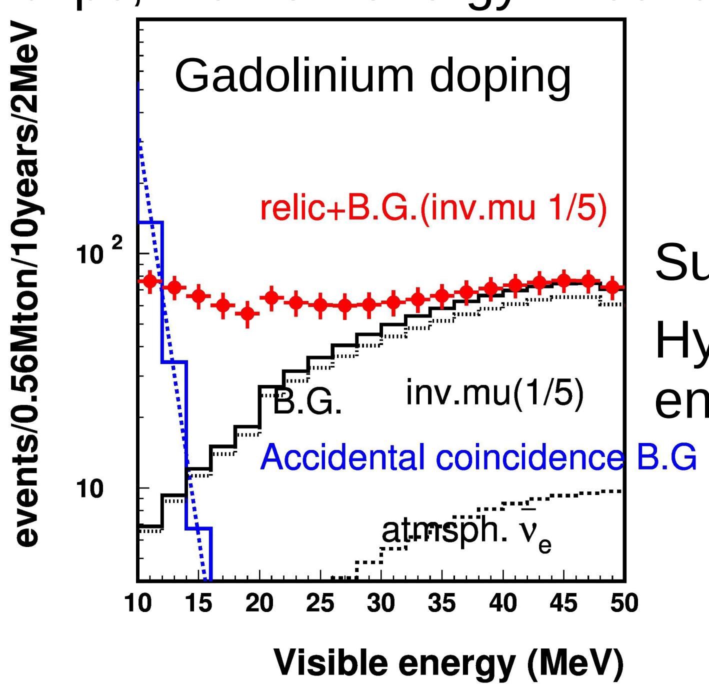
Baseline Analysis
Improved Analysis cuts
BKG Reduced by 50% (neutron tagging)
BKG Reduced by 70% (neutron tagging)

- Super-Kamiokande has demonstrated neutron tagging via
  $n + p \rightarrow d + \gamma$ (2.2 MeV)
- Hyper-K's tagging depends on detector configuration, photocoverage, Gd doping etc.
- Background reduction is an essential component of the Hyper-K nucleon decay program.

Neutrino Astrophysics

Supernova burst neutrino: 200k ν's from Supernova at Galactic center (10kpc)
→ time variation & energy can be measured with high statistics. Important data to cross check explosion models.
Expected number of event
~168000 evnts ($\bar{\nu}_e$ IBD)
~2300 evnts (^{16}O CC)
~7000 evnts (ν-e es)
~8300 evnts (^{16}O NC γ)
at 10kpc, 4.5MeV energy threshold

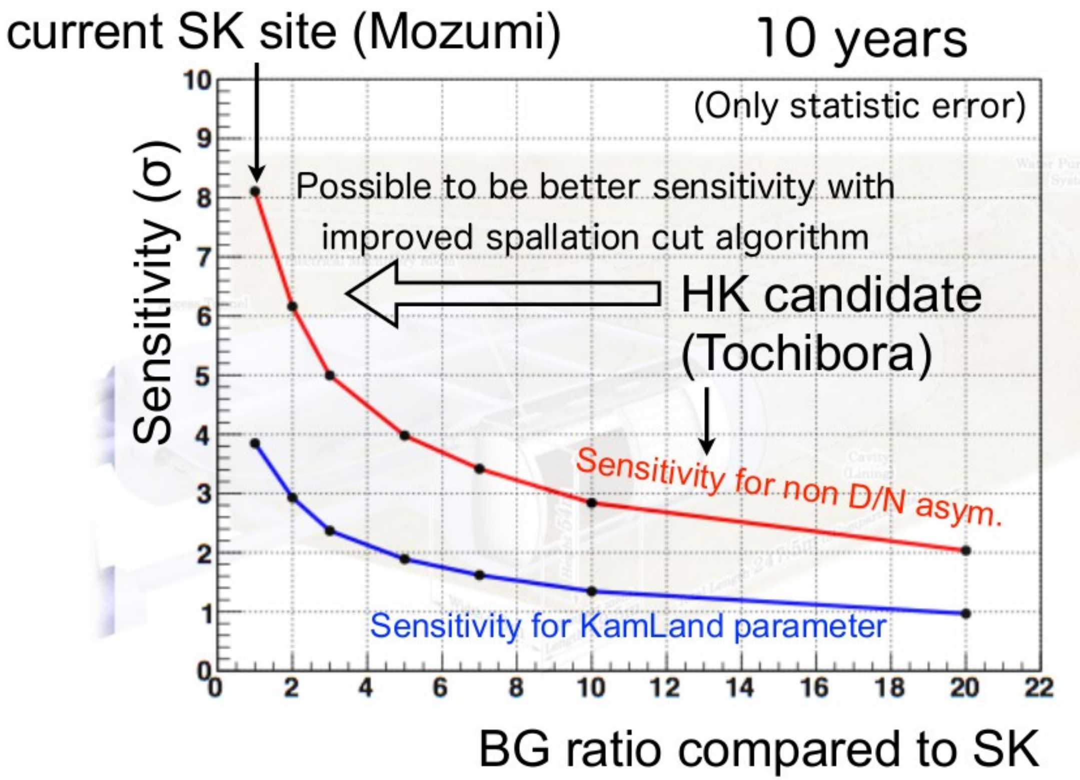




Supernova relic neutrino: possible G$_d$-doping of Hyper-K. ~830 events in 10 years in 10-30 MeV energy range.

Solar Neutrinos

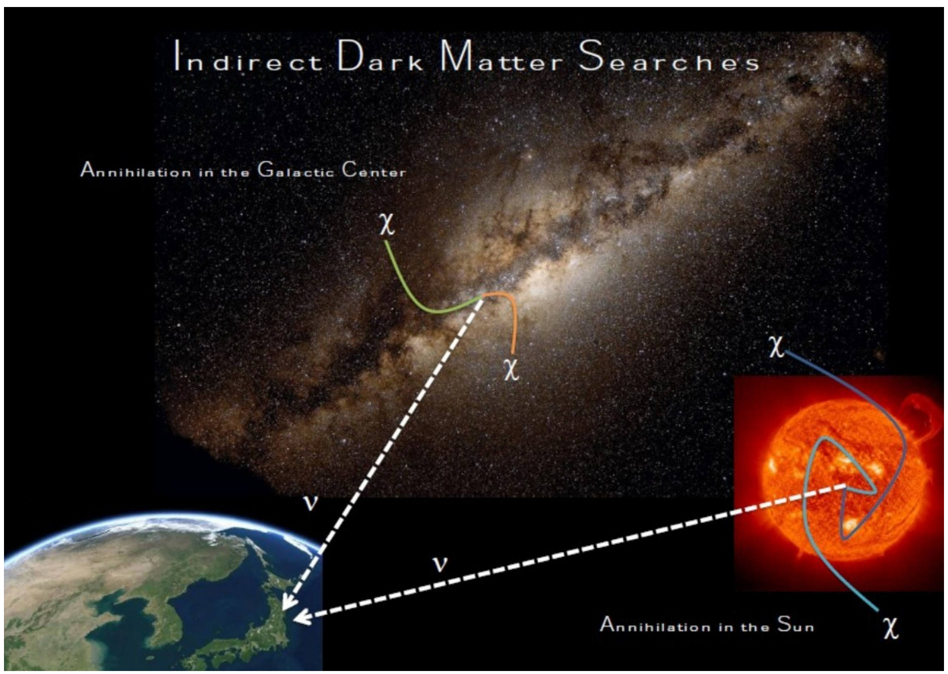
Solar Neutrinos: ^{8}B 200 ν's / day from Sun → day/night asymmetry of the solar neutrinos flux can be precisely measured at HK (<1%). Day/night asymmetry

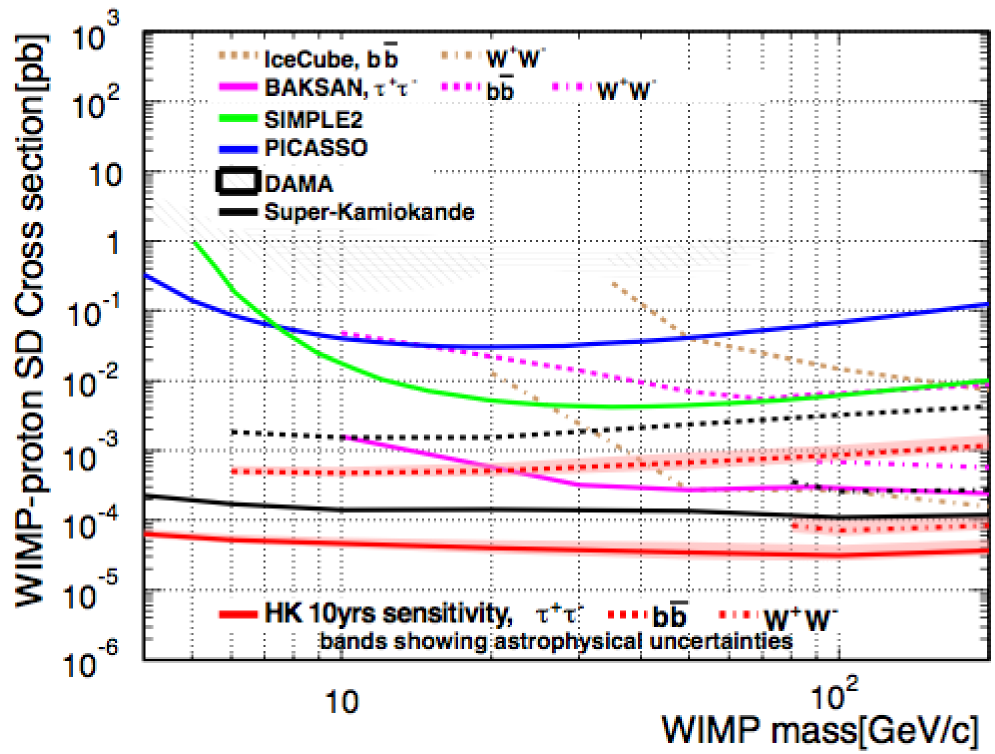


- Possible observation of up-turn requires low neutrino energies
- Current studies under way in the DR.

Neutrino Astrophysics

Indirect Searches for Dark Matter: 1) search for excess of neutrinos from the center of the Earth, Sun and galactic centre as compared to atmospheric neutrino background 2) Search for diffuse signal from Milky Way halo.



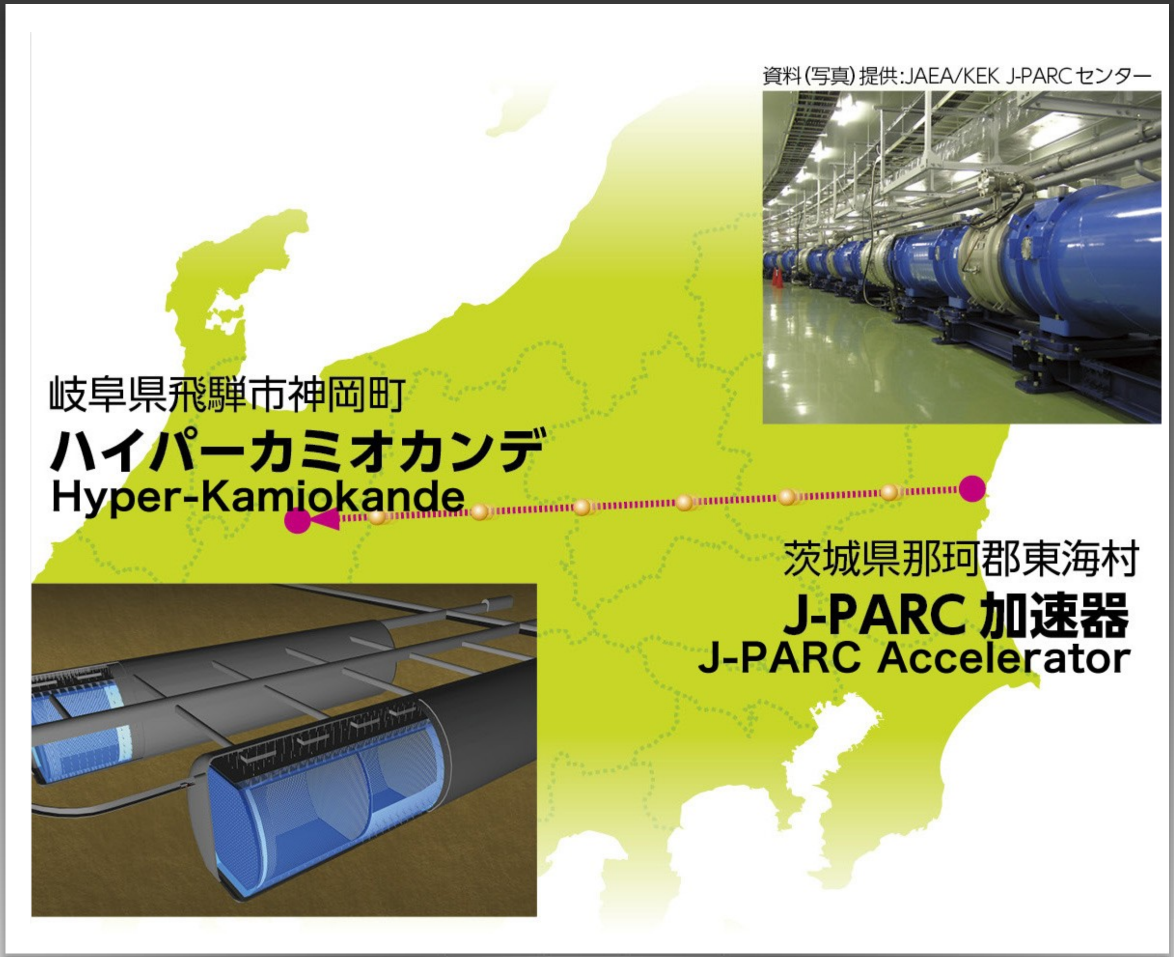


“Other” Beam Physics

Apart from the mixing parameters, there is a rich landscape of physics topics:

- Cross section measurements – mainly at the near detector suite.
- Consistency checks of three flavour framework (e.g. PMNS unitarity), combination with other LBN and atmospheric experiments, etc.
- Physics that goes beyond the three flavour paradigm, examples:
  - Non-standard interactions → deviations from the three-flavor mixing model
  - Lorentz and CPT violation → sidereal neutrino oscillations
  - New long-distance potentials arising from discrete symmetries
  - Sterile neutrino states that mix with the three known active neutrino states

Conclusions



Conclusions

- Formed proto-collaboration (Jan 2015).

- KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.

- Next generation multi-purpose experiment
  - Oscillation physics:
    - able to measure δ_{CP} at 3σ for 76% of its phase space
    - solve octant degeneracy, mass hierarchy (atmospherics), θ_{32}, Δm^2_{32}
  - Atmospheric neutrinos allow to measure MH.
  - Excellent sensitivity to proton decay.

- Data taking around 2025 with current schedule.

- Work ongoing worldwide on all the aspects of HK.

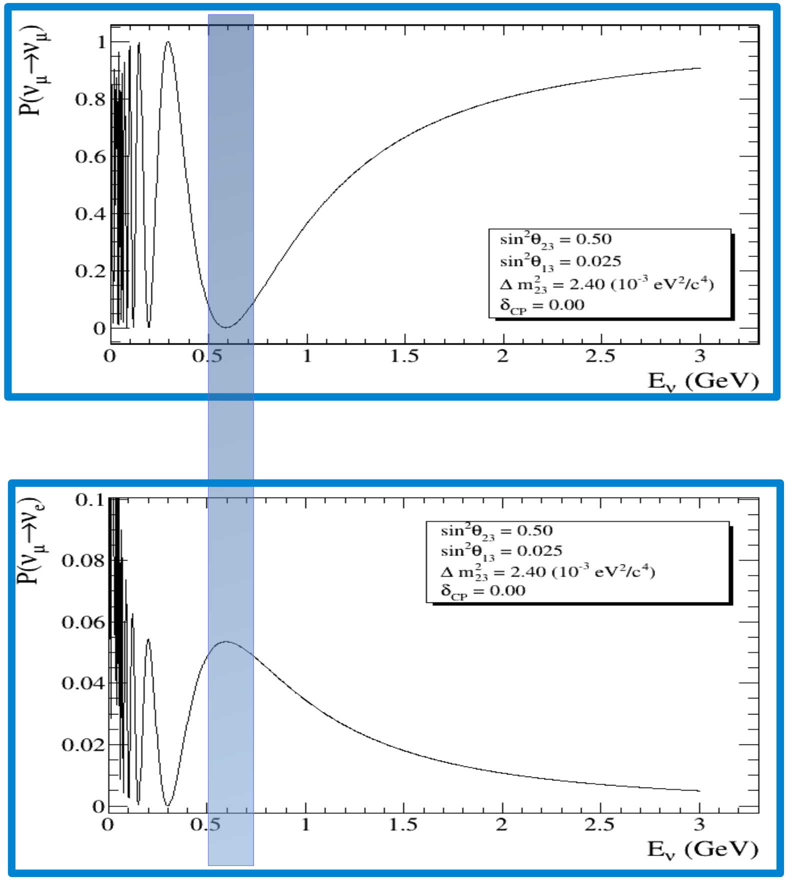
- Optimizing the detector and writing design report to form the basis for the submission to SCJ and MEXT to be added to roadmap.

Stay tuned for many more exciting news from Hyper-Kamiokande!

Additional Slides

Oscillation Searches at Hyper-K

HK is optimized for both appearance and disappearance searches



T2HK ν beam energy peak

ν_μ **Disappearance:** determine θ_{23} and Δm_{32}^2

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{\Delta m_{23}^2 L}{4E_\nu}\right)$$

ν_e **Appearance:** determine θ_{13}, constrain δ_{CP}

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$

$$-\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right)$$

$$\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) \sin\delta_{CP} + CPC$$

$$+\, matter + solar\ terms$$

For maximum power fit both data samples **jointly**

J-PARC MR power mid/longer-term plan

FX: Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, rf cavities, ...
SX: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 –300 (400)			750
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50			100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D	2.48 s		Manufacture installation/test		1.3 s
Present RF system New high gradient rf system	Install. #7,8	Install. #9 R&D		Manufacture installation/test			
Ring collimators	Additional shields	Add.collimato rs and shields (2kW)	Add.collimat ors (3.5kW) C,D,E,F	Back to JFY2012 (2kW)	Add. coll. C,D	Add. coll. E,F	
Injection system FX system	Inj. kicker	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test					
SX collimator / Local shields	SX collimator					Local shields	
Ti ducts and SX devices with Ti chamber		SX septum endplate	Beam ducts	Beam ducts	ESS		

- ~320kW (Mar. 2015) → 750kW in a few years w/ power supply replacement.
- Middle term: continue to lead ν physics with T2K while preparing for Hyper-K
- Longer term: Several ideas under discussion towards multi-MW facility