The Hyper-Kamiokande Experiment

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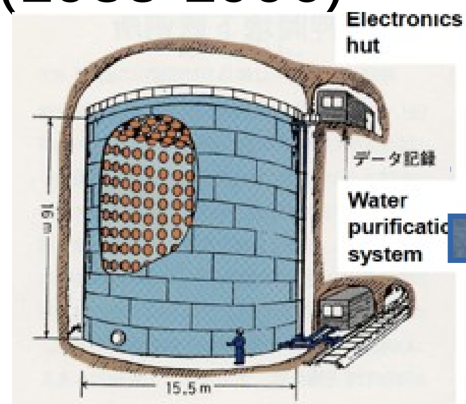
Kamiokande Evolution

Three generations of large Water Cherenkov in Kamioka

Kamiokande
(1983-1996)

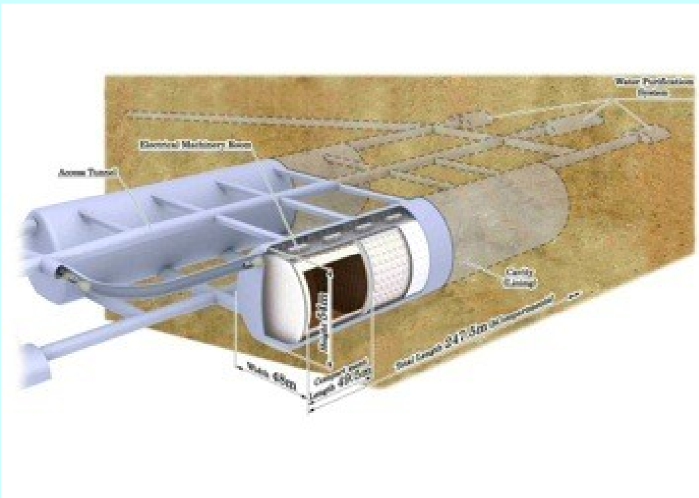


3kton

Super-Kamiokande
(1996-)

50kton

Hyper-Kamiokande
(202?-)



1Mton=1000kton

(560kton fiducial)

Discovery of neutrino oscillation (1998)

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

x17

x20
(x25 fiducial mass)

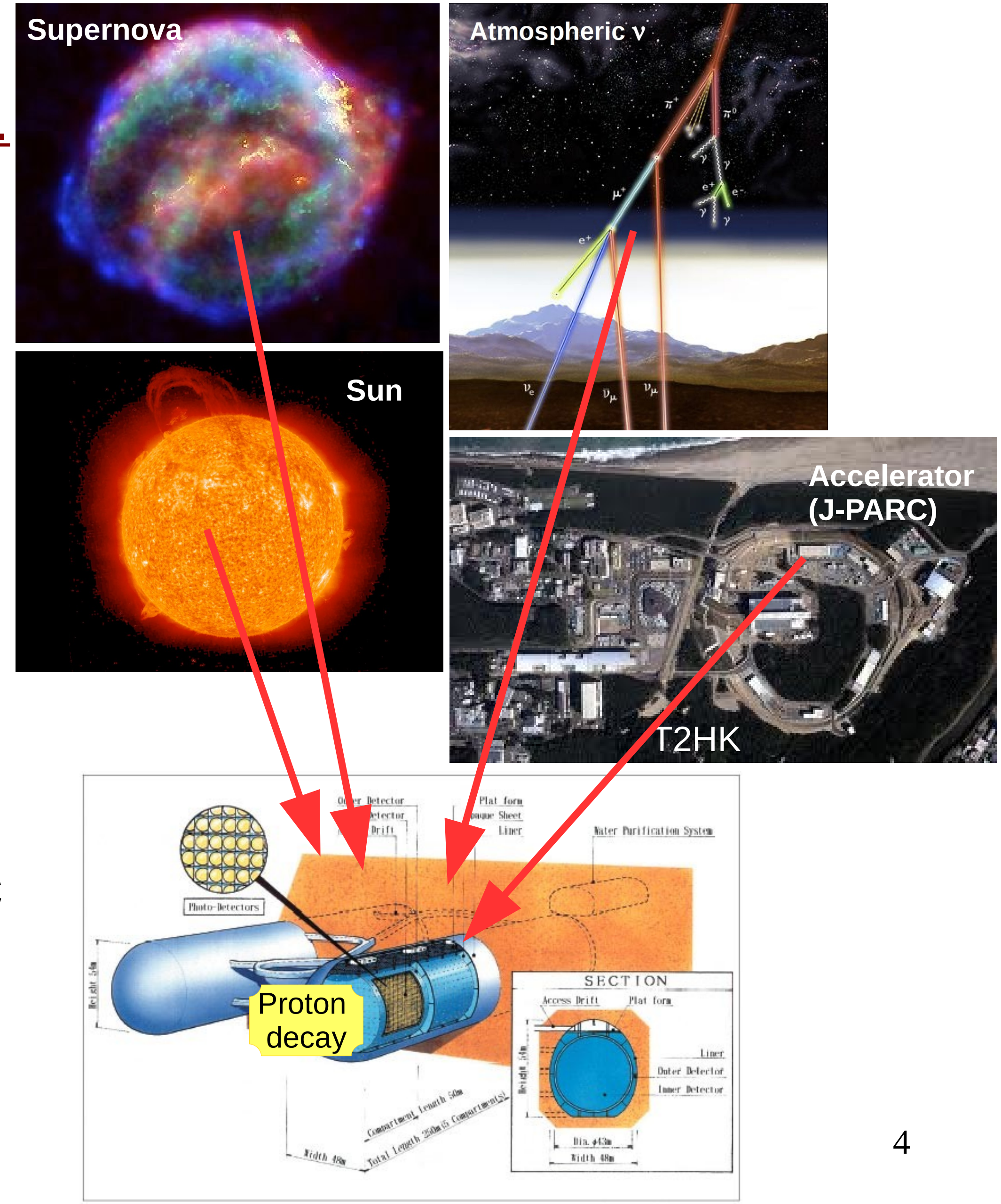
Outline

- Overview
  - Latest updates
- Beam & Atmospheric Physics:
  - Oscillation parameters
- Non-beam Physics:
  - Proton decay
  - Astrophysics
- Experiment Design:
  - Cavern and tank
  - Photosensors
  - Near Detectors

The Hyper-Kamiokande Project

<u>Multi-purpose neutrino experiment.</u>
Wide-variety of scientific goals:

- <u>Neutrino oscillations</u>:
  - Neutrino beam from J-PARC
  - Atmospheric neutrinos
  - Solar neutrinos
- Search for <u>proton decay</u>
- <u>Astrophysical neutrinos</u>
(supernova bursts, supernova relic neutrinos, dark matter, solar flare, …)



Hyper-K Proto-Collaboration

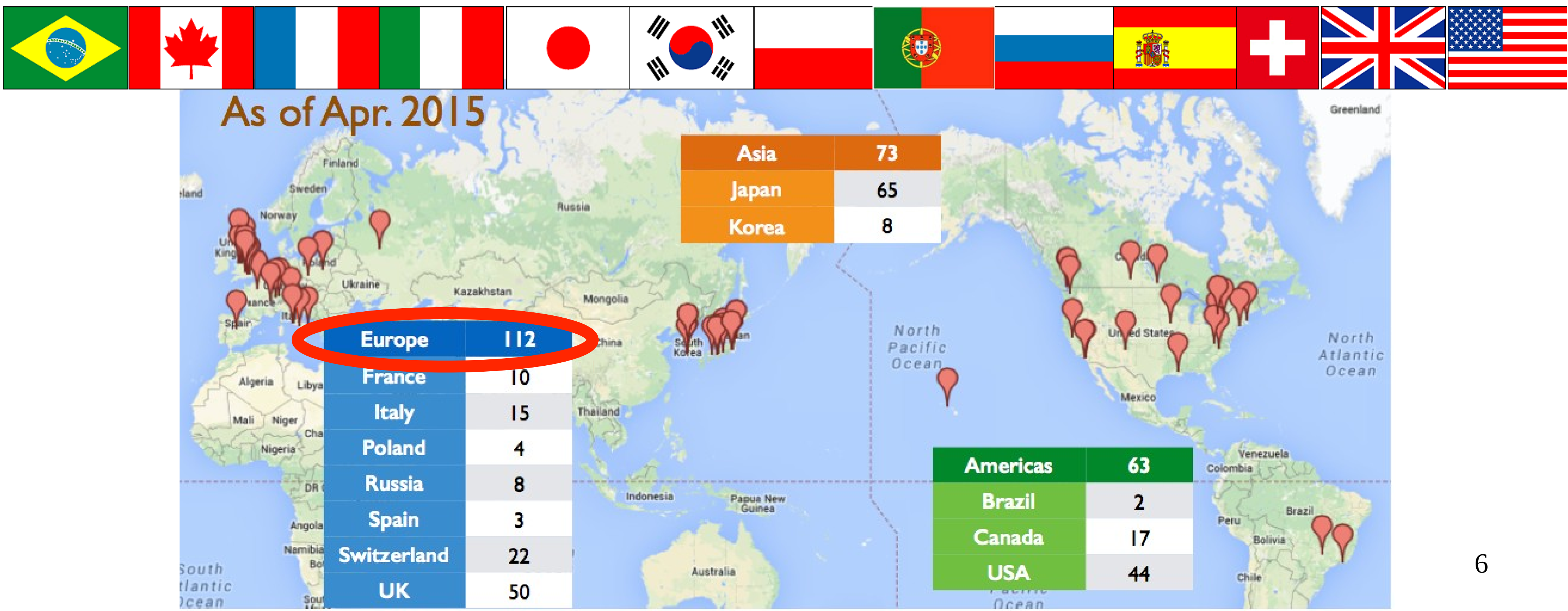
Inaugural Symposium on January 31, 2015

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

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

Third EU-Hyper-K Meeting

Most recent meeting: 3rd Hyper-K EU meeting at CERN (27-28 April):
http://indico.cern.ch/e/ThirdEUHyperK

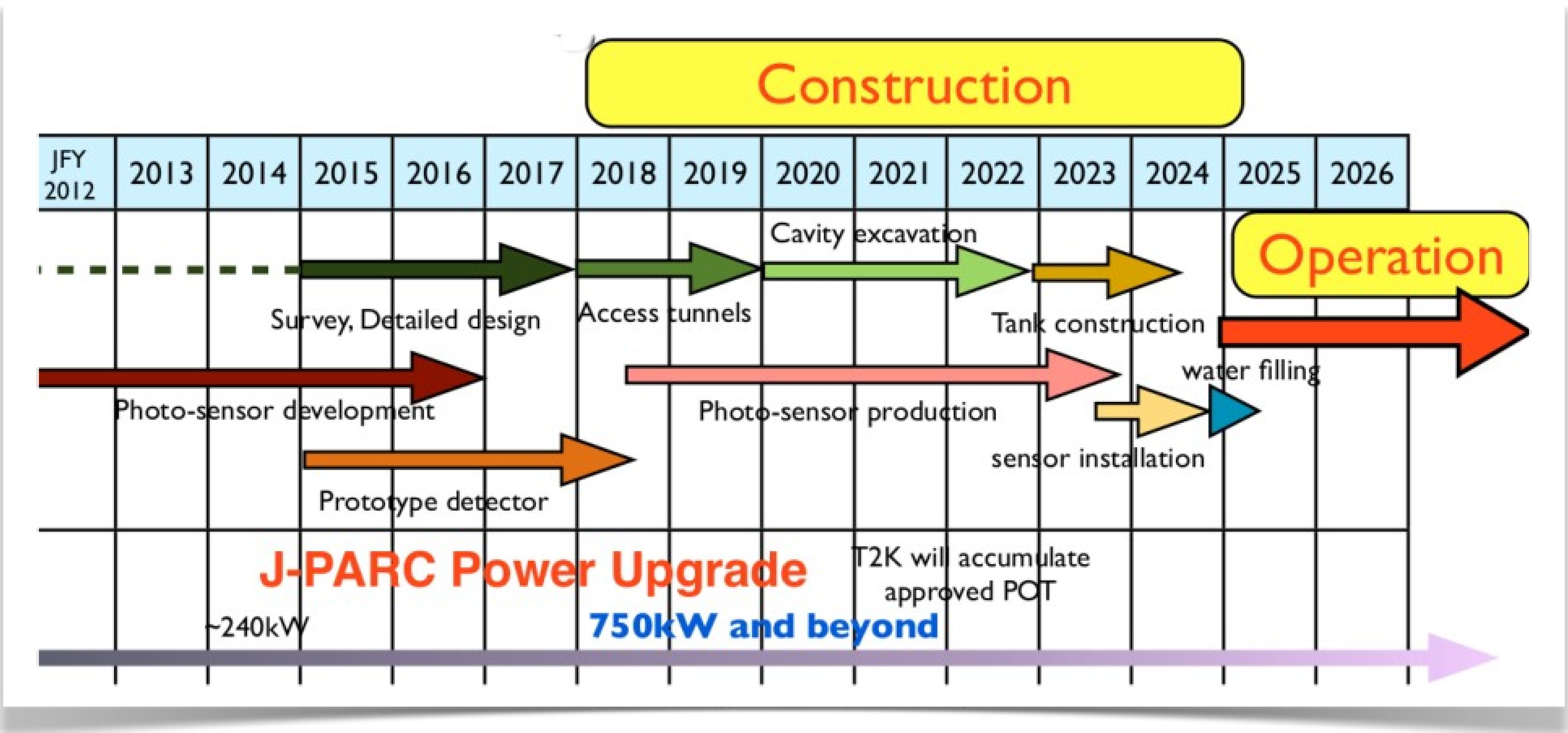
Next Steps

- Design Report being prepared.
- It will be submitted to KEK/ICRR in the Autumn to be reviewed by an international panel.
- The next update of Japanese science roadmap (SCJ master-plan and MEXT roadmap) expected in 2016-2017.
- Optimum design, construction cost & period, beam & near detector, international responsibilities.
- Once the budget is approved, the construction can start in 2018 and the operation will begin in ~2025.

First Meeting of the proto-collaboration:

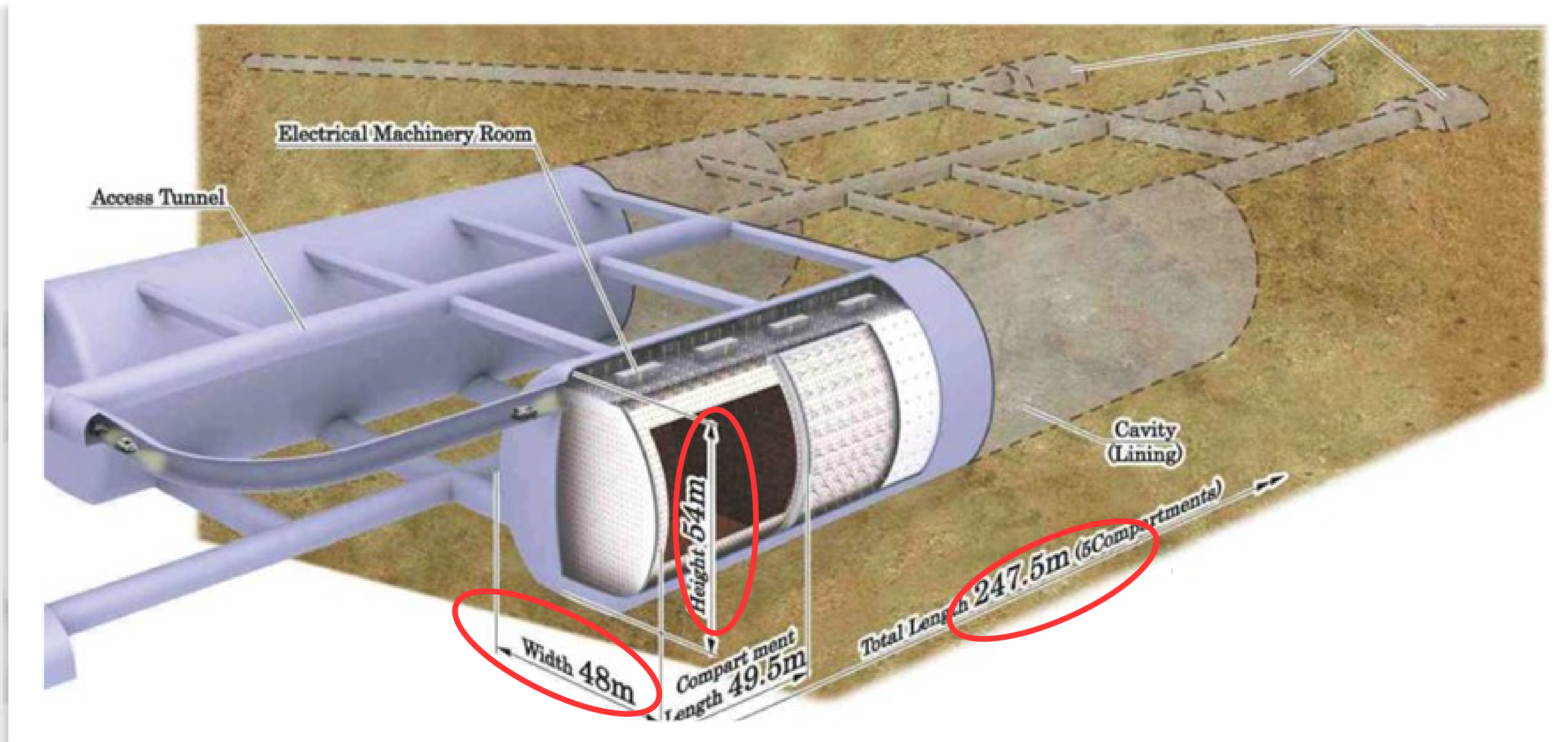
June 29-July 1, @Kashiwa/Japan

The Hyper-Kamiokande Timeline

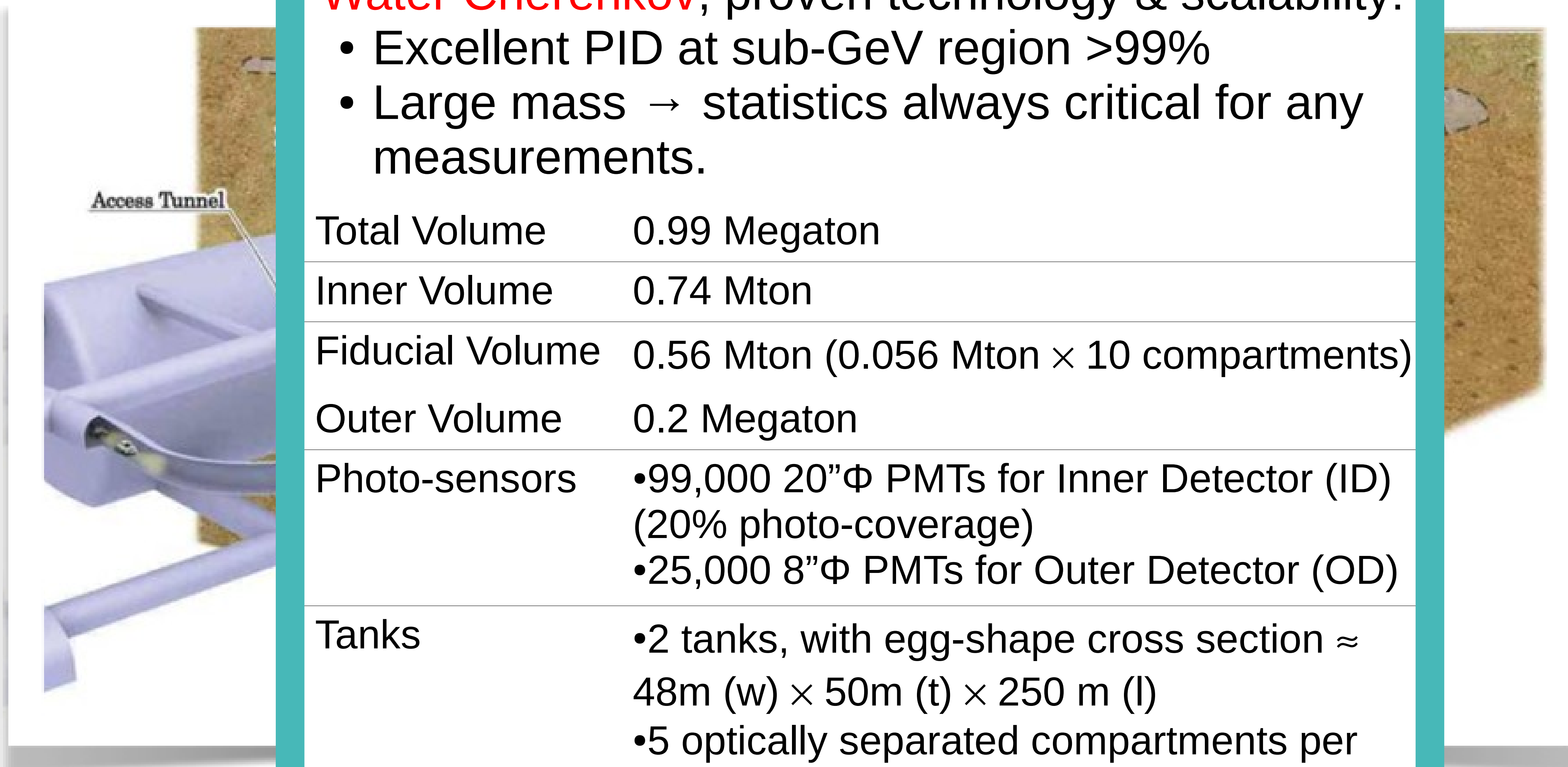


~2017 Major design decisions finalized
~2018 Construction starts
~2025 Data taking start
> 2025 Discoveries!

The Hyper-Kamiokande Detector



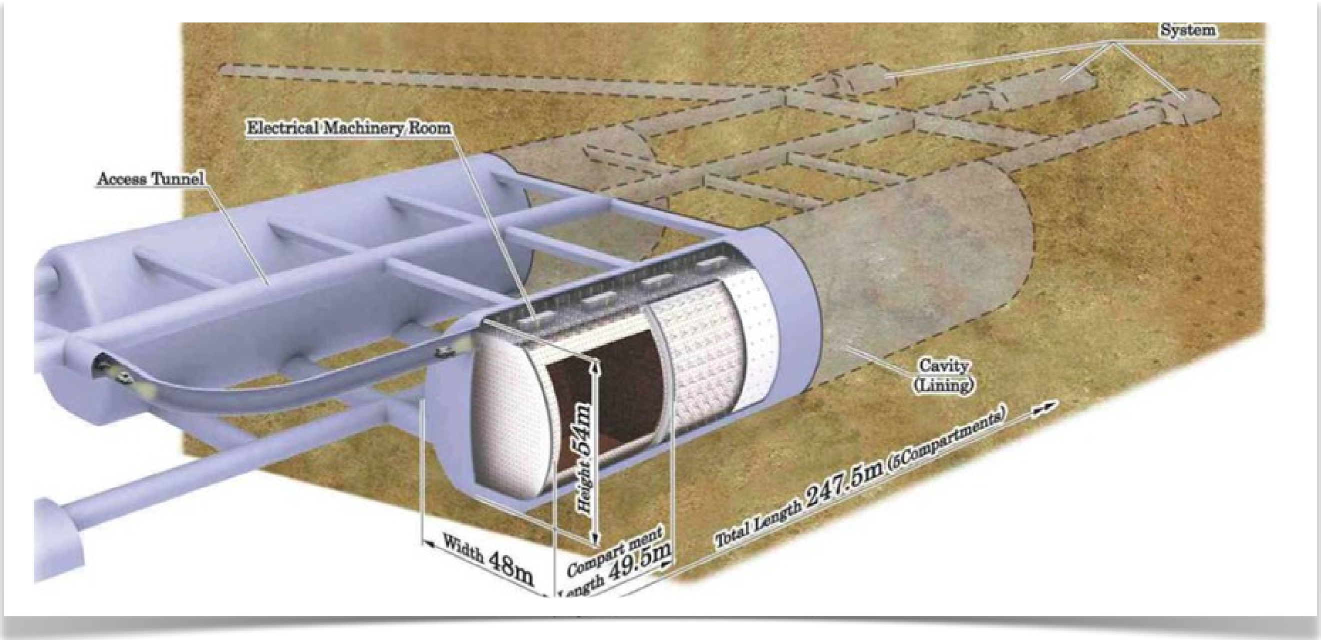
The Hyper-Kamiokande Detector

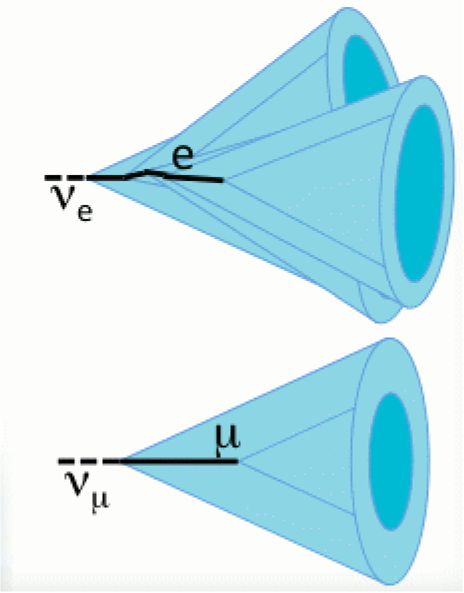


- Water Cherenkov, proven technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

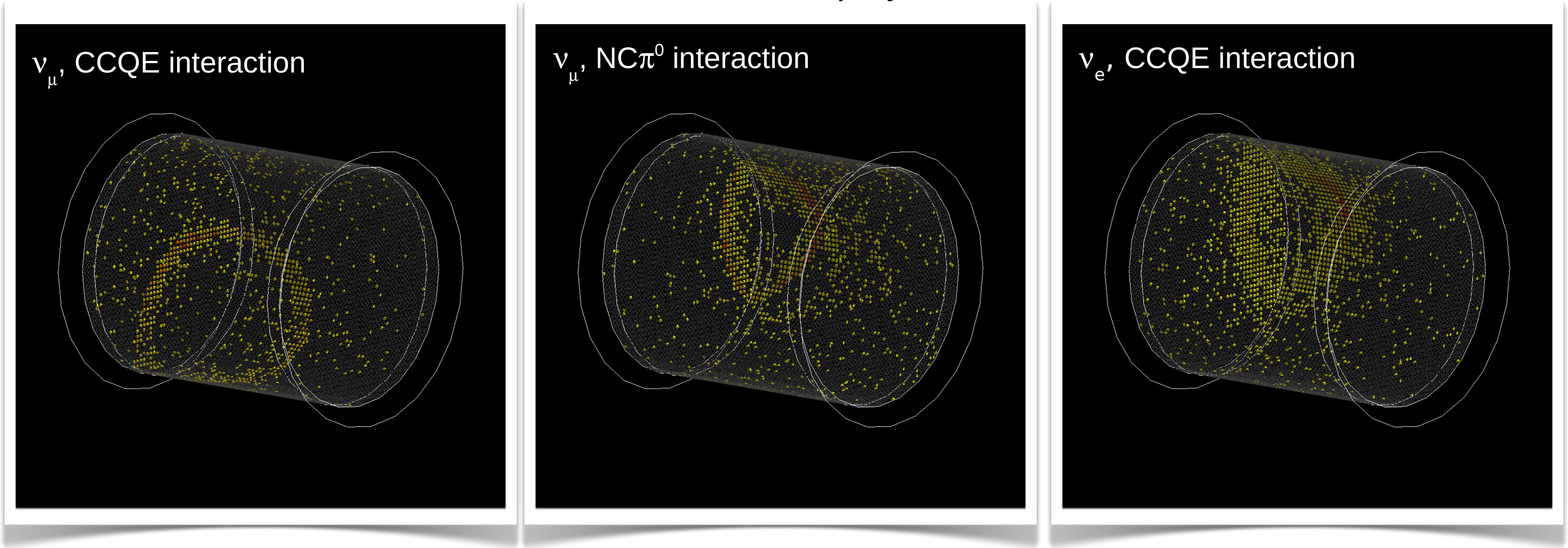
Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	•99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage) •25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	•2 tanks, with egg-shape cross section ≈ 48m (w) × 50m (t) × 250 m (l) •5 optically separated compartments per tank

The Hyper-Kamiokande Detector



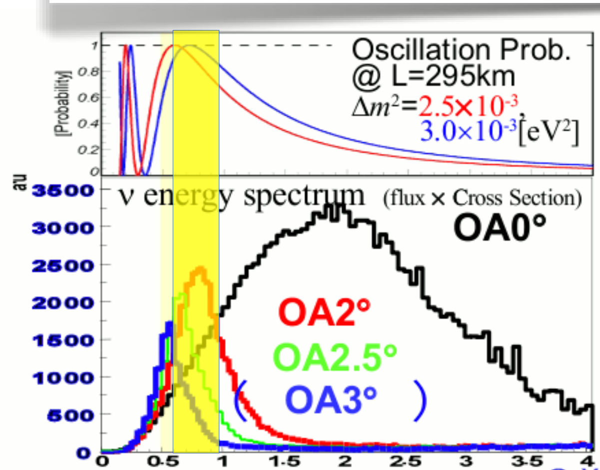


GEANT4 event displays



Tokai to Hyper-Kamiokande

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

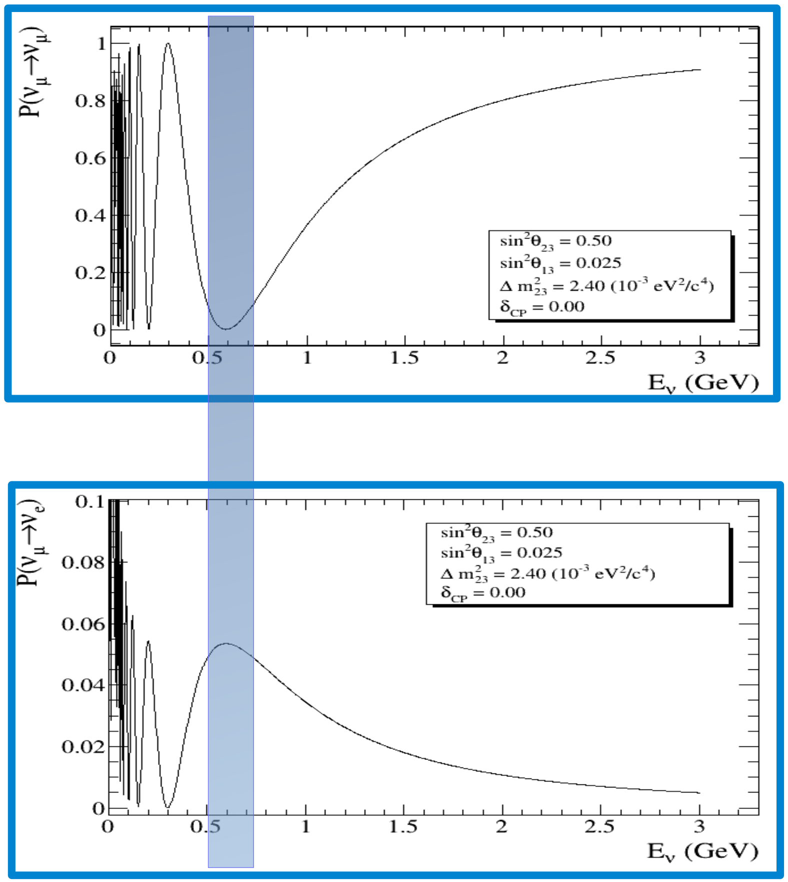


Near Detectors

- 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

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

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

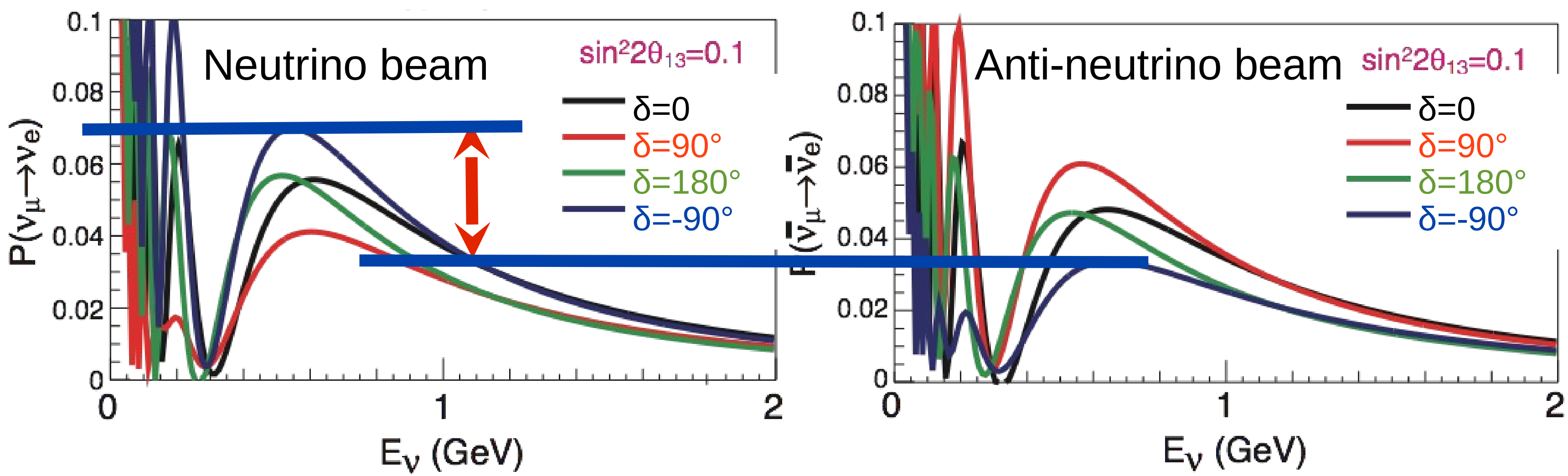
ν_e Appearance: determine θ_{13}, constrain δ_{CP}

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$
$$-\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right)$$
$$\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) \sin\delta_{CP} + CPC$$
$$+ matter + solar\ terms$$

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

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

L=295km, NH

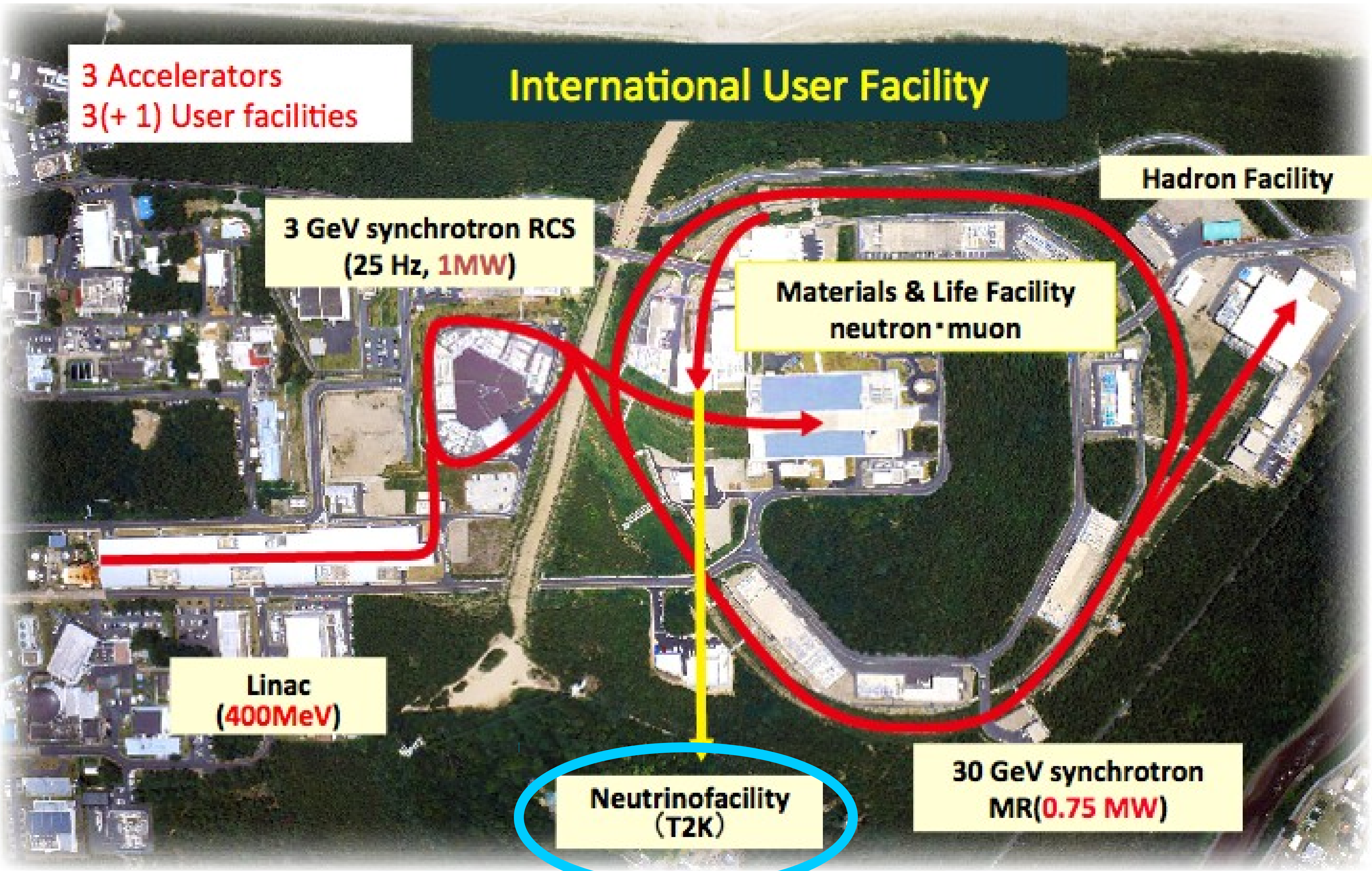


- CP violation will manifest itself in neutrino oscillations:

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

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

Hyper-Kamiokande Beam



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.

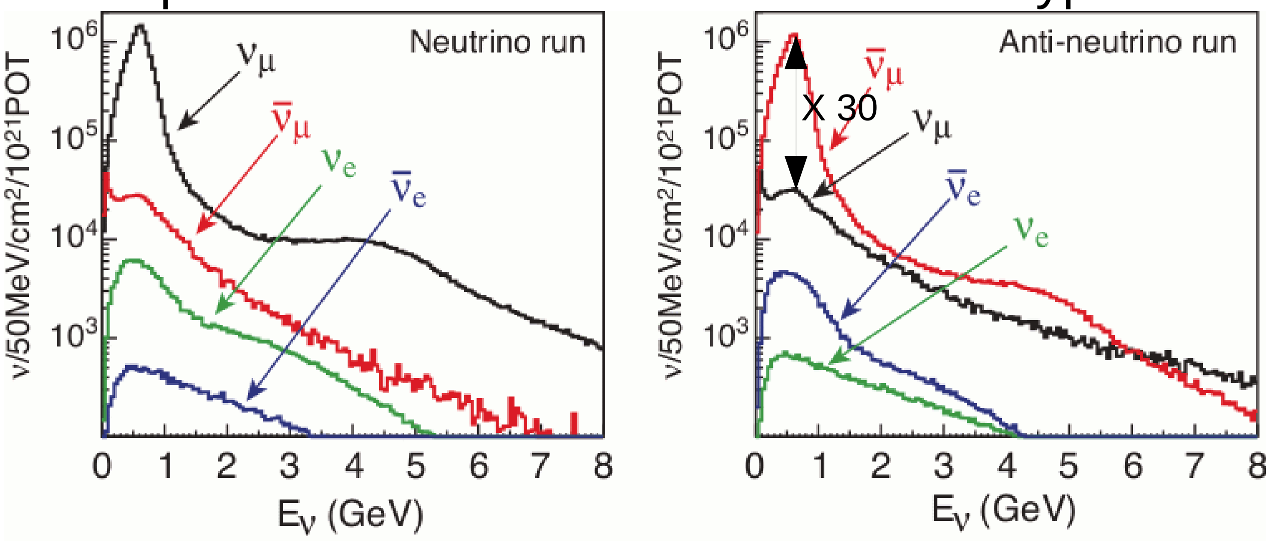
JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 –300 (400)			750
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50			100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D	2.48 s		Manufacture 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

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
  - Less time for higher beam power

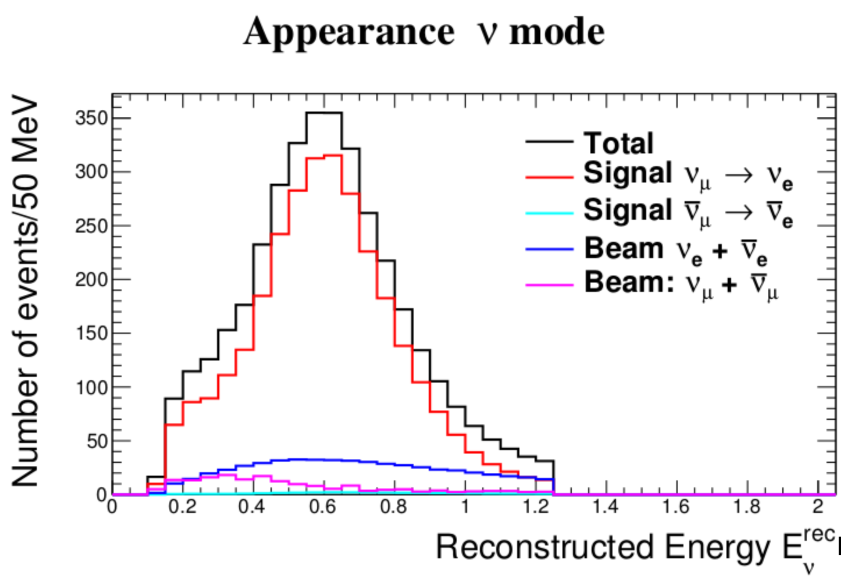
Expected unoscillated neutrino flux at Hyper-K



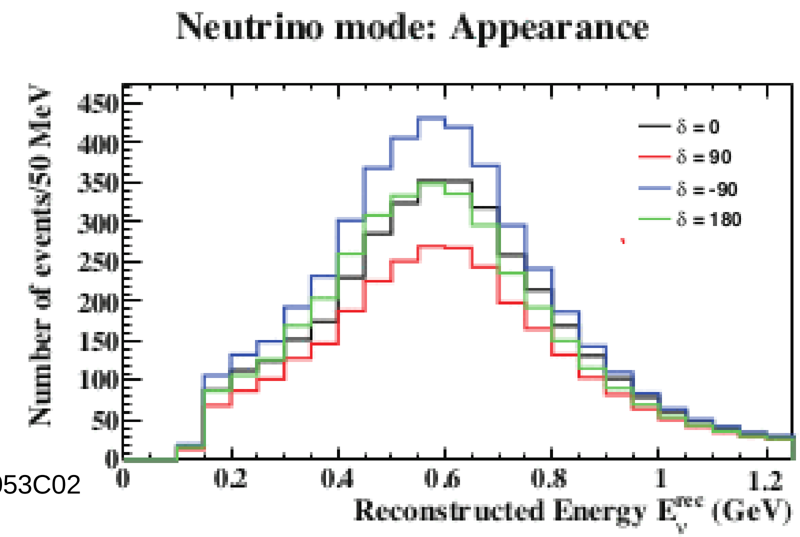
Nominal beam sharing between neutrinos and anti-neutrinos in the following sensitivity plots:

ν-mode: $\bar{\nu}$-mode
1y : 3y

Expected Events



PTEP 2015 053C02



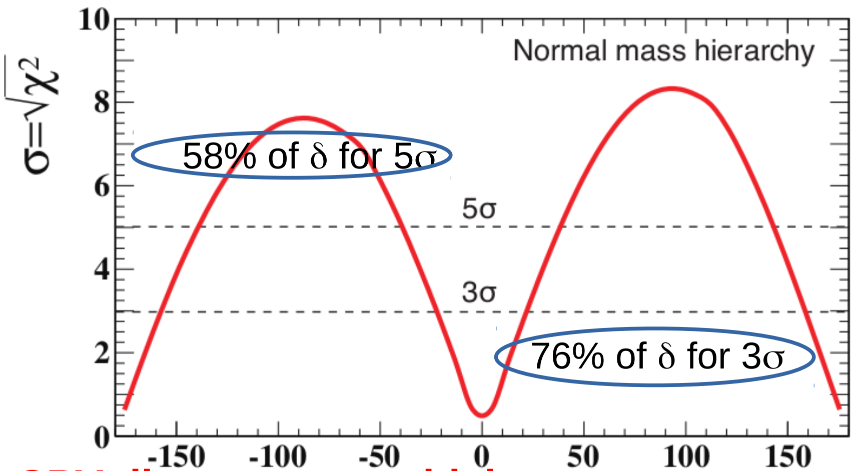
Appearance	Signal		Background					Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	265	265	3397

Disappearance	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	$\nu_\mu \rightarrow \nu_e$	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 δ_{CP} = 0

PTEP 2015 053C02

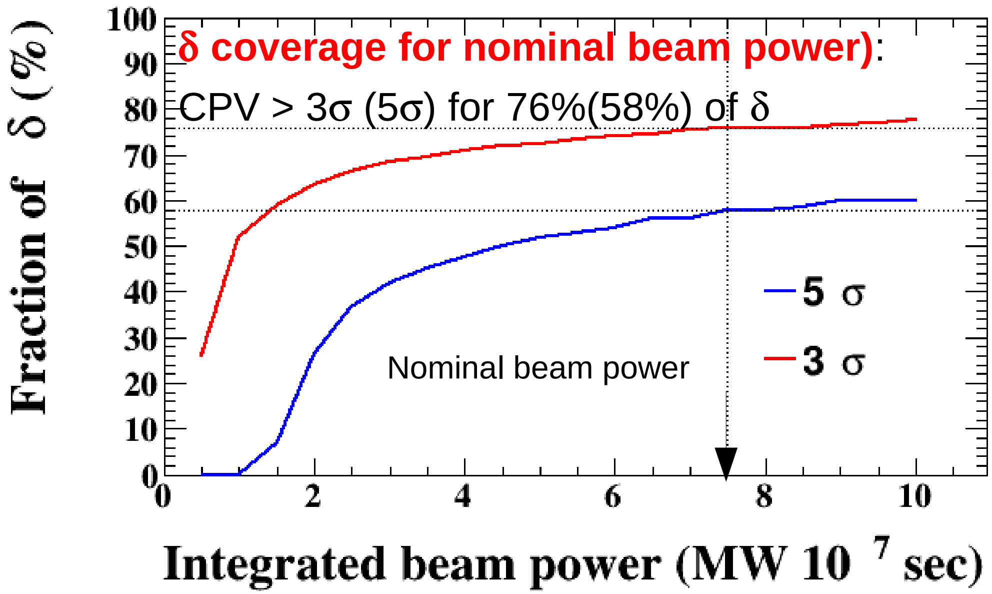
Hyper-K Sensitivity to δ_{CP}



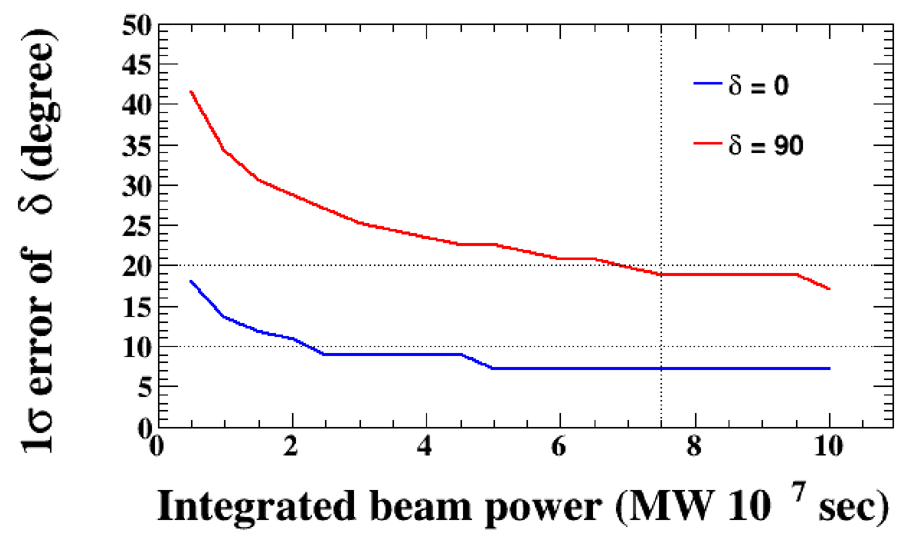
CPV discovery sensitivity
to δ_{CP}=0,π w/ MH known

Errors (%) on the expected number of events				
	ν mode		$\bar{\nu}$ mode	
	ν_e	ν_μ	ν_e	ν_μ
Flux & 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

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



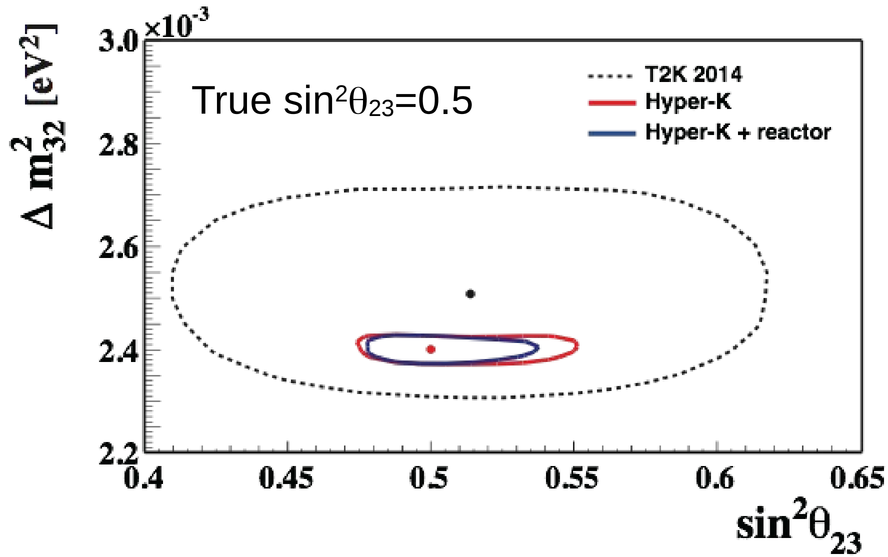
1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)



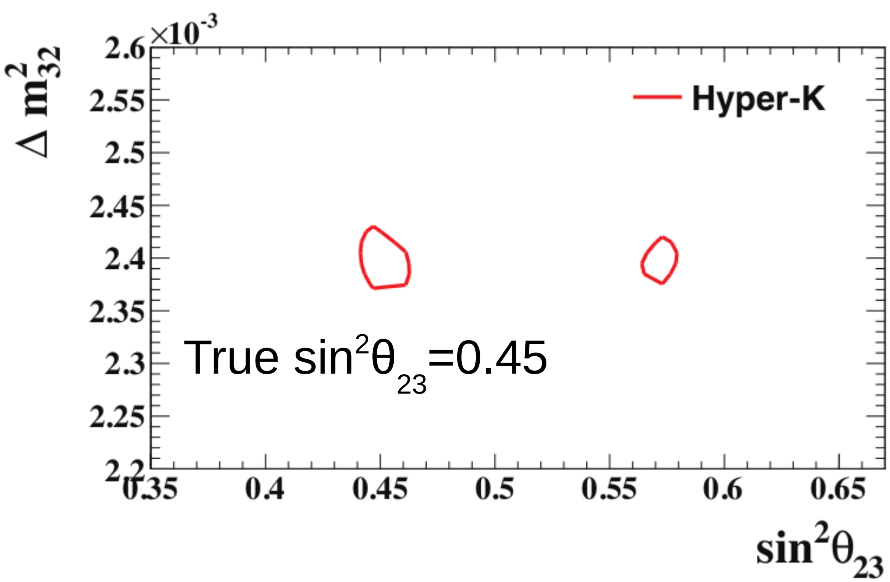
PTEP 2015 053C02

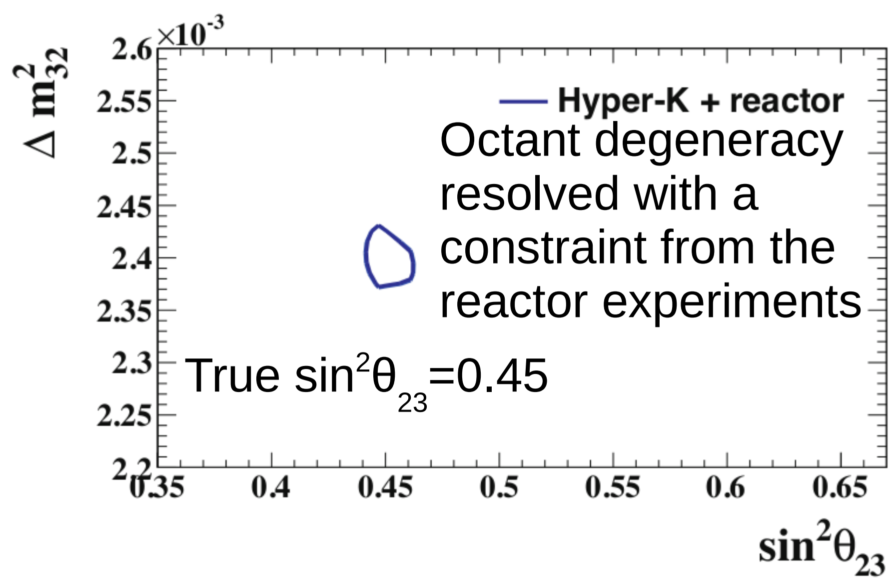
Sensitivity to θ_{23}

- $\sin^2 2\theta_{23}$ 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



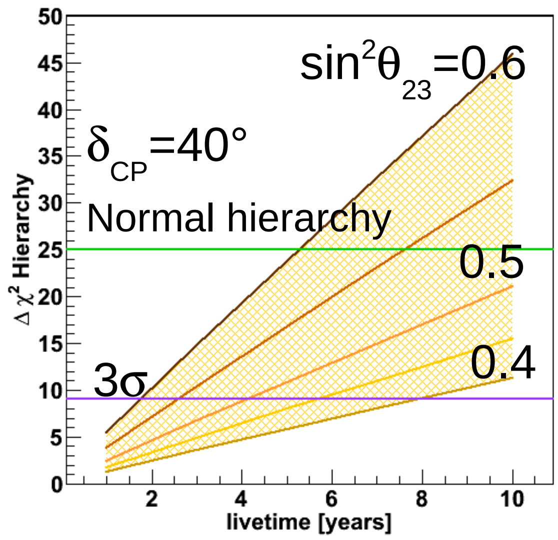
True $\sin^2\theta_{23}$	1σ err $\sin^2\theta_{23}$	1σ err Δm^2_{23} (eV^2)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

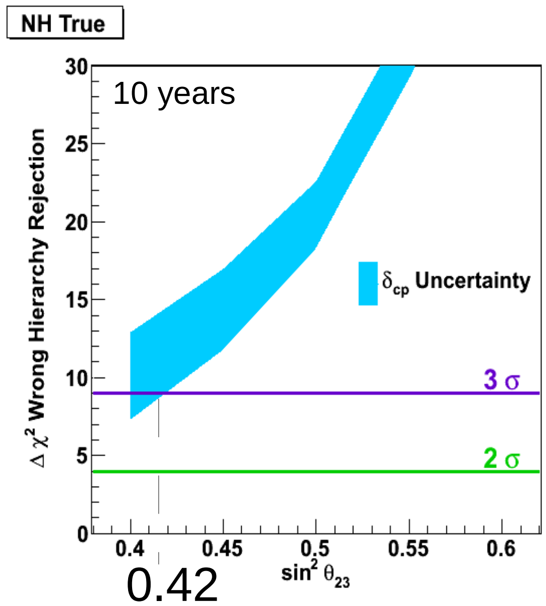


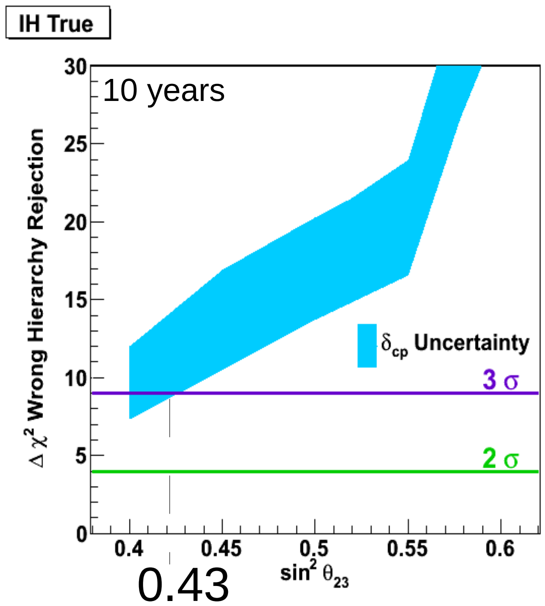


Hyper-K Sensitivity to MH

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





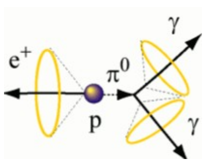


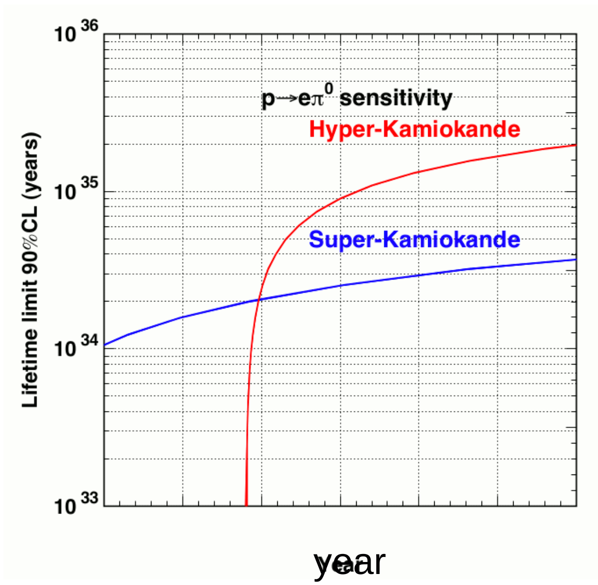
- Use atmospherics for 3σ mass hierarchy determination.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.

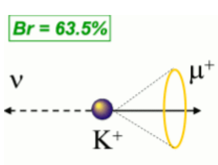
Proton Decay Sensitivity

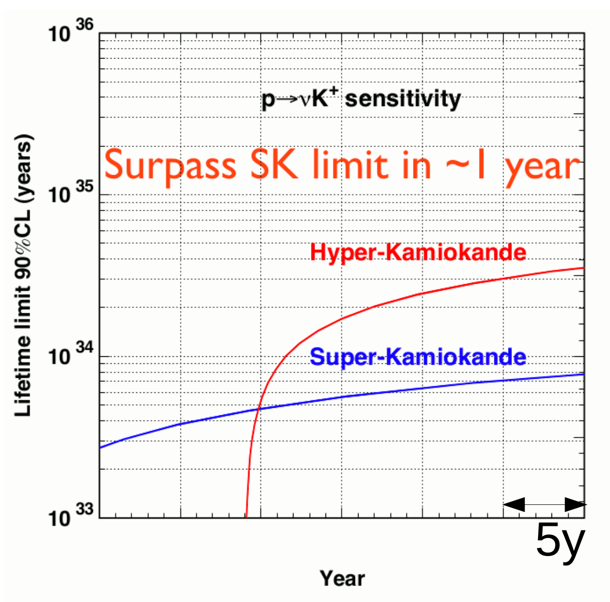
arXiv:1109.3262

Surpass SK limit in ~1 year

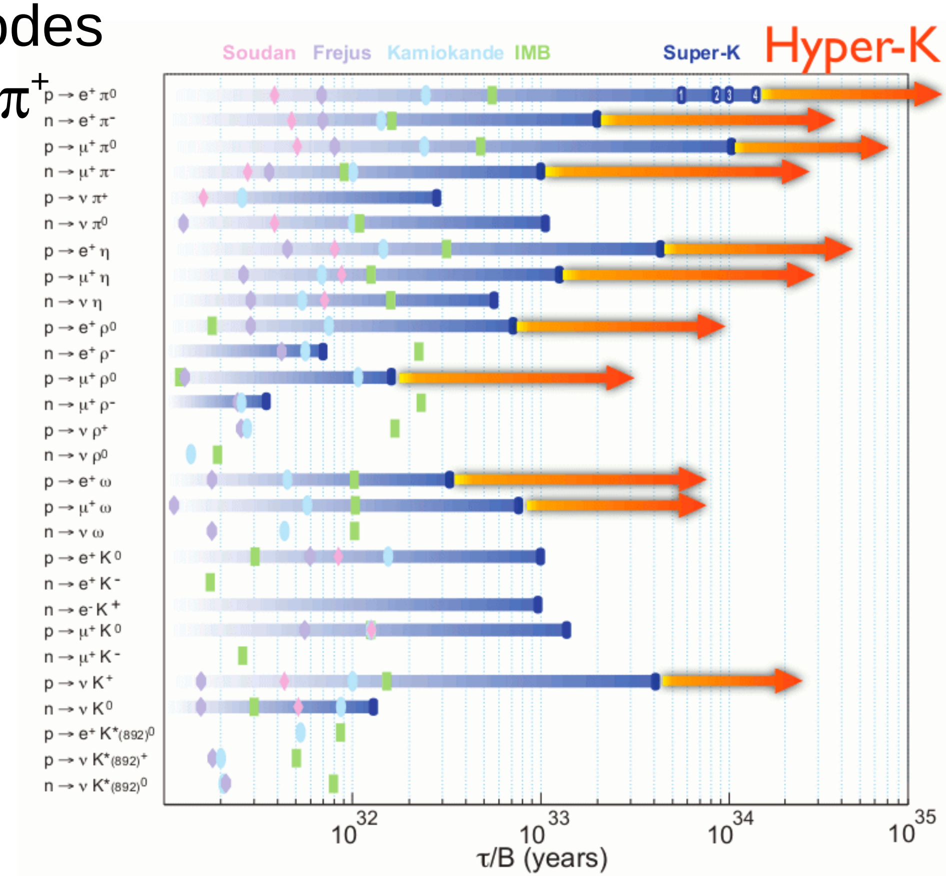




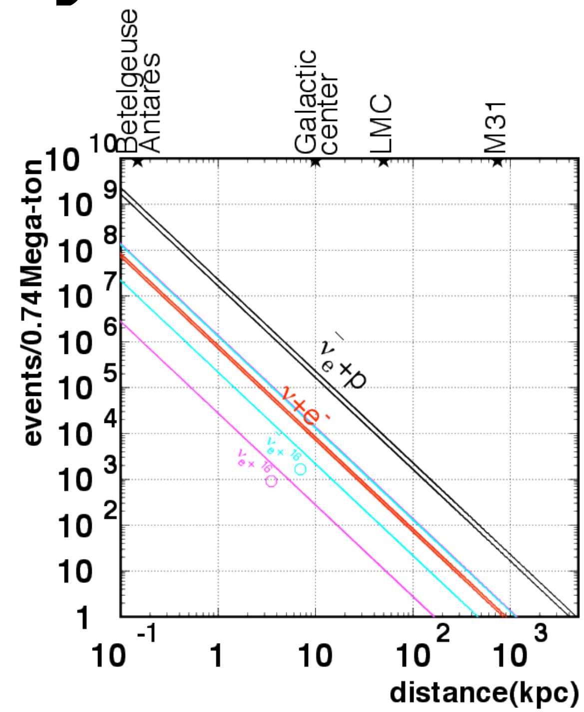




- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
- Hyper-K is sensitive in every single mode
  - $p \to e^+\pi^0$: 1.3×10^{35} y at 90% CL
  - $p \to \bar{\nu}K^+$: 3×10^{34} y at 90% CL
  - Many other modes:
    - p,n → $(e^+,\mu^+) + (\pi,\rho,\omega,\eta)$; $10^{34\text{-}35}$y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



Neutrino Astrophysics

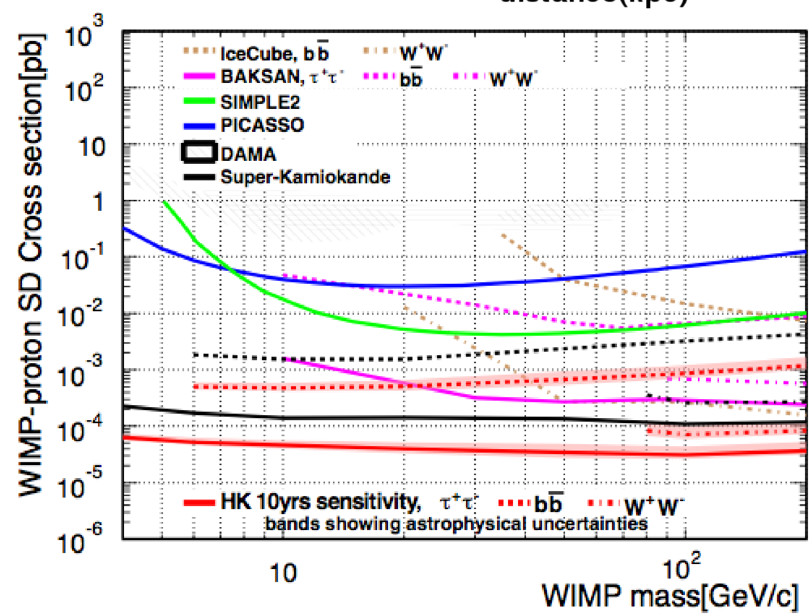


Supernova burst neutrino: 200k ν's from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics. Important data to cross check explosion models

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

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

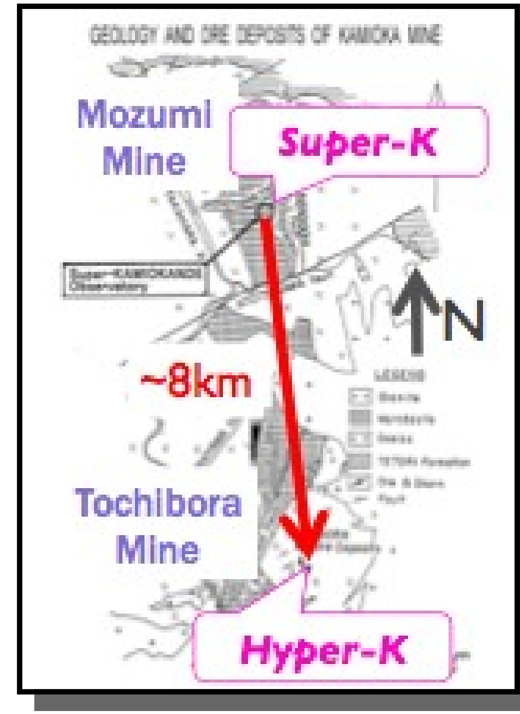
Indirect Searches for Dark Matter: 1) search for excess of neutrinos from the center of the Earth, Sun and galactic centre as compared to atmospheric neutrino background 2) Search for diffuse signal from Milky Way halo.

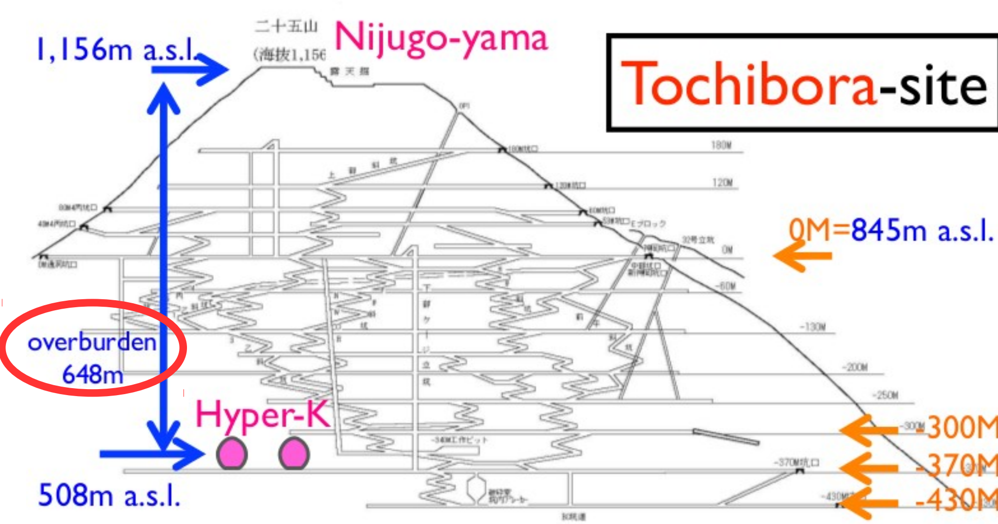


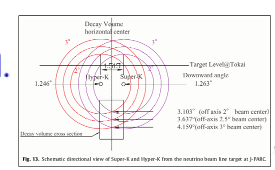
Site(s) and Cavern(s)

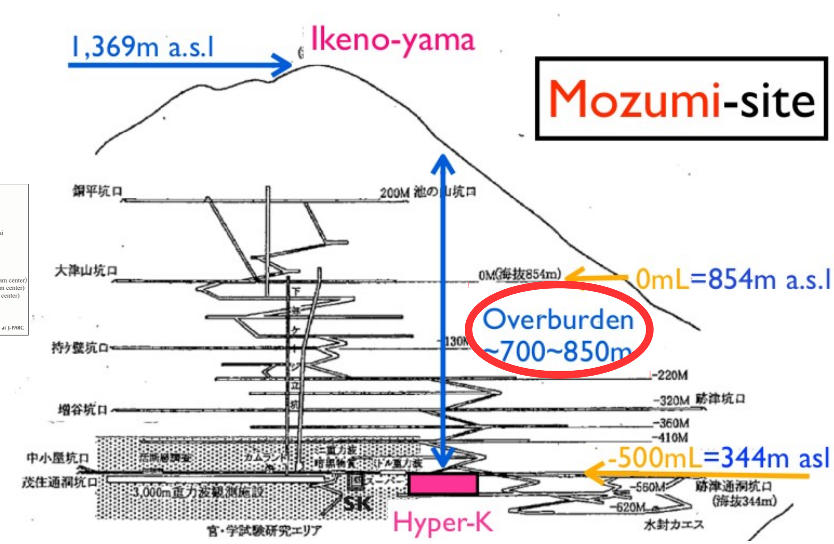
Two sites are being investigated:

- 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



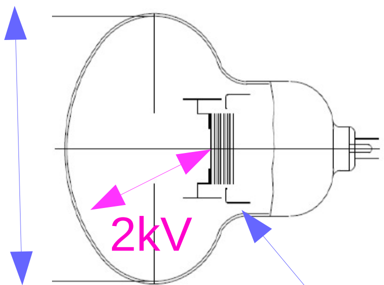
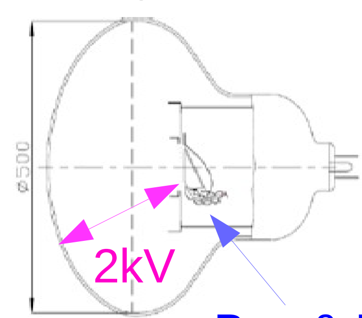
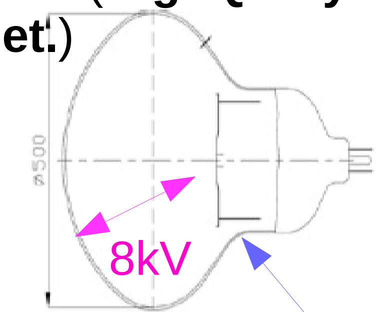






Photosensors Candidates

R&D going to get better perfomance and lower costs

	Established (**SK PMT**)	R&D (**HighQE/CE PMT**)	R&D (**HighQE hybrid det.**)
			
	Venetian blind dynod	Box & Line dynod (unique drift path)	Avanlance diode
Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

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

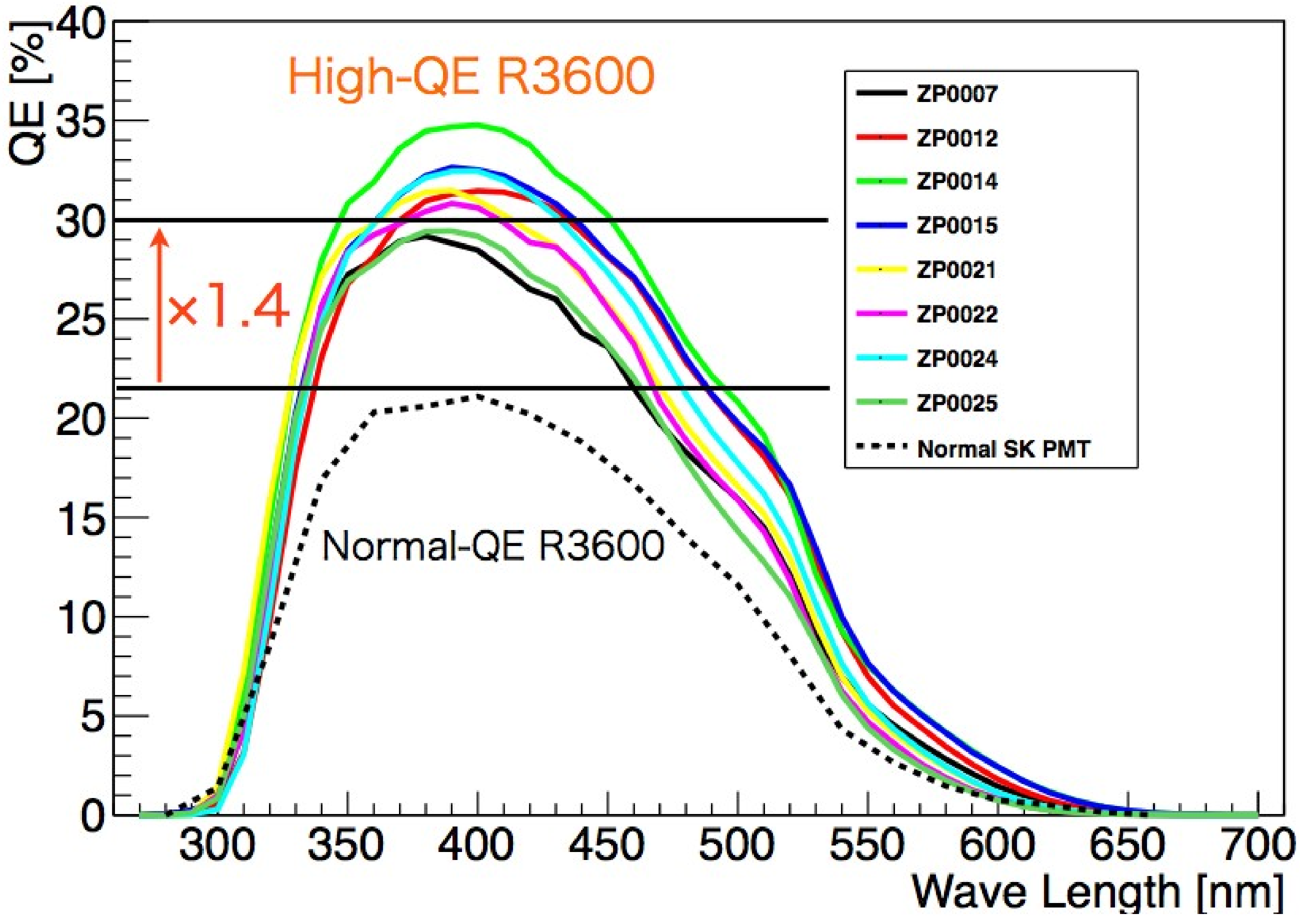
R&D (HighQE/CE PMT)
- Under development
- Better performance
- Same technology → Lower risk

R&D (HighQE hybrid det.)
- Under development
- Far better performance
- Simple structure →Lower cost
- New technology →Higher risk

Photosensors covered by protective case (currently under R&D)

Lower Risk ⟵ ⟶ Higher Performance

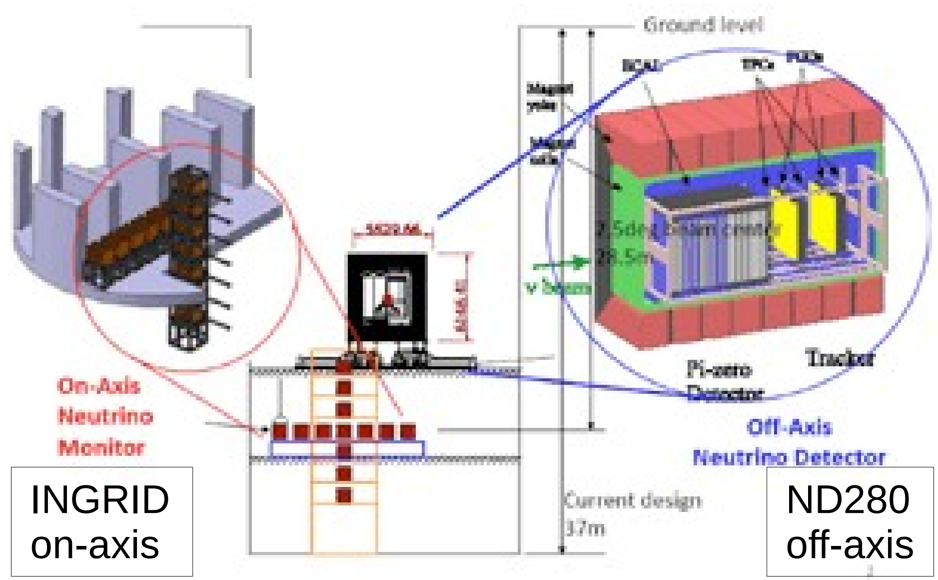
High QE achieved



- 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

Near Detectors

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



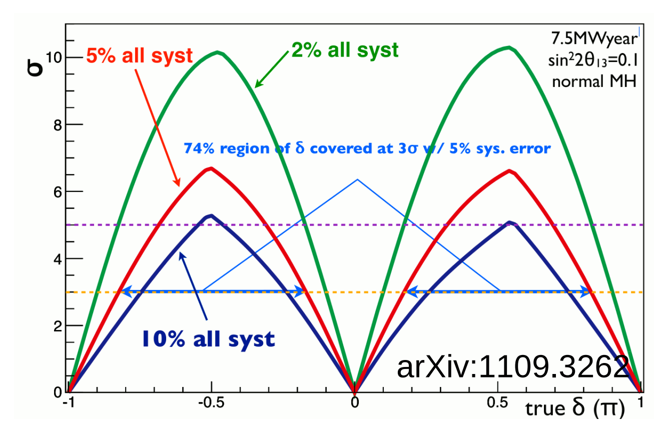
Under investigation three (complementary?) options:

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

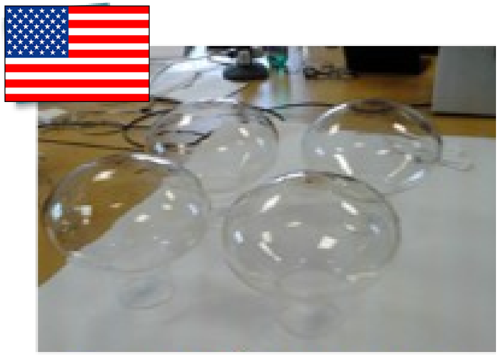
Optimization criteria based on reducing systematic errors for oscillations.

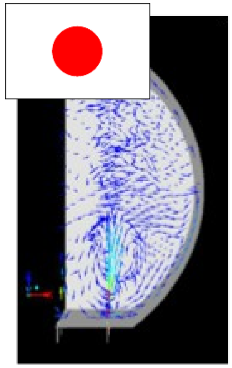
Current T2K systematic errors for oscillations

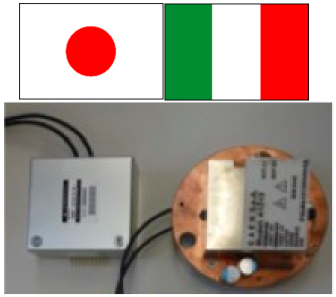
ν_e	Systematic sources(%)	ν_μ
3.1	Flux & Combined Cross-Sections	2.7
4.7	Independent Cross Sections	5.0
2.4	Pi Hadronic Interactions (FSI)	3.0
2.7	SK Detector Efficiencies	4.0
6.8	**TOTAL**	**7.6**



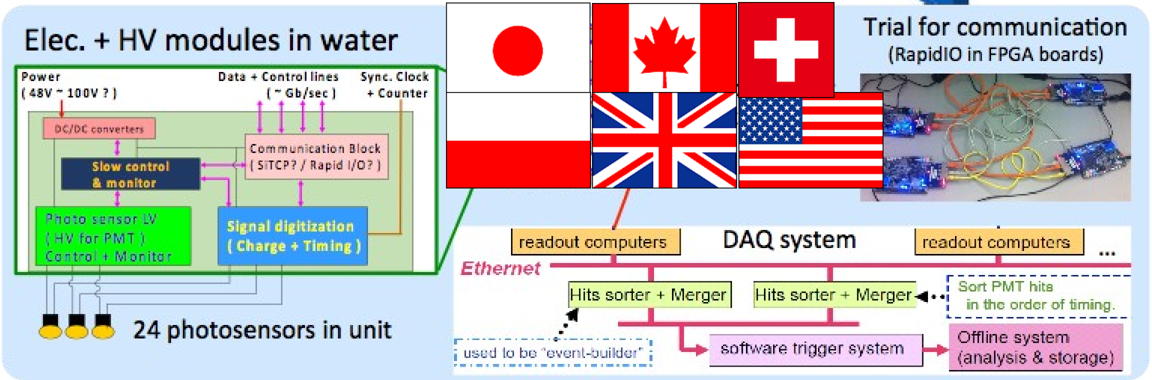
World-wide R&D

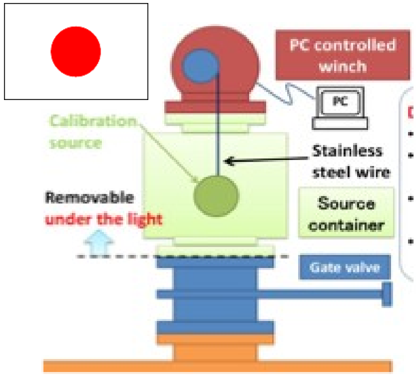






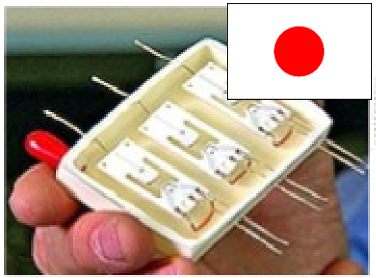
CERN
Neutrino
platform



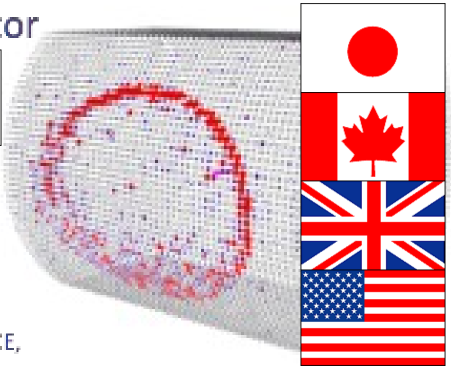


LED

Compact neutron generator



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

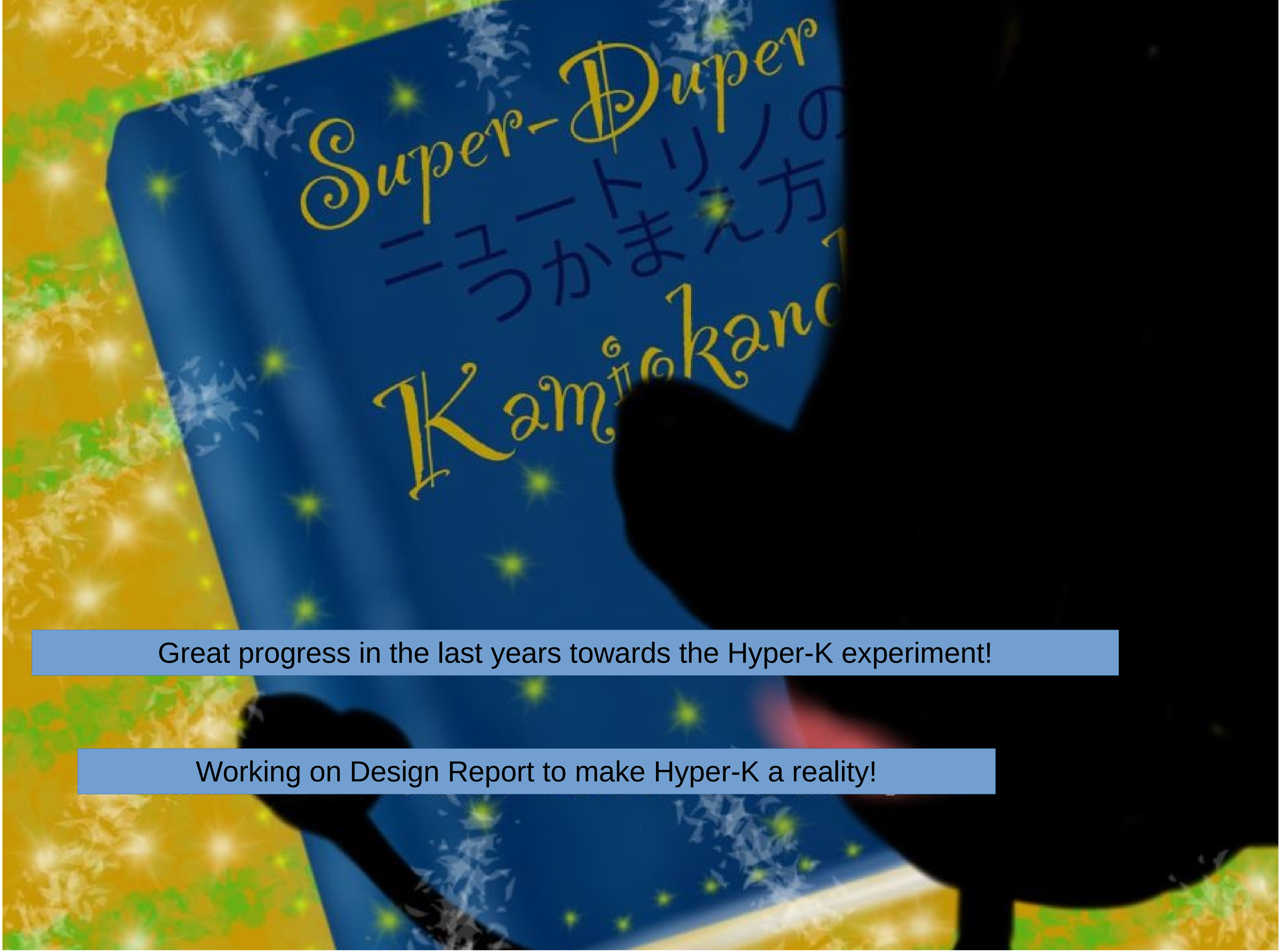


Intense R&D world wide, but large number of things to do.
Open to new collaborators.

Conclusions

- 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}
  - Proton decay discovery potential for $10^{34\text{-}35}$ y.
  - Astro and other physics:
    - very sensitive to supernovas burst and relic supernova neutrinos, indirect dark matter, transient astrophysical phenomena, etc.

- Data taking around 2025 with current schedule
- Work ongoing worldwide in all the aspects of the experiment
- Boost promoting the project
  - International proto-collaboration has been formed
  - Cooperation with KEK-IPNS/ICRR to develop the project
  - Design Report to be prepared in 2015



Great progress in the last years towards the Hyper-K experiment!

Working on Design Report to make Hyper-K a reality!

Additional Slides

J-PARC long-term plan

Several ideas under discussion, towards multi-MW facility

Rapid Cycling Synchrotron (RCS) energy increase to reduce space charge effect

- ➔ ~1.5MW

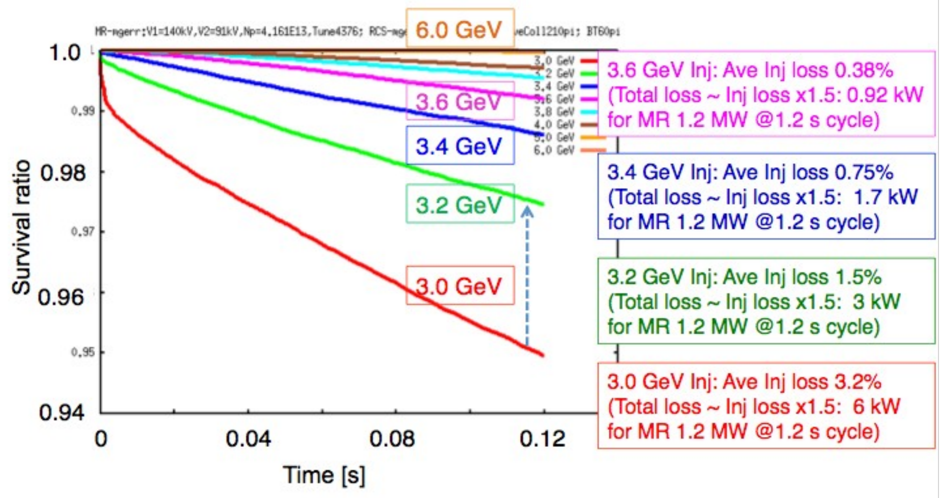
New Booster Ring (8GeV) between RCS & slow-cycling main ring synchrotron (MR)

- ➔ >2MW

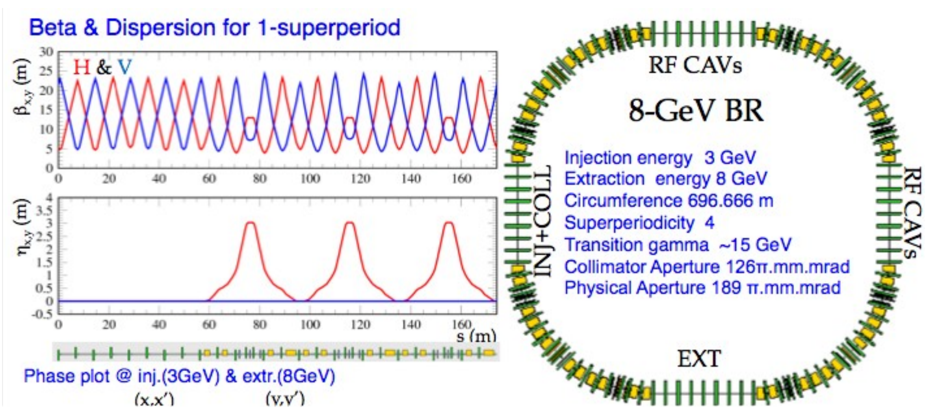
New Super-Conducting (SC) proton linac for neutrino beam (conceptual study)

- ➔ ~9MW linac with >9GeV energy

Using KEKB tunnel at Tsukuba?



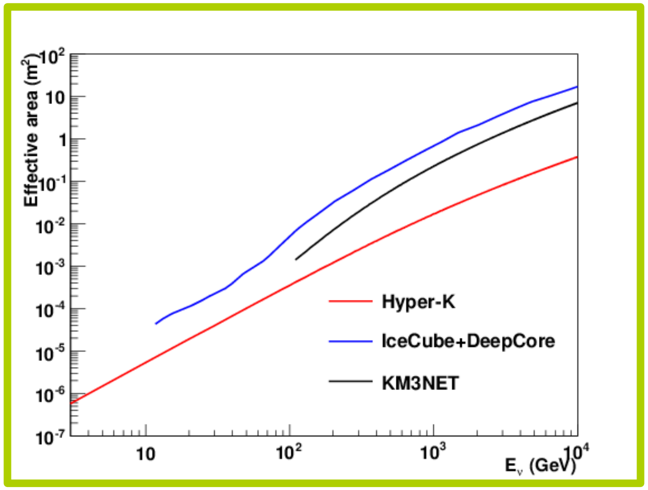
8GeV booster ring

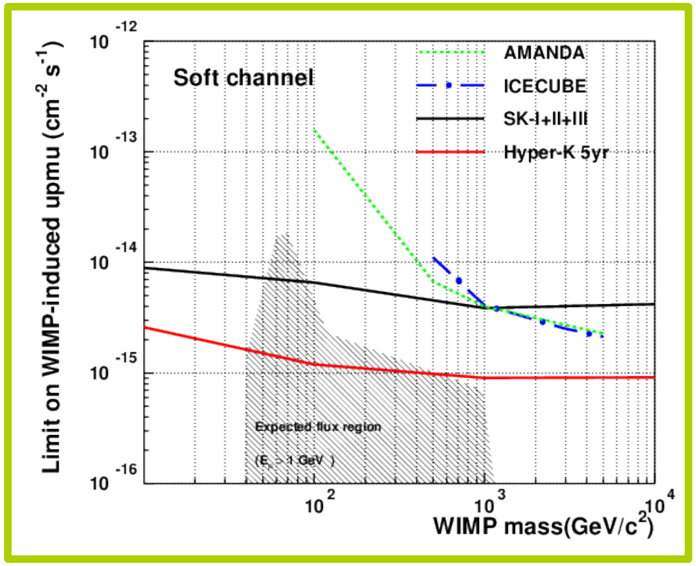


'Other' Physics Topics at Hyper-K, Cont'ed

arXiv:1109.3262

- 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.





Limits on the WIMP-induced upward-going muon rate as a function of the WIMP mass

- Search for transient astrophysical phenomena: solar flares, GRBs, etc.

- Neutrino geophysics: neutrino radiography w/ atmospheric neutrinos for surveying the internal structure of the Earth.

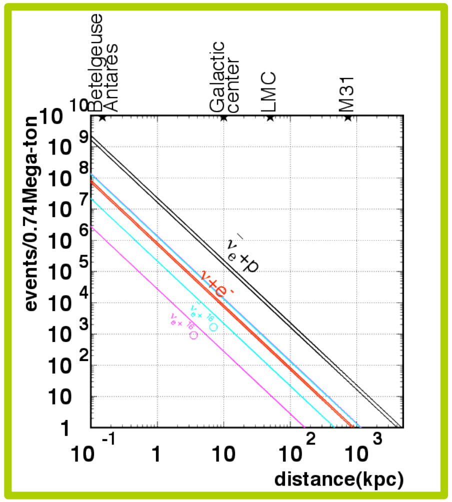
'Other' Physics Topics at Hyper-K

arXiv:1109.3262

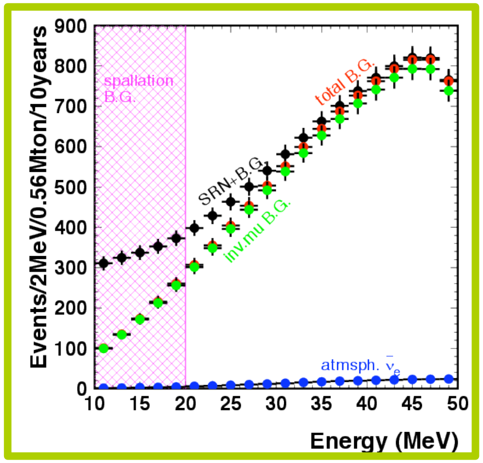
More physics topics can be investigated by Hyper-Kamiokande:

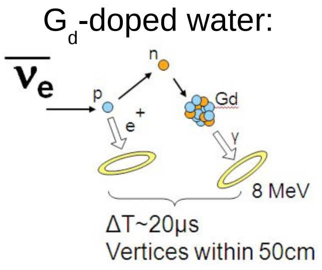
- Solar Neutrinos: ^{8}B 200 ν's / day from Sun → day/night asymmetry of the solar neutrinos flux can be precisely measured at HK (<1%).

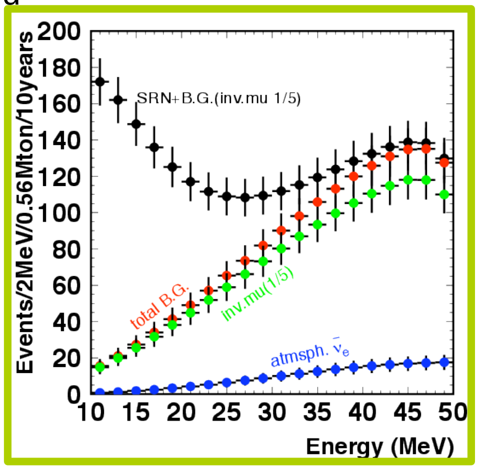
- Astrophysical neutrinos:
  - 200k ν's from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics. Important data to cross check explosion models



- Supernova relic neutrinos → possible G_d-doping of Hyper-K







Upgrade

Plans for upgrade up to 750kW (to be reached during T2K running):

1. LINAC (400 MeV, 25Hz, 50mA peak current)
   - 30 mA peak current now. → upgrade in 2014
2. RCS, Rapid Cycling Synchroton (3 GeV, 25Hz, 1.0 MW)
   - 600 kW operation demonstrated with 180 MeV injection.
   - 300kW stable operation
3. MR, Main Ring (30 GeV, 1.3Hz, 0.75MW)
   - 230 kW achieved with 1.2E14 protons/pulse
   - In 2017, the magnet power supply and high gradient RF core upgrade are planned for 750 kW design.

Futher upgrades:

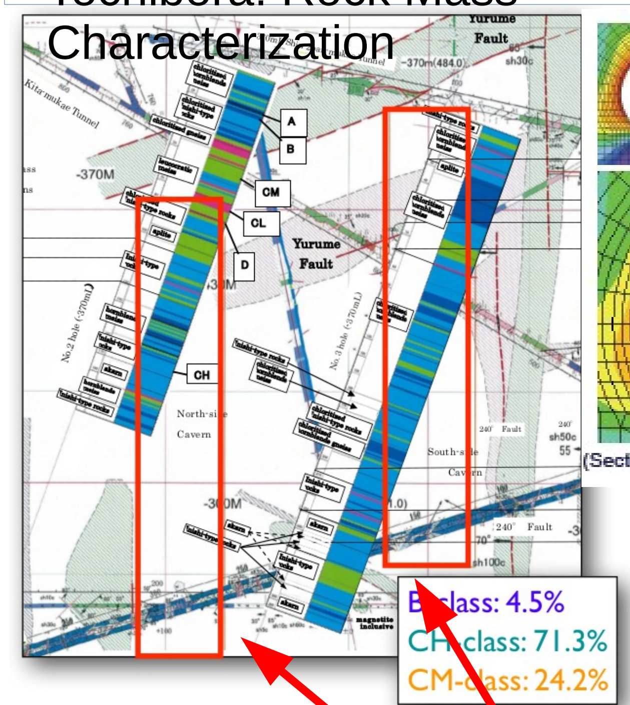
neutrino beam facility can accept up to 3MW

- w/ target/horn/window upgrade
- w/ additional system/blds for handling radio-active waste

Site(s) and Cavern(s), cont'd

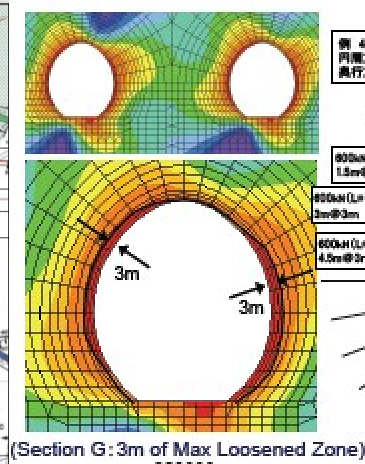
- Rock quality in the two sites is similar.
- Design of the cavity, support structure studies based on geological survey
- Confirmed that the HK cavern can be constructed w/ existing techniques
- Construction schedule for the Tochibora mine: ~2y tunnels, ~3y cavern

Tochibora: Rock Mass Characterization

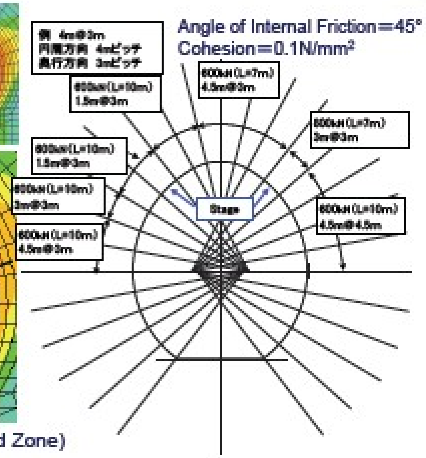


HK tank location

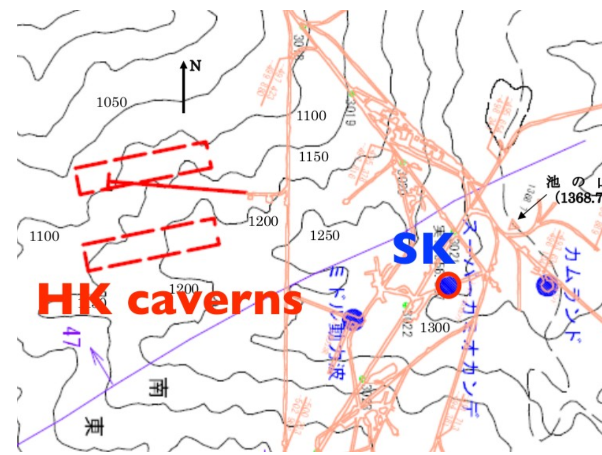
Cavern



Support Structure



Mozumi

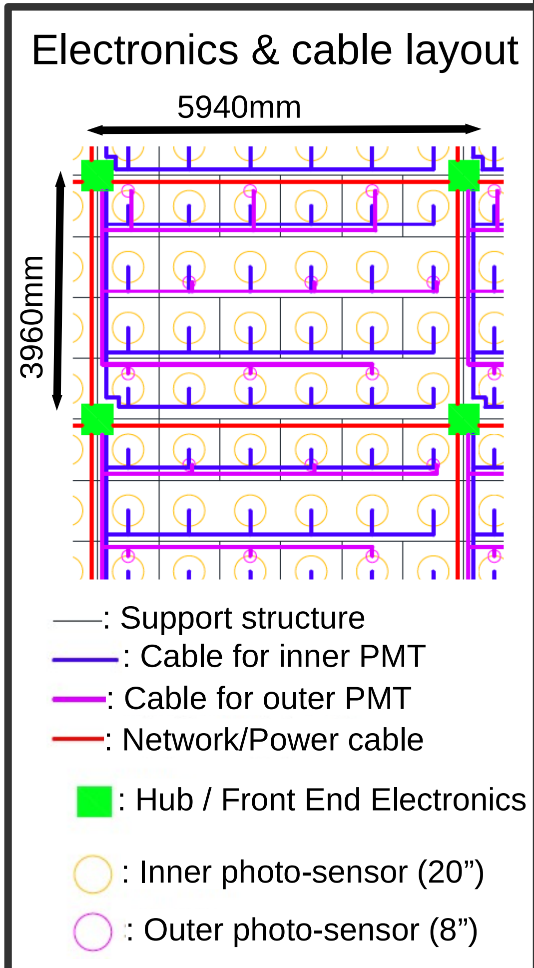


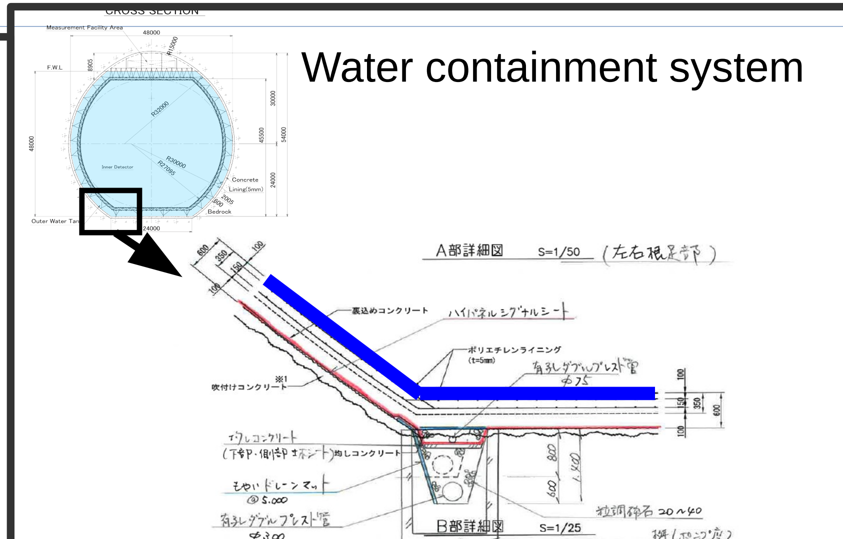
Mozumi:
- geological survey performed in 2013
- cavern stability analyses just completed
- Access and approach-tunnels being designed
- ..

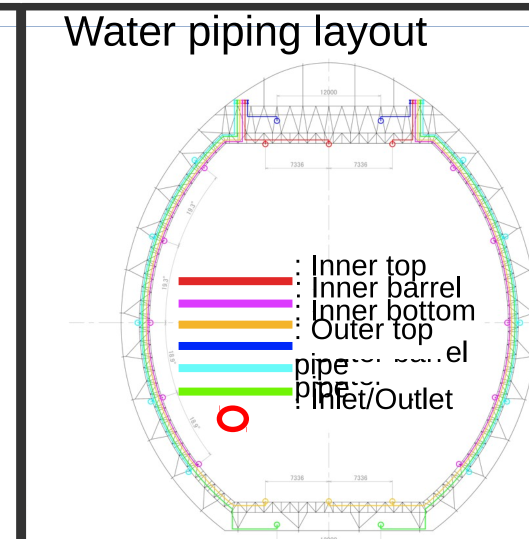
Baseline design expected to finish soon

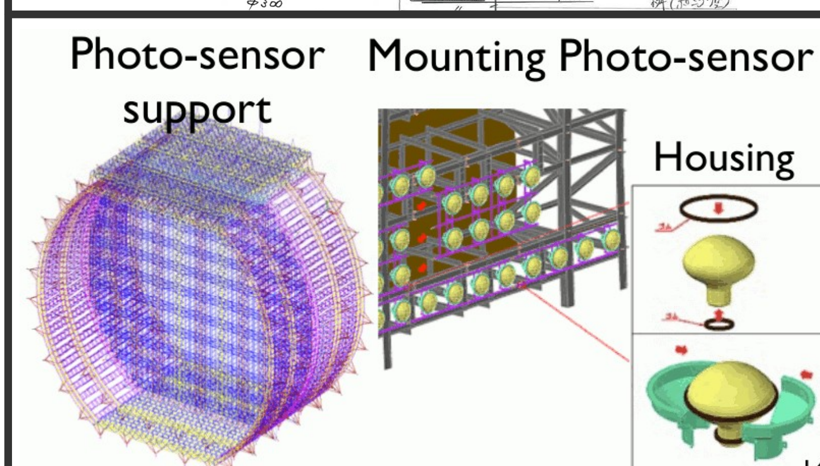
Tank Design Work

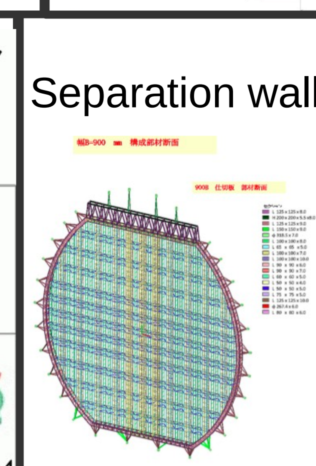
- All major parts of HK tank have been designed: water containment system, photosensors support, layout of water pipes, front-end electronics, cables, calibration holes, plug manholes, etc.



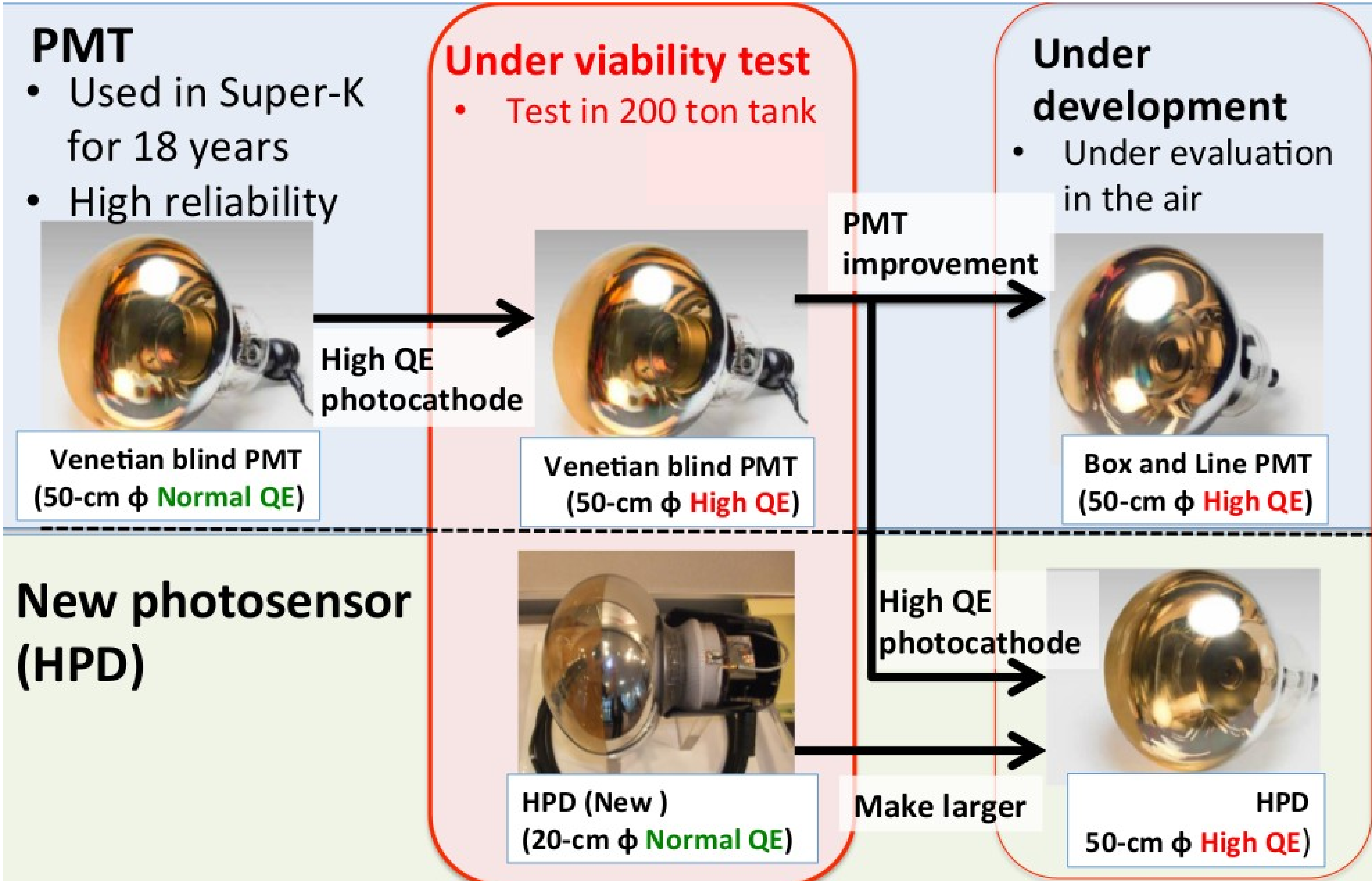








Photodector Development



Photodector Development

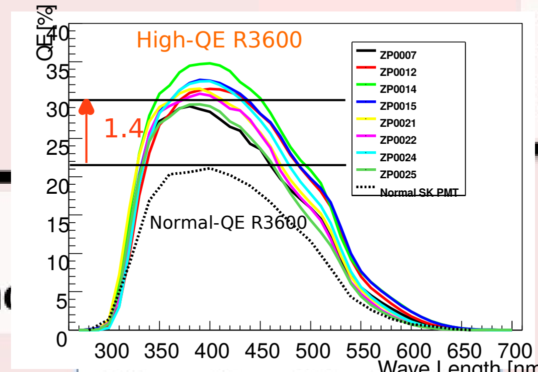
PMT
- Used in Super-K for 18 years
- High reliability

High QE photocath

Venetian blind PMT
(50-cm ϕ Normal QE)

Under viability test
- Test in 200 ton tank

High-QE SK PMT



Venetian blind PMT
(50-cm ϕ High QE)

PMT improvement

Under development
- Under evaluation in the air

Box and Line PMT
(50-cm ϕ High QE)

New photosensor (HPD)

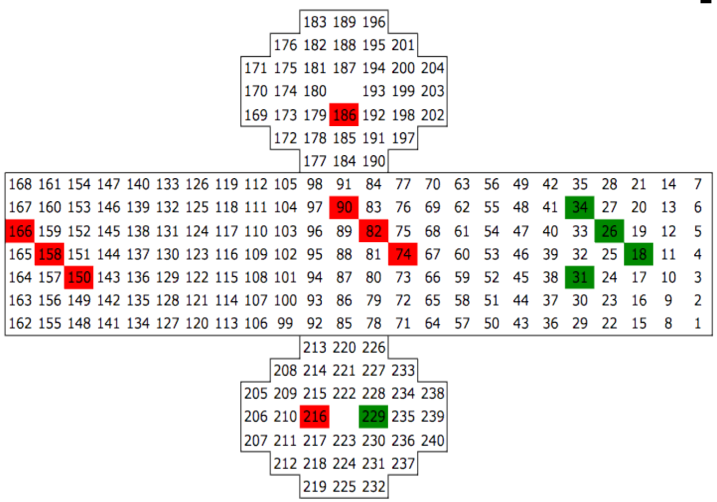
HPD (New)
(20-cm ϕ Normal QE)

High QE photocathode

Make larger

HPD
50-cm ϕ High QE)

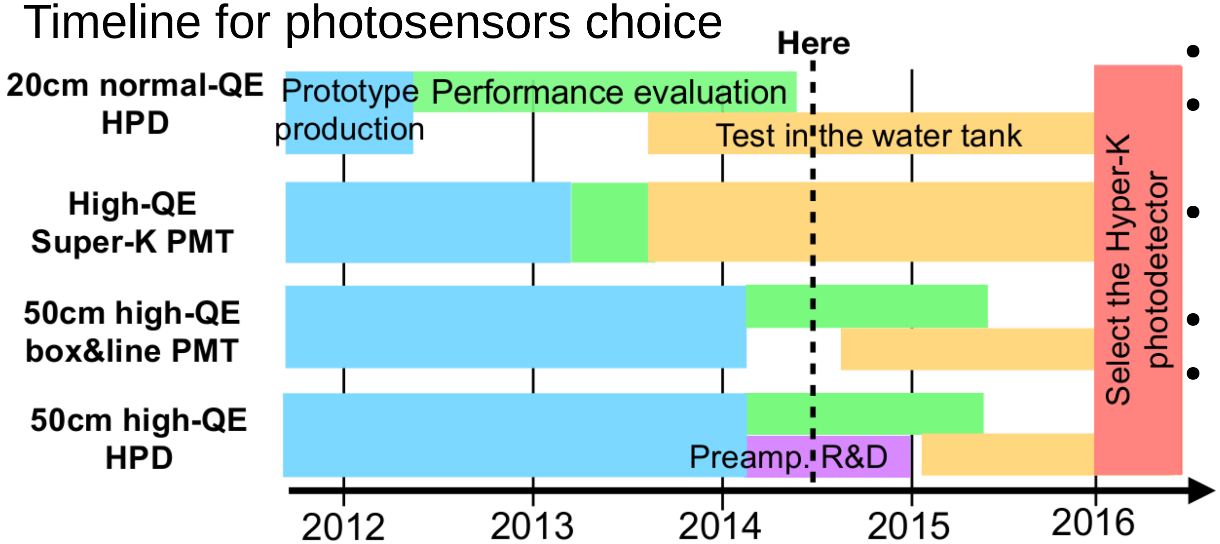
Photosensors Tests in Water Tank



8″ HPDs
20″ high-QE PMTs

- EGADS (for G_d-doped water tests)
- 240 inward-facing PMTs
- EGADS used to test high-QE PMTs
- 227 PMTs (R3600; currently in SK) for reference for photo-detector evaluation
- 8" HPDs, 20" high-QE PMTs

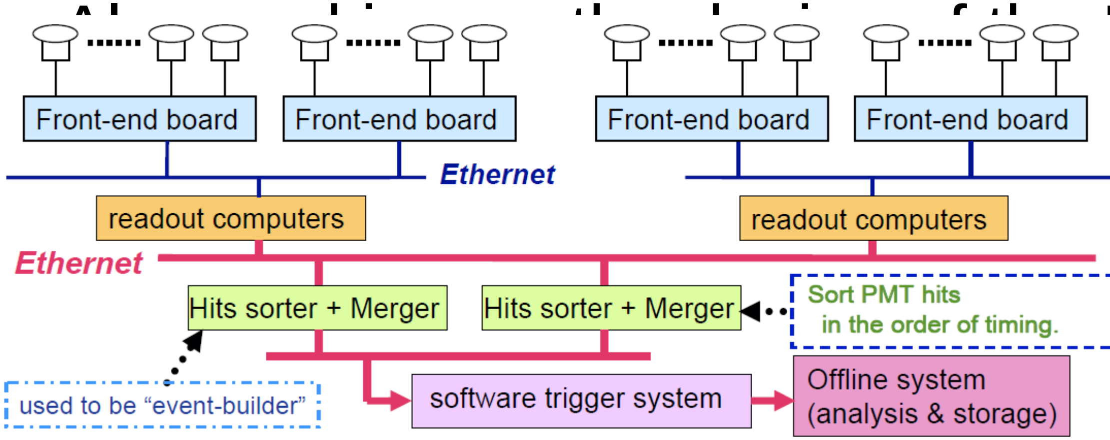
Timeline for photosensors choice



- **Data taking: Sept 2013, May 2014**
- Viability tests performed – ongoing process up to 2016.
- Adding (Aug 2014) Box-and-Line PMTs and 2 HPD.
- **More tests planned.**
- **Photosensor choice will be made in 2016**, needed to allow time for making mass production

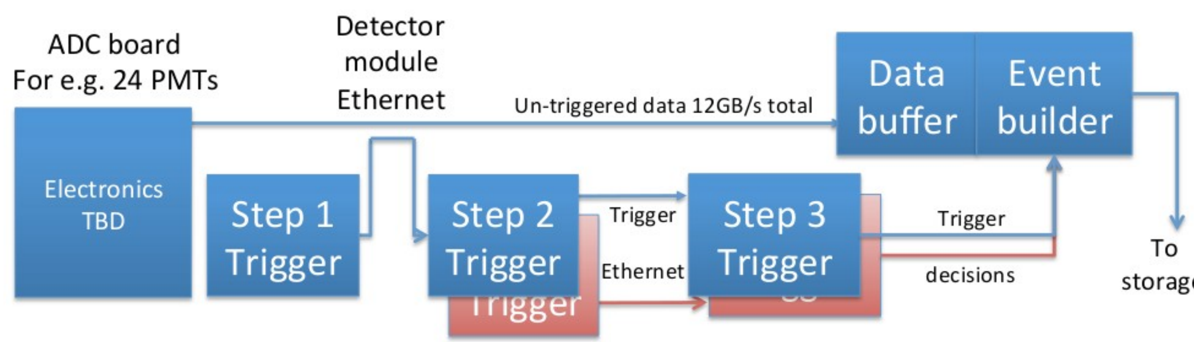
Electronics/DAQ

- Investigating a few approches for the electronics, eg:
  - QTC (ADC) + TDC (similar to SK4)
  - FADC
- Will evaluate their performance with the WC prototype detector
- [illegible] DAQ



- Digitize all the signal (timing and charge) above ~ 1/4 p.e.
- Define events with software and store the event data.
- Nominal starting point: SK DAQ

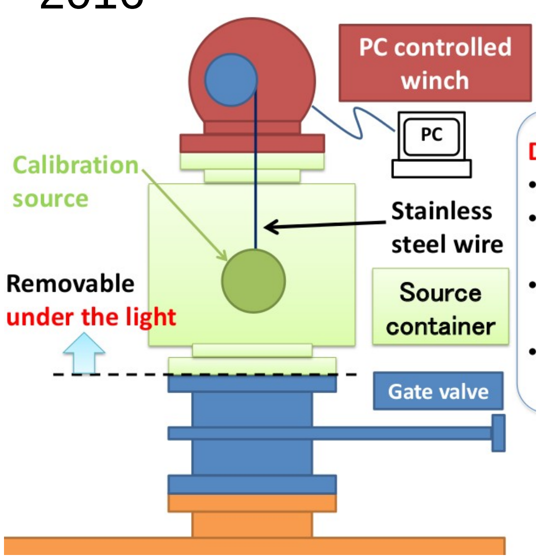
Investigating improved system for triggering (redundant, robust)



Calibration

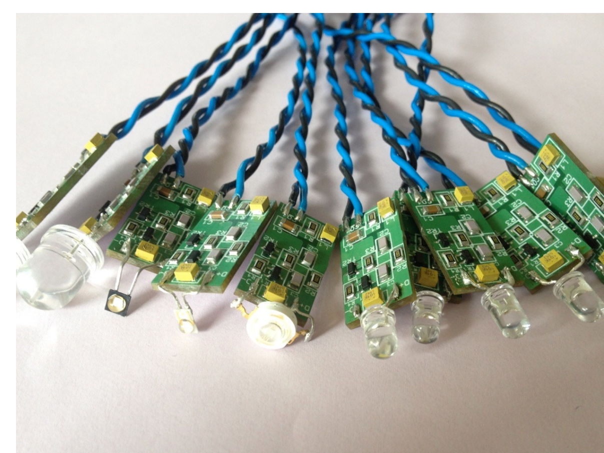
- Review systems used by several experiments (SK, SNO, SNO+, Borexino, KamLAND, Daya Bay) to help in the design of the calibration system for Hyper-K
- Several ongoing R&D activities, some examples:

- 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



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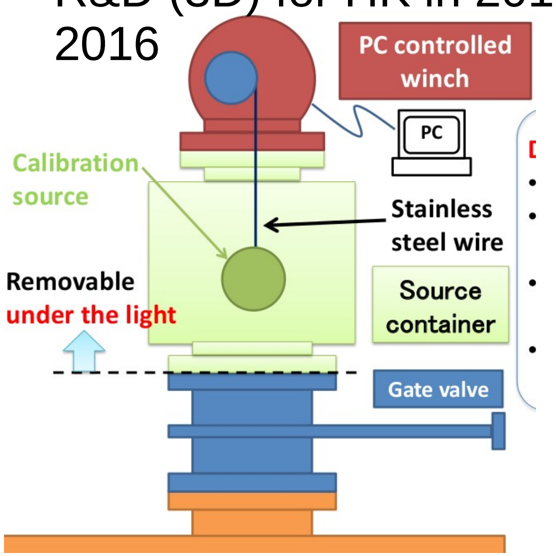

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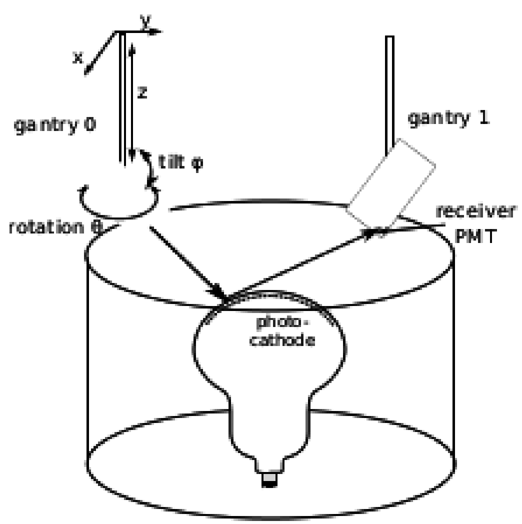

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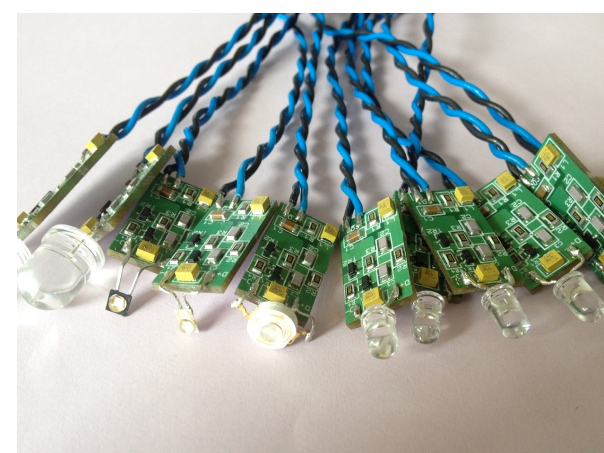


Options at 280m

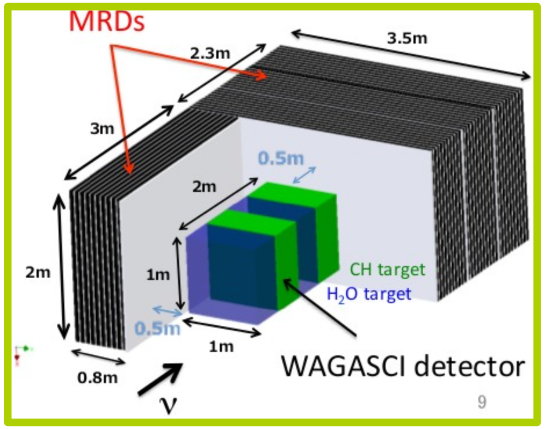
Three options currently envisages for Hyper-K. No final decision made yet on any of the projects. Some options may happen earlier for the T2K upgrade.

1) ND280 improvements:

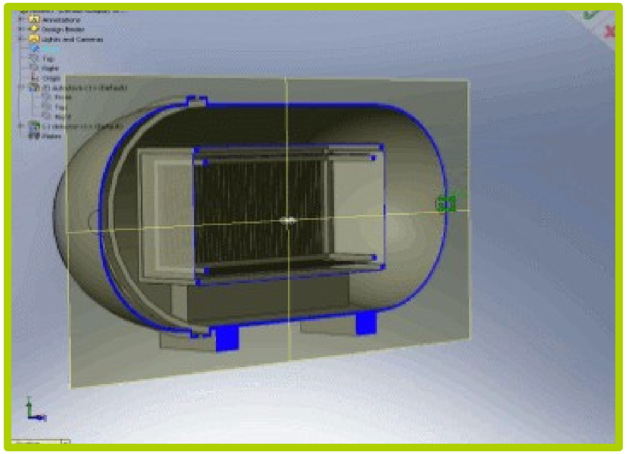
- Replace with D_2O to the FGD2 and P0D water layers. Quasi-free neutron target.
- Replace scintillator with WbLS to measure deposited charge from water/D_2O layers.

2) Add new detectors in the 280m pit:

Water-grid scintillator detector

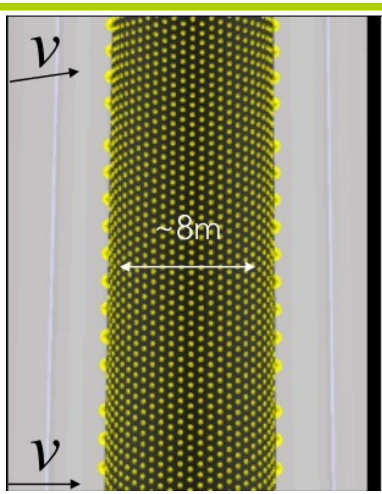


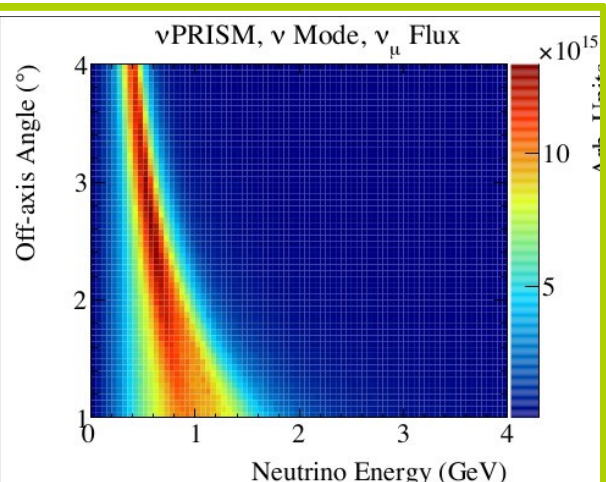
High pressure TPC to study low momentum final state particles and in particular resolve vertex



Intermediate Detector Concepts

3) Build new detectors at 1-2km:



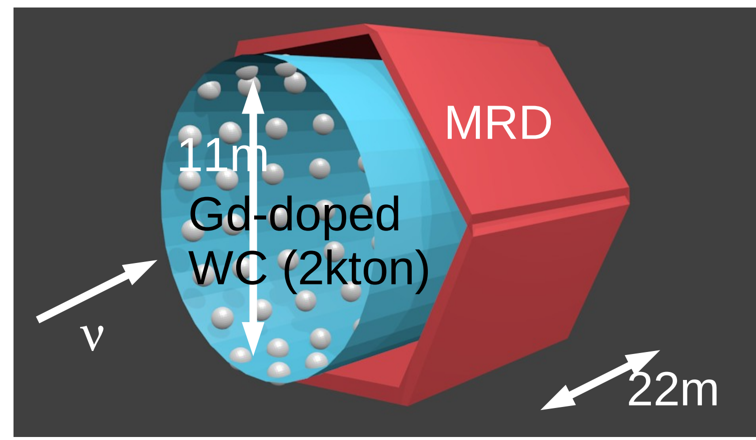


"ν-PRISM" (~1km)

- 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 HPDs and LAPPDs



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