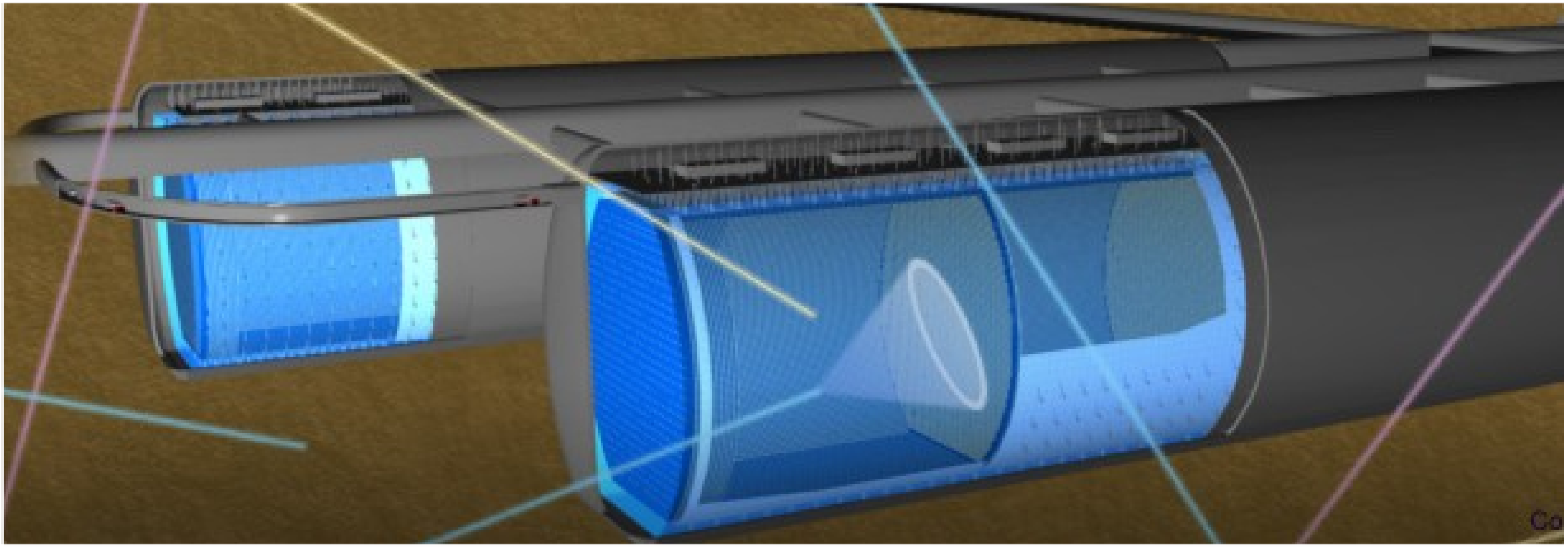
JENNIFER

WP4: Towards Hyper-Kamiokande

Task 4.1: Water Cherenkov Detector



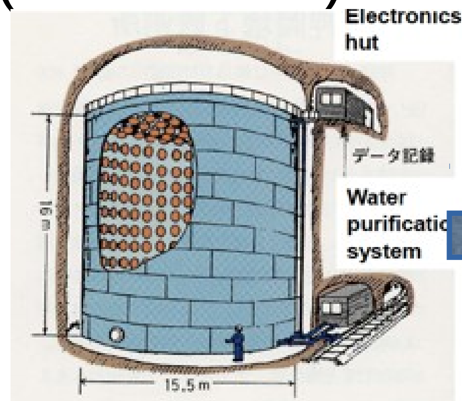
JENNIFER Consortium General Meeting
Rome, 10-12 June 2015

Francesca Di Lodovico
Queen Mary University of London
On behalf of the JENNIFER WP4 members

Kamiokande Evolution

Three generations of large Water Cherenkov in Kamioka

Kamiokande
(1983-1996)

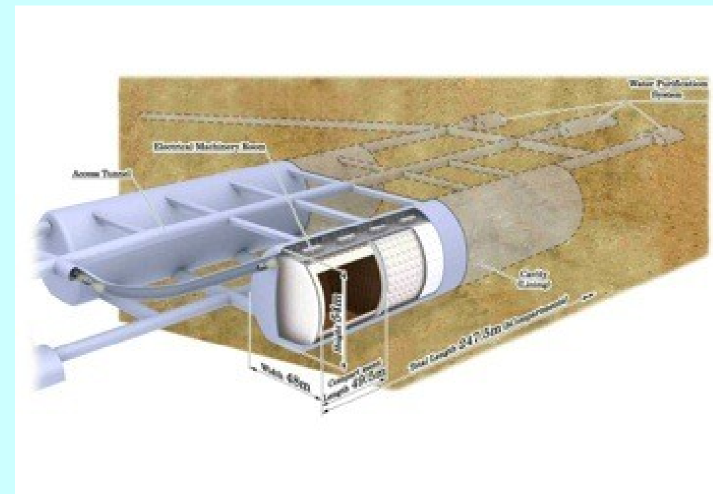


3kton

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)

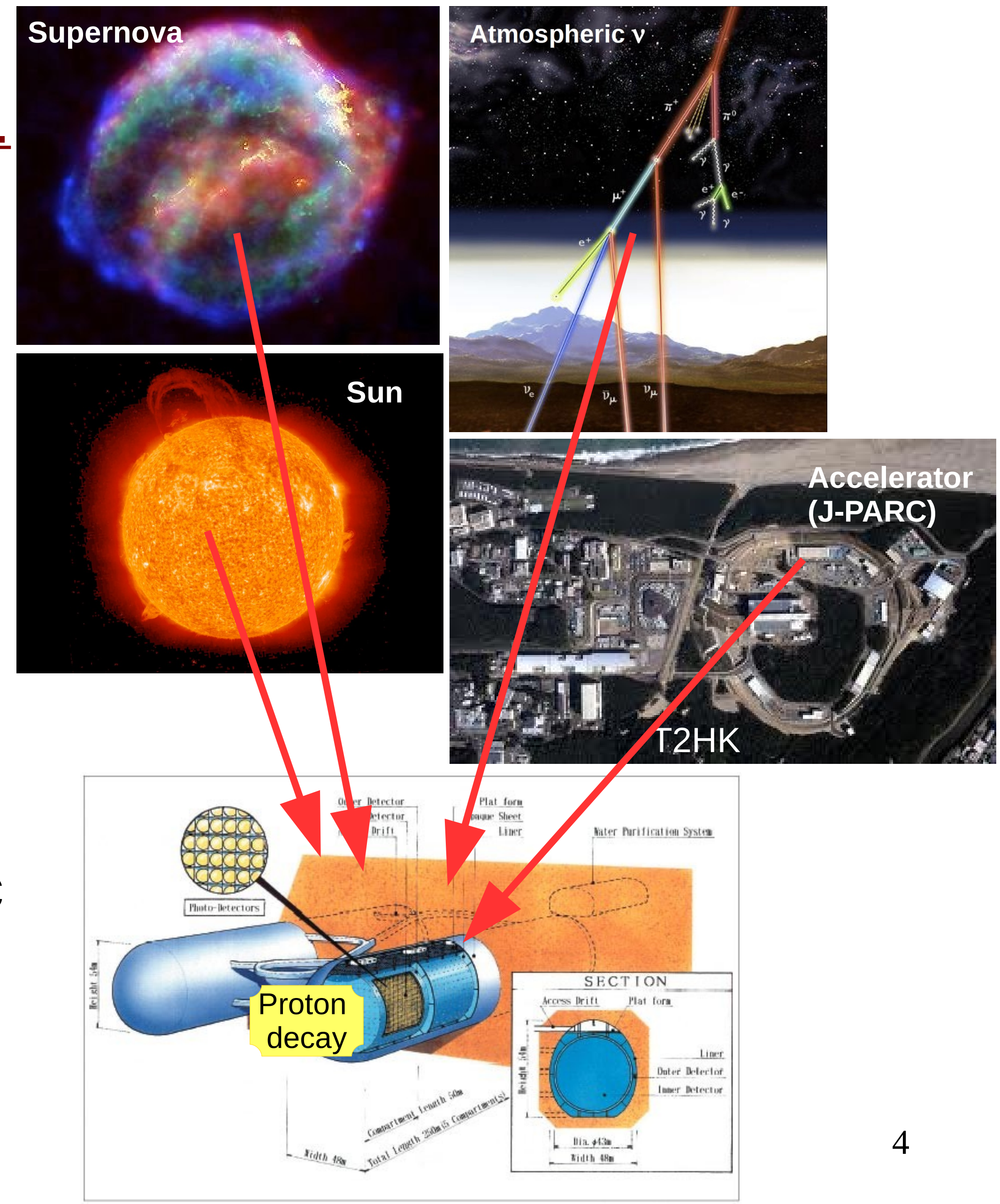
Outline

- Overview
  - Latest updates
- Beam & Atmospheric Physics:
  - Oscillation parameters
- Non-beam Physics:
  - Proton decay
  - Astrophysics
- JENNIFER Task 4.1

The Hyper-Kamiokande 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, …)



Hyper-K Proto-Collaboration

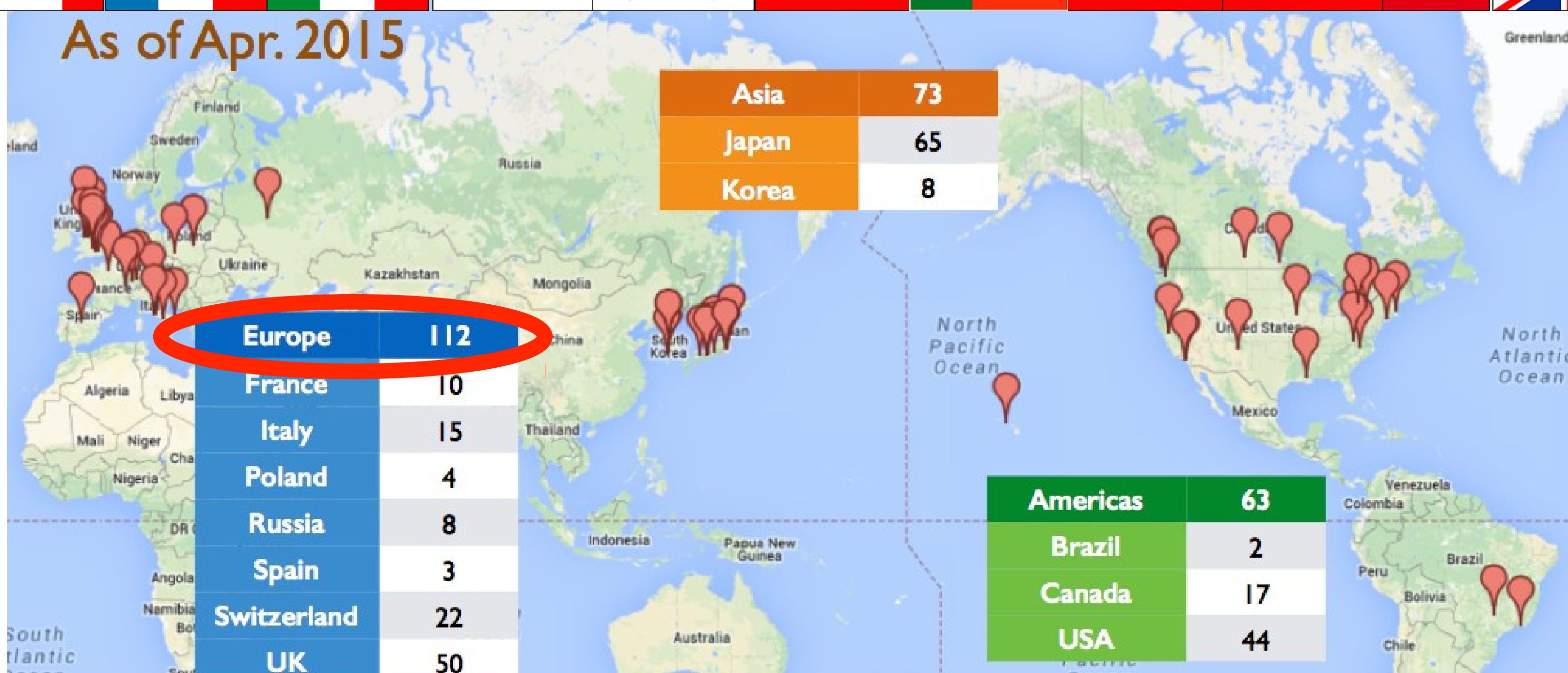
Inaugural Symposium on January 31, 2015

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.



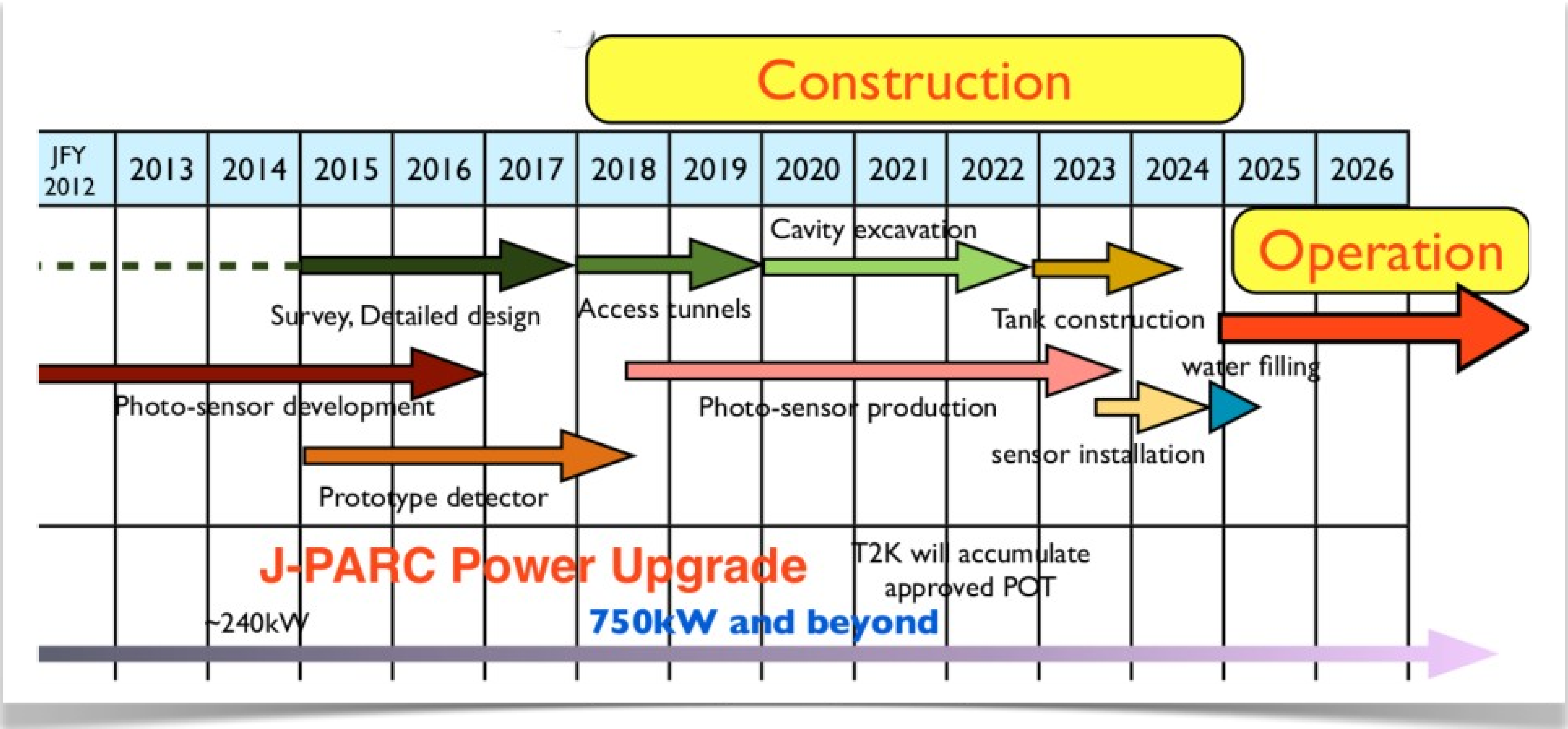
Next Steps

- 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:

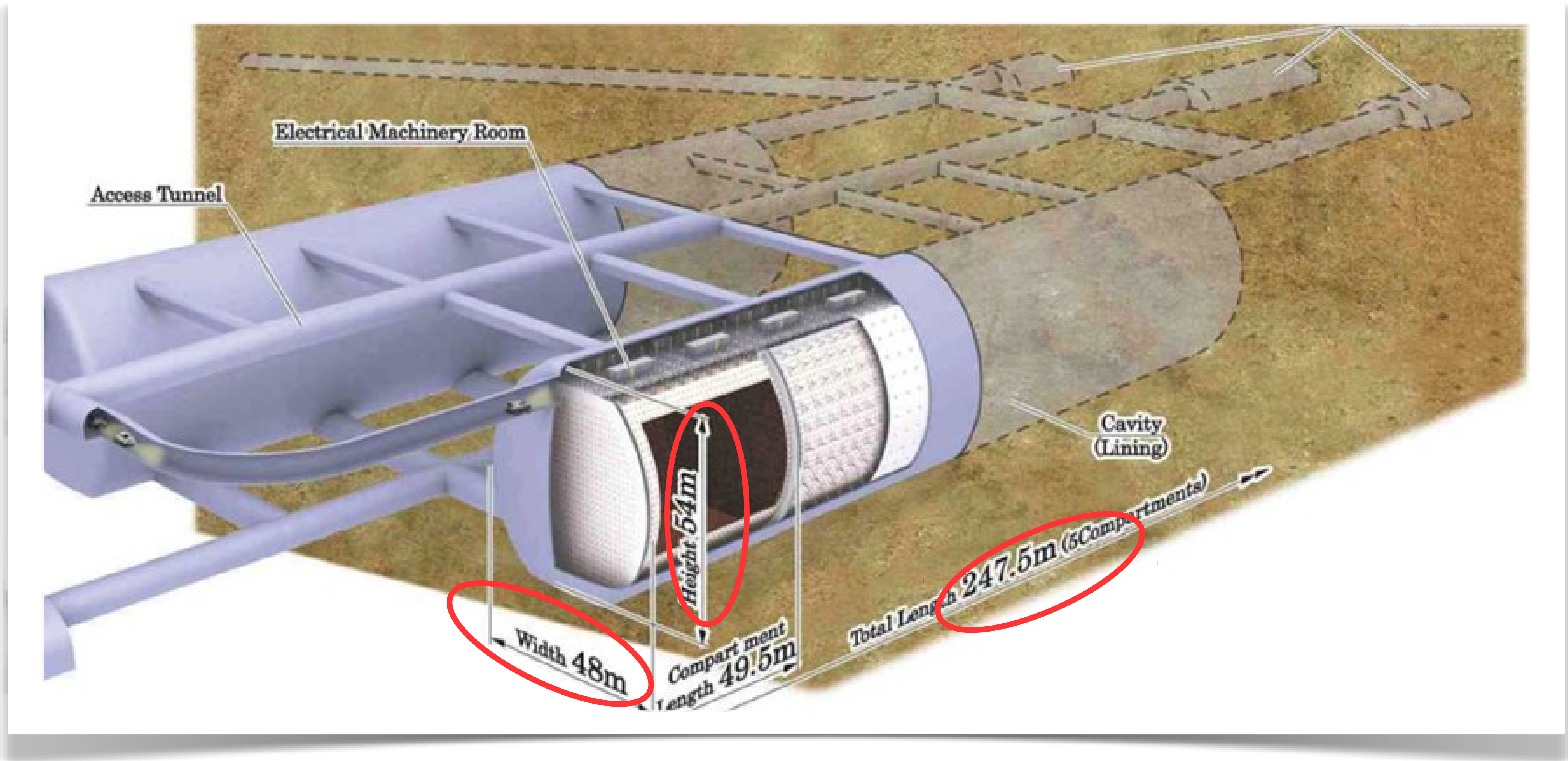
June 29-July 1, @Kashiwa/Japan

The Hyper-Kamiokande Timeline



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

The Hyper-Kamiokande Detector

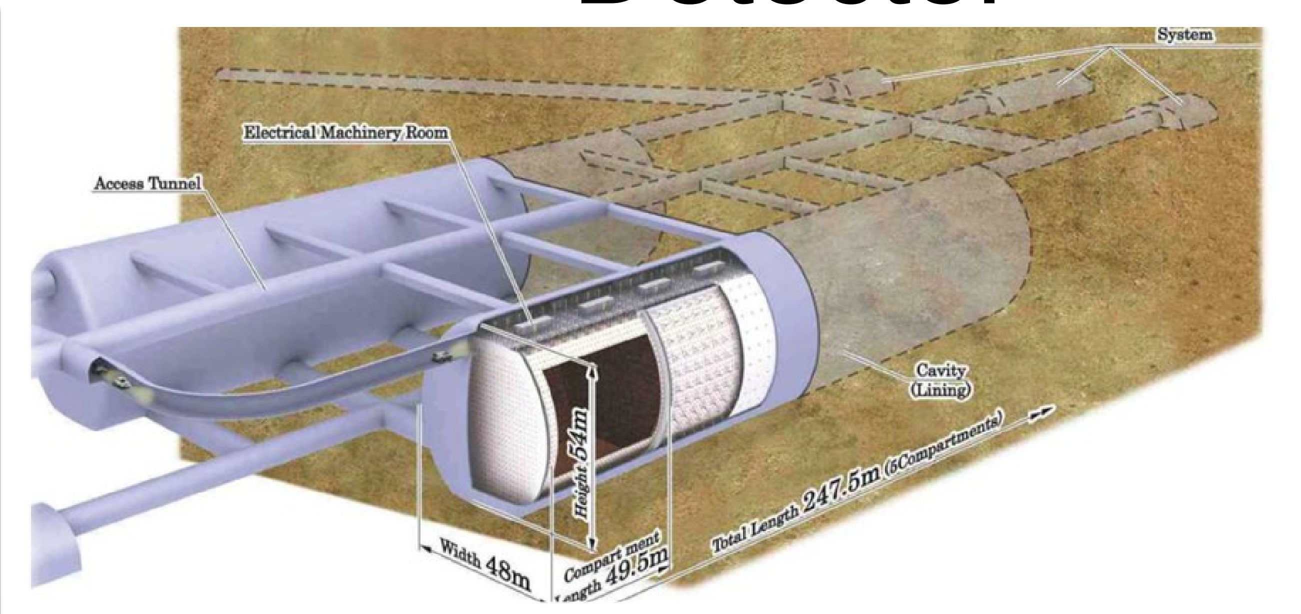


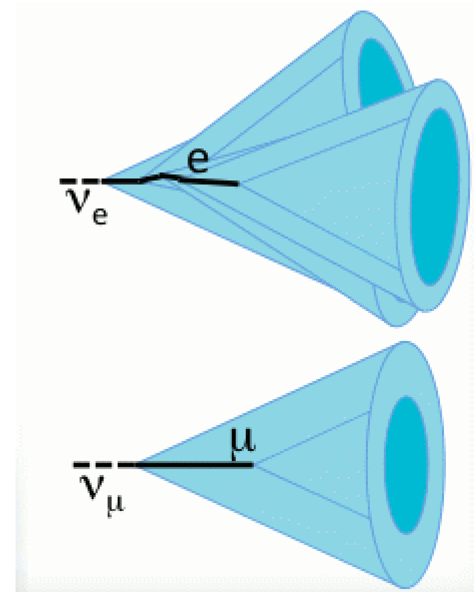
The Hyper-Kamiokande Detector

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

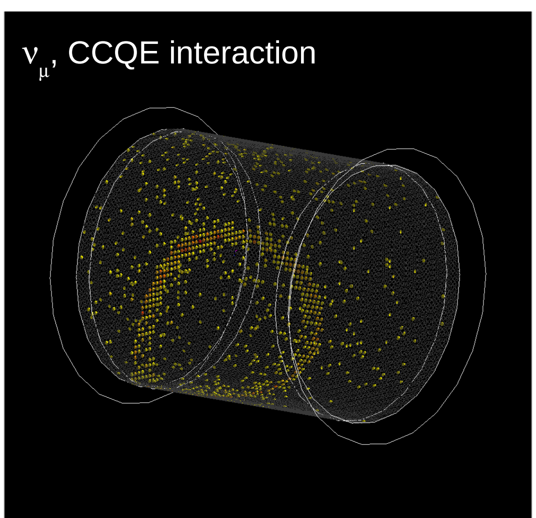
Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	•99,000 20”Φ PMTs for Inner Detector (ID) (20% photo-coverage) •25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	•2 tanks, with egg-shape cross section ≈ 48m (w)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

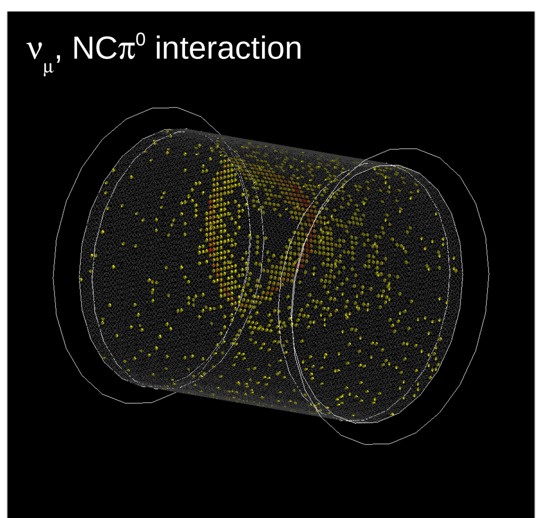
The Hyper-Kamiokande Detector

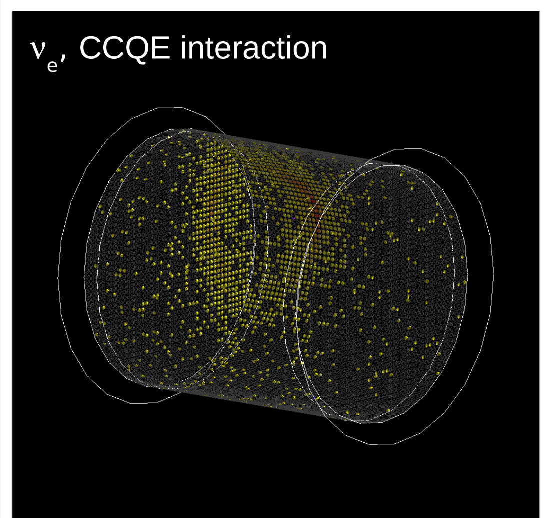




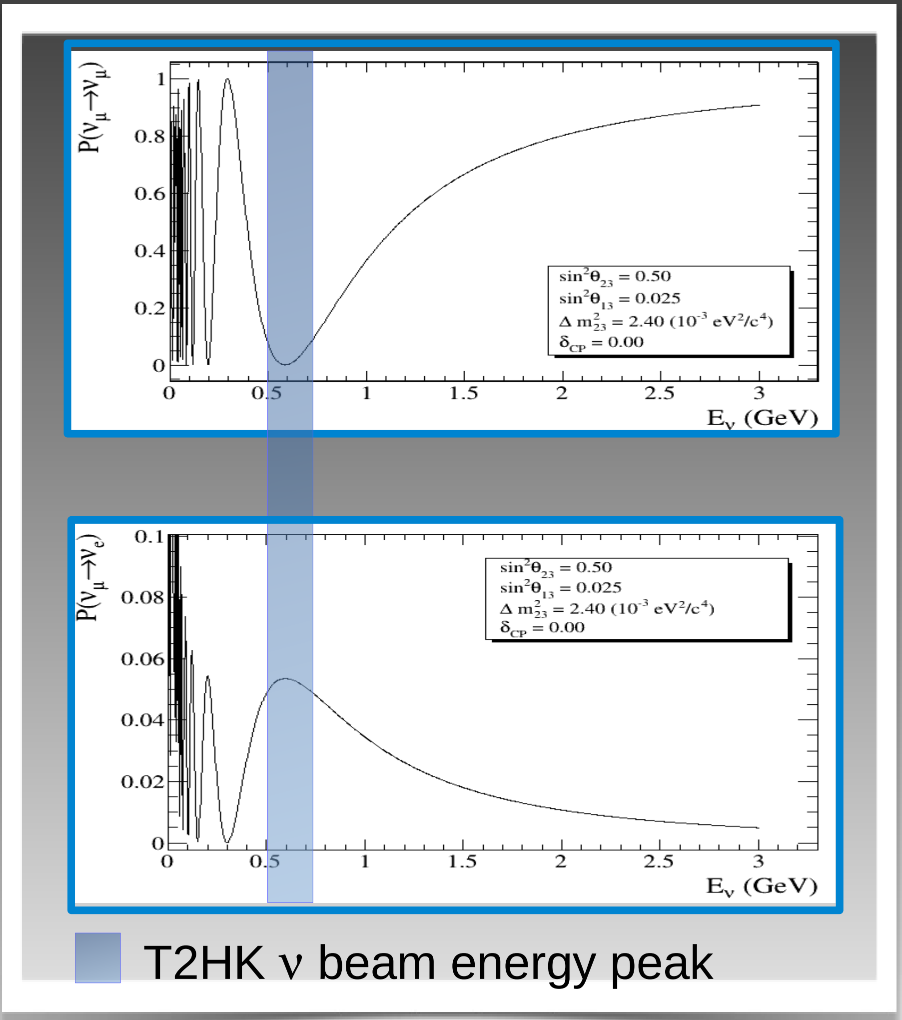
GEANT4 event displays





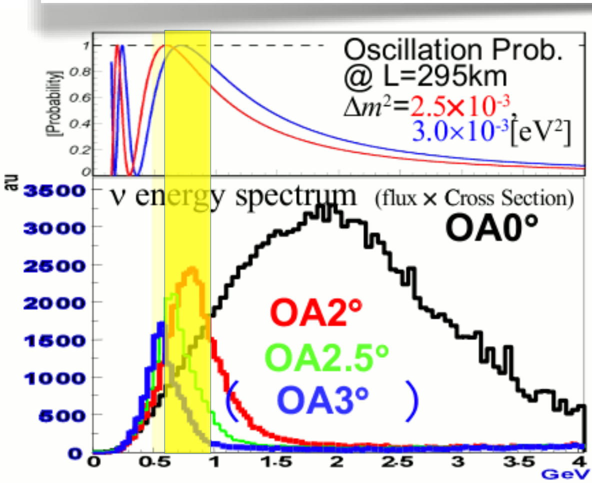


Physics Potential



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

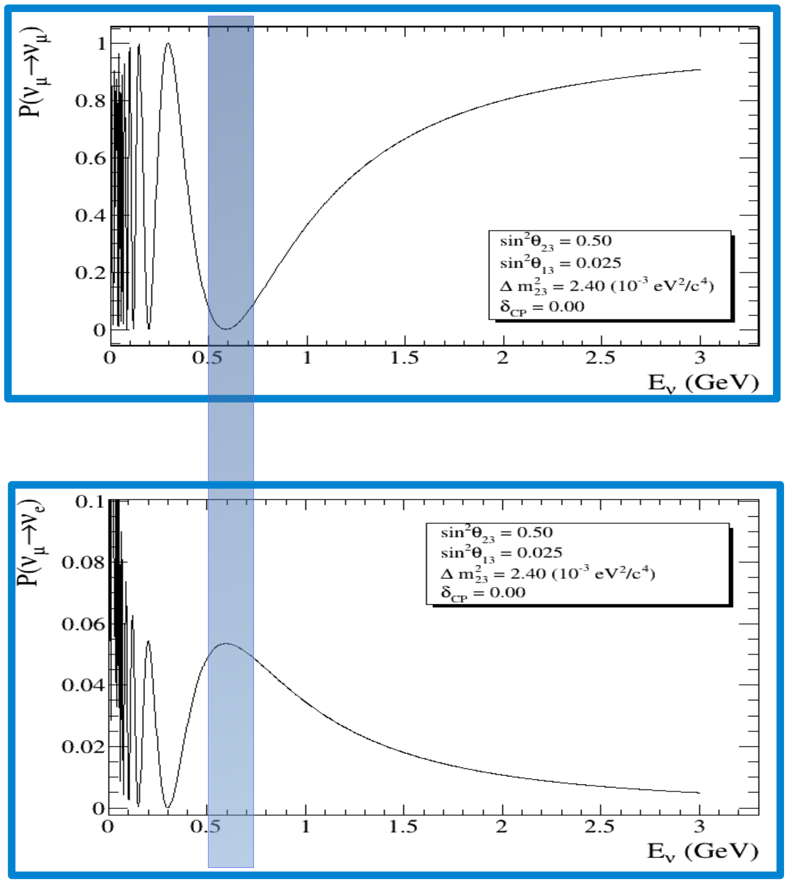
- Narrow-band beam at ~600MeV at 2.5° off-axis

- 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

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

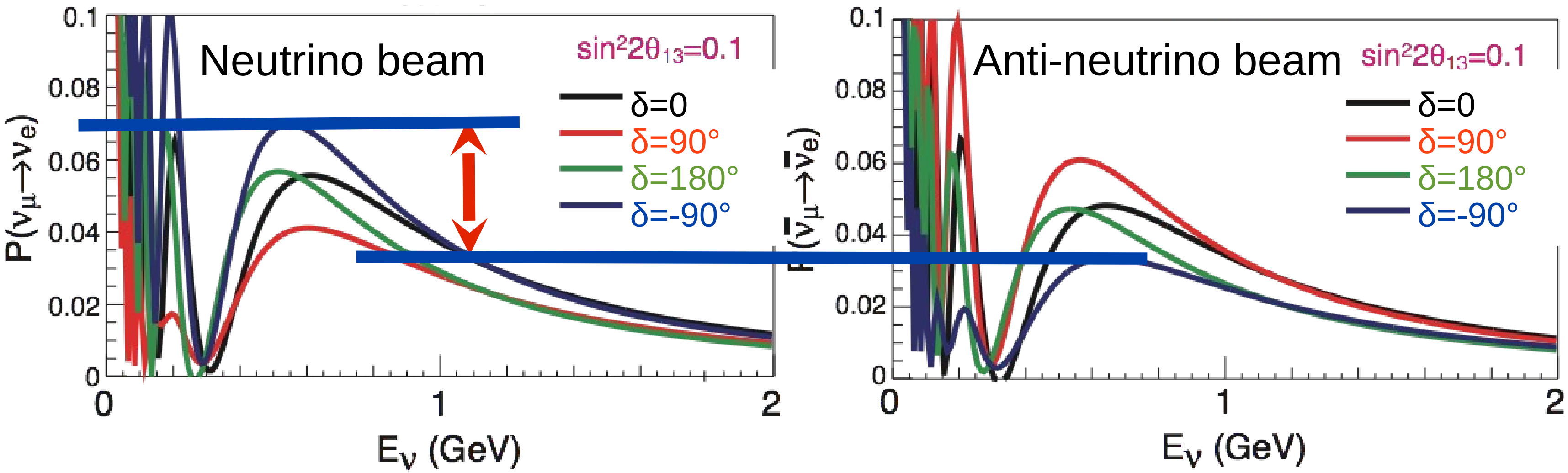
ν_e Appearance: determine θ_{13}, constrain δ_{CP}

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

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

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

L=295km, NH

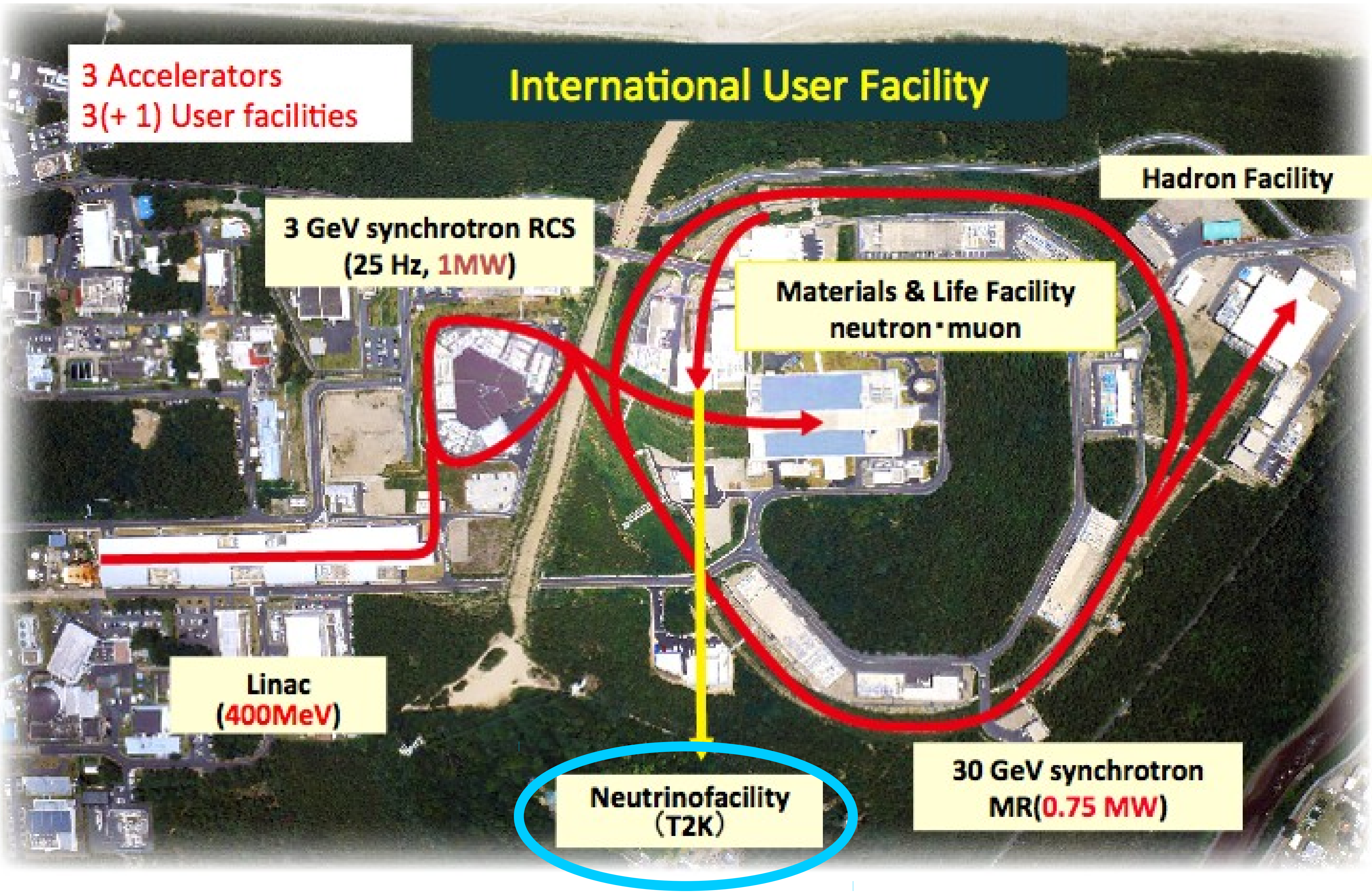


- CP violation will manifest itself in neutrino oscillations:

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

- 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.

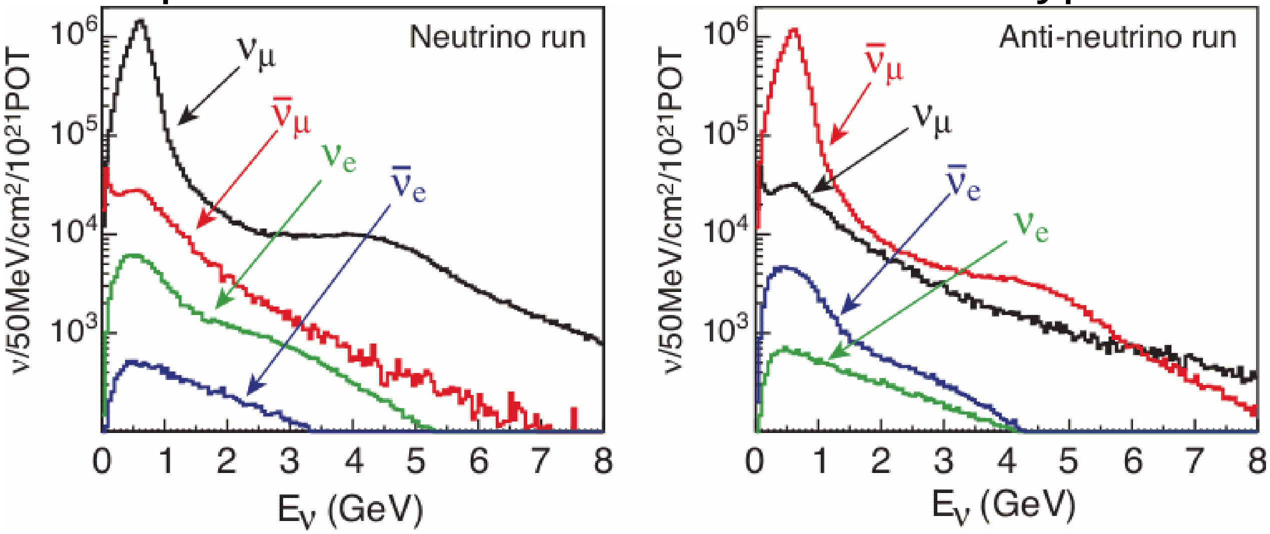
JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 –300 (400)			750
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50			100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D	2.48 s		Manufacture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

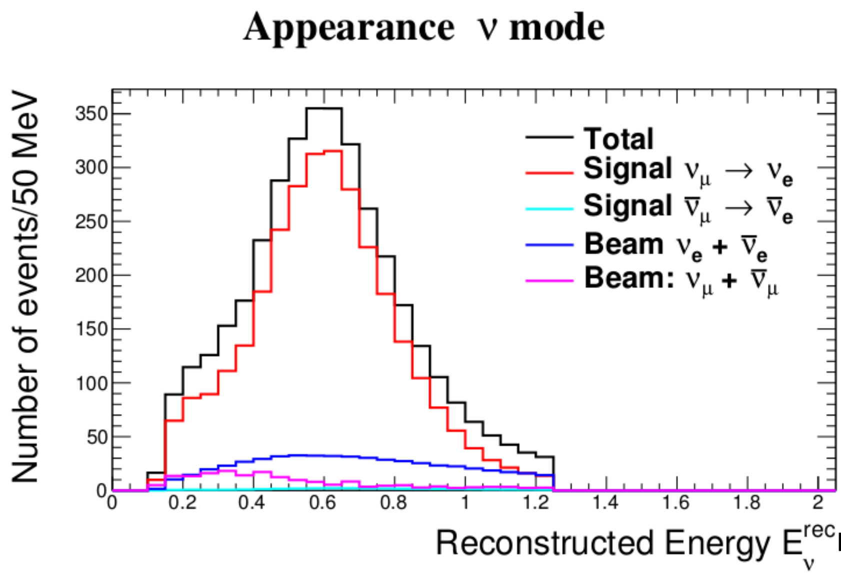


Nominal beam sharing between neutrinos and anti-neutrinos in the following sensitivity plots:

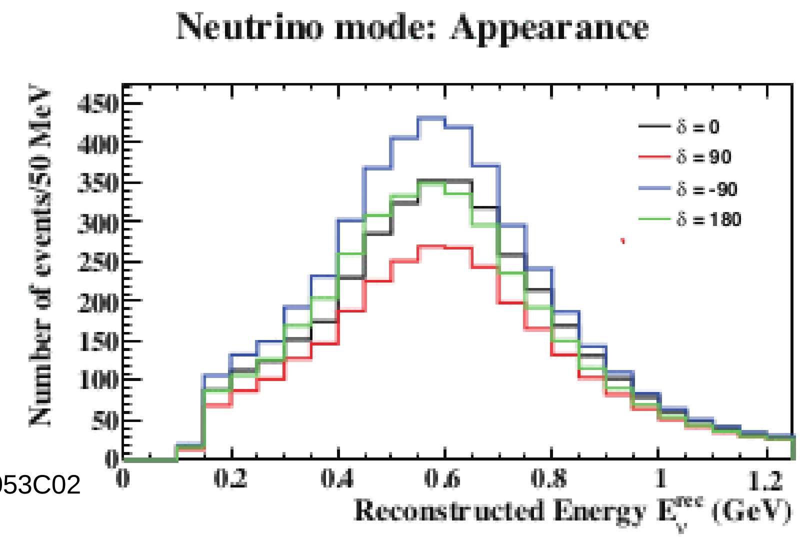
ν-mode: ν̄-mode
1y : 3y

Expected Events

PTEP 2015 053C02



PTEP 2015 053C02



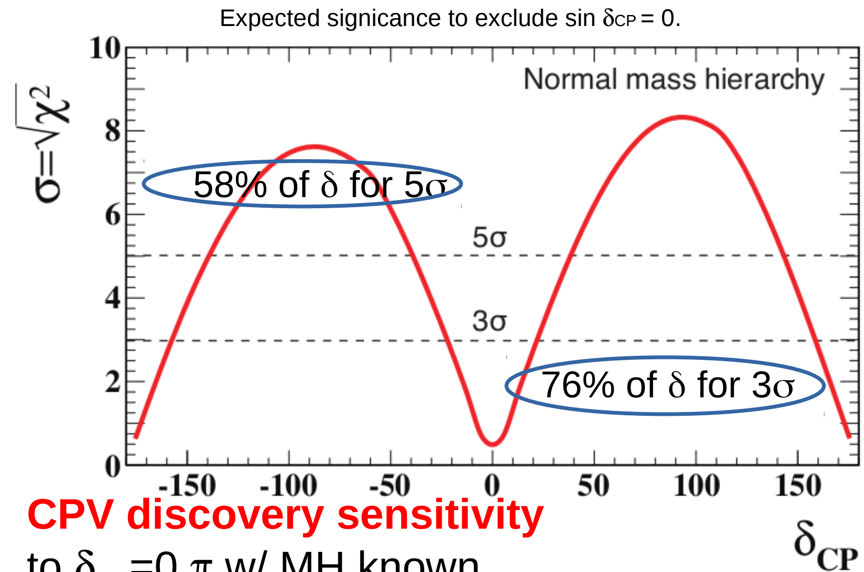
Appearance	Signal		Background					Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	265	265	3397

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 $\delta_{CP} = 0$

PTEP 2015 053C02

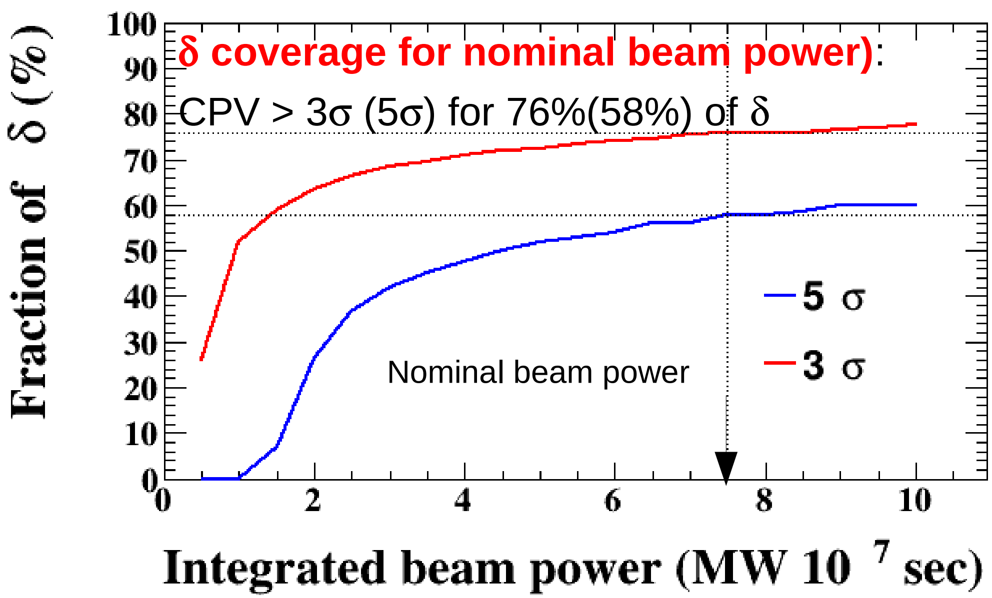
Hyper-K Sensitivity to δ_{CP}



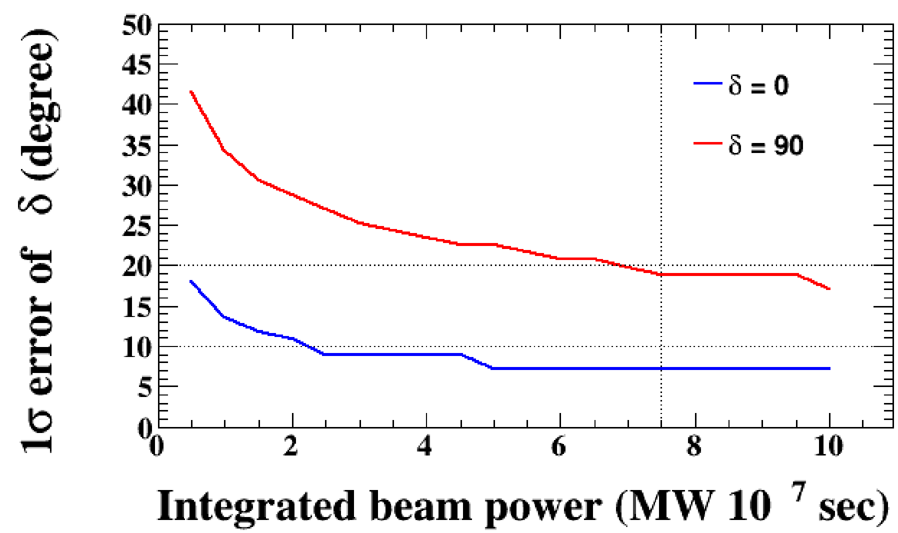
CPV discovery sensitivity
to δ_{CP}=0,π w/ MH known

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°)

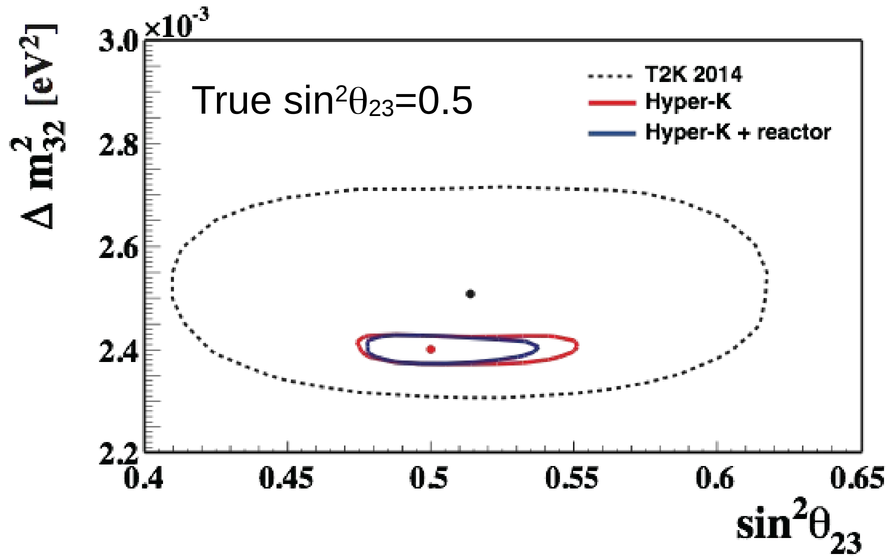


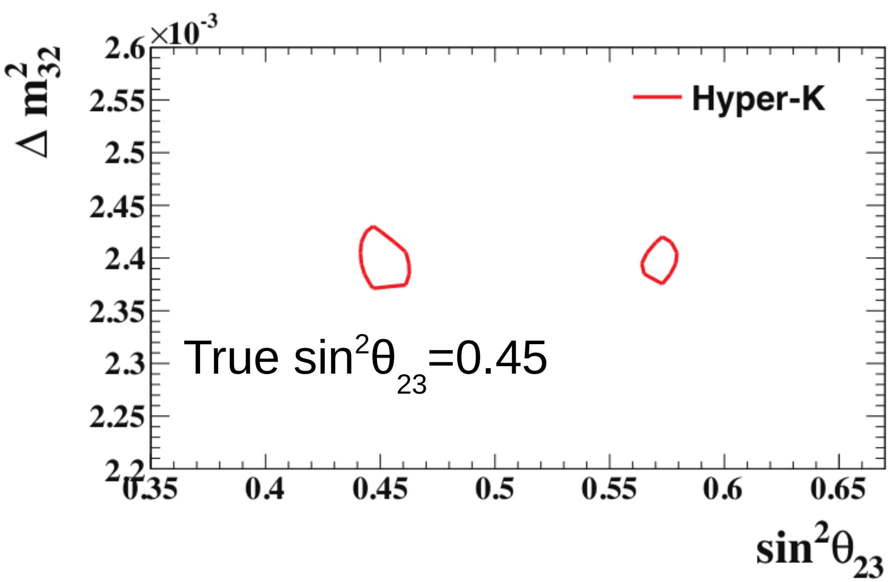
PTEP 2015 053C02

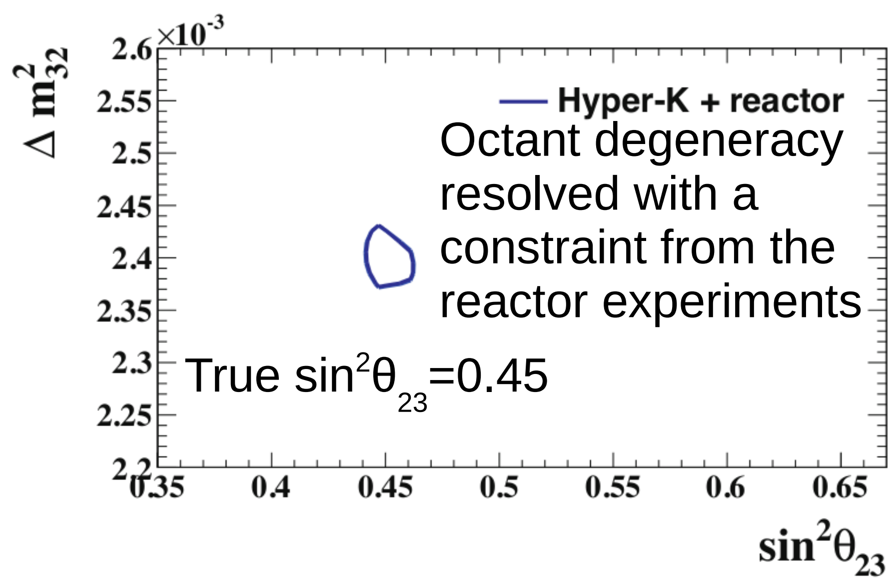
Sensitivity to θ_{23}

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



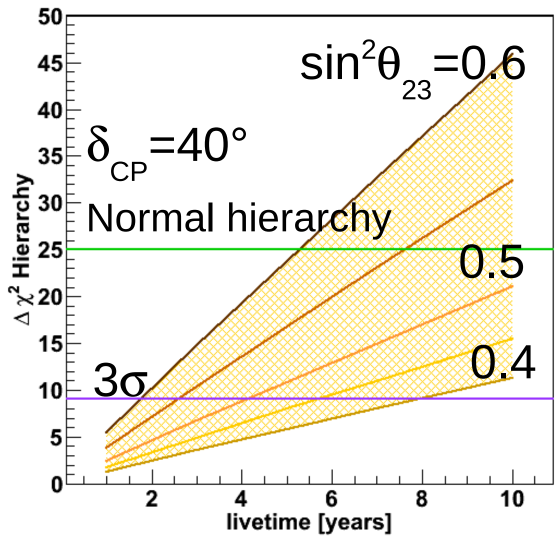


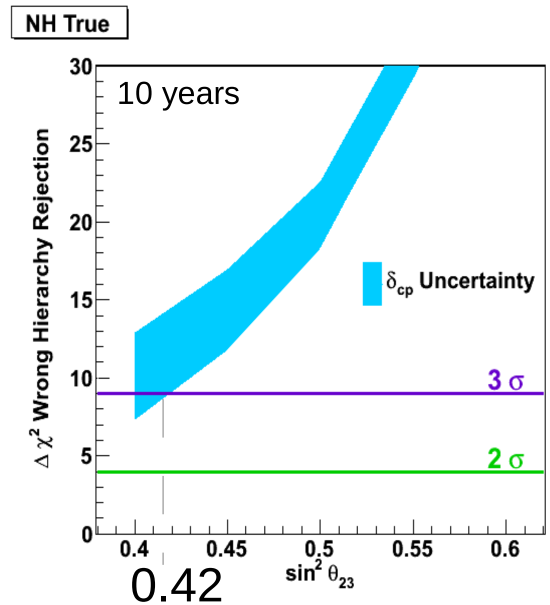


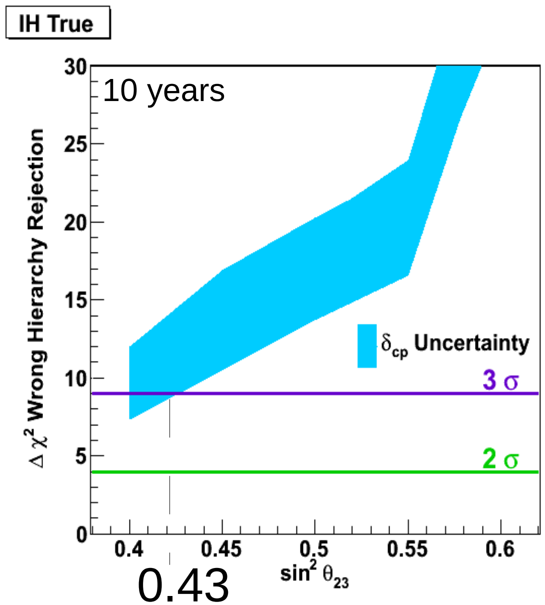
PTEP 2015 053C02

Hyper-K Sensitivity to MH

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





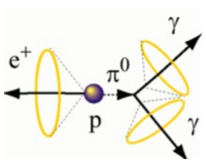


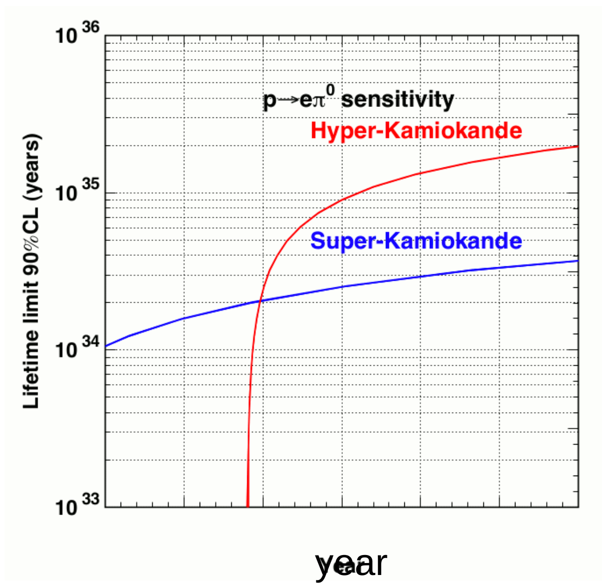
- Use atmospherics for 3σ mass hierarchy determination.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.

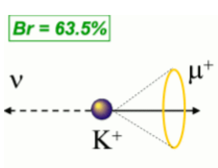
arXiv:1109.3262

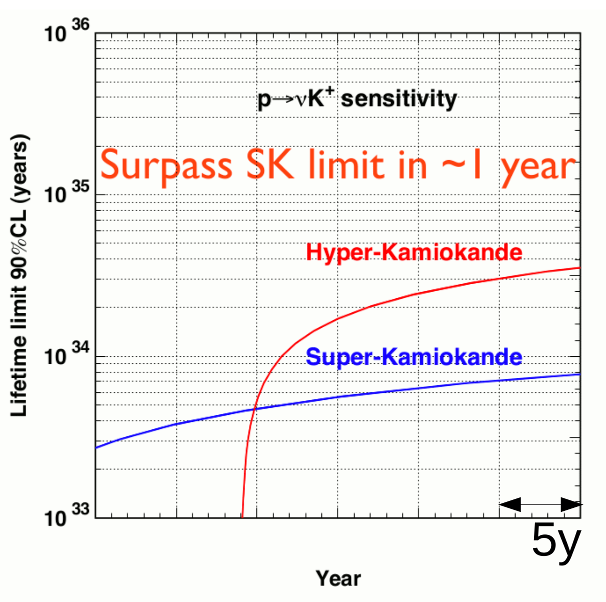
Proton Decay Sensitivity

Surpass SK limit in ~1 year

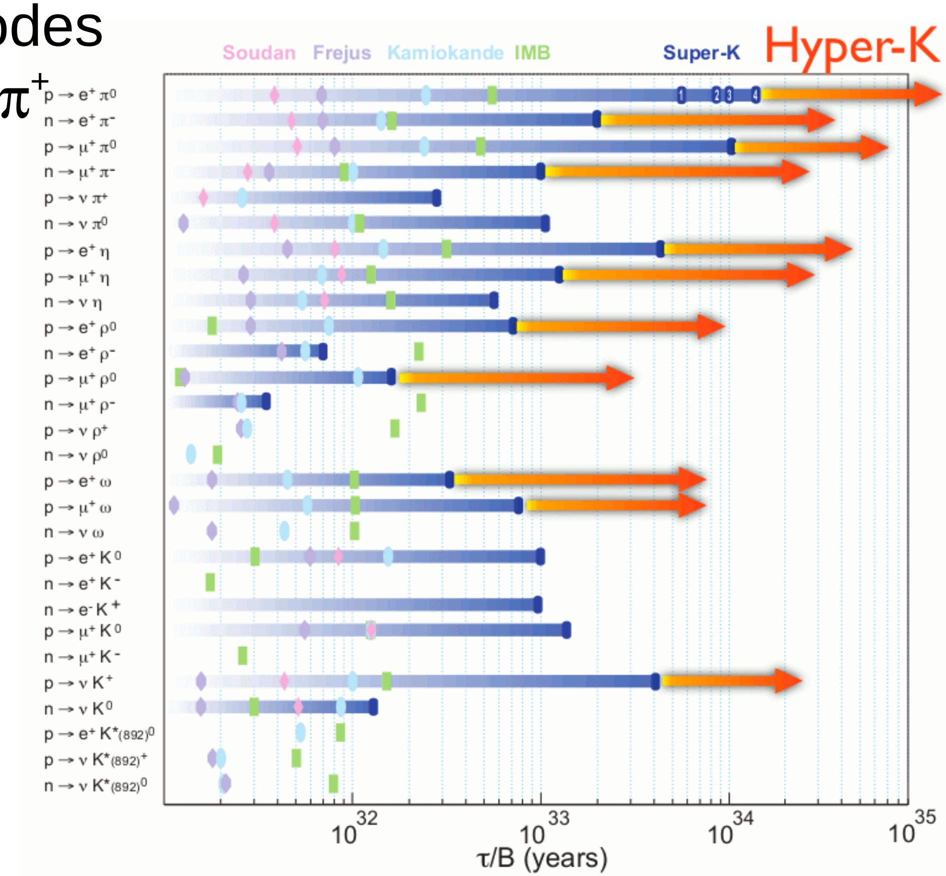






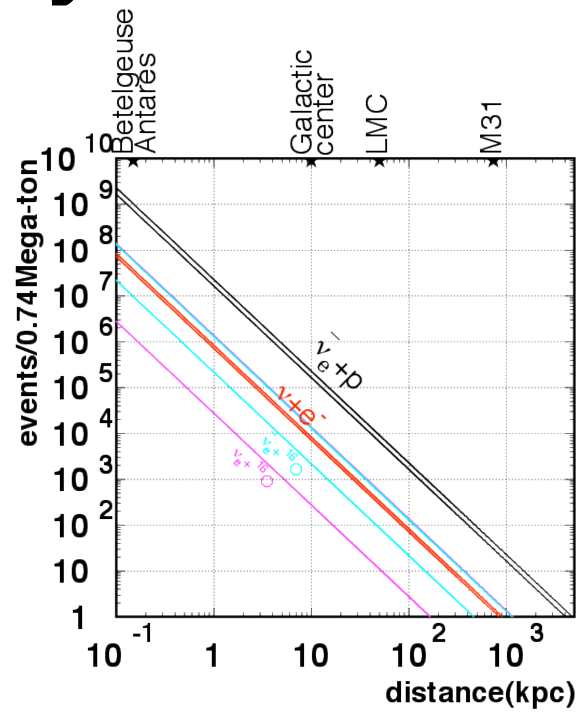


- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
- Hyper-K is sensitive in every single mode
  - $p \to e^+\pi^0$: 1.3×10^{35} y at 90% CL
  - $p \to \bar{\nu}K^+$: 3×10^{34} y at 90% CL
  - Many other modes:
    - p,n $\to$ $(e^+,\mu^+) + (\pi,\rho,\omega,\eta)$; $10^{34\text{-}35}$y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



arXiv:1109.3262

Neutrino Astrophysics

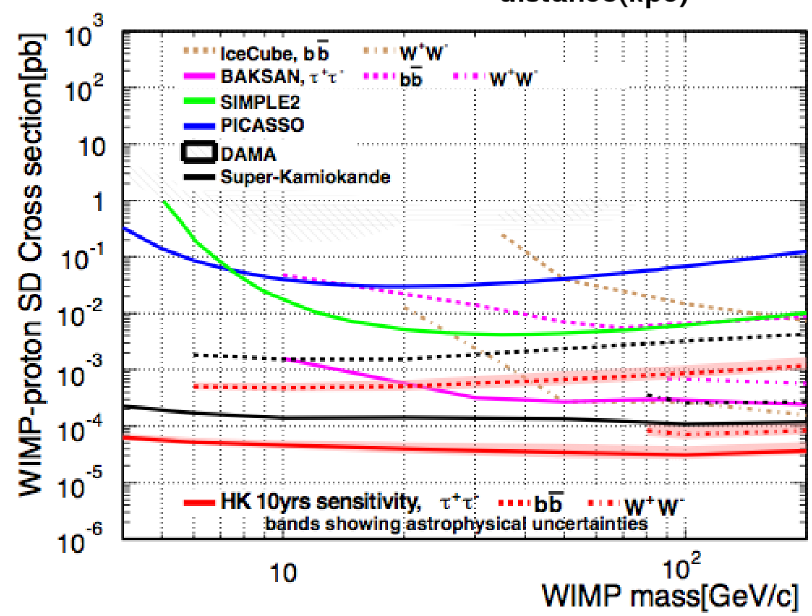


Supernova burst neutrino: 200k ν's from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics. Important data to cross check explosion models

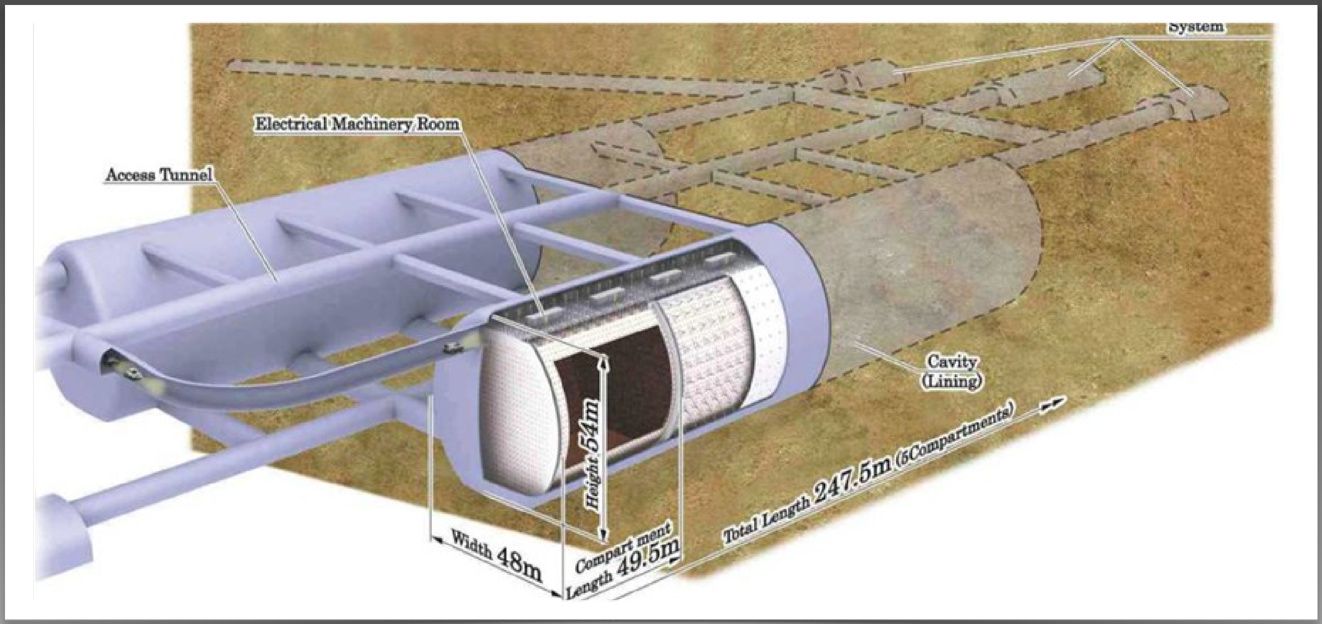
Supernova relic neutrino: possible G_d-doping of Hyper-K. ~830 events in 10 years in 10-30 MeV energy range.

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.



JENNIFER Task 4.1



JENNIFER

Task 4.1

Includes both far and intermediate WC detectors.

Sub-tasks:

- Software code for the Hyper-Kamiokande experiment including ND:
  - Sensitivity studies
  - Software release and computing → this afternoon session

- Electronics and DAQ:
  - For both far and intermediate detectors

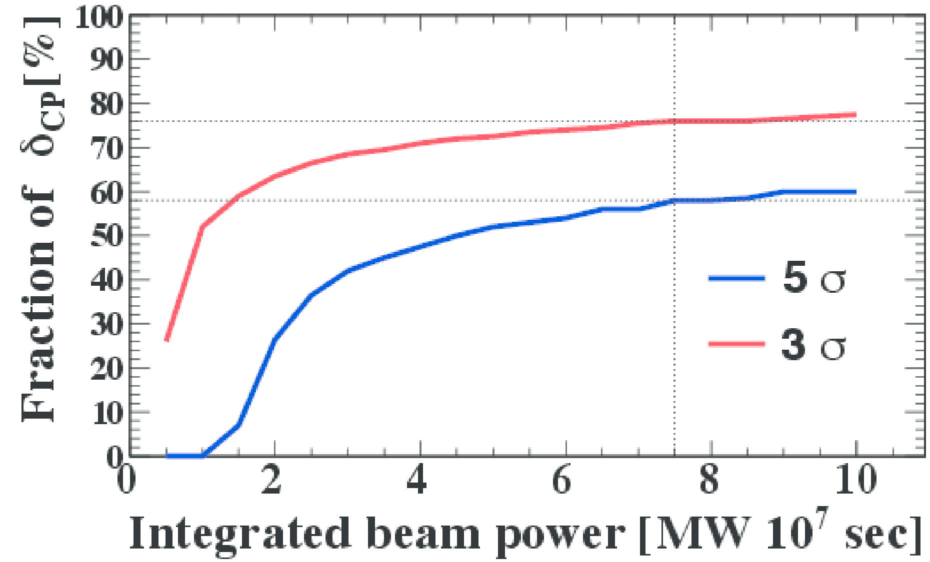
- Photodetectors → this afternoon session

- Calibration.

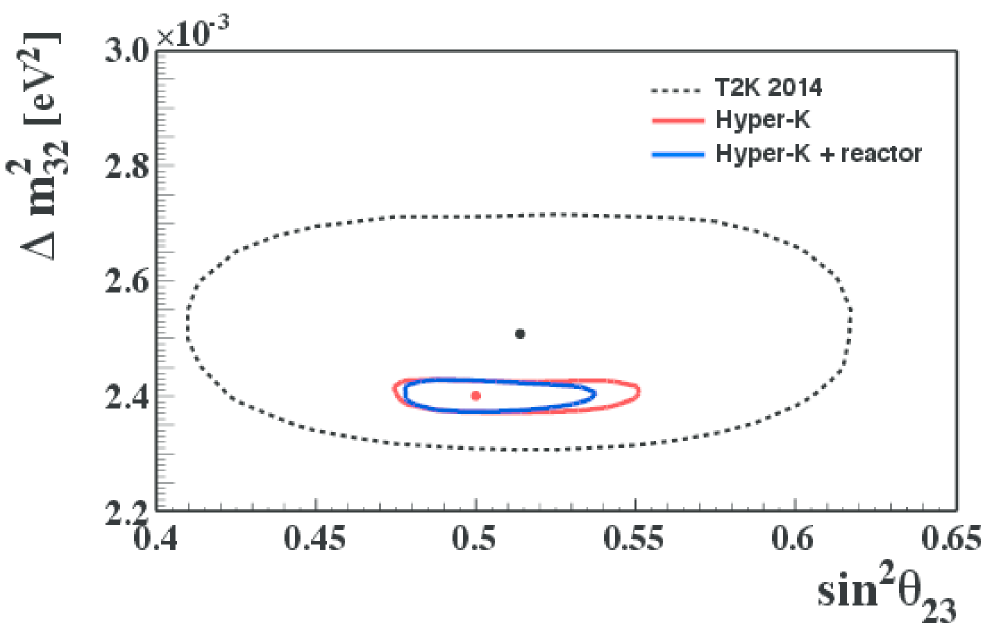
Hyper-K Sensitivity

- Used SimpleFitter
- Results published in: PTEP 2015 (2015) 5, 053C02 (arXiv:1502.05199 [hep-ex])
- More sensitivity studies ongoing.

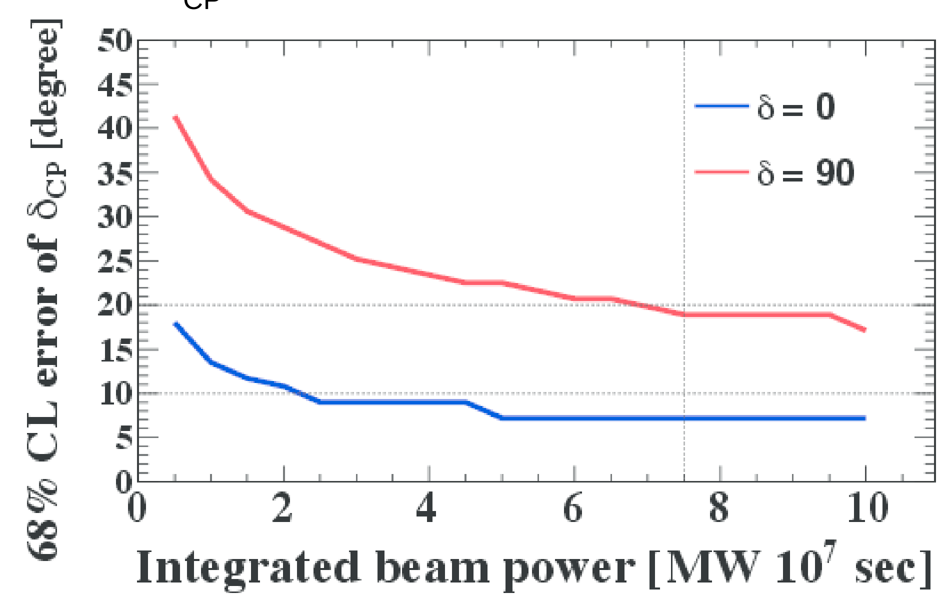
Fraction of δ_{CP} for which $\sin\delta_{CP}=0$ versus the beam power.



90% CL allowed regions in the $\sin^2\theta_{23}$-Δm^2_{23} plane (true $\sin^2\theta_{23}$=0.5. m^2_{23} =2.4 10^3 eV^2 point).

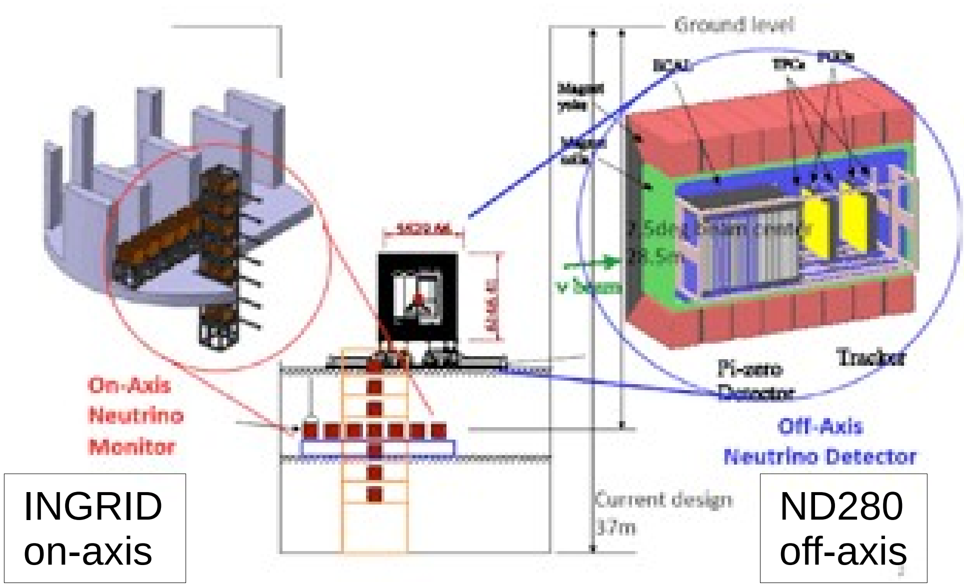


Expected 68% CL uncertainty of δ_{CP} versus integrated beam power



Near Detectors

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



Under investigation three (complementary?) options:

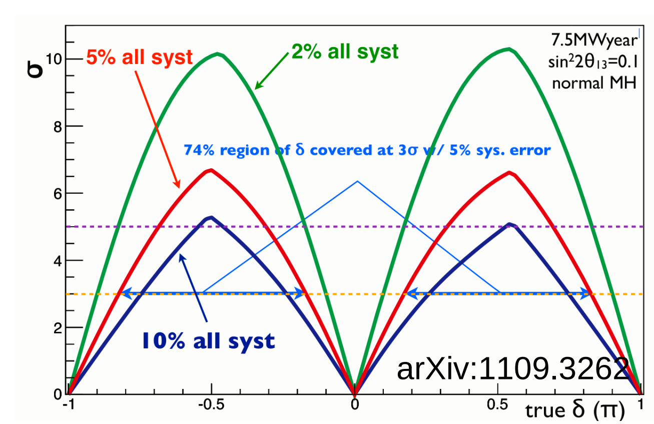
- Refurbished ND280/INGRID detectors
- New detectors in the 280m pit
- New “intermediate” WC detector at ~1-2km

Optimization criteria based on reducing systematic errors for oscillations.

Contributions from all the JENNIFER groups.

Current T2K systematic errors for oscillations

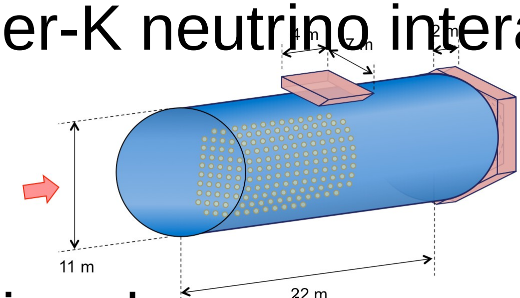
ν_e	Systematic sources(%)	ν_μ
3.1	Flux & Combined Cross-Sections	2.7
4.7	Independent Cross Sections	5.0
2.4	Pi Hadronic Interactions (FSI)	3.0
2.7	SK Detector Efficiencies	4.0
6.8	**TOTAL**	**7.6**



Intermediate WC Detector

TITUS: Tokai Intermediate Tank for Unoscillated Spectrum

- 2 kton Gd-doped water Cherenkov detector ~ 2km from J-PARC
- Main aim to reduce systematics for Hyper-K
- Location/design chosen to match Hyper-K neutrino interactions and beam spectrum
- Baseline design:
  - 22m long, 11m diameter tank

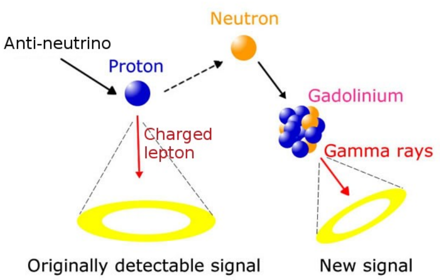


- Muon Range Detector partially enclosing downstream end
- 0.1% Gadolinium doping for neutron capture signal
- Physics programme:
  - Precise measurement of J-PARC beam spectrum for Hyper-K
  - Cross-section measurements
  - Neutron multiplicity
  - Sterile neutrinos
  - Detect supernova burst neutrinos for SN alarm

Gadolinium Doping

Neutron capture on Gadolinium:

- Cross section of 49,000b compared to 0.3b for H
- 8MeV gamma cascade with 4-5MeV visible energy
- 100% detection efficiency on Gd (<20% on H in SK)
- 0.1% Gd doping: ~90% of neutrons capture on Gd

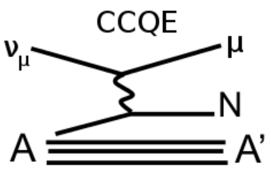


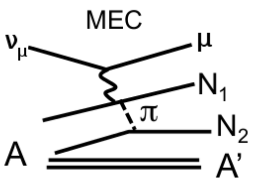
Distinguish ν / $\bar{\nu}$ events and different interaction modes:

- ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ 0 neutrons
- $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ 1 neutron
- ν_μ MEC: $\nu_\mu + (n + n) \rightarrow \mu^- + p + n$ 0.2 neutrons average
- $\bar{\nu}_\mu$ MEC: $\bar{\nu}_\mu + (p + p/n) \rightarrow \mu^+ + n + p/n$ 1.8 neutrons average

Greatly enhanced sample purities:

- ν_μ CCQE: 36% → 67%
- $\bar{\nu}_\mu$ CCQE: 63% → 88%

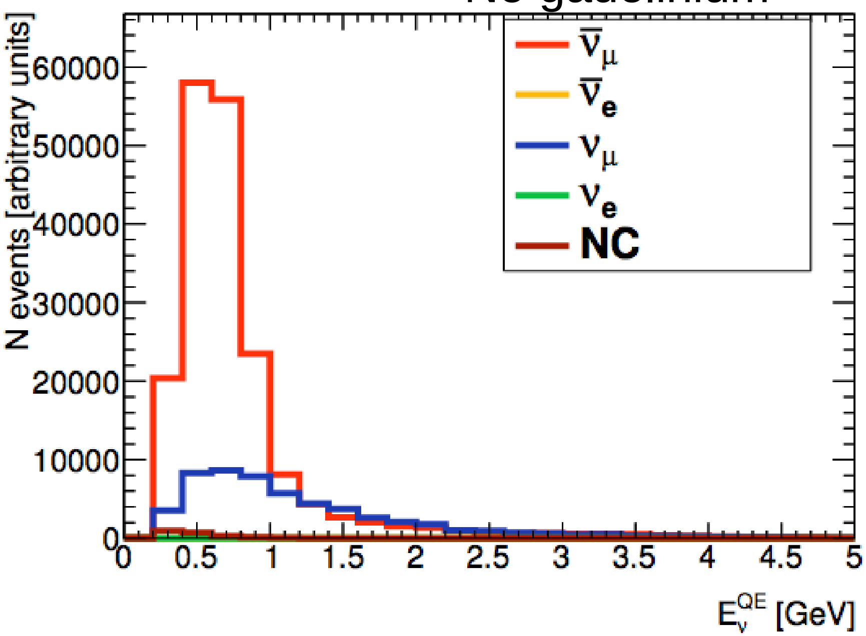




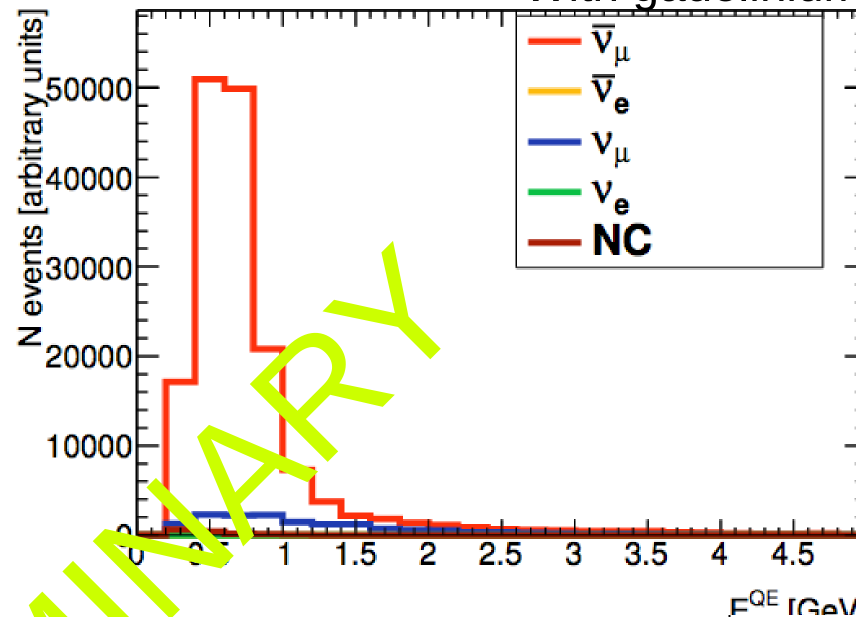
Feasibility of Gd in water Cherenkov detector being tested in EGADS (arXiv:1201.1017)

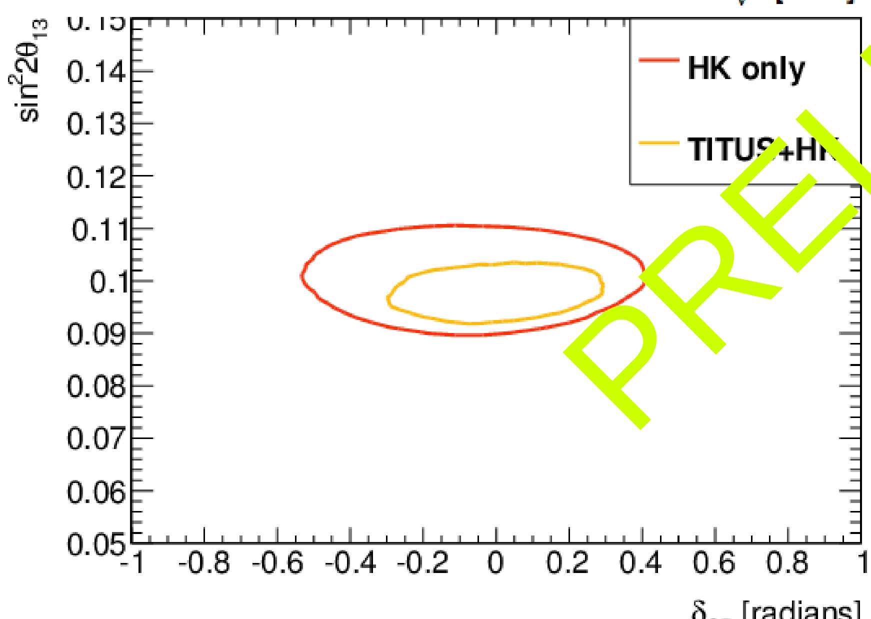
Physics Potential Sensitivity

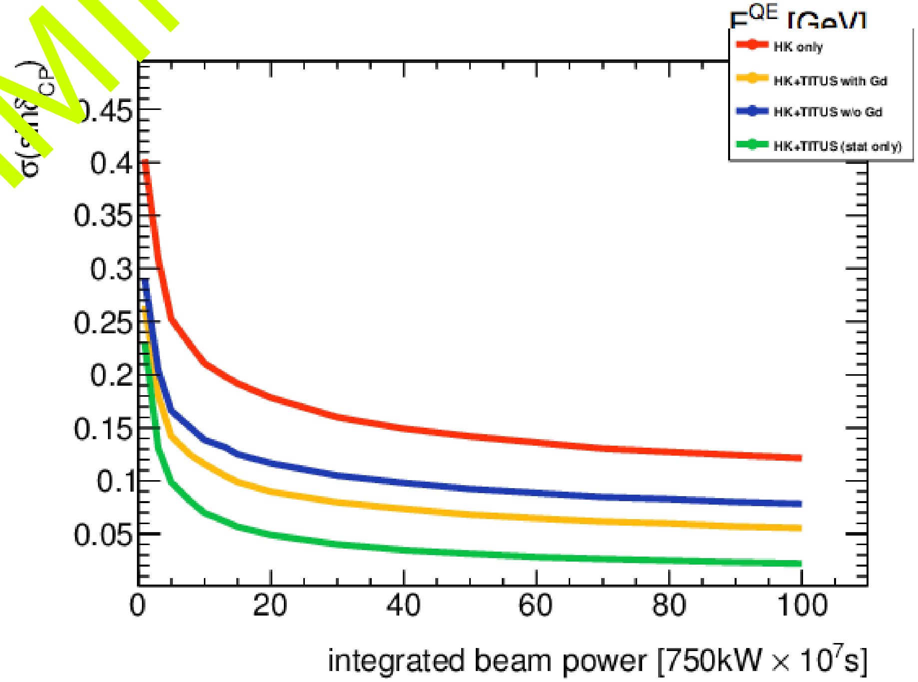
No gadolinium



With gadolinium





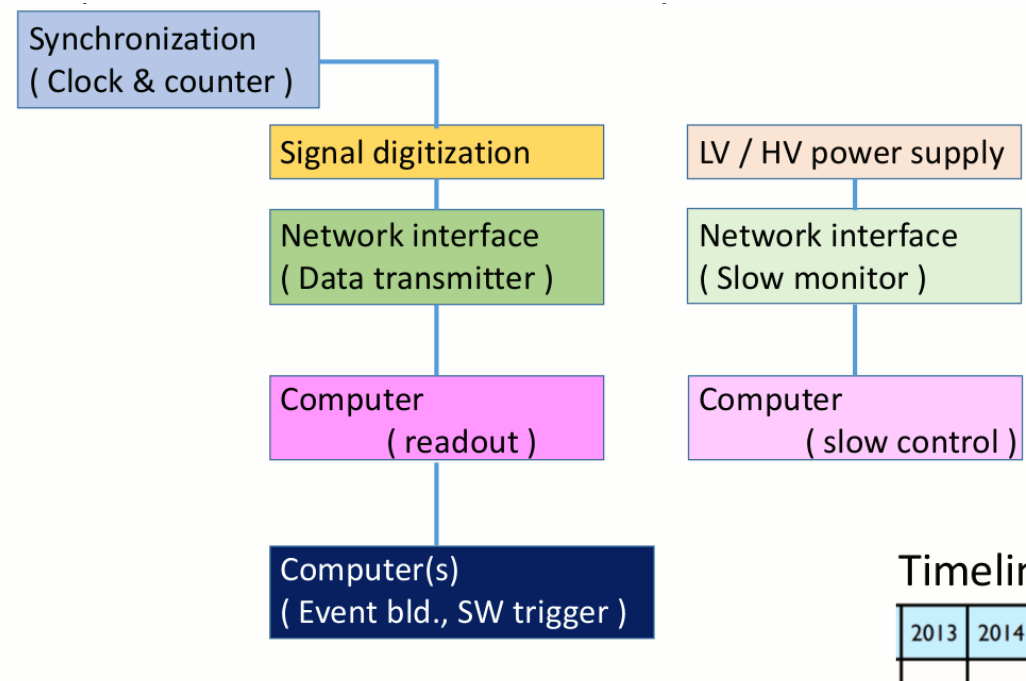


Based on MC fast reconstruction

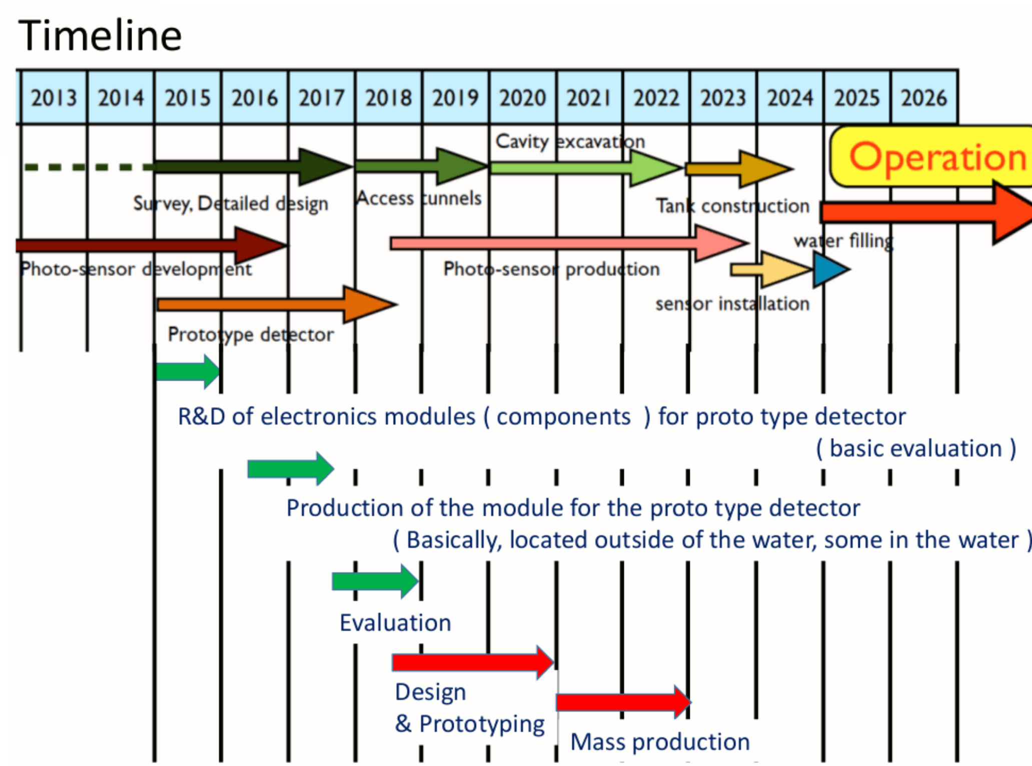
Ongoing work

- Developed global reconstruction for simulated events (“fast” simulation).
- Implenting code for sensitivity studies for the ND280, intermediate and far detector.
- Estimating effects to low and high (beam) energies.
- Exploiting similarities with far detector for technical choices for the detector (eg electronics, DAQ etc).

Components of the Electronics System



- Work started on all the components of the electronic system.
- Effort mainly lead by Japan/US and Canada/Poland.
- Related to ongoing work on DAQ.



Main decision of whether the electronics will be in water or not needs to be taken.

Main Items for Electronics

- List of major R&D items
  - Connectors, cables and chassis
  - Water tolerant connector (for signal & HV/LV)
  - Water tolerant connector (data transfer)
  - Pressure tolerant cable (for data transfer)
  - Water tolerant chassis (realistic one)

- Signal digitization:
  - Evaluation of QTC + FPGA-based TDC
  - Evaluation of FADC + FPGA (contribution from Poland)

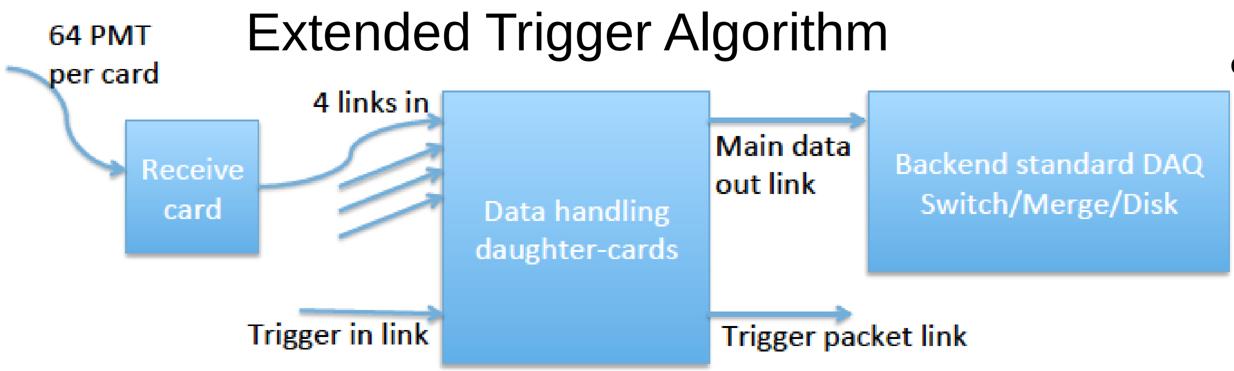
- Evaluation of data transfer system with SiTCP, Rapid I/O and possible other solutions

- Slow control system
  - Need decision on sensors

- Reliability tests (method, environment and tools)

DAQ

- DAQ started in the UK
- Started work in the software to address physics needs of the experiment.
- Several possibilities for hardware design are being developed.



- N_{hits} trigger is main trigger

What additional trigger algorithm opportunities exist?

- Can cause trigger to select between readout options
  - E.g. Read all compartments, read one compartment
  - E.g. Length of readout window around trigger
  - E.g. Some more sophisticated tricks to optimize supernova trigger
- One we are thinking about first: sub-N_{hits} trigger
  - For events with <Nhits, look for combinations of hits in time and PMT position in a tighter coincidence time window. [Solar, supernova, etc.]

- Trying to keep design independent of some hardware choices, eg electronics signal digitization, type and number of photosensors etc.
- Example of “Extended Trigger Algorithm”

Calibration

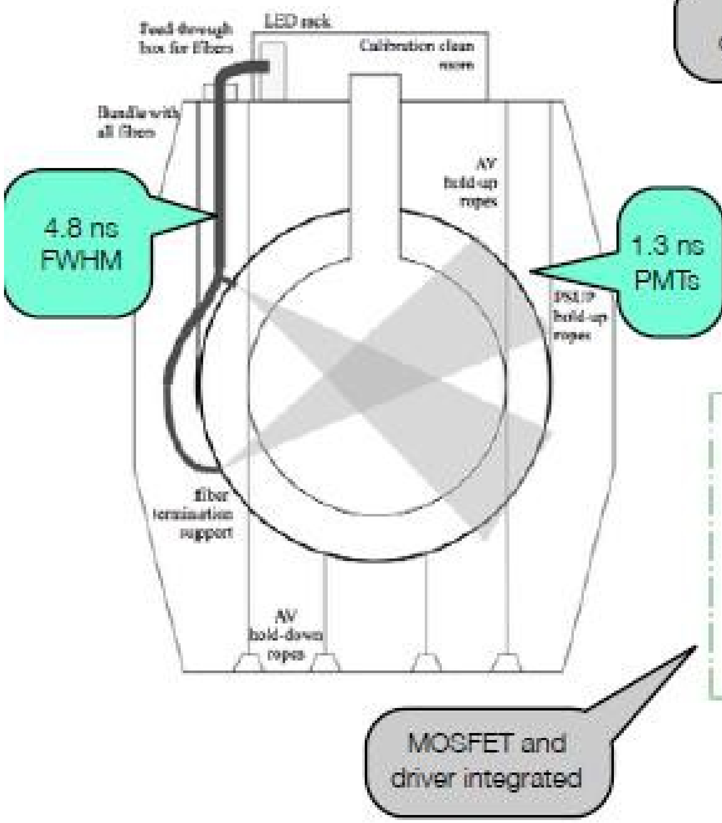
Current EU work on two systems, mainly UK:
- LED pulser
- Pseudo Muon Source

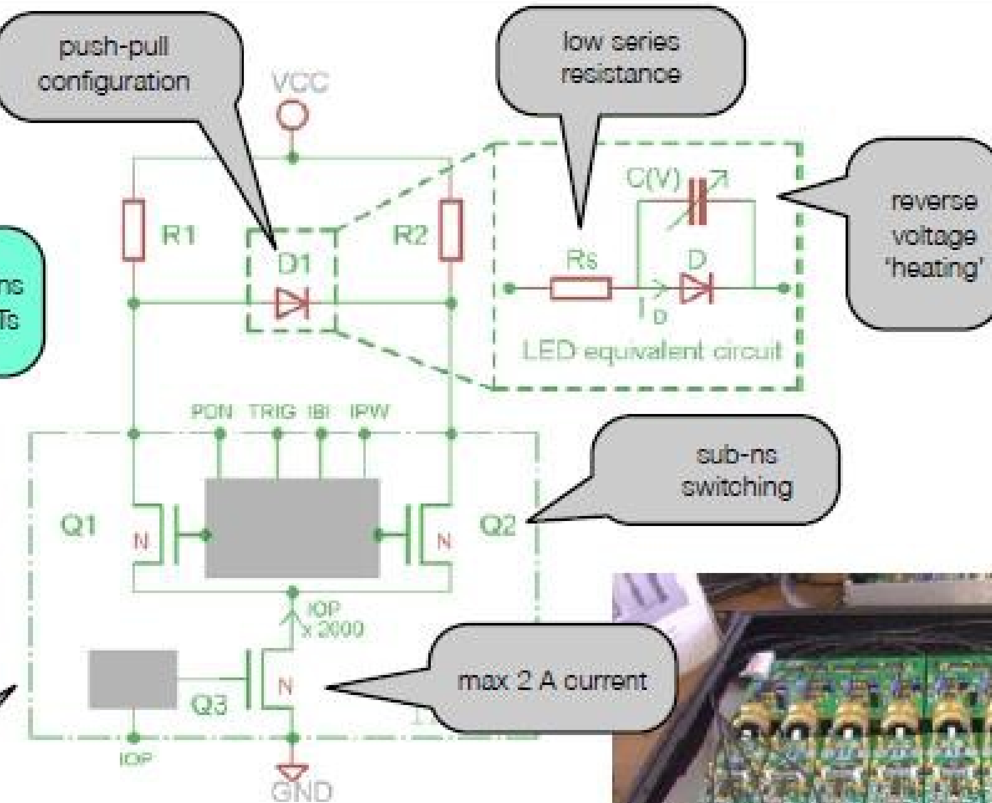
Use an LED rather than a laser as a light source.
Advantages:
  - Cheap per channel cost. (~£10 for LED and basic driver electronics)
  - Compact device possible
  - Stable wavelength distribution ~ 10 nm spread
  - Wide range of wavelengths available
  - ~1-2 ns pulses.
  - Simple coupling to fibres

Disadvantages
  - Higher current requirements
  - Large light loss into fibres.

Questions
  - Can we produce the required dynamic range?

LED System in SNO+



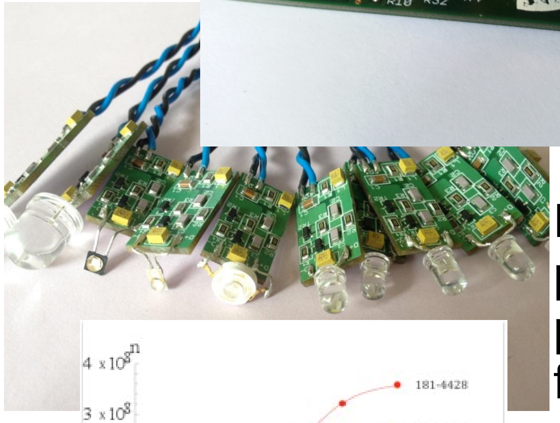


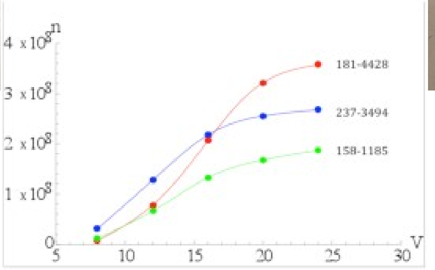
Original design requirement (LED end):
- > **10^6 photons per pulse**
- – **1 ns optical pulse width**

Later additional requirement (wet end):
10^3 photons per pulse (stable) at **1 pulse per second** repetition rate

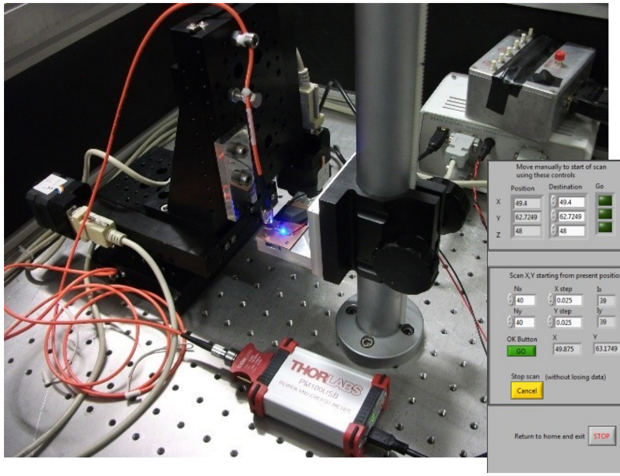
Calibration using LEDs

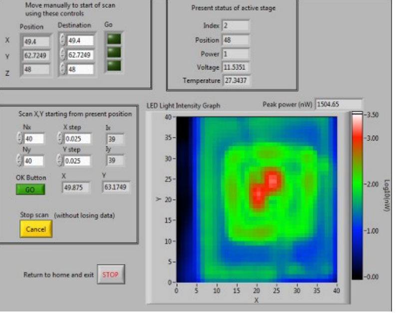
- Developed three prototype pulser circuits capable of flashing LEDs as well as other solid state optical devices such as laser diodes.
- Identifying suitable LEDs, characterizing LEDs and LED/pulser combinations.
- In addition, LED electrical properties are measured (typical resistance and capacitance values) using an impedance analyser.
- Investigating the optical setup of the system, needed fibers and coupling with LEDs





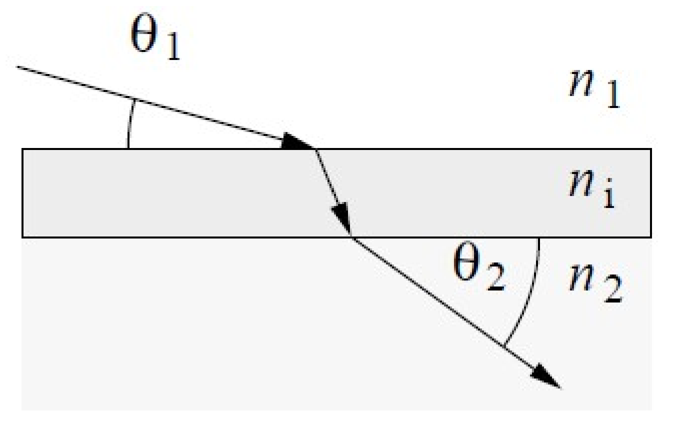
Number of photons per pulse as a function of pulser DC voltage for 4 LED models.





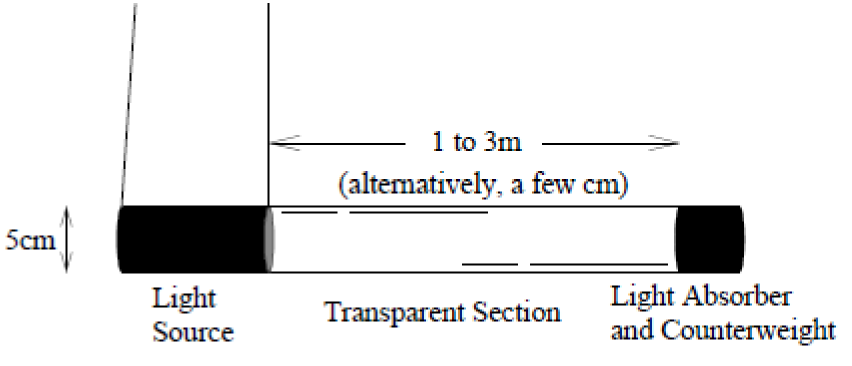
A Pseudo Muon Source

- A source to simulate muons and test reconstruction.
- A narrow transparent tube with a light source producing almost parallel light at one end.
- Light emitted at the Cherenkov angle.



As $\theta_1 \rightarrow 90^\circ$ $\sin(\theta_2) \rightarrow 1/n_c$

Light emitted at Cherenkov angle.



Third EU-Hyper-K Meeting

Most recent meeting: 3rd Hyper-K EU meeting at CERN (27-28 April): http://indico.cern.ch/e/ThirdEUHyperK
Attended by the JENNIFER groups. Ongoing collaboration on all fronts.

Conclusions

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.

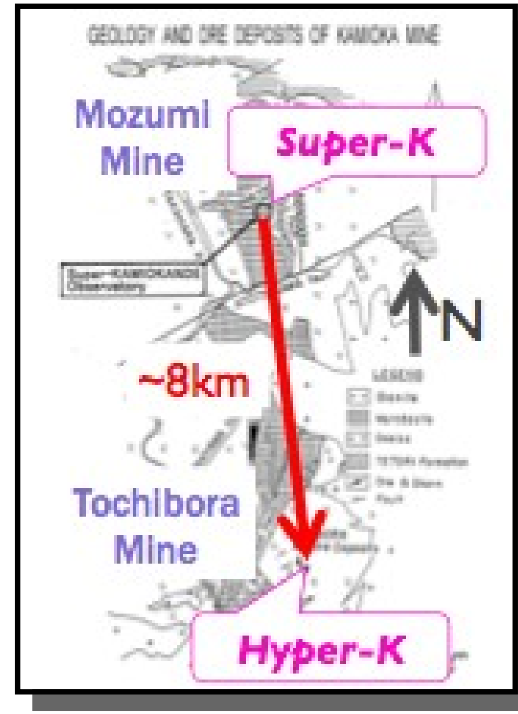
- Data taking around 2025 with current schedule
- Work ongoing on main aspects of the experiment.
  - Work in the different tasks of WP4 on track with expectations.

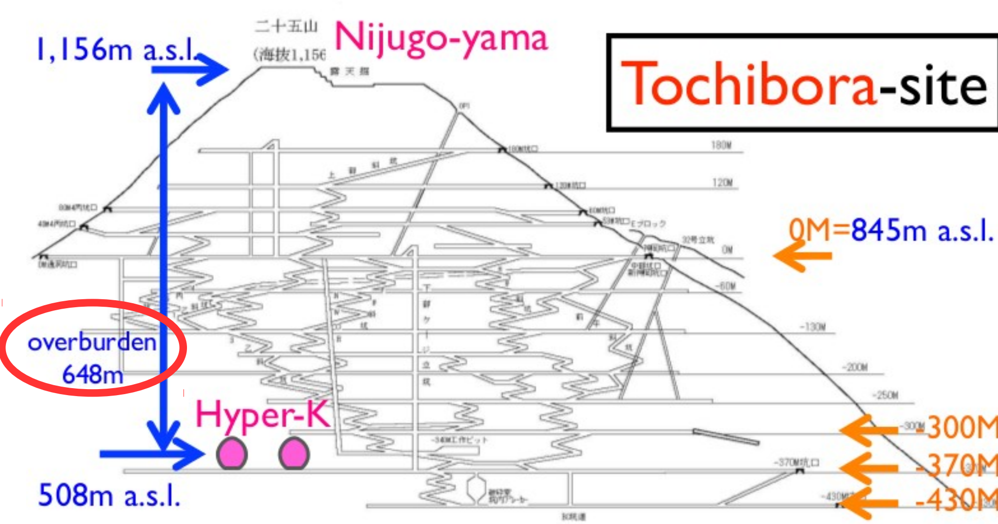
Extra Slides

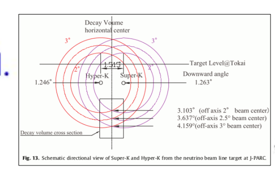
Site(s) and Cavern(s)

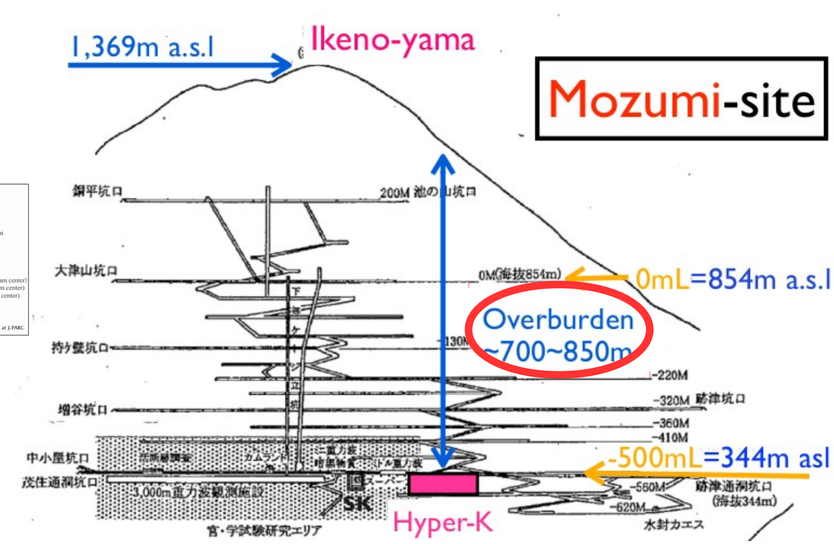
Two sites are being investigated:

- 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



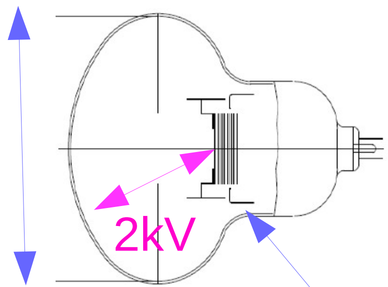
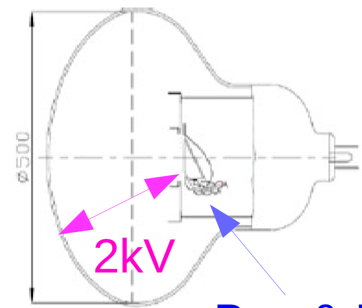
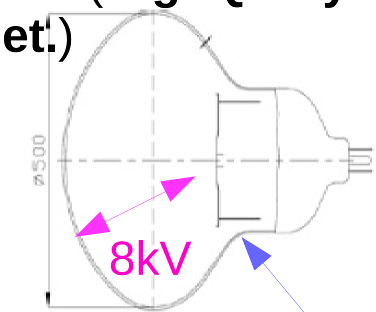






Photosensors Candidates

R&D going to get better perfomance and lower costs

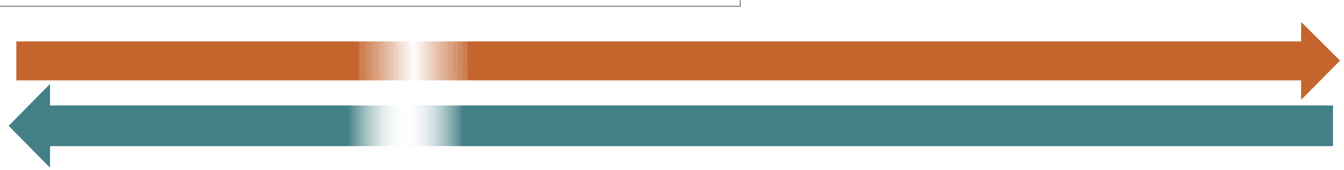
	Established (**SK PMT**)	R&D (**HighQE/CE PMT**)	R&D (**HighQE hybrid det.**)
			
Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

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

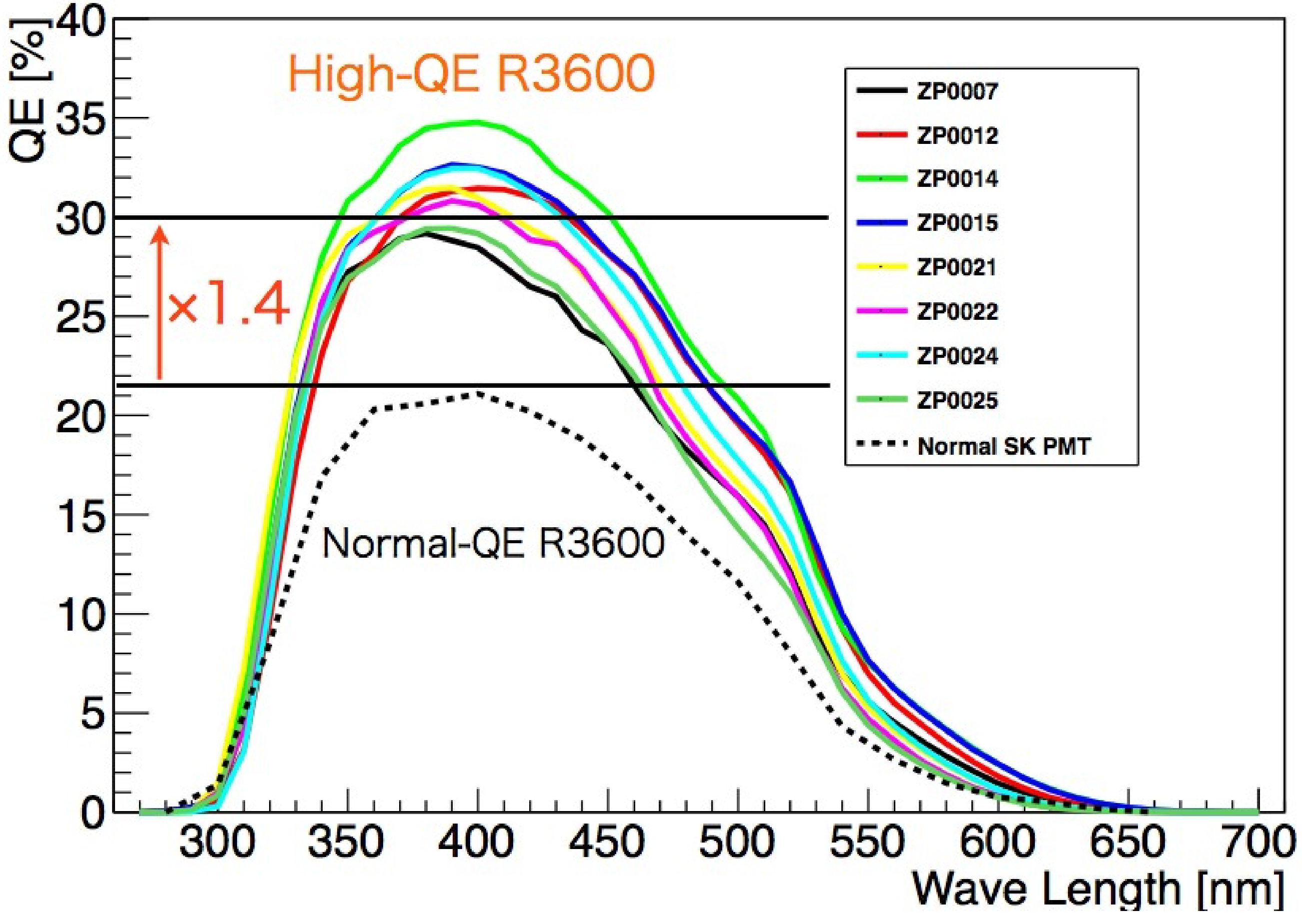
R&D (HighQE/CE PMT)
- Under development
- Better performance
- Same technology
  → Lower risk

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)



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

World-wide R&D

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