The Hyper-Kamiokande Experiment

Physics with the J-PARC beam

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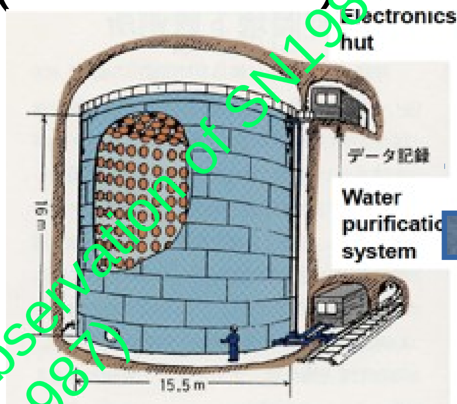
Workshop for Neutrino Programs with facilities in Japan
J-PARC - August 4-6, 2015

Kamiokande Evolution

Three generations of large Water Cherenkov in Kamioka

Kamiokande
(1983-1996)



3kton

Observation of SN1987A
(1987)

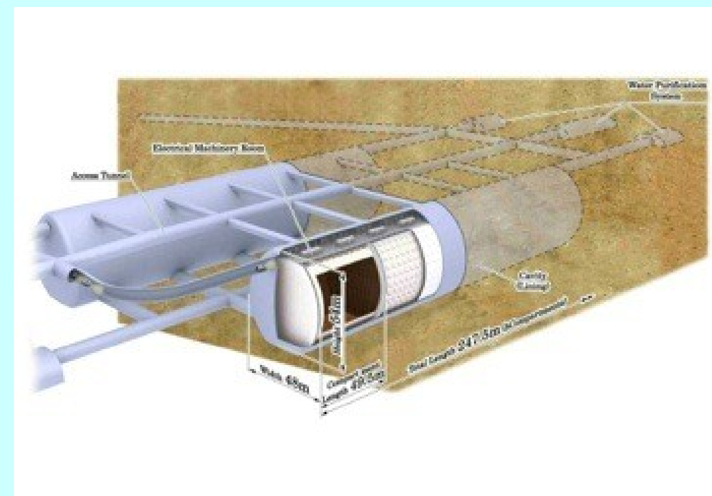
Super-Kamiokande
(1996-)

50kton

Discovery of neutrino oscillation (1998)

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

Hyper-Kamiokande
(202?-)



1Mton=1000kton

(560kton fiducial)

x17

x20
(x25 fiducial mass)

Hyper-Kamiokande in 2001

A long time in the coming. Let's build it!

- In 2001, Letter of Intent for T2K.
- Hyper-Kamiokande introduced as 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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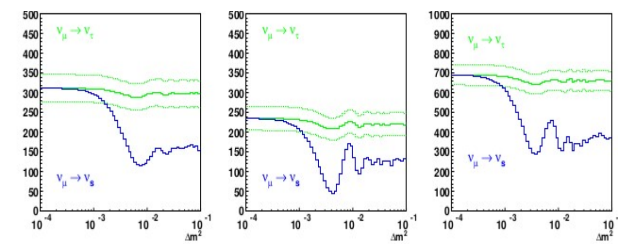


Figure 15: Expected number of events with various Δm^2 for (a) 1 year of WBB, (b) 5 years of LE2π and (c) 5 years of OA2°. The solid lines show the expected numbers of events assuming $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$. The dotted lines show the 90% C.L. regions of $\nu_\mu \to \nu_\tau$ oscillation.

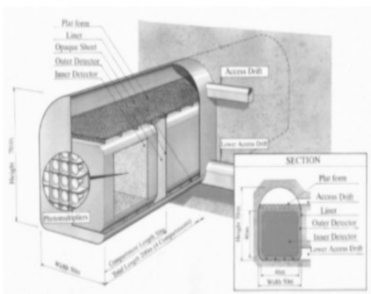


Figure 16: Schematic view of the Hyper-Kamiokande detector.

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

22

The Hyper-K Project

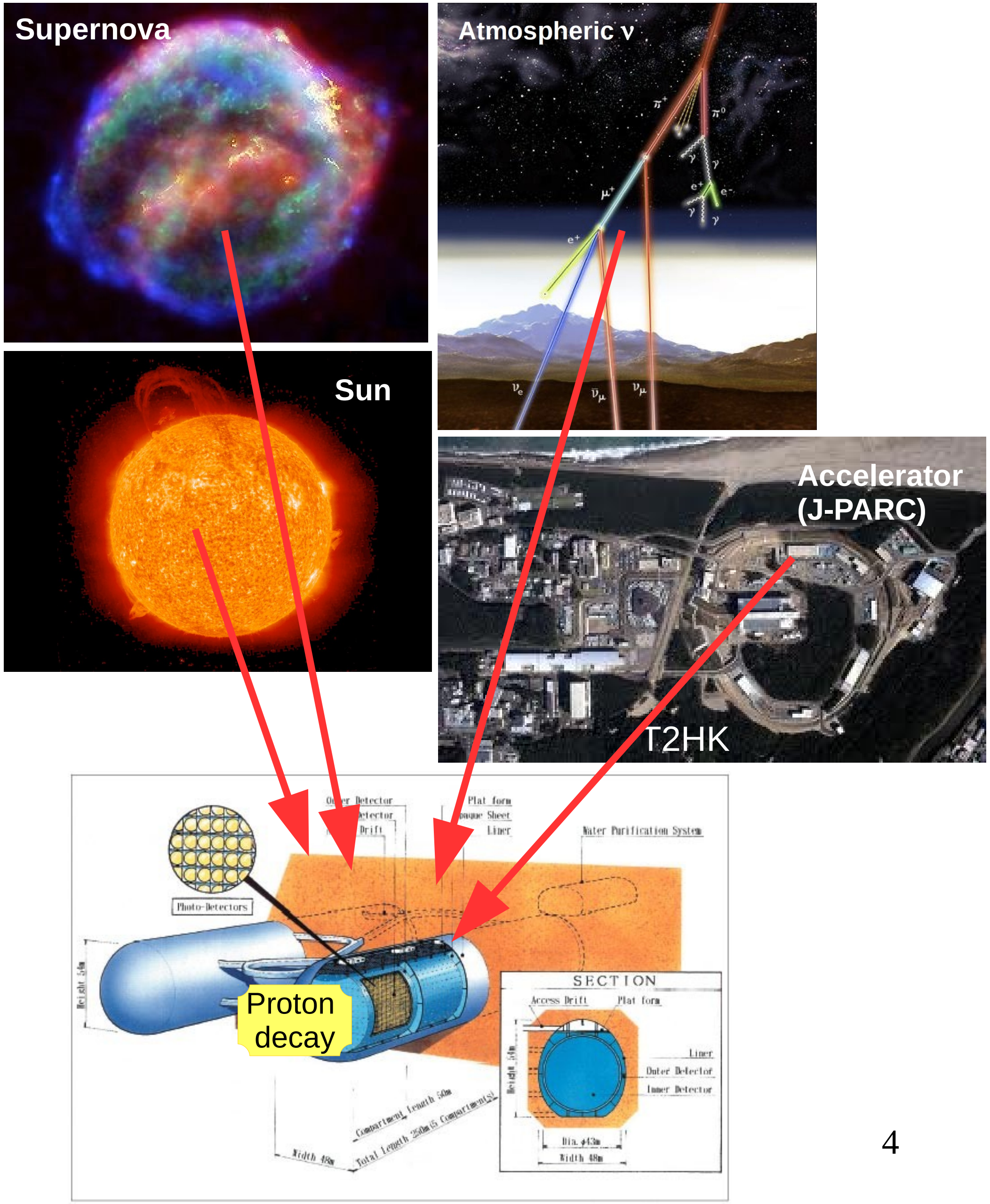
A very rich physics portfolio!

<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, …)



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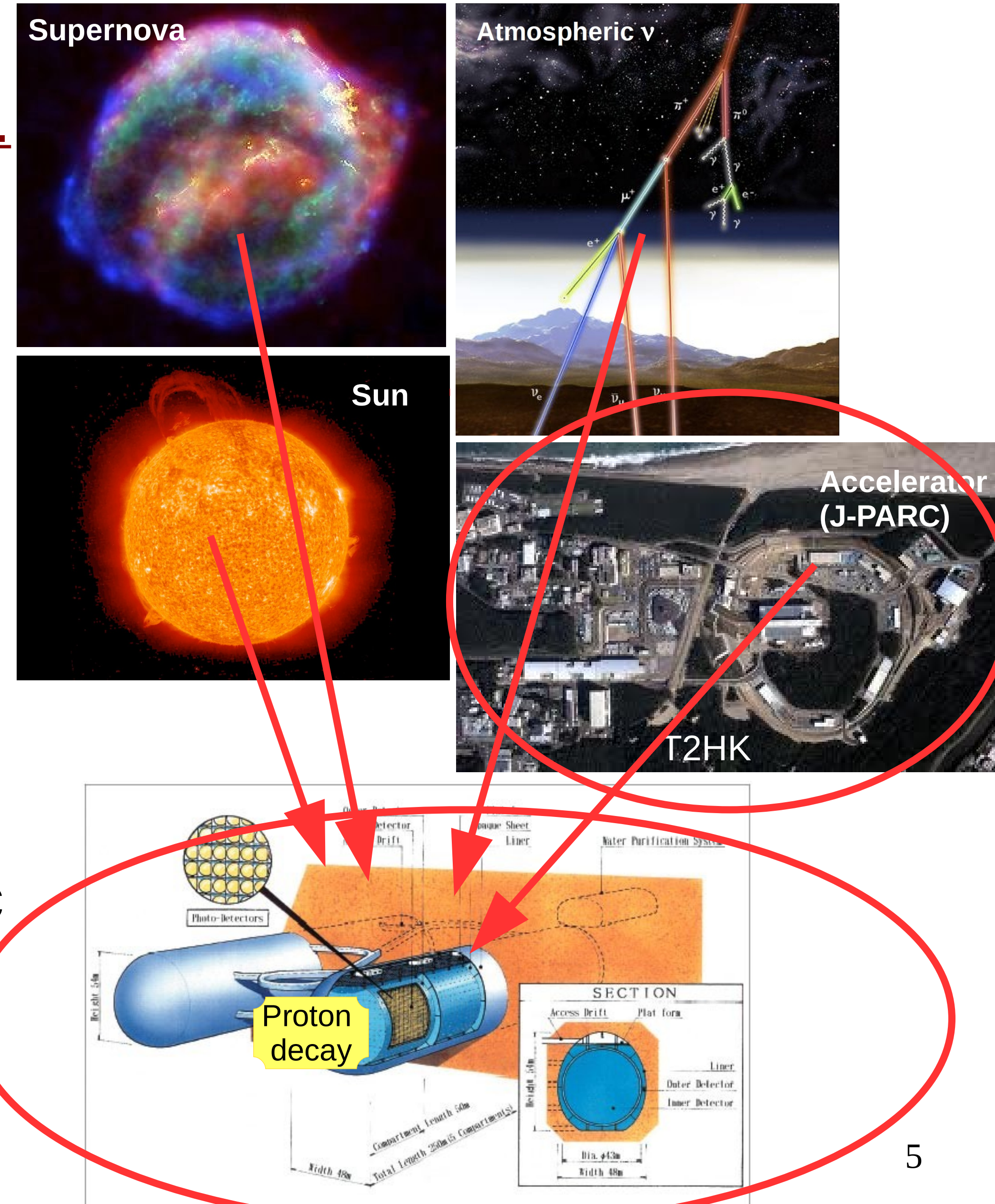


Outline

- Overview
  - Status of the Project

Evolving to an international collaboration!

- Experiment Design

Currently being optimized!

- Beam Physics:
  - Systematic Errors
  - Oscillation parameters
    - CP
    - θ_{13}, θ_{23} precision
    - Octant degeneracy
    - W/ Atmospherics
  - Non standard physics

Non-beam physics results presented in the next talks. Relevance and synergy with other experiments also shown

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.

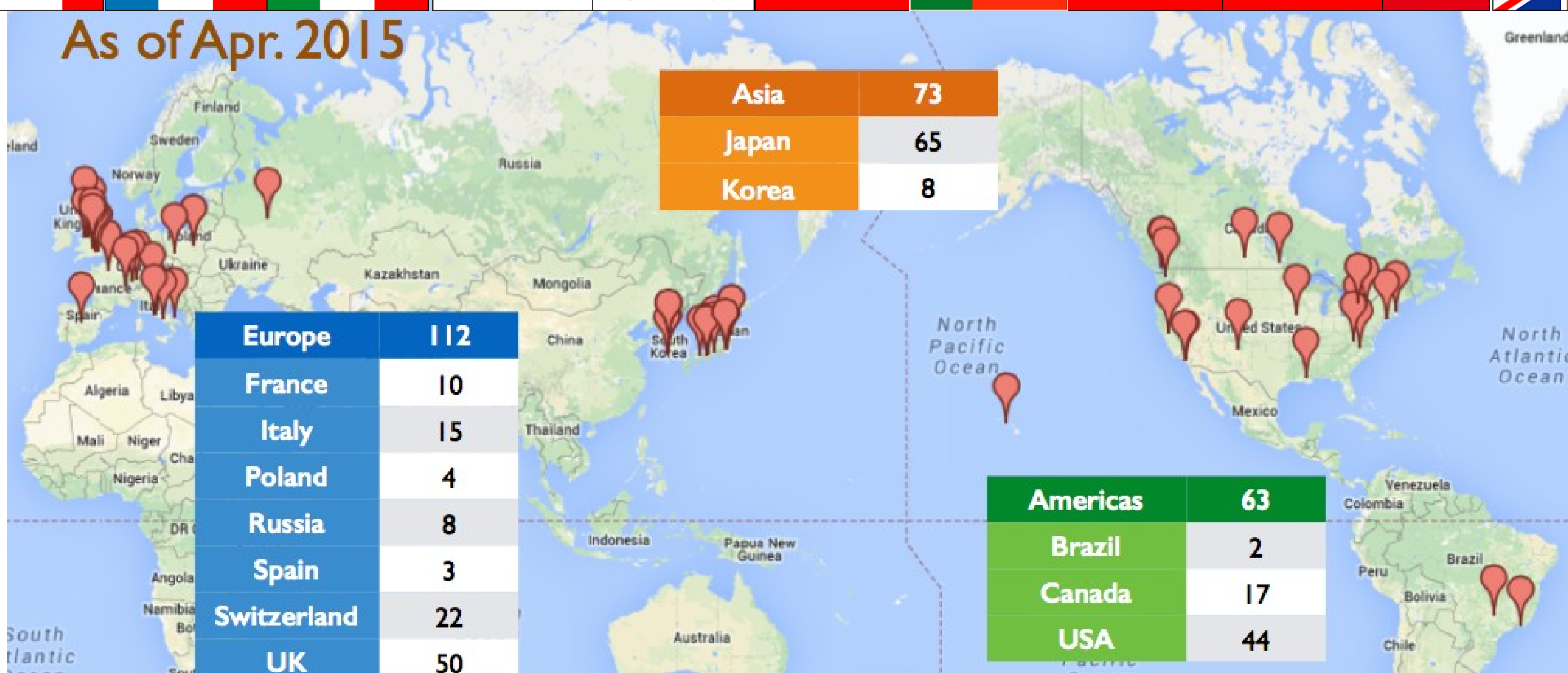
First Meeting of the proto-collaboration: June 29-July 1, @Kashiwa

Hyper-K in the World

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

We are many, but more are welcome!

- 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

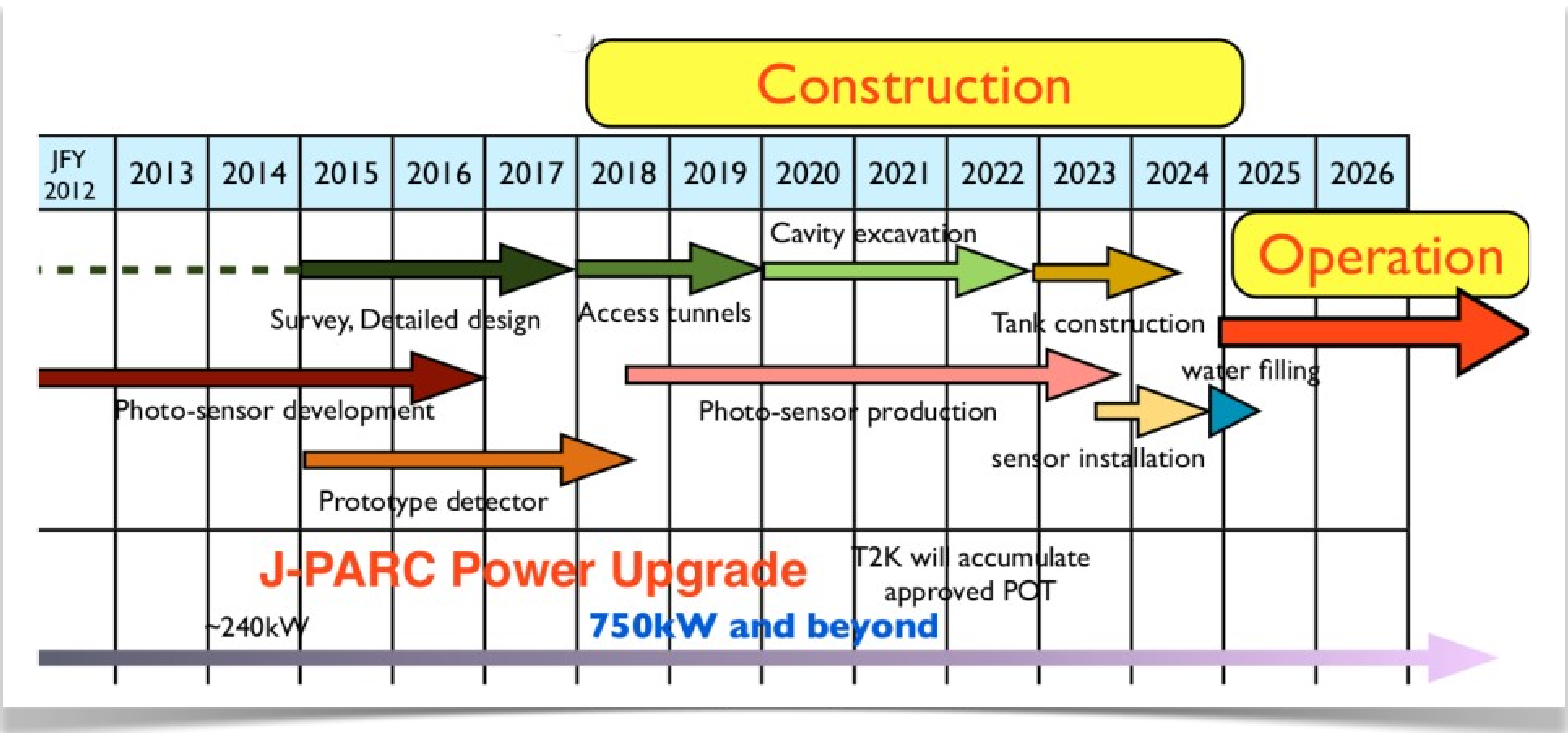
Americas	63
Brazil	2
Canada	17
USA	44

Future Steps for the proto-collaboration

- Design Report (DR)
  - Next update of Japanese science roadmap expected in 2016-2017
  - DR will be reviewed by international committee to assess readiness of the experiment.
  - Current ongoing work:
    - R&D for far detector, including tank optimization
    - Construction cost & period
    - Beam & near detector
    - International responsibilities
- Once the budget is approved:
  - Construction can start in 2018
  - Operation will begin in ~2025
  - From proto-collaboration → collaboration

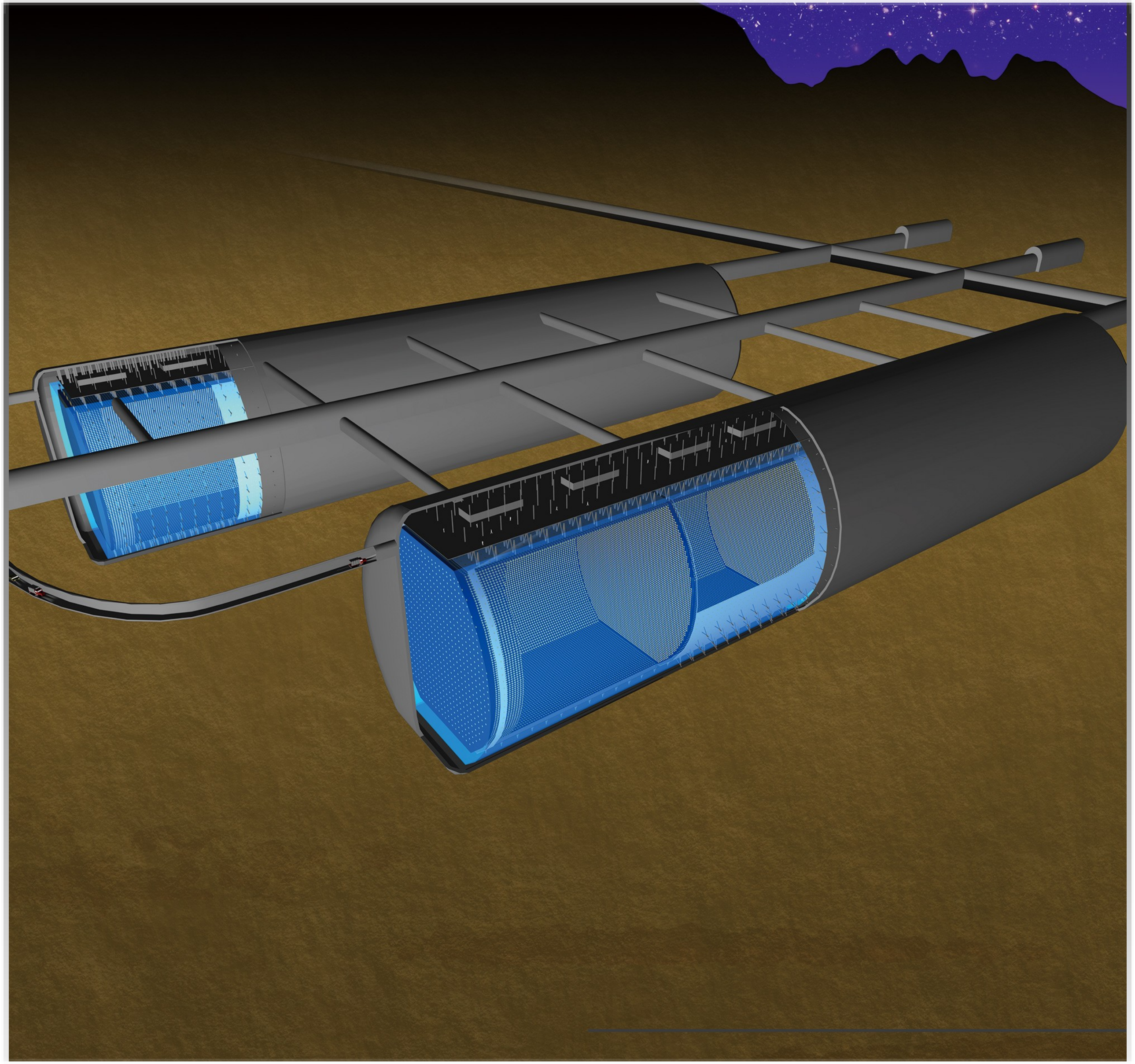
Ongoing design optimization
Keeping the same physics expectation for Hyper-K.
Results not yet official.
Nominal configuration presented.

The Hyper-Kamiokande Timeline

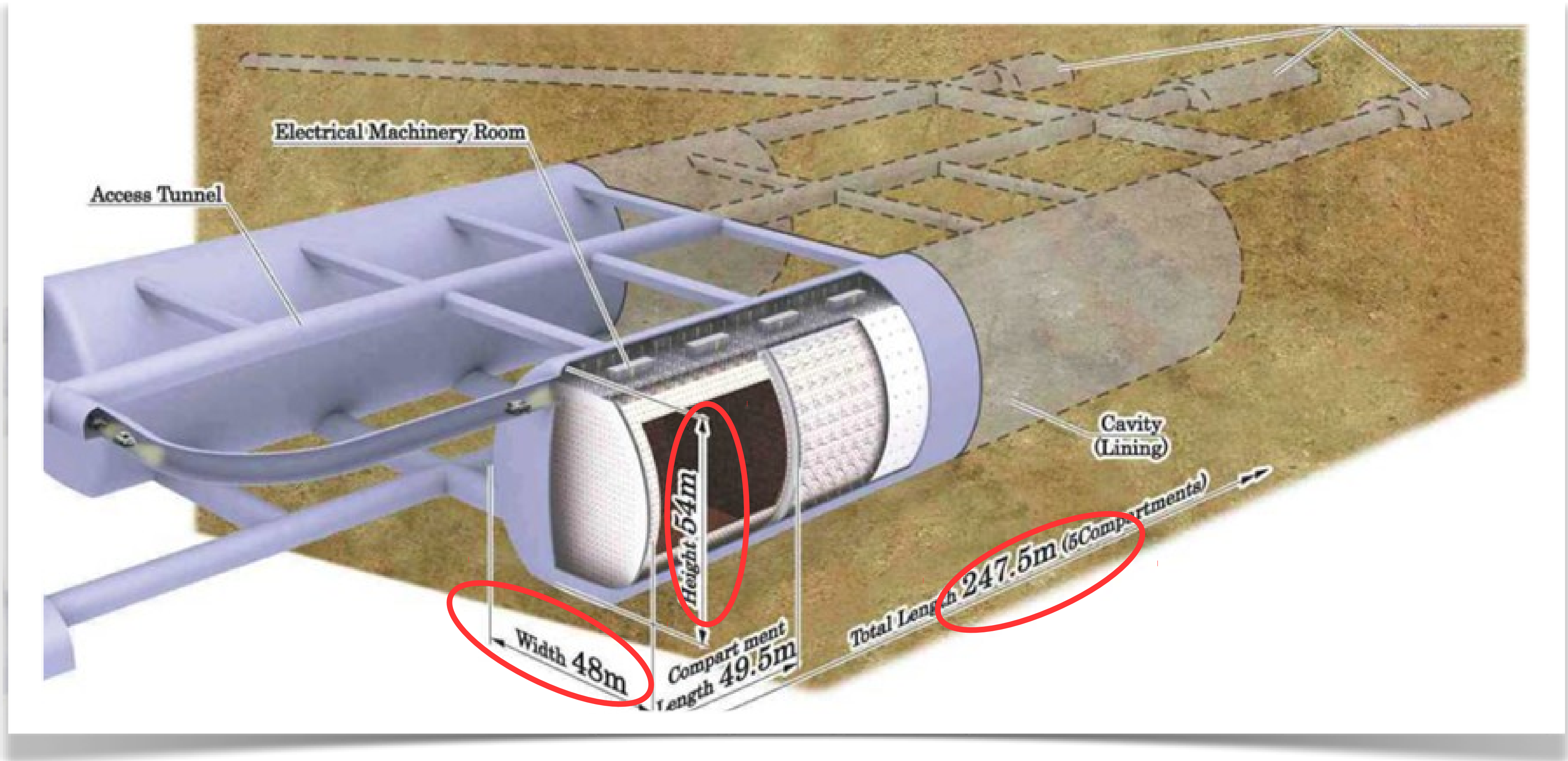


~2017 Major design decisions finalized
~2018 Construction starts
~2025 Data taking start
> 2025 Discoveries!

The Experiment



The Hyper-Kamiokande Detector

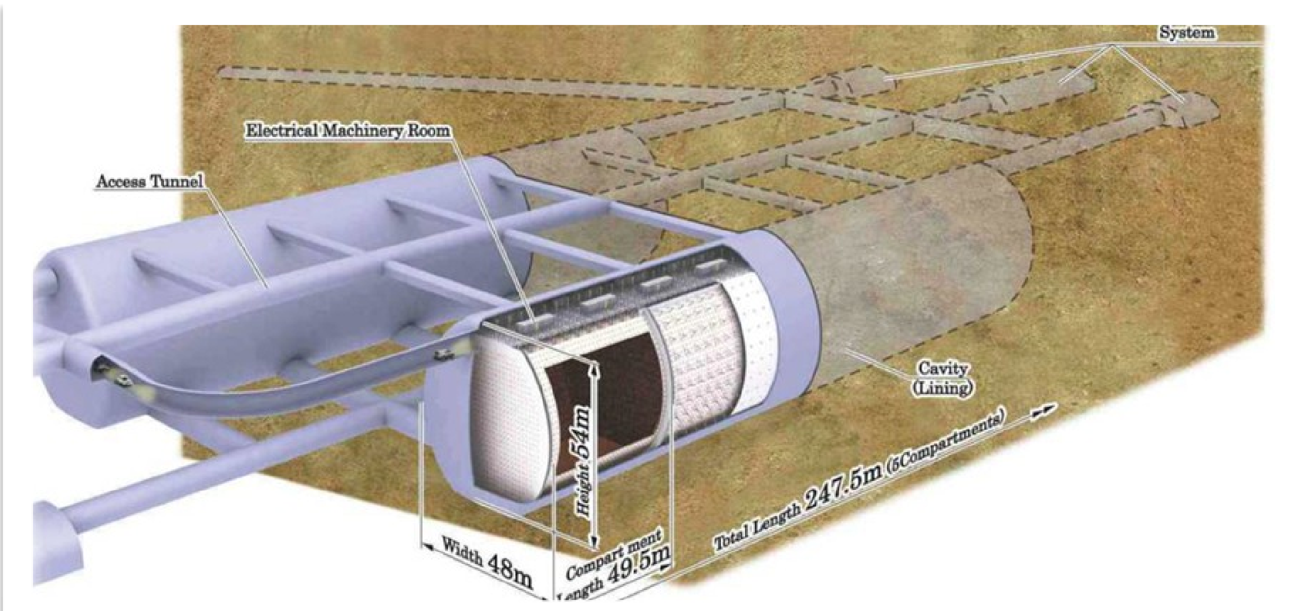


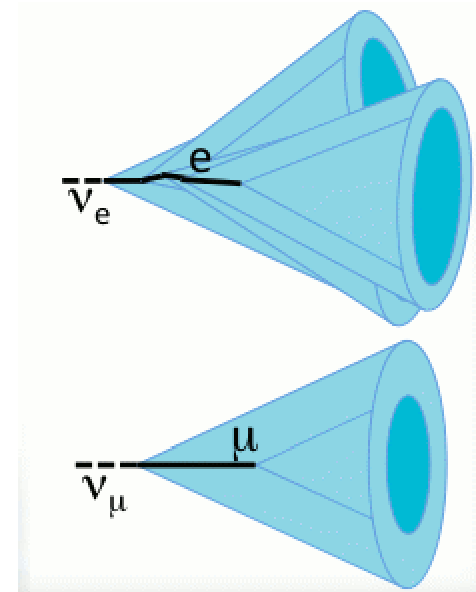
The Hyper-Kamiokande Detector

- 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

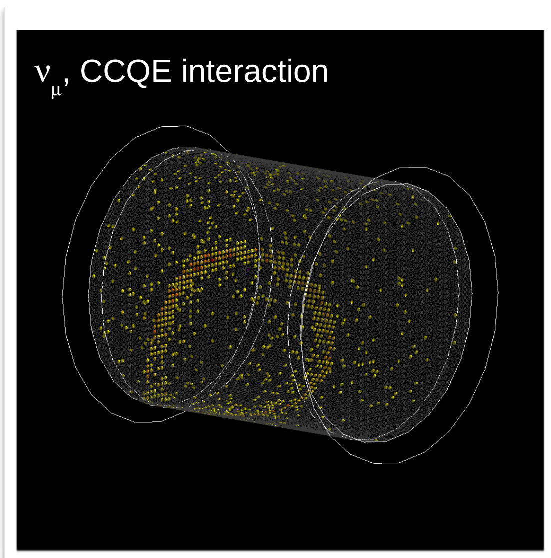
The Hyper-Kamiokande Detector

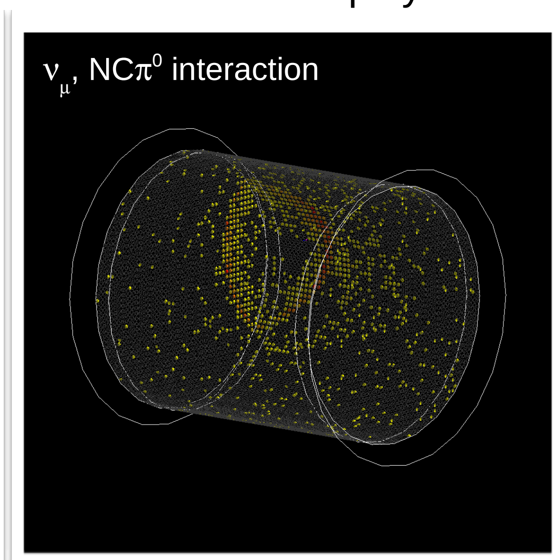


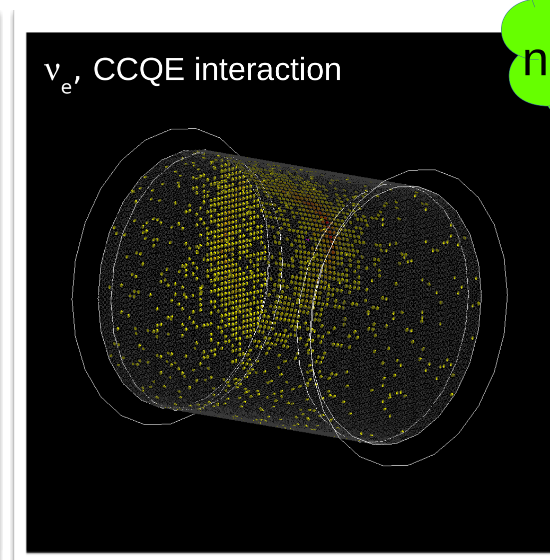


Water – nominal case

GEANT4 event displays





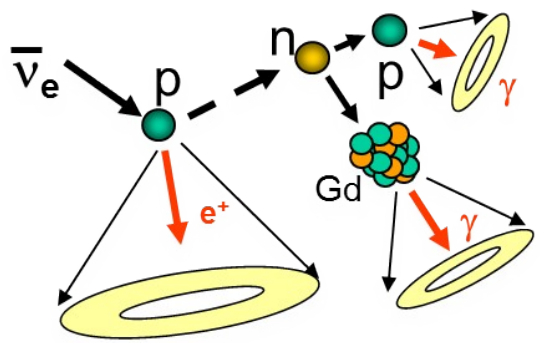


Gadolinium Option

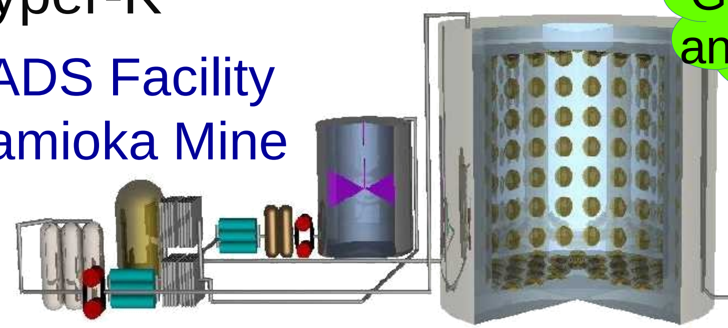
Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004 [226 citations]

- Gd-doping proposed in 2004 mainly to greatly enhance 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

SK will have Gd. It could be an option for HK

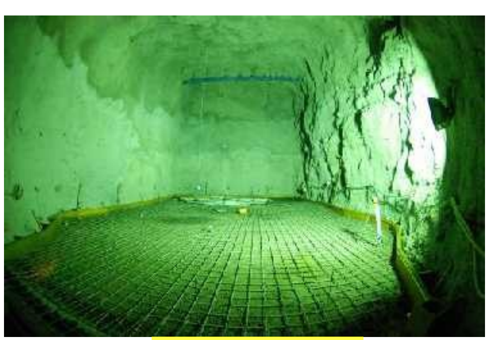


EGADS Facility in Kamioka Mine



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

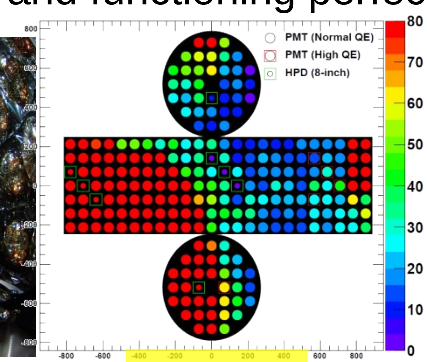
EGADS:



12/2009

11/2011

8/2013



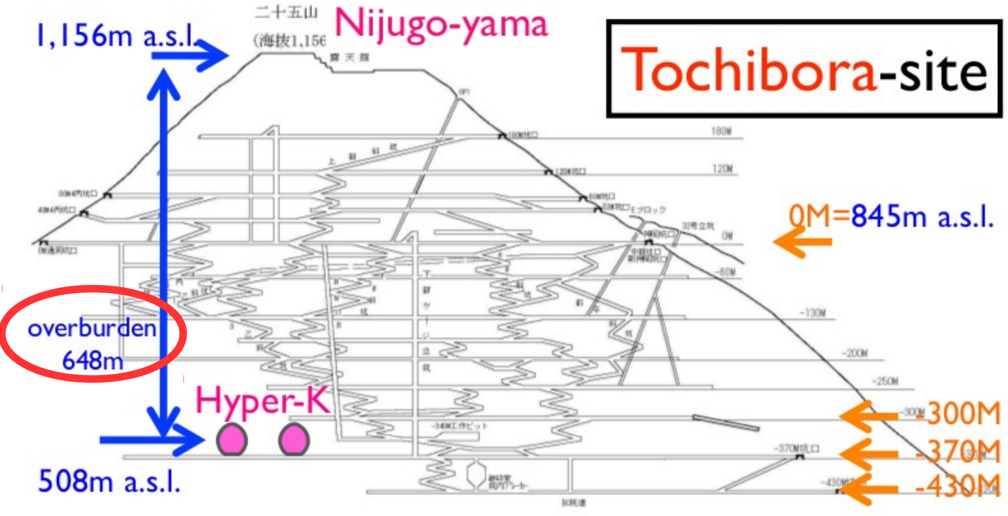
6/2015

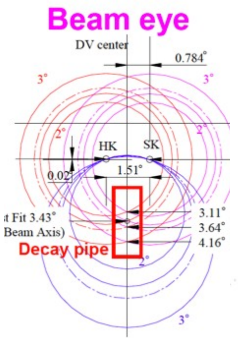
Site(s) and Cavern(s)

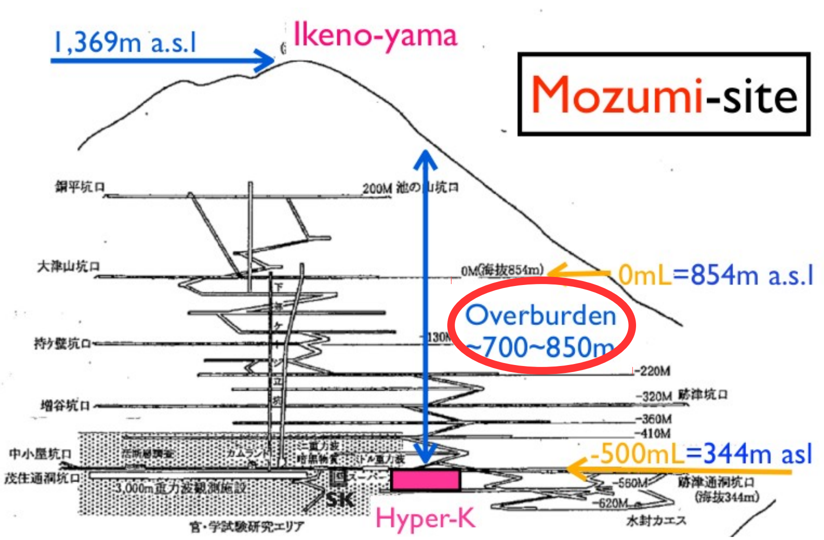
Two options but nominal case is Tochibora.

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





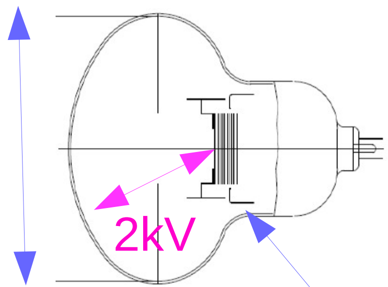


Photosensors Candidates

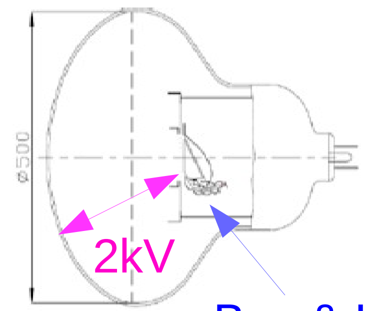
R&D going to get better performance and lower costs

	Established (**SK PMT**)	R&D (**HighQE/CE PMT**)	R&D (**HighQE hybrid det.**)

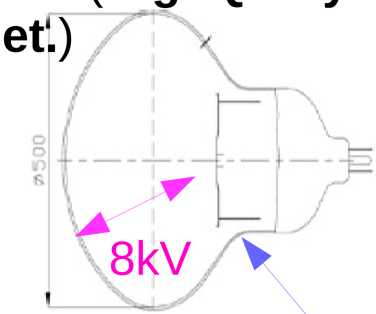
50cm



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

Ongoing tests in EGADS

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

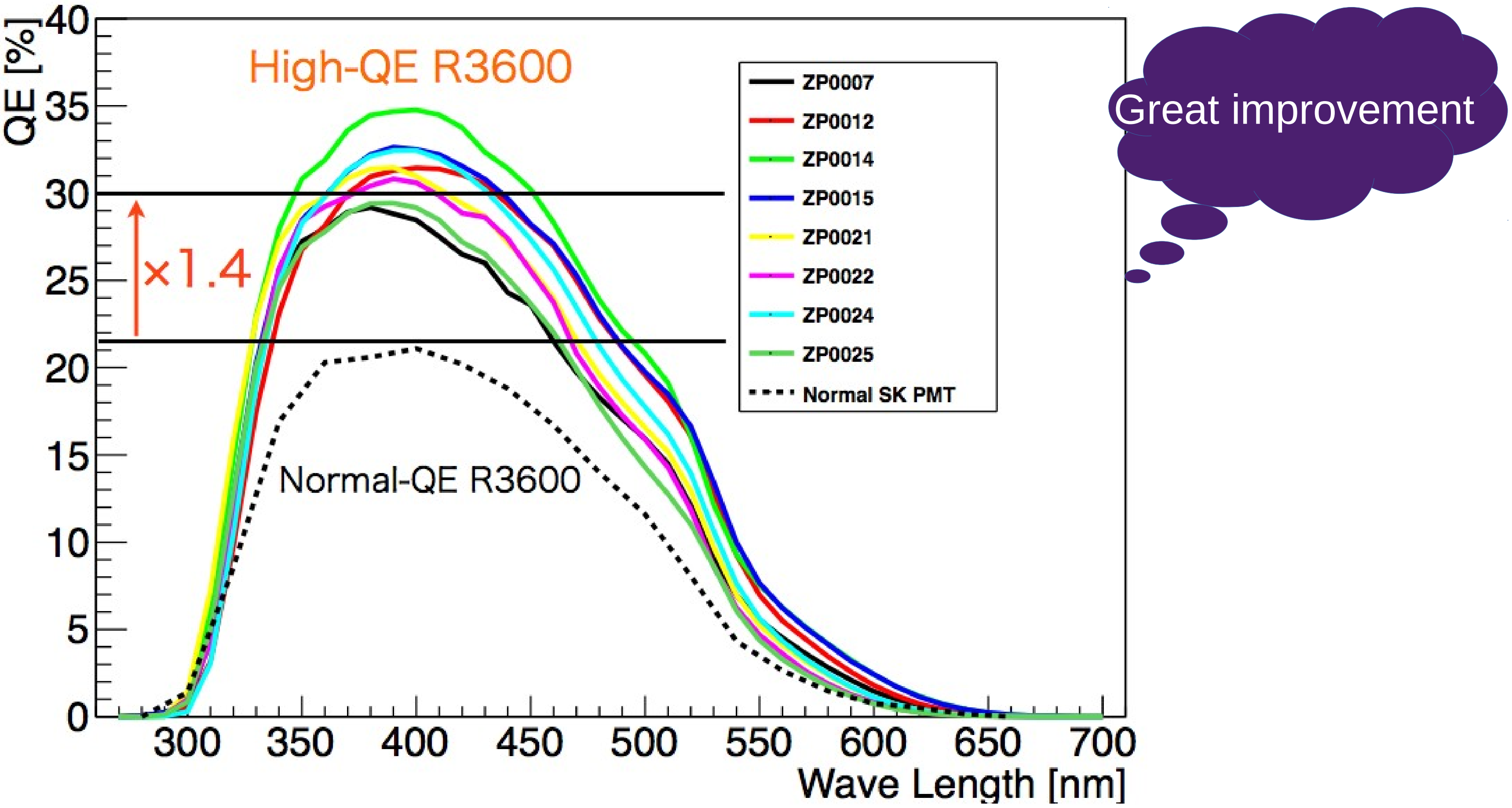
HighQE/CE PMT:
- Under development
- Better performance
- Same technology → Lower risk

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

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

Lower Risk ⟵ ⟶ Higher Performance

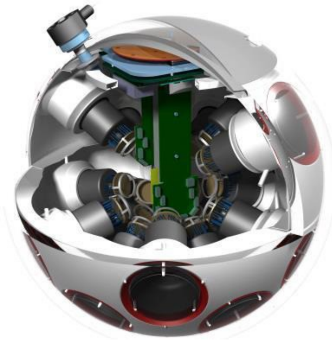
High QE achieved



- 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

Alternative Options

Synergy with KM3NET

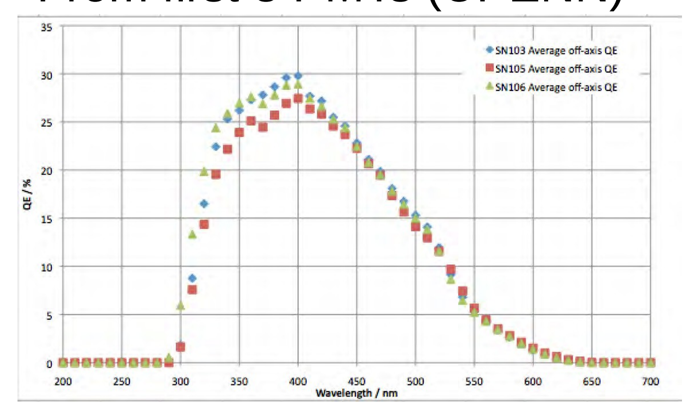


- MultiPMTs with 3inch PMTs based on KM3Net design seems to be promising and affordable alternative.
- MultiPMTs automically solve problems with pressure, in-water electronics, magnetic field cancellation and provide options for an integrated OD.
- Current 3inch PMTs are sufficient for Hyper-K.

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)

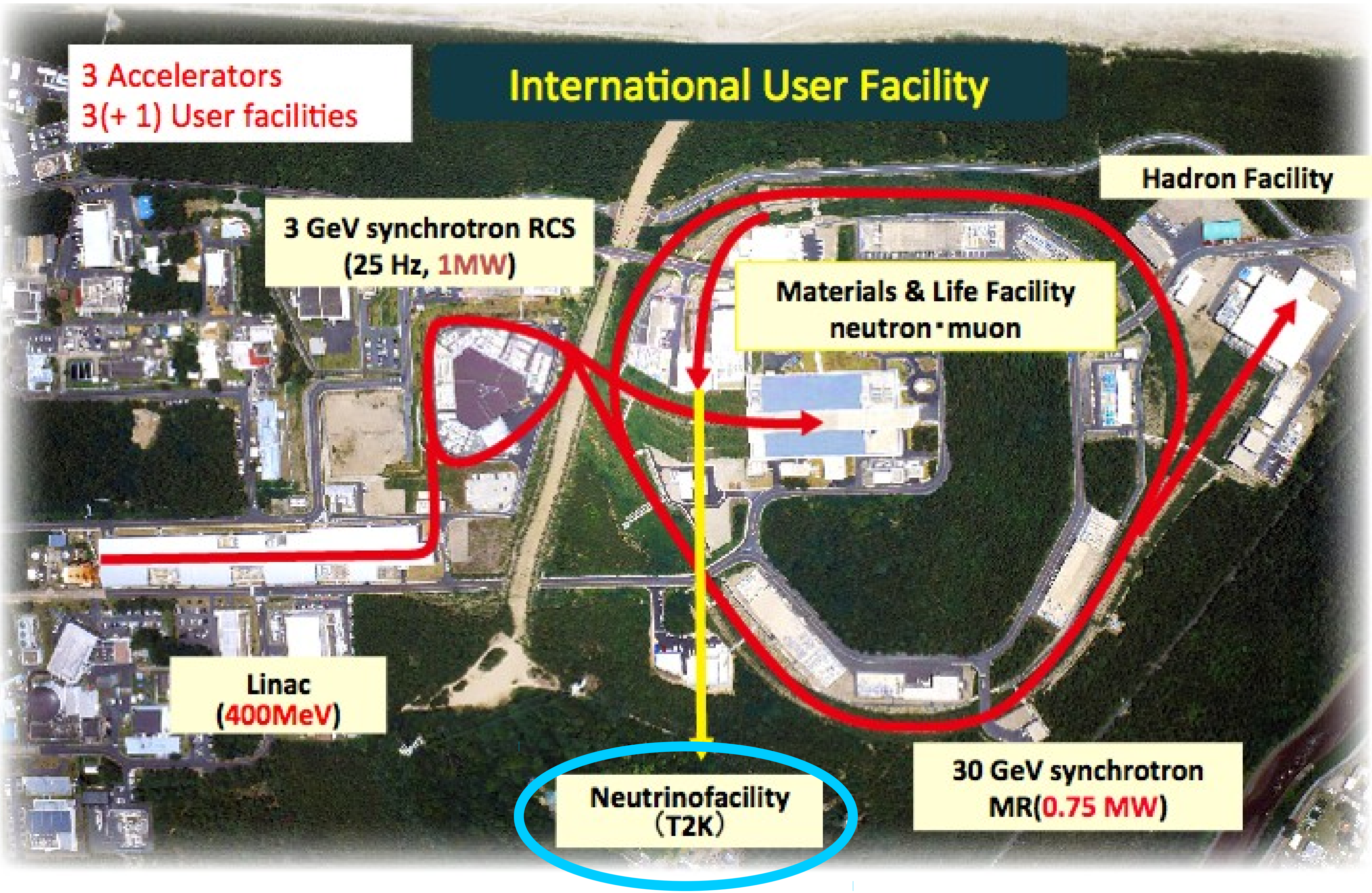


World-wide R&D

Lot's of activities started

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

Hyper-Kamiokande Beam



Neutrino Flux for Hyper-Kamiokande

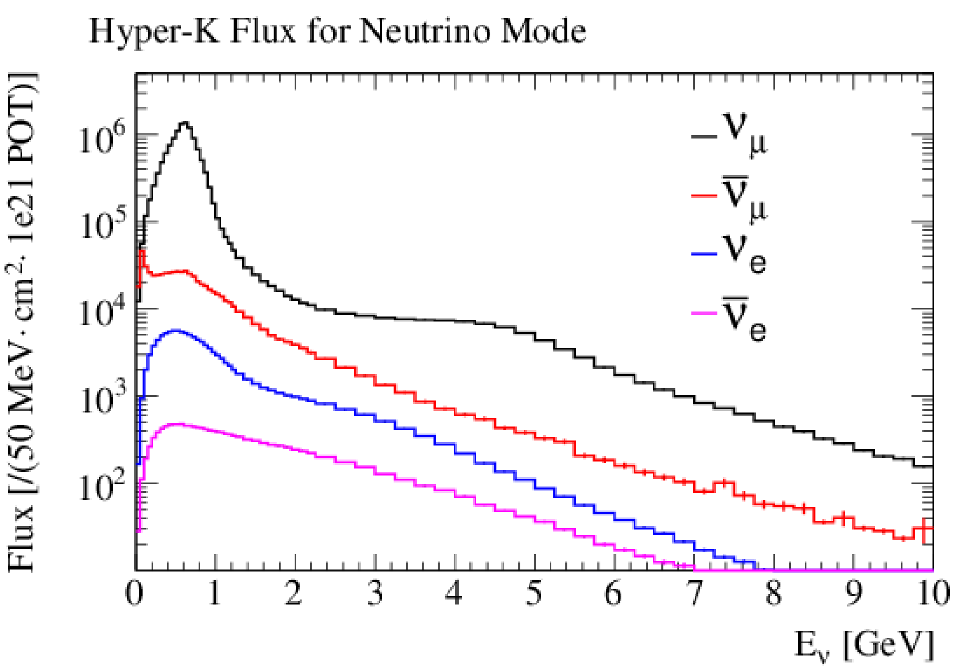
- At least 750kW expected at the starting of the experiment.
- Assumed **7.5MW × 10^7 s** (1.56 × 10^{22} POT) for the following sensitivity studies
  - 10 years are needed if 750kW per 10^7s/year
  - 5 years assuming 1.5MW per 10^7s/year
  - Nominal beam sharing between ν and $\bar{\nu}$-mode beams

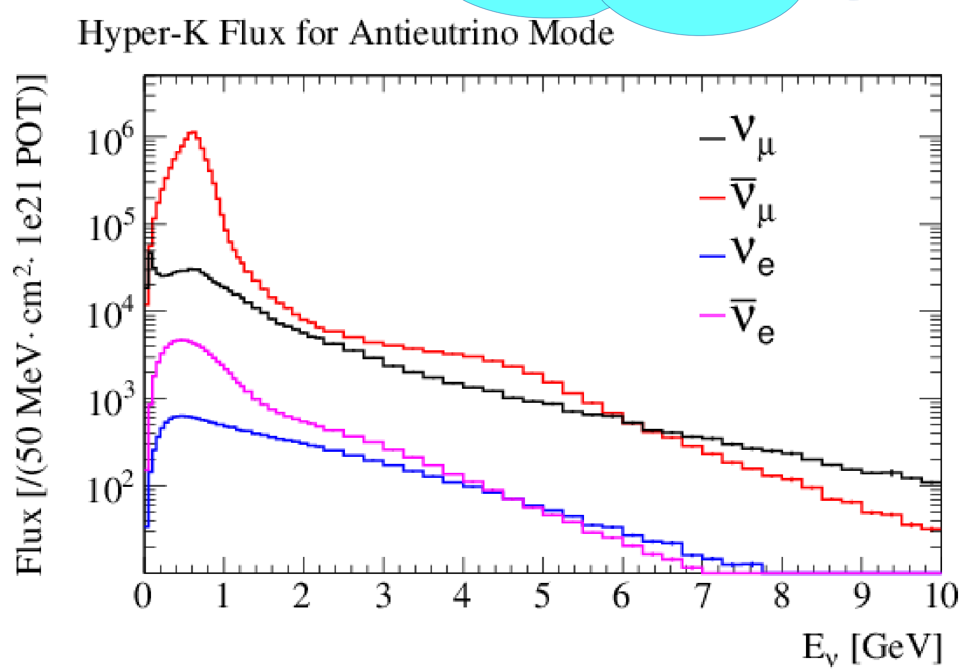
ν-mode: $\bar{\nu}$-mode => 1 : 3

To take into account latest plans on the accelerator

Neutrino vs antineutrino optmized in 2014. Can be-reoptimized with latest errors,

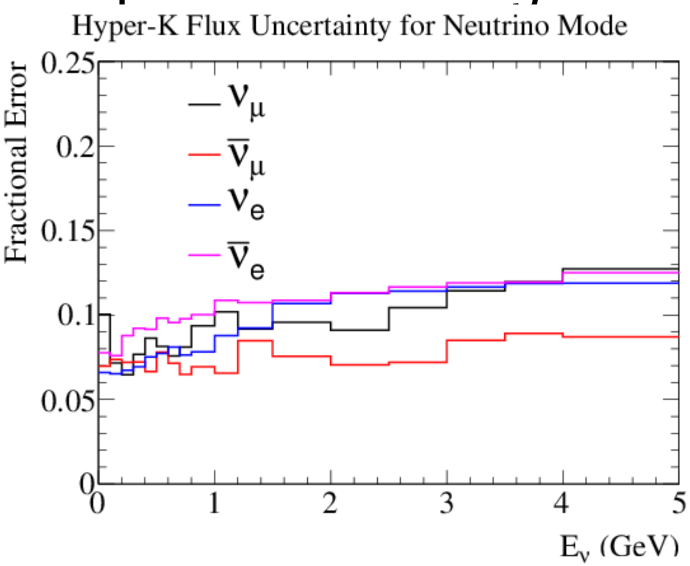
Expected unoscillated neutrino flux at Hyper-K

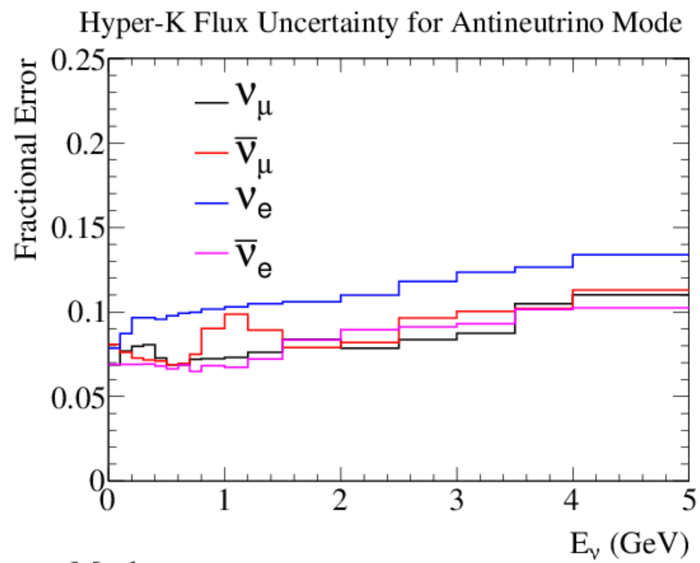




Flux Calculation

- 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

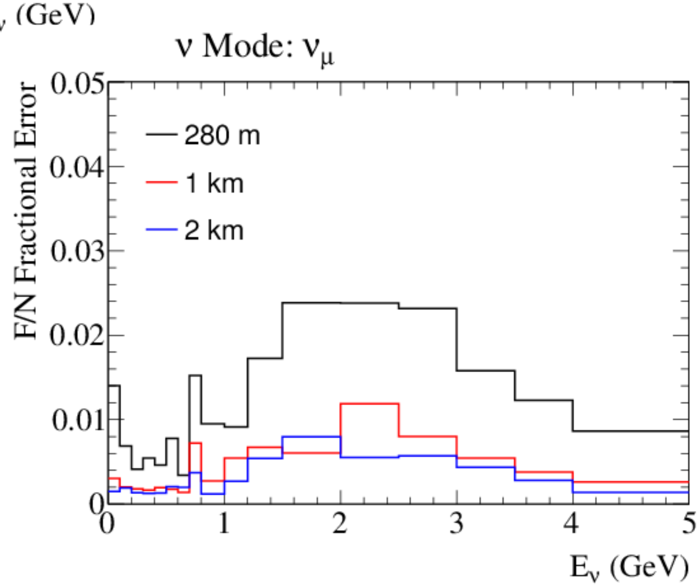


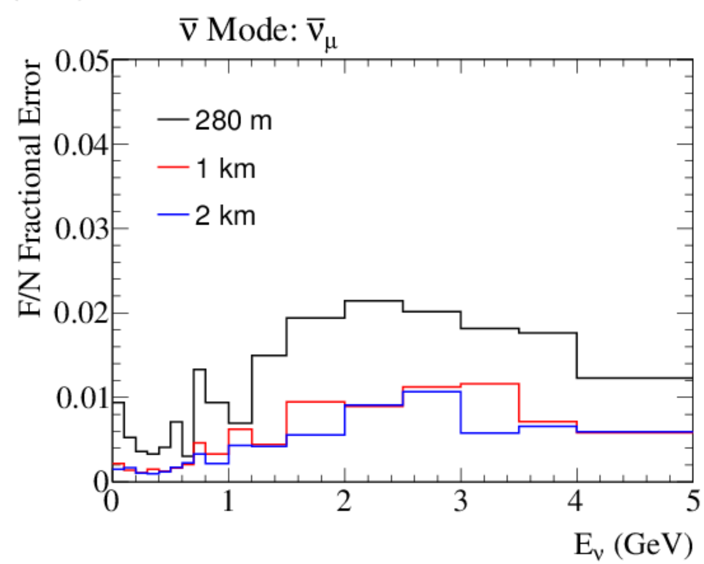


Predicted uncertainty in the neutrino flux calculation assuming replica target hadrn production data

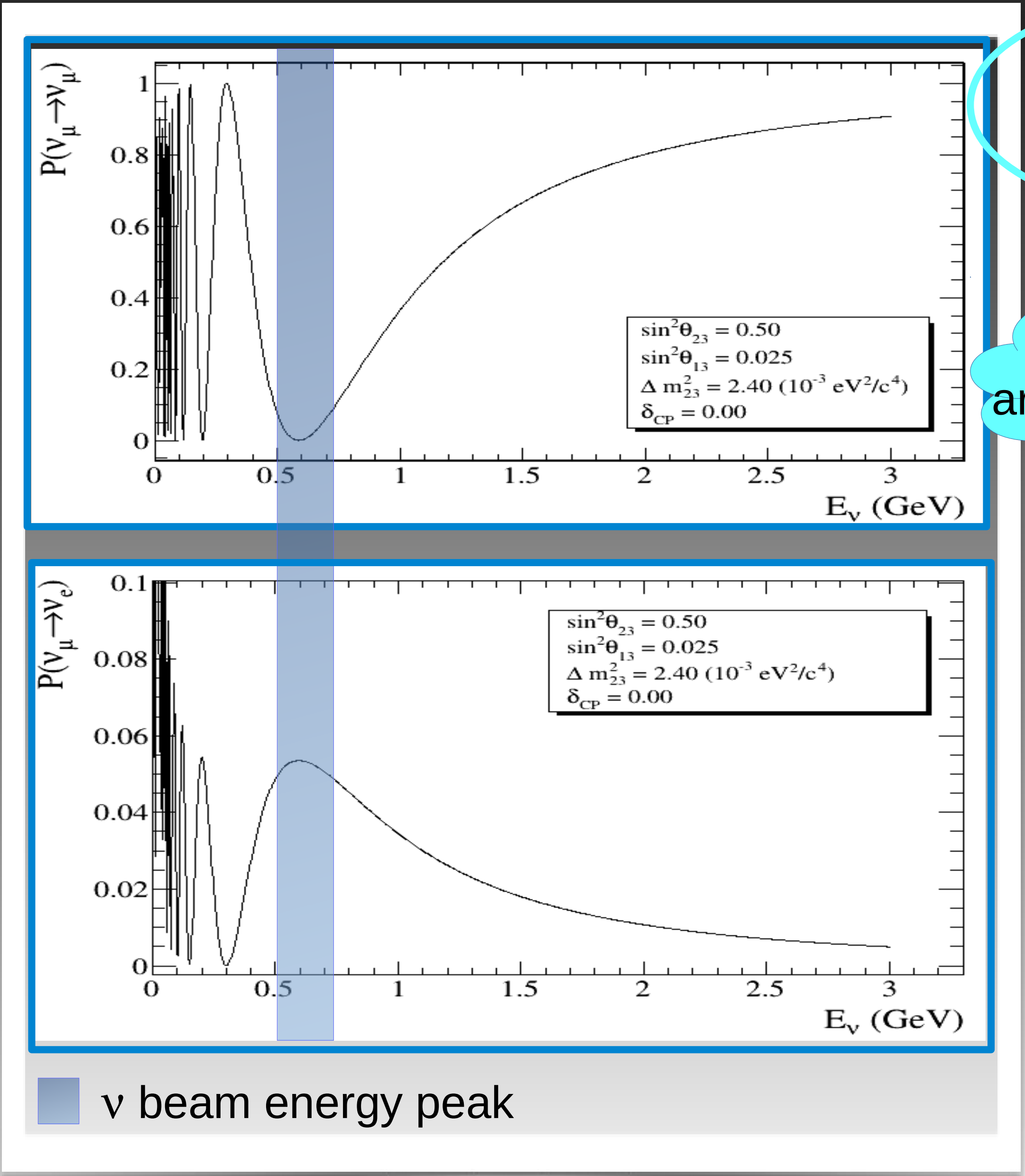
The uncertainty on the near-to-far flux ratio for near detectors at 280m/1km/2km

Possible baselines for near/intermediate detectors





The Physics Potential



Results published in:

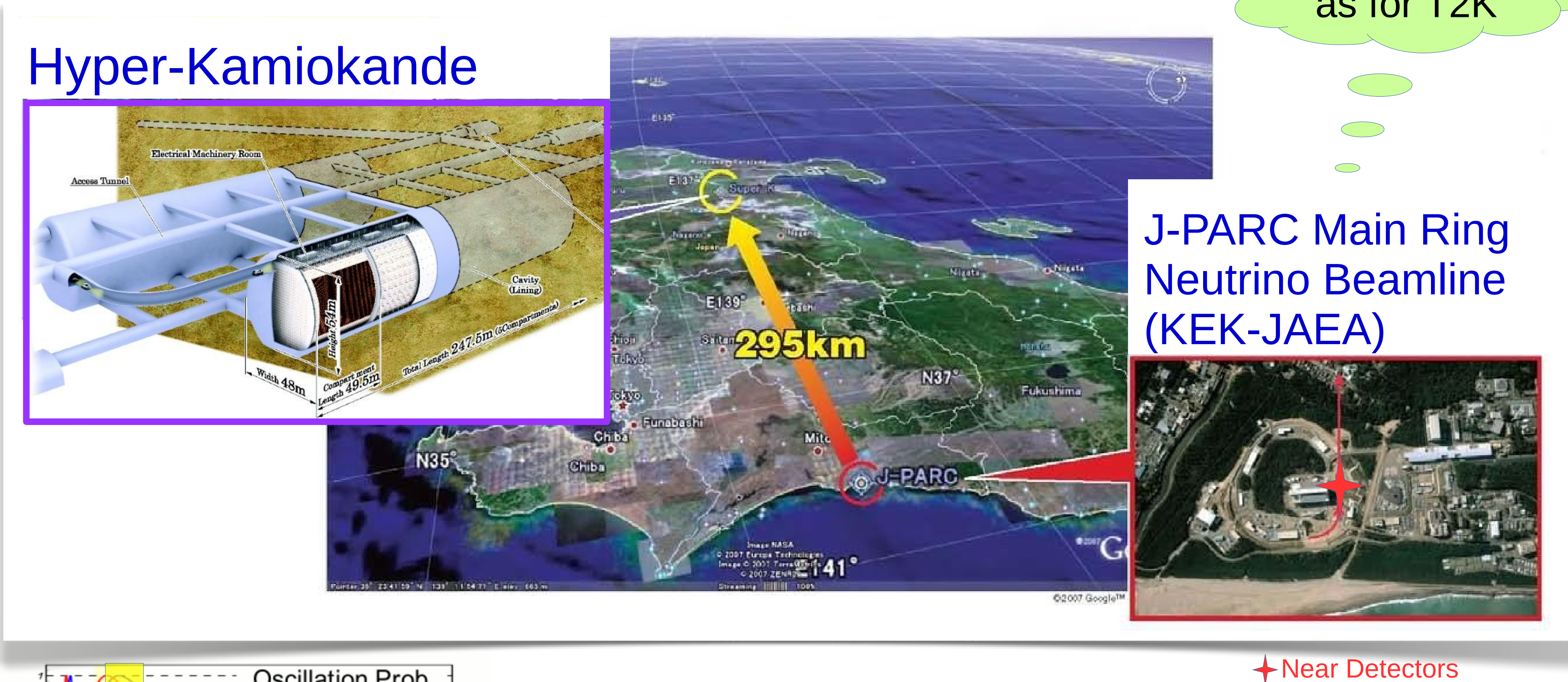
PTEP 2015 053C02

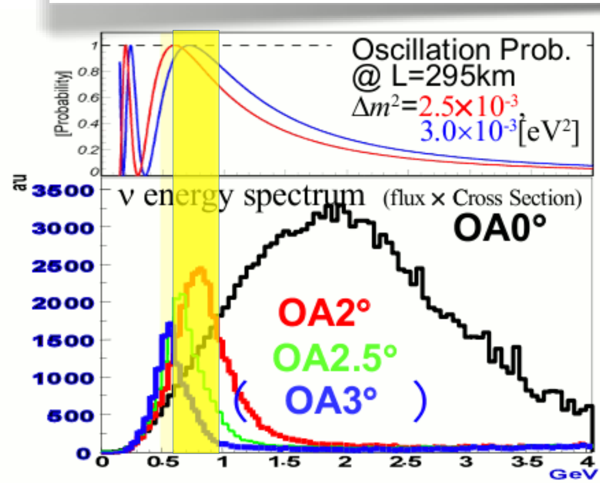
Updated results are being worked on

Tokai to Hyper-Kamiokande

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

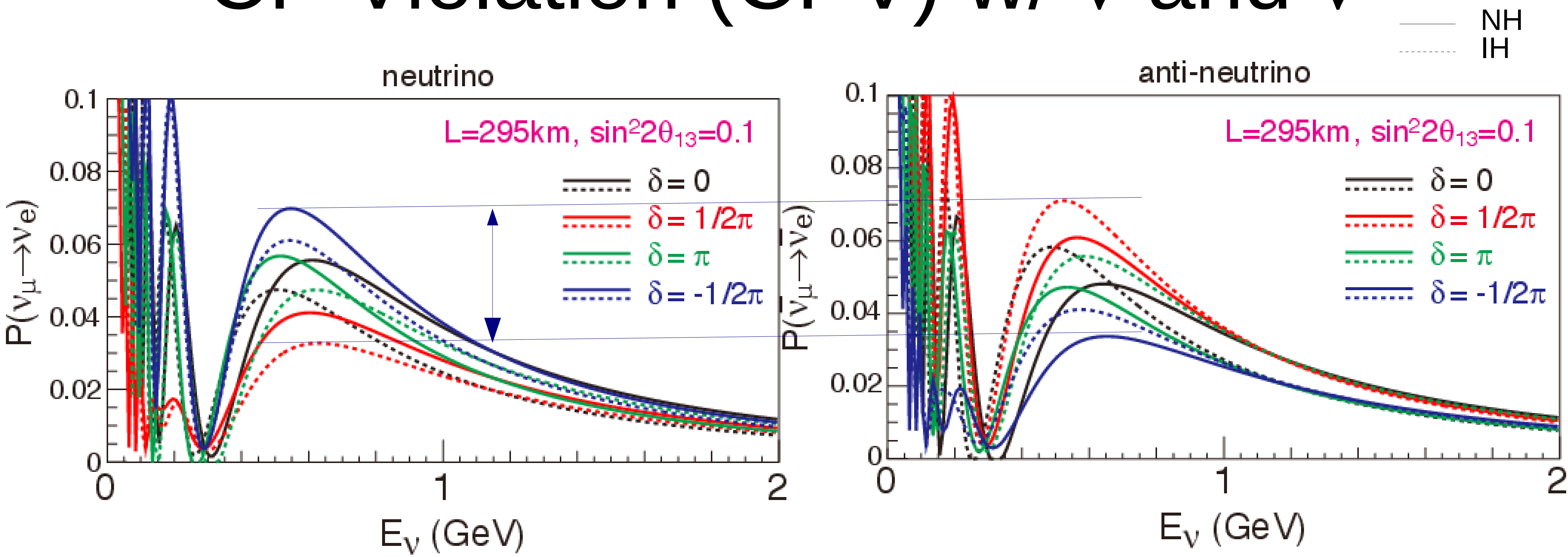
Same strategy as for T2K





- 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 $\bar{\nu}$



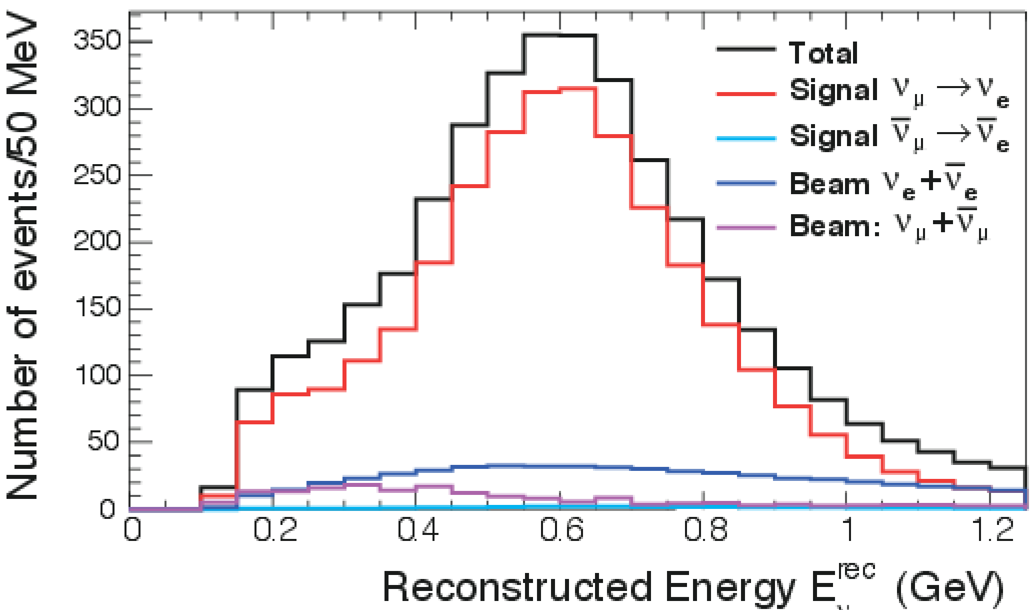
- CP Violation will manifest itself in neutrino oscillations:

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

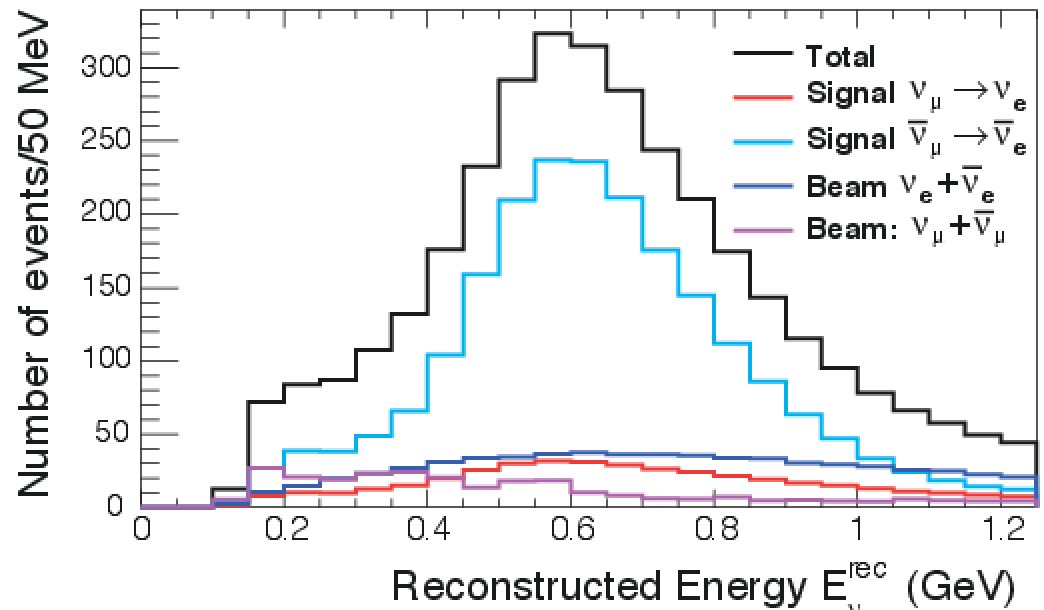
- CPV cannot show up in the disappearance oscillations ($\alpha = \beta$).
- CPV requires all mixing angles to be non zero.
- For Hyper-K: max. ~±25% change from δ=0 case.
- Sensitive to exotic (non-PMNS) CPV source

Expected Events

Appearance ν mode



Appearance $\bar{\nu}$ mode



Appearance	Signal		Background					Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	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

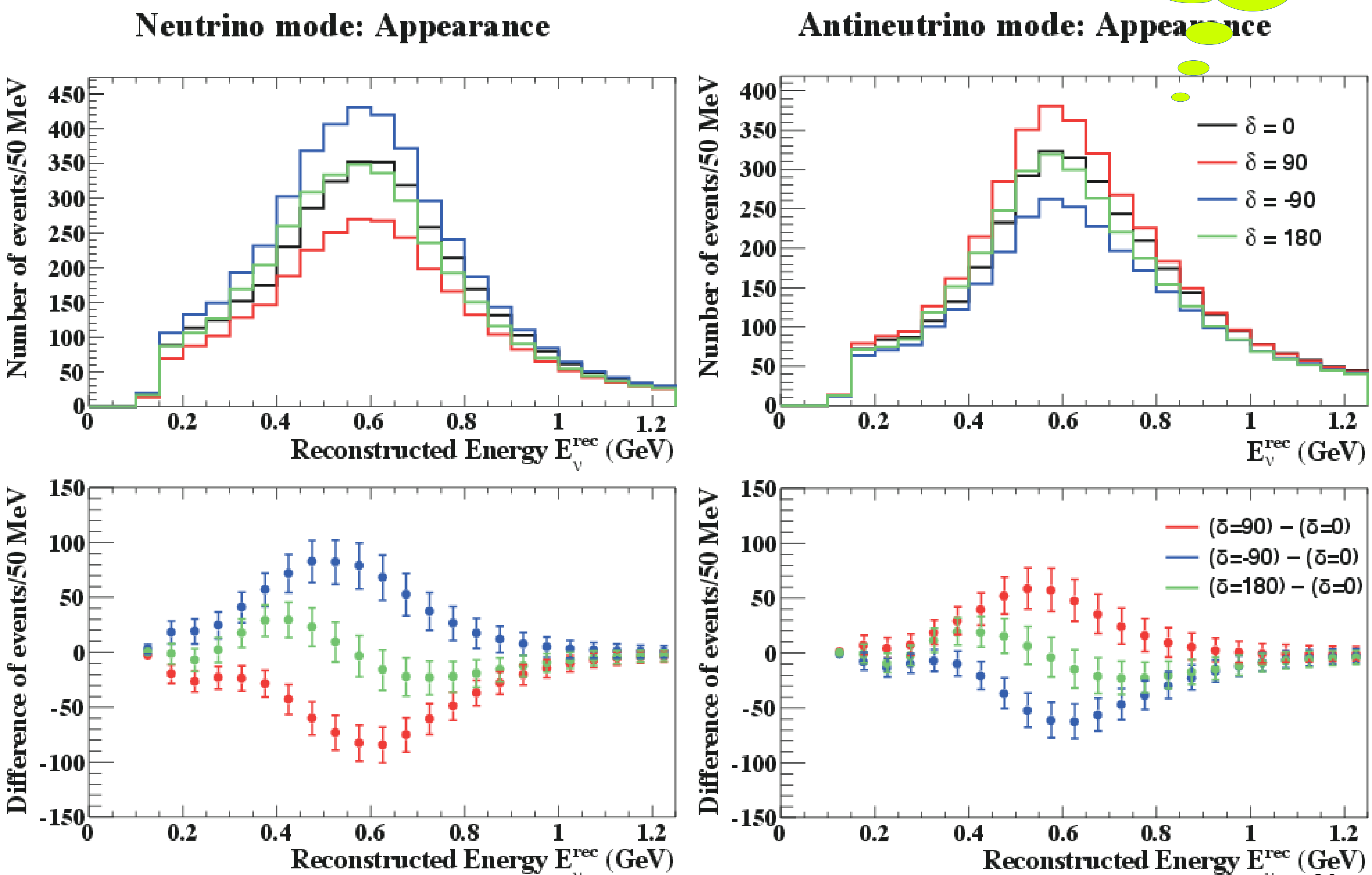
Disappearance	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	$\nu_\mu \rightarrow \nu_e$	Total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

Large statistics

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

Expected Events

Also shape relevant for CPV



Hyper-K Sensitivity to δ_{CP}

Errors being re-evaluated

- 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

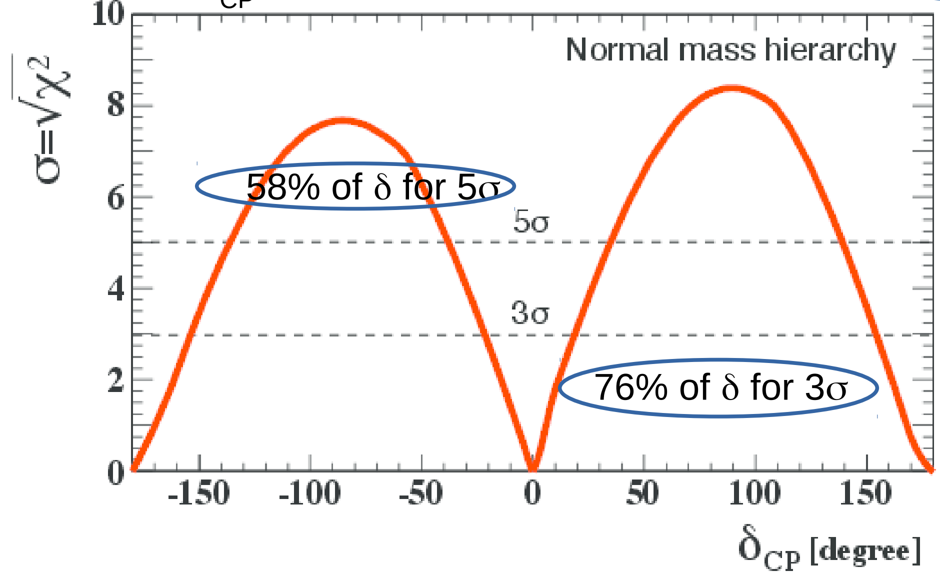
- Planning to update errors and thus sensitivities based on the discussions on the T2K upgrade.

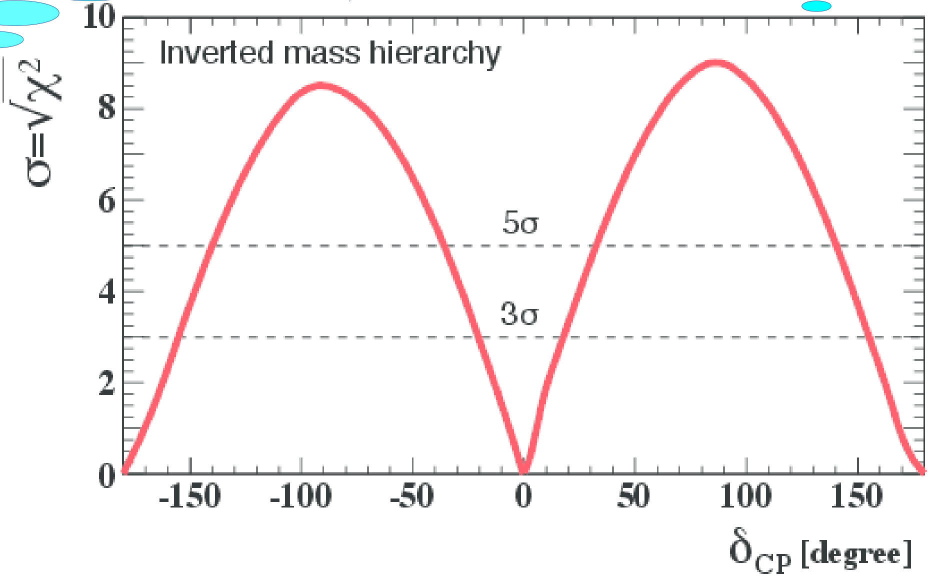
Hyper-K Sensitivity to δ_{CP}

Will improved with updated errors

Assume MH is known

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



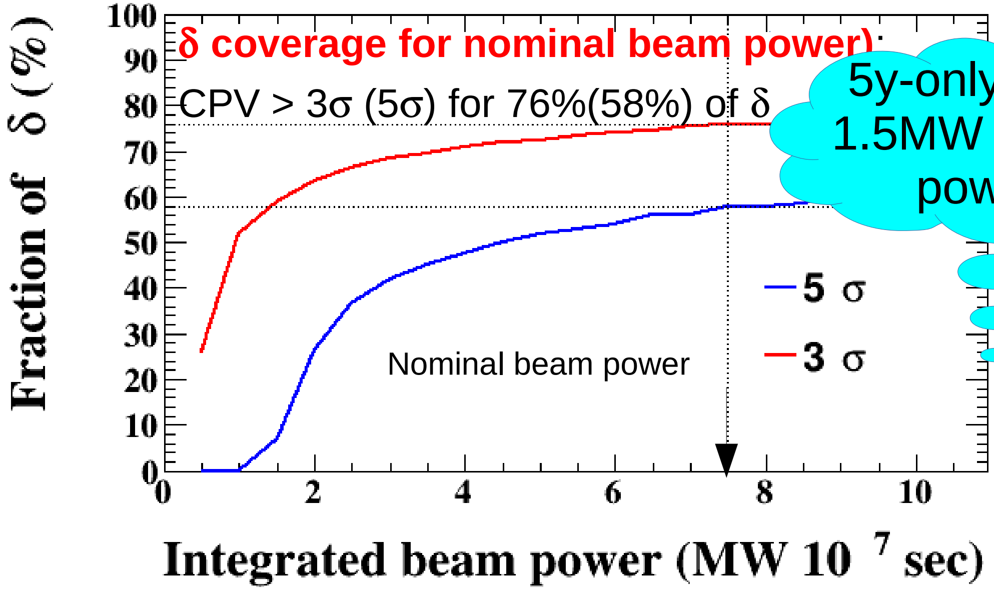


Fractional region of δ(%) for CPV (sin δ ≠0) > 3,5 σ

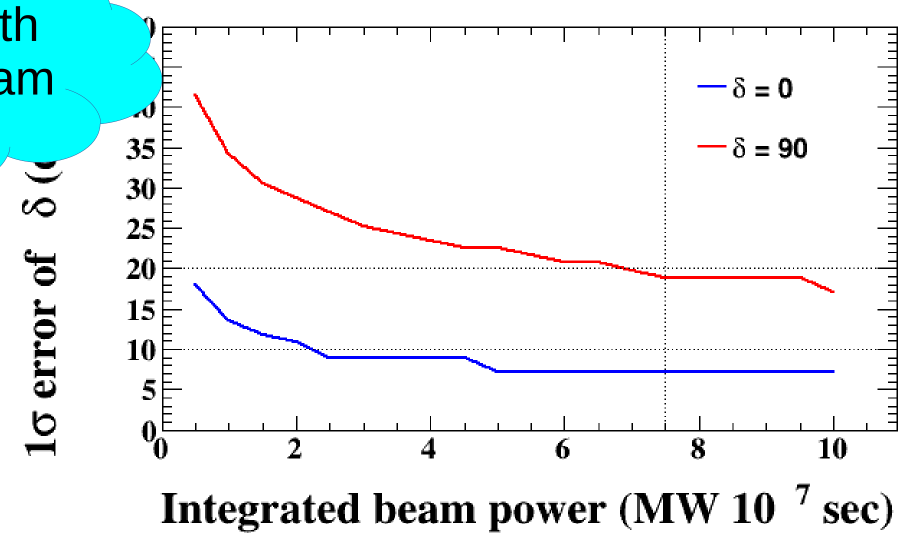
δ coverage for nominal beam power:

CPV > 3σ (5σ) for 76%(58%) of δ

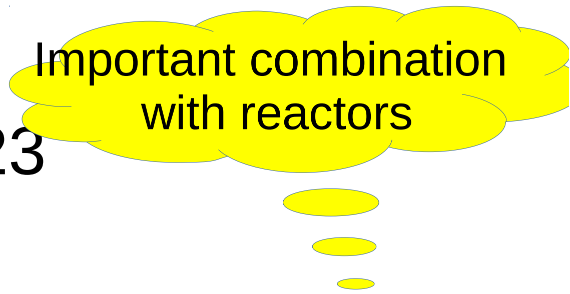
5y-only with 1.5MW beam power



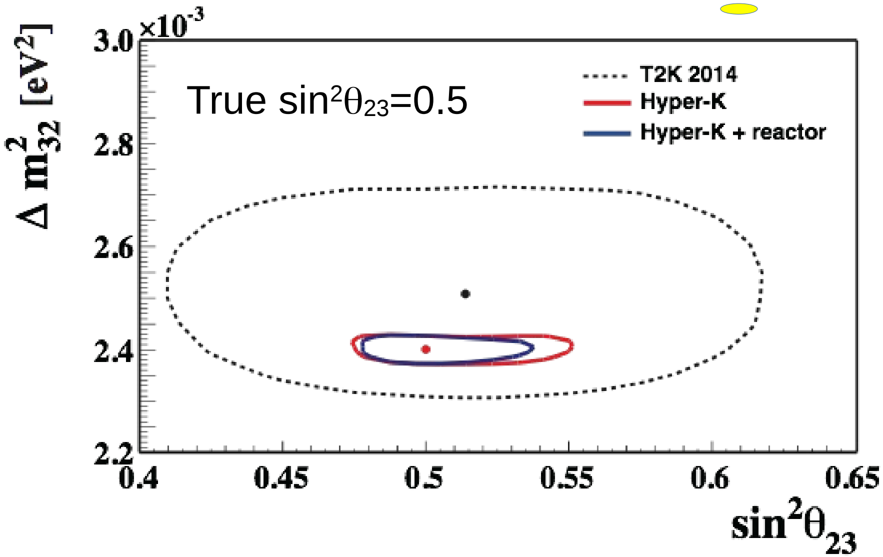
1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)



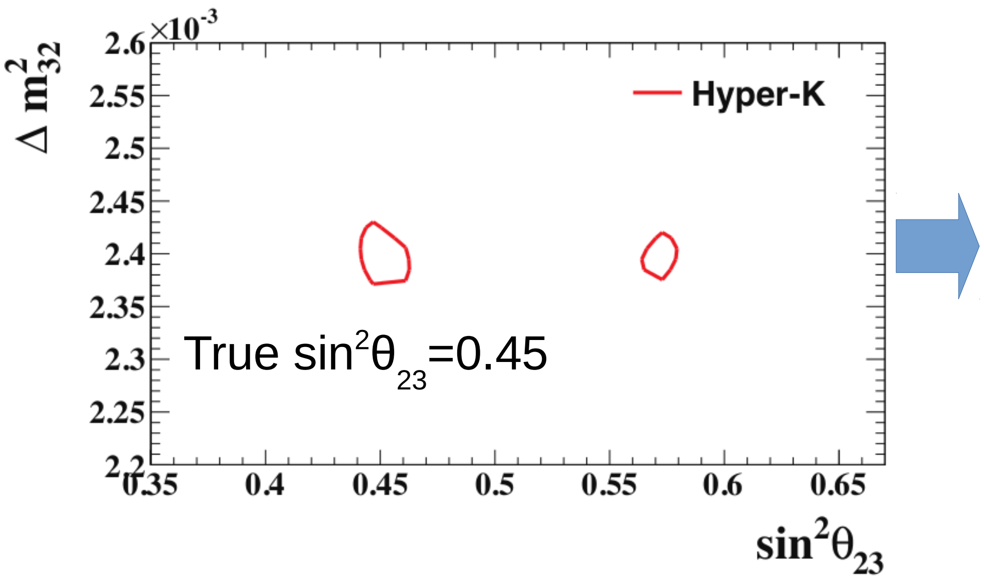
Sensitivity to θ_{23} and Δm^2_{23}

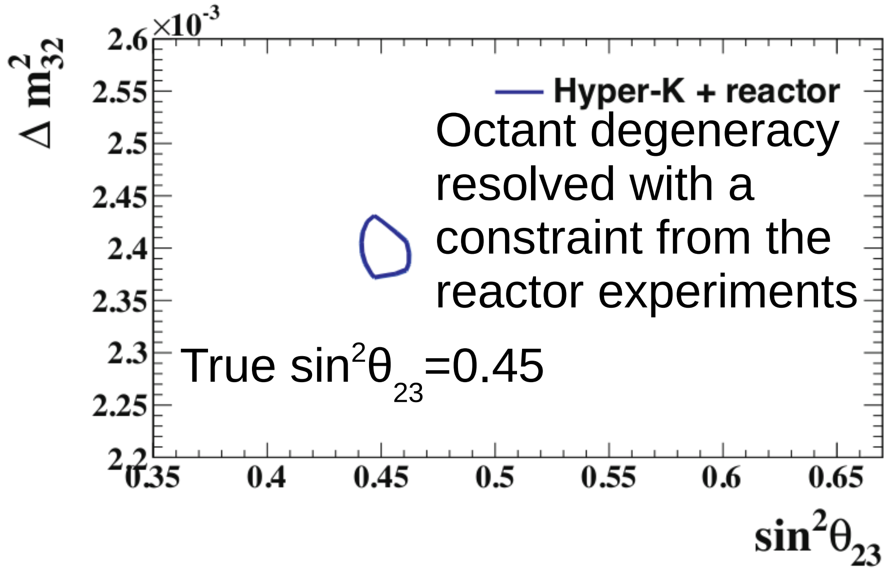


- $\sin^2 2\theta_{23}$ and Δm^2_{23} free parameters as well as $\sin^2 2\theta_{13}$ and δ_{CP} in the fit.
- Octant resolution w/ reactor θ_{13}: ~3σ wrong octact rejection for $\sin^2\theta_{23}$<0.46 or >0.56



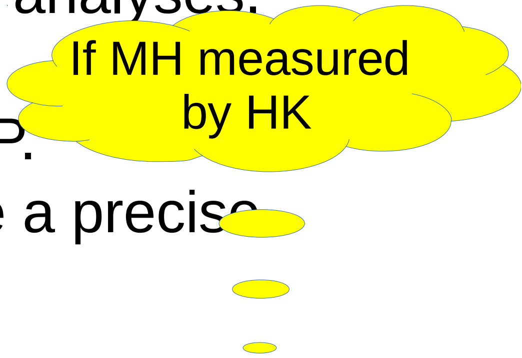
True $\sin^2\theta_{23}$	1σ err $\sin^2\theta_{23}$	1σ err Δm^2_{23} (10^{-5}eV²)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

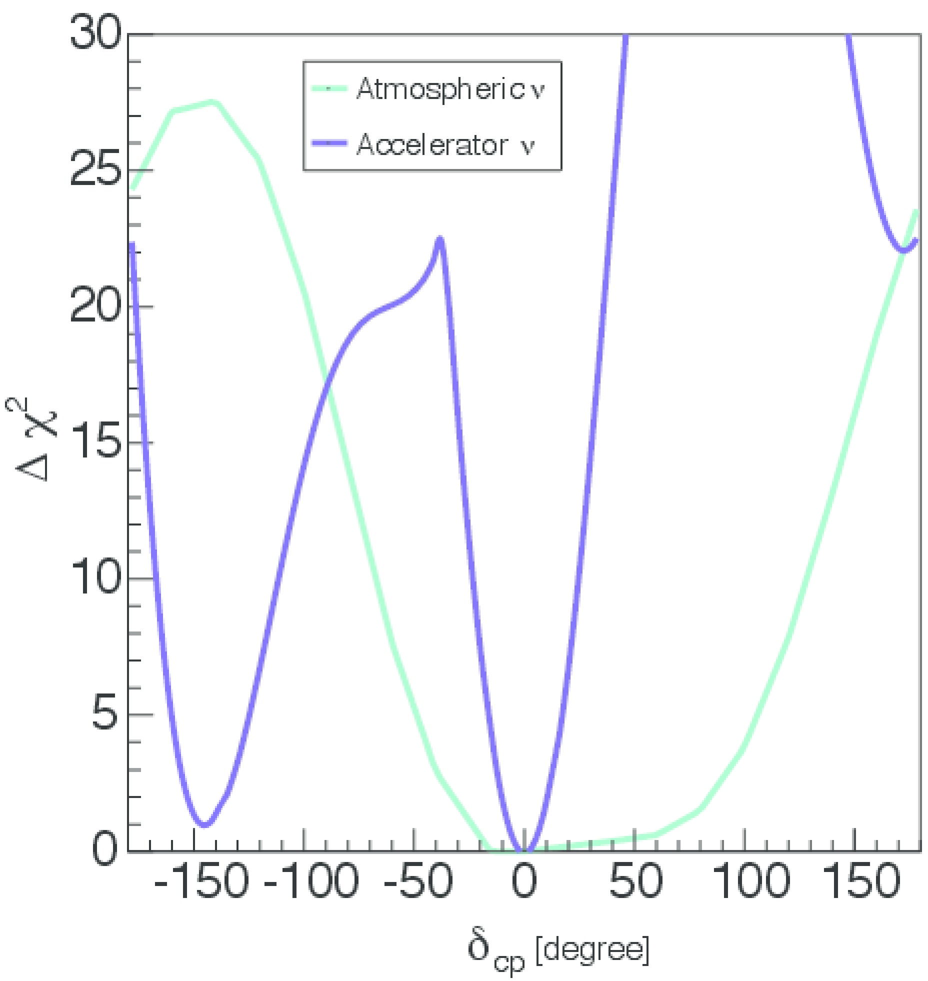


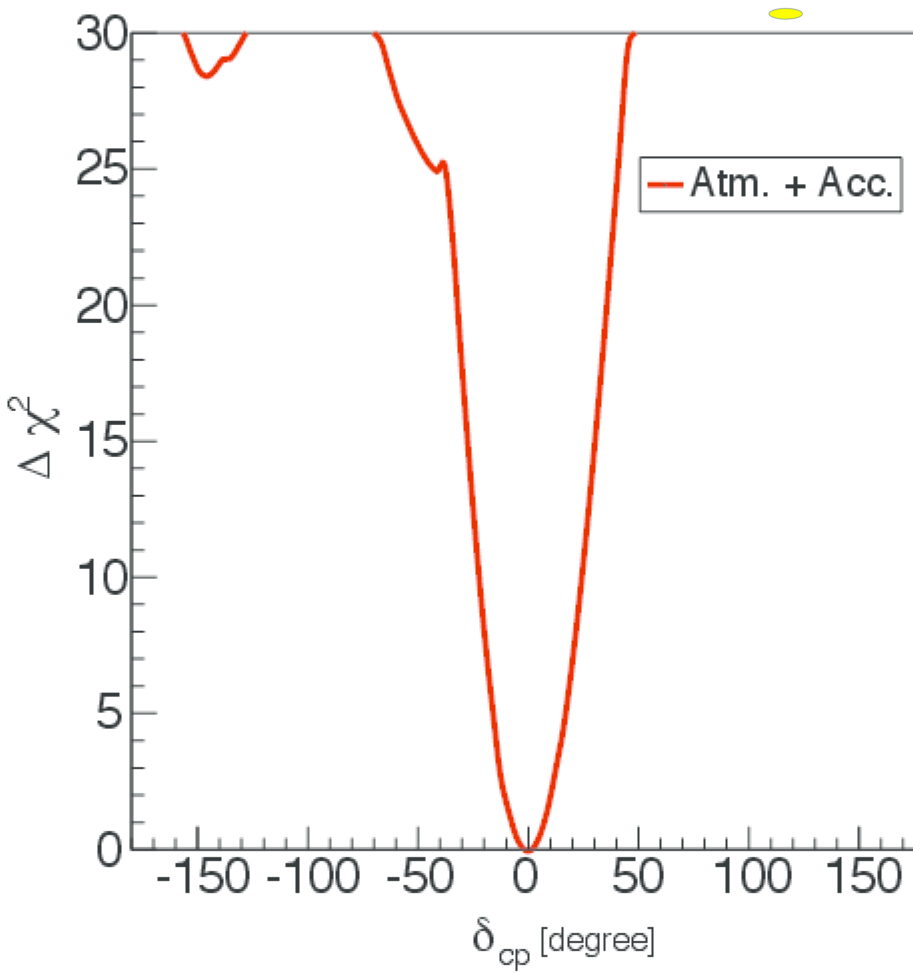


HK ATMP Sensitivity to CPV

- 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.







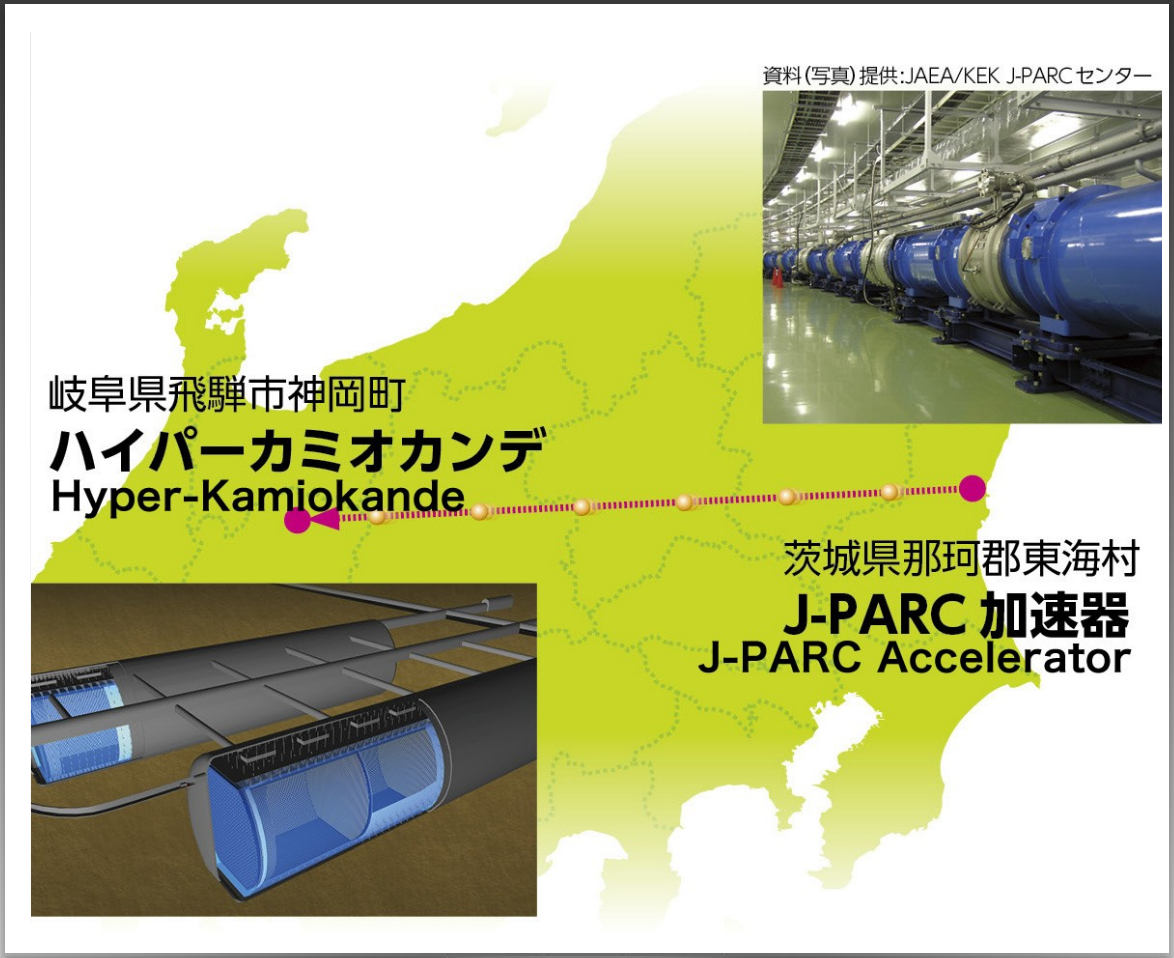
“Other” Beam Physics

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

Studies currently under way
to estimate the sensitivity

Conclusions



Conclusions

Very important latest events

- Formed proto-collaboration (Jan 2015).

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

Great Physics

- 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}
  - Other physics can be addressed.

- Data taking around 2025 with current schedule.

Optimizing design. Seeking approval of the experiment

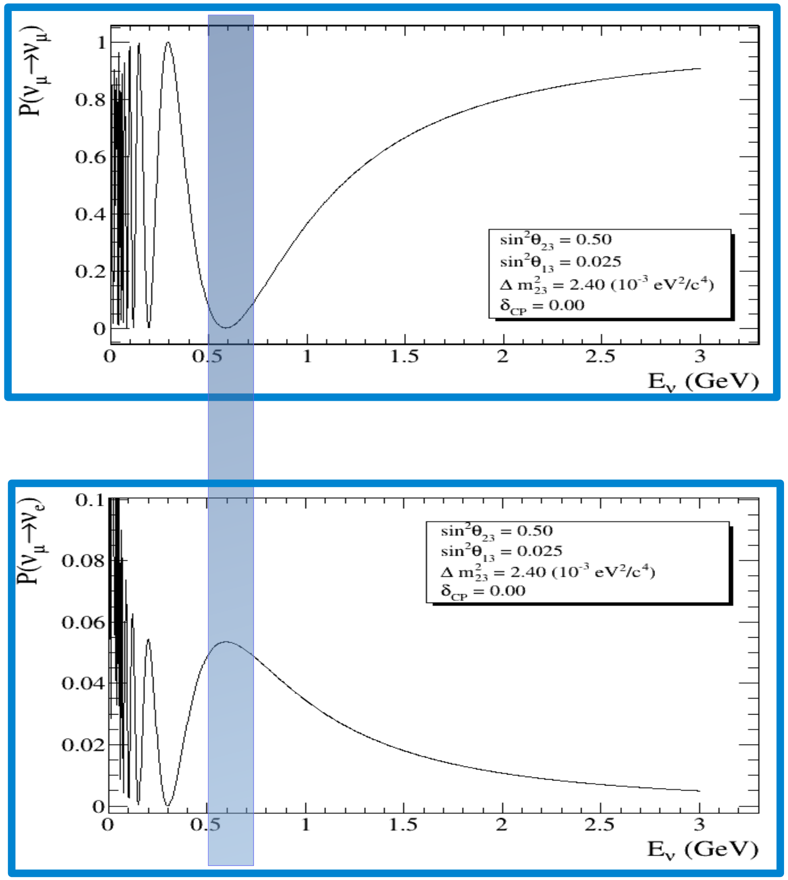
- Work ongoing worldwide on all the aspects of HK

- Optimizing the detector and writing design report. Submit project to SCJ and MEXT to be added to roadmap.

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

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

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**

J-PARC MR power mid/longer-term plan

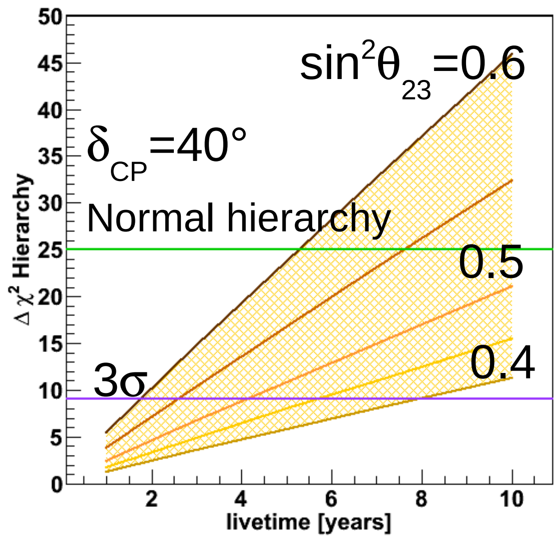
FX: Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, rf cavities, ...
SX: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose.

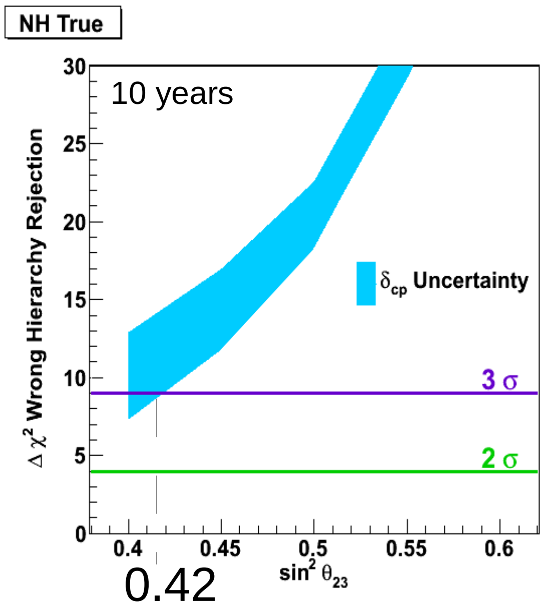
JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 –300 (400)			750 →
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50	→	→	100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s →	2.56 s R&D →	2.48 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.collimators and shields (2kW)	Add.collimators (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		

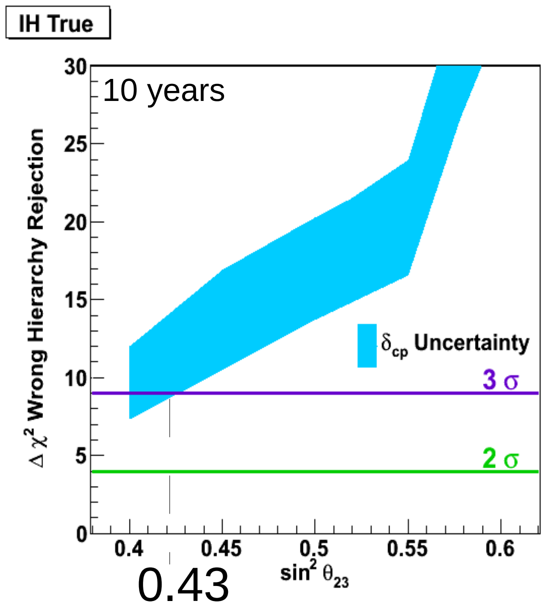
- ~320kW (Mar. 2015) → 750kW in a few years w/ power supply replacement.
- Middle term: continue to lead ν physics with T2K while preparing for Hyper-K
- Longer term: Several ideas under discussion towards multi-MW facility

Hyper-K ATMP Sensitivity to MH

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



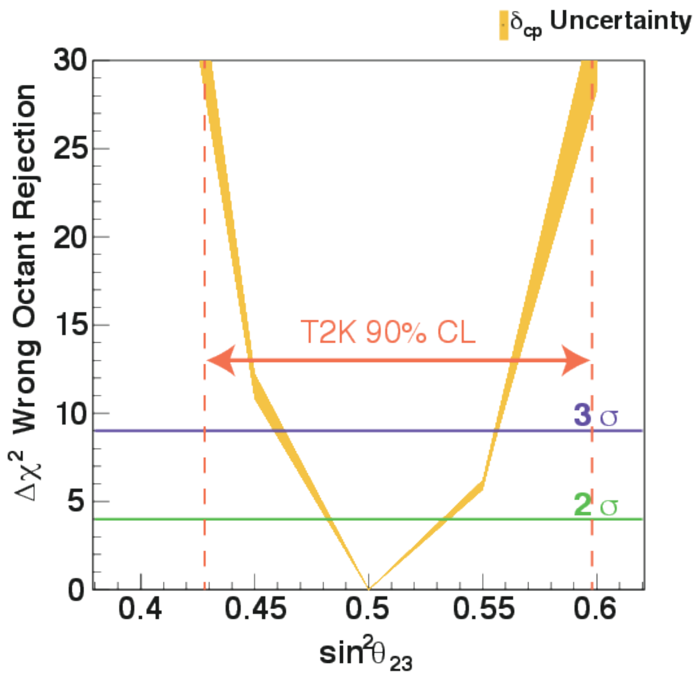




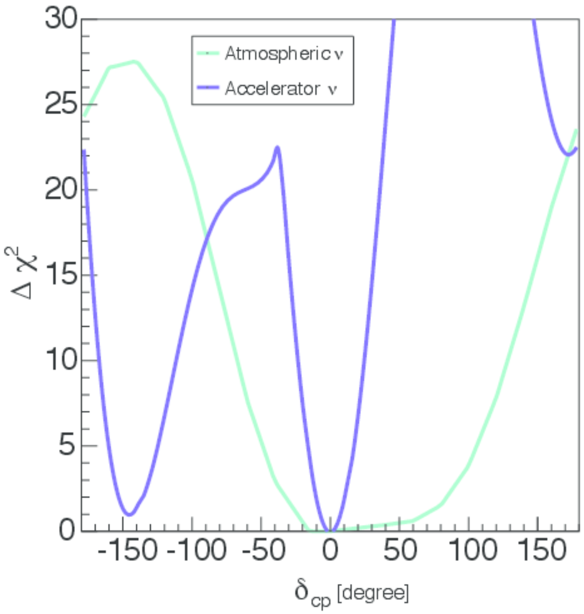
- Use atmospherics for 3σ mass hierarchy determination.
- 3σ mass hierarchy determination for $\sin^2\theta_{23}$ > 0.42 (0.43) for normal (inverted) hierarchy for 10y data taking.
- Also combine with beam data to enhance physics capability.

HK ATMP Sensitivity to Octant & CPV

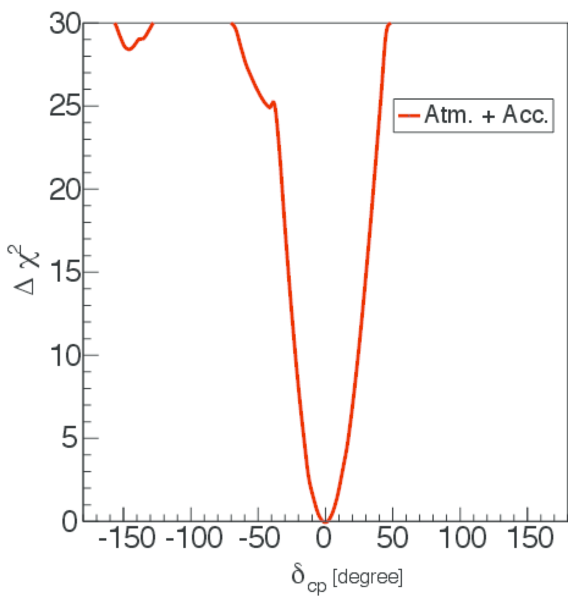
- Using ATMP neutrino events the θ_{23} octant can be determined.
- Discrimination between the wrong octant per each value of $\sin^2\theta_{23}$:



- Accelerator and atmospheric data
- Assumed MH unknown.

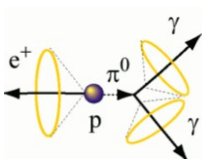


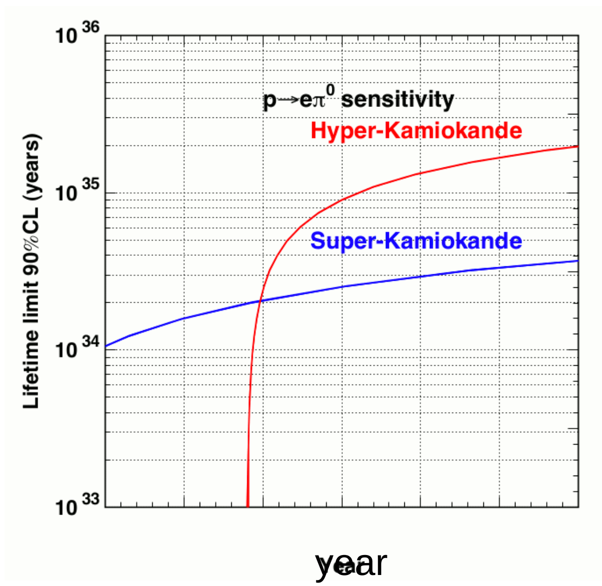
- By combining the two measurements, the CP sensitivity can be enhanced.

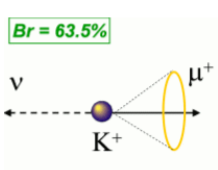


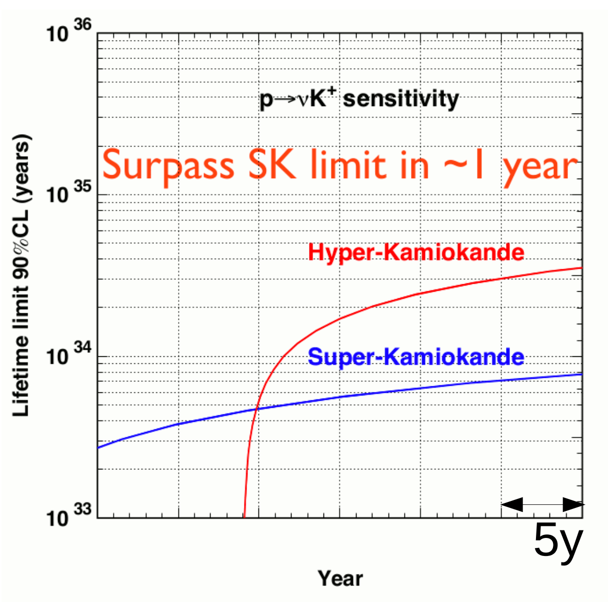
Proton Decay Sensitivity

Surpass SK limit in ~1 year

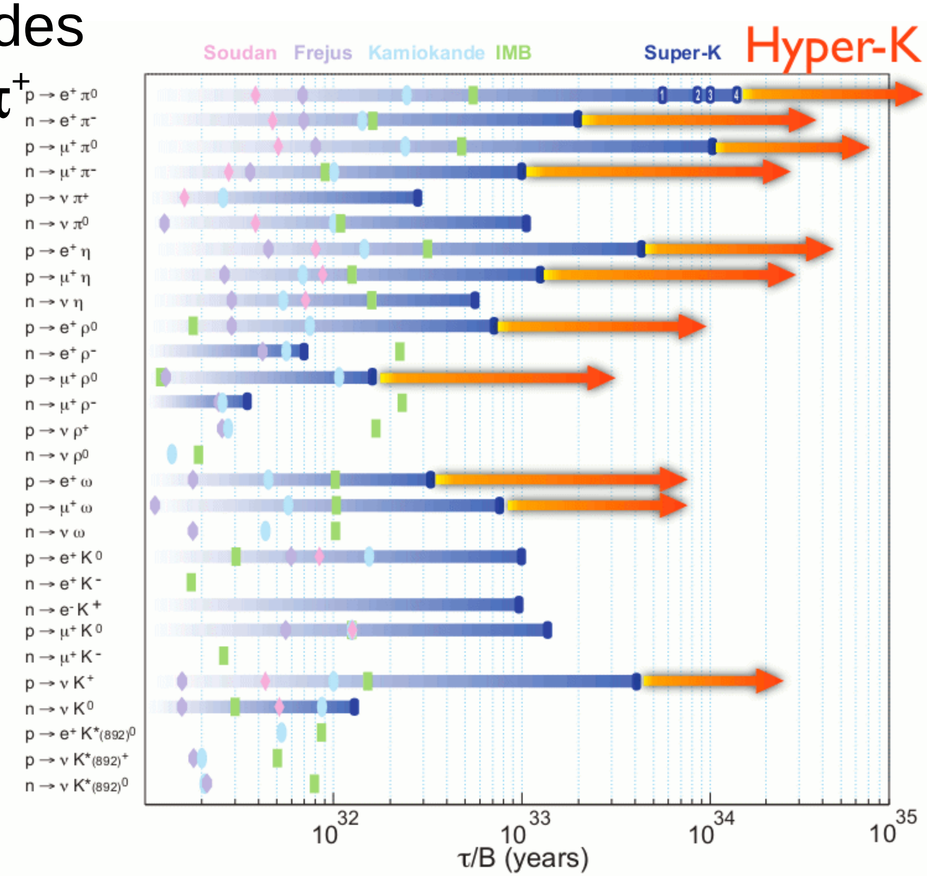








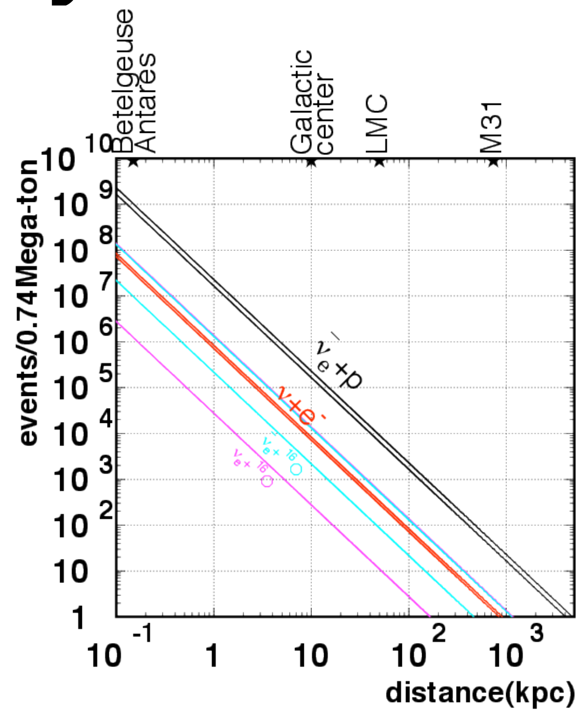
- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
- Hyper-K is sensitive in every single mode
  - $p \to e^+\pi^0$: 1.3×10^{35} y at 90% CL
  - $p \to \bar{\nu}K^+$: 3×10^{34} y at 90% CL
  - Many other modes:
    - p,n → $(e^+,\mu^+) + (\pi,\rho,\omega,\eta)$; $10^{34\text{-}35}$y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



arXiv:1109.3262

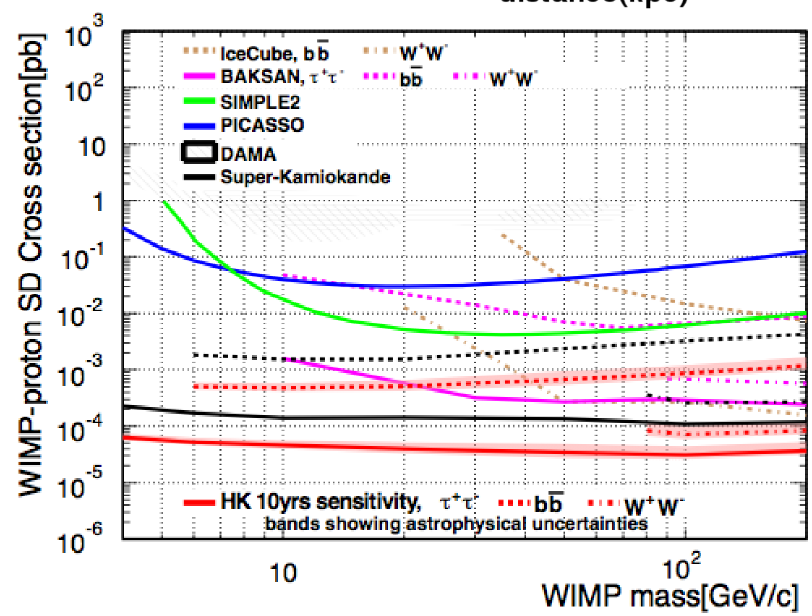
Neutrino Astrophysics

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.