April 21, 2015
@The Second International Meeting
for Large Neutrino Infrastructures

Hyper-Kamiokande

- Exploring Neutrino CP violation -

T. Nakaya (Kyoto/Kavli IPMU)
for the Hyper-K collaboation

A door to Neutrino CP violation is opened

Physics
spotlighting exceptional research

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Viewpoint: Neutrino Experiments Come Closer to Seeing *CP* Violation

Joseph A. Formaggio and , *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Published February 10, 2014 | Physics **7**, 15 (2014) | DOI: 10.1103/Physics.7.15

The T2K experiment has measured the largest number of events associated with muon neutrinos oscillating into electron neutrinos, an important step toward seeing *CP* violation in neutrino interactions.

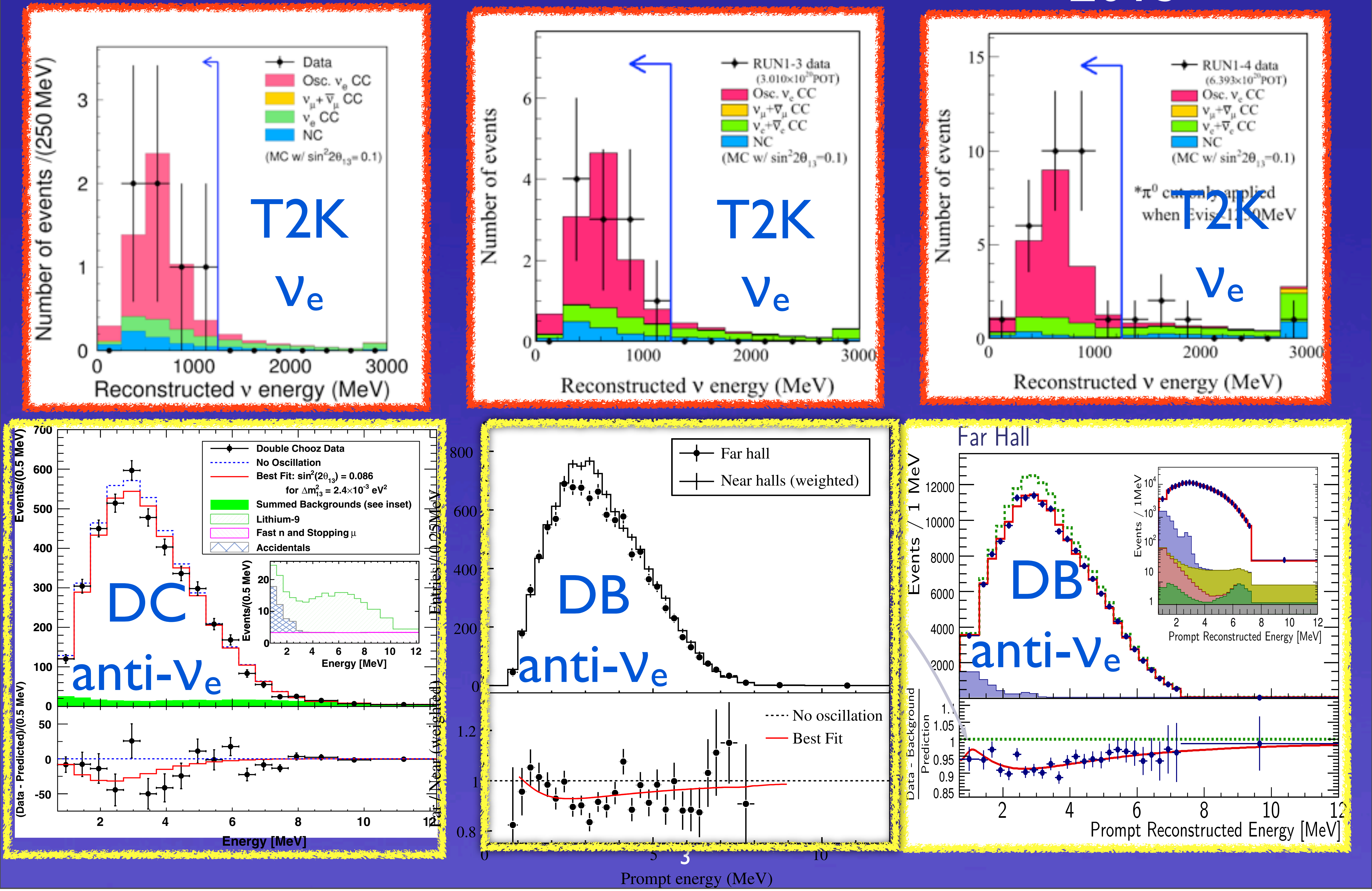
Charge-parity (*CP*) violation—evidence that the laws of physics are different for particles and antiparticles—is often invoked as a "must" to explain why we observe more matter than antimatter in the universe. But the *CP* violation observed in interactions involving quarks is insufficient to explain this asymmetry. As a result, many theorists are looking toward leptons—and, specifically, neutrinos—for additional sources of *CP* violation. Researchers running the Tokai to Kamioka (T2K) experiment—a particle physics experiment at the Japan Proton

Observation of Electron Neutrino Appearance in a Muon Neutrino Beam
K. Abe *et al.* (T2K Collaboration)
Phys. Rev. Lett. **112**, 061802 (2014)
Published February 10, 2014 | PDF (free)

- Indication in 2011 [PRL 107, 041801 (2011)]

History with large θ_{13}

2011 | 2012 | 2013



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Brainstorming

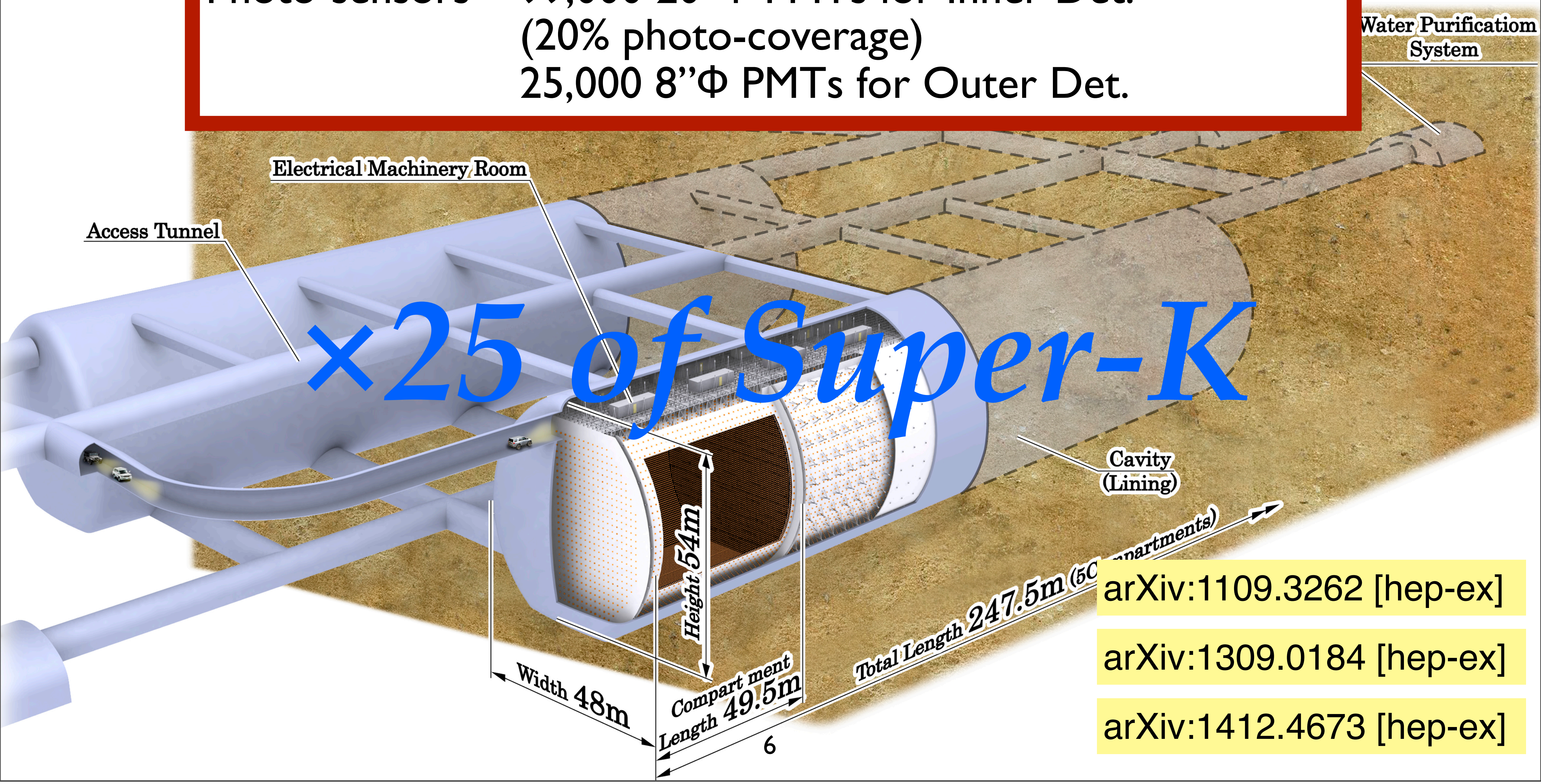
- 28 ν_e events in T2K (~10% of the proposal)
  - Background expected: 4.3 events
    - 3.2 events from beam ν_e
    - 1.0 events from NC interaction (π^0 dominant)
    - 0.1 events from CC ν_μ interaction
  - Signal ($\nu_\mu \rightarrow \nu_e$) calculation: 28-4.3 = 23.7 events.
    - Maximum CPV effects ~25% of the leading term
      - 23.7 * 0.25/(1+0.25) = 4.74 CPV events
- With 100% T2K, we will have ~290 events.
  - ~50 CPV events (An evidence of ν CPV could be seen)

A definitive answer to neutrino CPV

Hyper-Kamiokande

Hyper-K Overview

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 Det. (20% photo-coverage) 25,000 8"Φ PMTs for Outer Det.



arXiv:1109.3262 [hep-ex]

arXiv:1309.0184 [hep-ex]

arXiv:1412.4673 [hep-ex]

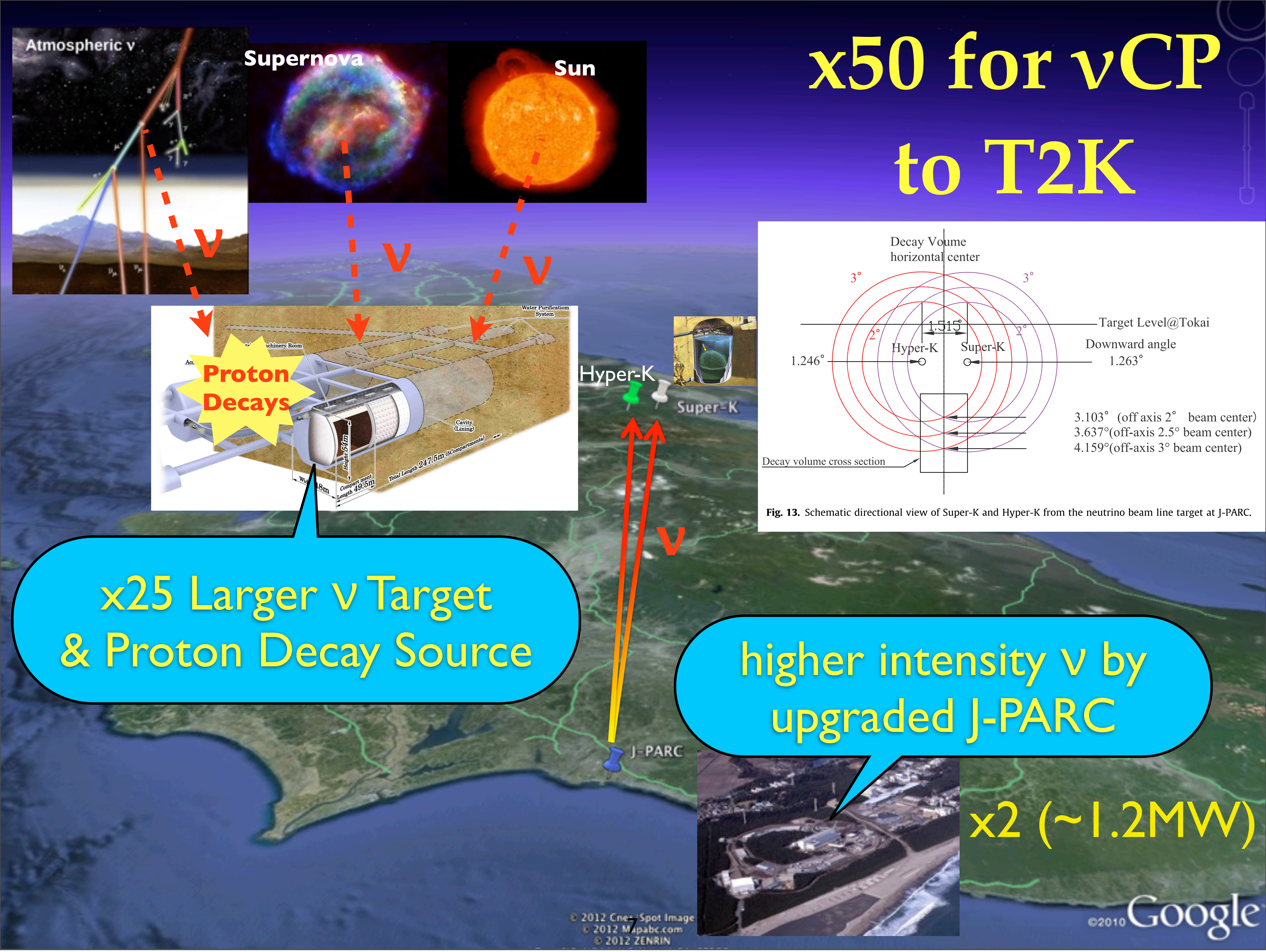


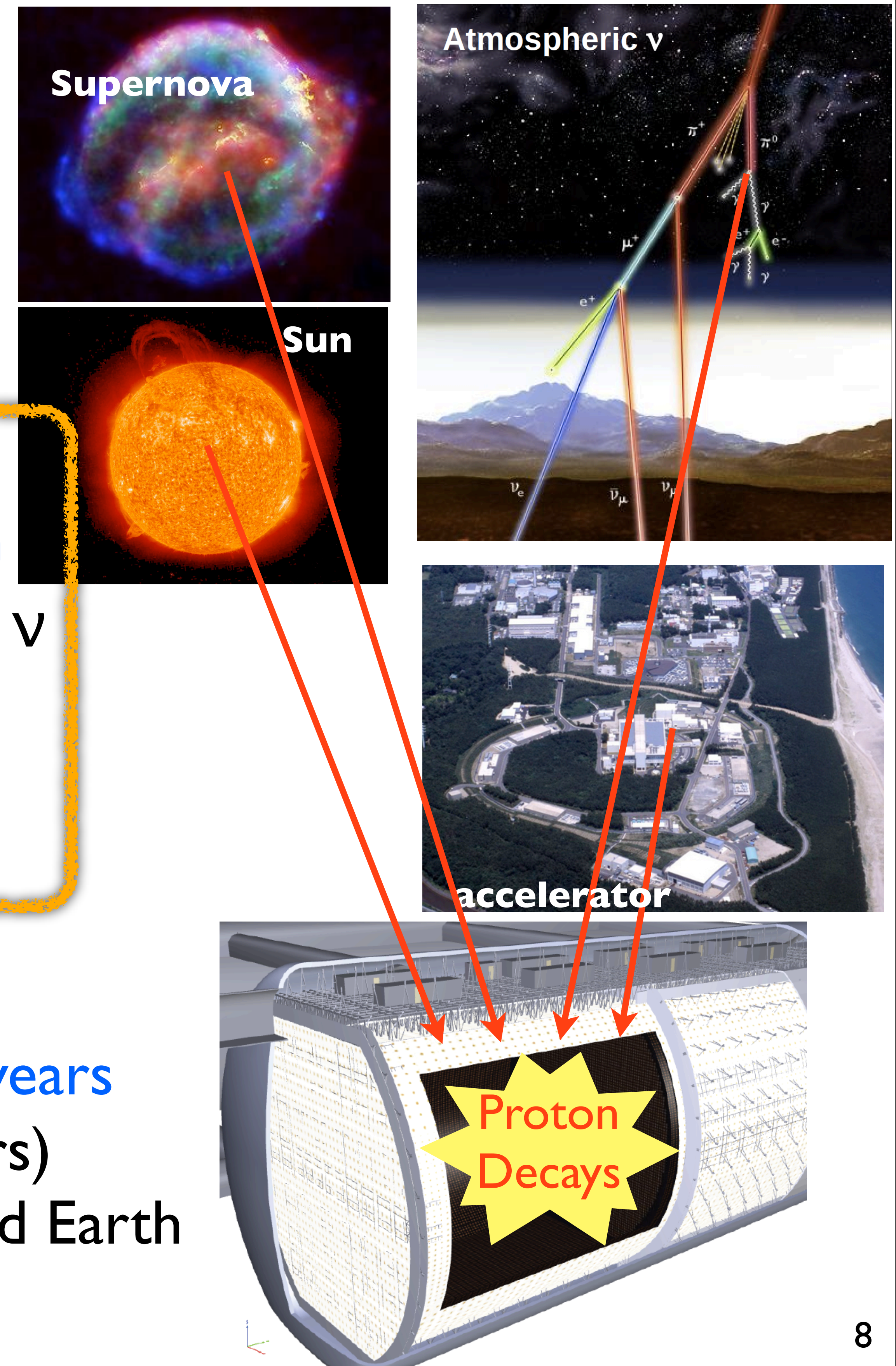
Fig. 13. Schematic directional view of Super-K and Hyper-K from the neutrino beam line target at J-PARC.

Multi-purpose detector, Hyper-K

Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

LBL study, Hyper-K WG, arXiv:1502.05199 and submitted to PTEP

- Proton decay 3σ discovery potential
  - 5×10^{34} years for $p\to e^{+}\pi^{0}$
  - 1×10^{34} years for $p\to \nu K^{+}$
- Comprehensive study on ν oscillations
  - CPV (76% of δ space at 3σ), <20° precision
  - MH determination for all δ by J-PARC/Atm ν
  - θ_{23} octant: $\sin^2\theta_{23}<0.47$ or $\sin^2\theta_{23}>0.53$
  - <1% precision of Δm^2_{32}
  - test of exotic scenarios by J-PARC/Atm ν
- Astrophysical neutrino observatory
  - Supernova up to 2Mpc distance, ~1SN /10 years
  - Supernova relic ν signal (~200ν events/10yrs)
  - Dark matter neutrinos from Sun, Galaxy, and Earth
  - Solar neutrino ~200ν events/day



Hyper-K status in Japan

- **Recommendation by HEP community**
    - http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
- **KEK roadmap includes Hyper-K**
    - http://kds.kek.jp/getFile.py/access?sessionId=1&resId=0&materialId=0&confId=11728
- **Cosmic Ray community endorses Hyper-K as a next large-scale project**
- **Science Council of Japan selects Hyper-K as a top priority project in the "Japanese Master Plan of Large Research Projects" (27 chosen out of 192 in all science area).**
    - http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-22-t188-1.pdf
- It is not in the list of MEXT roadmap 2014. **We seriously challenge the roadmap 2017 for the approval of budget.**

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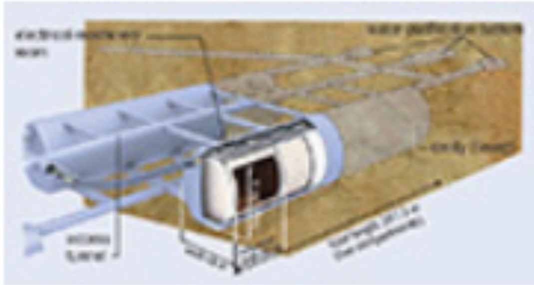
Apr 9, 2015

Proto-collaboration formed to promote Hyper-Kamiokande



Proposed detector

The Inaugural Symposium of the Hyper-Kamiokande Proto-Collaboration, took place in Kashiwa, Japan, on 31 January, attended by more than 100 researchers. The aim was to promote the proto-collaboration and the Hyper-Kamiokande project internationally. In addition, a ceremony to mark the signing of an agreement for the promotion of the project between the Institute for Cosmic Ray Research of the University of Tokyo and KEK took place during the symposium.

The Hyper-Kamiokande project aims both to address the mysteries

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Hyper-K proto-collaboration w/ cooperation of KEK-IPNS and UTokyo-ICRR

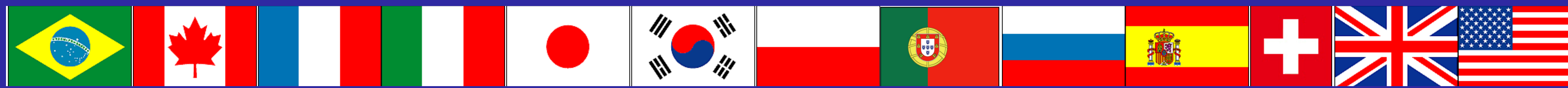
Inaugural Symposium on 1/31, 2015

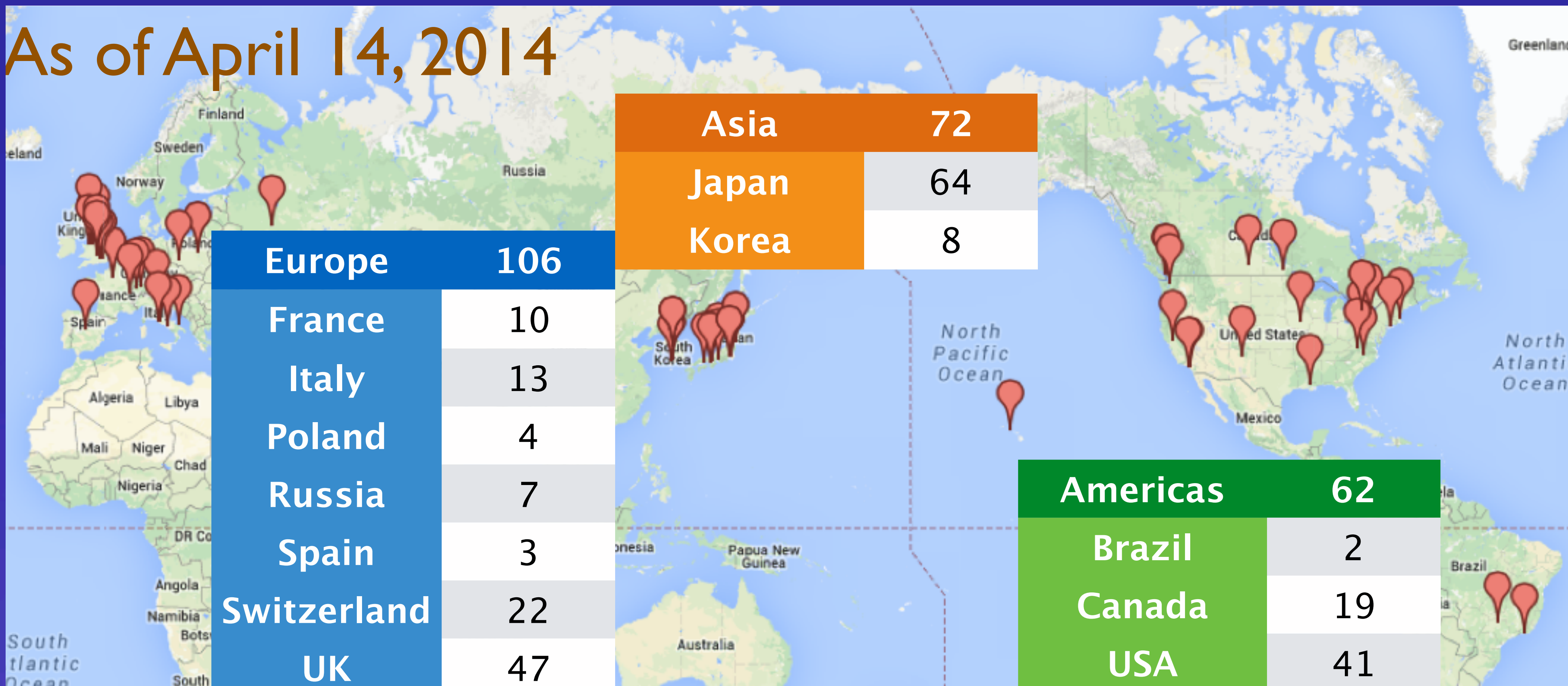
Hyper-K Proto-Collaboration has been formed

- **KEK-IPNS** and **Tokyo-ICRR** signed the **MOU** of the cooperation in promoting the Hyper-Kamiokande.

MoU signing by KEK/ICRR

Hyper-K Collaboration





Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

Asia	72
Japan	64
Korea	8

Americas	62
Brazil	2
Canada	19
USA	41

- 240 members from 13 countries
- The collaboration governance structure is defined.
  - Steering Committee, International Board Representatives, and Working Group with project leaders
  - R&D fund and travel budget already secured in some countries, and more in securing processes.

Hyper-Kamiokande EU meeting@CERN 27-28 April 2015

- Meeting to discuss the European effort in Hyper-K
- Open to anyone who has interest in Hyper-K, or is planning to join Hyper-K, or is contributing
- http://indico.cern.ch/e/ThirdEUHyperK

Third Hyper-Kamiokande EU meeting

27-28 April 2015

CERN

Europe/Zurich timezone

Search

- Overview
- Timetable
- Registration
- Participant List
- Accommodation
- Past Hyper-Kamiokande EU meetings

- Meeting to discuss the European effort in the Hyper-Kamiokande experiment.
- Open to anyone who has interests in Hyper-K, or is planning to join Hyper-K, or is contributing.
- Detailed information about your Country in Hyper-K can be discussed with your representatives in the Hyper-Kamiokande International Board Representatives, its chair if no representatives are available yet or the international Steering Committee chair.

Starts 27 Apr 2015 11:00
Ends 28 Apr 2015 18:00
Europe/Zurich

CERN
IT Amphitheatre

Registration for this event is now open
Deadline: **26 Apr 2015**

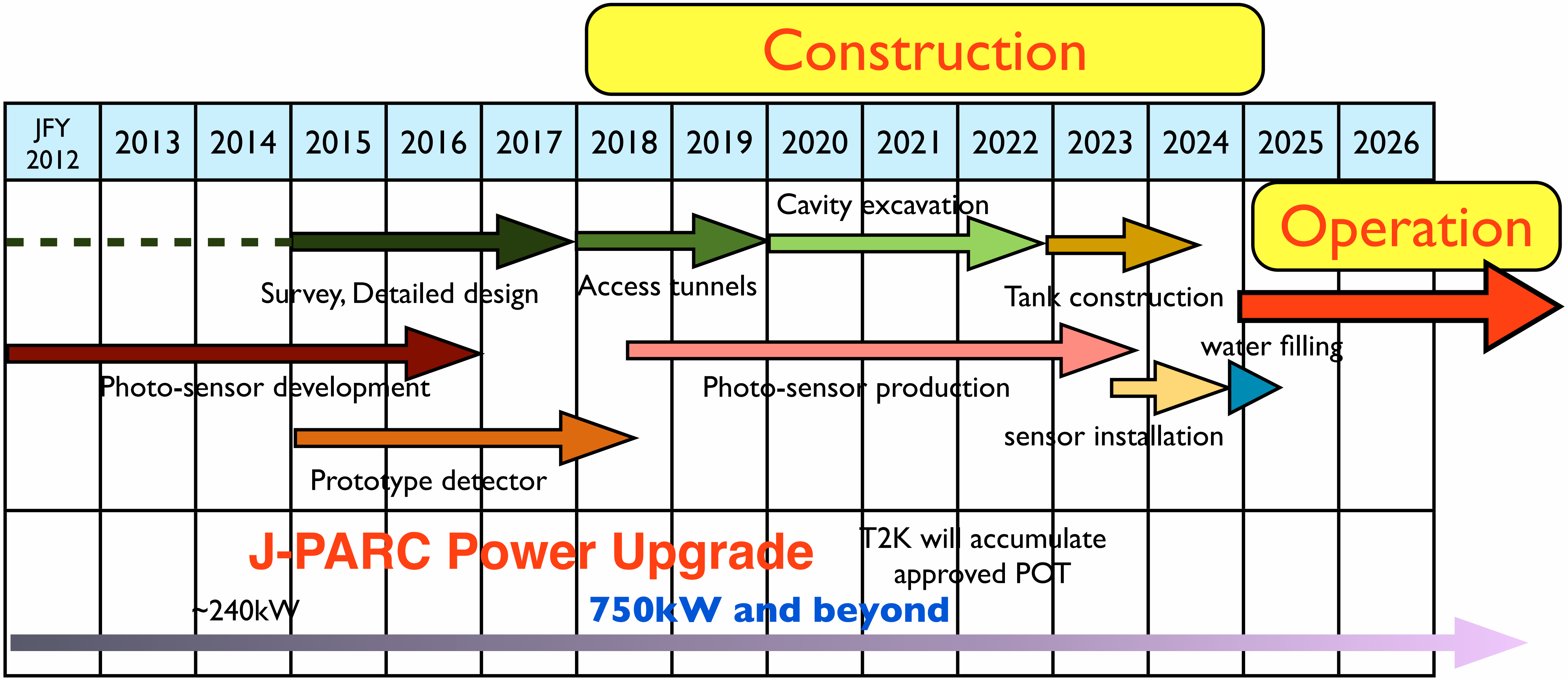
Register now

The next action

- Design Report is requested by KEK/ICRR.
  - To be prepared in 2015 toward the budget request. The next processes of the SCJ master-plan and MEXT roadmap will be in 2016-2017.
  - Optimum design, Construction cost&period, Beam & Near detector, International responsibilities
  - The international review will proceed under KEK/ICRR to promote the project.
- Once the budget is approved, the construction can start in 2018 and the operation will begin in ~2025.

- **It is a critical time to promote the project.**
- **Open for new Collaborators**

Target Schedule

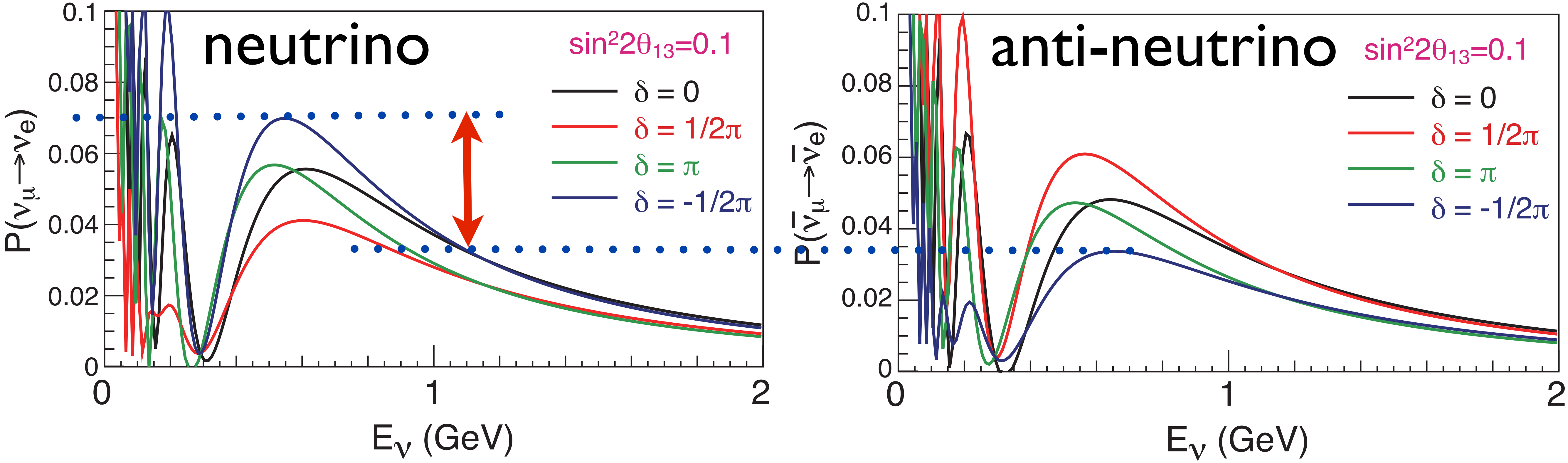


- -2018 Construction starts
- -2025 Data taking start
  - -2028 Discovery of Neutrino CP violation？
  - -2030 Discovery of Proton Decay？
  - -20xx Detection of supernova neutrinos
  - -20xx Discovery of new phenomena

Physics with Hyper-Kamiokande

Measuring CP asymmetry w/ J-PARC ν beam

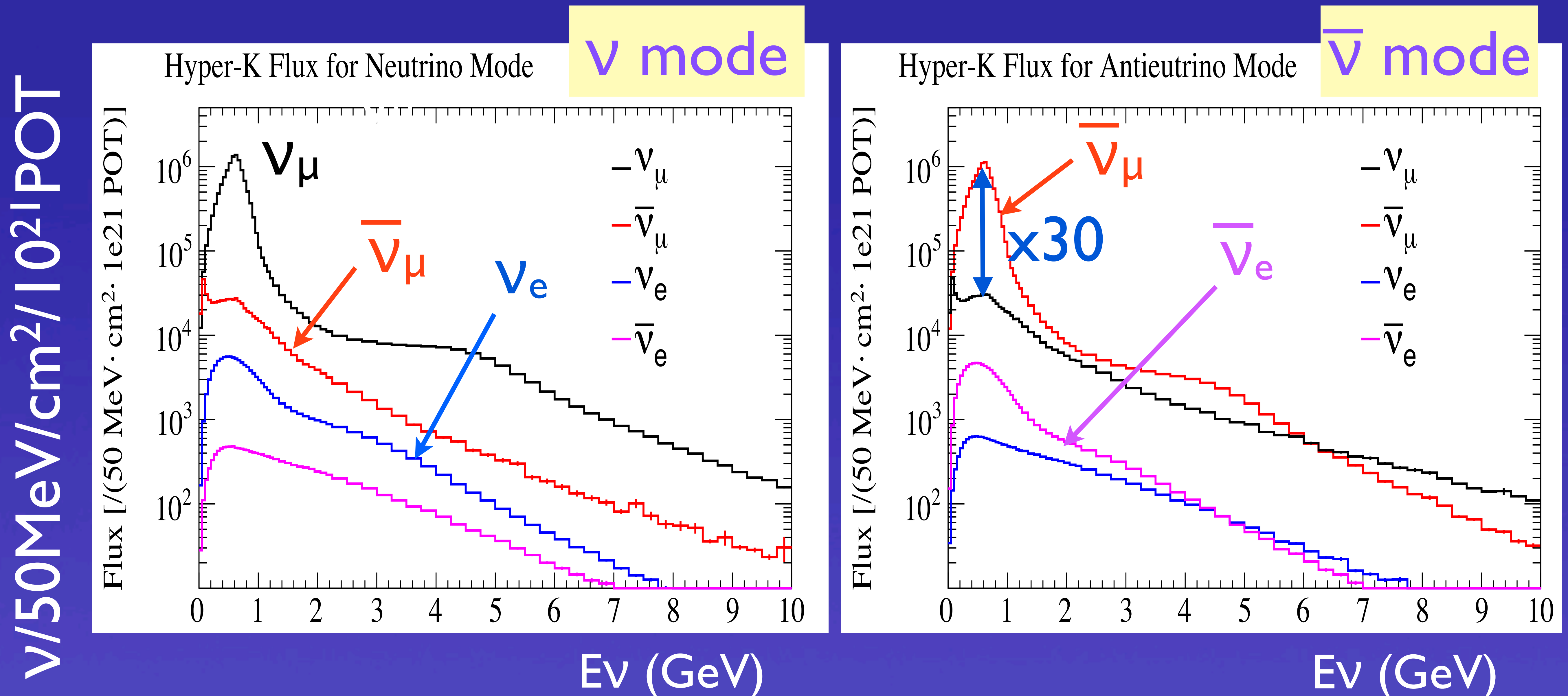
$P(\nu_\mu \to \nu_e)$ appearance probability (normal hierarchy)



- Comparison between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - as large as ~27% from nominal (at $\theta_{23}=\pi/4$).
  - also sensitive to any CPV (such as >3 neutrinos)

The ν beam (ν : $\bar{\nu}$=1 : 3)

Expected neutrino flux at Hyper-K (unoscillated)



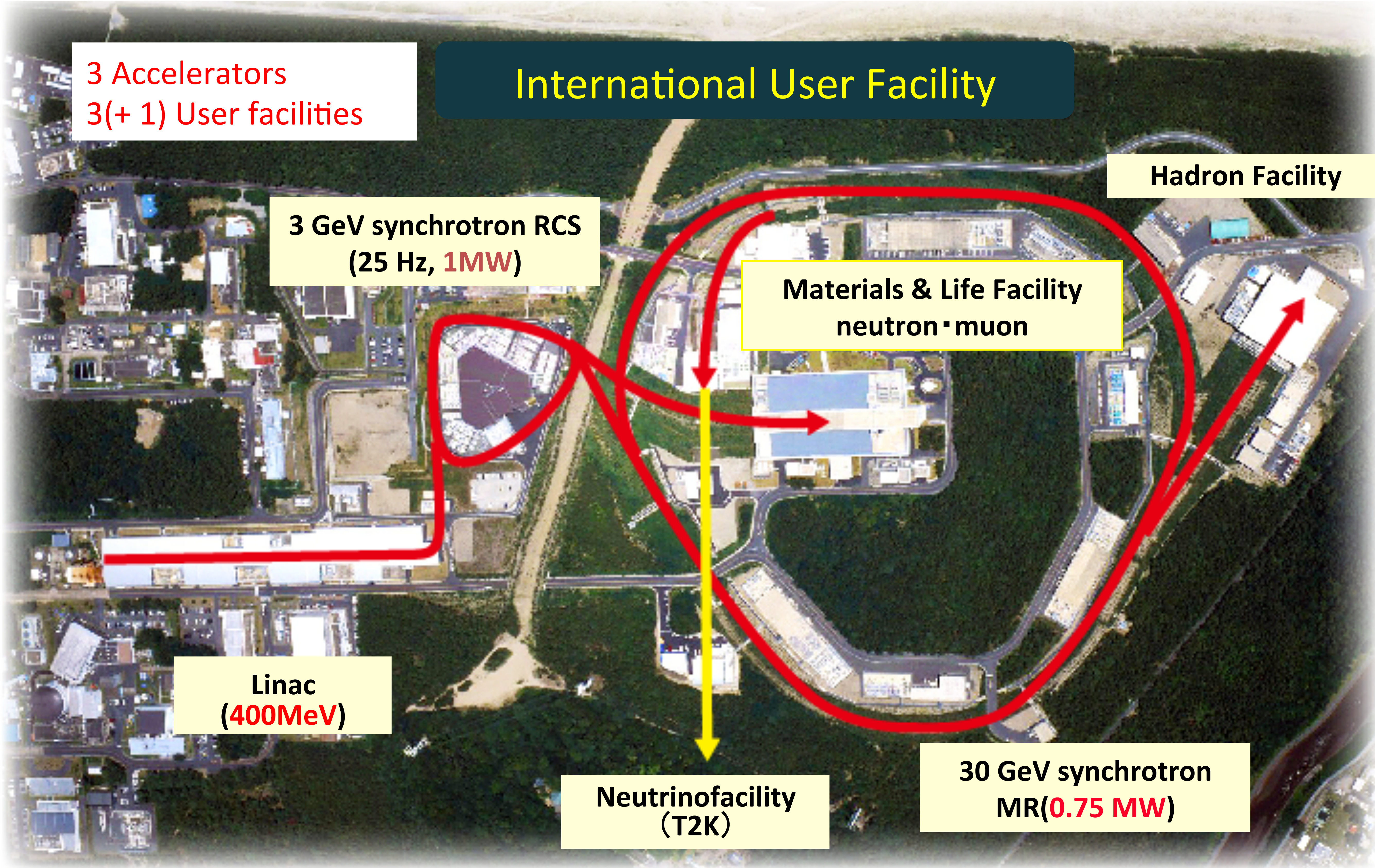
2.5° off-axis beam from J-APRC
Peaked at oscillation maximum
Suppress BG from high energy component (ν_τ negligible)

CP measurement with ***Hyper-K***

- Strength of water Cherenkov detector
  - LARGE mass – statistics is always critical
  - Excellent reconstruction/PID performance especially in sub-GeV region (quasi-elastic→single ring)
- Best matched with low energy, narrow band beam
  - Off-axis beam with relatively short baseline
    - Sensitive to CPV with less matter effect

(natural extension of technique proved by T2K)

J-PARC Japan Proton Accelerator Research Complex



J-PARC MR for neutrinos

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)	~320 kW →		750 →
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50			100
Cycle time of main magnet PS	3.04 s	2.56 s	2.48 s				1.3 s
New magnet PS for high rep.	R&D →	R&D →	R&D →	R&D →	Manufacture installation/test →	Manufacture installation/test →	→
Present RF system	Install. #7,8	Install. #9					
New high gradient rf system	R&D →	R&D →	R&D →	Manufacture installation/test →	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	Inj. kicker	Kicker PS improvement, Septa manufacture /test →	→	→	→	→	
FX system		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		

J-PARC MR for neutrinos

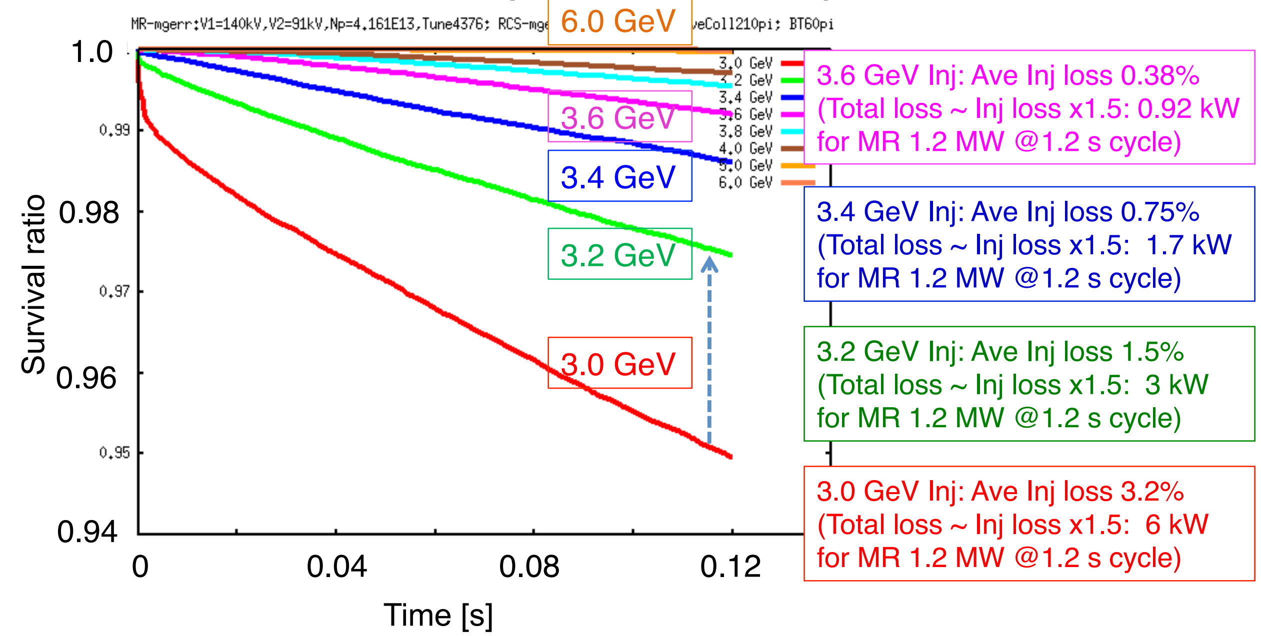
- The maximum power in JFY2014 is **329.9kW**.
- The beam power is limited by the beam loss in MR (not injection). The LINAC/RCS can feed 500~600 kW equivalent beam to MR even now. The T2K seriously requests the operation at higher beam power beyond 330 kW.
  - It results in more beam power in the era of Hyper-K, 1.2MW or beyond with the update of power supply system.

Mid・Long-term plan

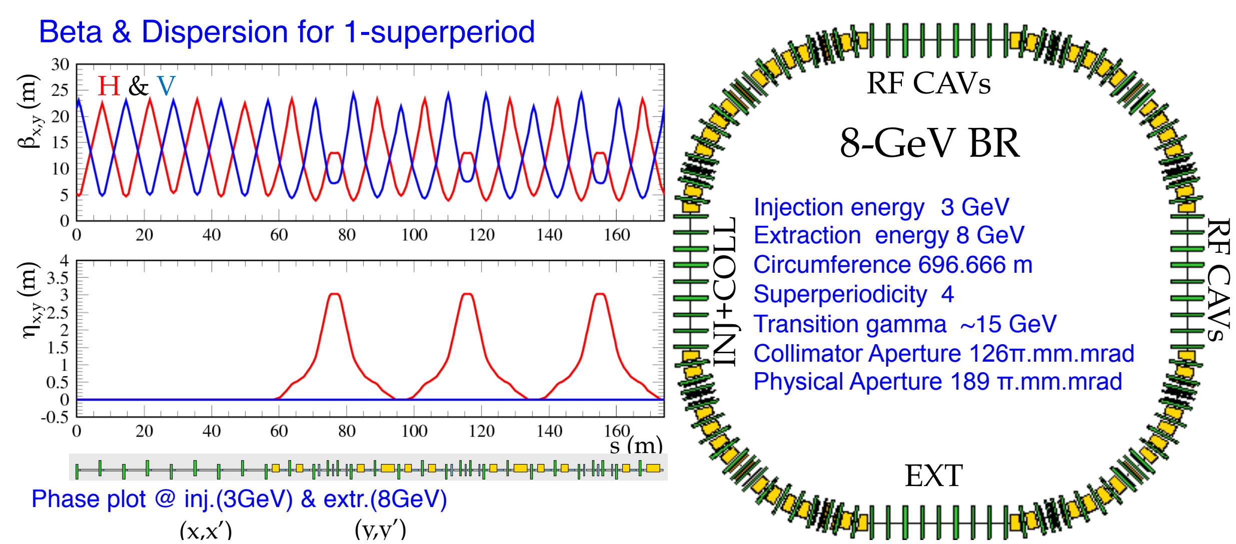
Several ideas under discussion, towards multi-MW facility

- RCS energy increase to reduce space charge effect
  - ~1.5MW
- New Booster Ring (8GeV) between RCS &MR
  - >2MW
- New SC proton linac for neutrino beam (Conceptual study)
  - ~9MW linac with >9GeV energy
  - Using KEKB tunnel?

MR injection energy and beam loss (simulation)



8GeV booster ring



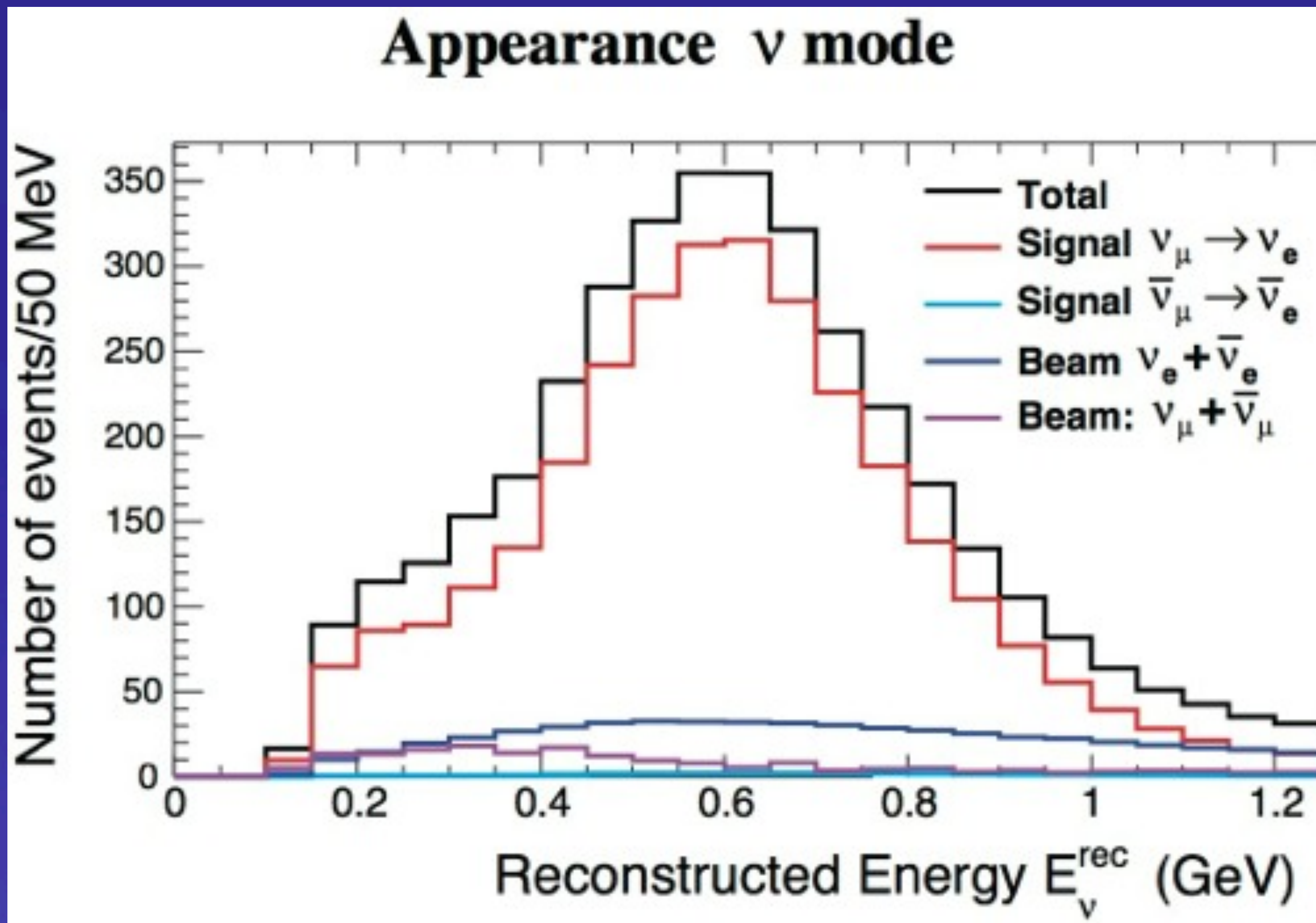
Acceptance of T2K neutrino beam line

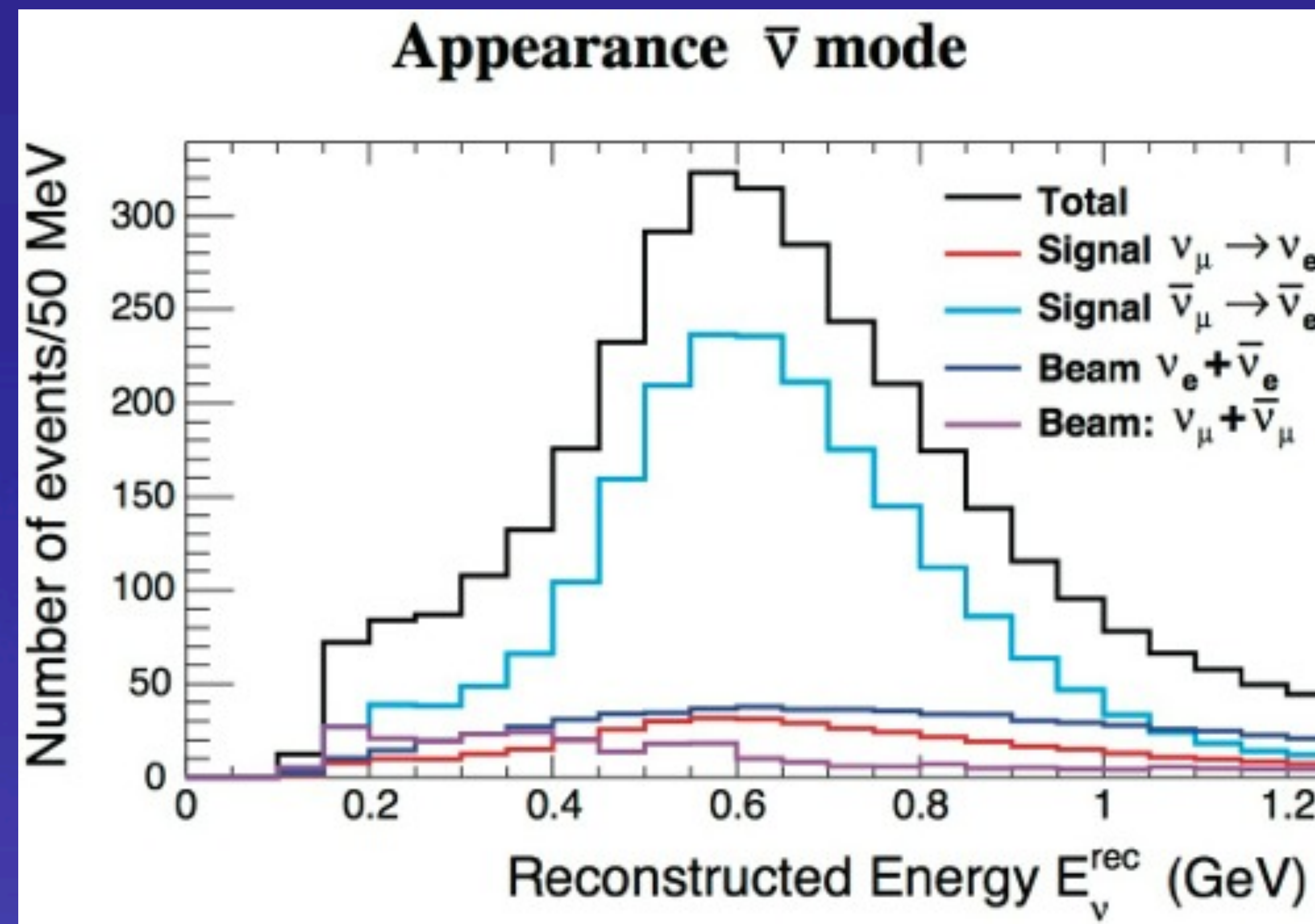
- ~2MW beam can be accepted with moderate updates.

Component	Beam power/parameter	
Target	3.3×10^{14} ppp	
Beam window	3.3×10^{14} ppp	
Horn		
Cooling for conductors	2 MW	
Stripline cooling	1~2 MW	(400 kW)
Hydrogen production	1~2 MW	(300 kW)
Horn current	320 kA	(250 kA)
Power supply repetition	1 Hz	(0.4 Hz)
Decay volume	4 MW	
Hadron absorber/beam dump	3 MW	
Water cooling facilities	~2 MW	(750 kW)
Radiation shielding	4 MW	(750 kW)
Radioactive air leakage to the TS ground floor	~2 MW	(500 kW)
Radioactive cooling water treatment	~2 MW	(600 kW)

ν_e candidate events after selection

$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH





	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (1.875MW · 10^7s)	3,016	28	11	523	172
$\bar{\nu}$ (5.625MW · 10^7s)	2,110	396	9	618	265

LARGE θ_{13} => good for Hyper-K

- High Signal ($\nu_\mu \rightarrow \nu_e$) and Low Background ($\pi^0$, beam ν_e, etc..)
  - Systematic error is more reliable (under control) for the ν_e signal than BG (example, π^0)
  - Sensitivity is studied assuming a realistic systematic errors.

- >10% larger asymmetry is expected for δ between 20 and 160 degrees (200 and 340) which corresponds to ~77% region of δ.

Systematic Uncertainty

Realistic estimation based on SK/T2K

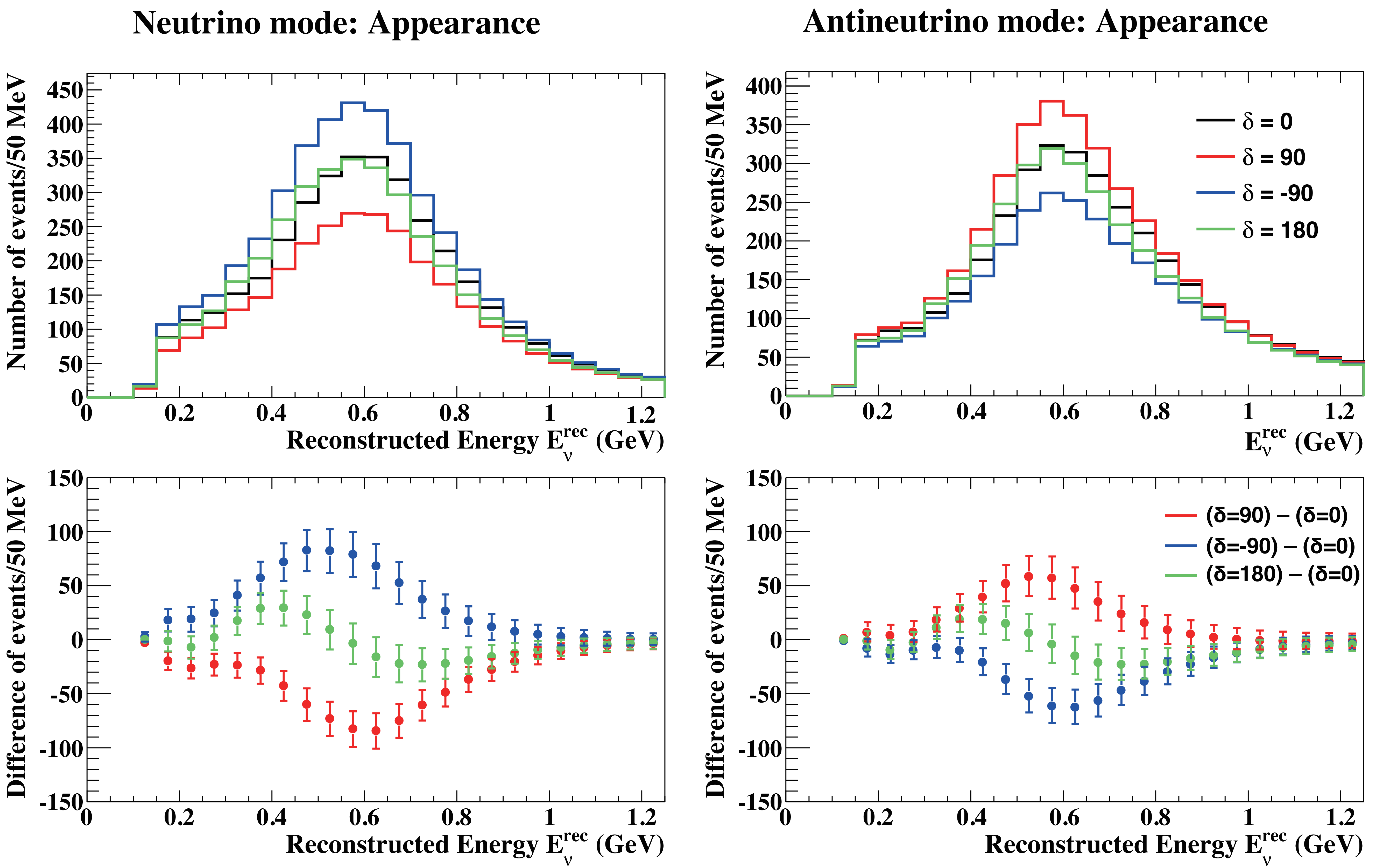
- Beam flux + near detector constraint
  - Conservatively assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode	
	νe	$\nu\mu$	$\bar{\nu}e$	$\bar{\nu}\mu$
Flux&ND	3.0	2.8	5.6	4.2
XSEC model	1.2	1.5	2.0	1.4
Far Det. +FSI	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

(T2K 2014)	
νe	$\nu\mu$
3.1	2.7
4.7	5.0
3.7	5.0
6.8	7.6

δ dependence of #events and E shape



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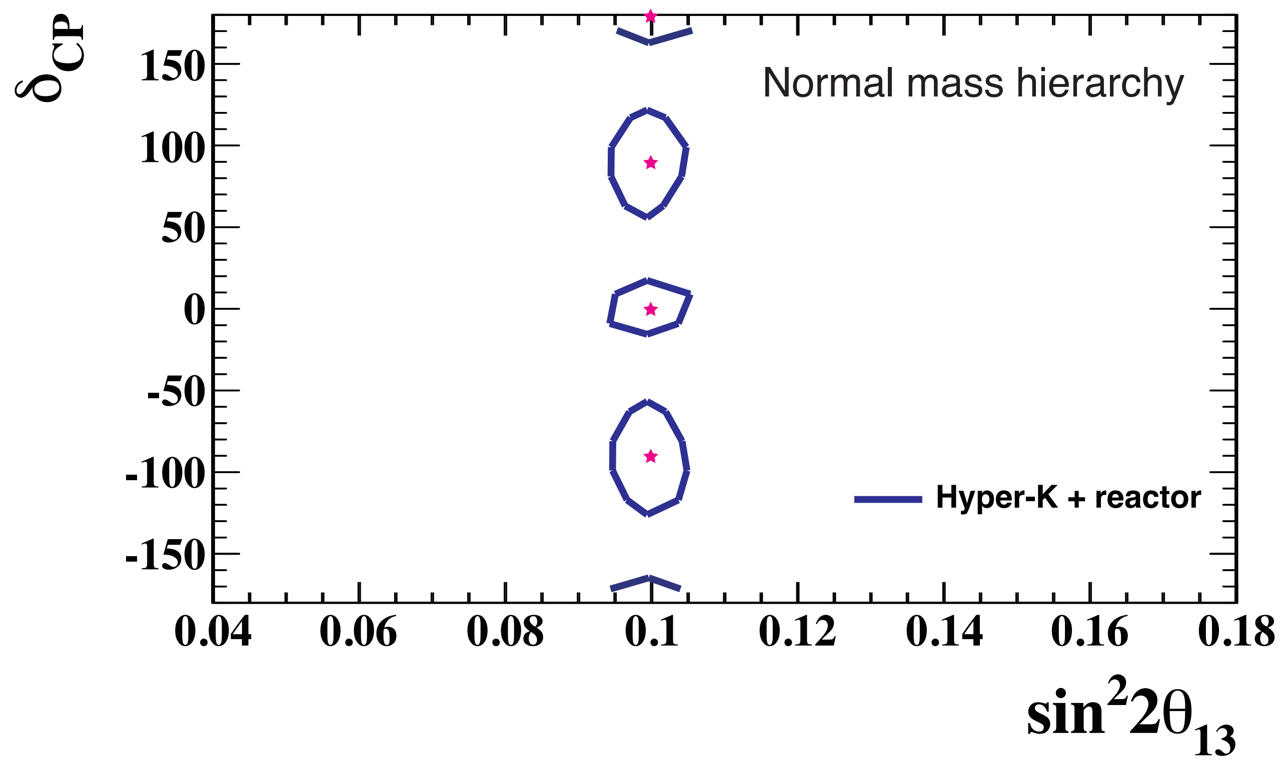
CP Sensitivity

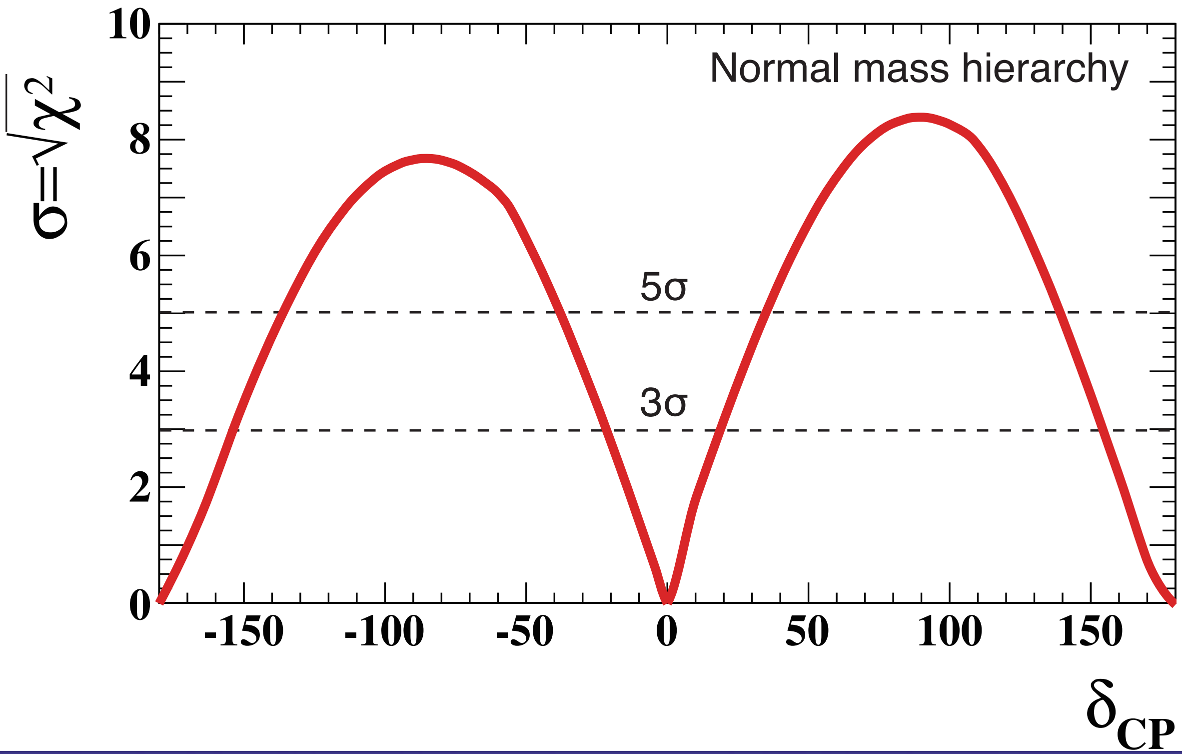
PTEP (2015)
arXiv:1502.05199

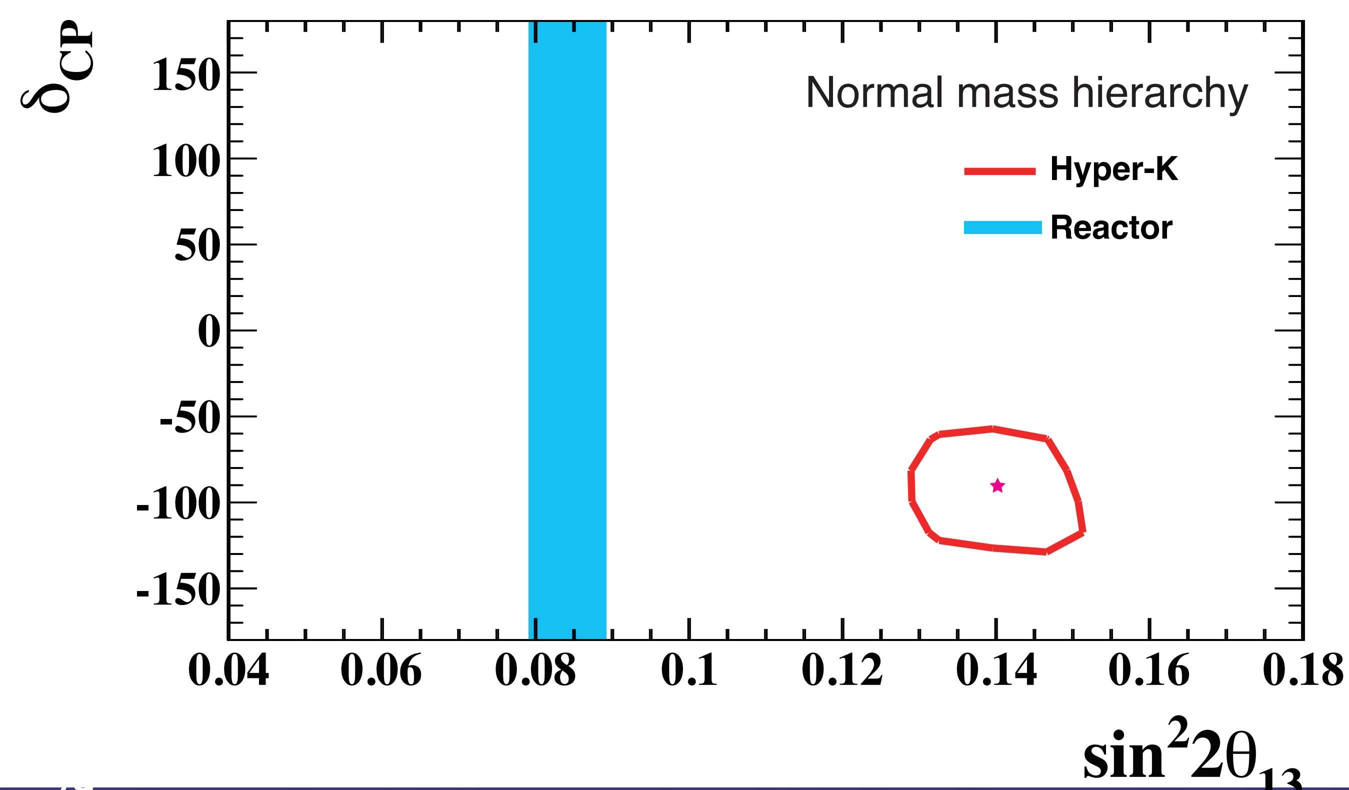
90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)



- CPV establish ($\sin\delta \neq 0$)
  - 76% (58%) of δ for >3σ (>5σ)
- δ resolution: 8°-19°

sinδ≠0 exclusion





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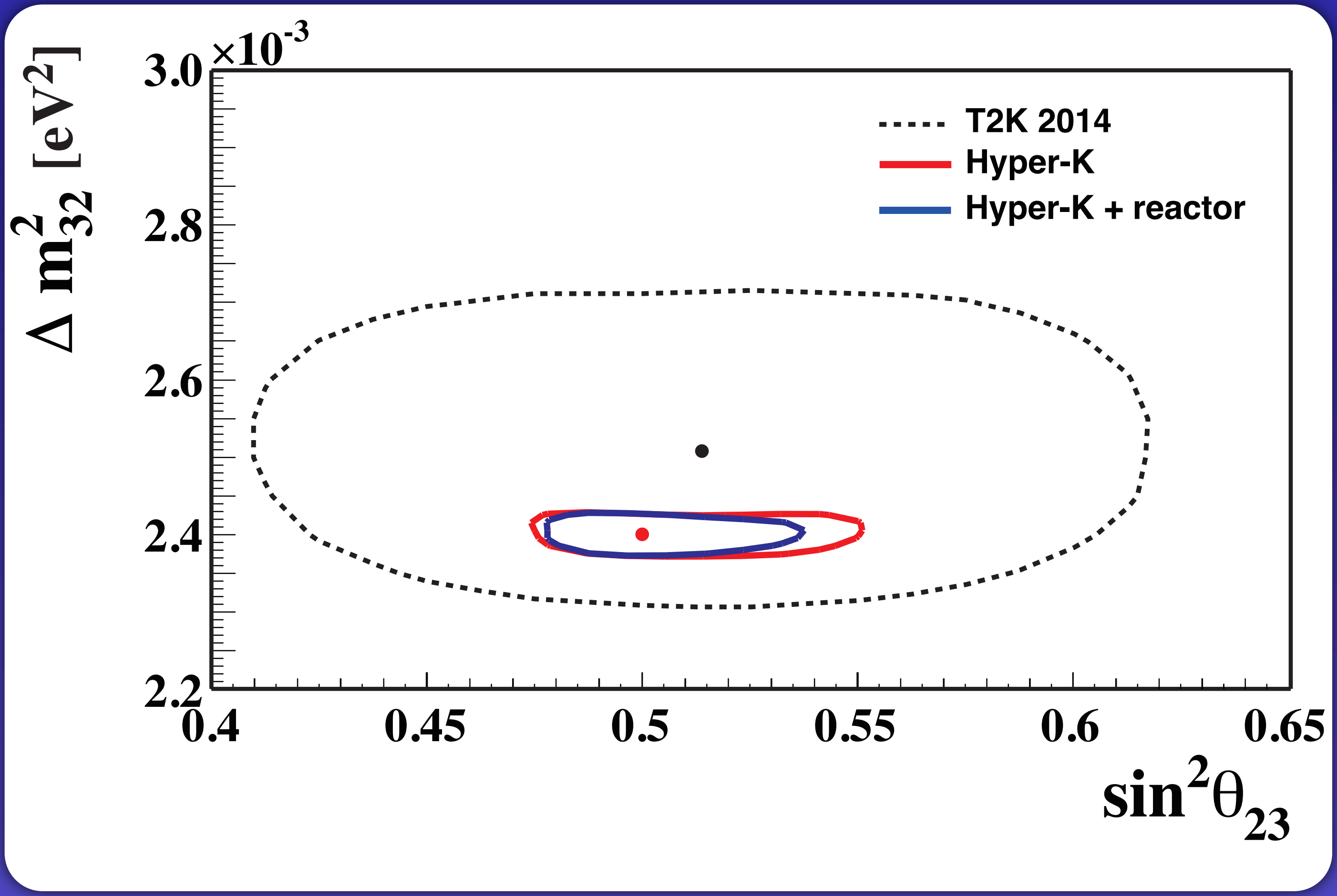
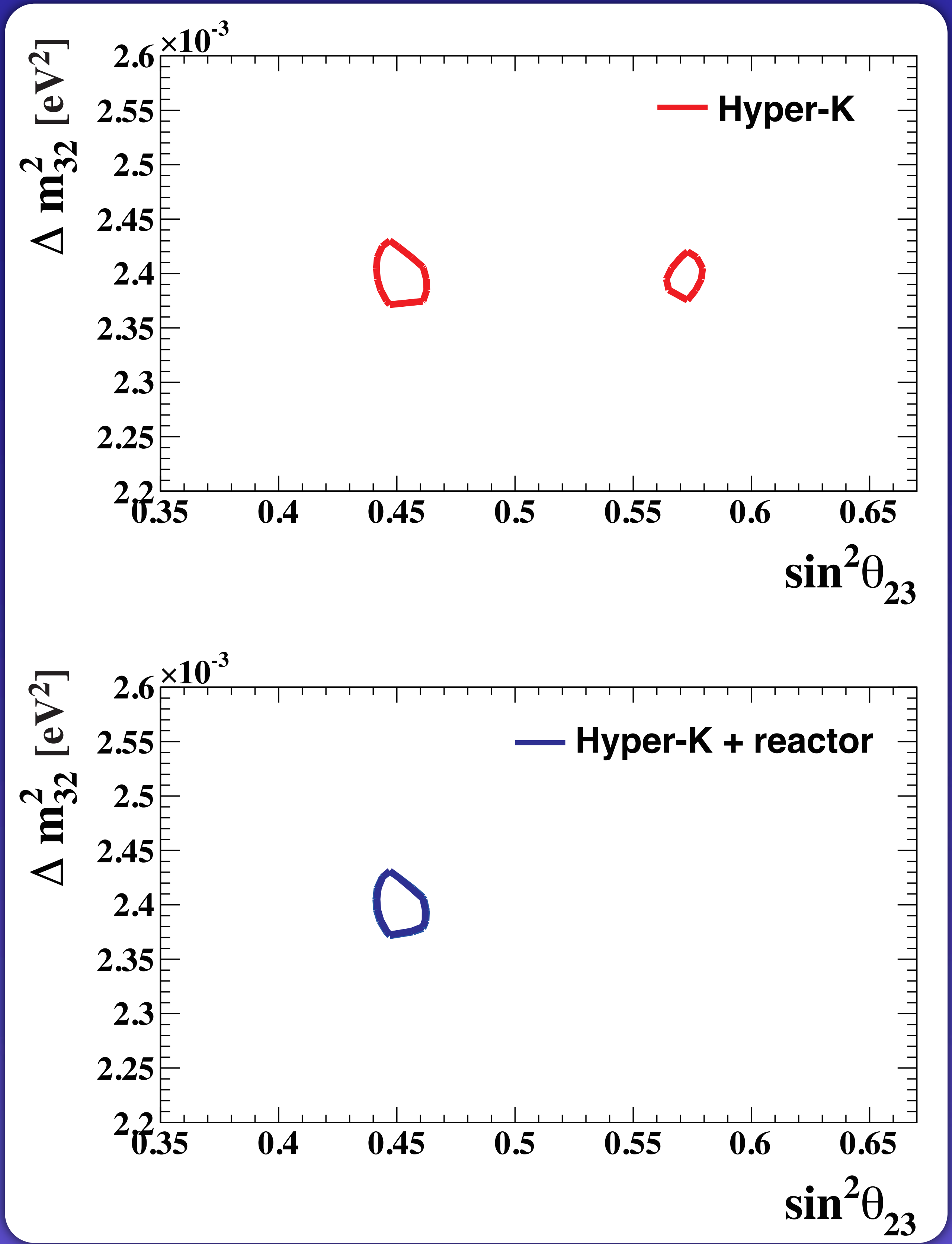
Oscillation Parameter measurements

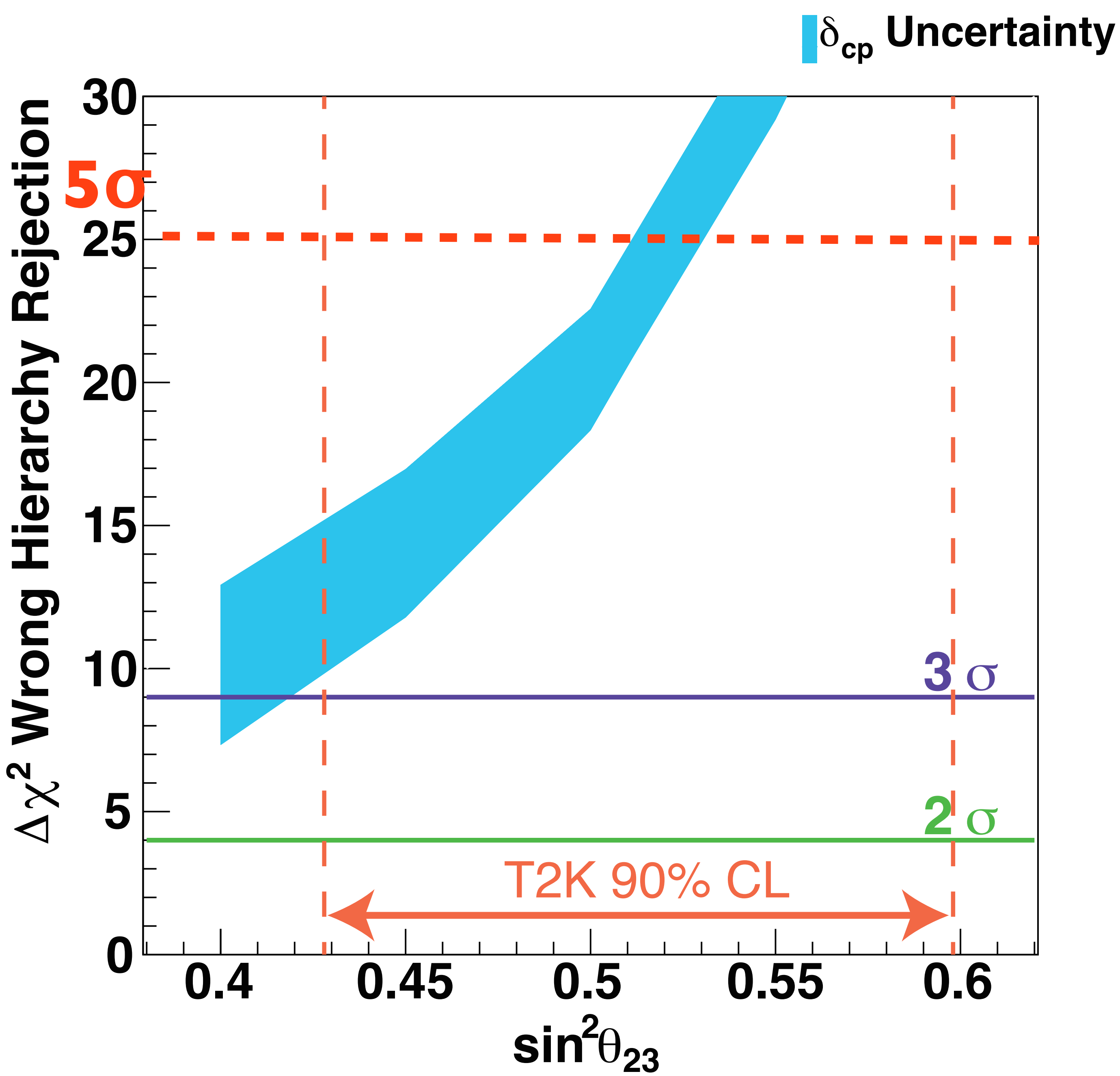
$\sin^2\theta_{23}$ vs Δm^2_{32}

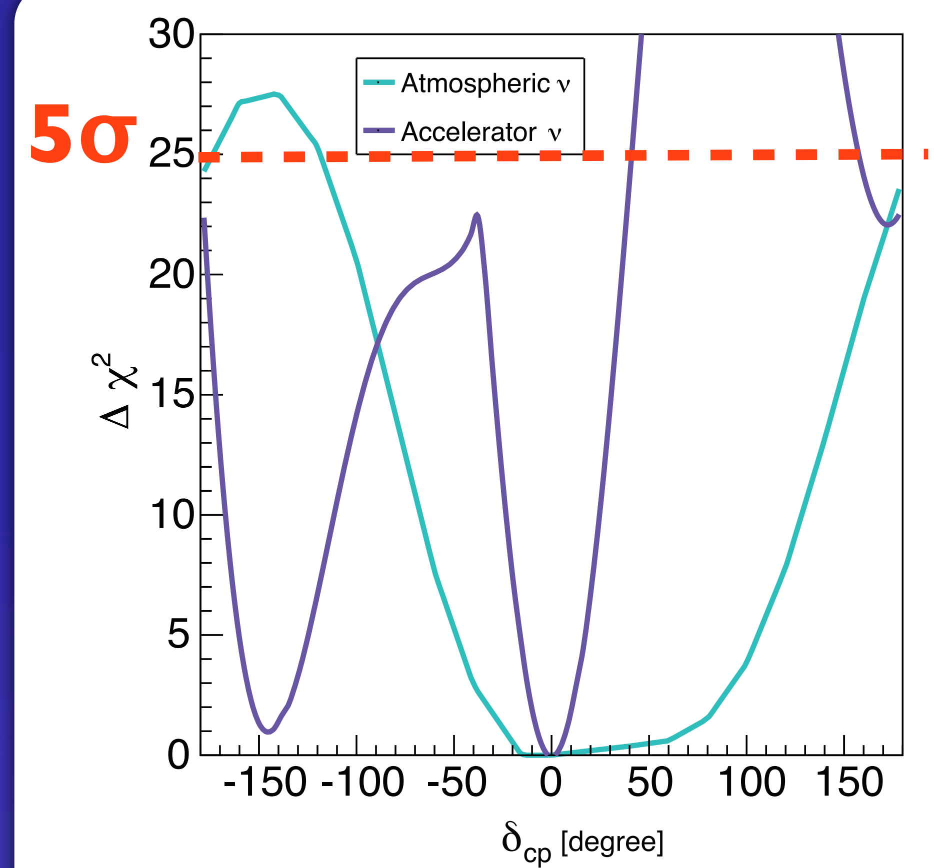


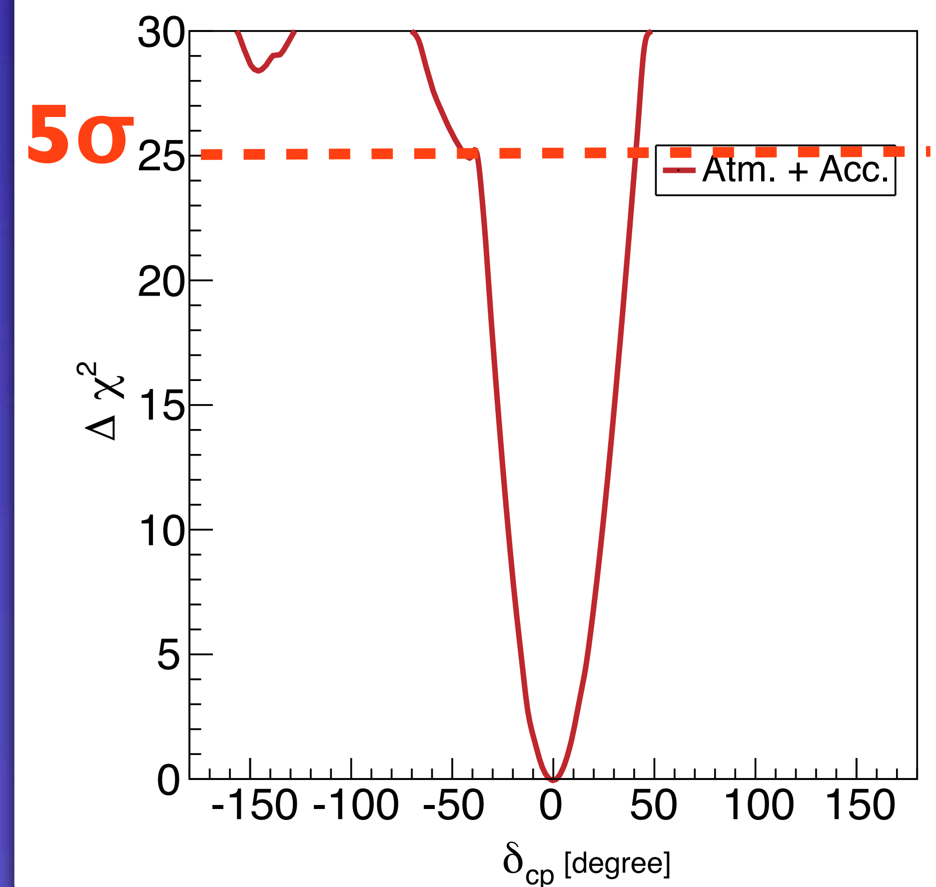


With beam and atmospheric neutrinos

Resolve mass hierarchy w/ >3~5σ!







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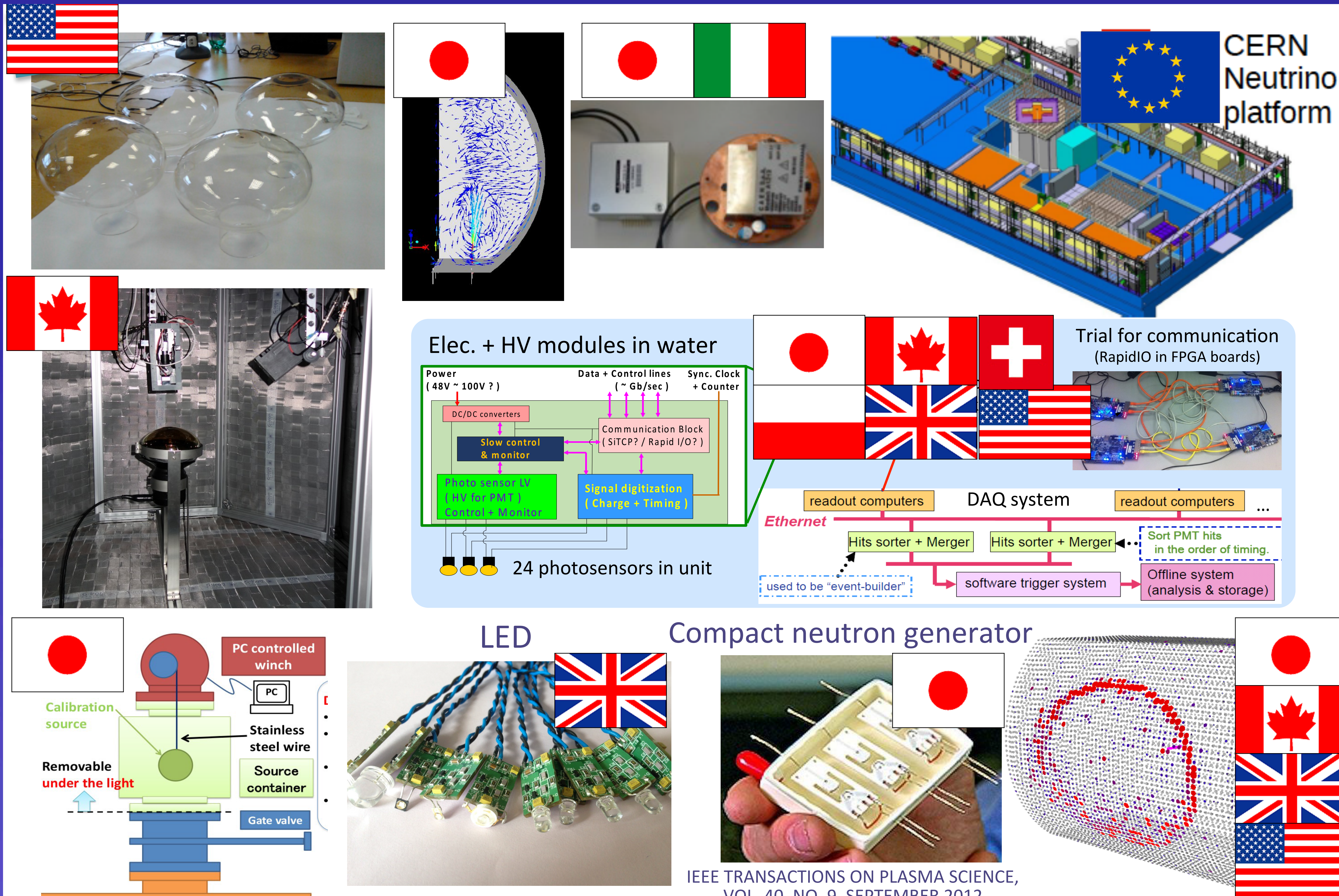
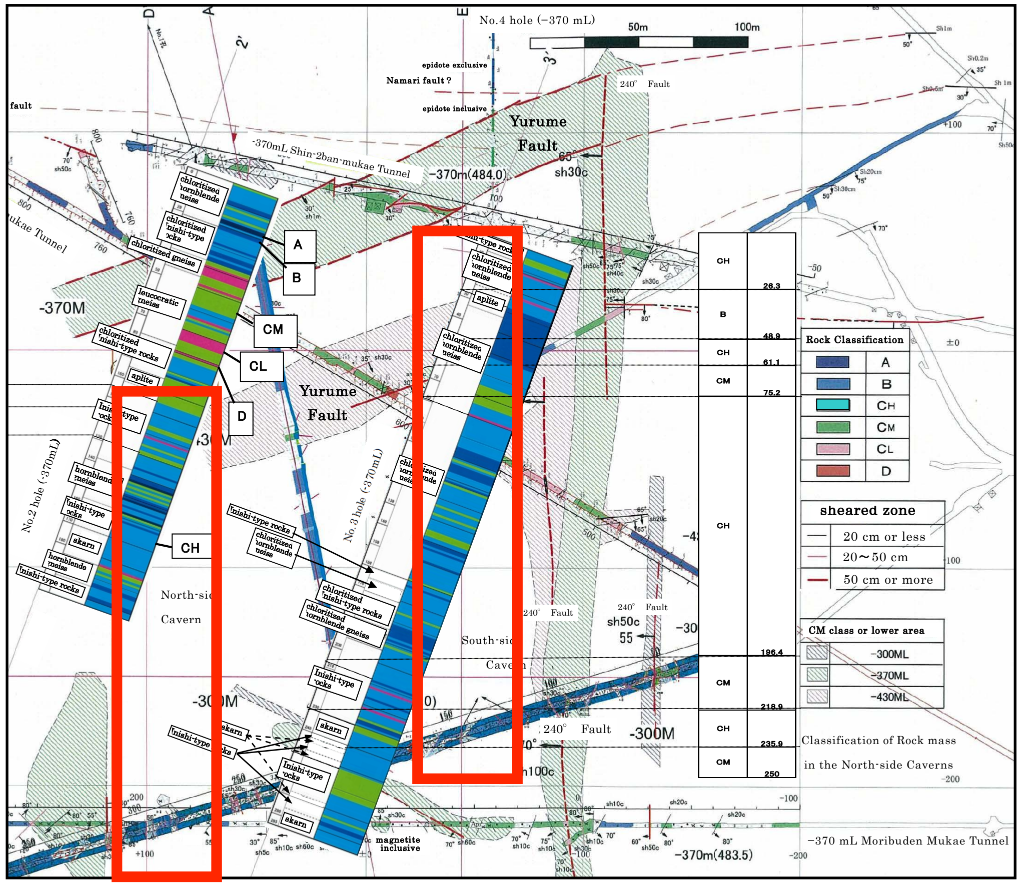
Status of R&D

Worldwide R&D



Geological survey & Cavern stability

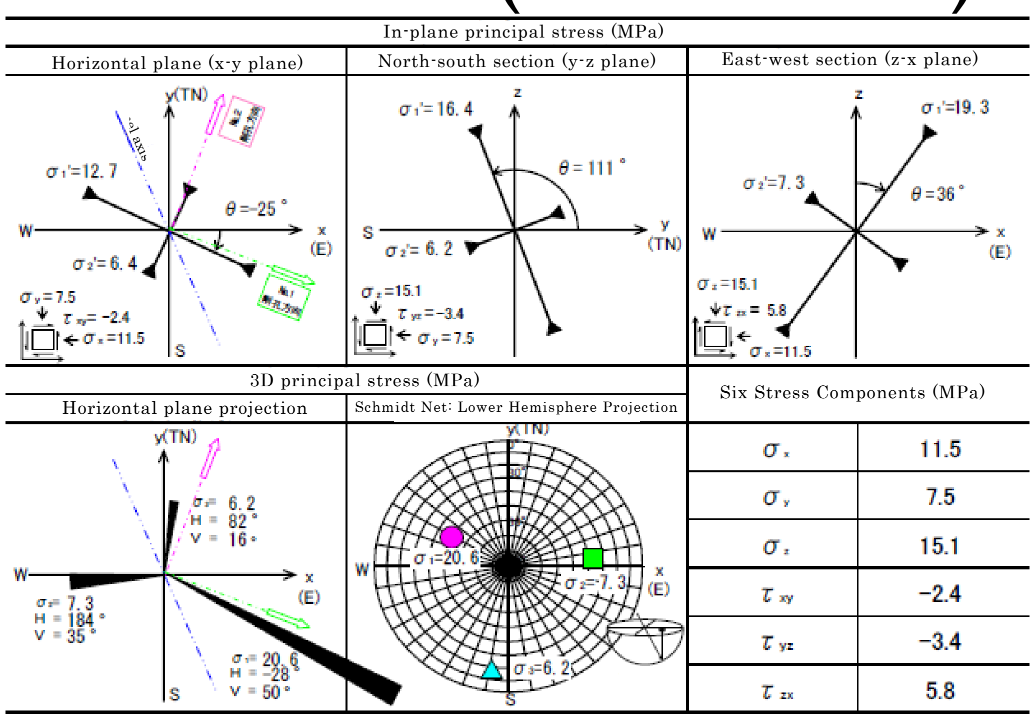
Rock mass characterization



- Detailed geological surveys at the candidates site vicinity
- Cavern stability and its supporting method has been studied
- Confirmed that the HK cavern can be constructed with the existing techniques

Survey in the Mozumi (Super-K) area is on-going.

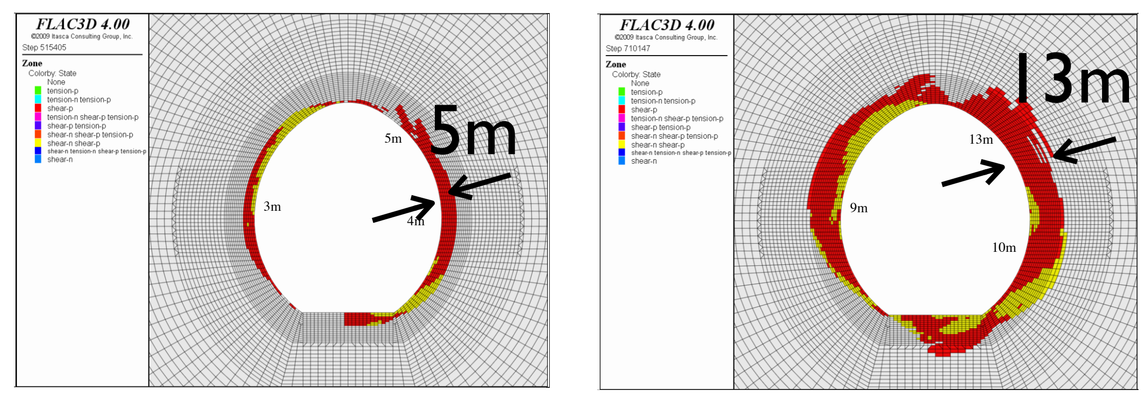
Initial stress (in-situ meas.)



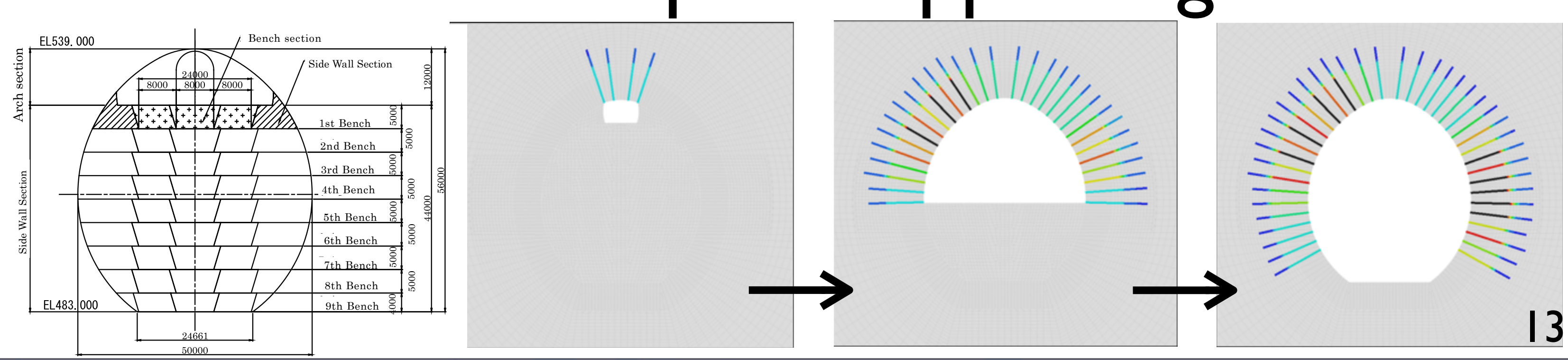
Six Stress Components (MPa)

σ_x	11.5
σ_y	7.5
σ_z	15.1
τ_{xy}	-2.4
τ_{yz}	-3.4
τ_{zx}	5.8

Cavern stability



Excavation steps & supporting method



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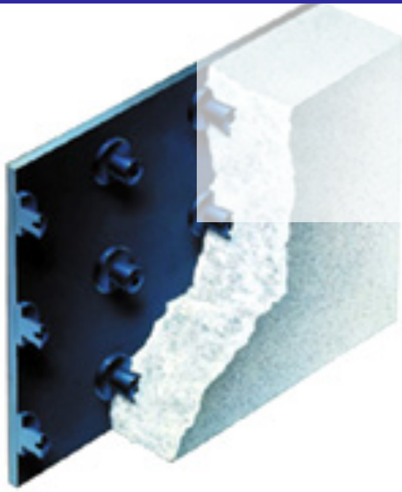
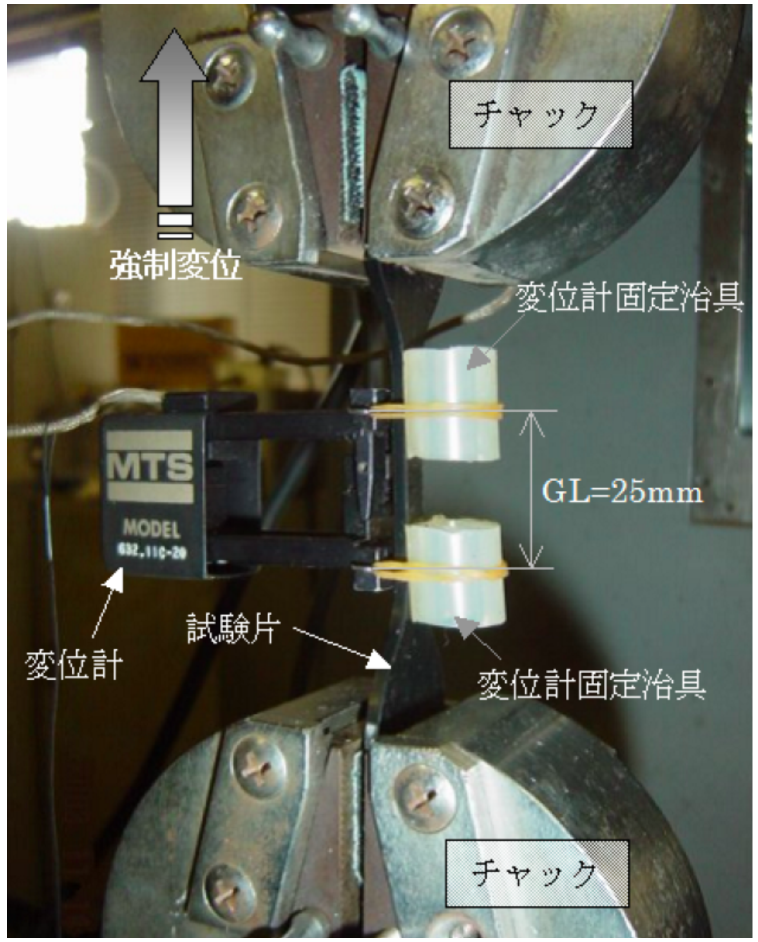
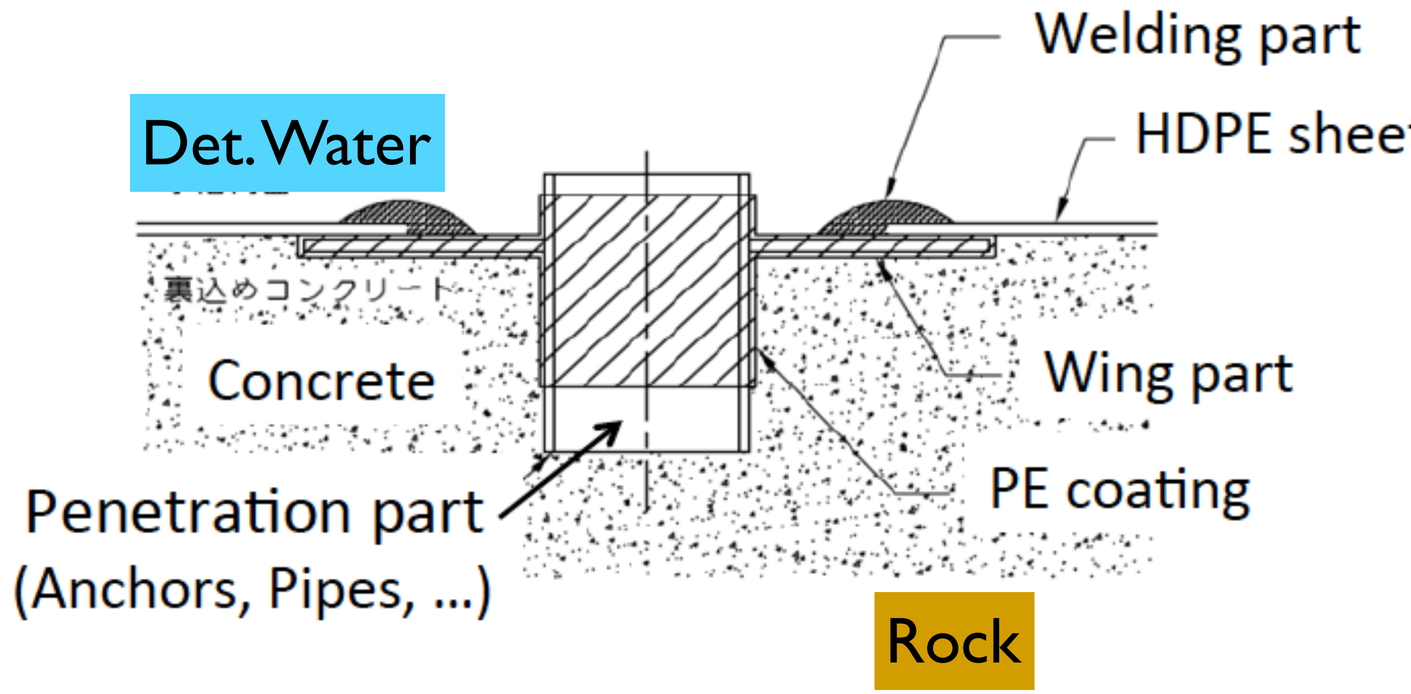
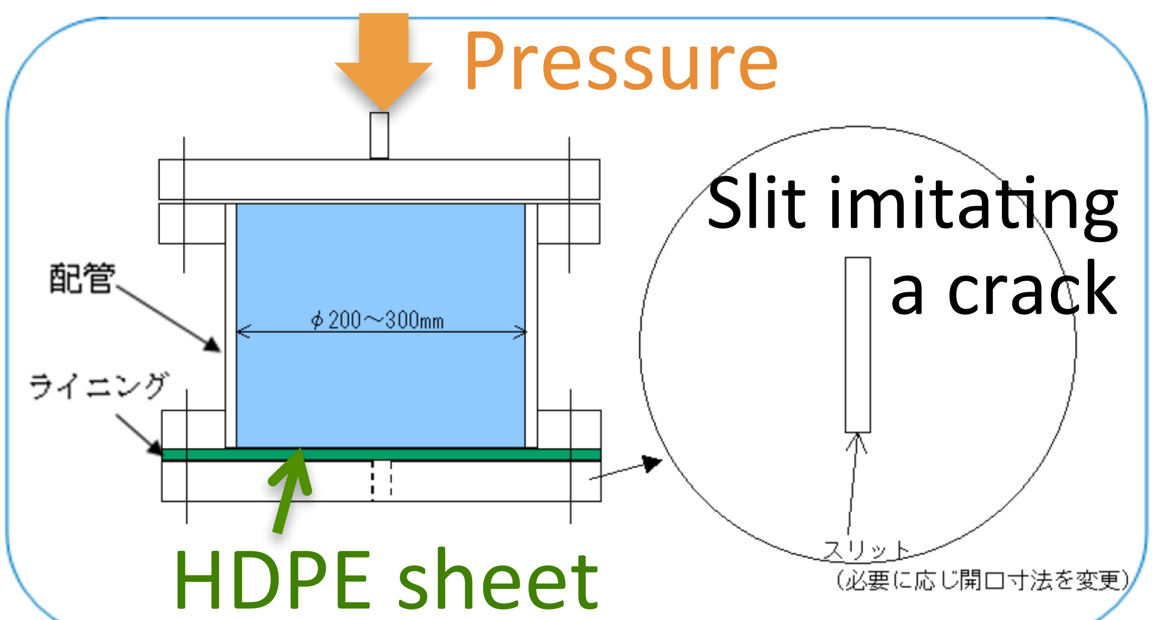
Tank liner material

5mm High Density Polyethylene





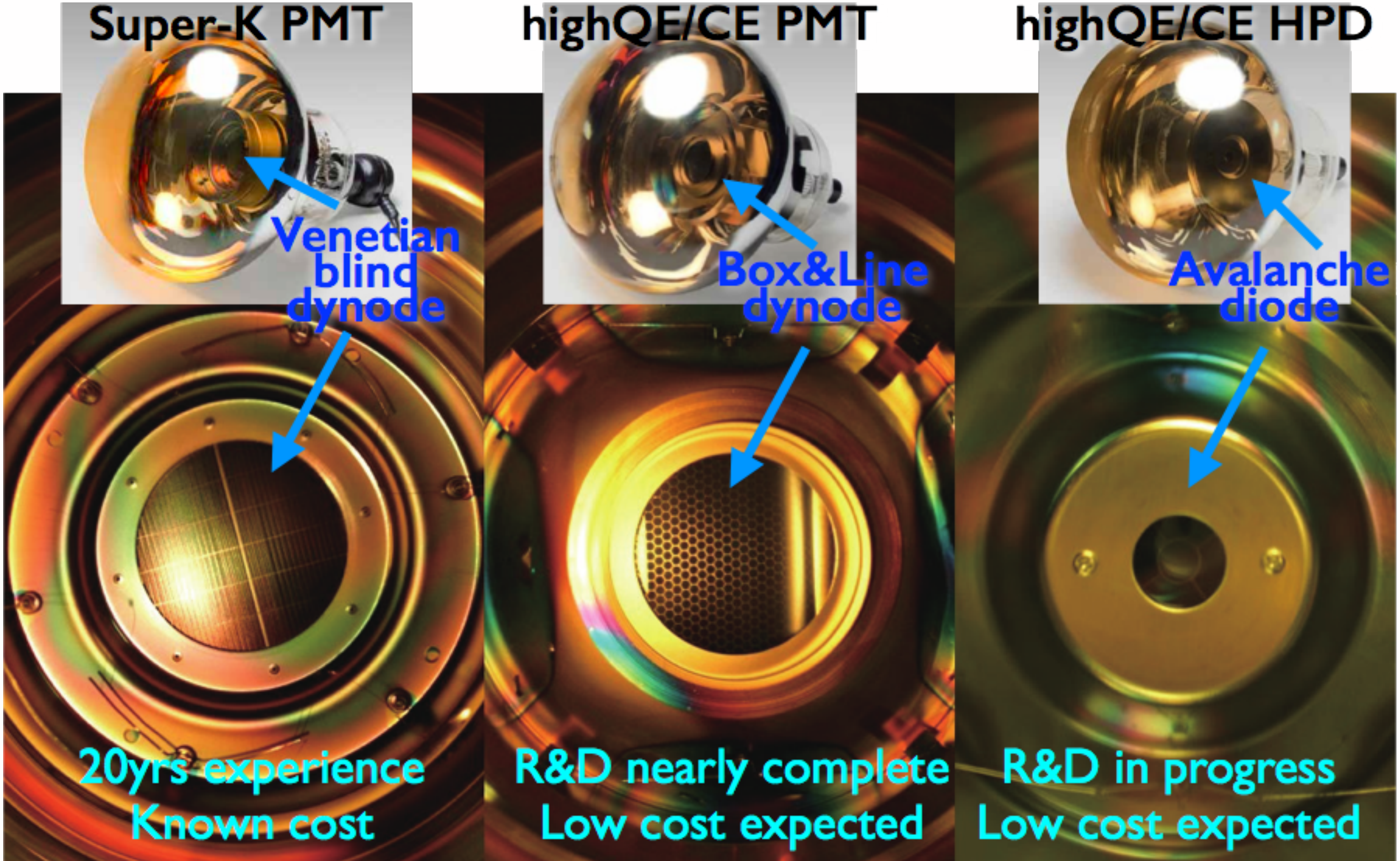




- Soak test
  - pure water, 1% $Gd_2(SO4)_3$ loaded
- Tensile creep test
- pressure test
- leak test at the penetrating part

Satisfactory results for Hyper-K

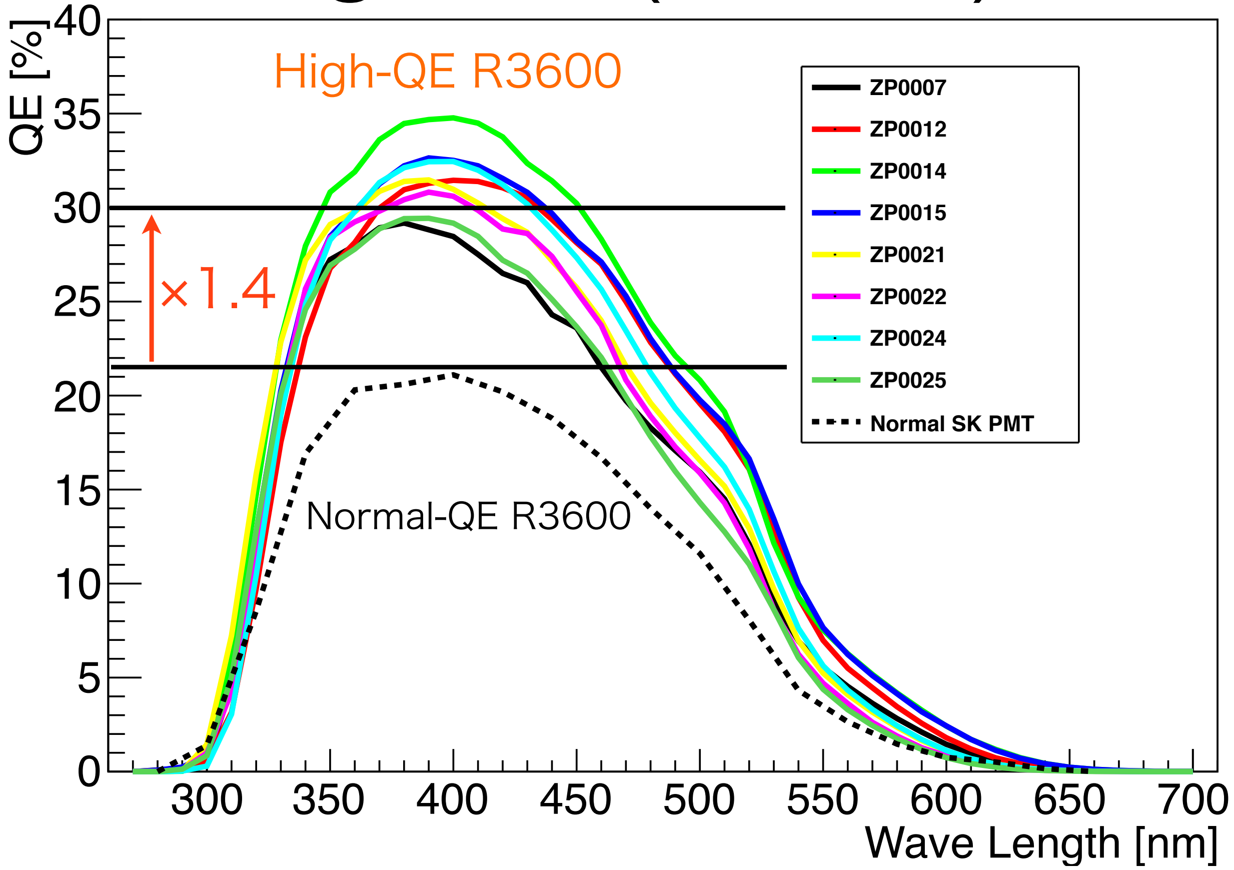
New Photon Sensors



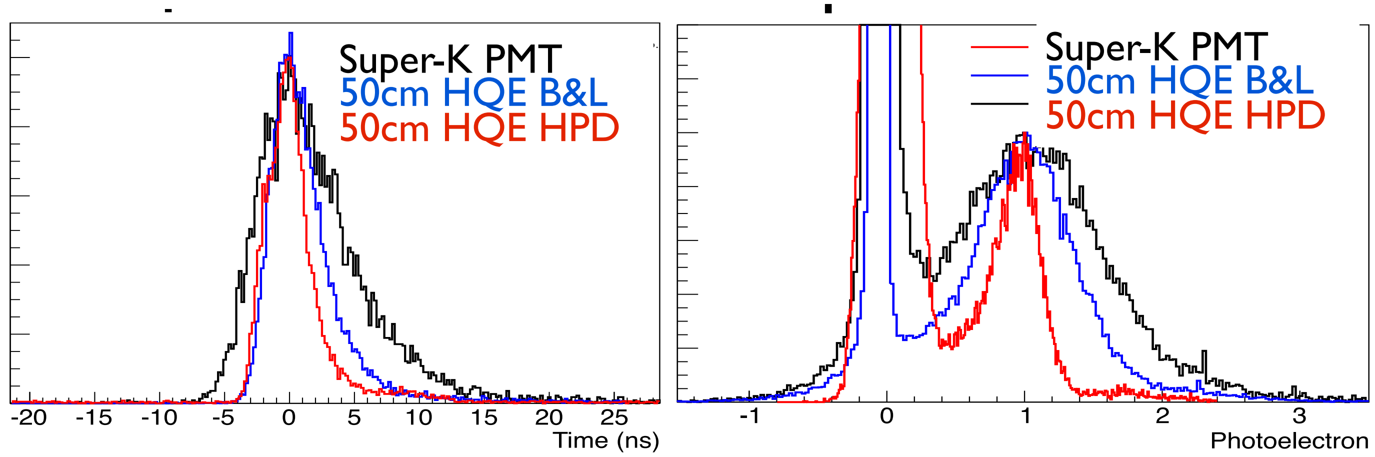
QE 22%	30%	30%
CE 80%	93%	95%

Performance of New photon-sensors

High QE (50cmΦ)



1 p.e. Time resolution / charge resolution



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

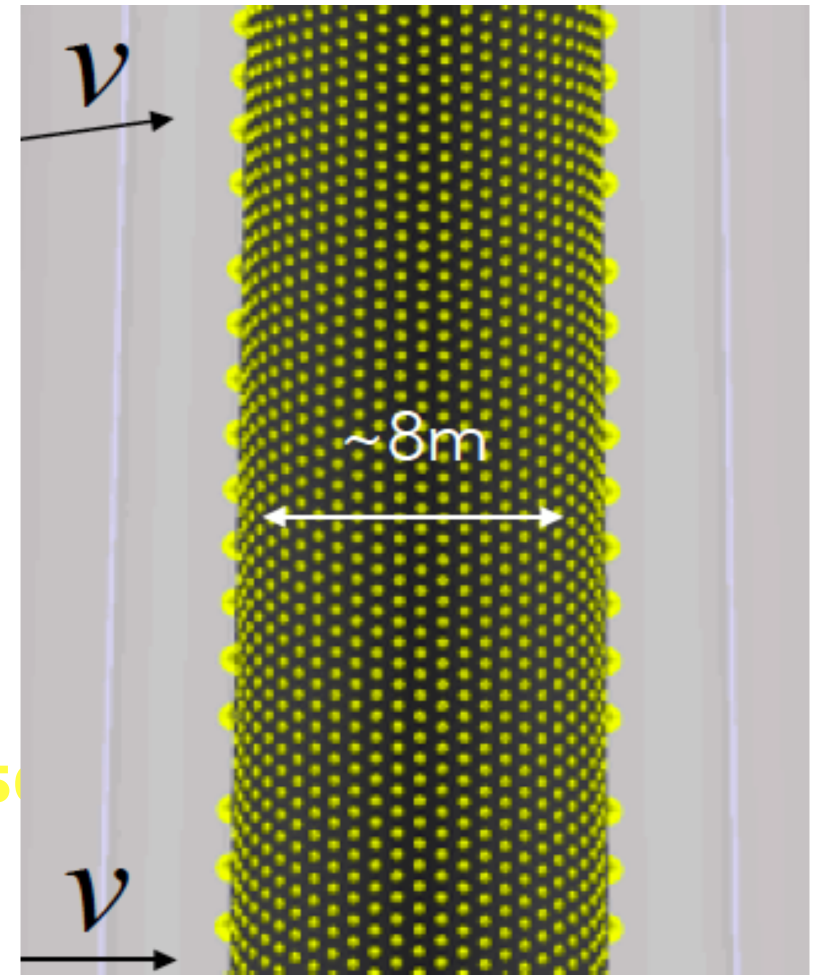
- Better timing and charge resolutions w/ High QE
- The proof-test in wanter is on-going
- R&D will be completed in 2016 to select one technology.

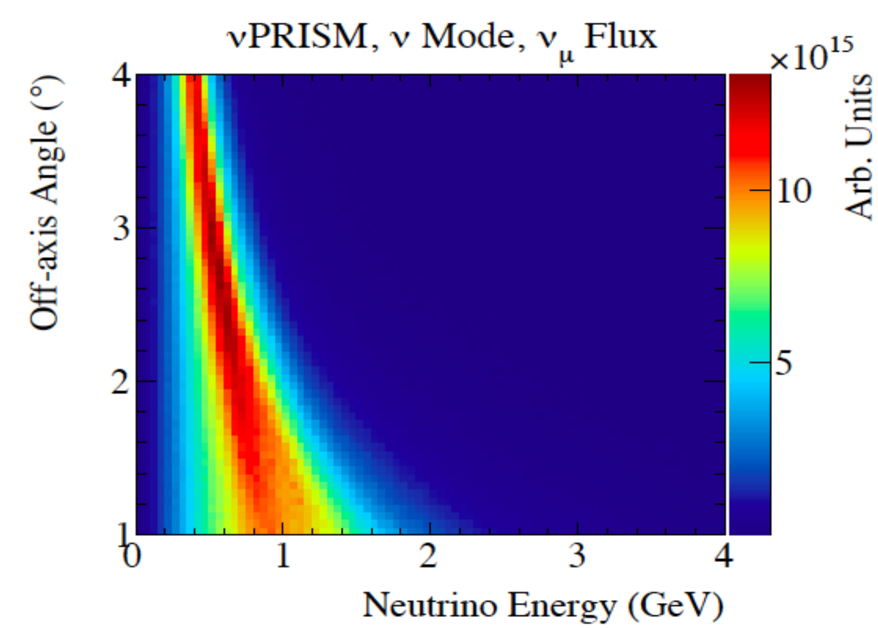
Near Detectors

Conceptual design

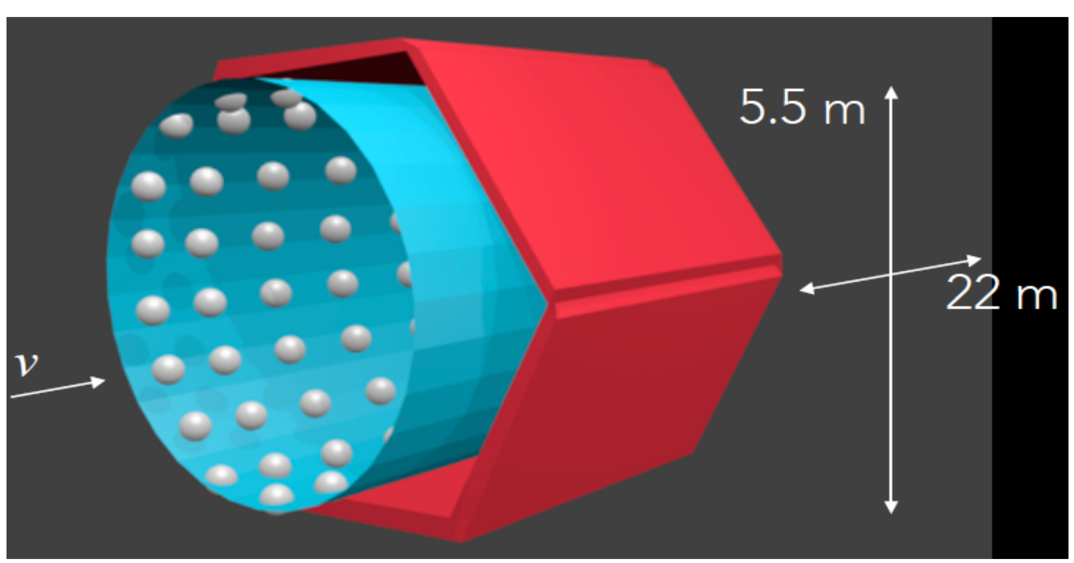
- Oscillation study
  - Water target (same w/ the far detector, minimize nuclear uncertainty)
  - NCπ^0 BG measurement
  - beam νe BG
- Other physics
  - $\nu\mu$, νe interaction studies
  - Sterile ν searches

νPRISM
50m tall WČ



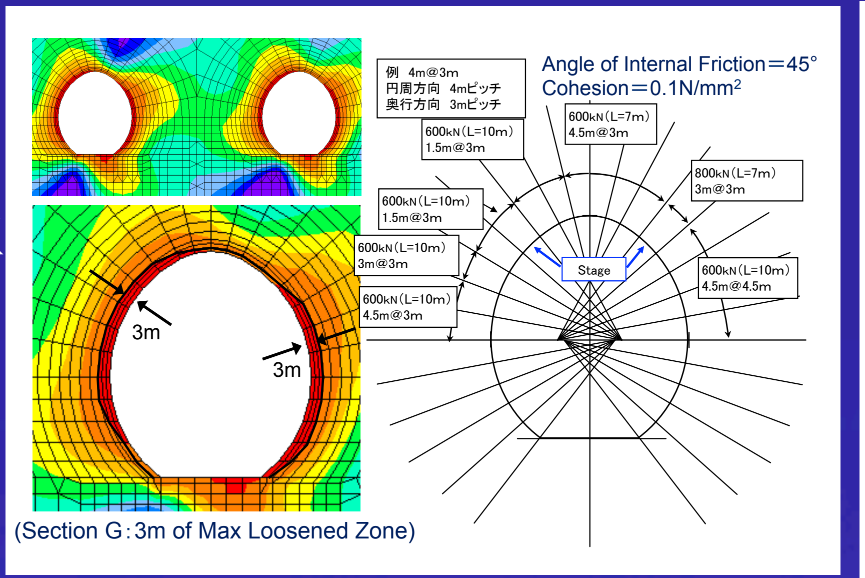


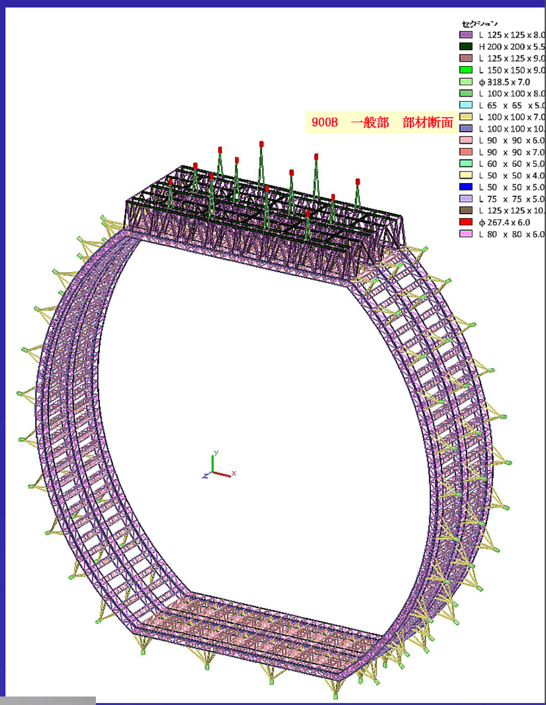
TITUS
WČ+MRD

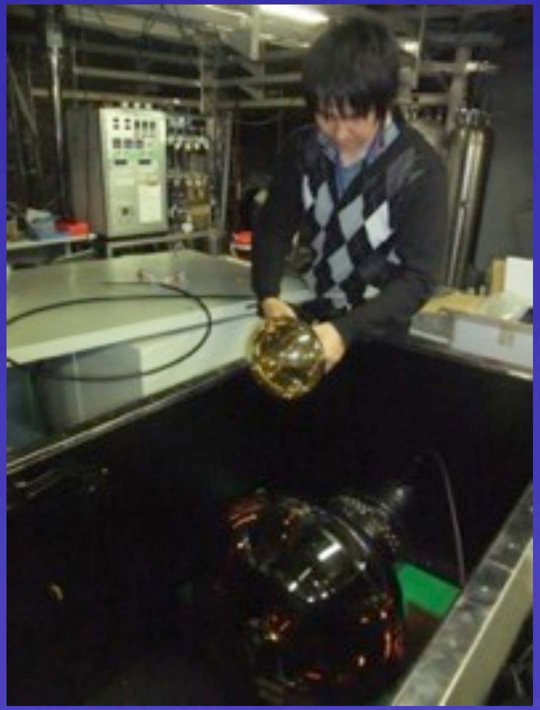


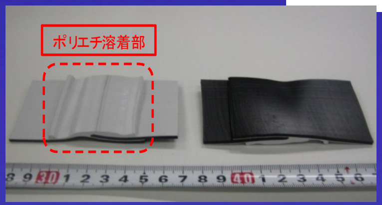
Development works

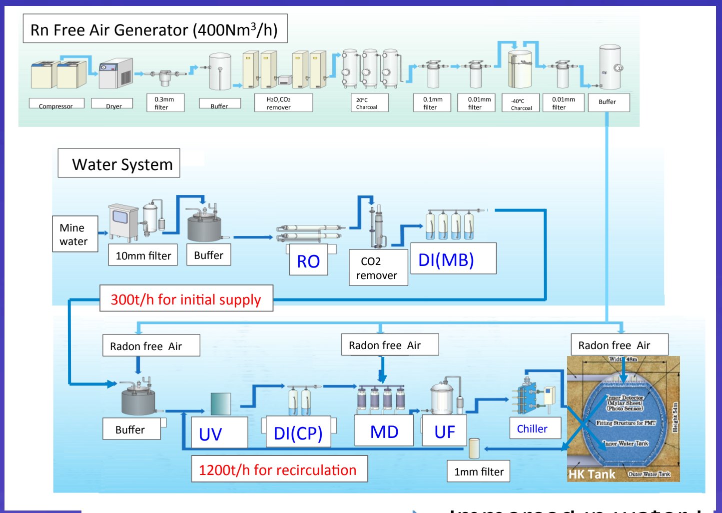
- Detector design optimization
  - tank shape, segmentation wall, tank liner, PMT support structure
- Water purification system, water quality control
- DAQ electronics (under water?)
- Calibration source deployment system
  - automated, 3D control
- Software development
  - Detector geometry optimization, enhance physics capabilities
- Physics potential studies
  - requirements for near detectors

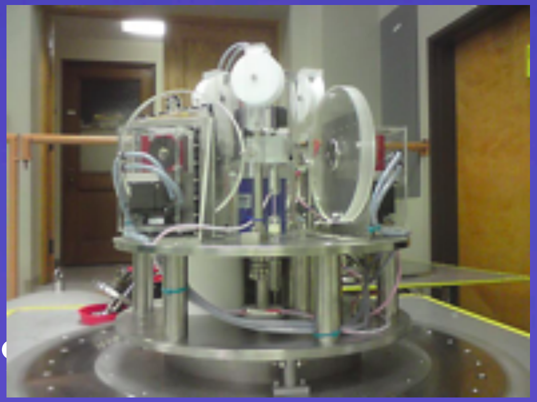


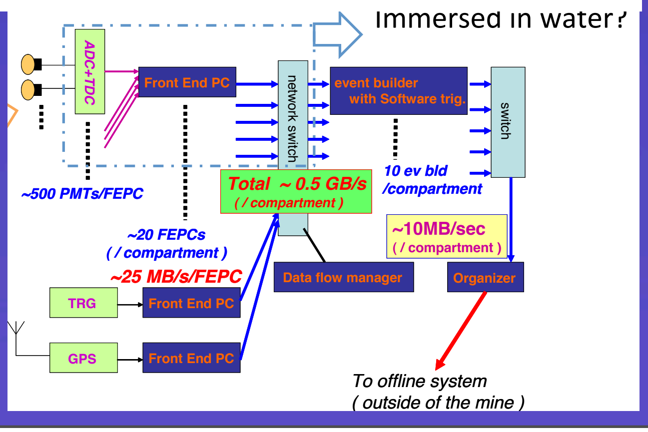












Summary

- **Wide Physics topics, many discovery potentials**
  - Neutrino CPV (76% of δ space at 3σ), δ precision of <20°
    - Proton decay discovery
    - SN burst, relic SN, WIMP annihilation ν

- **Many good results in development works**
  - Cavity and support design
  - Plastic liner
  - 50 cm high sensitivity photon-sensors
  - Many rooms to be contributed

- **Boost promoting the project**
  - International proto-collaboration has been formed
  - Cooperation with KEK/ICRR to develop the project
  - Design Report to be prepared in 2015 w/ international review
  - Open for new collaborators

Physics Digest

Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

LBL study, Hyper-K WG, arXiv:1412.4673 [hep-ex]

- Proton decay 3σ discovery potential
  - 5×10^{34} years for $p\rightarrow e^{+}\pi^{0}$
  - 1×10^{34} years for $p\rightarrow \nu K^{+}$
- Study on full parameters of ν oscillations
  - CPV (76% of δ space at 3σ), <20° precision
  - MH determination for all δ by J-PARC/Atm ν
  - θ_{23} octant: $\sin^2\theta_{23}<0.47$ or $\sin^2\theta_{23}>0.53$
  - <1% precision of Δm^2_{32}
  - test of exotic scenarios by J-PARC/Atm ν
- Astrophysical neutrino observatory
  - Supernova up to 2Mpc distance, ~1SN /10 years
  - Supernova relic ν signal (~300ν events/10yrs)
  - Dark matter neutrinos from Sun, Galaxy, and Earth
  - Solar neutrino ~200ν events/day