THE HYPER-KAMIOKANDE EXPERIMENT

MARK HARTZ FOR THE HYPER-K PROTO-COLLABORATION

KAVLI IPMU/TRIUMF

NUFACT 2016, ICISE, QUY NHON, VIETNAM

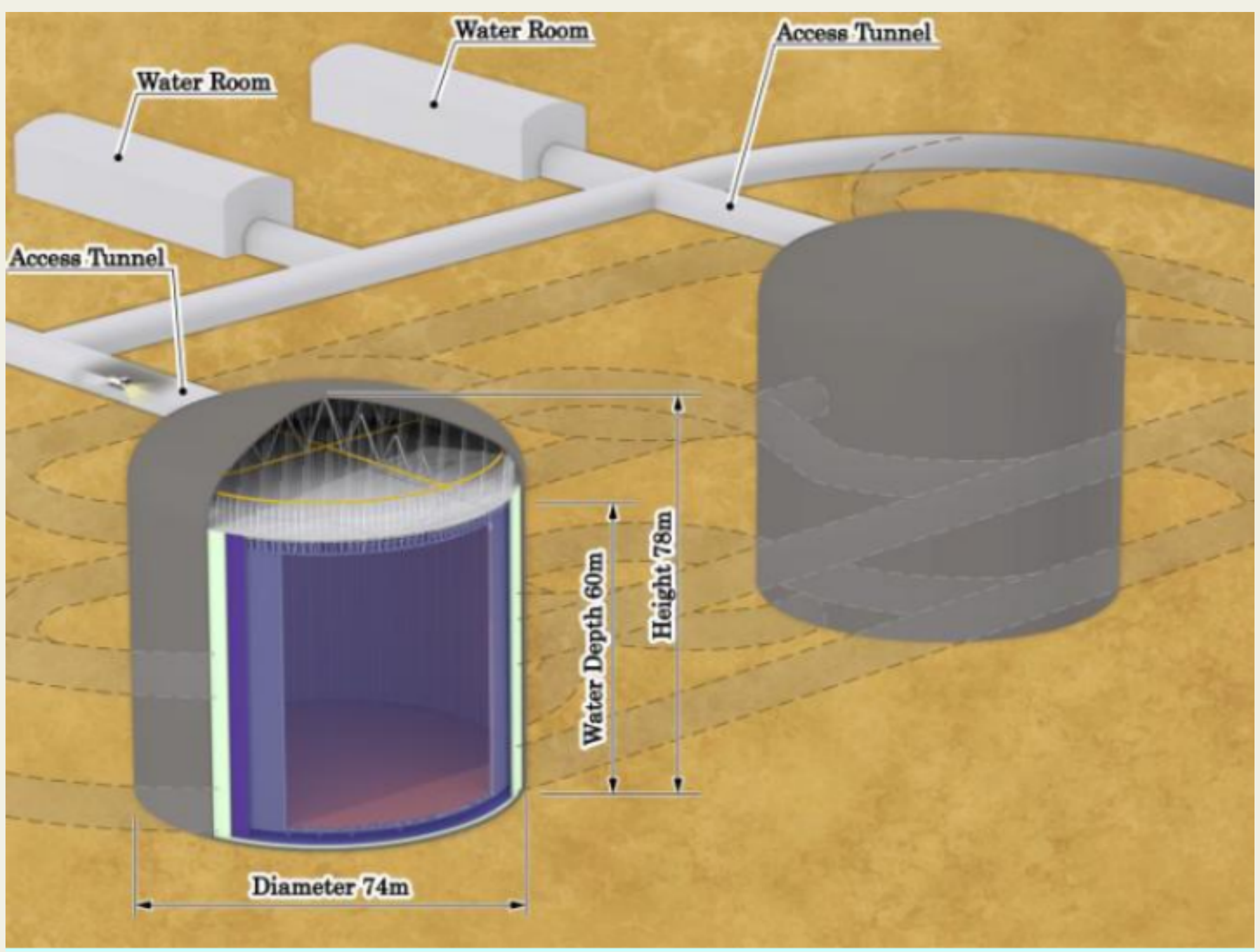
Hyper-Kamiokande

OUTLINE

- Overview of the Hyper-K experiment
- The physics of Hyper-K
- Systematic errors and near/intermediate detectors
- Technical developments of the Hyper-K experiment
- Option for a Hyper-K tank in Korea
- Timeline of the Hyper-K experiment
- Summary

HYPER-K EXPERIMENT

520 kton Water Cherenkov Detector



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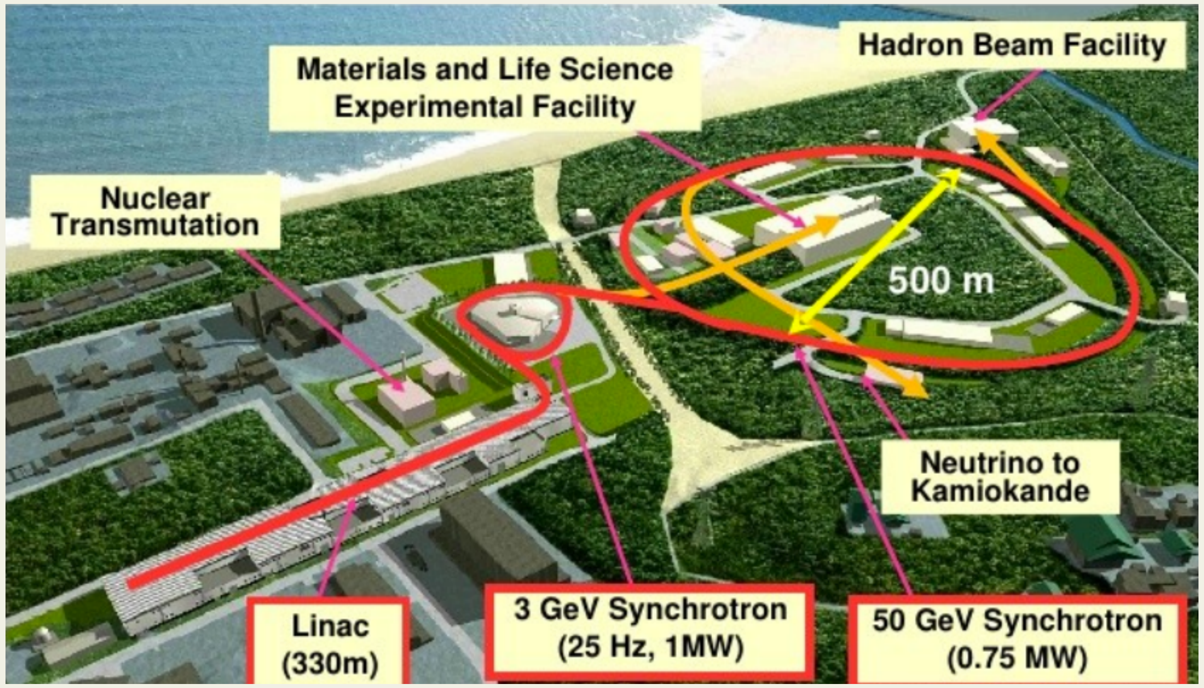
Upgrade of J-PARC neutrino beam to 1.3 MW beam power. New/upgraded near detectors.



HYPER-K EXPERIMENT

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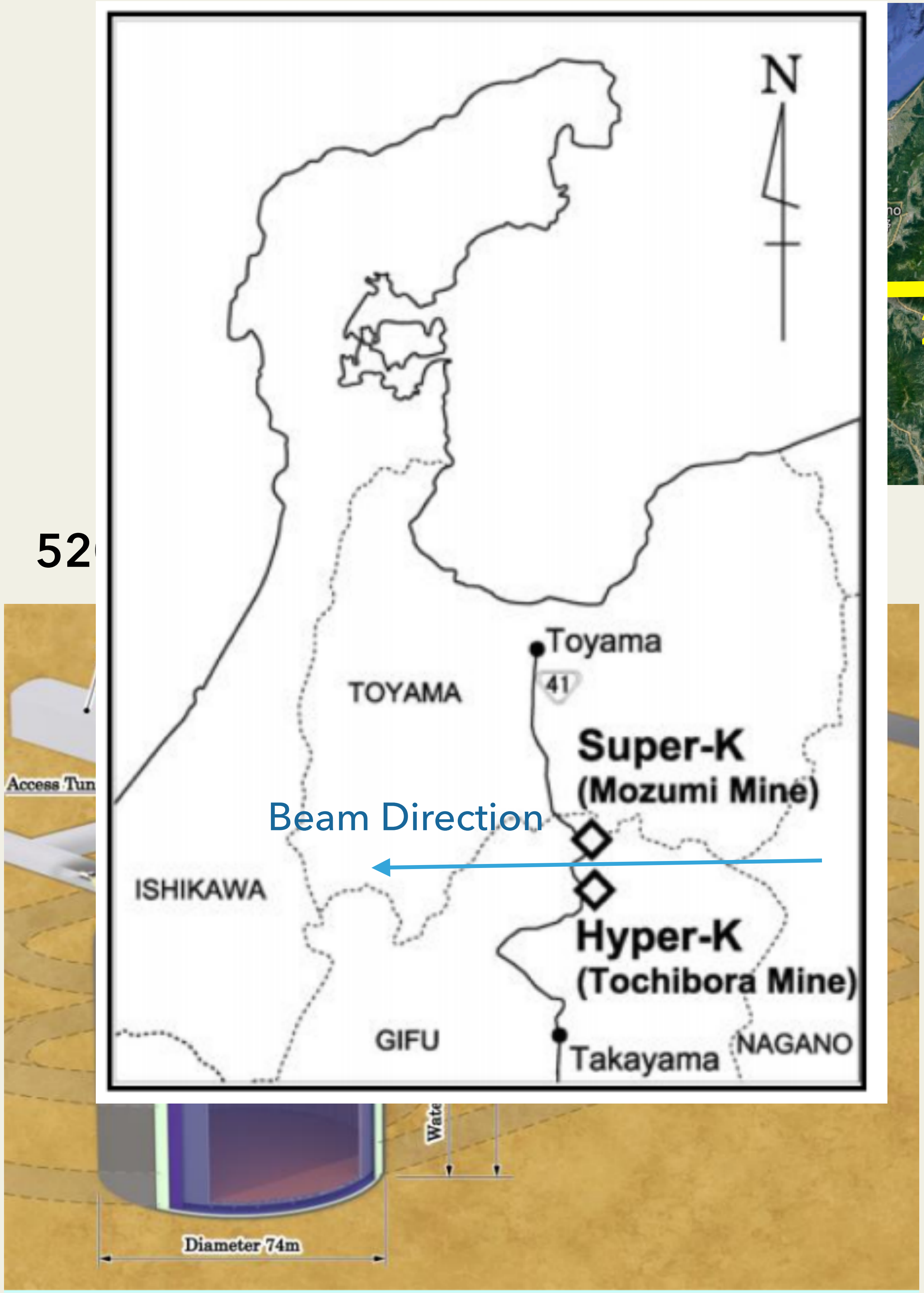

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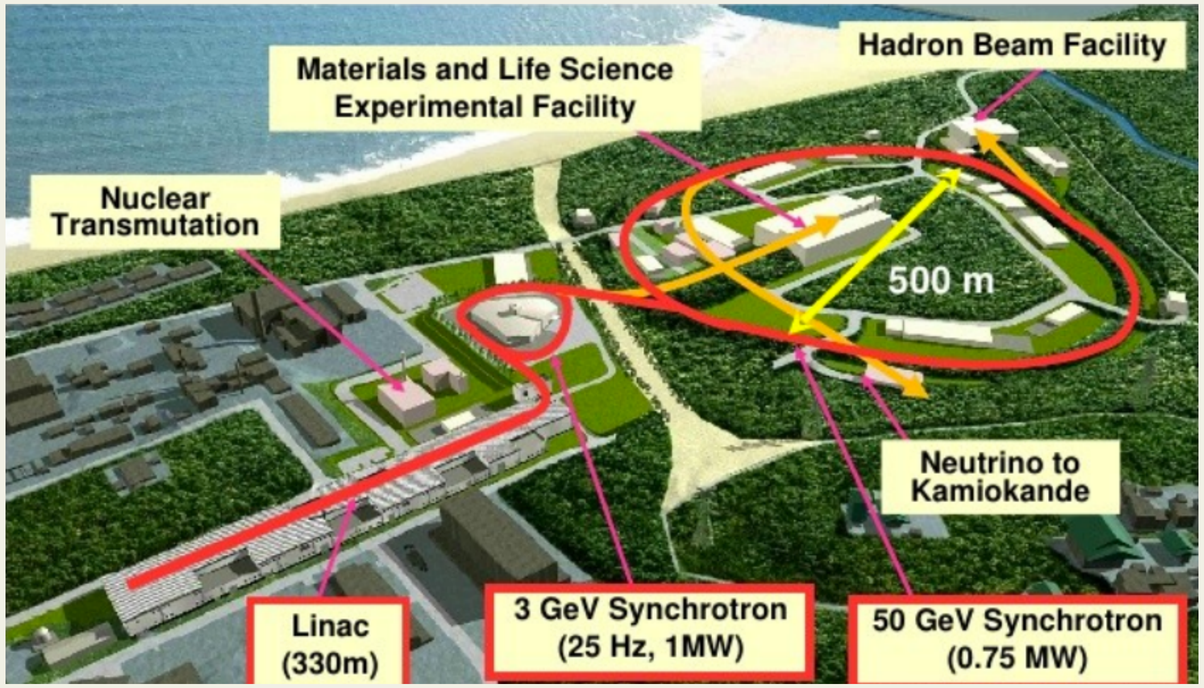
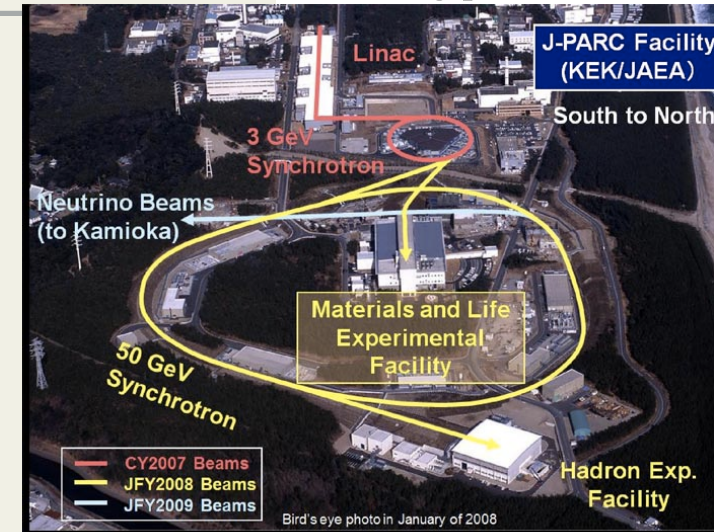


PHYSICS GOALS FOR HYPER-K



Probing/searching for physics beyond the standard model:

Search for CPV in the lepton sector

Determination of the neutrino mass hierarchy

Precision oscillation parameter measurement

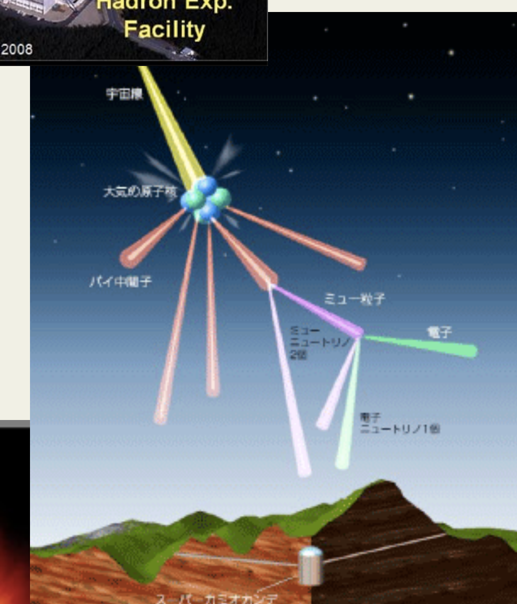
Search for nucleon decay

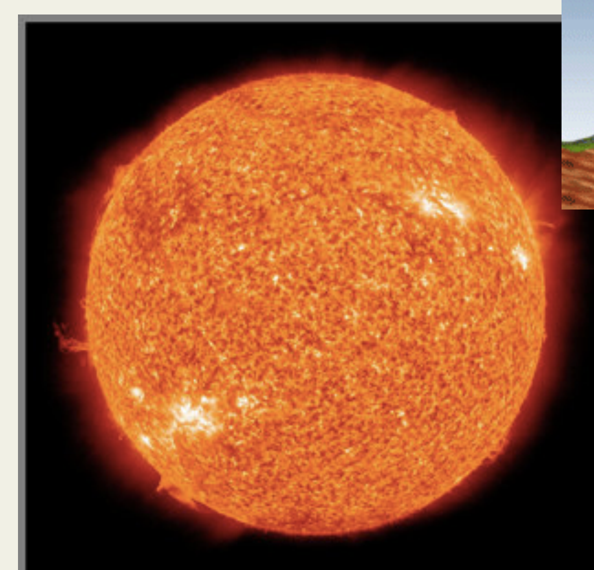
Astrophysics Observatory:

Precision measurement with solar ν

High statistic supernova burst ν

Detection of supernova relic ν





THE HYPER-K COLLABORATION

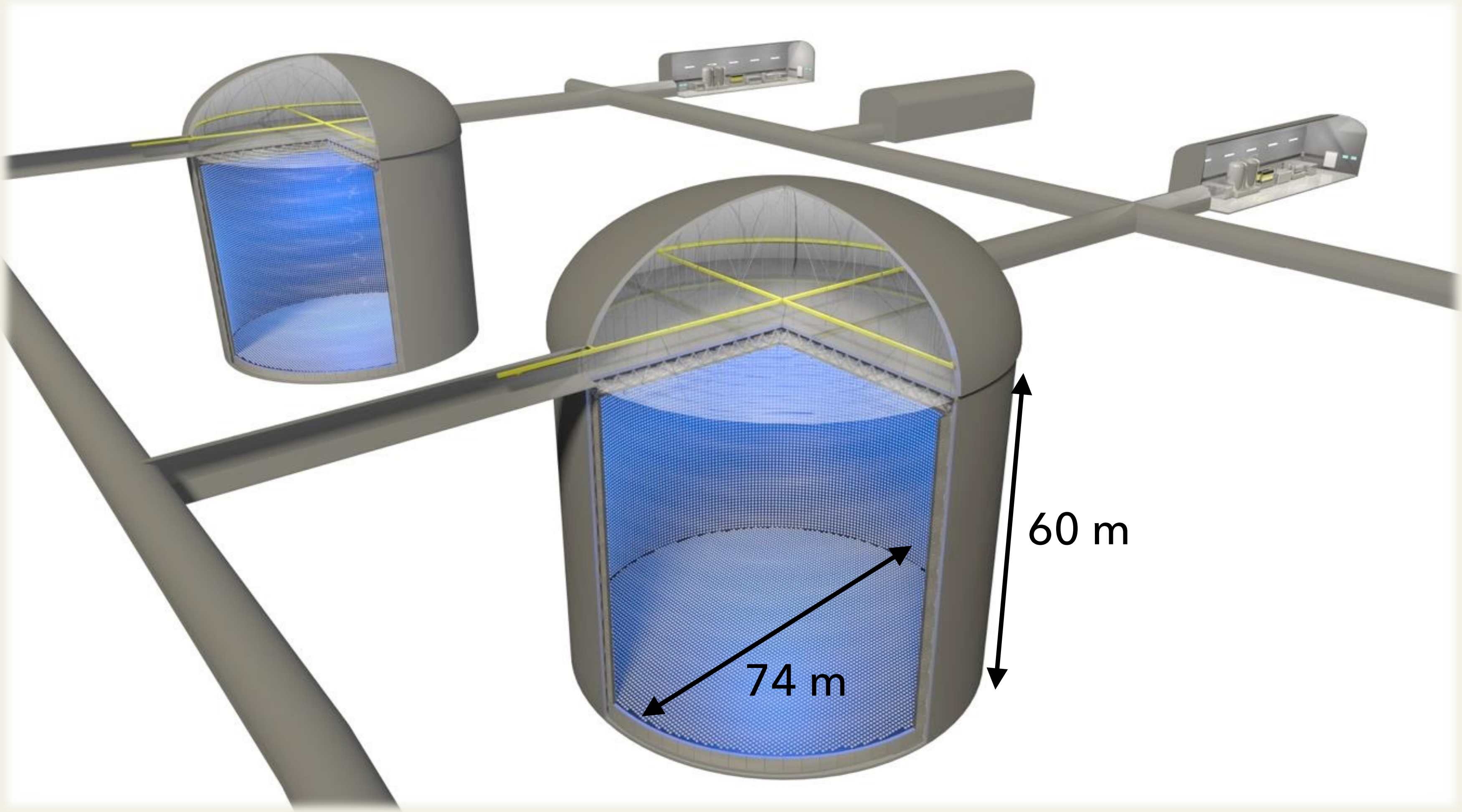
Collaboration formed in January 2015

~250 member and growing from 12 countries

MOU between Tokyo University, ICRR and KEK IPNS signed for cooperation on the Hyper-K project

Hyper-K given the highest priority from the KEK Project Implementation Plan (PIP) review

THE HYPER-K DETECTOR



<u>Hyper-K Tank:</u>

60 m tall x 74 m diameter

40,000 50cm ϕ PMTs → 40% photo-coverage

260 kton mass (187 kton fiducial volume is ~10x larger than Super-K)

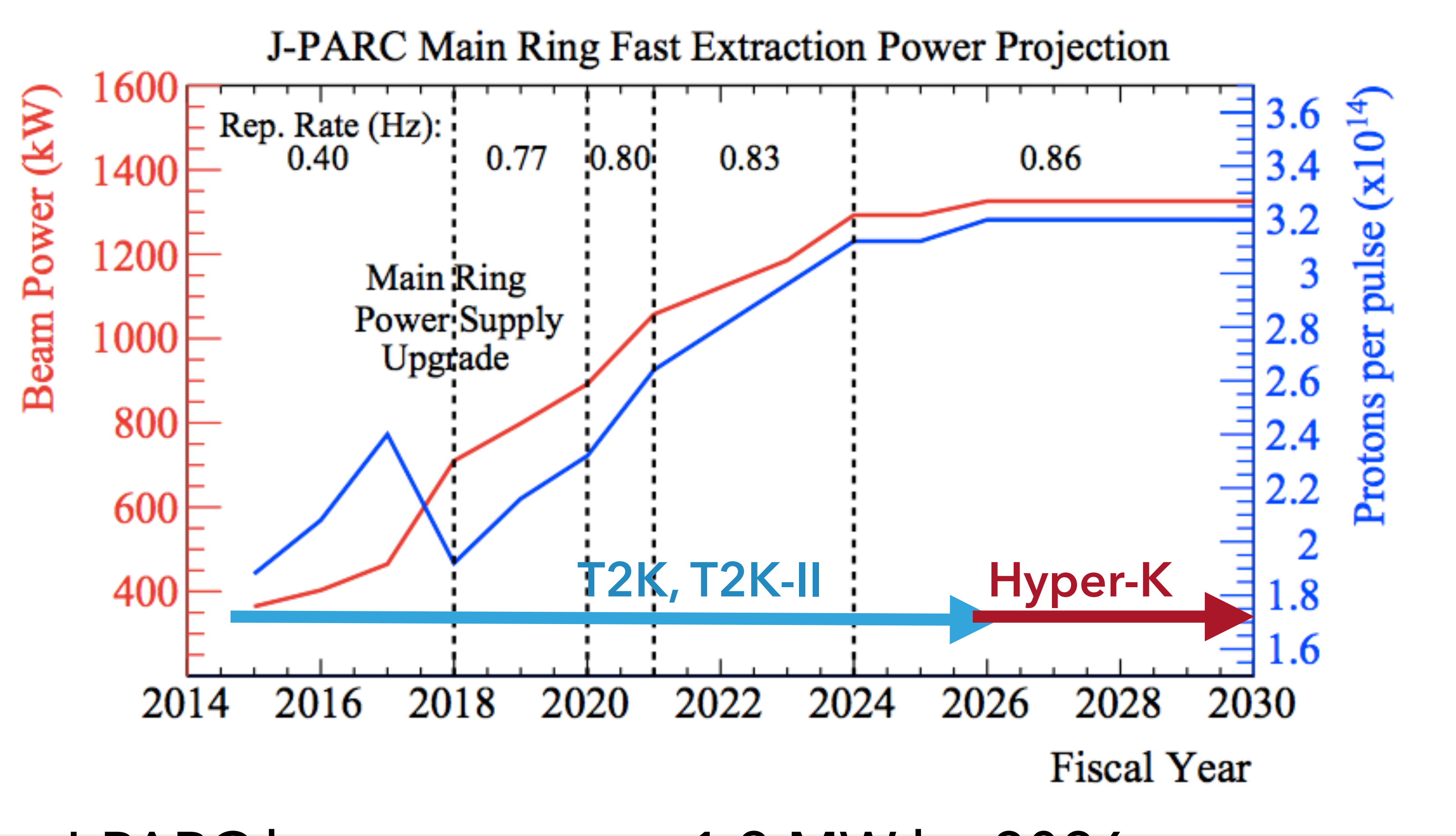
<u>2 Tanks with staging:</u>

Design was updated from original design of 2 horizontal egg-shaped tanks

Goal of design update: maintain the physics while minimizing cost → Fiducial volume is 2/3 of original while cost is significantly reduced

Staged construction of the tanks with the second tank 6 years after first tank

THE NEUTRINO BEAM



Increase of the J-PARC beam power to 1.3 MW by 2026

750 kW will be achieved after 2018 Main Ring power supply magnet upgrade

Power improvement largely achieved through rep. rate increase from 0.4 to 0.86 Hz

Increase of protons per pulse from current 2.1e14 to 3.2e14

See WG3 parallel talks:

Horns: T. Sekiguchi in Parallel Session #1

Neutrino beam line: K. Sakashita in Parallel Session #2

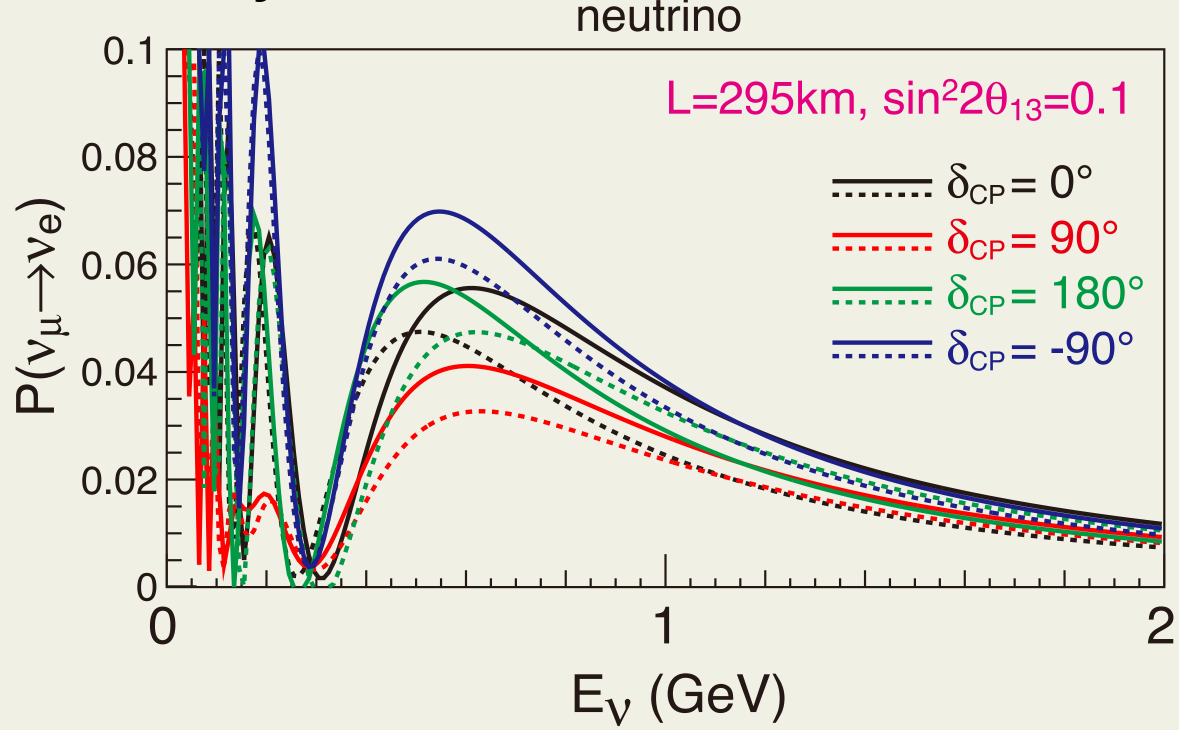
Accelerator: Y. Sato in Parallel Session #2

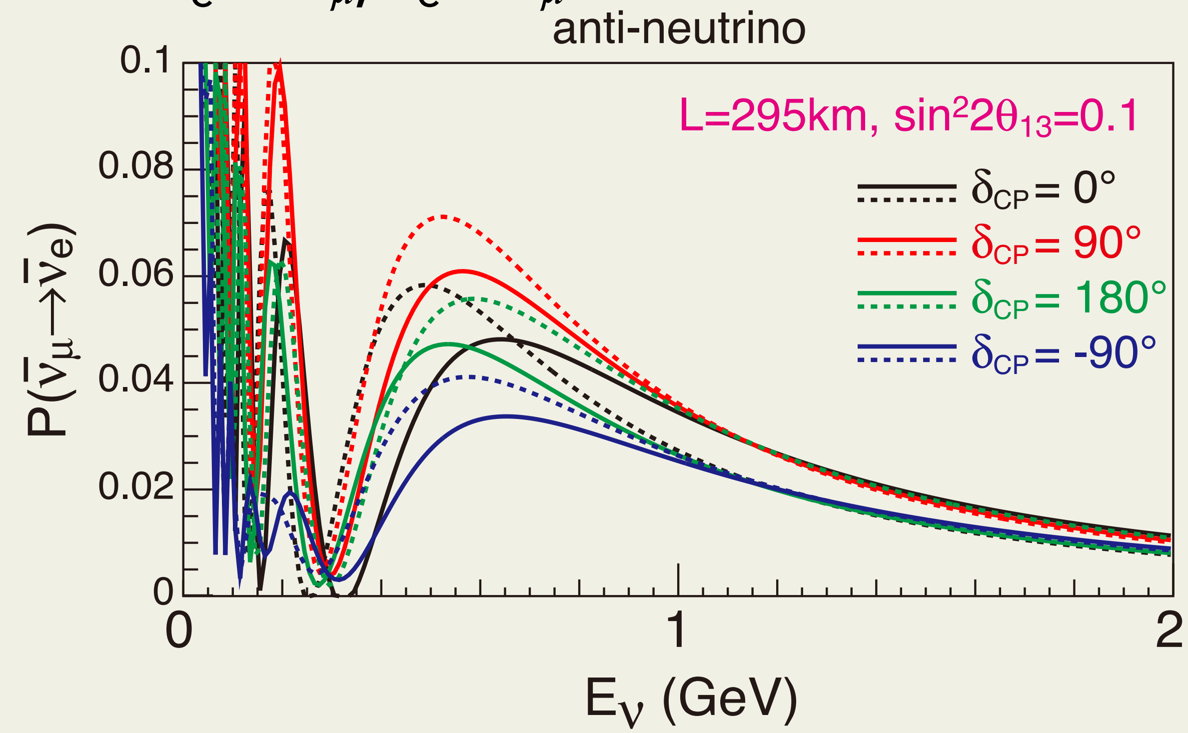
HYPER-K PHYSICS

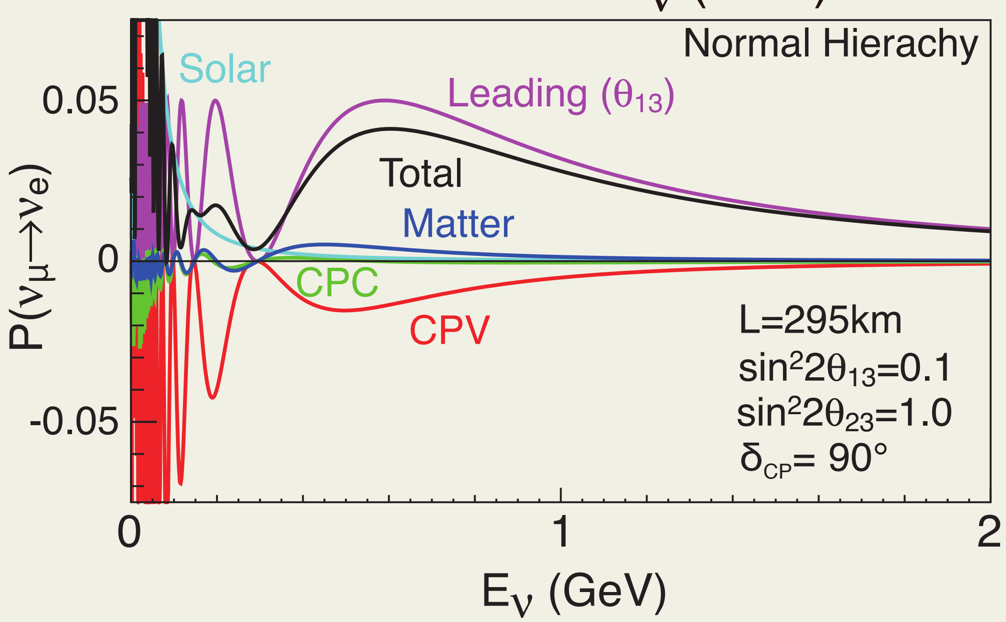
LONG BASELINE PHYSICS

Hyper-Kamiokande

Primary Goal: Detection of CP violation in the $\nu_e \rightarrow \nu_\mu$, $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$ channels







At 295 km baseline, the CPV effect dominates over the matter effect

Precision measurement of the θ_{23}, Δm^2_{32}, δ_{cp} and θ_{13} parameters

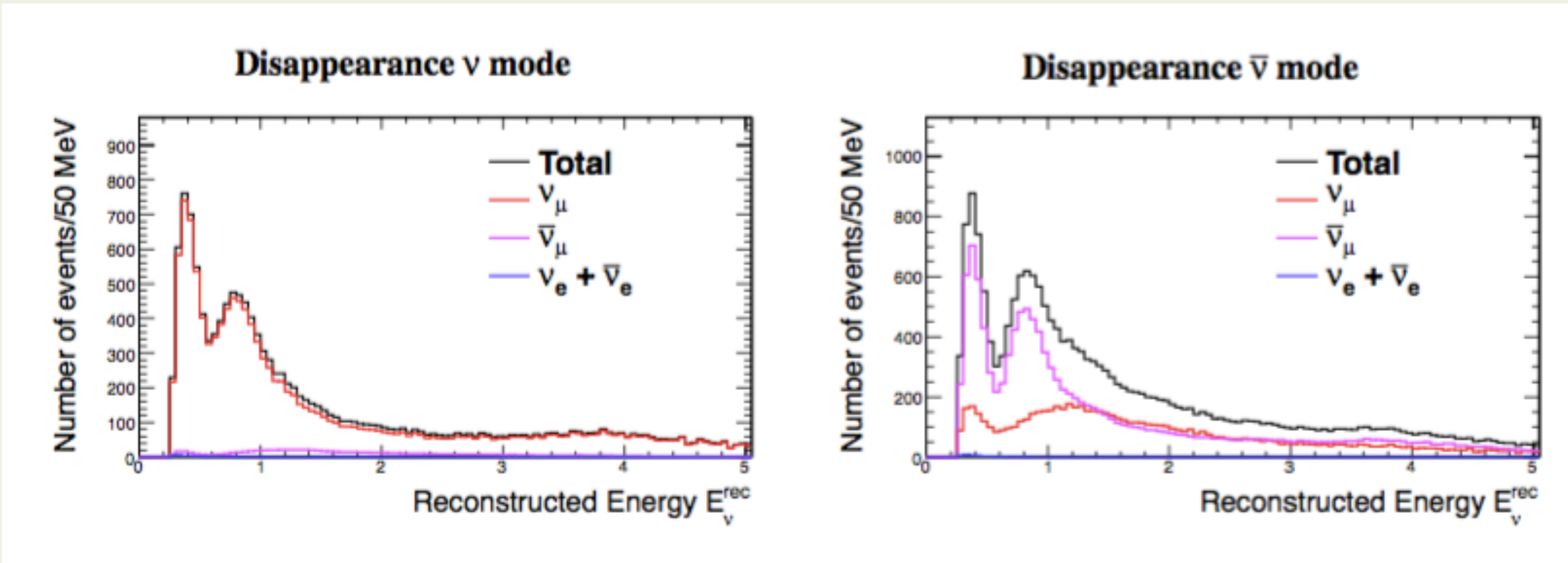
10 years operation with 1.3 MW beam from J-PARC, 3:1 $\overline{\nu}$ to ν ratio

See talk by Y. Obayashi in WG1, Parallel Session #4

DISAPPEARANCE MODE EVENT RATES

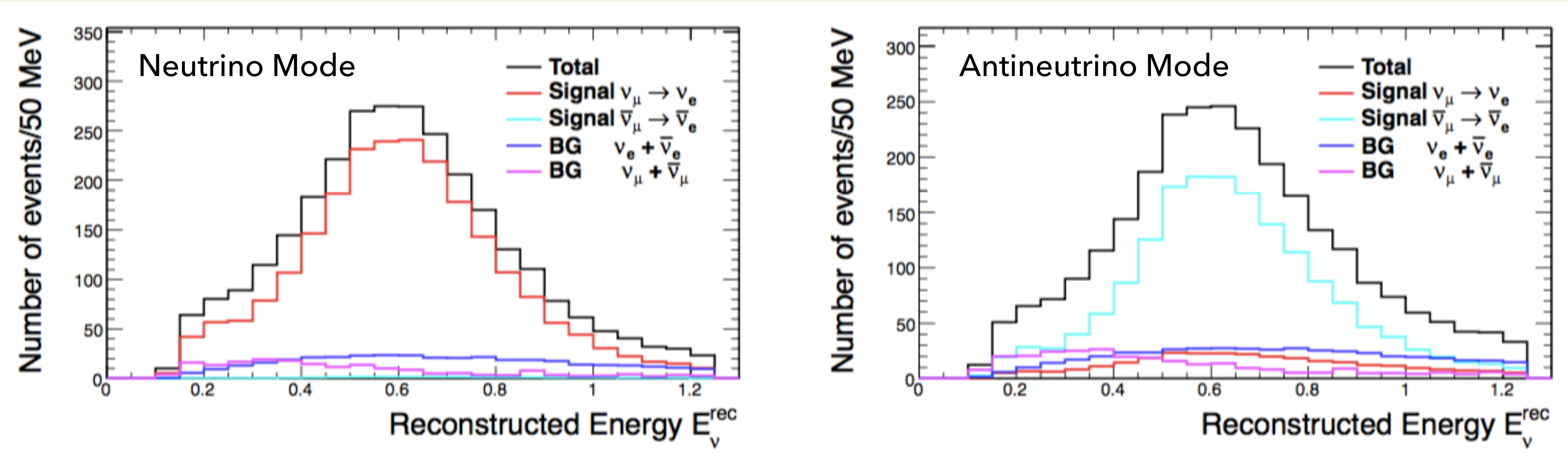
Use kinematic energy reconstruction

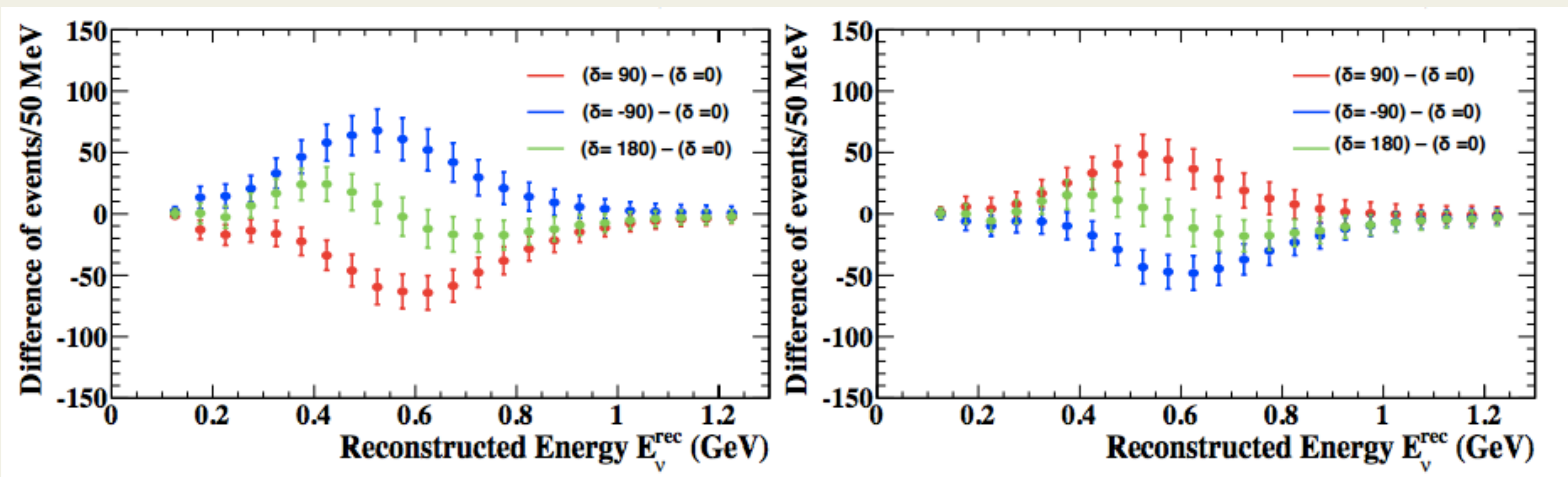
$$E_\nu^{\mathrm{rec}} = \frac{2(m_n - V)E_\ell + m_p^2 - (m_n - V)^2 - m_\ell^2}{2(m_n - V - E_\ell + p_\ell \cos\theta_\ell)}$$



	CCQE	CC non-QE	NC	Total
ν beam	8947	4444	672	14110
$\bar{\nu}$ beam	12317	6040	844	19214

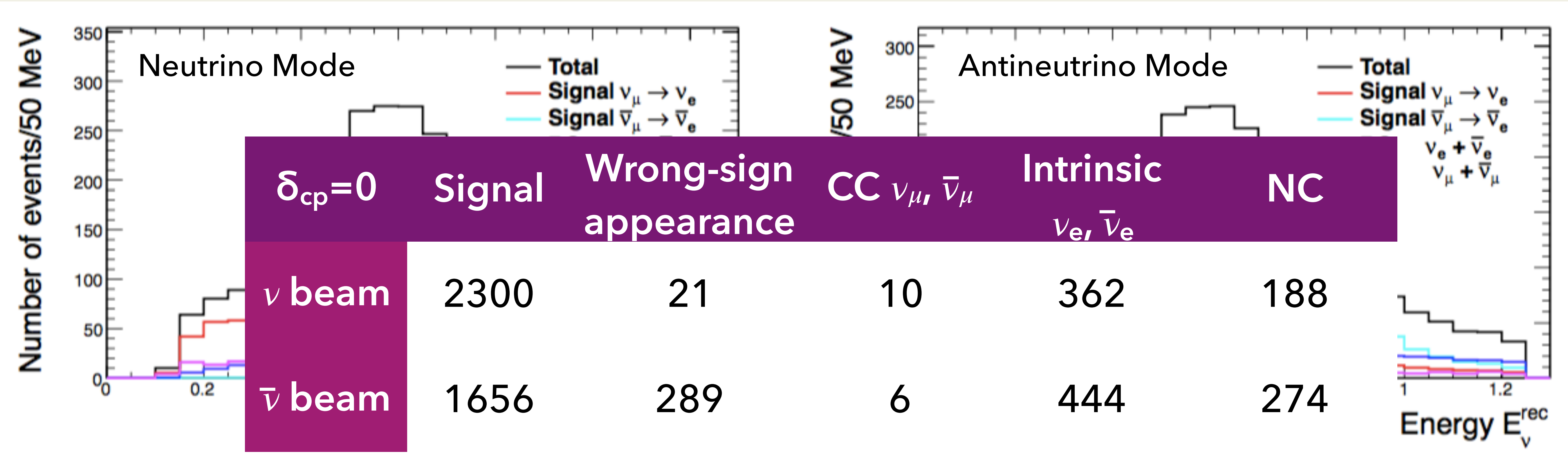
APPEARANCE MODE EVENT RATES



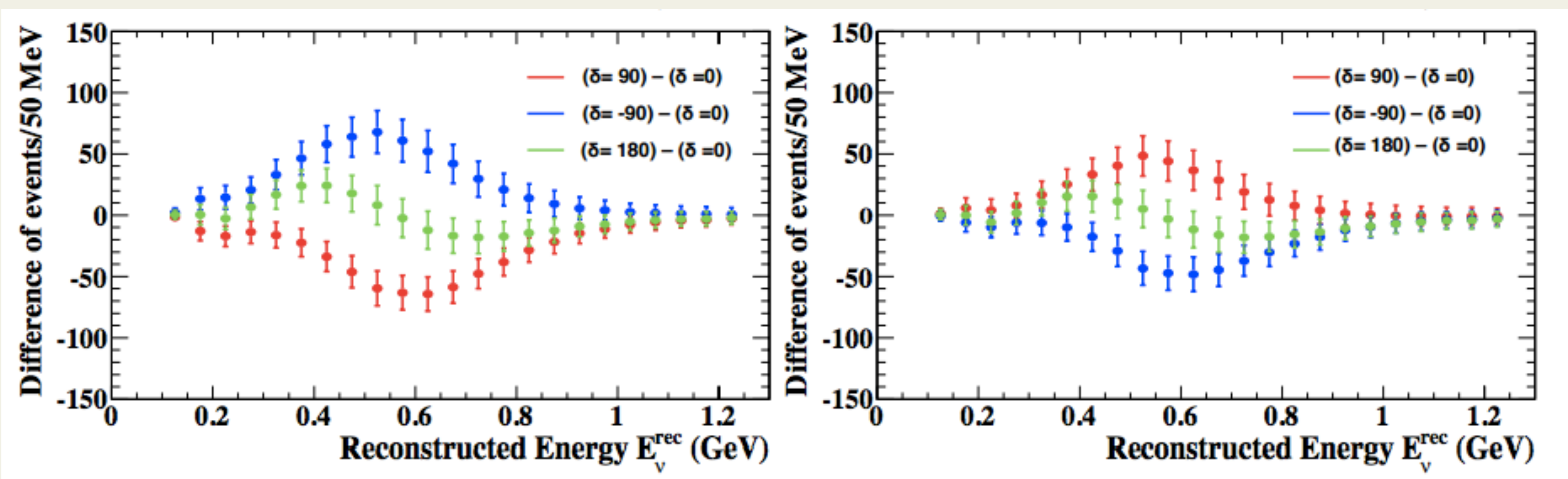


Sensitivity to sin(δ) through normalization change, cos(δ) through spectral change

APPEARANCE MODE EVENT RATES

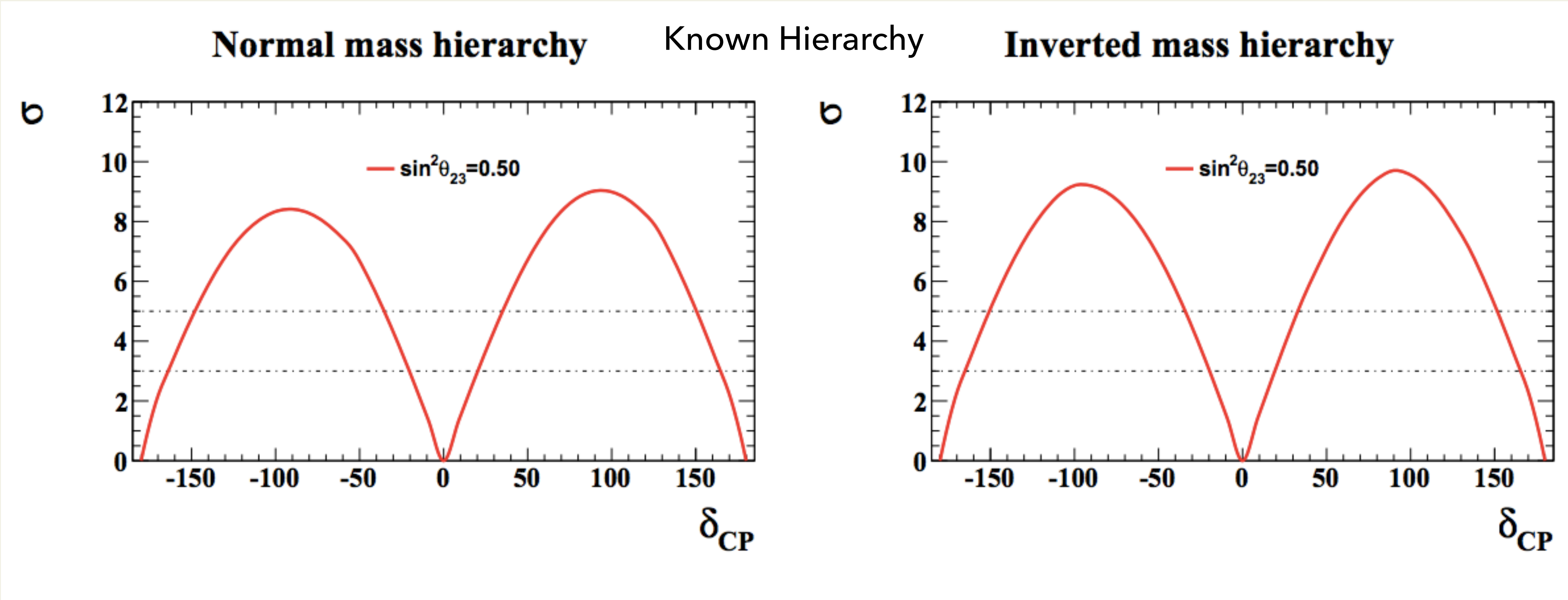


δ_{cp}=0	Signal	Wrong-sign appearance	CC ν_μ, $\bar{\nu}_\mu$	Intrinsic ν_e, $\bar{\nu}_e$	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274



Sensitivity to sin(δ) through normalization change, cos(δ) through spectral change

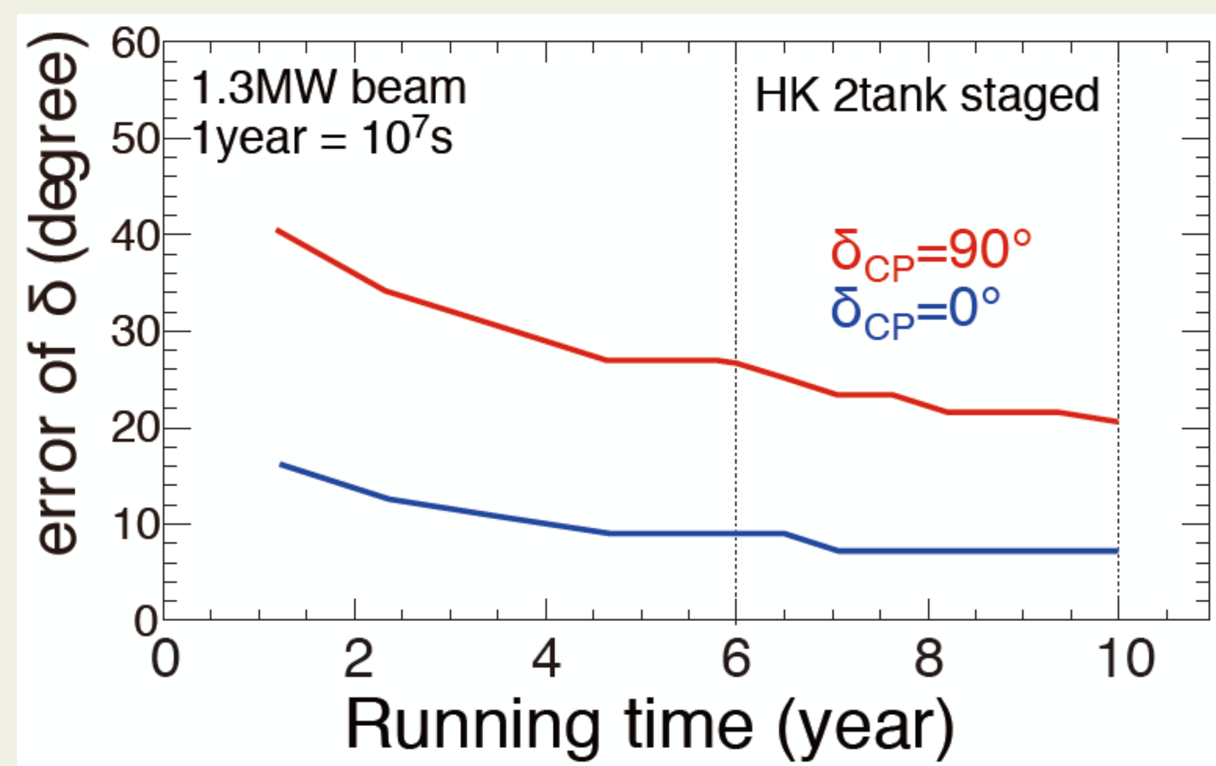
CP VIOLATION SENSITIVITY



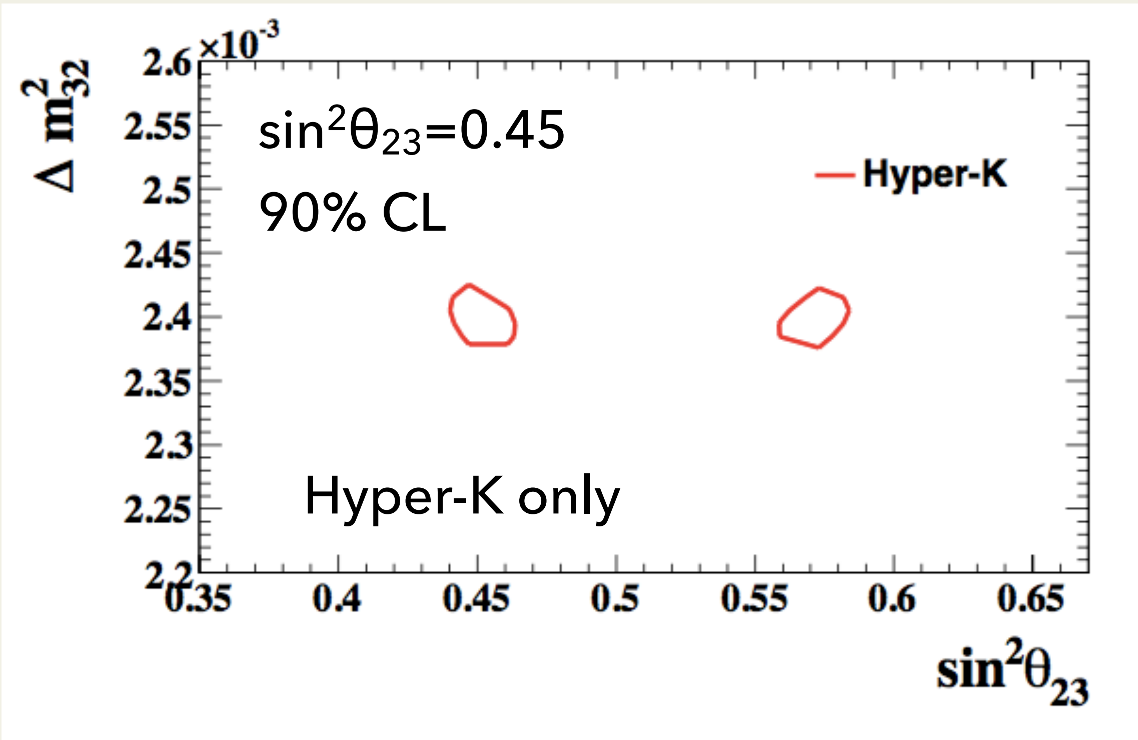
Exclusion of $\sin(\delta_{cp})=0$ at 3σ for 78% of δ_{cp} values at 5σ for 62%

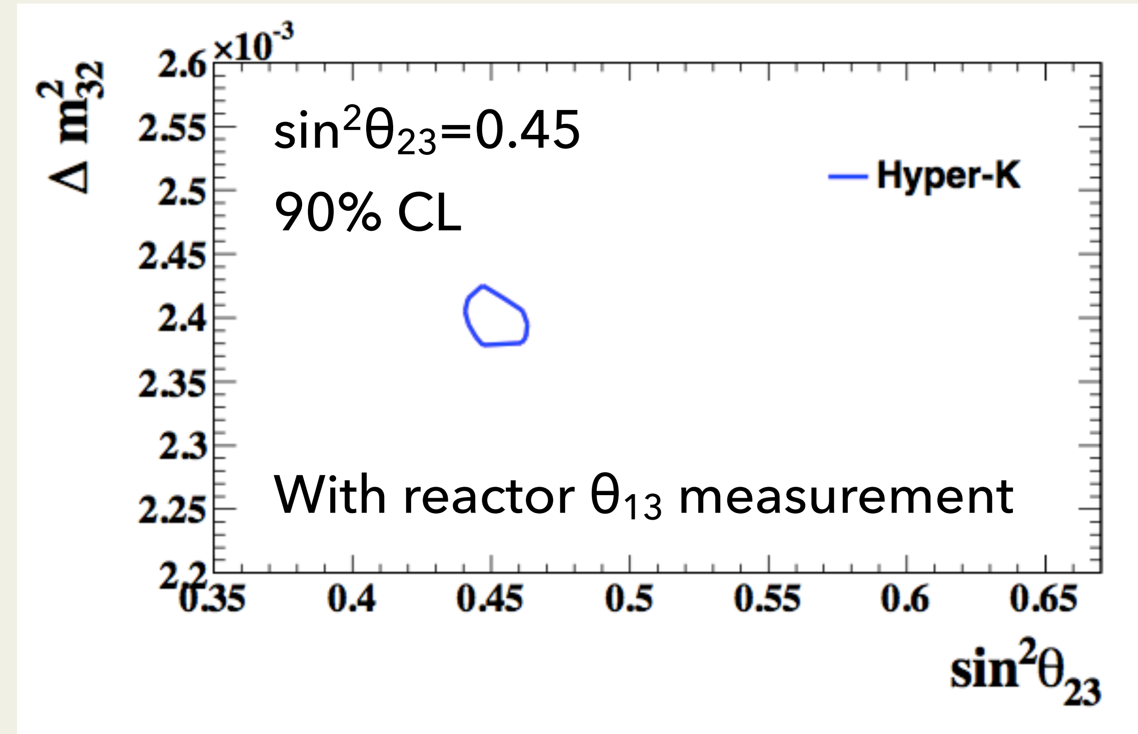
21° precision at $\delta_{cp}=90°$

7° precision at $\delta_{cp}=0°$



ATMOSPHERIC PARAMETER DETERMINATION

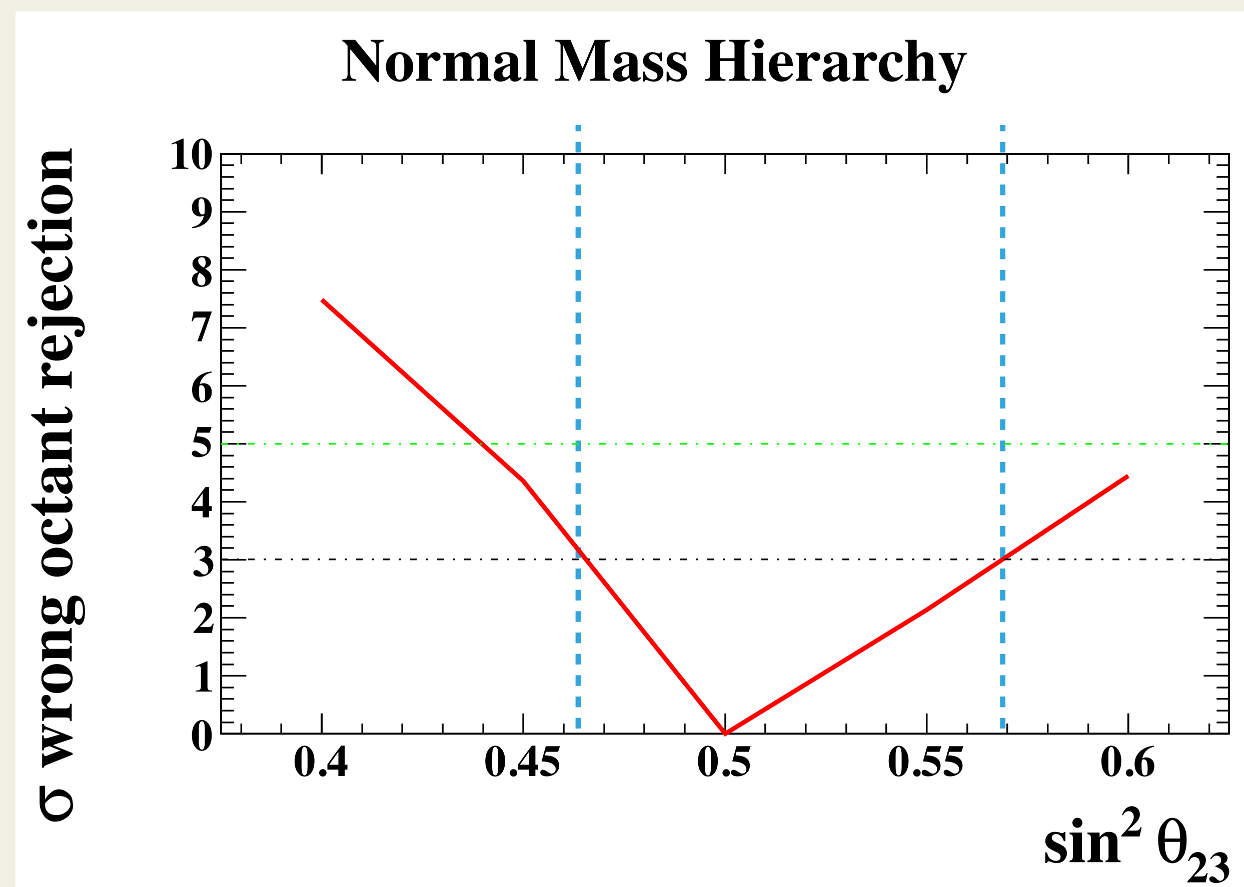




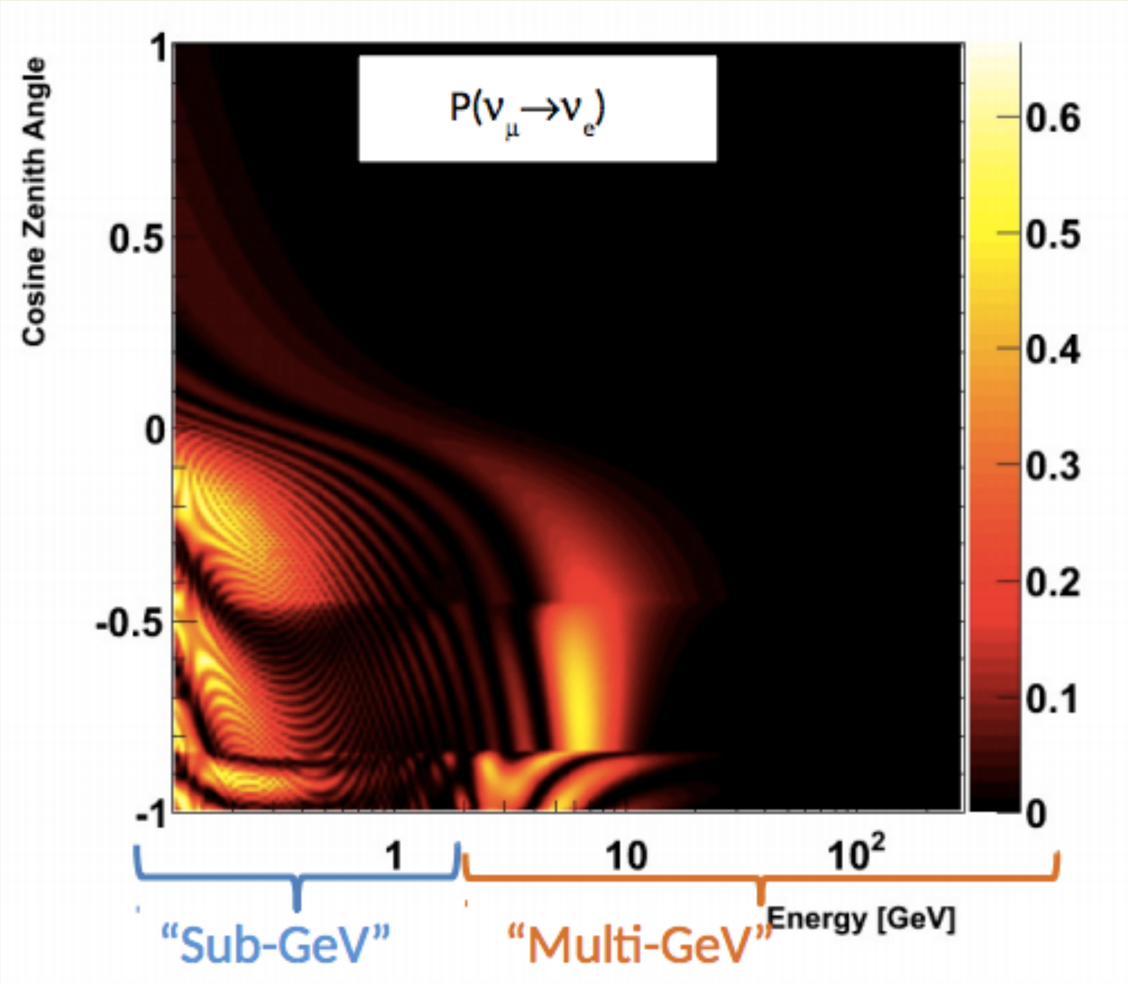
0.6% uncertainty on Δm^2_{32}

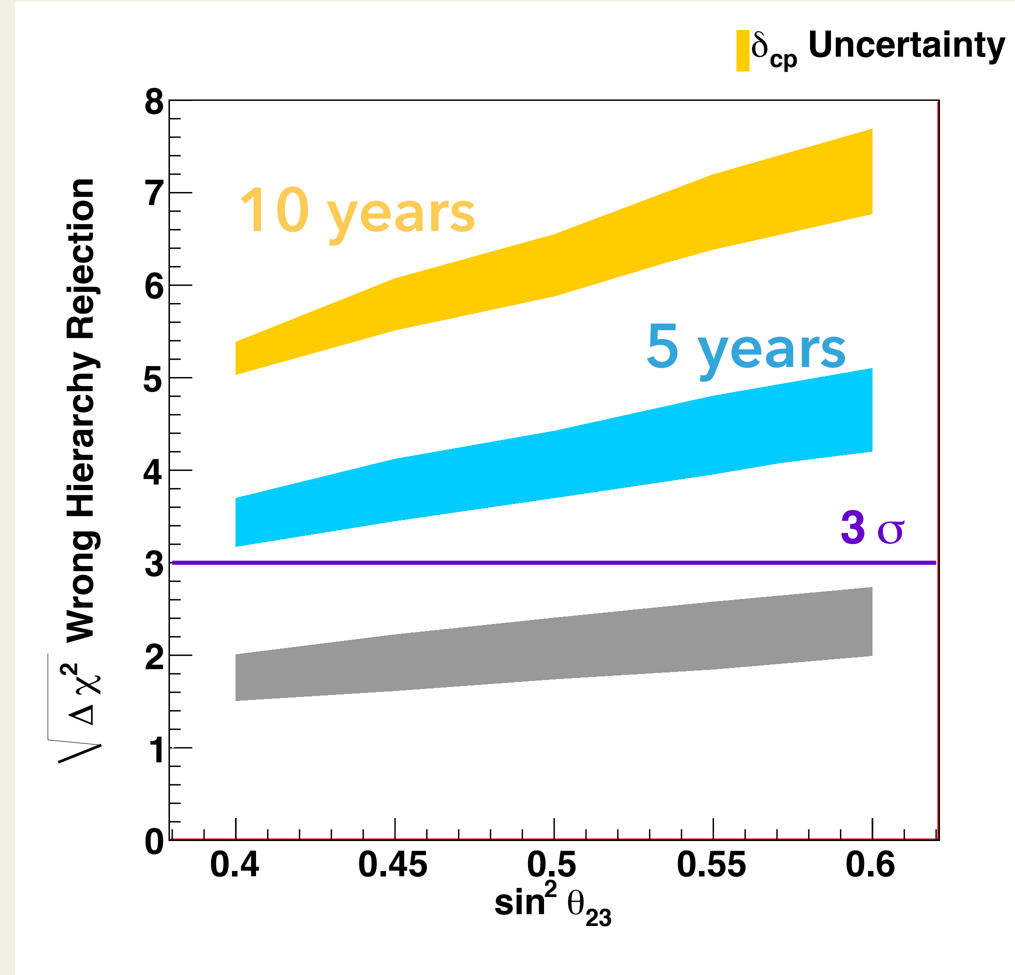
Error on $\sin^2\theta_{23}$ of 0.015 (at 0.5), 0.006 (at 0.45)

Rejection of the wrong octant for non-maximal mixing values of θ_{23}



ATMOSPHERIC NEUTRINOS – MASS HIERARCHY





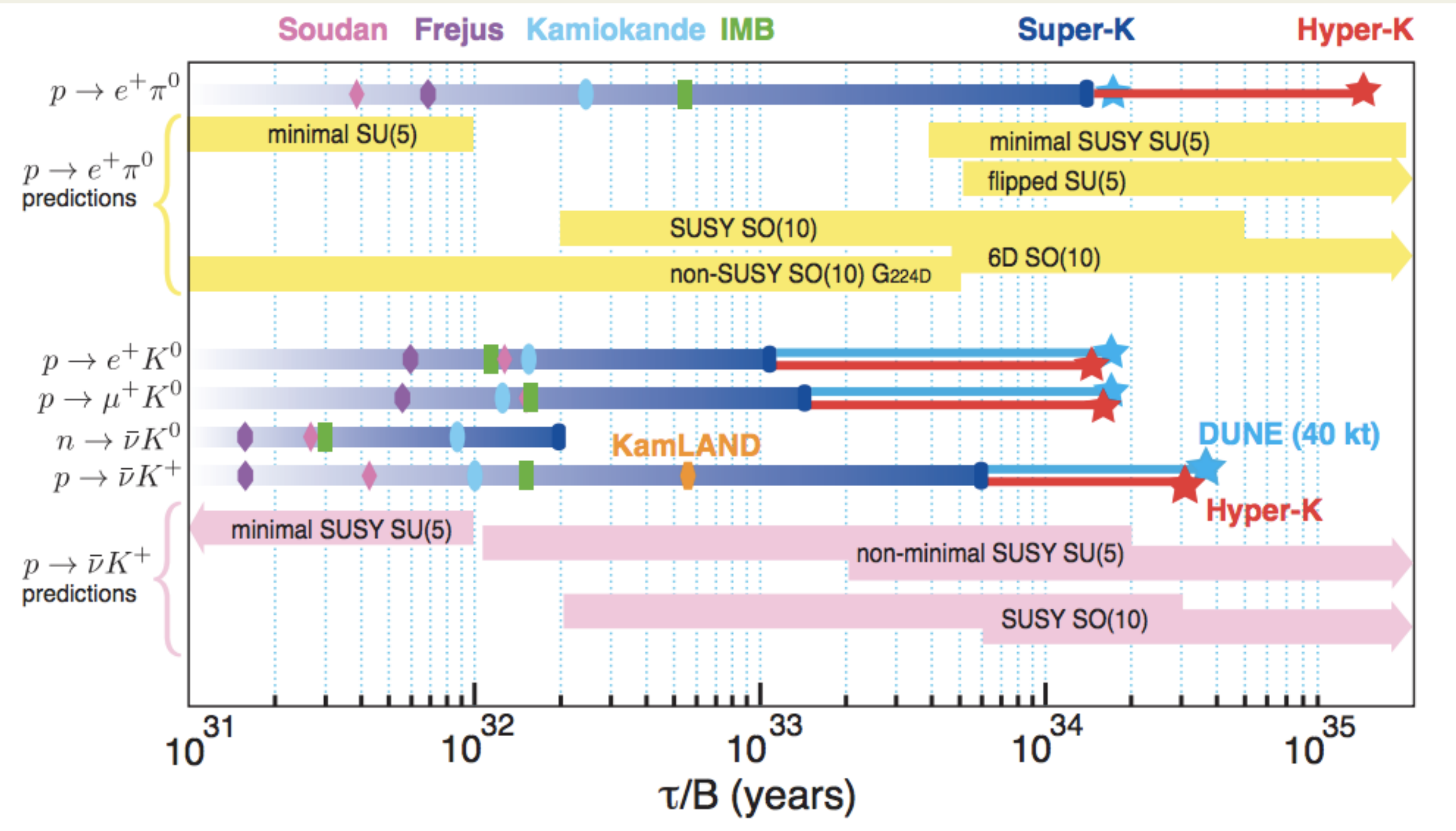
Hyper-K has sensitivity to the mass hierarchy through the atmospheric neutrinos (parametric resonance in the multi-GeV region)

Sensitivity is further improved in combination of accelerator and atmospheric neutrinos

Can determine the hierarchy at >3σ after 5 years, >5σ after 10 years

See talk by J. Kameda in WG1, Parallel Session #10

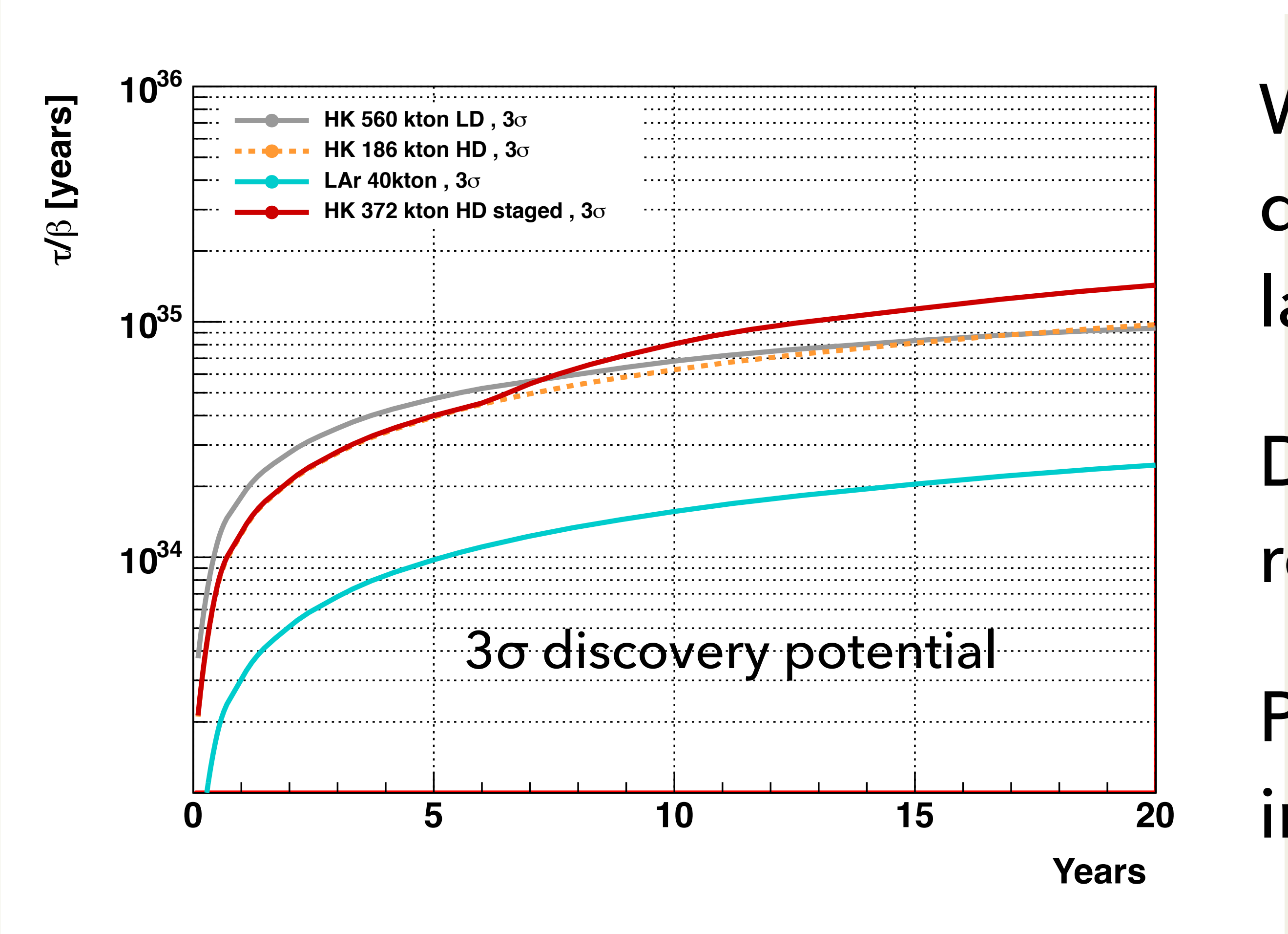
NUCLEON DECAY



1 order of magnitude sensitivity improvements

Leading measurement in $e\pi^0$ mode

Competitive with DUNE in the kaon modes



With smaller tank/high photo-detector density, can achieve same performance as larger tank

Detection of neutron capture on H to reject atmospheric backgrounds

Possible due to PMT efficiency improvements

SUMMARY OF PHYSICS POTENTIAL

		2Tanks (10 yrs)
Beam (1.3 MW)	δ_{CP} precision (0°,90°)	7°-21°
	CPV coverage (3/5σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.015
Atmospherics+Beam	MH determination ($\sin^2\theta_{23}$=0.40)	>5.3σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay	$p \to e^+ \pi^0$ 90%CL	1.2×10^{35} yrs
	$p \to \bar{\nu} K^+$ 90%CL	2.8×10^{34} yrs
Solar	Day/Night (from 0/from KamLAND)	12σ/6σ
	Upturn	~5σ
Supernova	Burst	104k-158k
	Nearby galaxies	2~20 events
	Relic	98evt/4.8σ

SYSTEMATIC ERRORS AND NEAR/INTERMEDIATE DETECTORS

SYSTEMATIC ERRORS

Hyper-Kamiokande

Current T2K systematic errors

Systematic Error Type	1Re Neutrino Mode	1Re Antineutrino Mode
Far Detector Model	2.39%	3.09%
Final State/Secondary Interactions	2.50%	2.46%
Extrapolation from Near Detector	2.88%	3.22%
ν_e(bar)/ν_μ(bar)	2.65%	1.50%
NC1γ	1.44%	2.95%
Other	0.16%	0.33%
Total	6.86%	7.39%

Uncertainty at the 6-7% level. Need reduction to ~3% for Hyper-K.

Dominant errors: electron (anti)neutrino cross section, near-to-far extrapolation of event rates, far detector modeling

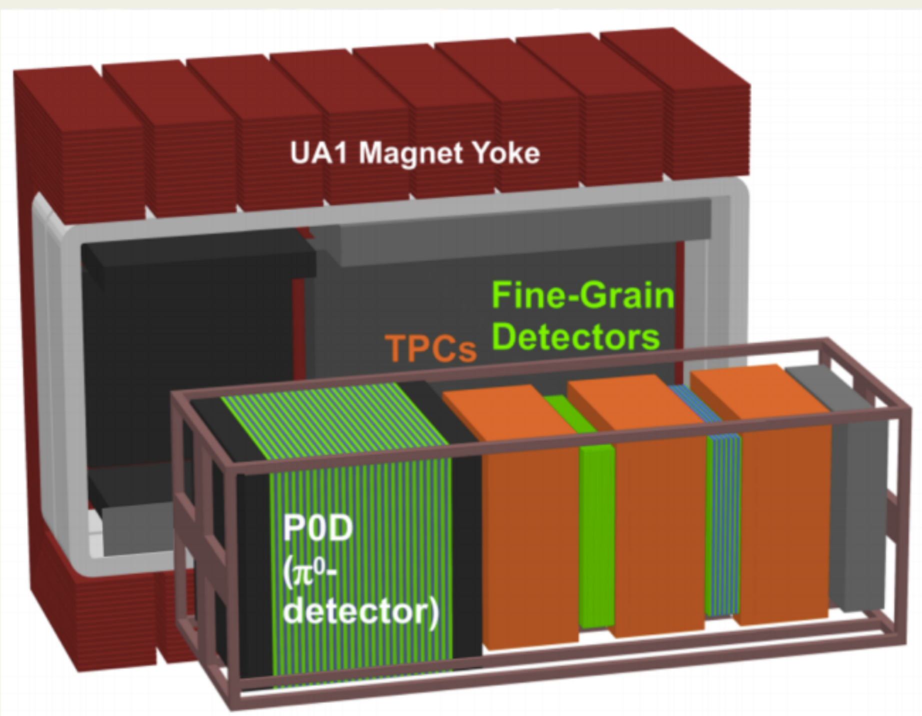
NEAR DETECTOR UPGRADE

Near and intermediate detectors for Hyper-K are being developed to control flux and cross-section systematic errors

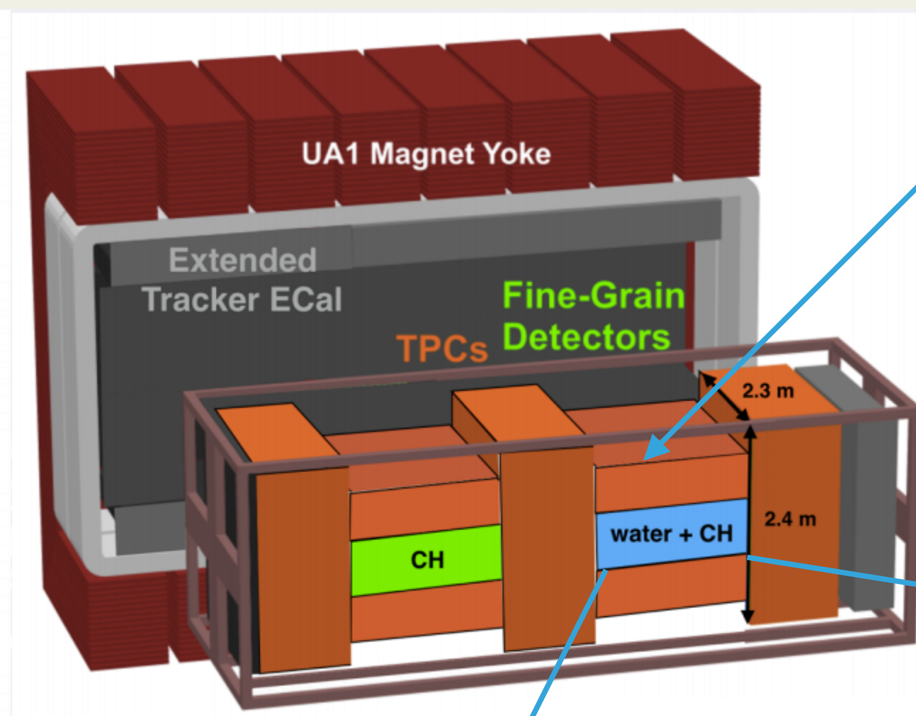
Will continue using the INGRID on -axis and magnetized ND280 detectors

Work within T2K to upgrade ND280 detector

Current ND280 Detectors

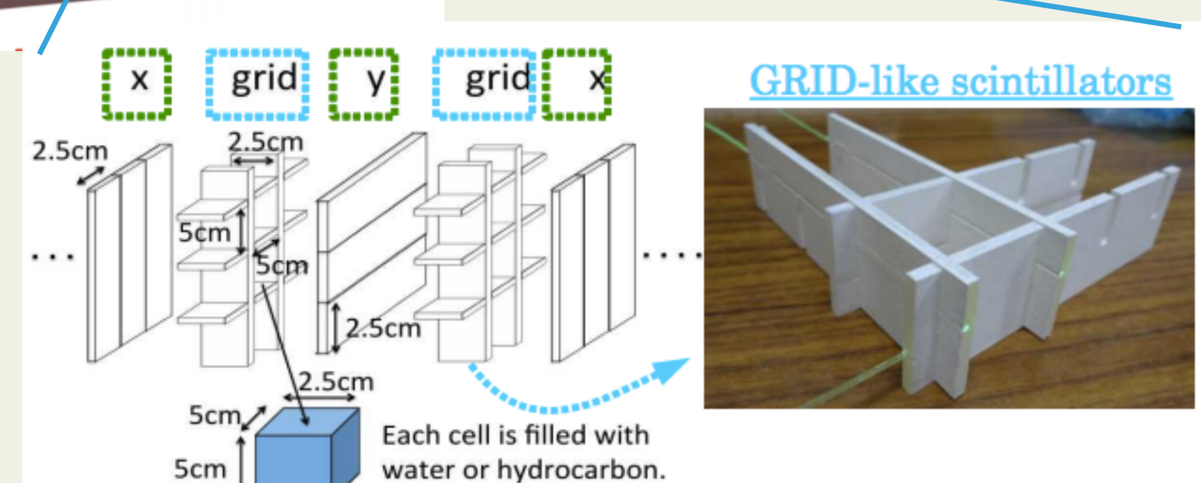


Concept for Upgrade



TPC reconfiguration for high angle track reconstruction

Potential upgrade for tracking target is WAGASCI tracker

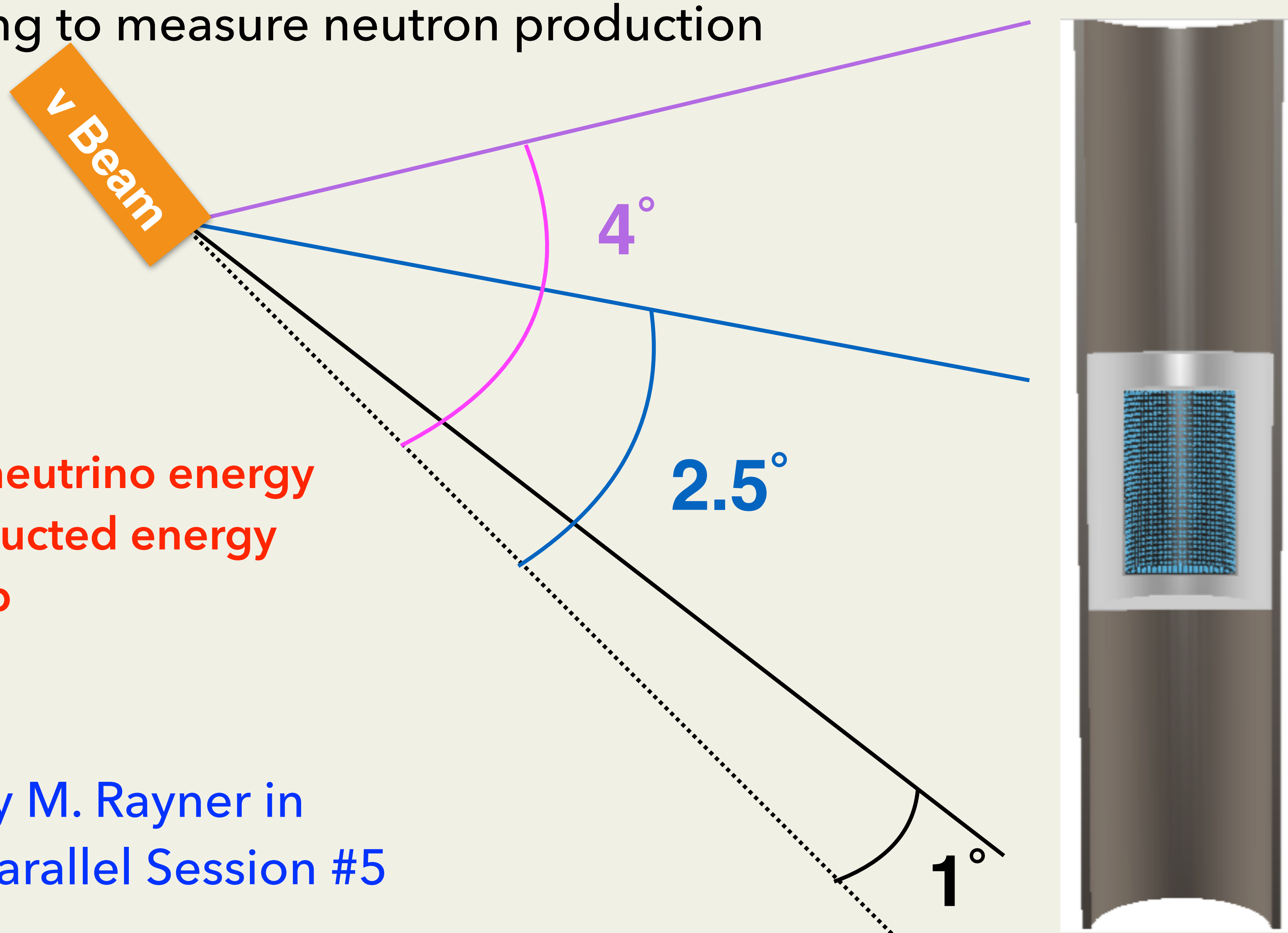


INTERMEDIATE WATER CHERENKOV DETECTORS

Two intermediate water Cherenkov detectors proposed (NuPRISM and TITUS)

Now converging on a single detector design:

- off-axis spanning to probe neutrino energy vs. final state kinematics relationship (reduced extrapolation error)
- Gd loading to measure neutron production



Probe the neutrino energy vs. reconstructed energy relationship

See talk by M. Rayner in WG1+2, Parallel Session #5

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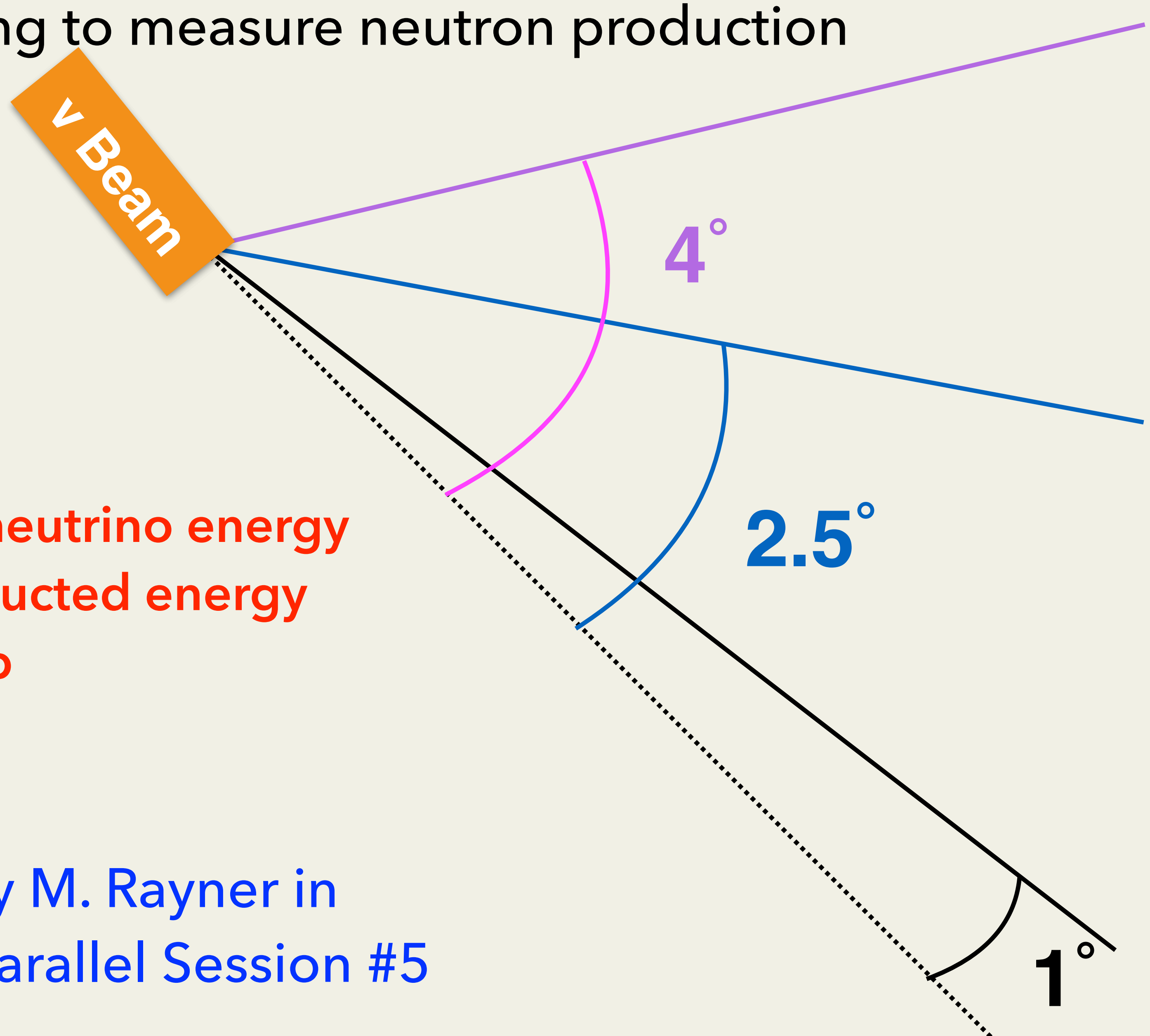

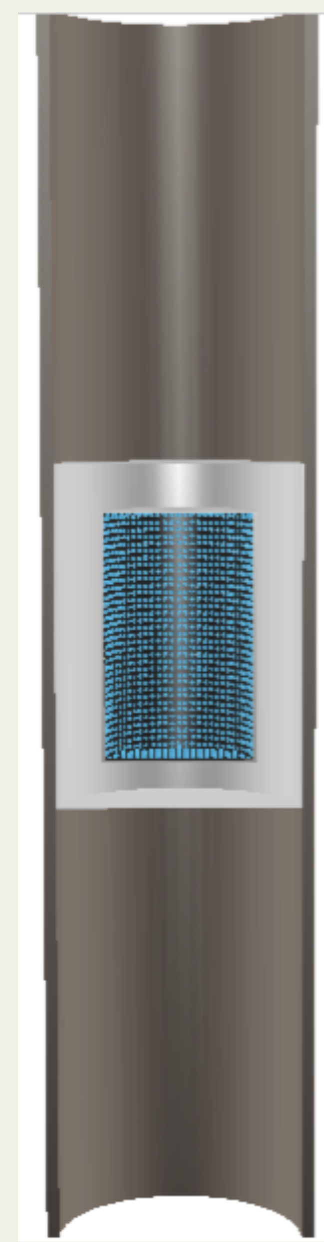

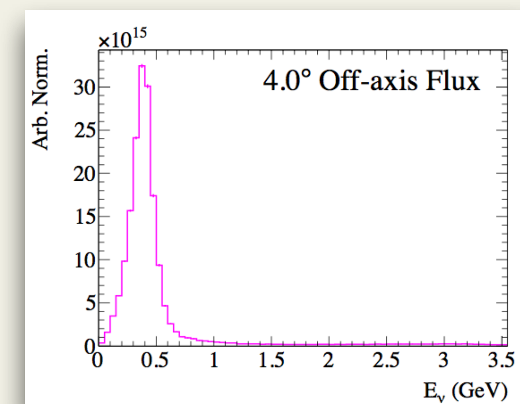

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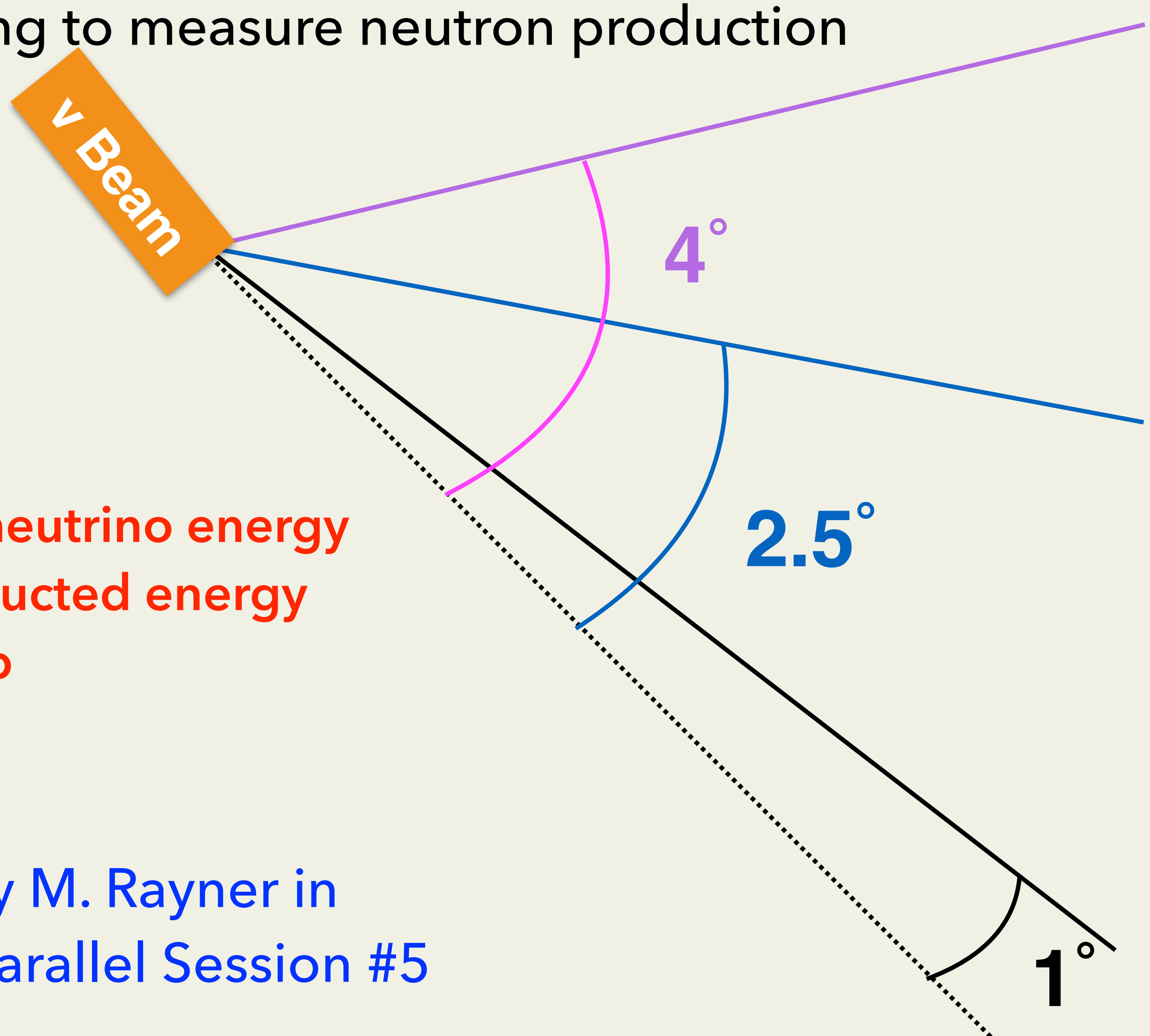

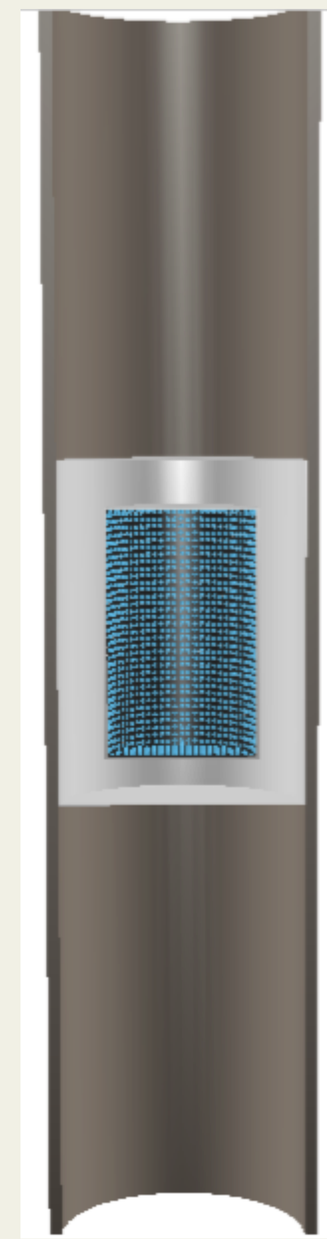

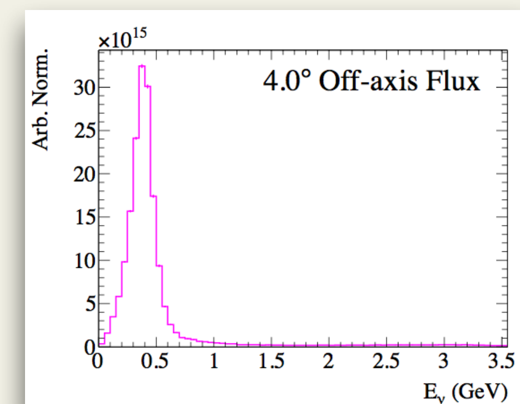

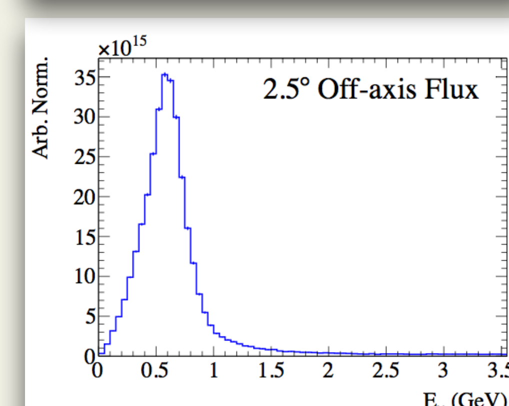

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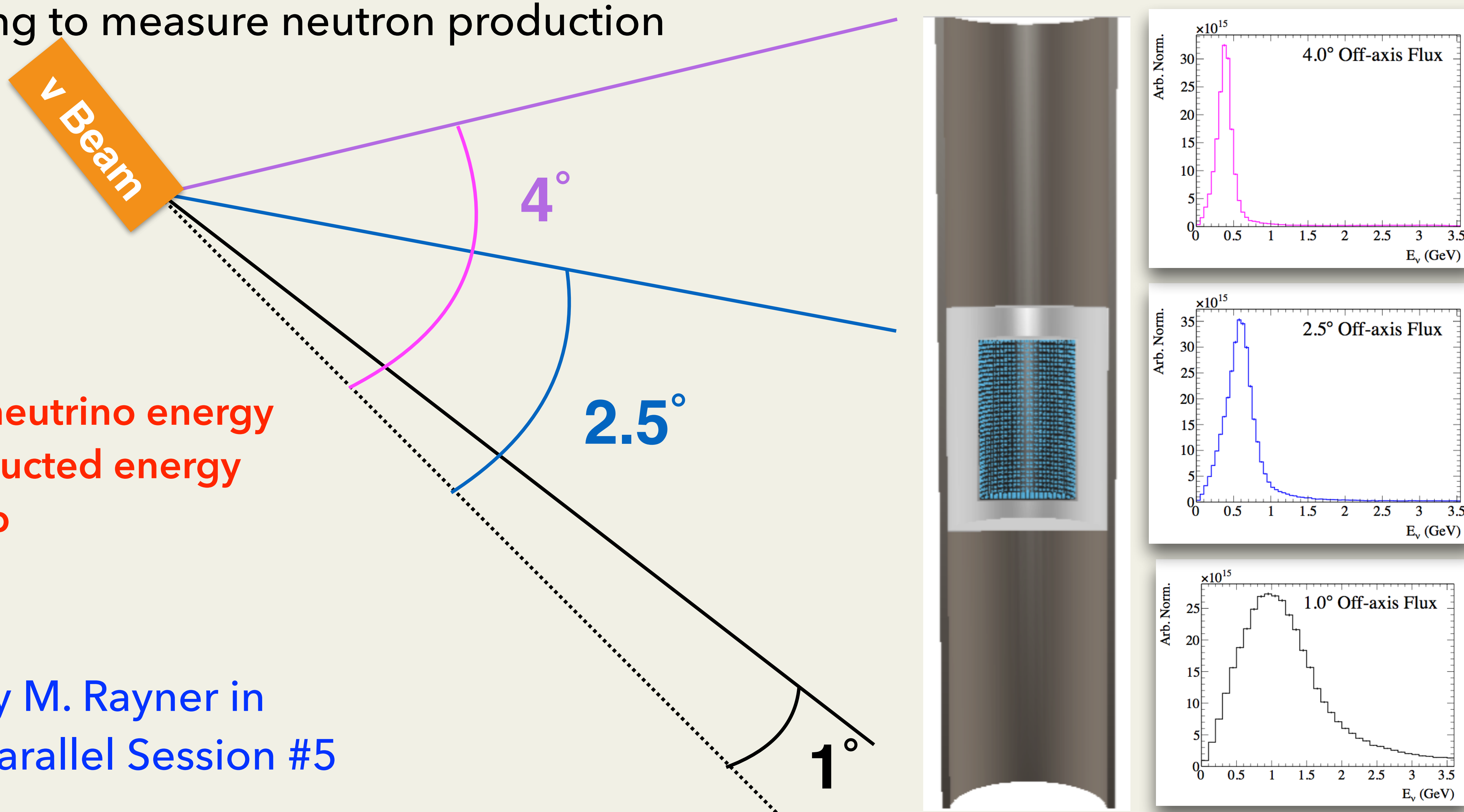

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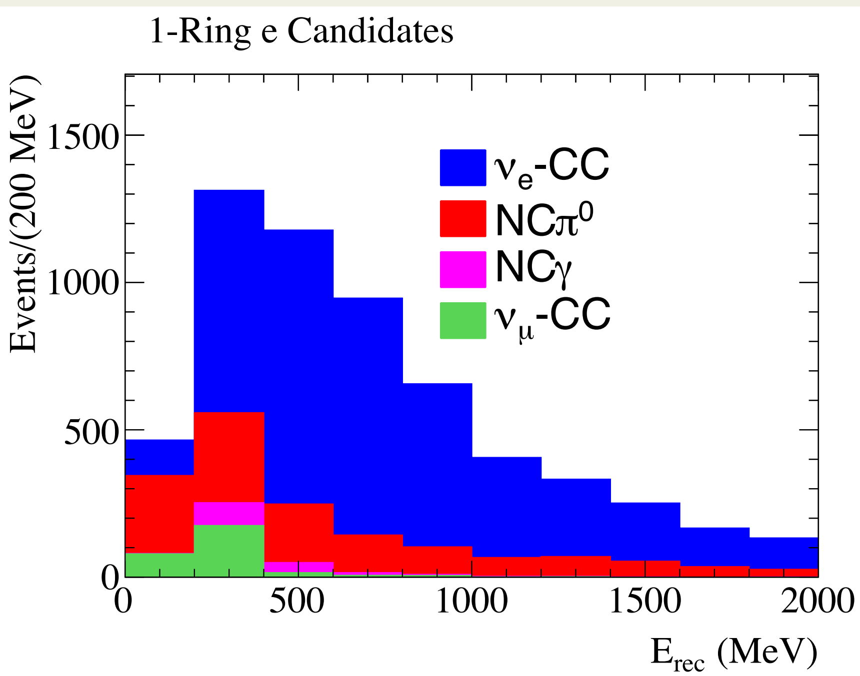
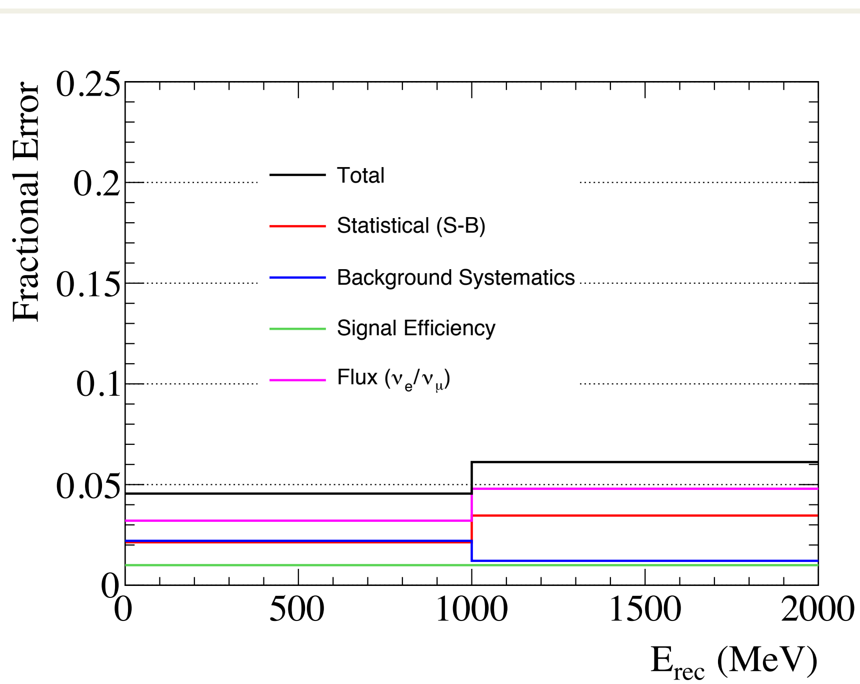
ELECTRON NEUTRINO CROSS SECTION

The ν_e fraction in the beam increases with off-axis angle

Off-axis angle (°)	ν_e Flux 0.3-0.9 GeV	ν_μ Flux 0.3-5.0 GeV	Ratio ν_e/ν_μ
2.5	1.24E+15	2.46E+17	0.507%
3.0	1.14E+15	1.90E+17	0.600%
3.5	1.00E+15	1.47E+17	0.679%
4.0	8.65E+14	1.14E+17	0.760%





Reconstructed candidates in 2.5-4.0° span of NuPRISM for 1.5e21 POT

Purity for E_{rec}<1.2 GeV = 71%

ν_e Signal for E_{rec}<1.2 GeV = 3501

A 5% systematic error on the ν_e/ν_μ cross section ratio is feasible

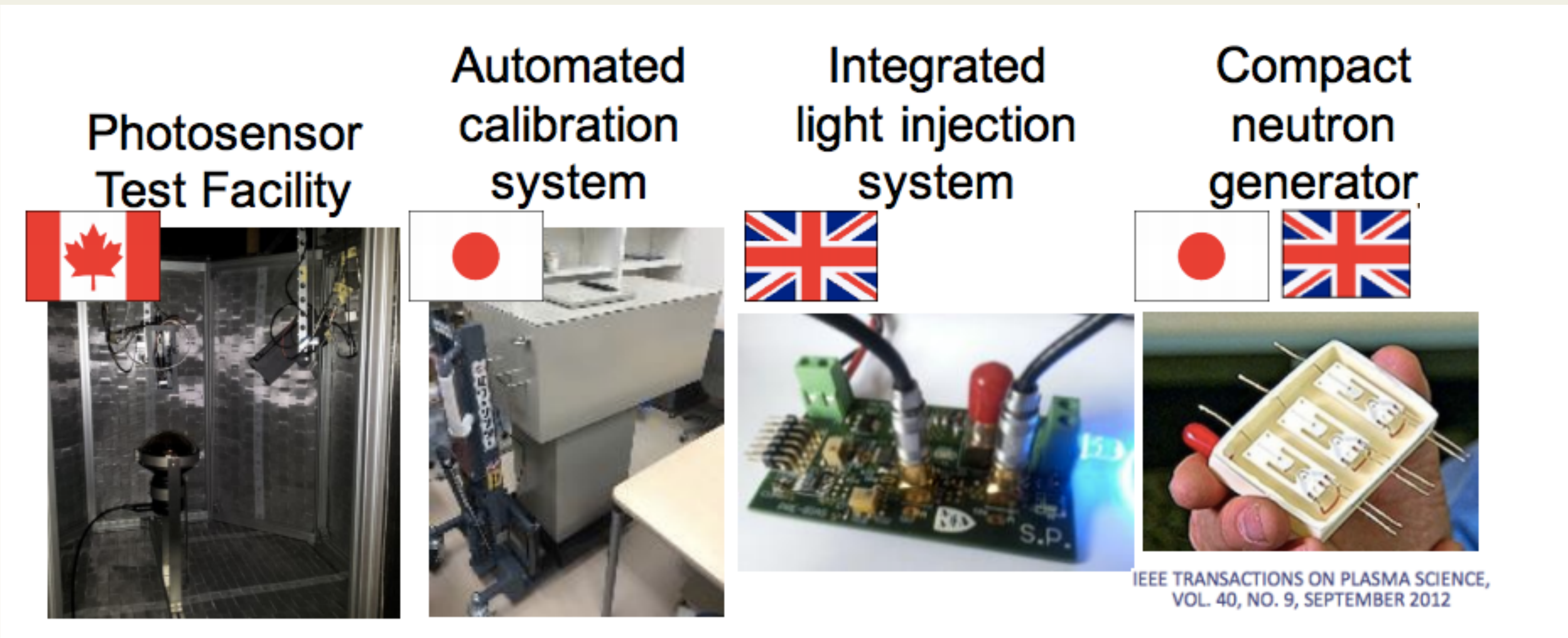
Working on improvements

- Higher purity selection
- Prospects for reducing flux errors

FAR DETECTOR CALIBRATION

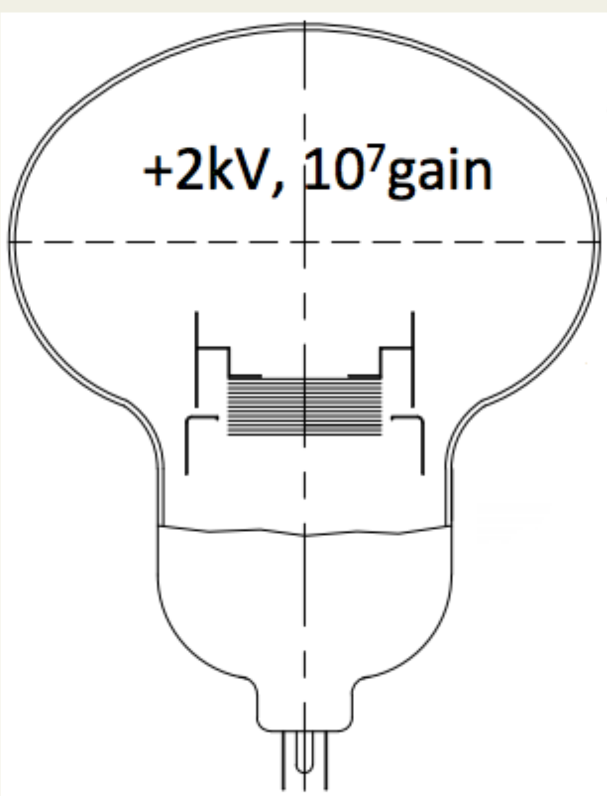
Baseline calibration system based on Super-K

R&D projections are in progress to develop more sophisticated calibration sources and methods for Hyper-K



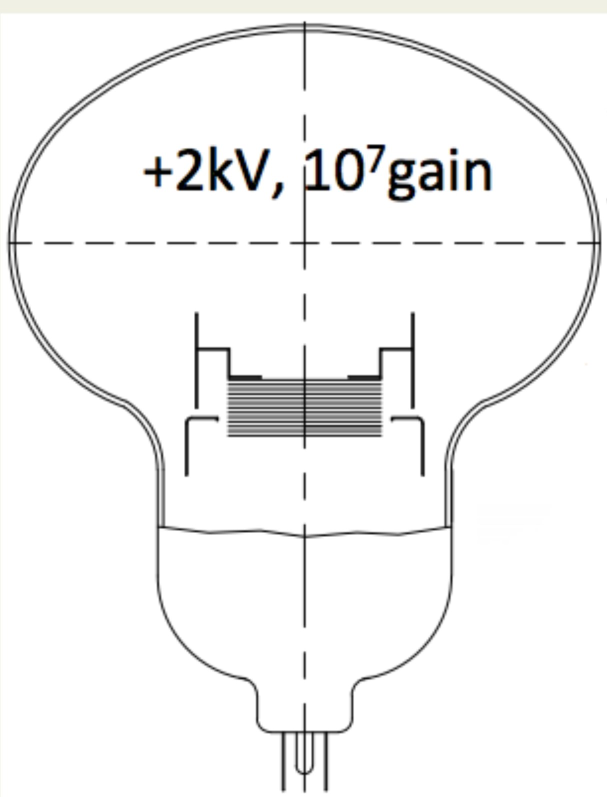
DETECTOR R&D

NEW PHOTODETECTORS

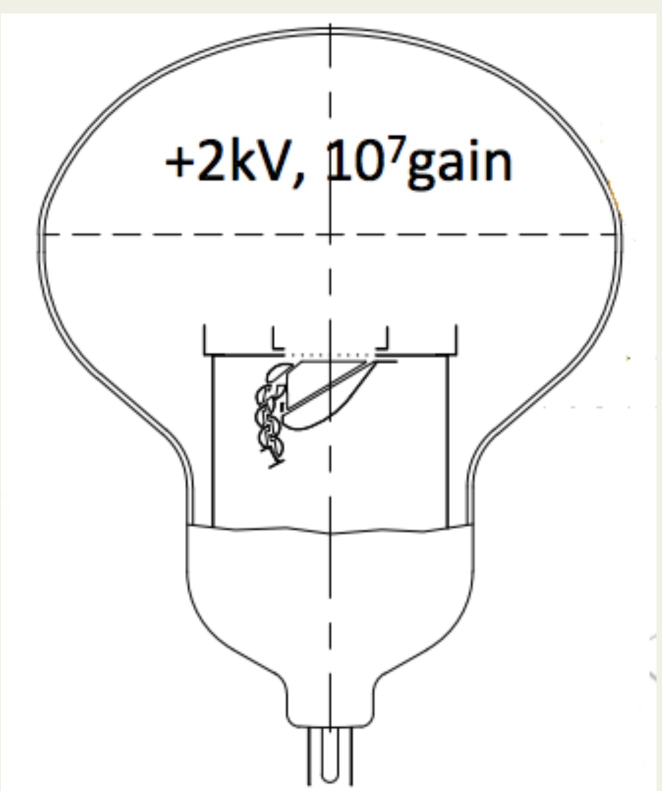


Super-K PMT

NEW PHOTODETECTORS



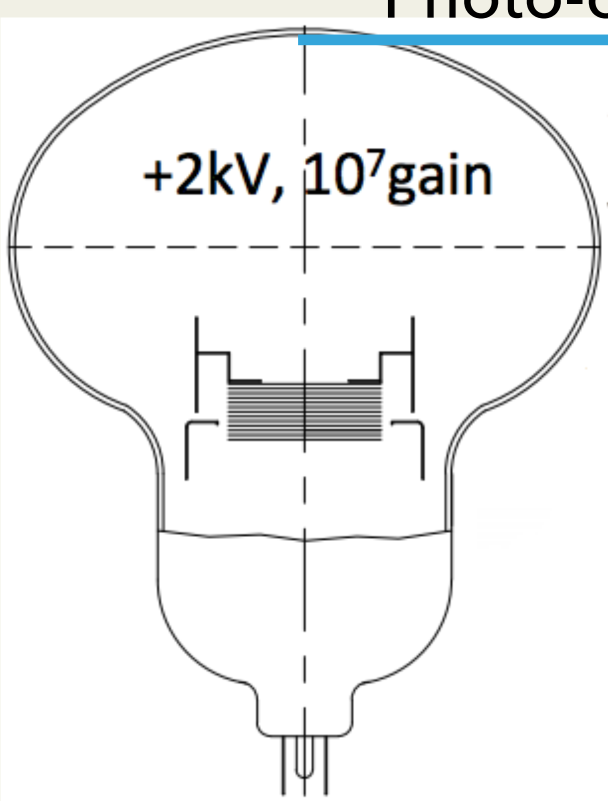
Super-K PMT



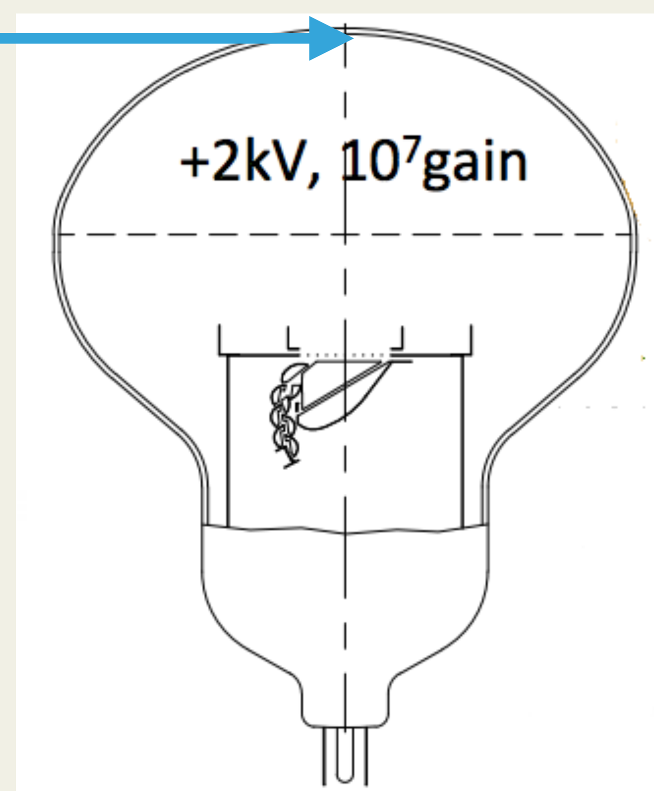
HQE Box&Line

NEW PHOTODETECTORS

High Quantum Efficiency
Photo-cathode



Super-K PMT



HQE Box&Line

NEW PHOTODETECTORS

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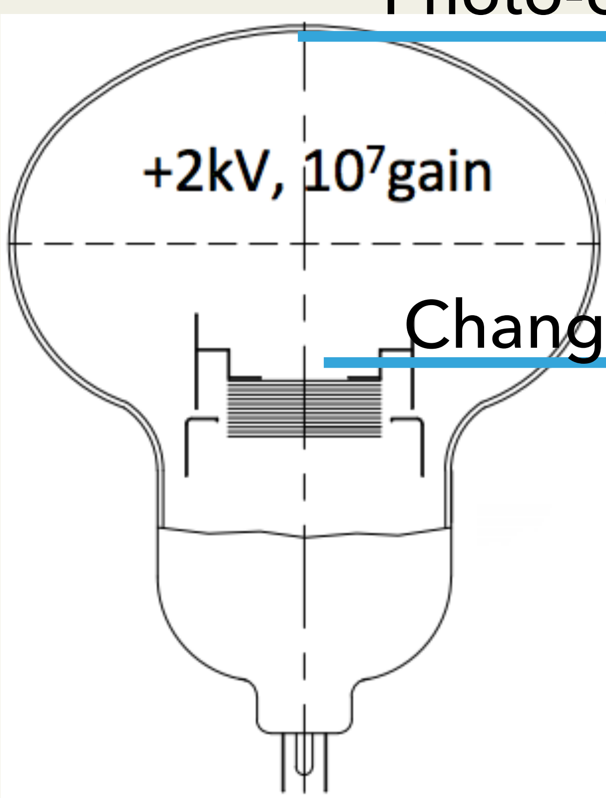
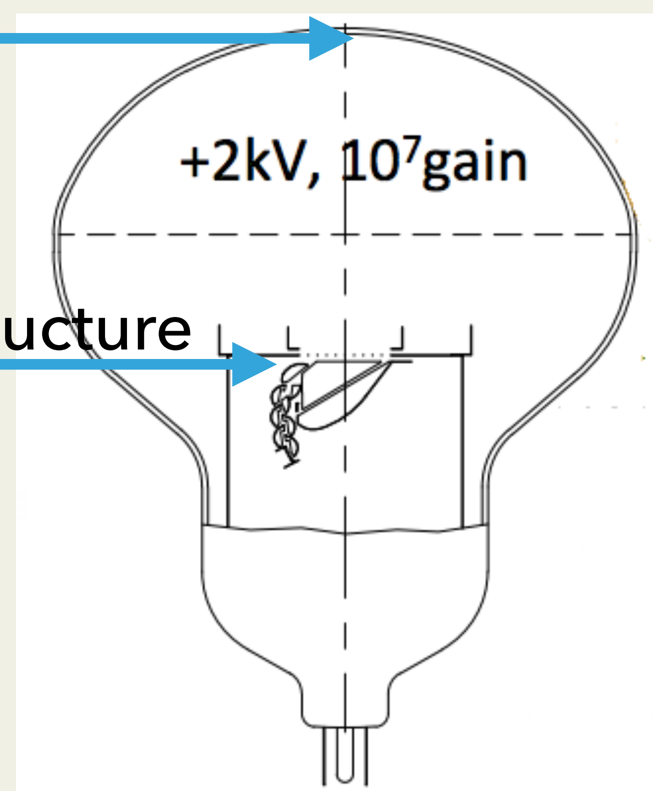
Change dynode structure



Super-K PMT



HQE Box&Line

NEW PHOTODETECTORS

50 cm Box&Line PMT

R12860-HQE (Box&Line dynode)

Developed
→ Photo-detector in Hyper-K baseline design

50 cm Hybrid Photo-Detector (HPD)

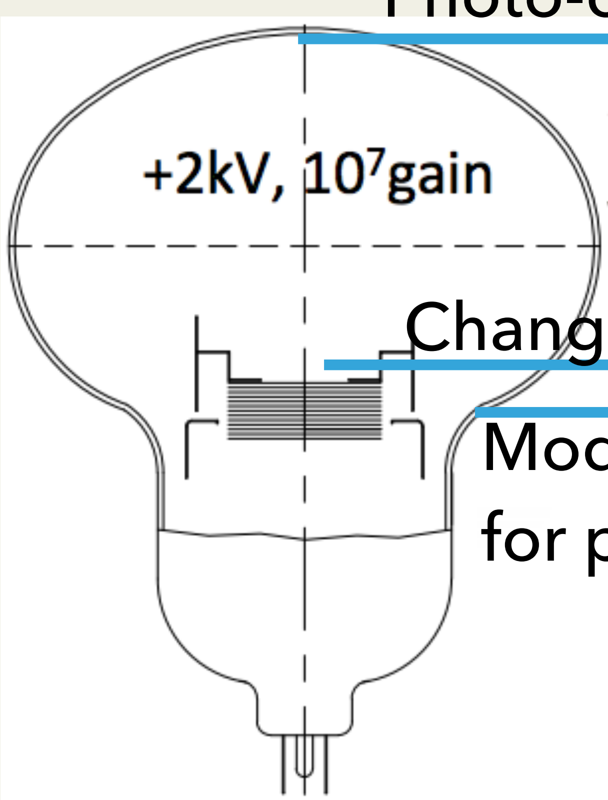
R12850-HQE (Avalanche diode)

Under development
→ Possible further improvement of Hyper-K

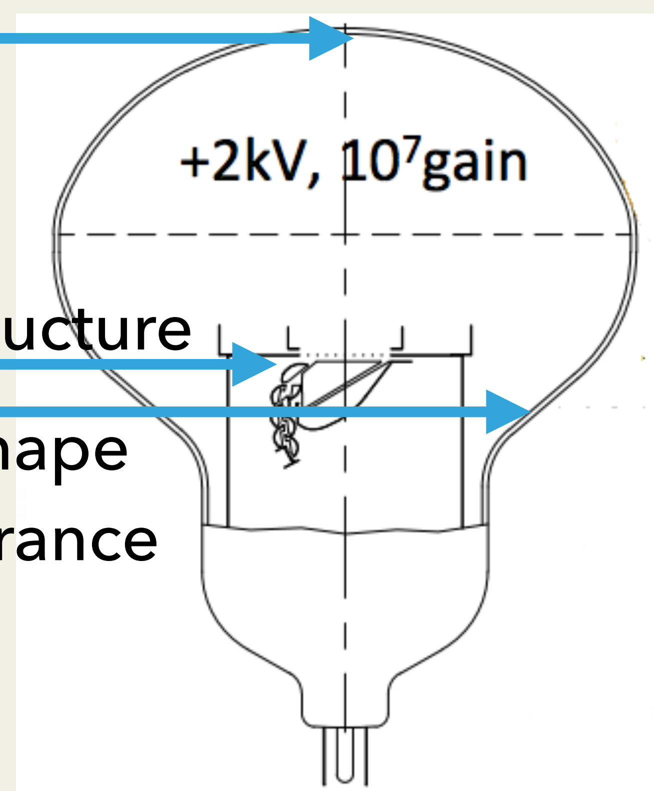
High Quantum Efficiency Photo-cathode

Change dynode structure

Modified tube shape for pressure tolerance



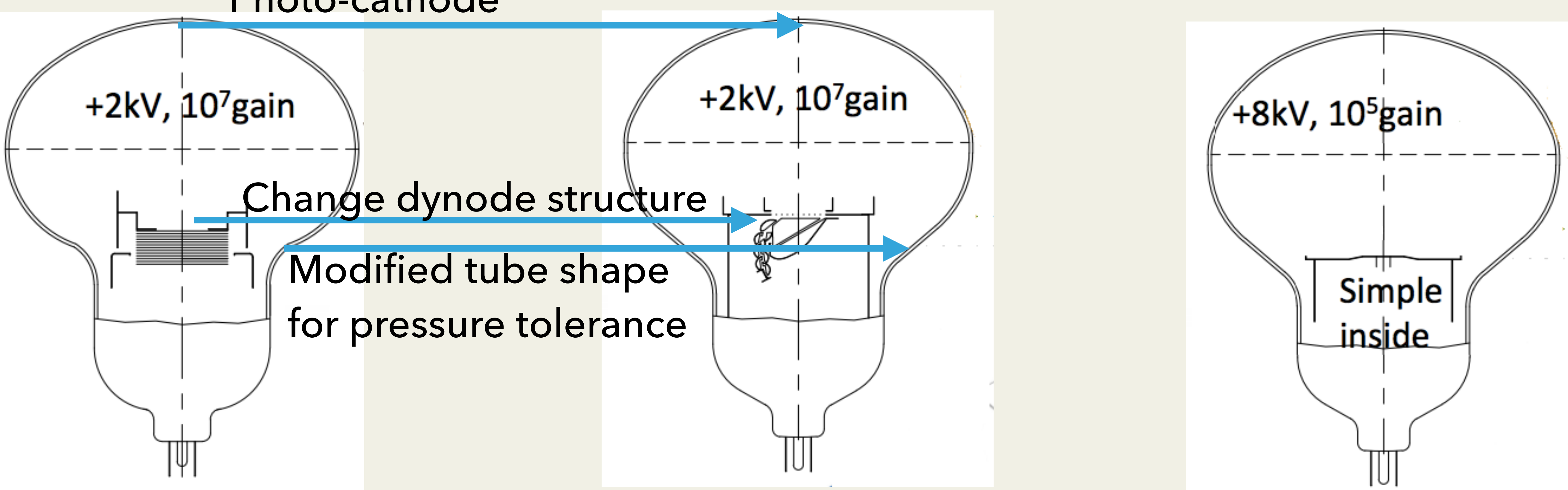
Super-K PMT



HQE Box&Line

NEW PHOTODETECTORS

High Quantum Efficiency
Photo-cathode



Super-K PMT

HQE Box&Line

HQE HPD

NEW PHOTODETECTORS

50 cm Box&Line PMT

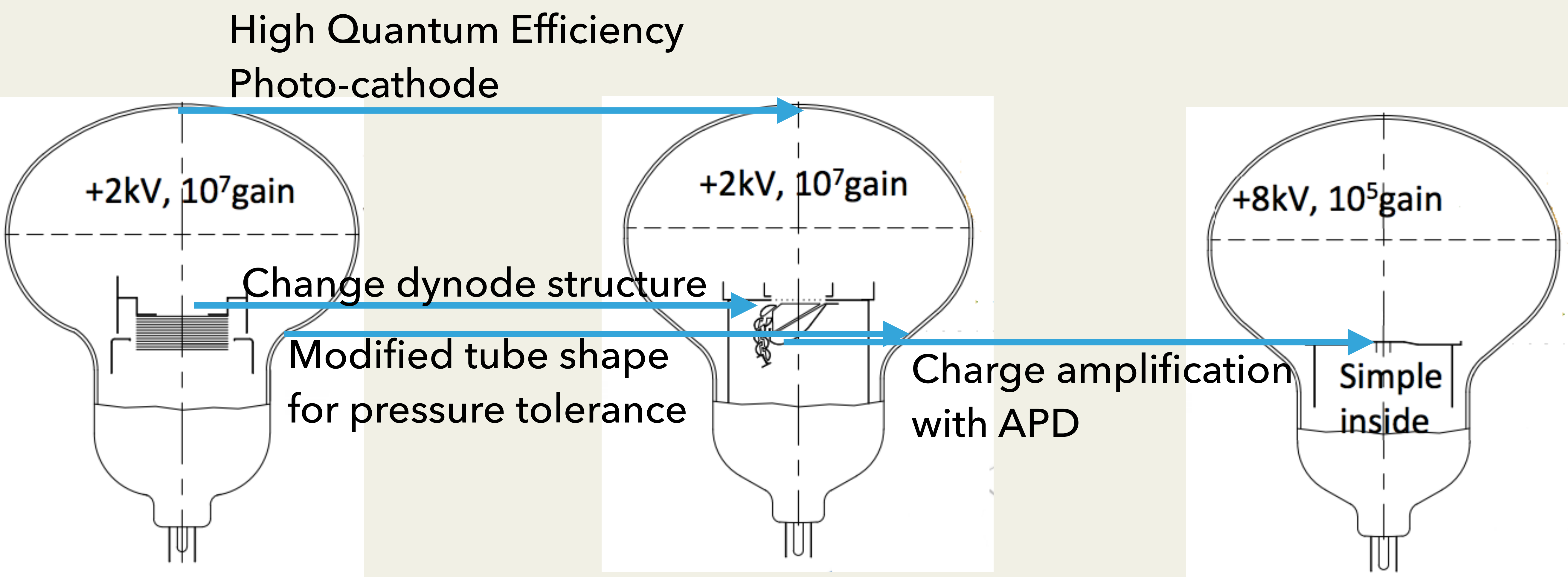
R12860-HQE (Box&Line dynode)

Developed
→ Photo-detector in Hyper-K baseline design

50 cm Hybrid Photo-Detector (HPD)

R12850-HQE (Avalanche diode)

Under development
→ Possible further improvement of Hyper-K

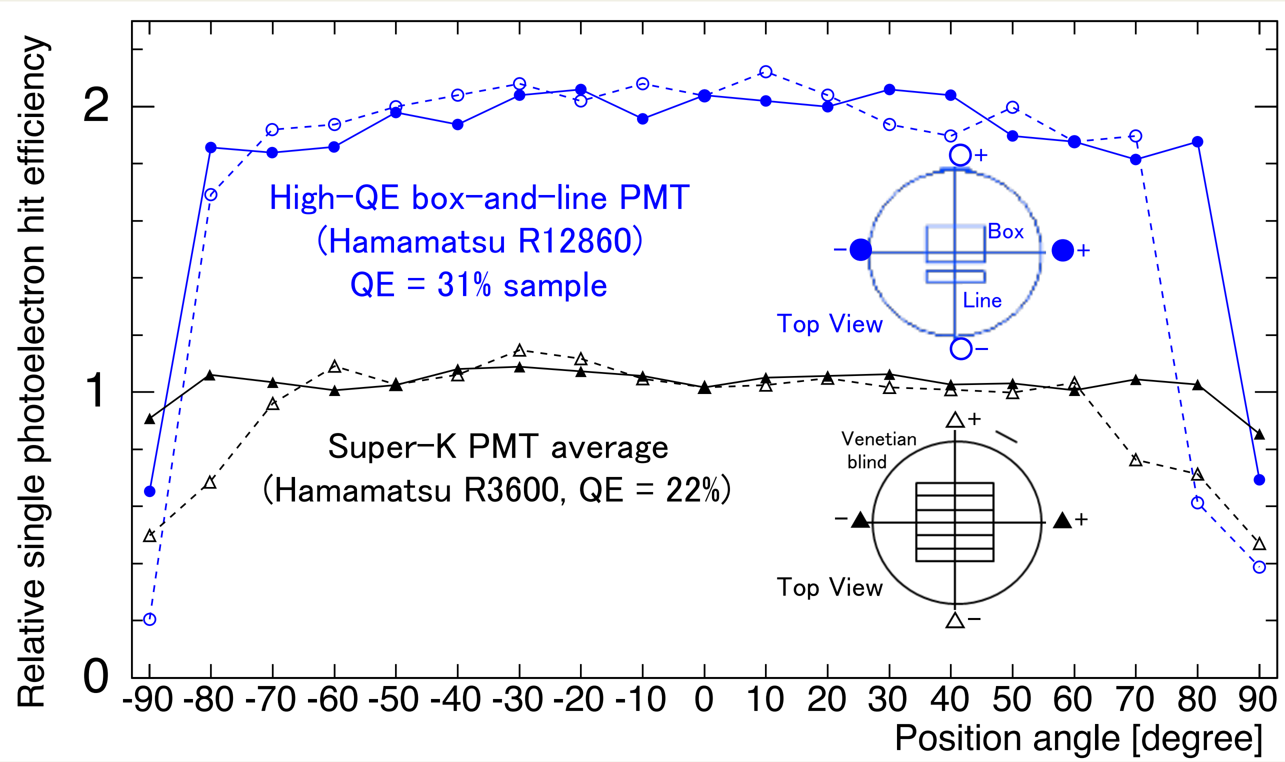


Super-K PMT

HQE Box&Line

HQE HPD

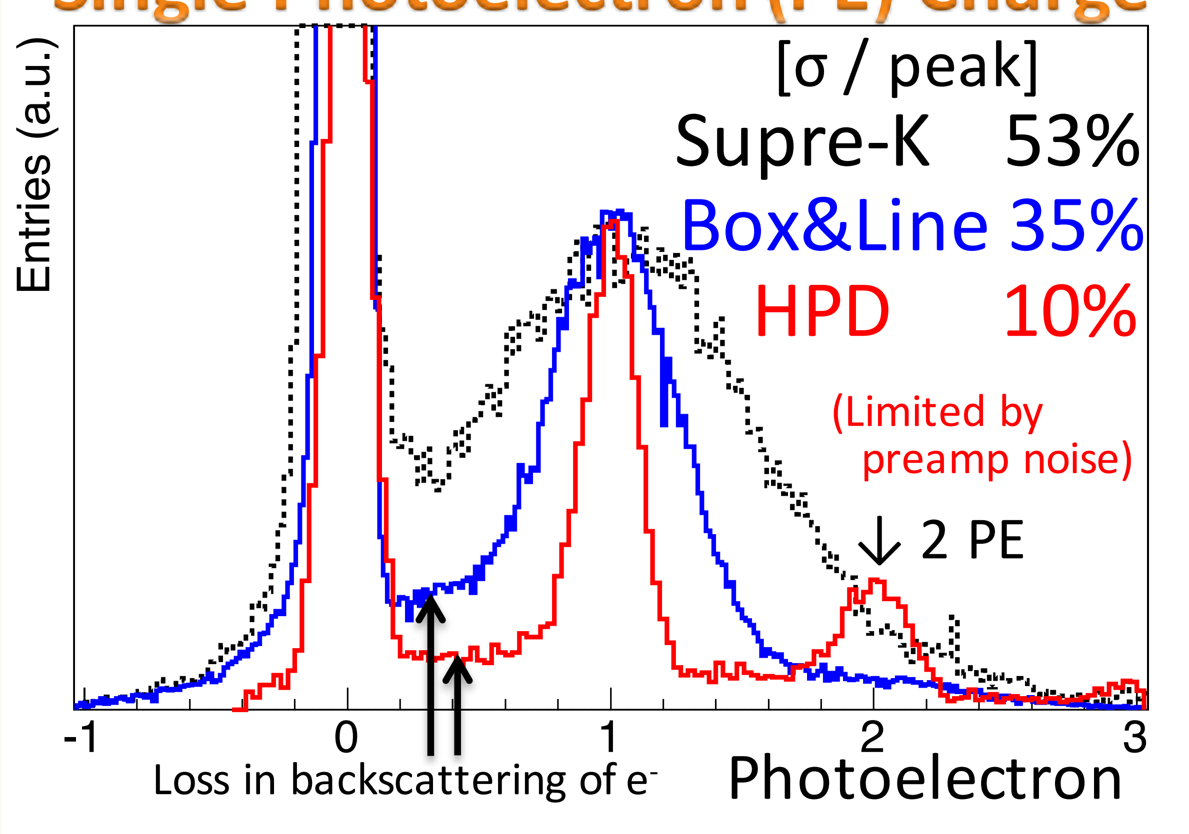
PERFORMANCE COMPARISONS



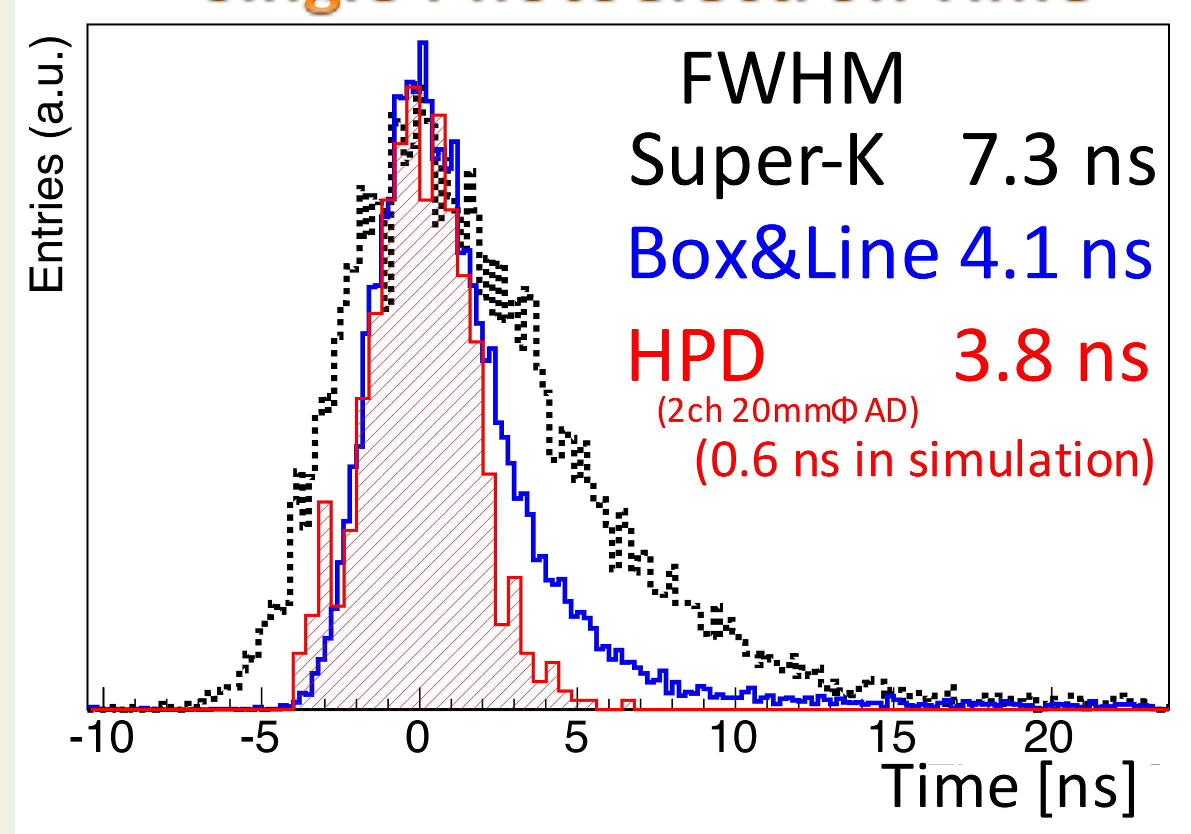
High quantum efficiency photo-cathode +improved collection efficiency with Box&Line dynode

x2 improvement in photo detection efficiency!

Single Photoelectron (PE) Charge

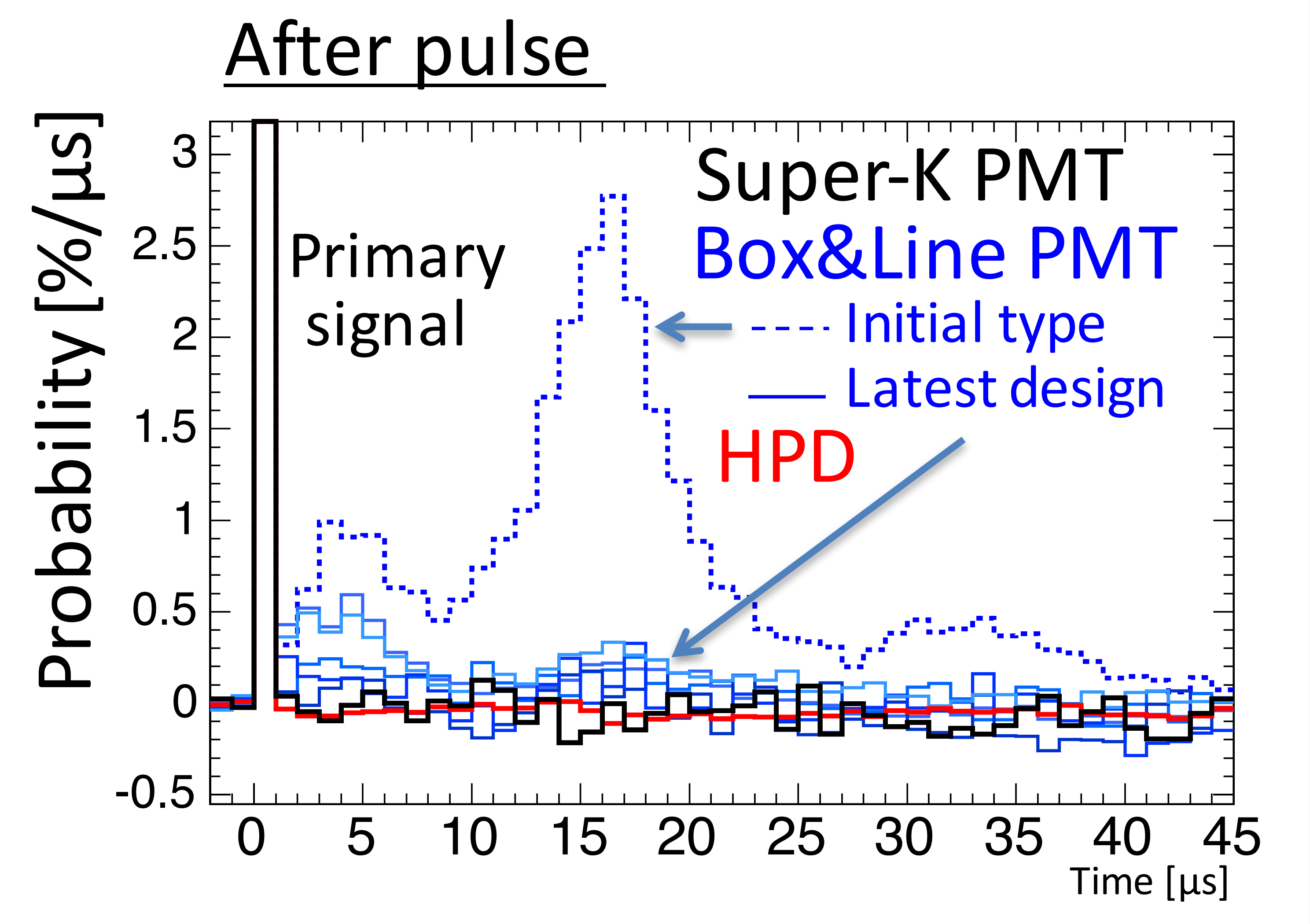


Single Photoelectron Time



Charge and time resolution improved relative to Super-K PMT

PMT AFTERPULSING



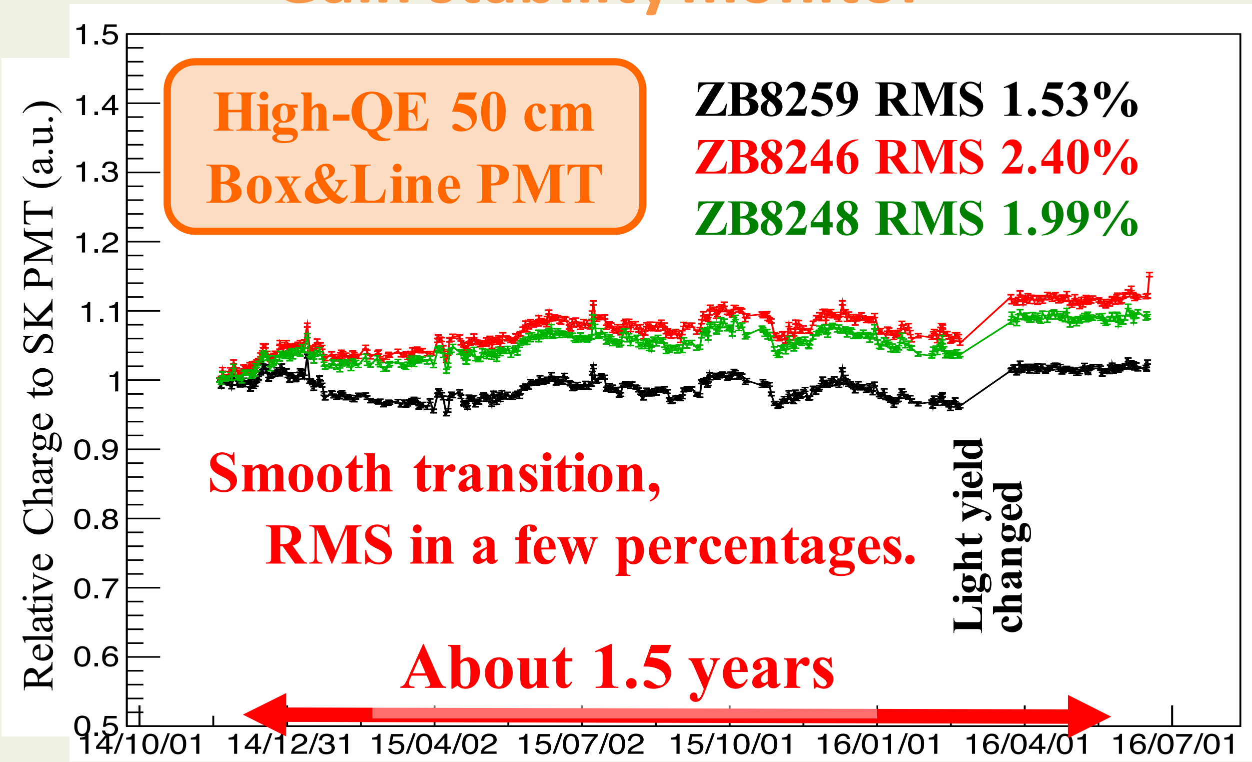
- Initially, a high after-pulse rate observed in the Box&Line PMT
- Hamamatsu optimized the dynode shape, adding a hood to prevent feedback of ionized gas or light inside the dynode
- Afterpulsing rate reduced to an acceptable level

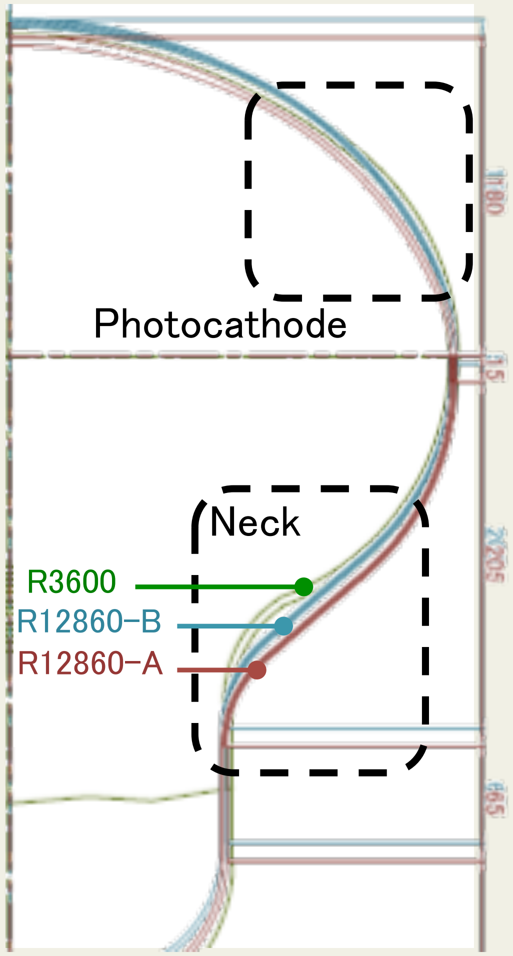
PMT TESTING

Long term testing in EGADS tanks for 1.5 years so far

- 3 Box&Line HQE PMT
- 5 Venetian Blind HQE PMTs
- 6 20 cm HPD

Gain stability monitor





Two step approach to protect against chain reaction implosion:

1. Pressure tolerance of PMTs with x1.9 safety factor
2. PMT cover to prevent shockwave

Redesign of tube at neck region to increase pressure tolerance

50 tubes tested a 1.25 MPa with no failure

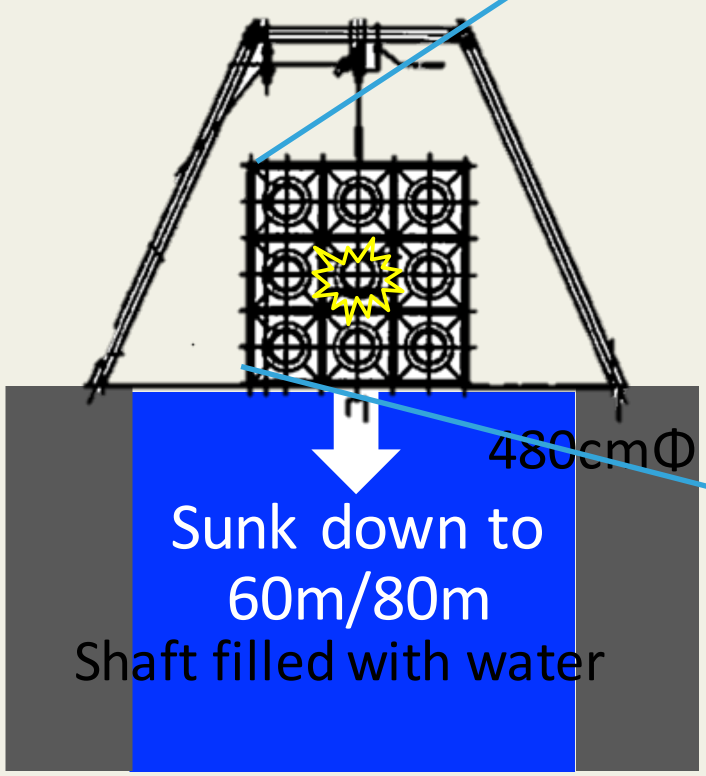
PMT COVER

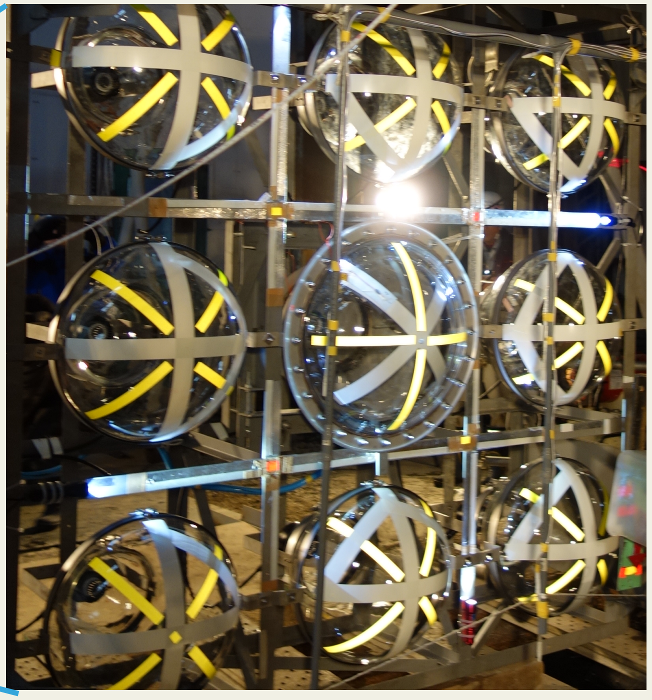
Prototype acrylic + stainless steel cover has been developed

Limit the flow of water into evacuated area if PMT implodes → avoid shockwave

Optimization and reduction of cost are under consideration

Initial prototype
for 60 m water depth





Test in Furano, Hokkaido

Implosion test carried out at 60 m and 80 m water depths

No chain implosion observed

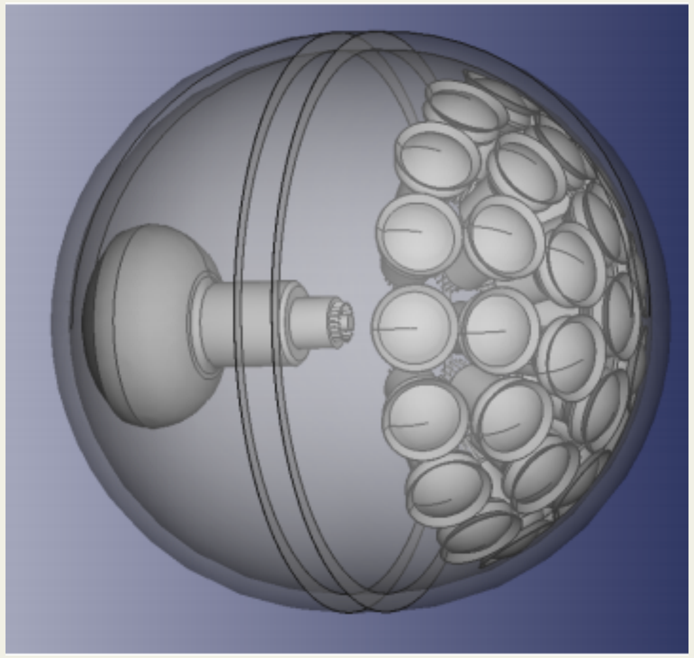
MULTI-PMT OPTION

A KM3NeT inspired multi-PMT module is also being investigated

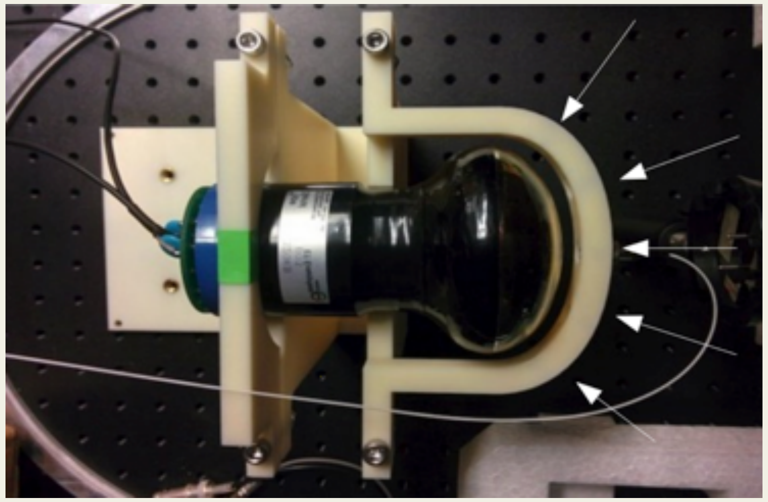
Less strict pressure requirement: glass → acrylic

Advantages:

- Pressure tolerance
- Directional information from PMTs, finer granularity
- Natural housing for in-water electronics



One Concept: 33 inner detector facing 3in PMTs

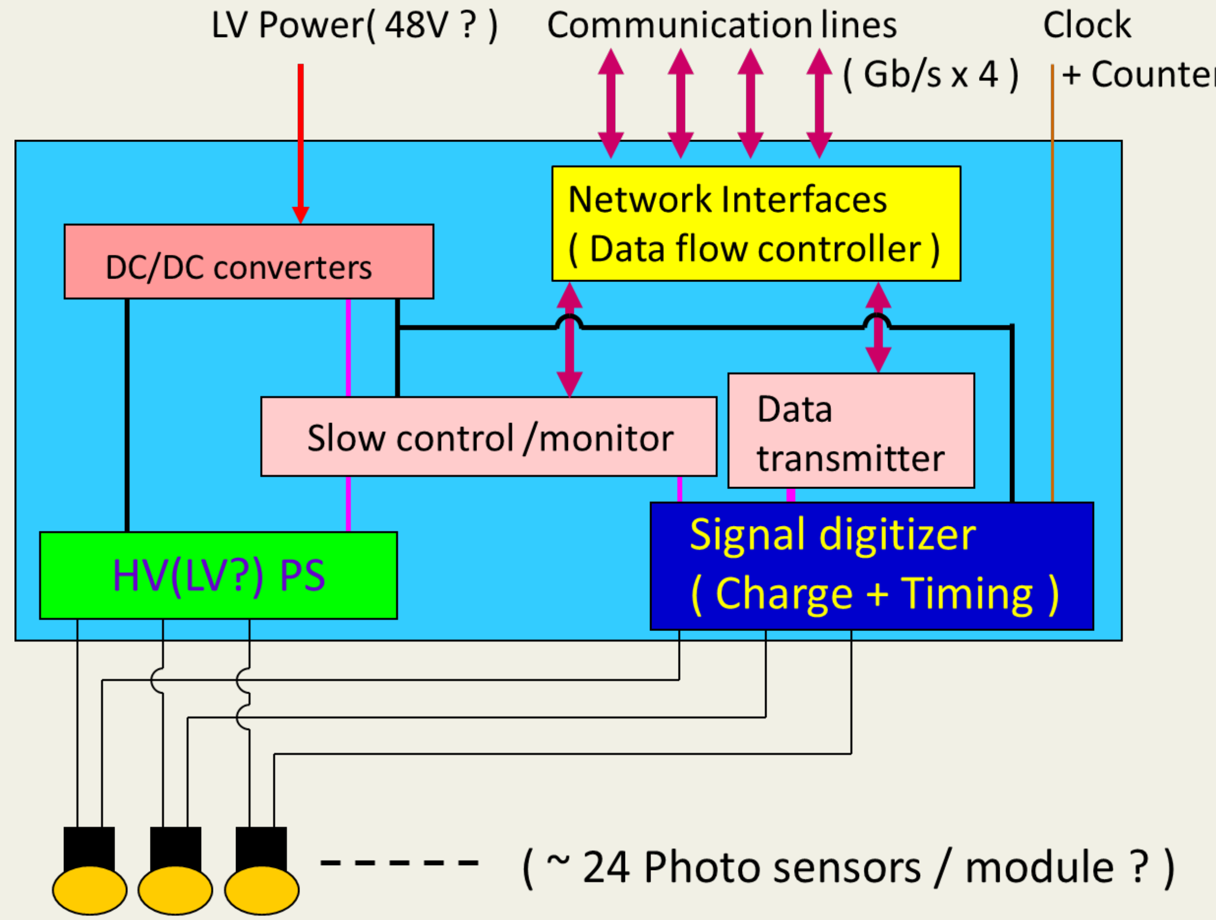


R&D including testing and optimization of 3in PMTs has begun

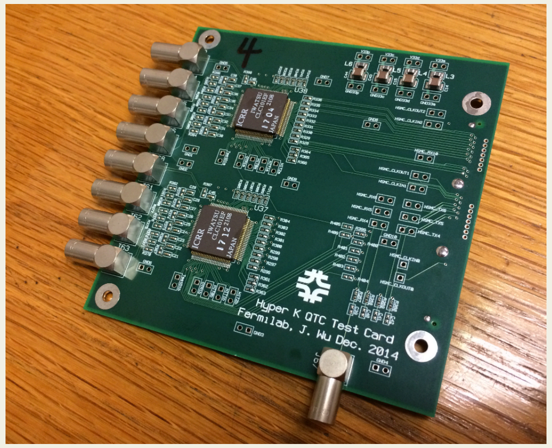
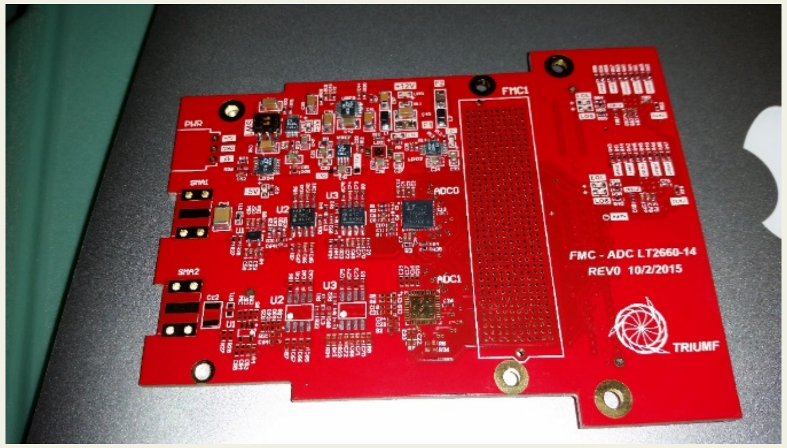
FRONT END ELECTRONICS

Front-end electronics requirements

- Wide charge dynamic range
  0.1 ~ 1250 p.e.
- Good timing resolution
  ~ sub ns
- Self triggering
  ~ channel by channel
- Low power consumption
  < 1W/ch
- Place modules in the water



Possible use of
Charge to Time converter or FADC (~ 100MHz) are being studied.

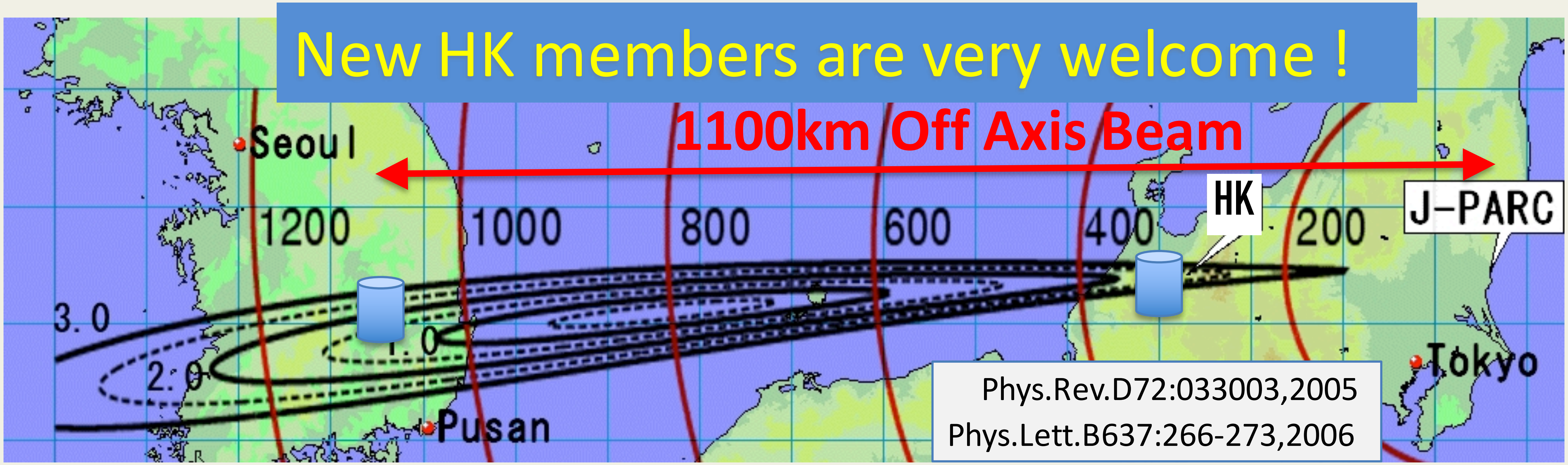
KOREAN DETECTOR OPTION

KOREAN OPTION FOR SECOND TANK

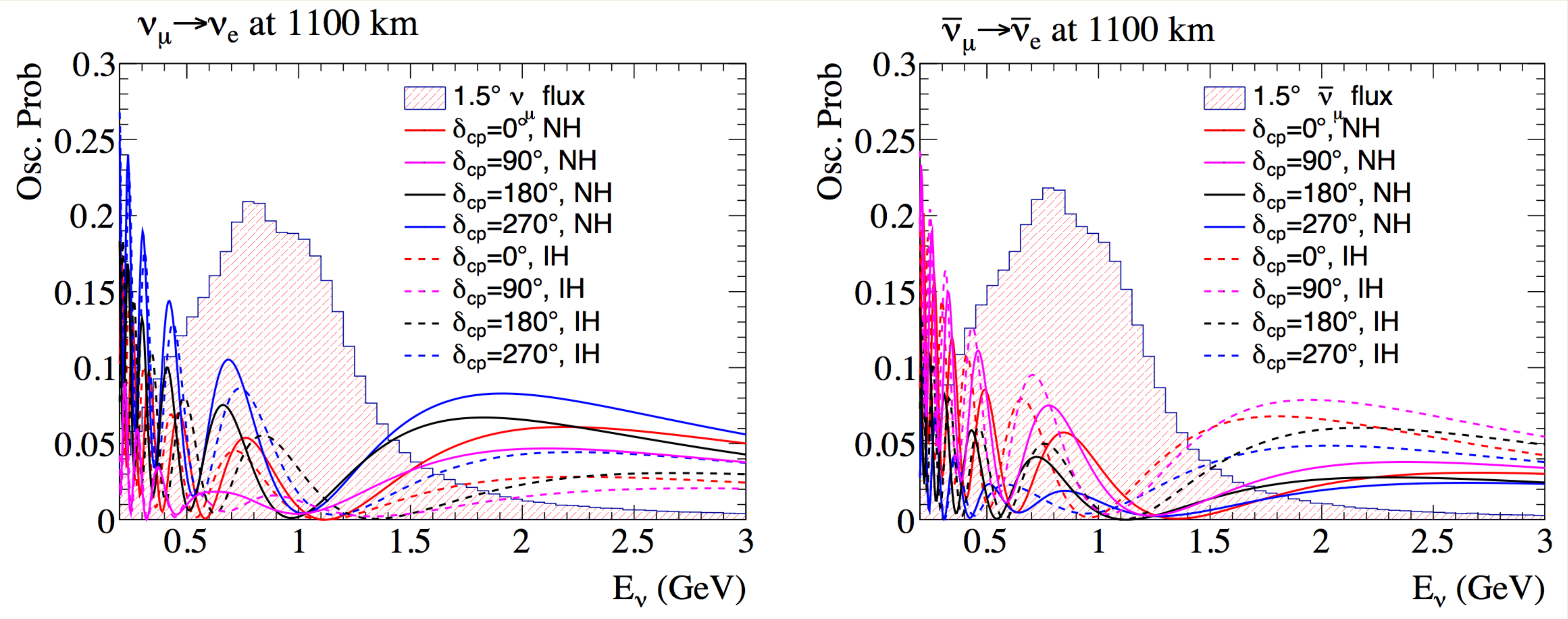
Given the two tank design with staging, may benefit from building the second tank at a different baseline.

The concept for a second tank in Korea has been studied for >10 years

It is now being considered by the HK collaboration



ADVANTAGES FOR SECOND TANK IN KOREA



Advantages of second detector in Korea:

Measure CP effect at second oscillation maximum: 3 times larger

Mass hierarchy sensitivity to complement the measurement with atmospheric neutrinos

Hyper-Kamiokande

Announcement of The 1st T2HKK International Workshop

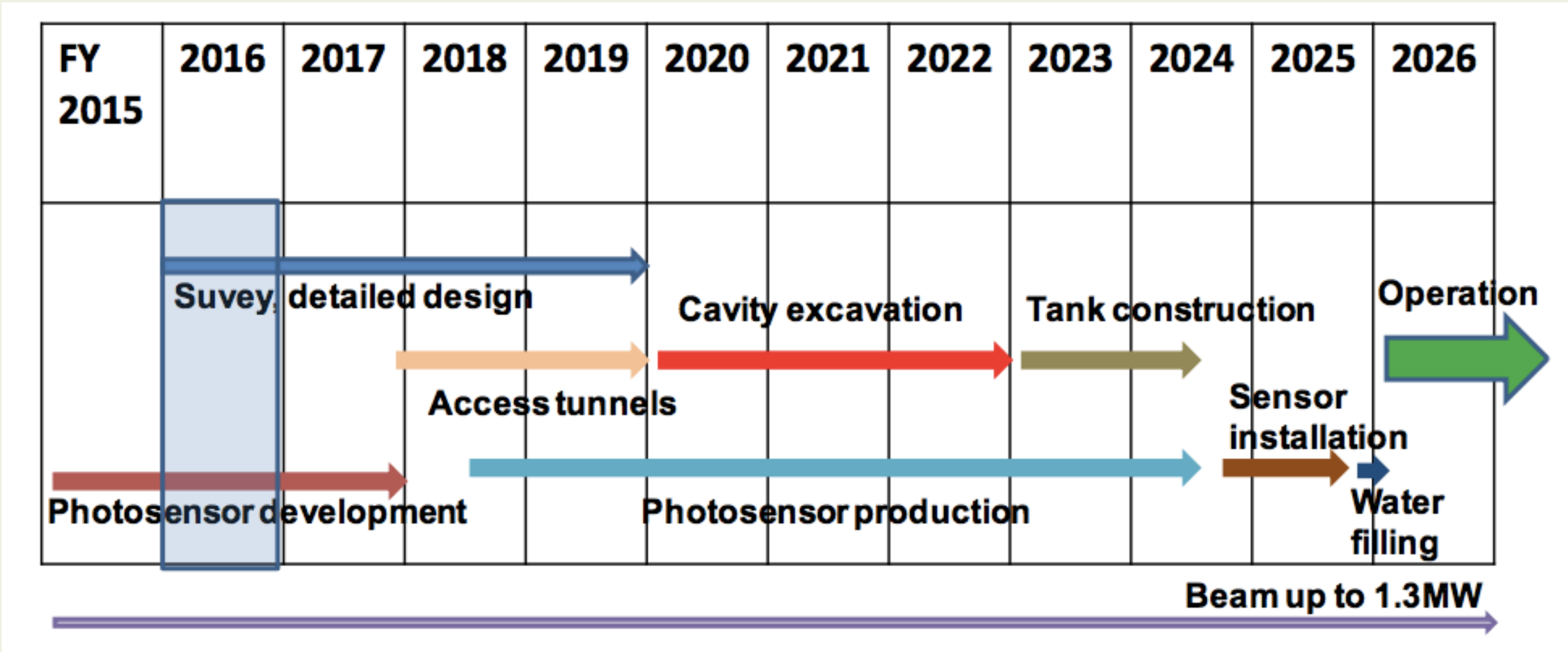
- When : Nov. 21 - 22
- Where: Seoul National Univ., Korea

We invite all of you !

"Anyone" is very welcome to join this workshop !

More details of workshop coming soon

TIMELINE



2018-2025: Photo-sensor production and Hyper-K construction

Physics starts from 2026 with 1.3 MW neutrino beam

Second tank starts operation 6 years after the first tank

SUMMARY

- Hyper-K builds on the success of Kamiokande, Super-K and T2K to achieve great potential for CP violation discovery
- Broad physics program includes mass hierarchy determination, precision oscillation parameter measurements, nucleon decay searches, solar and supernova neutrino physics
- The tank design has been re-optimized for cost savings while maintaining physics
  - Taller tank possible thanks to improved pressure tolerance of PMTs
  - Nucleon decay sensitivity maintained thanks to improved photo-detection efficiency of PMTs
- Near and intermediate detector program to address dominant systematic errors
- Option for second tank in Korea is now being considered
- Look forward to a ground-breaking and exciting physics program!

THANK YOU

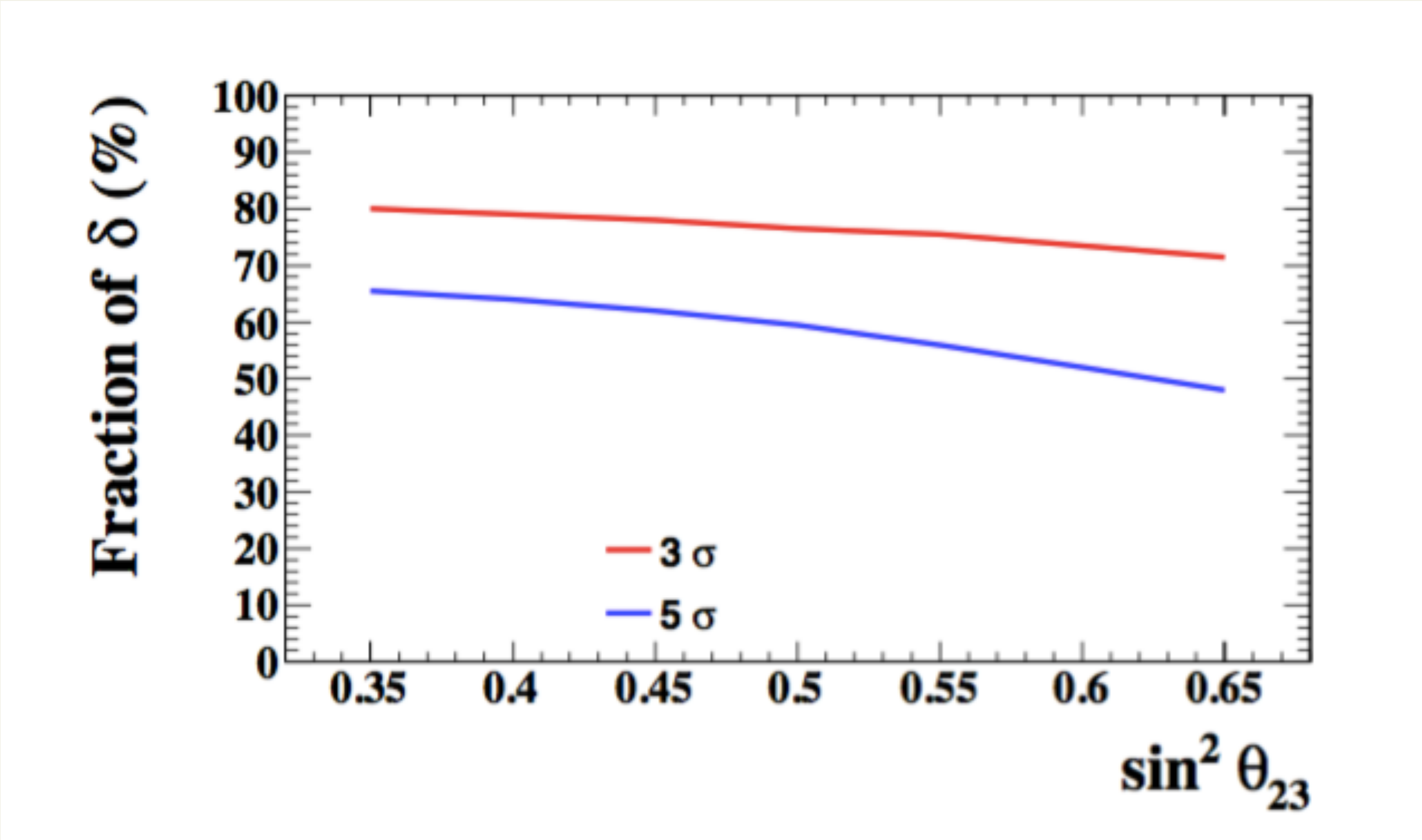
PHOTOSENSORS

Super-K R3600

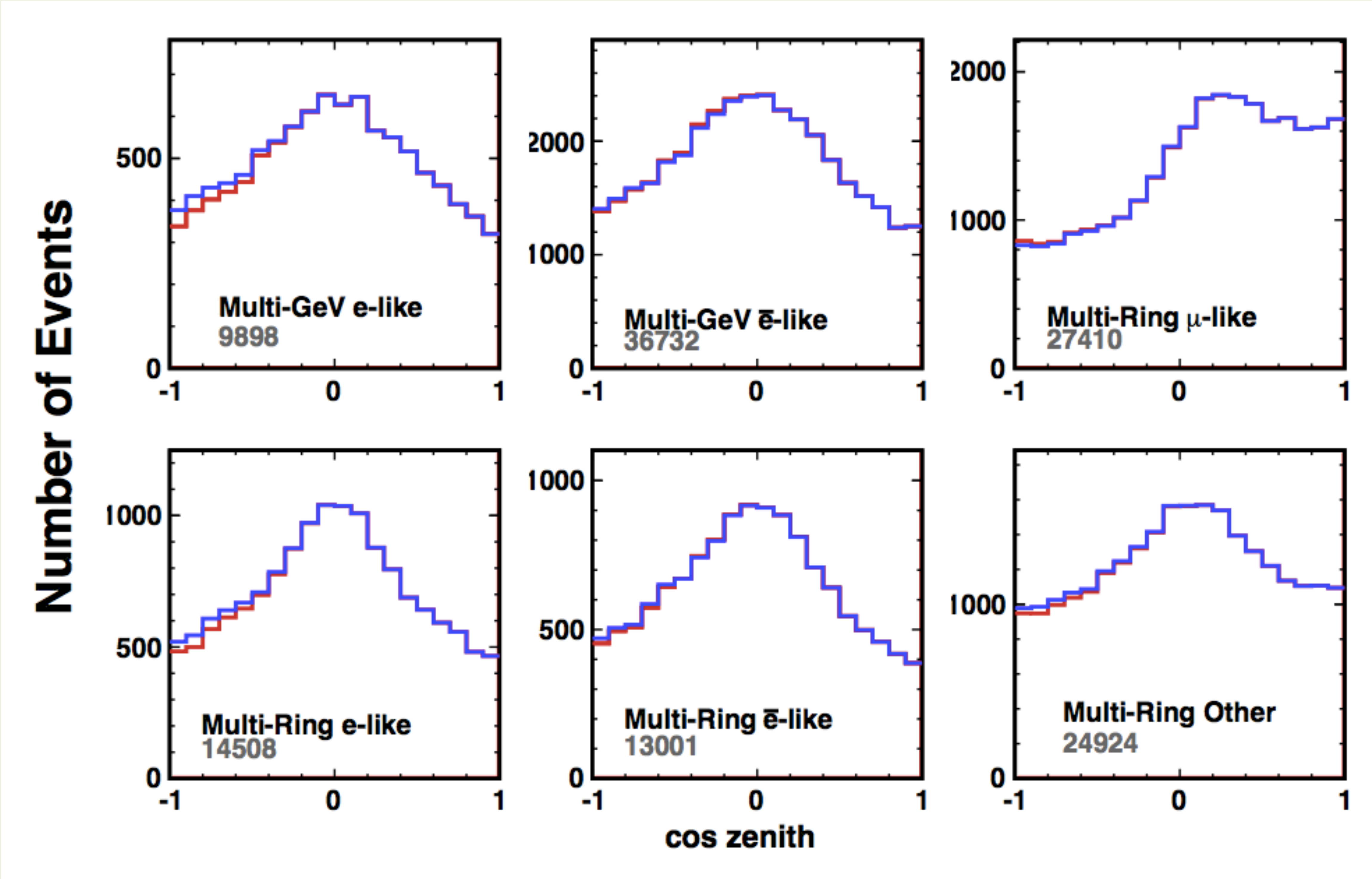
- Venetian blind dynode
- 11,000 employed in Super-K
  - Up to 40 m depth
- Neutrino oscillation discovery

- Goals for Hyper-K photosensors:
  - 2x increased pressure tolerance for 60 m deep tank
  - 2x increased photon detection efficiency
  - Improved time and charge resolution

CPV DISCOVERY

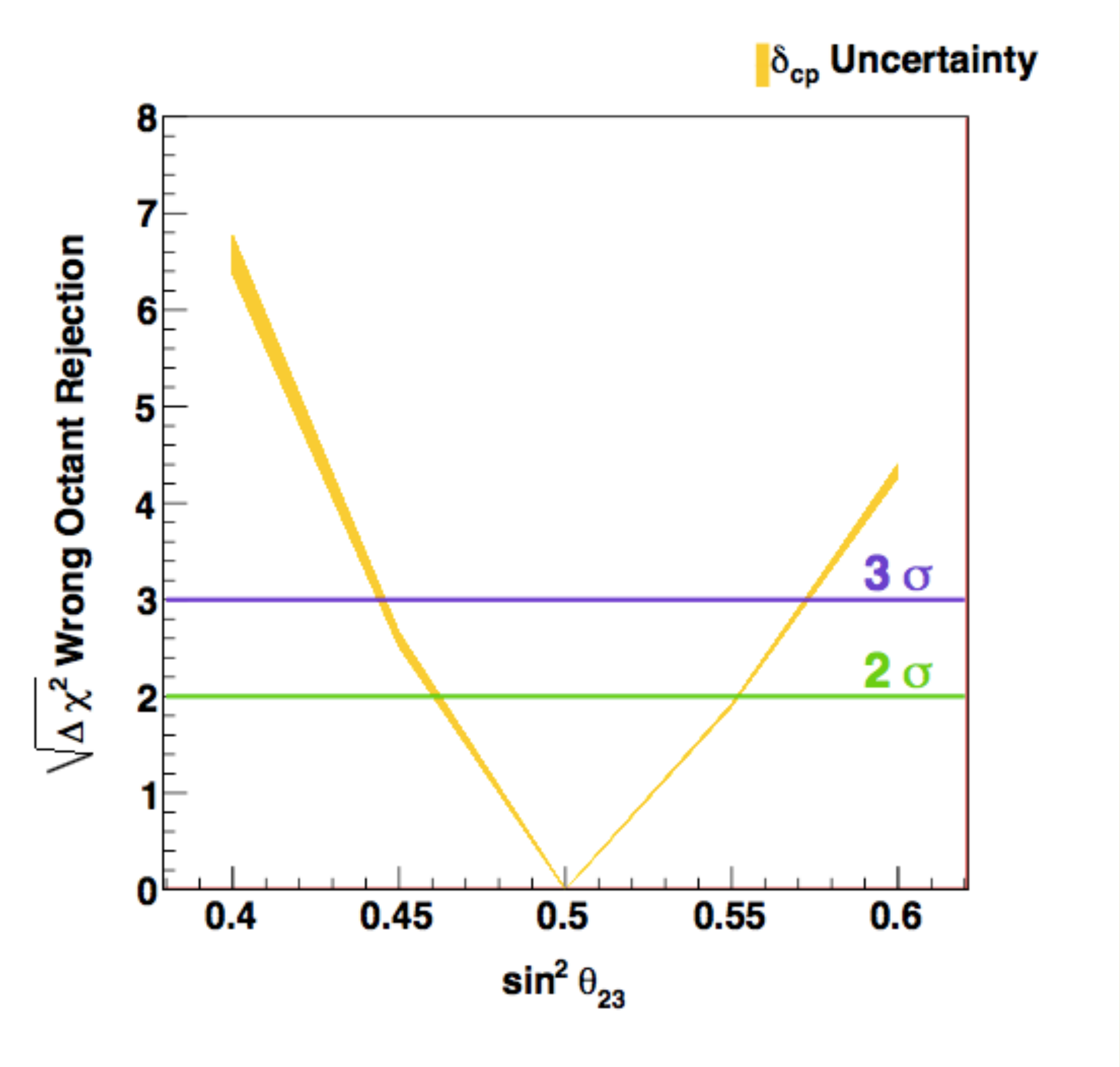


ATMOSPHERIC NEUTRINO EVENT RATES



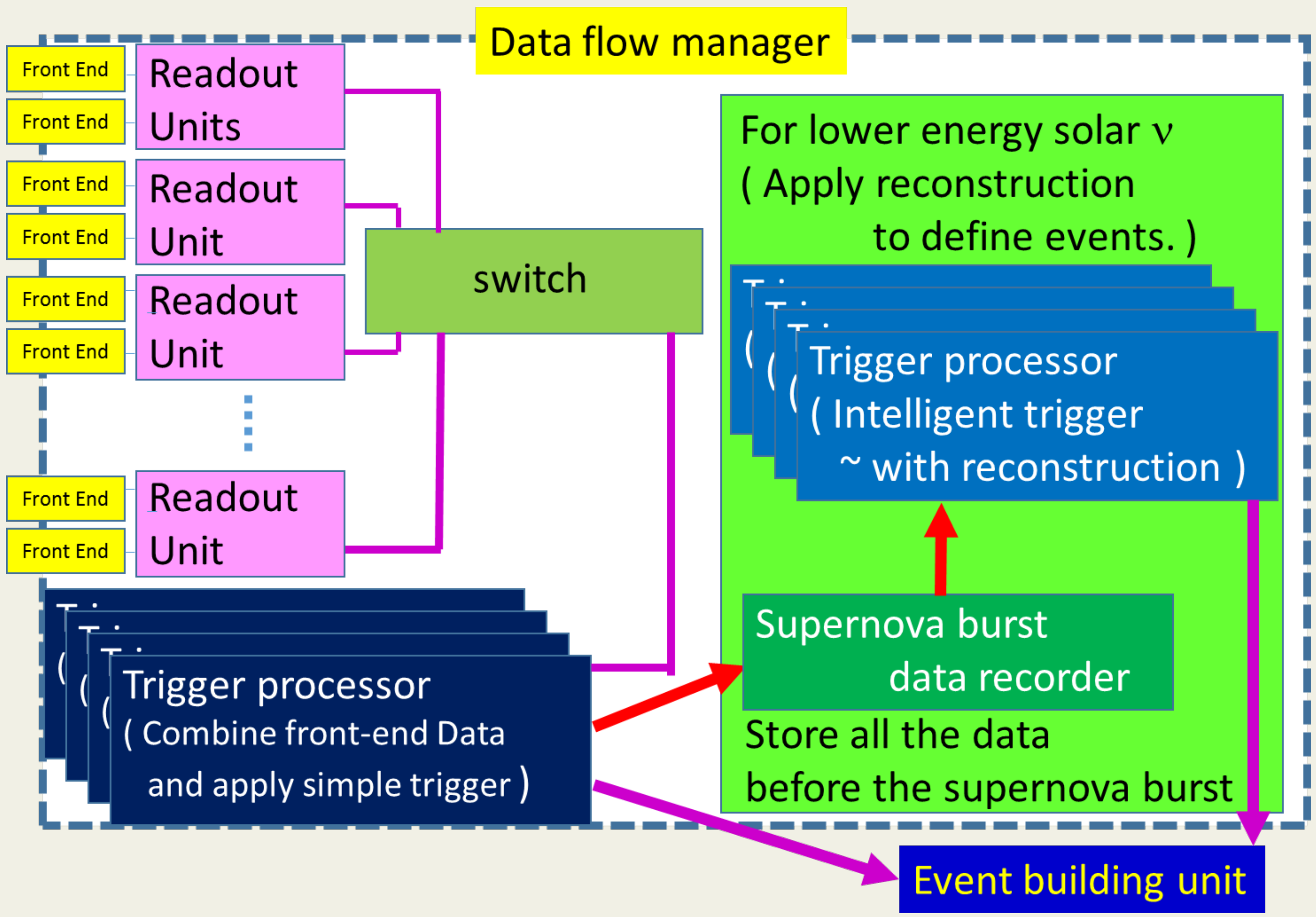
Blue = normal hierarchy, red = inverted hierarchy

OCTANT REJECTION WITH ATMOSPHERIC



DATA ACQUISITION

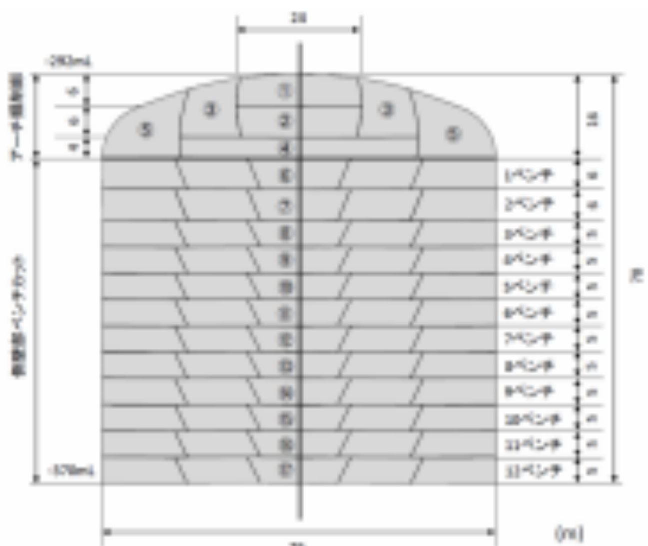
Capable in taking
events from low energy solar neutrino
to high energy atmospheric neutrinos
Capable in handling
extremely high trigger rates from Supernova bursts.
System has to be Stable and fault-tolerant not to lose rare events.



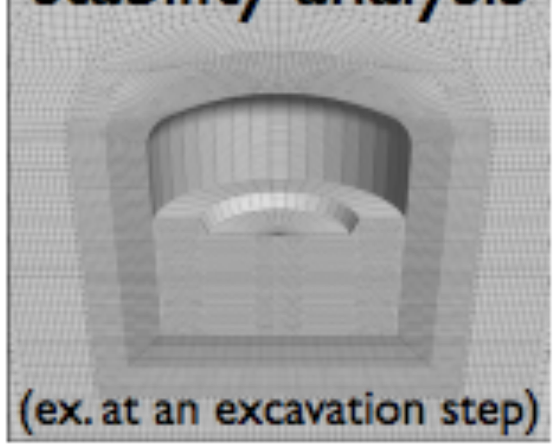
H. Tanaka

Cavern stability analysis

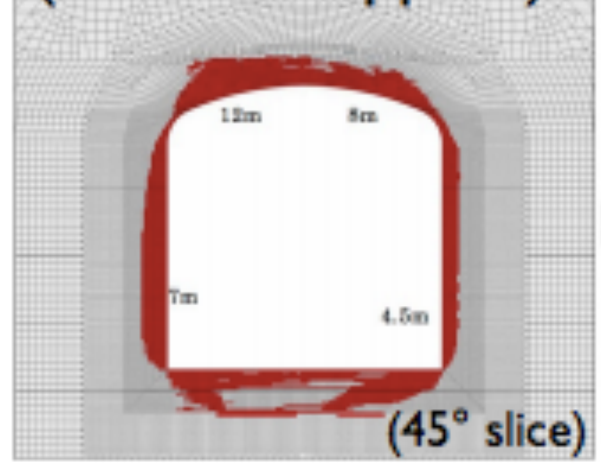
Excavation steps



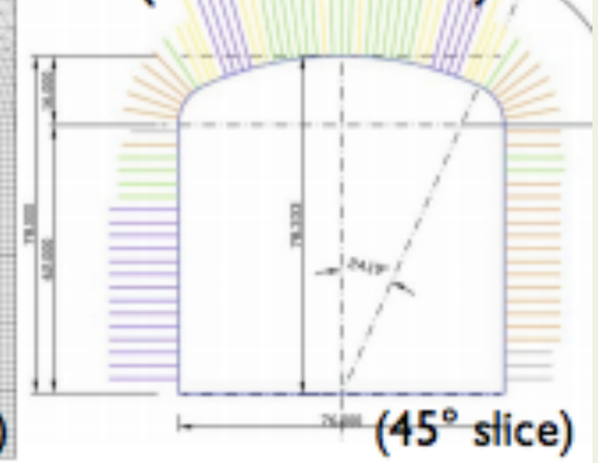
3D model for stability analysis



Plastic region depth (without support)



Cavern support (PS-anchors)



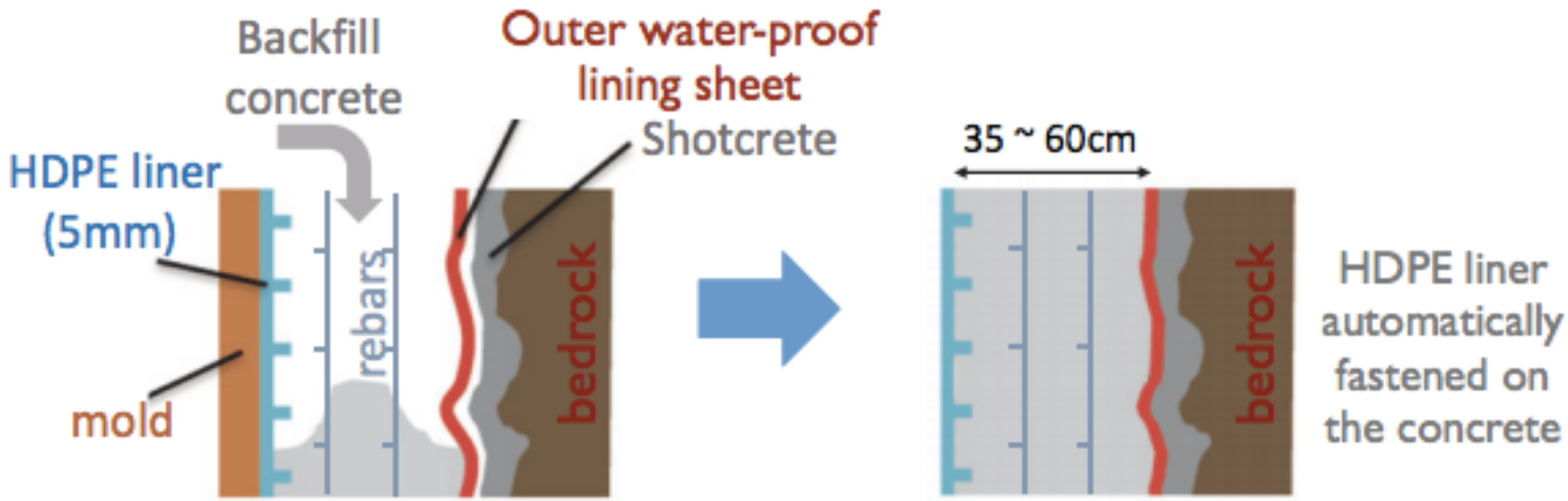
- Cavern stability analyses based on geol. survey results
  - 3D finite element analysis adopting Hoek-Brown model
    - Adopt a model to treat the elastic and inelastic behaviors of rock
  - Excavation steps taken into account in stability analysis
  - Evaluate plastic region depth and design cavern support
- Confirmed the Hyper-K cavern can be constructed with the existing technologies

Hyper-Kamiokande

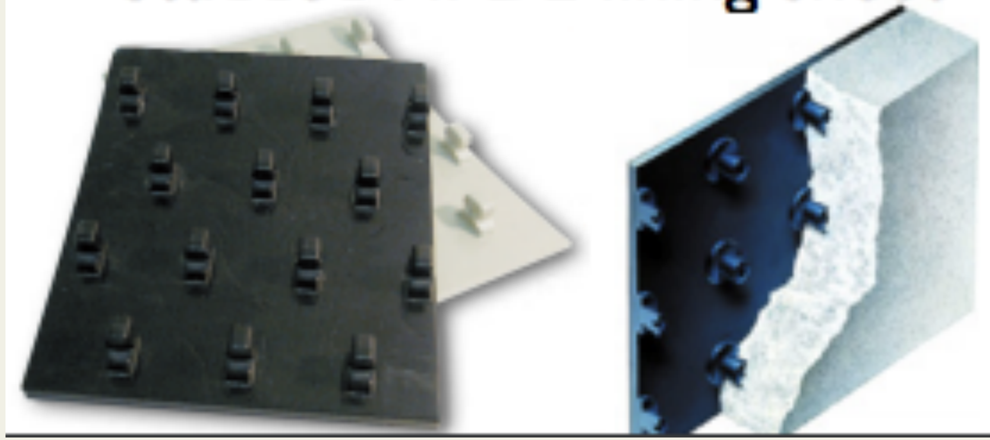
H. Tanaka

Water containment system

- Water containment system consists of three layers of lining system:
  - Outer water-proof sheet, Concrete lining, High Density Polyethylene (HDPE) lining



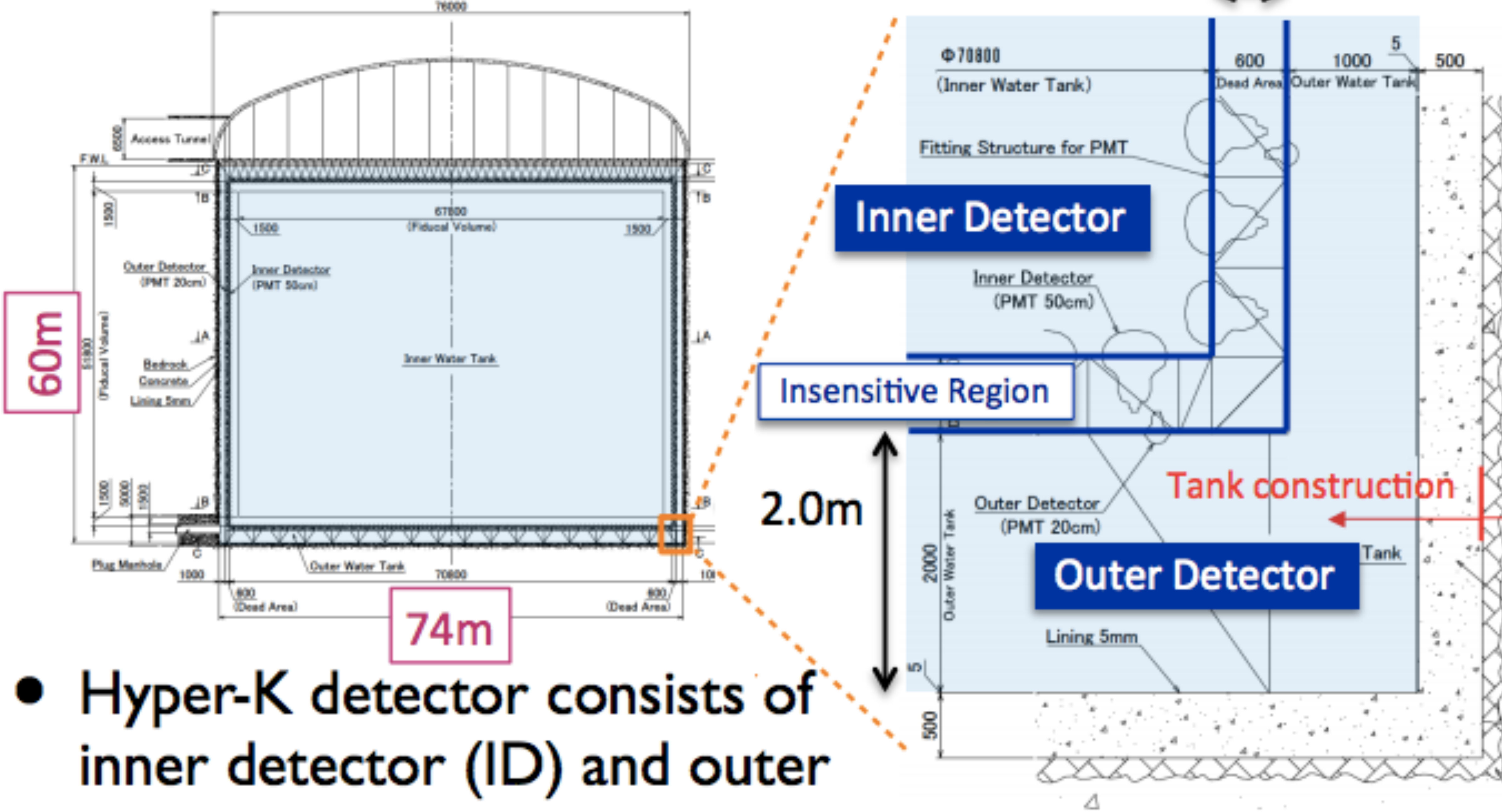
Studded HPDE lining sheet



Three layers of liners are constructed simultaneously
→ Minimize the const. time

H. Tanaka

Hyper-K detector



- Hyper-K detector consists of inner detector (ID) and outer detector (OD)
  - and 'insensitive region' in between
  - ID & OD are optically separated

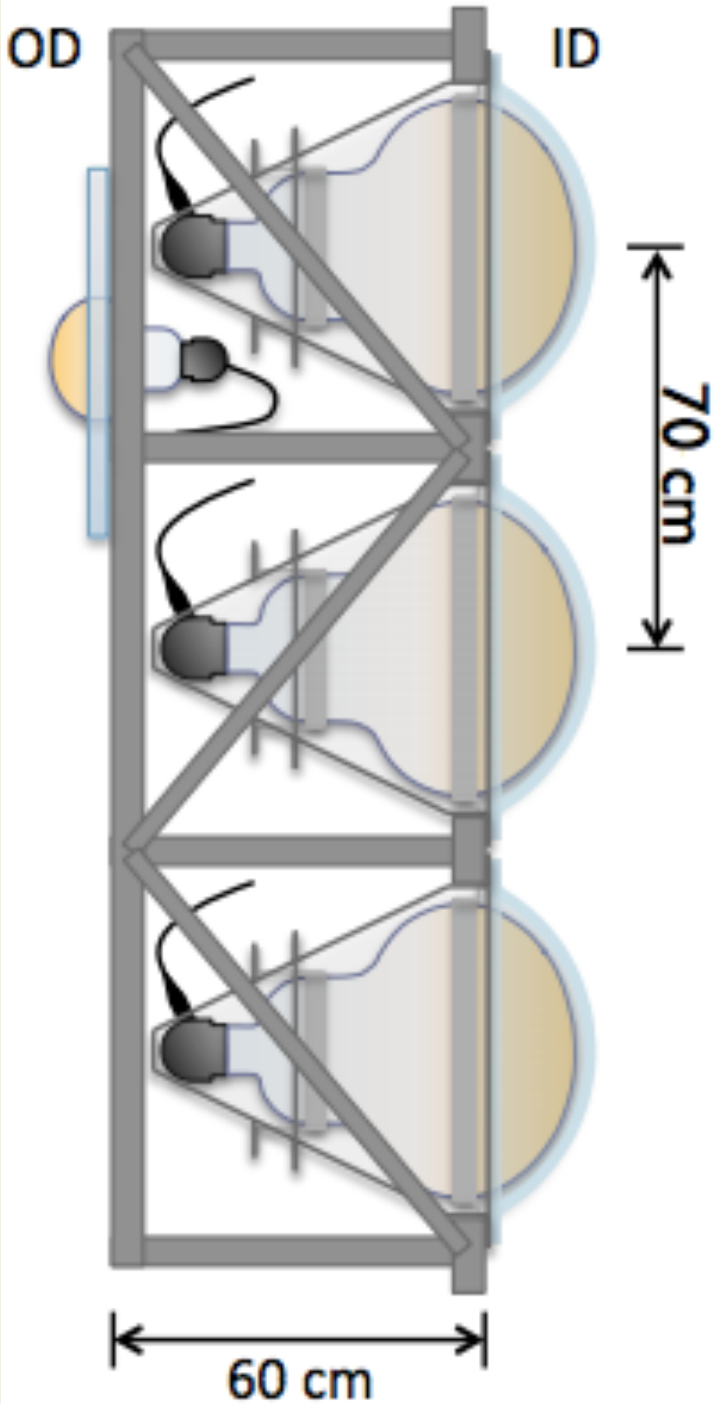
1 ID-PMT/0.5m² (40% coverage)

→ ~40,000 ID-PMTs/tank

~6,700 OD-PMTs/tank

PMT support structure

H. Tanaka



- PMT support structure adopts a truss structure made of SUS members (angles)
- Seismic response analysis confirmed earth quake do not make damage to the detector
  - even if no water in the tank

- Top/Barrel → Hung from the ceiling
- Bottom → Set on the ground