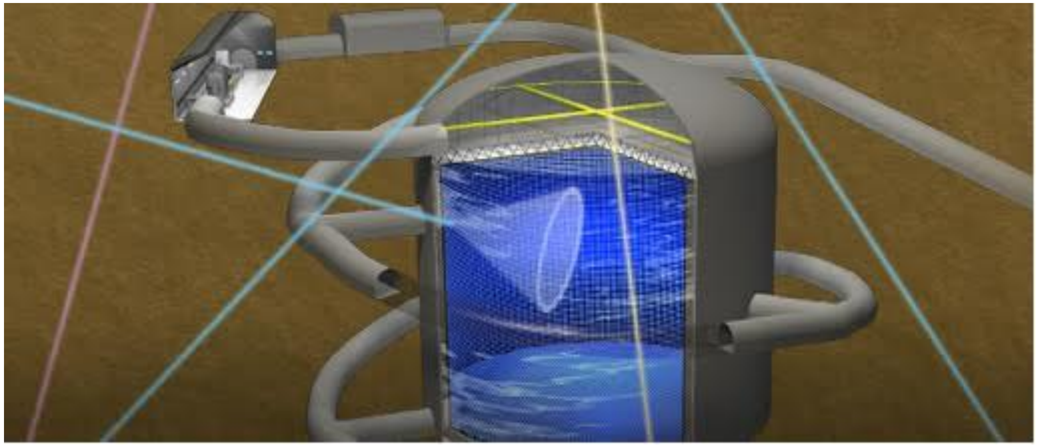
Hyper-Kamiokande

http://hyperk.org

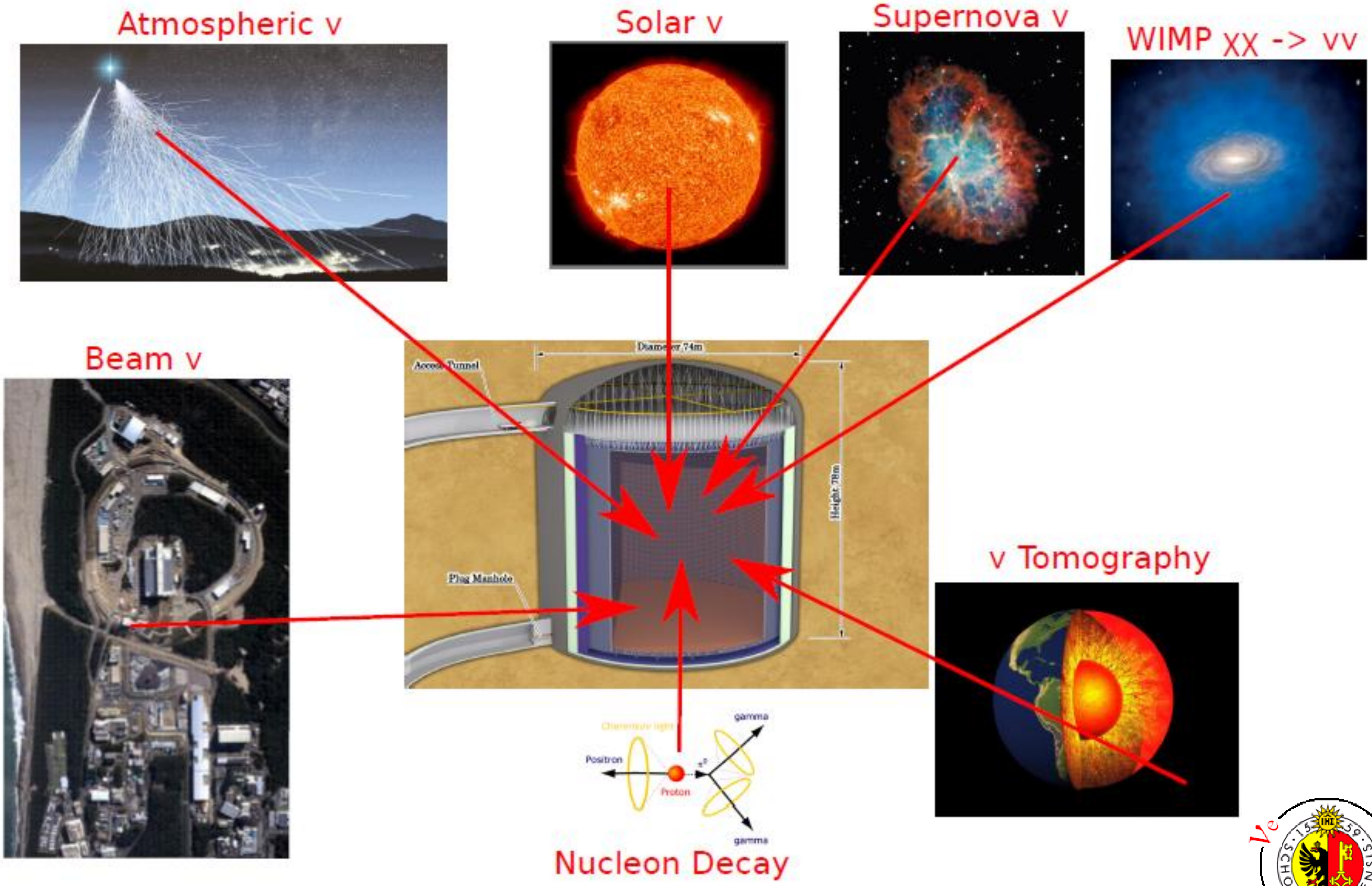


The Hyper-Kamiodande Project
A New Adventure in ν Physics

Alessandro Bravar
on behalf of the HK Proto-Collaboration

ICNFP2017
Kolymbari, Crete
August 26, ‘17

Hyper-K Physics Overview



Atmospheric ν

Solar ν

Supernova ν

WIMP χχ -> νν

Beam ν

ν Tomography

Nucleon Decay

Broad Science Program with Hyper-K

Neutrino oscillation physics

- comprehensive study with beam and atmospheric neutrinos
  - determination of neutrino mass hierarchy
  - determination of θ_{23} octant
  - measurement of CP Violation in leptonic sector
  - reveal exotic scenarios

Search for nucleon decay

- possible discovery with ~ 10 × SK sensitivity
- all visible modes including $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu} K^+$
- reach 10^{35} years sensitivity

Solar neutrino physics

- precision measurement of Δm^2_{21}
- measurement of energy spectrum up-turn
- discovery & measurement of hep neutrinos

Neutrino Astrophysics

- high statistics measurement of SN burst neutrinos
- detection and study of relic SN neutrinos
- indirect Dark Matter search from Galactic Core, Sun, Earth

Geophysics (“neutrinography” of Earth’s interior)

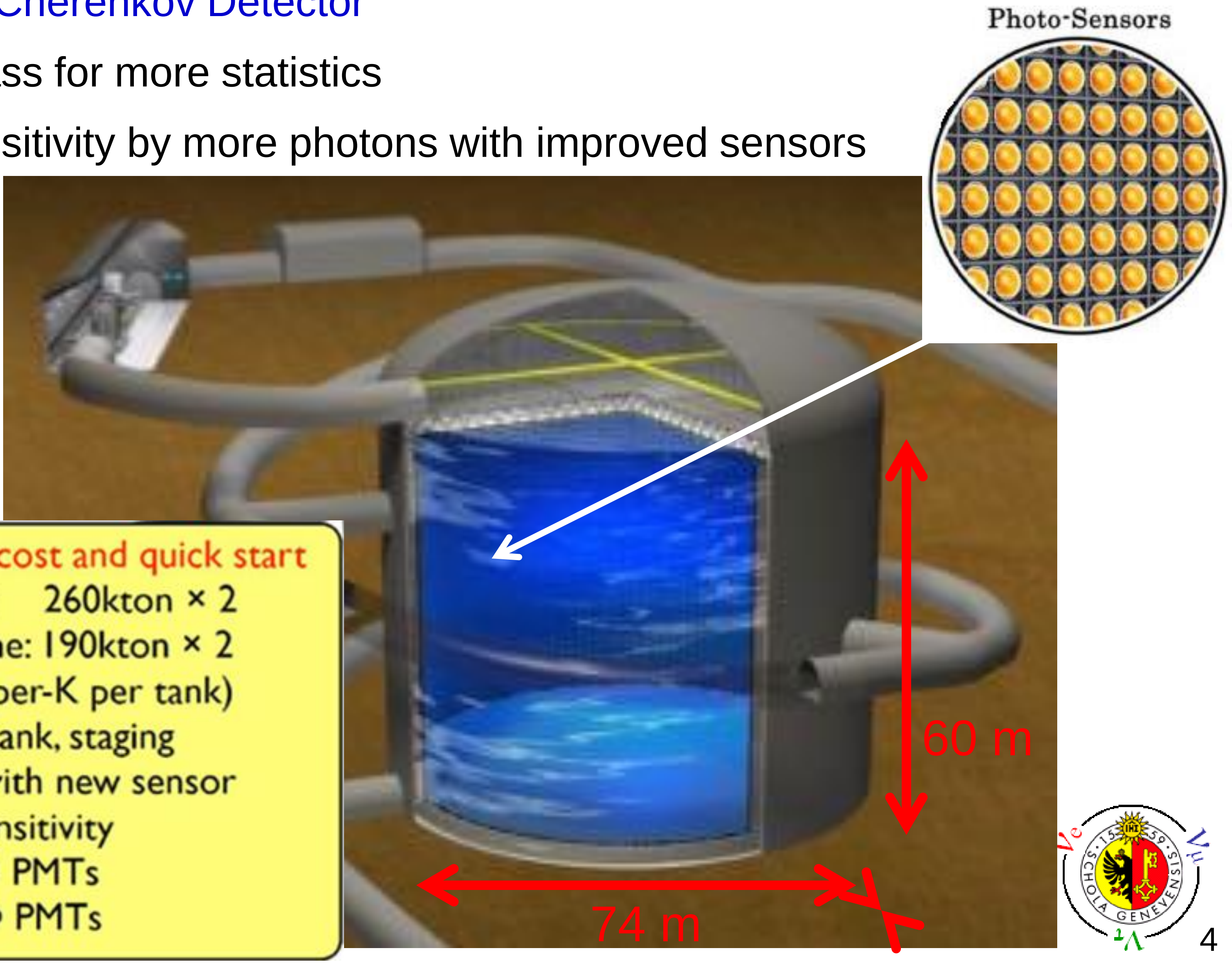
+ unexpected
(unknown)

The Hyper-Kamiokande Detector

Large Water Cherenkov Detector

Larger mass for more statistics

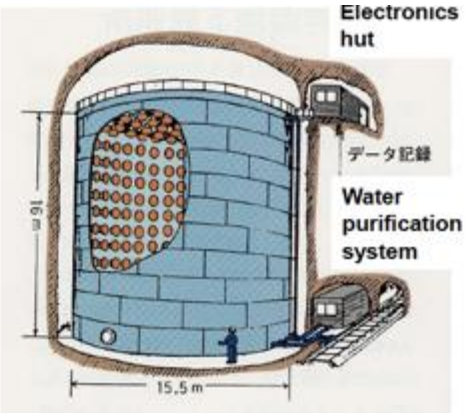
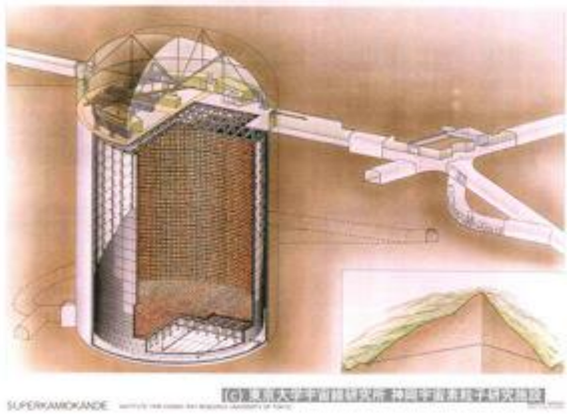
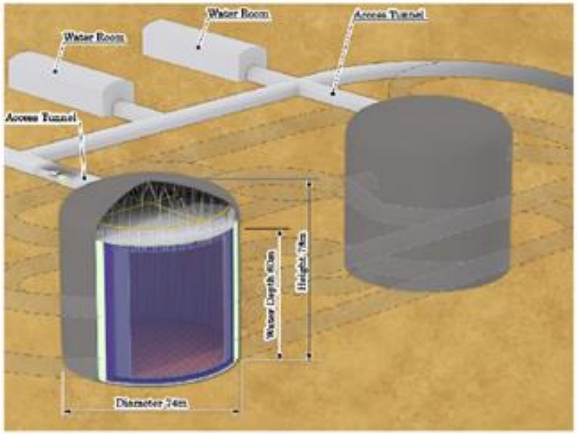
Better sensitivity by more photons with improved sensors



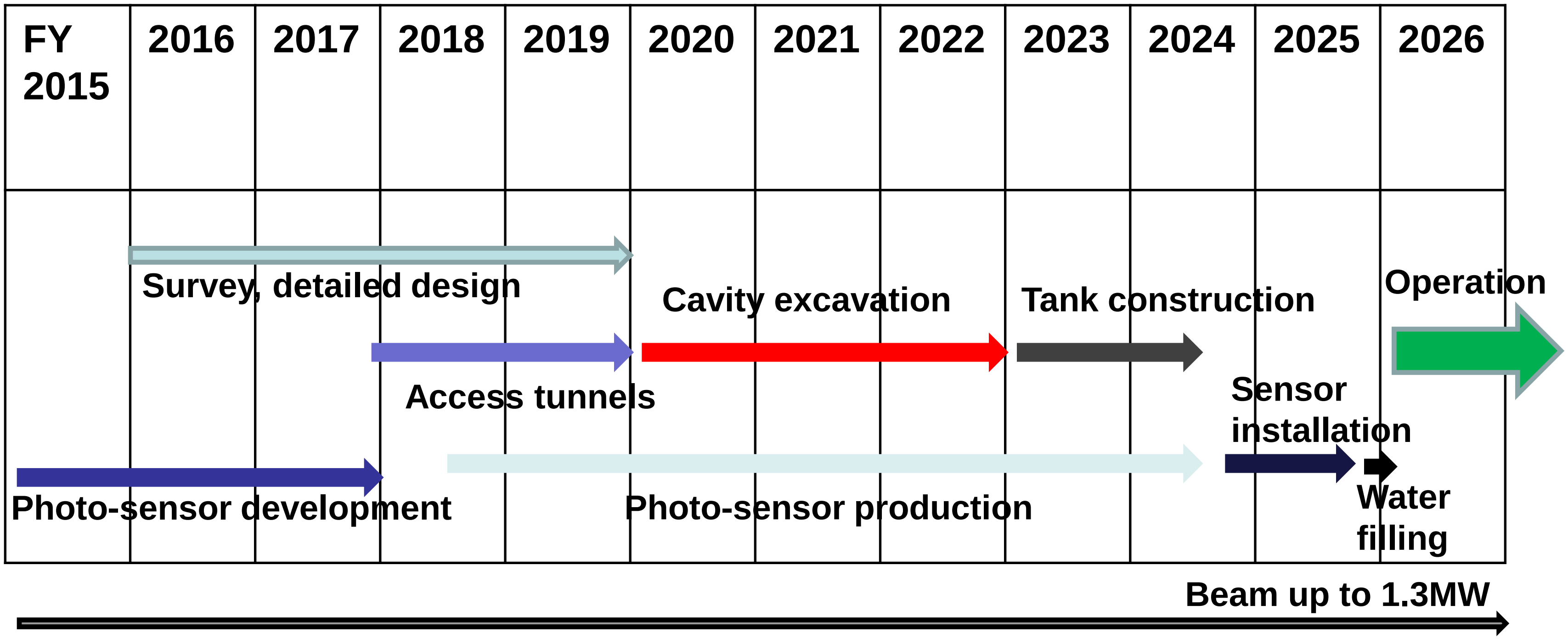
Optimized for cost and quick start

Total volume: 260kton × 2
Fiducial volume: 190kton × 2
(~×10 of Super-K per tank)
Start with one tank, staging
40% coverage with new sensor
×2 photon sensitivity
40,000 50cm ID PMTs
6,700 20cm OD PMTs

3 Generations of Kamioka Detectors

Kamiokande (1983-1996)	Super-Kamiokande (1996-)	Hyper-Kamiokande (~2026-)
		
3 kton 20% coverage with 50 cm PMT	50 kton 40% coverage with 50 cm PMT	260 kton x 2 40% coverage with high-QE 50 cm PMT
		?
Observation of SN1987A	Discovery of ν oscillations	Prepare for the unknown

The Hyper-K Timeline



FY 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026

Survey, detailed design

Cavity excavation

Tank construction

Operation

Access tunnels

Sensor installation

Photo-sensor development

Photo-sensor production

Water filling

Beam up to 1.3MW

Hyper-K is listed in the MEXT (funding agency) Large Projects Roadmap

2018 – 2015 Hyper-K construction

2026 onwards
CPV study, Atmospheric ν, Solar ν, Supernova ν, Proton decay, …

Staged approach: 2nd identical tank starts operation 6 years after the first one

The Hyper-K Collaboration

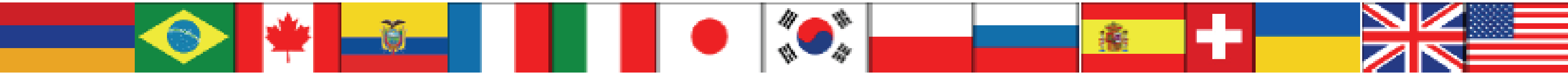
January 2015

Formed in Jan. 2015

15 countries

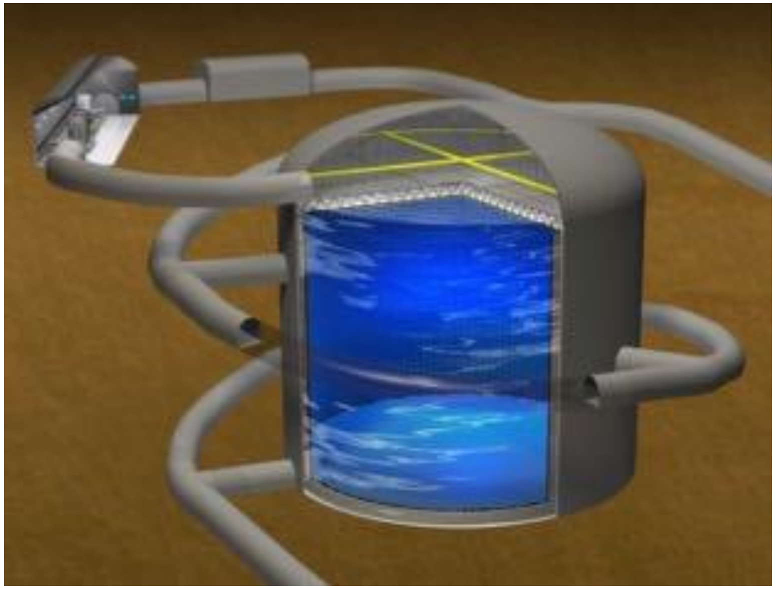
~300 members
(and gowing)

July 2016



From J-PARC to Kamioka

260 kton Water Cherenkov Detector



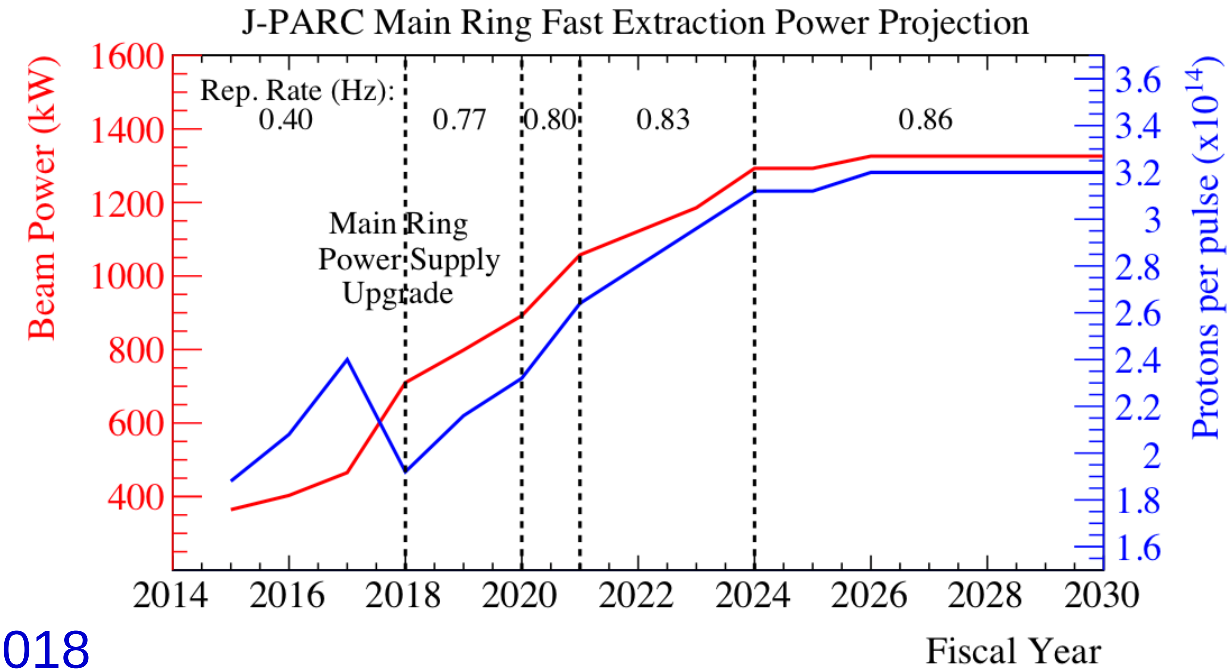
\+

Upgraded J-PARC neutrino beam
New / upgraded near detectors

Nominal design:
1st tank in Tochibora with the second tank following after 6 years

J-PARC Neutrino Beam Upgrade

Continuous upgrade plan of the neutrino beam



0.75 MW in 2018

MR power supply upgrade

1.3 MW by ~2026

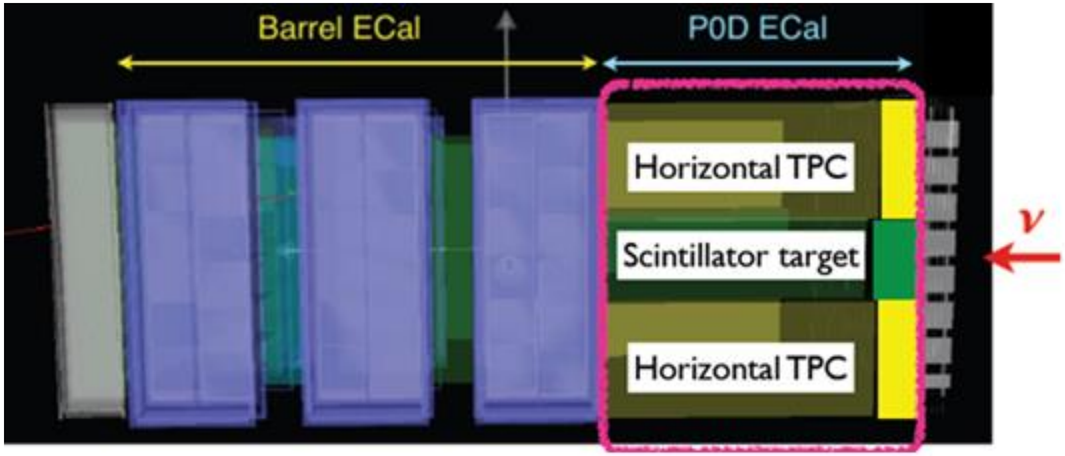
repetition cycle from 2.48 s to 1.3 s

protons 2.4 × 10^{14} / spill to 3.2 × 10^{14} / spill

Given highest priority in KEK Project Implementation Plan (2016)

The Near Detectors @ J-PARC

Upgraded ND280 Near Detector



Designed to address ν – Nucleus interactions and modeling

Enlarge phase space (4π coverage)

Efficiency for short hadron tracks with proton reconstruction

Improve electron neutrino selection

New: horizontal TPCs
scintillator target

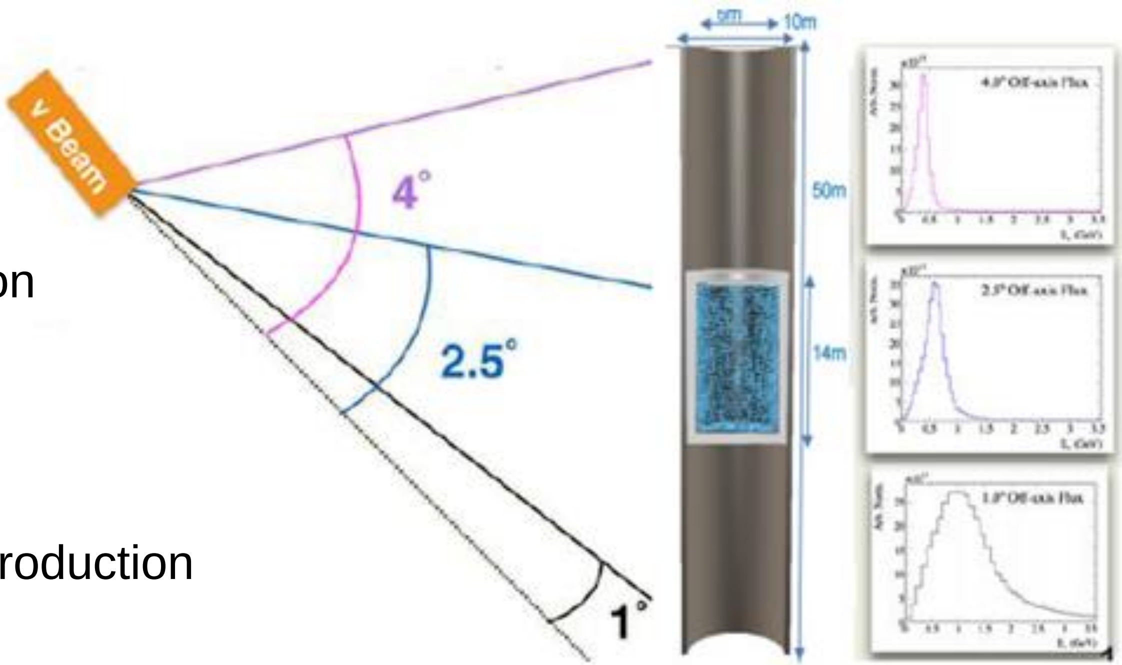
Intermediate Water Cherenkov

located at ~1 km from ν source

Off-axis angle spanning orientation vary ν peak energy

probe neutrino energy vs. reconstructed energy

Gd loading to measure neutron production



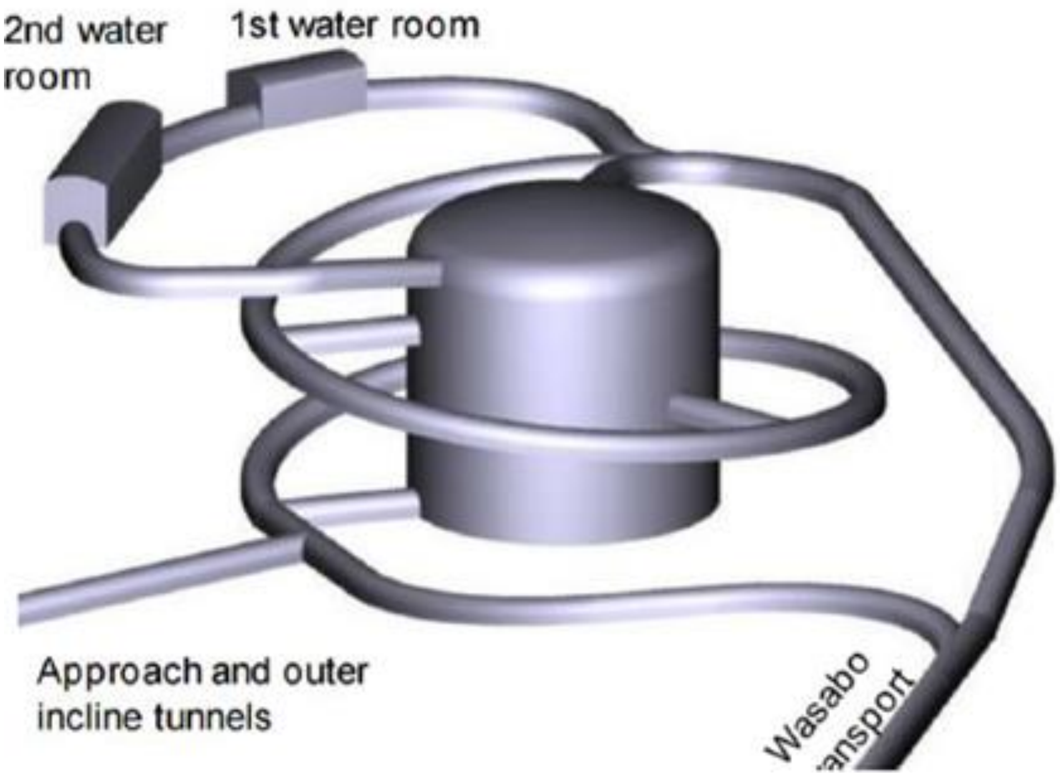
The Kamioka Site

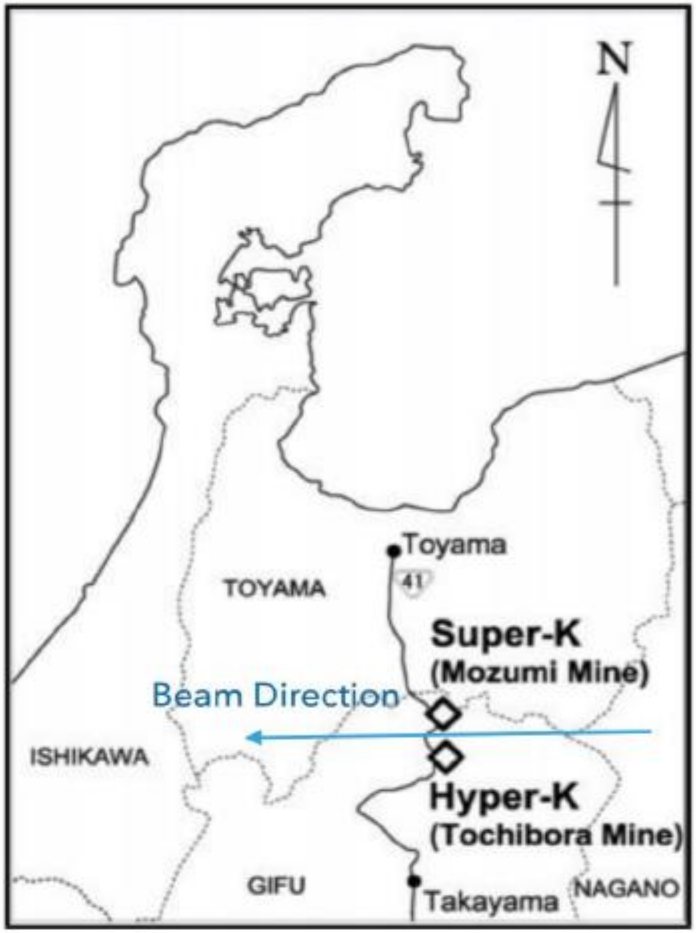
The candidate site located in Tochibora, under Mt. Nijugo-yama

~8 km south from Super-K, 295 km from J-PARC, 2.5° off-axis

overburden ~650 m (~1755 m w.e.)

Cavern can be built with existing technologies



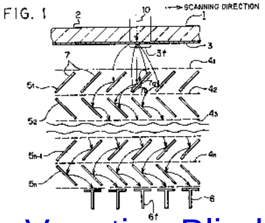


Upgraded Photo-Sensors

Super-K PMT

used in SK for 20 yrs

High QE Photocathode

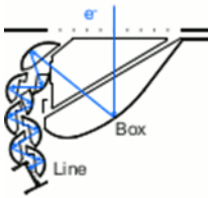


Venetian Blind

HQE SK PMT

under validation

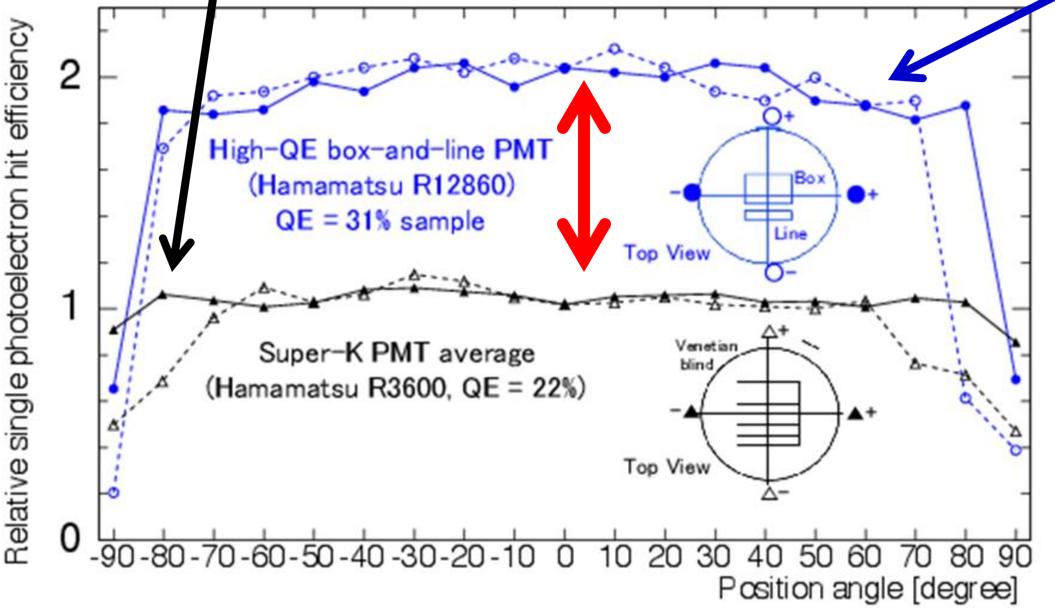
Dynode Improvement



Box-and-Line Dynode

50 cm HQE Box&Line PMT

under validation



Enhanced performance

Photo Detection Efficiency 2 × bigger

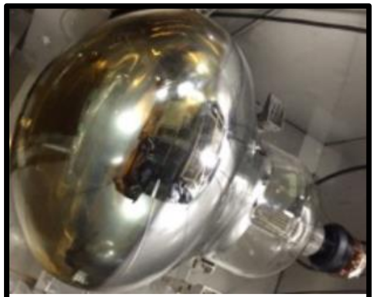
Timing resolution 50% better

Increased Pressure tolerance × 2

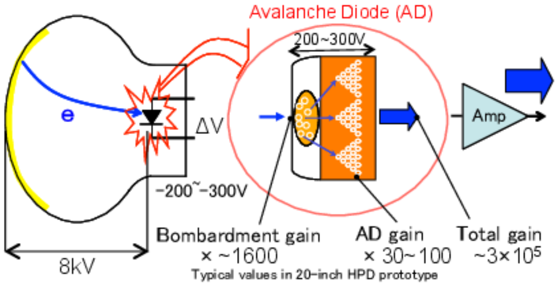
- enhance $p \to \bar{\nu} K^+$ signal
- solar ν lower threshold
- neutron capture signature
  ($n + p \to d + \gamma$ - 2.2MeV γ)

Photo-Sensor Developments

Hybrid Photo Detectors (HPDs)

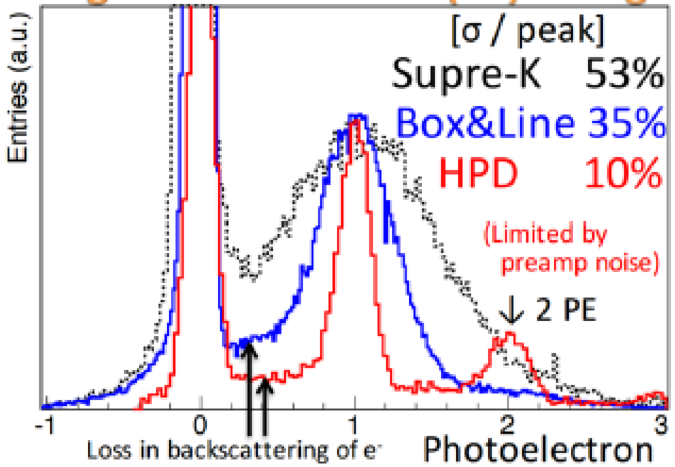


50 cm HQE HPD
w/ 20mm ϕ AD

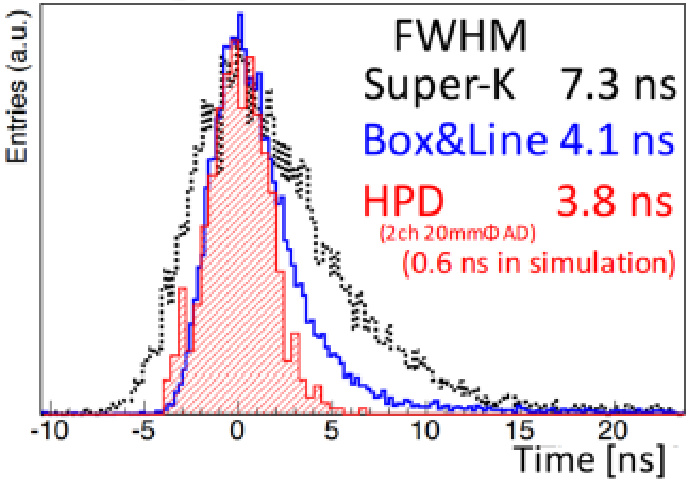


R&D
development and validation

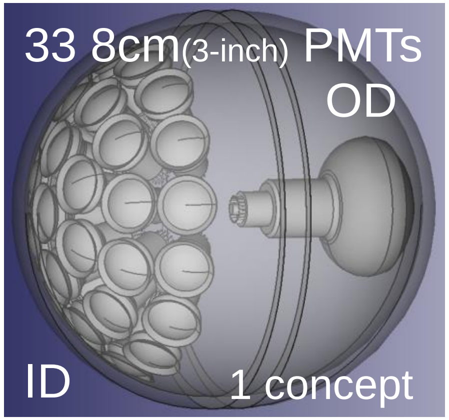
Single Photoelectron (PE) Charge



Single Photoelectron Time



Multi-PMT



directional sensitivity

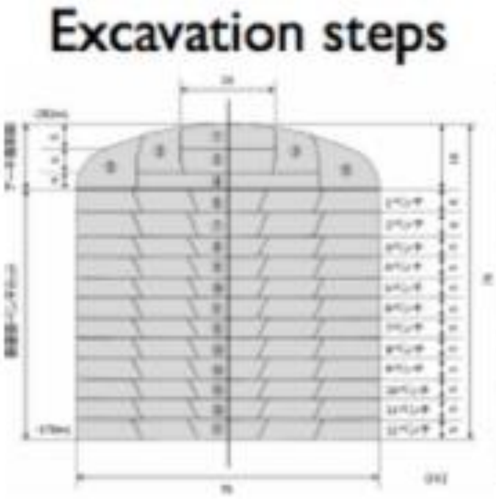
usage for ID/OD

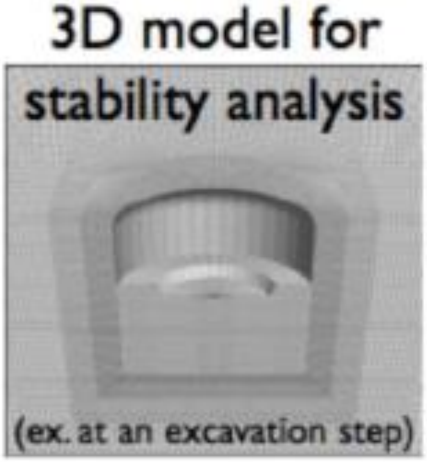
higher pressure tolerance

no geomegnetisem compensation

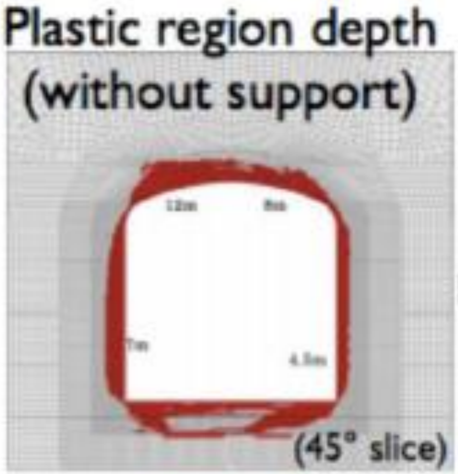
Cavern and Tank

Cavern geological survey and find analysis undertaken

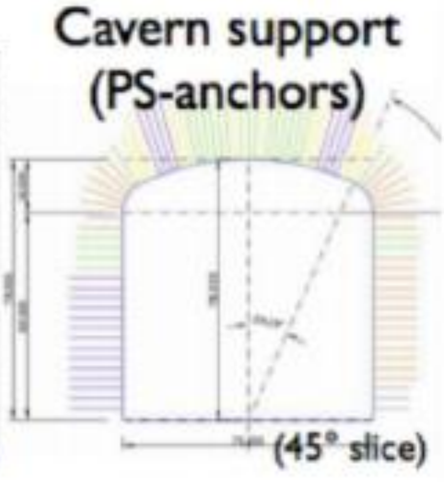

Excavation steps


3D model for stability analysis

(ex. at an excavation step)


Plastic region depth (without support)

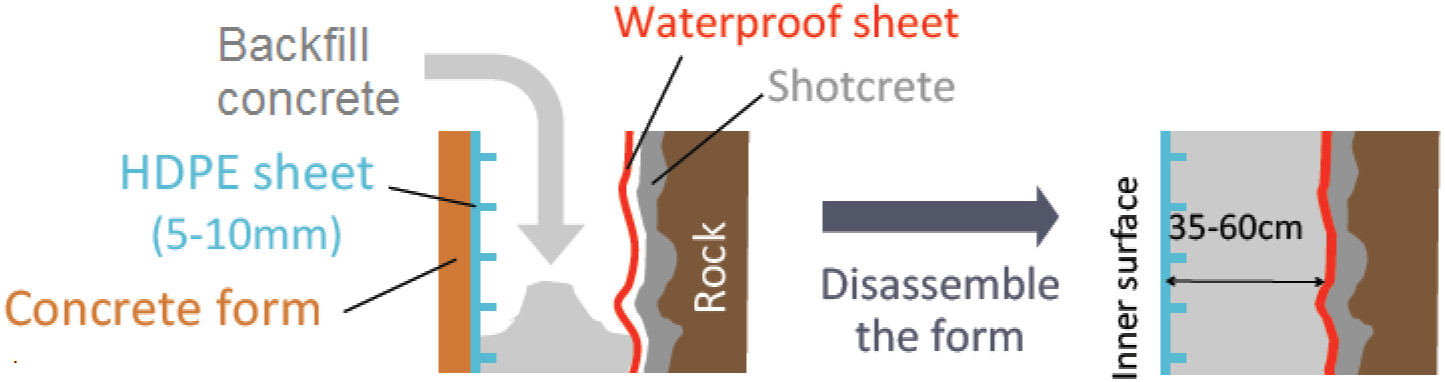
(45° slice)


Cavern support (PS-anchors)

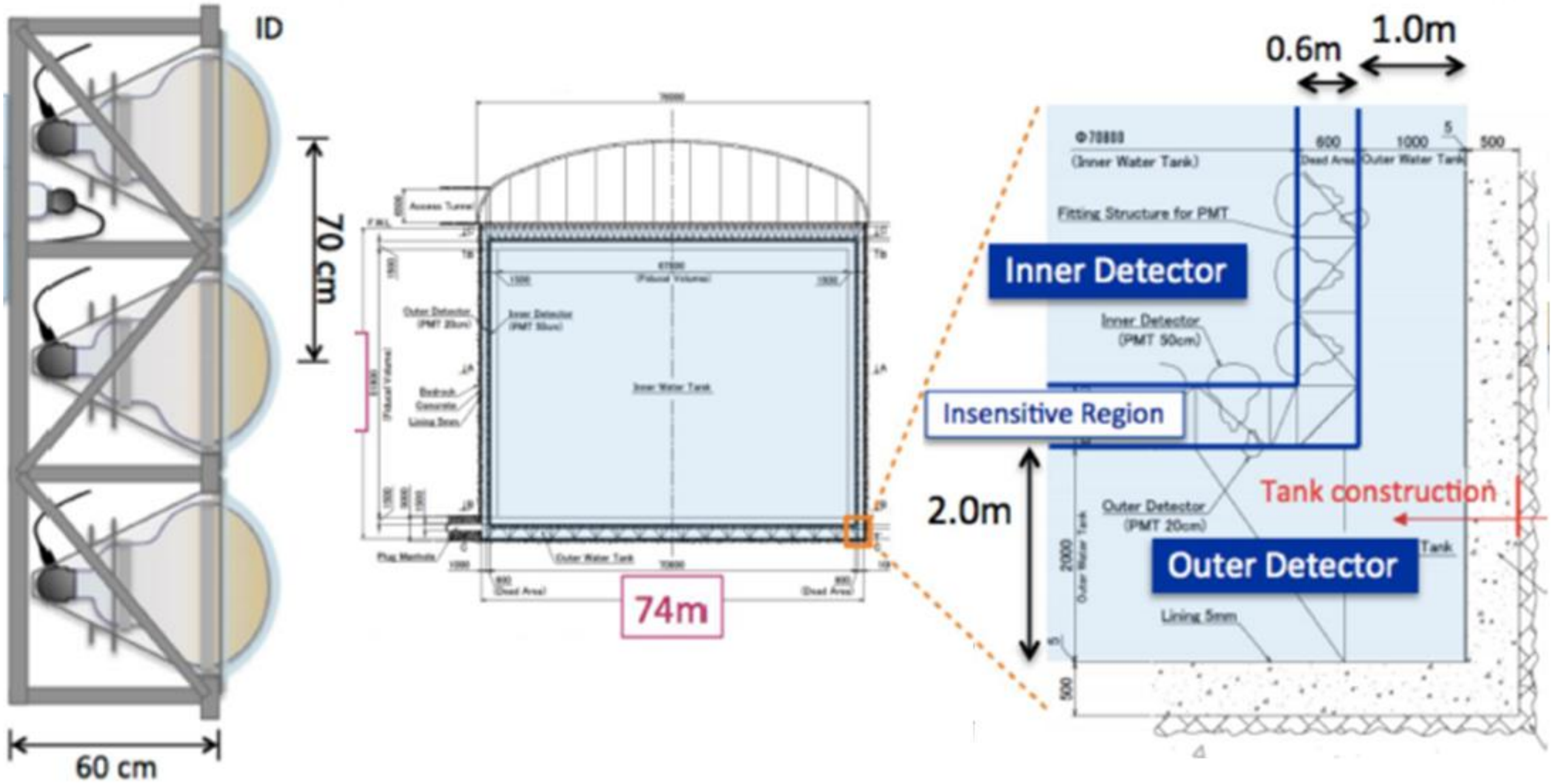
(45° slice)

Water containment: 3 layers of lining

outer water-proof sheet; concrete; High Density Polyethylene (HDPE) sheet (constructed simultaneously to reduce cost and time)



The Tank



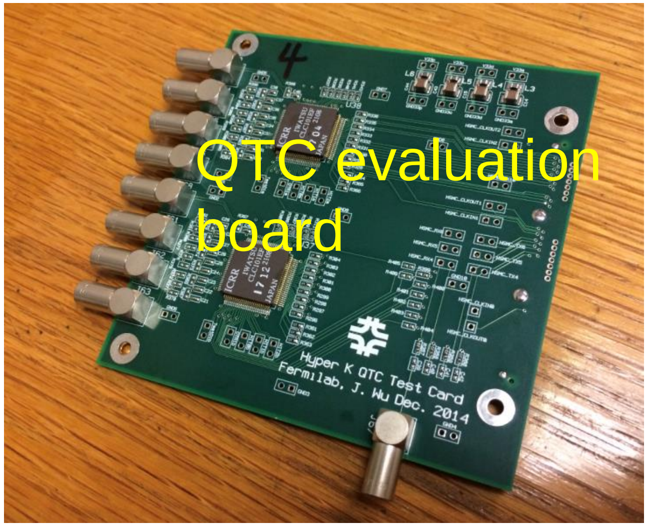
Hyper-K detector consists of inner detector (ID) and outer detector (OD)

Seismic response analysis shows that earthquake does not damage the detector (PMTs) even if no water in the tank

Electronics

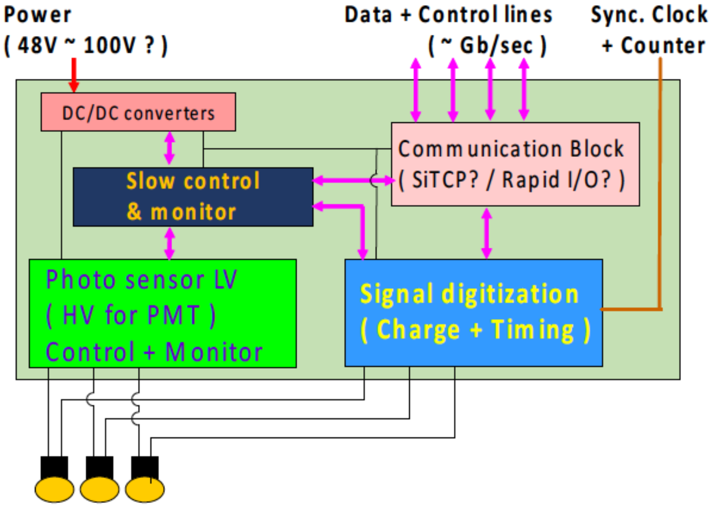
Candidates for signal digitization:

1. Charge to Time converter with FPGA-based TDC (similar to SK)
2. ~100MHz FADC + digital signal processing
3. GHz digitizers based on capacitor arrays


QTC evaluation board

Front-end electronics requirements:

- wide charge dynamic range
  0.1 to 1250 p.e.
- good time resolution
  ΔT = sub-nsec,
- self triggering
  (channel by channel)
- low power consumption
  < 1W/ch



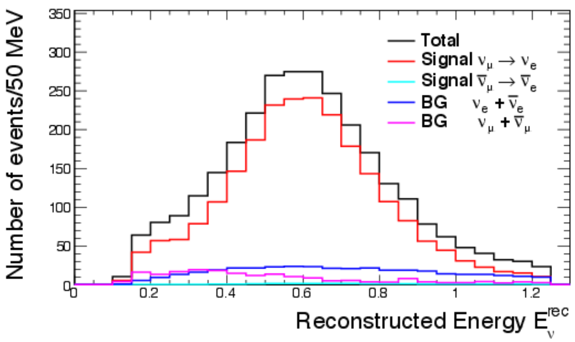
Front-end electronics and network connections under water

Beam Events in Hyper-K

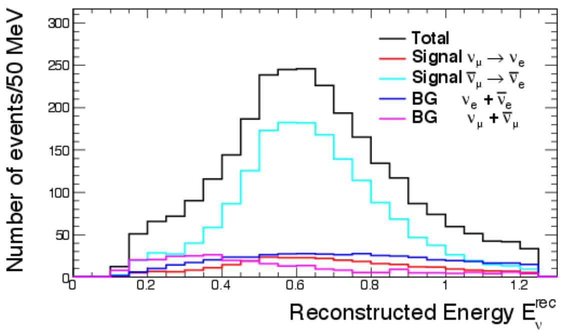
10 years data taking

ν_e appearance

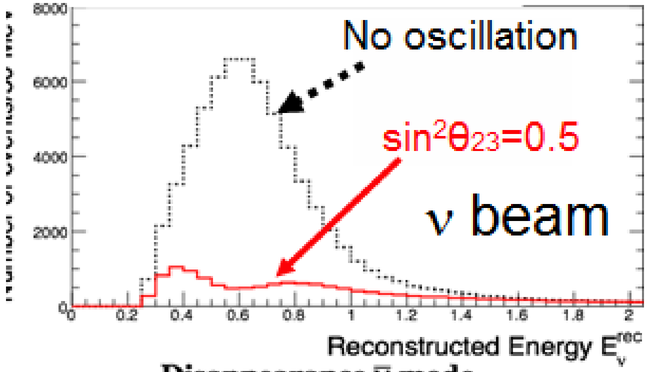
Appearance ν mode



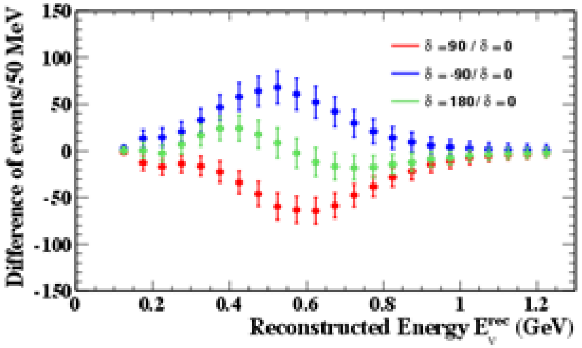
Appearance $\bar{\nu}$ mode

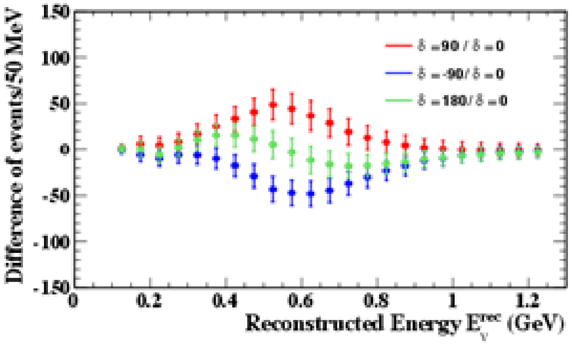


ν_μ disappearance

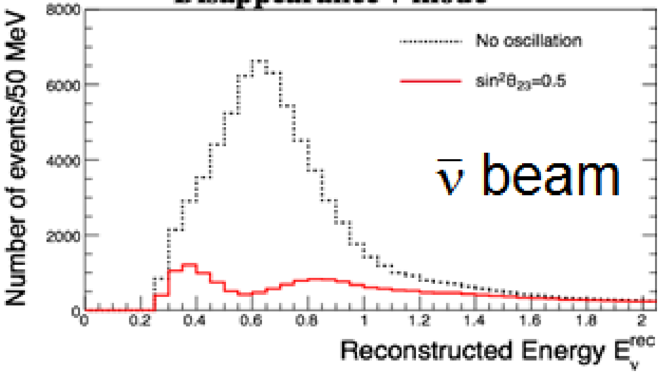


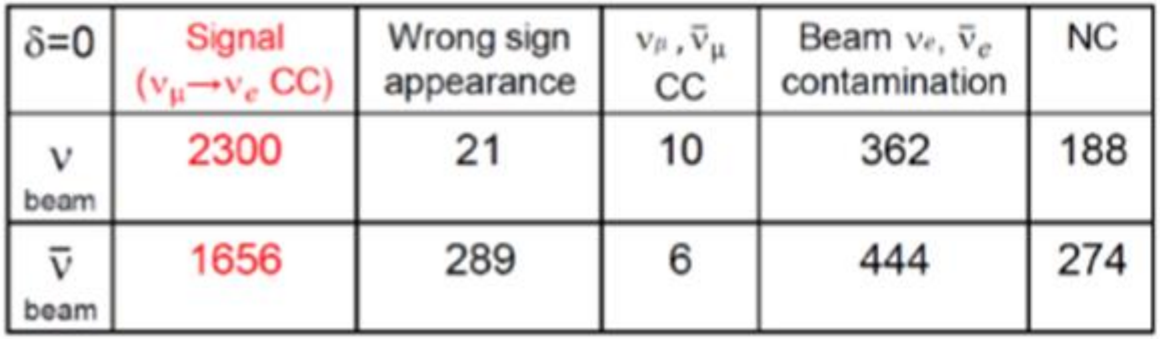
difference from $\delta_{CP} = 0$



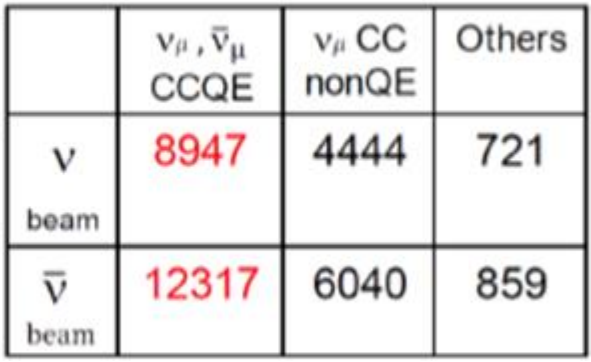


Disappearance $\bar{\nu}$ mode





δ=0	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	ν_μ, $\bar{\nu}_\mu$ CC	Beam ν_e, $\bar{\nu}_e$ contamination	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274



	ν_μ, $\bar{\nu}_\mu$ CCQE	ν_μ CC nonQE	Others
ν beam	8947	4444	721
$\bar{\nu}$ beam	12317	6040	859

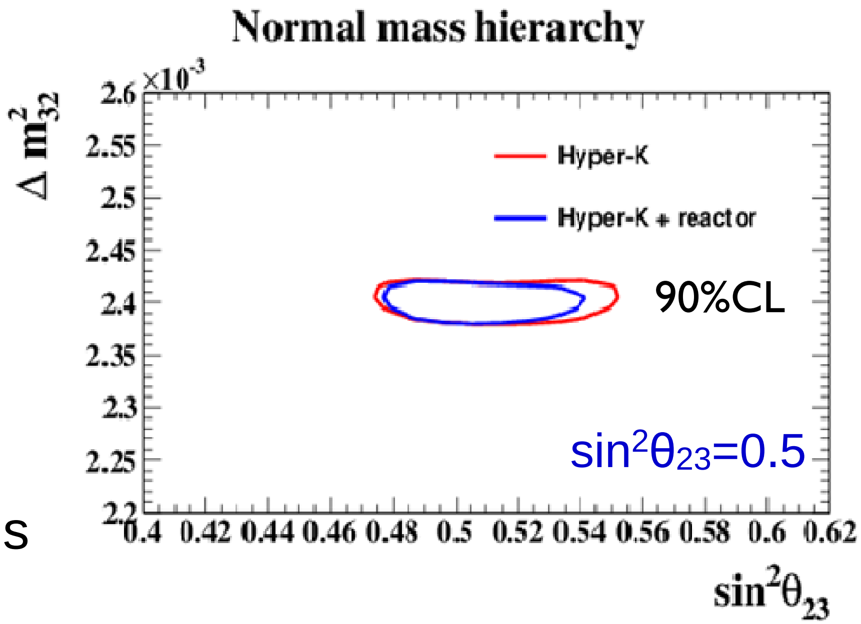
θ_{23} and $|\Delta m^2_{32}|$ Precision Measurements

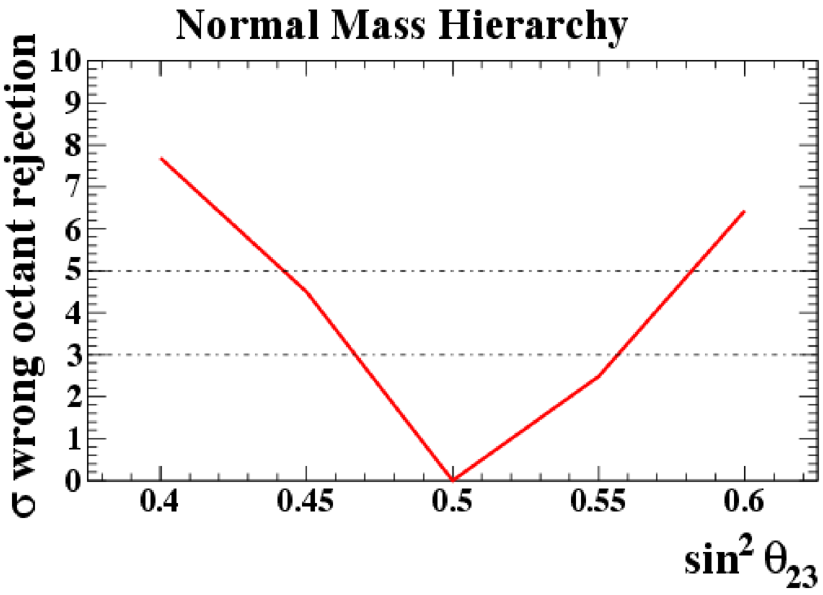
$\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5}$ eV^2

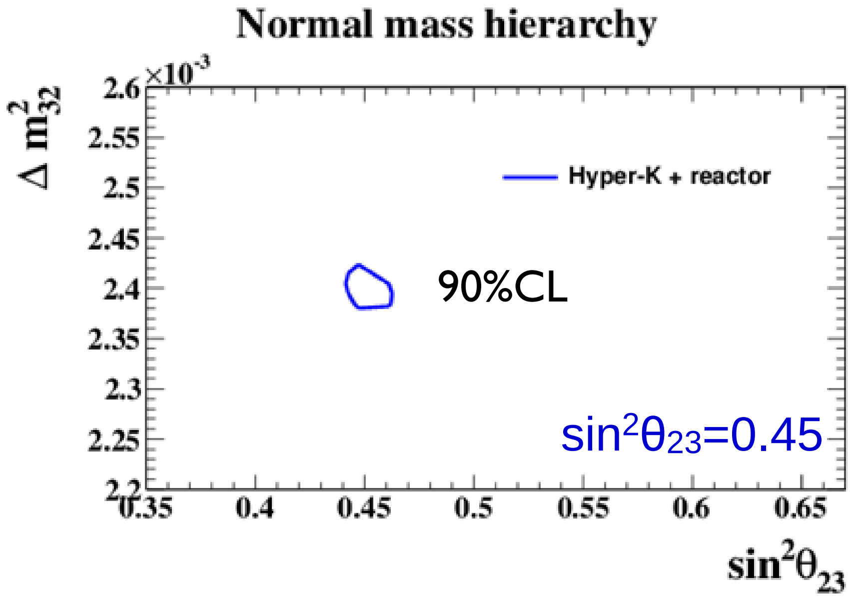
→ mass hierarchy sensitivity
in combination with reactor

$\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23} = 0.5$)
~ 0.006 (for $\sin^2\theta_{23} = 0.45$)

→ octant determination input to models

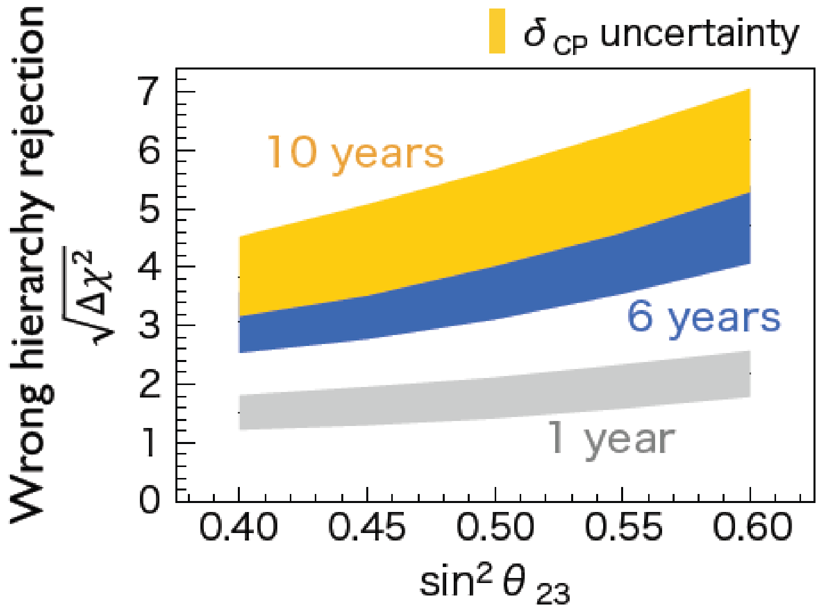






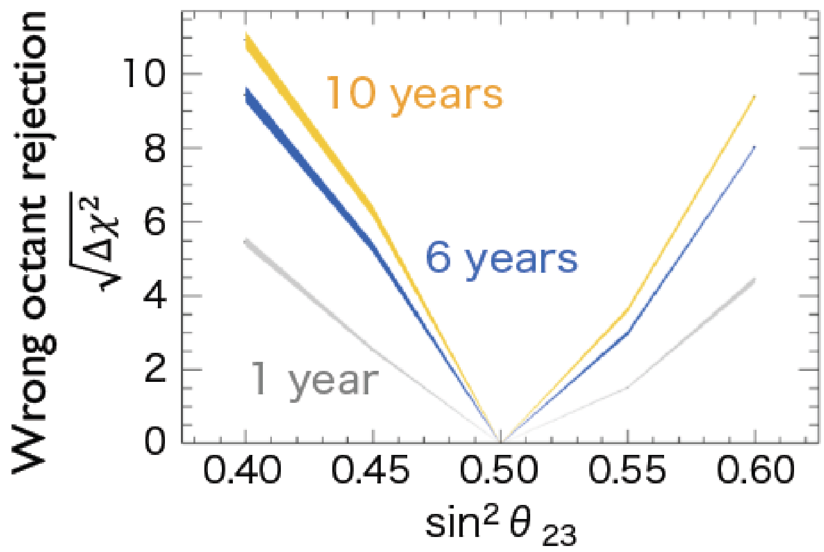
Mass Hierarchy and Octant Sensitivities

Mass Hierarchy



θ_{23} octant

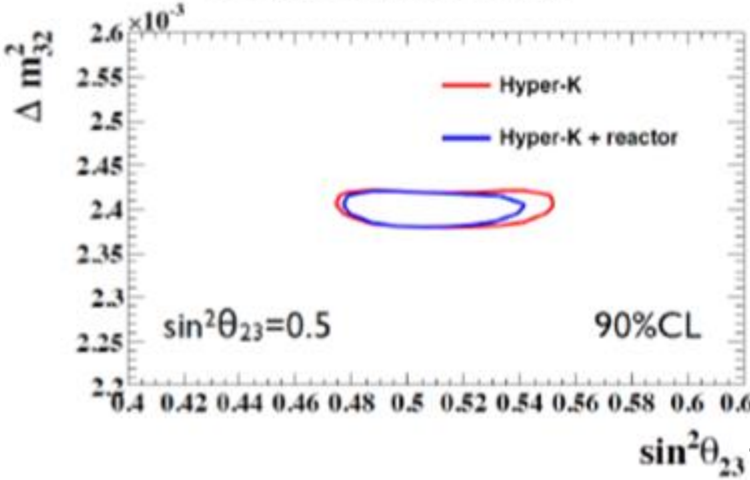
(θ_{23}=45° exclusion)



Mass hierarchy can be determined (≥3-σ)
within several years for
nearly entire parameter space

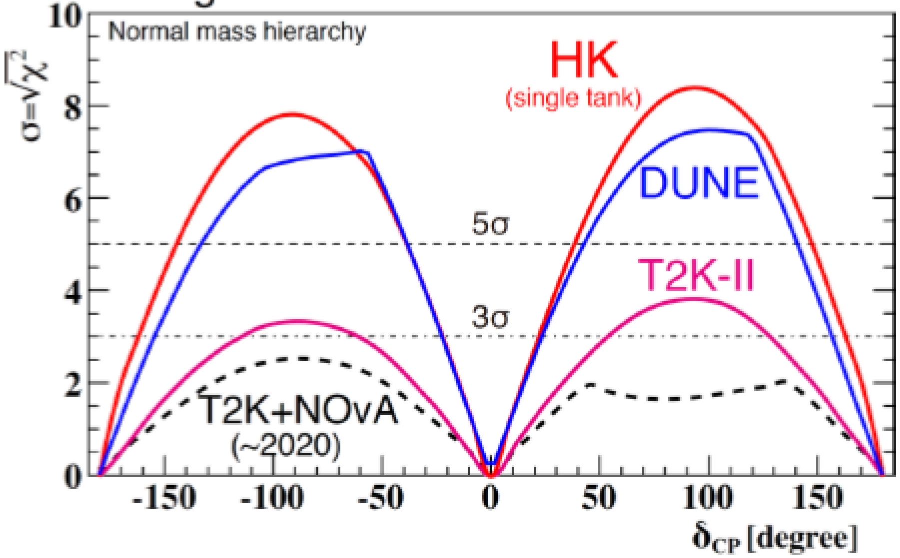
>3-σ octant determination for $|\theta_{23} - \pi/2| > 8^0$

Normal mass hierarchy

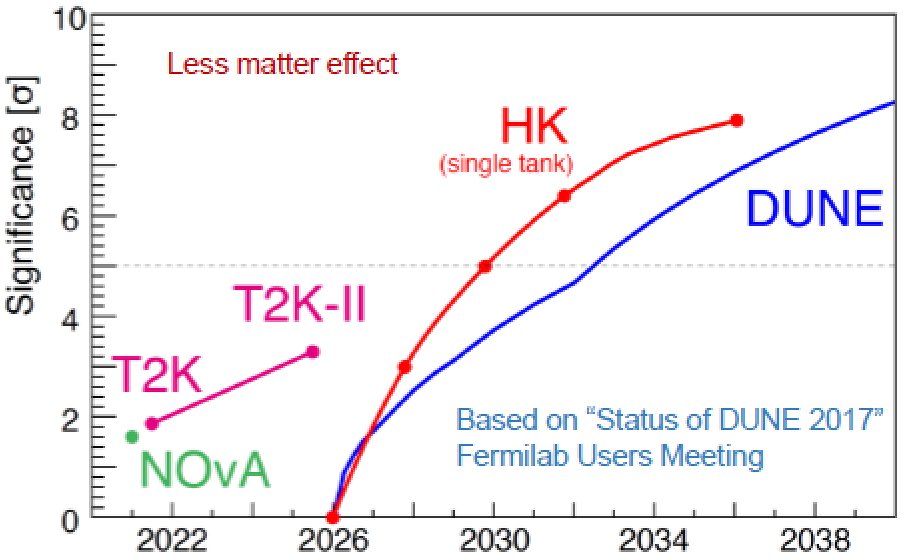


Hyper-K Sensitivity to δ_{CP}

Significance for sinδ_{CP}=0 exclusion



CPV significance for δ_{CP}=-90°, normal hierarchy



Based on "Status of DUNE 2017"
Fermilab Users Meeting

sin δ_{CP} = 0 exclusion:

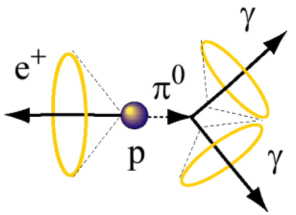
- ~8-σ significance if δ_{CP} = ±90°
- ~6-σ significance if δ_{CP} = ±45°
- ~80% coverage of δ_{CP} parameter space

error	
δ=0°	δ=90°
7.2°	**23°**

sinδ=0 exclusion	
>3σ	>5σ
76%	**57%**

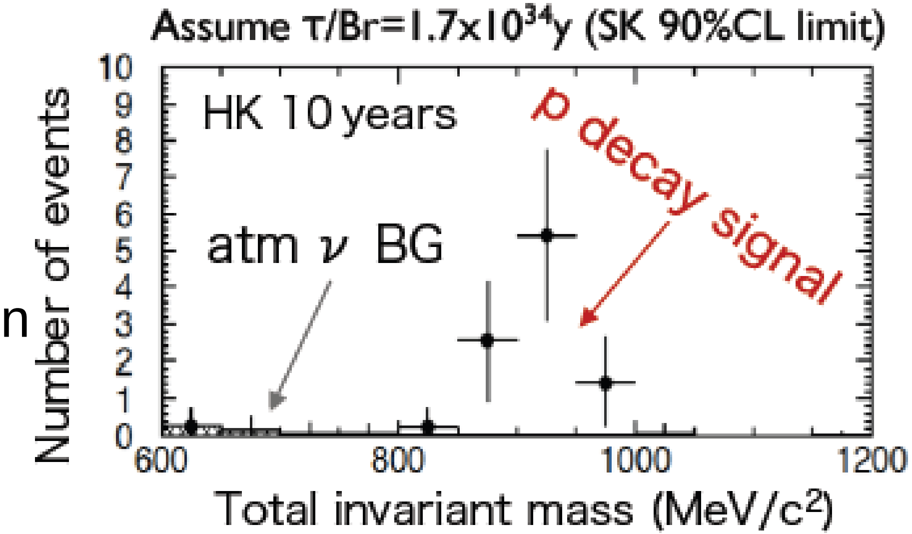
The comparison with DUNE is just for a reference
The real sensitivity depends on the assumption

Proton $p \rightarrow e^+ \pi^0$ Decay Sensitivity



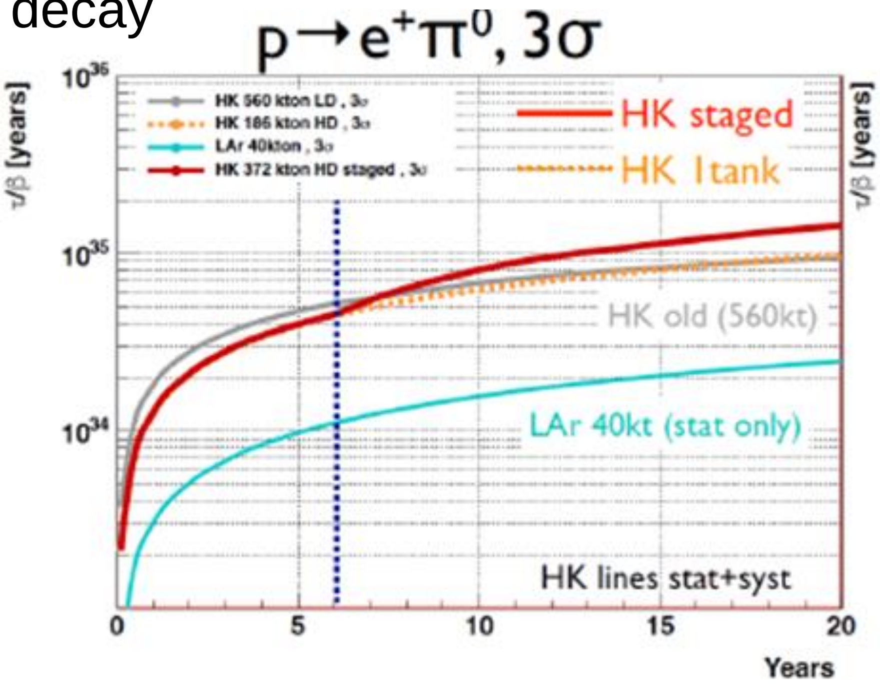
Proton decay $p \rightarrow e^+ \pi^0$ is a favoured model of many GUTs.

Similar analysis as in SK but with neutron Tagging (remove events with a tagged neutron) thanks to improved PMTs.



"Background free" measurement of proton decay

- 0.06 Bkg events / Mt × year
- Bkg atm-ν events are largely reduced by "neutron tag" with H capture
- eff.~70% with new PMT ($n + p \rightarrow d + \gamma$ (2.2MeV γ))



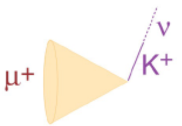
3-σ discovery sensitivity reaches $\tau_p/BR = 10^{35}$ years for $p \rightarrow e^+ \pi^0$

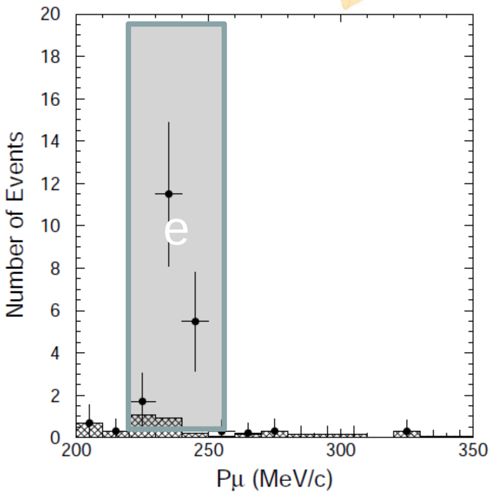
Best discovery potential for GUT signal!

Other Proton Decay Channels

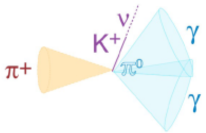
Proton decays into a lepton and a kaon are one of the most prominent features of Supersymmetric GUTs

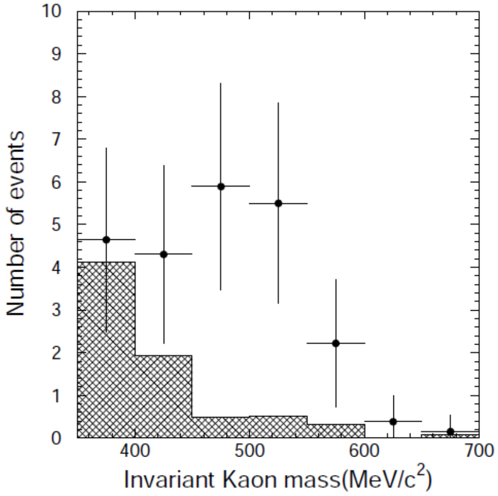
$K^+ \rightarrow \mu^+ \nu_\mu$
(BR 65%)

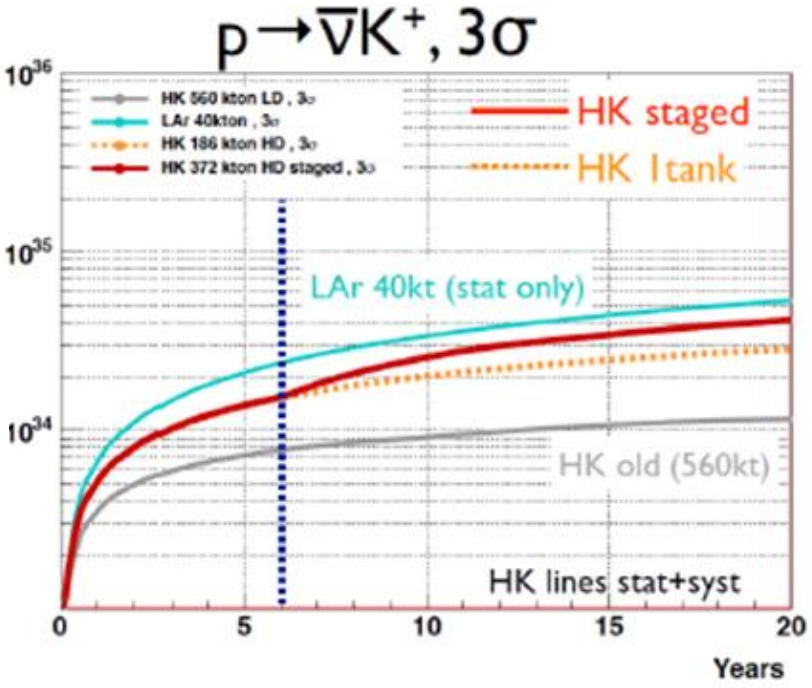




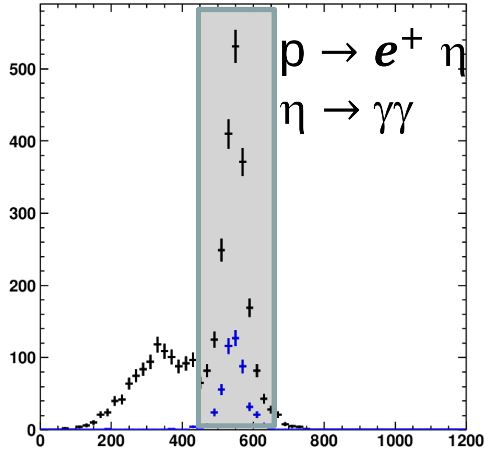
$K^+ \rightarrow \pi^+ \pi^0$
(BR 21%)







$\tau_{\text{proton}}=6.6\times10^{33}$ years (SK 90% CL limit)



Hyper-K will be sensitive to a wide variety of further proton decay modes, and is expected to have sensitivity that exceeds current limits by an order of magnitude or more.

Nucleon Decay Searches

Will be sensitive to a wide variety of nucleon decay modes

Robust estimate based on Super-K performance

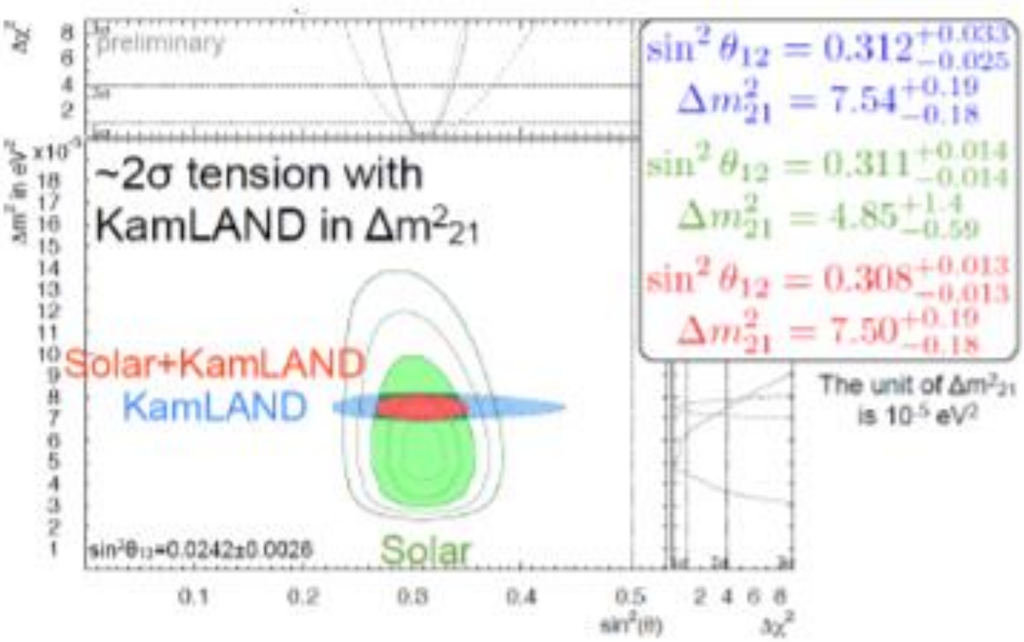
3-σ potential exceeds current limits by an order of magnitude (or more)

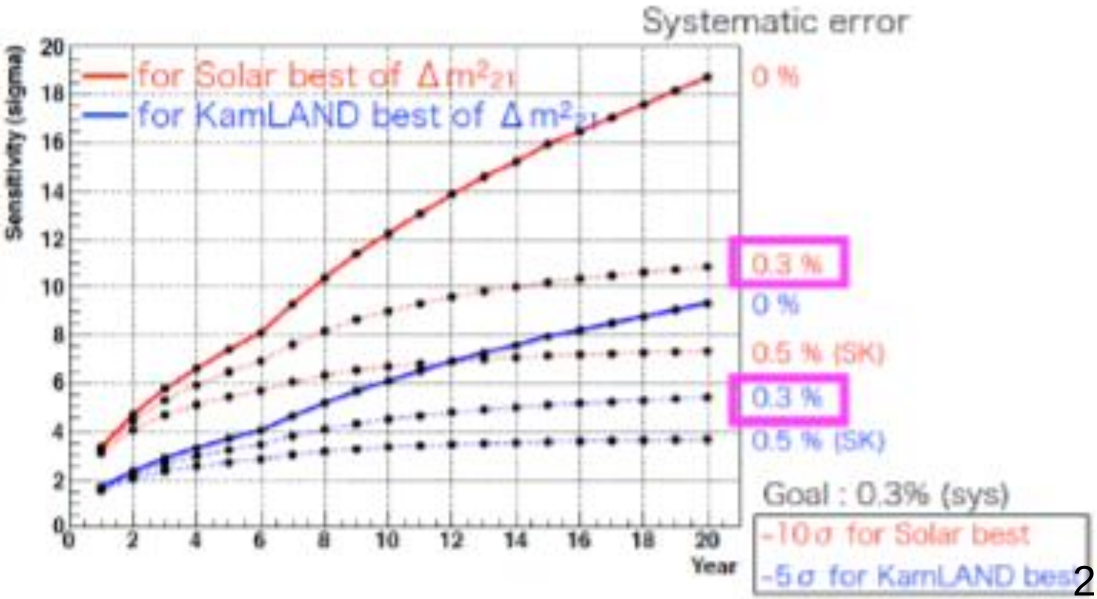
Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	1.2×10^{35}	1.4×10^{34}
$p \to \overline{\nu}K^+$	2.8×10^{34}	0.7×10^{34}
$p \to \mu^+\pi^0$	9.0×10^{34}	1.1×10^{34}
$p \to e^+\eta^0$	5.0×10^{34}	0.42×10^{34}
$p \to \mu^+\eta^0$	3.0×10^{34}	0.13×10^{34}
$p \to e^+\rho^0$	1.0×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.37×10^{34}	0.02×10^{34}
$p \to e^+\omega^0$	0.84×10^{34}	0.03×10^{34}
$p \to \mu^+\omega^0$	0.88×10^{34}	0.08×10^{34}
$n \to e^+\pi^-$	3.8×10^{34}	0.20×10^{34}
$n \to \mu^+\pi^-$	2.9×10^{34}	0.10×10^{34}

Discovery possible !

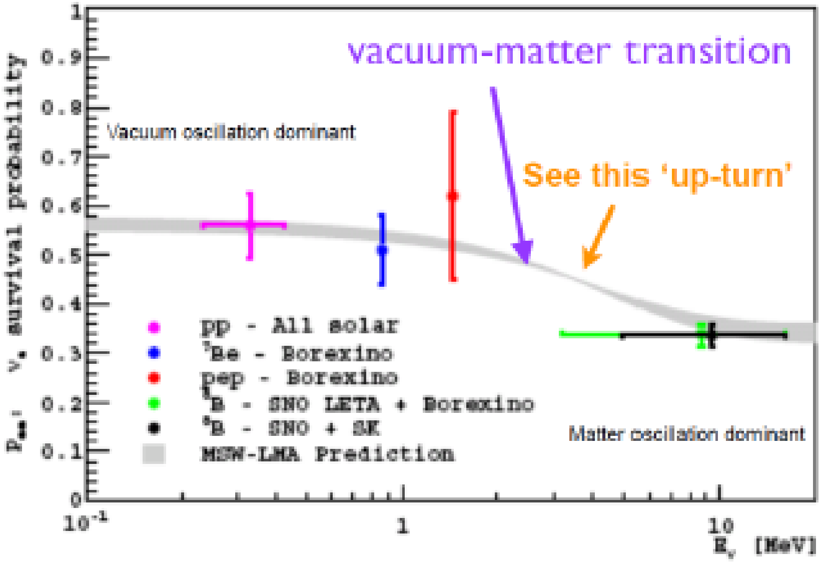
Day / Night Asymmetry of Solar ν

- ~2σ tension of Δm^2_{21} by solar and KamLAND
  - Measurement with ν_e only possible w/ solar ν
- Day-Night asymmetry due to Earth matter effect sensitive to Δm^2_{21}
  - ~4% for solar best
  - ~2% for KL best
- ~5σ resolution expected with 0.3% syst error (0.5% achieved by SK)

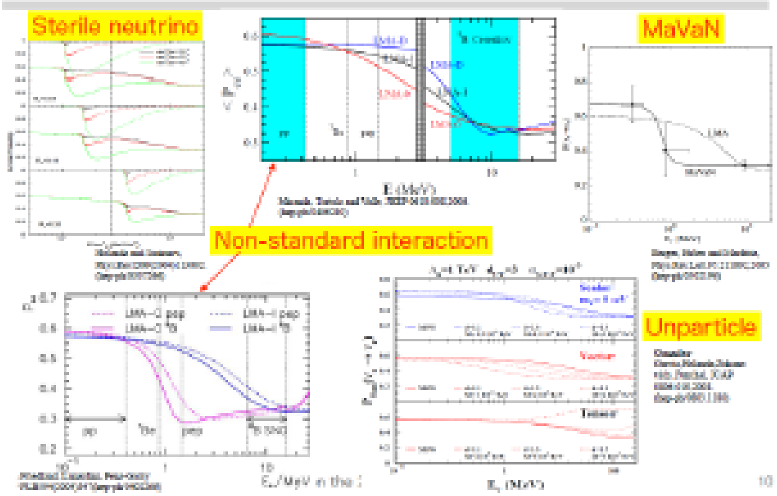




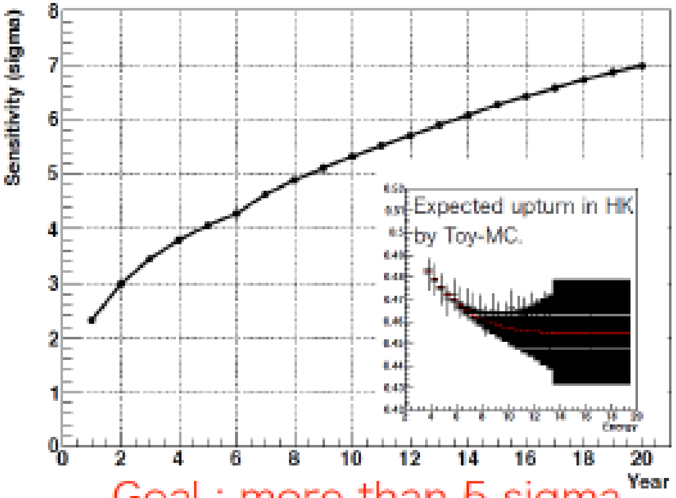
Spectrum Upturn of Solar ν



Various non-standard models



- Spectrum upturn in low energy not yet seen
  - Various non-standard scenario possible
- >5σ possible with BG/ calibration similar to SK
  - Low E threshold w/ high photon efficiency essential



Goal : more than 5 sigma

Also solar physics: short time variation, hep neutrinos, …

Solar Burst Neutrinos

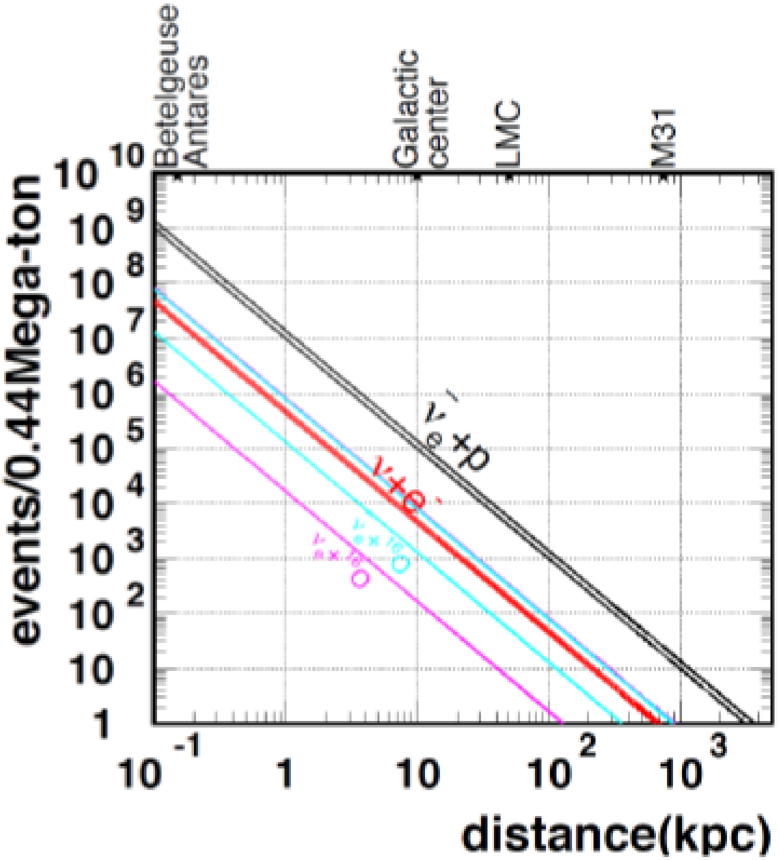
- Measurements of neutrino flavor, energy, time profile will provide detailed information of core-collapse supernova

Expected number of event

98k~136k ev (IBD)
4.2k~5k ev (ve ES)
(12~80 for neutronization)
160~8200 ev (ν_e CC)
1300~7800 ev ($\overline{\nu_e}$ CC)

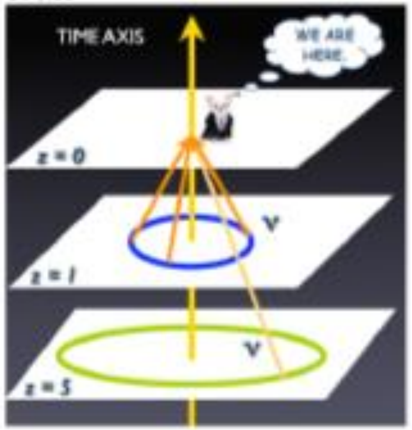
at 10kpc

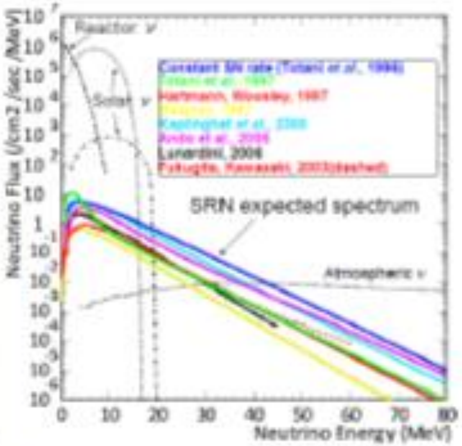
Livermore simulation



Supernova Relic Neutrinos

S.Ando





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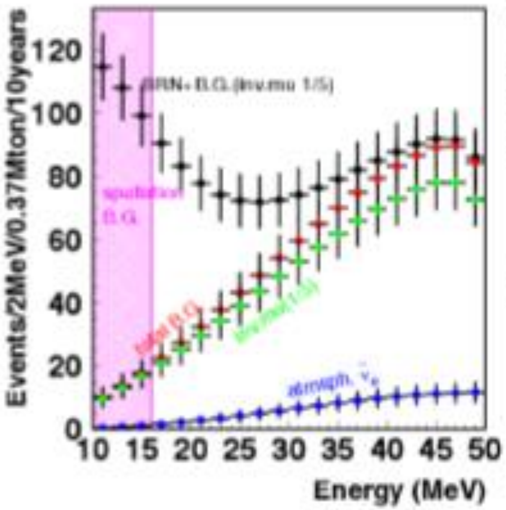
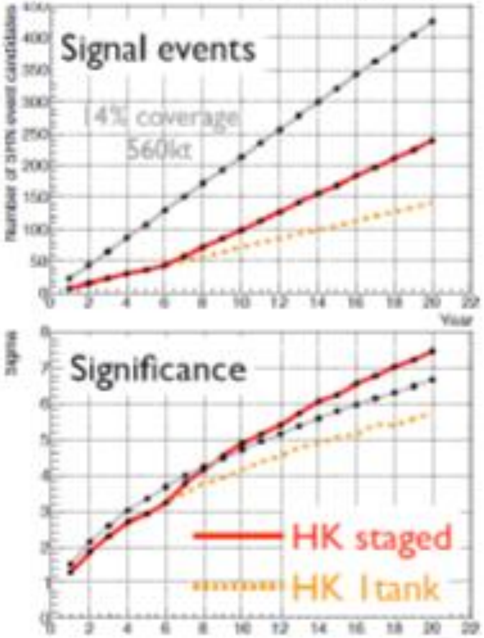


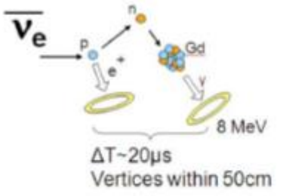


- Neutrinos from past SN fill our universe
  - History of star formation and black hole generation process encoded
- BG suppression with more light → Measurement with >5σ signal

Investigate dim-SN's and BH formation

- Use neutron tagging.
- Expected events in HK in 10y: ~98 ± 20 (4.8σ).

Install Gadolinium

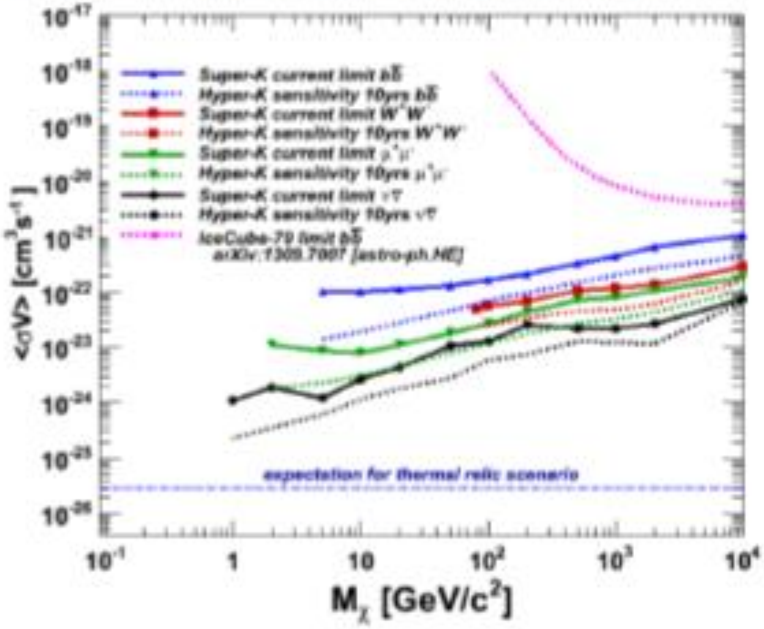


ΔT~20μs
Vertices within 50cm

Indirect Dark Matter Searches

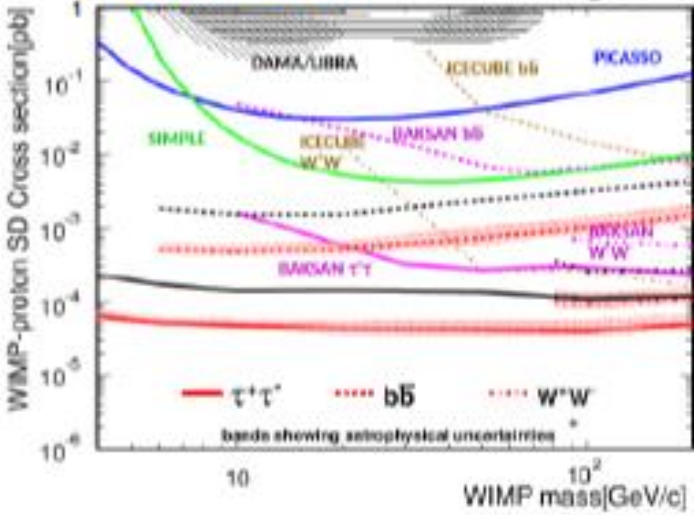
- Unique sensitivities, especially for low mass region
- Improve ×3-10 over SK limit

From Galactic center

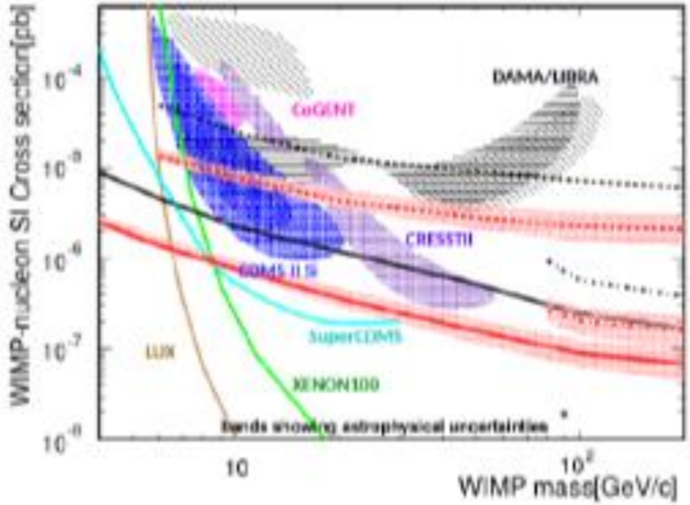


From Sun

SD



SI

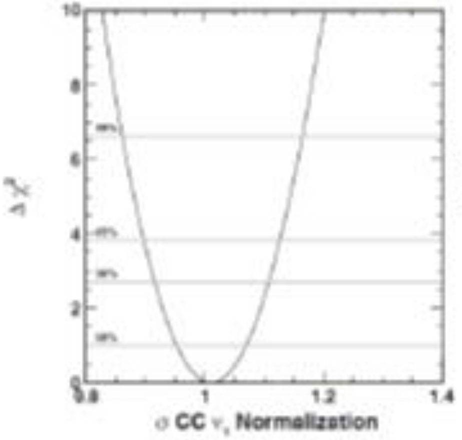


Other Physics with Atmospheric ν

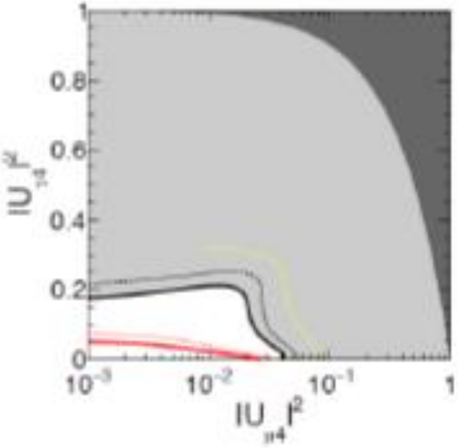
Provides neutrinos with various energy, flight length, and flavor

- ν_τ cross section measurement
- Sterile neutrino
- Lorentz violation
- Geophysics
  - Information on the chemical composition of Earth's outer core using matter effect

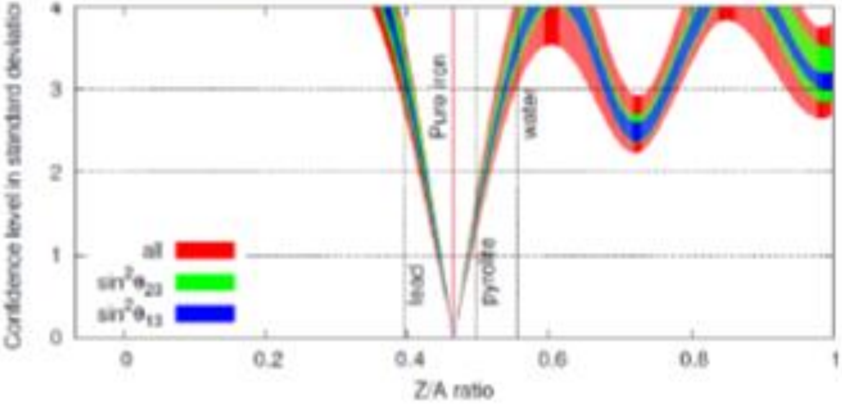
ν_τ cross section



Sterile limit



Sensitivity to outer core chemical composition (10Mtyr)



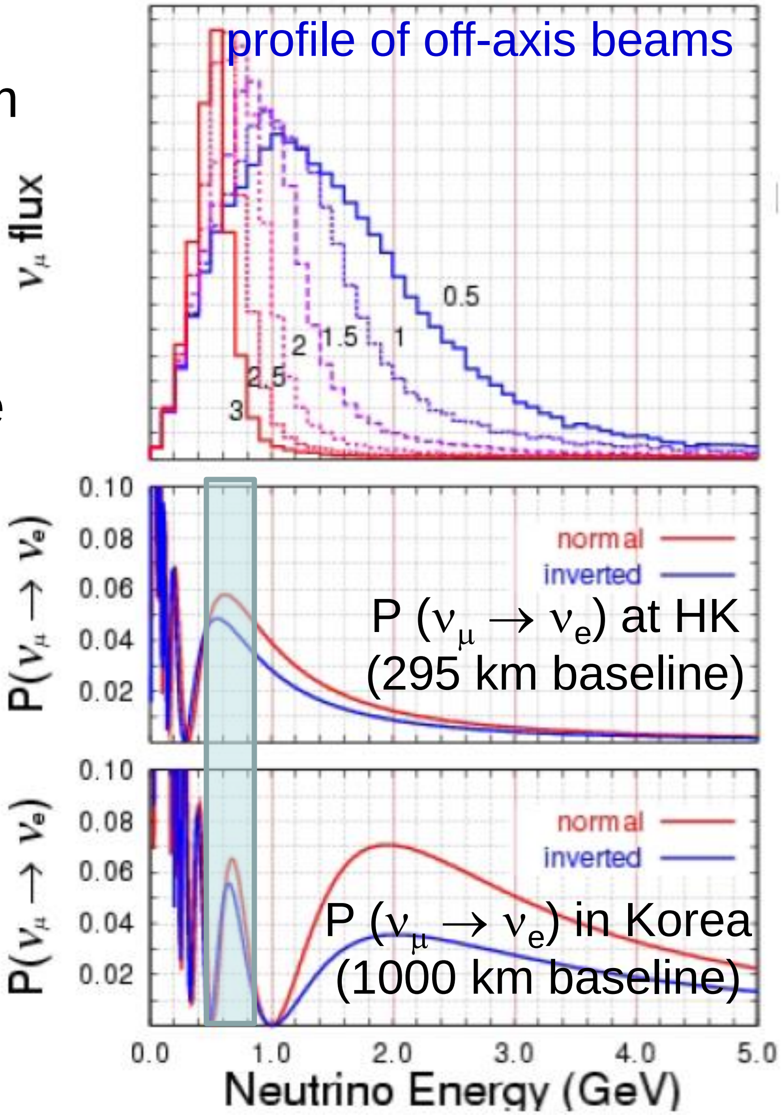
New Idea: 2nd Tank in Korea

Advantages of a second tank in Korea

Measure CP effect at 2nd oscillation maximum (3 × larger)

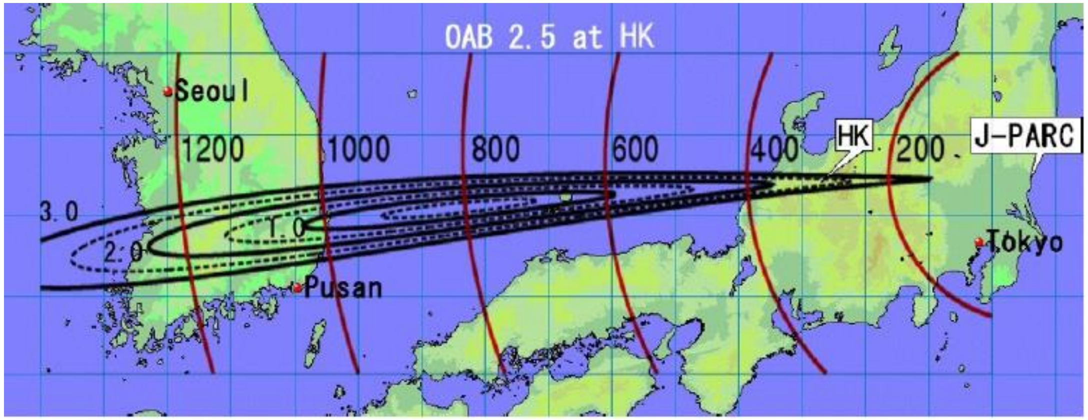
Enhanced mass hierarchy sensitivity (longer baseline)

Reduced backgrounds due to the deeper site

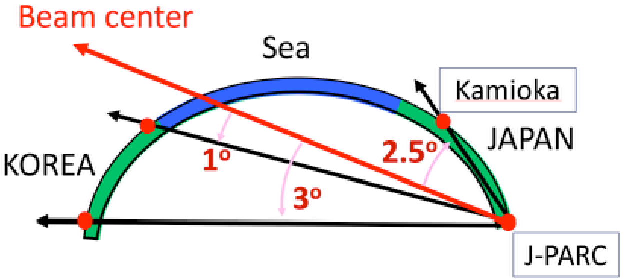

profile of off-axis beams

P ($\nu_\mu \to \nu_e$) at HK (295 km baseline)

P ($\nu_\mu \to \nu_e$) in Korea (1000 km baseline)



2.50 Off-axis ~1100 km baseline



Conclusions

Proto-Collaboration established on January 15th 2015
Collaboration growing ~300 members from 15 countries

A rich physics program:
- atmospheric, SN, solar, accelerator neutrinos
- proton decay

Optimized detector configuration:
- built on successful technology established with past/ongoing experiments
- higher photo-coverage
- improved PMTs (higher QE)

International R&D efforts underway
- photo-sensors
- electronics and DAQ
- calibrations
- geological surveys

Hyper-K is listed in the MEXT (funding agency) Large Projects Roadmap
Construction to begin in 2018, start physics in 2016

Hyper-K Physics Potential

		HK (2TankHD w/ staging)
LBL (13.5MWyr)	δ precision	7°-21°
	CPV coverage (3/5σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	>5.3σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}
	νK 90%CL	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	6σ/12σ
	Upturn	4.9σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8σ