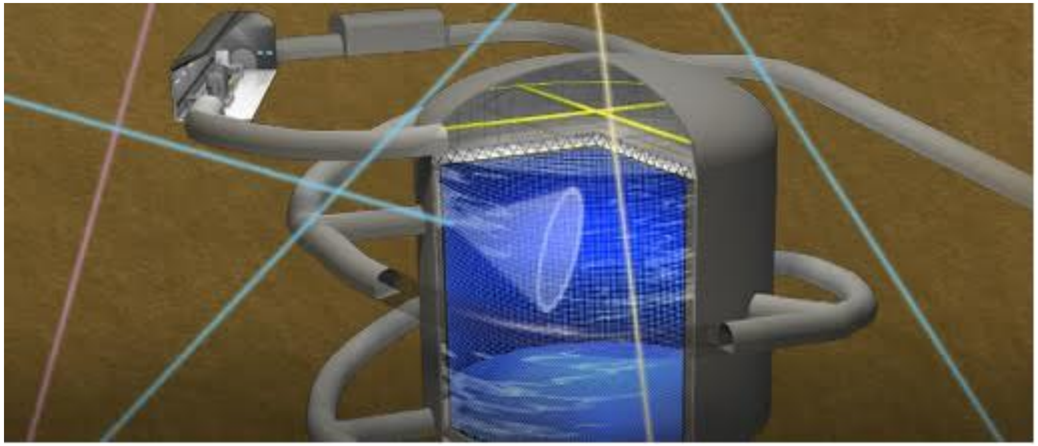
Hyper-Kamiokande

http://hyperk.org

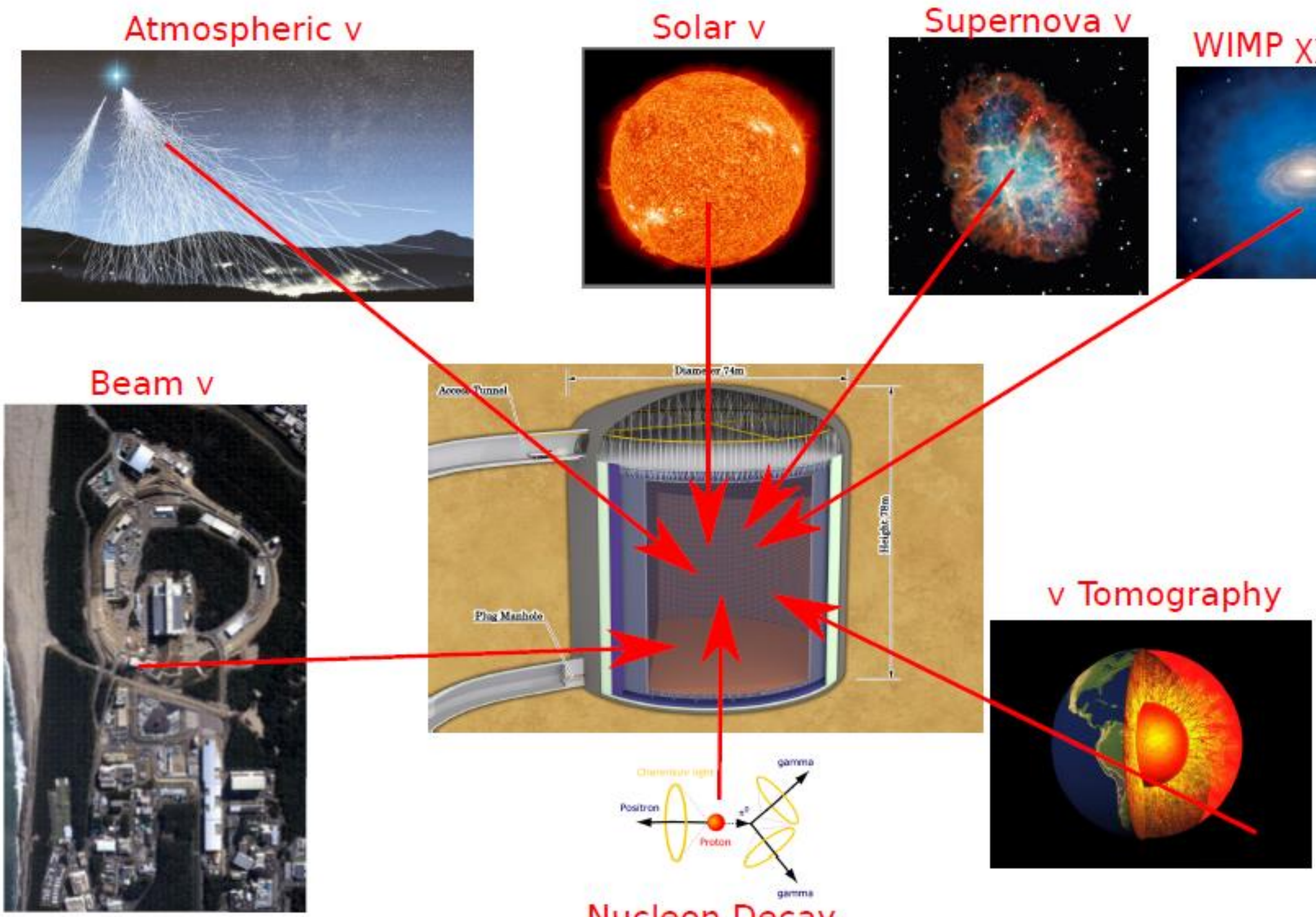


The Hyper-Kamiokande Project
A New Adventure in ν Physics

Alessandro Bravar
on behalf of the HK Proto-Collaboration

ICNFP2017
Kolymbari, Crete
August 26, 2017

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 upturn
- 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

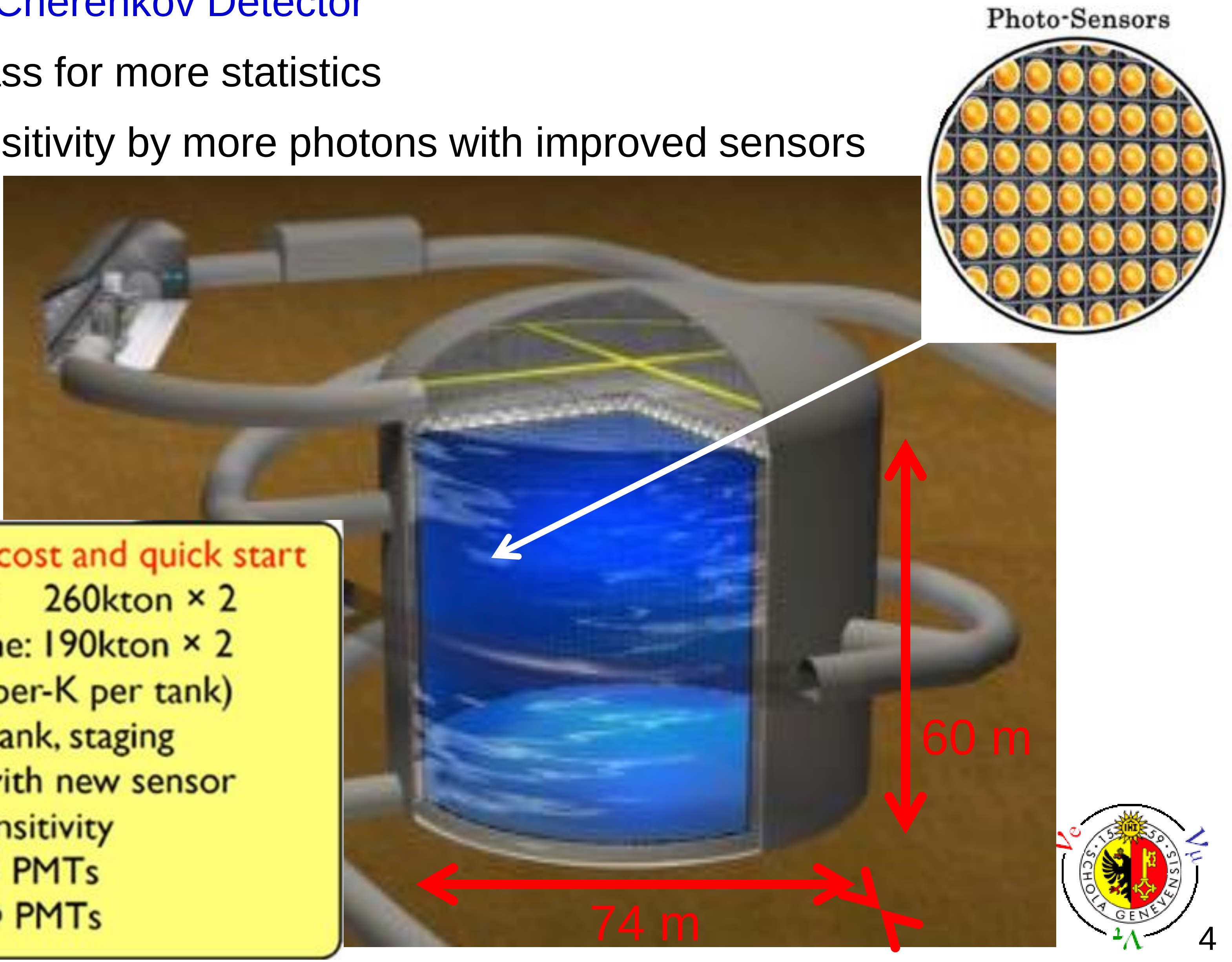
Geophysics (“neutrinography” of Earth’s interior)

+ unexpected
(unknown)

The Hyper-Kamiokande Detector

Large Water Cherenkov Detector

- Larger mass for more statistics
- Better sensitivity by more photons with improved sensors

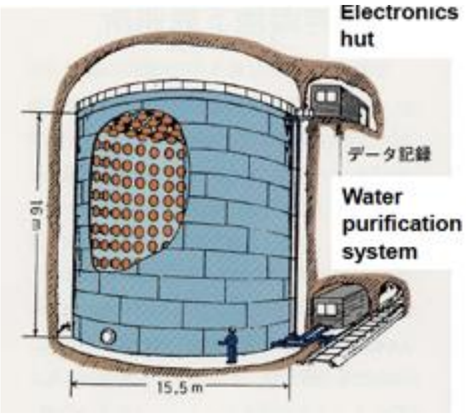


Optimized for cost and quick start

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

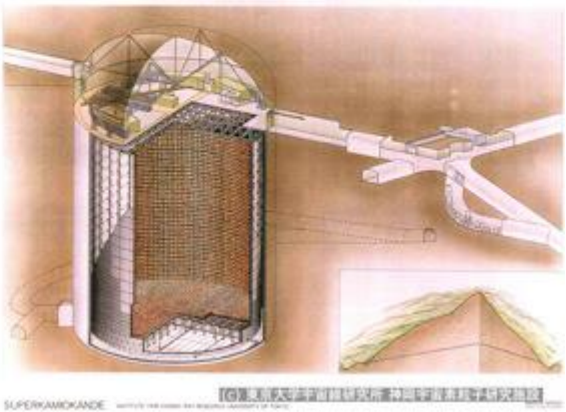
Kamiokande
(1983-1996)



3 kton
20% coverage
with 50 cm PMT

Observation of SN1987A

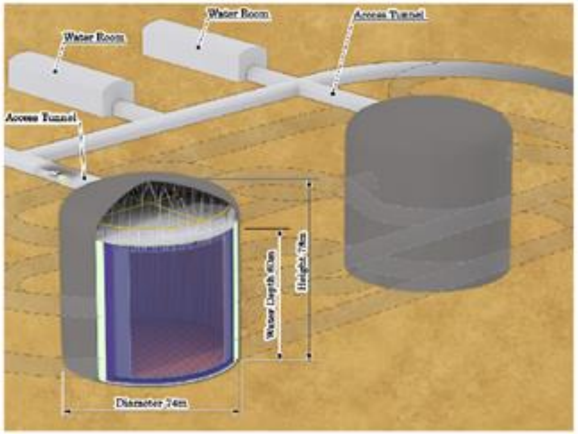
Super-Kamiokande
(1996-)



50 kton
40% coverage
with 50 cm PMT

Discovery of
ν oscillations

Hyper-Kamiokande
(~2026-)

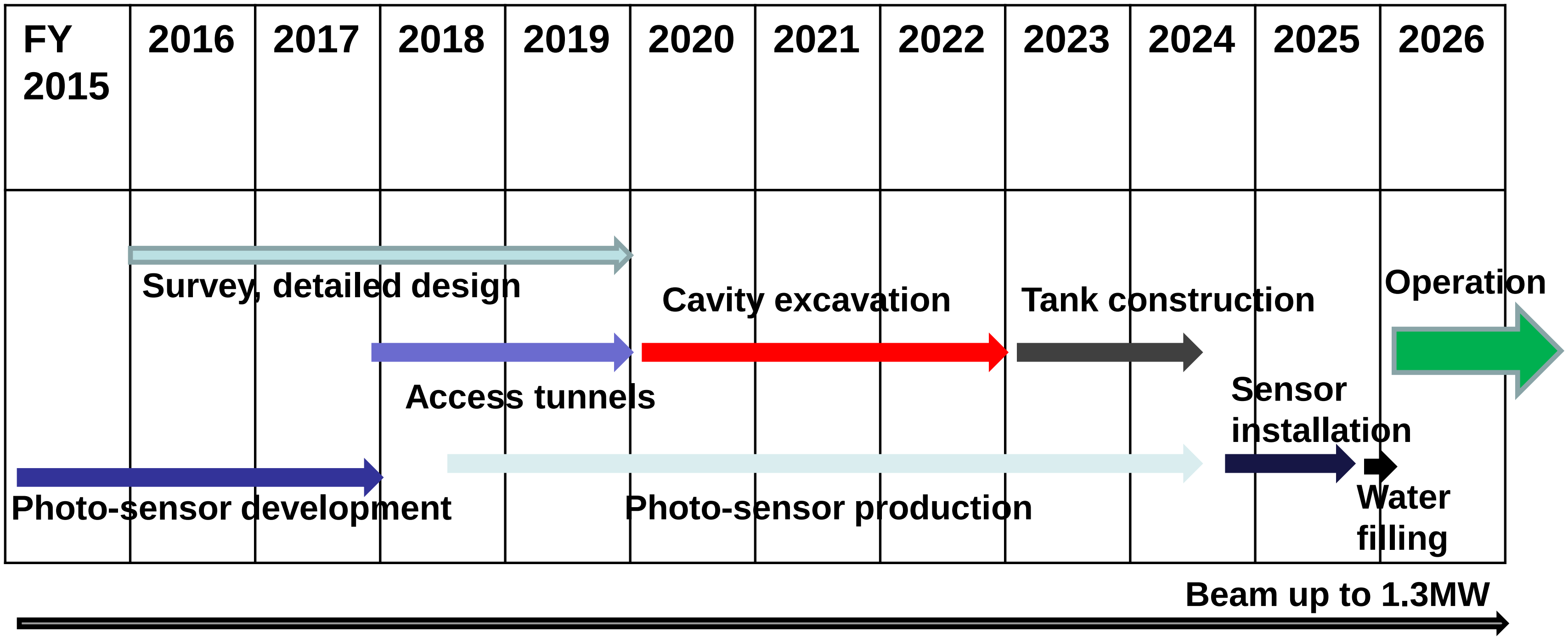


260 kton × 2
40% coverage with
high-QE 50 cm PMT

?

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 – 2025 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

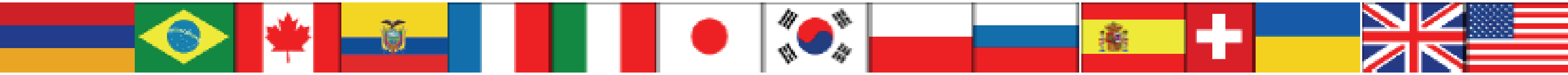
January 2015

Formed in Jan. 2015

15 countries

~300 members
(and gowing)

July 2016

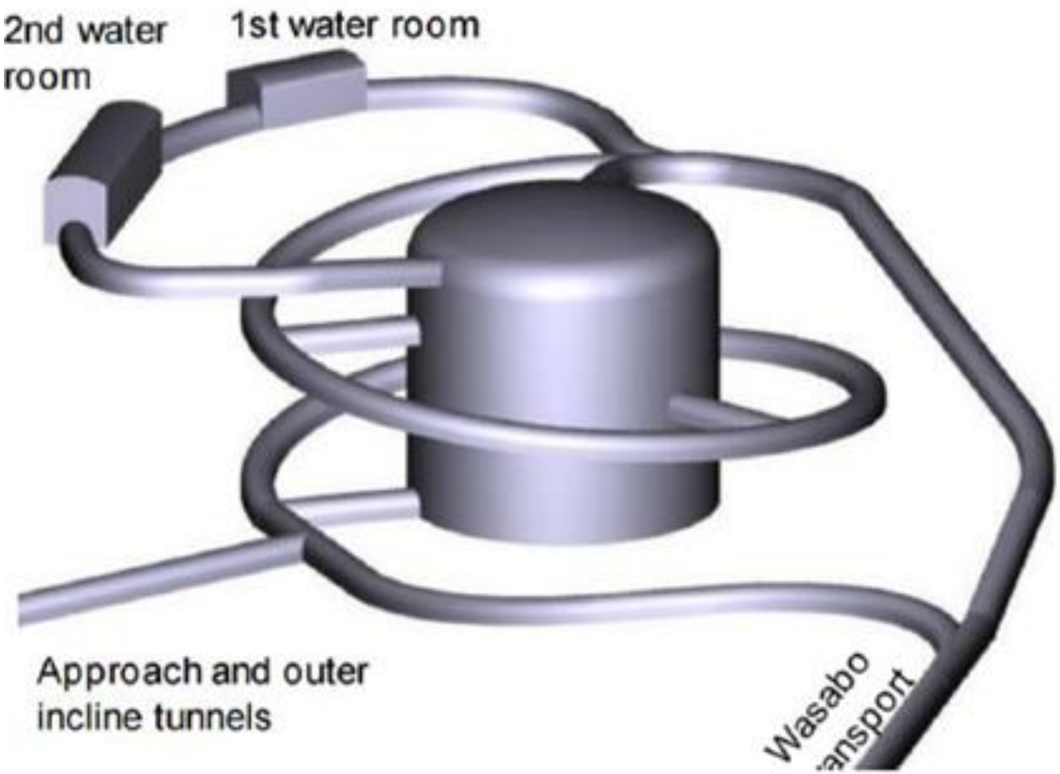


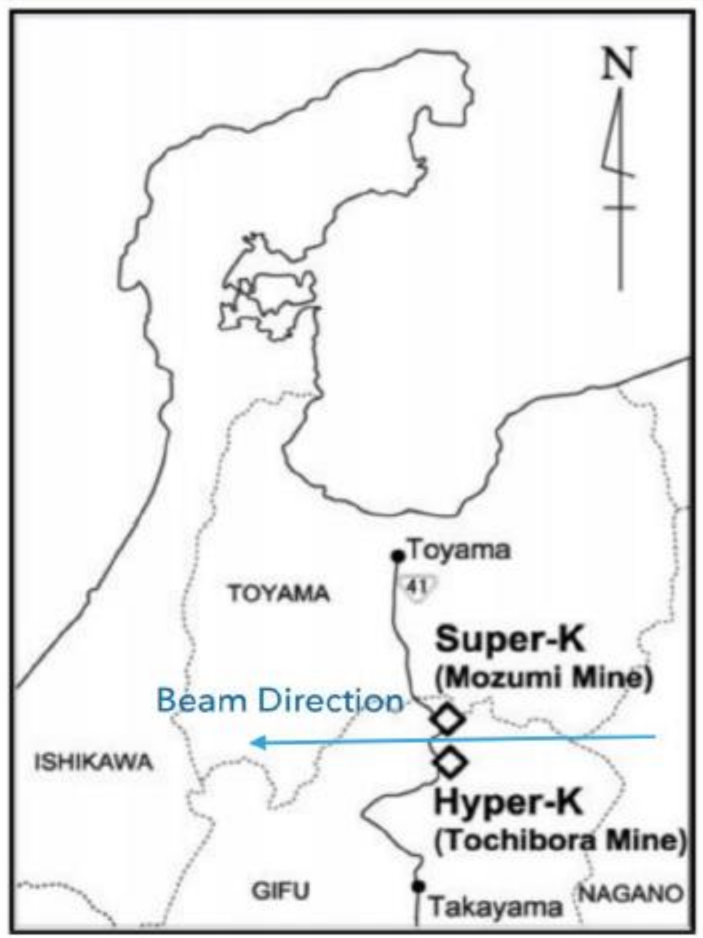
The Kamioka Site

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



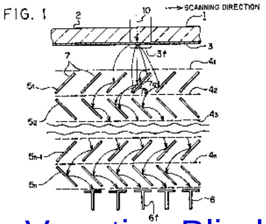


Upgraded Photo-Sensors

Super-K PMT

used in SK for 20 yrs

high QE photocathode

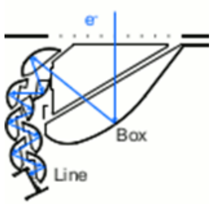


Venetian Blind

HQE SK PMT

under validation

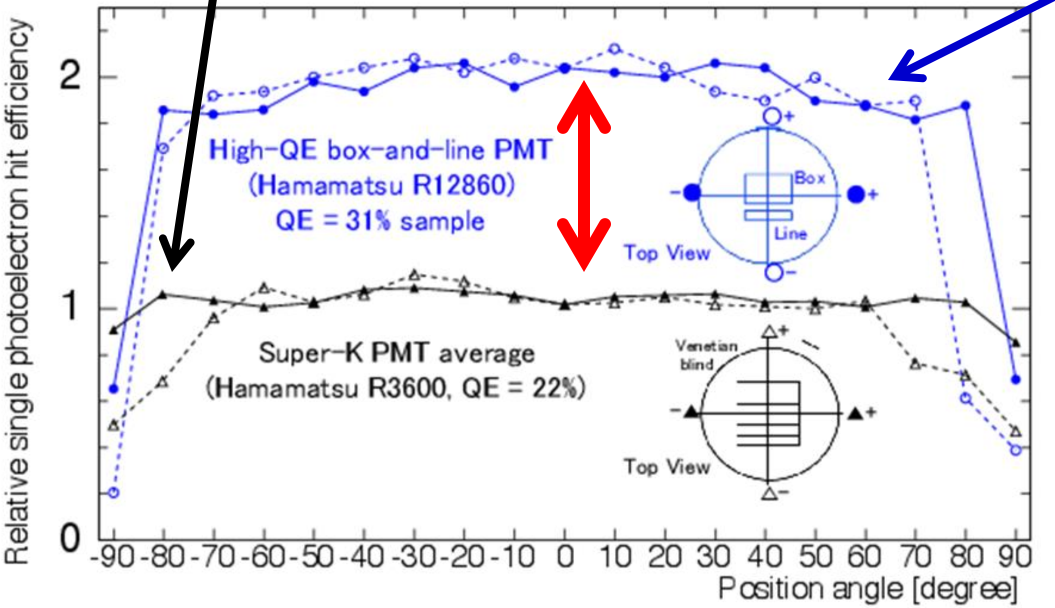
dynode improvement



Box-and-Line Dynode

50 cm HQE Box&Line PMT

under validation



Enhanced performance

Photo Detection Efficiency 2 × bigger

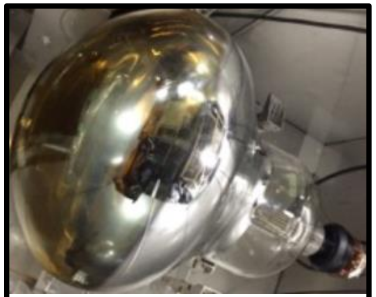
Timing resolution 2 × as good

Increased Pressure tolerance × 2

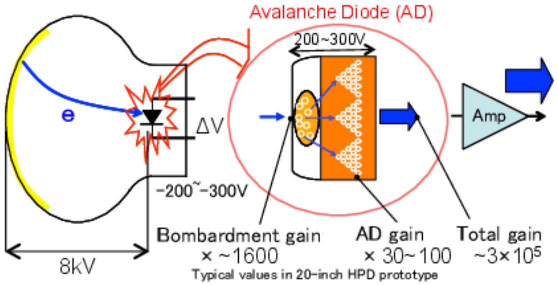
- enhance $p \to \bar{\nu} K^+$ signal
- solar ν lower threshold
- neutron capture signature
  $(n + p \to d + \gamma\ \ \text{- 2.2MeV}\ \gamma)$

Photo-Sensor Developments

Hybrid Photo Detectors (HPDs)

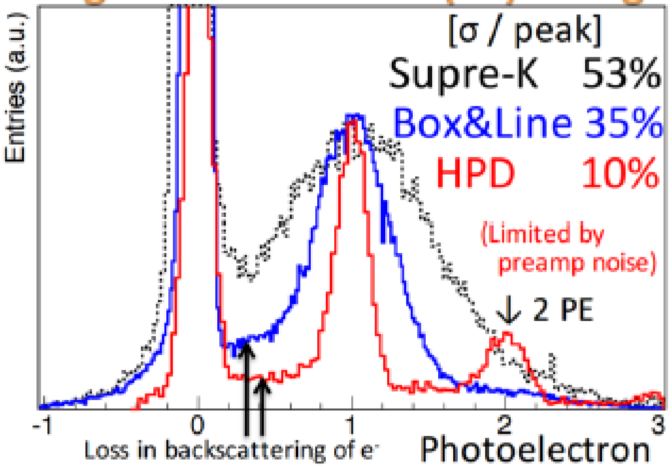


50 cm HQE HPD
w/ 20mm ϕ AD

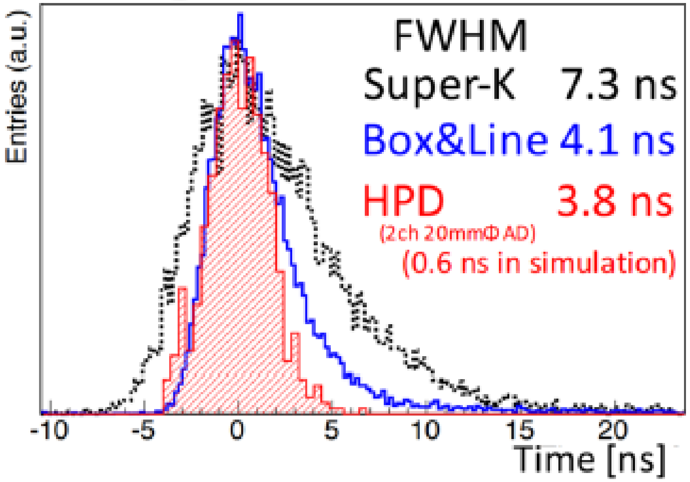


R&D
development and validation

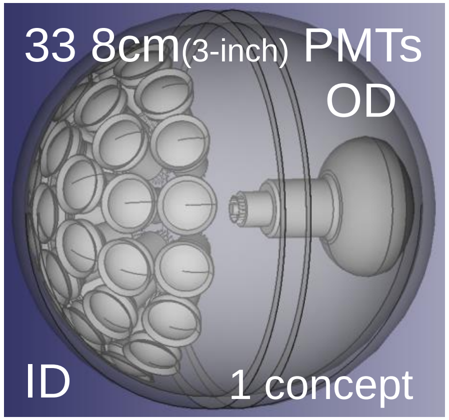
Single Photoelectron (PE) Charge



Single Photoelectron Time



Multi-PMT



directional sensitivity

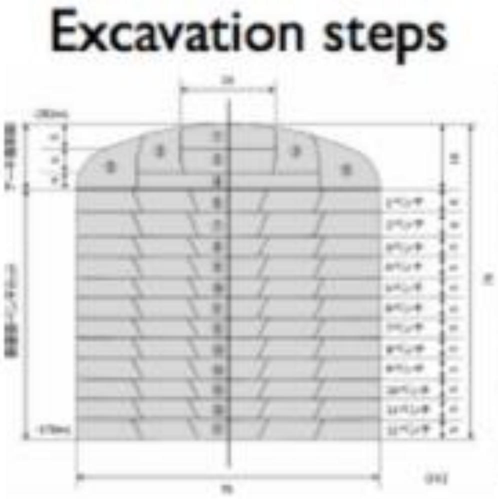
usage for ID/OD

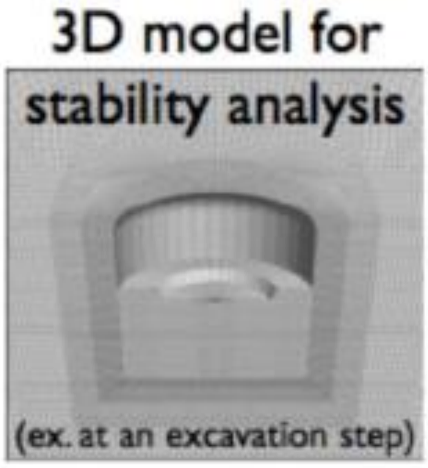
higher pressure tolerance

no compensation for geomagnetism needed

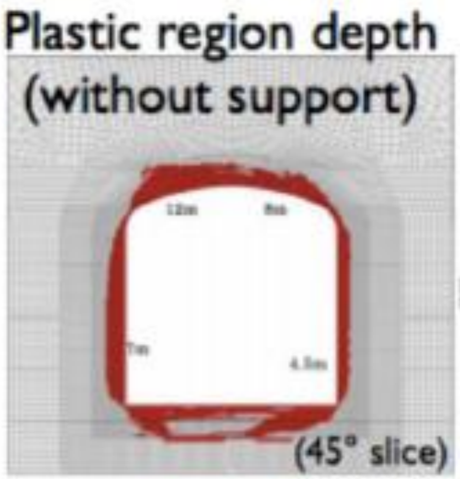
Cavern and Tank

Cavern geological survey and find analysis undertaken

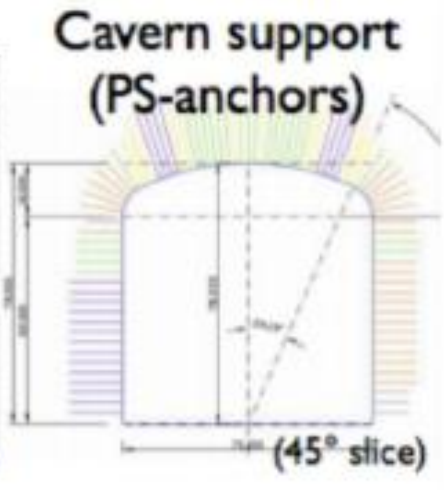

Excavation steps


3D model for stability analysis

(ex. at an excavation step)


Plastic region depth (without support)

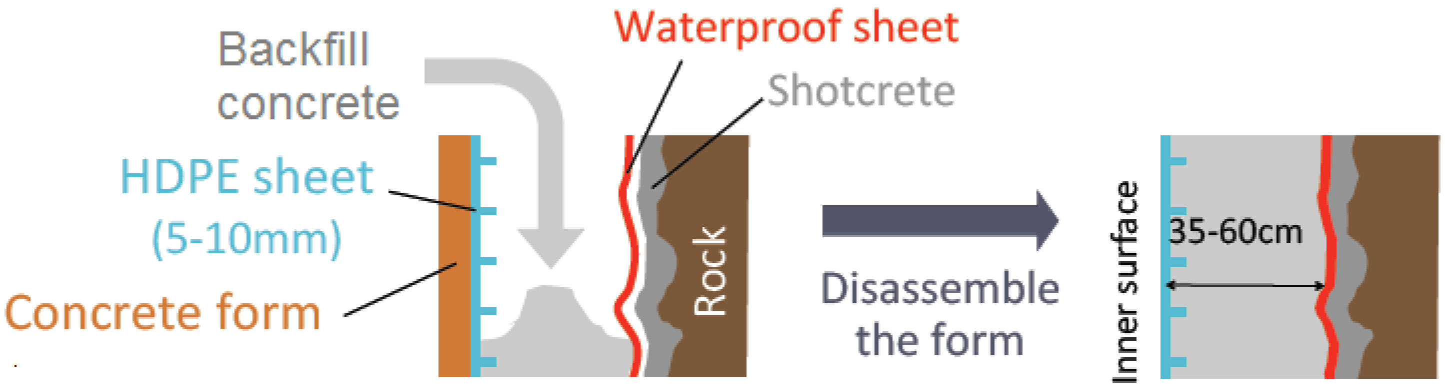
(45° slice)


Cavern support (PS-anchors)

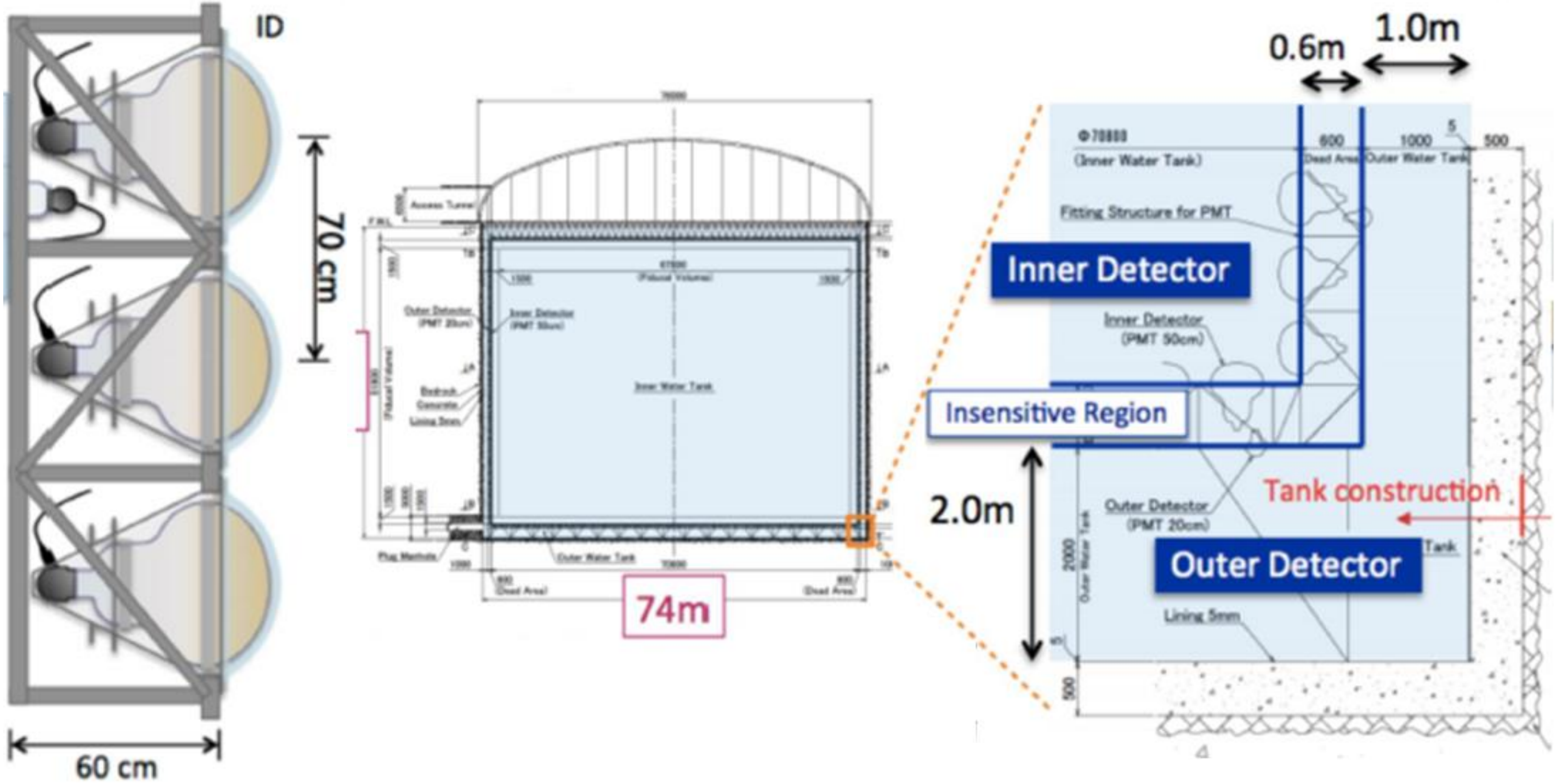
(45° slice)

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: earthquakes do not damage the detector (PMTs) even if no water in the tank

Electronics

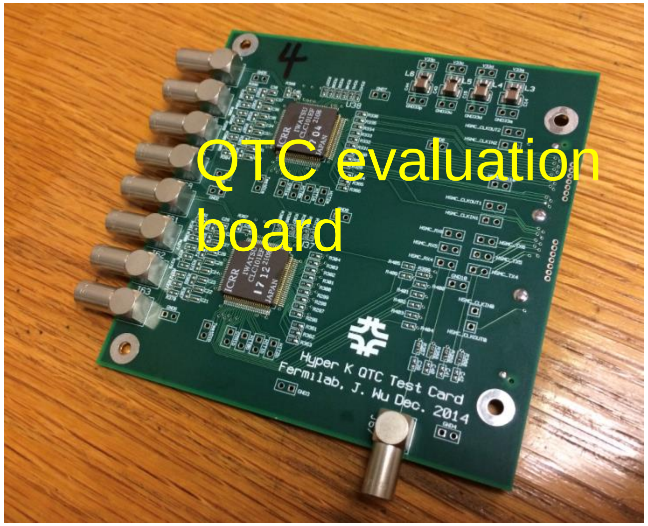
Candidates for signal digitization:

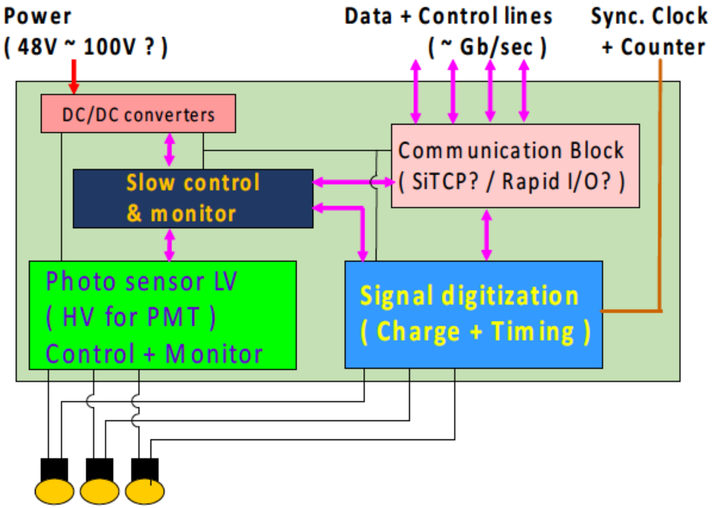
1. Charge to Time converter with FPGA-based TDC (similar to SK)
2. ~100MHz FADC + digital signal processing
3. GHz digitizers based on capacitor arrays

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

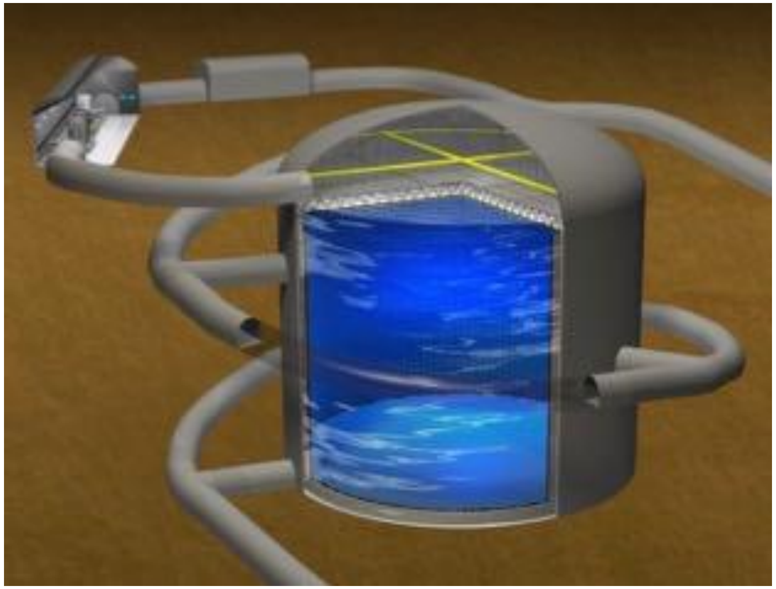
Front-end electronics, HV, and network connections under water


QTC evaluation board



From J-PARC to Kamioka

260 kton Water Cherenkov Detector



+

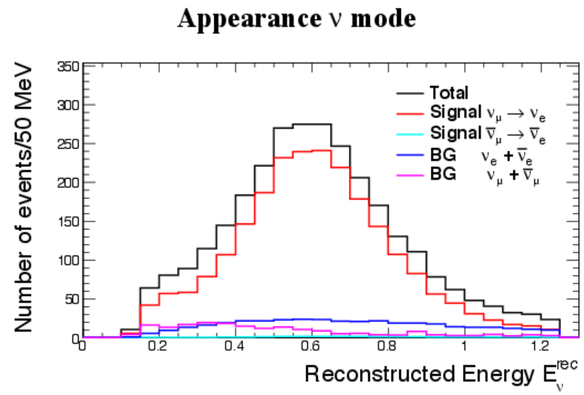
Upgraded J-PARC neutrino beam
New / upgraded near detectors

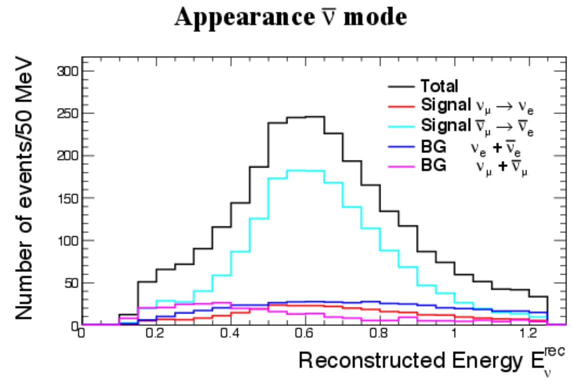
Nominal design:
1st tank in Tochibora with the second tank following after 6 years

Beam Events in Hyper-K

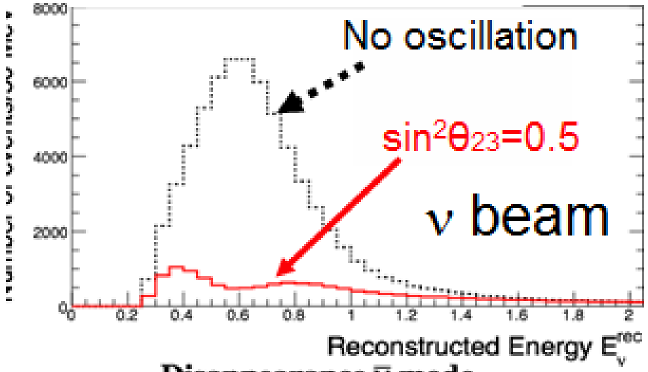
10 years data taking

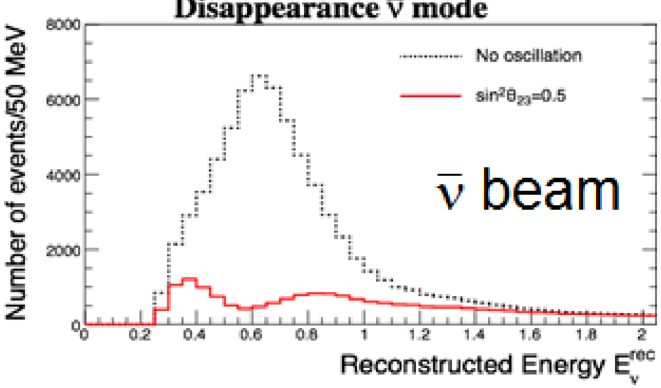
ν_e appearance



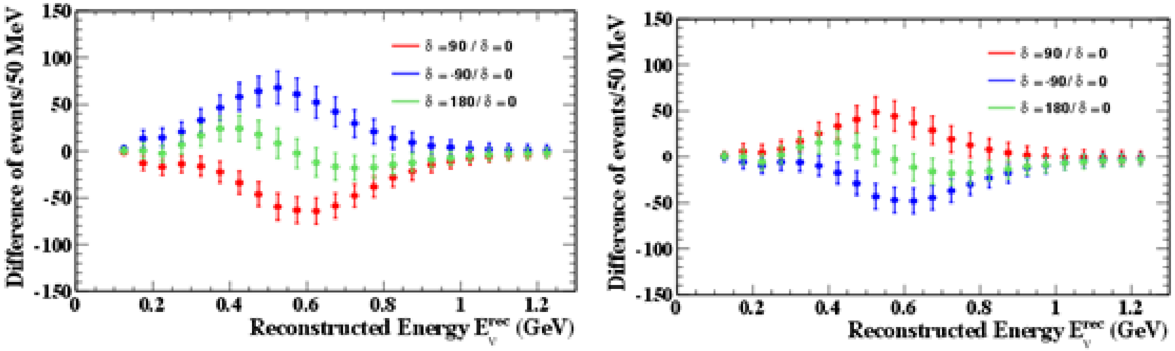


ν_μ disappearance





difference from $\delta_{CP} = 0$

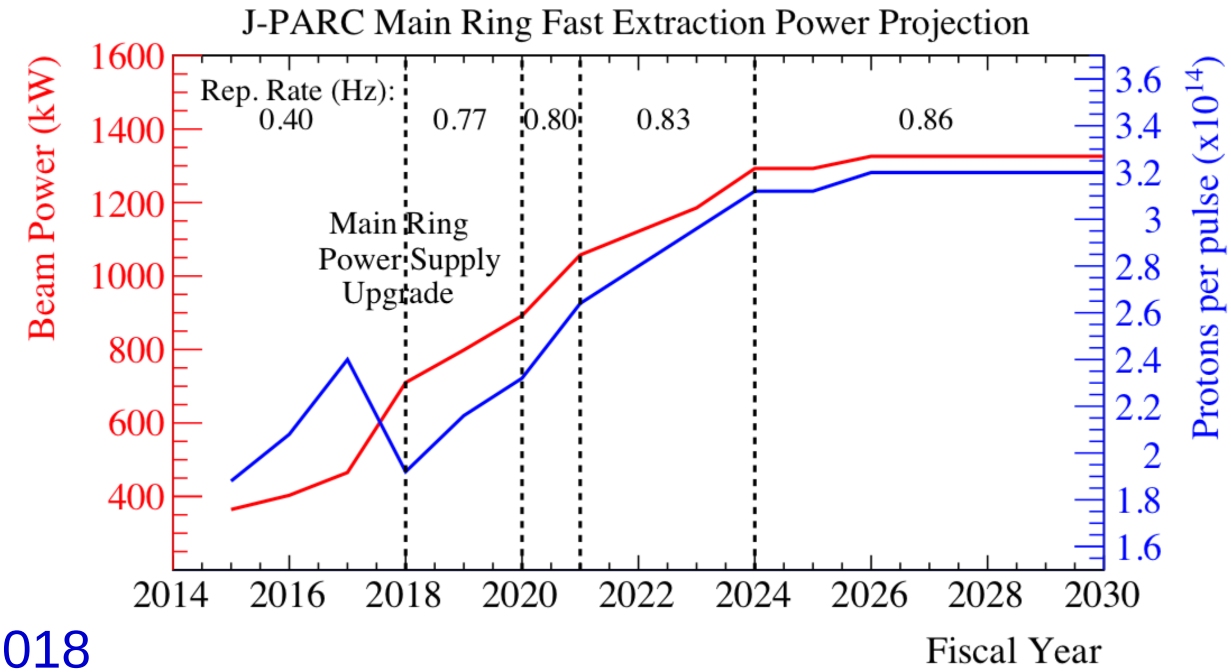


δ=0	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu, \bar{\nu}_\mu$ CC	Beam $\nu_e, \bar{\nu}_e$ contamination	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274

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

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

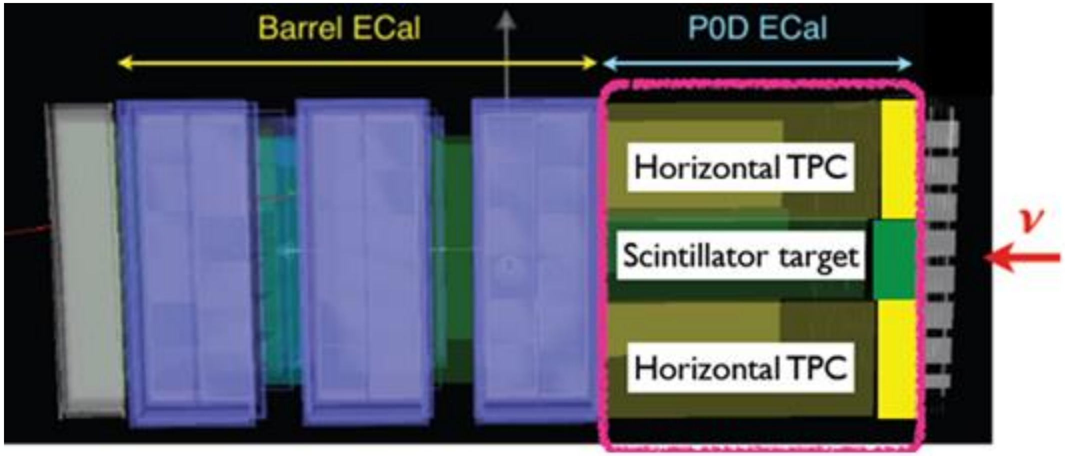
repetition cycle from 2.48 s to 1.3 s

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

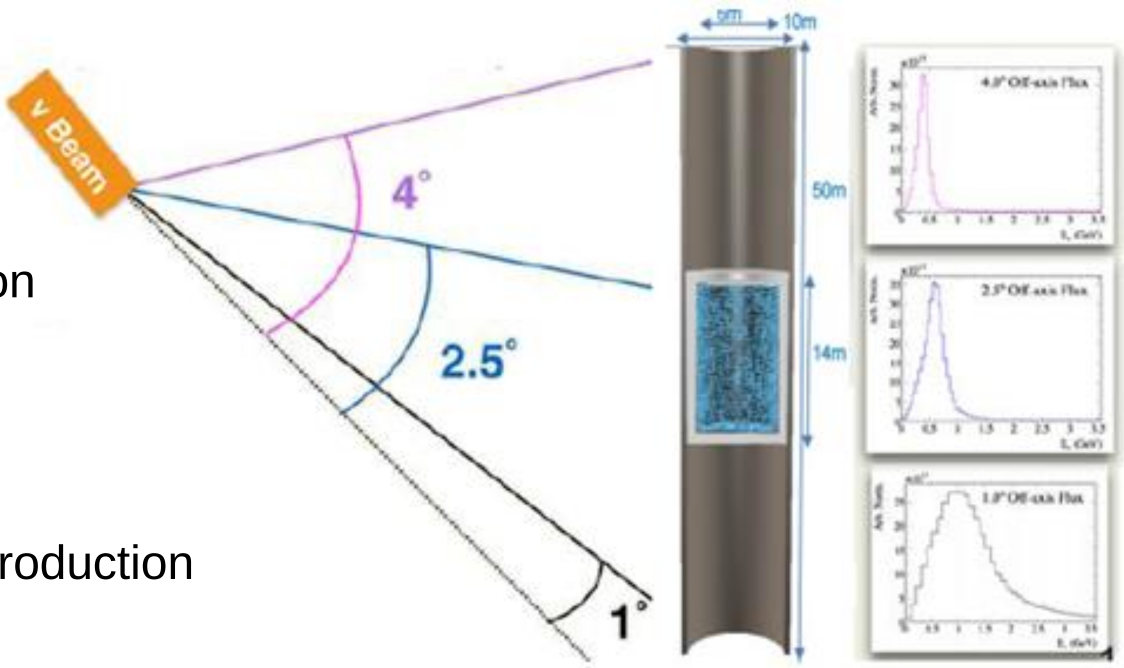
Enlarge phase space (4π coverage)

Efficiency for short hadron tracks with proton reconstruction

Improve electron neutrino selection

New: horizontal TPCs
scintillator target

Intermediate Water Cherenkov



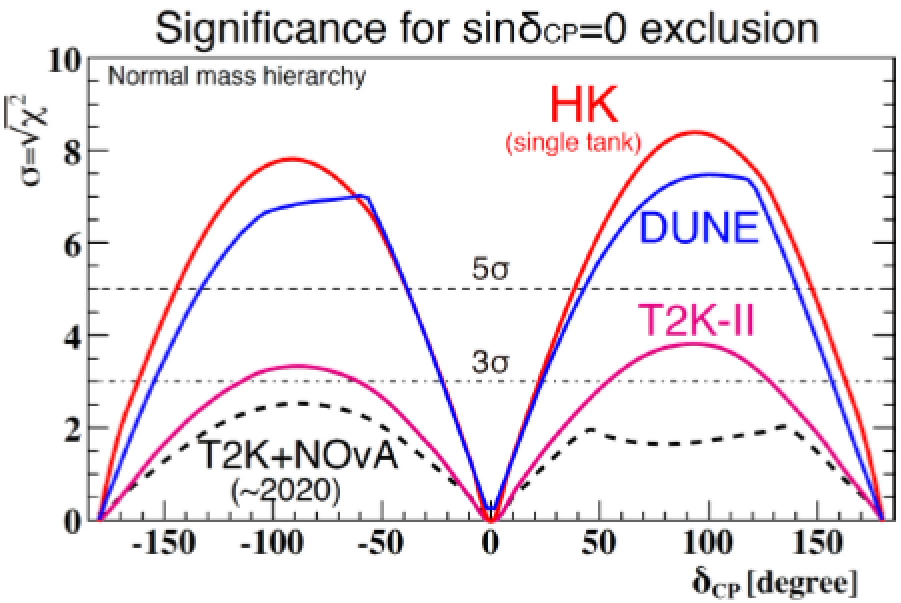
located at ~1 km from ν source

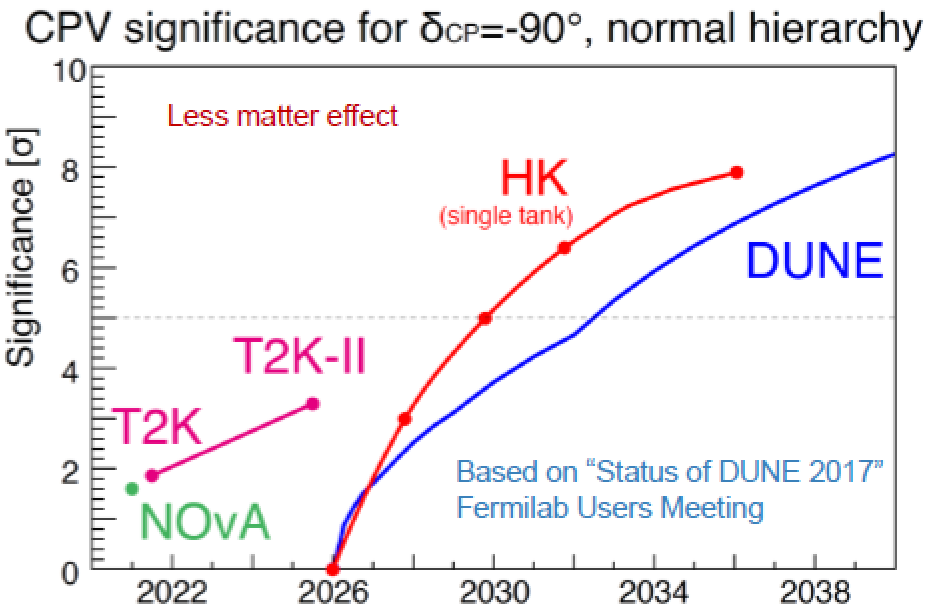
Off-axis angle spanning orientation vary ν peak energy

probe neutrino energy vs. reconstructed energy

Gd loading to measure neutron production

Hyper-K Sensitivity to δ_{CP}





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

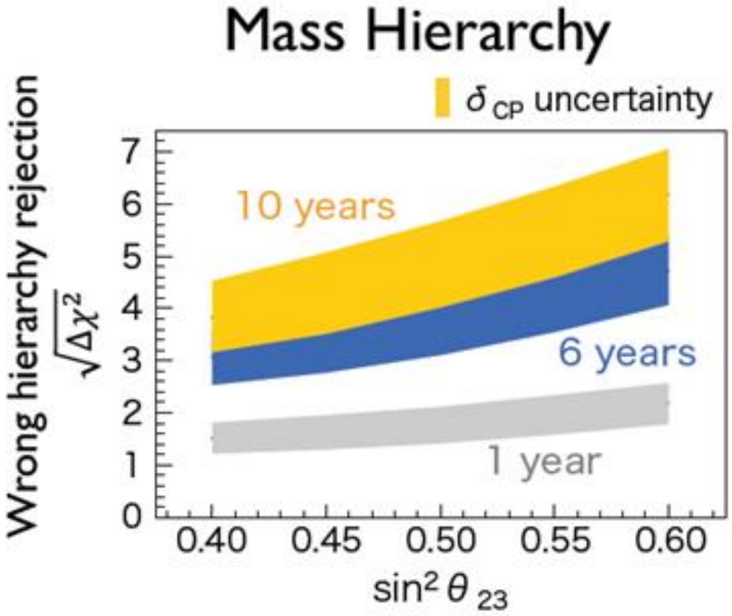
error	
δ=0°	δ=90°
7.2°	**23°**

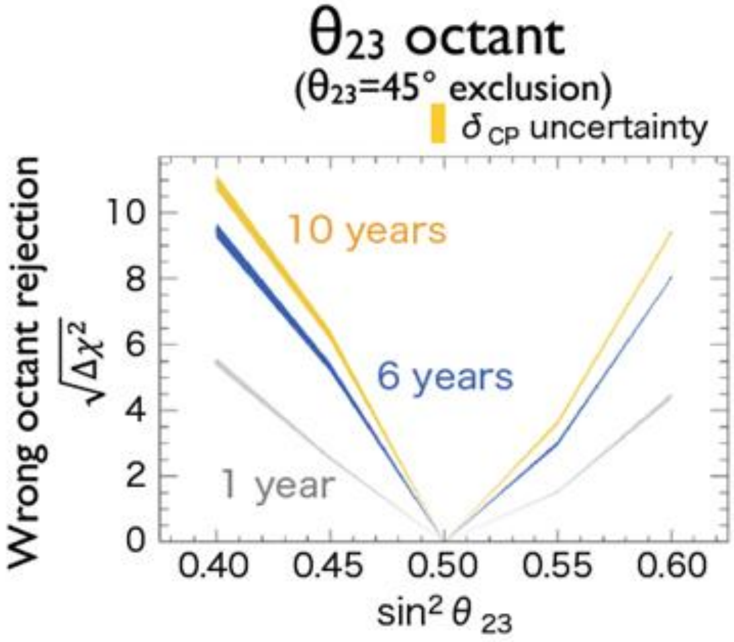
sinδ=0 exclusion	
>3σ	>5σ
76%	**57%**

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

Mass Hierarchy and Octant Sensitivities

beam + atmospheric ν



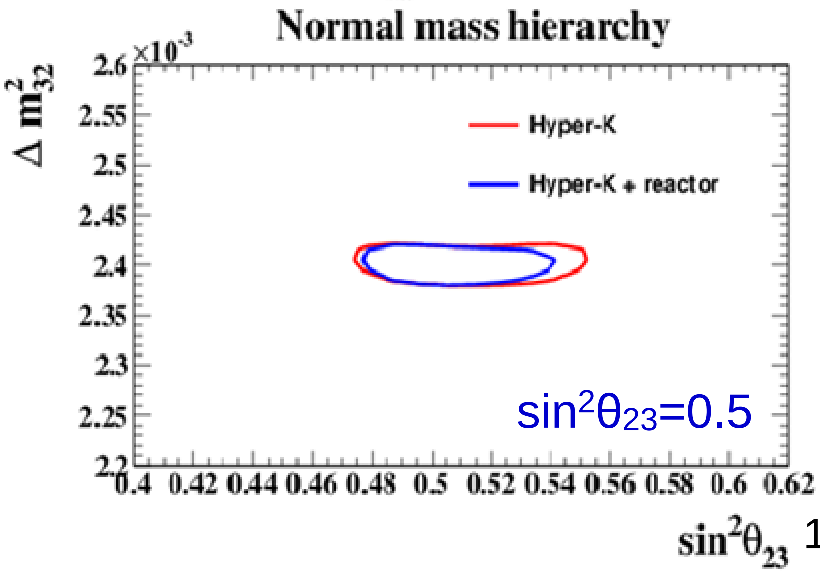


$\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5}\ \mathrm{eV}^2$

→ mass hierarchy sensitivity
in combination with reactor

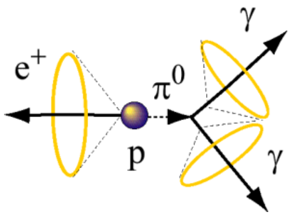
$\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23} = 0.5$)
~ 0.006 (for $\sin^2\theta_{23} = 0.45$)

→ octant determination input to models

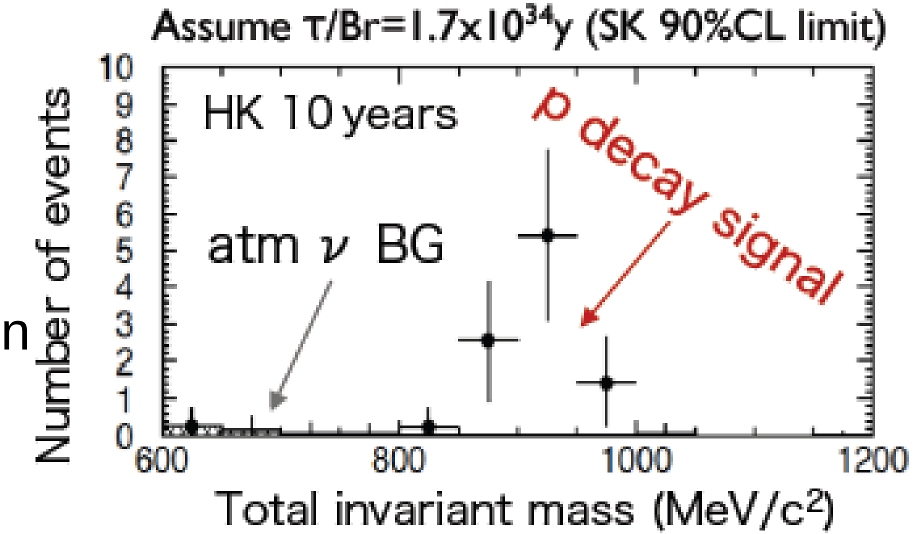


$\sin^2\theta_{23}=0.5$

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



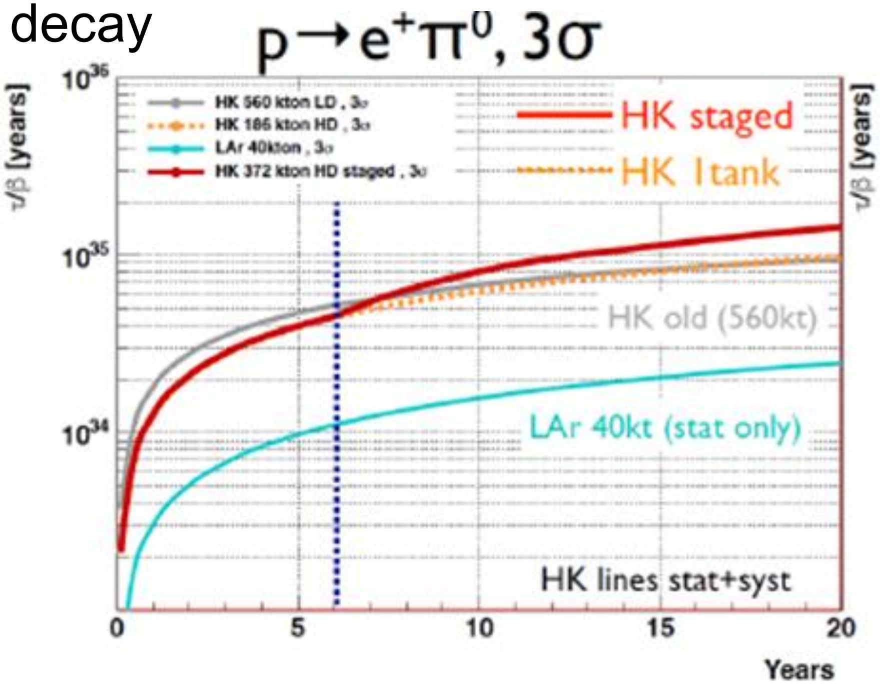
Proton decay $p \rightarrow e^+ \pi^0$ is a favoured model of many GUTs



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))

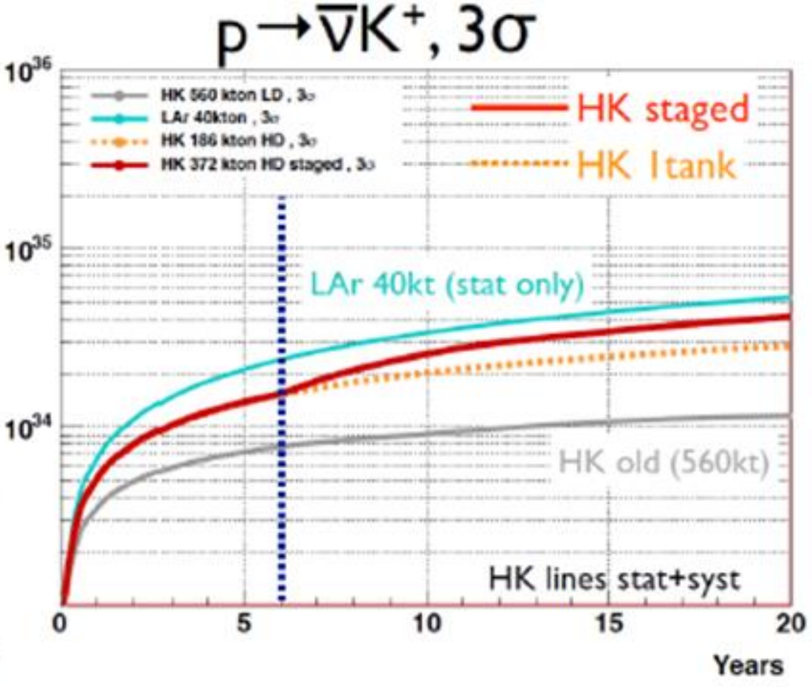


3-σ discovery sensitivity reaches $\tau_p/BR = 10^{35}$ years for $p \rightarrow e^+ \pi^0$

Best discovery potential for GUT signal!

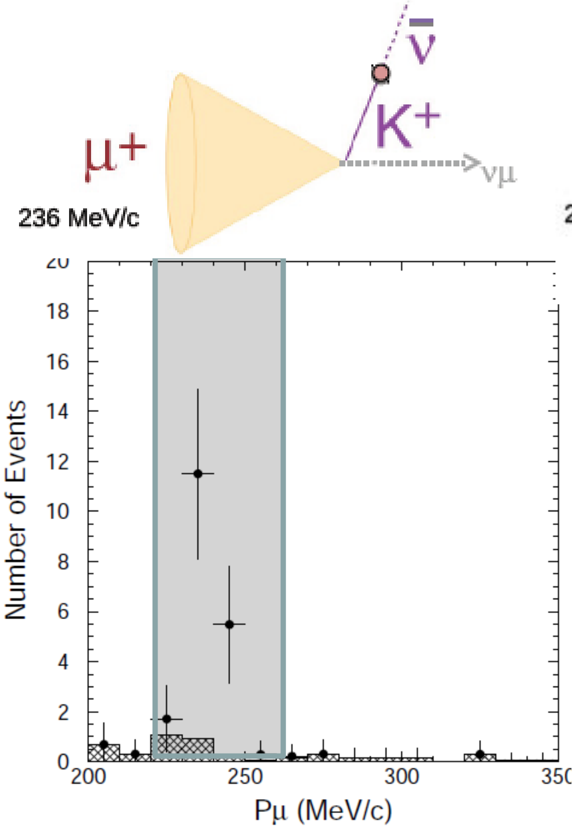
Proton p → $\bar{\nu}$ K^+ Decay Sensitivity

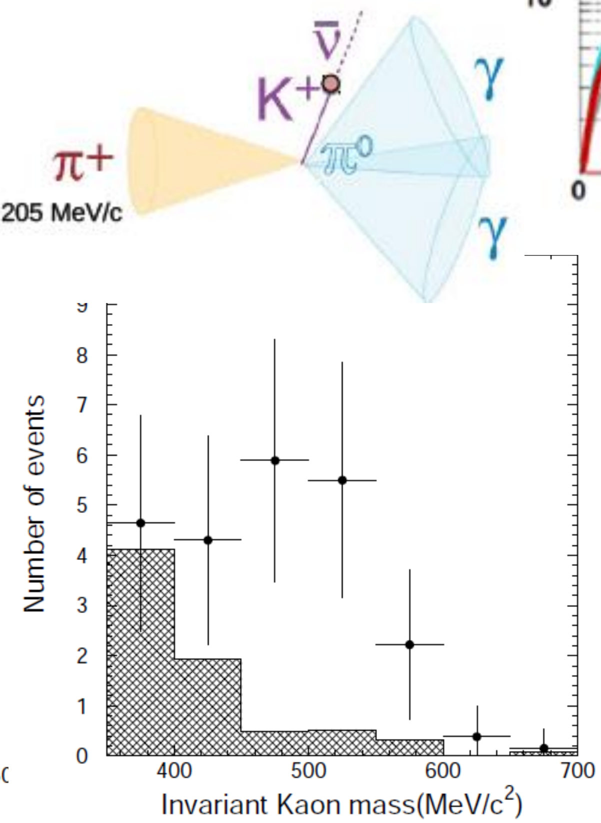
p → ν K^+ decays are one of the most prominent features of Supersymmetric GUTs



K^+ below Cherenkov threshold
→ observe K^+ decay

$K^+ \rightarrow \mu^+ \nu_\mu$ (BR 65%) $K^+ \rightarrow \pi^+ \pi^0$ (BR 21%)

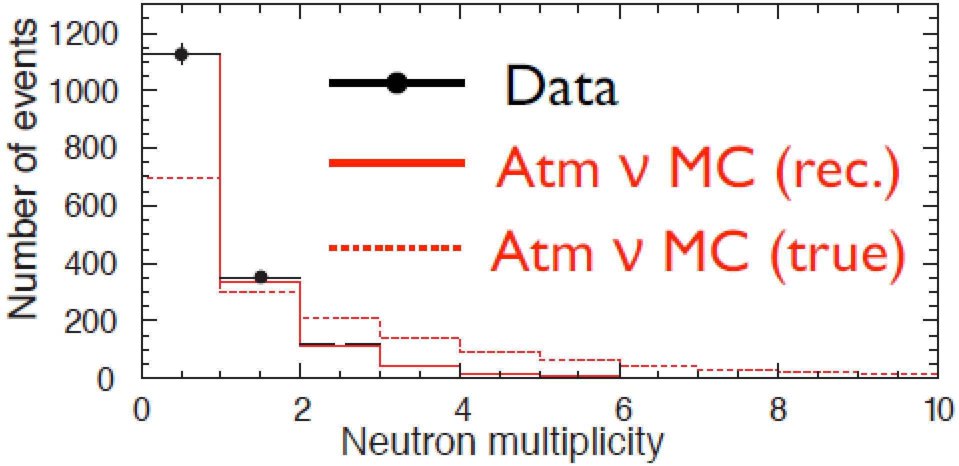


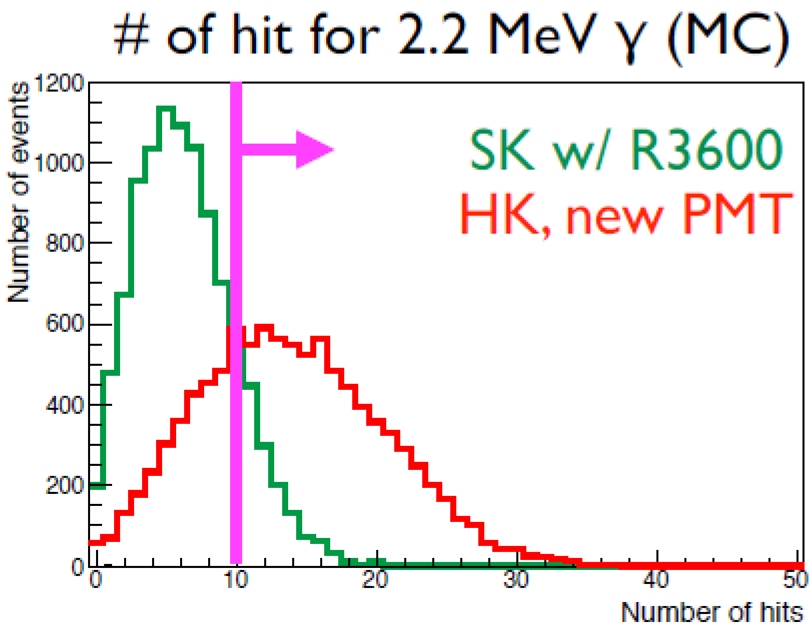


3-σ discovery sensitivity $\tau_p/BR = 3 \times 10^{34}$ years for p → $\bar{\nu}$ K^+

Bkg Suppression in Proton Decay

- Neutron tagging with hydrogen capture (2.2 MeV γ)
  - Tag and suppress atmospheric ν background
  - Already in use for p-decay search in SK-4 (~20% eff.)
- Extrapolated to Hyper-K with 40% high-QE PMT
  - 70% tagging efficiency possible
  - Gadolinium option also under consideration



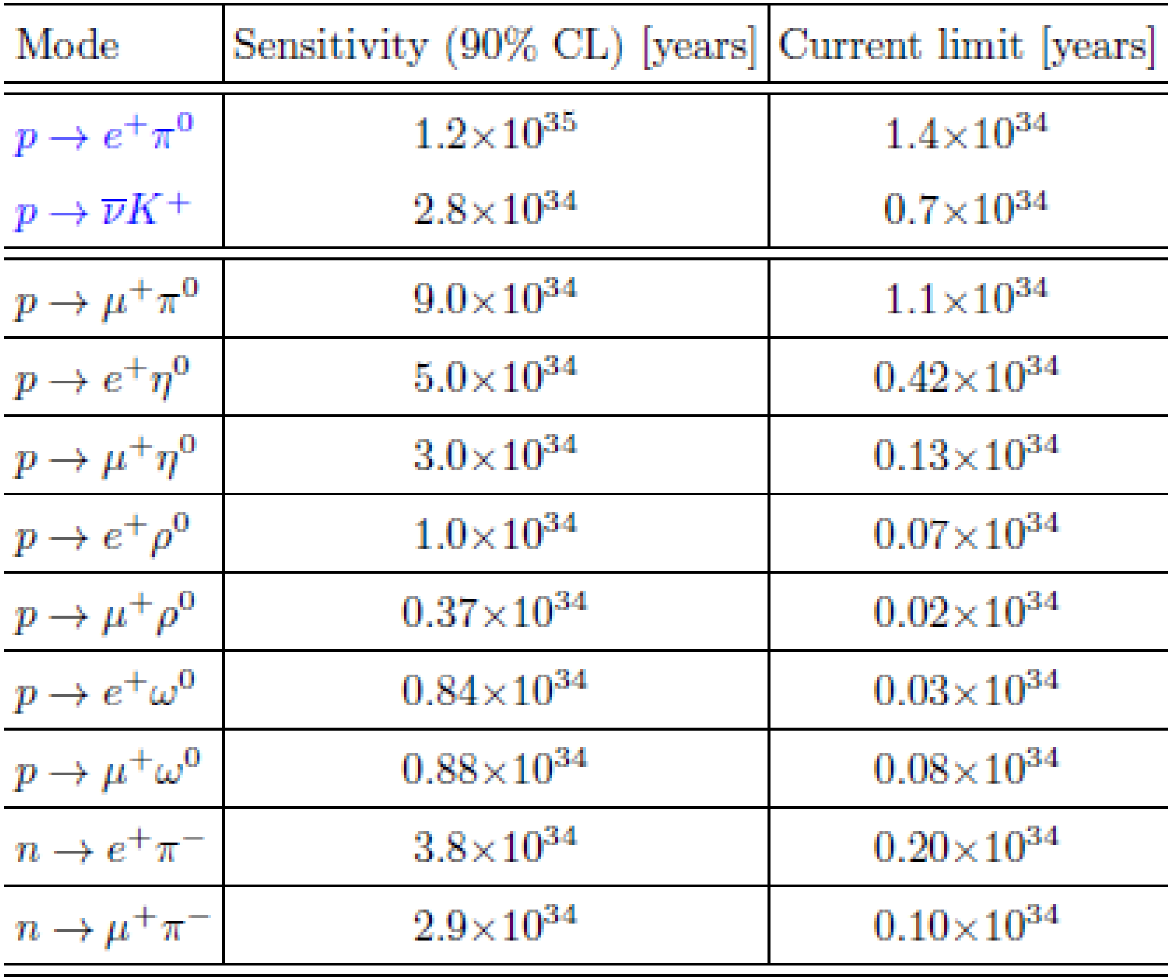

# of hit for 2.2 MeV γ (MC)

Nucleon Decay Searches

Need broad searches including other possible 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 !

Solar Neutrino Physics

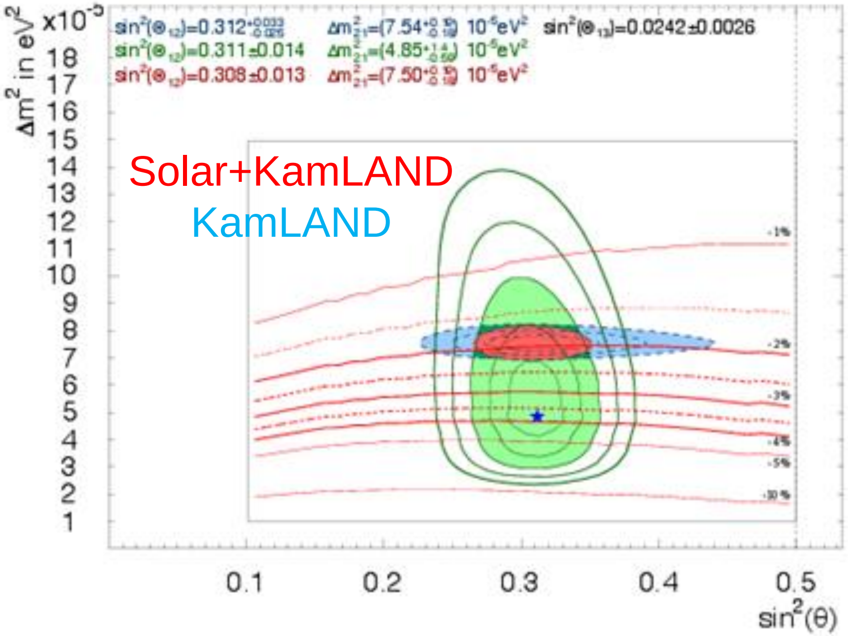
2-σ tension between Solar and reactor (KamLAND) neutrinos on Δm^2_{21}

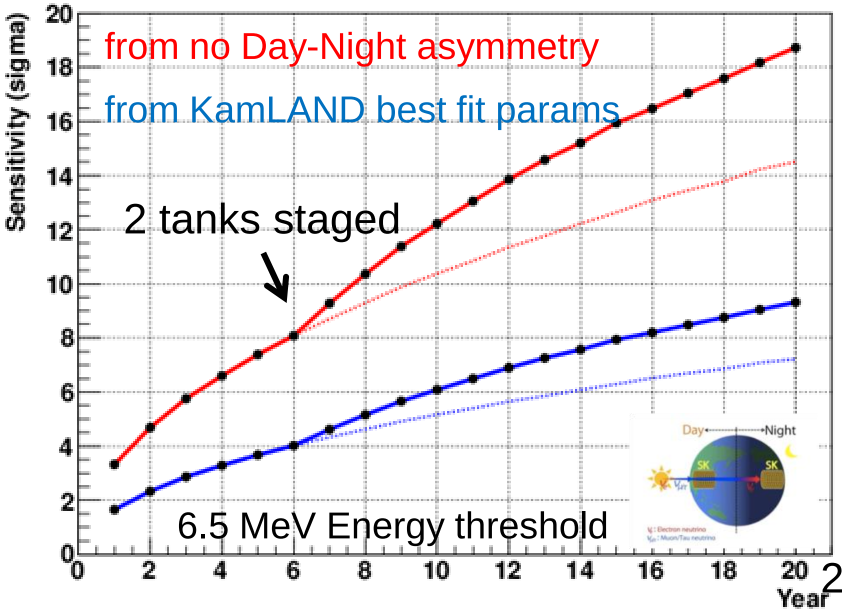
measurement with ν_e possible only with Solar neutrinos

sensitivity to address solar and reactor neutrinos discrepancy

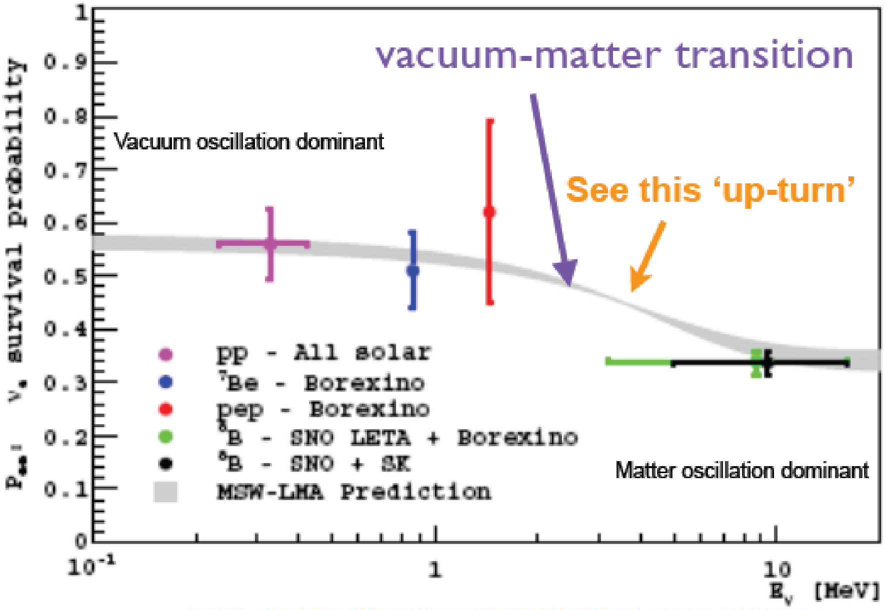
Definite observation (5-σ) of Day-Night asymmetry due to Earth matter effects

sensitive to Δm^2_{21}

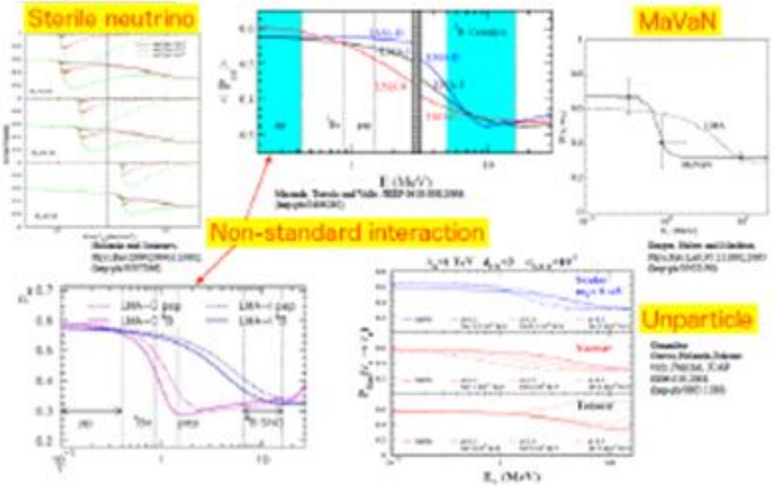




Spectrum Upturn of Solar ν



Various non-standard models

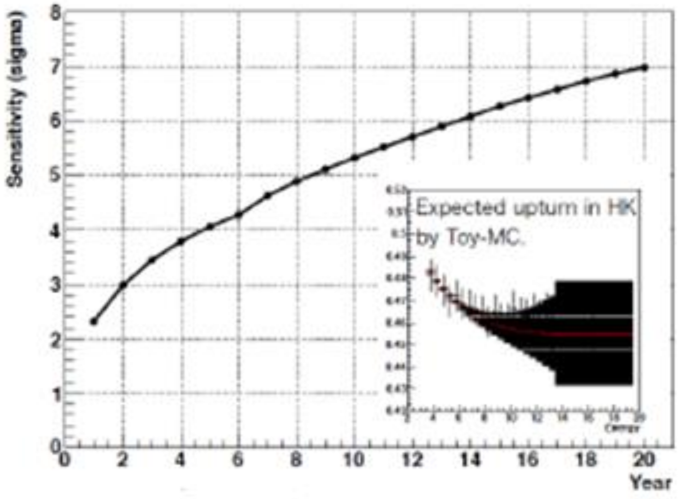


Spectrum upturn in low energy not yet seen

various non-standard scenario possible

> 5-σ possible with BG/ calibration similar to SK

low E threshold w/ high photon efficiency essential



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

More Physics with Atmospheric ν

Atmospheric ν:
  neutrinos with various energy, flight length, and flavor

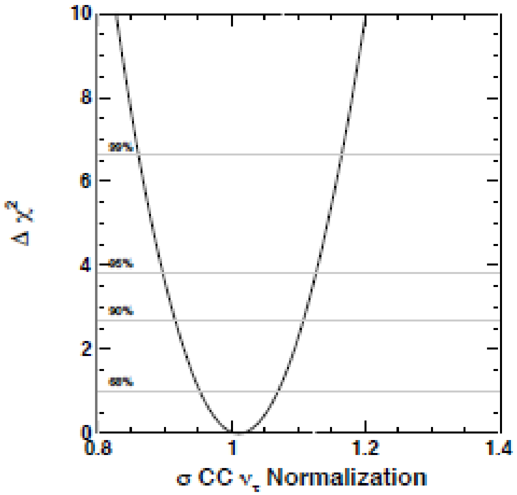
ν_τ cross section measurement

Sterile neutrinos

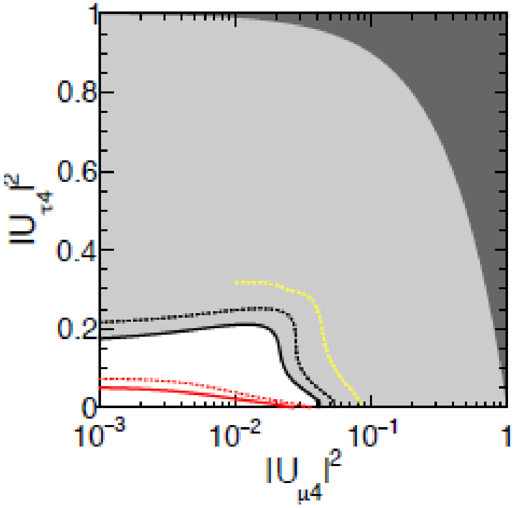
Lorentz violation studies

Geophysics
  chemical composition of Earth's outer core using matter effect

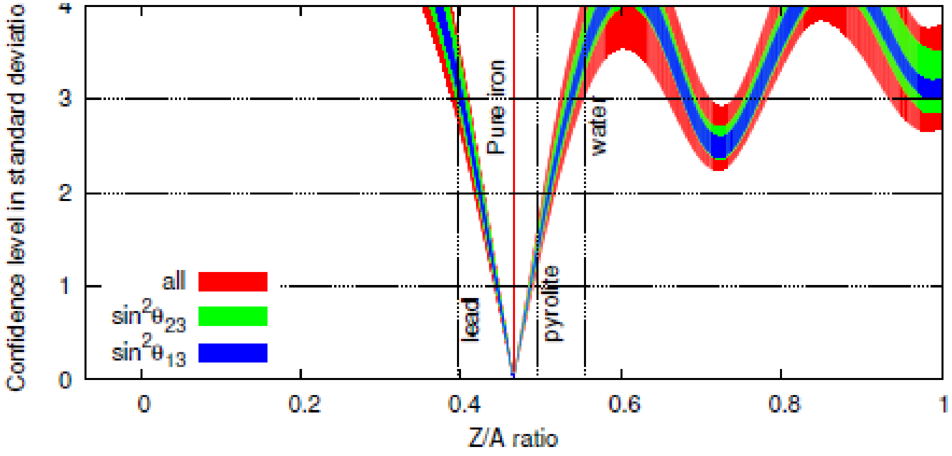
ν_τ cross section



Sterile limit



Sensitivity to outer core chemical composition (10Mtyr)

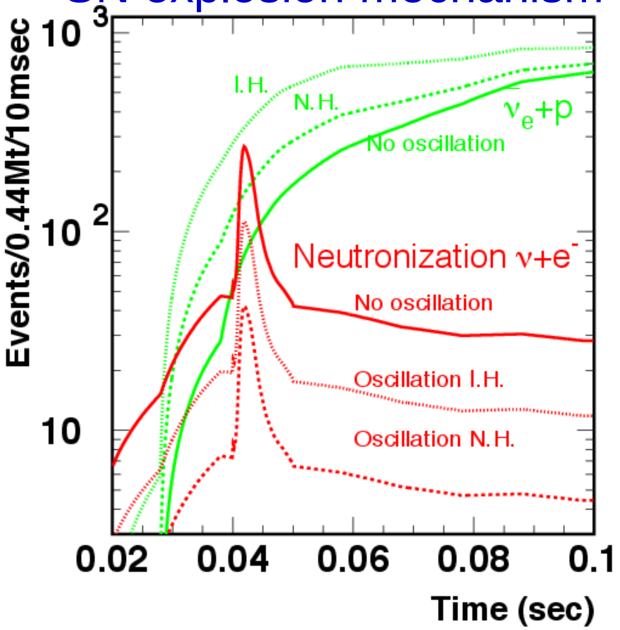


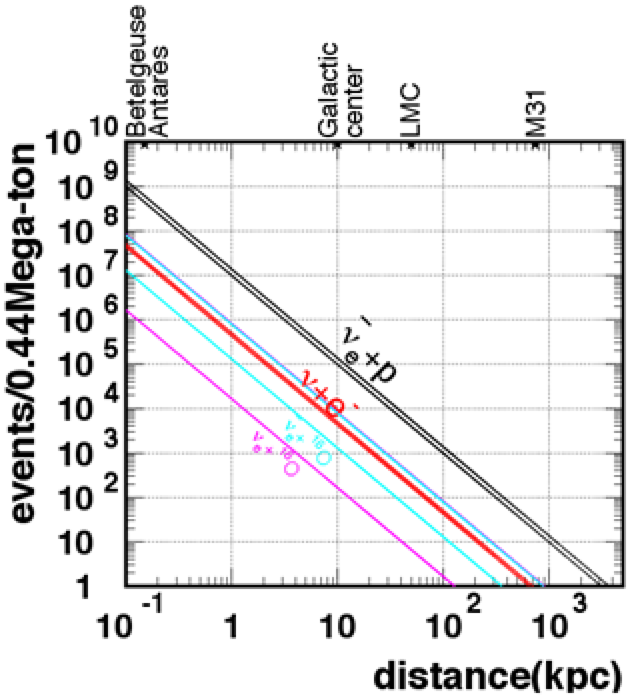
Supernova Burst Neutrinos

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

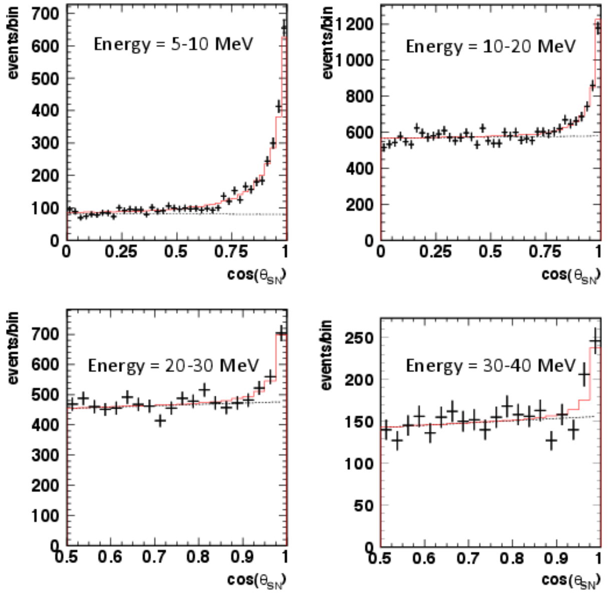
ν_e from neutronization: 12 ~ 80 events

SN explosion mechanism





SN directional info by ν + e scattering



Galactic SN

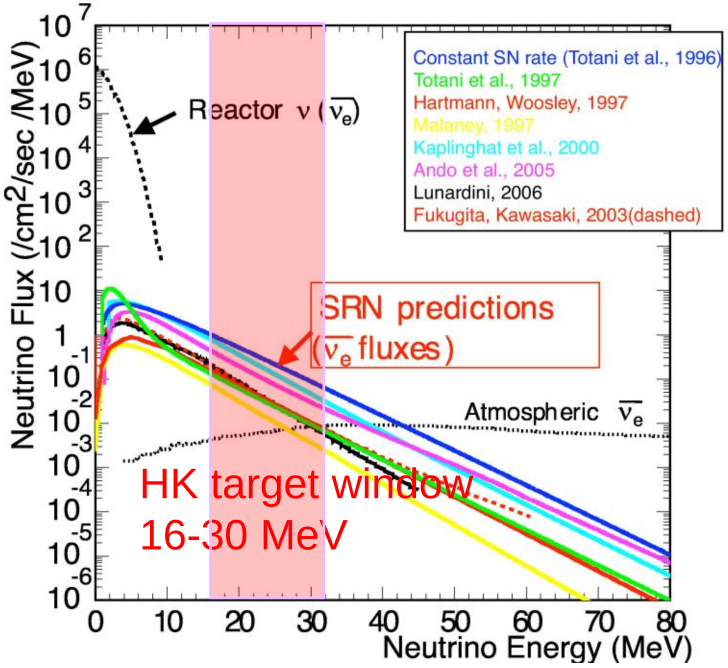
- Large statistics: 104,000 ~ 158,000 events (10 kpc)
- Time spectrum of SNν: SN model separation, SN burst time
- Energy spectrum measurement: ΔE/E ~ 20% at 10-20 MeV
- Direction, time, fluctuations of ν flux
- Expect tens of events from Andromeda

Supernova Relic Neutrinos

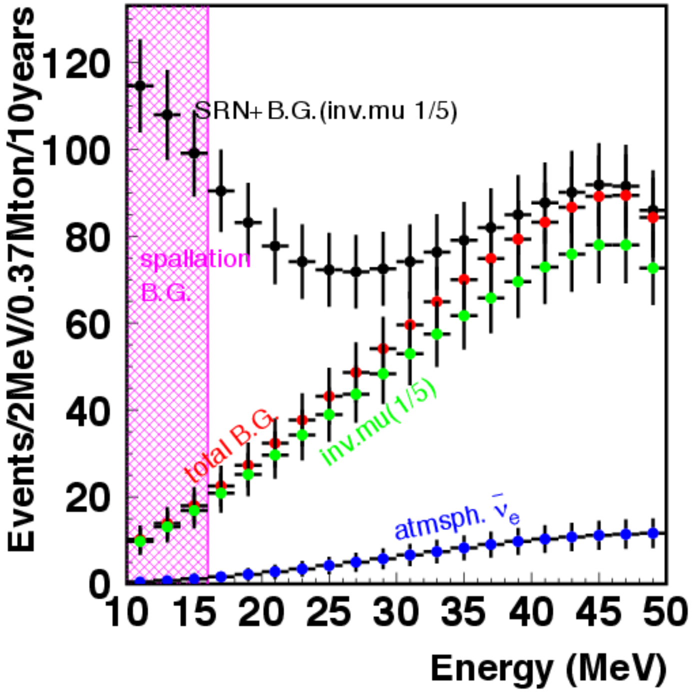
Neutrinos from past SN fill our Universe

Detectable with enough sensitivity

Measurement will probe:
- star formation rate
- black hole generation
- energy spectrum SN ν



HK target window
16-30 MeV



Bkg suppression with neutron tagging

Expected events in HK in 10 years
~98 ± 20 (4.8σ).

Indirect Dark Matter Searches

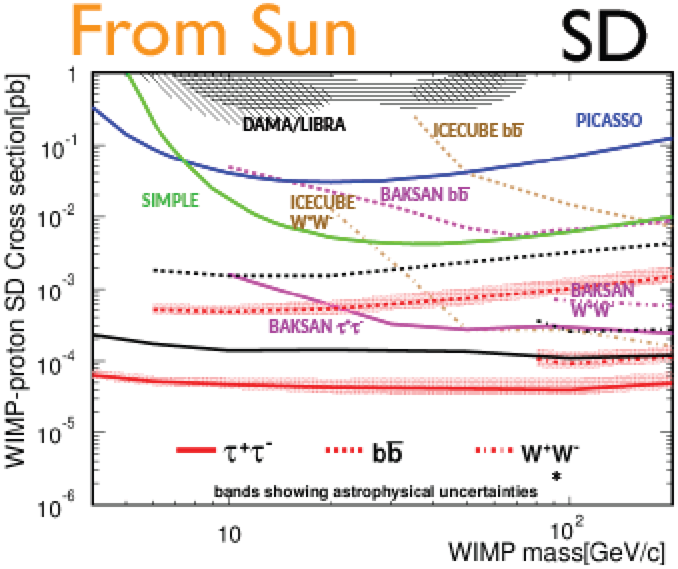
WIMP annihilation in Sun
and/or Galaxy center

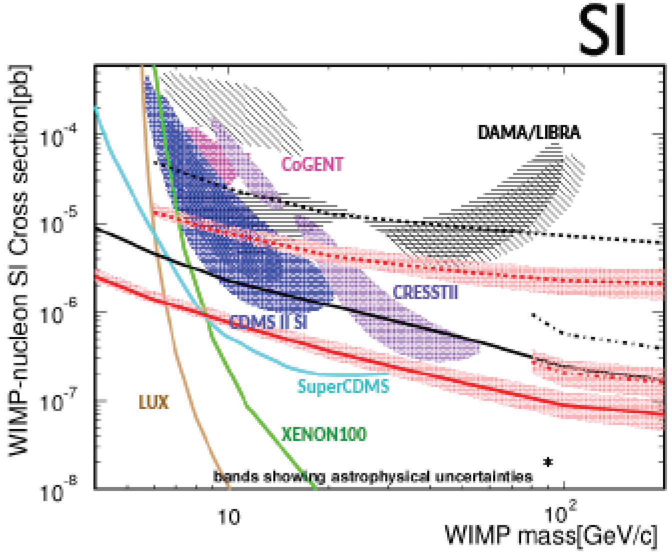
$$\chi\chi \rightarrow \nu\nu$$

Unique sensitivity
especially for low mass region

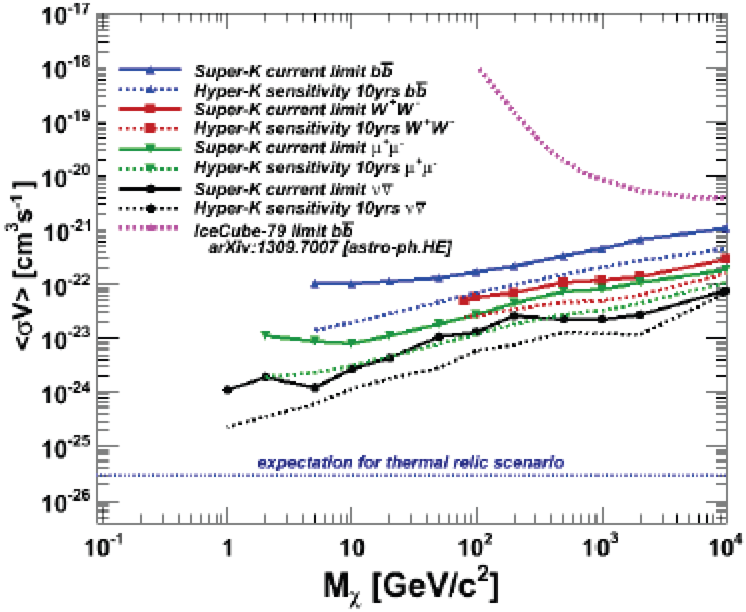
Improve 3-10 × over SK limit

From Sun





From Galactic center



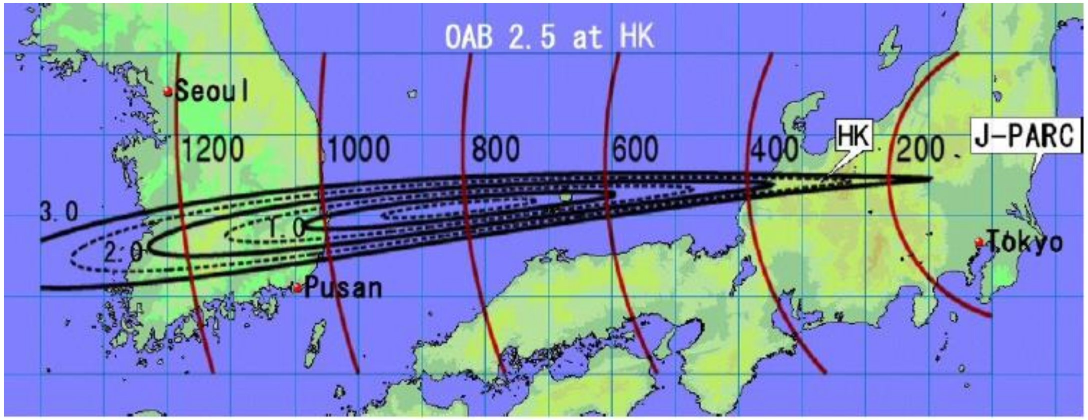
New Idea: 2nd Tank in Korea

Advantages of a second tank in Korea

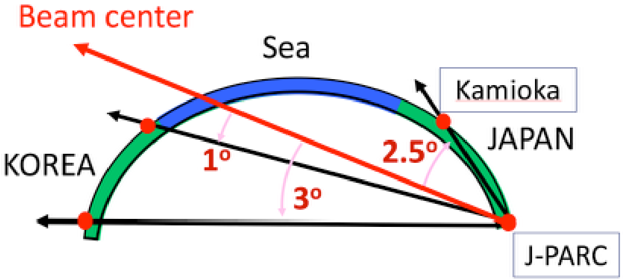
Measure CP effect at 2nd oscillation maximum (3 × larger)

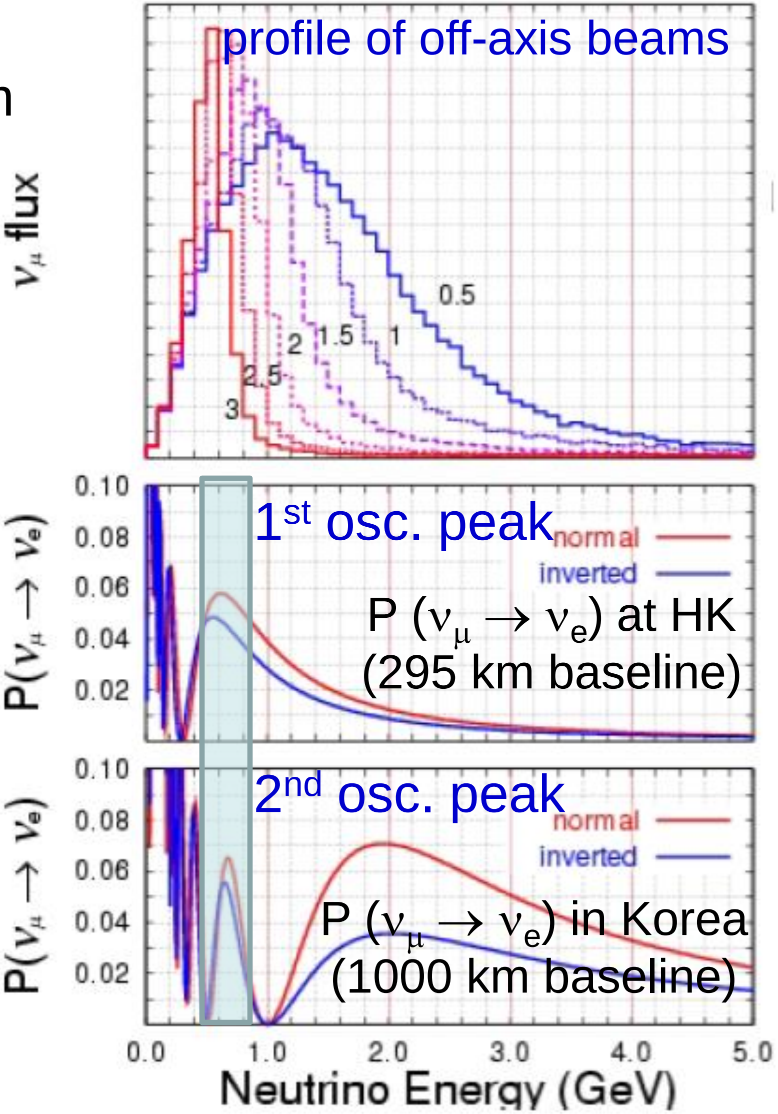
Enhanced mass hierarchy sensitivity (longer baseline)

Reduced backgrounds due to the deeper site



2.50 Off-axis ~1100 km baseline





profile of off-axis beams

1st osc. peak

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

2nd osc. peak

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

Conclusions

A new adventure in ν Physics to start

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 2026

Hyper-K Physics Potential

		HK (2TankHD w/ staging)
LBL (13.5MWyr)	δ precision	7°-21°
	CPV coverage $(3/5\sigma)$	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	± 0.017
ATM+LBL (10 years)	MH determination	$>5.3\sigma$
	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)	$6\sigma/12\sigma$
	Upturn	4.9σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8σ