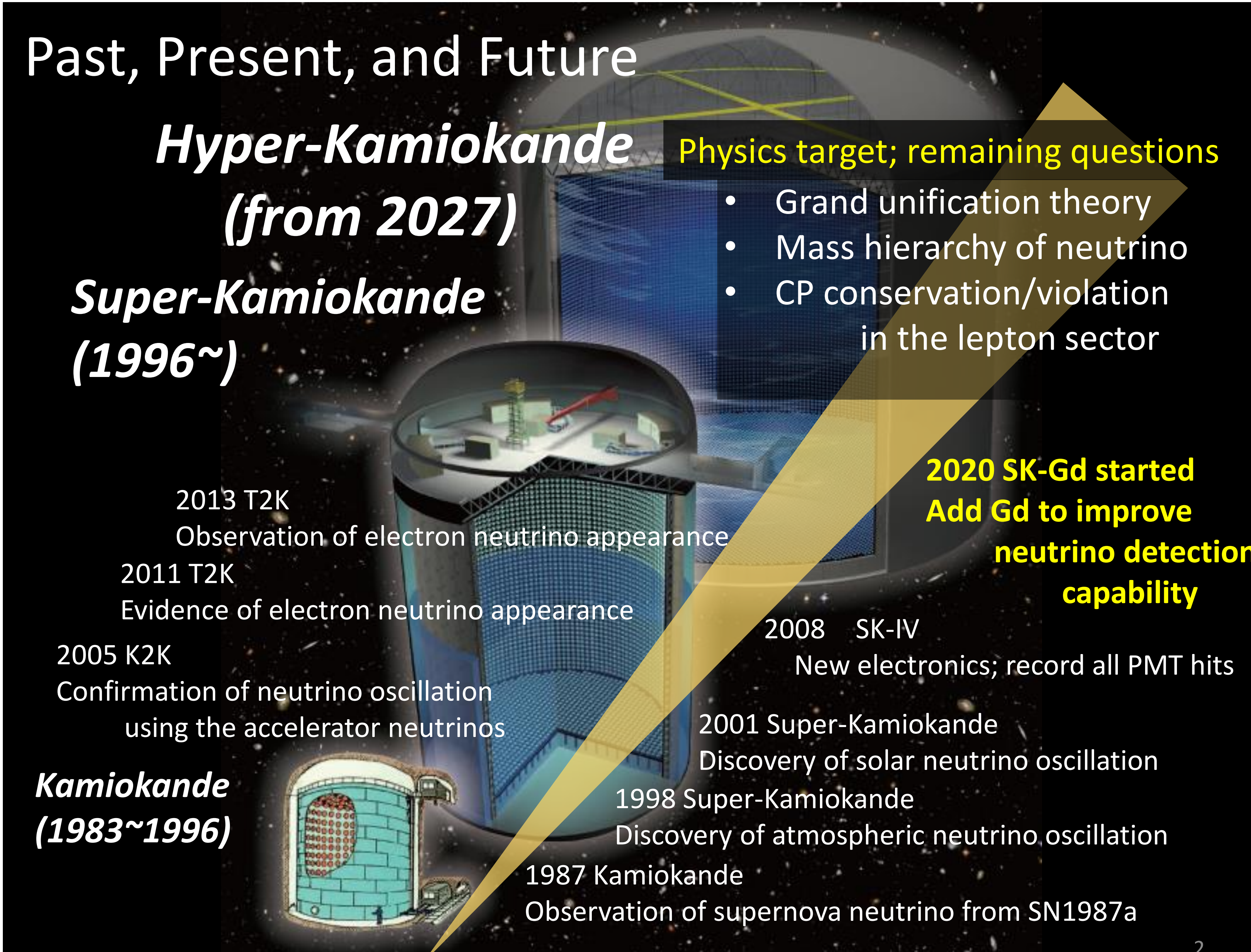
Exploring the new era of particle physics through the observation of natural neutrinos and the proton decay search

Summary of our achievements from 2018 to 2022.

Yoshinari Hayato
(Kamioka Obs., ICRR, The Univ. of Tokyo)
for
the A01 group in Grant-in-Aid for Scientific Research on Innovation Areas “Exploration of Particle Physics and Cosmology with Neutrinos”.

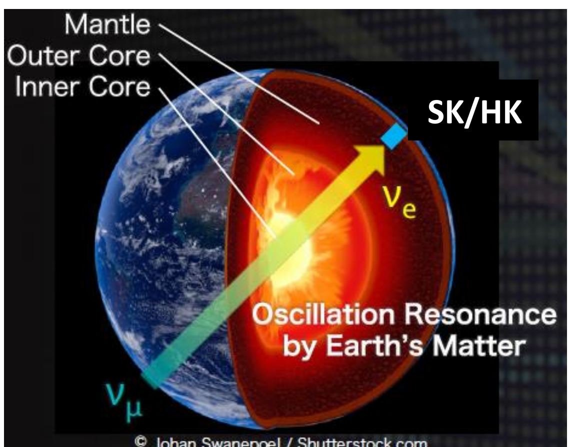
Plenary talks of
SK by T. Mueller
HK by B. Quilain

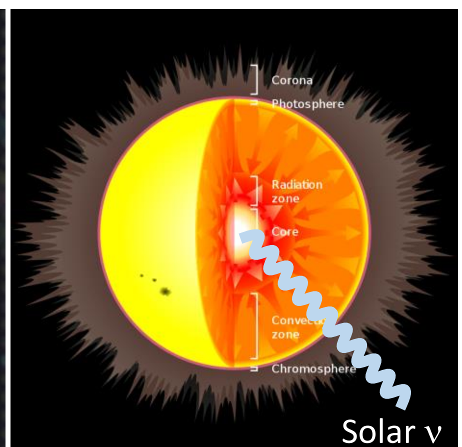

Past, Present, and Future
Hyper-Kamiokande
(from 2027)
Super-Kamiokande
(1996~)
Kamiokande
(1983~1996)
Physics target; remaining questions
• Grand unification theory
• Mass hierarchy of neutrino
• CP conservation/violation in the lepton sector
2020 SK-Gd started
Add Gd to improve neutrino detection capability
2013 T2K
Observation of electron neutrino appearance
2011 T2K
Evidence of electron neutrino appearance
2005 K2K
Confirmation of neutrino oscillation using the accelerator neutrinos
2008 SK-IV
New electronics; record all PMT hits
2001 Super-Kamiokande
Discovery of solar neutrino oscillation
1998 Super-Kamiokande
Discovery of atmospheric neutrino oscillation
1987 Kamiokande
Observation of supernova neutrino from SN1987a

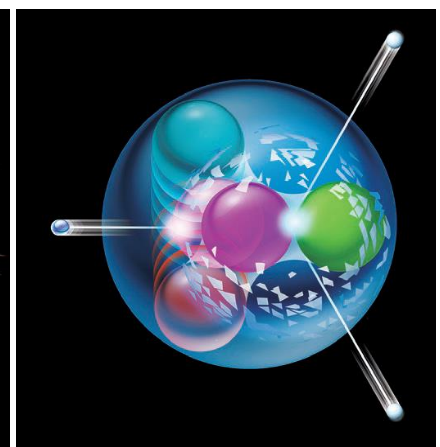
Physics targets of A01

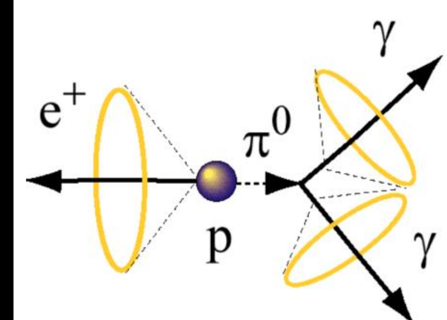
- Neutrino mass hierarchy using the atmospheric neutrino
- CP violation in the lepton sector
  using the atmospheric and accelerator neutrinos (with A02)
- Solar neutrino matter effects
- Comprehensive search for the proton decay

- R&D to maximize the performance of Hyper-Kamiokande







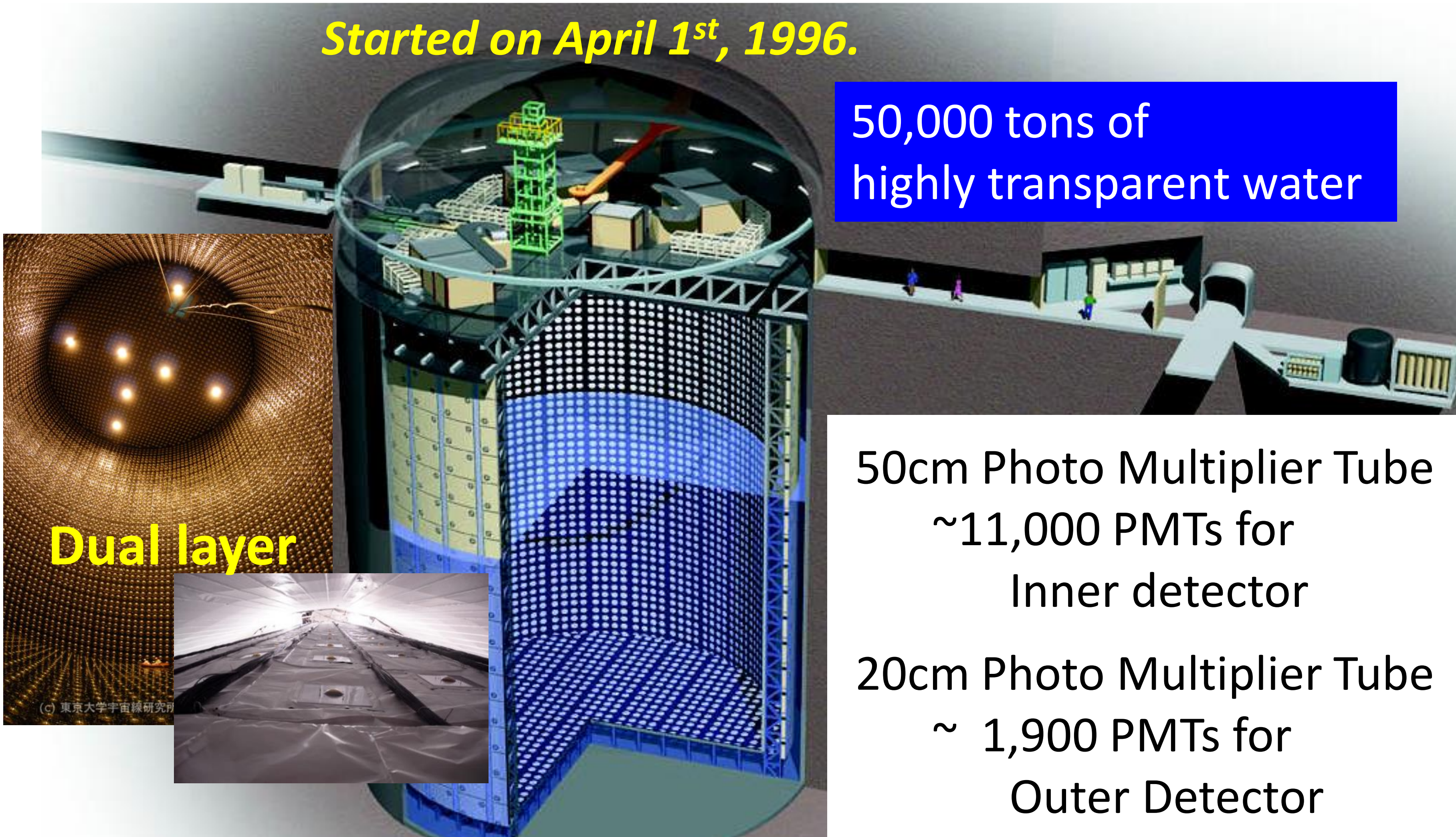


Atmospheric neutrino Mass hierarchy (CP violation with T2K)	Solar neutrino Matter effects New physics?	Proton decay (Grand Unification Theory)

Super-Kamiokande

Ring imaging Water Cherenkov detector

Started on April 1st, 1996.



50,000 tons of highly transparent water

Dual layer

50cm Photo Multiplier Tube
~11,000 PMTs for
Inner detector

20cm Photo Multiplier Tube
~ 1,900 PMTs for
Outer Detector

All data since 1996 are available and used for various analyses.

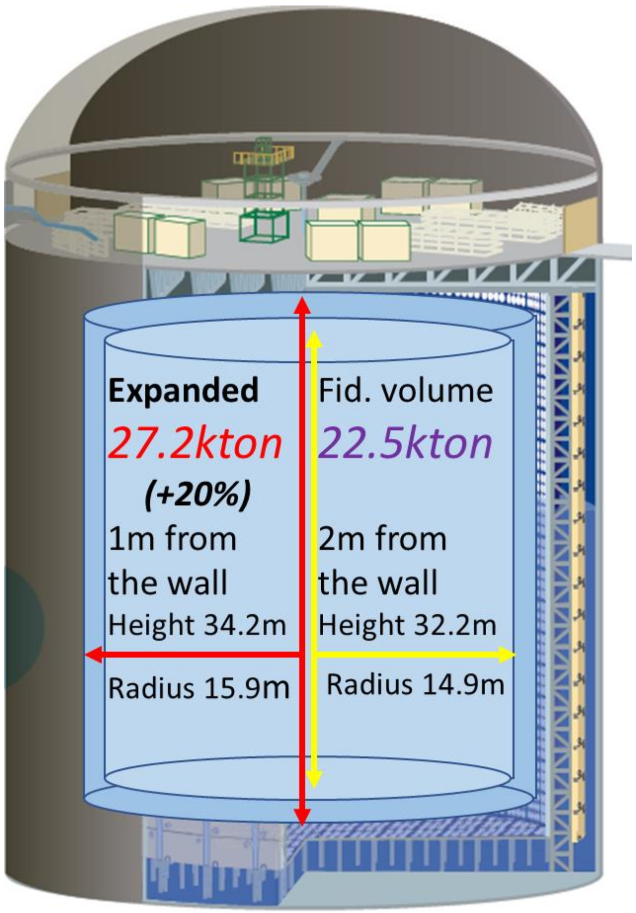
Super-Kamiokande analysis tool improvements

Accumulated data at the end of SK-VI is ~7,100 days. (~2022)

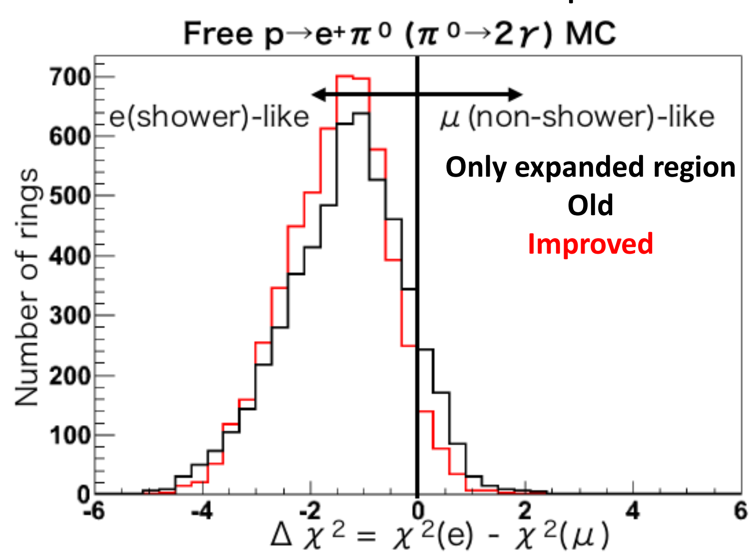
We developed new tools for atmospheric neutrino analyses and proton decay searches.

With the new tools, we succeeded in expanding the fiducial volume by ~20% for the entire SK period.

These new reconstruction tools have better particle (ring) finding efficiency and particle ID performances.



Particle ID Likelihood in the expanded region



Atmospheric neutrino oscillation results

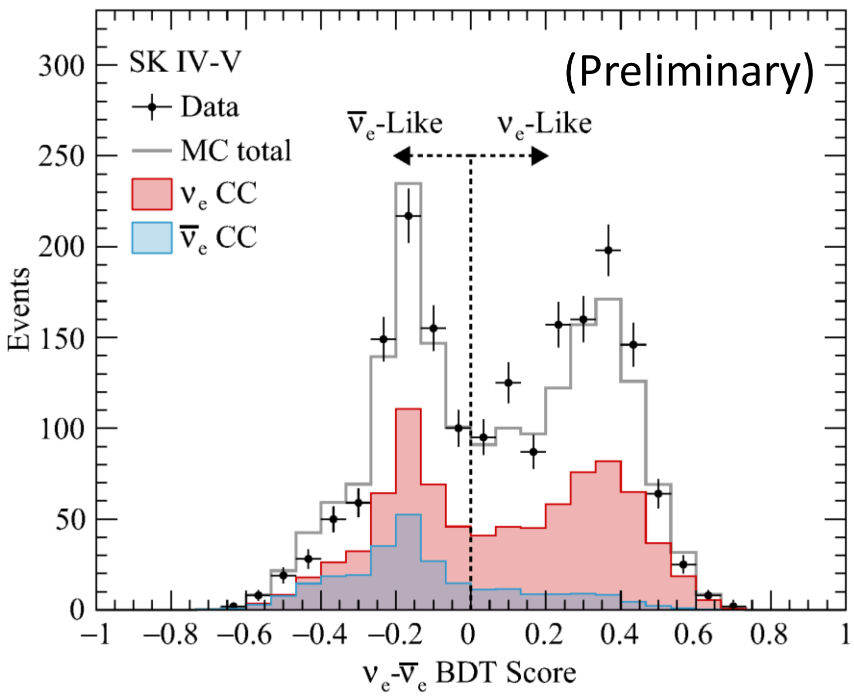
Expanded fiducial volume (27.2 kton) from SK I to SK V

(6511 days, 484 kton·years)

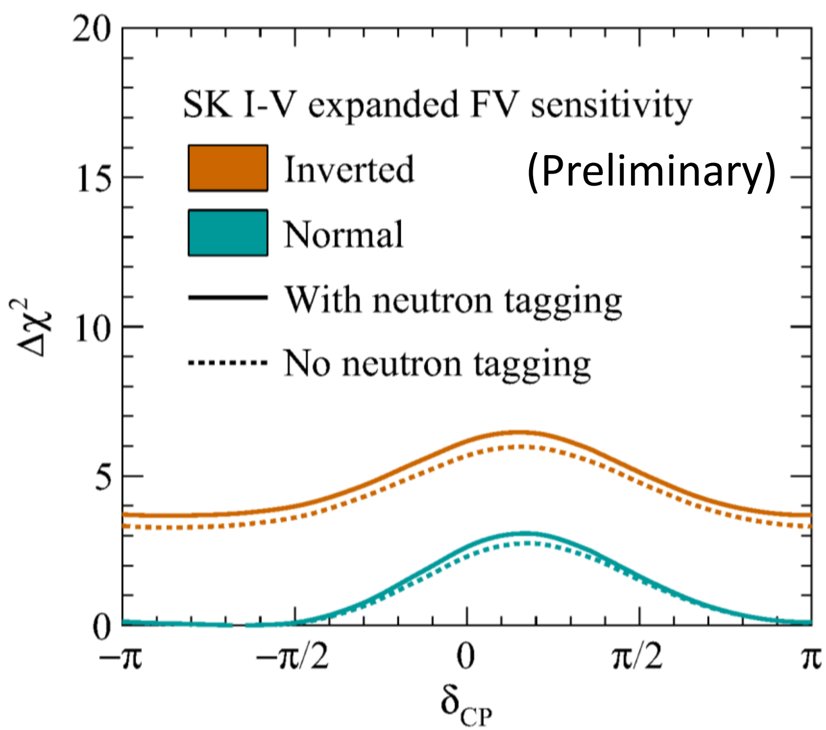
Analysis improvements other than the fiducial volume expansion;

- New multi-ring ν_e / $\overline{\nu_e}$ classification using BDT
- Event selection using the neutron information for SK IV.
  (Neutron ID efficiency is about 25%.)

BDT score of multi-ring ν_e / $\overline{\nu_e}$ classification



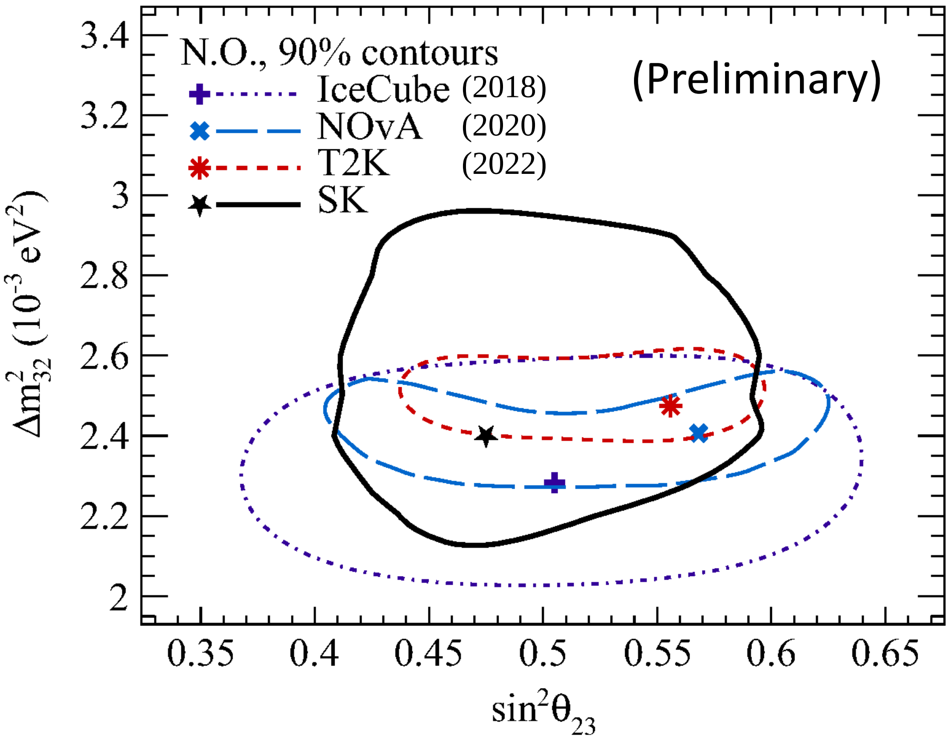
Improvements in CP parameter sensitivity

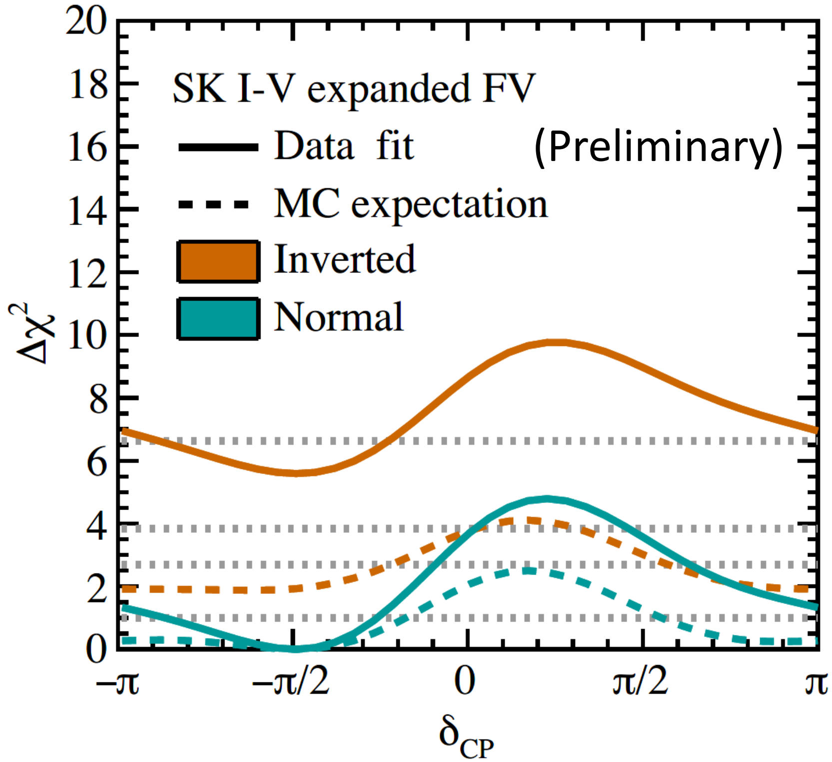


Atmospheric neutrino oscillation results

Expanded fiducial volume (27.2 kton) from SK I to SK V

(6511 days, 484 kton·years)

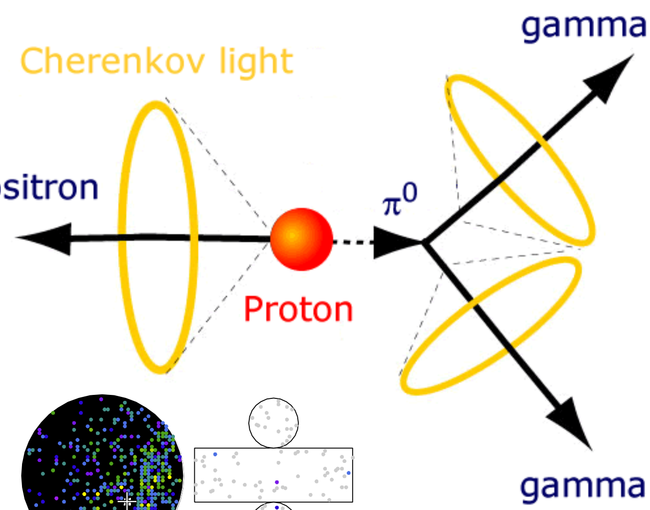


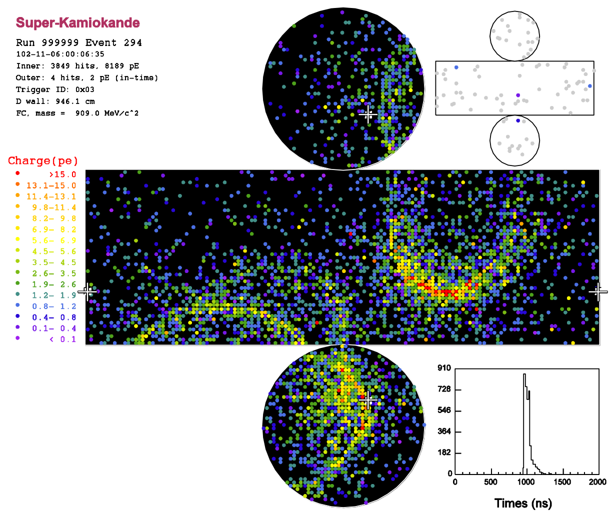


(Preliminary)	Mass ordering	$\lvert\Delta m^2_{32,31}\rvert$ $(10^{-3}\mathrm{eV}^2)$	$\sin^2\theta_{23}$	δ_{CP}	χ^2	$\chi^2_{N.O.-I.O.}$
SK ($\sin^2\theta_{13}$ constrained)	Normal Inverted	$2.40^{+0.24}_{-0.05}$ $2.40^{+0.11}_{-0.06}$	$0.475^{+0.057}_{-0.036}$ $0.475^{+0.063}_{-0.039}$	4.71 4.71	1004.56 1010.15	-5.59

Proton decay search results

$p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$



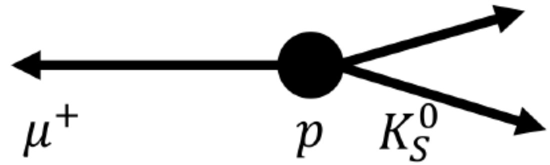


Lifetime limits (SK I to IV, 450 kt·yrs.)

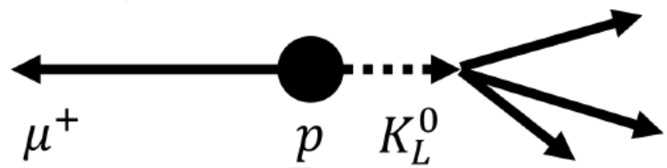
$p \rightarrow e^+ + \pi^0$	2.4x10^{34} yrs.
$p \rightarrow \mu^+ + \pi^0$	1.6x10^{34} yrs.

A. Takenaka et al. (SK Collab.), Phys. Rev. D 102, 112011 (2020)

$p \rightarrow \mu^+ K^0$



$K_S^0 \rightarrow \pi^+\pi^-$ (Branch 69.2%)
$K_S^0 \rightarrow \pi^0\pi^0$ (Branch 30.7%)



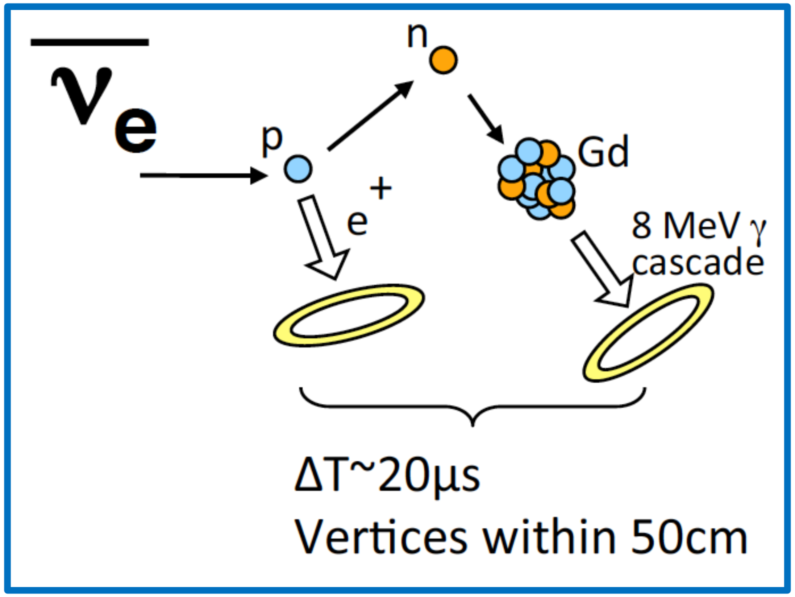
$K_L^0 \rightarrow \pi^\pm l^\mp \nu_l$ (Branch 67.6%)
$K_S^0 \rightarrow \pi^0\pi^0\pi^0$ (Branch 19.5%)
$K_S^0 \rightarrow \pi^+\pi^-\pi^0$ (Branch 12.5%)

$p \rightarrow \mu^+ K^0$ lifetime limits

New analysis(SK IV)	200 kt·yrs	4.5 x 10^{33} yrs.
Previous search (SK I to III)	170 kt·yrs	1.6 x 10^{33} yrs.
Combined	370 kt·yrs	3.6 x 10^{33} yrs.

R. Matsumoto et al. (SK Collab.), Phys. Rev. D 106, 072003

Upgrade of the Super-Kamiokande detector (SK-Gd)

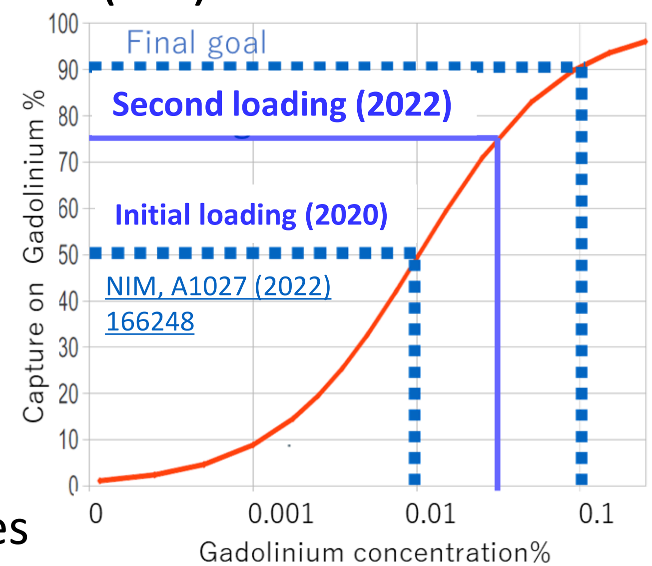


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Gadolinium captures neutron and emit **~ 8 MeV γ**

Detection efficiency of 8MeV γ ~ 100%

Add Gadolinium (Gd) to the SK water.



Neutrino / anti-neutrino discrimination

- Discovery of supernova(SN) diffuse ν search and pointing accuracy improvement for SN burst
- Improve Discrimination power of ν and $\bar{\nu}$ in T2K and atmospheric neutrino analyses

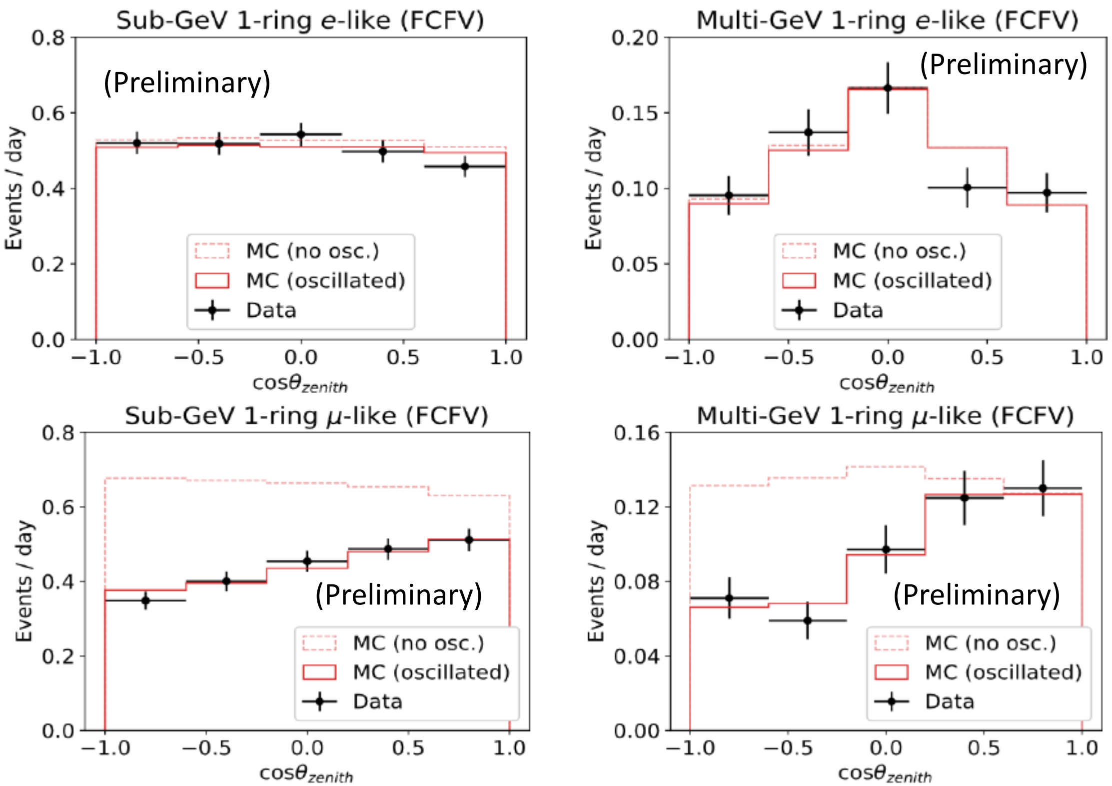
Nucleon decay background rejection

Early detection of supernova etc.

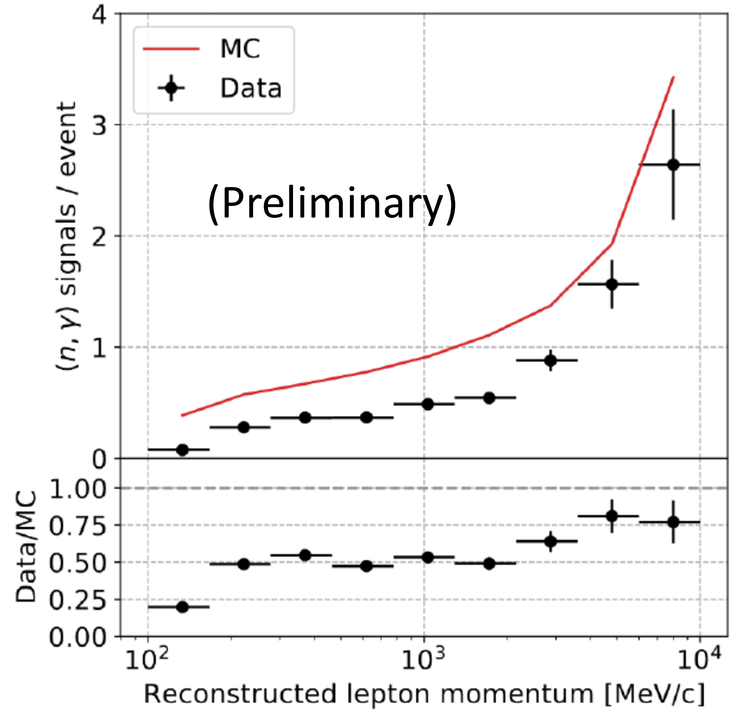
2nd loading was completed successfully!

Atmospheric neutrino data with 0.01% Gd (SK VI)

SK-VI (2020.7-2022.5)



Neutron multiplicity

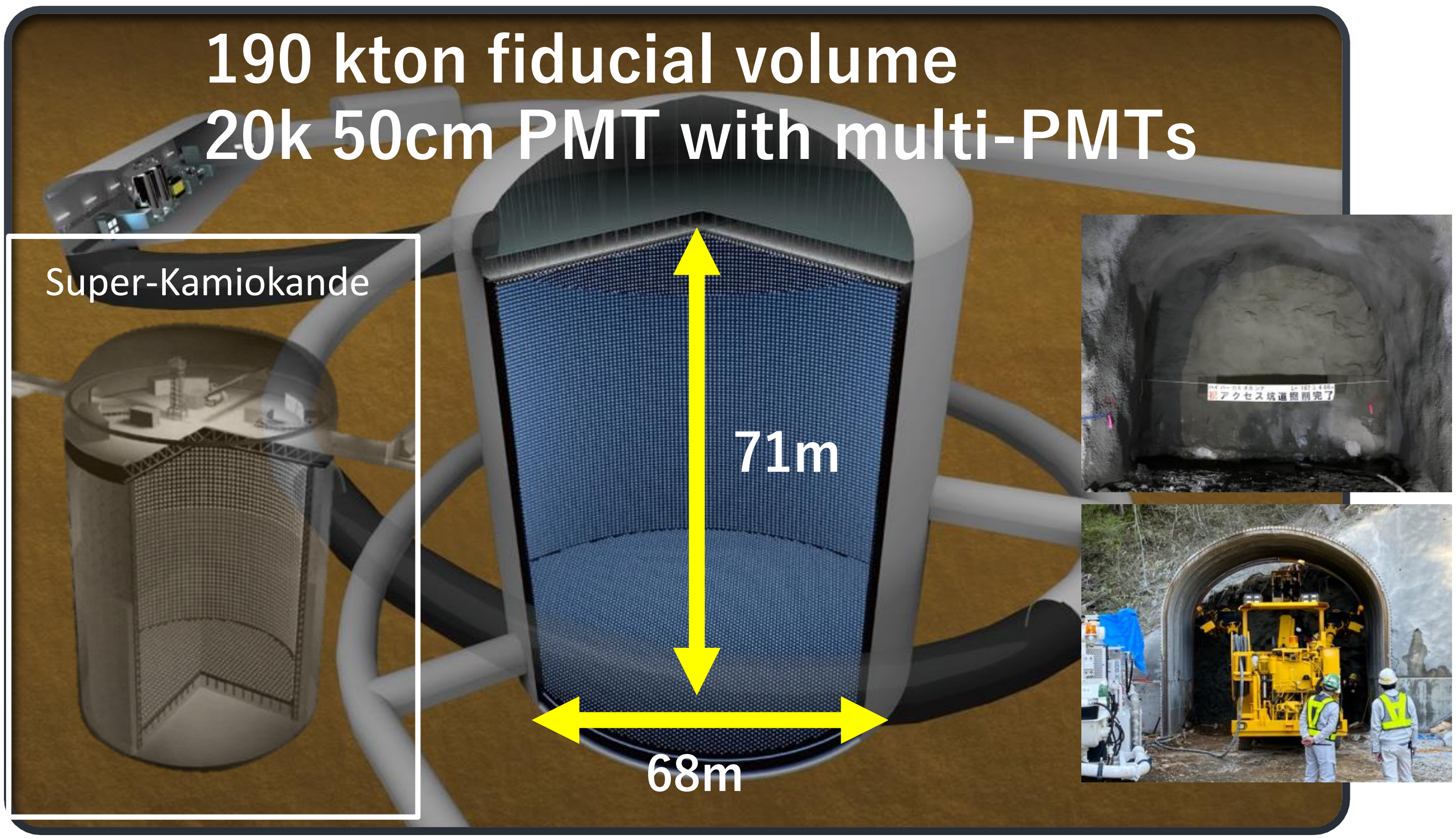


- Atmospheric neutrino data is well reproduced by the MC.
- Also confirmed that SK-6 data is consistent with the previous data taken with pure-water SK.
- Neutron multiplicity needs to be studied further.

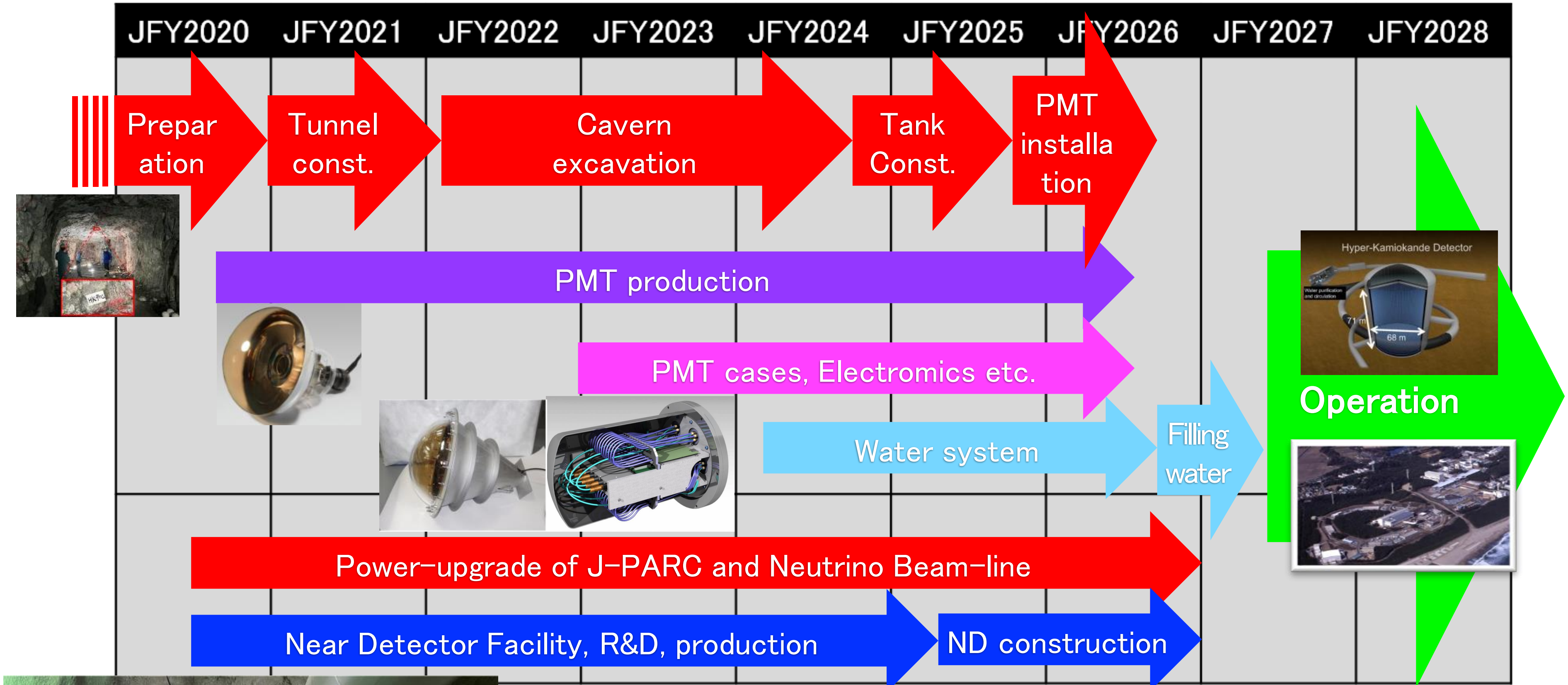
Hyper-Kamiokande

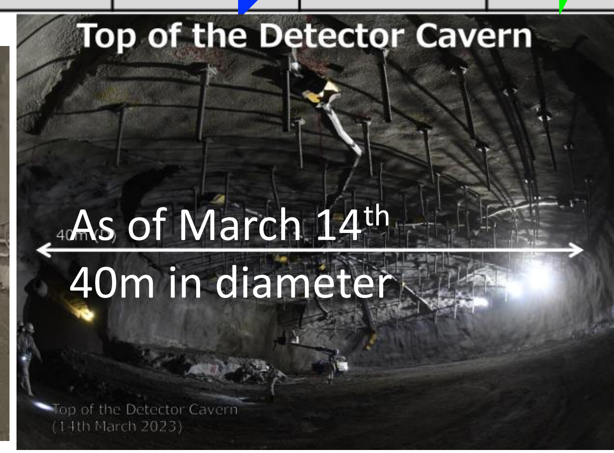
Need much higher statistics

- Lepton CP violation (discovery, parameter measurement)
- Neutrino mass hierarchy
- Nucleon decay search (discovery, decay branch, branching ratio)
- Neutrino from astronomical objects (Sun, Supernova)



Hyper-Kamiokande long term schedule





Hyper-Kamiokande detector components

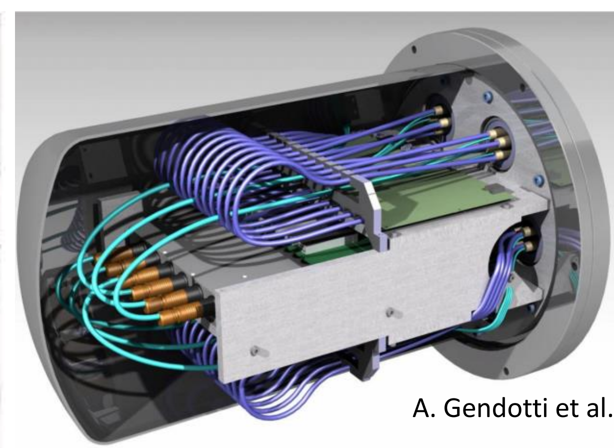
50cm PMT and PMT shockwave protection cover

- Various improvements reduced the noise rate.
- PMT mass production has been started.
- Completed one working design of the protection cover.

Underwater electronics assembly

- Designed and evaluated custom underwater pressure-tolerant cables, feedthrough, and connectors.
- Designed and prototyped the electronics housing in the water.
- Basic designs of these components are completed.

Finalization of the designs for mass production is going on.



A. Gendotti et al.

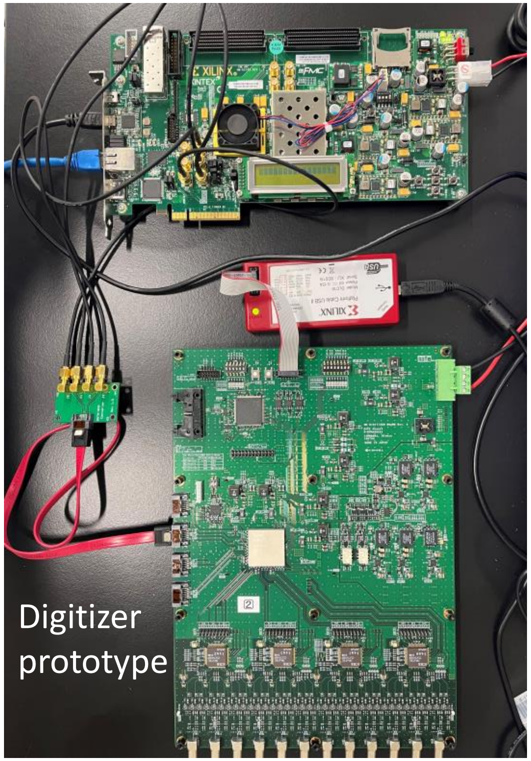
Hyper-Kamiokande detector components

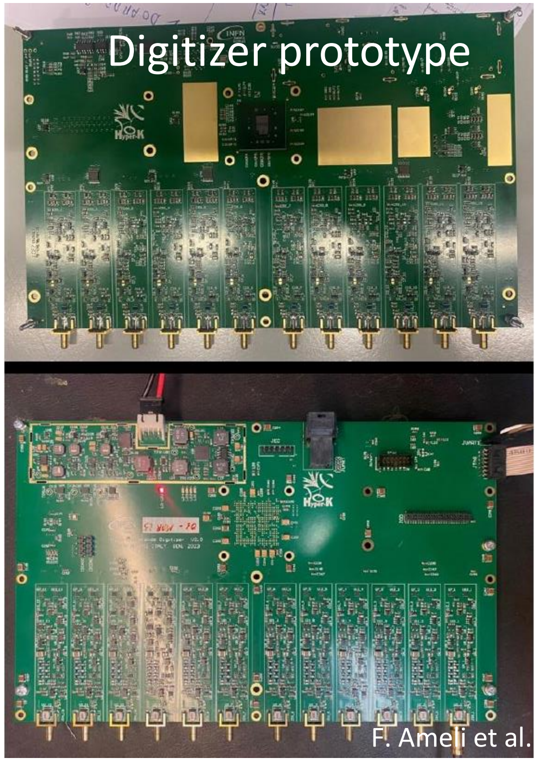
Electronics modules

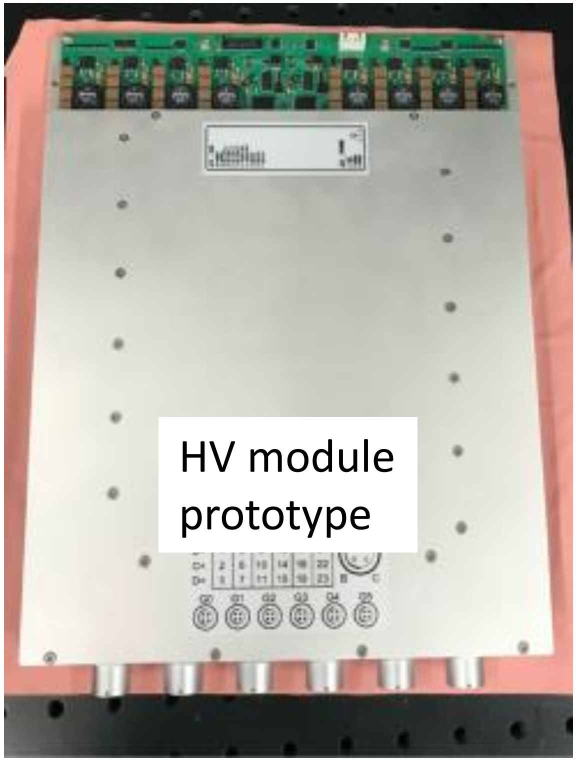
Digitizers, HV power supply module, and synchronization system

Developed prototypes and evaluated them with international collaborators.

Basic designs have been completed.







Finalize the design for mass production by the end of 2023.

Summary (SK)

- Since 2018, we have successfully improved various analysis tools.
- With the help of these improvements, we expanded the fiducial volume by 20%, from 22.5 kton to 27.2 kton.
- Available pure-water phase data set of atmospheric neutrino is now 484 kt·yr and we finished the neutrino oscillation analysis.

(Preliminary)	**Mass ordering**	$\left\|\Delta m^2_{32,31}\right\|$ $(10^{-3}\mathrm{eV}^2)$	$\sin^2\theta_{23}$	δ_{CP}	χ^2	$\chi^2_{N.O.-I.O.}$
SK ($\sin^2\theta_{13}$ constrained)	Normal	$2.40^{+0.24}_{-0.05}$	$0.475^{+0.057}_{-0.036}$	4.71	1004.56	-5.59
	Inverted	$2.40^{+0.11}_{-0.06}$	$0.475^{+0.063}_{-0.039}$	4.71	1010.15	

- New results of proton decay searches have been published.

$p \to e^+ + \pi^0$ — τ/Branch > 2.4x10^{34} yrs. (SK1 to SK4, 450 kt·yrs.)

$p \to \mu^+ + \pi^0$ — τ/Branch > 1.6x10^{34} yrs. (SK1 to SK4, 450 kt·yrs.)

$p \to \mu^+ K^0$ — τ/Branch > 4.5x10^{33} yrs. (SK4, 200 kt·yrs.)

(τ/Branch > 3.6x10^{33} yrs. (SK1 to 4, 370 kt·yrs.)

A. Takenaka et al. (SK Collab.), Phys. Rev. D 102, 112011 (2020)
R. Matsumoto et al. (SK Collab.), Phys. Rev. D 106, 072003

Summary (HK)

- Construction of the detector is going on as scheduled.
- Plan to start the experiment in 2027.

- Since 2018, we have developed various components for Hyper-Kamiokande.
- Basic designs of the critical components are completed.
  Mass production of PMT has been started.
  Performances of developed components have been confirmed.
- Now finalizing the design for mass production by the end of 2023.

Parallel session talk and posters from the SK and HK groups

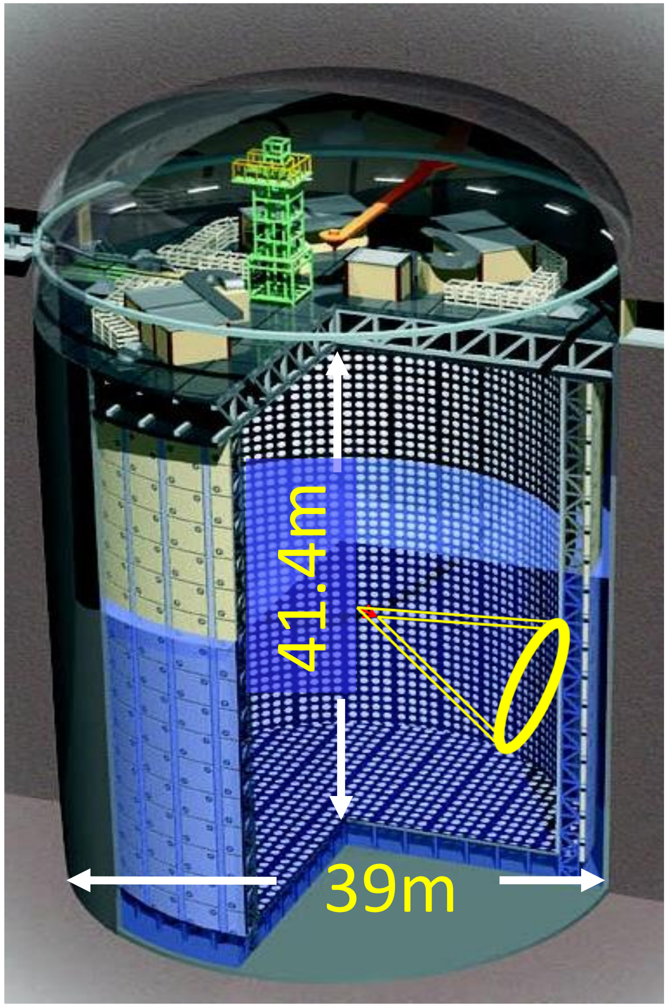
- “Detecting Supernova neutrino bursts in Super-Kamiokande”, Guillaume Pronost
- “A Noise Reduction Analysis of Photomultiplier Tubes for Neutron Tagging at Super-Kamiokande”, Yuto Maekawa
- “Measurement of the charge ratio and the spin polarization of the cosmic-ray muons with the Super-Kamiokande”, Tomoaki Tada
- “Lower Energy Extension in Anti-Electron Neutrino Measurement for DSNB Search”, Shota Izumiyama
- “Search for neutrinos associated with solar flares in the Super-Kamiokande detector”, Yuuki Nakano

- “Atmospheric neutrino reconstruction and oscillation analysis with neutron detection in SK-Gd”, Shintaro Miki
- “Measurement of cosmogenic Li-9 in SK-Gd”, Masataka Shinoki
- “Study of energy scale calibration and monitoring of detector stability using cosmogenic neutron in SK-Gd”, Shizuka Shima

- “Development of the Electronics for Hyper-Kamiokande”, Yousuke Kataoka
- “Performance evaluation of 50cm PMTs for calibration of the Hyper-Kamiokande detector”, Eiichiro Watanabe
- “Status of anti-chain-implosion cover for 20inch PMT in Hyper-Kamiokande”, Jun Kameda

Super-Kamiokande

50000 tons Ring imaging Water Cherenkov detector



Inner detector photo coverage 40%
(except for SK II)

Pure water phases

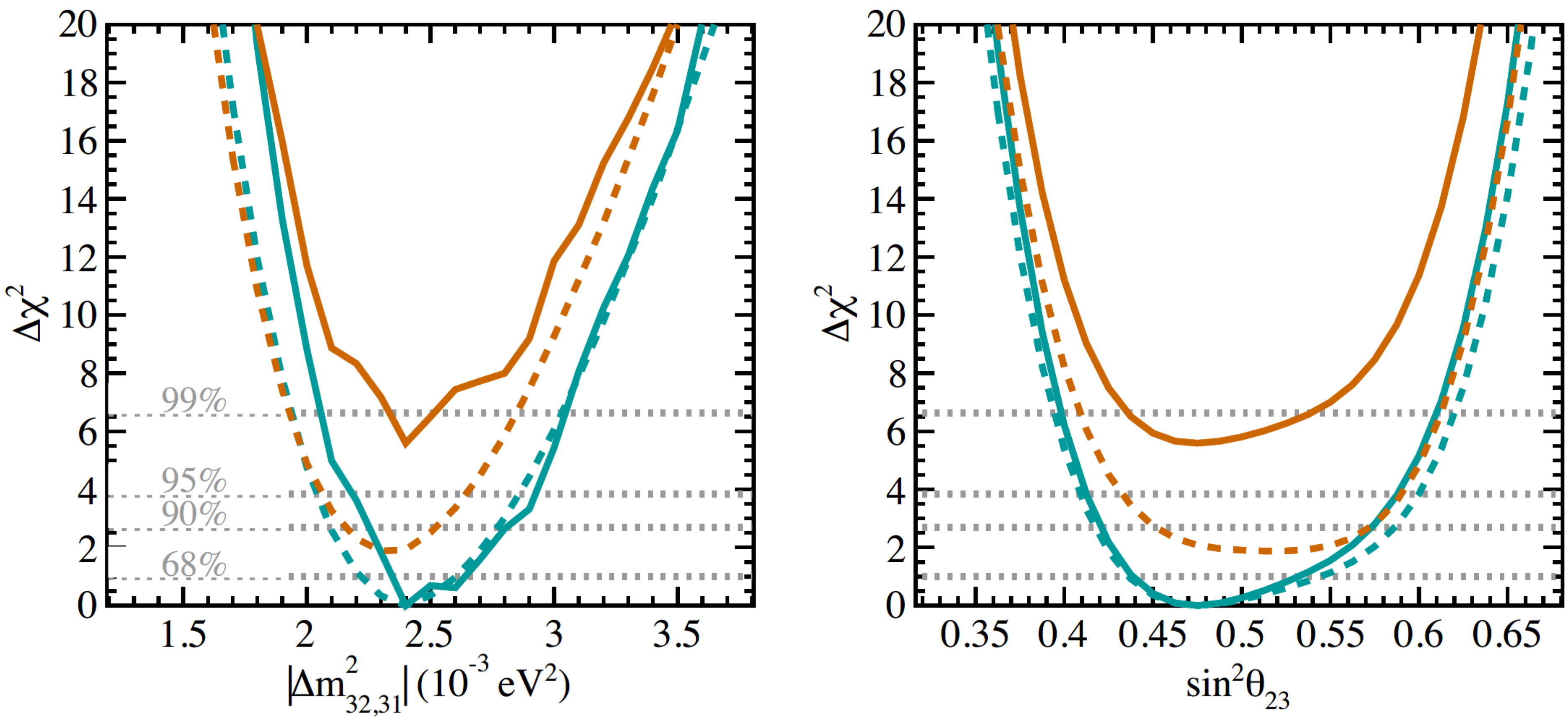
Super-Kamiokande I (Apr. 1996 to Jul. 2001)
Super-Kamiokande II (Oct. 2002 to Oct. 2005)
(half density)
Super-Kamiokande III (Jul. 2006 to Aug. 2008)
Super-Kamiokande IV (Sep. 2008 to May 2018)
Super-Kamiokande V (Jan. 2019 to Jul. 2020)

Gadolinium loaded phases (SK-Gd)

Super-Kamiokande VI (Jul. 2020 to May 2022)
with 0.01% Gd.
Super-Kamiokande VII (Jul. 2022 ～)
with 0.03% Gd.

Inner detector 11129 20” PMTs

Outer detector 1885 8” PMTs



20
18
16
14
12
10
8
6
4
2
0
$\Delta\chi^2$
99%
95%
90%
68%
1.5
2
2.5
3
3.5
$|\Delta m^2_{32,31}|$ $(10^{-3}$ eV$^2)$
0.35
0.4
0.45
0.5
0.55
0.6
0.65
$\sin^2\theta_{23}$