ハイパーカミオカンデの建設状況とマルチメッセンジャー天文学に対する展望

Construction status of Hyper Kamiokande and its prospects for multi-messenger astronomy

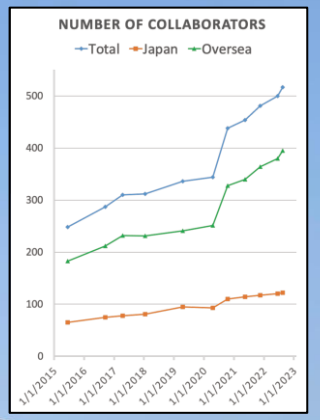
Yoichi Asaoka (UT/ICRR, Kamioka Observatory)
on behalf of the Hyper-Kamiokande collaboration

「次世代ニュートリノ科学・マルチメッセンジャー天文学連携研究機構」キックオフ研究会

HYPER-K COLLABORATION

Broadening of the international collaboration

~600 collaborators (incl. 25% of Japanese), 22 countries, and 102 institutes. Funding secured in several countries.



March 2023, 1st in-person Collaboration Meeting @ Toyama

Outline

- Introduction
  - Hyper-Kamiokande project
  - HK physics
- Construction Status
  - Cavern excavation
  - Detector components
  - Neutrino beam upgrade
- Multi-Messenger Astronomy w/ Hyper-K
  - Supernova neutrino
  - Sensitivity for Transient Objects
- Summary and Prospects

Introduction

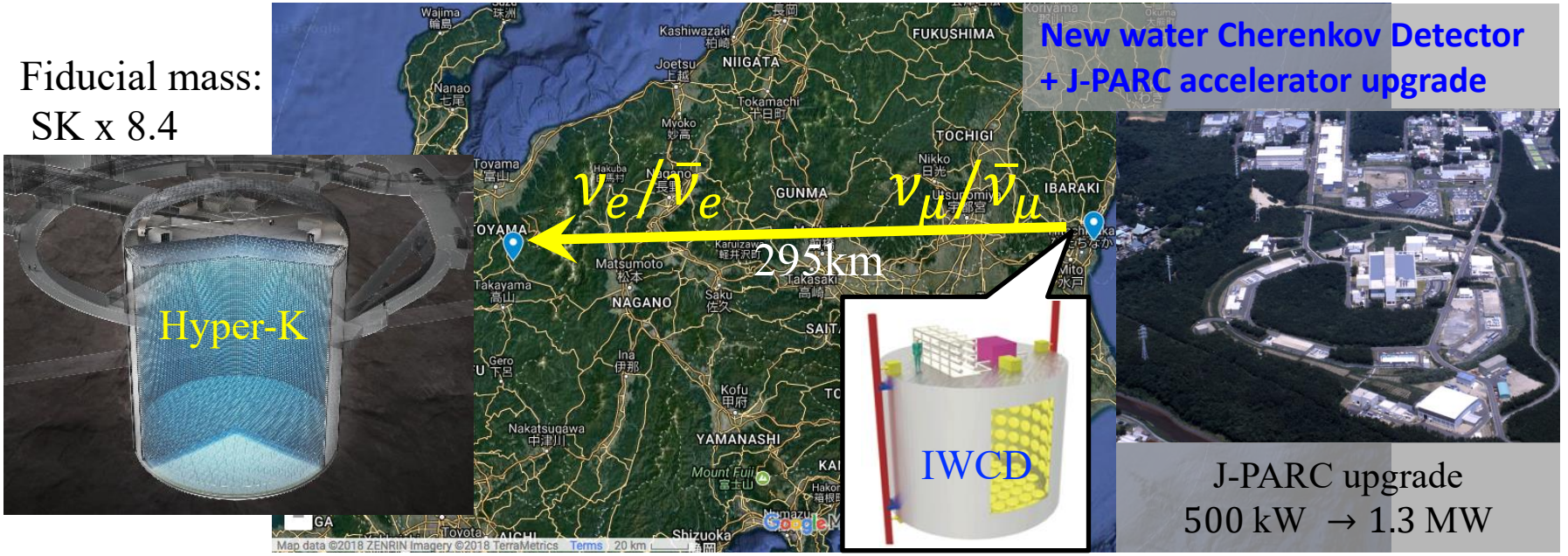
Hyper-Kamiokande Project

University of Tokyo and KEK host the project

HK officially started construction on 2020 and will start operations on 2027.

HK will provide international core equipment for particle physics and astrophysics for more than 20 years.

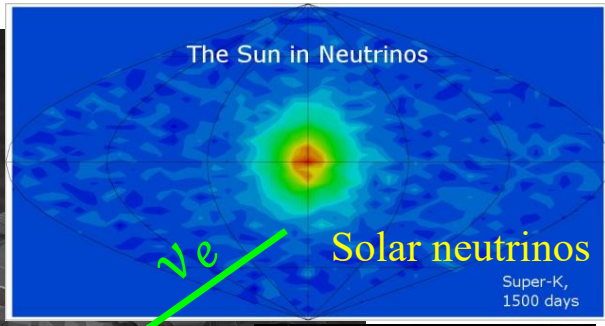
Fiducial mass:
SK x 8.4

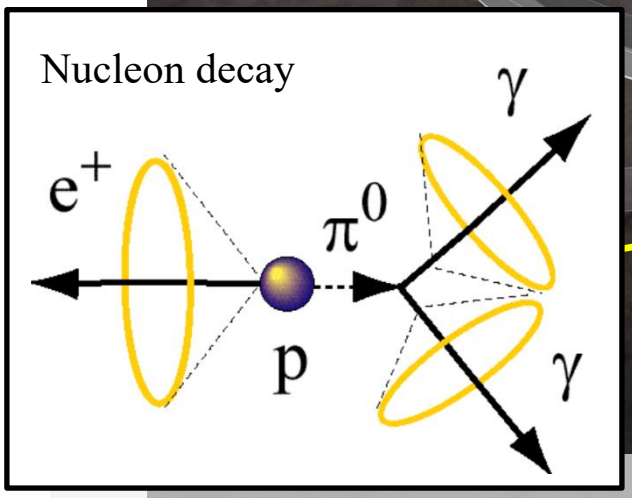


Key features:

1. The world's largest detector for nucleon decay and neutrino experiment
2. World's most-intense neutrino beam
3. New and upgraded near detectors to control systematics

Hyper-K Observation Target





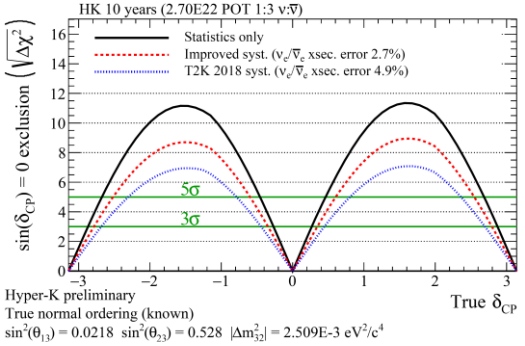
Physics Target :

Lepton CPV measurement, Nucleon decay discovery,
precision measurement of neutrino oscillations, SN neutrinos, and more.

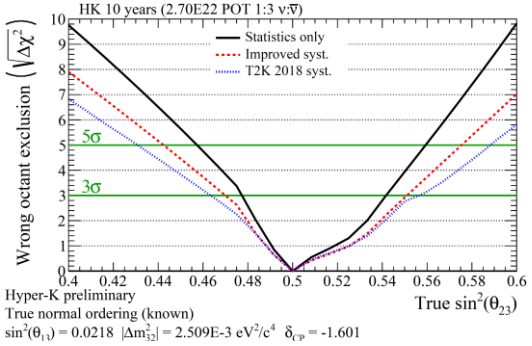
Broad Physics and Discovery Potential

Understanding of neutrino oscillation

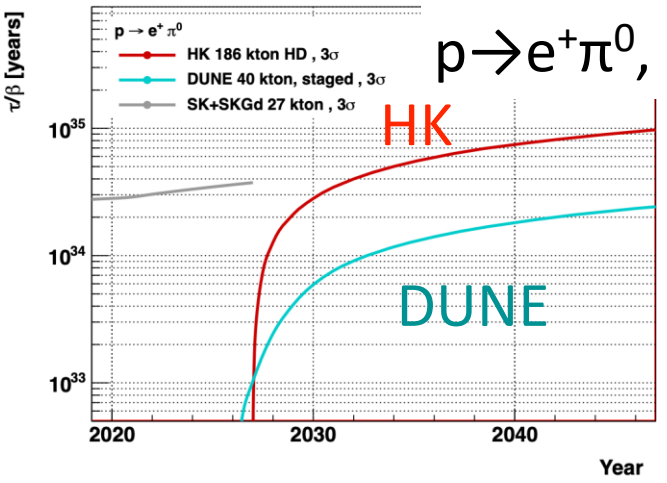
CPV discovery



Wrong octant exclusion



Nucleon decay search

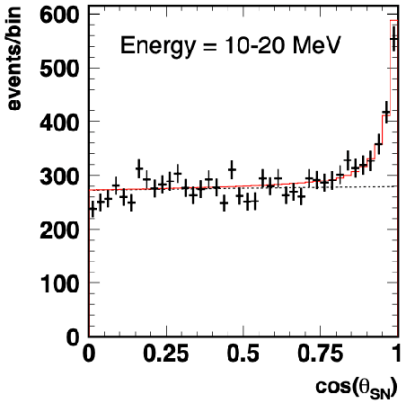


$p \rightarrow e^+\pi^0$, 3σ

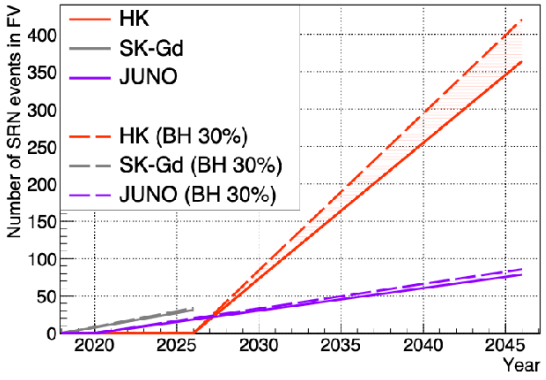
10^{35}yr

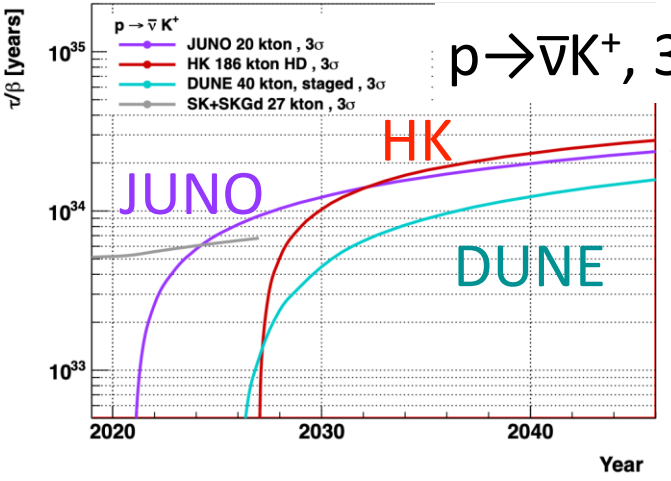
Neutrino astronomy

ν burst from SNe



Supernova relic neutrinos

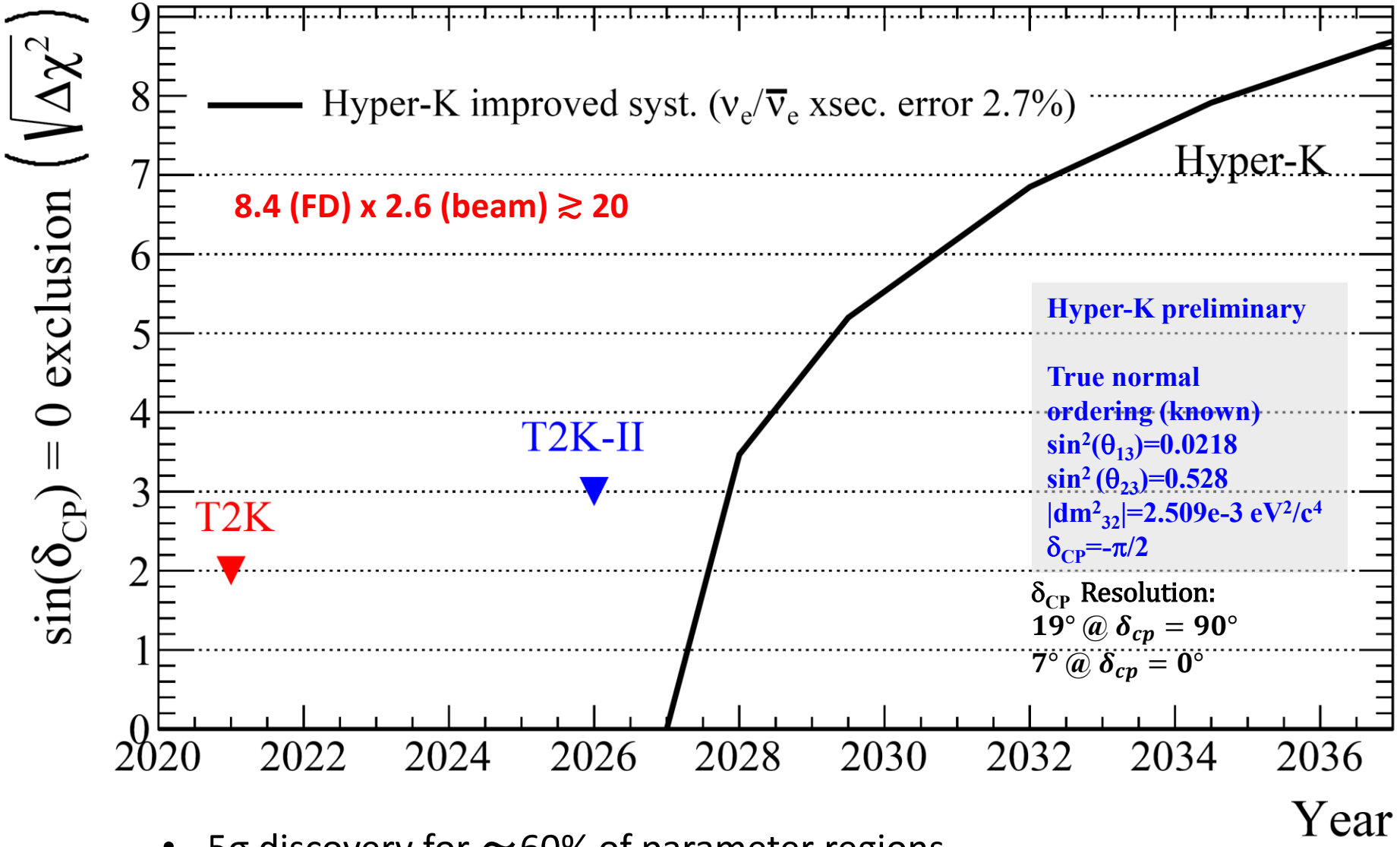




$p \rightarrow \bar{\nu}K^+$, 3σ

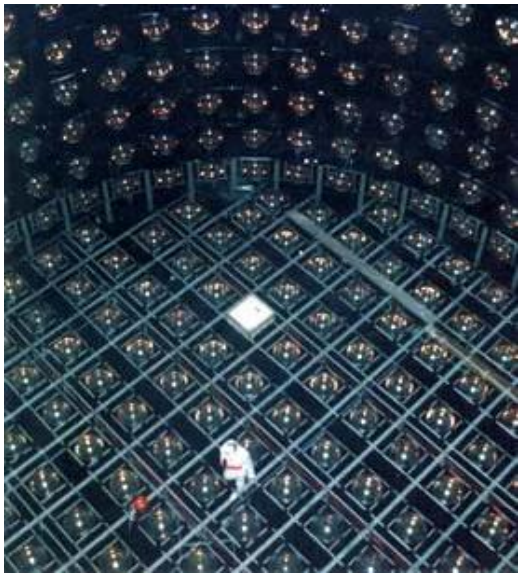
3×10^{34}yr

Lepton CPV: Sensitivity and Measurement Capability



- 5σ discovery for ~60% of parameter regions
- Severe competition and important synergies with DUNE

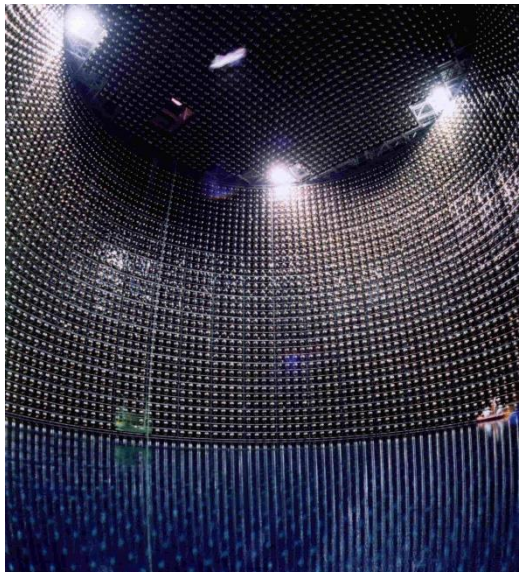
Three Generations of Water Cherenkov Detector in Kamioka



Kamiokande
(1983-1996)

Birth of neutrino astrophysics

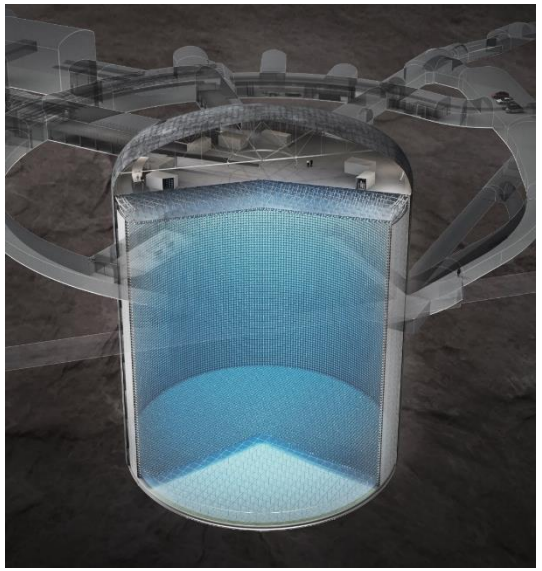
M_{tank} = 3kt, M_{eff} = ~1kt
#PMTs = 948



Super-Kamiokande
(1996 - ongoing)

Discovery of neutrino oscillations

M_{tank} = 50kt, M_{eff} = 22.5kt
#PMTs = 11,146



Hyper-Kamiokande
(start operation in 2027)

Explore new physics

M_{tank} = 260kt, M_{eff} = 188kt
#PMTs = 40,000 (T0~20,000)

1. Area vs volume: effective scale up as long as water transparency allows.
2. Optimization of the detector configuration based on experience.

Construction Status

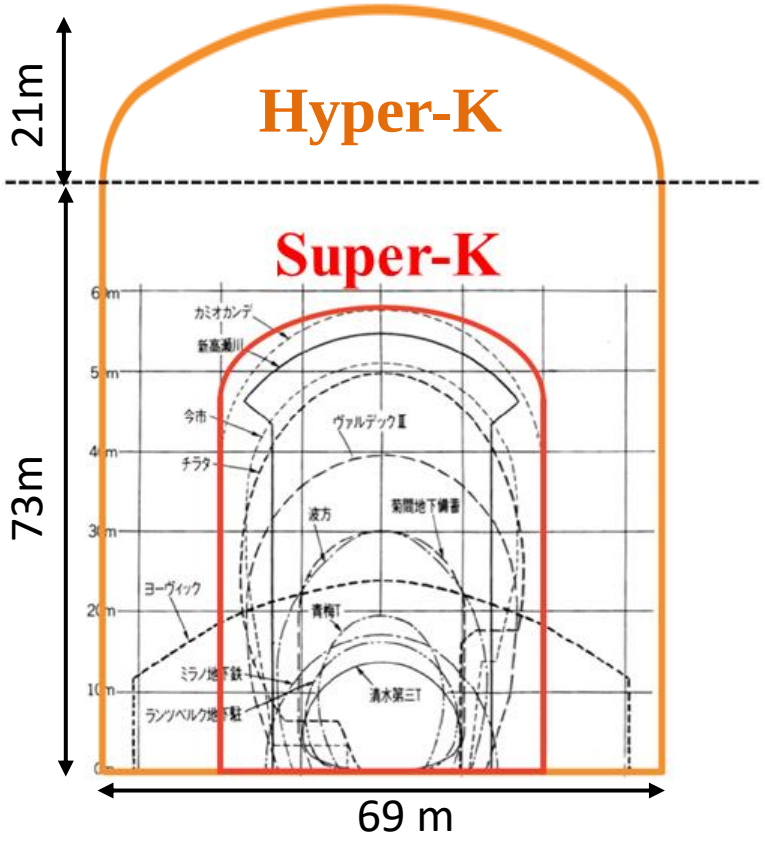
231003 Completion of the Dome Section

Huge underground space excavated: Diameter = 69m, Height = 21m
The dome section supporting 600m ground pressure is a key to the cavern stability.

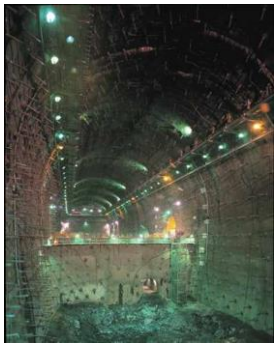
https://www-sk.icrr.u-tokyo.ac.jp/news/detail/1299/

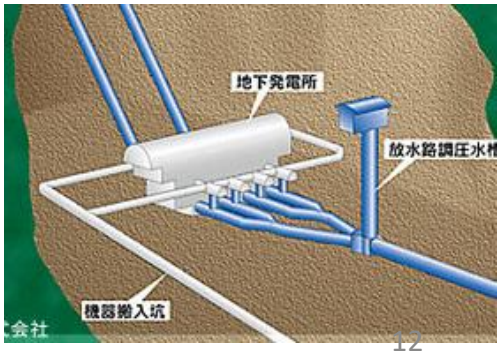
Cavern Excavation

- Excavation of world's largest cavern:
  one of the major milestone for Hyper-K
  - Past huge caverns in Japan: Underground power plants excavated 20-30 years ago.
- Design of the HK cavern:
  based on the cavern stability analysis using the various geological survey
  - 3D analysis necessary due to axisymmetric ground pressure and cylindrical cavern shape.
  - Recent progress in CPU and storage made 3D analysis possible.
- Information-oriented excavation:
  mandatory to approach necessary and sufficient conditions
  - Impossible to survey all surrounding rock mass.
  - Measurements and geological information readily available during the excavation are used to update the rock support design.
- Short construction period and safety
  - 48 months total, 2 shifts 2 crews per day
  - Early contractor involvement (ECI)

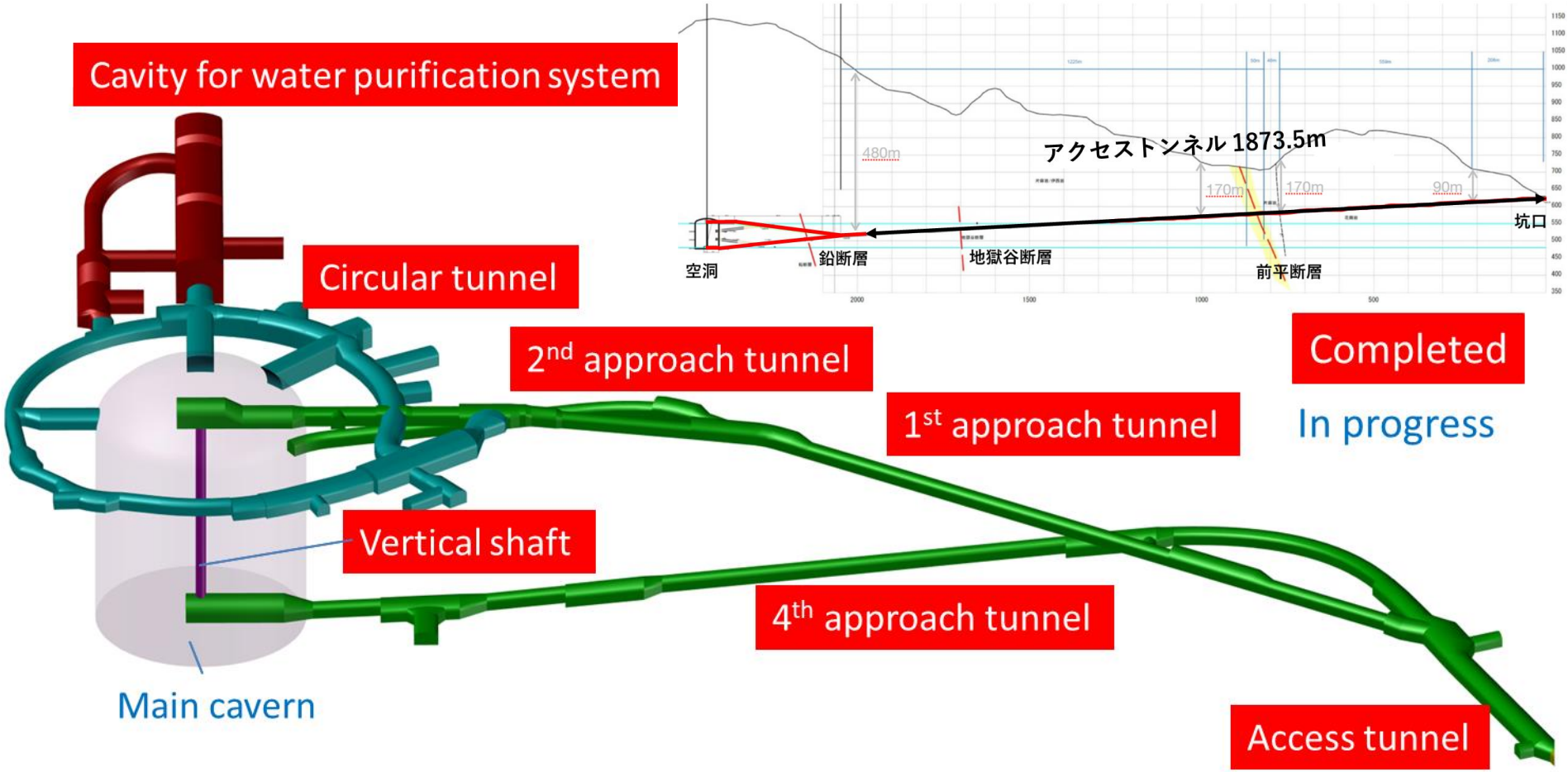


An example of underground power plants



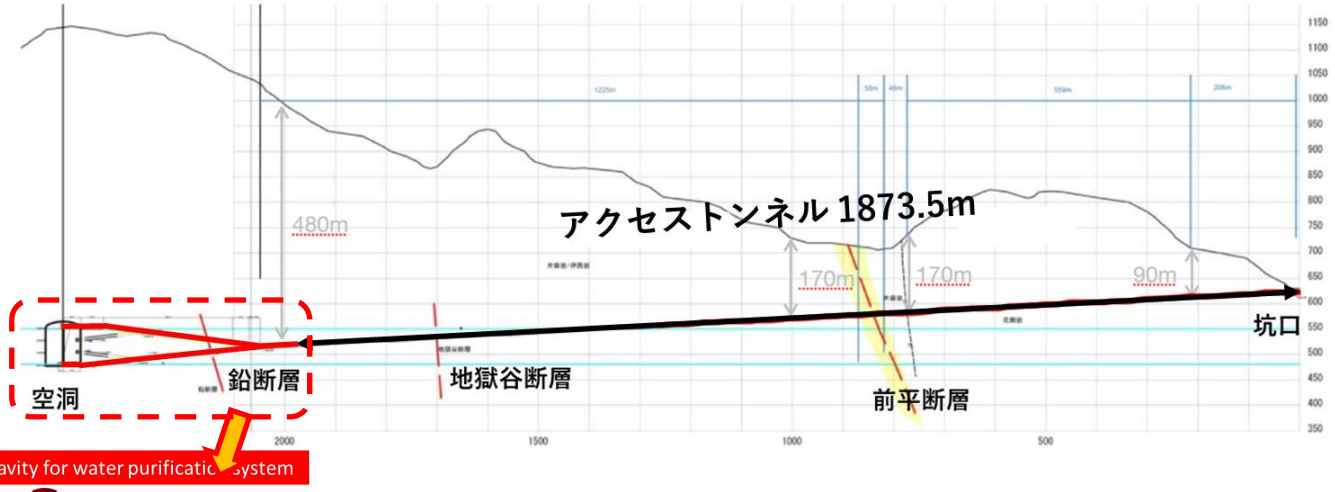


Overview of the HK Cavern Excavation



- Excavation of all tunnels completed.
- Excavation of the water system cavity was completed in May 2023.
- Excavation of the dome section of the main cavern has been completed in Oct. 2023.

Progresses of the HK Cavern Excavation (2021-2022)



A survey tunnel excavated from the existing mine tunnel was connected to HK tunnel.

Cavity for Water Purification System

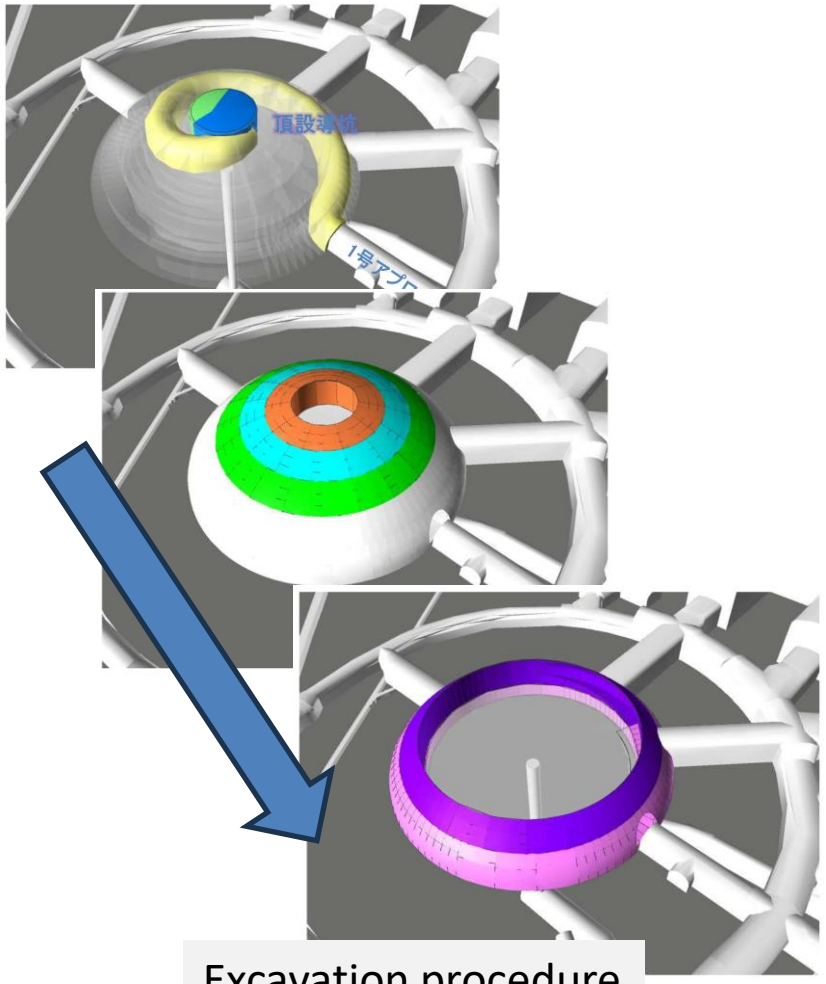
Completed on May 29, 2023

Size: 16m (W) x 17m (H) x 101m (L)

added for web version

Excavation Step and Rock Support Design

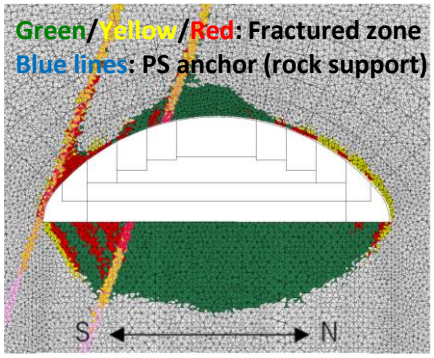
- After excavating a spiral-shaped tunnel to top of the dome, actual dome excavation finally started on November 2022.
- Cavern stability analysis and rock support design was fixed to start excavation at that time and is continuously updated by information-oriented excavation.



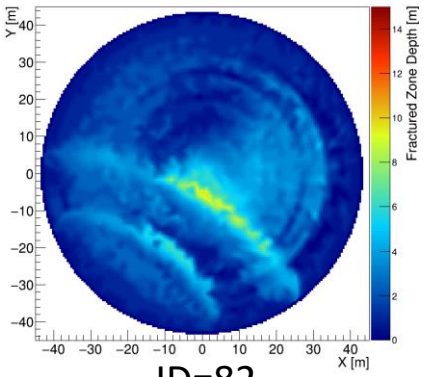
Excavation procedure

Original Model

Damaged Zone (NS)



Damaged Zone Depth



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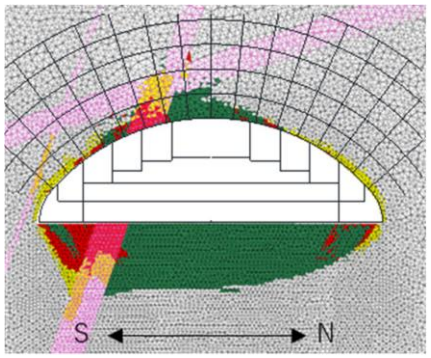
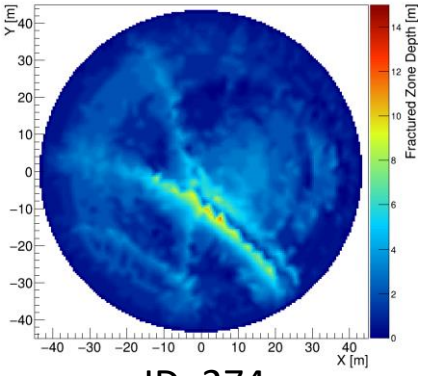
Updated Model

Damaged Zone (NS)



Damaged Zone Depth



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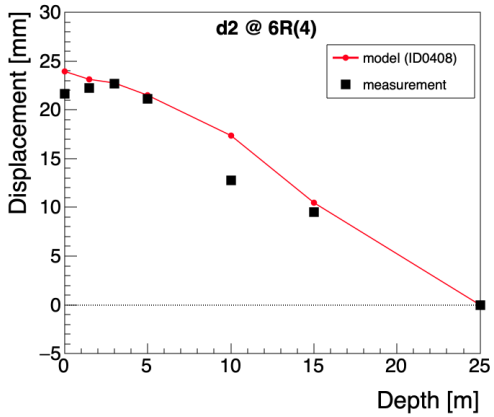
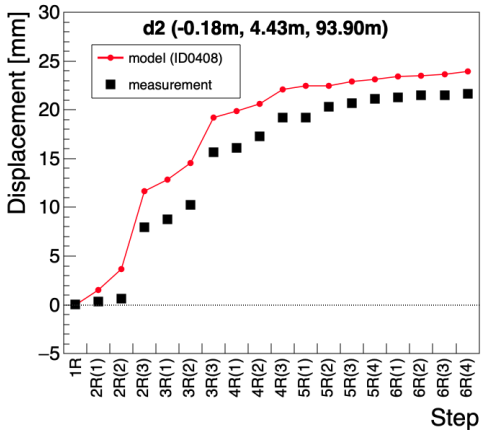
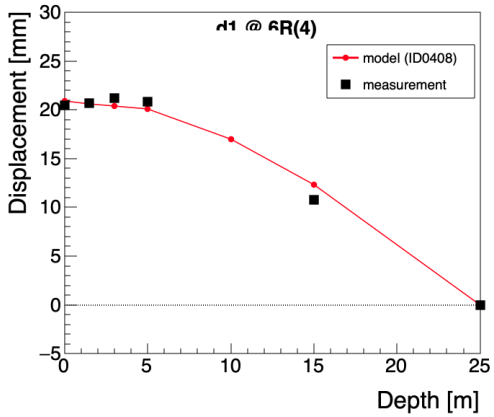
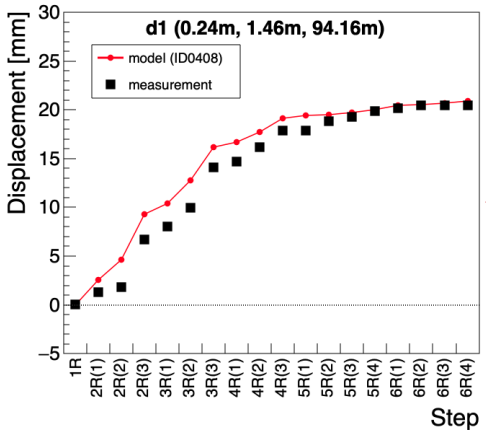
Rock support design

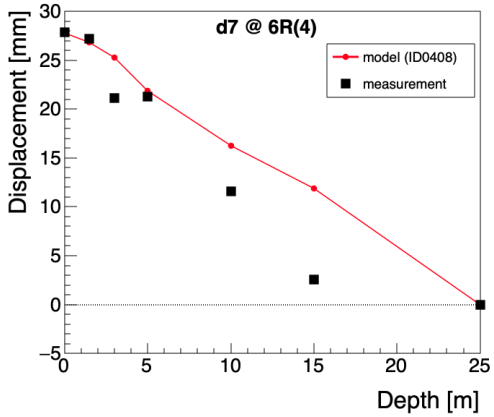
Information-Oriented Excavation

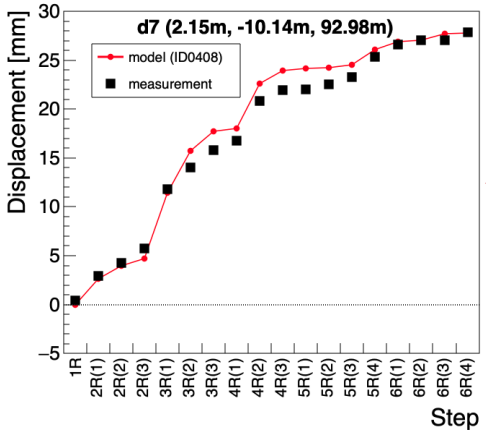




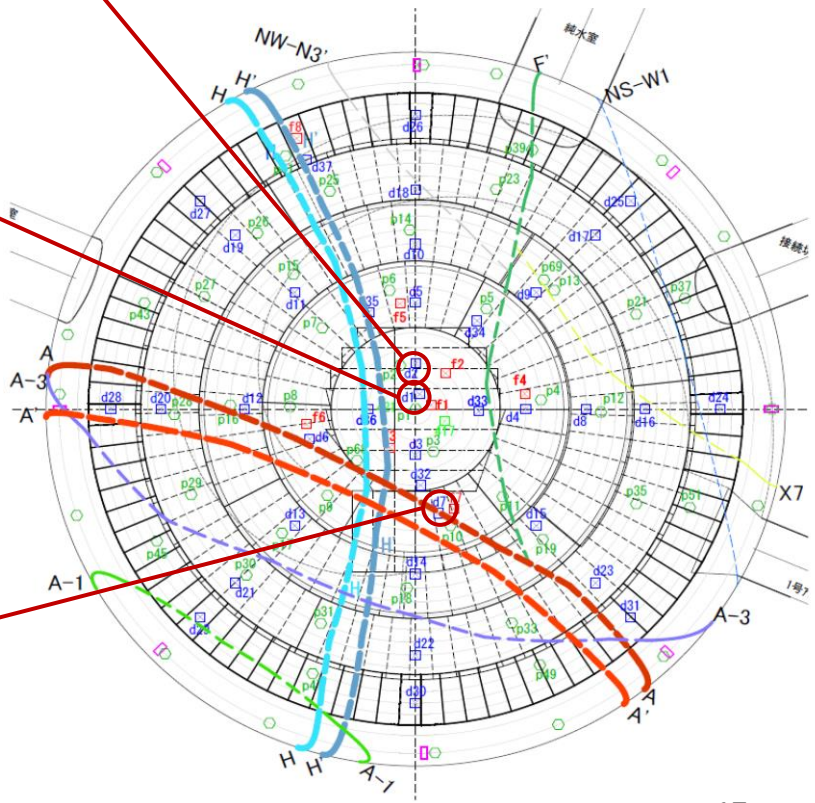








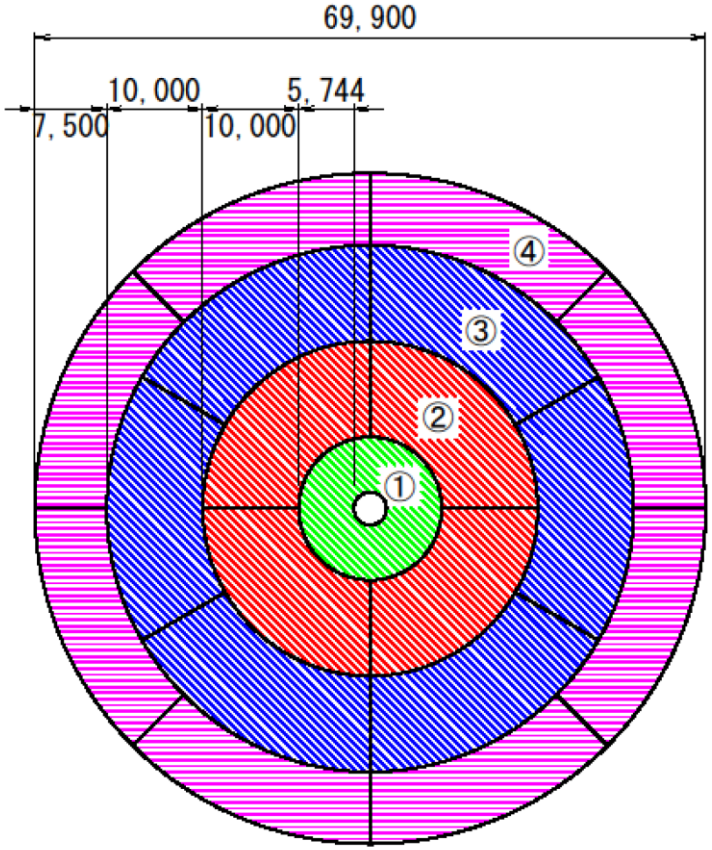
- Currently 37displacement sensors and 39 stress sensors are installed to monitor the behavior of the rock mas during the excavation.
- The history and depth dependence of the displacement measurements generally agree with the cavern stability simulation result.

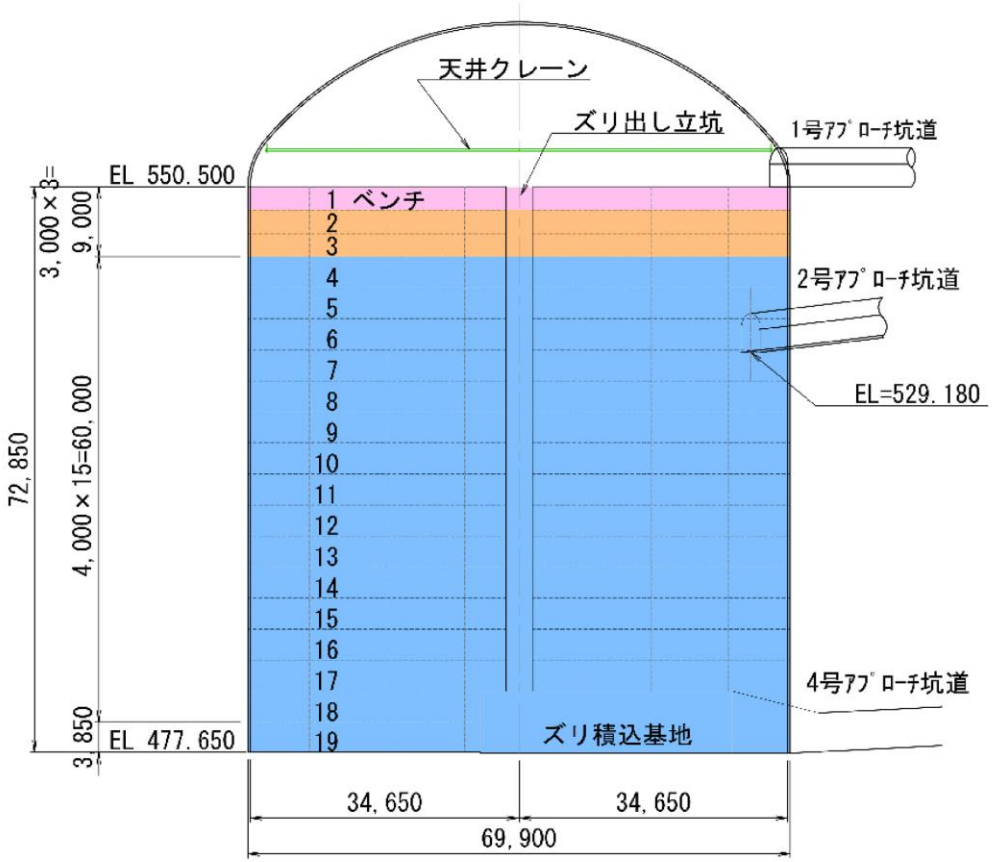


計器配置　平面図

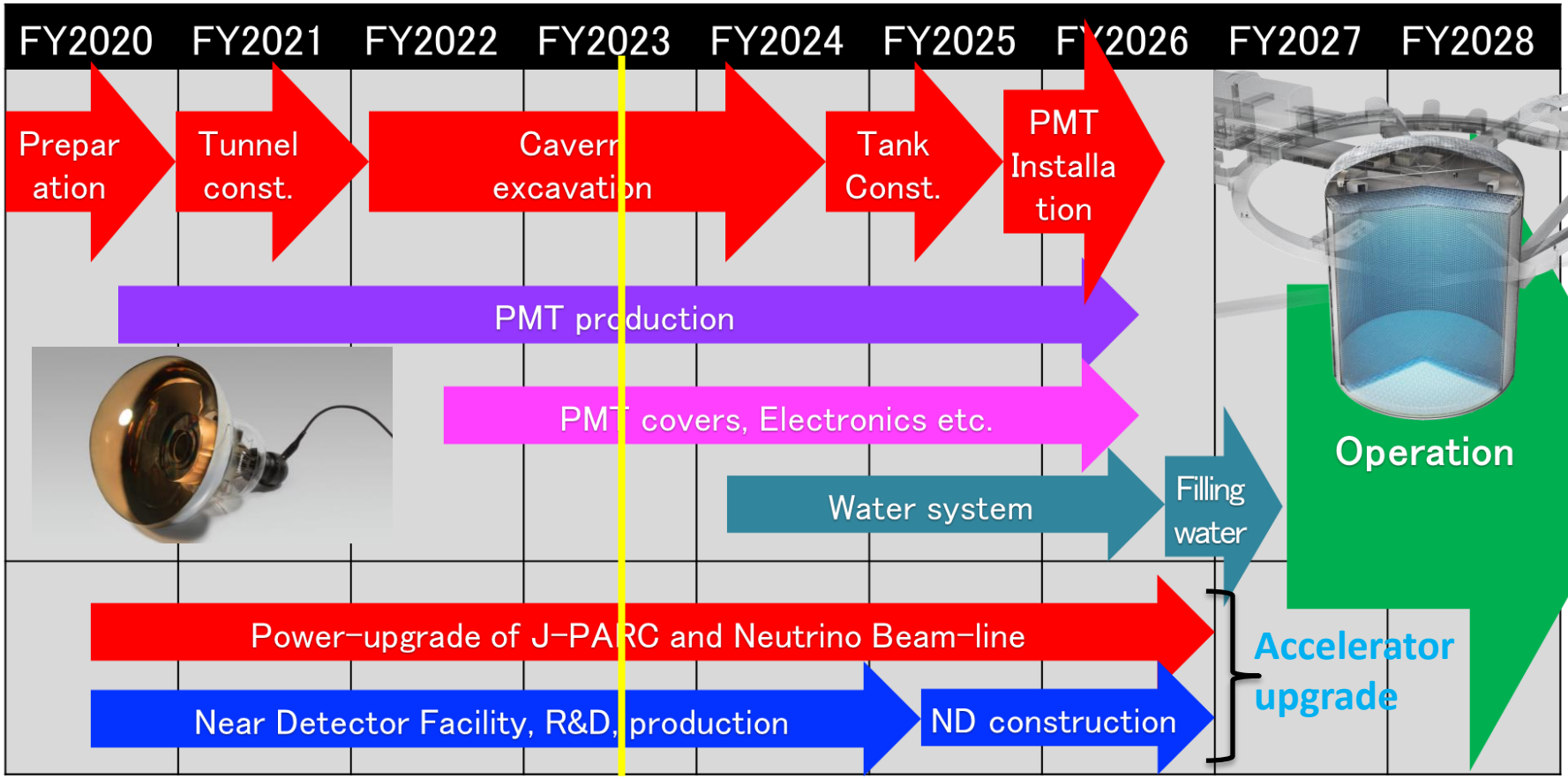
Barrel Excavation

- Excavation from top to bottom by 3 or 4 meters.
- Efficient disposal of excavated rocks by using vertical shaft.





Hyper-K Construction Schedule



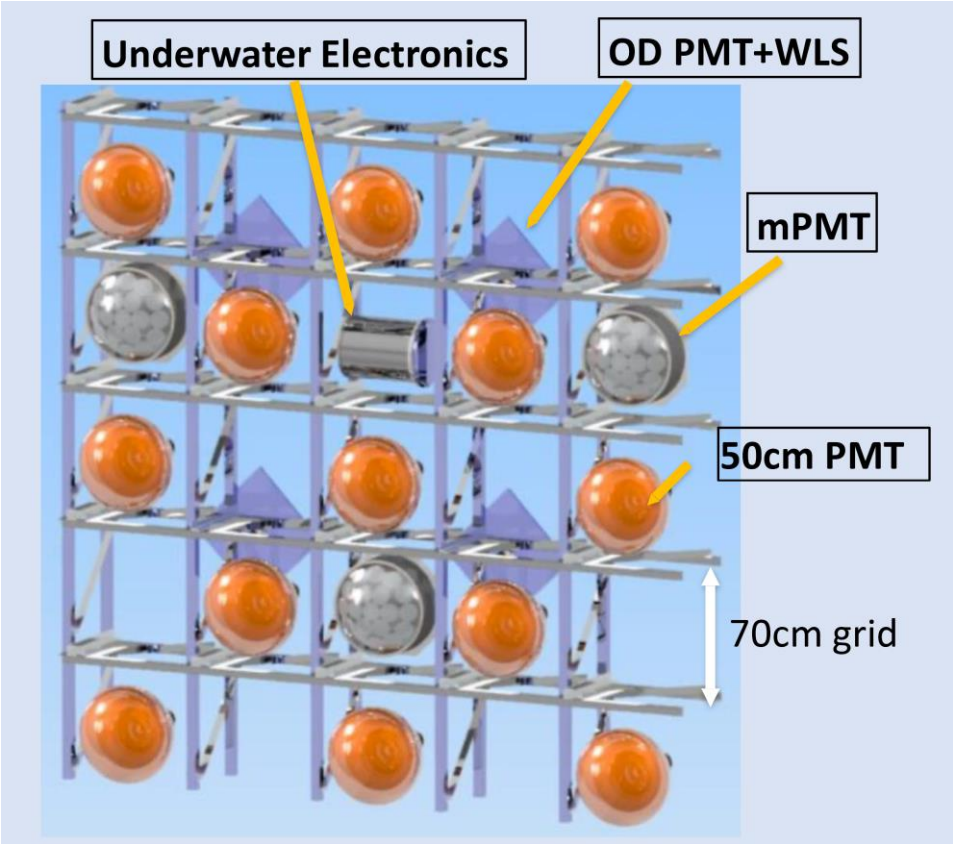
- HK construction is in progress as scheduled.
  - Main cavern's dome section completed!
  - Achieved a critical milestone in HK construction.
- Hyper-K is becoming a reality.

50cm Photo-Sensors

- Mass production started in Dec. 2020.
- Production suspended in April 2022 to investigate higher defect rate.
- From May 2023, production resumed after improvement and screening by manufacture.
- The date of completion of delivery remains unchanged.
- Constant quality inspections ongoing.

Hyper-K Detector Configuration

- Inner Detector (ID)
  - ϕ64.8m, H65.8m
  - 50cm PMTs will be installed.
  - Multi-PMT (mPMT) modules will be integrated as hybrid configuration
- Outer Detector (OD)
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered by high-reflectivity Tyvek sheets
- Under water electronics
  - Mitigate disadvantage of long cables



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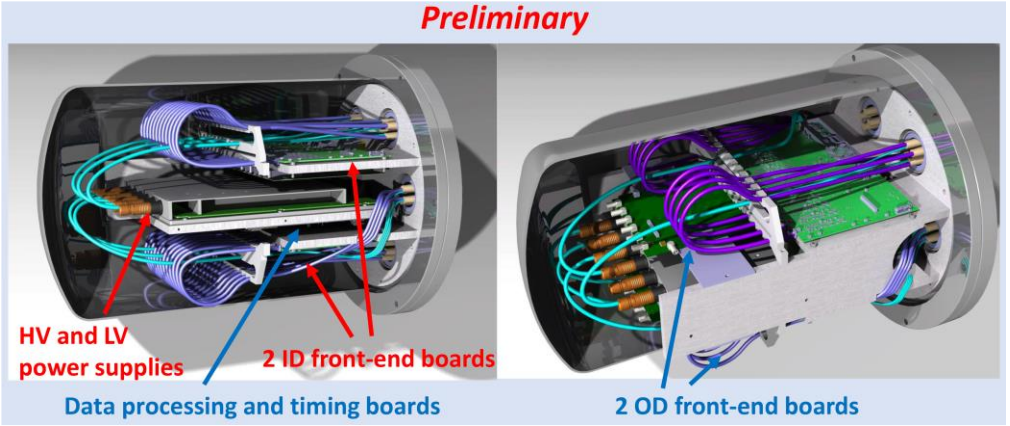
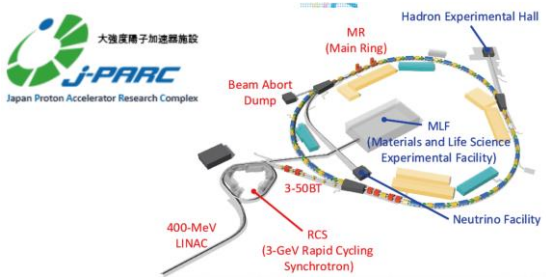


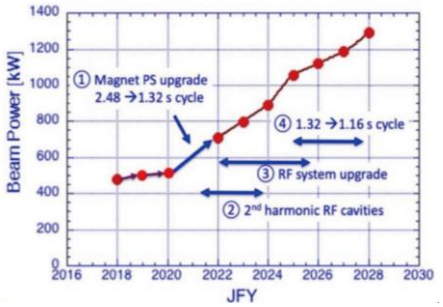
- Under water electronics
  - Mitigate disadvantage of long cables

Design finalization is ongoing!

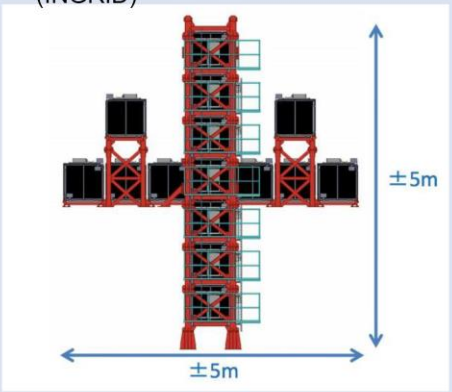
J-PARC & Near Detector Complex

- J-PARC:
  - Neutrino beam upgrade to 1.3 MW ongoing.
    - Power supply upgrade: 250kA -> 320kA
    - Cycle: 2.48s -> 1.32s -> 1.16s/cycle
- Near Detector complex:
  - Upgrade by T2K experiment ongoing.
  - Design of Intermediate Water Cherenkov Detector (IWCD) being finalized.

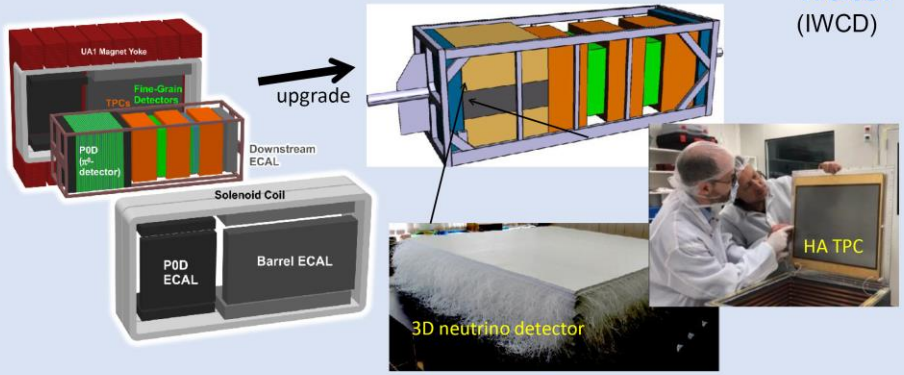




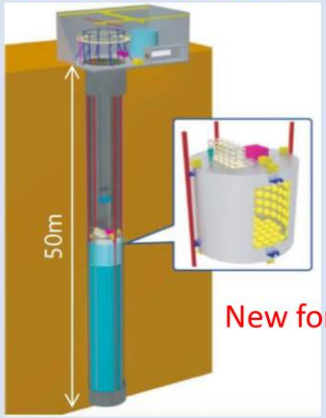
On-axis Detector
(INGRID)



Off-axis Magnetized Tracker
(ND280→Upgrade for T2K →Upgrade for HK)



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)

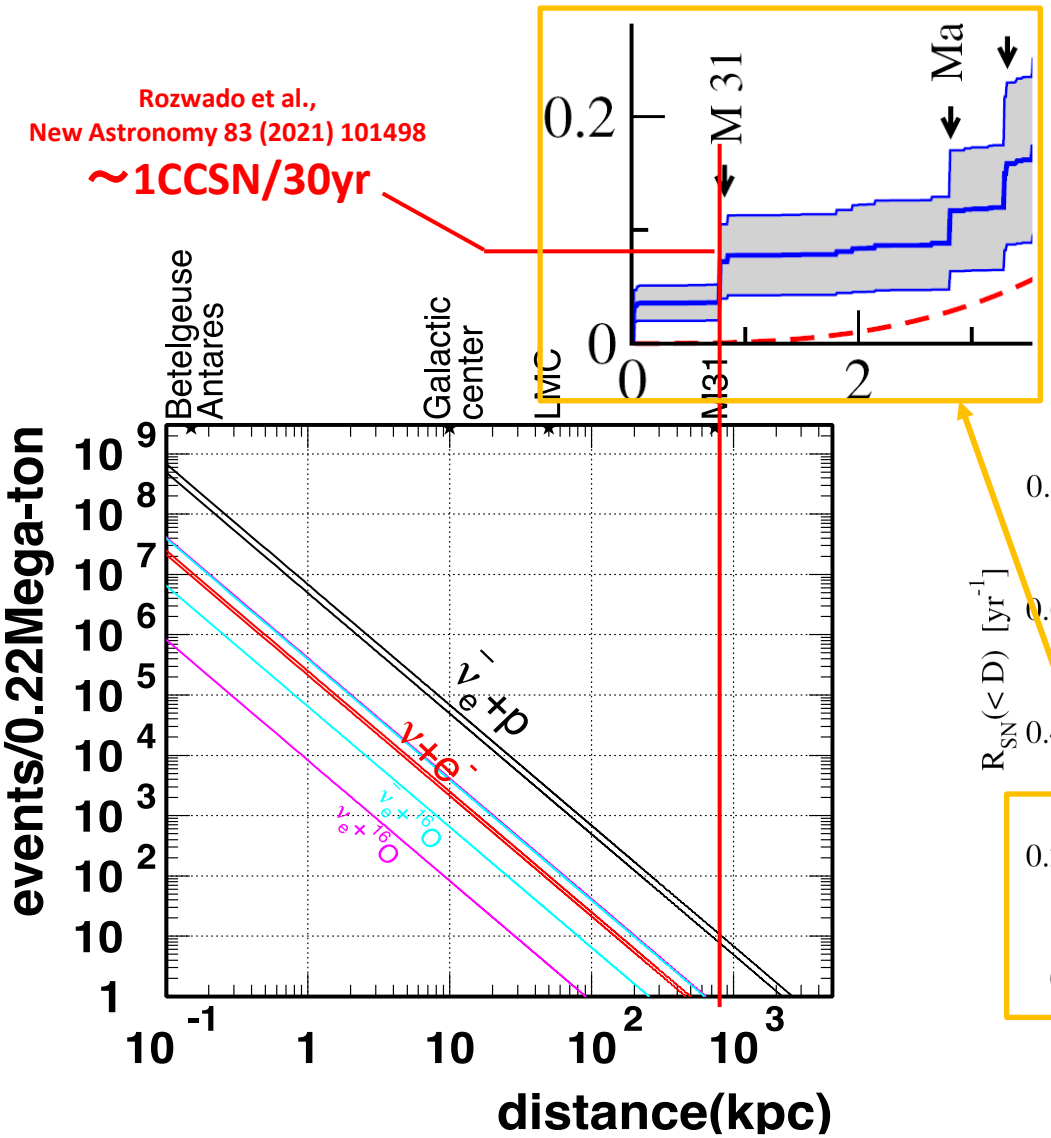


Multi-Messenger Astronomy w/ HK

Supernova Neutrino Detection

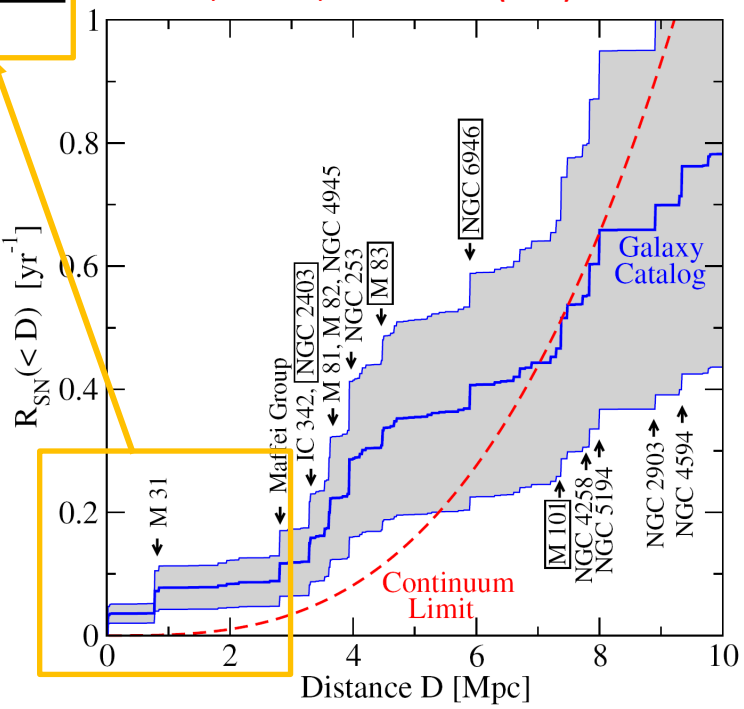
Heart of the multi-messenger astronomy with HK: 8.4 times larger effective mass than SK

Rozwado et al.,
New Astronomy 83 (2021) 101498
~1CCSN/30yr



- 100% detection of CCSNe at M31/M33
- Real time follow up may be possible due to limited number of corresponding galaxies.

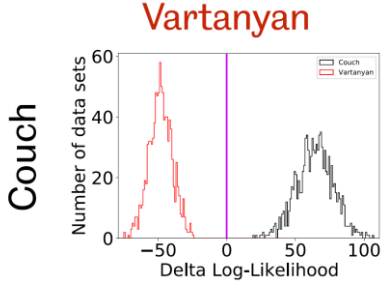
Ando, Beacom, Yuksel PRL 95 (2005) 171101



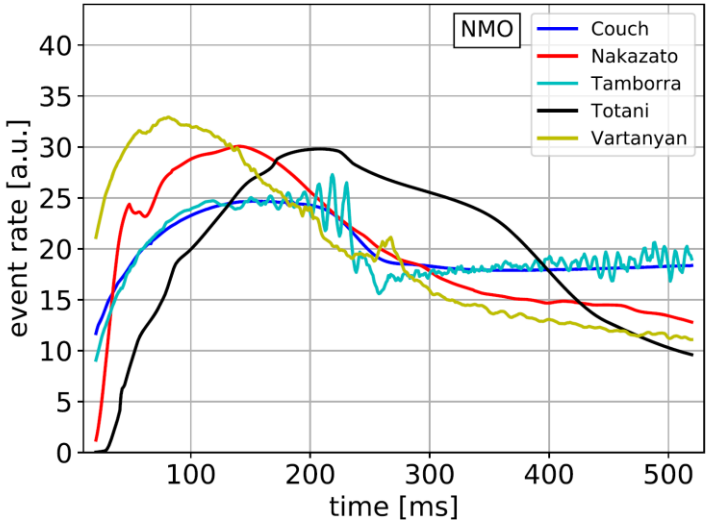
Supernova Model Discrimination

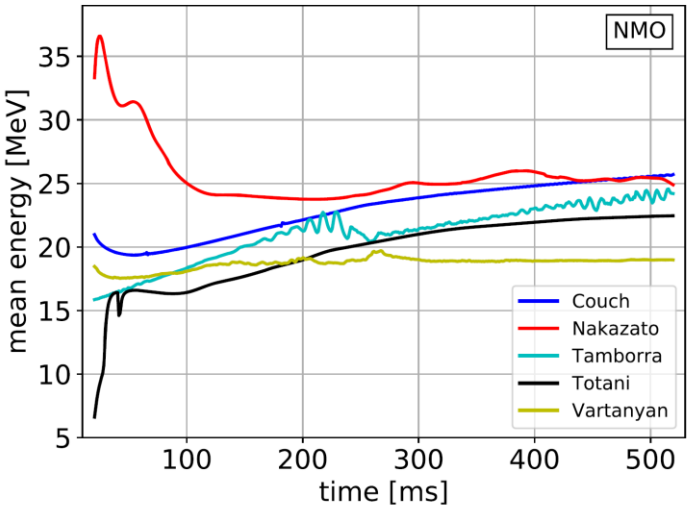
- To understand explosion mechanism, need to compare observation with simulations.
- 5 representative models are compared by using energy & time of events detected 20-520ms after core bounce.
  - Full detector simulation
  - Unbinned likelihood
- Model discrimination is surely possible at LMC (50kpc).

An example (300ev)



HK Collab., ApJ 916:15, 2021





Model	Normal Mass Ordering		
	$N_{10\ \mathrm{kpc}}$	d_{100}	d_{300}
Totani	20021	141 kpc	82 kpc
Nakazato	17978	134 kpc	77 kpc
Couch	27539	166 kpc	96 kpc
Vartanyan	10372	102 kpc	59 kpc
Tamborra	25025	158 kpc	91 kpc

Coincidence Search with GW/HEν/HEγ

Energy Flux Sensitivity of Hyper-Kamiokande **Preliminary**

Simple rescaling of SK sensitivity (performed with full simulation/reconstruction) in terms of $A_{\rm eff}$ and background rate.

Assuming E^{-2} spectrum and $\begin{cases} E_{\rm min} - E_{\rm max} = 0.1 - 100 \text{ GeV for FC+PC} \\ E_{\rm min} - E_{\rm max} = 1.6 - 10^5 \text{ GeV for UPMU} \end{cases}$

Sample	Flavour	Average $E^2 dn/dE$ sensitivity [GeV.cm^{-2}] *Super-Kamiokande*	*Hyper-Kamiokande*
FC+PC	ν_μ	$3.16 \cdot 10^3$	$3.78 \cdot 10^2$
FC+PC	$\bar{\nu}_\mu$	$7.35 \cdot 10^3$	$8.78 \cdot 10^2$
UPMU	ν_μ	$3.76 \cdot 10^1$	9.95
UPMU	$\bar{\nu}_\mu$	$5.43 \cdot 10^1$	$1.44 \cdot 10^1$

- SK -> HK scaling
  - FC/PC (4π) x ~8 improvement (by effective volume)
  - UPMU (2π) x ~4 improvement (by cross-sectional area)
- Depending on the source neutrino spectrum, i.e., steeper spectrum and/or high energy cutoff, lower energy can be more relevant for coincidence detection.

Studied by M. Lamoureux

updated for web version

Summary and Prospects

- Hyper-K will provide international core equipment for particle physics and astrophysics for more than 20 years.
- **Multi-messenger astronomy with Hyper-K:**
  - A CCSN detection will trigger the “once-in-a-lifetime event”.
  - Counterpart search with a better sensitivity than Super-K for all transients, e.g. GW events.
- **Hyper-K is becoming a reality.**
  - Dome section (ϕ69m x 21m H) completed; key to the cavern stability.
  - Barrel section will be completed within a year.
  - 50cm PMTs are delivered.
  - Desing finalization of various detector components are ongoing.
  - J-PARC neutrino beam and ND complex upgrades are in progress.
  - Design of IWCD (new for HK) is being finalized.