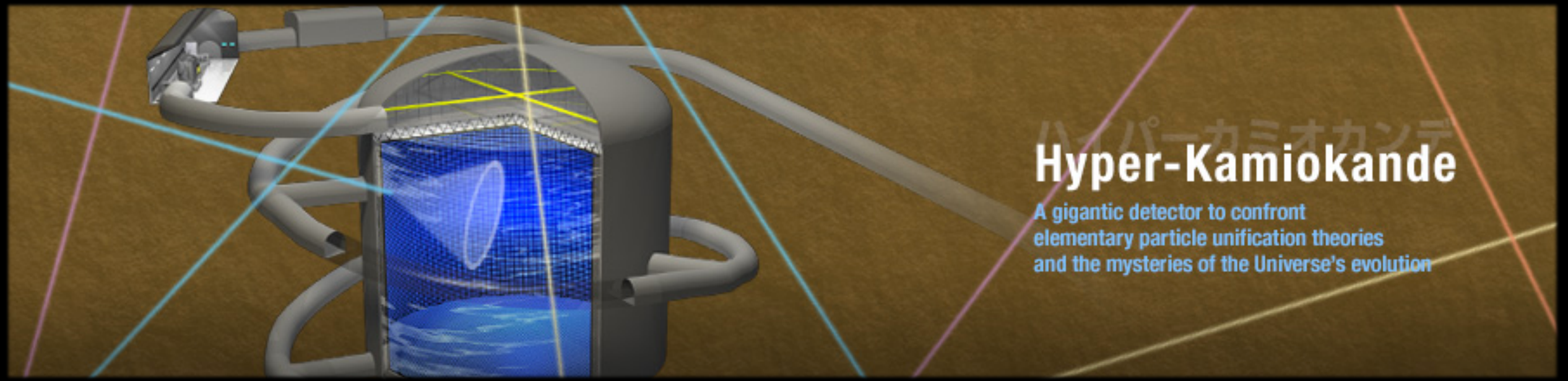
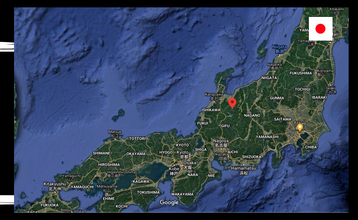
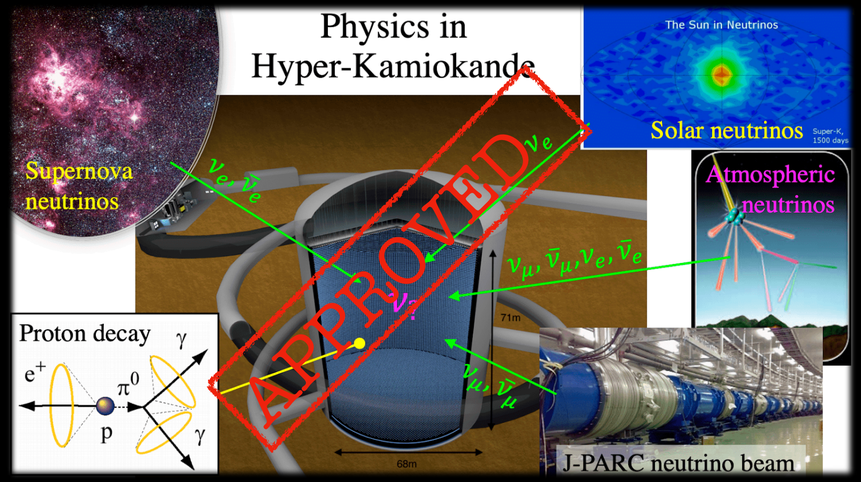


Hyper-Kamiokande Construction

Francesca Di Lodovico for the Hyper-Kamiokande Collaboration

The Hyper-Kamiokande Experiment

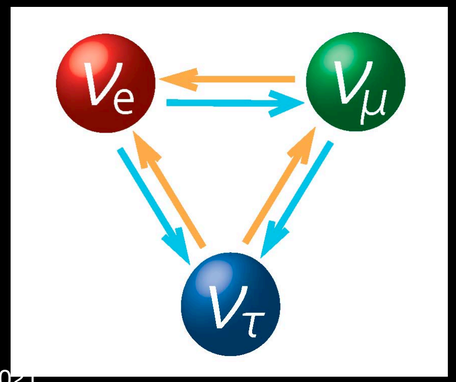




- Multi-purpose experiment
  - Beam physics
  - Astrophysical observatory
  - Rare (e.g.proton) decays

Neutrino Oscillations

Neutrino Oscillations will be measured based on **accelerator** and **atmospheric** neutrinos

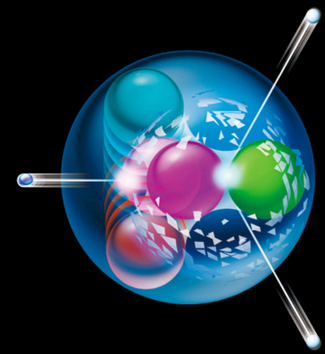


Astrophysical Neutrinos

Solar, **supernova**, and **supernova relic** neutrinos will be explored for astronomical research.

Rare Decays

Rare processes such as p**roton decay** or **neutron decay** processes that violate baryon number will be searched



Kamioka"NDE"

Nucleon Decay Experiment
Neutrino Detection Experiment

Super-Kamiokande
(1996-)

Kamiokande
(1983-1996)

3kton

20% coverage
with 50cm PMT

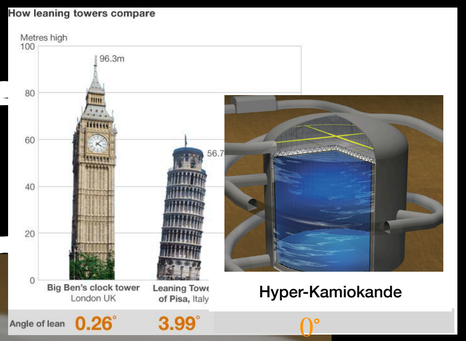
20x

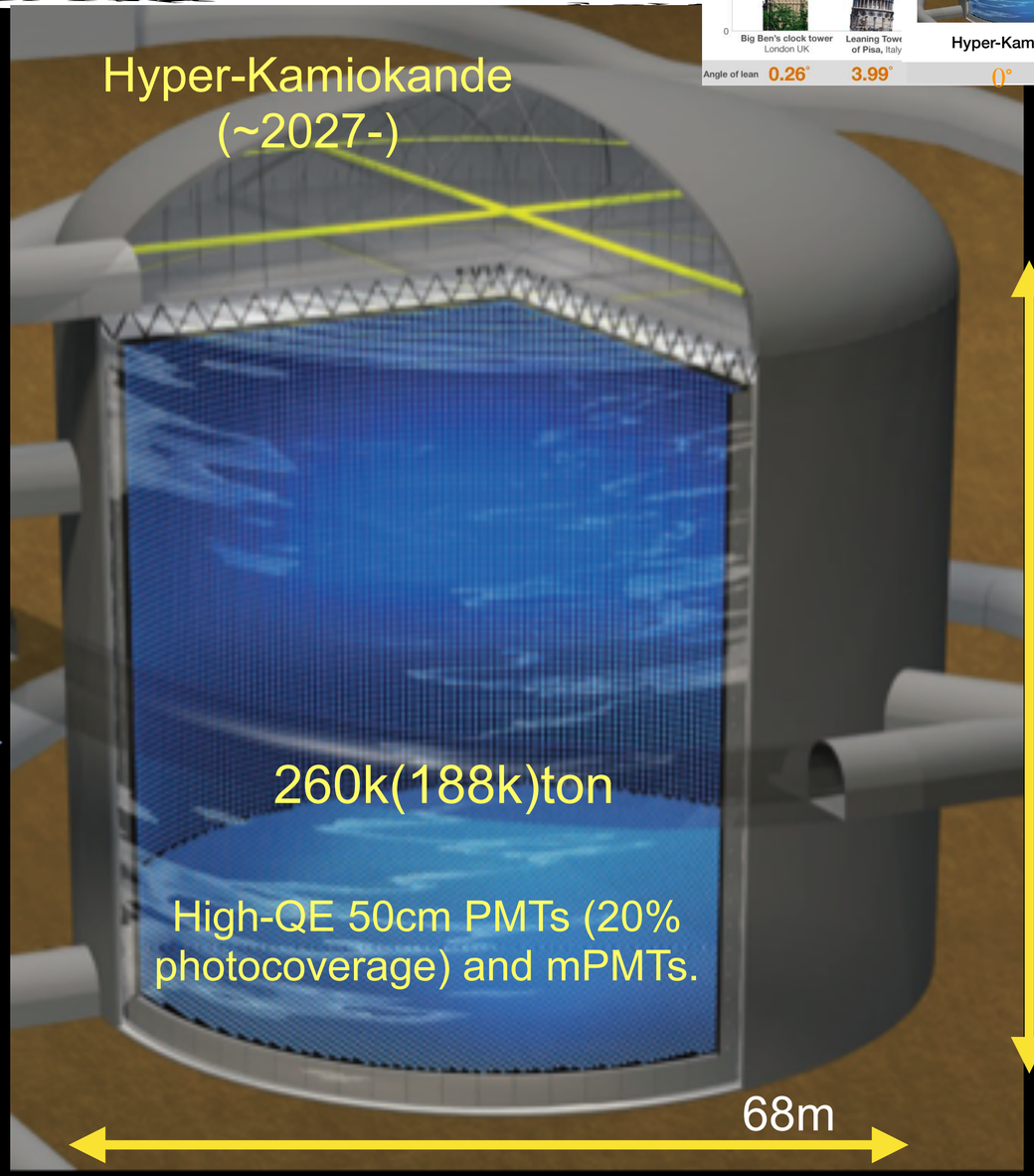
50k(22.5k)ton

40% coverage
with 50cm PMT

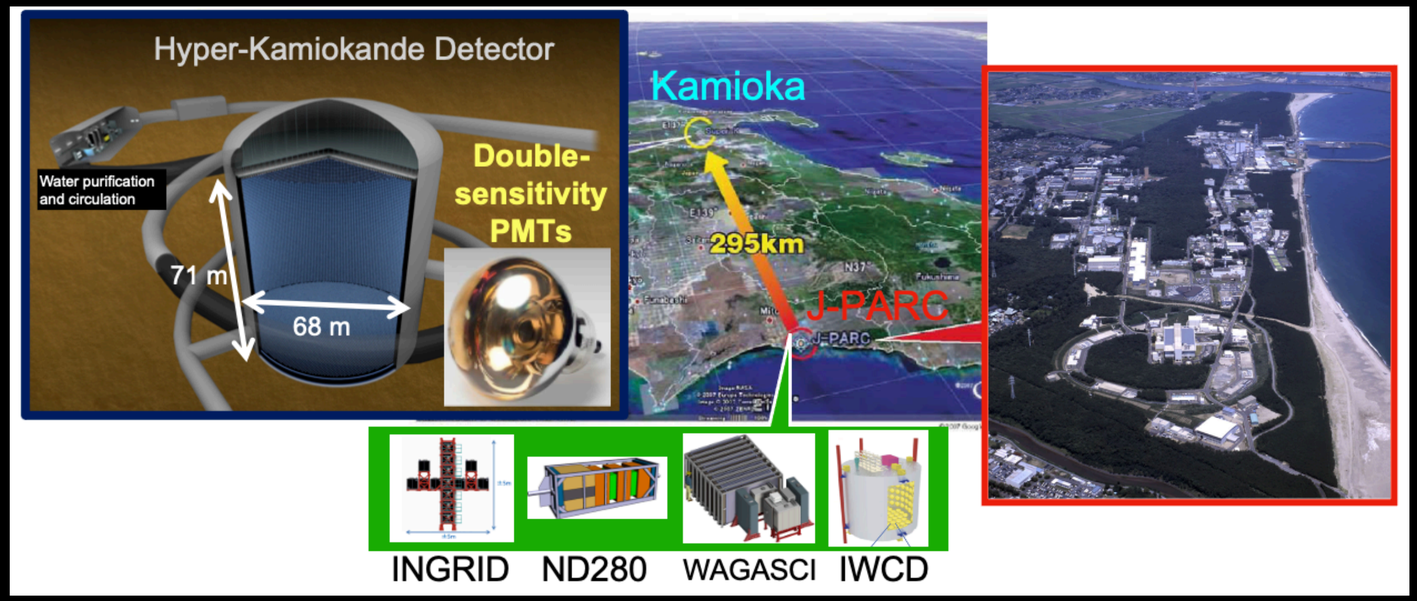
8.4x

Unprecedented scale of underground cavern

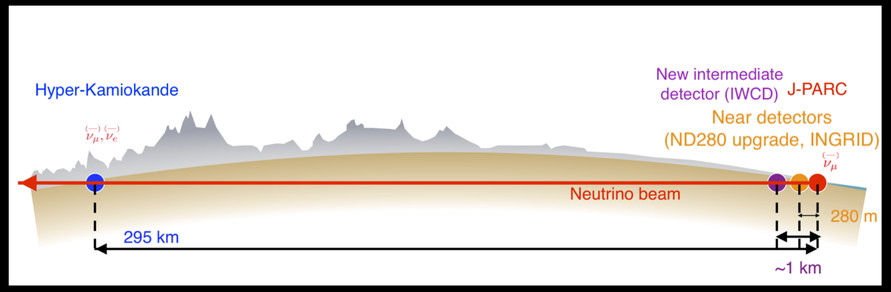


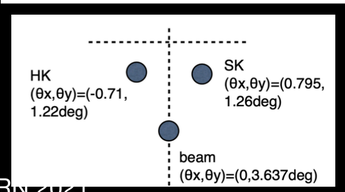


Hyper-Kamiokande Experiment

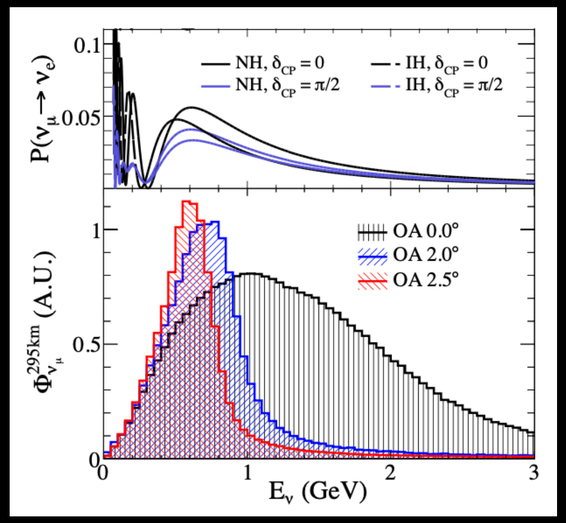


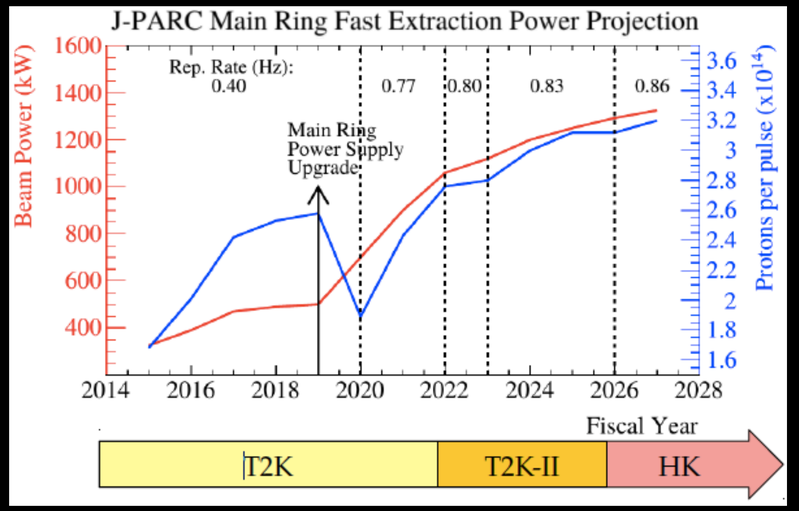
- Hyper-K detector with **8.4 times larger fiducial mass** (190 kiloton) than Super-K with **double-sensitivity PMTs**
- New (IWCD) and upgraded (@280m) near detectors to control systematic error.
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3MW (**x2.5** higher than current T2K beam power)





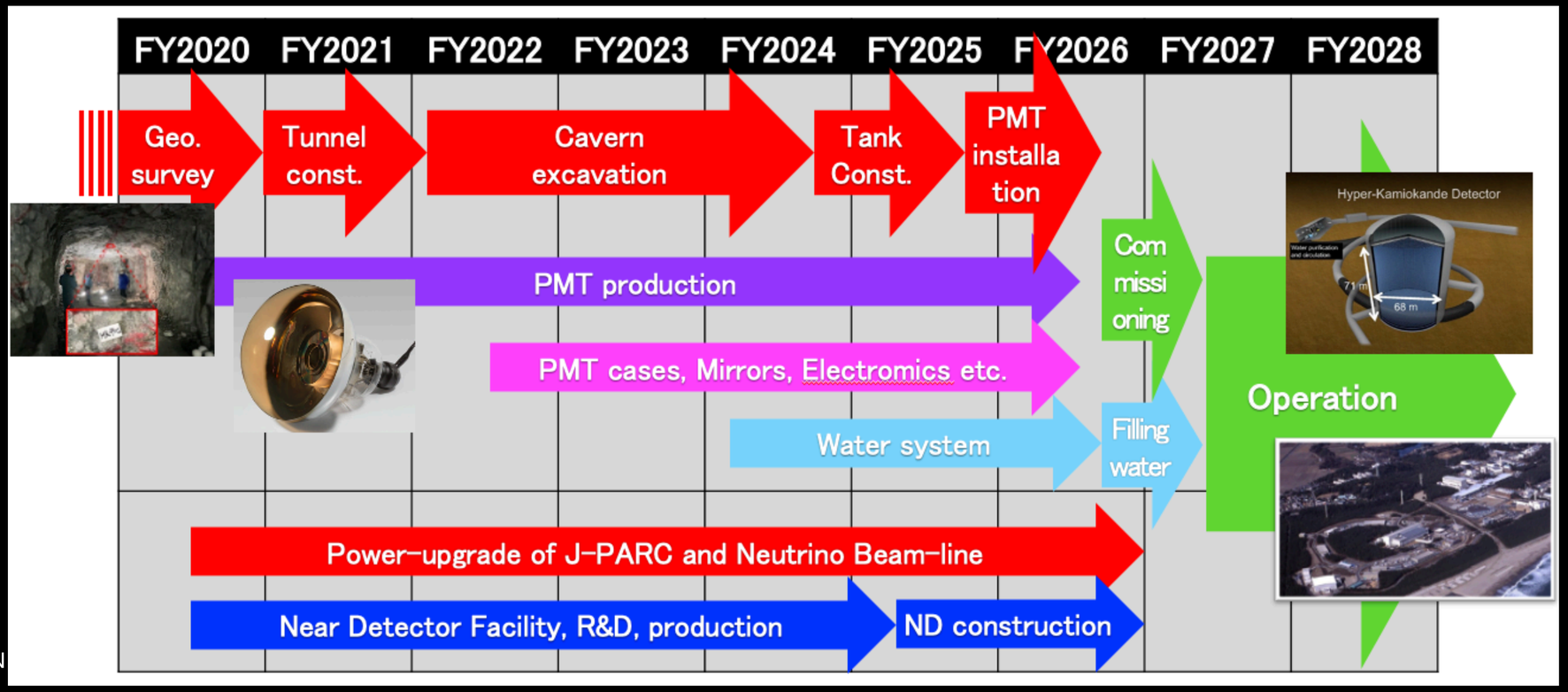
- J-PARC neutrino beam is directed at both 2.5° for Super-K and Hyper-K





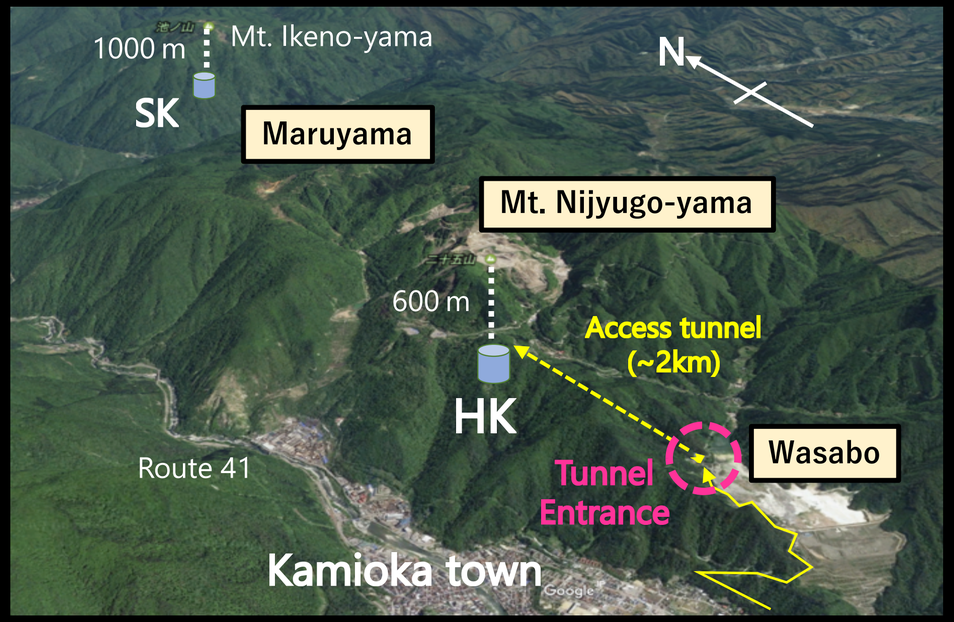
Hyper-K Schedule

- 7 years construction from year 2020; 5 years excavation + subsequent 2 years detector construction. Data taking from 2027.
- We will start water filling and detector commissioning in Dec.-2026.
- The participating countries need to be ready to start installation of their components by Dec.-2025 (We have ~5 years for preparation).

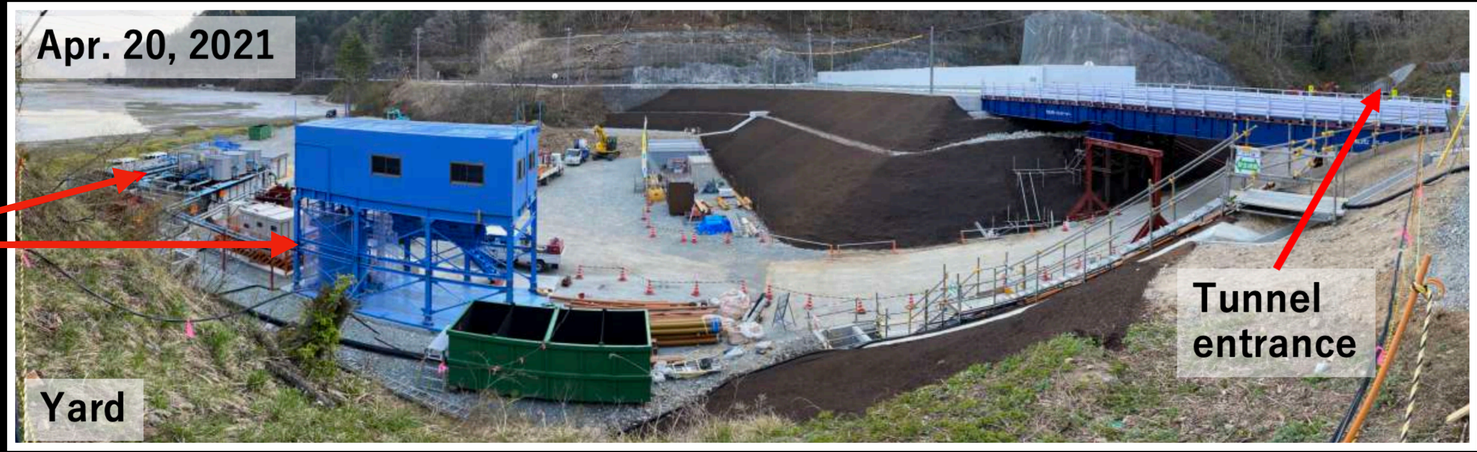


- It is vital that the contributions by the international partners to key components are secured as soon as possible and certainly by the end of 2022.

Entrance Yard Construction

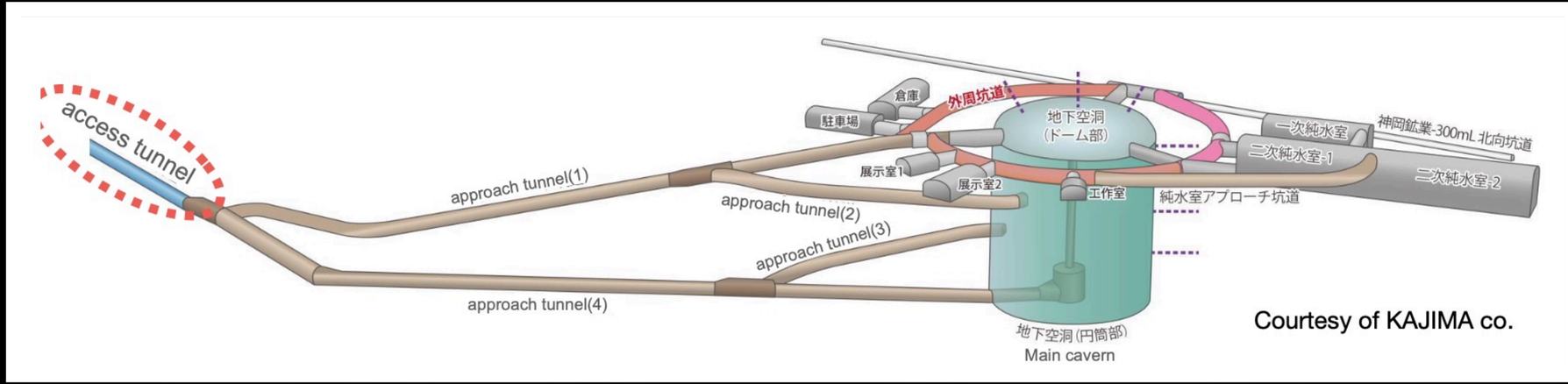


- Construction of entrance yard in Wasabo is completed.
- Construction of the waste water treatment facility at the entrance yard.



Access Tunnel Excavation has Started!

- Cavern excavation started in May 2021
- Groundbreaking ceremony on May 28 2021
- Blasting started. Day/night excavation started
- Access tunnel excavation started in May 2021



Hyper-K Collaboration

20 countries, 95 institutes, ~480 people as of Nov 2021, and growing

Collaborating Institutes

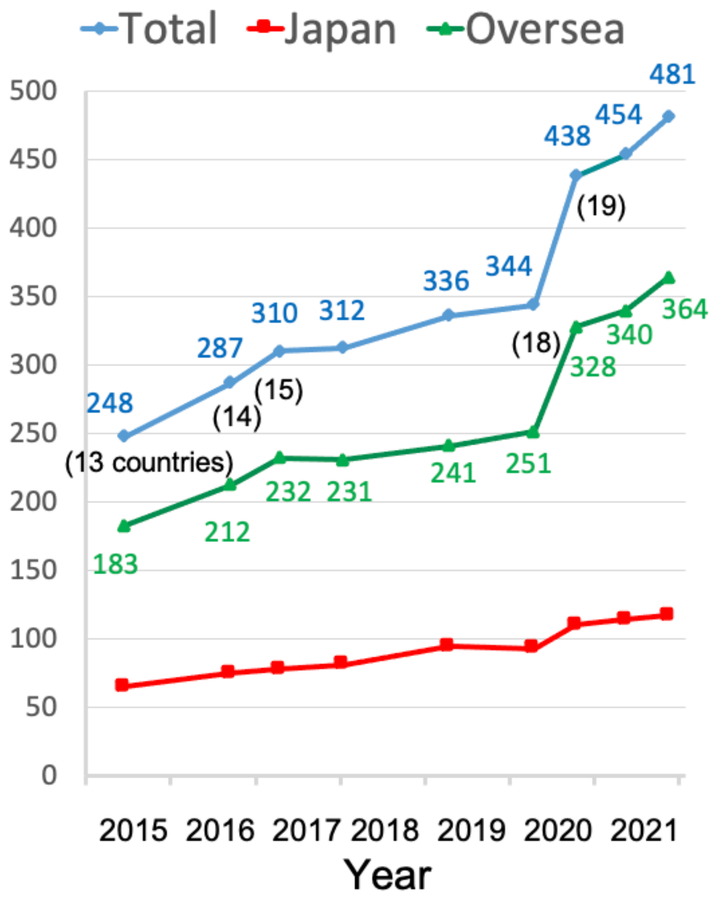
Europe	273 members
Armenia	3
Czech	3
France	28
Germany	1
Italy	55
Poland	37
Russia	21
Spain	30
Sweden	5
Switzerland	7
Ukraine	4
UK	79

Asia	145 members
India	10
Korea	18
Japan	117

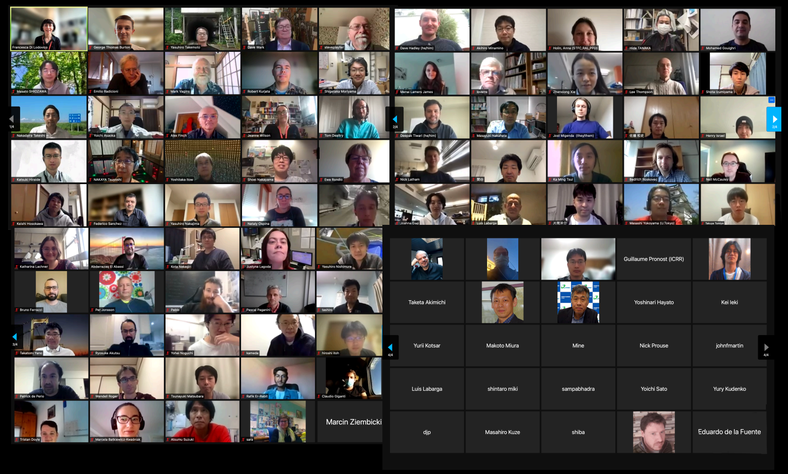
Americas	54 members
Brazil	3
Canada	31
Mexico	11
USA	9

Africa	9 members
Morocco	9

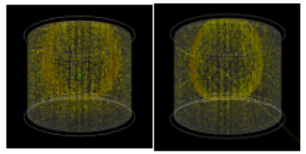
Number of Collaborators



20 countries, 95 institutes, ~480 people as of November 2021, and growing



Hyper-K Experiment (Far Detector)



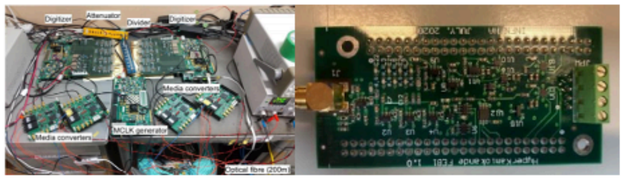
Neutrino interactions

Water system:
1st stage system
2nd stage system for 155 + 155 m^3/hour

Photosensors

Photosensors:
PMT
Cover
Light Collection
Coils…

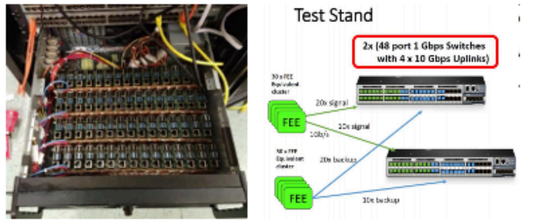
Half of ID PMTs



Electronics

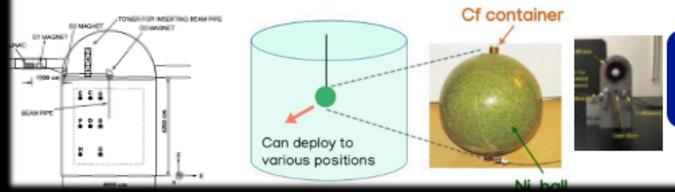
Electronics:
Digitizer
Boards
High Voltage Supply
Network
Waterproof'd box, connectors, cabling…

Part of ID Electronics



Data Acquisition and triggering

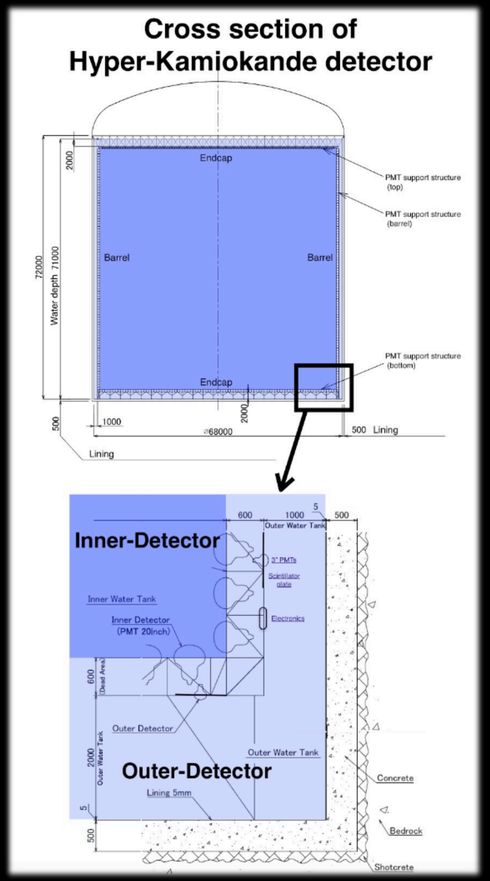
DAQ & Triggering:
Readout
Event builder
Software Triggers



Calibration

Calibration:
Electron LINAC
Deployment system
Other RI sources, light sources et

Two components:
- Inner Detector (ID)
- Outer Detector (OD)



Hyper-K Detector Construction has Started

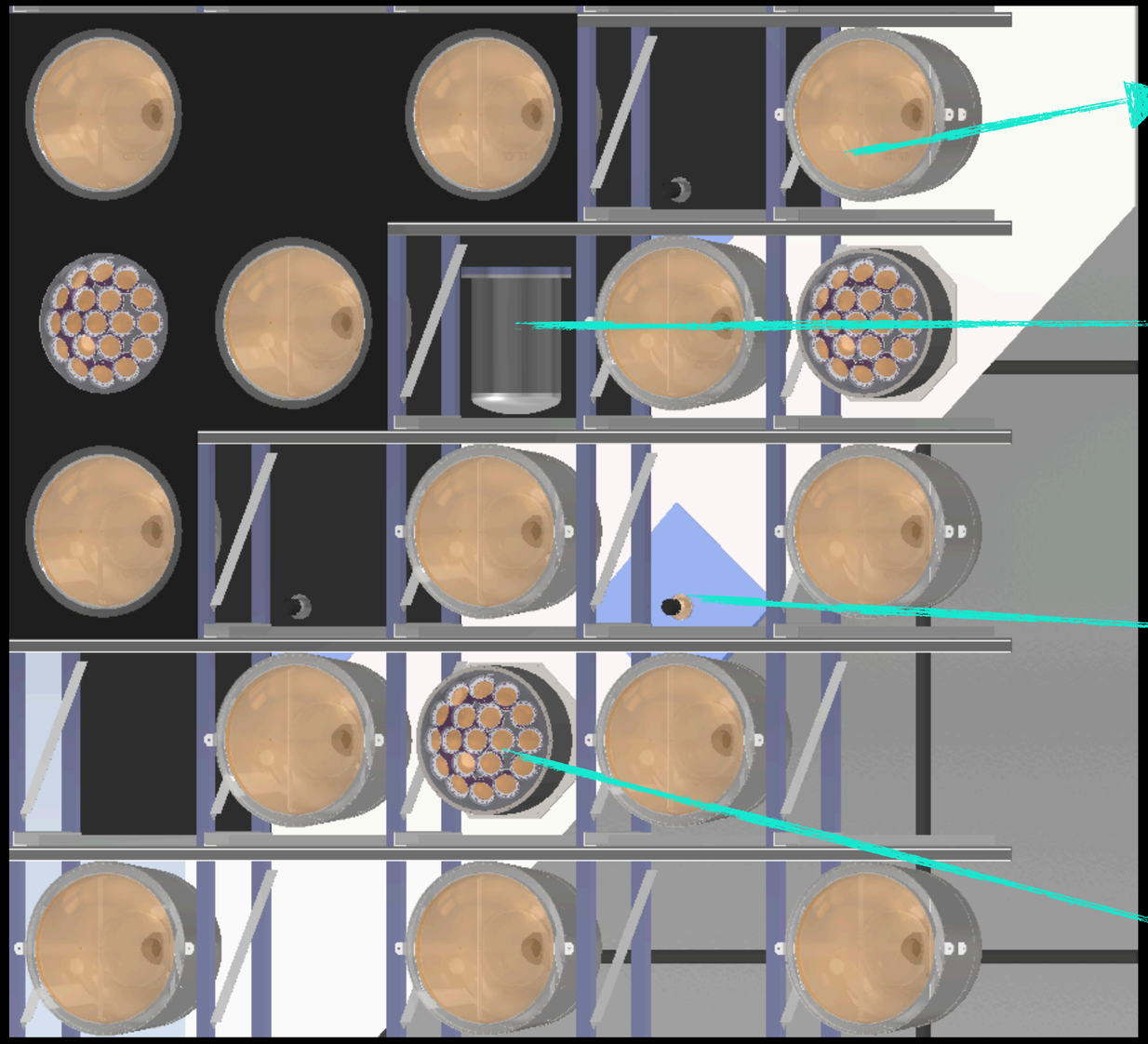
PMTs for the Inner Detector

	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

2020/12 First six PMTs delivered to Kamioka

- Production has started on time for the 50cm PMTs with Box&Line dynode.
- 300 PMTs by March, 20,000 PMTs in total by 2026 according to the Japanese budget profile.

Far Detector

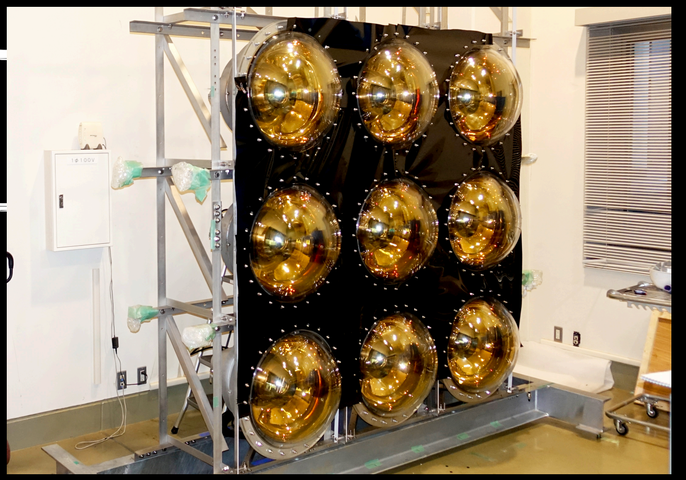


50cm PMTs

ID+OD Electronics

OD

mPMTs



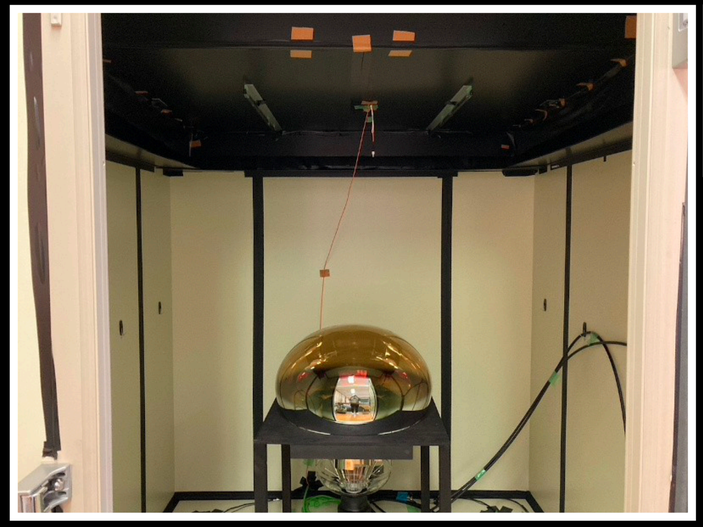
Mockup (Kashiwa, UTokyo)

50cm PMT production

Storage

Visual inspection

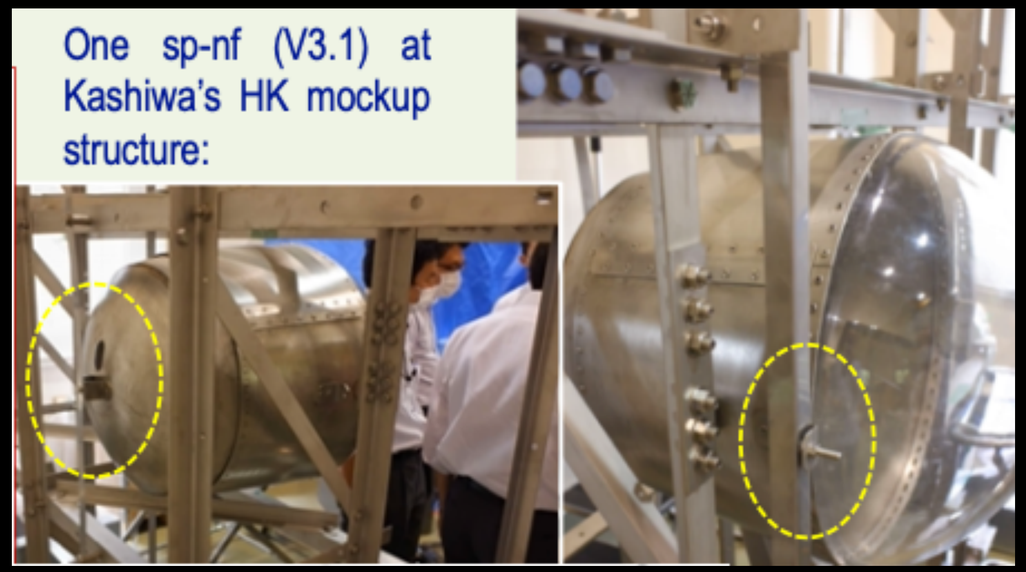
Testing signal



PMT Dark Rooms

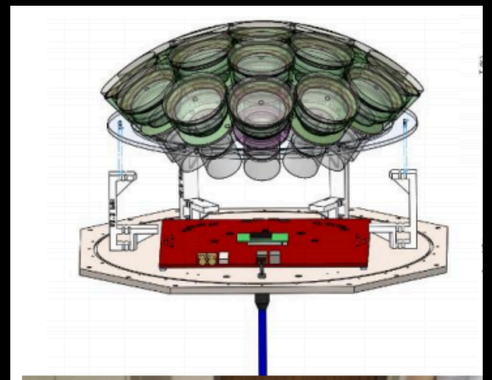
50cm PMT Covers

- Covers are vital components to protect the PMTs in case of implosion.



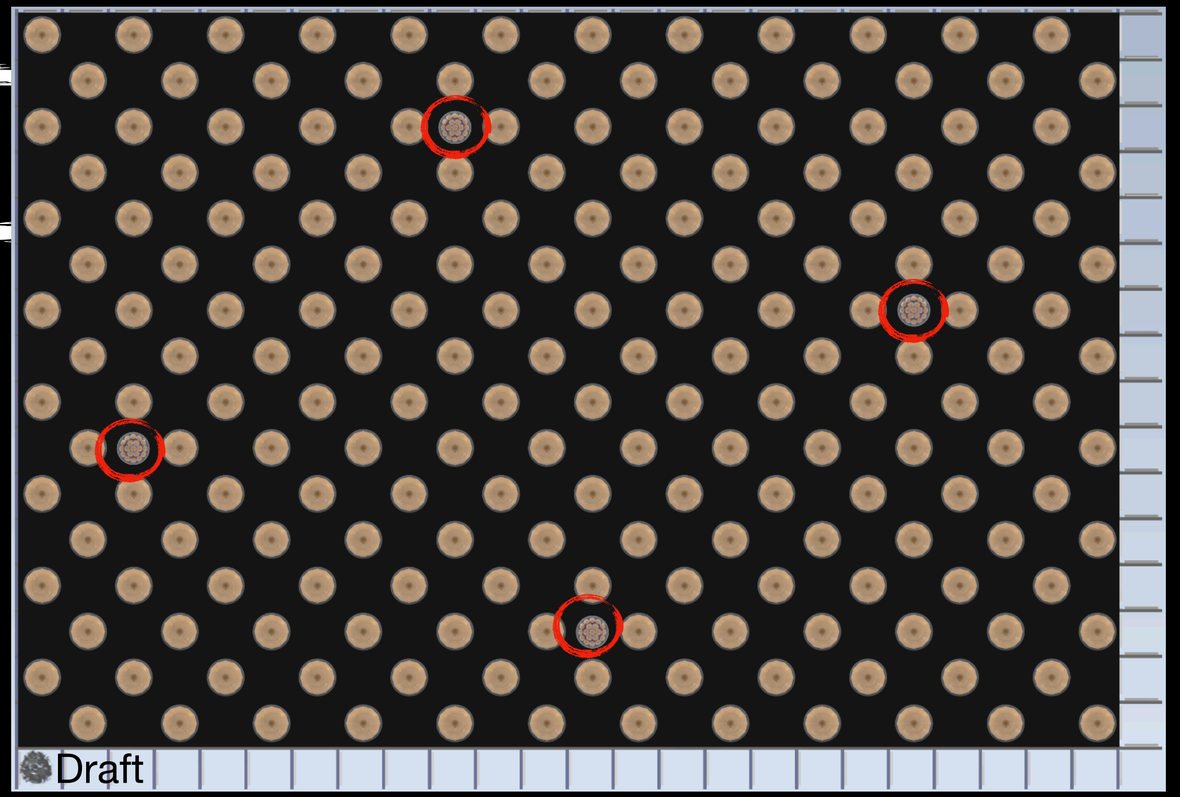
- Several tests being performed to check robustness of design (material test, fabrication method, full validation under water pressure, etc).

mPMTs

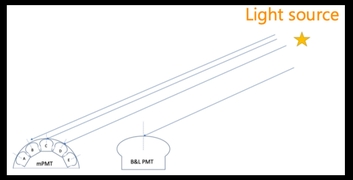


Prototype at TRIUMF

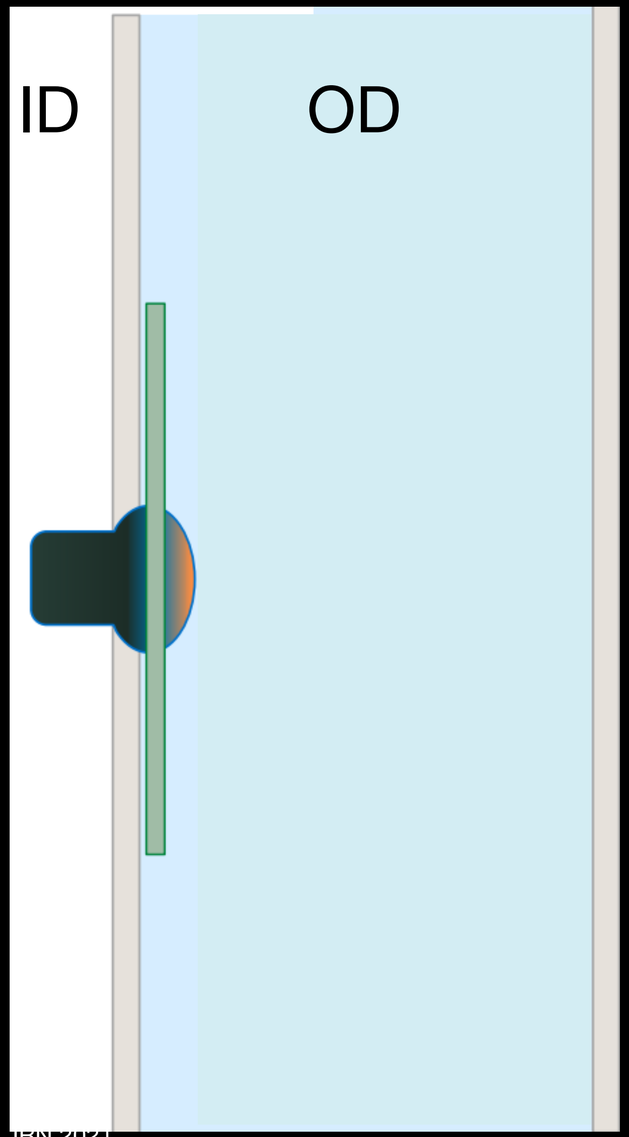
HK FD mPMT Electronics at INFN



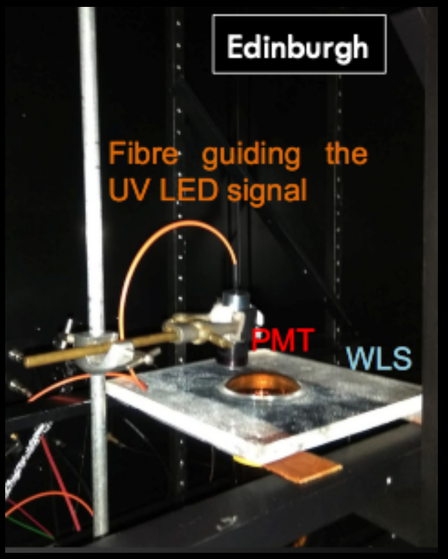
- Far Detector: hybrid configuration of 20” PMTs and mPMTs
- IWCD will be instrumented only with mPMTs.
- mPMT is a vessel which houses and protects an array of 19 3” PMTs:
  - improves the granularity and timing;
  - additional intrinsic directional information.
- Different constraints on far detector and IWCD mPMTs.
- Innovative idea for Water Cherenkov detectors.

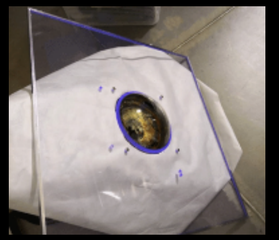


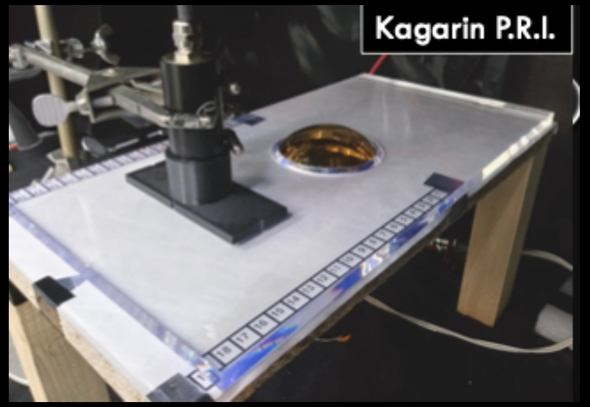
Outer Detector (OD) Photosensing



- Photosensing system composed of
  - 3” PMTs
  - Wave-length shifter plate
  - High-reflective Tyvek
- Crucial to reject external background.

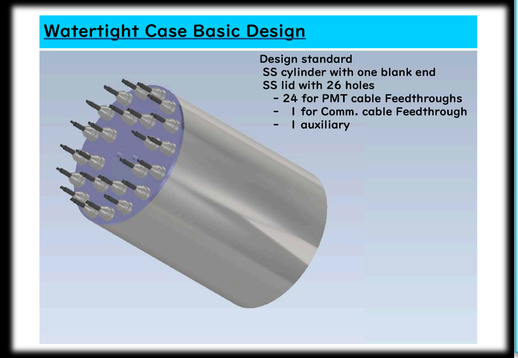


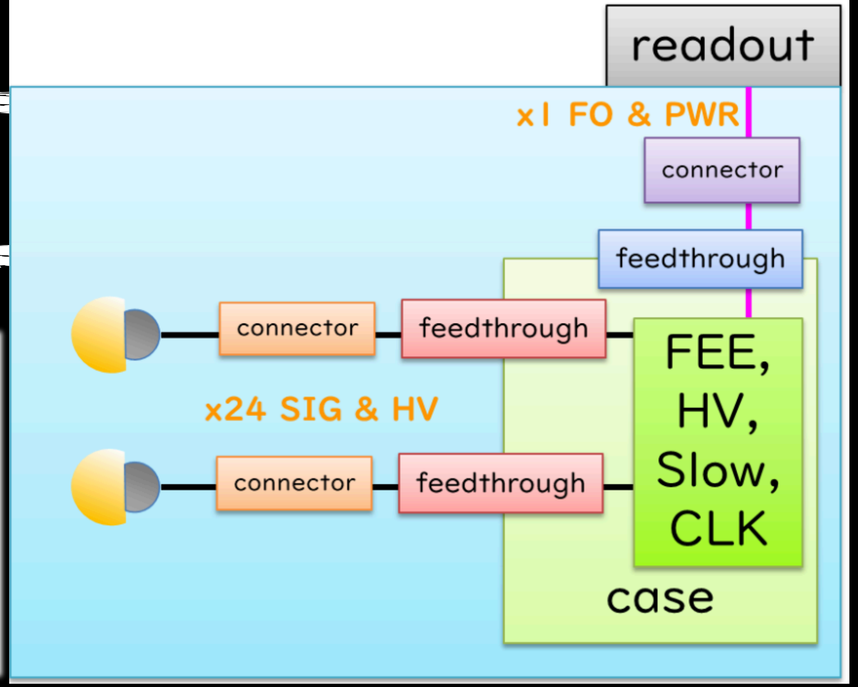


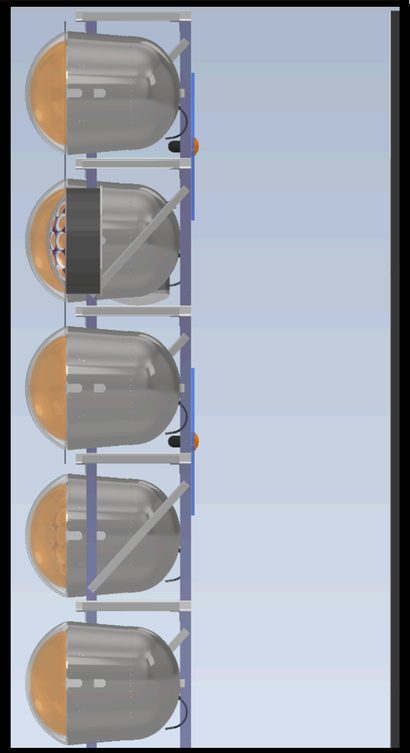


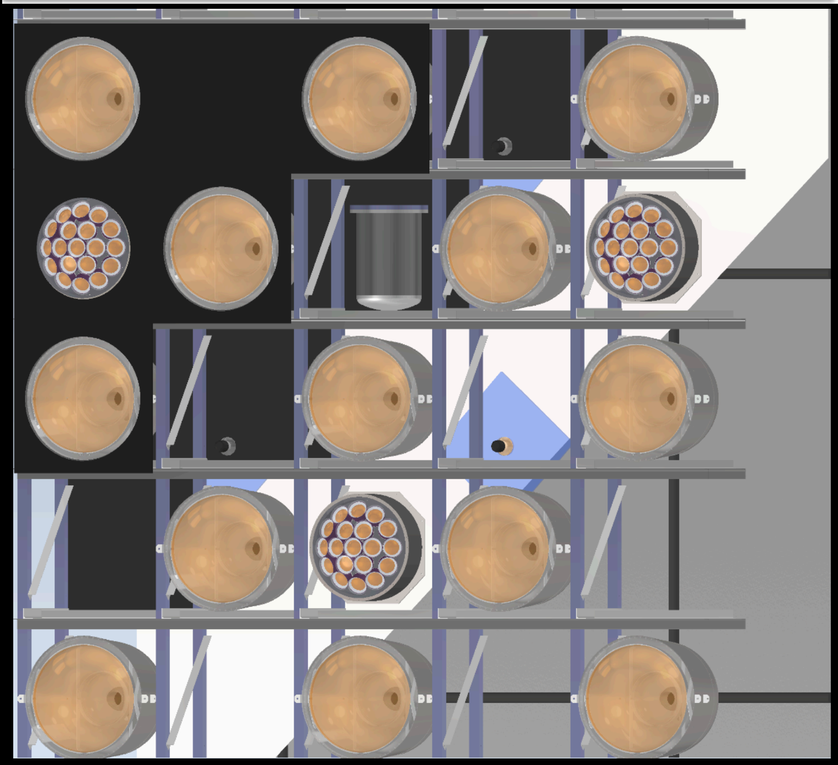
Electronics

- Critical components which define the HK detector performance and its systematics. There are many technical challenges as
  - Mechanical design of a box for water tightness
  - High performance, long life digitisers, high voltage PS, communication system, timing synchronisation system, and so on.



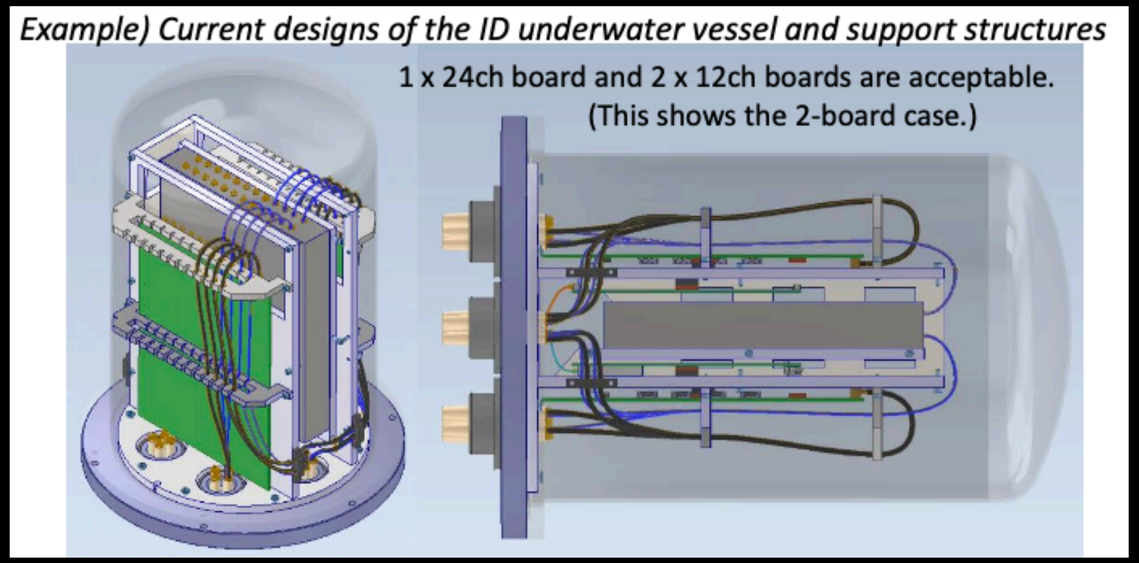


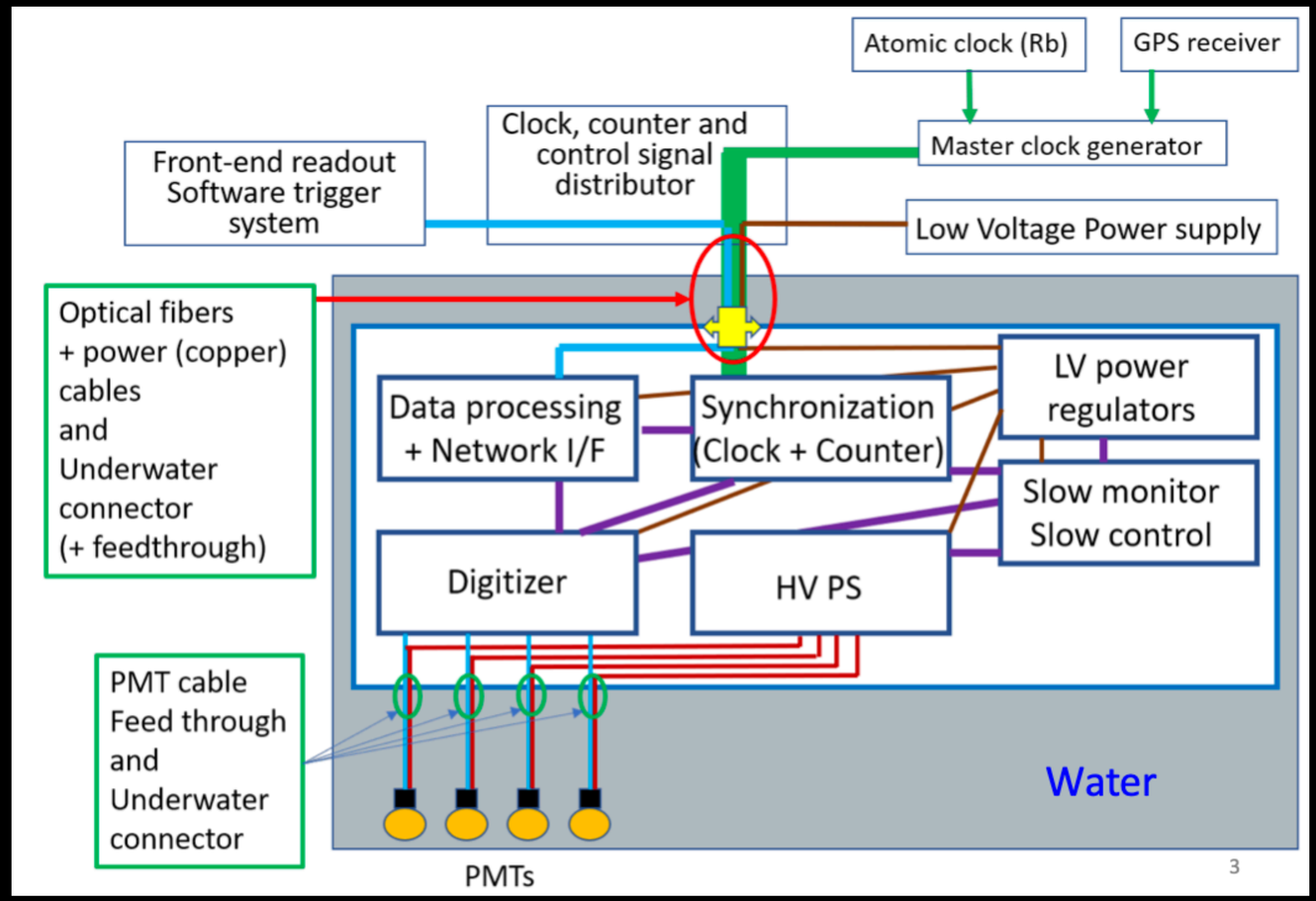




ID+OD Electronics

- The electronics package can be split in several blocks shared by different countries.
- Long-term reliability is vital.

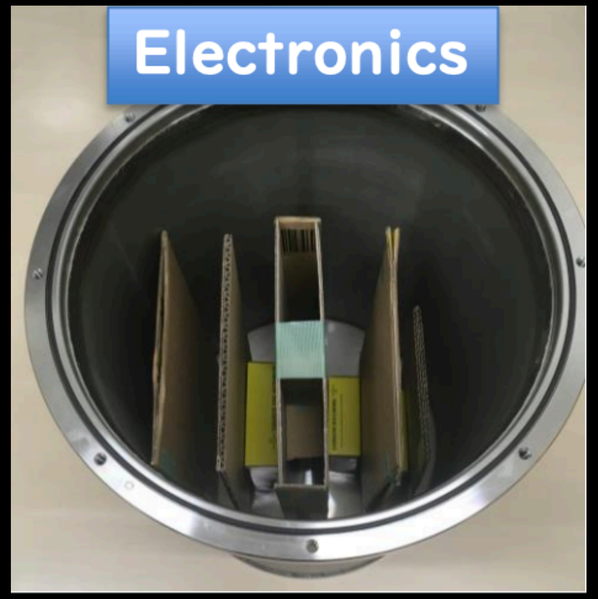


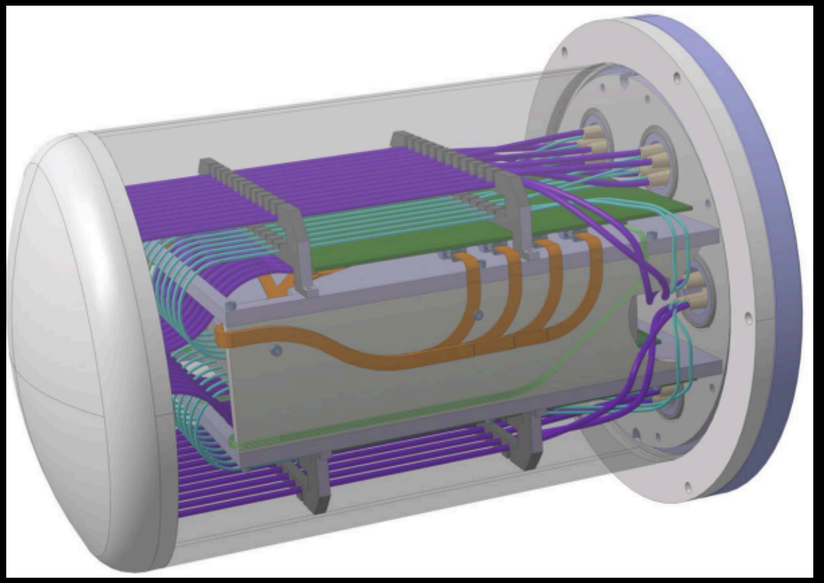


Electronics Canisters

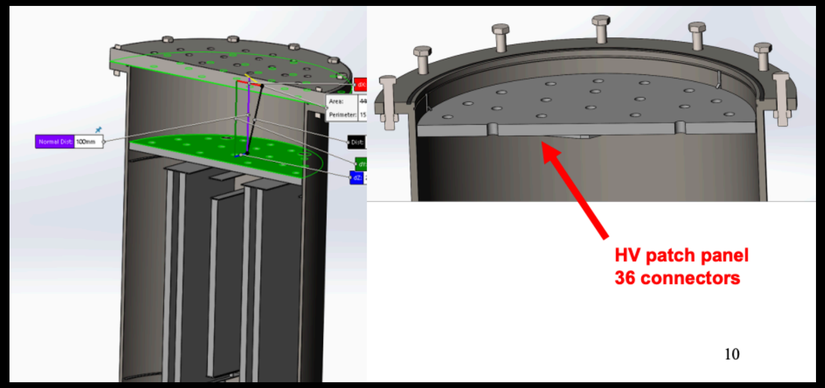
- Canisters will contain electronics boards and will be in water.

ID



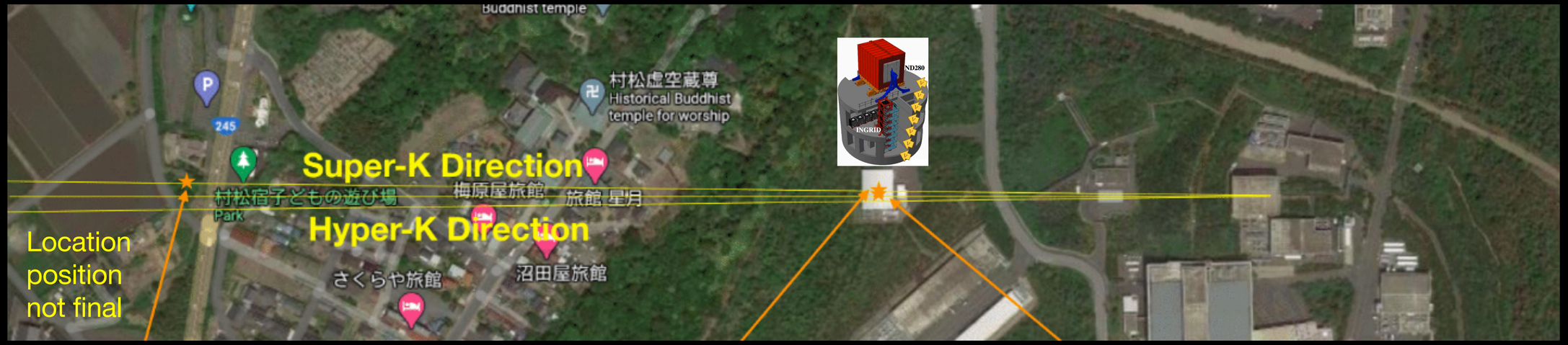


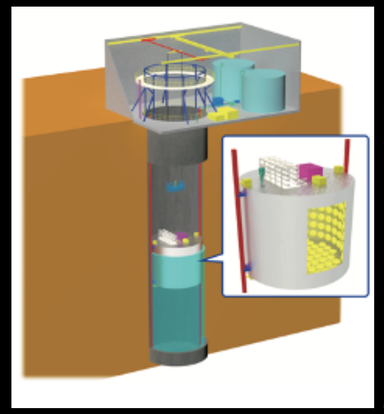
OD



Suite of Near Detectors

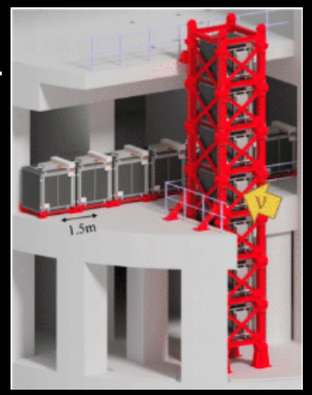
- Critical components to precisely understand J-PARC beam and neutrino interactions.





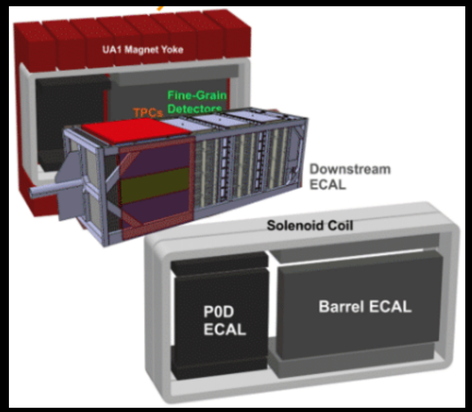
IWCD

Off-axis spanning water Cherenkov detector: intrinsic backgrounds, electron. (anti)neutrino cross-sections, E_ν vs. observables, H_2O target.



INGRID

On-axis detector: measure beam direction, monitor event rate.

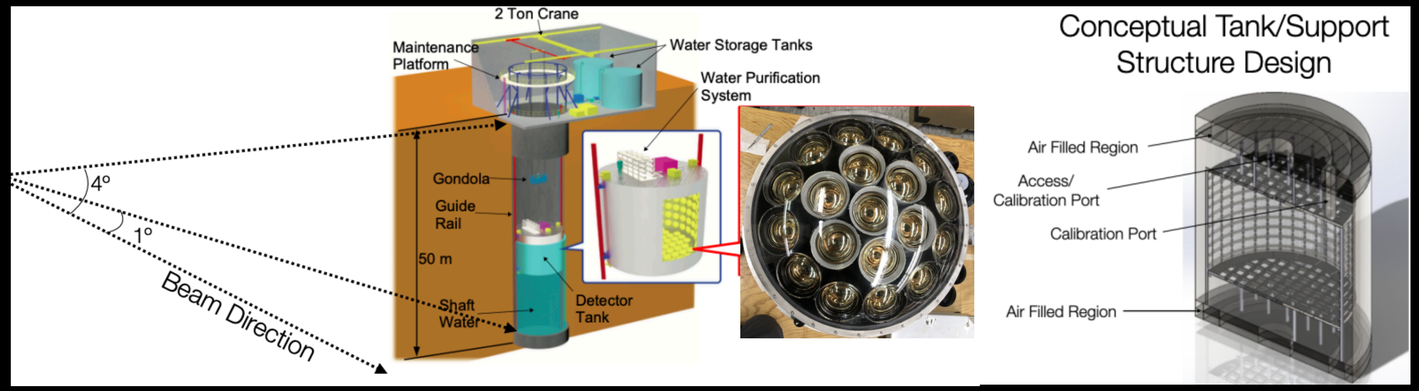


ND280

Off-axis magnetised tracker: charge separation (wrong-sign background), recoil system

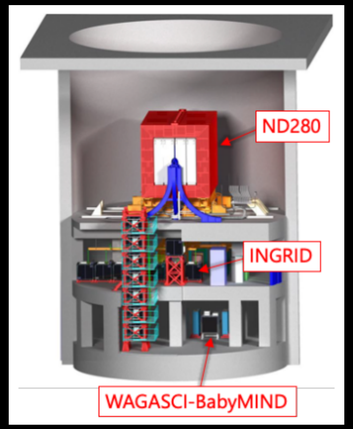
Suite of Near Detectors

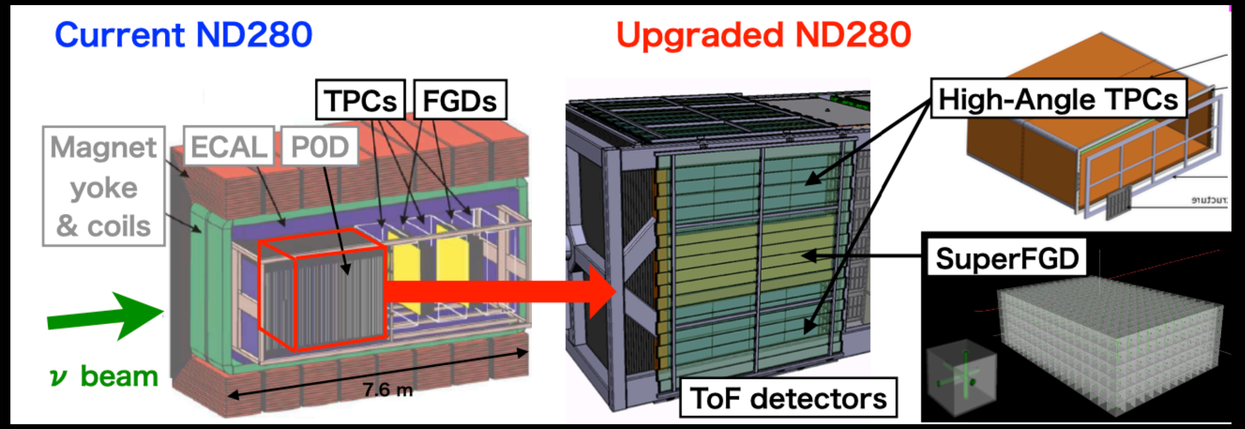
IWCD



- New 1kton-scale water Cherenkov detector at ~1km baseline
- Detector can vertically move → measurement at different off-axis angles
- Progress in site choice and detector development.
- Using mPMTs as Far Detector.

ND280

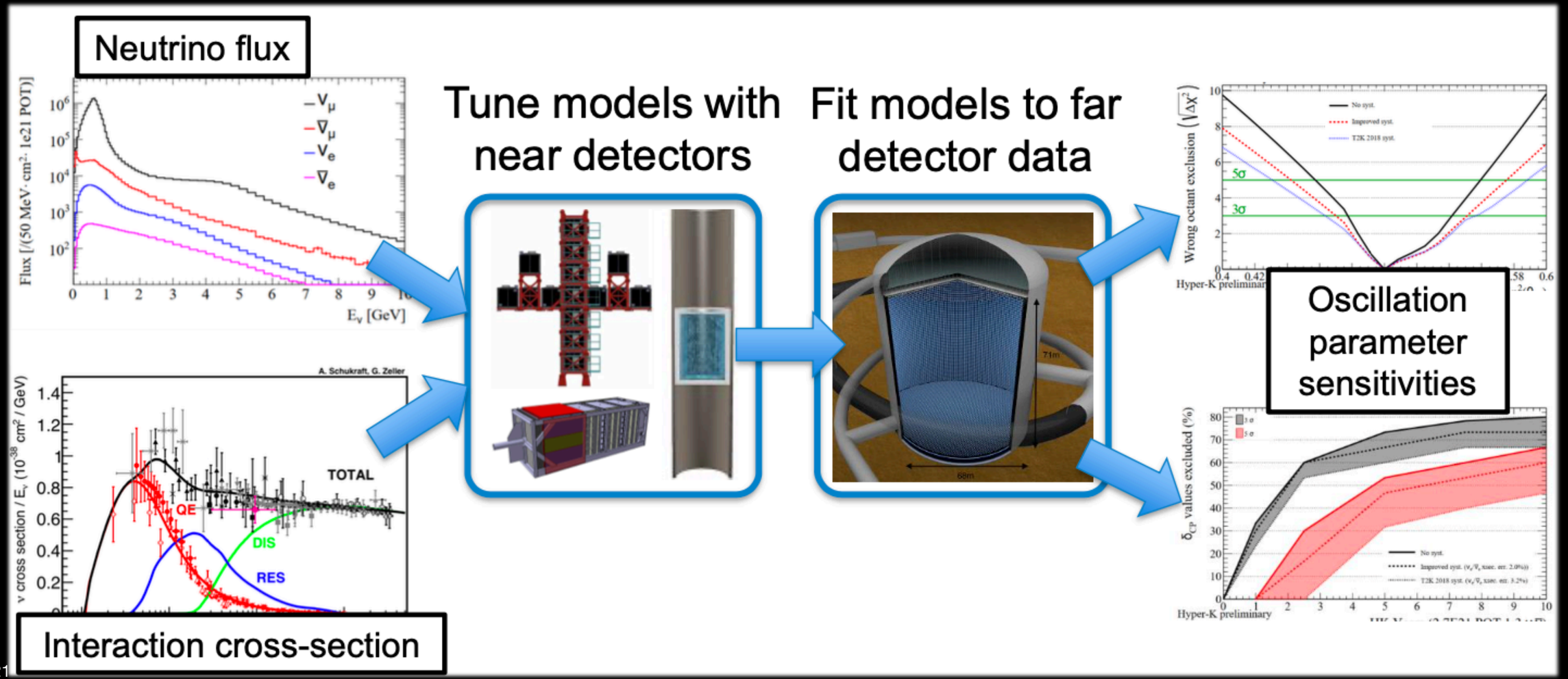




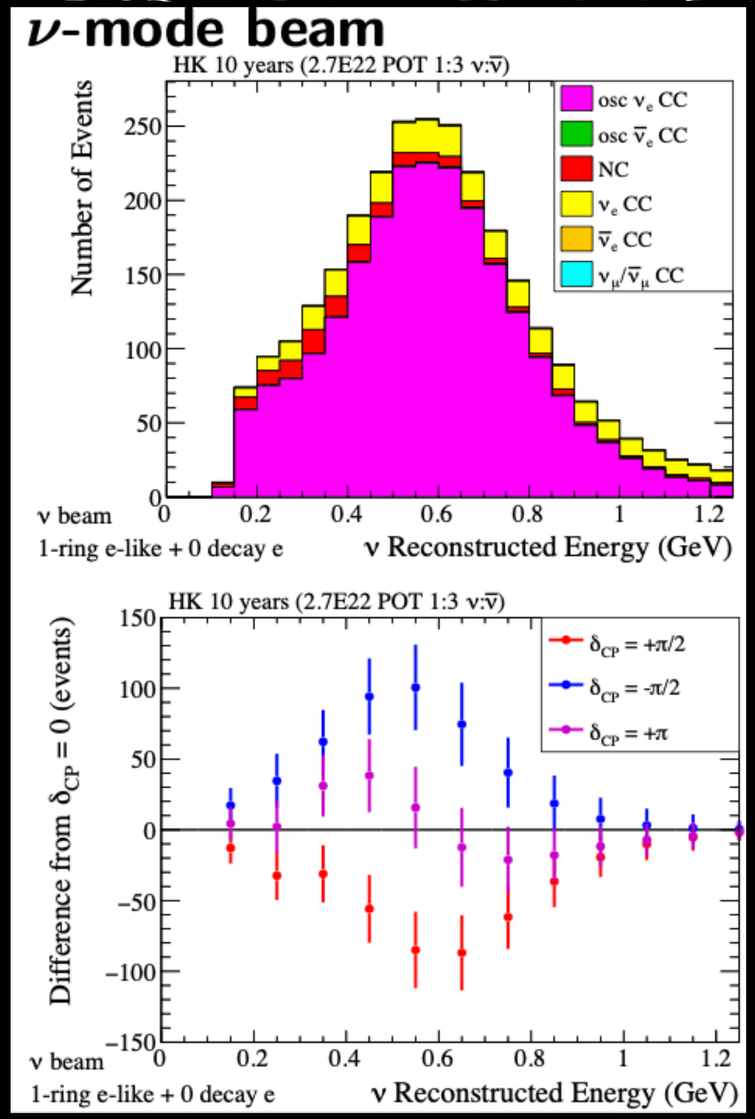
- Data taking planned from 2022.
  - Large angle acceptance.
  - High efficiency for short tracks.
- Under investigation future upgrade during Hyper-K era.

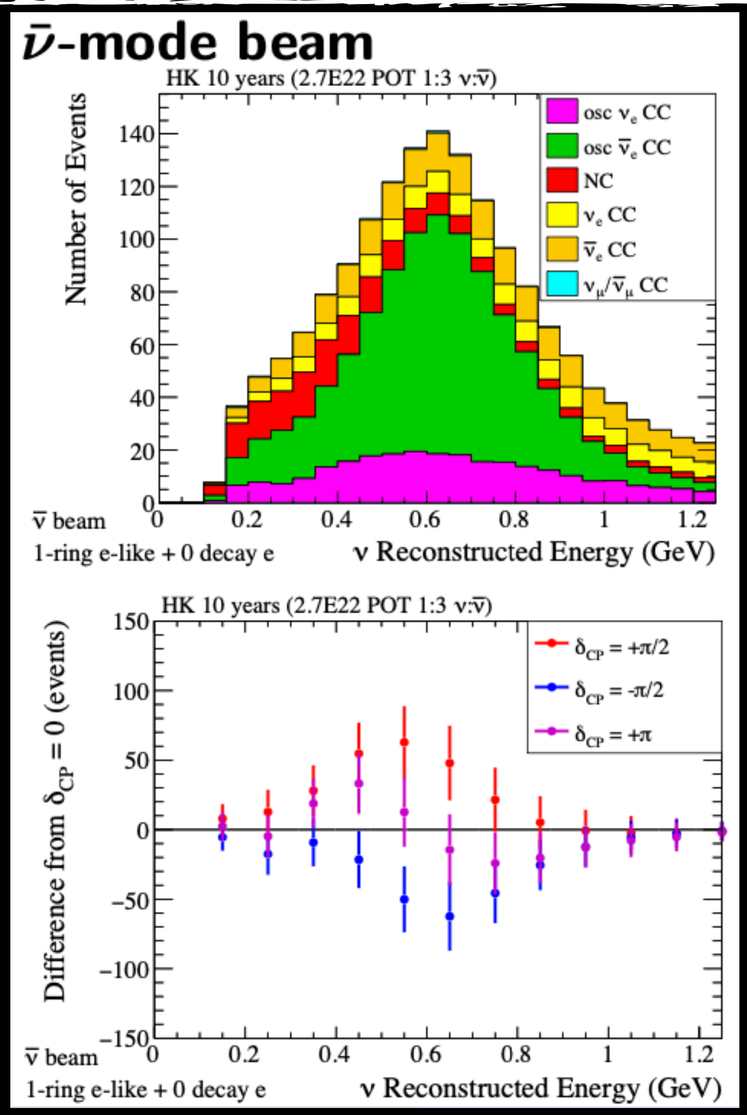
Hyper-K Beam Oscillation Analysis

- Based on T2K oscillation method.



Hyper-K Beam Oscillation Analysis



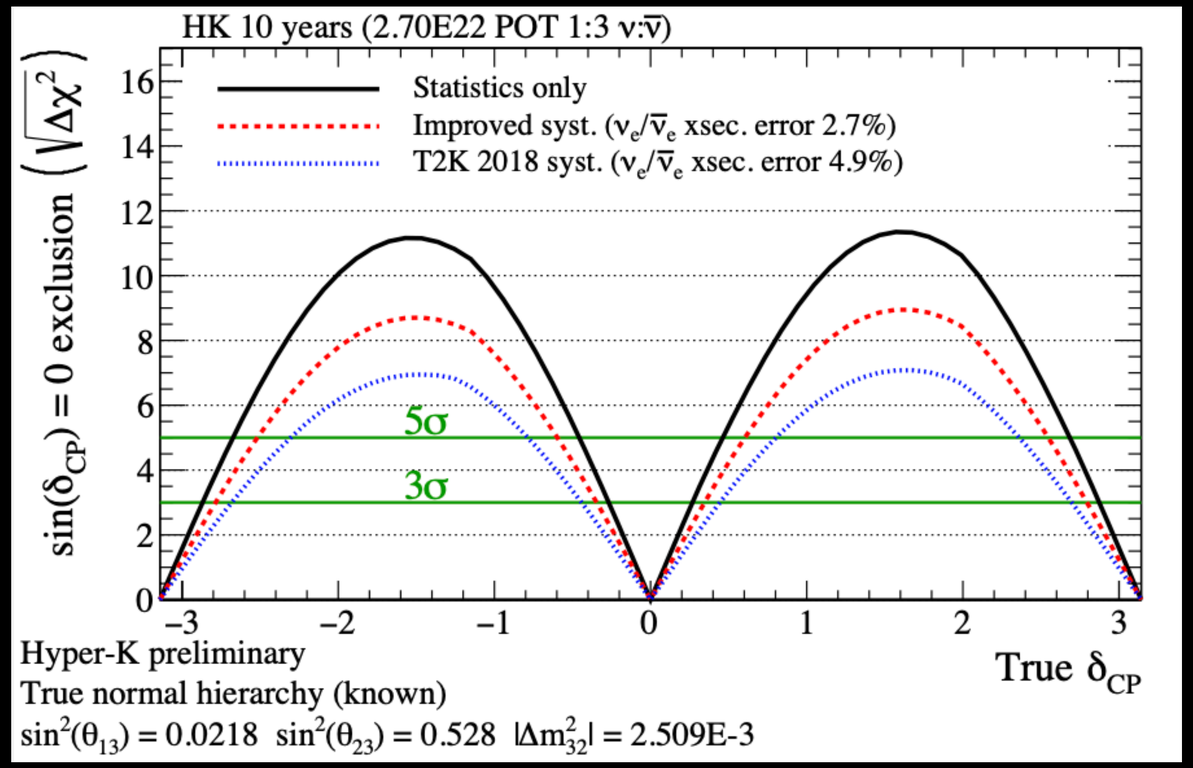


10 years (2.7E22 POT), $\nu : \bar{\nu} = 1 : 3$

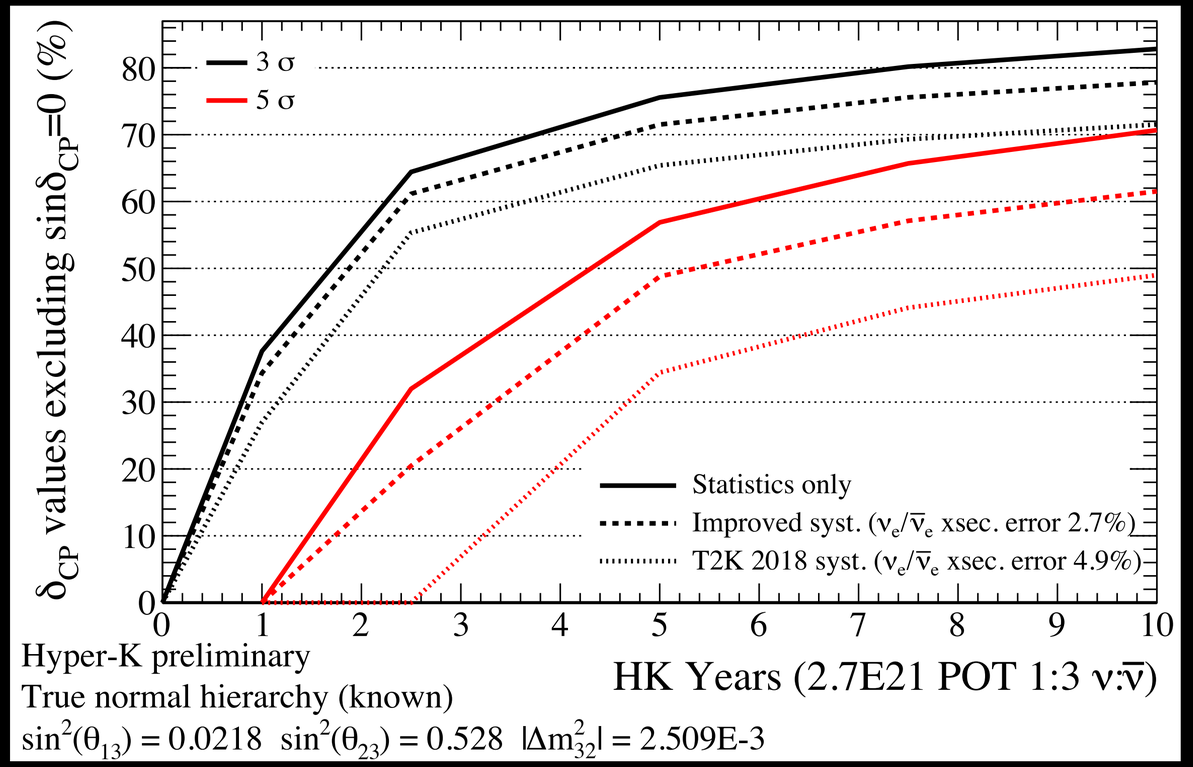
- Use Super-K MC, scaled to HK volume and exposure
- Expect approx:
  - 2300 ν_e events
  - 1900 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$
- Difference between neutrino and antineutrino rates gives δ_{CP}

$\sin\delta_{CP} \neq 0$ *Sensitivity*

Sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, for 10 HK-years. knowledge. T2K 2018 systematic error is assumed.



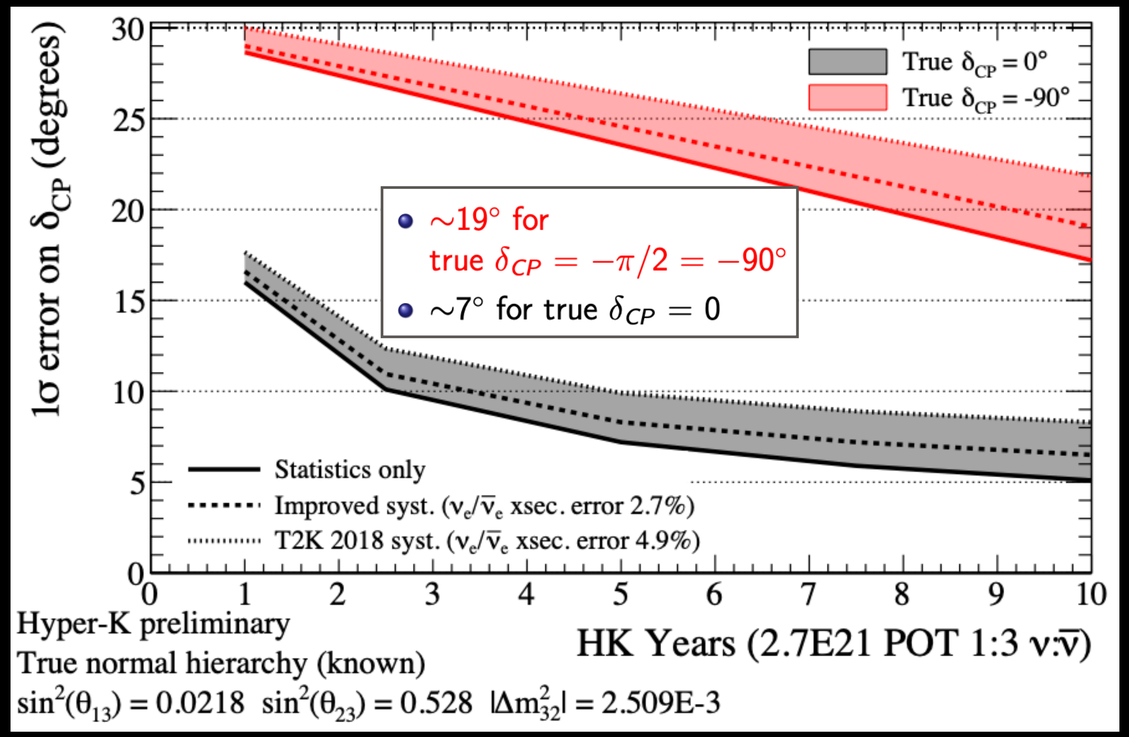
Percentage of true δ_{CP} values for which $\sin(\delta_{CP}) = 0$ can be excluded, as a function of HK-years. The areas below the curves show the span of possible values, for varying systematic error models.



- Reduction of systematic error has a large impact to the sensitivity.
- $\sim 8\sigma$ for $\delta_{CP} = -\pi/2$ (favoured by T2K).
- Good opportunity to make discovery of CP violation in neutrino sector at $> 5\sigma$ ($\sim 60\,\%$ fraction of δ_{CP} values w/ 10years data taking).

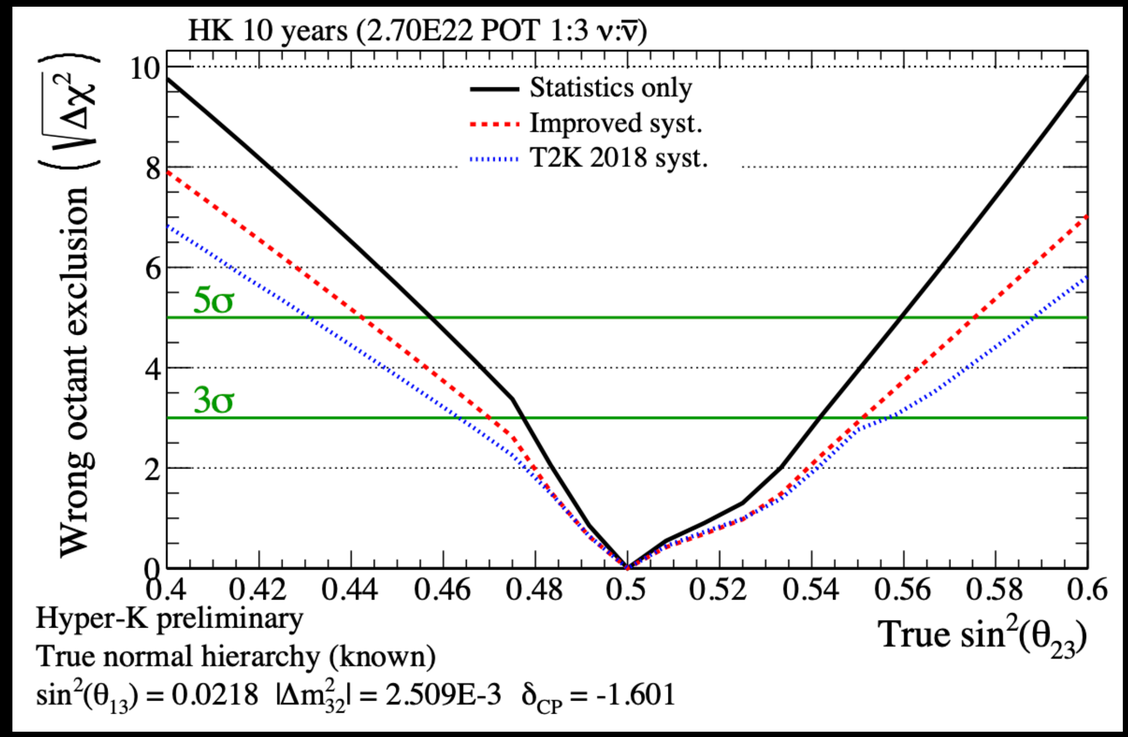
Resolution on δ_{CP} and measurement of $\sin^2\theta_{23}$

- How accurately can we measure the value of δ_{CP}?



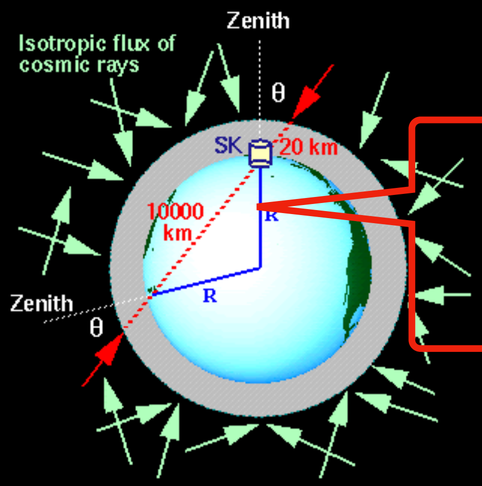
- 1σ error on δ_{CP} is:
  - $\sim 19^\circ$ for $\delta_{CP} = -\pi/2$
  - $\sim 7^\circ$ for $\delta_{CP} = 0$

- For a true value of $\sin^2\theta_{23}$, how much can we exclude the wrong octant? ($\sin^2\theta_{23}$ < or > 0.5)

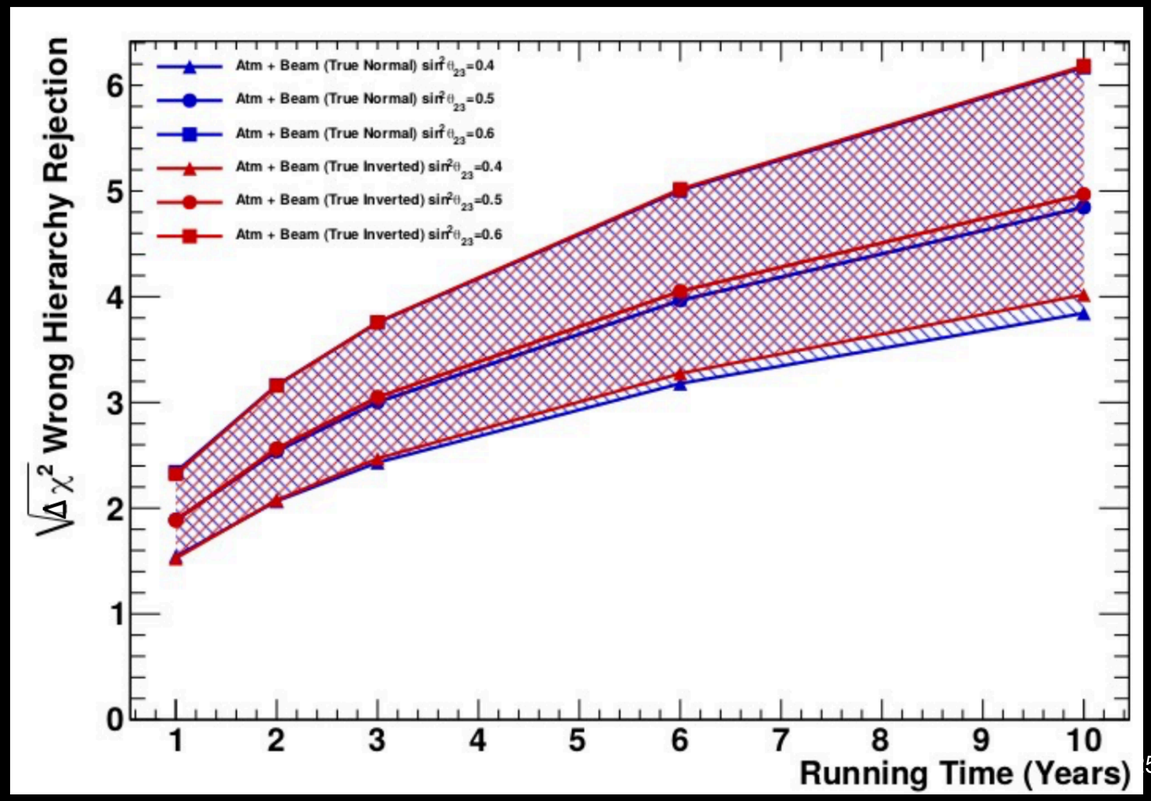


- The wrong octant can be excluded at 3σ for true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$ with the Improved syst. error model

Adding Atmospherics



- Neutrinos penetrating the Earth are affected by the mass effect.
  - Normal mass ordering : $\nu_\mu \rightarrow \nu_e$ is enhanced
  - Inverted mass ordering: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is enhanced

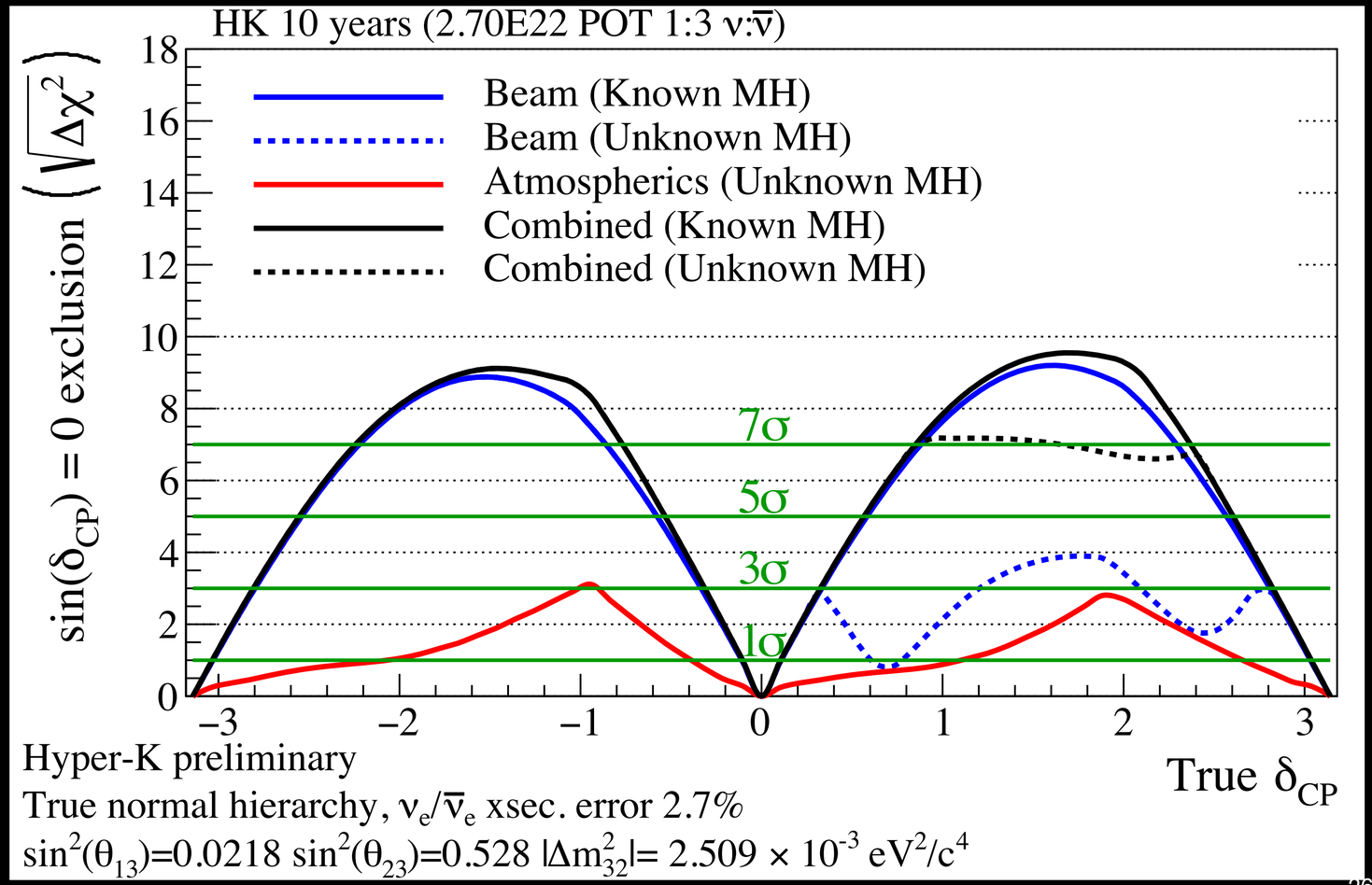


- Comparison between neutrinos and antineutrinos oscillations can be used to determine the hierarchy.
- Can exclude incorrect mass ordering at $\mathbf{4-6\sigma}$ significance (depending on value of $\sin^2\theta_{23}$)

Adding Atmospherics

- If mass ordering unknown, beam analysis less sensitive for some values of δ_{CP}.
- Joint atmospheric and beam analysis increases sensitivity above 5σ
- The power of the atmospheric sample improves the sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, particularly in the unknown mass ordering case:

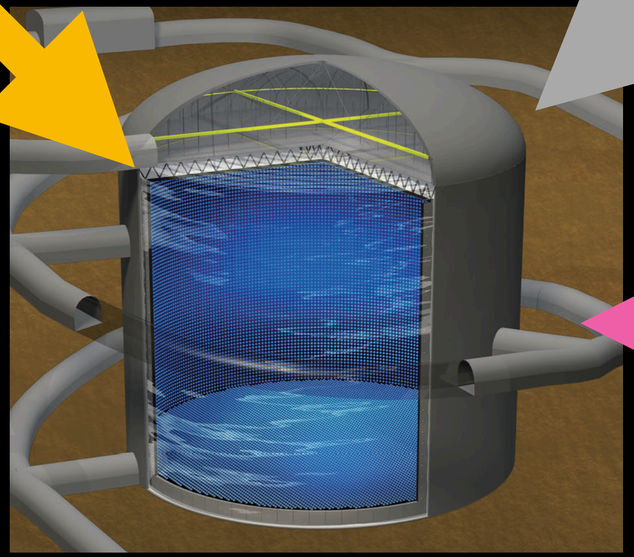
- Sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, for 10 HK-years and true normal mass ordering.



Astrophysics Neutrinos at Hyper-K

Solar Neutrinos
- Burning processes, modelling of the Sun
- Property of neutrino

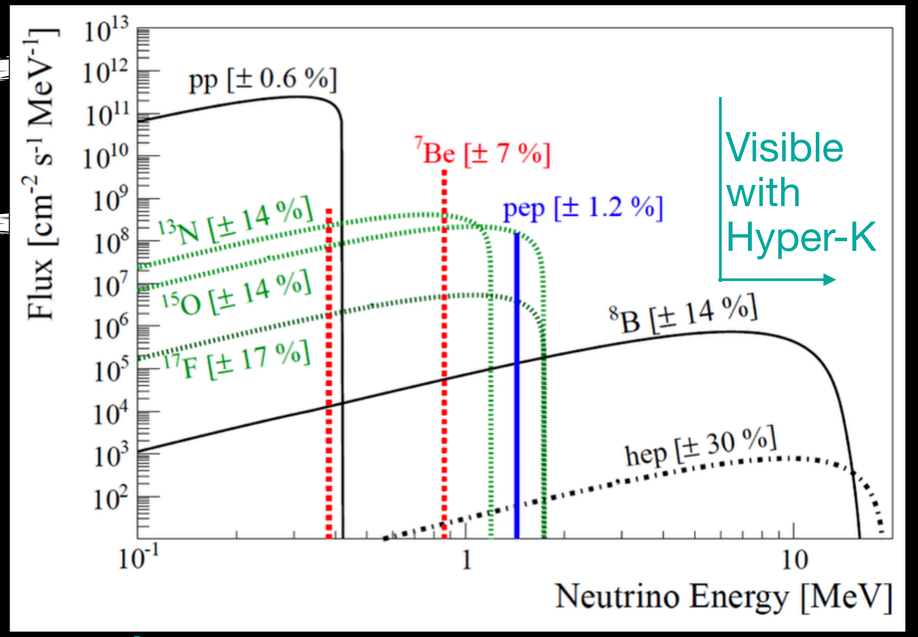
Supernova Neutrinos
- SN explosion mechanism
- SN monitor
- Nucleosynthesis



Supernova Relic Neutrinos
- SN mechanism
- Star formation history
- Extraordinary SNe

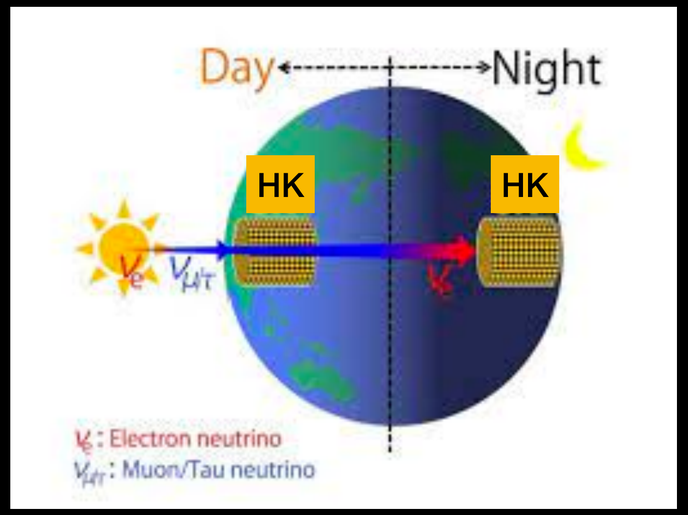
Solar Neutrinos

- Solar neutrinos are the neutrinos originated from the nuclear reactions in the Sun.
- Large statistics: 130 ν ev./day/tank, E_{vis}>4.5MeV
- Highlights of solar ν measurements:



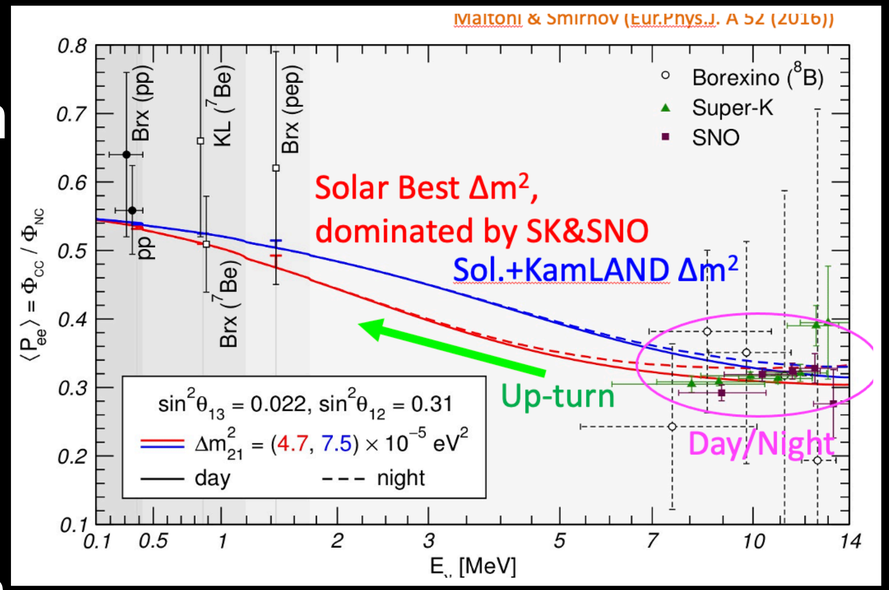
Day/Night (D/N) Asymmetry

- The terrestrial matter effect can result in **D/N asymmetry**.
- This can affect Δm^2_{12} measurement.



Upturn of the spectrum

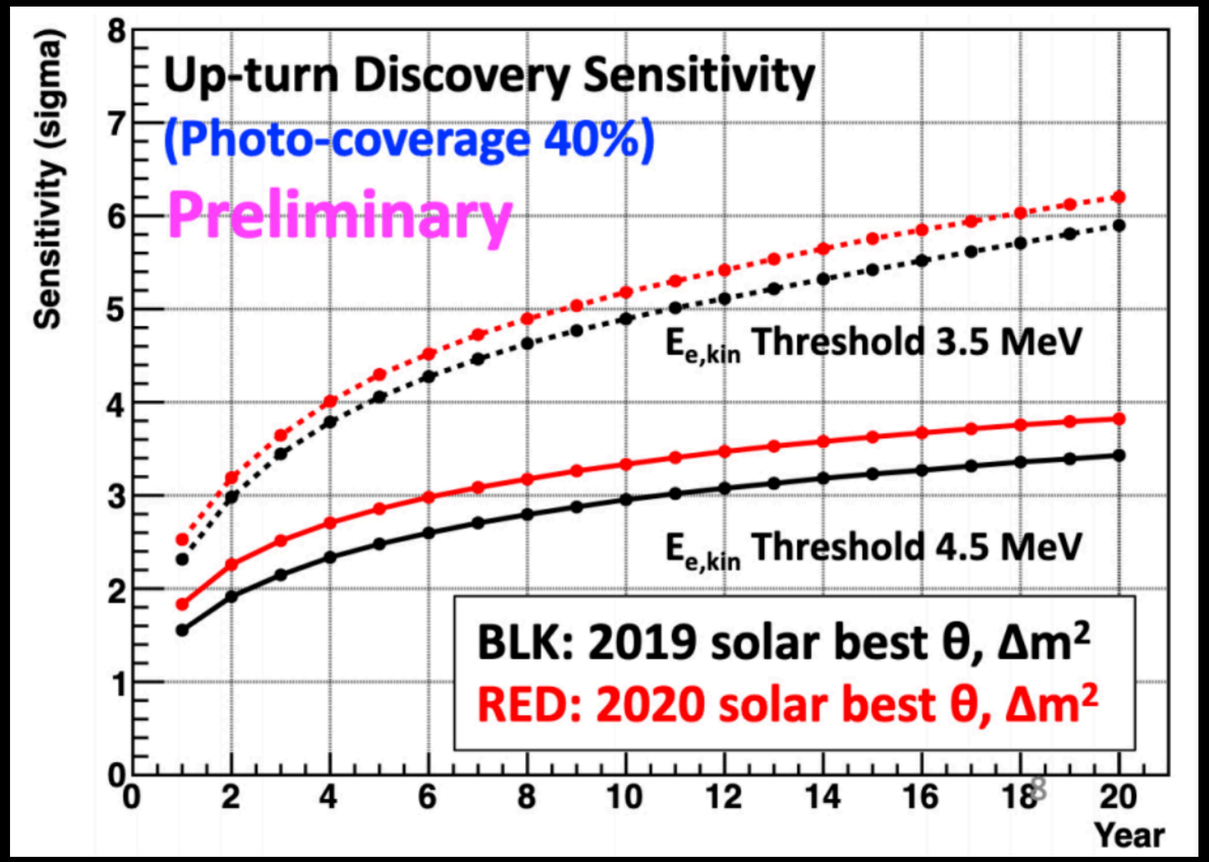
- Upturn is the variation of th oscillation probability between the vacuum and MSW dominated energy region.

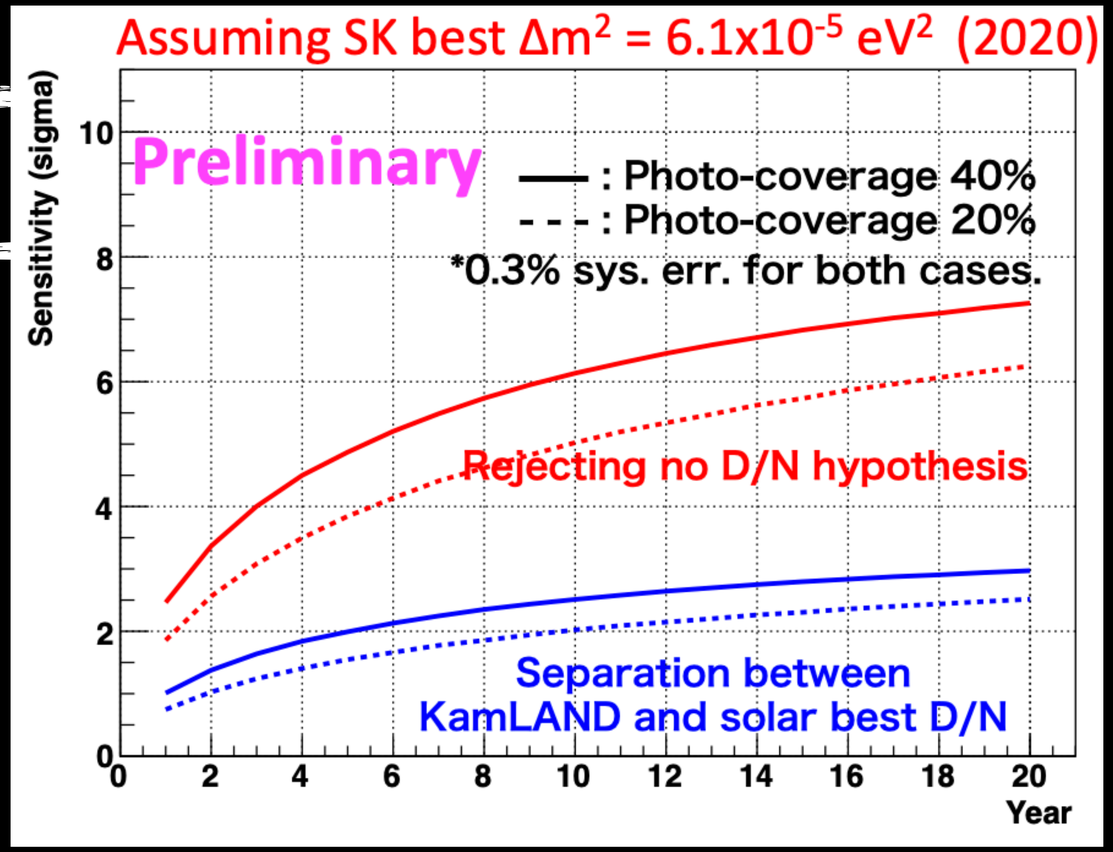


- Upturn not observed yet.

Solar Neutrinos

- Large D/N asymmetry is expected to be observed with $> 5\sigma$ after 10 years of operation

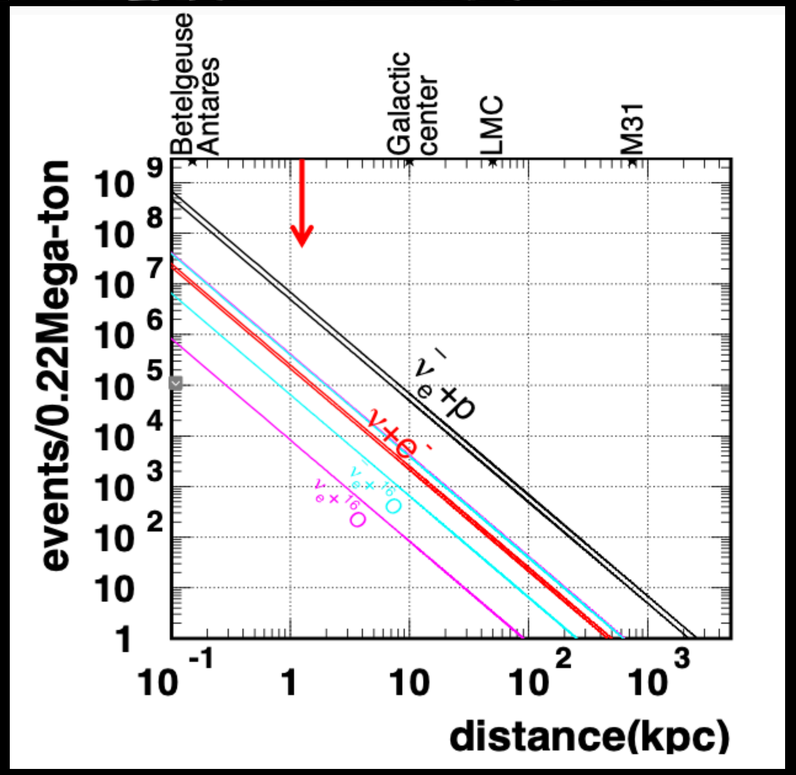




- In the upturn analysis, it is expected that **the sensitivity exceeds** $3(5)\sigma$ after 10y operation with the threshold of 3.5(4.5 MeV)

Supernova Neutrinos

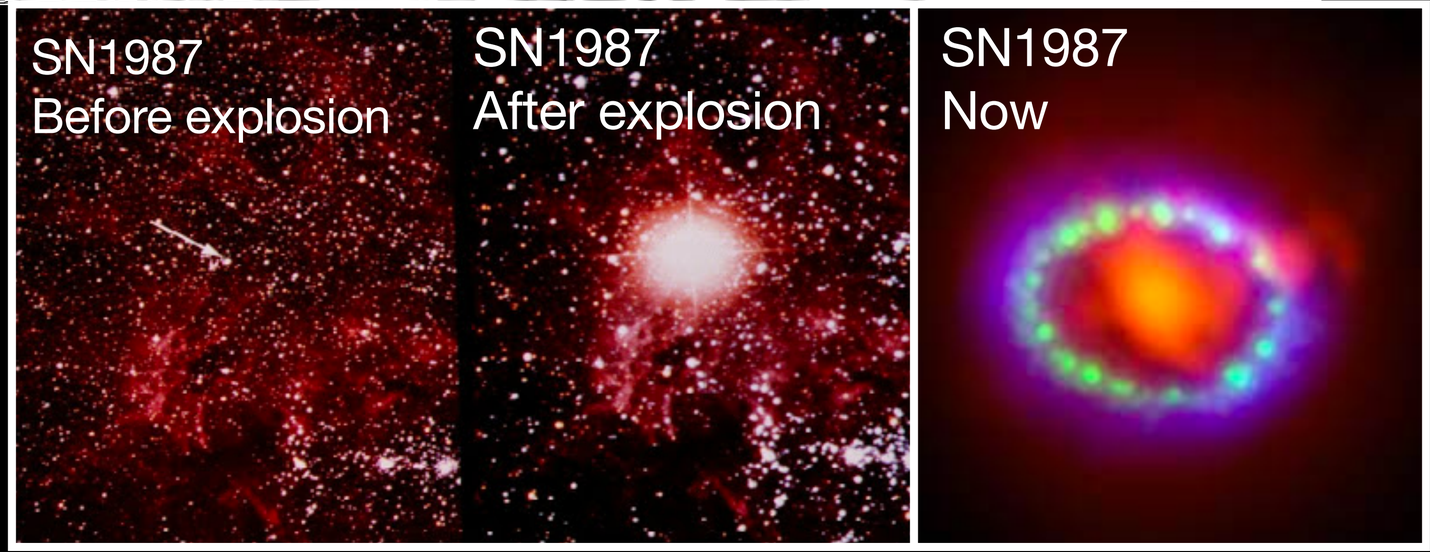
- Supernova neutrino observation:
  - 54-90k events for SN at 10 kpc (most sensitive to $\bar{\nu}_e$)
  - Precise Neutrino Time profile
  - Precise spectrum measurement
  - Investigation of the SN mechanism (SASI/ Rotation/Convection)

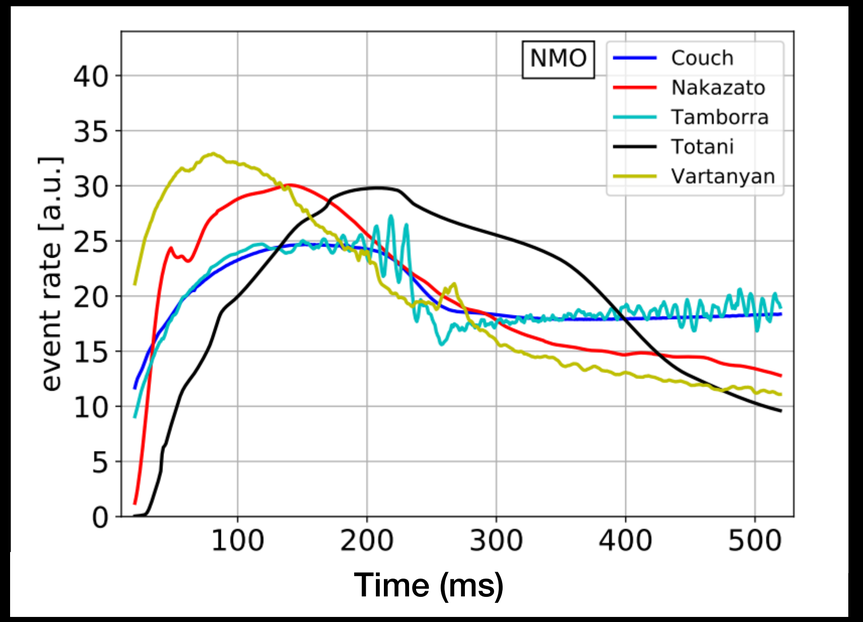


- Models by different groups, using various approximations → telling models apart can help understand the explosion mechanism

Supernova paper

- First Hyper-K paper!
- Published by *Astrophysical Journal* on April 13, 2021.
- arXiv:2101.05269 [astroph.IM]
- Hyper-K has the potential to have a large statistics if there is a supernova burst
- Hyper-K can distinguish between different explosion mechanism models.

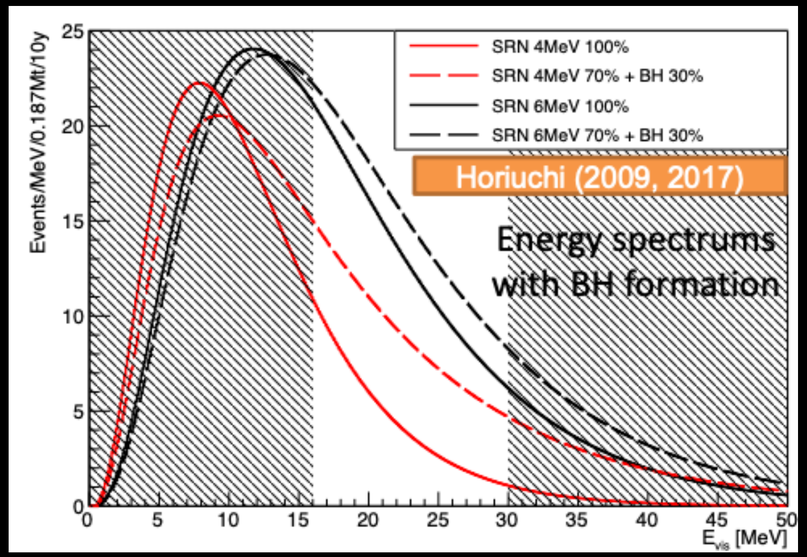




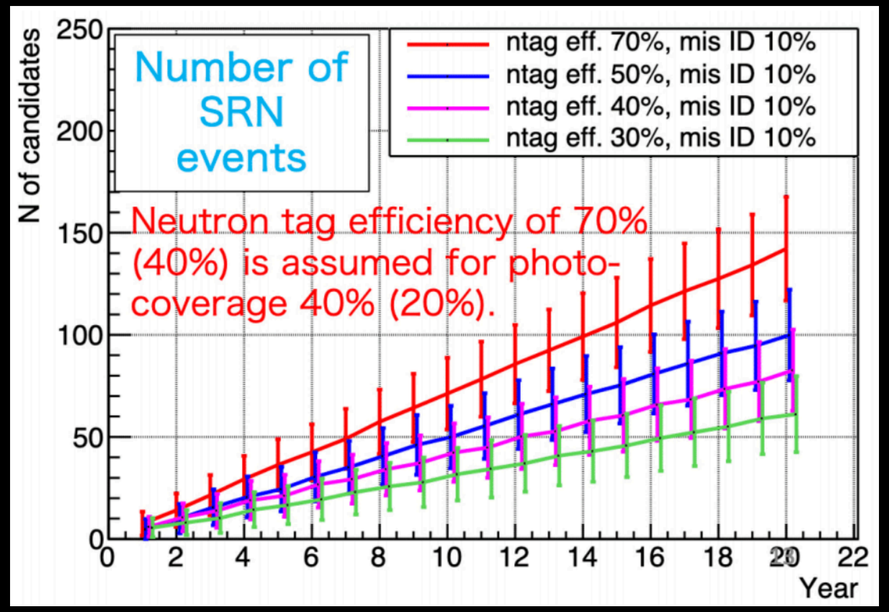
Event rate in Hyper-K from supernova burst for different explosion models

Supernova Relic Neutrinos

- Supernova Relic Neutrino (SRN)
- Diffused neutrinos coming from all past supernovae.
- Not discovered but promising extra-galactic ν.
- SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

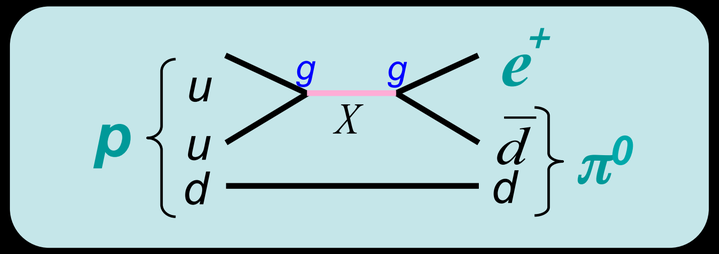


- The number of detected SRN events is predicted for various neutron-tagging configurations.
- In the case of 70% efficiency, ~70 events will be observed within 10 operation years. This corresponds to 4σ **sensitivity**

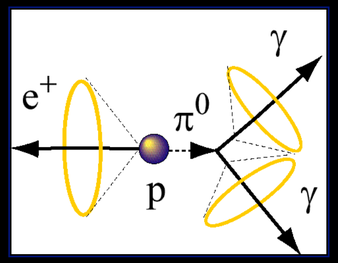


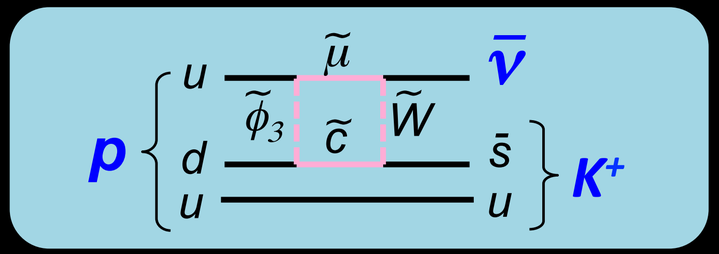
Proton Decay Searches

- Two major modes predicted by many models

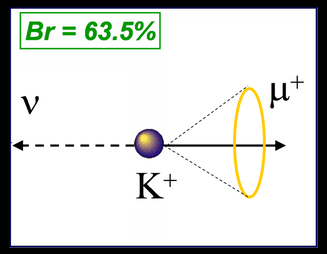


p→e⁺π⁰

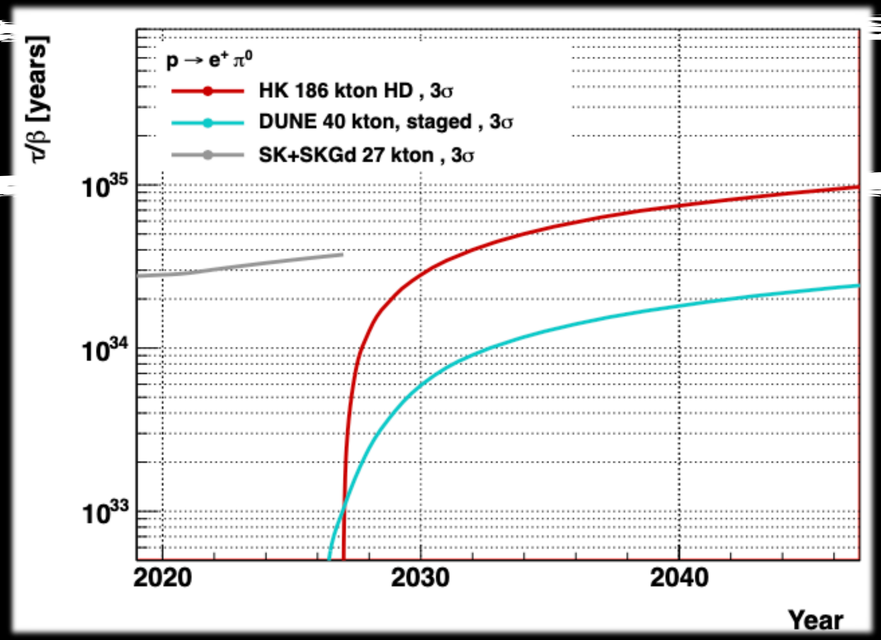


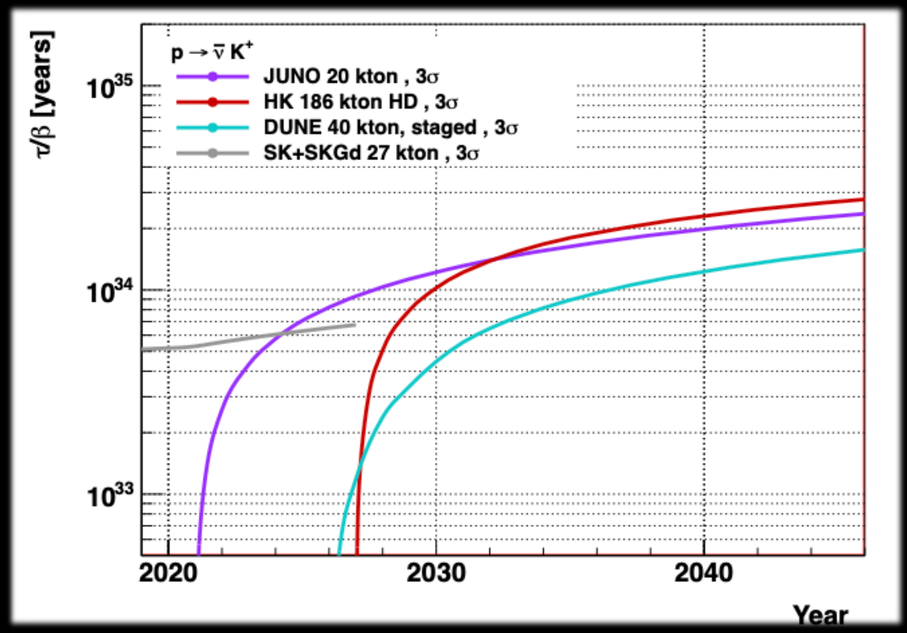


p→ν̄K⁺



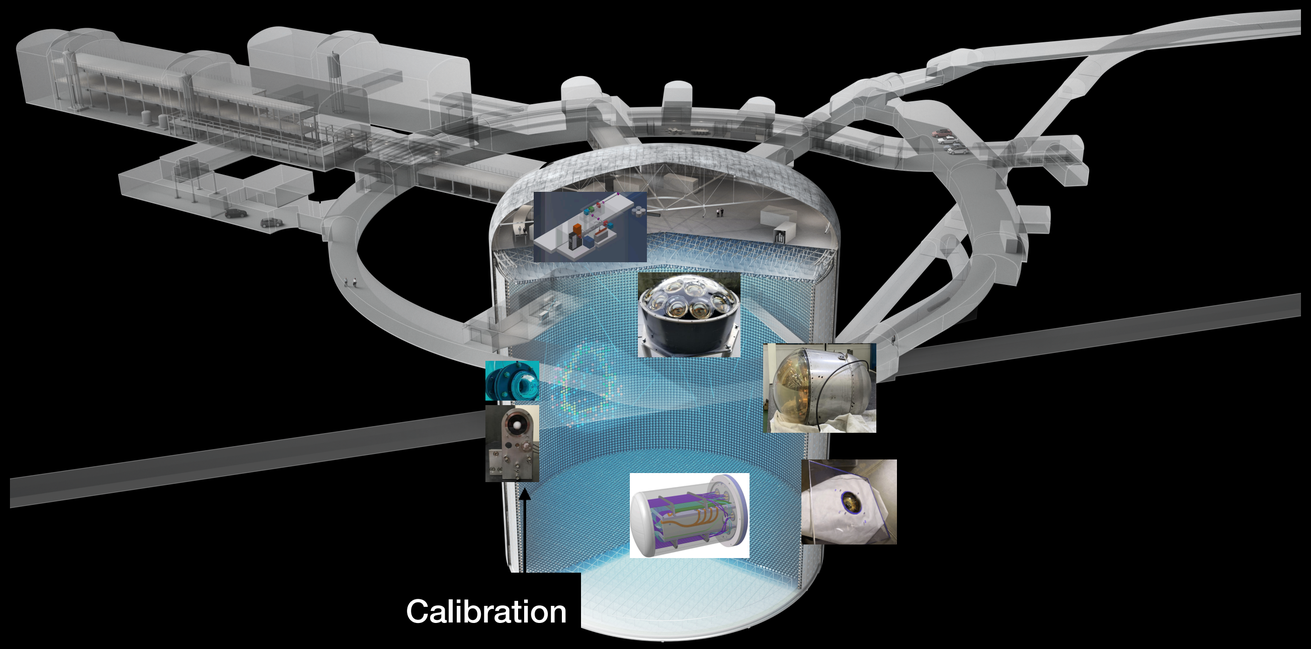
- Hyper-K is able to pursue these and other final states with the highest precision.





Conclusion

- A groundbreaking experiment is being built in Japan.
- Major progress in the last year in the construction of the experiment.
- It will address major open questions in science! Multipurpose experiment!
- It will start to take data in 2027!!



- Underwater components ready to be installed in the Far Detector by ~December 2025.
- R&D completion in 2022, mass production to start in 2022-2023.

Backup Slides

- Additional slides for perusal

New Research Building in Kamioka

New research building at Kamioka

- It is now being constructed. It will be completed by next summer.
- It has 4 floors and 3,050 m^2 total floor area.

Dormitory rooms.

Many physicists and engineers will come to Kamioka during the HK construction. They can use this research building.

Dinning rooms.

Many visiting researcher's Rooms in 2nd and 3rd floors.

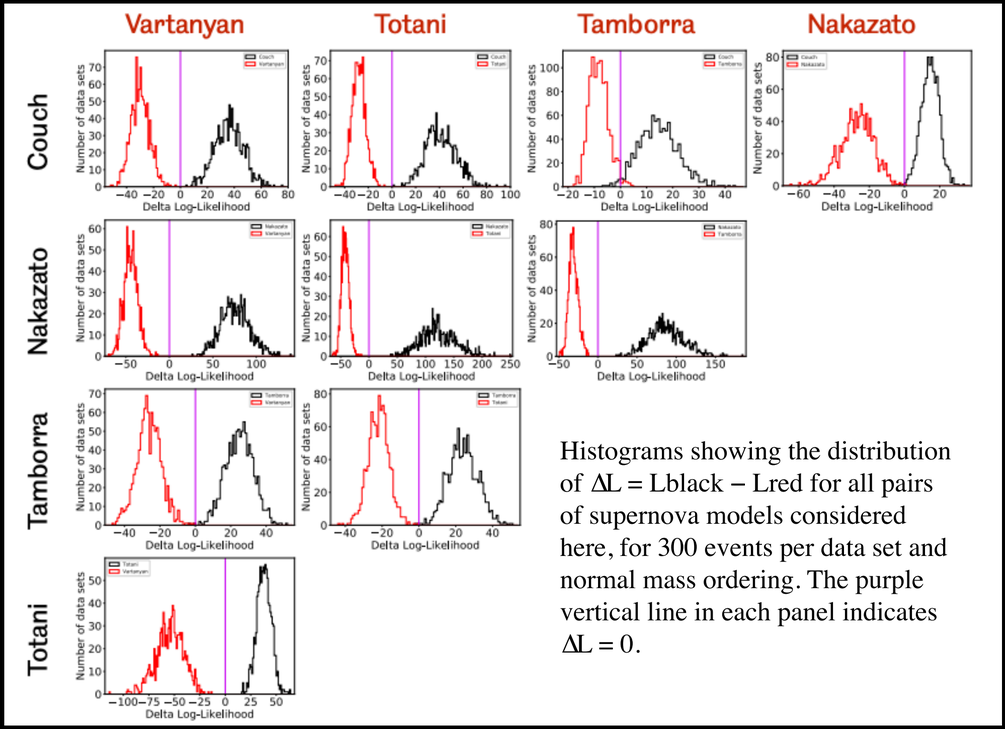
Lab. Rooms to construct detector components.

Big hall to accommodate about 150 people on the 1st floor.

Image of new research building

Supernova Neutrinos

- Supernova Model Discrimination with Hyper-Kamiokande
- e-Print: 2101.05269 [astro-ph.IM]



Histograms showing the distribution of ΔL = Lblack − Lred for all pairs of supernova models considered here, for 300 events per data set and normal mass ordering. The purple vertical line in each panel indicates ΔL = 0.

Accuracy with which the true model can be identified, for 300 events per data set

Normal mass ordering.

True Model (Normal)	Reconstructed Model: Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**98.2**	0.2	1.6	0.0	0.0
Nakazato	0.1	**99.9**	0.0	0.0	0.0
Tamborra	1.6	0.0	**98.0**	0.2	0.2
Totani	0.0	0.0	0.0	**100.0**	0.0
Vartanyan	0.0	0.0	0.0	0.0	**100.0**

Inverted mass ordering.

True Model (Inverted)	Reconstructed Model: Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**99.9**	0.1	0.0	0.0	0.0
Nakazato	0.0	**100.0**	0.0	0.0	0.0
Tamborra	0.0	0.0	**97.4**	0.1	2.5
Totani	0.0	0.0	0.0	**100.0**	0.0
Vartanyan	0.0	0.0	0.8	0.0	**99.2**

- With 300 events, corresponding to SN at 60-100 kpc, >97% identification is realized.

Major Milestones

R&D completion

50 cm PMT covers	**2/22**
mPMTs	7/22
OD PMTs, Plates	2/22, 12/22
Electronics	6/22
Calibration systems	12/22

Assembly

50 cm PMTs+ covers	**12/25-9/26**
mPMTs @ 5 sites	5/24-5/26
OD PMTs + Plates	2/24-5/26
Electronics module assembly start	5/25
Calibration systems	6-12/25

Production

50 cm PMTs, covers	**3/21-9/26, 7/22-8/26**
mPMTs module parts	7/23-12/25
OD PMTs, plates	7/23-12/25, 11/23-12/25
Electronics final prototypes	9/23-5/24
Electronics mass production	6/24
Calibration Linac	8/23-8/25
Calibration light injection	4/24-5/25

Installation

All systems	1-11/26

- R&D (i.e. baseline design) will finish in 2022.
- Production will start in 2022-2023.
- It is essential to keep timely contributions.