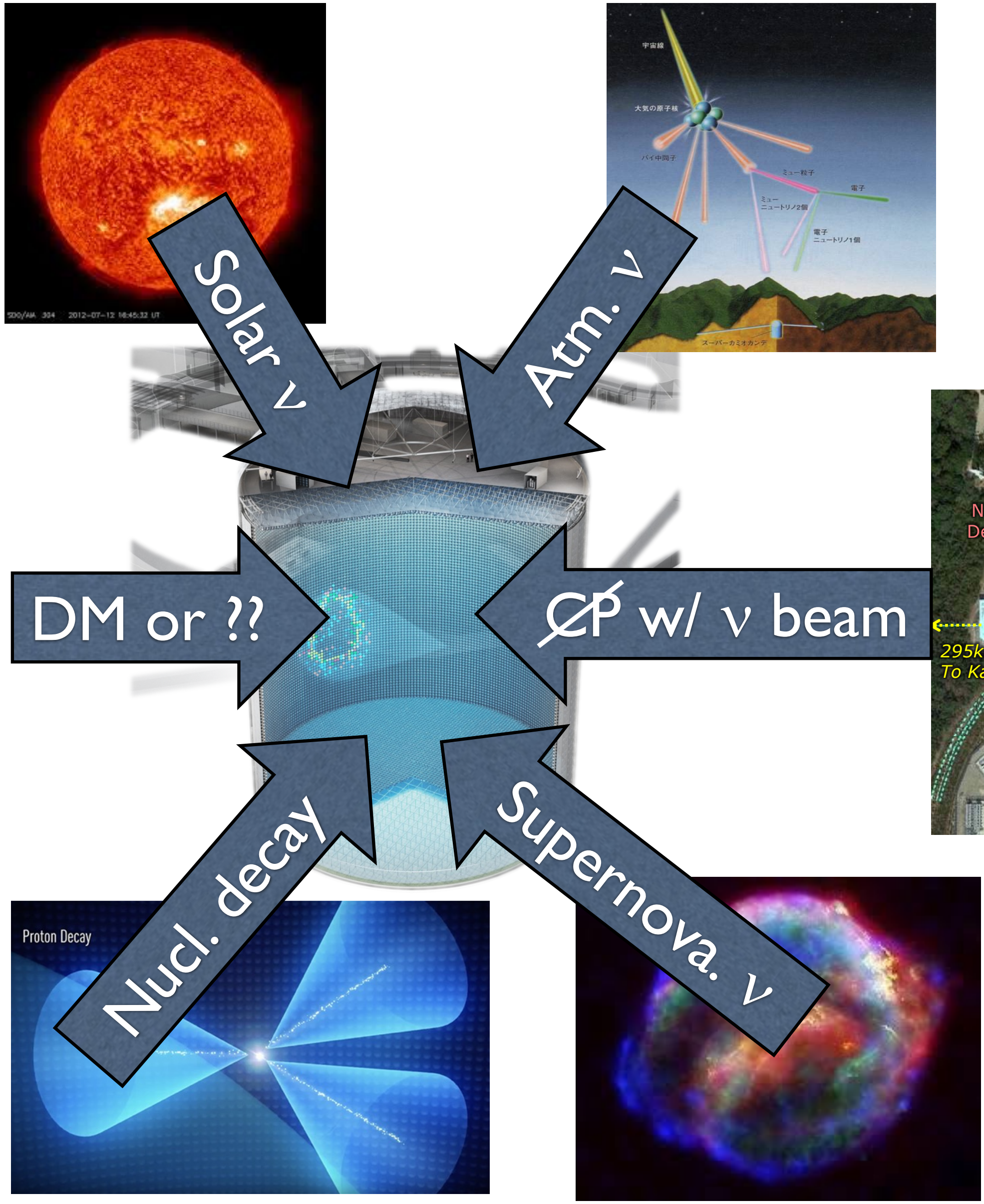
Hyper-Kamiokande

Shigetaka MORIYAMA, on behalf of
the Hyper-Kamiokande collaboration

Kamioka Observatory, Institute for Cosmic Ray Research,
Next-generation Neutrino Science and Multi-messenger Astronomy Organization, and
Kavli Institute for the Physics and Mathematics of the Universe (WPI), U of Tokyo

XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024 Milan, Italy

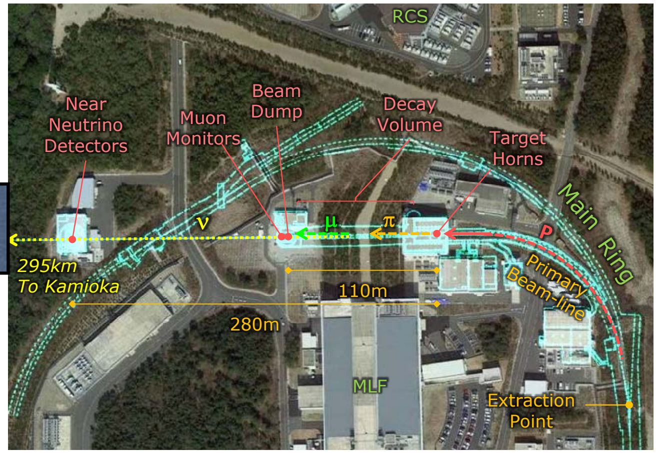


Hyper-Kamiokande Project

Rich physics & discovery potential

<u>Construction started in 2020</u>

<u>Operation will start in 2027</u>

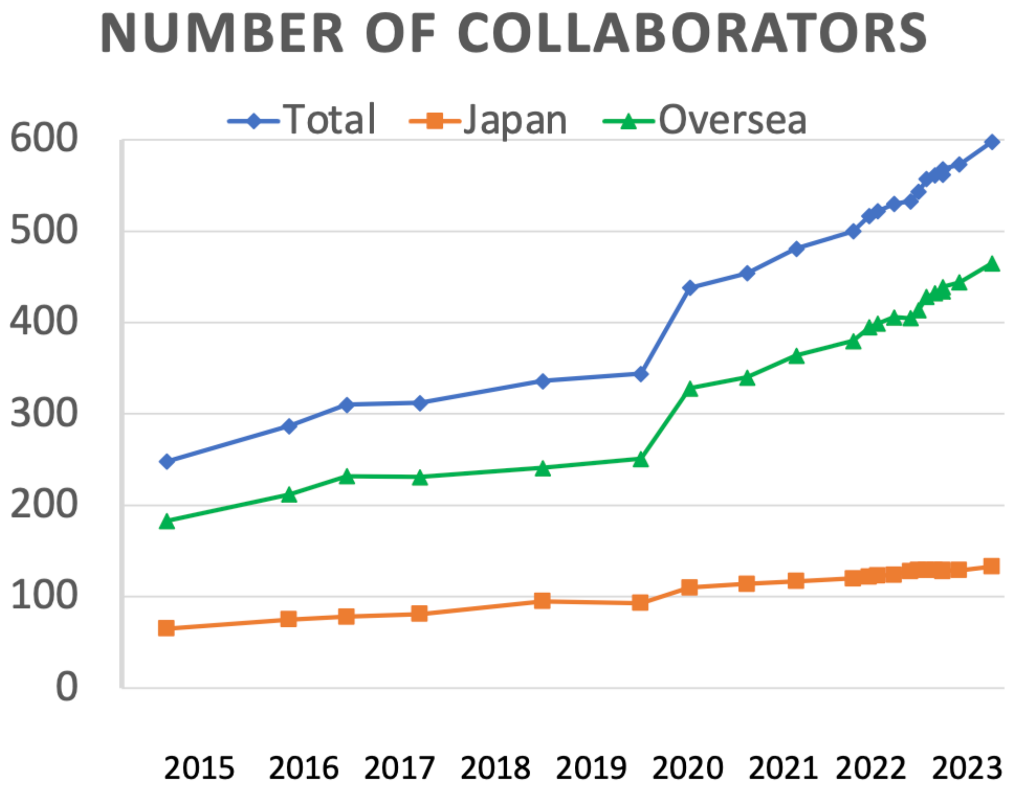


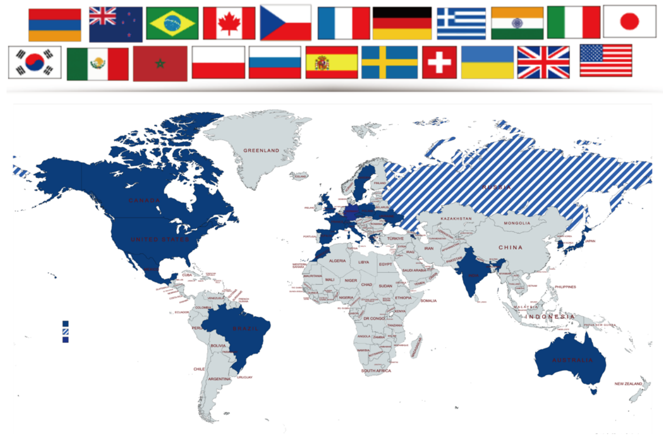
Two host institutes:

U. Tokyo for HK detector

KEK J-PARC for beam/NDs

International Hyper-K collaboration and a new UTokyo building at Kamioka



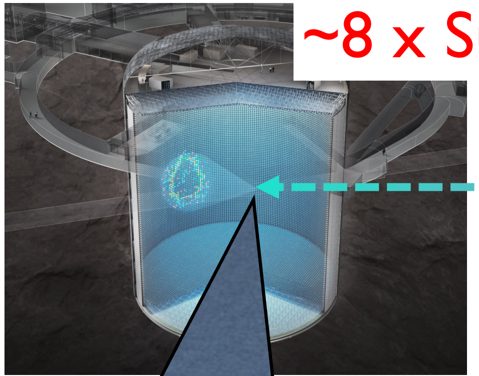


Hyper-K meeting @Kamioka Oct. 2023

22 countries, 104 institutes, 583 members as of April 1, 2024

<u>Still linearly increasing</u>

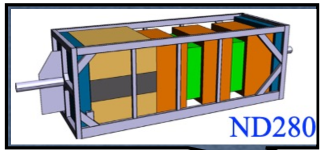
J-PARC off-axis ν_μ & $\overline{\nu}_\mu$ beam (~0.6 GeV, ~295 km)

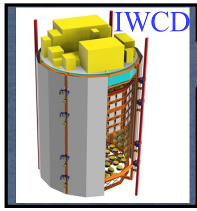


~8 x Super-K

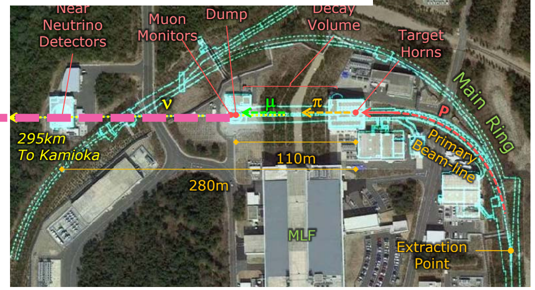
The Japanese Alps

$\nu_e / \overline{\nu}_e$ $\nu_\mu / \overline{\nu}_\mu$

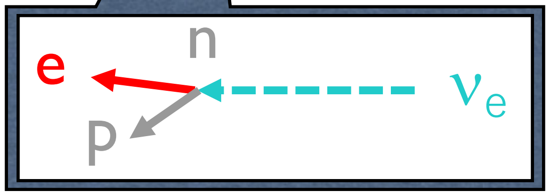




0.5→1.3MW



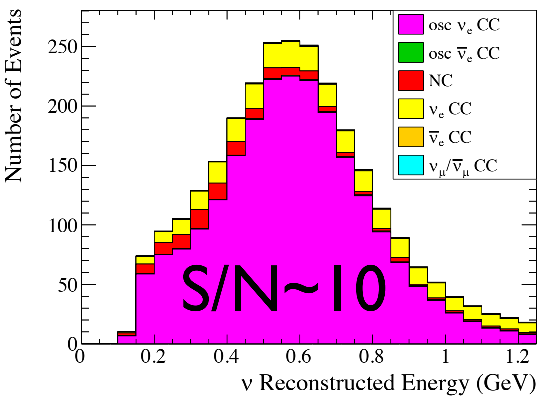
2.5 deg. off-axis

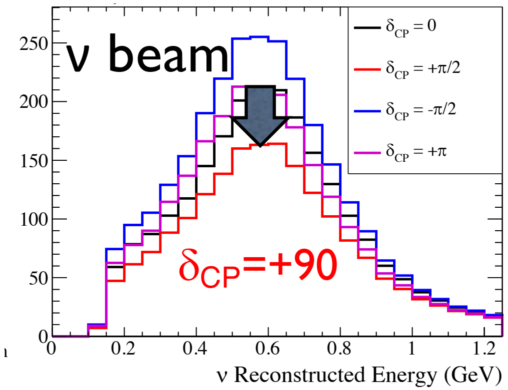


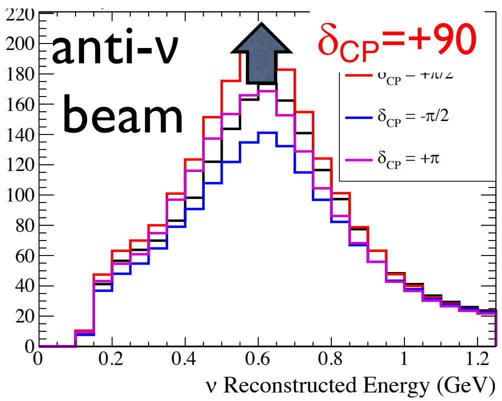
ν_e appearance signal = single e event

CCQE : ν_e + n → **e** + p

(dominant process at J-PARC beam energy)







Relatively Small matter Effect & Large CPV Effect

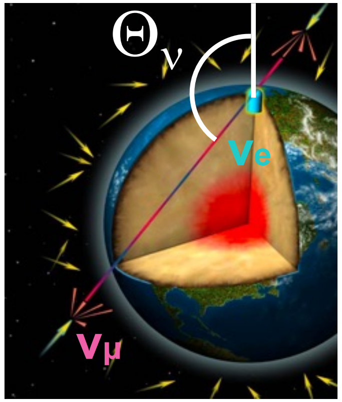
HK 10 yr, 2.7x10^{22} POT 1:3 ν:$\overline{\nu}$, 1-ring e-like + 0 decay e, > 1000 events each

Atmospheric 3-flavor ν beam (0.1-10^3 GeV, 10-13,000 km)

- The wide range of E (0.1~10^3 GeV) and L (10 km ~13,000 km) provide an excellent opportunity to study various properties of ν.
- Study of the earth matter effect to determine neutrino mass ordering
- Unique tests of exotic properties

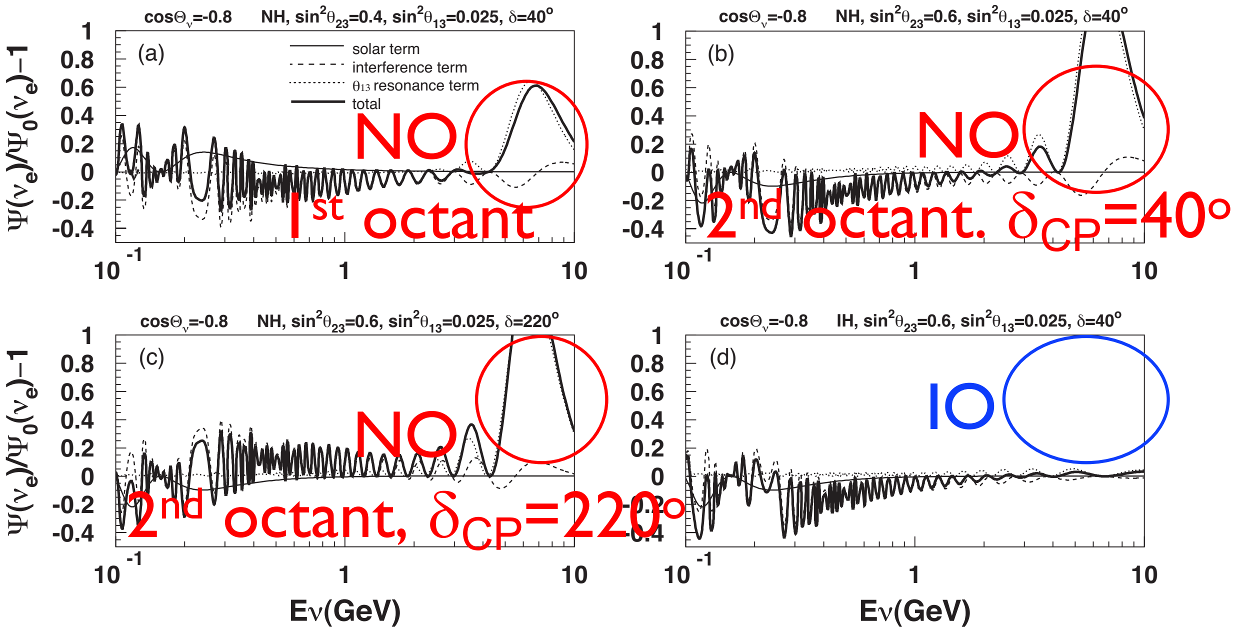
~80 events/day

Oscillation studies with wide range of E and L. The matter effect solves MO.



In case of $\cos\Theta_\nu$=-0.8, the effect of MO can be observed.

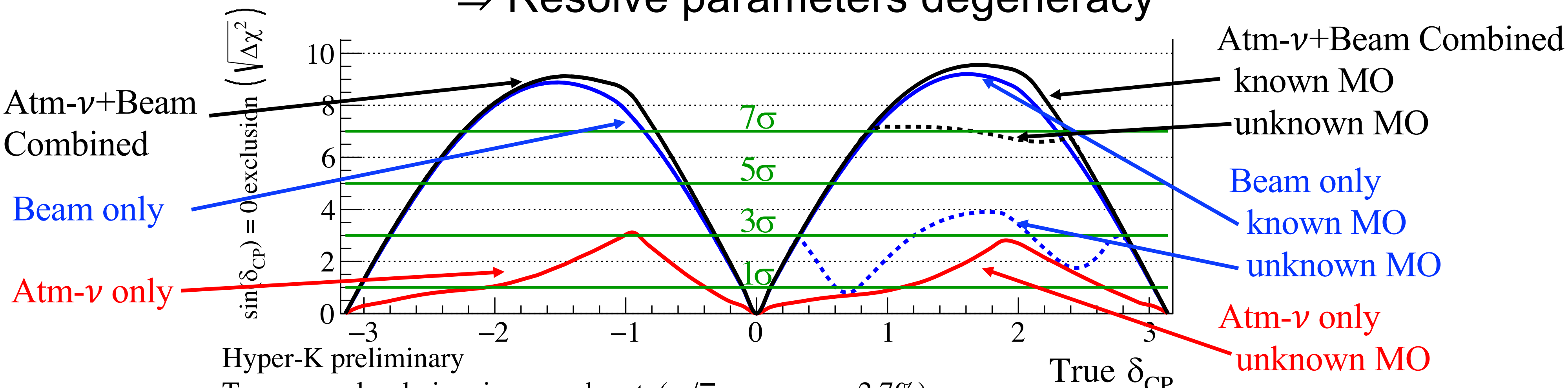
Effect of Mass Ordering (MO) and ~~CP~~ on ν_e flux



Strategy of oscillation measurement at Hyper-K

Combination of long-baseline and atm. ν observations

⇒ Resolve parameters degeneracy



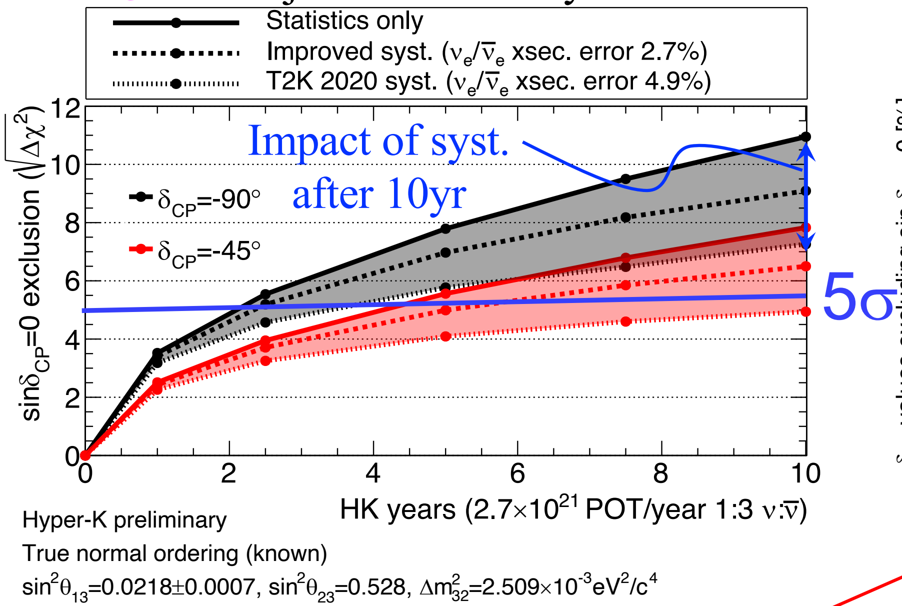
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ →	3.8 σ
	0.60	4.9 σ →	6.2 σ
θ_{23} octant	0.45	2.2 σ →	6.2 σ
	0.55	1.6 σ →	3.6 σ

10 years with 1.3MW, normal mass ordering is assumed

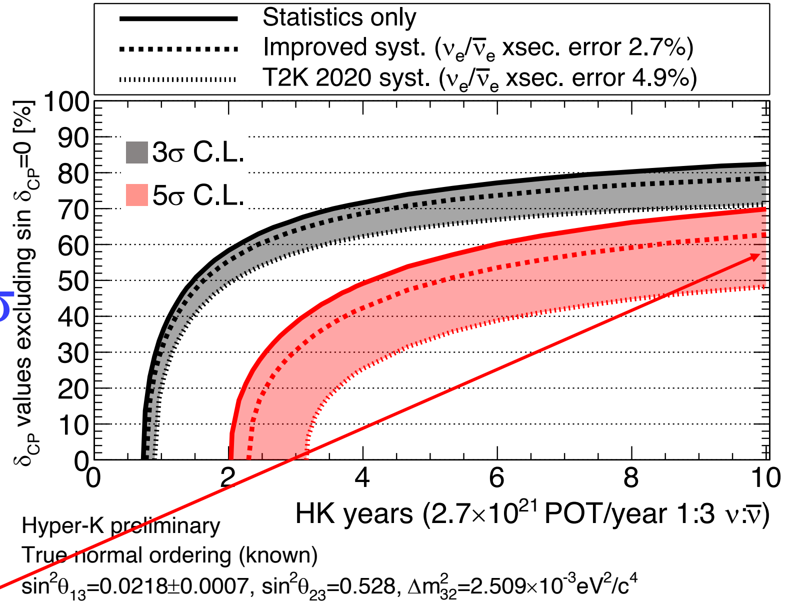
Atmospheric neutrino:
sensitive to mass ordering by the earth matter effects
→ Constraints on mass ordering enhance sensitivity to CP violation by long-baseline

Precision measurement of neutrino oscillations

δ_{CP} Projected sensitivity to CPV



δ_{CP} Fraction of δ_{CP} to exclude $\sin\delta_{CP} = 0$



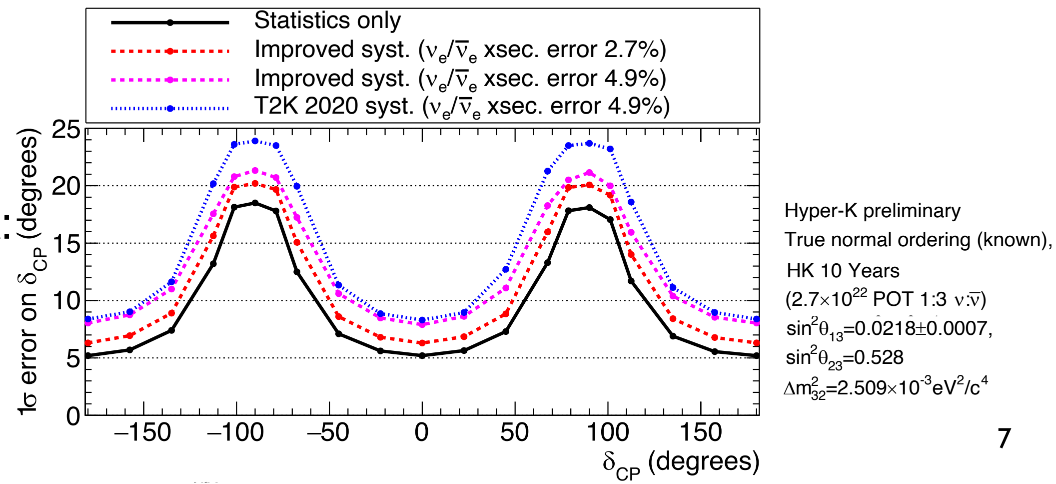
Discovery of CP violation at >5 σ for >60% of δ_{CP}

1σ resolution of δ_{CP} in 10 yrs

~20° for $\delta_{cp} = -90°$ / ~6° for $\delta_{cp} = 0°$

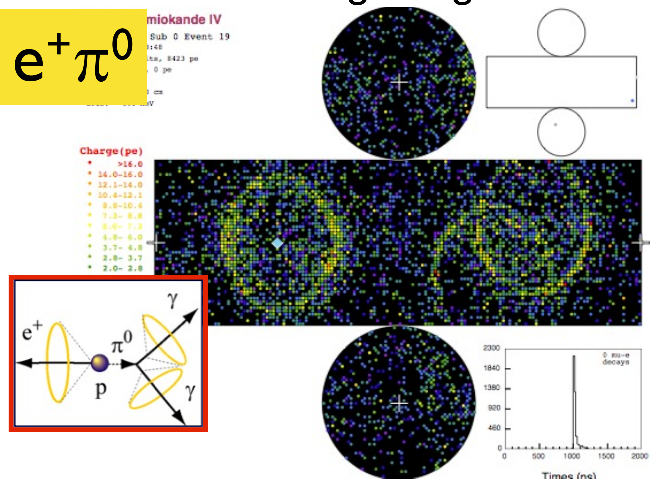
Reduction of systematic uncertainty has sizable impact:

- Upgrade of ND280 + ~600 ton Intermediate Water Cherenkov detector (IWCD)
- Aim to suppress detector error below 1%

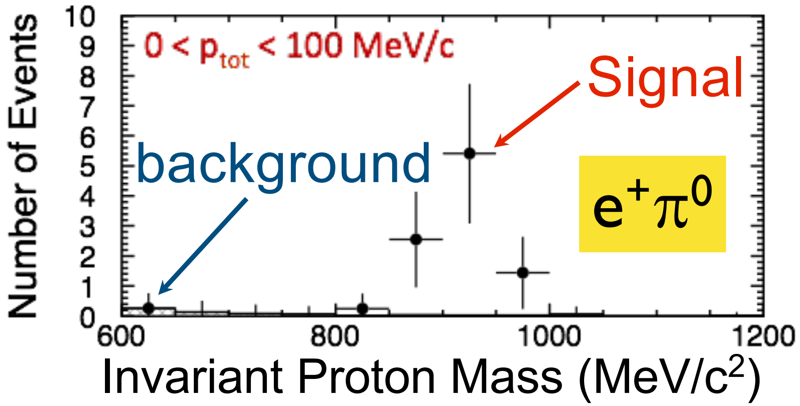


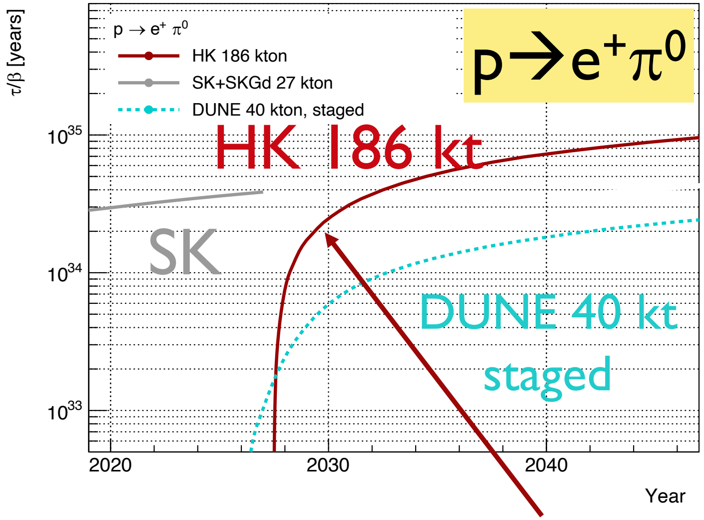
Proton decay searches (note: FV ~8 x Super-K)

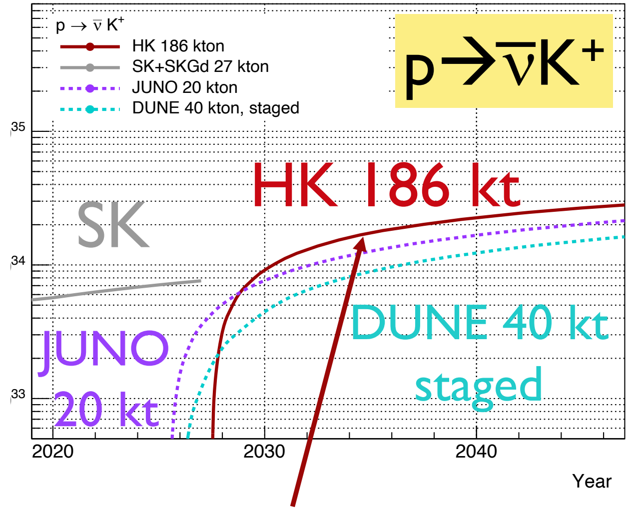
Cherenkov ring image $e^+\pi^0$ in SK



Hyper-K 10 years operation assuming $\tau_{proton}=1.7\times10^{34}$ years (~Super-K limit)







3σ discovery potential

HK 10 years

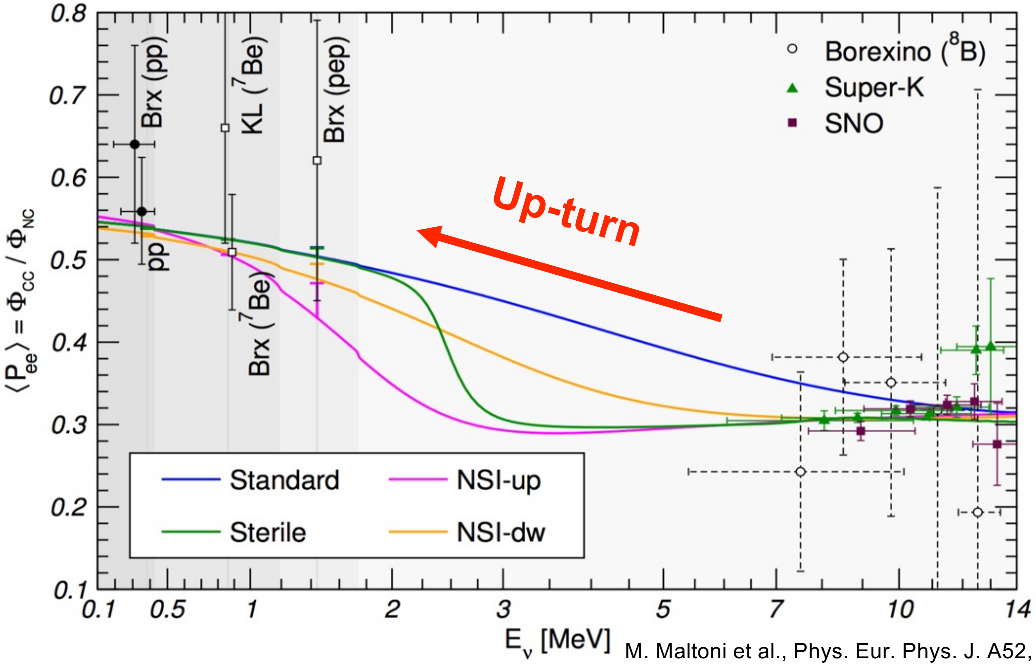
- $p\rightarrow e^+\pi^0$: ~6x10^{34} yrs
- $p\rightarrow \nu K^+$: ~2x10^{34} yrs
- …

Hyper-K will play a leading role in the next-generation proton decay search

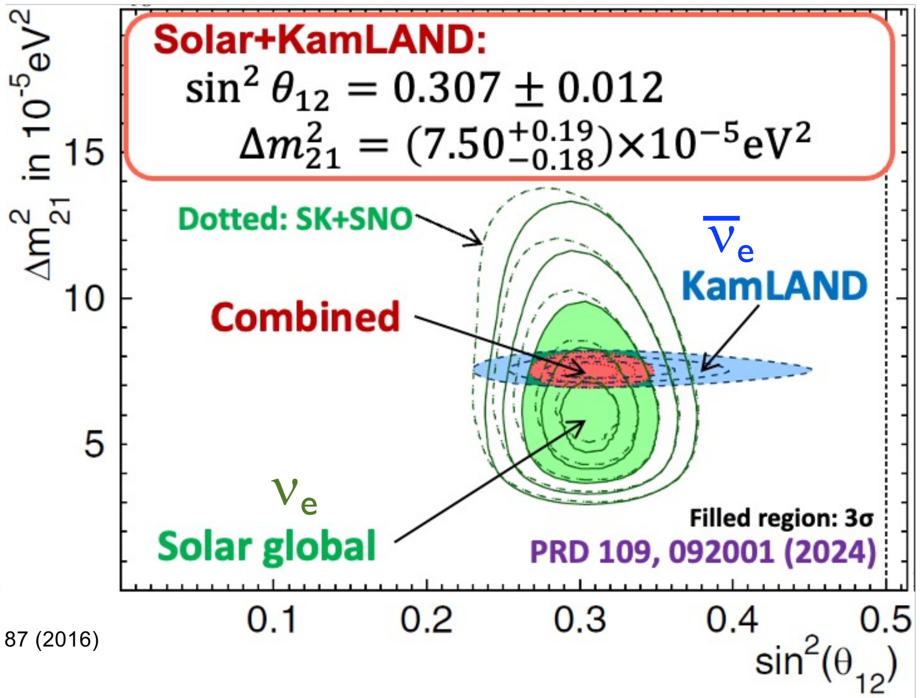
Solar ν spectrum & possible differences in $\nu_e/\overline{\nu}_e$ oscillation

Confirm MSW effect by observing spectrum distortion "up-turn"

Compare ν_e, $\overline{\nu}_e$ oscillation (currently ~1.5σ tension in solar/reactor ν)



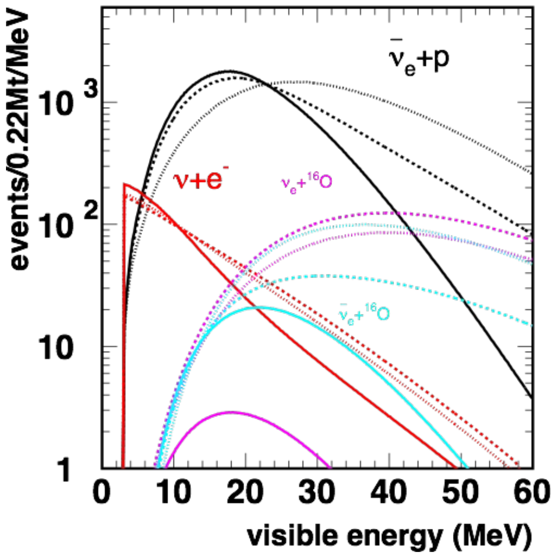
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

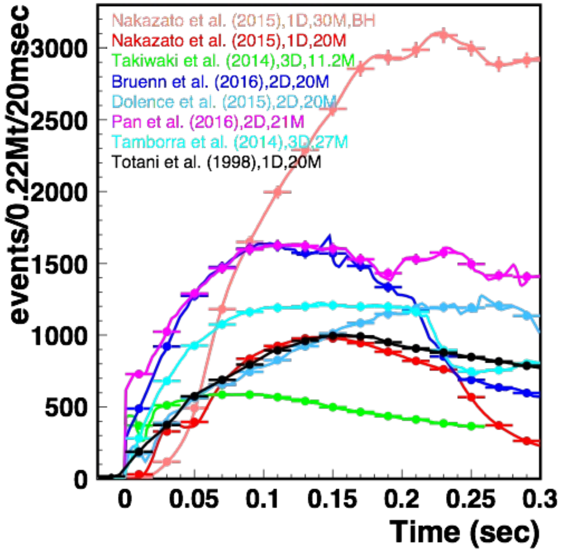


~130 events/day

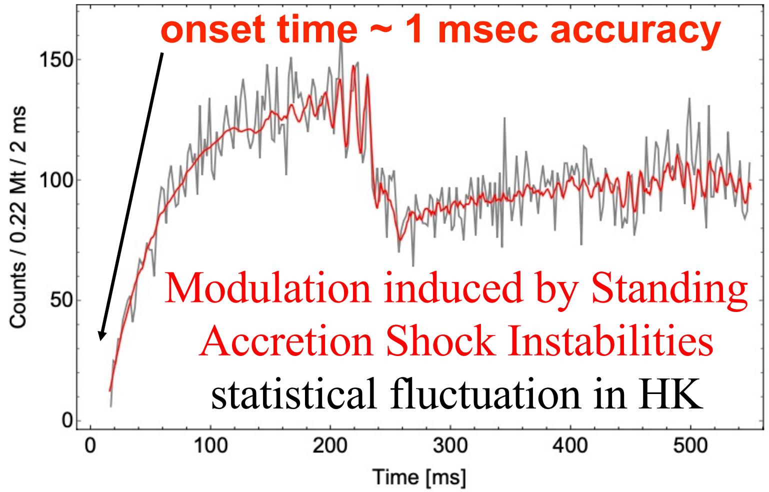
- > 3σ sensitivity for the spectrum up-turn in 10 yrs (E_{th}=4.5 MeV).
- ~2σ day/night sensitivity expected for the difference in $\nu_e/\overline{\nu}_e$ osc. in 20 yrs.

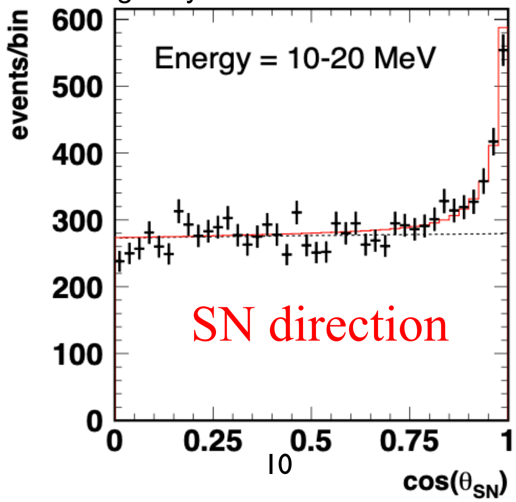
Astrophysics: Supernova burst ν

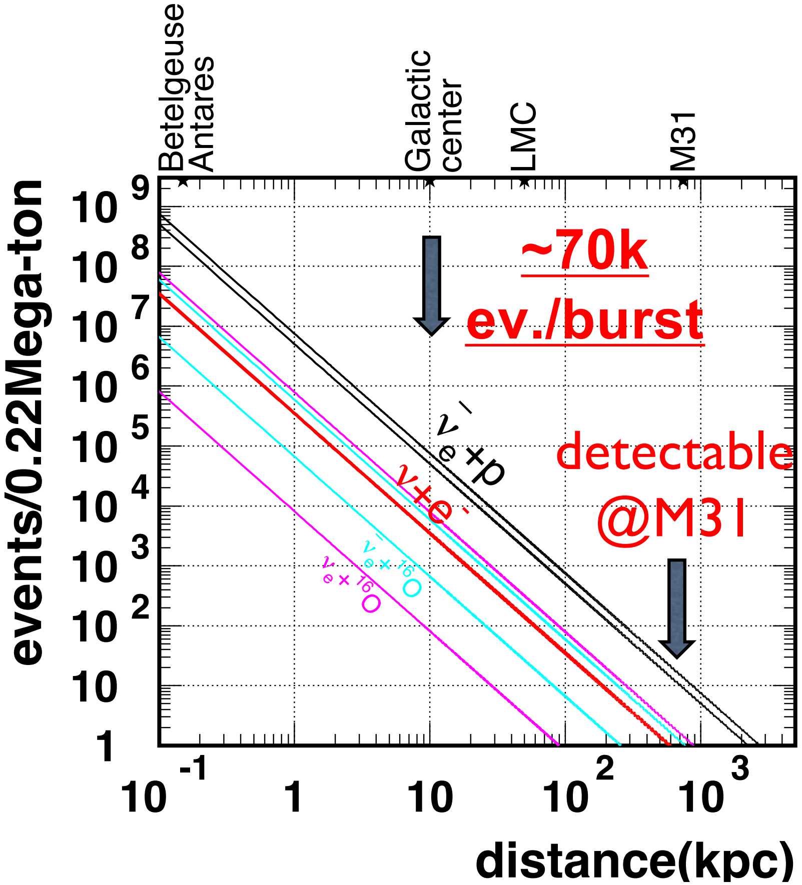




galactic supernova at 10 kpc (our r_{galaxy}= 8 kpc)





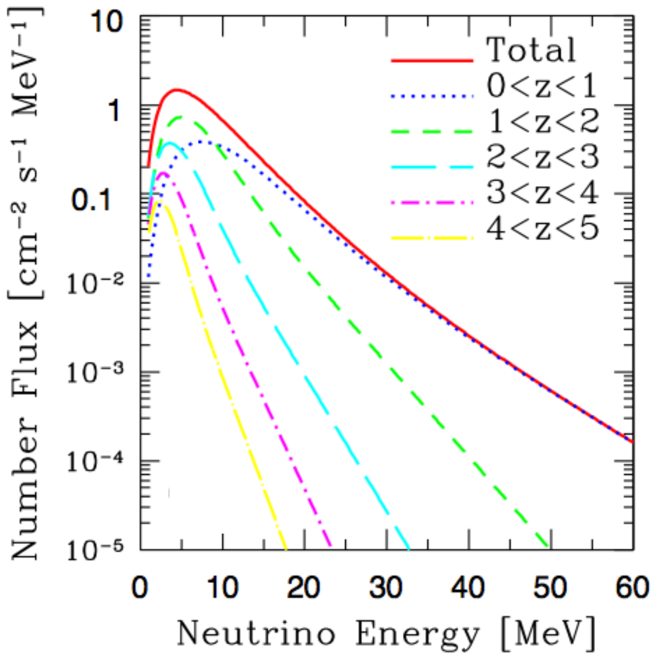


~70k events/burst at 10 kpc

- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

Diffuse Supernova Neutrino Background (DSNB)

DSNB energy spectrum including red shift



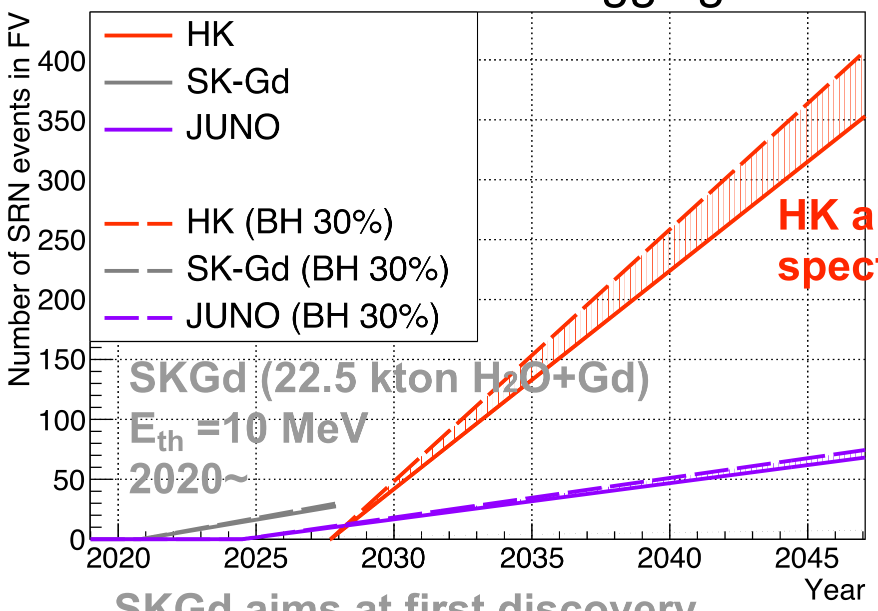
S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{\rm max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\frac{dz}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}},$$

Neutrinos from supernova explosions in the early universe to the present day

integrated flux ~10 $cm^{-2}sec^{-1}$

Number of DSNB events before neutron tagging



HK (187 kton H_2O)
E_{th} =16 MeV
2027~

HK aims for precise flux & spectrum measurement.

JUNO (20 kt LS)
E_{th} =12 MeV
2024~

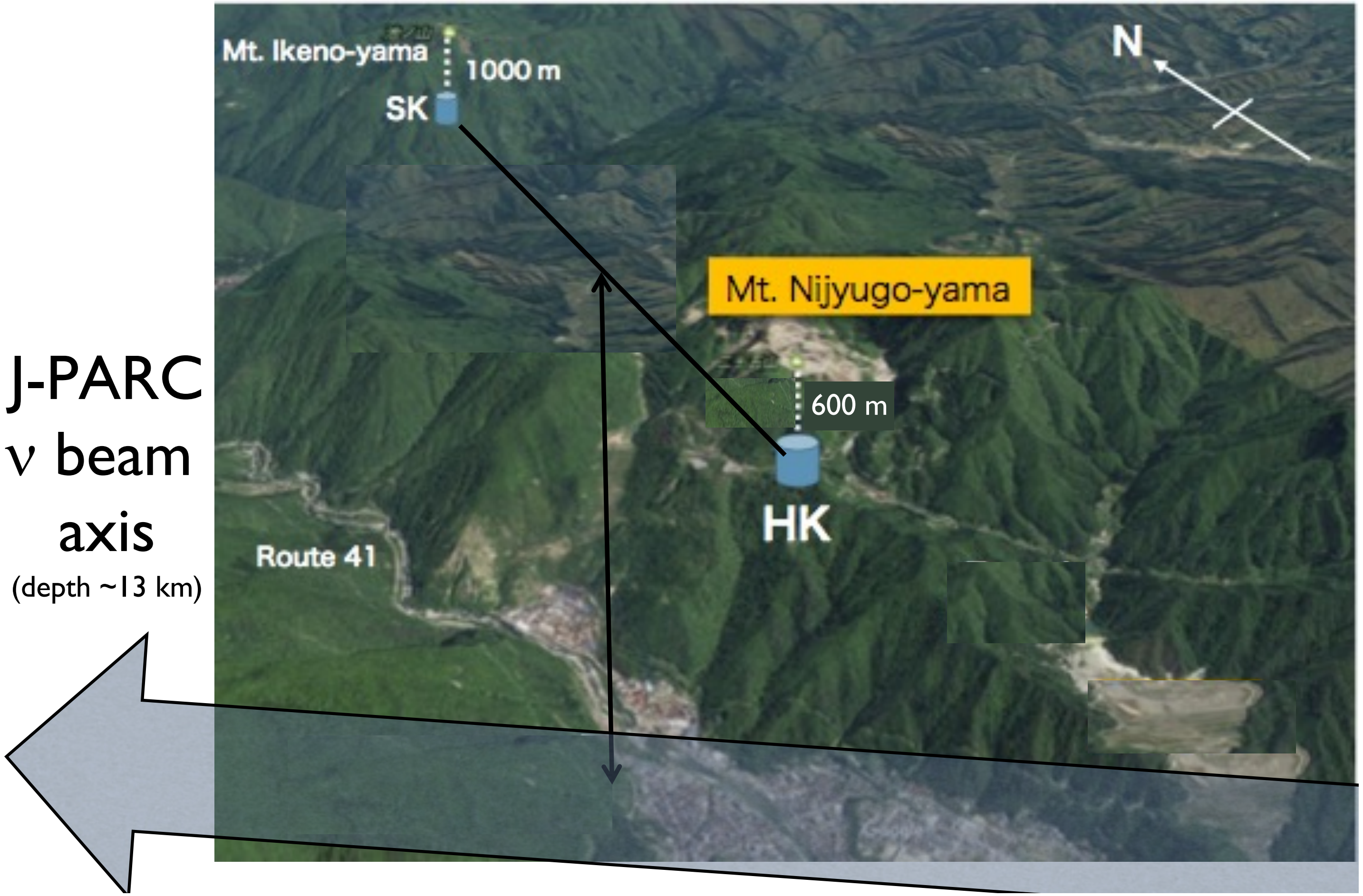
SKGd aims at first discovery.

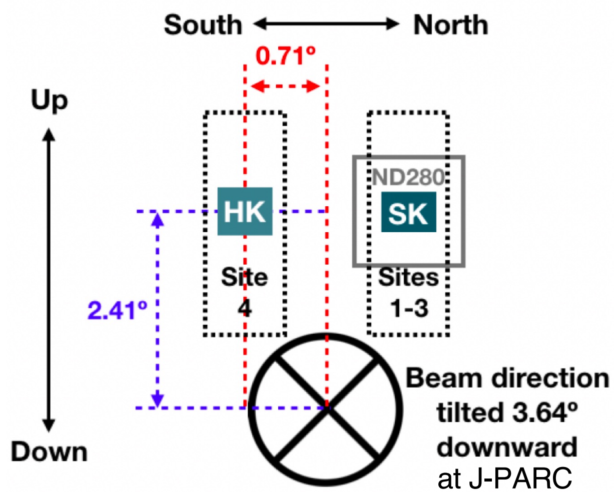
~4 ev/yr after neutron tagging w/ H_2O

- Stellar collapse
- Star formation rate
- Heavy element synthesis

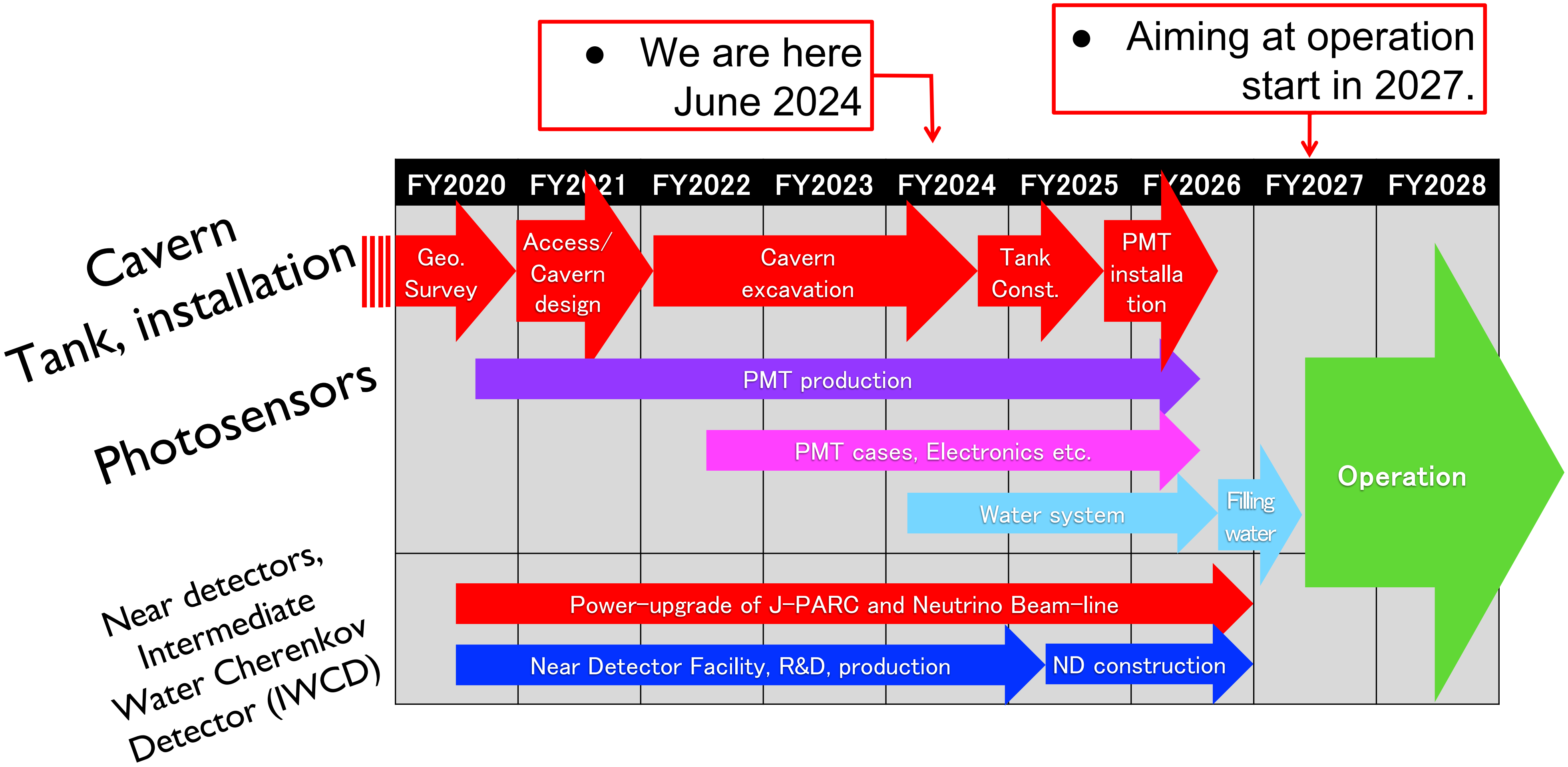
Detector Location and J-PARC ν beam

- 8 km south of Super-K
- 295 km from J-PARC and 2.5 deg. off-axis beam (same as Super-K)
- 600 m rock overburden

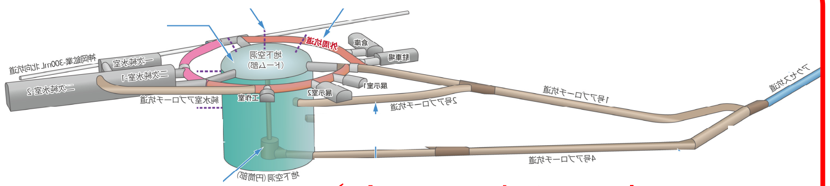




Construction Schedule



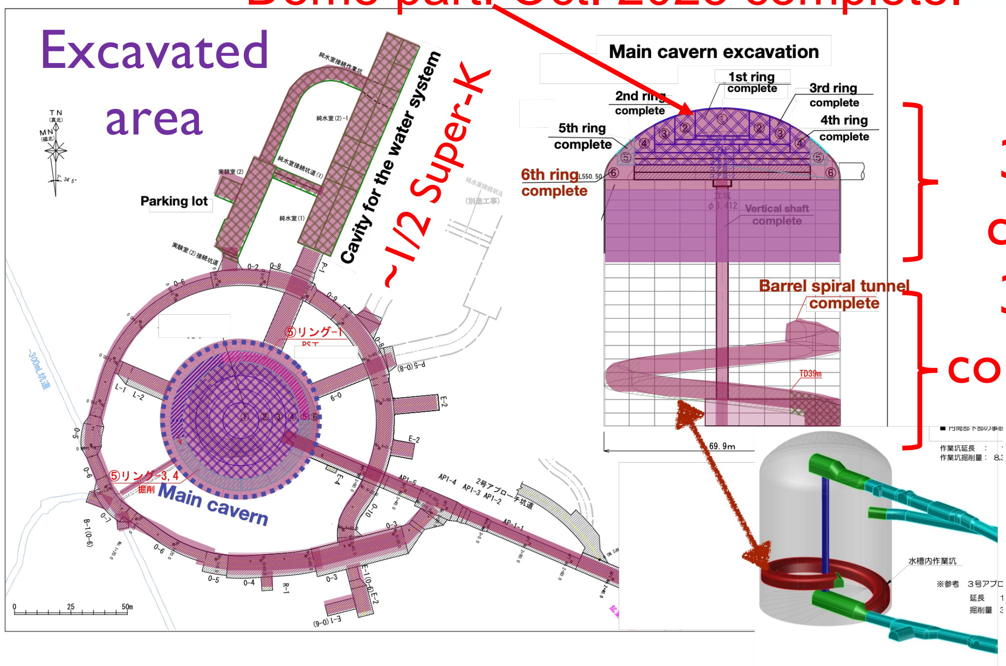
Excavating the world's largest human-made cavern



✓ Approach tunnels:
Aug. 2022 complete.

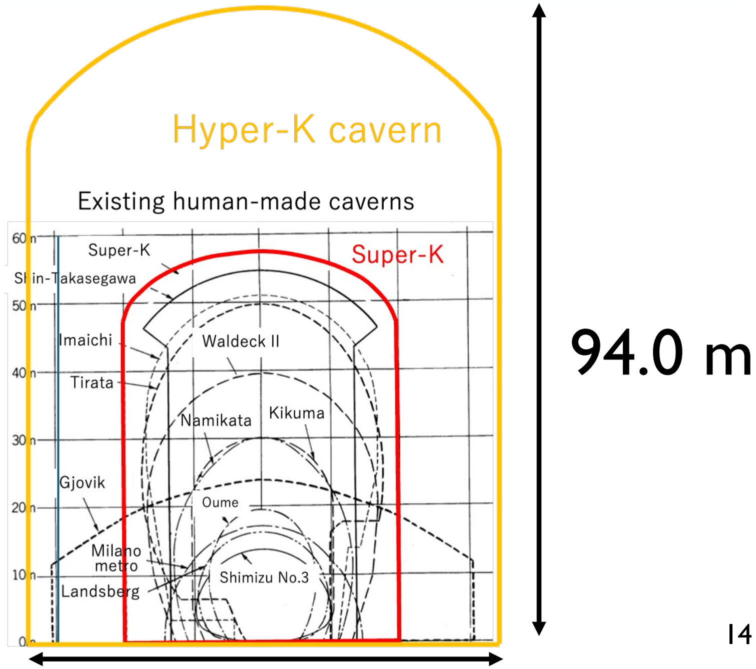
✓ Access tunnel: Feb. 2022 complete.

✓ Dome part: Oct. 2023 complete.



3 Super-K completed.

3 Super-K coming ~1/2yr



69.0 m

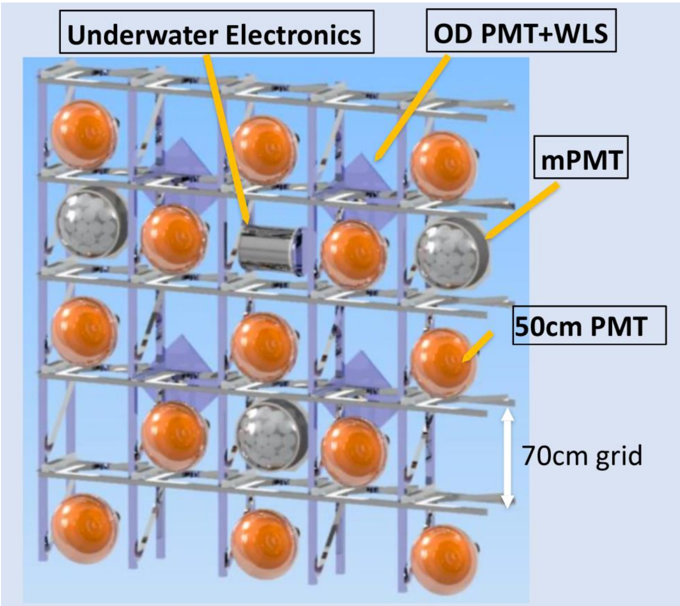
94.0 m

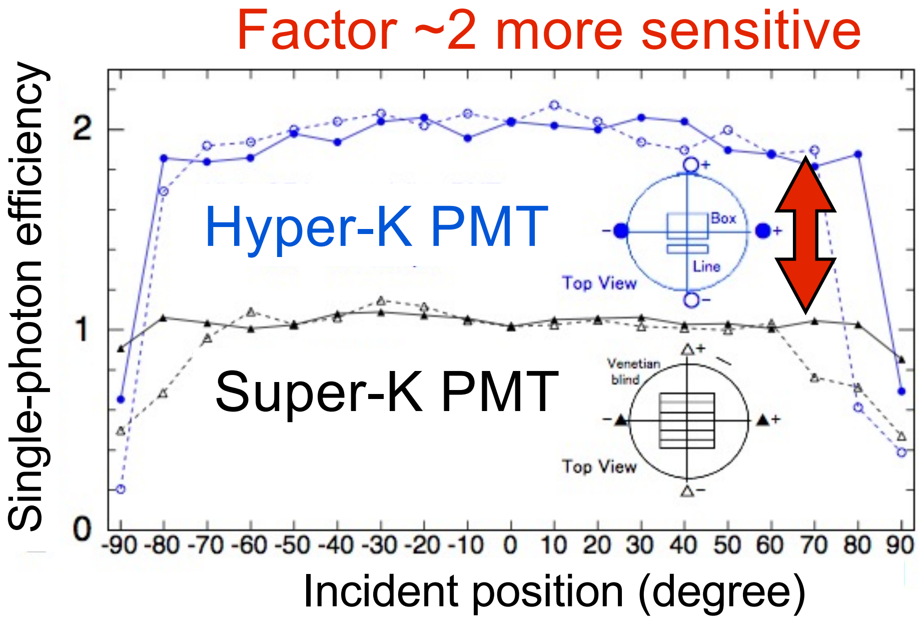
Oct. 3, 2023   Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)


Excavation of the HK cavern will be completed by the end of this year!

Photo-detection system

- Detailed design of the tank lining and photosensor support structure completed.



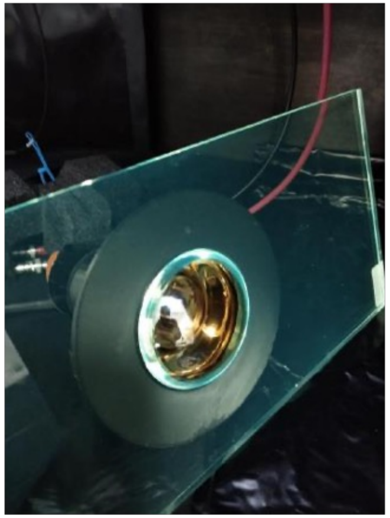


- New features of 50 cm PMT (B&L-dynode) include
  - High QE, T resolution, pressure tolerance (x2 better than Super-K)
  - dark rate reduction, low radioactivity, cover development
  - long-term performance evaluation already in Super-K
  - ➔ 20 000 of 50 cm PMTs from Japan

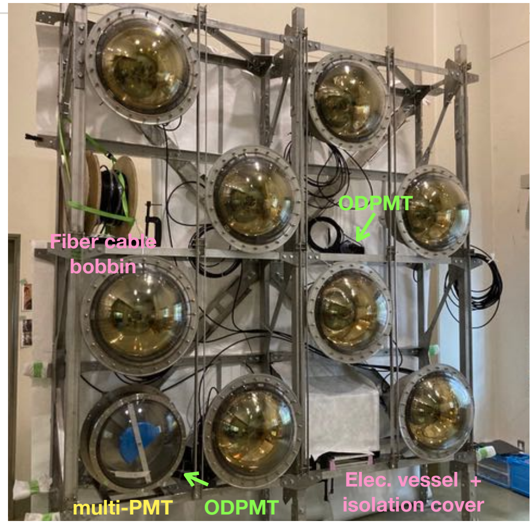

PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

Photosensors and underwater electronics

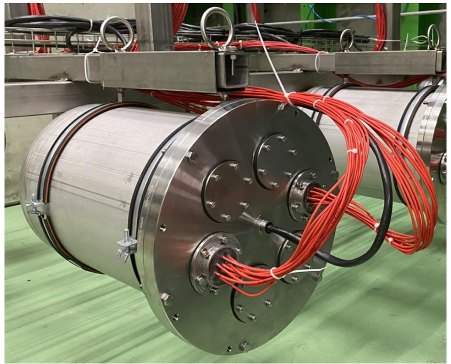
Outer detector: PMT+WLS plate

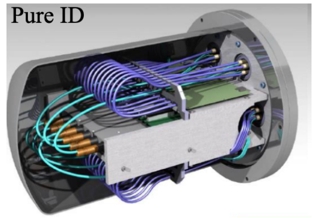


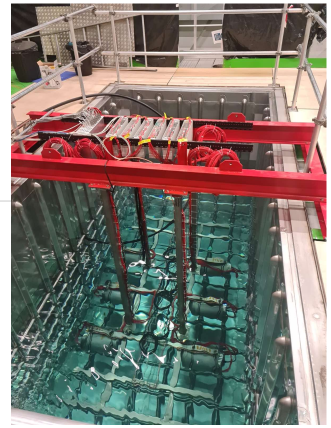
Photosensors/elec. mockup



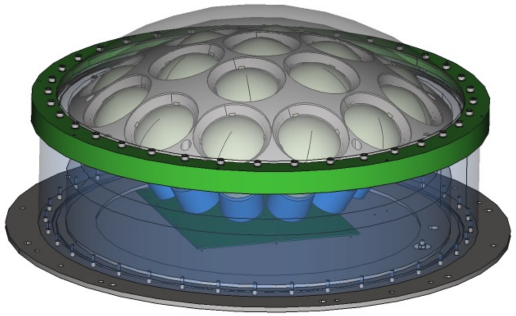
Underwater electronics: Case design and feedthrough



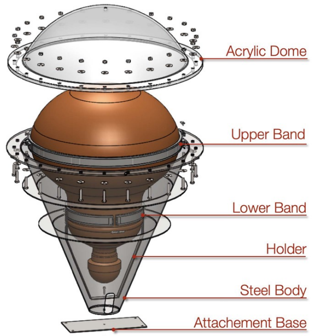


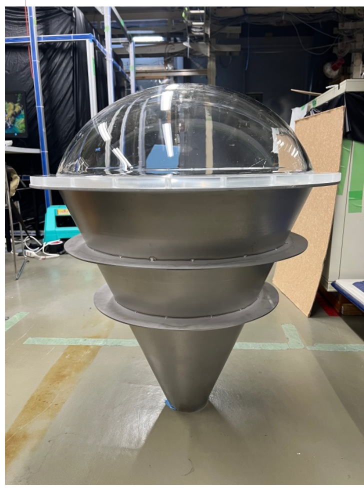


Multi-PMT module:

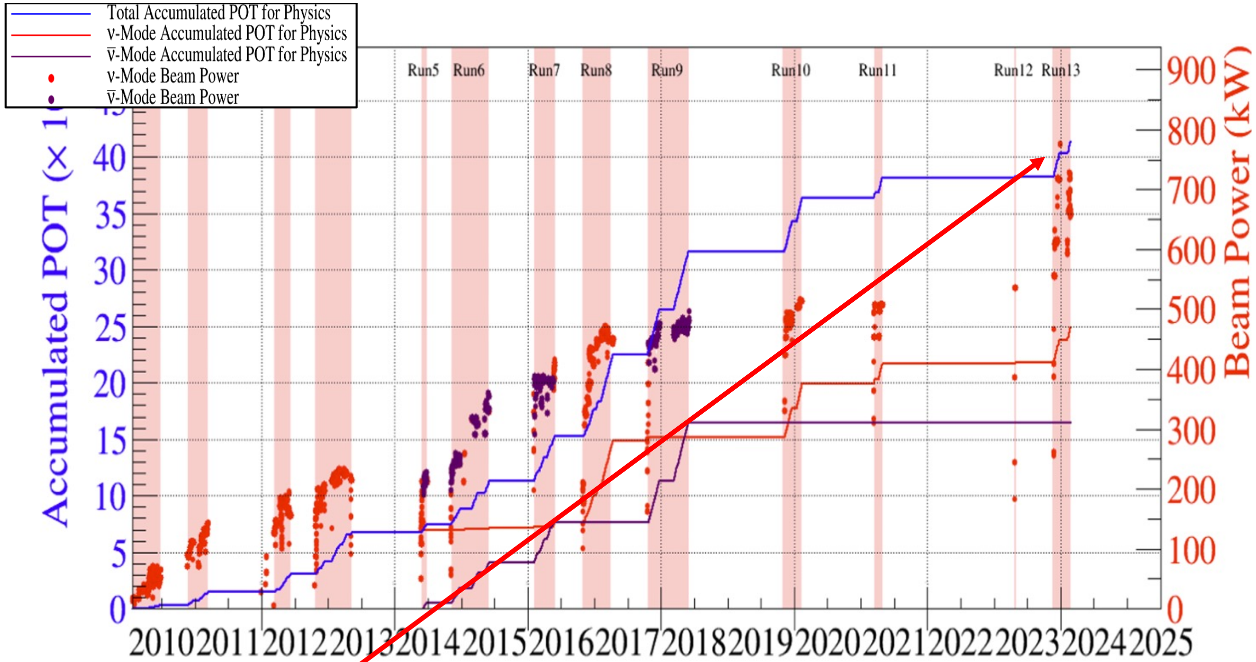


PMT cover





Beam: status and plan of power increase

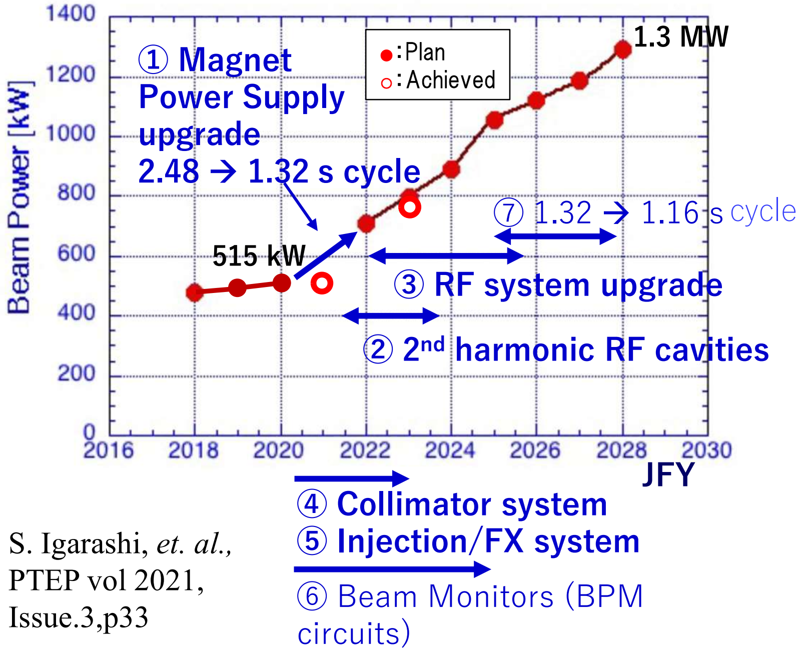


760 kW achieved already and 800 kW last week!

Further beam power increase requires:

- Seeking beam loss with optics improvements
- More protons/pulse by upgrading RF system
- Further beam intensity increase will be done by 1.36 → 1.16 sec cycle

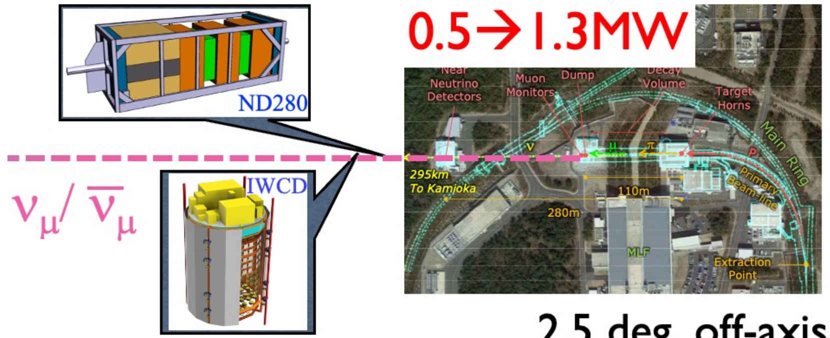
Original power projection in MR Upgrade Plan



S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

Near Detectors: ND280 and IWCD

- CPV: difference in $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- Statistical uncertainty of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
  - ~5% for 3 years, ~3% in 10 years
- T2K-ND280 demonstrated that systematics on fluxes and cross-sections can be controlled to ~3-4%
- Further improvements are expected in HK thanks to the combination of ND280 Upgrade and IWCD



2.5 deg. off-axis

Number of single ring e-like events in 10 years ($\nu : \bar{\nu} = 1:3,\ \delta_{CP} = -90°$)

	total	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	Beam $\nu_e, \bar{\nu}_e$	NC	Other BG
Neutrino Mode (0+1 decay e)	2785.33	81%	< 1%	12%	6%	< 1%
Anti Neutrino Mode (0 decay e)	1542.72	15%	51%	24%	10%	< 1%

Wrong sign component: 15% ➔
Will be measured by magnetized detector ND280

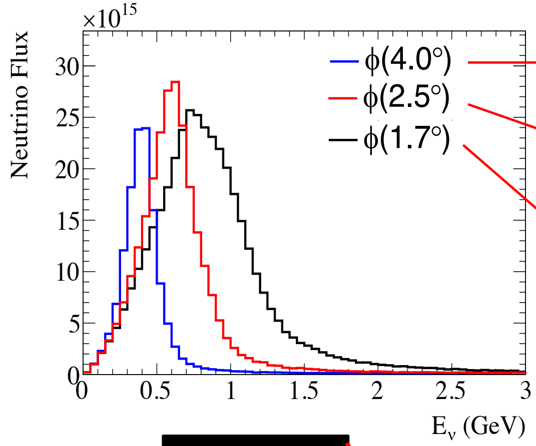
Successful upgrade for T2K: large acceptance and short track by hadrons to reduce systematic errors.
→ Super-FGD, High-angle TPC
Full operation started in the current T2K run!

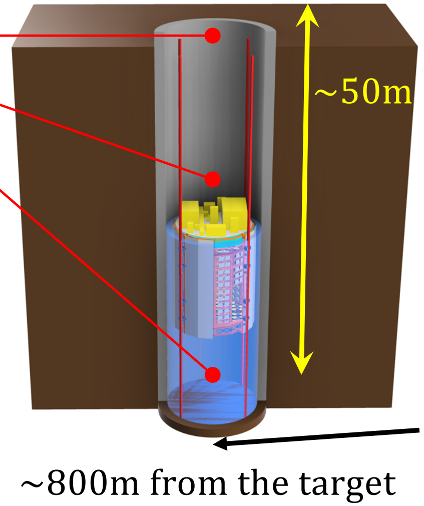
cf. recent progress: T2K talk by C. Giganti

Beam $\nu_e, \bar{\nu}_e$ & NC background: ~30% ➔
Will be measured by IWCD, at 2.5 degree OAA

$$\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$$ xsec ratio ➔ Will be measured by IWCD off-axis angle (OAA) span (next page)

Intermediate Water Cherenkov Detector (IWCD)



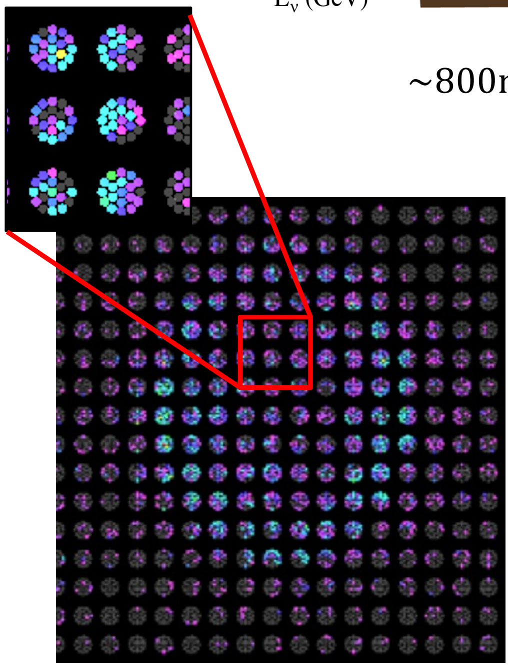


Measurements at IWCD with OAA 1.7°-4.0°

- $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$
  - 3-4% accuracy at 600 MeV (work in progress)
- Background (beam ν_e, NC) for $\nu_\mu \rightarrow \nu_e$
  - Same flux at 2.5 deg. off axis for Hyper-K
- Correlation $(p_l, \theta_l) \leftrightarrow E_\nu$
  - Combination of data with different off-axis angles

Detector site secured, depth & diameter proposed.

- 8.8 m detector diameter, and 7 m diameter for the inner volume. Entire mass ~ 600 ton.
- Multi-PMTs are useful for resolving vertices close to the wall and accurate particle identifications.
- Basic design is ongoing, and installation procedure is being considered.
- **International contributions welcome!**



Summary

- Hyper-K will play a central role in exploring the future of particle physics and contribute to the future of astronomy. Expectations in 10 yrs HK:
    - Mass ordering: 3.8-6.2σ depending on $\sin^2\theta_{23}$
    - CP violation: 5σ discovery, > 60%
    - Proton decay: $p \rightarrow e^+\pi^0$: ~$6x10^{34}$ yrs etc.
    - > 3σ sensitivity for the solar ν spectrum up-turn
    - ~70k events @10 kpc supernova
    - ~4 events/yr diffuse supernova neutrino background
- The highlight of the civil construction, the dome excavation, was completed. Detailed design of tank lining and photosensor support structure completed.
- 50 cm PMT delivery is ongoing and on schedule.
- Beam intensity increase/IWCD construction is on the way.
- Data-taking is expected to start in 2027!

Poster presentations

1. Recent T2K oscillation analysis results and Hyper-K sensitivity to **accelerator neutrino oscillations** (D. Carabadjac)
2. **The intermediate Water Cherenkov Detector** for the Hyper-Kamiokande Experiment (L. Cook)
3. **Diffuse Supernova Neutrino Background**: Insights from Super-Kamiokande & Prospects with Hyper-Kamiokande (A. Beauchene)
4. Enhanced Event Reconstruction at Hyper-Kamiokande and WCTE using **Graph Neural Networks** (A. Ershova, C. Quach)
5. **Neutrino Beam Simulations** for the Hyper-Kamiokande experiment and target alternatives (L. N. Machado)
6. Large scale measurement of the performance of the Hyper-Kamiokande **50cm PMTs** (C. Bronner)