Detectors and Physics: Hyper-Kamiokande

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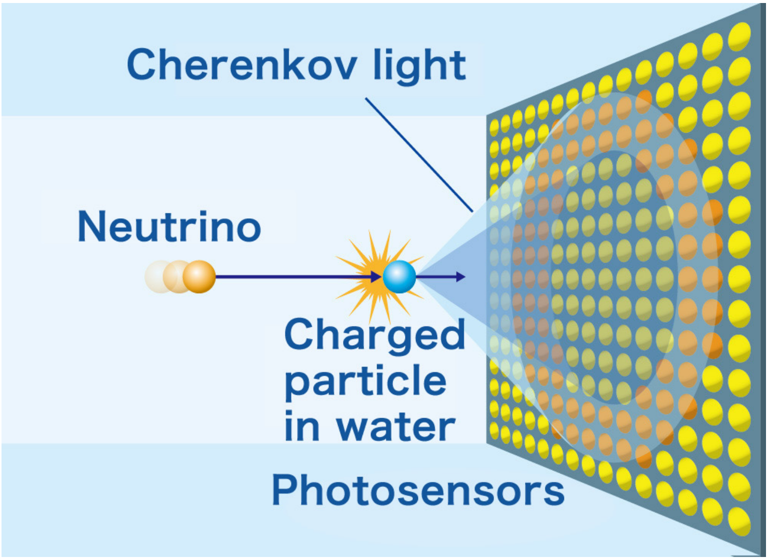
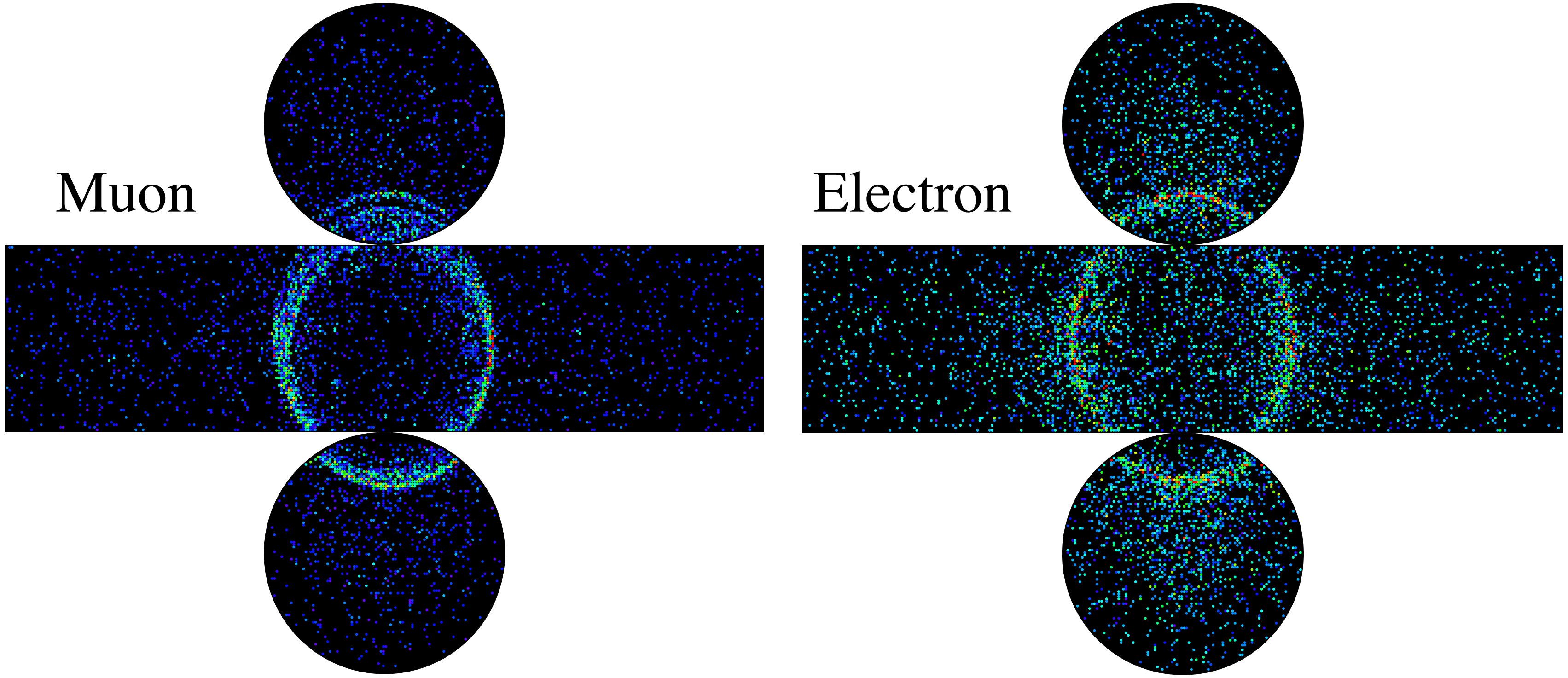
Workshop on the evolution of advanced electronics and instrumentation for Water Cherenkov experiments

April 11, 2022

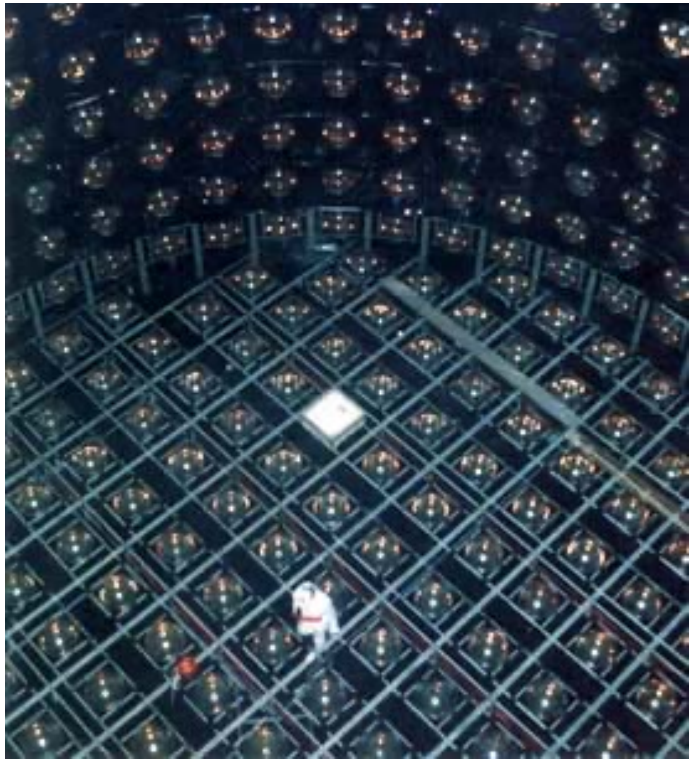
Water Cherenkov detector





- Cherenkov ring
  - Particle identification (>99% efficiency for μ/e separation)
  - Momentum reconstruction (energy and direction)
- Scalable to larger mass ⇒ rare process (proton decay search and neutrino observation)
- Well established technology → next slide

Three generations of water Cherenkov detectors in Kamioka

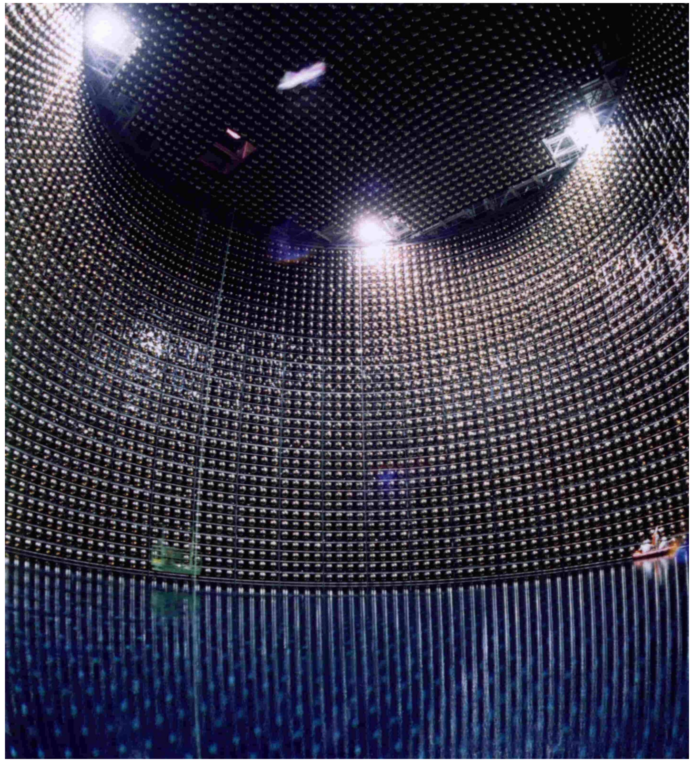


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Birth of neutrino astrophysics

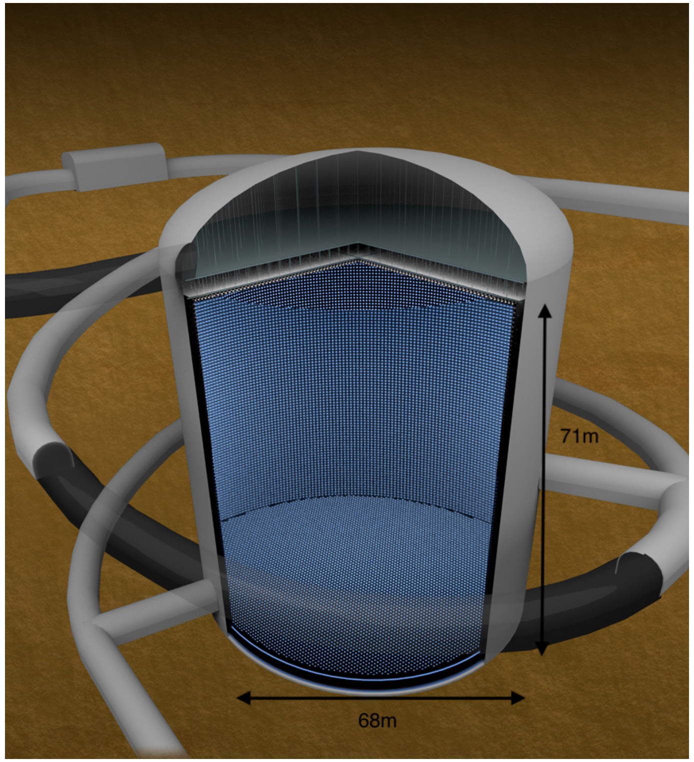


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - ➢ All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



Hyper-Kamiokande

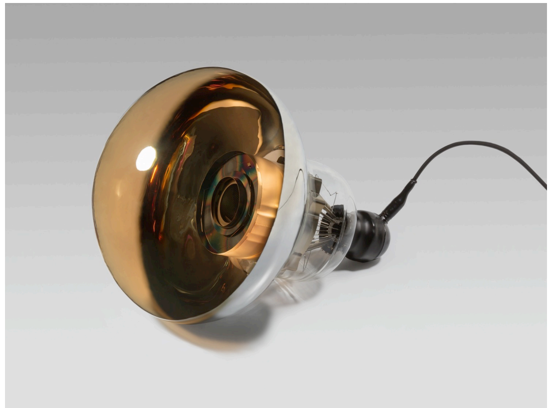
(start operation in 2027)

- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

The Hyper-Kamiokande detector

High QE Box&Line PMT



×2 pressure tolerance

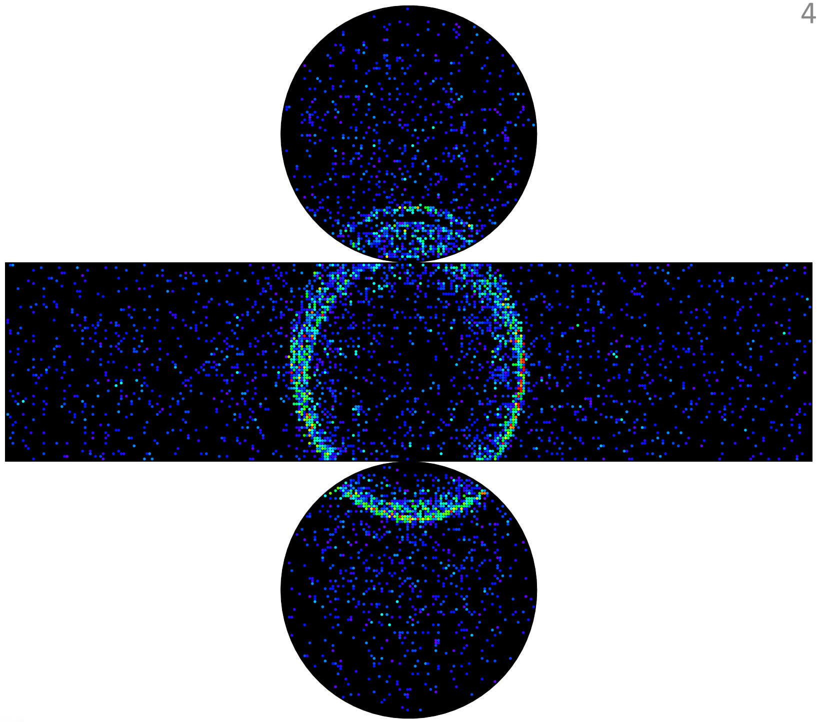
×2 photon detection

×2 timing resolution

Recent update:

- Lower dark rate (similar level to SK)
- Lower radioactive contamination

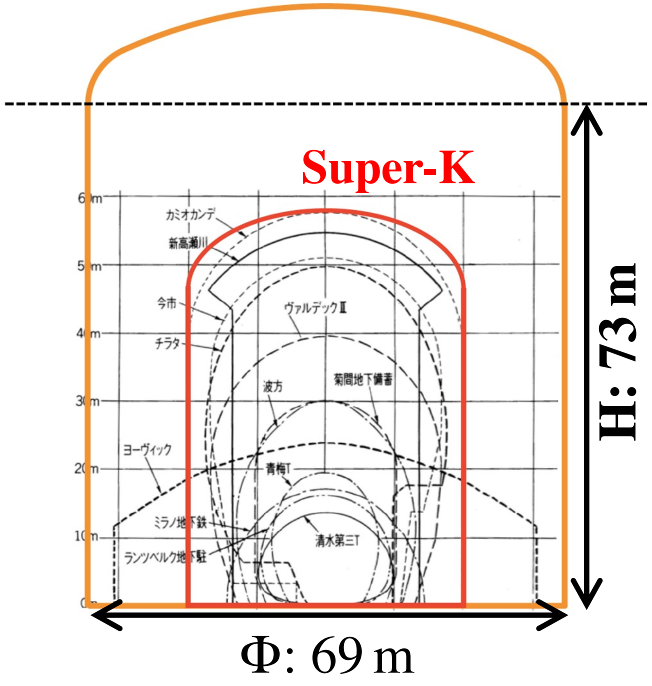
Precision measurement



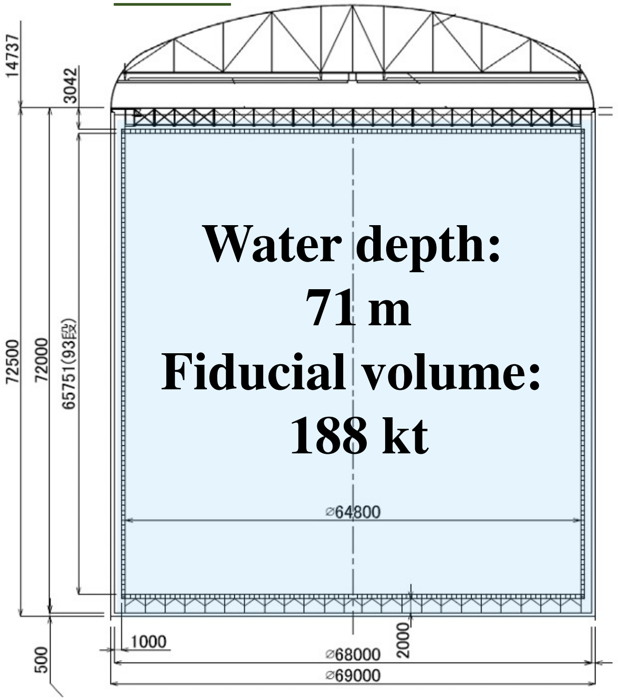
New detector design (cost reduction)

R&D for large cavern

Cavern



Tank



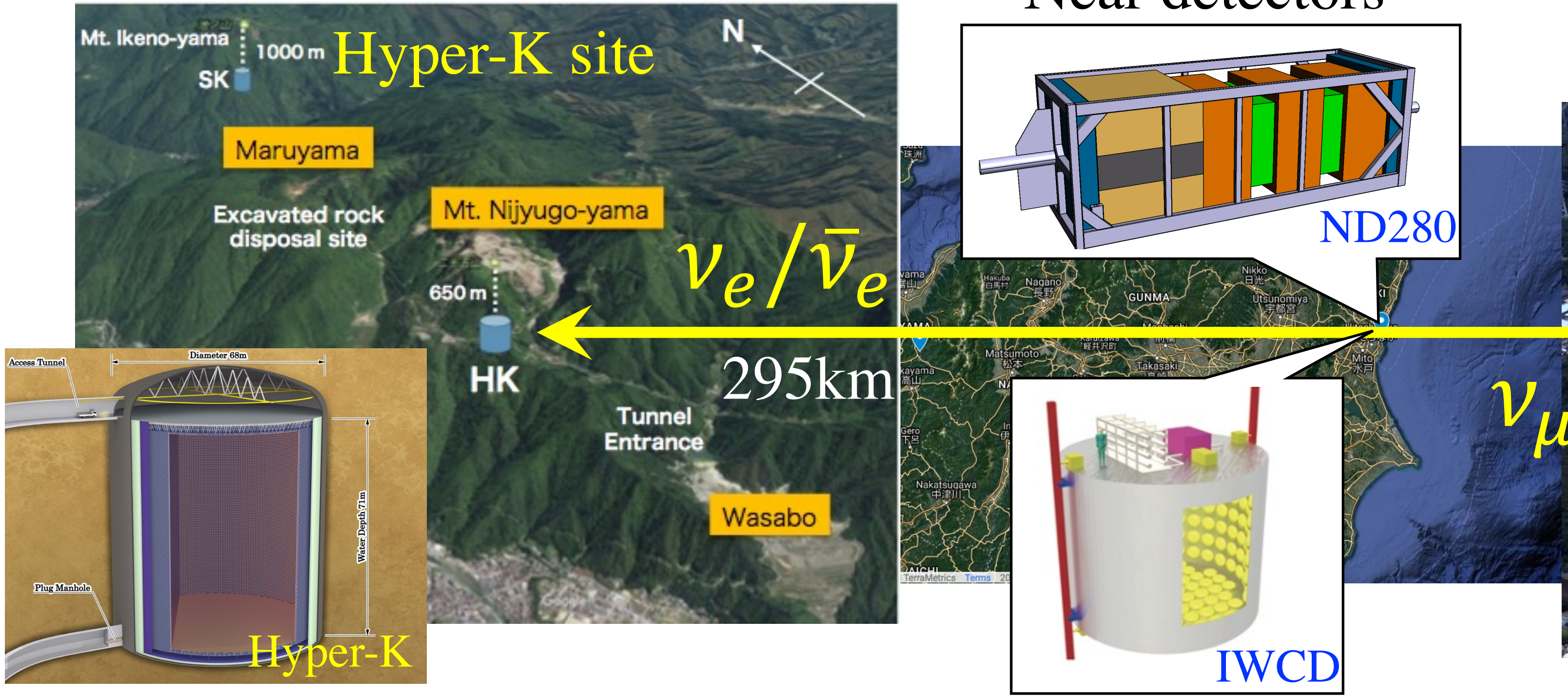
High statistics neutrino data

New detector design by synergy of different technologies

Experimental setup of Hyper-Kamiokande

Near detectors

J-PARC upgrade:
500 kW → 1.3 MW



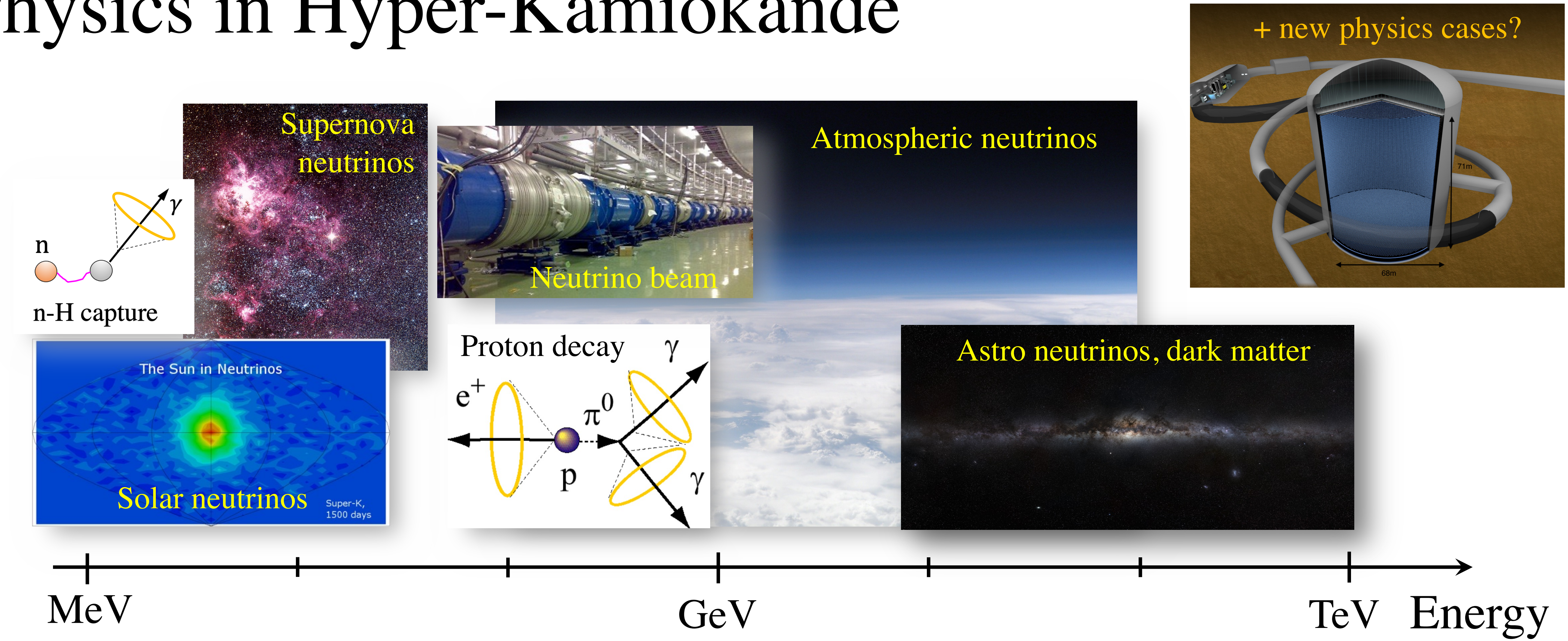
	Super-K	Hyper-K
Overburden	1000 m	650 m
ID PMT	20-inch	20-inch (HQE+B&L) multi-PMT (3-inch ×19)
Total/Fiducial vol.	50 / 22.5 kton	260 / 188 kton

× 8.4 fiducial volume (SK → HK)

× 2.6 beam power (J-PARC upgrade)

→ **More than 20 times statistics**

Physics in Hyper-Kamiokande

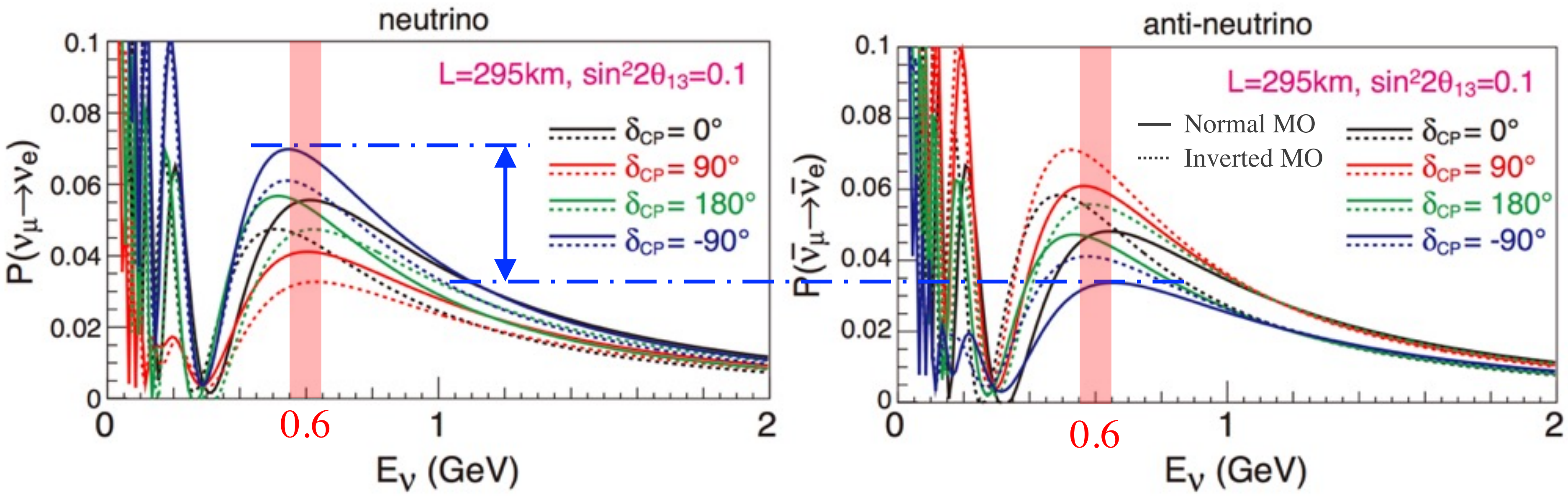


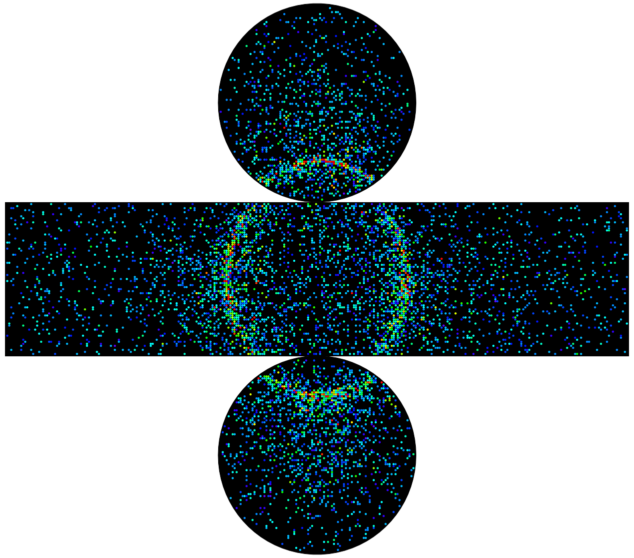
- Hyper-Kamiokande is a multi-purpose detector with the capabilities
  - Real time measurement of vertex, direction, energy and particles types
  - Large fiducial mass with low radioactive background
  - Wide dynamic range to observe neutrinos from MeV to TeV energy scale

Long-baseline measurement with J-PARC neutrino beam

Experimental setup

- 2.5° off-axis beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - ➢ Major component is QE: E_ν determined from outgoing lepton
    ↔ Suppress non-QE/NC contamination by selecting single-ring event
- Measures CP violation in neutrino sector from comparison of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$





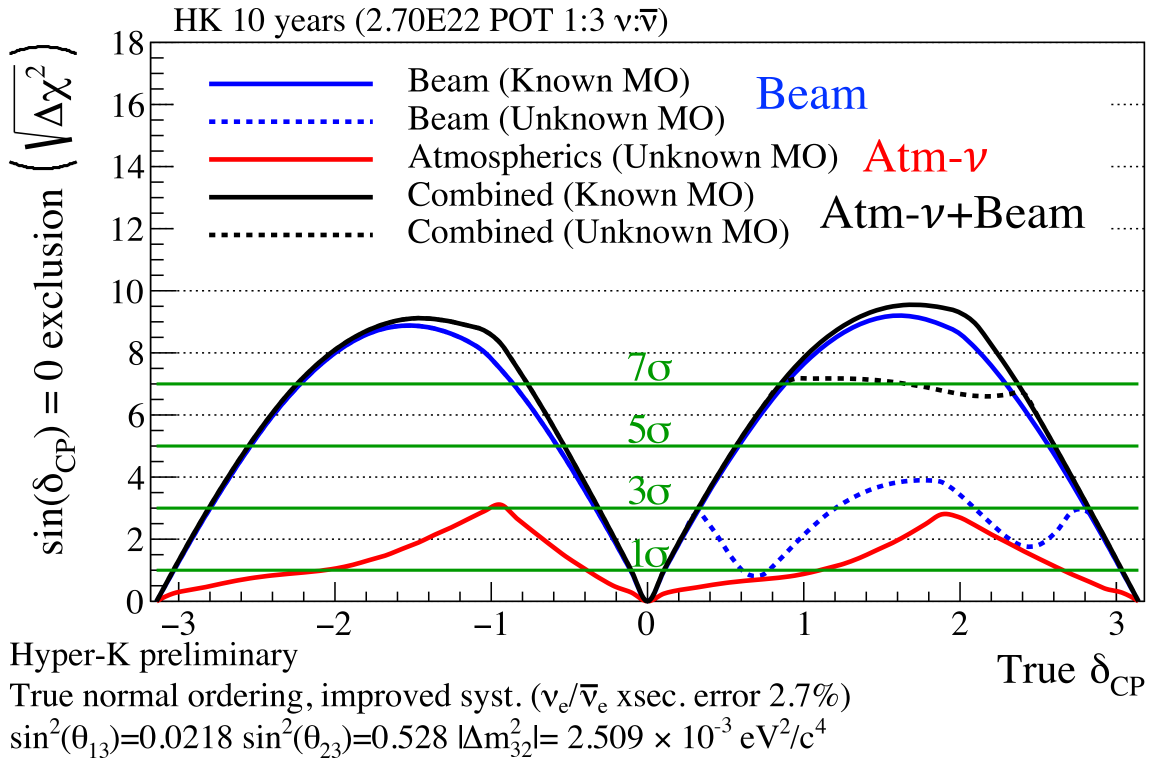
- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals
- Projected sensitivity based on T2K systematics uncertainties + improvements for HK

Strategy of oscillation measurement at Hyper-Kamiokande

Combination of long-baseline and atmospheric neutrino observations
⇒ Resolve parameters degeneracy

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

10 years with 1.3MW, normal mass ordering is assumed



Atmospheric neutrino: sensitive to mass ordering by Earth's matter effects

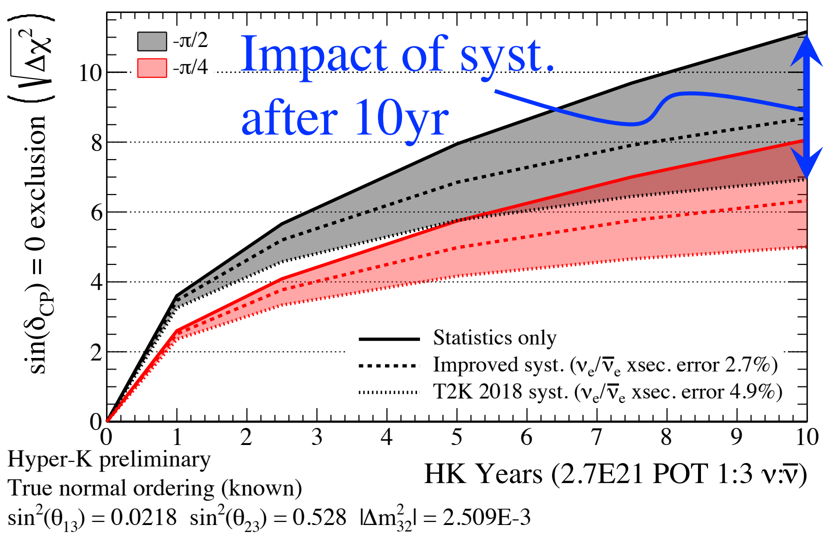
→ Constraints on mass ordering enhance sensitivity to CP violation by long-baseline

Precision measurement of neutrino oscillations

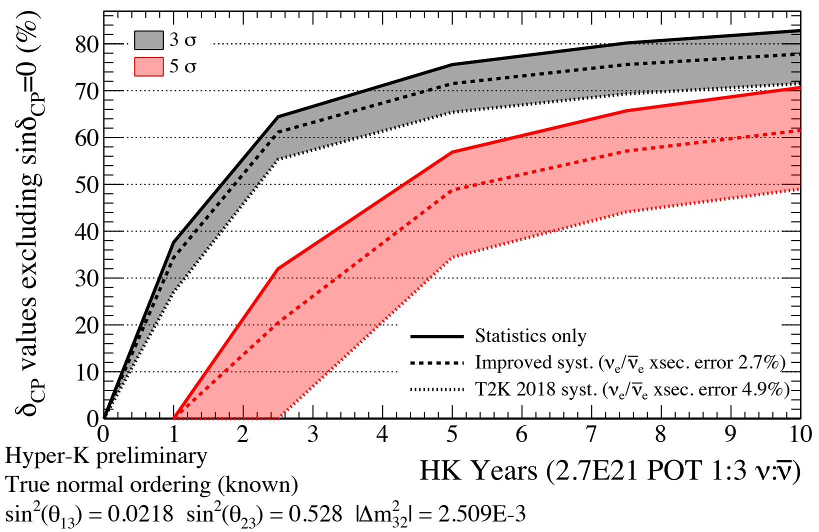
1.3MW, 10 years

δ_{CP}

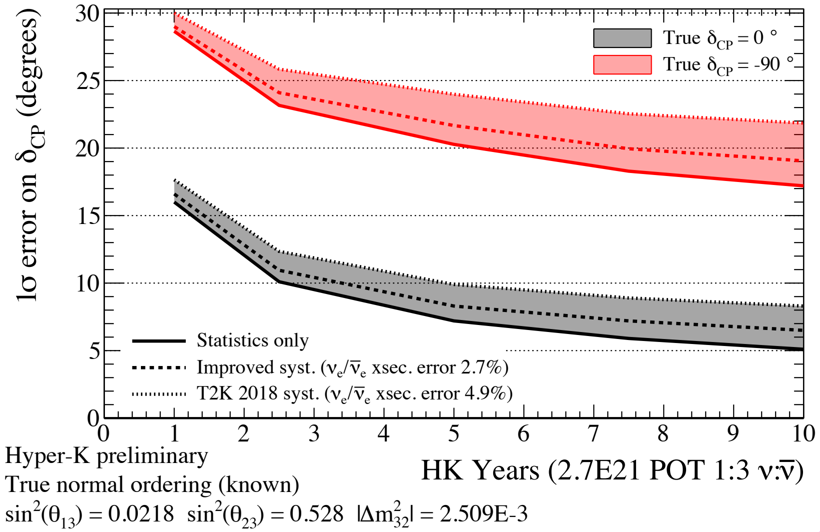
Projected sensitivity to CPV



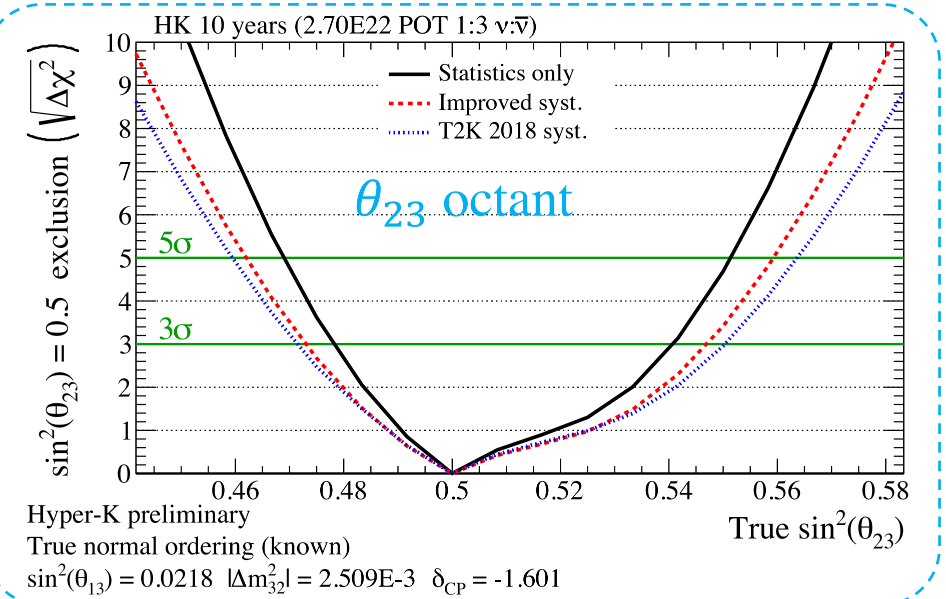
Fraction of δ_{CP} to exclude $\sin\delta_{CP} = 0$



Precision of δ_{CP} measurement

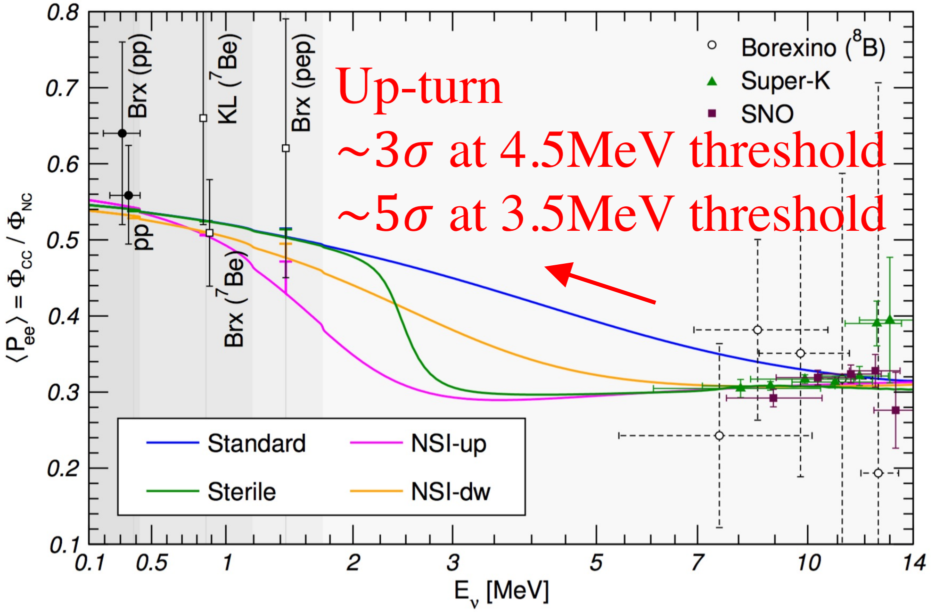


- Good opportunity to make discovery of CP violation at >5 σ
- Measurement of δ_{CP}
  - ➢ ~20° for $\delta_{cp} = -90°$ / ~7° for $\delta_{cp} = 0°$
- Reduction of systematic uncertainty has sizable impact
  - ➢ Upgrade of ND280 + 1kton scale water Cherenkov (IWCD)
  - ➢ Aim to suppress detector error below 1%

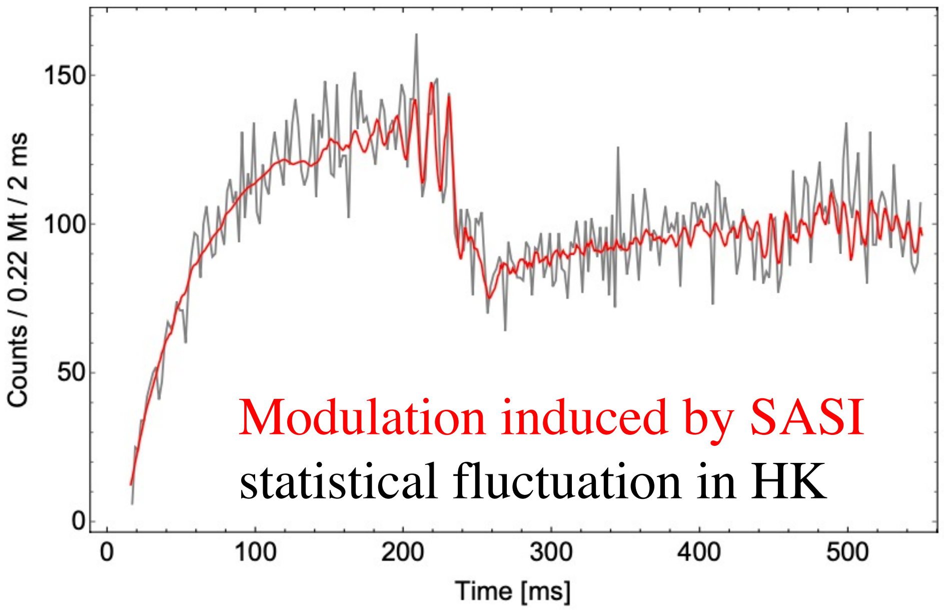


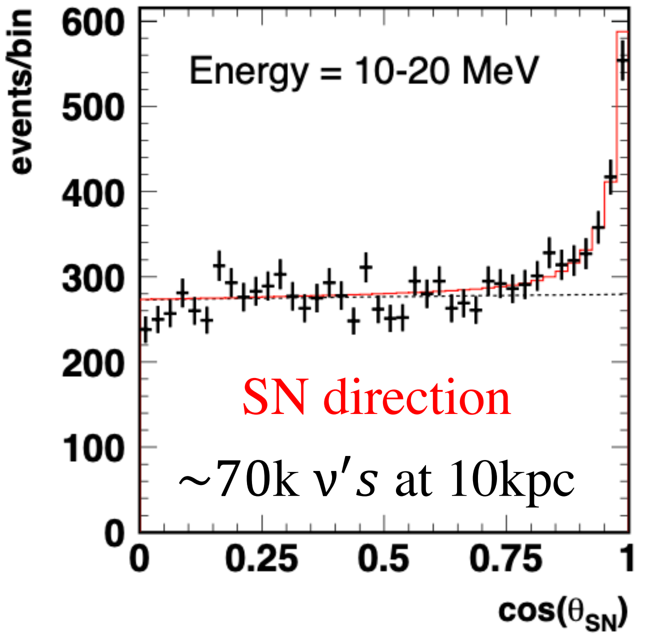
Neutrino astrophysics

- Observation of ~10 MeV neutrinos with the time, energy and direction
  - ➢ Unique role in multi-messenger observation
  - ➢ Sensitivities depend on the energy thresholds
- Solar neutrinos (~130/day): up-turn at vacuum-MSW transition region, D/N, hep ν
- Supernova burst (~50k/burst): explosion mechanism, BH/NS formation, alert with 1° pointing
- Supernova Relic Neutrino (~10/yr): stellar collapse, nucleosynthesis and history of the universe

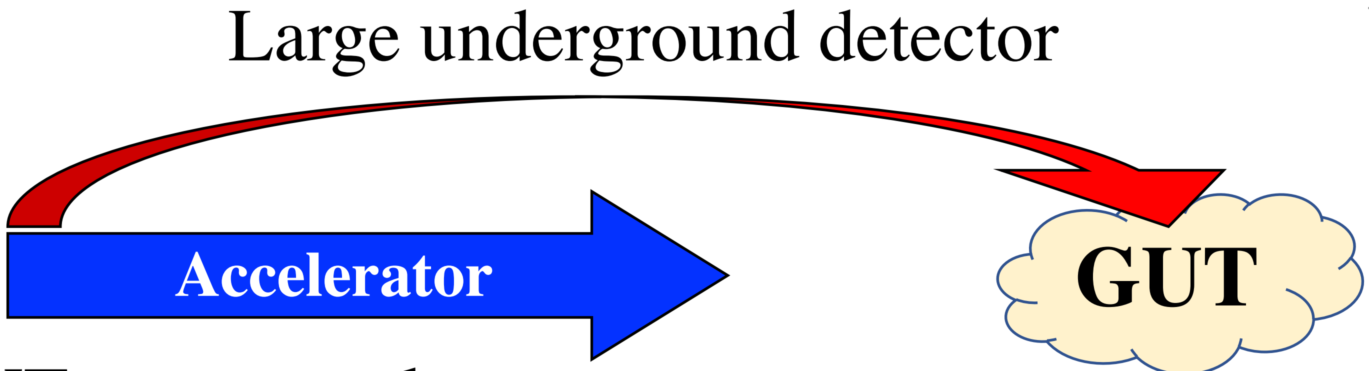


M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



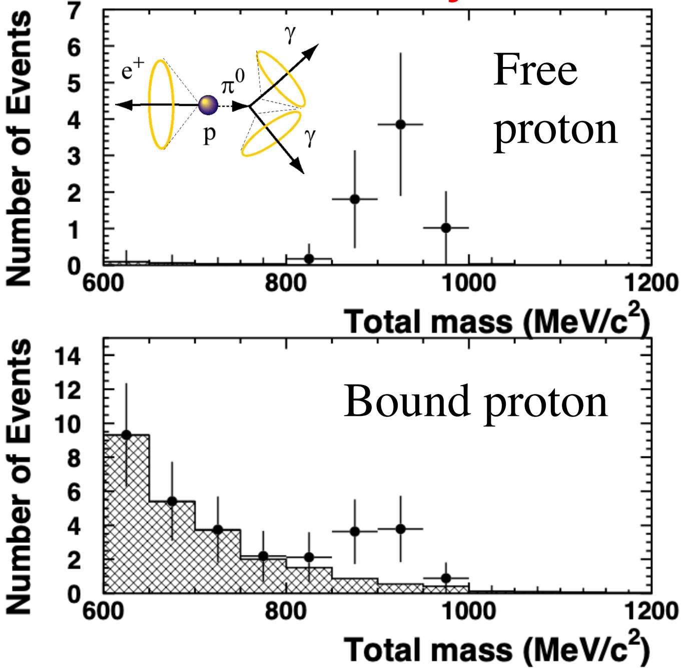


Proton decay search

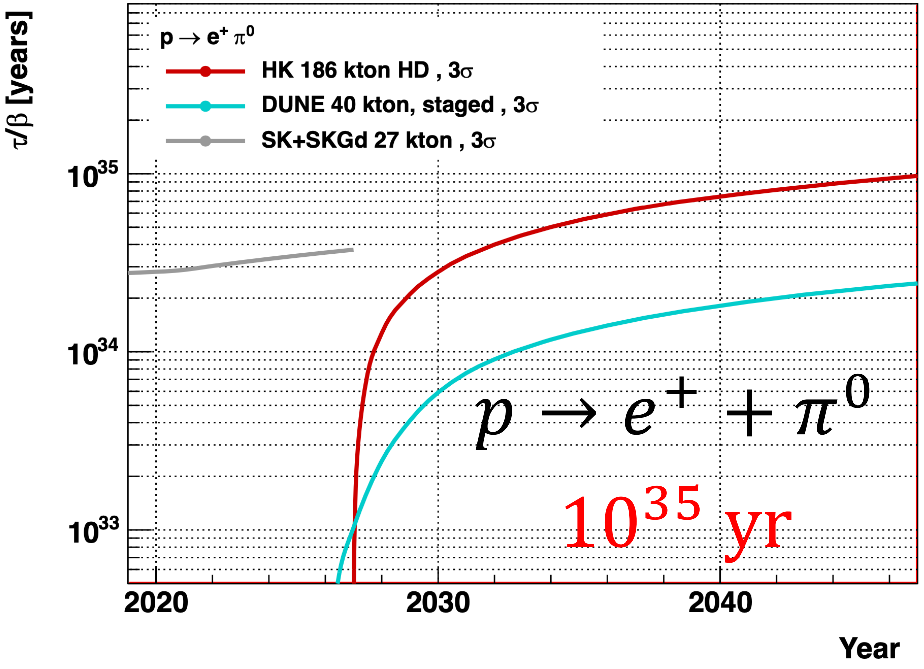


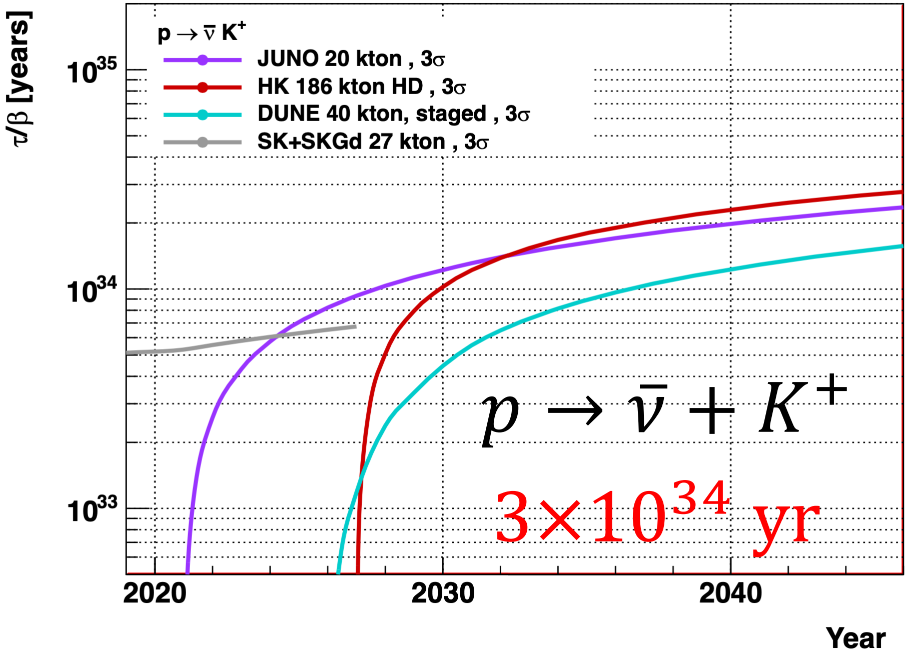
- One possible approach to reach GUT energy scale
- Extend proton decay search by one order of magnitude beyond the current limits

After 10 years of HK
if $\tau = 1.7\times10^{34}$ years …



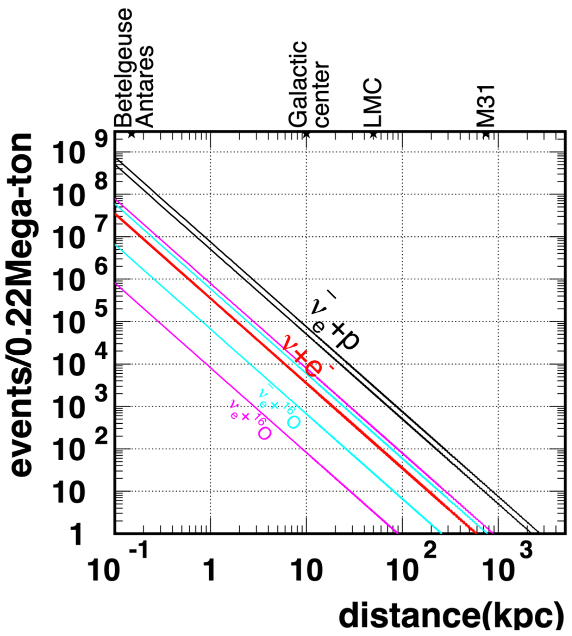
JUNO: J. Phys. G 43 (2016) 030401 (arXiv:1507.05613)
DUNE: FERMILAB-PUB-20-025-ND (arXiv:2002.03005)



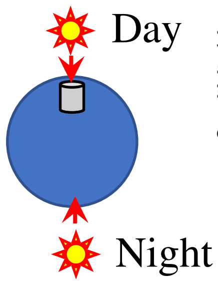


Requirements for the detector/electronics/calibration

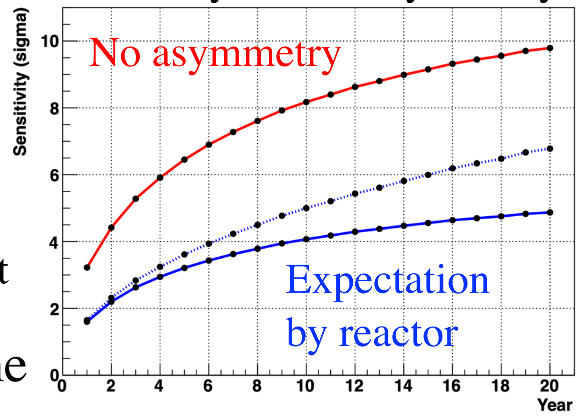
- Trigger
  - Peak event rate reaches 50kHz for SN at galactic center
  - Detection of delayed signals
    - Michel electrons ~2μs after muons
    - Neutron tagging: 2.2 MeV γ-ray ~200μs after neutrino interactions



- Energy scale
  - Wide dynamic range from single p.e. (a few MeV) to >1000 p.e. (>100 GeV)
  - GeV-scale (atmospheric/LBL/proton decay):
    - ~2% uncertainty in SK → Aim for < 1% uncertainty at HK to realize precision measurement
  - MeV-scale (solar/supernova)
    - ~0.5% uncertainty in SK with LINAC
    - Major source due to position dependence (uniformity in detector)
      → Important for Day/Night asymmetry measurement



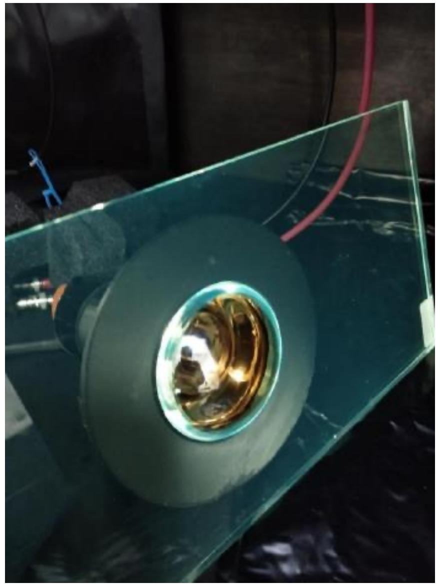
Sensitivity to D/N asymmetry



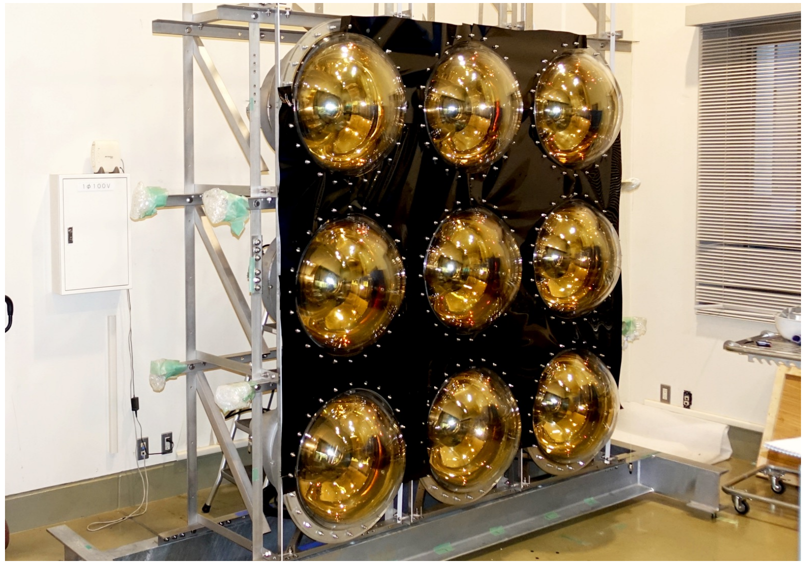
- Timing
  - ~1ns resolution required for vertex position reconstruction (~20 cm)
    → BG rejection (spallation, external γ from rock/PMT), control of fiducial volume
- Long term stability
  - Stable for >10 years without repair (dead channel, detector response)

Detector R&D for Hyper-Kamiokande

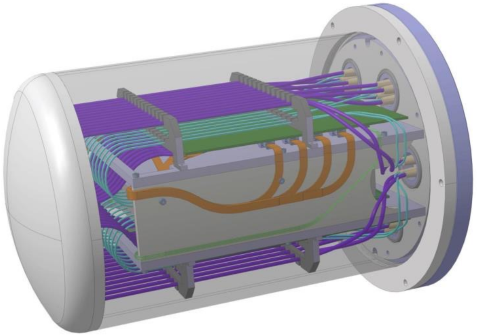
Outer detector: PMT+WLS plate



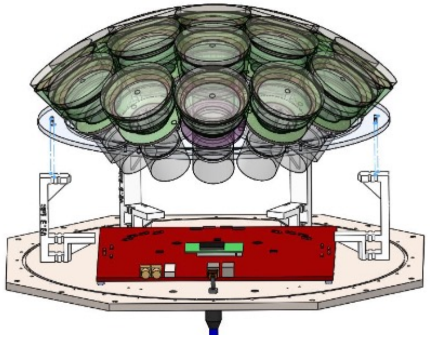
ID mockup



Underwater electronics:
Case design and feedthrough



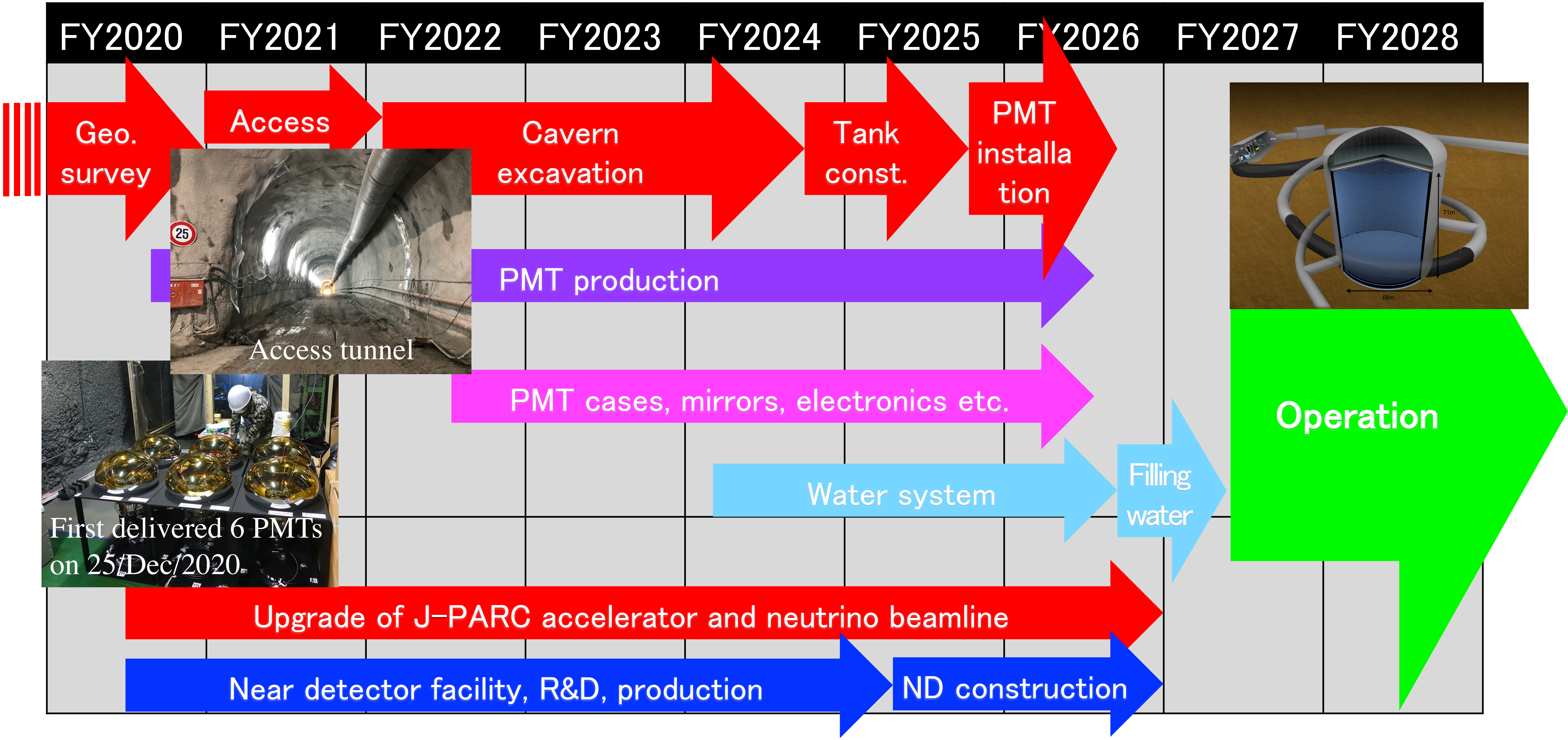
Multi-PMT module:
(ref. KM3NeT)



PMT cover

Box&Line PMT in Super-K

Hyper-Kamiokande schedule



Summary

- Hyper-Kamiokande is currently under construction and will begin operation in 2027
- Hyper-Kamiokande is a multi-purpose detector aiming for various physics in wide energy range
  - ◆ Low energy (MeV scale)
    - ➢ Unique contribution to astrophysics by the neutrino observations (solar, SN burst, SRN)
  - ◆ High energy (GeV scale)
    - ➢ Reveal full picture of neutrino oscillations including CP violation and mass ordering
      - Unprecedented high statistics neutrino data will be available with upgraded J-PARC neutrino beam
    - ➢ Search for proton decay by one order of magnitude beyond the current limits
  - ◆ Very-high energy (>100 GeV)
    - ➢ Neutrinos from astrophysical sources including as yet unobserved dark matter annihilation

⇒ These will be realized by a high performance detector and the detector calibration

- > 50kHz trigger rate
- Detection of delayed signals
- ~1ns timing resolution
- Wide dynamic range from 1 p.e. to >1000 p.e.
- Stability for >10 years
- < 1% uncertainty on the energy scale
- < 0.5% uniformity in detector