Advancing the Neutrino Frontier

to the Megaton Regime and Beyond

Science Case and Status

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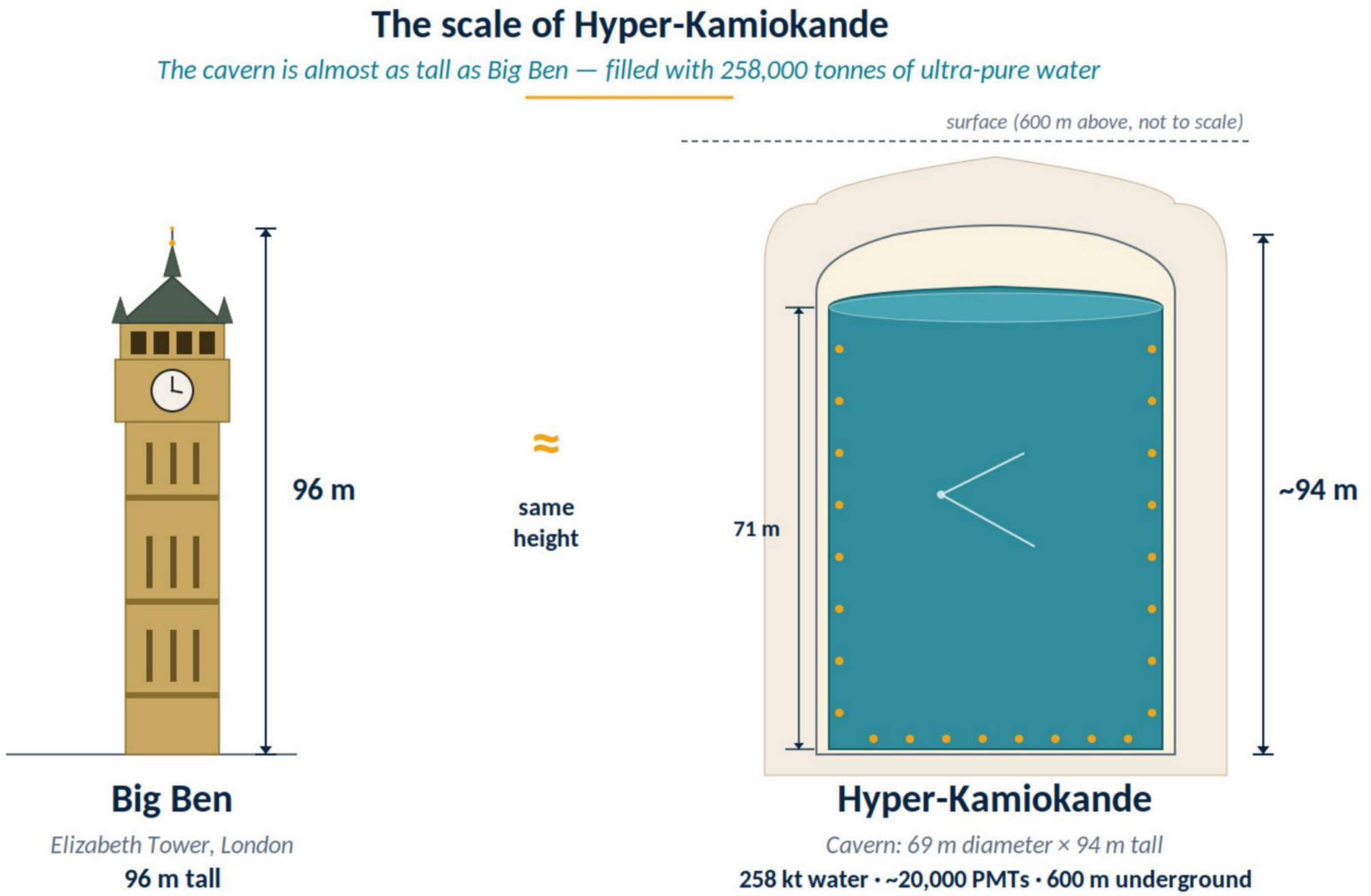
Outline

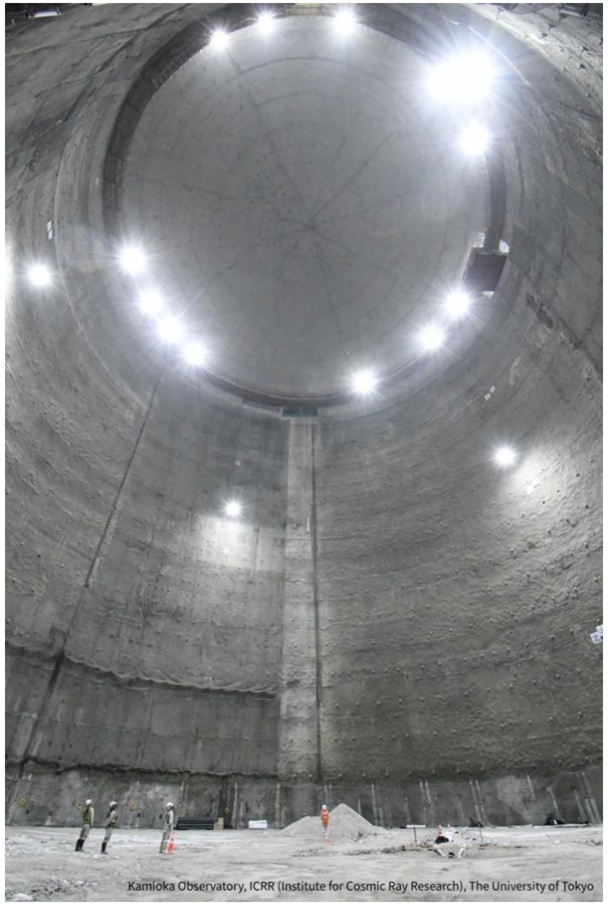
Why megaton scale?

Statistics × clean Water Cherenkov technique × broad physics reach

Statistics | **Multi-purpose** | **Complementarity**

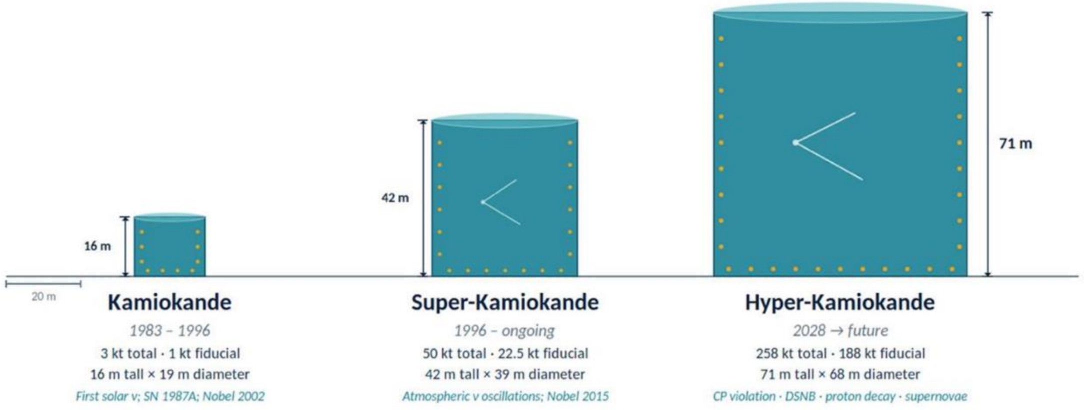


Hyper-Kamiokande cavern - July 2025.



From Kamiokande to Hyper-K

A four-decade Japanese Water Cherenkov programme



1983
Kamiokande
3 kt — first solar ν, SN 1987A neutrinos, Nobel 2002

1996
Super-K
50 kt — atmospheric ν oscillations (1998), Nobel 2015

2009
T2K
$\vartheta_{13} \neq 0$ (2013), hint of δ_{CP}

2020
SK-Gd
Gd-loaded Super-K — DSNB era begins

2028
Hyper-K
258 kt — 8.4× SK, J-PARC 1.3 MW beam

Legacy

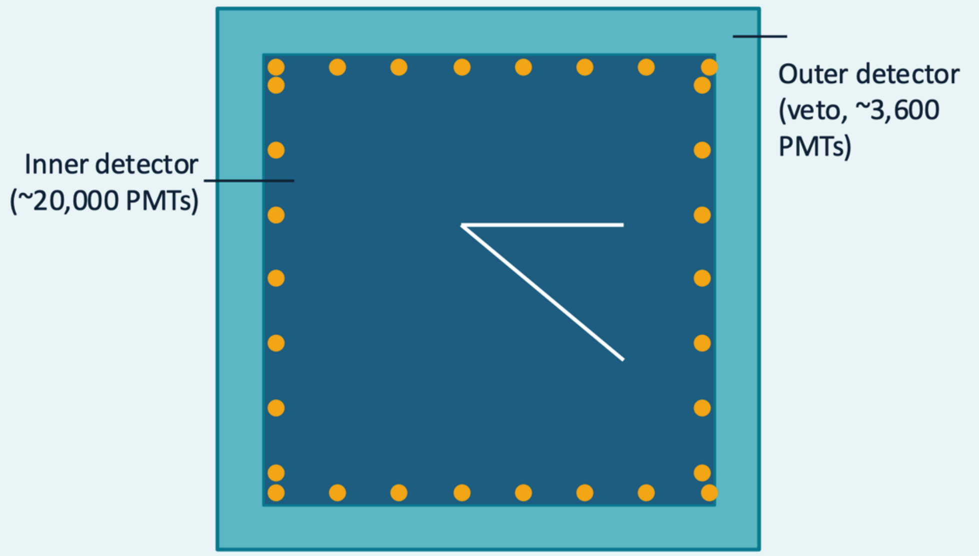
Two Nobel Prizes · discovery of neutrino oscillations · direct detection of solar & SN neutrinos · most stringent proton-decay limits · established ϑ_{13}, hint of δ_{CP}.

The Hyper-Kamiokande detector

Next-generation Water Cherenkov, 600 m underground in Tochibora

- **258 kt total (188 kt fiducial)** — 8.4× Super-K fiducial volume
- **~20,000 newly developed 50-cm PMTs** — inner detector
- **~800 multi-PMT modules**
- **~3,600 outer-detector PMTs** — on WLS plates
- **20% photocoverage** — of the inner detector
- **260,000 m^3 ultra-pure water**

Schematic cross-section



260,000 m^3 ultra-pure water

(schematic — see HK Design Report arXiv:1805.04163 for detail)

Beam & near complex

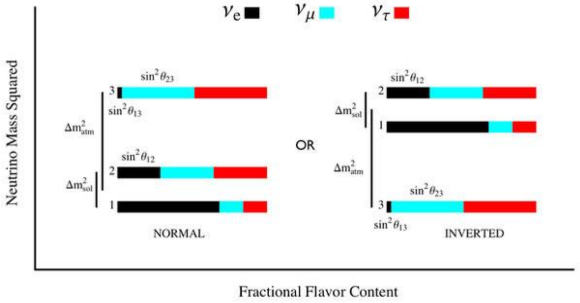
J-PARC 0.8 MW → 1.3 MW · baseline 295 km, 2.5° off-axis · upgraded ND280 + IWCD.

Three-flavour oscillations: the open questions

What the next generation of experiments must resolve

Is CP violated in the lepton sector? — Measure δCP — connection to leptogenesis and the matter–antimatter asymmetry.

What is the mass ordering? — Normal or inverted? Atmospheric ν provide an independent constraint.

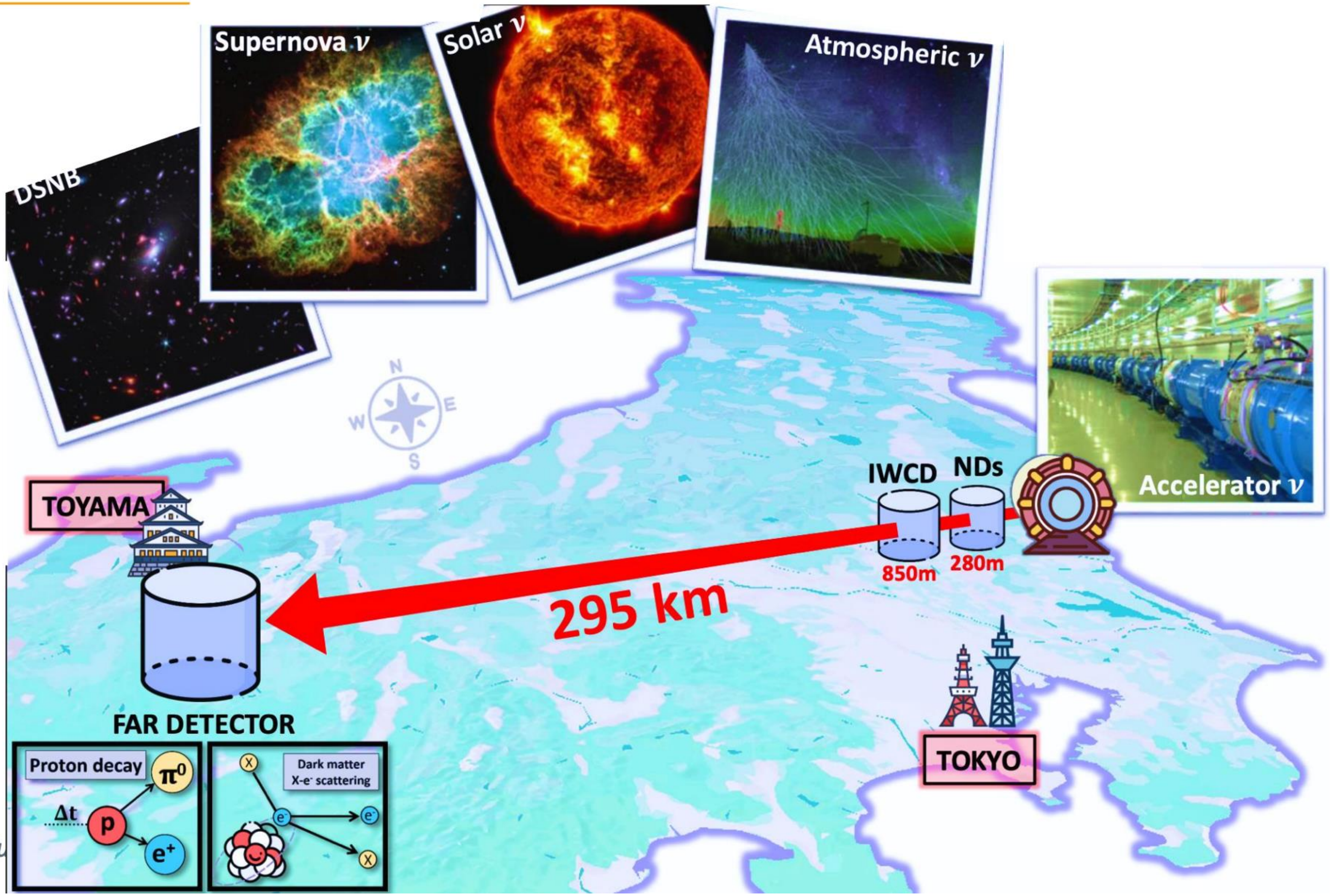


What is the θ_{23} octant? — Maximal mixing? Below / above 45°? — implications for flavour models.

How precisely can we measure Δm^2_{32} and $\sin^2\theta_{23}$? — Sub-percent precision now within reach — tests of unitarity, BSM.

Three-flavour oscillations: the open questions

What the next generation of experiments must resolve



A dual-purpose observatory

The Hyper-Kamiokande Water Cherenkov detector serves a dual purpose: it acts as the far detector for a long-baseline neutrino experiment and functions as a standalone neutrino observatory.

This enables a broad and ambitious programme covering a wide range of neutrino sources.

The long-baseline configuration is completed by the J-PARC neutrino beam and a suite of near detectors (ND280 and IWCD).

Where the field stands today

30 years of oscillations — key questions still open

Current global picture (NuFit 6.1, 2025):

- Δm^2_{31} to ~1%, $\sin^2\theta_{13}$ to ~3%, $\sin^2\theta_{23}$ to ~5% — most parameters at few-% precision
- $\delta_{CP} = \pi/2$ excluded at 3σ in both orderings; CPV preferred in IO
- Mass ordering and θ_{23} octant still unresolved
- JUNO first physics: world-leading θ_{12} and Δm^2_{21}
- PMNS unitarity barely tested — a generic window onto new physics.

NuFIT 6.1 (2025)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.5$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC23 without SK atmospheric data	$\sin^2\theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \to 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \to 0.3295$
	$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \to 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \to 35.03$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.432 \to 0.587$	$0.555^{+0.013}_{-0.016}$	$0.437 \to 0.590$
	$\theta_{23}/^\circ$	$43.27^{+1.0}_{-0.82}$	$41.11 \to 50.02$	$48.15^{+0.75}_{-0.92}$	$41.40 \to 50.21$
	$\sin^2\theta_{13}$	$0.02249^{+0.00057}_{-0.00057}$	$0.02070 \to 0.02420$	$0.02261^{+0.00056}_{-0.00056}$	$0.02091 \to 0.02433$
	$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.27 \to 8.95$	$8.65^{+0.11}_{-0.11}$	$8.31 \to 8.97$
	$\delta_{CP}/^\circ$	207^{+23}_{-20}	$114 \to 405$	283^{+24}_{-28}	$202 \to 347$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \to 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \to 7.822$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.521^{+0.026}_{-0.018}$	$+2.454 \to +2.592$	$-2.500^{+0.024}_{-0.023}$	$-2.569 \to -2.430$

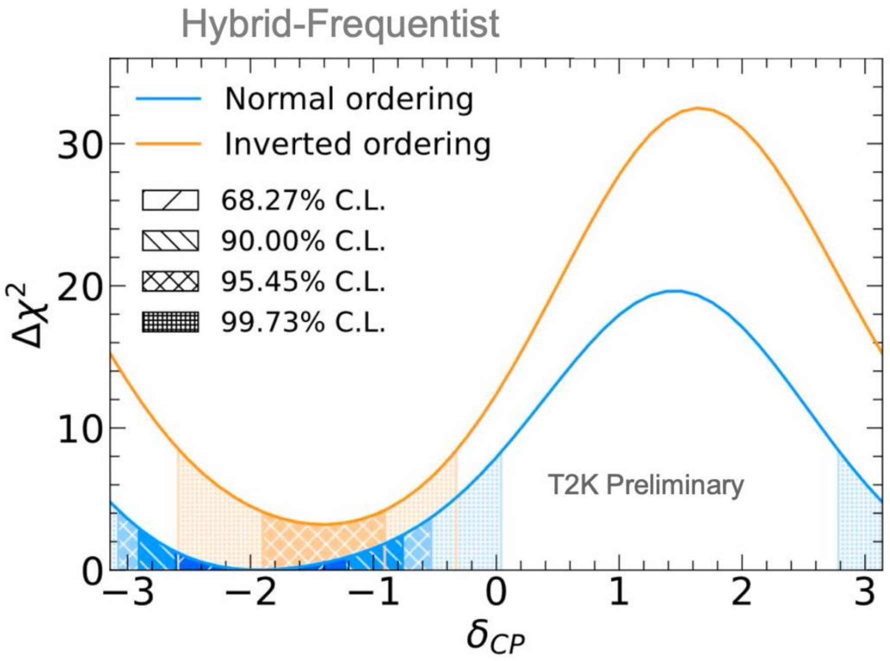
The next-generation goal

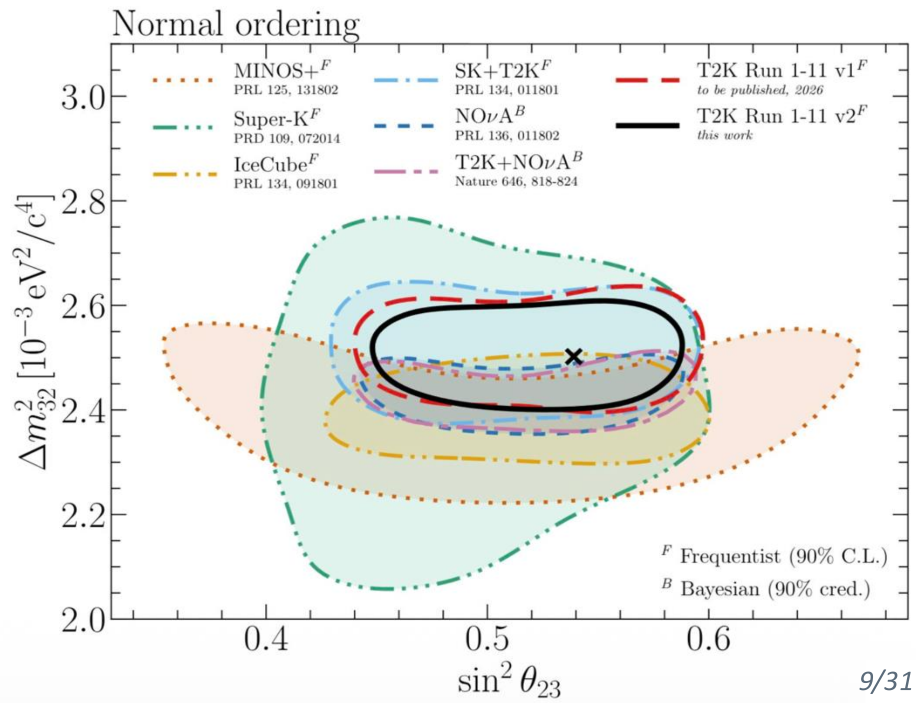
Discover CP violation, fix the mass ordering and octant, and reach sub-percent precision — the task for Hyper-K, DUNE and JUNO in the coming decade.

T2K — latest oscillation results

Neutrino 2026 (Run 1–11 v2) — toward CP violation

- **CP conservation excluded at 95% CL** — preference for near-maximal CP violation ($\delta_{CP} \approx -\pi/2$)
- **Weak preference for normal ordering** — 78% → 81% posterior with the 2D reactor Δm^2_{32} constraint
- **Inverted ordering rejected** — 93% CL (Bayesian) / $(2.01 \pm 0.06)\sigma$ (frequentist)
- **1.9% total error on Δm^2_{32}** — weak upper-octant preference, shift toward maximal mixing
- **Joint fits** — T2K–NOvA Nature 646, 818 (2025); T2K–SK PRL 134, 011801 (2025)

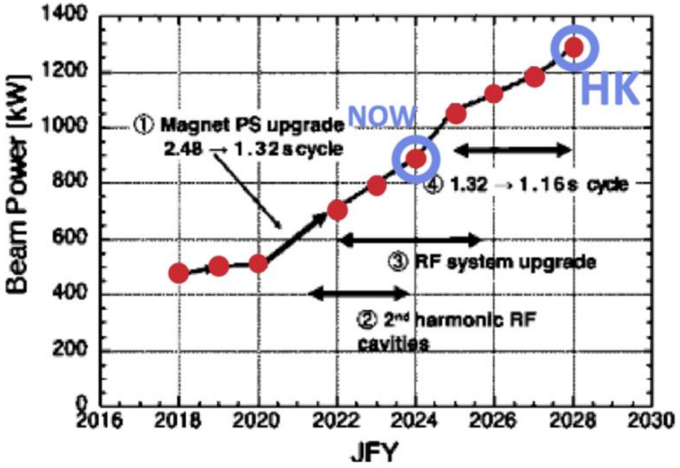


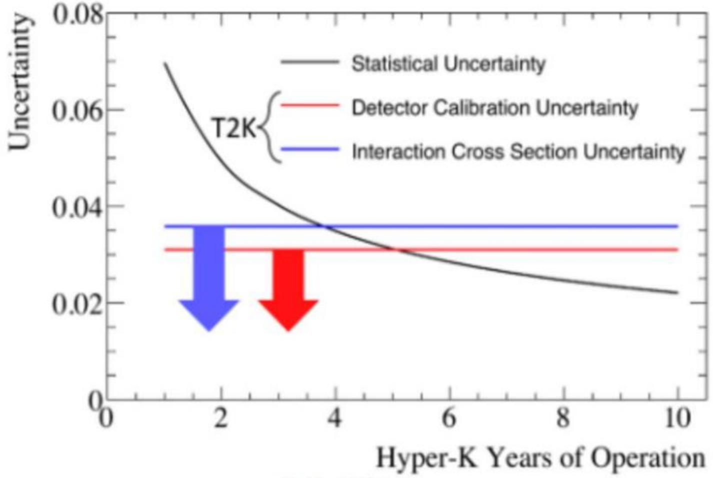


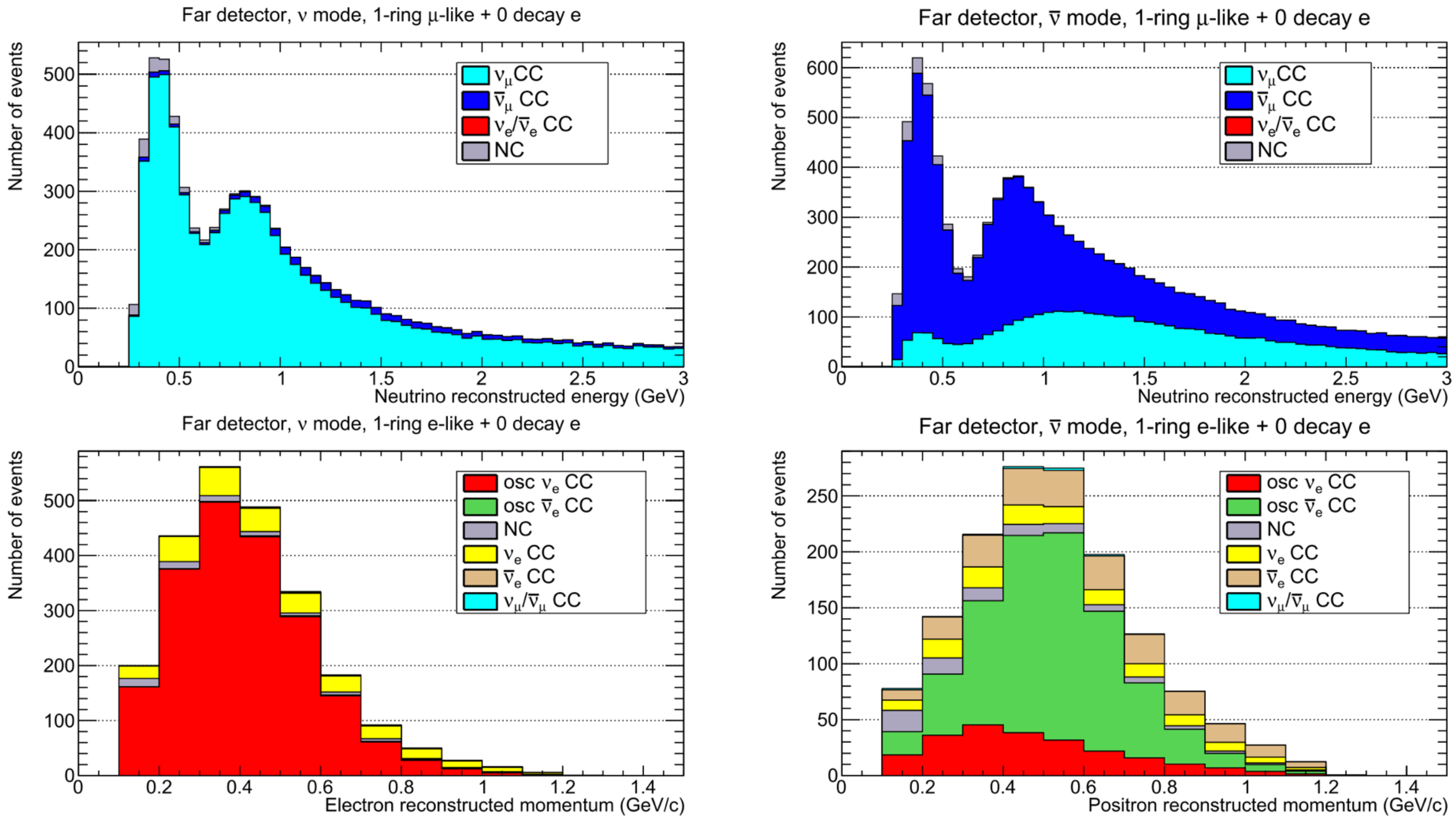
Long-baseline strategy: from T2K to Hyper-K

Same proven technique, 1.3 MW beam (vs ~0.8–0.9 MW at the end of T2K)

- **Step change in statistics** — In one year, Hyper-K collects the same amount of data as T2K's entire programme.
- **1.3 MW J-PARC beam** — 295 km baseline, 2.5° off-axis — narrow band at the first oscillation maximum.
- **Upgraded near complex** — ND280 upgrade + IWCD constrain flux and cross-sections.







EPJC (2026)

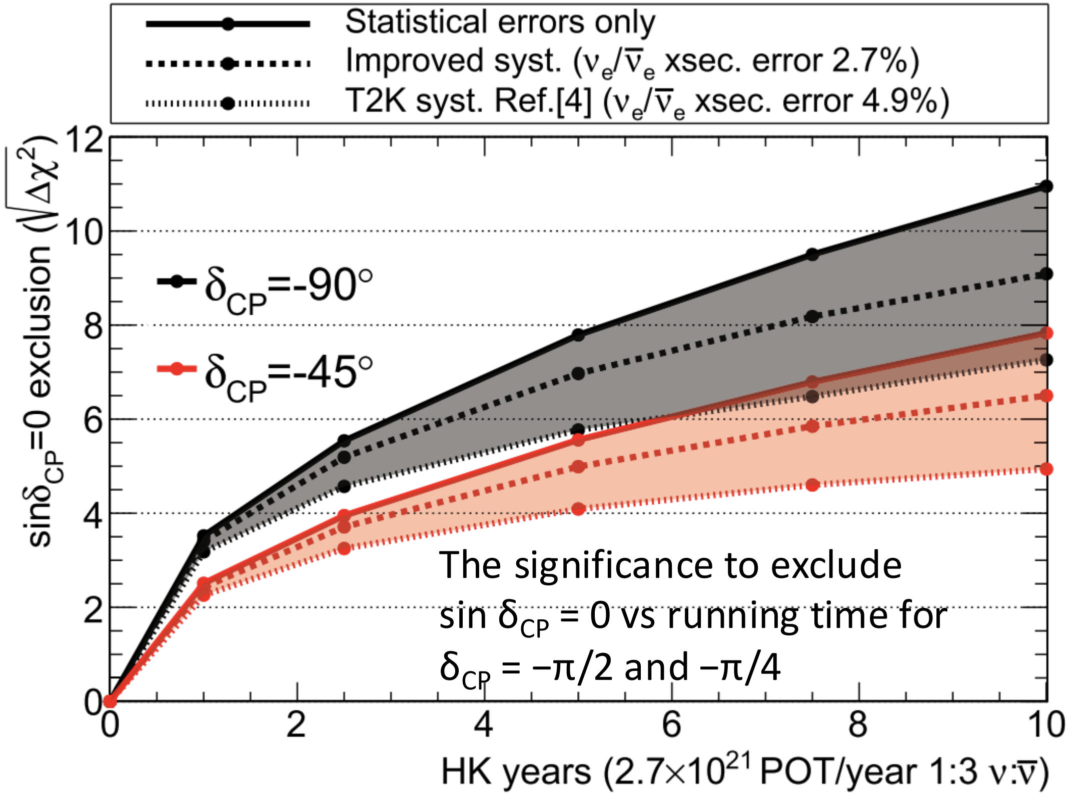
Discovering leptonic CP violation

5σ reach for >60% of δCP values after 10 years

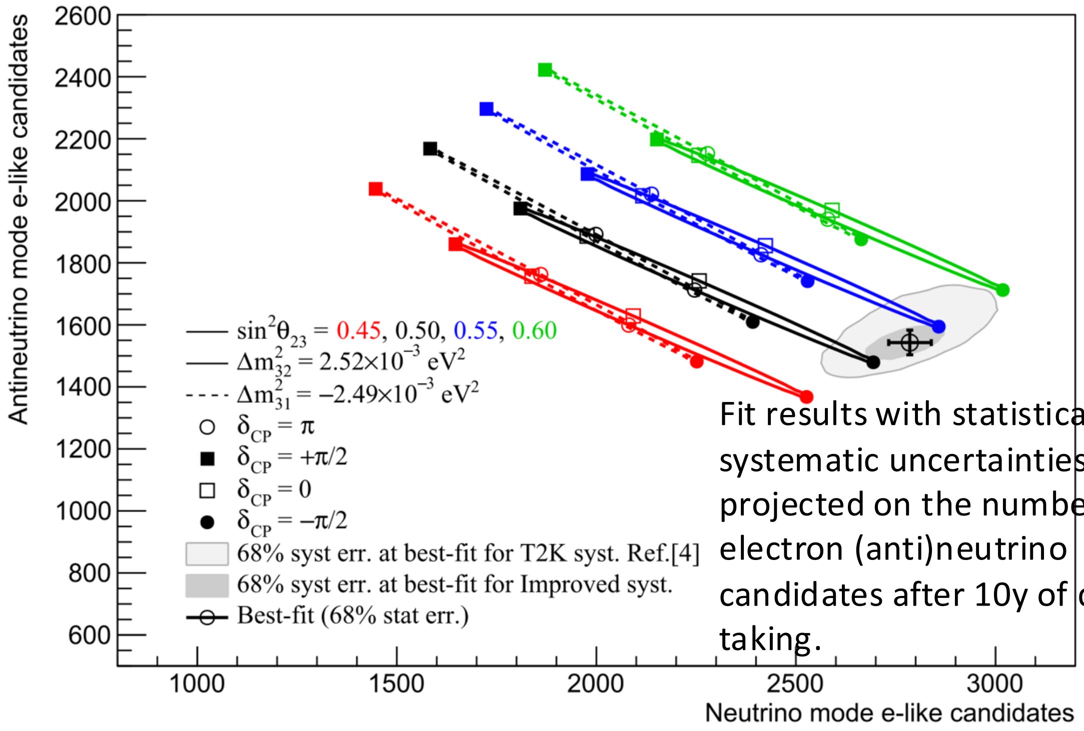
Headline results

<3 yr to 5σ CPV discovery — best case ($\delta_{CP} = -\pi/2$).

>60% of δ_{CP} space gives 5σ discovery in 10 yr (NO).



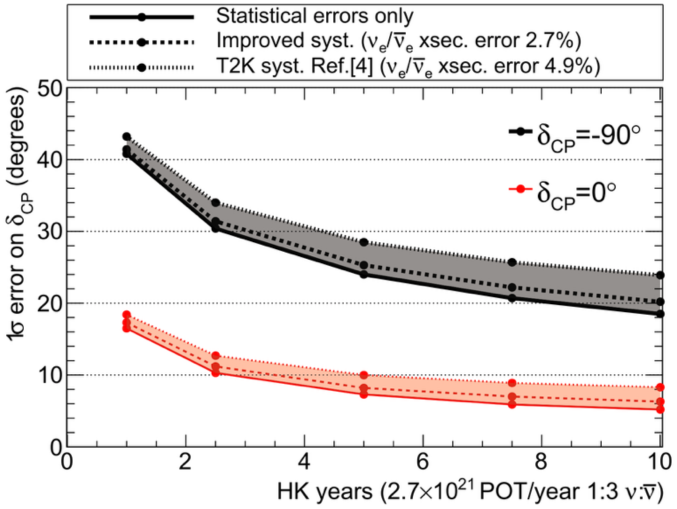
The significance to exclude $\sin\delta_{CP} = 0$ vs running time for $\delta_{CP} = -\pi/2$ and $-\pi/4$

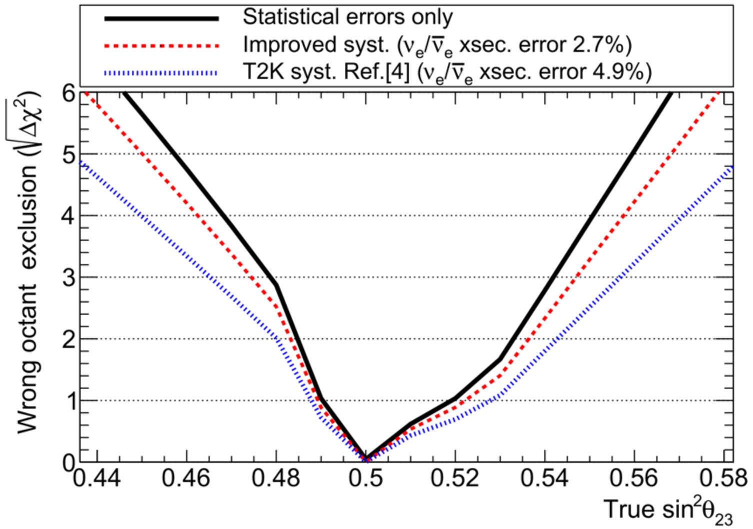


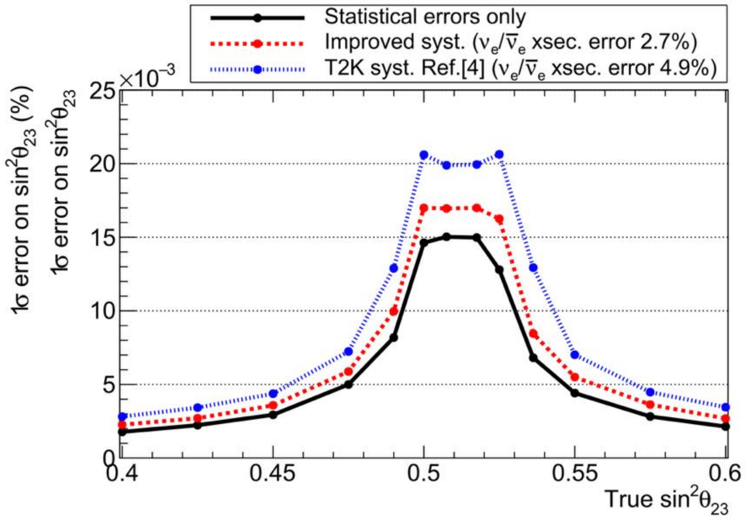
Fit results with statistical and systematic uncertainties projected on the number of electron (anti)neutrino candidates after 10y of data taking.

Precision measurements of oscillation parameters

Beyond CPV: per-cent precision on the entire 3-flavour sector







Parameter	Current world (2025)	HK 10-yr target	Notes
δCP	~25°–40°	6°–20°	Precision depends on true δCP value
$\sin^2\theta_{23}$	~3–4%	0.5%–3%	Best precision near maximal mixing
Δm^2_{32}	~1%	0.5%	Limited mainly by ν energy scale
$\sin^2\theta_{13}$	reactor: ~2%	comparable	Reactor constraint folded in

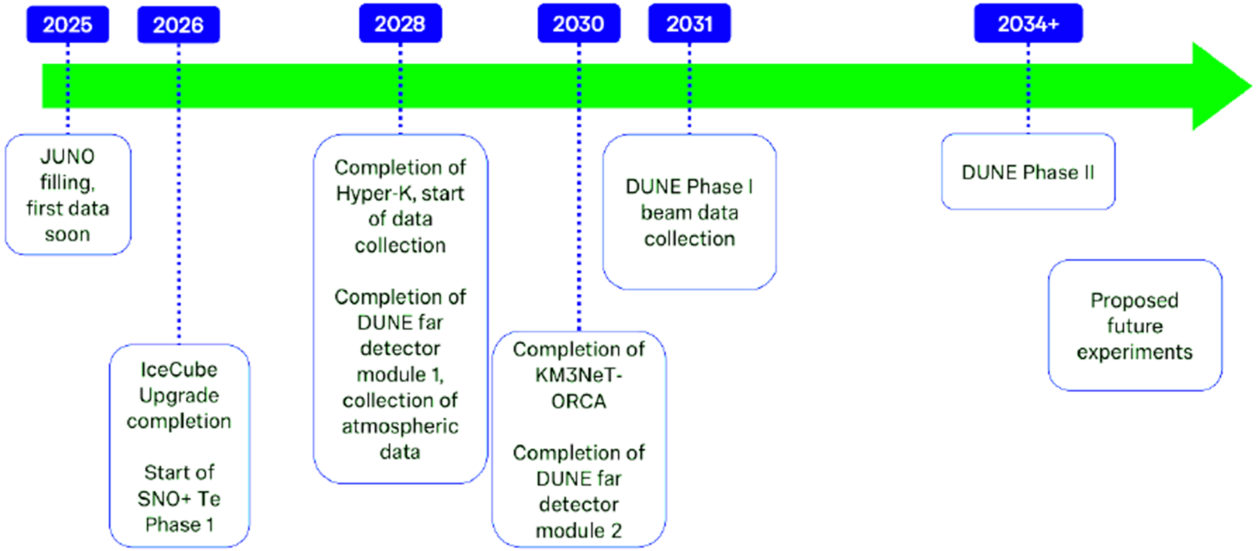
A global, complementary oscillation programme

Hyper-K · DUNE · JUNO probe different energies, baselines, systematics

Experiment	Technique	Baseline · ⟨Eν⟩	Key strength
Hyper-Kamiokande	Water Cherenkov	295 km · ~0.6 GeV	Statistics, CPV in dominant region, atmospheric ν
DUNE	Liquid Argon TPC	1300 km · ~2–3 GeV	Mass ordering from matter effects, BSM searches
JUNO	Liquid scintillator	53 km · few MeV	Mass ordering via reactor spectrum, Δm^2_{21} precision

Different systematics. Different degeneracies. Different timescales.

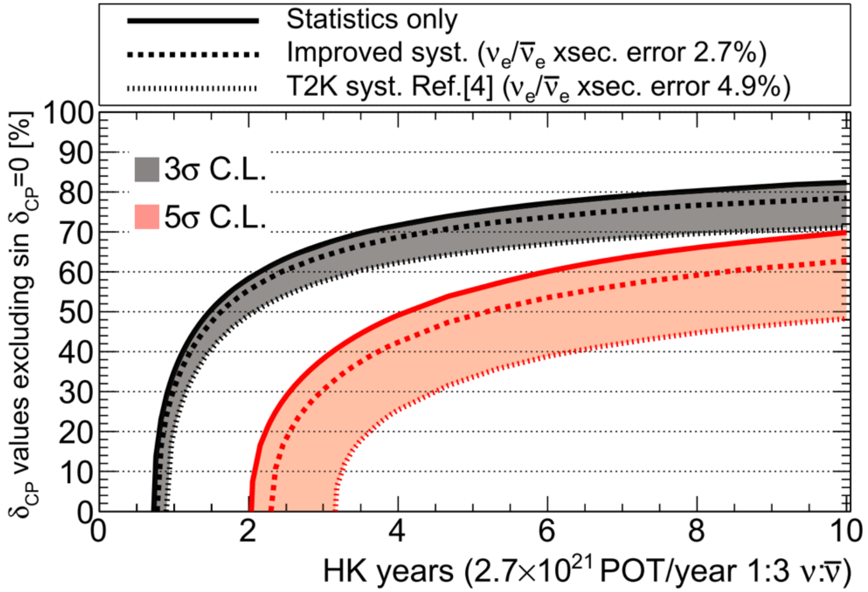
Combined, the three experiments deliver redundant determinations of every PMNS parameter, robust against unknown-unknowns. The 2030s will be the precision era of three-flavour oscillations.

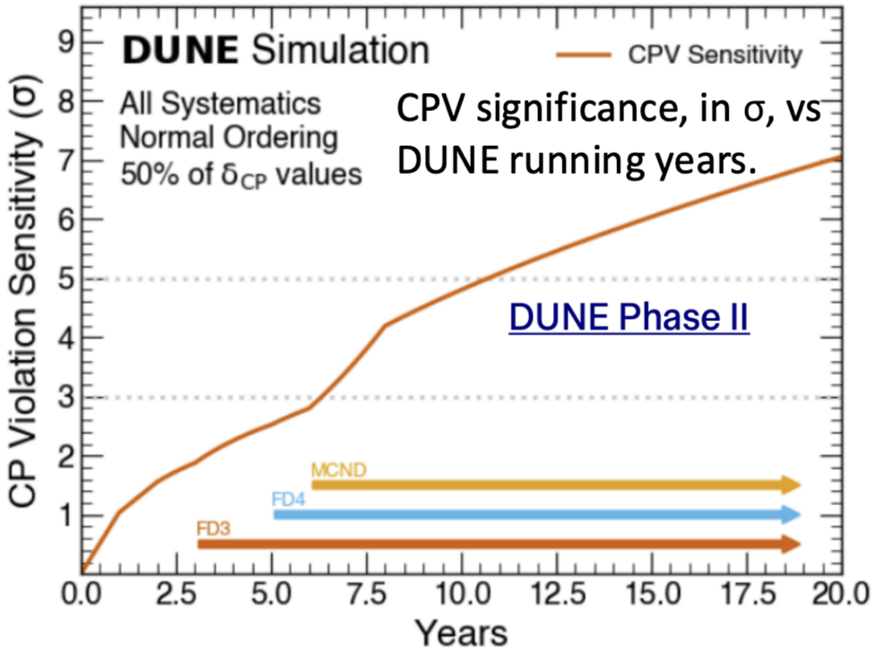


Hyper-K and DUNE: comparable, complementary reach

Different baselines, energies and systematics — similar ultimate sensitivity

Percentage of true δCP values for which CP conservation can be excluded vs HK running years





Neutrino 2026 — DUNE status (Gollapinni)

- Installation phase begun; far-site caverns excavated & outfitted at SURF; cryostat assembly starting
- Both LArTPC technologies validated.
- First far-detector data ~2030

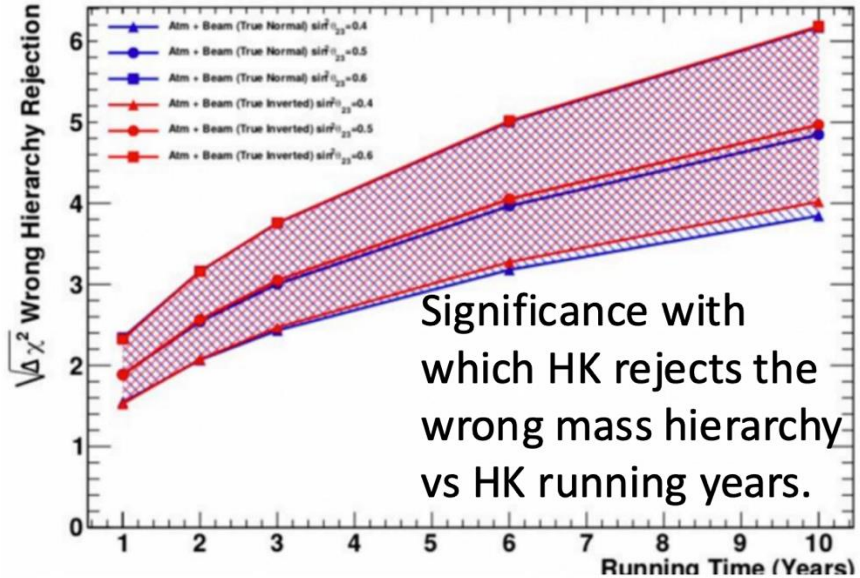
Capability	Hyper-K	DUNE
5σ CPV	5σ for ~55% (6 yr) → >60% (10 yr) of δ_{CP}; <3 yr at $\delta_{CP} = -\pi/2$	50% of δ_{CP} — 600 kt·MW·yr (10 y)
δ_{CP} precision	~6°–20°	~6°–19°

Atmospheric neutrinos: an independent handle

Hyper-K continues Super-K's 25-year legacy at 8.4× the statistics

Independent sensitivity to:

- Neutrino mass ordering — matter effects in upward-going multi-GeV ν
- θ_{23} octant — sub-GeV electron-like samples
- δ_{CP} — orthogonal degeneracy directions compared to beam ν
- Non-standard interactions, sterile ν, Lorentz / CPT violation

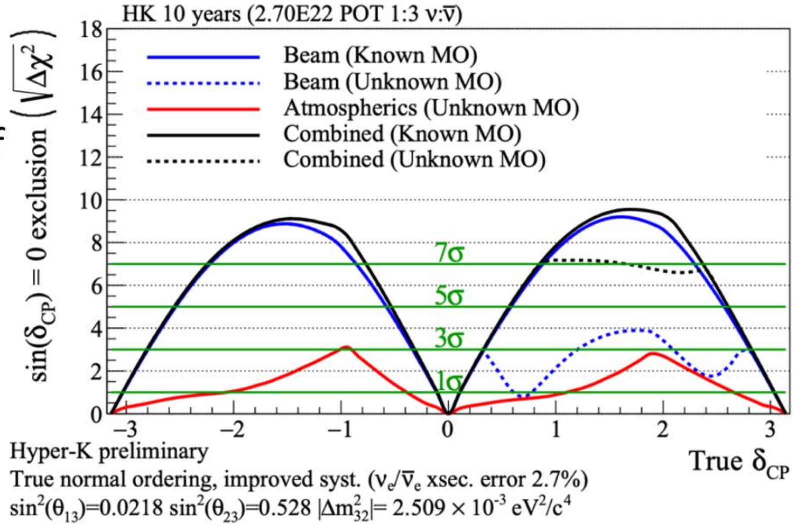


Significance with which HK rejects the wrong mass hierarchy vs HK running years.

Combined beam + atmospheric analysis

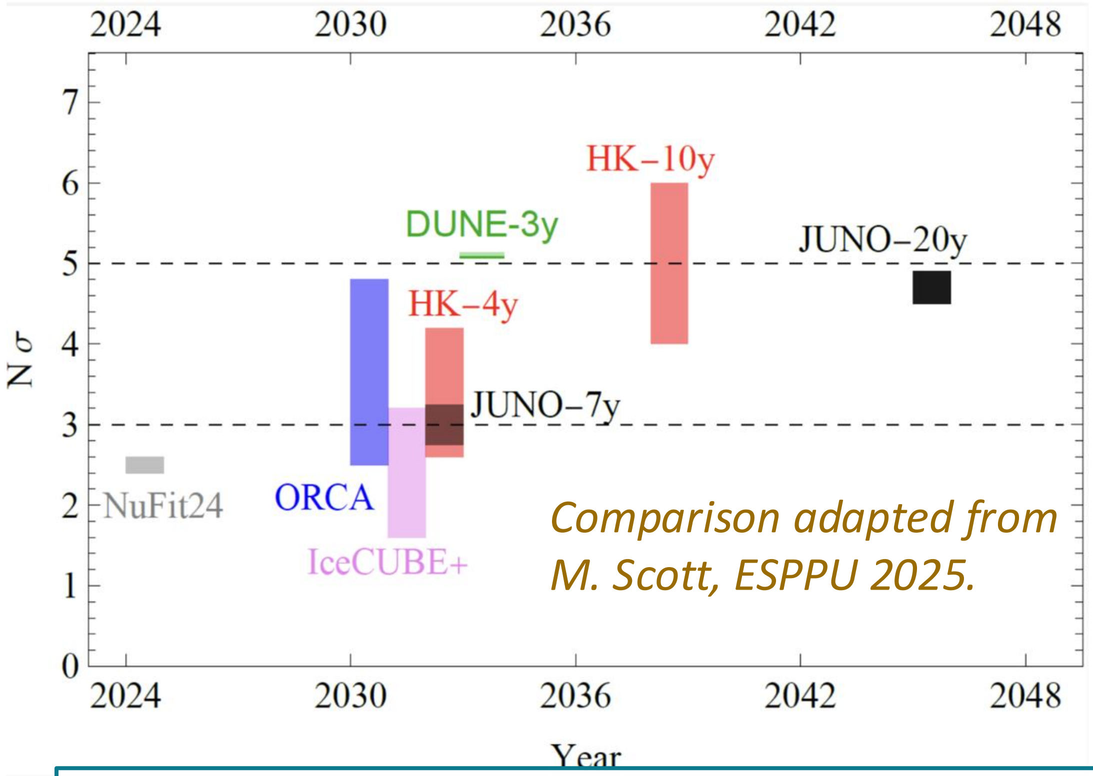
Joint fit breaks octant–δCP–ordering degeneracies in ways neither sample can alone. Particularly powerful in the first years of running.

Significance significance of excluding CP conservation vs HK running years.



Future determination of mass ordering

Different experiments, different approaches



Comparison adapted from M. Scott, ESPPU 2025.

Independent sensitivities to MO:

- Sensitivity vs time; width from uncertainty on other oscillation parameters — primarily $\sin^2\theta_{23}$
- Early 2030s: many experiments reach 3σ; multiple sources and methods
- DUNE: 5σ shortly after beam starts (assumes $\sin^2\theta_{23} = 0.58$; less for smaller values)

Neutrino 2026 — mass ordering (NOvA · JUNO · global)

- NOvA (PRL 136, 01180): NO at 77% (Bayes 3.3); 3-flavour subsample fits consistent — paradigm holds
- JUNO first results (207 d): Δm^2_{21} to 1.06%, first Δm^2_{31} ~1%; NO at 2.3σ; geo-ν 73±11 TNU
- NOvA + JUNO Δm^2_{32}: NO ~16× more likely than IO (Bayes 15.74, 1.9σ); global fit near-degenerate but SK & IceCube atmospherics pull NO at ~2.5σ

The Water Cherenkov programme is delivering now

Recent results from Super-K and Super-K-Gd

Atmospheric ν oscillations

*SK I–V (6511 livedays, 484 kt·yr): NO favoured at 92.3% (PRD 109, 072014). First SK+T2K joint fit: 1.9σ exclusion of JCP=0; 1.2σ exclusion of IO (*PRL 134, 011801 (2025)*).*

DSNB — SK-Gd

956 days SK-VI+VII (arXiv:2511.03921). World-leading limits on the DSNB ν̄e flux; SK-Gd now at the threshold of DSNB discovery; combined with JUNO, 5σ within the decade (arXiv:2201.12920).

Proton decay

$\tau(p \to e^+\eta) > 1.4\times10^{34}$ yr and $\tau(p \to \mu^+\eta) > 7.3\times10^{33}$ yr at 90% CL (0.373 Mton·yr; ~1.5× previous). PRD 110, 112011 (2024); Taniuchi et al., arXiv:2409.19633.

WCTE first physics

CERN test experiment, 2024–25. Beam-tagged particles entering a water Cherenkov detector with multi-PMT readout; first Gd-loaded operation — direct technology validation for HK's IWCD.

On the horizon — Water Cherenkov R&D & future beams (Neutrino 2026)

- ANNIE — Gd-doped water + LAPPDs on the BNB; neutron tagging for ν-energy reconstruction.
- ESSnuSB — proposed ESS superbeam at the 2nd oscillation maximum + megaton-scale Water Cherenkov for δ_{CP}

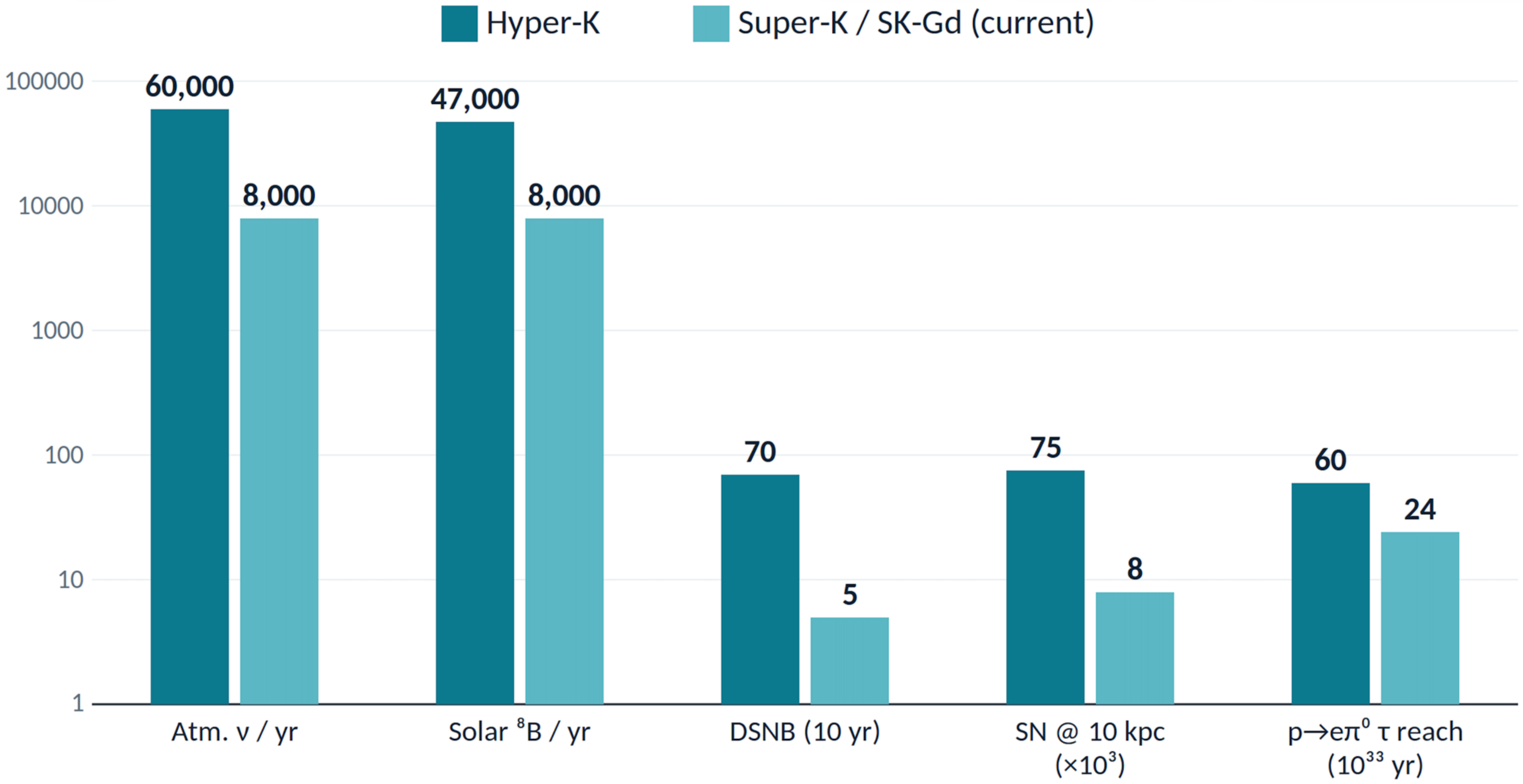
Astrophysical neutrinos

Where Water Cherenkov uniquely contributes

Solar · Galactic supernova burst · Diffuse SN background · Multi-messenger

Hyper-K in numbers — by physics channel

Expected yields and discovery reach across channels



Sources

Atm. ν: ~60,000/yr (HK), ~8,000/yr (SK). HK Design Report (arXiv:1805.04163).

Solar ^{8}B: ~130/day above threshold at HK → ~47,000/yr (Akutsu, Neutrino 2026; HK Design Report).

DSNB: 4–7/yr → ~40–70 in 10 yr at HK, 16–30 MeV (HK Design Report; arXiv:2201.12920).

SN burst: ~50,000–75,000 events from a 10 kpc SN at HK; reach to M31 (HK Design Report; arXiv:2101.05269).

$p \to e\pi^0$: HK 10-yr reach $\tau \sim 6\times10^{34}$ yr (HK Snowmass WP arXiv:2203.02029). Current SK limit $\tau > 2.4\times10^{34}$ yr (PRD 102, 112011).

Beam ν_e - like candidates: 2,474 (ν) / 1,542 ($\bar{\nu}$) over 10 yr at 1:3 ν:$\bar{\nu}$ (EPJC 86, 170 (2026)) — ~T2K's full-programme yield each year. **JUNO:** complementary low-E DSNB reach. **DUNE:** complementary ν_e SN channel via ^{40}Ar.

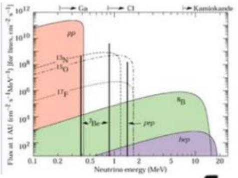
Solar neutrinos

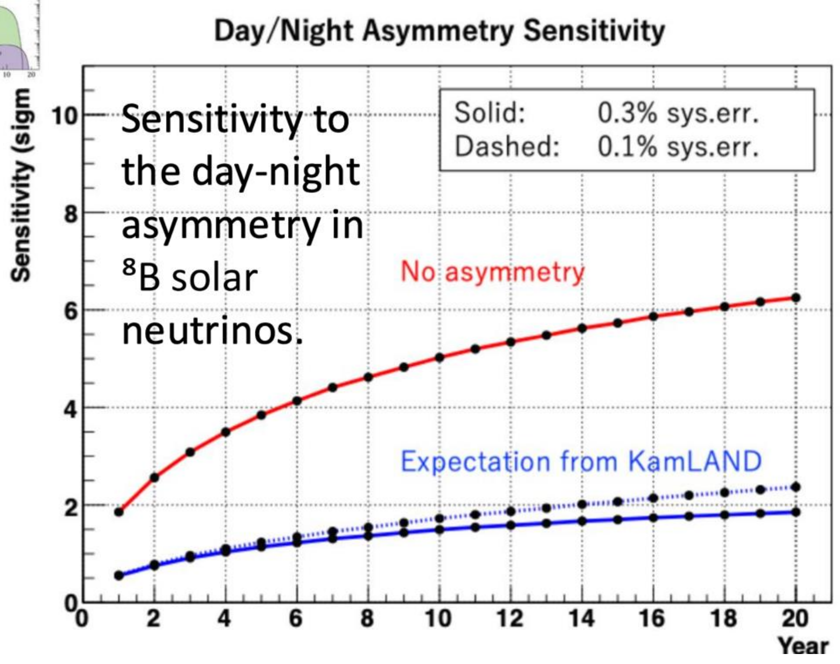
Continuing Super-K's legacy with order-of-magnitude more statistics

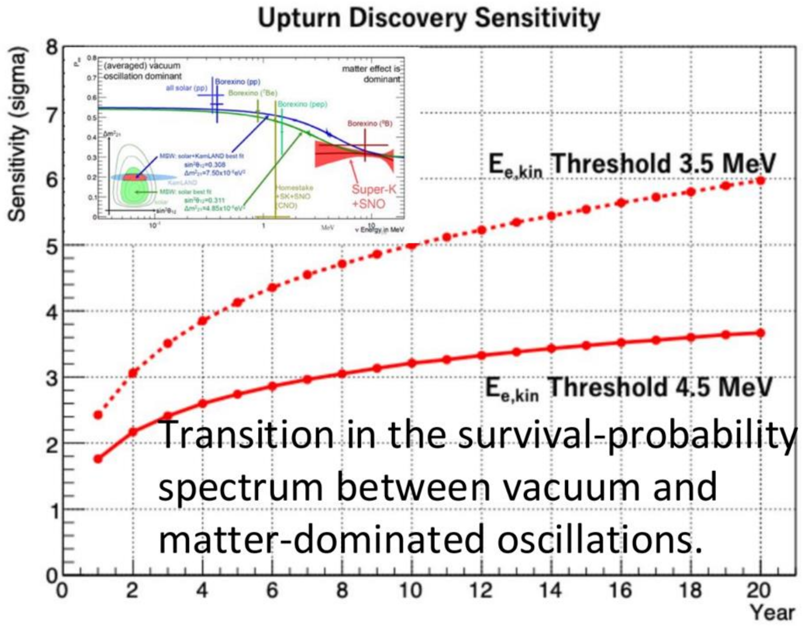
- **^{8}B flux** — precision day–night asymmetry — direct probe of MSW matter effects
- **Upturn region** — transition between vacuum- and matter-dominated oscillations
- **Possible reach to hep neutrinos** — endpoint ~19 MeV
- **Tension probe** — solar vs reactor Δm^2_{21} (currently ~1.5σ)

Why it matters

A confirmed solar–reactor tension would point to new physics in the few-MeV regime — sterile ν, NSI, or beyond-standard solar models.







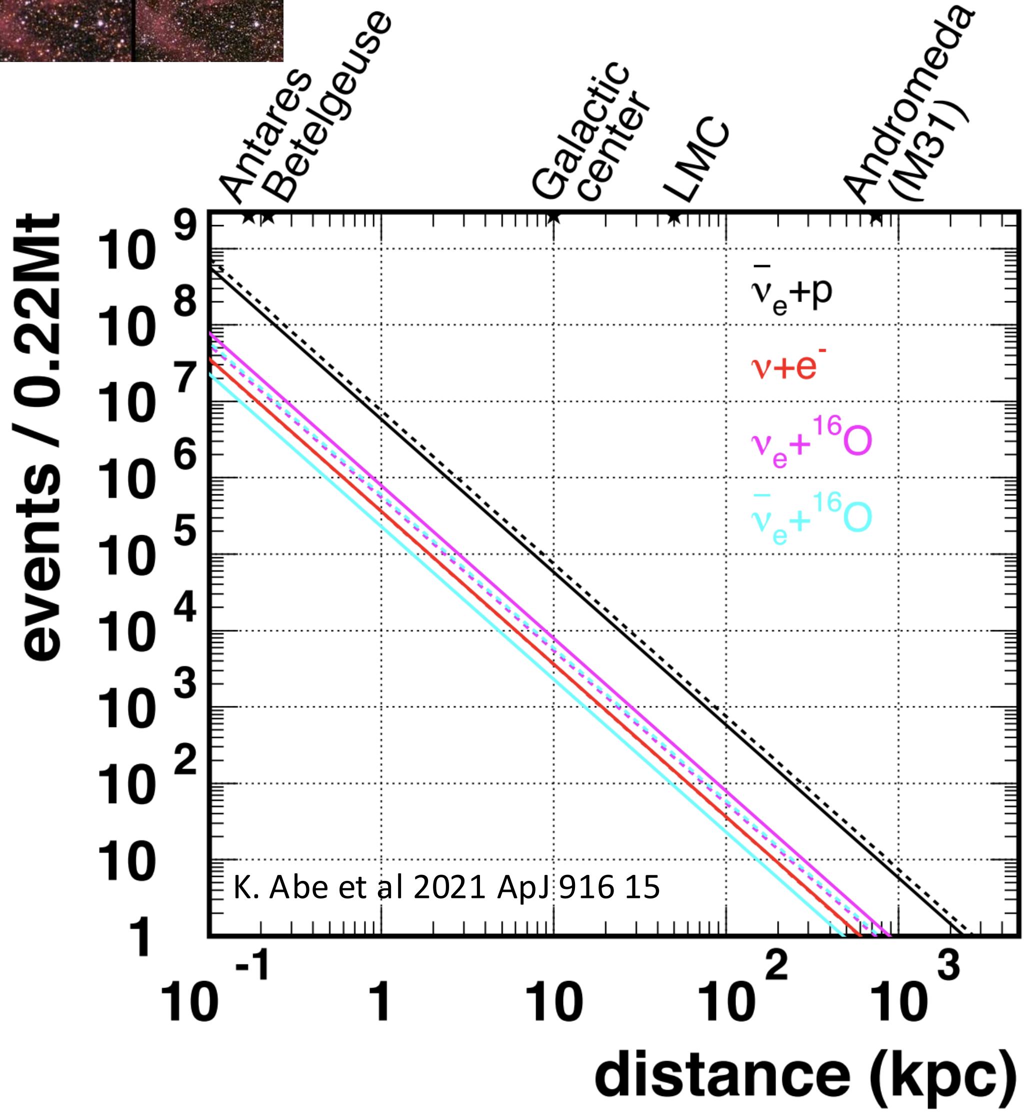
PASCOS 2026 — F. Di Lodovico — SK solar: 3.2σ day-night, 2.1σ upturn (SK+SNO) — PRD 109, 092001 (2024); NuTel 2025

Galactic supernova burst

The once-in-a-generation observation Hyper-K is built for

~50,000–75,000 events from a 10 kpc galactic core-collapse supernova

- Sensitivity to supernovae as far as Andromeda (~770 kpc)
- Sub-second time resolution: neutronisation burst, accretion, cooling
- Pointing to the supernova — directional ν–e scattering
- Multi-messenger early warning to optical / gravitational-wave observatories
- Test of neutrino mass ordering via spectral signatures

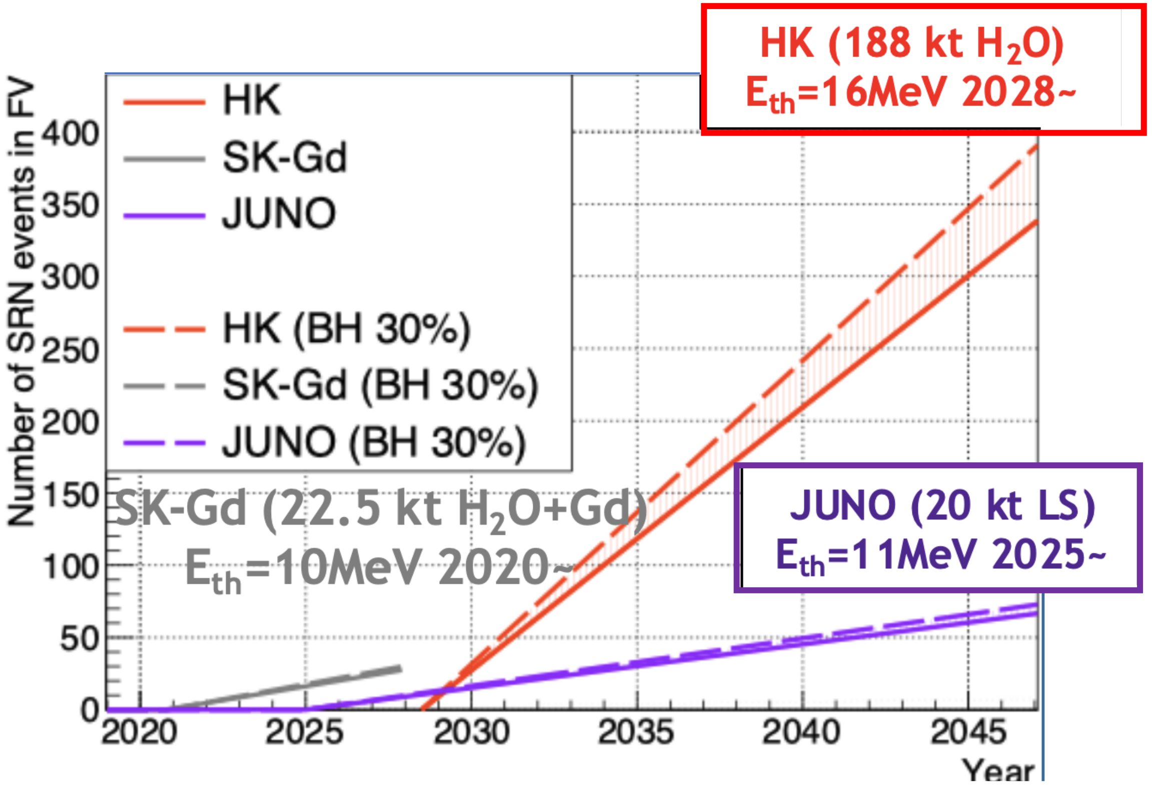


Diffuse Supernova Neutrino Background

Cosmic flux from all past core-collapse supernovae

First detection era is now opening:

- SK-Gd already operating: combined 6779-day fit shows 2.3σ excess over background-only — first hints (NuTel25, prelim.)
- Hyper-K: ~4σ DSNB signal in 10 yr at 40% photocoverage (~70 ± 17 events)
- Complementary to JUNO (low-E threshold) and DUNE (νe channel)
- Probes star-formation rate and the fraction of failed (black-hole-forming) supernovae



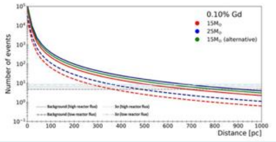
Astrophysics + neutrino physics

DSNB spectrum sensitive to non-radiative ν decay, ν self-interactions, sub-GeV dark-matter annihilations to ν.

Multi-messenger astronomy

Neutrinos as a clean, prompt, penetrating messenger

Pre-burst alerts



Sub-second neutrino burst arrives before the electromagnetic signal — alerts to optical and GW observatories

Pointing

Neutrino–electron elastic scattering preserves source direction; HK can localise to within ~few degrees

GW coincidence

Joint analyses with LIGO/Virgo/KAGRA on binary mergers, magnetar flares, SGRBs

Solar flares

Search for ν production in solar-flare acceleration sites

Galactic transients

Sustained sensitivity to nearby supernovae, novae, and other transient ν sources

Dark matter

Indirect WIMP-annihilation searches in the Sun, Earth, Galactic centre

Proton decay

Probing grand unification at the megaton scale

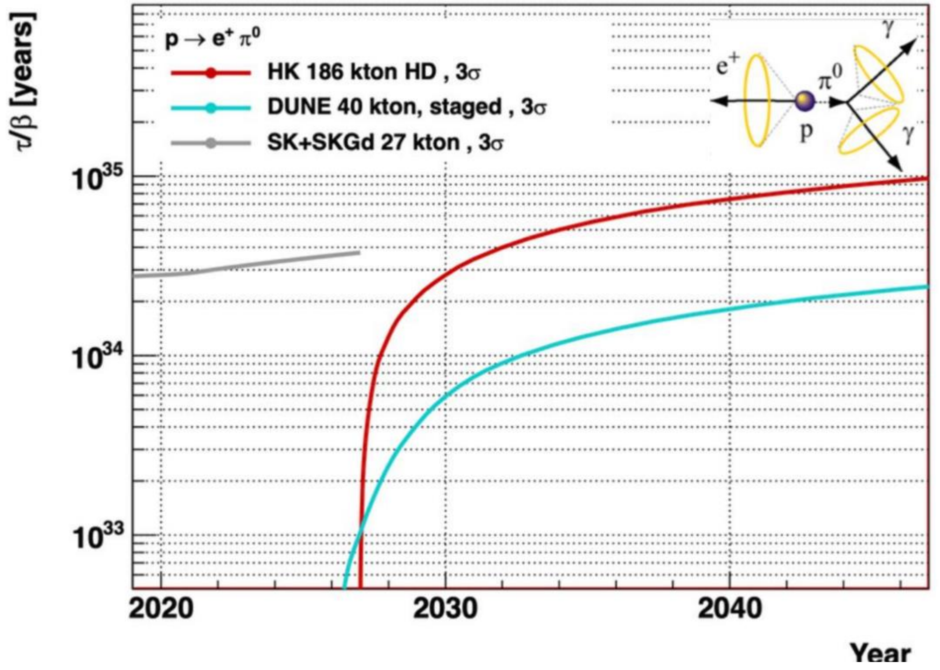
The other historic Water Cherenkov physics:

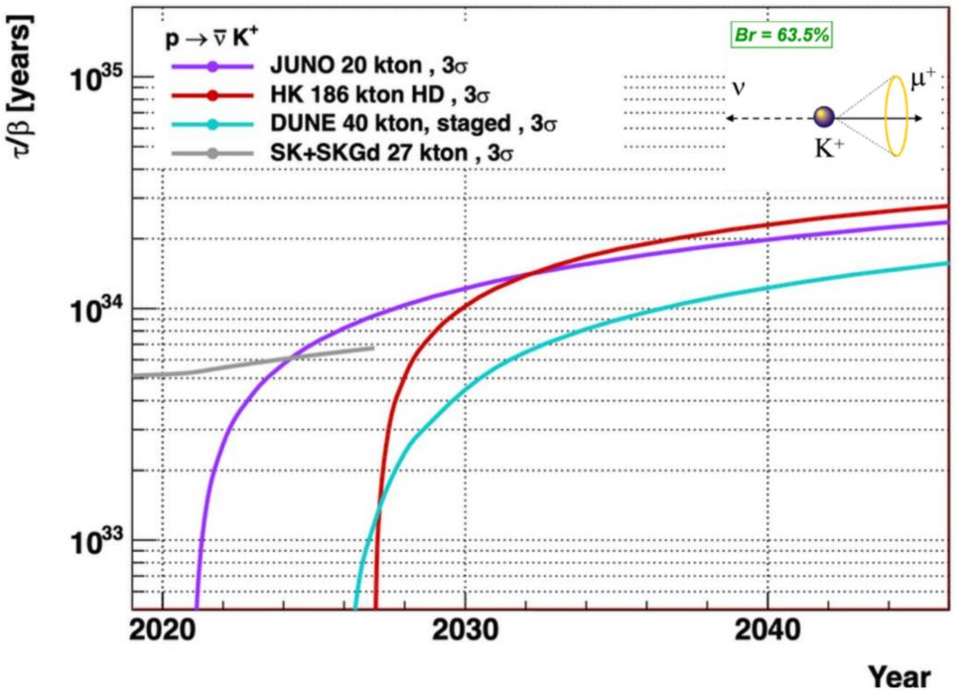
- **$p \to e^+\pi^0$ —** clean back-to-back EM-shower topology, fully reconstructable
- **$p \to \bar{\nu} K^+$ —** complementary mode favoured in SUSY-GUT scenarios
- **Other modes —** $\mu^+\pi^0$, $e^+\eta$, $e^+\rho^0$, $\nu\pi^+$ …

Sensitivity with 20 years exposure

$\tau(p \to e^+\pi^0) \sim 10^{35}$ yr

$\tau(p \to \bar{\nu} K^+) \sim 3 \times 10^{34}$ yr





Construction status (June 2026)

On track for 2028 data taking

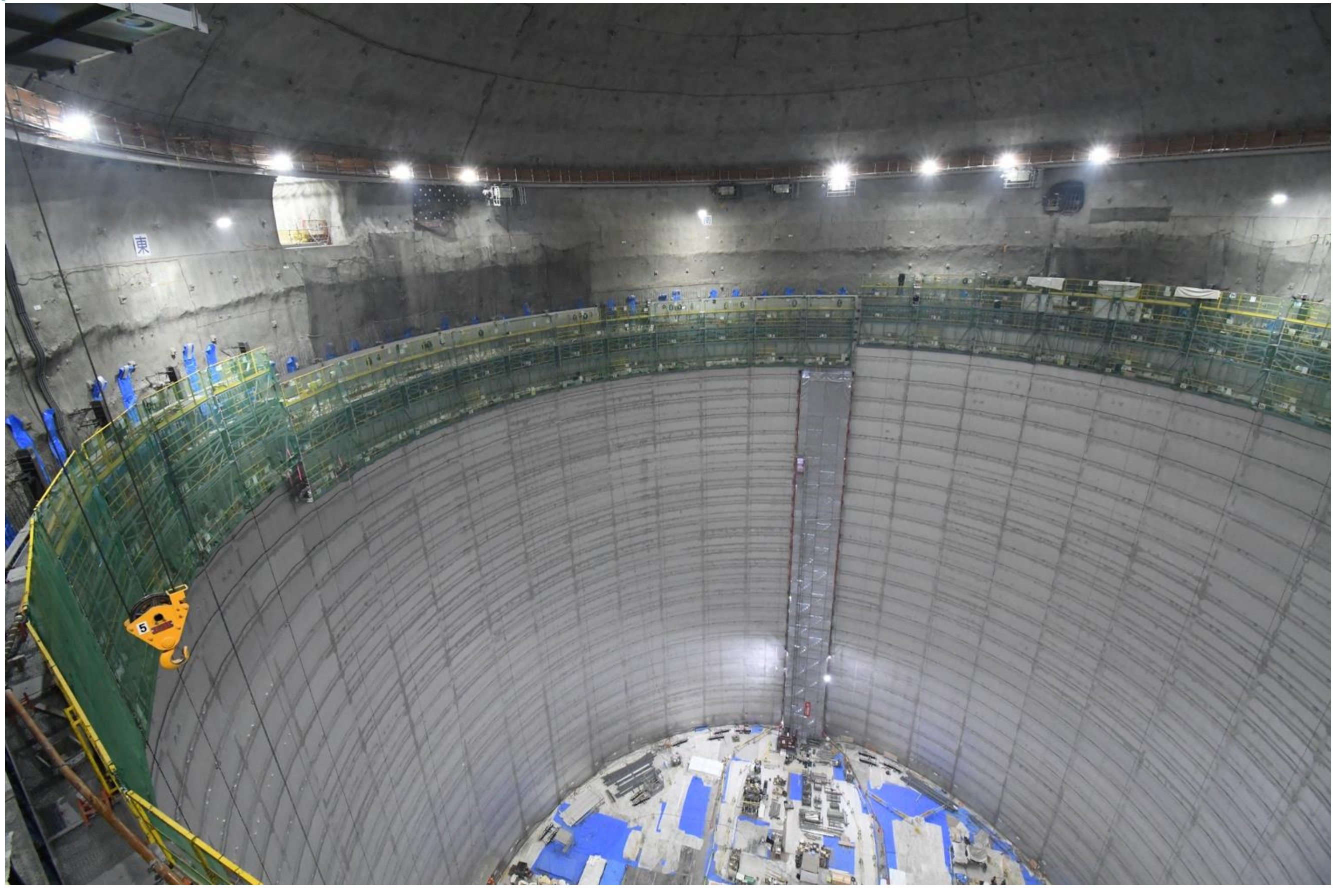
- ✓ Cavern excavation complete (July 2025)
- ✓ IWCD ground-breaking 4 Nov 2025; facility building & pit excavation started
- ◐ Tank lining & water-containment structure in progress (2026)
- ◐ 50-cm PMT mass production in Japan (16,703 of 20,000 delivered, Oct 2025)
- ◐ International production: multi-PMTs, OD photodetectors, underwater electronics
- ○ Detector internal construction starts 2026; PMT installation through 2027
- ○ J-PARC beam upgrade 0.8 → 1.3 MW underway
- ○ Water filling 2027–2028 → operations 2028

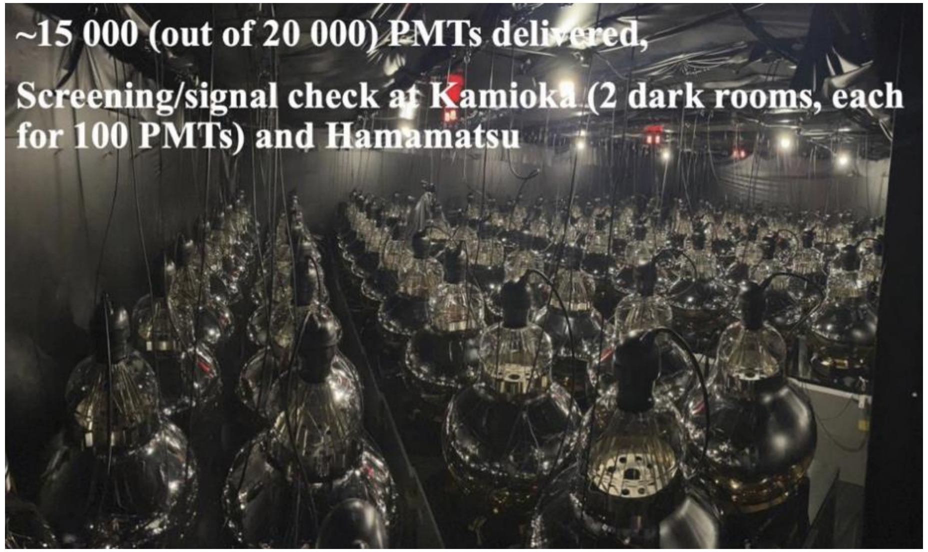
Collaboration

~630 researchers · 22 countries · 105 institutes.

From the cavern to the detector

Hyper-Kamiokande cavern — June 2026





Scale of the engineering

Cylindrical cavern 69 m diameter × ~73 m tall (94 m tall including dome), 600 m underground — one of the largest man-made underground spaces ever excavated.

Hyper-K timeline

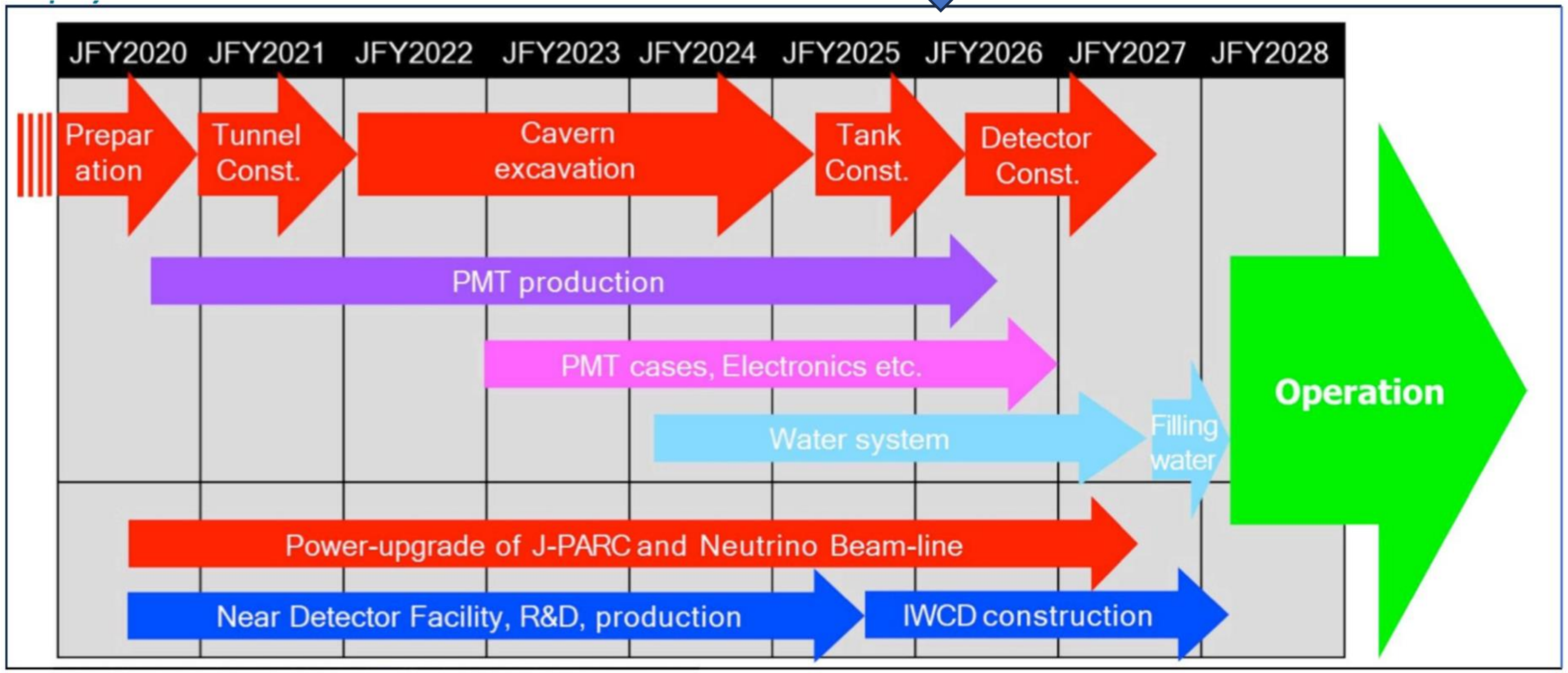
From cavern to first physics

Now

Cavern Tank Installation

Photosensors

Beamline & Near Detectors



Cavern excavation
2020–25

2026
Tank construction, PMT installation begins

Detector internals complete, water filling
2027

2028
First physics data taking

10-yr exposure: CPV for >60% of δ_{CP}
~2038

A global programme this decade

Multiple experiments, sources and techniques coming online together

2025
JUNO data taking (filled Aug 2025; first results 2026); IceCube Upgrade & KM3NeT-ORCA

2028
Hyper-K data taking begins

~2030
DUNE first far-detector data; atmospheric data; ~3σ MO from several experiments

~2031
DUNE Phase I beam

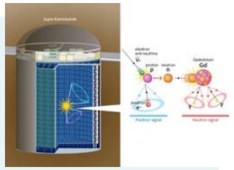
2034+
DUNE Phase II; combined 5σ CPV & MO reach

The longer pathway: R&D for the next decade

Water Cherenkov technology continues to evolve

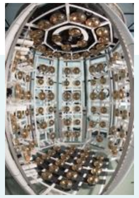
Hyper-K is the flagship; a complementary R&D programme is paving the way for future generations of Water Cherenkov and hybrid detectors.

Super-K-Gd



Operating now — Gd-loaded Super-K demonstrating neutron tagging: the proof-of-concept for the DSNB-sensitive era.

ANNIE



Fermilab — small Gd-water detector with LAPPDs; fast timing, neutron tagging and reconstruction in the few-GeV regime.

IWCD / WCTE

Intermediate Water Cherenkov Detector + CERN Test Experiment: validate reconstruction, calibration, multi-PMT technology.

THEIA

Hybrid Cherenkov + scintillator (water-based LS): low-threshold solar, geoneutrinos, 0νββ — broad multi-purpose programme.

Outlook

The Water Cherenkov technique is not standing still: Hyper-K delivers in the late 2020s; THEIA-class hybrid detectors extend the reach in the 2030s and beyond. ESSnuSB: proposed ESS superbeam at the 2nd oscillation maximum + megaton WC.

Summary

The megaton era of neutrino physics is at hand

A multi-purpose observatory

One detector — beam ν, atmospheric ν, solar ν, supernova burst, DSNB, proton decay, dark matter

CPV at 5σ within reach — with DUNE & JUNO

Megaton water Cherenkov + LAr + reactor: a complementary global CPV & precision programme

Astrophysics in a new regime

Up to 75,000 events from a galactic SN; DSNB first detection; precision solar

Order-of-magnitude proton-decay reach

10^{35} yr in $p \to e^+\pi^0$; complementary to DUNE and JUNO

Construction on track

Cavern complete; PMTs in production; data taking from 2028

The global neutrino-detector landscape

Water Cherenkov at the core — complemented by large liquid-based detectors

Water Cherenkov

Super-K / SK-Gd (50 kt) · Hyper-K (258 kt, 2028) · IWCD + WCTE

Highest statistics; beam, atmospheric, solar, SN burst, DSNB and proton decay in one detector.

Liquid Argon TPC

DUNE (1300 km, ~2–3 GeV)

Imaging calorimetry; mass ordering from matter effects, BSM, ^{40}Ar SN ν_e channel.

Liquid Scintillator

JUNO (20 kt, reactor) · SNO+ · KamLAND-Zen

Low threshold, fine energy resolution; reactor MO, Δm^2_{21}, $0\nu\beta\beta$, geo/solar ν.

Ice / sea-water optical

IceCube + Upgrade · KM3NeT-ORCA

Gigaton scale; atmospheric mass ordering and high-energy astrophysical ν.

Water Cherenkov spans the widest range of sources; liquid-based detectors add orthogonal baselines, energies and systematics.

Thank you

Questions welcome.