

Hyper-Kamiokande

Federico Nova

CPNR 2025

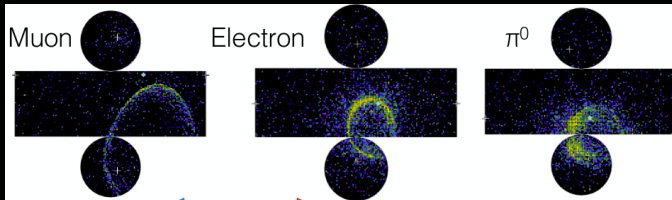
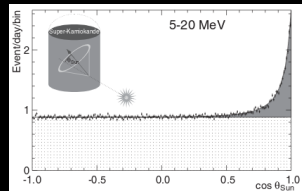
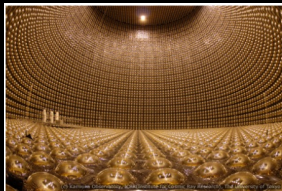
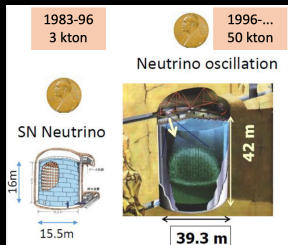


Outline:

1. detector
2. physics program

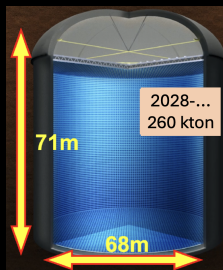


Kamiokande family



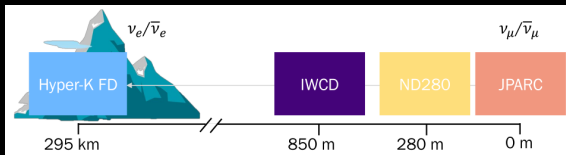
- ▶ vertex
- ▶ direction
- ▶ energy
- ▶ id

Hyper-Kamiokande detector

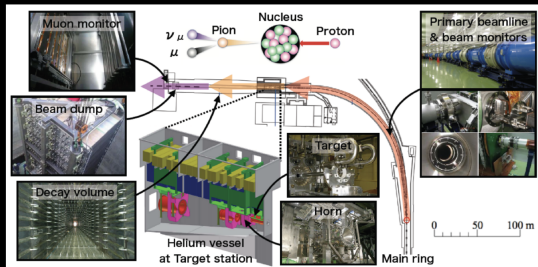


	SuperKamiokande	Hyper-Kamiokande
site	Mozumi	Tochibora
(rock overburden)	(1 km)	(600 m)
ID PMTs	~11k	~20k
(50 cm)	(50 cm)	(50 cm)
photo-coverage	40%	20%
		× 2 single p.e. efficiency
OD PMTs	2k	3.6k
(20 cm)	(20 cm)	(8 cm)
mass	50 kton	260 kton
(fiducial mass)	(22.5 kton)	(188 kton)

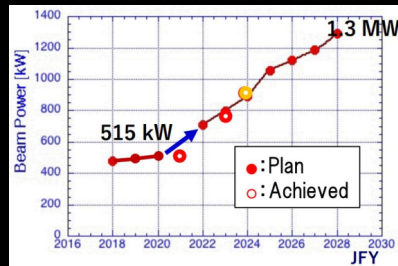
- ▶ 8× SK fiducial volume
- ▶ improved photo-sensors
- ▶ begin data taking 2028



J-PARC neutrino beamline

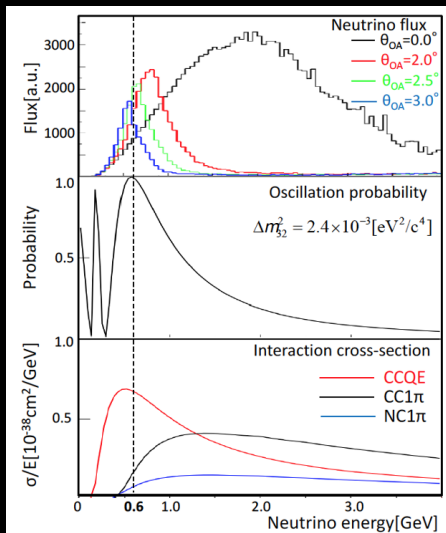


- ▶ narrow-band neutrino beam ($E \approx 600$ MeV)
- ▶ beam power to reach 1.3 MW (T2K ran stably at 800 kV in 2024)
 - ▶ upgrade main ring RF system:
 $2.6 \rightarrow 3.3 \cdot 10^{14}$ protons/pulse
 - ▶ improved horns power: 250 $\rightarrow$ 320 kA
 - ▶ increase repetition rate (1.35 $\rightarrow$ 1.16 sec/cycle)
 - ▶ 10% increased ν flux at HK

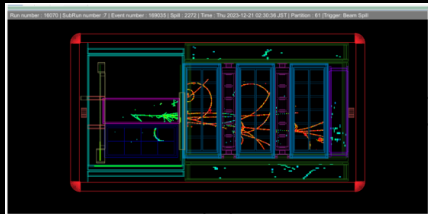


near detector complex (280 m downstream)

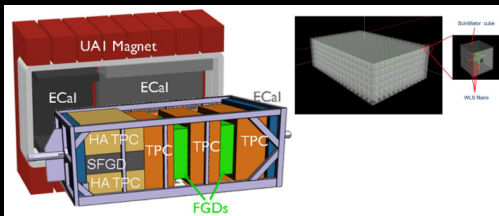
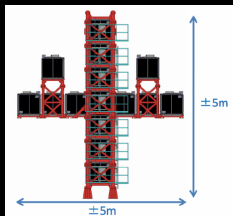
- ▶ monitor flux before oscillations
- ▶ measure cross-sections
- ▶ essential to tune fits and reduce systematics
- ▶ interaction dominated by CCQE
 - ▶ → single ring
 - ▶ → kinematic reconstruction of E_ν
- ▶ interaction rates uncertainty 3%
 - ▶ → systematic errors 5 – 6% in T2K
 - ▶ must be reduced to 3% for HK



near detector complex (280 m downstream)



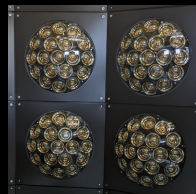
- ▶ on-axis beam monitor (Fe + scintillator), 0.3 mrad already achieved in T2K
- ▶ off-axis magnetized detectors to identify wrong-sign bkg
- ▶ 2024 upgrades: TOF detectors, high-angle TPCs, scintillator superFGD
- ▶ improvements: finer granularity and wider solid angle



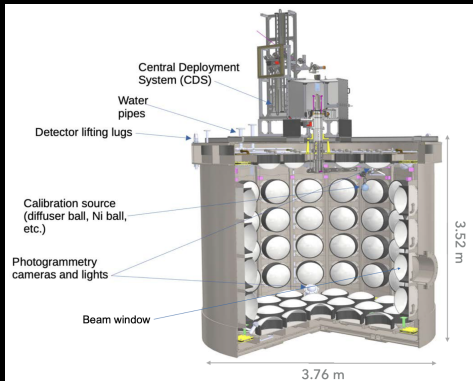
intermediate water-Cerenkov detector (IWCD)



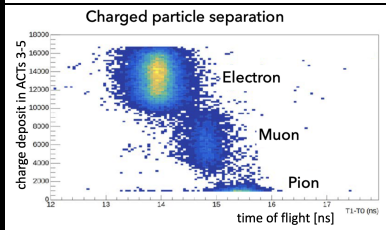
- ▶ 640 t water Cerenkov cylinder (like FD)
- ▶ 368 ID 8 cm multiPMTs (+ 368 OD)
- ▶ 850 m downstream (reduce pile-up wrt ND)
- ▶ located on surface in 50 m pit
- ▶ movable to sample (1° , 4°) off-axis angles (2.5° in HK)
- ▶ match the flux between near and far detectors
- ▶ direct measurement of ν_e/ν_μ cross-section as a function of energy (main systematic in δ_{CP})
- ▶ measure intrinsic ν_e and NC components (more abundant off-axis)



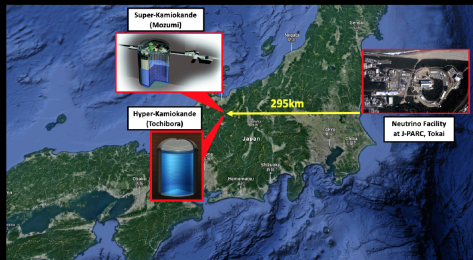
prototype tested @ CERN



- ▶ IWCD half-sized prototype (same photosensors, calibration and water system)
- ▶ data taking 2024-2025 (including Gd phase)
- ▶ operated in CERN T9 (East Hall) beam line
- ▶ particles: $e^{\pm}, \mu^{\pm}, \pi^{\pm}, p^{+}$, tagged γ
- ▶ momentum: 0.2 – 1.1 GeV/c
- ▶ beam detectors provide PID, calorimetry and triggering



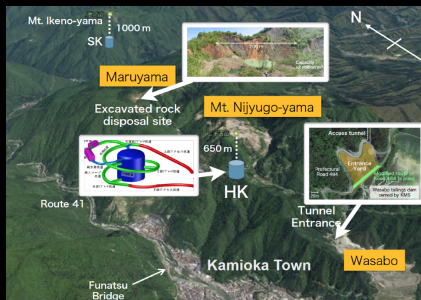
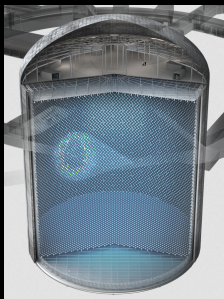
Hyper-Kamiokande far detector site



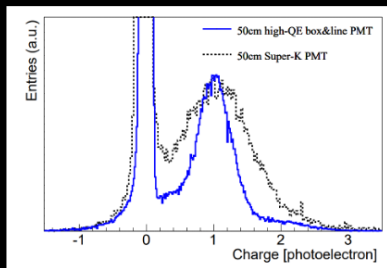
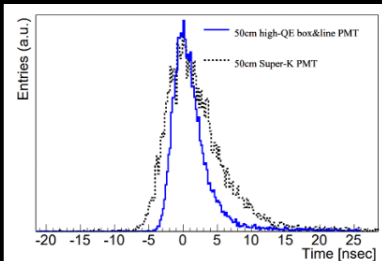
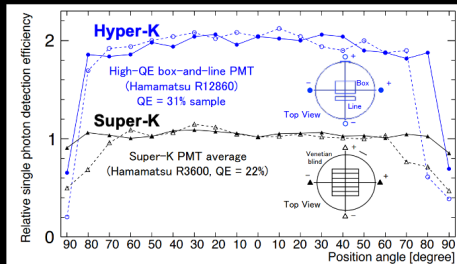
same choices as T2K:

- ▶ 295 km baseline
- ▶ 2.5° off-axis angle

HK will be started while SK keeps running

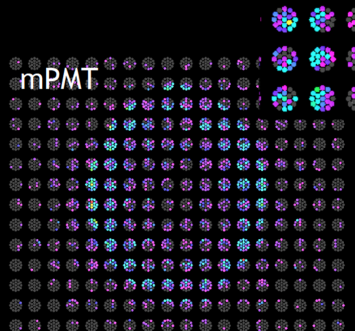


ID photosensors: 50 cm PMTs



- ▶ 20k 50 cm Hamamatsu B&L PMT
- ▶ wrt SK: **2× single p.e. efficiency**
- ▶ **2× increased charge** (35%, 50% in SK) **and time resolution** (1.1 ns transit time spread, 2.1 ns in SK)
- ▶ 2× increased pressure resistance (70 m water depth)
- ▶ 6 kHz dark rate
- ▶ pressure-resistant acrylic cover

ID photosensors: 800 mPMTs



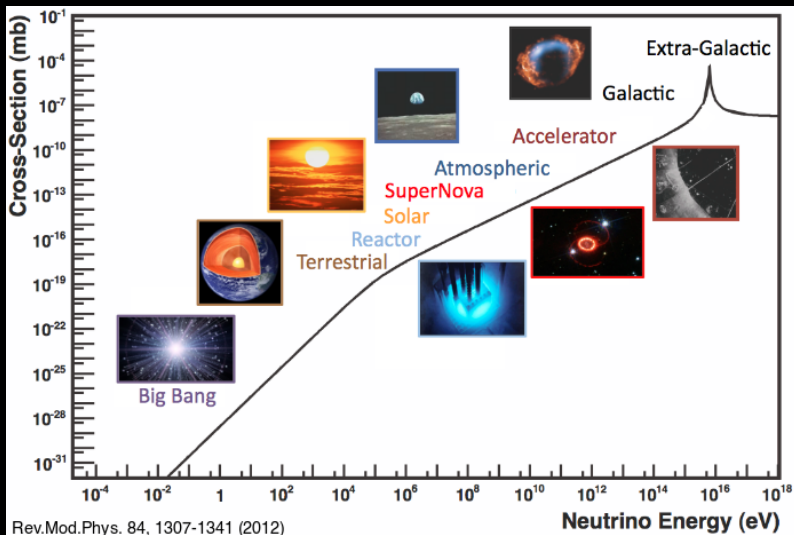
- ▶ module with 19 3" PMTs
- ▶ high granularity and good time resolution (0.6 ns TTS, 2× better than B&L)
- ▶ directional sensitivity from local coincidences
- ▶ small magnetic field sensitivity
- ▶ combined with 50 cm PMTs in HK and adopted also in IWCD

PMTs status

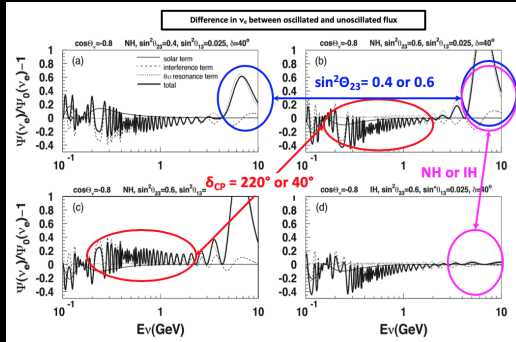
- ▶ mass production of 50 cm PMTs ongoing
- ▶ >15k PMTs have been delivered
- ▶ screen testing signal and visual inspection ongoing at Kamioka and Hamamatsu
- ▶ testing of covers using mock-up frame in Mediterranean sea



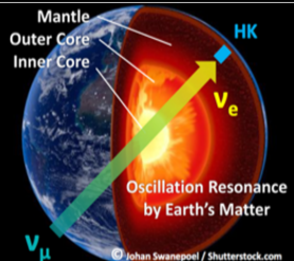
very wide physics program



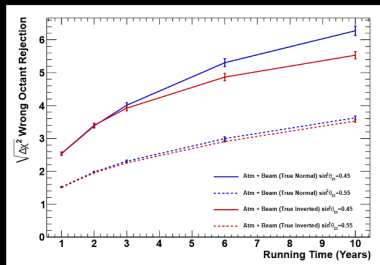
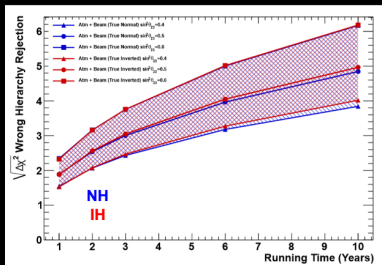
atmospheric neutrinos



- ▶ wide energy range (peak 1 GeV) and long travel distance
- ▶ precision mixing parameters
- ▶ ν_e flux enhanced depending on mass ordering, θ_{23} and δ_{CP}

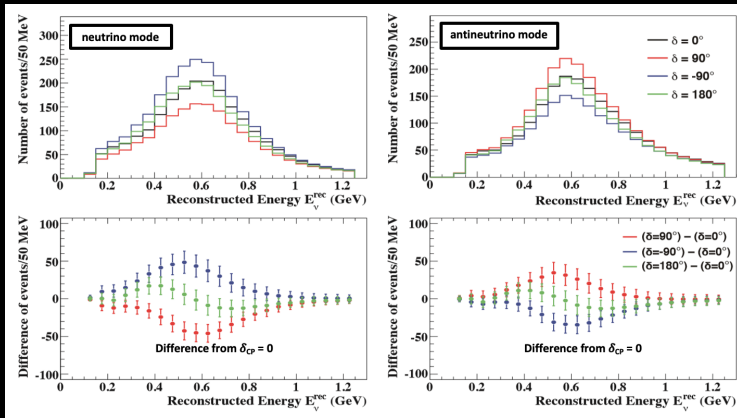


mass ordering and octant sensitivity



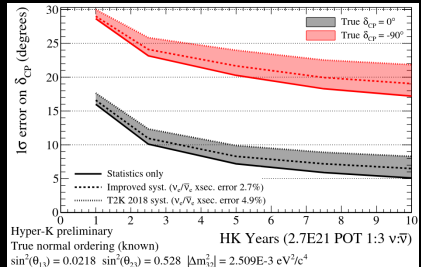
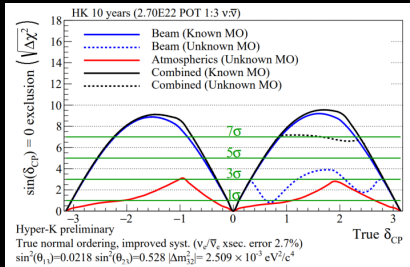
- ▶ earth matter effect for ν 's passing through core allow measurement of δ_{CP} , mass ordering and θ_{23} octant
- ▶ measure mass ordering at 3σ for all values of θ_{23}
- ▶ determine octant at 3σ for $|\theta_{23} - 45^\circ| \geq 2^\circ$

beam: CP violation



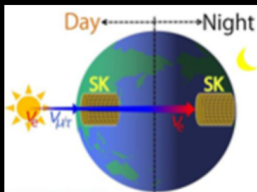
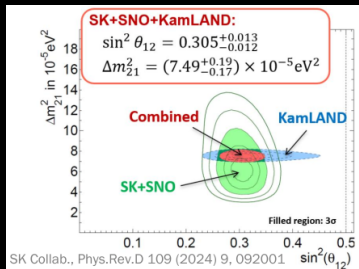
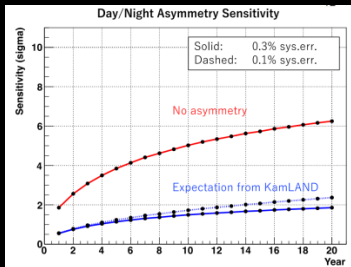
- ▶ ν_e appearance in ν_μ beam
- ▶ T2K disfavour CP conservation ($\delta = 0, \pi$) at $\sim 3\sigma$ level
- ▶ effect of δ_{CP} clearly seen in reconstructed spectra (10 years, NH)

beam: CP violation



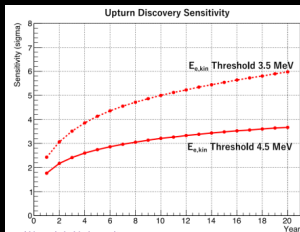
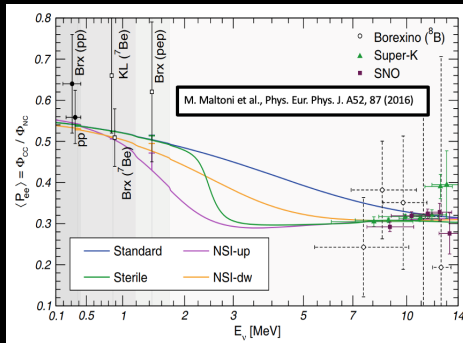
- ▶ assume 10 years exposure, 1:3 ν to $\bar{\nu}$ beam operation, known mass ordering, 3-4% systematic uncertainty
- ▶ exclude $\sin \delta_{\text{CP}} = 0$ at 5σ for 60% of range
- ▶ measure δ_{CP} with $\pm(7^\circ, 22^\circ)$ for $\sin \delta_{\text{CP}} = (0, 1)$
- ▶ sensitivity paper: <https://arxiv.org/abs/2505.15019>

solar neutrinos



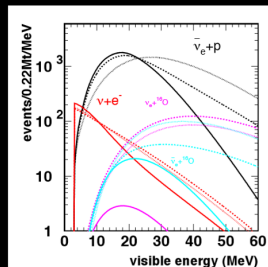
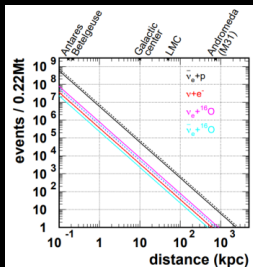
- ▶ regeneration of ν_e due to earth matter effect $\rightarrow$ higher ν_e flux at night
- ▶ can reject no day/night asymmetry to 5σ after 10 years
- ▶ also, resolve 1.5σ tension between solar experiments and KamLAND on Δm_{21}^2

solar neutrinos



- solar neutrinos up-turn: increase in low-energy survival probability
- $3 - 5\sigma$ measurement of up-turn spectrum after 10 years

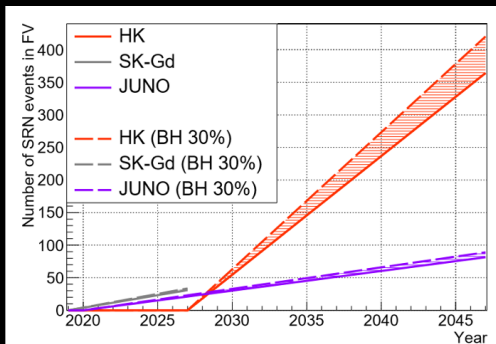
supernovae neutrinos: $\bar{\nu}_e + p^+ \rightarrow e^+ + n$



SN location	n events/tank
galactic centre (10 kpc)	70k
SN1987a (50 kpc)	3k
Andromeda (0.8 Mpc)	10

- ▶ first and only detection of supernova neutrinos SN1987a (11 ± 8 events @ 50 kpc)
- ▶ 50-80k events for a 10 kpc supernova → neutrino properties, SN mechanism
- ▶ sensitive to 1 Mpc (Andromeda)
- ▶ 1.3° pointing for SN alert

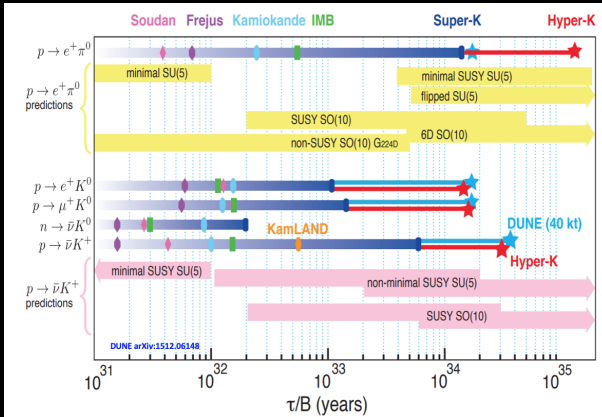
diffuse supernova neutrino background



- ▶ neutrinos from all SN since the beginning of the universe
- ▶ relevant for stellar formation rate, heavy elements synthesis, black-hole formation
- ▶ expect 4 events/year with neutron tagging, 4σ discovery after 10 years
- ▶ 16-30 MeV window limited by spallation backgrounds

also: dark matter annihilation in the sun $\rightarrow$ neutrinos!

proton decay

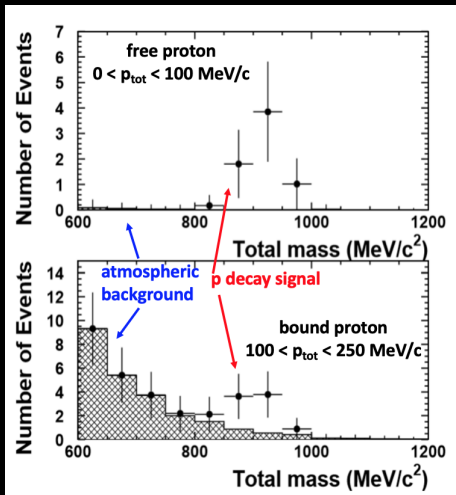
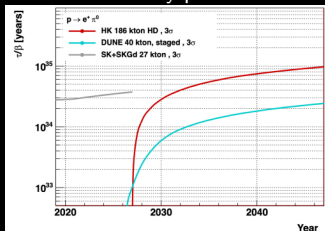


- ▶ predicted by many GUT models
- ▶ water Cerenkov sensitive to several decay modes
- ▶ suppress backgrounds with improved neutron tagging
- ▶ reach 10^{35} y lifetime

proton decay: $p^+ \rightarrow e^+ + \pi^0$

golden channel

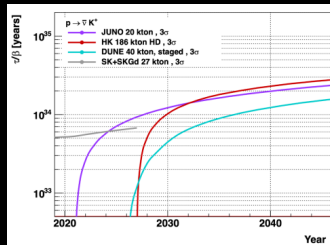
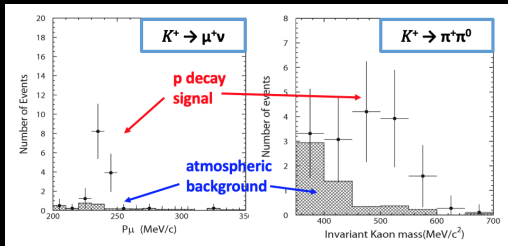
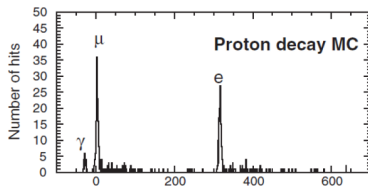
- ▶ favoured by many GUTs
- ▶ HK can see all products
- ▶ background-free search thanks to neutron tagging ($n + p^+ \rightarrow d + \gamma$, $E_\gamma = 2.2$ MeV)
- ▶ 3σ discovery potential



proton decay: $p^+ \rightarrow \bar{\nu} + K^+$

- ▶ K^+ below Cerenkov threshold (visible in DUNE), detect via decay $K^+ \rightarrow \mu^+ + \nu$ (64%) or $K^+ \rightarrow \pi^+ + \pi^0$ (21%)
- ▶ prompt gamma de-excitation, followed by μ^+ from K^+ decay (12 ns) and e^+ from μ^+ decay (2 ms)
- ▶ 3σ discovery

Time distribution of an event after TOF subtr.

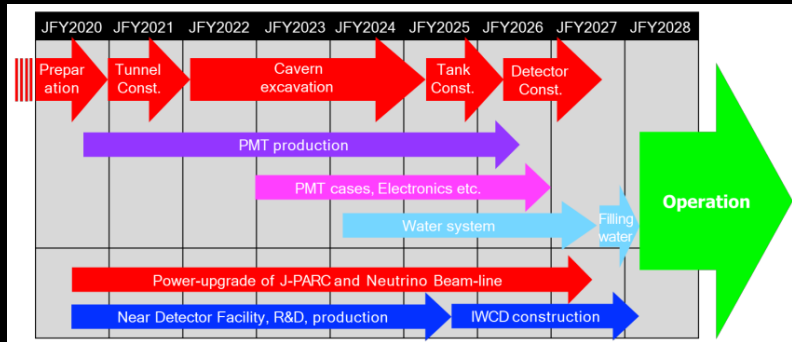


many other modes improved by 1 order

excavation status



timeline



- ▶ design report released 2018
- ▶ cavern excavation finished 2025
- ▶ water filling 2027
- ▶ data taking 2028

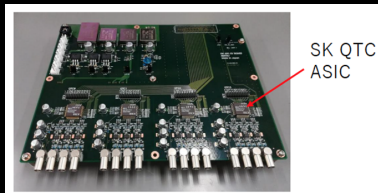
summary

- ▶ Hyper-Kamiokande is the next-generation neutrino experiment
 - ▶ $8\times$ larger than SK
 - ▶ improved photo-sensors
 - ▶ upgraded 1.3 MW beam
 - ▶ intermediate water Cerenkov to reduce systematic errors
- ▶ rich physics program
 - ▶ precise neutrino oscillation: δ_{CP} , mass ordering
 - ▶ astrophysics: solar neutrinos, supernovae etc.
 - ▶ new physics: proton decay, dark matter ...
- ▶ data taking will start in 2028

Back-up slides

Electronics

- ▶ electronics timing resolution $<$ PMT TTS
- ▶ frontend electronics and HV module in water
- ▶ timing delivered by GPS
- ▶ communication via fiber (200 m)
- ▶ large buffer for SN burst
- ▶ prototype developed with: SK QTC ASIC (charge to time), FPGA TDC 4GHz
- ▶ electronics resolution: 0.2 ns at 1 p.e., 10% charge resolution at 1 p.e., 2000 p.e. range with 1% linearity



mPMT electronics:

- ▶ 0.4 ns for 1 p.e., 0.1 ns for larger pulses
- ▶ charge resolution: 0.05 to 25 p.e.
- ▶ power consumption: 3-4 W/mPMT for HK (driven by water circulation requirements), 5-10 W/mPMT for IWCD

Systematic errors

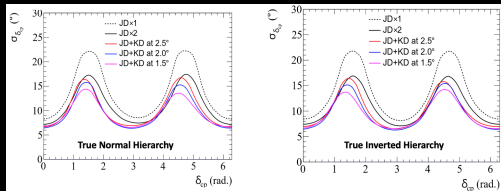
- ▶ statistical error will be 3% in HK
- ▶ require 3% systematic error on interaction rates (through upgraded ND280 and IWCD)

Source of uncertainty	ν_μ CC	ν_e CC	$\bar{\nu}_\mu$ CC	$\bar{\nu}_e$ CC
Flux and common cross sections				
(w/o ND280 constraint)	10.8%	10.9%	11.9%	12.4%
(w/ ND280 constraint)	2.8%	2.9%	3.3%	3.2%
Unconstrained cross sections	0.8%	3.0%	0.8%	3.3%
SK	3.9%	2.4%	3.3%	3.1%
FSI + SI(+ PN)	1.5%	2.5%	2.1%	2.5%
Total				
(w/o ND280 constraint)	11.9%	12.2%	13.0%	13.4%
(w/ ND280 constraint)	5.1%	5.4%	5.2%	6.2%

Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
$\sigma(\nu_\mu/\sigma(\nu_e))$	3-5%	CP Violation, δ_θ precision at $\sin(\theta_{13})=0$, θ_{13} precision at $\sin(\theta_{13})=0.5$	IWCD	3.5-5%
$\sigma(\nu_e/\sigma(\nu_\mu))$	3-5%	CP Violation, δ_θ precision at $\sin(\theta_{13})=0$, θ_{13} precision at $\sin(\theta_{13})=0.5$	IWCD	4-7%
Wrong-sign background normalization	9%	CP Violation, δ_θ precision at $\sin(\theta_{13})=0$	ND280	TBD (expect <9%)
Intrinsic ν_μ , $\bar{\nu}_\mu$ and NC backgrounds	3-4%	CP Violation, δ_θ precision at $\sin(\theta_{13})=0$	IWCD	2.3% (neutrino)
Normalization of non-GE with $E_\nu > 0.7$ GeV	5%	θ_{13} precision at $\sin(\theta_{13}) \neq 0.5$	IWCD	5% (neutrino)
Normalization of non-GE with all energies	5%	δ_θ precision at $\sin(\theta_{13})=0$ Δm^2_{32} precision	IWCD, ND280*	5% (IWCD neutrino) <4% (ND280 neutrino) <7% (ND280 antineutrino)

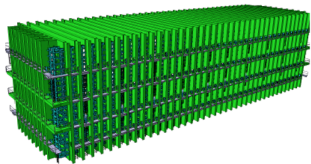
Systematic Source	Required Precision	For Which Measurement	Detector	Achievable Precision
Beam Direction	0.6 mrad (4 MeV shift)	δ_θ precision at $\sin(\theta_{13})=0$ Δm^2_{32} precision	INGRID	<0.3 mrad (<2 MeV)
Removal (binding) energy	4 MeV*	δ_θ precision at $\sin(\theta_{13})=0$ Δm^2_{32} precision	IWCD, ND280	2.6 MeV (IWCD on O) -1 MeV (ND280 on C)**
High angle measurement ($\cos\theta < 0.2$)	4%	CP Violation, δ_θ precision at $\sin(\theta_{13})=0$	IWCD, ND280	<4% statistical precision in both detectors
Beam rate monitoring	~1% per day	General monitoring of beam quality	INGRID	<0.5% per day for neutrinos and antineutrinos
Neutron Multiplicity	TBD	Atmospheric neutrino Nucleon decay	IWCD, ND280	<5% IWCD <4% ND280
μn^0 cross section & neutron multiplicity	TBD	en^0 proton decay	IWCD	TBD

Second tank in Korea



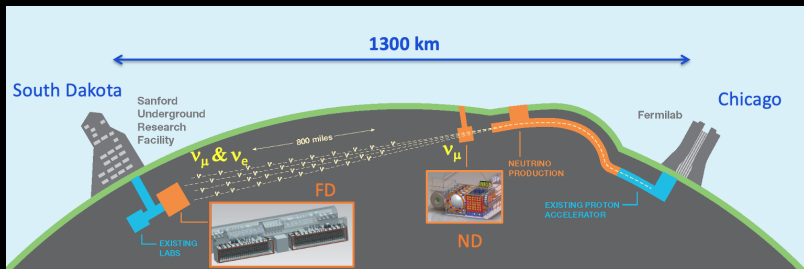
- ▶ 1100 km
- ▶ 2nd oscillation maximum
- ▶ higher precision on δ_{CP}

HyperK and DUNE

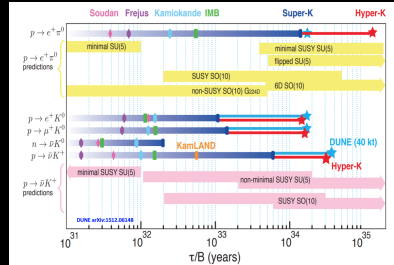
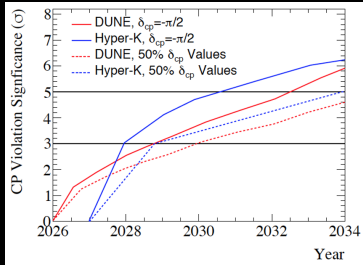


20→40kton liquid Ar

- ▶ HK: 188 kton water, 1.3 MW beam
- ▶ DUNE: 20 → 40 kton liquid Ar, 1.2 → 2.4 MW beam



HyperK and DUNE



- ▶ similar sensitivities for δ_{CP}
- ▶ similar sensitivities for proton decay
 - ▶ DUNE has excellent event reconstruction, high efficiency, low backgrounds, golden $p^+ \rightarrow \bar{\nu} + K^+$
 - ▶ HK has larger volume and covers several decay modes, golden $p^+ \rightarrow e^+ + \pi^0$
- ▶ supernovae
 - ▶ DUNE observes $\nu_e \rightarrow$ time and flavour profile of collapse
 - ▶ HK has larger mass (188 kton vs 20/40 kton fiducial mass)

Hyper-Kamiokande collaboration

- Growing collaboration.
- 22 countries, 106 institutes, ~650 members (2025).

Collaboration Meeting Toyama, Japan, July 2025



NUMBER OF COLLABORATORS

