Hyper-Kamiokande status

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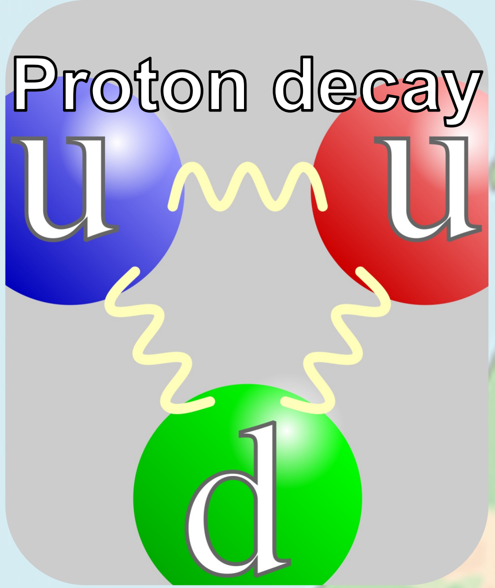
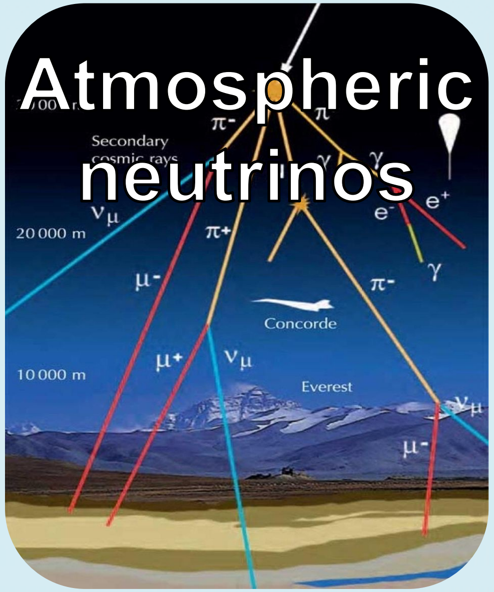
IRN meeting

10.10.2024

- Hyper-Kamiokande is the third-generation of Water Cherenkov experiment in Japan
- Broad physics program
- Inherits successful approaches from T2K and SK
- x8.4 expansion in fiducial volume and x2.6 increase in accelerator power
- Many improvements to keep systematics under control

Hyper-K has an extensive physics program





- GUT probe

- MSW effect
- Hep neutrino search
- Day-night asymmetry

- SN neutrino detection
- Dark matter indirect detection

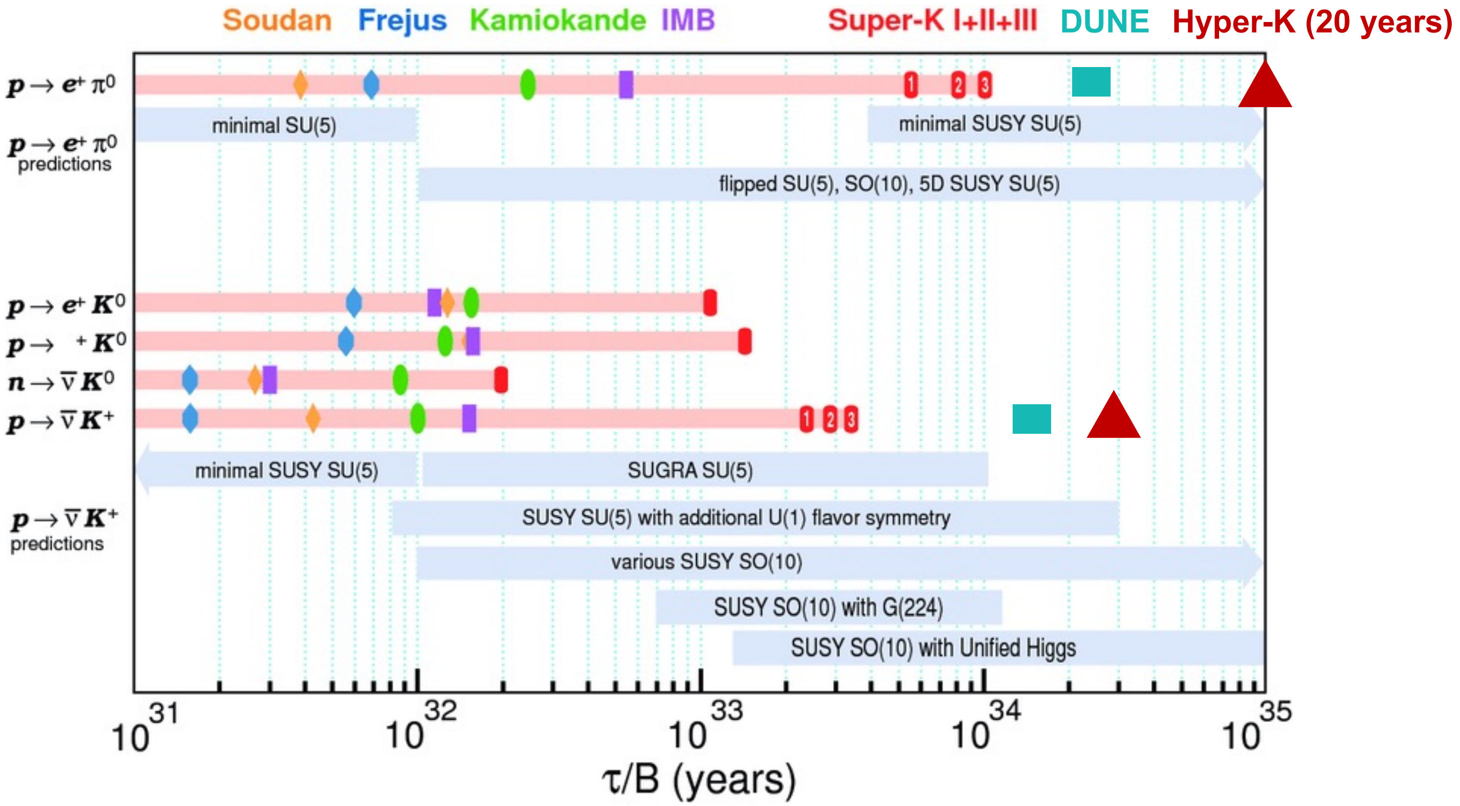
- Precise measurements of neutrino oscillations
  - ➢ Searching for CP-violation → matter-antimatter asymmetry
  - ➢ Neutrino mass ordering

Physics potential:

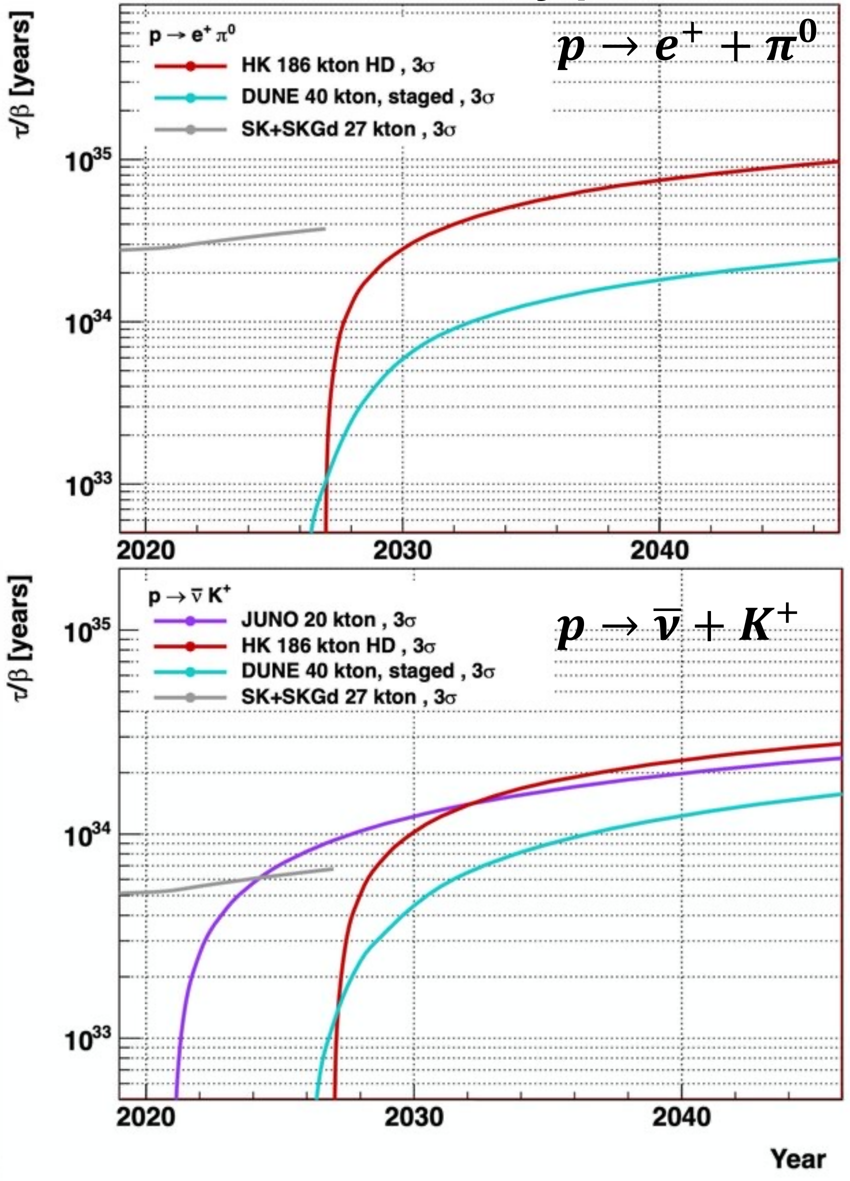
Proton decay search

Proton decay search

- Nucleon decay - direct probe for GUT
- Hyper-K provides world leading sensitivity for proton decay due to large mass and free protons in target material (H_2O)
- 3σ discovery potential - half-life of 10^{35} years for $p \rightarrow e^+ + \pi^0$ and 3×10^{34} years for $p \rightarrow \bar{\nu} + K^+$ after 20 years



3σ discovery potential



Physics potential:

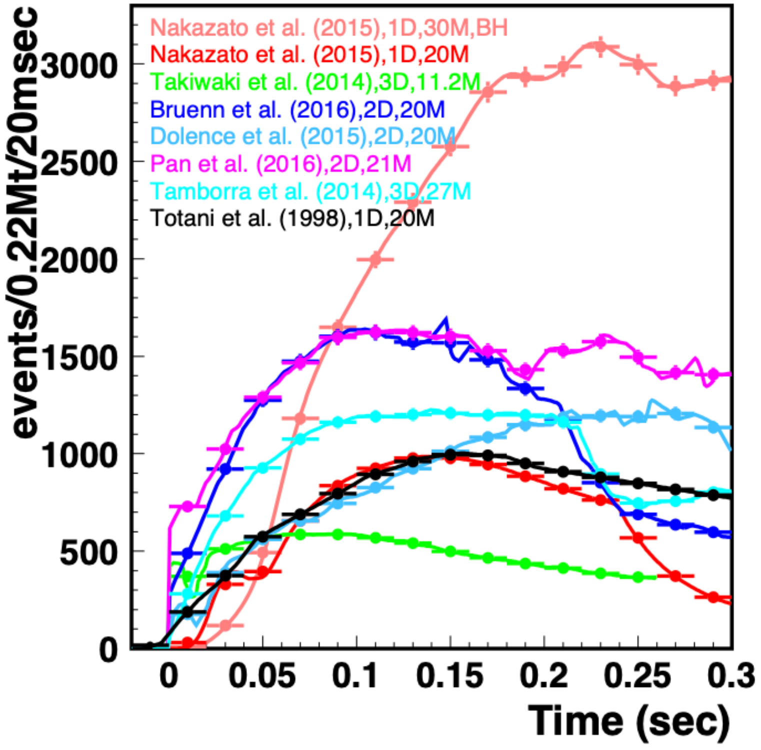
Astrophysics neutrino

Supernovae neutrino

Direct SNν

Tens of thousand events (~from centre of Milky Way)
+ precise timing information

- accurate supernovae models tests
- mass ordering measurement
- absolute mass of neutrinos sensitivity (0.5 to 1.3 eV)



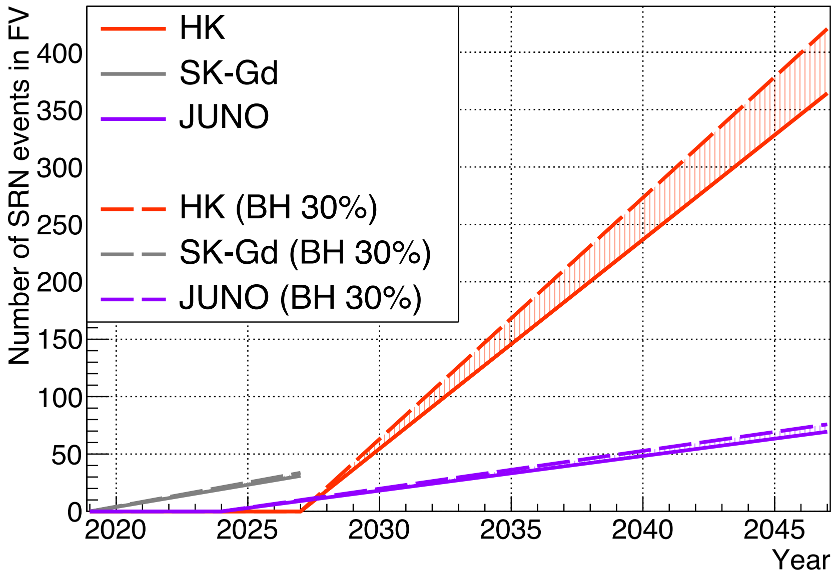
Interaction detection	Integrated number of events	
	NO	IO
$\bar{\nu}_e + p$	57836	74852
$\nu + e^-$	3615	3580

10 kpc supernova using the Livermore model

DSNB

- 4.2 (5.7) σ sign. after 10 (20) years*

Total number without event selection efficiency



* Assumed the flux prediction from model described here arXiv:astro-ph/0202450 and $E_\nu \in [16; 30]$ MeV after spallation bkg reduction

Physics potential:

Beam and atmosph. neutrino

Long-baseline program: Sensitivity

- New extensive LBL sensitivity studies have been updated last year
- All analysis have been performed by **French** PhD students: Claire Dalmazzone (LPNHE) and myself (LLR, IRFU)
- The paper on LBL sensitivity studies is under preparation on behalf of the HK collaboration

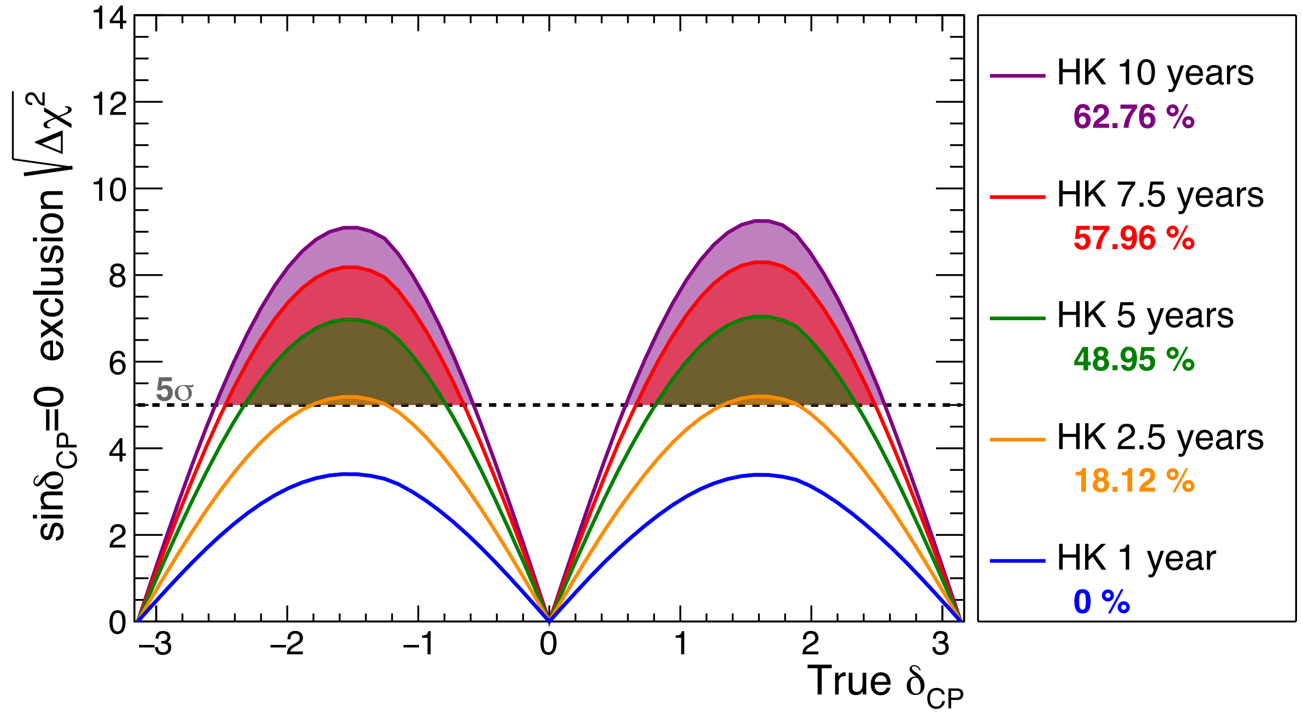
- Based on T2K analysis (Neutrino2020 version):
  - $\mathrm{Hyper-K\ MC\ =\ Super-K\ MC \times Reweights\ (flux, detector, POT)}$
  - Event selections, fitting strategy and statistical treatment adopted from T2K
  - Systematics parametrisation adopted from T2K

- Three systematics models considered:
  - **Statistics only** - no systematics
  - **T2K 2020 syst**. - T2K constraints
  - **Improved syst**. – expected improved constraints from IWCD, upgraded ND280 measurements and high statistics
- MO assumed to be known

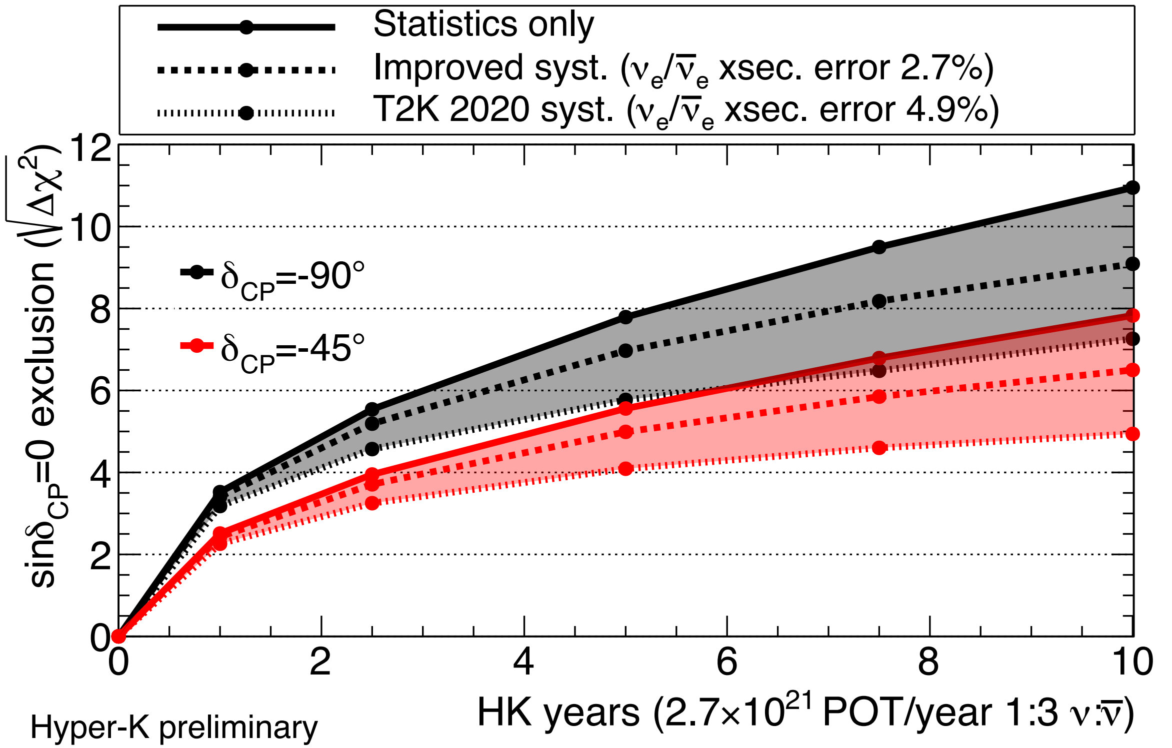
Long-baseline program: CP-violation

Long-baseline experiment provides unique possibility for precise CP-V measurement

- Allows direct CP-V search having well-controlled ν and $\bar{\nu}$ beams
- **5σ** sensitivity to CP-V discovery for **62% of true δ_{CP}** values in 10 years (improved syst.)
- After **2.5 years 5σ CP-V discovery** for maximal CP-V



Hyper-K preliminary
True normal ordering (known), Improved systematics
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$



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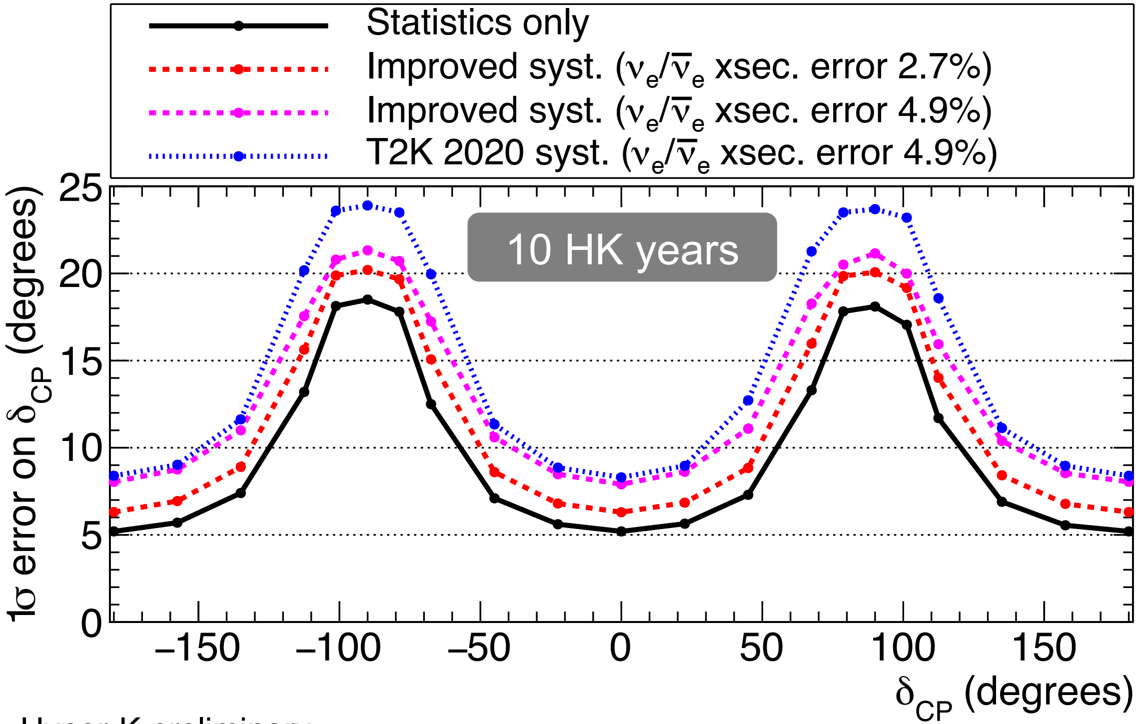
Long-baseline program: δ_{CP} precision

Long-baseline experiment provides unique possibility for precise δ_{CP} measurement

- $\mathbf{5° - 22°}$ for 1σ precision δ_{CP} measurement
- Depends on true value of δ_{CP} and highly on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$
- Small impact from reactor constraint (1:3 $\nu{:}\bar{\nu}$ allows to split the degeneracy with $\sin^2\theta_{13}$)



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 $\nu{:}\bar{\nu}$)

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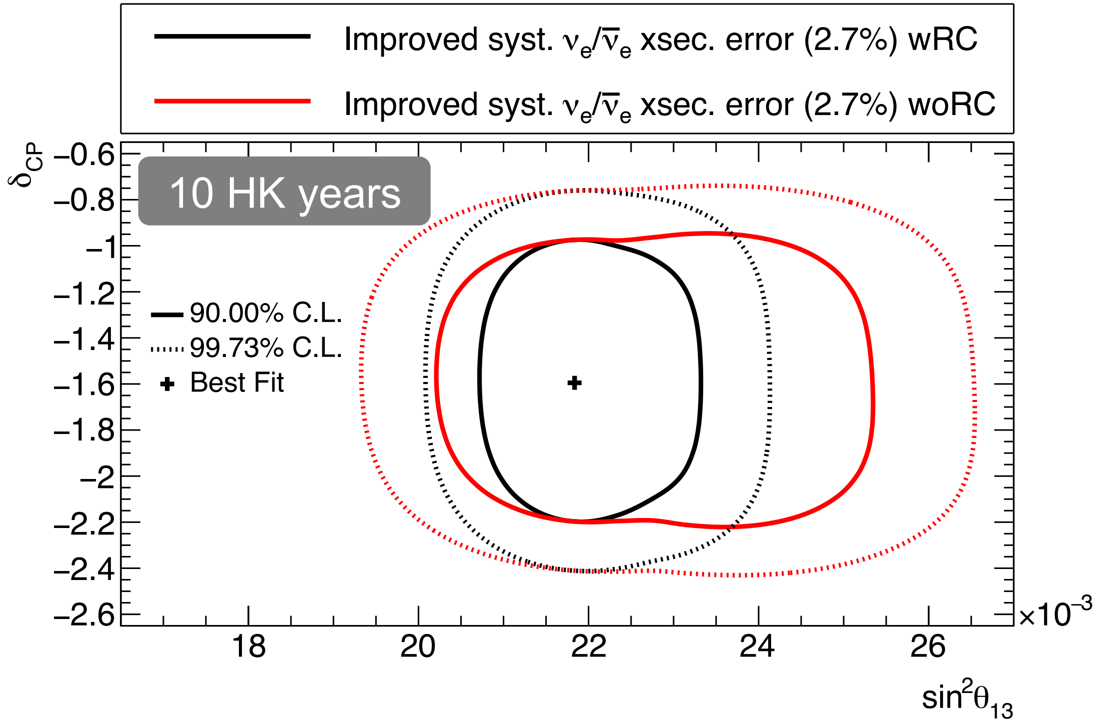

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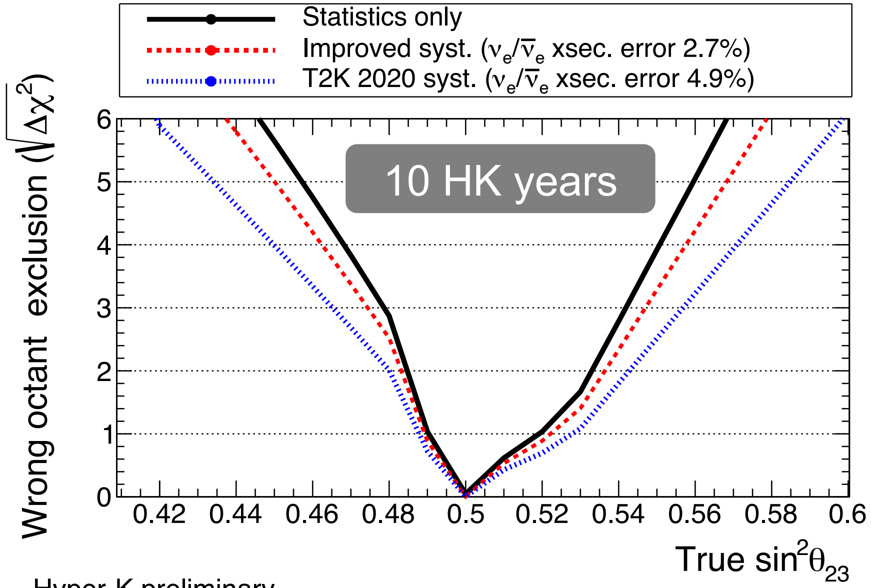
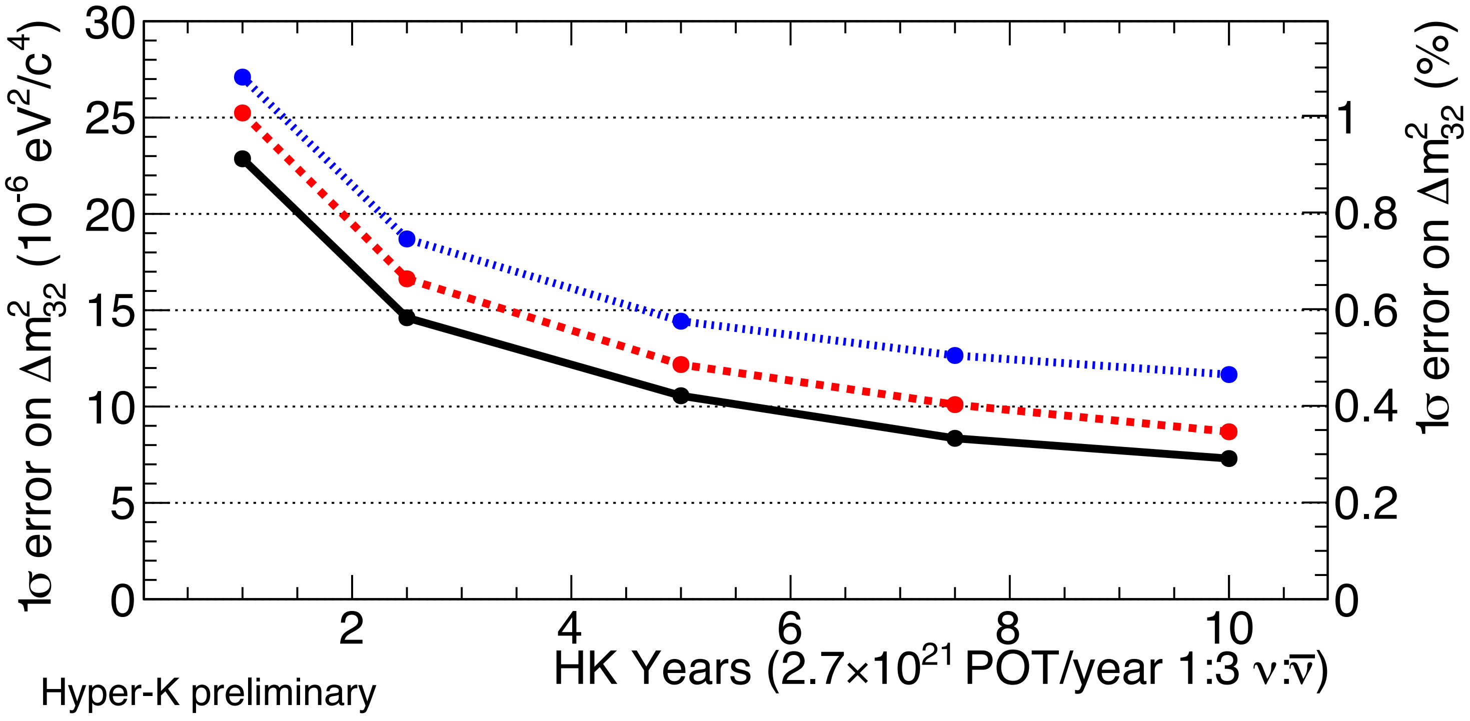
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$, $\delta_{CP}=-1.601$

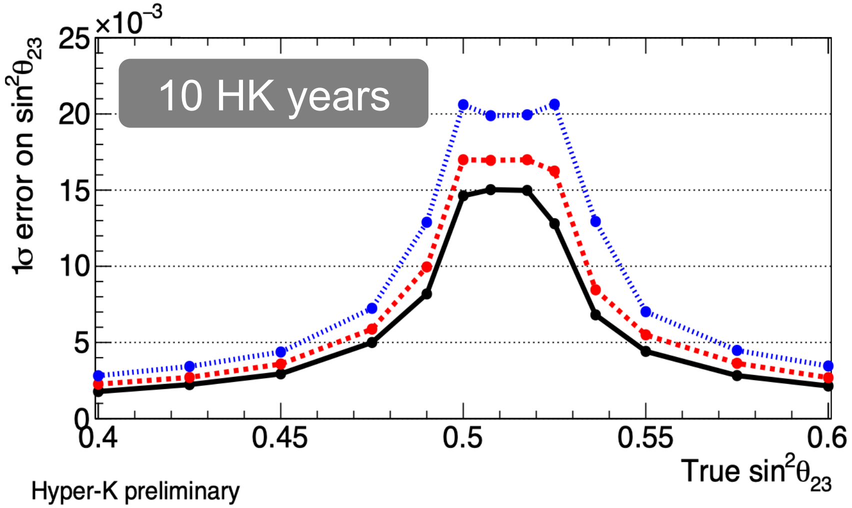
Long-baseline program: atm. parameters

Long-baseline experiment provides precise measurements on atmospheric parameters

- 5σ wrong octant rejection for $\sin^2\theta_{23} < 0.45$ and $\sin^2\theta_{23} > 0.57$
- $\sim\mathbf{0.5 - 3.5\%}$ res. for $\boldsymbol{\sin^2\theta_{23}}$ (depending on true $\sin^2\theta_{23}$)
- $\sim\mathbf{0.5\%}$ res. for $\boldsymbol{\Delta m^2_{32}}$





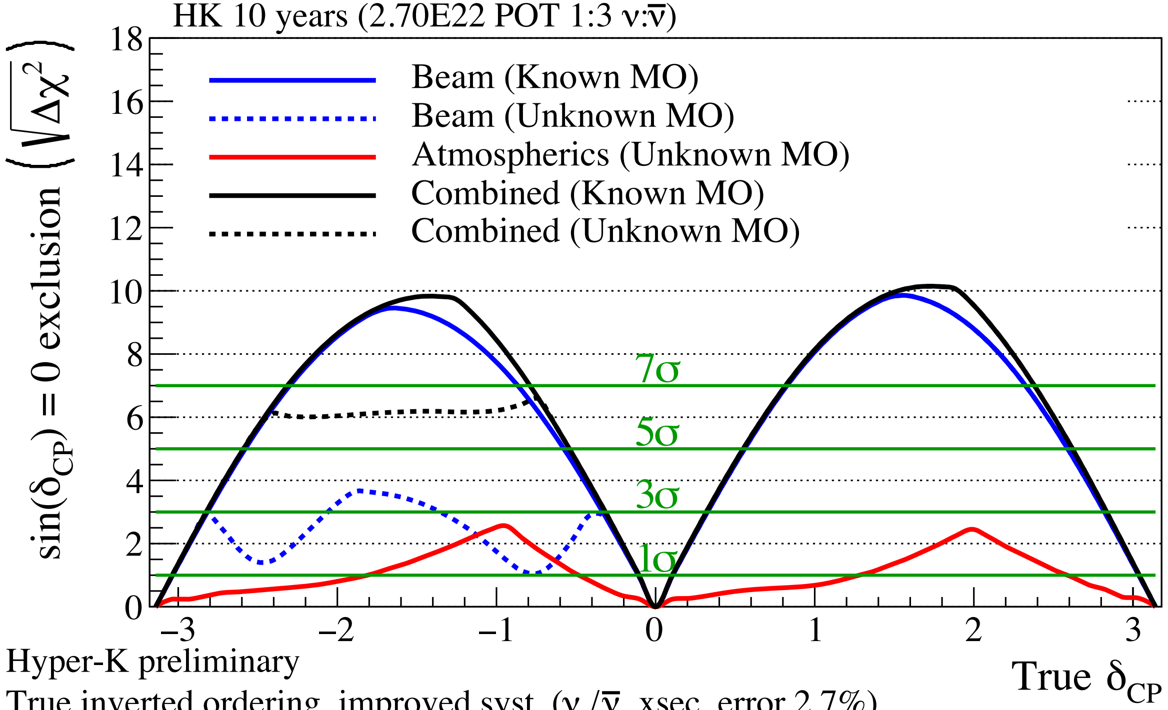


Beam + atmospherics

- Previous slides assumed known mass ordering
- MO unknown → degeneracies can degrade sensitivity to δ_{CP} and octant (depending on true MO and δ_{CP})

New Beam+Atm analysis is in progress basing on T2K+SK joint fit (arxiv/2405.12488)

Beam + Atm → MO–δ_{CP} degeneracy breaking → Recovery of δ_{CP} sensitivity, boosts octant and MO sensitivity



Hyper-K preliminary
True inverted ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}$ eV^2/c^4

	$\sin^2\theta_{23}$	Atm. only	Atm. + Beam
Mass ordering	0.4	2.2 σ	3.8 σ
	0.6	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

Based on older version of T2K analysis

Experimental setup:

Hyper-Kamiokande detectors

Hyper-Kamiokande detector

- Hyper-Kamiokande is third generation of Water Cherenkov detector in Japan
- To meet the physics goals mentioned above numerous improvements are incorporated:
  - **Increased Detector Volume**: 188.4 kton FV (x8.4 of SK FV)
  - **Improved photo detector system (20k 50 cm PMT, ~1k mPMT)**
  - **Improved electronics and readout system**
  - **New calibration methods**

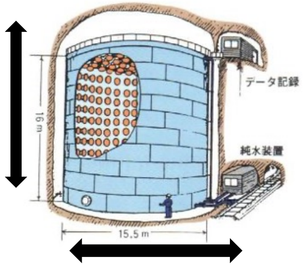
Hyper-K PMT
Hamamatsu R12860

- Box-and-line dynode
- $\mathrm{QE} = 35 - 40\%$
  - x2 photo-detection eff.
  - x2 timing resolution
  - x2 charge resolution

wrt to SK

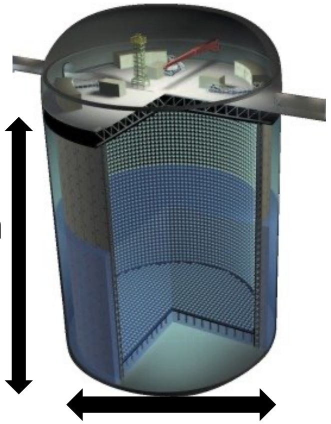
Details in backup

16 m

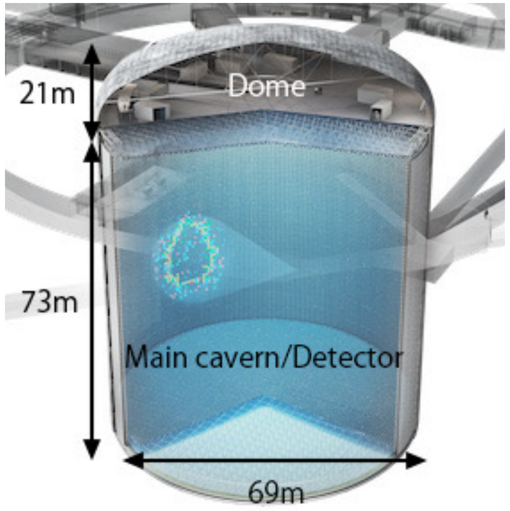


15.5 m
Kamiokande
1 kton

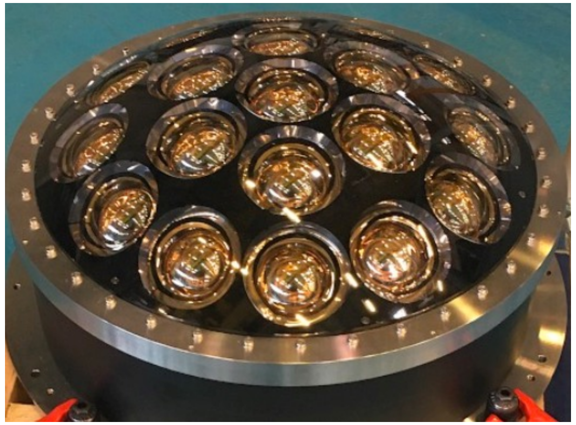
42 m

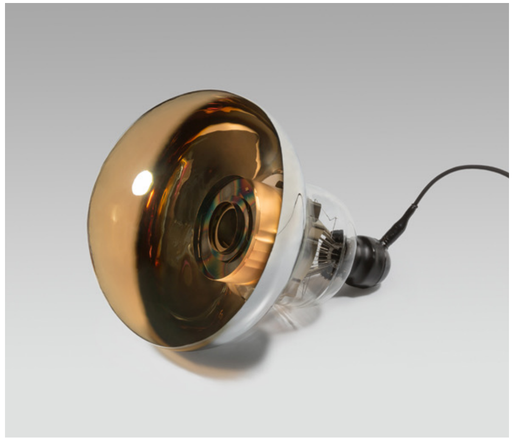


39 m
Super-Kamiokande
50 kton



Hyper-Kamiokande
260 kton

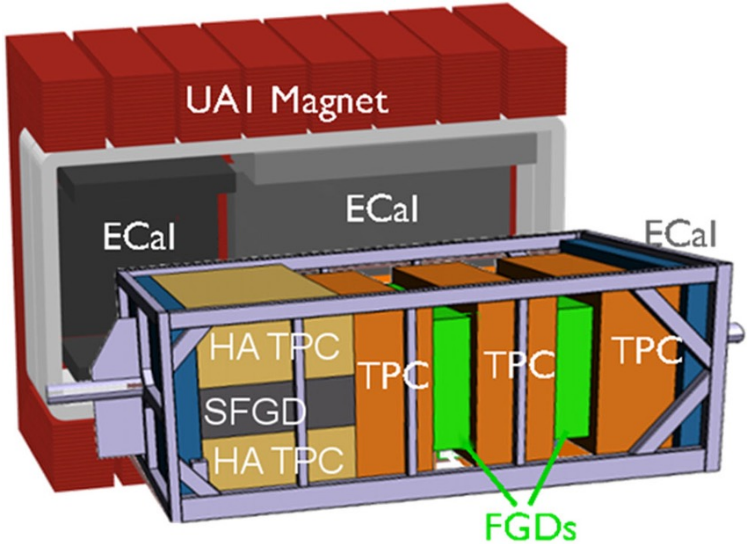


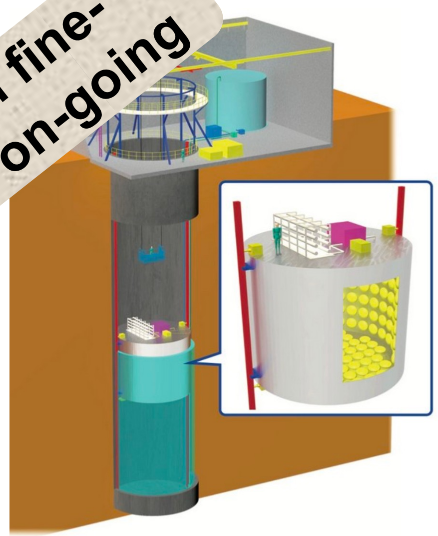


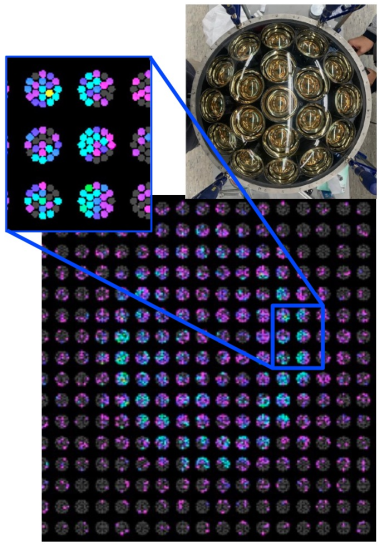
Near Detector complex

ND280 IWCD

Design fine-tuning on-going







- Off-axis near detector ($2.5°$)
- **Constrains flux** and **x-sec** syst. in the oscillation analysis
- **Upgraded in 2024**, with **successful operation** demonstrated in the T2K experiment.

- Additional “near” detector ~850m from target
- 600 ton Water Cherenkov detector instrumented with mPMTs
- Movable detector covering off-axis angles $1.5° - 4°$

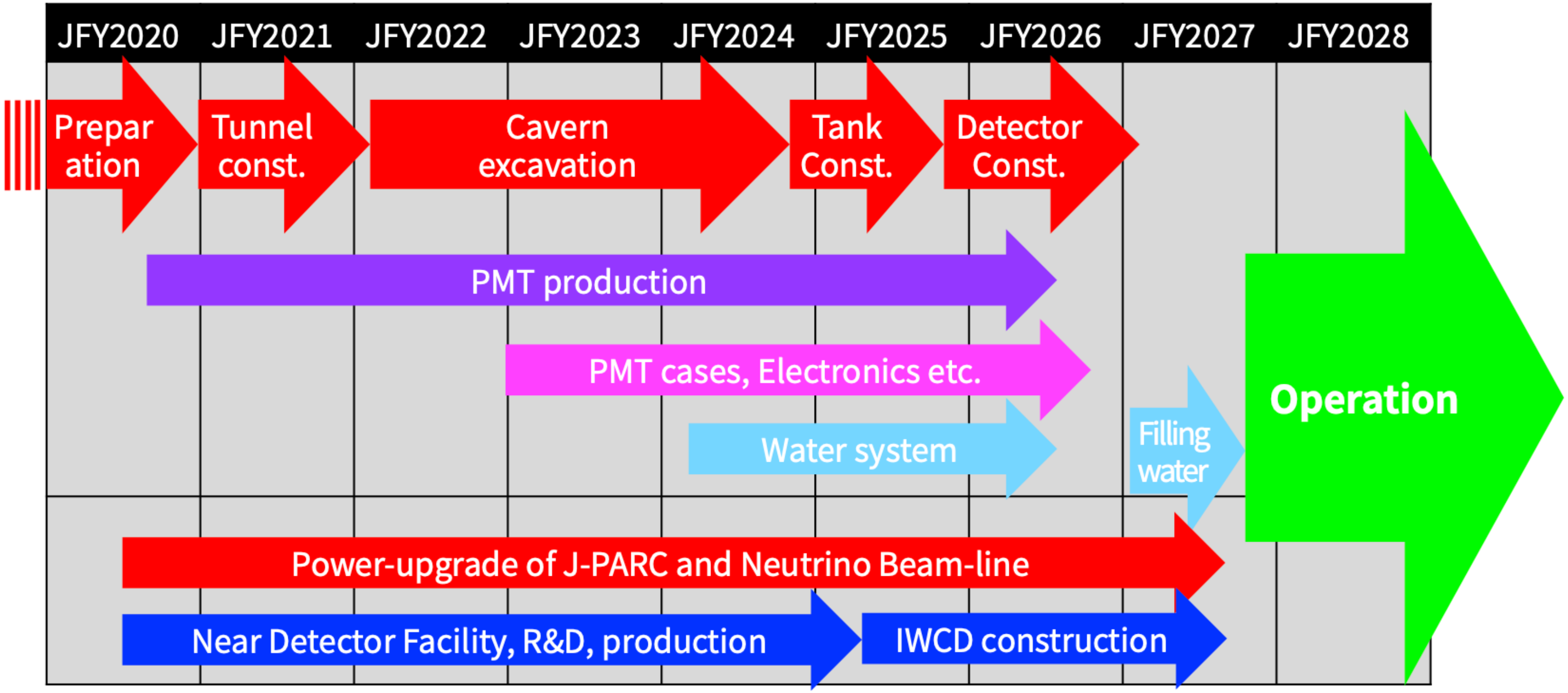
- Same target material and 4π acceptance as FD
- Probe different neutrino energy spectra

Crucial reduction of systematics uncertainties

Current status

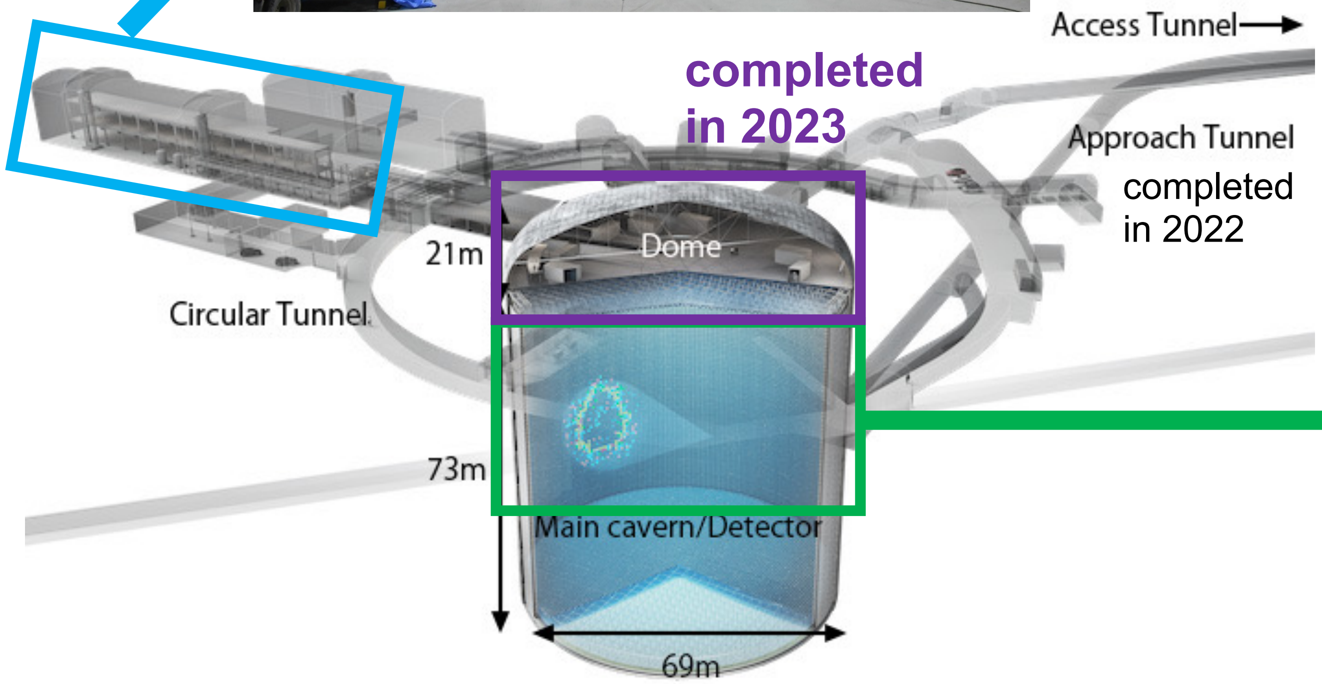
Current status

- Cavern excavation and PMT delivery&tests are ongoing
- Construction phase extended by 6 months, mainly due to changes to the top structure of the detector
- End of detector construction and start water filling May 2027
- **Start of operations Dec. 2027**



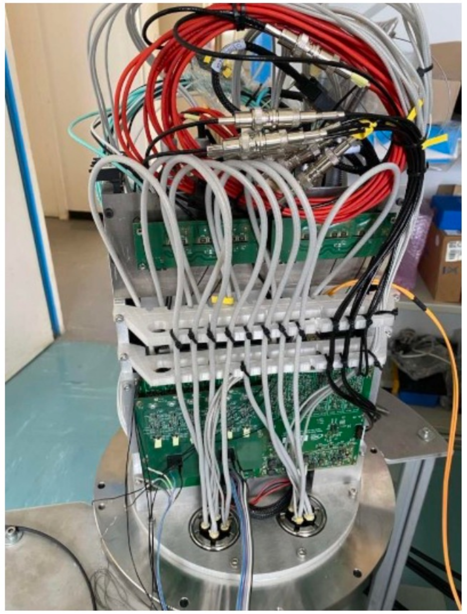
Note: JFY=Japanese Fiscal Year starts on April 1st

Current status: Far detector

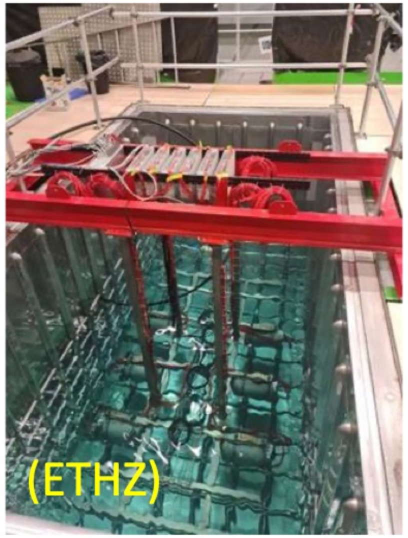


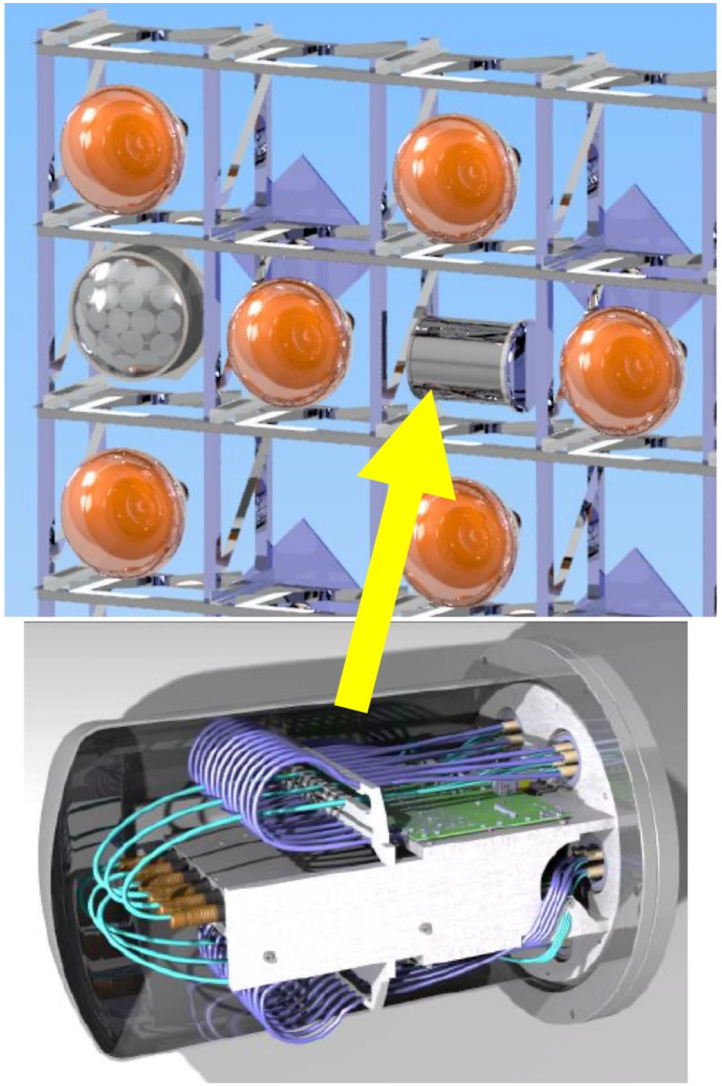
Current status: Electronics

- Electronics will be underwater, in pressure vessels
- The development of individual components is nearly complete (digitiser, LV, HV, timing/synchronisation, calibrator etc)
- Fully assembled module tests in the water are on-going at CERN and Kamioka
- Calibration and assembly of mass produced components from Summer 2025 at CERN



10-unit test @ CERN



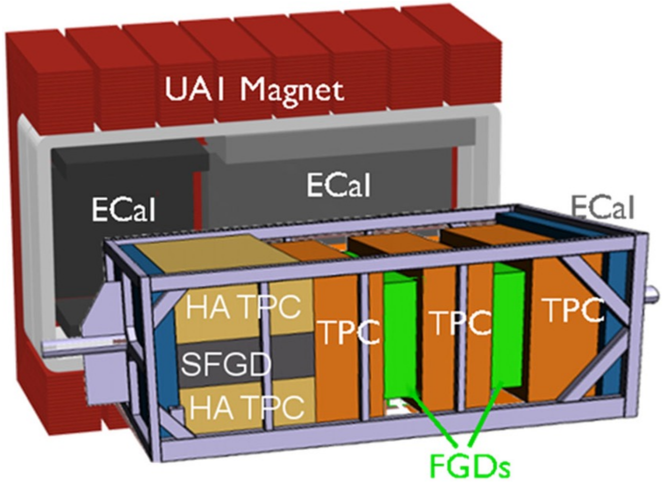


French contribution

French contribution

Hardware

- Contribution and expertise to the T2K Near Detector complex which will become a part of Hyper-Kamiokande experiment
  - ND280 HA-TPC and SFGD maintenance
  - Discussions started for further upgrade ND280++



- Direct contribution to the HK far detector electronics

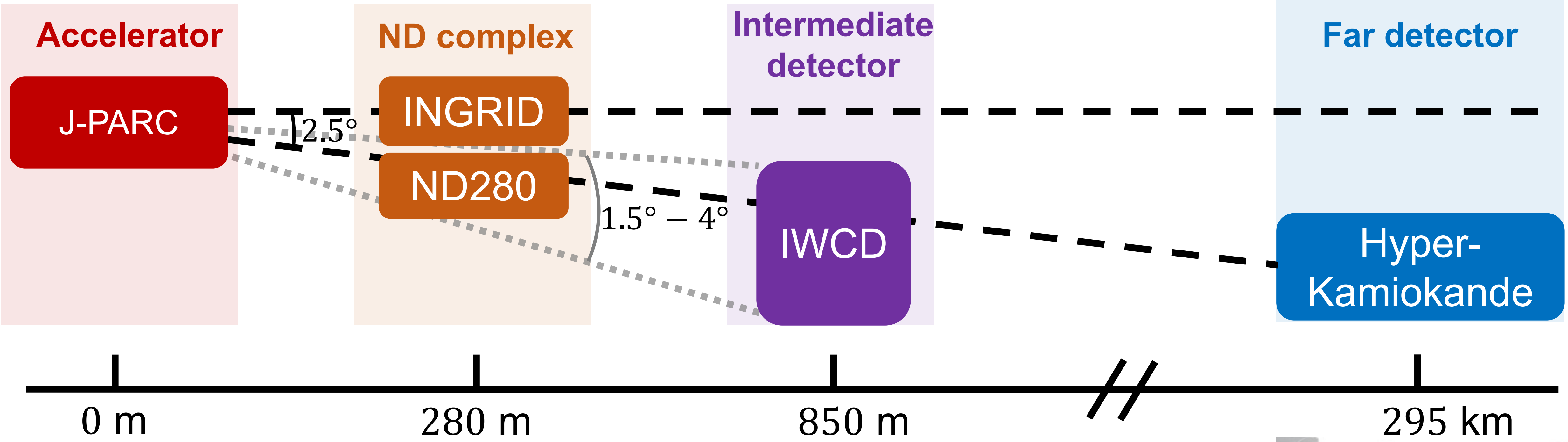
Contribution	Purpose	Current status
The time generation and distribution system	• Time synchronization of all detector components • Global timing reference	• Final prototype is almost completed • The time distribution module mass production should start in early 2025 and finish by end 2025
Electronics testbench	• Perform precise calibration of ~1800 digitisers at CERN • Qualify underwater unit before shipment to Japan	• Tests at French testbench almost finalised • Selection of the waveform generator (critical step) has been completed
Vertical slice tests	• Validation of all subsystems compatibility in electronic chain	• Tests are ongoing at CERN and Kamioka

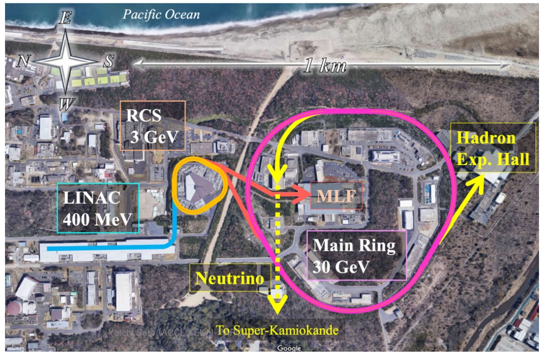
Conclusions

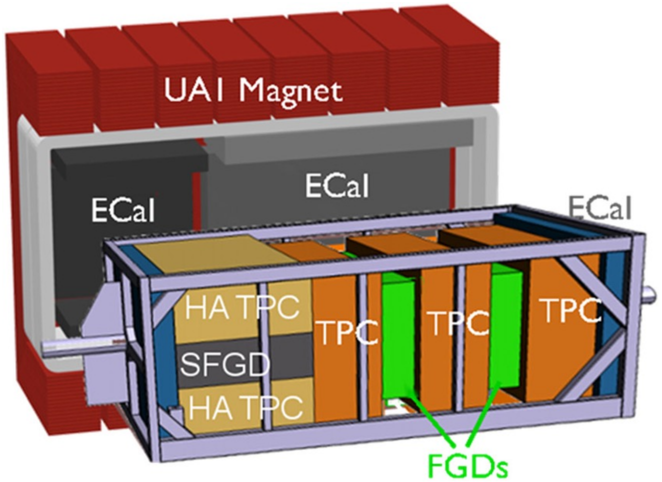
- Large statistics will allow high precisions studies of the oscillation of atmospheric, accelerator and solar neutrinos, as well as searches for new physics (proton decay in particular)
- For δ_{CP} favoured from T2K data, **CP-V discovery** in **less than 3 years**
- Can **exclude CP conservation** at $\boldsymbol{5\sigma}$ in neutrino oscillations for **62% of true** $\boldsymbol{\delta_{CP}}$ values in 10 years of operation
- Detector construction and PMTs delivery&tests on-going, excavation of the far detector cavern will be completed by the end of 2024
- French institutes are actively contributing to various aspects of Hyper-K: hardware for FD, maintance of ND, physics analysis, software development and computing
- Start of operation planned for **December 2027**

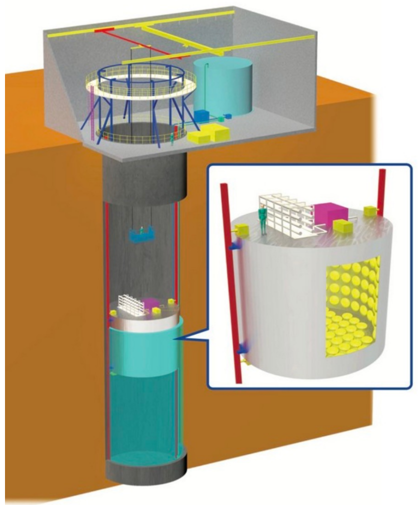
BACKUP

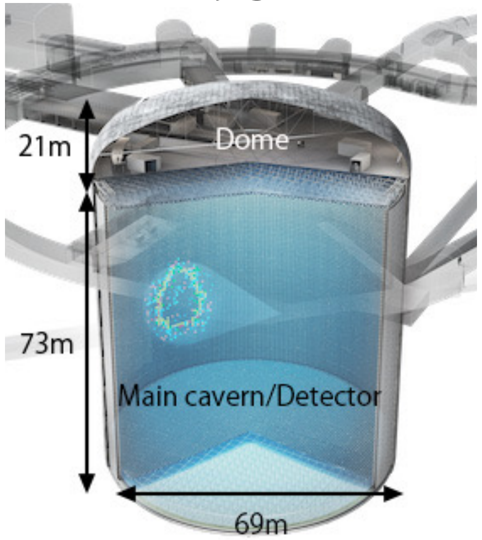
Long-baseline program





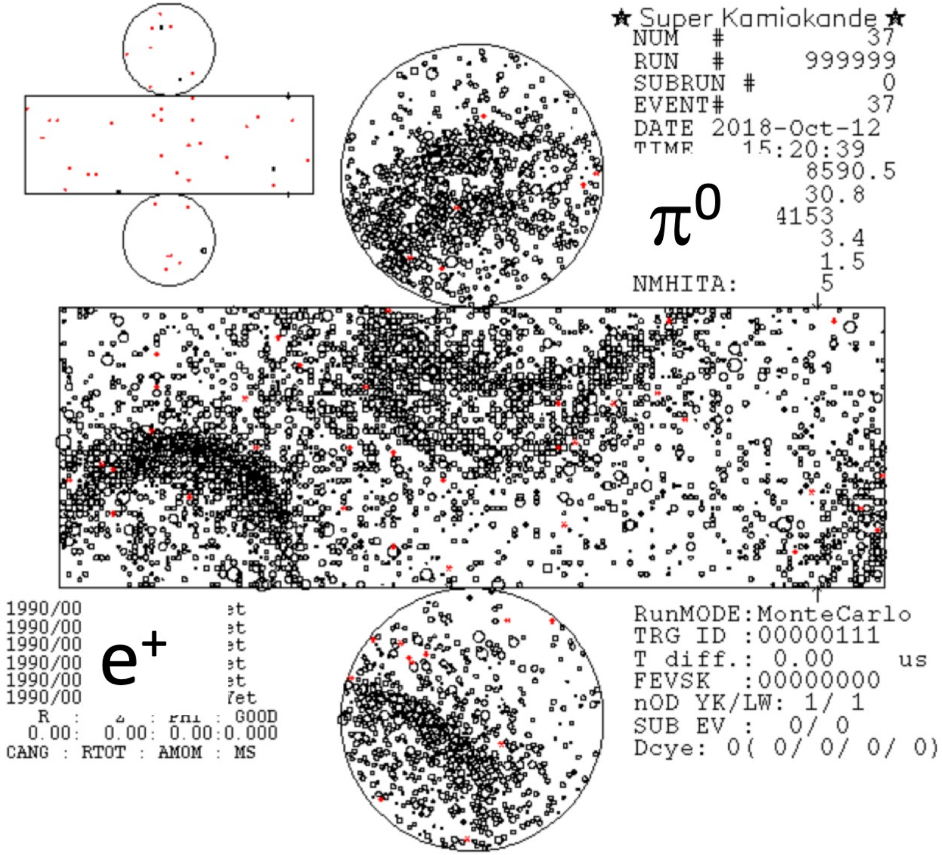






Main channels

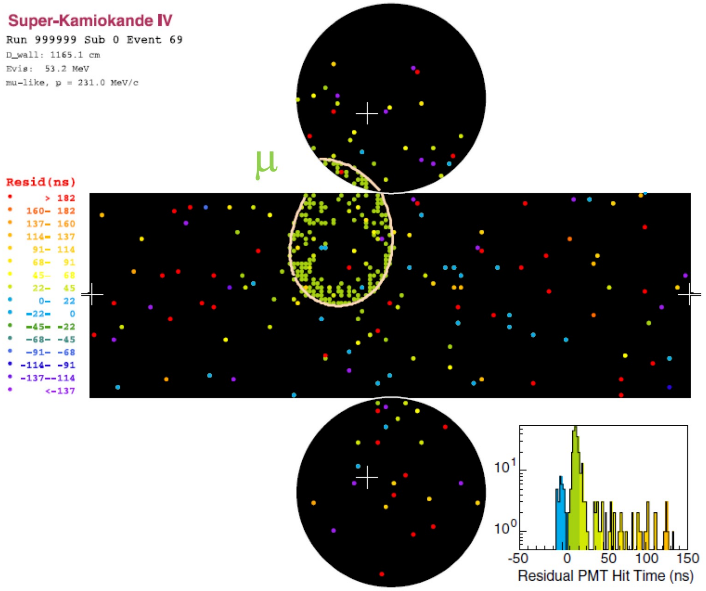
$\underline{p \rightarrow e^{+} + \pi^{0}}$



Search for three e-like rings
Cut based analysis, almost bkg free

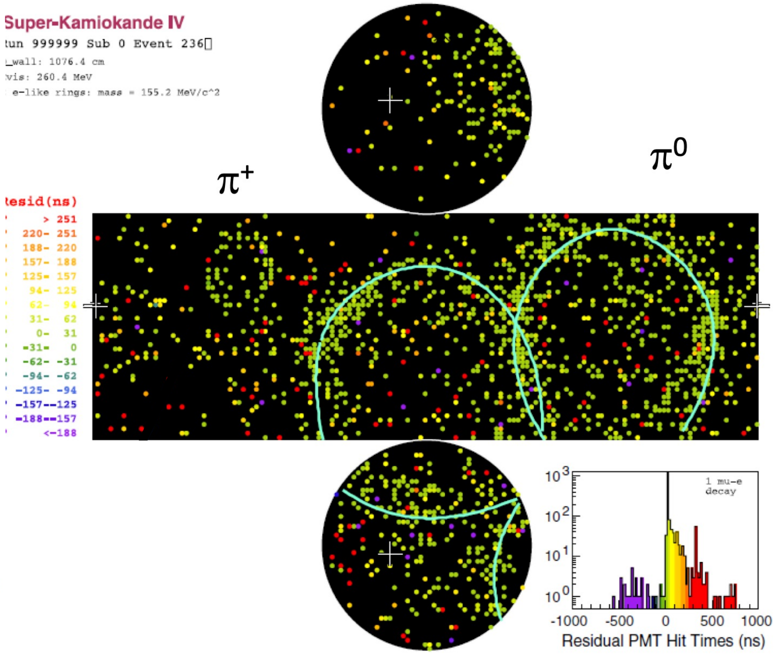
$\underline{p \rightarrow K^{+} + \bar{\nu}}$

$K \rightarrow \mu^{+}\nu_{\mu}$ (64%)



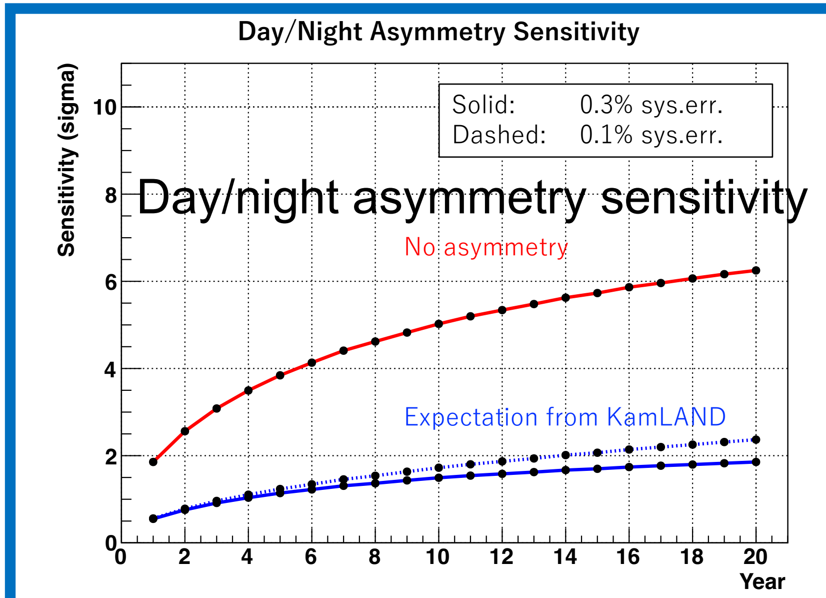
Search for data excess around 236 MeV/c of μ + Michel electron

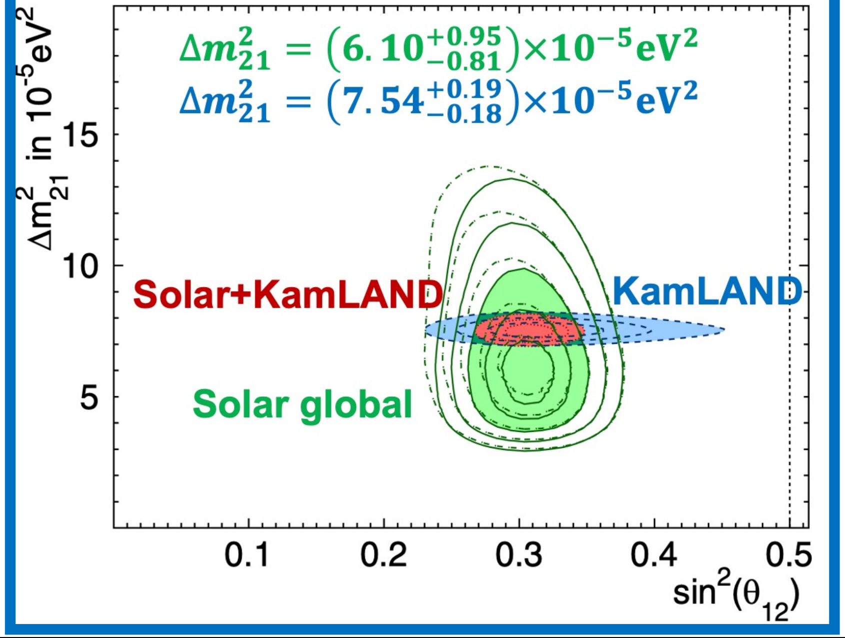
$K \rightarrow \pi^{0}\pi^{+}$ (21%)



Search for 206 MeV/c π^0 + Michel electron

Solar neutrino

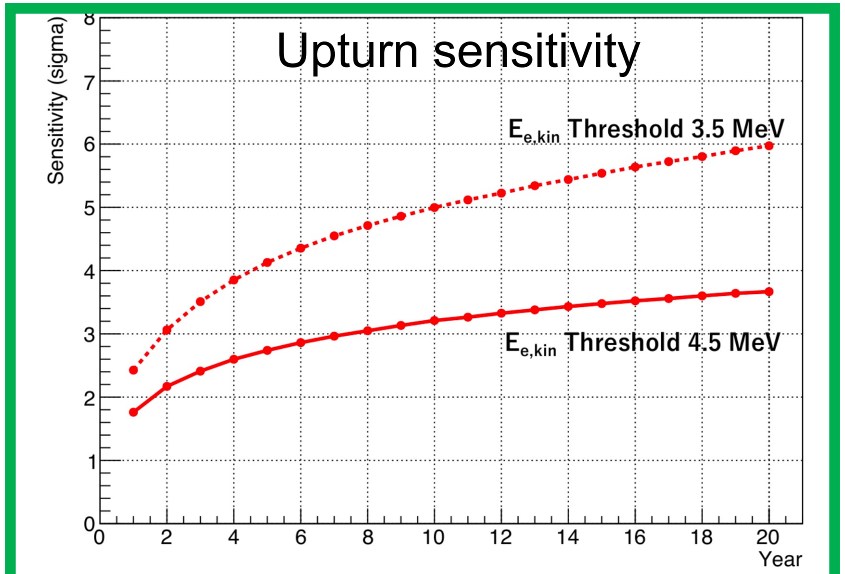


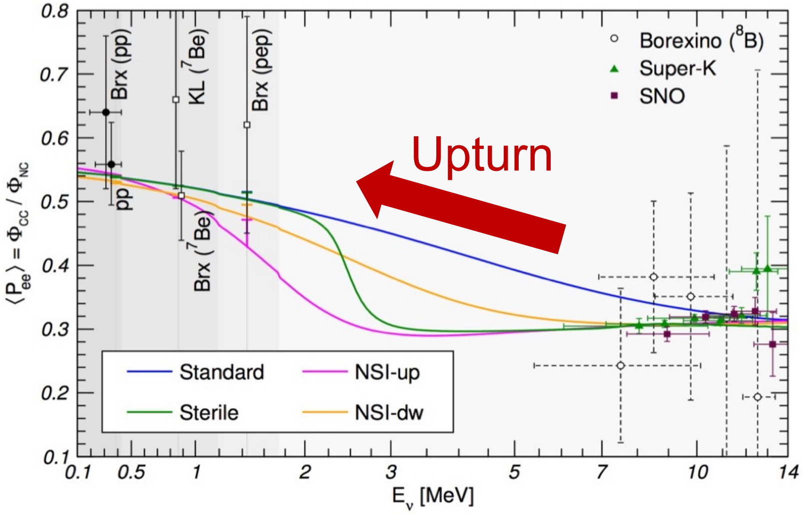


Hyper-K can shed light on remaining questions on solar neutrino oscillations

- 1.5σ tension between KamLAND ($\bar{\nu}_e$) and solar global fit (ν_e) (CPT invariance? BSM physics?)
- 5σ significance of a non-zero day/night asymmetry after 10 years
- 2σ day/night sensitivity expected for the difference in ν_e / $\bar{\nu}_e$ osc. in 20 yrs.

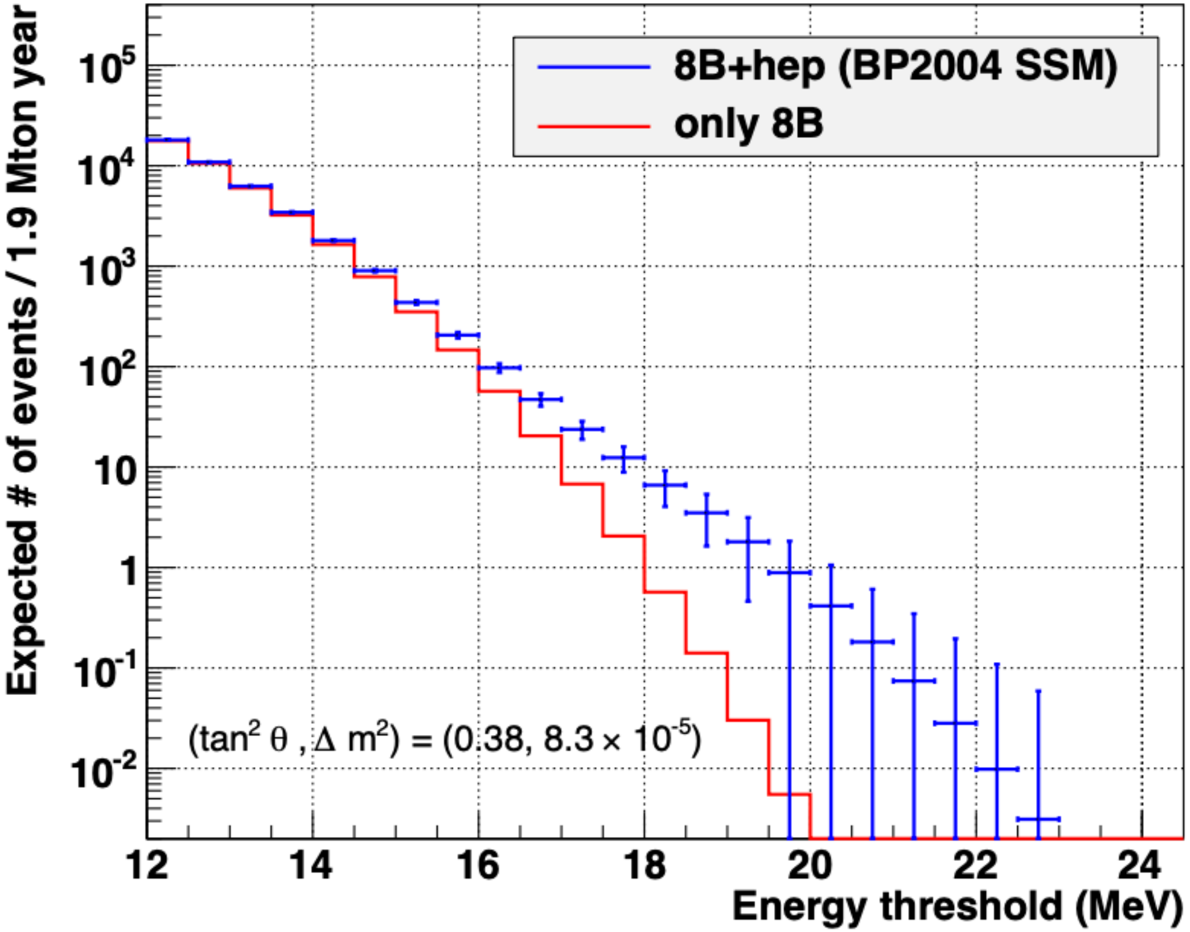
- $> 3\sigma$ sensitivity to upturn [3-7] MeV region after 10 HK yrs. ($E_{th} = 4.5$)
- Sensitive to sterile neutrino, NSI





Solar neutrino

- One of other goals of solar neutrino program is to detect hep neutrinos



Proton decay search

Why **water** is used for proton decay search ?

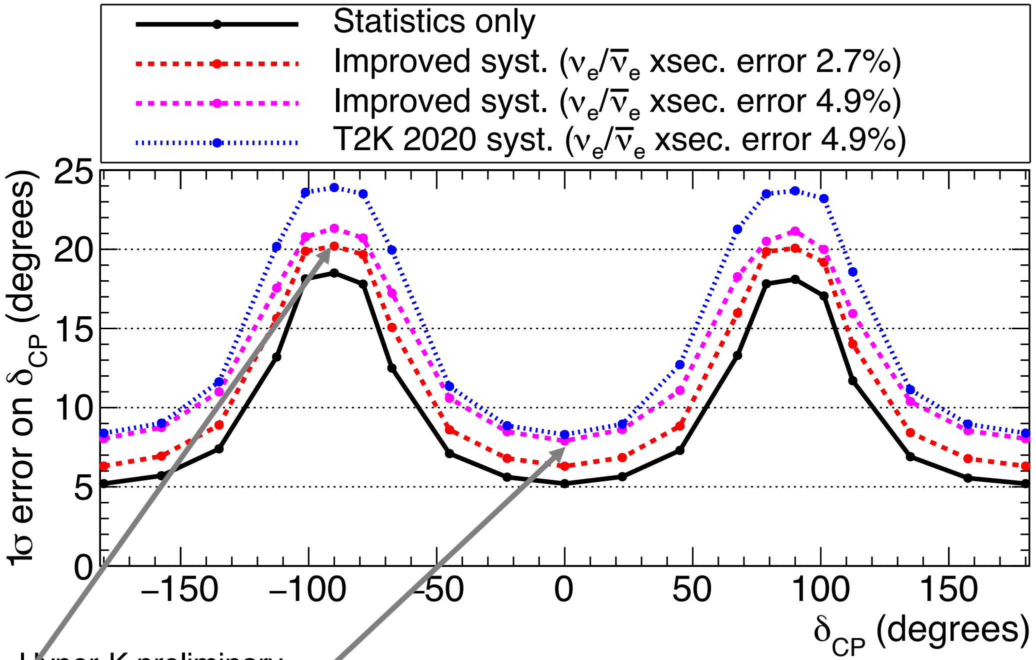
- Easy to construct larger detector.
- ❑ Much cheaper than iron or gas.
- ❑ You can find large water tank everywhere (common technology).

- High efficiency and low uncertainty.

- H_2O has two hydrogens which are not affected by nuclear effect . They are regarded as "free" proton.

- Free protons contribute high selection efficiency and low uncertainty.

Long-baseline program: CP-violation



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CP-asymmetric term

CP-symmetric term
Impacts spectrum shape

$$P = A\sin\delta + B\cos\delta + C$$

$$\frac{\partial P}{\partial \delta} = A\cos\delta - B\sin\delta$$

$\frac{\partial P}{\partial \delta}(\delta\sim 90°)\sim B$ → CP-even term domination → resolution dominated by the measurement of the energy spectra

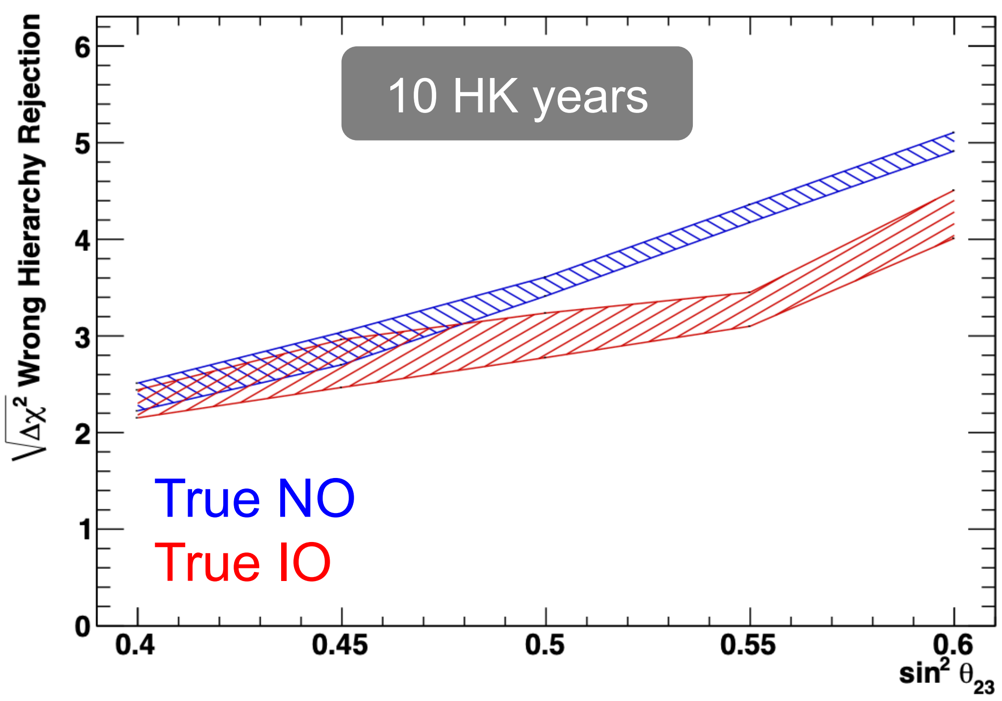
$\frac{\partial P}{\partial \delta}(\delta\sim 0)\sim A$ → CP-odd term domination → resolution dominated by $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ error

Atmospheric neutrino

- $> 3\sigma$ mass hierarchy sensitivity for $\sin^2\theta_{23} > 0.53$
- $> 3\sigma$ $\sin^2\theta_{23}$ octant sensitivity for $\sin^2\theta_{23} < 0.43$ and $\sin^2\theta_{23} > 0.6$

Sensitivity studies based on SK analysis:
- Scaled SK MC
- No improvement of Super-K systematics assumed

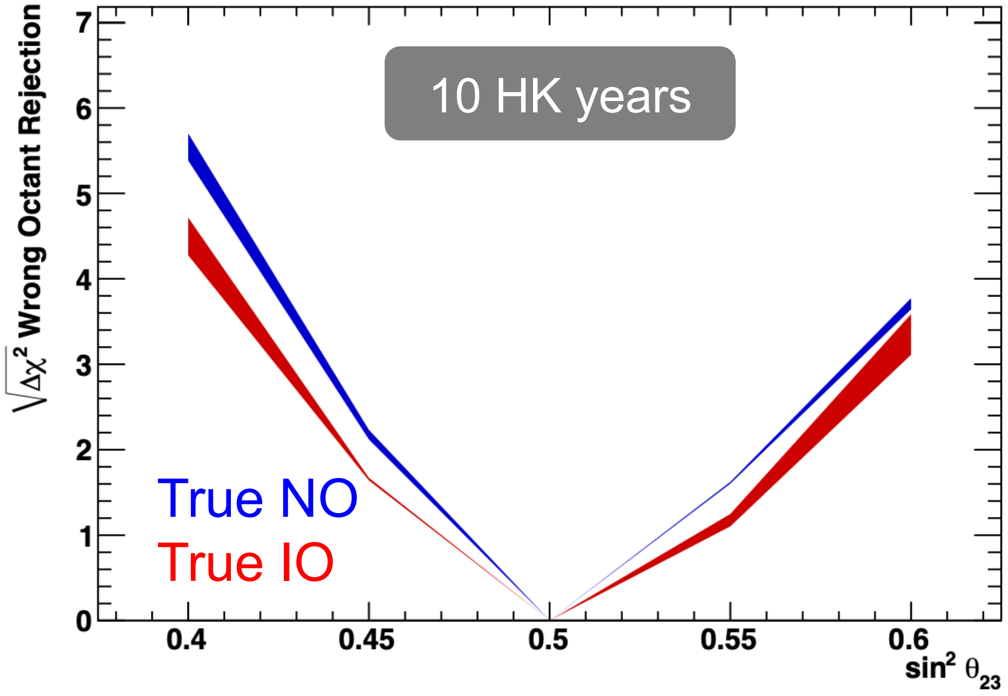
Mass ordering sensitivity



Asymmetry between ν and $\bar{\nu}$

Appearance and disappearance interplay

$\sin^2\theta_{23}$ octant sensitivity



Hyper-Kamiokande detector: photo-detection system

- HK will use **20k 50cm** PMTs to instrument **ID** (20% coverage)
- Improved model compared to SK

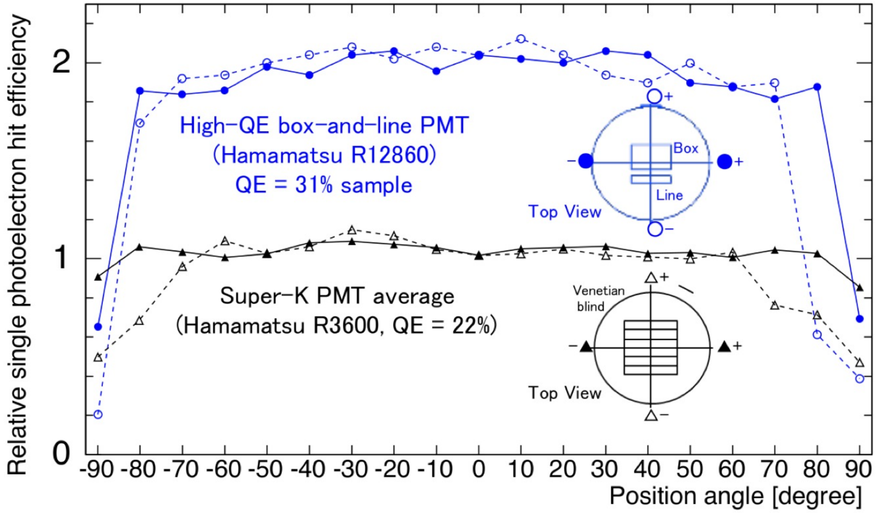
Super-K PMT
Hamamatsu R3600

- Venetian blind
- $QE = 20 - 25\%$

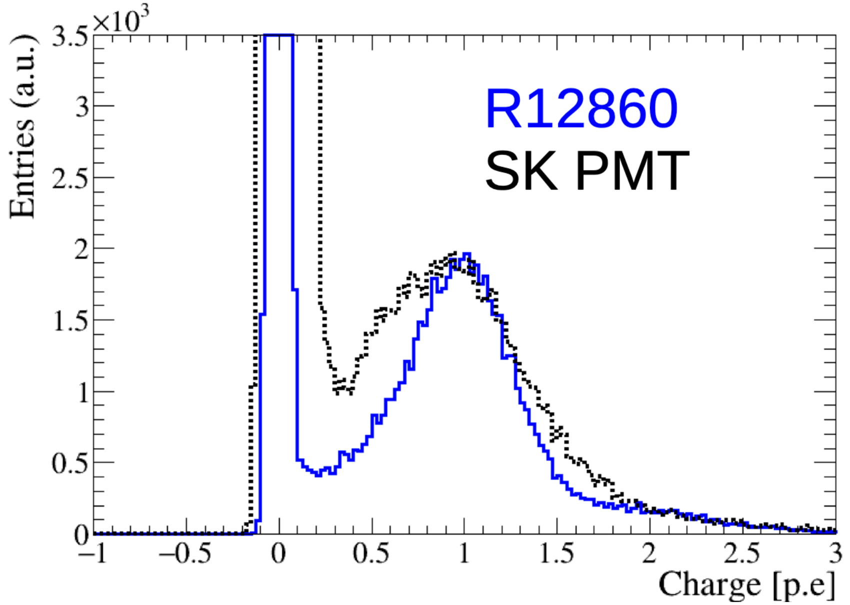
→

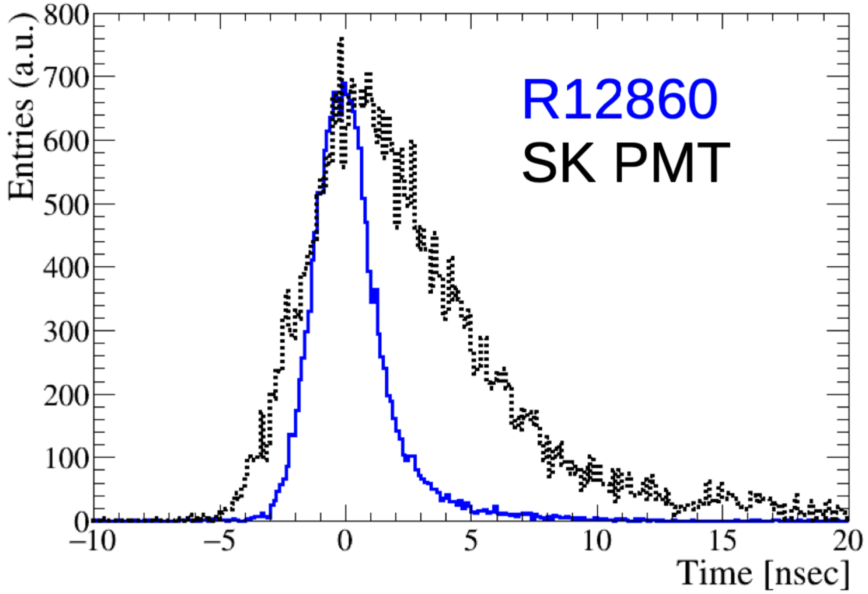
Hyper-K PMT
Hamamatsu R12860

- Box-and-line
  - higher collection efficiency
  - more uniform gain
  - more uniform electron drift path → (better timing and charge res.)
- $QE = 35 - 40\%$



- **~2x** photo-detection efficiency
- TTS: **6.73 ns → 2.59** ns (FWHM)
- **Charge resolution: 60.1% → 30.8%**



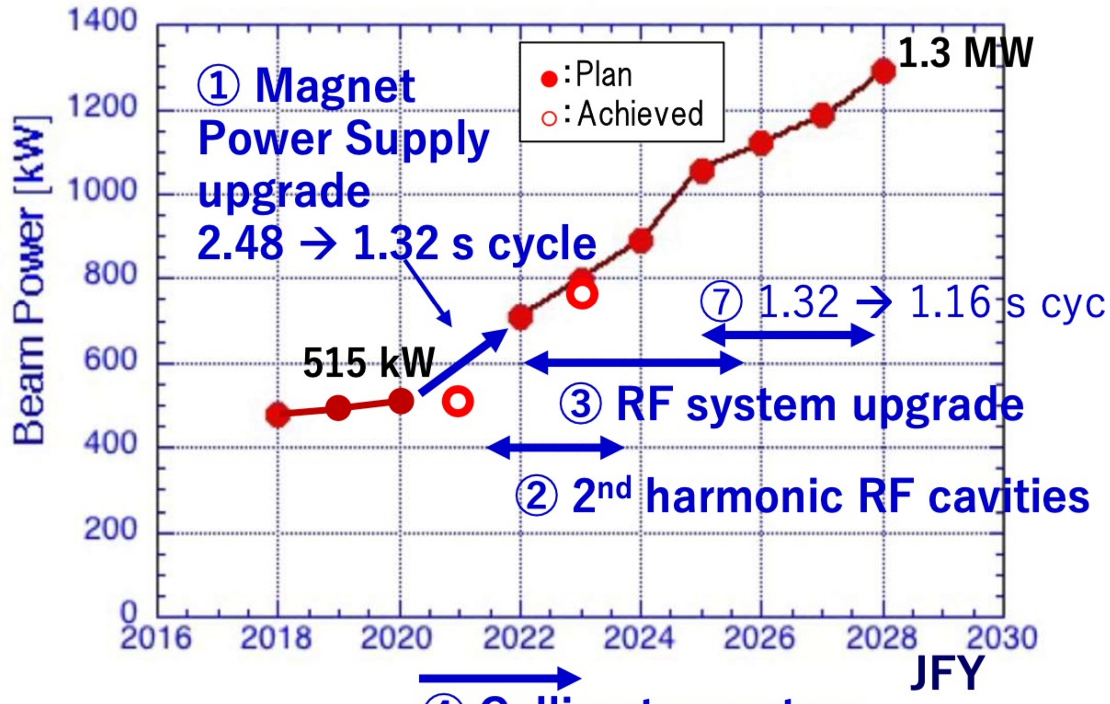


Power Projection in MR Upgrade Plan

Beam Power = Energy (30GeV) × 1/Trep (pulse/s) × # of protons (/pulse)

Original power projection in MR Upgrade Plan

JFY2021	**515 kW**	2.48 s	2.66×10^{14} ppp
*JFY 202**	***> 940 kW***	*<1.36 s*	2.66×10^{14} ppp



④ Collimator system

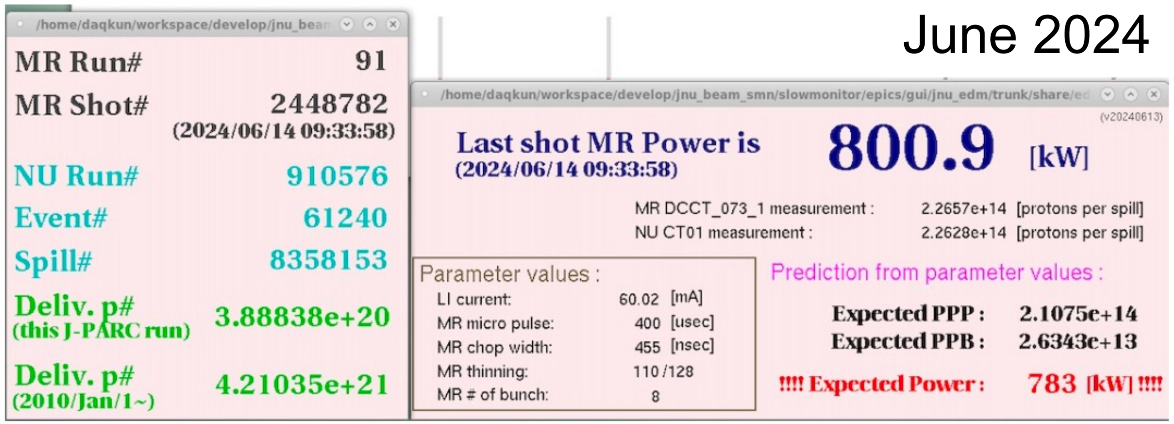
⑤ Injection/FX system

⑥ Beam Monitors (BPM circuits)

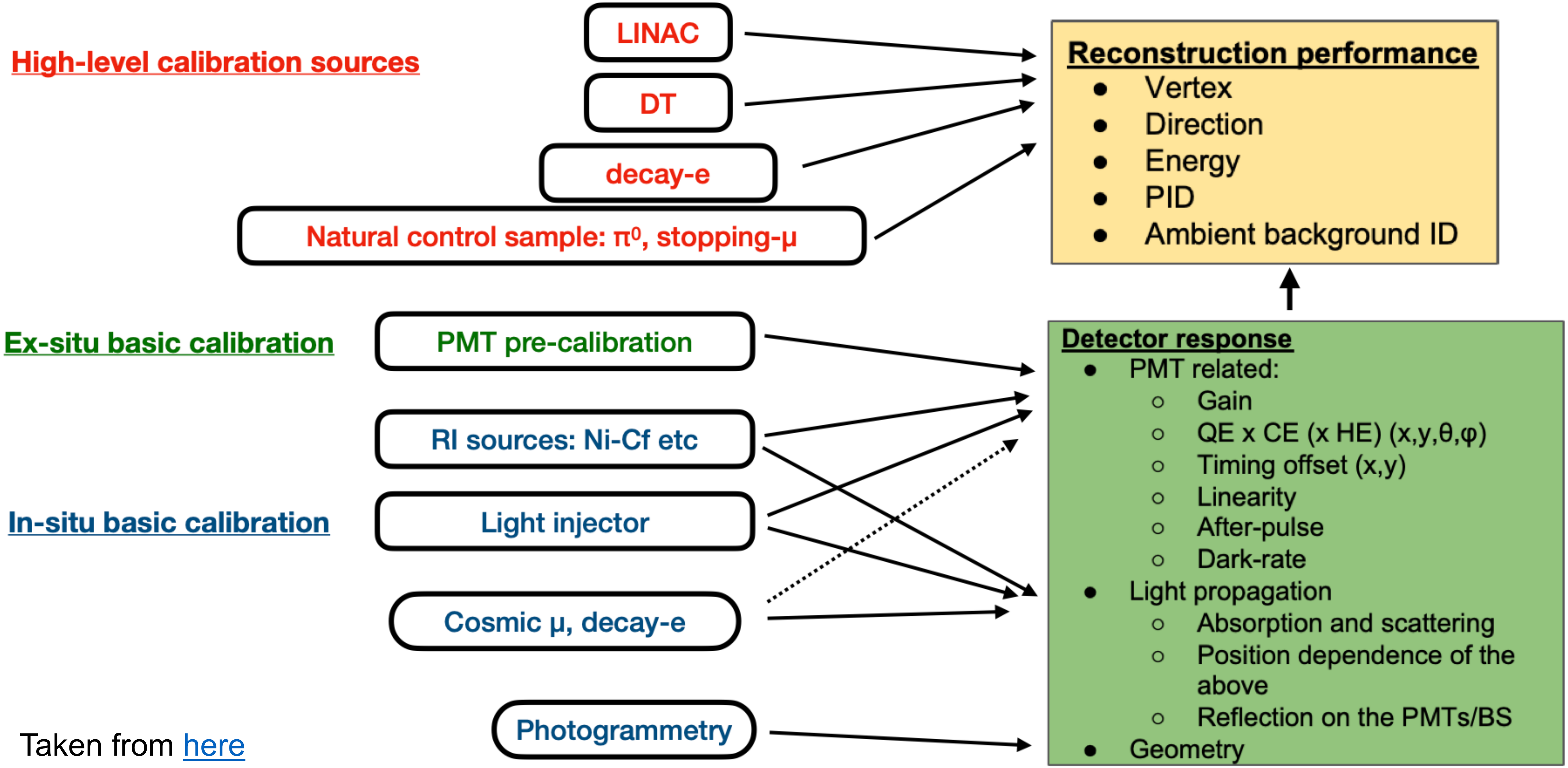
S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

- Consecutive demonstration of 760 kW in Dec. 2023
- 800 kW reached in Summer 2024
- 1.3 MW by JFY2028
  - "1.36 → 1.16 s cycle" & "More protons/pulse"

June 2024



Calibration methods overview

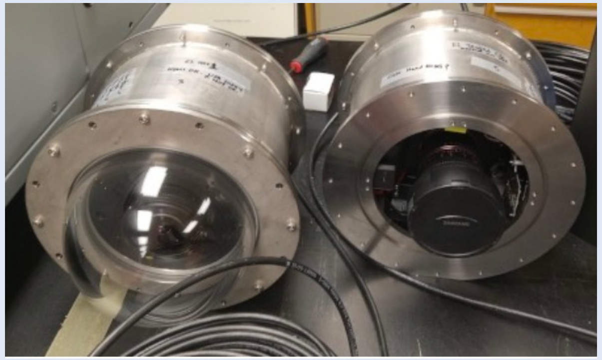


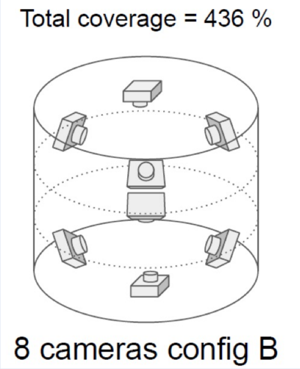
Taken from here

Calibration systems

Photogrammetry

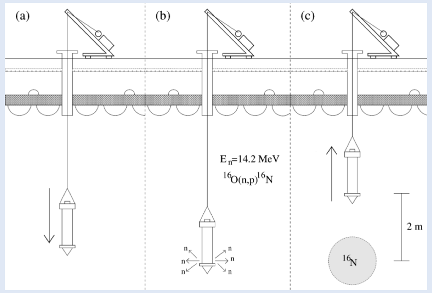
- Cameras for precise PMT position determination
- Illumination from LED system innside mPMT





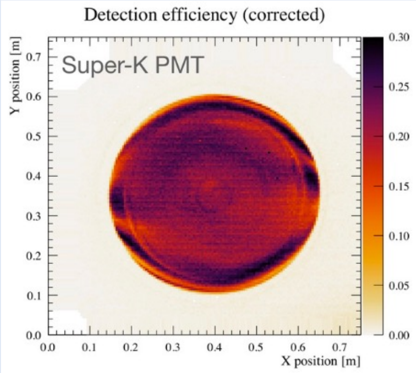
Radioactive sources

- Measure detector response, PMT efficiency
- ^{16}N source ($\beta\gamma$ source with well understood spectrum)
- NiCf source (uniform Cherenkov light)



Precise PMTs pre-calibration

- Make detailed measurement of responses prior to the installation for subset of the PMTs

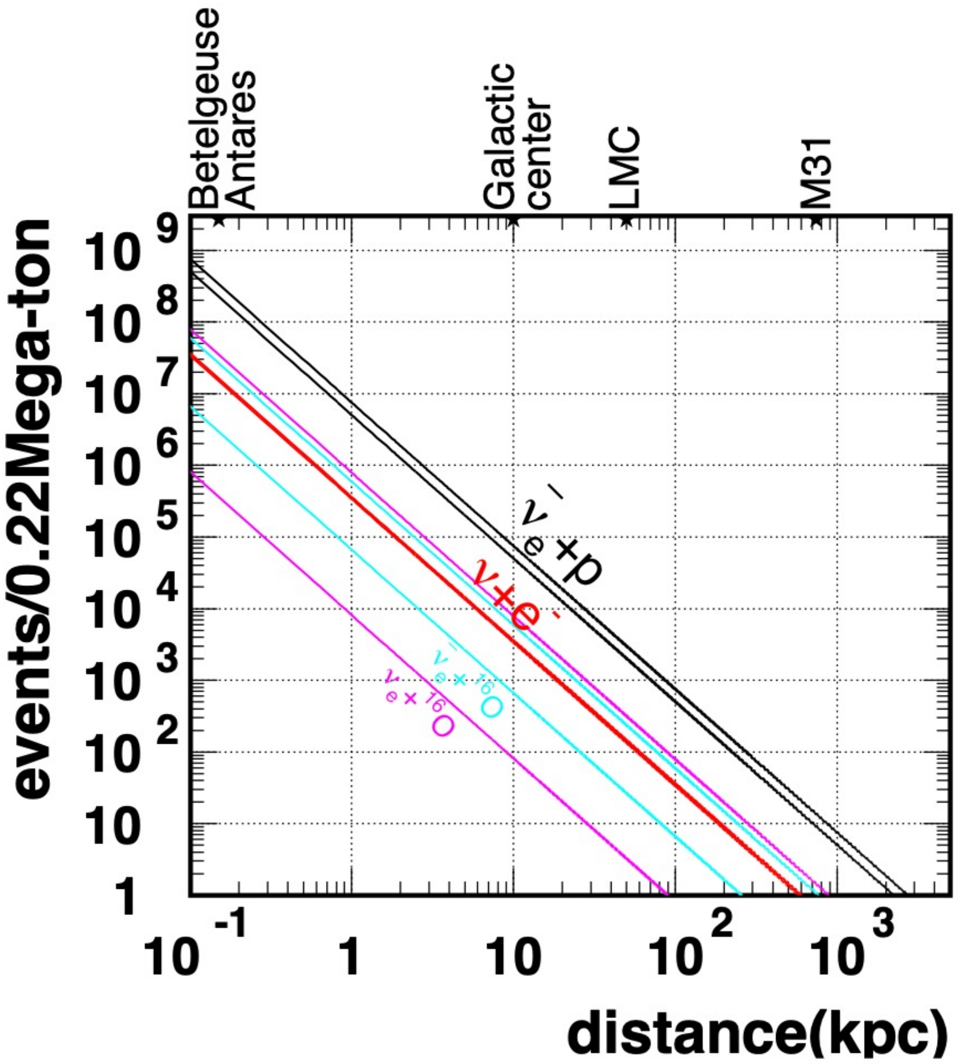


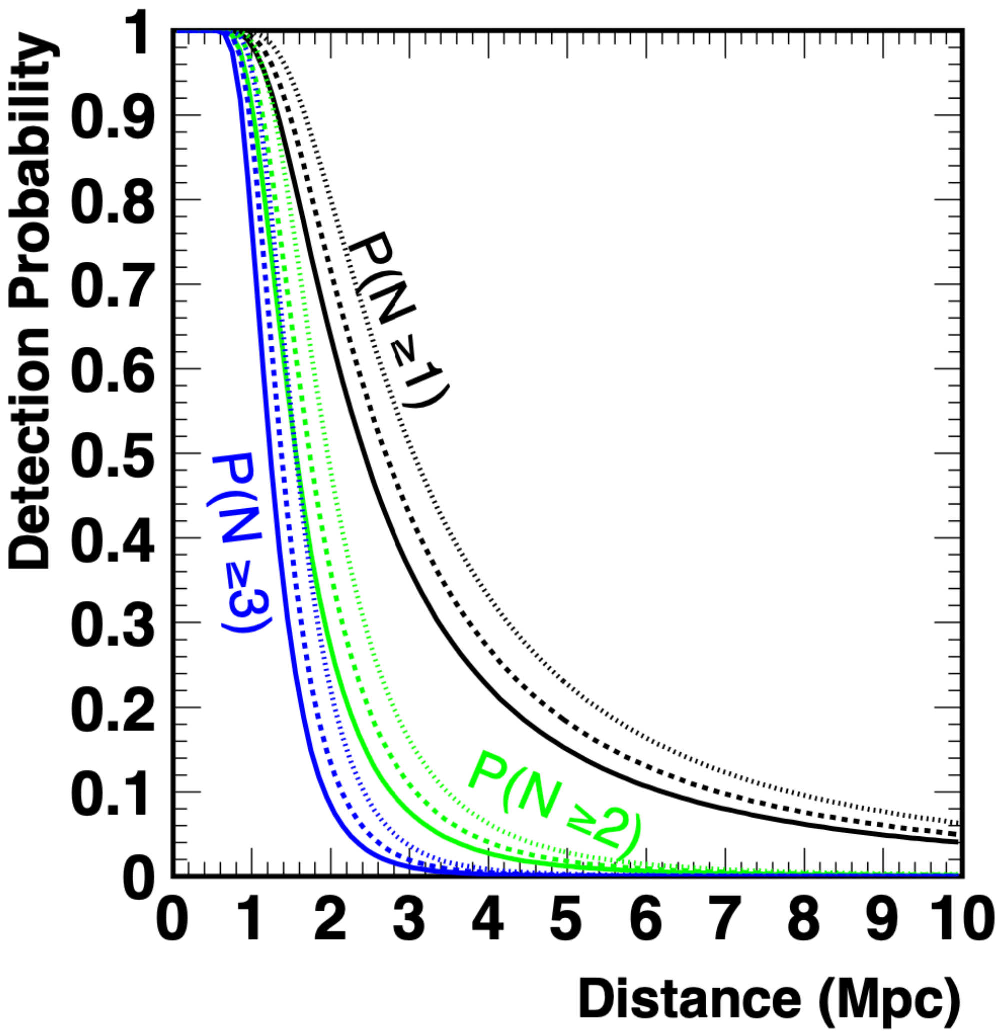
mPMTs

- Cross-calibration
  - ➢ Disentangle PMT angular response and light traveling direction (granularity)
  - ➢ Better separation of indirect photons (precise timing)

- LED source in 200 mPMT
  - ➢ 300 nm for Raman scattering

Supernovae neutrino





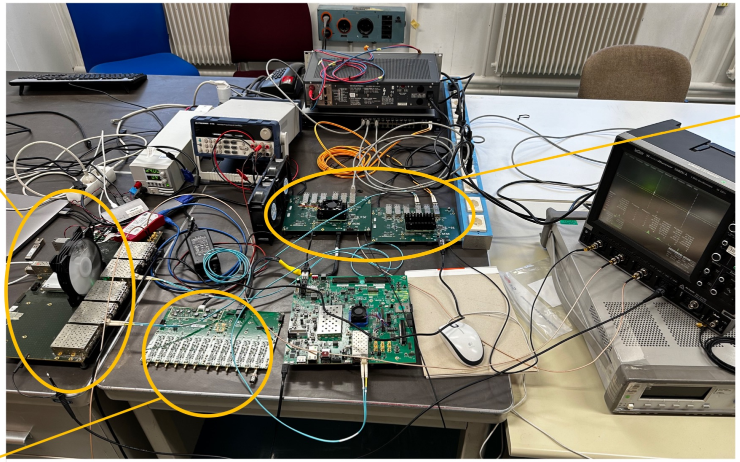
French contribution (plots)

Test Setup

TDS

TDM

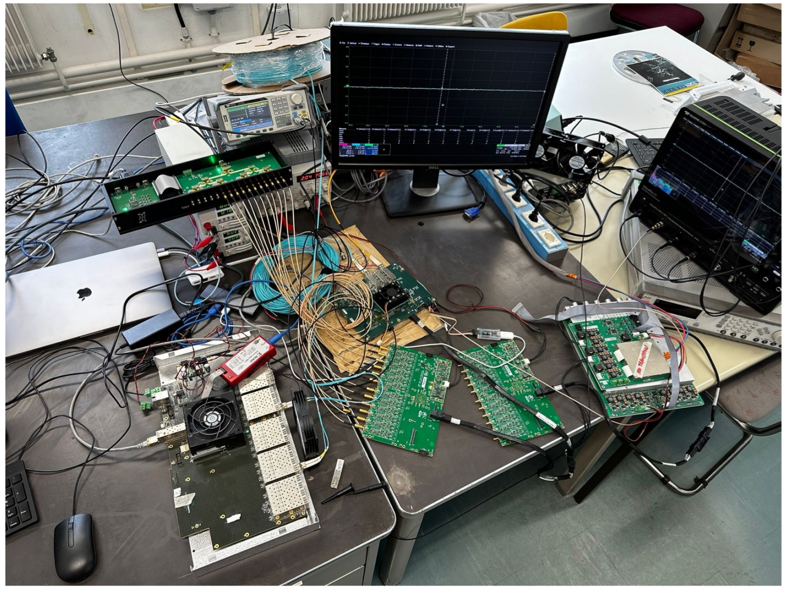
DPB (2)



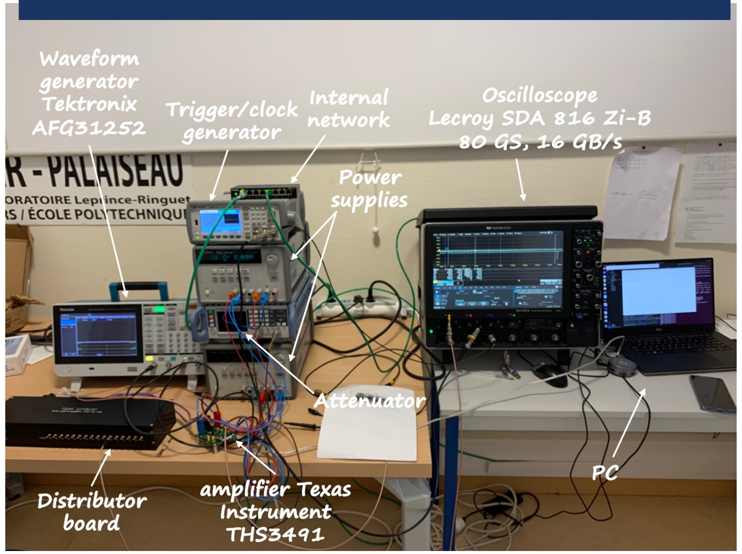
Digitizer

Lab instruments:
- 24V PS
- 12V PS
- Scope Wavepro 254HD-MS
- Patter gen.
- Ethernet switch

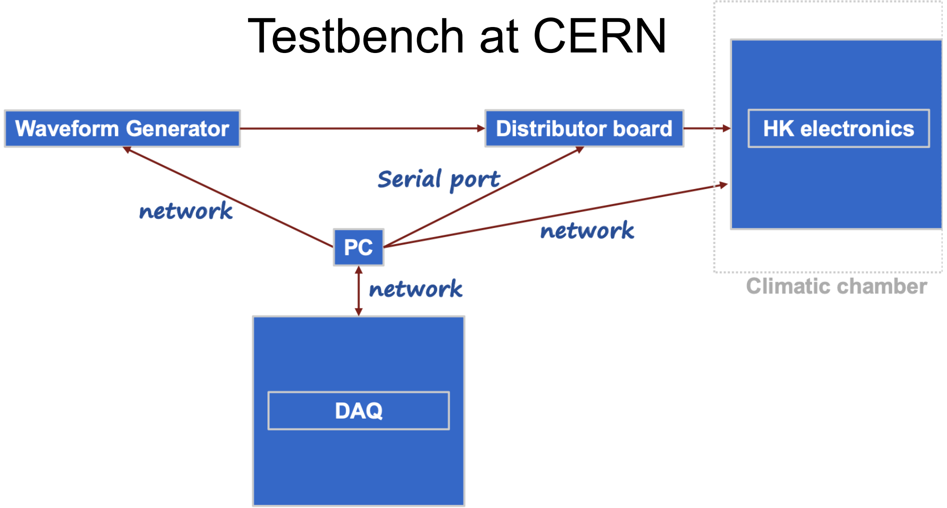
VST



Testbench @ LLR



Testbench at CERN



Current status: PMT production

- Mass production of 50cm PMTs started in 2020
- Production suspended in 2022 due to higher than expected failure rate
- PMT delivery restarted in May 2023, with sampling test of delivered PMTs at Kamioka
- So far, in line to complete delivery of 20.5k by Sep. 2026

- For mPMT: design complete outside of LED part. Production not started yet.

(19 3” PMTs)

- 3600 PMTs for OD will be produced

French contribution

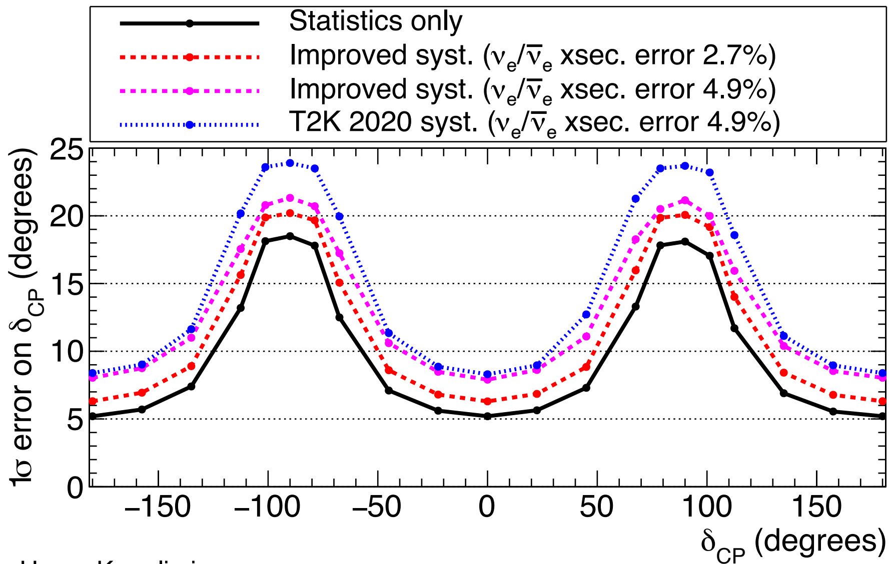
Computing

- Make CC-IN2P3 a Tiers-1 site of HK experiment
  - Host HK database
  - Discussions with collaboration are ongoing

Detector	MC (HS06 CPU.h)	MC Storage (TB)
INGRID	0.13M	7
ND280	19.2M	2,250
IWCD	97M	52
Far detector	20M	500
Total	136.33M	2,824

Software

- Oscillation analysis (beam neutrinos, joint beam+atm)
  - Porting T2K and SK tools and accommodating them for Hyper-K
  - Provide comprehensive osc. sensitivity results
  - Develop more robust systematic model
- Hyper-K events reconstruction
  - Porting SK standard algorithm
  - Develop ML approach
- DSNB
  - Phenomenological studies
  - Preparation of new sensitivity studies



Hyper-K preliminary
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/c^4$