Oscillation Physics at Hyper-Kamiokande

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For the Hyper-Kamiokande Collaboration

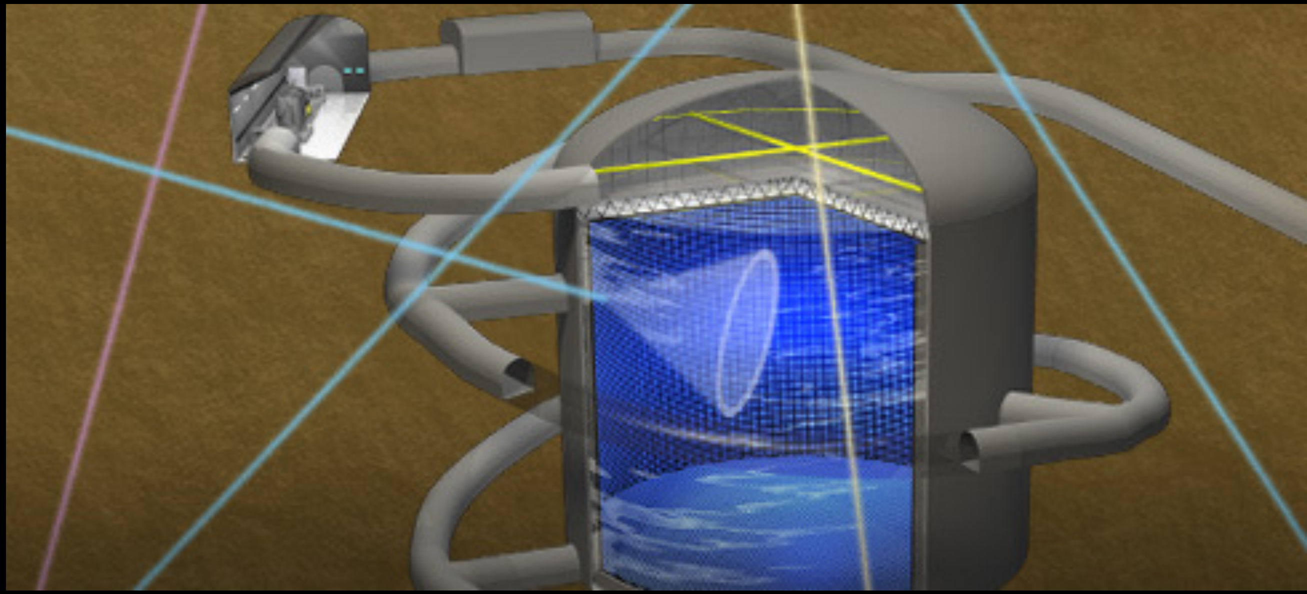
Hyper-Kamiokande

NOW 2024
Neutrino Oscillation Workshop

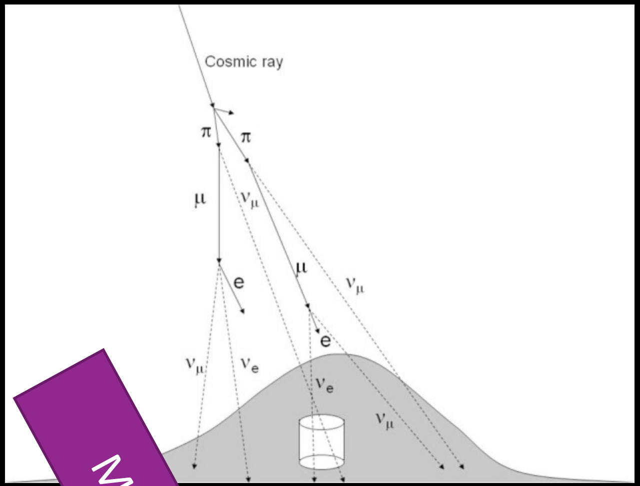
KING'S College LONDON

Outline

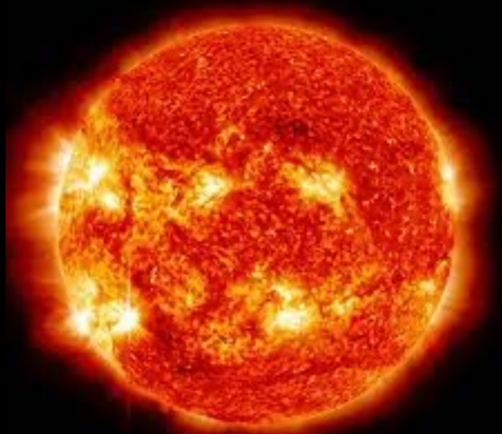
- Overview
- Collaboration
- Beam oscillations
- Atmospheric oscillations
- Systematics and Statistics
- Detector Developments
- Schedule
- Summary



The Hyper-Kamiokande Project

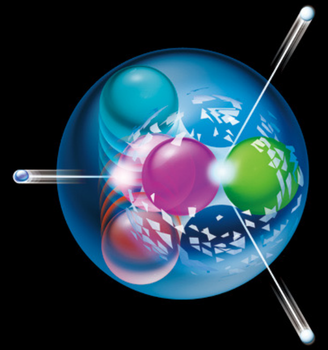


Atmospheric neutrinos:
$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$



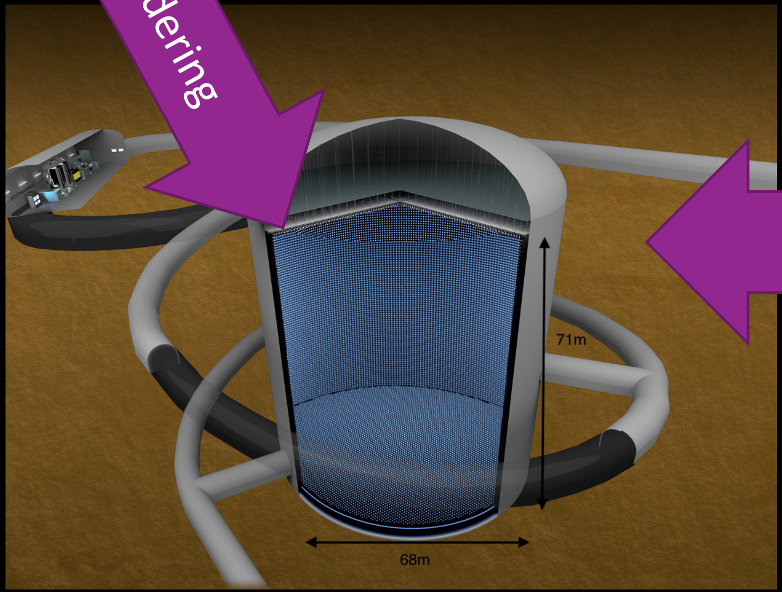
Solar neutrinos, ν_e

Supernova bursts
Diffuse Supernova Background Neutrinos



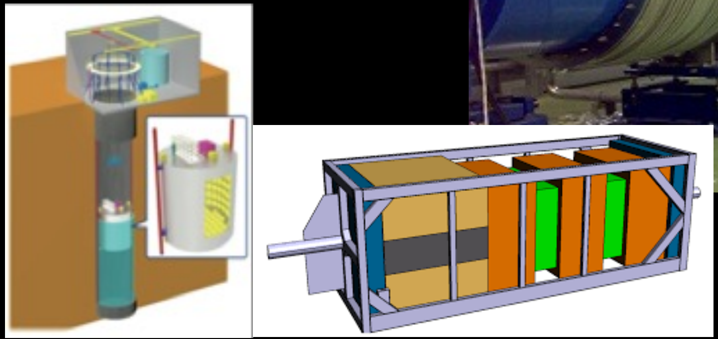
Proton Decay Search

Mass Ordering



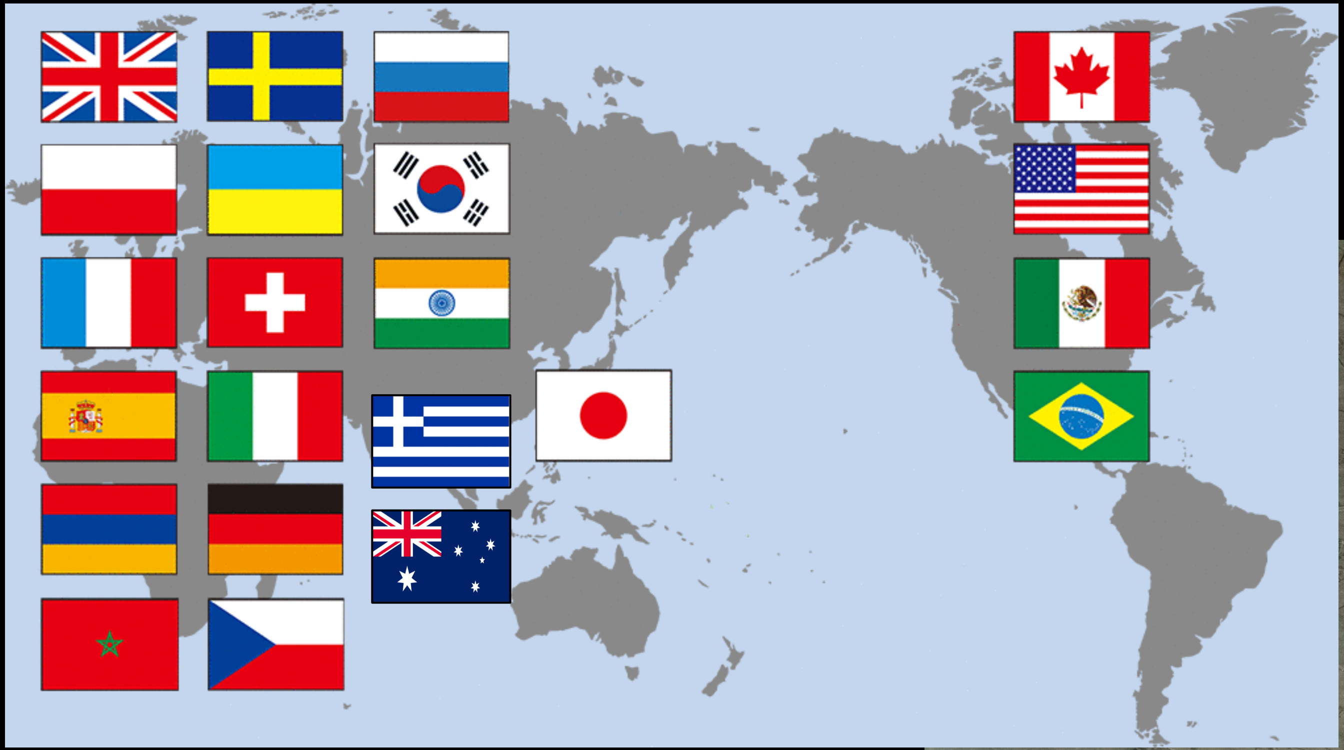
J-PARC neutrino beam: $\nu_\mu, \bar{\nu}_\mu$

CP violation, oscillation parameters



Near Detectors

Hyper-Kamiokande Collaboration



22 countries, 104 institutes, 583 members as of 1/4/2024

Still increasing

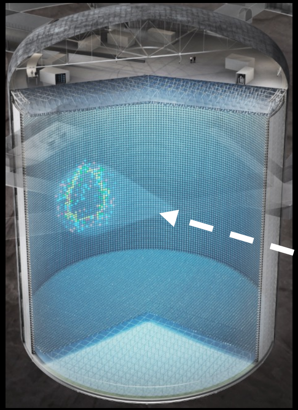
Hosts:

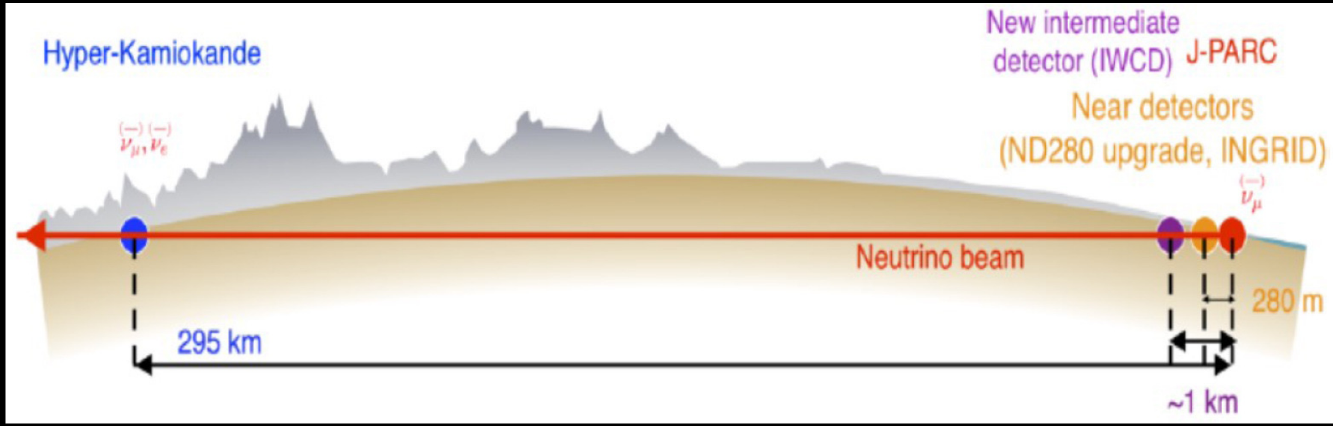
University of Tokyo – Hyper-K detector

KEK/JPARC – Beam and Near Detectors

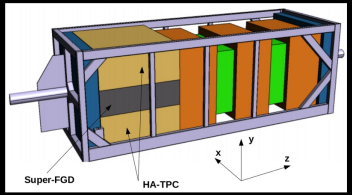
October 2023

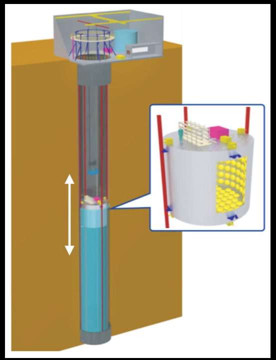
Long Baseline Oscillations

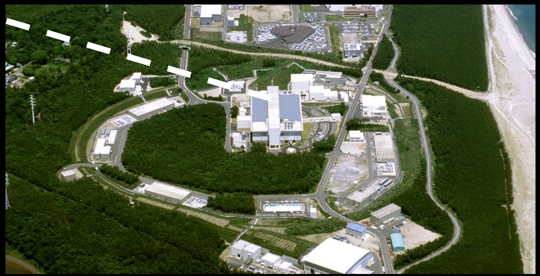


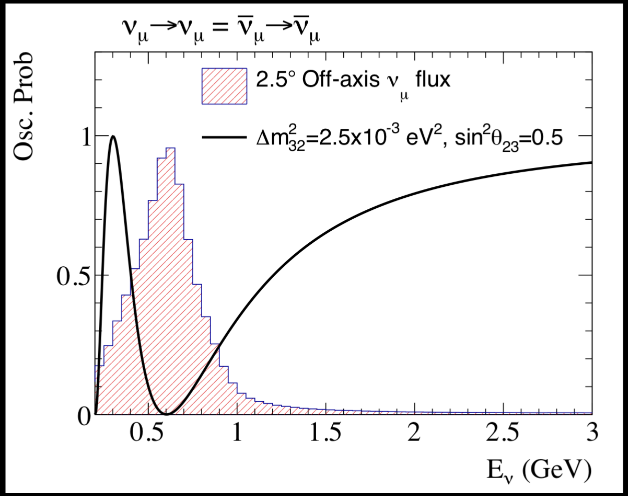


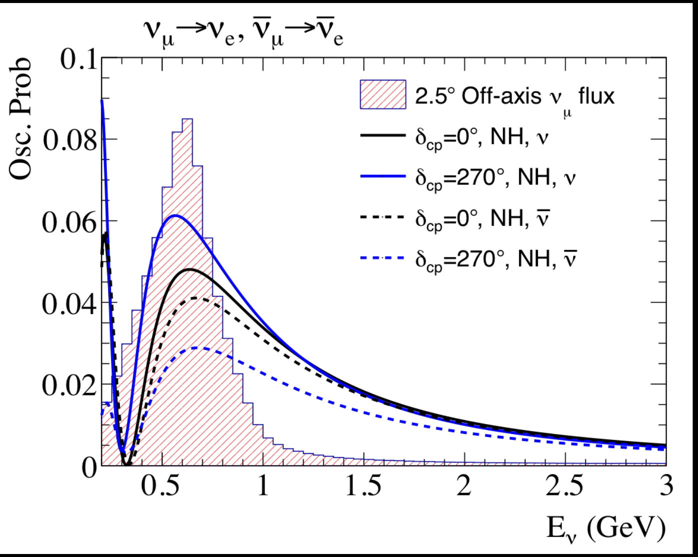
ν ν ν ν ν ν ν



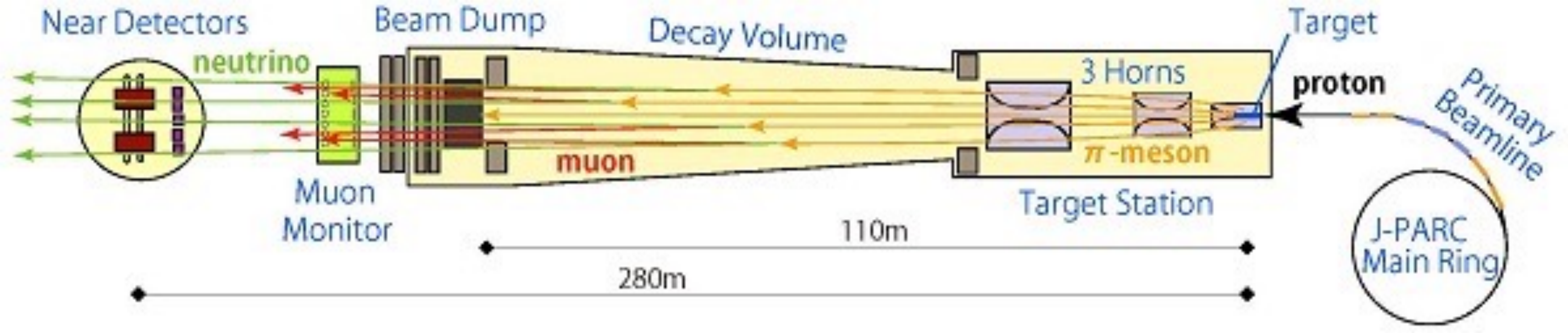






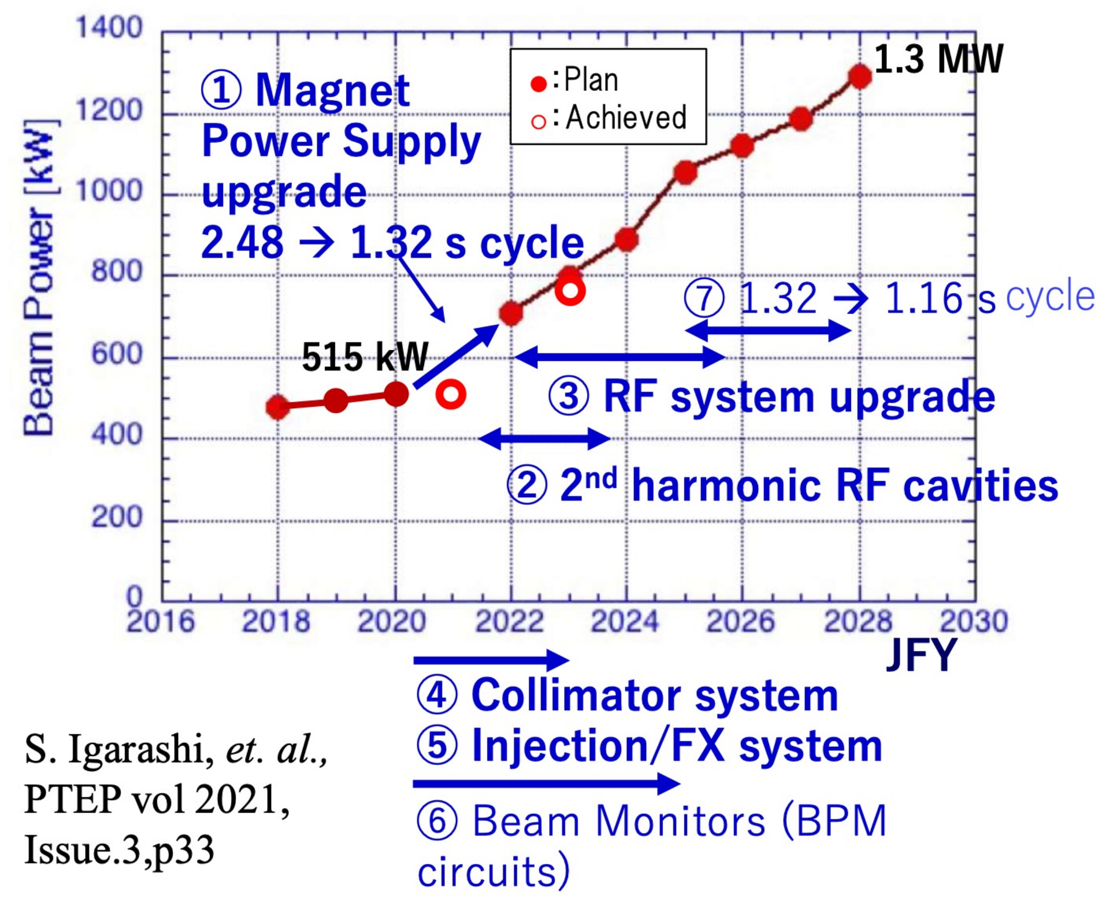


Beam



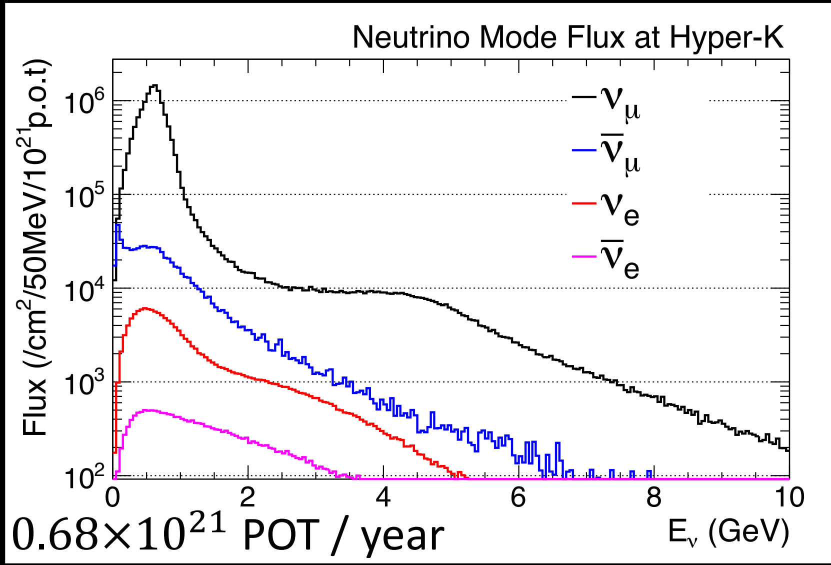
https://j-parc.jp/Neutrino/en/nu-facility.html

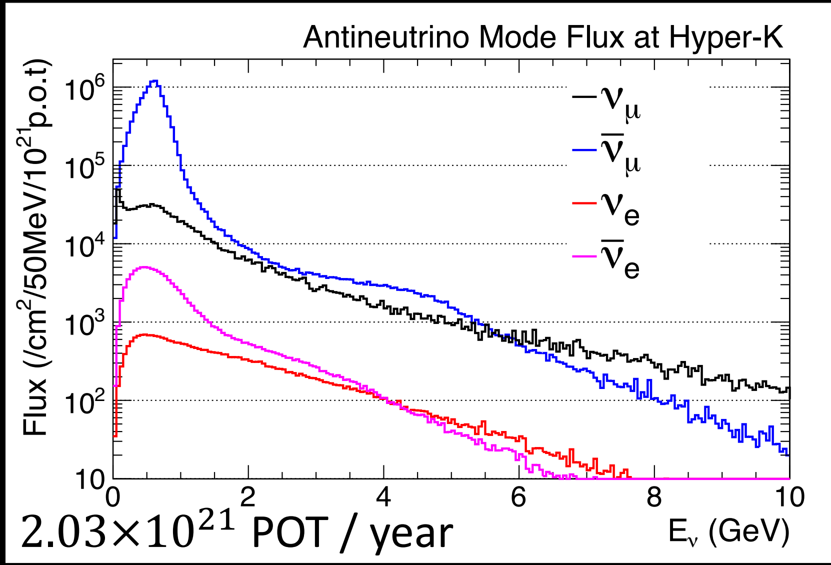
- ν_μ or $\bar{\nu}_\mu$ selected by horn current
- 2.5° off-axis ν / $\bar{\nu}$ beam peaked at 0.6 GeV
- Predominantly QE interactions
- J-PARC upgrade 500kW →1.3 MW
- 800kW beam achieved in summer 2024
- Further upgrades:
  - Optics improvements to reduce beam loss
  - Upgraded RF system → more protons/pulse
  - Increase repetition rate 1.32 → 1.16s/cycle



Sensitivity inputs

- 10 years of data taking with $1:3\ \nu : \bar{\nu}$ ratio





T2K 2020 error model:

Uncertainties on expected numbers of events

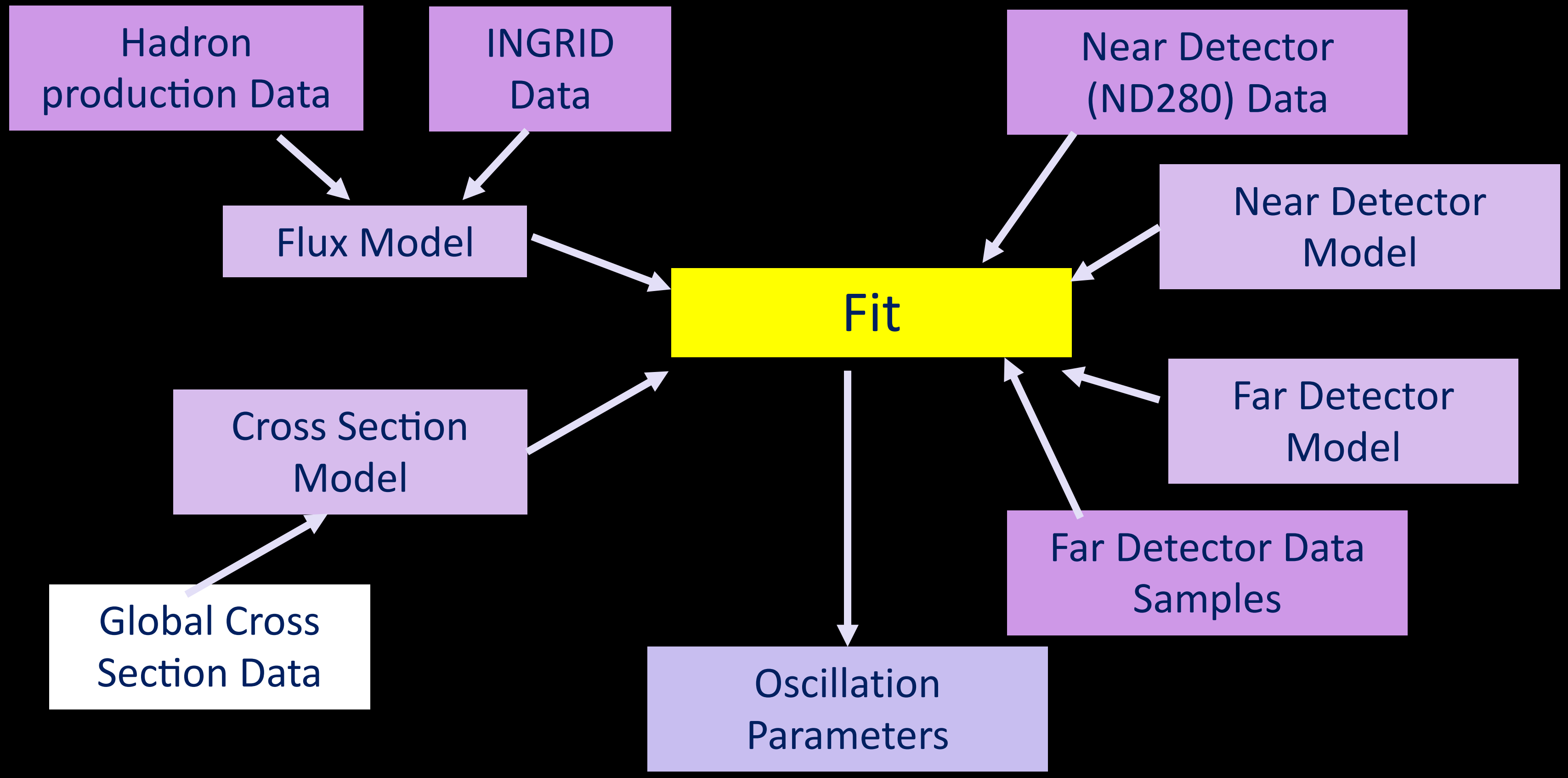
T2K 2020	1 ring μ-like		1 ring e-like			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode + 0 decay	$\bar{\nu}$-mode + 0 decay	ν-mode + 1 decay	$\nu/\bar{\nu}$-mode + 0 decay
ND constrained Flux + Cross section	2,1 %	3,4 %	3.6 %	4.3 %	4,9 %	4,4 %
Not ND constrained Cross-section	0,5 %	2,6 %	3.0 %	3.7 %	2,7 %	4,1 %
Detector	2,1 %	1,9 %	3.1 %	3.9 %	13,2 %	1,1 %
All systematics	3,0 %	4,0 %	4.7 %	5.9 %s	14,1 %	4,6 %

Improved error model:

ν_e / $\bar{\nu}_e$ cross-section ratio error fixed to 2.7%

Improved	1 ring μ-like		1 ring e-like			
Error source	ν-mode	$\bar{\nu}$-mode	ν-mode + 0 decay	$\bar{\nu}$-mode + 0 decay	ν-mode + 1 decay	$\nu/\bar{\nu}$-mode + 0 decay
ND constrained Flux + Cross section	0,9 %	0.9 %	1.8 %	1,6 %	1,8 %	1,9 %
Not ND constrained Cross-section	0,4 %	0.4 %	1.6 %	1,4 %	1,6 %	1,9 %
Detector	0,8 %	0.7 %	1.1 %	1,5 %	4,9 %	0,4 %
All systematics	1,2 %	1.1 %	2.1 %	2,2 %	5,2 %	2,0 %

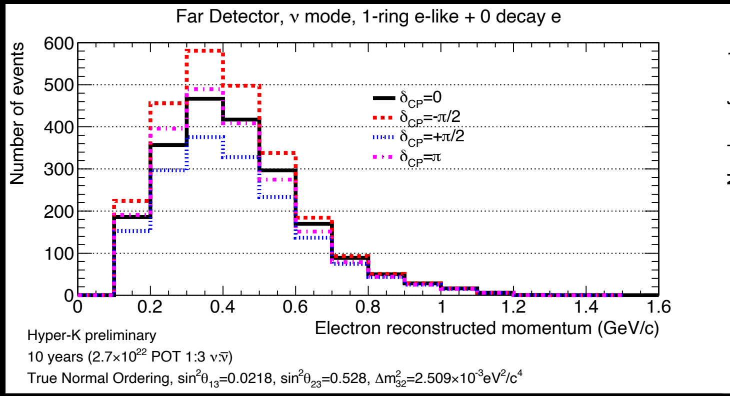
Oscillation Analysis

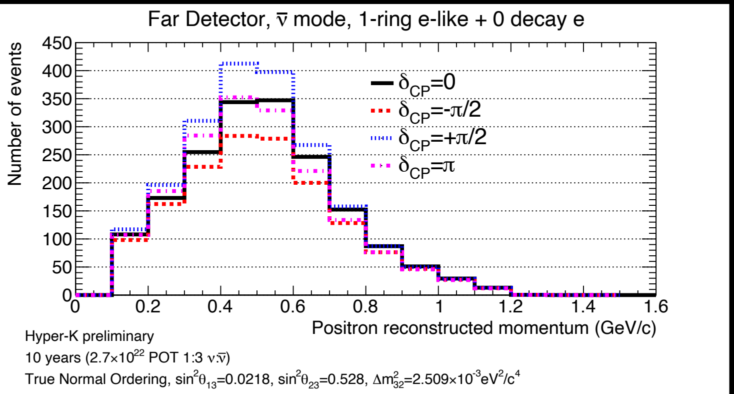


Long Baseline Physics - δ_{CP}

Probe CP-violation through comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- Select 1 ring e-like events in far detector

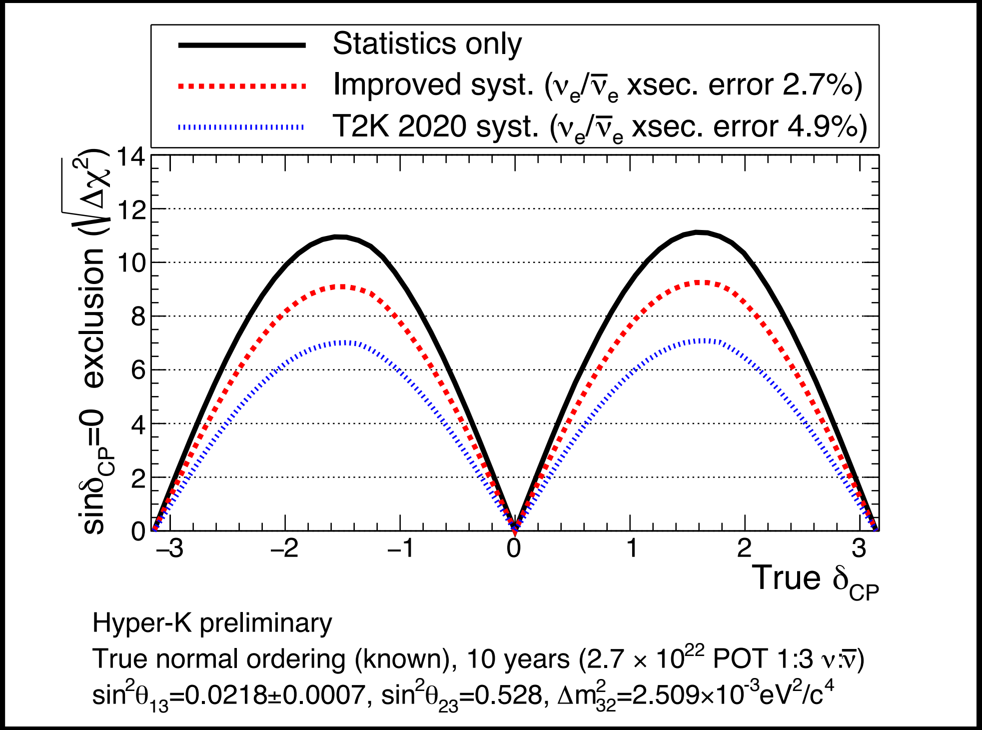


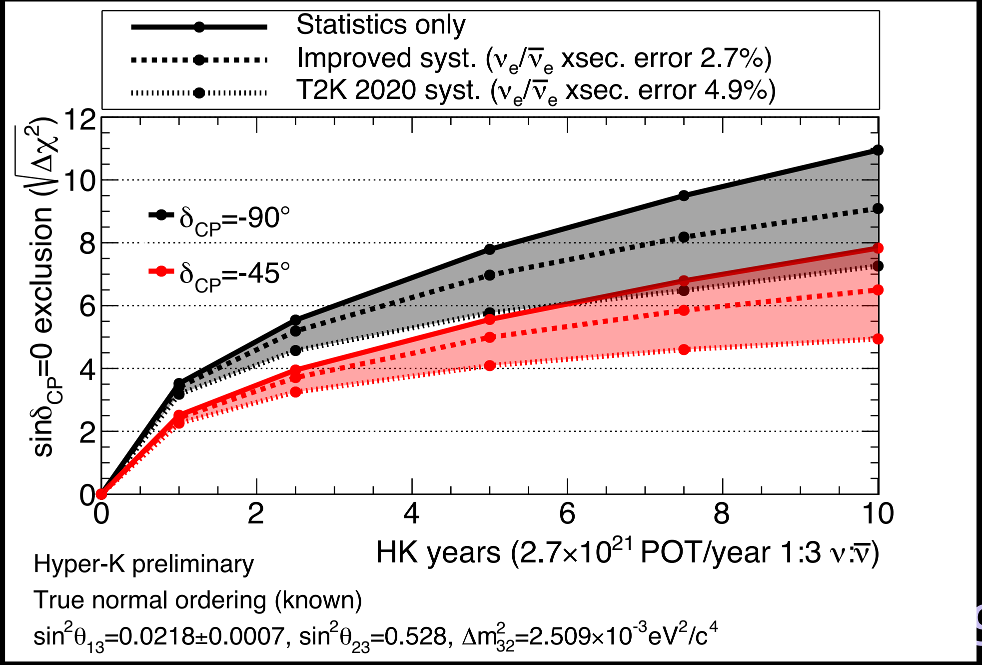


- >1000 ν_e and $\bar{\nu}_e$ signals

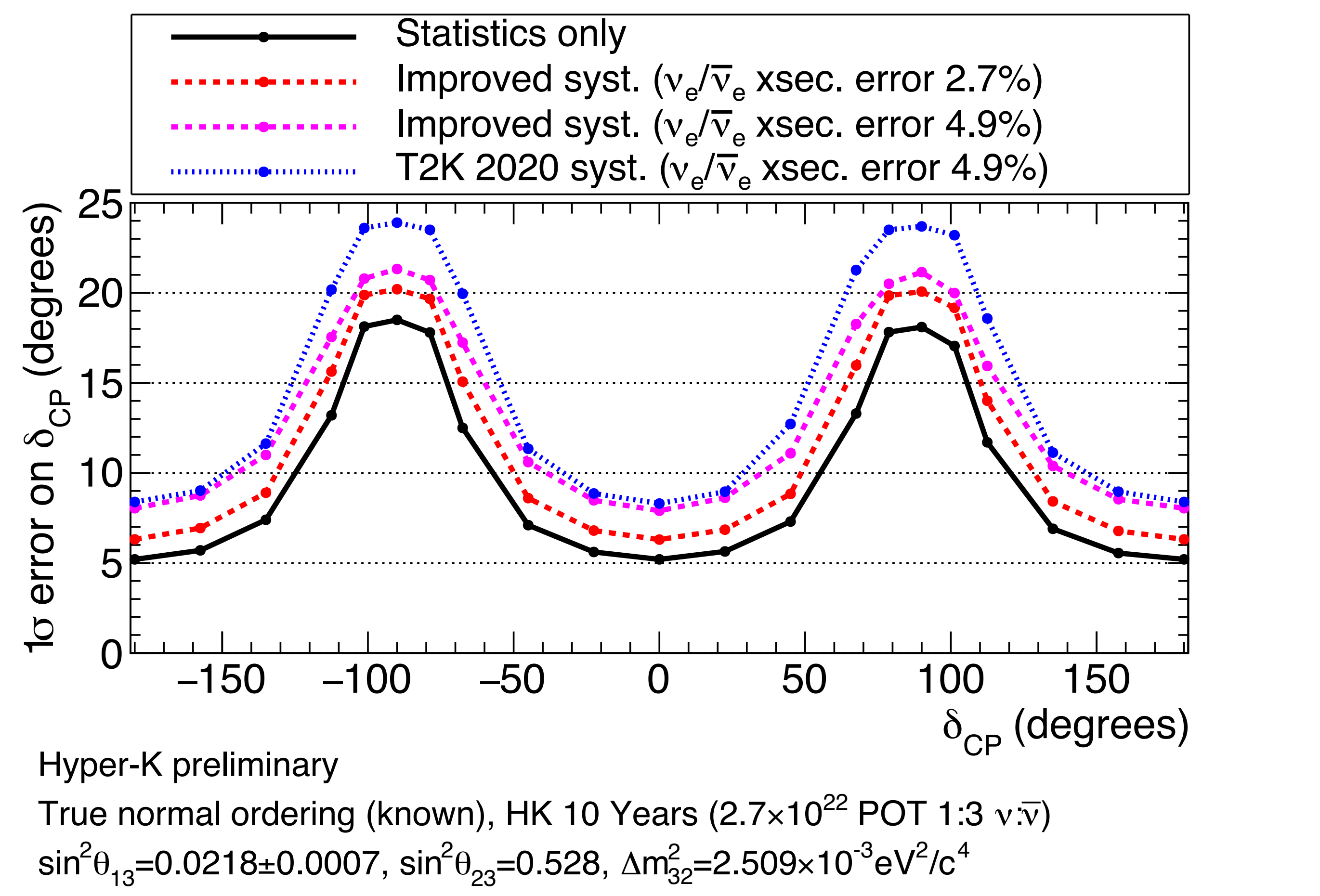
Assume normal mass ordering is known → Projected sensitivity based on T2K systematics plus improvements for Hyper-K

After 10 HK-years, 63% of true δ_{CP} values can be excluded at 5 sigma





Long Baseline Physics - δ_{CP}



True δ_{CP} (rad)	$-\pi/2$	$-\pi/3$	$-\pi/4$
Statistics only	10.95σ	9.64σ	7.82σ
Improved systematics	9.09σ	8.02σ	6.49σ
T2K2020 systematics	6.99σ	6.11σ	4.94σ

$\sin\delta_{CP}=0$ exclusion

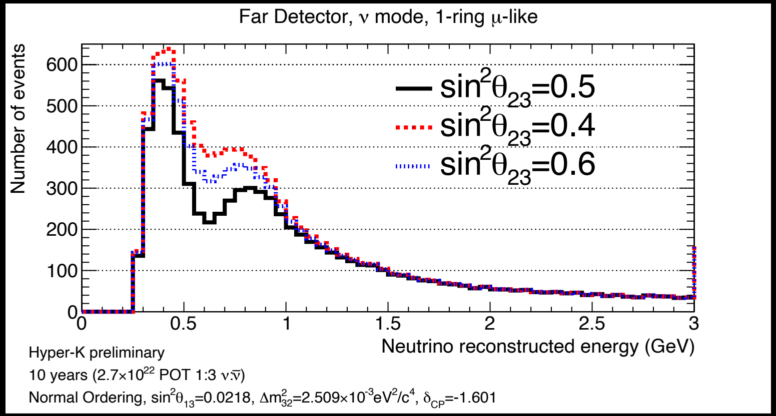
C.L.	3σ	5σ
Statistics only [%]	83.38	69.87
Improved systematics [%]	78.48	62.76
T2K2020 systematics [%]	71.37	48.55

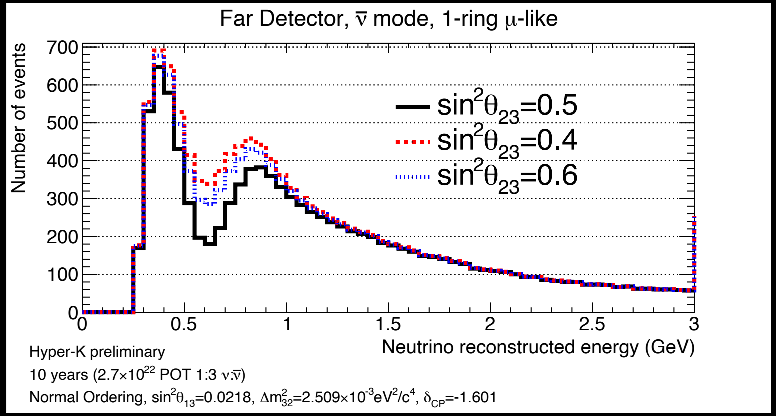
percentage of true δ_{CP} excluding $\sin\delta_{CP}=0$ at 3 and 5 sigma C.L.

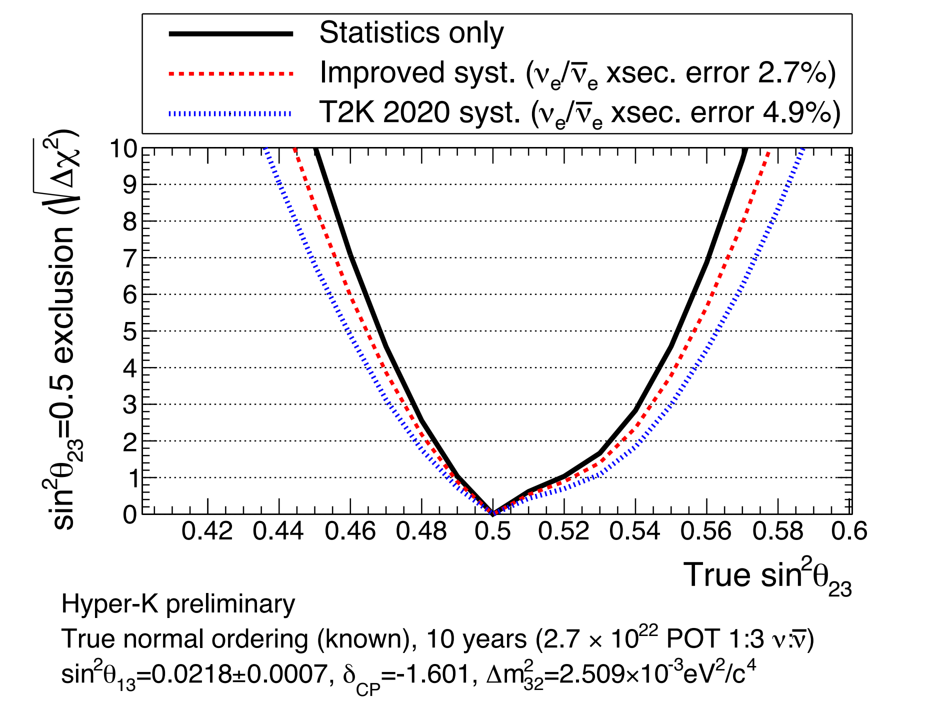
$\sin^2\theta_{23}$

Probe 2-3 mixing through dip in $P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

- Select 1 ring μ-like events in far detector

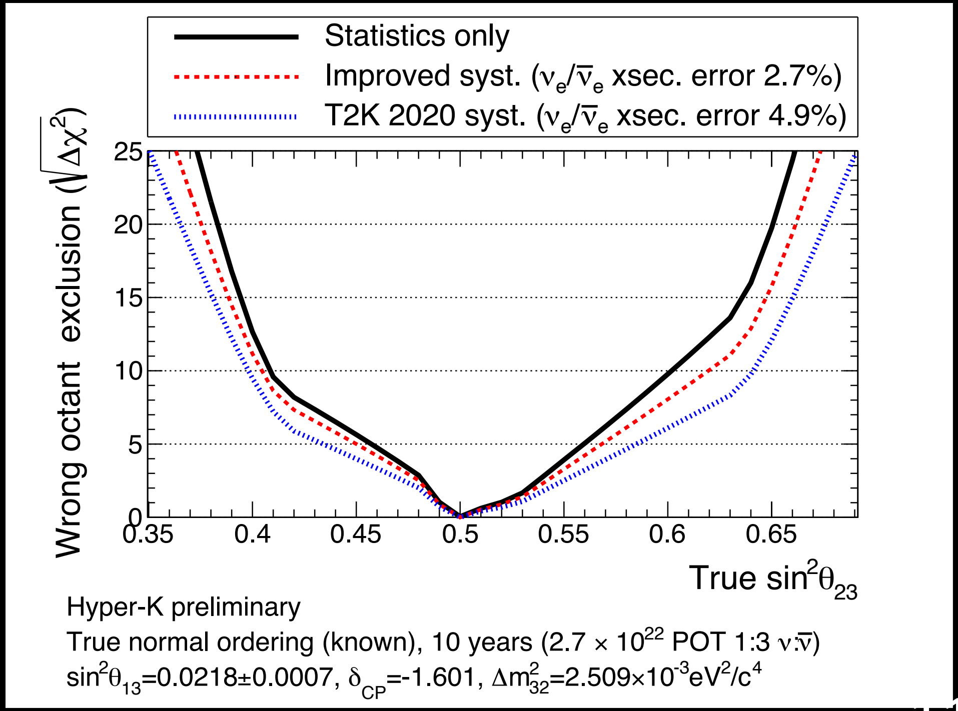




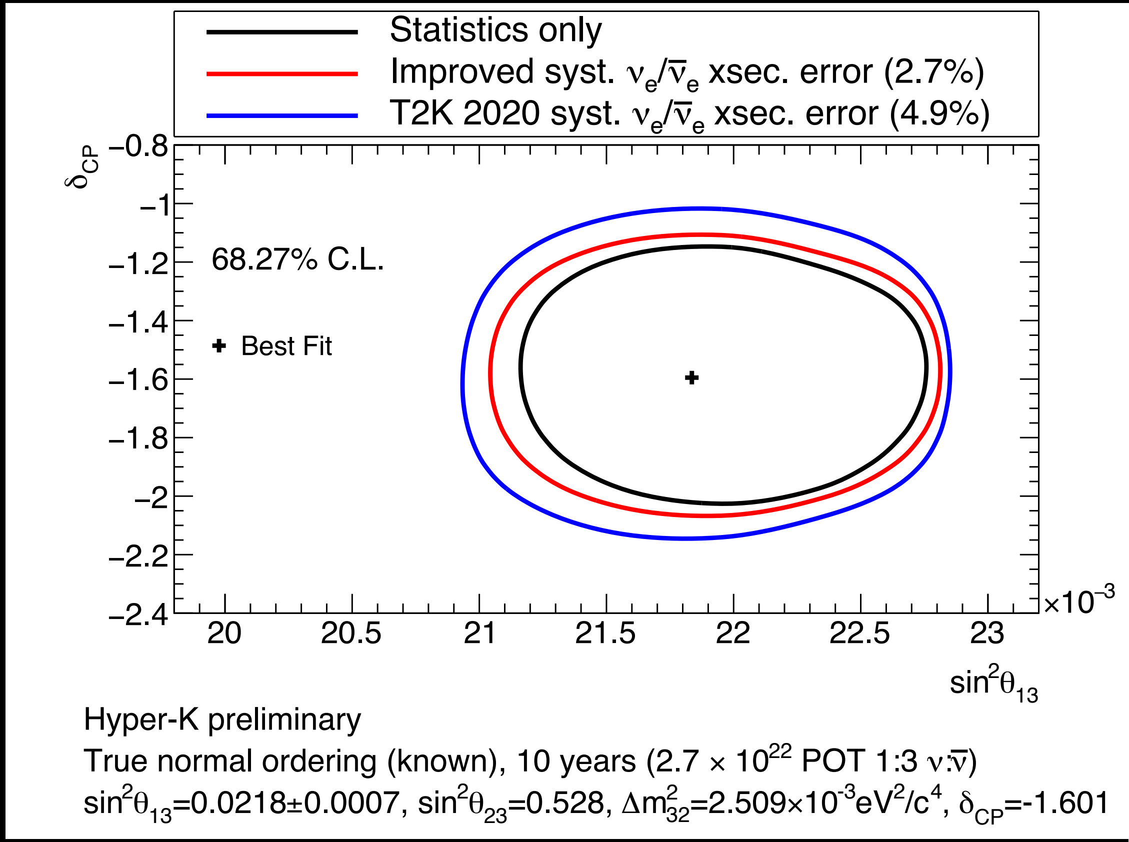


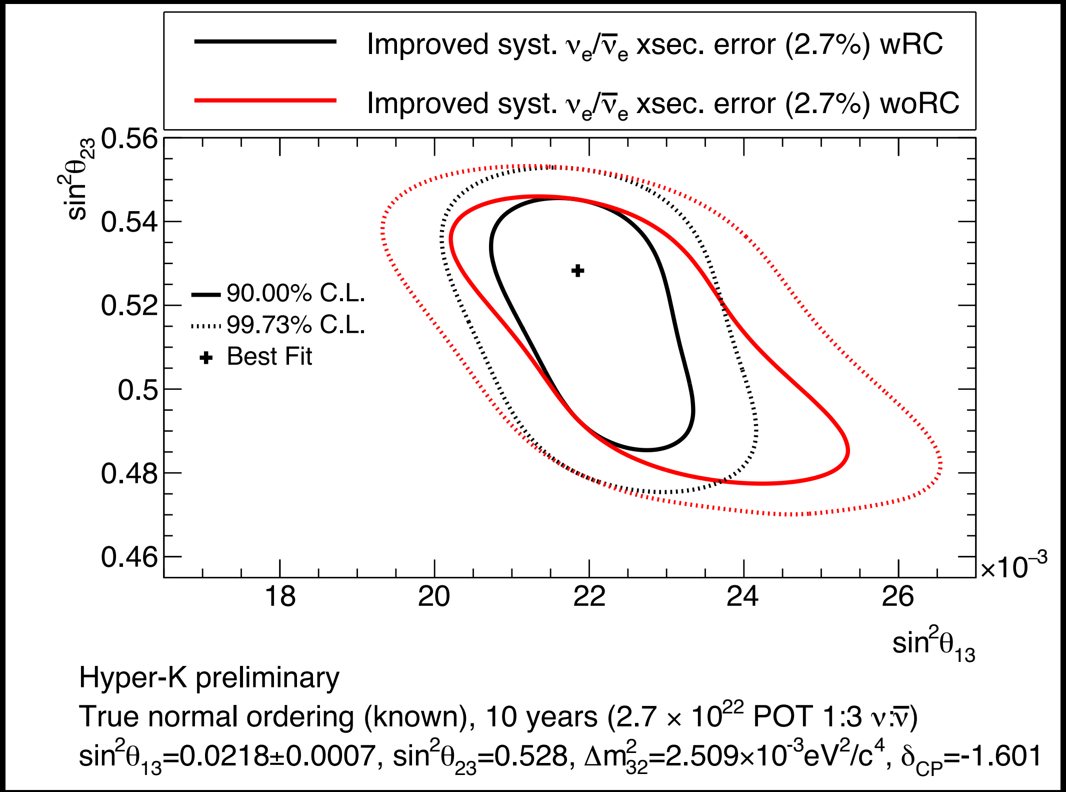
← Exclude maximal mixing at 3σ for true $\sin^2\theta_{23} < 0.475$ and $\sin^2\theta_{23} > 0.545$

Exclude wrong octant at 3σ for true $\sin^2\theta_{23} < 0.47$ and $\sin^2\theta_{23} > 0.55$ →



$\sin^2\theta_{13}$

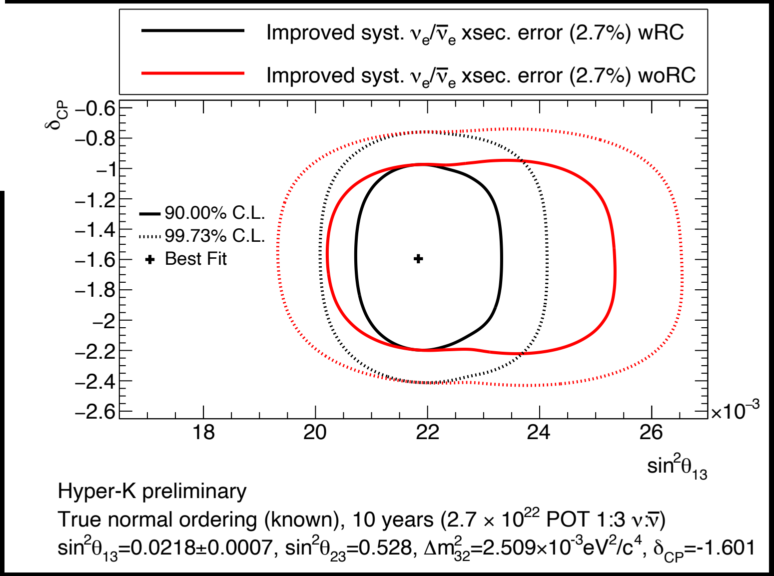




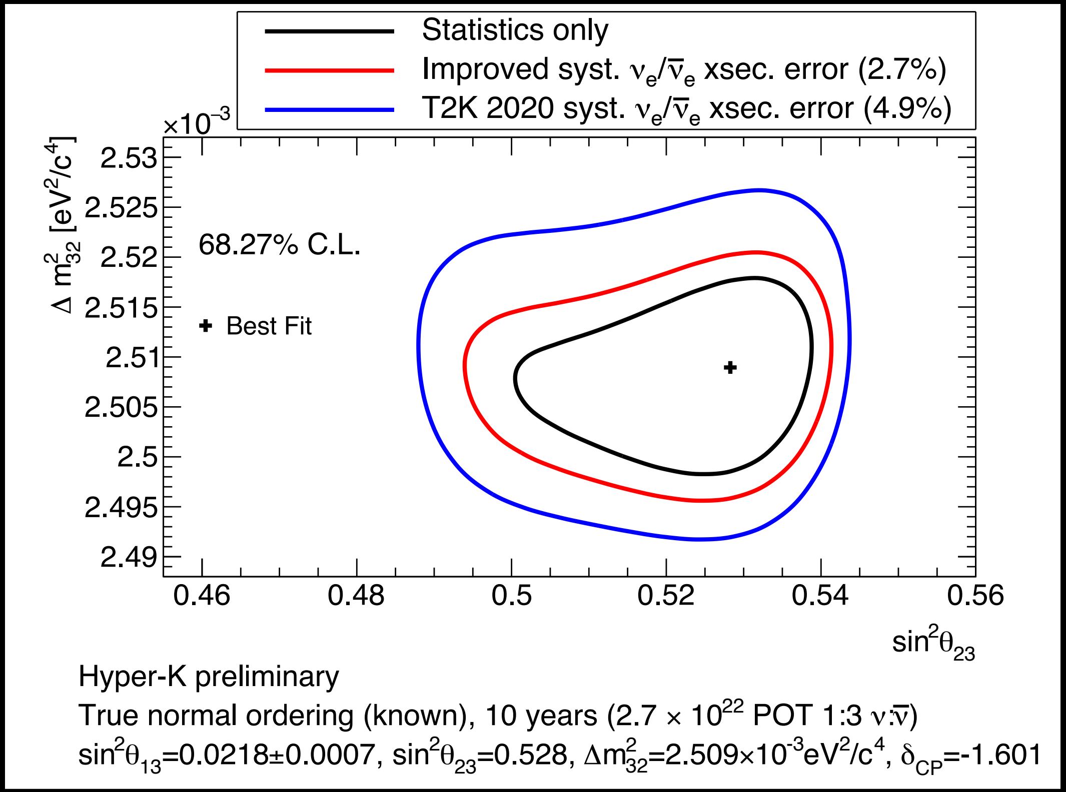
↑ Reactor constraints help lift degeneracy between $\sin^2\theta_{13}$ and $\sin^2\theta_{23}$

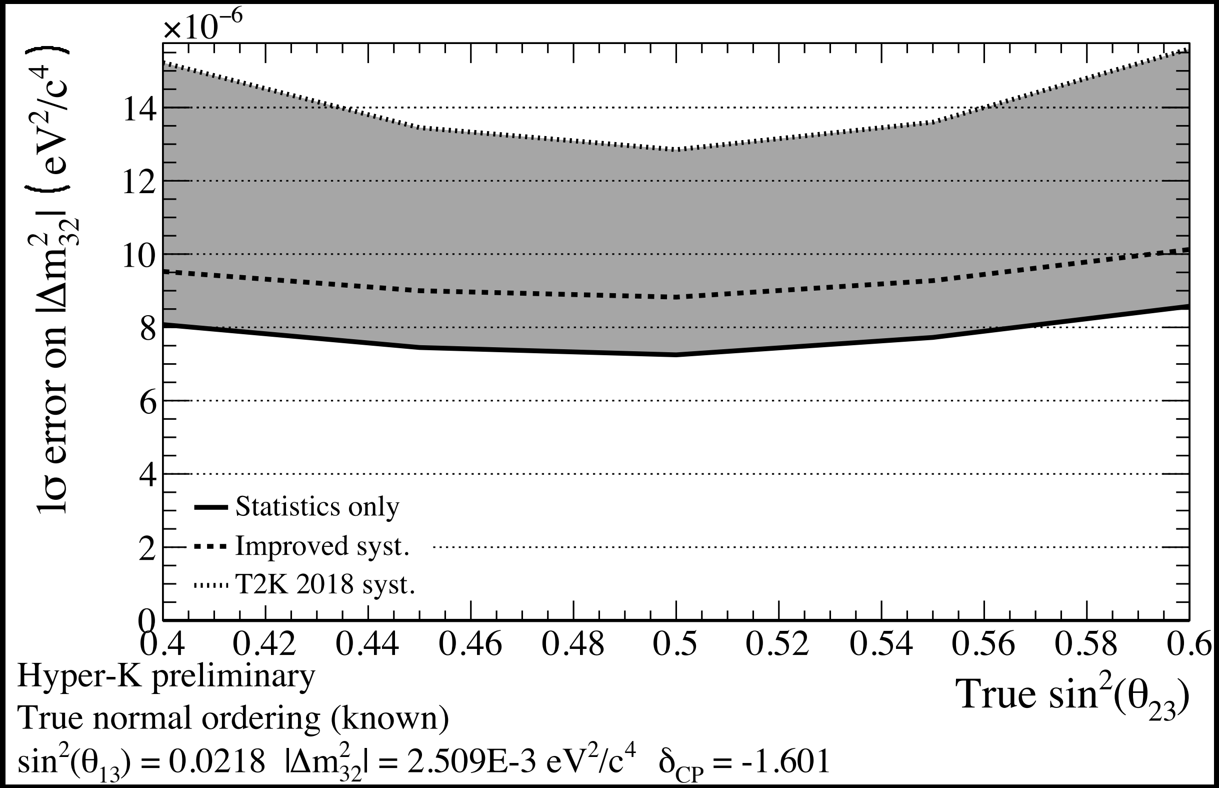
1σ contours on δ_{CP} and $\sin^2\theta_{13}$

Reactor constraints don't significantly impact on δ_{CP} →



Δm^2_{32}





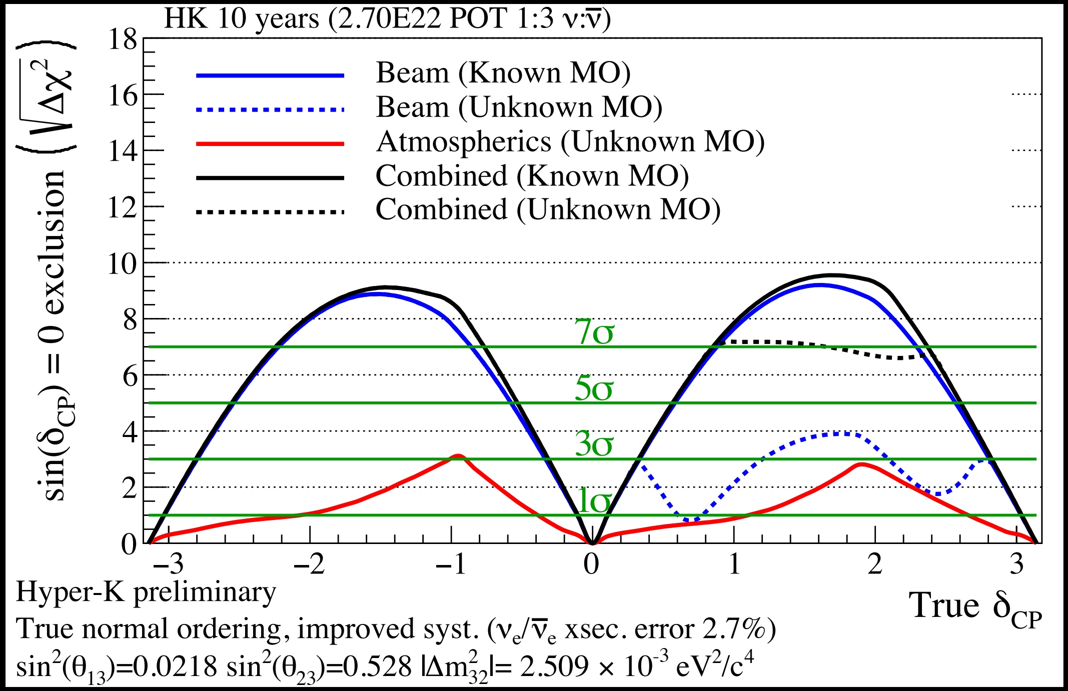
1σ contours on Δm^2_{23} and $\sin^2\theta_{s3}$
(long baseline beam data only)

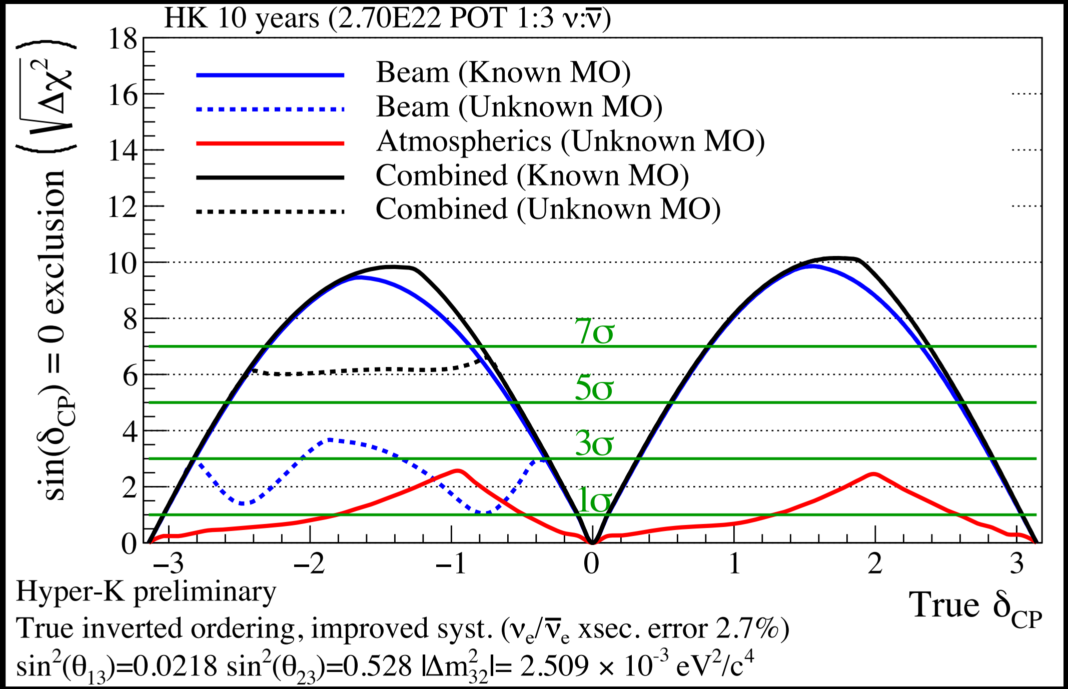
1σ resolution of Δm^2_{32} as a function of true $\sin^2\theta_{23}$

Mass Ordering

	$\sin^2\theta_{23}$	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

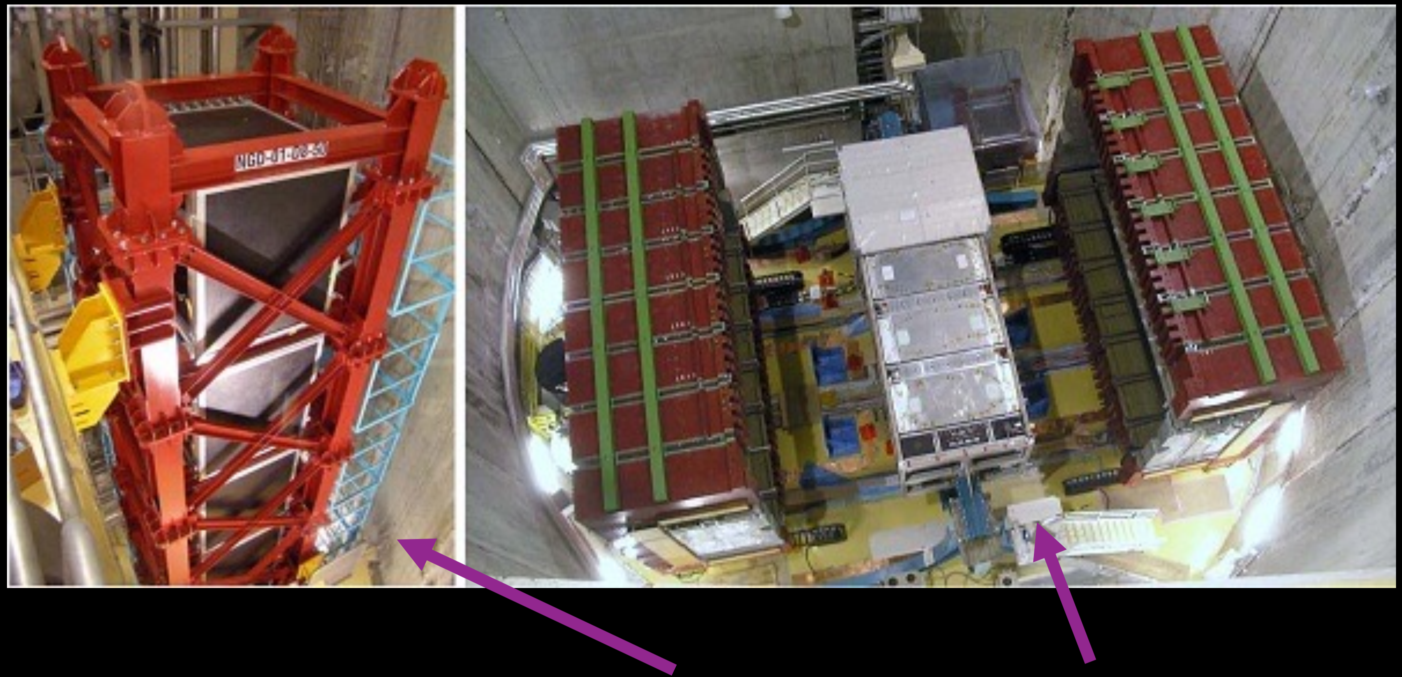
10 years with 1.3MW, normal mass ordering is assumed

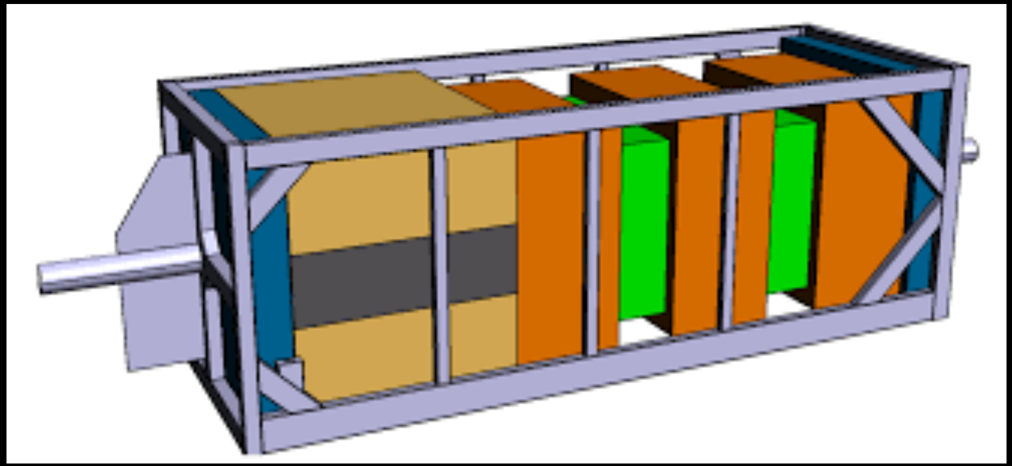




- If mass ordering is not known, combination of beam measurements with atmospheric neutrino observations resolves parameter degeneracy

Near Detectors

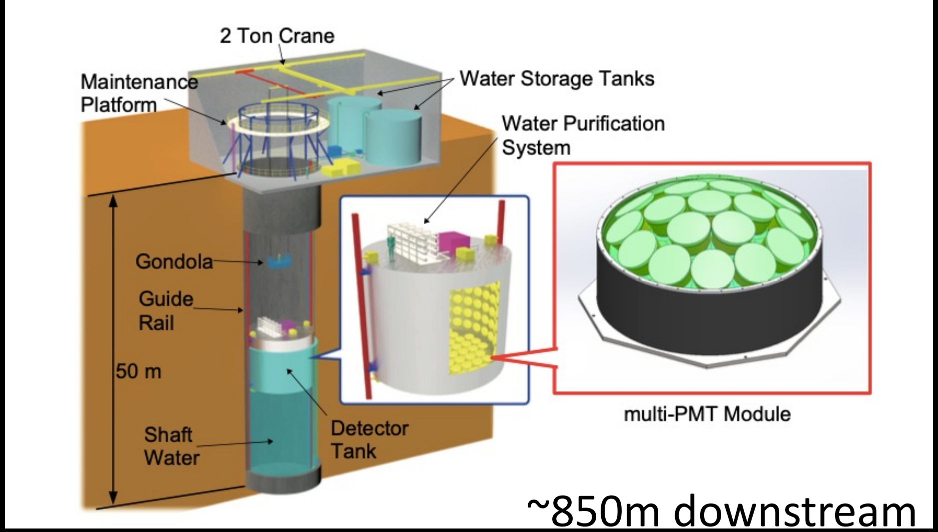


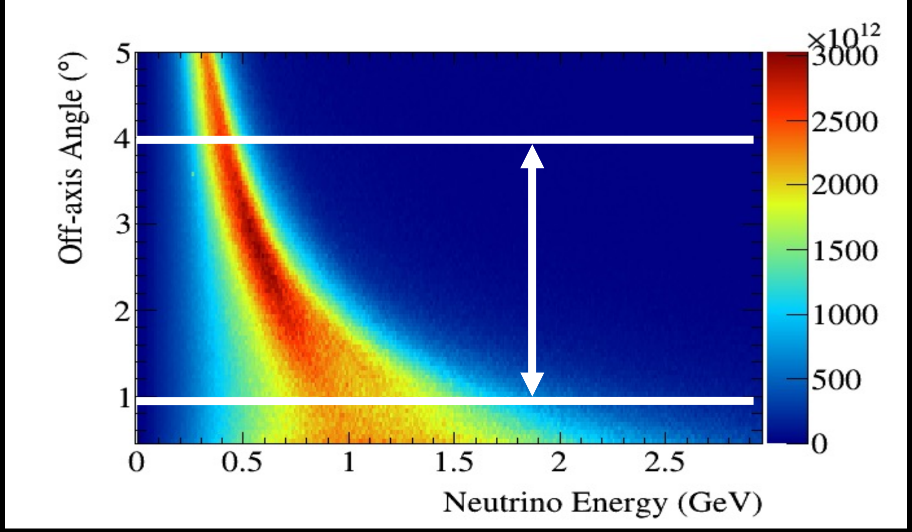


- T2K Near detectors INGRID and ND280 measure beam structure and composition 280 m downstream.
  - Measurements constrain uncertainty on flux and neutrino interaction models
  - Events samples from ND280 used in oscillation fit to near and far detector data
- Upgrades installed to improve angular acceptance of the ND280 tracking detector

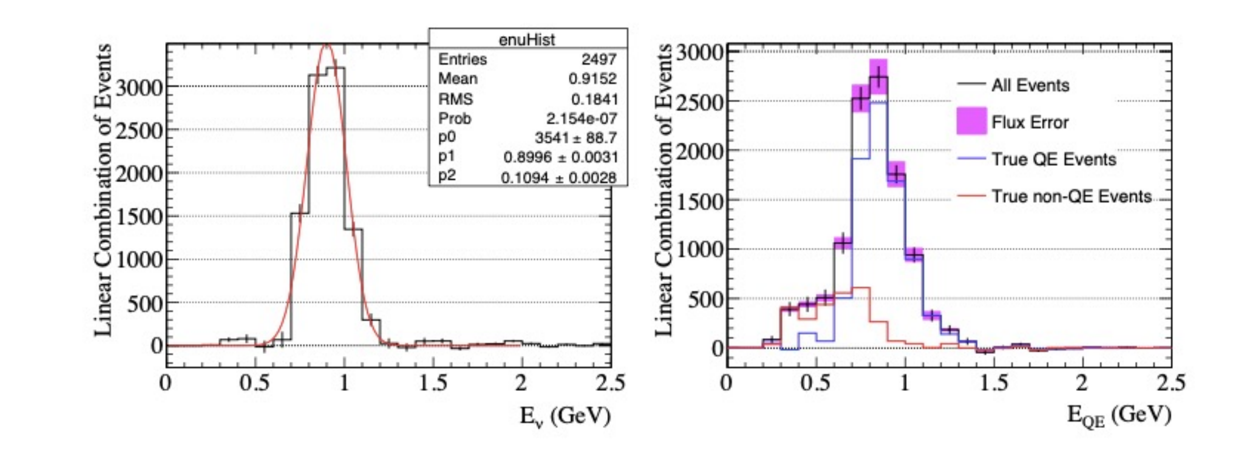
T2K upgrade - Talk by Lorenzo Magaletti tomorrow

The Intermediate Water Cherenkov Detector (IWCD)

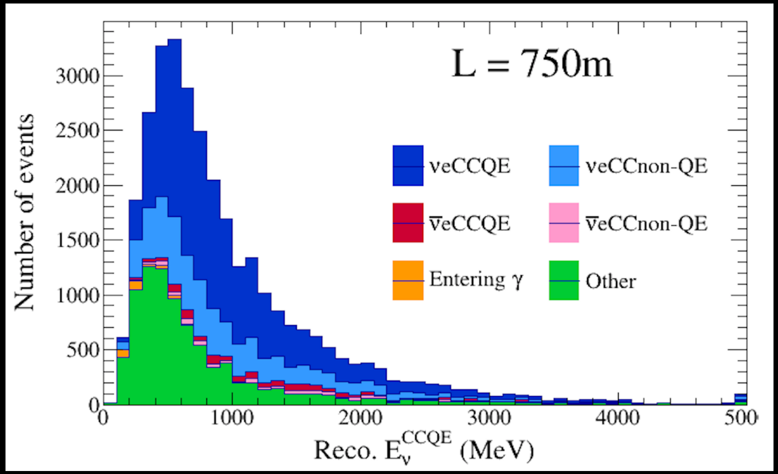




- Moving detector → measurements at different off-axis angles → energy spectrum changes → constrain relationship between reconstructed quantities and neutrino energy



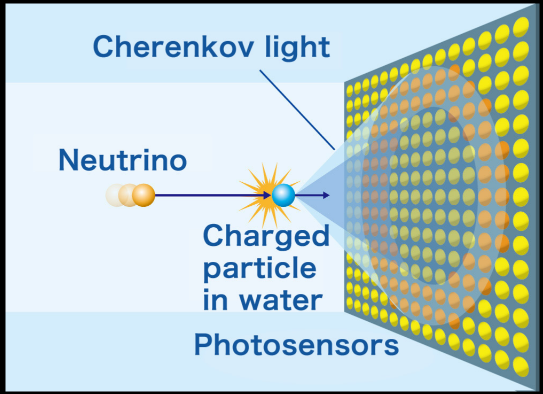
Create "mono-chromatic" spectra to constrain non-QE feed-down with 5% precision



Measure $CC\nu_e/CC\bar{\nu}_e$ ratio with <4% precision

Use intrinsic electron (anti) neutrinos in beam

Kamioka Water Cherenkov Experiments



Hyper-Kamiokande

X 8.4

- ~2027 onwards
- 260 kton (188 kton FV)

Super-Kamiokande

X 20

- 1996 onwards
- 50 kton (22.5 kton FV)

Kamiokande

- 1983 – 1996
- 3 kton

Hyper-K = 71 m tall

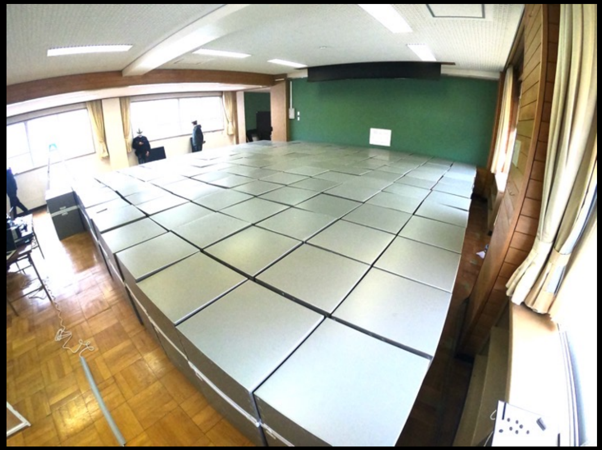
Leaning tower of Pisa = 55.89 - 56.7m tall

68 m diameter

Hyper-K Far Detector – R&D highlights

20k 50 cm Box and Line Dynode ID PMTs

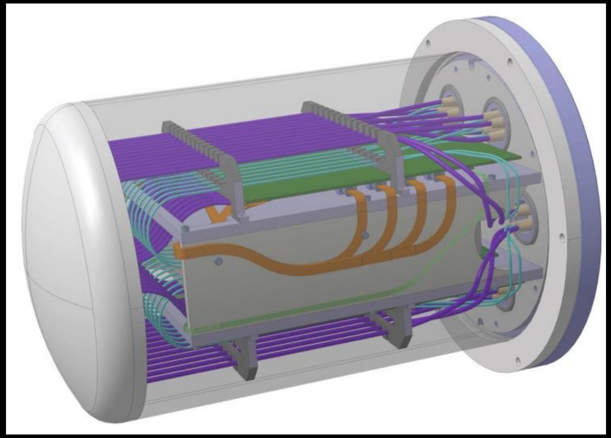
- 2.6 ns timing resolution
- 2 × SK PMT efficiency
- Mass production and QA commenced 2021



mPMT units

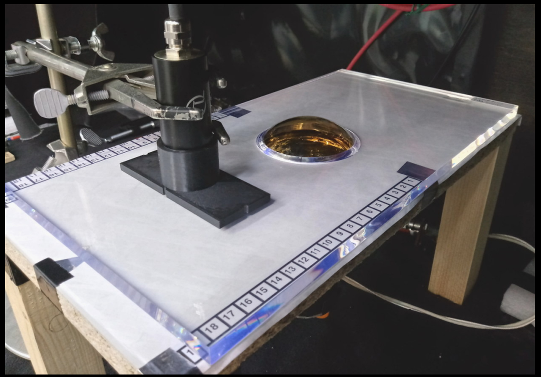
- 19 8 cm PMTs + electronics inside single pressure vessel
- Directional information, improved spatial and timing resolution

Installation mock-up



Underwater electronics

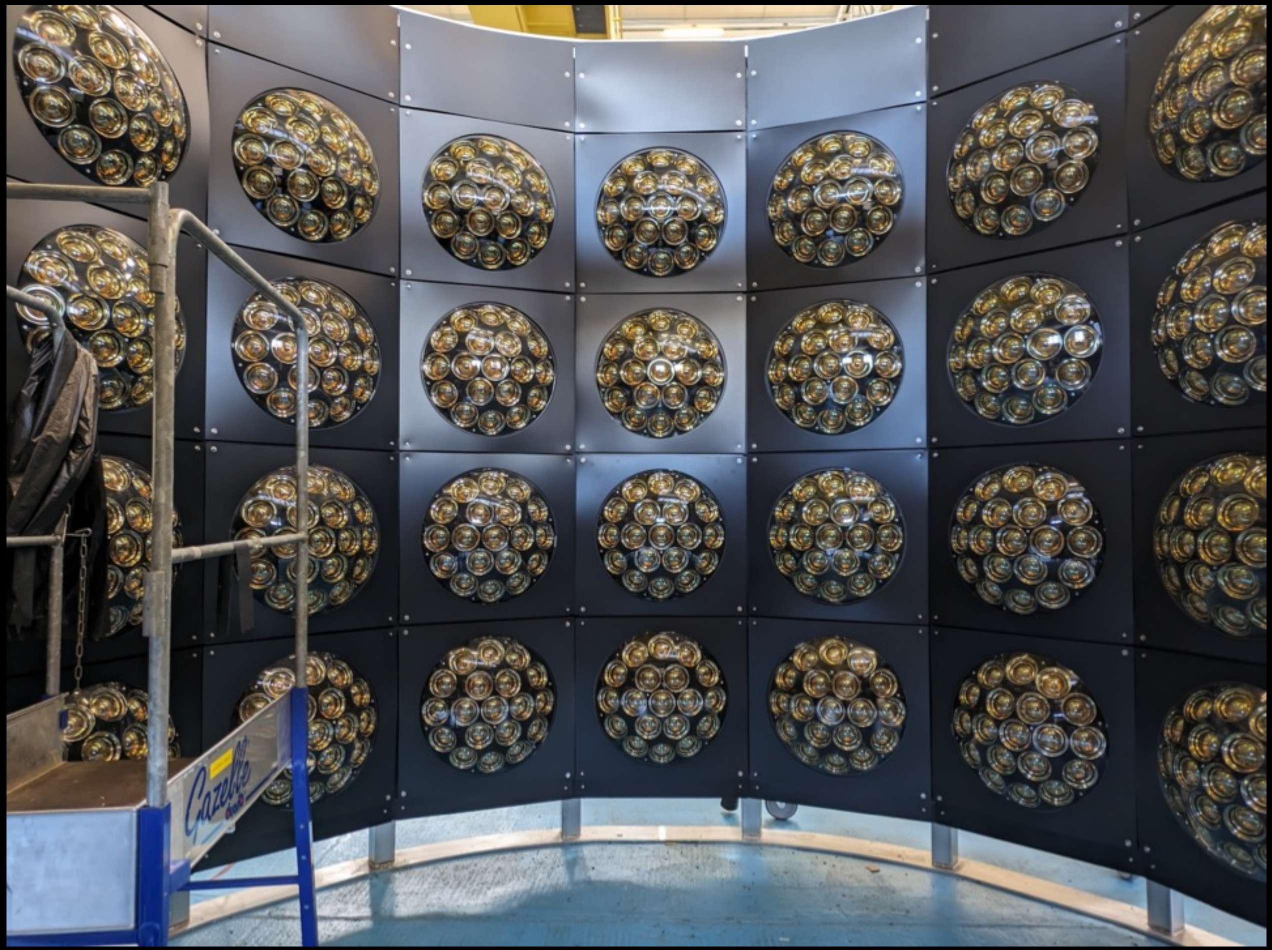
Outer Detector:



8 cm PMTs + WLS plates

WCTE @ CERN under construction

Pictures Aug '24
Courtesy of the WCTE collaboration



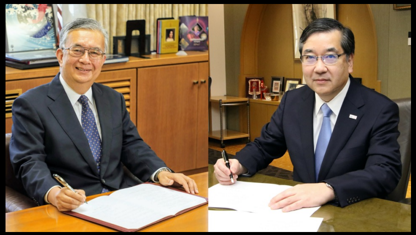
- 4m scale test detector to validate performance of mPMTs and IWCD approach
- mPMT installation is complete, water system commissioning and integration underway

Project Status

NOW 2024 Neutrino Oscillation Workshop

2020 → 2021 → 2022 → 2023 → 2024 → 2025 → 2026 → 2027

MOU signed, May 2020



Ground-breaking May 2021

Access tunnel complete, Feb 2022

Approach and Peripheral tunnels, Summer 2022

Operation starts 2027

Cavern Excavation

Tank Construction

Installation

Water filling

PMT production

Cavern now excavated to 37m depth (over halfway)

Photograph taken
June 2024

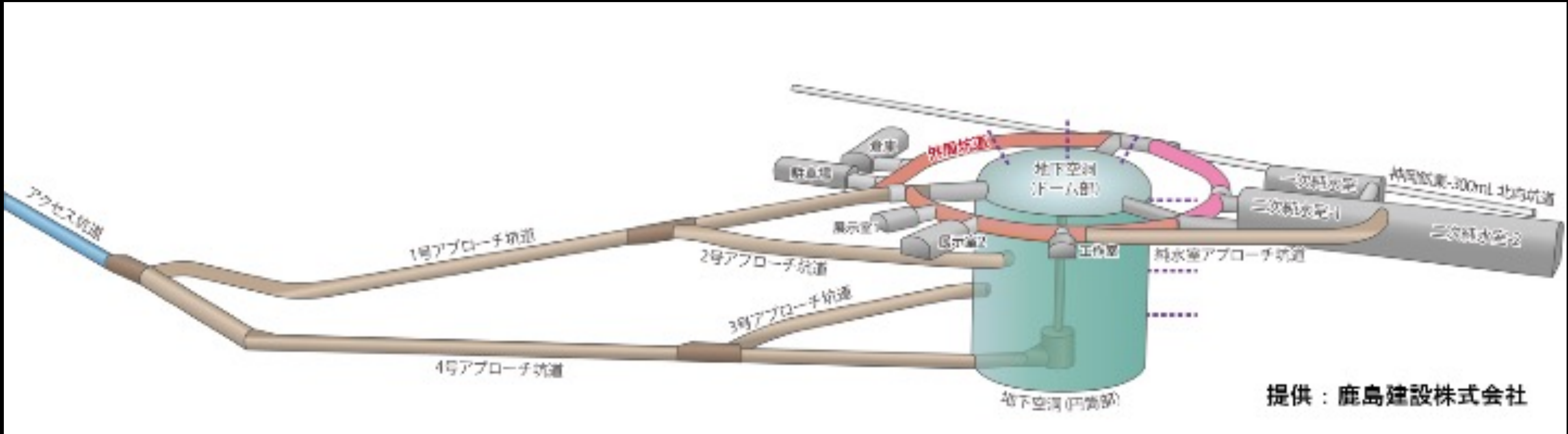
Summary

- Hyper-Kamiokande is the next generation neutrino experiment in Japan
  - 260 kton Underground water Cherenkov far detector
  - 1.3 MW upgraded neutrino beam from JPARC
  - Upgraded and additional near detectors
- Construction is underway, aim to begin operation in 2027
- Hyper-K aims to reveal the full picture of neutrino oscillations
  - CP violation, mass ordering, θ_{23} octant…
- International R&D ongoing to improve physics potential
- New collaborators welcome

Hyper-Kamiokande

Back up slides

Thank you for listening

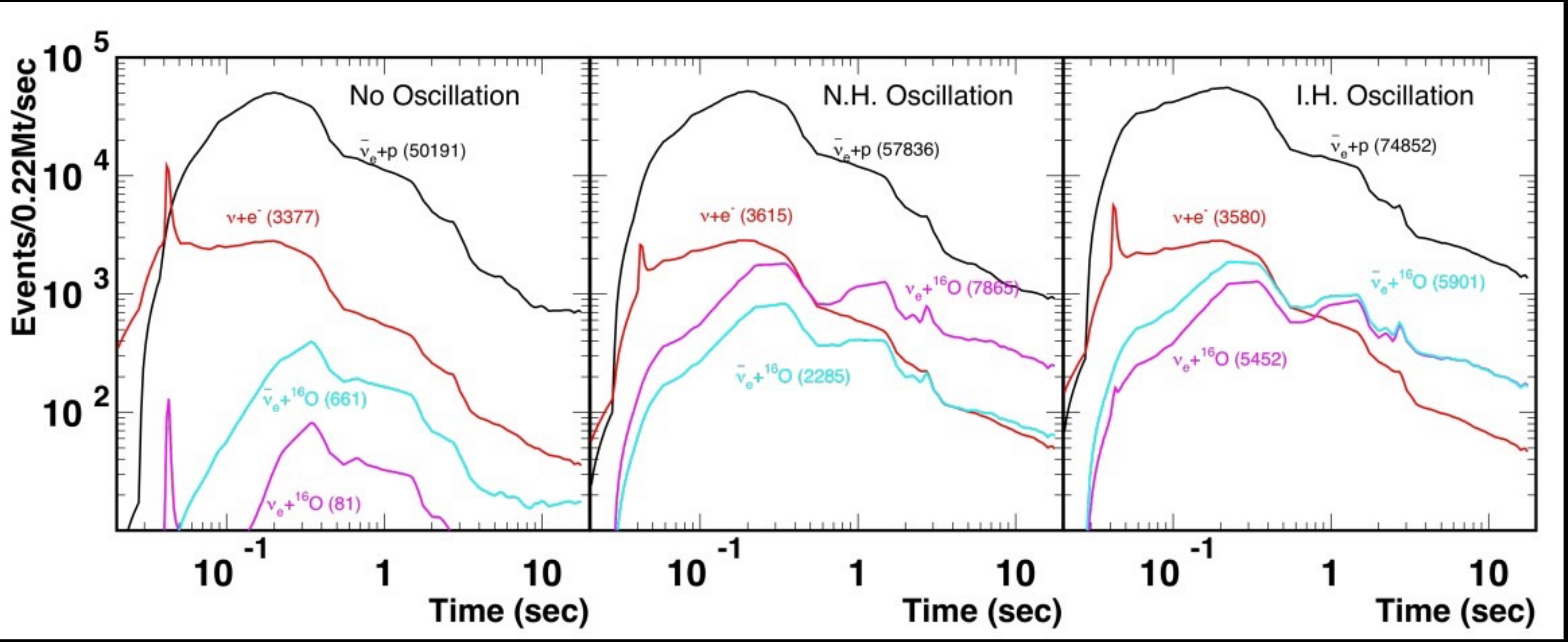

アクセス坑道
1号アプローチ坑道
2号アプローチ坑道
3号アプローチ坑道
4号アプローチ坑道
倉庫
展示室1
展示室2
工作室
地下空洞
(ドーム部)
地下空洞(円筒部)
純水室アプローチ坑道
一次純水室
二次純水室1
二次純水室2

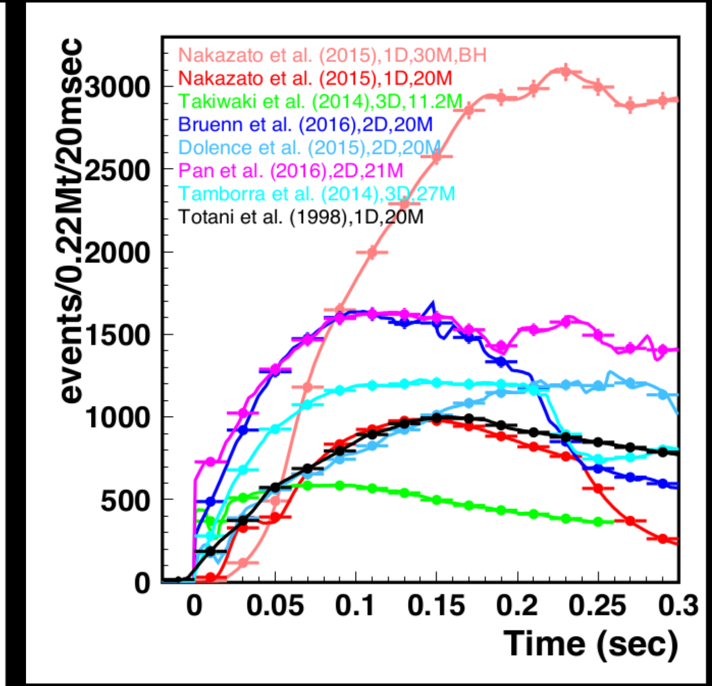
提供：鹿島建設株式会社

Neutrino Astrophysics – Supernova Bursts

- Expected time profile and event numbers in HK for a supernova at 10 kpc (Livermore simulation)
  - numbers in brackets total interactions integrated over the 10 s burst
  - peak event rate of inverse beta decay events (black) reaches ~50 kHz
  - Model discrimination - **arXiv:2101.05269**

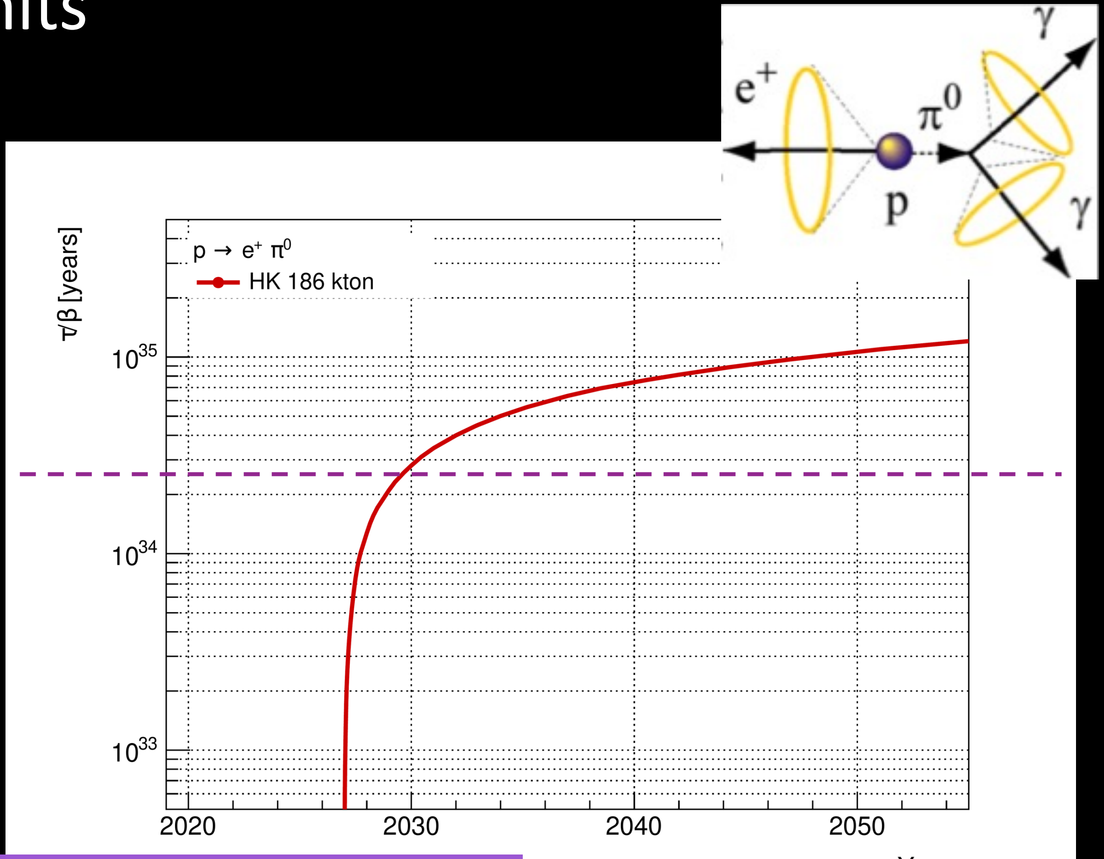
DAQ designed to cope with peak data rates from very close SN (eg. Betelgeuse)



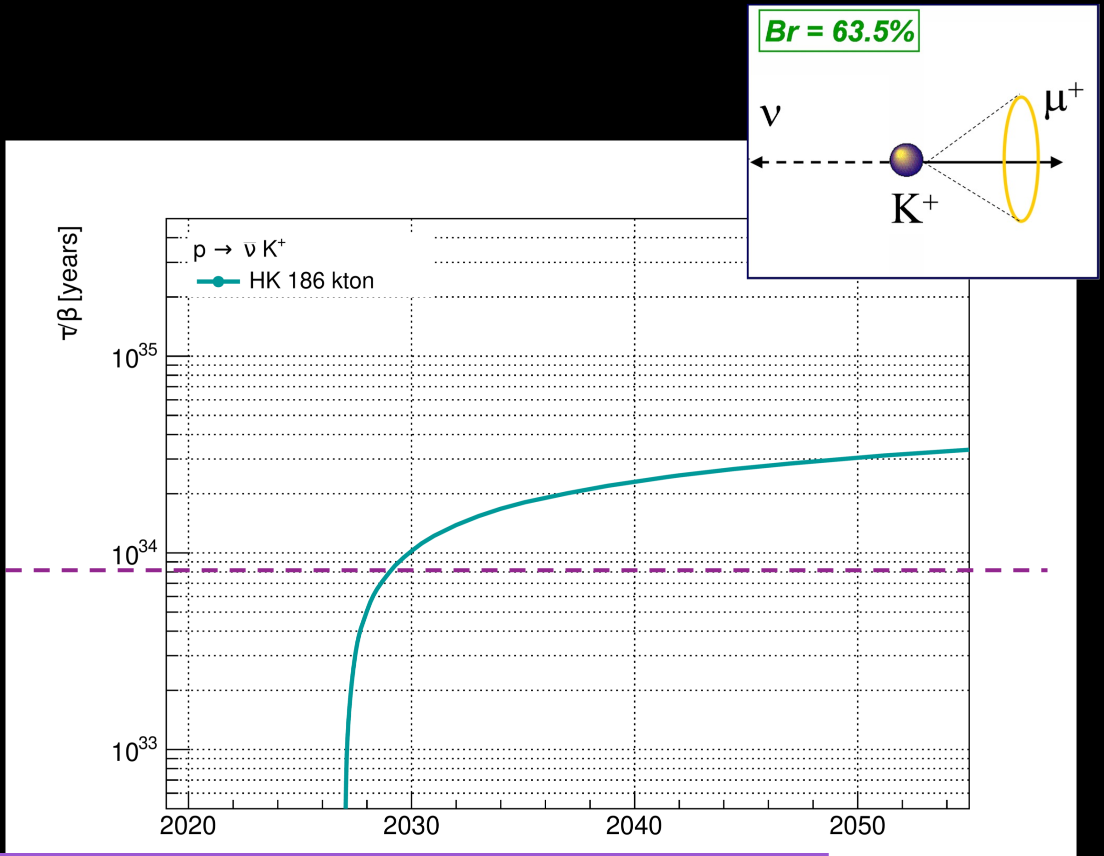


Proton Decay

- Hyper-K far detector has many protons!
- Can extend proton decay search by an order of magnitude beyond current limits

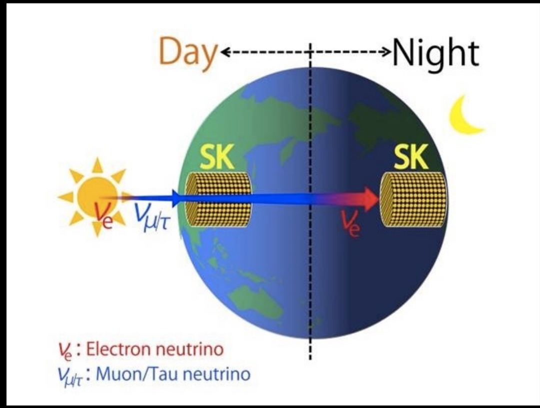


$\tau > 2.4{\times}10^{34}$years (Super-K)
Phys. Rev. D 102, 112011 (2020)

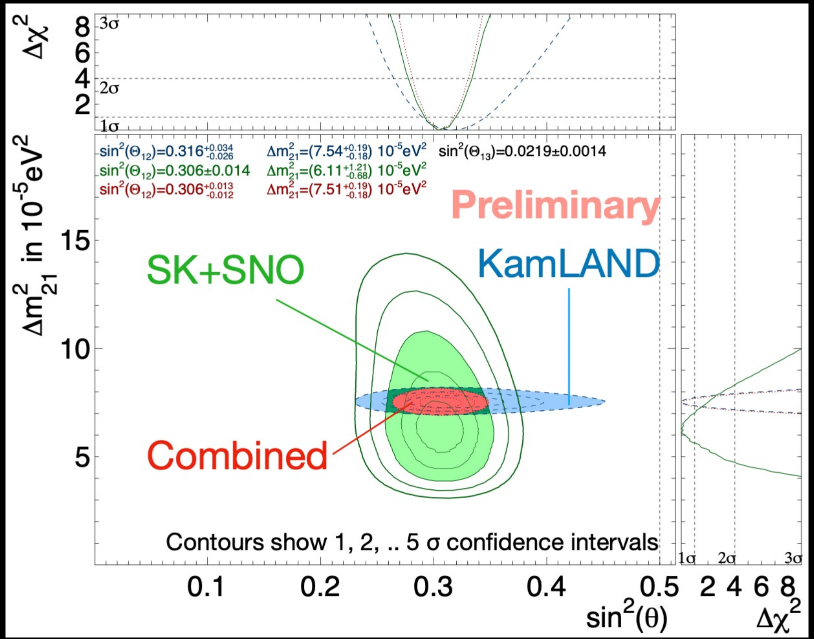


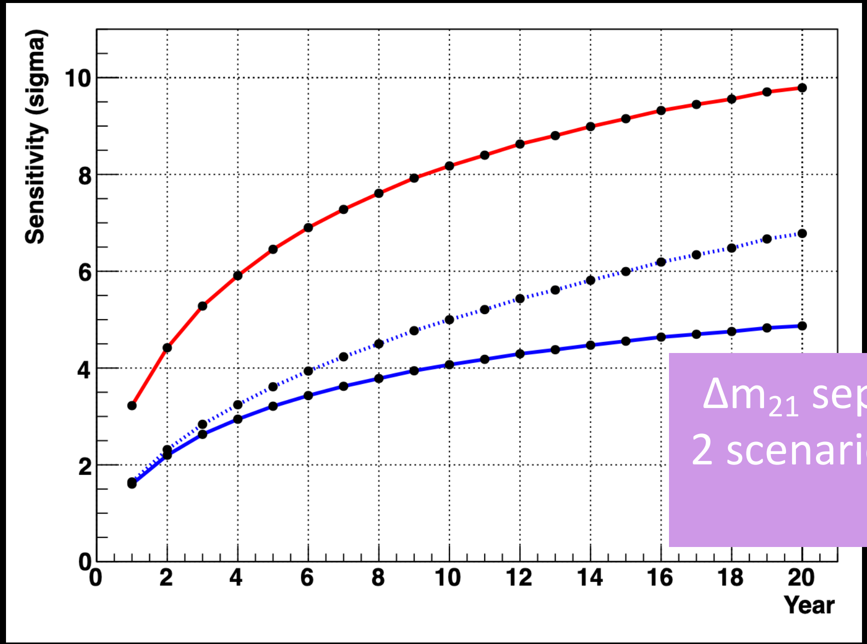
$\tau > 0.82{\times}10^{34}$years (Super-K)
Nucl.Instrum.Meth.A 952 (2020) 161634

Solar Neutrinos



Governed by the oscillation parameters θ_{12} and Δm^2_{21}



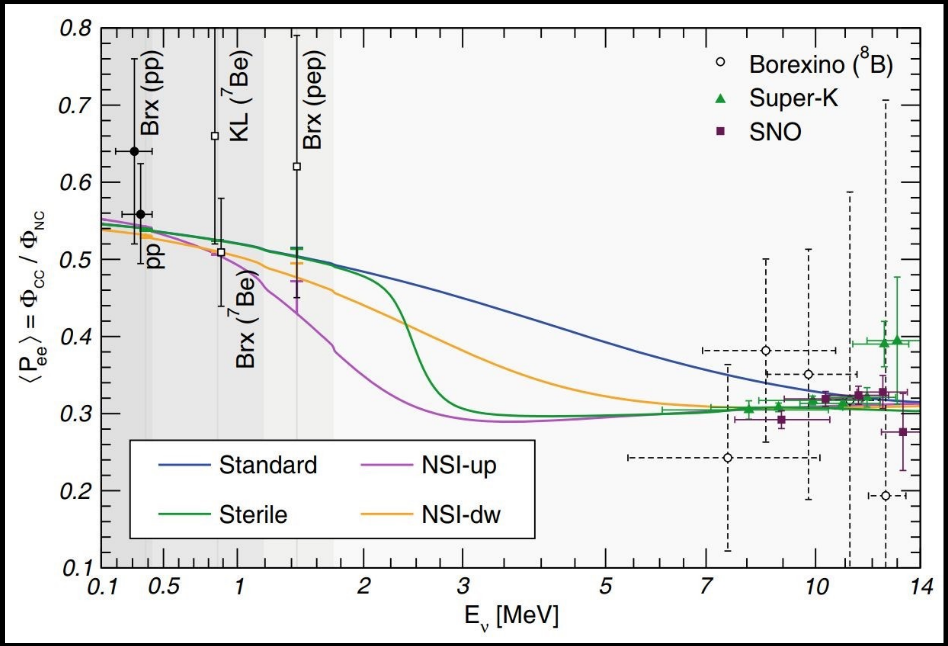


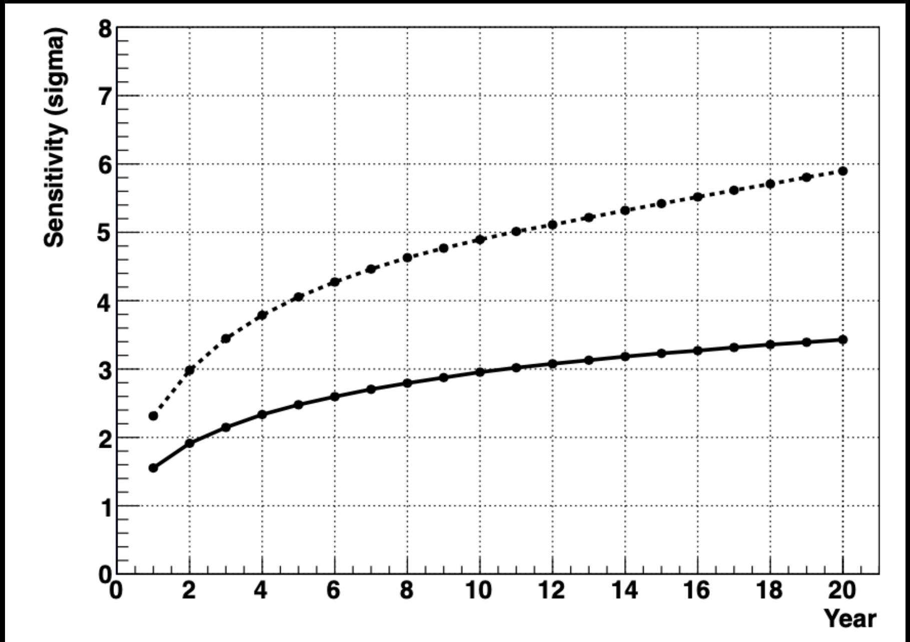
Δm_{21} separation ability between the 2 scenarios is expected to reach 4−5σ level with 10y data

- ~2σ tension exists in Δm^2_{21} between reactor (KamLAND) and Solar data
- Super-K observed day-night flux asymmetry is ~4%, higher than the expectation from reactor data

- Day-night asymmetry observation sensitivity
- red line = sensitivity from no asymmetry
- blue line = asymmetry expected by the reactor neutrino oscillation
- Systematic from remaining background direction 0.3% (solid) 0.1% (dashed)

Solar Neutrinos

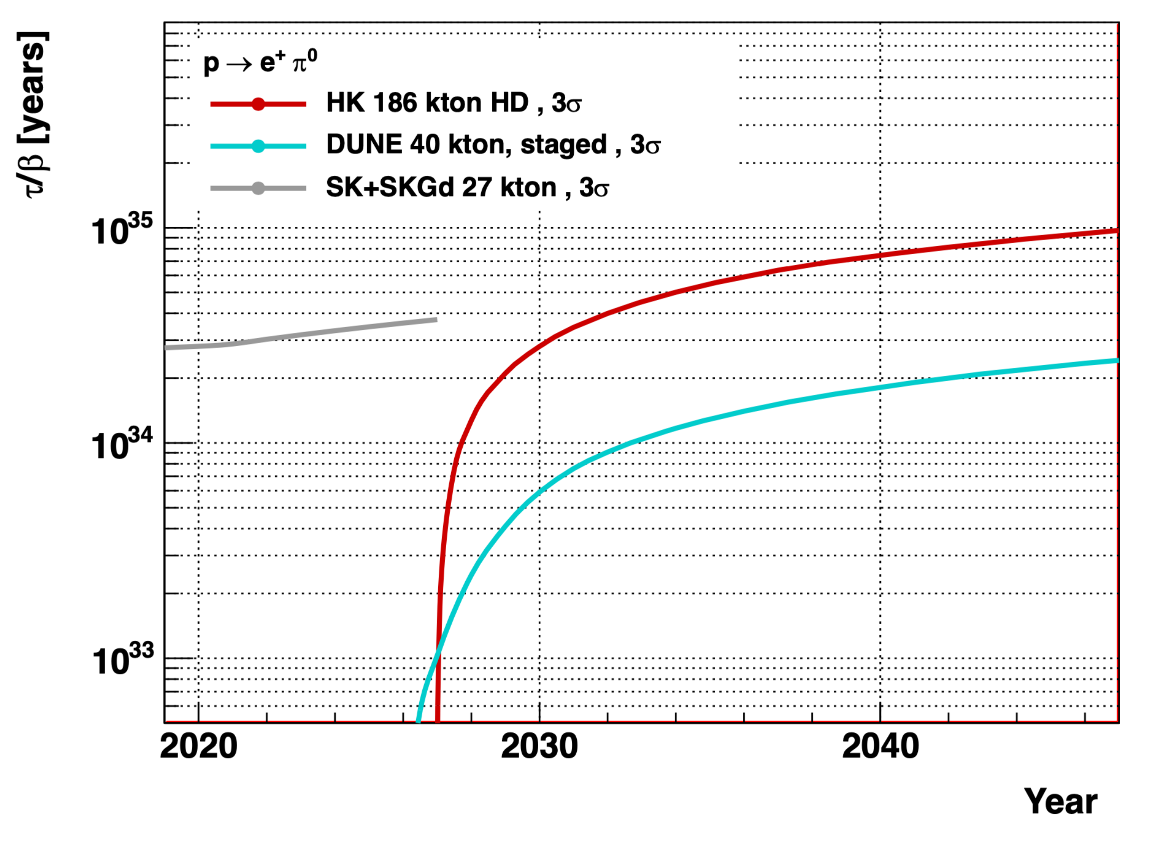


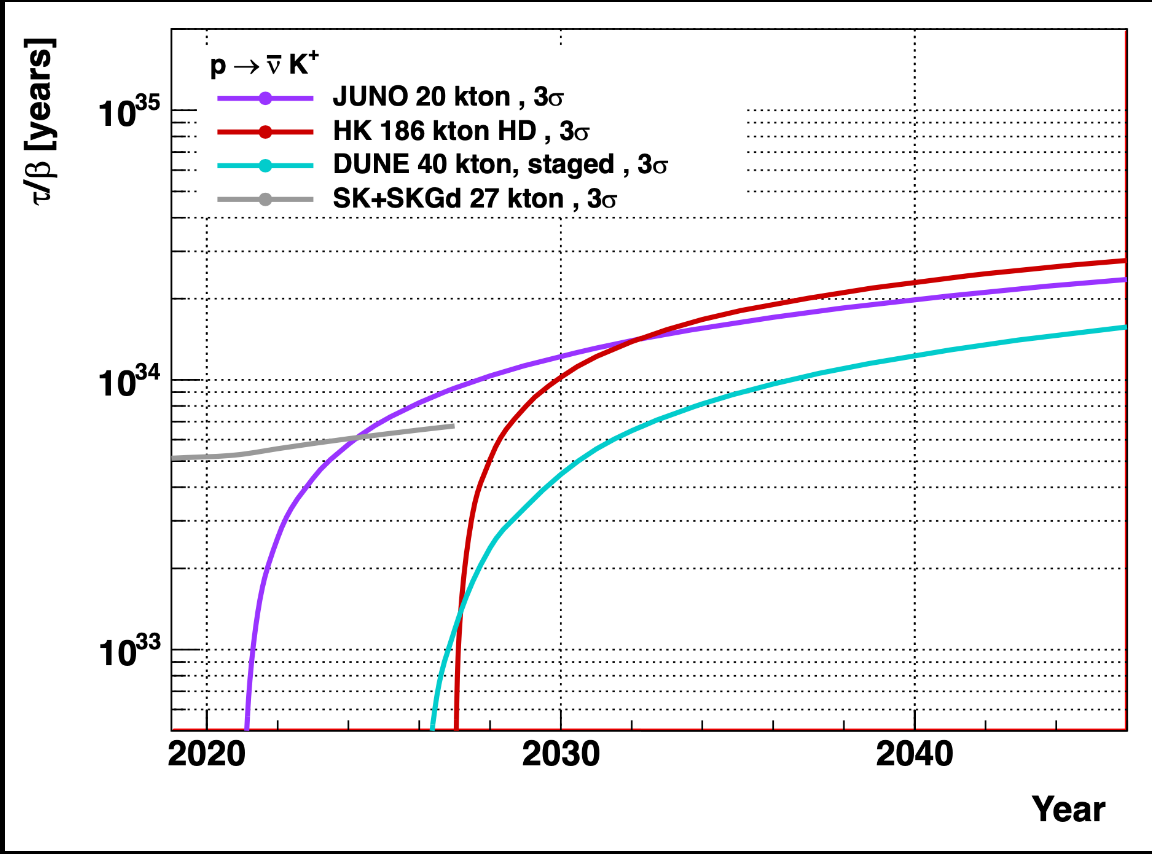


- If energy threshold is lowered, observation of the upturn in the solar neutrino survival probability might be possible
- Distinguish standard neutrino oscillations from several exotic models

- Spectrum upturn sensitivity in Hyper-K with
  - 4.5MeV threshold (solid line)
  - 3.5MeV threshold (dashed line)

Proton Decay vs other experiments (wrong timescales)





Project Status

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027

MOU signed, May 2020

Ground-breaking May 2021

Access tunnel complete, Feb 2022

Approach and Peripheral tunnels, Summer 2022

Operation starts 2027

Cavern Excavation

Tank Construction

Installation

Water filling

PMT production