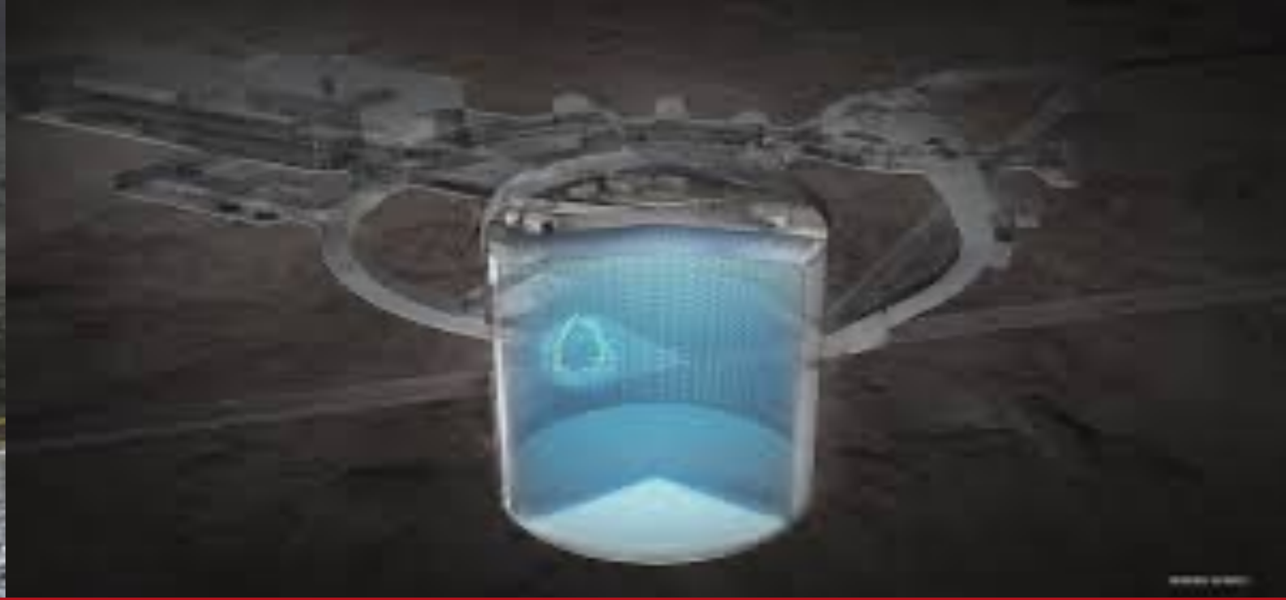

Status and Opportunities of the Hyper-Kamiokande Experiment

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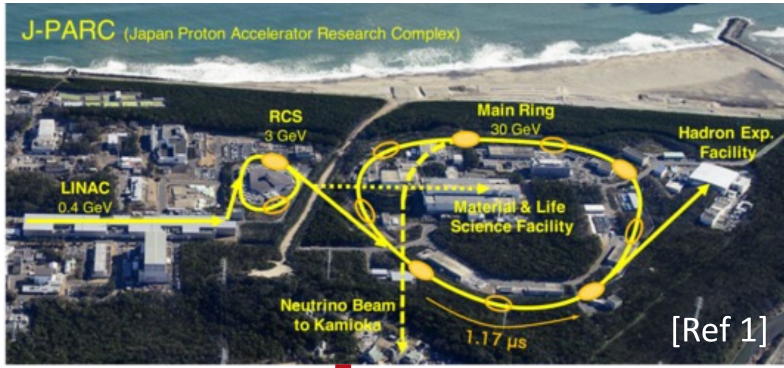
Contents

Introduction

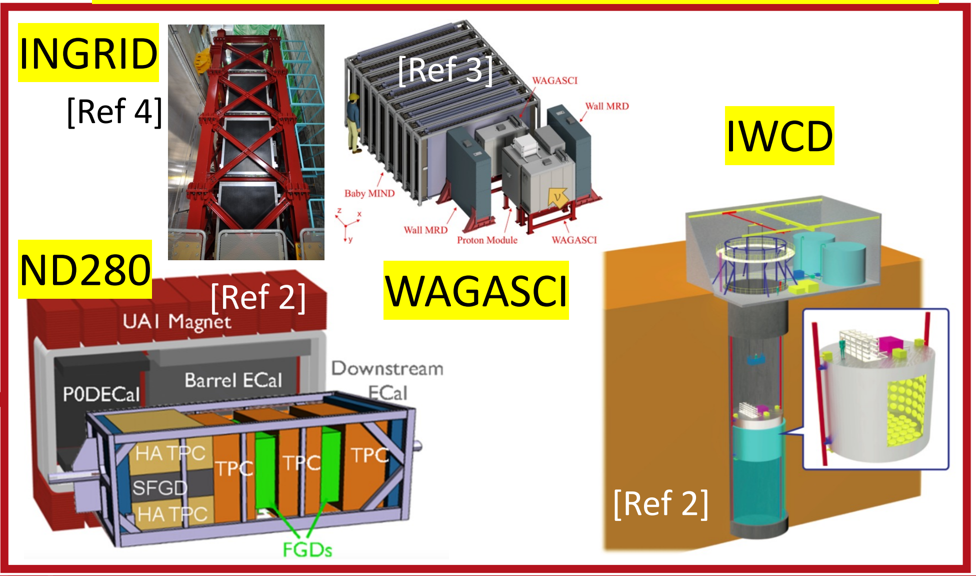
What is Hyper-K?

- **Hyper-Kamiokande** is the third-generation underground water Cherenkov detector in Kamioka, following Kamiokande and Super-Kamiokande
- **Fiducial mass ~186 kton** : roughly **8 times larger than Super-K**!
- Designed both as a **long-baseline neutrino detector** and as a **rare-event / neutrino-astronomy observatory**



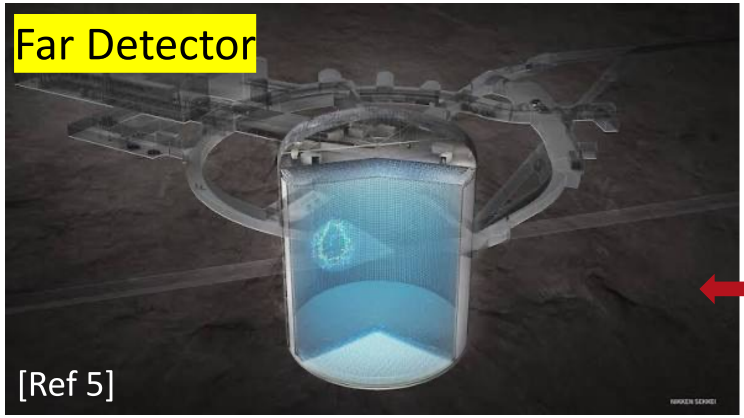
J-PARC

Upgraded Near and Intermediate Detectors



Why Hyper-K?

- **Not just bigger: higher statistics + improved systematics**
- Primary aim of constraining the **CP violating parameter**, δ_{CP}



Neutrino Physics Motivation

- **Neutrino oscillations** show that neutrinos have mass, requiring physics beyond the original Standard Model

$$|\nu_\alpha(t)\rangle = \sum_{j=1}^{3} U_{\alpha j} e^{-i(E_j t)} |\nu_j\rangle$$

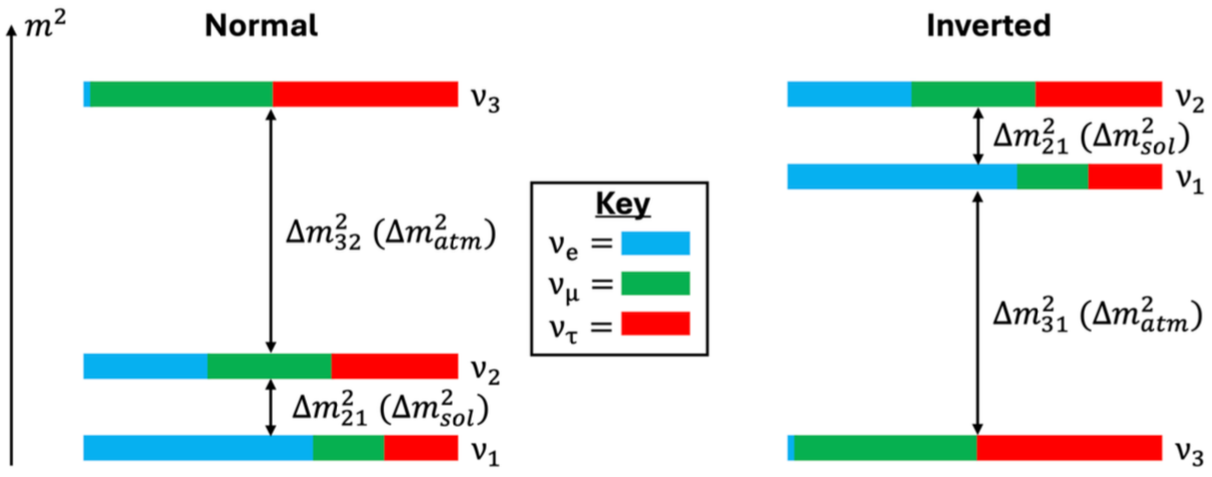
Flavour Eigenstates — PMNS Mixing Matrix — Mass Eigenstates

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

Atmospheric Neutrinos (ν_μ disappearance) — ν_e appearance in ν_μ beam OR Reactor Neutrinos — Solar Neutrino Oscillations — Majorana Neutrino Phases ($0\nu\beta\beta$)

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

The Neutrino Mass Ordering

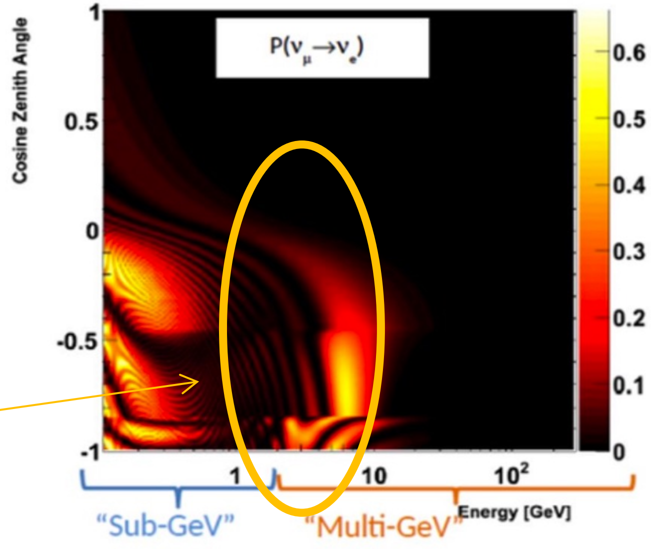


- The remaining unknowns include the **CP violation phase**, the **neutrino mass ordering**, the precision **structure of the PMNS matrix**, and whether θ_{23} is **maximal**

- Hyper-K will address these questions using **accelerator**, **atmospheric**, **solar**, and **astrophysical neutrinos**, while also searching for rare processes such as **proton decay**

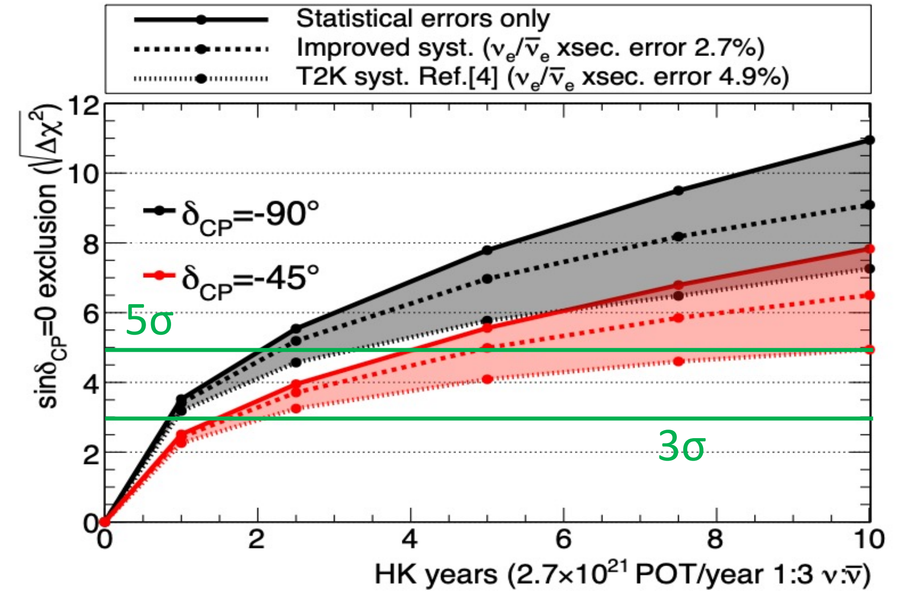
Atmospheric & Long-Baseline Neutrinos

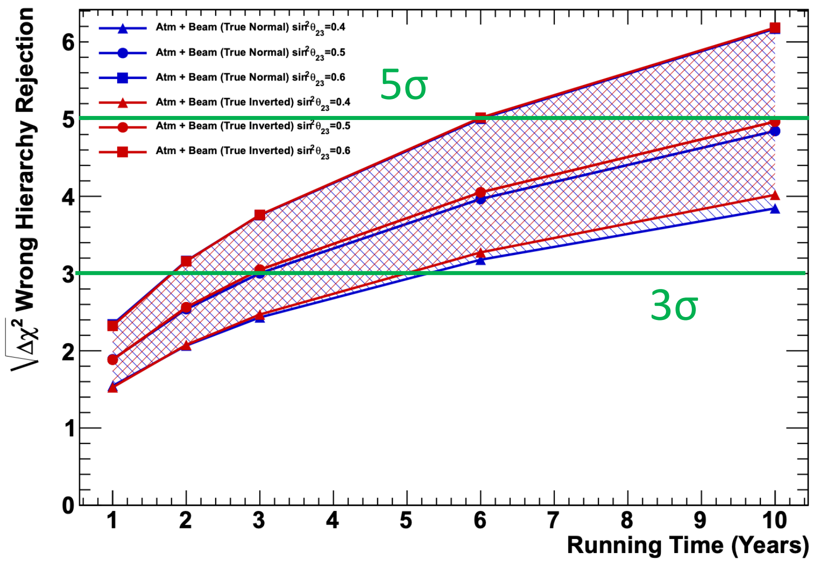
- **Atmospheric neutrinos** add sensitivity to the **mass ordering** through Earth matter effects.
- **Long-baseline ν_μ disappearance** constrains Δm^2_{32} and $\sin^2\theta_{23}$
- **ν_e / $\bar{\nu}_e$ appearance** gives sensitivity to δ_{CP} through differences between neutrino and antineutrino oscillation probabilities
- **World-leading** experiment to measure δ_{CP} and constrain CP violation in the next 10 years
- **Observe CP violation:** exclude $\sin\delta_{CP} = 0$
- For maximal CP violation ($\pm\,^{\pi}/_{2}$): **discover CP violation at 5σ in 2-3 years**



- $P(\nu_\mu \to \nu_e)$ for NO
- Matter Effect at 2–10 GeV
- [Ref 7]

Exclusion of $\sin\delta_{CP} = 0$ [Ref 6]



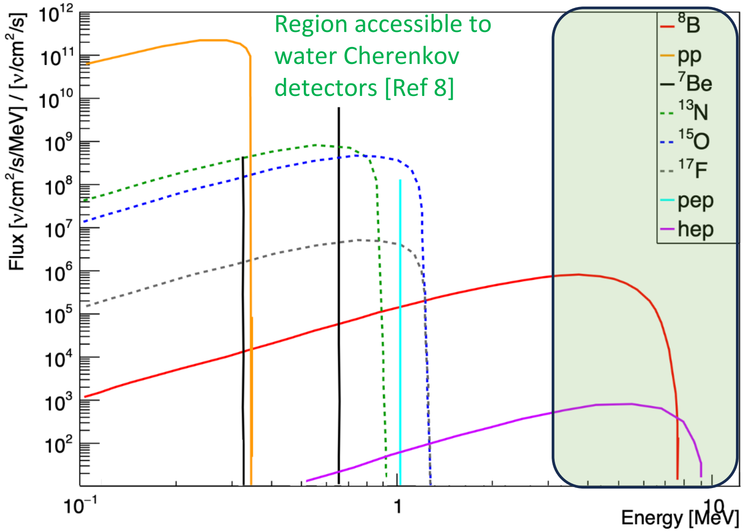


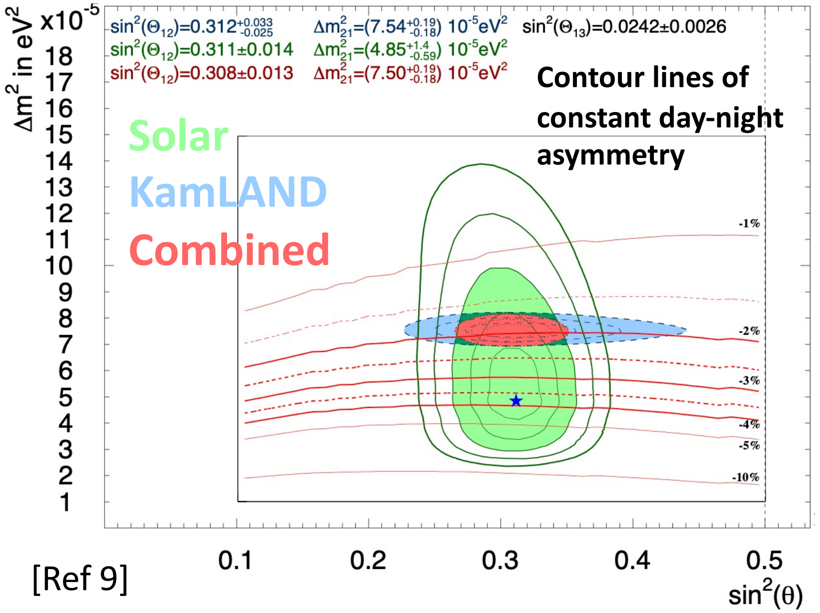
With 10 years of data taking, Hyper-K will determine the mass ordering "internally" at $\sim 4-5\sigma$ [Ref 9]

Solar Neutrinos

- Hyper-K will observe a high-statistics sample of solar neutrinos through $\nu - e$ **elastic scattering**, providing precision tests of **solar neutrino oscillations** and **matter effects**
- A key goal is to measure the solar **day-night asymmetry** with > 5σ significance (achievable with **10 years of data**), helping to resolve the **current mild tension** in Δm^2_{21} between Super-K and KamLAND, which is currently $\sim 1.5\sigma$
- Hyper-K also aims to observe the **low-energy upturn** in the solar ν_e survival probability, expected from the transition between matter-dominated and vacuum-dominated oscillations

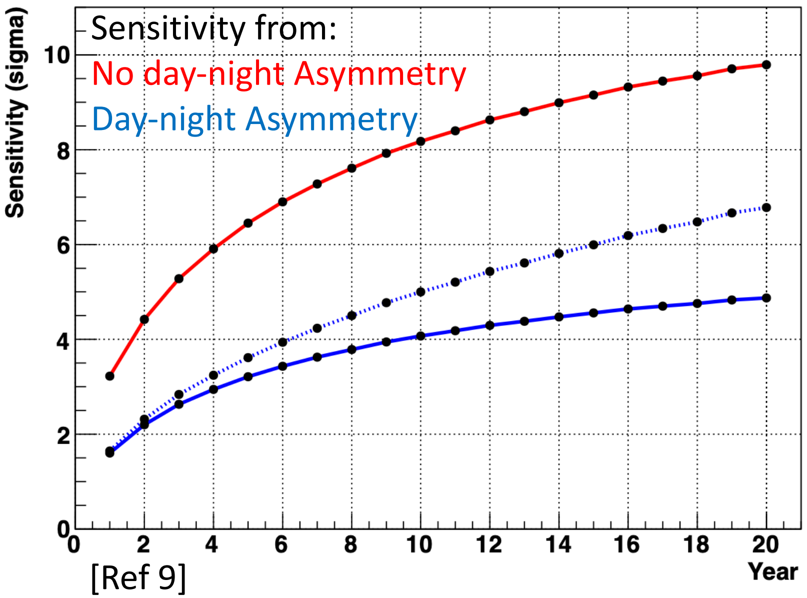
Solar Neutrino Flux Spectrum



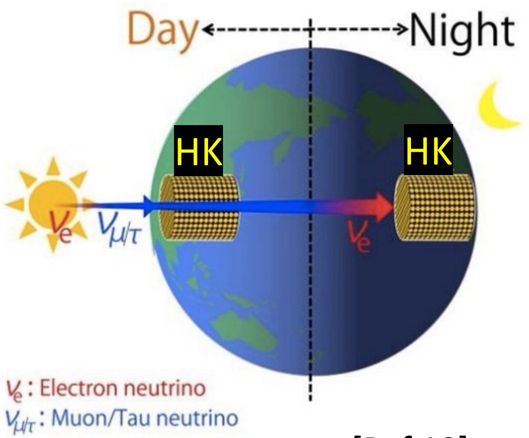


[Ref 9]

Day-night Asymmetry Observation Sensitivity



[Ref 9]



ν_e flux differs between night and day due to matter effects!

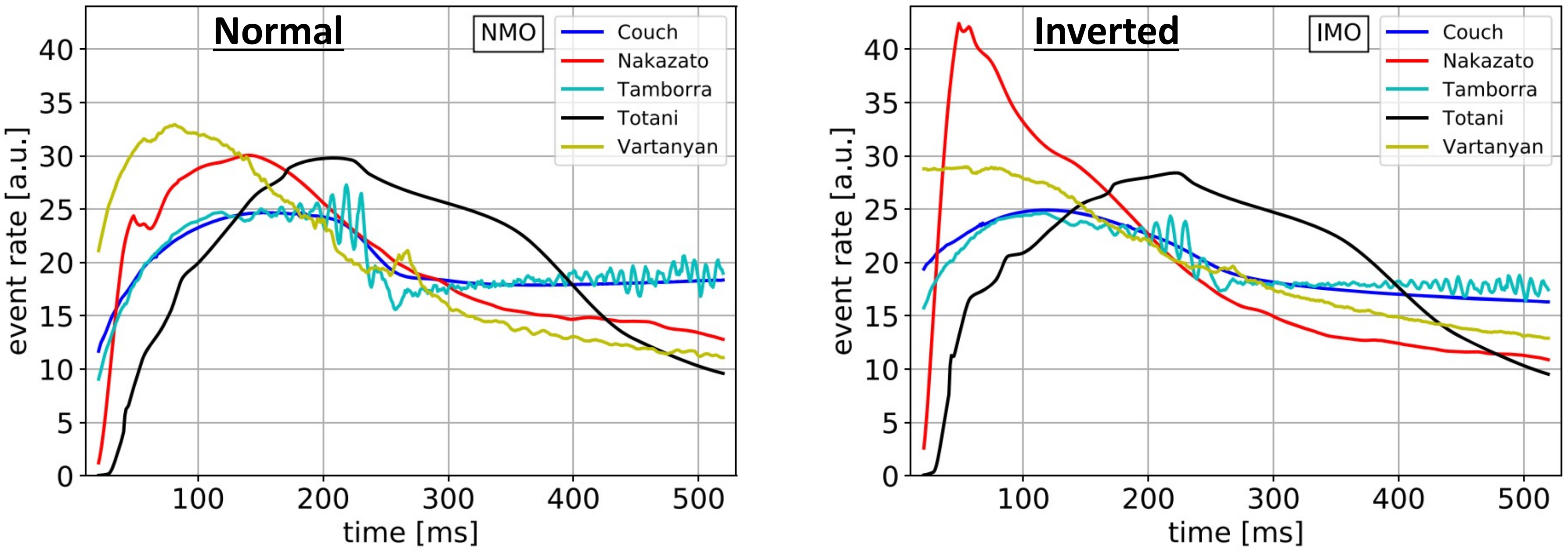
[Ref 10]

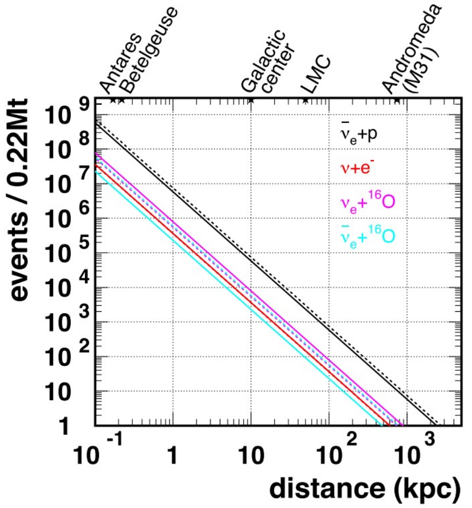
Supernova Neutrinos

- A **Galactic core-collapse supernova (SN)** would produce a very high-statistics **neutrino burst** in Hyper-K
- Time, energy, and flavour information probe supernova core dynamics and neutrino properties
- Hyper-K can contribute to **early warning** and pointing through elastic-scattering events
- **70k events for a SN at 10 kpc** (SN1987A at 50 kpc was observed with ∼25 events)

Event rate of observed events in Hyper-K predicted by different SN models (events are normalized because distance to supernova is unknown) →

[Ref 11]



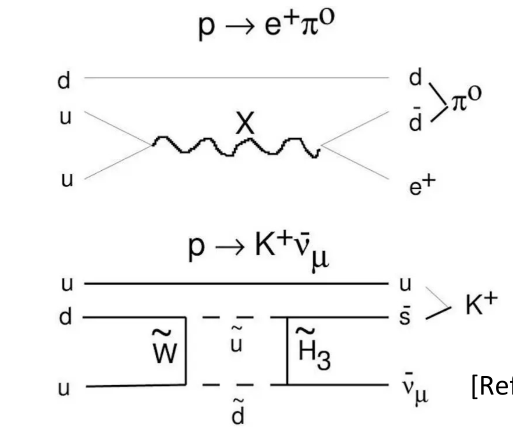


← Expected number of events as a function of SN distance [Ref 11]

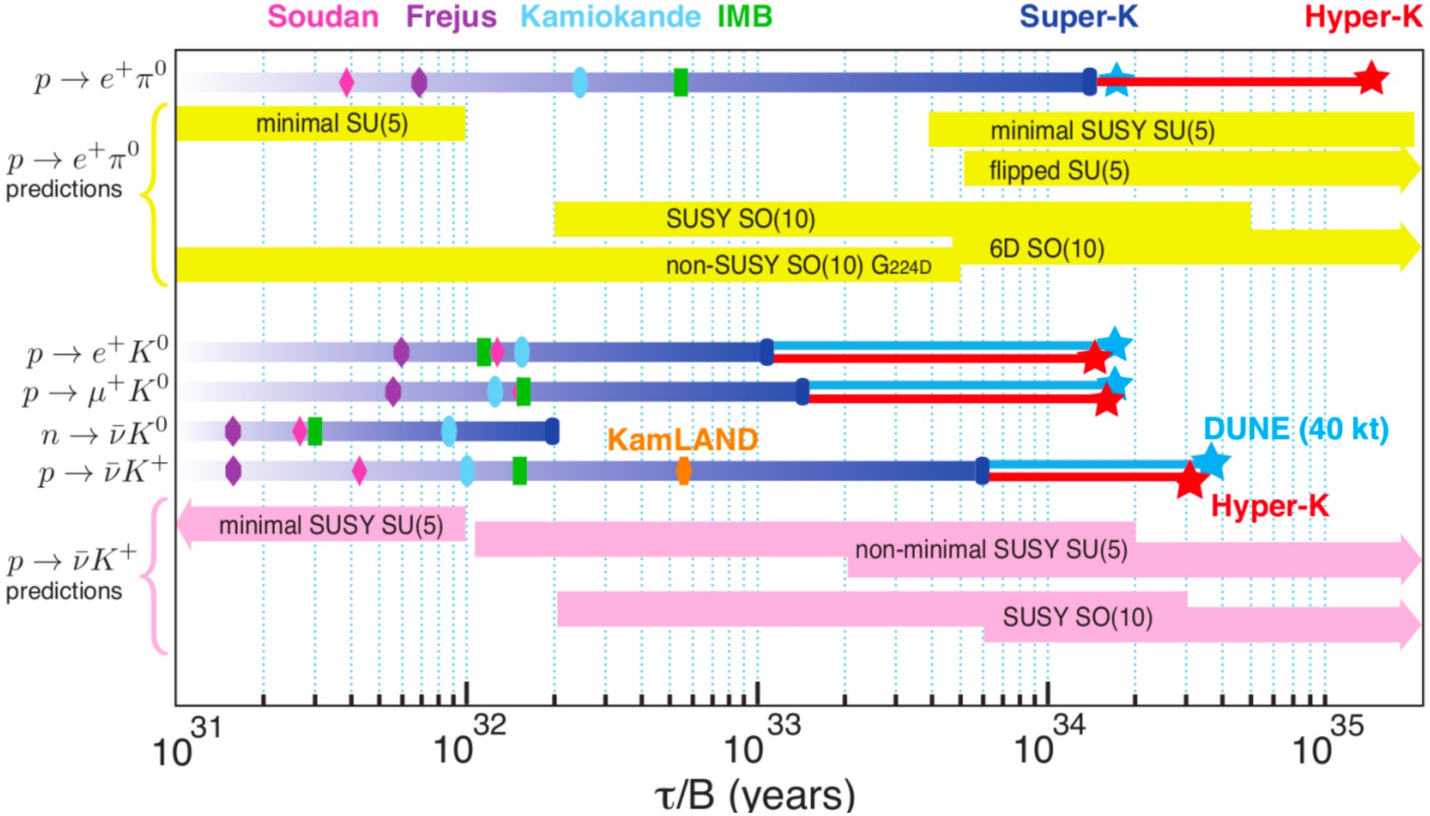
- **Provides sensitivity to the mass ordering!**
- **Hyper-K can build discriminators, to constrain SN models, using the time profile. See [Ref 11] for details**

Proton Decay

- Proton decay is a direct test of baryon-number violation and **Grand Unified Theories**
- Hyper-K greatly improves sensitivity through its large mass and excellent e/γ ring reconstruction
- Improve upon the half-life calculated by Super-K by a **factor of 10** in the main channel $p \rightarrow e^{+}\pi^{0}$
- Competitive with DUNE (4 modules) for other modes (e.g. $p \rightarrow K^{+}\bar{\nu}_{\mu}$)

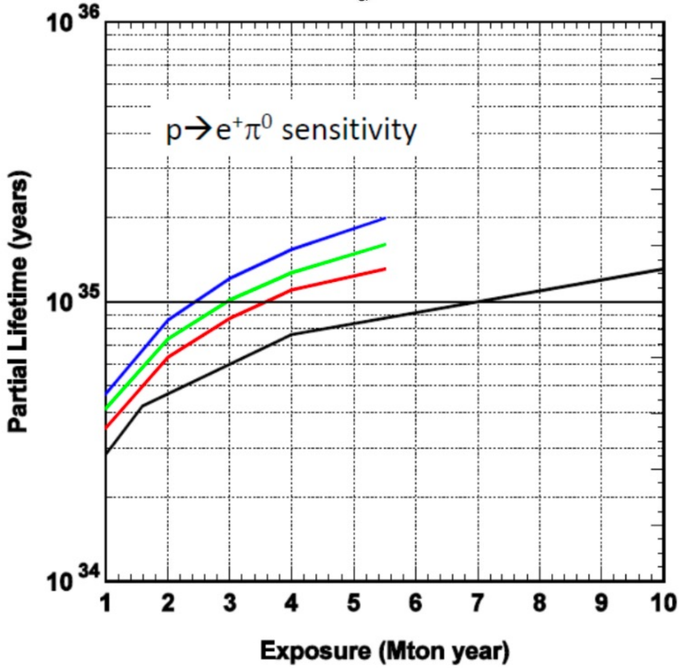


[Ref 12]



Calculated lifetime as a function of Hyper-K exposure [Ref 9] →

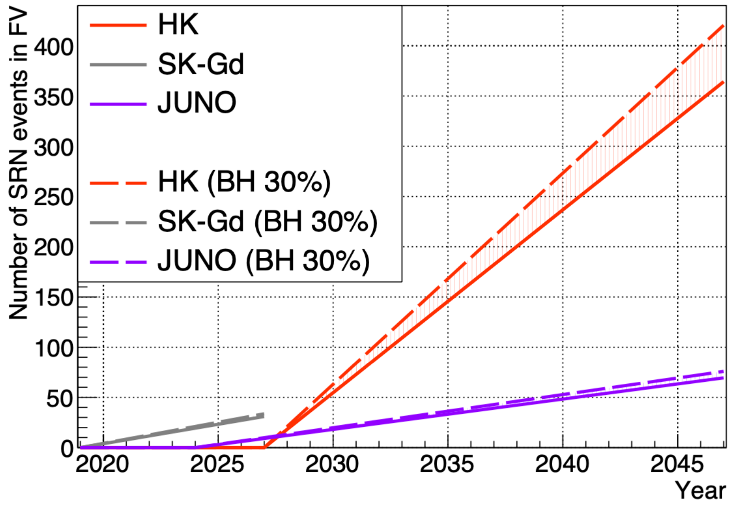
- Equivalent to Super-K
- Finer Binned Signal Region
- + 50% reduction in background
- Or 70% reduction



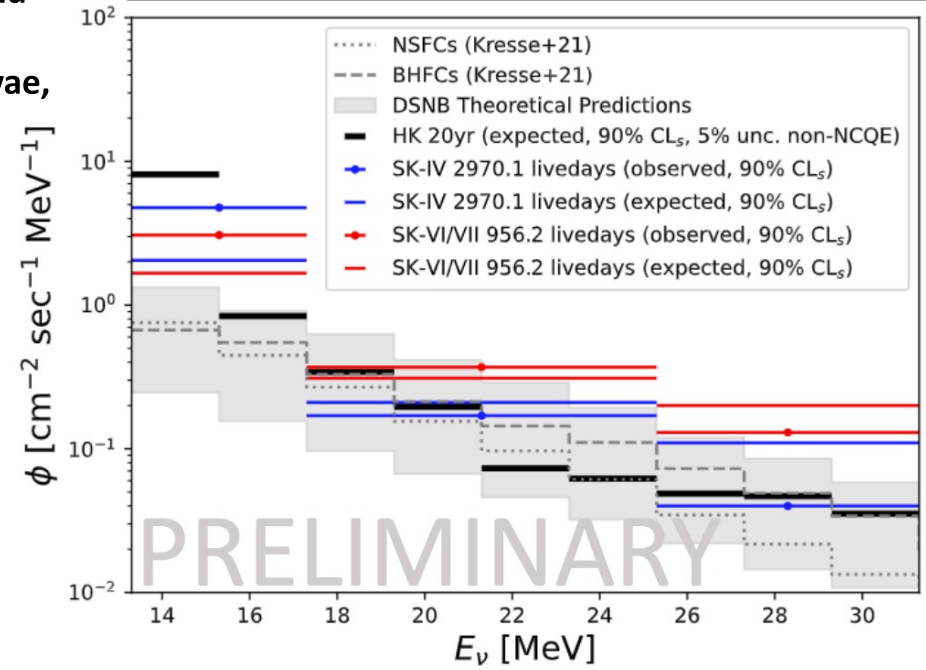
Astrophysical Neutrinos

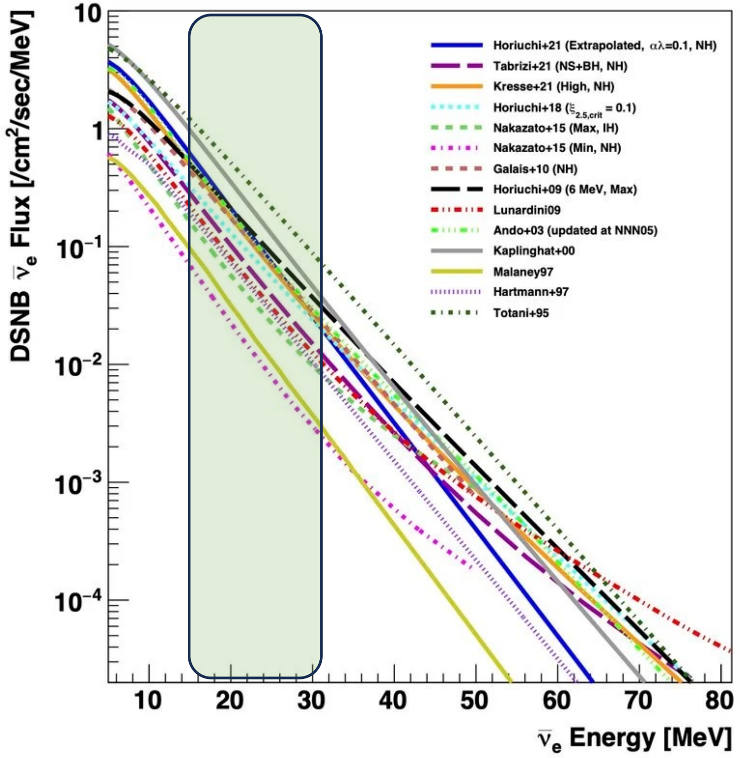
- Hyper-K will search for the **Diffuse Supernova Neutrino Background / Supernova Relic Neutrinos** (DSNB/SRN): the integrated signal from all past core-collapse supernovae
- Important to study because it probes the history of **heavy element synthesis in stars**
- The **10–30 MeV** region is especially important, between solar/reactor and atmospheric backgrounds
- Due to its **large mass**, Hyper-K will improve on the sensitivity of SK-Gd

Projected cumulative SRN events in Hyper-K, SK-Gd, and JUNO [Ref 9]. * Solid: standard 6 MeV supernova spectrum. * Dashed: 30% black-hole-forming supernovae, giving a higher-energy 8 MeV neutrino spectrum



Predicted Hyper-K Flux after 20 years [Ref 13]



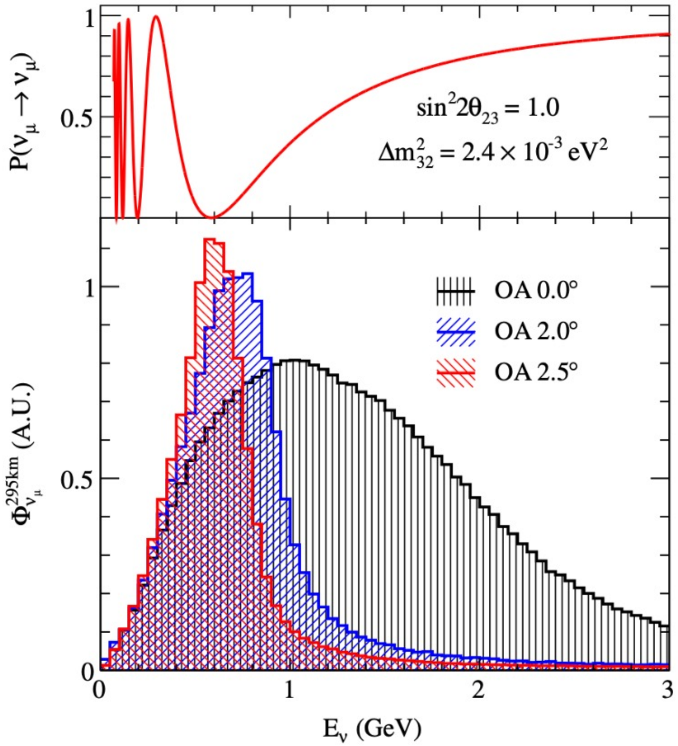


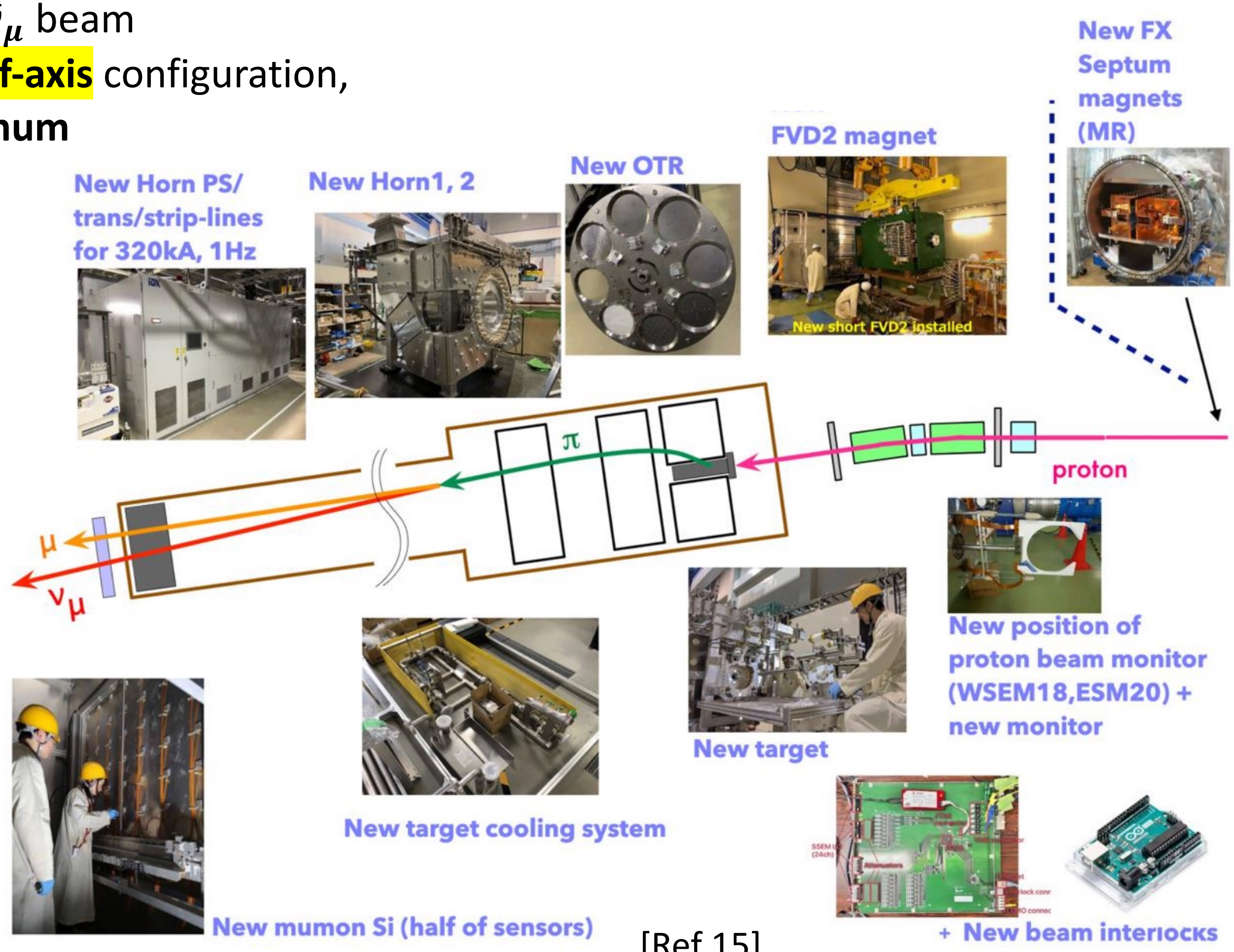
DSNB energy spectrum for different models. Below the optimal region, solar and spallation backgrounds dominates. Above this, atmospheric backgrounds dominate [Ref 14]. With future neutron tagging, backgrounds can be reduced, and the energy threshold may be improved

J-PARC Neutrino Beam

- **30 GeV protons** at J-PARC produce a high-intensity ν_μ / $\bar{\nu}_\mu$ beam
- Hyper-K keeps the **T2K-style 295 km baseline** and **2.5° off-axis** configuration, giving a narrow spectrum near the **first oscillation maximum**
- Beam power upgrade towards **1.3 MW** is essential for CP-violation sensitivity

Need an off-axis detector, to produce a neutrino flux peaked around the energy where oscillation effects are most likely to occur [Ref 16]

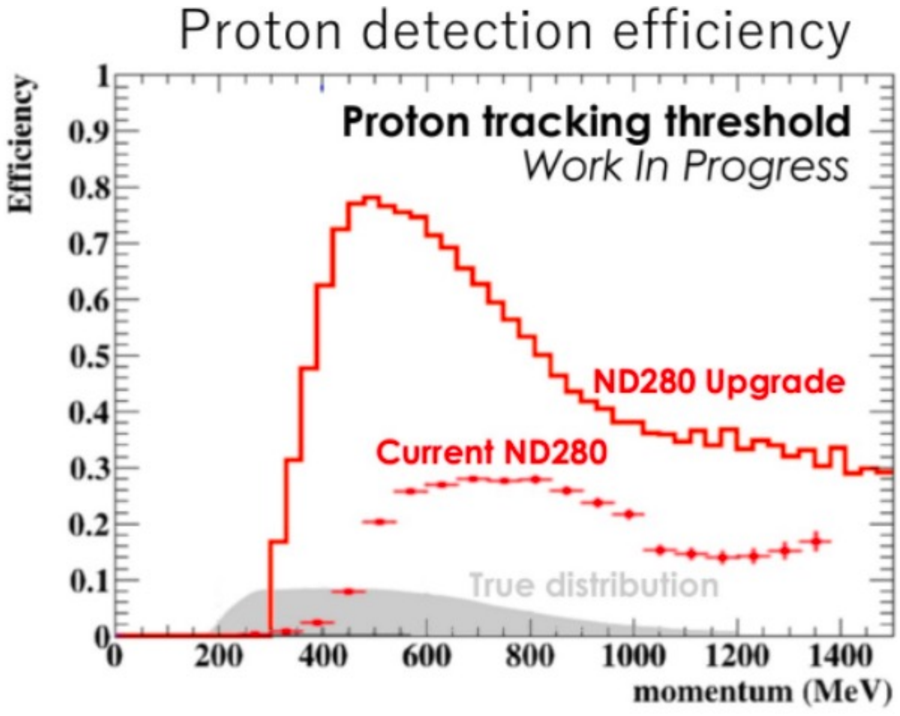




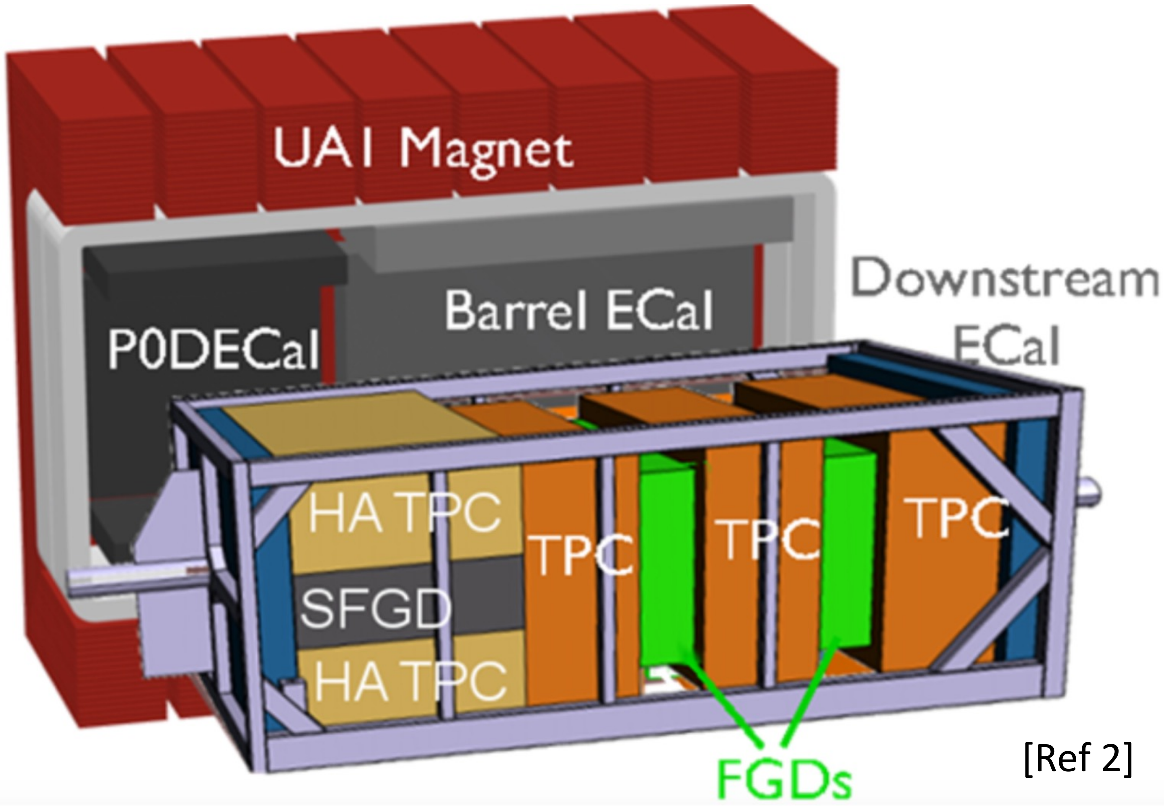
[Ref 15]

ND280

- Upgraded **Near Detector at 280 m** (ND280): High Angle-TPC, Time of Flight (ToF) detector, super Far-Grained Detector (sFGD)
- ND280 **constrains the unoscillated flux** and neutrino interaction model before extrapolating to Hyper-K
- Upgrade **improves acceptance** for high-angle tracks and gives finer-grained reconstruction of final-state particles
- Key for **reducing cross-section** and **detector-model systematics** in the long-baseline analysis
- Reduce uncertainties from 5% to 3%



[Ref 17]

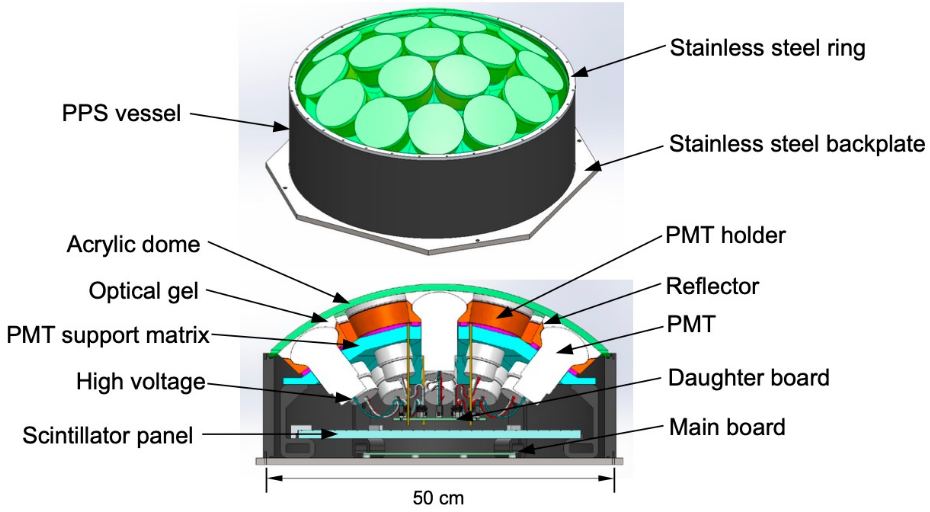


[Ref 2]

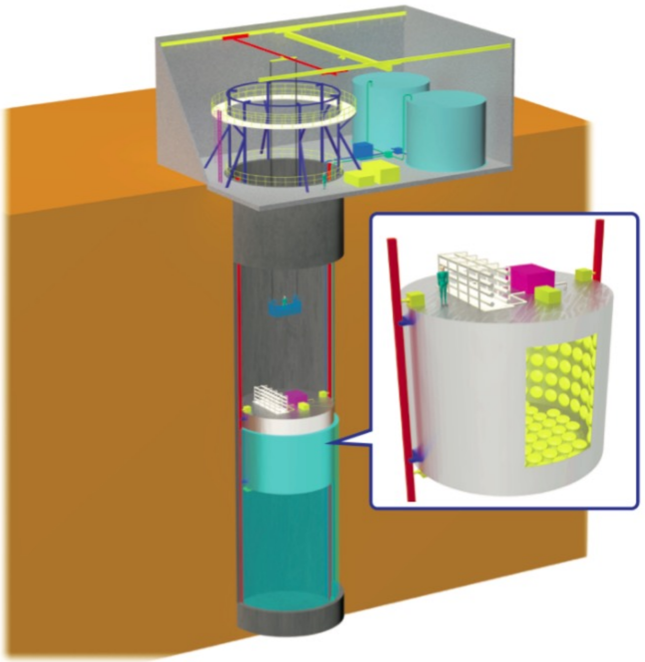
IWCD

- **The Intermediate Water Cherenkov Detector** (IWCD) is a water Cherenkov detector at an intermediate baseline, using the **same target medium** as Hyper-K (so **constrains flux and cross-section systematics** before extrapolating to the far detector)
- It can **move vertically** in a water-filled shaft, sampling different off-axis angles and therefore different neutrino energy spectra
- This helps separate **neutrino flux effects** from **neutrino interaction/cross-section effects**, which is crucial for precise measurements of δ_{CP}, θ_{23} and Δm^2_{32}
- Contains **480 multi-PMT modules** (19 x 3-inch PMTs per module)

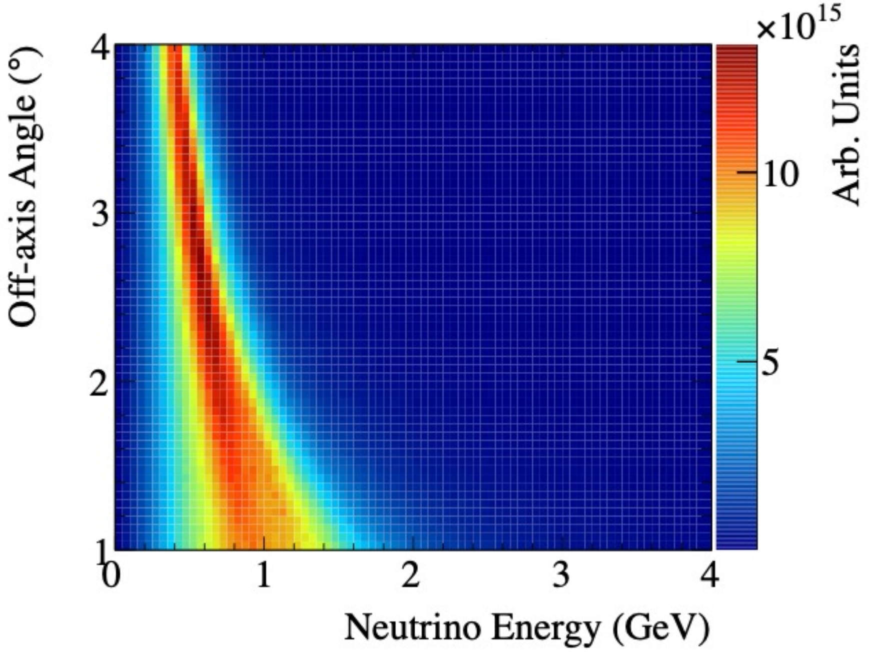
mPMT Module Design [Ref 18]



IWCD Design [Ref 2]

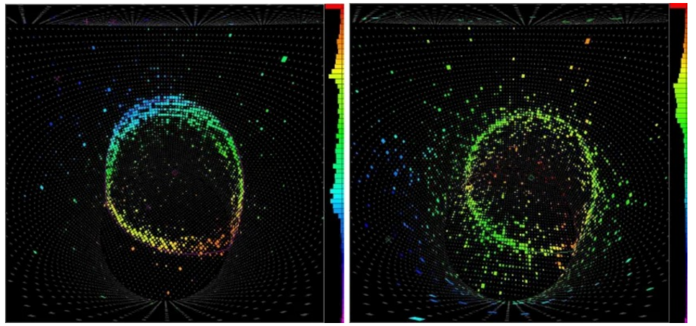


Neutrino Energy – Off-axis angle relation [Ref 9]

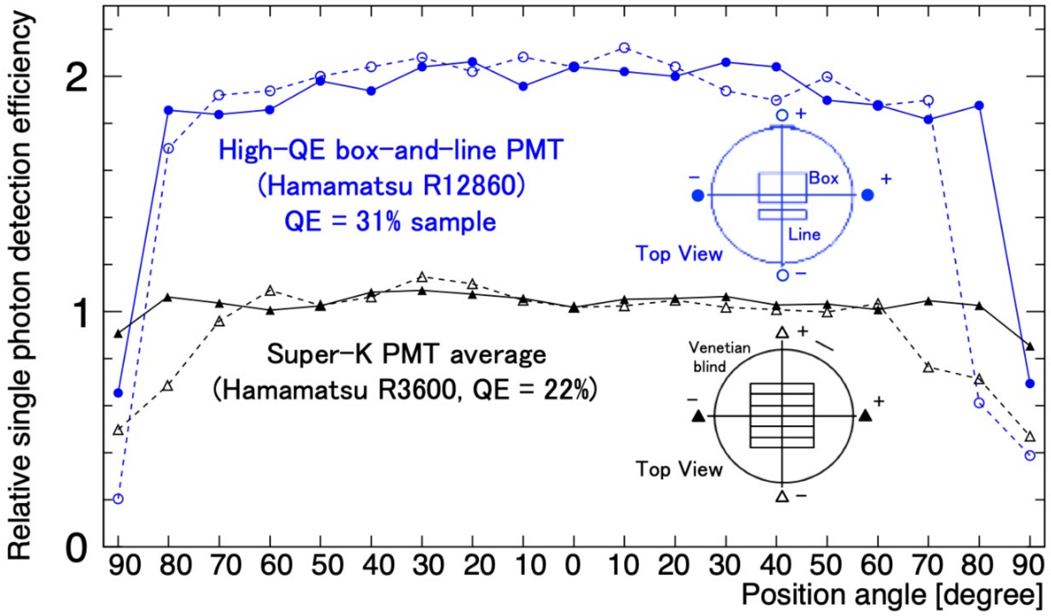


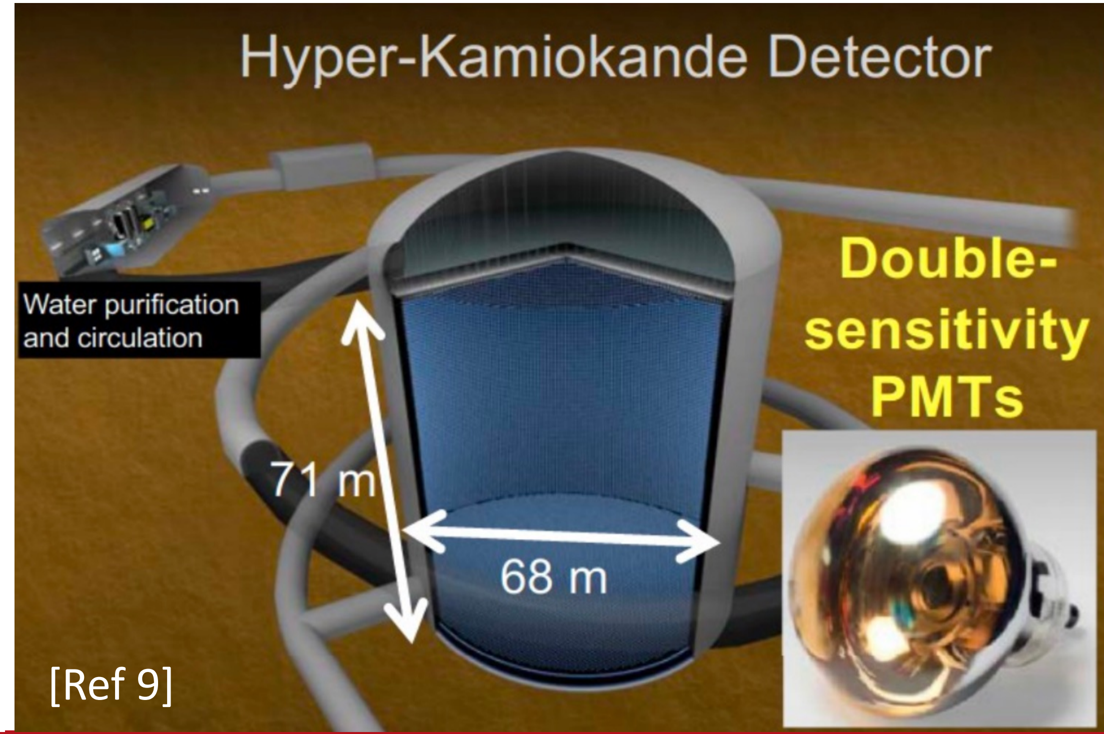
Hyper-K Far Detector – ID

- The Inner Detector (ID) is a cylindrical water Cherenkov detector: approximately **68 m diameter** and **71 m water depth**
- Reconstructs Cherenkov rings to **identify e-like and μ-like events**, determine vertex, direction, energy, and event topology
- **20,000** 20-inch high-sensitivity PMTs (Ø 50 cm)
- **808** multi-PMTs for increased angular resolution → **improved particle identification (PID)**
- **Less of a rock overburden than Super-K** (**650 m** compared to Super-K's 1000 m)



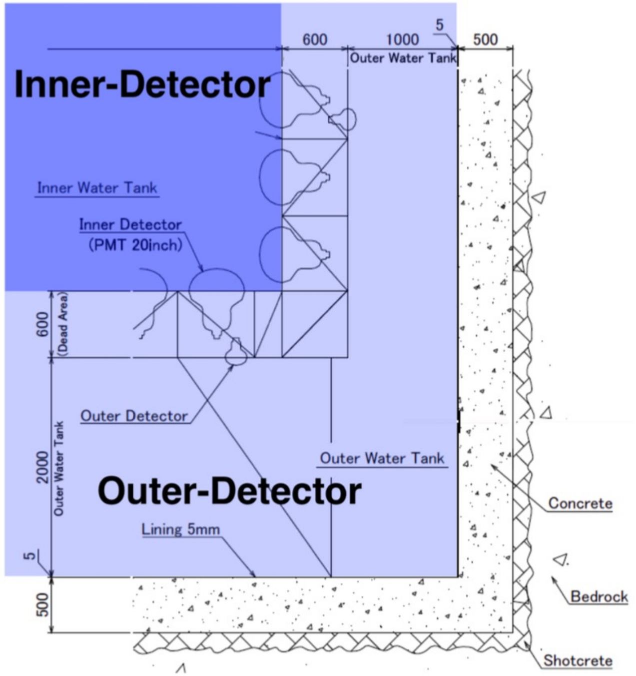
New 20-inch PMTs: higher single-photon detection efficiency than the Super-K reference PMT [Ref 9]





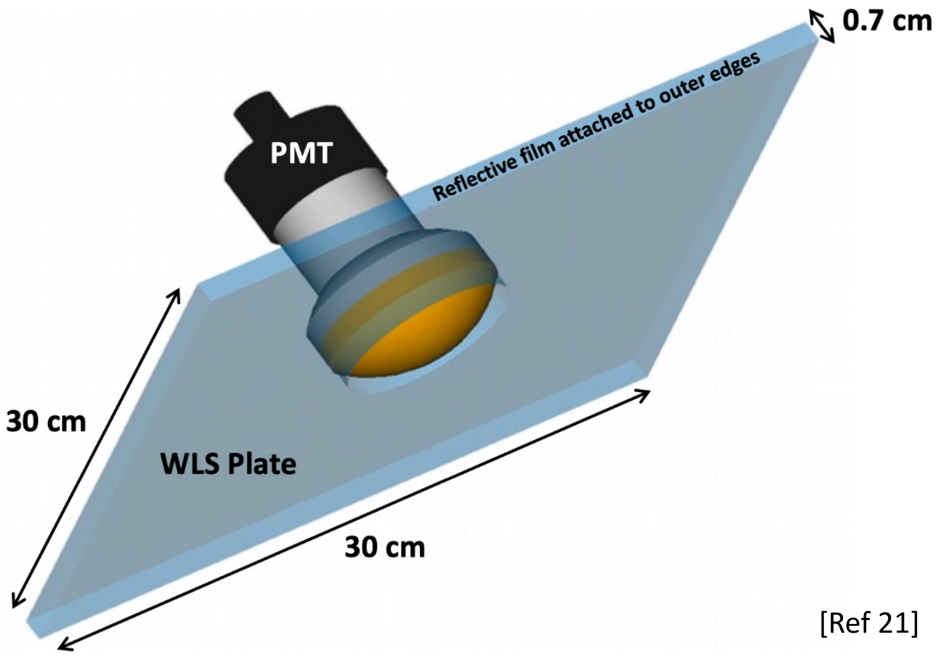
Hyper-K Far Detector – OD

- The **Outer Detector** (OD) **tags entering particles**, especially **cosmic-ray muons** and external backgrounds
- Improves **containment definition** & **background rejection** for atmospheric neutrinos, proton decay, and low-energy analyses
- Instrumented with **3,600 3-inch PMTs** and **wavelength-shifting (WLS) plates** around the ID
- WLS plates are **doped with fluorescent compounds**. They **absorb UV Cherenkov light** and re-emit it at blue/green wavelengths, **better matched to the PMT quantum-efficiency peak**
- **Reflective Tyvek** lines the OD walls, including the inner OD walls behind the WLS plates, helping to **recover otherwise lost Cherenkov light** through reflections



[Ref 19]

[Ref 20]



[Ref 21]

Current Status and Conclusions

- The main Hyper-K **cavern excavation has been completed** (31-07-2025), marking a major construction milestone
- Work is now progressing on the **water tank, ultra-pure water system, tank liner, photosensors, electronics, and detector-support infrastructure**
- 19th February 2026: J-PARC achieved a **beam power of 1 MW!** Onwards to 1.3 MW!
- **Detector assembly and installation** are expected to proceed through 2026–2027, followed by **tank filling and commissioning**
- Hyper-K is scheduled to **begin full-scale operation in early 2028**, opening a broad programme in long-baseline neutrino oscillations, atmospheric and solar neutrinos, supernova neutrinos, astrophysical neutrinos, and proton decay
- Virtual tour at https://www-sk.icrr.u-tokyo.ac.jp/en/hk/virtual/

Key Takeaway: Hyper-K is not only a bigger Super-K: it is a precision oscillation experiment and a multi-purpose neutrino observatory!

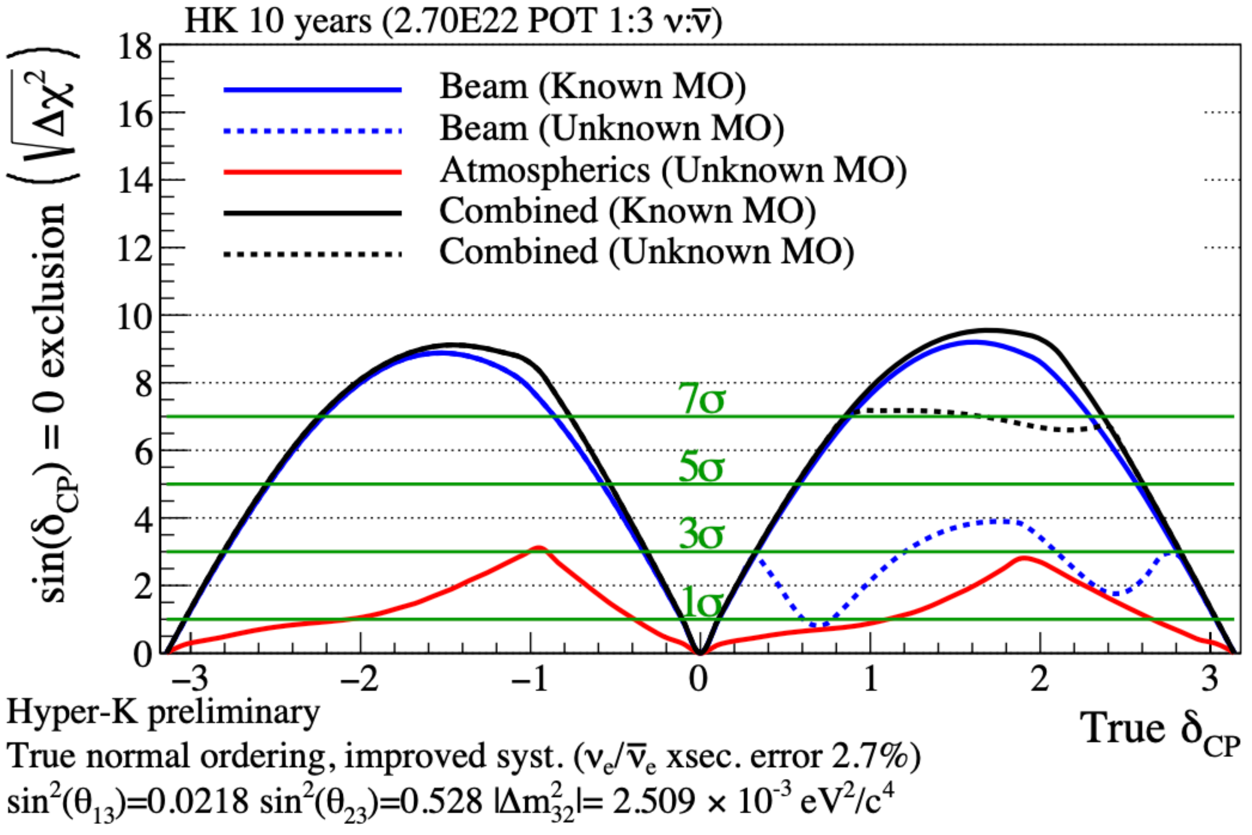
Thank you for listening!

Backup Slides

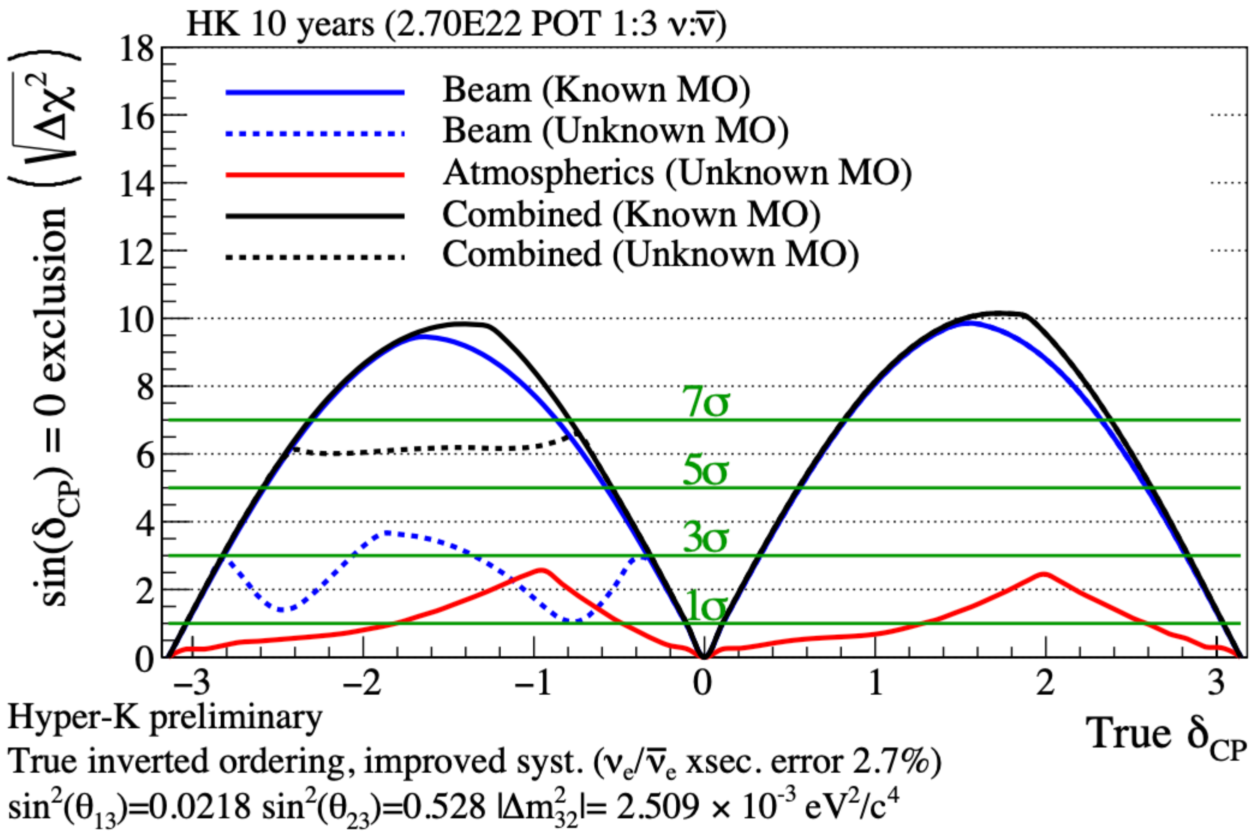
δ_{CP} Potential

- CP violation constraint is weaker if the MO is not known, but atmospheric samples allow HK to determine the MO
- The MO will be measured by JUNO, DUNE, KM3NET etc. (a binary input)

Normal Ordering [Ref 7]



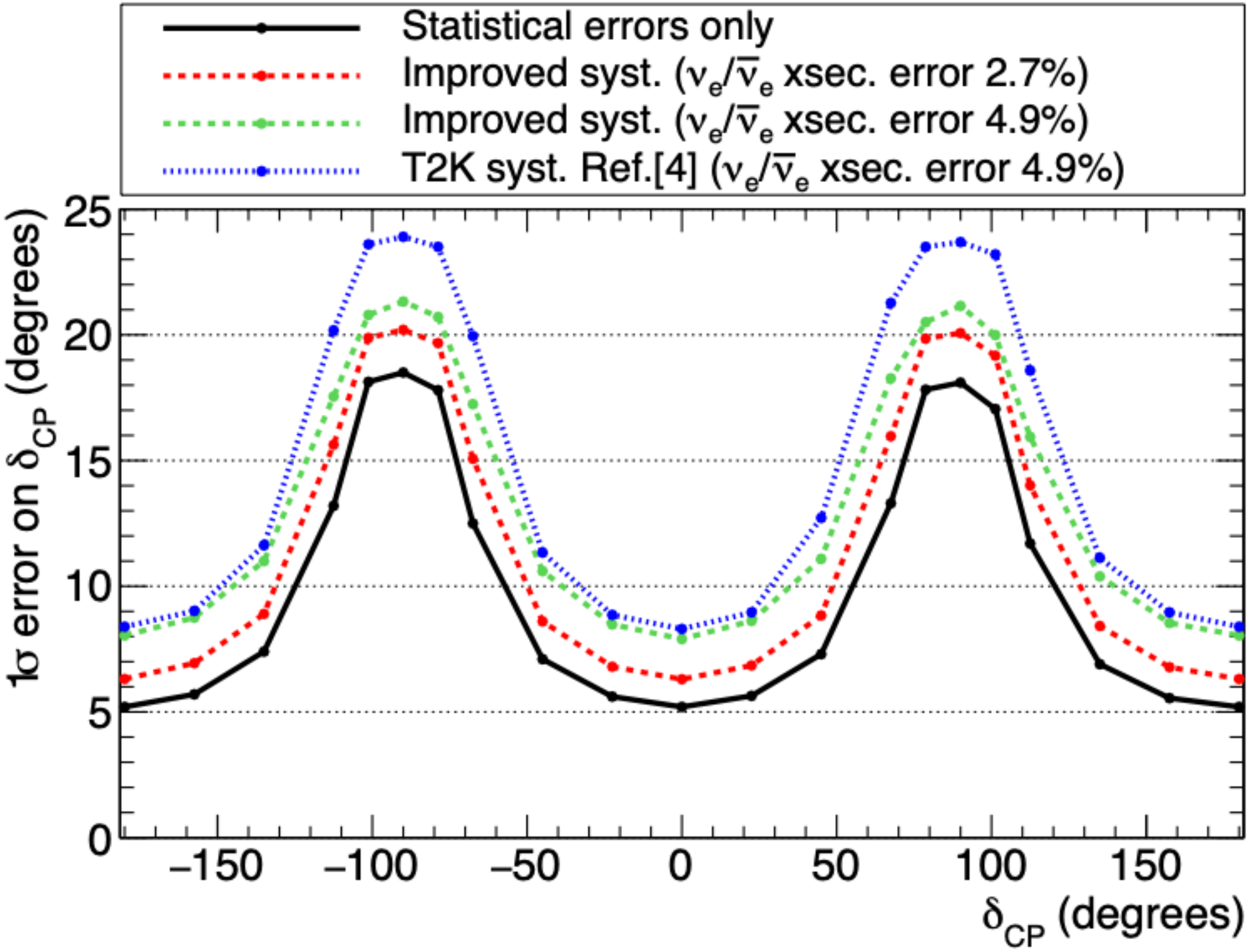
Inverted Ordering [Ref 7]



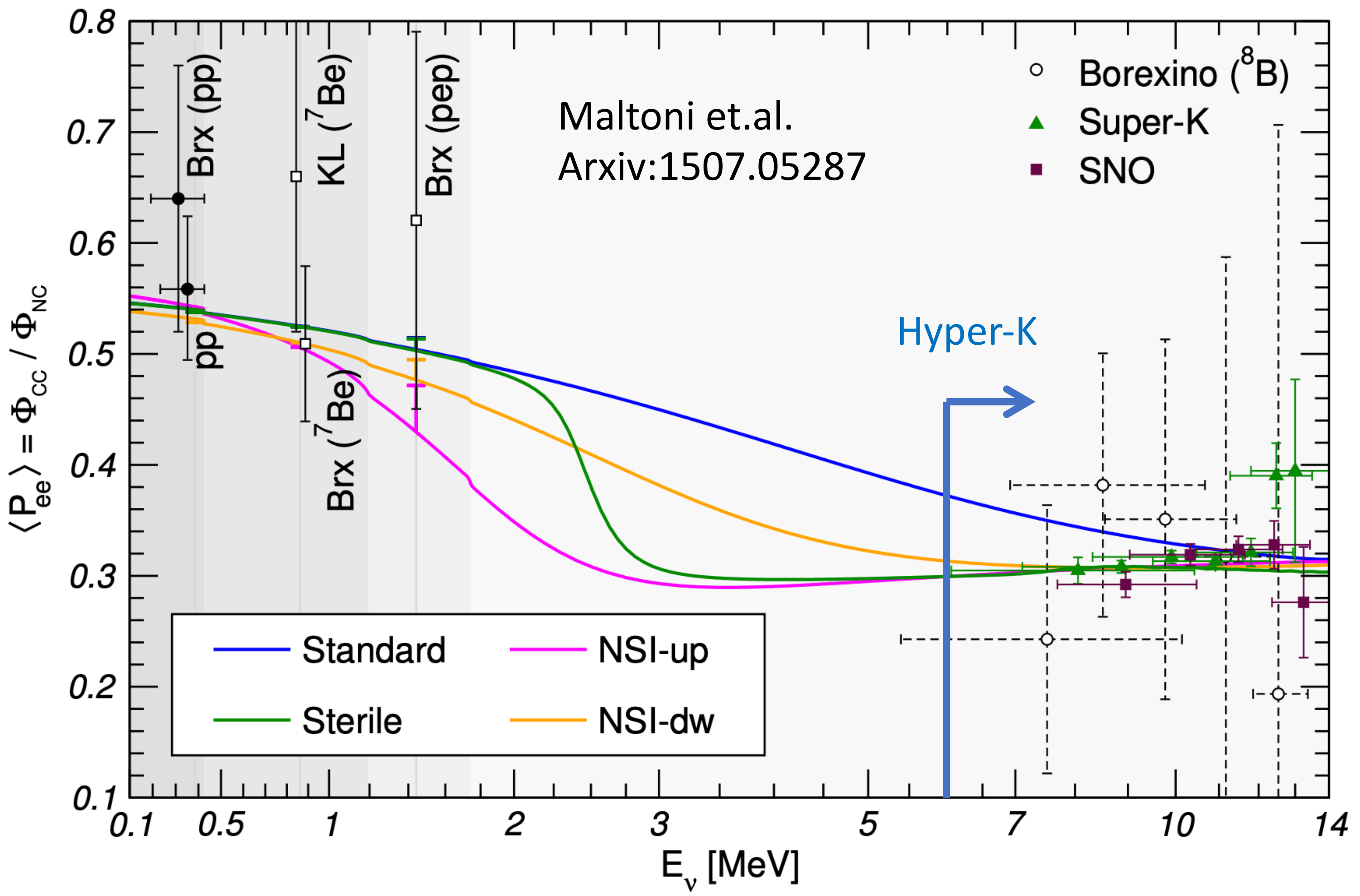
δ_{CP} Potential

<u>1σ Error on δ_{CP}</u>

- World-leading experiment to measure δ_{CP} and constrain CP violation in the next 10 years
- $\sigma(\delta_{CP})$ depends on its value: 5–18° (stat. only), 7–20° with projected systematics
- Higher precision CP-conserving values (from the neutrino oscillation formula)
- See [Ref 6] for details



Solar Neutrinos



Vacuum-dominated region

Matter Dominated Region

10 years of Hyper-K: upturn sensitivity $\sim 3\sigma$ for $T_e > 4.5$ MeV, rising to $\sim 5\sigma$ for $T_e > 3.5$ MeV

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