



University  
of Glasgow



# Status of the Hyper-Kamiokande Experiment

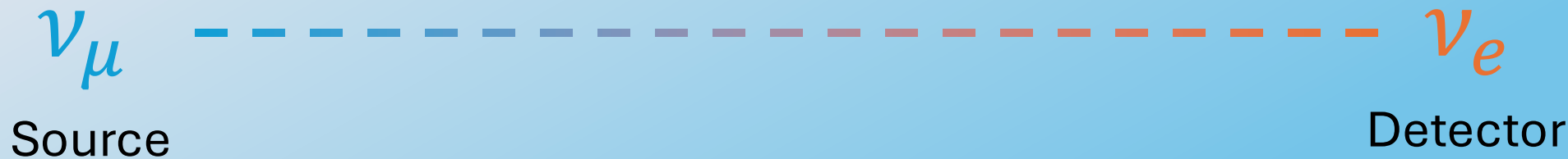
Dr. Veera Mikola on behalf of the HK collaboration

University of Glasgow

[veera.mikola@glasgow.ac.uk](mailto:veera.mikola@glasgow.ac.uk)

# Three Flavor Mixing in Lepton Sector

- Create neutrinos in one lepton flavour state, observe in another state
- Flavour and mass states mixing quantum mechanically; each flavour state is a superposition of different mass states



$$\begin{array}{c} \blackrightarrow \end{array} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \blackrightarrow P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j}^* e^{-i \frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

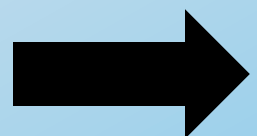
$\blackrightarrow$   $\Delta m_{21}^2, \Delta m_{32}^2, \Delta m_{31}^2$

# Three Flavor Mixing in Lepton Sector

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(c<sub>ij</sub> = cos θ<sub>ij</sub>, s<sub>ij</sub> = sin θ<sub>ij</sub>)  
"Atmospheric" sector, θ<sub>23</sub>
"Reactor" sector, θ<sub>13</sub> δ<sub>CP</sub>
"Solar" sector, θ<sub>12</sub>

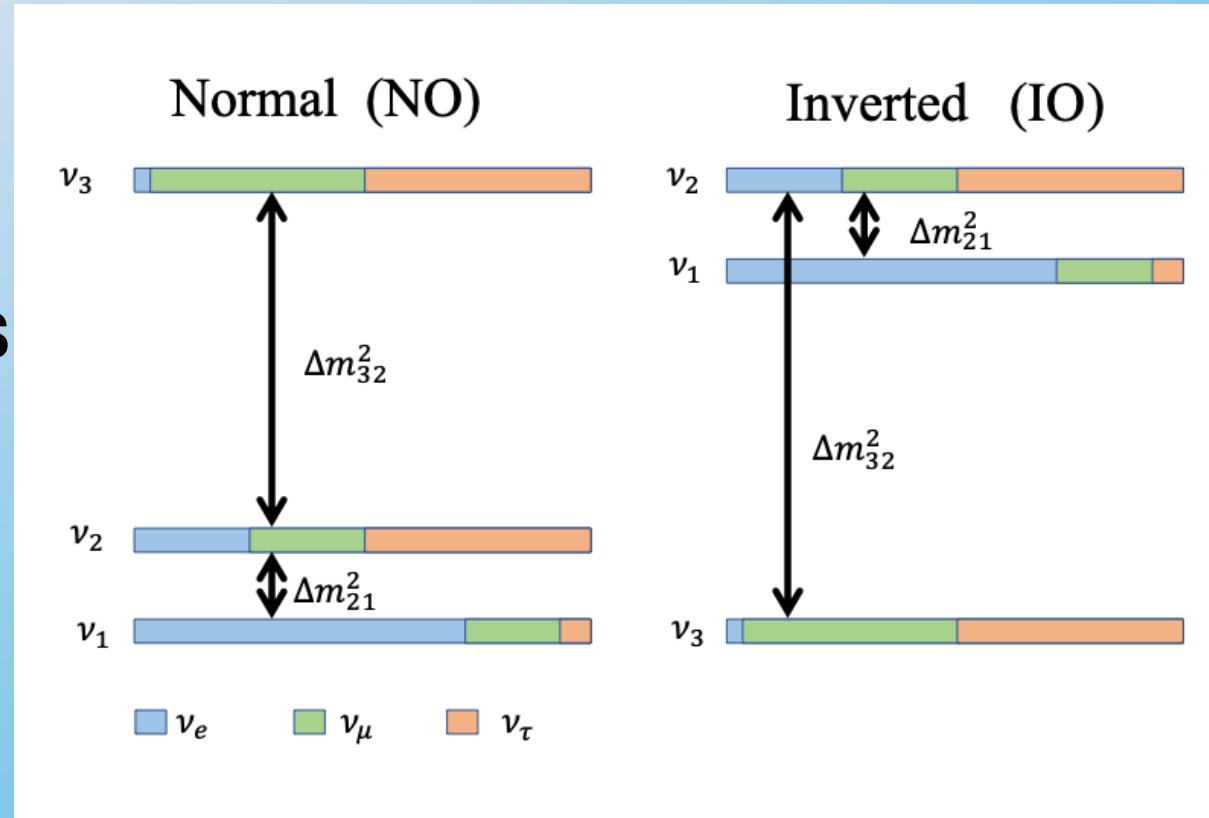
Accelerator Experiments



3 angles and 1 complex phase θ<sub>12</sub>, θ<sub>23</sub>, θ<sub>13</sub>, δ<sub>CP</sub>

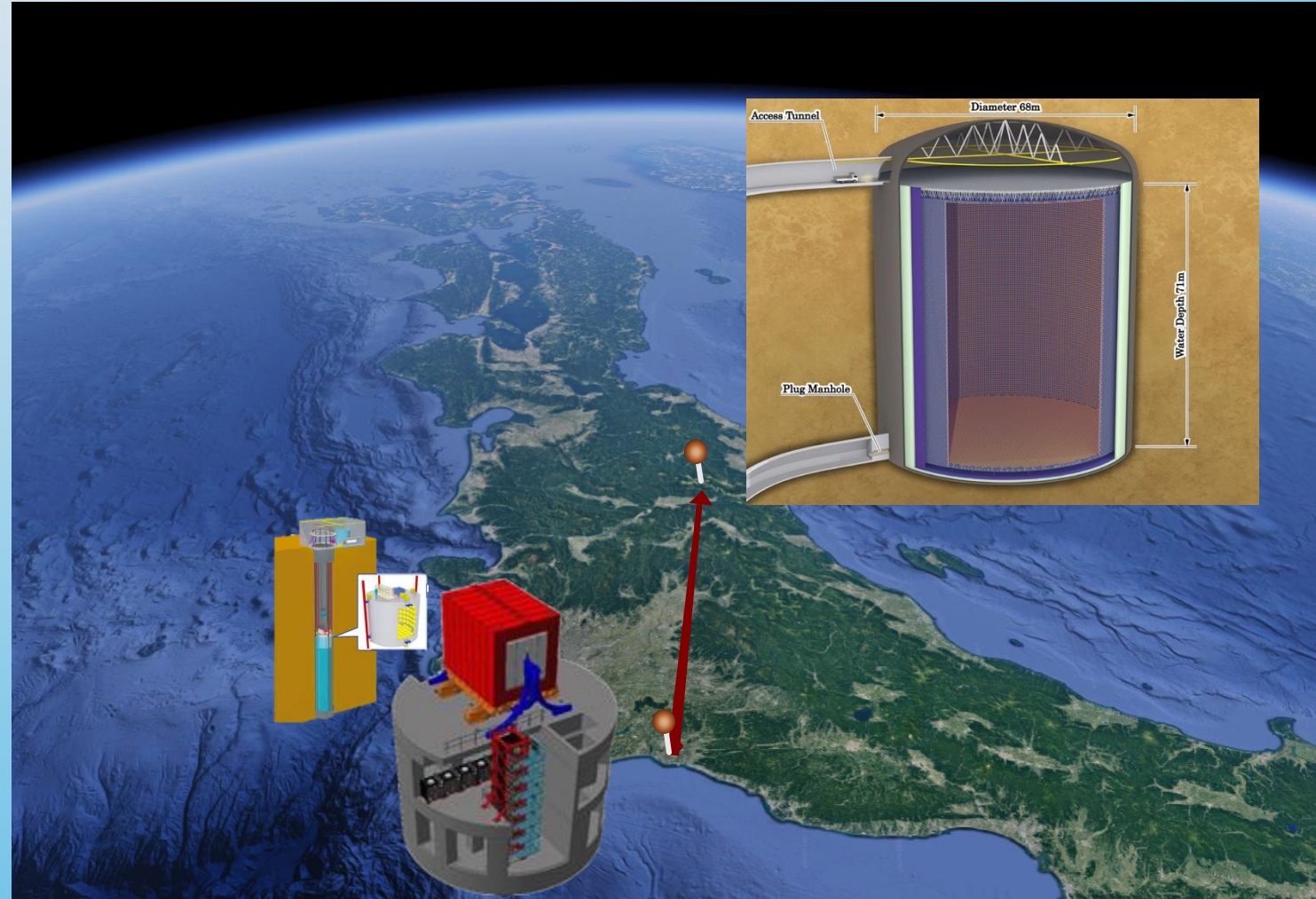
# Open Questions

- Is there CP Violation in the lepton sector? (value of  $\delta_{CP}$ )
- Mass ordering? Are neutrinos Majorana?
- Is  $\theta_{23} = 45^\circ$ ? If not, octant of  $\theta_{23}$ ?



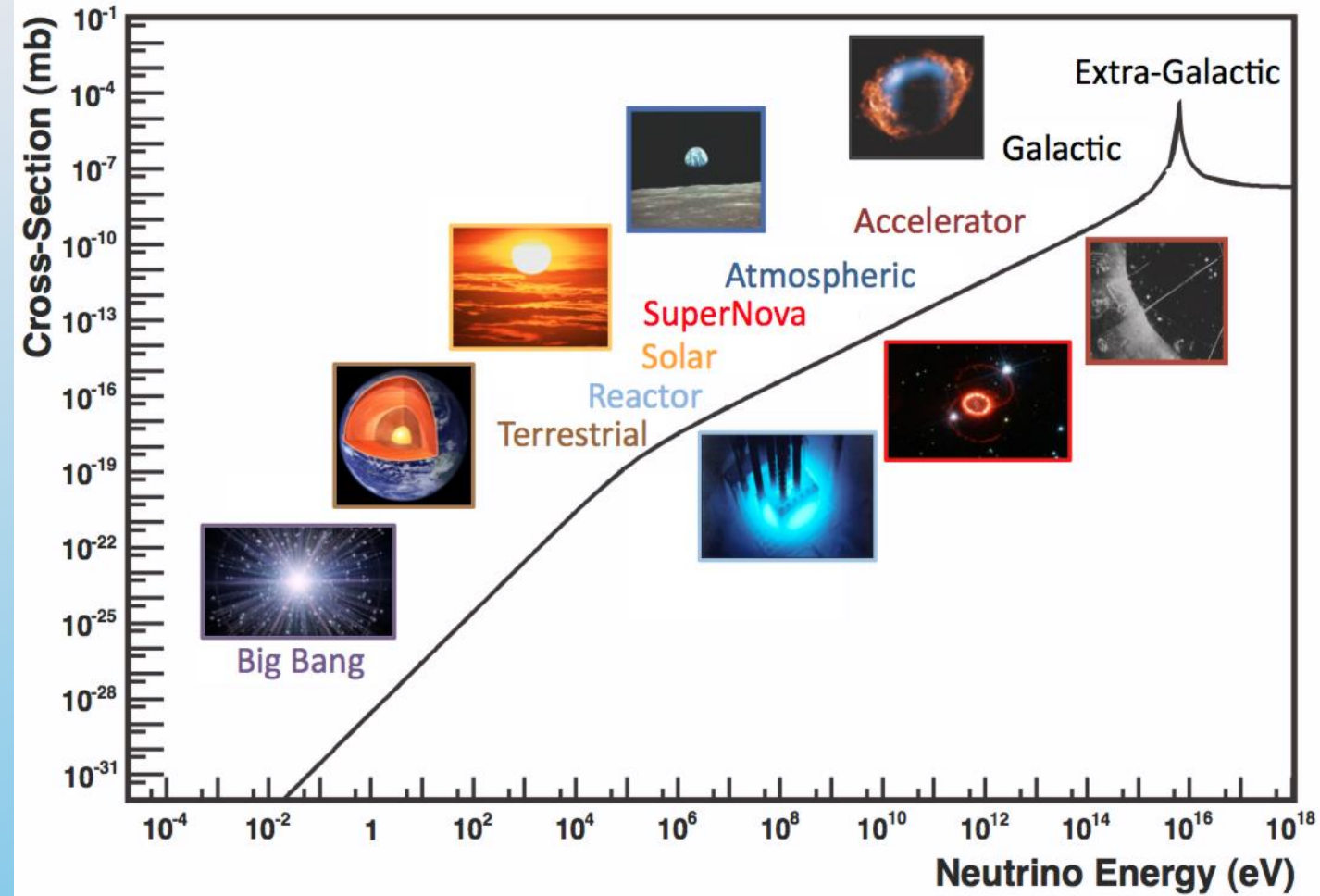
# Hyper-Kamiokande

- Future Neutrino Oscillation Experiment building on the success of Super-Kamiokande and Kamiokande
- Beam and near detectors located in J-PARC in Tokai, Japan, and far detector in Tochibora mine at Kamioka, Japan.



# Physics Goals

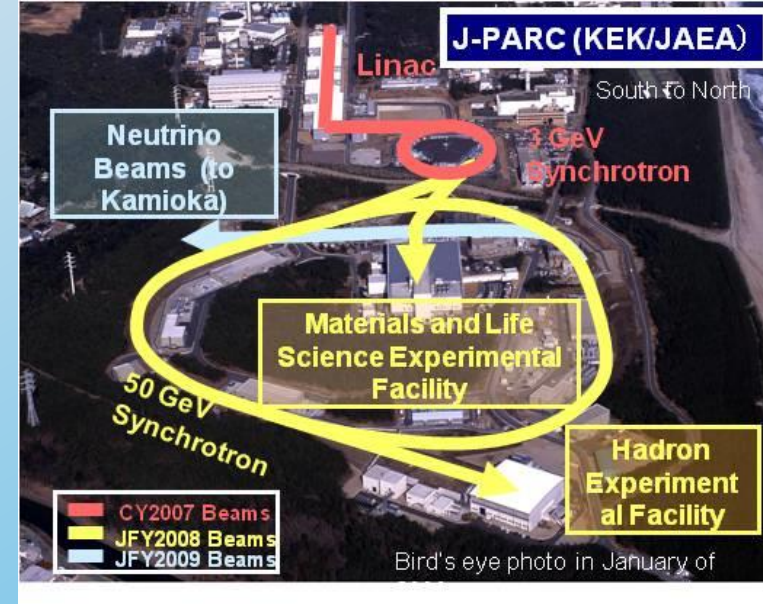
- Rich physics program
  - Long-baseline beam oscillations (LBL): CP-violation, precision measurements of neutrino oscillation parameters
  - Atmospheric neutrinos: mass ordering
  - Solar neutrinos
  - Supernova neutrinos
  - Proton decay



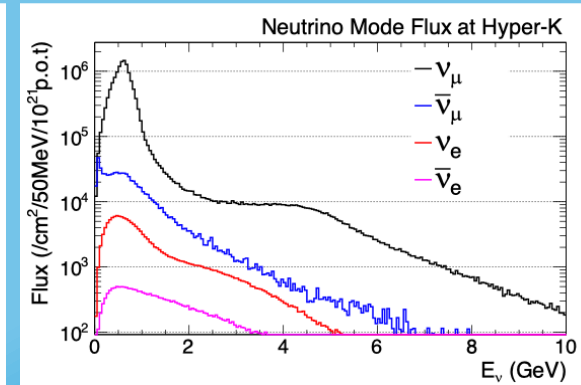
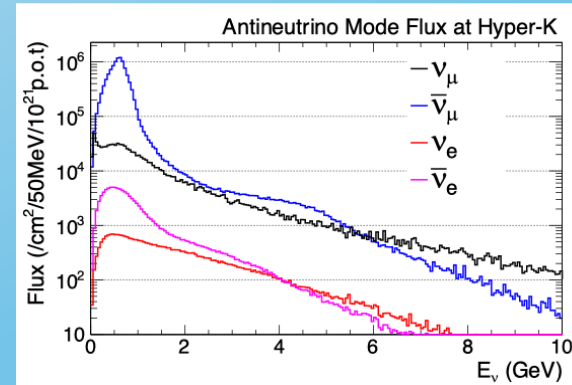
[10.1103/RevModPhys.84.1307](https://doi.org/10.1103/RevModPhys.84.1307)

# J-PARC Neutrino Beam

- A beam of 30 GeV protons being upgraded to 1.3 MW
- Expected to collect  $2.7 \times 10^{21}$  POT a year based on 6 cycles of 22 days with 87% running efficiency
- Planned running split:
  - 25% Neutrinos (forward horn current, FHC)
  - 75% Anti-neutrinos (Reverse horn current, RHC)



<https://j-parc.jp/en/jparc.html>



# J-PARC Neutrino Beam

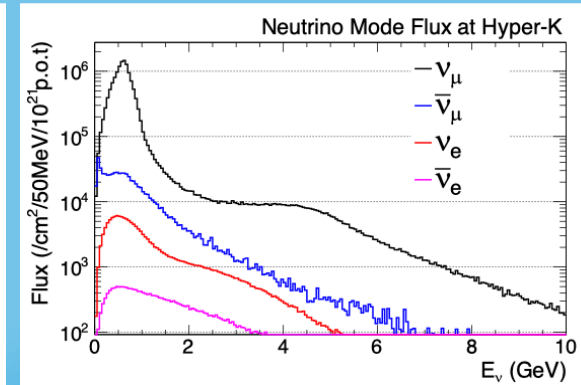
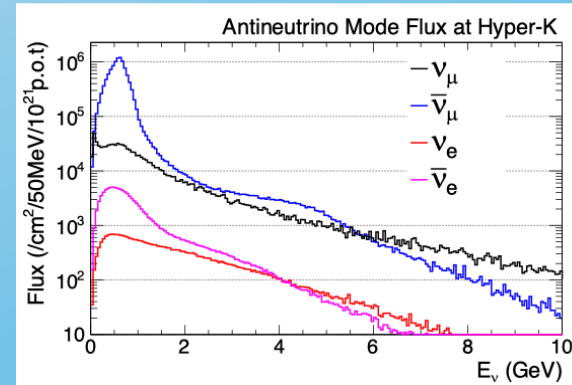
- A beam of 30 GeV protons being upgraded to 1.3 MW
- Expected to collect 10<sup>11</sup> neutrinos based on 6 cycles of 1000 s running efficiency

See Megan Friend's Talk on Accelerator Developments at JPARC at Friday plenary!

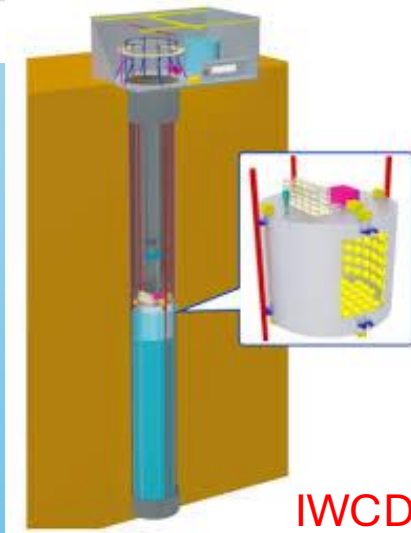
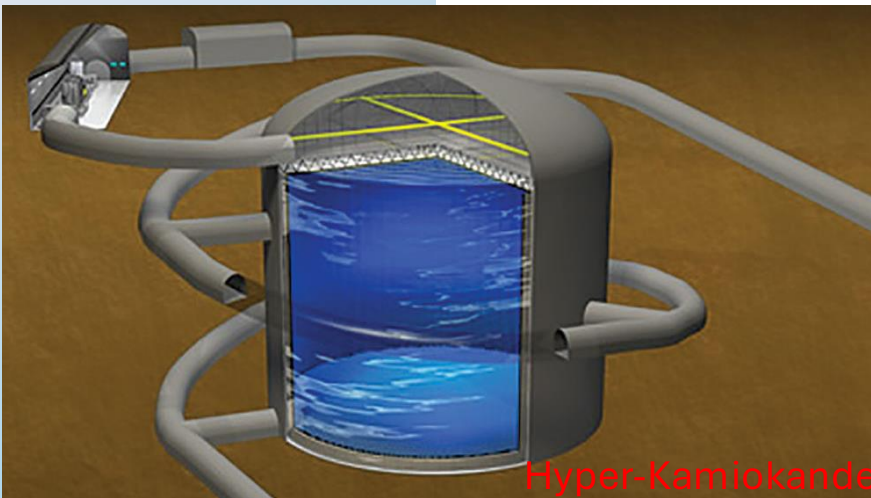
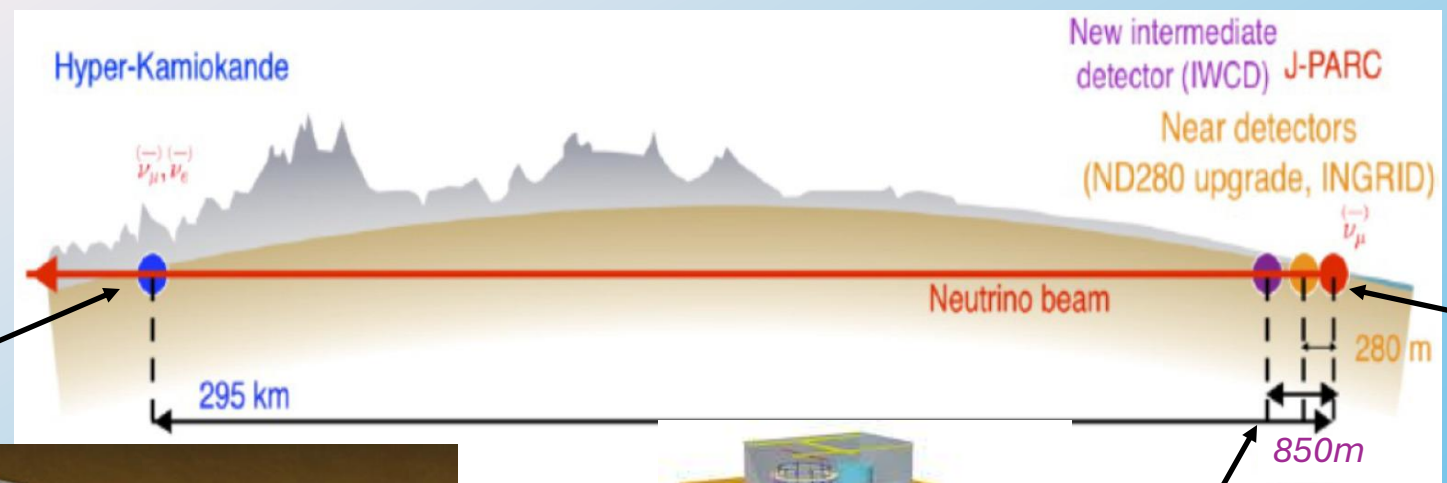


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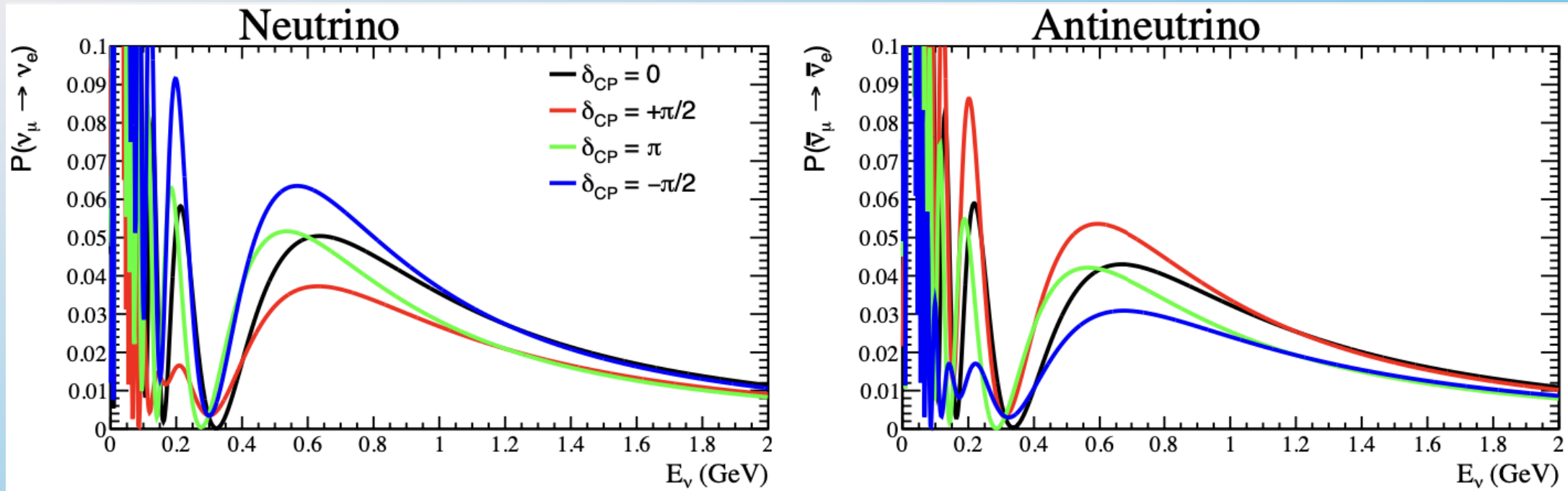


# Hyper-Kamiokande Detectors

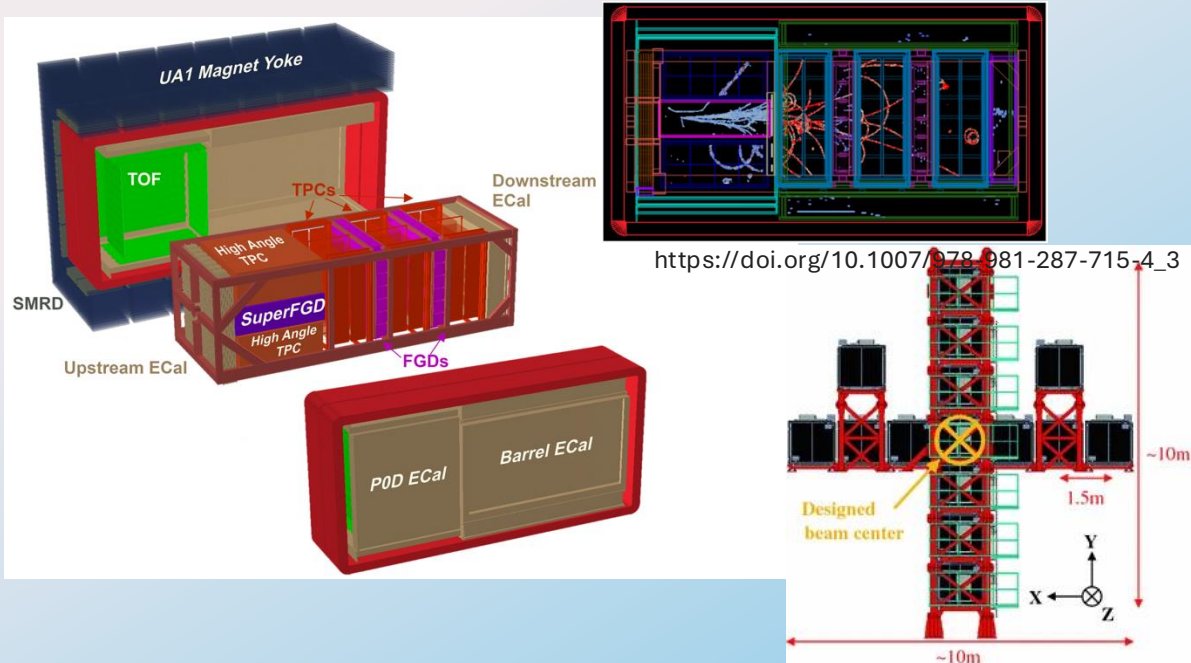


# Off-axis Concept

- Hyper-K detectors are located  $2.5^\circ$  off the neutrino beam axis to achieve maximum neutrino flux at oscillation maximum of 0.6 GeV
- Also helps with background rejection

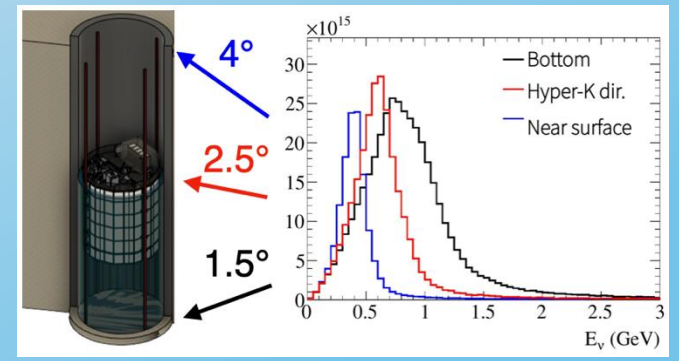
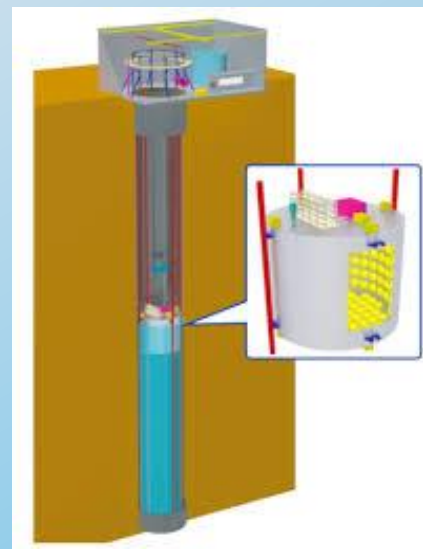


# Hyper-Kamiokande Detectors: Near



## ND280/INGRID

- Multidetector system with on-axis detector, INGRID, and a off-axis magnetised detector, ND280 with plastic scintillator tracking detectors with water layers and TPCs

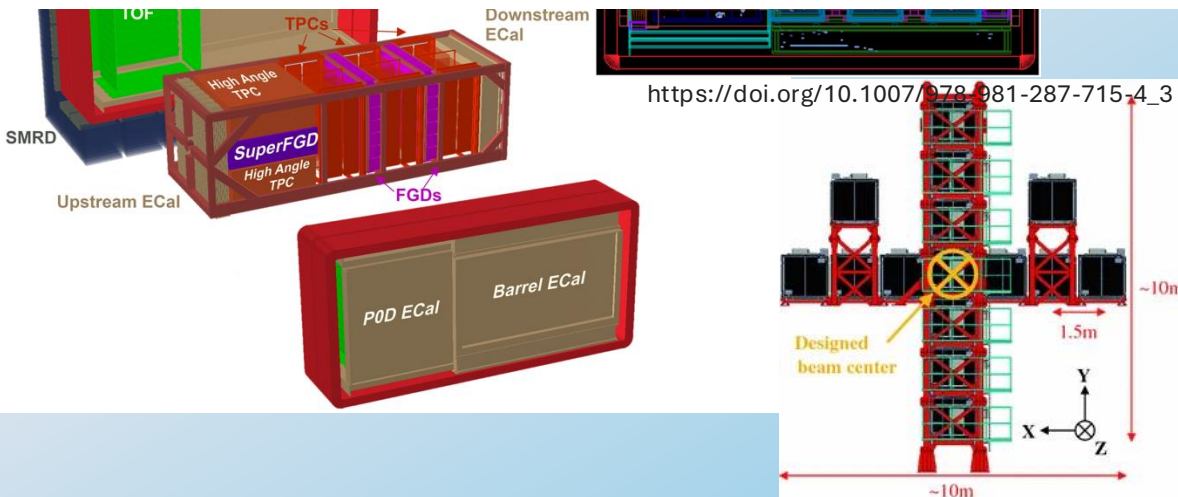


## IWCD

- Intermediate **W**ater **C**herenkov **D**etector 850m from the target, under development
- Neutrino interaction measurements across 1.5 to 4 degrees off-axis
- Cylindrical inner detector: 7 meters in diameter & 8 meters in height with fiducial mass of 150 tonnes

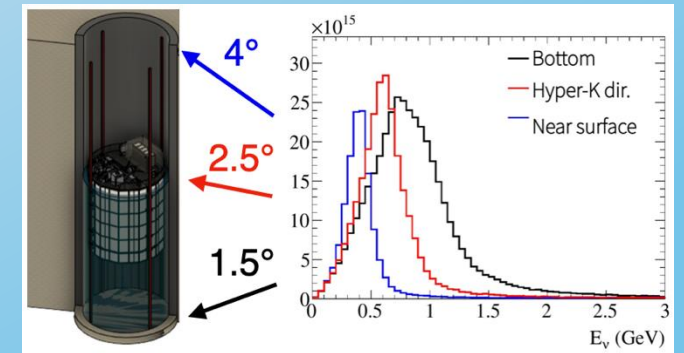
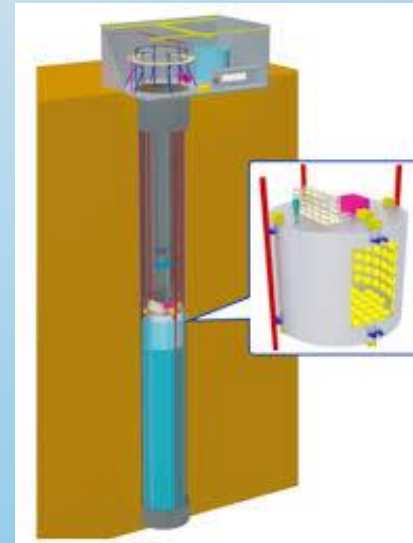
# Hyper-Kamiokande Detectors: Near

See Davide Sgalaberna's talk on Thursday at 14:35 in WG6



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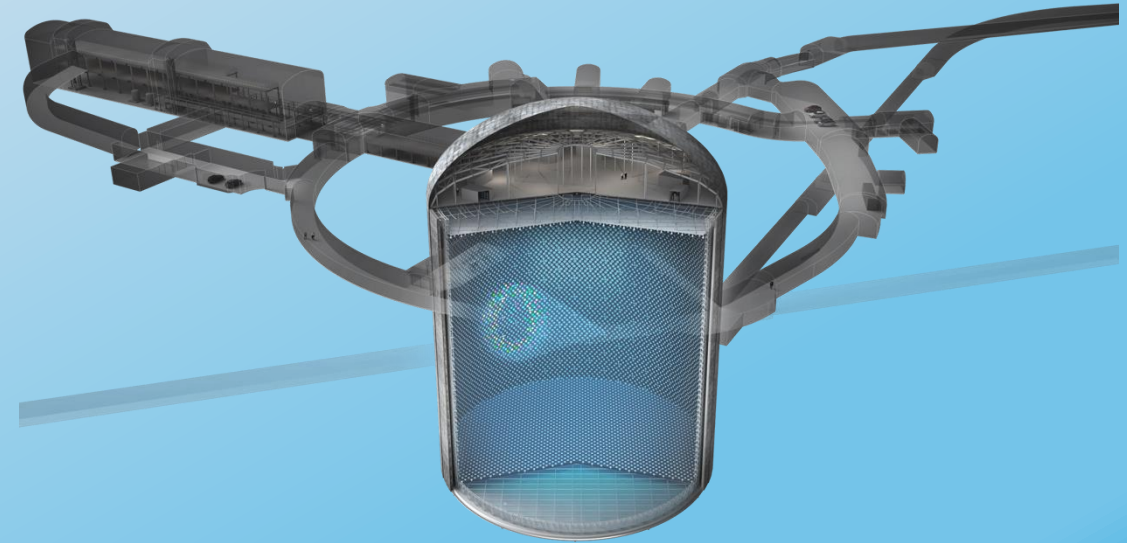
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# Hyper-Kamiokande Detectors: Far



Cavern excavation finished  
on 31<sup>st</sup> of July 2025!



- 187 kiloton fiducial volume water Cherenkov detector with inner and outer detector covered by PMTs
- The 20,000 PMTs will have double the detection efficiency to SK with 20% covering of the ID surface
- OD consists of 3600 PMTs with wavelength-shifting plates to improve efficiency
- 800 mPMTs units each with 19 8cm PMTs + electronics inside single pressure vessel, gives directional information and improves spatial and timing resolution.

# Hyper-Kamiokande Detectors: Far



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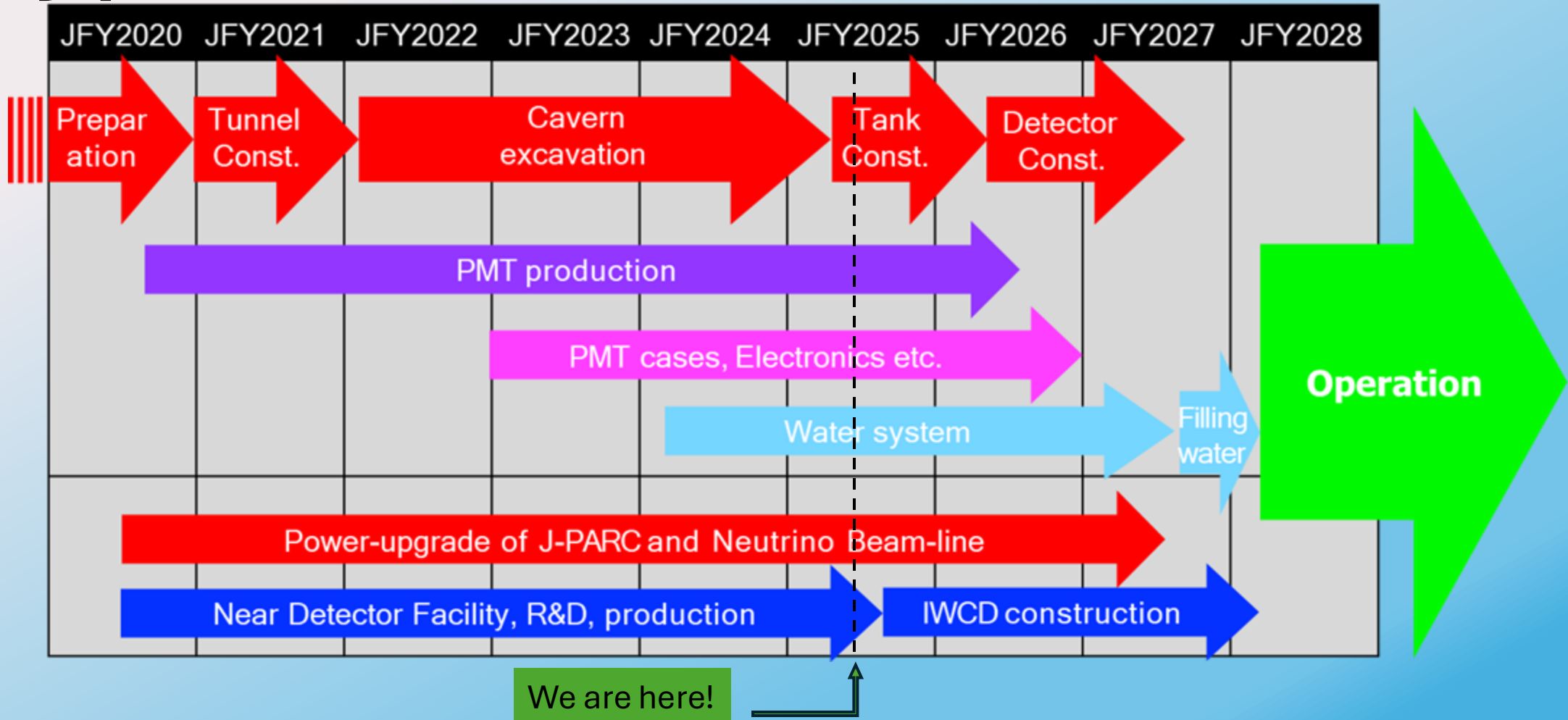


See talks by Sam Jenkins and Takuya Tashiro on Tuesday at 16.15 in WG6, and posters by Unik Limbu and Balint Bogdan

Also see talks on water cherenkov technologies by Lauren Anthony on Monday afternoon plenary, and a talk by Krzysztof Dygnarowicz on Tuesday at 16.15 in WG6

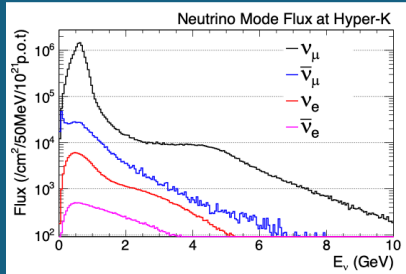
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# Hyper-Kamiokande Timeline

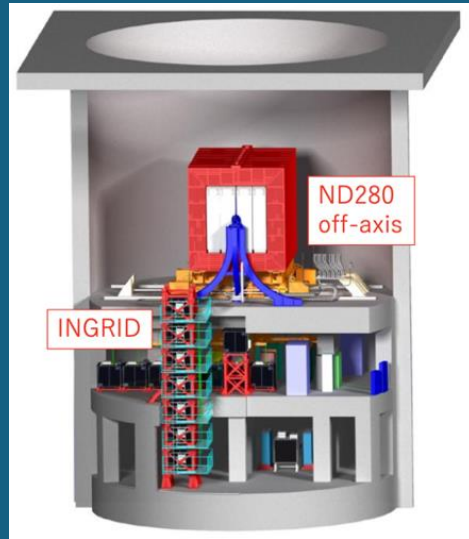


# LBL Oscillation Analysis Method

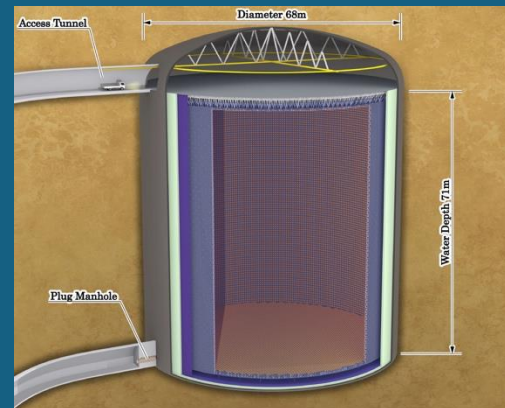
## Flux Model



ND280 & IWCD  
constrain this model



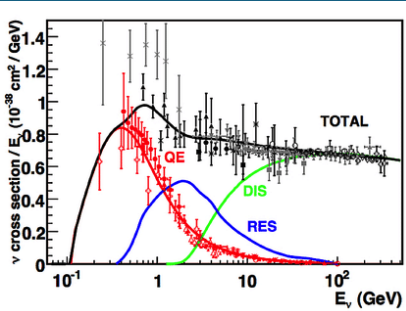
Fit constrained model to Far  
Detector



Results!



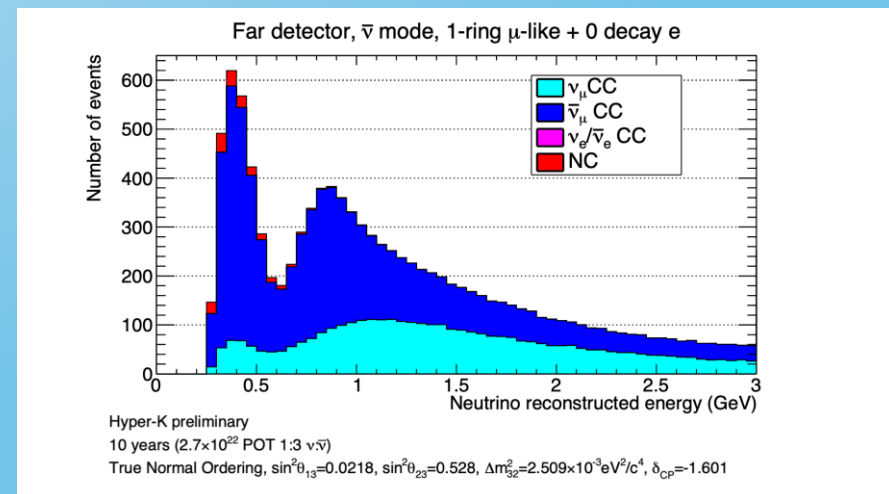
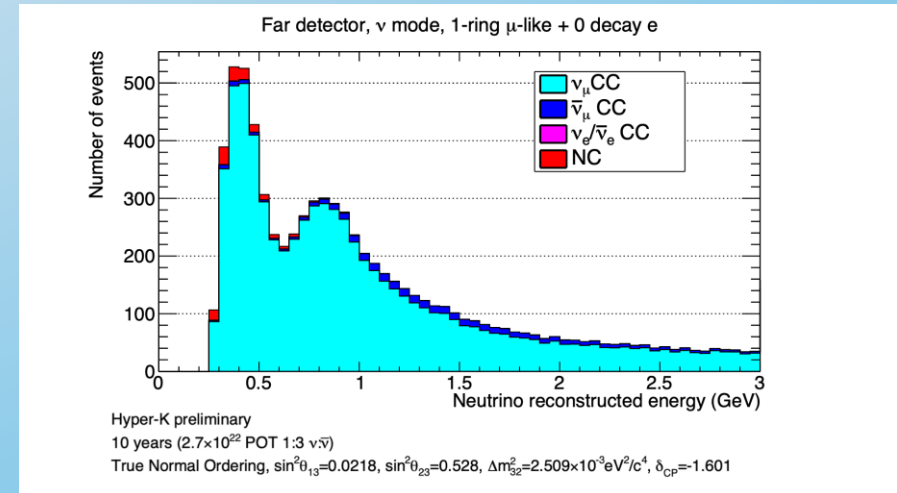
## Xsec Model



# $\nu_\mu$ and $\bar{\nu}_\mu$ Disappearance

$$P(\bar{\nu}_\mu^{(-)} \rightarrow \bar{\nu}_\mu^{(-)}) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} \times (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}) \sin^2 \left( 1.27 \frac{\Delta m_{32}^2 L}{E} \right)$$

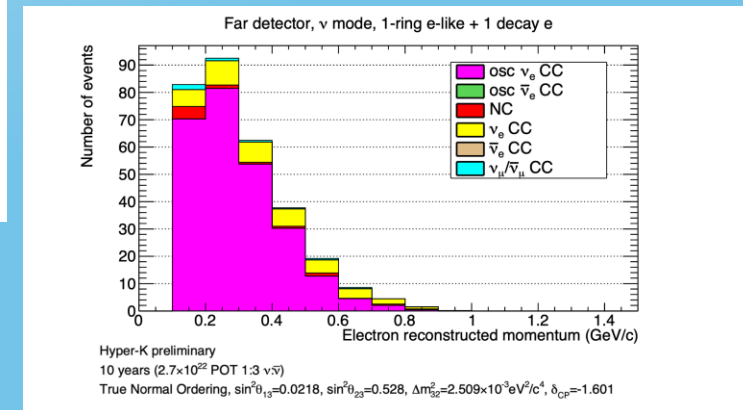
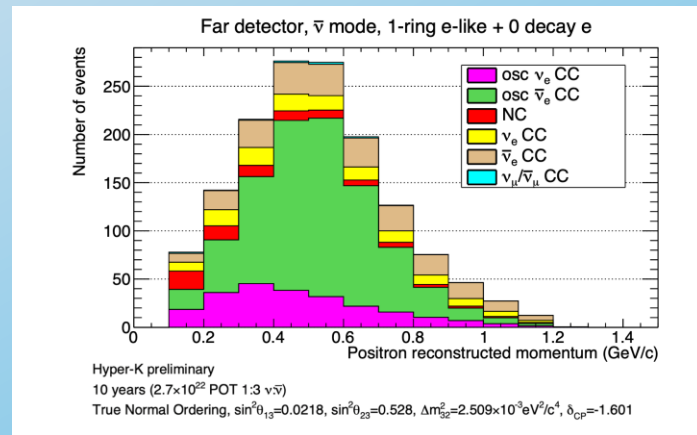
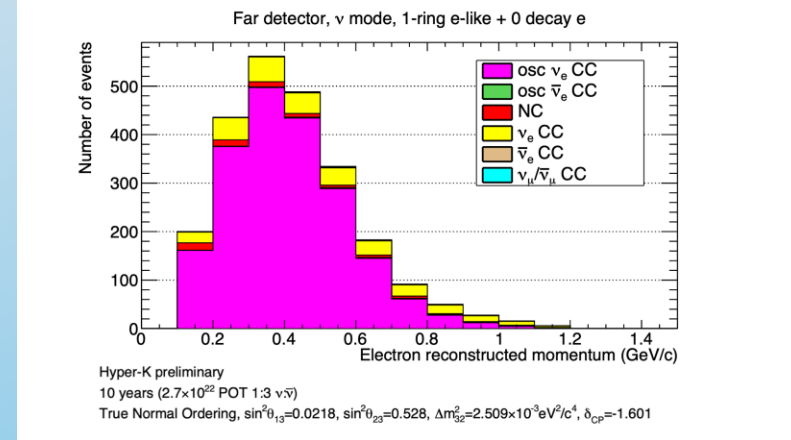
- The majority of HK events
- Measurements of  $\Delta m_{32}^2$  and  $\sin^2 \theta_{23}$
- Two samples:  $\nu_\mu$  and  $\bar{\nu}_\mu$  (FHC1R $\mu$  and RHC1R $\mu$ )



# $\nu_e$ and $\bar{\nu}_e$ Appearance

$$\begin{aligned}
 P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &\simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31} \\
 &+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta_{CP} - s_{12} s_{13} s_{23}) \\
 &\quad \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
 &- (+) 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta_{CP} \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
 &+ 4c_{13}^2 s_{12}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{13}^2 s_{23}^2 - 2c_{12} c_{23} s_{12} s_{13} s_{23} \cos \delta_{CP}) \\
 &\quad \cdot \sin^2 \Delta_{21}
 \end{aligned}$$

- Sensitivity to  $\delta_{CP}$  and  $\sin^2 \theta_{23}$
- Three samples in current studies: oscillation  $\nu_e$ ,  $\bar{\nu}_e$  and  $\nu_e$  with decay e (FHC1Re, RHC1Re, FHC1Re1de)
  - More samples to be added



# LBL Sensitivity

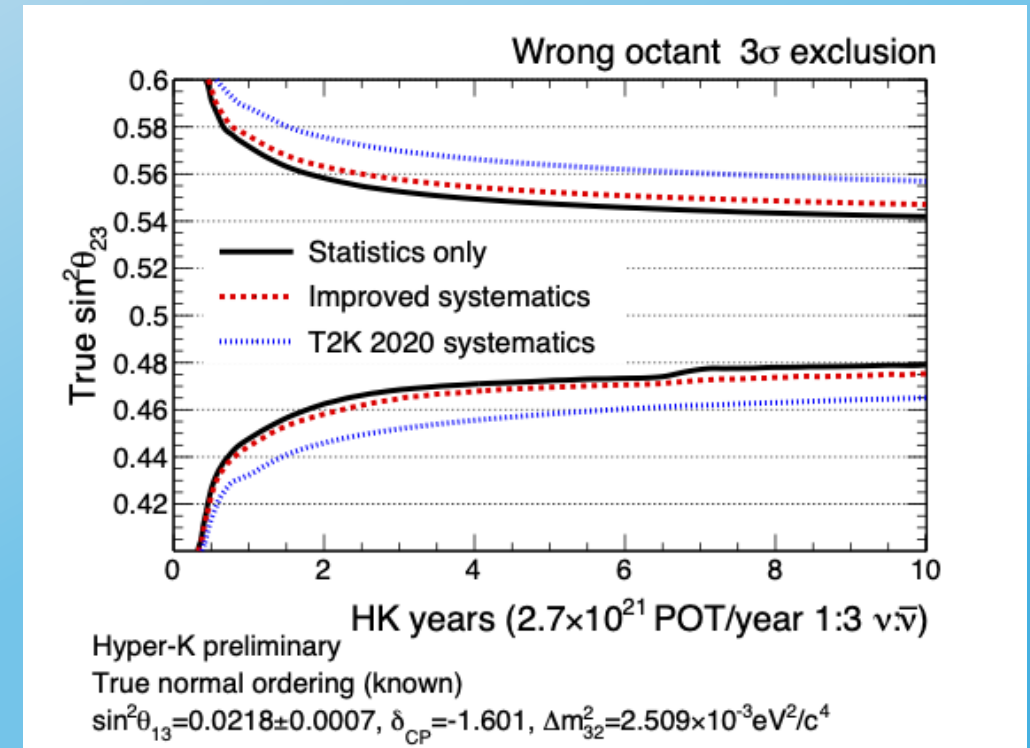
- Sensitivity study results recently published in Arxiv:  
<https://doi.org/10.48550/arXiv.2505.15019> (Submitted to EPJC)
- Three systematics models considered in sensitivity studies:
  - T2K 2020 systematic model ([10.1140/epjc/s10052-023-11819-x](https://doi.org/10.1140/epjc/s10052-023-11819-x))
  - Improved model: T2K systematics scaled based on ND280-upgrade/IWCD sensitivity
  - Statistics only, no systematics

T2K systematics	FHC 1Re	FHC 1R $\mu$	RHC 1Re	RHC 1R $\mu$	FHC 1Re1De	FHC/RHC 1Re
Flux-xsec	3.6%	2.1%	4.3%	3.4%	4.9%	4.4%
Detector	3.1%	2.1%	3.9%	1.9%	13.2%	1.1%
All	4.7%	3.0%	5.9%	4.0%	14.1%	4.6%
Improved systematics	FHC 1Re	FHC 1R $\mu$	RHC 1Re	RHC 1R $\mu$	FHC 1Re1De	FHC/RHC 1Re
Flux-xsec	1.8%	0.9%	1.6%	0.9%	1.8%	1.9%
Detector	1.1%	0.8%	1.5%	0.7%	4.9%	0.4%
All	2.1%	1.2%	2.2%	1.1%	5.2%	2.0%

# $\sin^2 \theta_{23}$ Octant Sensitivity

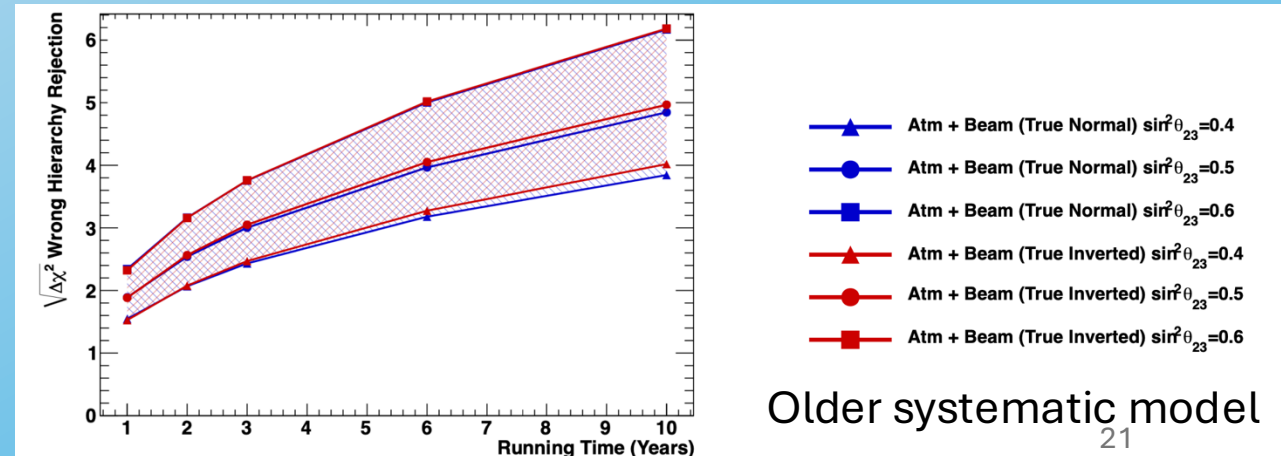
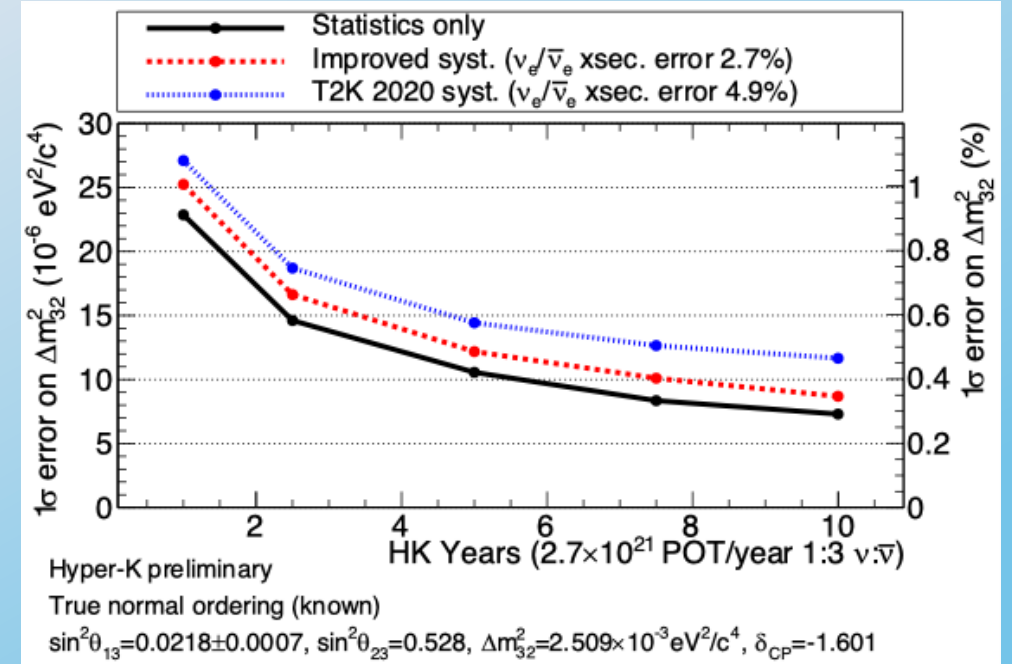
- Resolution achievable between 2% to 0.4% depending on true value
  - Most challenging case if mixing maximal
- With the improved systematics  $3\sigma$  *C.L.* exclusion outside the range of true  $\sin^2 \theta_{23}$  [0.474, 0.547] in 10 years

- For a true value of  $\sin^2 \theta_{23}$  how much can we exclude all values of  $\sin^2 \theta_{23}$  in the other (wrong) octant?



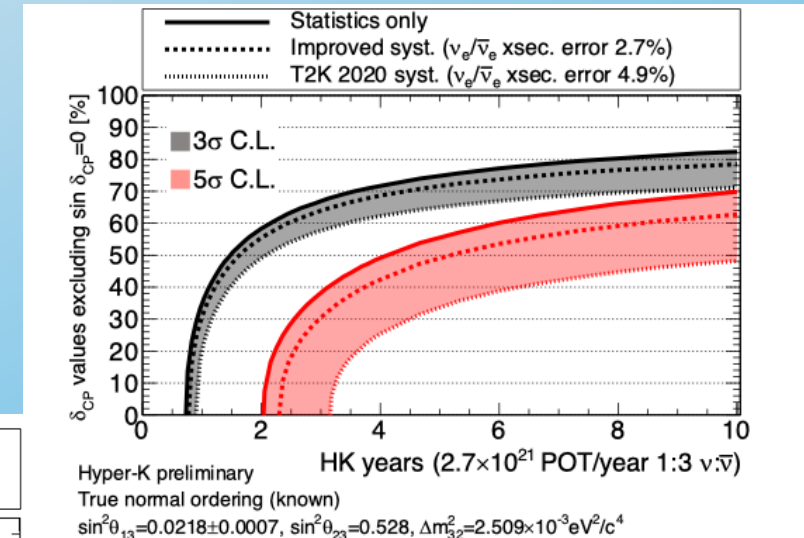
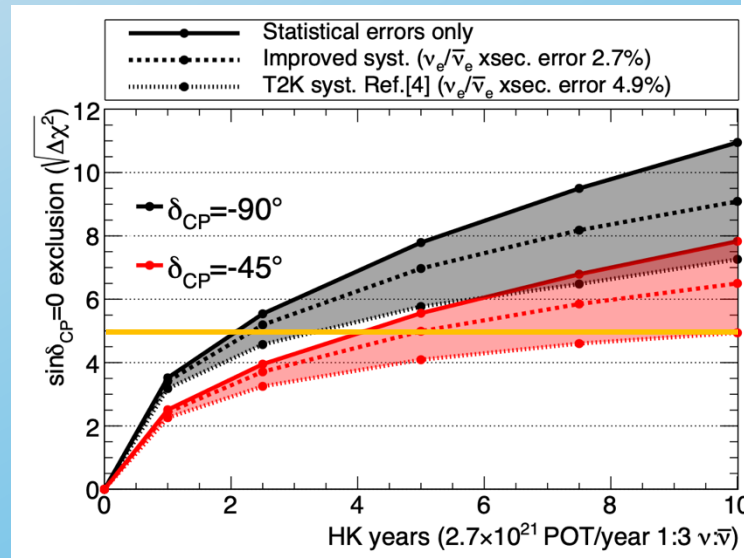
# $\Delta m_{32}^2$ Sensitivity

- Ultimate resolution possible to achieve 0.4%
- Exclude incorrect mass ordering at  $\sim 4\sigma$  to  $5\sigma$  in 10 years, depends on the true value of  $\sin^2\theta_{23}$



# $\sin\delta_{CP} \neq 0$ Sensitivity vs. time

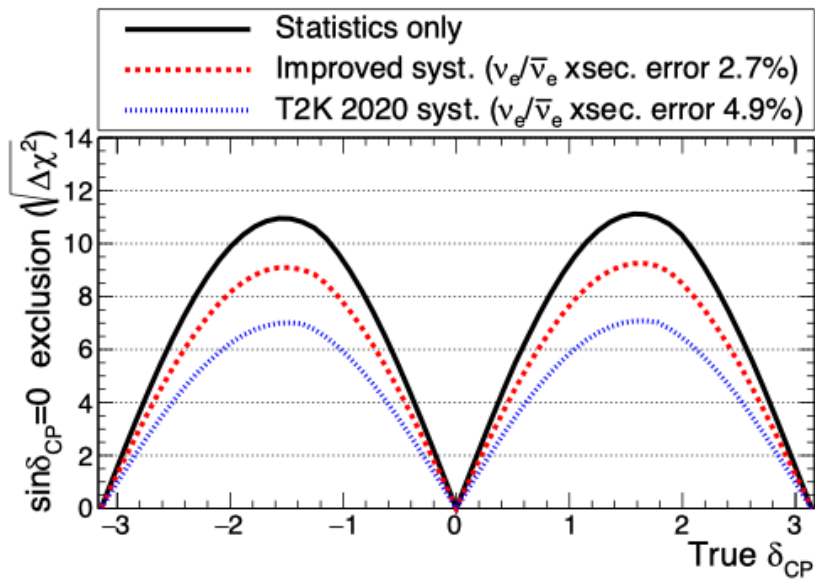
- Most optimistic scenario: discovery of CPV at  $5\sigma$  C.L. in less than 3 years (maximal CPV,  $\delta_{CP} = -90^\circ$ , known MO)
- Exclude CP conservation for 50% of true values of  $\delta_{CP}$  at  $5\sigma$  C.L. in 5 years ( $3\sigma$  C.L. in about two)



$5\sigma$

# $\sin\delta_{CP} \neq 0$ Sensitivity

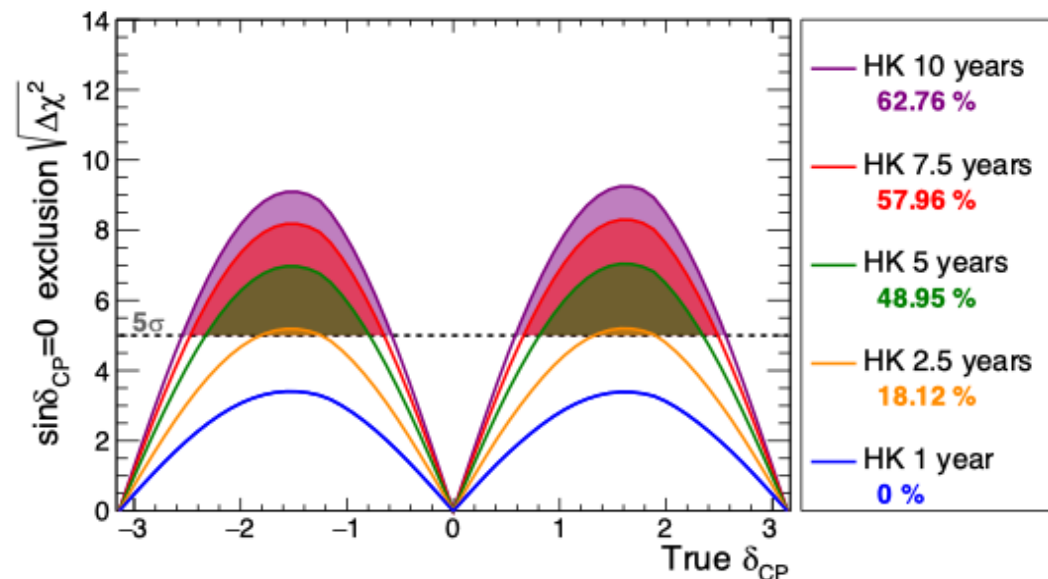
- Discovery of CPV at  $5\sigma$  *C.L.* for  $\sim 50\%$  of values in 5 years and  $\sim 60\%$  in 10 years
- All of the plots assume MO is known



Hyper-K preliminary

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

$\sin^2\theta_{13}=0.0218\pm 0.0007$ ,  $\sin^2\theta_{23}=0.528$ ,  $\Delta m_{32}^2=2.509 \times 10^{-3} \text{eV}^2/c^4$



Hyper-K preliminary

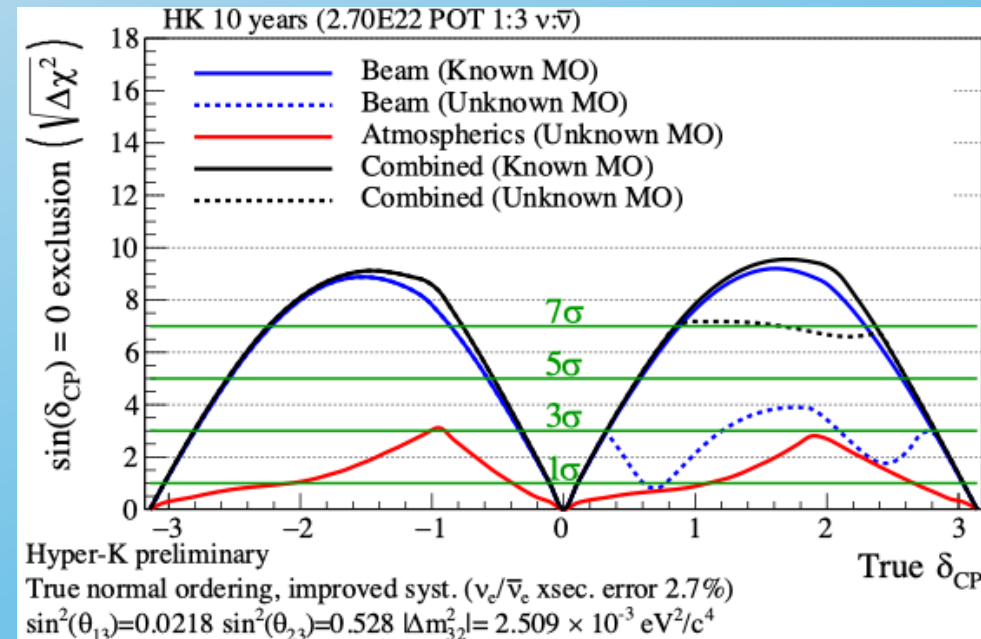
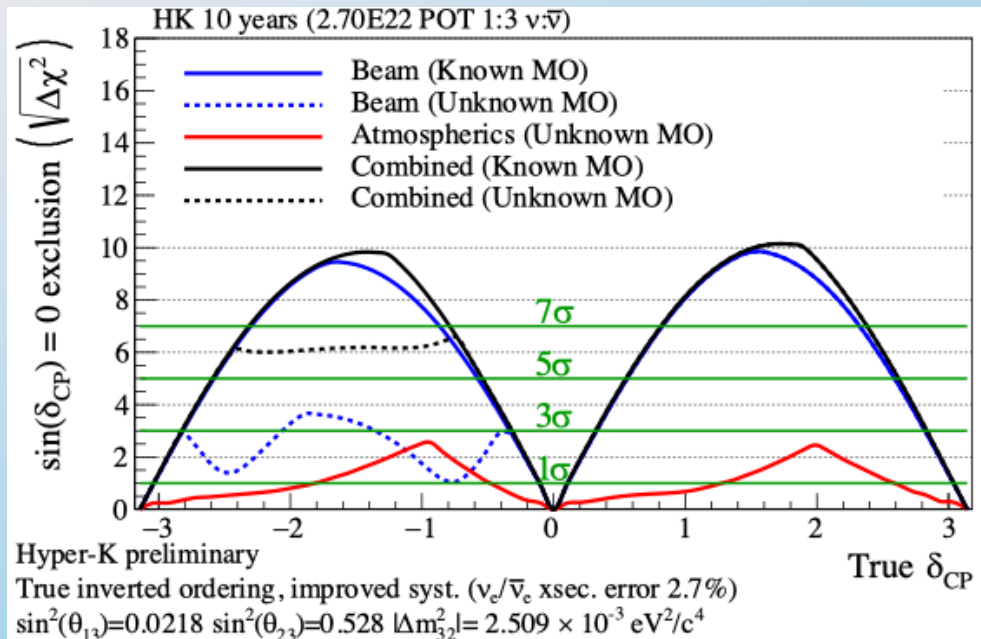
True normal ordering (known), Improved systematics

$\sin^2\theta_{13}=0.0218\pm 0.0007$ ,  $\sin^2\theta_{23}=0.528$ ,  $\Delta m_{32}^2=2.509 \times 10^{-3} \text{eV}^2/c^4$

# Atmospheric Oscillations

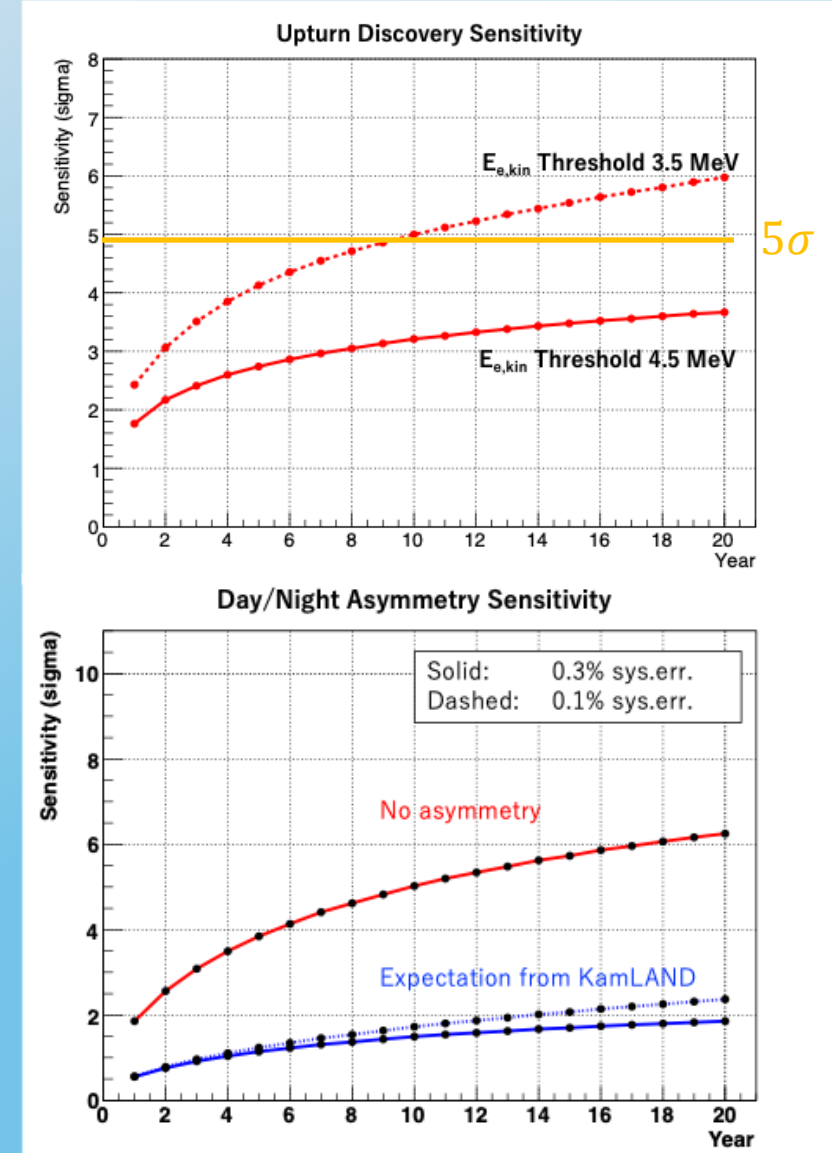
- Default HK results will combine atmospheric and beam results
  - Done previously by T2K and SK (<https://doi.org/10.1103/PhysRevLett.134.011801>)
- Enhancement in sensitivity to oscillation parameters
- Improve MO sensitivity

Based on old T2K systematic model (2018) with improved systematics



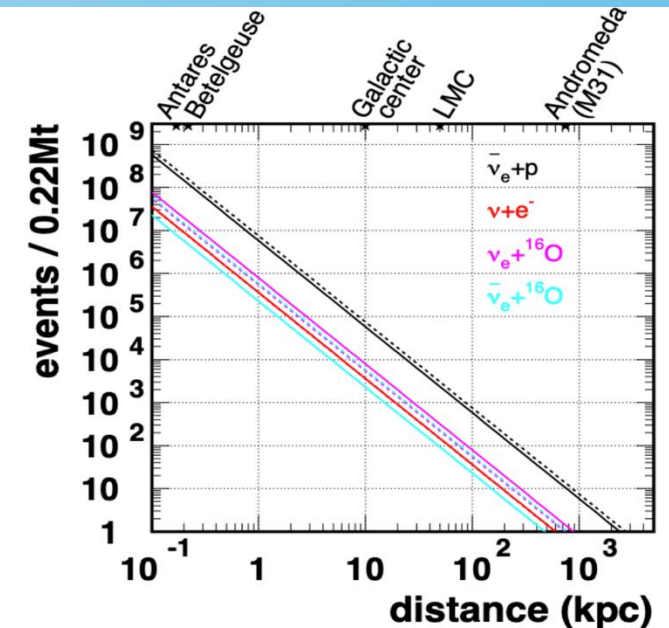
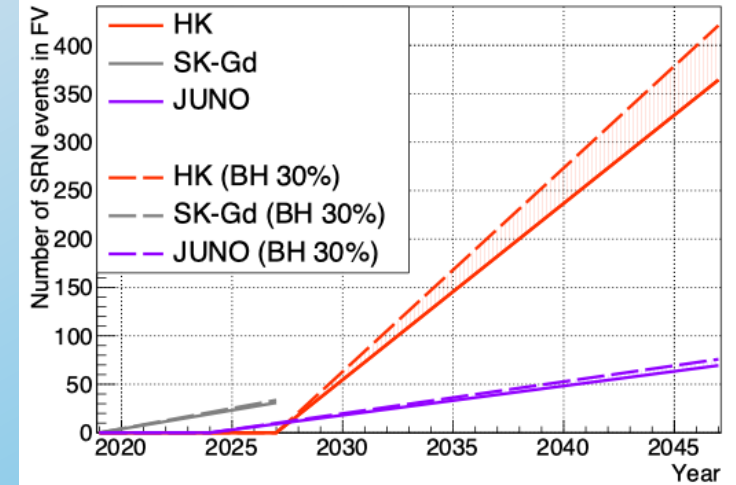
# Solar Neutrinos

- Measurements for oscillation parameters  $\Delta m_{21}^2$  and  $\sin^2 \theta_{12}$
- Upturn in  $\nu_e$  survival probability due to transition between vacuum and matter-dominated oscillations with 4.5 MeV and 3.5 MeV threshold
  - $\sim 3\sigma$  in 10 years
- Day-night asymmetry in MSW effect observation sensitivity
  - $\Delta m_{21}^2$  separation ability between these two scenarios expected to reach  $\sim 4\sigma$  to  $5\sigma$  in 10 years



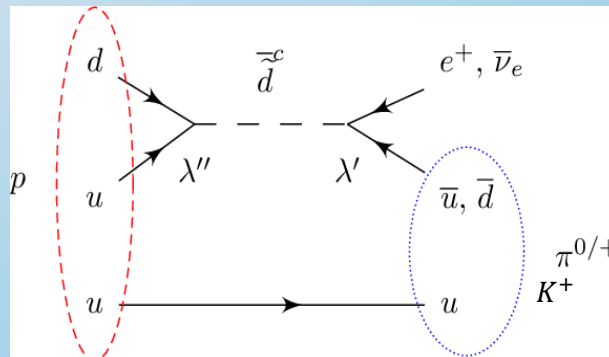
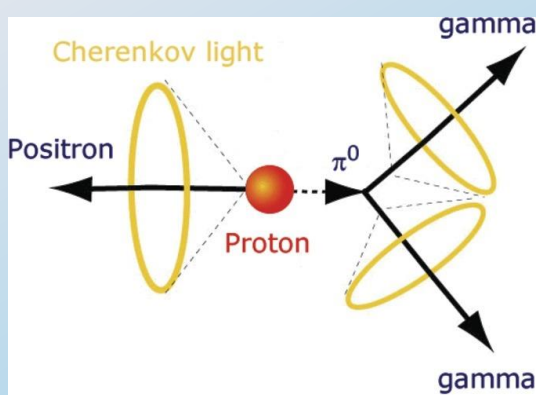
# Supernova Sensitivity

- Hyper-K sensitive to neutrinos from pre-supernova, core-collapse supernova bursts and relic supernova neutrino background (16-30MeV in HK)
- Can detect supernova burst neutrinos beyond the Milky way
  - Large Magellanic Cloud at 50kpc: ~ 3000 events
  - Andromeda Galaxy at 780kpc: ~ 10 events



# Proton Decay

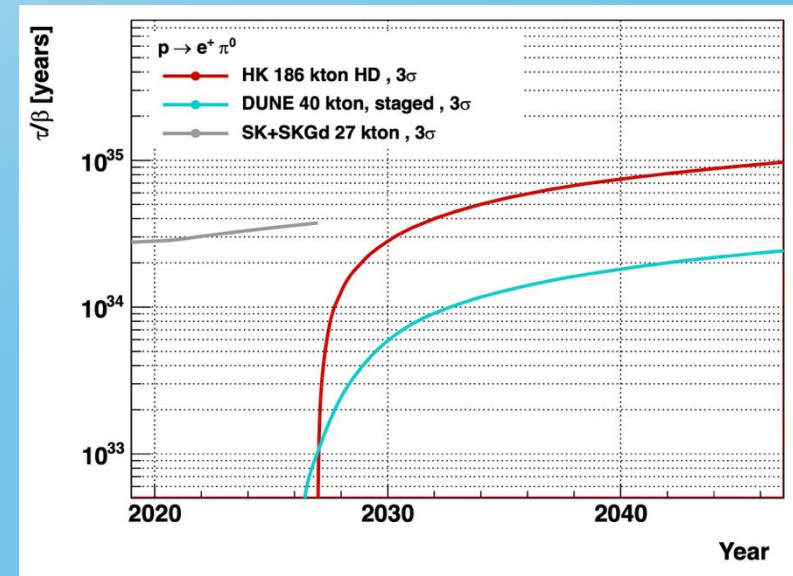
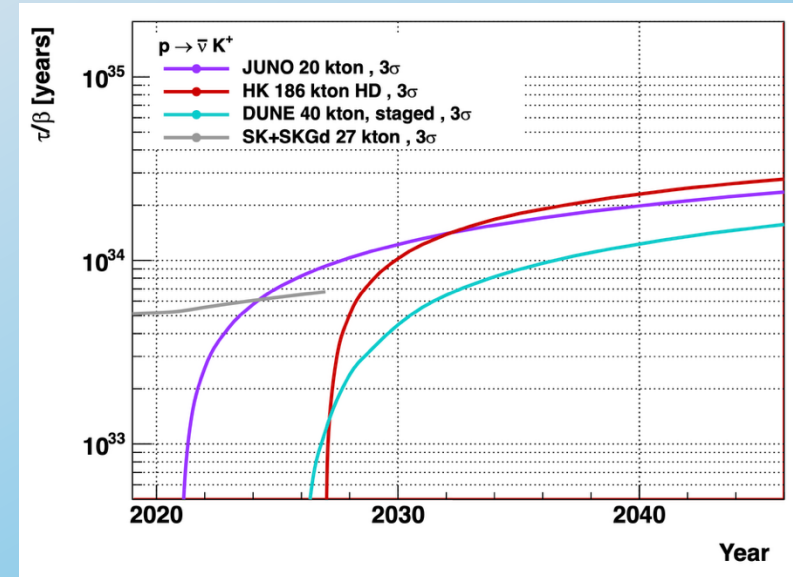
- Dominant in many GUT models
- Hyper-K can significantly extend the sensitivity beyond the current limits from SK
- Two modes:  $p \rightarrow \bar{\nu} K^+$  and  $p \rightarrow e^+ \pi^0$



[10.3204/DESY-THESIS-2013-031](https://arxiv.org/abs/10.3204/DESY-THESIS-2013-031)

<https://doi.org/10.1016/j.nuclphysb.2023.116268>

HK arXiv:1805.04163  
DUNE arXiv:2002.03005  
JUNO arXiv:1508.07166



# Summary

- Hyper-Kamiokande is a future neutrino experiment with a rich physics programme looking to start data taking in 2028
- The value of the CP-violation parameter discovered (at  $5\sigma$  *C.L.*) in less than 3 years in the most optimistic scenario, 60% of all values covered at  $5\sigma$  *C.L.* in 10 years for known MO
- $\sin^2\theta_{23}$  measured with resolution of 2% to 0.4% and  $\Delta m_{32}^2$  with resolution of 0.4%
- Exclude incorrect mass ordering at  $\sim 4\sigma$  to  $5\sigma$  in 10 years
- Great capability to measure solar neutrino oscillations, supernova neutrinos and proton decay



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Thank you!



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Backup

# Systematics in more detail

T2K 2020	1 ring $\mu$ -like		1 ring e-like			
	$\nu$ -mode	$\bar{\nu}$ -mode	$\nu$ -mode + 0 decay	$\bar{\nu}$ -mode + 0 decay	$\nu$ -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%

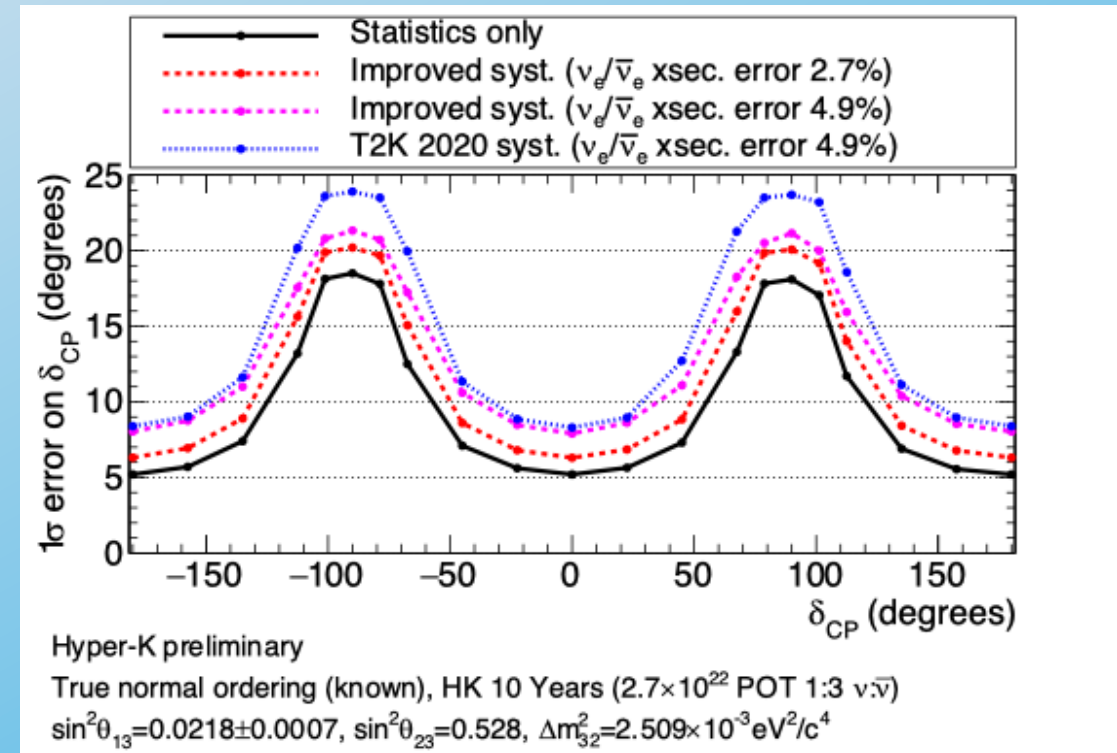
Improved	1 ring $\mu$ -like		1 ring e-like			
	$\nu$ -mode	$\bar{\nu}$ -mode	$\nu$ -mode + 0 decay	$\bar{\nu}$ -mode + 0 decay	$\nu$ -mode + 1 decay	$\nu/\bar{\nu}$ -mode + 0 decay
ND constrained Flux + Cross section	0.9%	0.9 %	1.8 %	1.6%	1.8%	1.9%
Not ND constrained Cross-section	0.4%	0.4 %	1.6 %	1.4%	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%

# Systematics in more detail

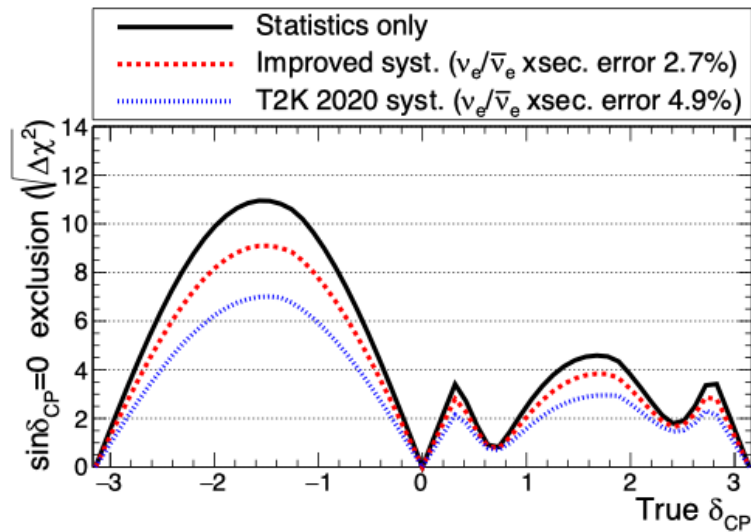
- The systematic error with the highest impact on CPV sensitivity:  $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$  in case of CPV values close to CP conserving values
- Maximal CPV highest impact from  $\cos\delta_{CP}$  shape effects on the energy spectrum

# Systematics in more detail

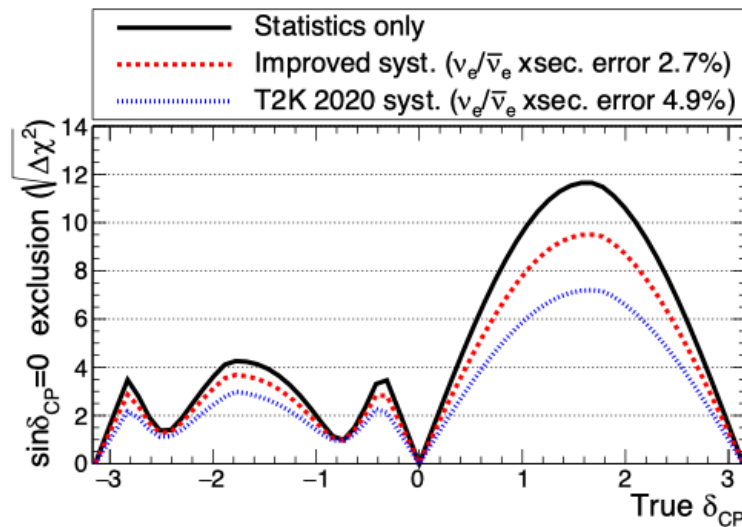
- The systematic error with the highest impact on CPV sensitivity:  $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$  in case of CPV values close to CP conserving values



# $\sin\delta_{CP} \neq 0$ Sensitivity, MO not known



Hyper-K preliminary  
True normal ordering (Unknown), 10 years ( $2.7 \times 10^{22}$  POT 1:3  $\nu:\bar{\nu}$ )  
 $\sin^2\theta_{13}=0.0218\pm 0.0007$ ,  $\sin^2\theta_{23}=0.528$ ,  $\Delta m_{32}^2=2.509 \times 10^{-3} \text{eV}^2/c^4$



Hyper-K preliminary  
True inverted ordering (Unknown), 10 years ( $2.7 \times 10^{22}$  POT 1:3  $\nu:\bar{\nu}$ )  
 $\sin^2\theta_{13}=0.0218\pm 0.0007$ ,  $\sin^2\theta_{23}=0.528$ ,  $\Delta m_{32}^2=2.509 \times 10^{-3} \text{eV}^2/c^4$

# $\bar{\nu}_e$ samples

