Hyper-Kamiokande Status and Prospectives

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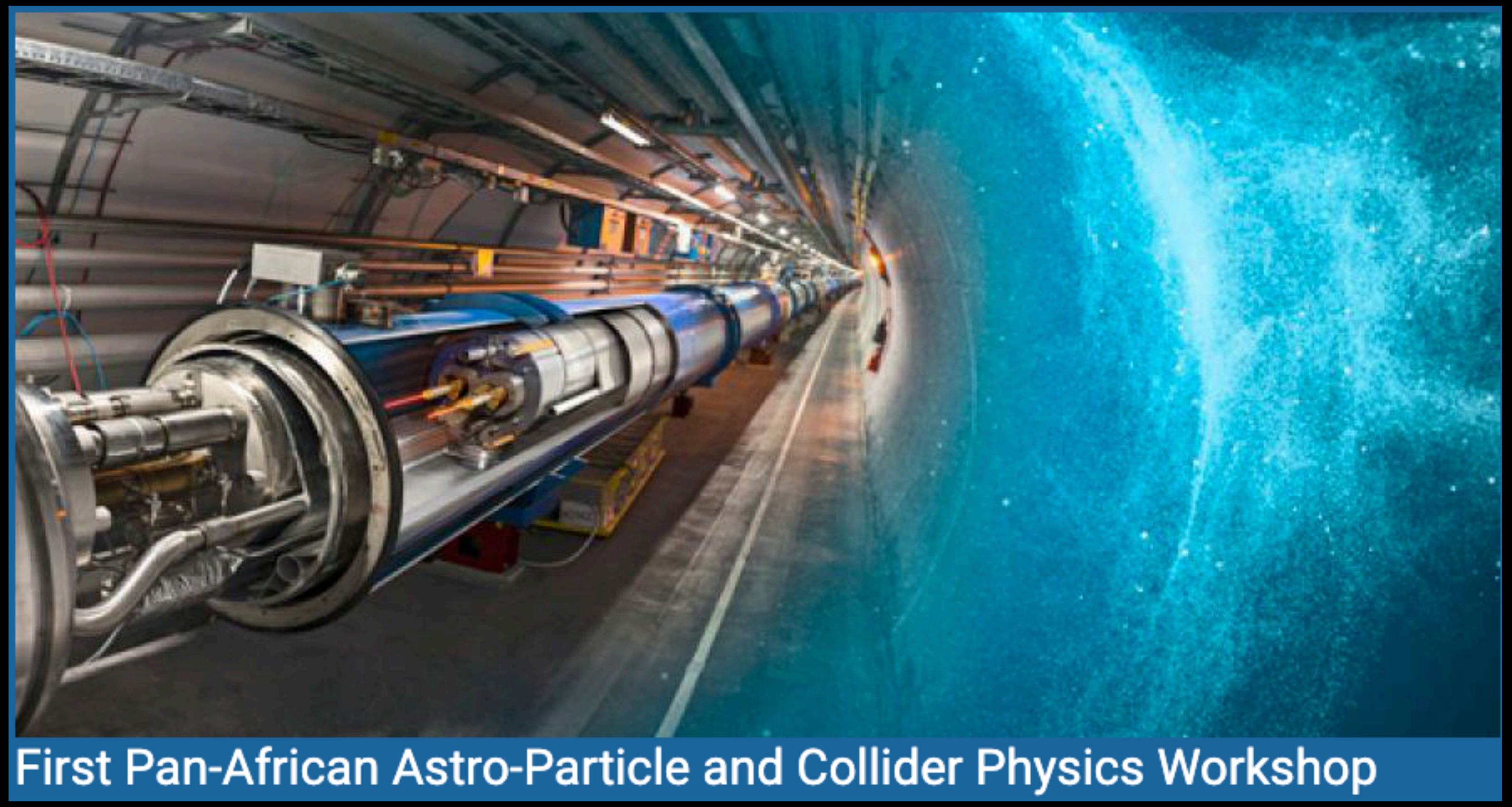
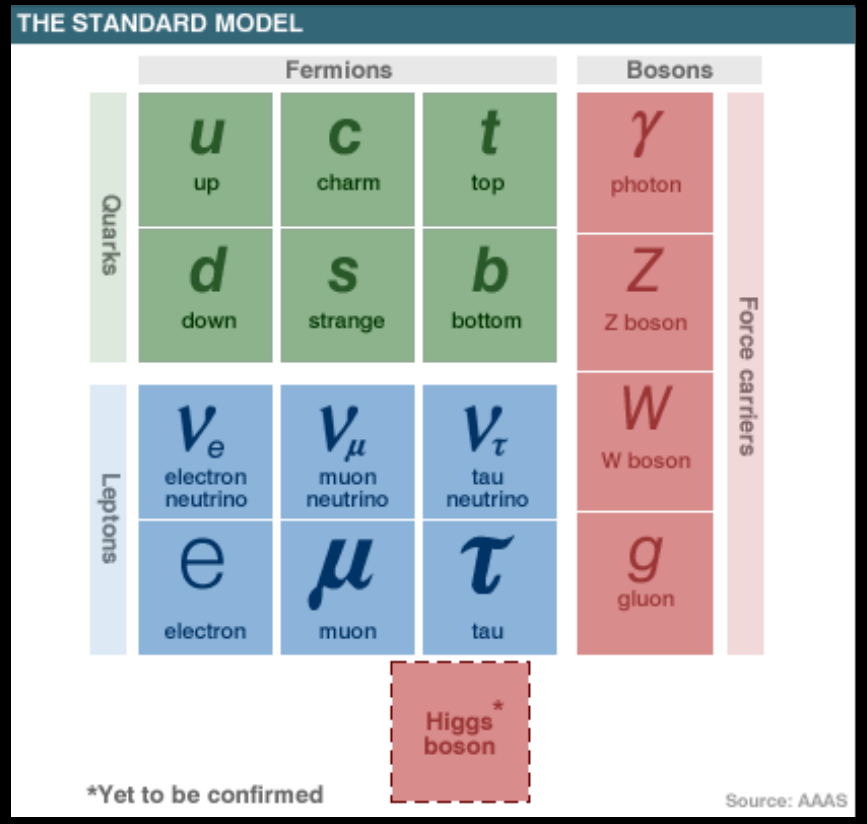
First Pan-African Astro-Particle and Collider Physics Workshop

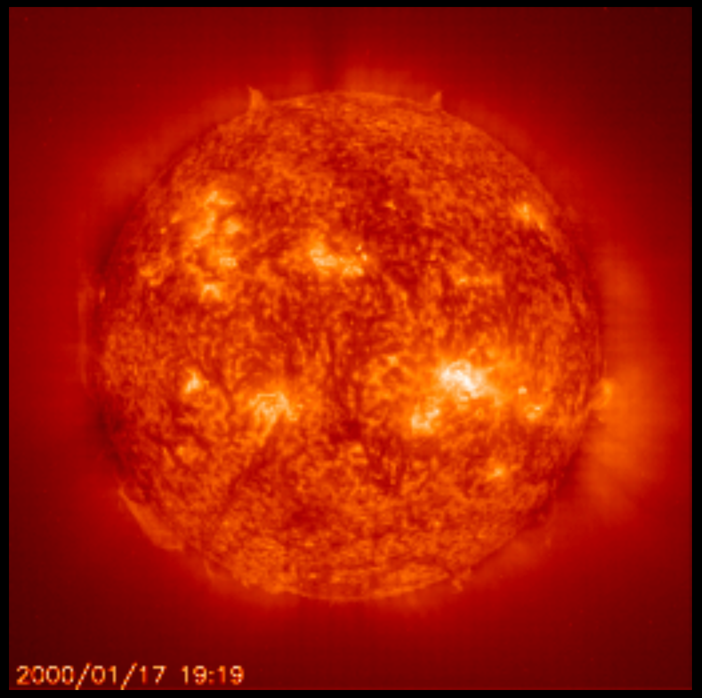
21 March 2022



Why neutrinos do matter?



Fundamental particles and interactions



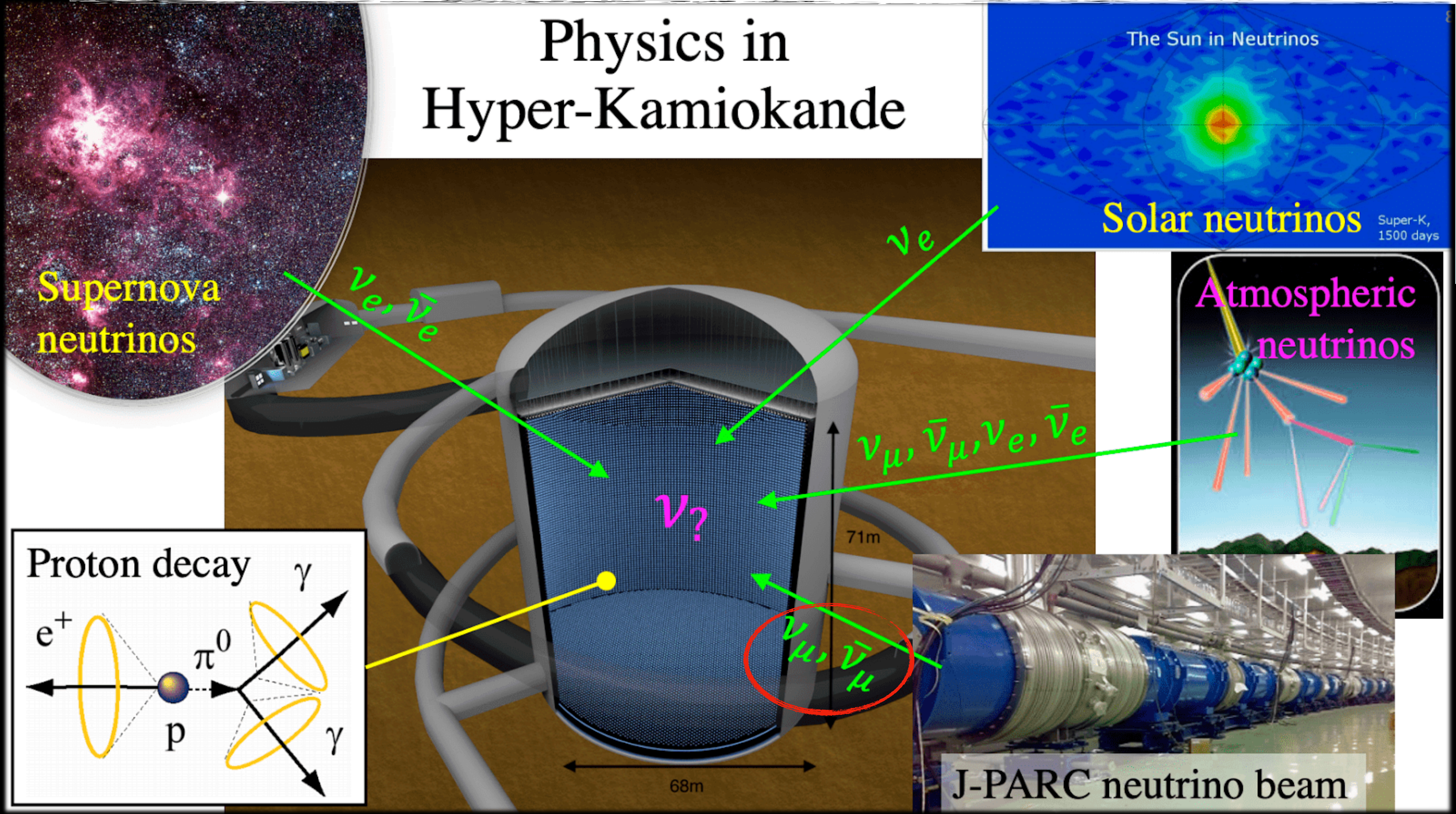
Astrophysics

Cosmology

Nuclear Physics

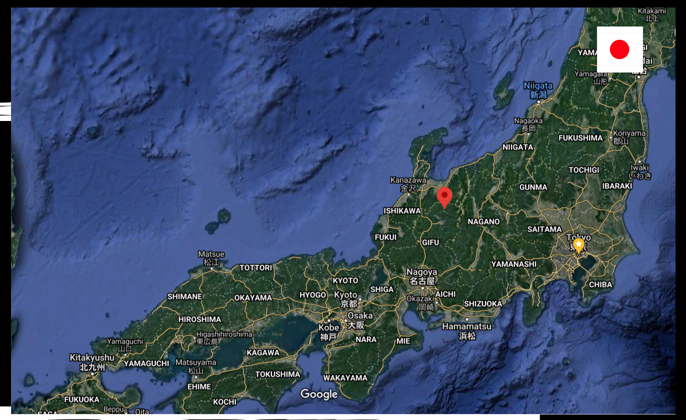
Neutrinos are important in understanding of history of structure formation; furthermore may give insight into matter-antimatter asymmetry

The Hyper-Kamiokande Experiment



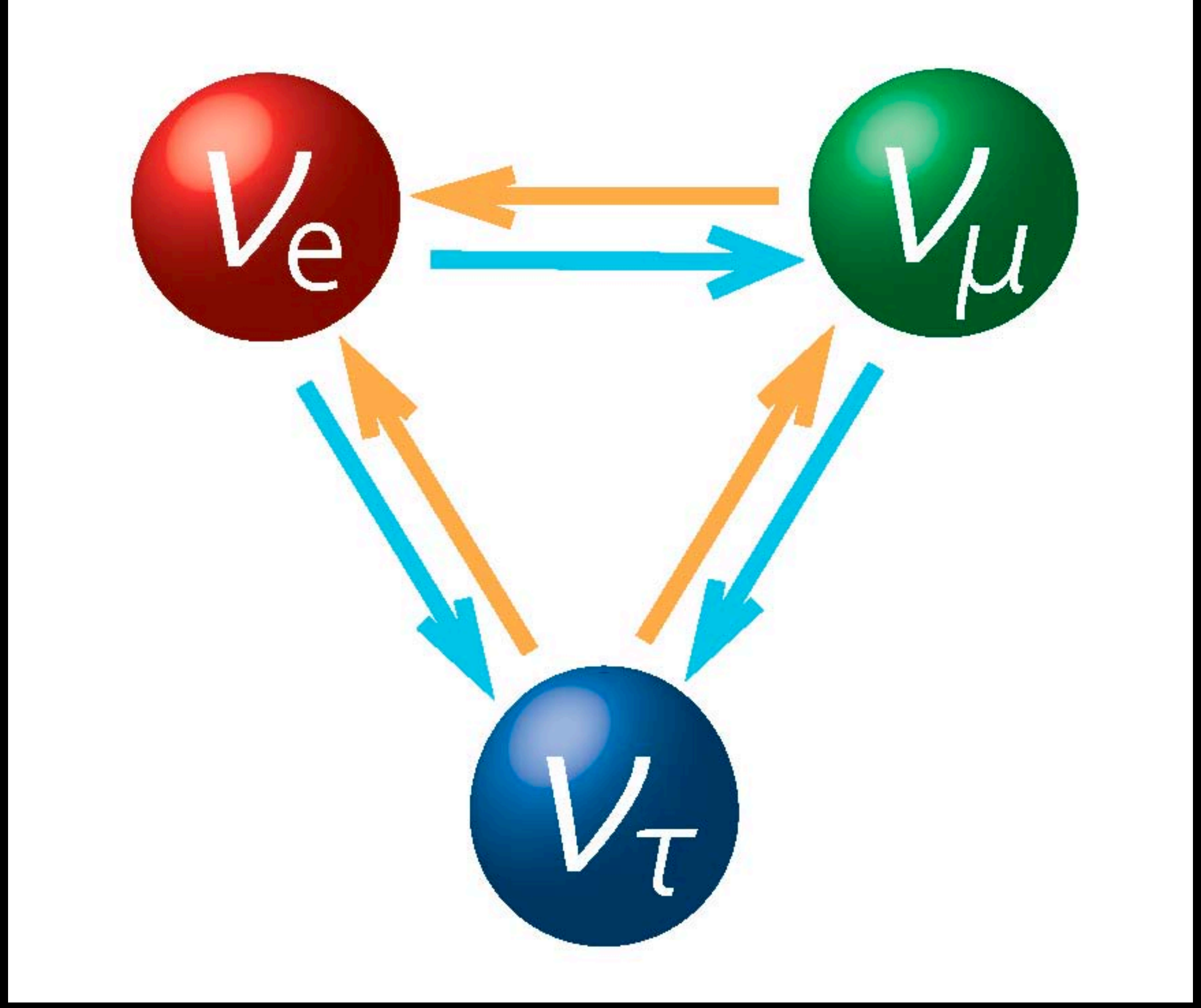
Hyper-Kamiokande will address broad science questions with unprecedented precision.

The Hyper-Kamiokande Experiment



Neutrino Oscillations

Neutrino Oscillations will be measured based on **accelerator** and **atmospheric** neutrinos.

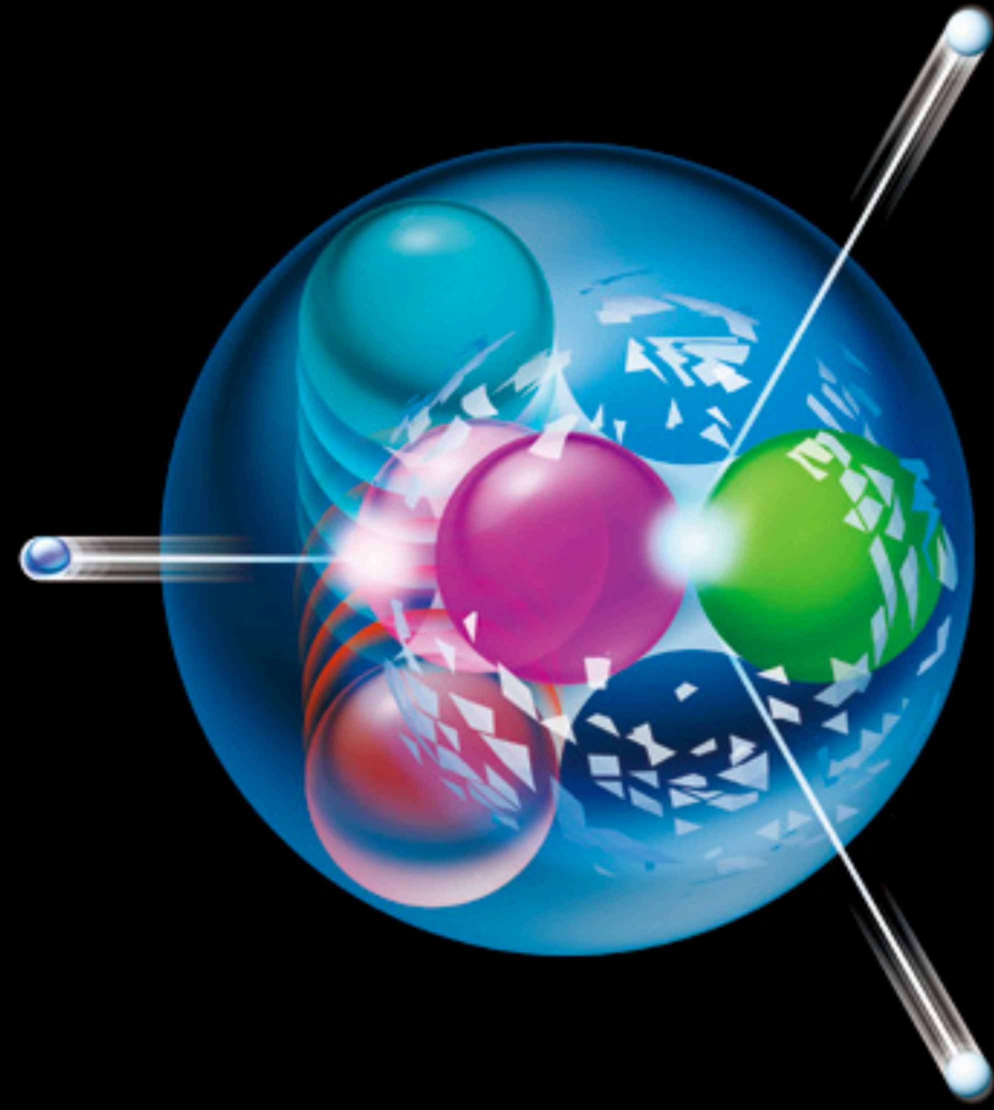


Astrophysical Neutrinos

Solar, **supernova**, and **supernova relic** neutrinos will be explored for astronomical research.

Rare Decays

Rare processes such as proton decay or **neutron decay** processes that violate baryon number will be searched.



Neutrino Oscillations

PMNS mixing matrix relates mass and flavour eigenstates $|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*} |\nu_i\rangle$

Free parameters usually written in terms of three rotation angles and one complex phase: $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$

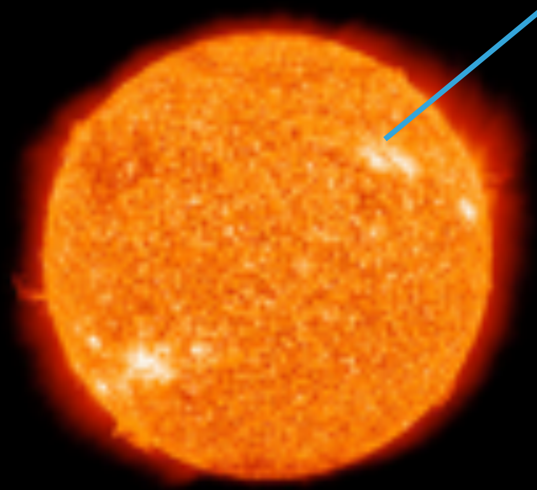
Parametrise mixing matrix U as:

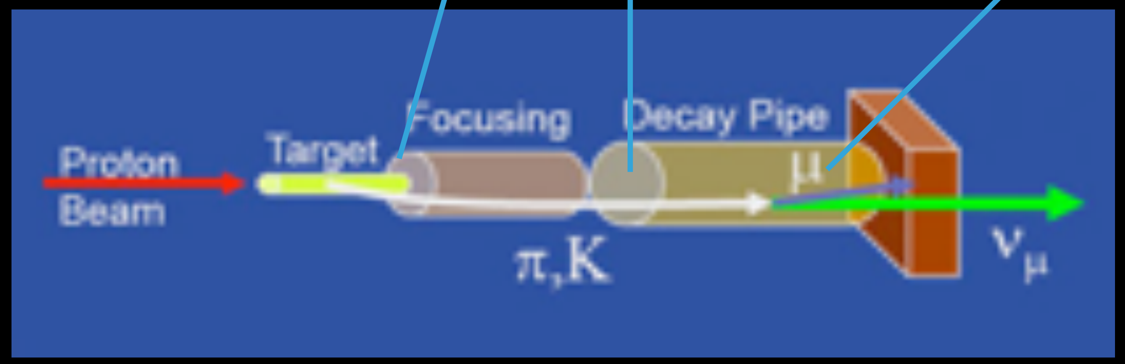
$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

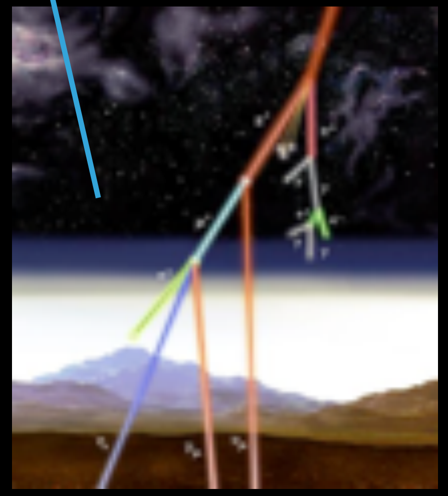
Solar — Accelerator/Reactor — Atmospherics

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

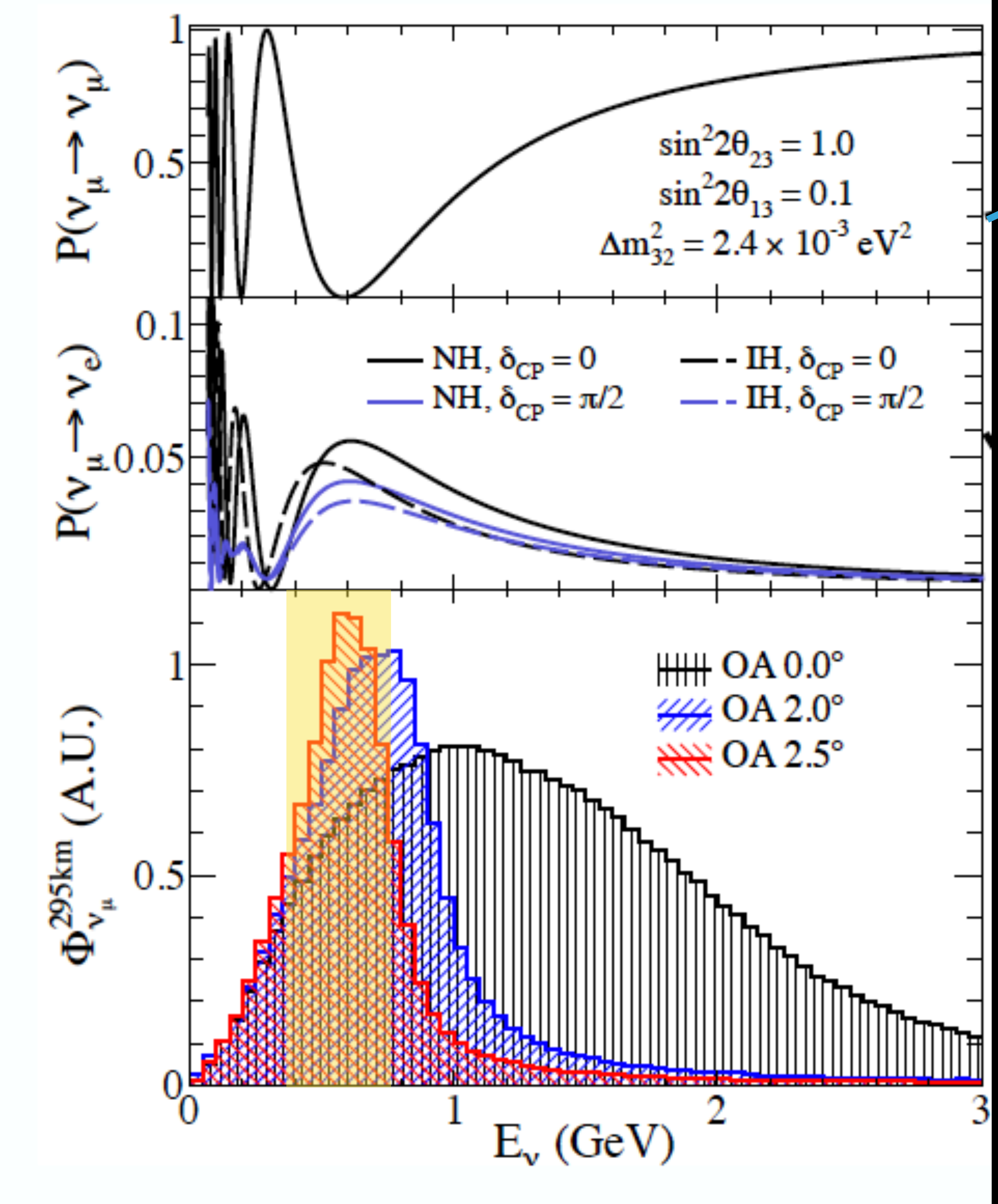
Hyper-Kamiokande will be able to study the solar, atmospheric and accelerator neutrinos.



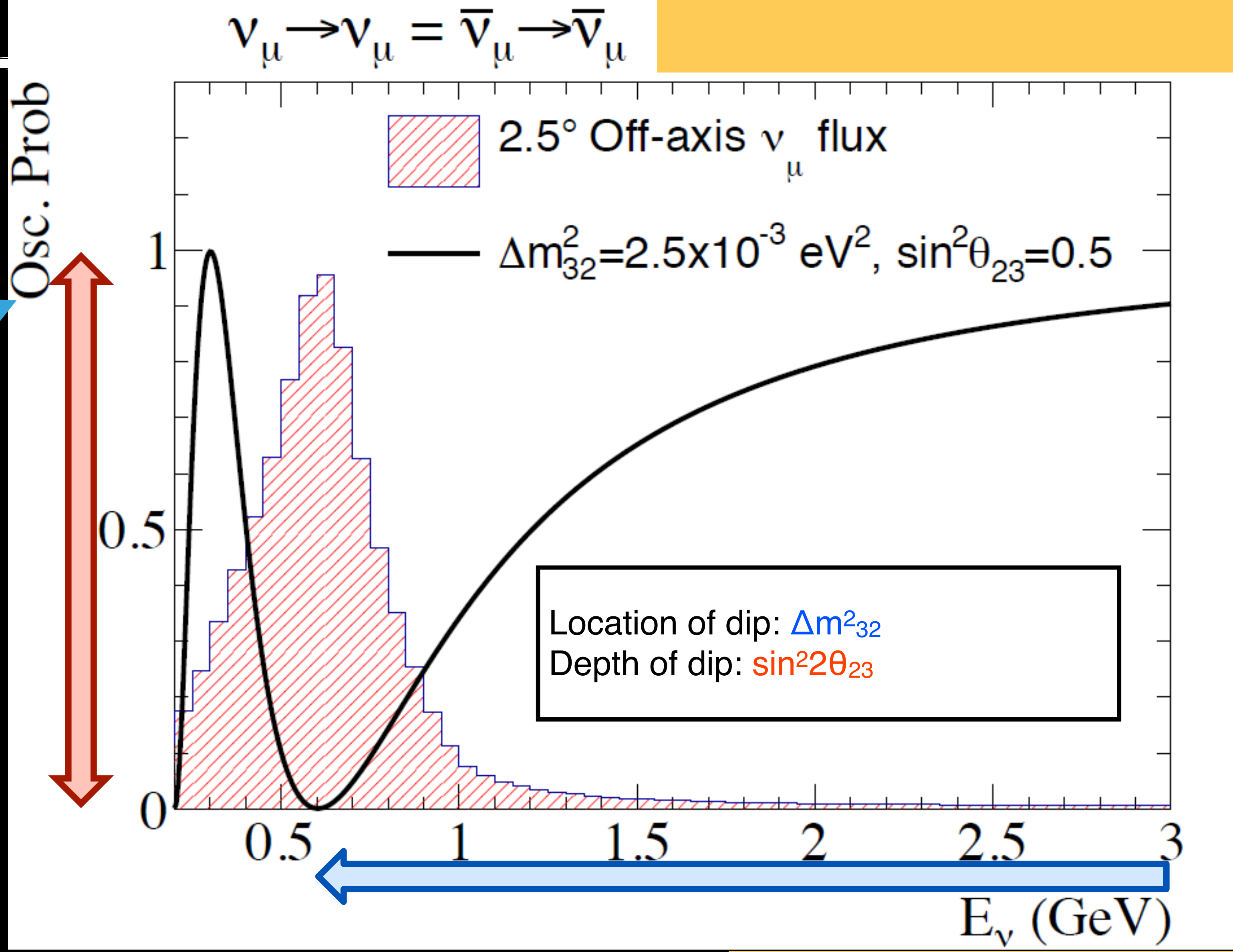




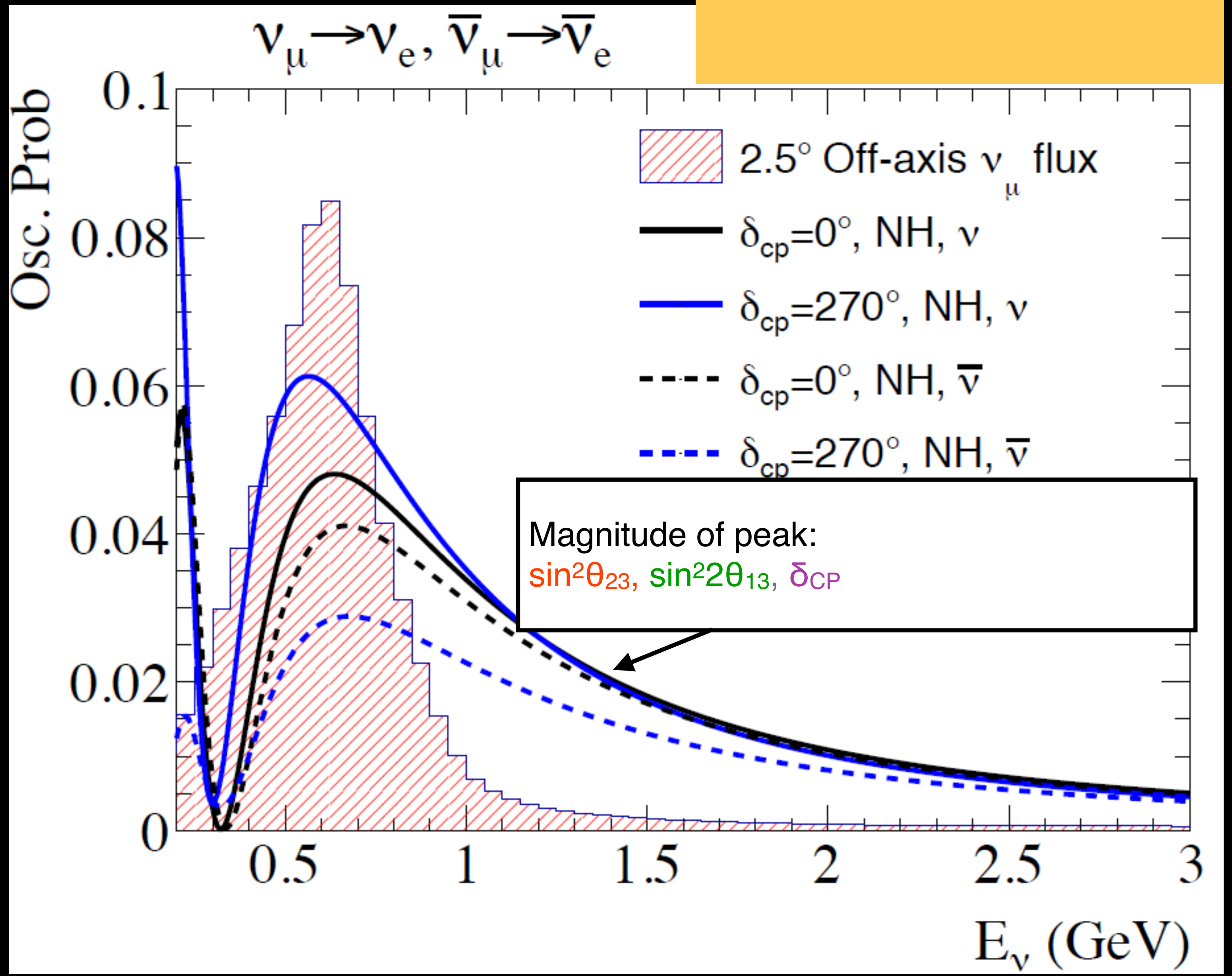
Neutrino Oscillations



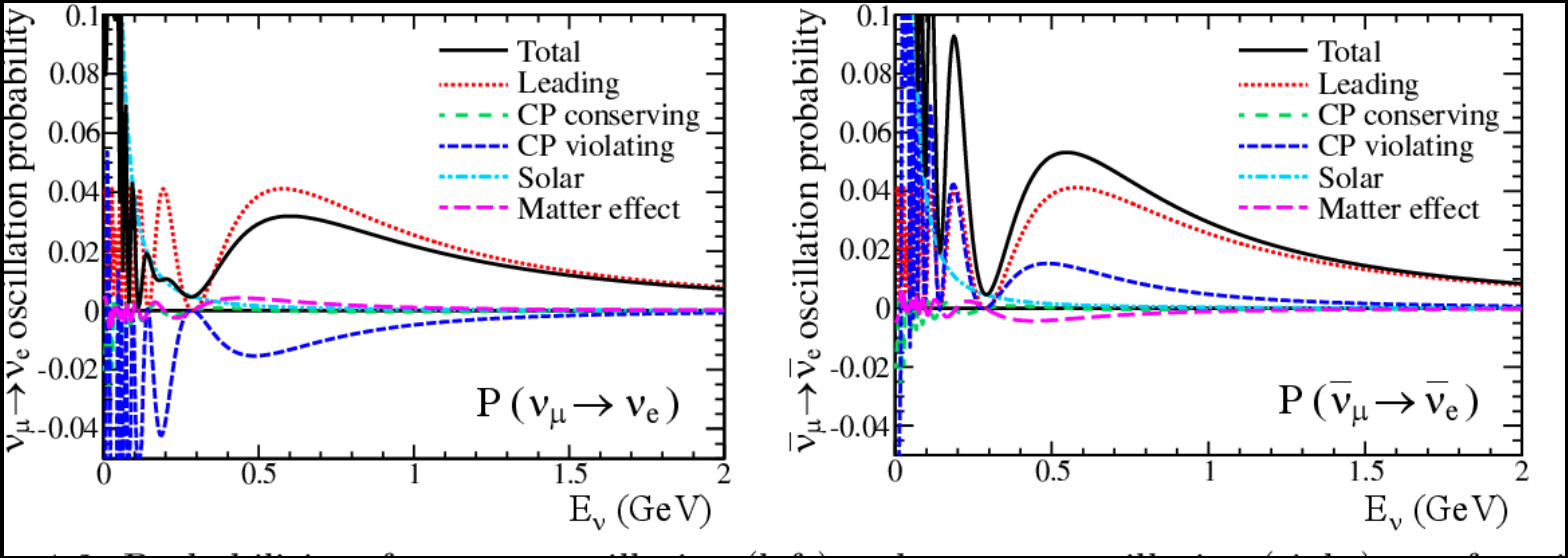
DISAPPEARANCE CHANNEL



APPEARANCE CHANNEL

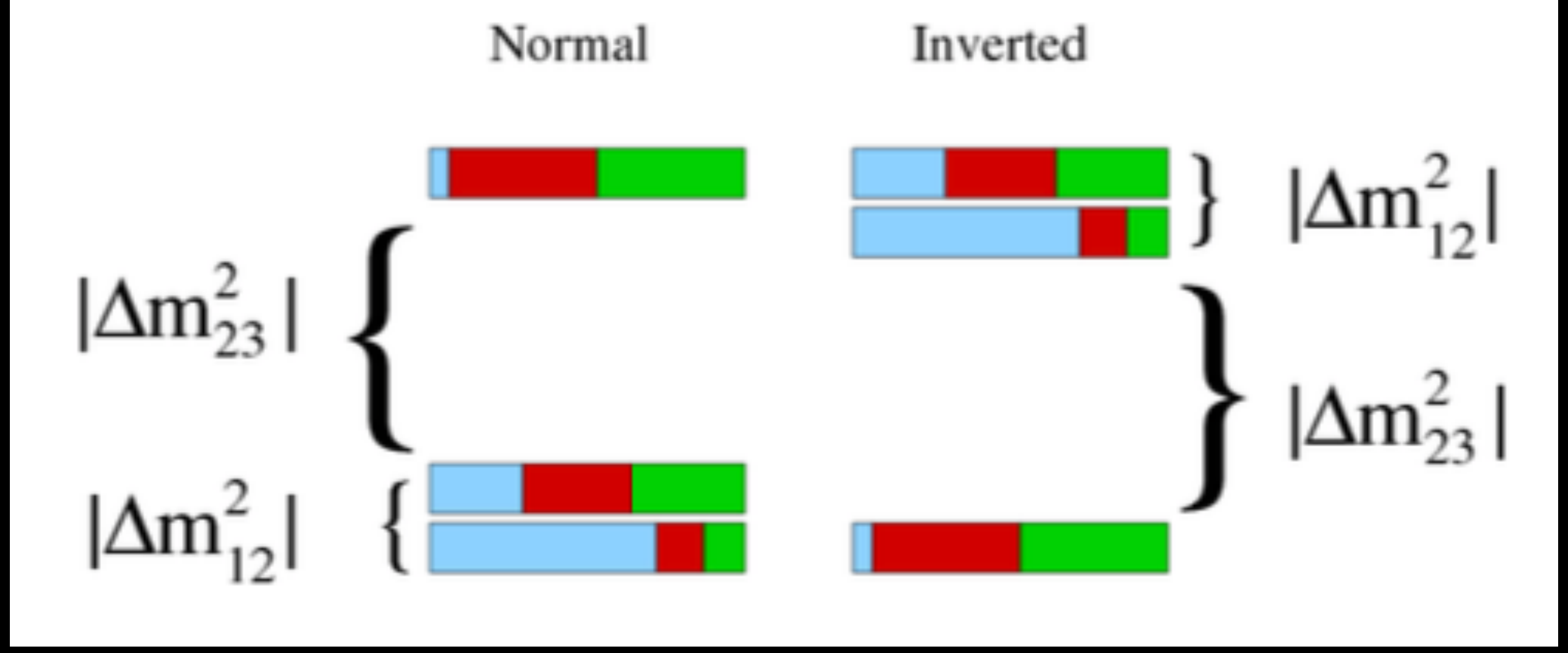


Neutrino Oscillations

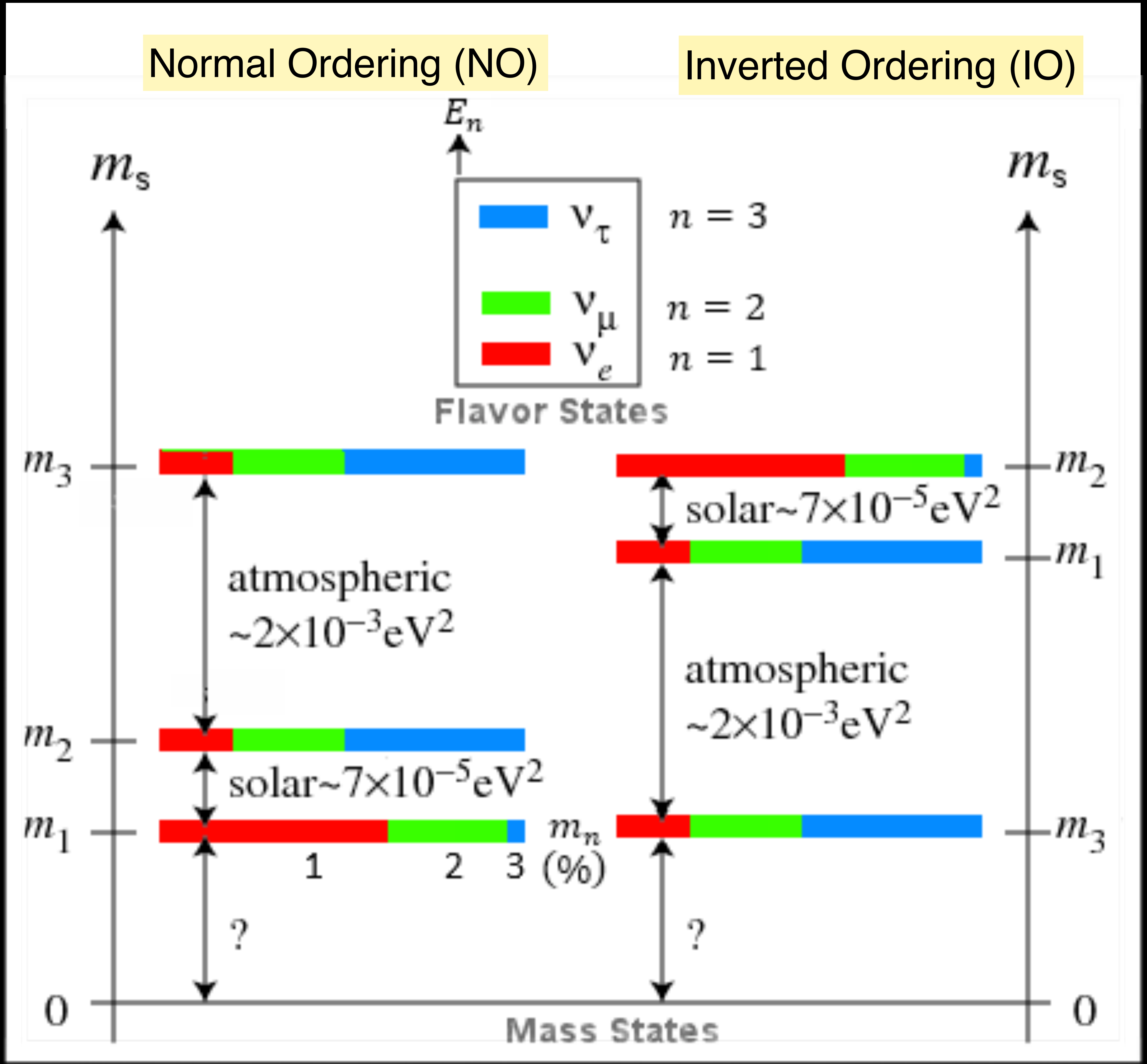


δ_{CP} measured comparing neutrinos ($\nu_\mu \to \nu_e$) and antineutrino ($\bar{\nu}_\mu \to \bar{\nu}_e$) oscillations.

Neutrino Masses



- Two possible mass ordering: normal and inverted.
  - Δm^2_{12} from solar neutrinos - sign known
  - $|\Delta m^2_{32}|$ from atmospheric neutrinos - sign not known
- Matter interaction needed to solve the ambiguity



Kamioka"NDE"

Nucleon Decay Experiment
Neutrino Detection Experiment

Kamiokande
(1983-1996)

3kton

20% coverage
with 50cm PMT

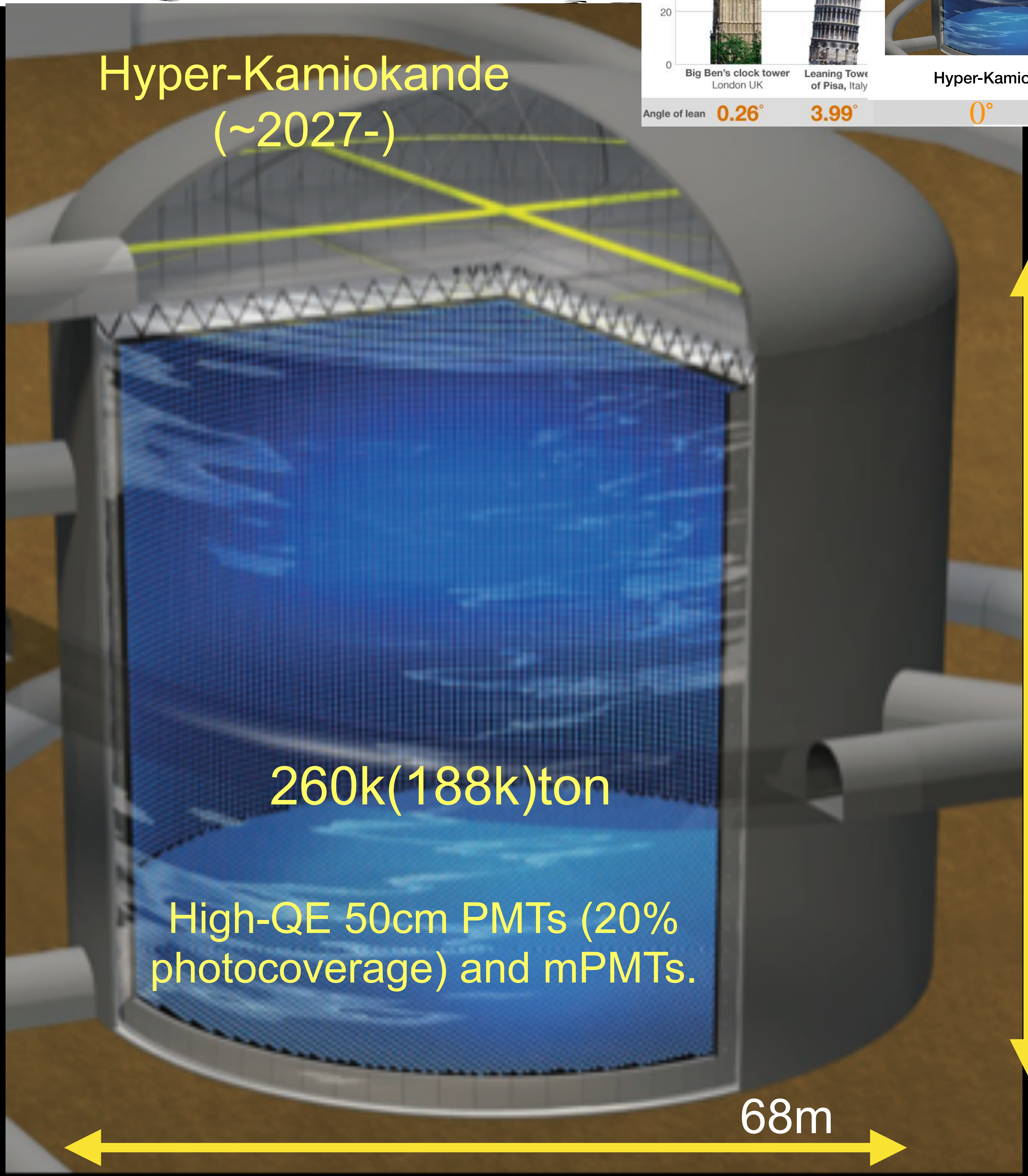
20x

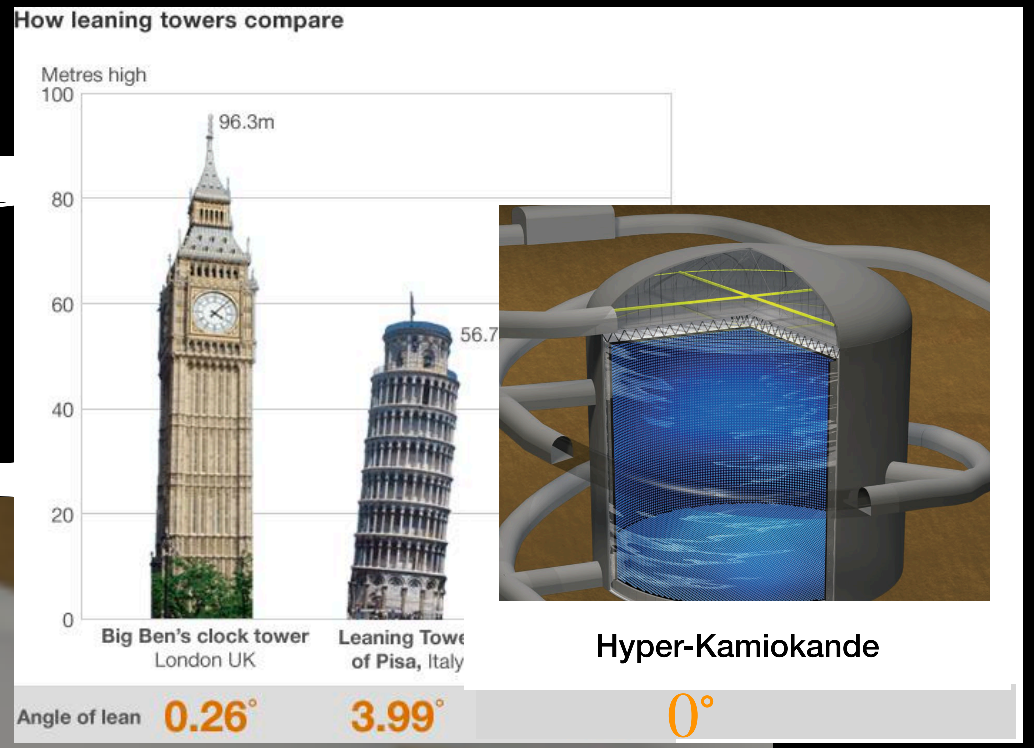
Super-Kamiokande
(1996-)

50k(22.5k)ton

40% coverage
with 50cm PMT

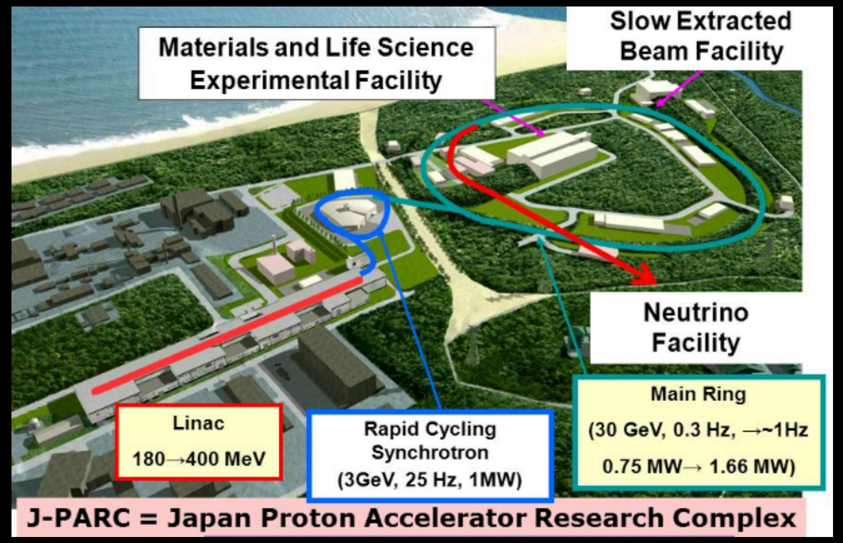
8.4x

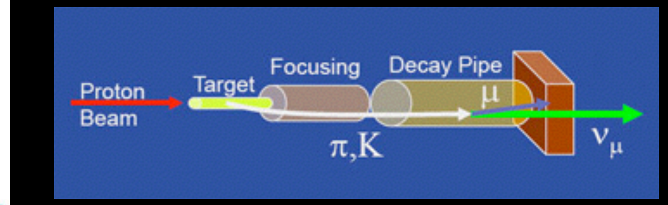




Unprecedented scale of underground cavern

Long-baseline neutrino experiment in a nutshell





ν beam

NEAR DETECTOR

ν beam

FAR DETECTOR

~100 m

~100-1000 km

$$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\varepsilon_{ND}$$

Neutrino flux prediction | Neutrino cross section model | Near detector selection, efficiency

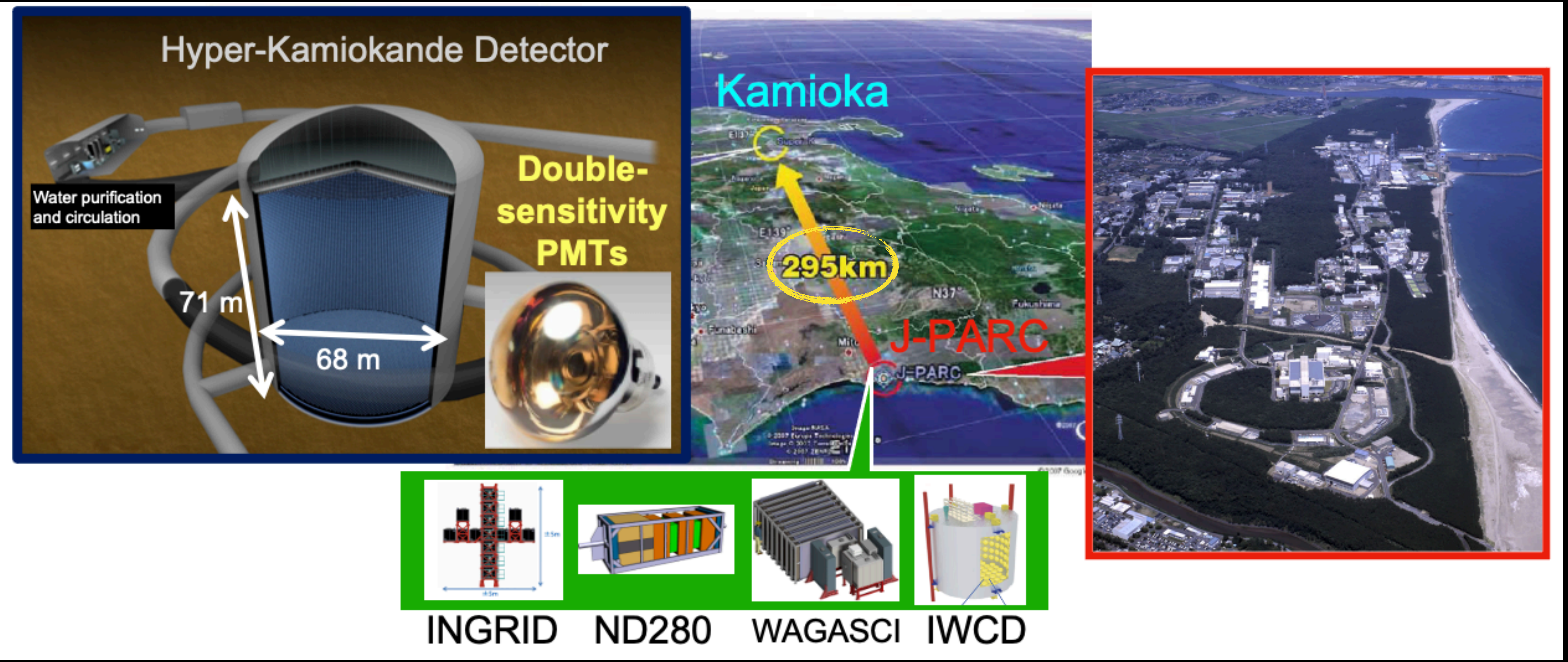
- Predicted events in the Near Detector.

$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\varepsilon_{FD} P(\nu_\alpha \to \nu_\beta)$$

Neutrino flux prediction | Neutrino cross section model | Far detector selection, efficiency

- Predicted events in the Far Detector.

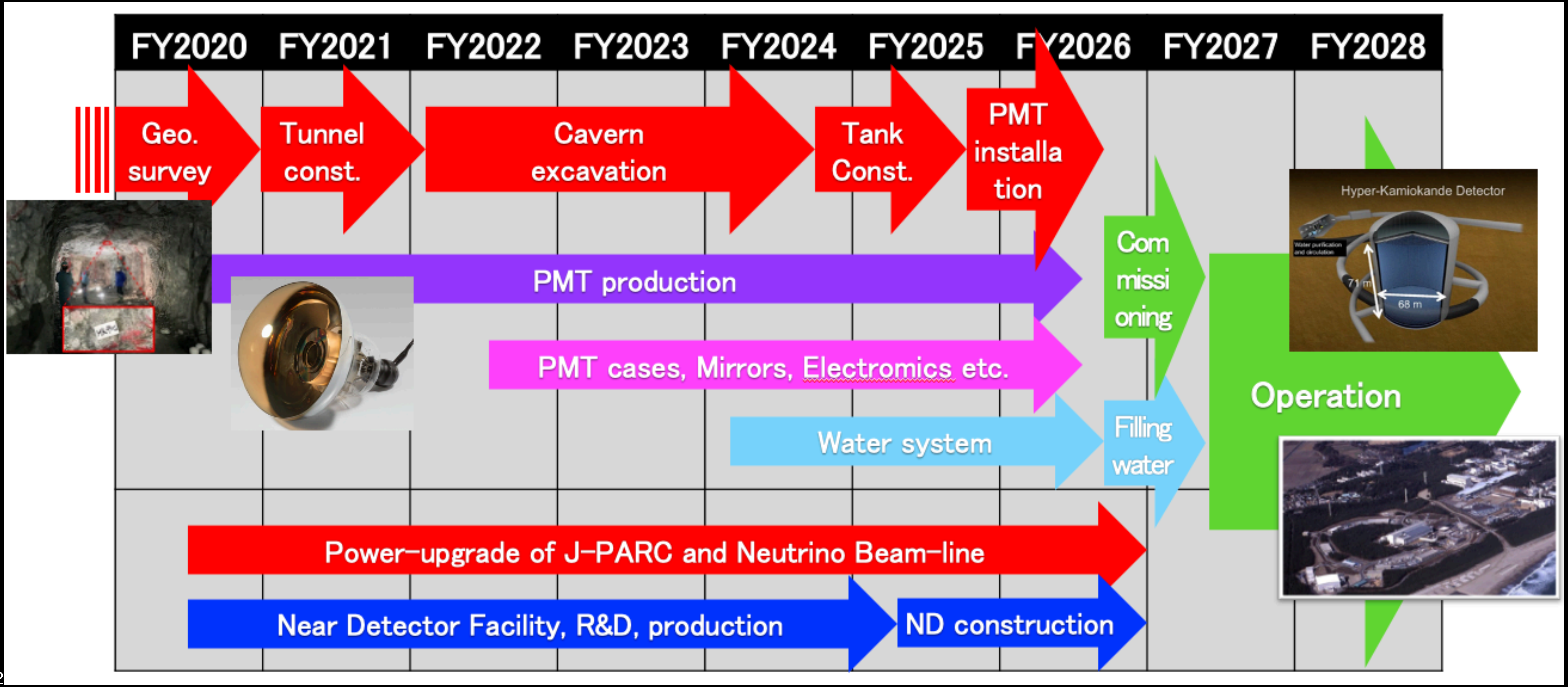
Hyper-Kamiokande Experiment



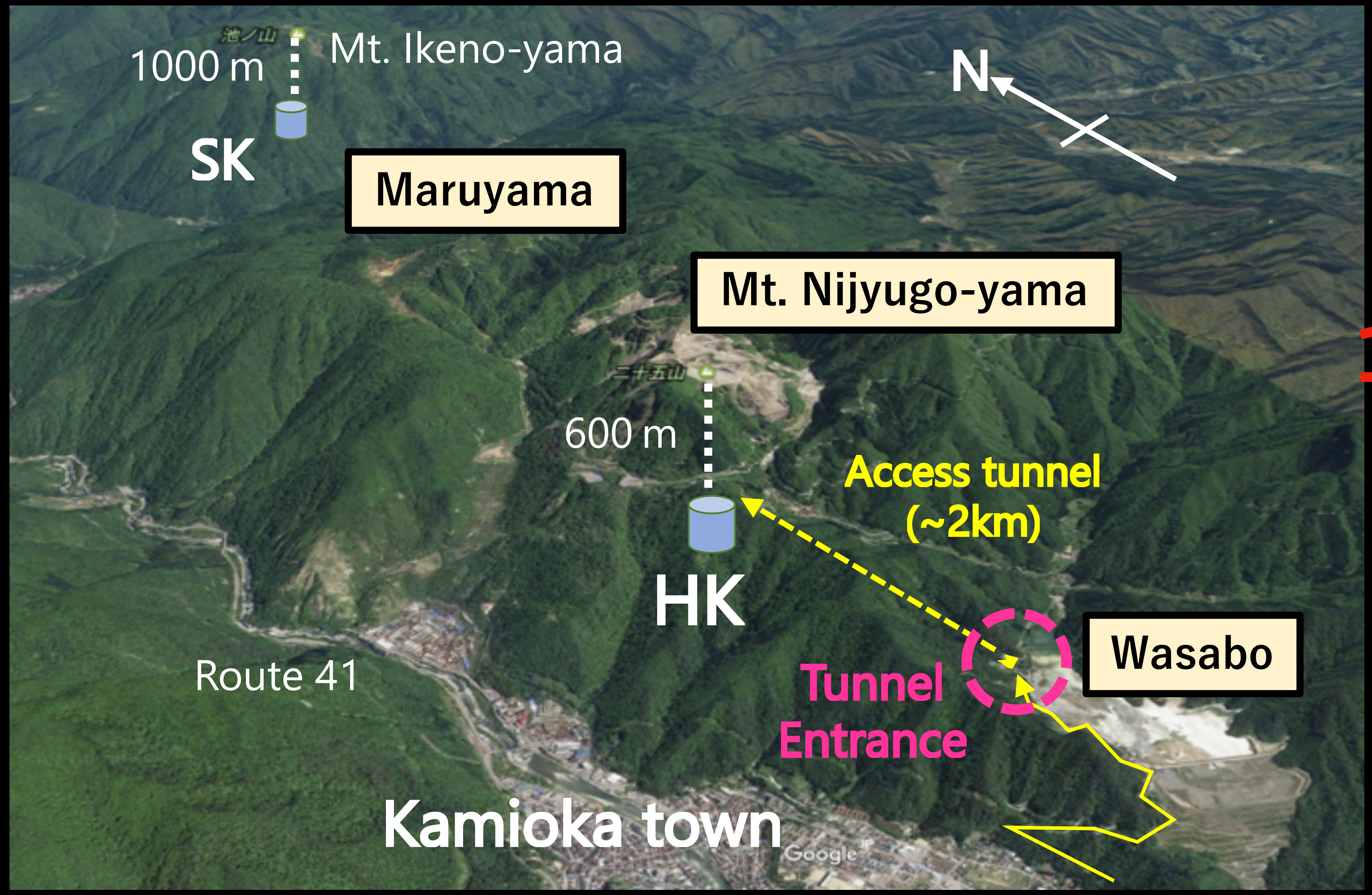
- Hyper-K detector with **8.4 times larger fiducial mass** (190 kiloton) than Super-K with **double-sensitivity PMTs**
- New (IWCD) and upgraded (@280m) near detectors to control systematic error.
- J-PARC neutrino beam will be upgraded from 0.5 to 1.3MW (**x2.5** higher than current T2K beam power)

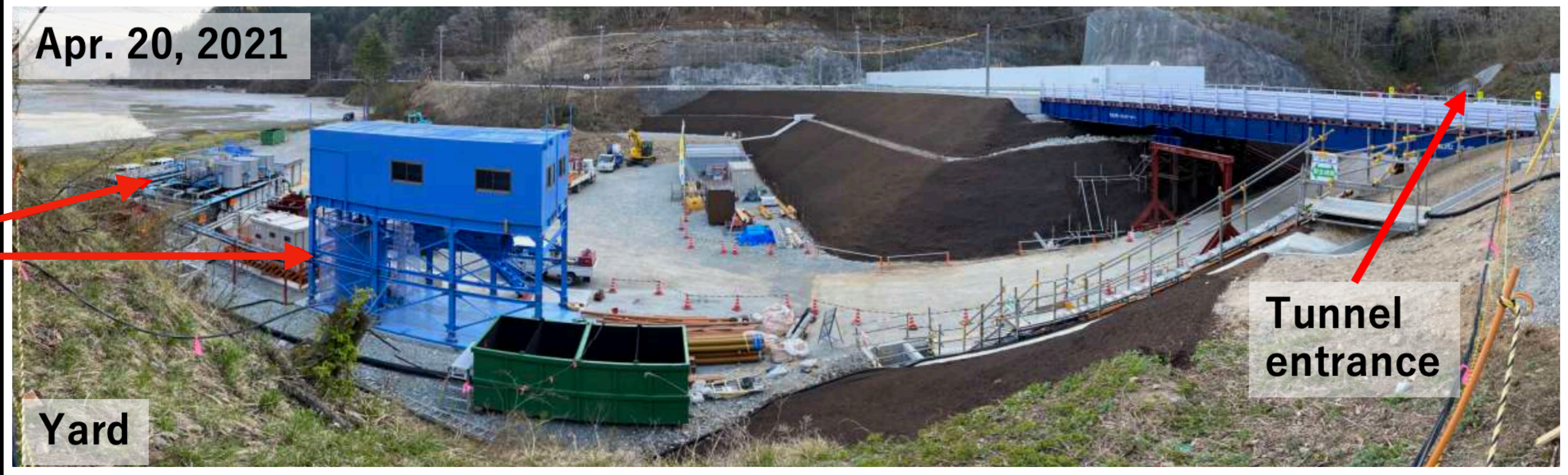
Hyper-K Schedule

- 7 years construction from year 2020; 5 years excavation + subsequent 2 years detector construction. Data taking from 2027.



Entrance Yard Construction





- Access tunnel (1873m) completed in February 2022.
- Approach tunnel started.

Hyper-K Collaboration

20 countries, 99 institutes, ~500 people as of Jan 2022, and growing

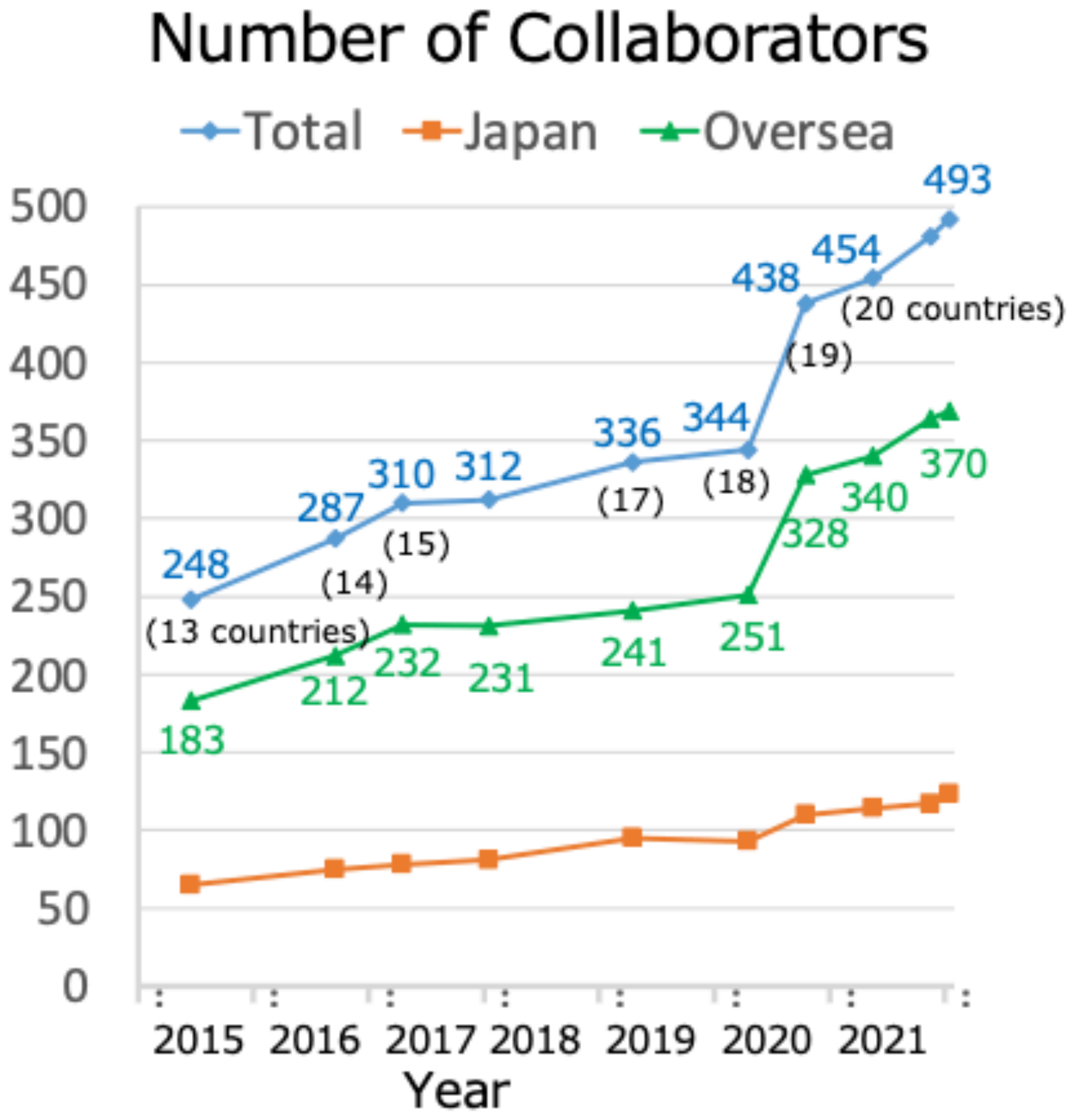
Collaborating Institutes

Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

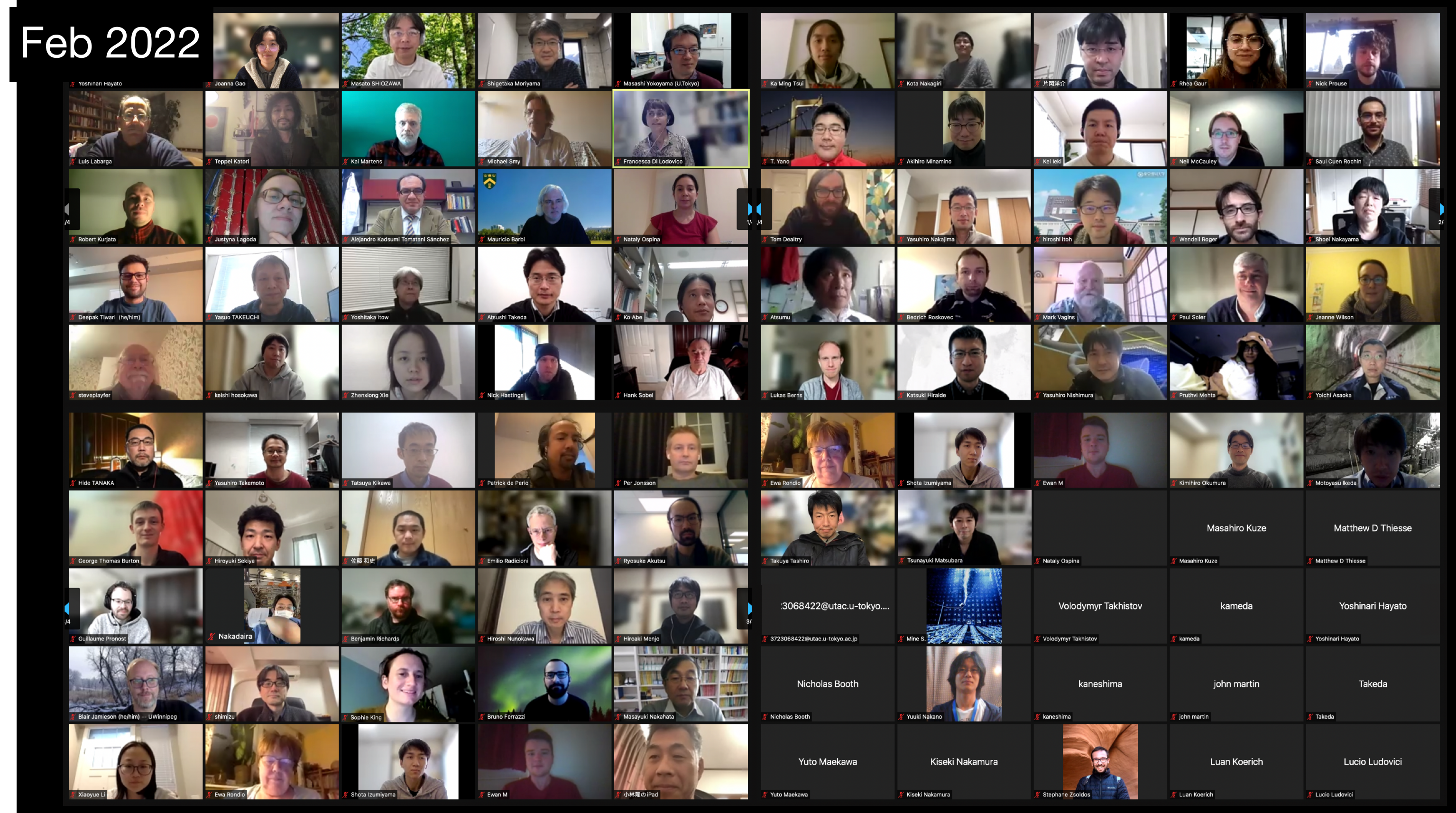
Asia	149 members
India	8
Korea	18
Japan	123

Americas	52 members
Brazil	3
Canada	32
Mexico	8
USA	9

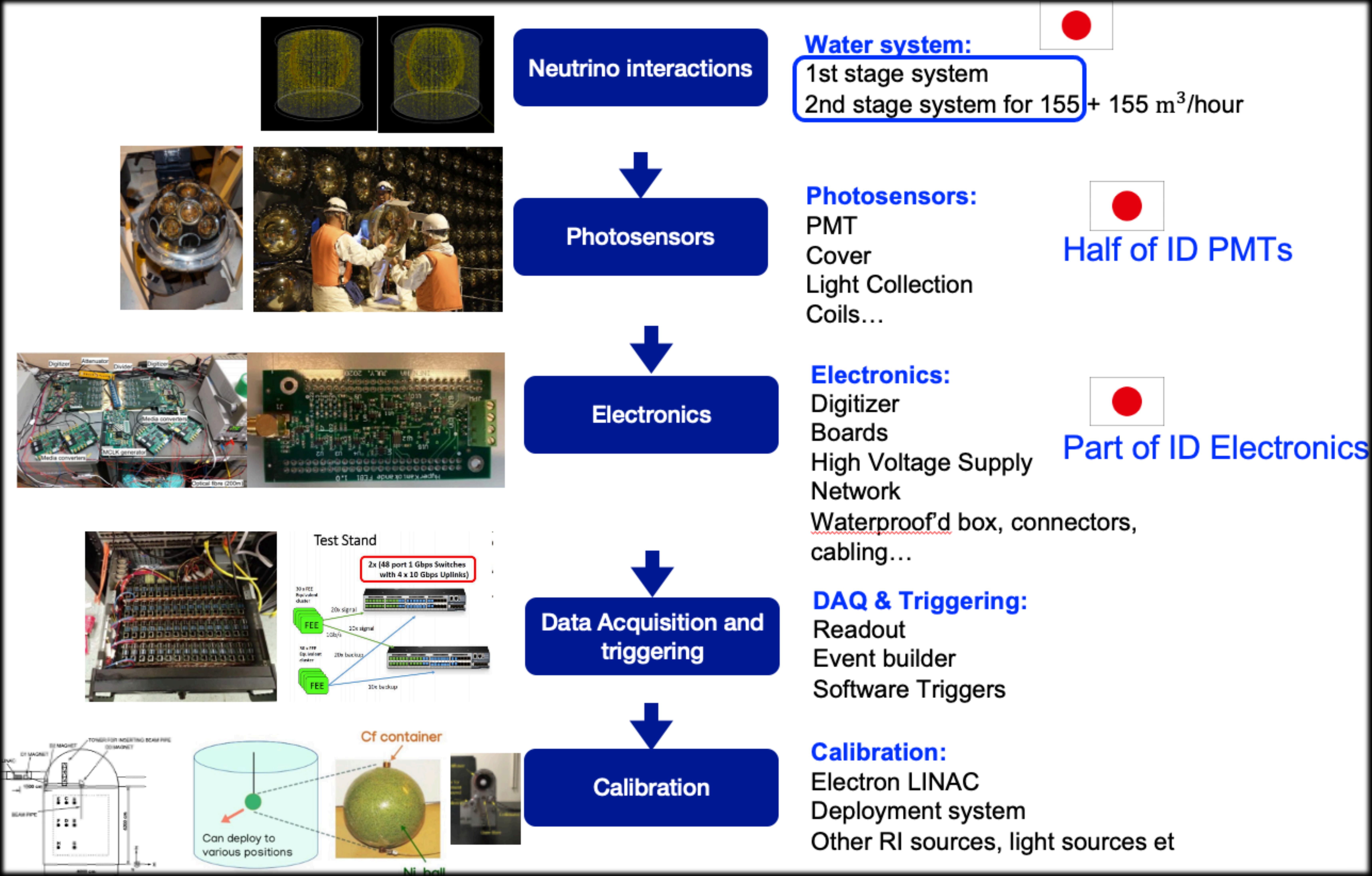
Africa	11 members
Morocco	11



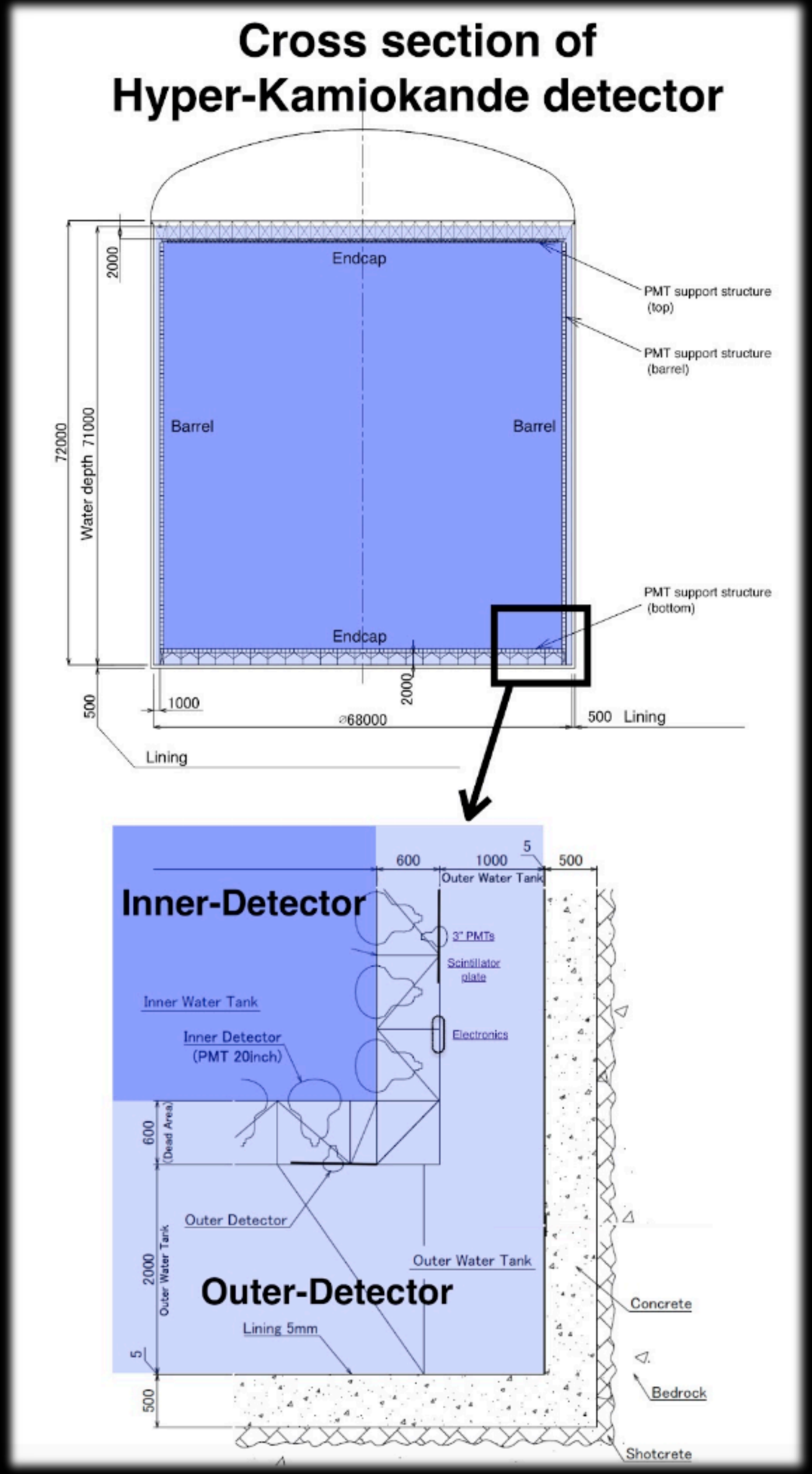
20 countries, 99 institutes, ~500 people as of January 2022, and growing



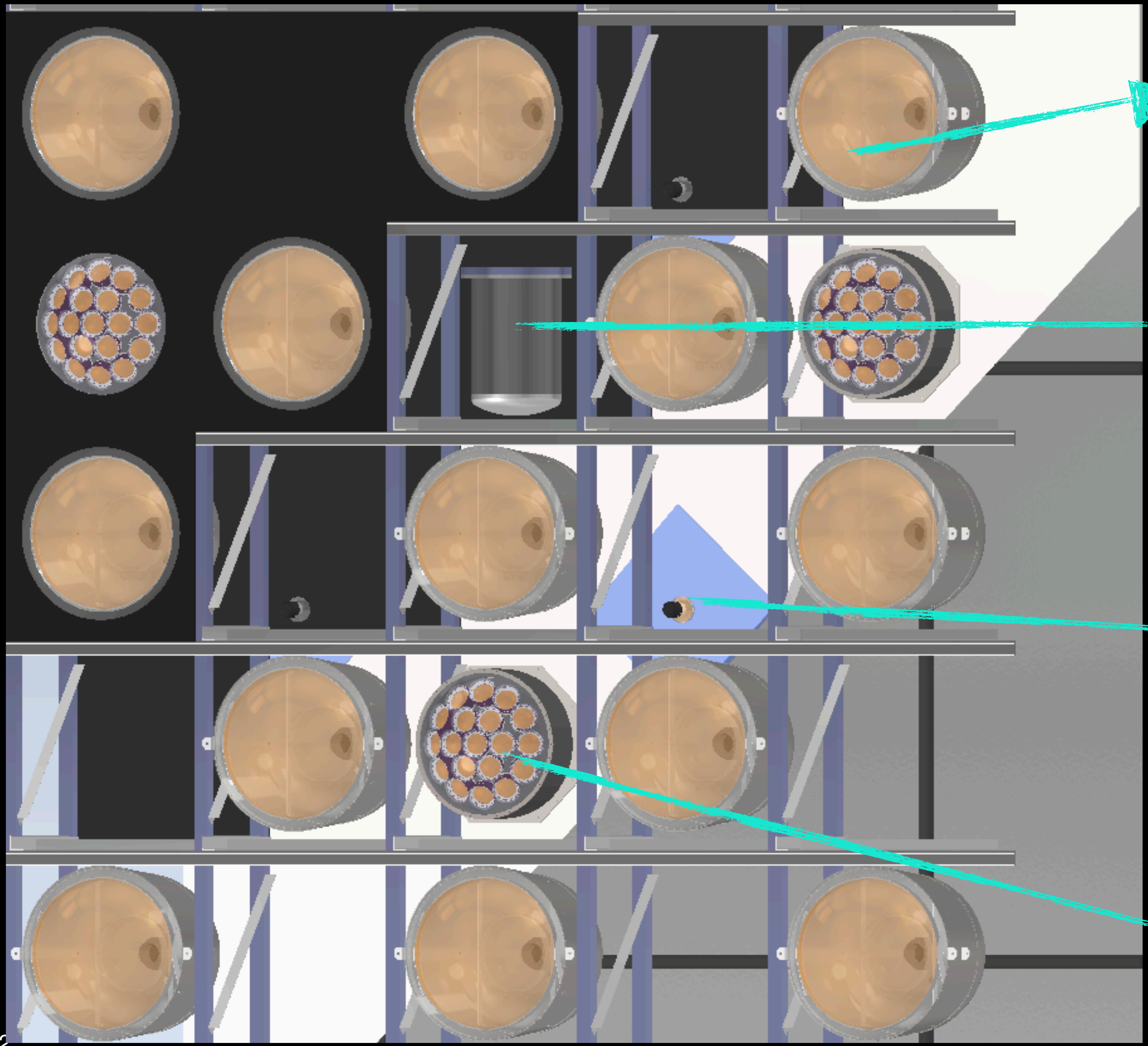
Hyper-K Experiment (Far Detector)



Two components:
- Inner Detector (ID)
- Outer Detector (OD)



Far Detector



50cm PMTs

ID+OD Electronics

OD

mPMTs

Mockup (Kashiwa, UTokyo)

Hyper-K Detector Construction has Started

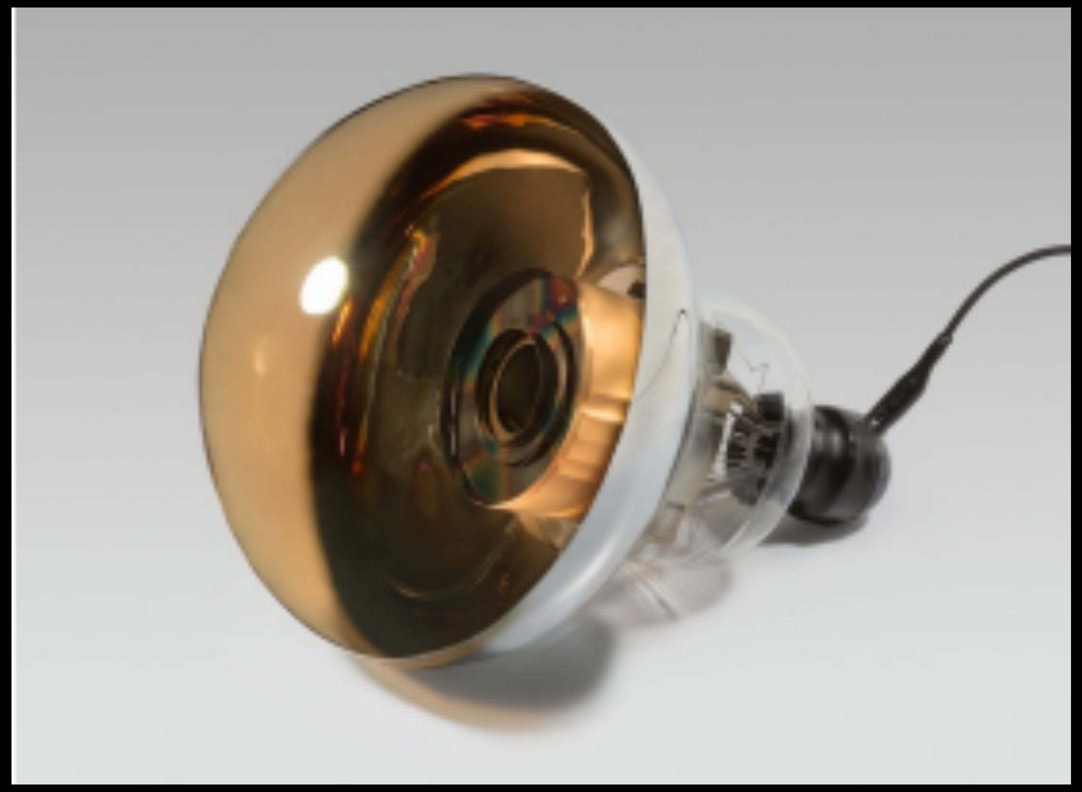
PMTs for the Inner Detector

	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

2020/12 First six PMTs delivered to Kamioka

- Production has started on time for the 50cm PMTs with Box&Line dynode.
- 300 PMTs by March, 20,000 PMTs in total by 2026 according to the Japanese budget profile.

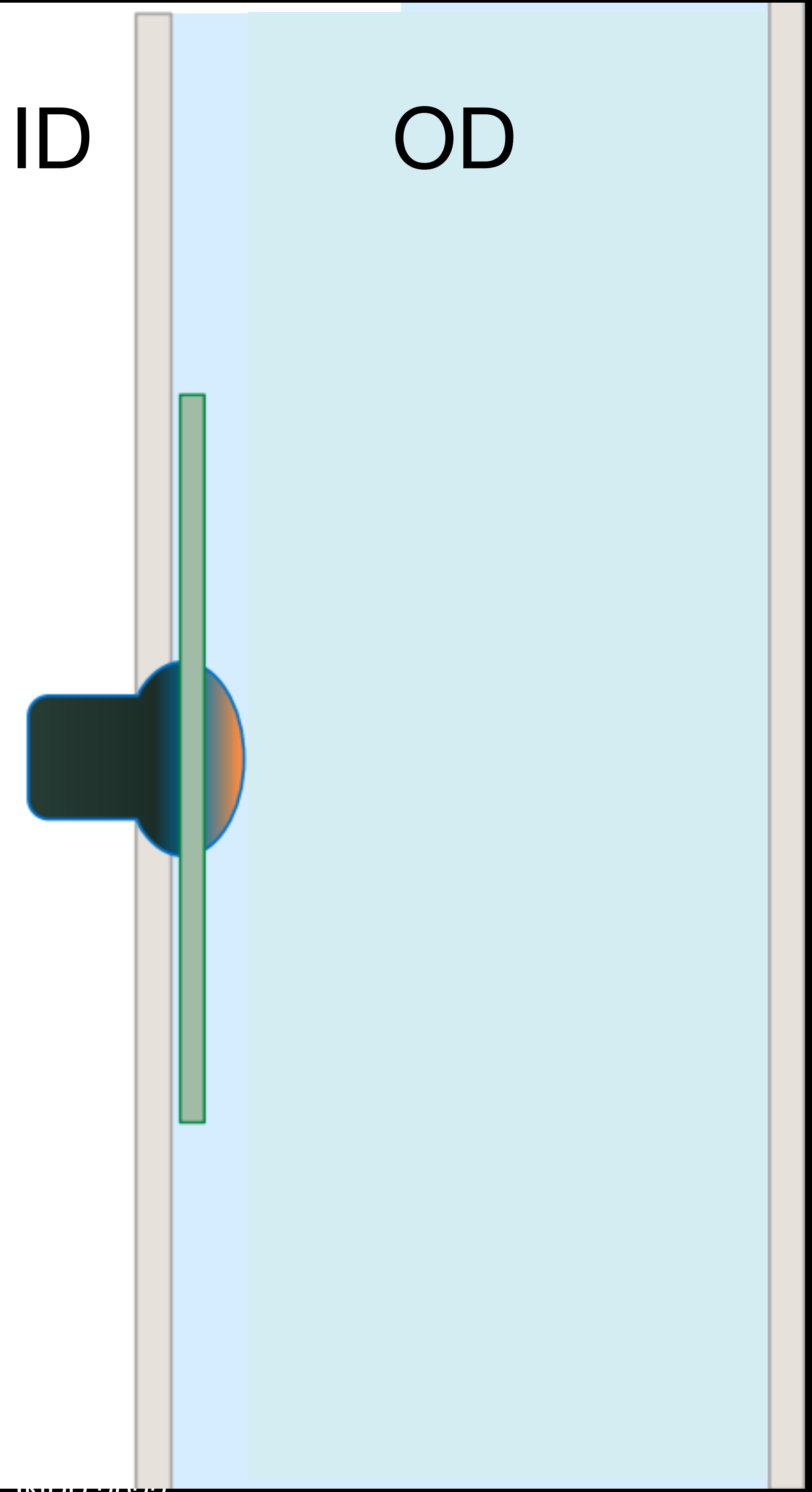
mPMTs



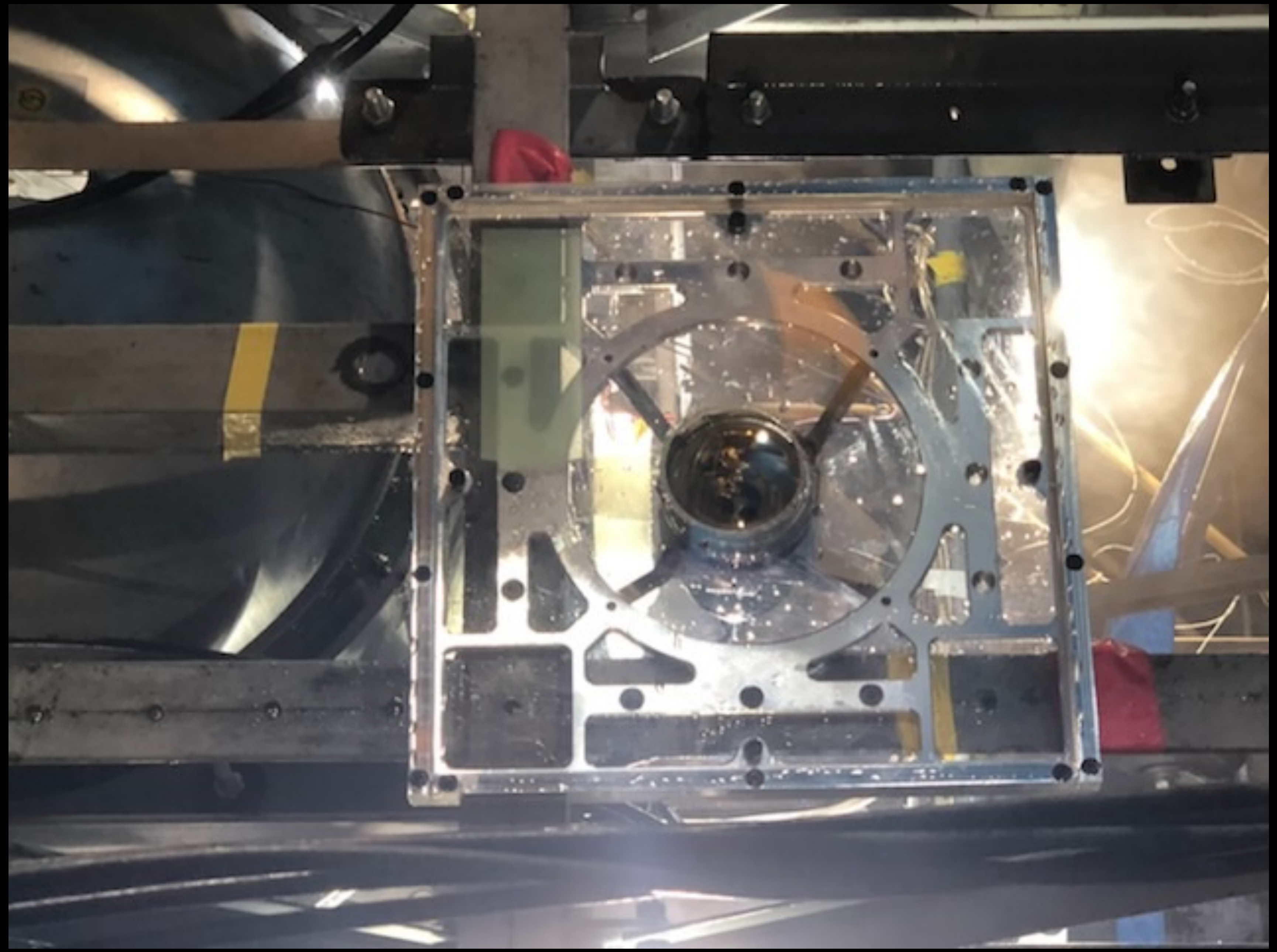
	20″ B&L PMT	mPMT (19 x 3″ PMT)
Photo-cathode area	2000 cm^2	870 cm^2
Photon detection	~6 hits/MeV/20k B&L	~1 hits/MeV/5k mPMT
Timing resolution (TTS)	2.7 ns	1.3 ns
Dark rate	4 kHz	200-300 Hz x 19 PMTs
Remarks	• Performance confirmed • High photon detection efficiency	• Granularity • Directionality • Better timing resolution

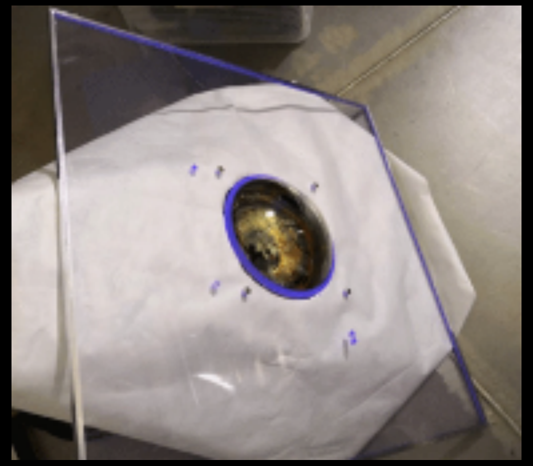
mPMTs will provide unique and complementary information to 20”PMTs.

Outer Detector (OD) Photosensing



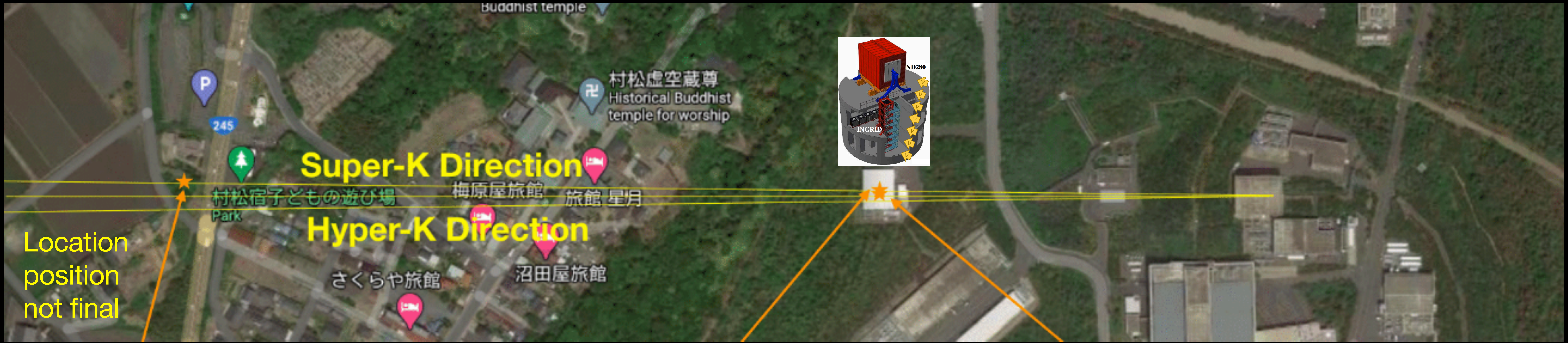
- Photosensing system composed of
  - 3” PMTs
  - Wave-length shifter plate
  - High-reflective Tyvek
- Crucial to reject external background.

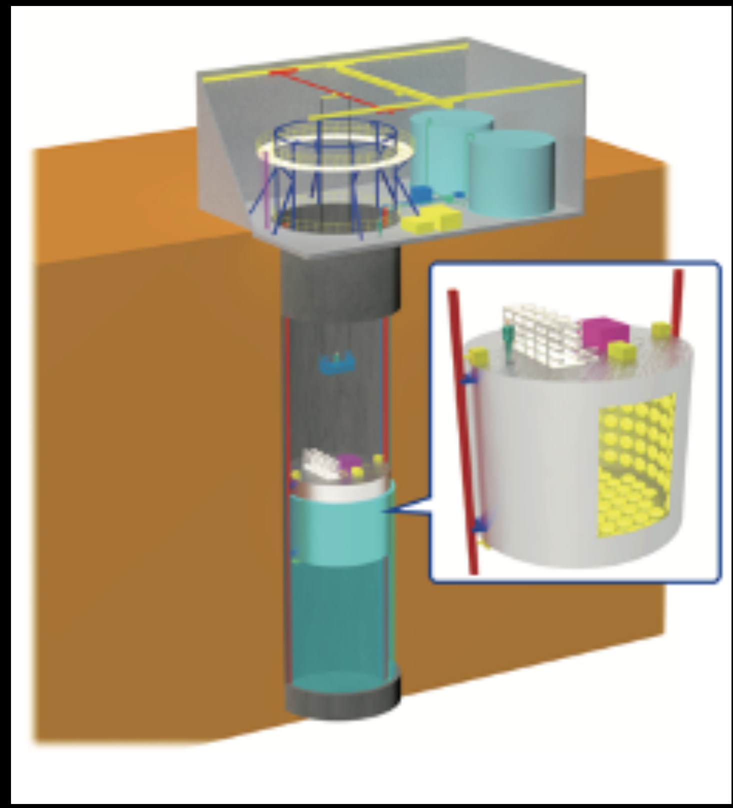




Suite of Near Detectors

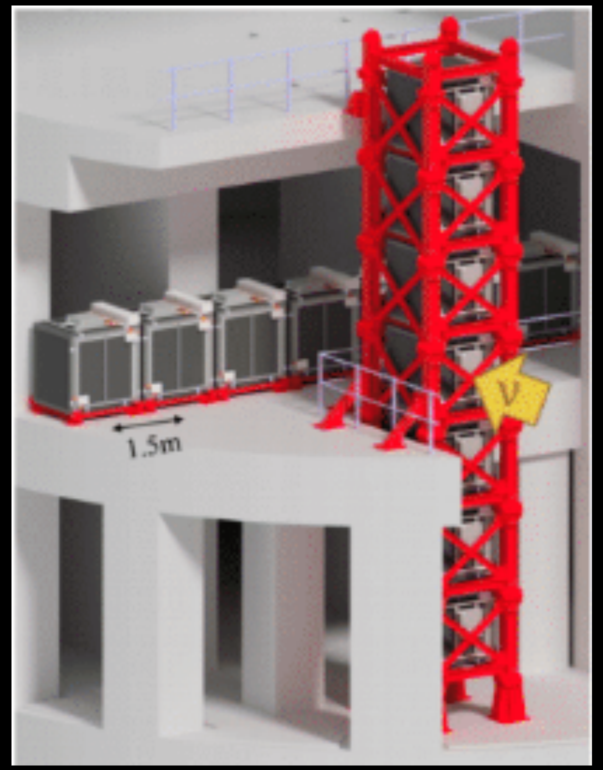
- Critical components to precisely understand J-PARC beam and neutrino interactions.





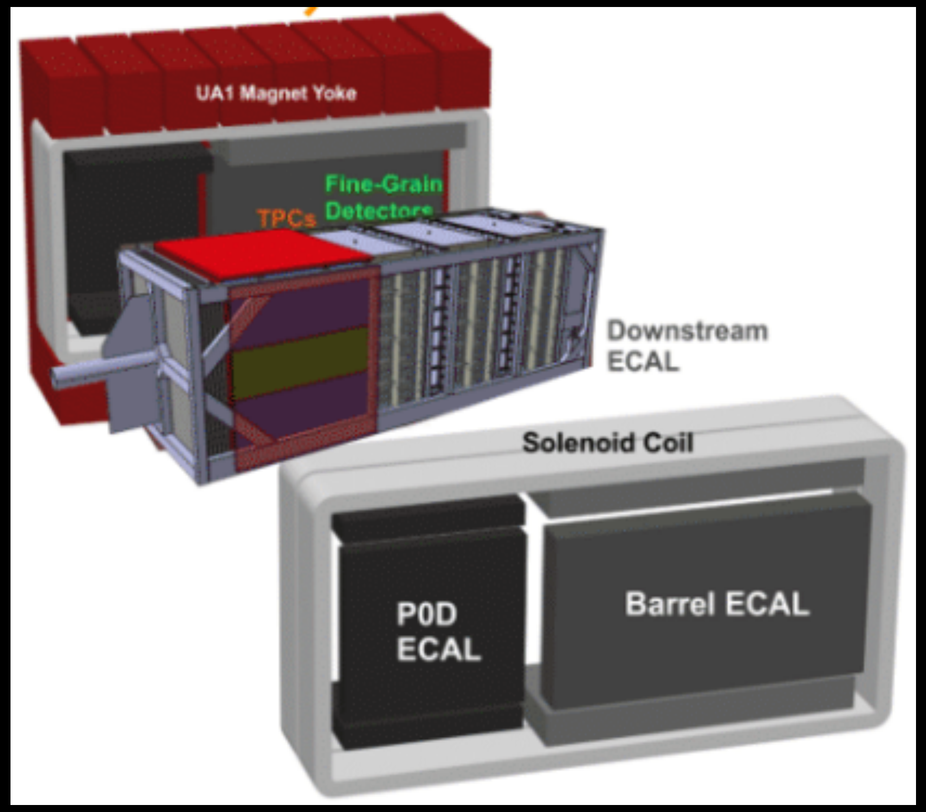
IWCD

Off-axis spanning water Cherenkov detector: intrinsic backgrounds, electron. (anti)neutrino cross-sections, E_ν vs. observables, H_2O target.



INGRID

On-axis detector: measure beam direction, monitor event rate.

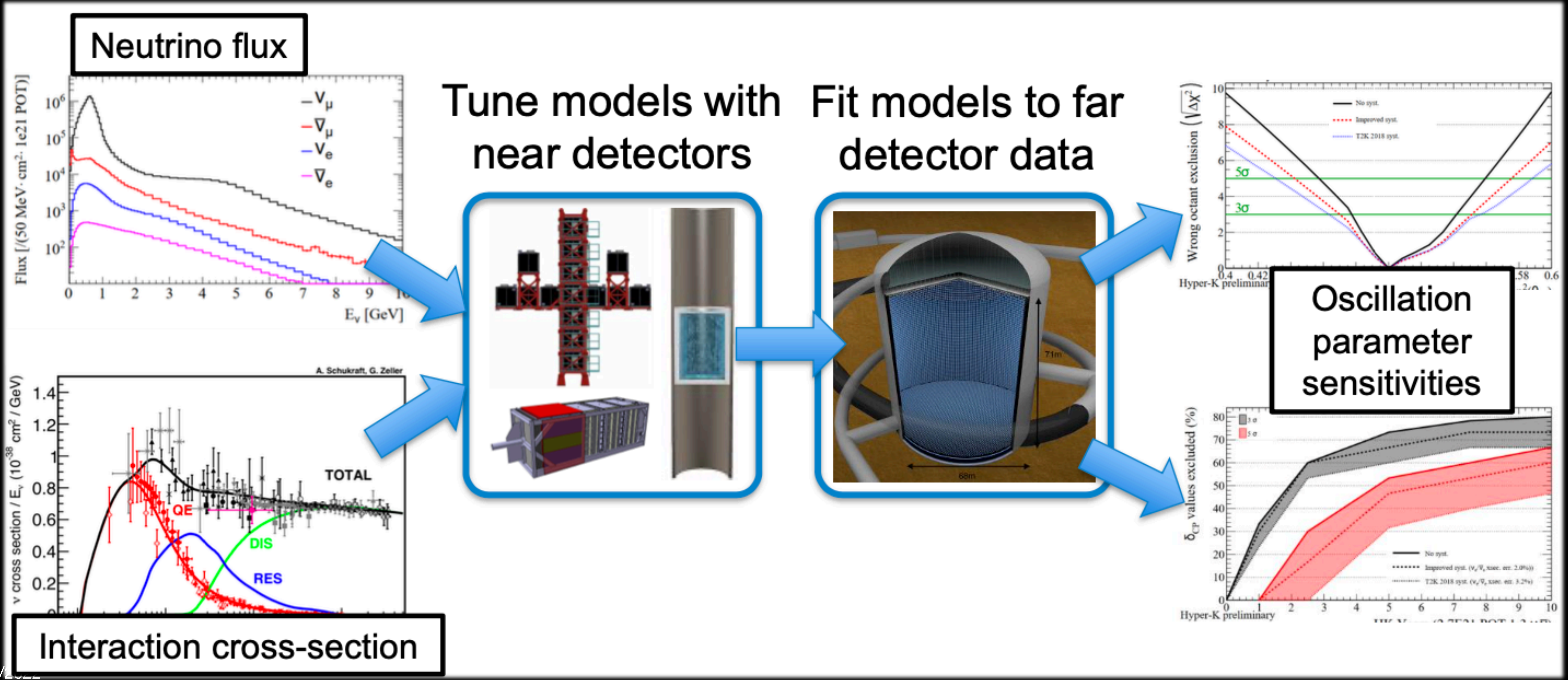


ND280

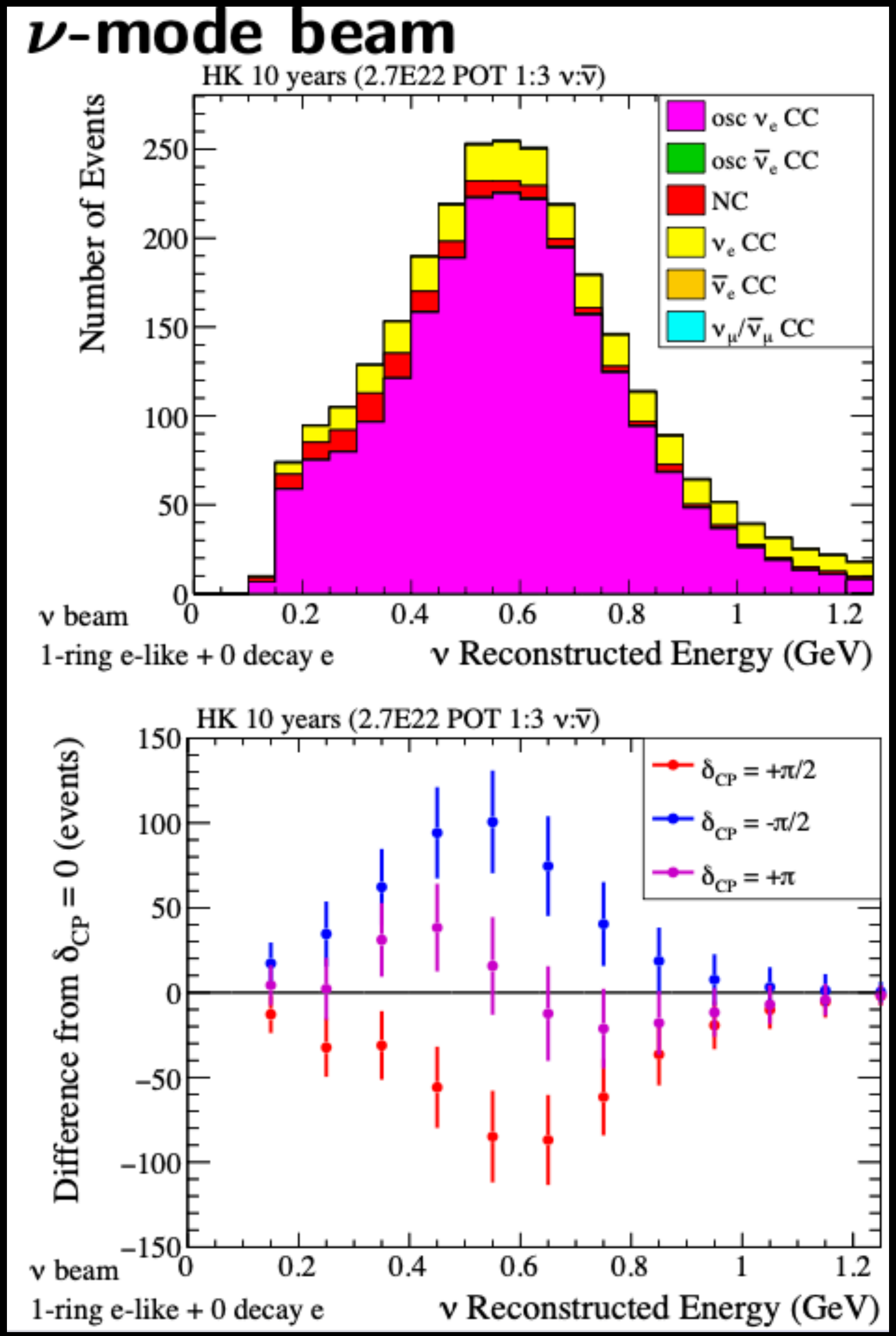
Off-axis magnetised tracker: charge separation (wrong-sign background), recoil system

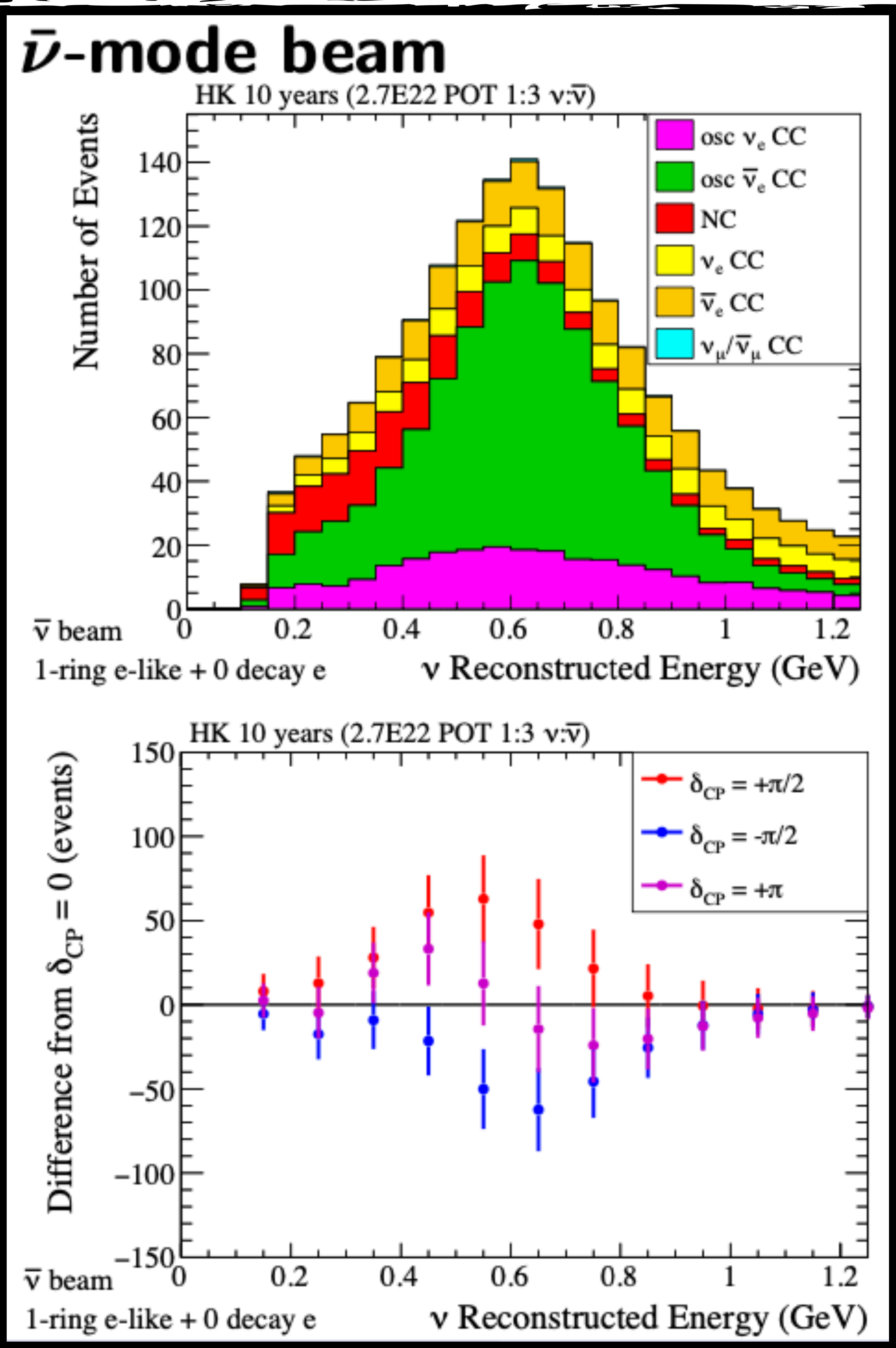
Hyper-K Beam Oscillation Analysis

- Based on T2K oscillation method.



Hyper-K Beam Oscillation Analysis

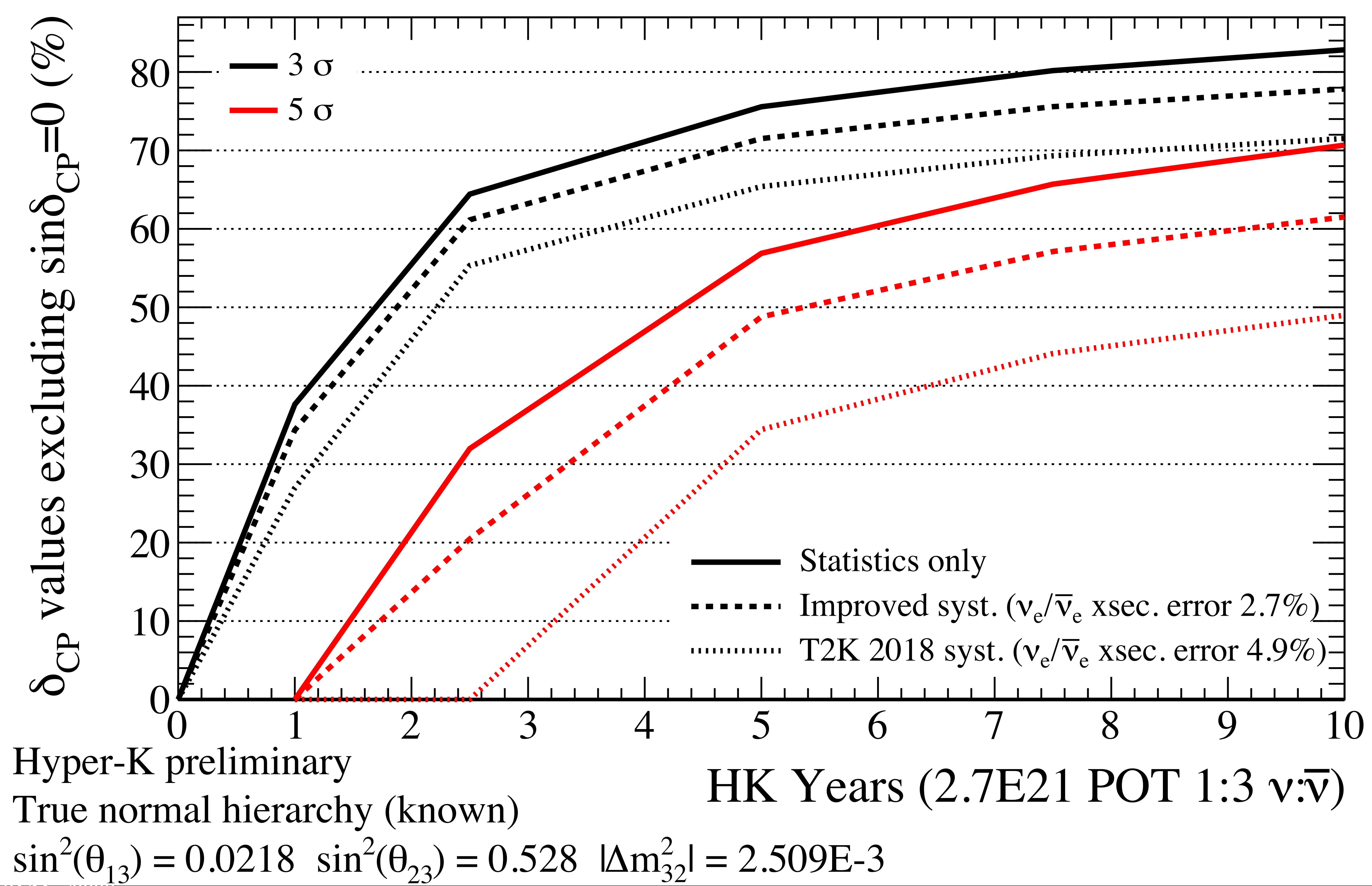




10 years (2.7E22 POT), $\nu : \bar{\nu} = 1 : 3$

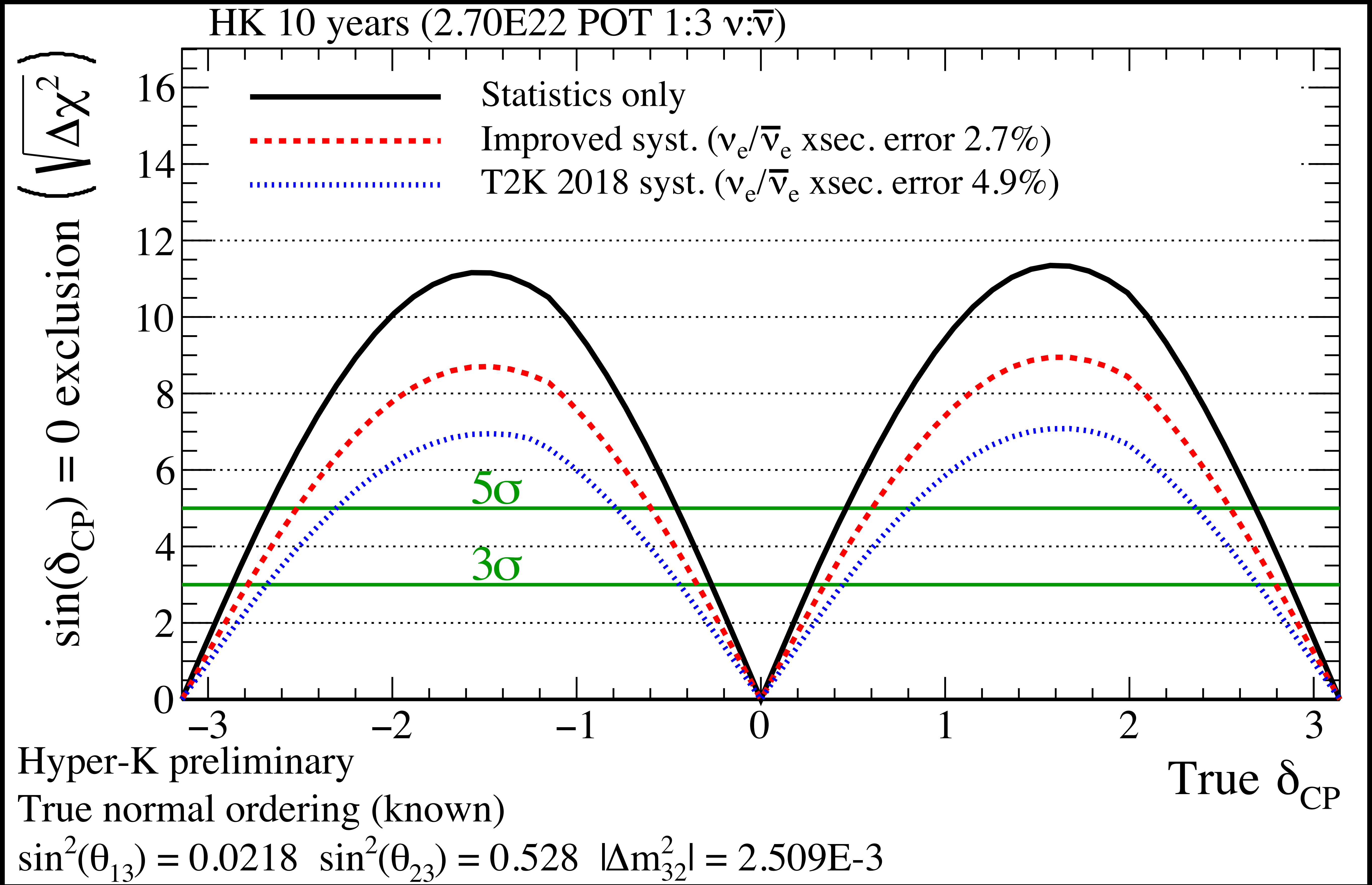
- Use Super-K MC, scaled to HK volume and exposure
- Expect approx:
  - 2300 ν_e events
  - 1900 $\bar{\nu}_e$ events
  - Assuming $\sin(\delta_{CP}) = 0$
- Difference between neutrino and antineutrino rates gives δ_{CP}

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



- Percentage of true δ_{CP} values for which $\sin(\delta_{CP}) = 0$ can be excluded, as a function of HK-years.
- The areas below the curves show the span of possible values, for varying systematic error models.

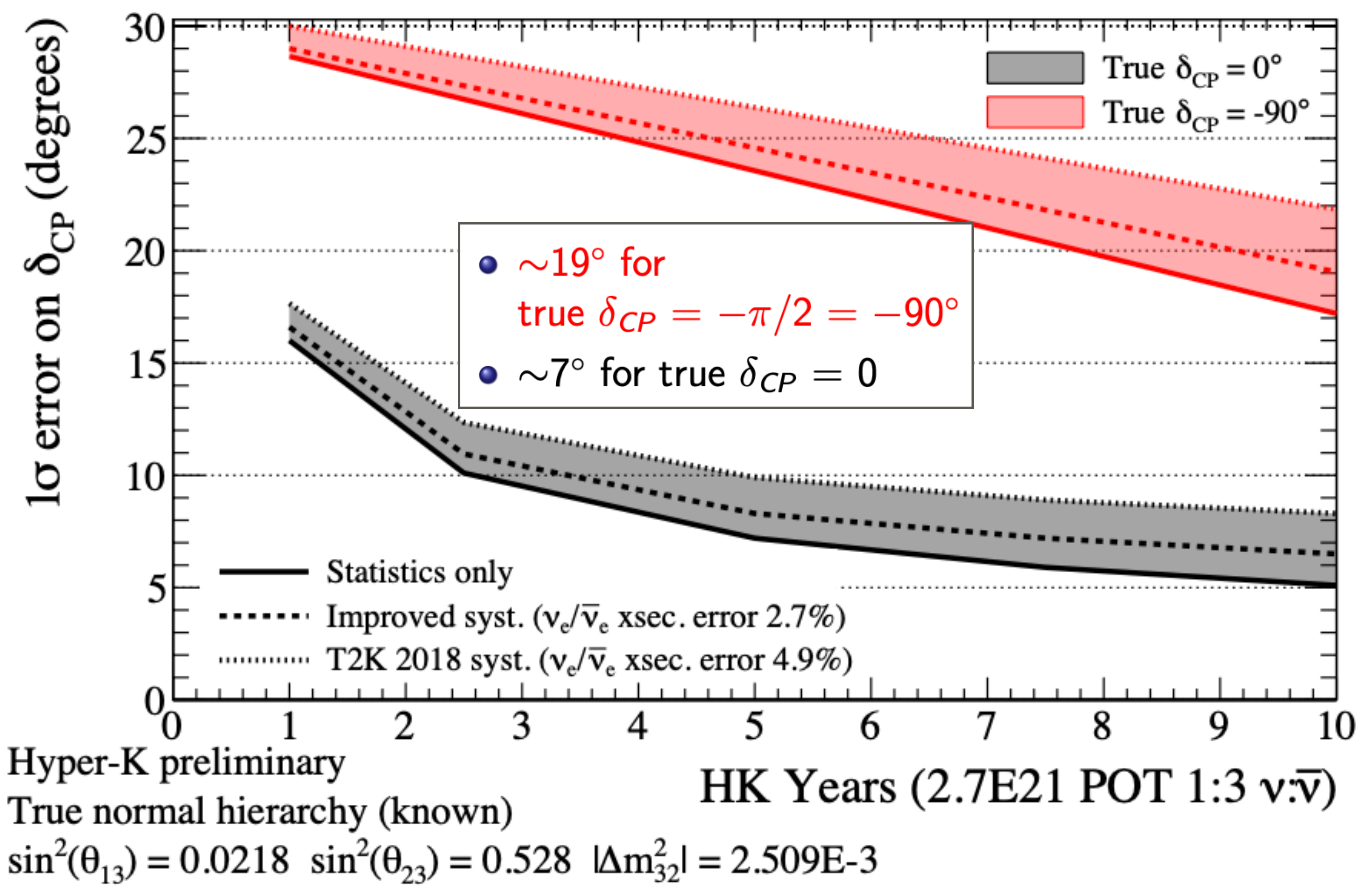
$\sin \delta_{CP} \neq 0$ *Sensitivity*



- Sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, for 10 HK-years.
- Good opportunity to discover CP violation in neutrino sector at $> 5\sigma$ (61% fraction of δ_{CP}values w/ 10years data taking).
- Reduction of systematic error has a large impact to the sensitivity.
- $\sim 8\sigma$ for $\delta_{CP} = -\pi/2$ (favoured by T2K).

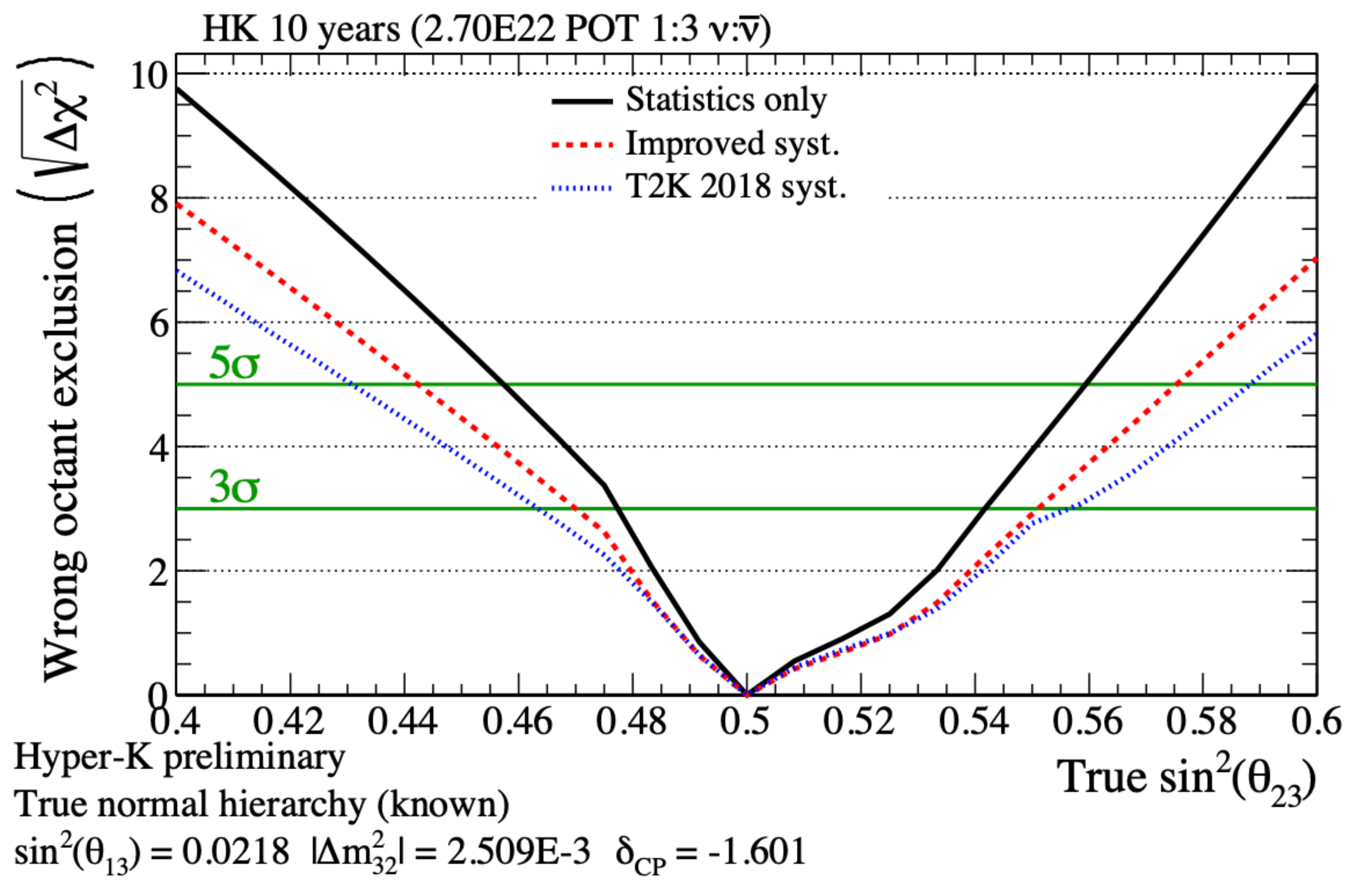
Resolution on δ_{CP} and measurement of $\sin^2\theta_{23}$

- How accurately can we measure the value of δ_{CP}?



- 1σ error on δ_{CP} is:
  $\sim 19°$ for $\delta_{CP} = -\pi/2$
  $\sim 7°$ for $\delta_{CP} = 0$

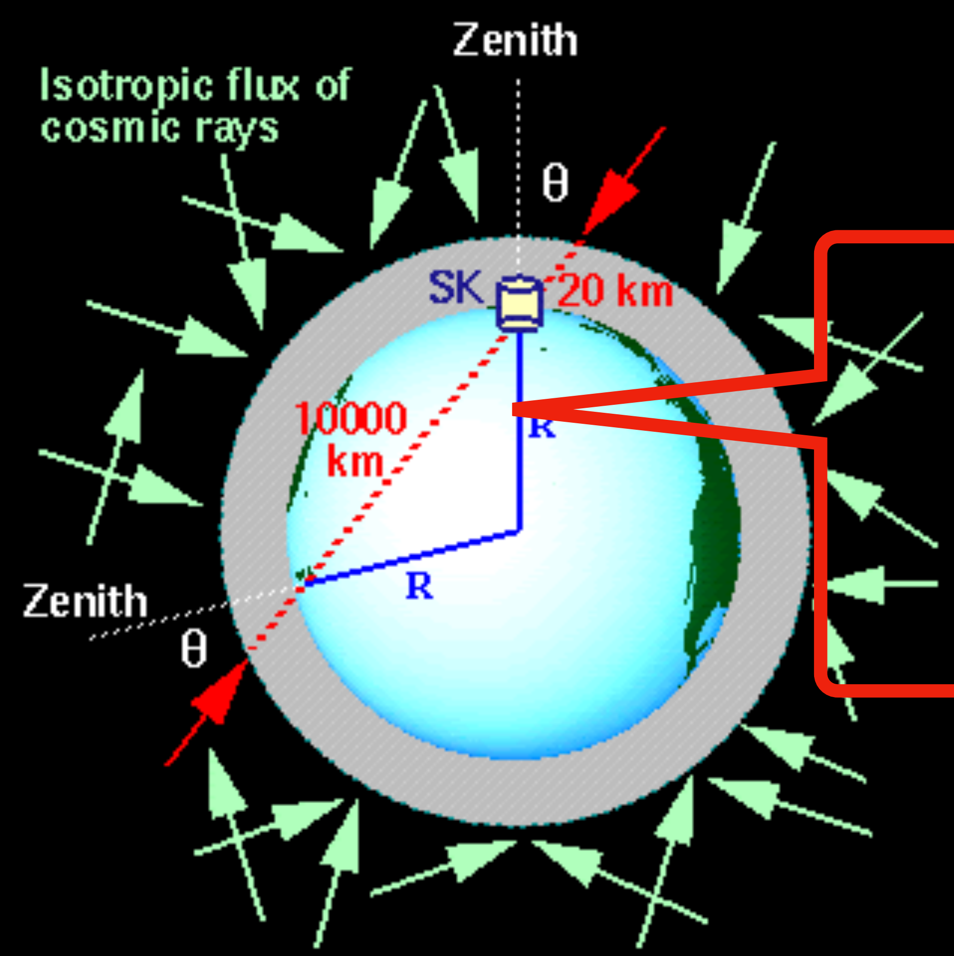
Resolution on δ_{CP} and measurement of $\sin^2\theta_{23}$



- For a true value of $\sin^2\theta_{23}$, how much can we exclude the wrong octant? ($\sin^2\theta_{23}$ < or > 0.5)

- The wrong octant can be excluded at 3σ for true $\sin^2\theta_{23} < 0.47$ and true $\sin^2\theta_{23} > 0.55$ with the Improved syst. error model

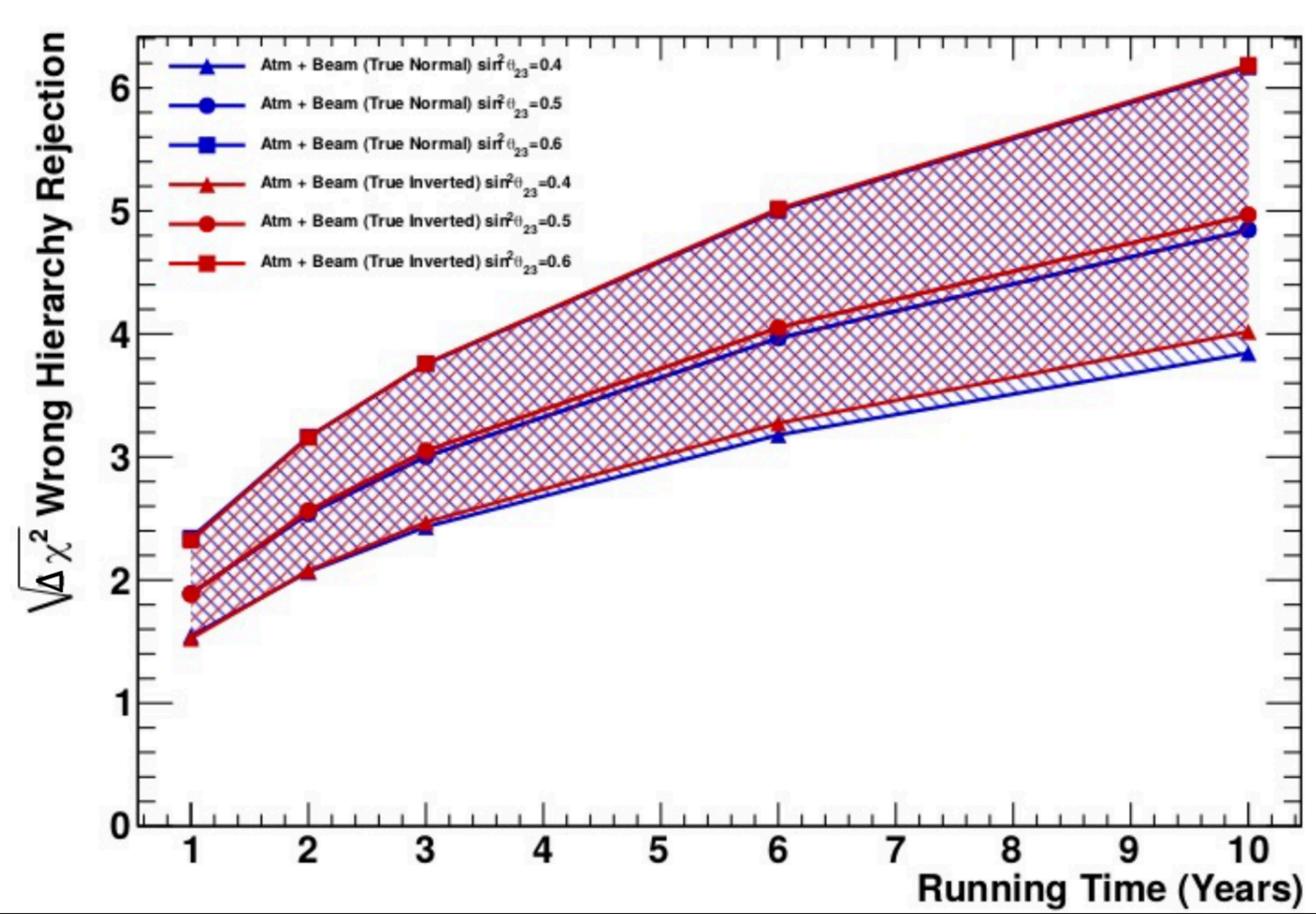
Adding Atmospherics



- Neutrinos penetrating the Earth are affected by the mass effect.
  - Normal mass ordering : $\nu_\mu \rightarrow \nu_e$ is enhanced
  - Inverted mass ordering: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is enhanced

- Comparison between neutrinos and antineutrinos oscillations can be used to determine the hierarchy.

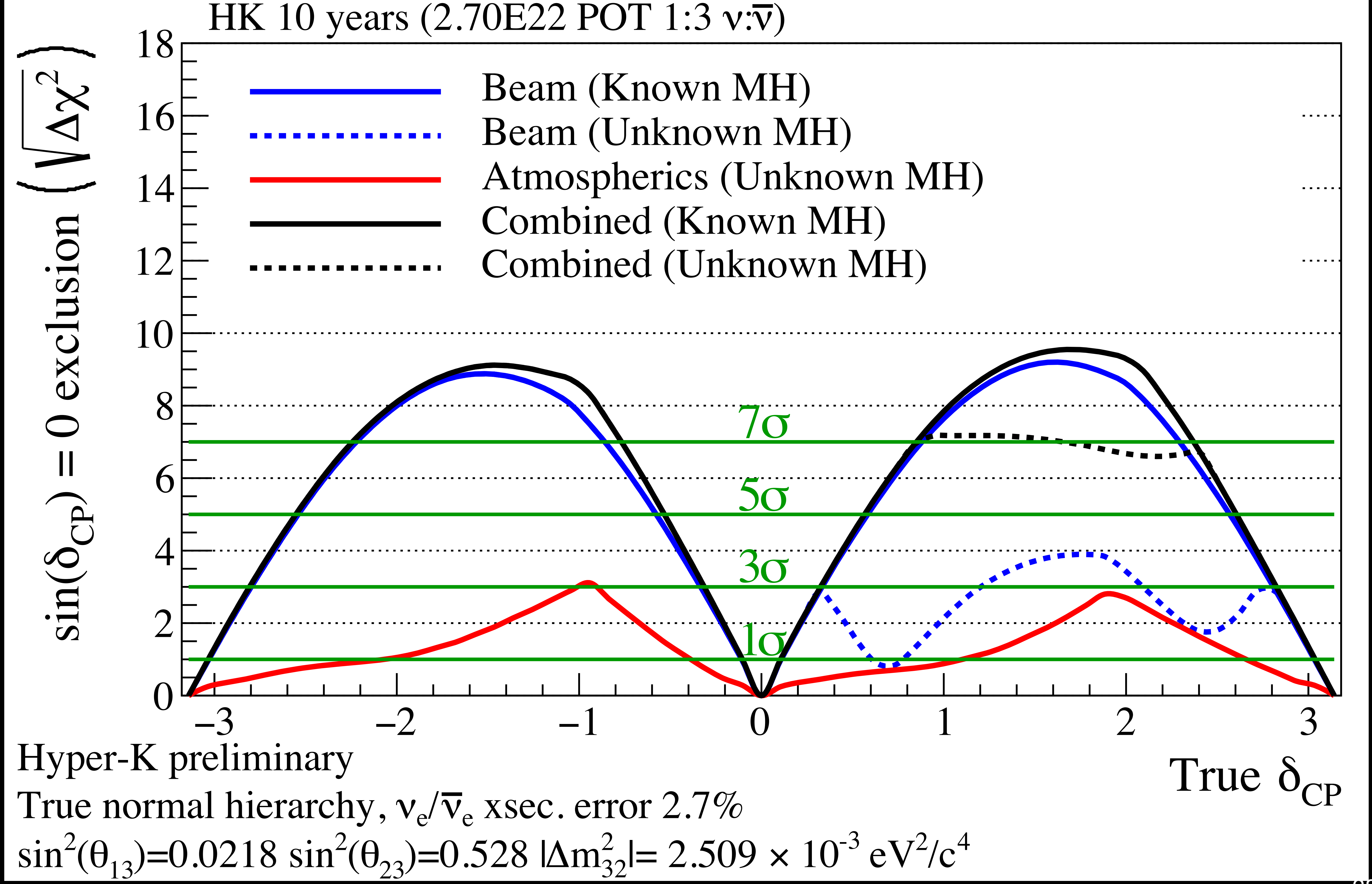
- Can exclude incorrect mass ordering at $\mathbf{4-6\sigma}$ significance (depending on value of $\sin^2\theta_{23}$)



Adding Atmospherics

- If mass ordering unknown, beam analysis less sensitive for some values of δ_{CP}.
- Joint atmospheric and beam analysis increases sensitivity above 5σ
- The power of the atmospheric sample improves the sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, particularly in the unknown mass ordering case:

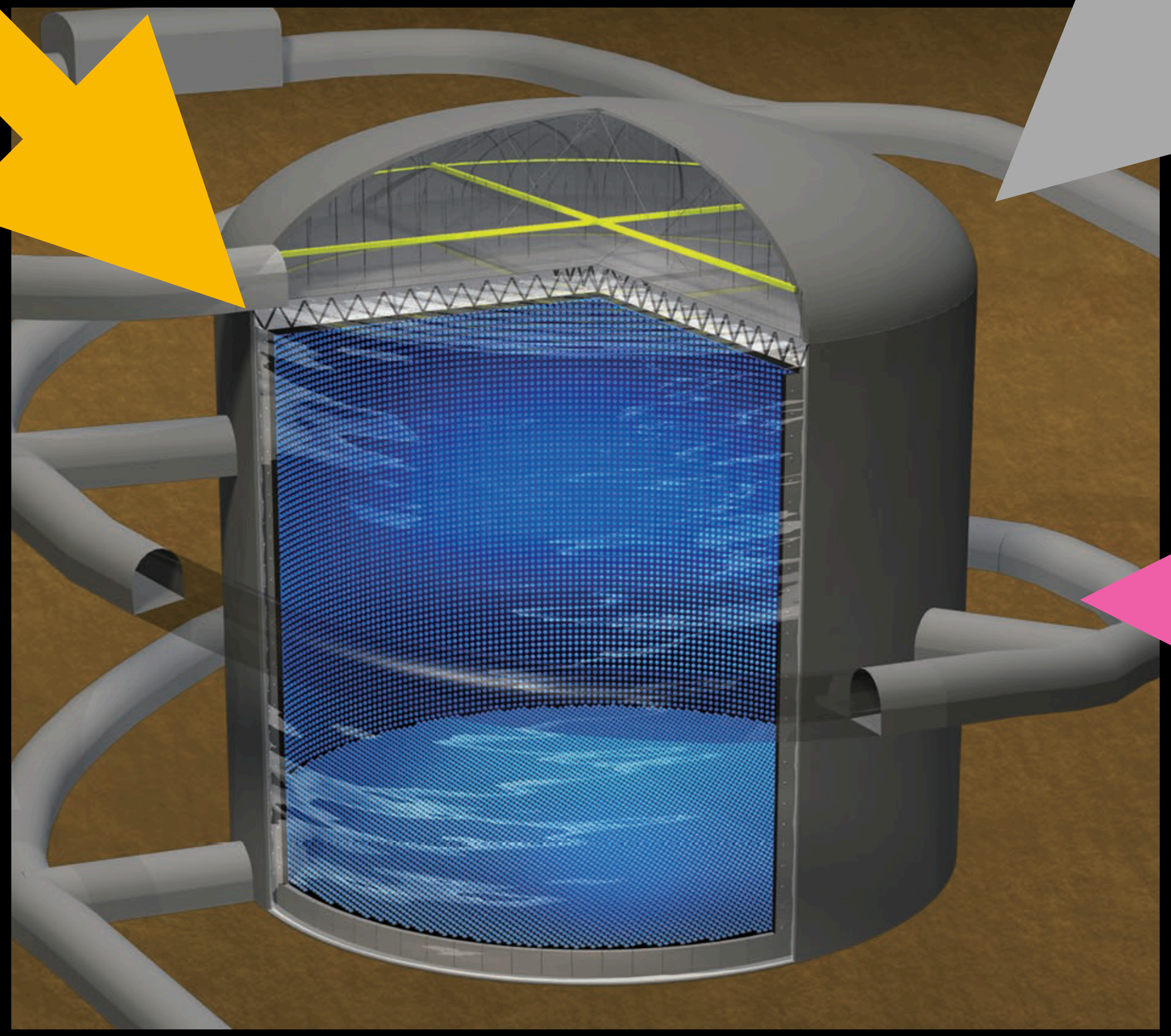
- Sensitivity to exclude $\sin(\delta_{CP}) = 0$, as a function of true δ_{CP} value, for 10 HK-years and true normal mass ordering.



Astrophysics Neutrinos at Hyper-K

Solar Neutrinos
- Burning processes, modelling of the Sun
- Property of neutrino

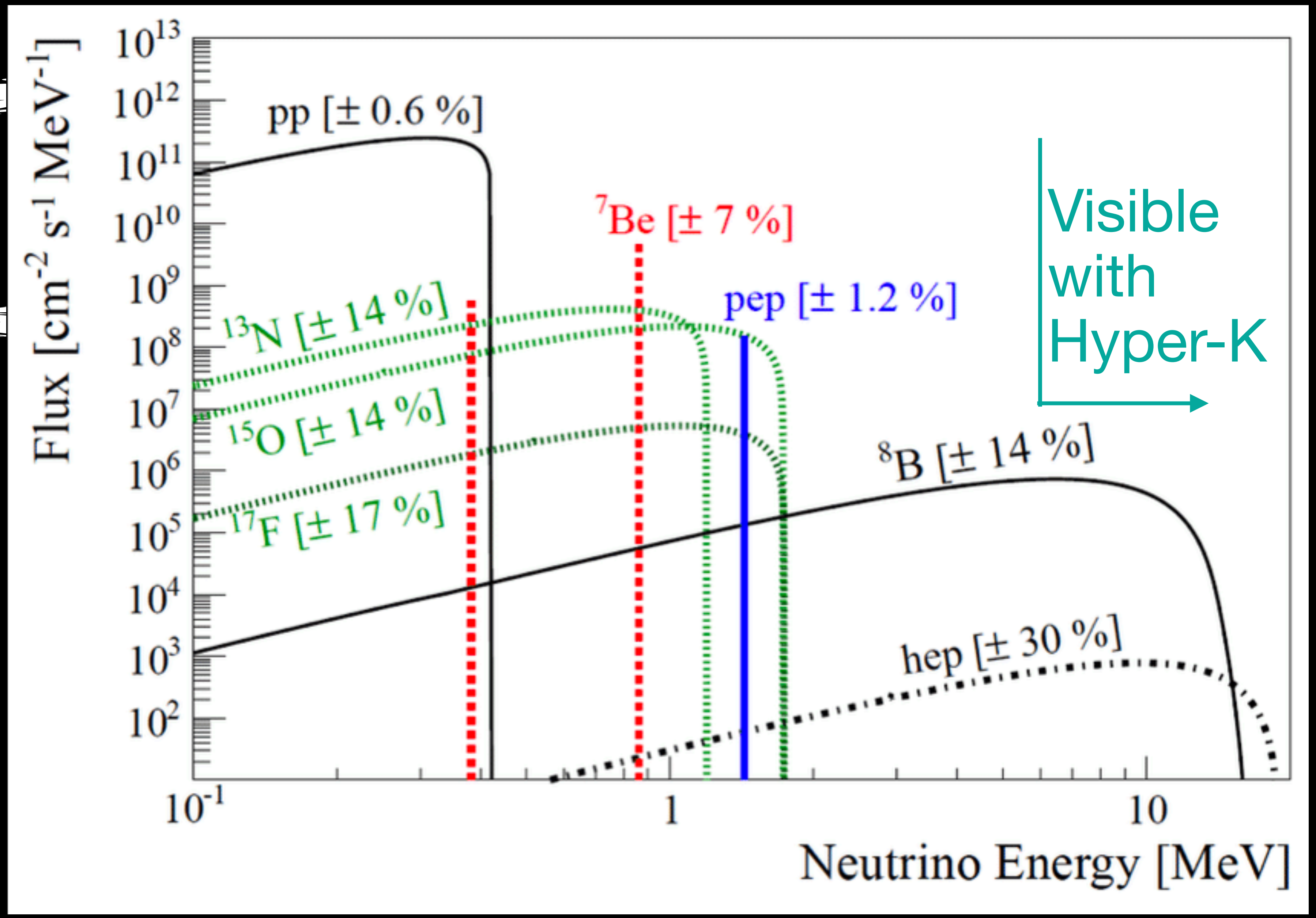
Supernova Neutrinos
- SN explosion mechanism
- SN monitor
- Nucleosynthesis



Supernova Relic Neutrinos
- SN mechanism
- Star formation history
- Extraordinary SNe

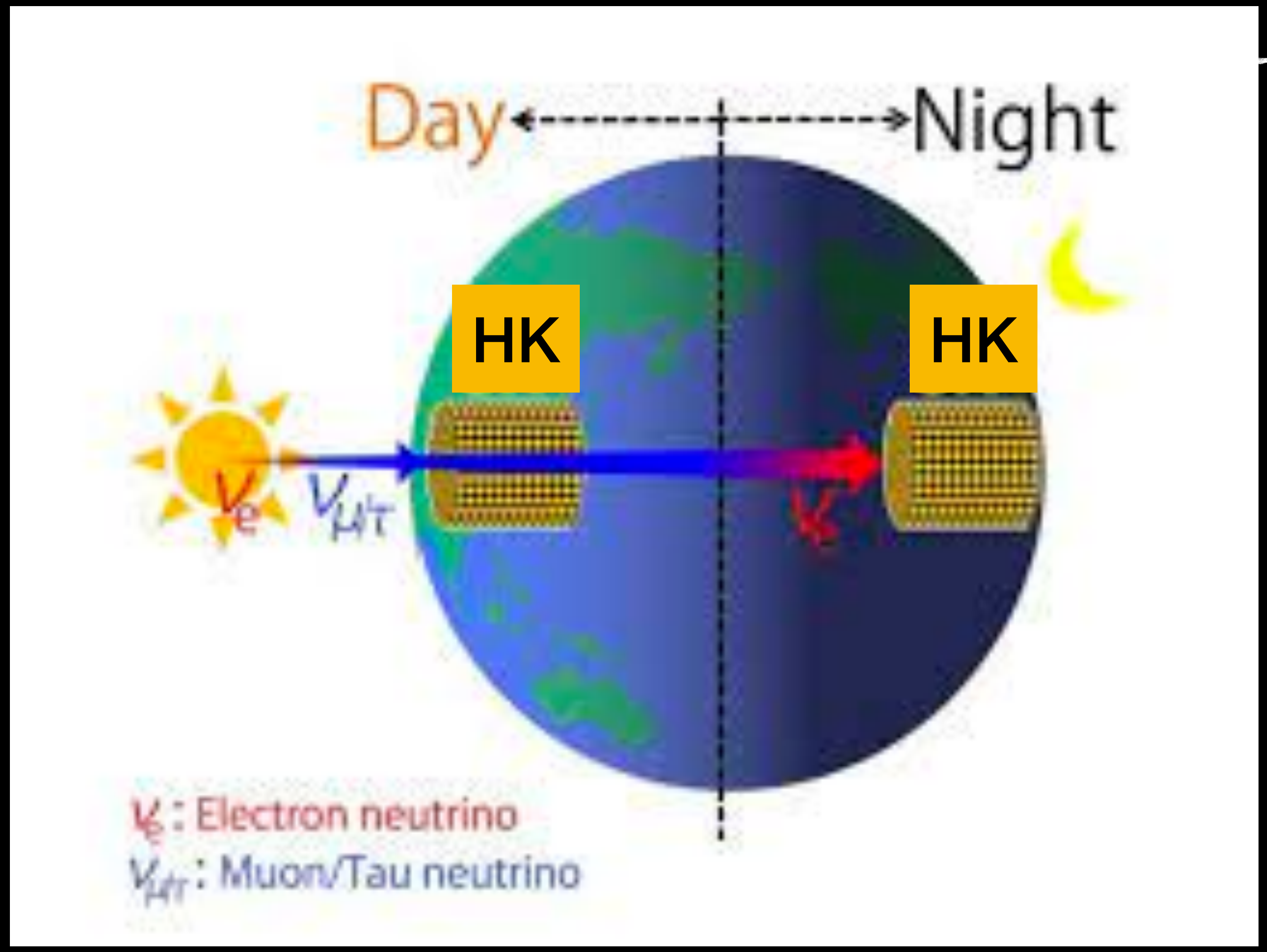
Solar Neutrinos

- Solar neutrinos are the neutrinos originated from the nuclear reactions in the Sun.
- Large statistics: 130 ν ev./day/tank, E_{vis}>4.5MeV
- Highlights of solar ν measurements:



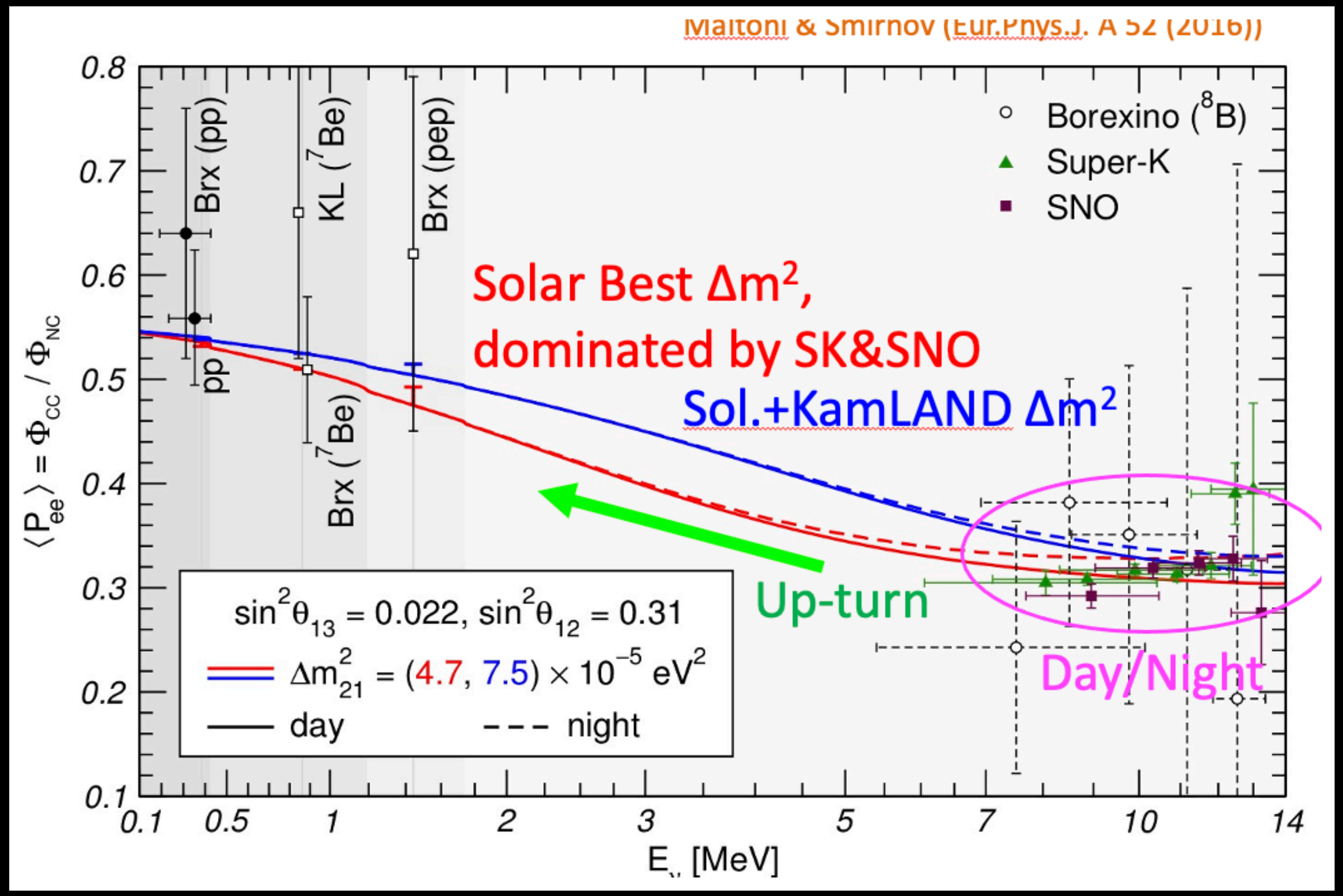
Day/Night (D/N) Asymmetry

- The terrestrial matter effect can result in **D/N asymmetry**.
- This can affect Δm^2_{12} measurement.



Upturn of the spectrum

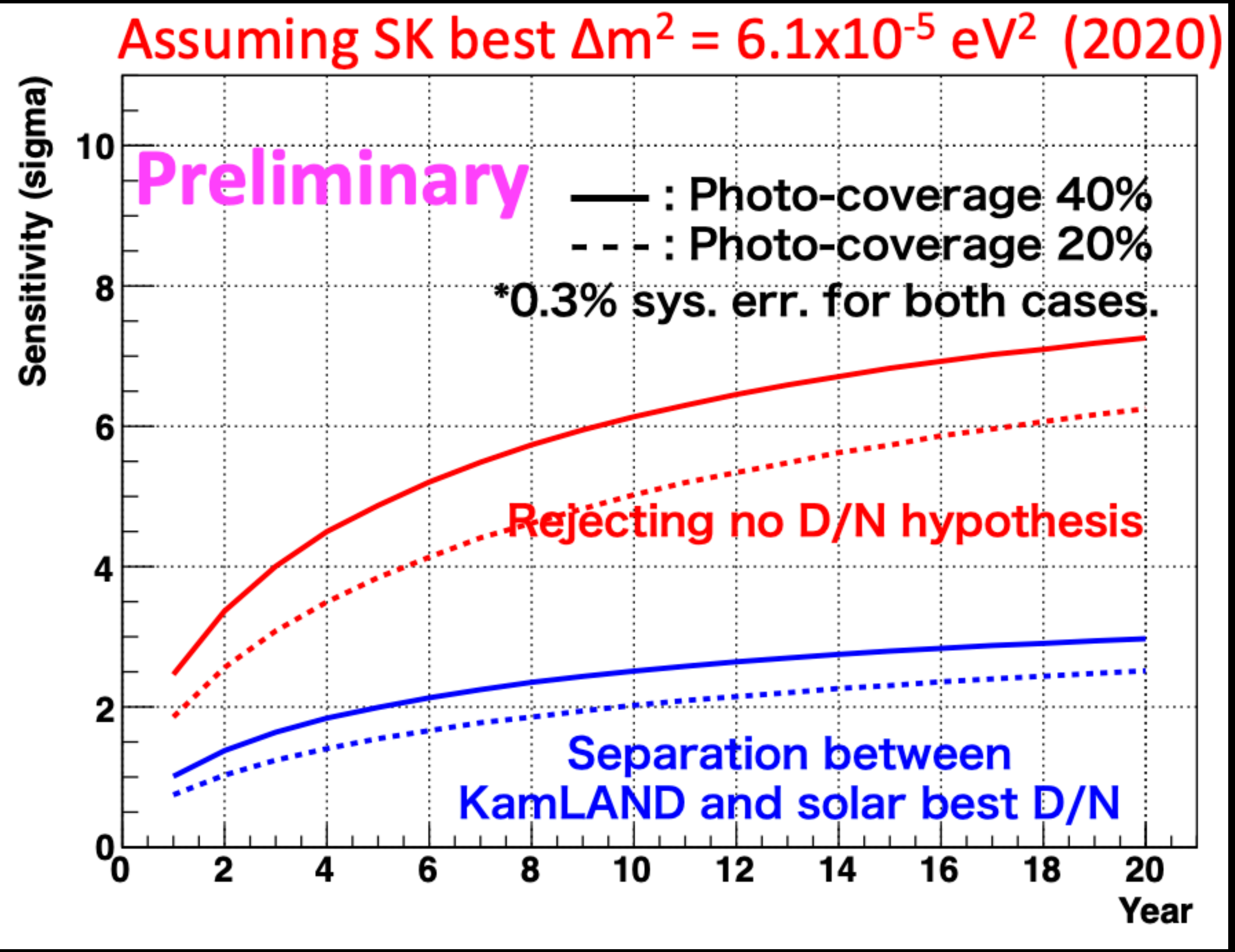
- Upturn is the variation of the oscillation probability between the vacuum and MSW dominated energy region.

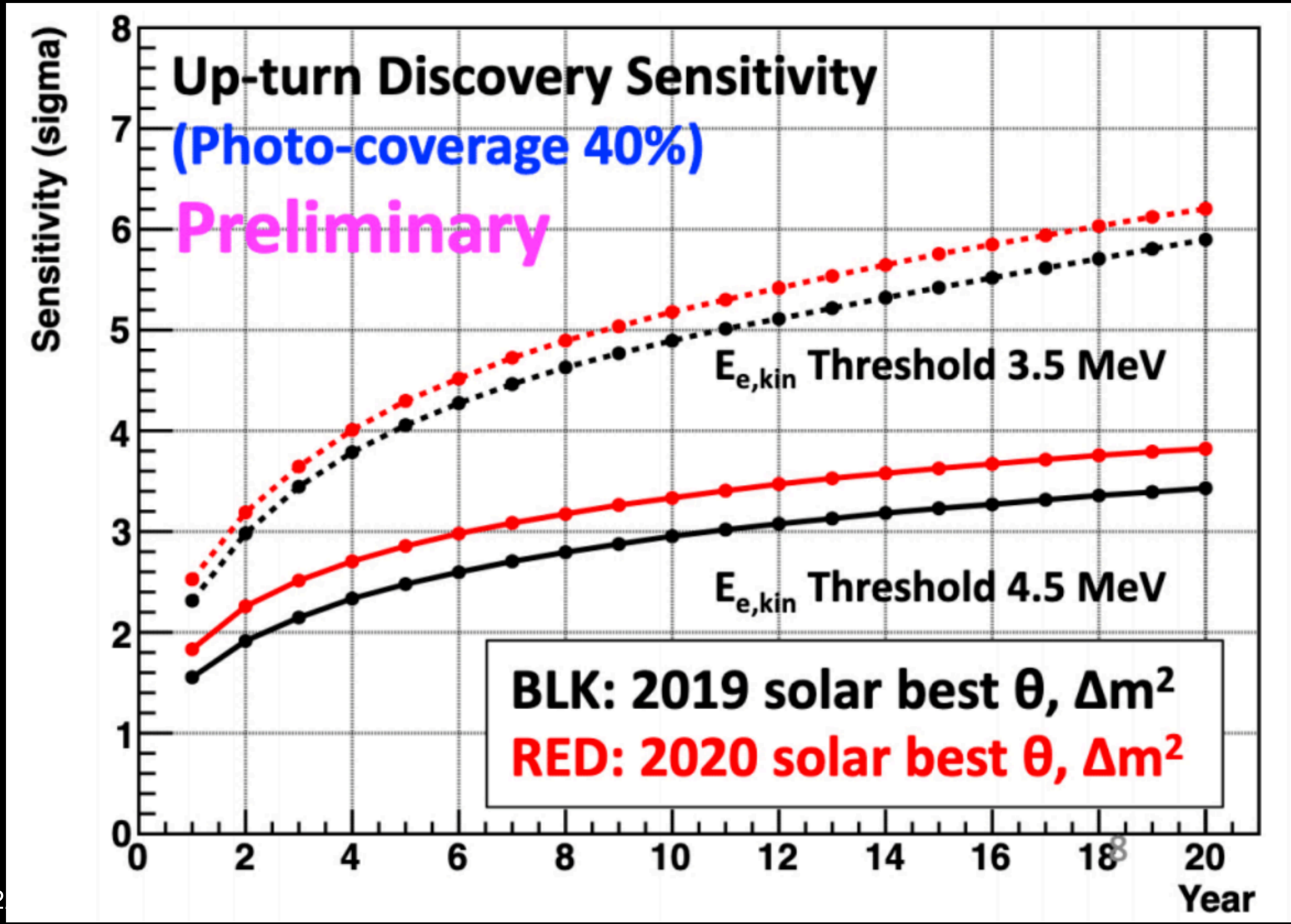


- Upturn not observed yet.

Solar Neutrinos

- Large D/N asymmetry is expected to be observed with $> 5\sigma$ after 10 years of operation

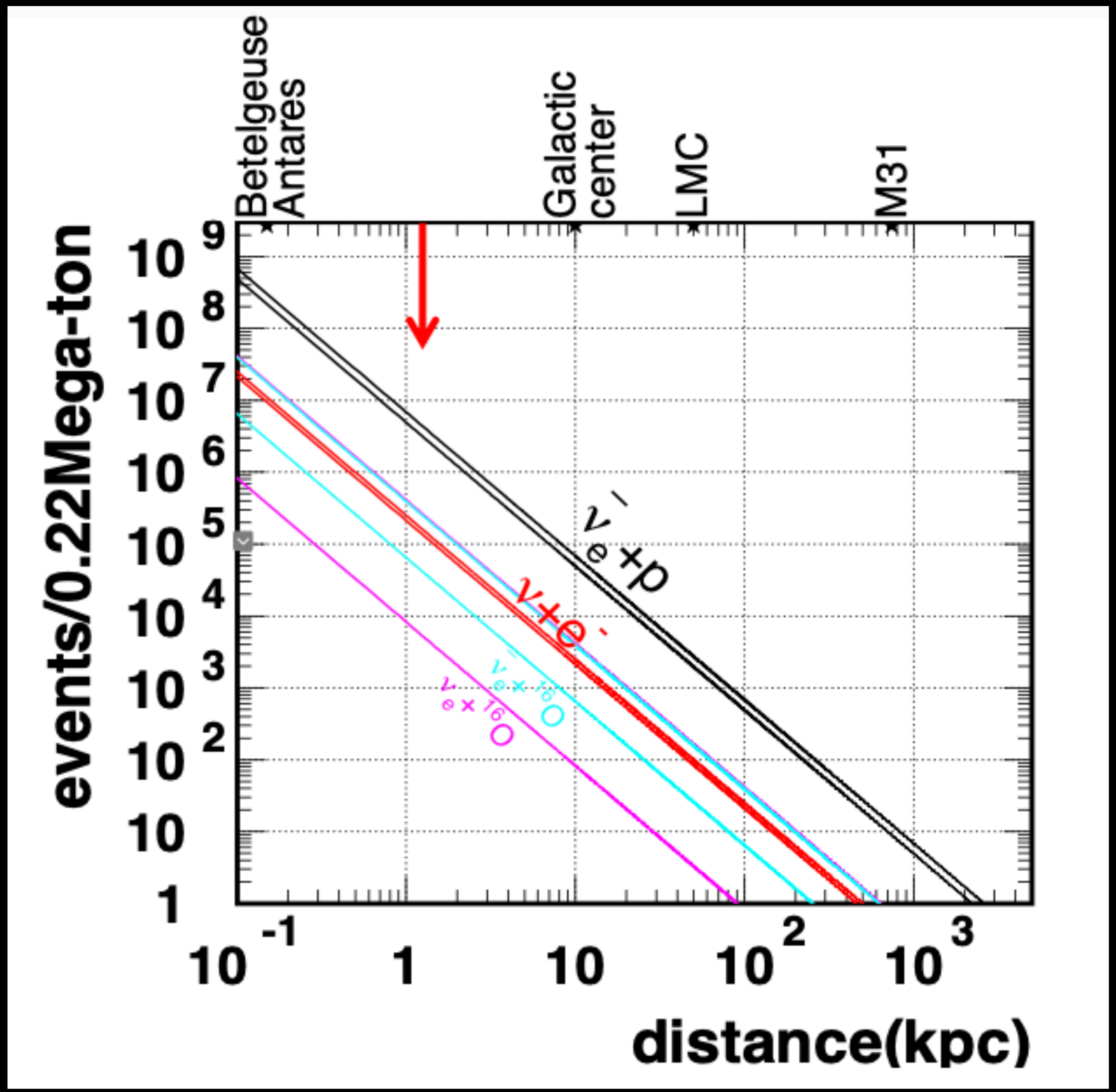




- In the upturn analysis, it is expected that **the sensitivity exceeds** $3(5)\sigma$ after 10y operation with the threshold of 3.5(4.5 MeV)

Supernova Neutrinos

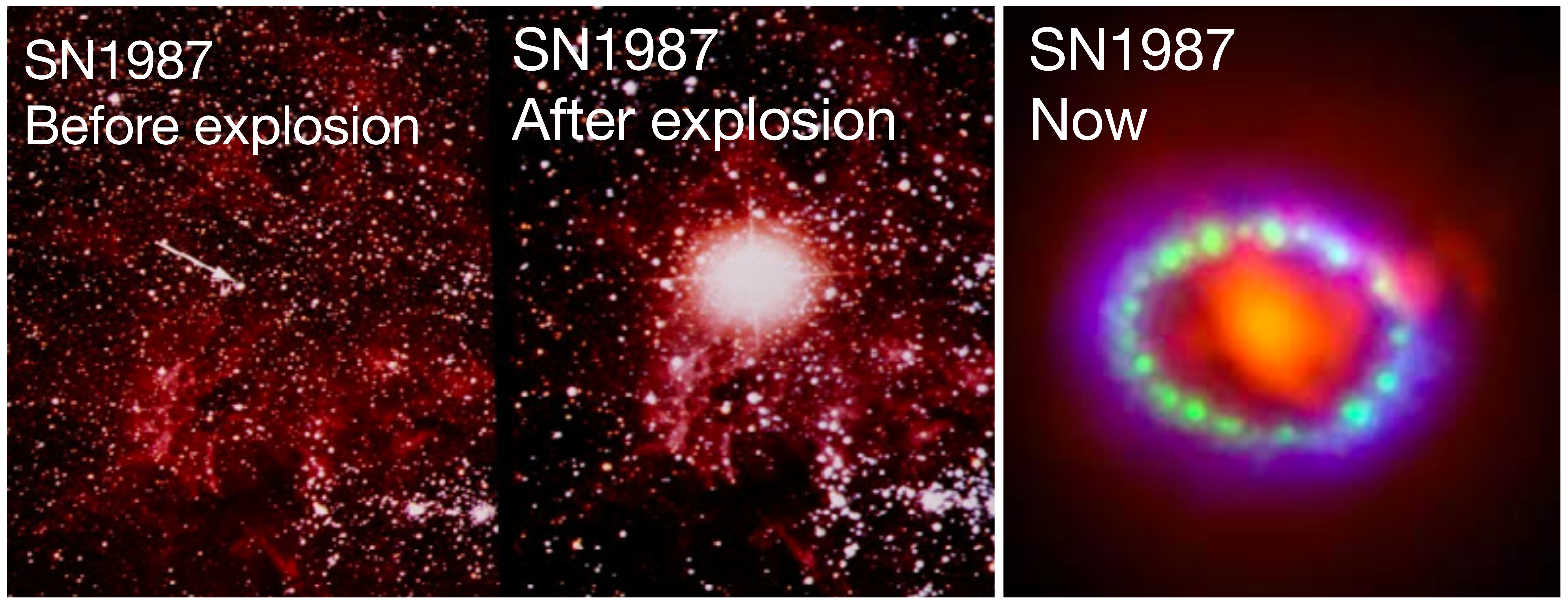
- Supernova neutrino observation:
  - 54-90k events for SN at 10 kpc (most sensitive to $\overline{\nu}_e$)
  - Precise Neutrino Time profile
  - Precise spectrum measurement
  - Investigation of the SN mechanism (SASI/Rotation/Convection)

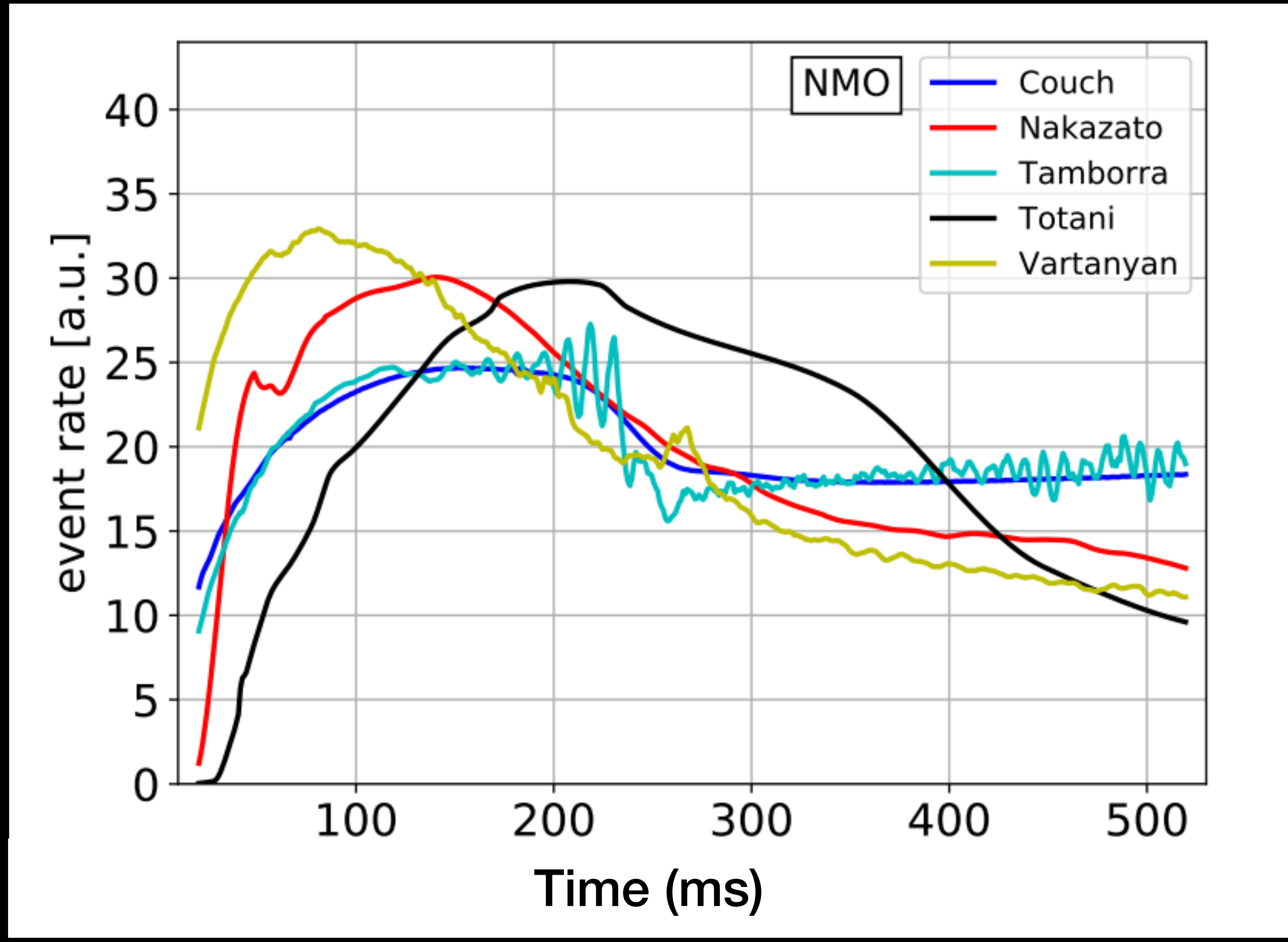


- Models by different groups, using various approximations ➔ telling models apart can help understand the explosion mechanism

Supernova paper

- First Hyper-K paper!
- Published by *Astrophysical Journal* on April 13, 2021.
- arXiv:2101.05269 [astroph.IM]
- Hyper-K has the potential to have a large statistics if there is a supernova burst
- Hyper-K can distinguish between different explosion mechanism models.

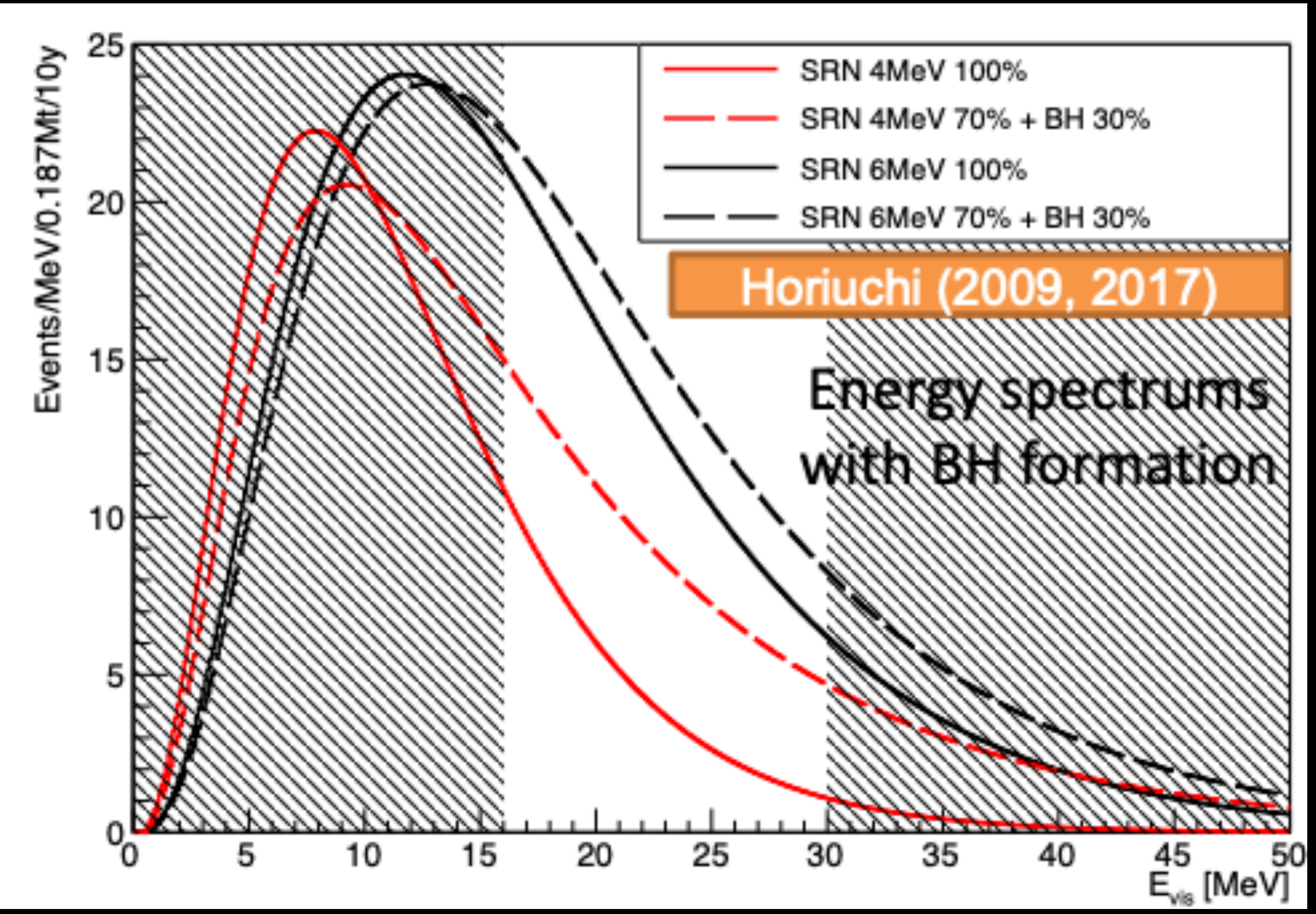




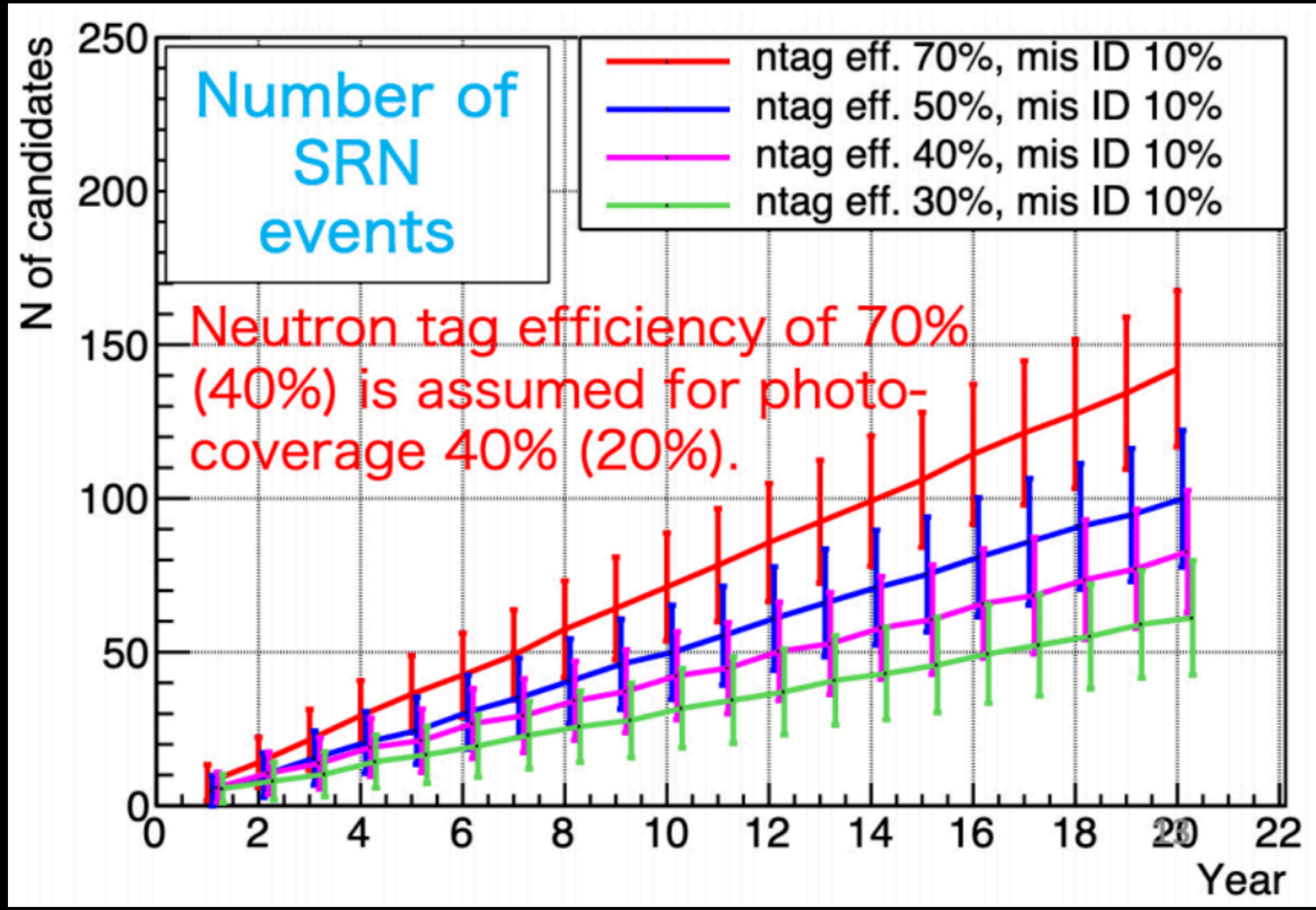
Event rate in Hyper-K from supernova burst for different explosion models

Supernova Relic Neutrinos

- Supernova Relic Neutrino (SRN)
- Diffused neutrinos coming from all past supernovae.
- Not discovered but promising extra-galactic ν.
- SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

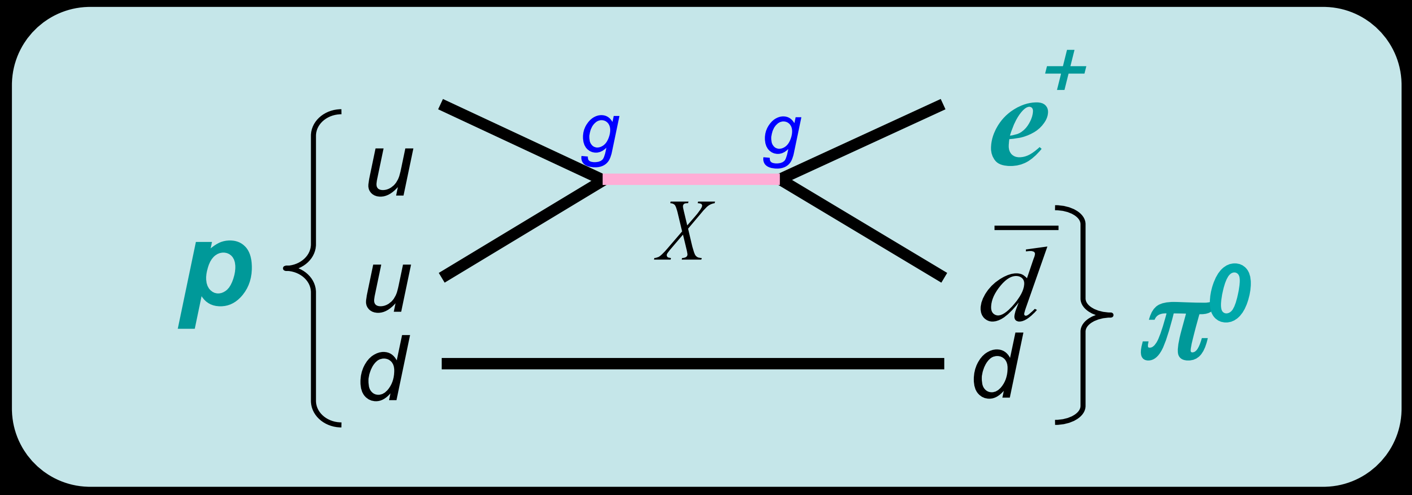


- The number of detected SRN events is predicted for various neutron-tagging configurations.
- In the case of 70% efficiency, ~70 events will be observed within 10 operation years. This corresponds to 4σ **sensitivity**

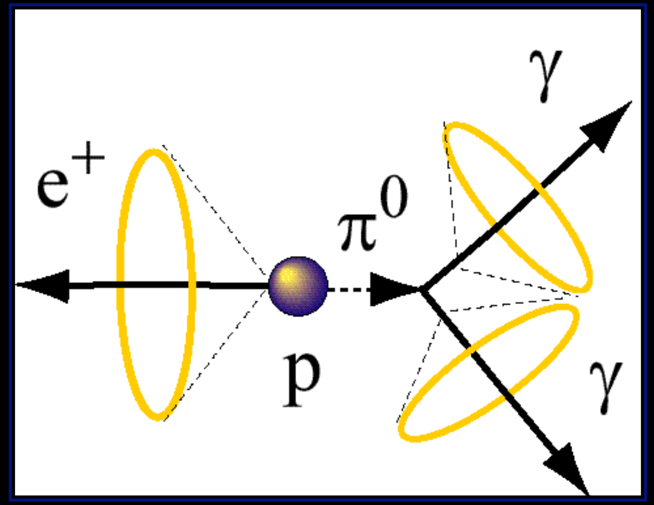


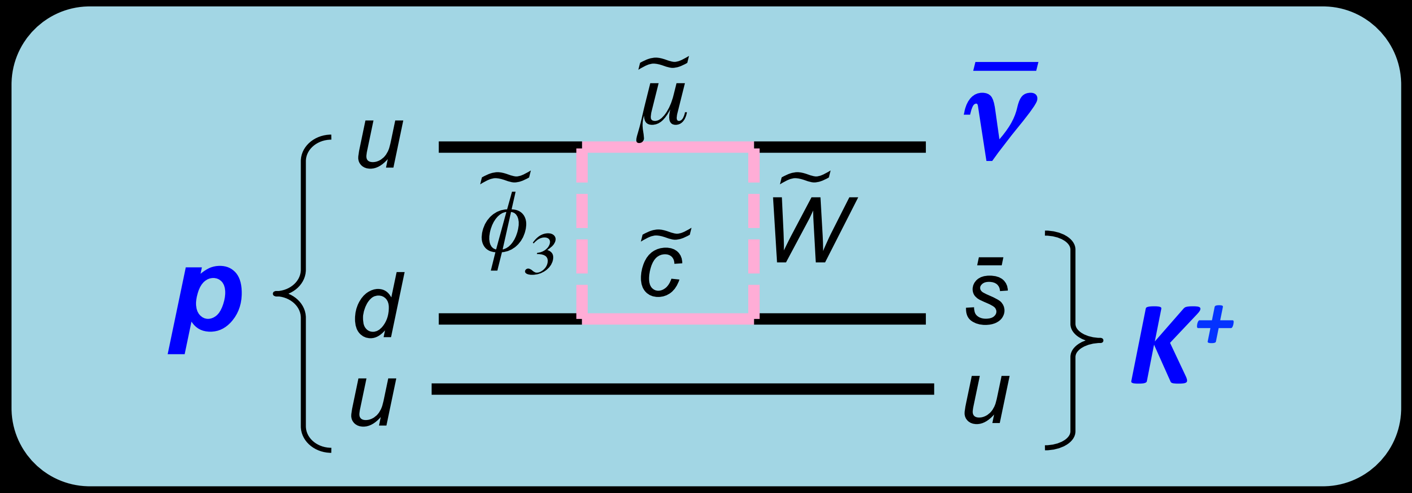
Proton Decay Searches

- Two major modes predicted by many models

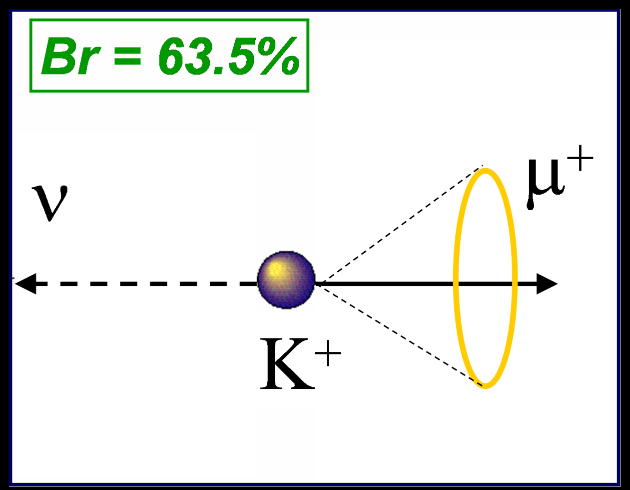


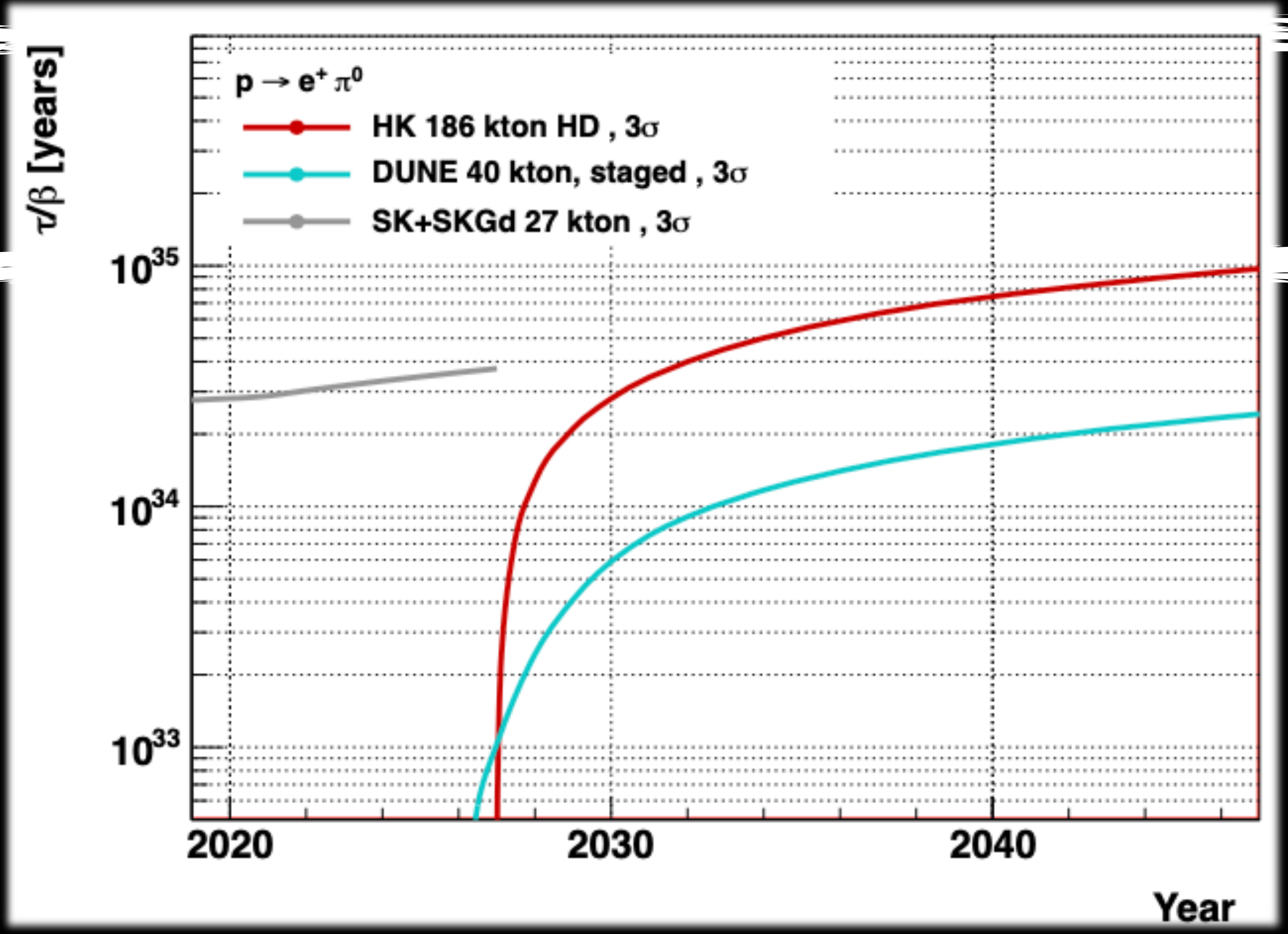
$p \to e^+ \pi^0$

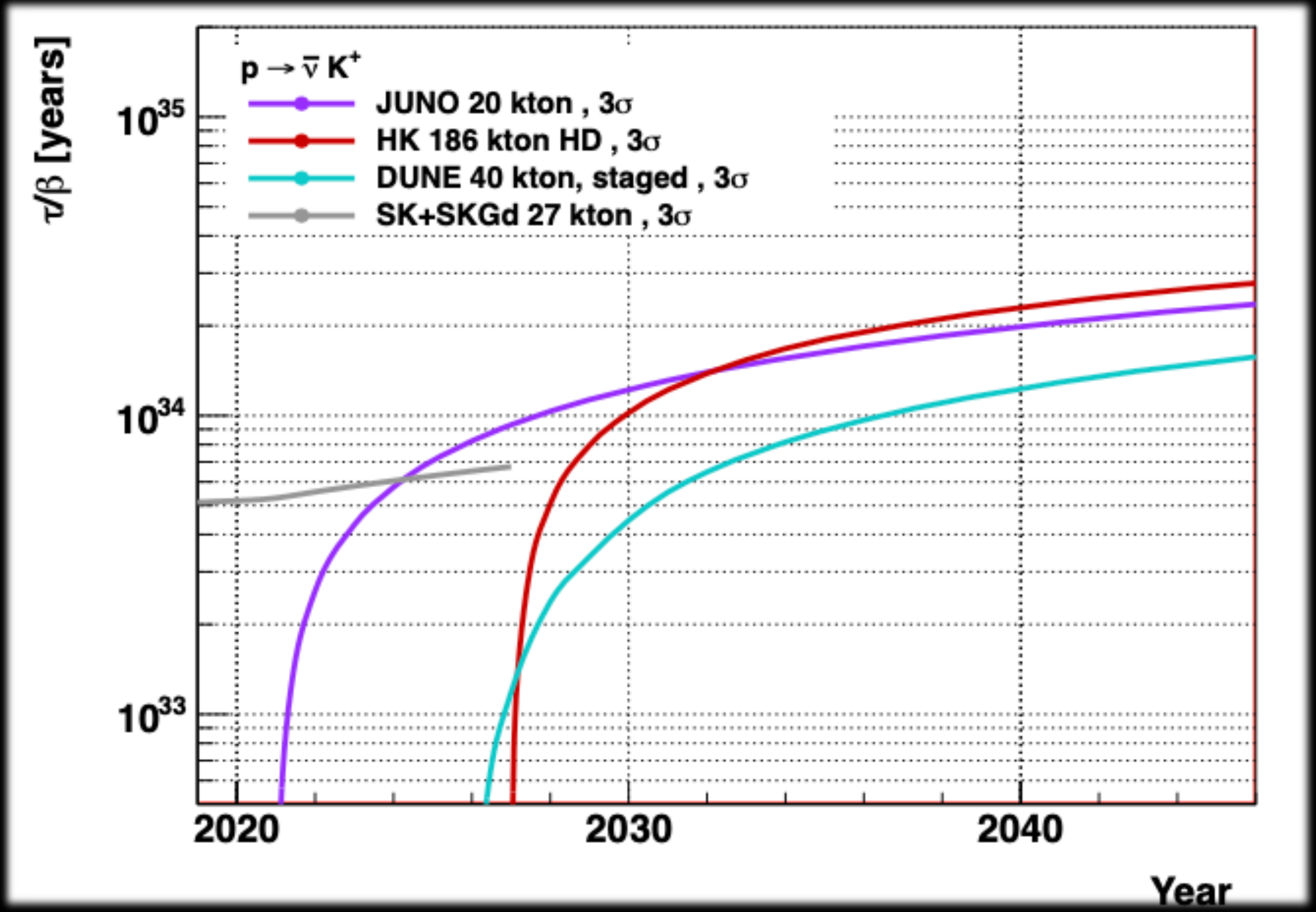




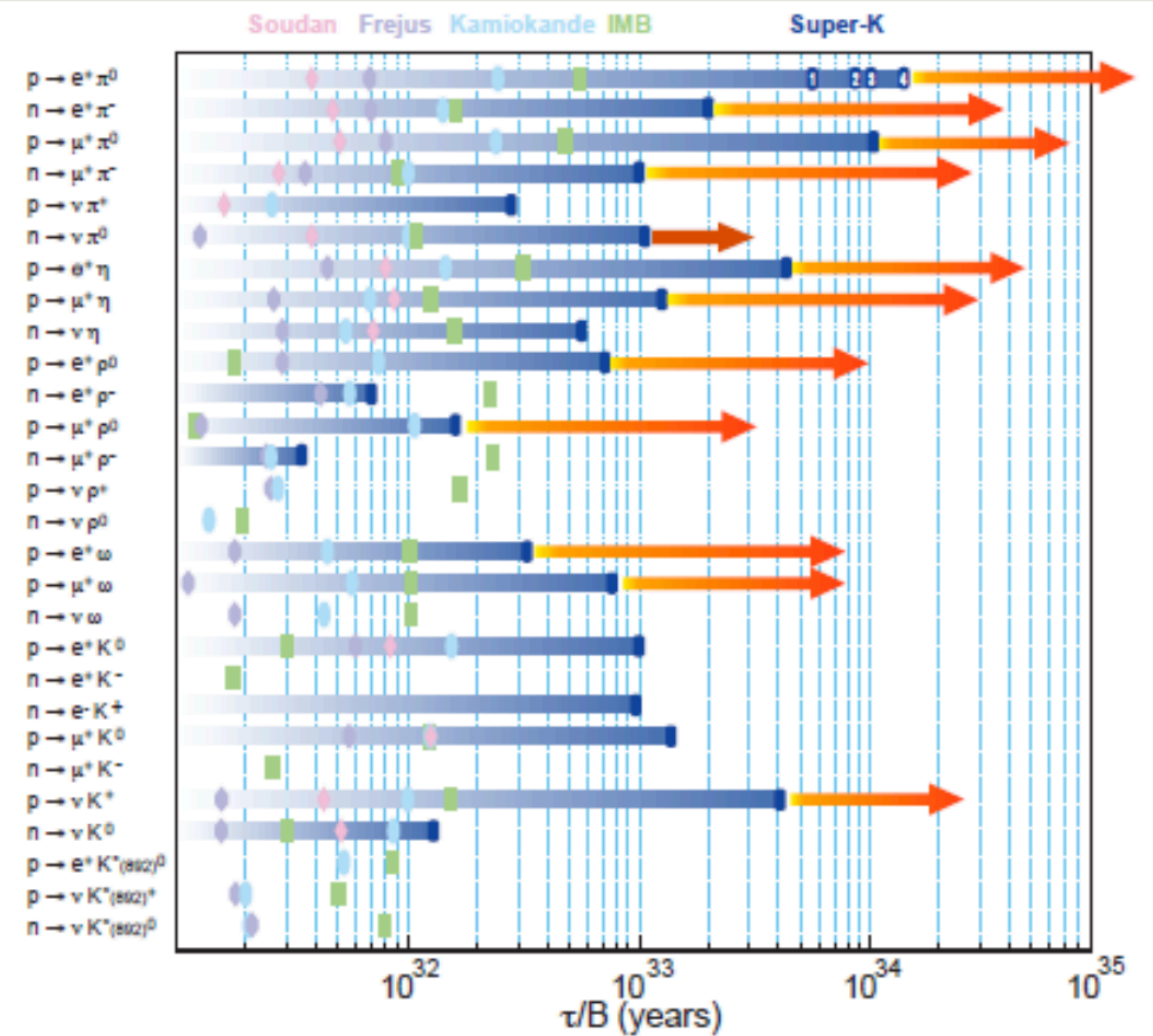
$p \to \bar{\nu} K^+$







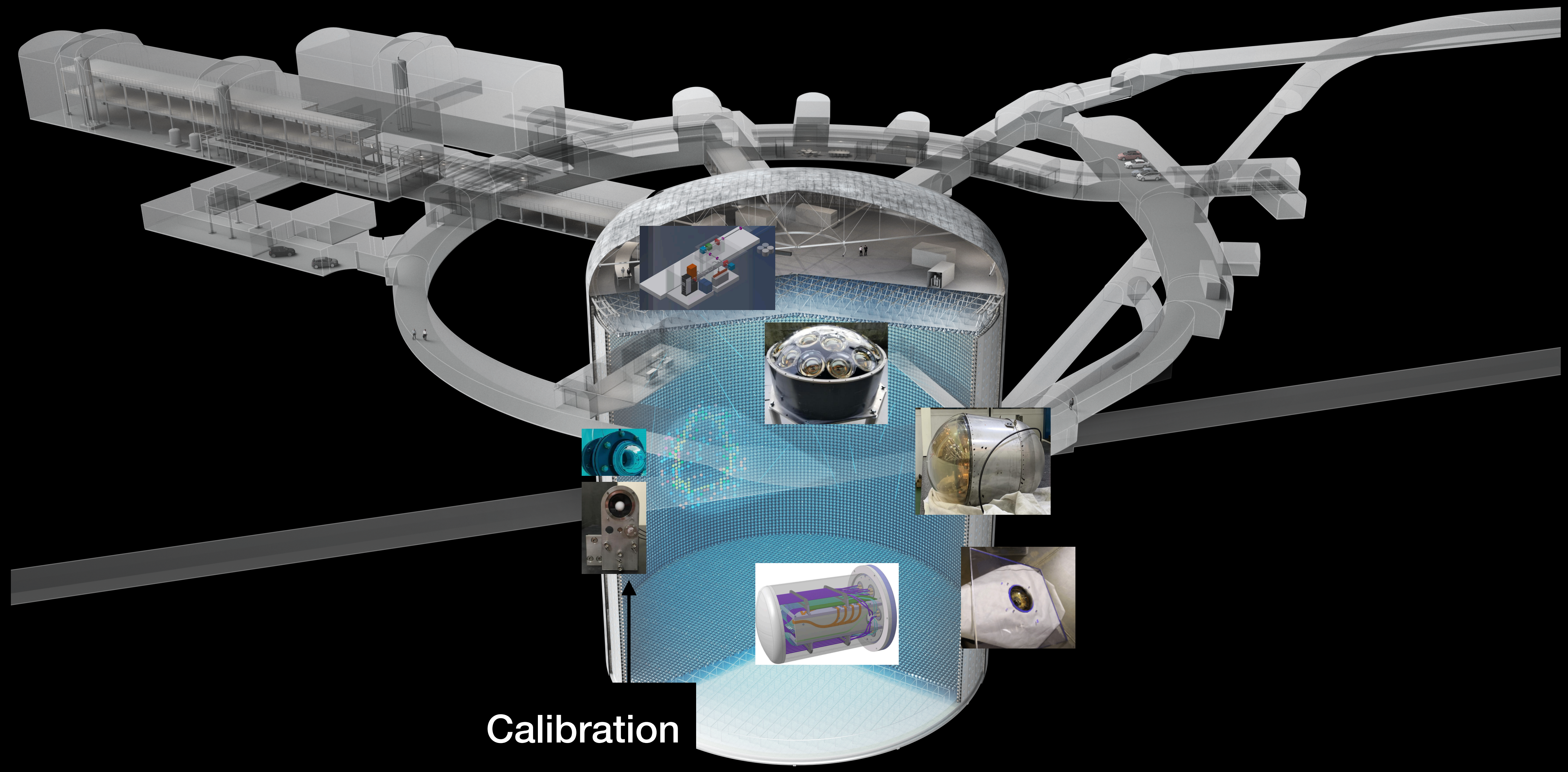
Proton Decay Searches



- Hyper-K is able to pursue also many other final states with the highest precision.

Conclusion

- A groundbreaking experiment is being built in Japan.
- Major progress in the last year in the construction of the experiment.
- It will address major open questions in science! Multipurpose experiment!
- It will start to take data in 2027!!



- Underwater components ready to be installed in the Far Detector by ~December 2025.
- R&D completion in 2022, mass production to start in 2022-2023.

Backup Slides

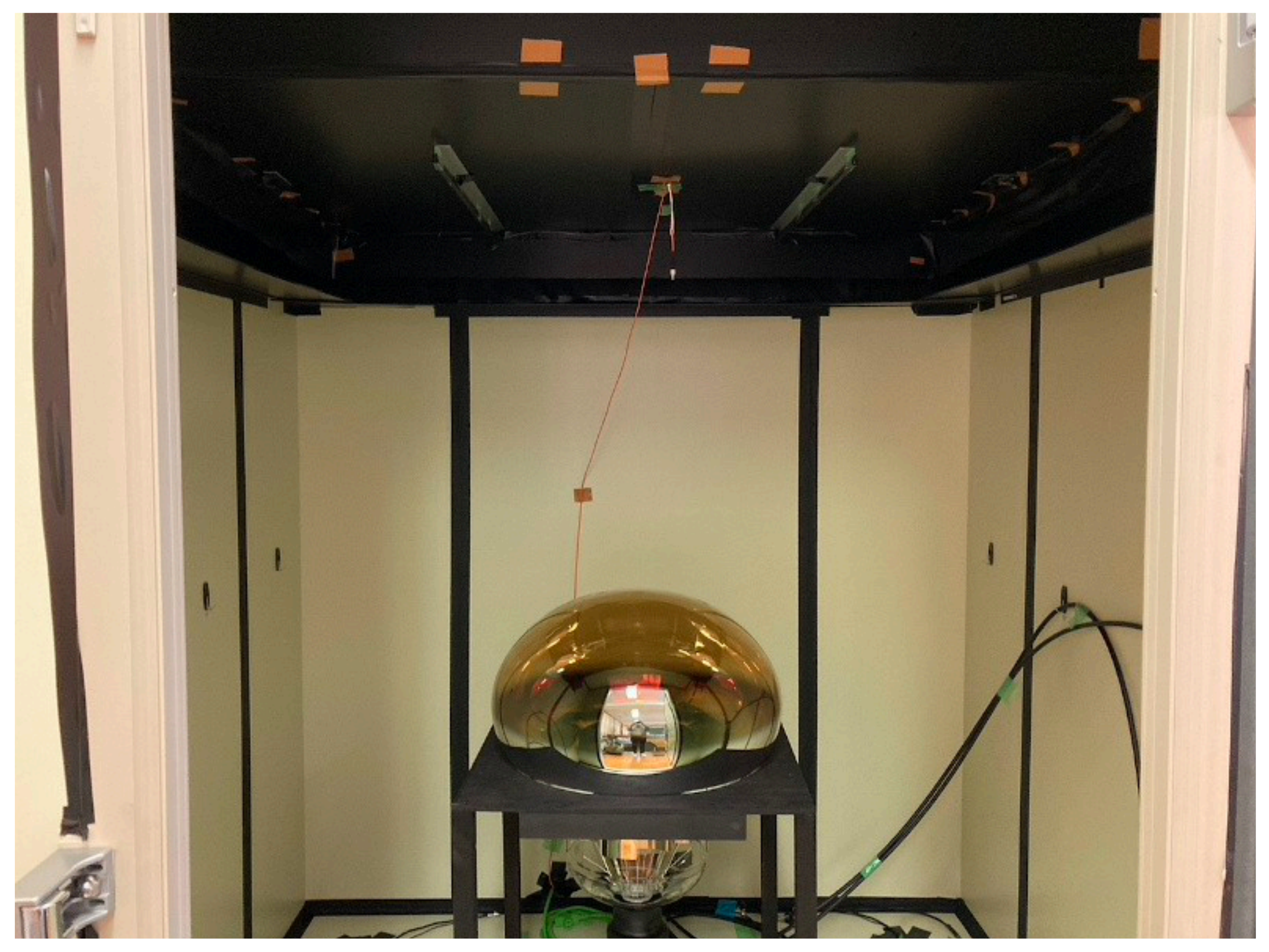
- Additional slides for perusal

50cm PMT production

Storage

Visual inspection

Testing signal

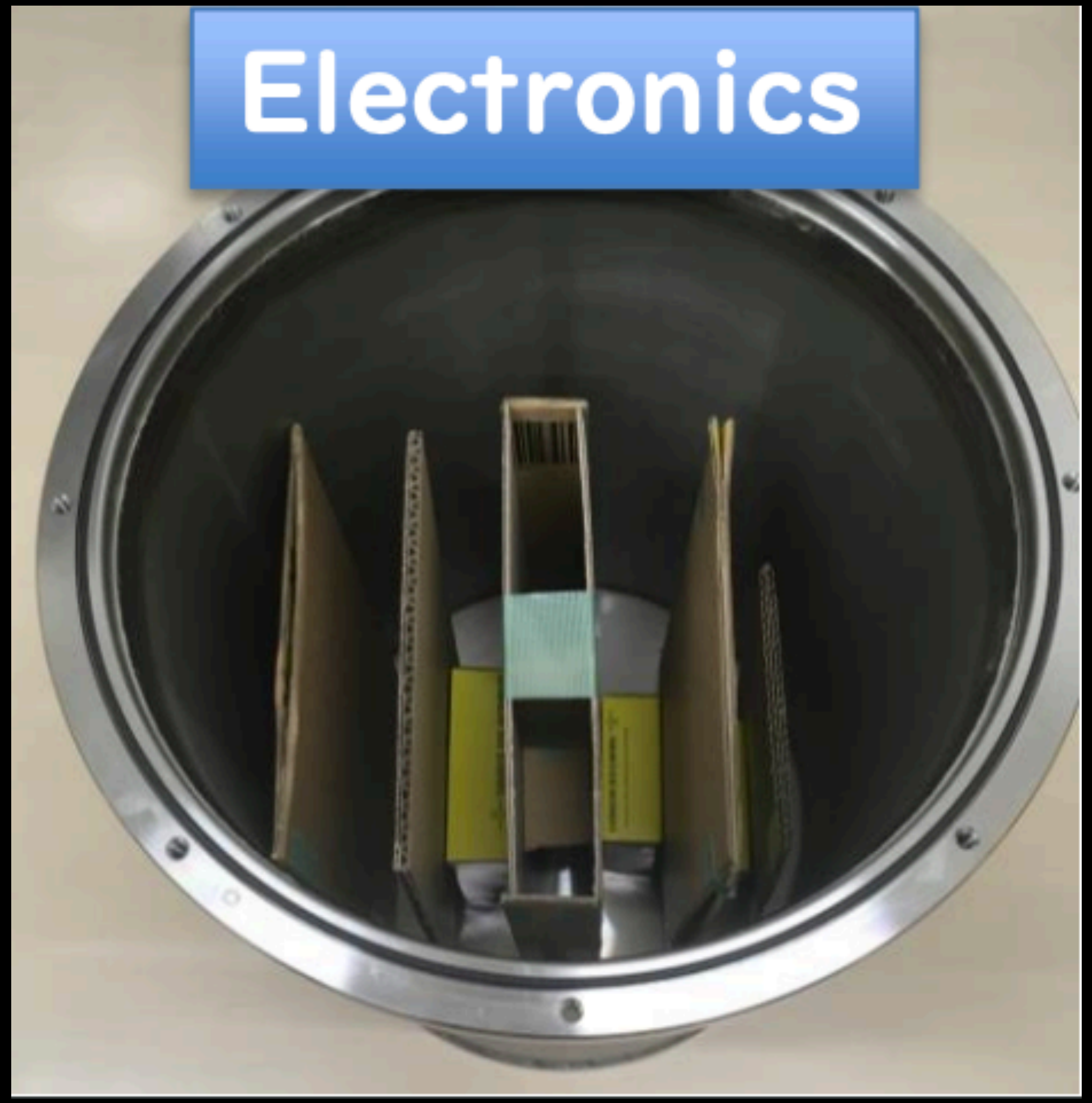


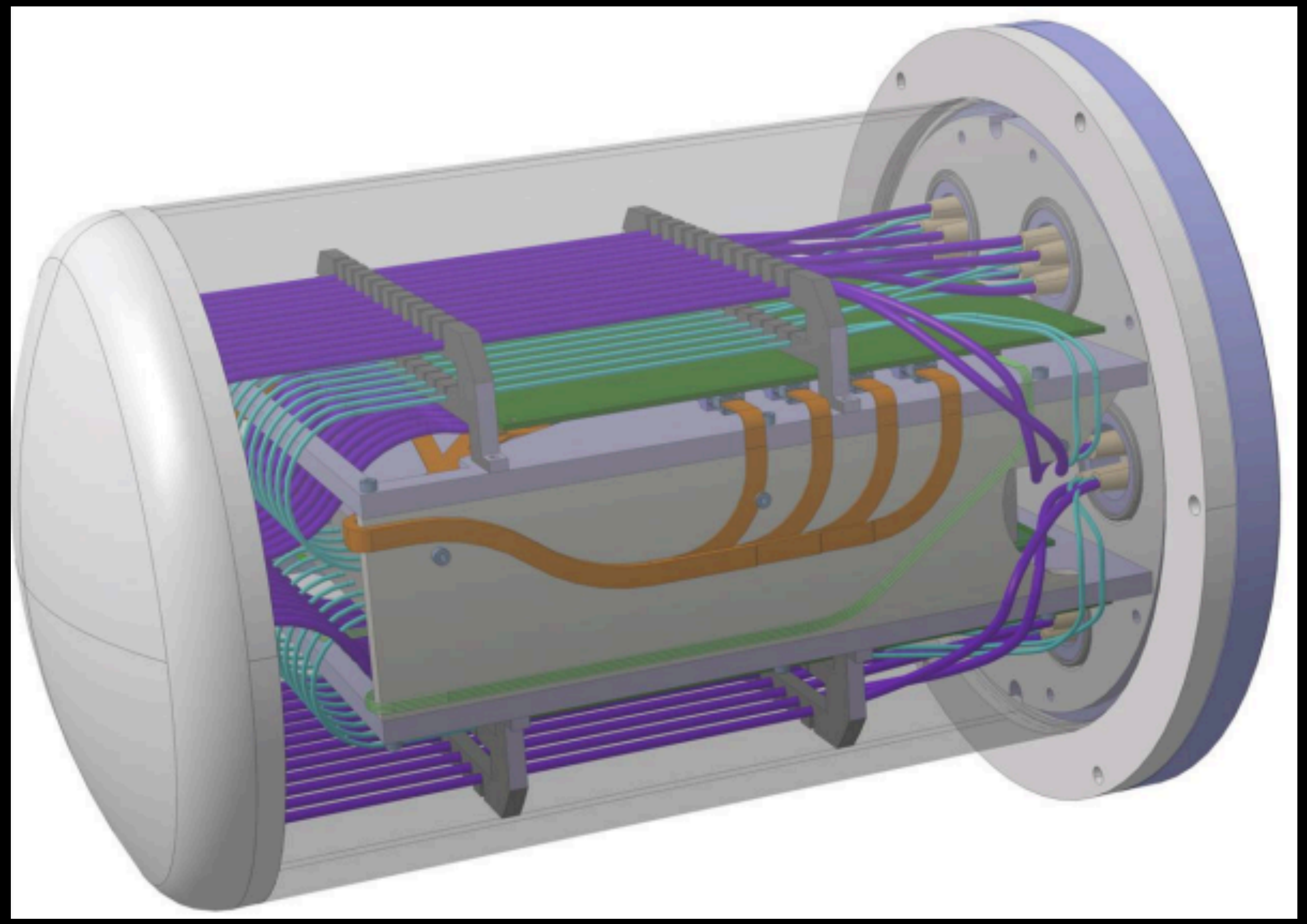
PMT Dark Rooms

Electronics Canisters

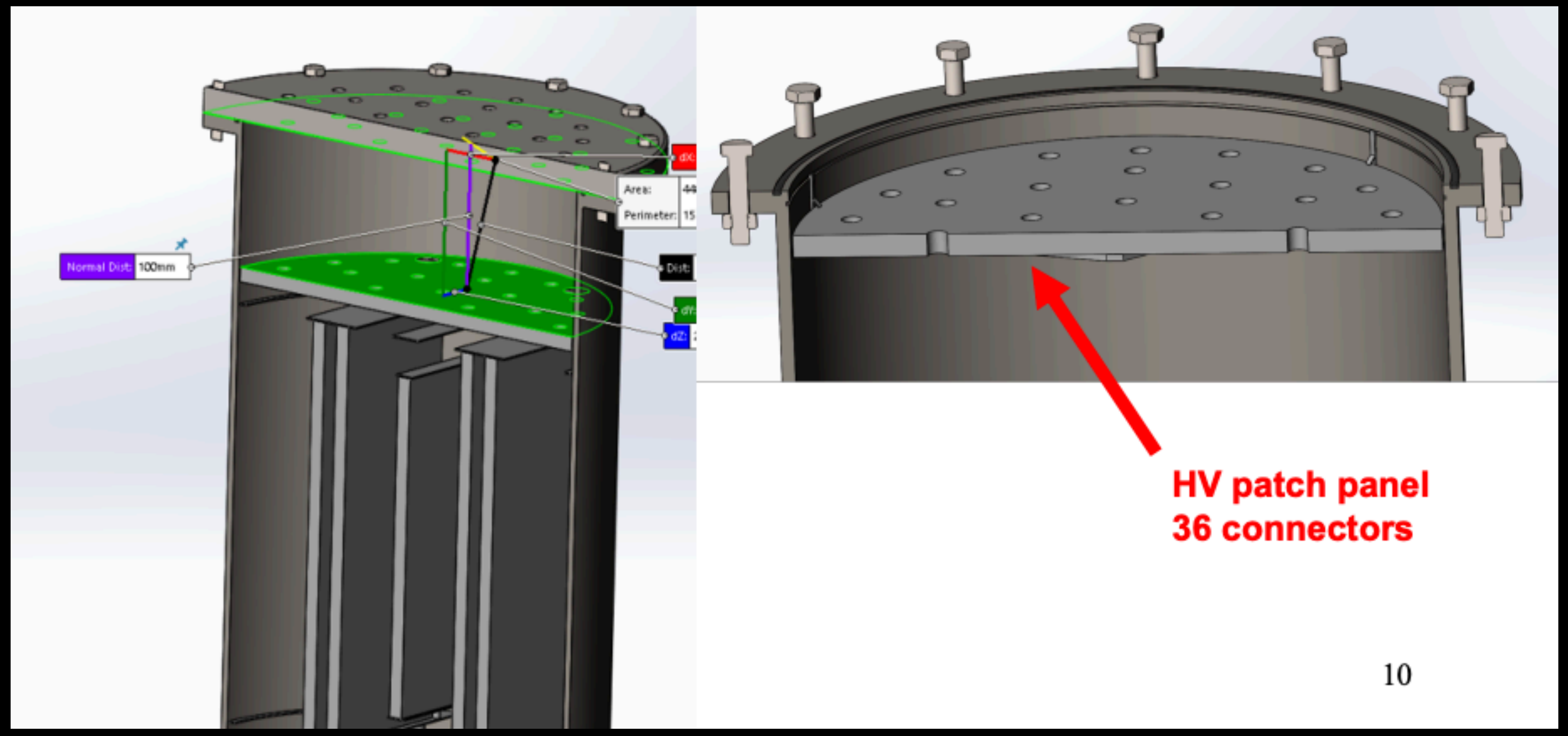
- Canisters will contain electronics boards and will be in water.

ID



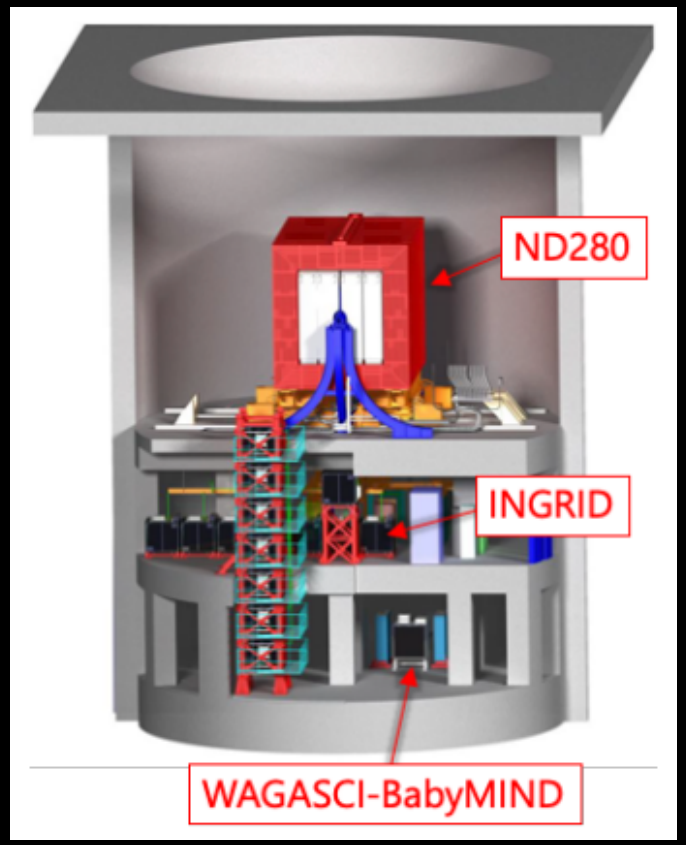


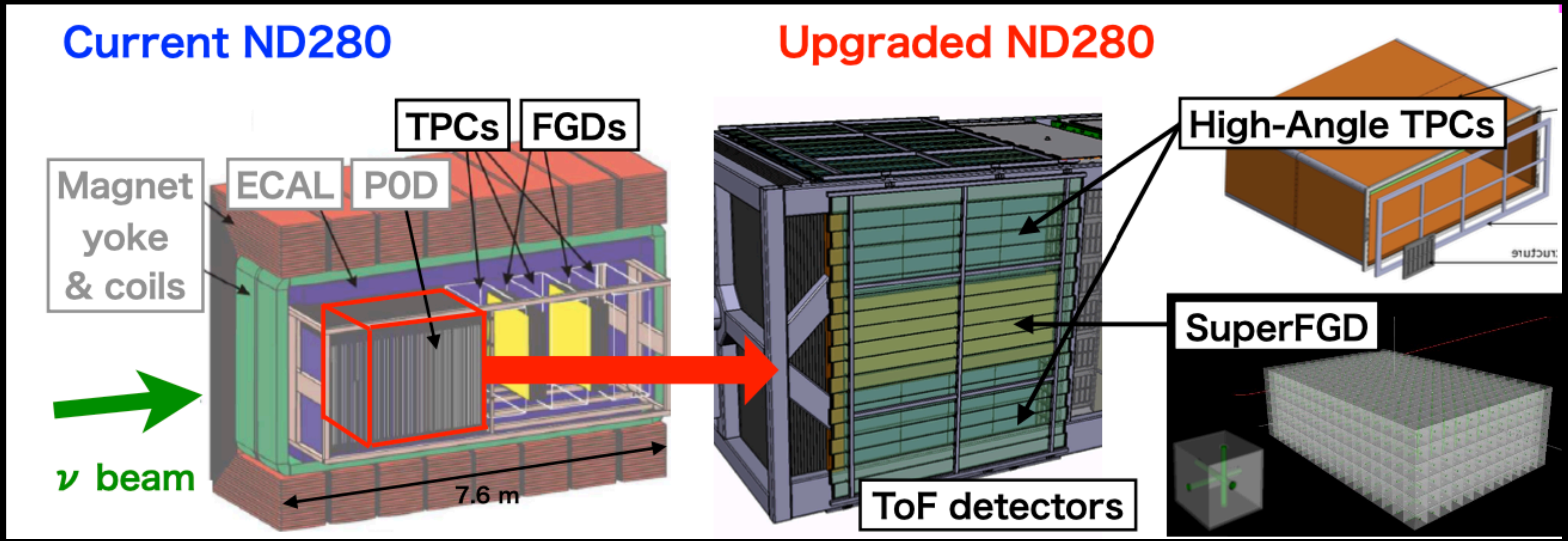
OD

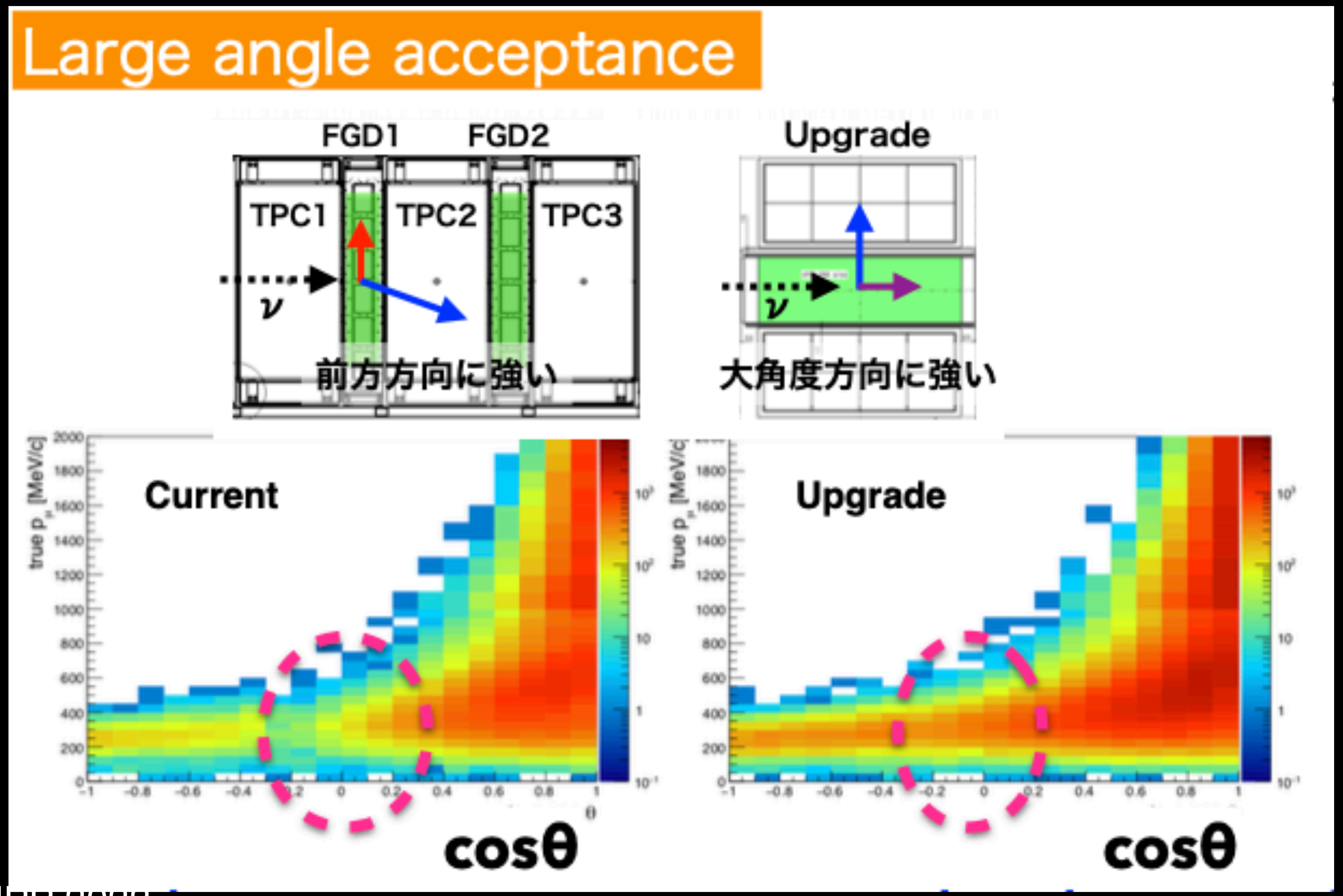


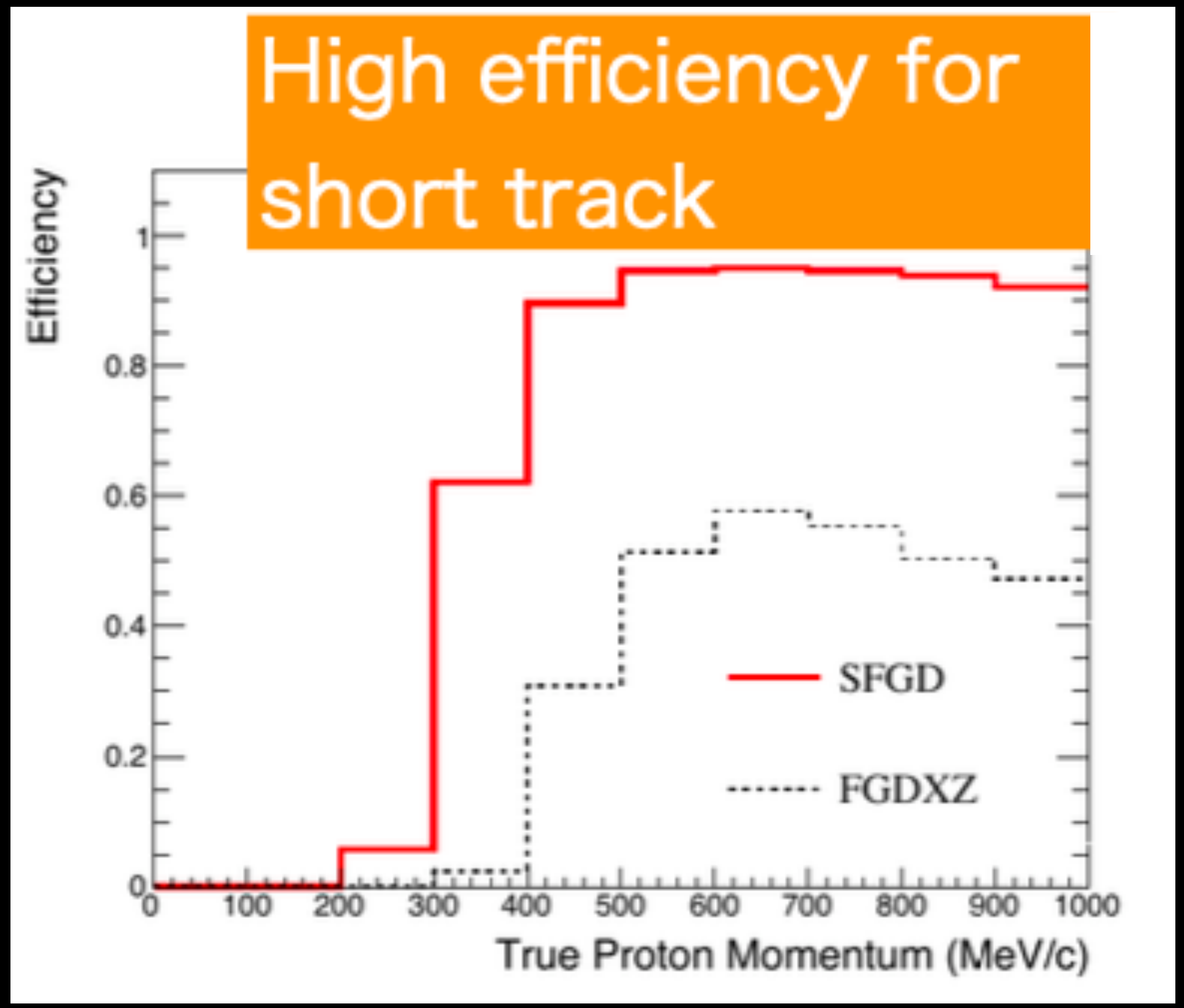
Suite of Near Detectors

ND280





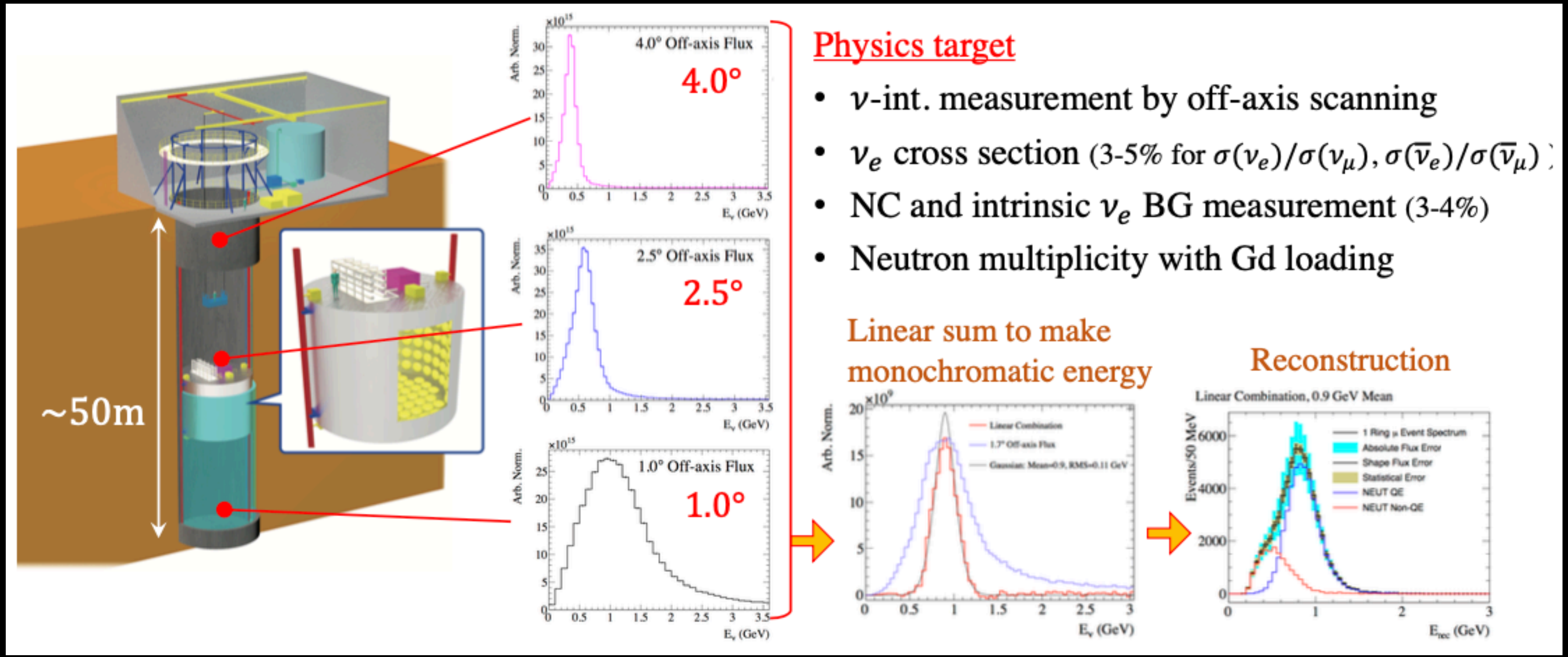




- Data taking planned from 2022.
  - Large angle acceptance.
  - High efficiency for short tracks.
- Under investigation future upgrade during Hyper-K era.

Suite of Near Detectors

IWCD



- New 1kton-scale water Cherenkov detector at ~1km baseline
- Detector can vertically move → measurement at different off-axis angles
- Progress in site choice and detector development.
- Using mPMTs as Far Detector.