The Hyper-Kamiokande Experiment

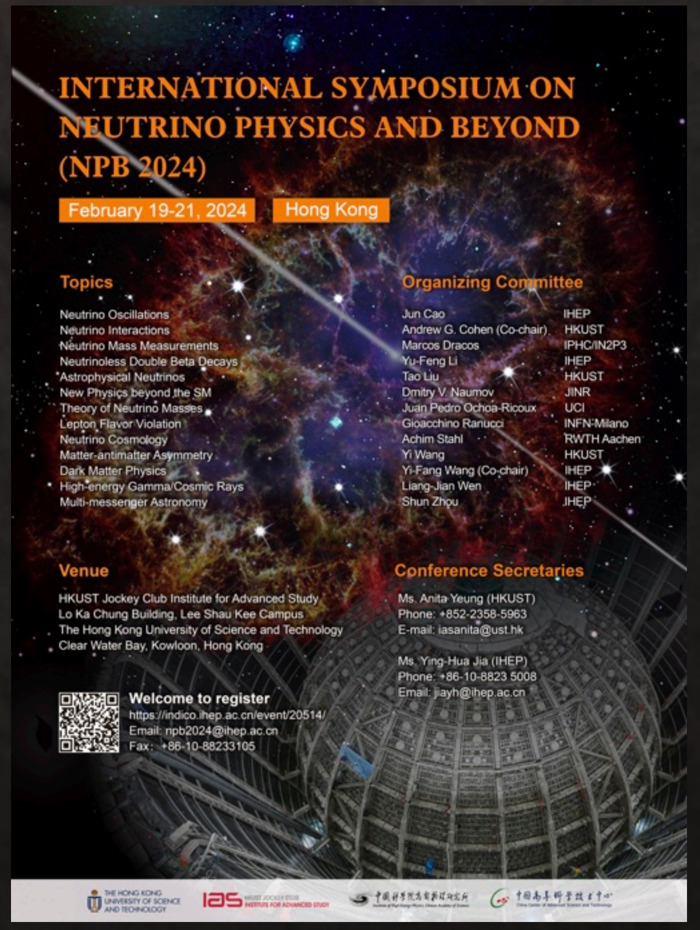
Hyper-K

Francesca Di Lodovico
King's College London

for the Hyper-Kamiokande Collaboration

International Symposium on Neutrino Physics and Beyond

HKUST - 19-21 February 2024



NIKKEN SEKKEI

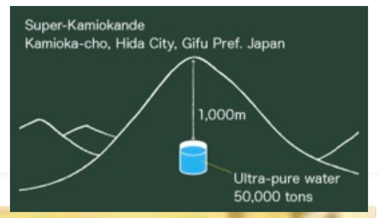
KING'S College LONDON

Three generations of Kamiokande

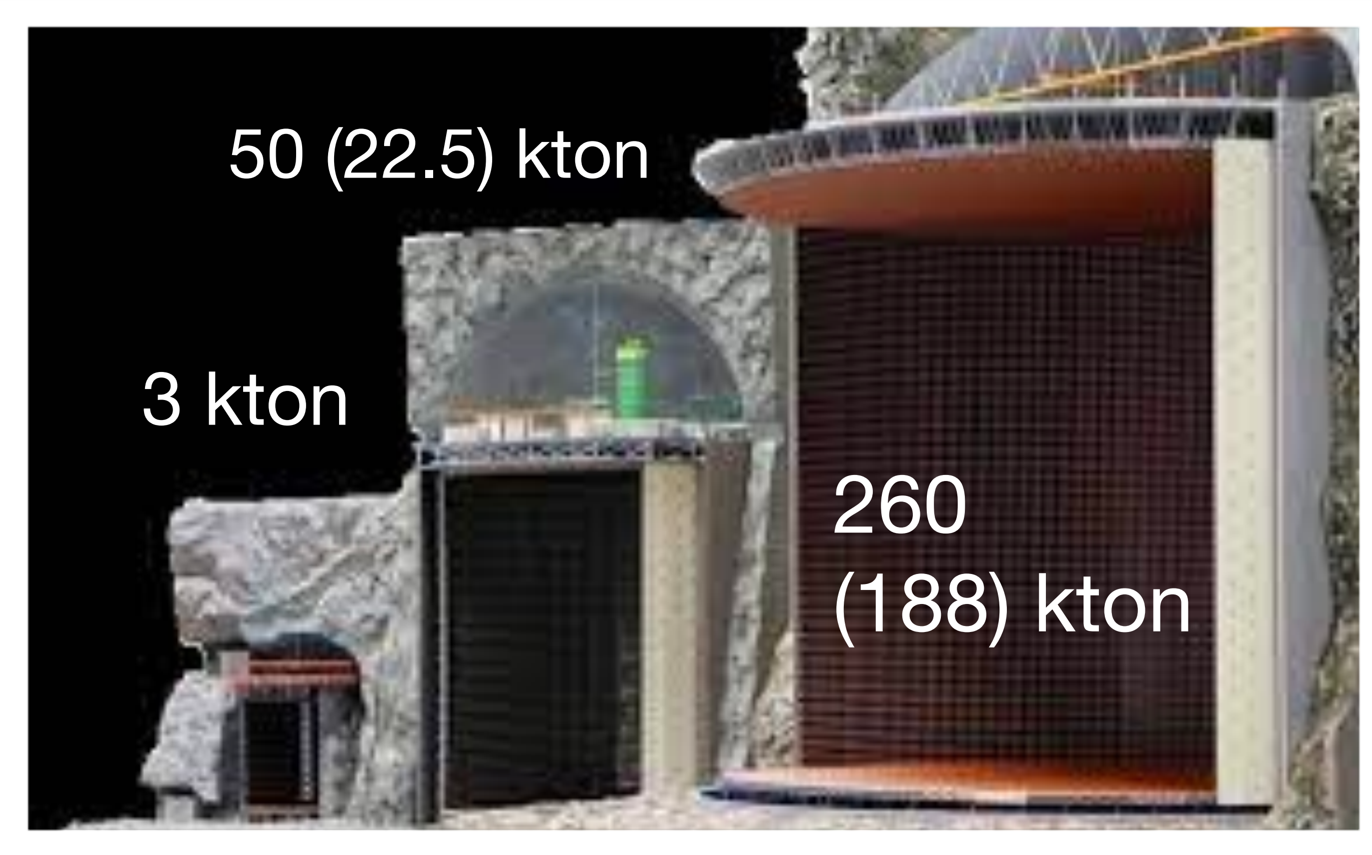
Kamiokande
(1983-1995)

20x

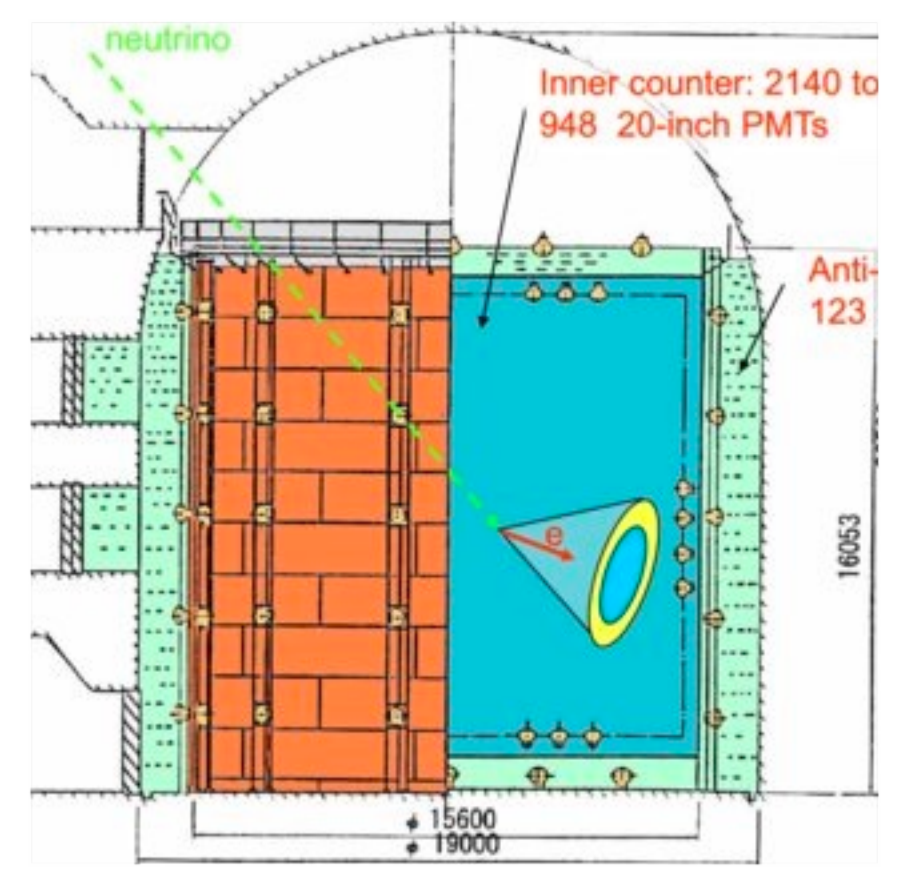
Super-Kamiokande
(1996-)



8.4x



Hyper-Kamiokande
(2027-)



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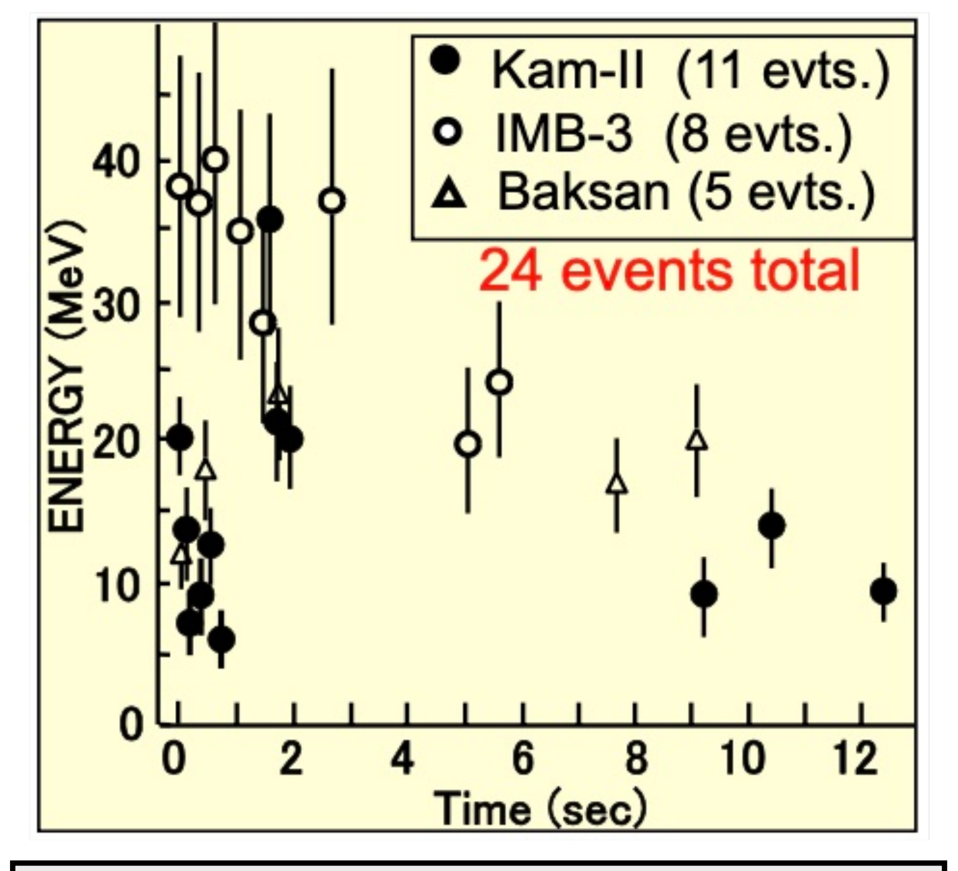
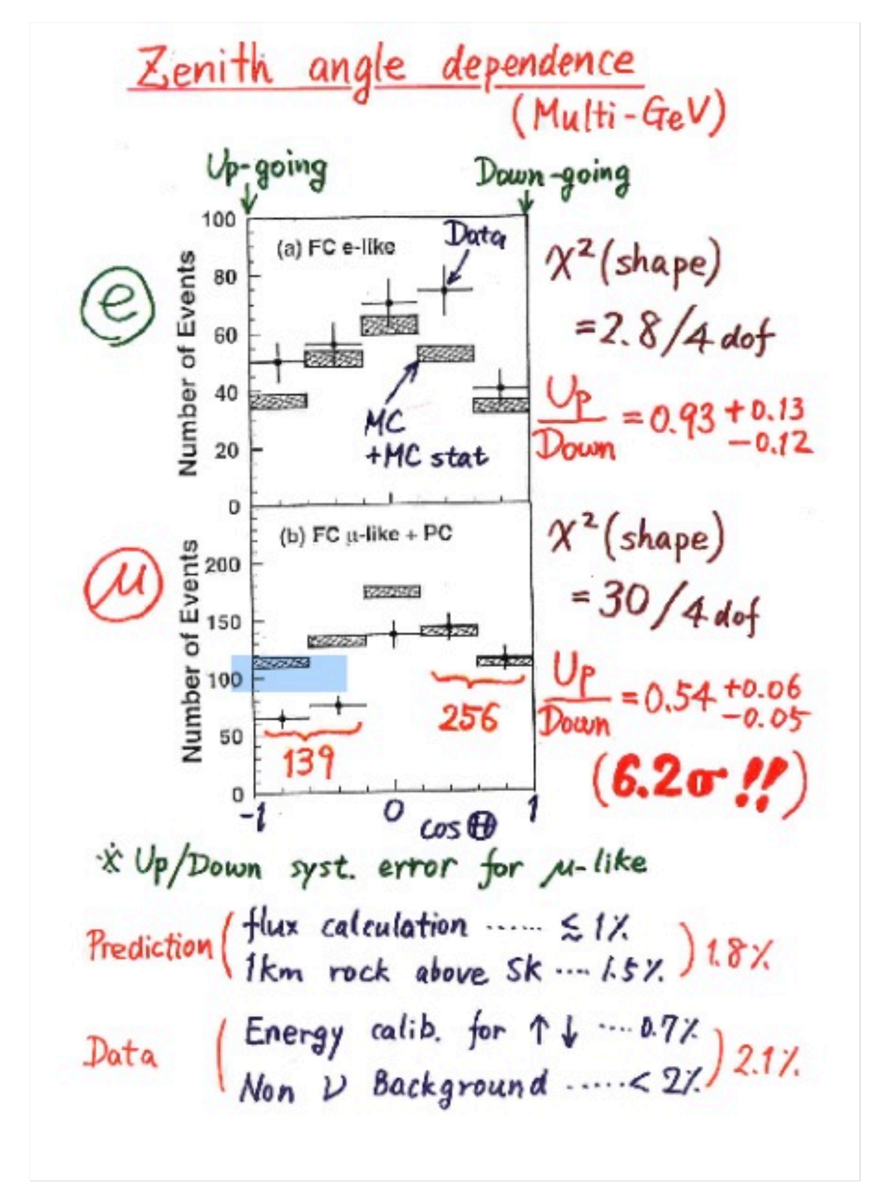
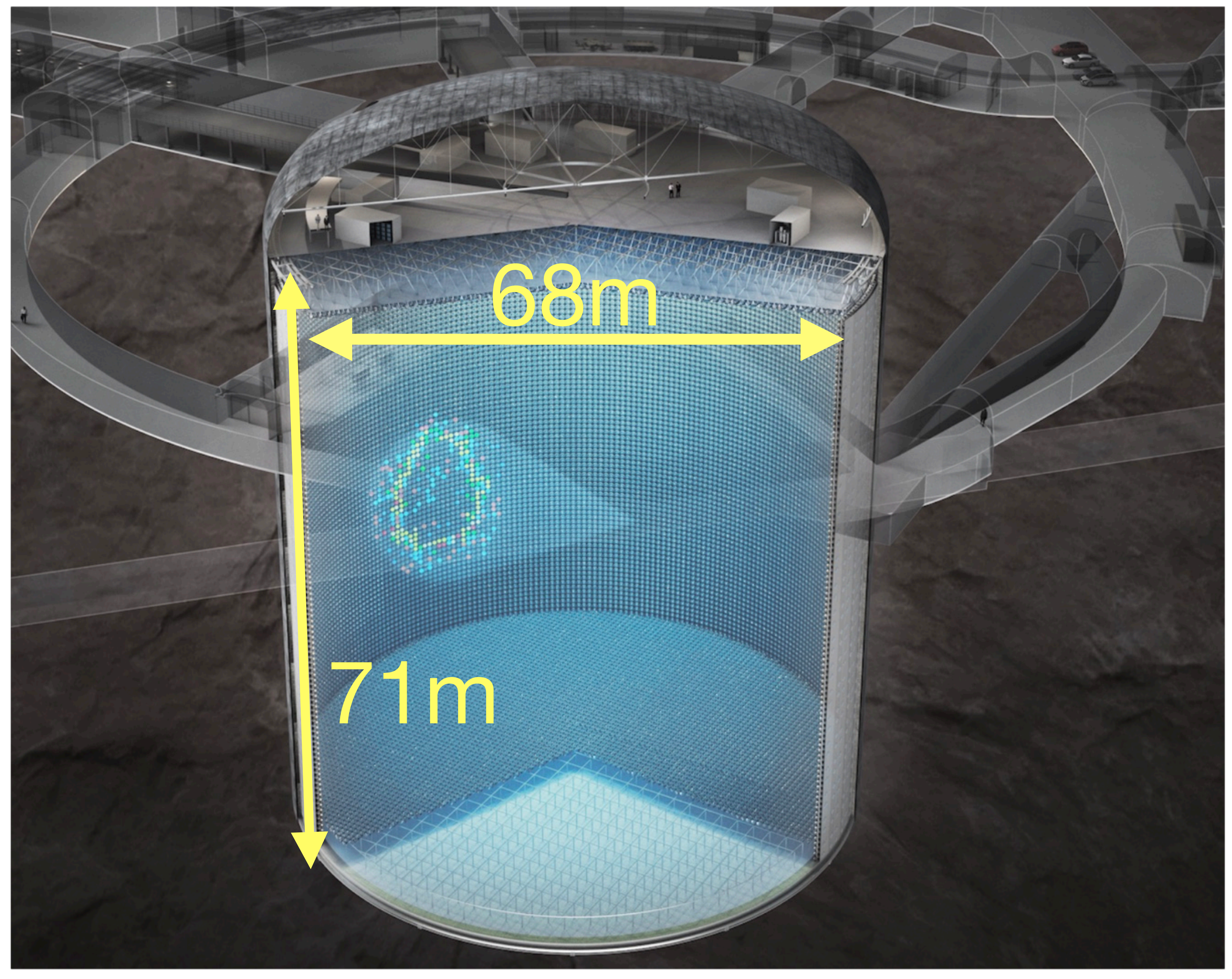


Birth of neutrino astrophysics

Discovery of neutrino oscillations

Takayama (1998)





CP, astrophysics, rare decays

Collaboration

- 22 countries, 104 institutes, ~580 people as of February 2024, and growing
- ~25% Japanese/~75% non-Japanese.

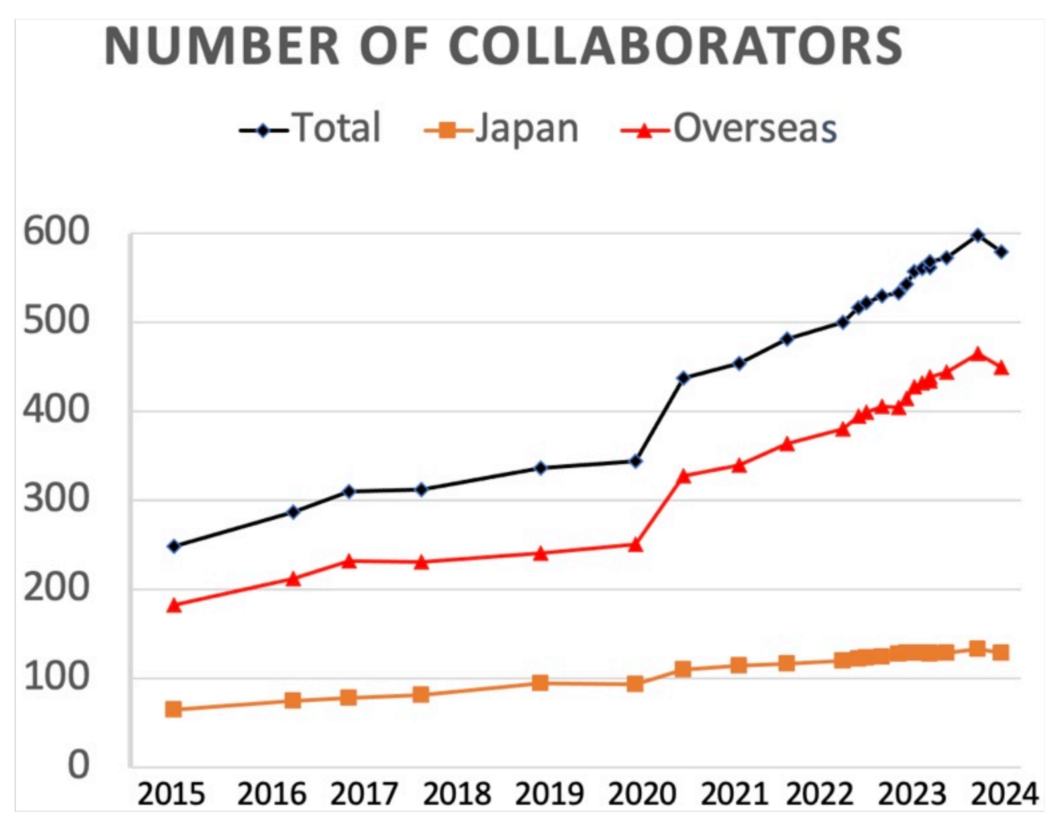
Europe	344 members
Armenia	3
Czech	8
France	43
Germany	1
Greece	4
Italy	58
Poland	45
Russia	22
Spain	46
Sweden	5
Switzerland	14
Ukraine	3
UK	92

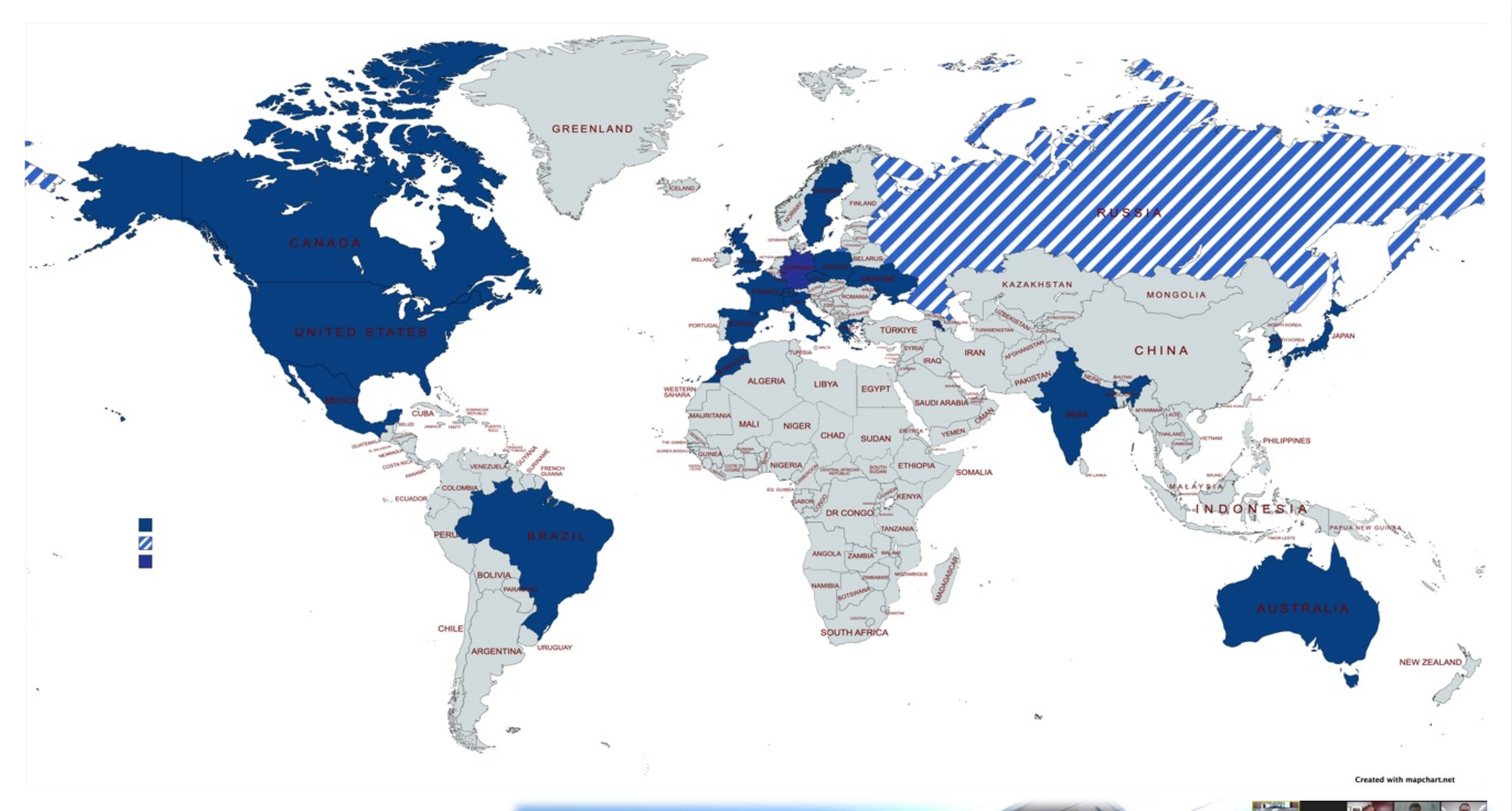
Asia	155 members
India	10
Korea	16
Japan	129

Oceania	7 members
Australia	7

Americas	62 members
Brazil	3
Canada	42
Mexico	9
USA	8

Africa	11 members
Morocco	11

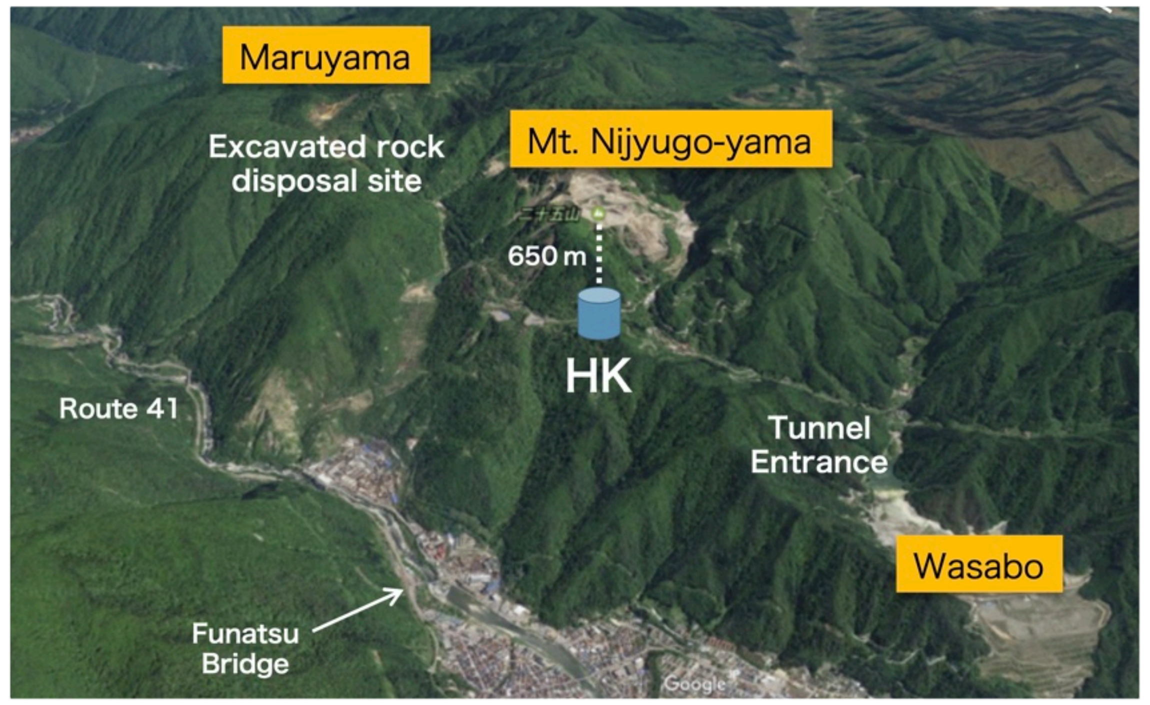




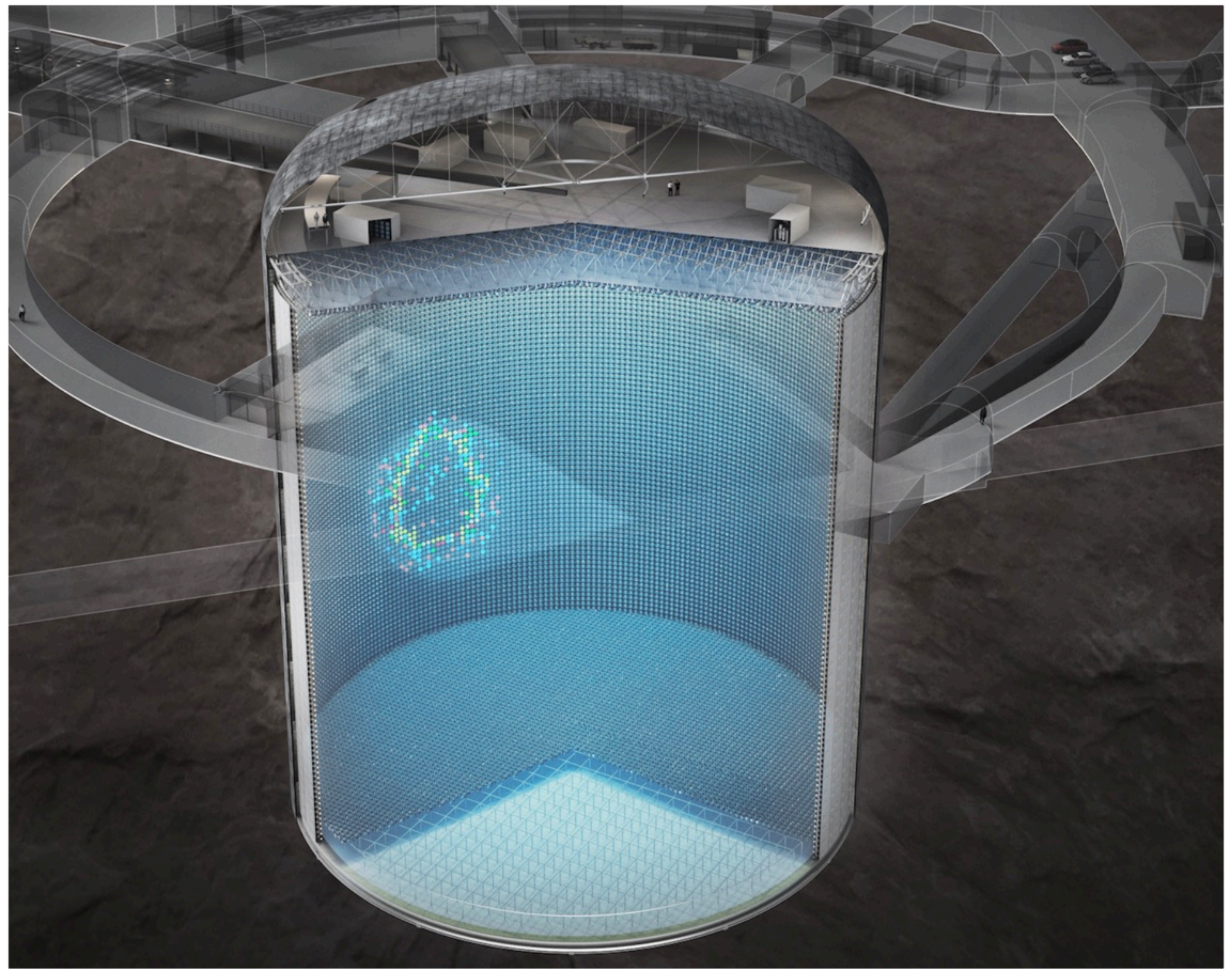
November 2023 Collaboration Meeting at Kamioka

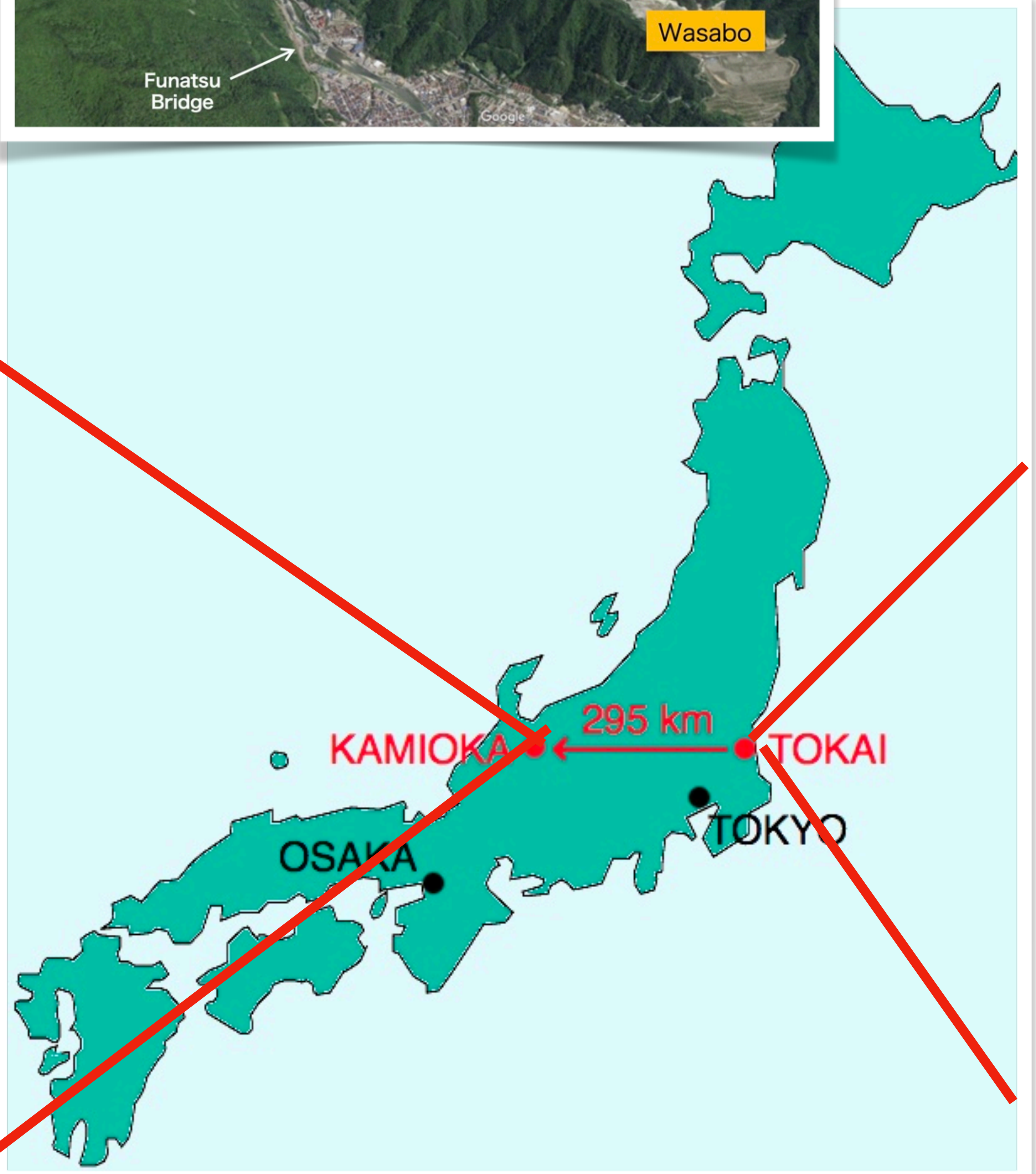
Hyper-Kamiokande Experimental Configuration

650 metres (2,130 ft) under the peak of Nijuugo Mountain

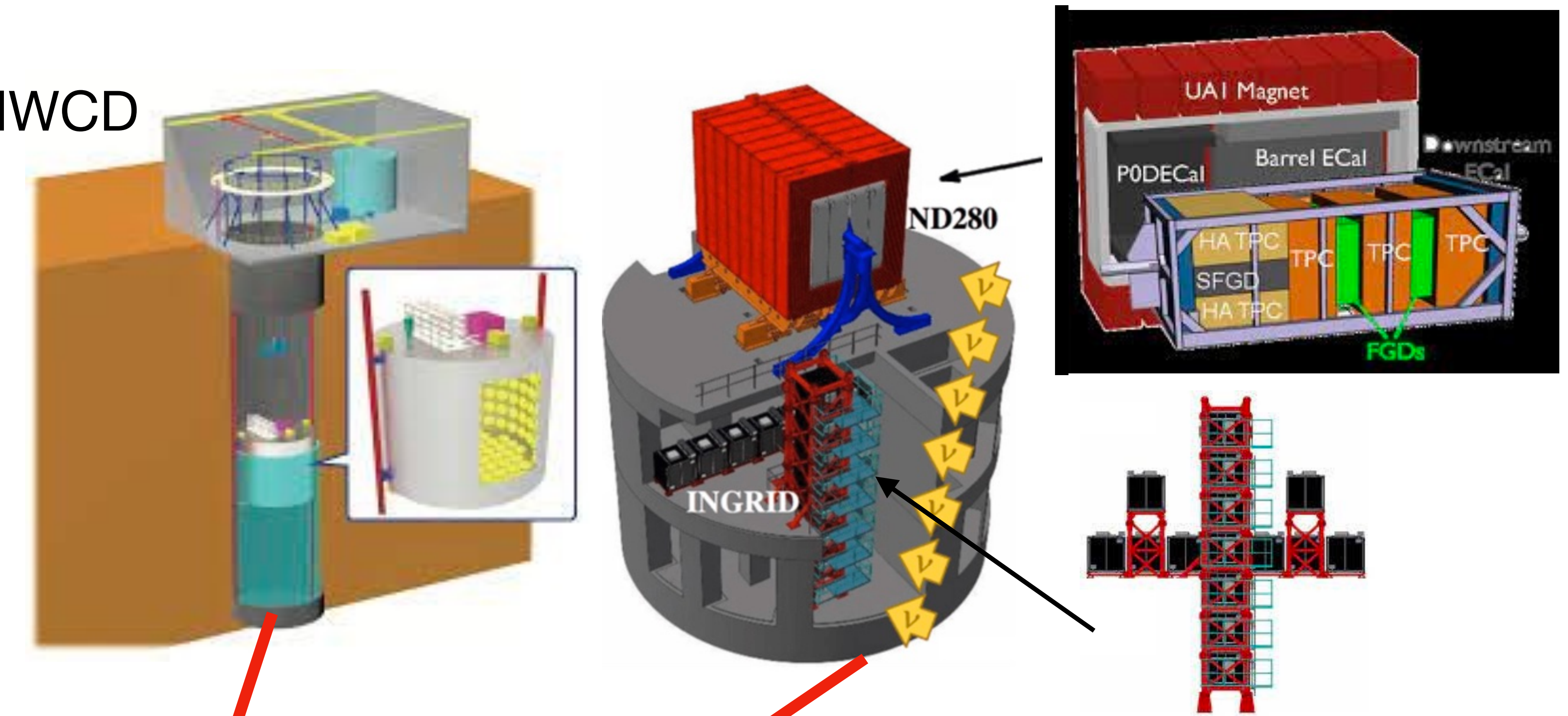


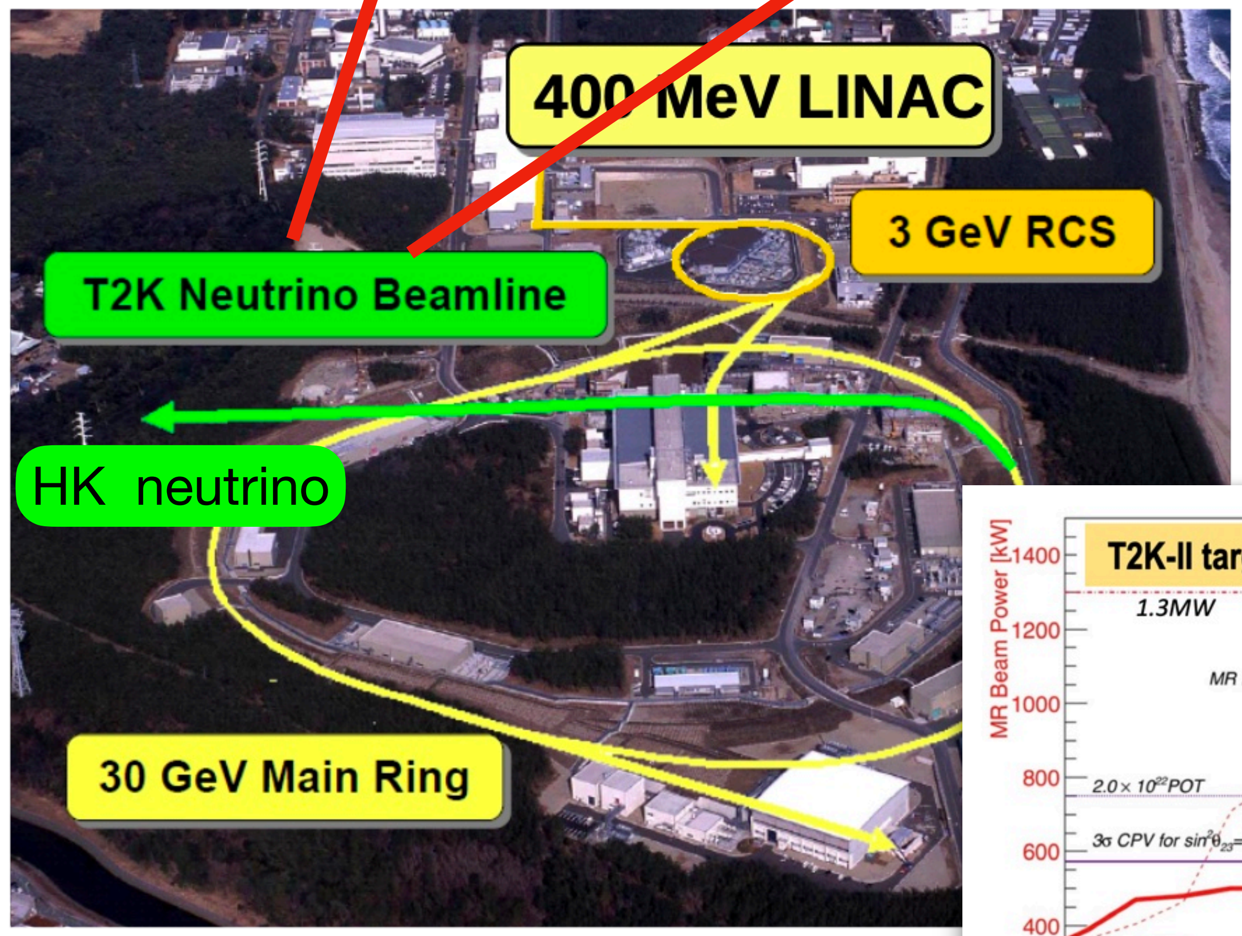
Hyper-Kamiokande “far” detector is L=295km away from the beam source.



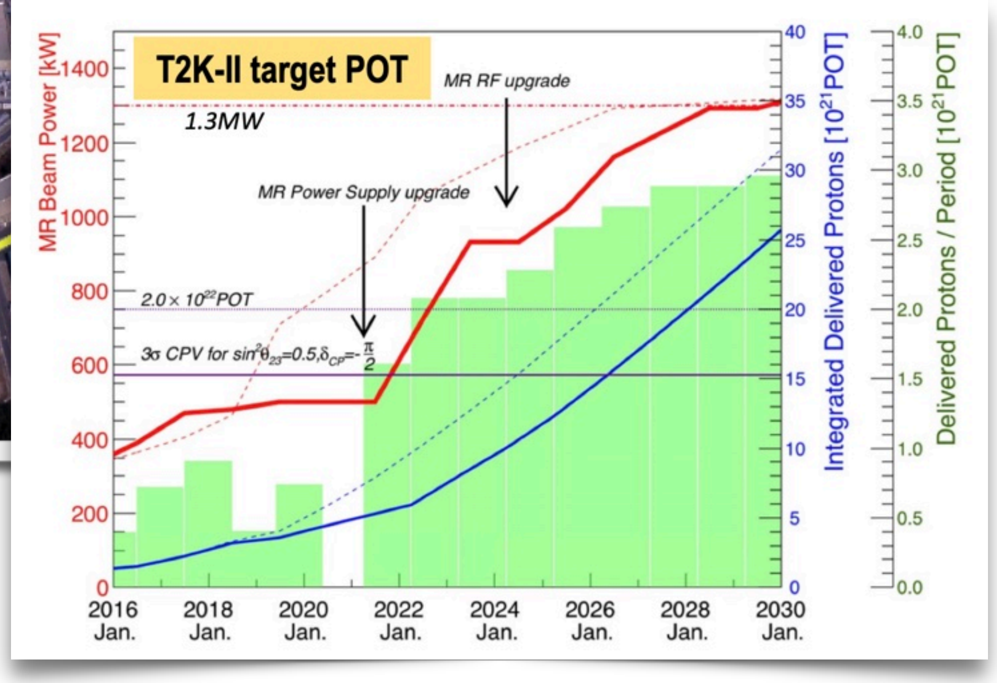


Near Detectors suite



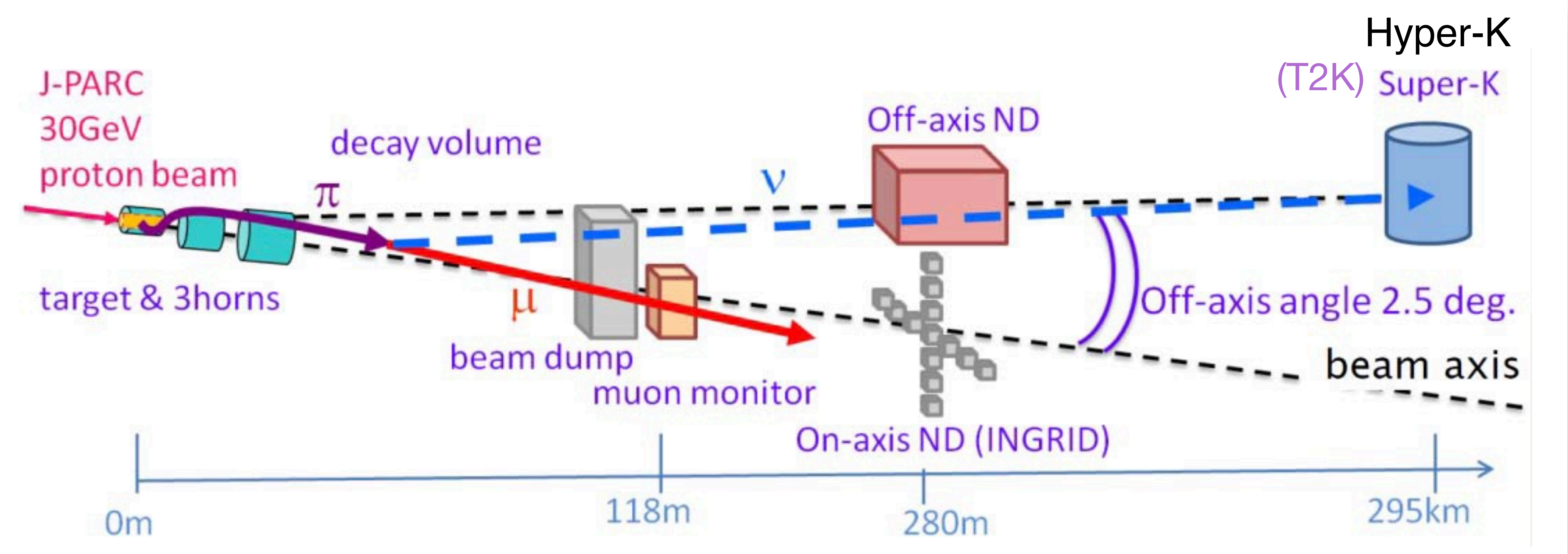


J-PARC Upgraded beam (1.3 MW)

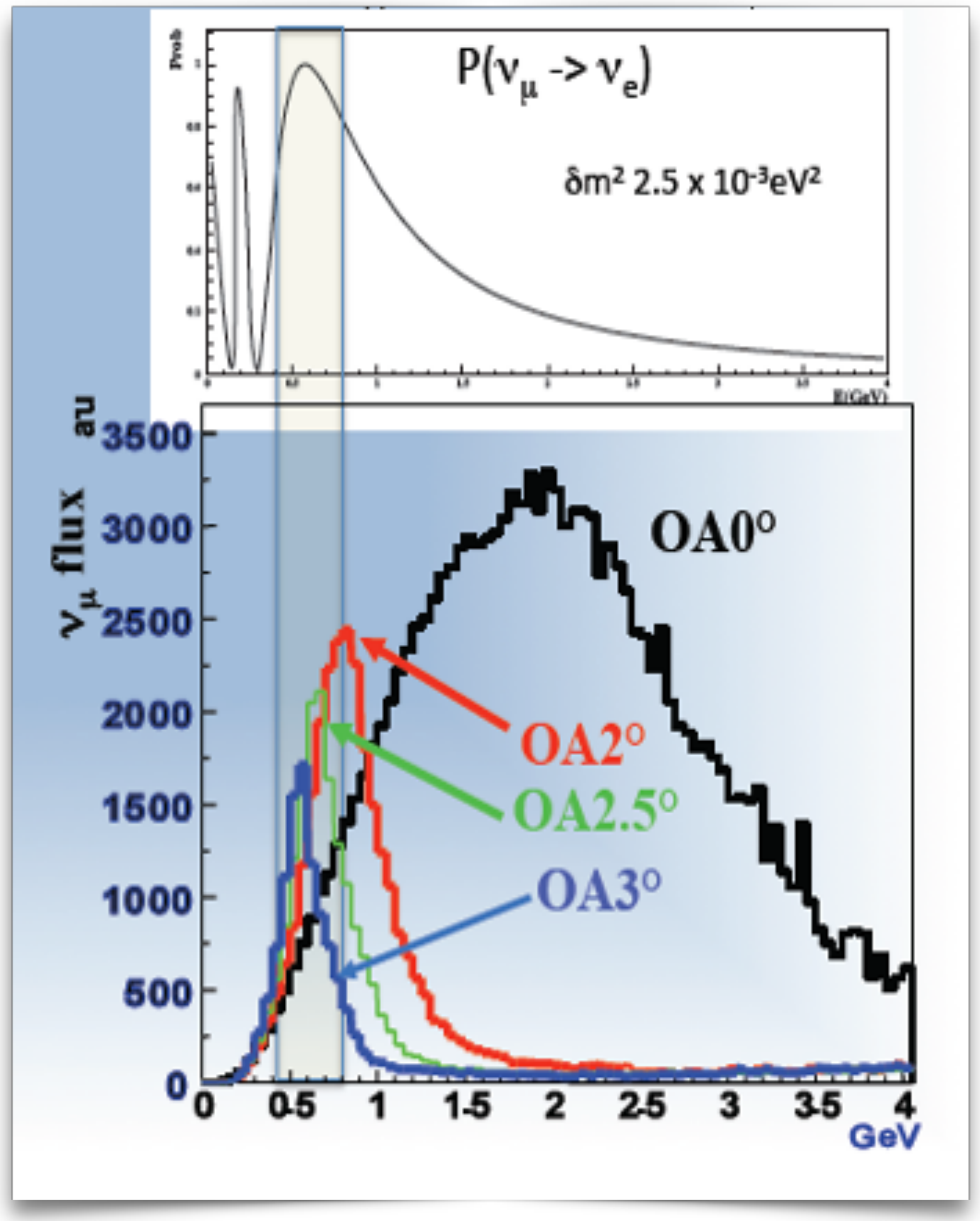


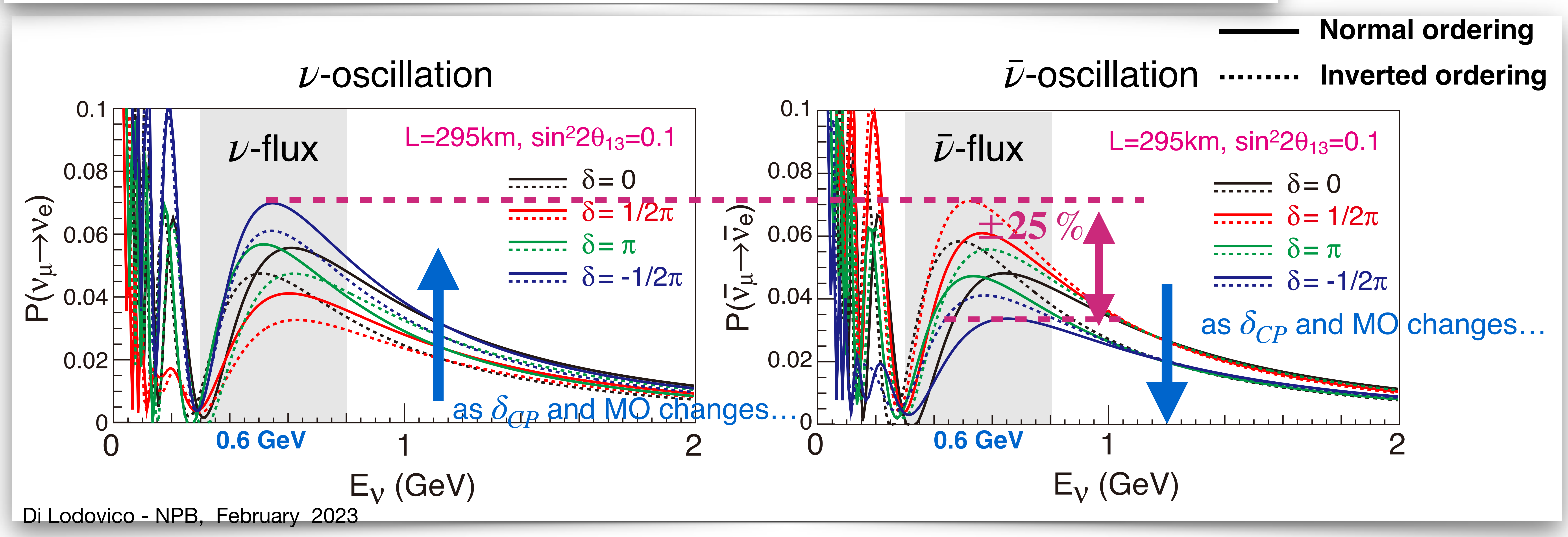
J-PARC Neutrino Beam

Off-axis at 2.5º neutrino beam to achieve maximum neutrino flux at oscillation maximum of 0.6 GeV.



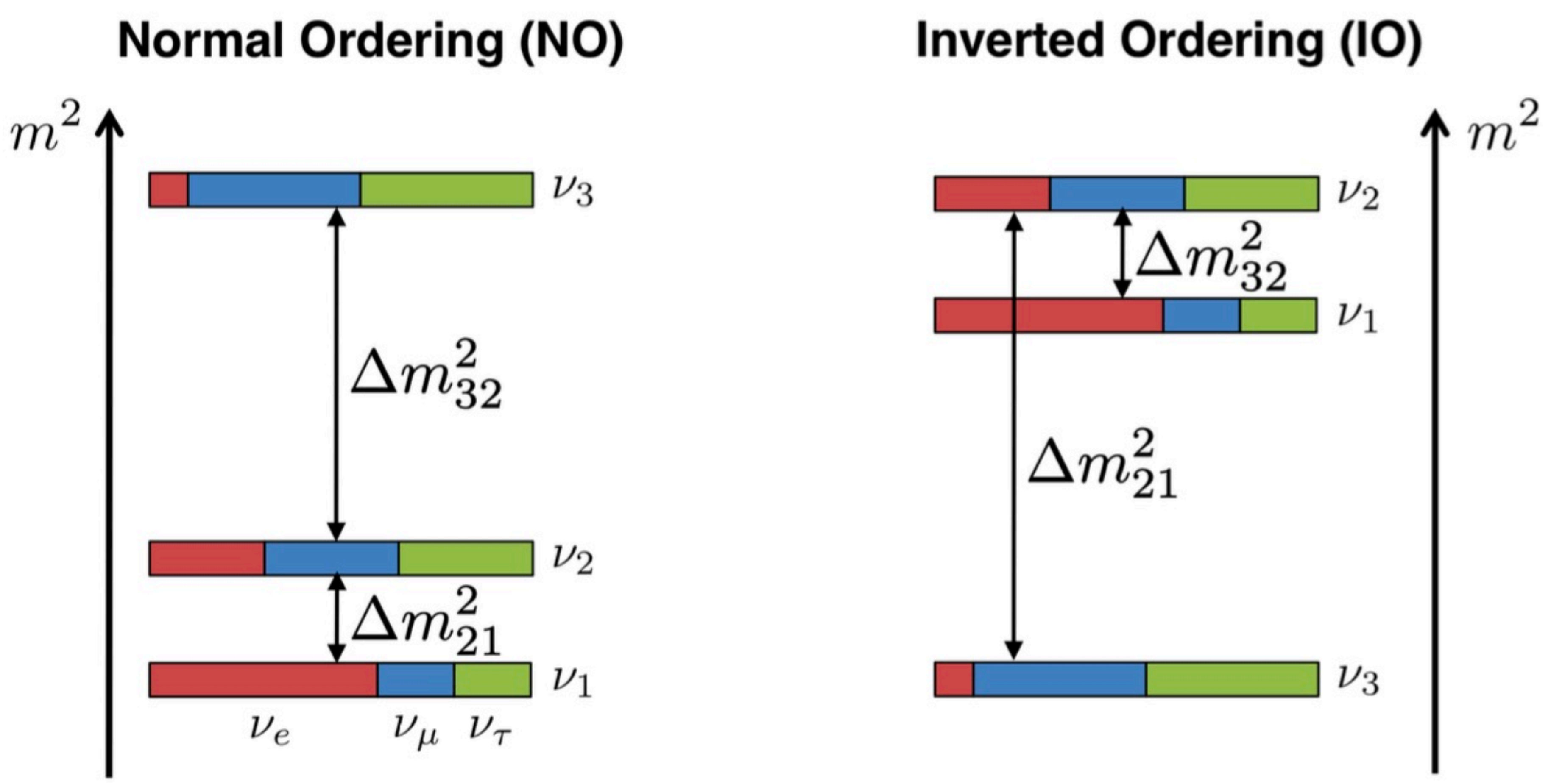
Hyper-K beam flux peaks ~0.6 GeV





- Unknown mass ordering (solid vs dashed) complicates δ_{CP} measurement
- Hyper-K can use atmospheric data to exclude incorrect MO

Neutrino Oscillation Open Questions



- Is there a CP violation? Does $\sin \delta_{CP} = 0$?
- Is θ_{23} maximal (= $45°$)?
  If not, which octant (< or > $45°$)?
- Which mass ordering? Δm^2_{23}<or>0?

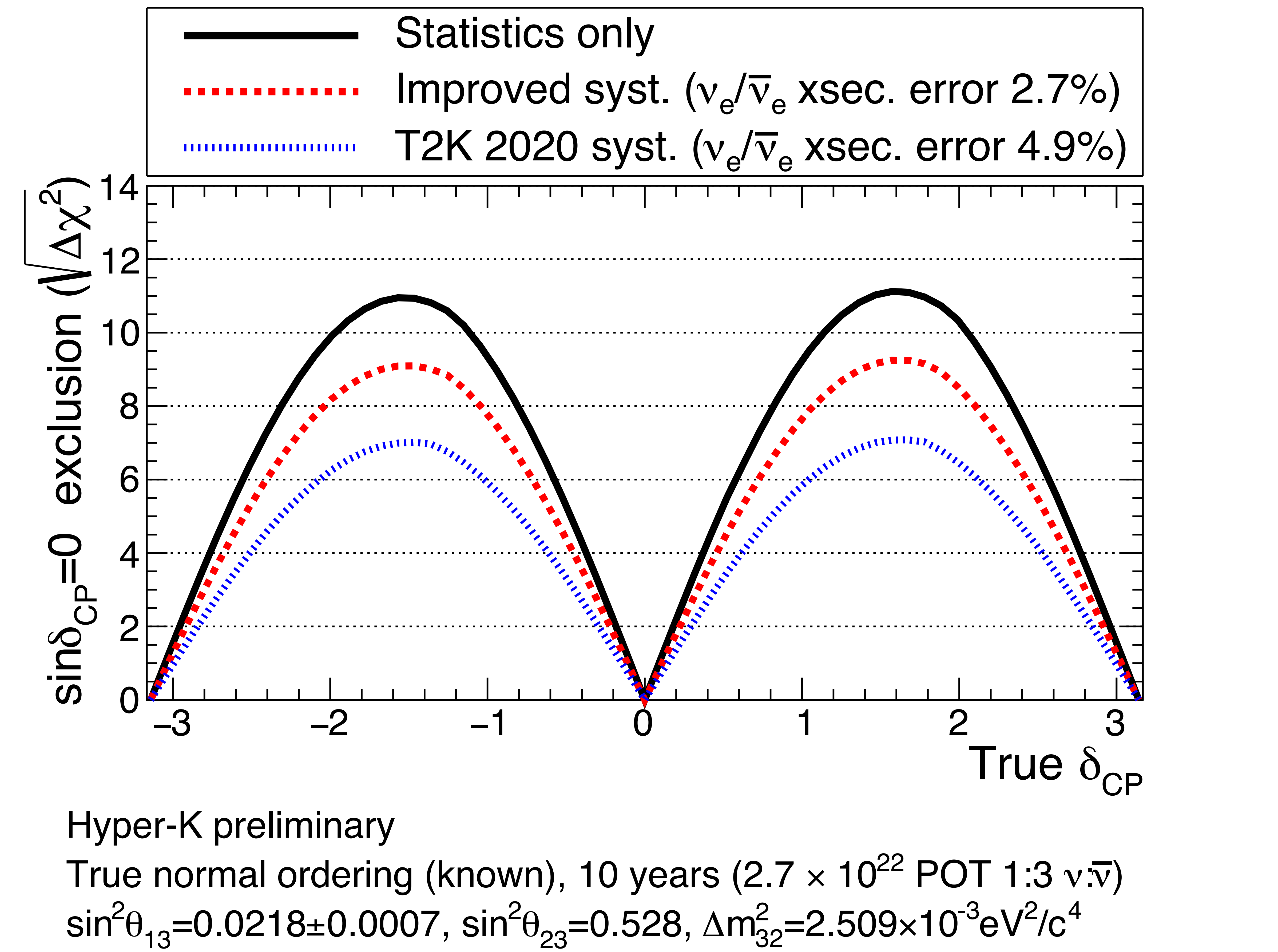
JHEP 09 (2020) 178 NuFIT 5.2 (2022)	Beam	Atmospheric	Solar
$\delta_{CP} \sim 200°$	✓	❍	✗
$\theta_{13} \sim 9°$	✓	❍	✗
$\theta_{23} \sim 49°$	✓	✓	✗
$\pm\Delta m^2_{32} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$	✓	✓	✗
Mass ordering	❍	✓	✗
$\theta_{12} \sim 33°$	✗	✗	✓
$+\Delta m^2_{21} \sim 7.4 \times 10^{-5}\,\mathrm{eV}^2$	✗	✗	✓

✓ Drives sensitivity
❍ Enhances sensitivity
✗ Negligible sensitivity

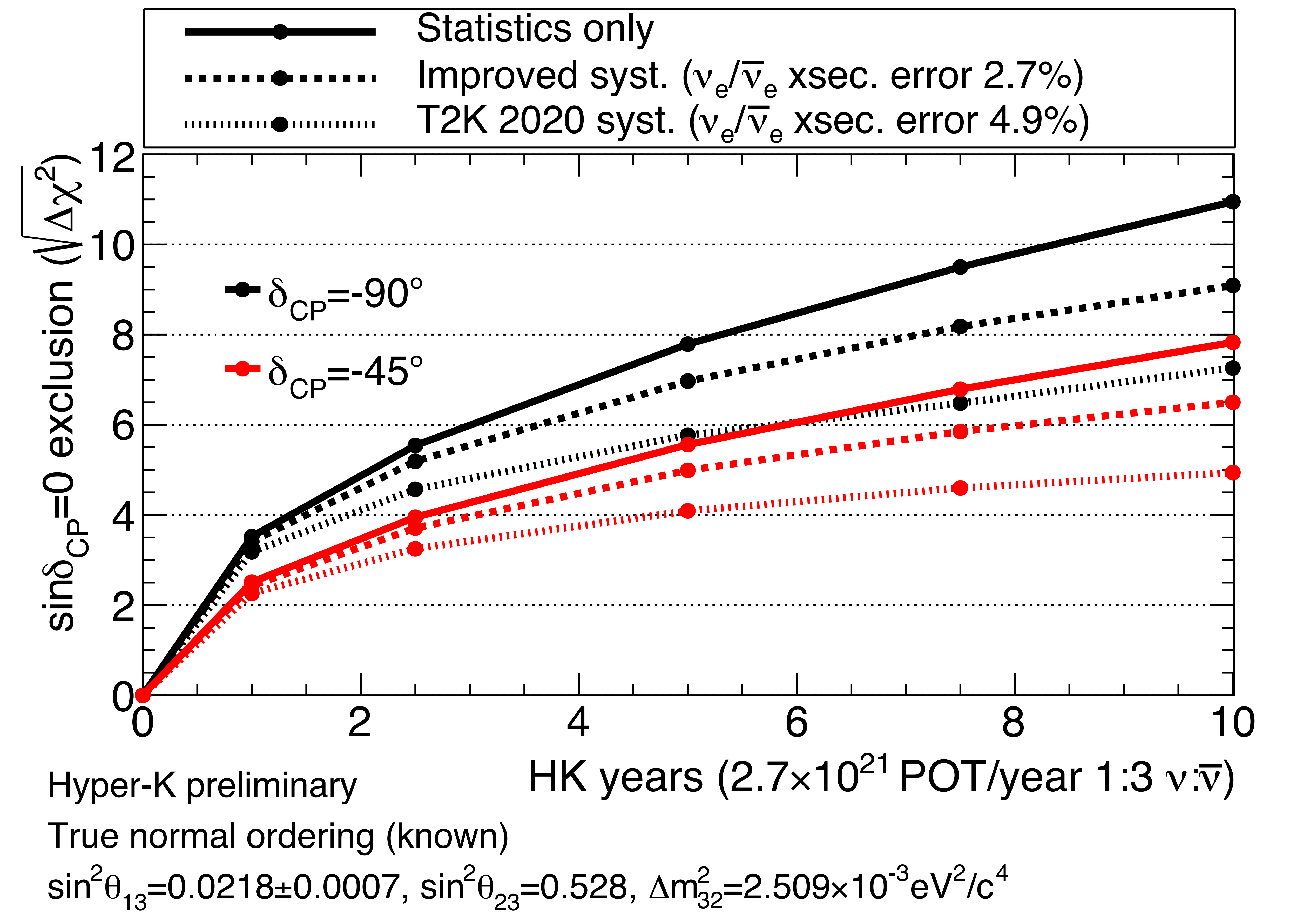
CP Violation Measurement Prospects with Beam

Sensitivities to exclude $\sin\delta_{CP} = 0$ for different systematic models obtained for a 1.3MW beam power and running 1:3 with $\nu : \bar{\nu}$ (best current estimate)

$\sin\delta_{CP} = 0$ exclusion as a function of true δ_{CP} for 10 HK-years



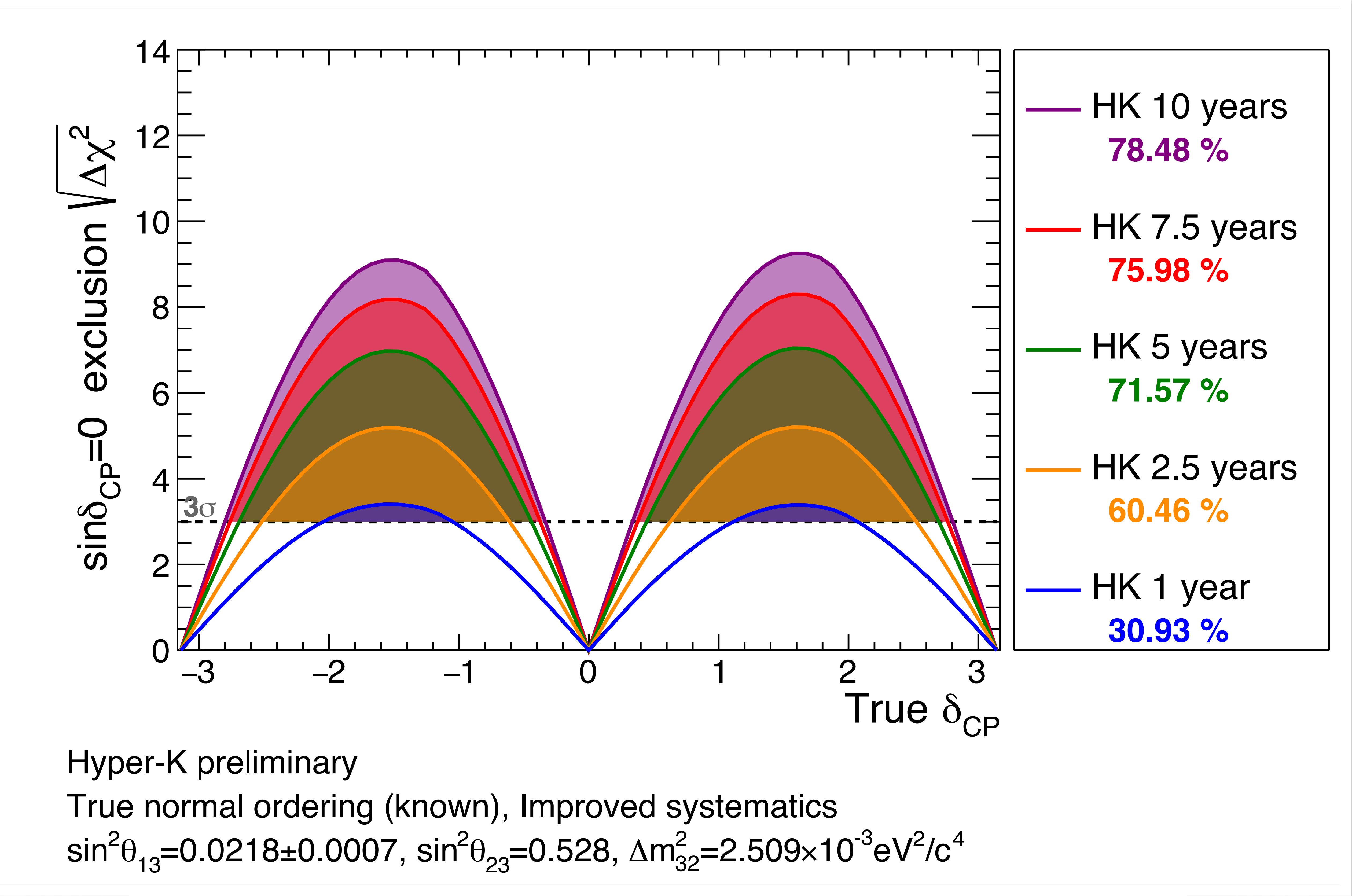
Sensitivity to exclude $\sin\delta_{CP} = 0$ as a function of HK-years for true $\delta_{CP} = -\pi/2$ and $\delta_{CP} = -\pi/4$.



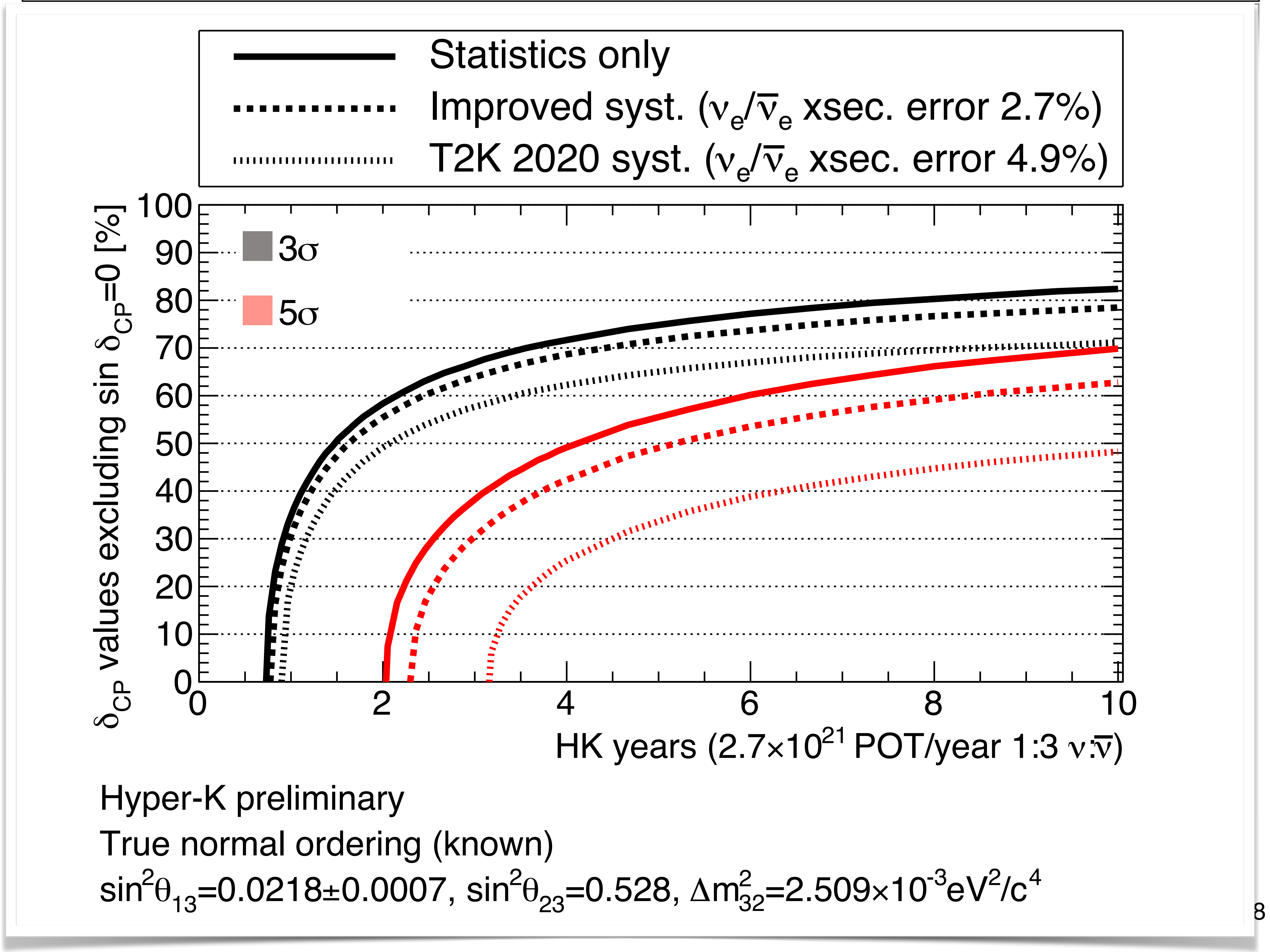
CP Violation Measurement Prospects with Beam

Sensitivities to exclude $\sin\delta_{CP} = 0$ for different systematic models. obtained for a 1.3MW beam power and running 1:3 with $\nu : \bar{\nu}$ (best current estimate)

$\sin\delta_{CP} = 0$ exclusion as a function of true δ_{CP} for for HK-years for improved syst. error at 3σ

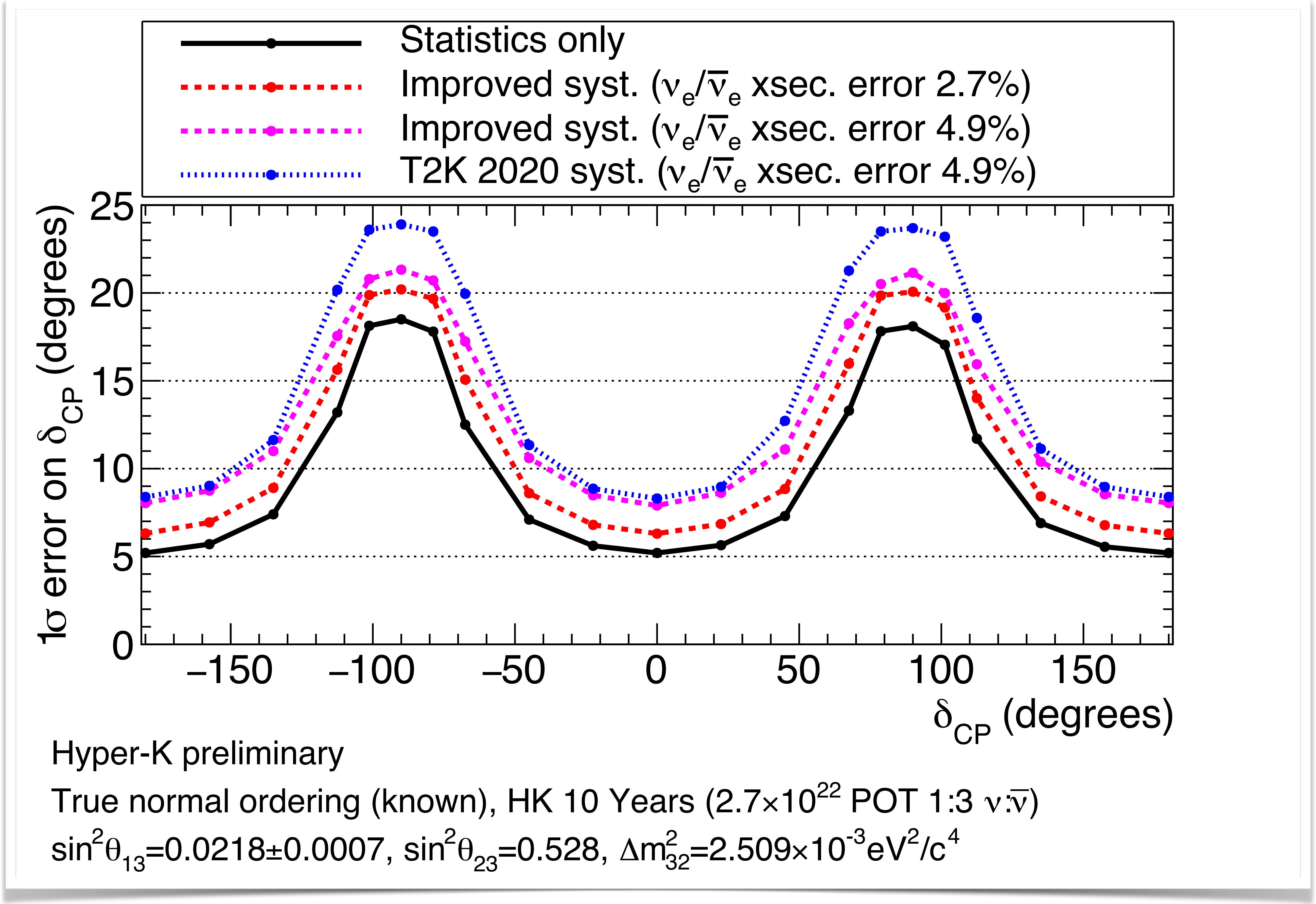


Proportion of true δ_{CP} values excluding $\sin\delta_{CP} = 0$ at 3σ and 5σ C.L. as a function of HK-years.



δ_{CP} resolution sensitivity

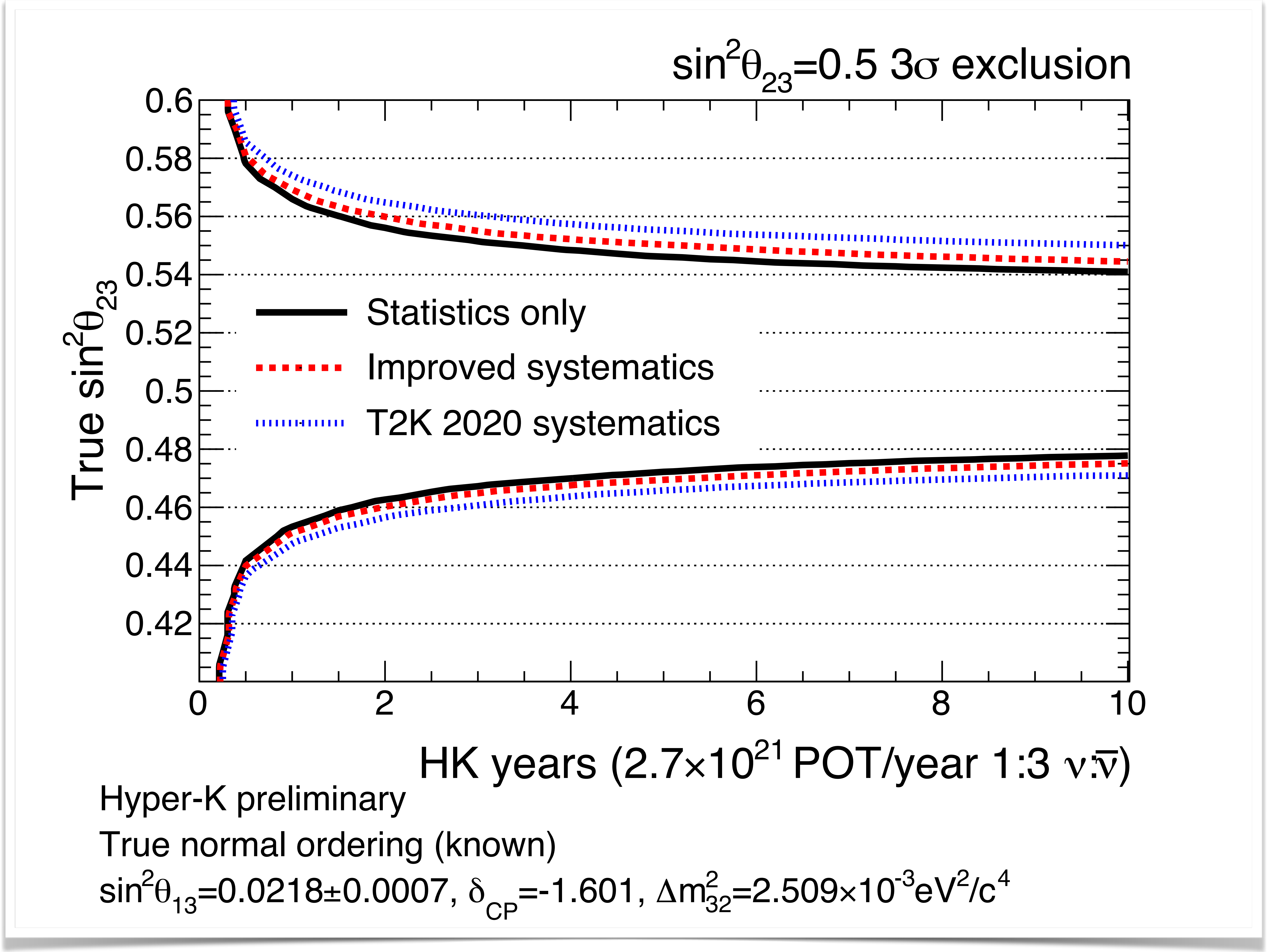
- How accurately can we measure the value of δ_{CP}, as a function of true δ_{CP}?



- With "Improved systematics ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)"
  - 20.2° for true $\delta_{CP} = -\pi/2 = -90°$
  - 6.3° for true $\delta_{CP} = 0$

$\sin^2(\theta_{23}) = 0.5$ exclusion sensitivity

- For a true value of $\sin^2(\theta_{23})$, how much can we exclude $\sin^2(\theta_{23}) = 0.5$?

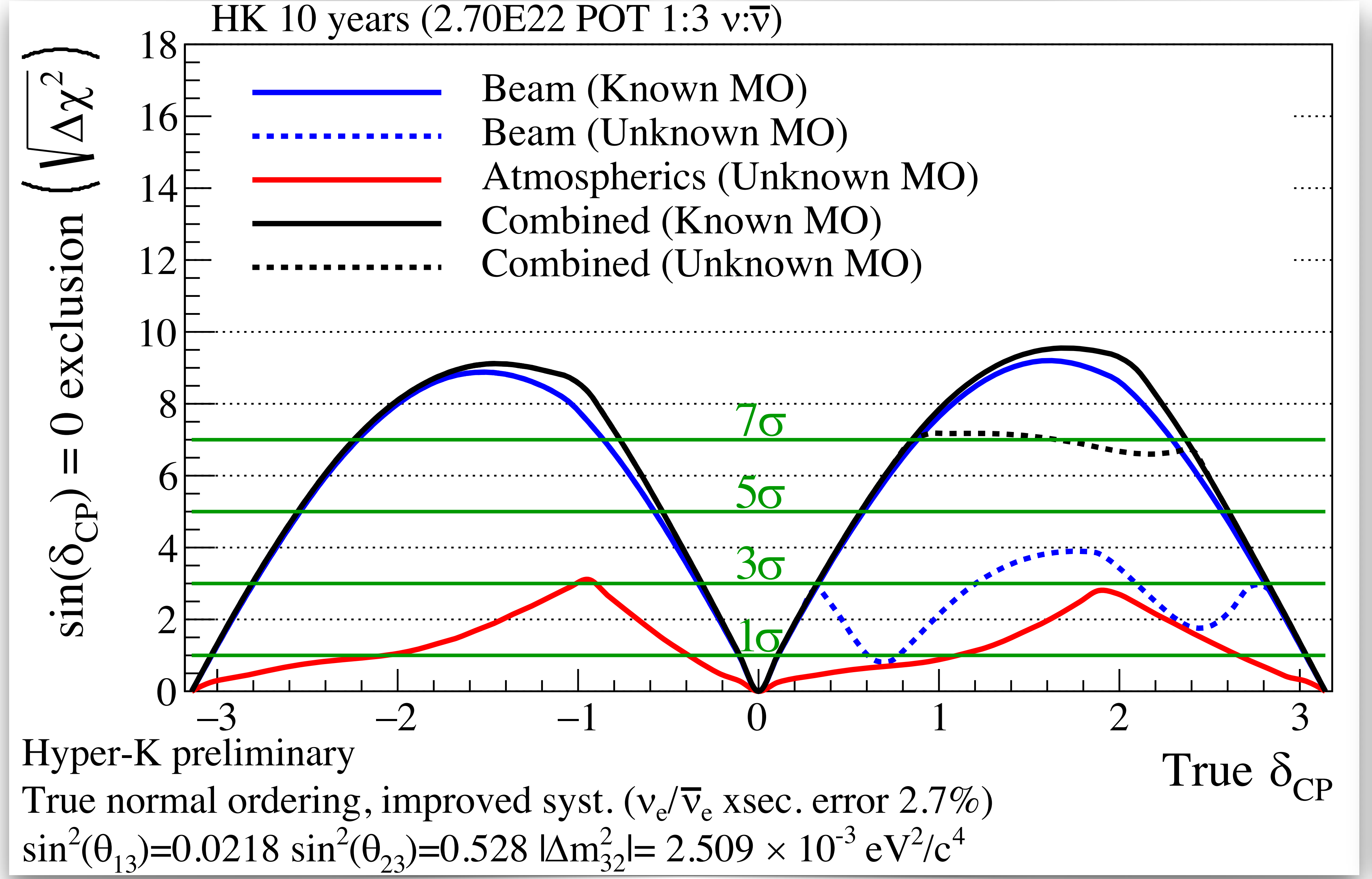


- With "Improved systematics ($\nu_e/\overline{\nu}_e$ xsec. error 2.7%)"
  - 3σ exclusion outside the range of true $\sin^2(\theta_{23})$ [0.475, 0.545]

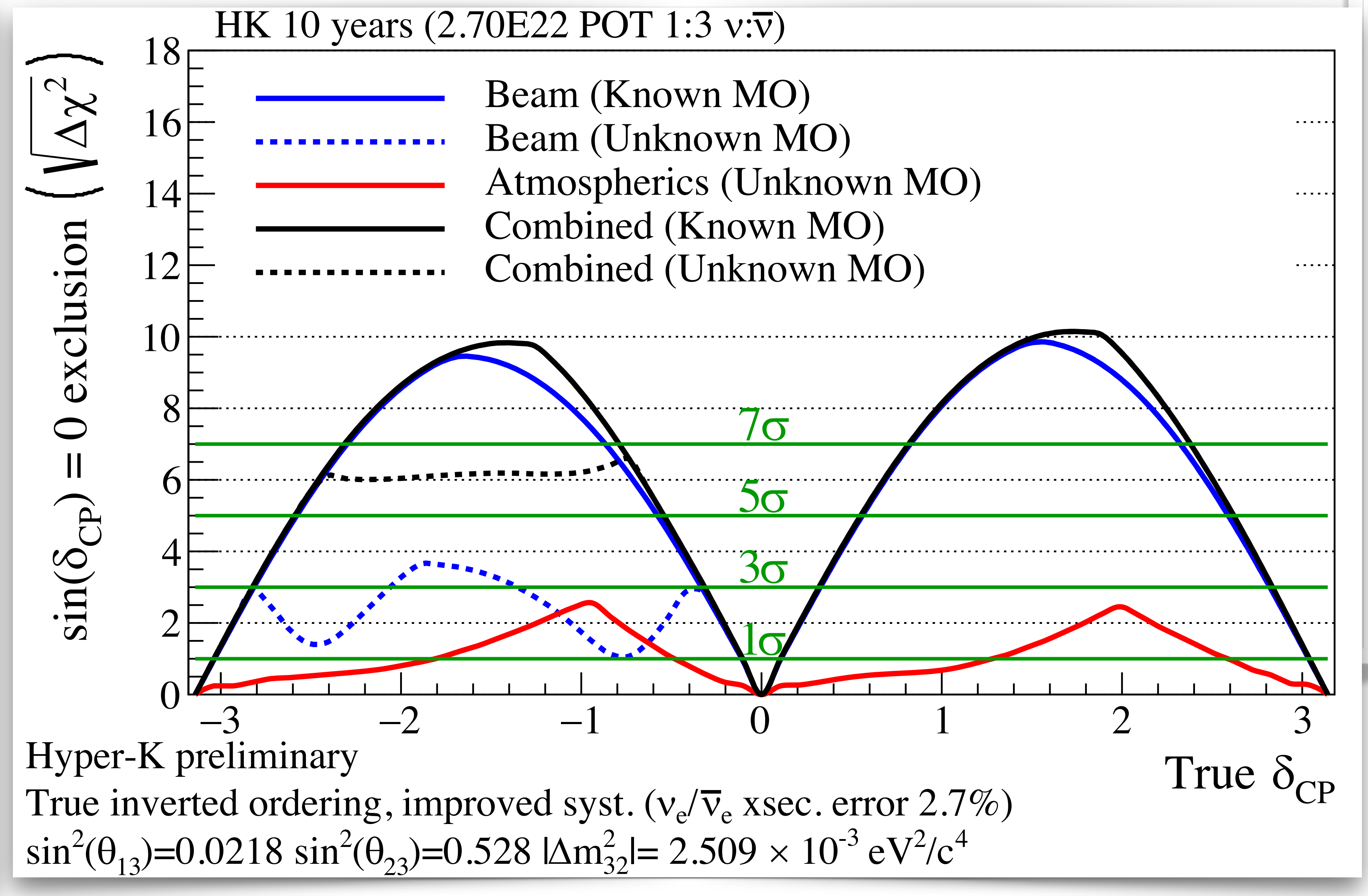
Adding Atmospheric Neutrinos

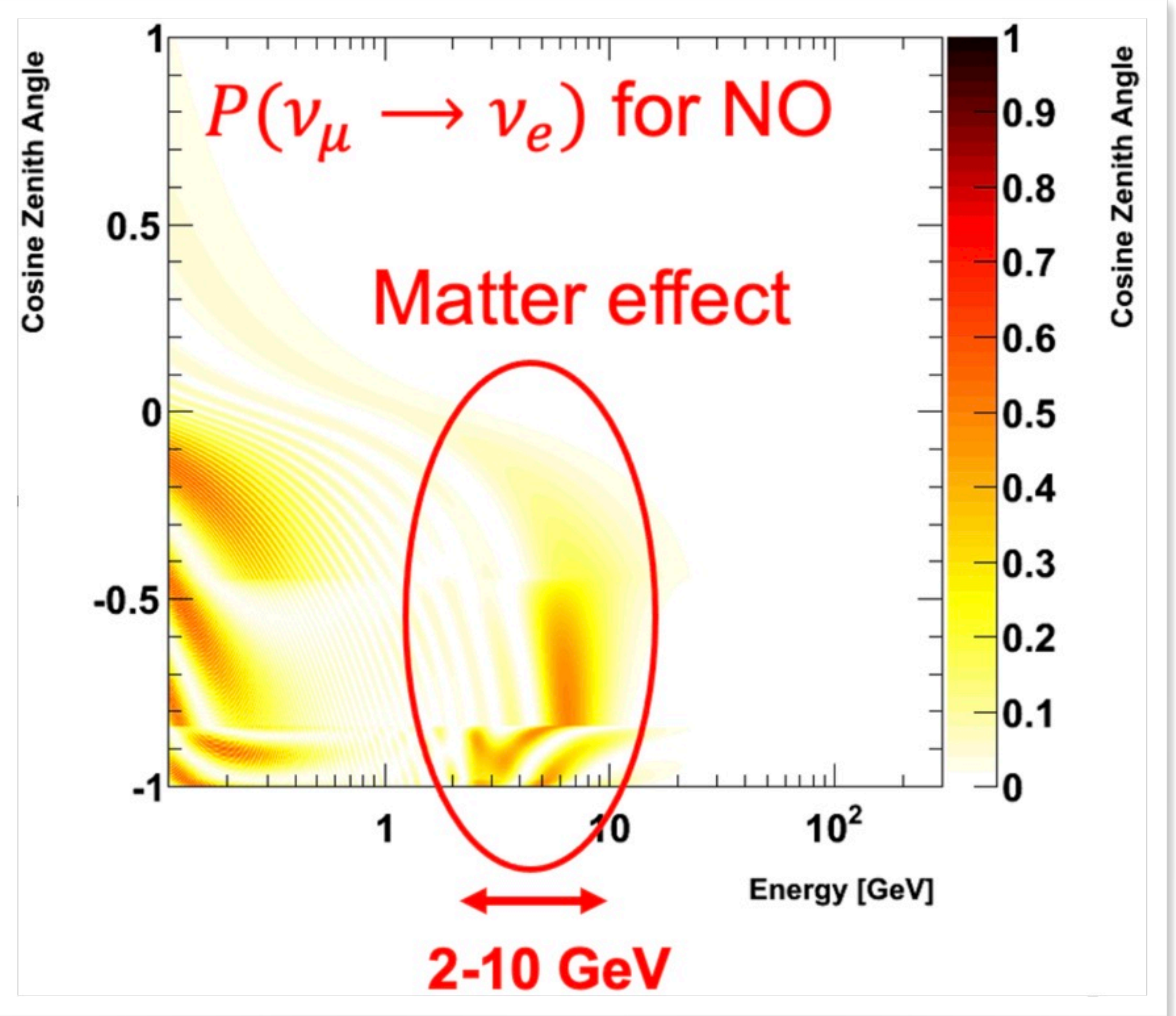
- Measurement of atmospheric neutrino flux direction [and energy] is sensitive to MO
- Propagation of atmospheric neutrinos through varying matter density profile of Earth. Enhancement of P($\nu_\mu \rightarrow \nu_e$) for NO and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) for IO
- Adding atmospherics can resolve mass ordering degeneraces.

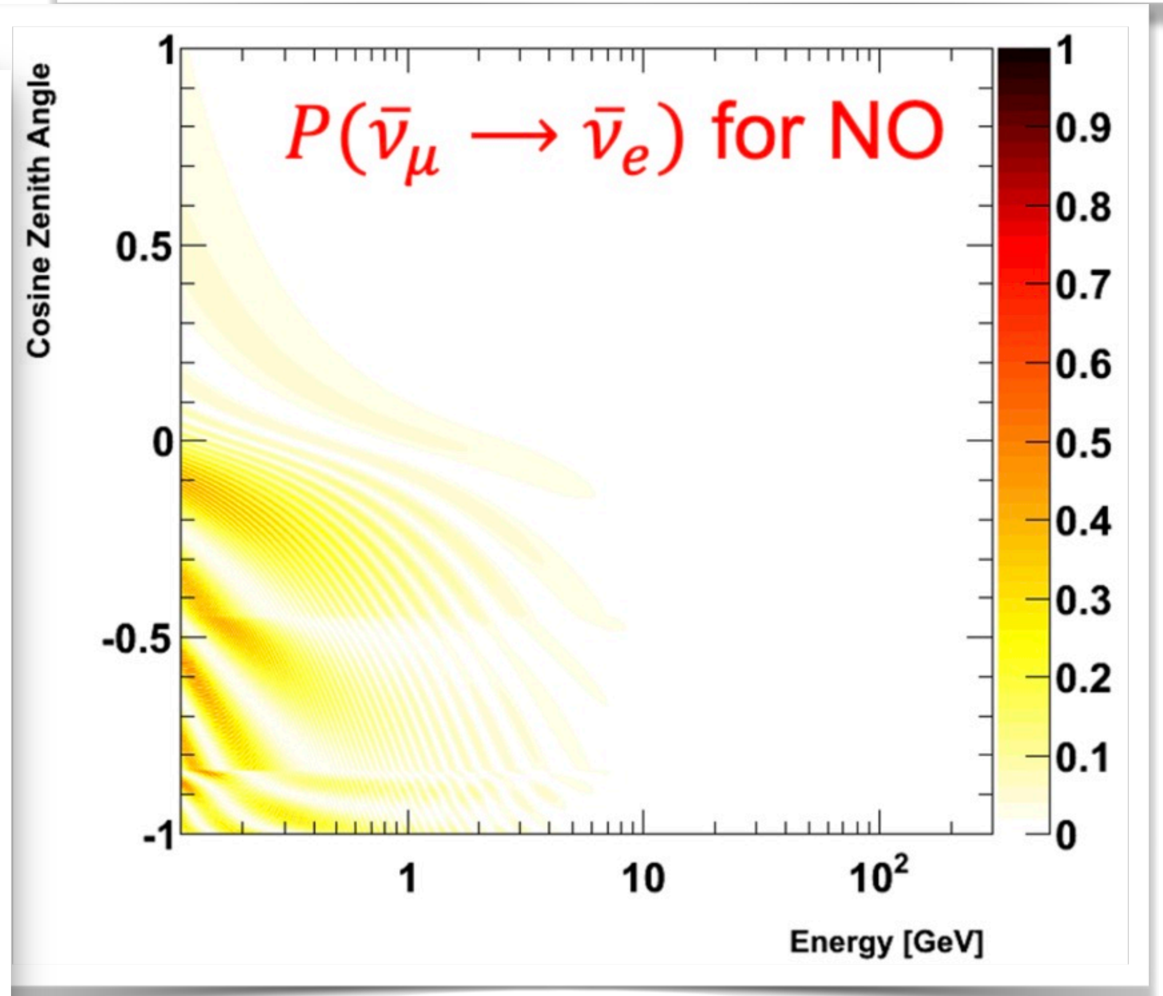
$\sin \delta_{CP} = 0$ exclusion as a function of true δ_{CP} for 10 HK-years and true NO



$\sin \delta_{CP} = 0$ exclusion as a function of true δ_{CP} for 10 HK-years and true IO





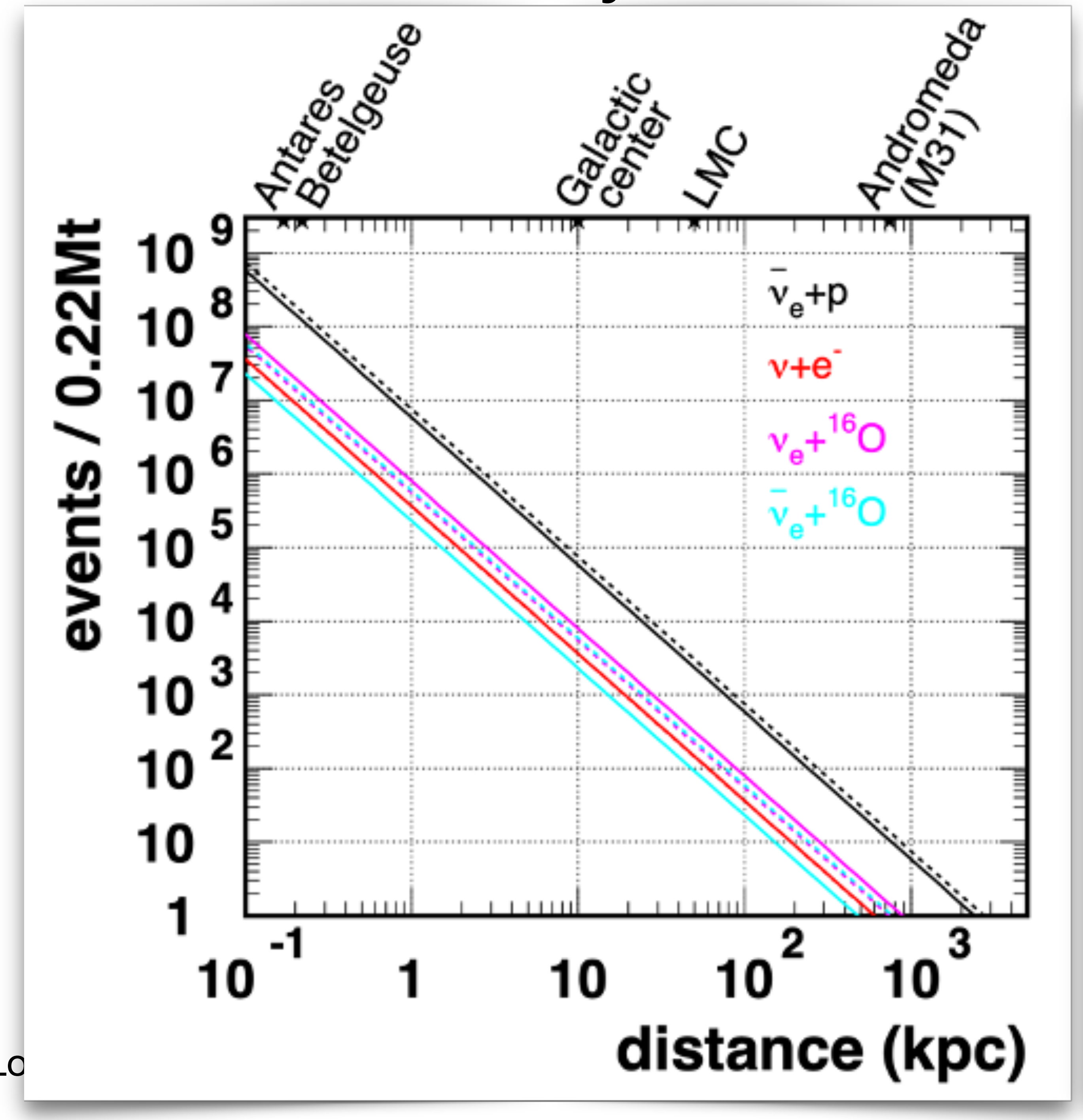


Super-K, Phys. Rev. D **97**, 072001

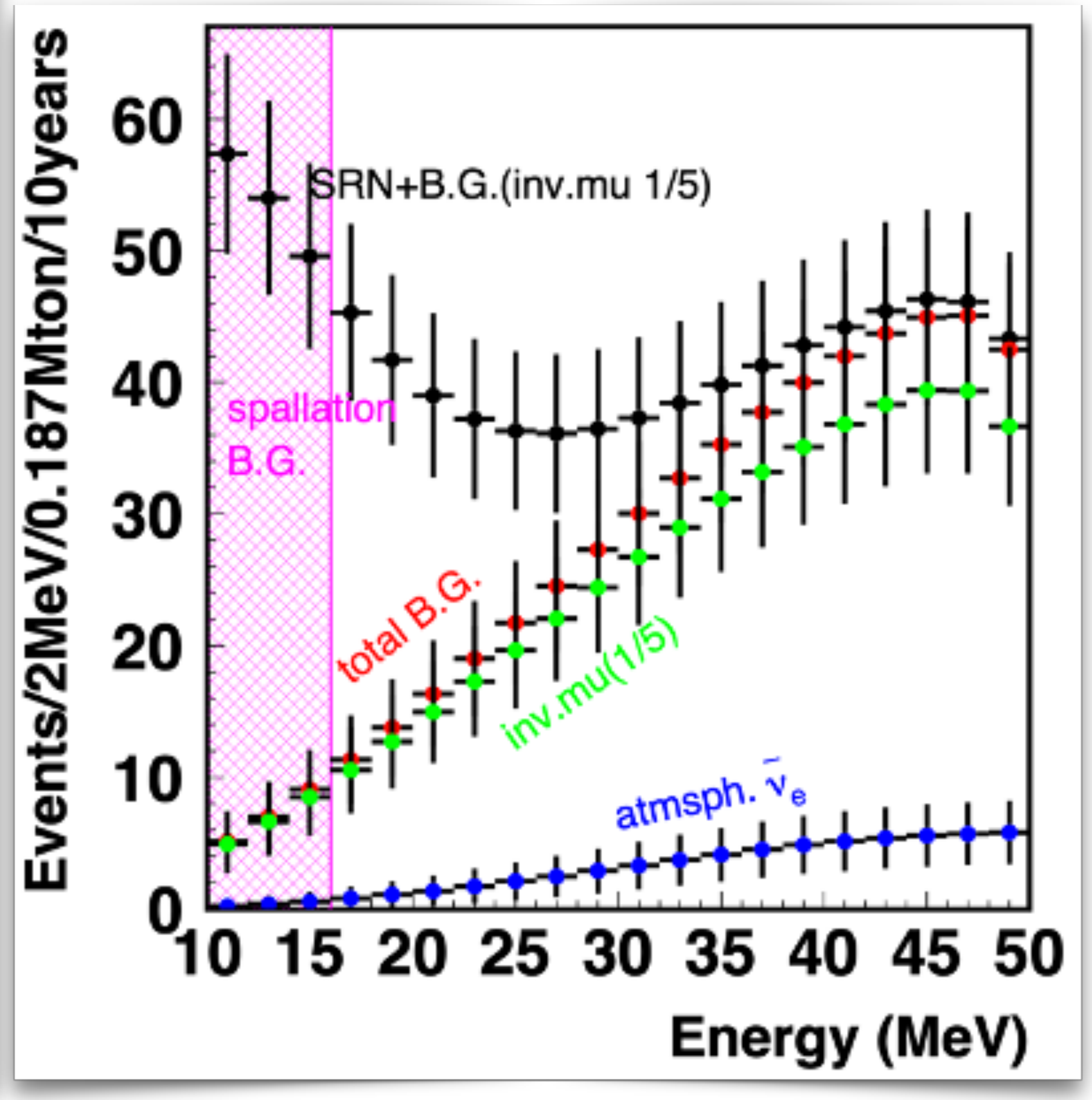
Matter effects appear in the antineutrino figure for IO.

Astrophysical Neutrinos: Supernova Neutrinos

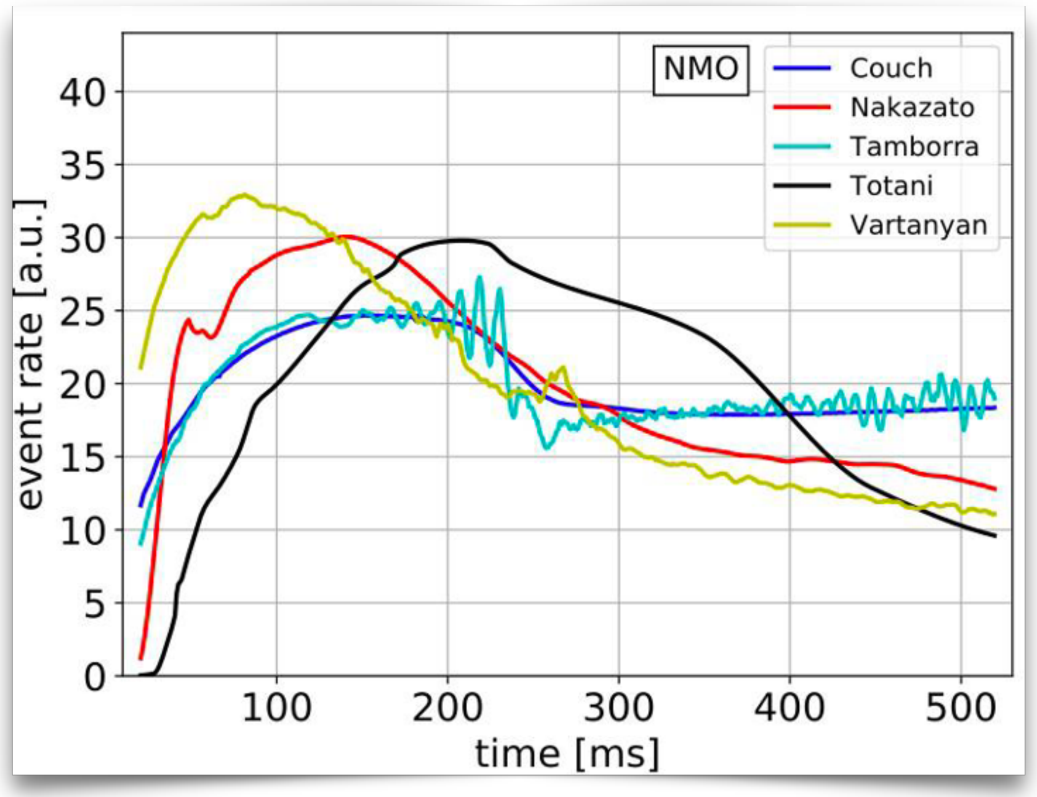
- Hyper-Kamiokande is sensitive to neutrinos from core-collapse supernova bursts and from integrated relic supernova neutrino background.
- Dominant signal: $\bar{\nu}_e + p \rightarrow e^+ + n$
- For a **supernova at 10 kpc**, many neutrino events above 7 MeV would be detected within a few seconds. SN direction accuracy 1°
- Study explosion mechanism and black hole/neutron star formation, model discrimination.
- Studying Supernova Relic neutrinos (SRN) provides information on stellar collapse, nucleosynthesis and the history of the universe.

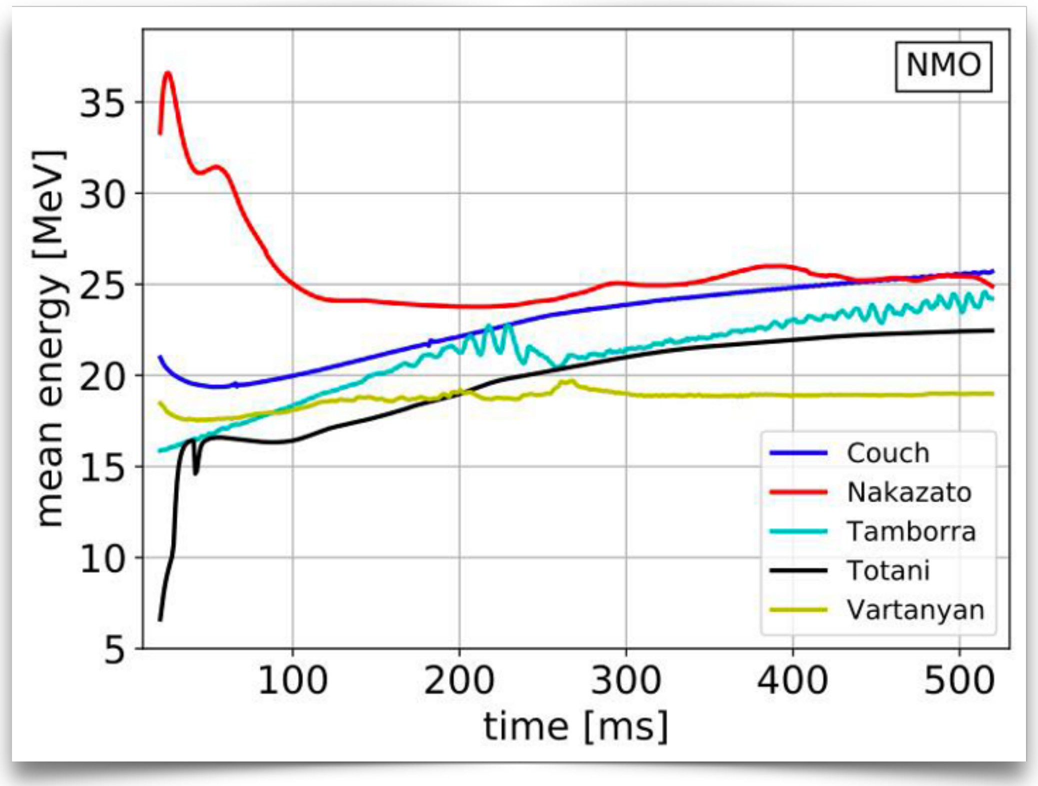


SRN with 67% neutron tag (10y)



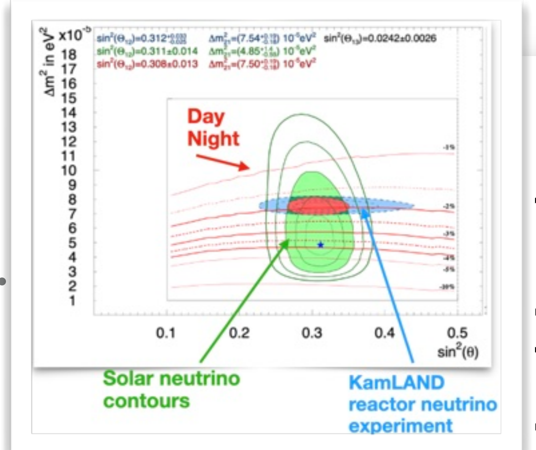
Supernova model discrimination with Hyper-Kamiokande: five supernova models were considered (K. Abe et al., Ap. J. 916 15 (2021))

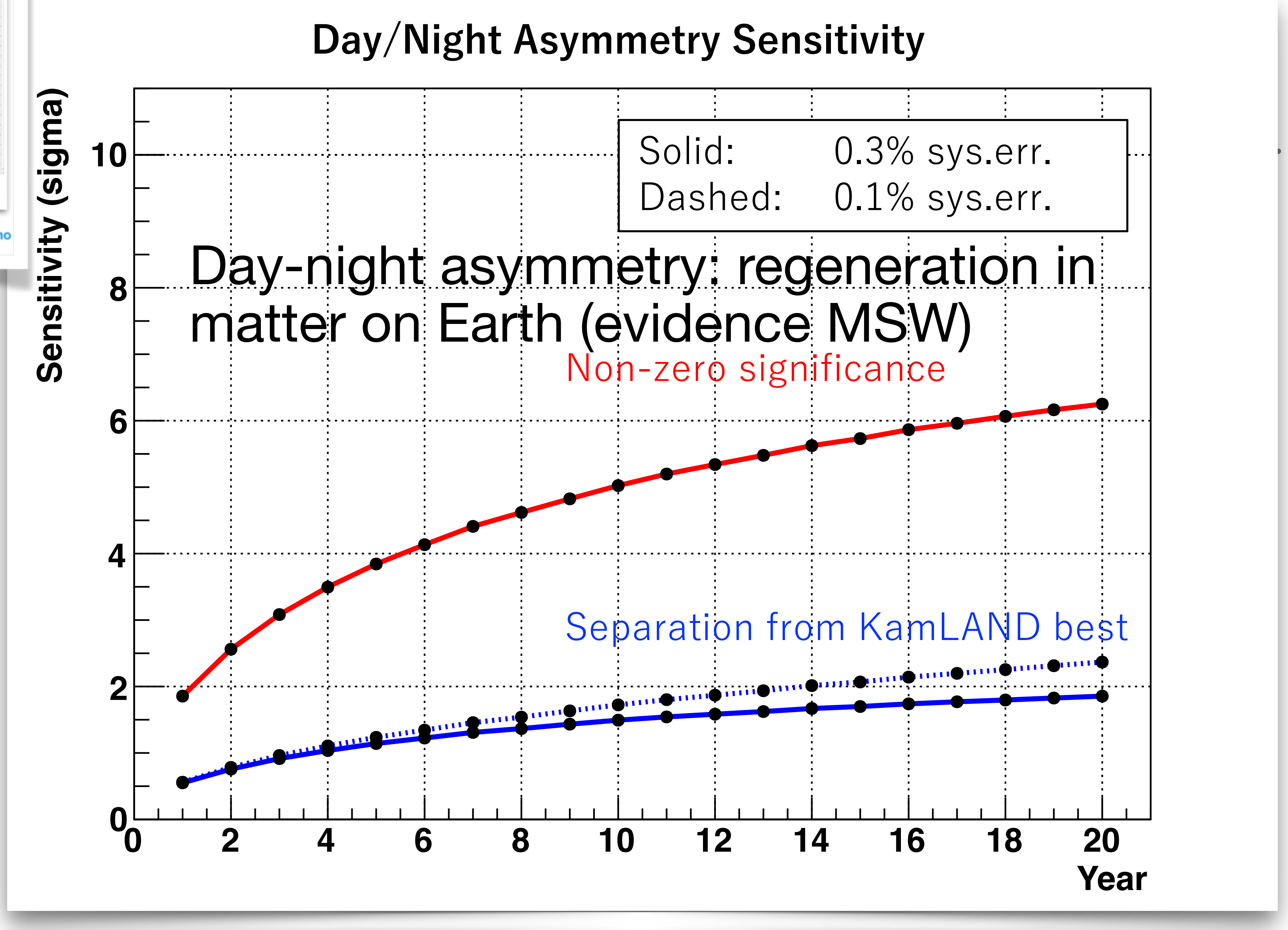


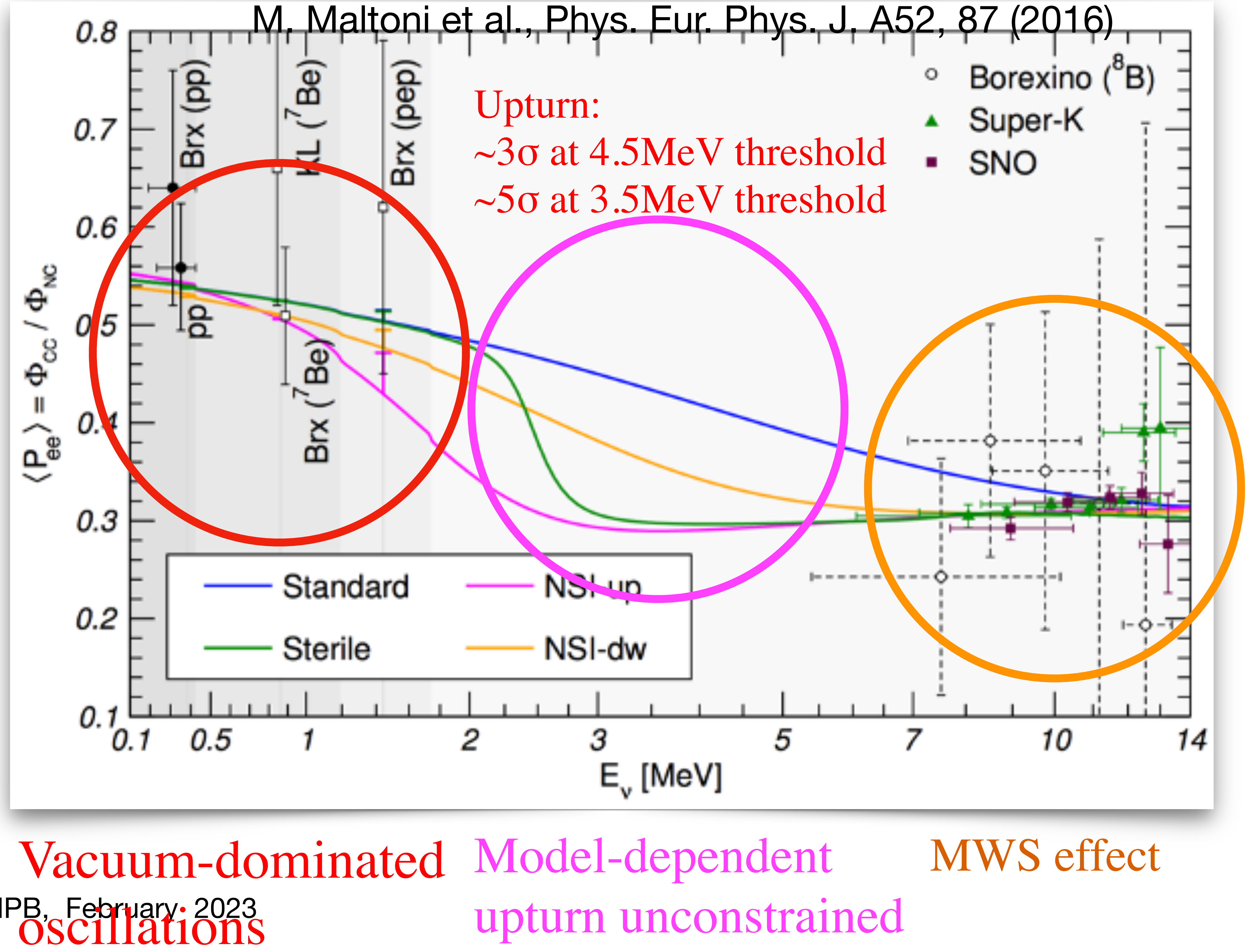


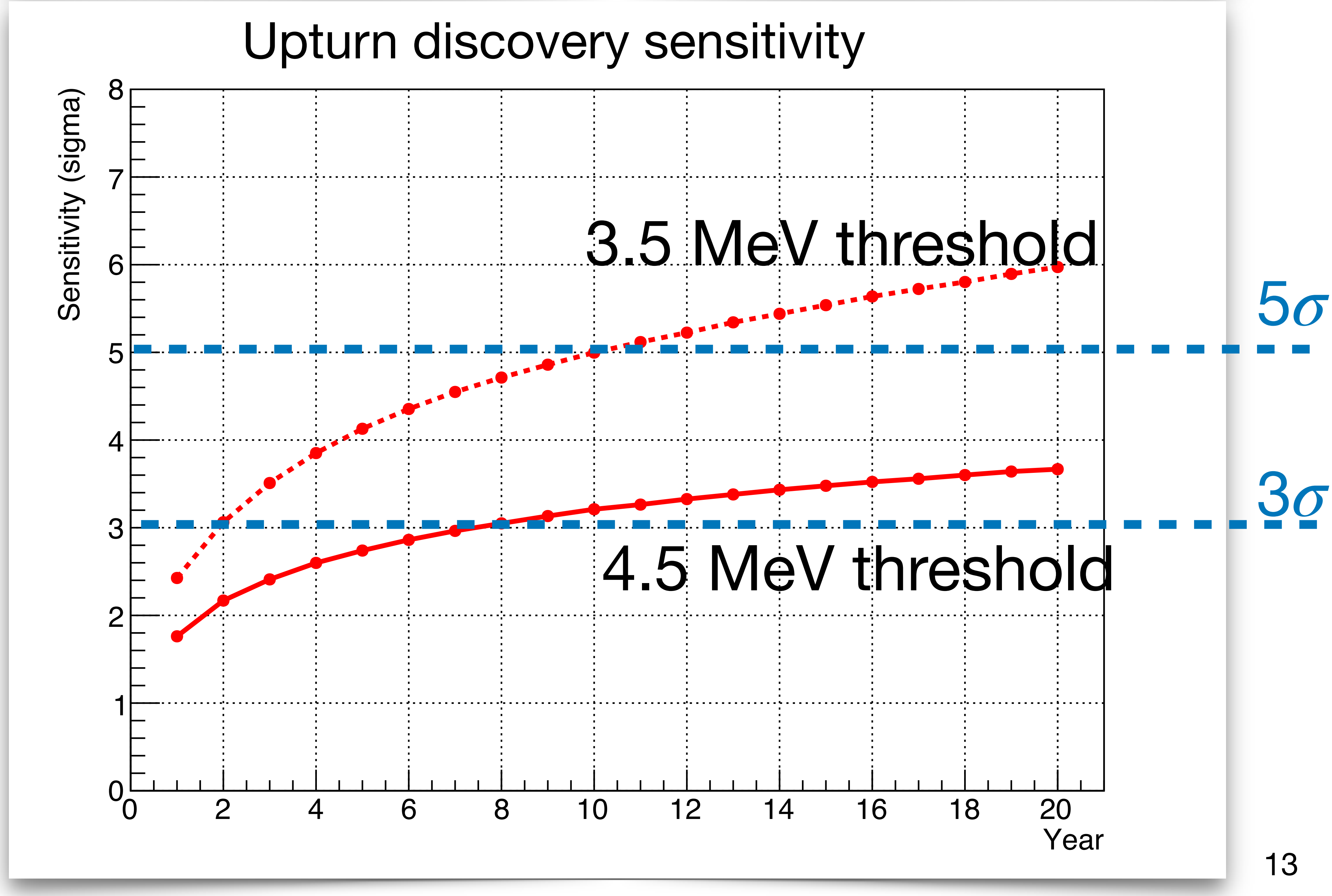
Solar Neutrinos

- Solar neutrino survival probability strong function of energy
- Sensitivity to new physics in transition region
- Hyper-Kamiokande will search for the up-turn and day-night asymmetry





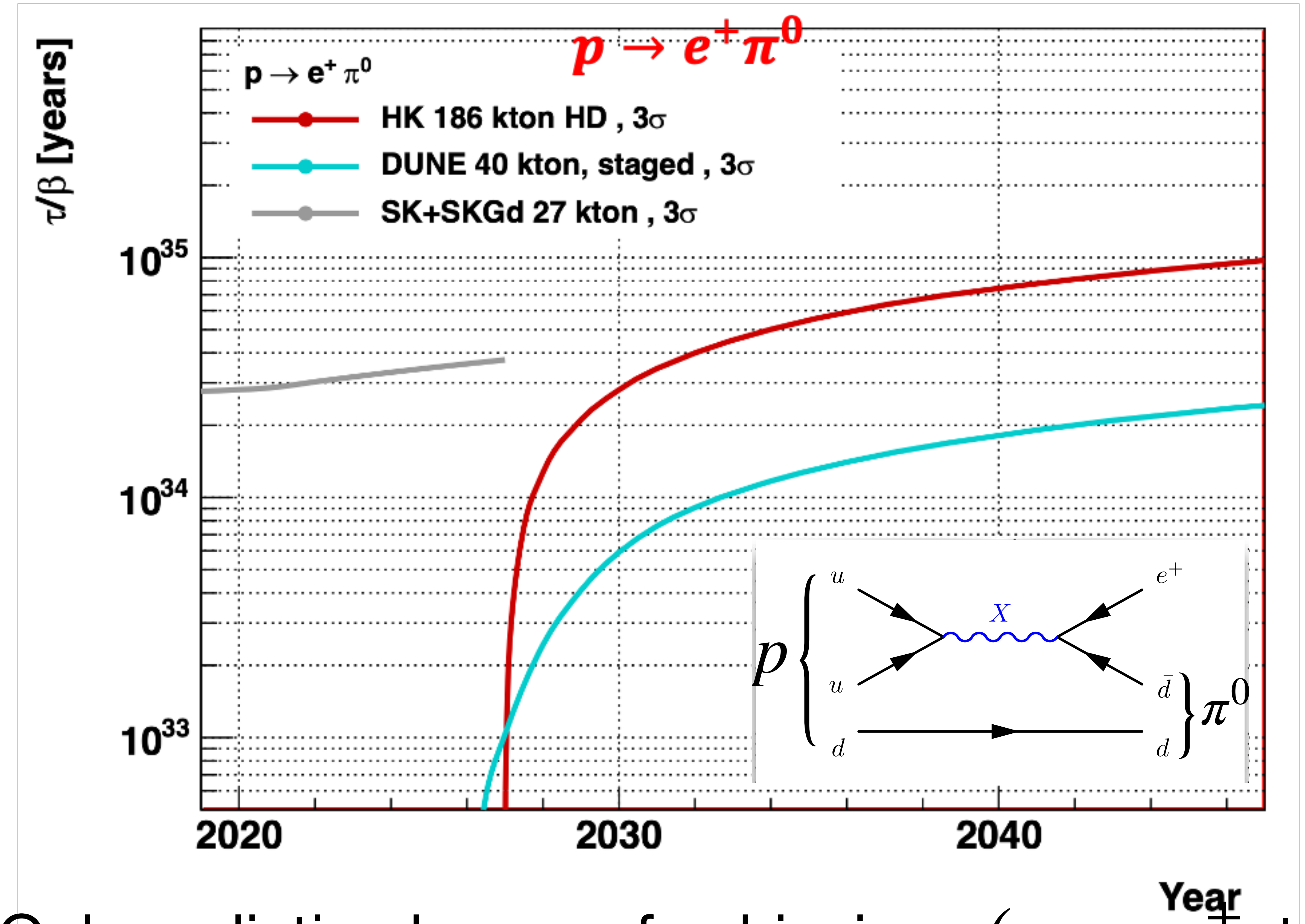


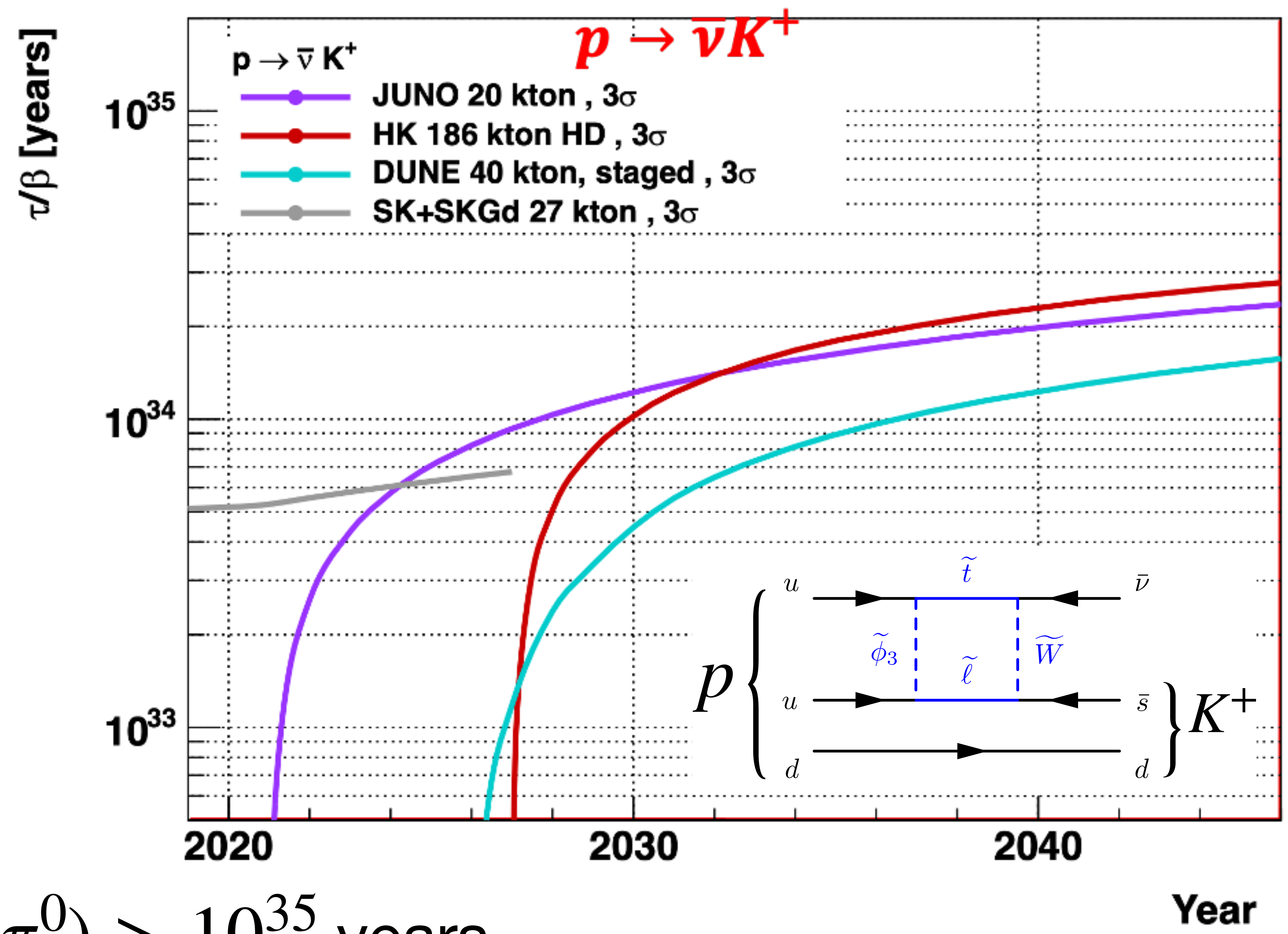


Proton Decay

Proton decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT).

Examples of proton decay sensitivity in two modes:





Only realistic chance of achieving $\tau(p \to e^+ + \pi^0) > 10^{35}$ years.

Similarly to Super-Kamiokande, Hyper-Kamiokande can study meson and leptonic final states.

Hyper-K Physics Summary

- “Multi-purpose experiment” sensitive to different neutrino physics.
- Wide energy span.

Timeline

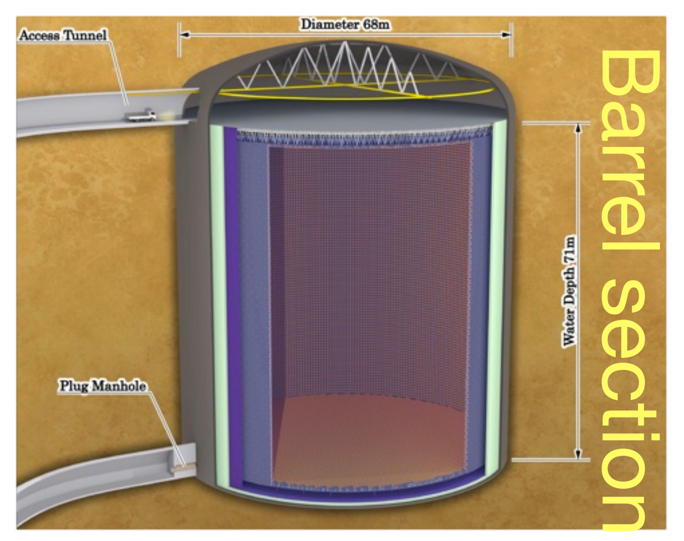
FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028
Preparation
Tunnel const.
Cavern excavation
Tank Const.
PMT Installation
PMT production
PMT covers, Electronics etc.
Water system
Filling water
Operation
Power-upgrade of J-PARC and Neutrino Beam-line
Near Detector Facility, R&D, production
ND construction
Accelerator upgrade

Cavern excavation

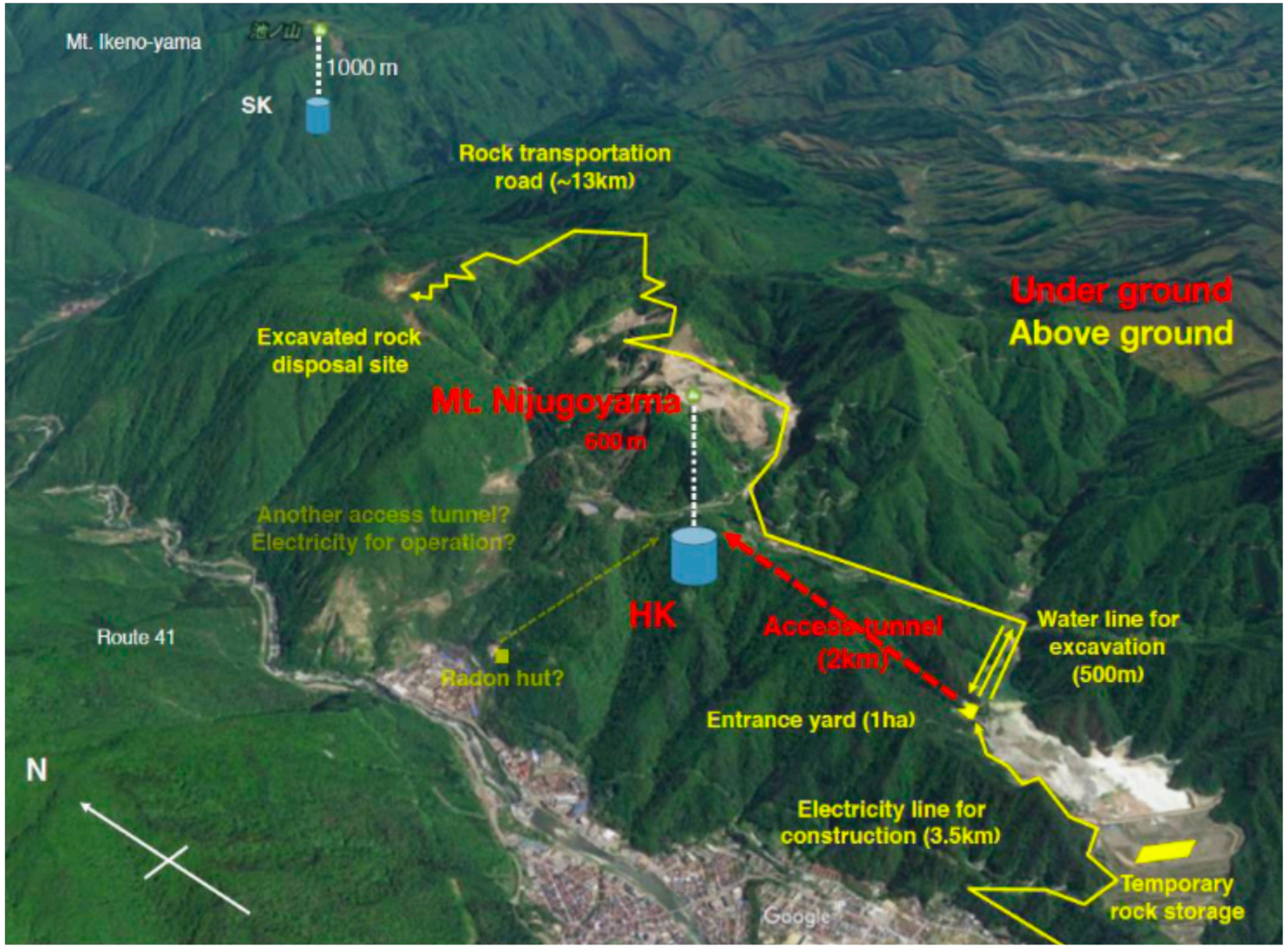
- Access tunnel excavation completed.
- Approach & circular tunnel excavation completed.
- Main cavern excavation has started on-time!

- October 3, 2023:
  - The excavation of the dome section was completed.
    - 69m diameter, 21m height.
  - Barrel section is ongoing (71m).
    - One of the largest human-made underground space.

Dome section



Barrel section



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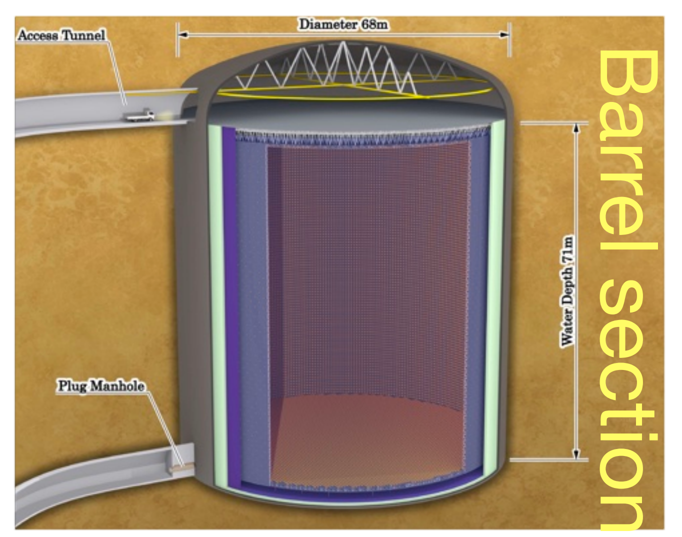
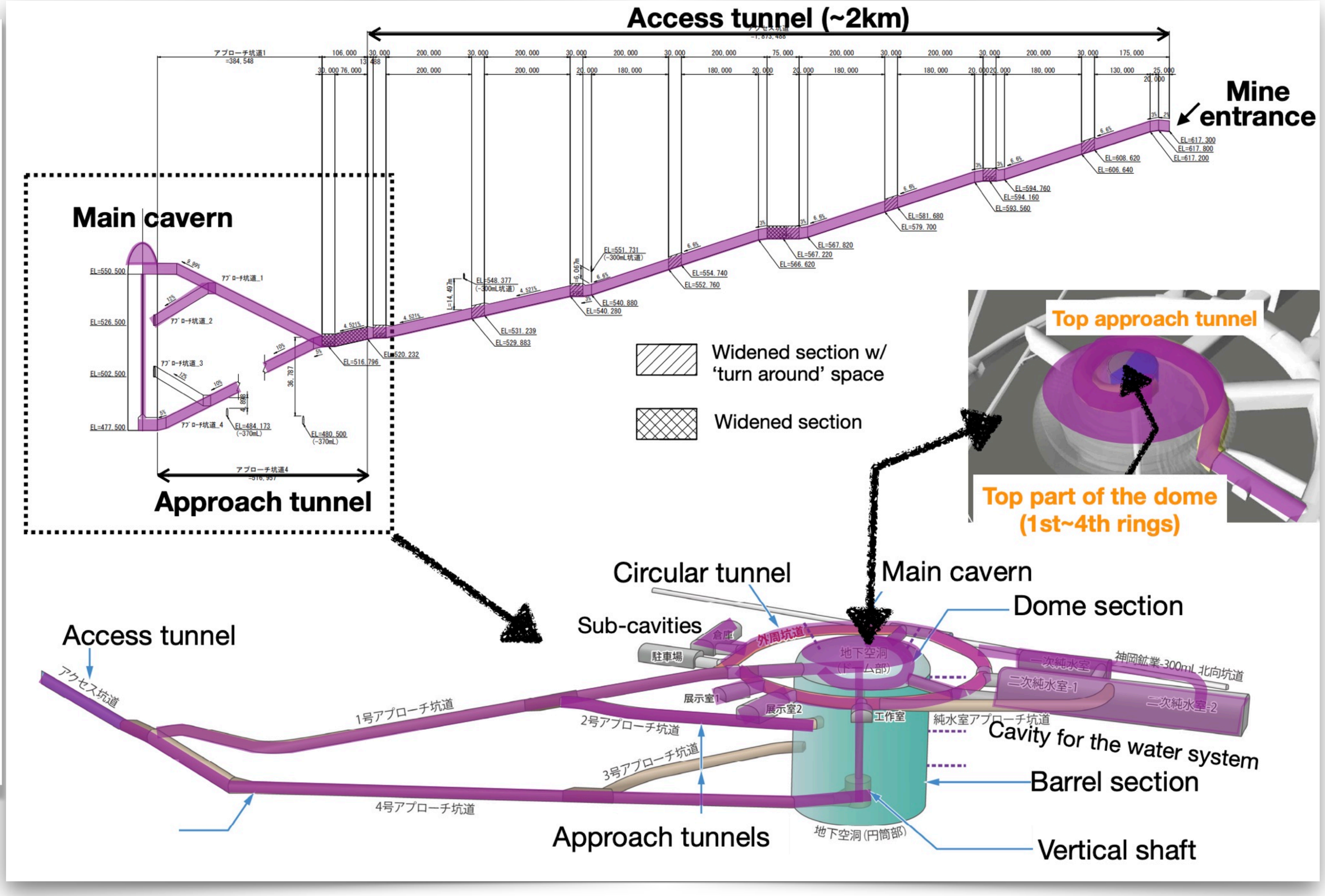
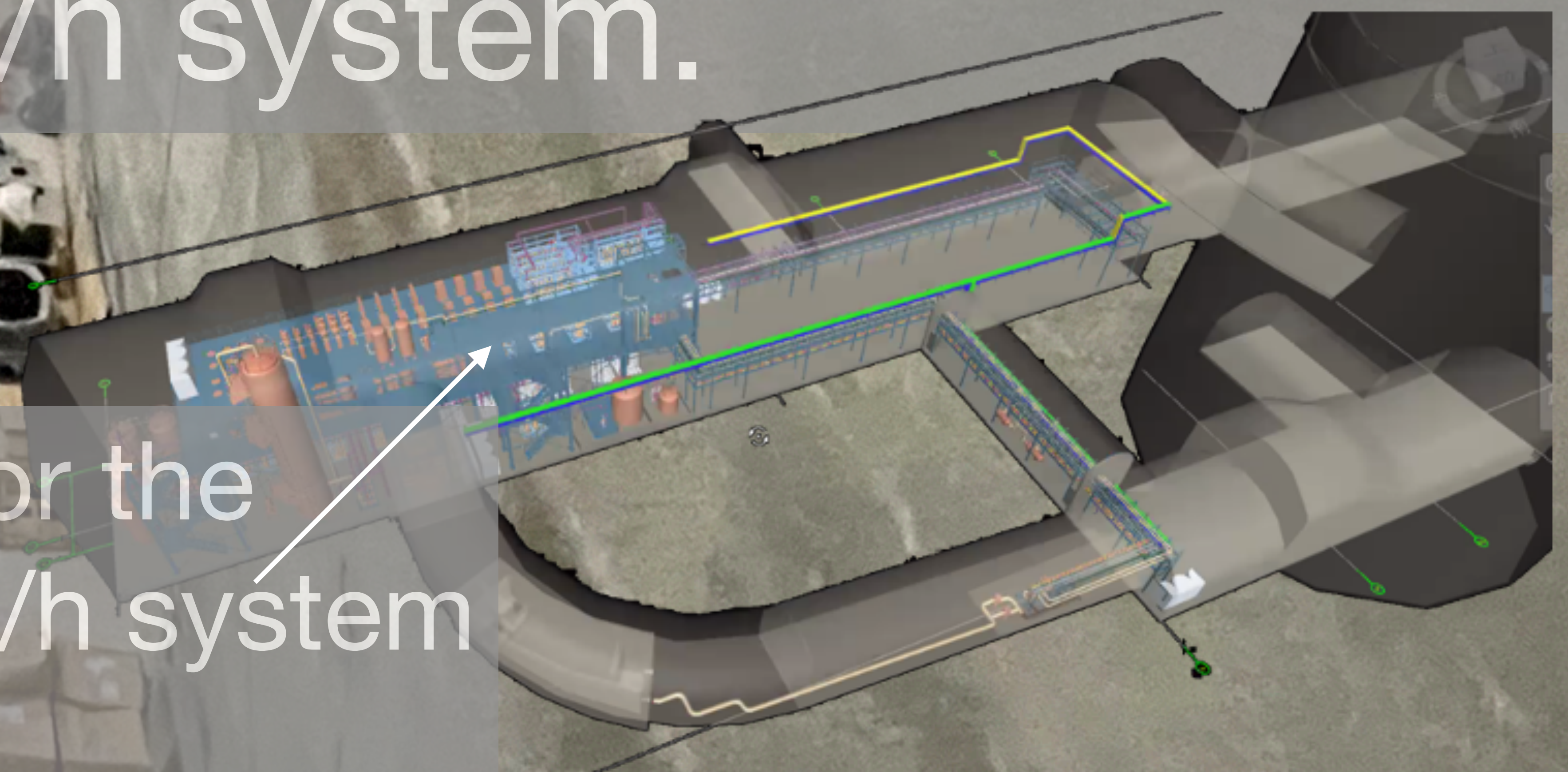




Water System

View from this direction.

- Completed room excavation on May 18, 2023.
- Basic design ready of the initial 155m^3/h system.



The layout for the initial 155m^3/h system

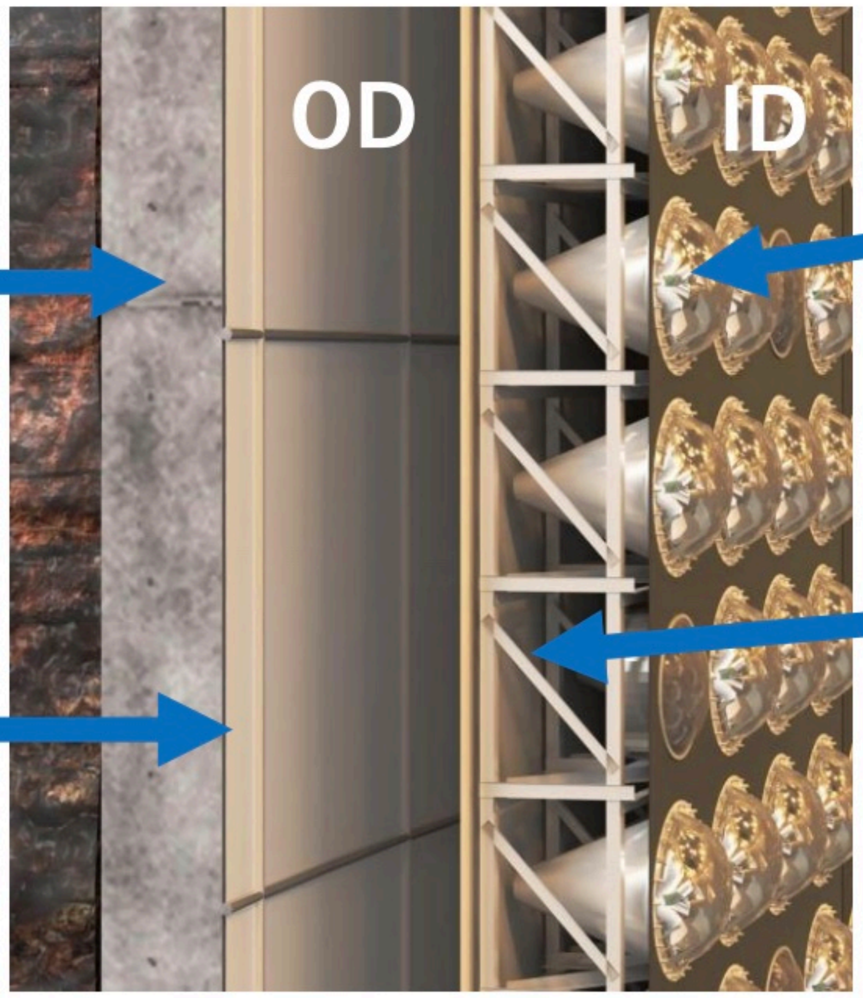
Far Detector

Construction of the water tank, PMT support structure, and infrastructures by Japan

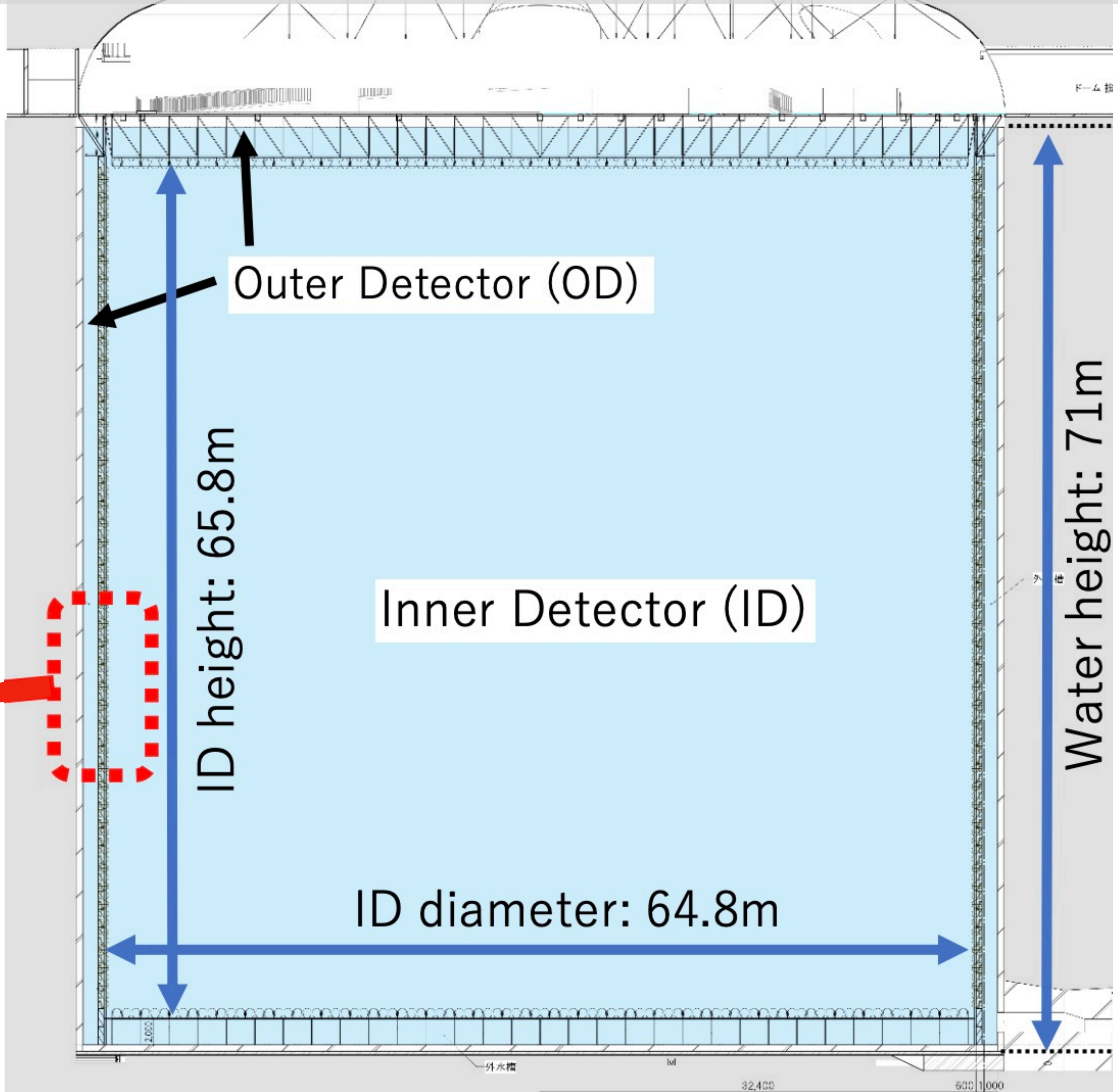
Size of the water tank.

Tank size	Φ68 m × H 72 m
Water height	71 m
ID volume	216.9 kt
Fiducial volume	188.4 kt
ID surface	19991.1 m^2

OD=Outer Detector ID = Inner Detector

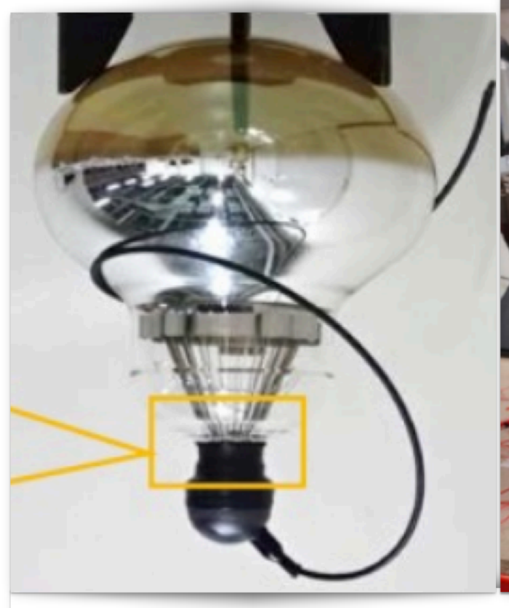


258 kton volume water Cherenkov detector
- 216 kton inner detector (~188 kton fiducial volume)
- 1 m thick outer detector used as a veto region
- Optically separated using high reflectivity Tyvek sheets

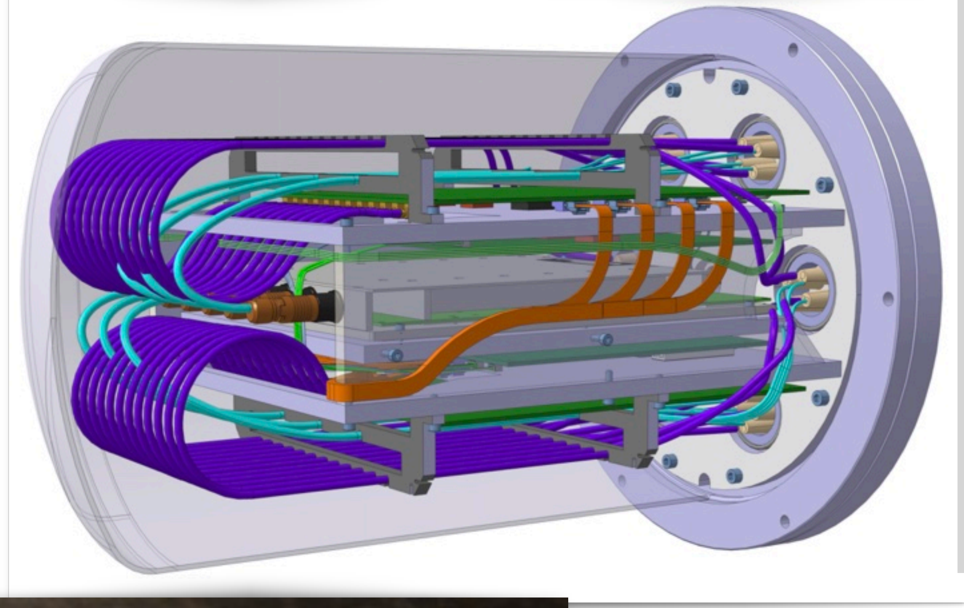


Tank Frame

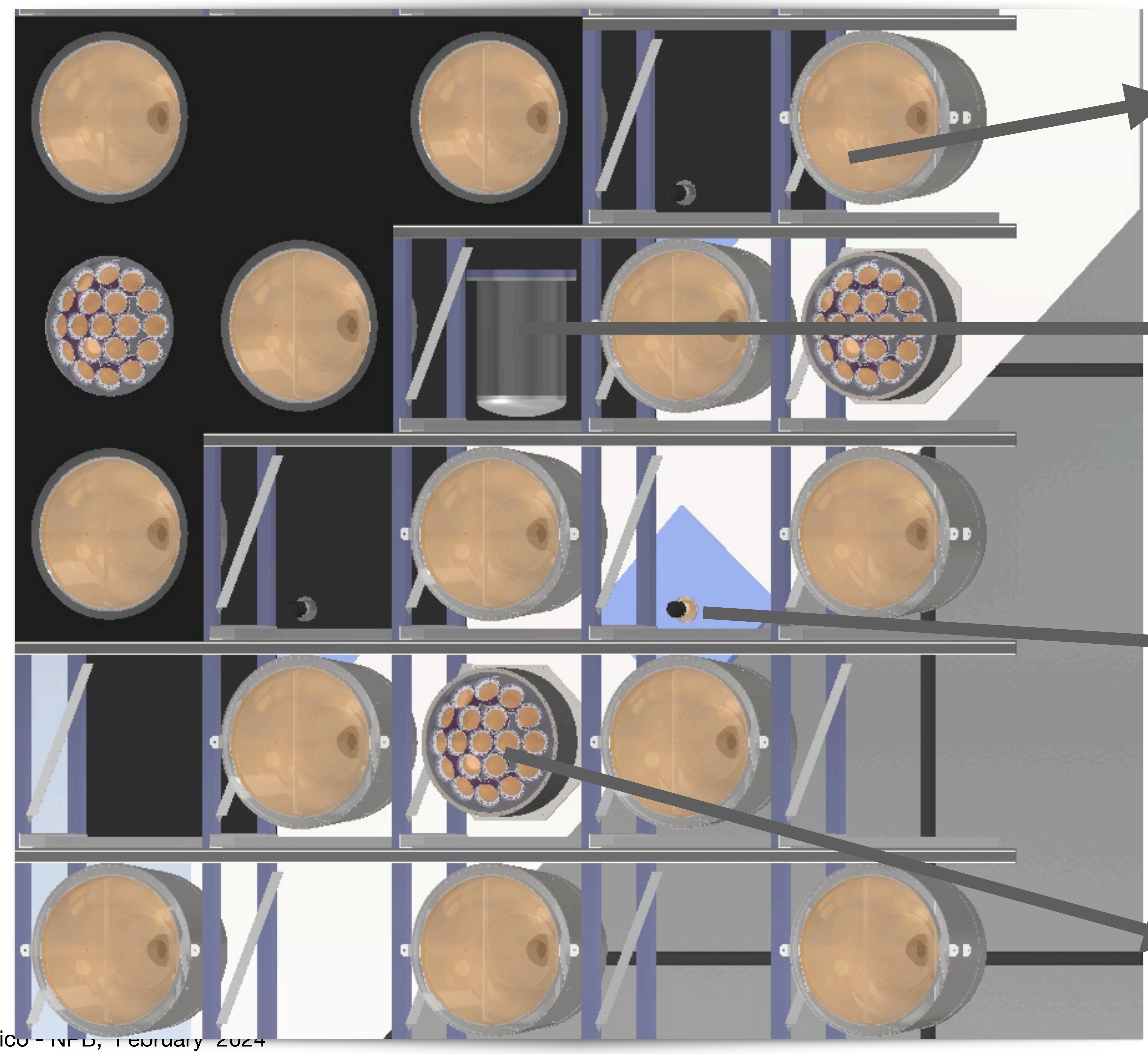
Mockup (Kashiwa,



Implosion tests ongoing to choose PMT cover.



Underwater vessels with electronics boards (ID, ID+OD)



50cm PMTs

#20,000

ID+OD Electronics

#~1,000

OD

#3,600

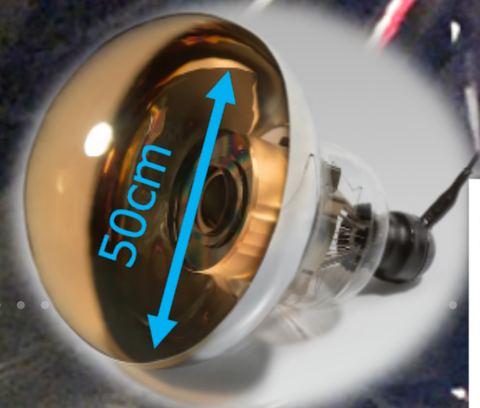
mPMTs

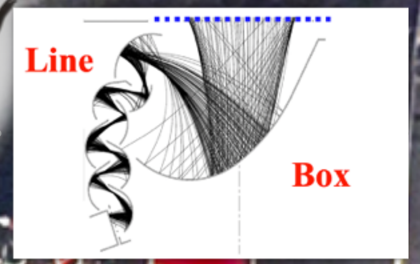
#~1,000

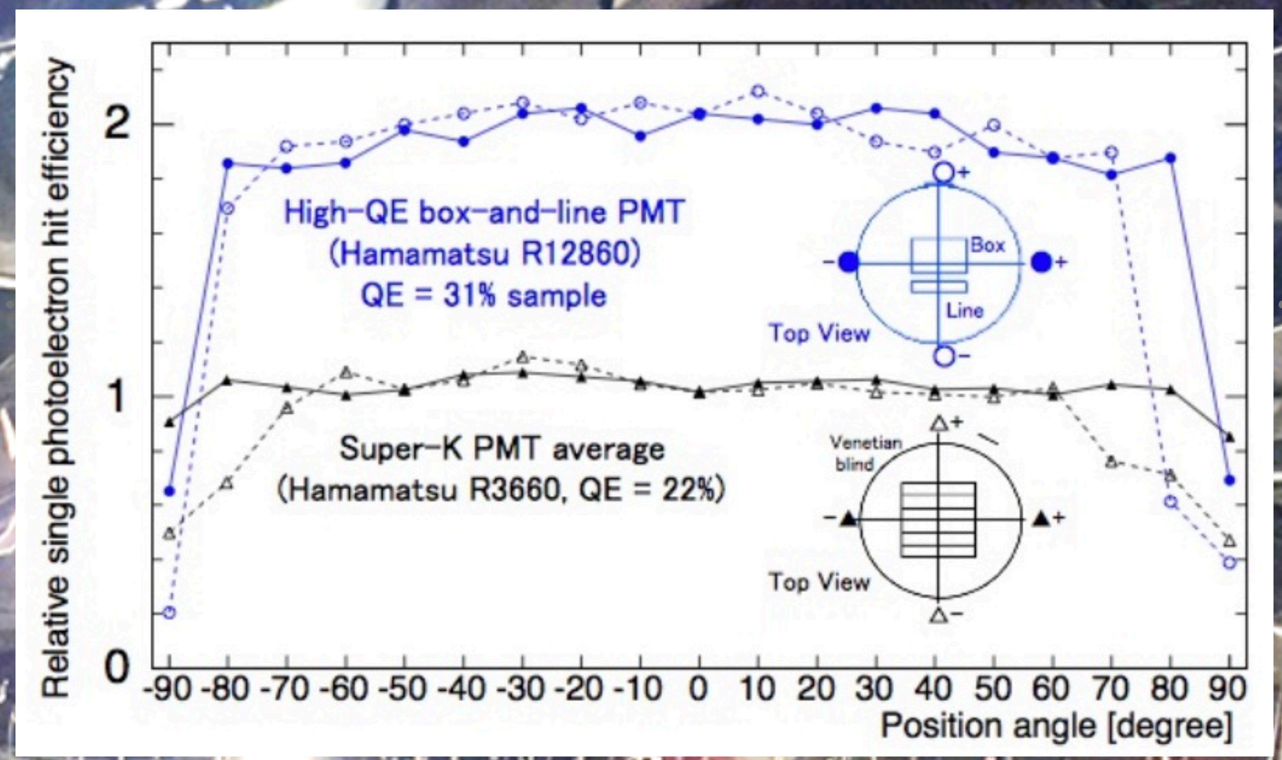
Full OD system includes 3” PMTs, WLS plate and high reflective Tyvek.

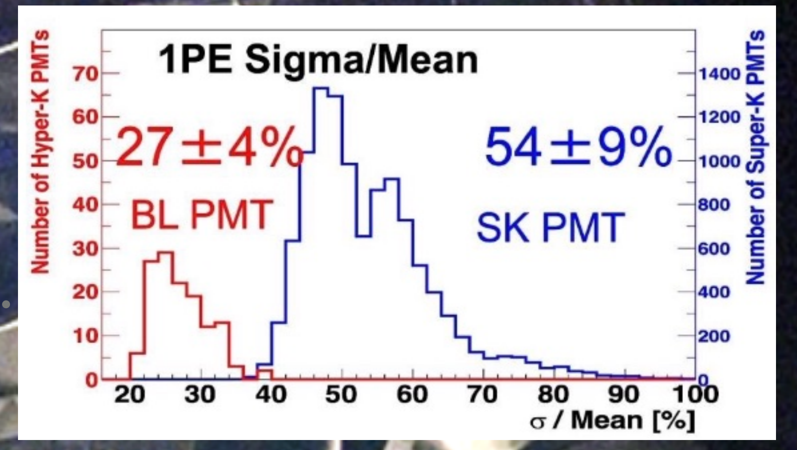
mPMTs provide improved timing and direction resolutions

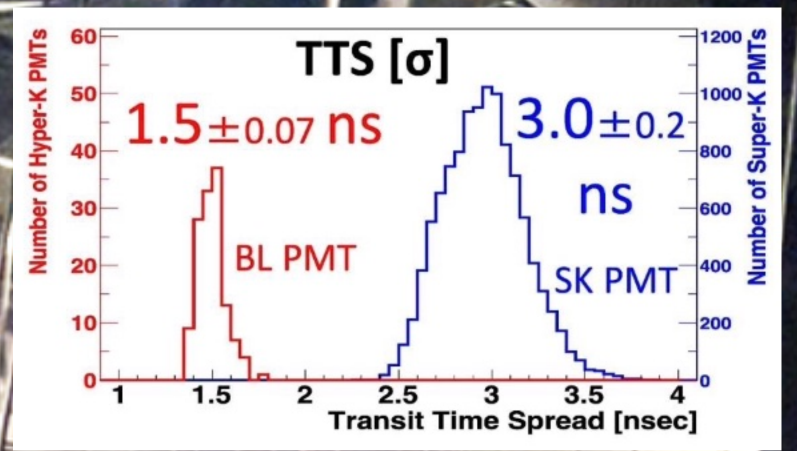
Inner Detector









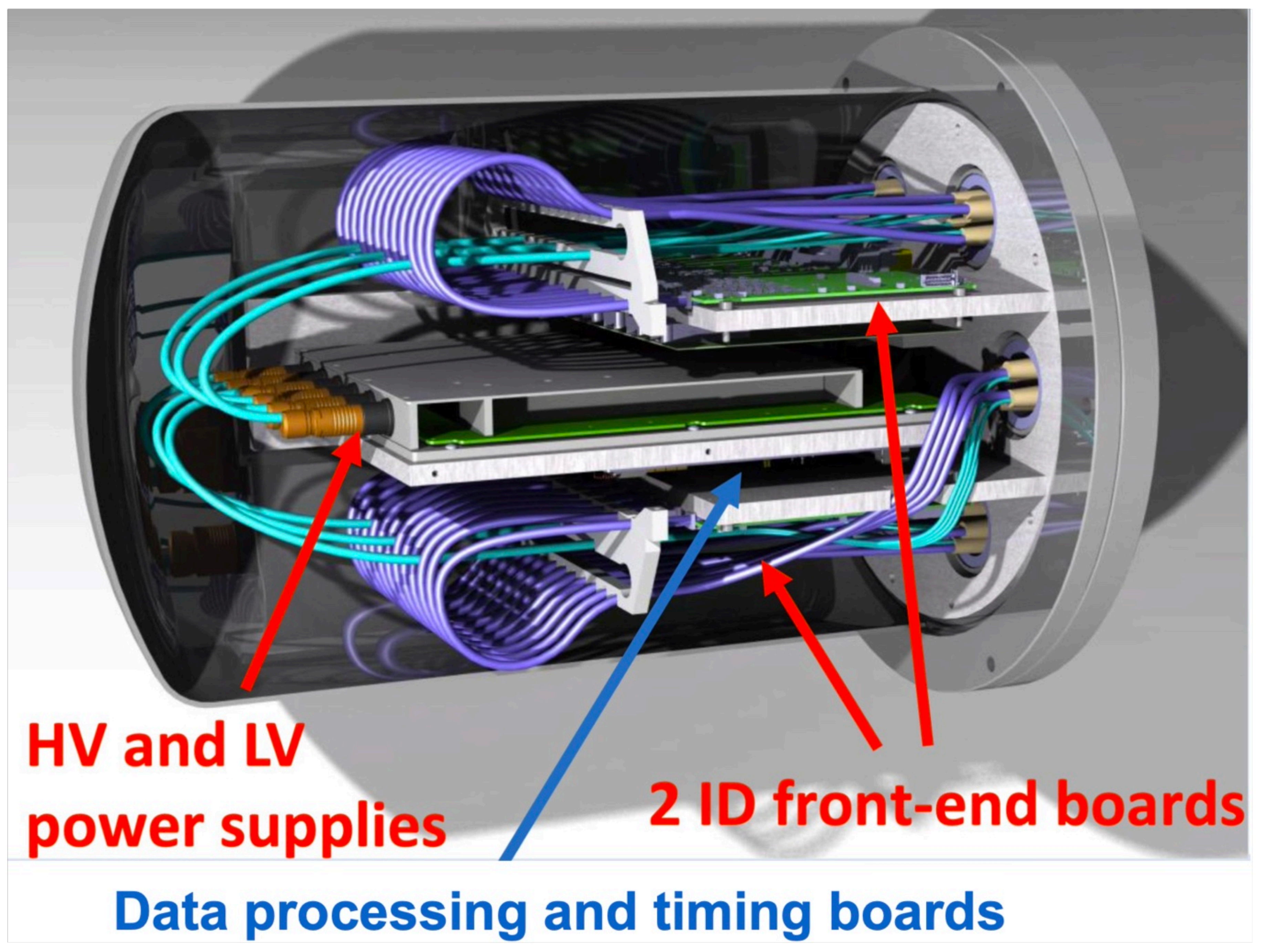


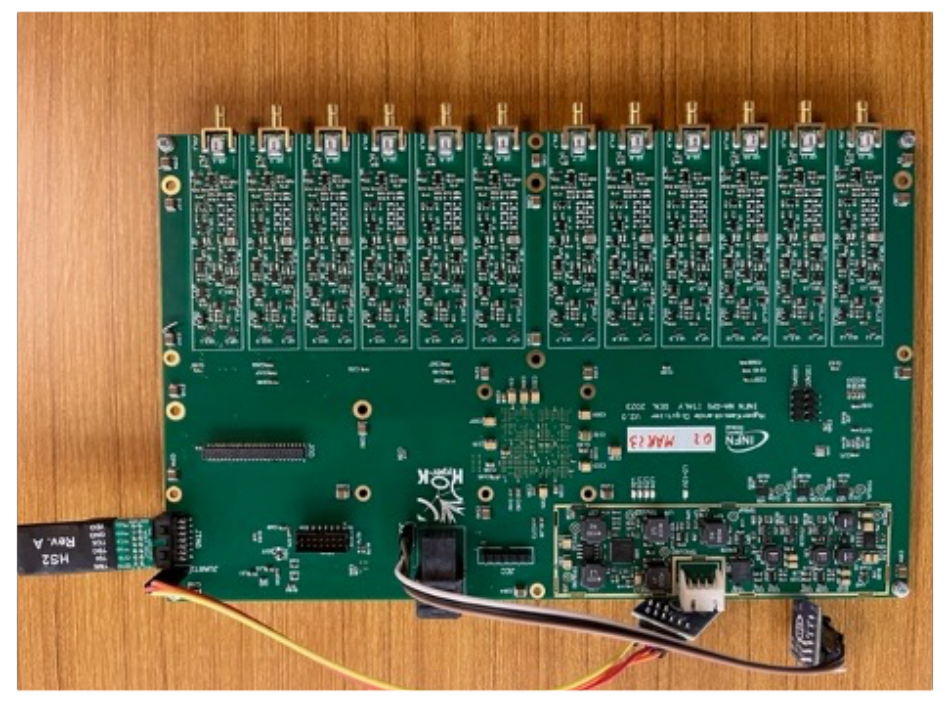
- Production started in Dec 2020, halted in March April 2022.
- Year 2022: Improved design and quality check
- Production resumed in May 2023.
- The completion of the delivery date is unchanged.
- Collaboration's shift for mass test
- Constant quality inspections at Kamioka are ongoing. >6,000 PMT delivers so far.

- x2 better photodetection efficiency
- x2 better charge resolutions
- x2 better time resolutions
- Low dark rate (4 kHz)
- X2 better pressure tolerance; enable deeper tank design

Hyper-Kamiokande Electronics

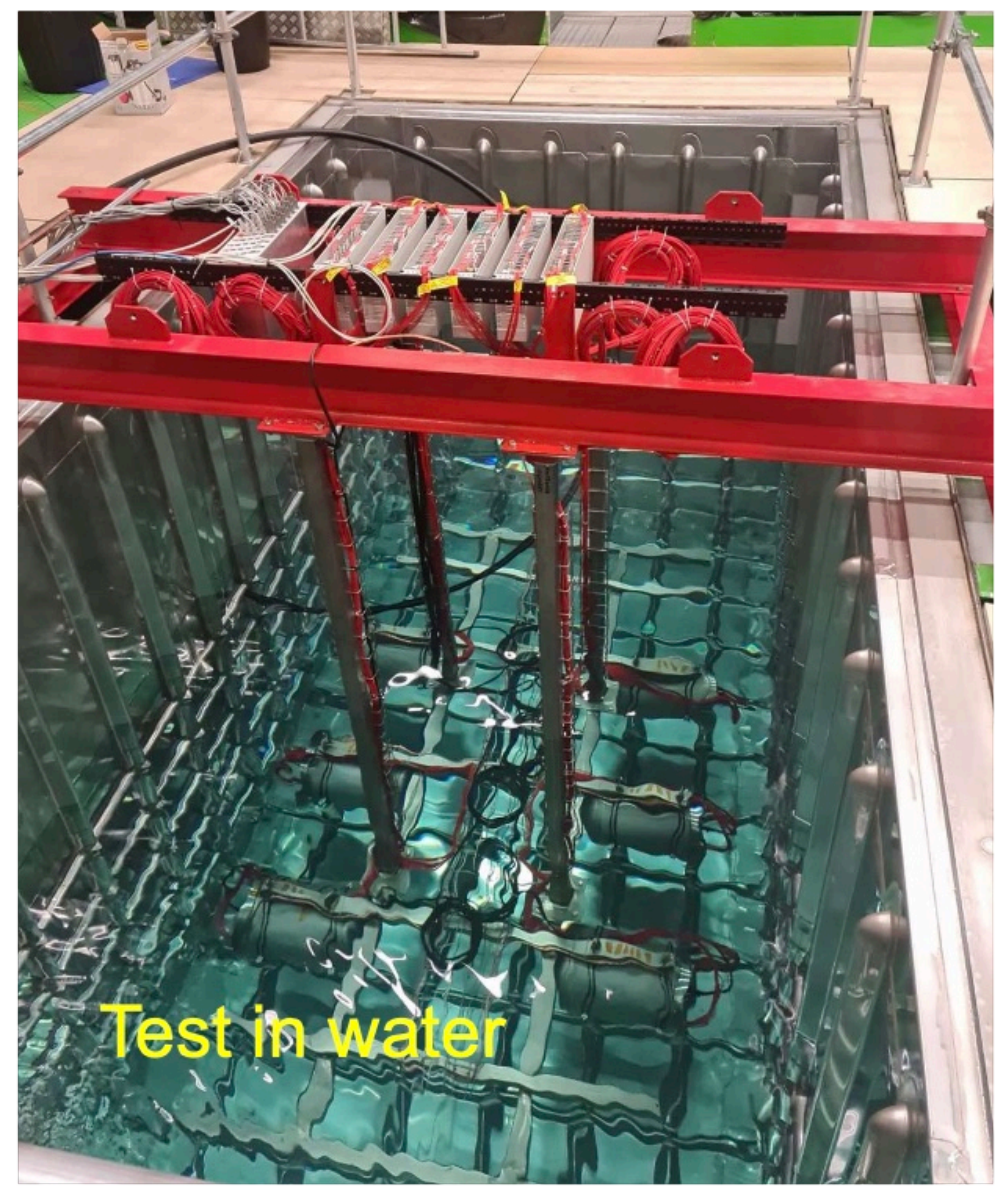
- Front-end electronics placed in underwater vessels
- Two types of underwater electronics vessels
  - ID vessels: 24 ID channels read out by two PCBs
  - Hybrid ID + OD vessels: 20 ID + 12 OD channels
- Custom design of Digitizers, DPB, OD HV/signal splitter, timing boards will be finalised
- Module assembly planned at CERN (~2025-2026)

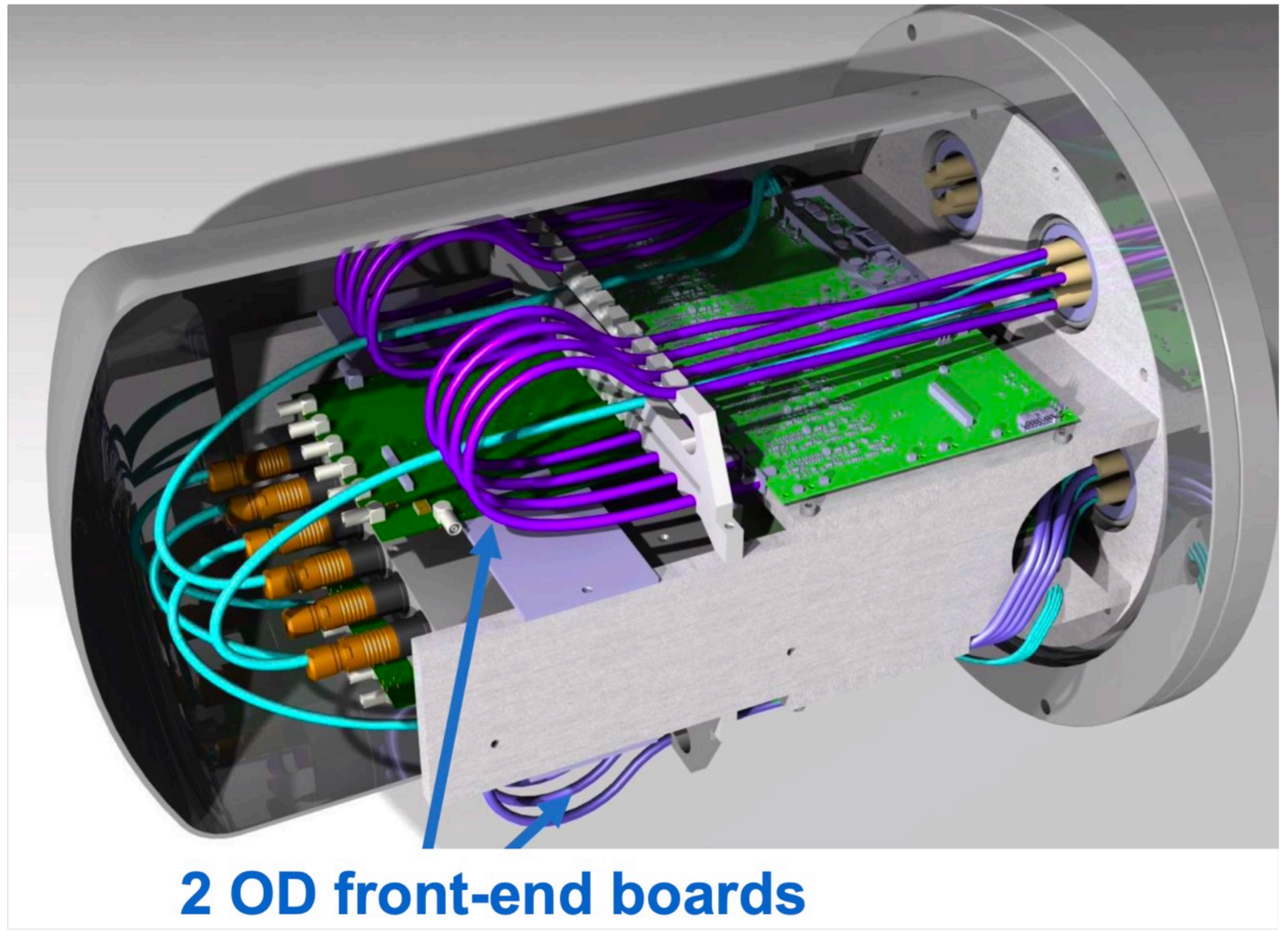




ID 12-channel front-end board.

OD 6-channel FE board.

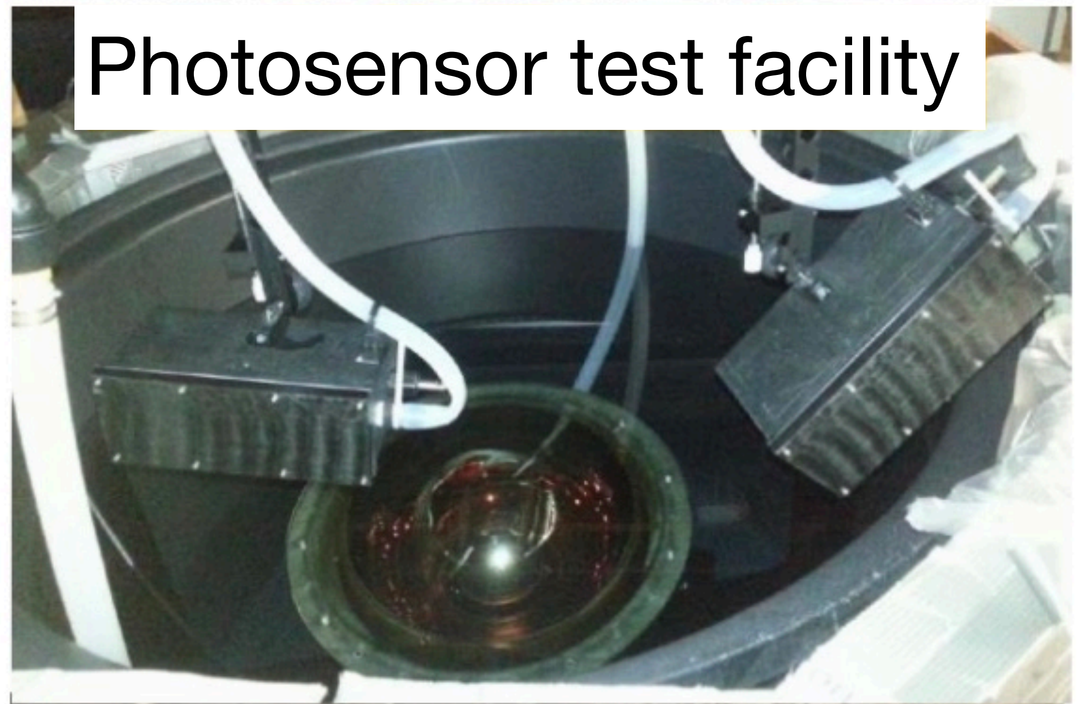




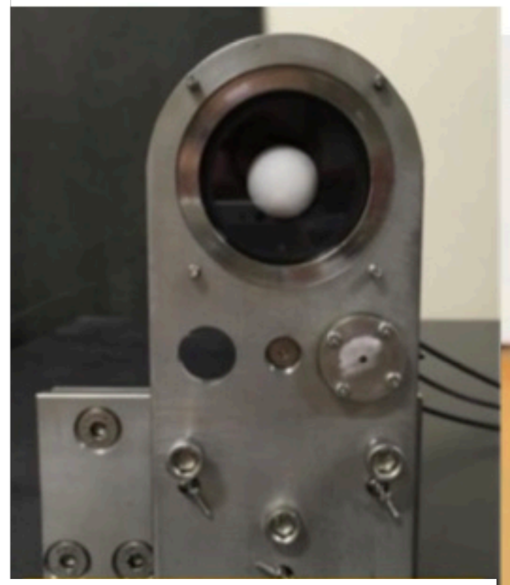
Hyper-Kamiokande Calibration

- An extensive program of calibration sources to determine detector parameters and measure systematics.
- Pre-calibration of photosensors.
- Photogrammetry.
- Light injection.
  - Diffusers and collimators.
  - mPMT system.
  - OD injections.
- Electron LINAC.
  - 3-24 MeV electrons.
- Radioactive sources
  - DT source - ^{16}N
  - AmBe + BGO - tagged neutrons.
  - Ni/Cf - 9 MeV γ cascade.

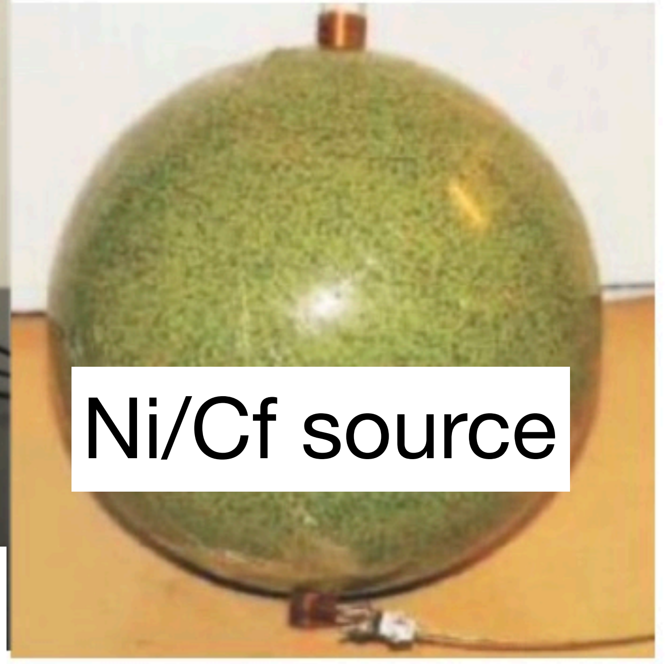
Photosensor test facility



Photogrammetry Testing

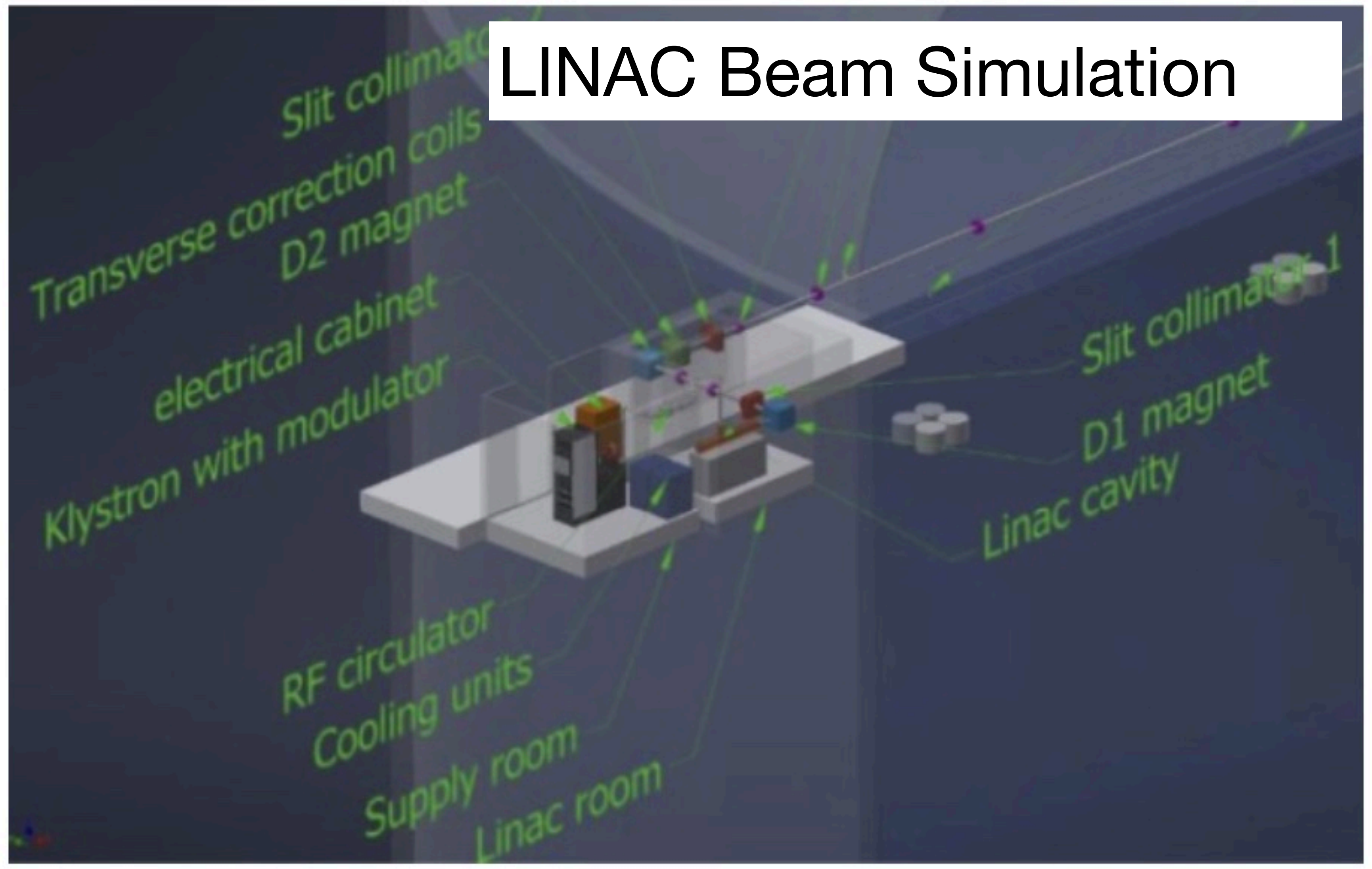


Light Injector

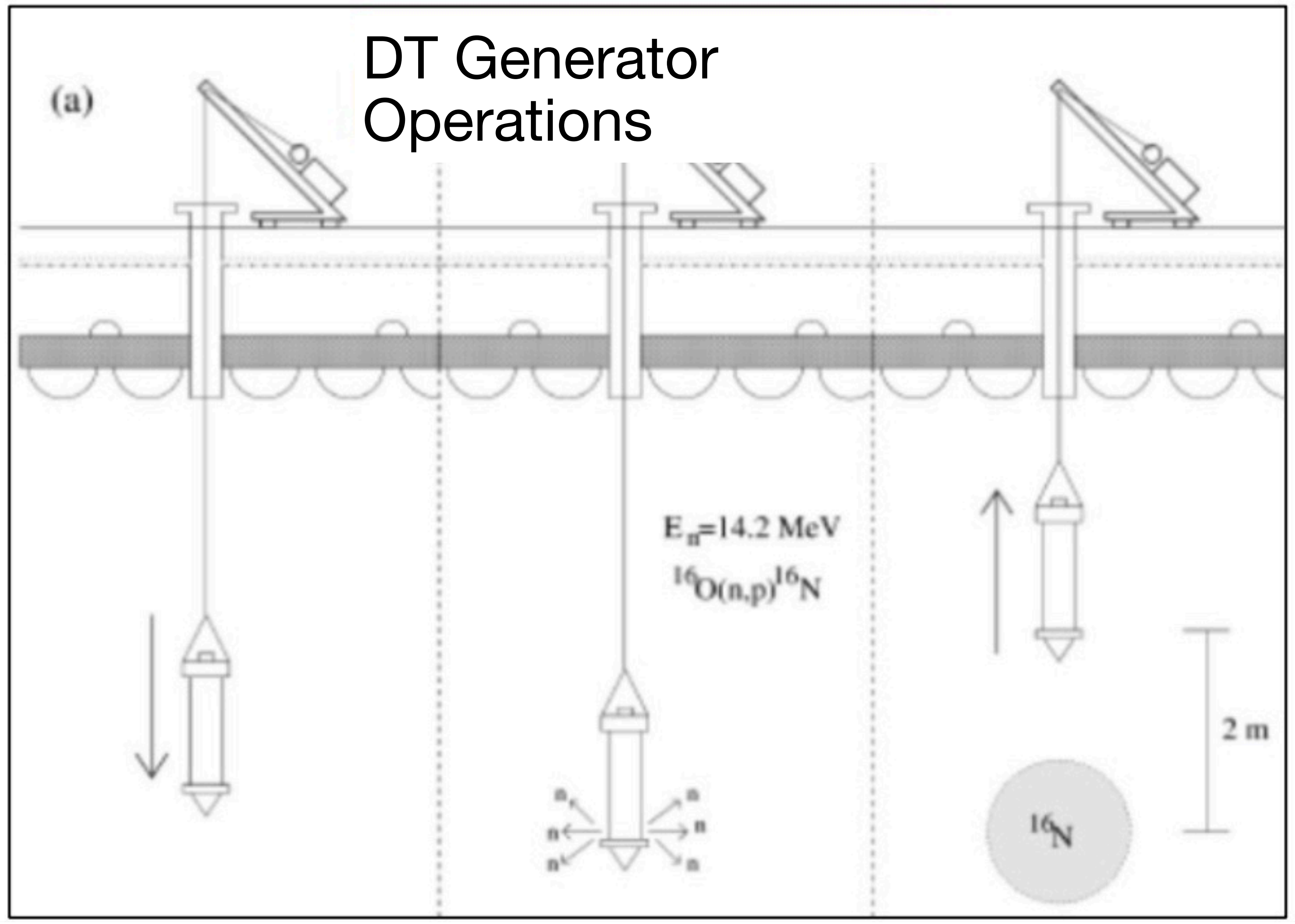


Ni/Cf source

LINAC Beam Simulation

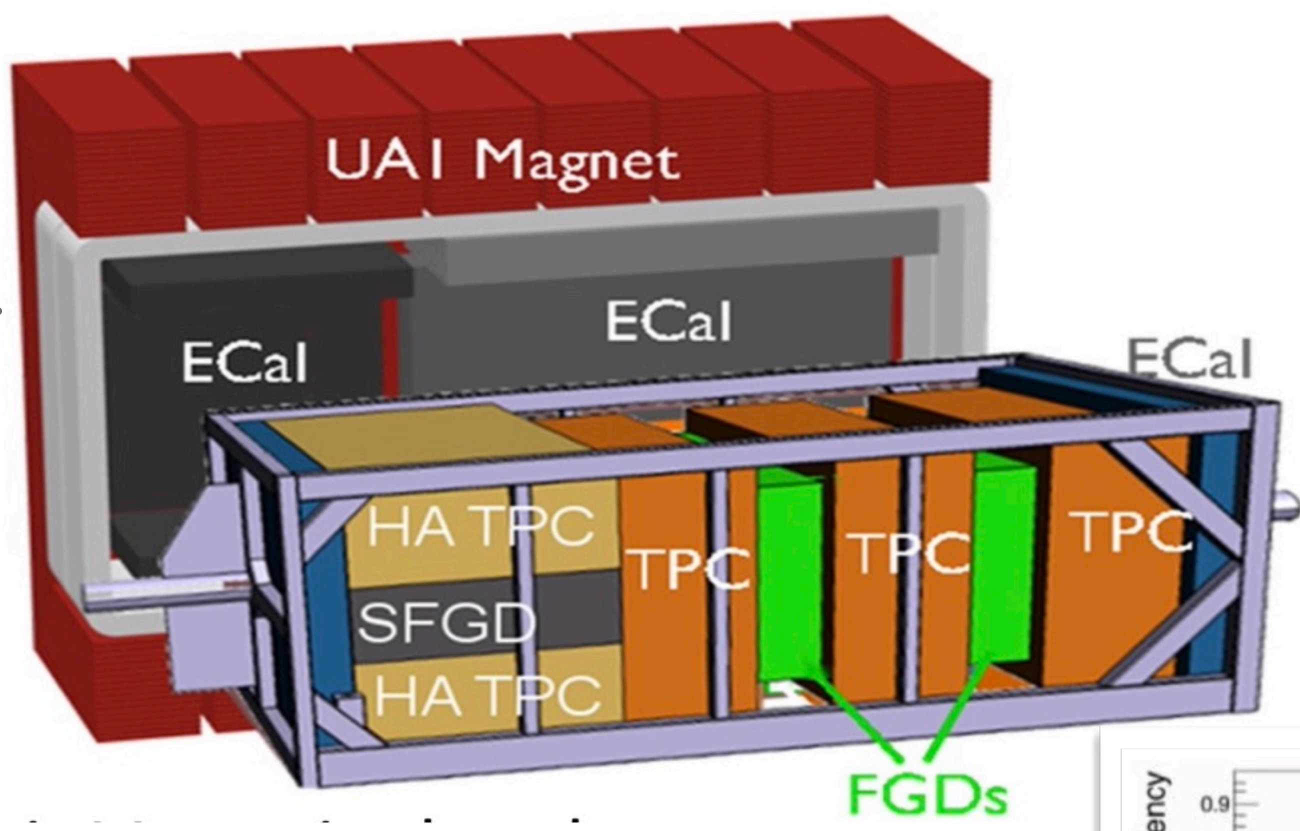


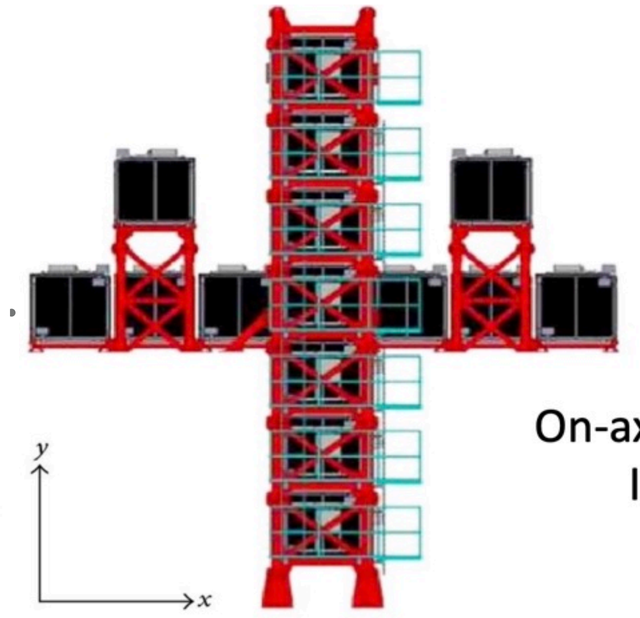
DT Generator Operations



Near Detectors

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



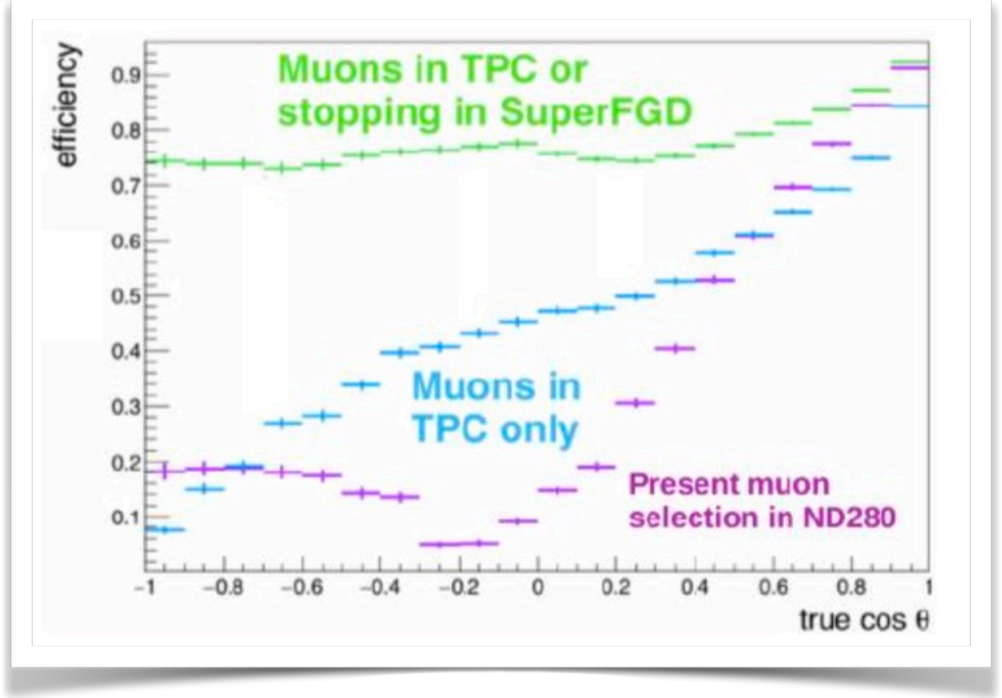


On-axis detector
INGRID

At 280m:

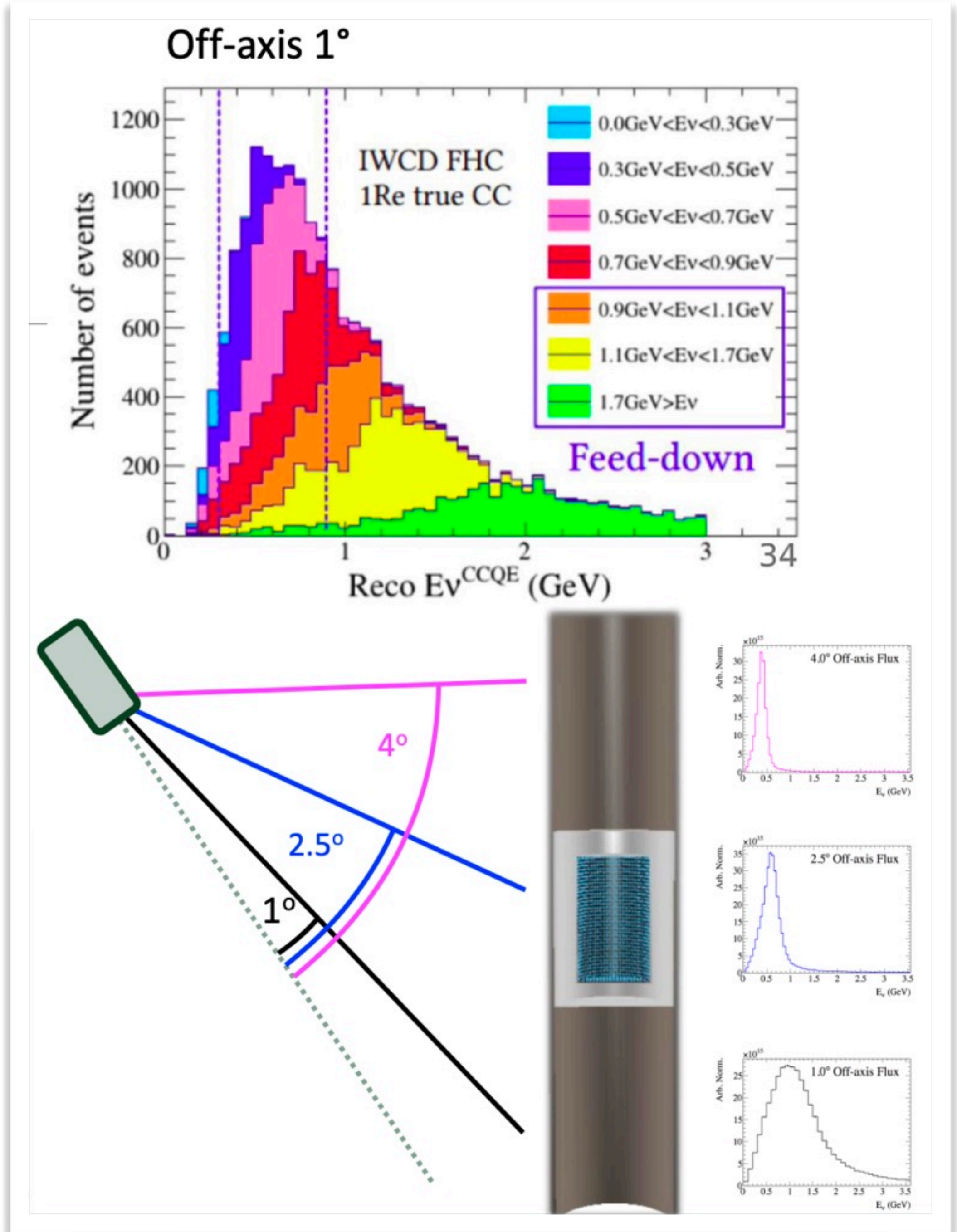
- On-axis detector: measure beam direction, monitor event rate.
- Off-axis magnetised tracker: charge separation (measurement of wrong-sign background), study of the recoil system.
- sFDG, High-Angle TPCs and TOF. Improved:
  - low-energy particles and neutrons reconstruction
  - angular acceptance

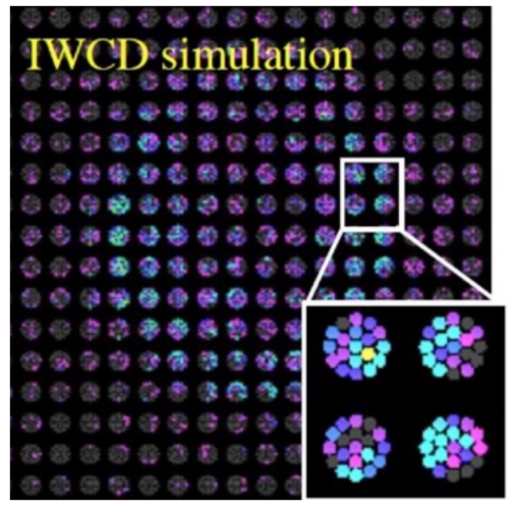
Improved performance on ND280 upgrade.



IWCD (~900m):

- Due to pion decay properties, neutrino spectrum varies with offaxis angle
- change off-axis angle ~1º – ~4º to change mean neutrino energy and constrain: $(\sigma(\nu_e)/\sigma(\nu_\mu))/(\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu))$
- ~400 mPMTs (high-granularity and time resolution)





Conclusions

- Hyper-Kamiokande is a next-generation neutrino detector.
- Aiming to measure CP violation.
- Wide physics reach.
- The experiment is currently being built, aiming to take data in 2027.
- It's an exciting time to work on the experiment!