Status and Prospects of the Hyper-Kamiokande Experiment

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on behalf of the Hyper-Kamiokande collaboration

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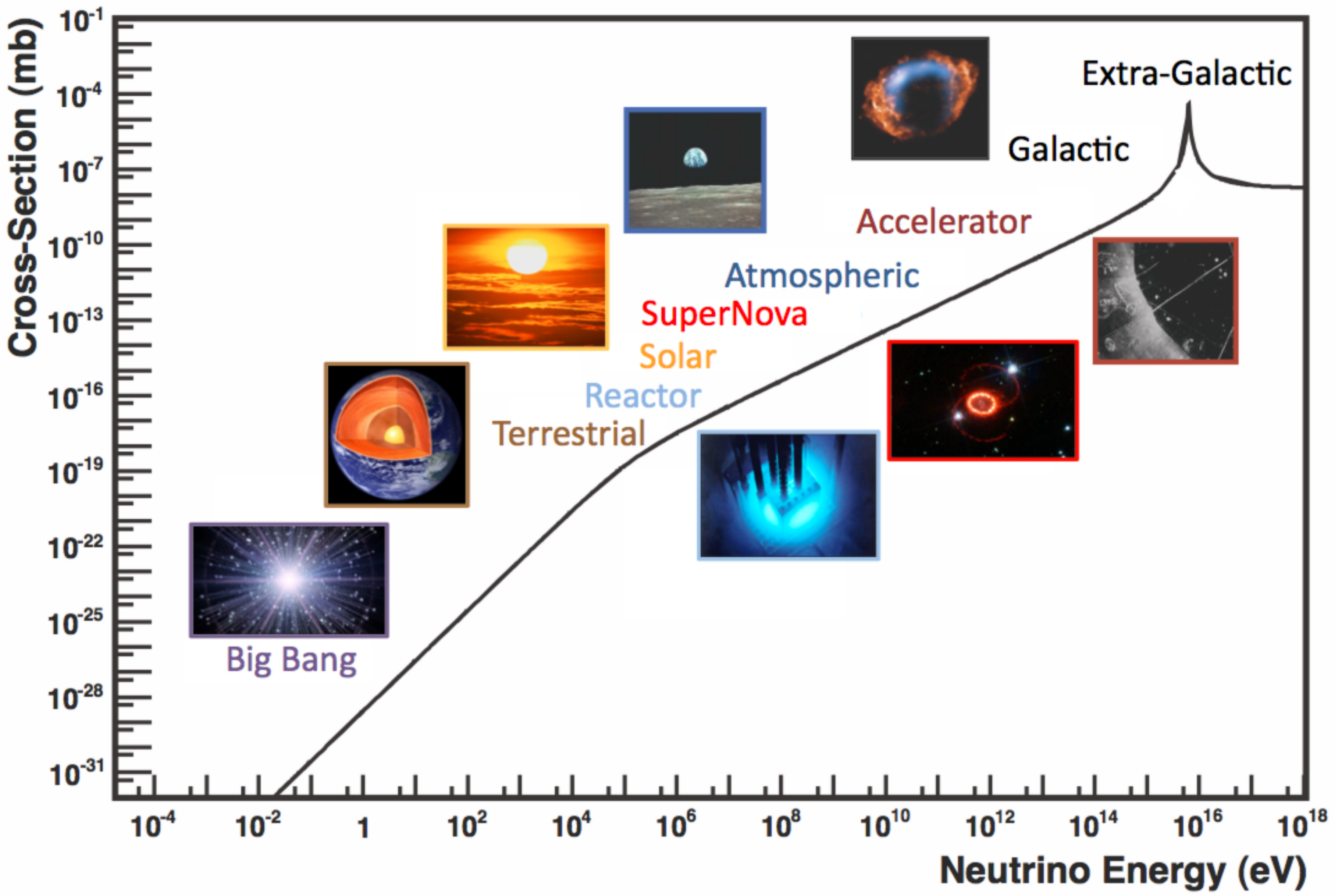
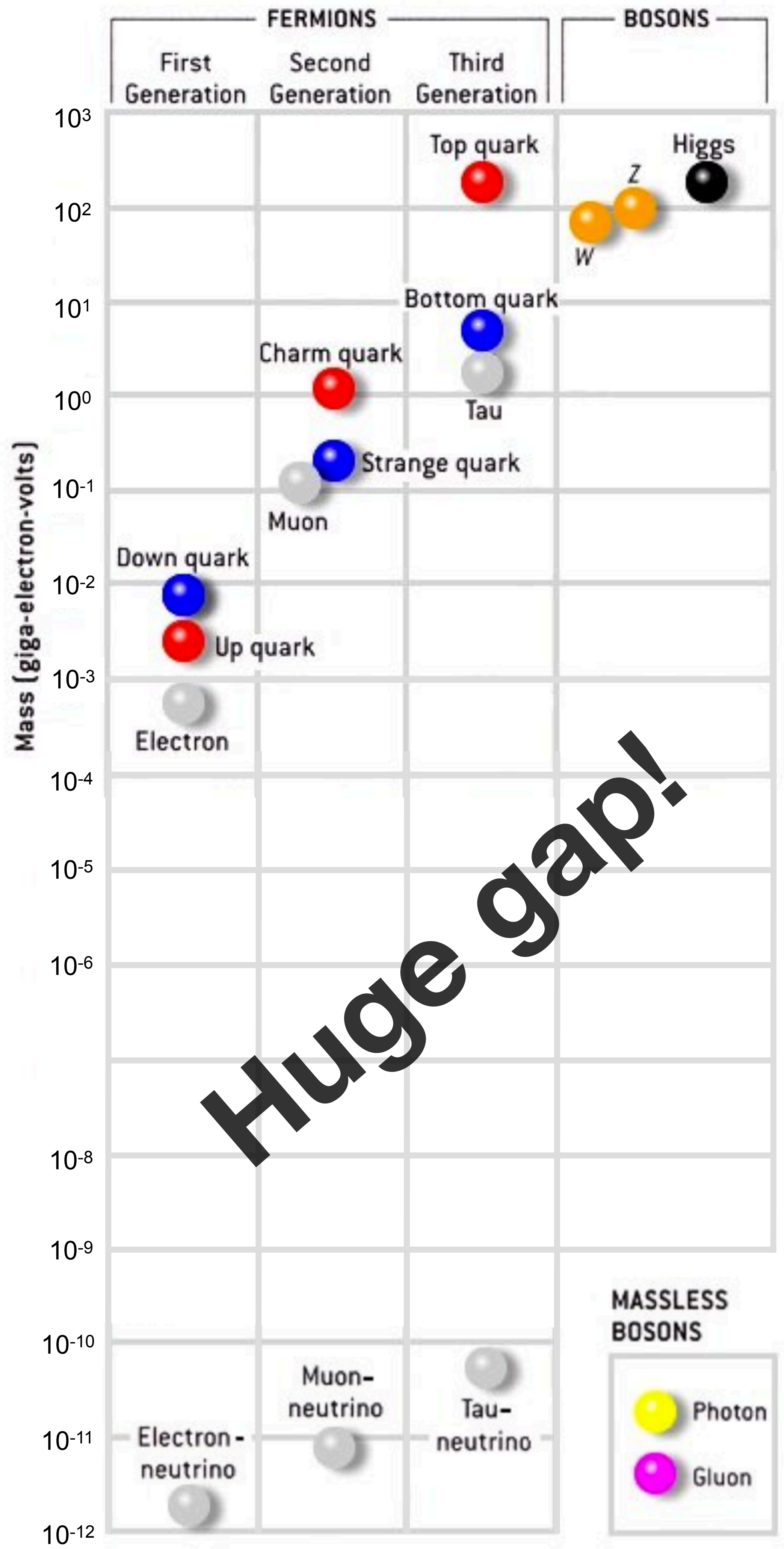
Neutrinos

- Second most abundant particle in the universe
- Odd particle of the Standard Model
  - Very light compared to the other particles
  - Non-zero mass - does not originate from the interaction with the Higgs ➔ evidence of the physics beyond the Standard Model
- Neutrinos come from various sources with broad range of energies
  - Bearers of key information
- **Understanding the neutrinos**

⇕

Understanding the universe



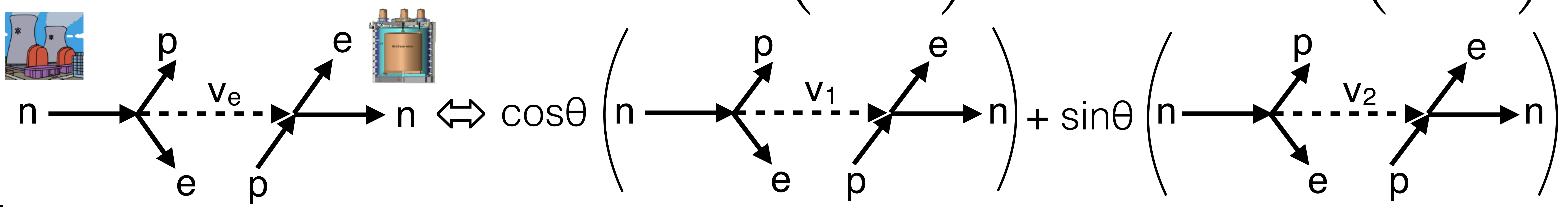


Basics of Neutrino Mixing and Oscillation (2ν)

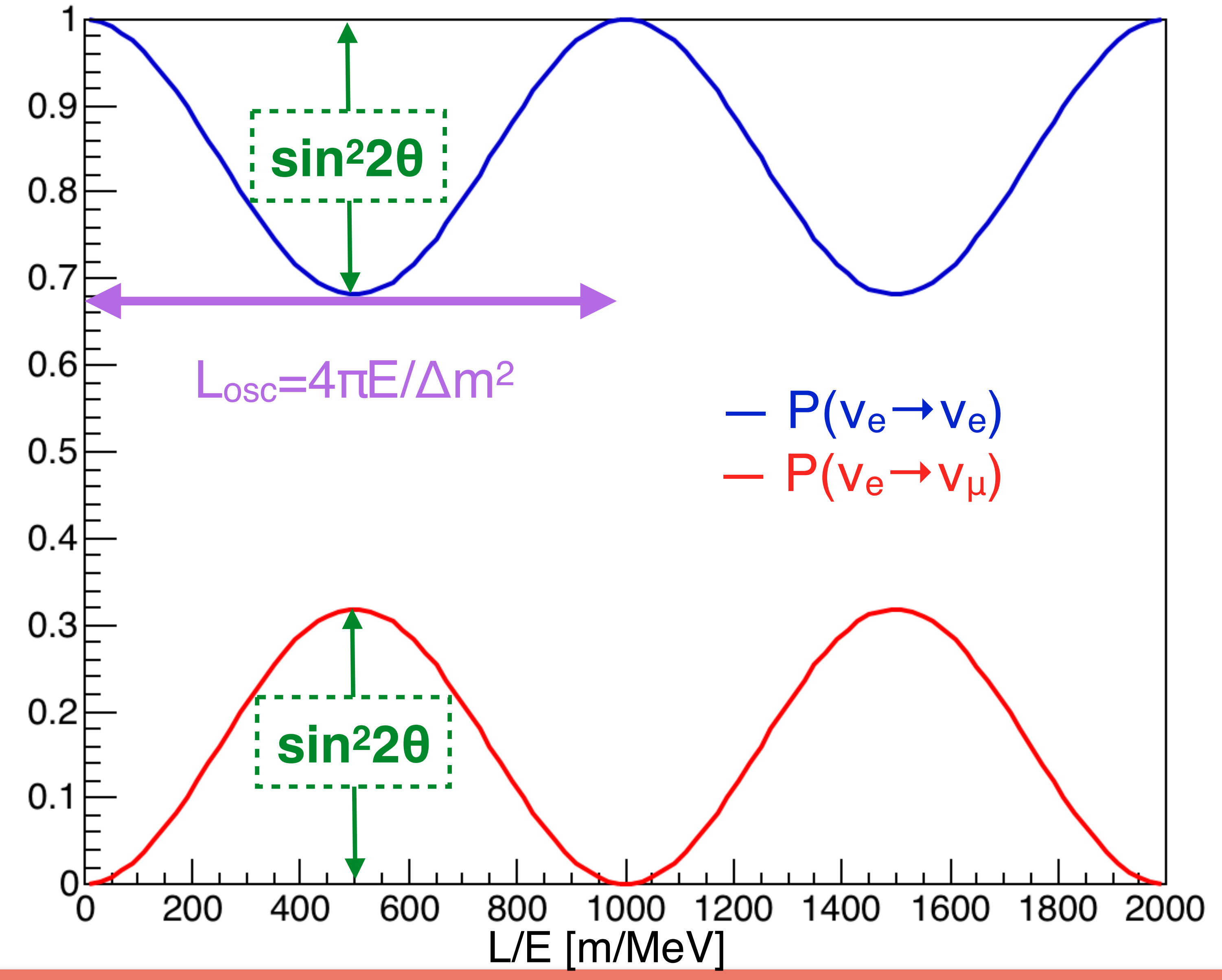
- Neutrino mixing: Flavor states ≠ Mass states

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$|\nu_1(L)\rangle = exp\left(-i\frac{m_1^2L}{2E}\right)|\nu_1(0)\rangle \quad |\nu_2(L)\rangle = exp\left(-i\frac{m_2^2L}{2E}\right)|\nu_2(0)\rangle$$



- Neutrino Oscillation:



Disappearance Channel

$$P_{\nu_e\to\nu_e}(L,E) = 1 - \sin^2 2\theta \sin^2\frac{\Delta m^2 L}{4E}$$

$$P_{\nu_e\to\nu_e} + P_{\nu_e\to\nu_\mu} = 1$$

Appearance Channel

$$P_{\nu_e\to\nu_\mu}(L,E) = \sin^2 2\theta \sin^2\frac{\Delta m^2 L}{4E}$$

Oscillation essentials:

- Probability oscillation in L/E
- Mass squared difference $\Delta m^2 \equiv m_1^2 - m_2^2$
  - drives the frequency
- Mixing angle θ
  - drives the amplitude

Neutrino Mixing and Oscillation (3ν)

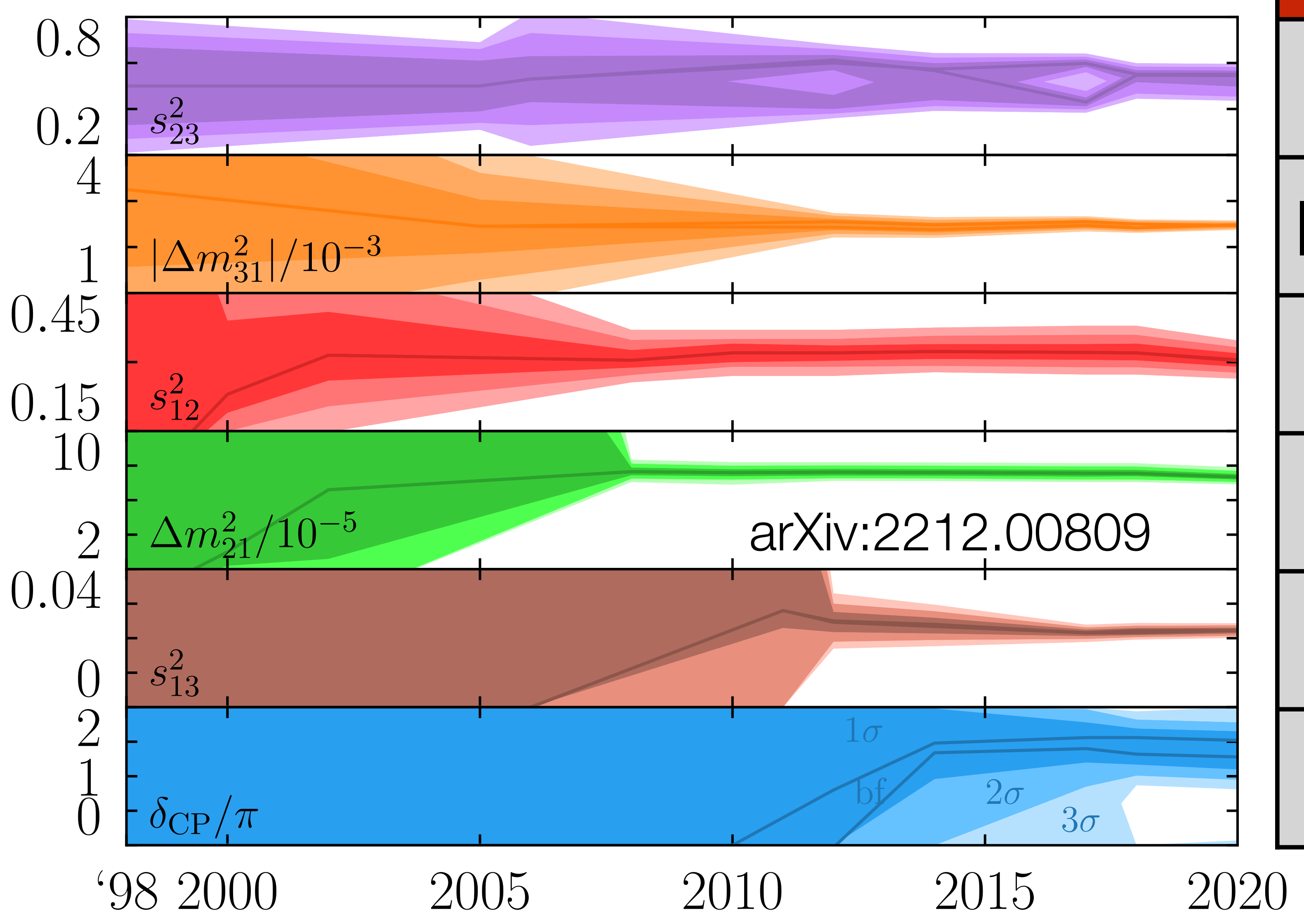
Three-neutrino mixing matrix:

Atmospheric, accelerator ν — Solar, reactor L~60 km ν — Reactor L~2 km, accelerator ν

$$\text{Flavor states}\quad \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}\quad \text{Mass states}$$

$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$
$\Delta m^2_{ij}\equiv m^2_i-m^2_j$

Oscillation parameters:



Parameter	Value	Precision
θ_{23}	47°	3.8%
$\lvert\Delta m_{32}^2\rvert \simeq \lvert\Delta m_{31}^2\rvert$	2.44×10^{-3} eV²	1.4%
θ_{12}	34°	4.2%
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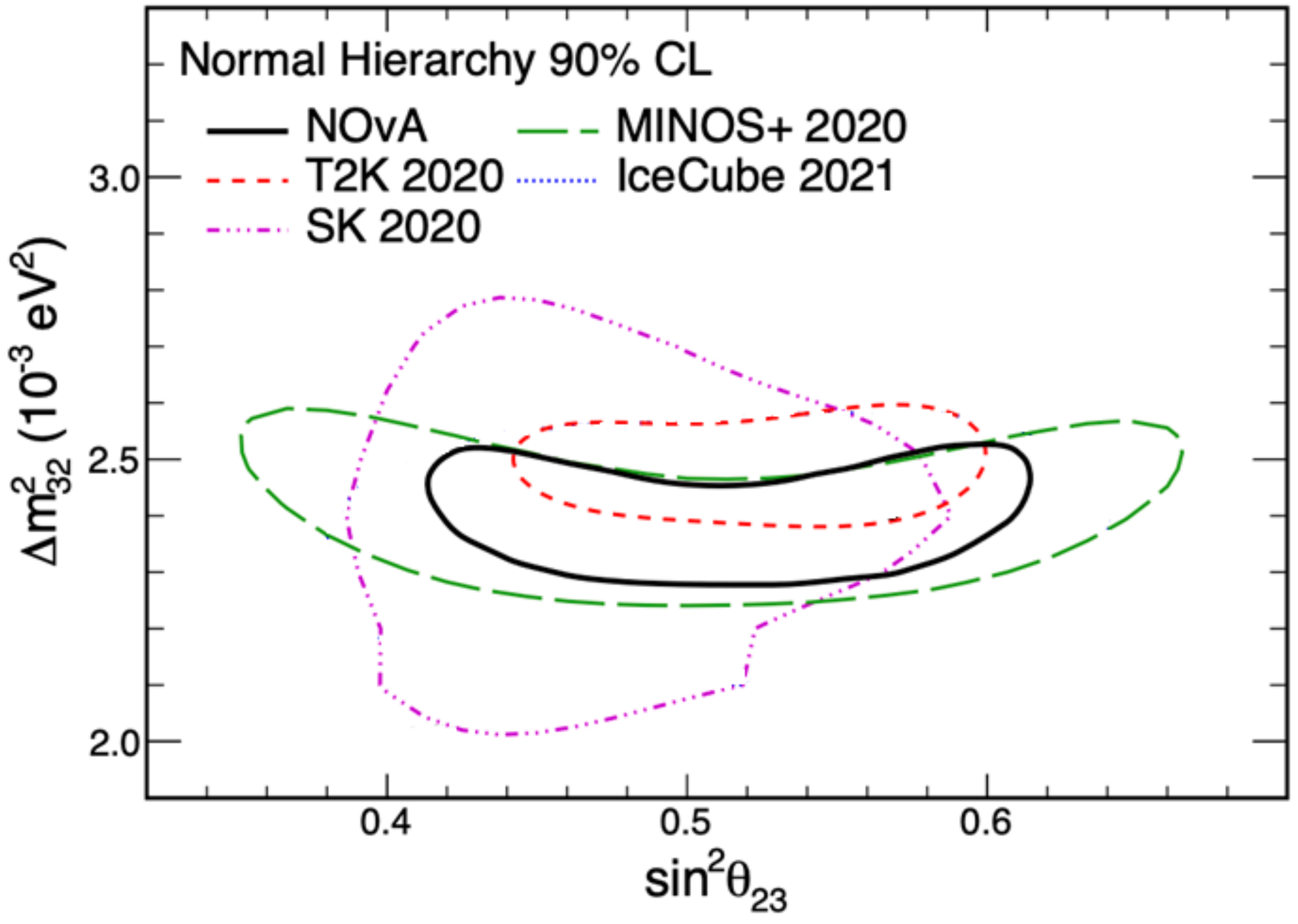

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Open questions in ν-physics:

- θ_{23} octant ⇔ $\theta_{23} \gtreqless 45°$?

Open Questions

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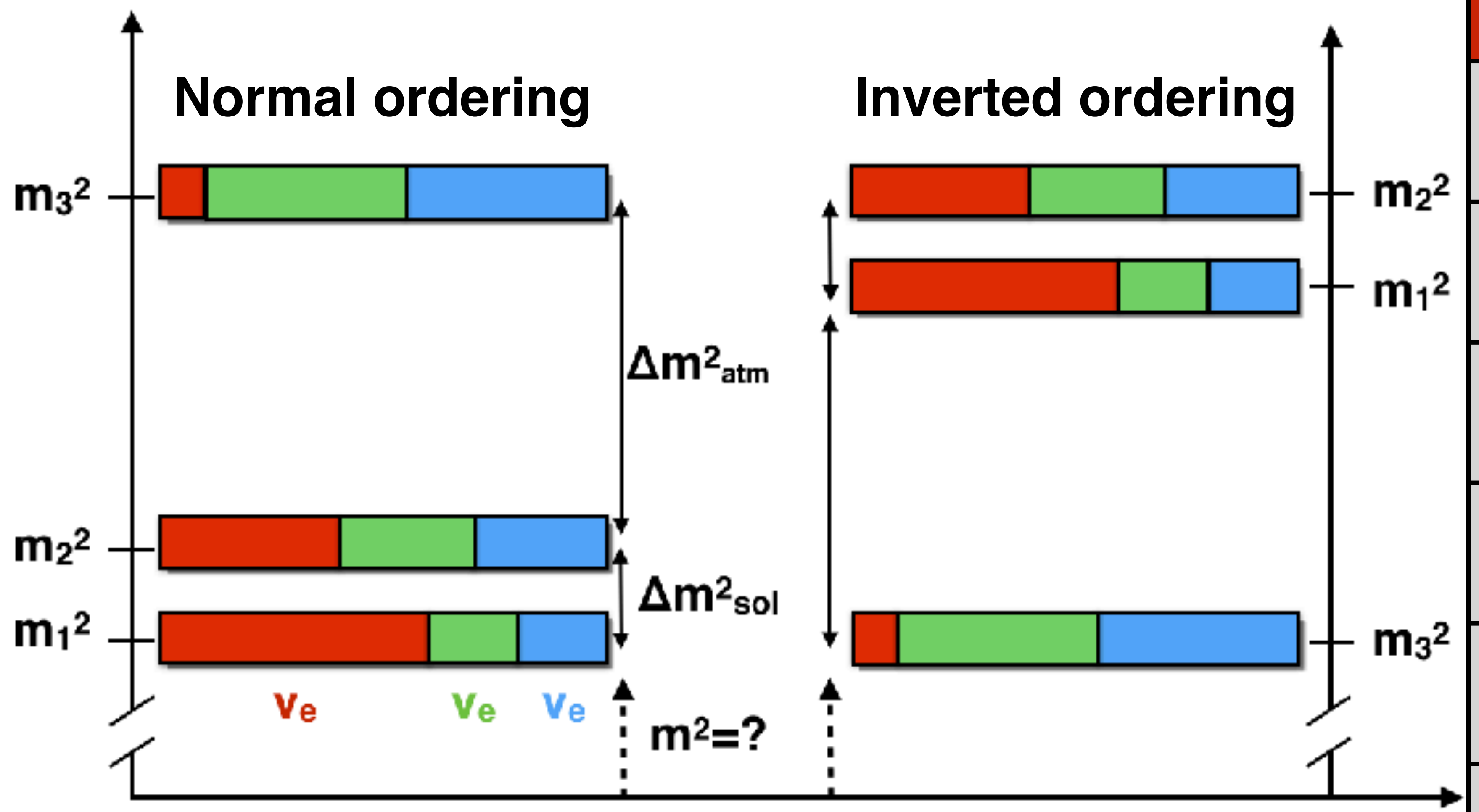

Normal $m_3>m_2$ (m_1) — **Inverted** $m_3<m_1$ (m_2)

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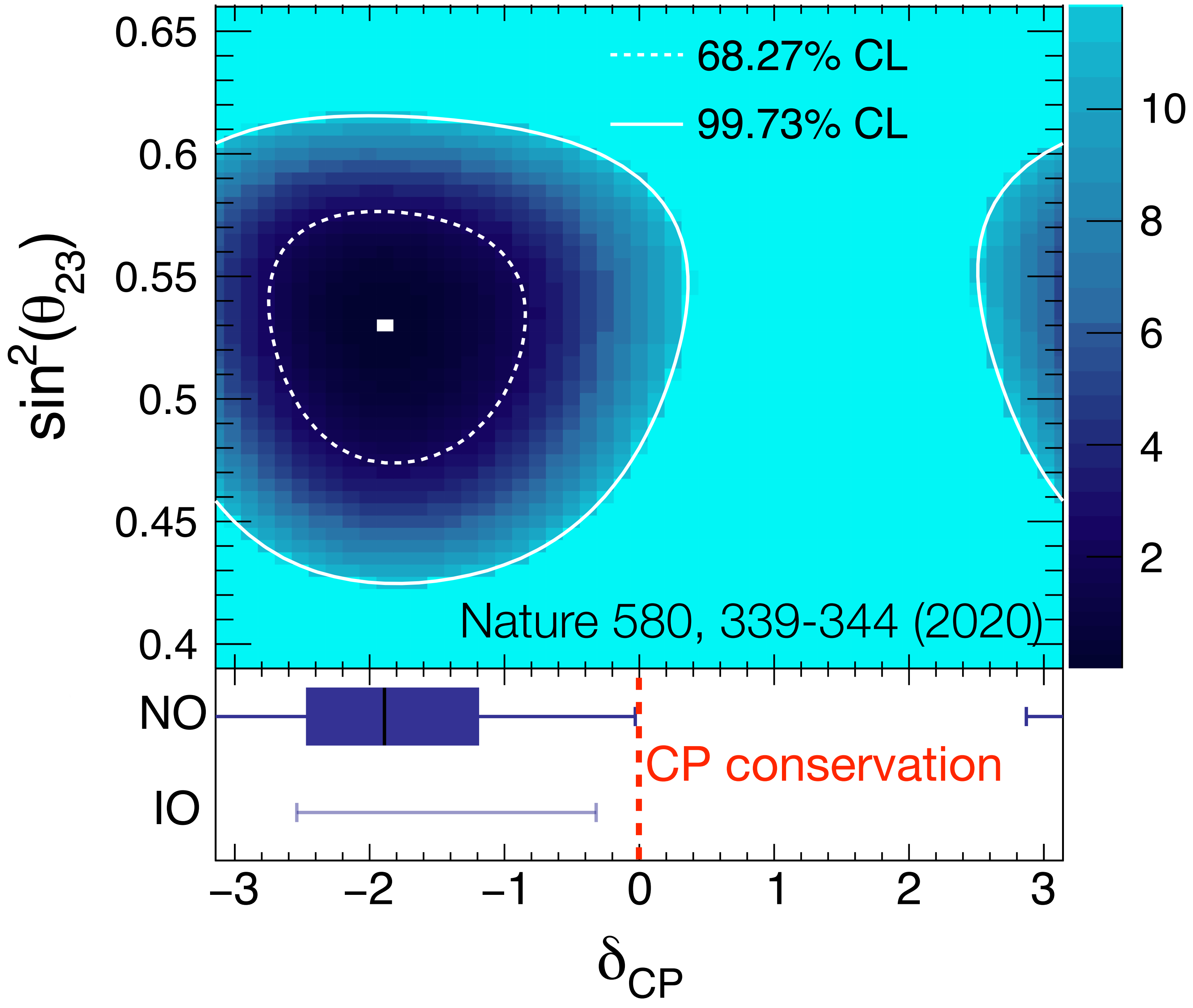

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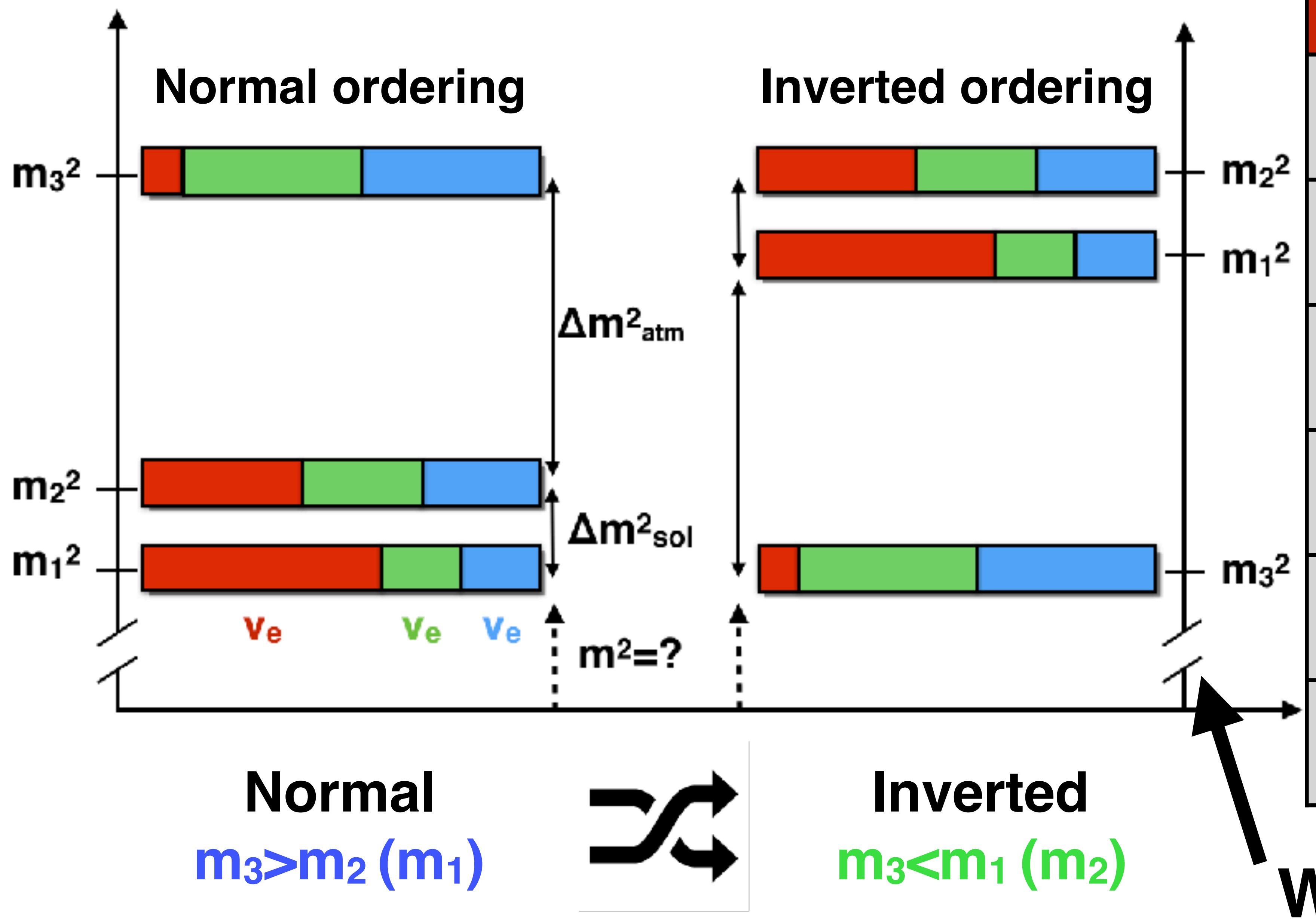

What is the absolute mass?

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Open questions in ν-physics:

- θ_{23} octant ⇔ $\theta_{23}\gtreqless45°$?
- Mass ordering
- Value of the δ_{CP}
- Absolute mass scale
- Are ν's Dirac or Majorana nature?

Open Questions

Three-neutrino mixing matrix:

Atmospheric, accelerator ν — Solar, reactor L~60 km ν

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Reactor L~2 km, accelerator ν

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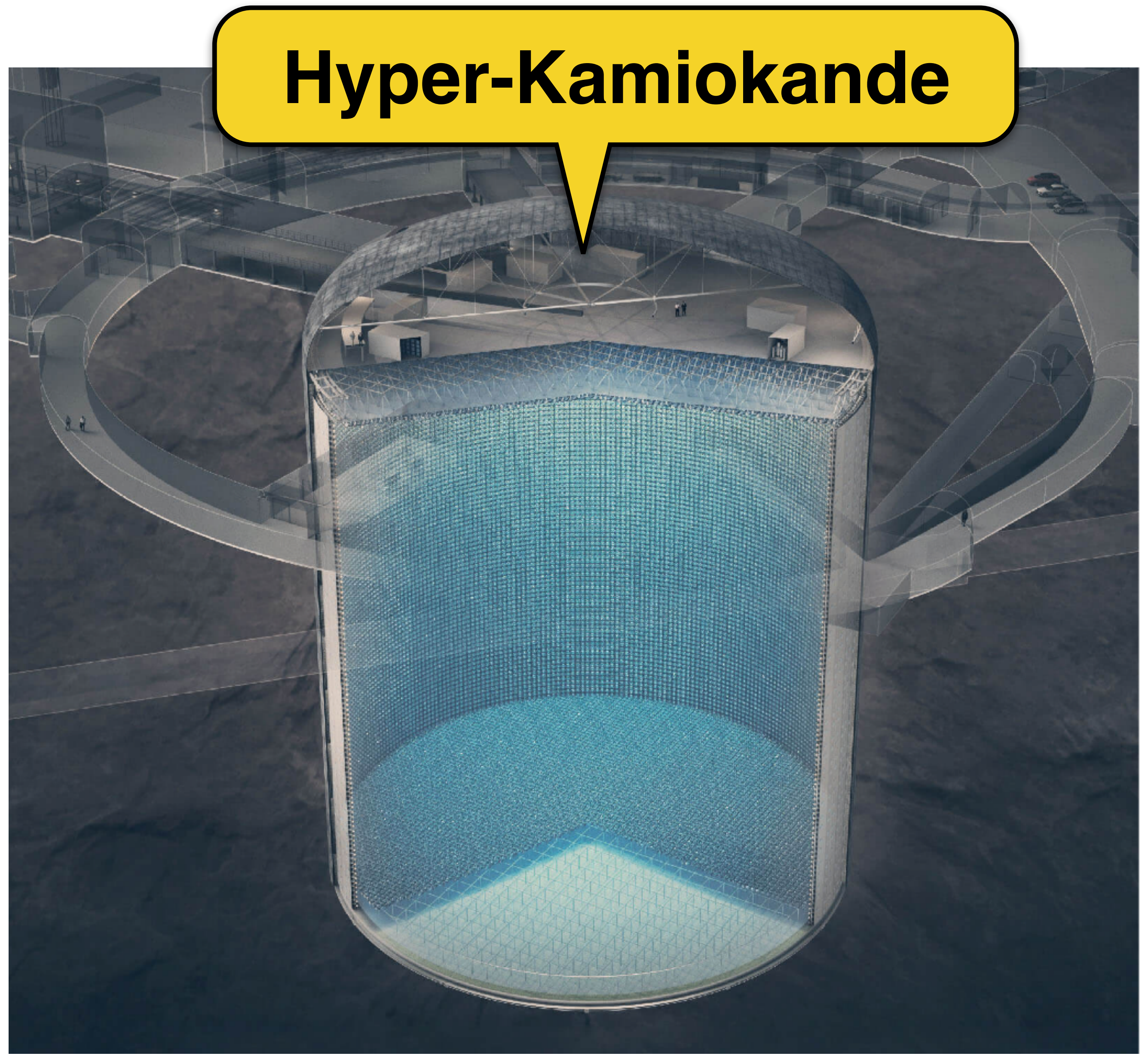

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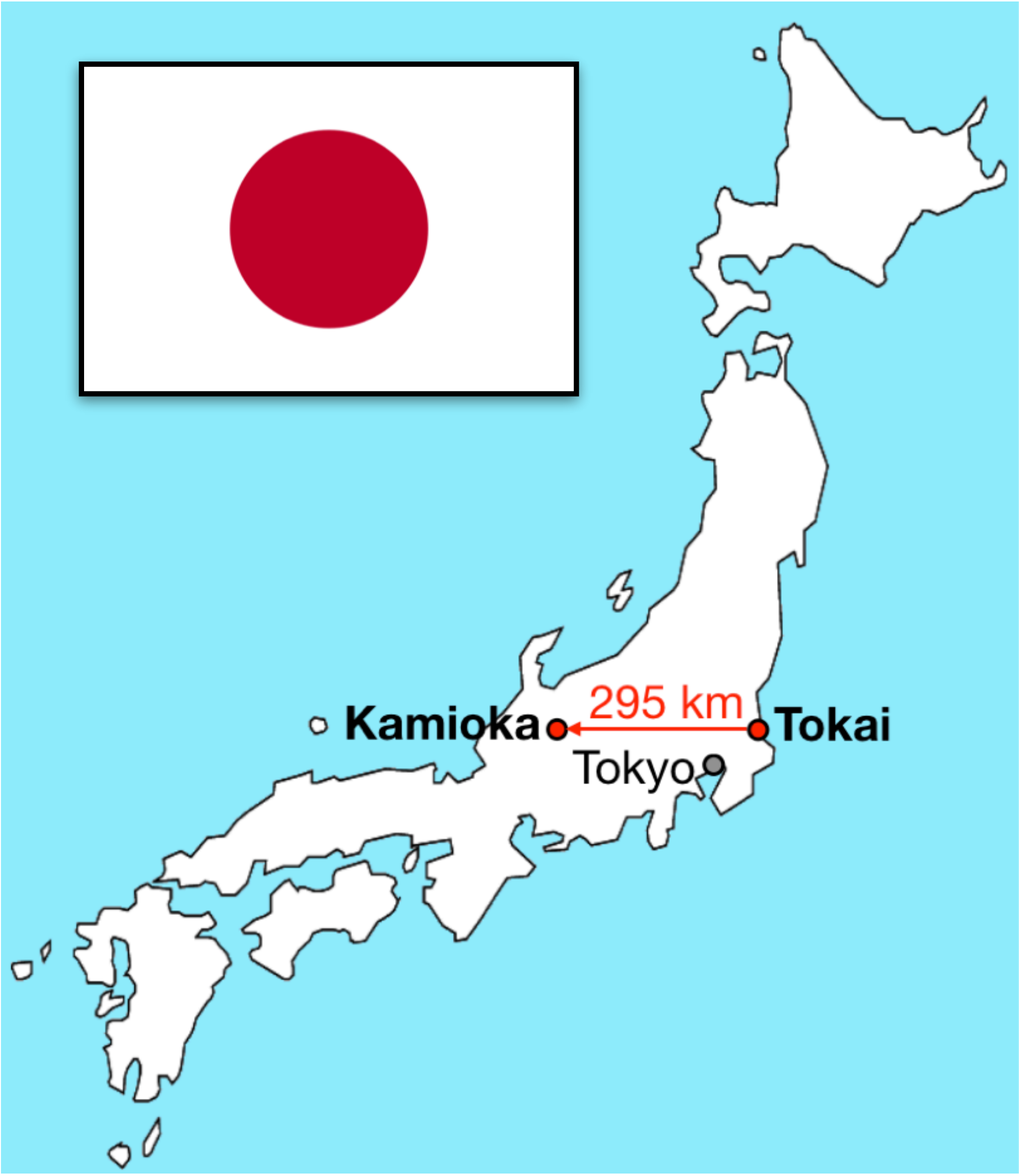
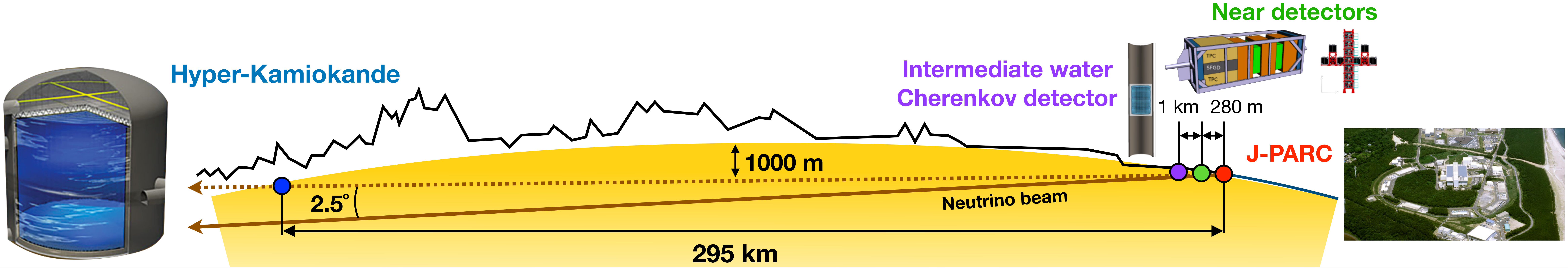
- **Mass ordering**
- **Value of the δ_{CP}**
- Absolute mas
- Are ν's Dirac o Majorana nature?

Will be addressed by Hyper-Kamiokande

- International multipurpose experiment under construction in Japan - long baseline neutrino oscillation as well as non-accelerator physics
- The world's most-intense neutrino beam from J-PARC (ultimately 1.3 MW)
- Near detectors to control the systematics (@J-PARC):
  - INGRID & ND280 (common with T2K) - further improved with upgrades
  - Intermediate Water Cherenkov detector - newly built movable detector
- Hyper-Kamioaknde (far) detector will be the largest neutrino and nucleon decay detector in the world with 260 kt of water (@Kamioka)



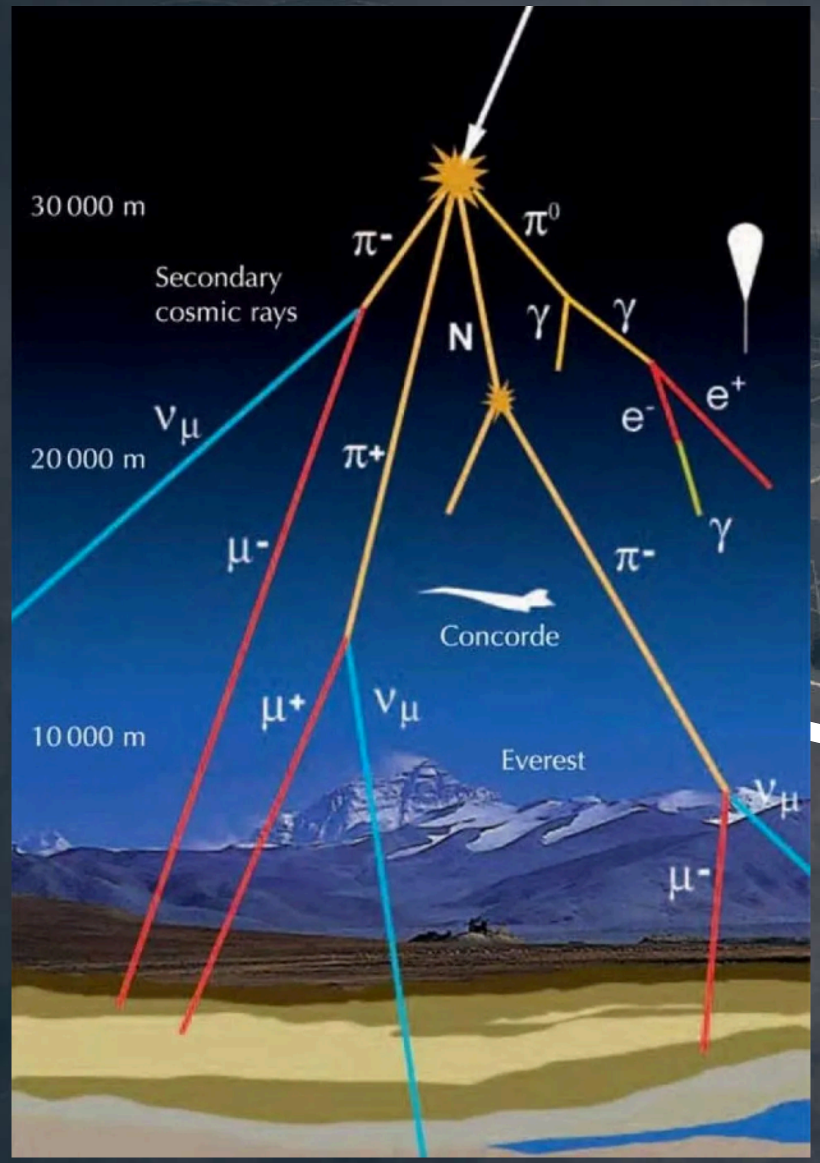


The Hyper-Kamiokande Collaboration

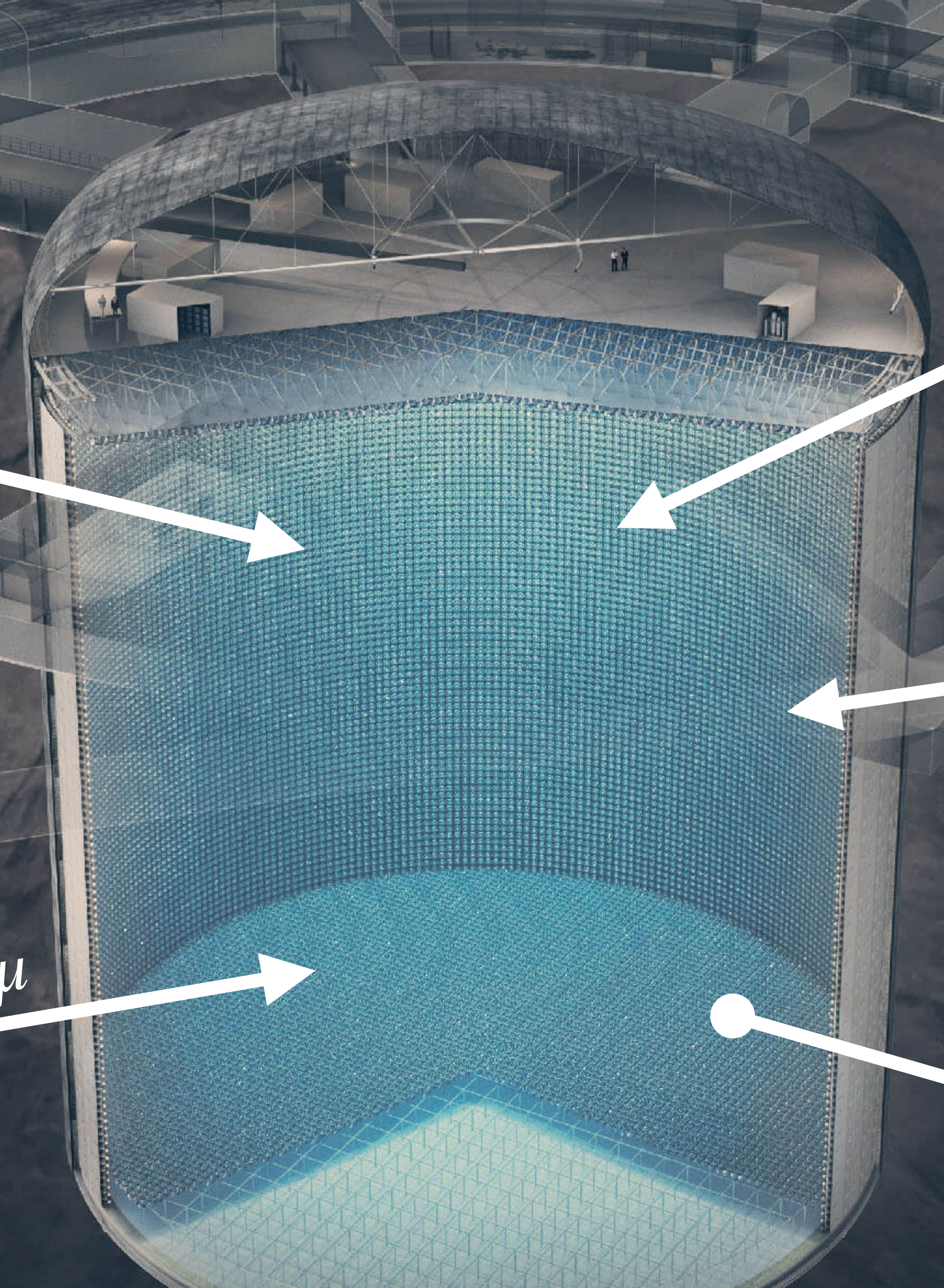
- About 560 scientists from 103 institutions from 22 countries

Physics Program in a Nutshell

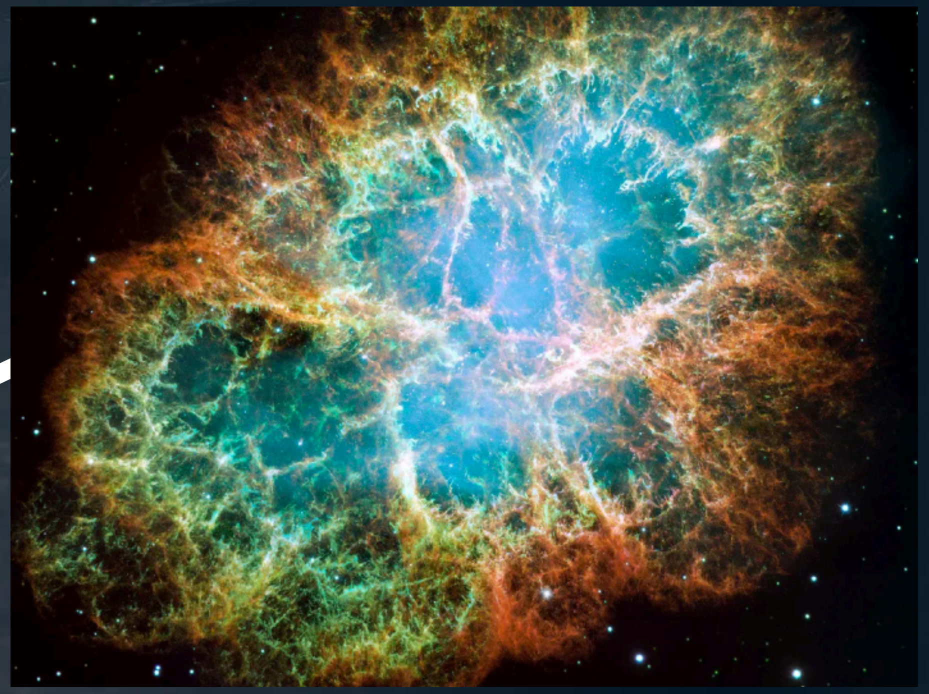
Atmospheric neutrinos



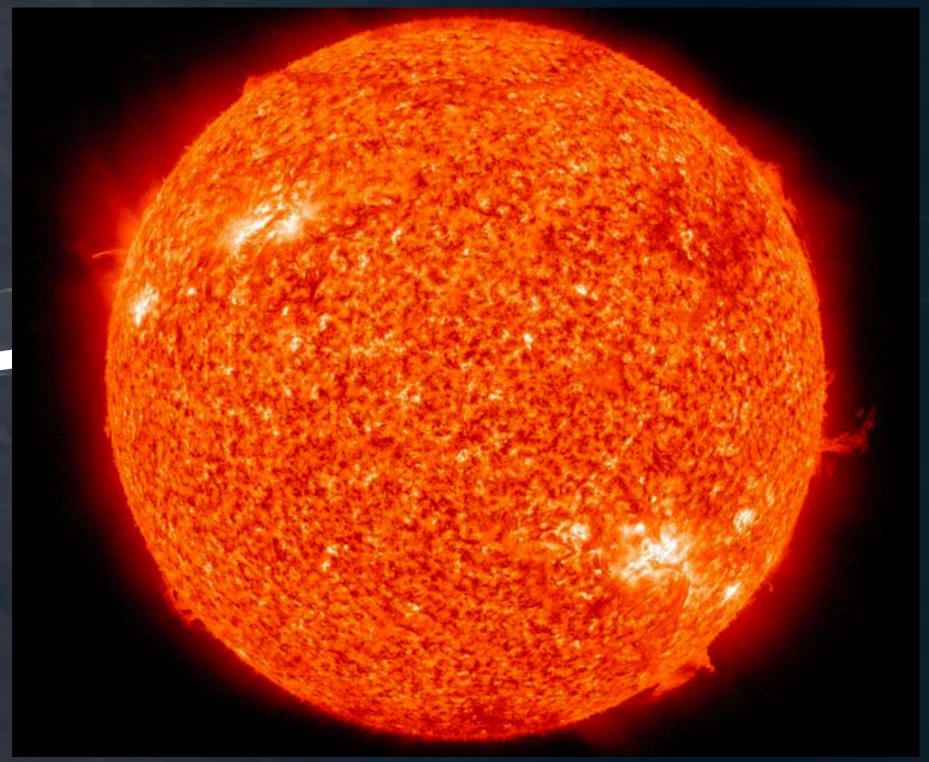
$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$



Supernova neutrinos

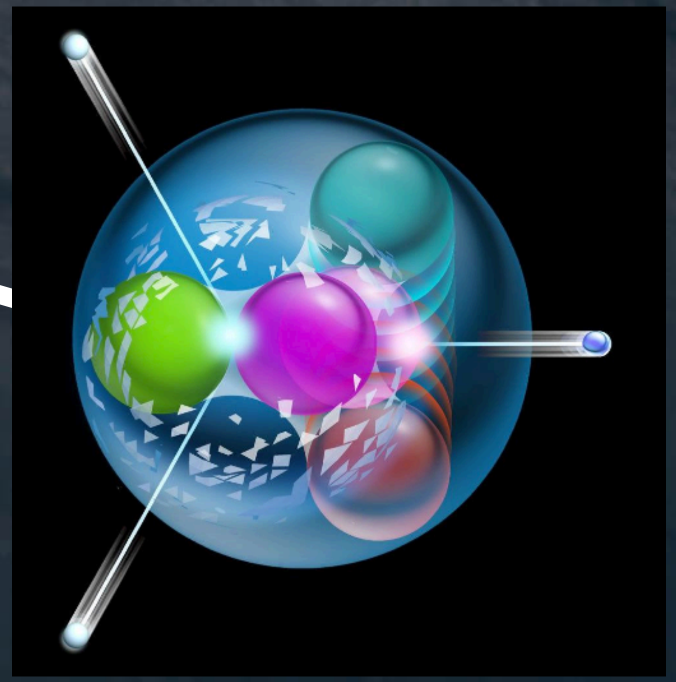


all flavores



ν_e

Solar neutrinos



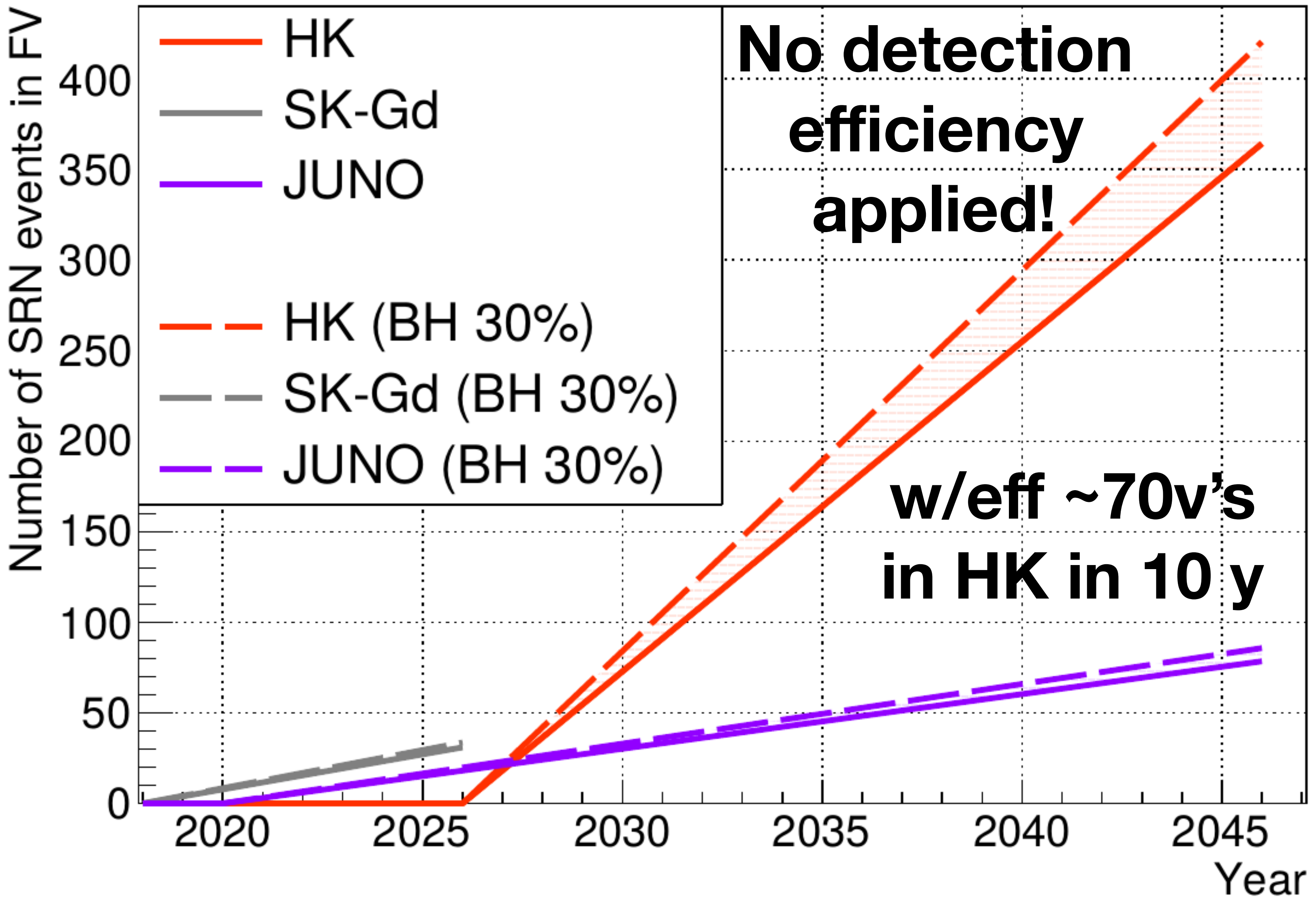
ν_μ or $\bar{\nu}_\mu$

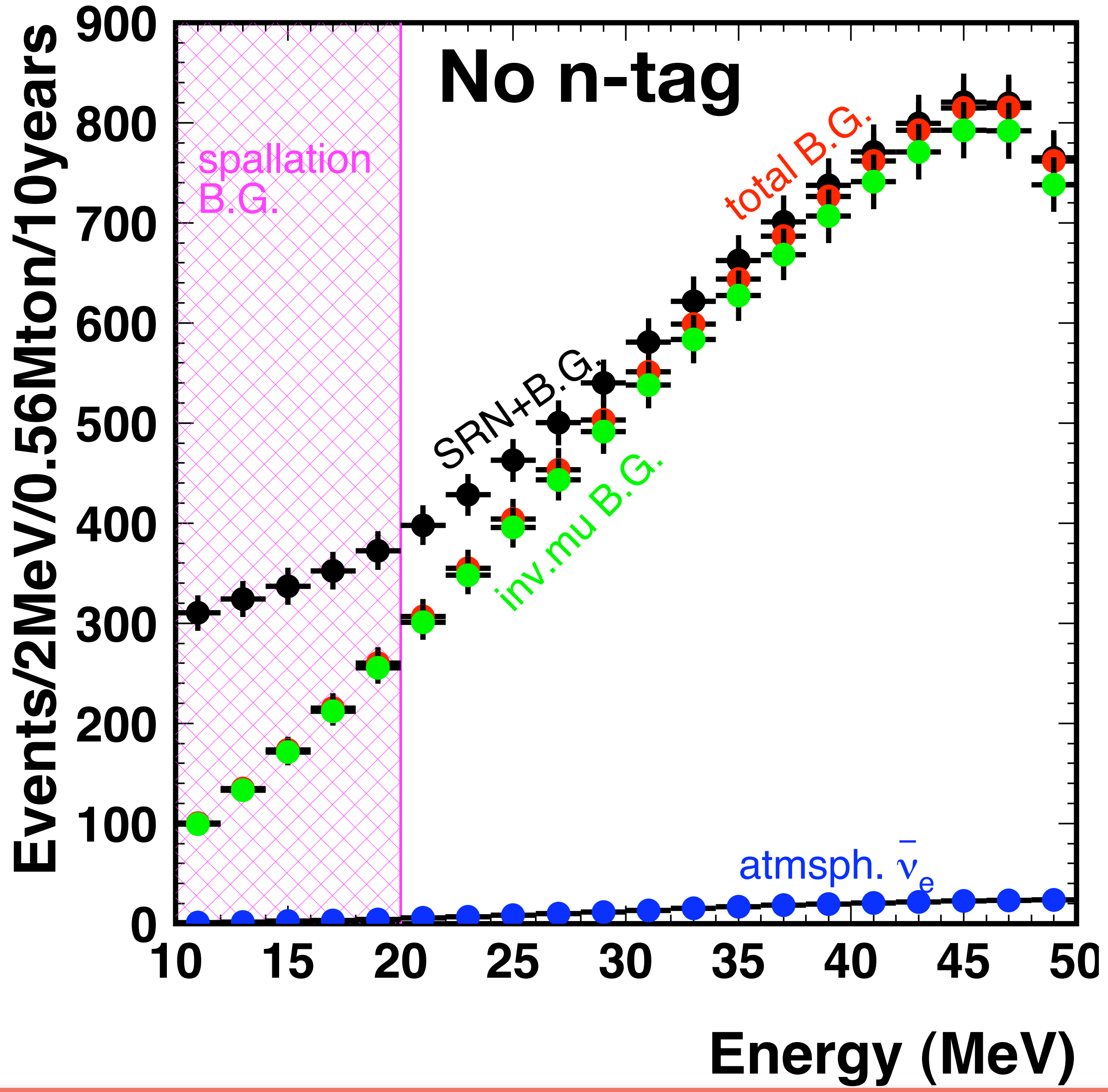
Accelerator neutrino from J-PARC

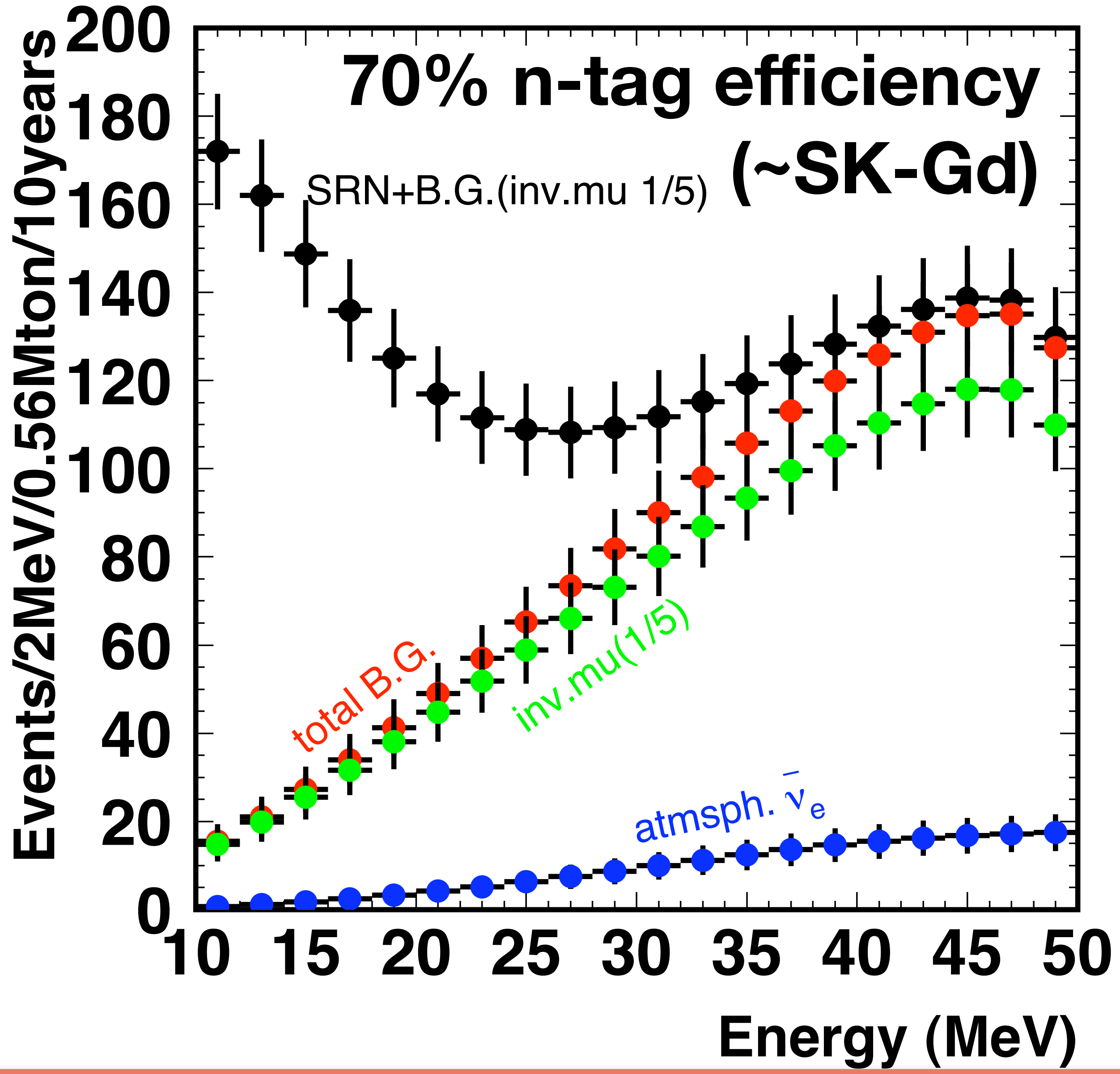
Nucleon decay

Neutrino Astrophysics - Supernova Neutrinos

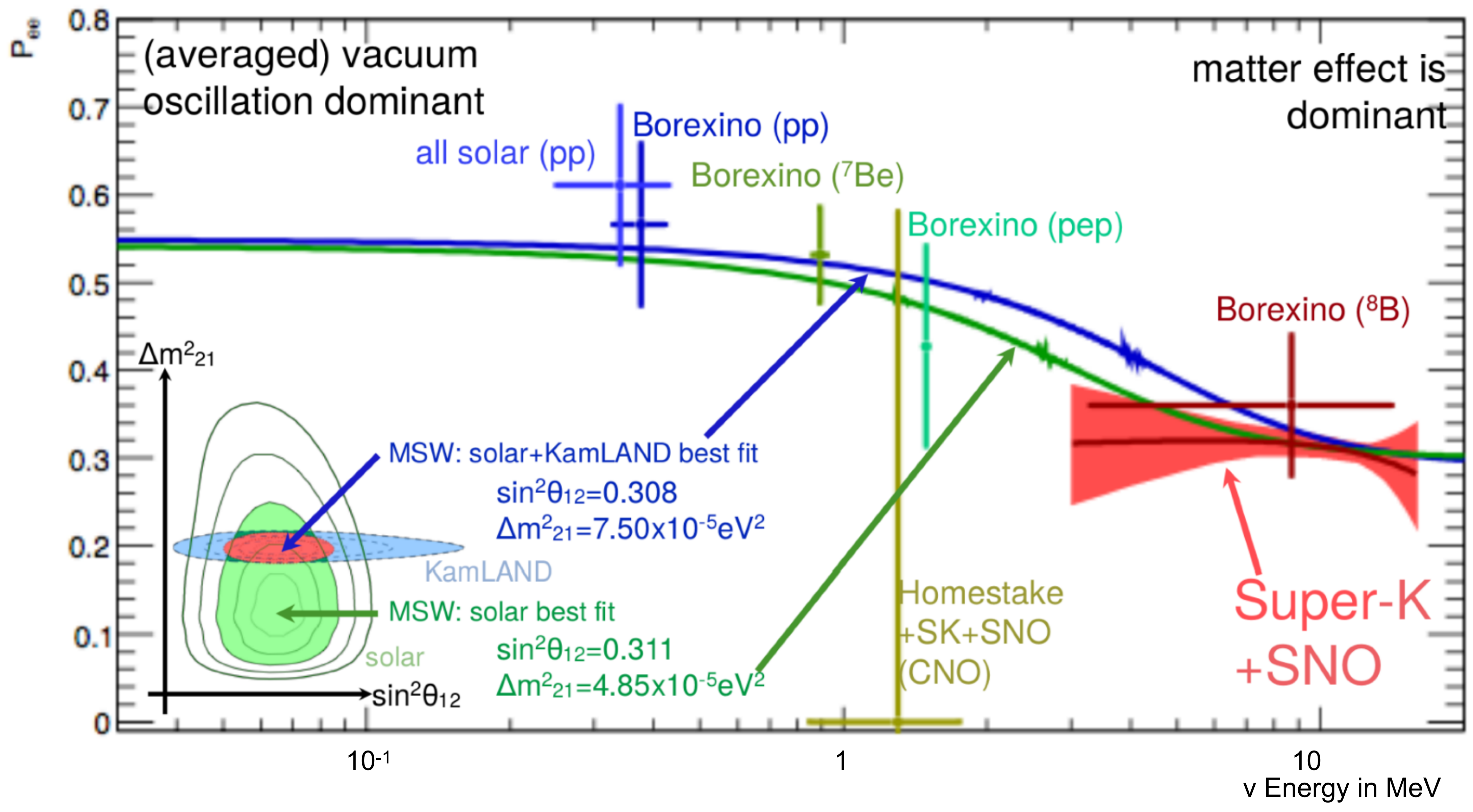
- 99% of the gravitational energy released in ν's with energy up to ~50 MeV
- Supernova burst neutrinos - 54k-90k events in HK for supernova @10 kpc
  - Distinguishing explosion mechanism through time and energy spectra (ApJ 916 15 2021)
  - Event alert with ~1° direction precision - multi-messenger astronomy
- Supernova relic neutrinos - not yet observed - determine the past stellar collapse rate
  - Detection through inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ - neutron tagging efficiency key aspect

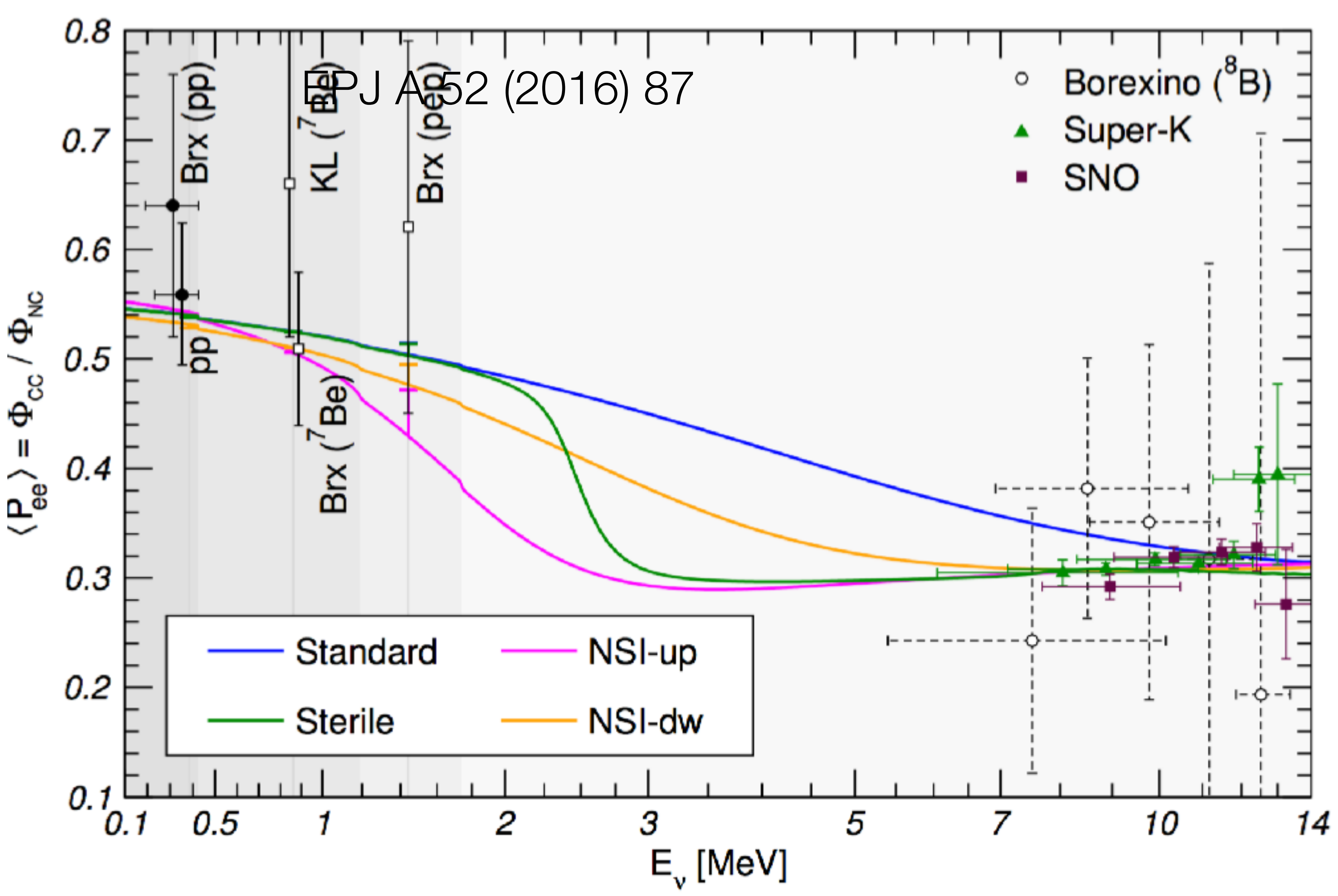






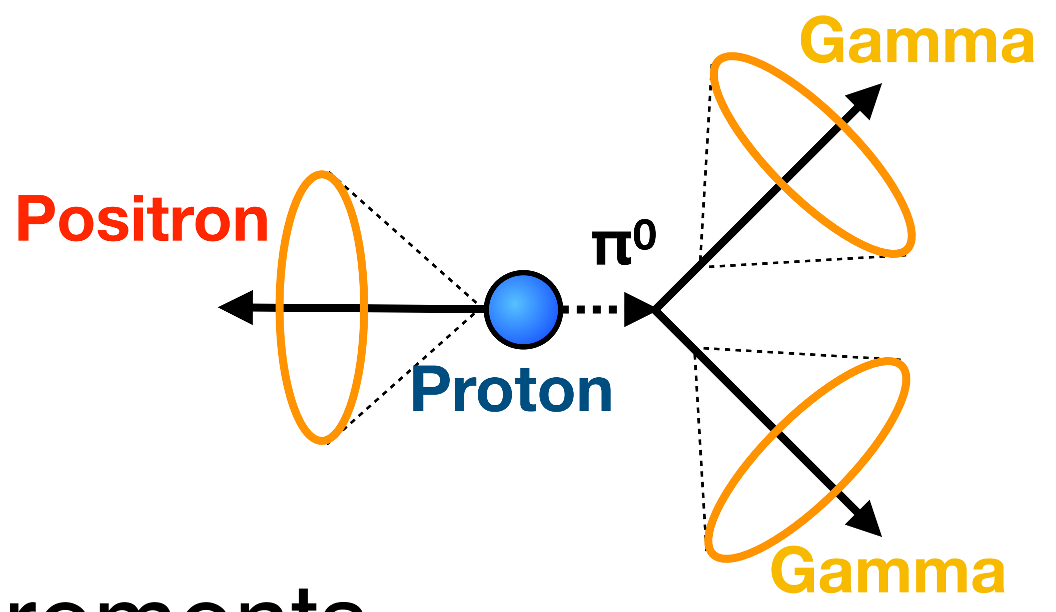
- So-called up-turn (transition between MSW-vacuum oscillations) - sensitive to various (non)standard parameters
  - Current tension between standard prediction and measurements
  - High-precision measurement by among others Hyper-Kamiokande separates between statistical fluke and other non-standard physics
- Hyper-K will further probe day/night asymmetry and measure high-energy solar neutrino flux (hep)





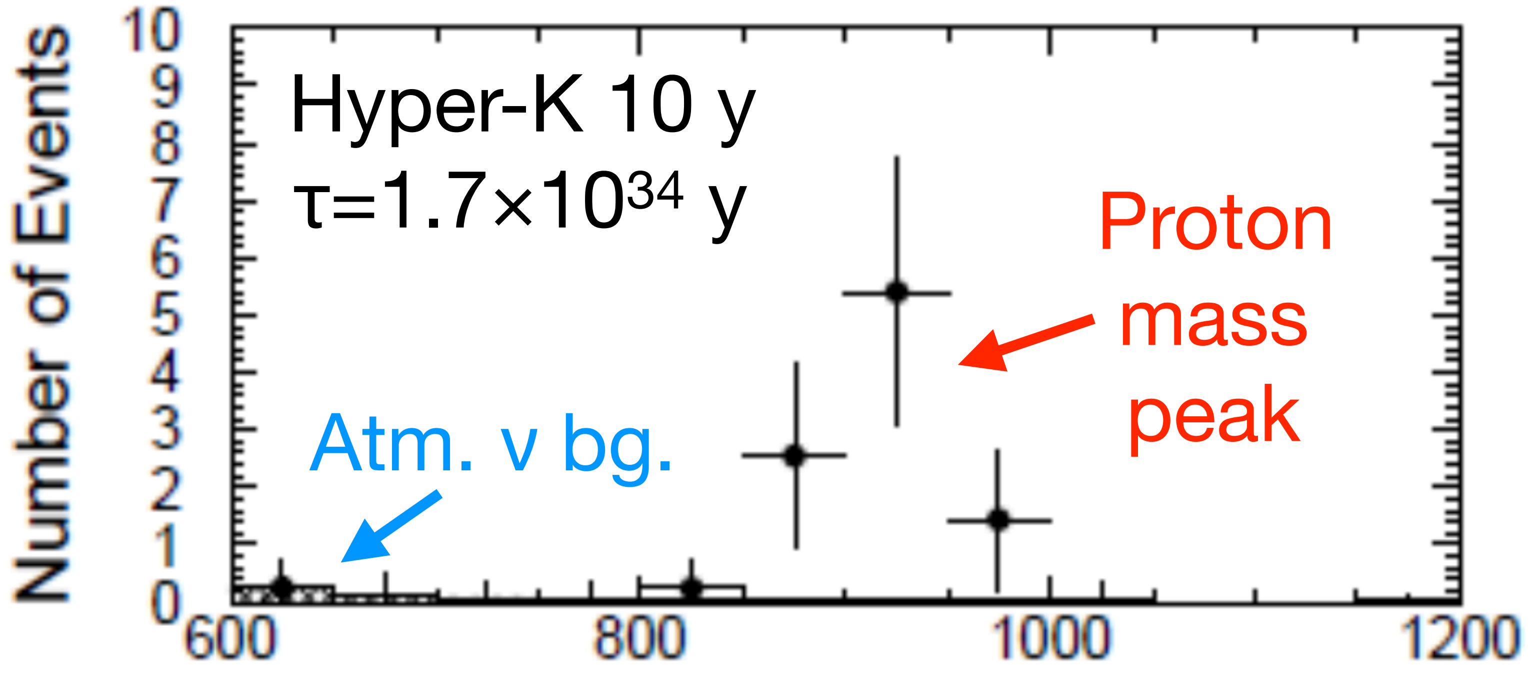
Nucleon Decay Search

- Nucleon decay present in majority of the Grand Unified Theories
- Very long lifetime - Hyper-Kamiokande balance this with very huge mass
- "Golden" channel $p \rightarrow e^+ + \pi^0$
  - Almost background free for free protons due to kinematics&topology requirements
  - Signal also from bound proton decays
- An order of magnitude improvement w.r.t. Super-K
- 3σ sensitivity for $\tau \sim 10^{35}$ y

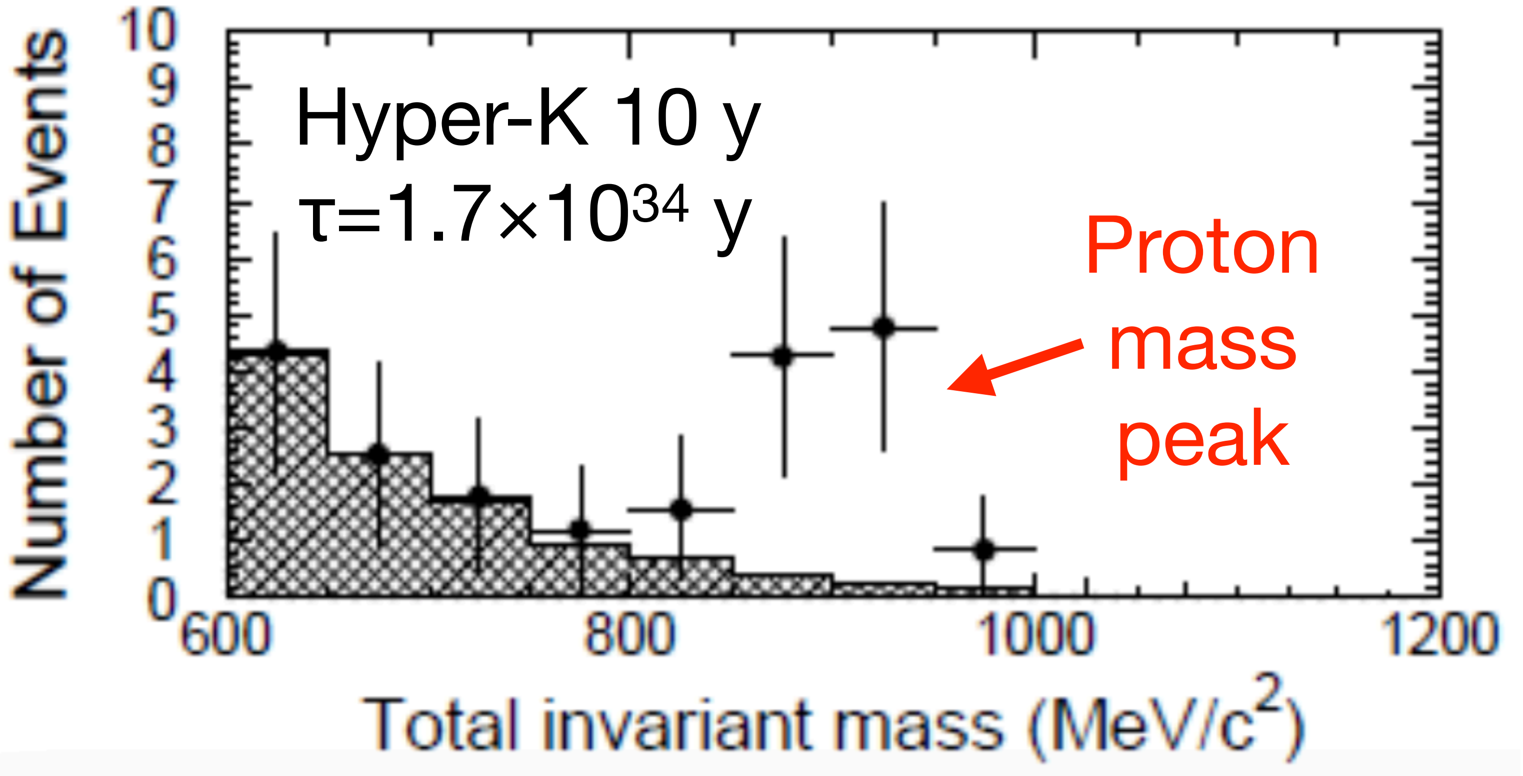


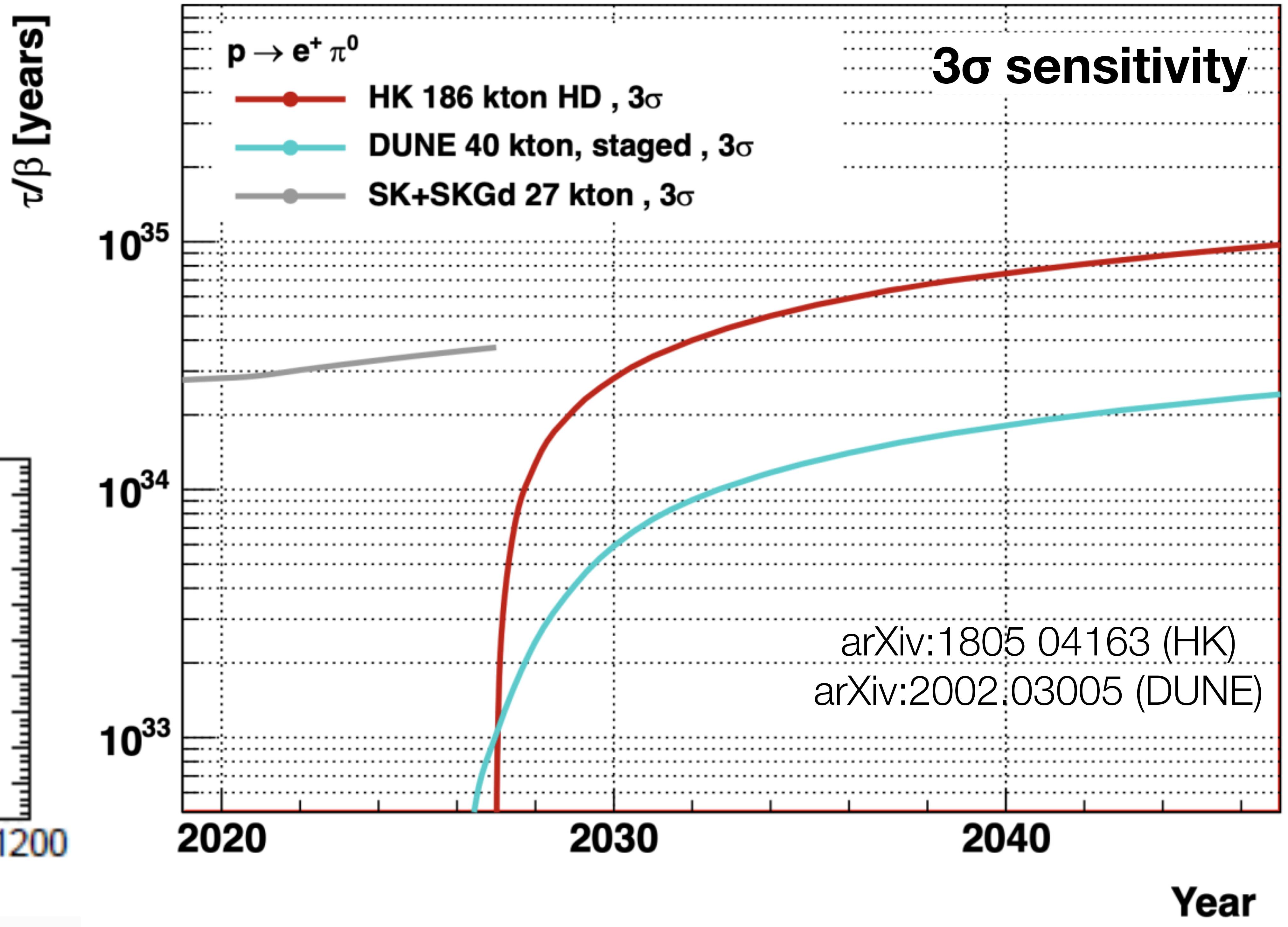
1.7×10^{34} y

Free protons



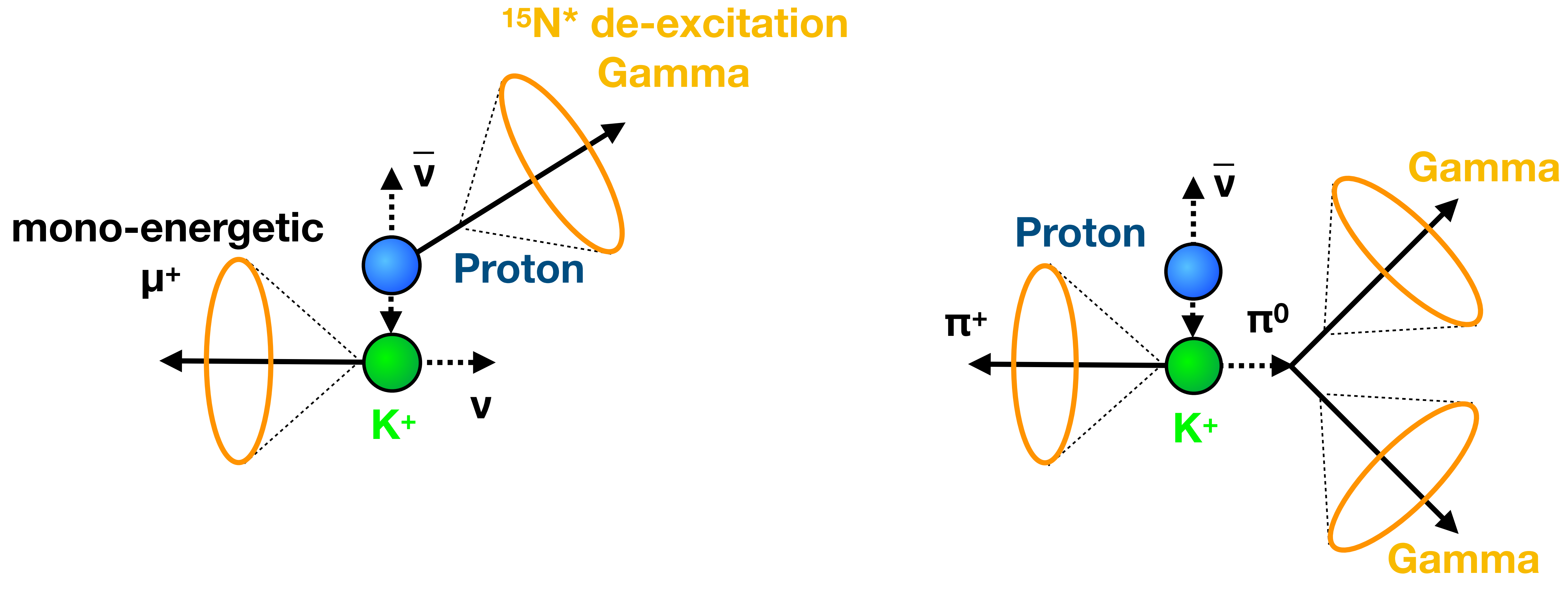
Bound protons

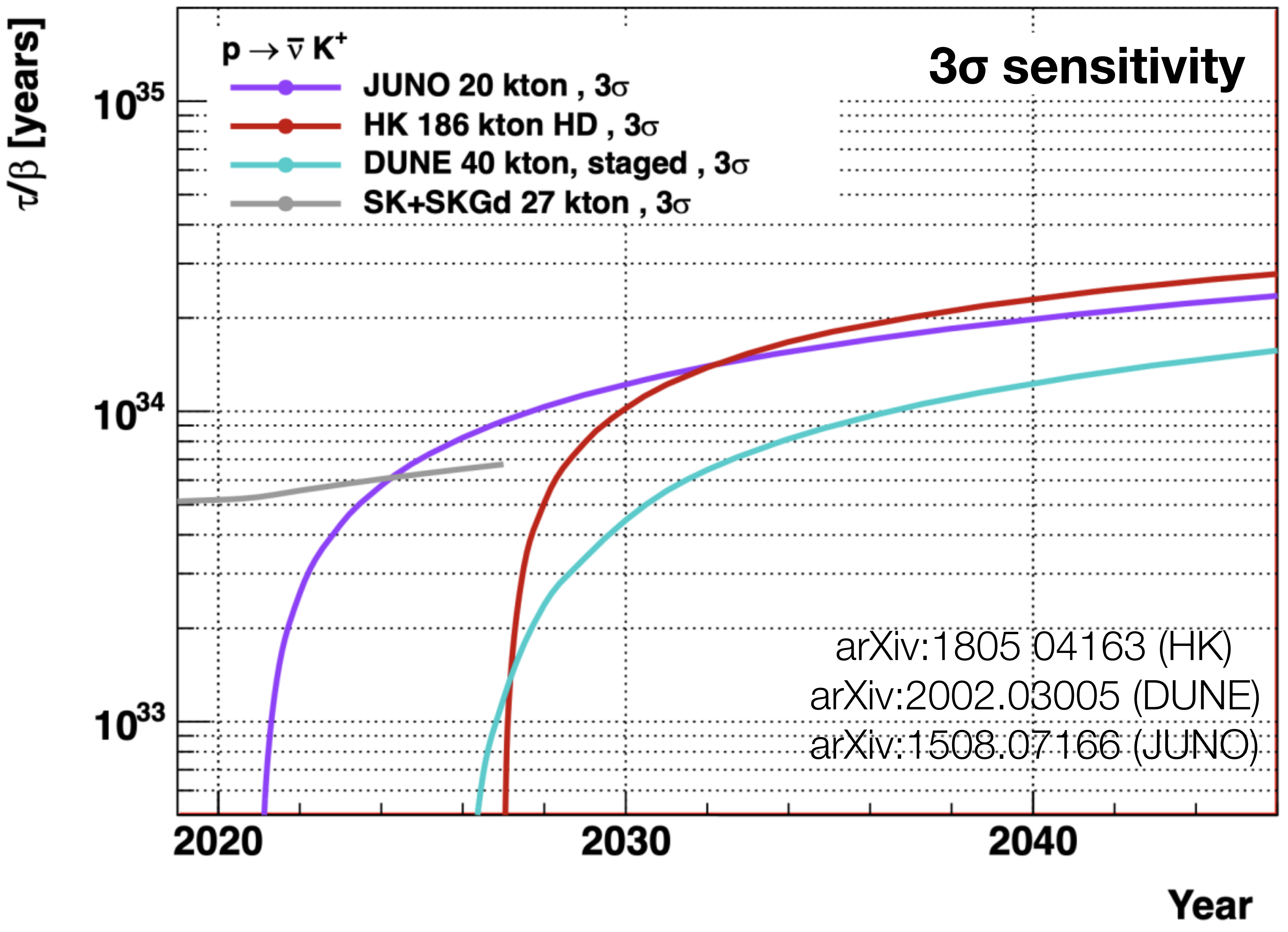




Nucleon Decay Search

- The $p \rightarrow K^+ + \bar{\nu}$ channel preferred by Supersymmetry theories
- Kaon decay signatures:
  - $K^+ \rightarrow \mu^+ + \nu_\mu$ (BR 64%) produces a mono-energetic 258 MeV muon and $^{15}N^*$ de-excitation gamma ➔ prompt-delayed signal coincidence greatly suppresses the background
  - $K^+ \rightarrow \pi^+ + \pi^0$ (BR 21%) with a clear kinematic&topology pattern
- Hyper-Kamiokande the most sensitive experiment in this channel in about a year of data taking

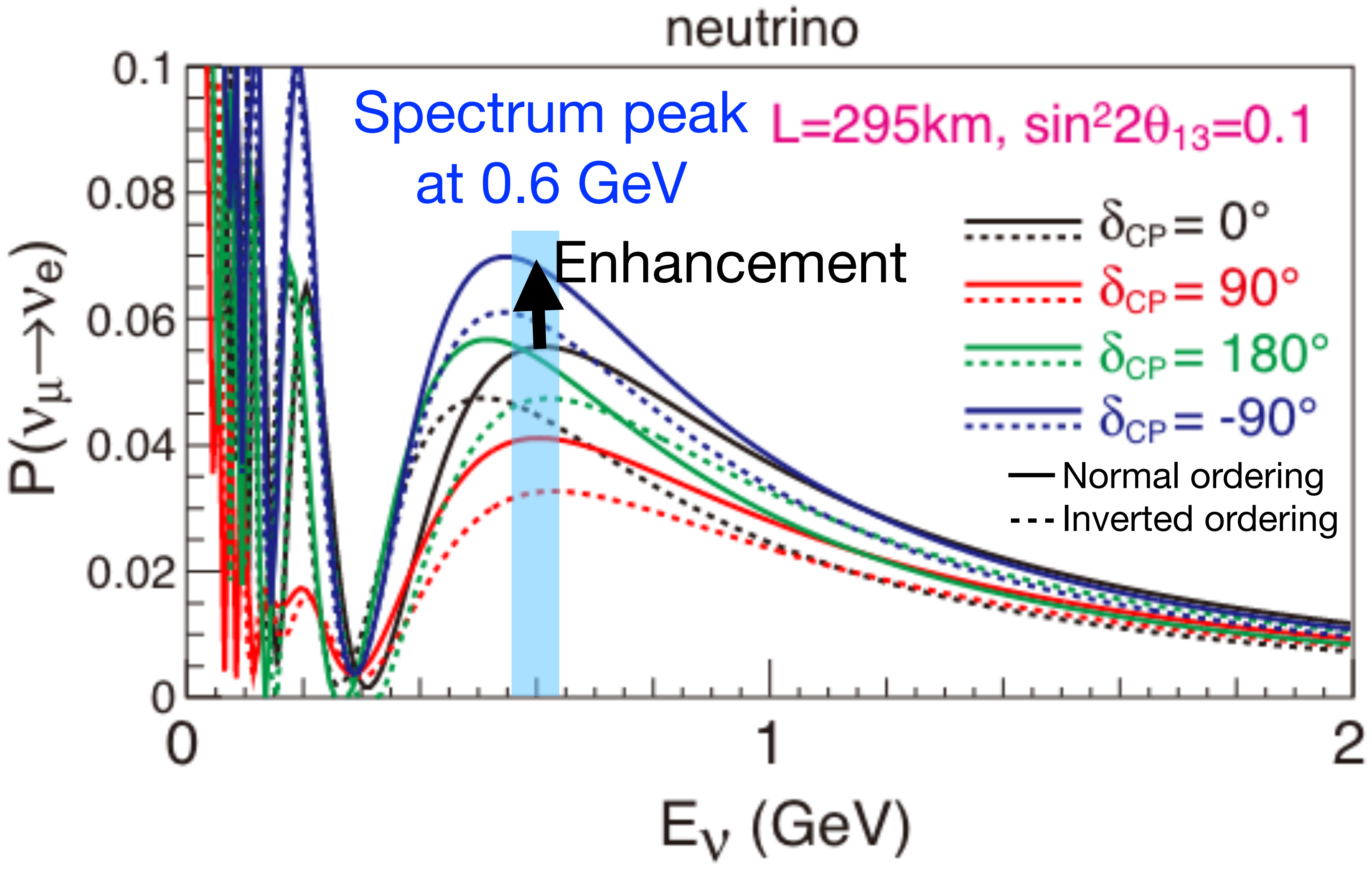


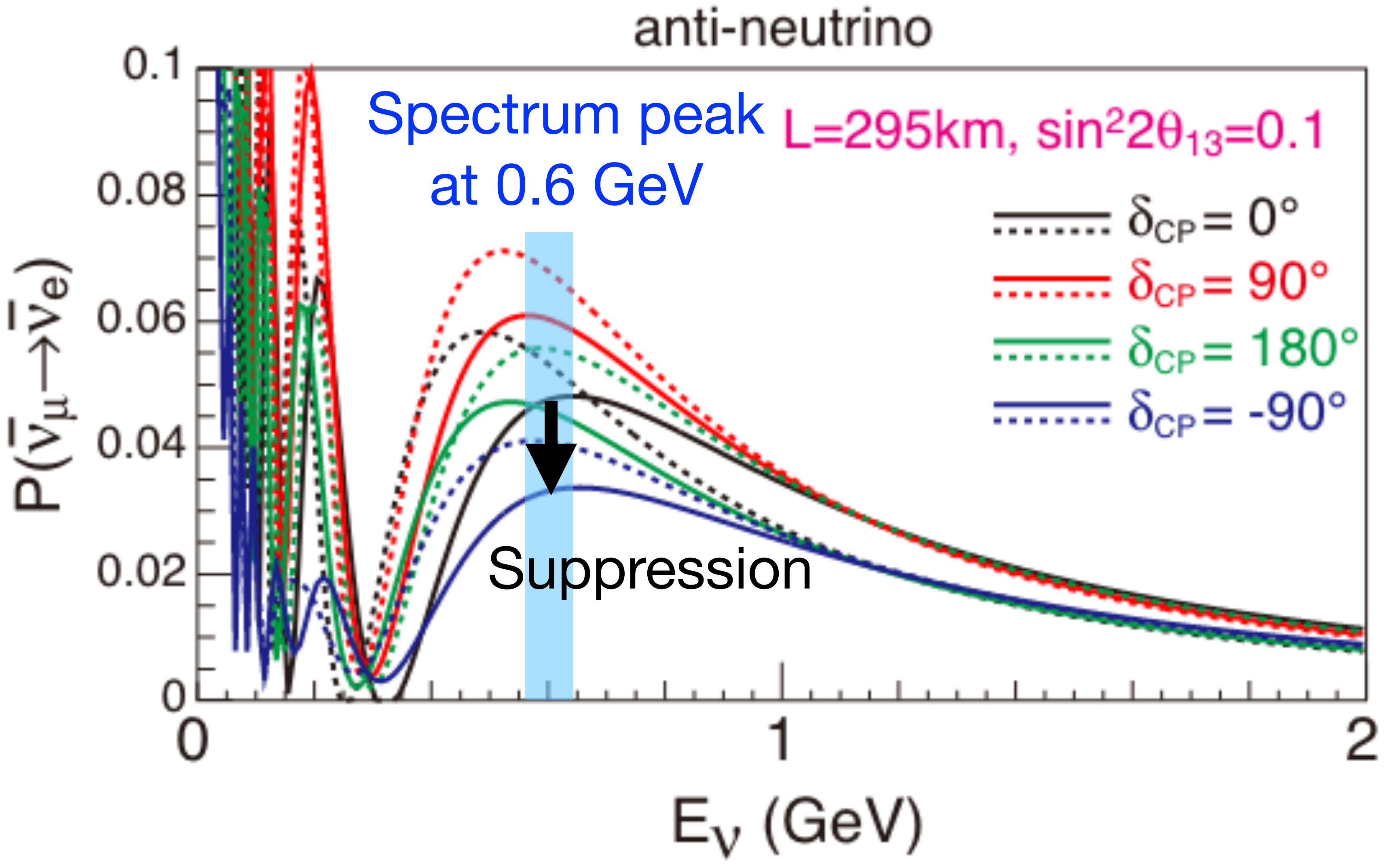


Accelerator Neutrino Long Baseline Measurement

- The narrow spectrum of 2.5° off-axis $\nu_\mu/\bar{\nu}_\mu$ beam peaks at 0.6 GeV (tuned to 295 km baseline)
- Strategy for the CP violation measurement - comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Example for δ_{CP}=-90°: probability enhancement for neutrinos vs. suppression for antineutrinos
- High statistics measurement (1.3 MW beam + huge HK det.) with ~2k events both for ν_e and $\bar{\nu}_e$ (1:3)
- Improved systematics with new/upgraded near detectors

Error model	μ-like		e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode 0 d.e.	$\bar{\nu}$-mode 0 d.e.	ν-mode 1 d.e.	$\nu/\bar{\nu}$ modes 0 d.e.
T2K 2020	3.0%	4.0%	4.7%	5.9%	14.1%	4.6%
Improved	1.2%	1.1%	2.1%	2.2%	5.2%	2.0%



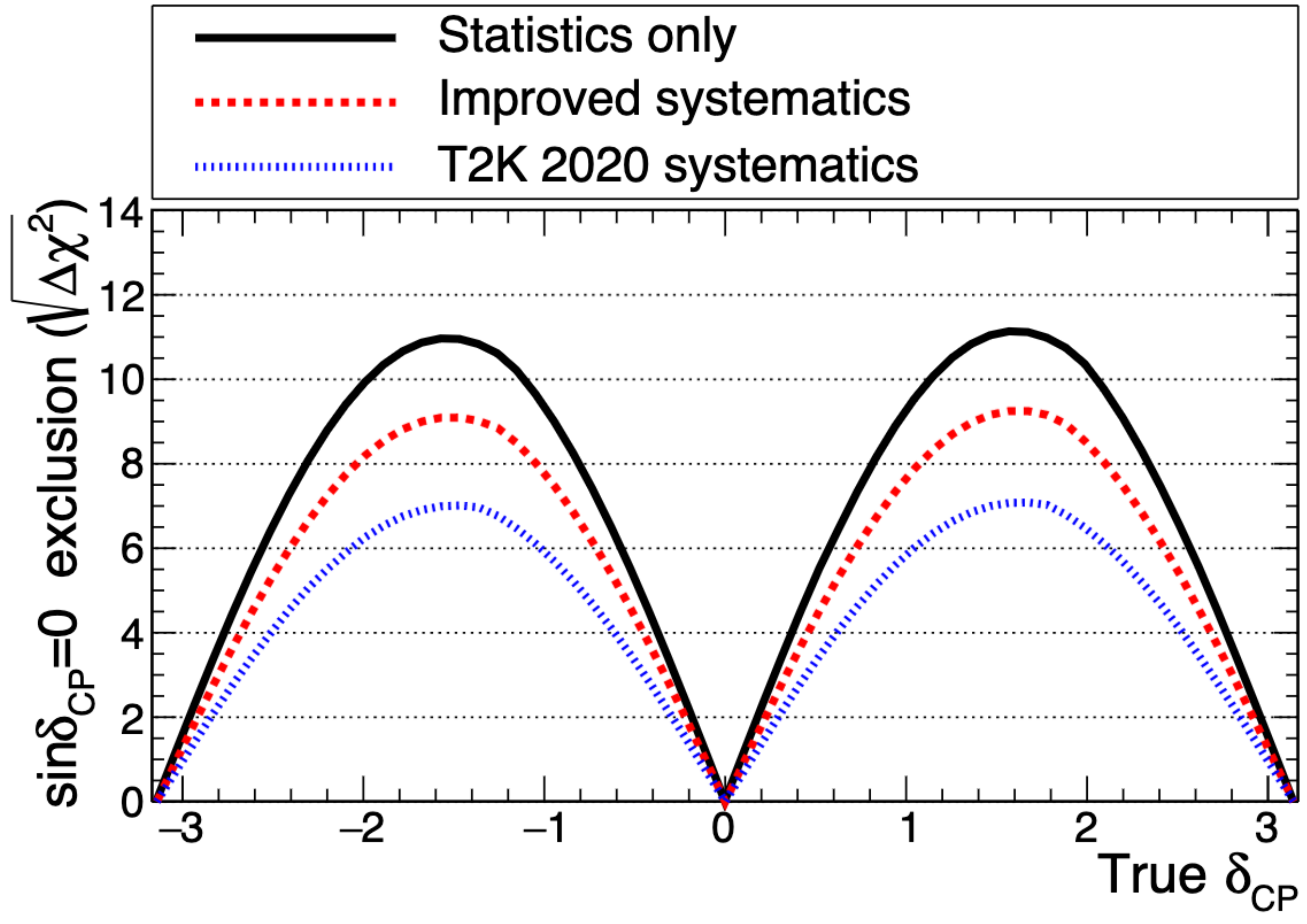


Expected event rate @ 10 years (2.7E22 POT), ν:$\bar{\nu}$ = 1:3, @ $\delta_{CP} = 0$

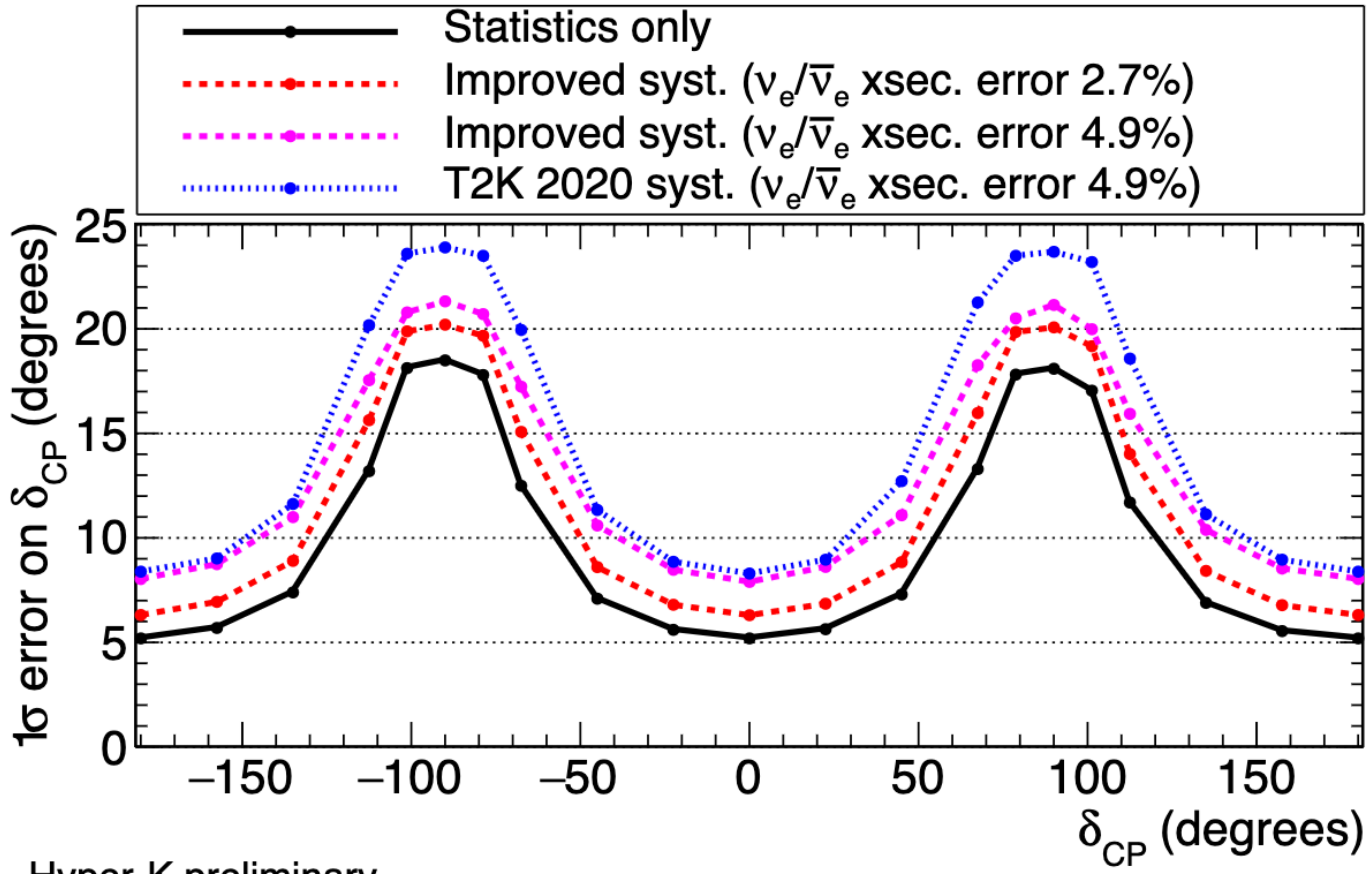
ν-mode, 1-ring μ-like	~8800
$\bar{\nu}$-mode, 1-ring μ-like	~12000
ν-mode, 1-ring e-like + 0 decay e	~2100
$\bar{\nu}$-mode, 1-ring e-like + 0 decay e	~1800
ν-mode, 1-ring e-like + 1 decay e	~300

CP Violation Sensitivity

- Excluding CP conservation for 62% of δ_{CP} parameter space @5σ in 10 y (assuming know mass ordering)
- Improved systematics has great impact
- 20.2° error at true δ_{CP}=-90°
- 6.3° error at true δ_{CP}=0°

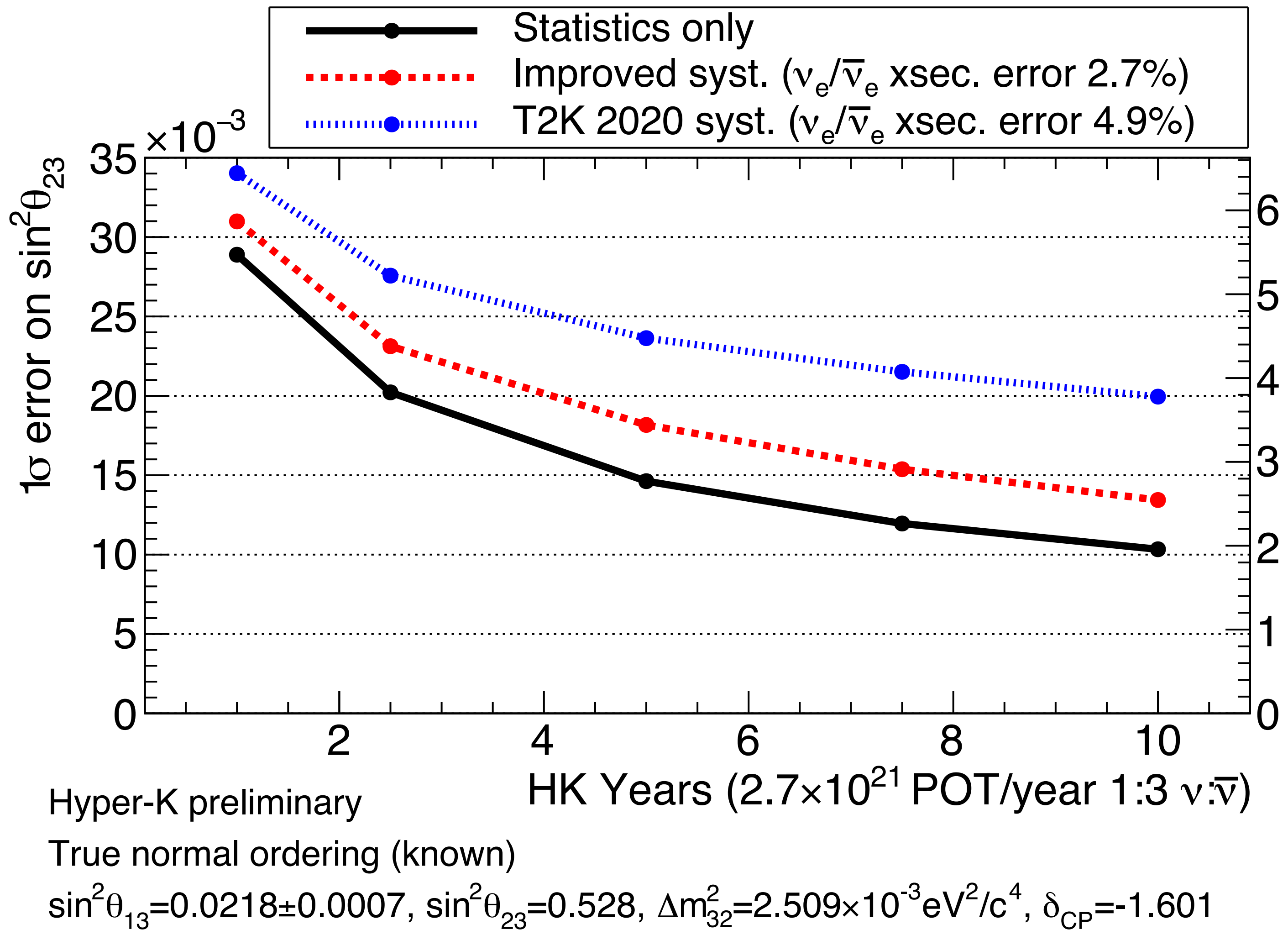


Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$

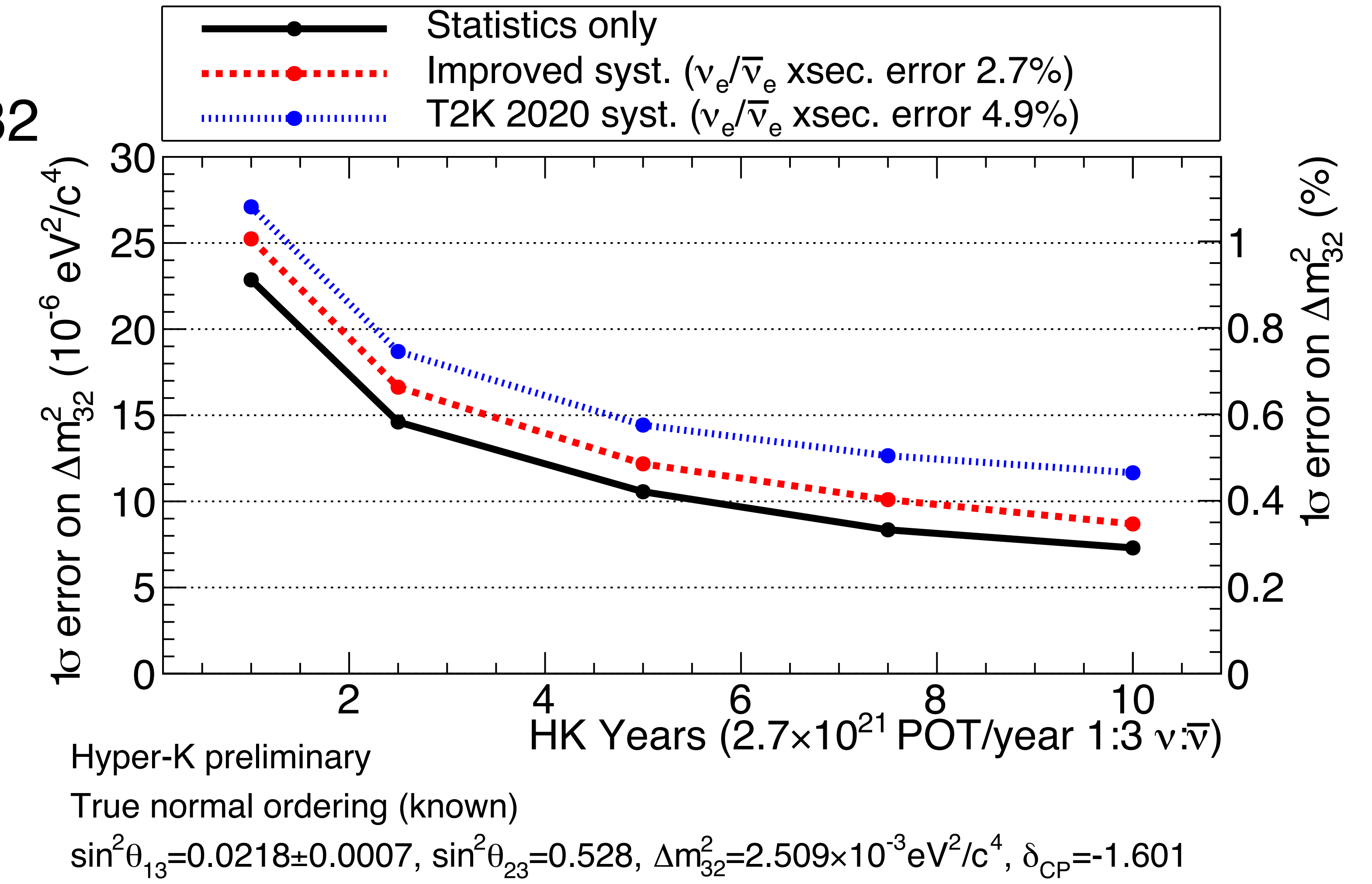


Hyper-K preliminary
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$

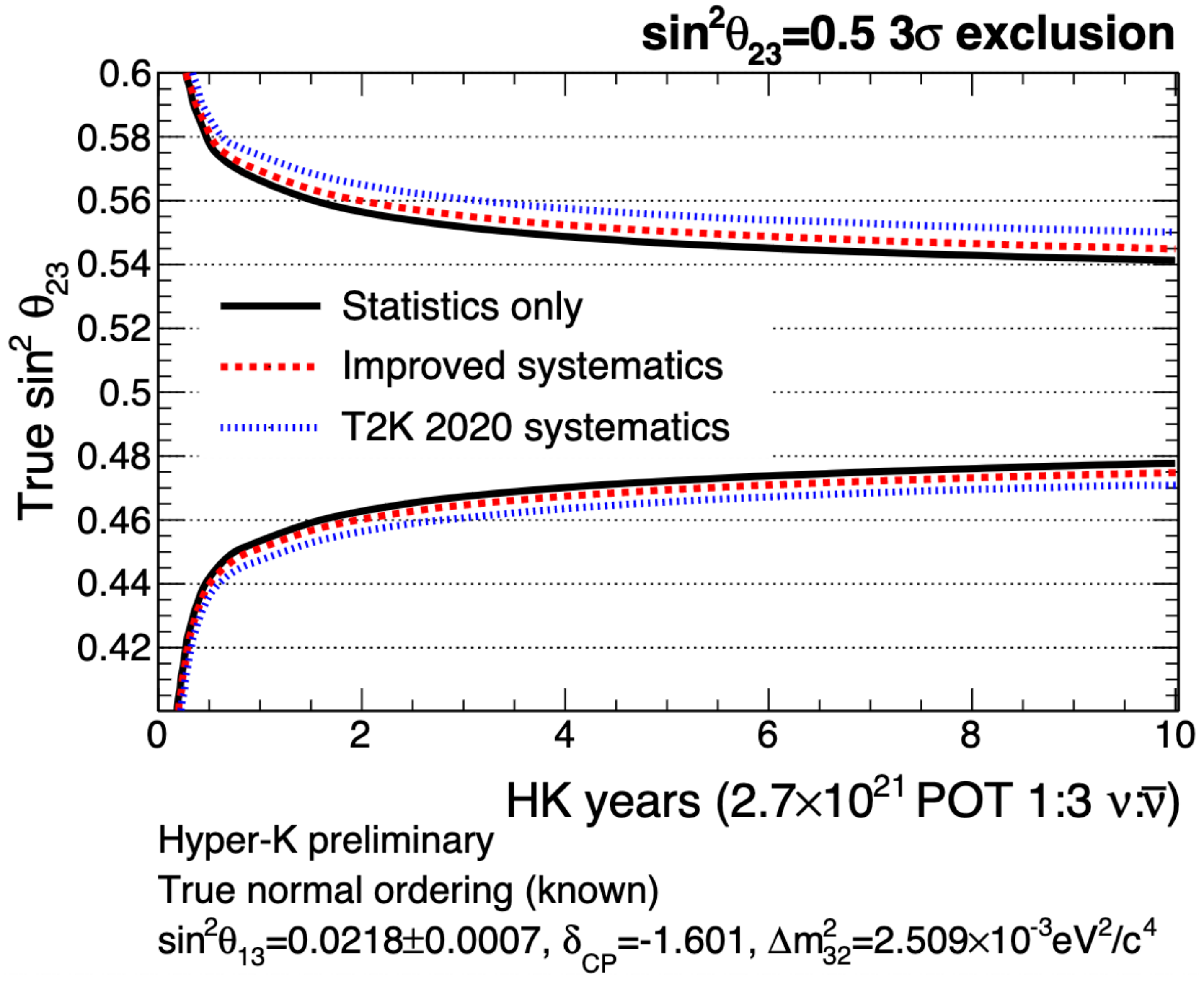
- Precision of θ_{23} 4%➔2.5%



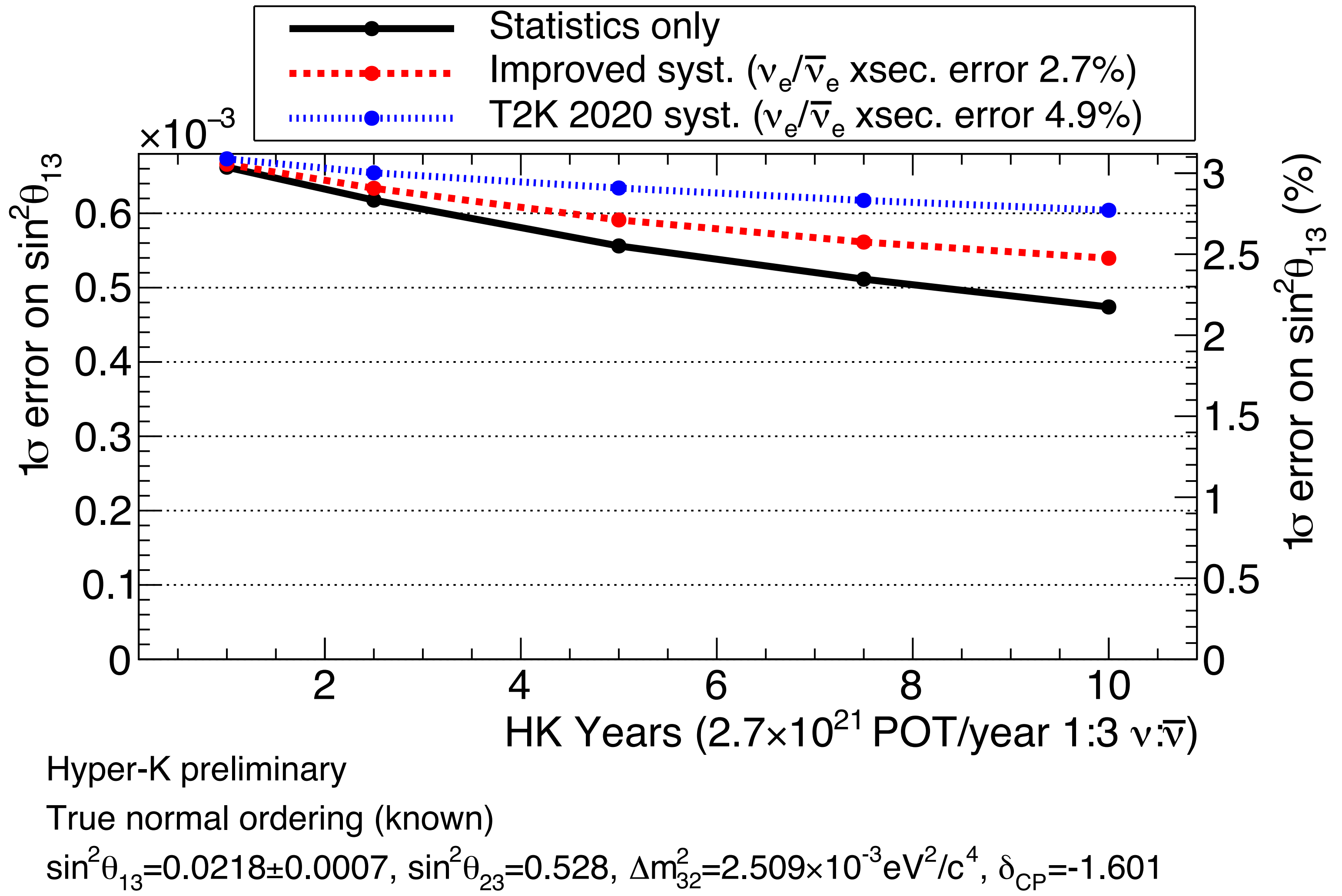
- Precision of Δm^2_{32} ~2%➔0.36%
- JUNO more precise



- Octant of θ_{23} determined at 3σ for $\Delta\theta_{23}\gtrsim2^\circ$

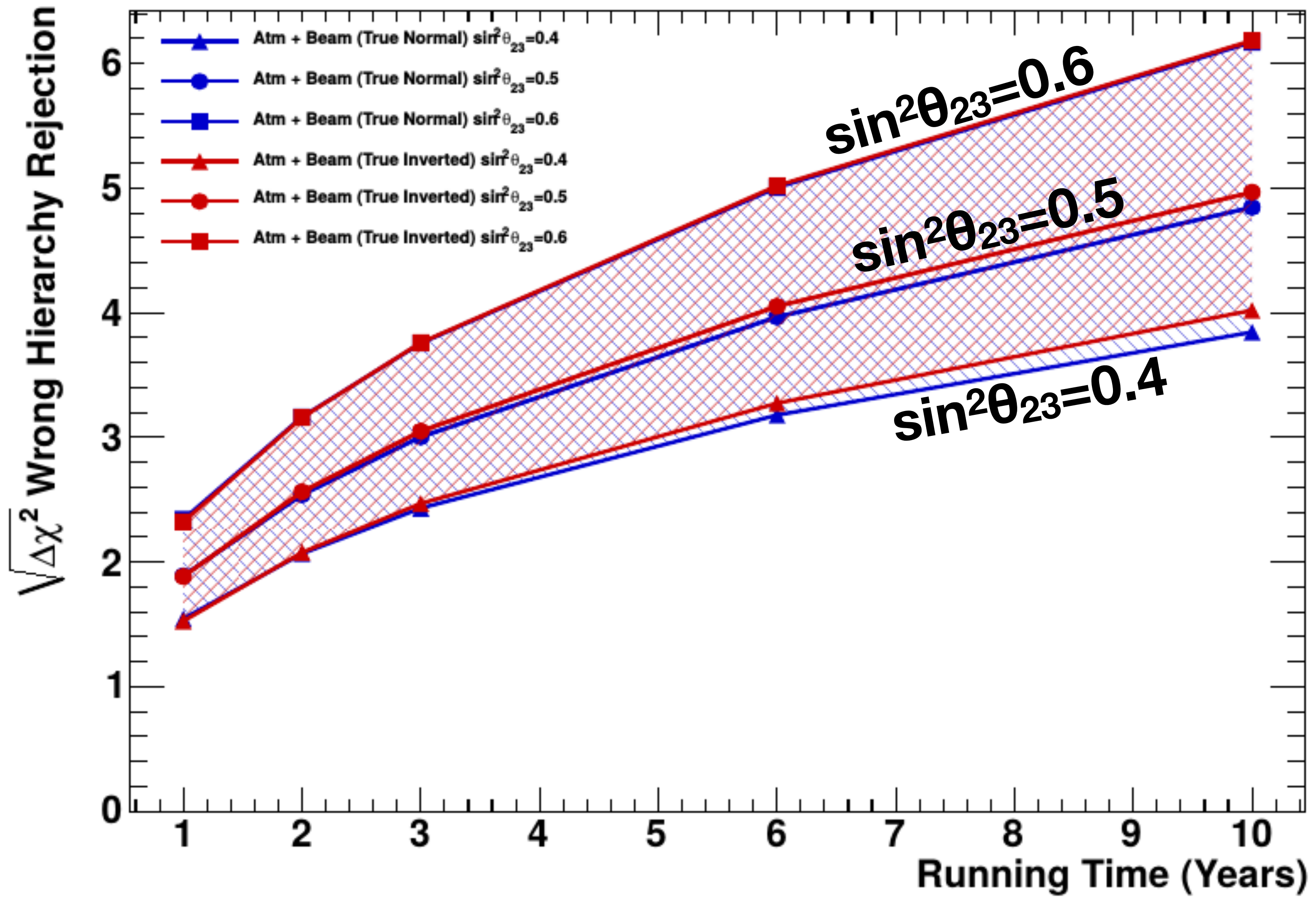


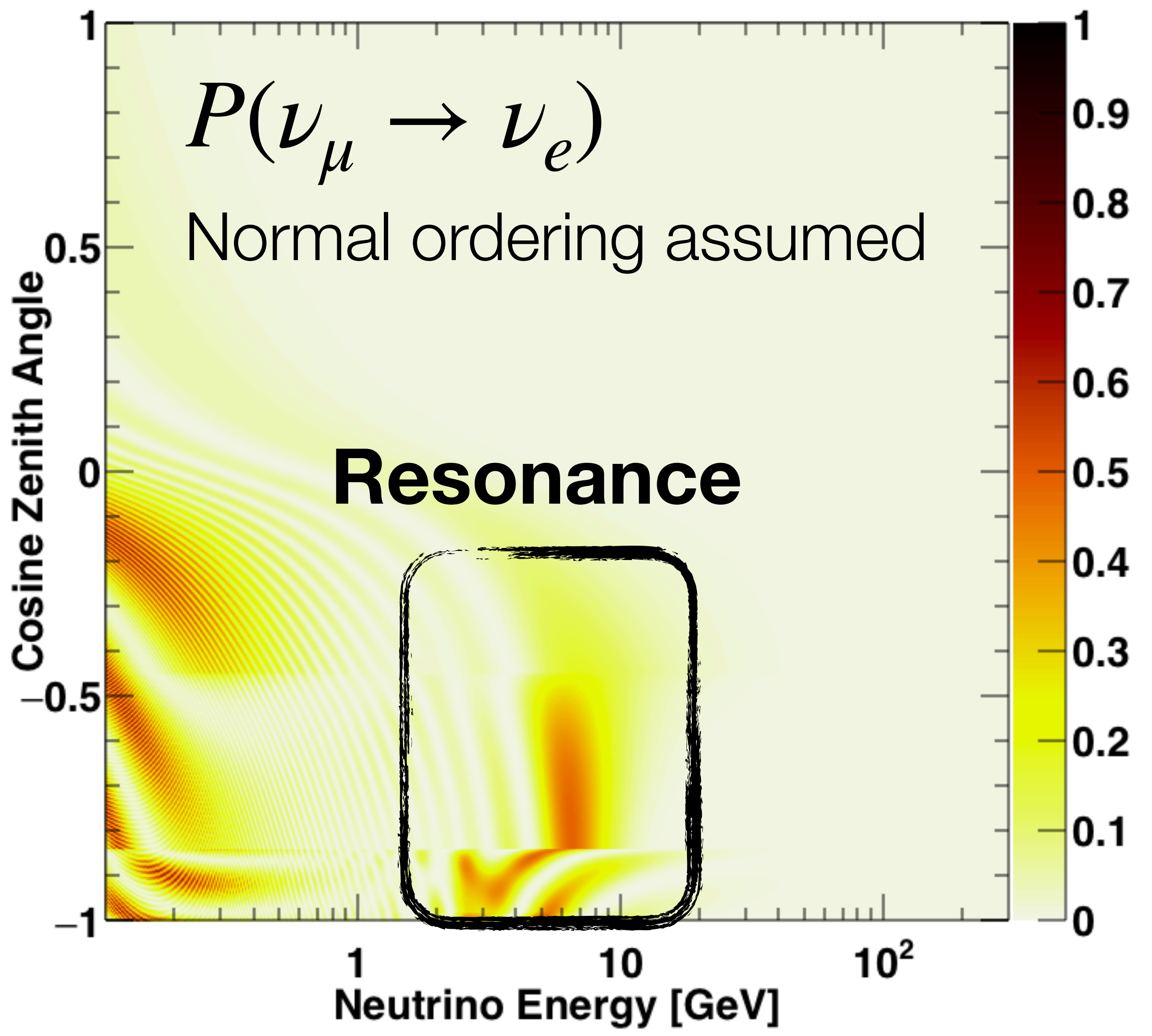
- Assuming react. constraints
- Precision of θ_{13} ~2.8%➔2.5%
- No improvement w/o constraints due to θ_{13}-θ_{23} correlation

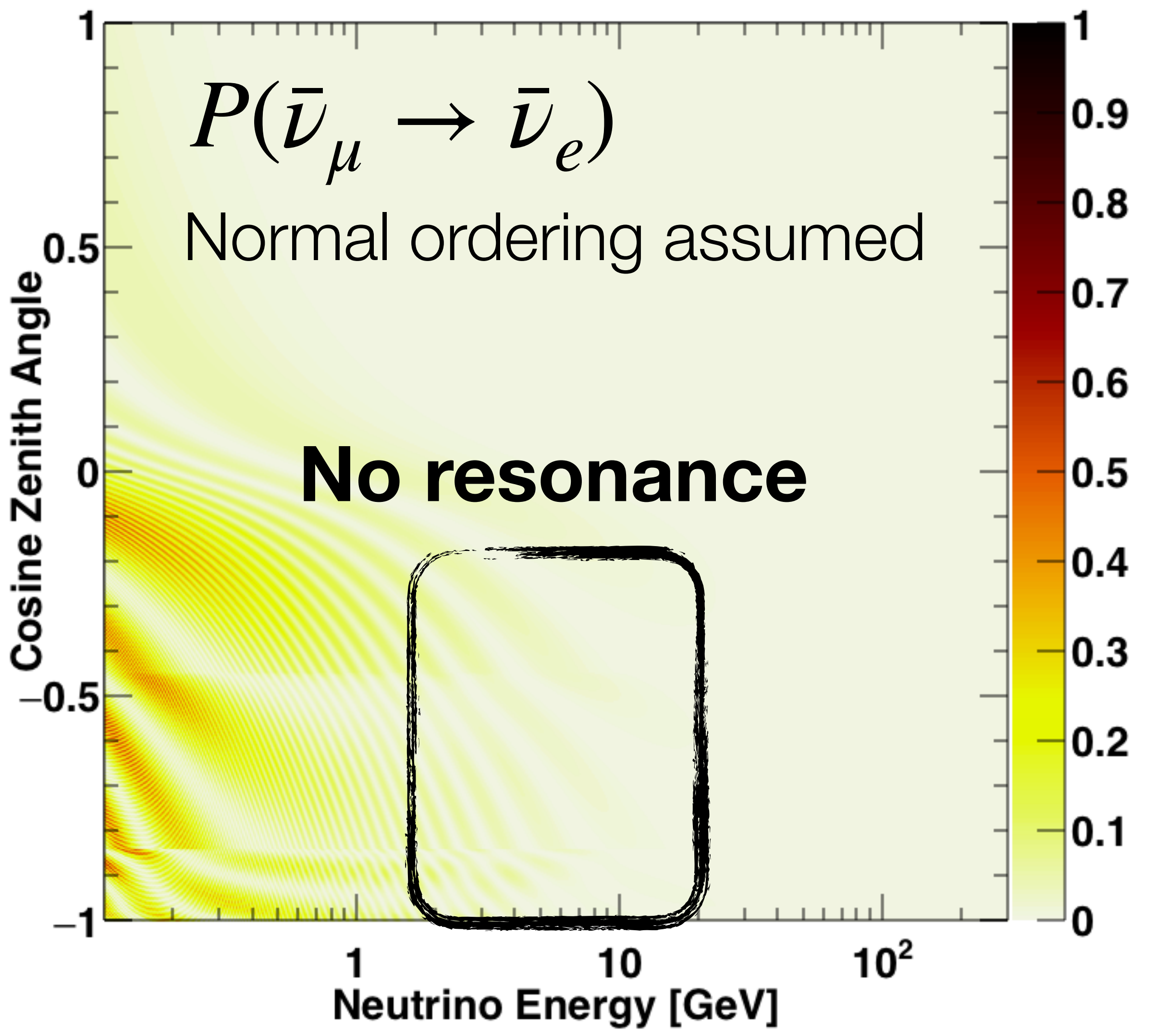


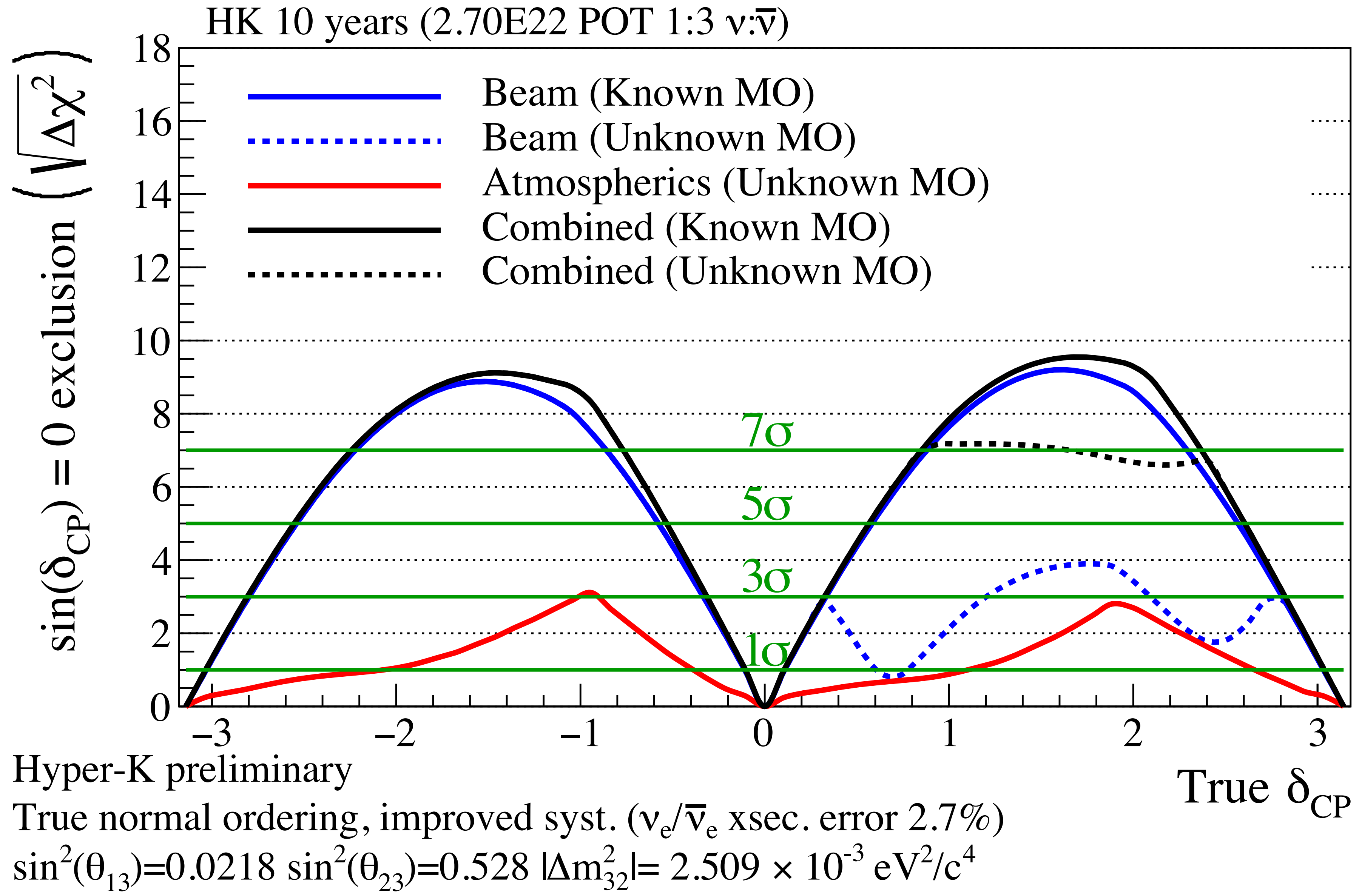
Atmospheric Neutrinos

- Atmospheric neutrinos sensitive to mass ordering through matter effect (higher energy + longer baseline in the matter)
- Breaks out degeneracy between mass ordering and δ_{CP}
  - Long baseline δ_{CP} measurement no longer relies on know ordering when combined with atmospheric neutrinos
  - Exclusion of wrong ordering on about 4-6σ in 10 y, depends on true value of θ_{23} (>3σ in 6 y)

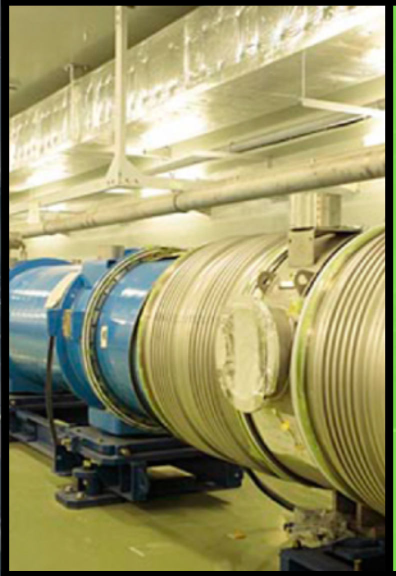
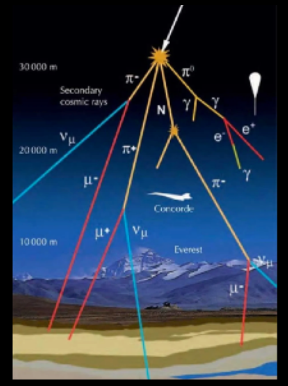
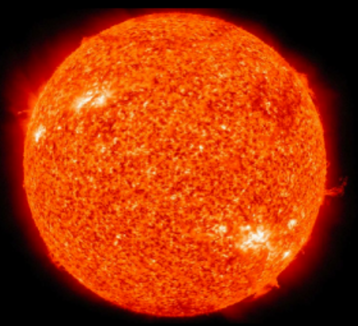
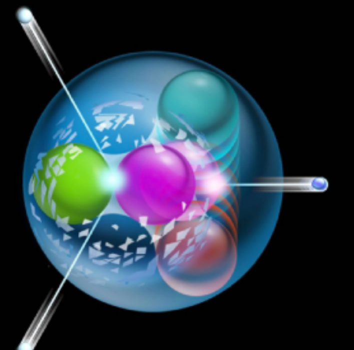






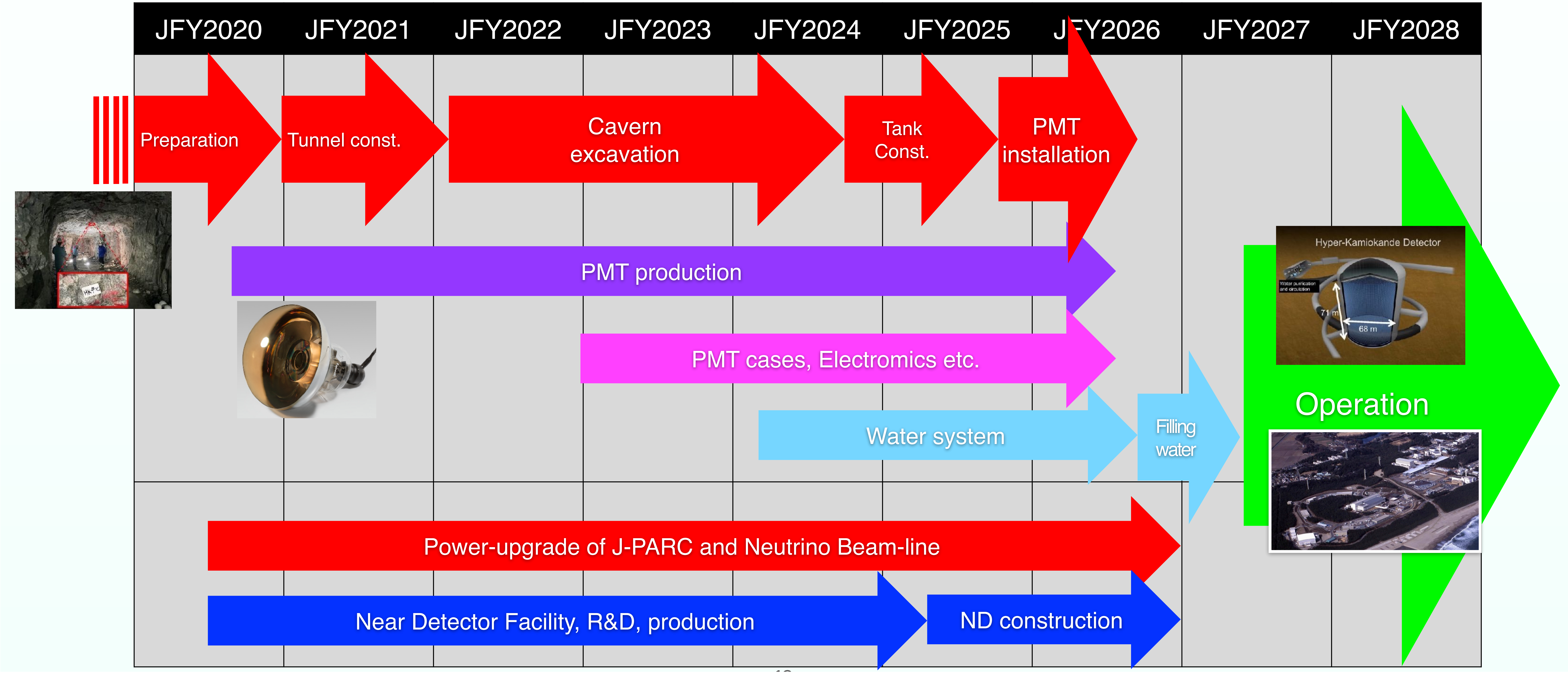


Physics Program Summary

	Physics	Parameter	Sensitivity
	Long baseline ν (1.3 MW × 10 y)	δ_{CP} precision	7-20°
		δ_{CP} coverage (3/5σ)	76%/58%
		$\sin^2\theta_{23}$ error (for 0.5)	±0.017?
	Atm. ν + LBL ν (10 y)	Mass ordering	>3.8σ
		θ_{23} octant (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
	Supernova ν	SN burst @ 10 kpc	54k-90k ν's
		SN Relic ν (10 y)	~70 ν's
	Solar ν (10 y)	Upturn	>3σ
		Day/Night asymmetry	8σ
	Proton decay (20 y)	τ for $p \rightarrow e^+\pi^0$ (3σ)	1×10^{35} y
		τ for $p \rightarrow K^+\nu$ (3σ)	3×10^{34} y

Schedule

- Construction: 2020-2027 - on time
- Operation: 2027 -

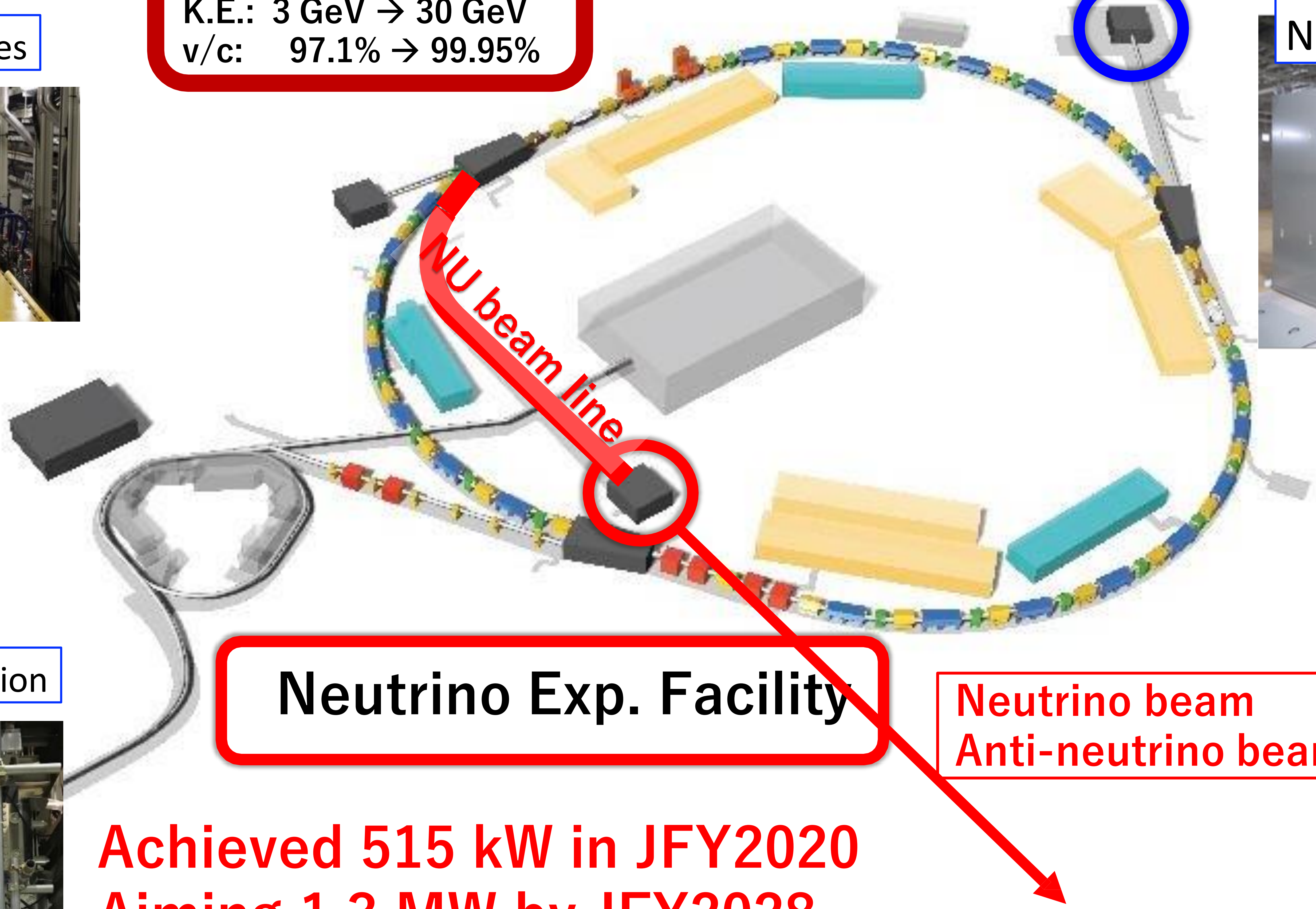


J-PARC Beam Upgrade

J-PARC

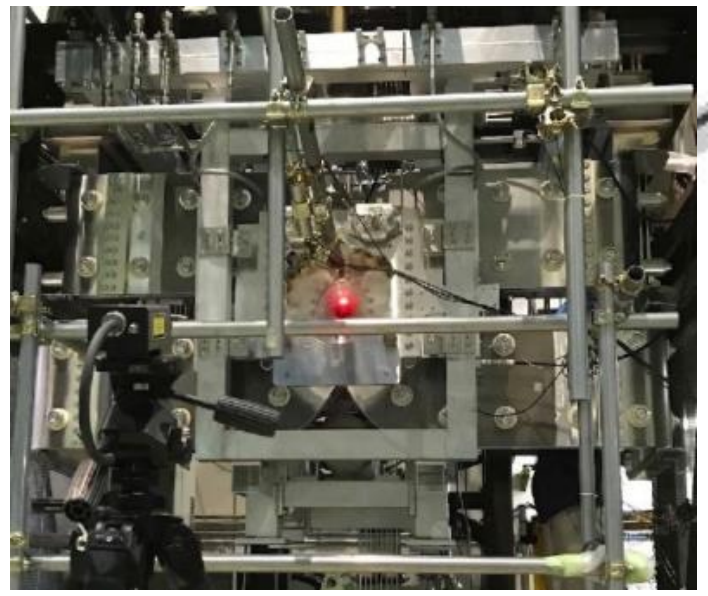
MR-RF cavities

Main Ring
Circumference 1.567.5 m
K.E.: 3 GeV → 30 GeV
v/c: 97.1% → 99.95%



New main magnet PS for high rep. rate

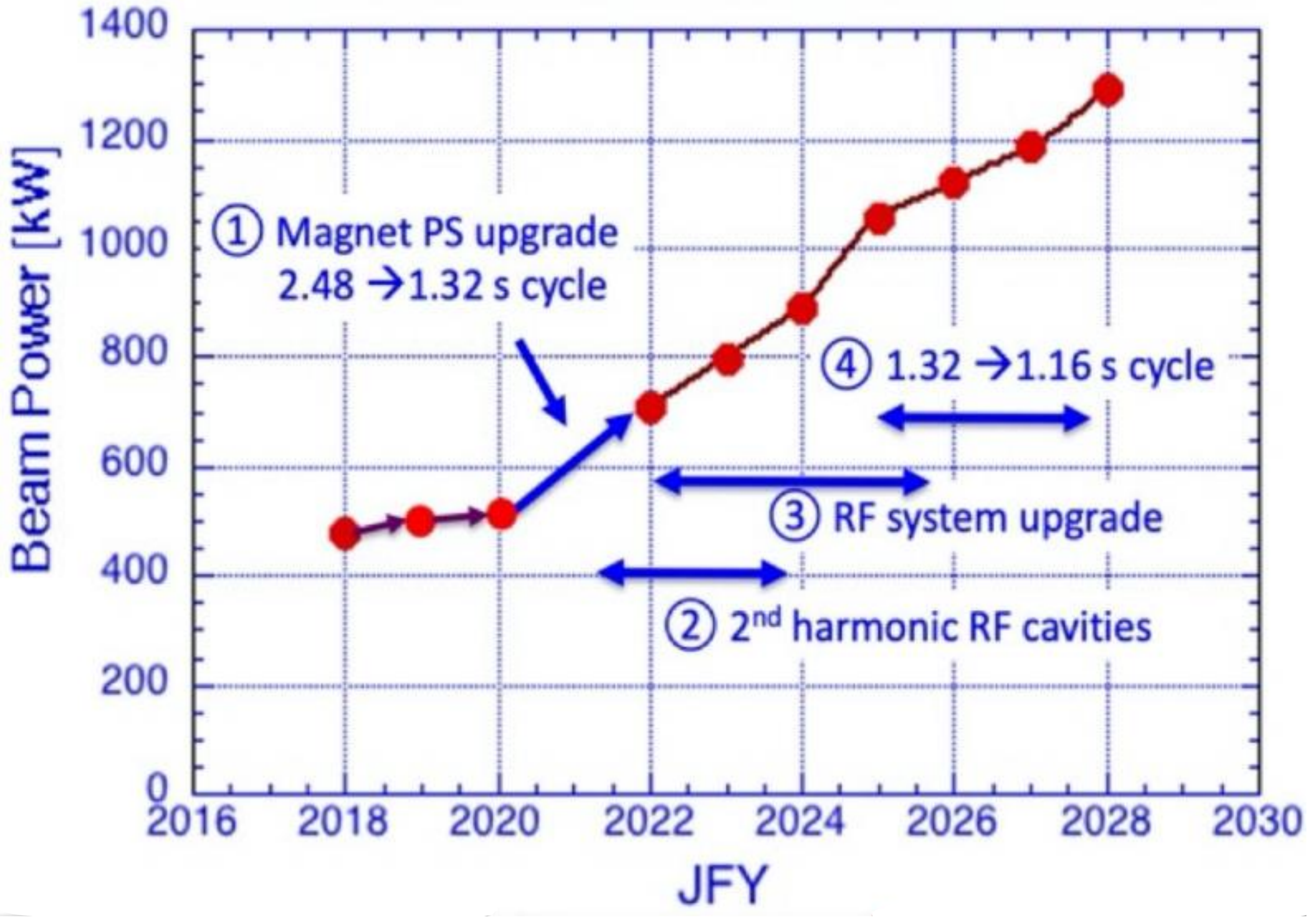
320kA horn operation



Neutrino Exp. Facility

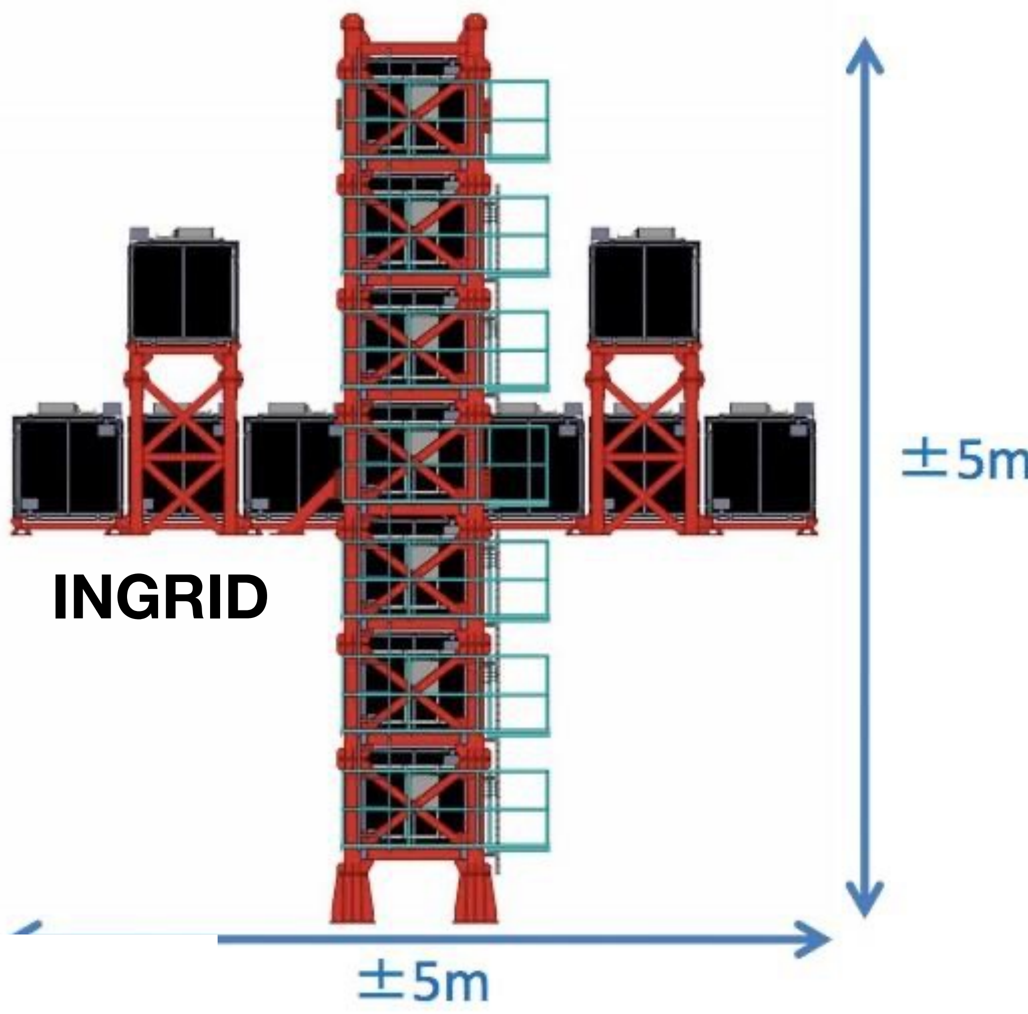
Neutrino beam
Anti-neutrino beam

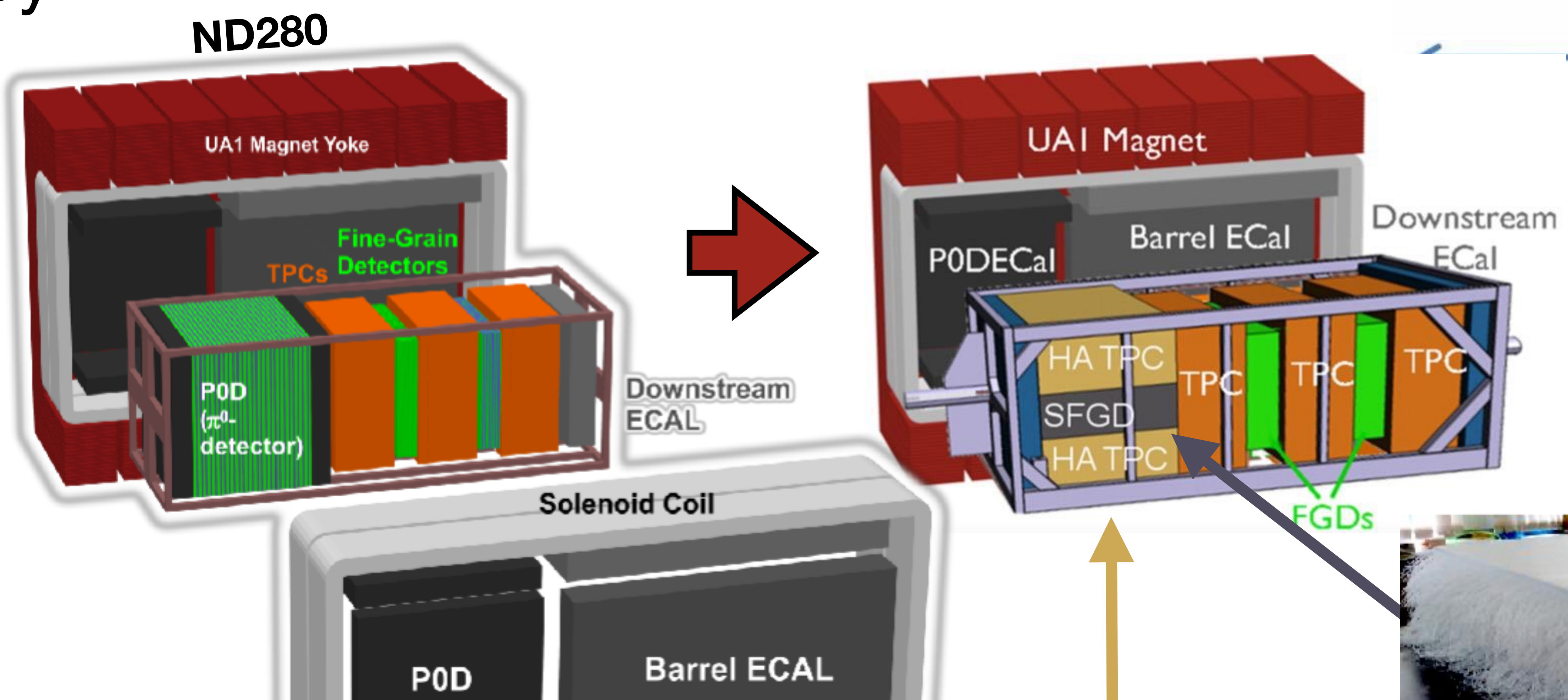
Achieved 515 kW in JFY2020
Aiming 1.3 MW by JFY2028

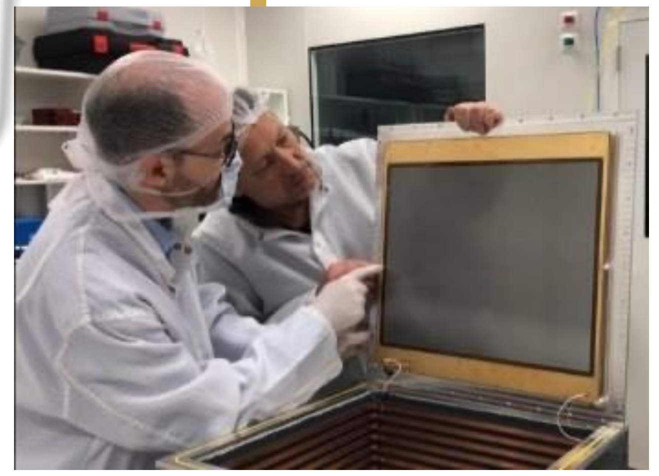


Near Detectors

- Near detectors common with T2K - upgrades planned for T2K and Hyper-K
- On-axis detector INGRID - measures beam direction and monitors flux
- Off-axis detector ND280 - primary measures (anti)neutrino rate and spectrum, magnetized to separate wrong-sign background
  - Upgrade for/by T2K: P0D replaced by
    - Super fine-grained detector
    - High-angle TPCs
    - Time-of-flight planes
  - Further upgrades for Hyper-K era under investigation





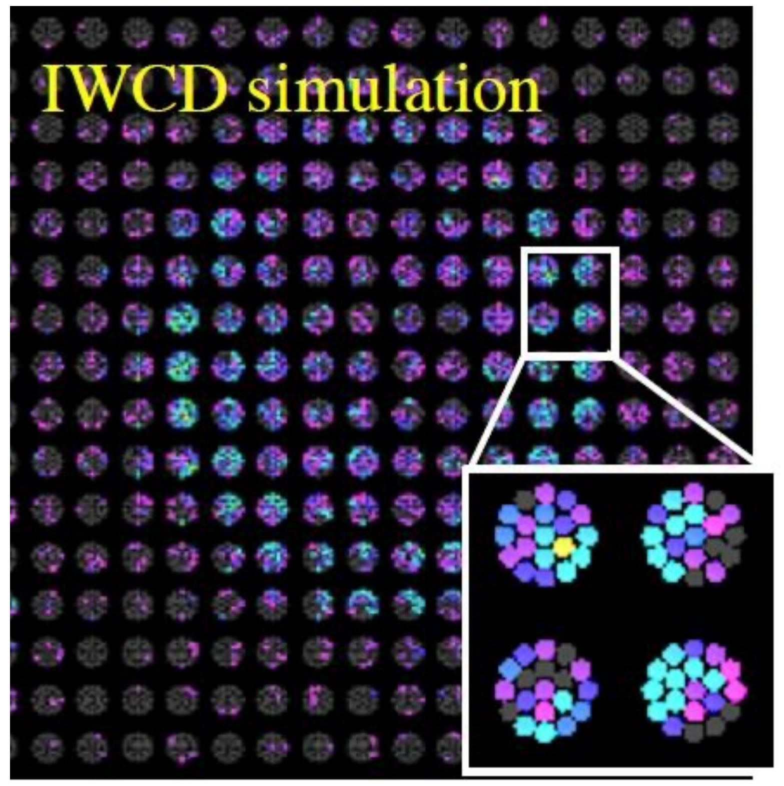


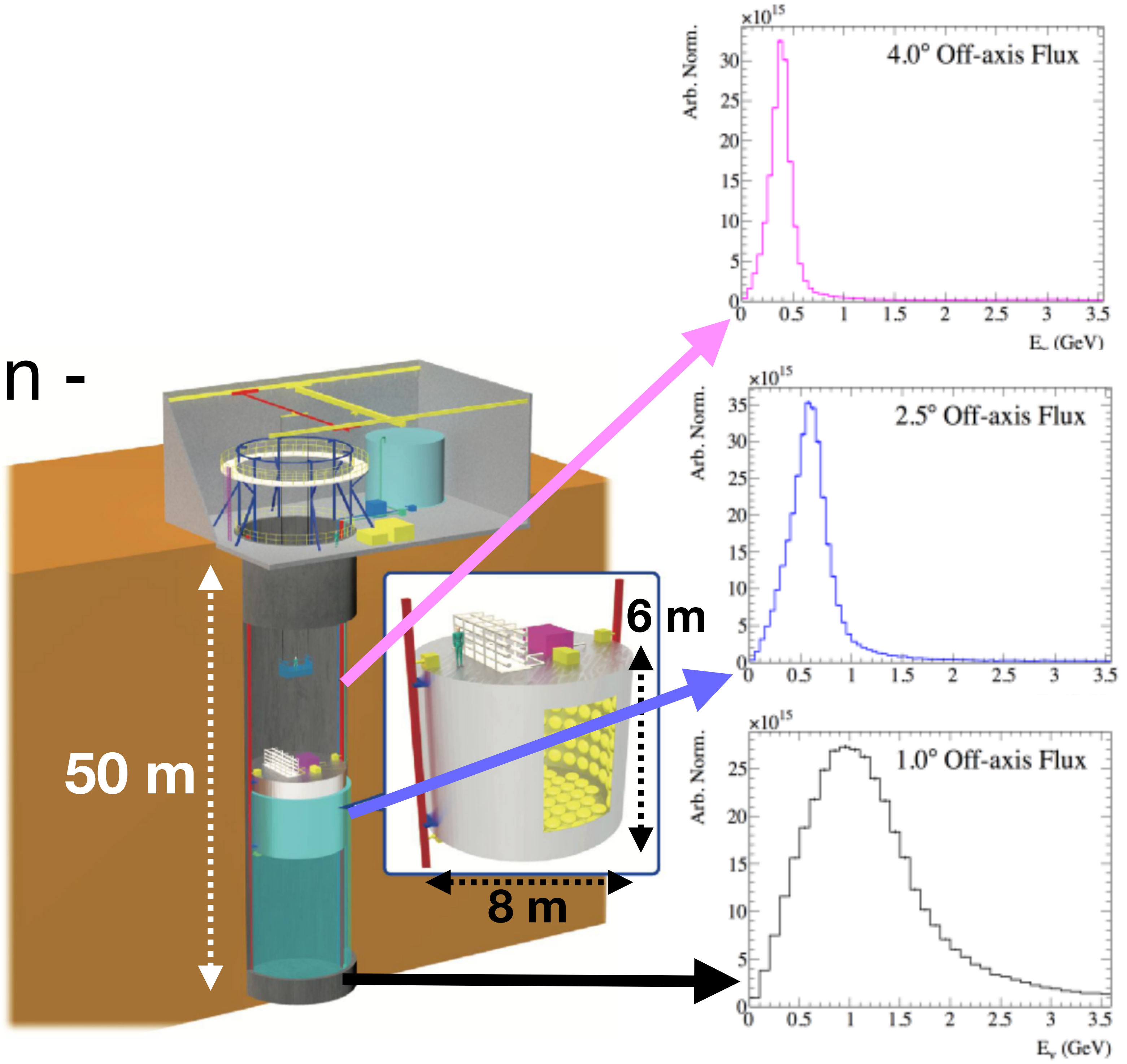
High-angle TPC

Super fine-grained det. (SFGD)

Intermediate Water Cherenkov Detector

- Newly constructed movable (1°to 4° off-axis) 1 kt water Cherenkov detector at ~1 km from target
- Instrumented with 400 multi-PMT modules
  - 19 8 cm PMTs, dedicated fast electronics, etc.
  - High granularity and superb time resolution
- Precise cross-section measurement
  - Same target material and detection technique as Hyper-K
  - Reduction of dominant systematics of $\nu_e/\bar{\nu}_e$ interaction cross section - ND280+IWCD complementary reduce the systematics ≲3% (alone ≲7.5% and ≲3.7% respectively)
- Precise measurement of the (anti)neutrino spectrum
  - Sampling at different off-axis angles to get a spectrum prediction for the Hyper-Kamiokande far detector





Far Detector - 3rd Generation of Successful Experiments

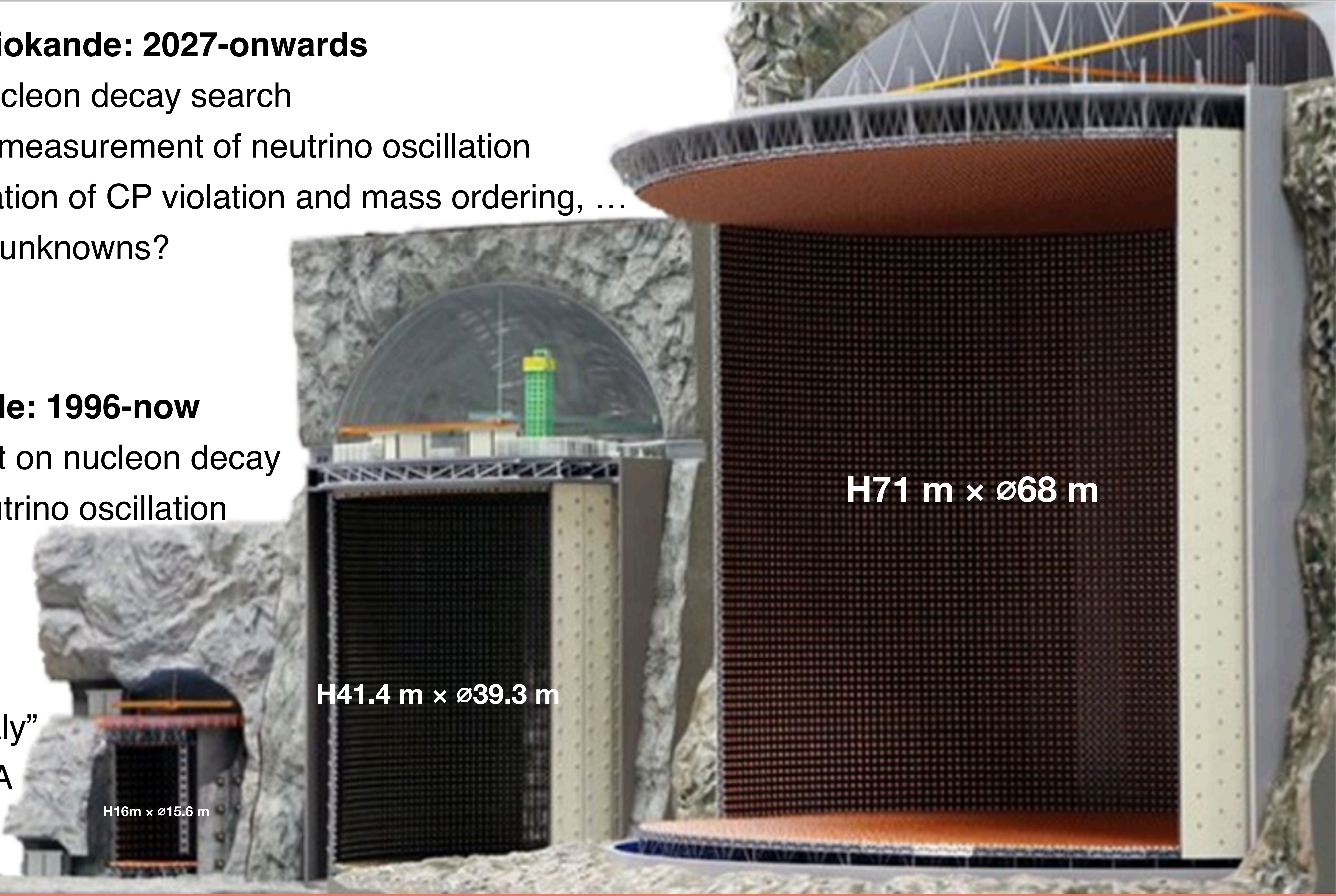
- **Hyper-Kamiokande: 2027-onwards**
  - Extend nucleon decay search
  - Precision measurement of neutrino oscillation
  - Determination of CP violation and mass ordering, …
  - Unknown unknowns?

×8.4 =

- **Super-Kamiokande: 1996-now**
  - World's best limit on nucleon decay
  - Discovery of neutrino oscillation

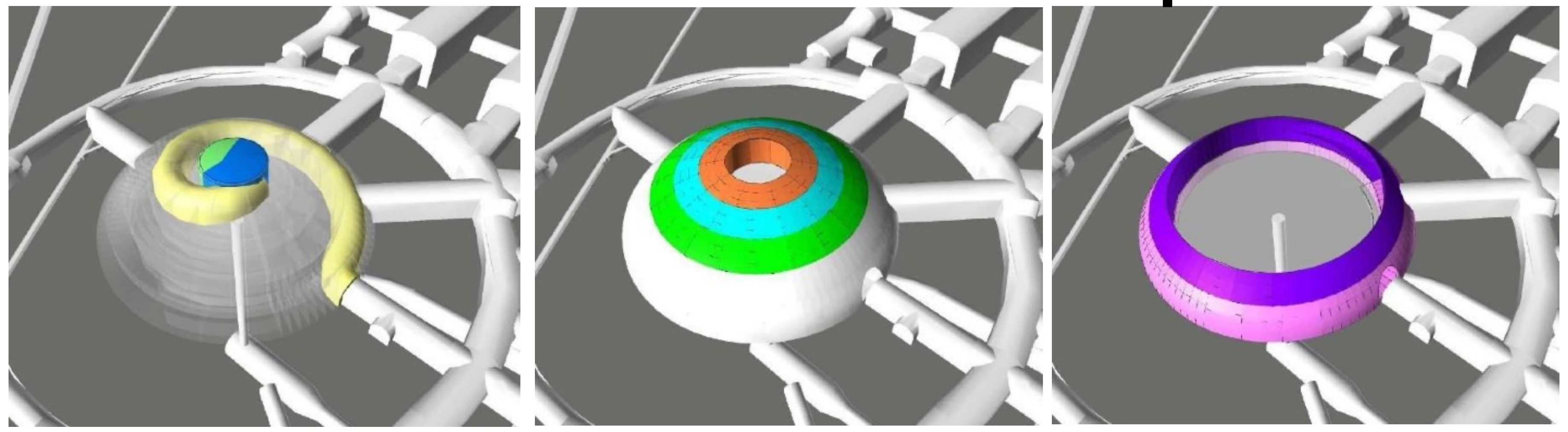
×20 =

- **Kamiokande: 1983-1996**
  - Atm. and solar neutrino "anomaly"
  - Neutrino from Supernova 1987A



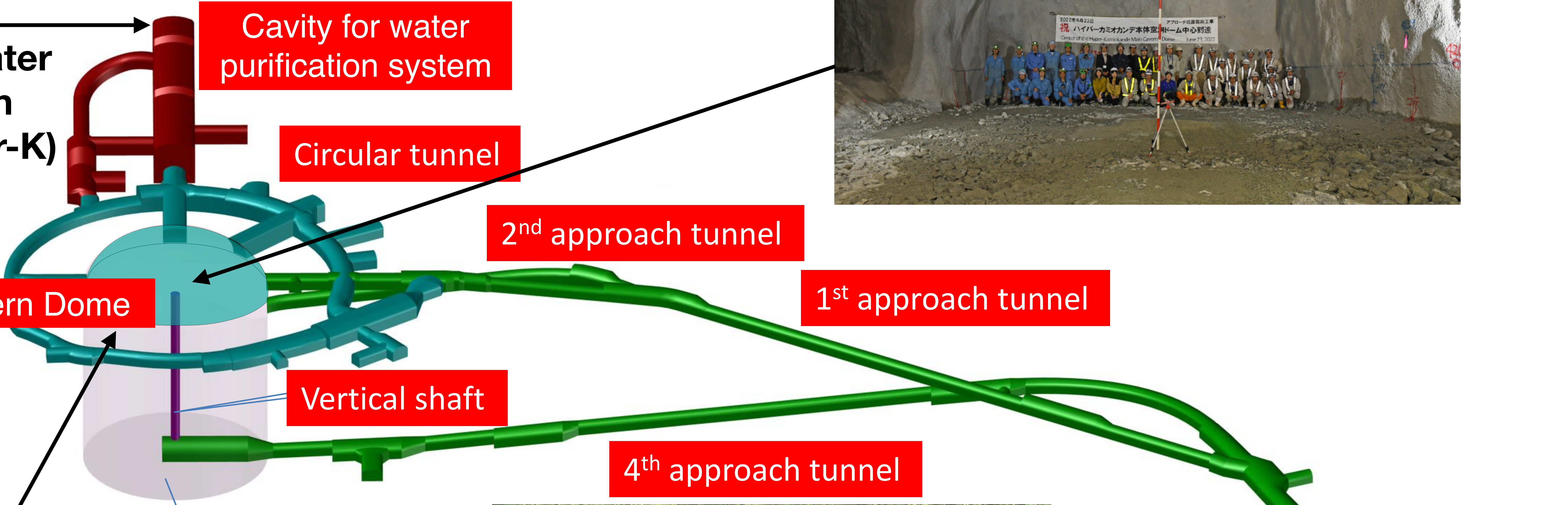
Far Detector Civil Construction on Schedule

Cavern dome excavation sequence



Center of the cavern dome reached **July 2022**

Cavity for water purification (size of Super-K)

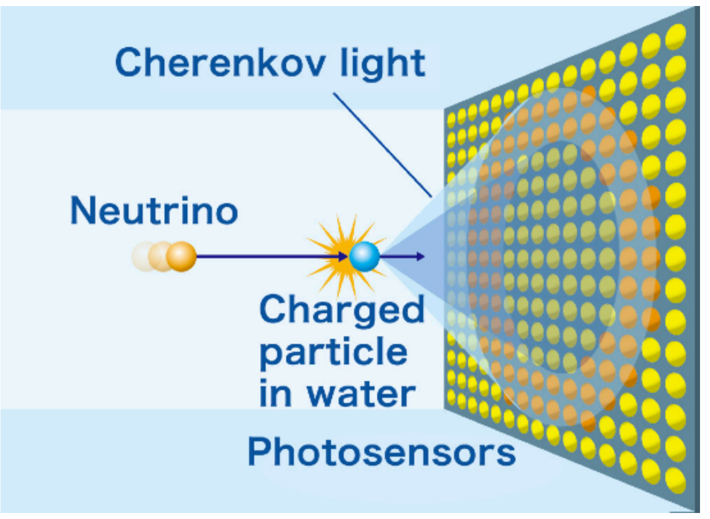


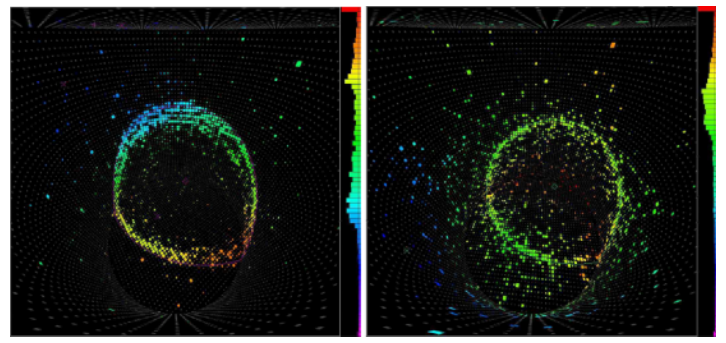
Cavern dome completed **October 2023**

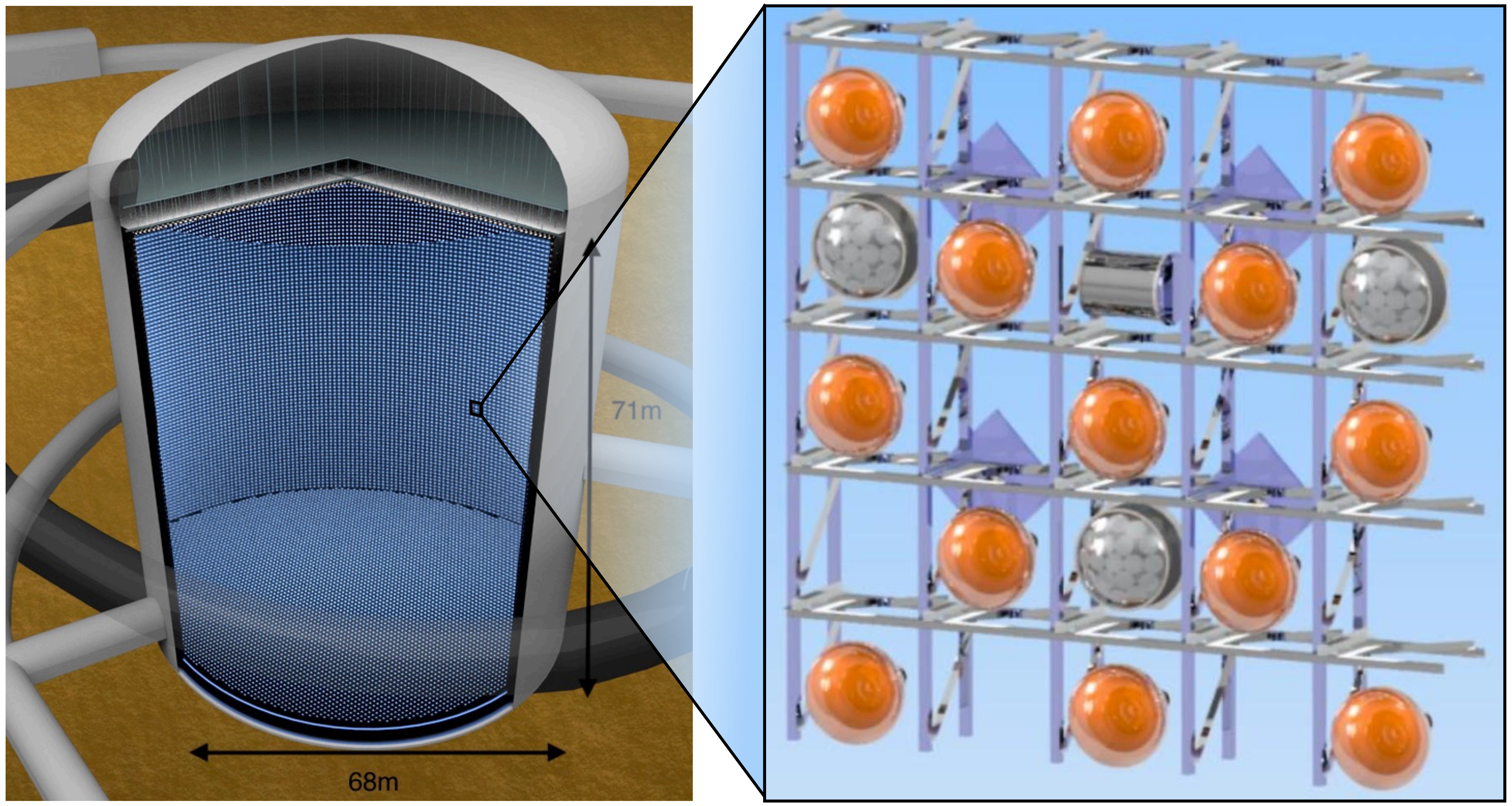
Ground-breaking ceremony **May 2021**

Hyper-Kamiokande Far Detector Overview

- 260kt water Cherenkov detector
  - 1700 m.w.e. underground
  - Inner detector (ID) H64.8 m × ⌀65.8 m
    - Fiducial mass of 190 kt (8.4×SK)
  - Outer detector (OD) 1m/2m thick



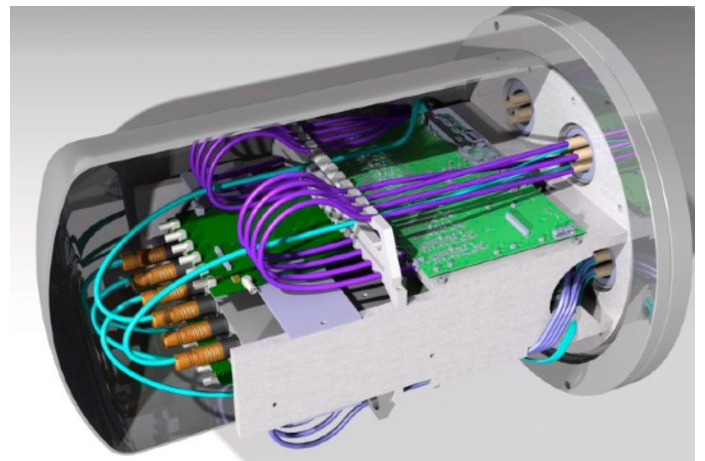




- 20k 50 cm PMTs
- Main detection system of ID
- 20% photo-coverage

- ~800 mPMTs modules
- Direction and time resolution
- Direct/scattered light

- 3600 OD modules
- 8cm PMT and WLS plate
- Provides veto agains muons

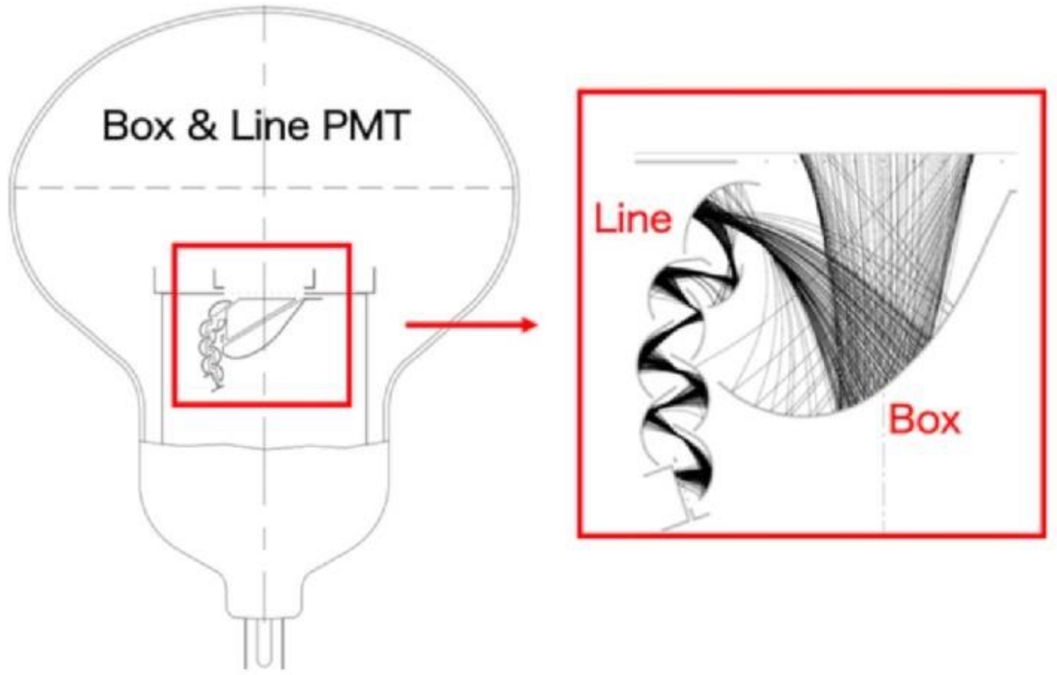


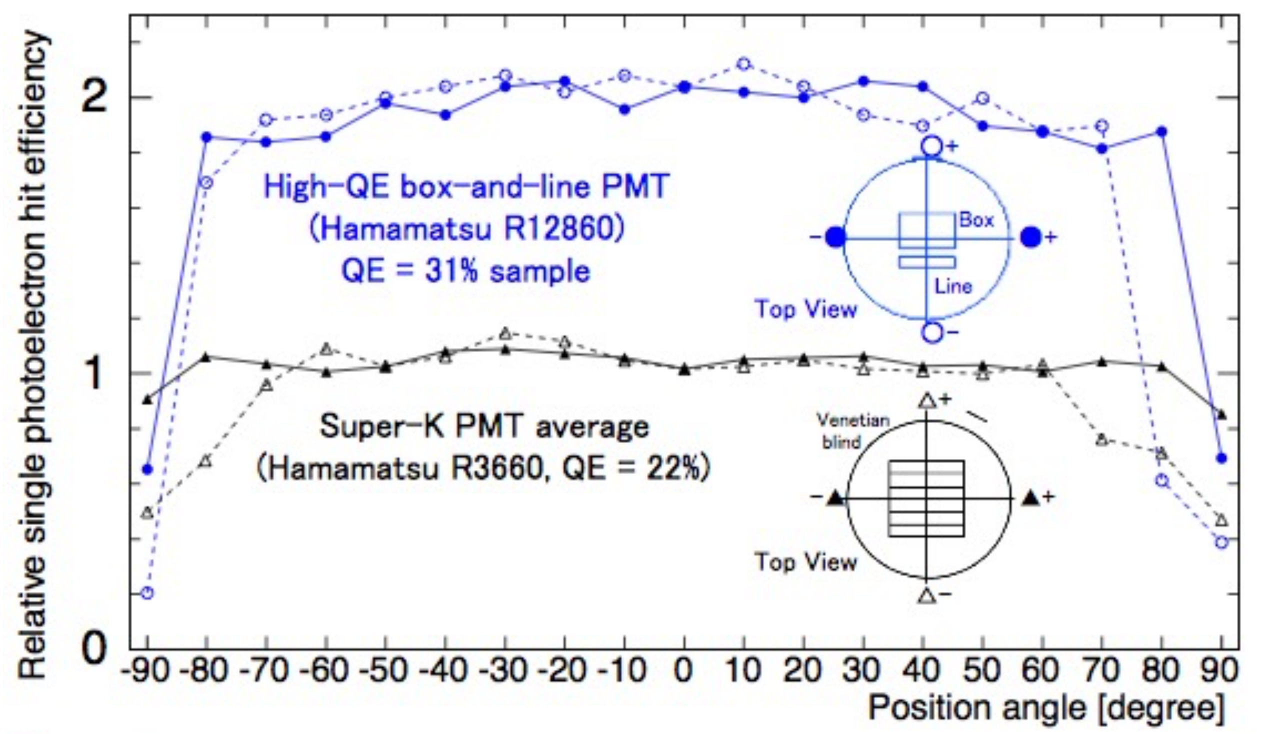
- Underwater electronics vessels
- ID & Hybrid (ID+OD) vessel
- mPMT signal-collecting vessel

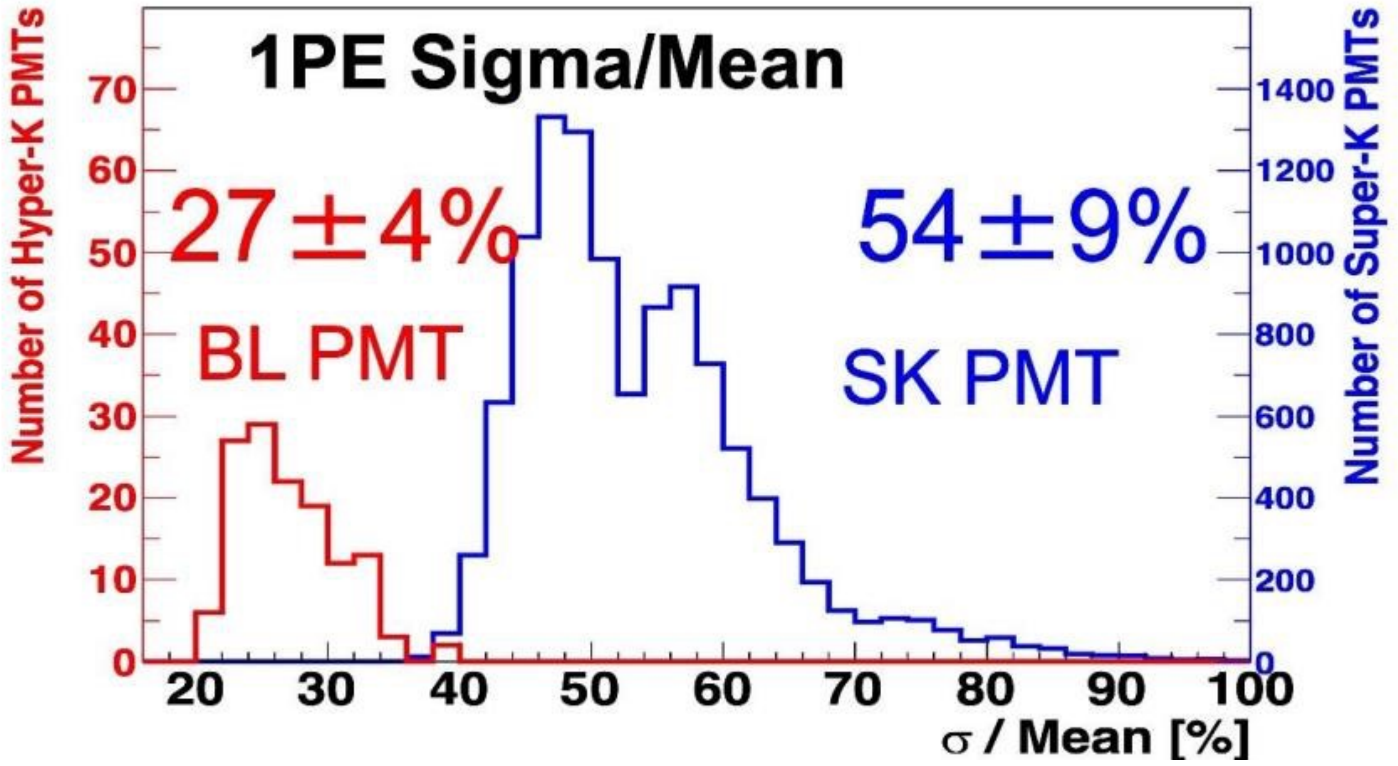
50 cm PMTs

- Hamamatsu Photonics R12860 Box&Line dynode PMTs
  - ×2 better photon detection efficiency
  - ×2 better single photoelectron resolution
  - ×2 better time resolution
  - ×2 higher pressure tolerance
  - Low dark rate of 4 kHz

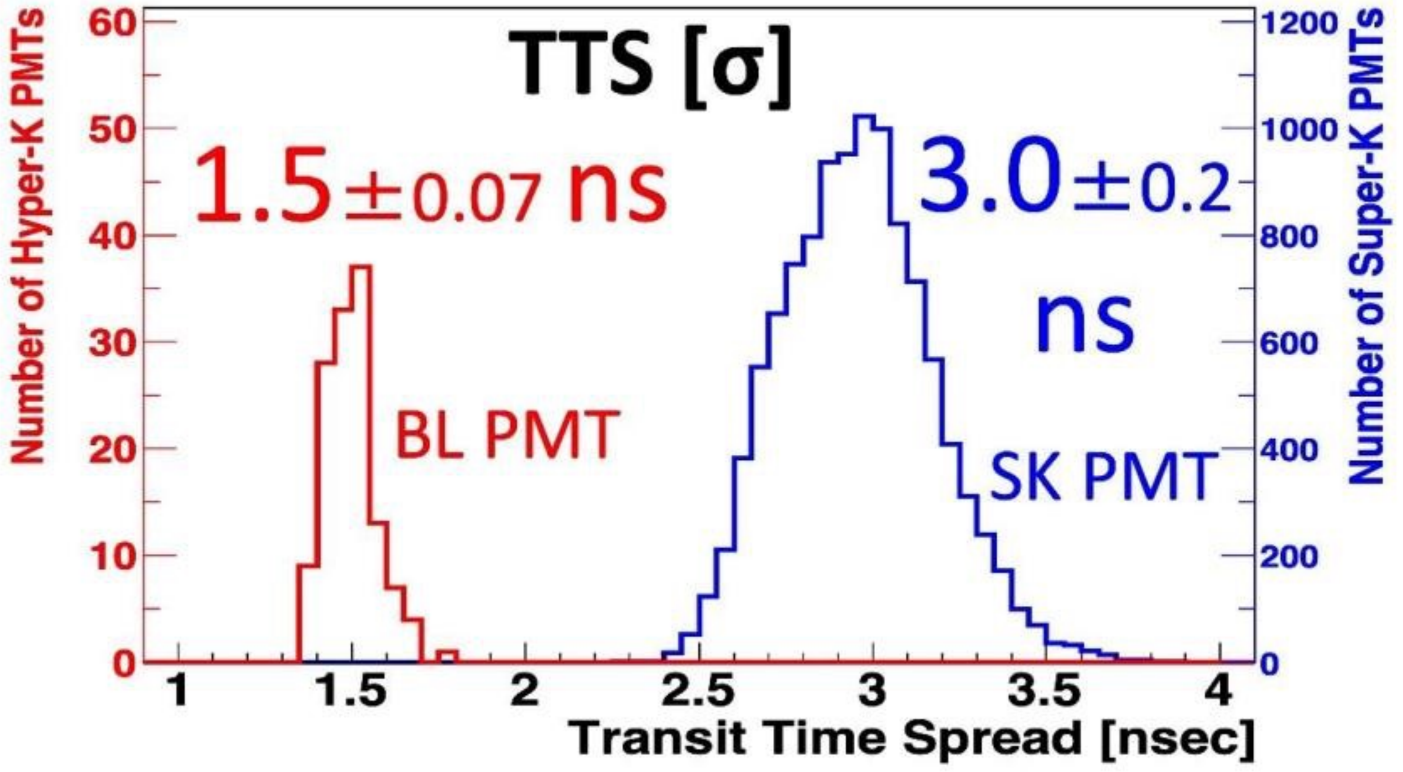
(all w.r.t. SK Hamamatsu R3660)





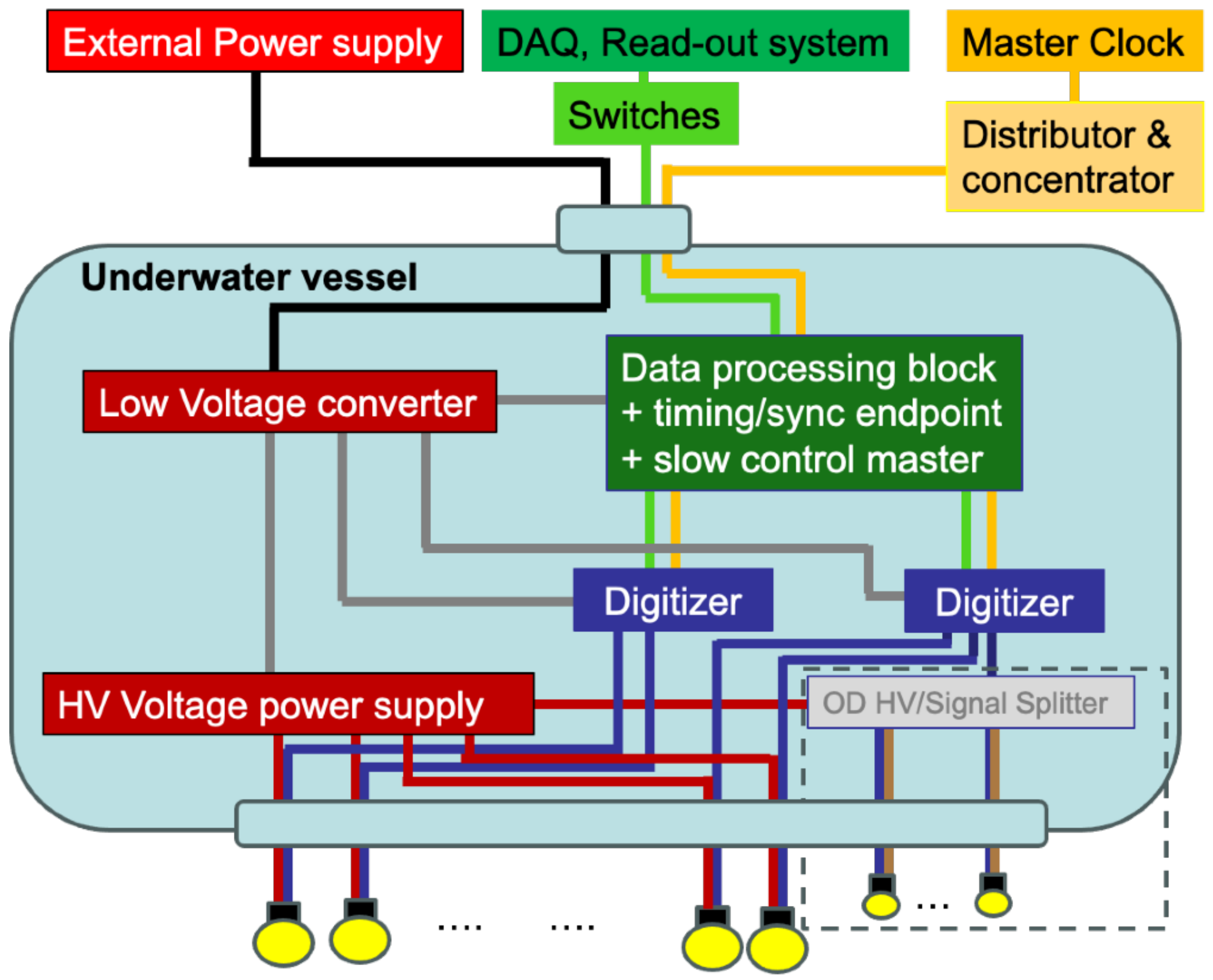


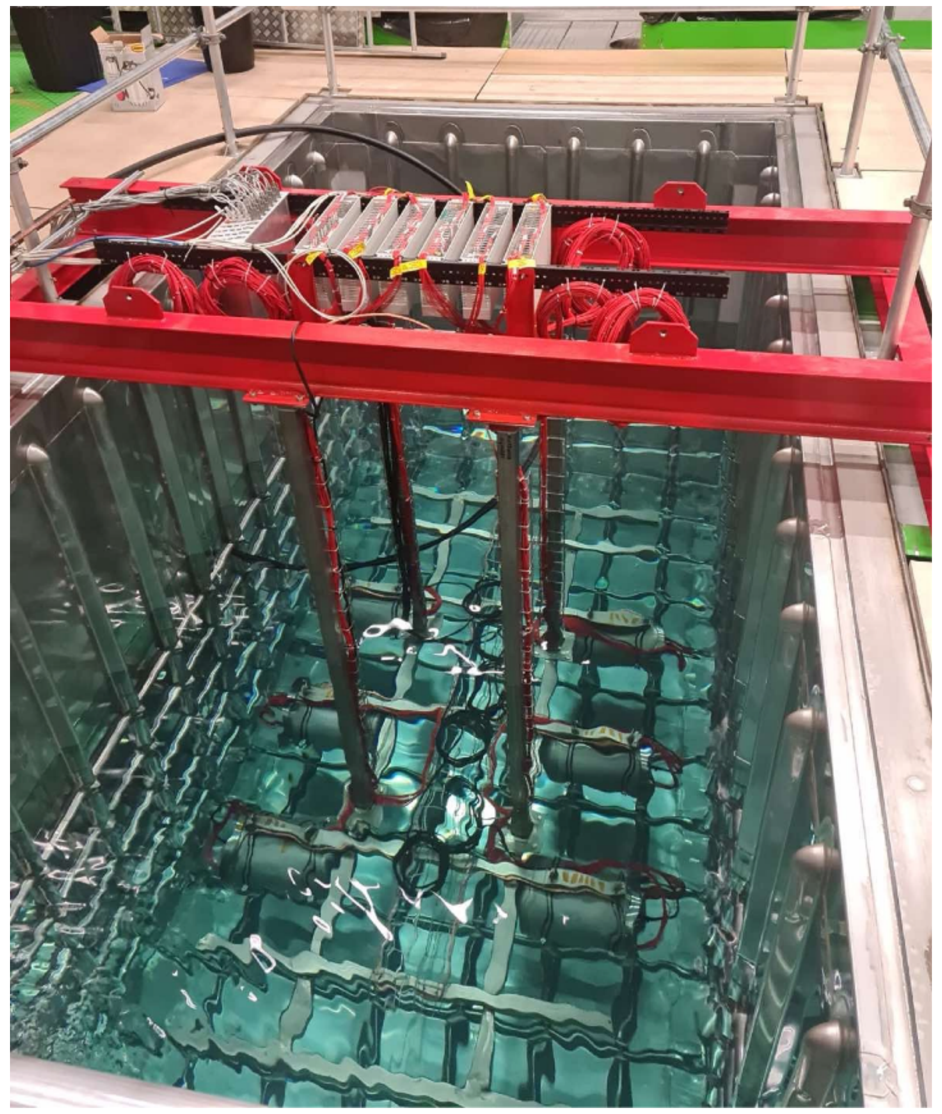
- Production resumed - 6000+ delivered and tested @Kamioka
  - Previous issues due to flashers successfully resolved

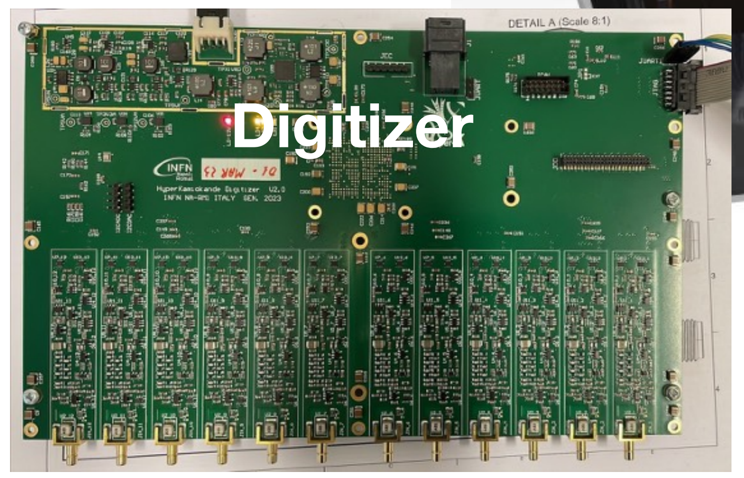


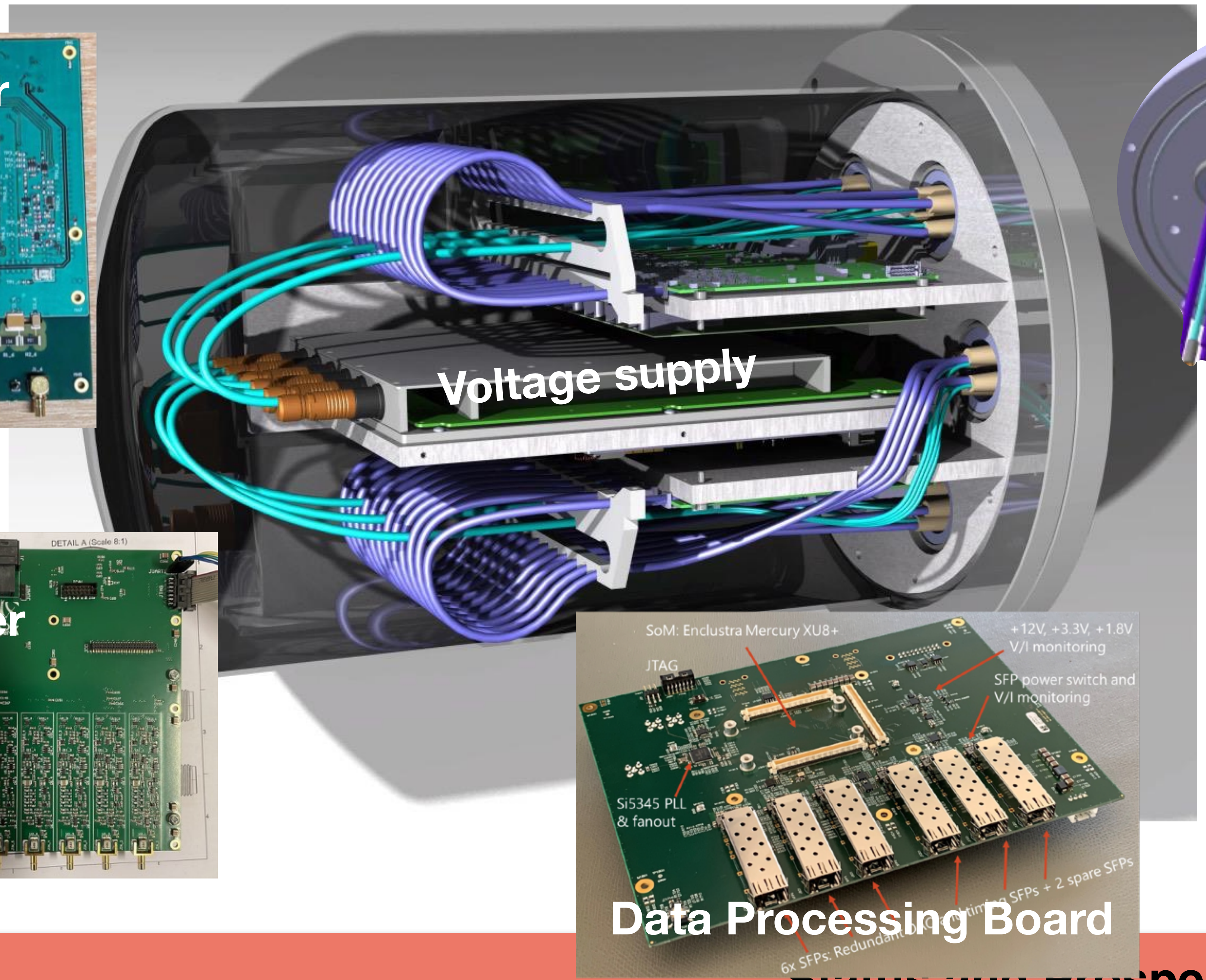
Underwater Electronics

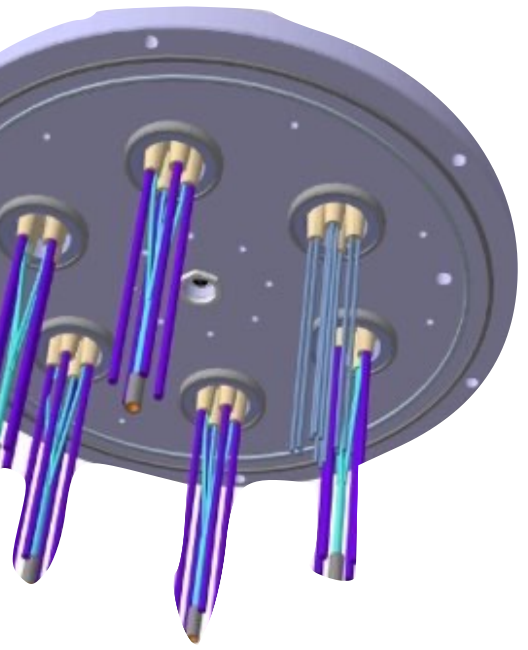
- Underwater electronics to reduce the cable length (signal quality, cost)
- El. vessel includes low-voltage & high-voltage power supply, data processing board, digitizer board
- Two configurations:
  - ID vessel services 24 ID PMTs
  - Hybrid (ID+OD) vessel services 20 ID PMTs and 12 OD modules
- Long-term underwater test conducted at CERN





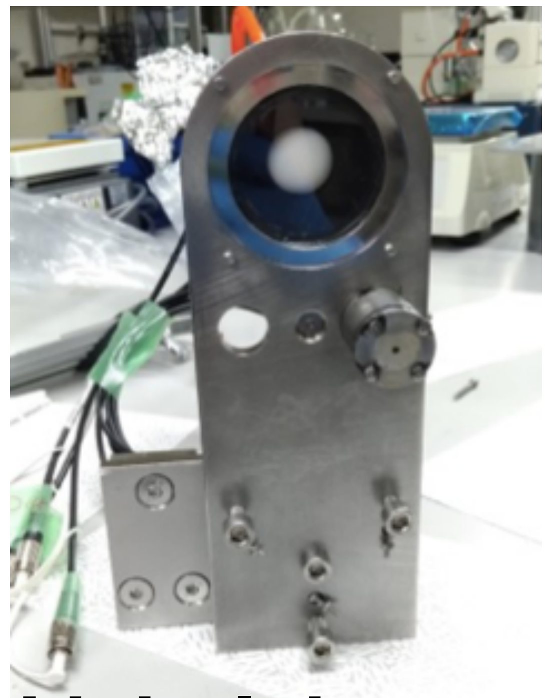




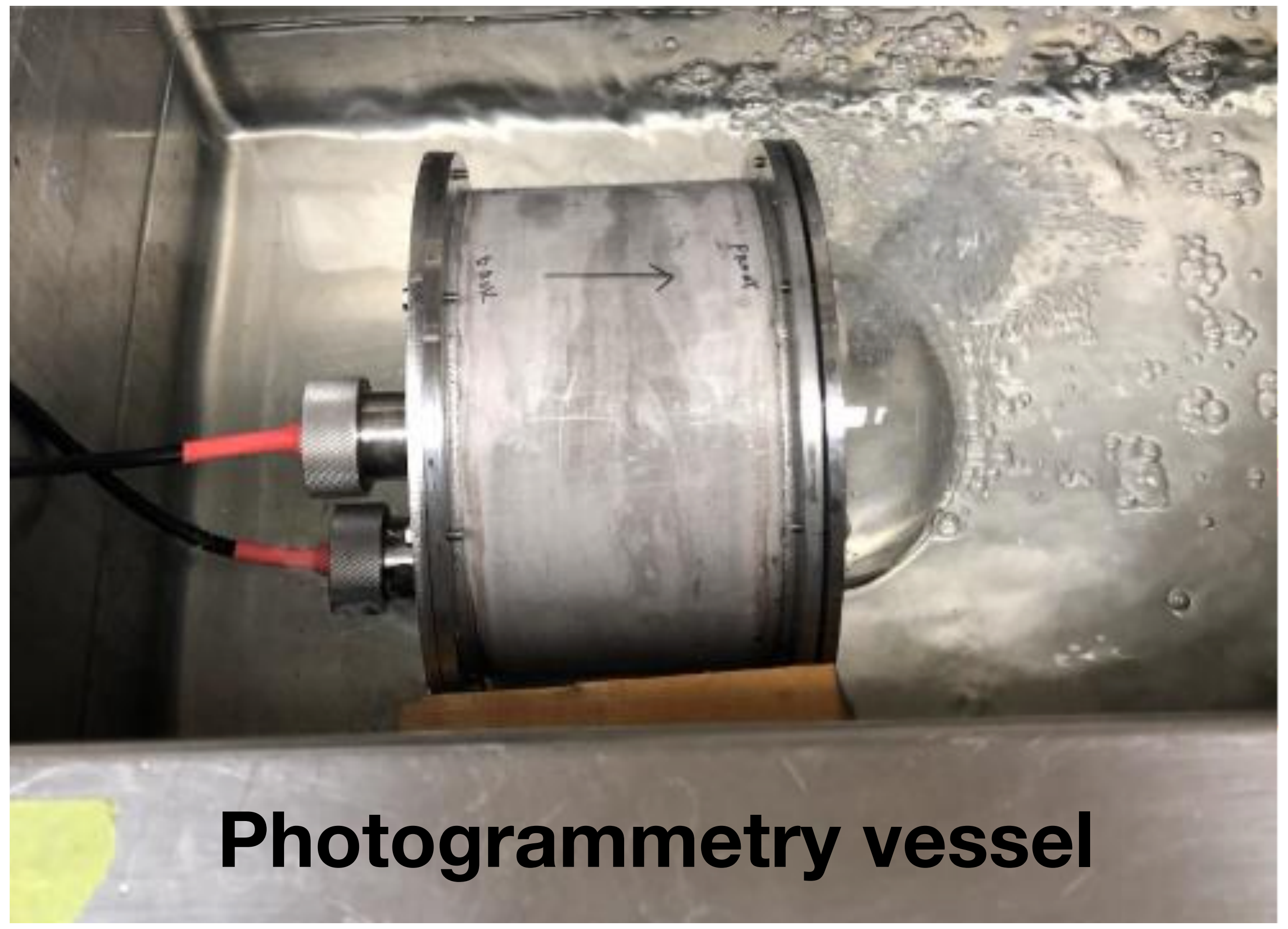


Far Detector Calibration

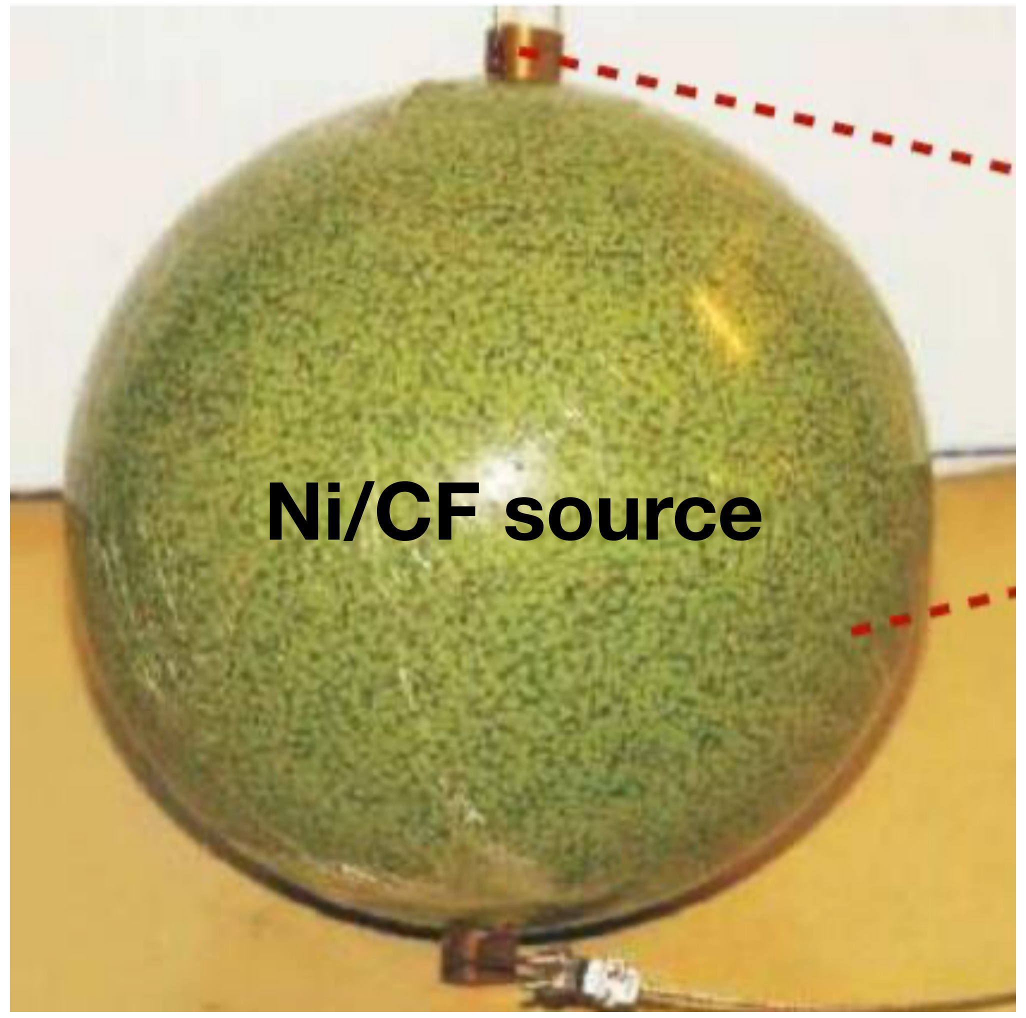
- Great experience from Super-K
- Calibration through optical&radioactive sources and control sample
- Pre-calibration: calibrated PMTs and photogrammetry
- Regular calibration
  - Light injection through diffusers and collimators
  - mPMT flashing LEDs
  - Outer detector light injectors
- Electron LINAC: 3-24 MeV electrons
- Radioactive sources
  - DT source
  - AmBe+BGO - tagged neutrons
  - Ni/Cf 9 MeV γ cascade



Light Injector

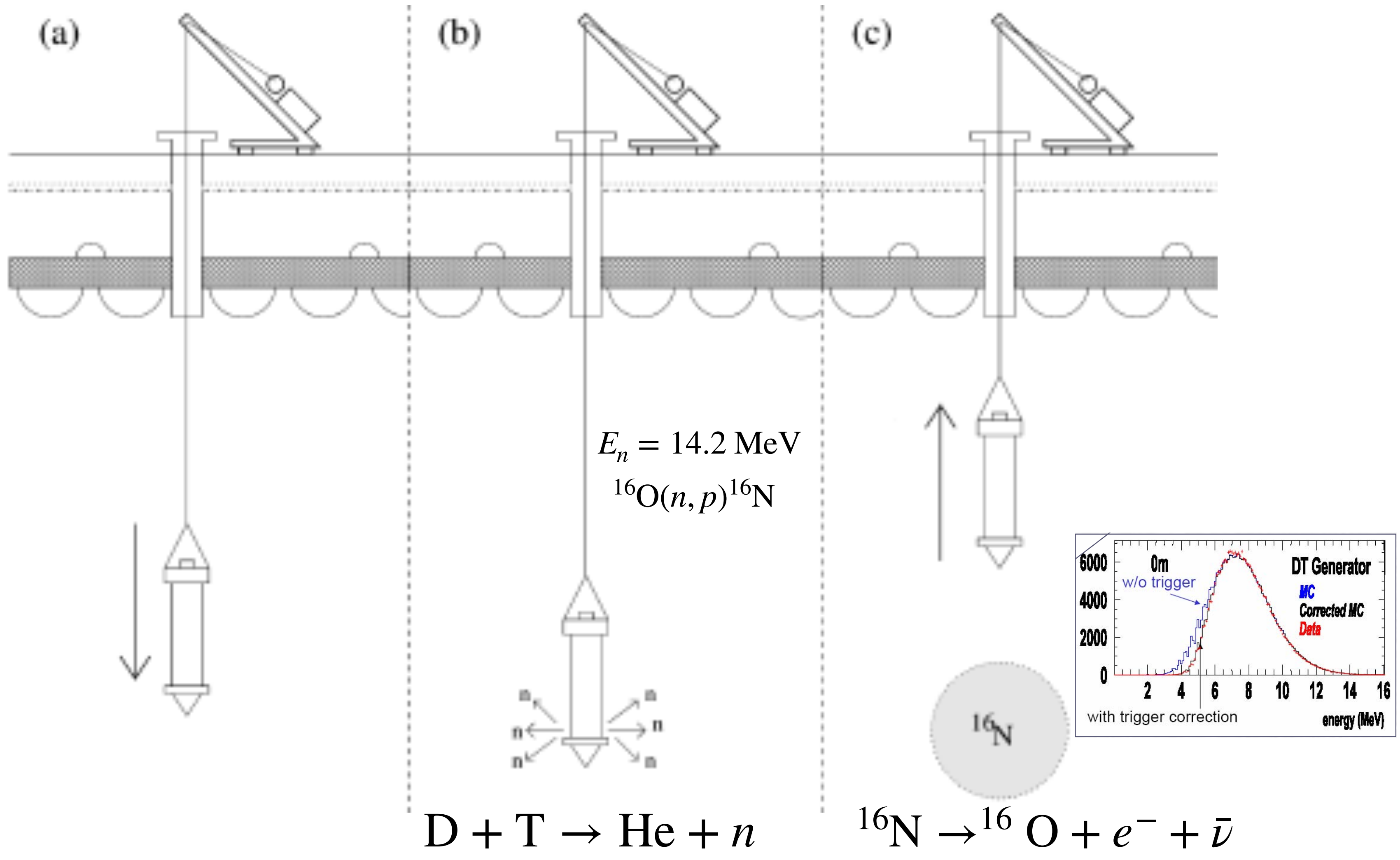


Photogrammetry vessel



Ni/CF source

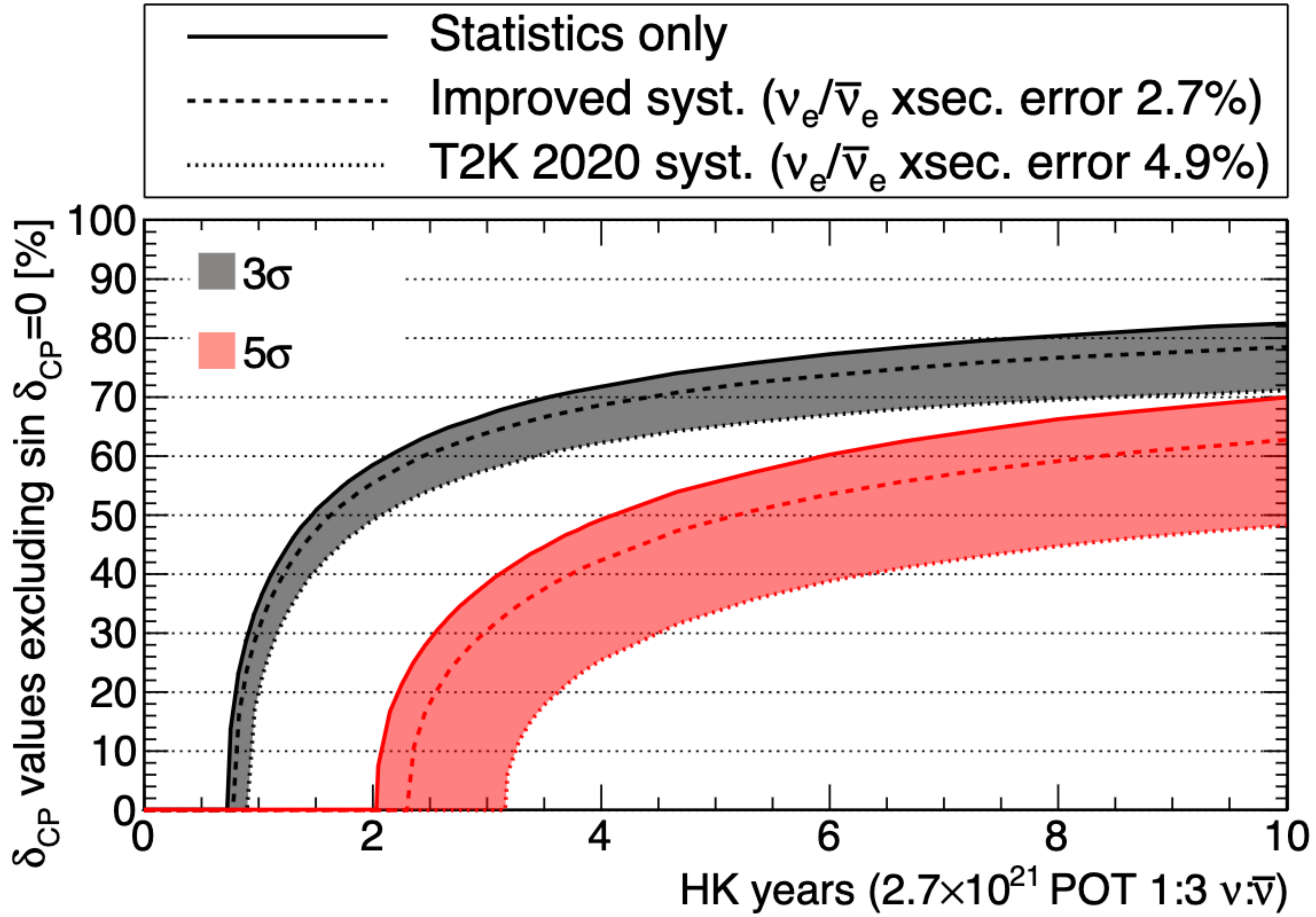
DT Source Principle



Conclusions

- Hyper-Kamiokande is a 3rd generation water Cherenkov experiment @ Kamioka
  - World's largest accelerator long baseline neutrino oscillation and nucleon decay detector
  - Built on well-proven technology
- Upgrade of the near detectors + introduction of the Intermediate Water Cherenkov Detector to reduce systematics
- Construction on time and on the way to start operation in 2027
- Many results in 20 years of data taking
  - CP violation in neutrino oscillation discovery for 62% of true δ_{CP} @5σ
  - Nucleon decay explored up to $\tau > 10^{35}$ y
  - A lot more…

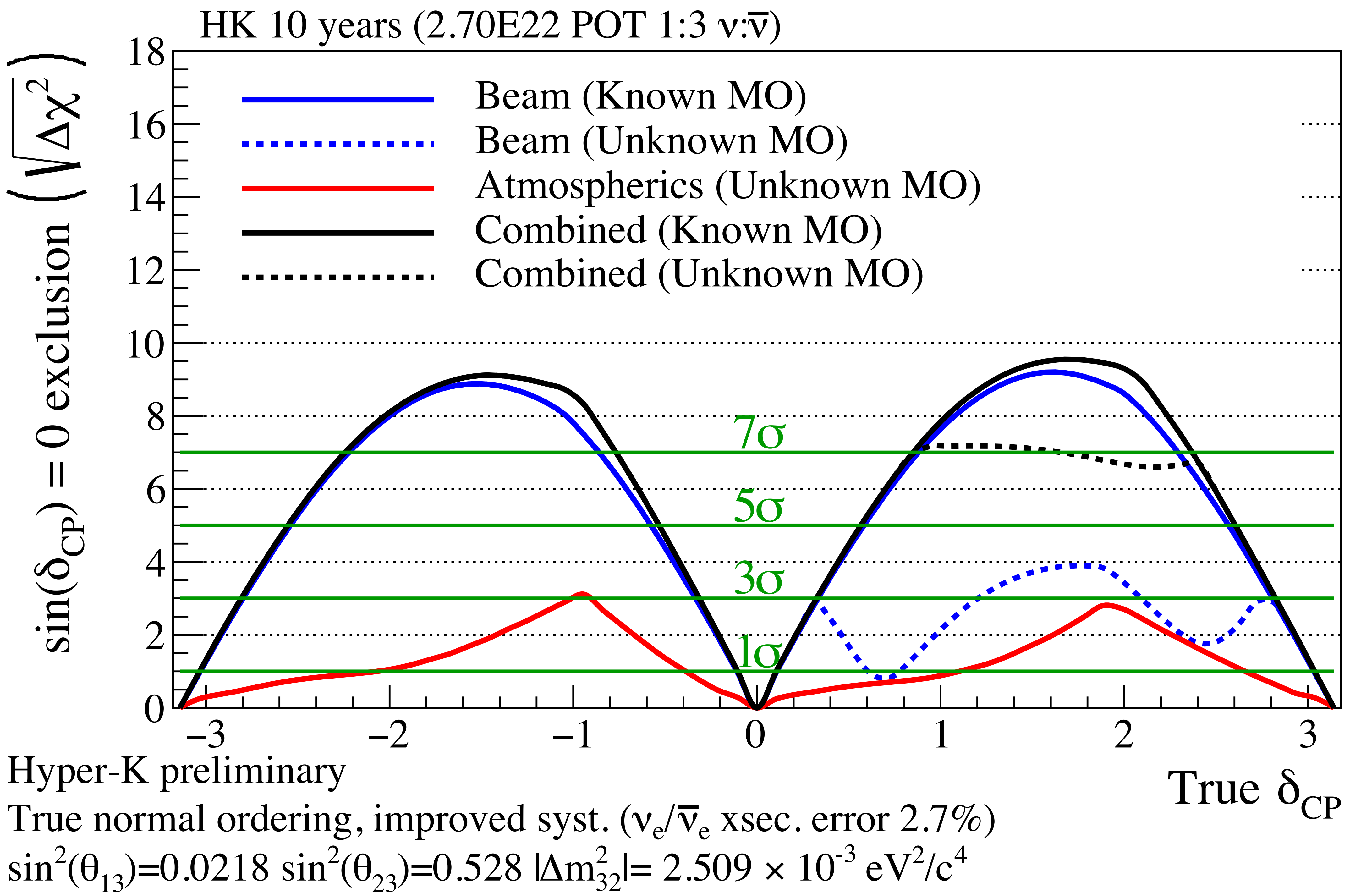
CP Conservation Exclusion with Time

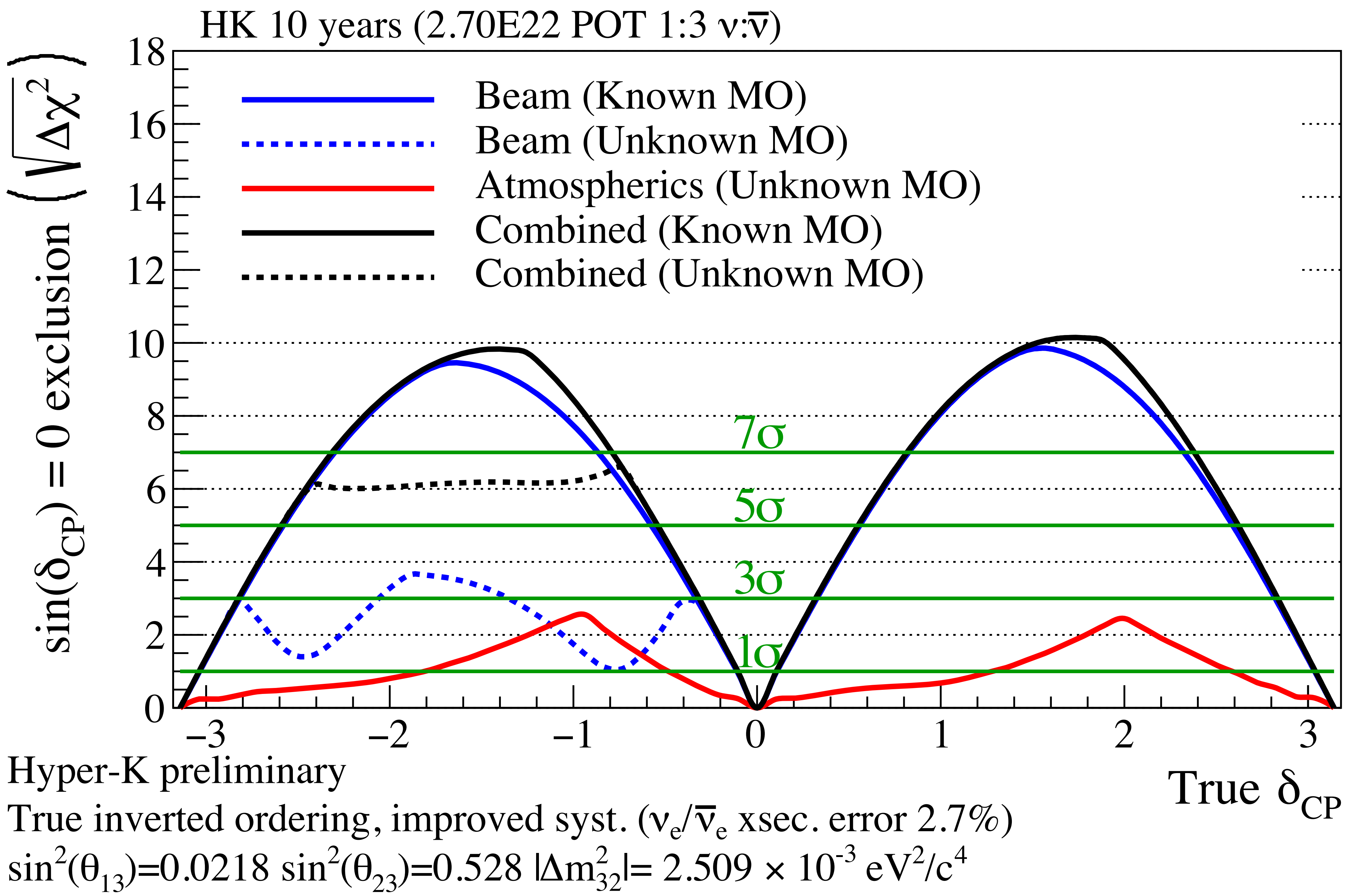


Hyper-K preliminary

True normal ordering (known))

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$


HK 10 years (2.70E22 POT 1:3 ν:ν̄)
Beam (Known MO)
Beam (Unknown MO)
Atmospherics (Unknown MO)
Combined (Known MO)
Combined (Unknown MO)
7σ
5σ
3σ
1σ
$\sin(\delta_{CP}) = 0$ exclusion $\left(\sqrt{\Delta\chi^2}\right)$
True δ_{CP}
Hyper-K preliminary
True normal ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}$ eV^2/c^4


HK 10 years (2.70E22 POT 1:3 ν:ν̄)
Beam (Known MO)
Beam (Unknown MO)
Atmospherics (Unknown MO)
Combined (Known MO)
Combined (Unknown MO)
7σ
5σ
3σ
1σ
$\sin(\delta_{CP}) = 0$ exclusion $\left(\sqrt{\Delta\chi^2}\right)$
True δ_{CP}
Hyper-K preliminary
True inverted ordering, improved syst. ($\nu_e/\bar{\nu}_e$ xsec. error 2.7%)
$\sin^2(\theta_{13})=0.0218$ $\sin^2(\theta_{23})=0.528$ $|\Delta m^2_{32}|= 2.509 \times 10^{-3}$ eV^2/c^4