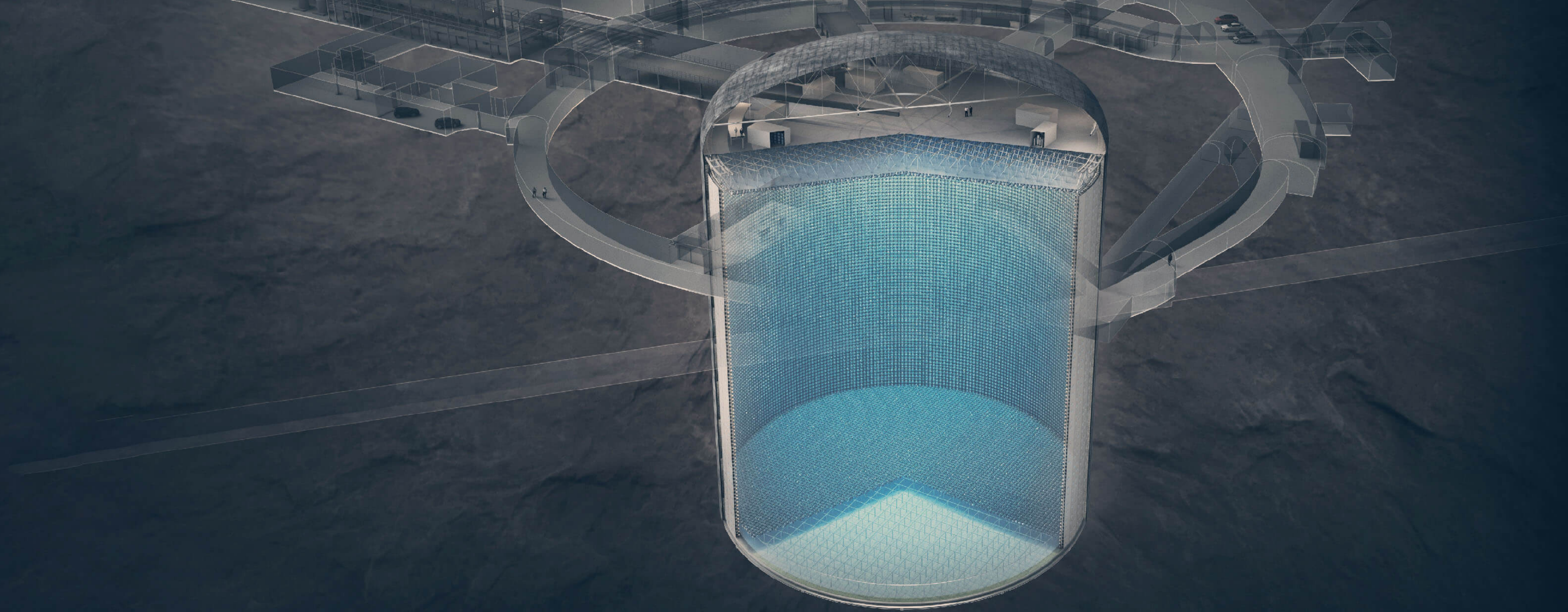
2023.7.17 @Neutrino Workshop at IFIRSE

Hyper-Kamiokande Status and Prospects with neutrino oscillation measurements

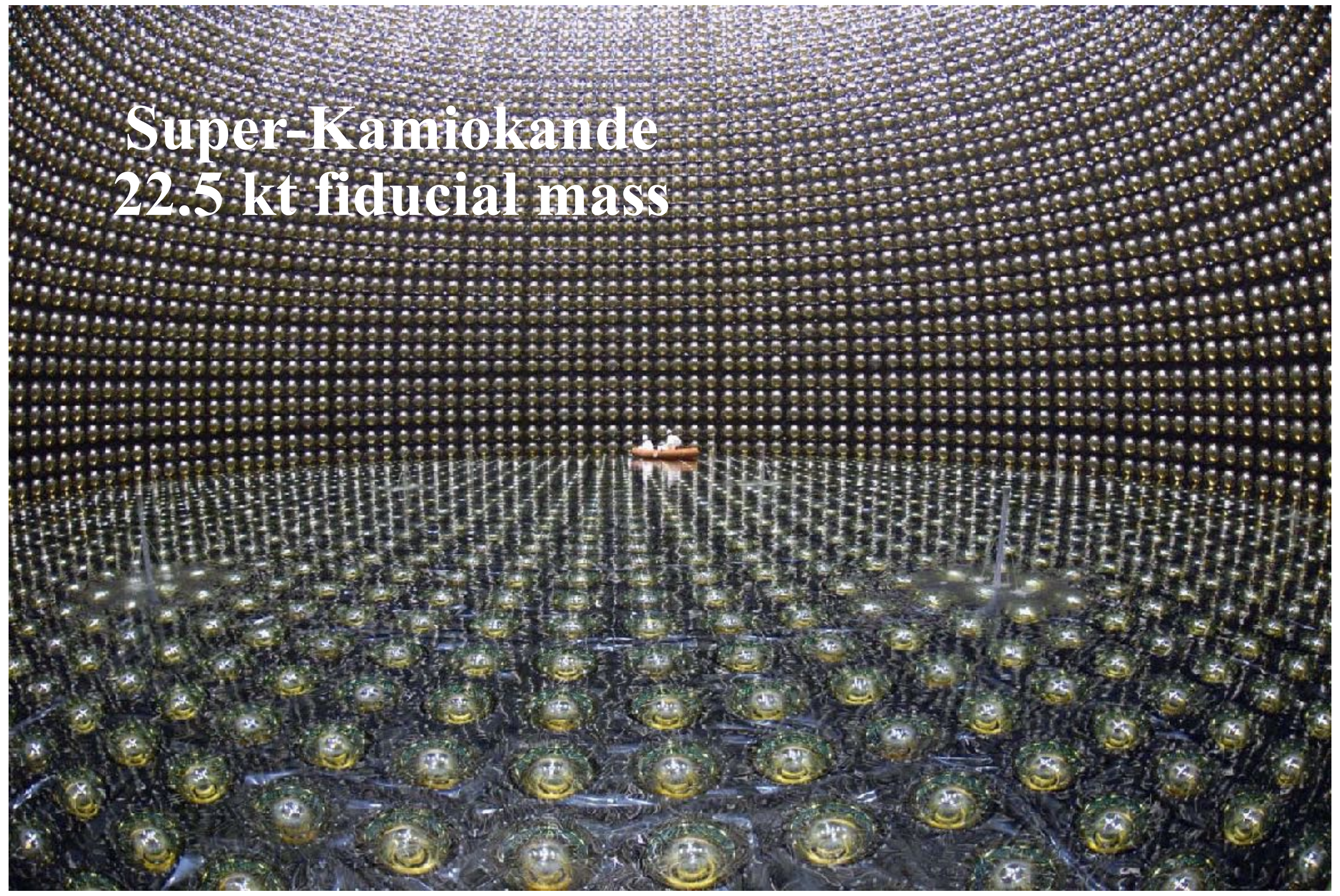


T. Nakaya (Kyoto U.)
for the Hyper-Kamiokande Collaboration

Hyper-Kamiokande

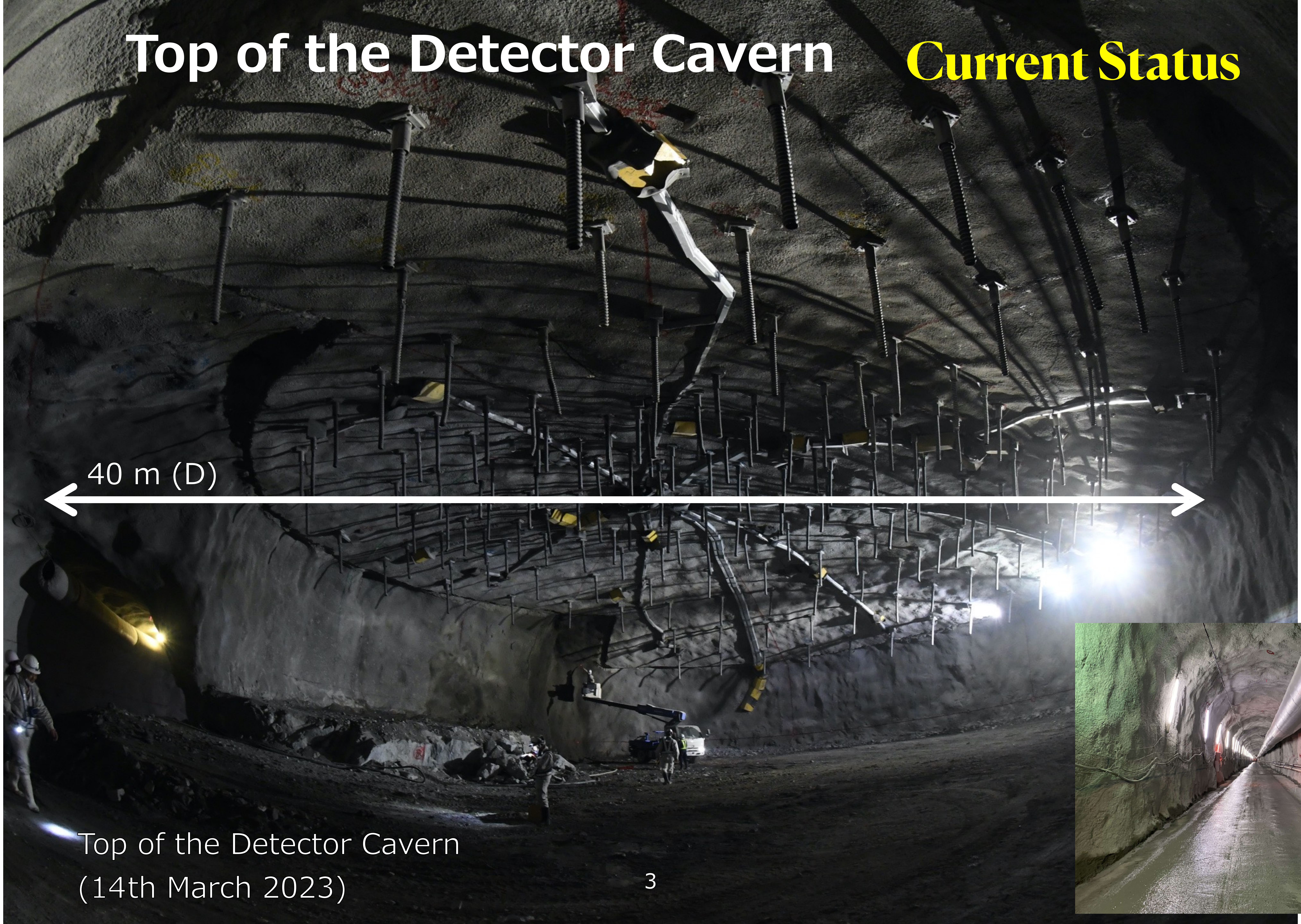
Hyper-Kamiokande

Water Cherenkov detectors in Kamioka



Top of the Detector Cavern

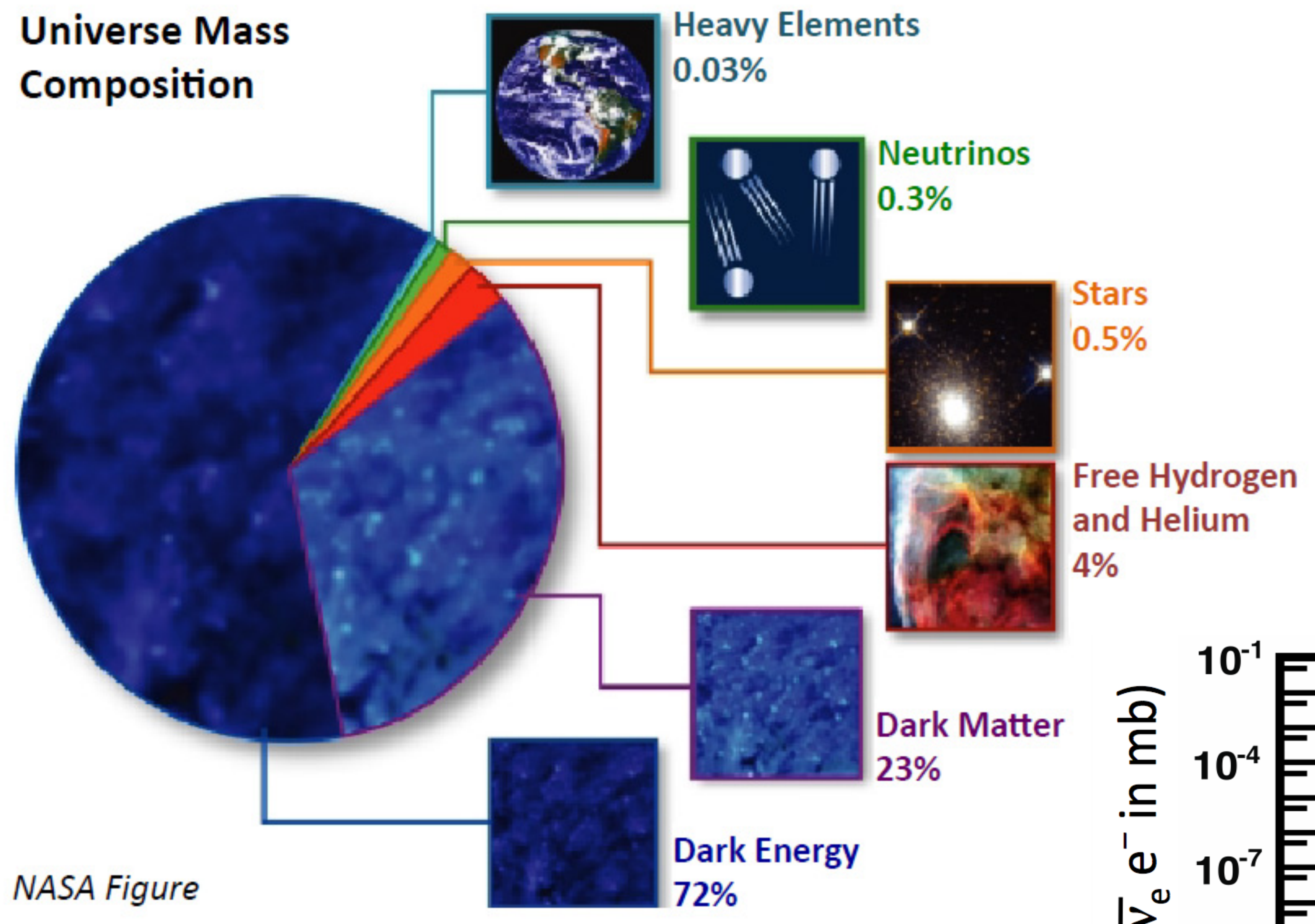
Current Status



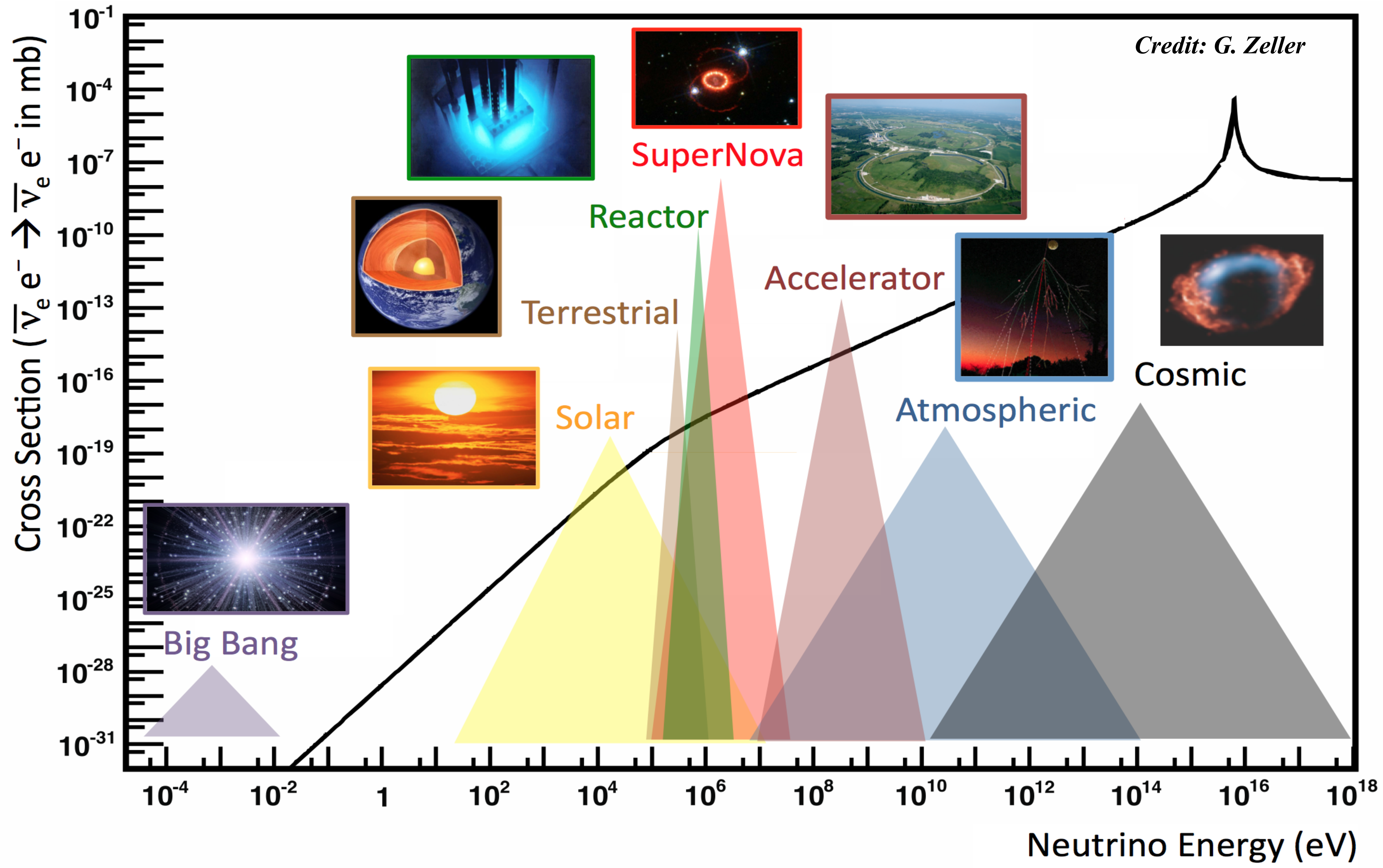
Top of the Detector Cavern
(14th March 2023)

Why Neutrinos?

They are always around us and mysterious!



- T_ν=1.95 K
- $\#N_\nu$=112×3 cm^{-3}



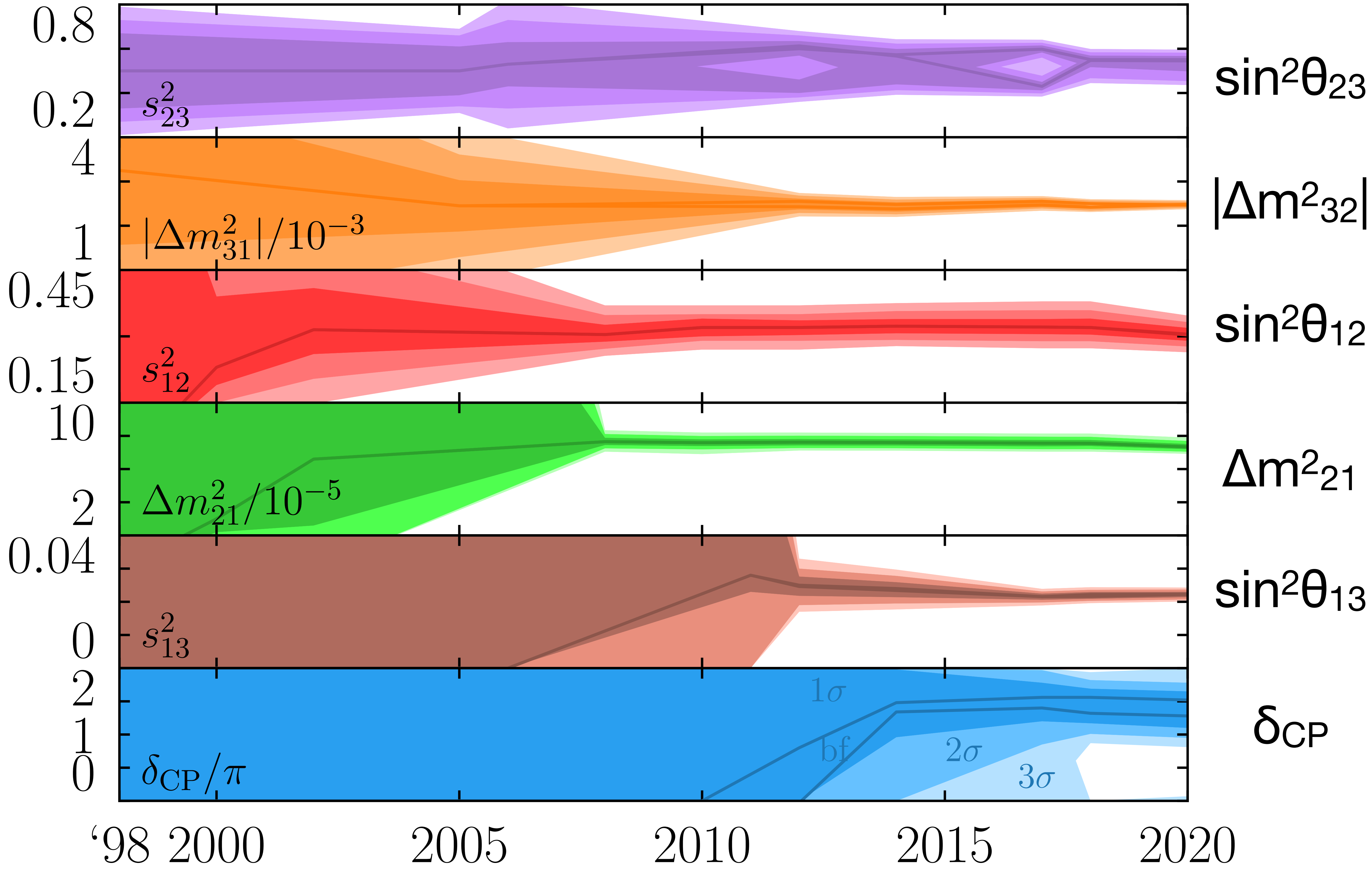
- Particle Physics
- AstroPhysics
- Cosmology
- High energy Astro-particle physics
- Nuclear physics

by S. Gollapinni @ICHEP2020

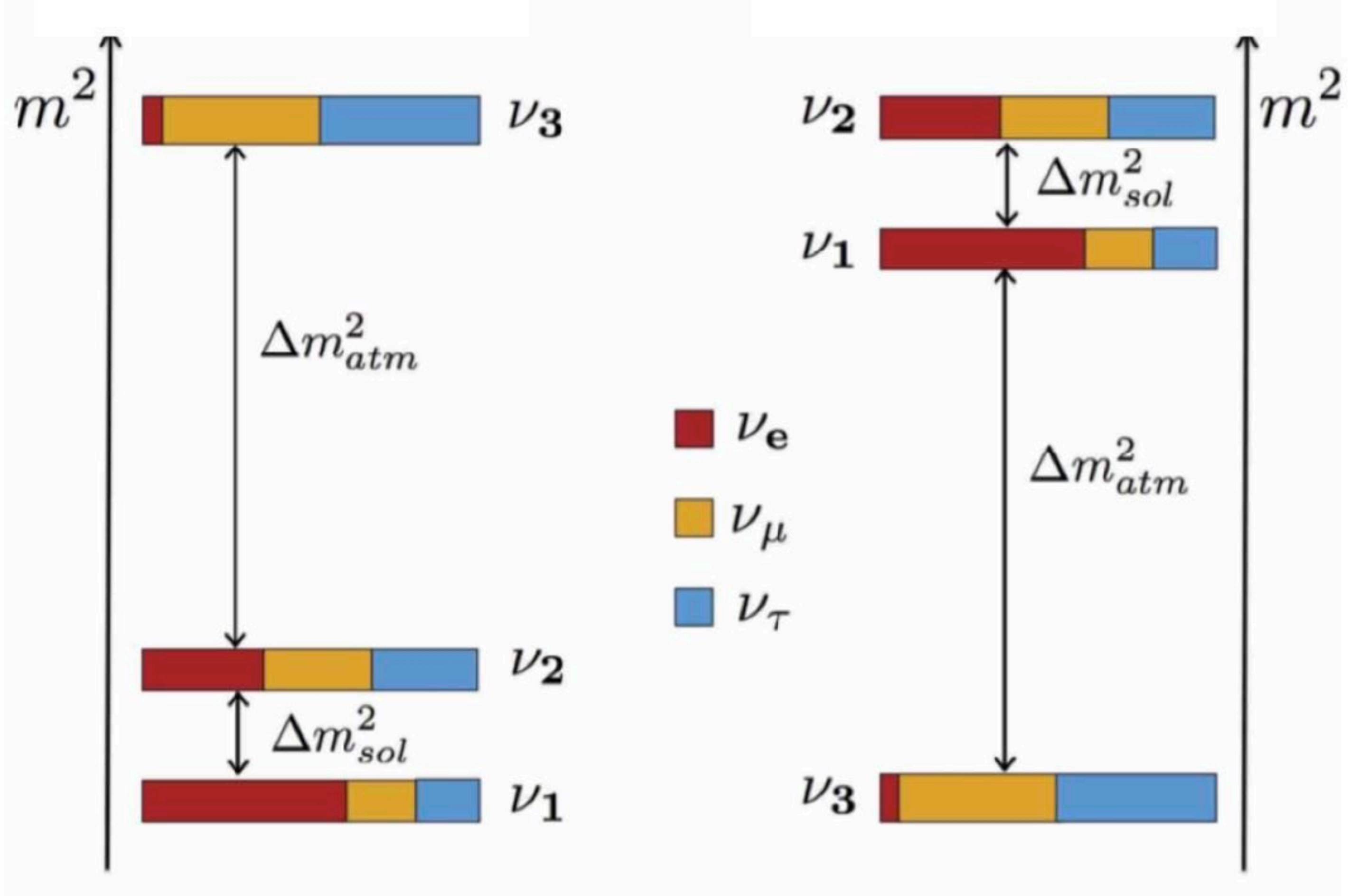
Neutrino Oscillations

Maki-Nakagawa-Sakata Mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



arXiv:2212.00809



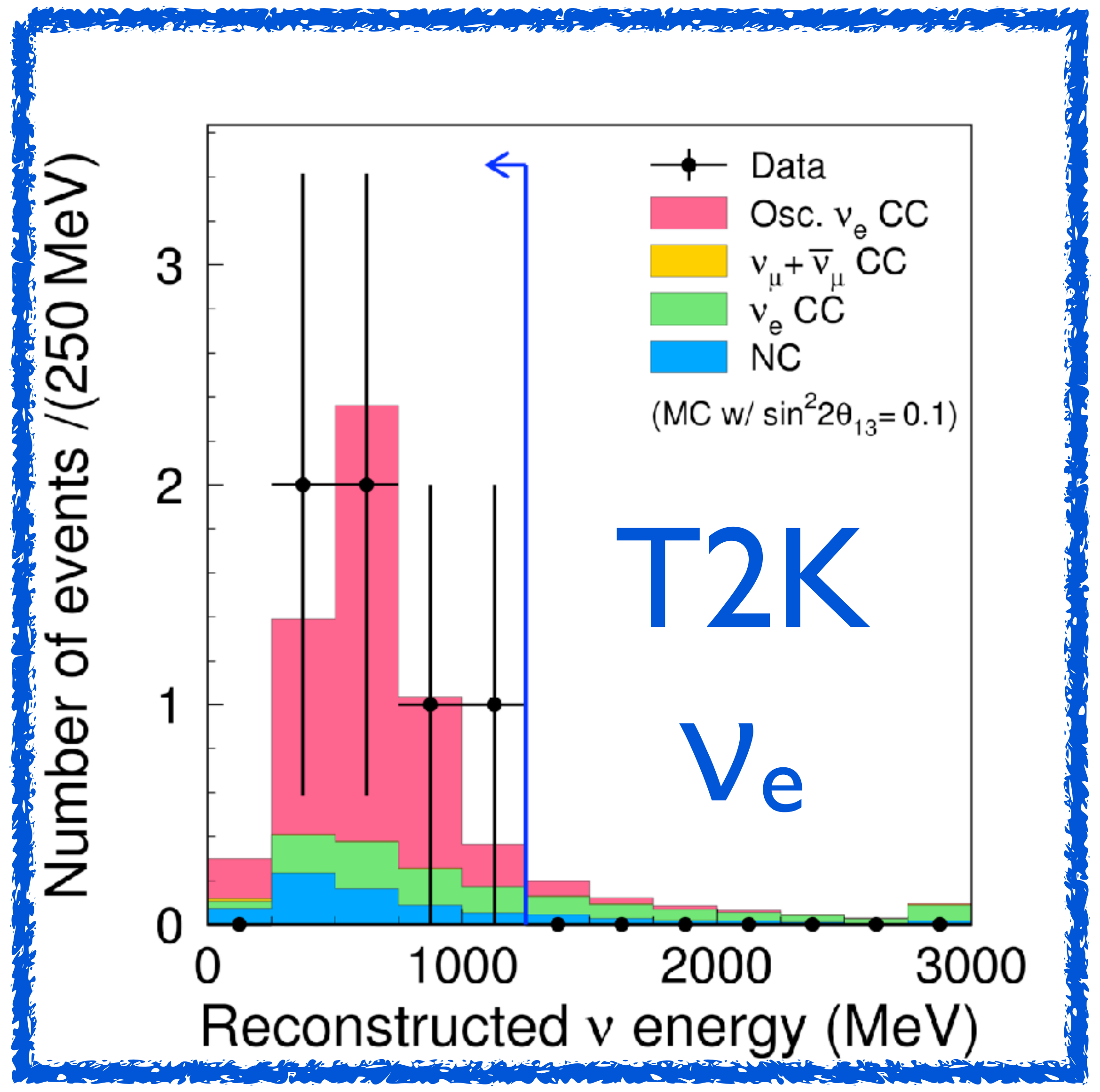
NO (Normal Ordering) **IO (Inverse Ordering)**

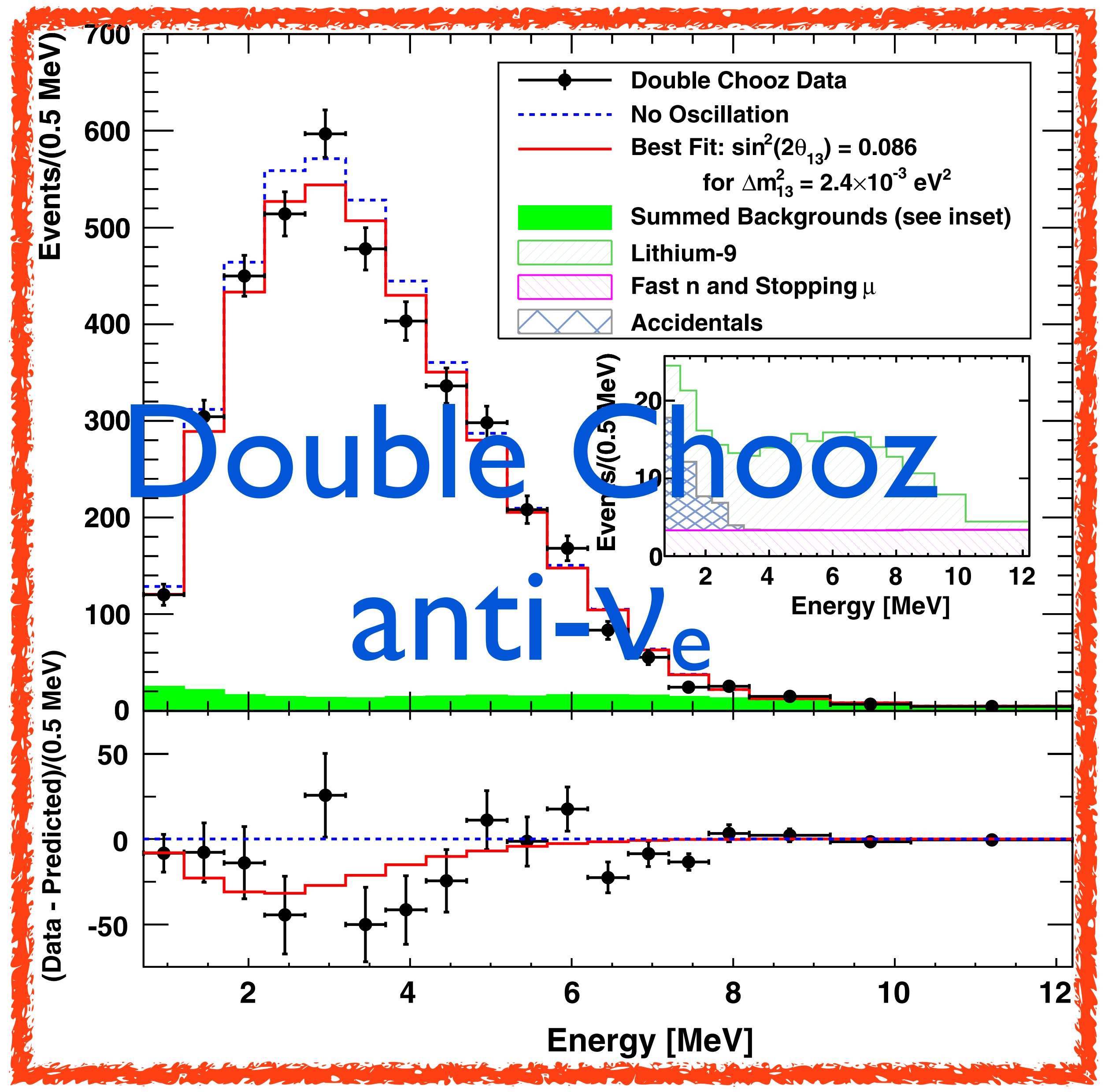
Current major targets

- **CP violation**
- Mass ordering (NO or IO)
- Precision
  - θ_{23} octant (<=>45°?)

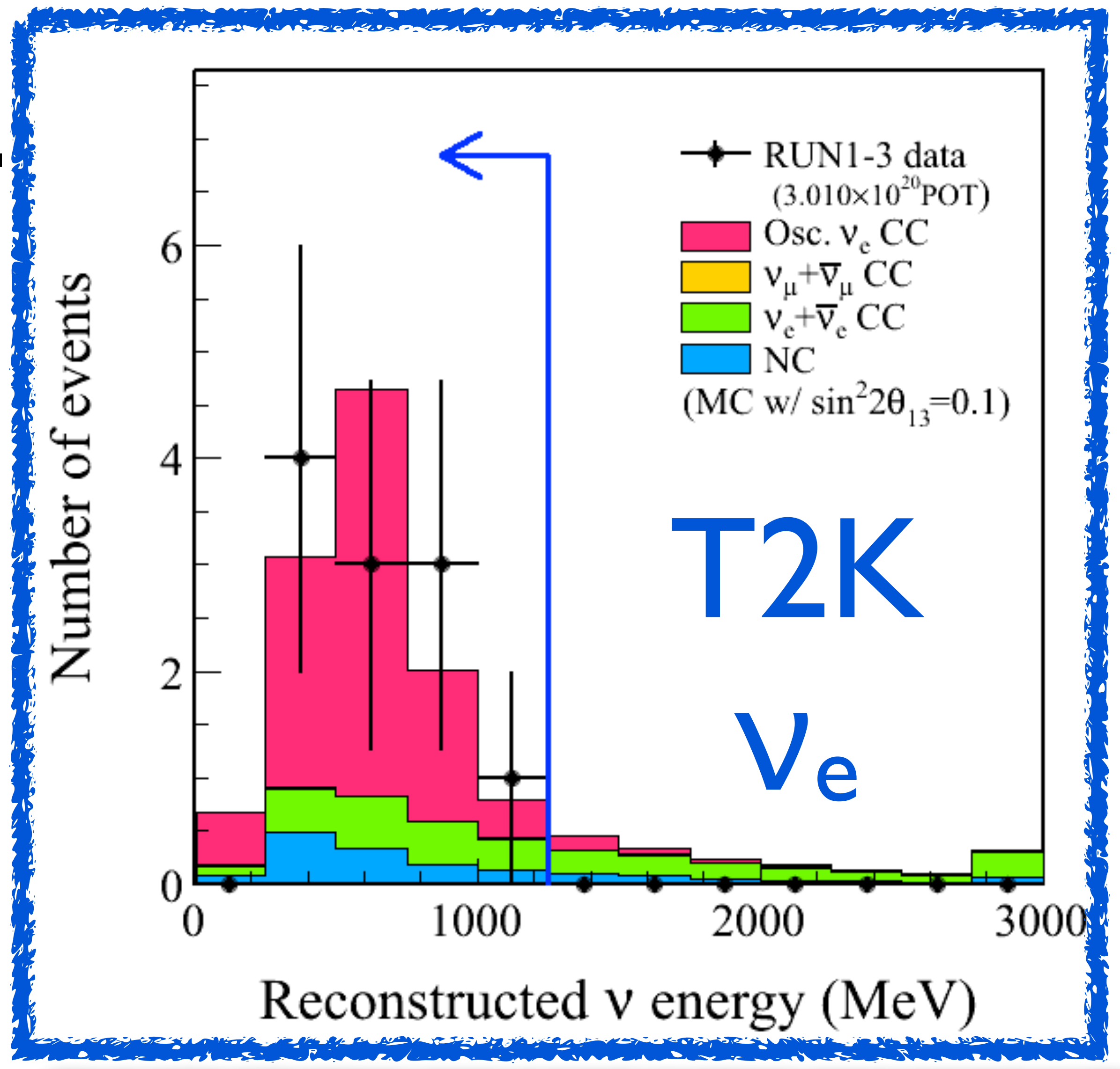
Large θ$_{13}$ opens the window to study CPV

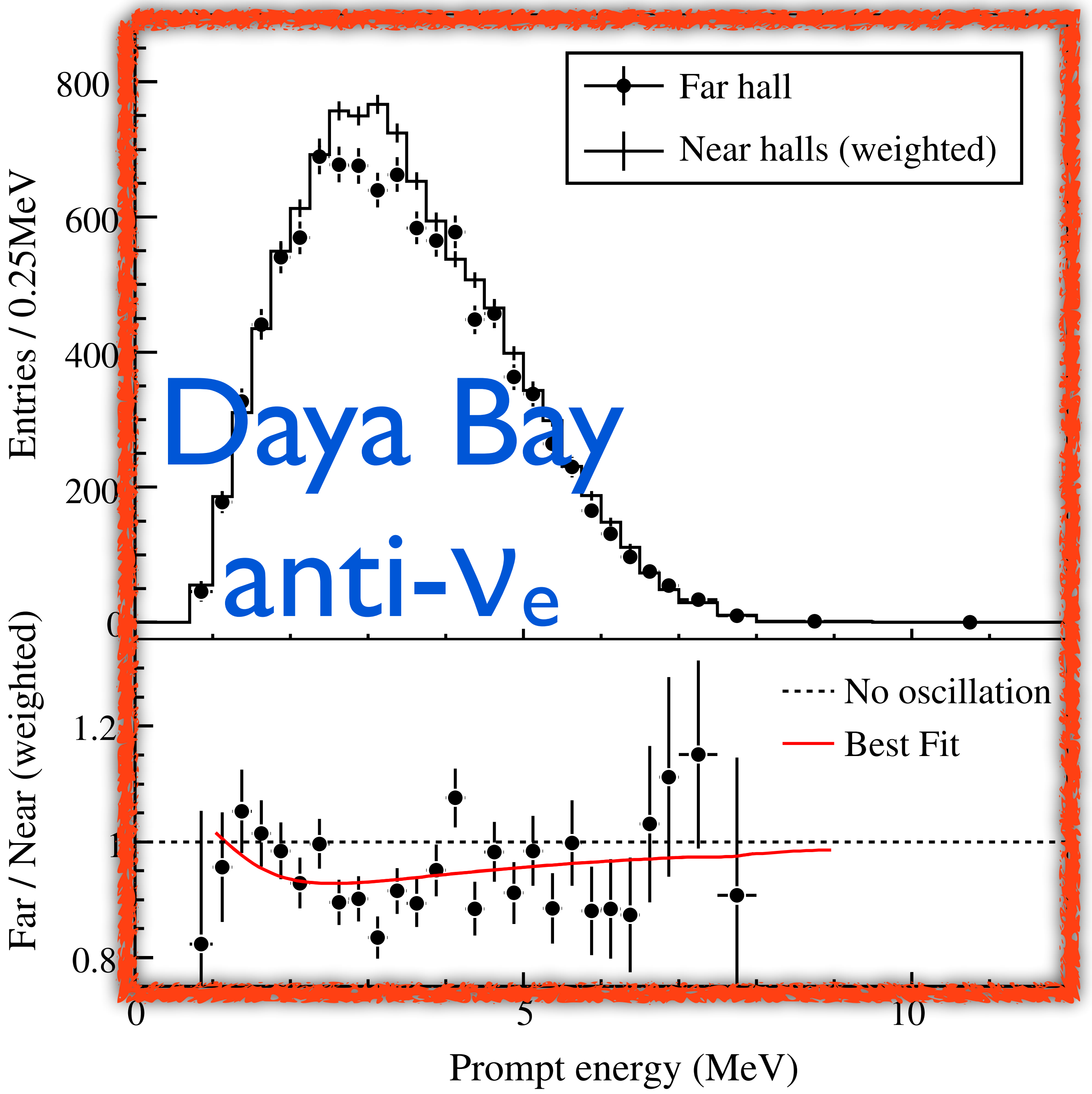
2011



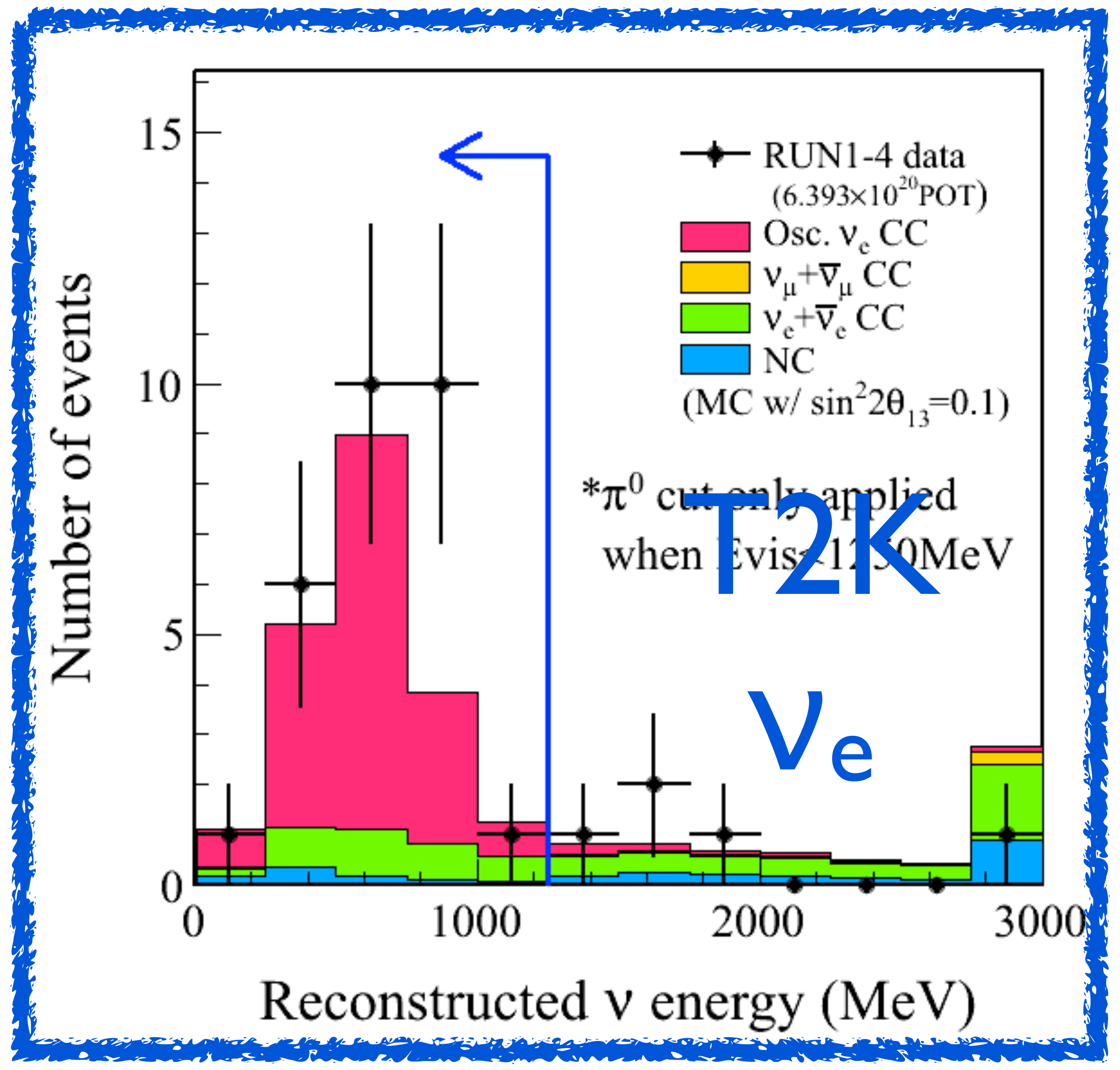


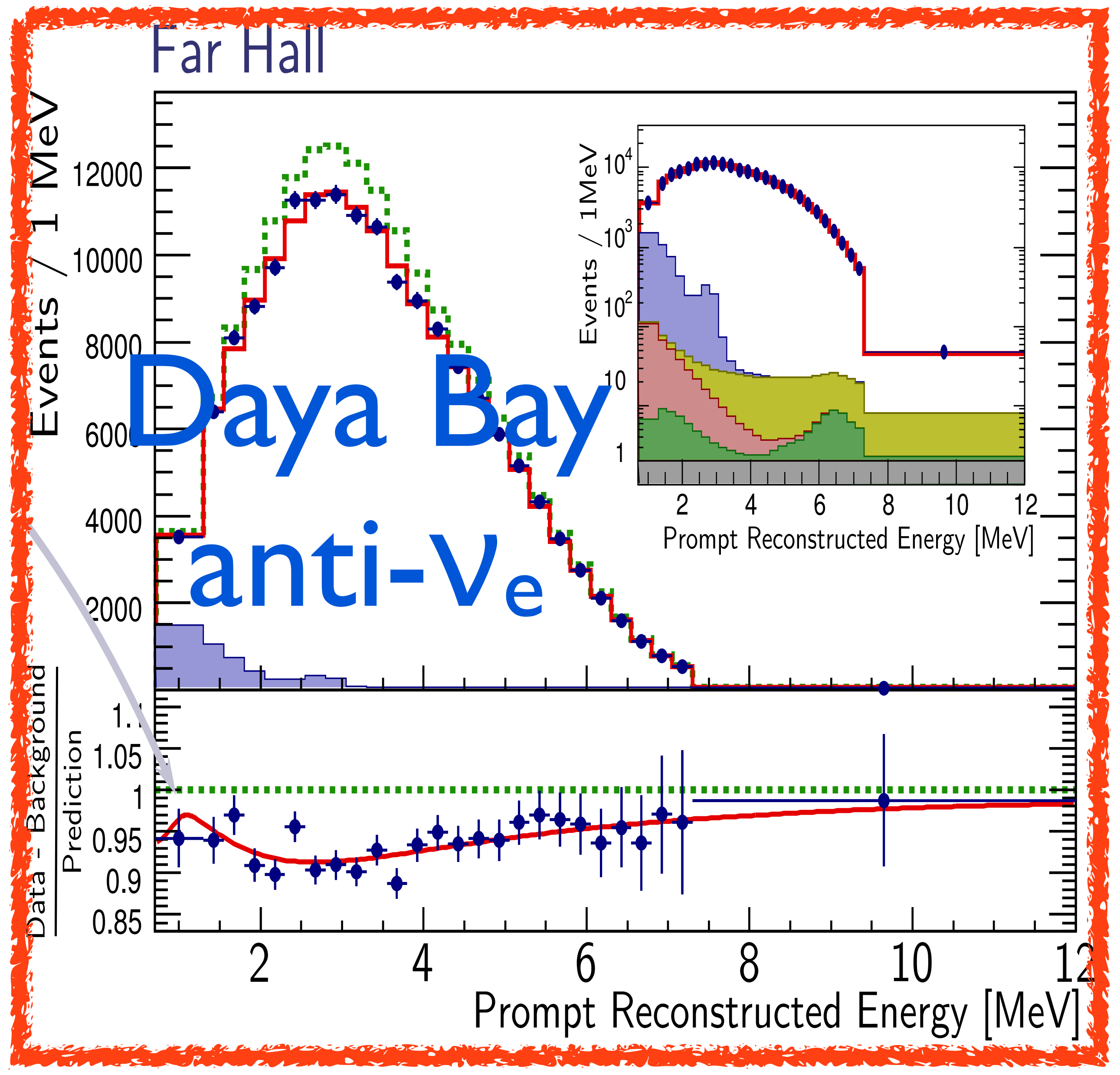
2012

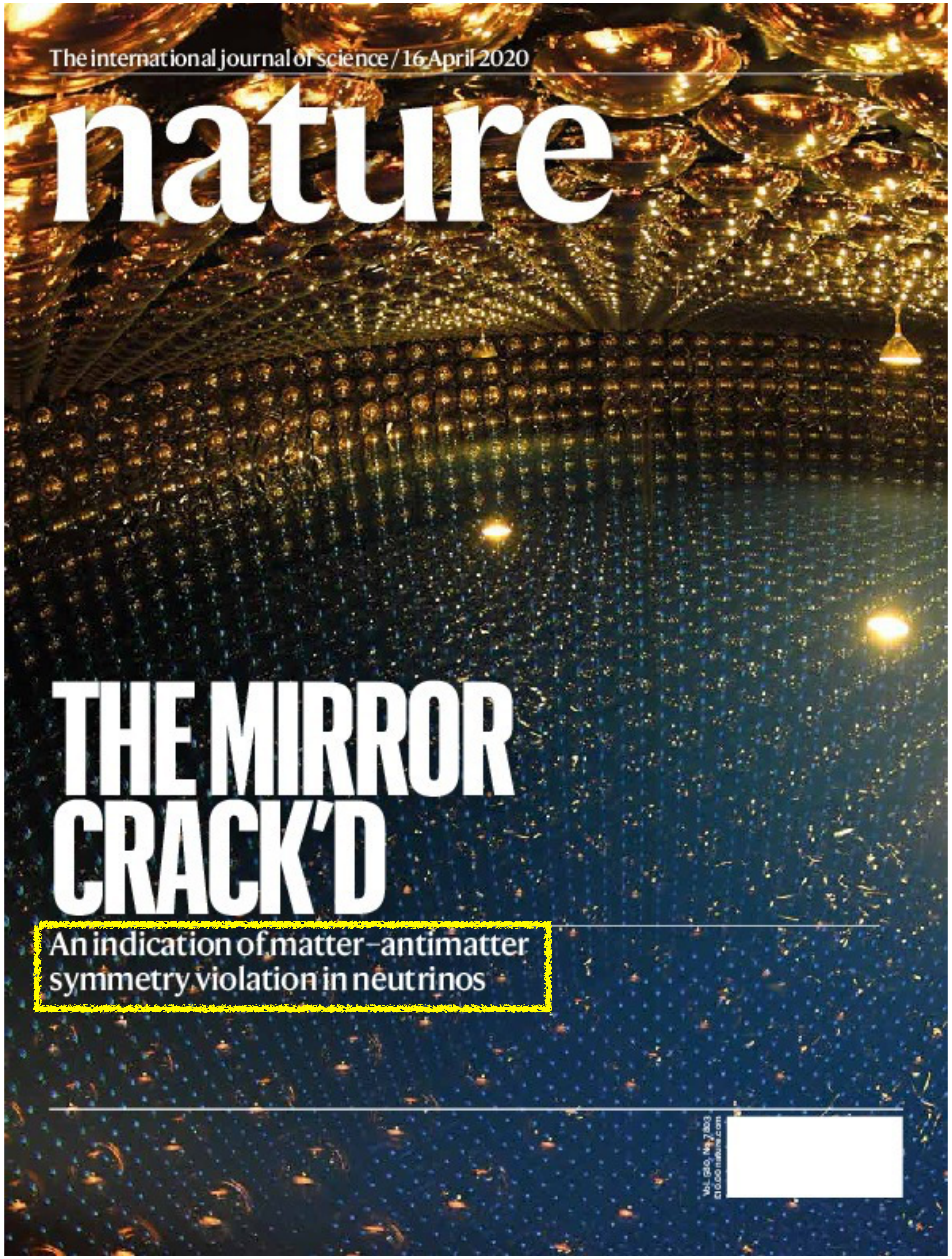


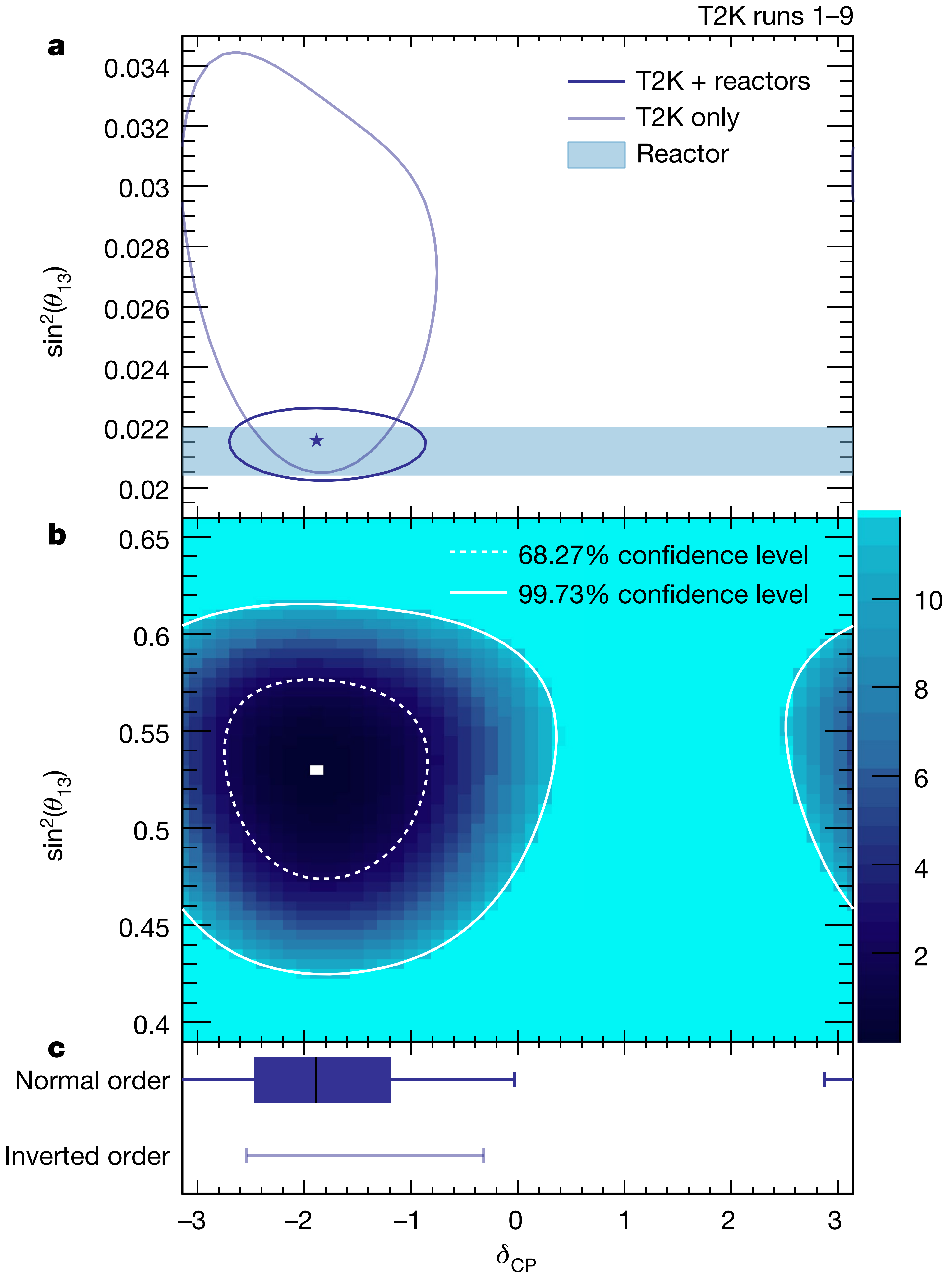


2013



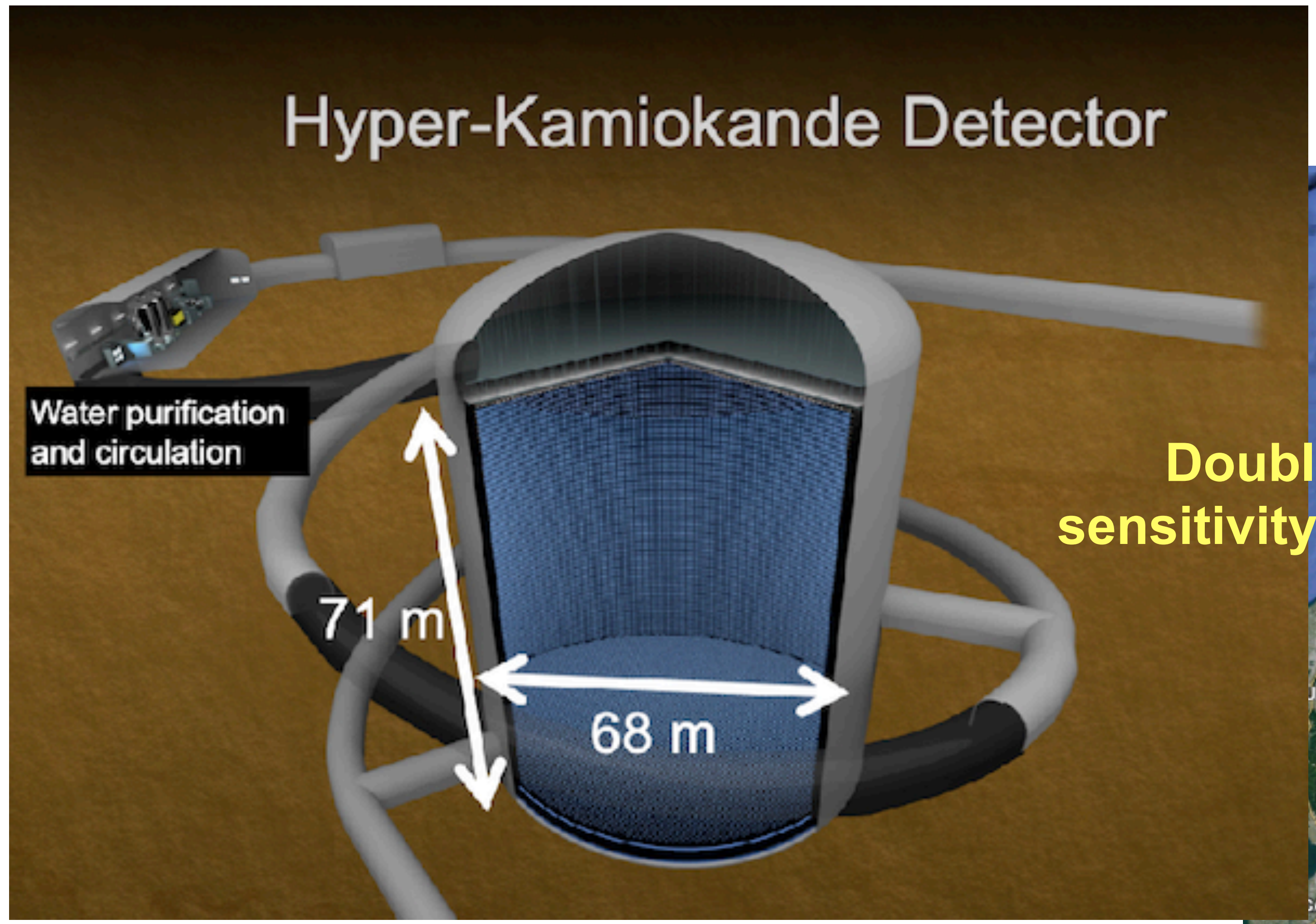



The international journal of science / 16 April 2020
nature
THE MIRROR CRACK'D
An indication of matter–antimatter symmetry violation in neutrinos

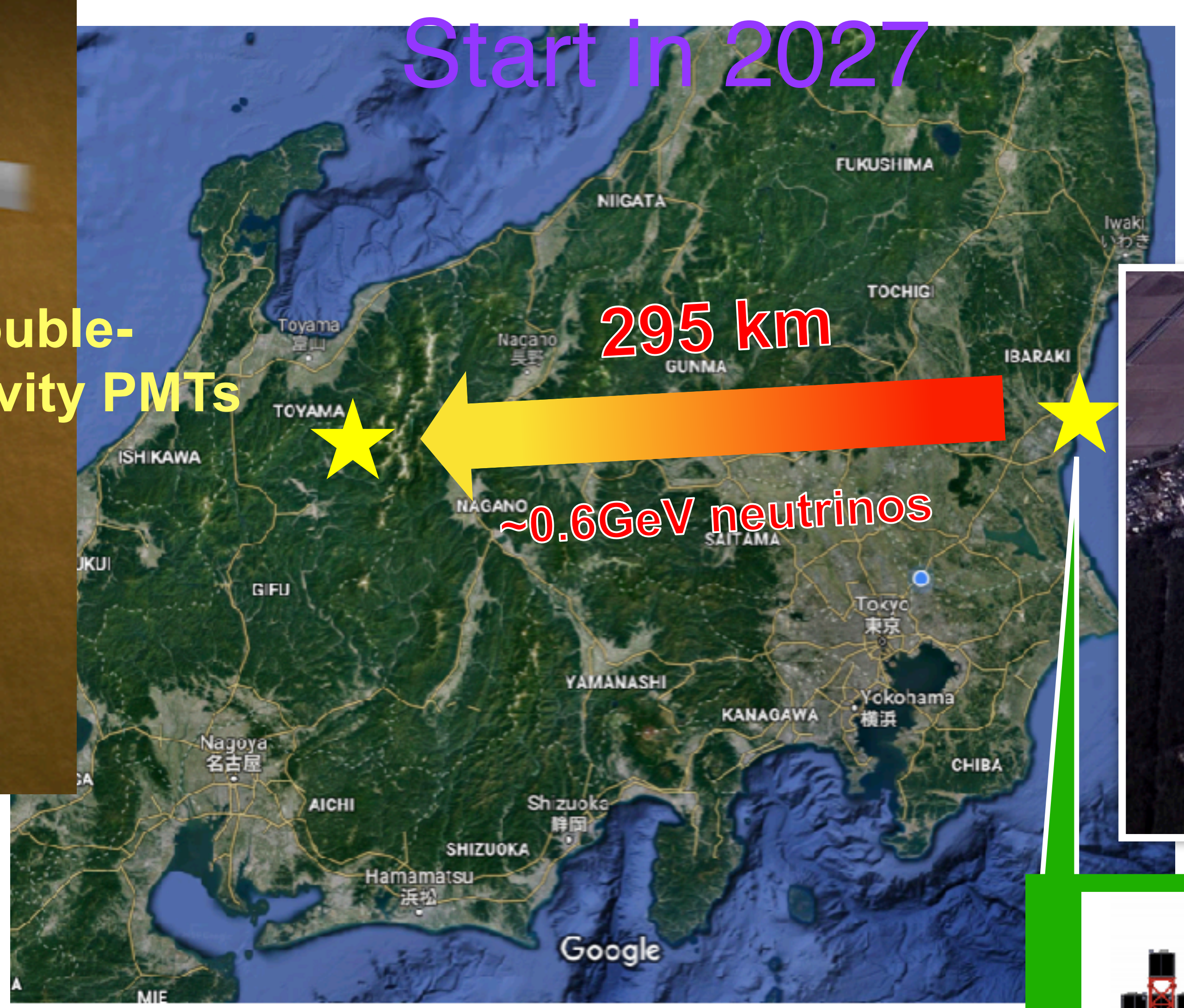

T2K runs 1–9
a
T2K + reactors
T2K only
Reactor
sin²(θ13)
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
b
68.27% confidence level
99.73% confidence level
sin²(θ13)
0.65
0.6
0.55
0.5
0.45
0.4
10
8
6
4
2
c
Normal order
Inverted order
−3
−2
−1
0
1
2
3
δCP

Hyper-Kamiokande Project

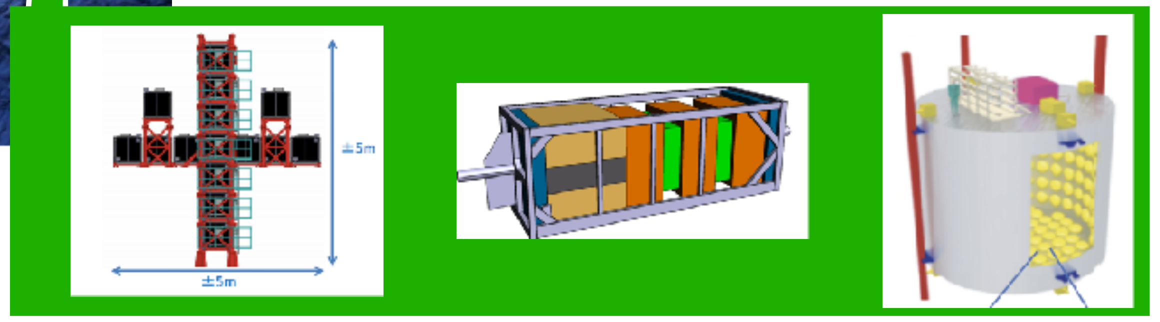
- Long baseline experiment and non-accelerator physics in a single project
- Based on the highly successful tradition of SuperK and T2K (expertise and collaboration)



Hyper-Kamiokande
(hosted by The University of Tokyo)



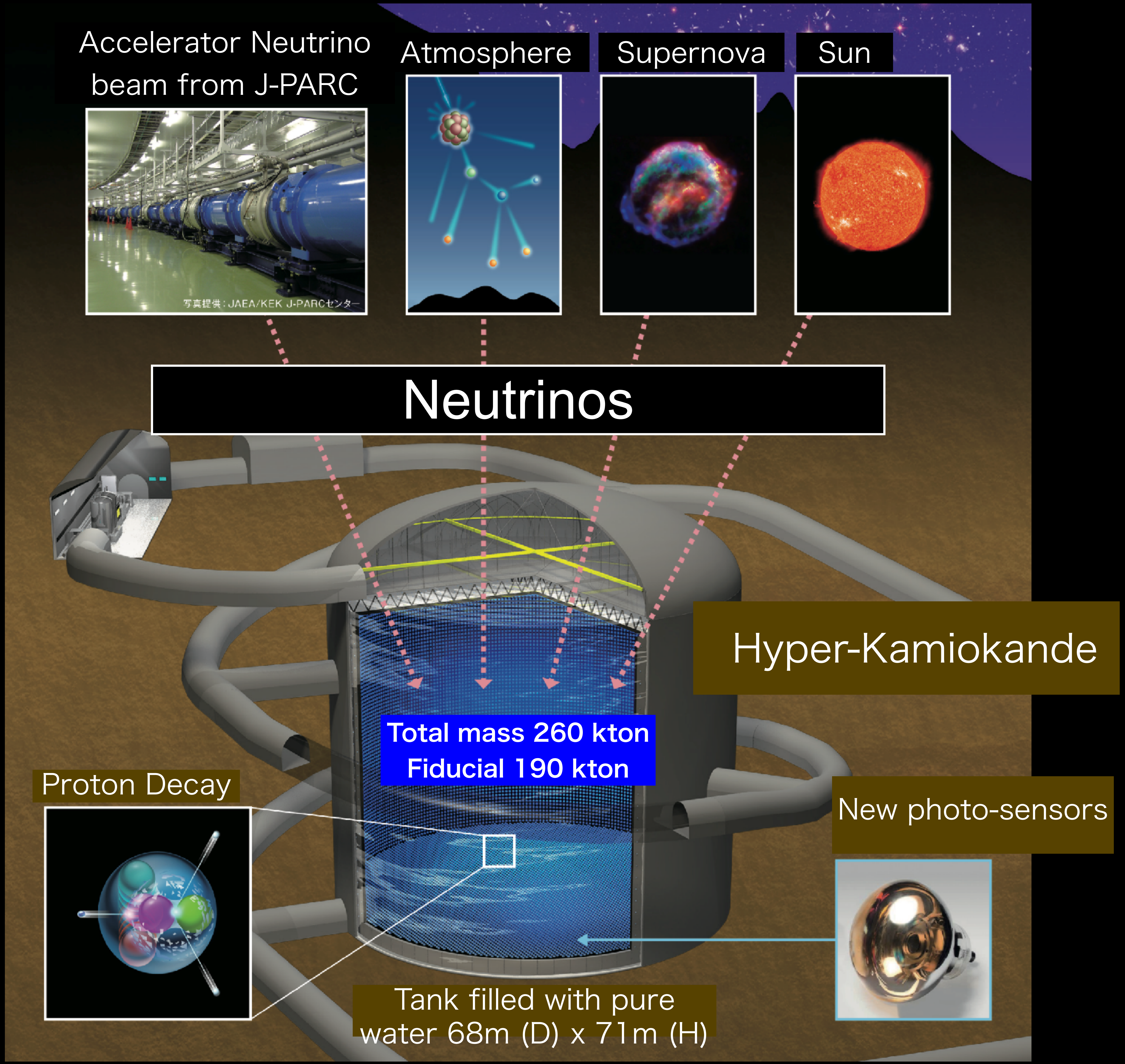
High power proton beams
J-PARC
(hosted by KEK)



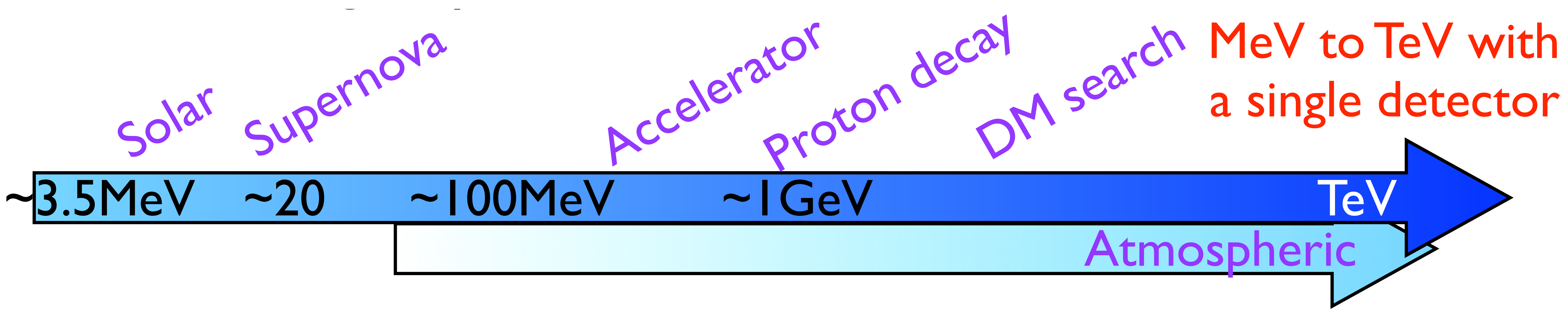
- World-largest detector for Nucleon-decay and Neutrino experiment
  - 8.4 times larger fiducial mass (190 kiloton) than Super-K instrumented with double-sensitivity PMTs
- World most-intense neutrino beam
  - J-PARC neutrino beam to be upgraded to 1.3 MW
- New and upgraded near detectors to control systematic errors

Physics Sensitivity

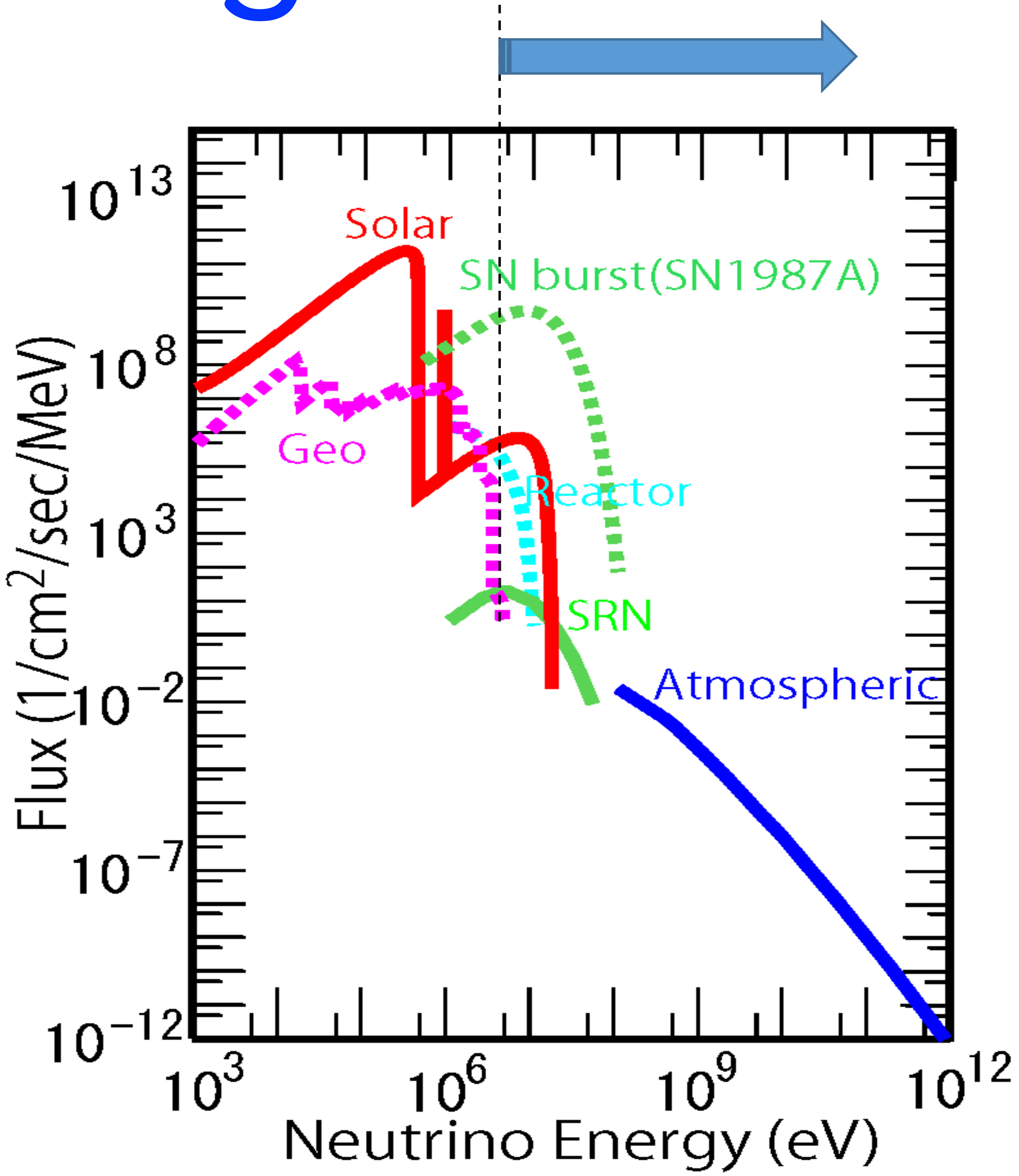
Hyper-Kamiokande program



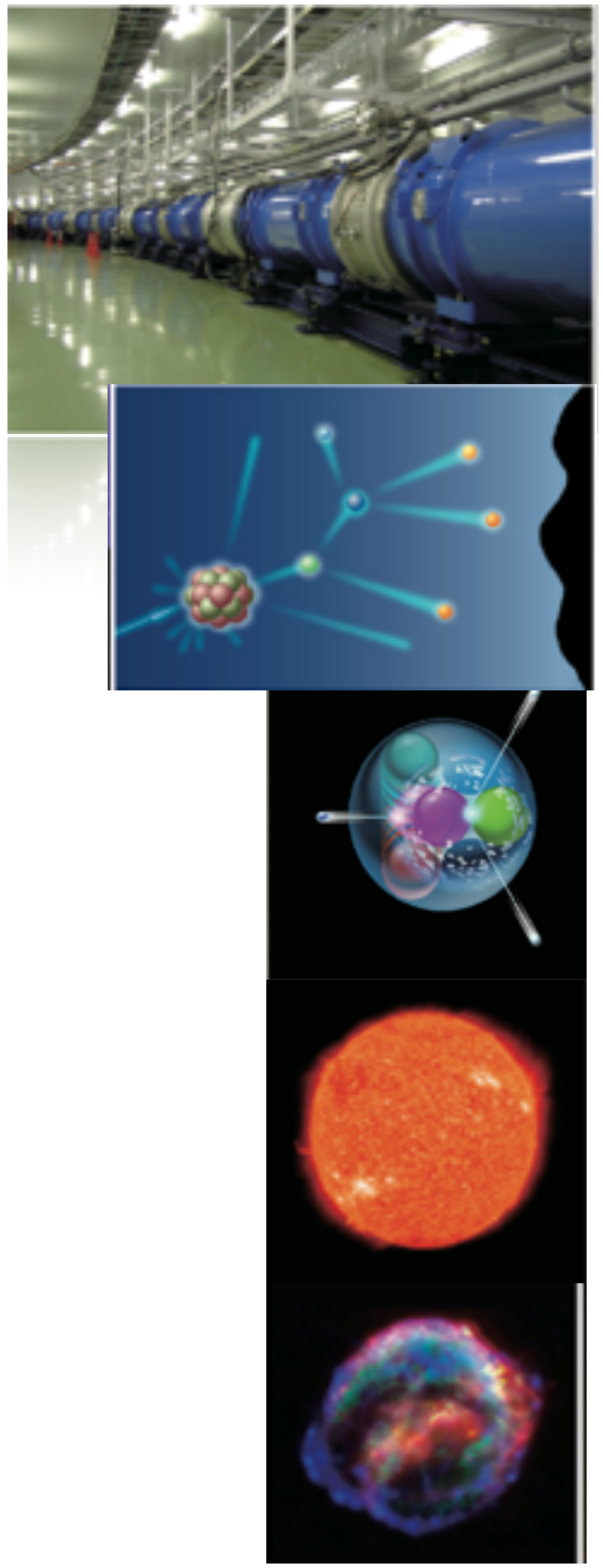
Many Physics targets



- The **mass** of the detector with the **wide energy coverage** is the Key to probe new physics.
- It is an only unique choice to search for the proton decay up to 10^{35} years.



Target sensitivity

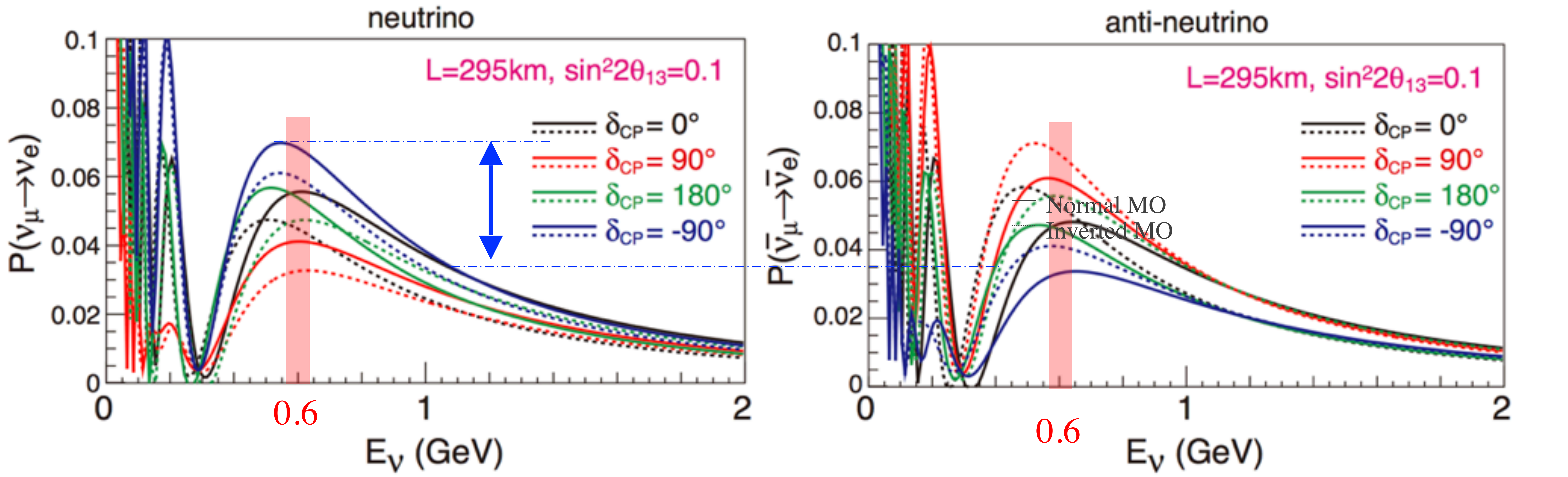


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}-45°\rvert>2°$
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)	1×10^{35}
	τ for $\bar{\nu}K$ (3σ)	3×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	8σ/4σ
	Upturn	>3σ
Supernova	Burst (10kpc)	54k-90k
	Relic	70ν's / 10 years

Long-baseline program with the J-PARC neutrino beam

Experimental setup

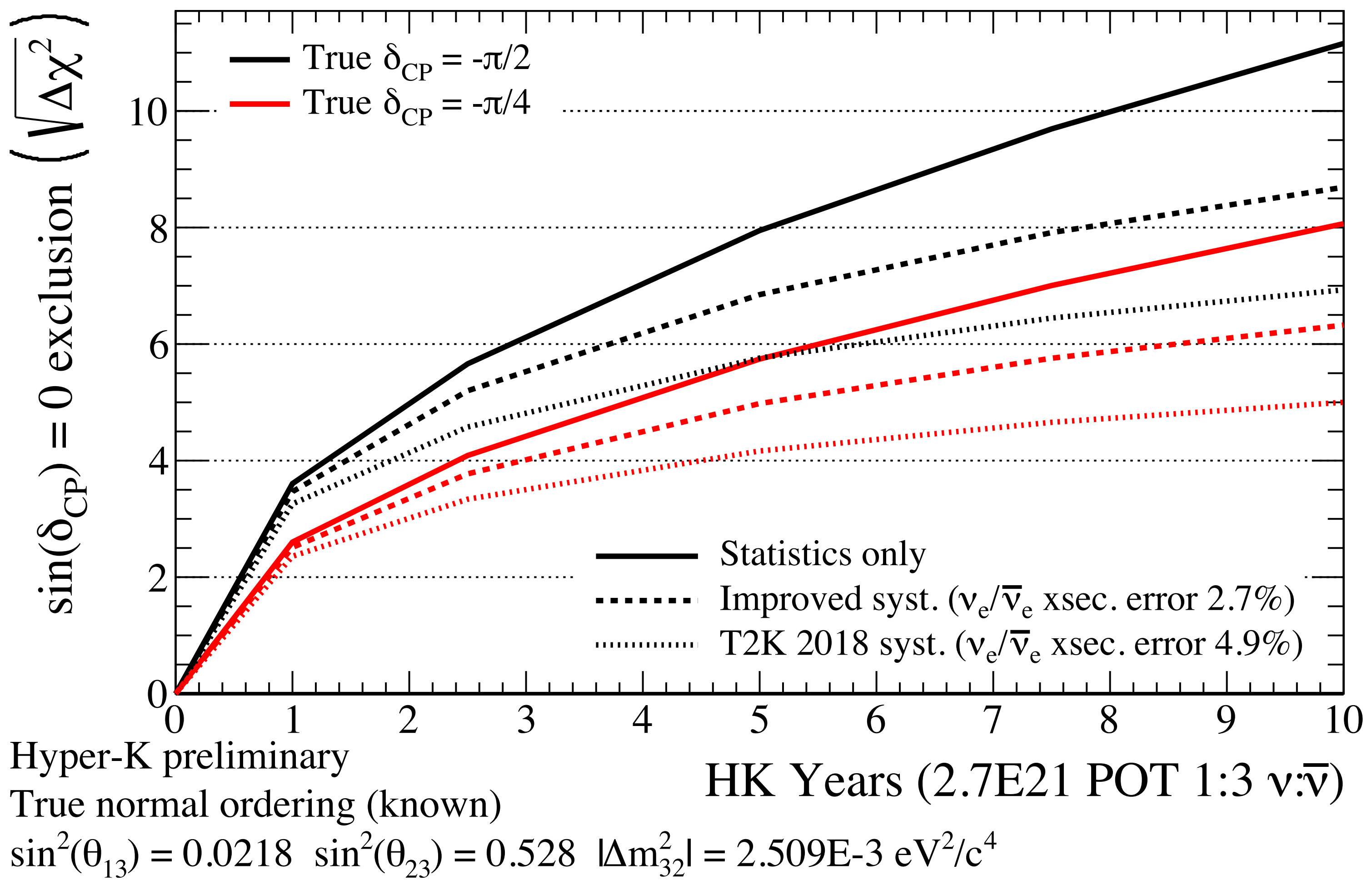
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - ➢ Major component is QE: E_ν determined from $(p,\ \theta)$ of charged lepton
- Measures CP violation in neutrinos by comparing $P\left(\nu_\mu \to \nu_e\right)$ and $P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$



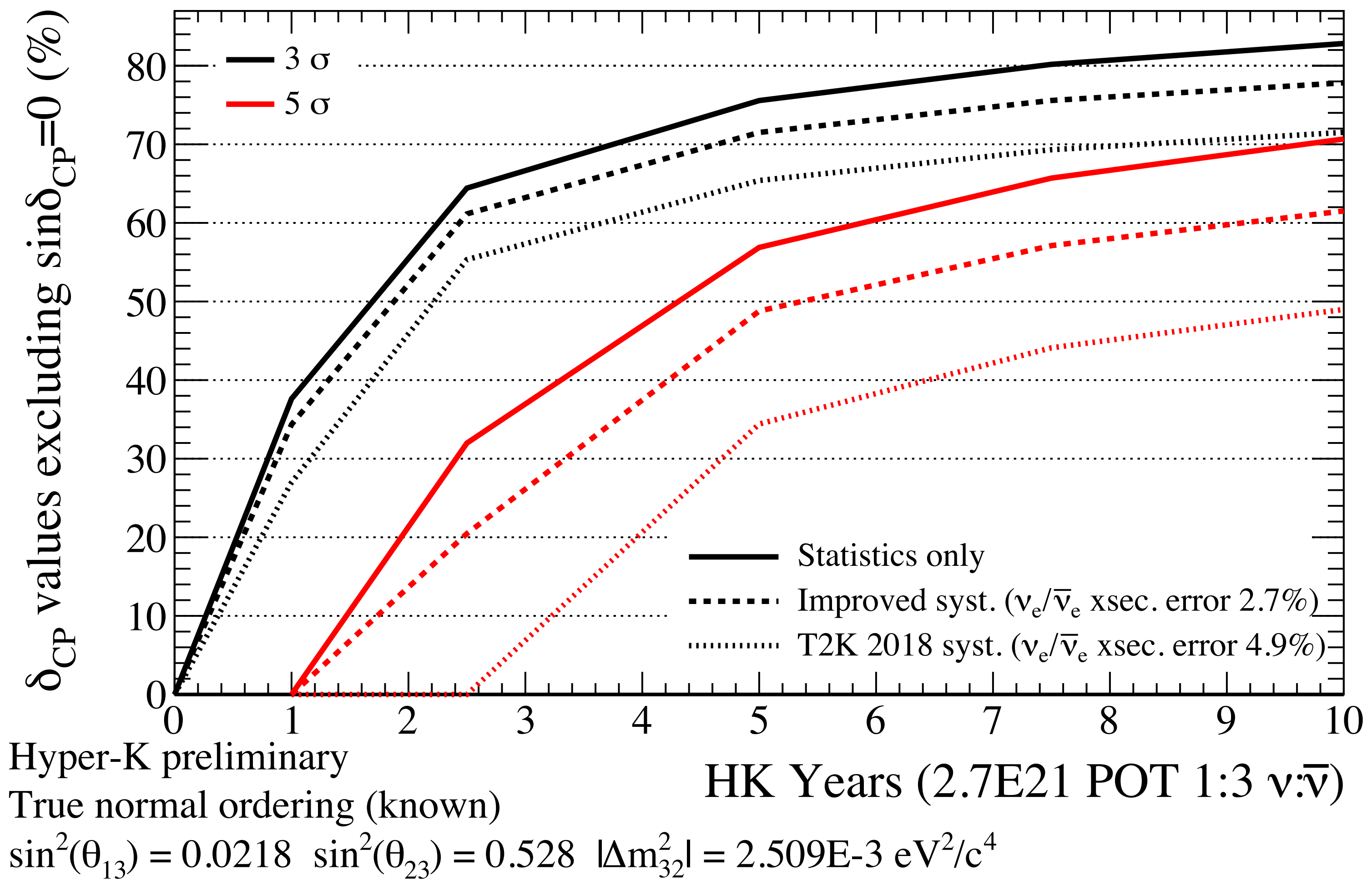
- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

Neutrino oscillation sensitivity

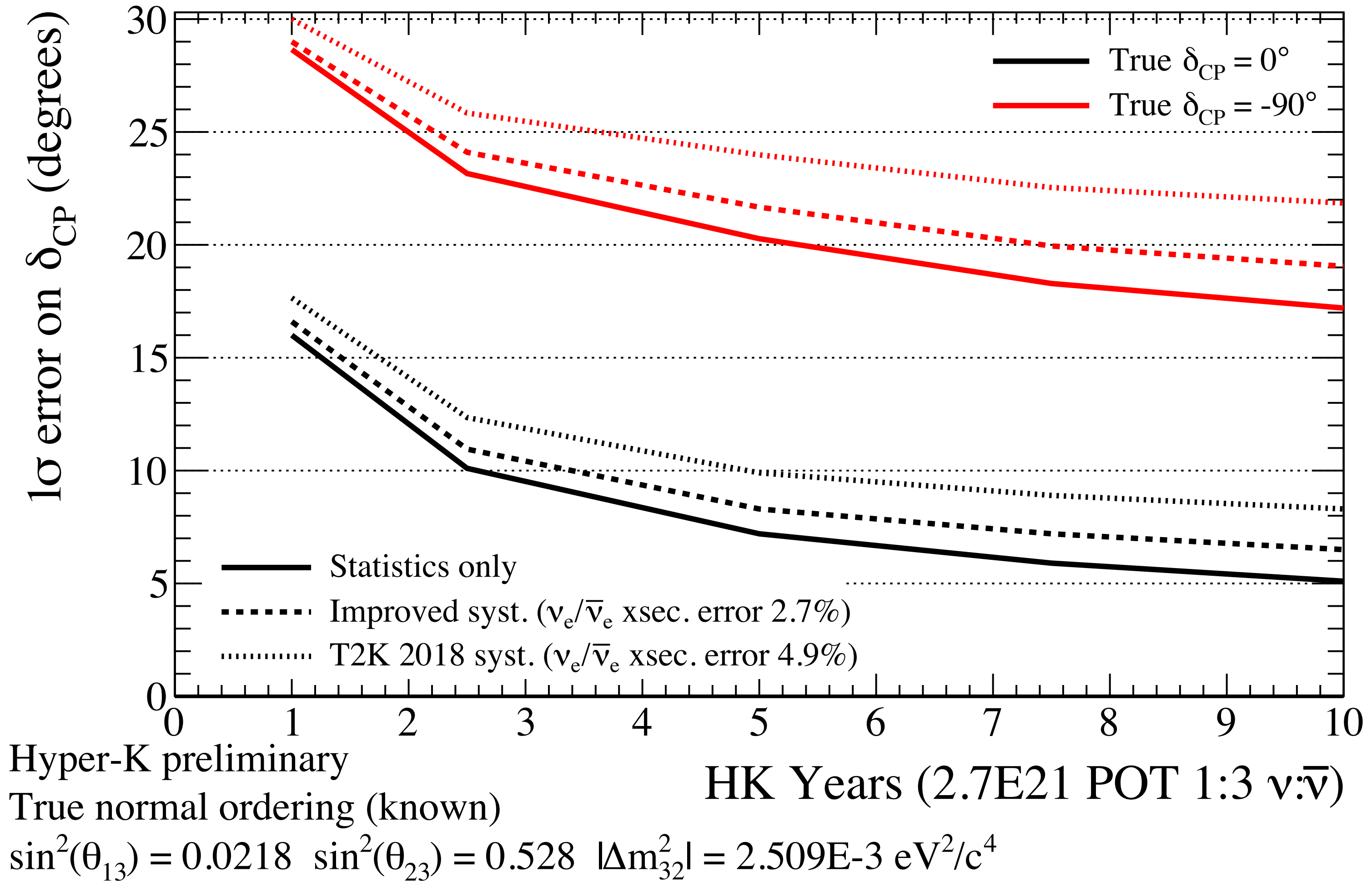
Sensitivity for δ_{CP}=-π/2 or -π/4



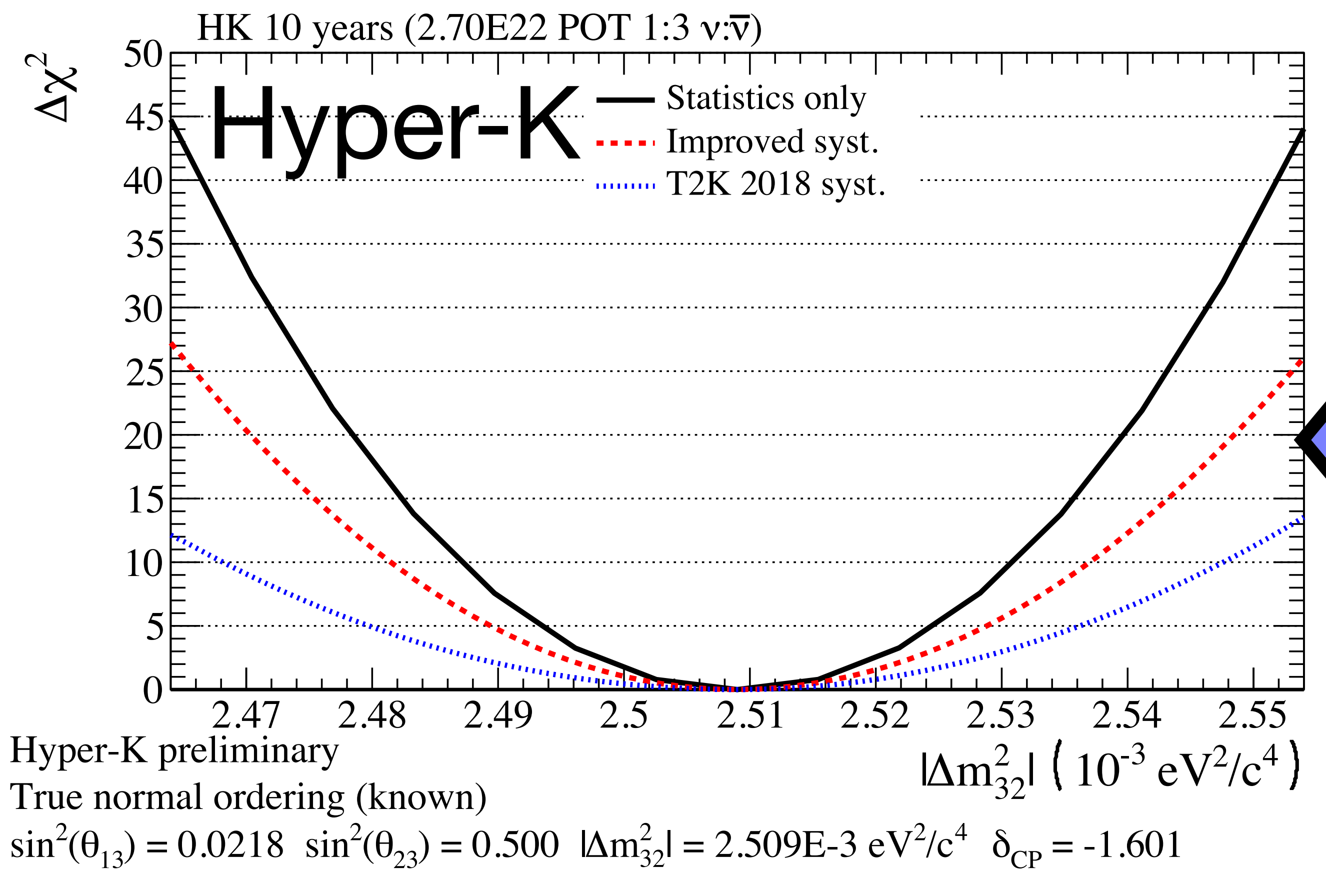
Fraction of δ_{CP} exclusion with 3σ or 5σ



Precision for δ_{CP}=0 or -π/2

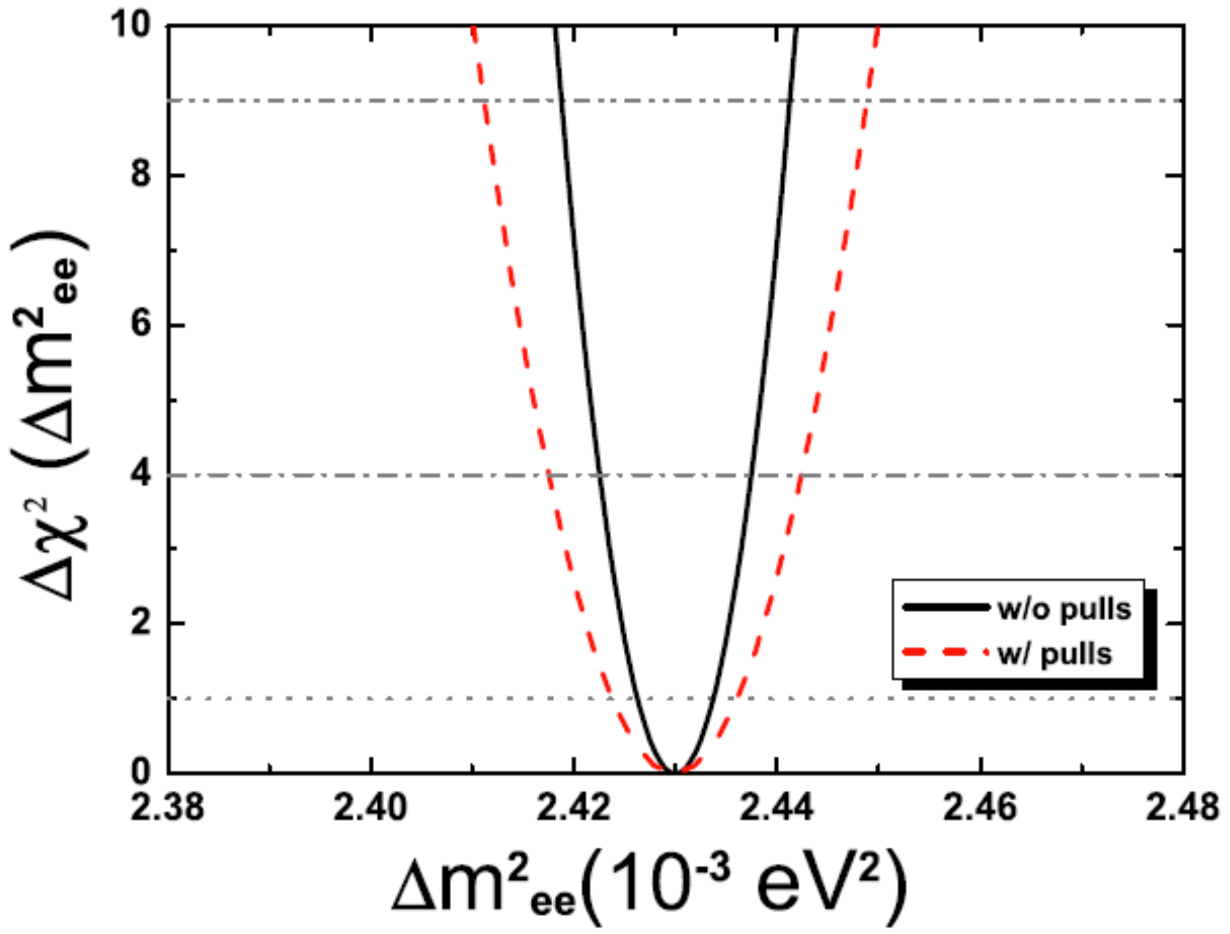


- Good chance for discovery of CP violation with > 5σ
  - Measurement of δ_{CP} with ~20° for $\delta_{cp} = -90°$ / ~7° for $\delta_{cp} = 0°$
- Combination of beam and atmospheric neutrinos enhances the sensitivity for mass ordering
- Reduction of systematic uncertainty has sizable impact
  - Upgrade of T2K ND280 + a new 1kton scale water Cherenkov (IWCD)



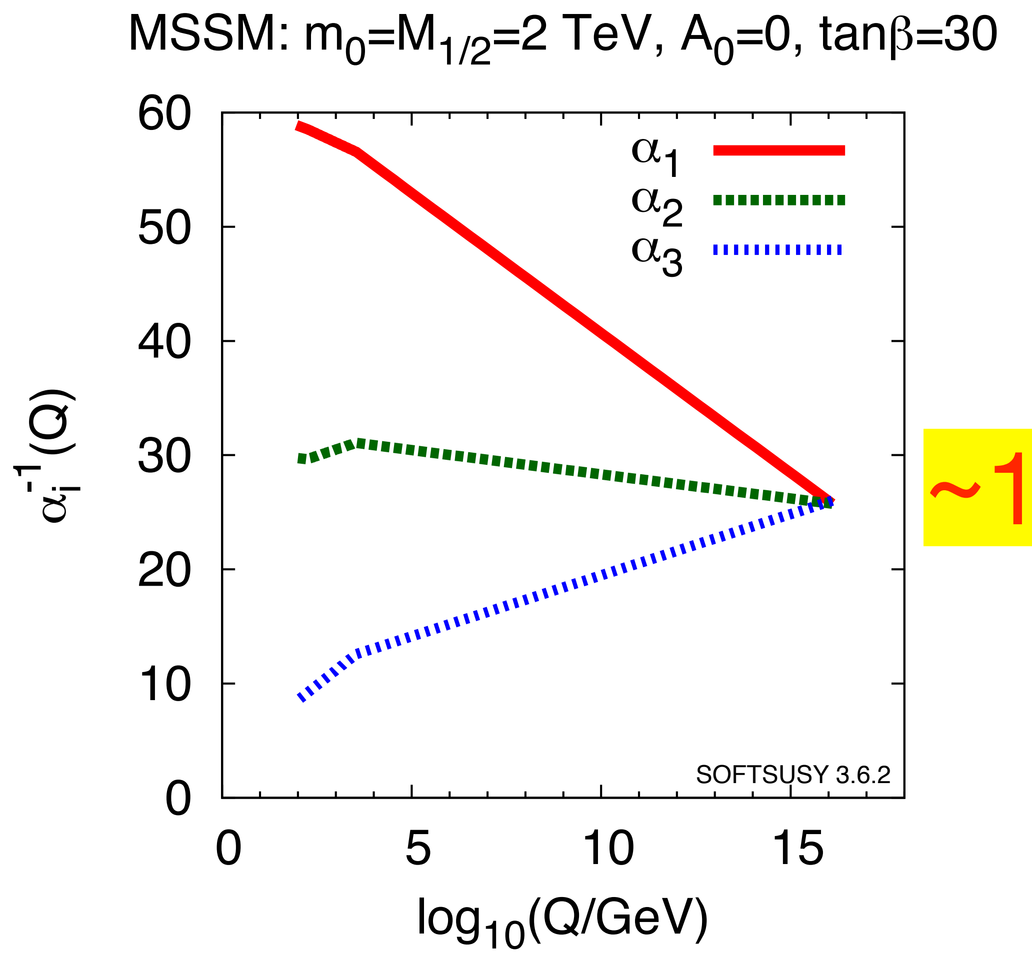
Δm^2

JUNO (reactor $\bar{\nu}_e$ at ~50km)



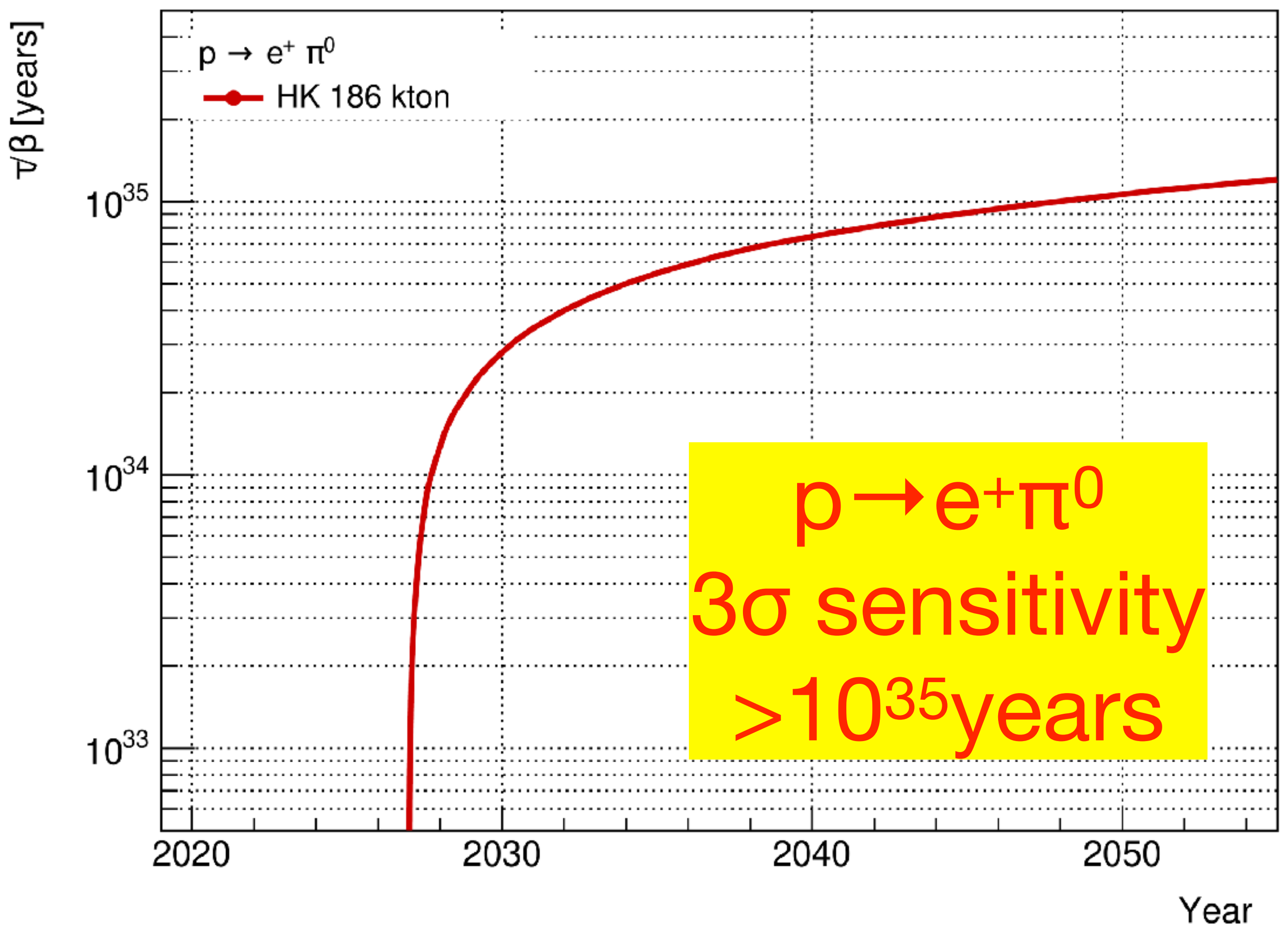
Proton decay Search

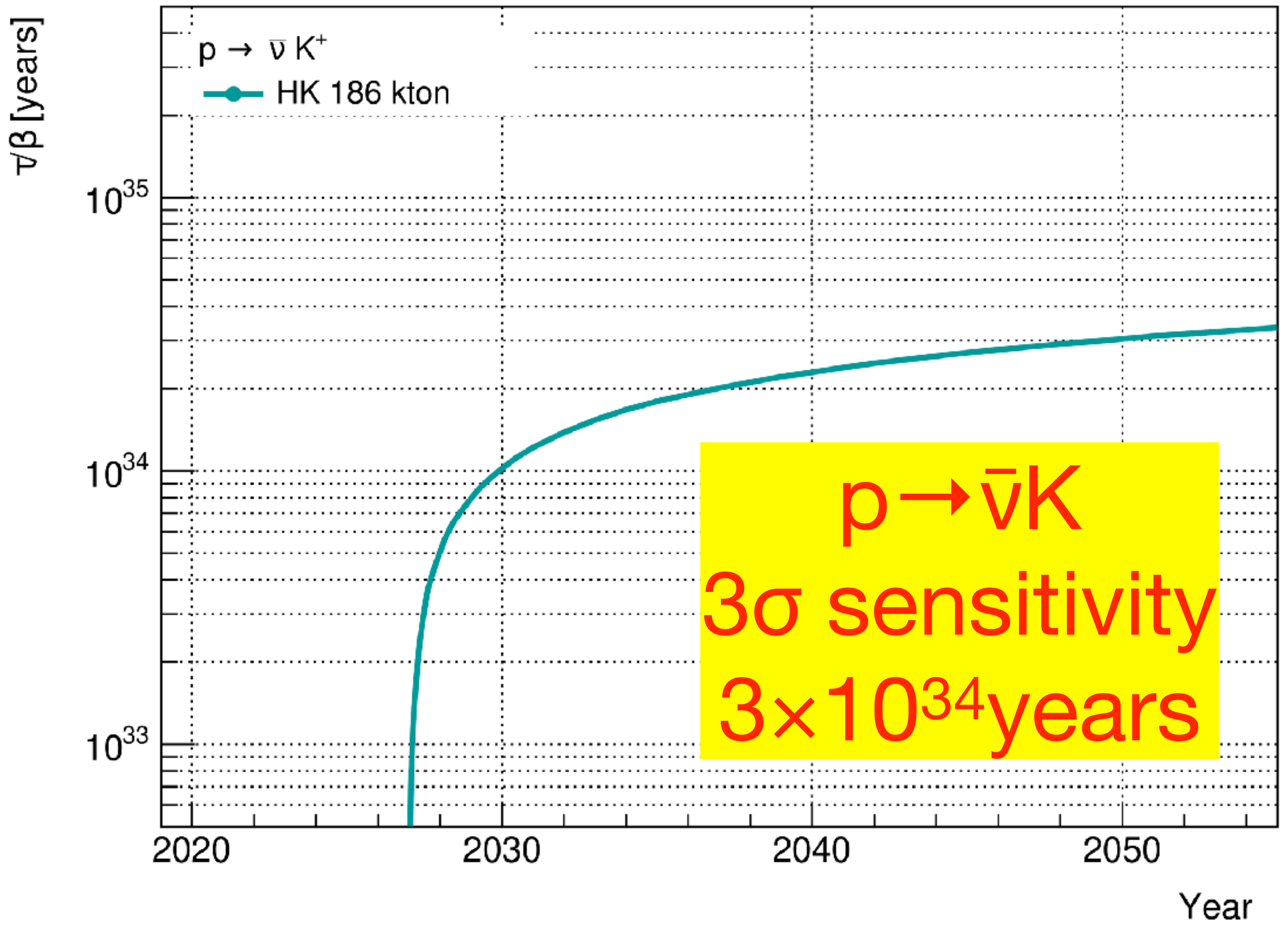
Nucleon decay:
clear evidence of GUT



~10^{16}GeV

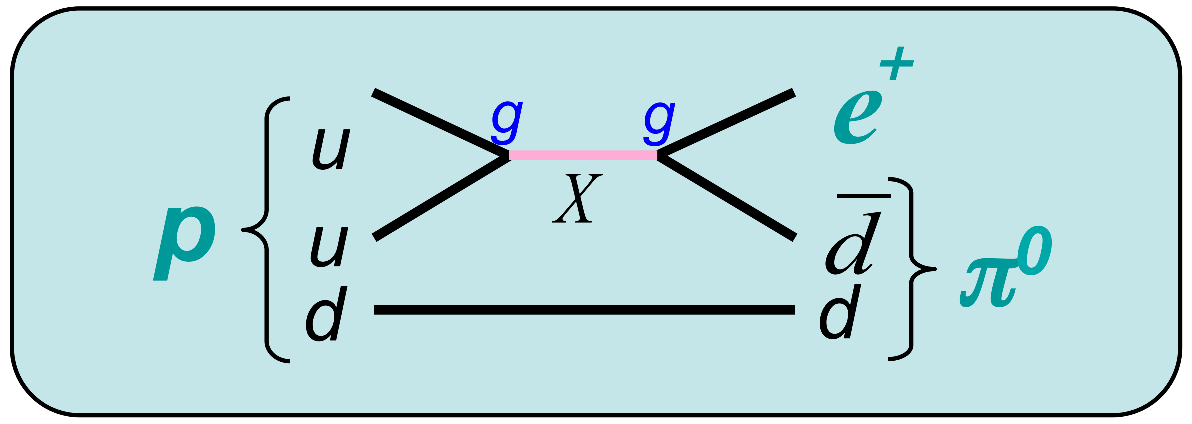
World's best sensitivity for most of possible modes, including p→ν̄K, thanks to huge mass and free protons





Two modes as benchmark

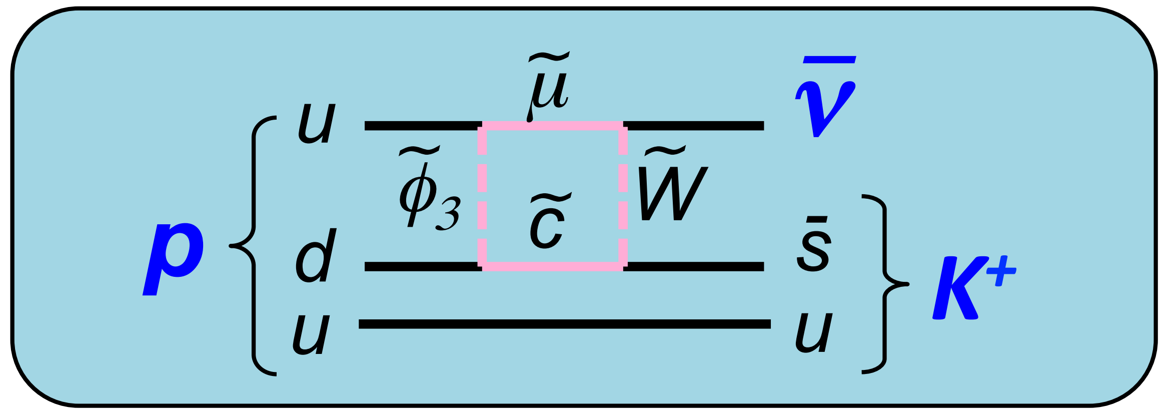
Mediated by gauge bosons



p→e⁺π⁰

$$\Gamma(p\rightarrow e^+\pi^0)\sim\frac{g^4 m_p^5}{M_X^4}$$

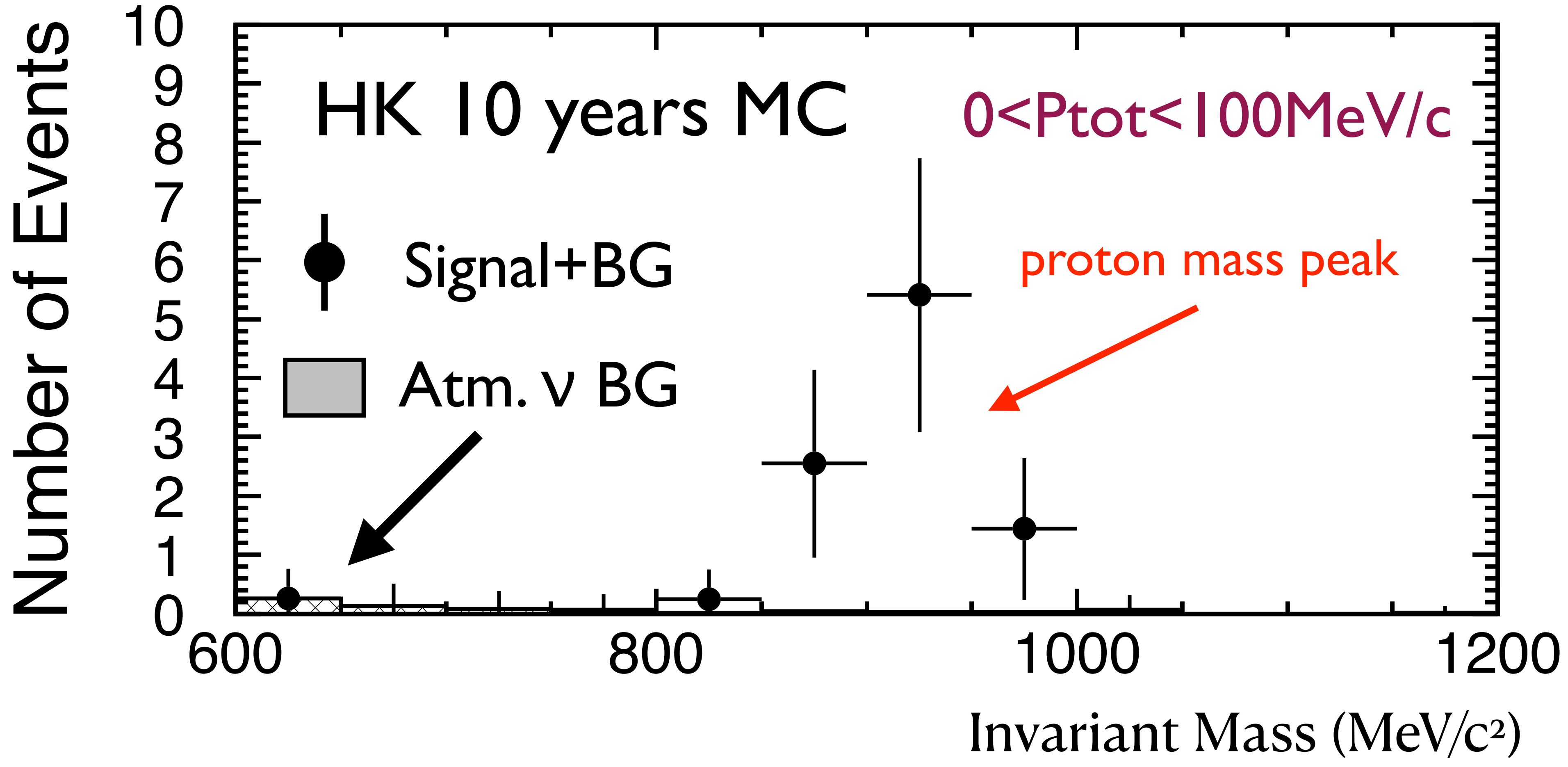
SUSY mediated



p→ν̄K⁺

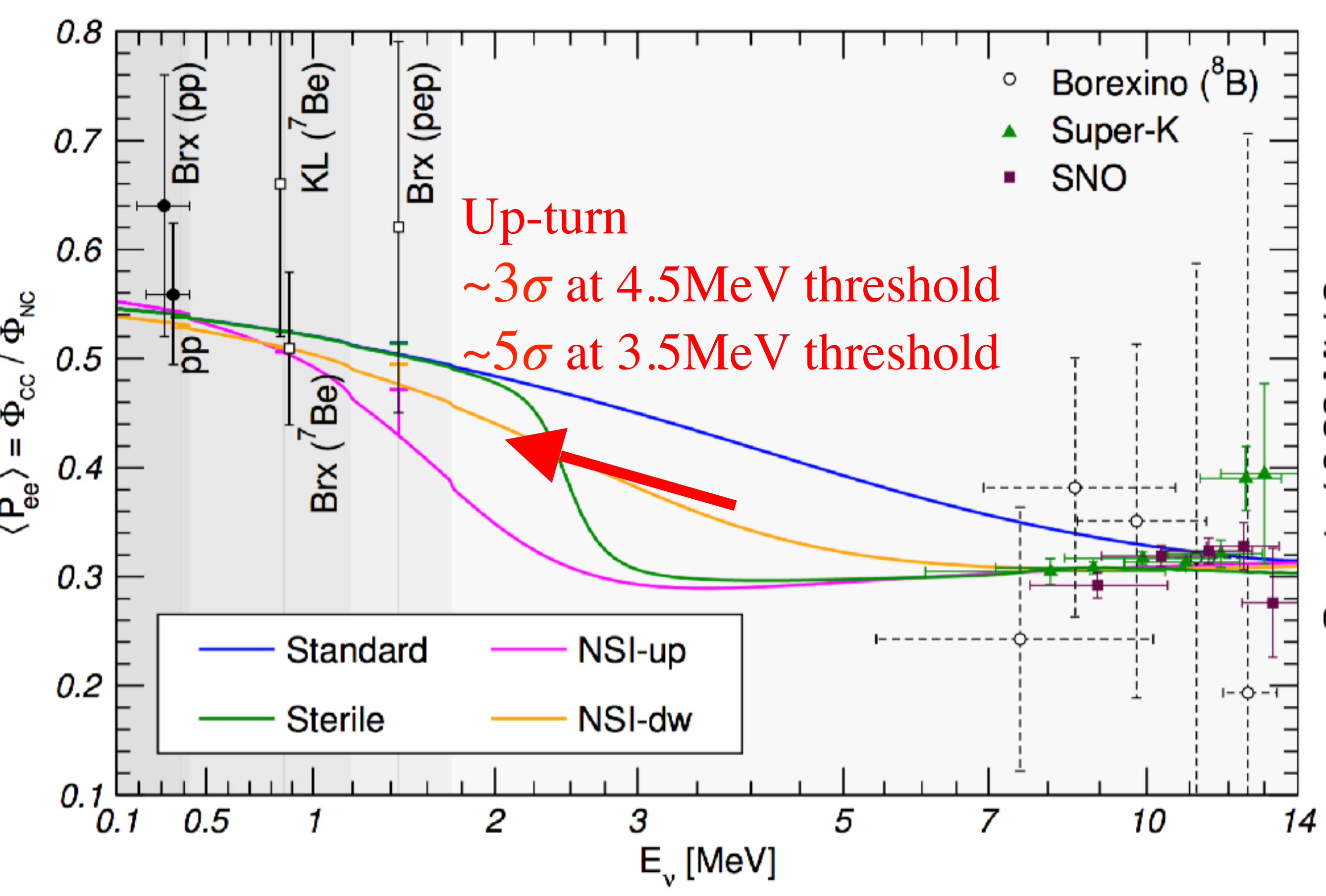
$$\Gamma(p\rightarrow\bar{\nu}K^+)\sim\frac{\tan^2\beta\times m_p^5}{M_{\tilde{q}}^2\times M_3^2}$$

p→e⁺π⁰

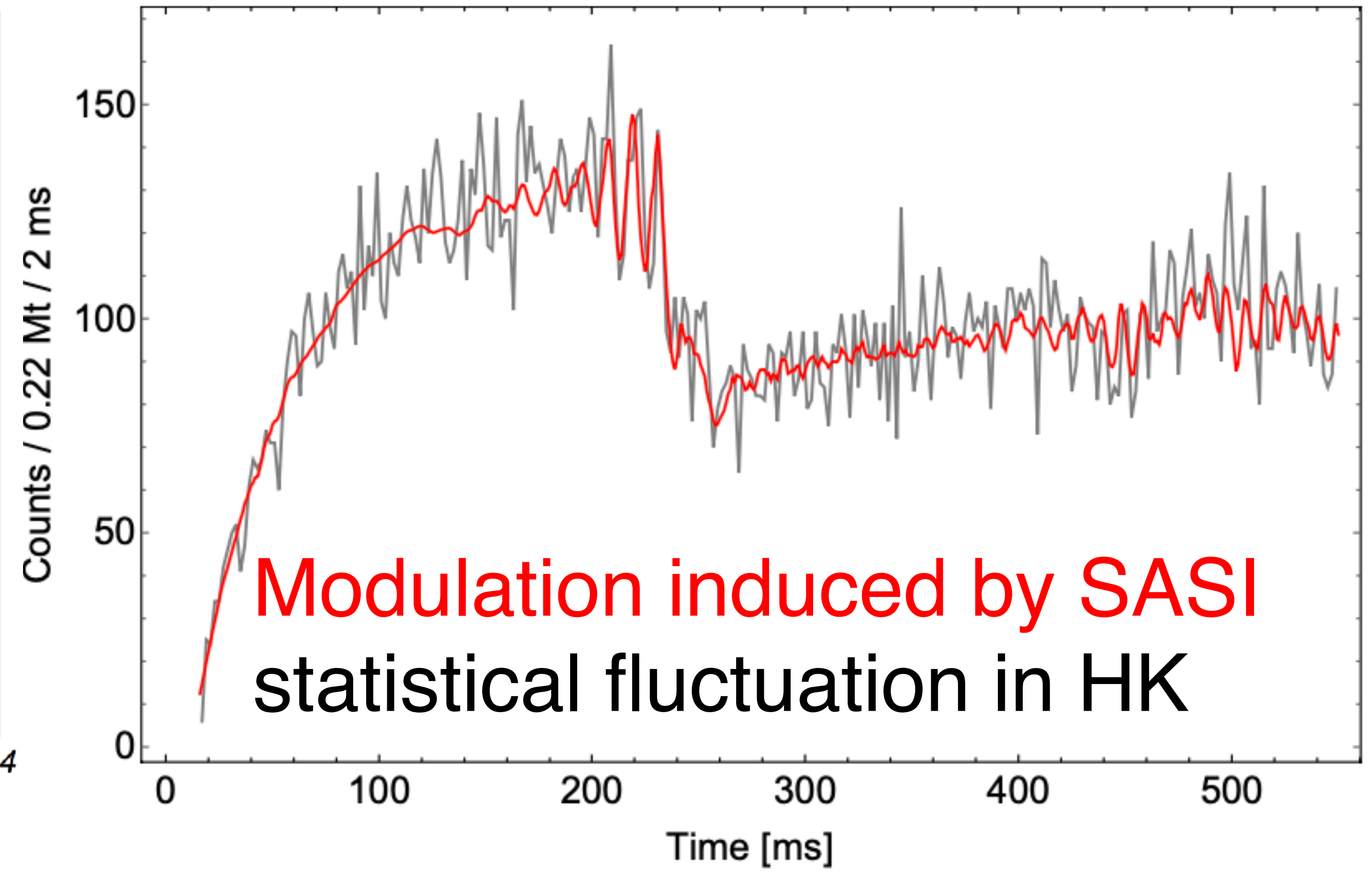


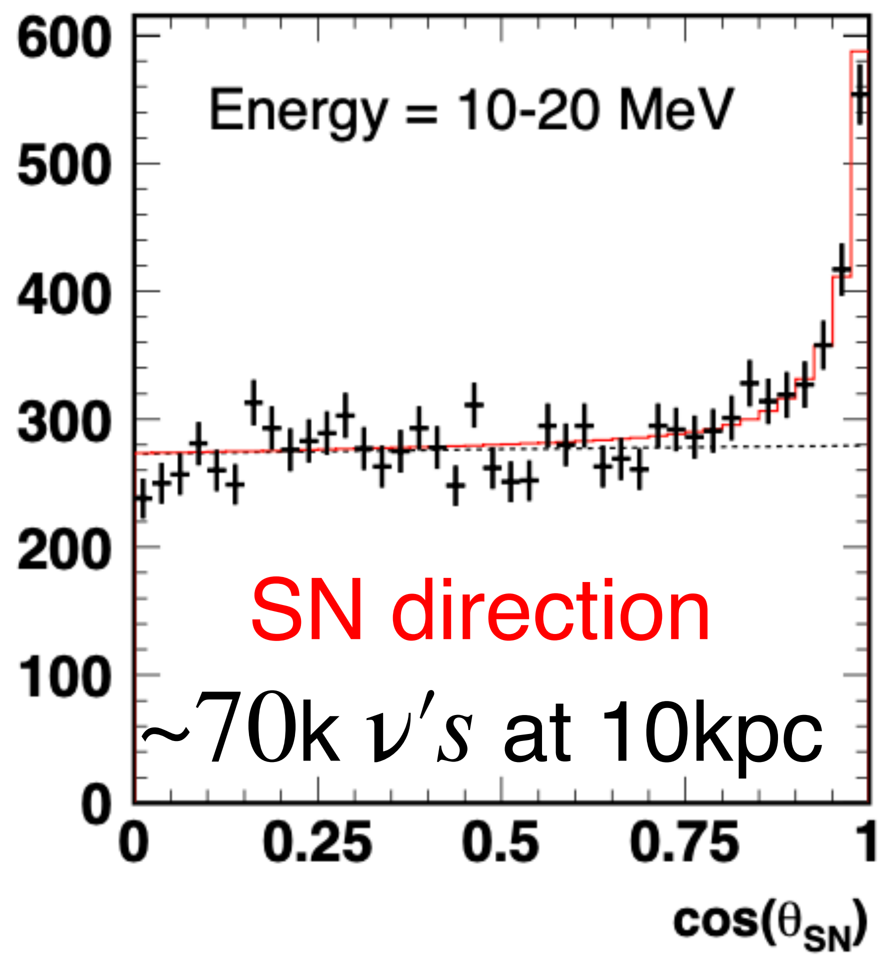
Neutrino Astrophysics

- Observation of a few~10MeV neutrinos with time, energy and direction information
  - Unique role in multi-messenger observation
- Solar neutrinos: up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- Supernova burst neutrinos: explosion mechanism, BH/NS formation, alert with ~1º pointing
- Supernova Relic Neutrinos (SRN): stellar collapse, nucleosynthesis and history of the universe



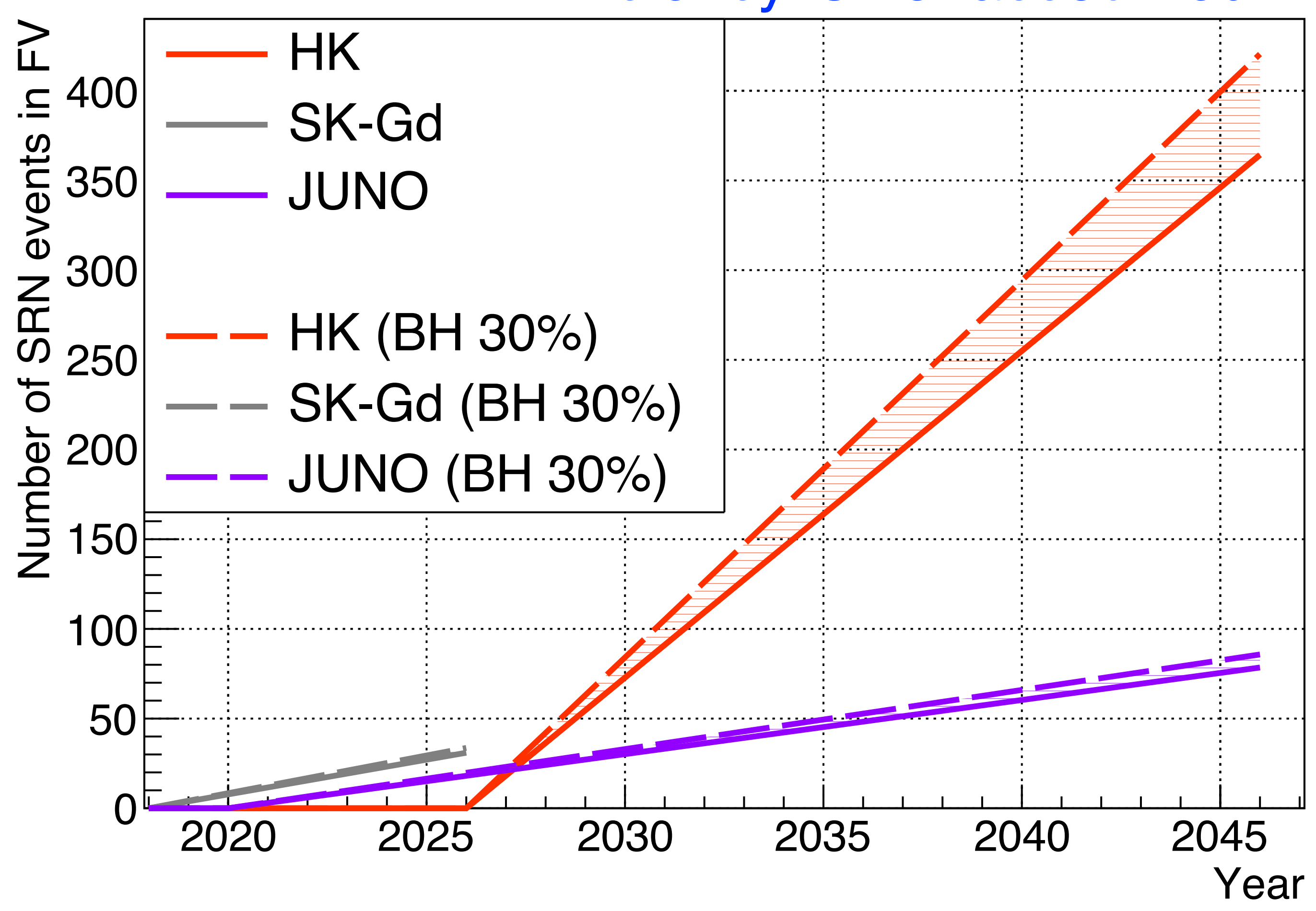
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)





SRN rate

Calculation from FV and E_{th}
Efficiency is not accounted

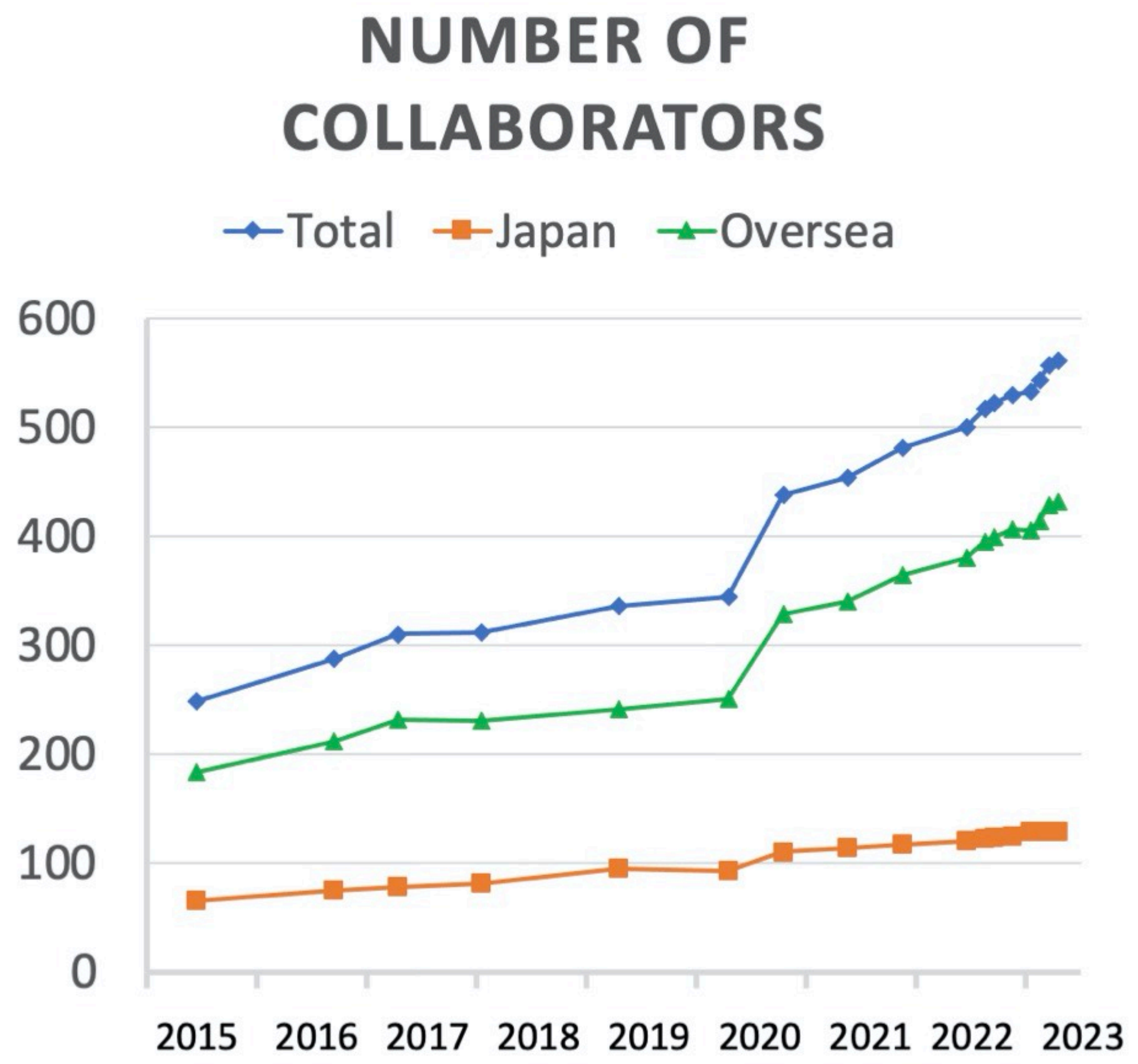


Project Status

Hyper-Kamiokande collaboration

Univ. of Tokyo and KEK host the project

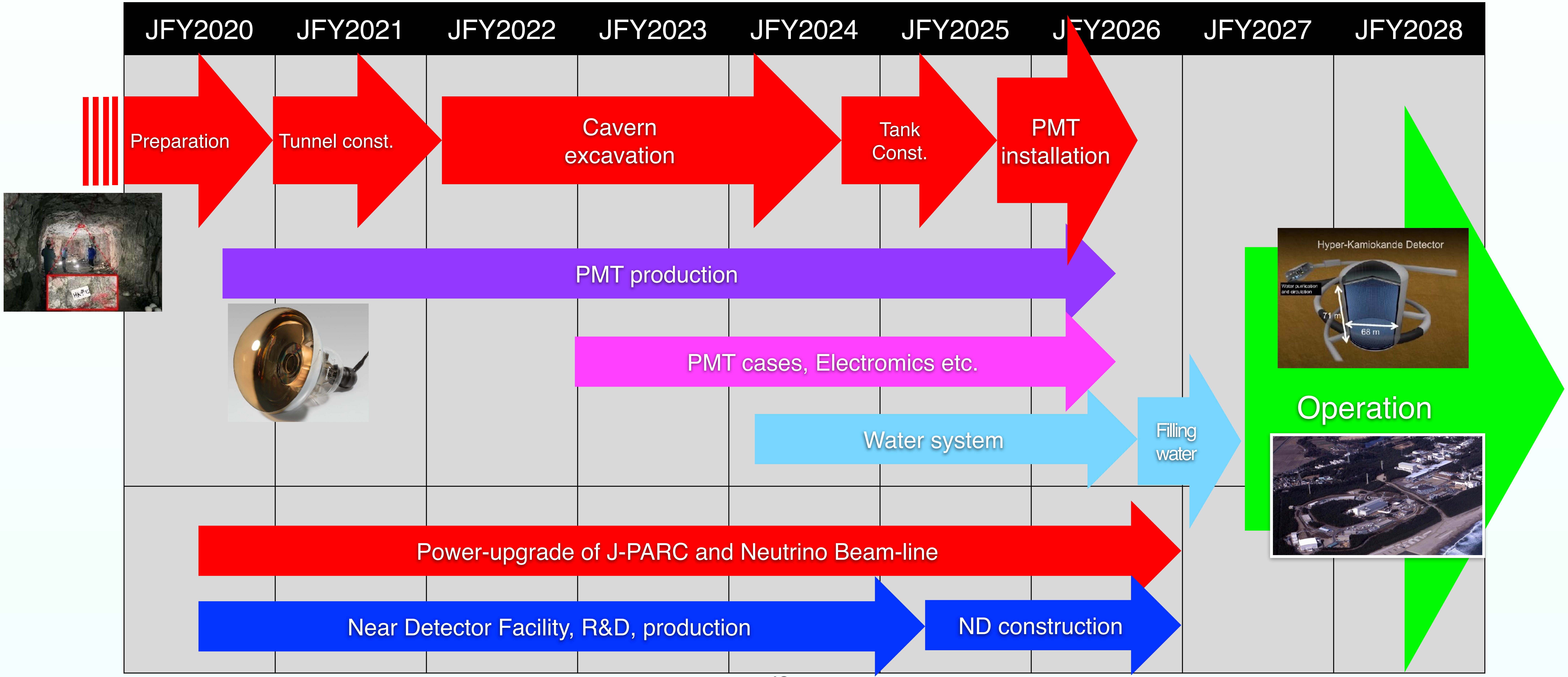
- ~560 people from ~20 countries, ~100 institutions
  - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN



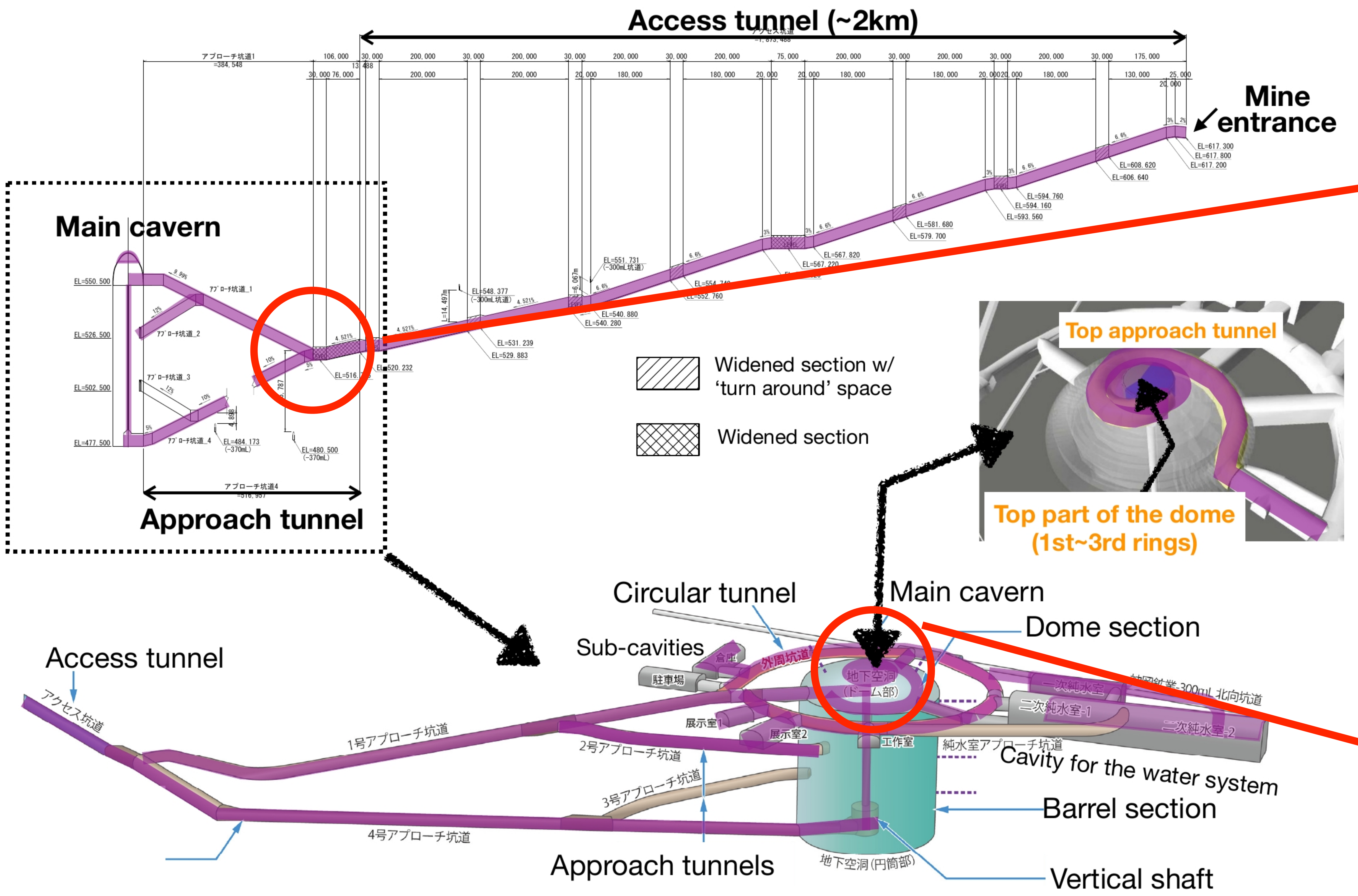
First face-to-face meeting after project approval

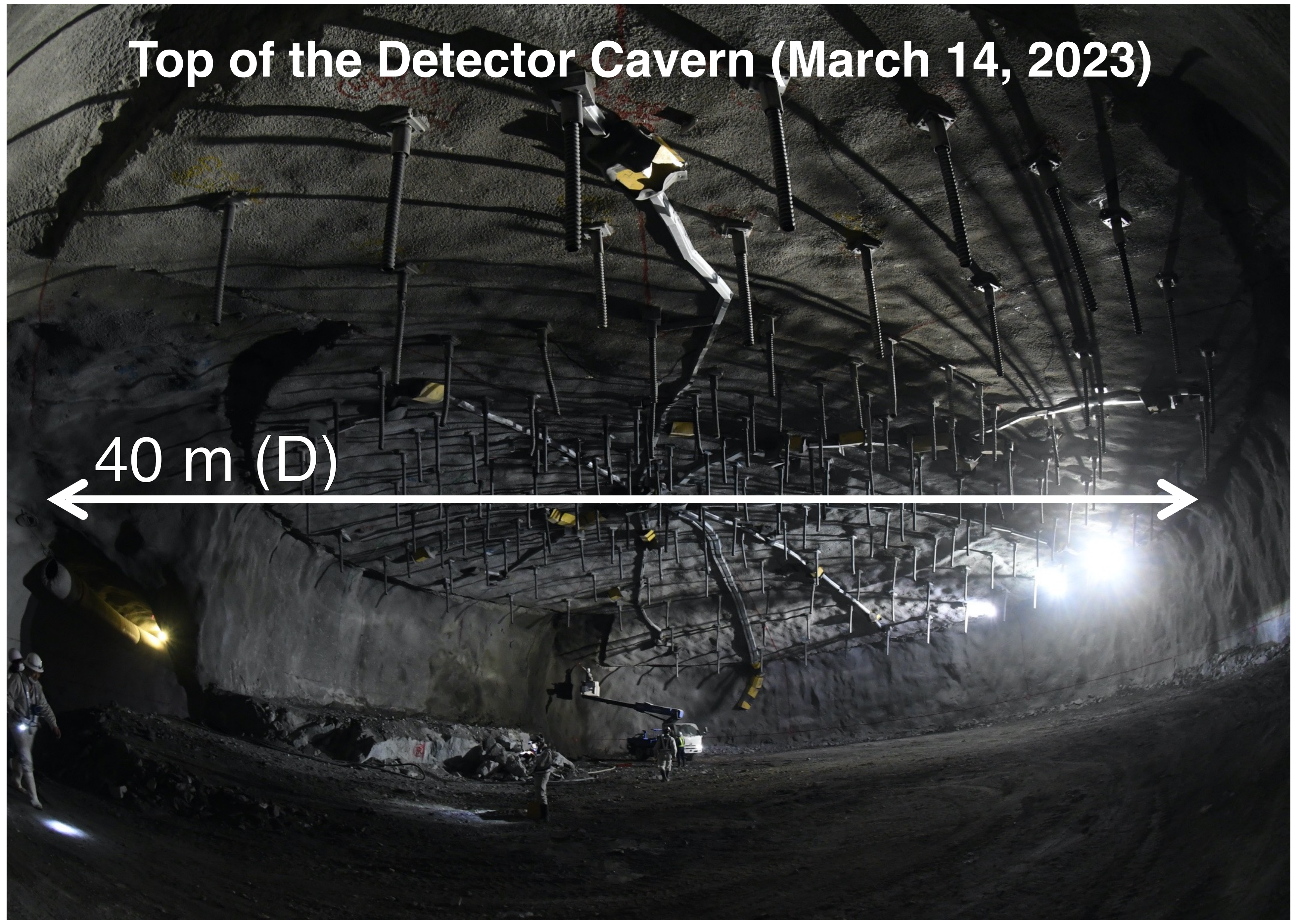
Timeline

- 2022-2027: Construction, 2027- : Operation
  - No change of schedule since the approval of project in 2020



Cavern excavation status

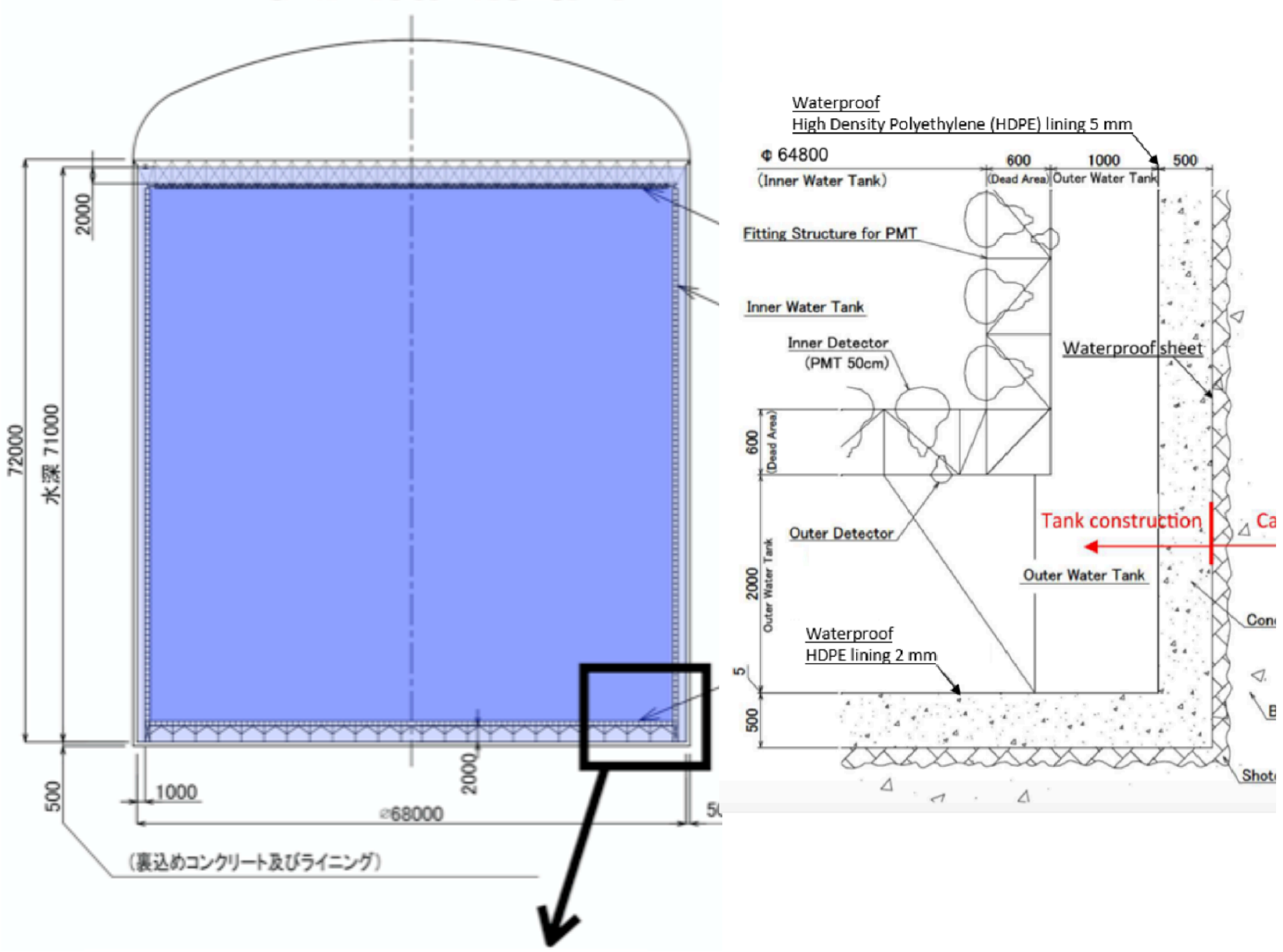


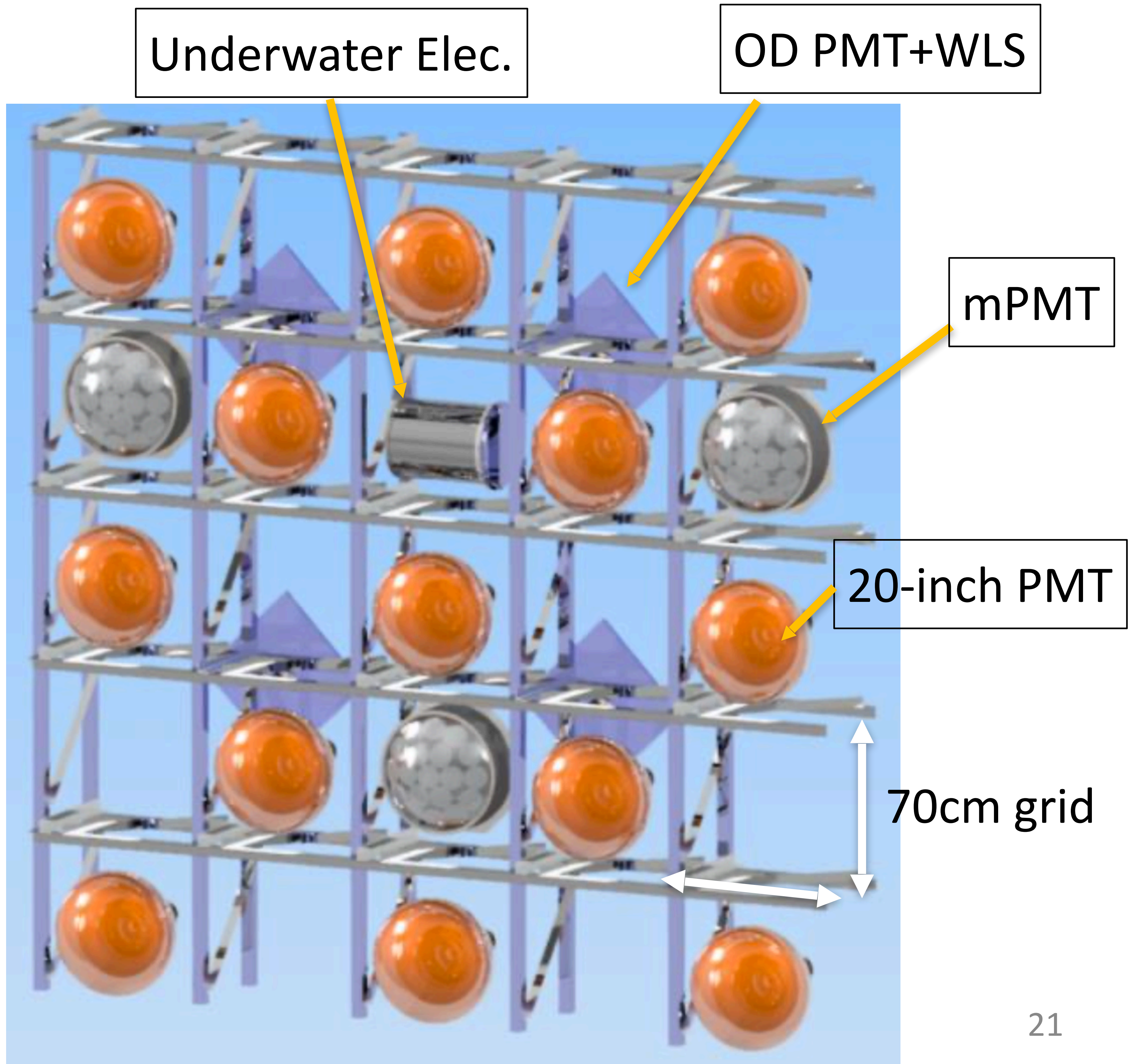


- Access tunnel (~2 km) completed in Feb. 2022
- Excavation of the main cavern started in fall 2022 and is proceeding as scheduled

Detector configuration

- 67 mΦ x 66 m Inner Detector (fiducial 190 kt)
  - 20,000 HPK HiQE (x2 SK) 20-inch PMTs will be installed
  - mPMT modules will be integrated as hybrid configuration.
- 1m(wall) or 2m(top/bottom) thick Outer Detector
  - 3” PMTs + WLS boards
- Under-water electronics module
  - Mitigate disadvantage of long cables

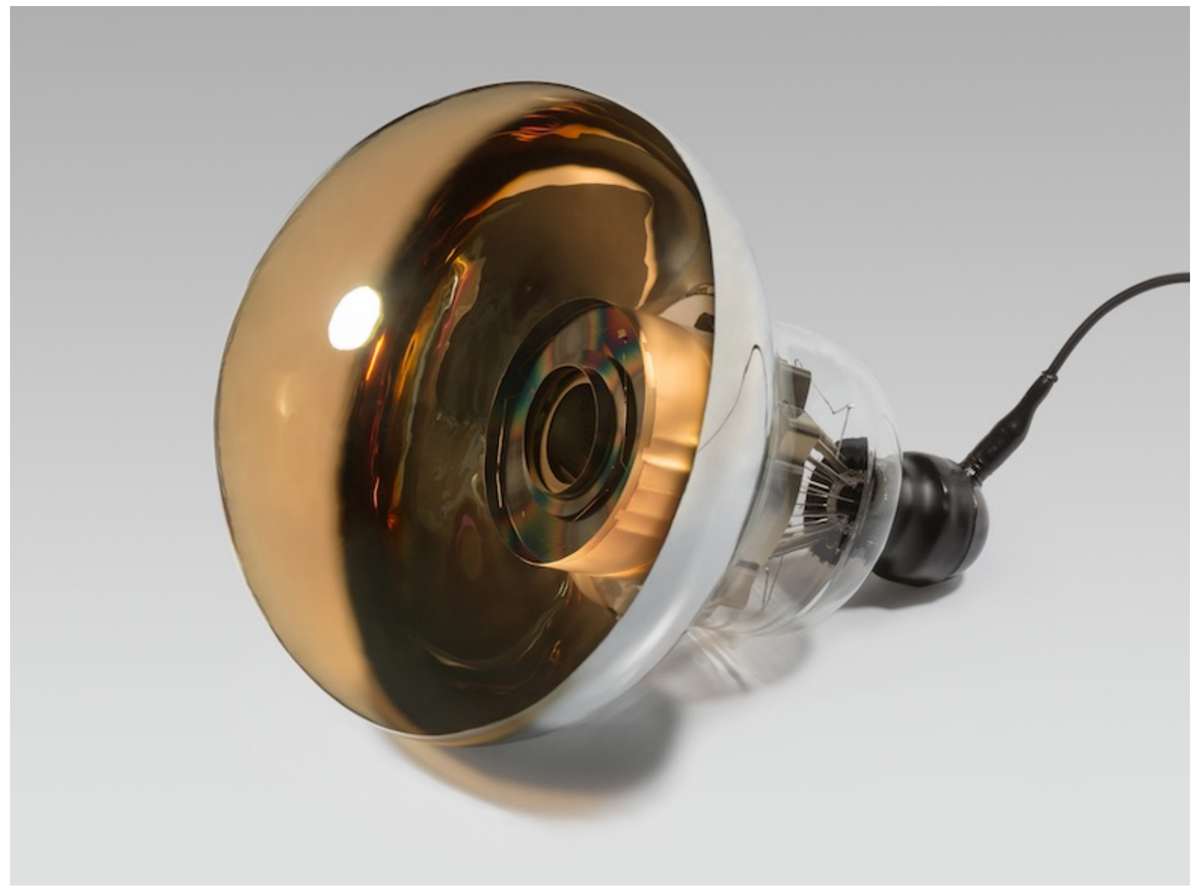




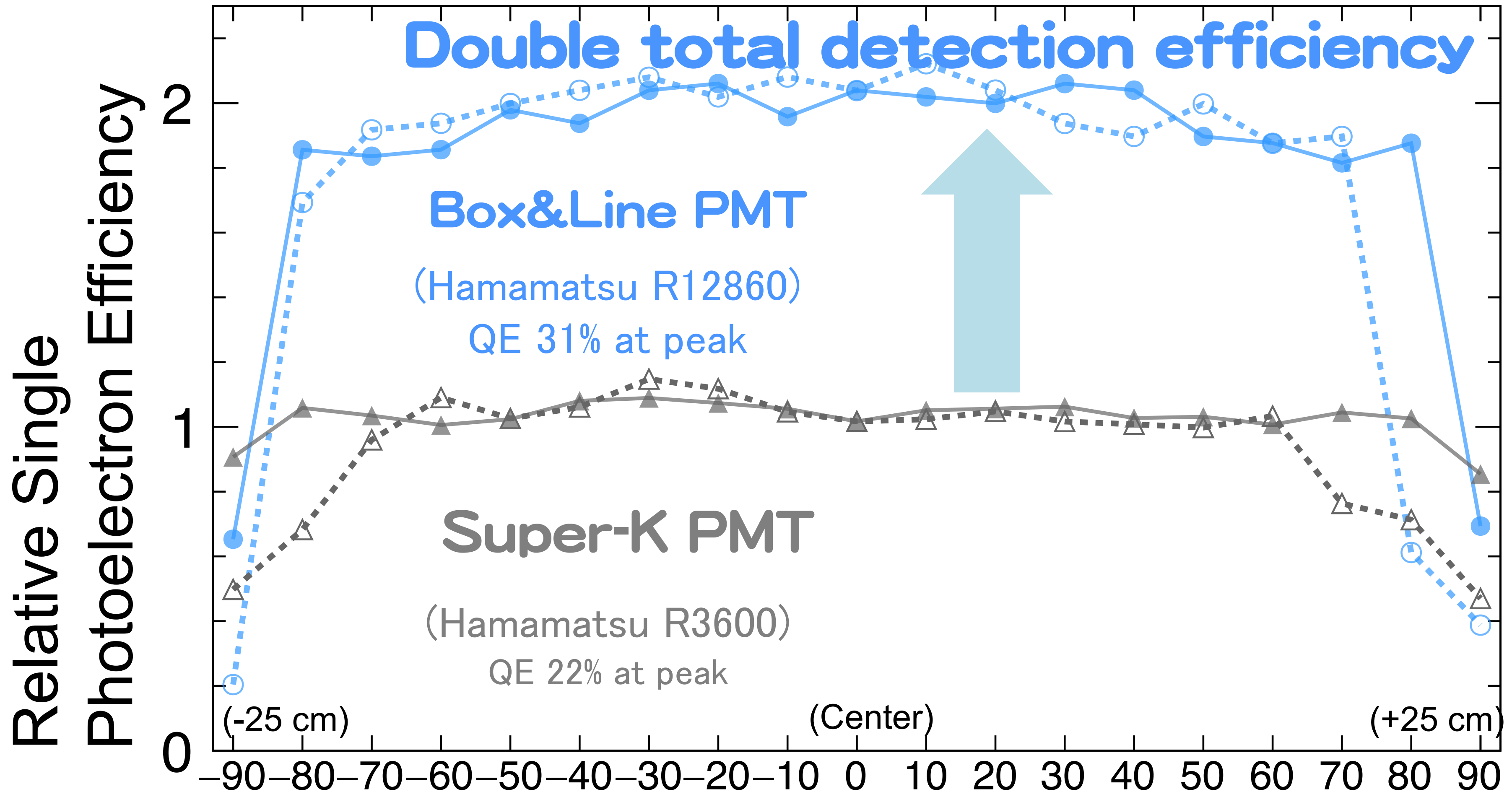
Hyper-K PMT Performance

Hamamatsu R12860

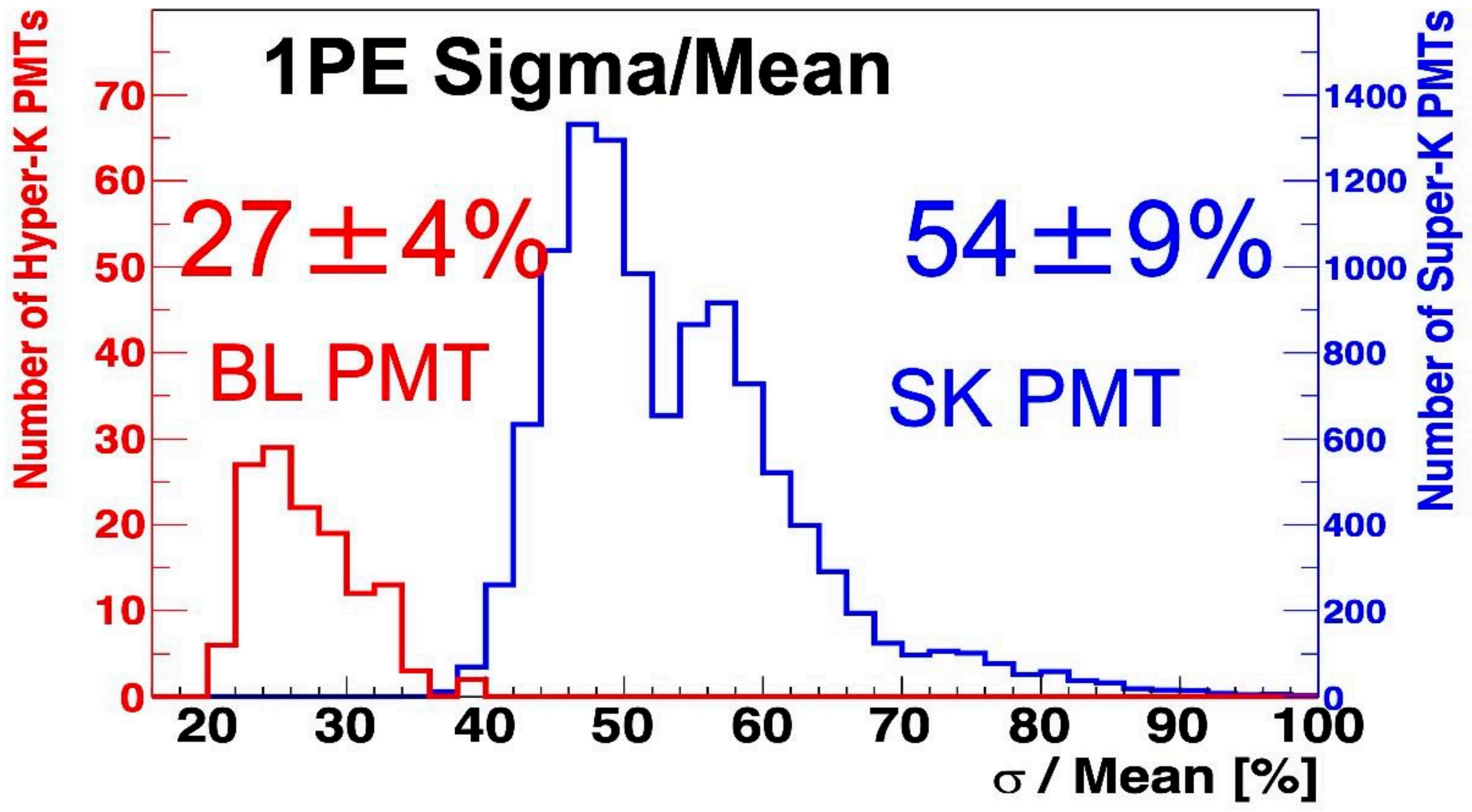
(Performance in SK tank, 1.7e7 gain)



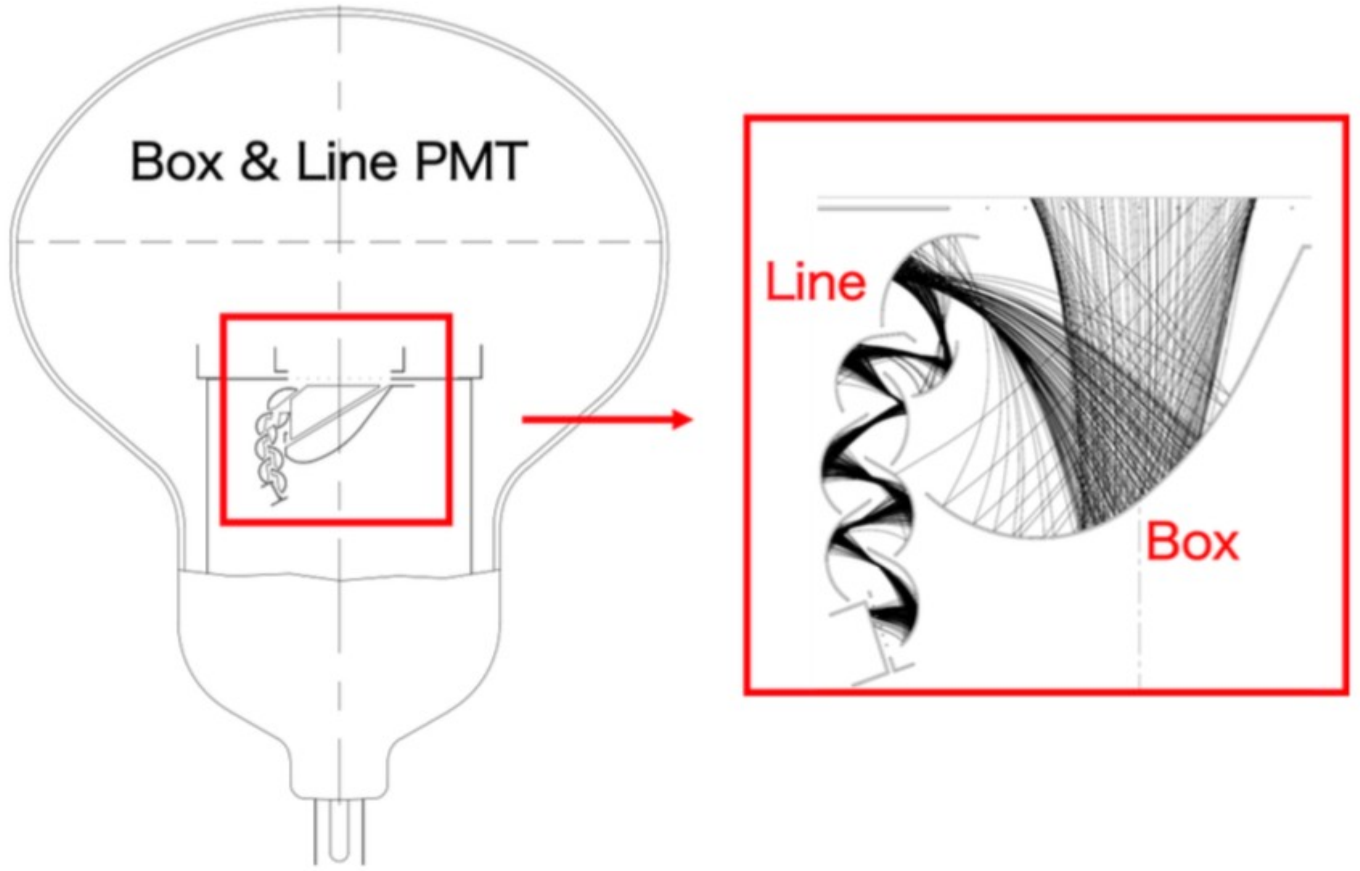
×2 better photodetection efficiency (QE×CE)



×2 better charge resolution



Box&Line dynode

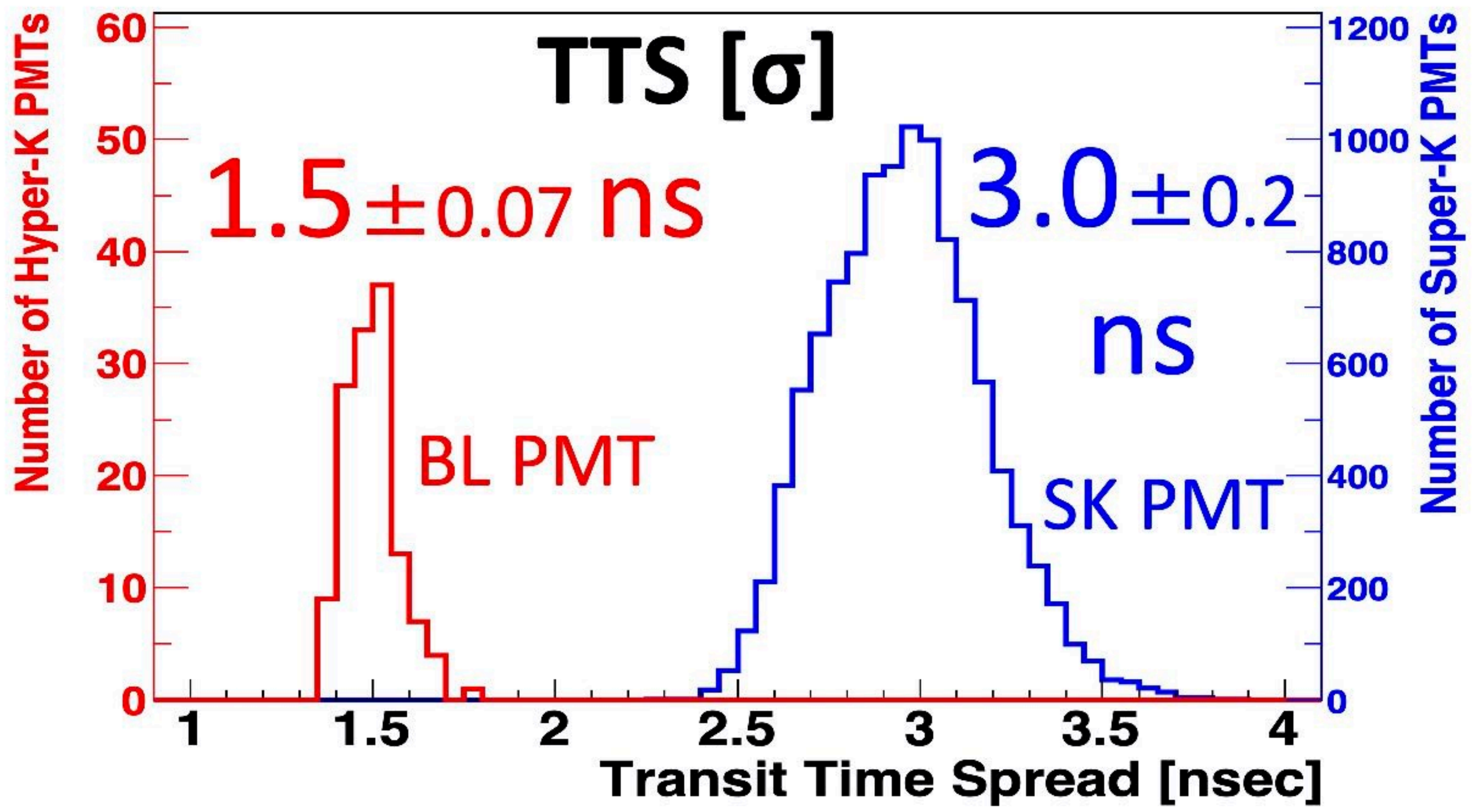


×2 better pressure tolerance
→ enable deeper tank design, project cost reduction

All PMTs will be tested >0.85MPa

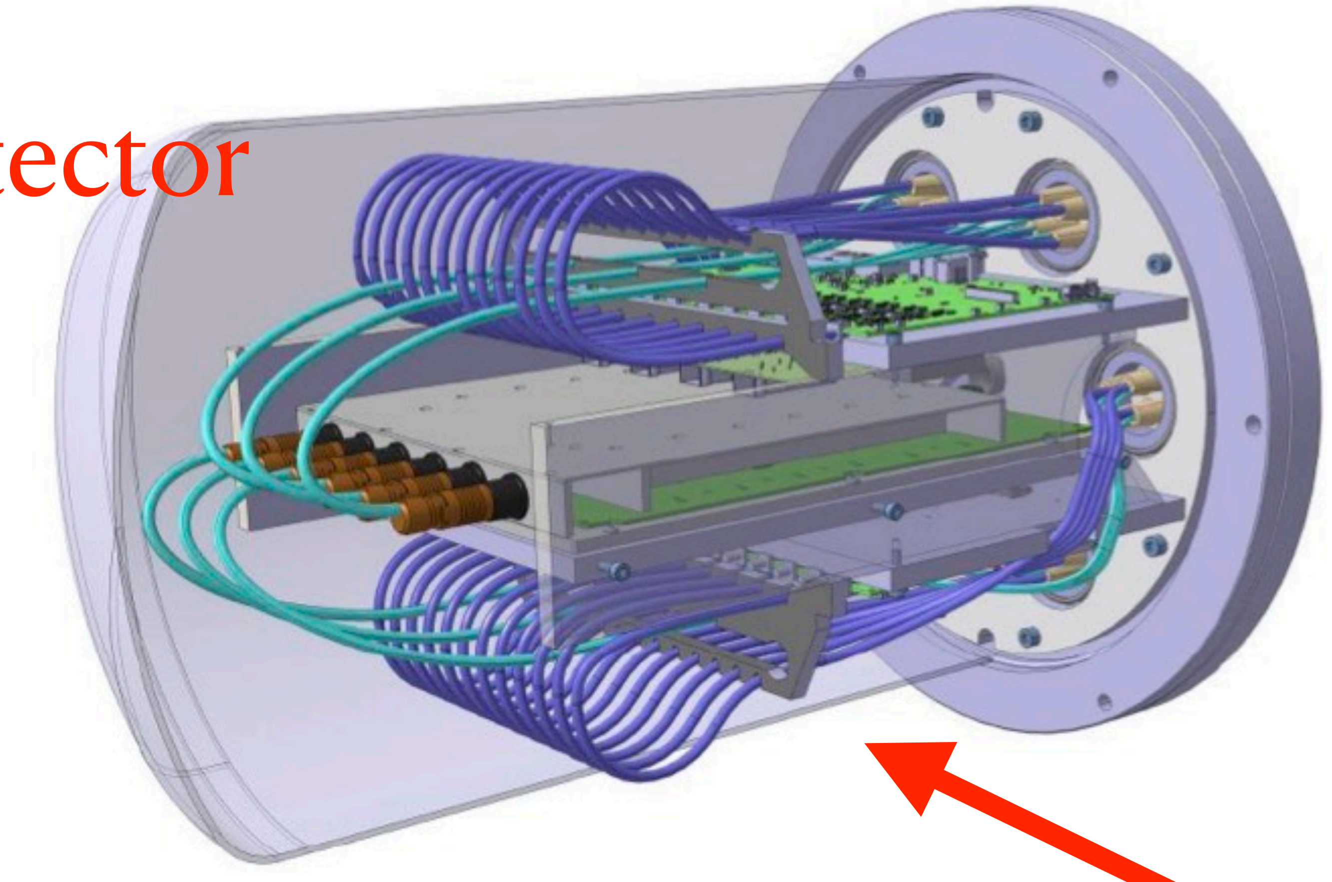
Low dark rate (4kHz) and RI

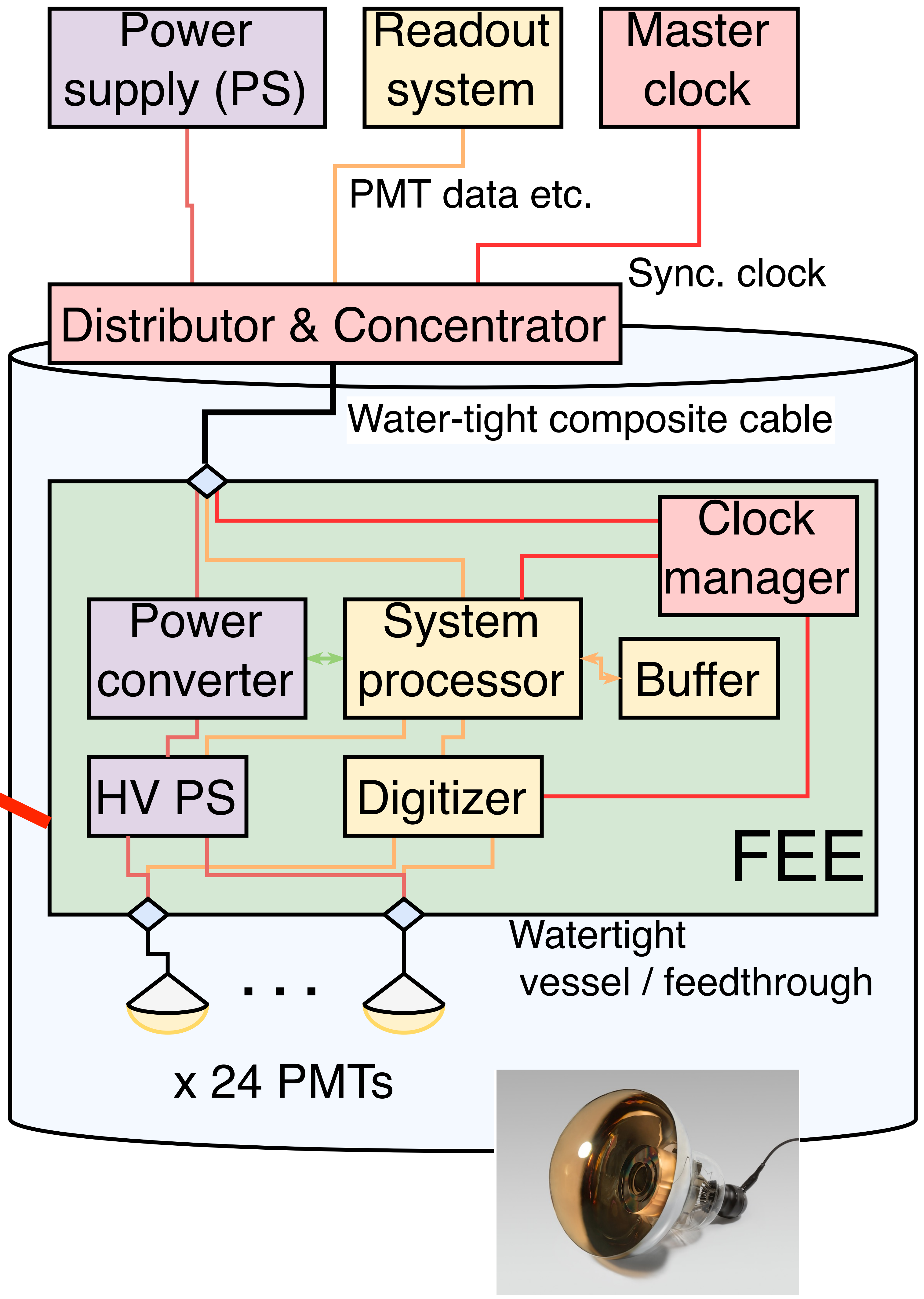
×2 better timing resolution



Electronics system

- Developed to maximize the performance of improved PMTs
- Frontend electronics placed underwater
  - Digitizing signals near PMTs
  - Maximize the performance of the detector
- Challenges
  - Everything in water-tight vessels
  - Water-tight connectors and cables
  - Very high reliability required
  - Synchronization of distributed components
- Large international collaboration project by itself
  - Development, production, assembly, testing, calibration, installation, ..
  - Planning assembly/testing at CERN





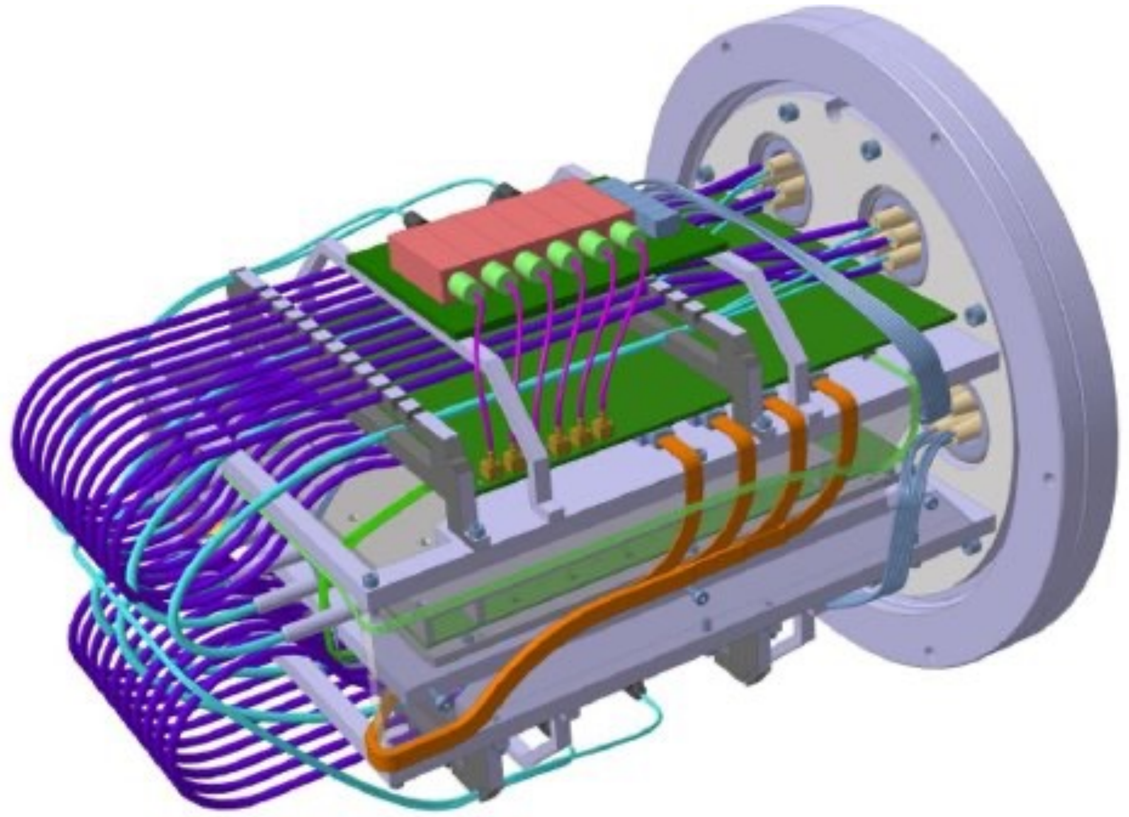
Detector component (some production starting)

PMTs

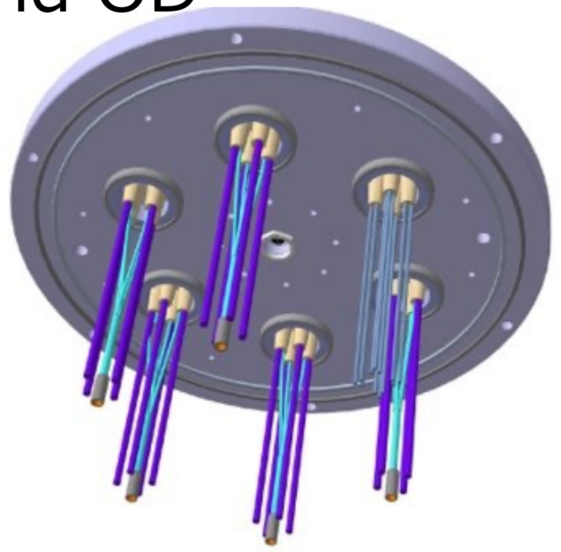
ID mockup

Underwater electronics:

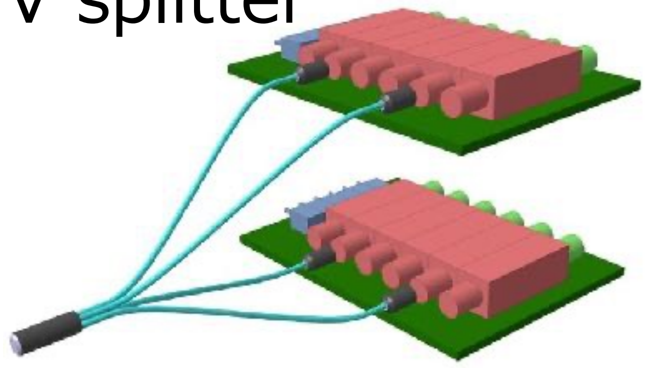
20 x 50 cm ID PMTs + 12 x OD PMTs



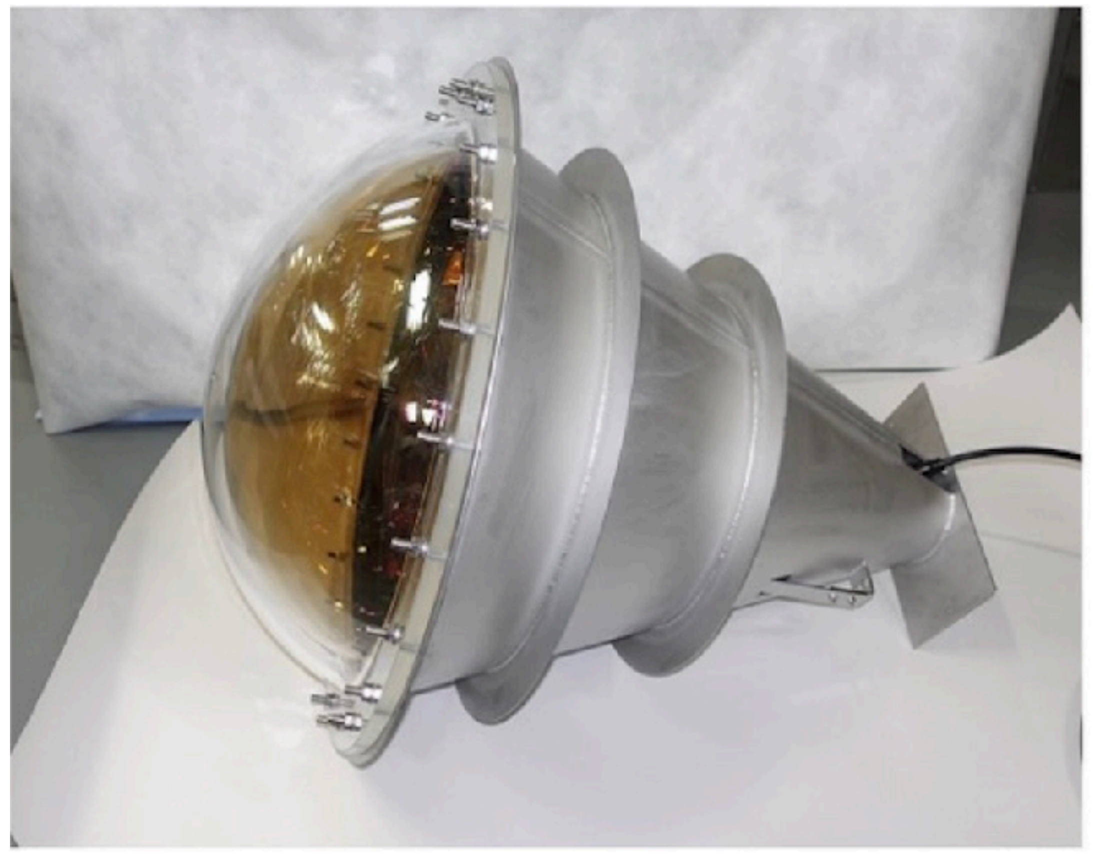
Feedthroughs
for ID and OD



OD signal +
HV splitter

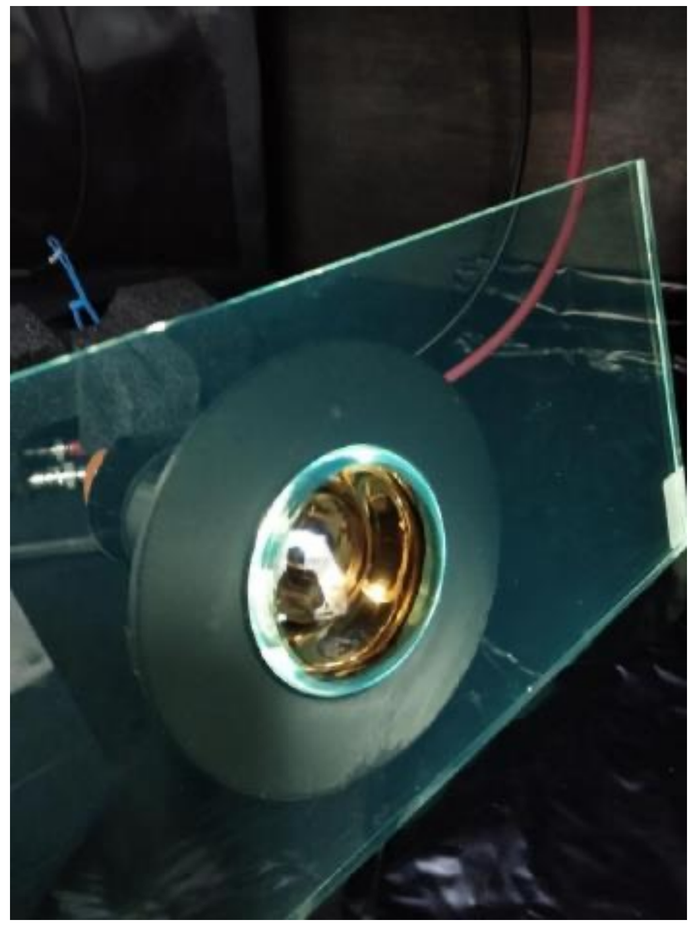


PMT cover



Multi-PMT module:

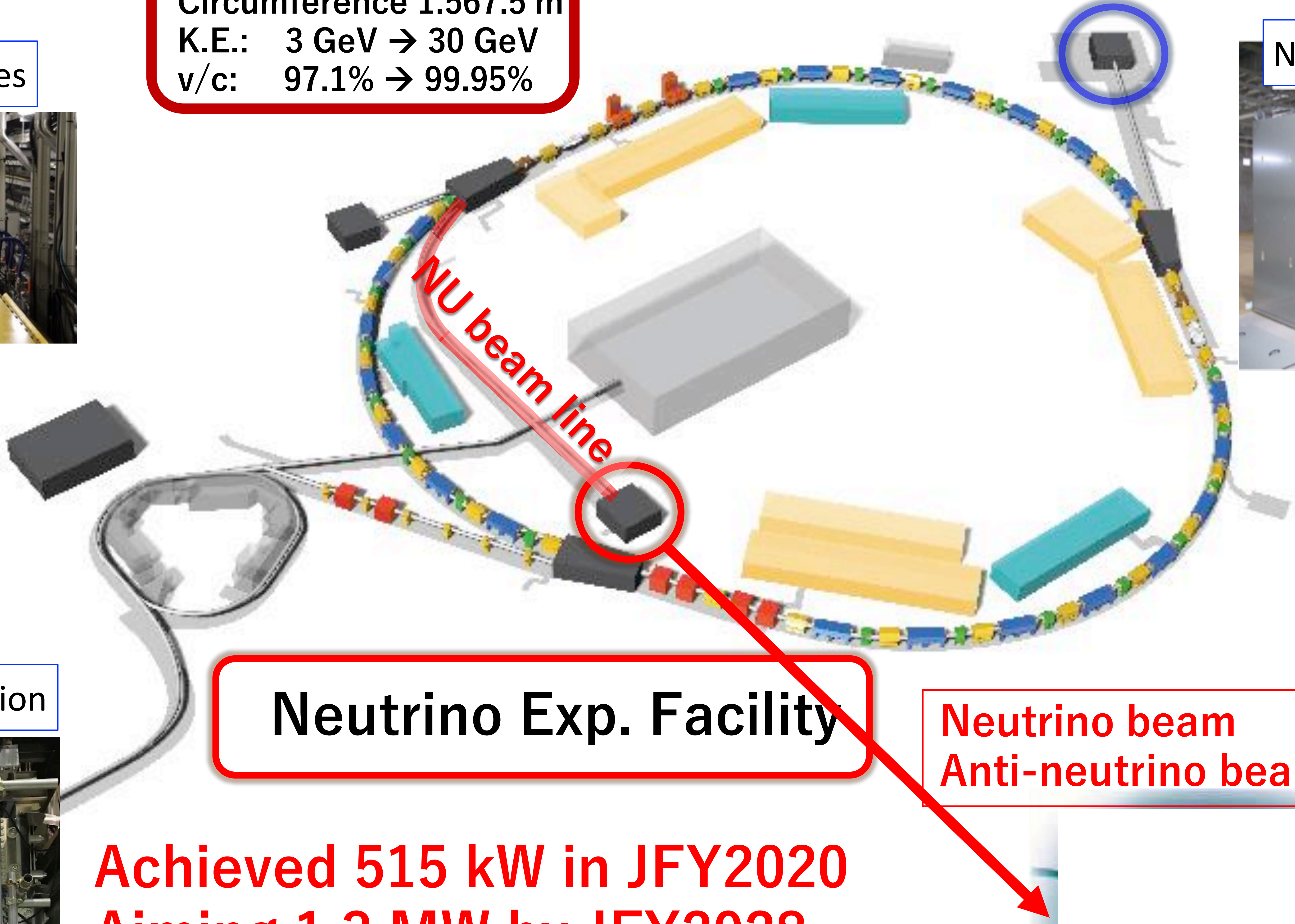
Outer detector: PMT+WLS plate



J-PARC Upgrade

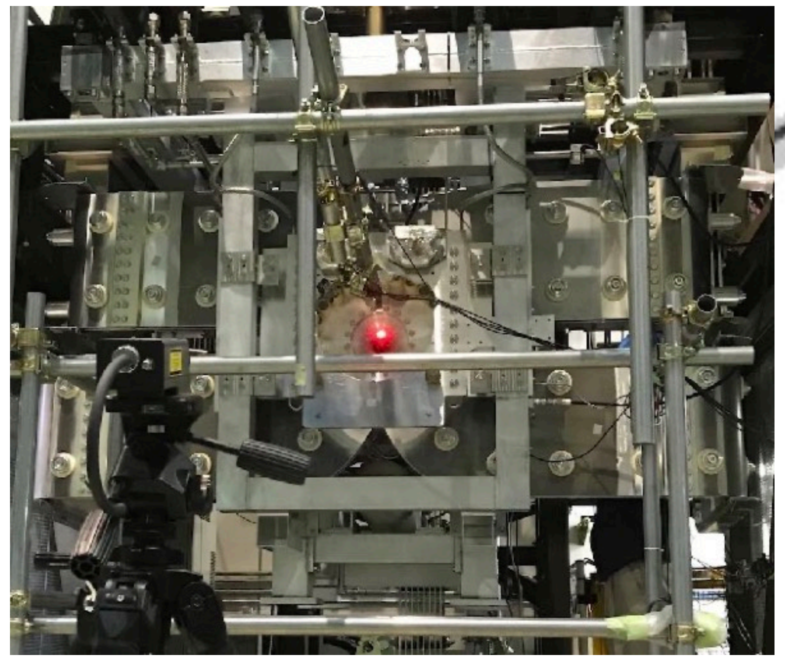
MR-RF cavities

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

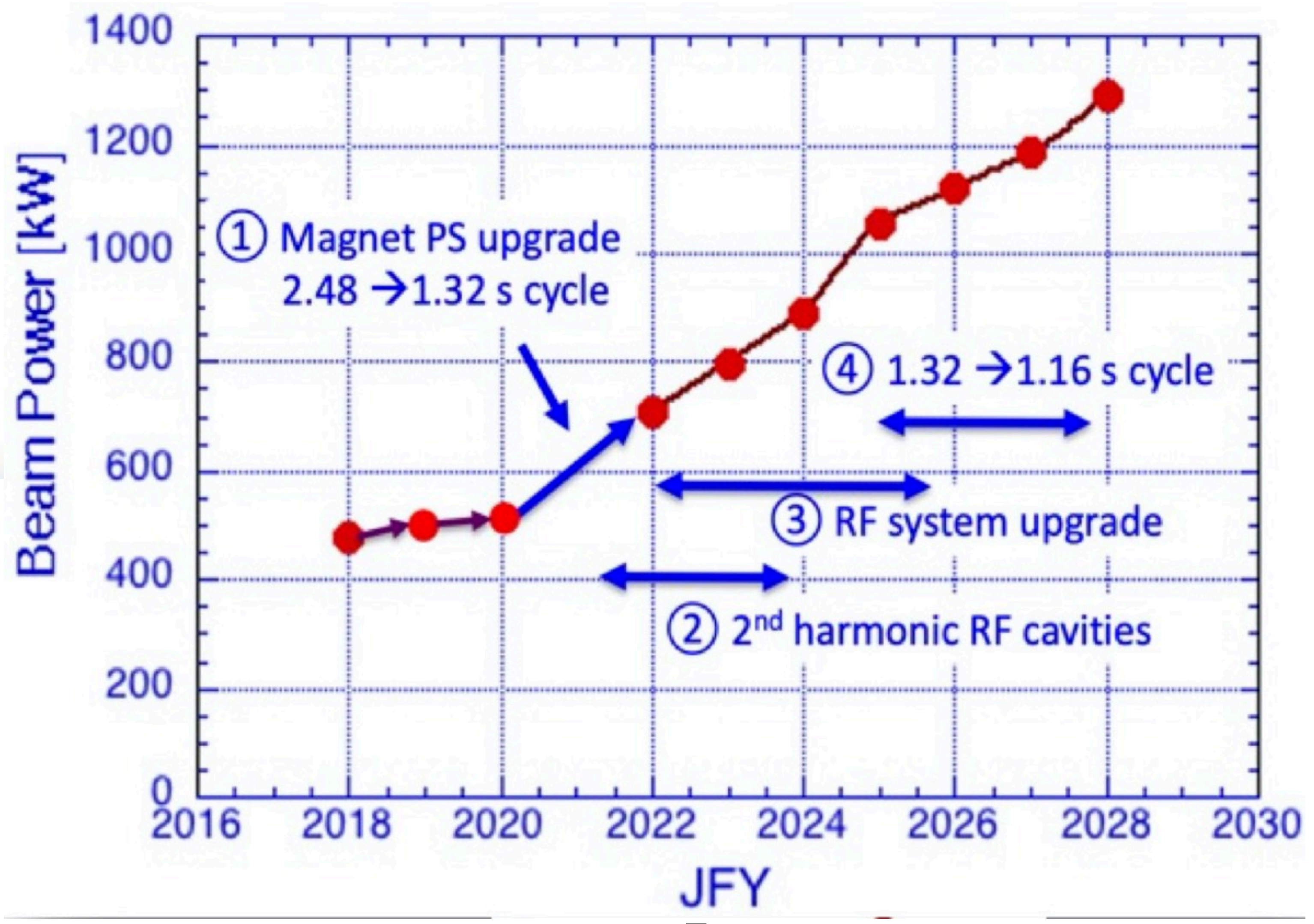
320kA horn operation



Neutrino Exp. Facility

Neutrino beam
Anti-neutrino beam

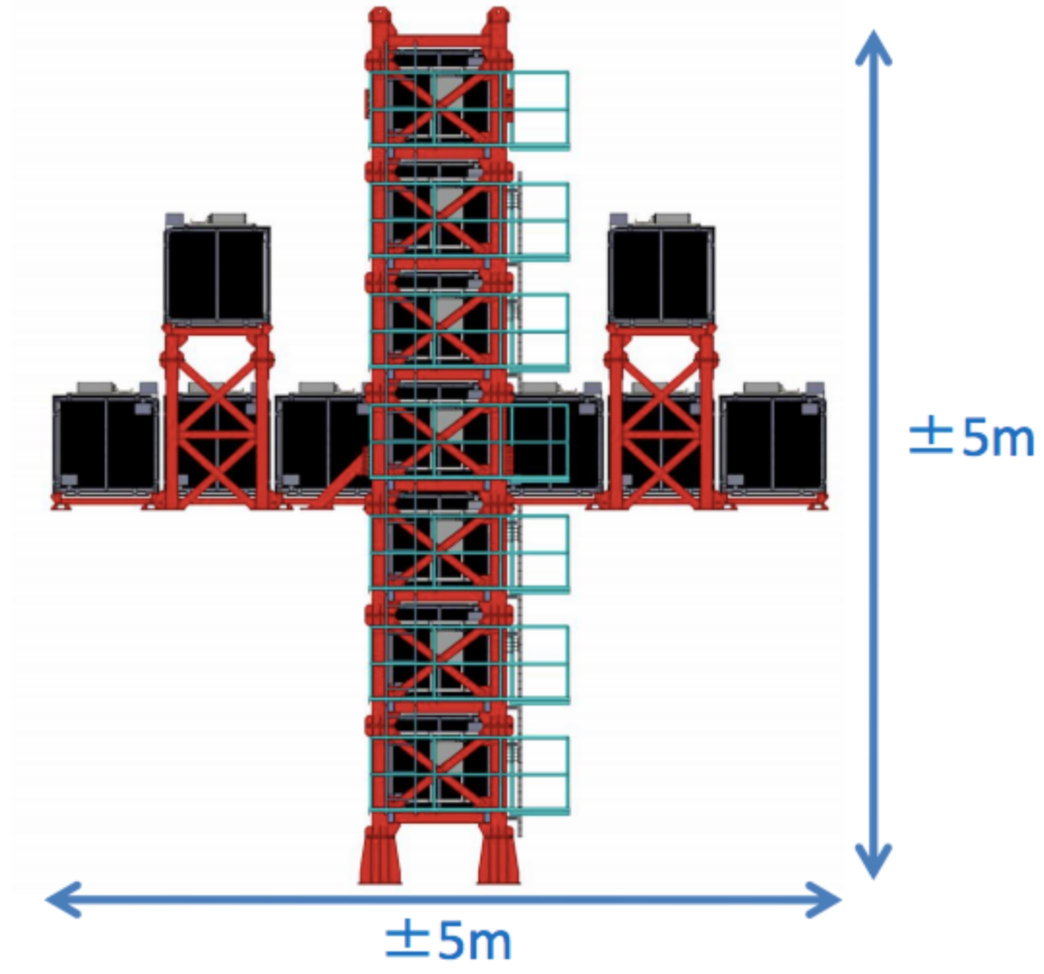
Achieved 515 kW in JFY2020
Aiming 1.3 MW by JFY2028



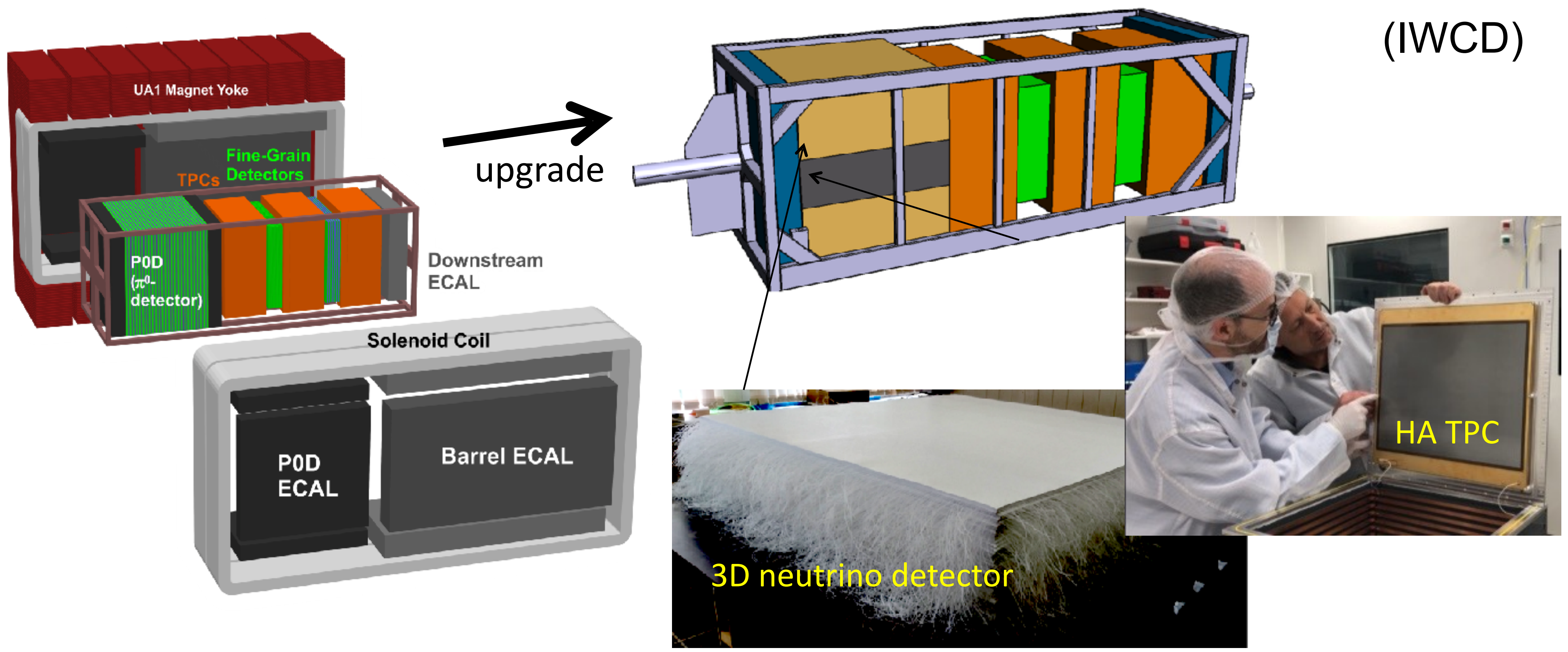
Neutrino detectors at J-PARC

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

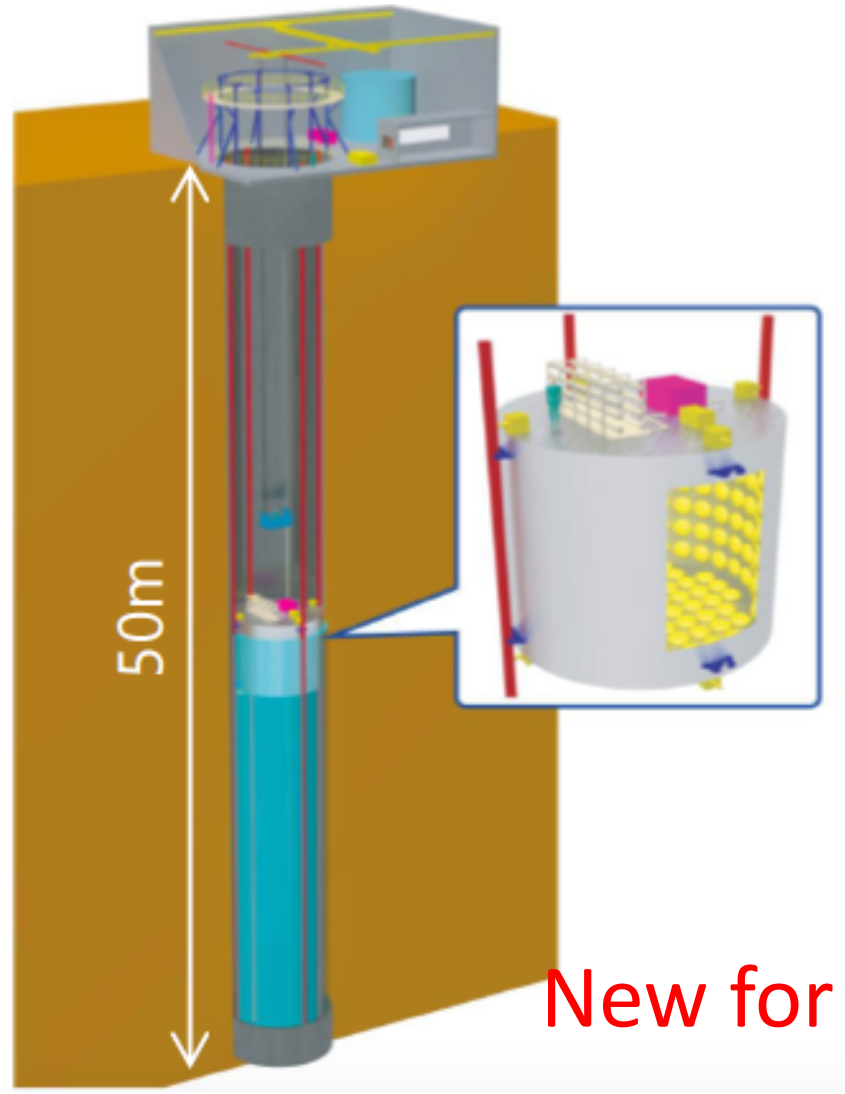
On-axis Detector
(INGRID)



Off-axis Magnetized Tracker
(ND280→Upgrade for T2K →Upgrade for HK)



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)



New for HK

- On-axis detector: Measure beam direction and event rate
- Off-axis magnetized tracker: Measure primary (anti)neutrino interaction rates, spectrum and properties. Charge separation to measure wrong-sign background
  → Upgrade by T2K experiment and Intensive discussion for further upgrade in HK-era is on-going.
- Intermediate WC detector: H_2O target with off-axis angle spanning orientation.
  → Detector site investigation and conceptual facility design is on-going.

Connection to FNAL and CERN: Beam test of detectors, Hadron production measurements forJ-PARC neutrino beam

Summary

Hyper-Kamiokande with J-PARC

- Important physics targets
  - Neutrino CP violation: Discovery with 5 σ for ~60% parameter regions
  - Nucleon Decay Search for testing GUT: $\tau > 10^{35}$ years for $p \rightarrow e^{+}\pi^{0}$
  - Neutrino Astrophysics: Supernova neutrinos
- Big Water Cherenkov detector with 190 kton fiducial mass
  - Facility and Detector construction are on-going for the operation starting in 2027
- J-PARC neutrino beam being upgraded toward 1.3 MW power
- Your support is essential!