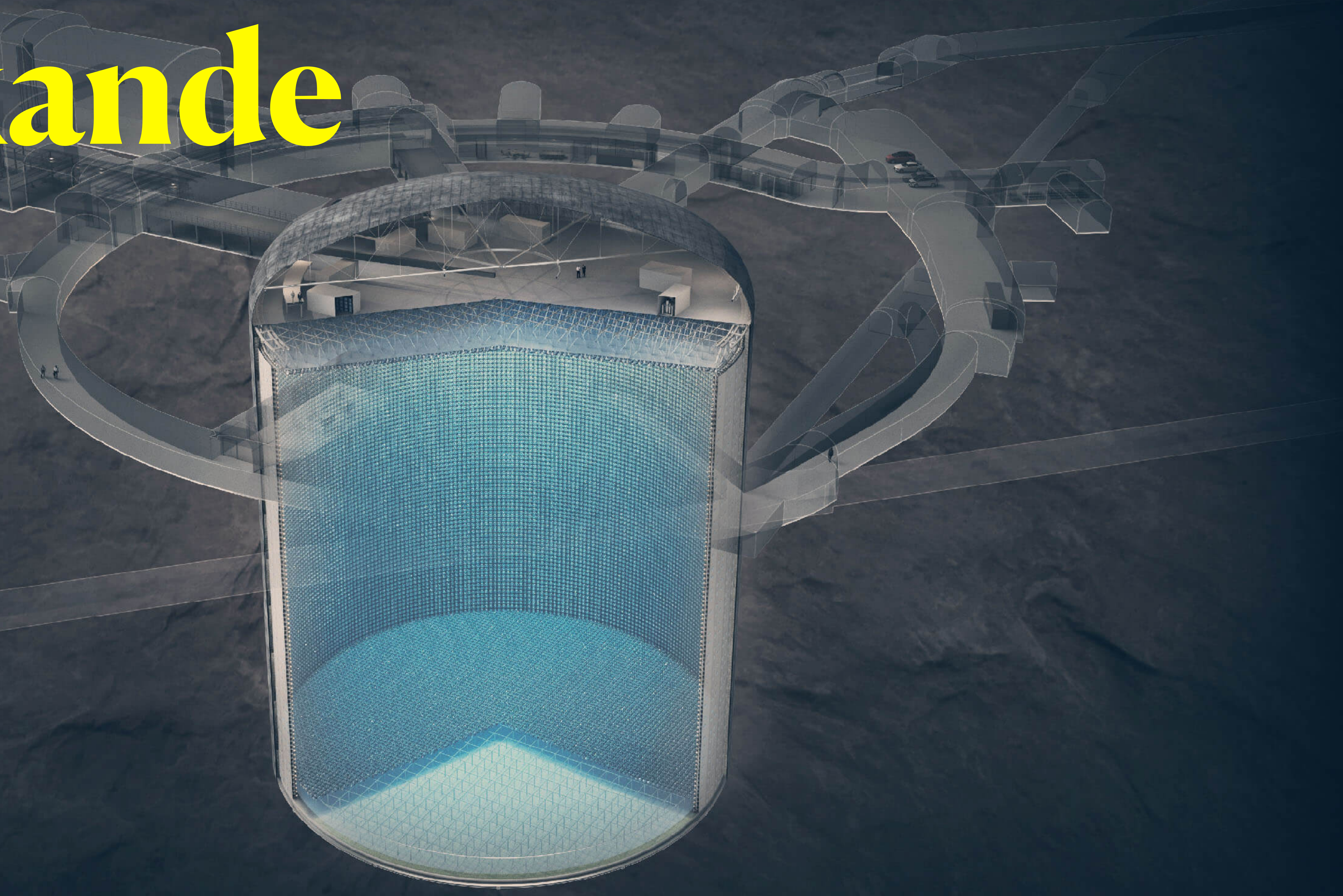
2023.5.22 @US-J Symposium in Hawaii

Hyper-Kamiokande Update

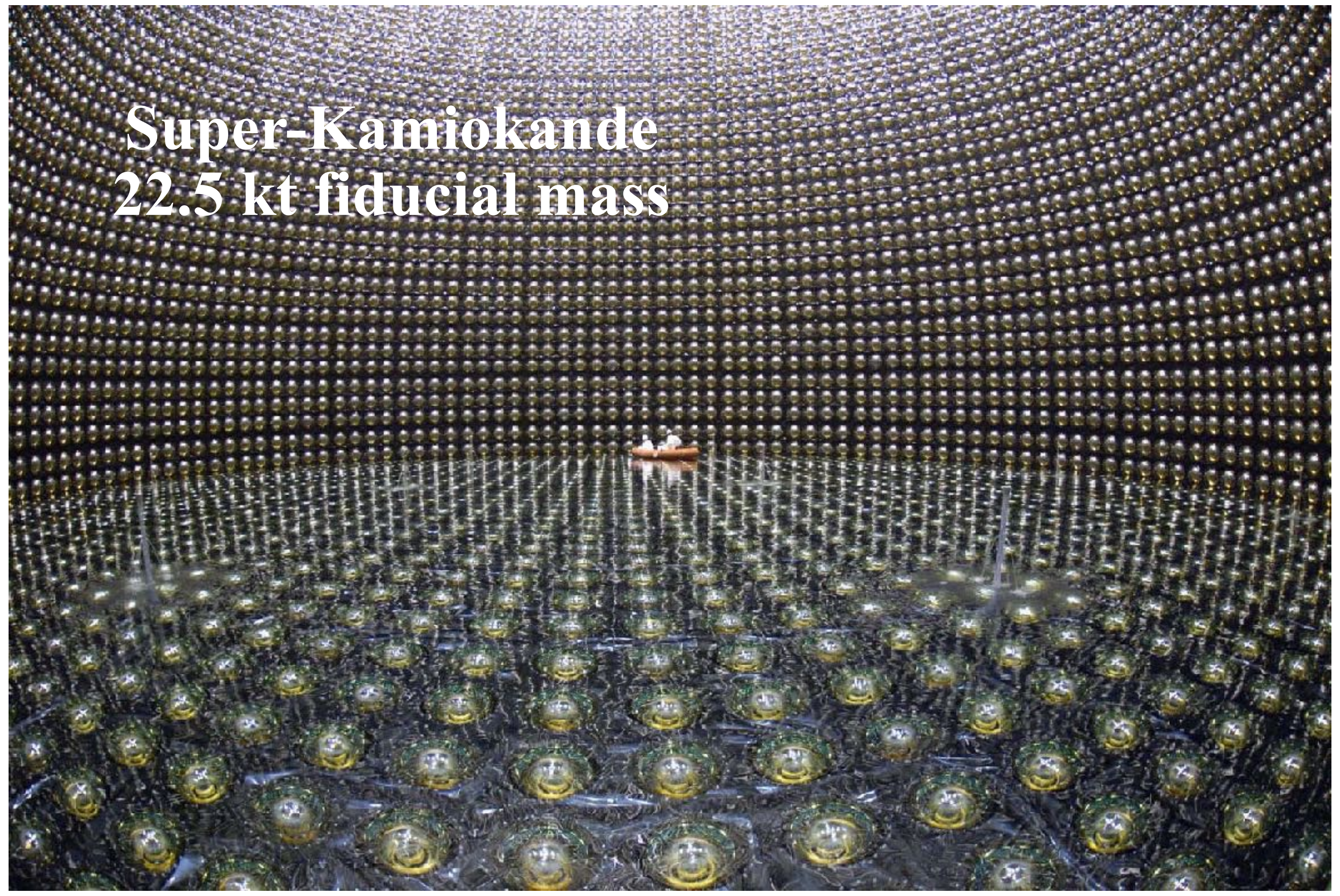


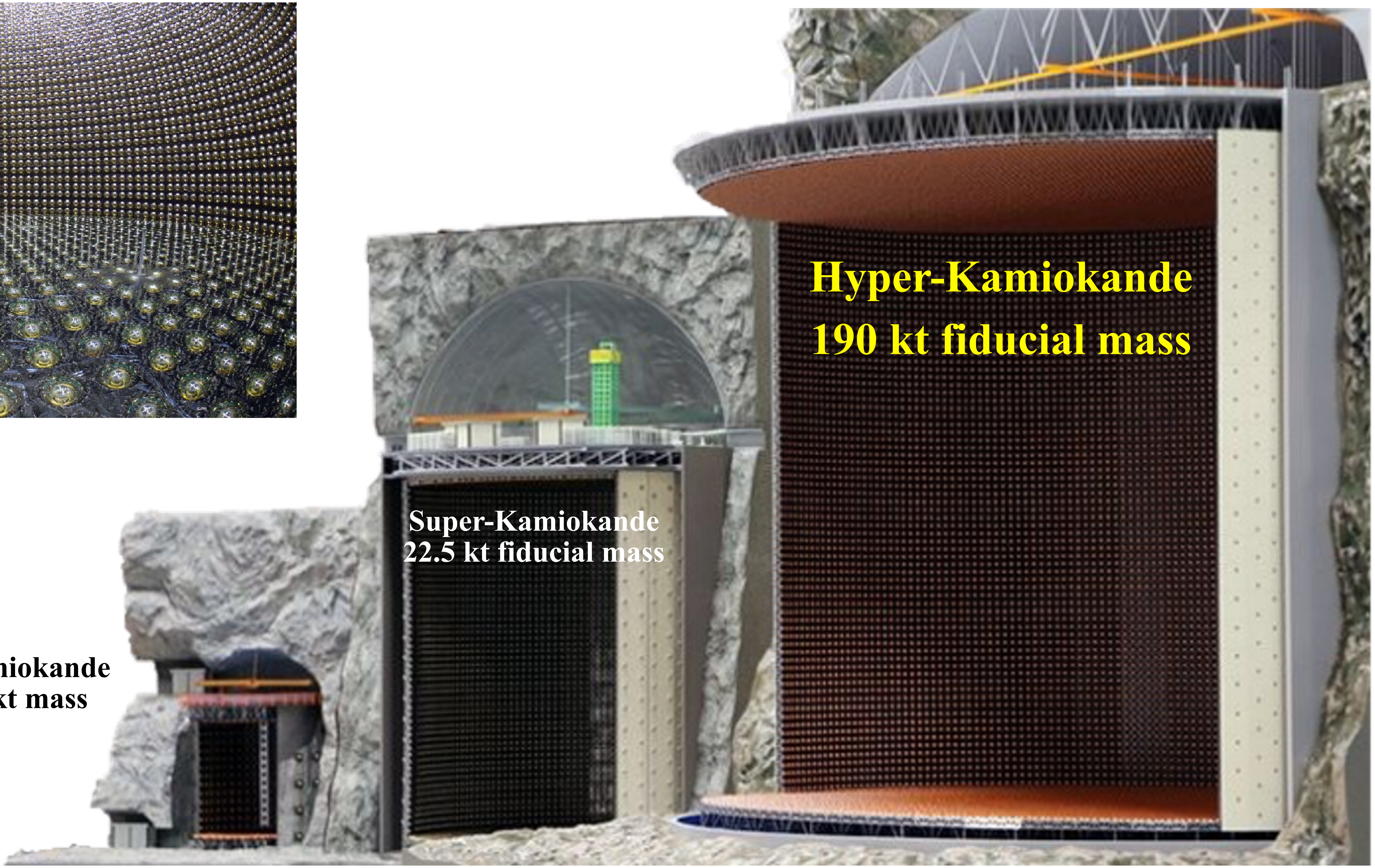
T. Nakaya (Kyoto U.)
for the Hyper-Kamiokande Collaboration

Hyper-Kamiokande

Hyper-Kamiokande

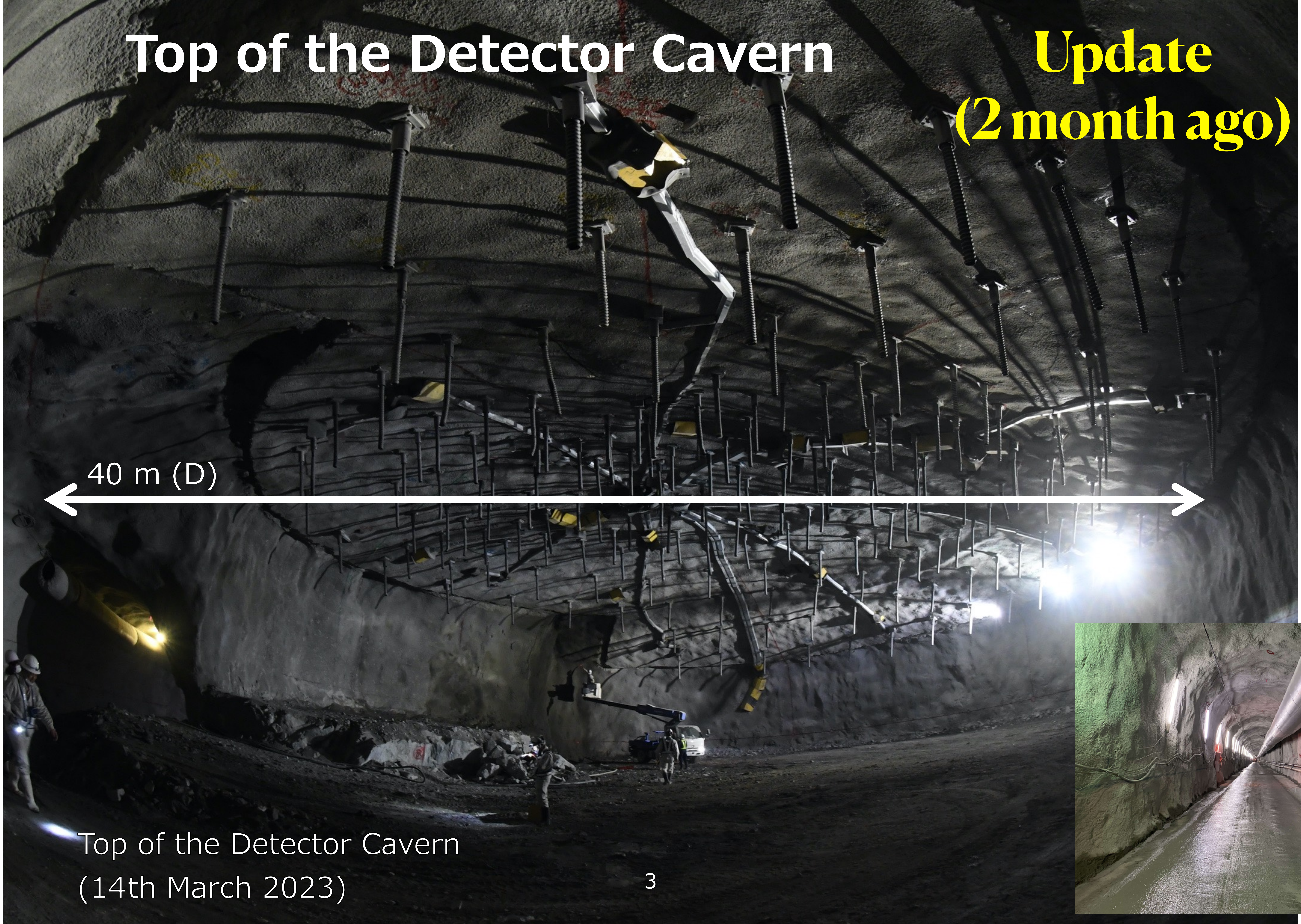
Water Cherenkov detectors in Kamioka





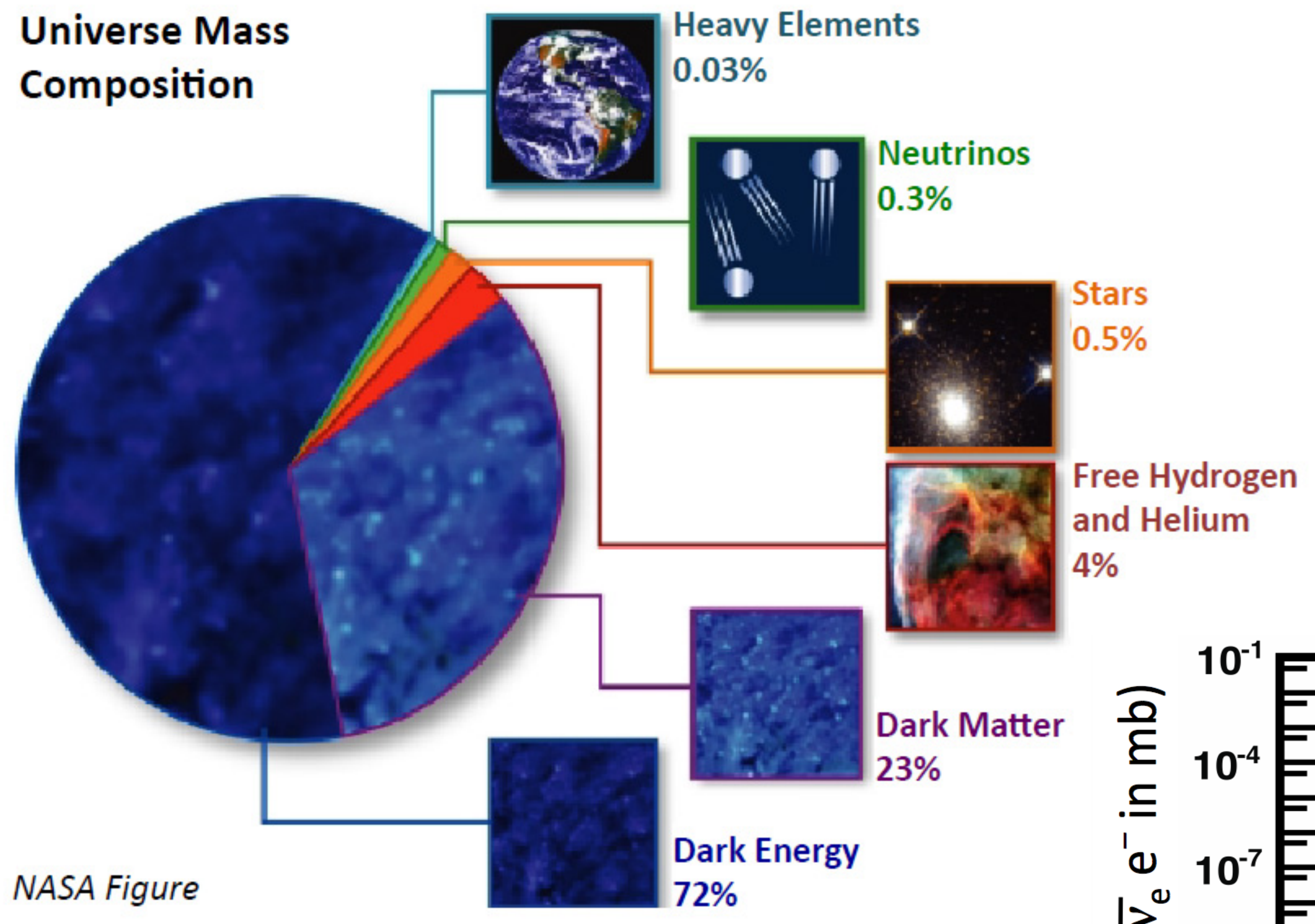
Top of the Detector Cavern

Update (2 month ago)



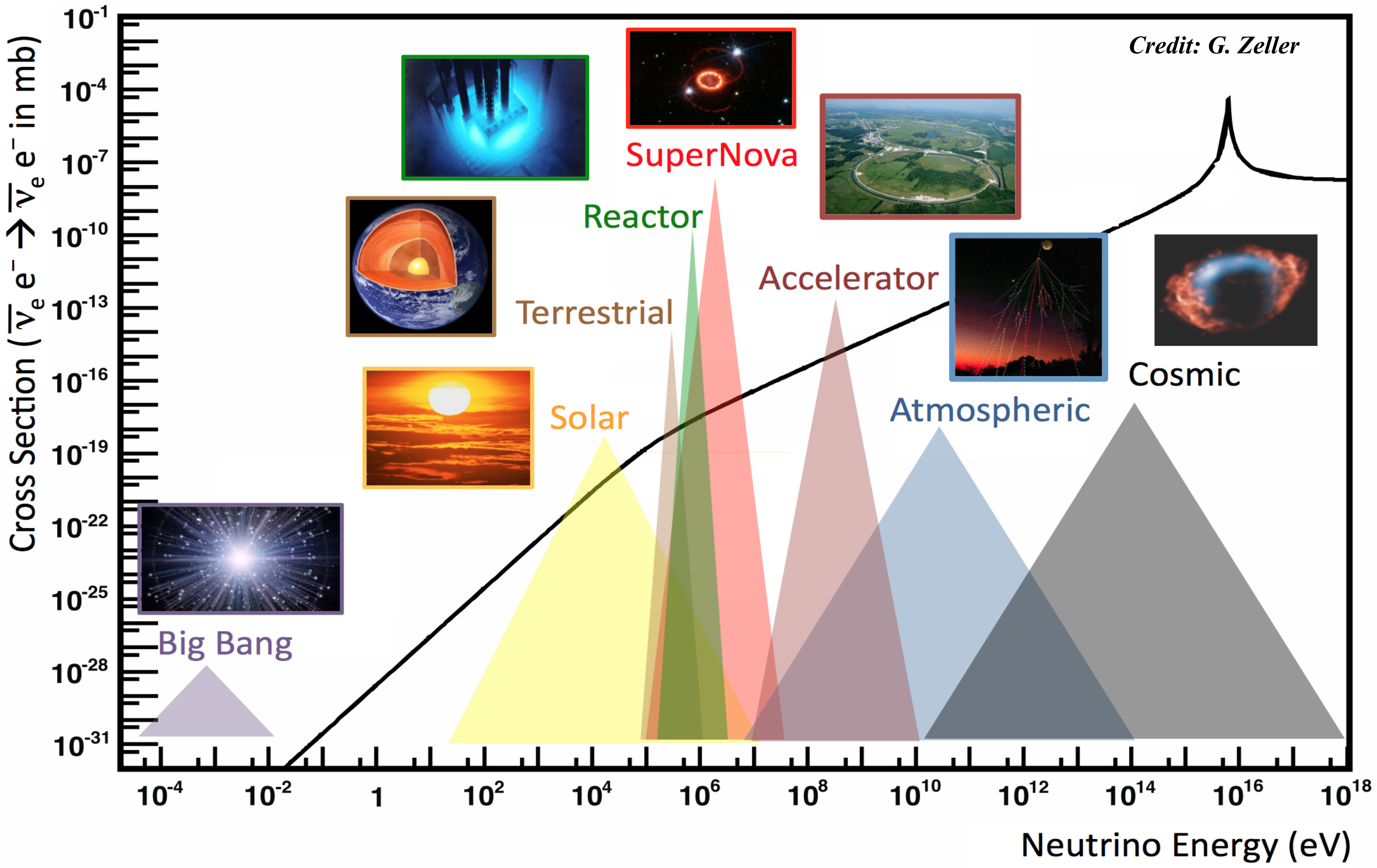
Top of the Detector Cavern
(14th March 2023)

Why Neutrinos?



They are always around us and mysterious!

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



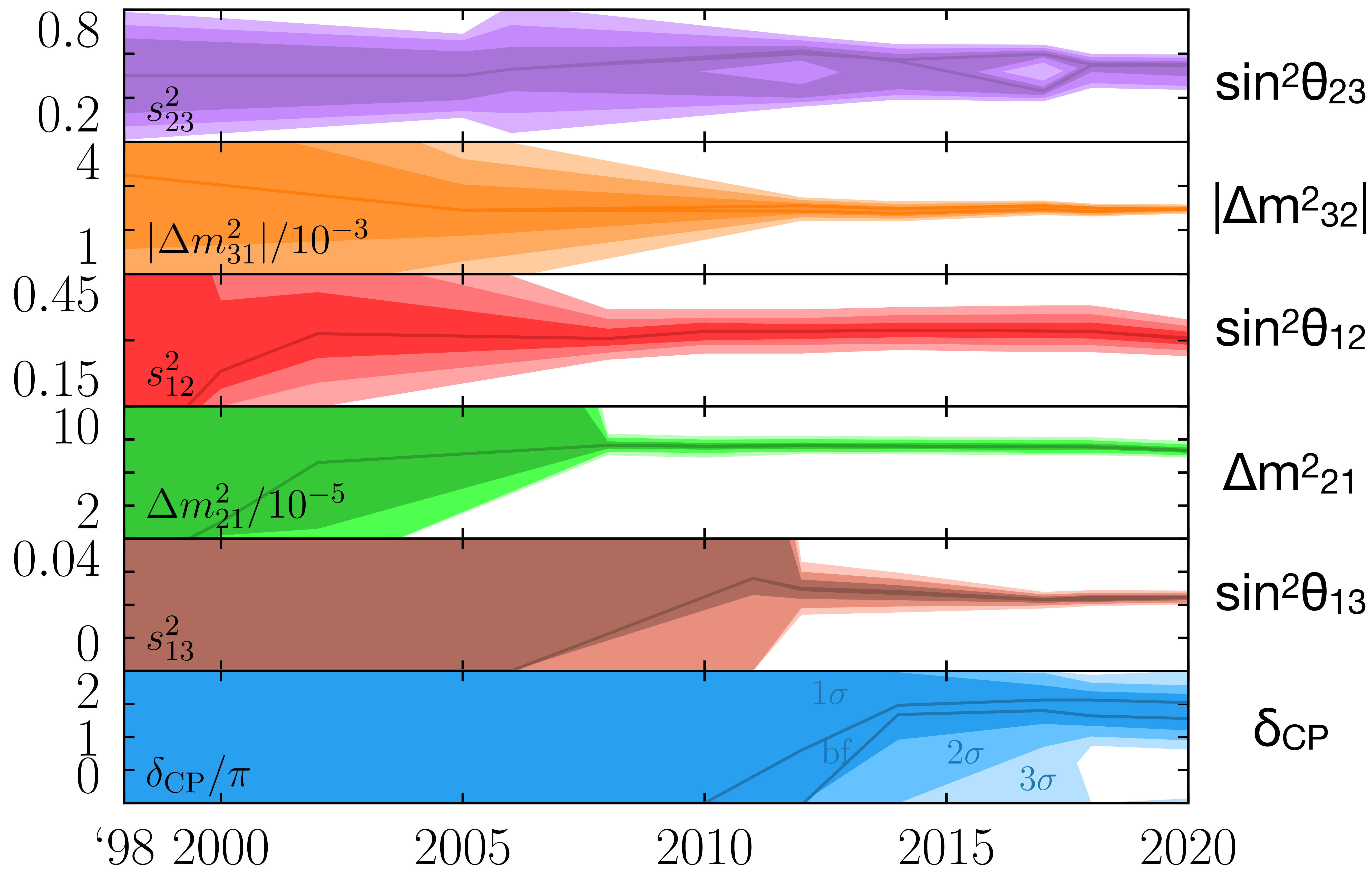
- Particle Physics
- AstroPhysics
- Cosmology
- High energy Astro-particle physics
- Nuclear physics

by S. Gollapinni @ICHEP2020

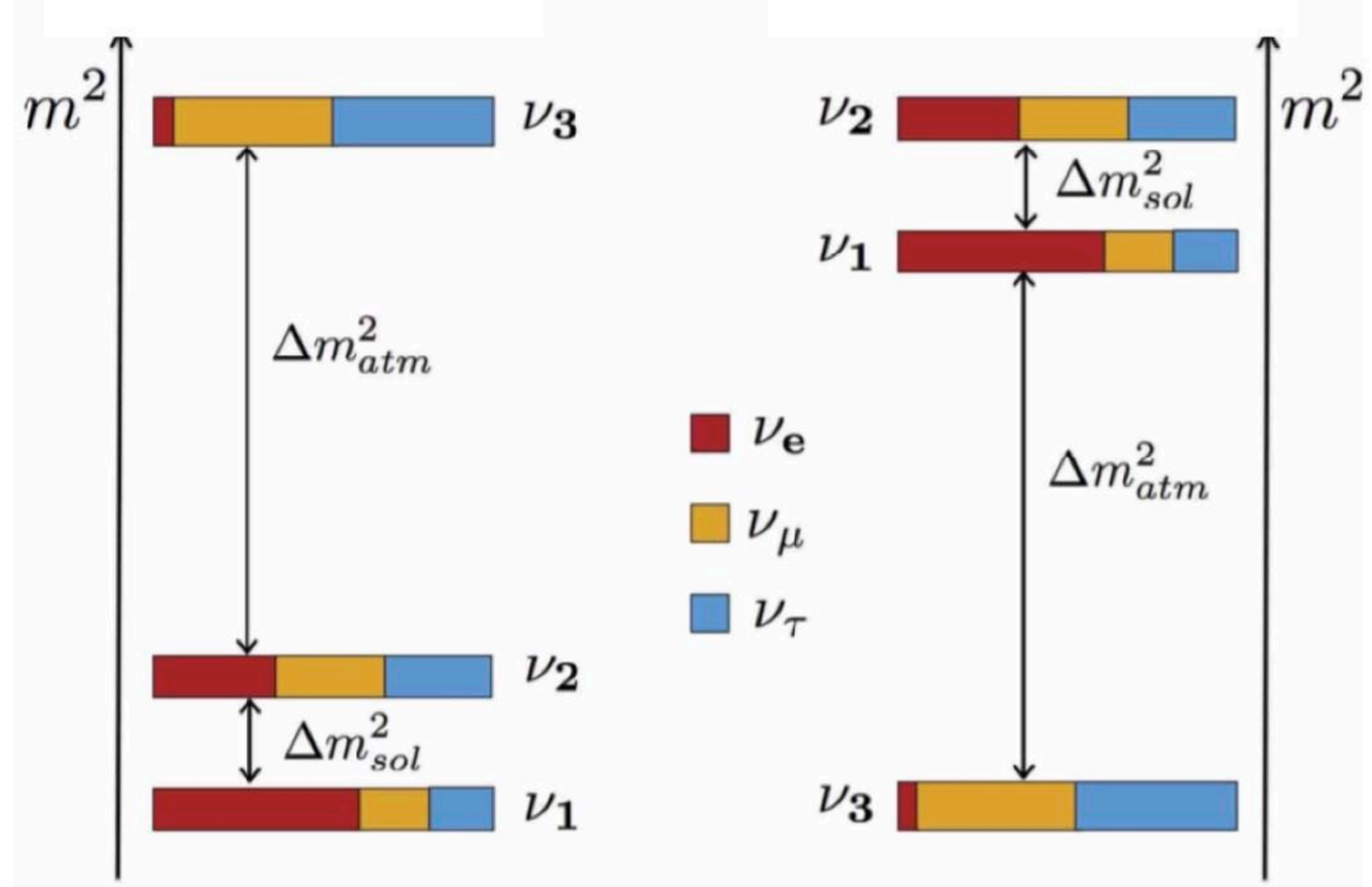
Neutrino Oscillations

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



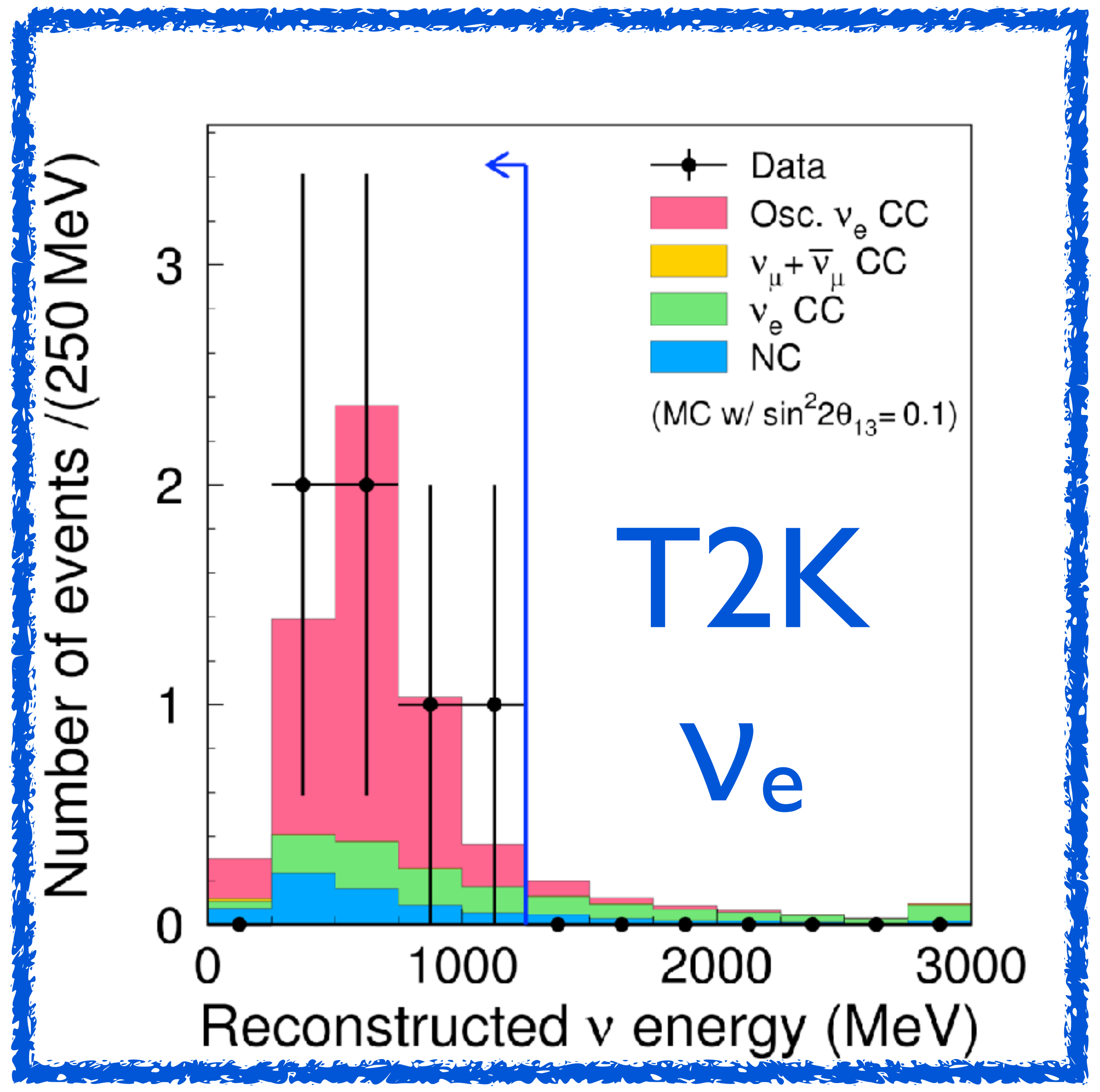
NO (Normal Ordering) **IO (Inverse Ordering)**

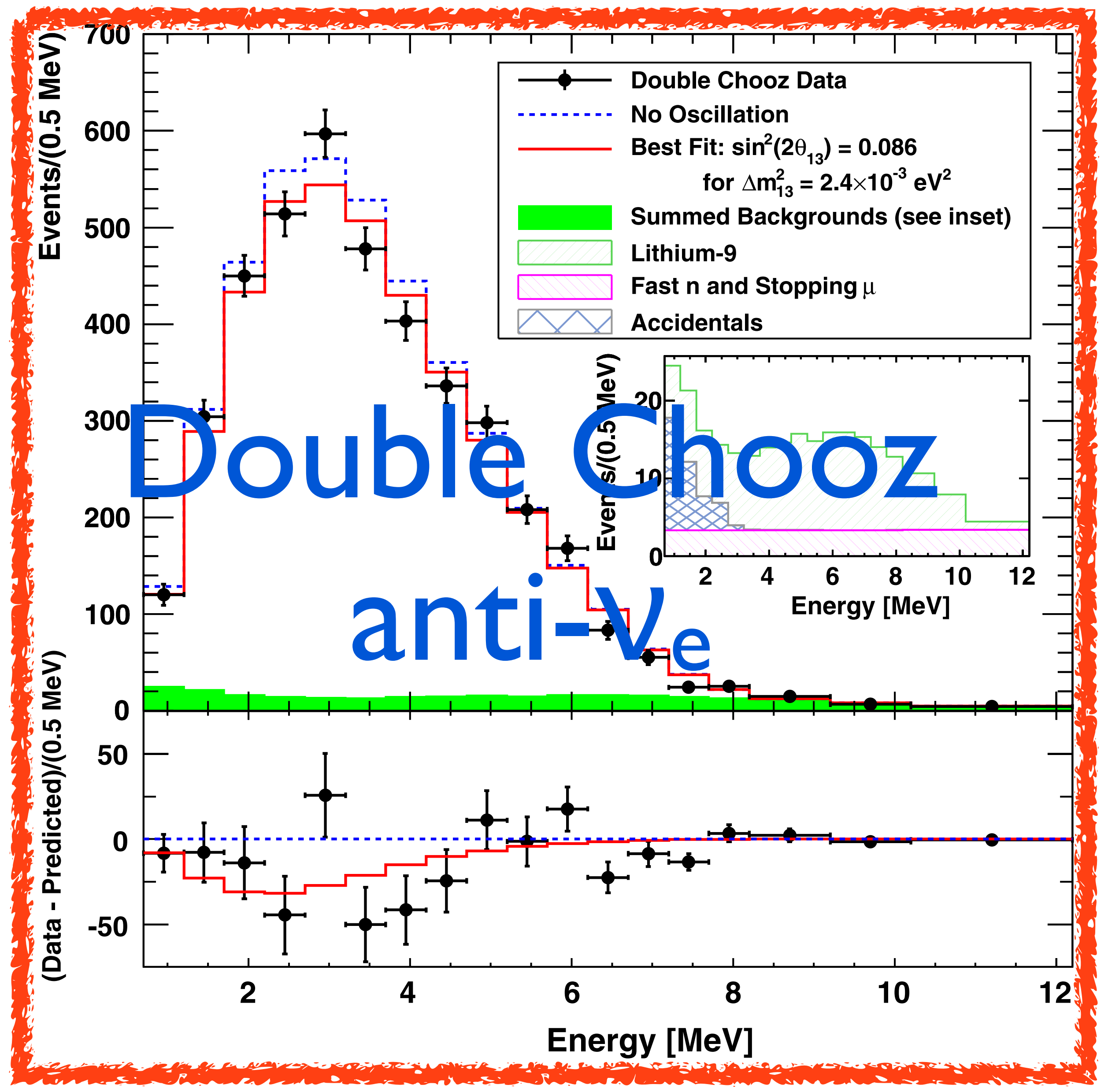
Current major targets

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

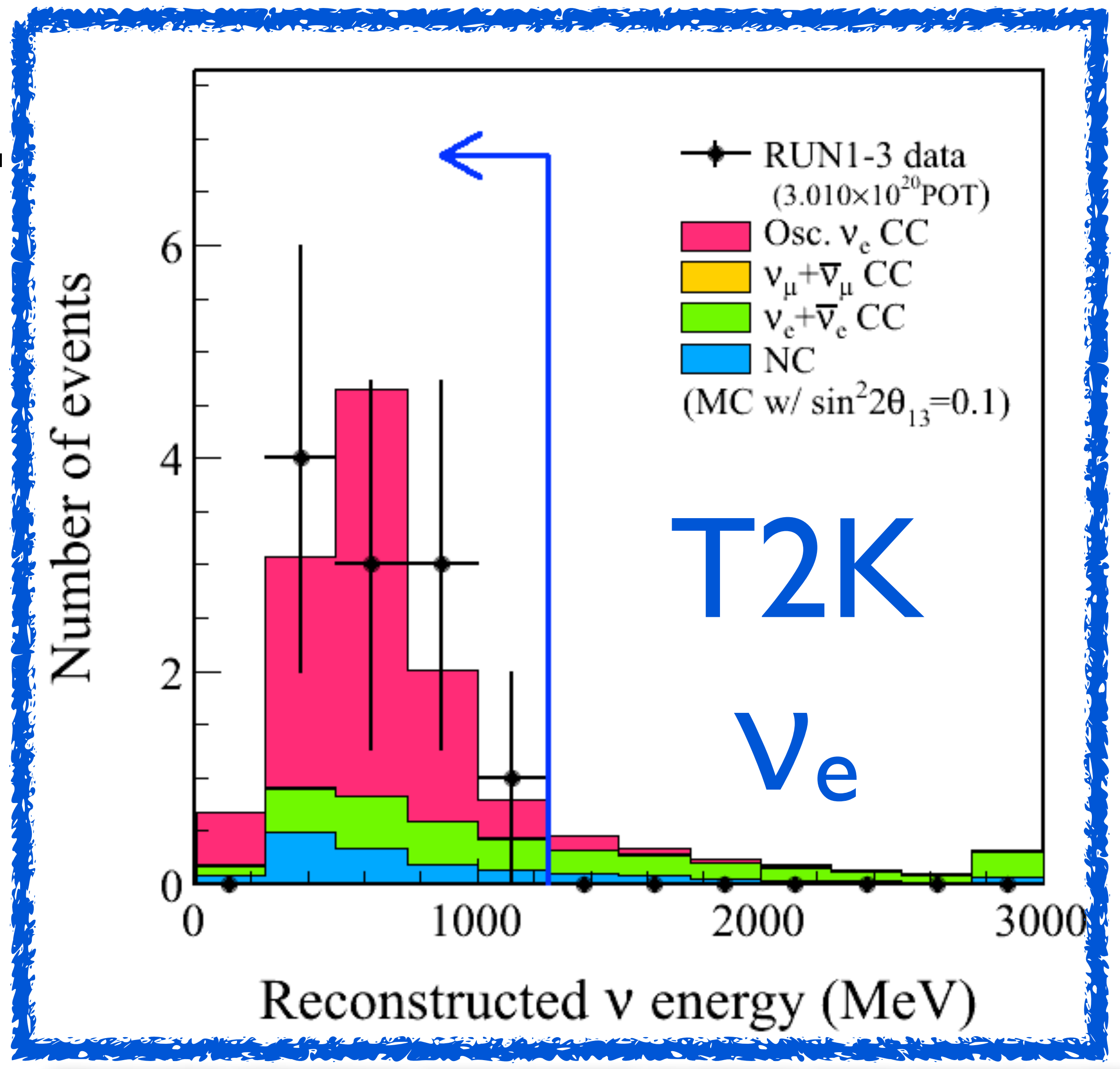
Large θ13 opens the window to study CPV

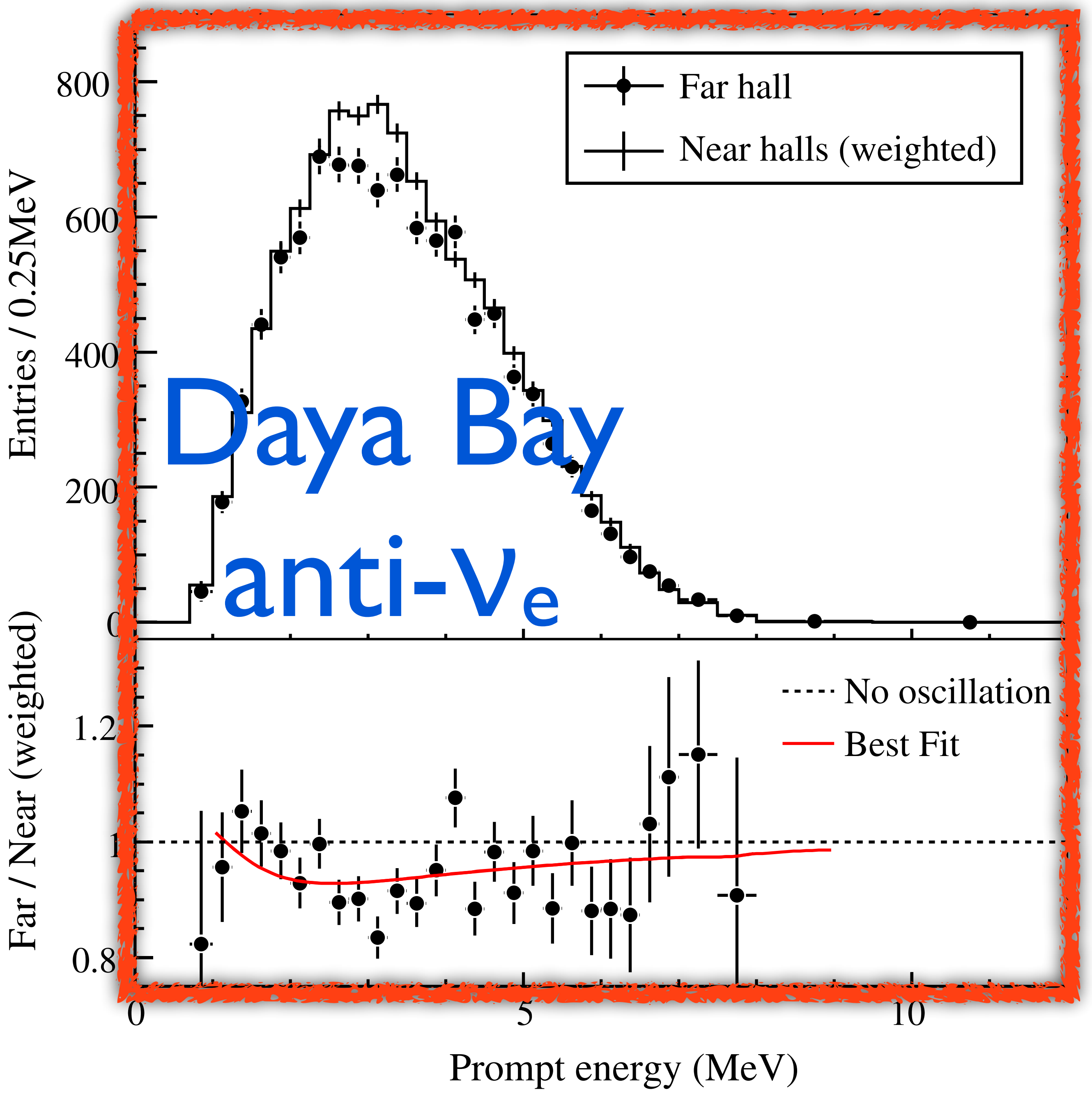
2011



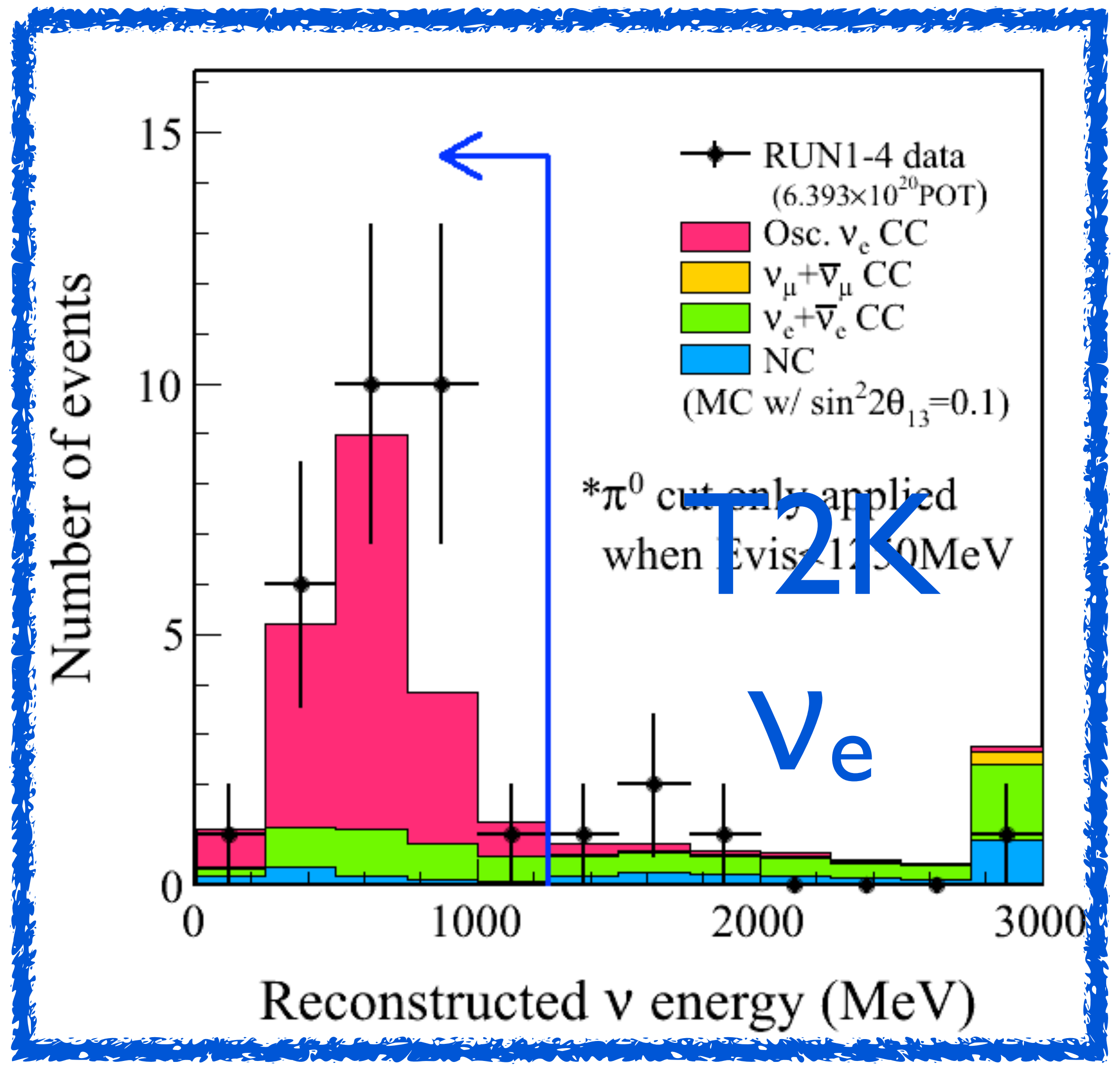


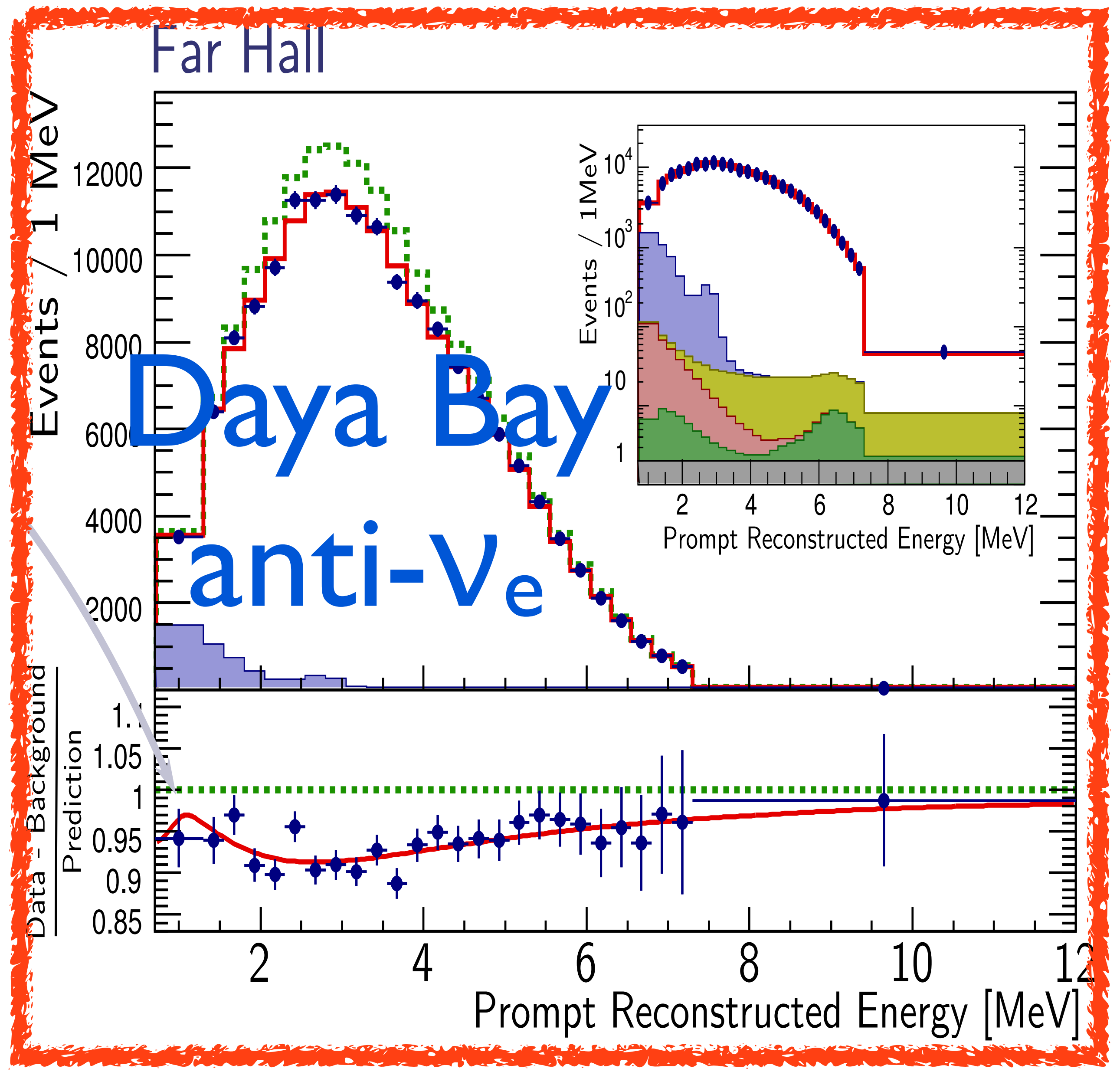
2012

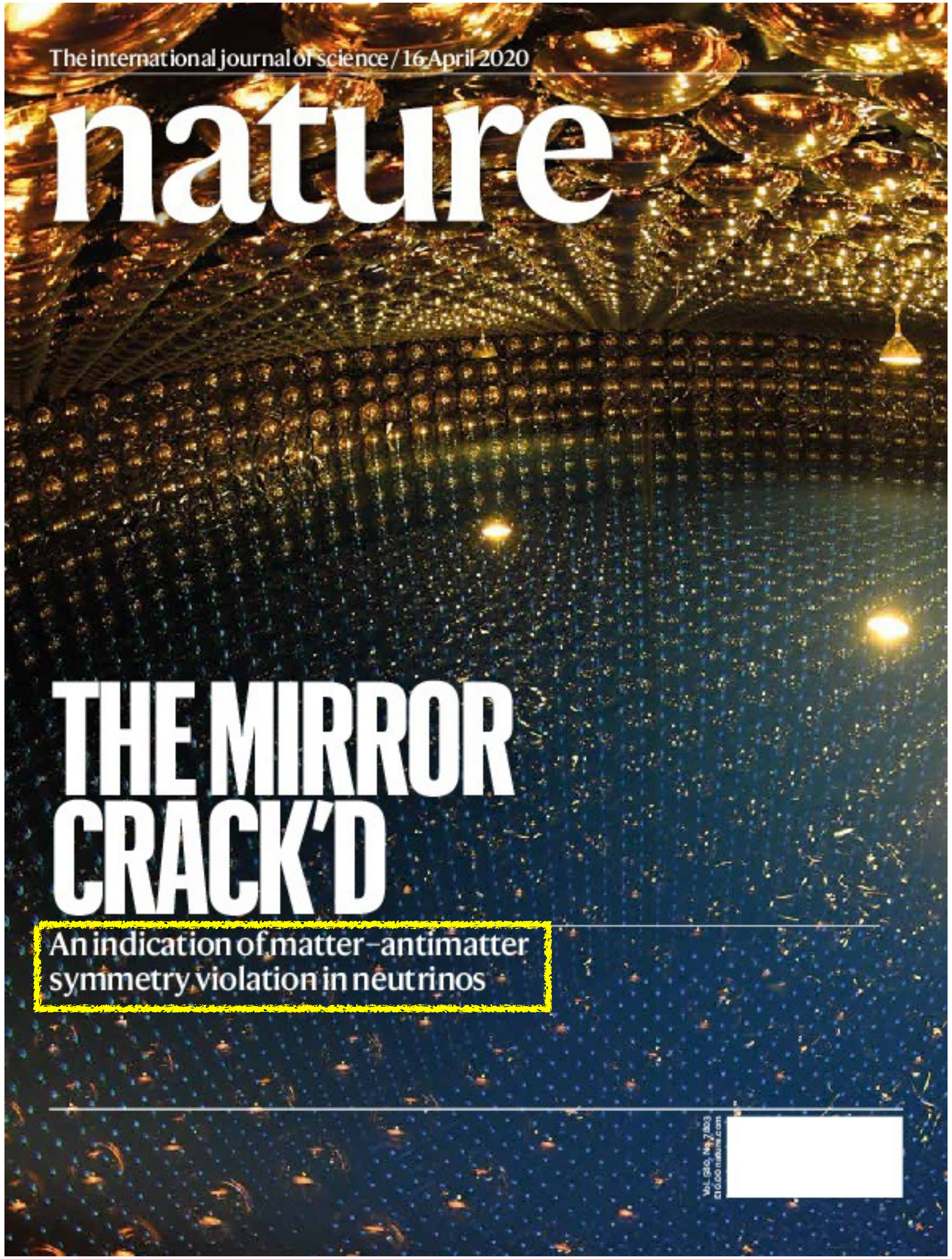




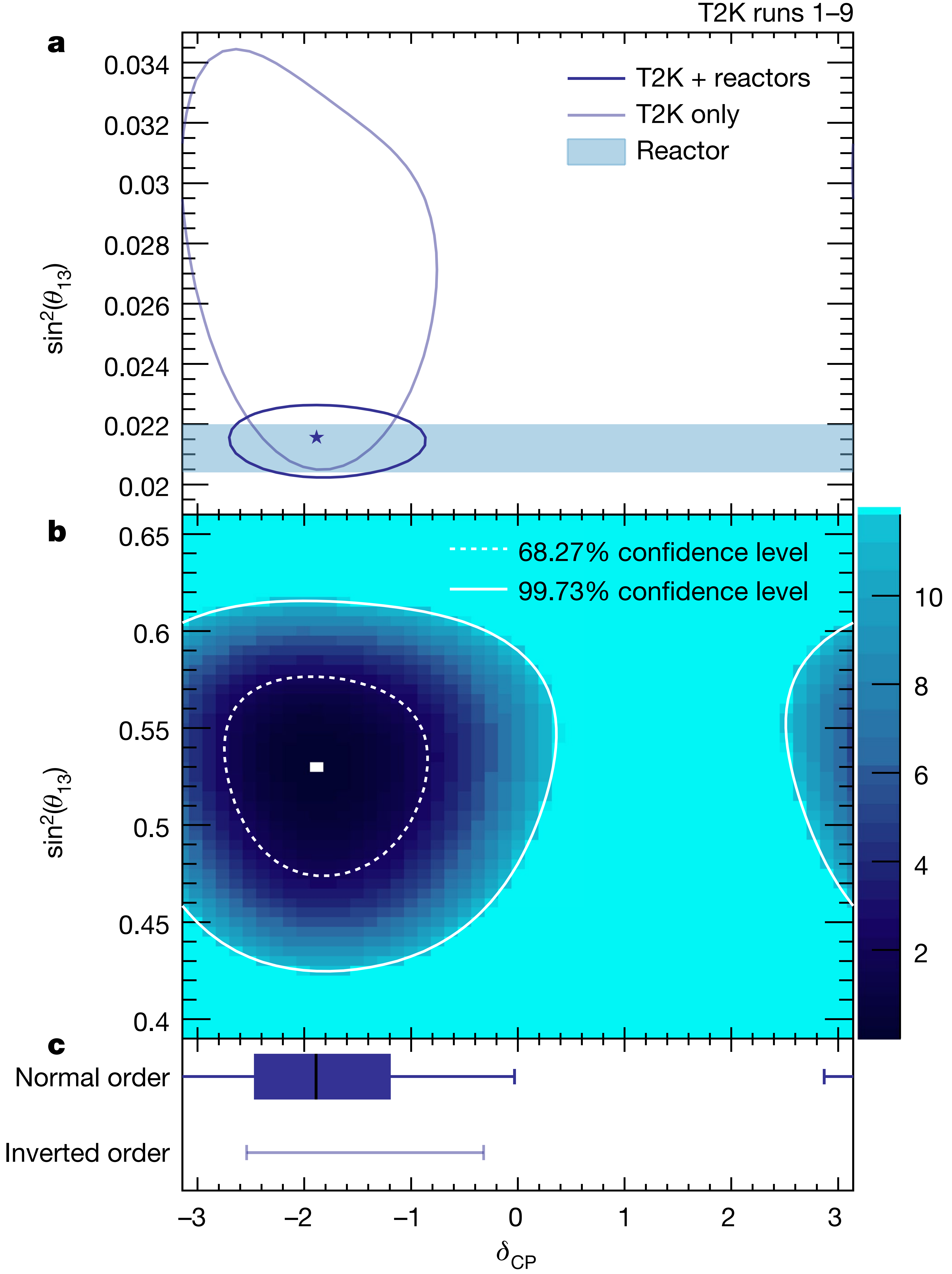
2013







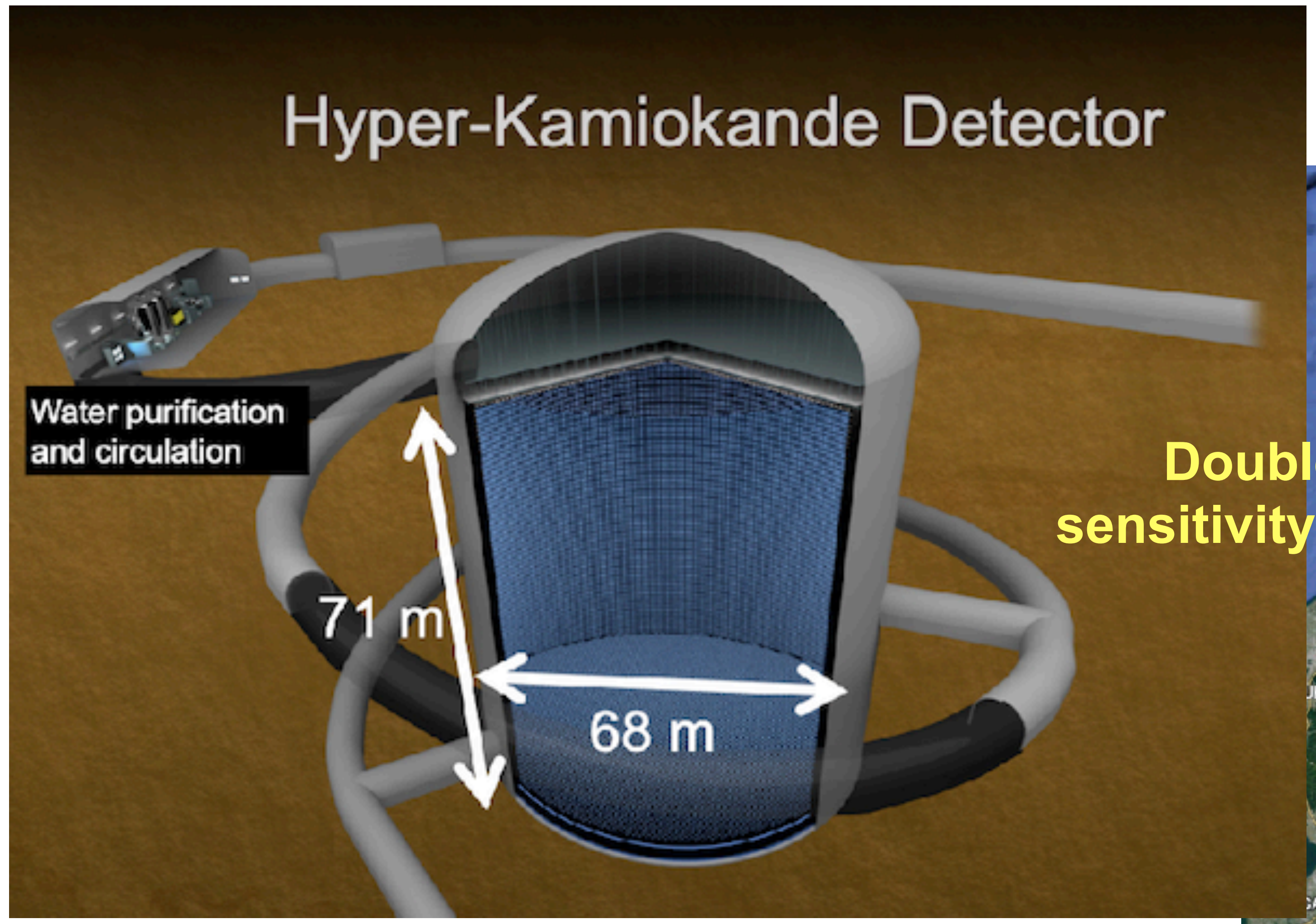
The international journal of science / 16 April 2020
nature
THE MIRROR CRACK'D
An indication of matter–antimatter symmetry violation in neutrinos



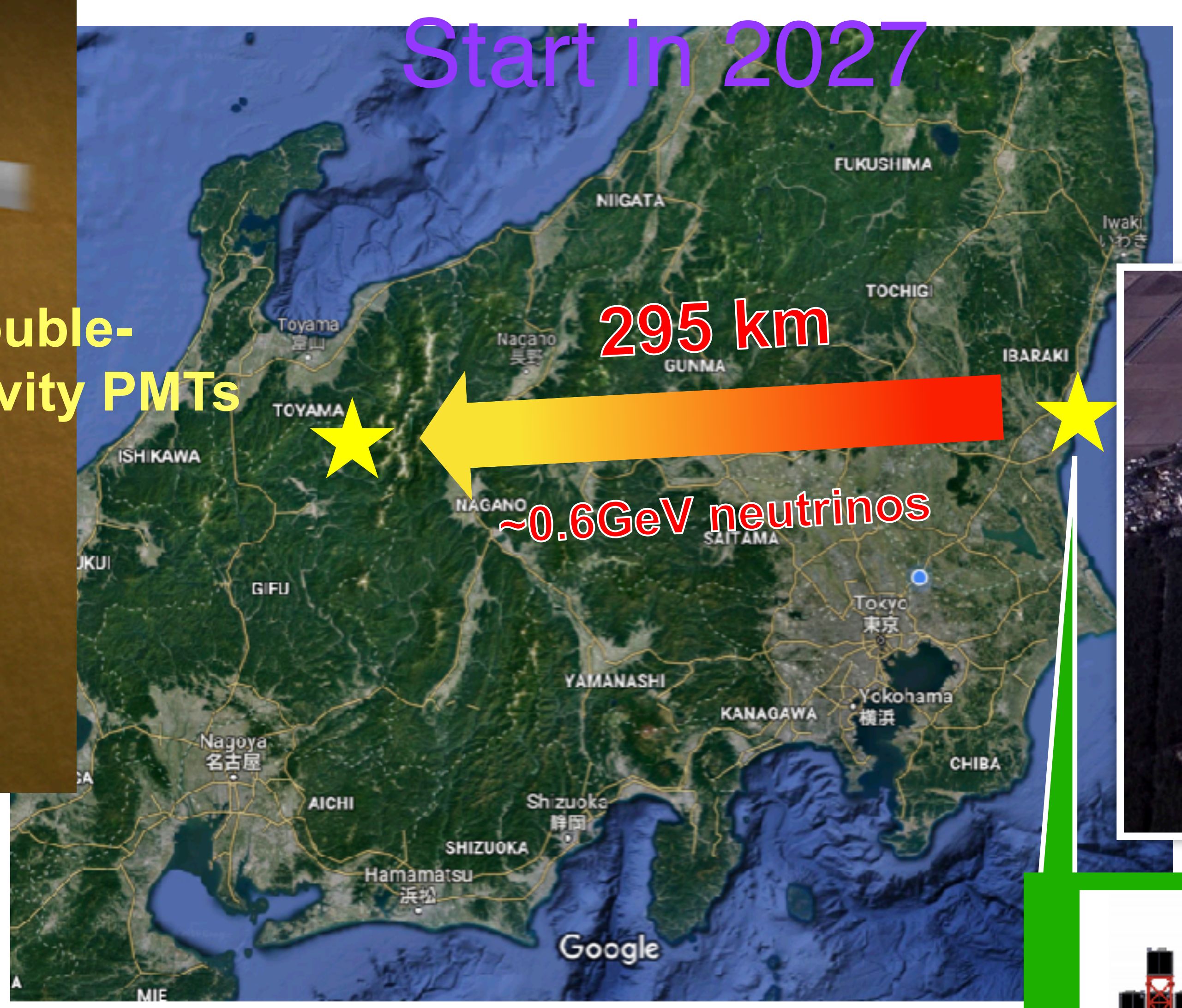
T2K runs 1–9
a
T2K + reactors
T2K only
Reactor
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
$\sin^2(\theta_{13})$
b
68.27% confidence level
99.73% confidence level
0.65
0.6
0.55
0.5
0.45
0.4
$\sin^2(\theta_{13})$
10
8
6
4
2
c
Normal order
Inverted order
−3
−2
−1
0
1
2
3
δ_{CP}

Hyper-Kamiokande Project

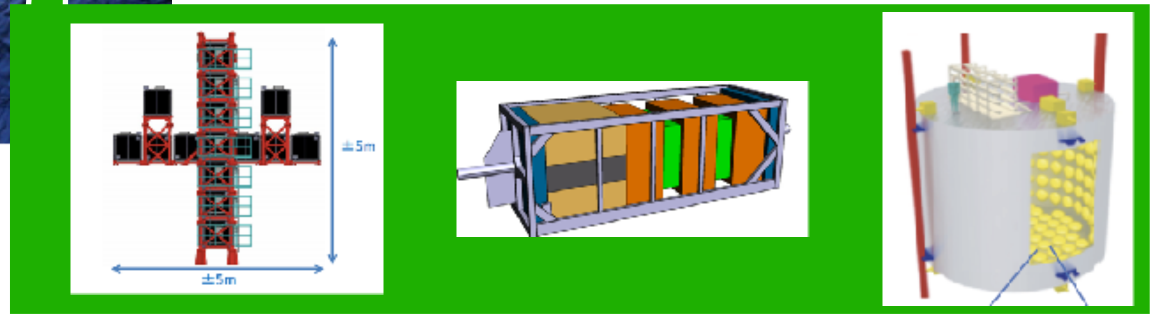
- Long baseline experiment and non-accelerator physics in a single project
- Based on the highly successful tradition of SuperK and T2K (expertise and collaboration)



Hyper-Kamiokande
(hosted by The University of Tokyo)



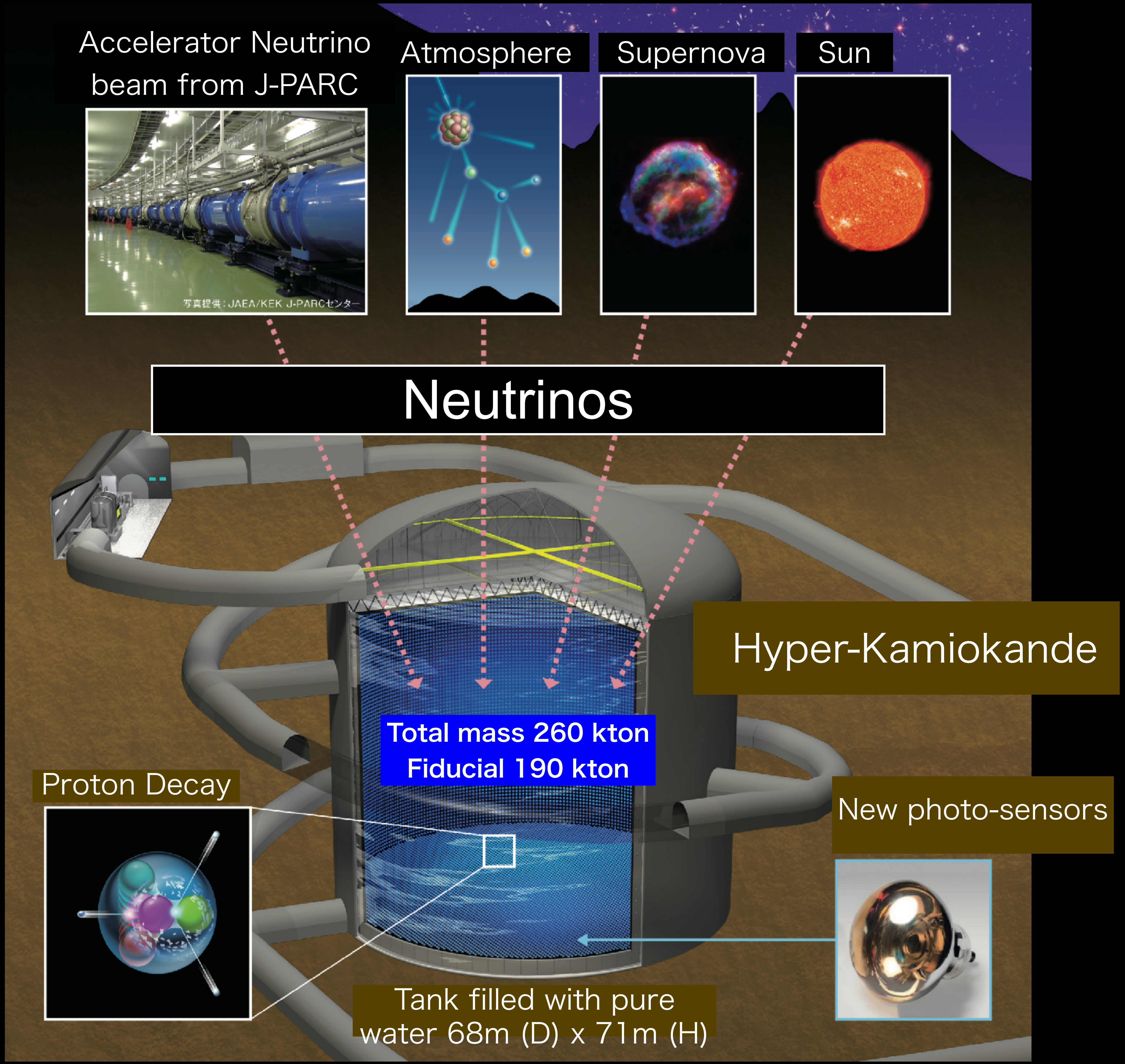
High power proton beams
J-PARC
(hosted by KEK)



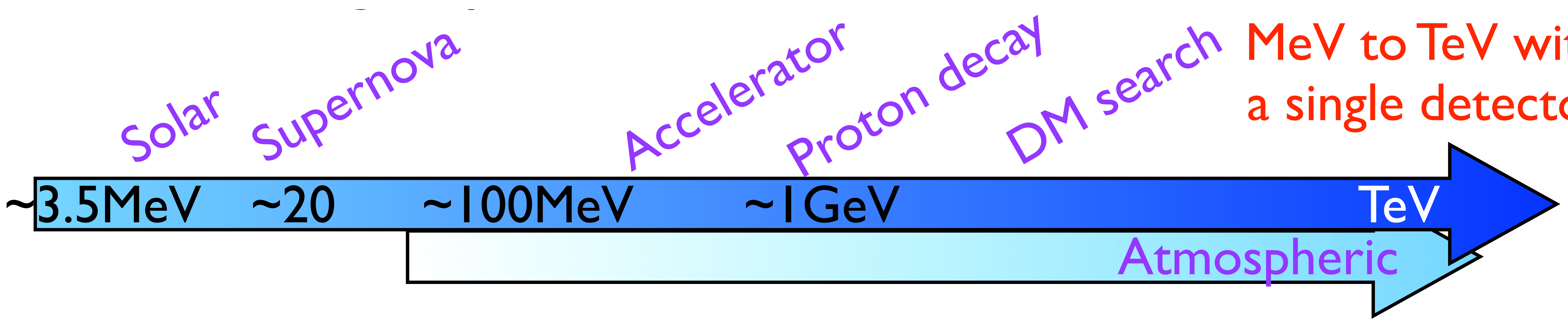
- World-largest detector for Nucleon-decay and Neutrino experiment
  - 8.4 times larger fiducial mass (190 kiloton) than Super-K instrumented with double-sensitivity PMTs
- World most-intense neutrino beam
  - J-PARC neutrino beam to be upgraded to 1.3 MW
- New and upgraded near detectors to control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

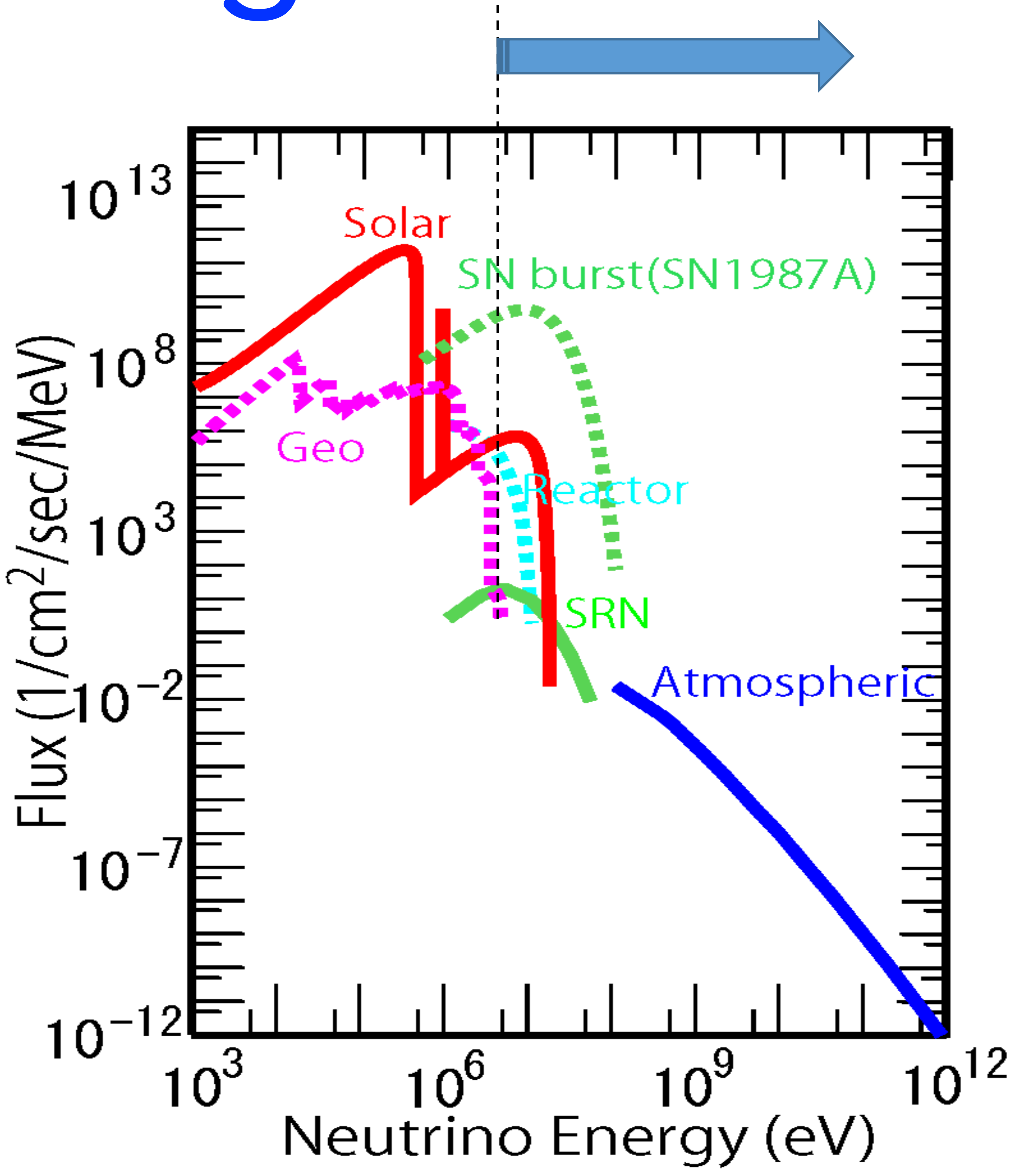
Physics Sensitivity

Hyper-Kamiokande program



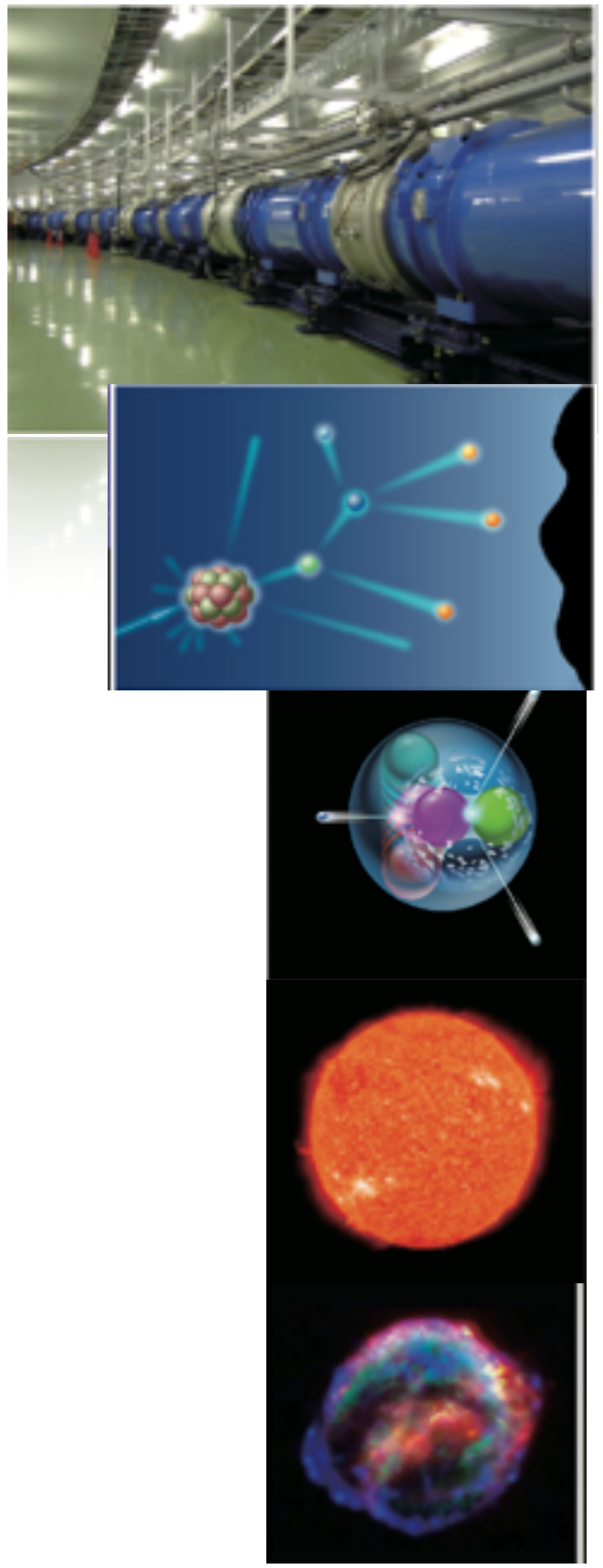
Many Physics targets





- 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

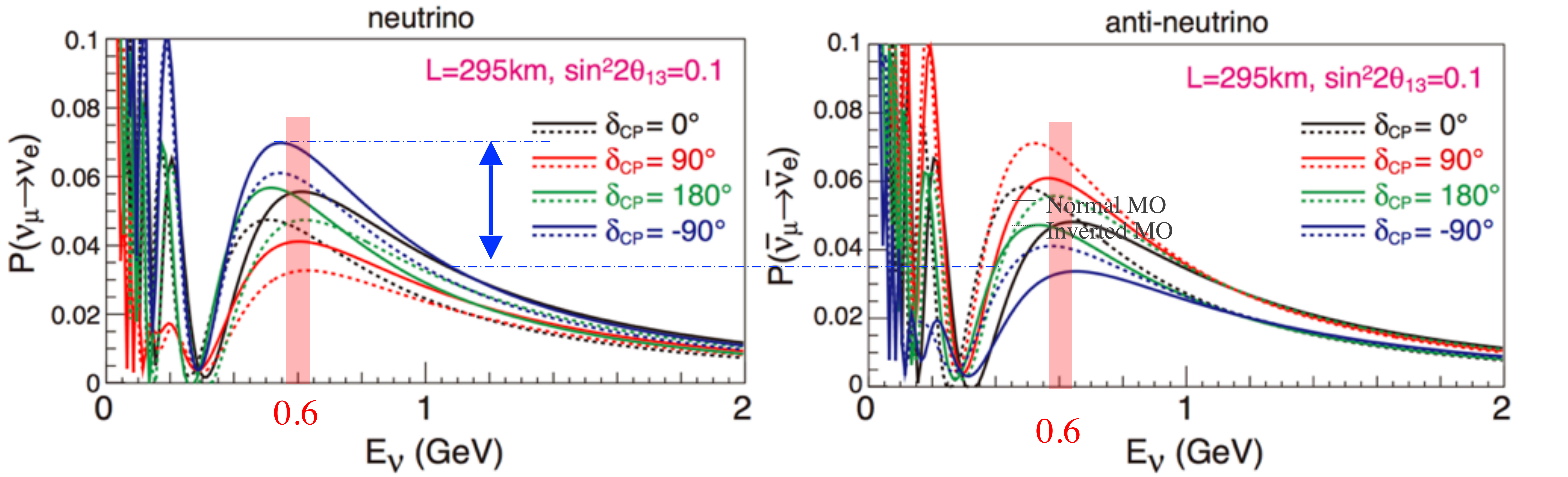


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)	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

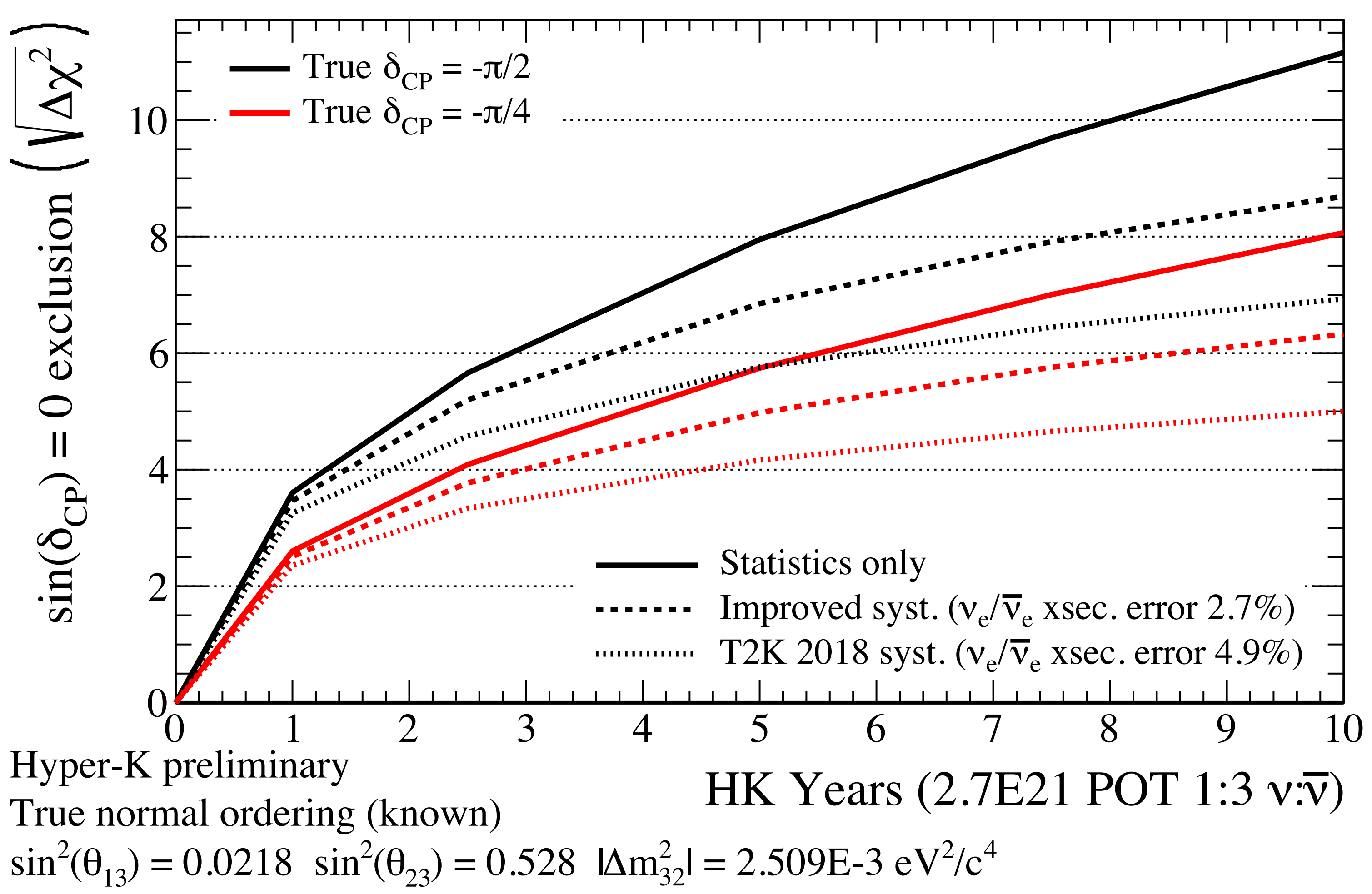
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - ➢ Major component is QE: E_ν determined from $(p,\ \theta)$ of charged lepton
- Measures CP violation in neutrinos by comparing $P\left(\nu_\mu \to \nu_e\right)$ and $P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$



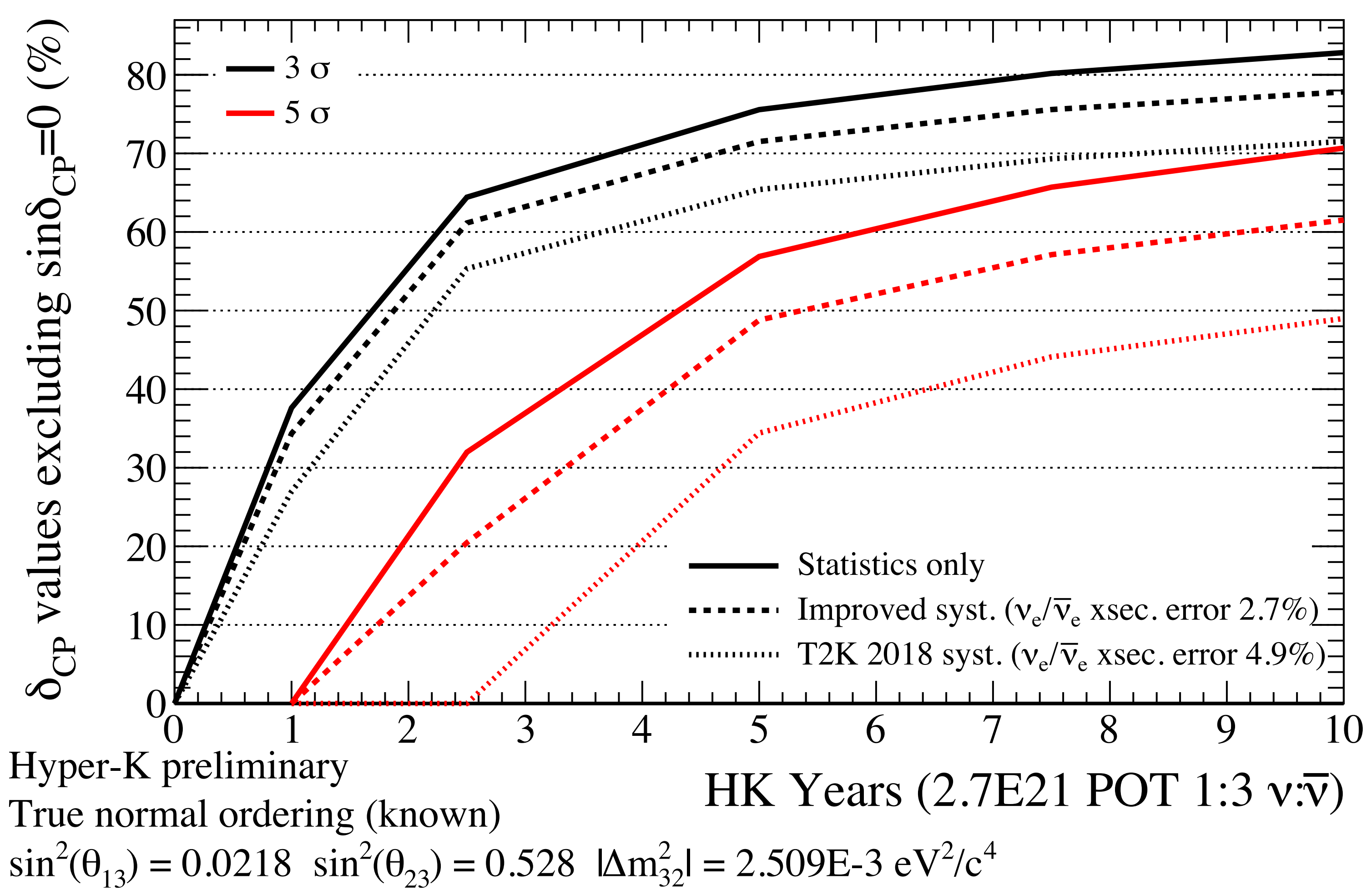
- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

Neutrino oscillation sensitivity

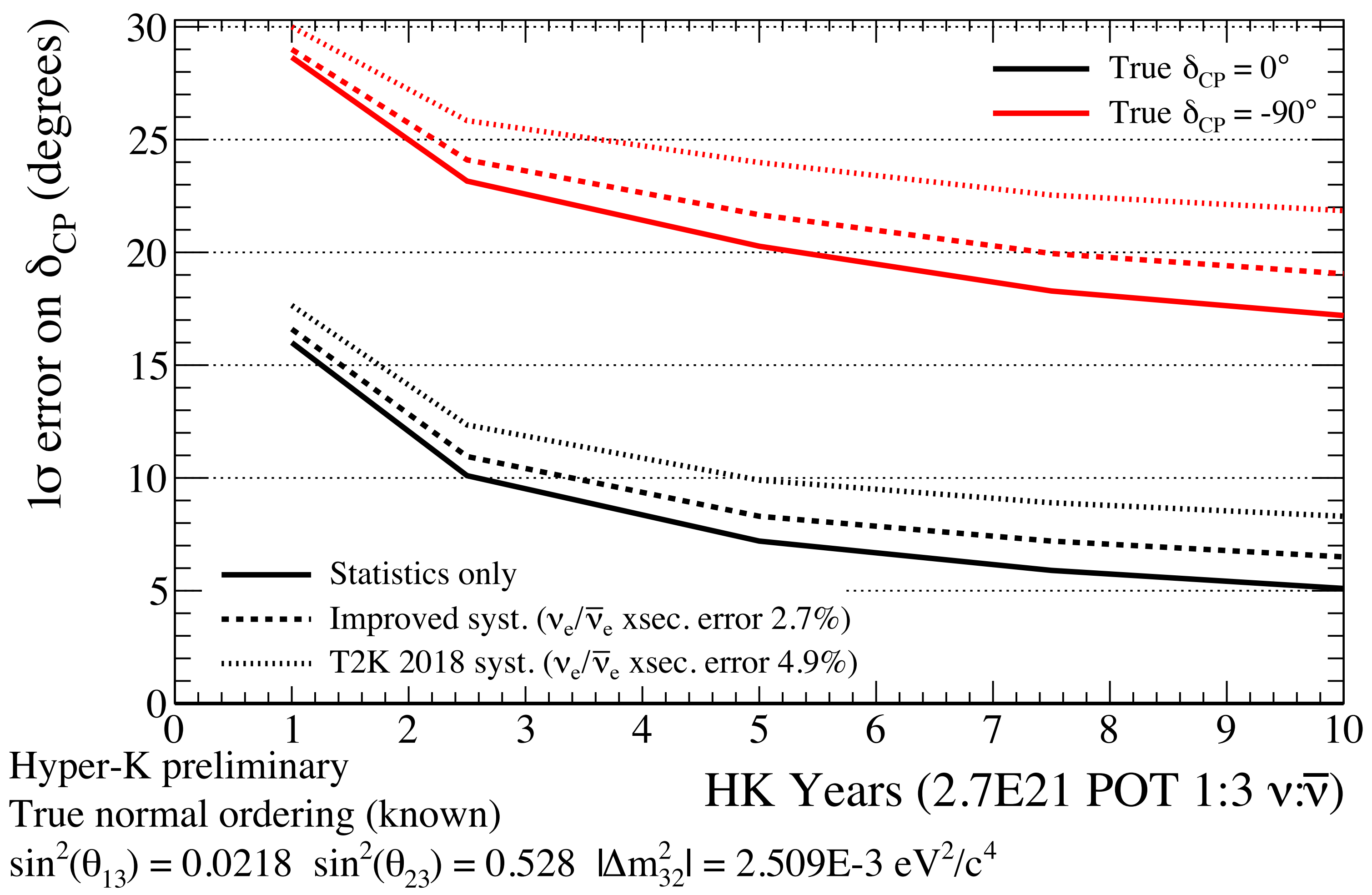
Sensitivity for δCP=-π/2 or -π/4



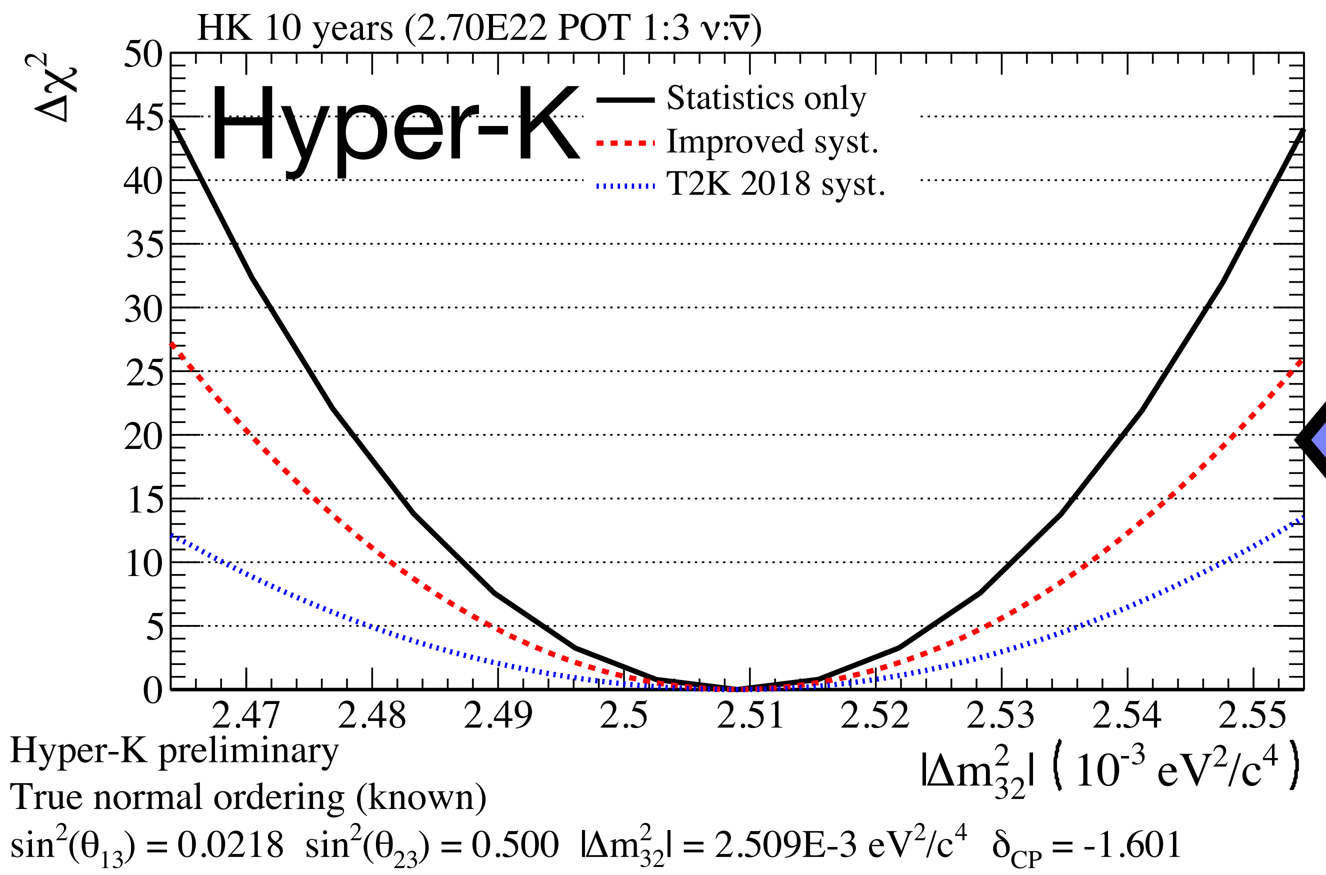
Fraction of δCP exclusion with 3σ or 5σ



Precision for δCP=0 or -π/2

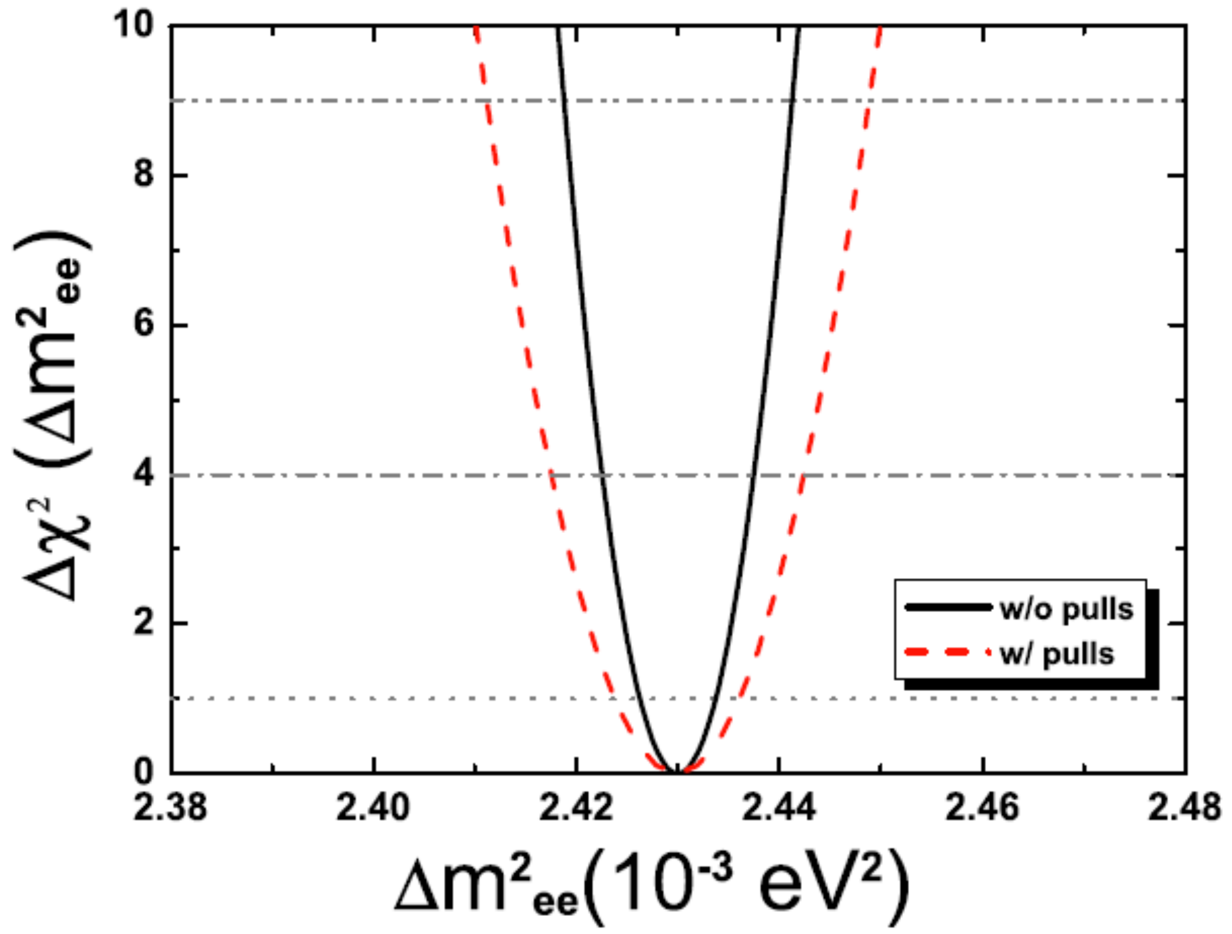


- Good chance for discovery of CP violation with > 5σ
  - Measurement of δ_{CP} with ~20° for $\delta_{cp} = -90°$ / ~7° for $\delta_{cp} = 0°$
- Combination of beam and atmospheric neutrinos enhances the sensitivity for mass ordering
- Reduction of systematic uncertainty has sizable impact
  - Upgrade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



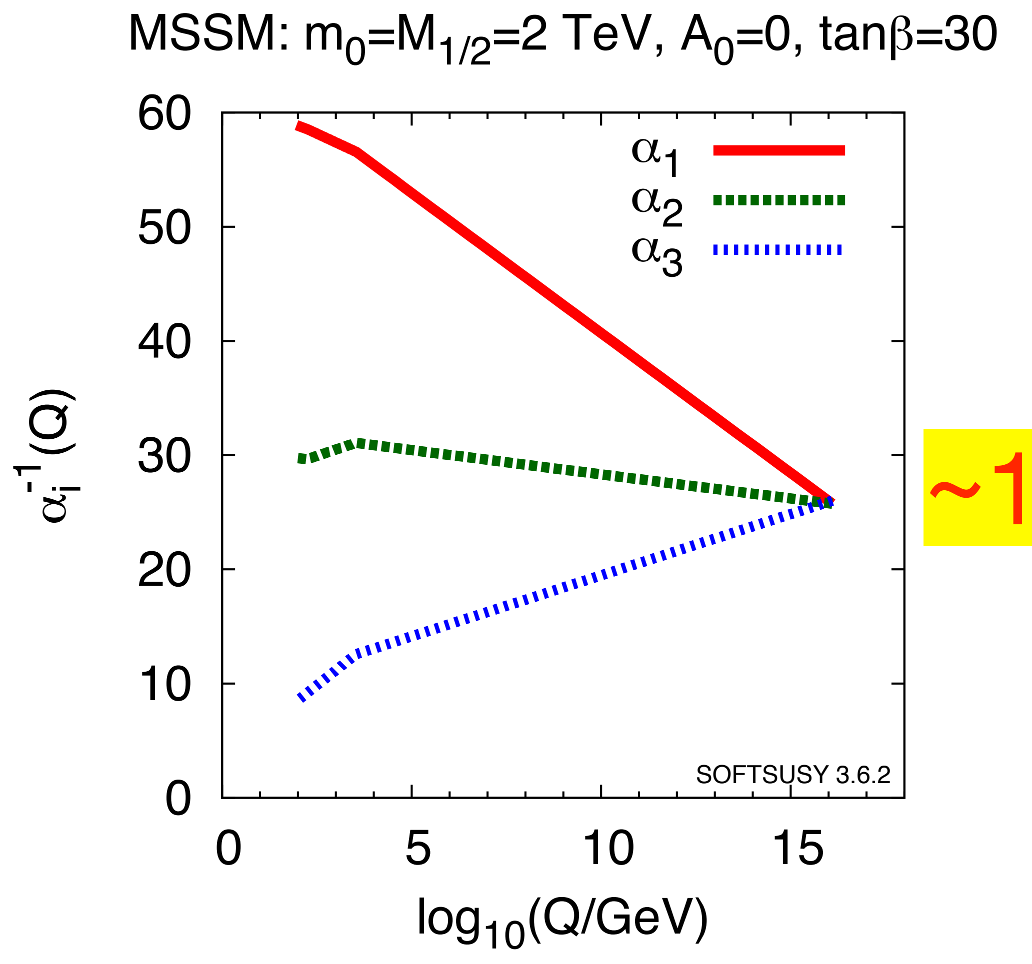
Δm^2

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



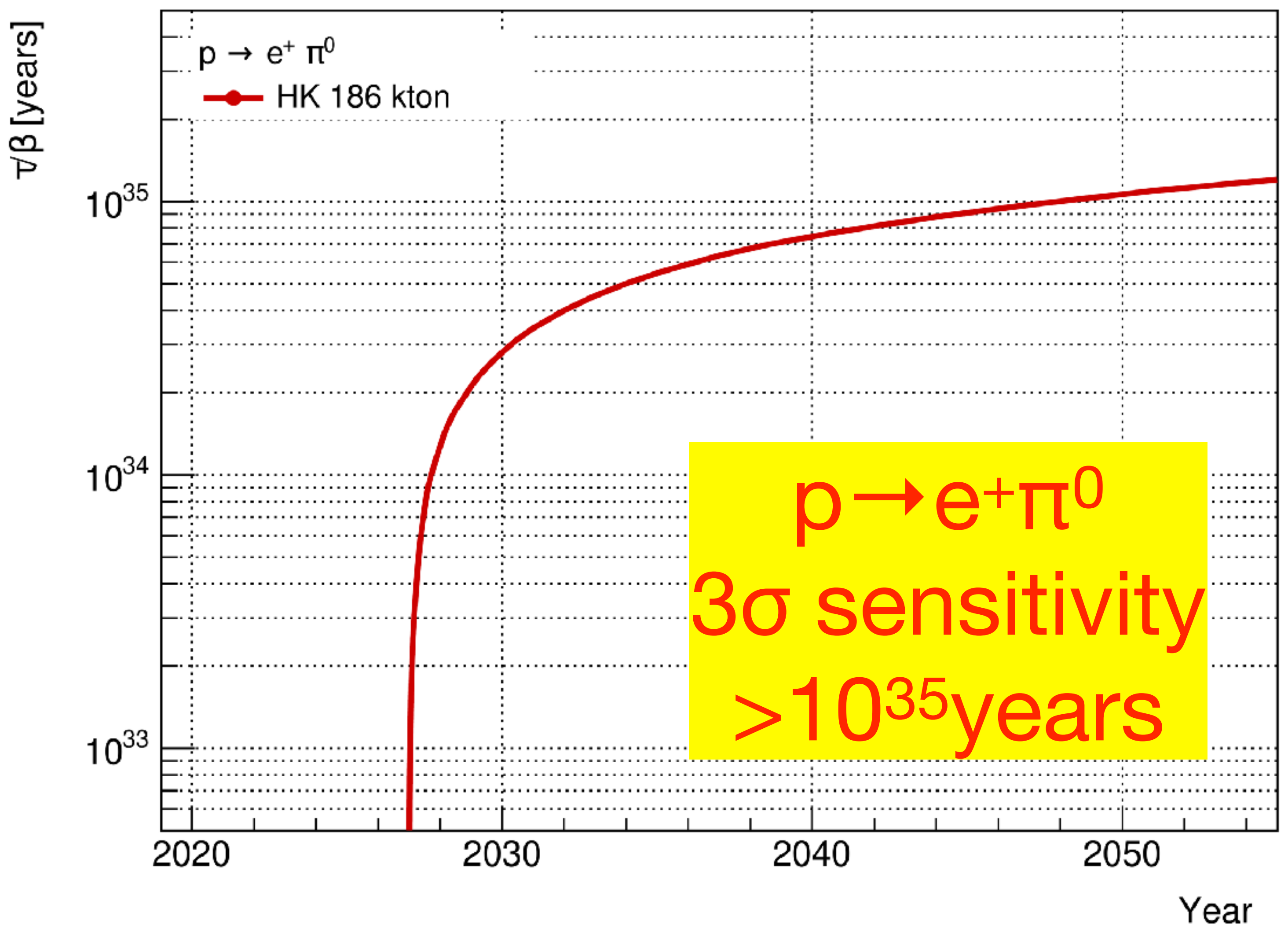
Proton decay Search

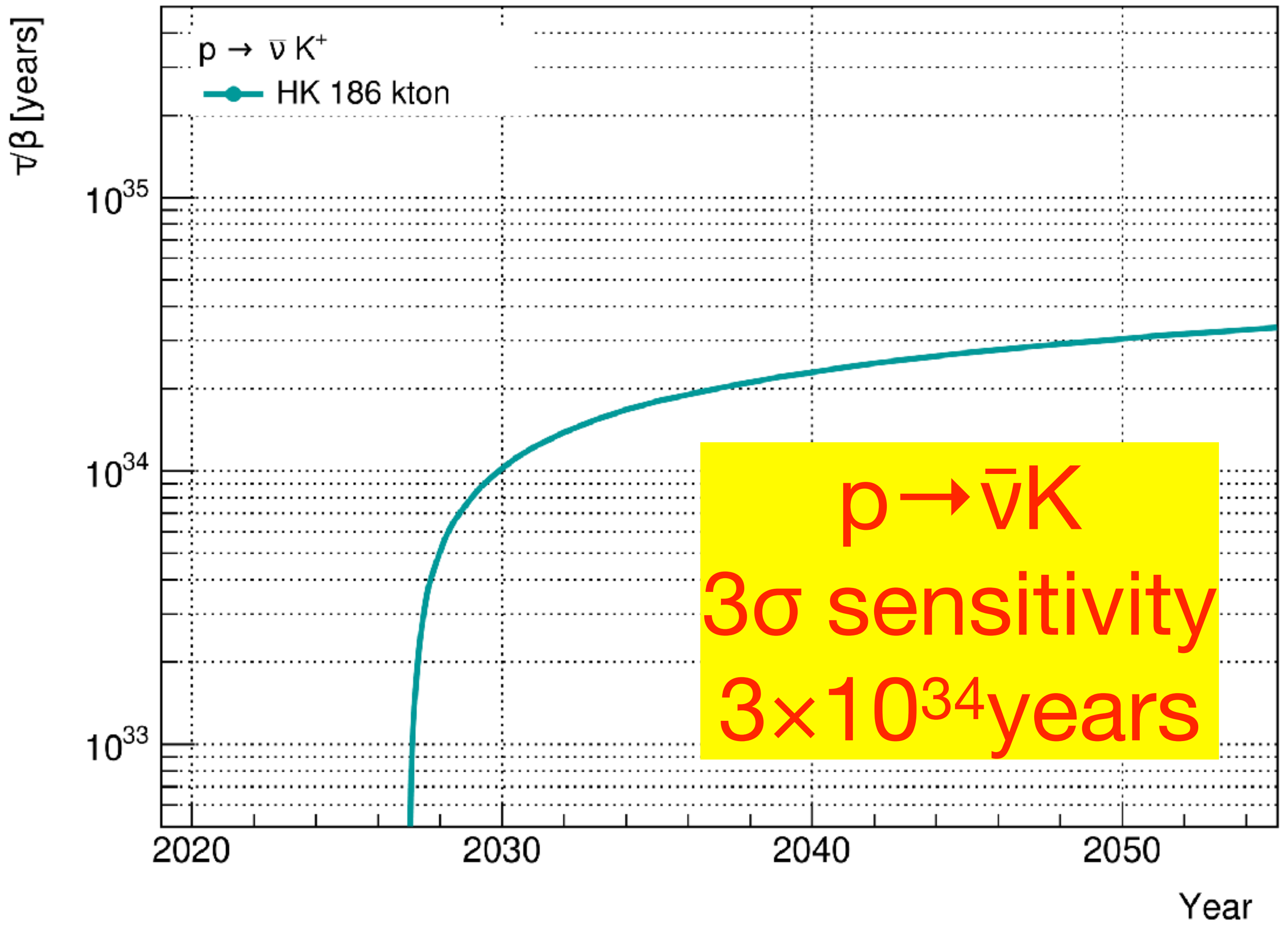
Nucleon decay:
clear evidence of GUT



~10^{16}GeV

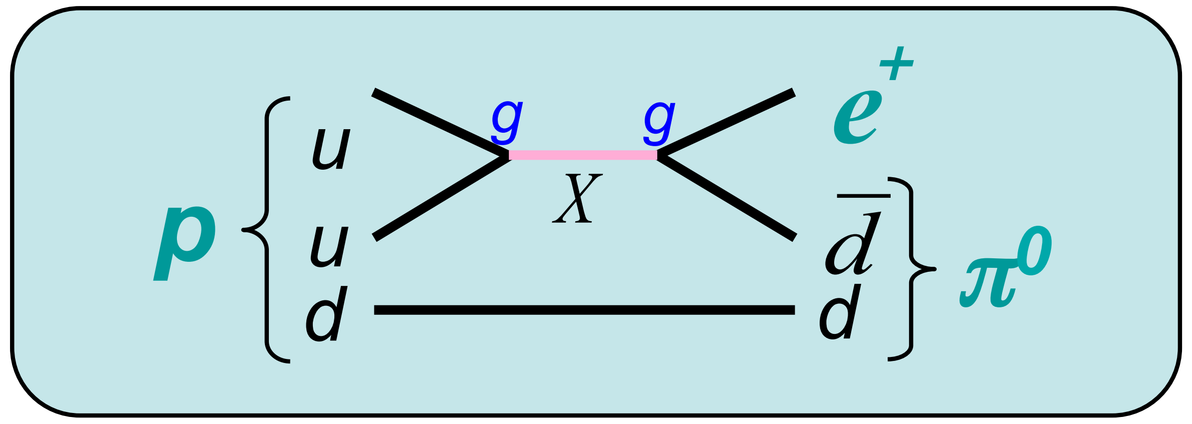
World's best sensitivity for most of possible modes, including p→ν̄K, thanks to huge mass and free protons





Two modes as benchmark

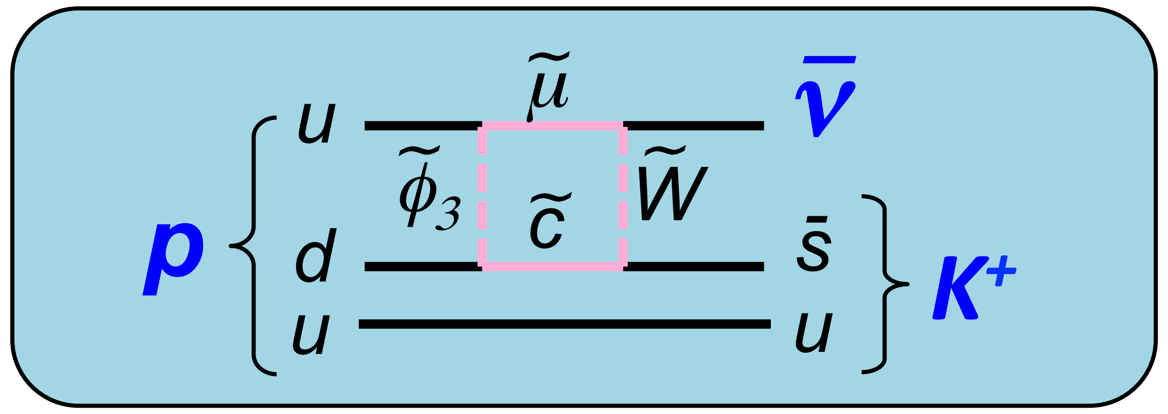
Mediated by gauge bosons



p→$e^+\pi^0$

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

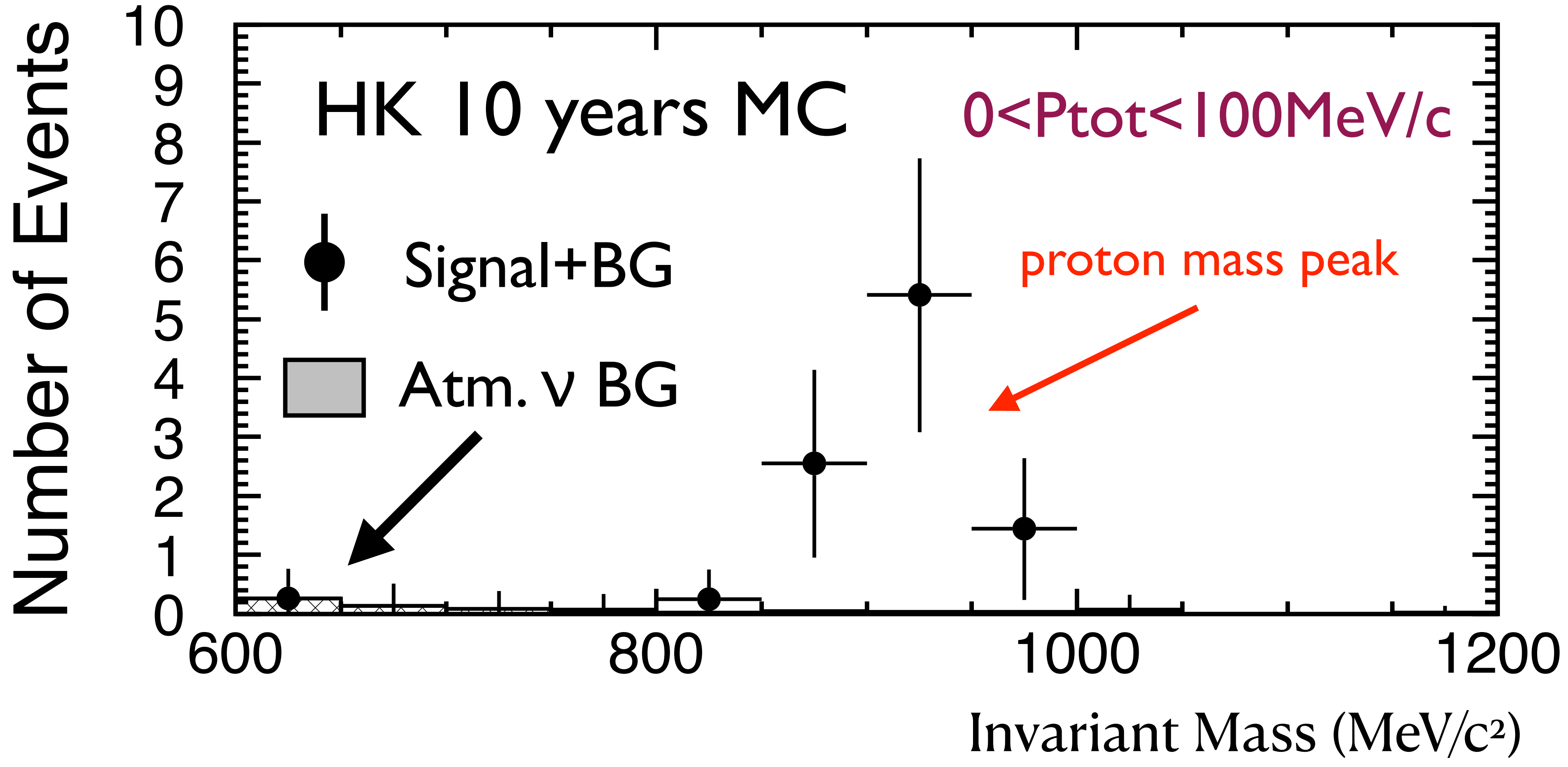
SUSY mediated



p→ν̄K^+

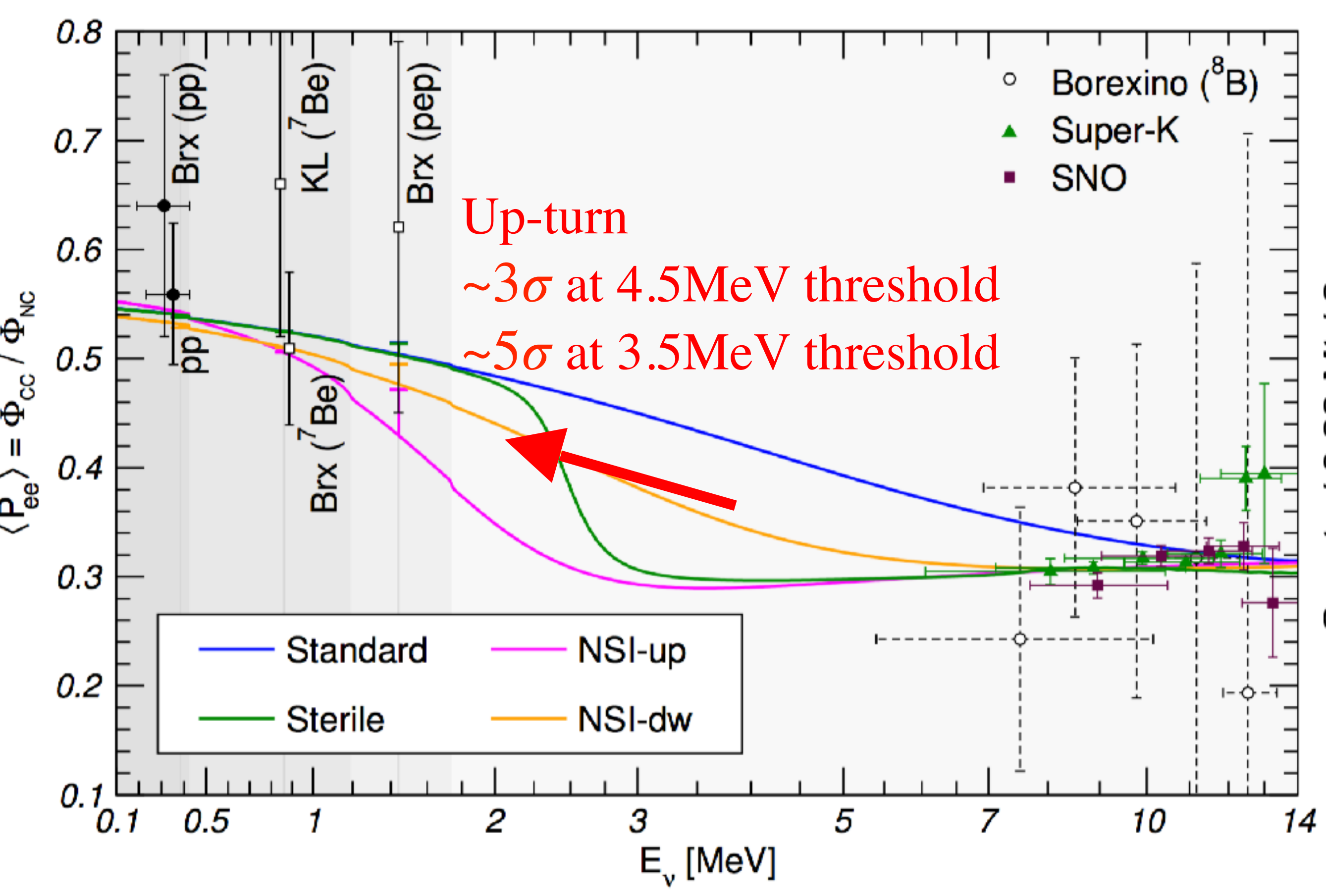
$$\Gamma(p \to \bar{\nu}K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

p→$e^+\pi^0$

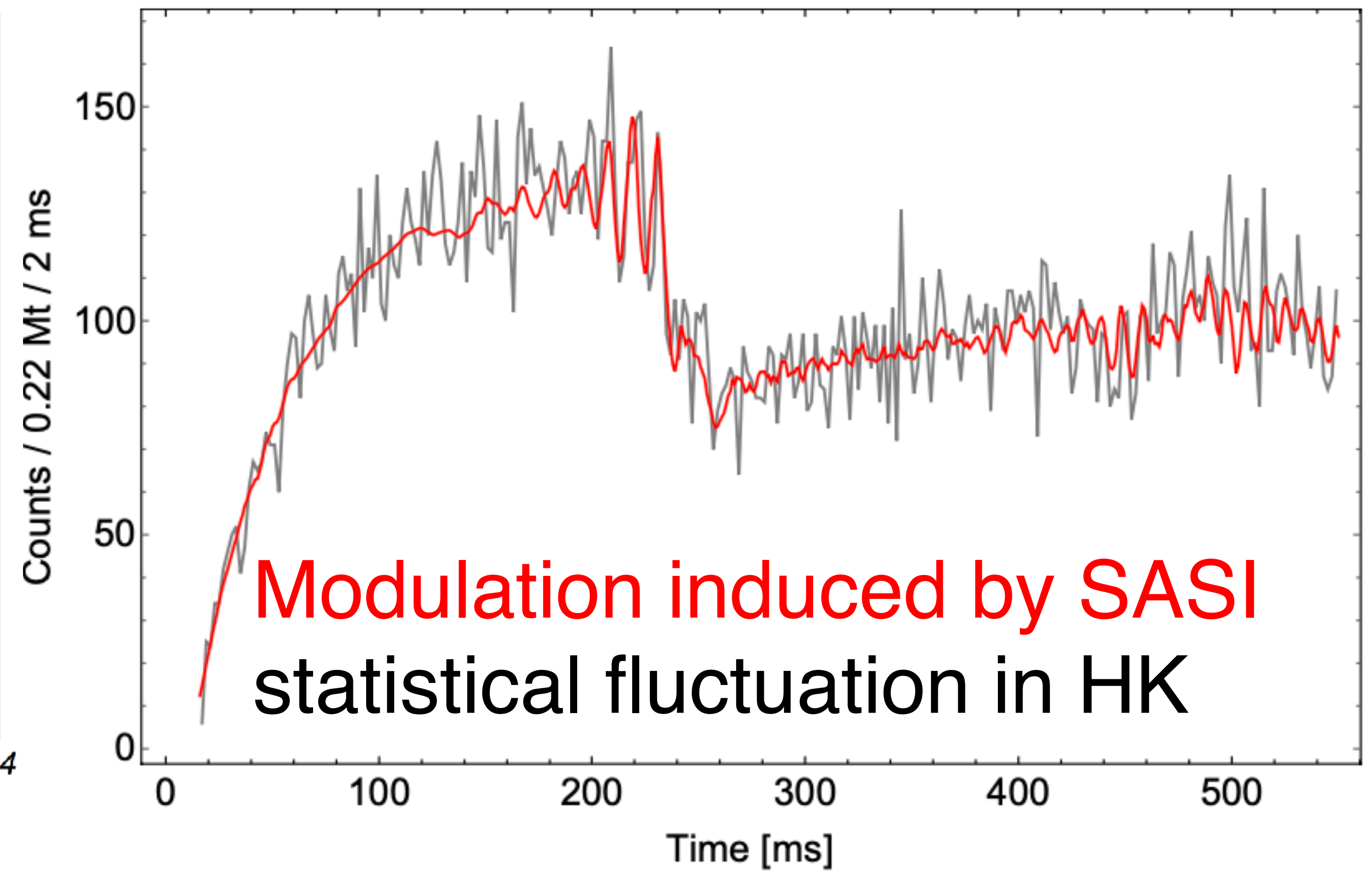


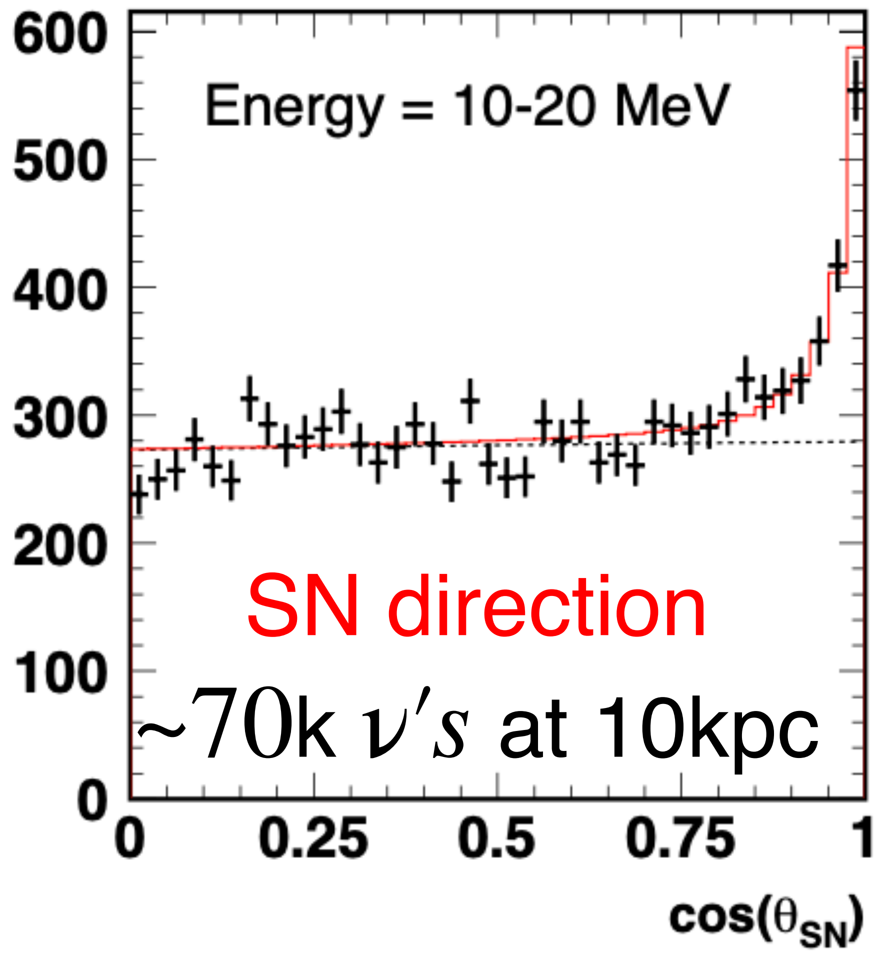
Neutrino Astrophysics

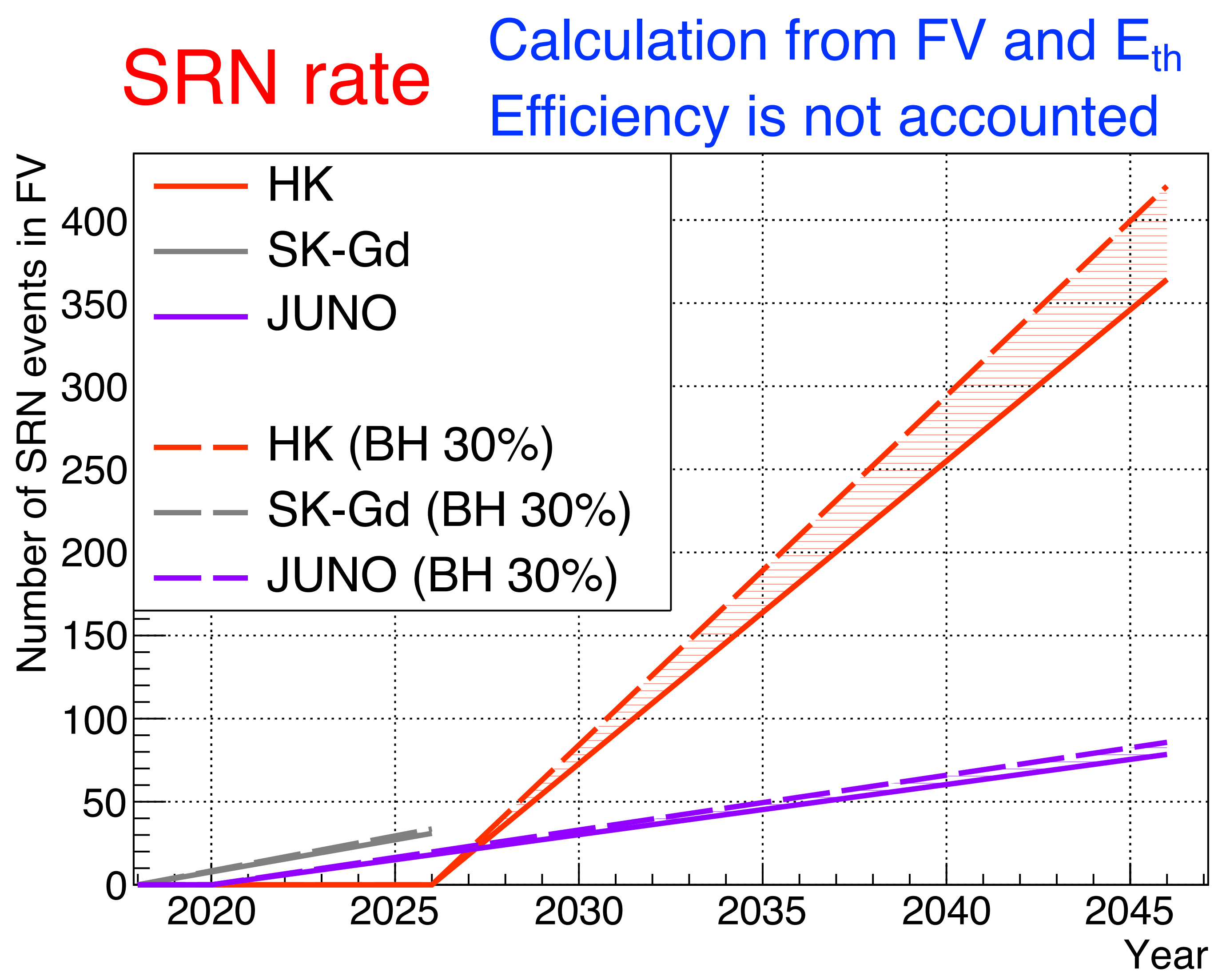
- Observation of a few~10MeV neutrinos with time, energy and direction information
  - Unique role in multi-messenger observation
- Solar neutrinos: up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- Supernova burst neutrinos: explosion mechanism, BH/NS formation, alert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



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





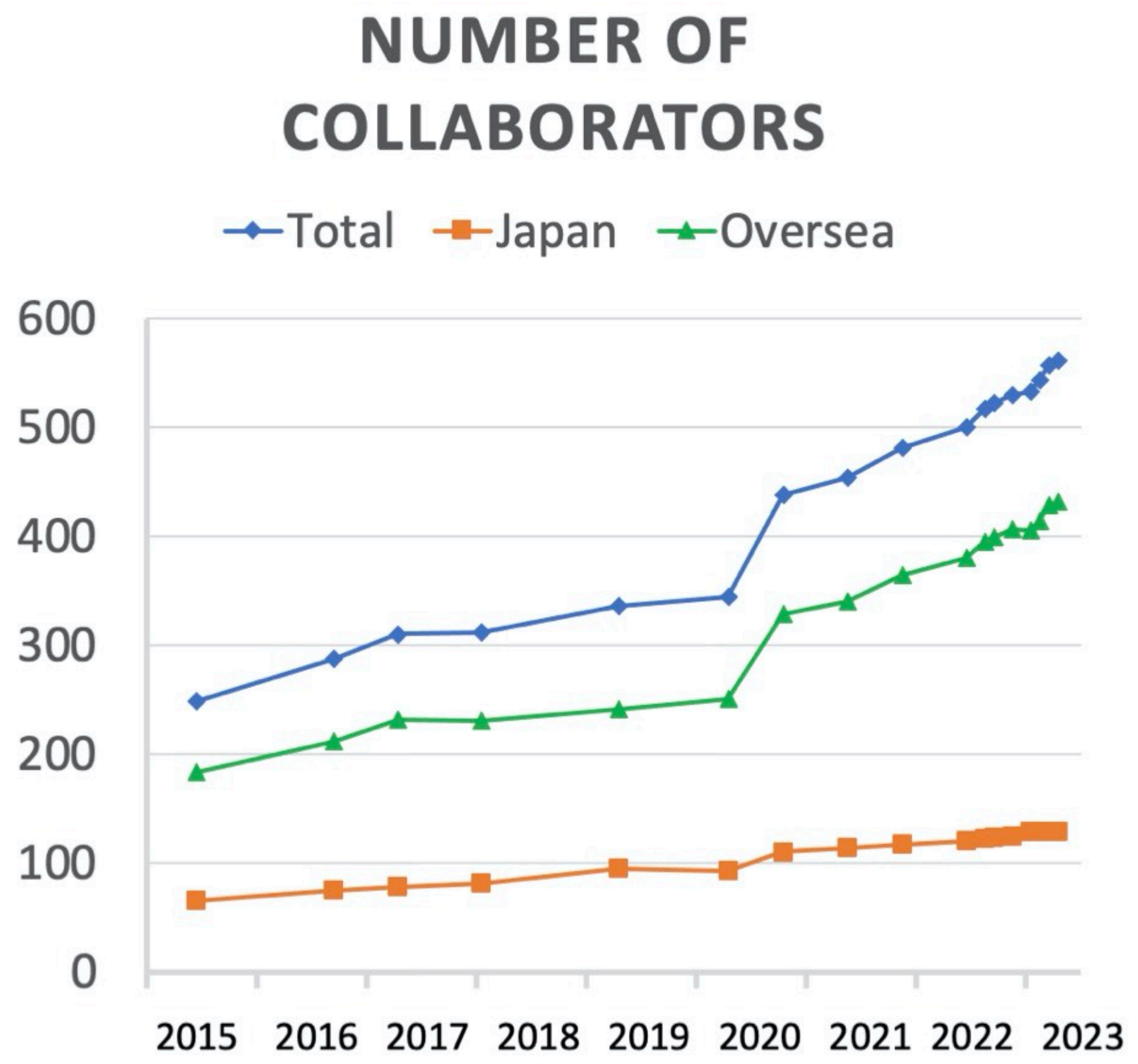


Project Status

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

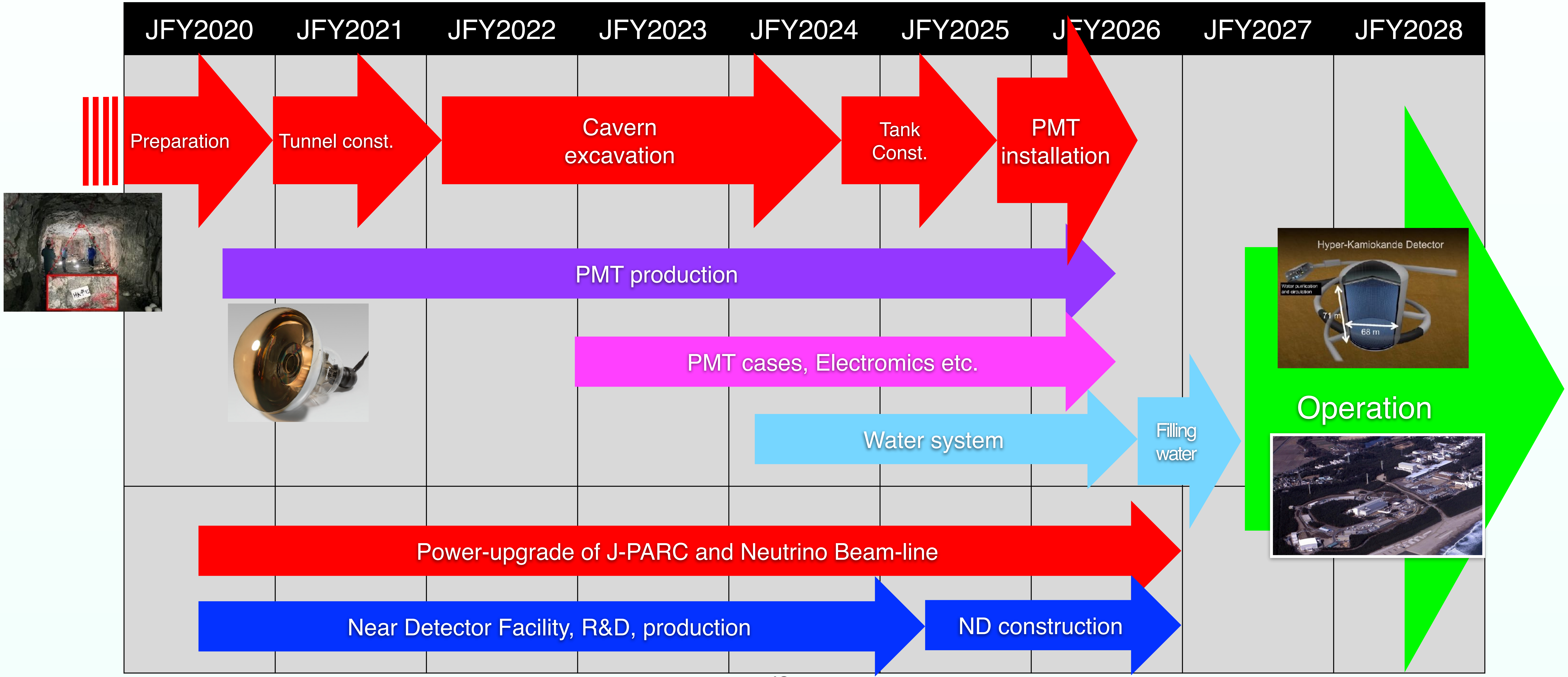


Collaboration Meeting, March 2023 @ Toyama

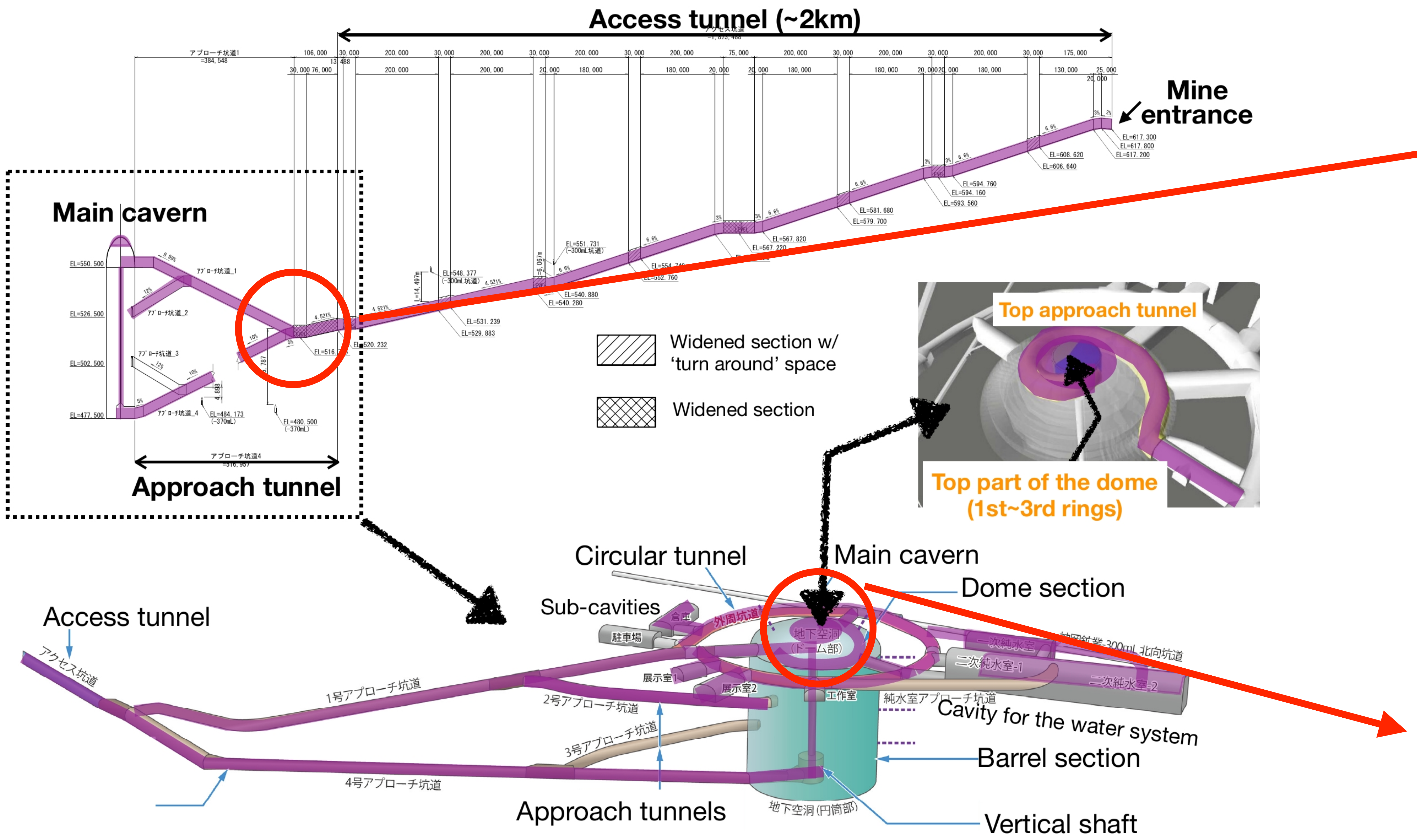
First face-to-face meeting after project approval

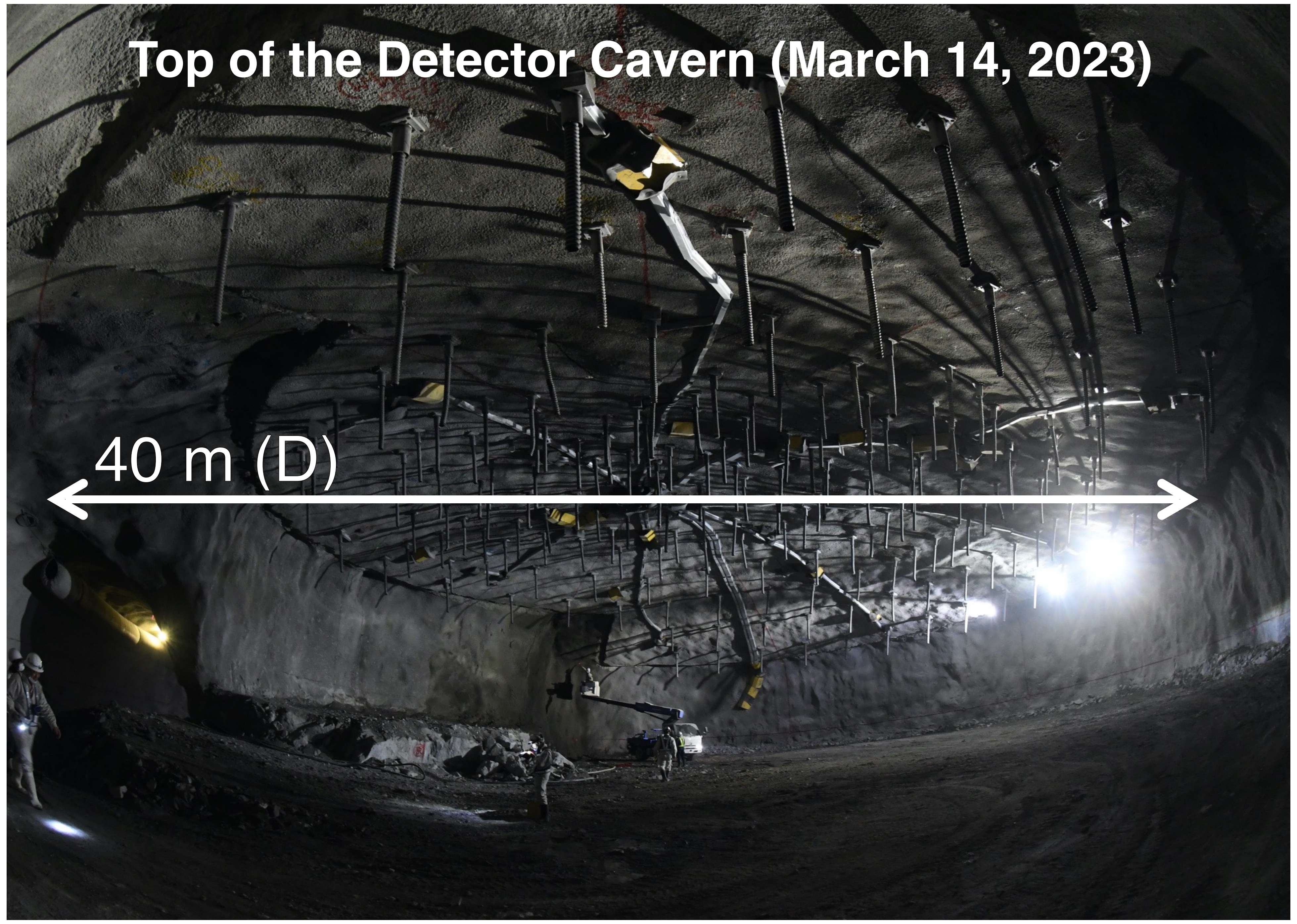
Timeline

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



Cavern excavation status

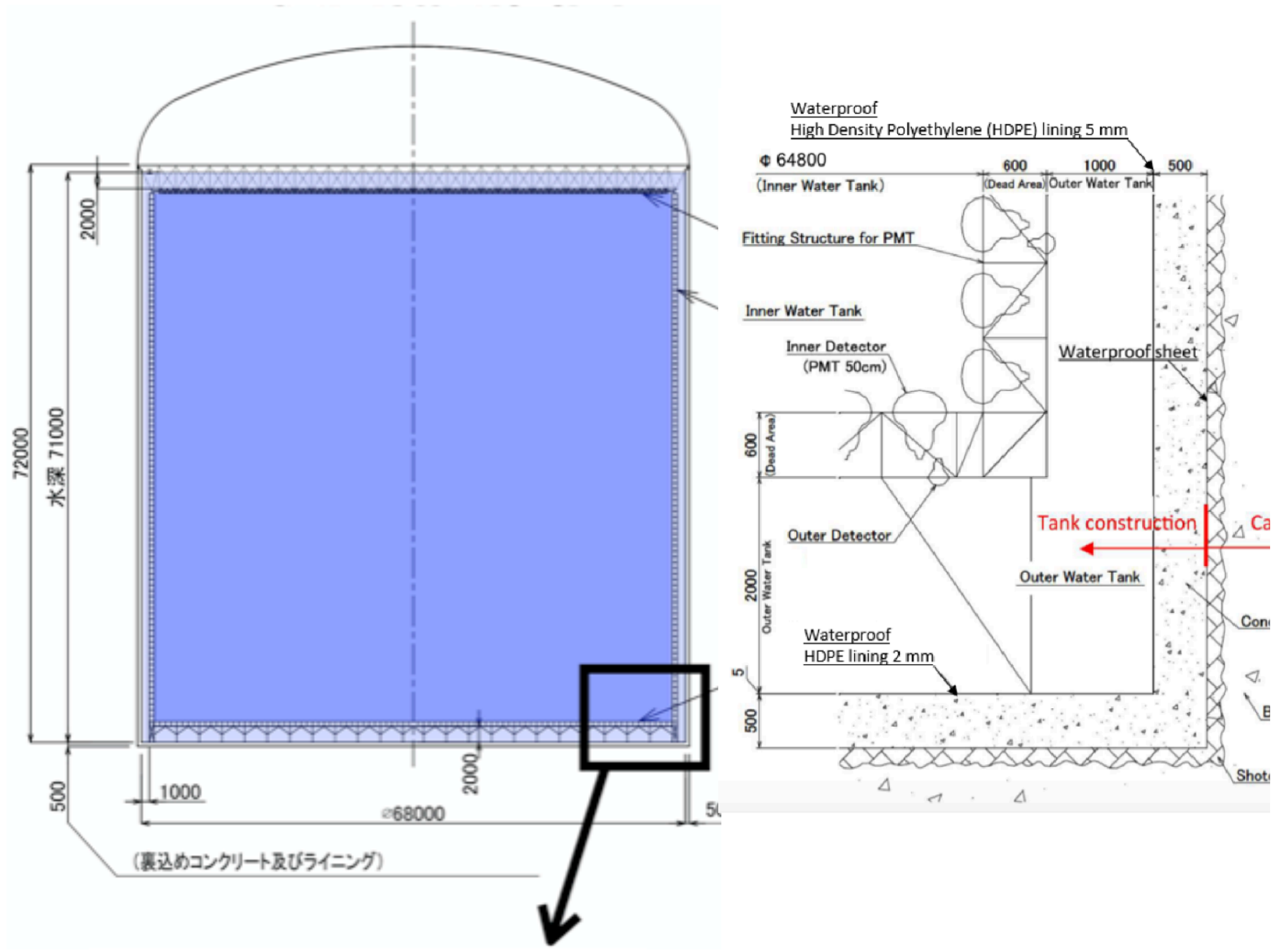


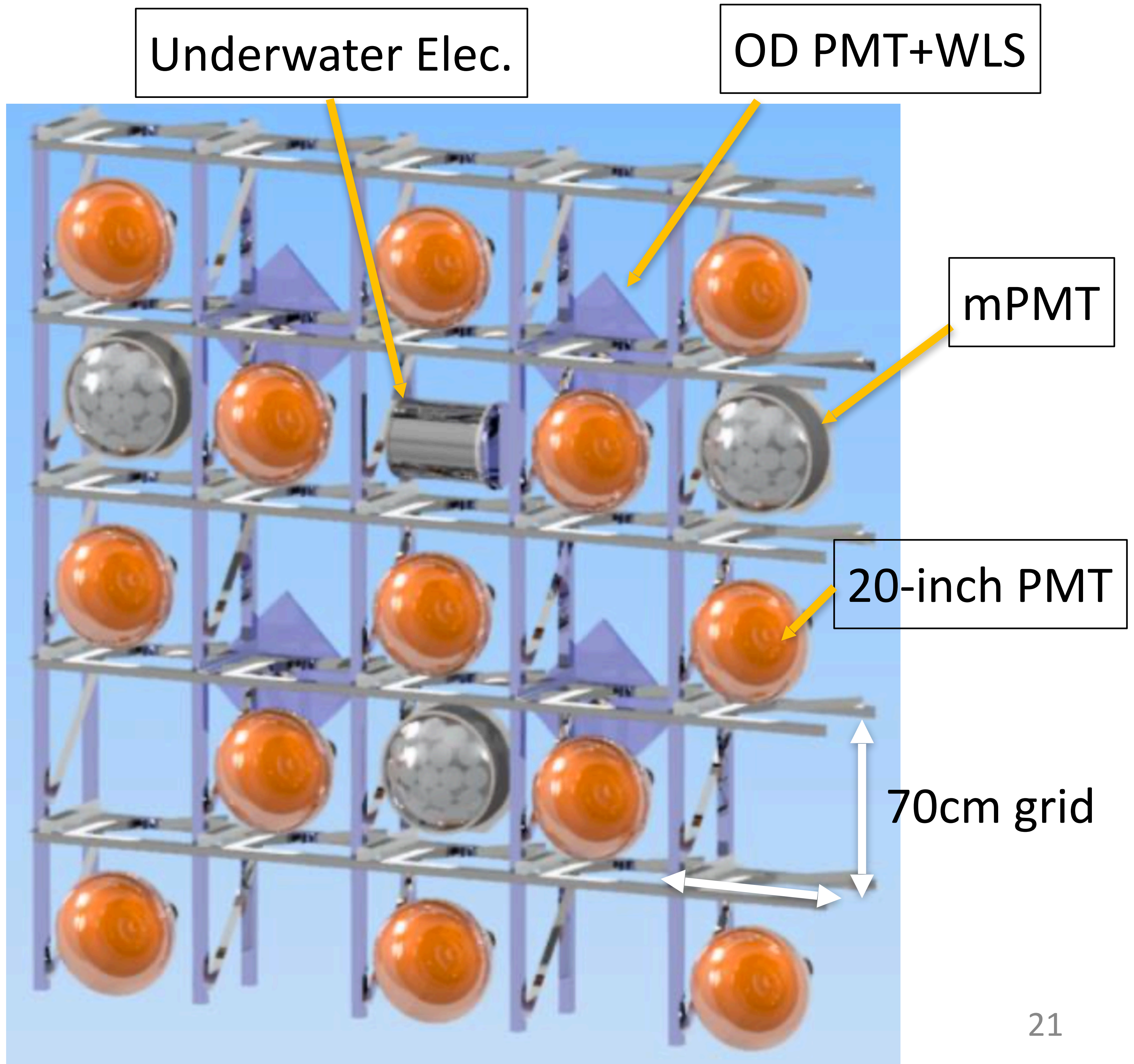


- Access tunnel (~2 km) completed in Feb. 2022
- Excavation of the main cavern started in fall 2022 and is proceeding as scheduled

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

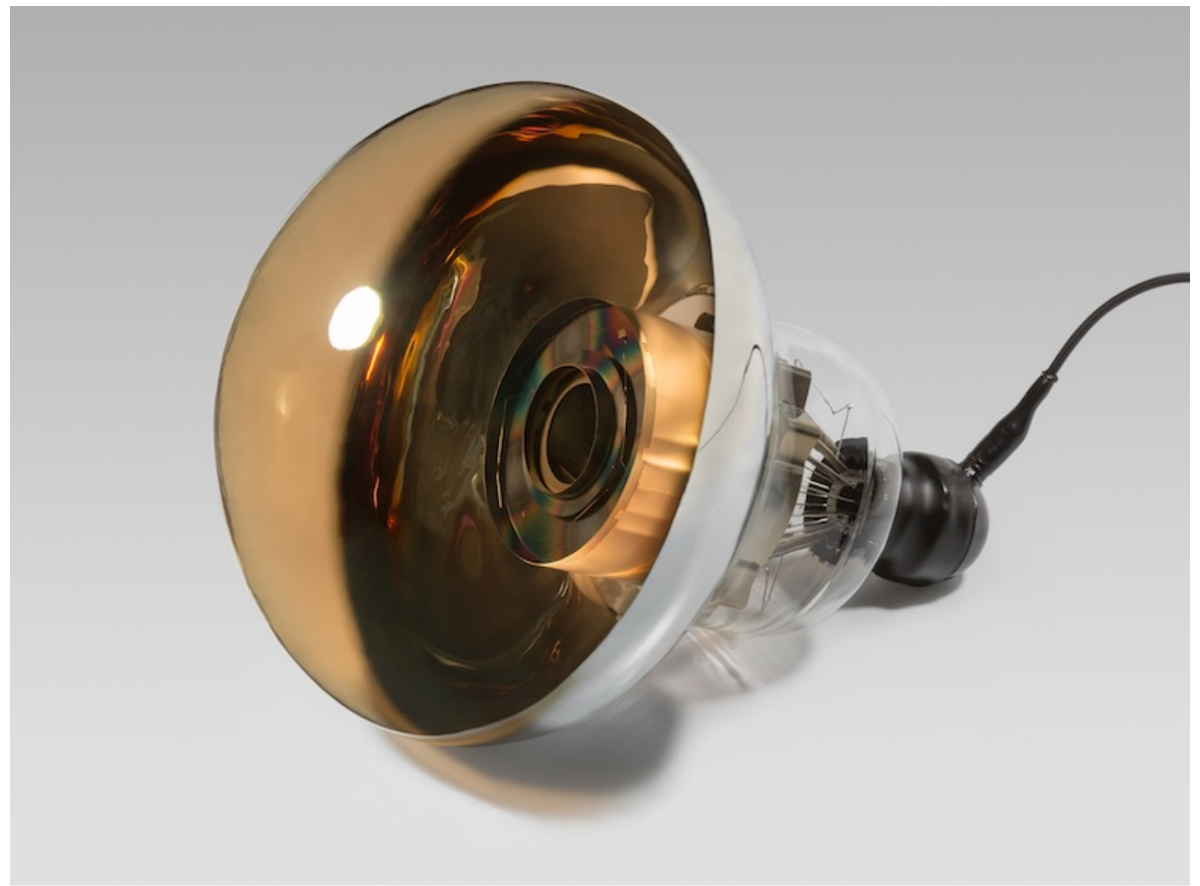




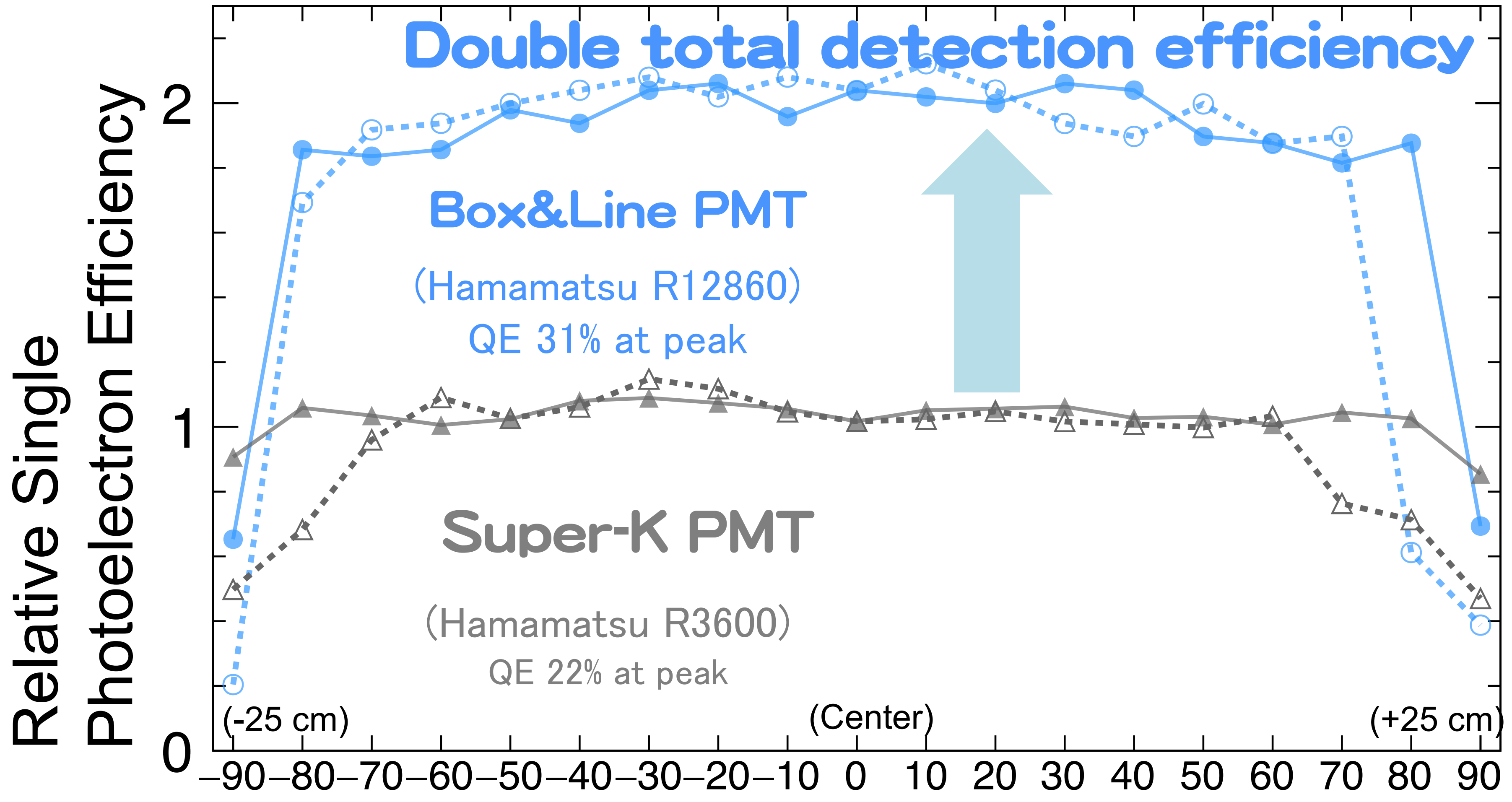
Hyper-K PMT Performance

Hamamatsu R12860

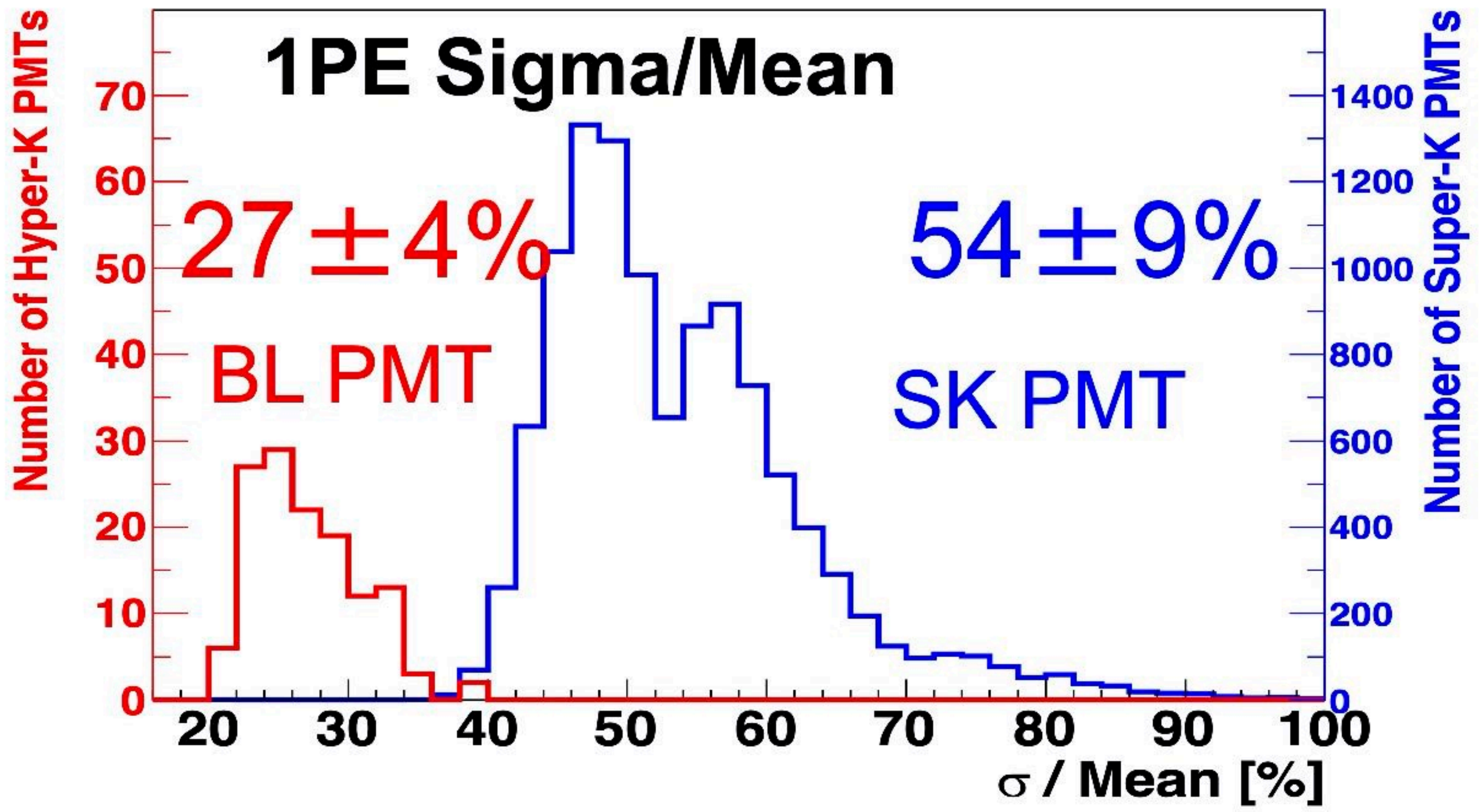
(Performance in SK tank, 1.7e7 gain)



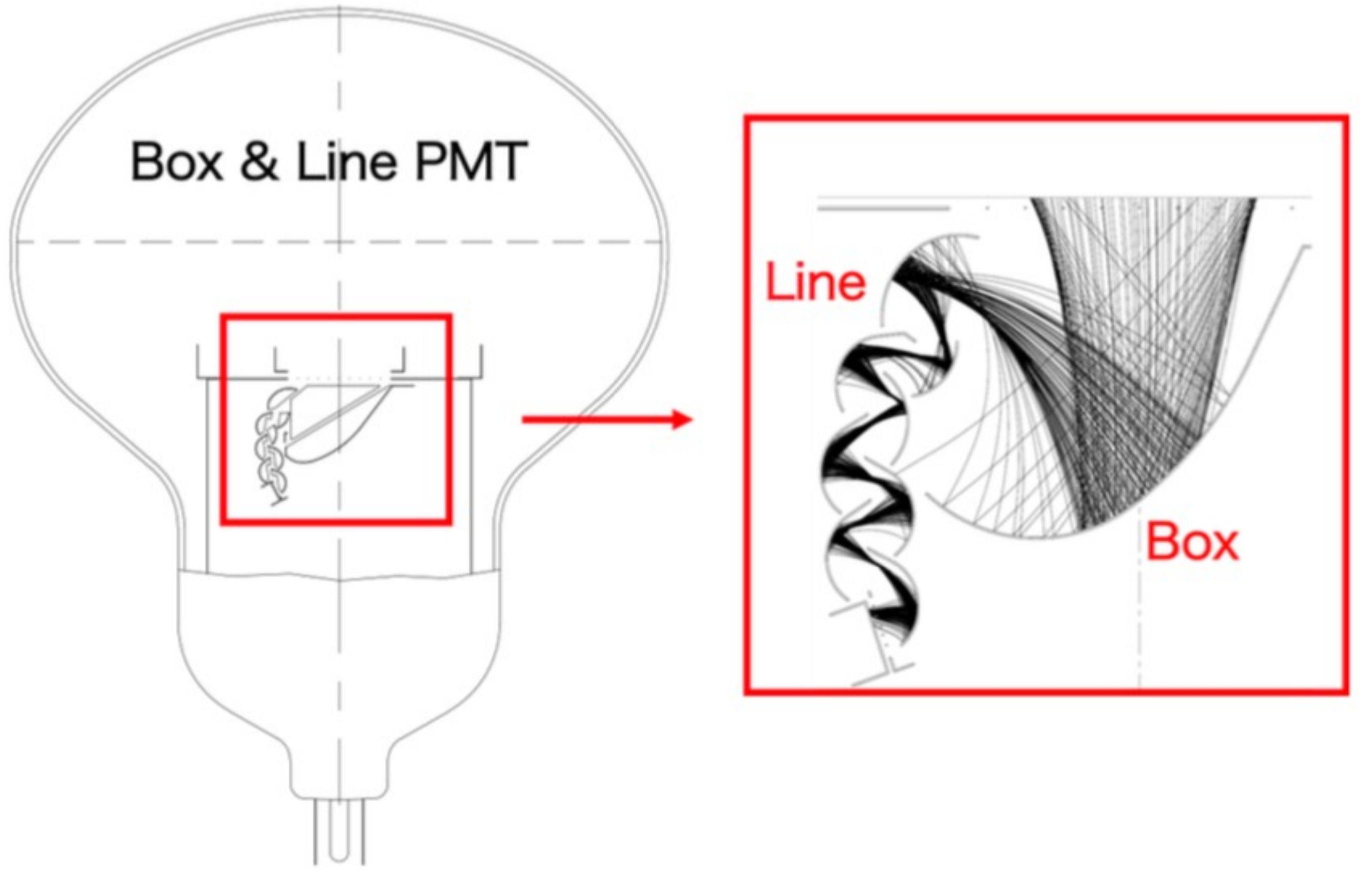
×2 better photodetection efficiency (QE×CE)



×2 better charge resolution



Box&Line dynode

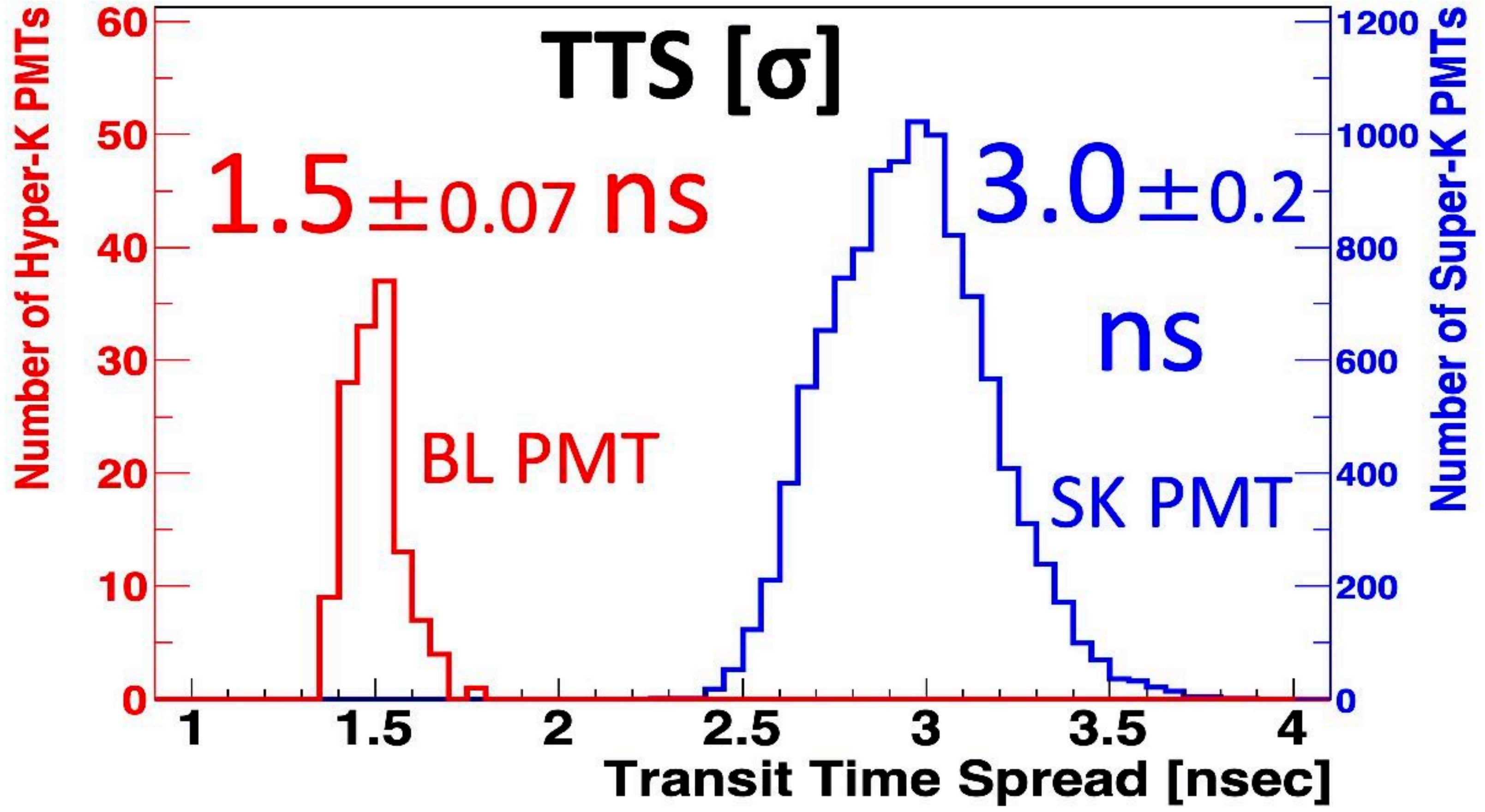


×2 better pressure tolerance
→ enable deeper tank design, project cost reduction

All PMTs will be tested >0.85MPa

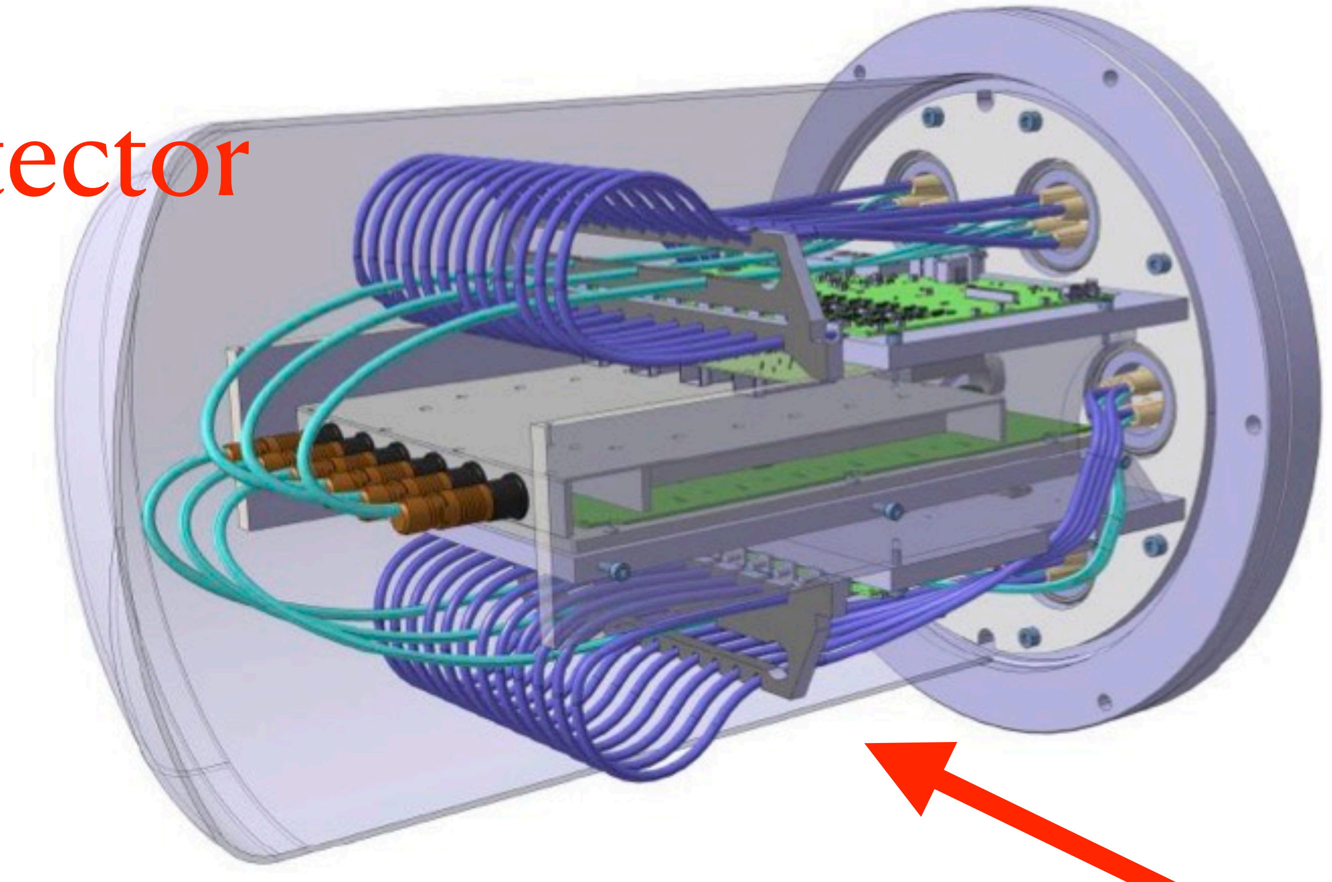
Low dark rate (4kHz) and RI

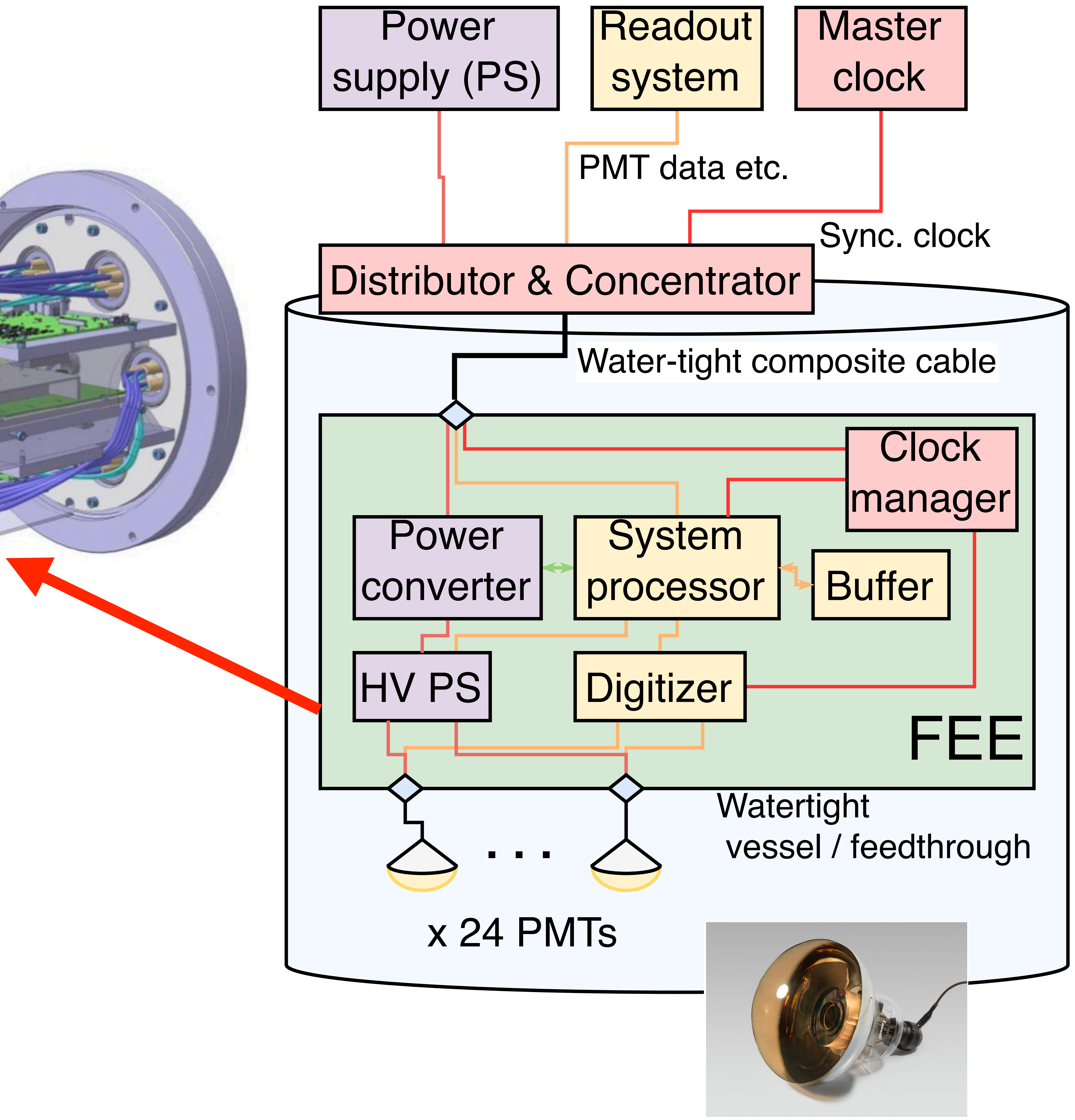
×2 better timing resolution



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





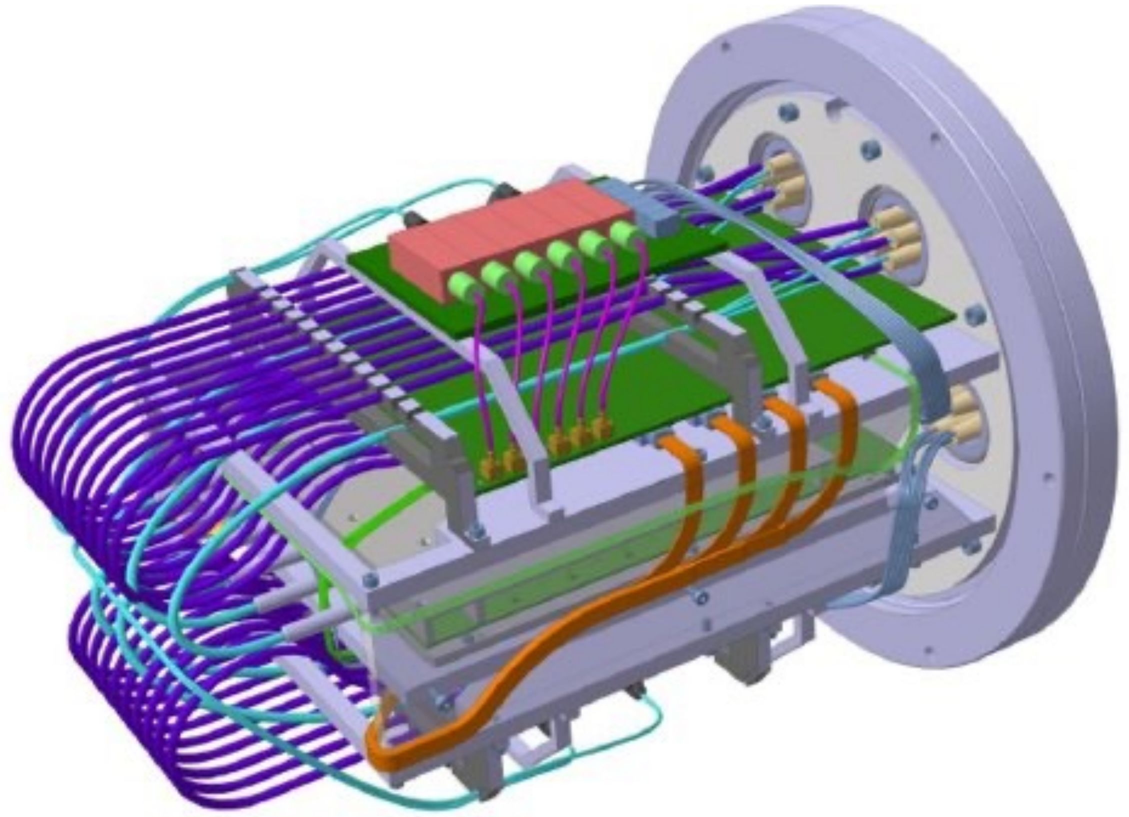
Detector component (some production starting)

PMTs

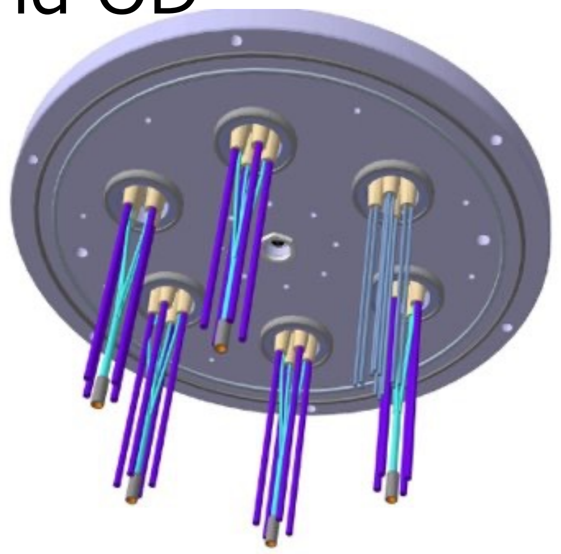
ID mockup

Underwater electronics:

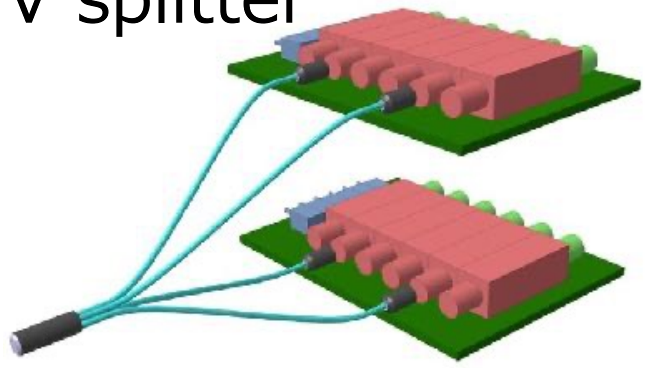
20 x 50 cm ID PMTs + 12 x OD PMTs



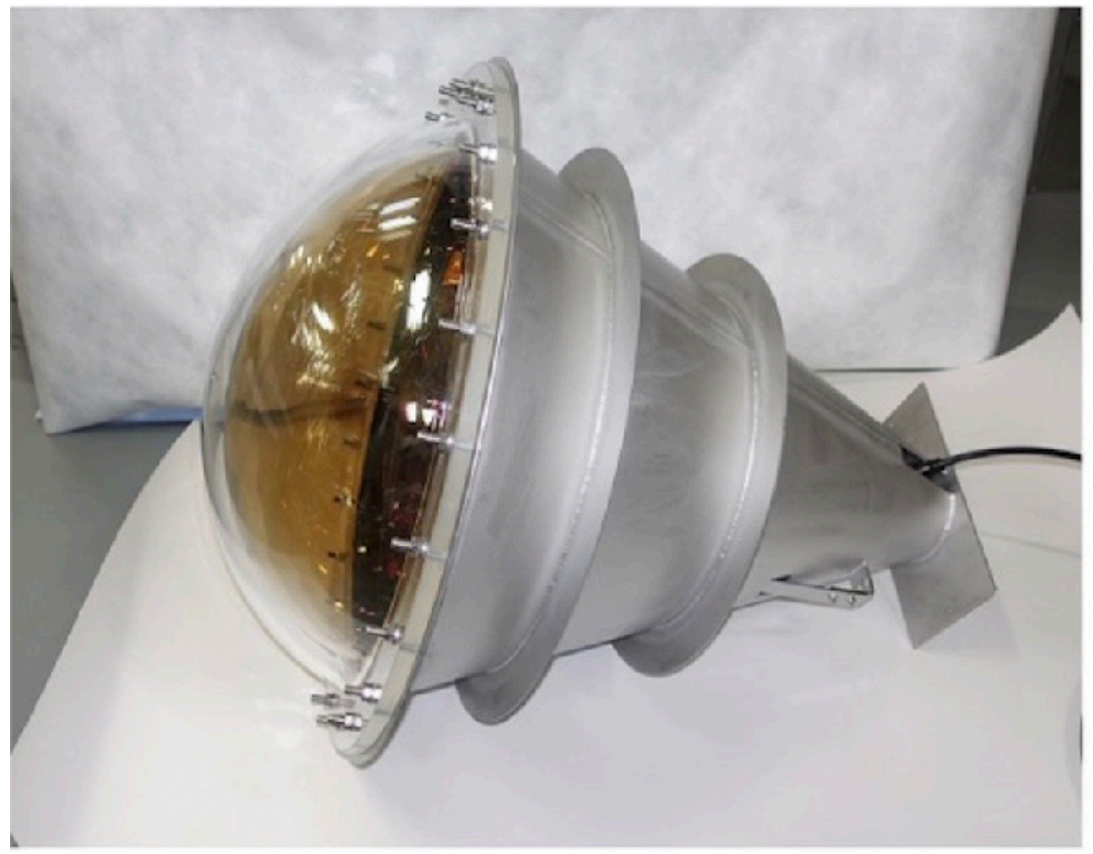
Feedthroughs
for ID and OD



OD signal +
HV splitter

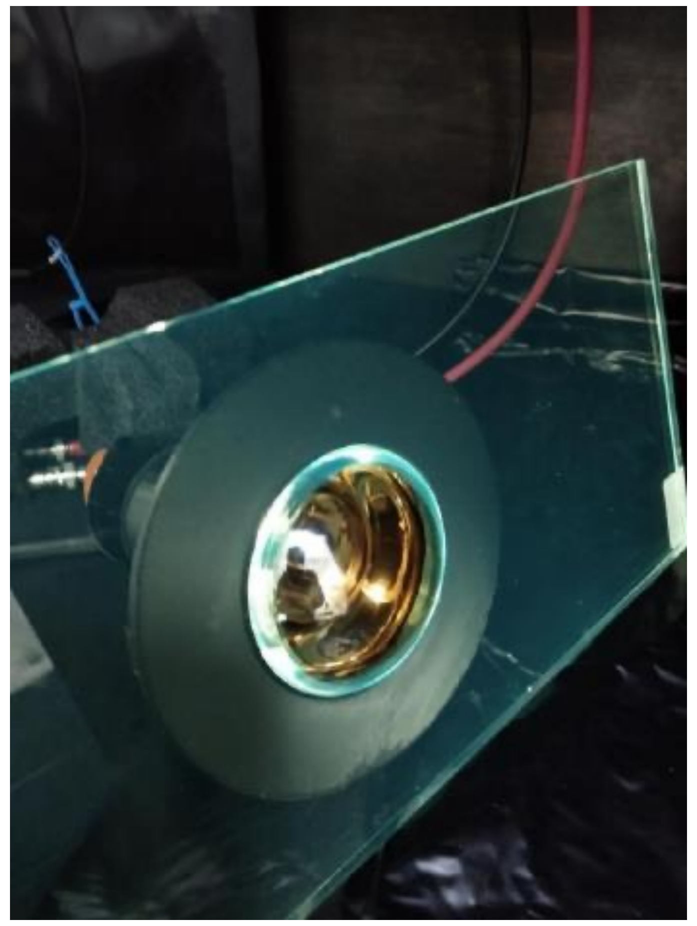


PMT cover



Multi-PMT module:

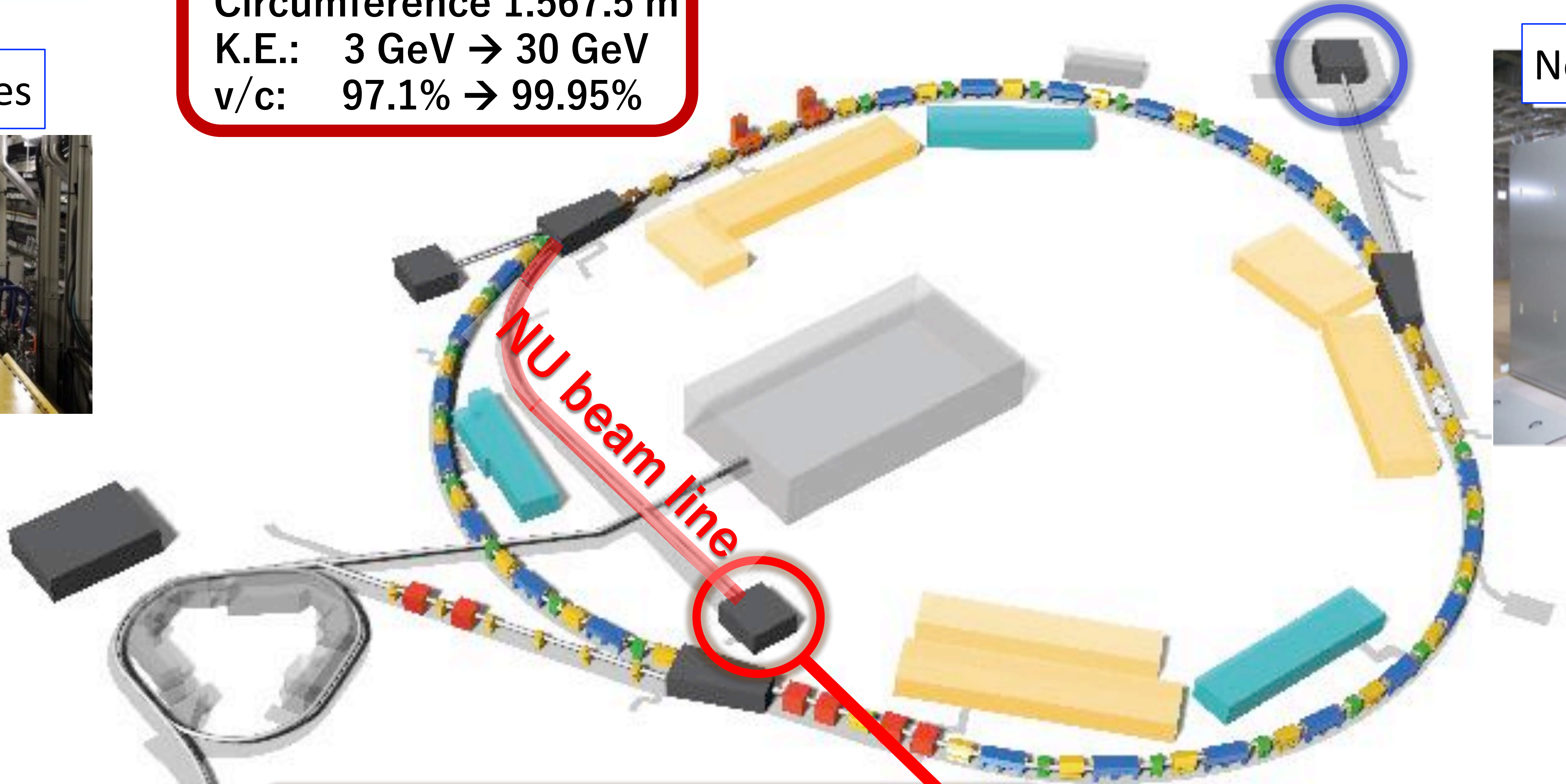
Outer detector: PMT+WLS plate



J-PARC Upgrade

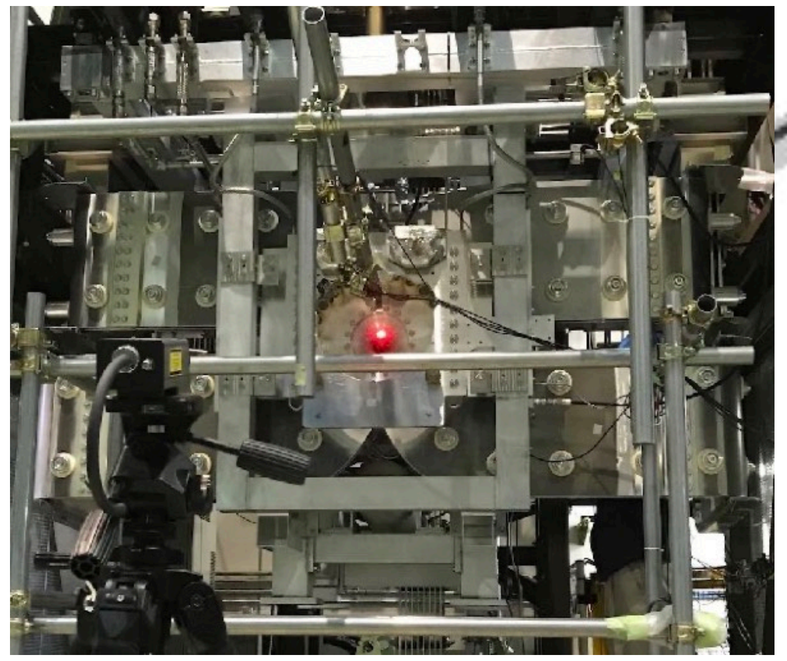
MR-RF cavities

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

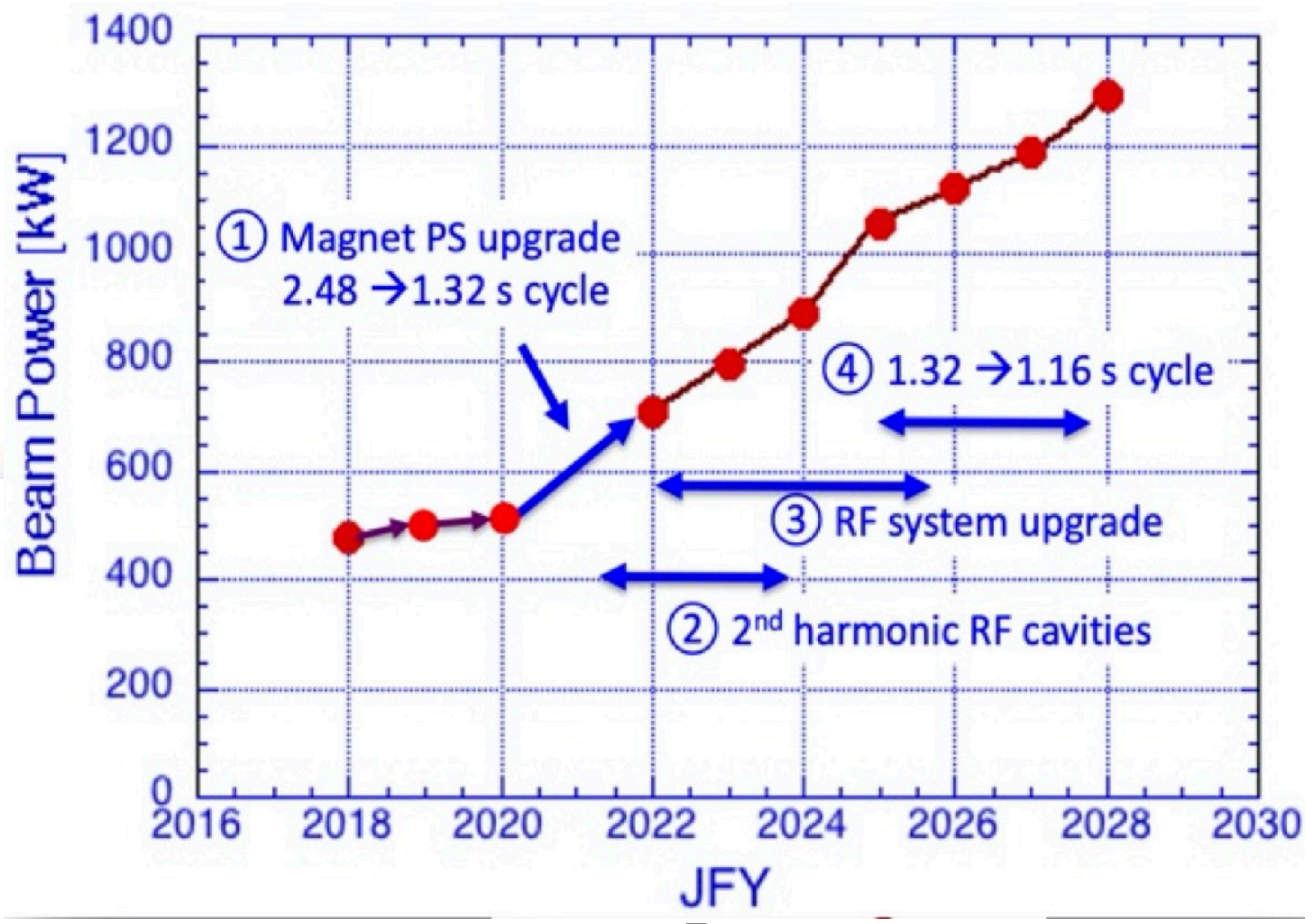
320kA horn operation



Neutrino Exp. Facility

Neutrino beam
Anti-neutrino beam

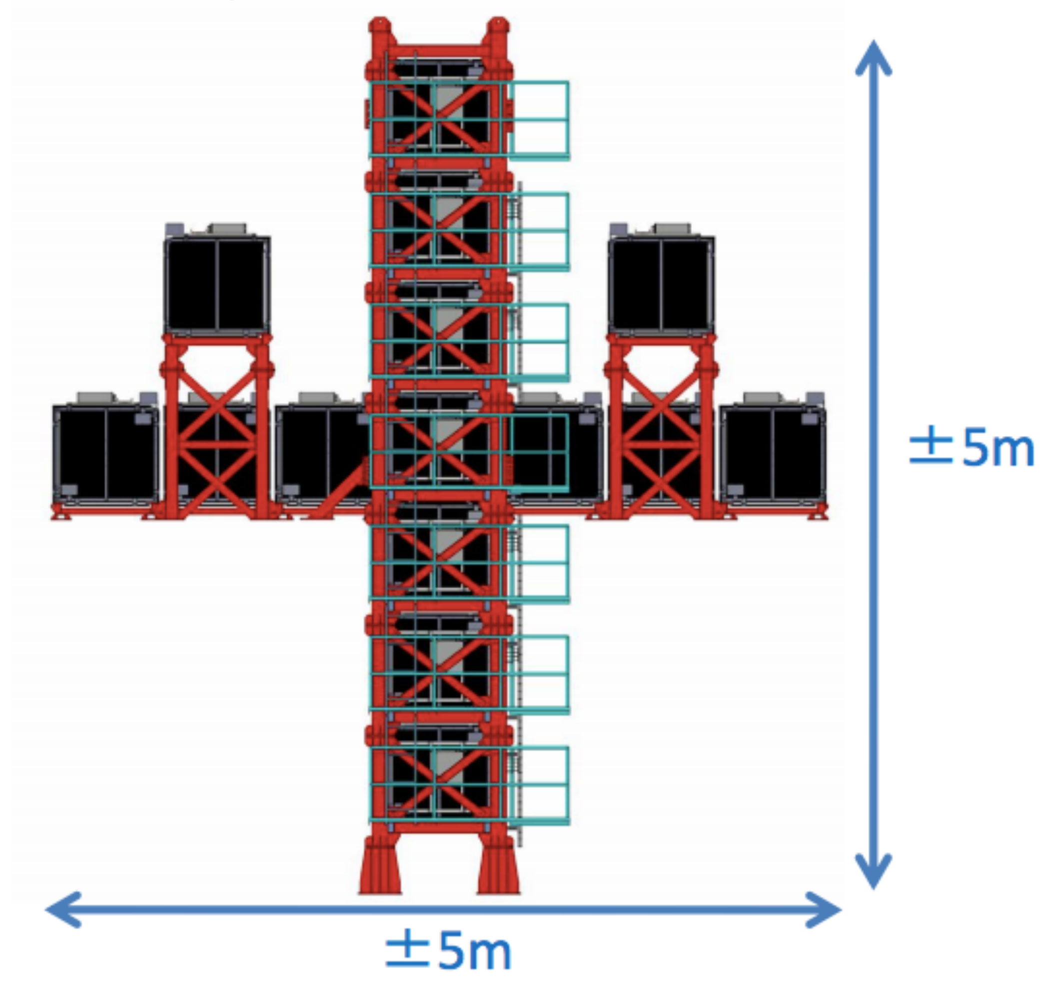
Achieved 515 kW in JFY2020
Aiming 1.3 MW by JFY2028



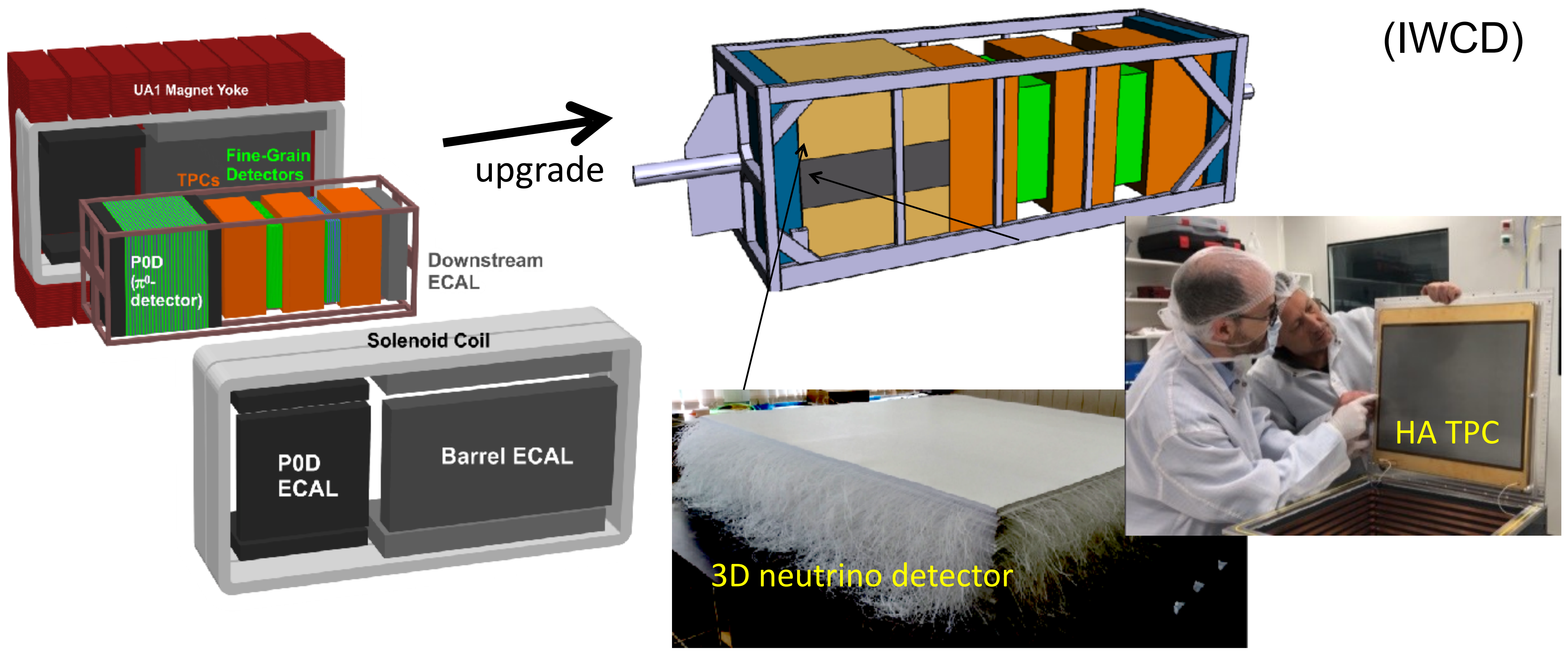
Neutrino detectors at J-PARC

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

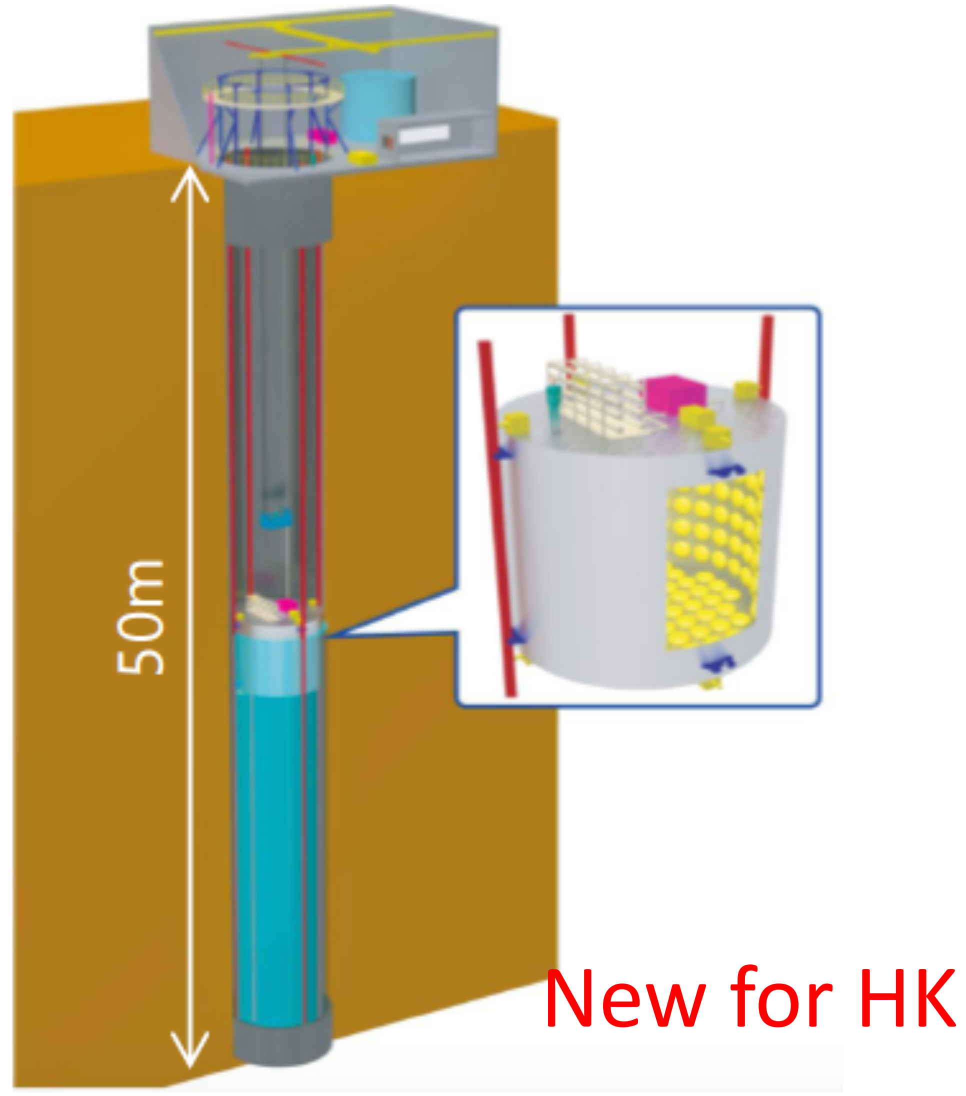
On-axis Detector
(INGRID)



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



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)



- 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

Successful collaboration with US

- There is long and successful US-Japan partnership
  - **Merged IMB and Kamiokande forces on Super-K and we also collaborated on K2K and T2K. US participation in SK and T2K is continuing.**
  - US contributions to SK, K2K and T2K:
    - outer detector
    - calibration
    - electronics
    - low energy trigger system
    - radon free air system
    - T2K near detector and horns
    - K2K near detectors and water system
  - (Successful collaboration in KamLAND, DONuT, and SciBooNE)

- US participation and leadership in the Hyper-K are truly welcome!

W.K.H Panofsky Prize in Experimental Particle Physics

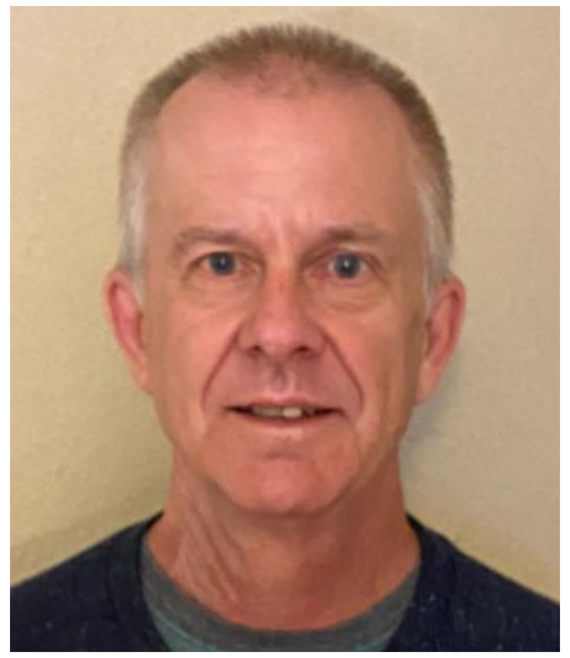
2021

Henry W Sobel
University of California, Irvine

Edward Kearns
Boston University

"For pioneering and leadership contributions to large underground experiments for the discovery of neutrino oscillations and sensitive searches for baryon number violation."

2022



Byron G Lundberg
Fermi National Accelerator Laboratory

Kimio Niwa
Nagoya University

Regina Abby Rameika
Fermi National Accelerator Laboratory

Vittorio Paolone
University of Pittsburgh

"For the first direct observation of the tau neutrino through its charged-current interactions in an emulsion detector."

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
- US-Japan partnership is essential!

Supplement