Moroccan Participation to the Hyper-Kamiokande Collaboration in Japan

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Outline

Brief overview on neutrino

- ✓ General introduction
- ✓ Oscillating neutrinos and the Universe

The Hyper-Kamiokande Experiment

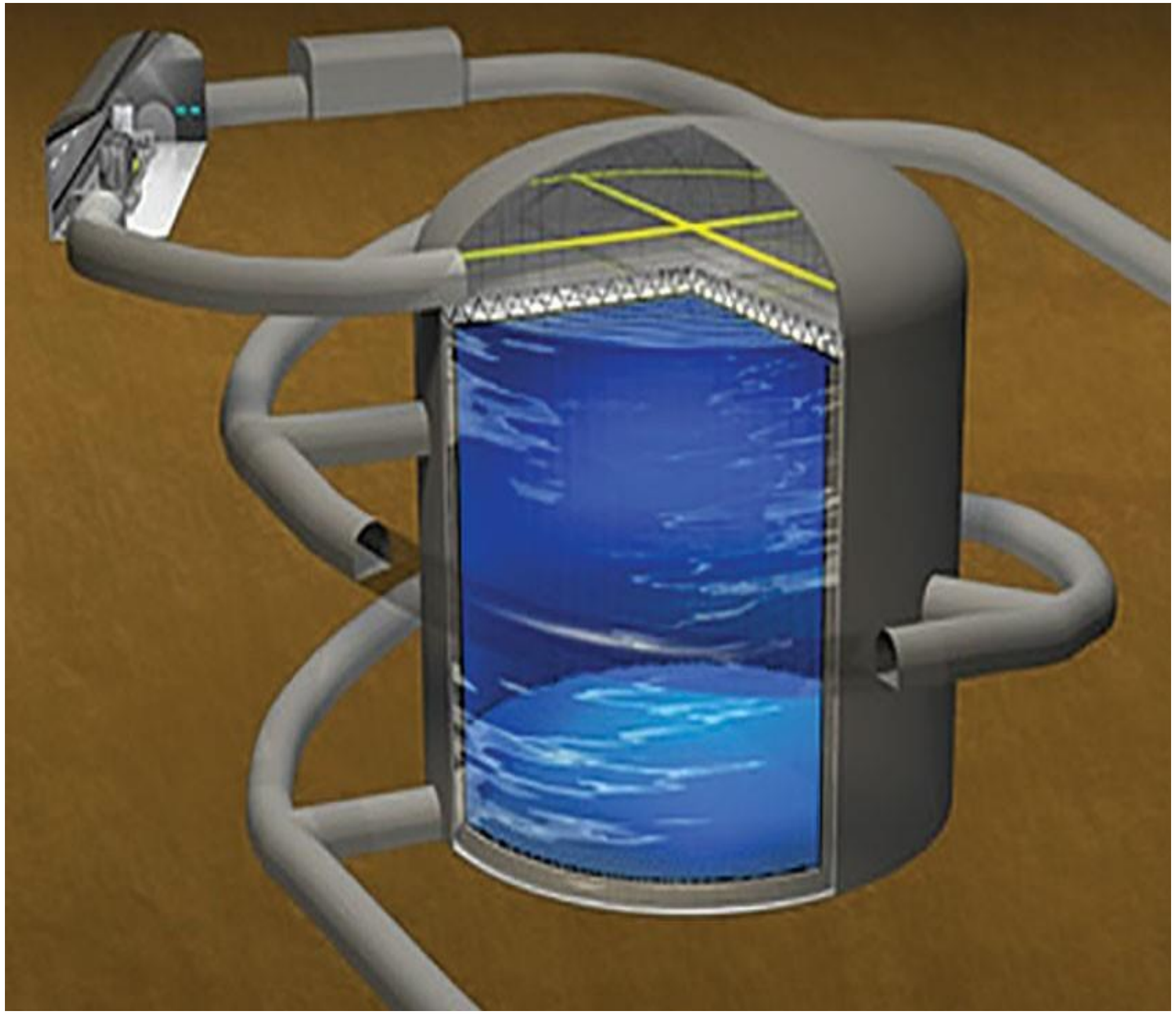
- ✓ Design overview
- ✓ Current status

Particle Physics

- ✓ Neutrino oscillation
- ✓ Proton Decay

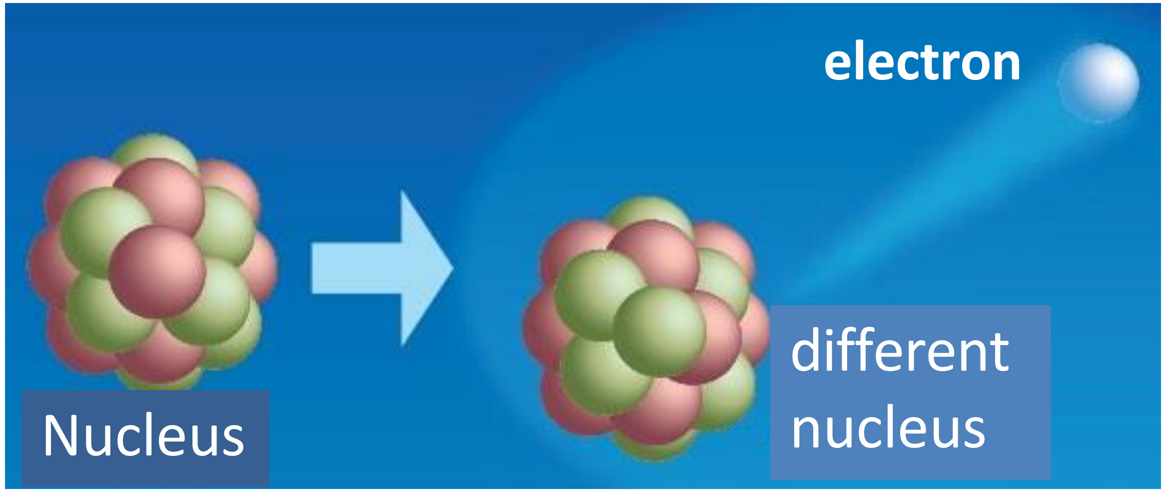
Moroccan Participation

- ✓ Detector Calibration
- ✓ Physics analysis program
- ✓ Software development



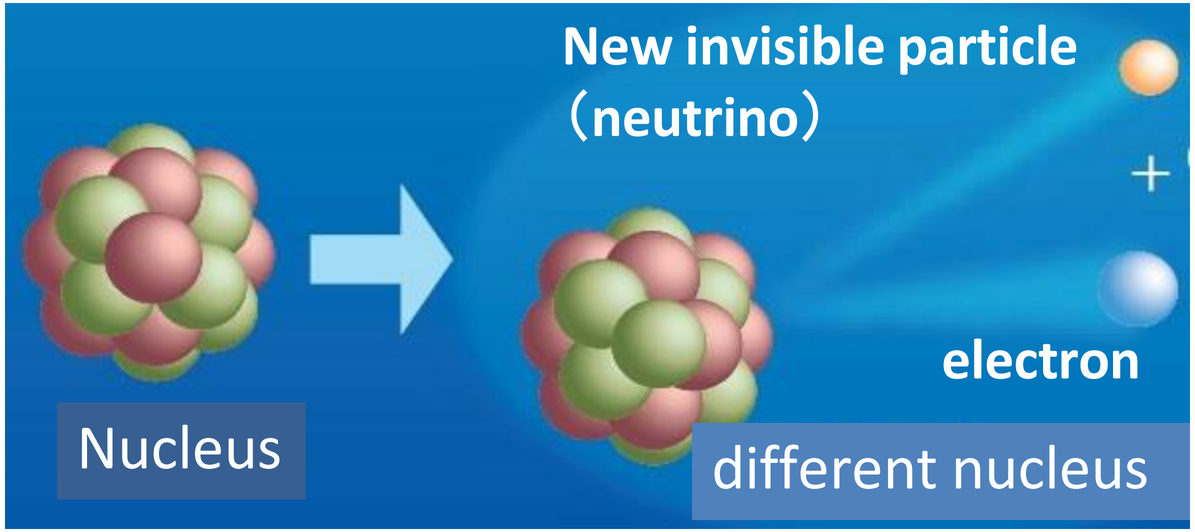
Initial hint for neutrinos

<u>Nuclear β decay (a nucleus change to a different nucleus by emitting an electron)</u>



In this case, the energy of the electron should be unique. But the observations suggested various or continuous electron energies....

(1930, W. Pauli)



What are neutrinos

Neutrinos;

- ✓ are fundamental particles like electrons and quarks,
- ✓ are something like electrons without electric charge,
- ✓ can easily pass through even the Earth, but can interact with matter very rarely,
- ✓ have, like the other particles, 3 types (flavors), namely
  electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and **tau-neutrinos (ν_τ),**

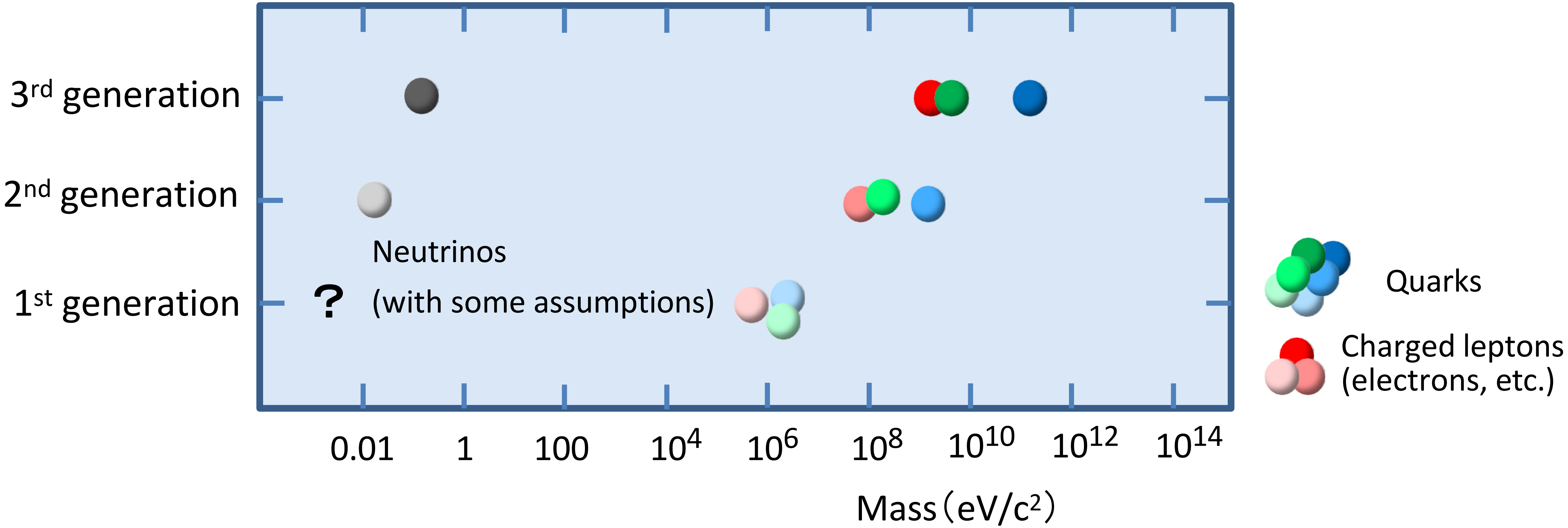
Electron-neutrino

Muon-neutrino
(or mu-neutrino)

Tau-neutrino

- ✓ have been assumed to have no mass.

Why are neutrinos so important?



The neutrino mass is approximately (or more than) 10 billion (10 orders of magnitude) smaller than the corresponding mass of quarks and charged leptons!
We believe this is the key to better understand elementary particles and the Universe.

A big mystery

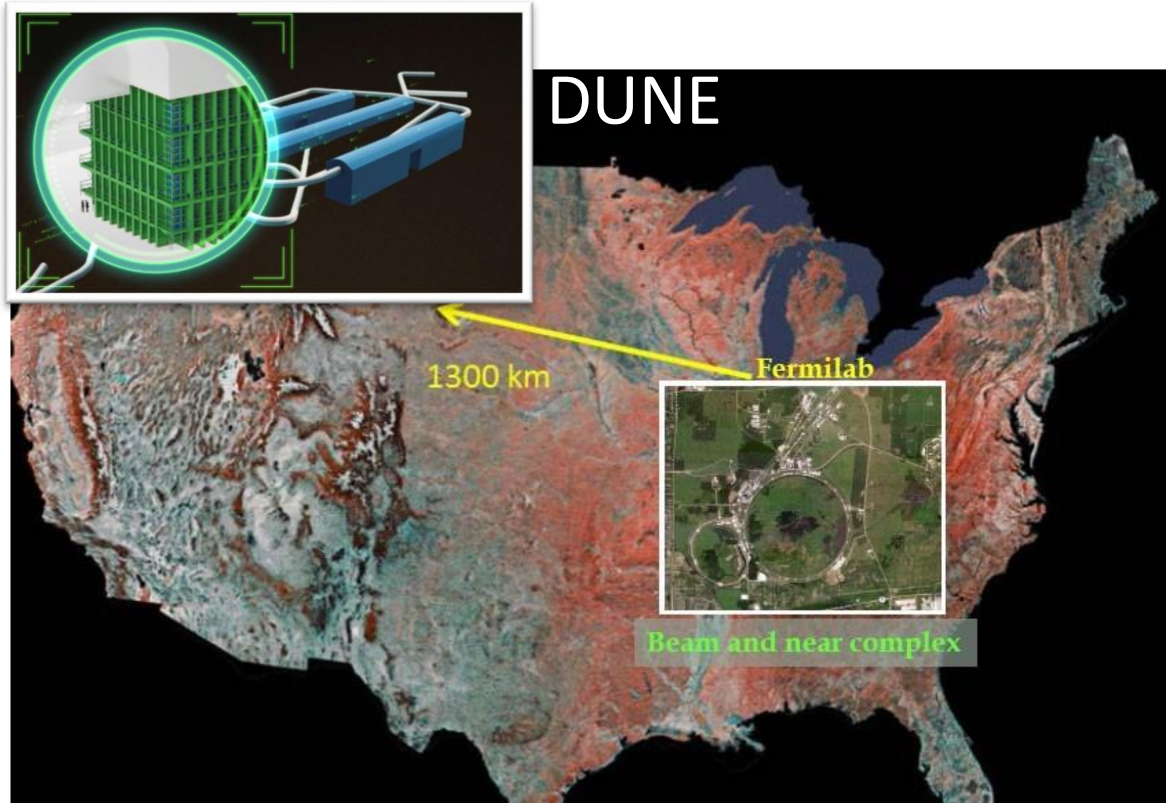
Big Bang (very hot universe) → Now

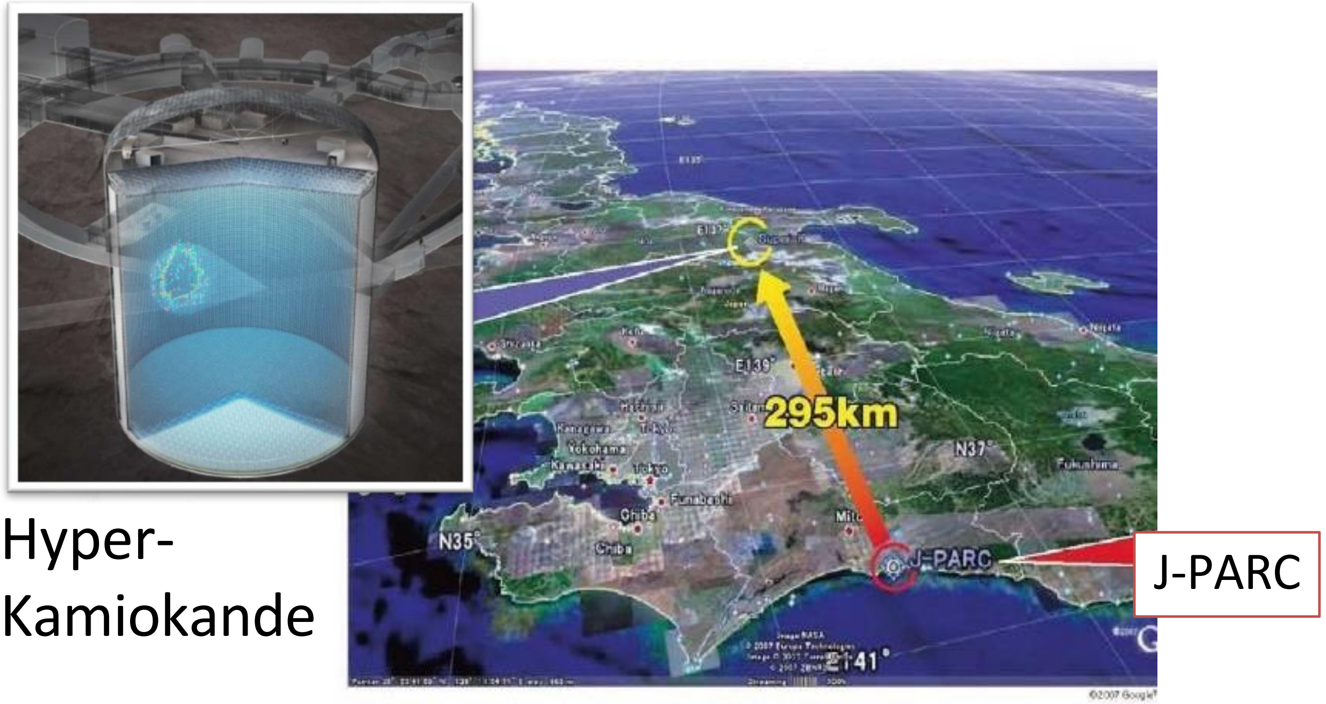
Number of protons (matter particles)		Number of anti-protons (anti-matter particles)		Number of protons (matter particles)
1,000,000,001	+	1,000,000,000	=	= 1

Neutrinos with very small mass might be the key to understand the big mystery of the matter in the Universe !

The future is exciting

- ✓ We would like to know if neutrinos are related to the origin of the matter in the Universe.
- ✓ We would like to observe if neutrino oscillations of neutrinos and those of anti-neutrinos are different. ➔ We need the next generation long baseline experiments with much higher performance neutrino detectors.



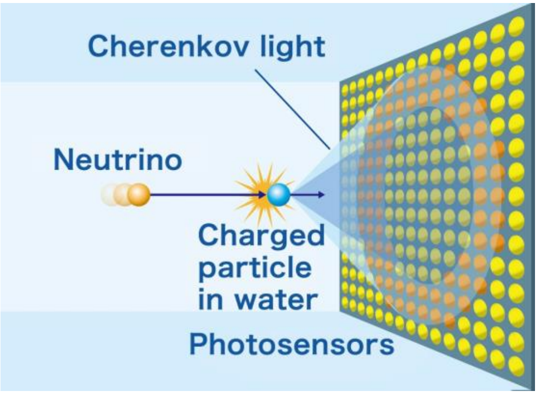


Hyper-Kamiokande

(Several other possibilities…)

Morocco in the Hyper-K project

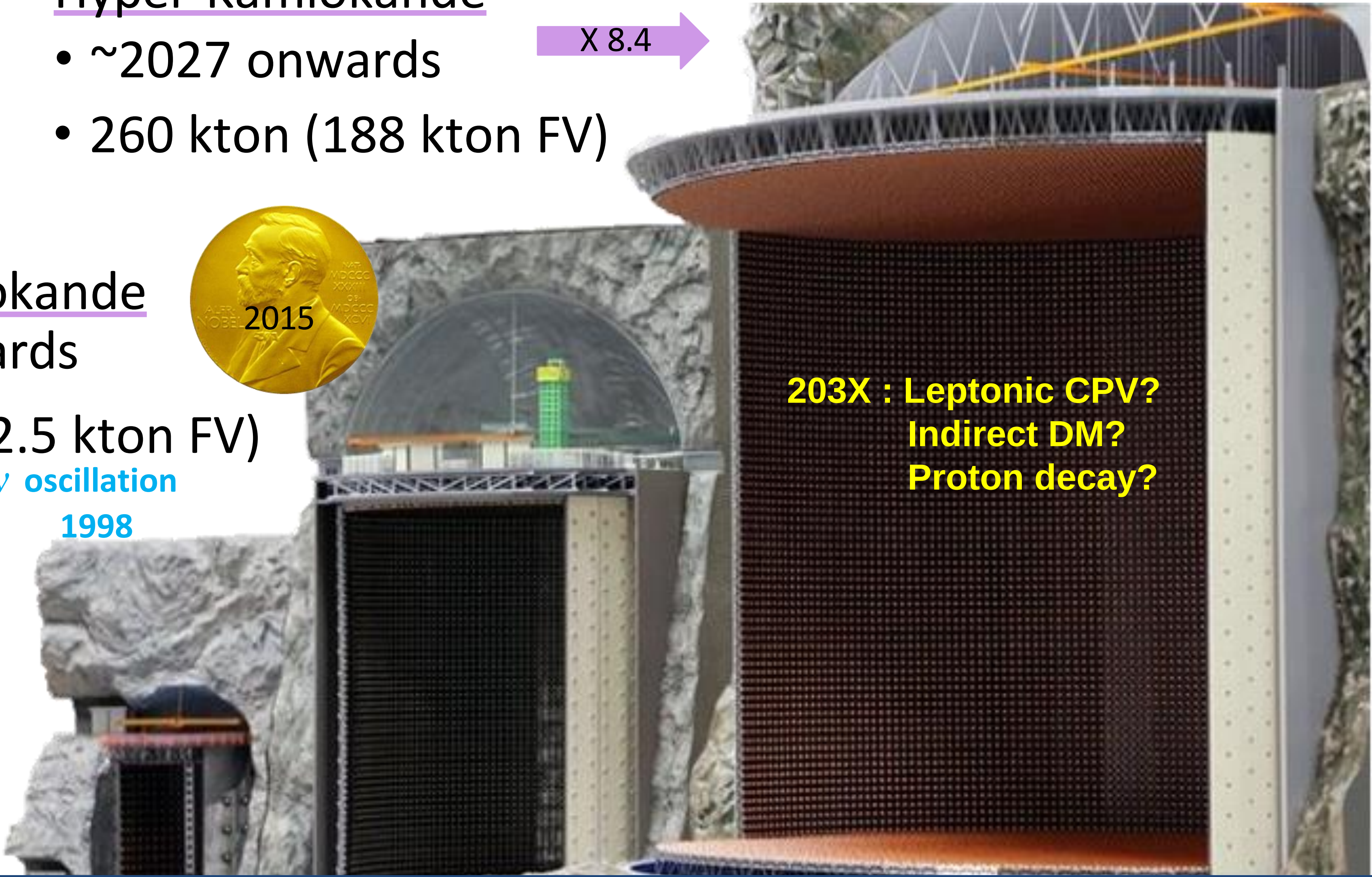
Kamioka Water Cherenkov Experiments



Hyper-Kamiokande

- ~2027 onwards
- 260 kton (188 kton FV)

X 8.4



Super-Kamiokande

2015

X 20

- 1996 onwards
- 50 kton (22.5 kton FV)

ν oscillation
1998

Kamiokande

- 1983 - 1996
- 3 kton

Supernova ν
1987

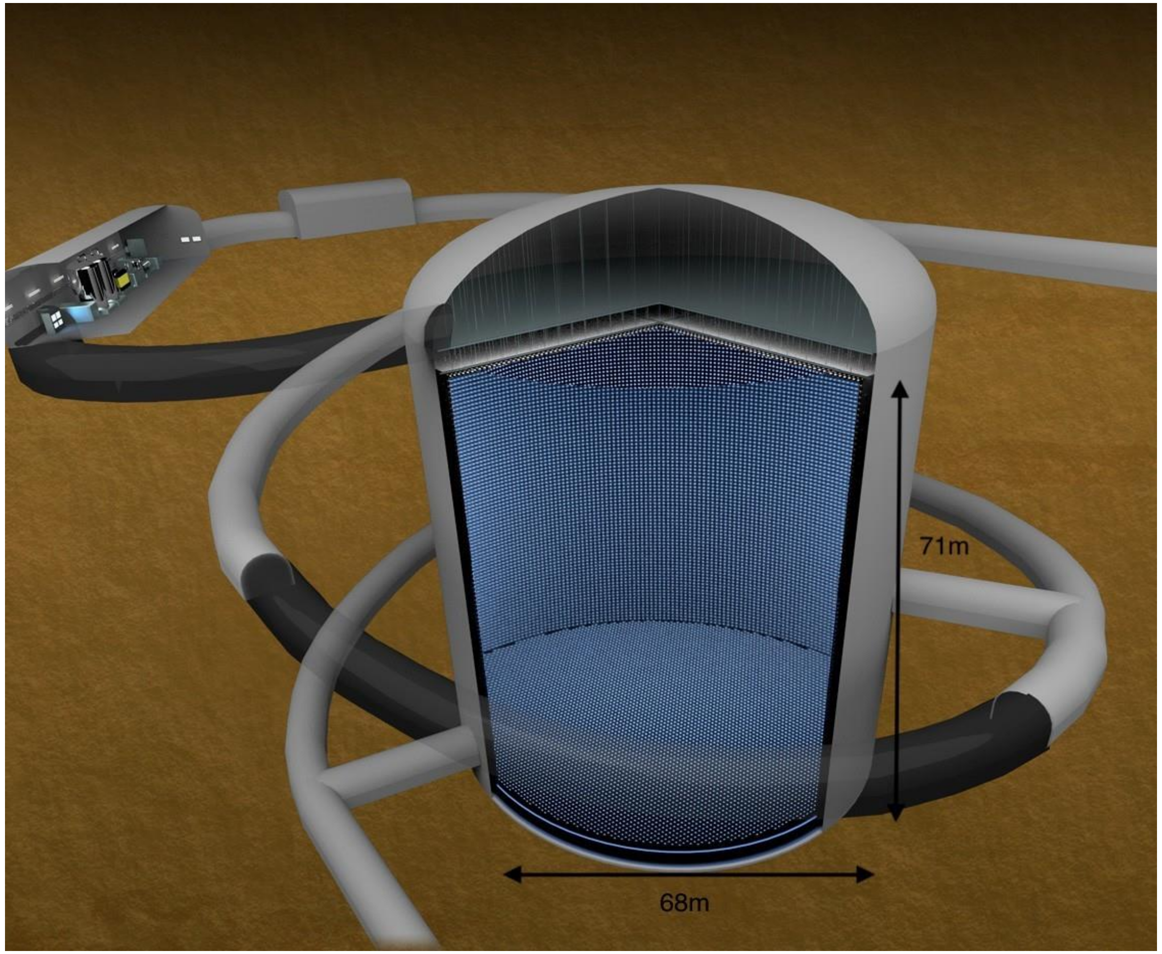
Kamioka Water Cherenkov Experiments

Location:

- ✓ Tochibora mine (Mt. Nijugoyama)
  650m overburden (1755 m.w.e.)

Size:

- ✓ 71m (height) x 68m (diameter)
  260 ktonnes total
  188 ktonnes fiducial

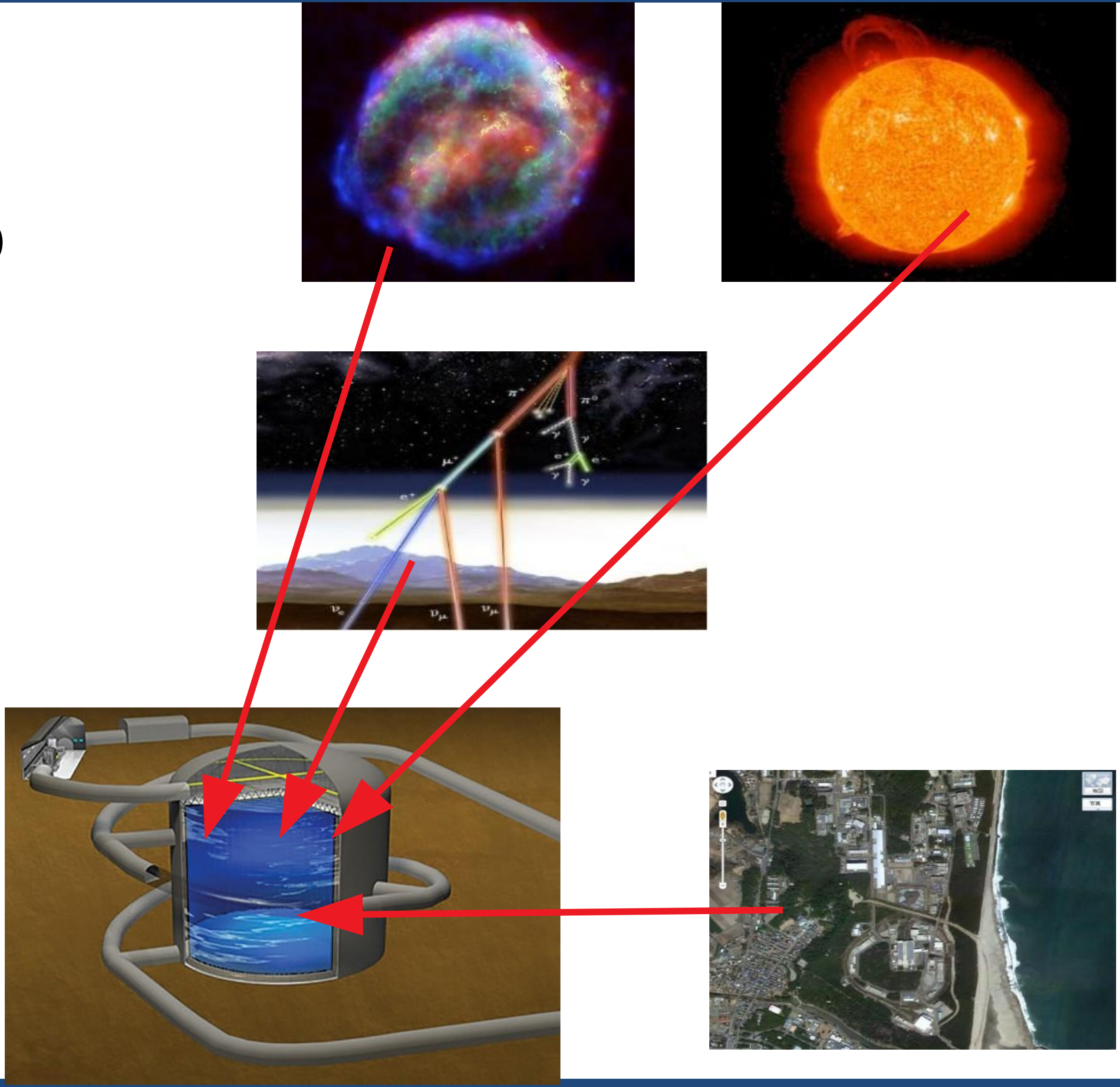


Photosensors:

- ✓ 20% photocathode coverage with new 50cm Hamamatsu 'box & line' PMTs
  - 1ns TTS; half that of SK PMTs
  - Quantum efficiency **double** that of SK PMTs.
- ✓ Supplemented by additional arrays of 3” multi-PMT (mPMT) assemblies

Broad physics programme

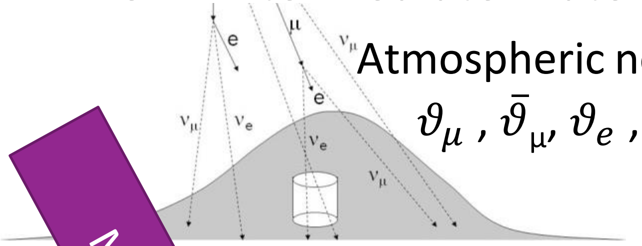
- ✓ **Neutrino oscillation**
  - Atmospheric neutrinos (still statistics limited!)
  - Accelerator neutrinos
    → focus on CP violation & mass ordering
  - Solar neutrinos
- ✓ **Proton decay**
- ✓ **Neutrino astrophysics**
  - Supernova burst
    O(10,000) events expected @ 10 kpc
  - Supernova relic neutrinos
- ✓ **Additional astrophysical topics**
  - Dark matter
    Indirect WIMP searches
  - Multimessenger astronomy
  - Gamma ray burst searches



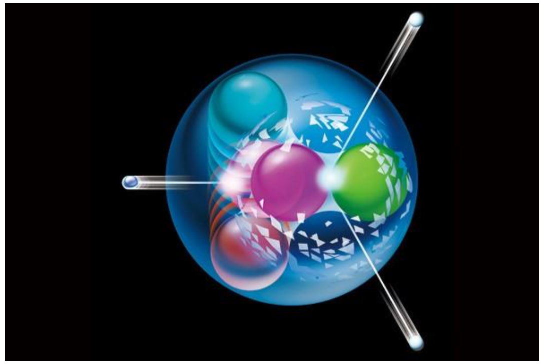
Hyper-Kamiokande : Other facilities

Much larger detector → significantly higher statistics → need better systematics

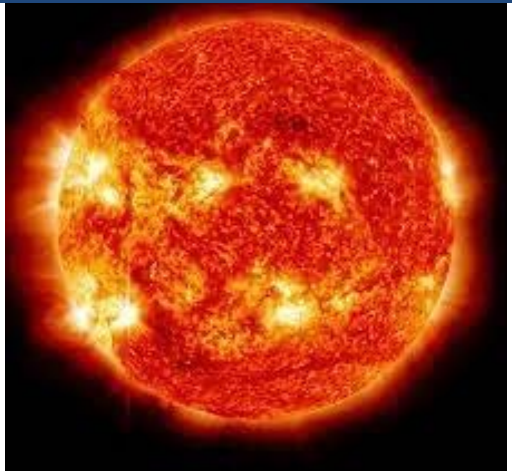
- Improved near detector (ND280) at Tokai
  New "Intermediate Water Cherenkov Detector"



Atmospheric neutrinos : ϑ_μ , $\bar{\vartheta}_\mu$, ϑ_e , $\bar{\vartheta}_e$



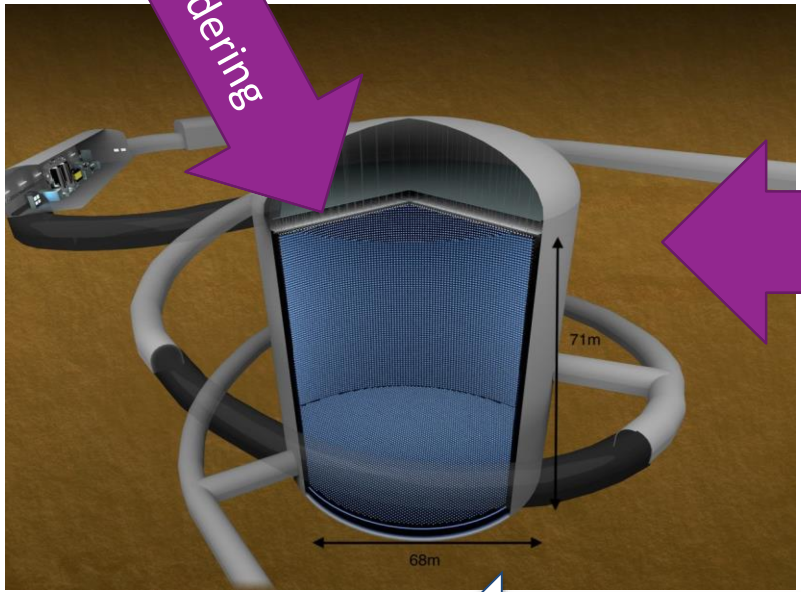
Proton Decay Search



Solar neutrinos, ϑ_e

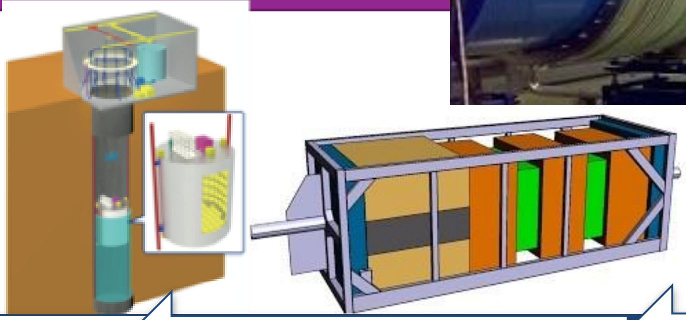
Supernova bursts
Diffuse Supernova Background Neutrinos

Mass Ordering



CP violation, oscillation parameters

J-PARC neutrino beam: ϑ_μ , $\bar{\vartheta}_\mu$



Near Detectors

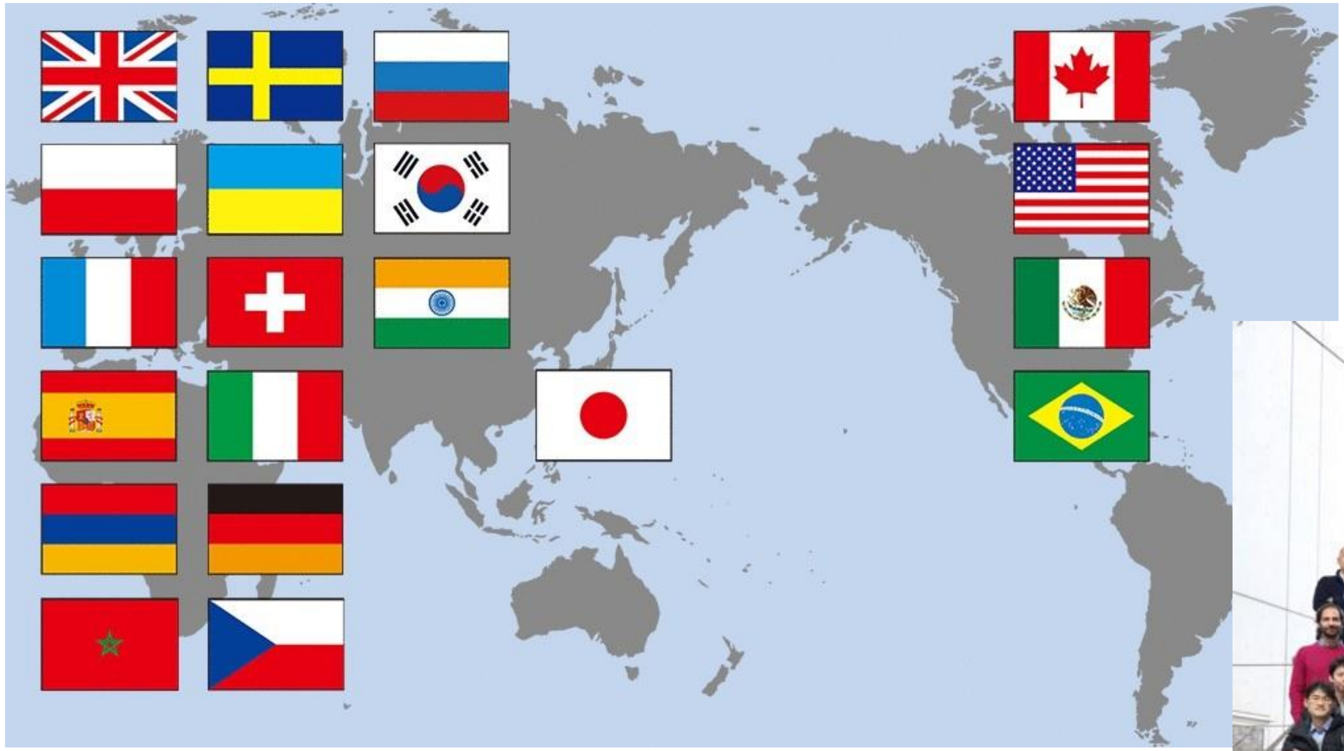
~ 295 km

~ 1 km

280 m

Hyper-Kamiokande Collaboration

~500 researchers, 99 institutions from 20 different countries



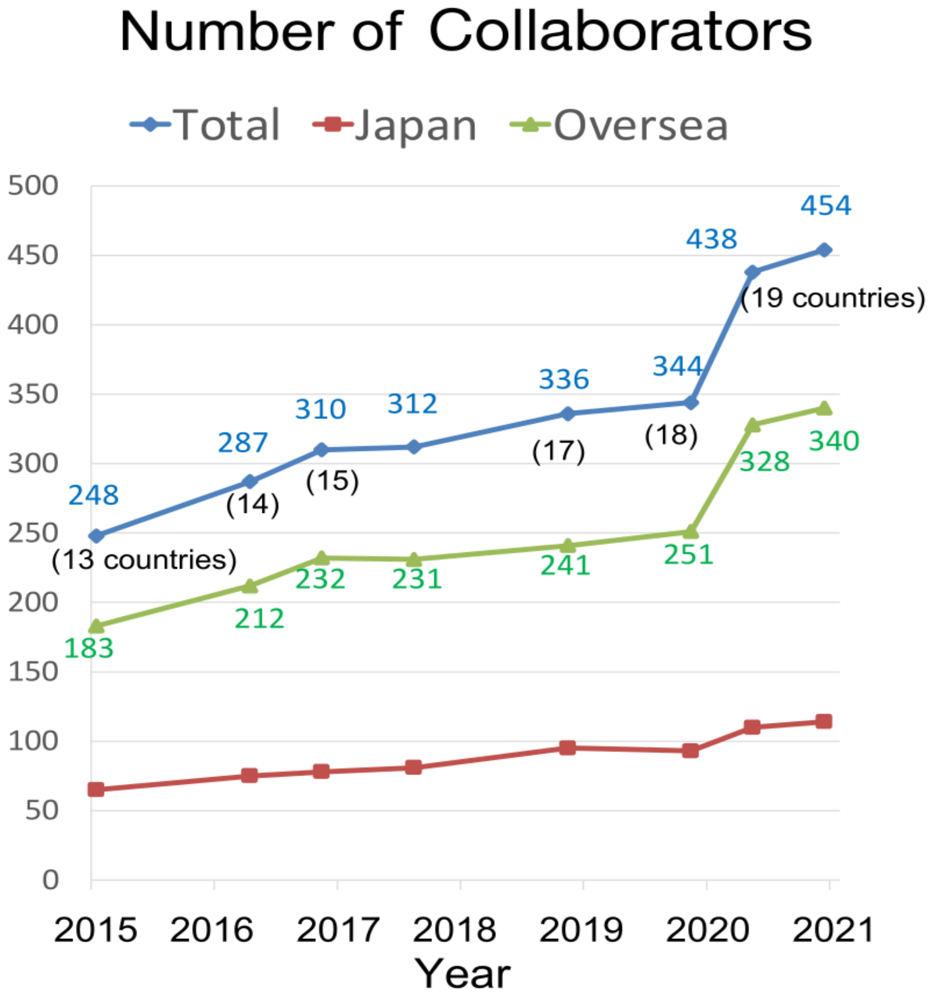
Last in-person meeting

February 2020

Hyper-Kamiokande Collaboration

~500 researchers, 99 institutions from 20 different countries

Morocco is the only country from the African continent



Four Universities : Mohammed VI (UM6P), Hassan II (UH2), Mohammed V (UM5) and Ibn-Tofail (UIT)

Timeline

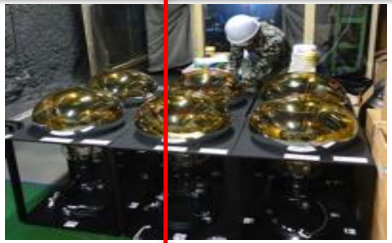
Today

2020	2021	2022	2023	2024	2025	2026	2027 and beyond

MOU signed, May 2020

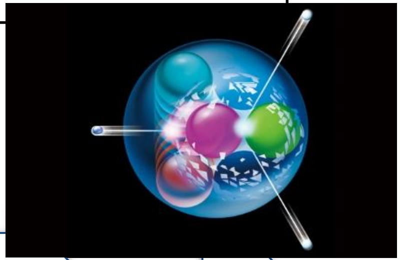
Tunnel construction → Cavern excavation → Tank construction → PMT installation

PMT production → Commissioning



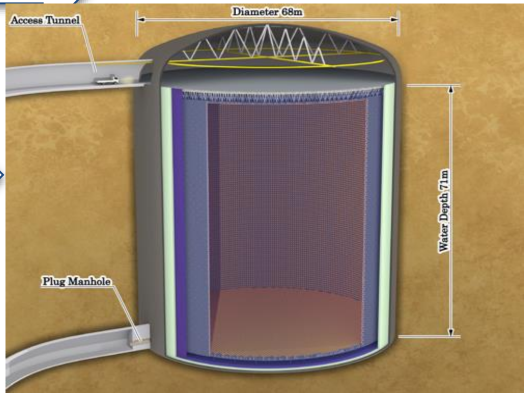
Water system → Water filling

Start of Hyper-K operation



Near & intermediate detector R&D, facility, production → Construction

Beam upgrade for > 750 kW → Beam upgrade for 1.3 MW

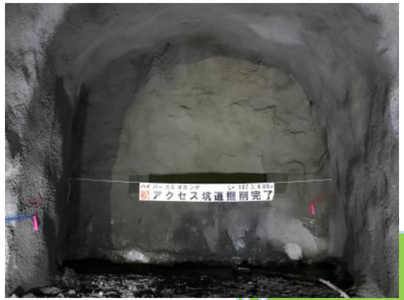


Project Status

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027

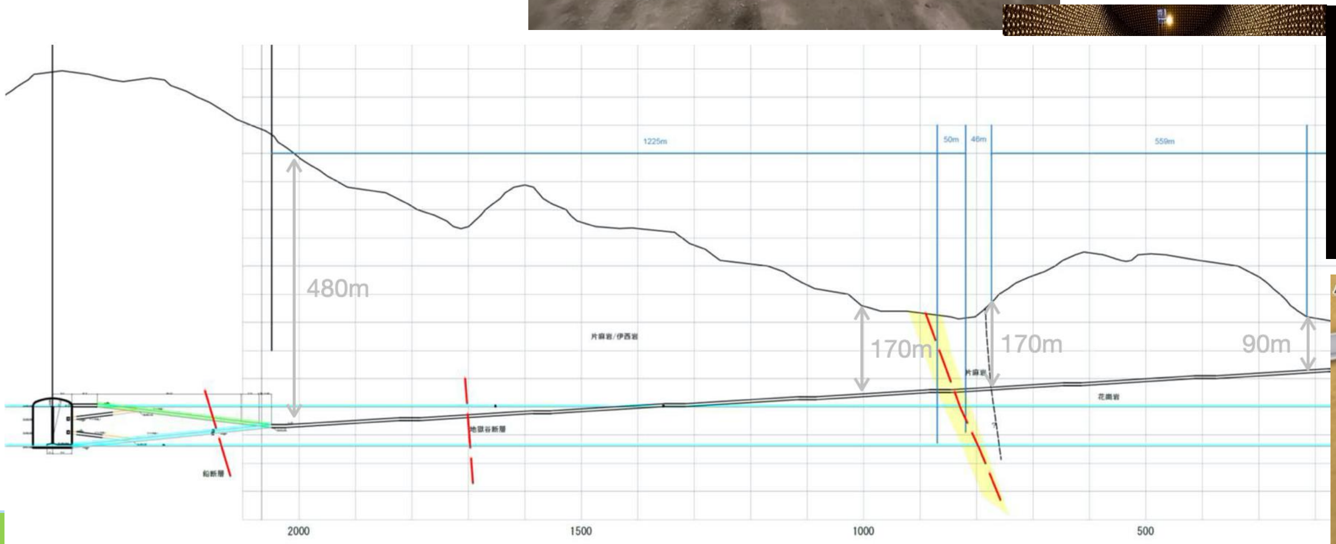
MOU signed, May 2020

Ground-breaking May 2021



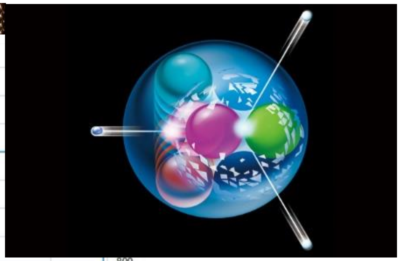
Access tunnel complete, Feb 2022

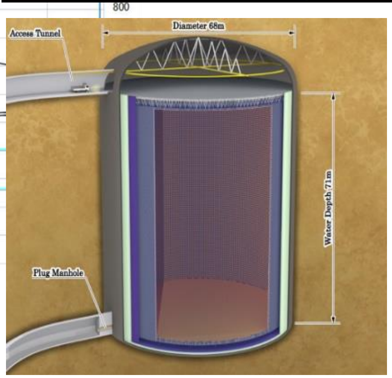
Approach and Peripheral tunnels, Summer 2022



PMT production

Operation starts 2027





Moroccan Participation : Tasks

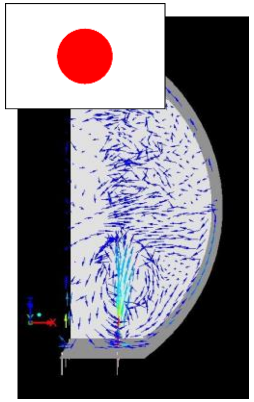
- ✓ The Moroccan contribution focus in three main parts : Detector Calibration, Physics analysis (algorithms developments) and the computing Grid.

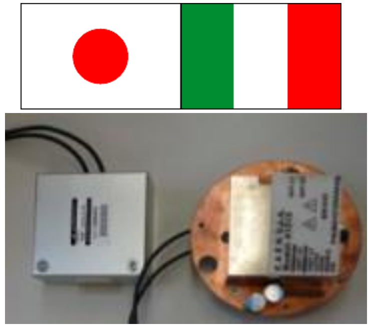
- ✓ Far detector calibration tasks:
  - D-T Generator
  - Source deployment system
  - Pre-calibration of photosensors

- ✓ Physics analysis : Three analysis already started at Kénitra : CPV in leptonic sector in collaboration with LSU (USA), Proton decay and atmospheric bkg

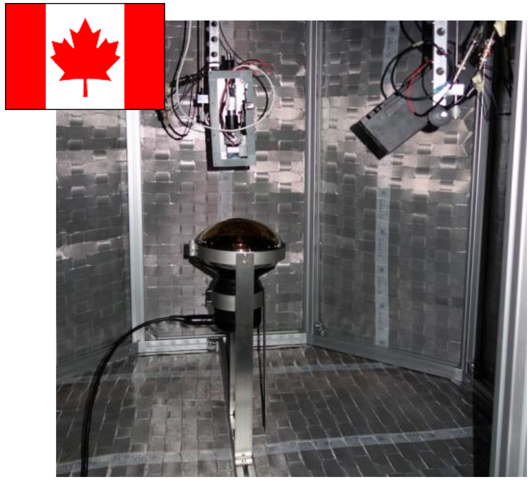
- ✓ The computing contribution :
  - Participate to the Hyper-K software development
  - Start with a Tier-3 at Ibn-Tofail University, Kénitra
  - With aim to have a Tier-2 at Toubkal HPC in UM6P, Ben-Guerir

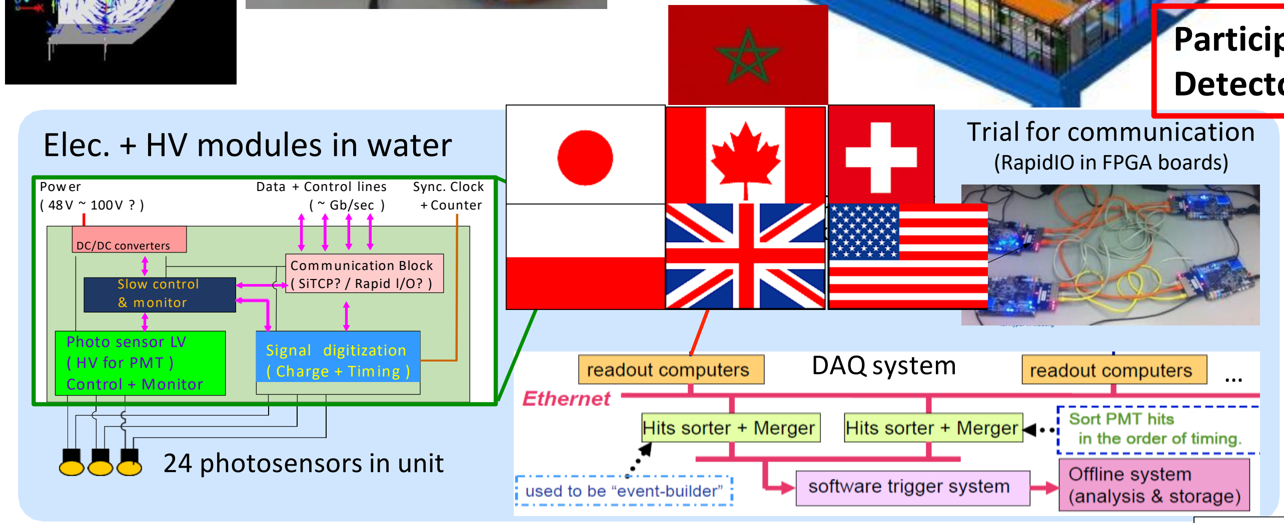
R&D : Moroccan Participation (construction phase)



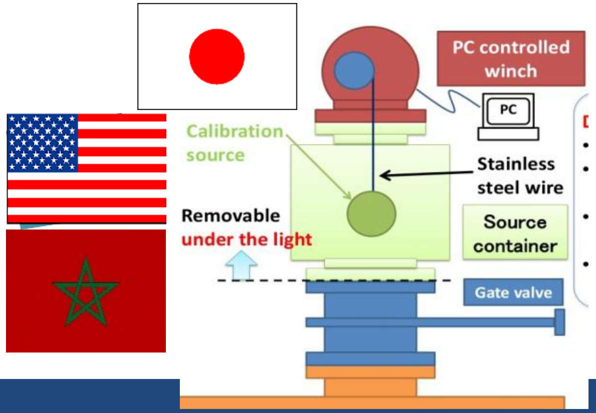


Participate to the TDAQ :
Detector Control System (DCS)

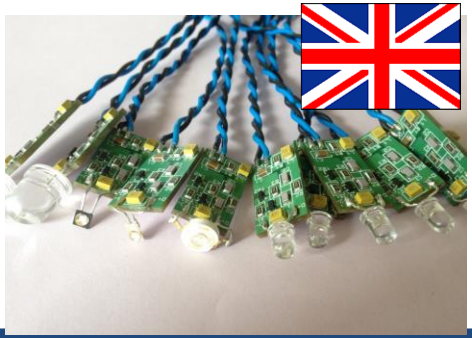




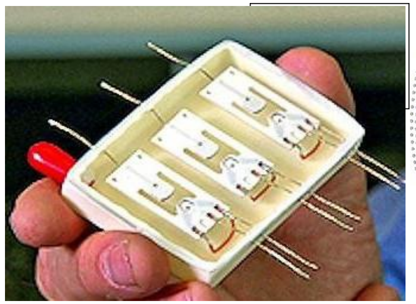
Two systems : DT-Generator
Deployement system



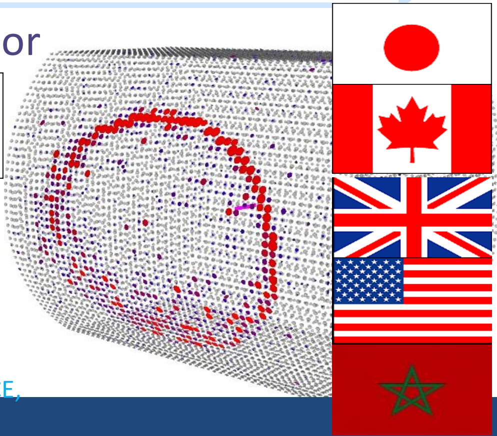
LED



Compact neutron generator



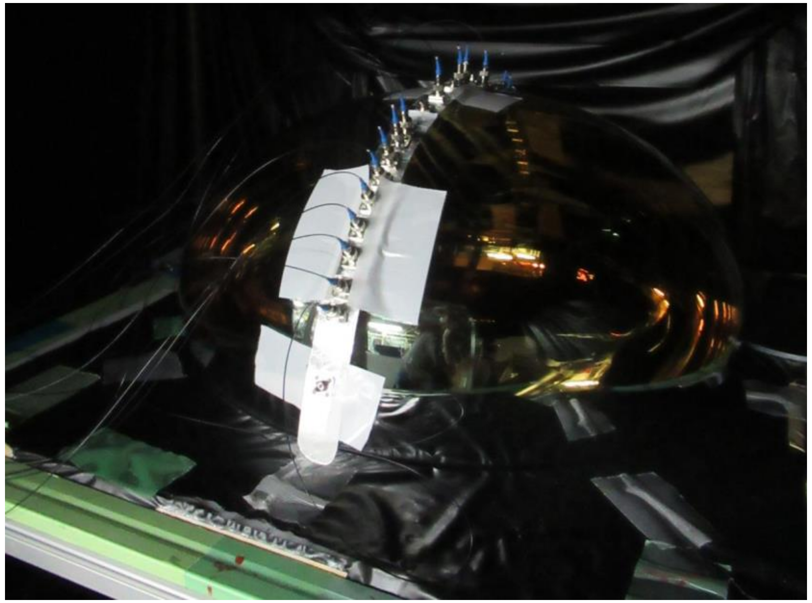
IEEE TRANSACTIONS ON PLASMA SCIENCE,
VOL. 40, NO. 9, SEPTEMBER 2012



Grid computing : Tier 2 in Morocco
Develop the analysis software

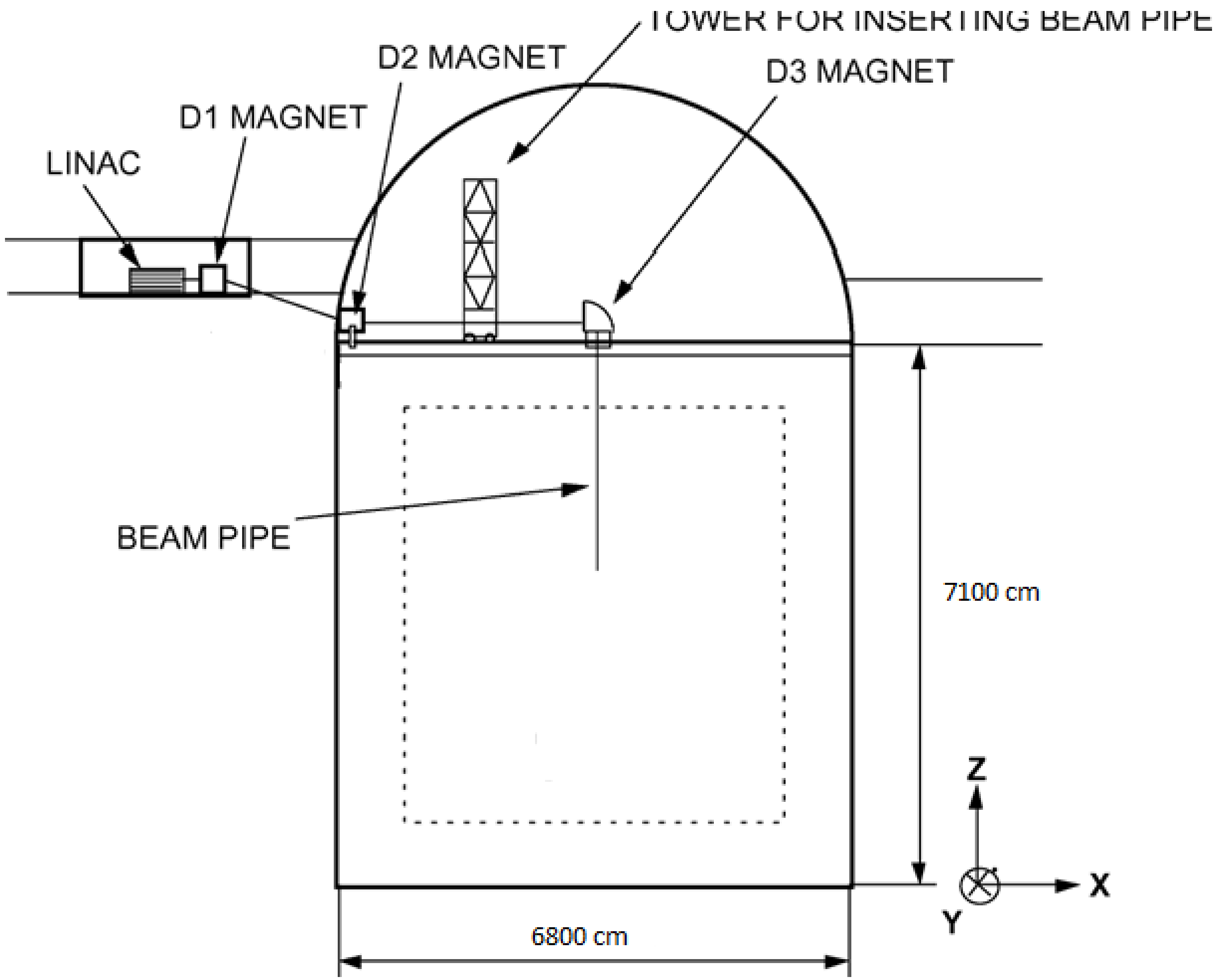
Pre-Calibration of PMTs

- ✓ Ex-situ calibration (Before the installation)
- ✓ All PMTs will go through basic set of tests (will take 6 months).
- ✓ 2% of the PMTs will go through a more detailed characterization programme, and will be distributed uniformly in the detector.
- ✓ Tests will be done in special dark rooms: the Photosensors Test Facilities (PTFs).

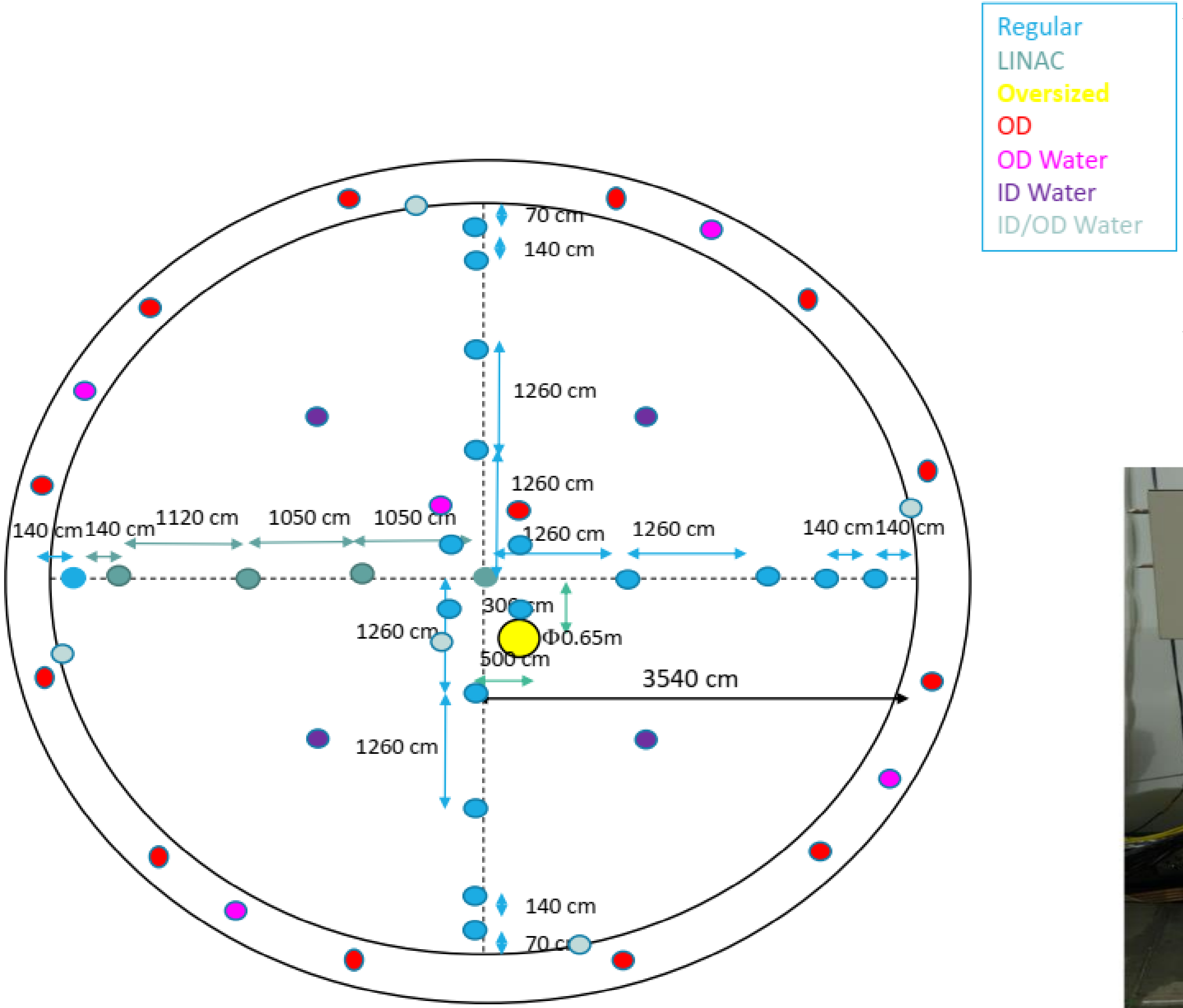


LINAC

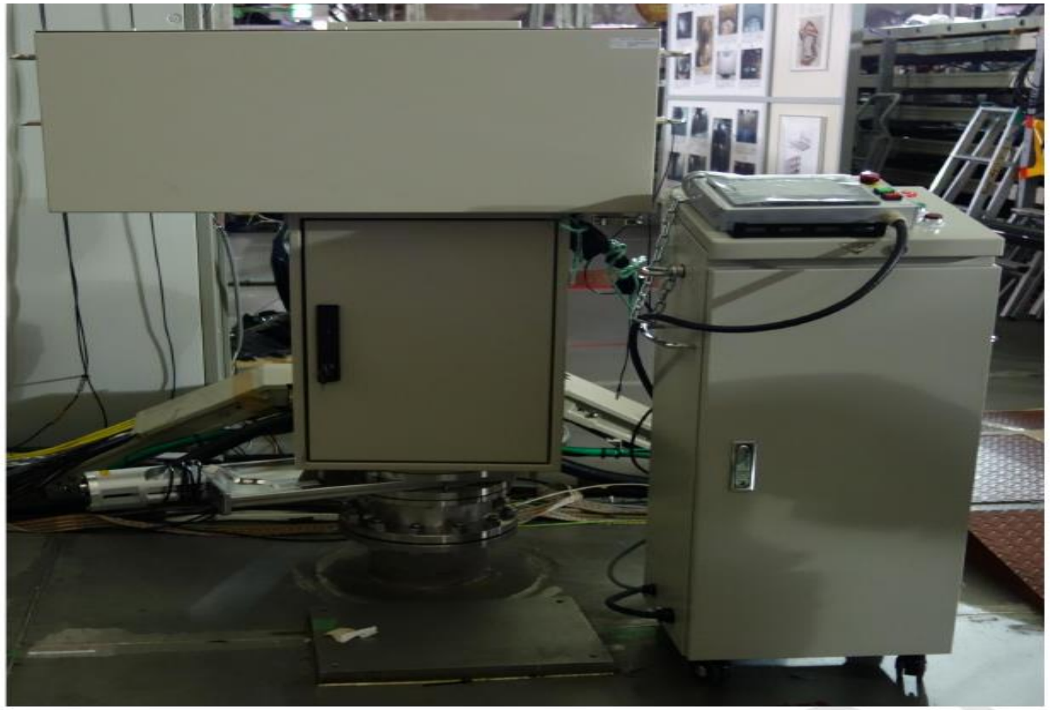
- ✓ Used to calibrate the energy scale for low energy physics.
- ✓ Delivers a low energy electron beam at periodical intervals (7 energies and 9 positions for SK).
- ✓ Uncertainties of 0.2-0.3% in the low energy scale and of 2% in the energy resolution are desirable.
- ✓ In SK the LINAC calibration was required, and so it will be for HK.



Calibration Infrastructure

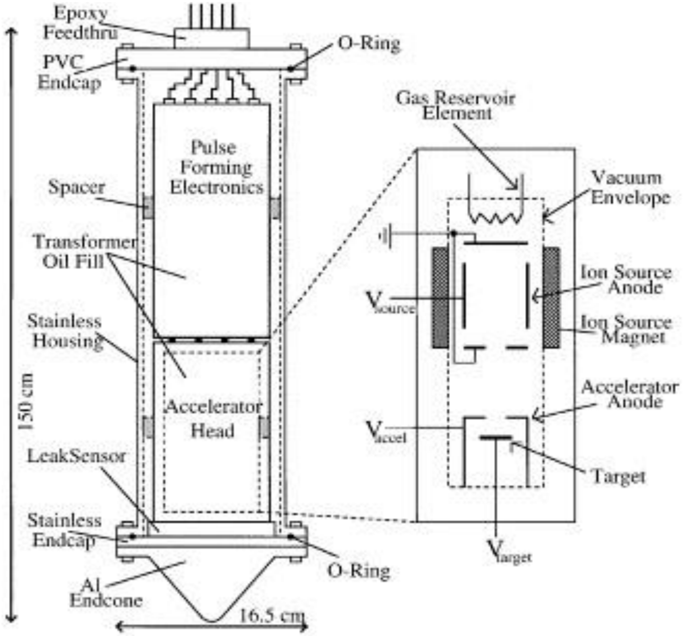


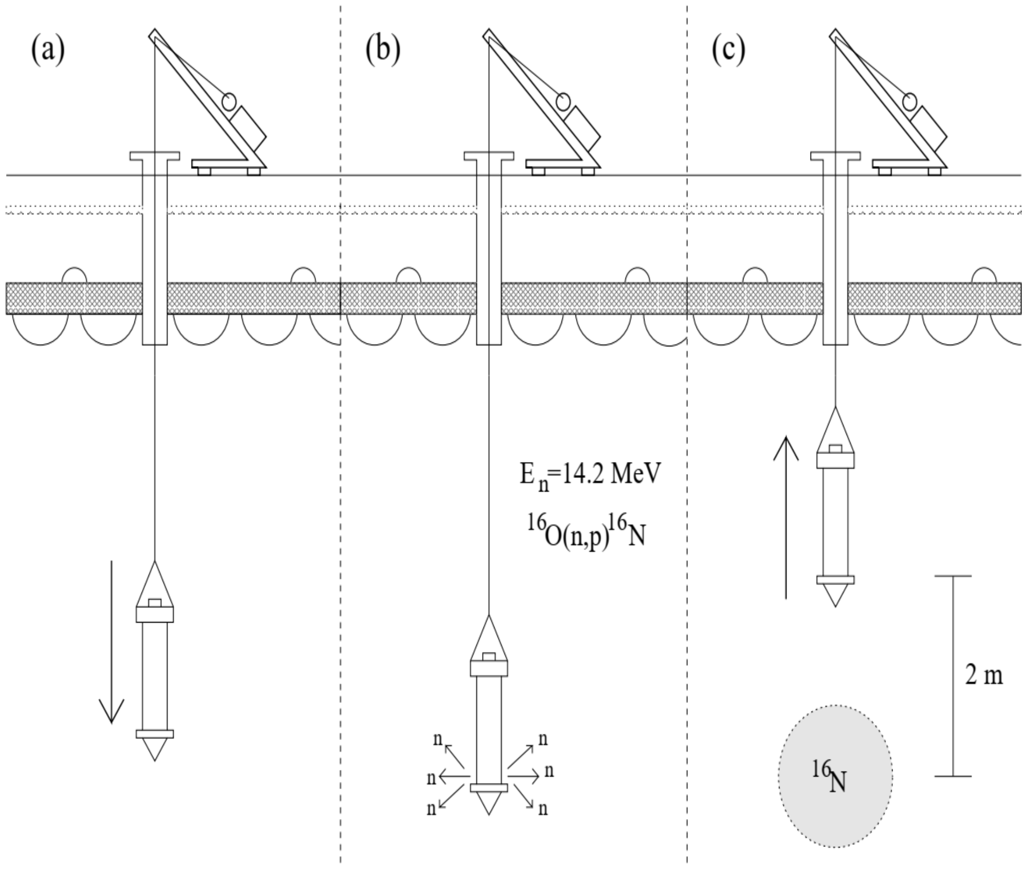
- ✓ Hyper-K will use a vertical deployment system that can be moved between calibration ports on the upper endcap.
- ✓ 50 calibration ports will be distributed across the detector.



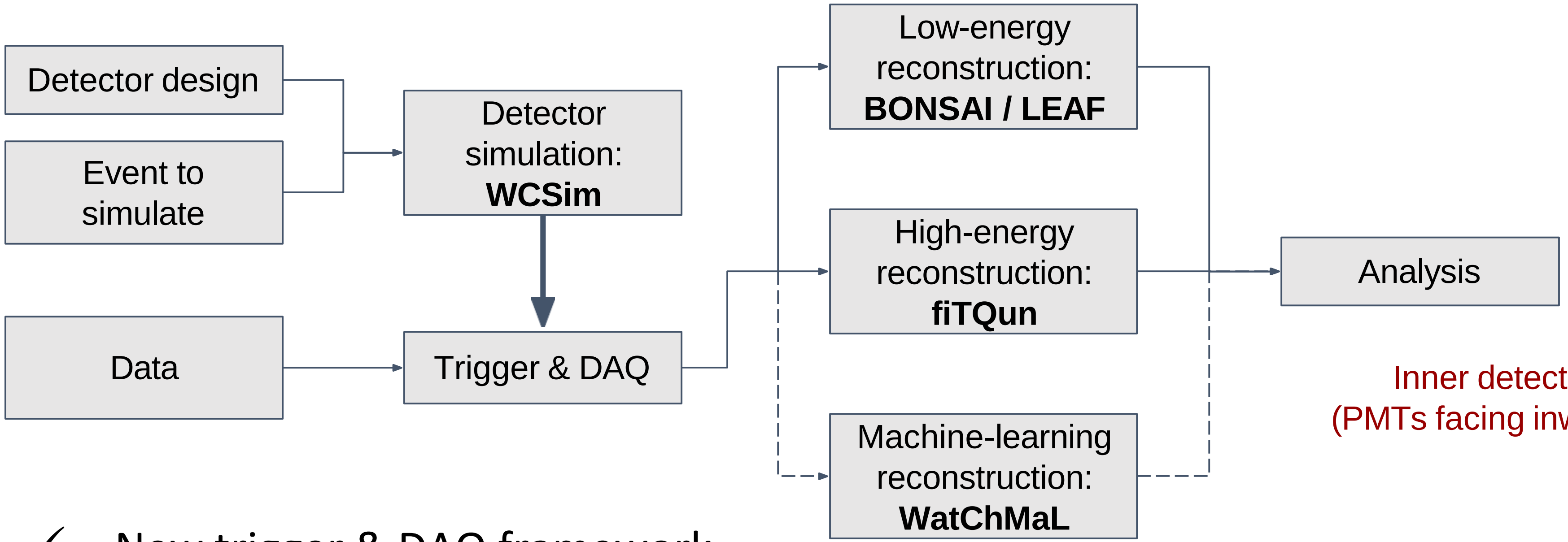
DT Generator (DT-G)

- ✓ Cross calibrates the energy.
- ✓ The deployment of the D-T generator will occur by lowering it into the water through several calibration ports and into different depths per port.
- ✓ The system design and production is co-shared between Moroccan institutes and both LSU and UCI Universities from USA



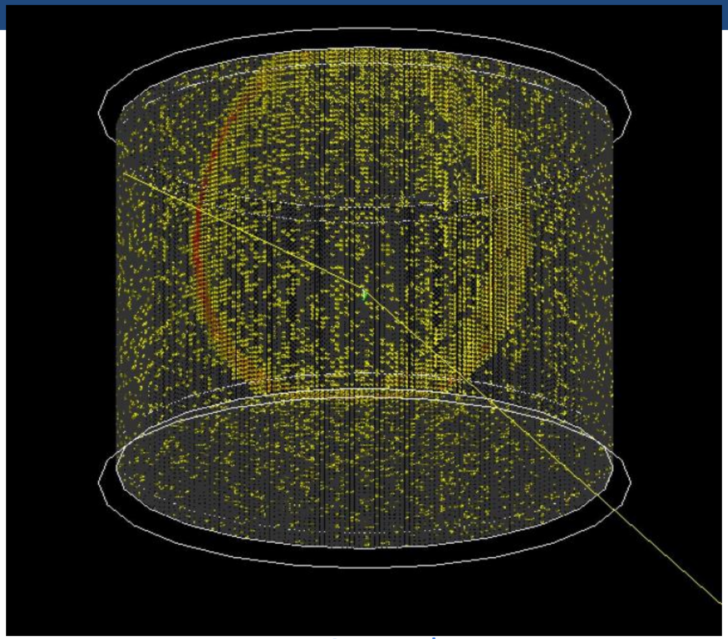


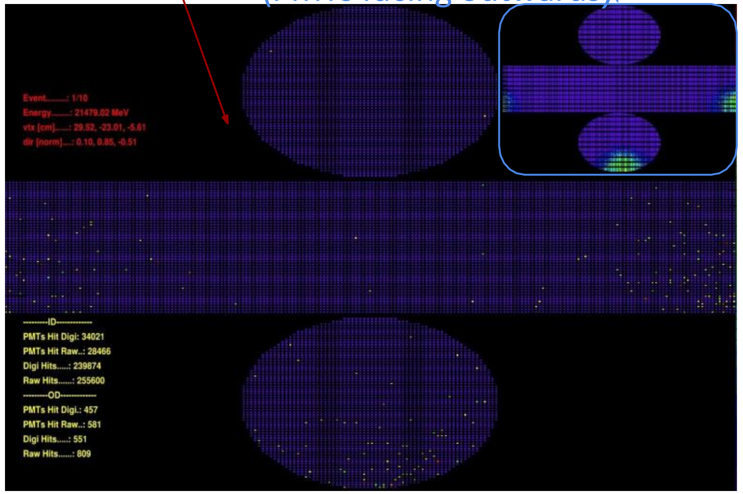
Simulation & reconstruction overview



- ✓ New trigger & DAQ framework to use same code for real and simulated data ToolDAQ : https://github.com/ToolDAQ

HK far detector (baseline design) simulation





WCSim can easily simulate different detector setups

Simulated muon in outer detector

Machine learning reconstruction

Limit of traditional reconstruction methods is being reached

- ✓ Computation time is becoming a limiting factor
  - ○ Larger detector with more PMTs
  - ○ Improving resolutions requires more complex algorithms

Machine learning algorithms have potential to push further

- ✓ Potential to use all available information without detector model assumptions / approximations
- ✓ Very fast to run once neural networks have been trained
- ✓ Now becoming common throughout HEP applications
- ✓ But many new challenges...

Conclusion

- ✓ Hyper-K detector is proposed as a next generation under-ground water Cherenkov detector with an extremely rich physics potential discovery.
- ✓ Hyper-K is capable of observing proton decays, HEP neutrinos, atmospheric and solar neutrinos, and neutrinos from other astrophysical origins.
- ✓ In order to achieve the desired level of systematic error, a detailed understanding of the detector must established, such that any data/MC discrepancies can be understood.
- ✓ Several in-situ calibration sources will deployed prior installation of PMTs, and integrated ones will be used for monitoring detector stability during data taking.
- ✓ Moroccan participation to the construction phase is so important, improve the physics potential discovery by development of two calibration systems locally, grid computing and many analysis physics.

Thank you so much for your attention

Back-up slides

Trilogy’s conclusion?

<u>Hyper-Kamiokande</u>

- ~2027 onwards
- 260 kton (188 kton FV)

X 8.4

<u>Super-Kamiokande</u>

- 1996 onwards
- 50 kton (22.5 kton FV)

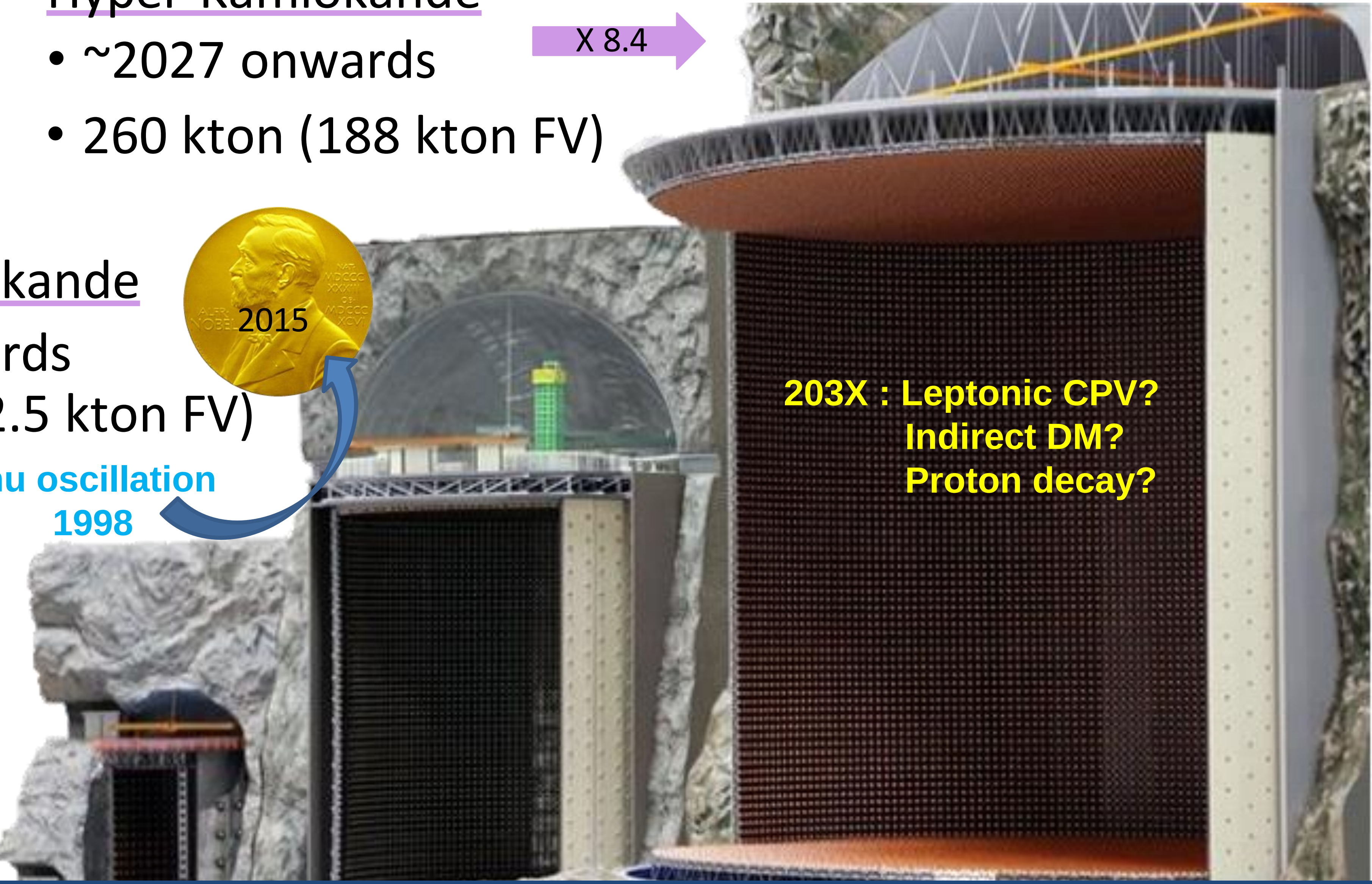
X 20

nu oscillation
1998

<u>Kamiokande</u>

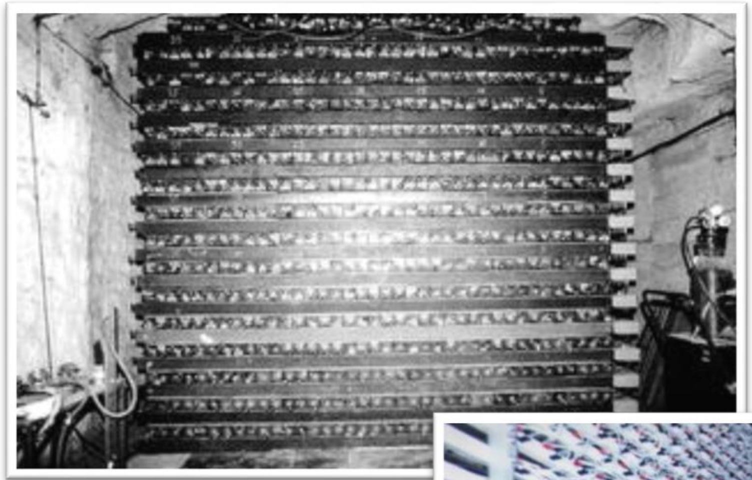
- 1983 - 1996
- 3 kton

Supernova nu
1987

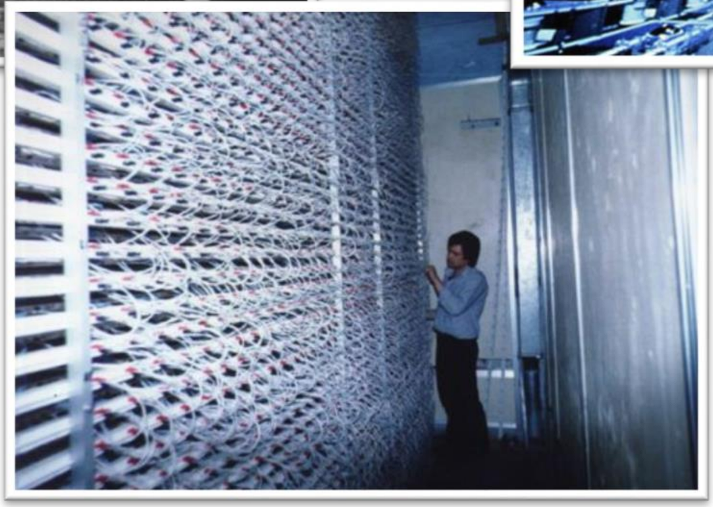


Bref History @Kamioka: Proton decay experiments

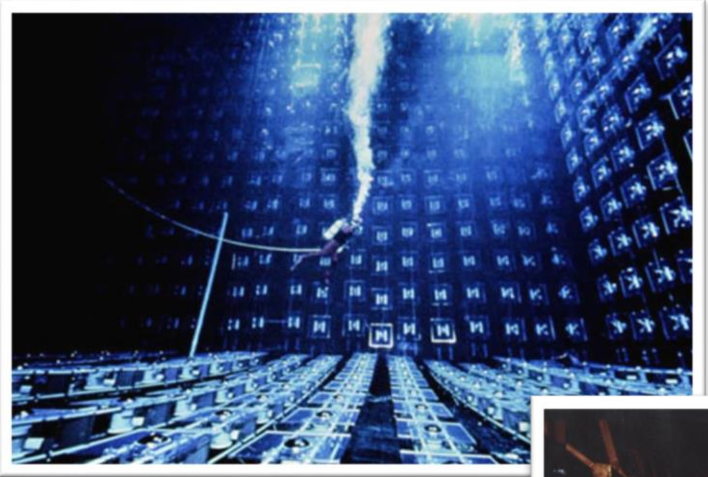
- ✓ In the 1970's, new theories of elementary particles predicted that protons should decay with the lifetime of about 10^{30} years.
- ✓ Several proton decay experiments began in the early 1980's.



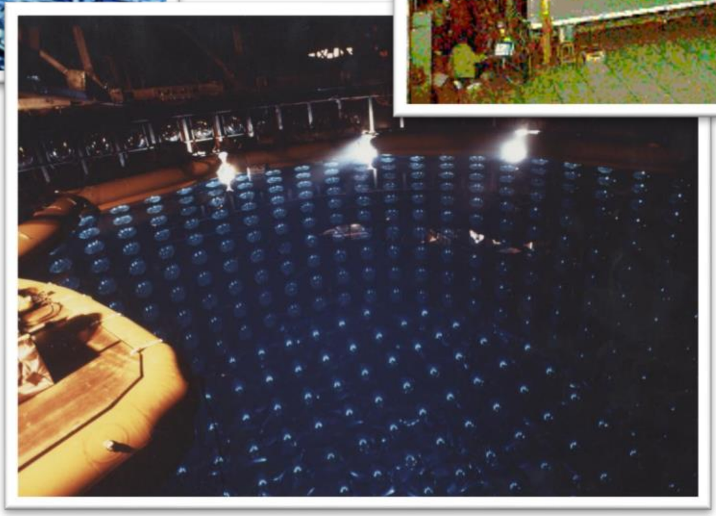
KGF (India)



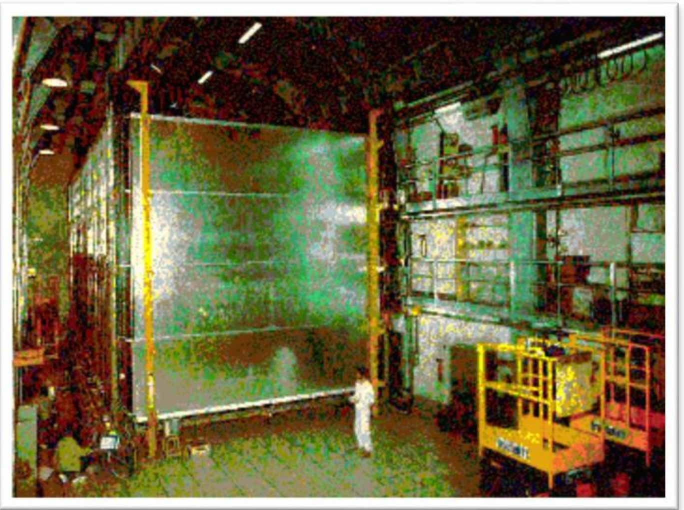
NUSEX (Europe)



IMB (USA)



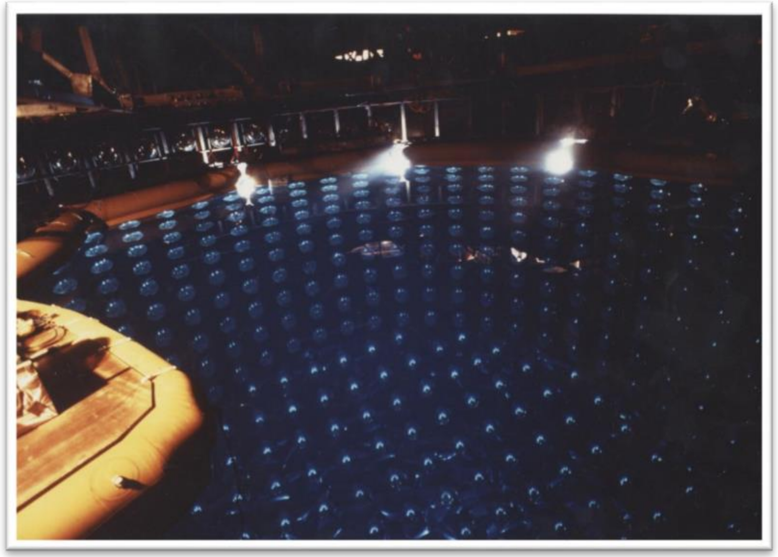
Kamiokande (Japan)



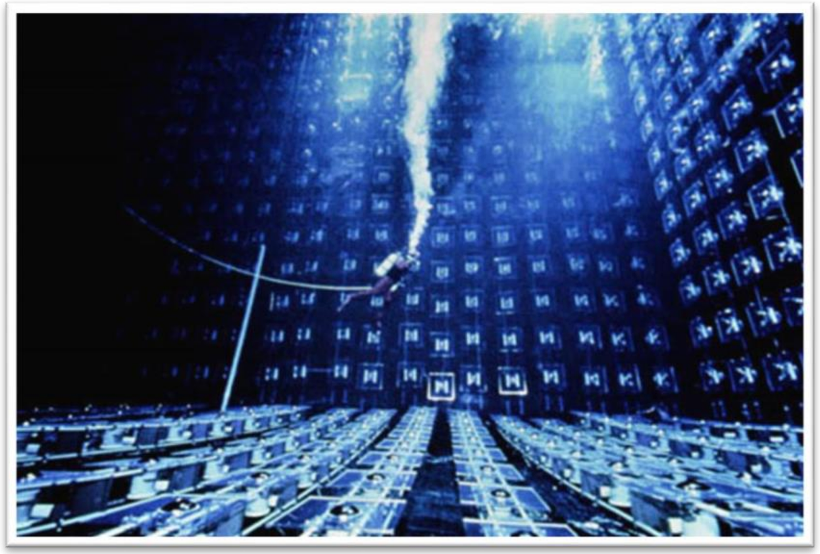
Frejus (Europe)

Atmospheric neutrino deficit (1980's to 90's)

- ✓ Proton decay experiments in the 1980's observed many atmospheric neutrino events.
- ✓ Because atmospheric neutrinos were the most serious background to the proton decay searches, it was necessary to understand atmospheric neutrino interactions.
- ✓ During these studies, **a significant deficit** of atmospheric mu-neutrino events was observed.



Kamiokande



IMB

Takaaki Kajita Said : Although we had no clear idea what was the cause of the deficit, I was most excited with the data. I thought that the data indicated something new. As a scientist, it was the most exciting time. I decided to concentrate on this topic.

Neutrino oscillations

If neutrinos have mass, neutrinos change their type from one type to the other.
For example, a mu-neutrino may change the type to a **tau-neutrino**.

http://dchooz.titech.jp.hep.net/nu_oscillation.html (slightly modified)

mu-neutrino **tau-neutrino** mu-neutrino **tau-neutrino**

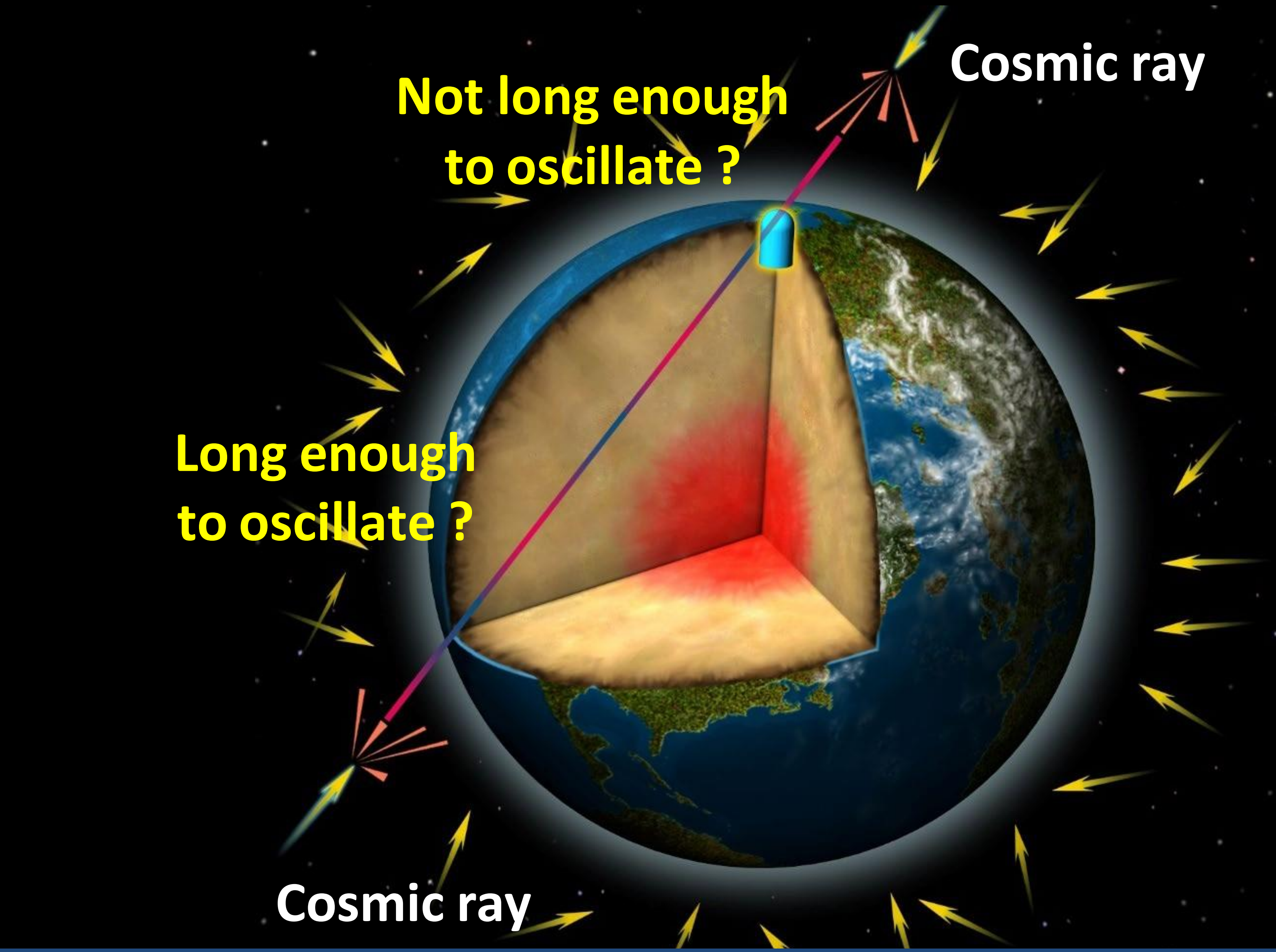
Neutrino oscillations were predicted more than 50 years ago by Maki, Nakagawa, Sakata, and by Pontecorvo.

S. Sakata, Z. Maki, M. Nakagawa

arXiv:0910.1657

B. Pontecorvo

What will happen if the deficit is due to neutrino oscillations

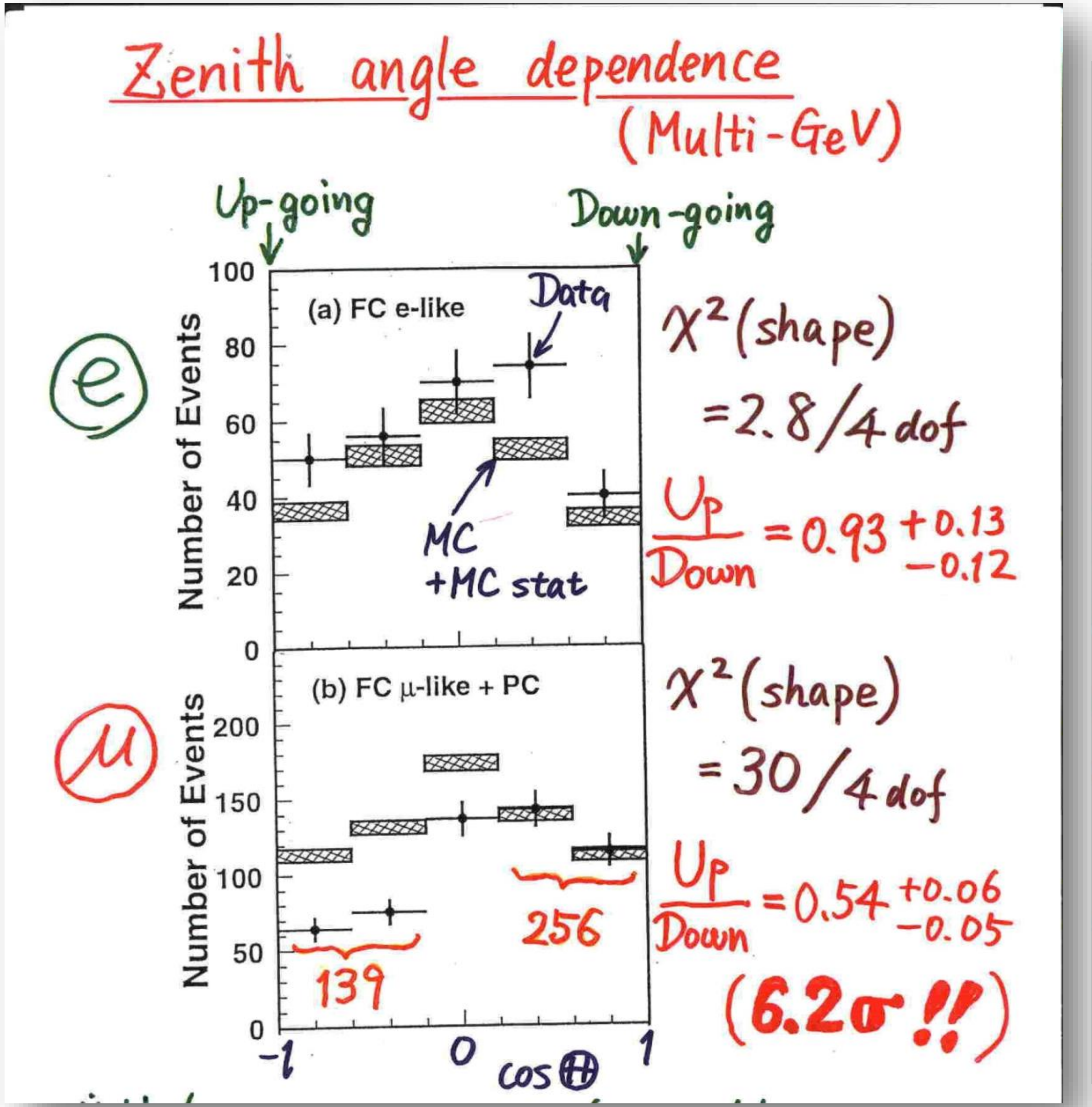


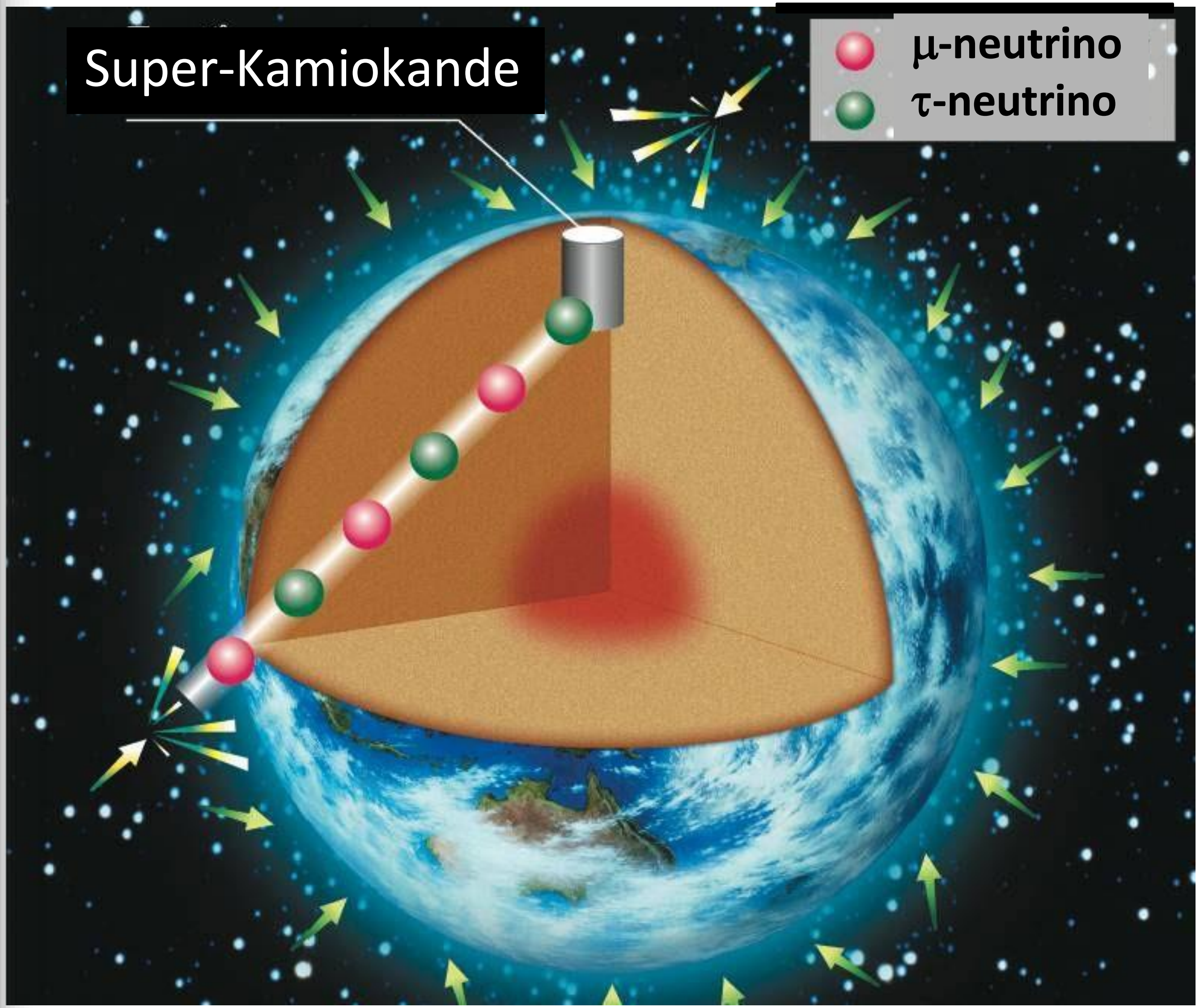
An asymmetry of the up- versus down-going flux of muon-neutrinos should be observed! However, Kamiokande was too small.

➔ Super-Kamiokande

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

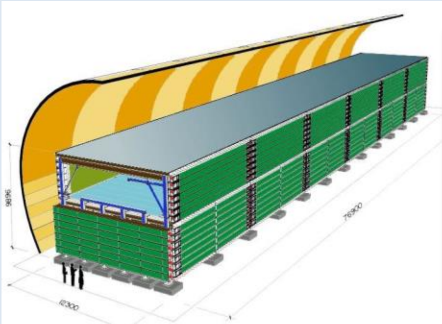
Y. Fukuda et al., PRL 81 (1998) 1562

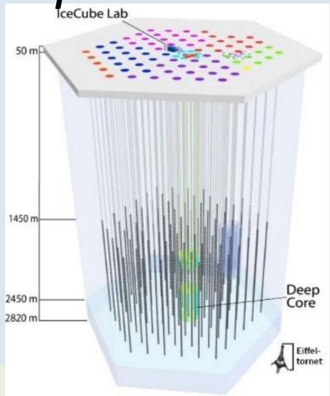


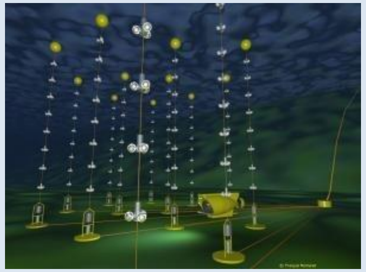


Many exciting results in neutrino oscillations (partial list)

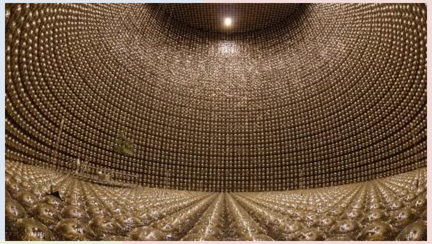
Atmospheric neutrino oscillation experiments

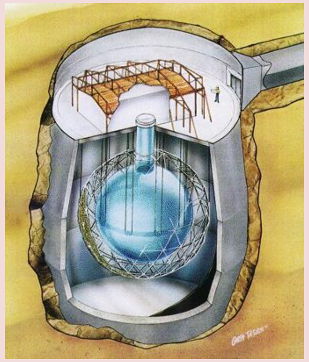




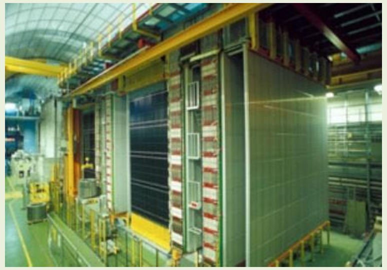


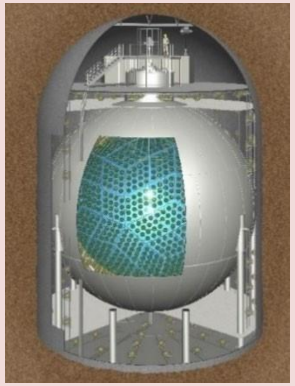
Solar neutrino oscillation experiments

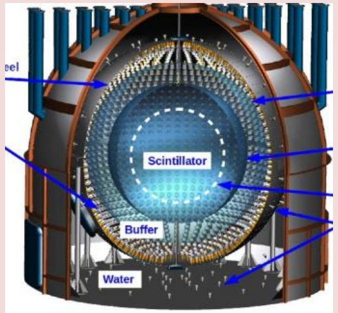




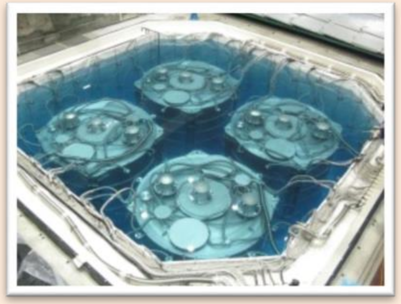
Accelerator based neutrino oscillation experiments





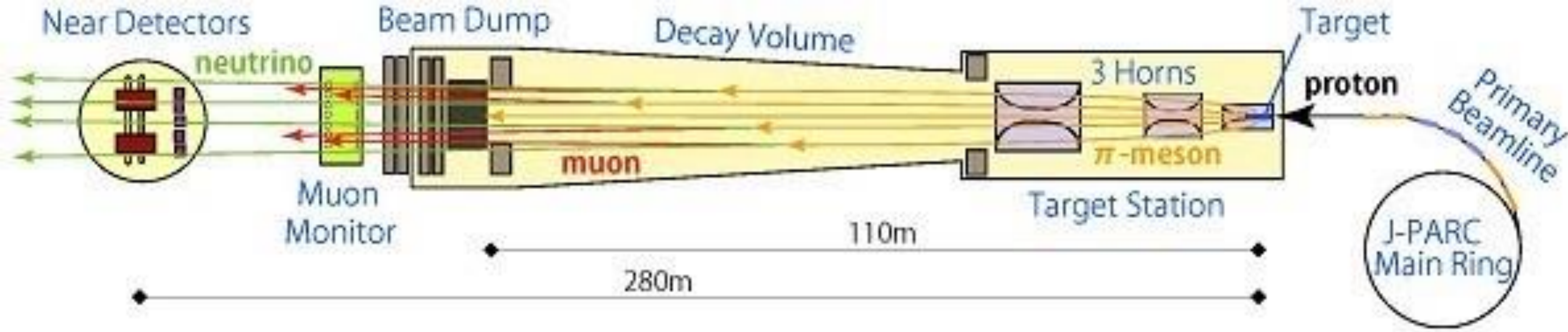


3 flavor(type) neutrino oscillation experiments



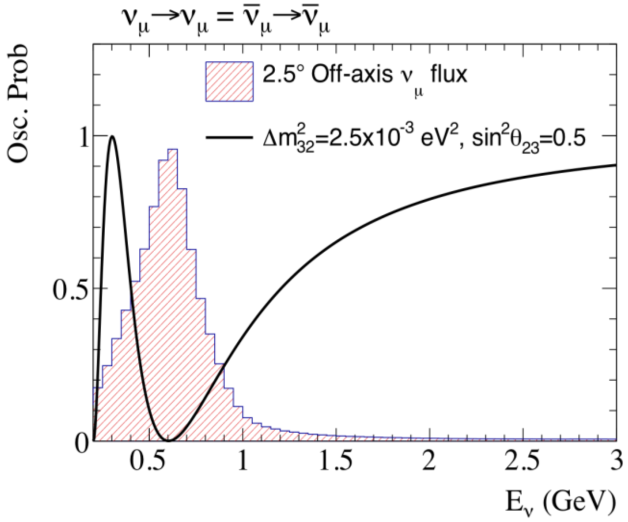
Beam with J-PARC

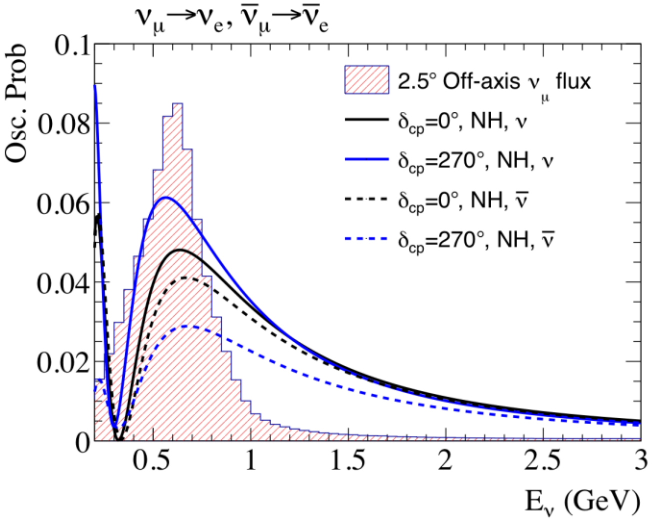
https://j-parc.jp/Neutrino/en/nu-facility.html

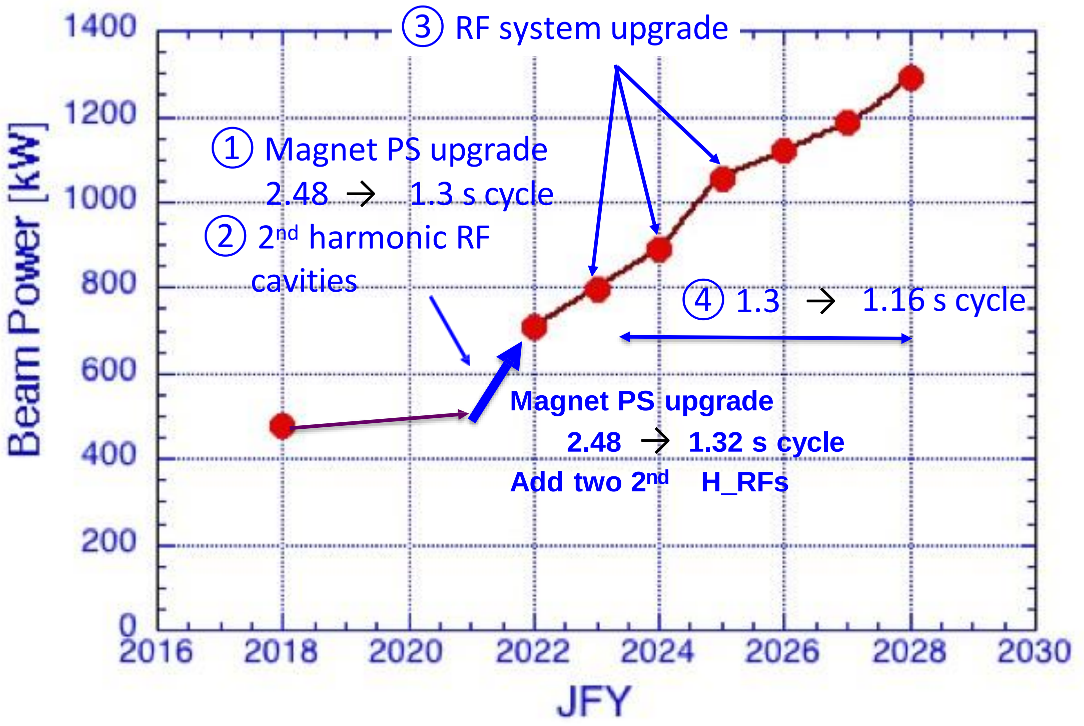


- 295 km baseline
- ϑ_{μ} or $\bar{\vartheta}_{\mu}$ selected by horn current
- 2.5° off-axis $\nu/\bar{\nu}$ beam peaked at 0.6 GeV
- Predominantly QE interactions
- J-PARC upgrade 500kW →1.3 MW

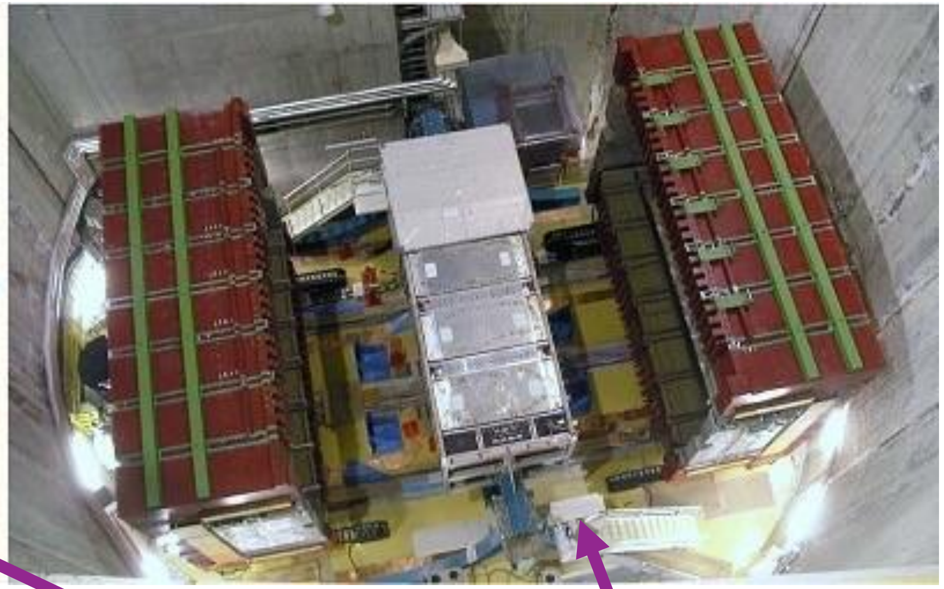
HK Beam Talk on Saturday (S19)- Tetsuro Sekiguchi

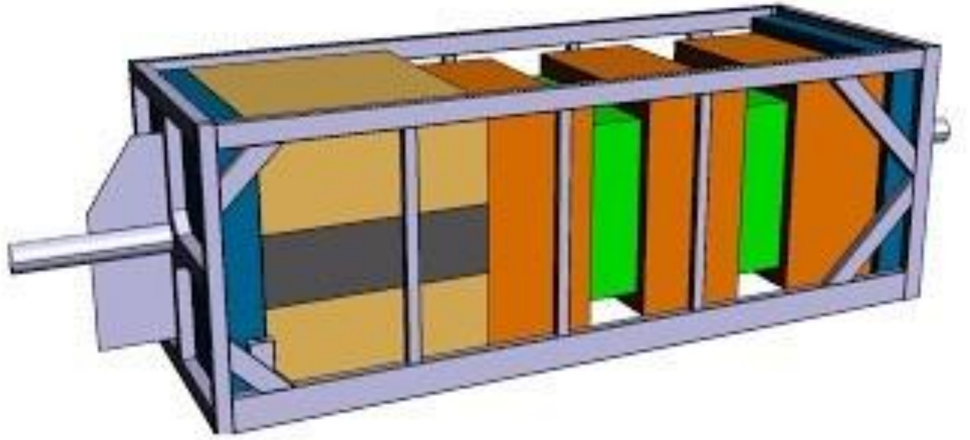






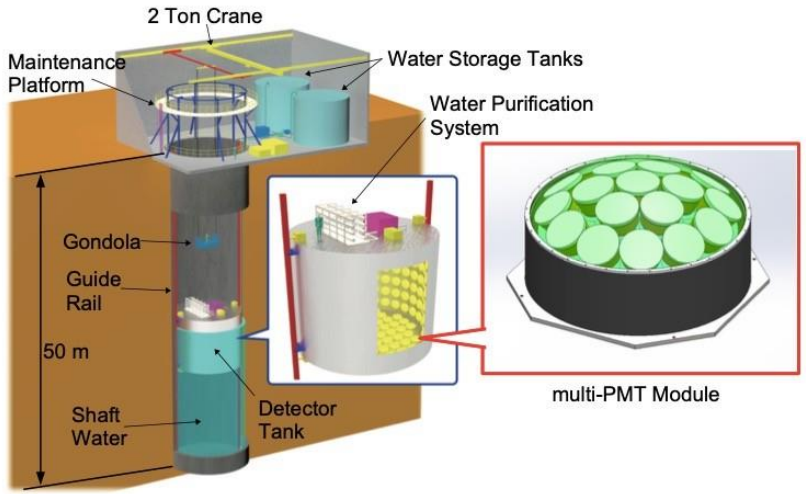
Near Detectors

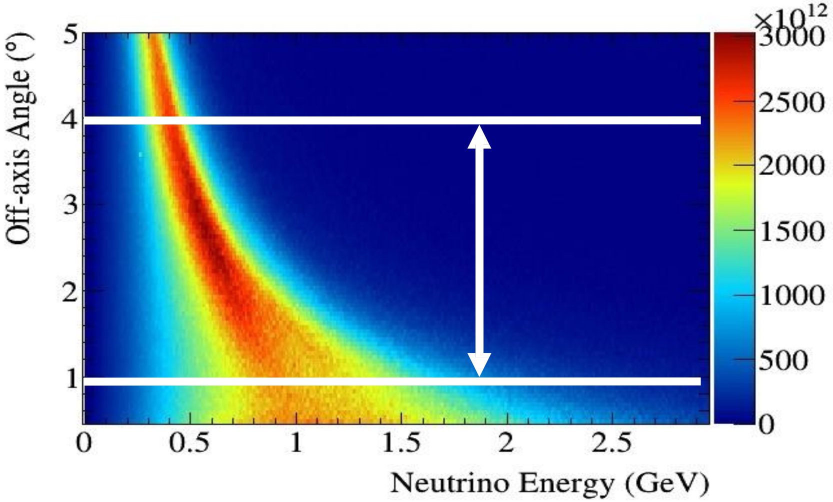




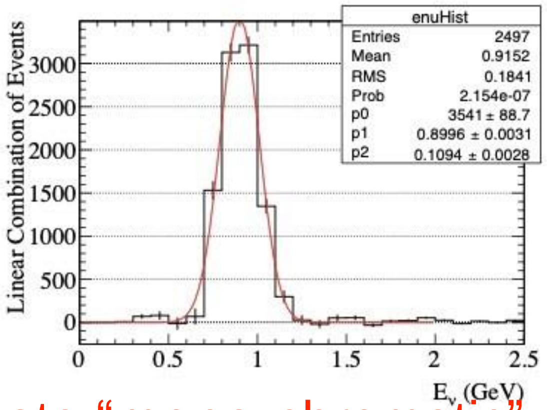
- T2K Near detectors INGRID and ND280 measure beam structure and composition 280 m downstream.
  - Measurements constrain uncertainty on flux and neutrino interaction models
  - Events samples from ND280 used in oscillation fit to near and far detector data
- Upgrades underway in 2022/23 to improve angular acceptance of the ND280 tracking detector

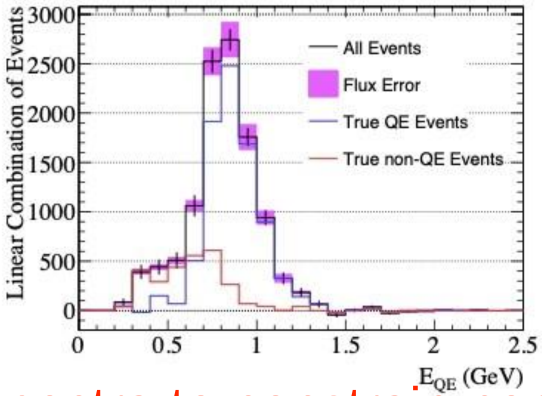
The Intermediate Water Cherenkov Detector (IWCD)



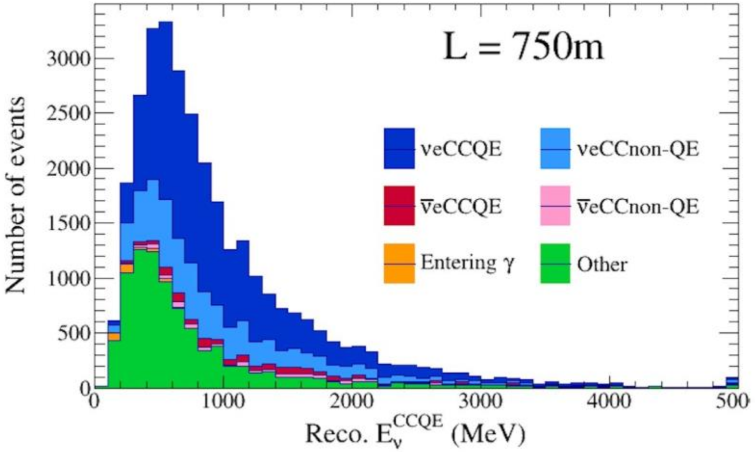


- Moving detector → measurements at different off-axis angles → energy spectrum → constrain relationship between reconstructed quantities and neutrino energy





Create "mono-chromatic" spectra to constrain non-QE feed-down with 5% precision



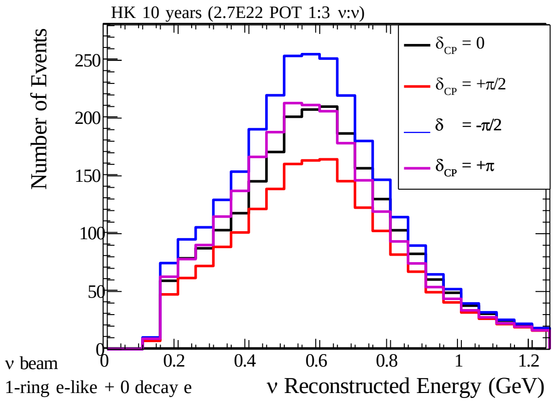
Measure CC ϑ_e /CC $\bar{\vartheta}_e$ ratio with < 4% precision

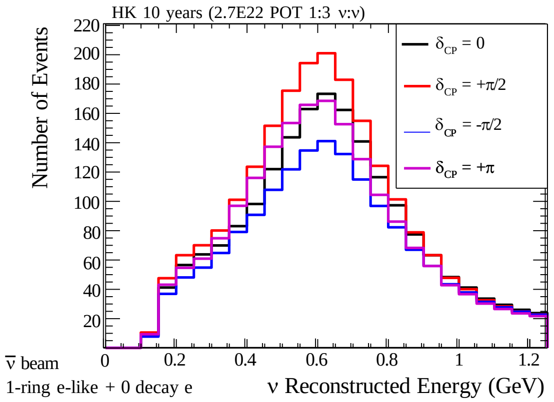
Long Baseline Physics δ_{CP}

Probe CP-violation through comparison of

$P(\vartheta_\mu \to \vartheta_e)$ and $P(\bar{\vartheta}_\mu \to \bar{\vartheta}_e)$

- Select 1 ring e-like events in far detector
- 10 years running, 1:3 $\vartheta_e : \bar{\vartheta}_e$ run plan

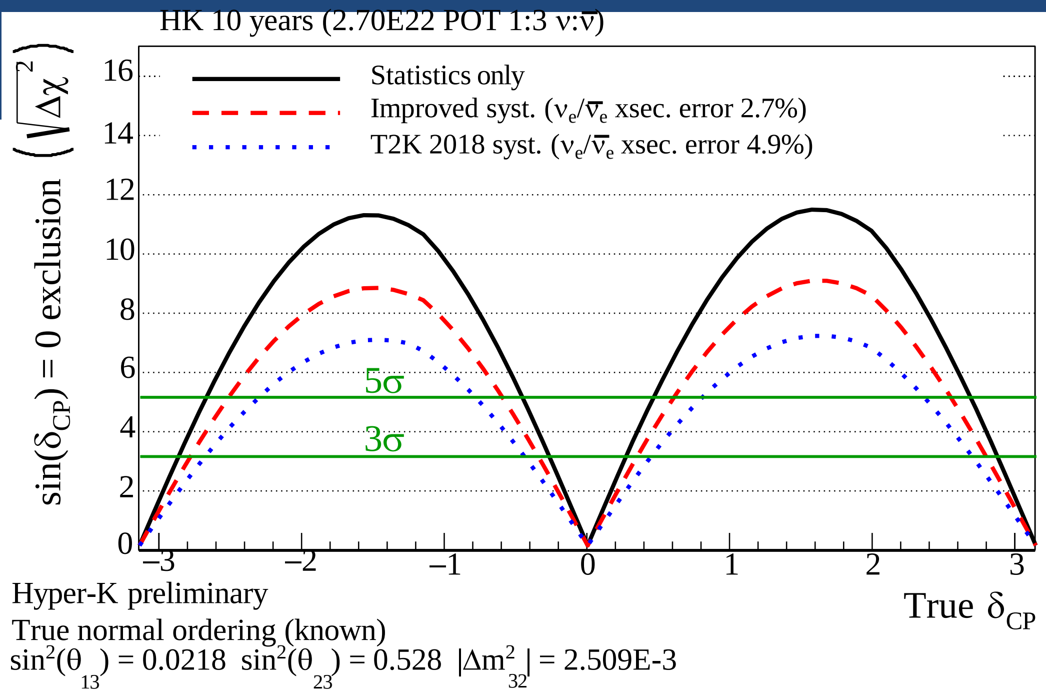


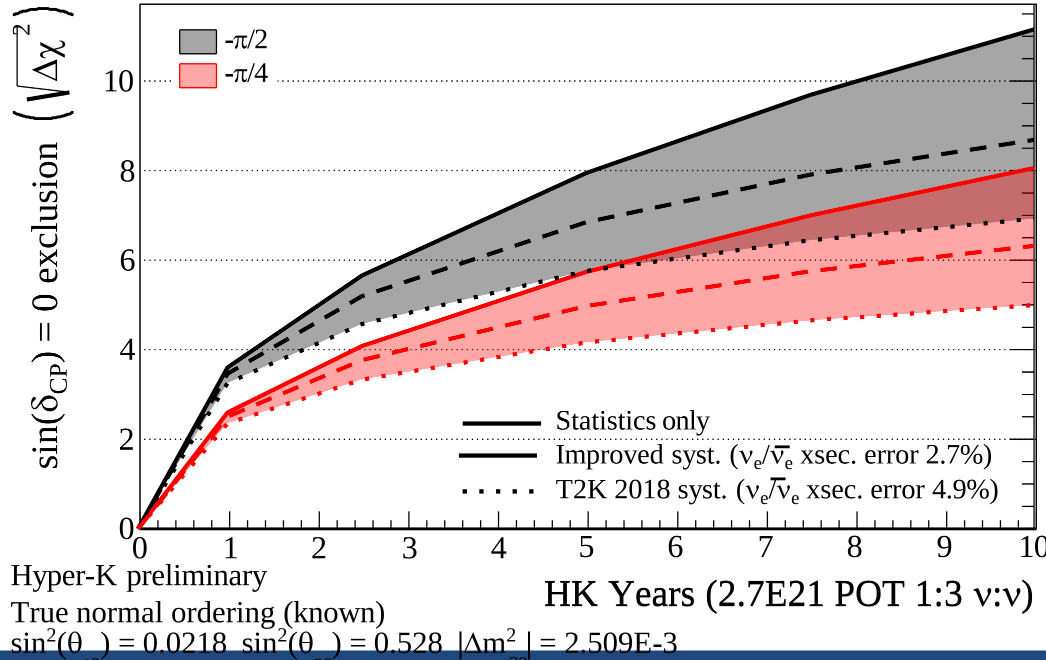


- >1000 ϑ_e and $\bar{\vartheta}_e$ signals

Assume normal mass ordering is known → Projected sensitivity based on T2K systematics plus improvements for Hyper-K

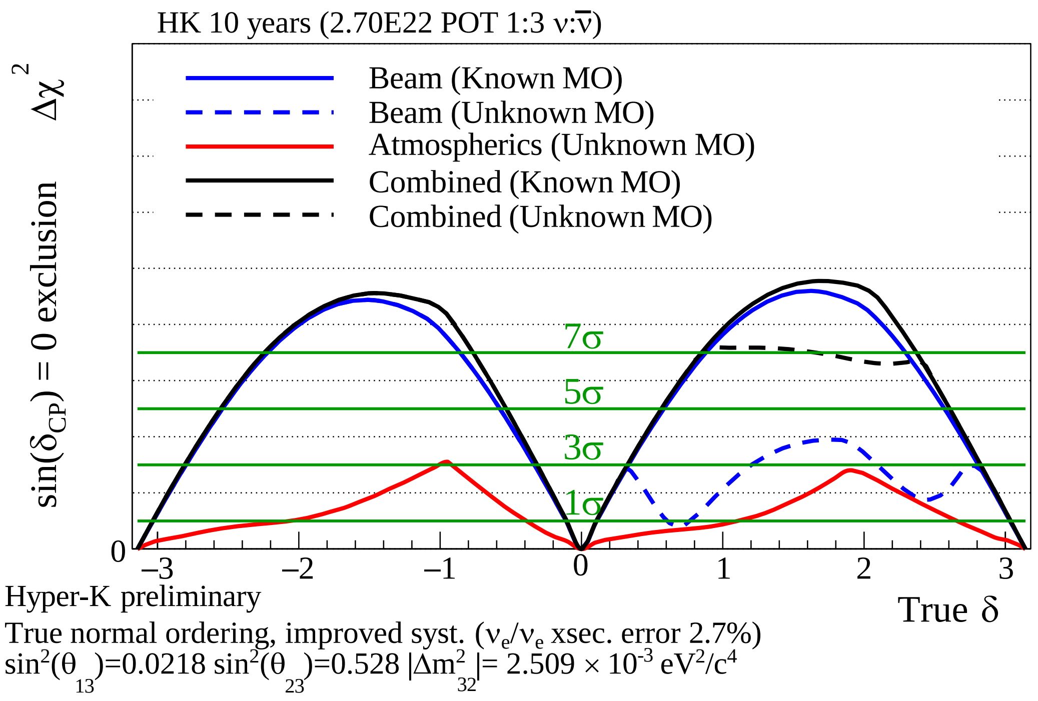
AZer 10 HK-years, 61% of true δ_{CP} values can be excluded at 5 sigma

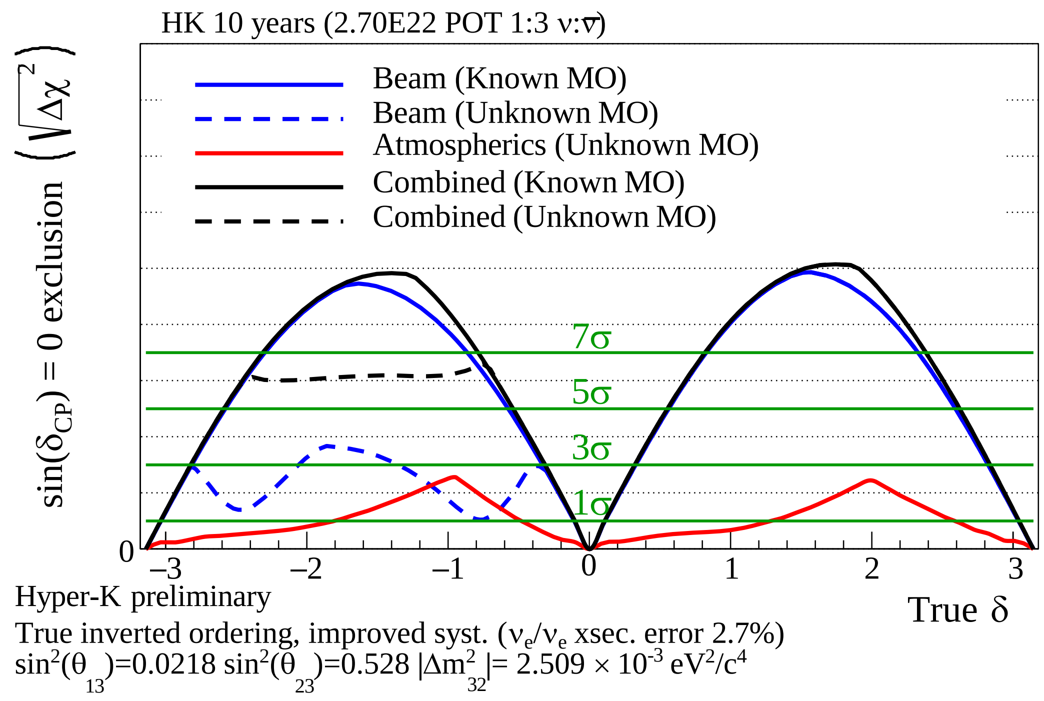




Mass Ordering

- If mass ordering is not known, combination of beam measurements with atmospheric neutrino observations resolves parameter degeneracy

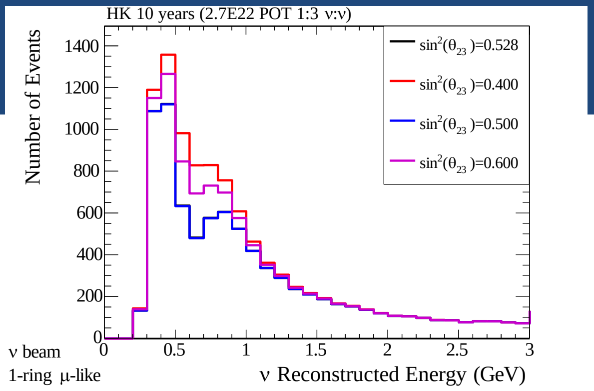


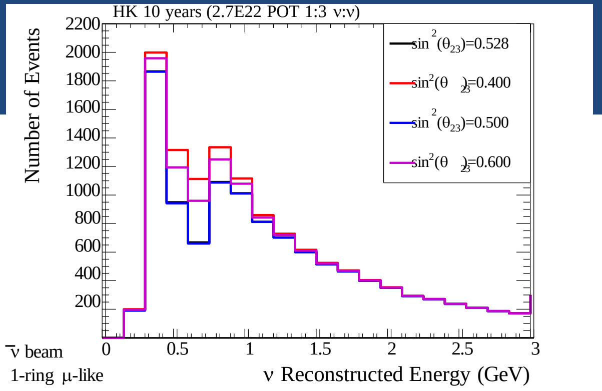


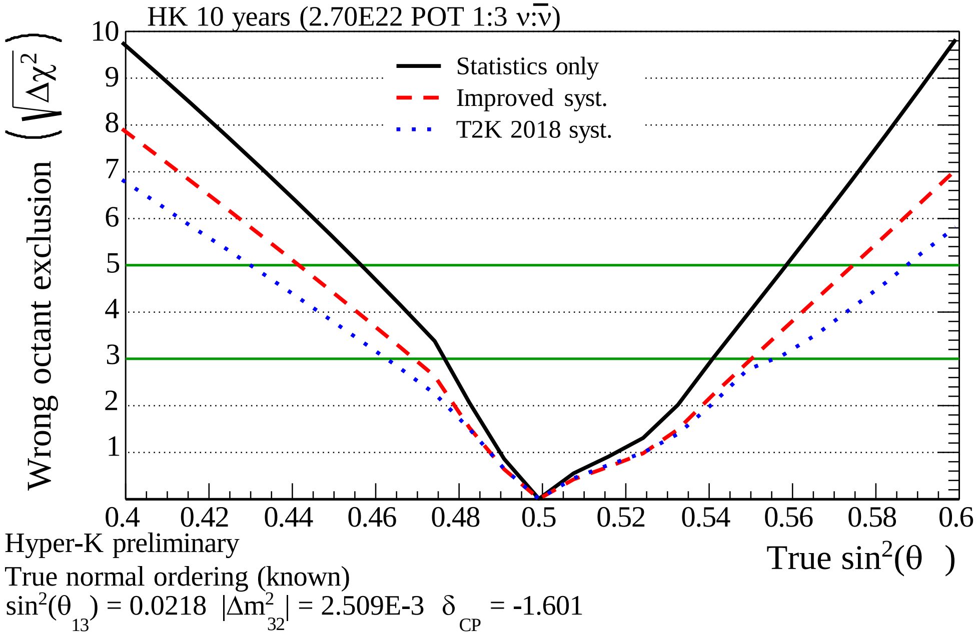
Δm^2_{32} $\sin^2\theta_{32}$

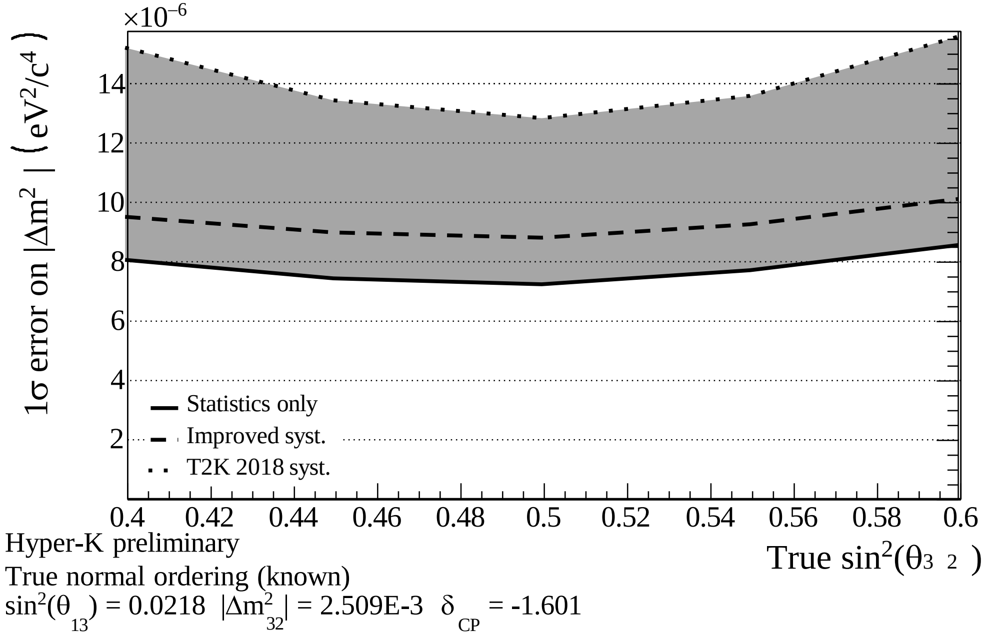
Probe 2-3 mixing through dip in $P(\vartheta_\mu \rightarrow \vartheta_\mu)$ and $P(\bar{\vartheta}_\mu \rightarrow \bar{\vartheta}_\mu)$

- Select 1 ring μ-like events in far detector
- 10 years running, 1:3 $\vartheta_e : \bar{\vartheta}_e$ run plan









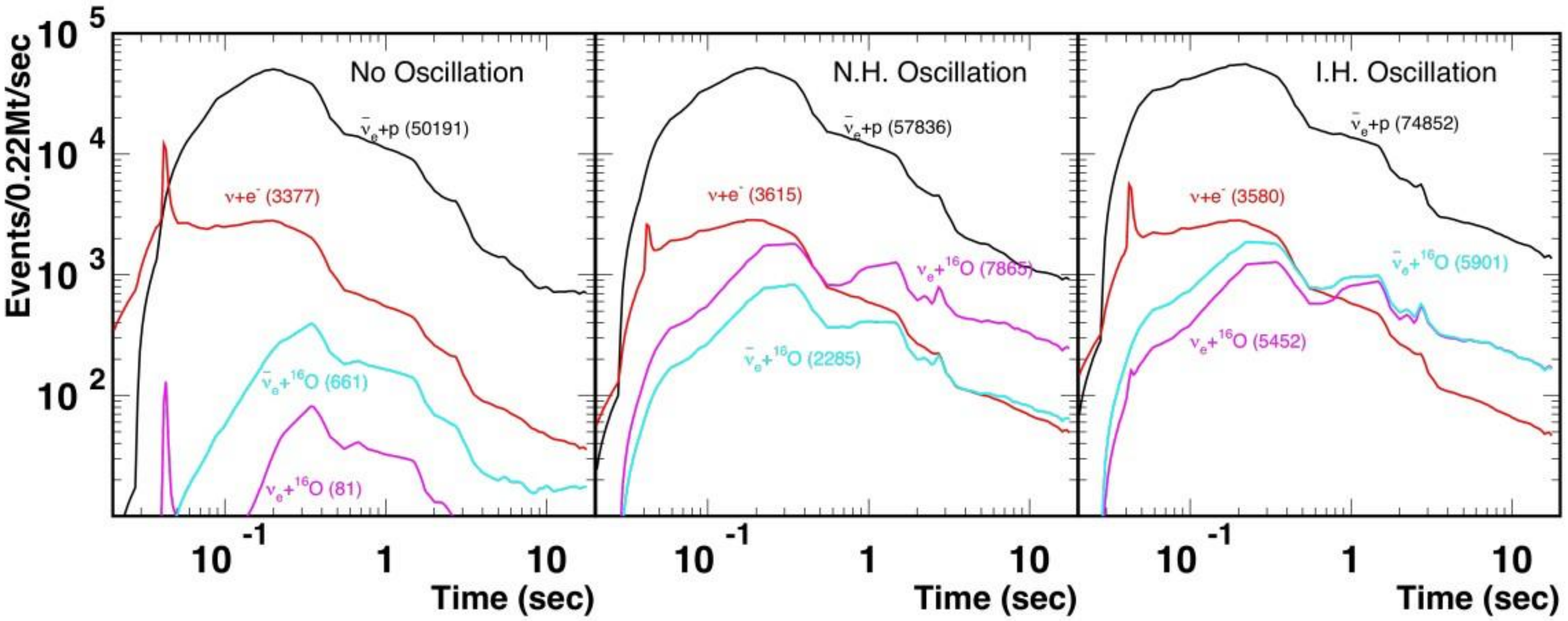
Wrong octant can be excluded at 3σ for true $\sin^2\theta_{32} < 0.47$ and true $\sin^2\theta_{32} > 0.55$

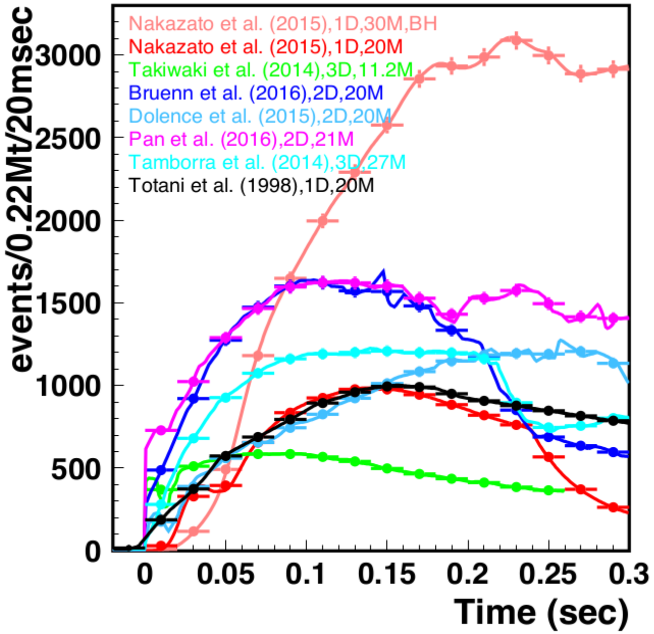
1σ resolution of Δm^2_{32} as a function of true $\sin^2\theta_{32}$

Neutrino Astrophysics – Supernova Bursts

- Expected time profile and event numbers in HK for a supernova at 10 kpc (Livermore simulation)
  - numbers in brackets total interactions integrated over the 10 s burst
  - peak event rate of inverse beta decay events (black) reaches ~50 kHz
  - Model discrimination - arXiv:2101.05269

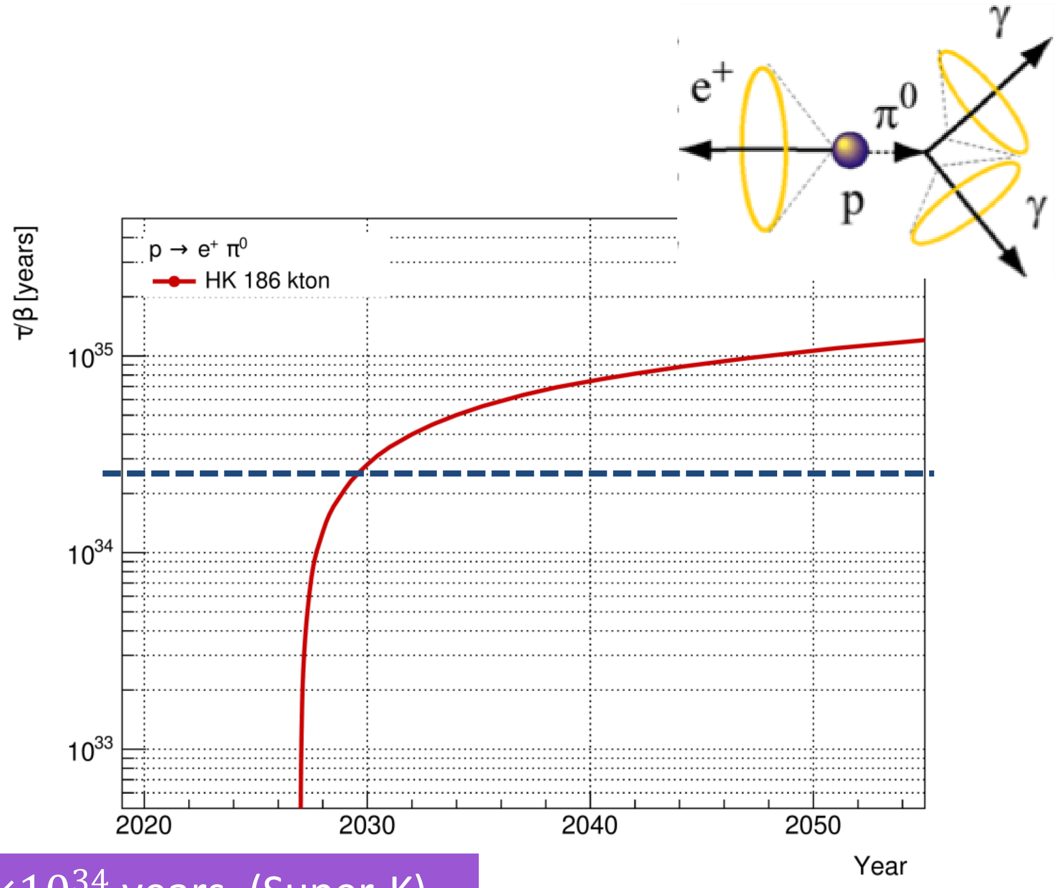
DAQ designed to cope with peak data rates from very close SN (eg. Betelgeuse)



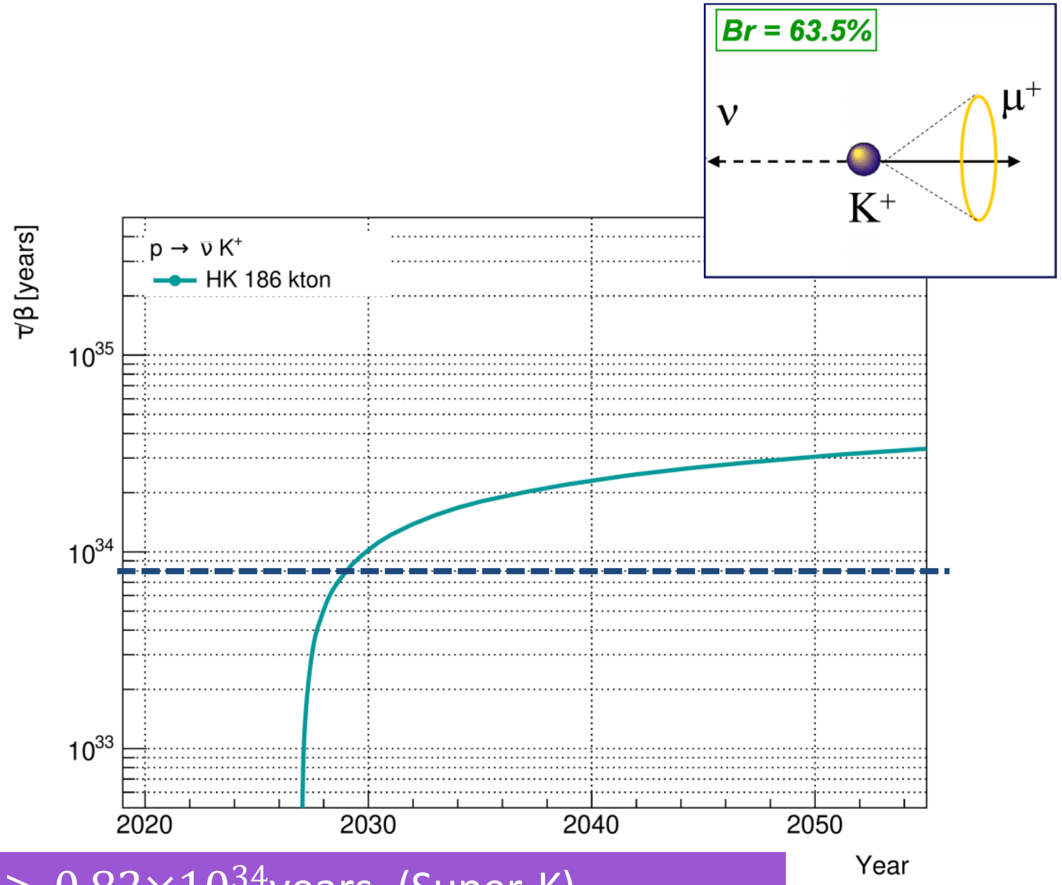


Proton Decay

- Hyper-K far detector has many protons!
- Can extend proton decay search by an order of magnitude beyond current



$\tau > 2.4{\times}10^{34}$ years (Super-K)
Phys. Rev. D 102, 112011 (2020)



$\tau > 0.82{\times}10^{34}$years (Super-K)
Nucl.Instrum.Meth.A 952 (2020) 161634

Hyper-K Far Detector – R&D highlights

20k 50 cm Box and Line Dynode ID PMTs

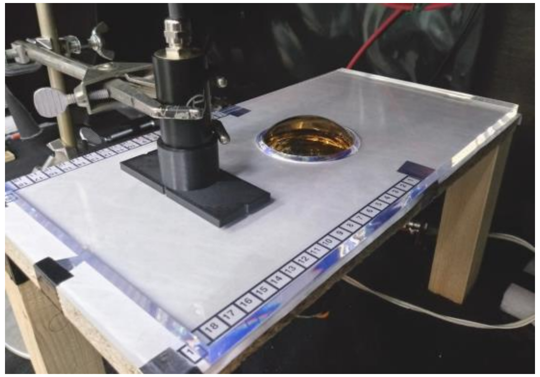
- 2.6 ns timing resolution
- 2 × SK PMT efficiency
- Mass production and QA commenced 2021

mPMT units

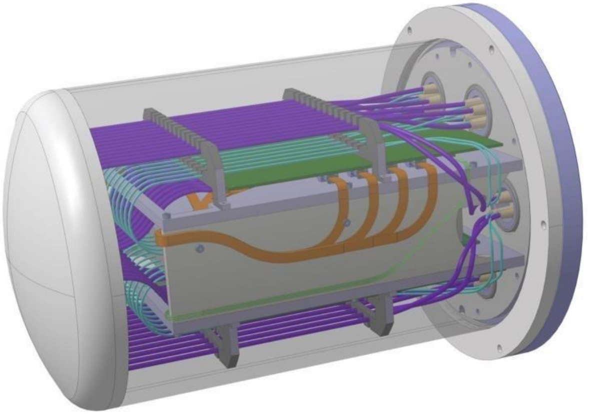
- 19,8 cm PMTs + electronics inside single pressure vessel
- Directional information, improved spatial and timing resolution

Outer Detector:

8 cm PMTs + WLS plates



Installation mock-up



Underwater electronics