Towards the Hyper-Kamiokande neutrino experiment

Hyper-Kamiokande

IFJ PAN seminar, 12 March 2026

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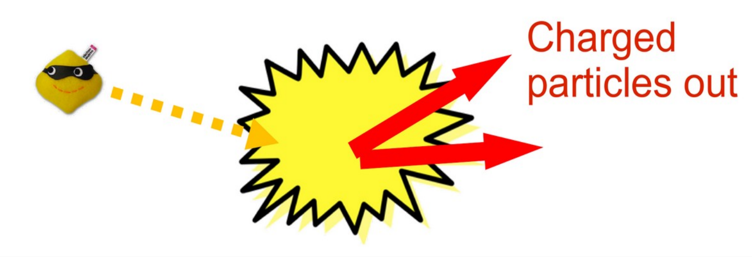
Outline

- **Introduction to neutrino physics**
- Water Cherenkov experiments in Japan
- Hyper-Kamiokande detector
- Physics goals
- Summary

Elusive particle

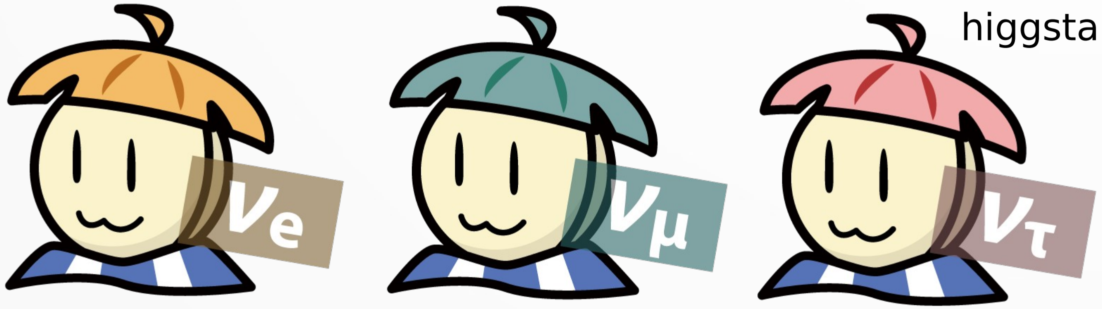
- Neutrinos have no electric charge and a very small mass ($\lesssim$1eV)
- They interact very weakly with matter and are notoriously difficult to detect.
- The interaction length of 1 MeV photon in lead is ~2 cm
- For neutrino of the same energy it's ~5 light years!
- $\sim 10^{14}$ neutrinos from the Sun pass through your body every second!
- When neutrino interacts in matter it may produce charged particles. They are easily detectable and seem to appear out of nowhere.

From A. Himmel



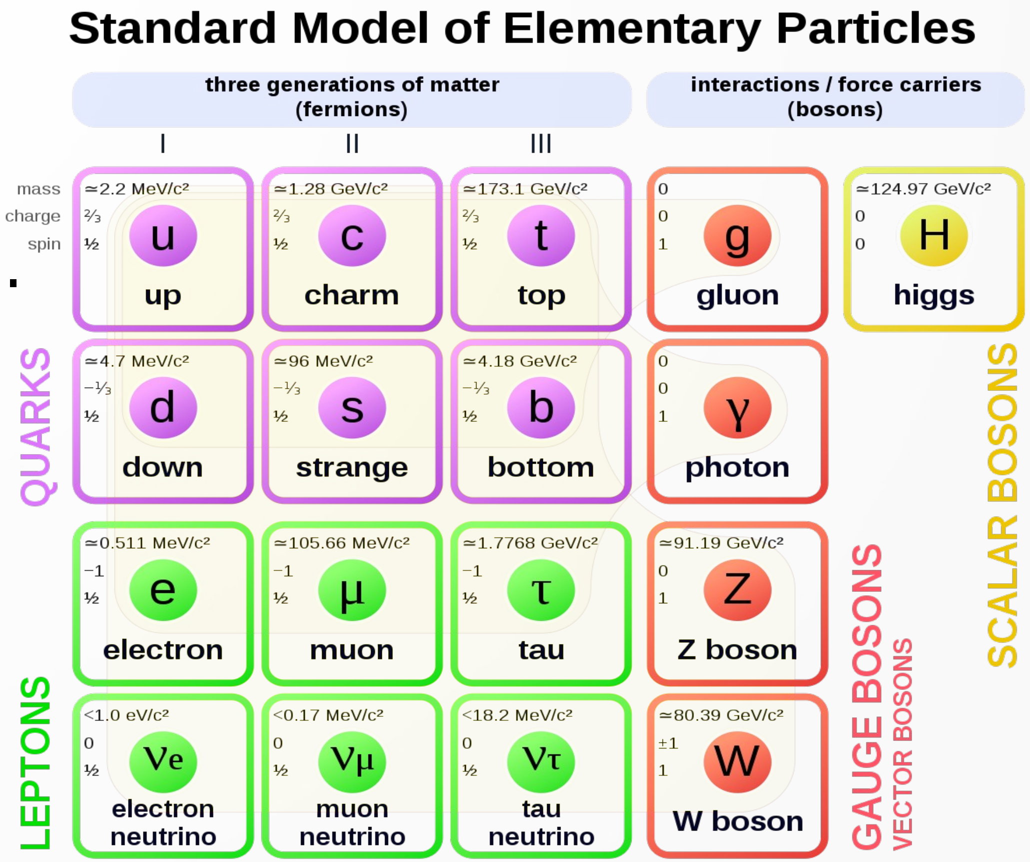
Neutrinos in the Standard Model

- Fermions, part of the lepton doublets.
- Interact only via weak interaction (CC – charged current, NC – neutral current).
- Three flavours: electron, muon, tau.



higgstan.com

- Neutrino masses predicted to be zero.
- Only left-handed neutrinos and right-handed antineutrinos are observed.

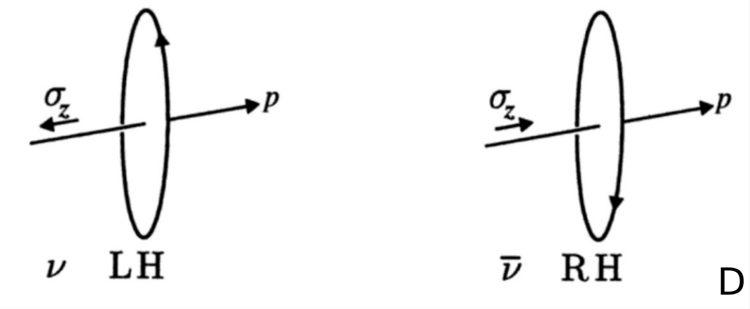


Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	

GAUGE BOSONS
VECTOR BOSONS

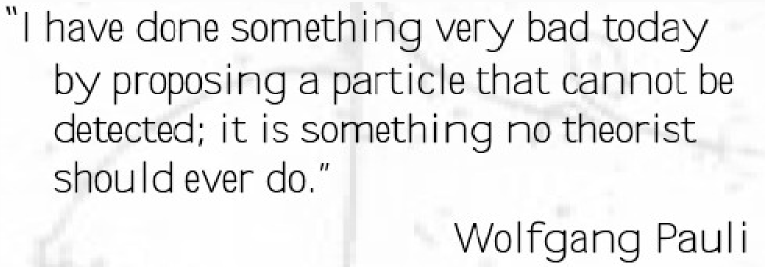
SCALAR BOSONS



D. H. Perkins

Short history of neutrino physics

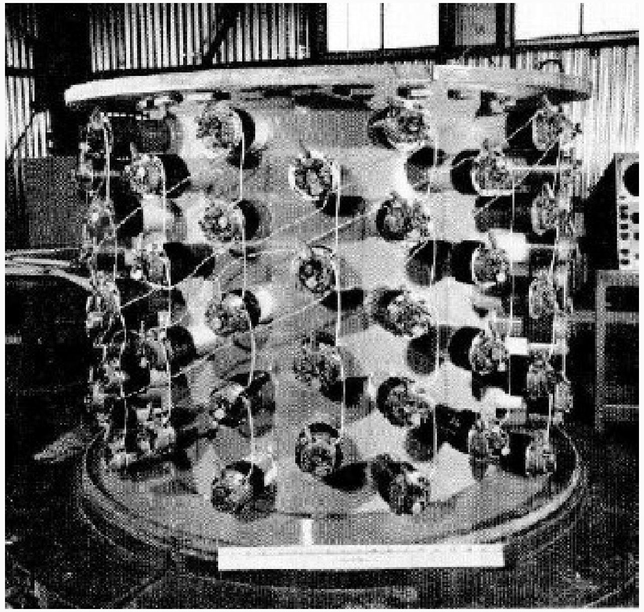
- 1930 – Wolfgang Pauli introduces hypothetical particle to solve the missing energy problem in beta decays.
- 1956 – First neutrino detected! Reines and Cowan observe for the first time neutrino interaction. Their detector was located close to the nuclear power plant (5 x 10^{20} ν/s) in Savannah River (USA).

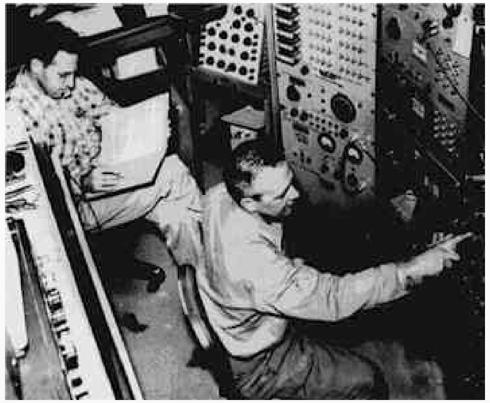


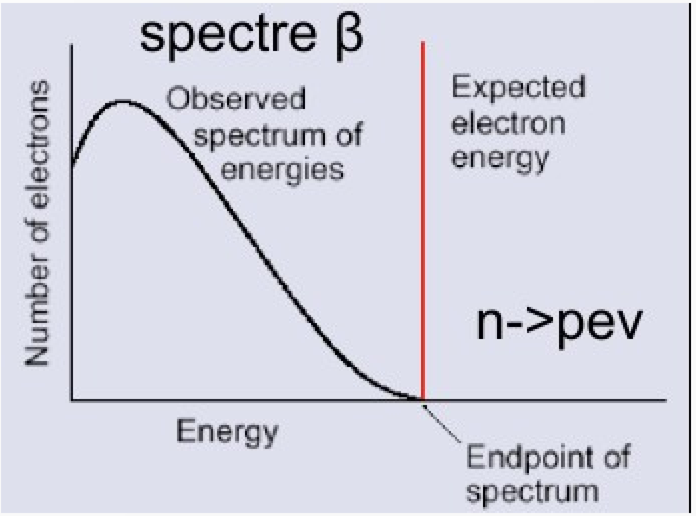
"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

Wolfgang Pauli

$$\overline{\nu}_e + p \rightarrow \beta^+ + n$$

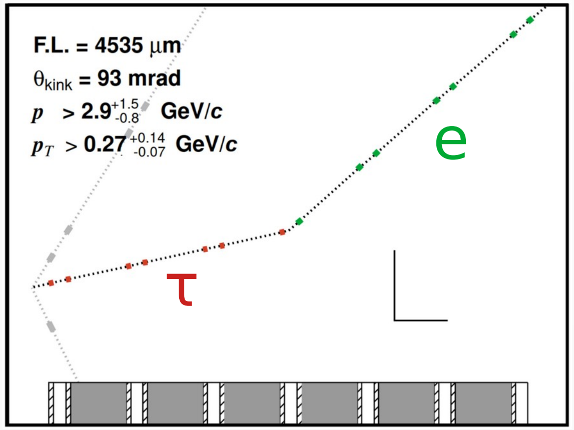


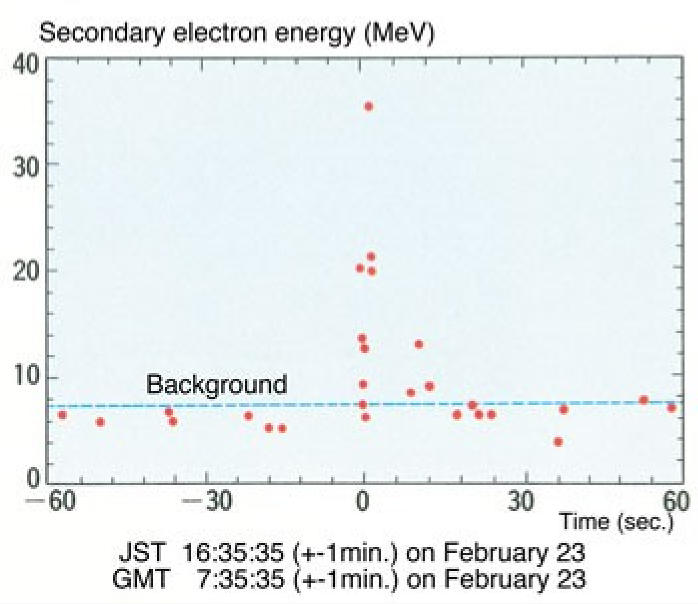




Short history of neutrino physics

- 1962 – Lederman, Schwartz, Steinberger discover muon neutrinos ν_μ with first experiment using 'accelerator neutrinos'. Nobel prize in 1988.
- 1975 – τ particle discovery at SLAC (USA) and ν_τ hypothesis
- 1987 – The first direct observation of neutrinos from supernova reported by several experiments.
- 2000 – DONUT experiment (Fermilab, USA) detects tau neutrinos

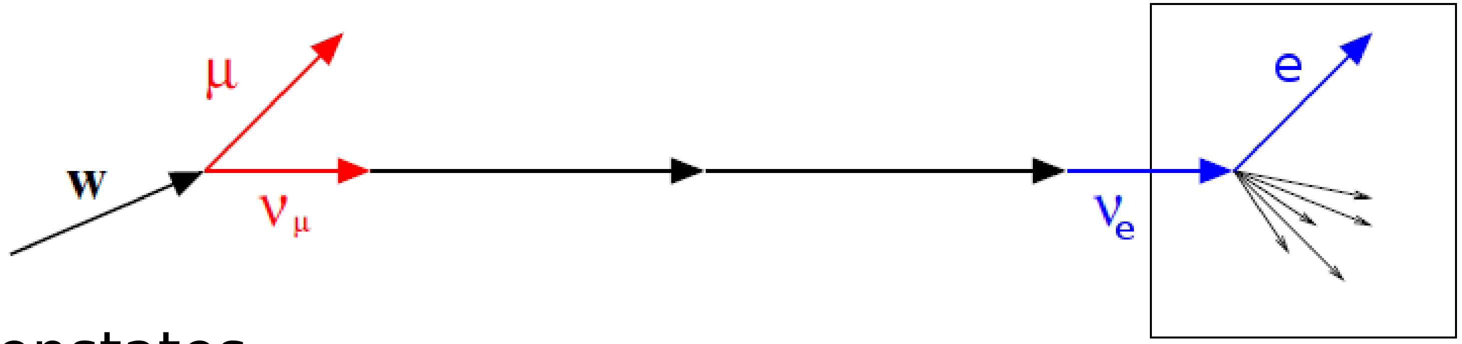




Supernova associated events observed by Kamiokande II

Neutrino oscillations

- The neutrino flavor may change when the particle propagates over a long distance.



- The flavor states are not eigenstates of the propagation Hamiltonian.
- Instead, we can describe them as a superposition of “mass eigenstates”.

Flavor eigenstates

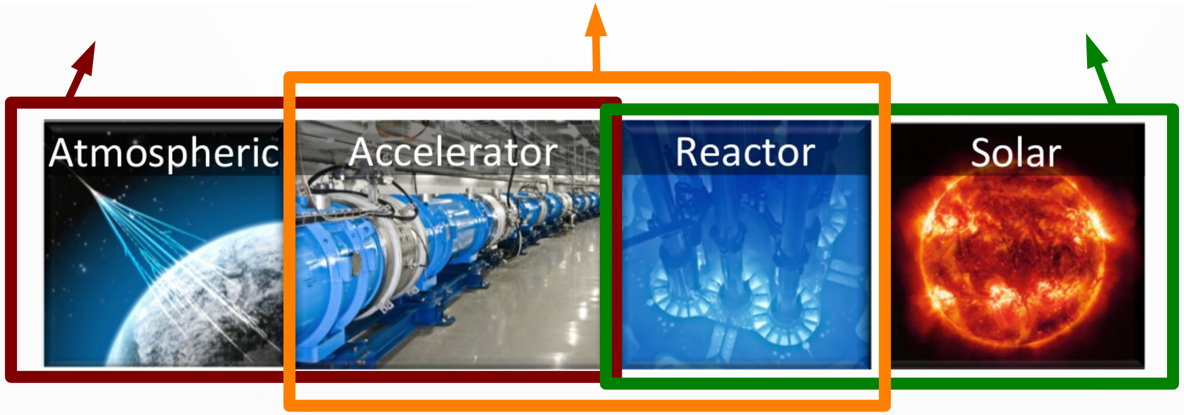
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass eigenstates

$$U=\begin{pmatrix}U_{e1}U_{\mu1}U_{\tau1}\\ U_{e2}U_{\mu2}U_{\tau2}\\ U_{e3}U_{\mu3}U_{\tau3}\end{pmatrix}$$

Flavor-mass mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

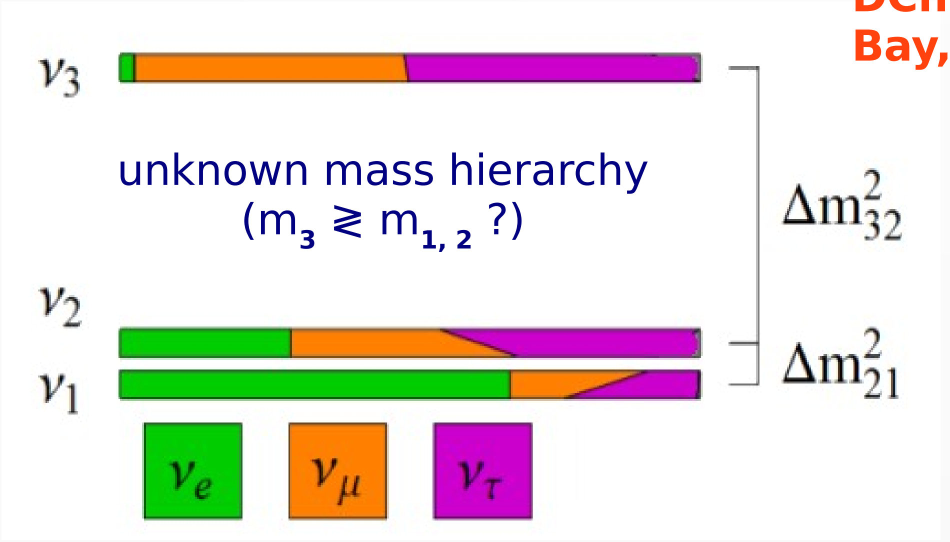


Super-K, K2K, MINOS, OPERA NOνA, T2K

DChooz, RENO, Daya Bay, MINOS, NOνA, T2K

Super-K, SNO, KamLAND

Flavor-mass mixing described with PMNS matrix



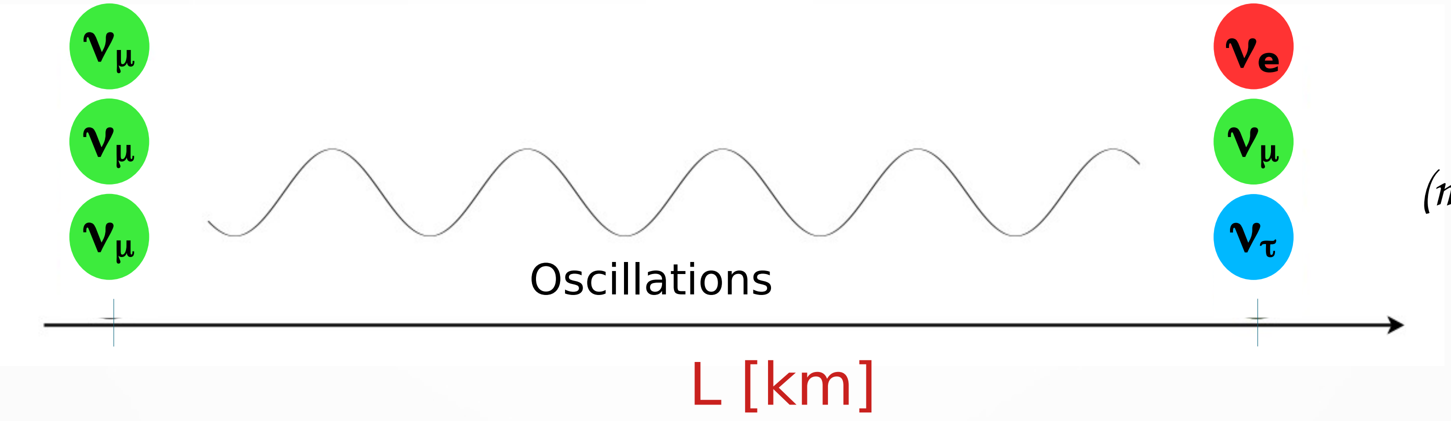
c_{ij}, s_{ij} – $\cos\theta_{ij}$, $\sin\theta_{ij}$ (θ_{ij} – mixing angles),
δ_{CP} – CP violation (CPV) phase

Hyper-K will be sensitive to all oscillation parameters.

Neutrino oscillation probability

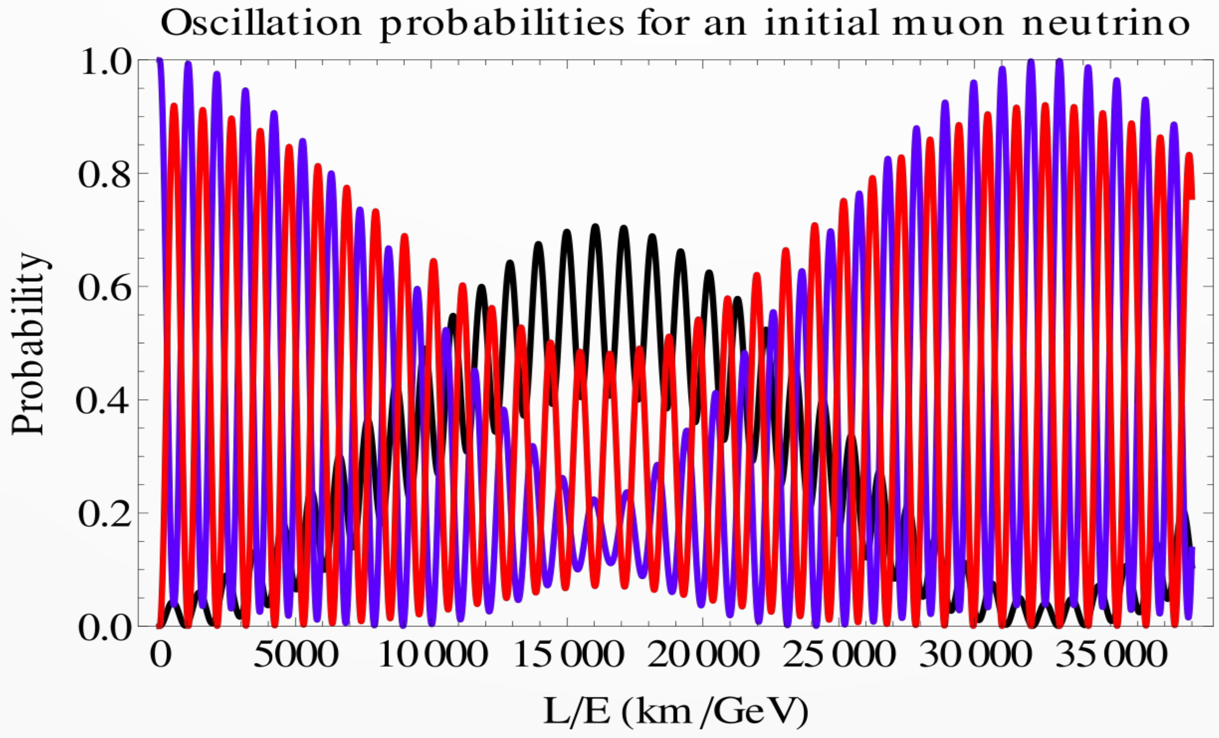
Example for muon neutrinos

Muon neutrinos
with energy E [GeV]



Detector
(mixture of neutrinos of
all three flavors)

Probability
of transition
$P(\nu_\alpha \rightarrow \nu_\beta)$
'oscillates'
with L/E



$P(\nu_\mu \rightarrow \nu_\mu)$

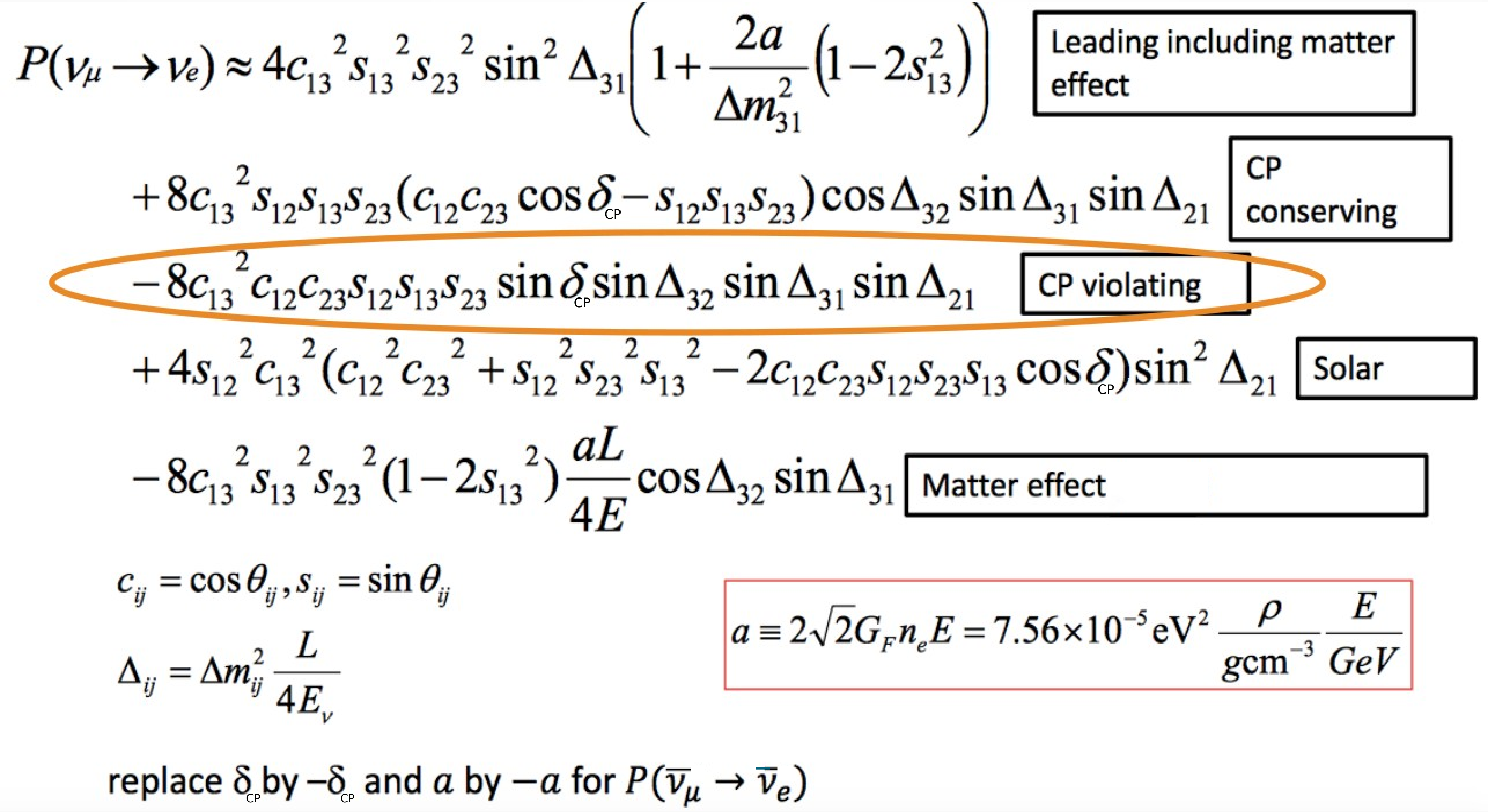
$P(\nu_\mu \rightarrow \nu_e)$

$P(\nu_\mu \rightarrow \nu_\tau)$

CP violation

- CP symmetry – combination of charge (C) and parity (P) symmetry.
- Violation of CP implies that there is a difference between particles and antiparticles.
- CP violation is one of Sakharov’s conditions for an explanation of the observed imbalance of matter and antimatter abundance in the Universe.
    - Discovered in quark sector.
- In neutrino sector it may be manifested in different oscillation probabilities for neutrinos and antineutrinos.

Three flavor $\nu_\mu \to \nu_e$ appearance probability



$$P(\nu_\mu \to \nu_e) \approx 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2s_{13}^2\right)\right)$$

Leading including matter effect

$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP}-s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP conserving

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$

CP violating

$$+4s_{12}^2c_{13}^2(c_{12}^2c_{23}^2+s_{12}^2s_{23}^2s_{13}^2-2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin^2\Delta_{21}$$

Solar

$$-8c_{13}^2s_{13}^2s_{23}^2(1-2s_{13}^2)\frac{aL}{4E}\cos\Delta_{32}\sin\Delta_{31}$$

Matter effect

$$c_{ij}=\cos\theta_{ij}, s_{ij}=\sin\theta_{ij}$$

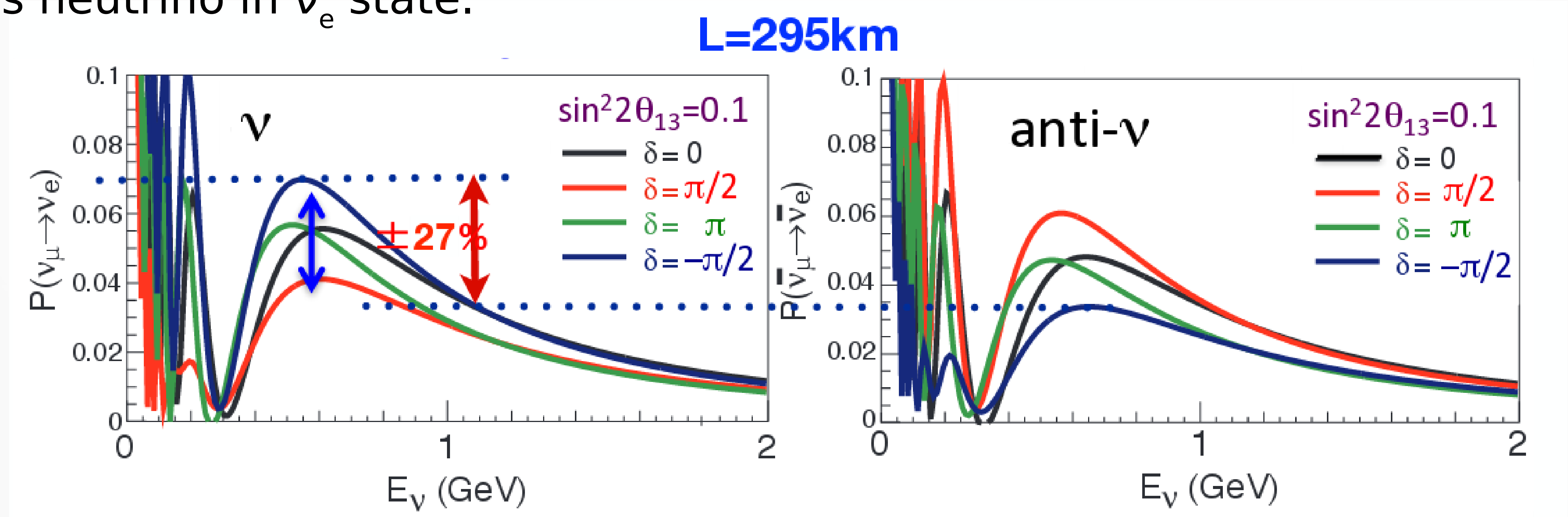
$$\Delta_{ij}=\Delta m_{ij}^2\frac{L}{4E_\nu}$$

$$a\equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2\,\frac{\rho}{\mathrm{gcm}^{-3}}\,\frac{E}{GeV}$$

replace δ_{CP} by $-\delta_{CP}$ and a by $-a$ for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

Neutrino oscillation probability

Probability that a neutrino produced in ν_μ flavor state will interact as neutrino in ν_e state.

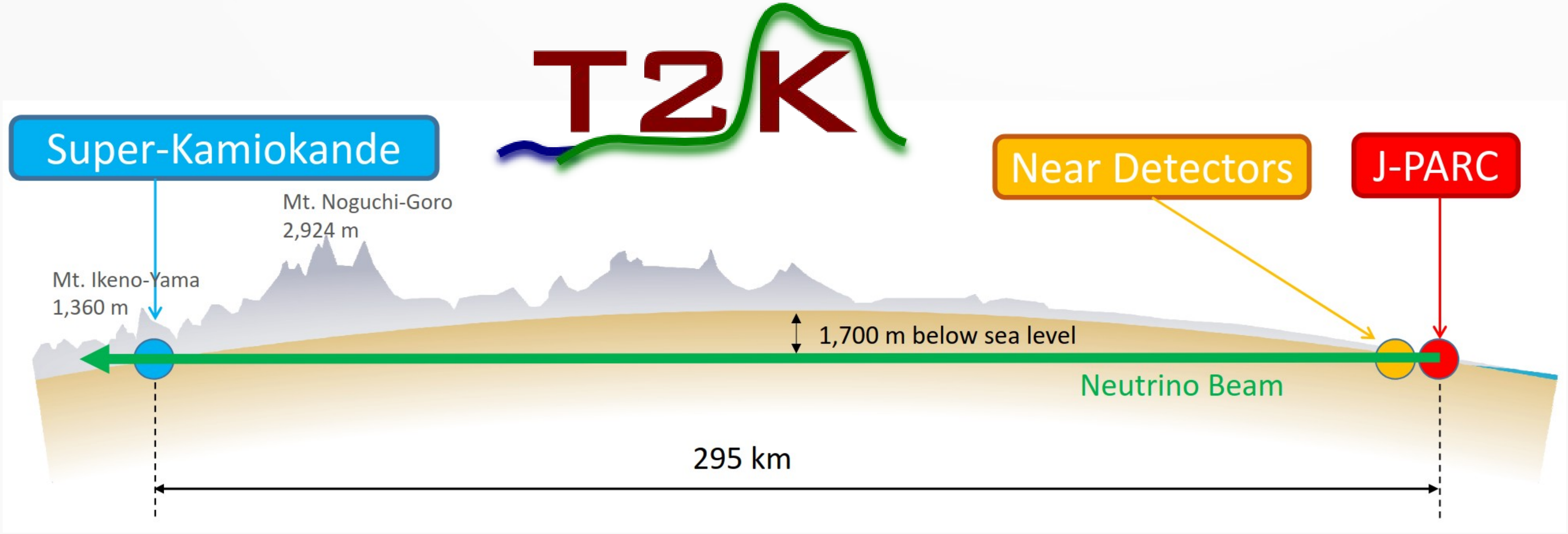


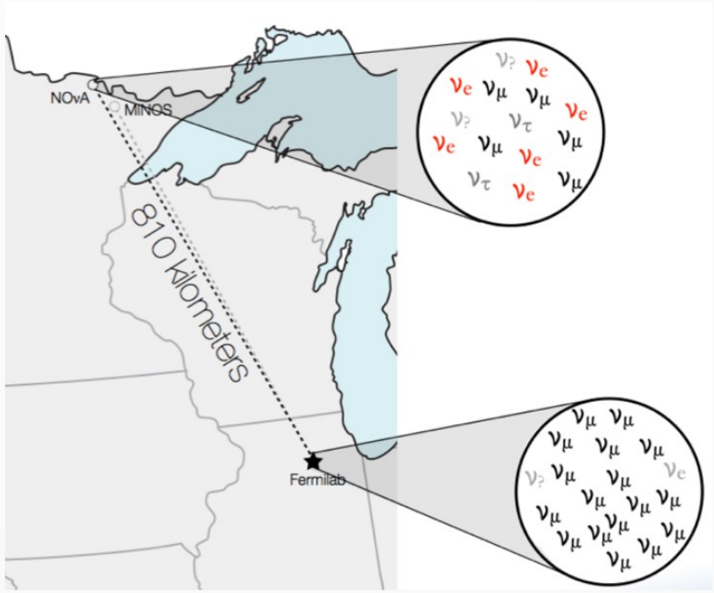
Impact of δ_{CP} violation phase for neutrinos and antineutrinos. Maximal CP violation results in approximately ±27% change of the ν_e appearance probability (wrt. CP conserving values).

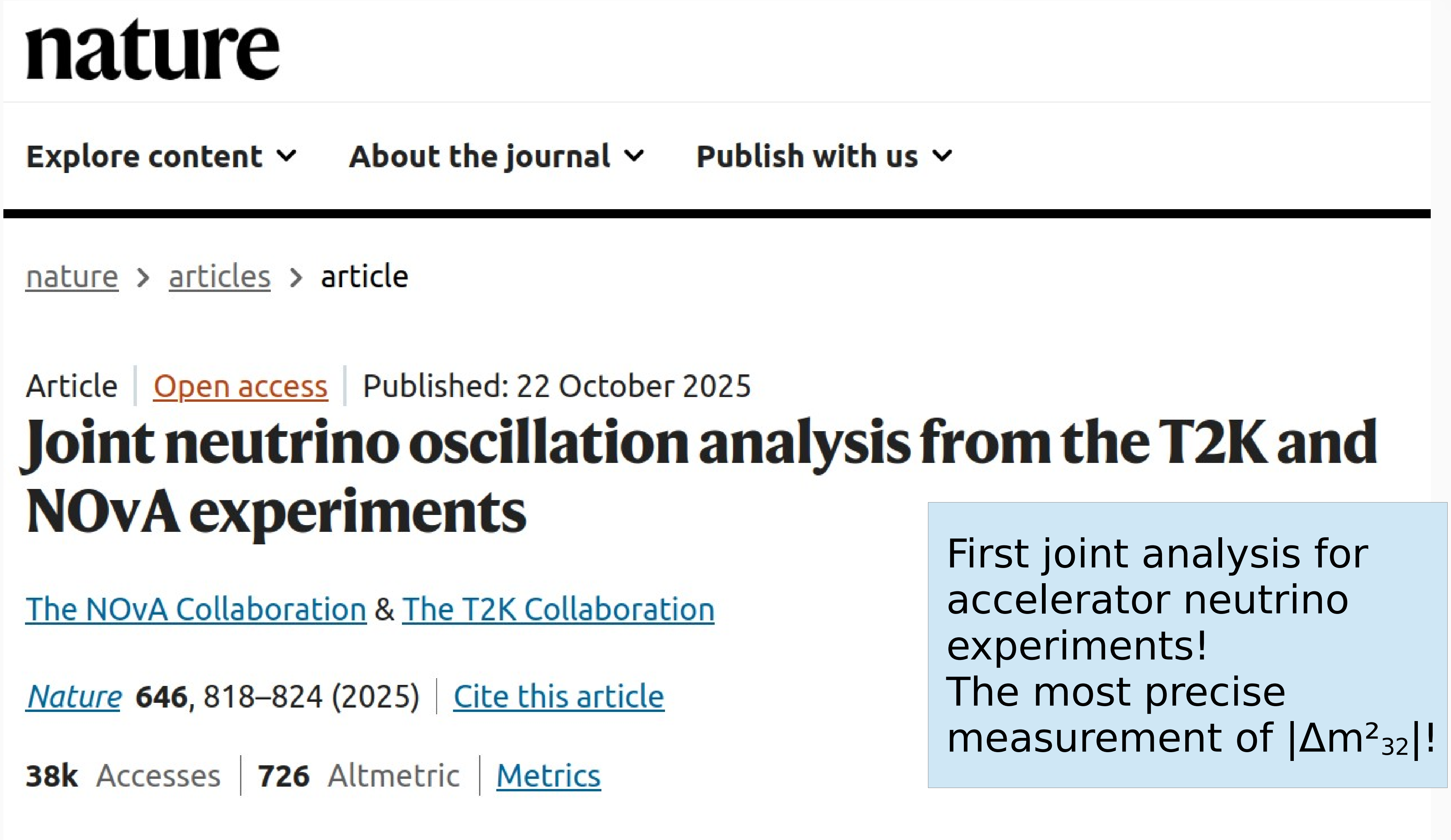
Matter effects small compared to CP violation (difference between $\delta_{CP} = 0, \pi$).

Accelerator long baseline experiments

- A class of neutrino oscillation experiments using the accelerator-produced beam of ν_μ.
- Primary proton beam is used to produce secondary particles decaying to muons and neutrinos.
- Historically: K2K, MINOS. Ongoing: T2K, NOvA. Near future: Hyper-Kamiokande, DUNE.







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Joint neutrino oscillation analysis from the T2K and NOvA experiments

The NOvA Collaboration & The T2K Collaboration

Nature **646**, 818–824 (2025) | Cite this article

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First joint analysis for accelerator neutrino experiments!
The most precise measurement of $|\Delta m^2_{32}|$!

https://www.nature.com/articles/s41586-025-09599-3

Outline

- Introduction to neutrino physics
- **Water Cherenkov experiments in Japan**
- Hyper-Kamiokande detector
- Physics goals
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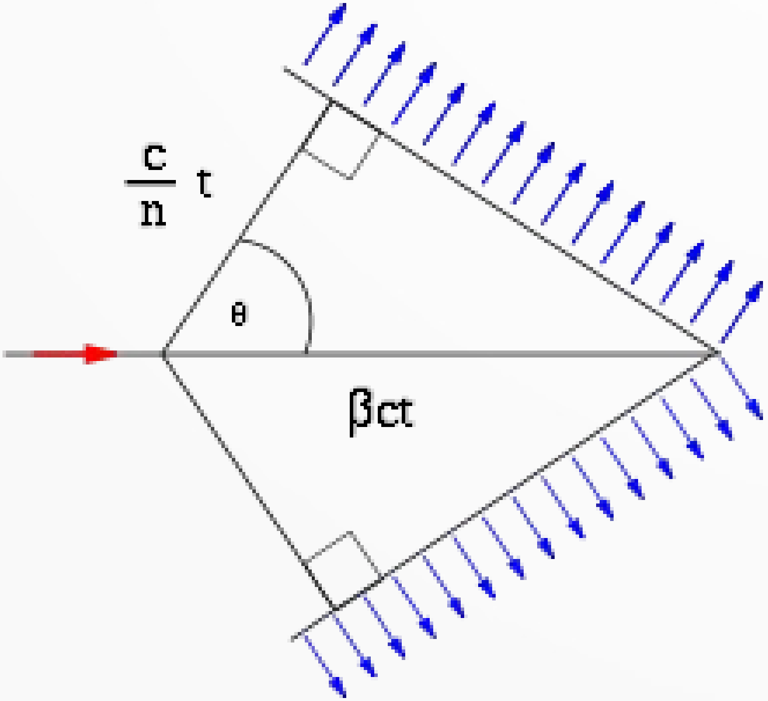
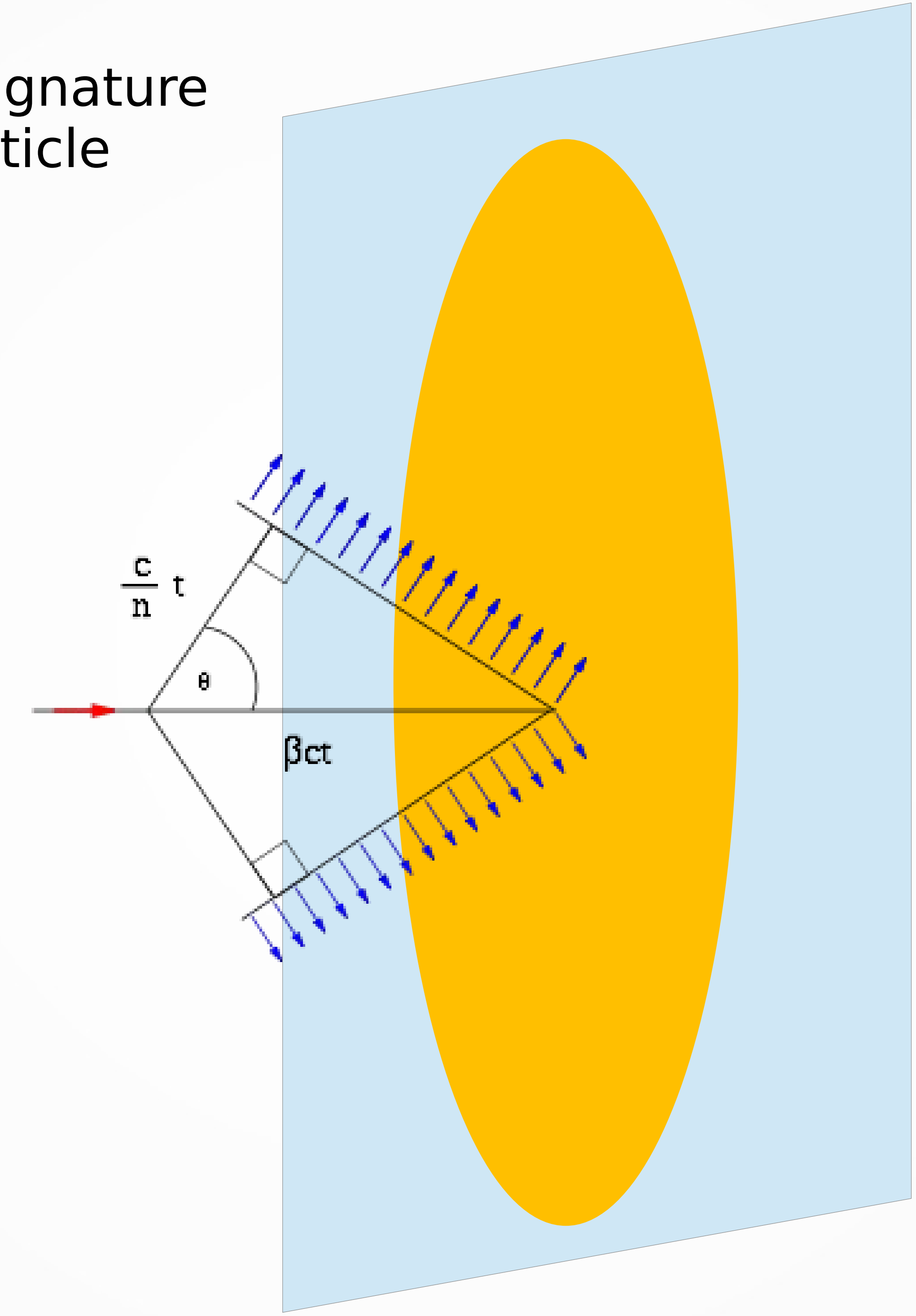
Cherenkov radiation signature

- Cherenkov radiation appears when charged particle propagates with velocity v > c/n
- For water Cherenkov threshold corresponds to momentum ≳ 1.14×mass



Getty Images

- Single circle or ring – signature of a single charged particle



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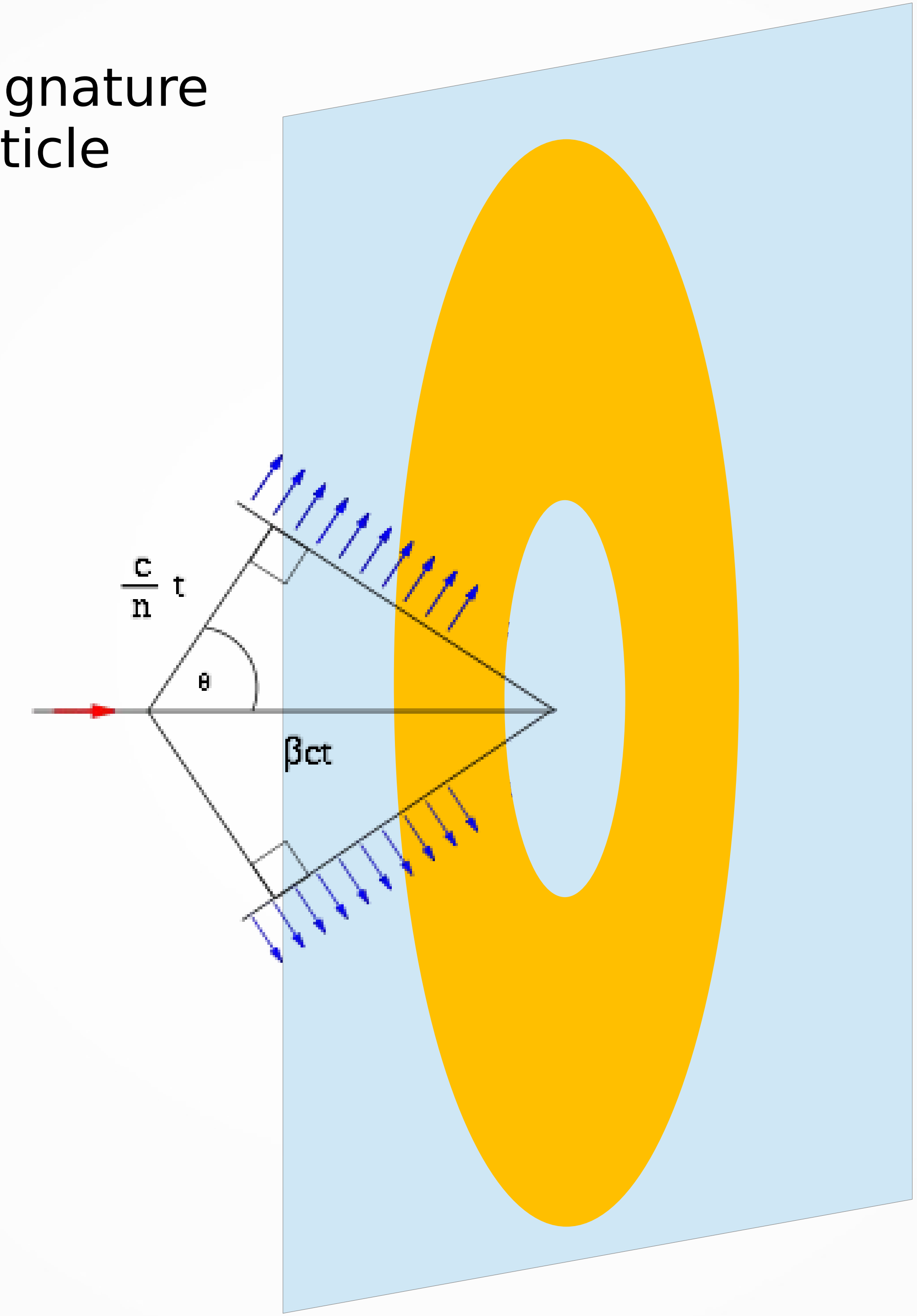
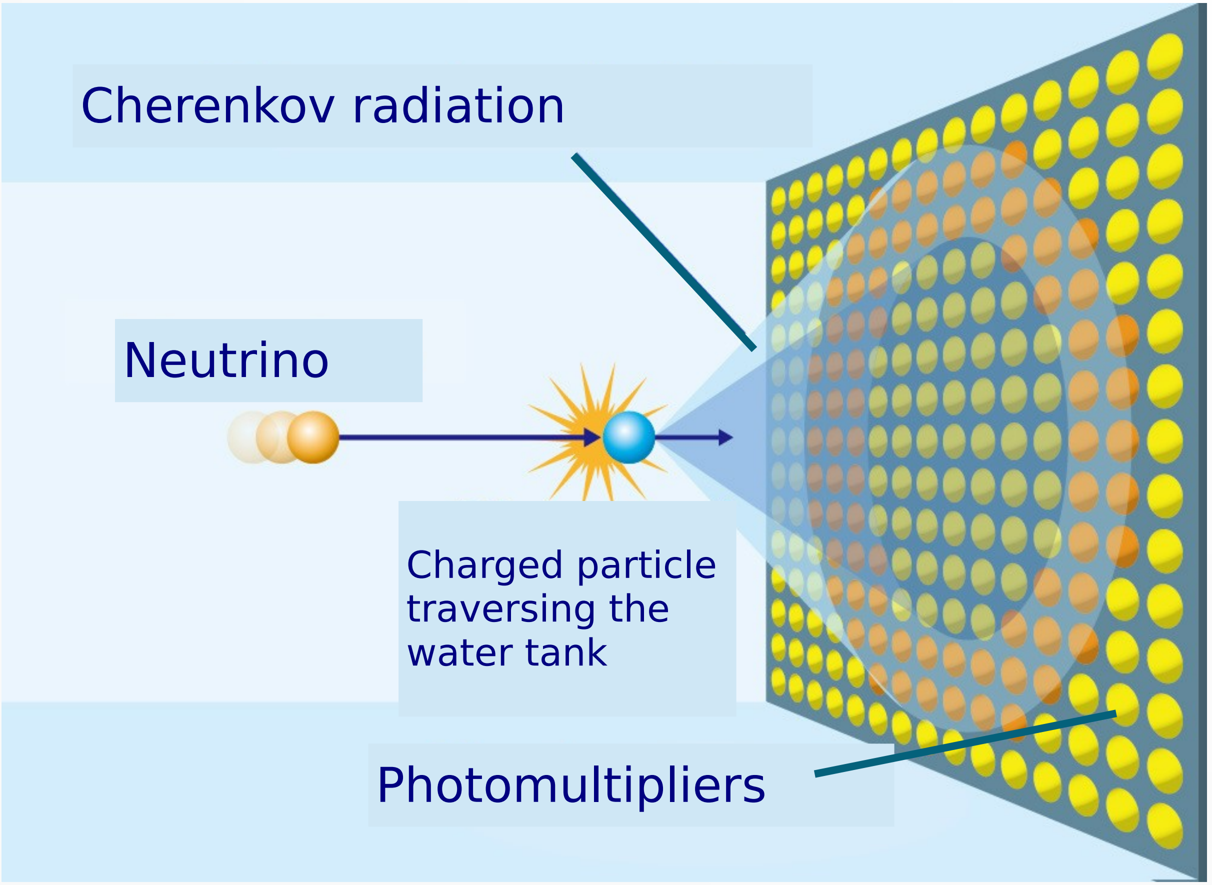


Cherenkov radiation detection



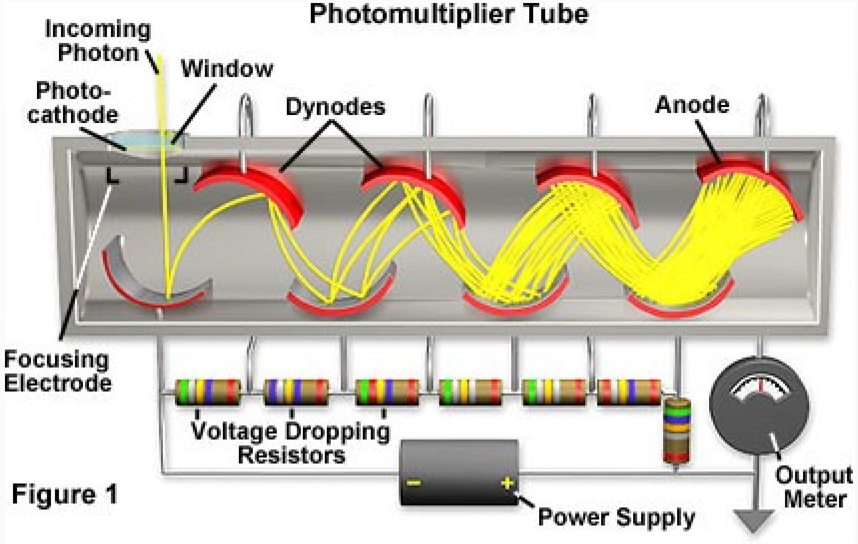
Cherenkov radiation

Neutrino

Charged particle traversing the water tank

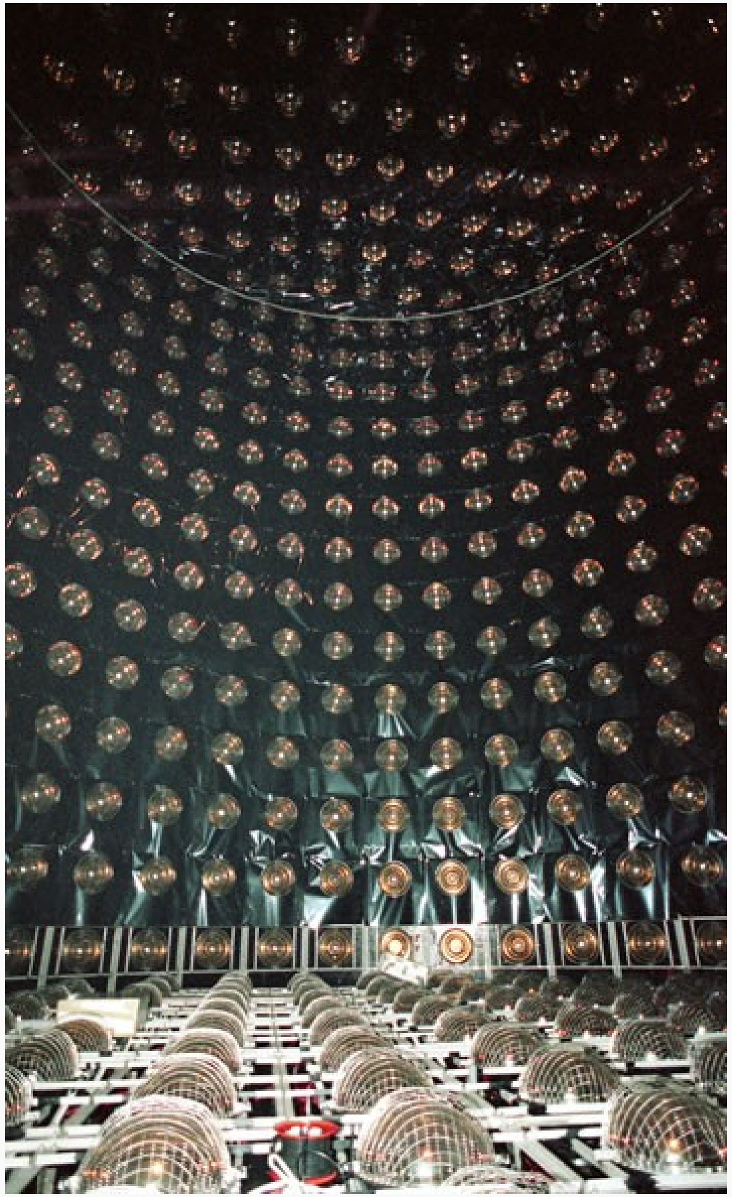
Photomultipliers

- Photomultipliers detect the characteristic signatures of the Cherenkov light.
- Spatial and time distribution of the Cherenkov light allow to reconstruct the direction of a charged particle.



Kamiokande

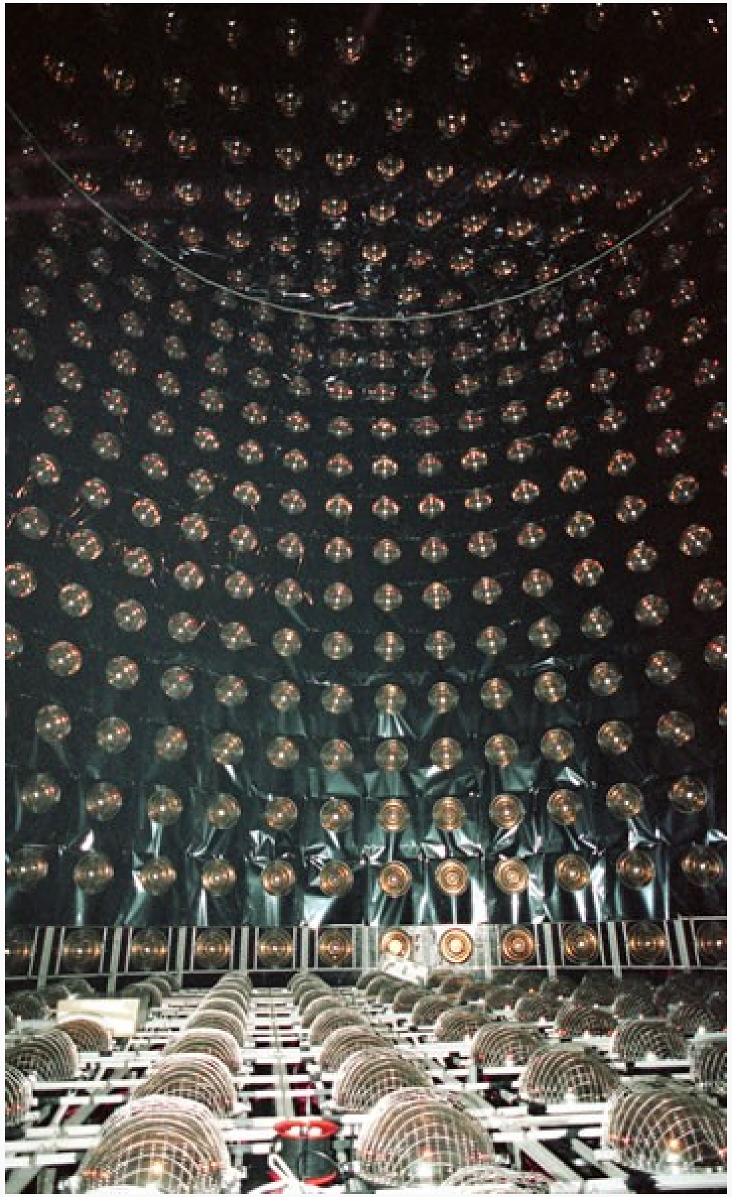
- Kamioka Nucleon Decay Experiment
- Started in 1983 to search for proton decay.
- Cylindrical detector filled with 3000 tons of water, 16 m wide and 16 m high. 948 photomultiplier tubes.



www-sk.icrr.u-tokyo.ac.jp

Kamiokande II

- Kamiokande II was the second phase of the experiment started in 1985, aimed at observing solar neutrinos.
- Increased sensitivity after 1986 upgrade.



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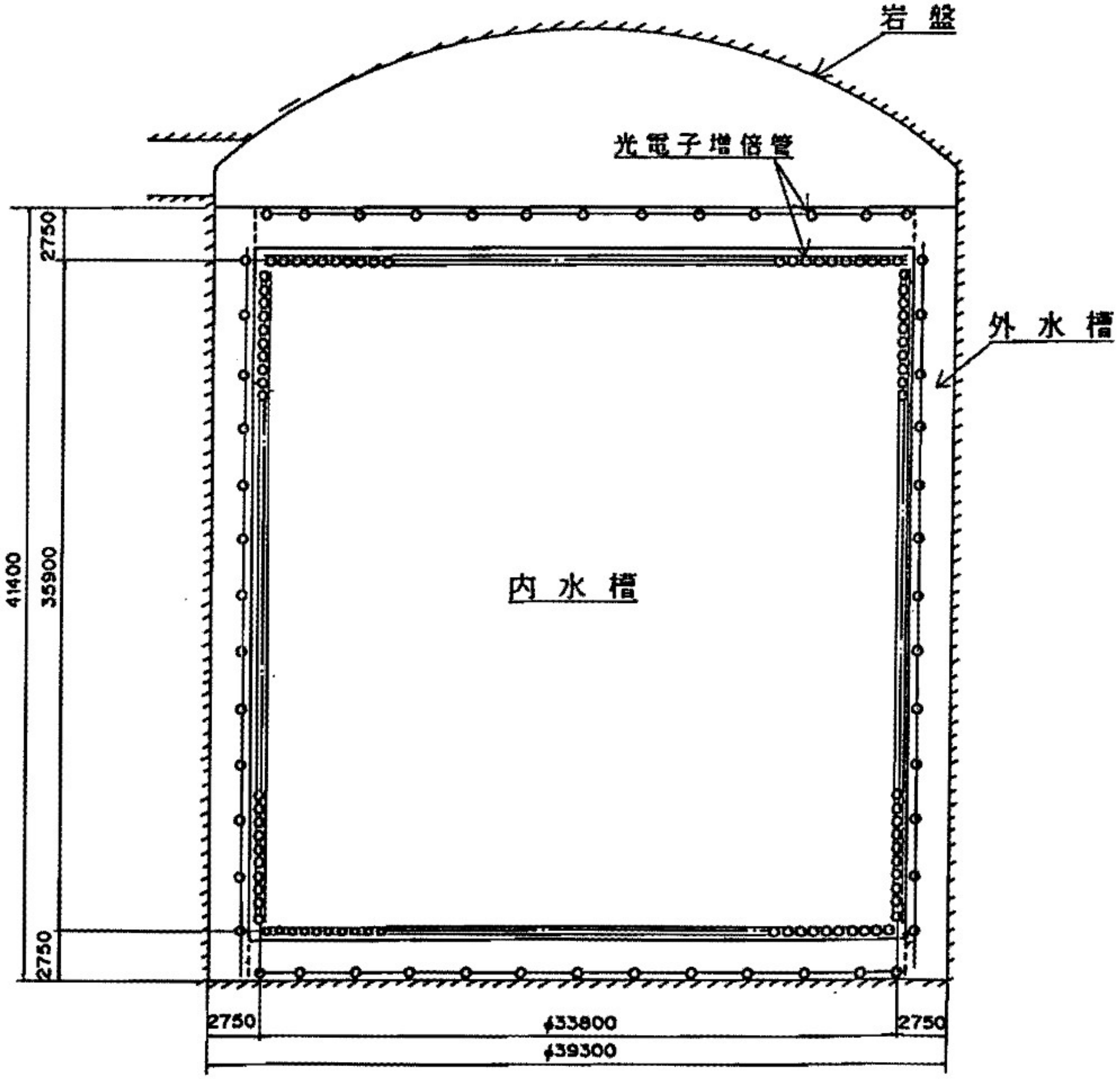
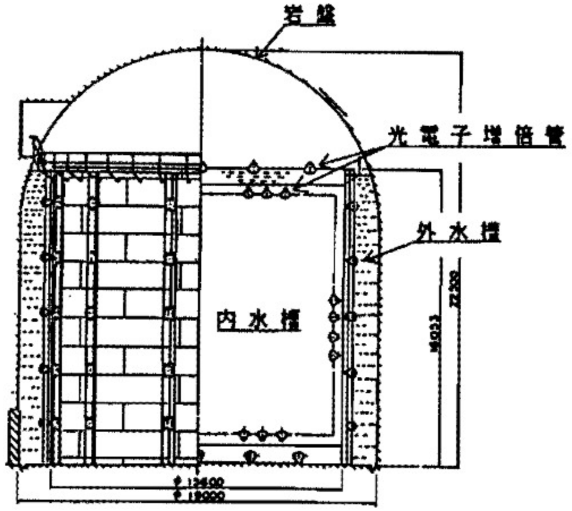
Super-Kamiokande

Superkamiokande



- The operation of the second generation detector, Super-Kamiokande started in 1996.

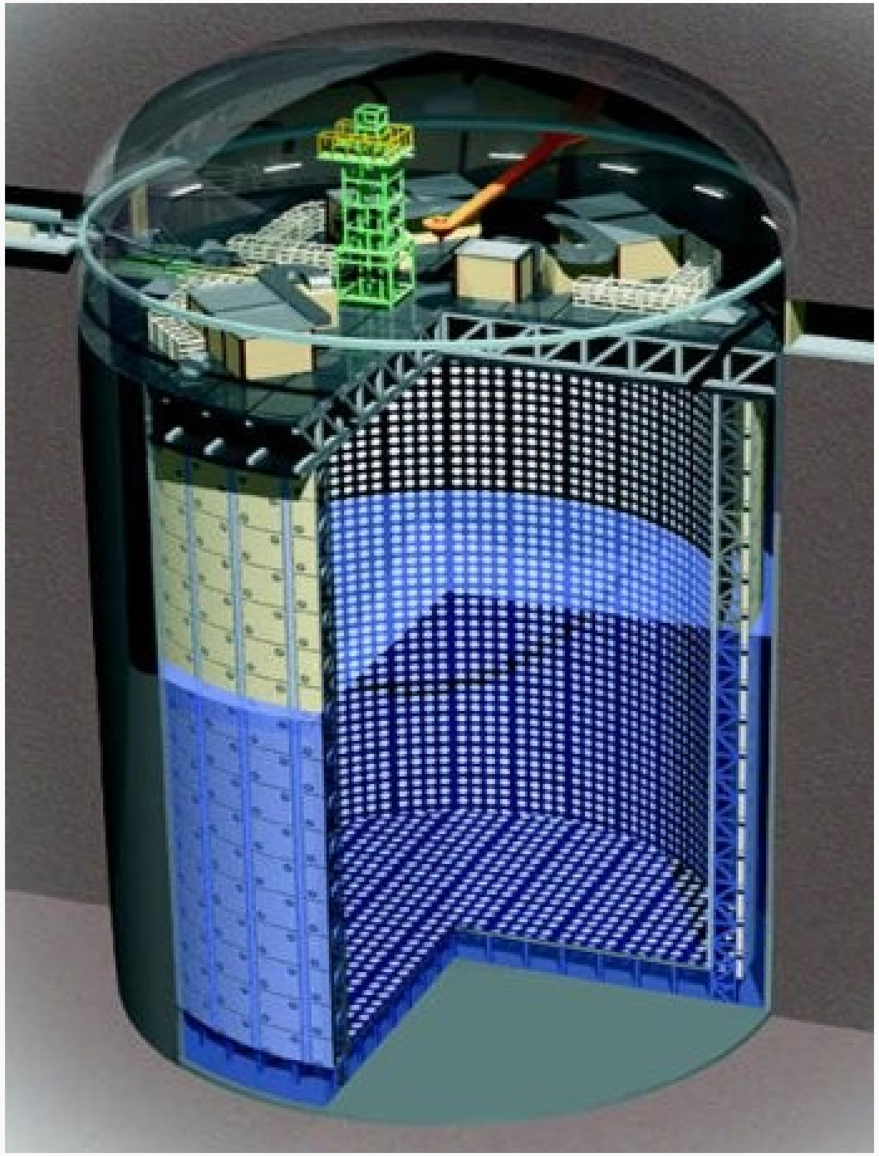
Kamiokande

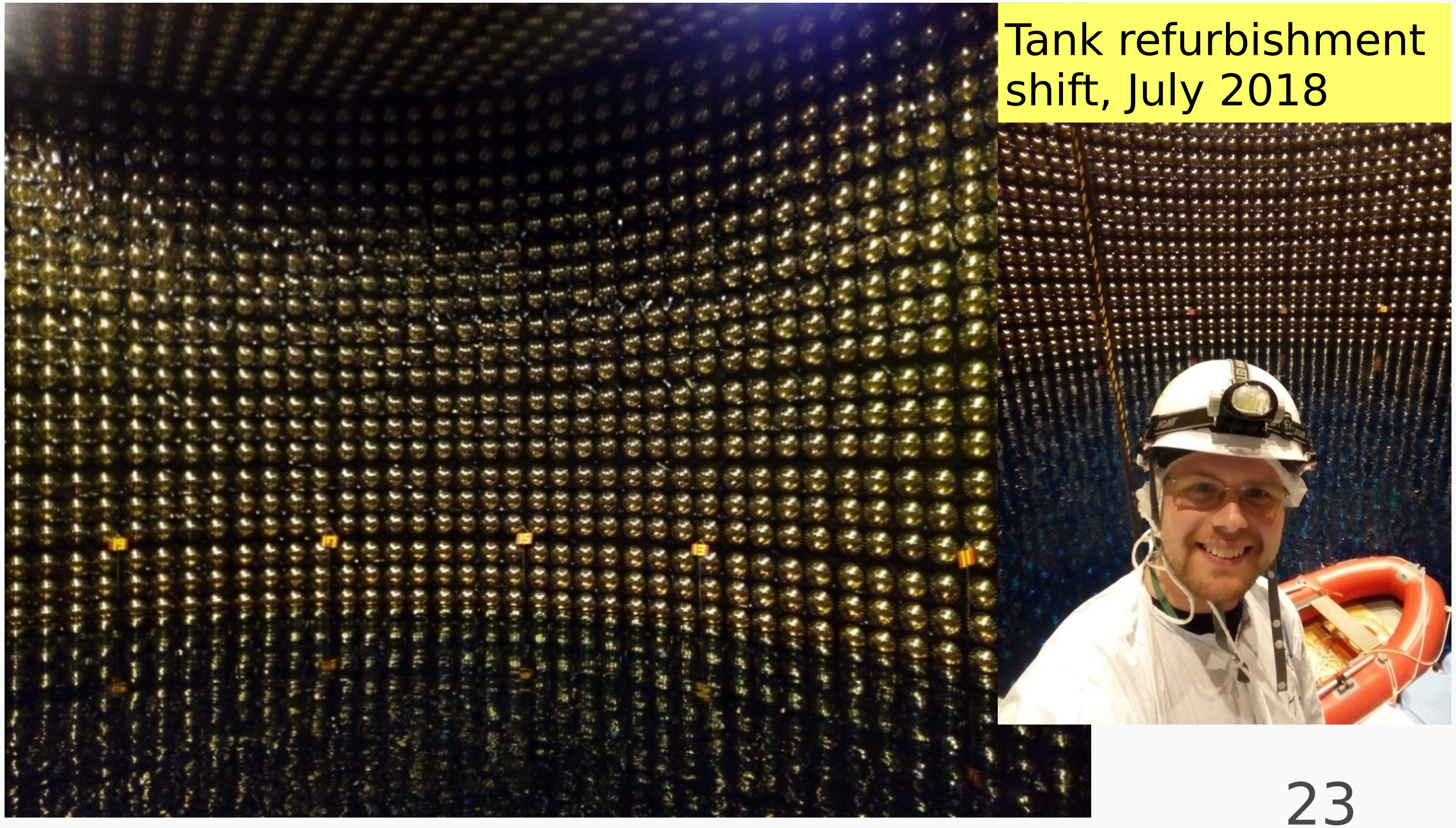


K. Nakamura, 3rd KEK Workshop on Physics at the TeV Energy Scale (1989)

Super-Kamiokande

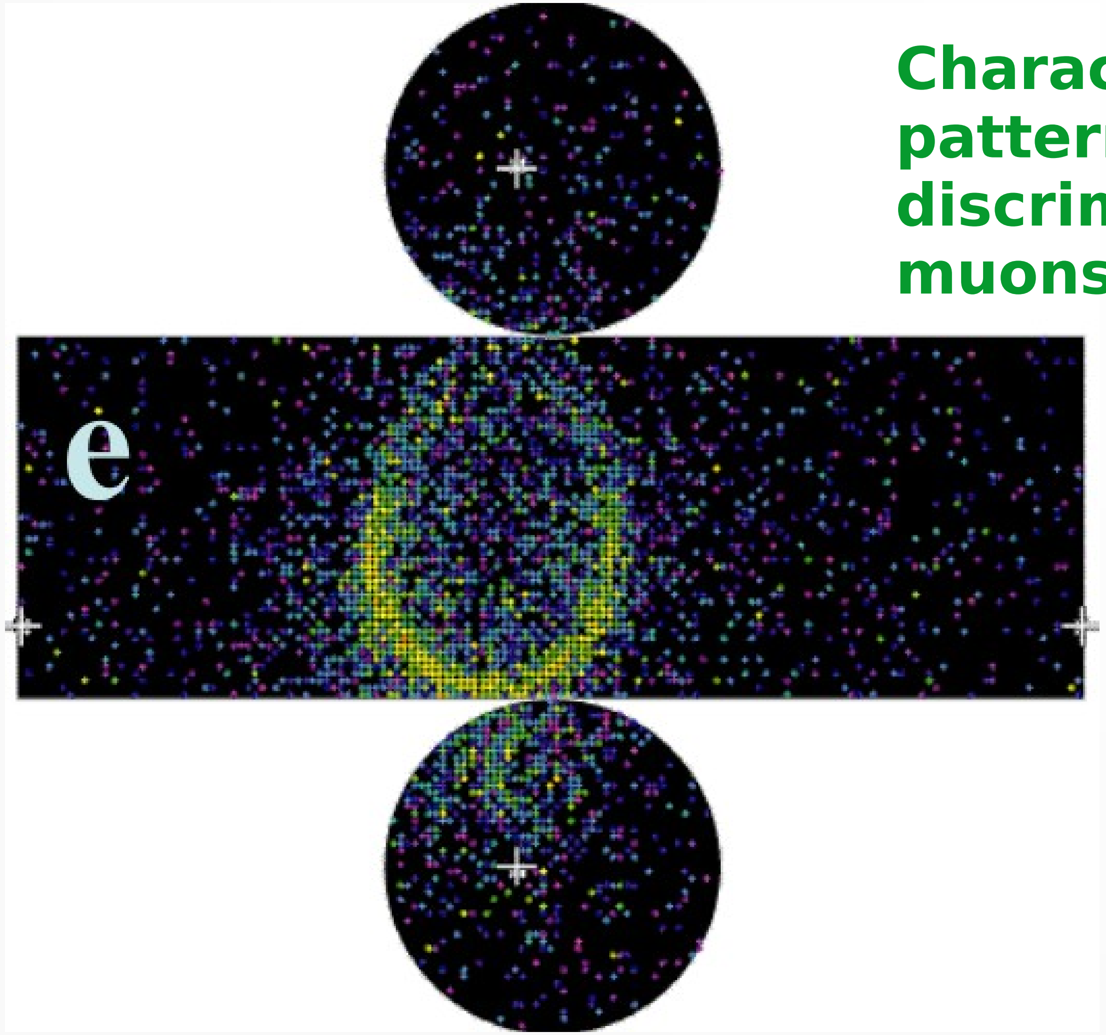
- The tank (41 m high, 39 m wide) was filled with 50,000 tons of water. The detector was equipped with ~11,000 PMTs.



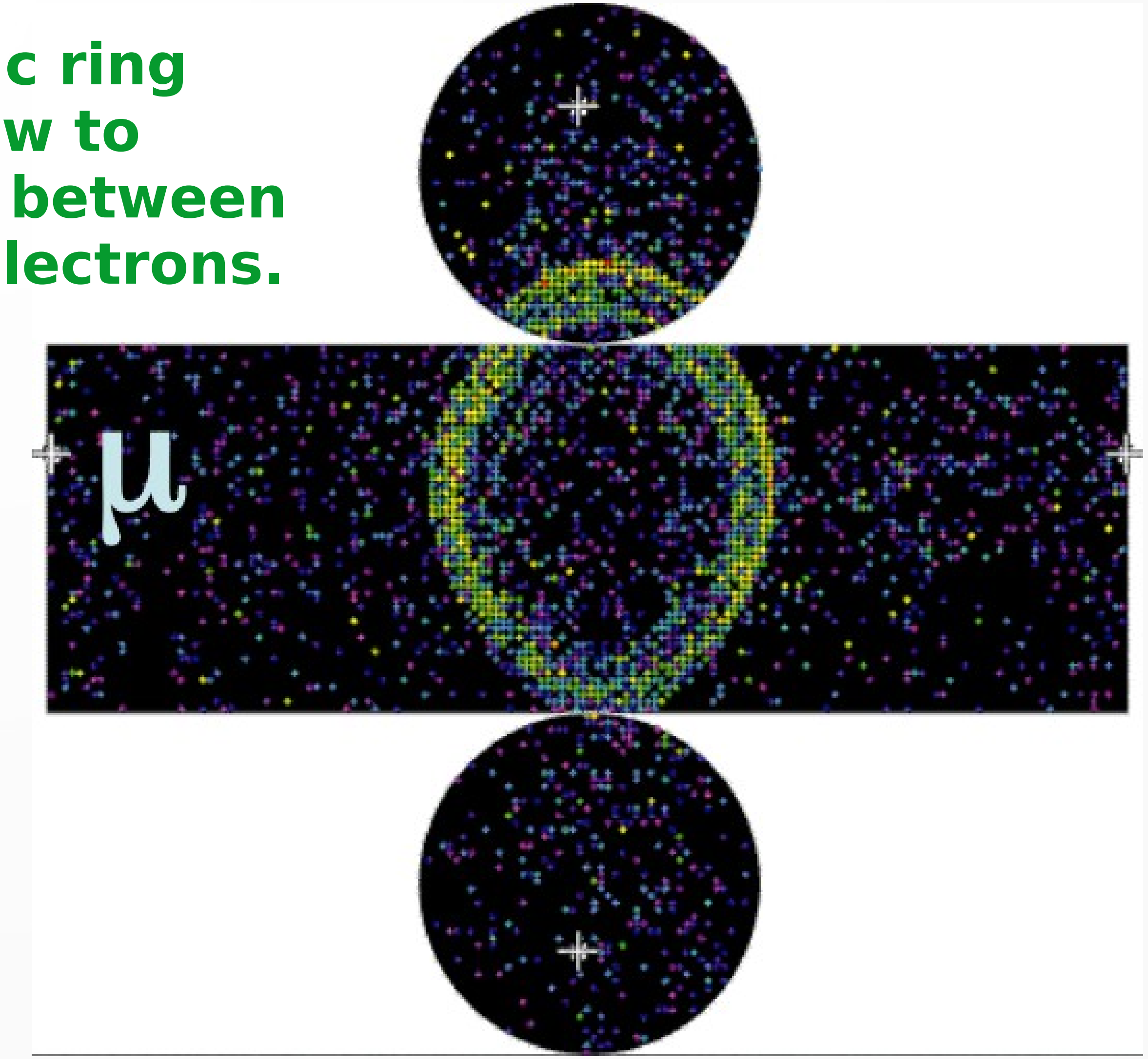


Tank refurbishment shift, July 2018

Super-Kamiokande event display



Characteristic ring patterns allow to discriminate between muons and electrons.



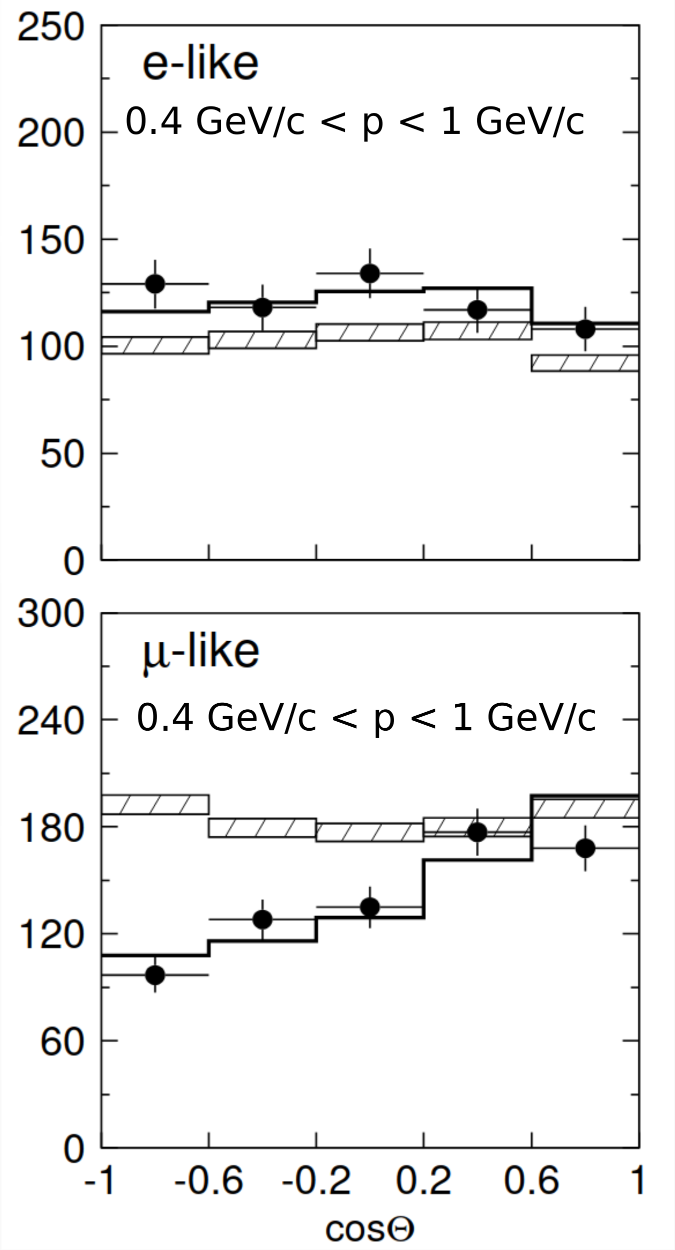
Discovery of atmospheric neutrino oscillations

- In 1998 it was discovered that the number of muon neutrinos coming from the other side of the Earth was significantly lower than expected.
- Bottom plot shows clear **zenith angle dependence**.
  - Negative cosθ → up-going neutrino
  - Positive cosθ → down-going neutrino
- **Solid evidence of neutrino oscillations!**

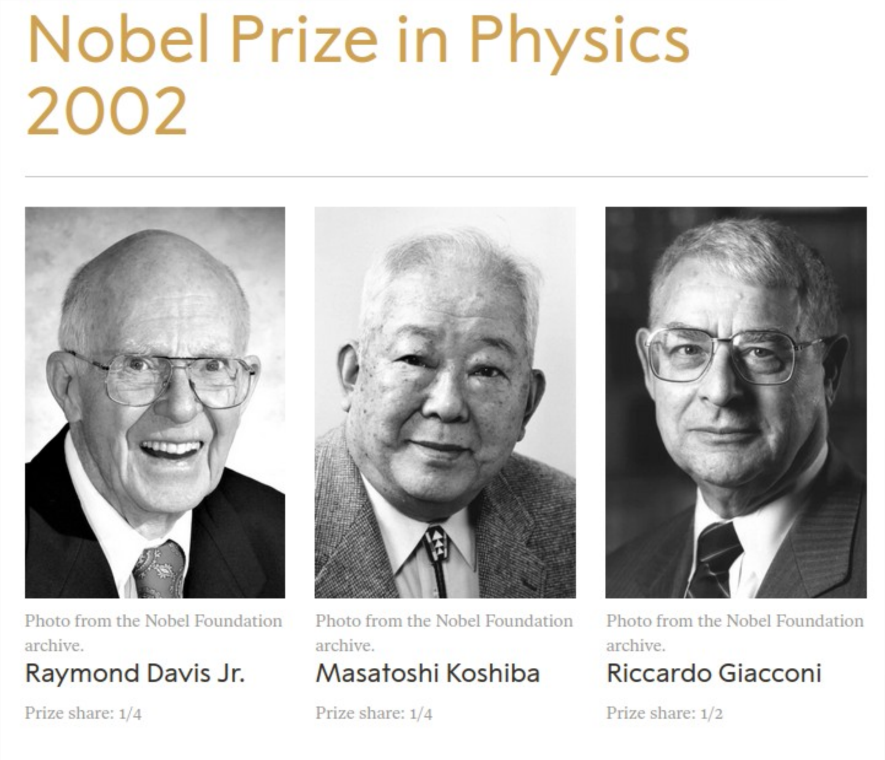
▨ Monte Carlo expected event rate for no oscillations

— Best fit to data assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations

DOI: 10.1103/PhysRevLett.81.1562



Impactful experiments



Nobel Prize in Physics 2002

Photo from the Nobel Foundation archive.
Raymond Davis Jr.
Prize share: 1/4

Photo from the Nobel Foundation archive.
Masatoshi Koshiba
Prize share: 1/4

Photo from the Nobel Foundation archive.
Riccardo Giacconi
Prize share: 1/2

One half jointly to Raymond Davis Jr. and Masatoshi Koshiba "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos".

Nobel Prize in Physics 2015

© Nobel Prize Outreach. Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

© Nobel Prize Outreach. Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

Jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

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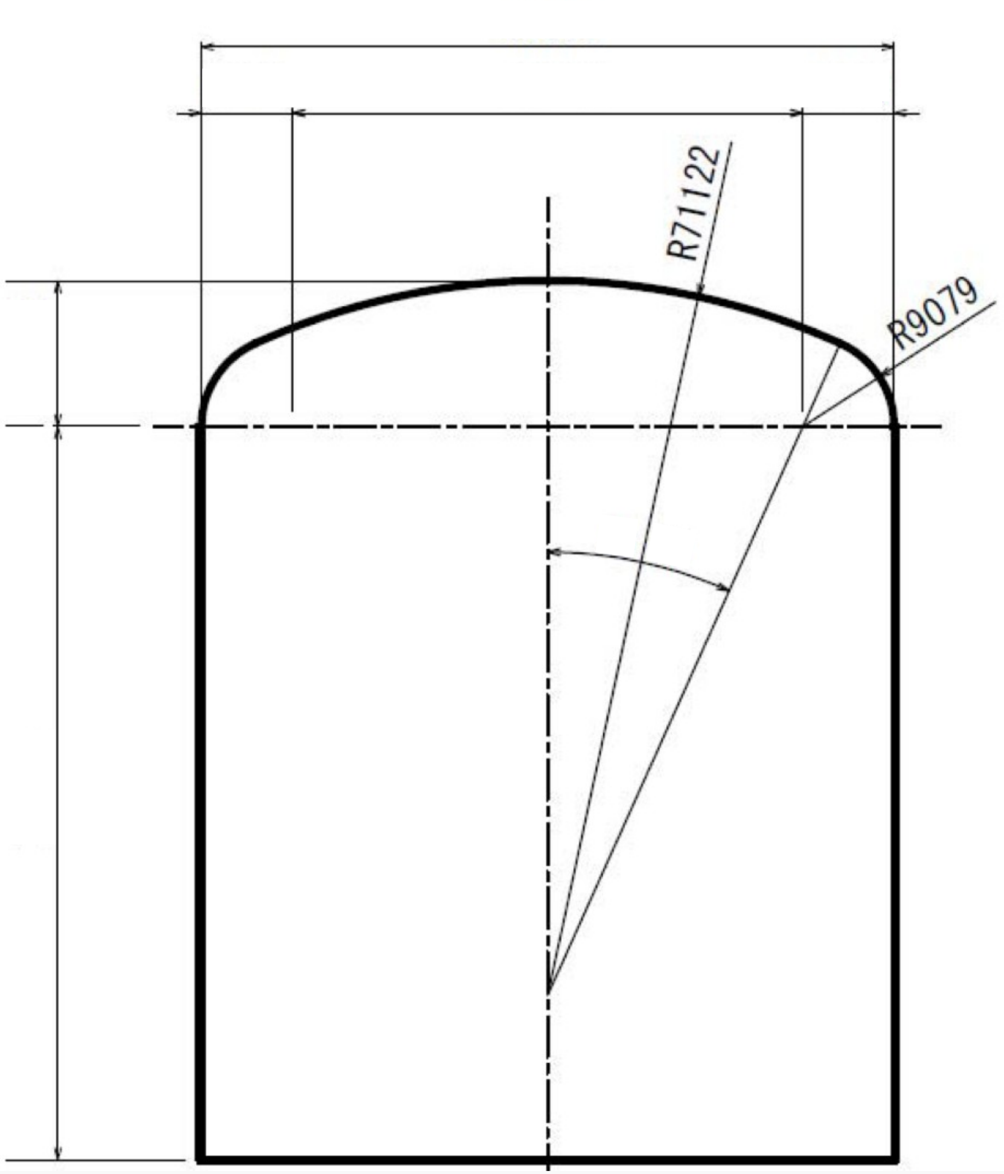
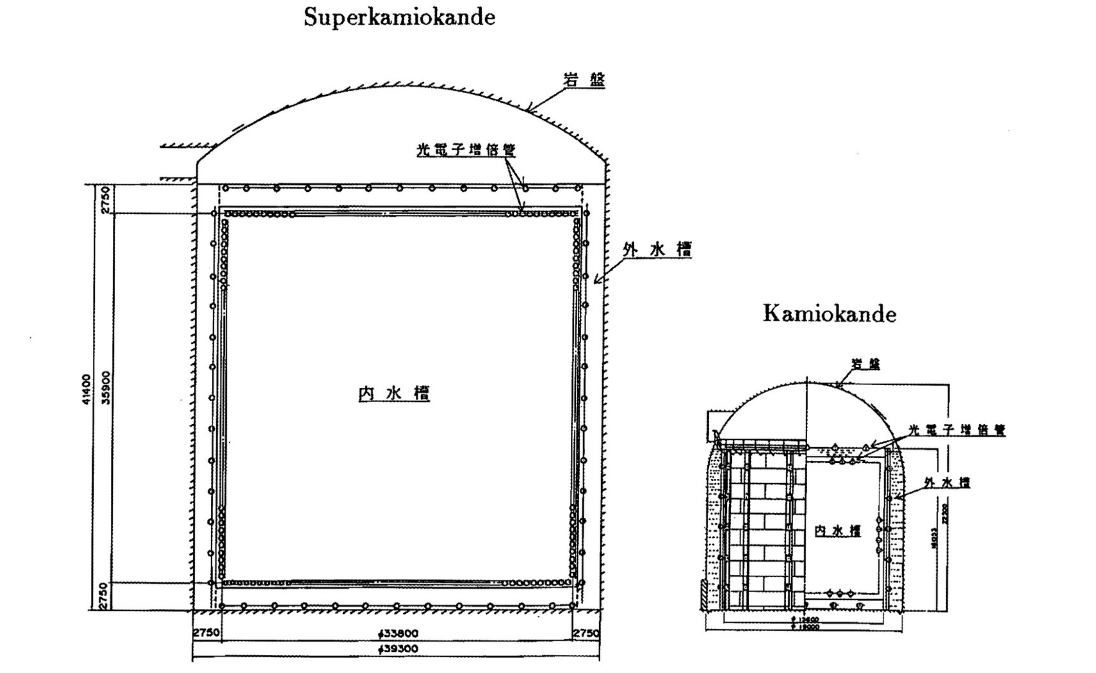
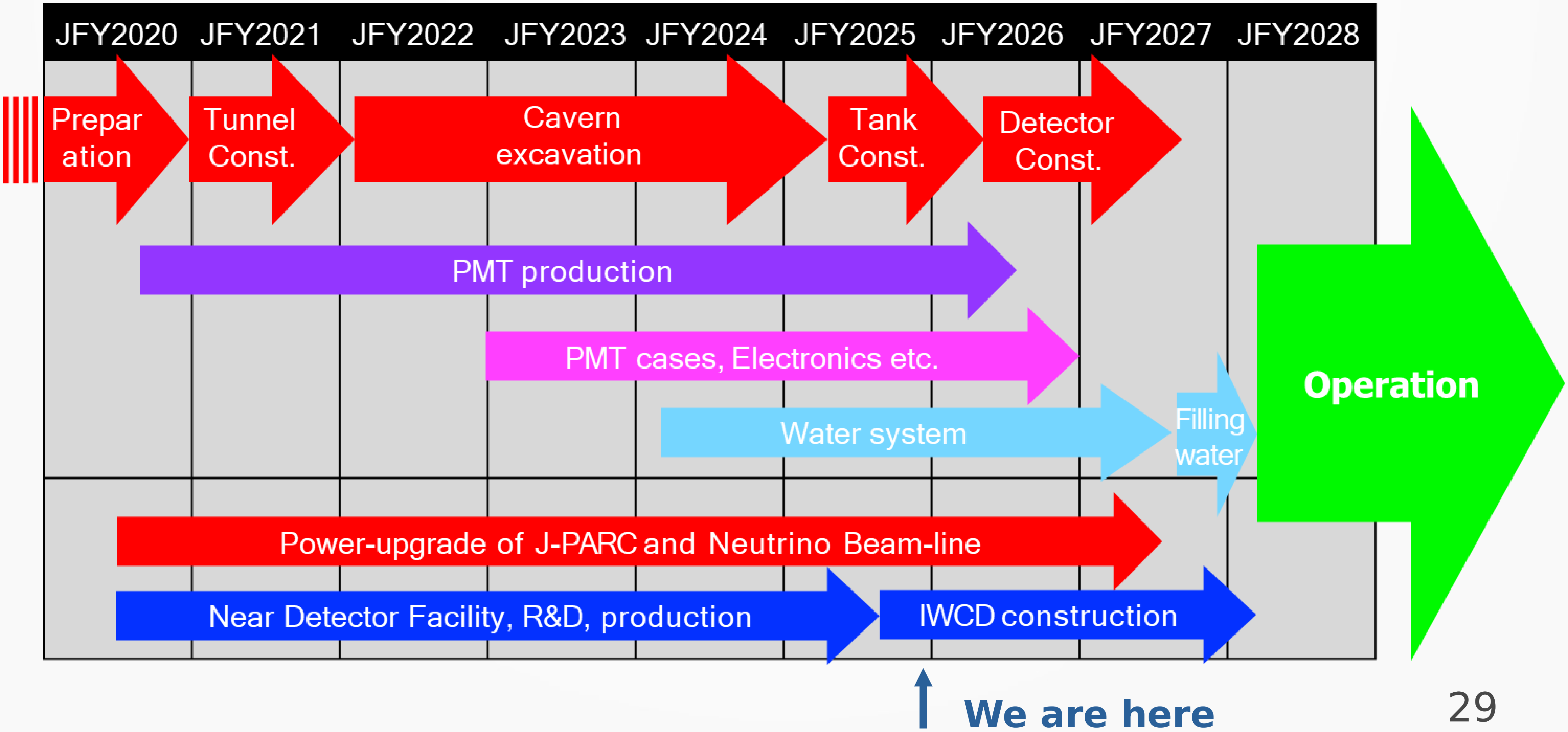
Hyper-Kamiokande



- The third generation detector!
- Water tank 71 m high and 68 m wide filled with 258,000 tons of water.
- Inner detector: 20,000 PMTs + 800 multiPMTs
- Outer detector: 3600 PMTs



Hyper-Kamiokande timeline



JFY2020 JFY2021 JFY2022 JFY2023 JFY2024 JFY2025 JFY2026 JFY2027 JFY2028

Preparation

Tunnel Const.

Cavern excavation

Tank Const.

Detector Const.

PMT production

PMT cases, Electronics etc.

Water system

Filling water

Operation

Power-upgrade of J-PARC and Neutrino Beam-line

Near Detector Facility, R&D, production

IWCD construction

We are here

Construction

Entrance yard under construction, May 2020

Excavation of the entrance tunnel, May 2021

Construction

Paved part of the access tunnel, January 2022

Center of the future Hyper-K Main Cavern's Dome reached, June 2022

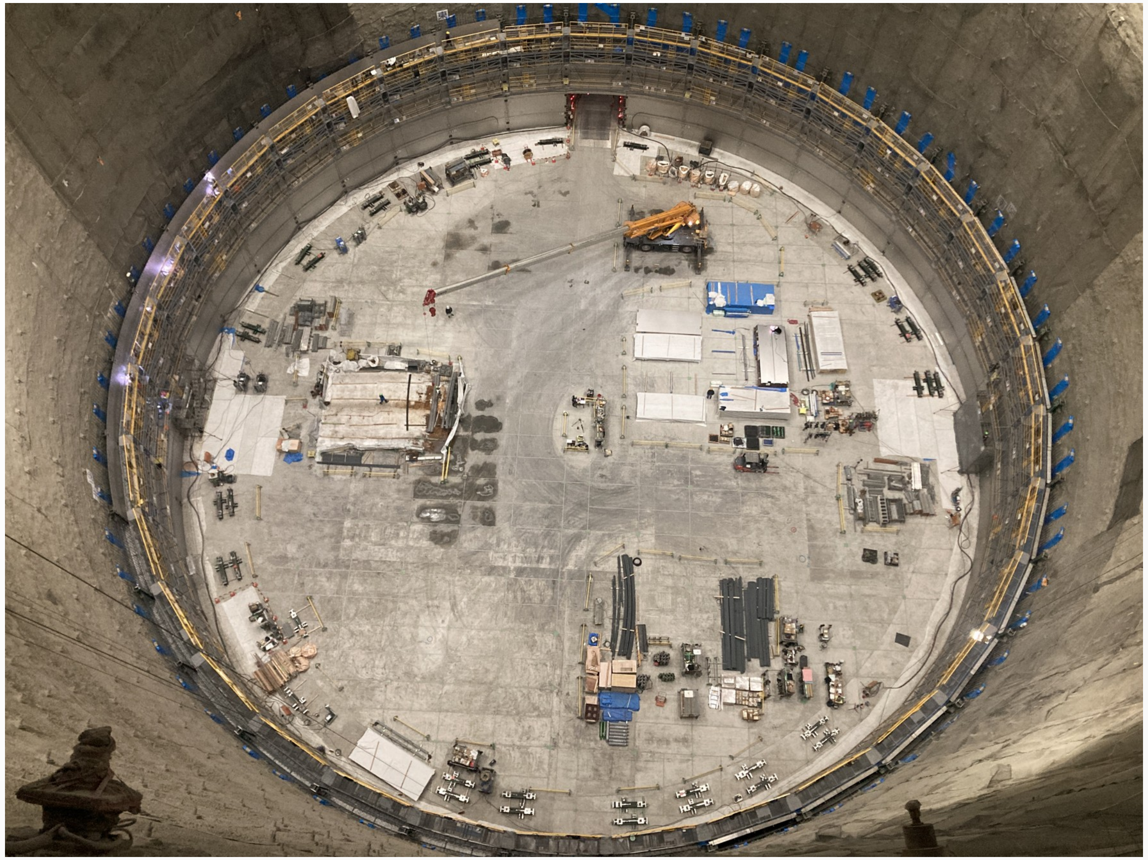
Construction

Dome height reaches 17 m, August 2023

The barrel section of the main cavern, March 2024

Construction

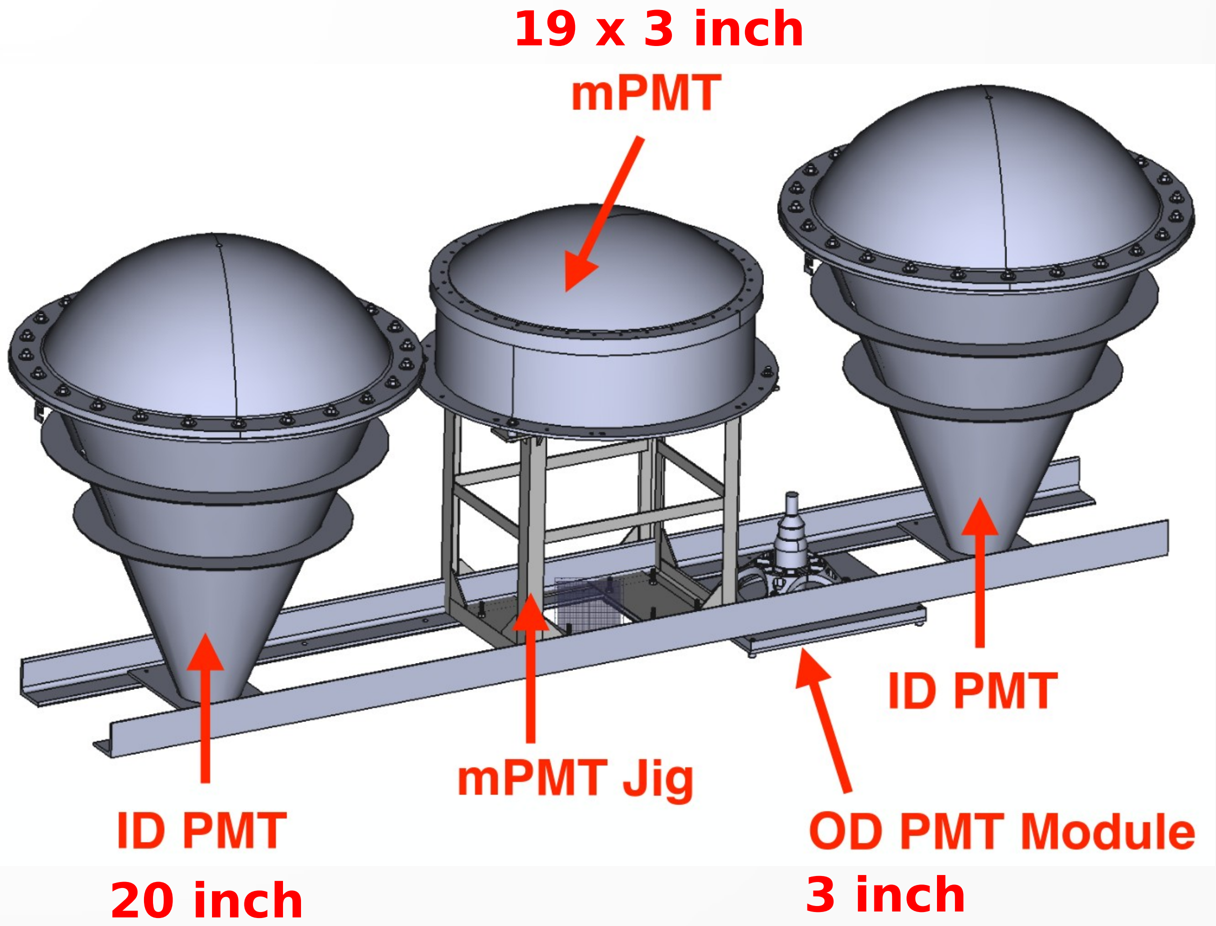
The main cavern completed, July 2025



The barrel section of the main cavern, January 2026

Photomultipliers (PMTs)

Dark room in Kamioka for PMT testing



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PHOTON IS OUR BUSINESS

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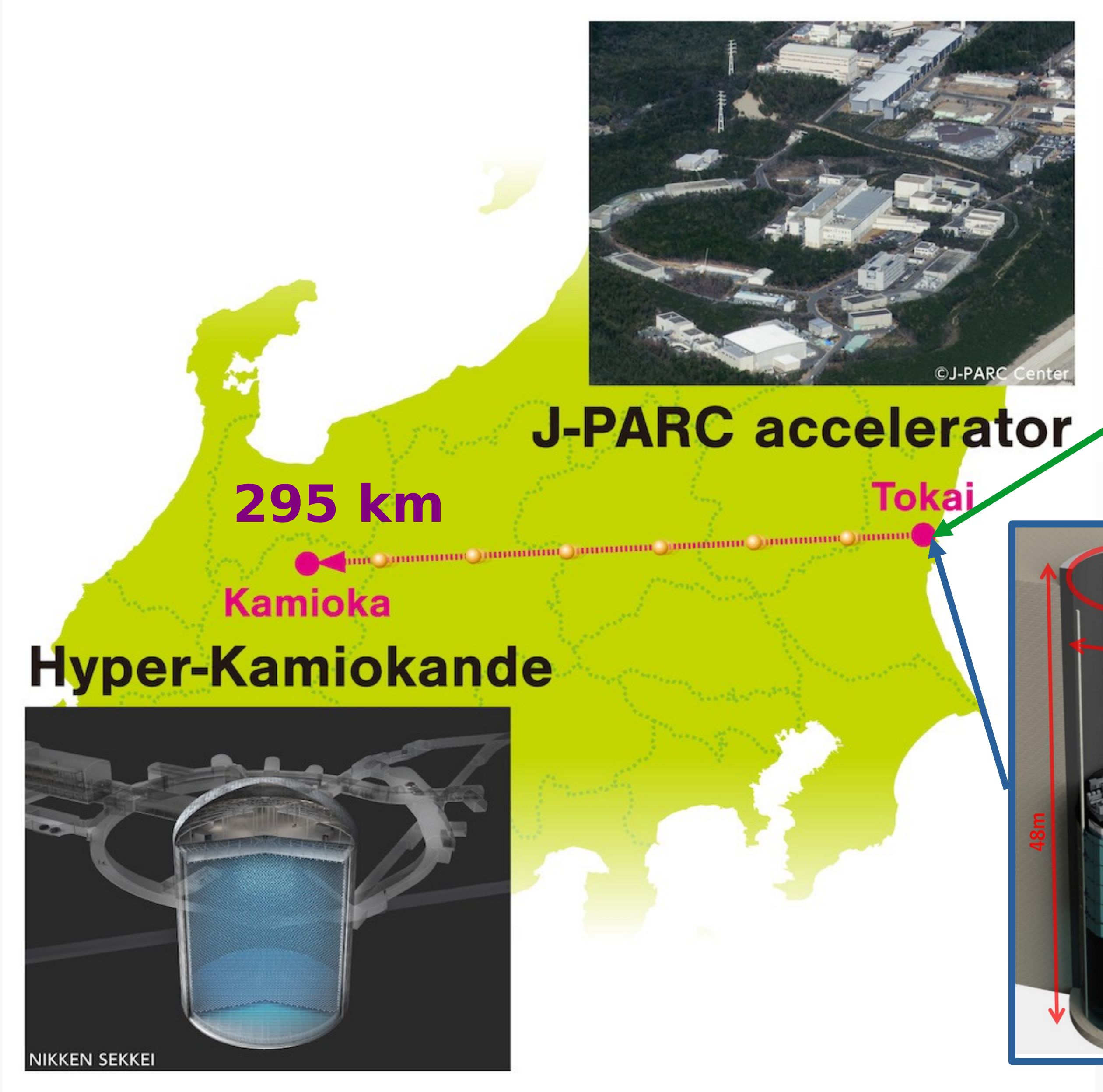
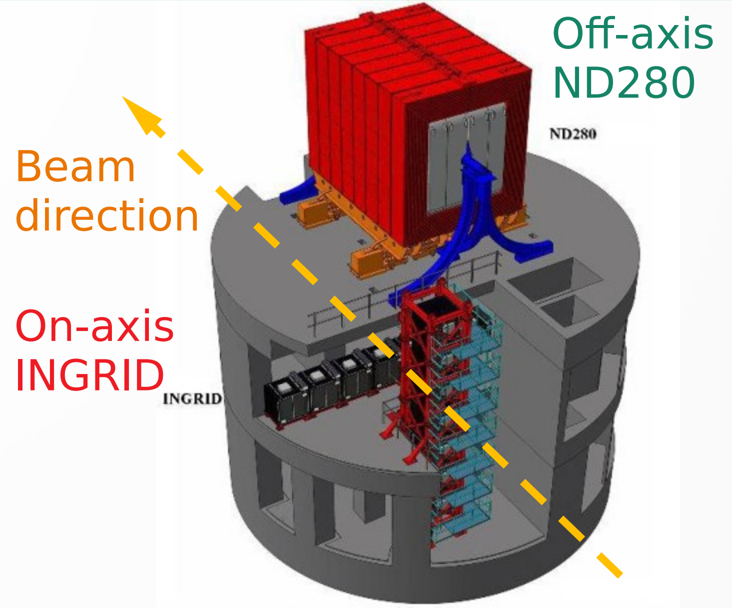
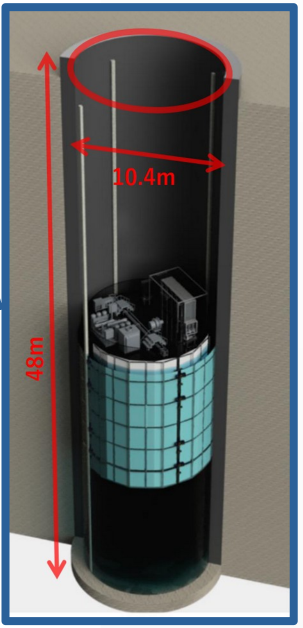
Far detector for the long-baseline neutrino experiment



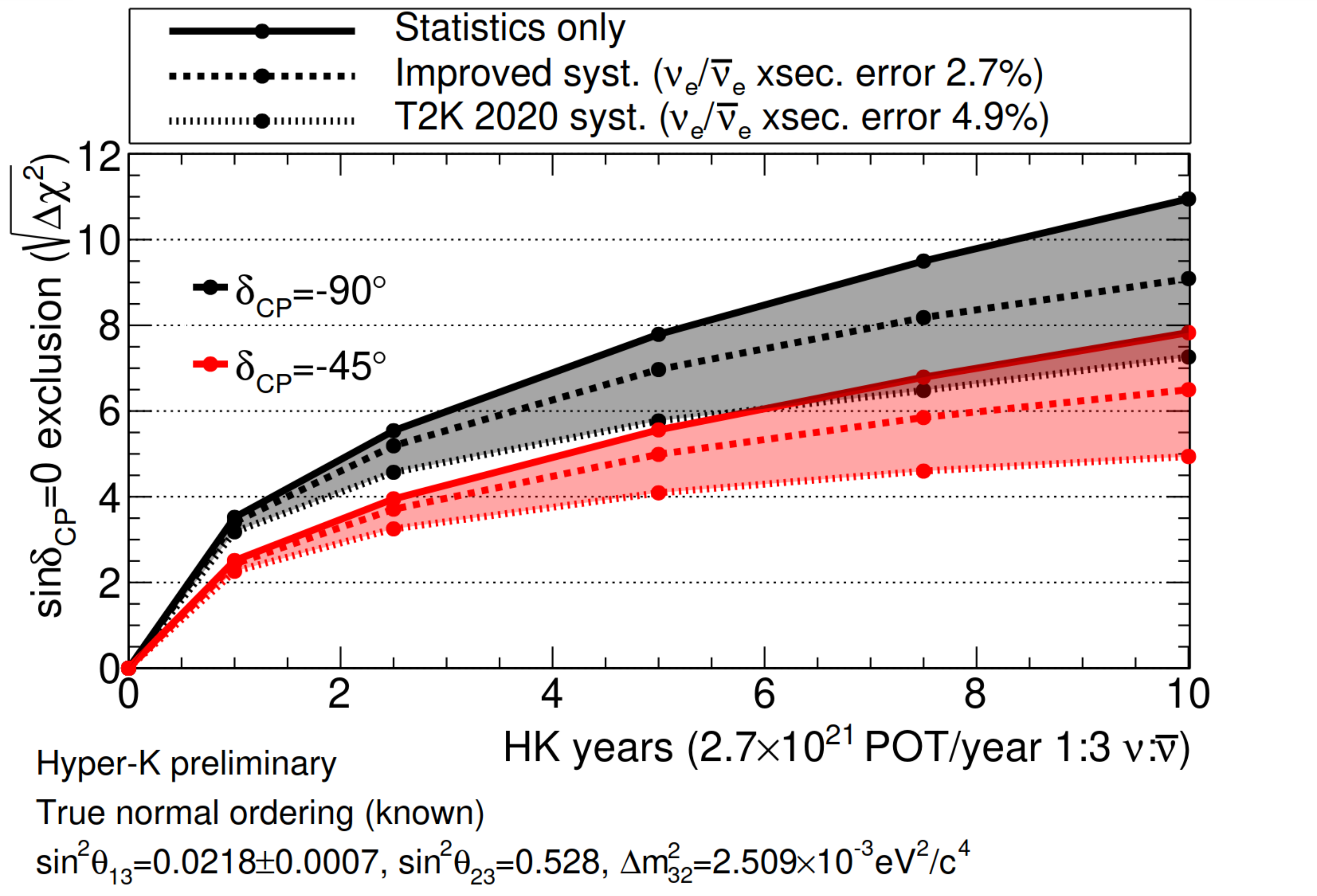


Near detectors ~280 m from the beam source

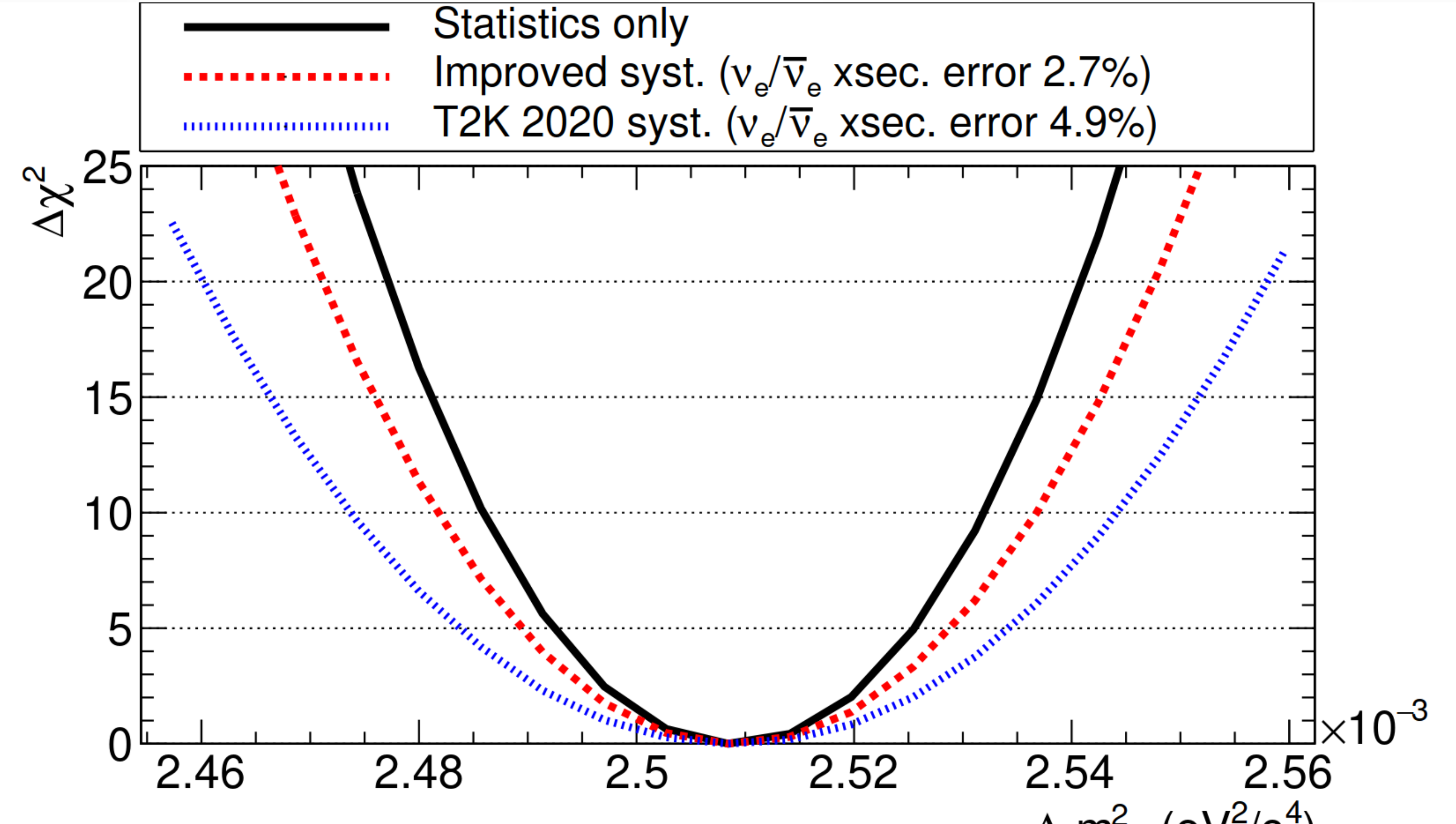


Intermediate Water Cherenkov Detector ~850 m from the beam source
Different off-axis angles

δ_{CP} sensitivity



$|\Delta m^2_{32}|$ measurement precision

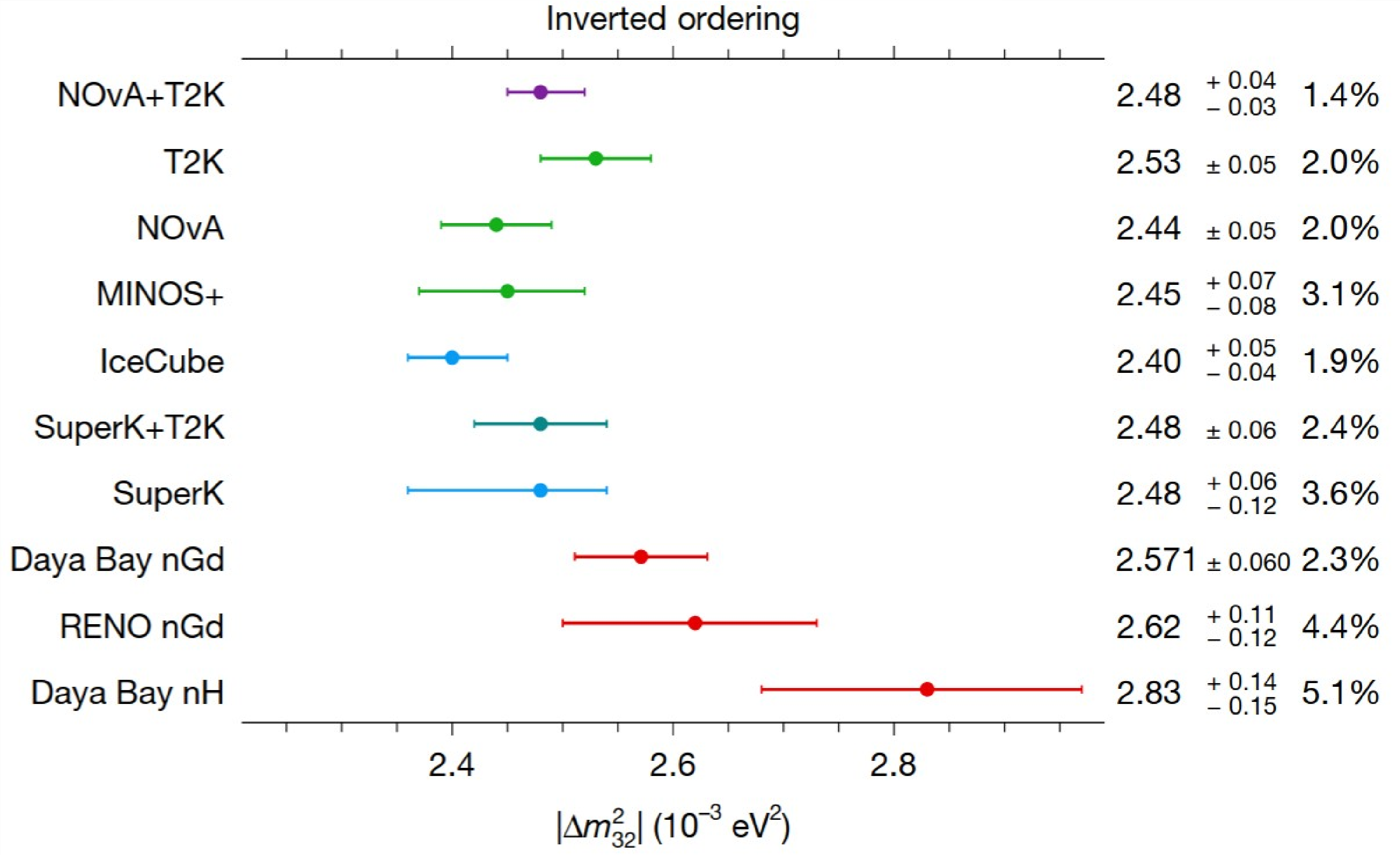


Hyper-K preliminary

True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}eV^2/c^4$, $\delta_{CP}=-1.601$

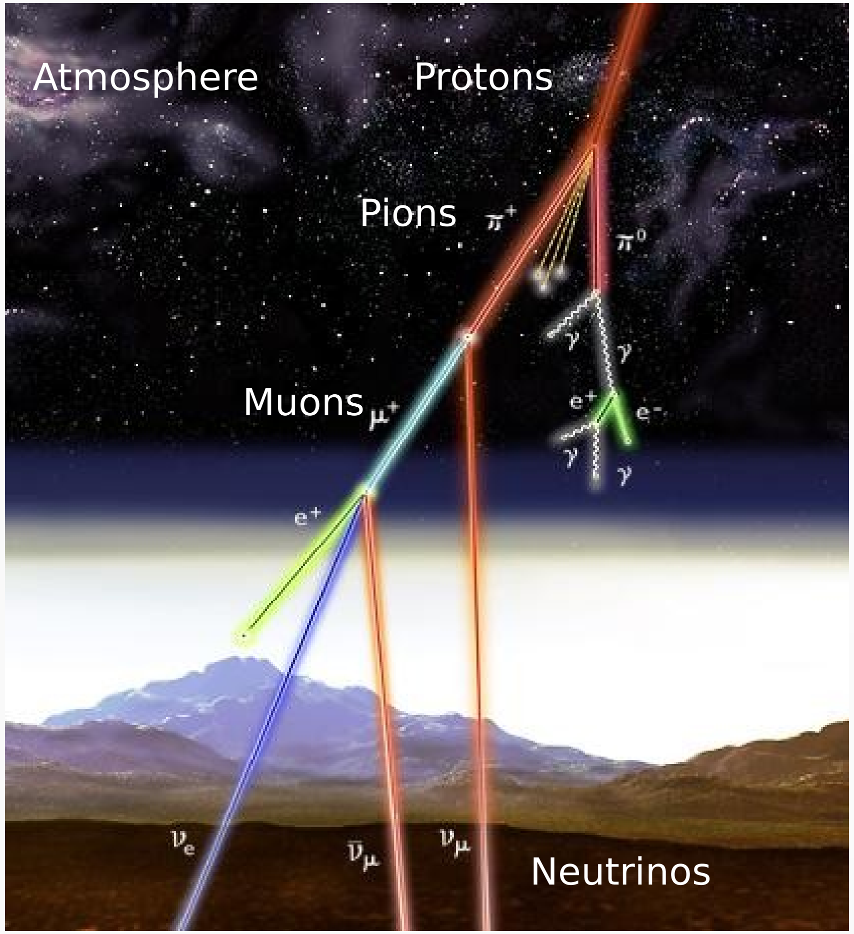
$|\Delta m^2_{32}|$ measurements so far



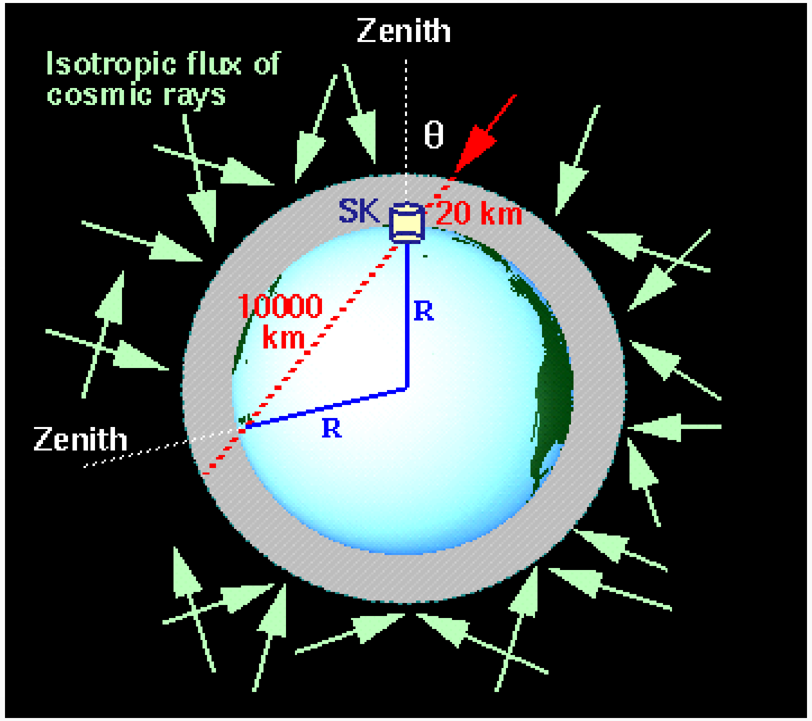
After 10 years of Hyper-K data taking the error would be below 0.5%.

Atmospheric neutrinos

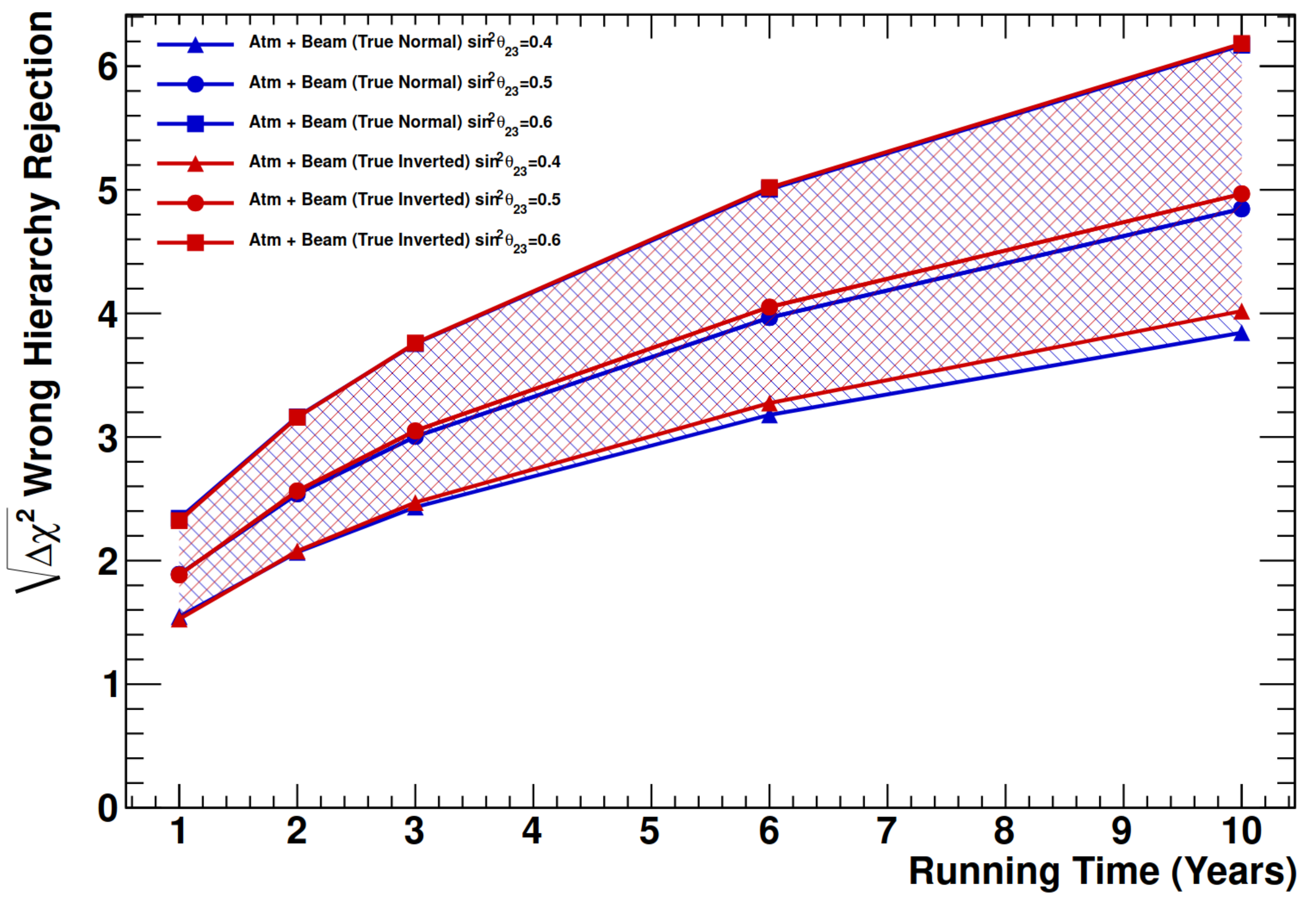
Primary cosmic rays interact with the nuclei in the higher parts of the atmosphere producing secondary particles, mainly pions. Charged pions decay into muons and muon neutrinos.



- Because of much longer distances the atmospheric neutrino oscillations are more influenced by the matter effects.
- Combining accelerator and atmospheric neutrino data improves sensitivity to the mass hierarchy.



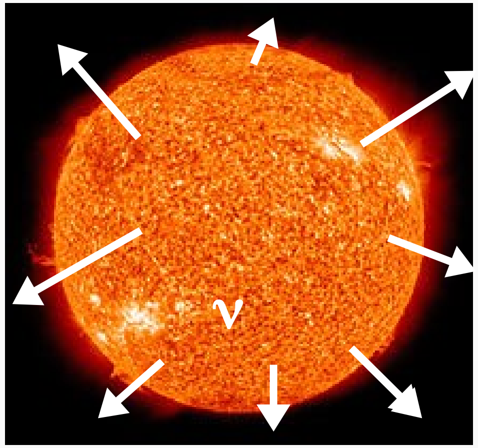
Wrong mass hierarchy rejection

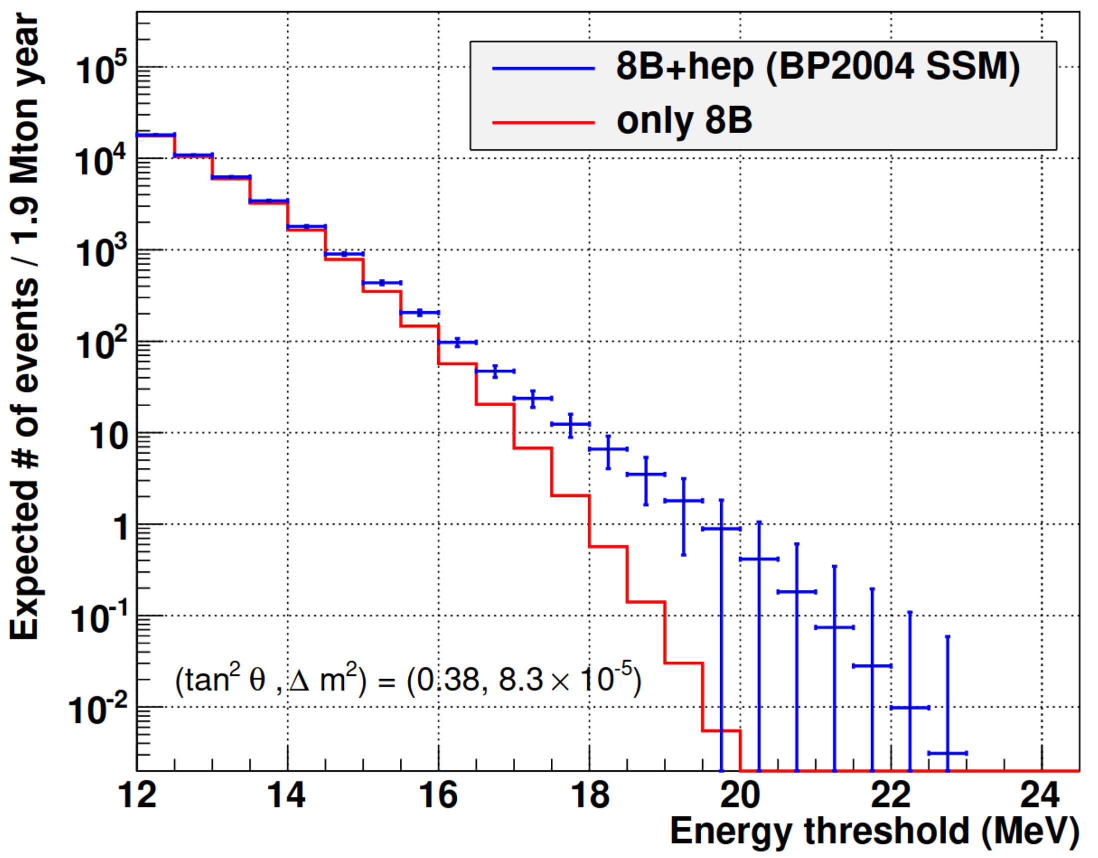


Solar neutrino measurements

- Day/night asymmetry studies will probe terrestial matter effects.
- Precise Δm^2_{21} measurement
- First direct observation of hep neutrinos is expected.

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$

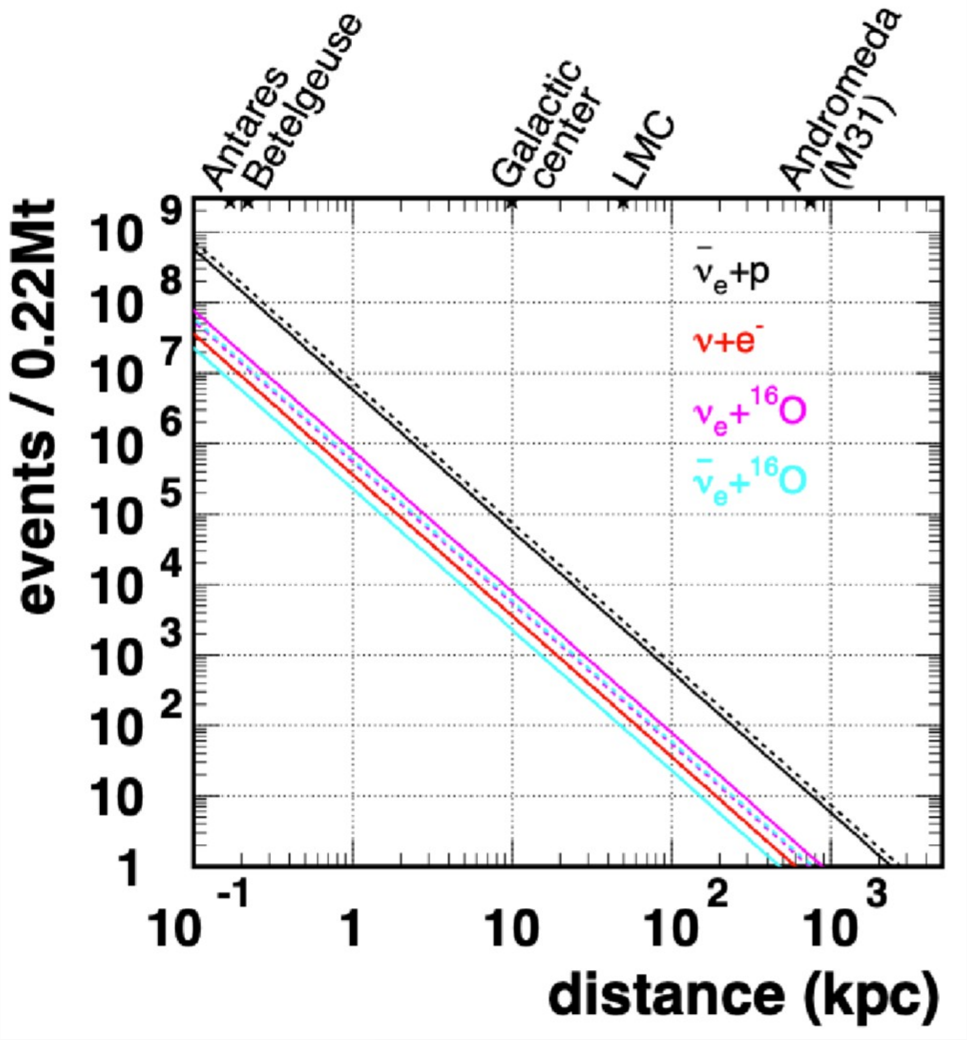


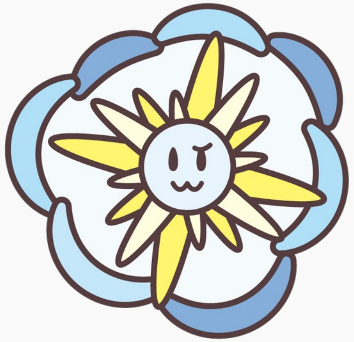


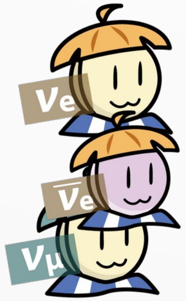
Energy range from the threshold up to 25 MeV
Hyper-Kamiokande Design Report

Hyper-K as an astrophysical observatory

- Signal from a core collapse supernova could be observed in unprecedented detail.
  - Mostly electron antineutrinos via inverse beta decay.
- Supernova in Large Magellanic Cloud (like 1987A) would result in ~3000 neutrino events!
- Hyper-K will be able to detect neutrinos with energy down to 3 MeV.







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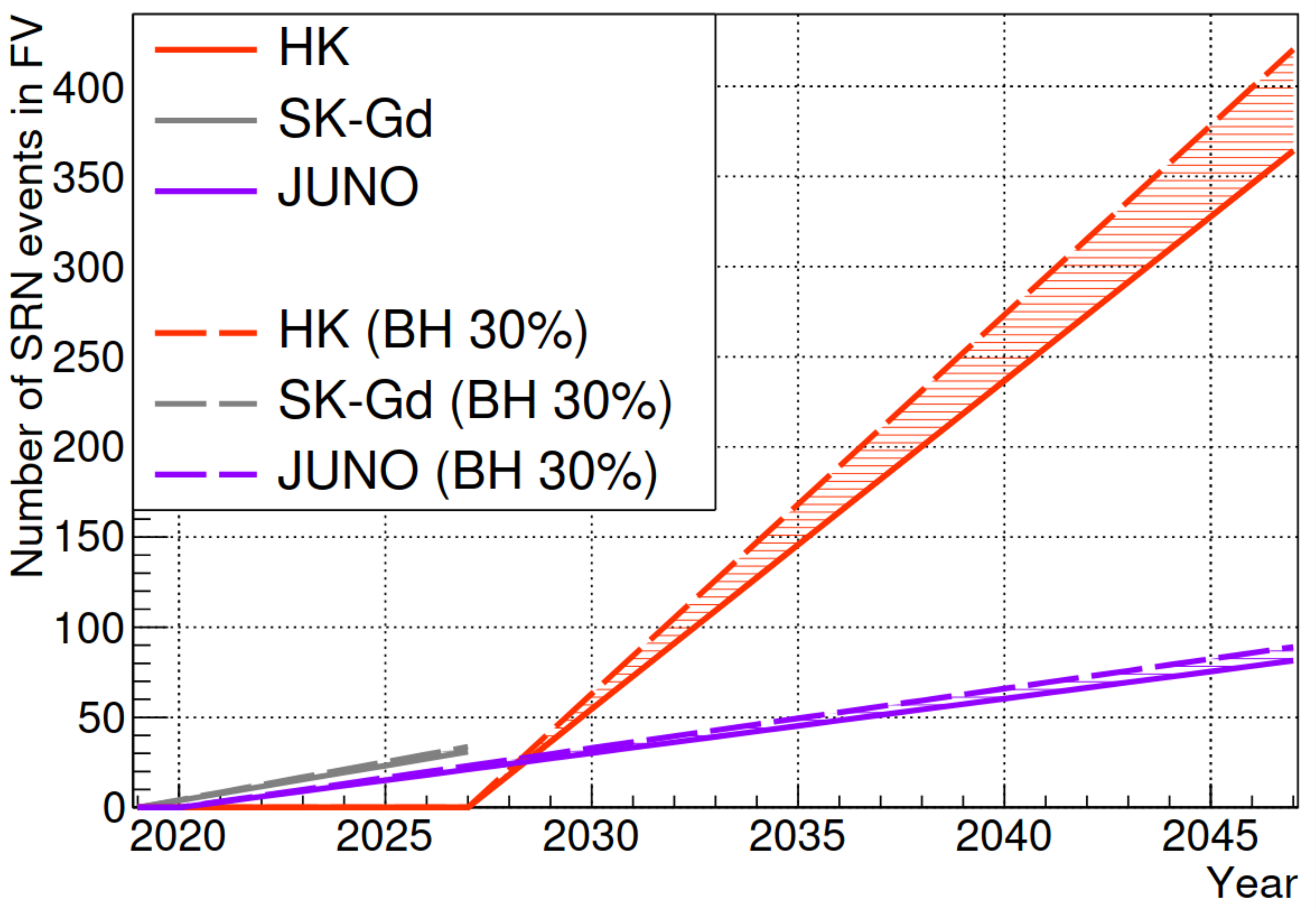
Hyper-K as an astrophysical observatory

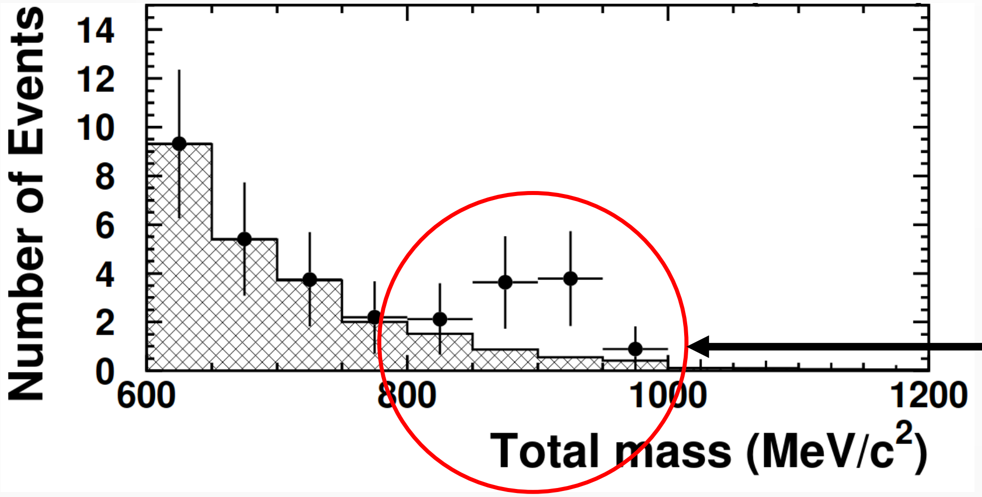
- Hyper-K will also be sensitive to the Diffuse Supernova Neutrino Background.
  - Neutrinos emitted by supernovae throughout the billions of years.
- Different spectrum if the core collapse supernova ends with a black hole or a neutron star.
  - Very model dependent!
- No conclusive results from Super-K yet.

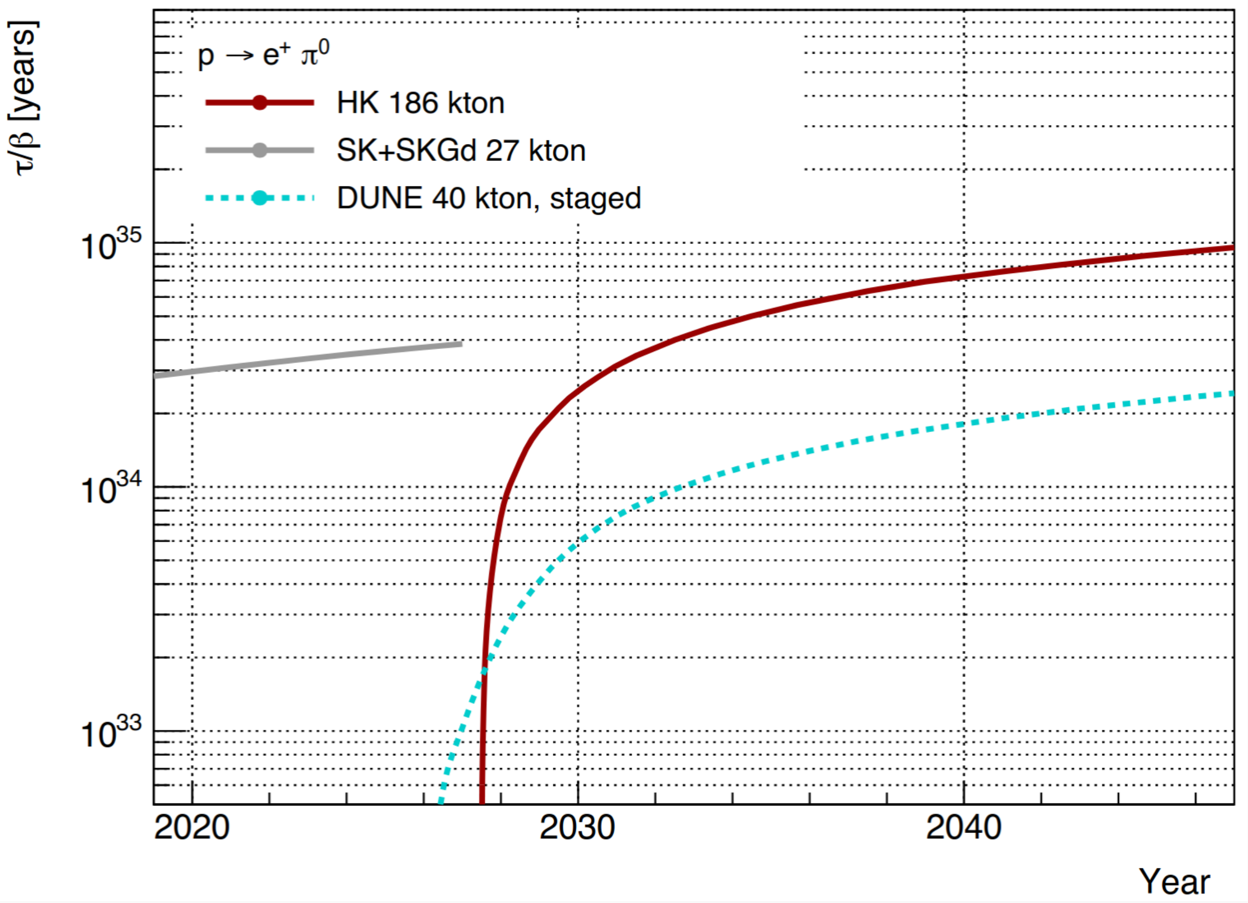


Hyper-Kamiokande Design Report

Proton decays search

- Hyper-Kamiokande will be capable of observing and discovering nucleon decay signal.
- Due to its huge mass, Hyper-K will surpass the limits found by Super-Kamiokande.
- Decay mode $p \rightarrow e^+ + \pi^0$ predicted to be dominant in many Grand Unified Theory (GUT) models.

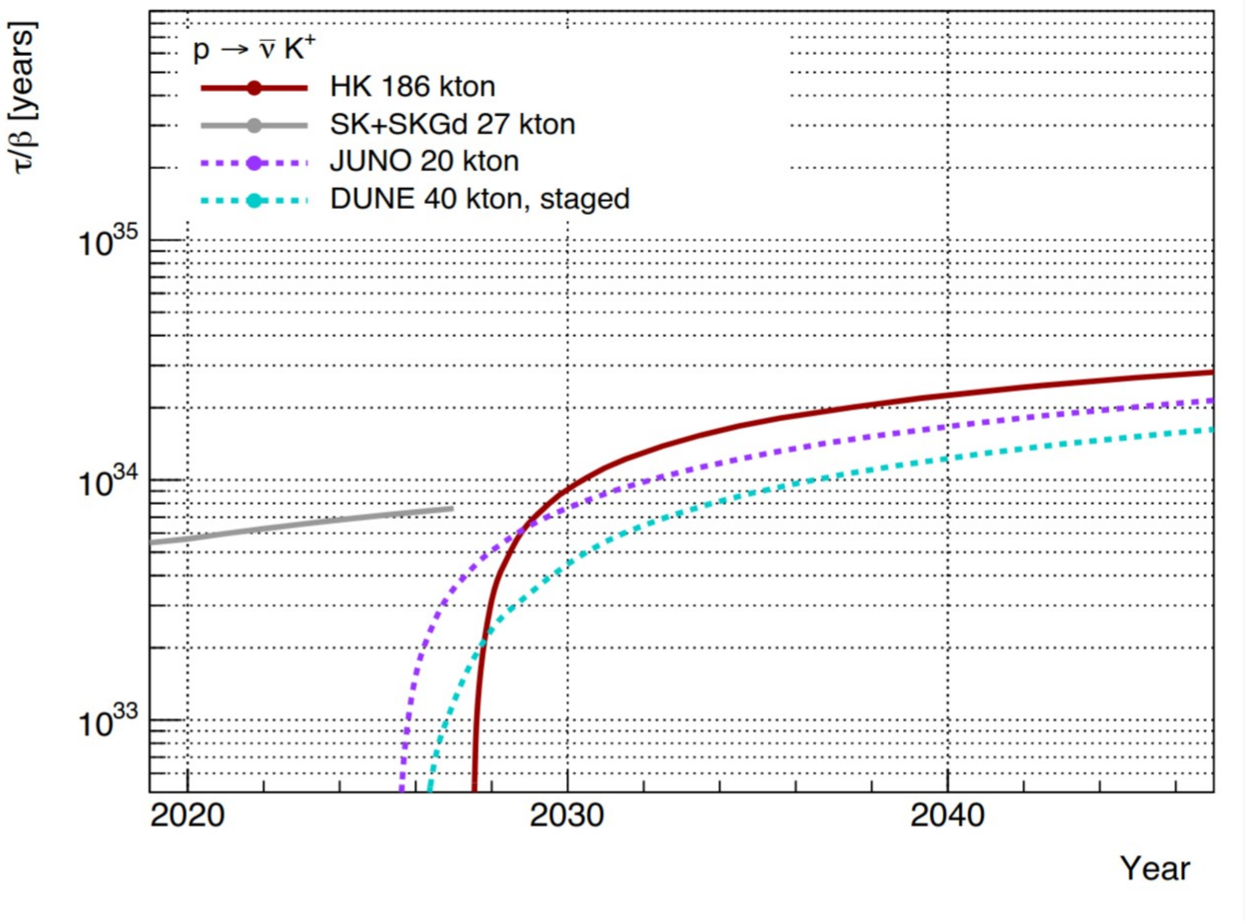




Simulated $p \rightarrow e^+ + \pi^0$ signal after 10 years of data taking, assuming $1.7\text{x}10^{34}$ years lifetime

Proton decays search

- A variety of other decay modes could be possible.
- Supersymmetric GUT models predict proton decay into lepton and kaon.
- p → anti-ν + K^+ as one of the most important channels
- K^+ would be below Cherenkov threshold, has to be identified by its decay products.



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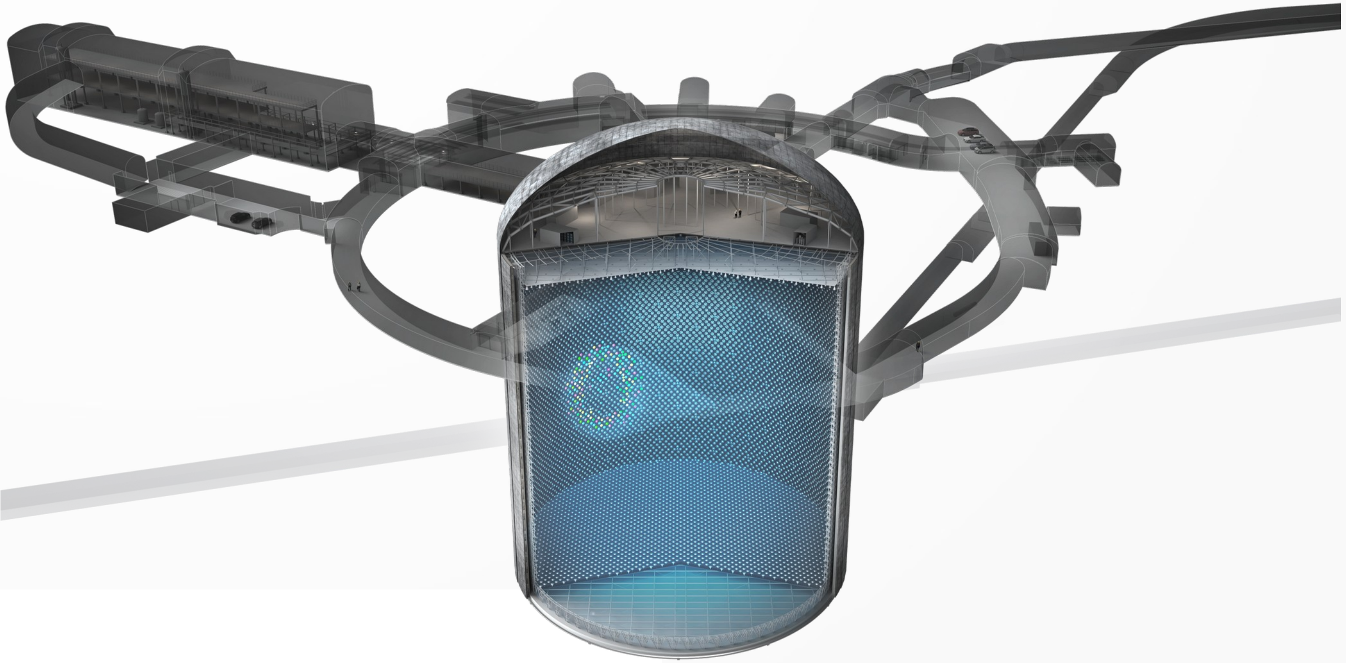
Summary

- Hyper-Kamiokande will be the next generation neutrino observatory in Japan.
- Currently under construction. Expected beginning of data taking ~2028.
- Rich research program:
  - long baseline experiment
  - atmospheric neutrinos
  - solar neutrinos
  - supernova neutrinos
  - nucleon decay search



NIKKEN SEKKEI

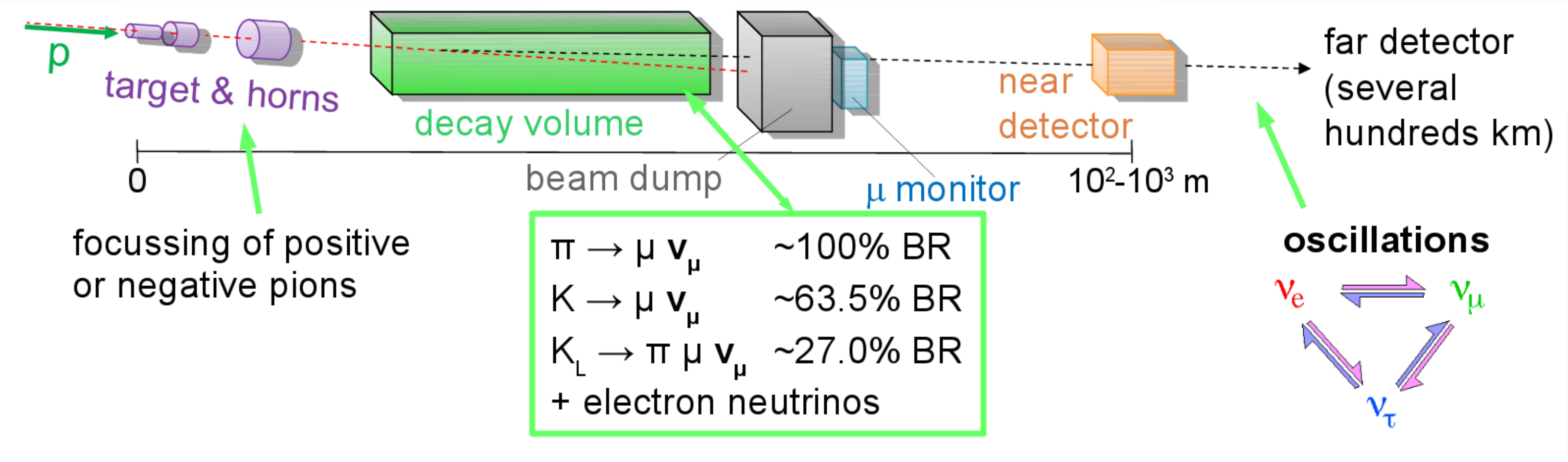
Hyper-Kamiokande

Backup

Comparison of future and current experiments

	T2K	NOvA	DUNE	Hyper-K
Baseline [km]	295	810	1300	295
Beam energy peak [GeV]	0.6	2	2.5-3	0.6
setup	off-axis	off-axis	on-axis	off-axis
Near Detector	Multi-purpose magnetized (FGD, TPC, ECal)	Extruded plastic cells filled with liquid scintillator	Multi-purpose (LAr TPC, magnetized HPGAr TPC w/ ECal, scint tracker)	Multi-purpose magnetized (SuperFGD, TPC, ECal) + Intermidiate
Far Detector	Water Cherenkov 50 kton	Extruded plastic cells filled with liquid scintillator 14 kton	Liquid Argon TPC 4 × 17 kton	Water Cherenkov 258 kton
Expected sensitivity to CPV	will reach >3σ	will reach >2σ	will reach >5σ	will reach >5σ
timescale	2010-2026	2014-2027	~2031-	~2028-

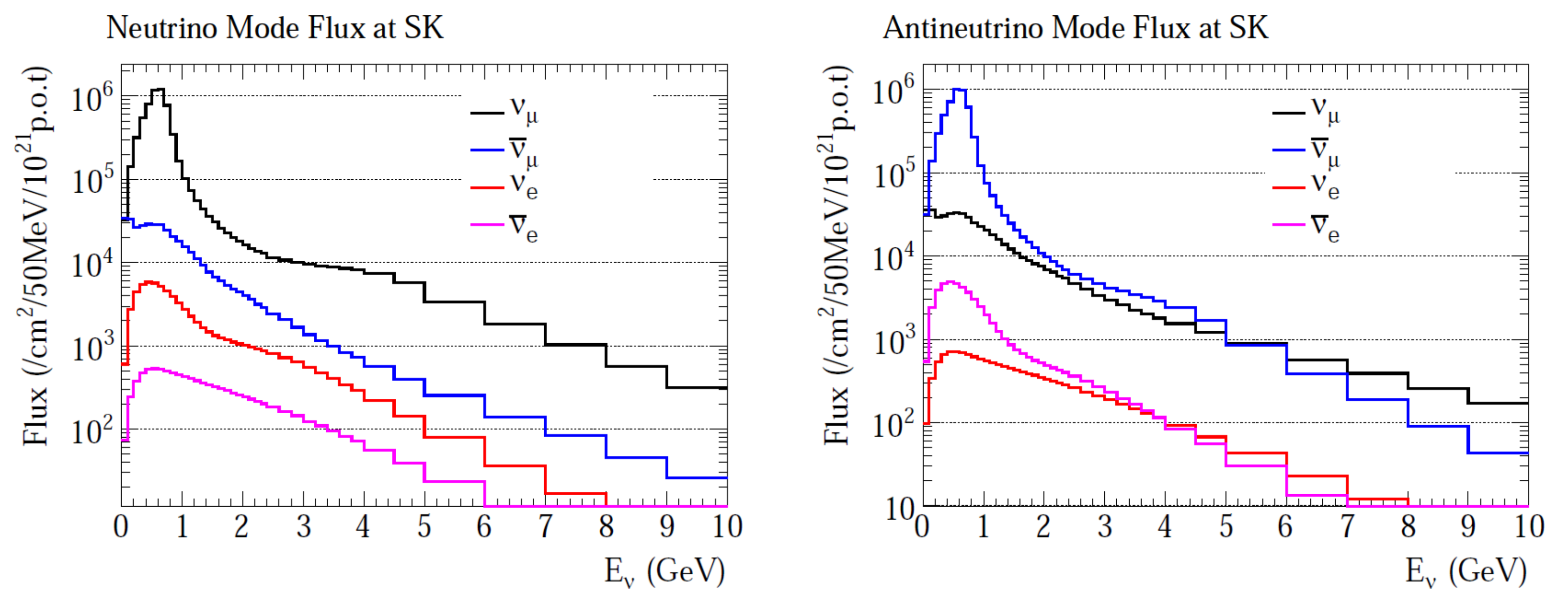
T2K beam



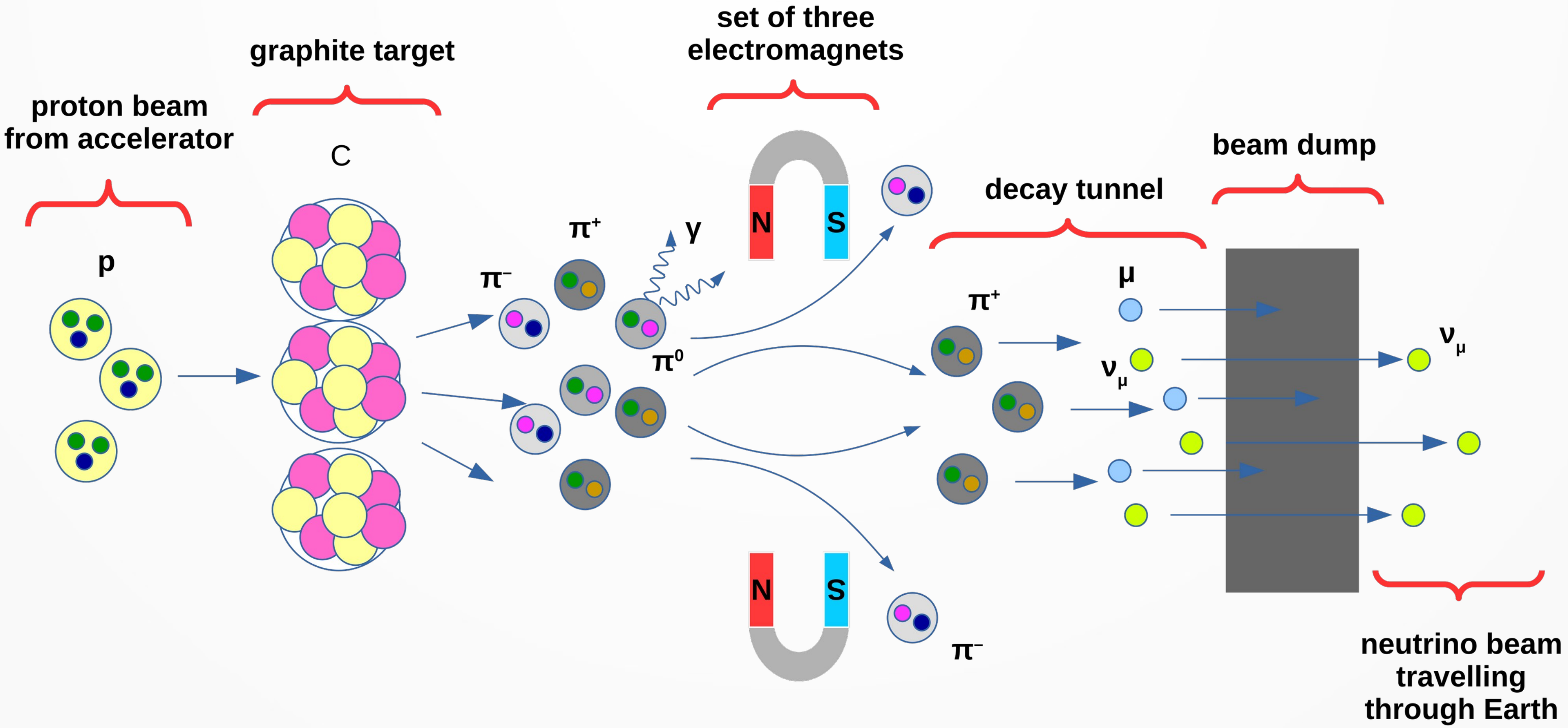
$\pi \rightarrow \mu\ \nu_\mu$ ~100% BR
$K \rightarrow \mu\ \nu_\mu$ ~63.5% BR
$K_L \rightarrow \pi\ \mu\ \nu_\mu$ ~27.0% BR
+ electron neutrinos

Flux predictions tuned for hadron production results from NA61/SHINE (measurements on T2K target replica)

Beam can operate in neutrino or antineutrino mode.

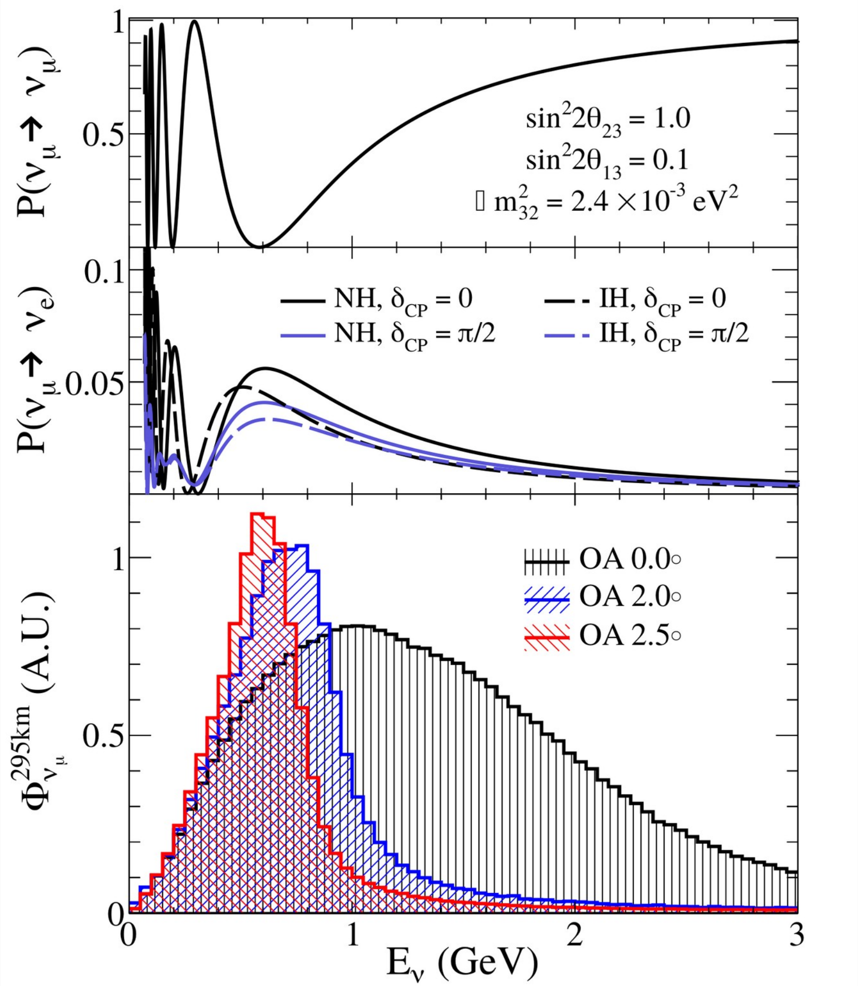


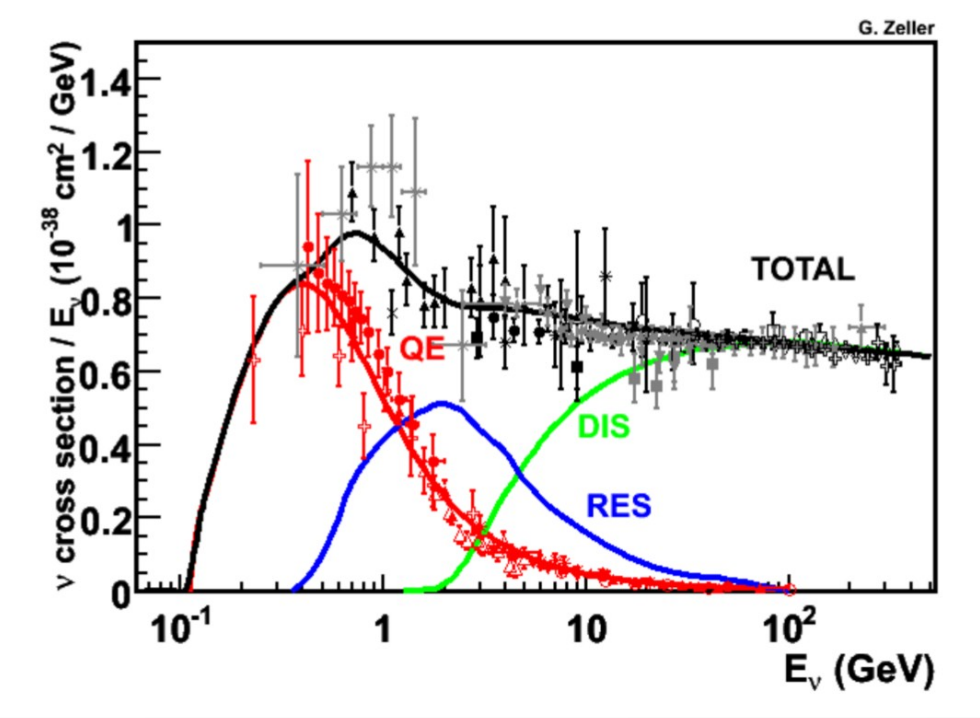
Neutrino beam production



M. Batkiewicz-Kwaśniak

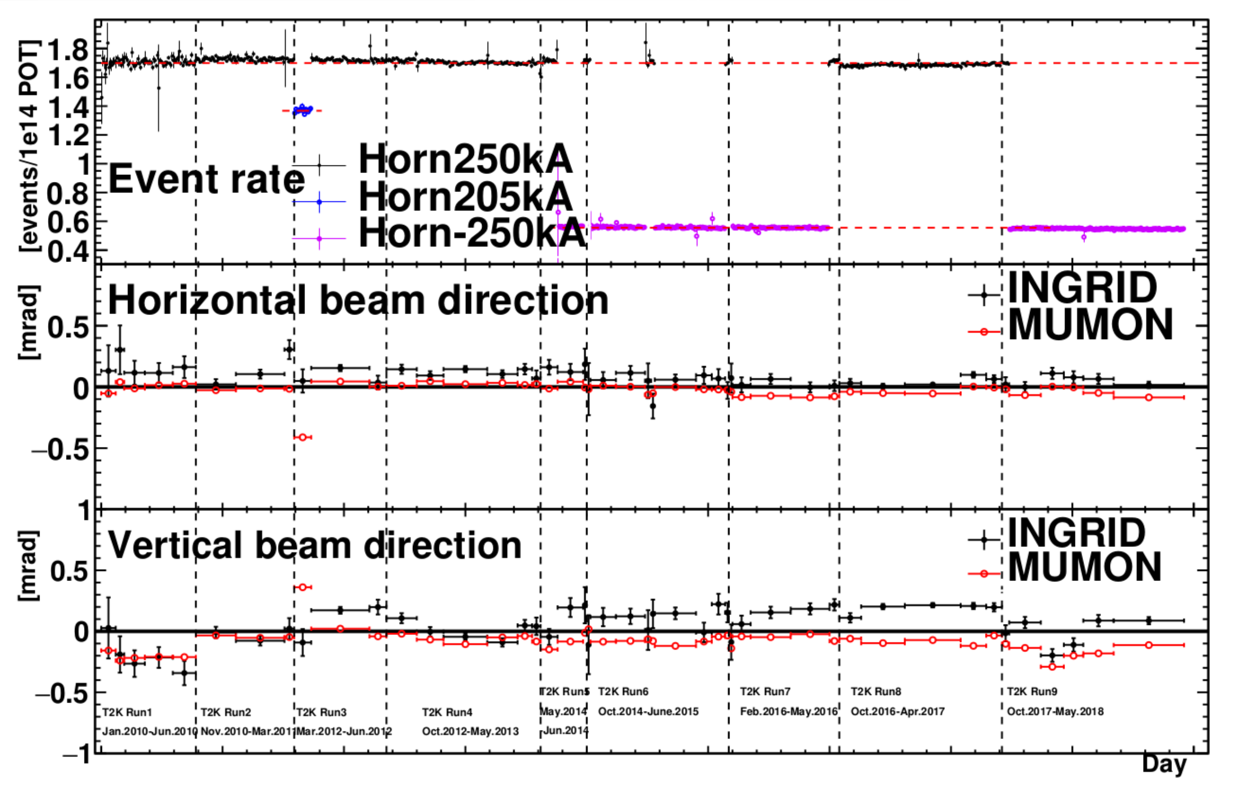
Off-axis strategy

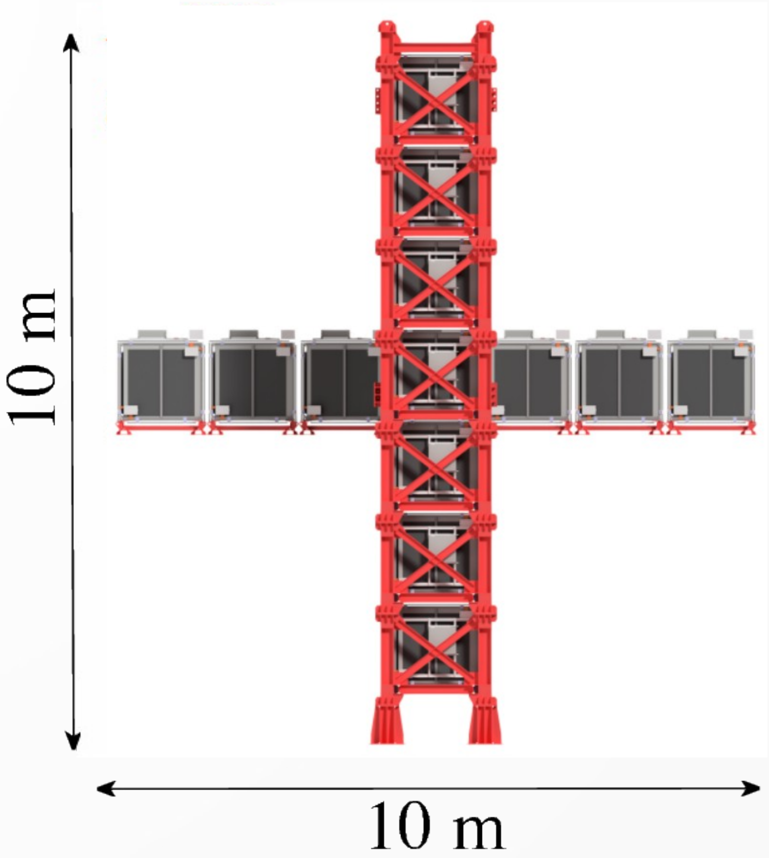




- Off-axis strategy enhances oscillation effect and contribution of CC quasielastic (CCQE) interactions.
- Around T2K beam peak (~600 MeV) mostly CCQE and resonant interactions occur.
- Shift in off-axis angle δOA~1mrad (0.057°) → shift in energy peak δE/E ~2% at far detector

On-axis near detector: INGRID

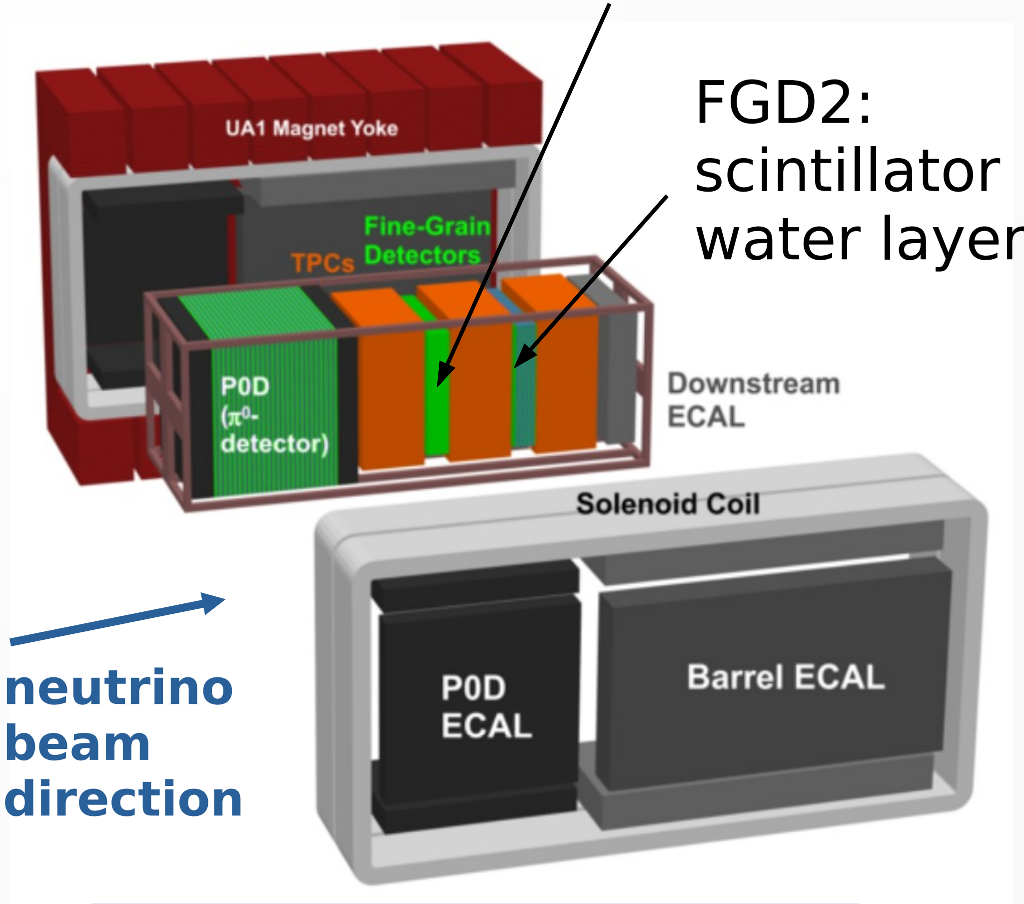




- Cross-shaped detector composed of 14 Fe/scintillator modules.
- Monitors beam’s direction, profile and intensity.
- MUMON – muon monitor (for muons exiting decay volume)

Off-axis near detector: ND280

- ND280 is a multipurpose detector used to constrain the off-axis flux and neutrino interaction models used in the oscillation analysis.
- CC interactions are studied in the tracker, made of two FGDs (fine grained detectors – scintillators) and three gaseous TPCs.
- FGDs serve as targets and provide good vertex and track resolution.
- Magnetic field allows for charge and momentum measurement.
- Energy loss in the TPCs allows for particle identification.



FGD1: scintillator layers

FGD2: scintillator + water layers

Exploded view of ND280
Old design 2010-2022

Matter effects

Presence of electrons modifies the oscillation probabilities as compared to those in vacuum. CC scattering on electrons is possible only for electron (anti-)neutrinos. The probability for (anti-)ν_e appearance with the first order approximation of matter effects is expressed as:

$$\begin{aligned}
P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e\right) \approx\ & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}] \\
& \overset{-}{(+)}\,\alpha\frac{J_0\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \\
& +\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \\
& +\alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta_{31})
\end{aligned}$$

where

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$

$$\Delta_{ij} = \Delta m^2_{ij}L/4E$$

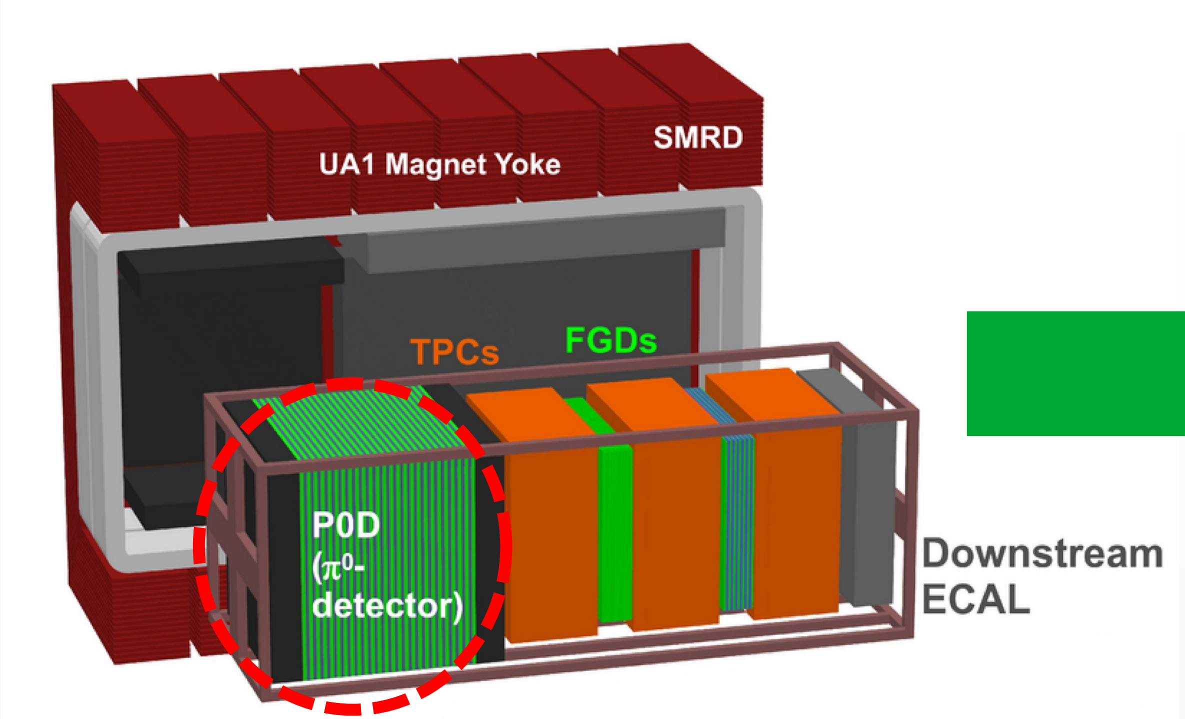
$$\boxed{A = (-)2\sqrt{2}G_F n_e E/\Delta m^2_{31}}$$

$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

Sign of the matter effects differs for neutrinos and antineutrinos.

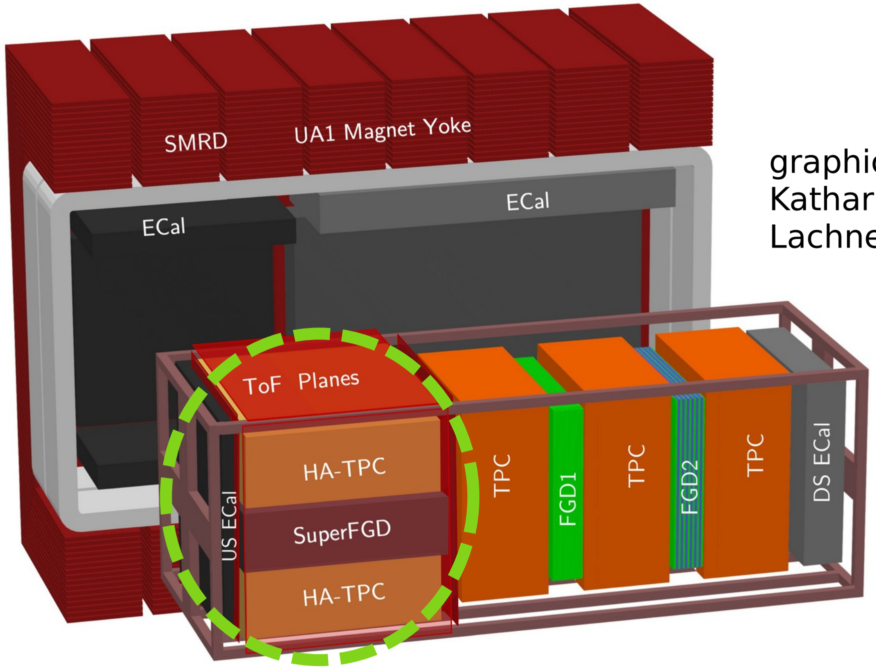
ND280 upgrade

2010-2022



P0D – pi0 detector built of scintillator, water, brass and lead layers

Completed in May 2024

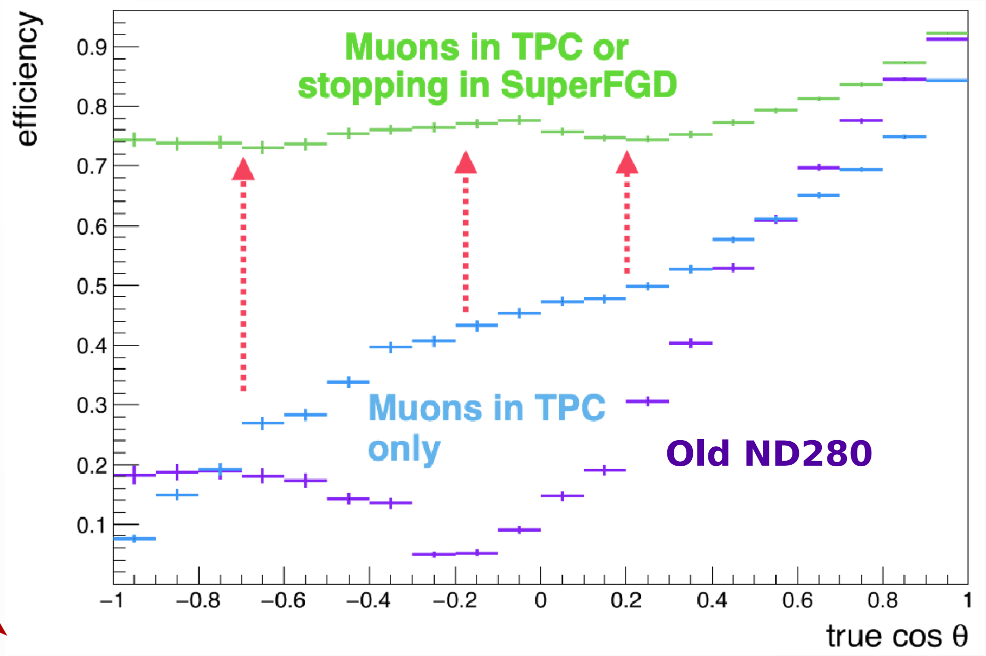


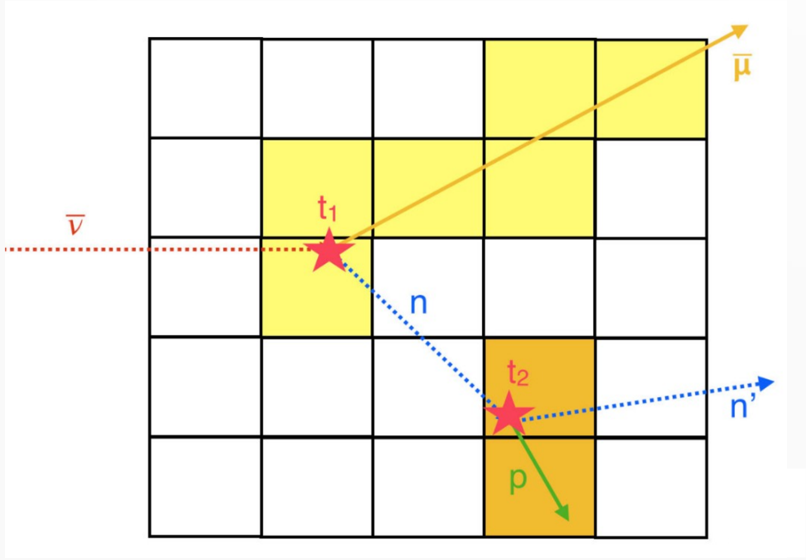
graphic by
Katharina
Lachner

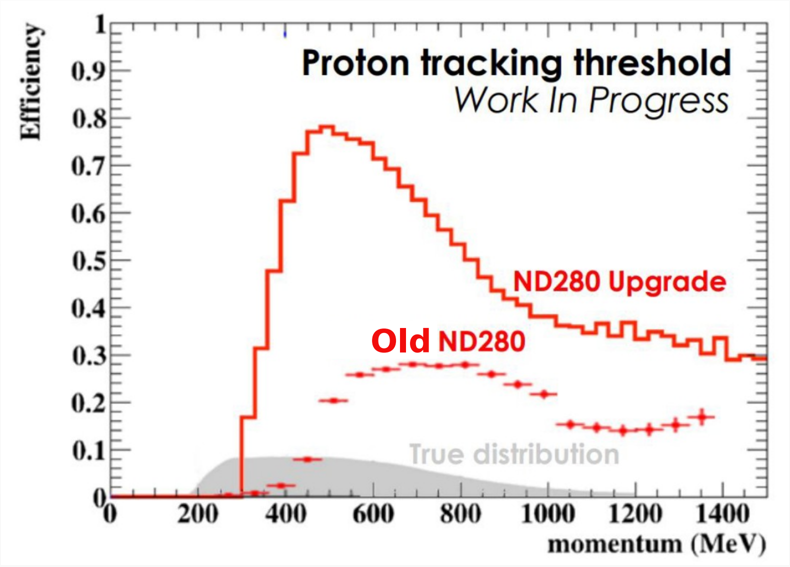
Super-FGD,
High-Angle TPCs,
Time of Flight Planes

Upgraded ND280 performance

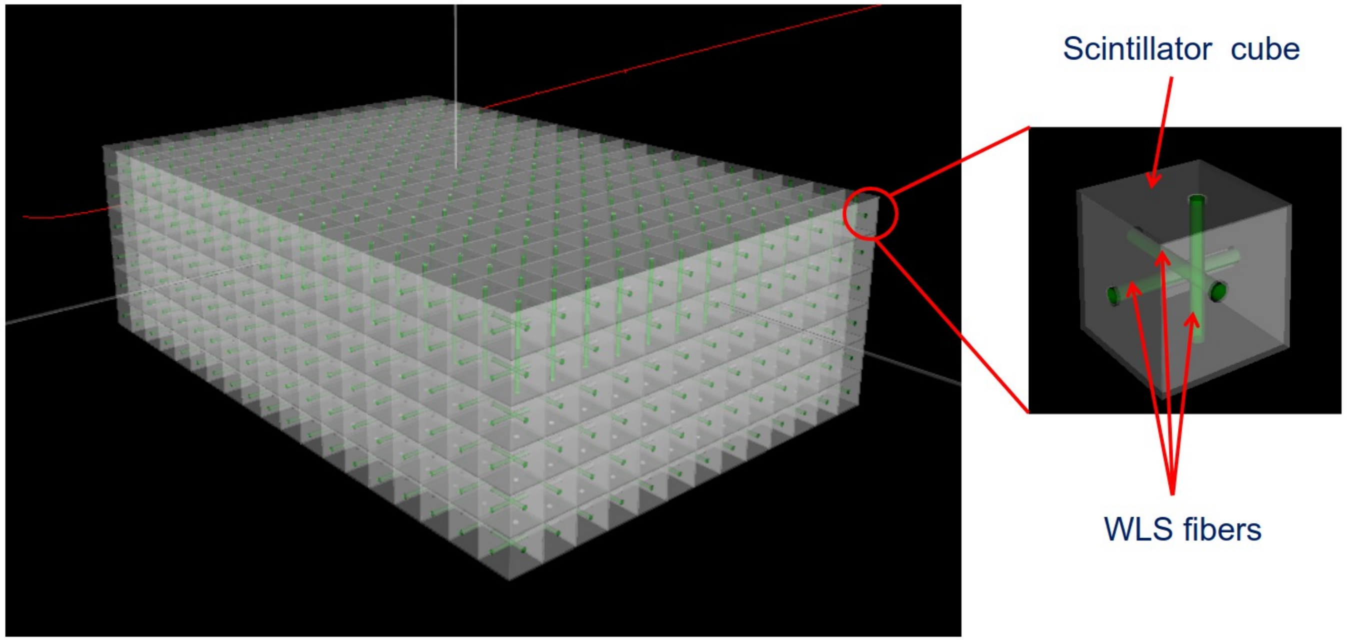
- Improved muon angular acceptance
- Lower threshold for proton tracking
- Neutron detection via proton recoil. Neutron energy estimation with time-of-flight.







SuperFGD



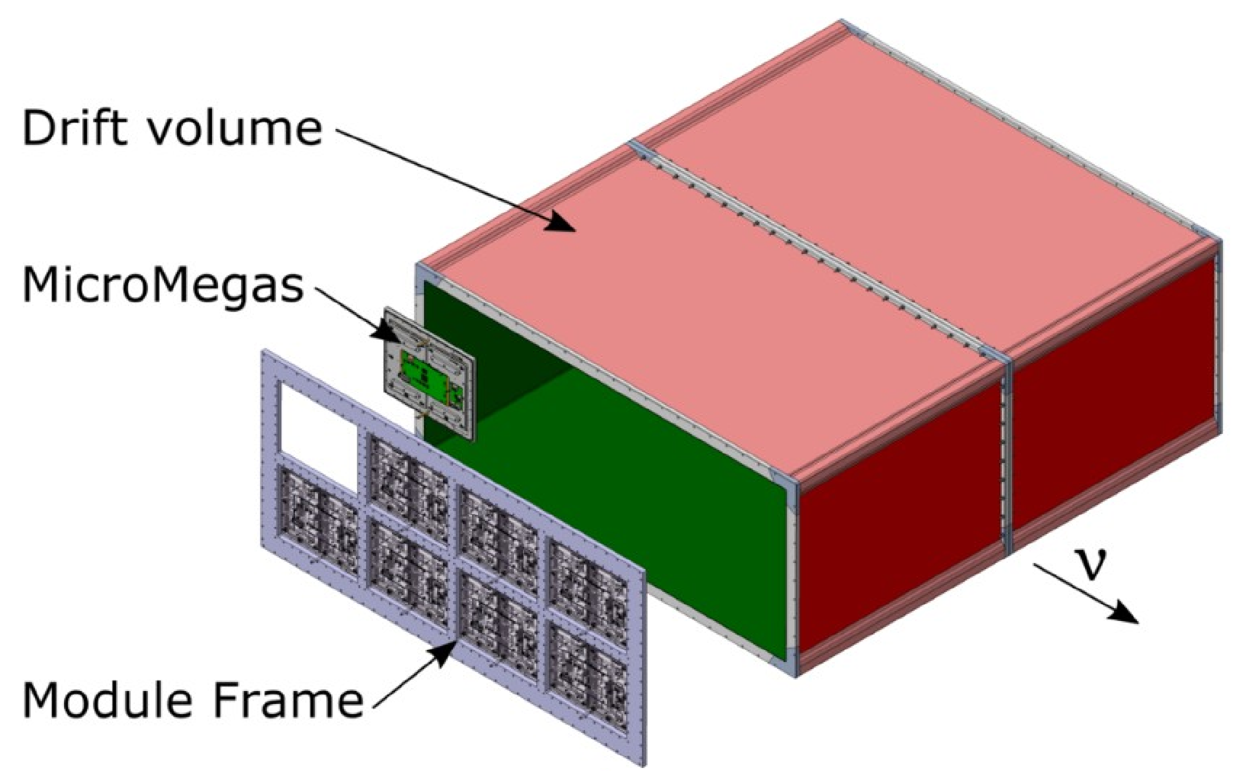
Schematic concept of the SuperFGD structure.

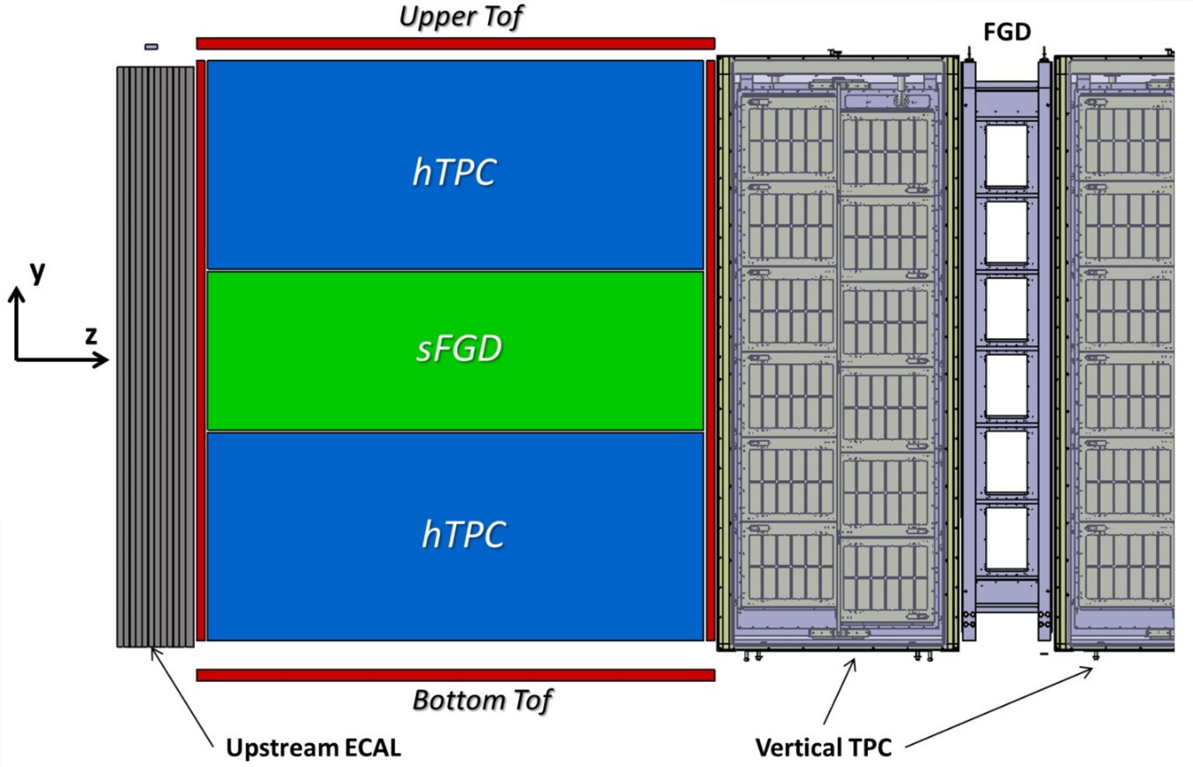
SuperFGD layers assembly at J-PARC

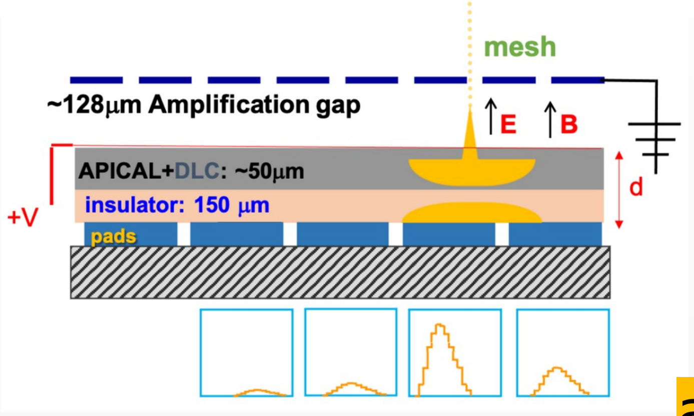
- The size of each cube is 1x1x1 cm³.
- The active part of SuperFGD is 192x192x56 cm³.
- Altogether ~2M cubes.

ND280 upgrade design report: arXiv:1901.03750

High angle TPCs



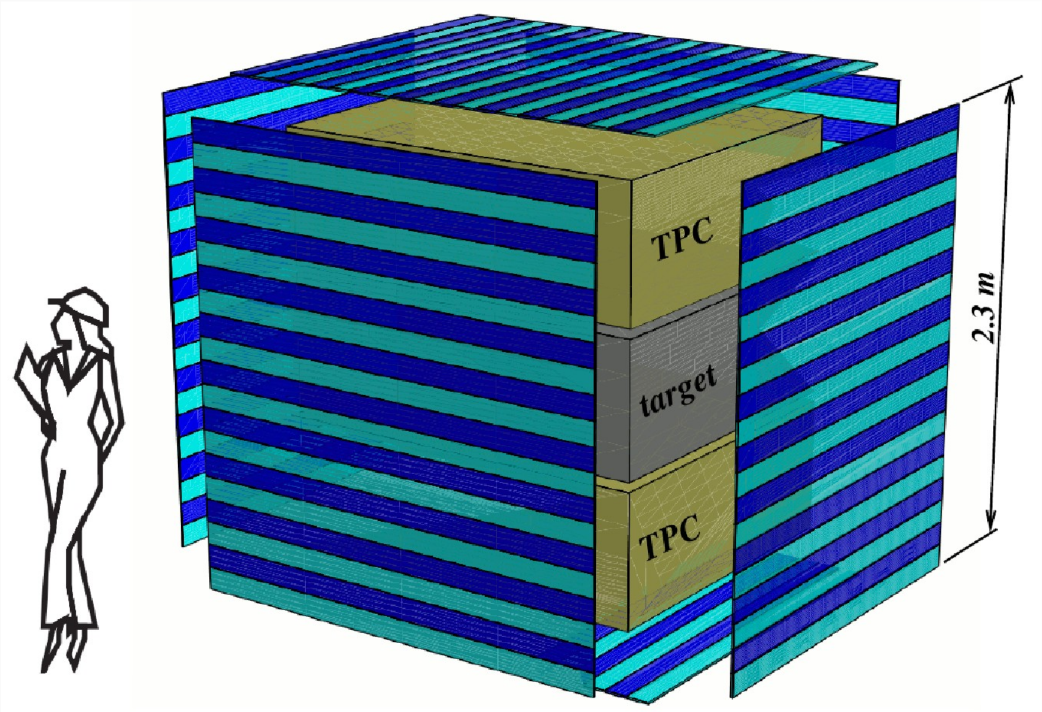




- Bottom and Top HATPC – nearly 4π acceptance of tracks starting in SuperFGD.
- 8 Encapsulated Resistive Anode Micromegas (ERAM).
- Tracks reconstruction resolution of 200-800 µm.

arXiv:2303.04481

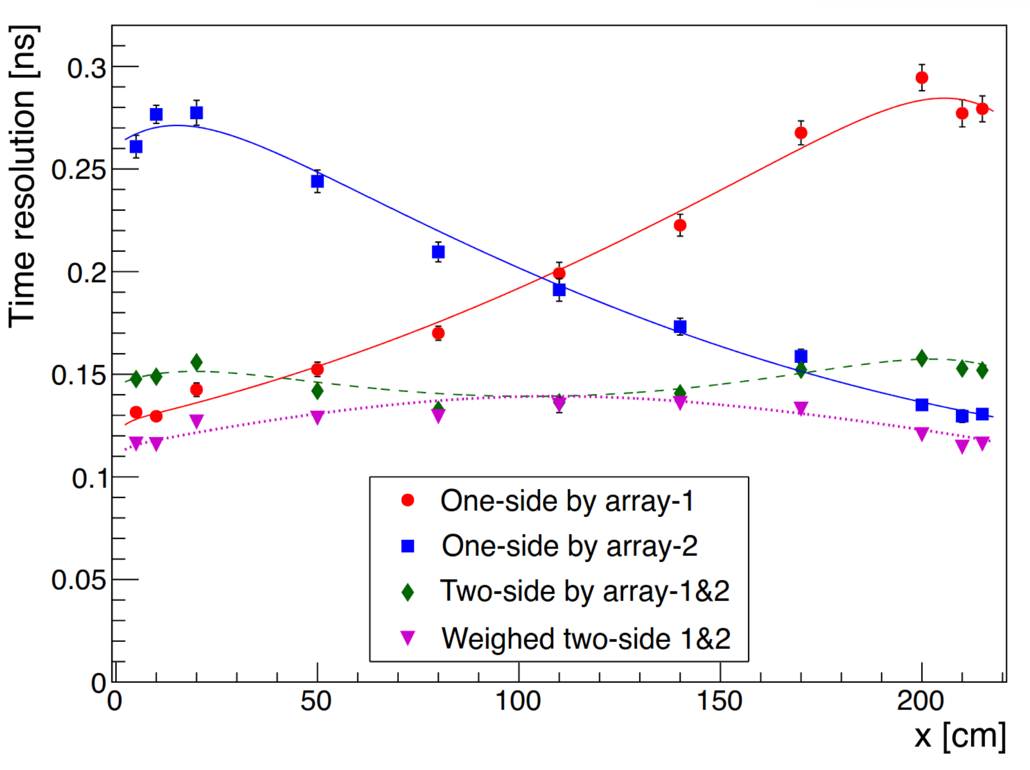
ToF Planes



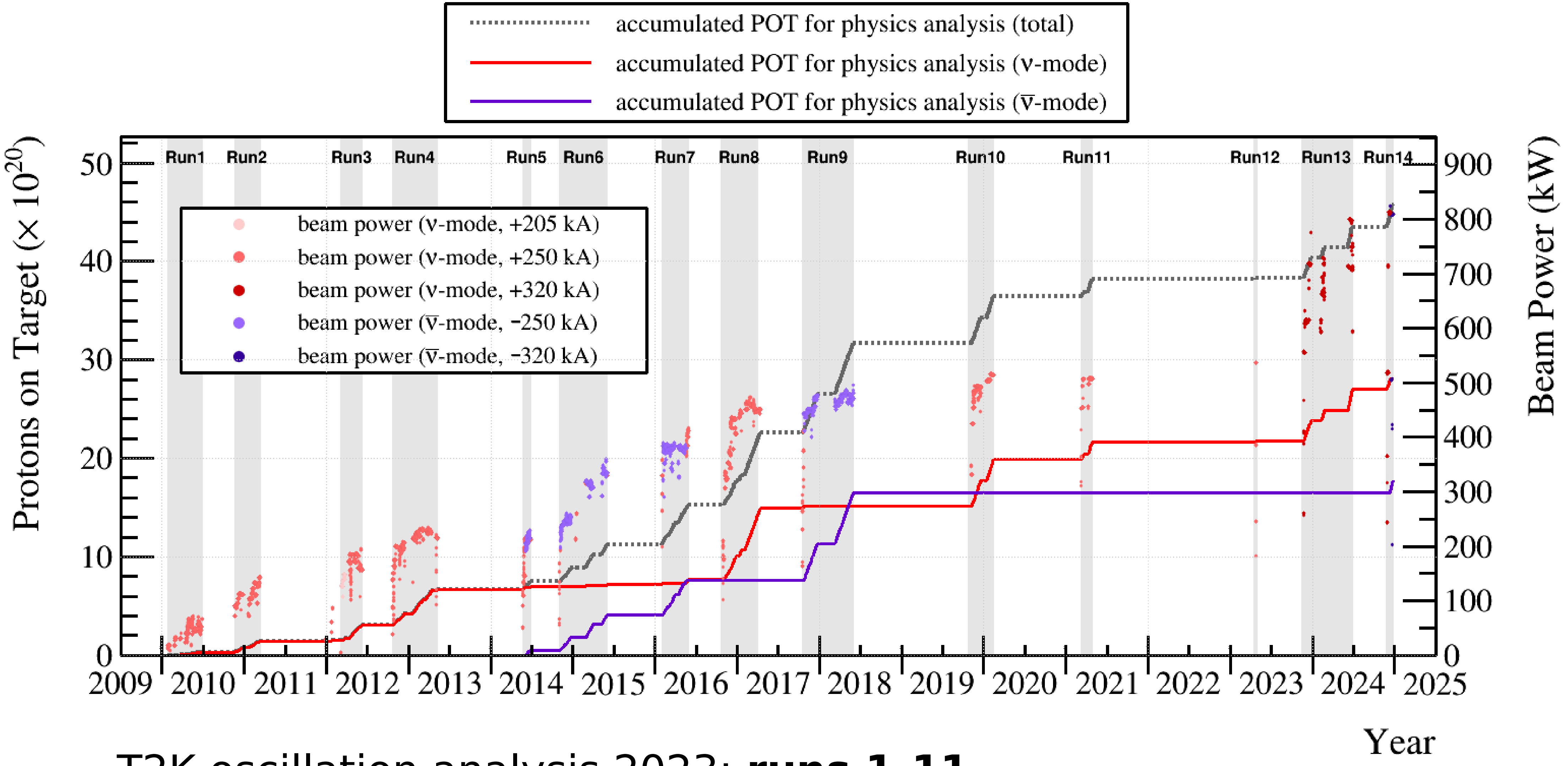
- Time-of-flight system designed to measure precisely the crossing time of charged particles in ND280.
- Time resolution ~0.15 ns

ToF modules tested at CERN

arXiv:2109.03078

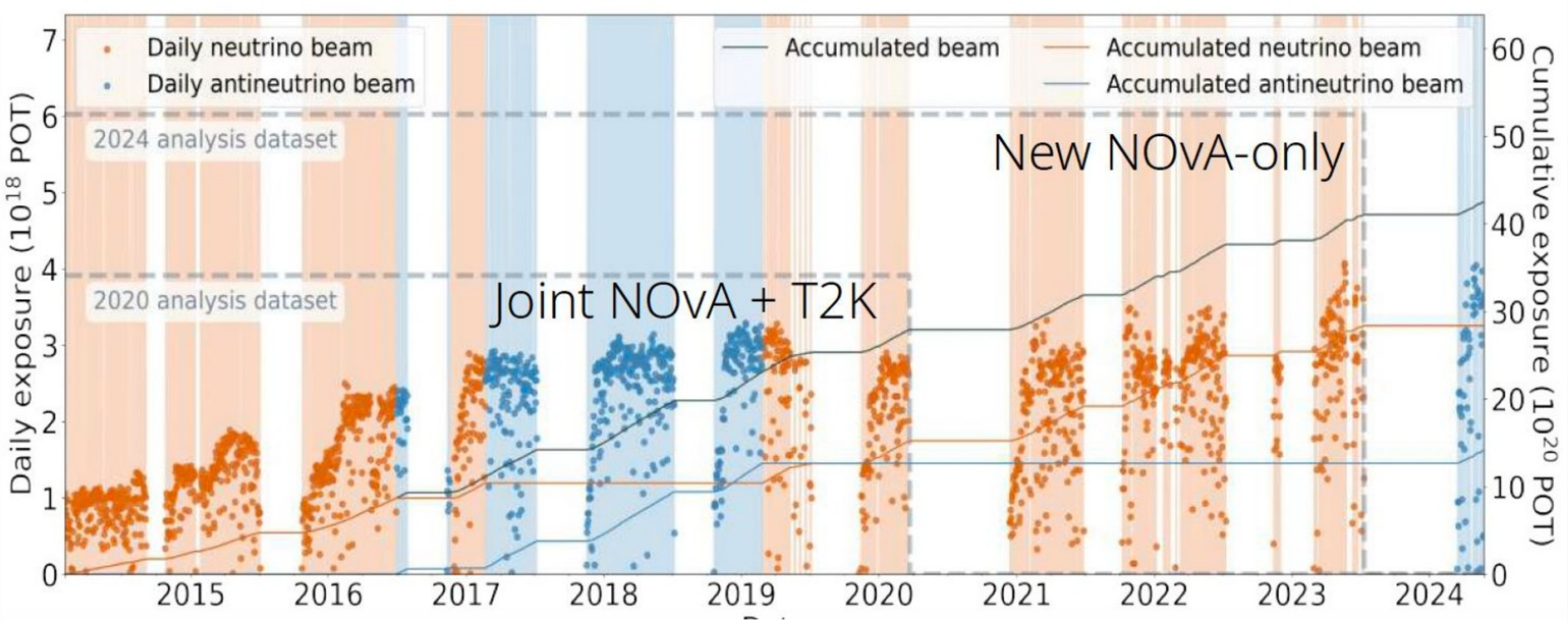


Accumulated POT (T2K)



T2K oscillation analysis 2023: **runs 1-11**
NOvA+T2K joint oscillation analysis: **runs 1-10**

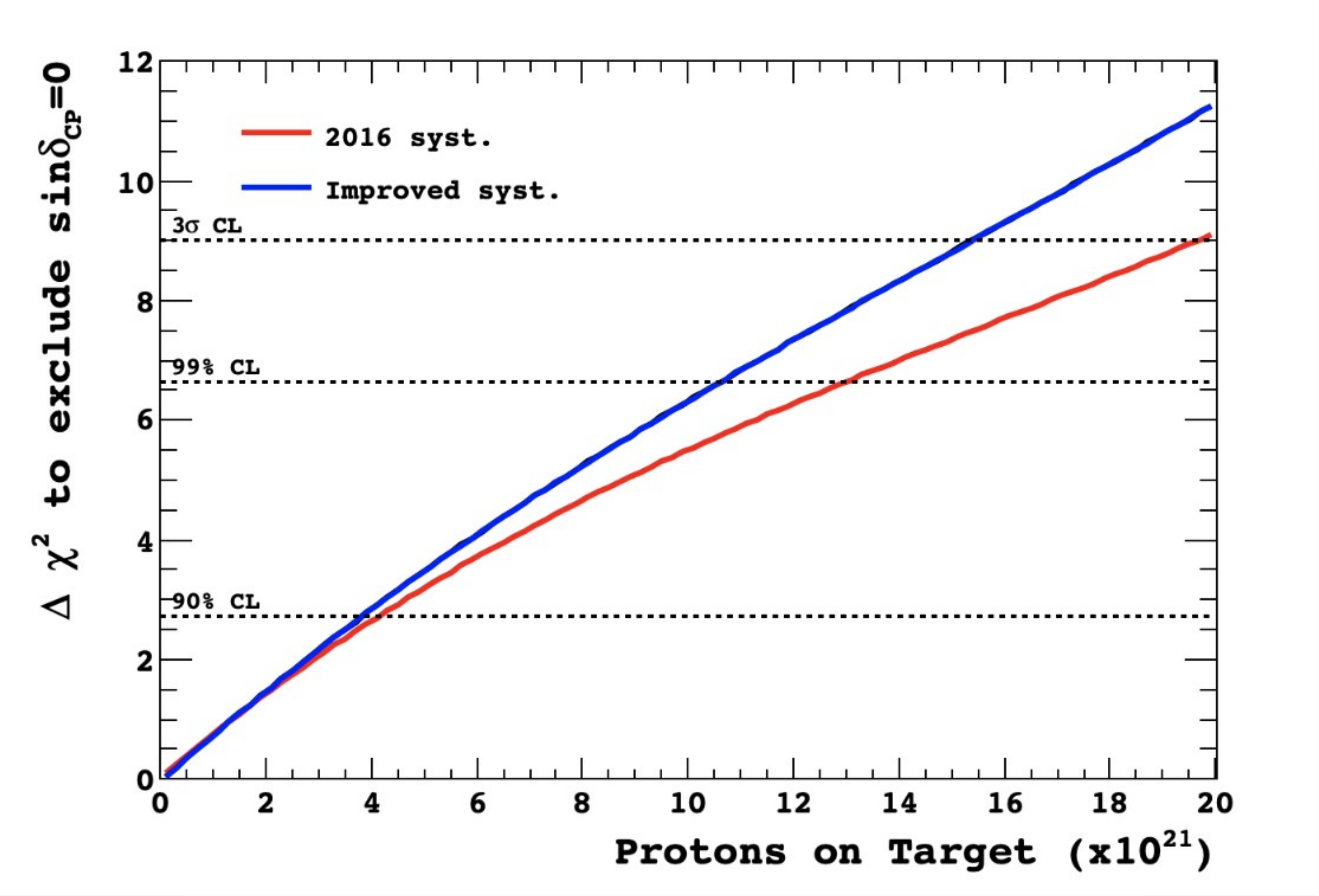
Accumulated POT (NOvA)



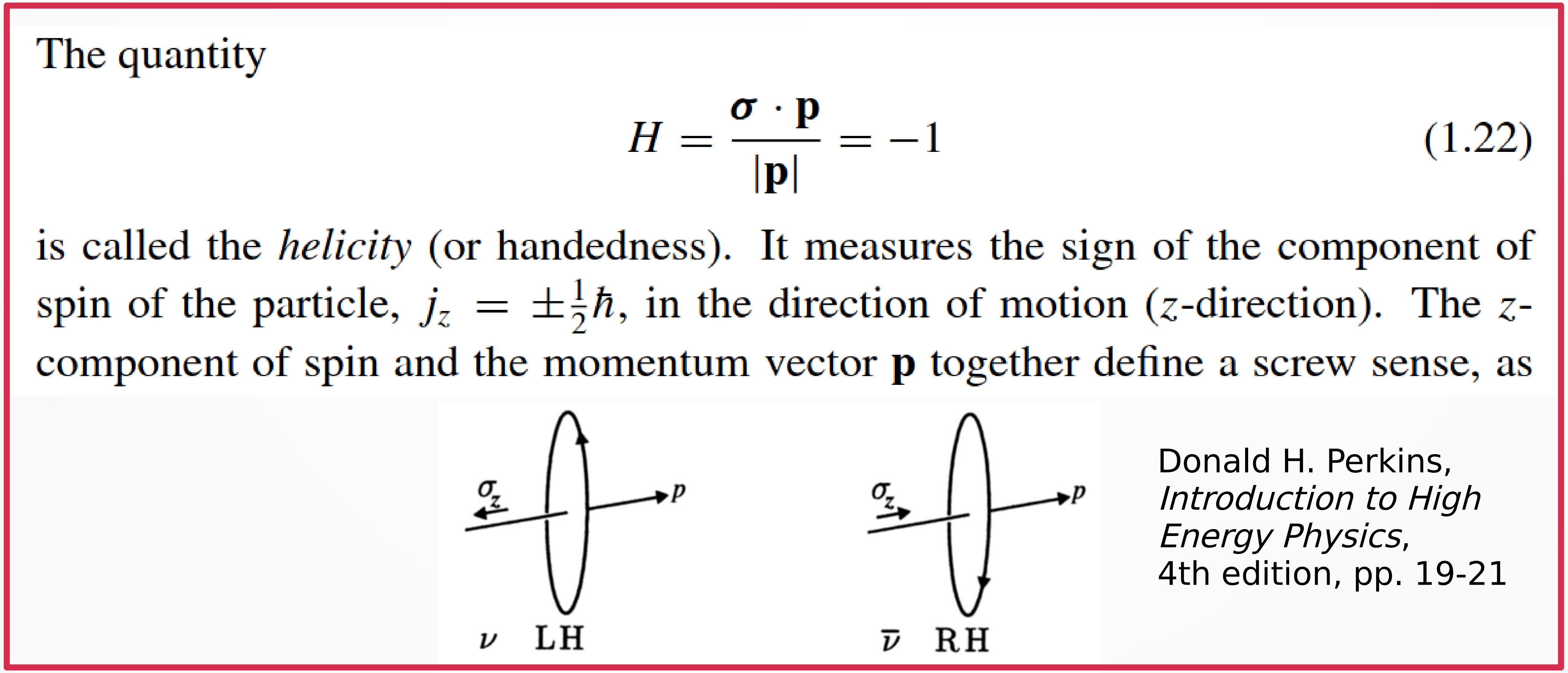
- 2014-2023: 10 years of beam to NOvA
- Neutrino beam data: 26.6x10^{20} Protons on Target (POT), (+96%)
- Antineutrino data: 12.5 x 10^{20} POT

NuFACT 2025 talk by
Jianming Bian

Upgrade impact on the CPV search in T2K



Neutrino helicity



The quantity

$$H = \frac{\boldsymbol{\sigma} \cdot \mathbf{p}}{|\mathbf{p}|} = -1 \tag{1.22}$$

is called the *helicity* (or handedness). It measures the sign of the component of spin of the particle, $j_z = \pm\frac{1}{2}\hbar$, in the direction of motion (z-direction). The z-component of spin and the momentum vector $\mathbf{p}$ together define a screw sense, as

Donald H. Perkins,
Introduction to High Energy Physics,
4th edition, pp. 19-21

Massless fermions are characterised by definite helicity states.
Good approximation for ultrarelativistic fermions.