

Report from the neutrino conference Rencontres du Vietnam 2025

Federico Nova
Tomislav Vladislavljevic

RENCONTRES DU VIETNAM



- series of conference on high-energy physics
- organized by Trần Thanh Vân
- held in Moriond (1966-88), Blois (1989-92) and Vietnam (1993-)
- 48 plenary talks
- 55 participants

SN1987A Kamioka history Supernova in Large Magellanic Cloud (LMC)



© Australian Astronomical Observatory

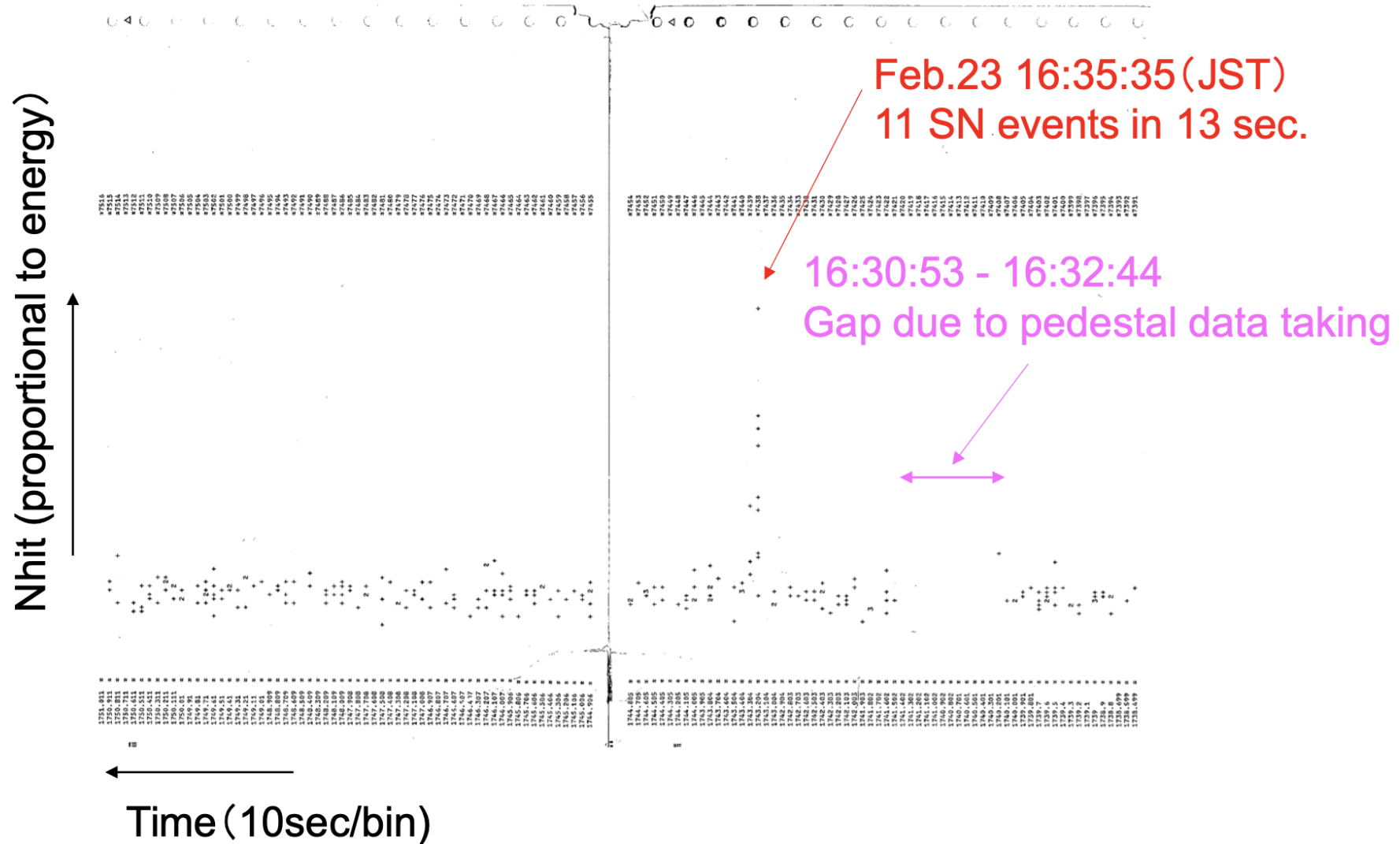
The first printout of the SN1987A signal

Kamioka history

2-dimentional HBOOK plot:

Horizontal axis: Time (10sec/bin),

Vertical axis: Nhit (number of hit PMTs) of each event



1988: First observation of solar neutrinos

Based on 450 days of data collected between Jan. 1987 and May 1988, Kamiokande successfully observed solar neutrino signals.

The observed flux was almost half of the expectation from the Standard Solar Model (SSM) and confirmed the “solar neutrino problem”.

However, we could not conclude that this was due to neutrino oscillations because the systematic uncertainty in the flux prediction in SSM was still large.

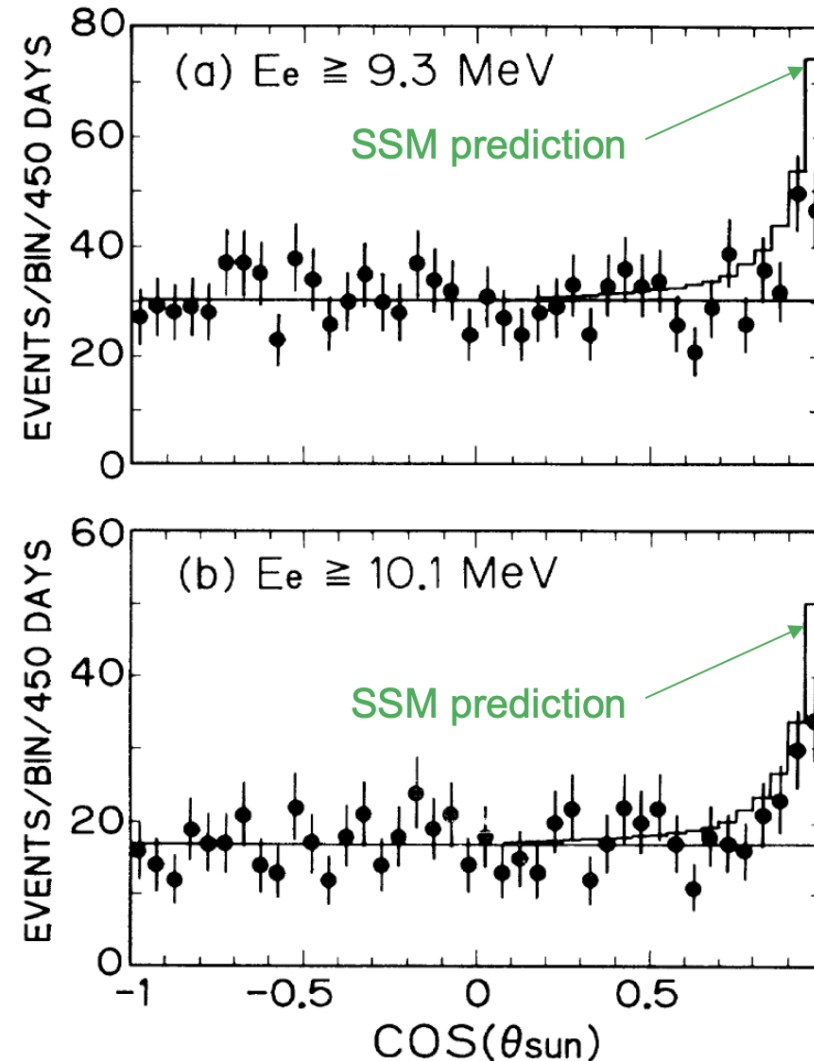
K.S. Hirata et al., Phys. Rev. Lett. 63, 16 (1989)

VOLUME 63, NUMBER 1

PHYSICAL REVIEW LETTERS

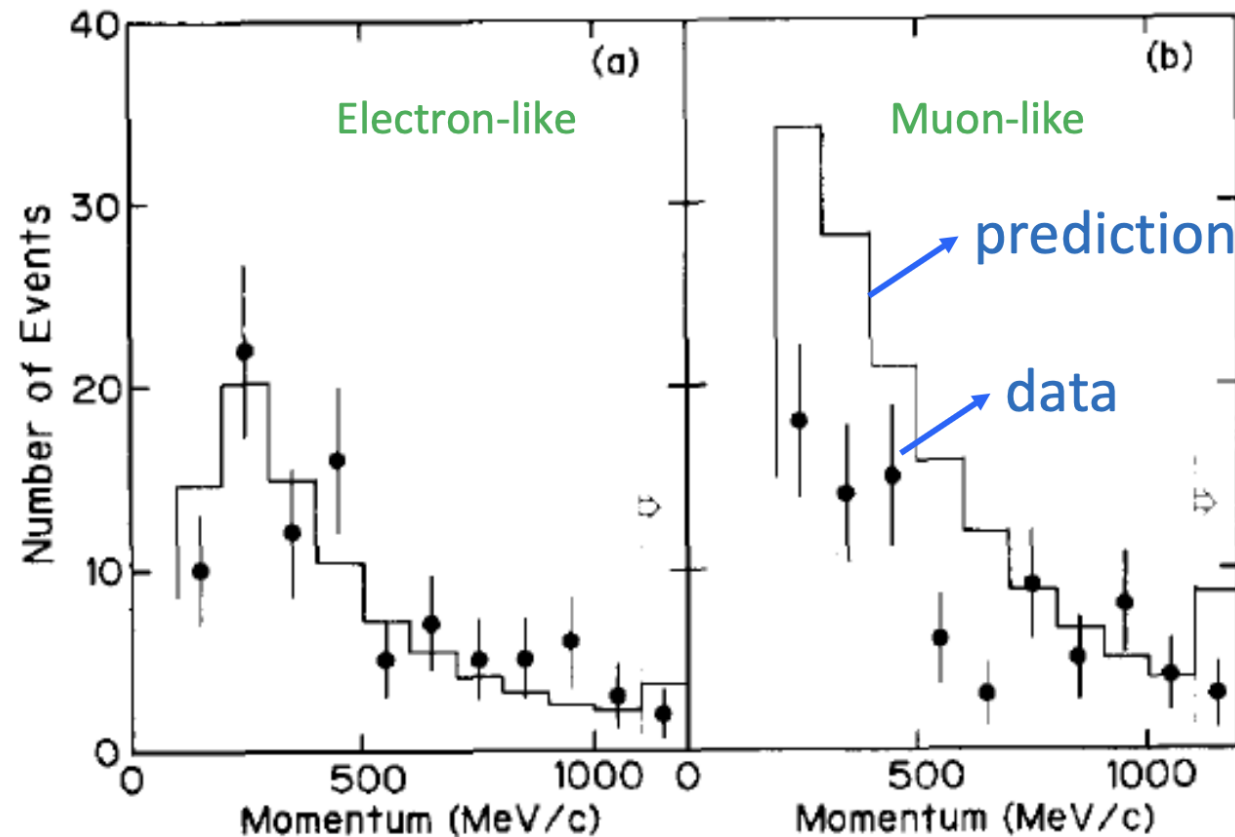
3 JULY 1989

Observation of ^8B Solar Neutrinos in the Kamiokande-II Detector



1988: Atmospheric neutrino anomaly at Kamiokande

Data in 1988 paper
(Phys. Lett. B205 (1988)416.)

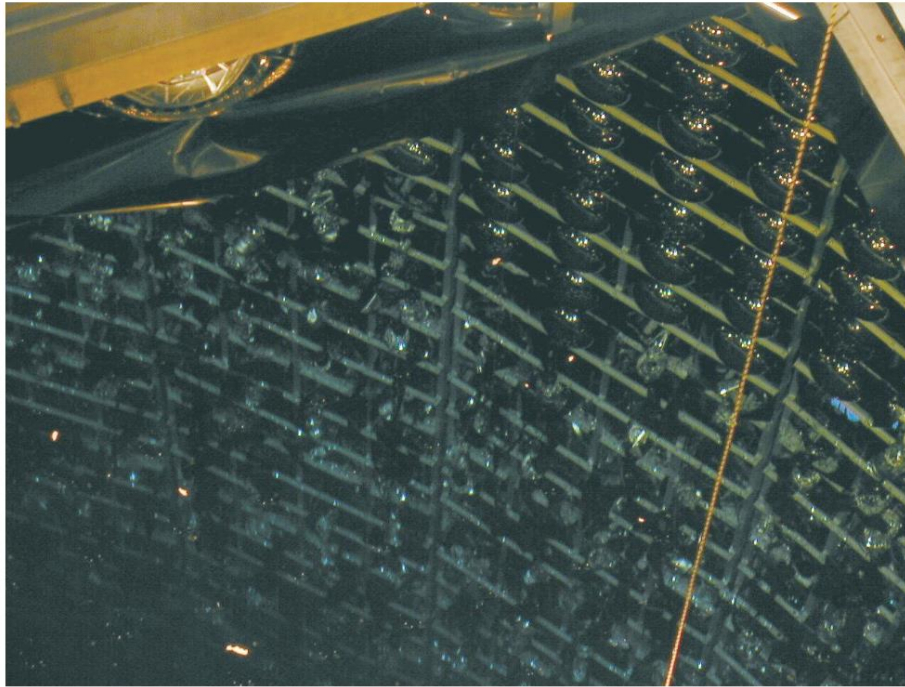


Electron-like data is consistent with prediction.

However, muon-like data is $59 \pm 7\%$ of prediction.

Neutrino oscillation was a possible explanation for this anomaly, but we were unable to convince the scientific community.

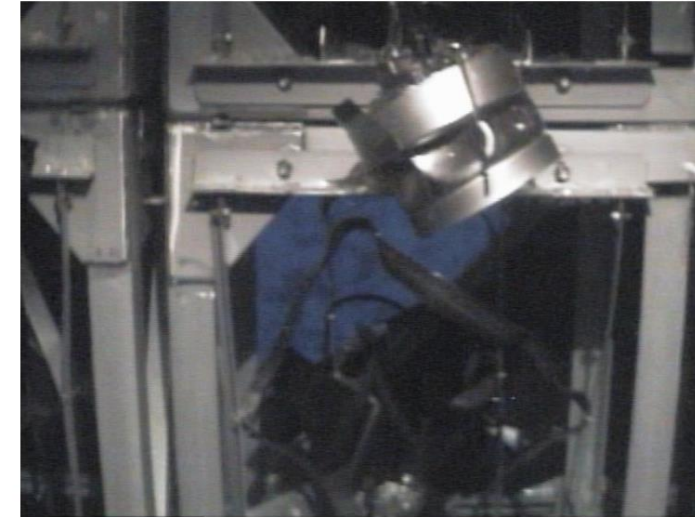
November 12, 2001 Super-K accident



Inner PMTs 6777 were destroyed

Outer PMTs 1100 were destroyed

Approximately 60% of the PMTs were destroyed. The initial trigger was the failure of a single PMT located at the bottom of the tank. This generated a shock wave, which caused a chain reaction that led to the destruction of many other PMTs.



Crashed dinode



Glass debris at the bottom of tank₂₉

e-mail from Totsuka-san on the next day(2001.11.13)

Dear colleague,

As a director of the Kamioka Observatory, which owns and is responsible to operate and maintain the Super-Kamiokande detector, it is really sad that I have to announce the severe accident that occurred on November 12 and damaged the significant part of the detector. Details of what happened and a preliminary evaluation of the damage are described in Appendix. Please DO NOT DISTRIBUTE it to outside people, as it is very preliminary and subject to a substantial change.

The cause and how to deal with the loss in future will be discussed by newly found committees.

However, even before discussing with my colleagues of the Super-K and K2K collaborations, I have decided to express my intension on behalf of the staff of the Kamioka Observatory.

We will rebuild the detector. There is no question. The strategy may be the following two steps, which will be proposed and discussed by my colleagues.

1. Quick restart of the K2K experiment.

(1) We will clear the safety measures which may be suggested by the committees, (2) reduce the number density of the photomultiplier tubes by about a half, (3) use the existing resources, (4) resume the K2K experiment as soon as possible; the goal may be within one year.

2. Preparation for the ~~JHF~~-Kamioka experiment.

(1) Restore the full Super-Kamiokande detector armed with the state-of-the-art techniques. (2) The detector will be ready by the time of the commissioning of the JHF machine. To achieve our objective is formidable but we are determined to do so. But we certainly need your encouragement, advice and help. I should appreciate it very much if you could support our effort as you have kindly done so before.

Best regards,

Yoji Totsuka

flavor
states

neutrino oscillations

mass
states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospherics and
LBL

$\theta_{23} \sim 45^\circ$

$|\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$

Reactors

$\theta_{13} \sim 10^\circ$

LBL

θ_{13} and δ_{CP}

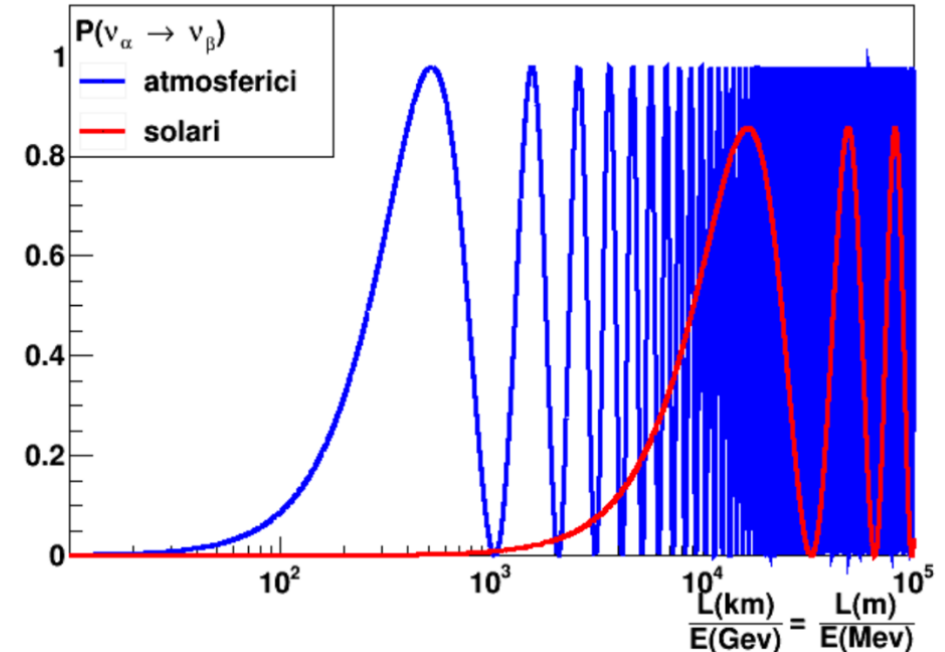
Solar and reactors

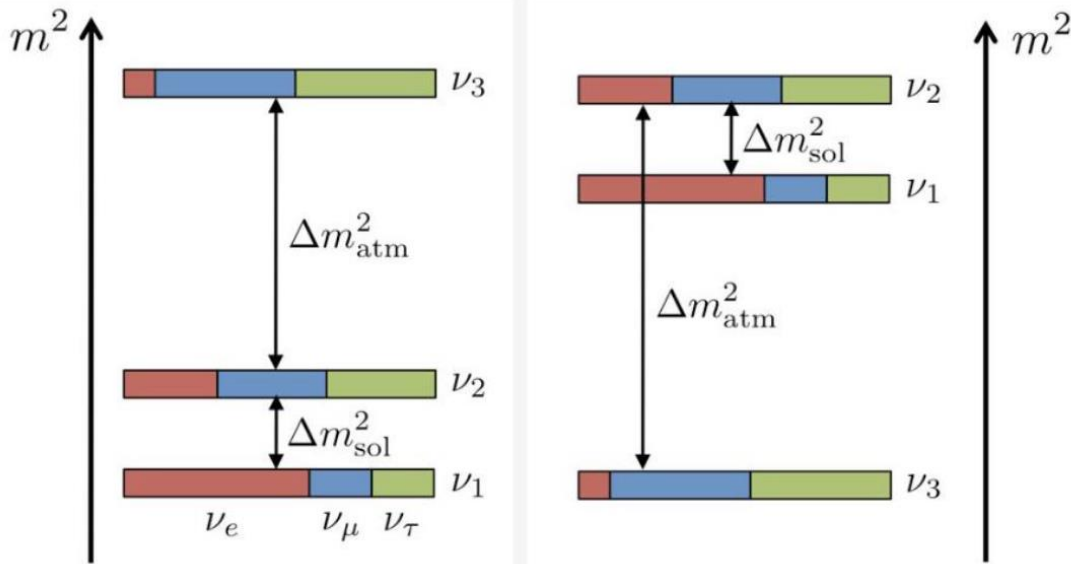
$\theta_{12} \sim 35^\circ$

$\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$

two-flavors approximation

$$P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$





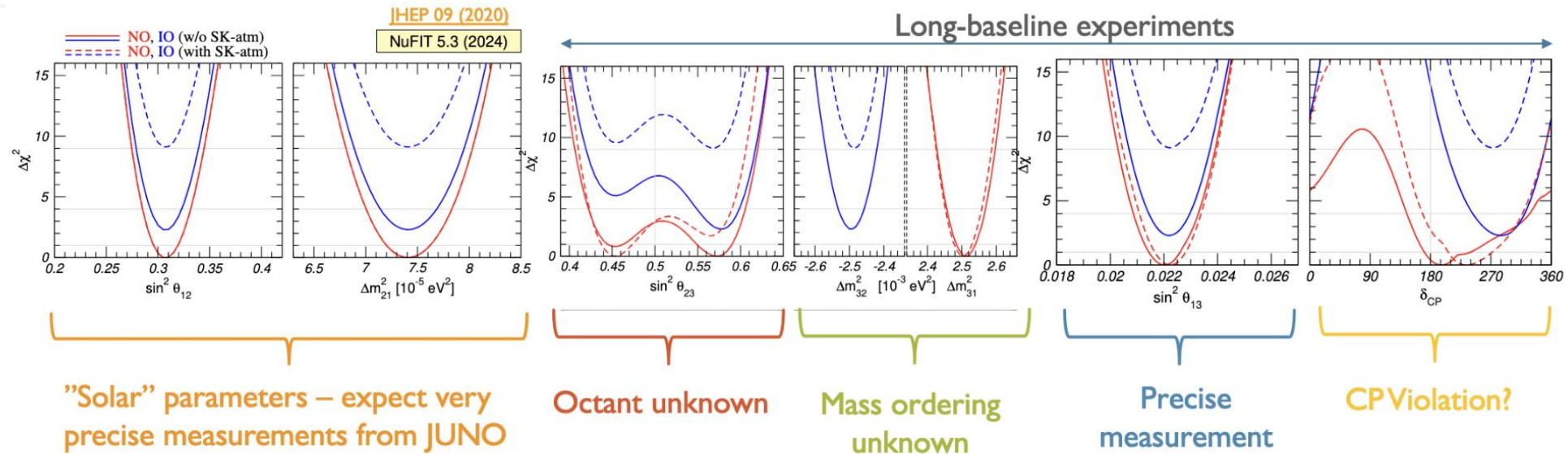
Future objectives:

- δ_{CP}
- θ_{23} max?
- Hierarchy?
- Majorana ν ?
- Absolute mass
- Sterile ν ?

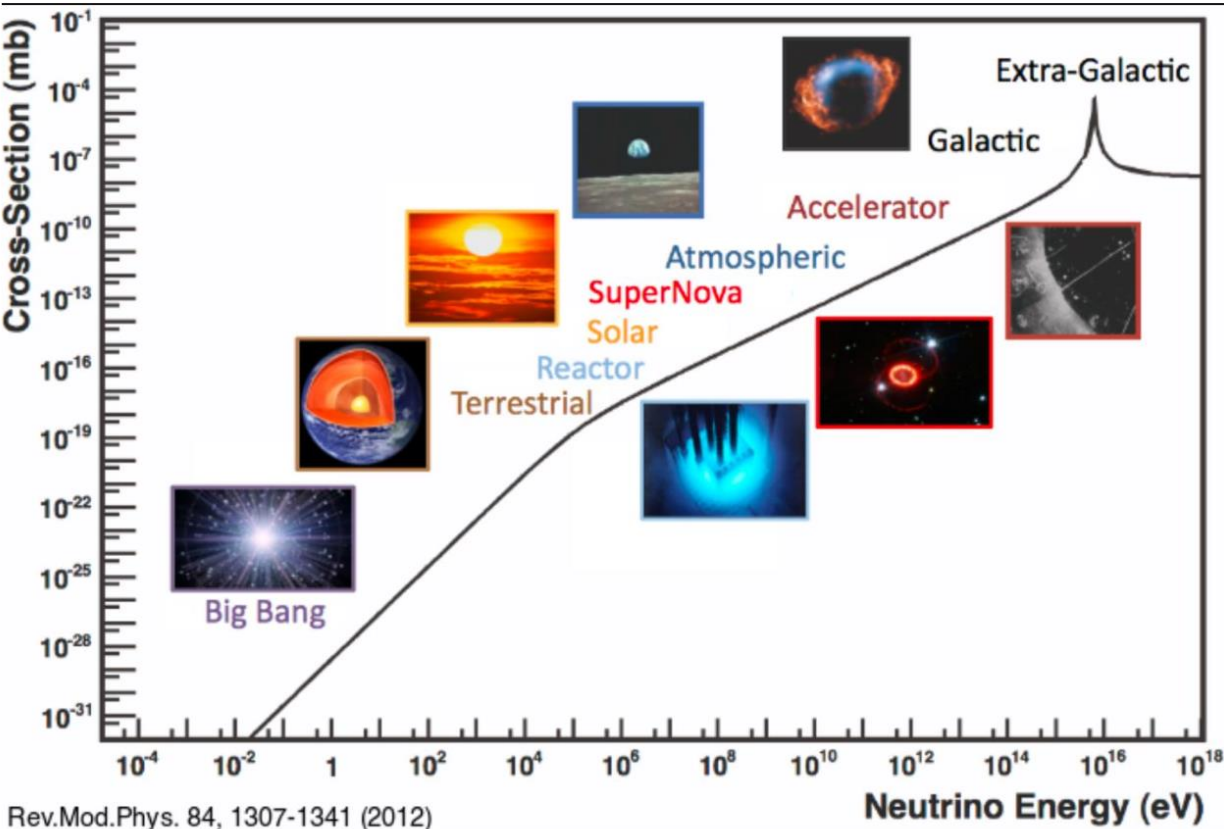
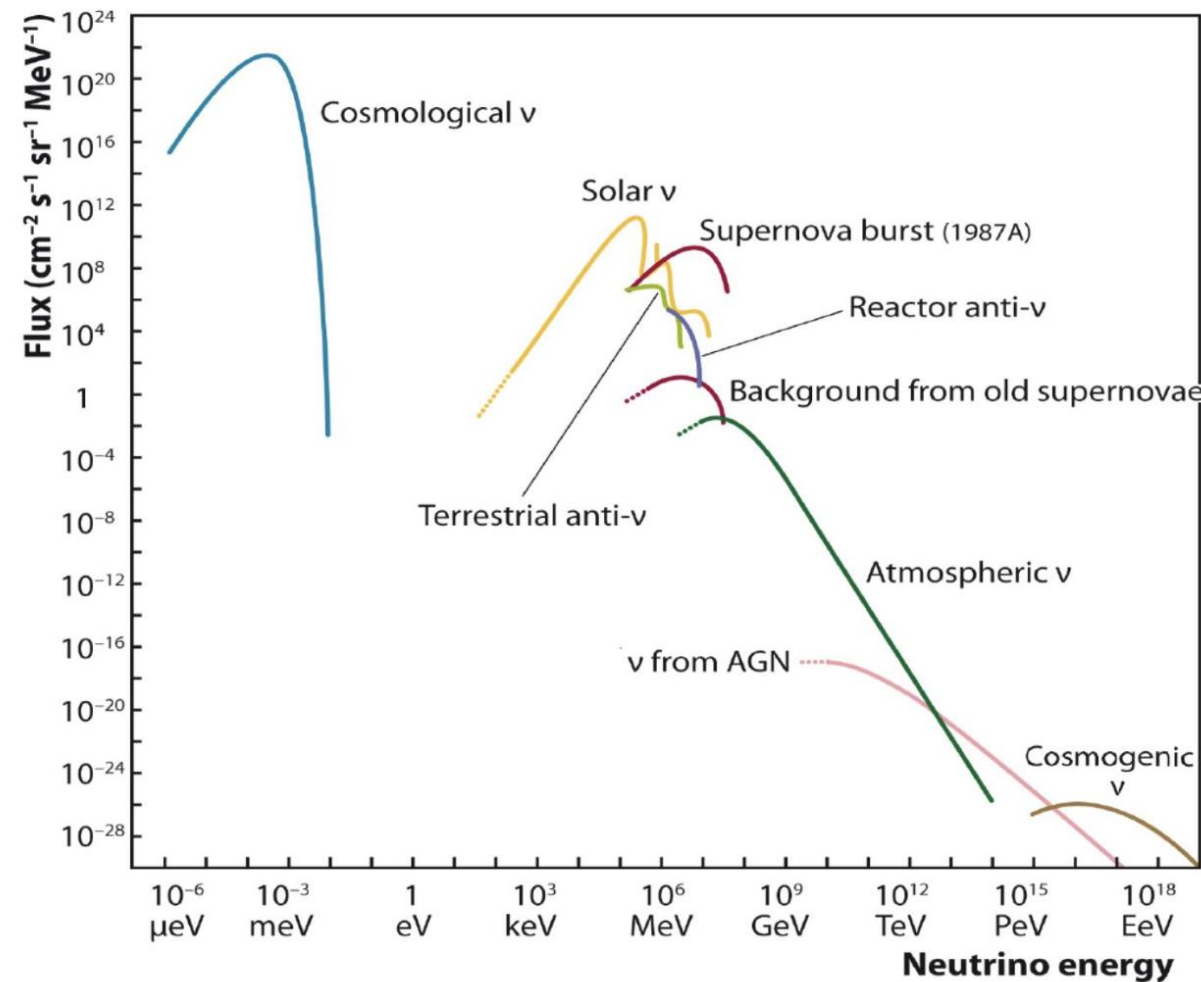
Accelerator, Reactor,
Atmospheric

$0\nu\beta\beta$, Cosmology,
Electron spectrometers,

Accelerator, Reactor,
Atmospheric



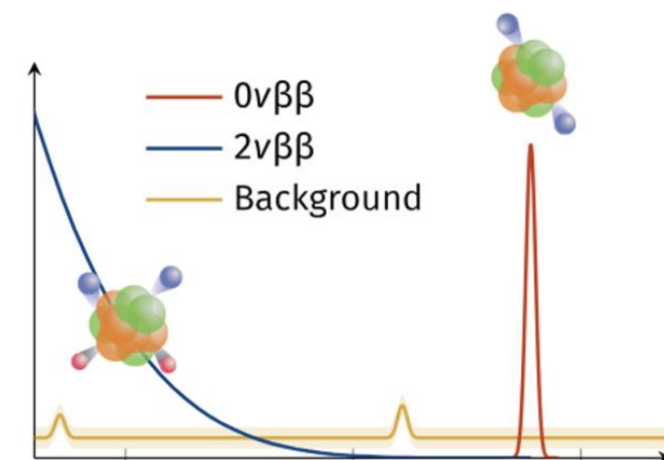
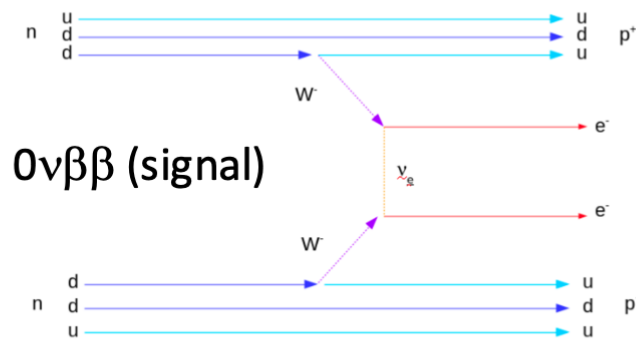
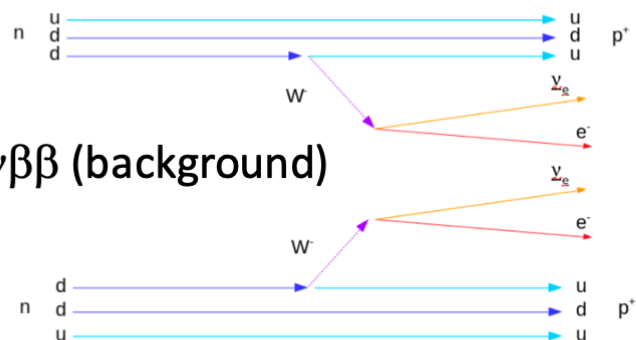
Neutrinos Reaching the Earth



double beta decay

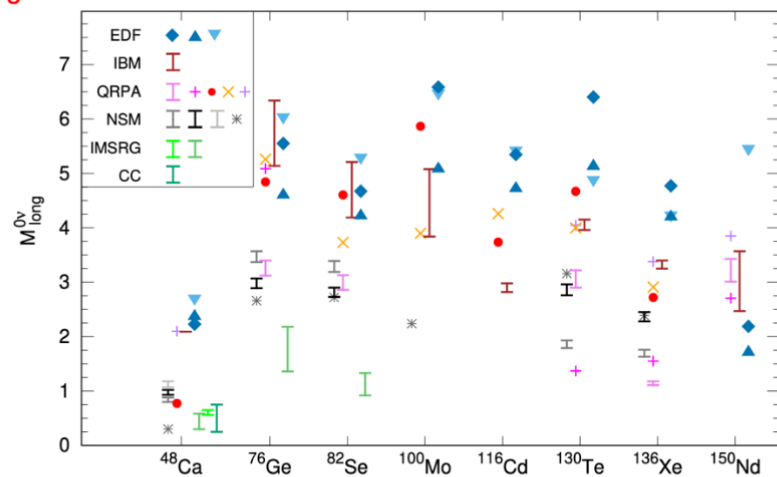
- KamLAND-Zen
- CUORE and CUPID
- PandaX
- SuperNEMO

double beta decay



$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations

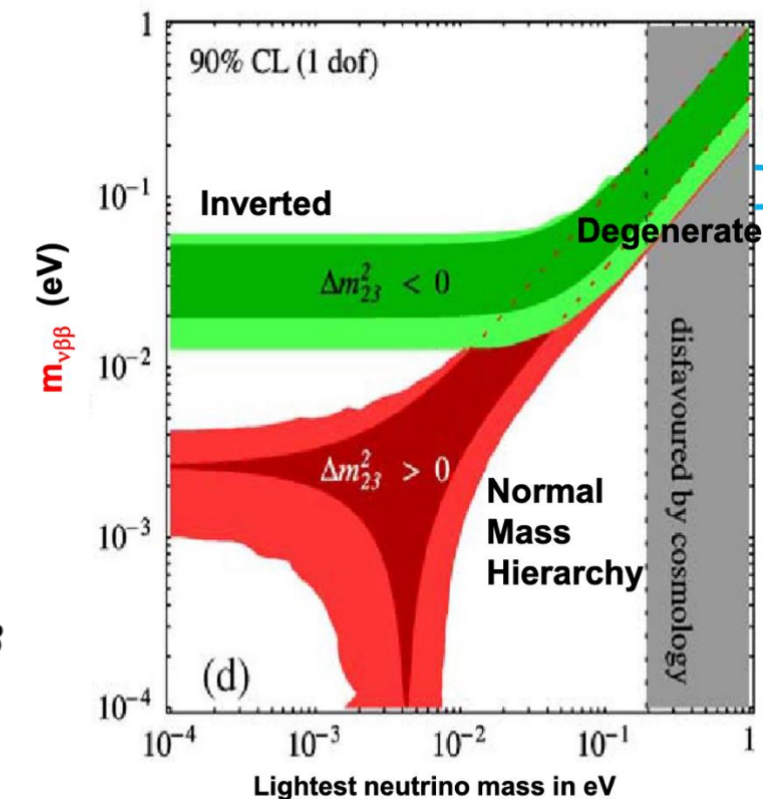


Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

- $2\nu\beta\beta$ very rare process
- $0\nu\beta\beta$ never observed
- find signal by total energy
- proves ν is Majorana particle
- proves lepton number is violated
- explain mass smallness
- measures ν mass

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 |M^{0\nu\beta\beta}|^2 m_{\beta\beta}^2$$

- uncertainty in nuclear matrix element



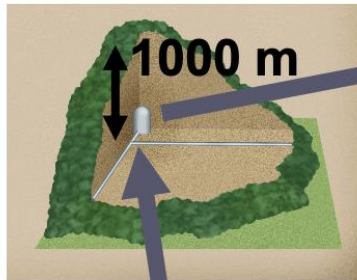


KamLAND-Zen

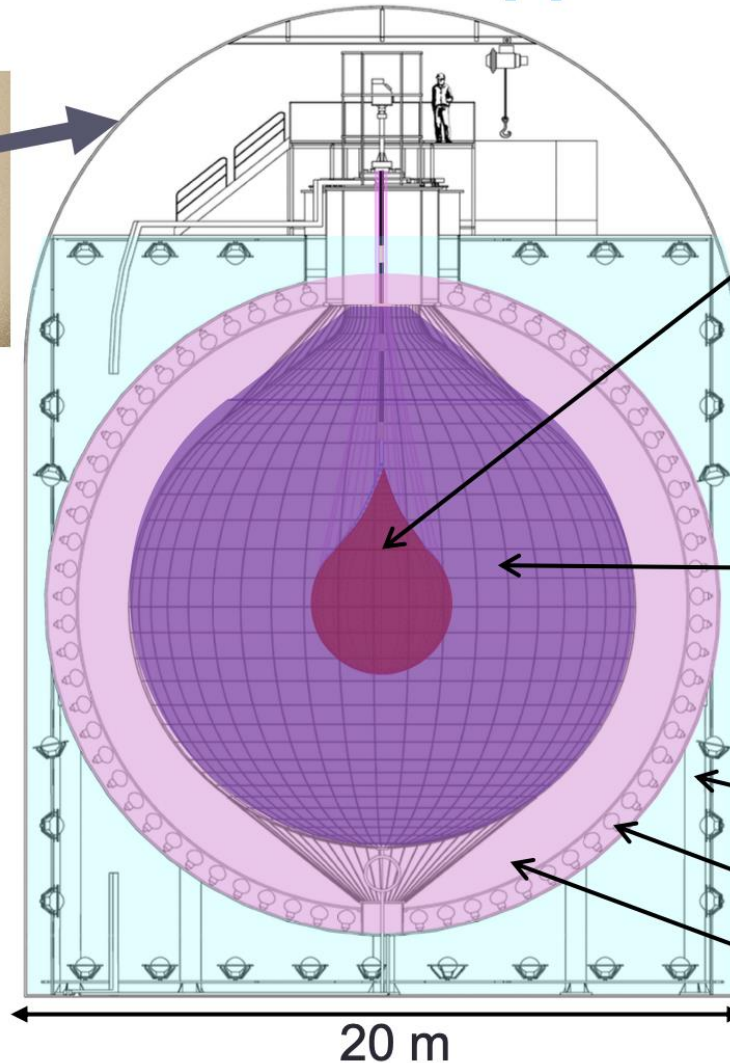
Zero Neutrino Double Beta

Cosmic-muon rate
~ 0.34Hz

$0\nu\beta\beta$ of ^{136}Xe search experiment



Kamioka,
Gifu, Japan



Xe loaded LS (XeLS)

- Enrichment ~90%
- Dissolved into LS 3%wt
- Xe is installed only within ultra-clean inner-balloon (IB)

1kton purified LS (KamLS)

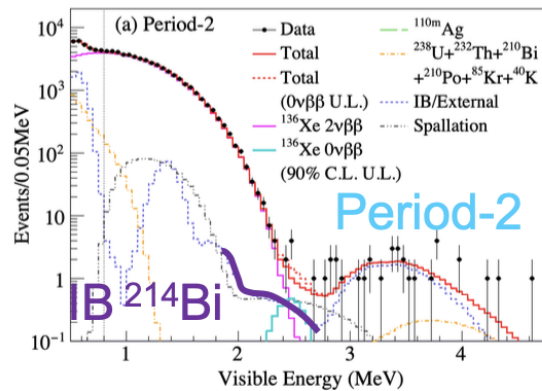
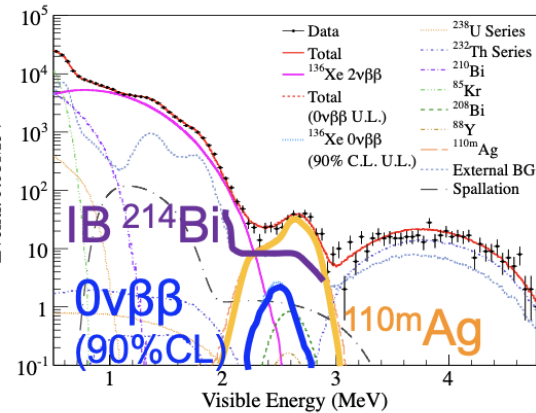
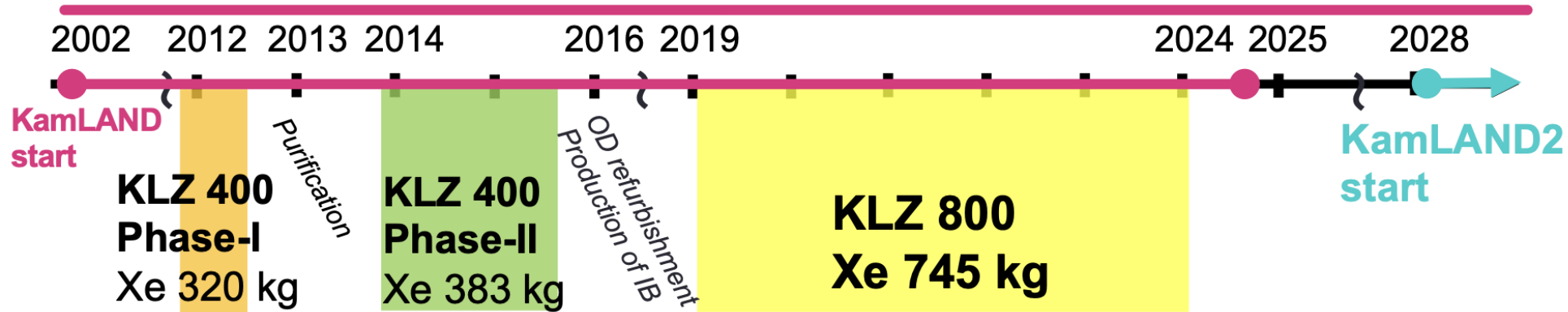
- $^{238}\text{U} \sim 5.0 \times 10^{-18} \text{ g/g}$
- $^{232}\text{Th} \sim 1.8 \times 10^{-17} \text{ g/g}$

3.2kton purified water

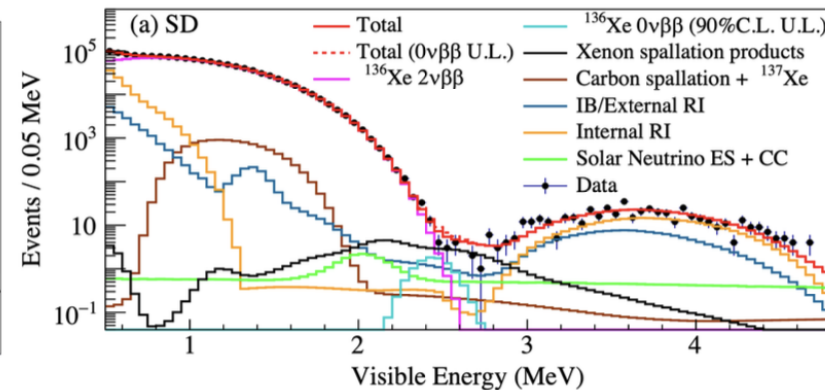
1879 PMTs

Buffer Oil

History of KamLAND-Zen



✓ **Reduced ^{110m}Ag by purification**



✓ **Successfully produced a low-BG IB (~1/10)**

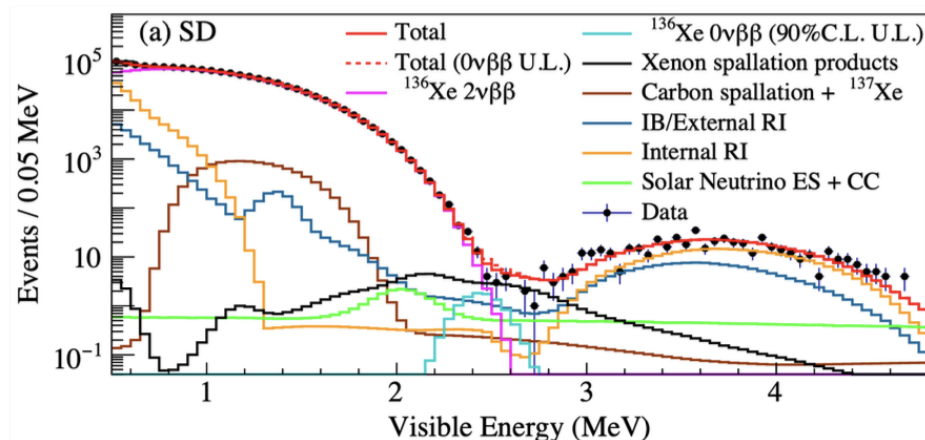
✓ **Double Xe**

- KamLAND-Zen 800 completed DAQ on Jan.11, 2024.
- We started detector upgrades in 2024 and plan to launch KamLAND2 in 2028!!

^{136}Xe $0\nu\beta\beta$ decay Half-life limit

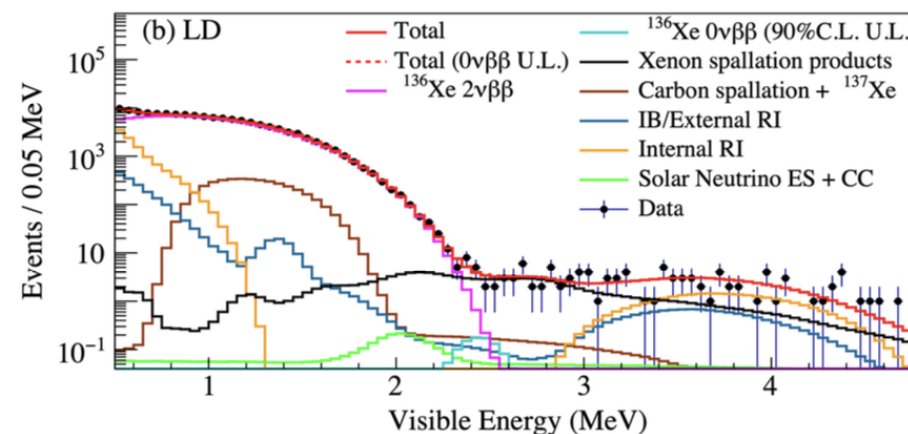
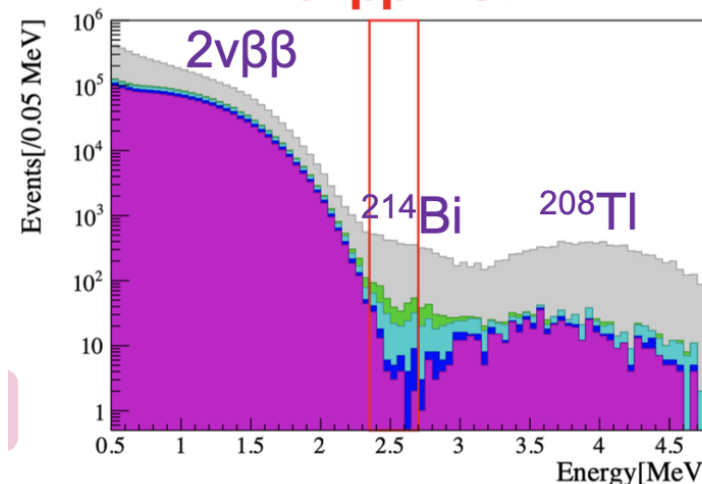
aiXiv: 2406.11438

Singles data (SD)

(sensitive to $0\nu\beta\beta$ signal)1131 days livetime, $R < 1.57$ m $0\nu\beta\beta$ best fit : 0 eventU.L. : < 10.0 event at 90% C.L.Half-life limit at 90% C.L.KLZ 400 $T_{1/2}^{0\nu} > 0.9 \times 10^{26}$ yrKLZ 800 $T_{1/2}^{0\nu} > 3.4 \times 10^{26}$ yrCombined $T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ yr

Long-lived product data (LD)

(Long-lived BG constraint)

111 days livetime, $R < 1.57$ m $0\nu\beta\beta$ ROI



CUORE

Cryogenic Underground Observatory for Rare Events

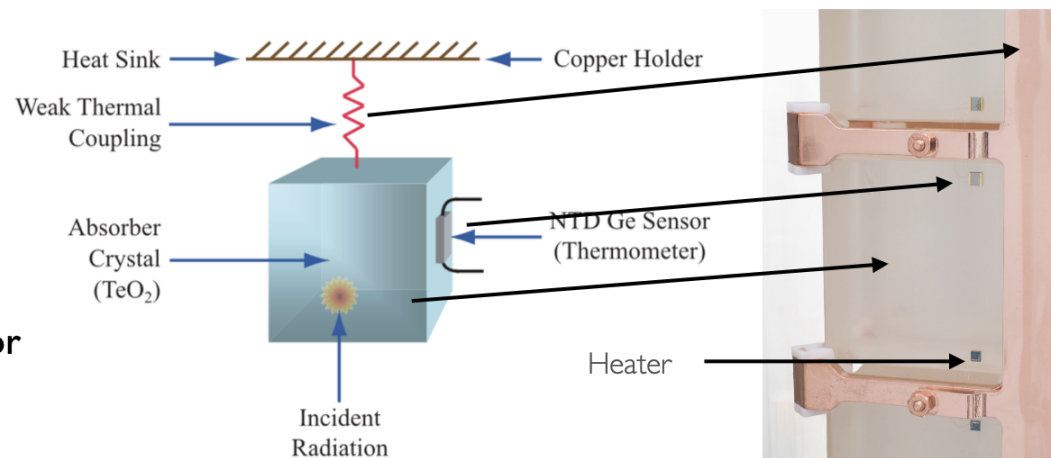
- Located in LNGS under the mountain of Gran Sasso
- **Primary Goal:** Search for $0\nu\beta\beta$ decay of ^{130}Te
- **Design:**
 - 19 towers (total of 988 TeO_2 crystals)
 - 206 kg of ^{130}Te : $Q_{\beta\beta} \sim 2.5 \text{ MeV}$
 - *Low background:* $\sim 10^{-2} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$
 - *Energy resolution:* $\sim 8 \text{ keV FWHM}$ at $Q_{\beta\beta}$



Cryogenic Calorimetric Technique

- Each crystal:

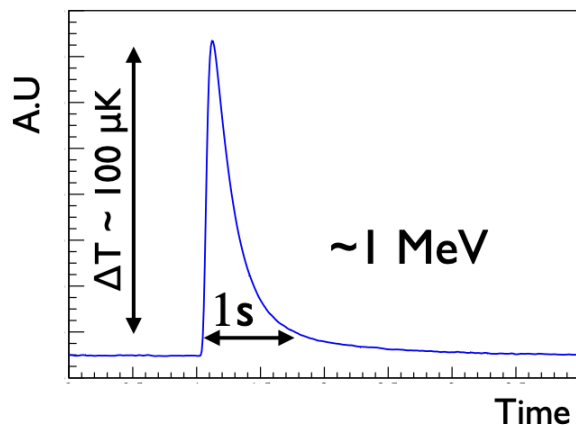
- **Absorber:** 5x5x5 cm³ TeO₂ crystal
- **Operational temperature:** ~10 mK
- **Thermal coupling:** PTFE holder and gold wires
- **Sensor:** Ge neutron transmutation doped (NTD-Ge) thermistor
- **Heater:** Gain stabilization and calibration



Crystal temperature rises when energy is deposited

$$\Delta T \propto \frac{E}{C(T)}$$

$$C(T) \propto T^3$$

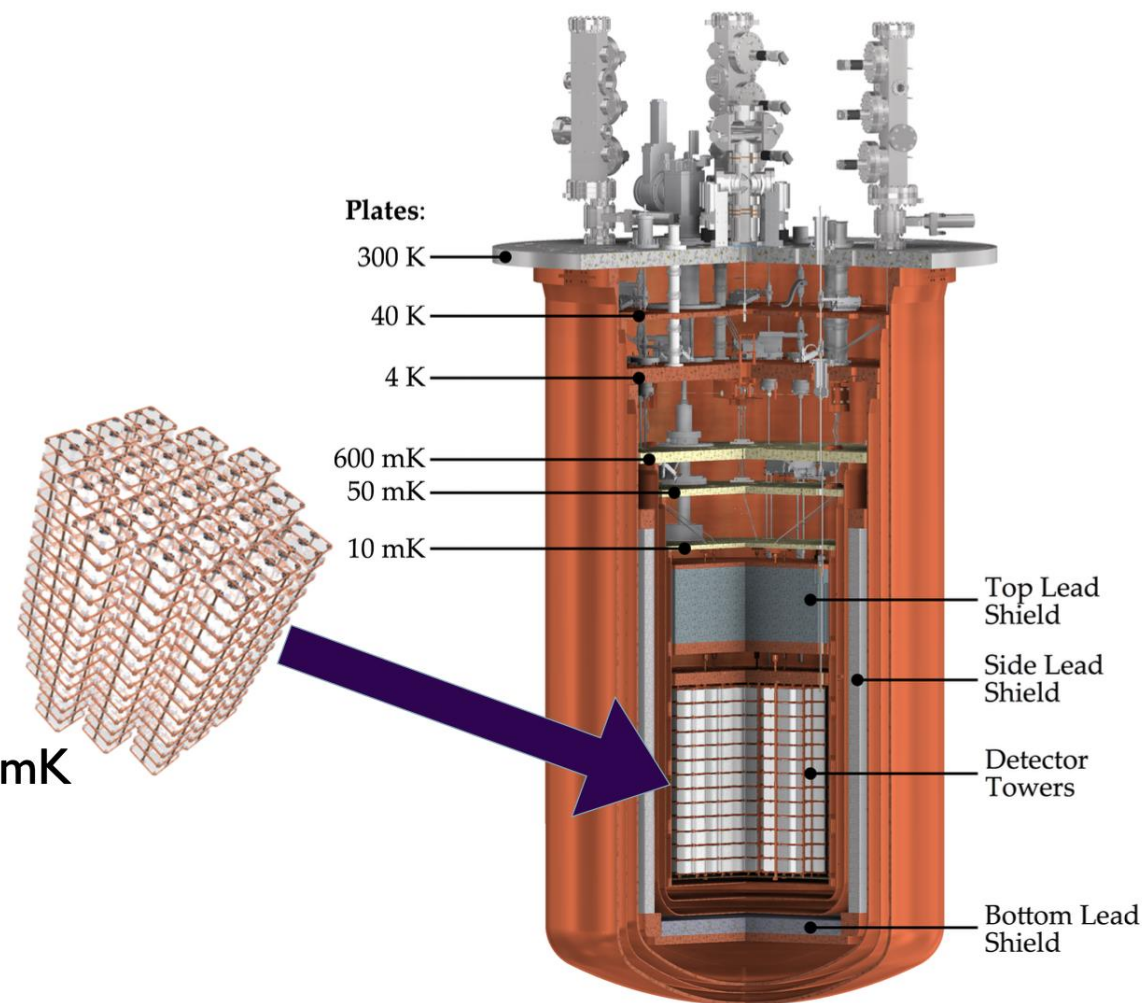


- Excellent energy resolution ($\sim 0.3\% \Delta E/E @ Q_{\beta\beta}$)
- Detector response independent of particle type
- Flexibility in $0\nu\beta\beta$ candidate choice



CUORE Cryostat

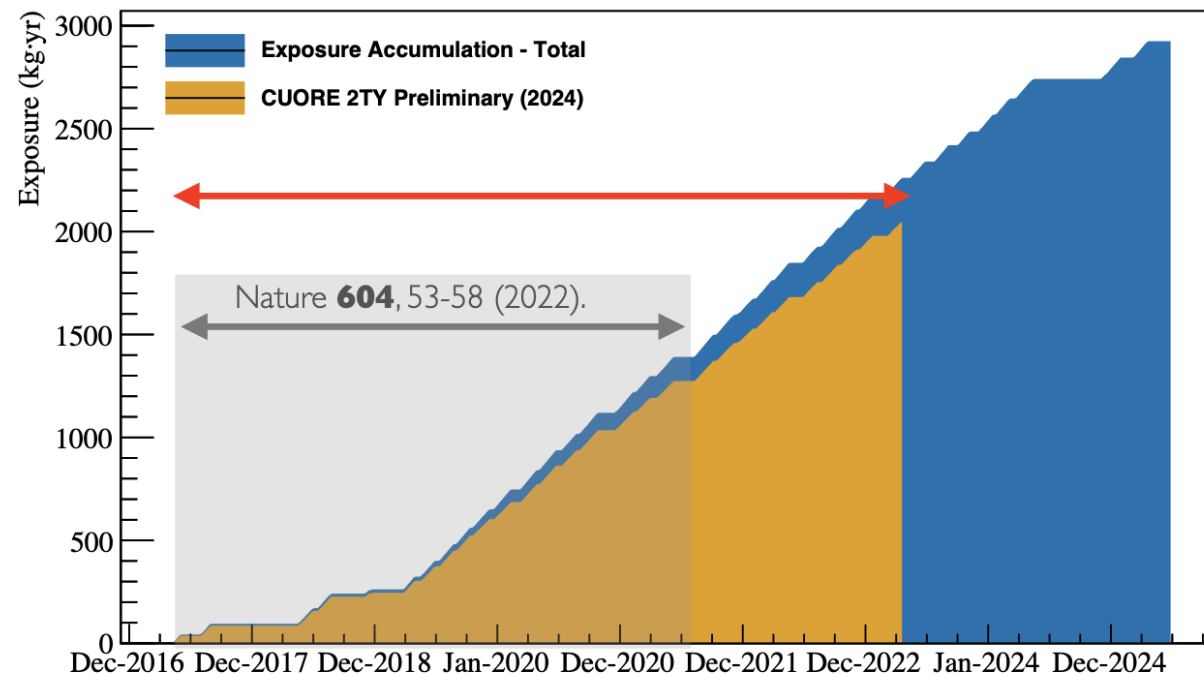
- Multiple stage cryogen-free cryostat:
 - Nested co-axial cylinders
 - Pulse Tubes for cooling **40 K** and **4 K** stages
 - Dilution Unit to cool rest of the stages
- Total cooled mass: ~**30 ton**
- First ever cryostat to have cooled ~1 tonne to 10 mK





Data Taking

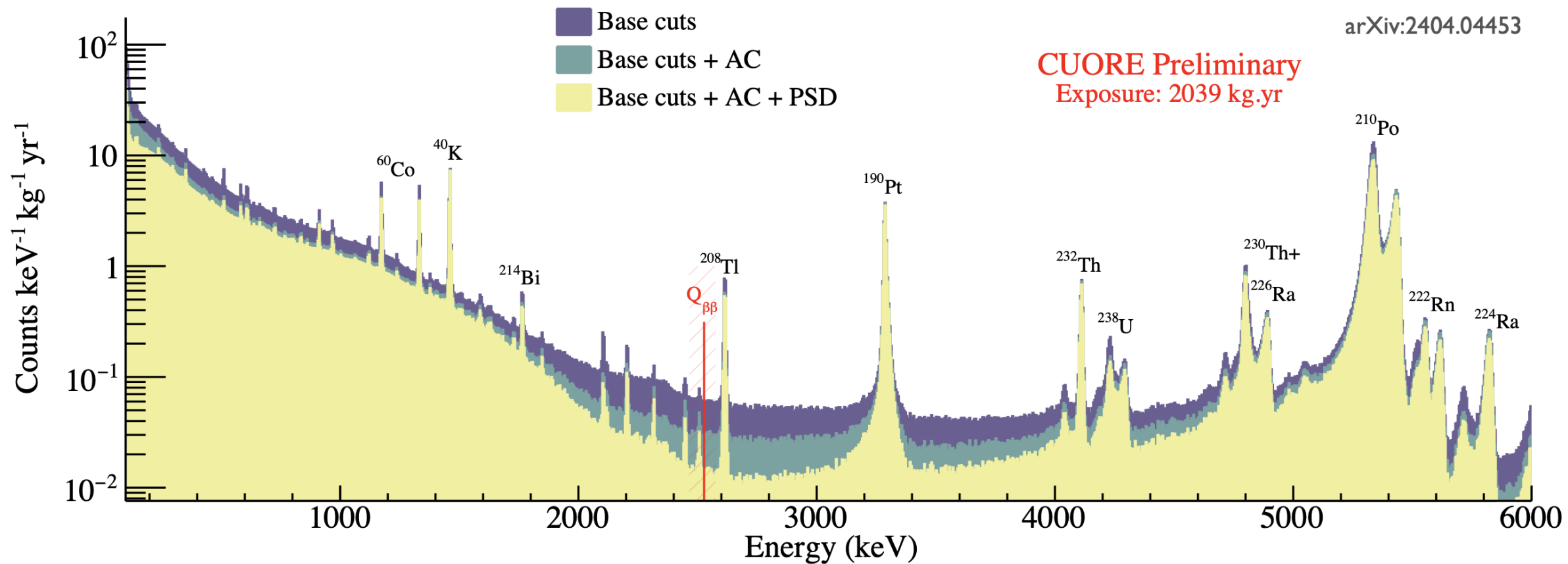
- Pauses in data taking for detector optimization during early detector operations
- Since 2019 continuous data-taking with very little down time
- 34 datasets collected so far, each dataset ~1 month long (~50 kg.yr/month)
- Published $0\nu\beta\beta$ search results in 2022 for the data collected up to 2020
- Updated search with data collected up to 2023 (~2 tonne.yrs of TeO_2 exposure)





CUORE

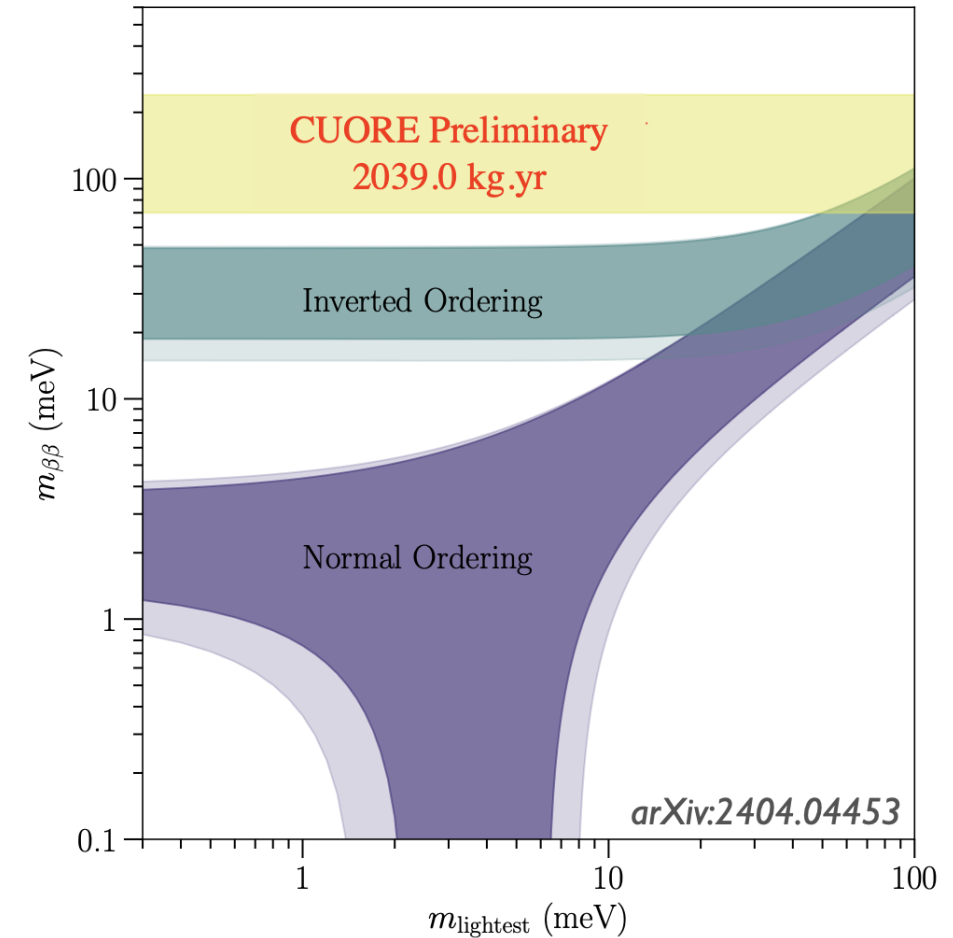
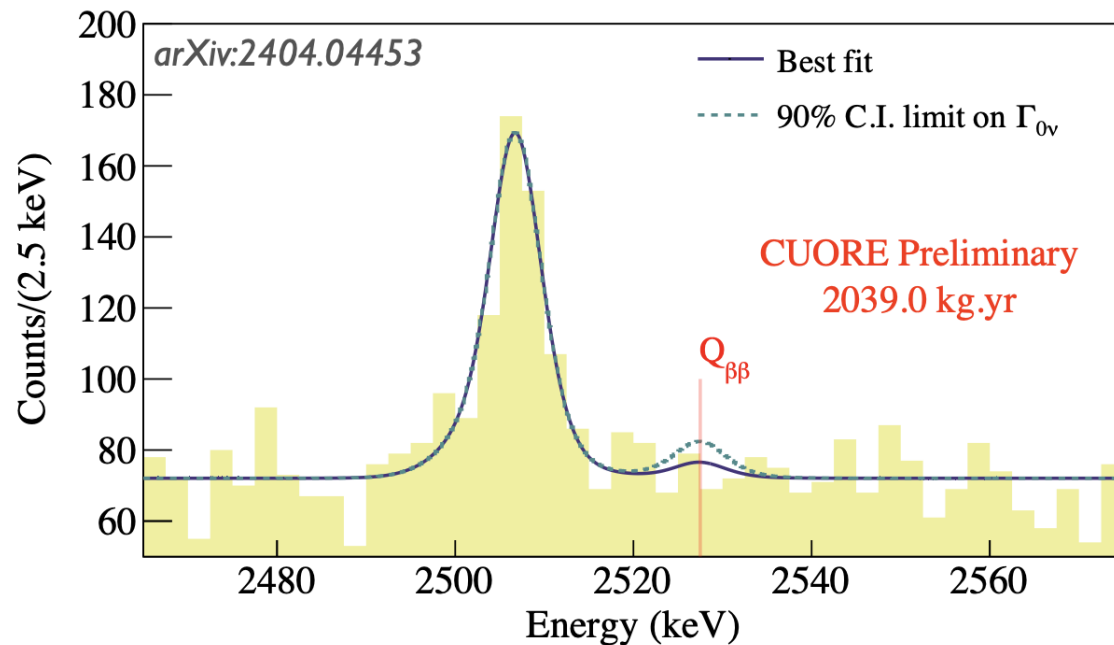
Spectrum





Limit on Neutrino Mass

- Fit performed over [2465, 2575] keV with fit parameters:
 - $0\nu\beta\beta$ decay rate @ $Q_{\beta\beta}$
 - ^{60}Co sum peak amplitude
 - Background (flat)
- No evidence of $0\nu\beta\beta$
- $T_{1/2}^{0\nu} > 3.8 \times 10^{25} \text{ yr}$ (90% C.I.)

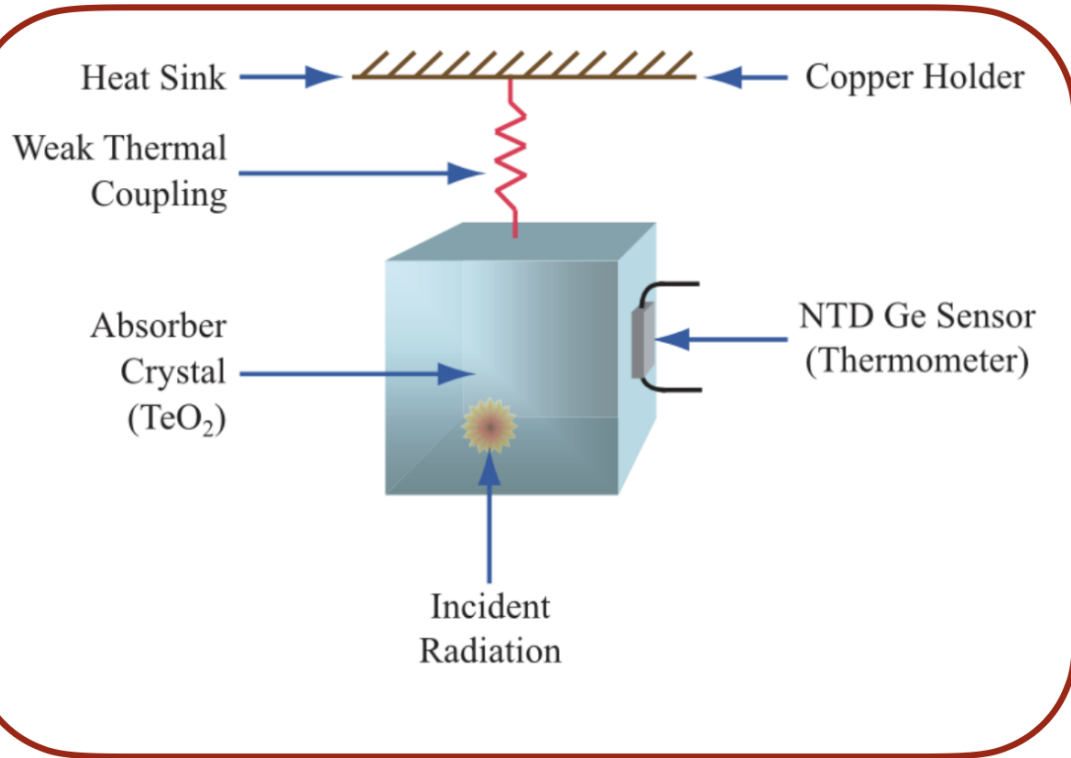


- Assuming light neutrino exchange:
 $m_{\beta\beta} < \mathbf{70\text{--}240 \text{ meV}}$



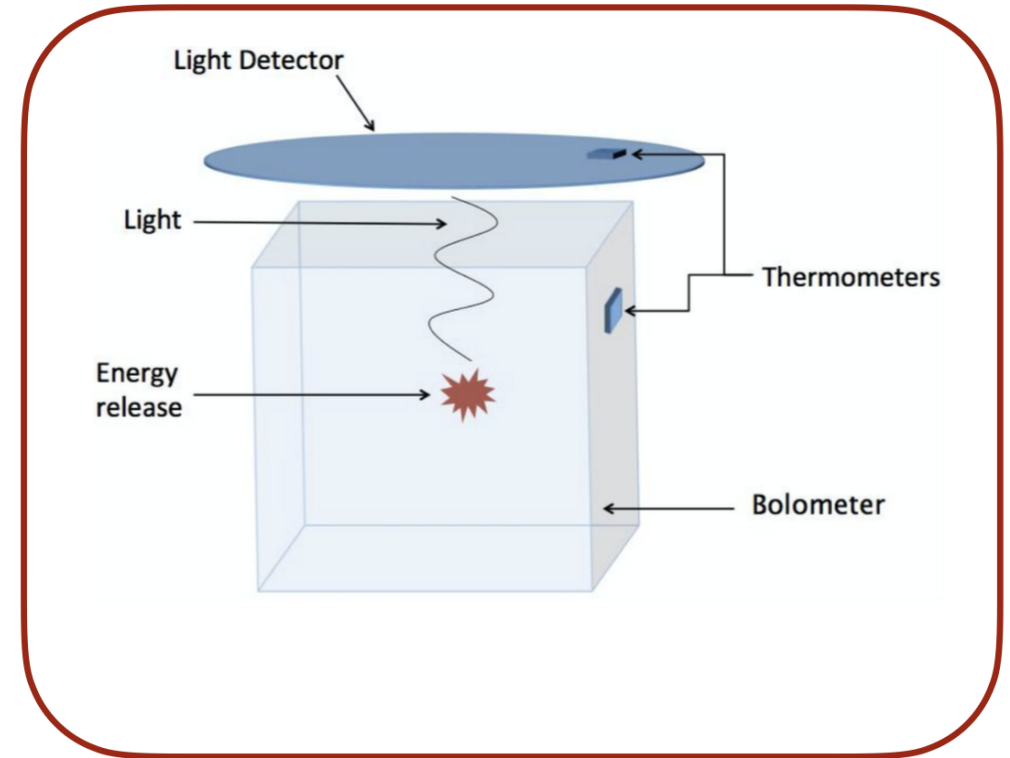
CUPID Concept

CUORE: ^{130}Te crystal



$Q_{\beta\beta} = 2527 \text{ keV} < 2615 \text{ keV peak}$
 Measure only heat
 No particle ID

CUPID: ^{100}Mo Scintillating Bolometer

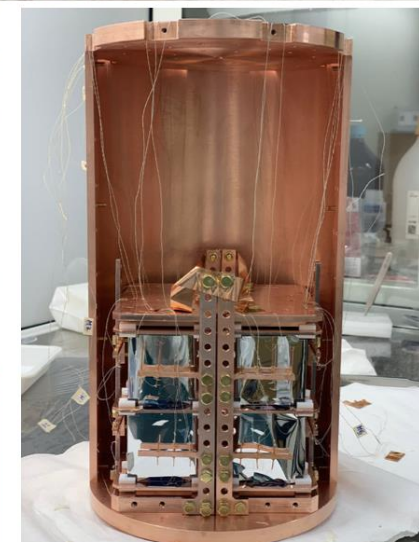
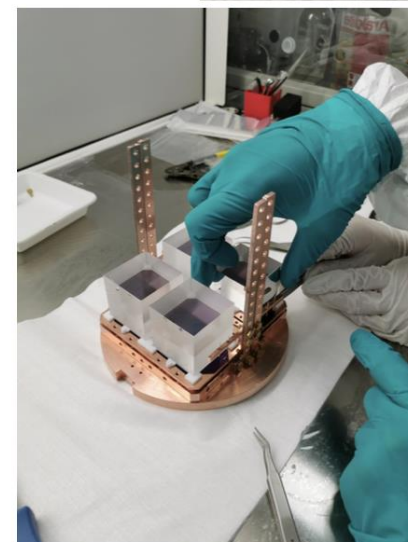
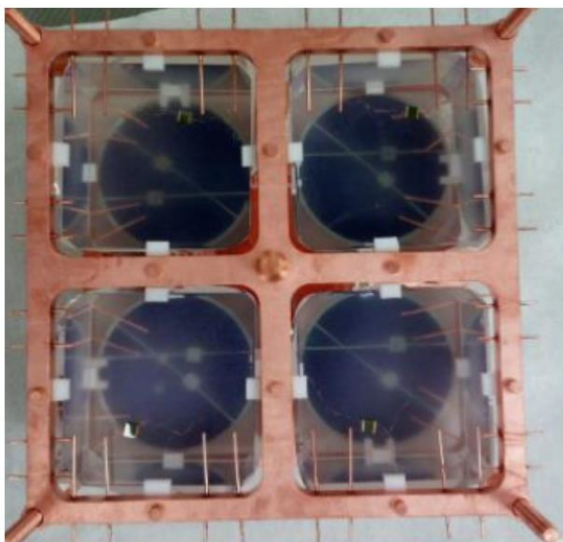
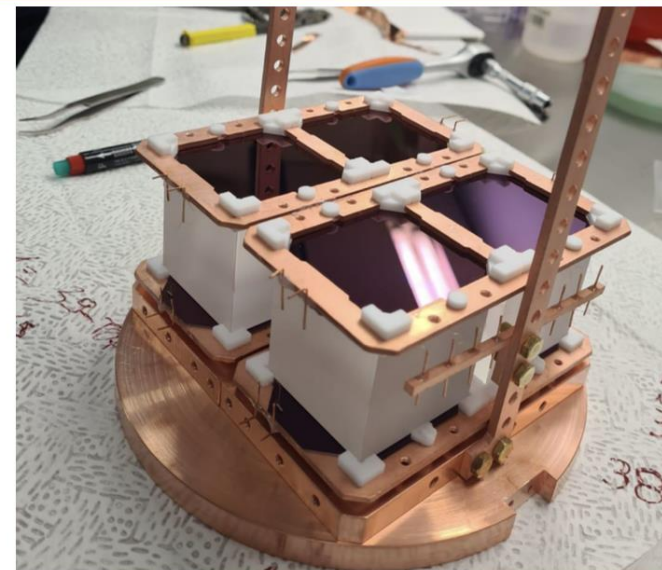


$Q_{\beta\beta} = 3034 \text{ keV}$: Most β/γ backgrounds reduced
 Measure both heat + light
 Particle ID to actively discriminate α s



Past and Ongoing R&D

- Final CUPID design based on several R&D tests
- Staged deployment enables first science data by 2030 with CUPID Stage I



PandaX pathway

- Increasing sensitive target volume
- Lowering radioactive background



2009



2010-2014

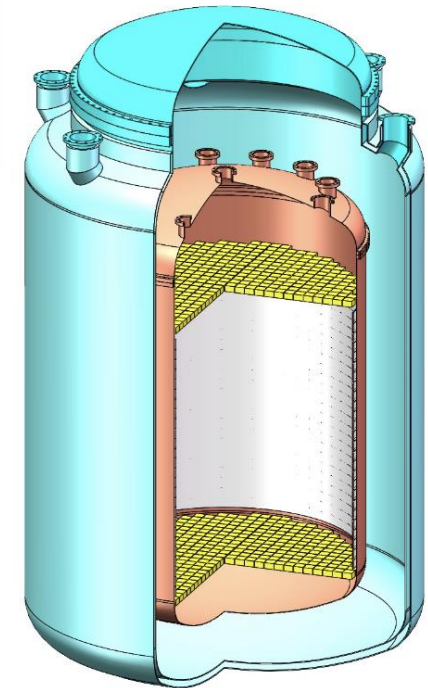


2015-2019



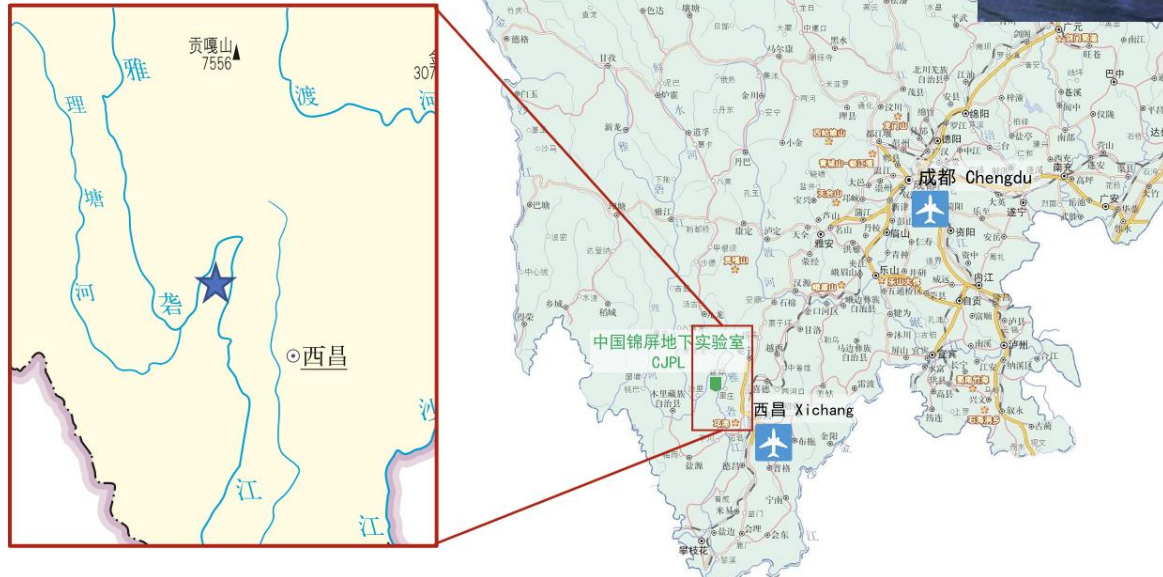
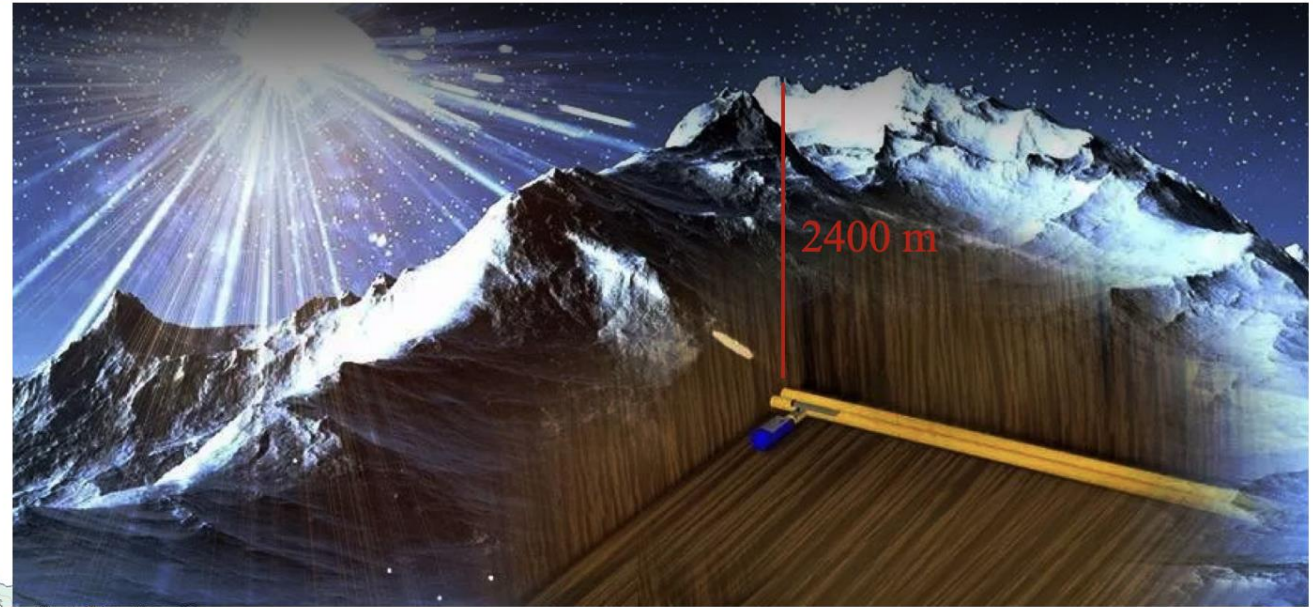
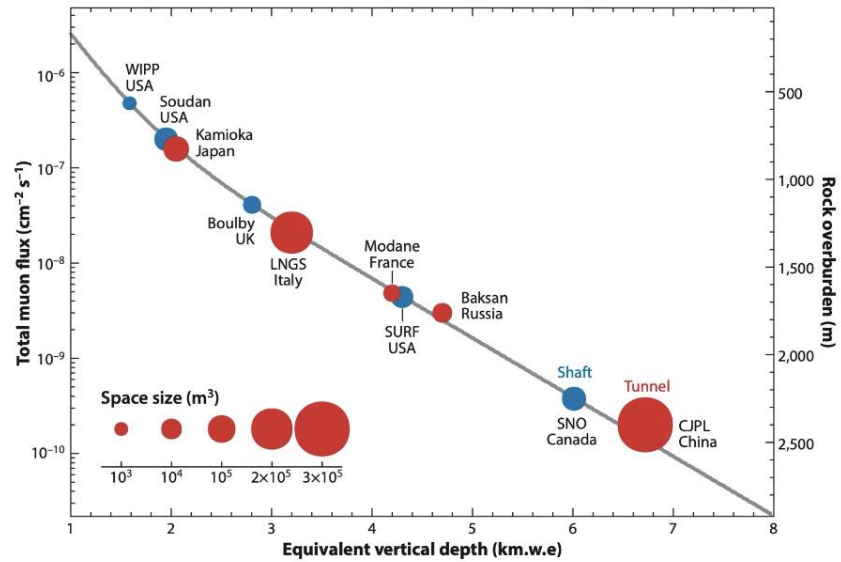
2020-

PandaX-xT
20 tonne -> 47 tonne



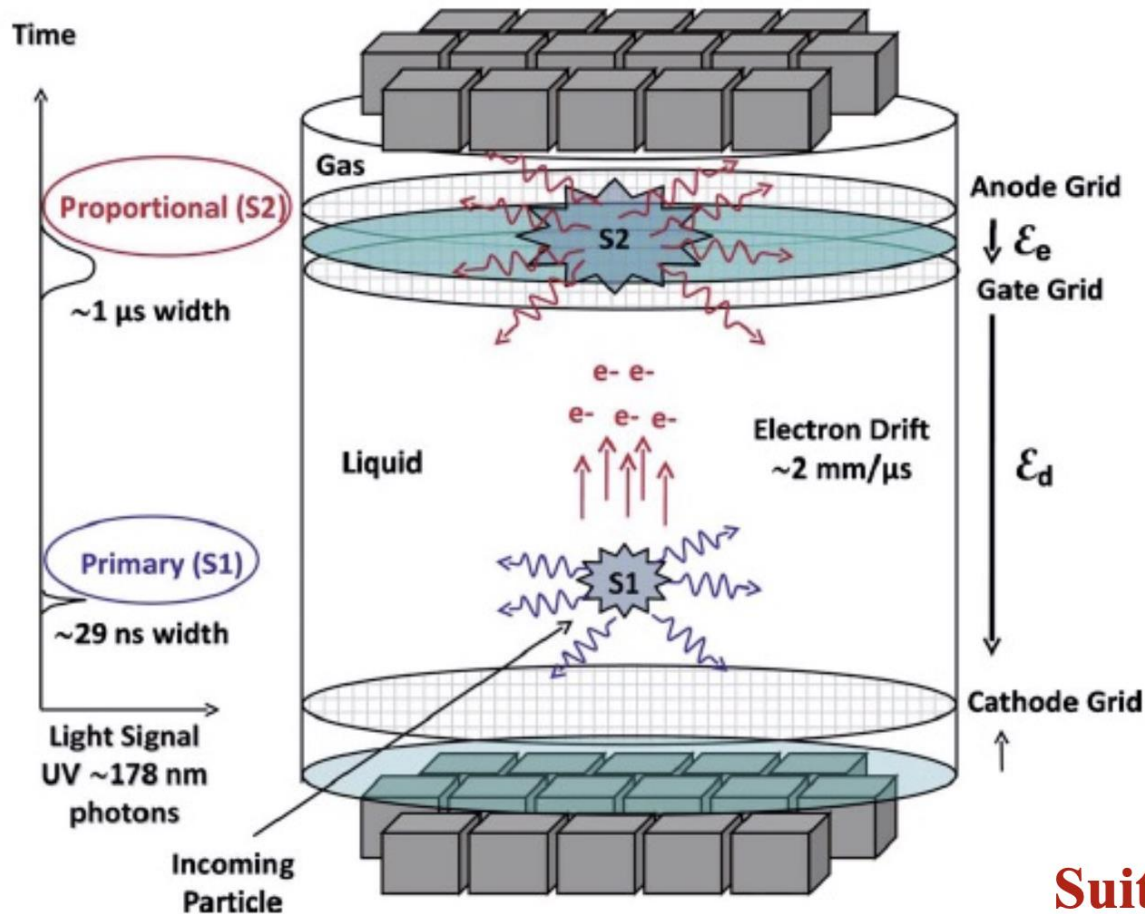
2027-

China Jinping Underground Laboratory (CJPL)



CJPL-II B2 Hall

Dual-phase Xenon Time Projection Chamber (TPC)



- **3D position reconstruction**
 - Fiducialization
 - Single-Site (SS) and Multi-Site (MS) discrimination
- **Particle identification among α , neutron, and γ /electron**
- **Calorimeter from sub keV to a few MeV**
- **Monolithic and scalable**

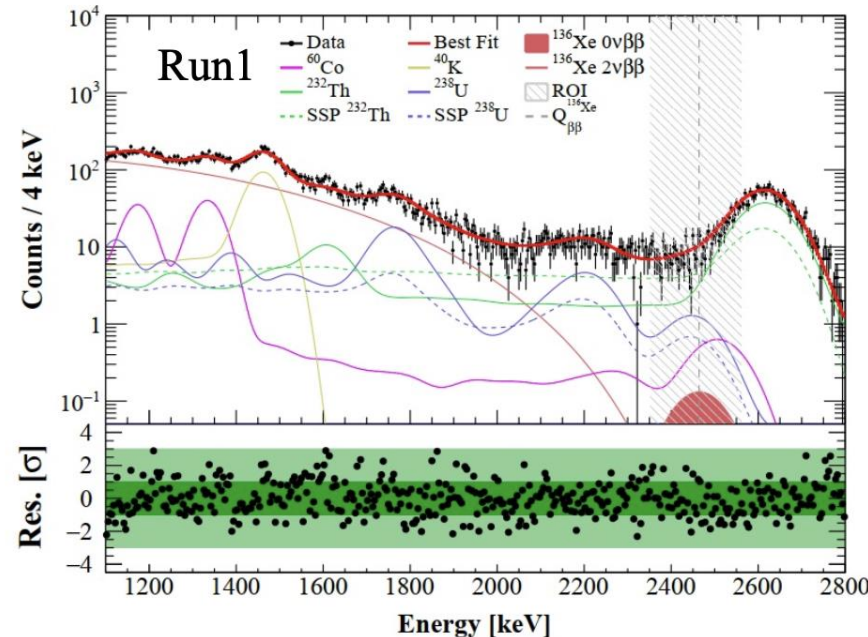
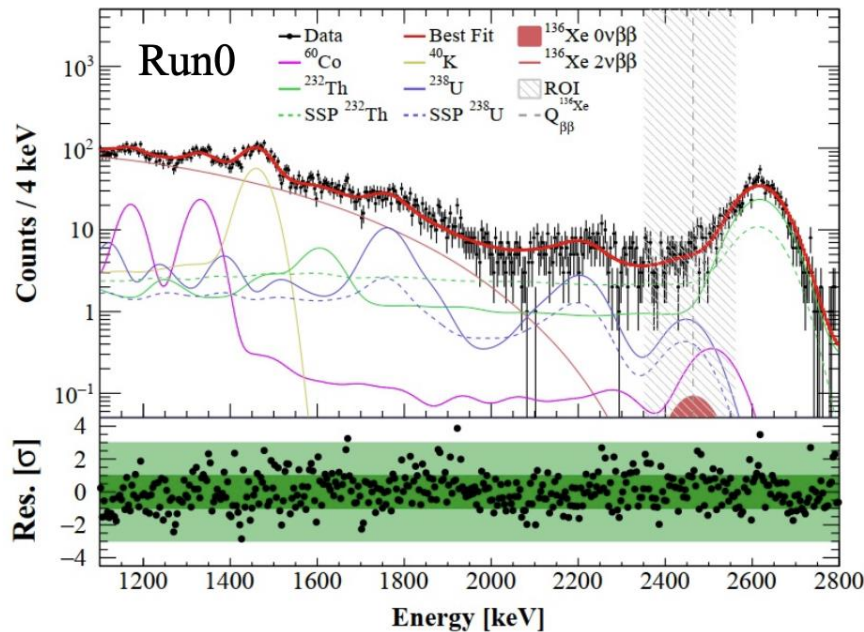


- **Low background**
- **Large target mass**
- **High detection efficiency**



Suitable for detection of dark matter, $0\nu\beta\beta$, and astrophysical neutrinos at the same time!

Unblinded fitting and results of ^{136}Xe $0\nu\beta\beta$



^{136}Xe exposure of
Run0+Run1: 44.6 kg-yr

Energy resolution
@ 2615 keV in FV:

- 2.0% in Run0
- 2.3% in Run1

^{136}Xe $0\nu\beta\beta$ event rate is fitted to be $14 \pm 37 \text{ t}^{-1}\text{yr}^{-1}$,
with a p-value of 0.49 for null results.

$$T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{24} \text{ yr at 90\% C.L.}$$

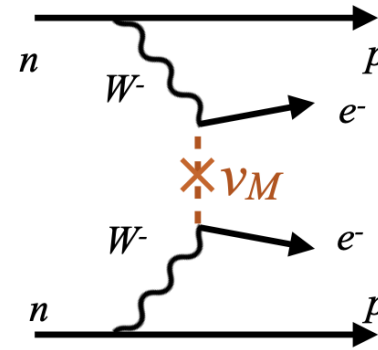
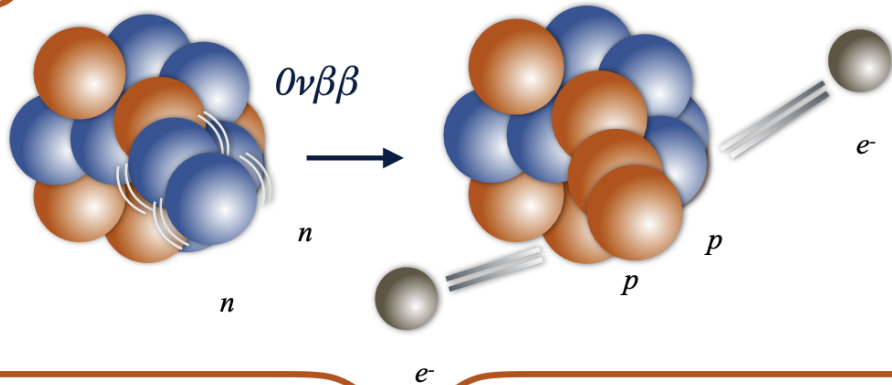
Upward fluctuation, the limit is consistent with
the median sensitivity within 1.1σ .

$$\langle m_{\beta\beta} \rangle = (0.4 - 1.6) \text{ eV}/c^2$$

- **Best results among natural xenon detectors so far**
- Improvement to our previous PandaX-II results by an order of magnitude and to the XENON1T results by a factor of 1.8
- Demonstrating the potential of ^{136}Xe $0\nu\beta\beta$ search with next-generation multi-ten-tonne natural xenon detectors

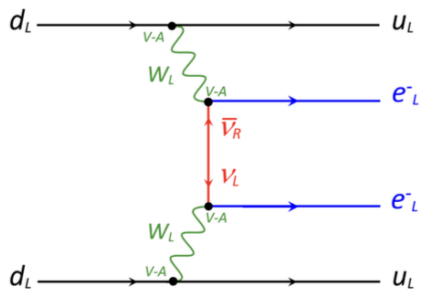
Science Bulletin 70, 1779-1785 (2025)

$0\nu\beta\beta$ requires BSM physics - but what kind?



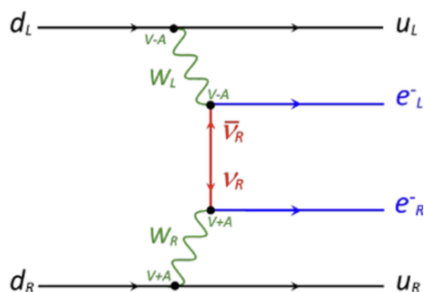
All mechanisms require Majorana neutrinos

Light-neutrino exchange (V-A)



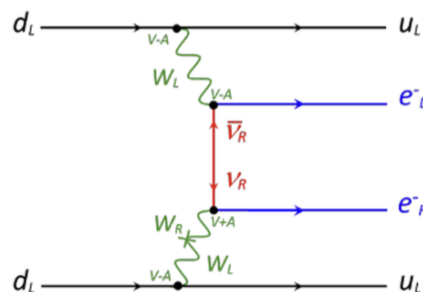
Assumed by most experiments

Left-right symmetry (λ) ($V+A$)_{*l*} + ($V+A$)_{*h*}

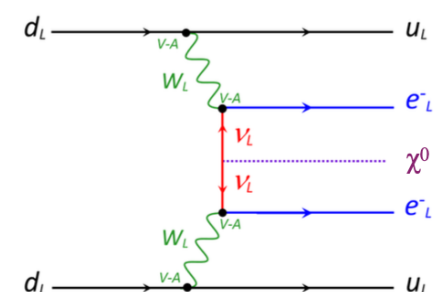


Distinguished by angle between electrons, and energy asymmetry

Left-right symmetry (η) ($V+A$)_{*l*}



Majoron emission



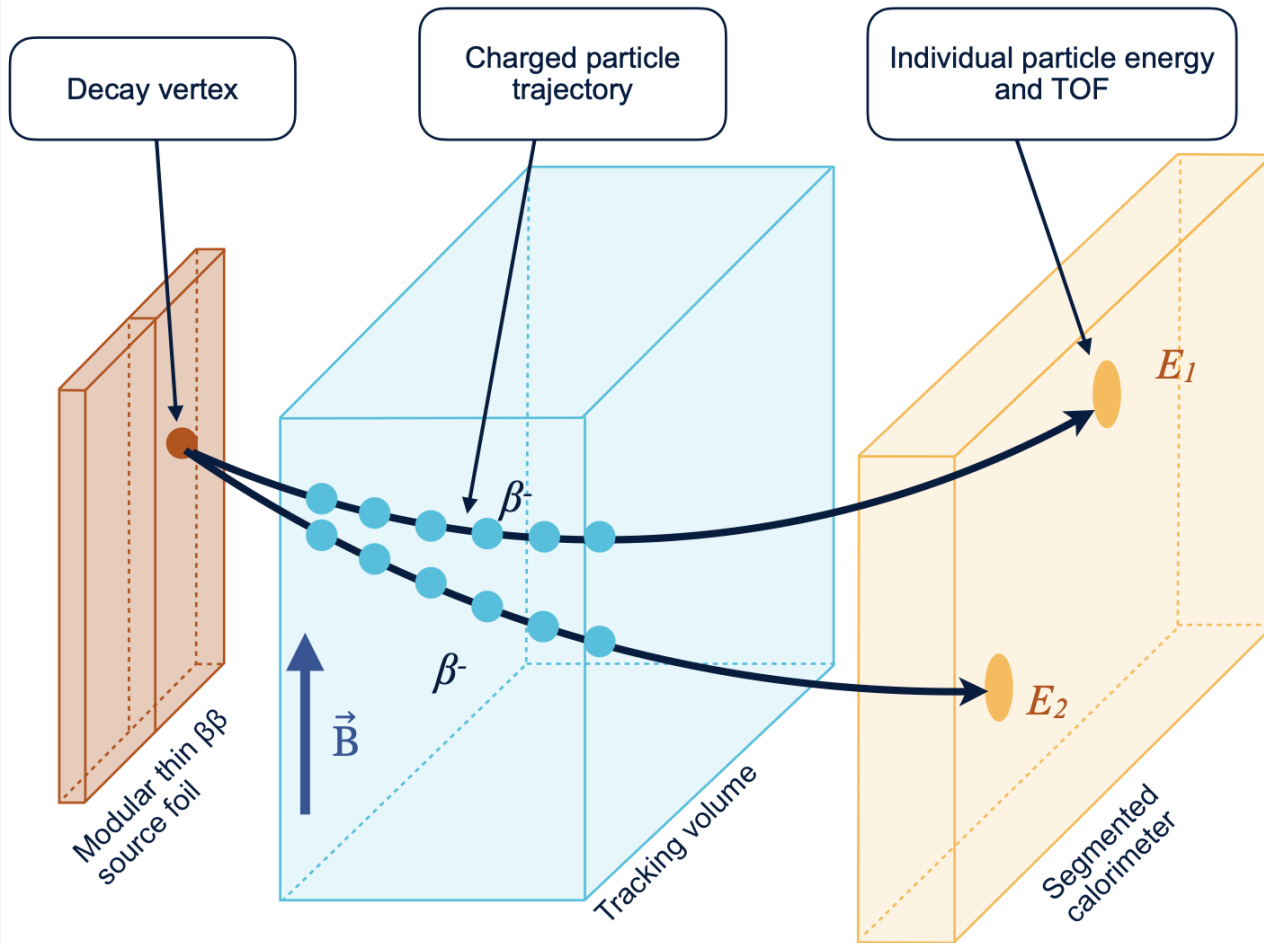
Energy $< Q_{\beta\beta}$

etc...

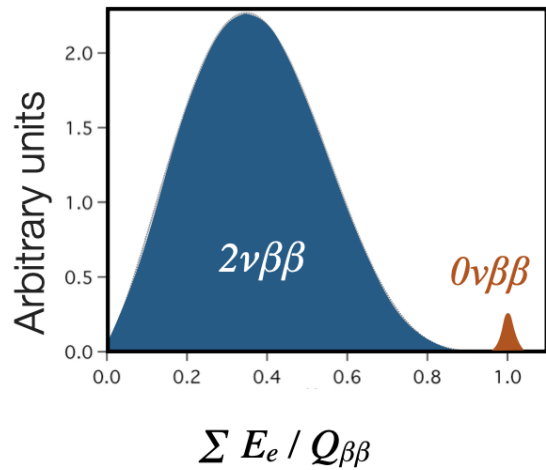
Summed energy spectrum is not enough to identify the mechanism - we need **more information!**



NEMO's unique approach



ALL EXPERIMENTS

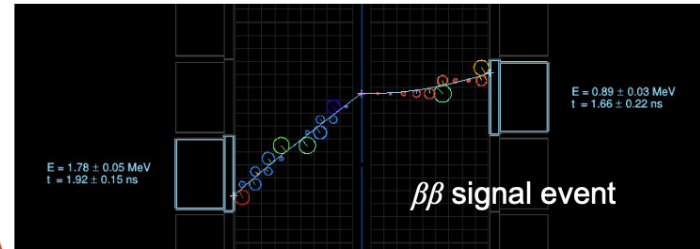


Total energy

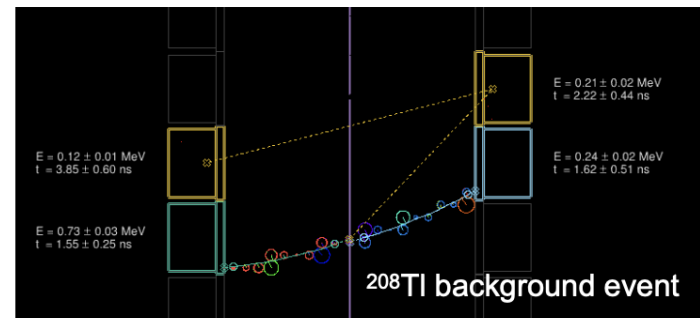


ONLY SUPERNEMO

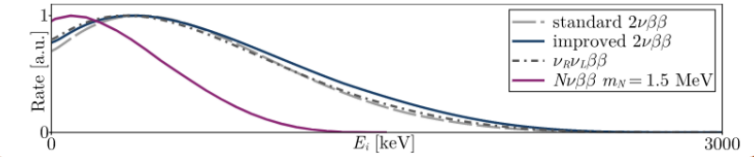
Golden event signature



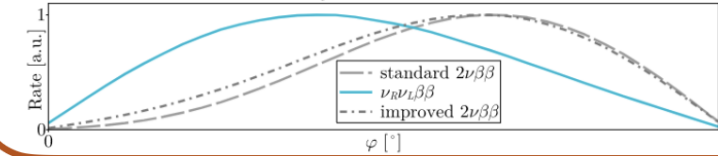
Excellent background rejection; background measurements (dedicated channels)



Individual electron energy



Angular correlation



**(Almost)
isotope-
agnostic**



**Key to probing and understanding
 $0\nu\beta\beta$ mechanism if it's discovered**

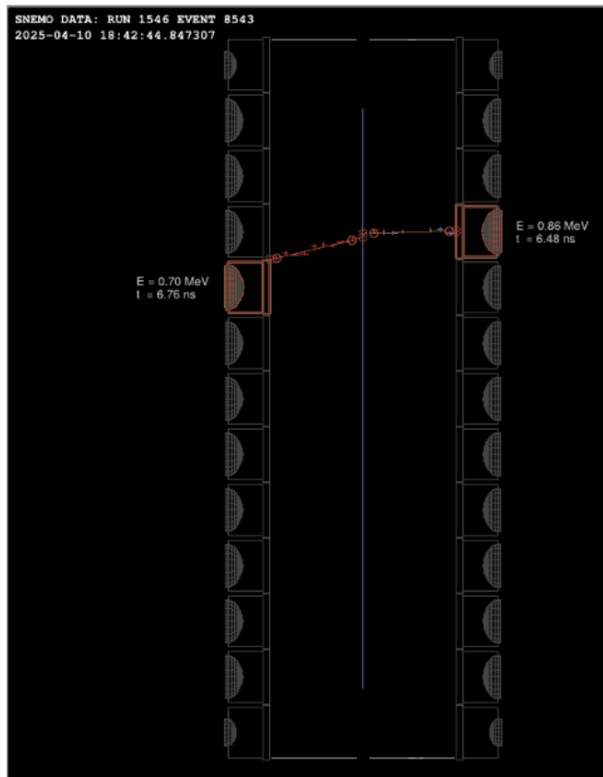


SuperNEMO's first $\beta\beta$ event candidate!

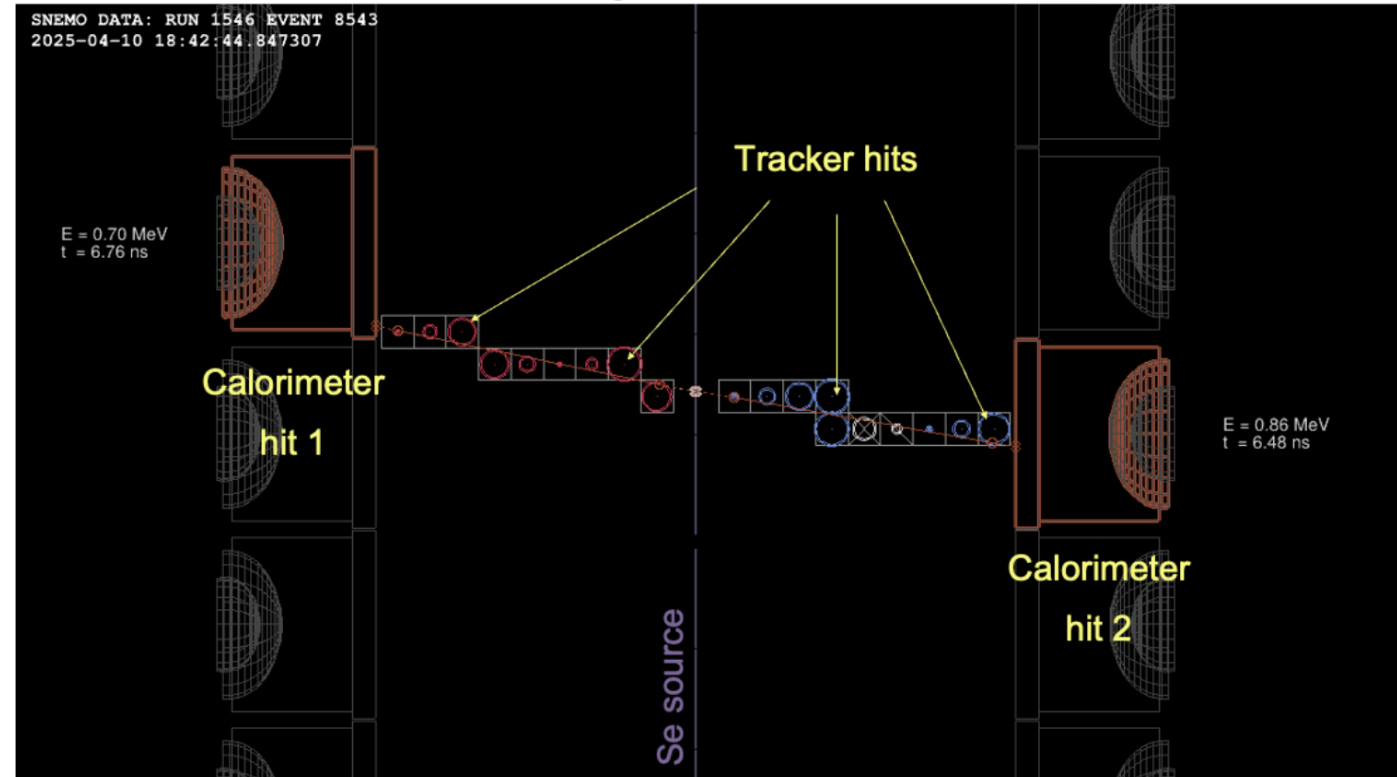
10 April 2025 18:42:44

$$E_{e1} + E_{e2} \sim 1.56 \text{ MeV}$$

Side view



Top view



long baseline

- neutrino beams
- NOvA
- T2K
- Hyper-Kamiokande
- DUNE
- JUNO

long baseline



NOvA/T2K



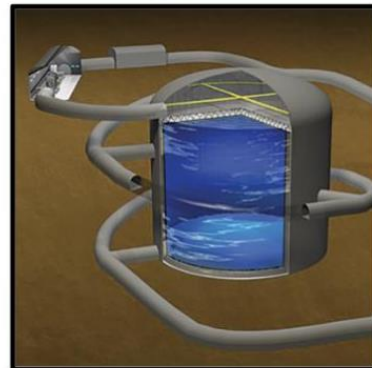
Results now!

JUNO



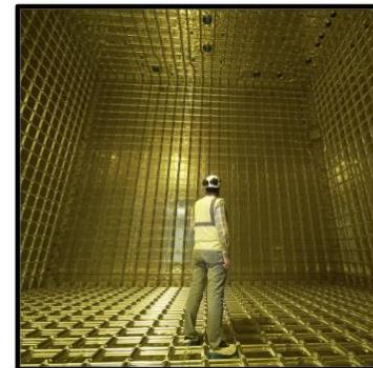
Taking data soon!

HyperK



UNDER CONSTRUCTION NOW!

DUNE



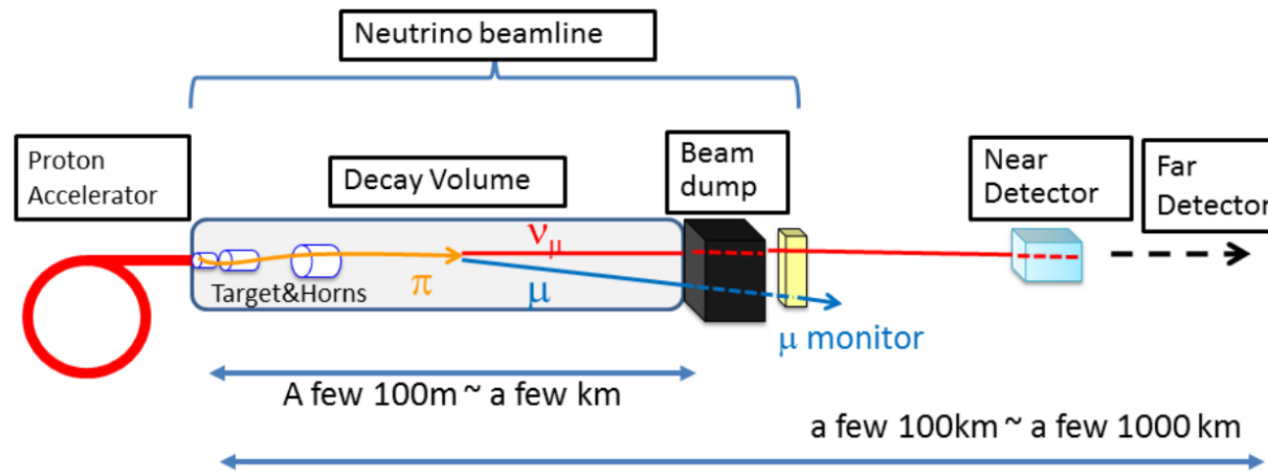
Next-next gen



Being designed now!

LBL PHENOMENOLOGY, ETW, NEUTRINO 2024

Producing a Conventional Neutrino Beam



- High-energy, high-intensity proton beam from an accelerator
 - Neutrino flux is directly proportional to number of protons
- Protons incident on a long target produce hadrons: π 's, K's, etc
- Outgoing hadrons are sign selected + focused in electro-magnetic focusing "horns"
- Hadrons decay in long decay volume: $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$, ...
 - Change horn polarity to switch between primarily ν_μ 's and $\bar{\nu}_\mu$'s
- Charged decay products can be monitored using a hadron or muon monitor then stop in shielding, earth
- ν 's continue on to near and far detectors for measurements



Off-Axis Beam Concept

J-PARC Flux + Osc. Prob.

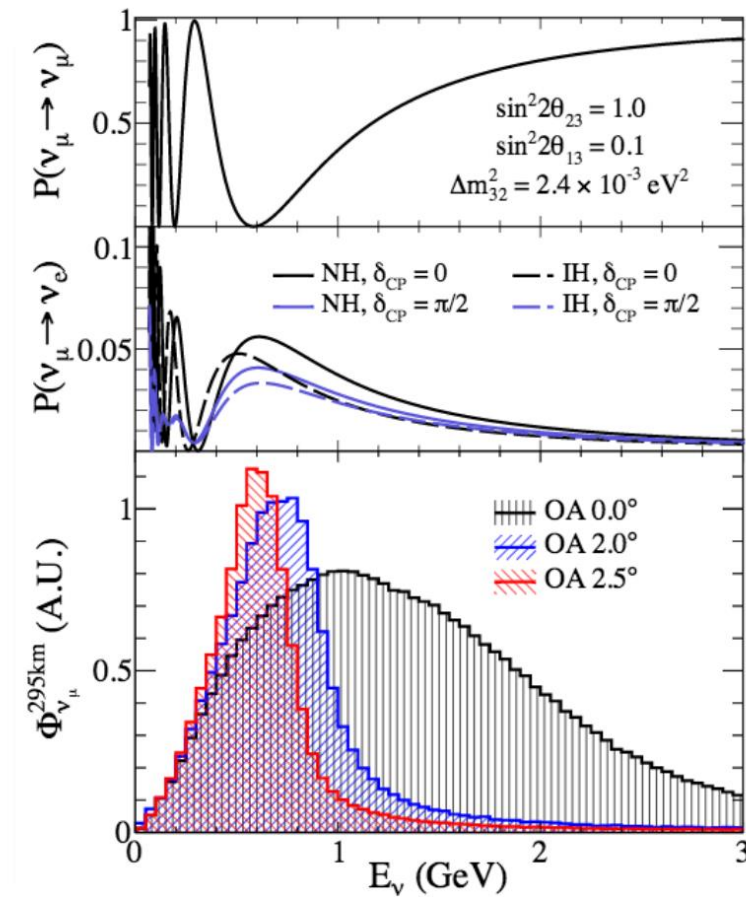
- “Off-axis” beam concept :
 - Due to pion decay kinematics, the neutrino energy depends on the outgoing neutrino angle:

$$E_\nu = \frac{(1 - (m_\mu/m_\pi)^2)E_\pi}{1 + \gamma^2\theta^2}$$

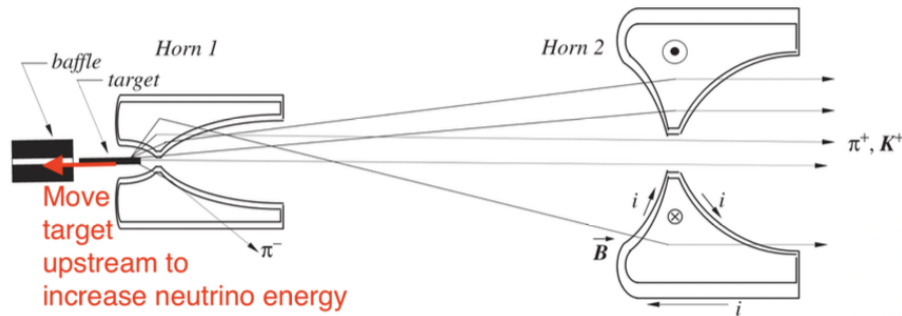
- So, an “off-axis” beam gives a smaller range of neutrino energies

- Many experiments use an off-axis beam to select a neutrino flux with a peak energy near the oscillation maximum

- Install detectors off-axis from the center of the neutrino beam to select the energy
- Precise understanding of the neutrino beam direction essential

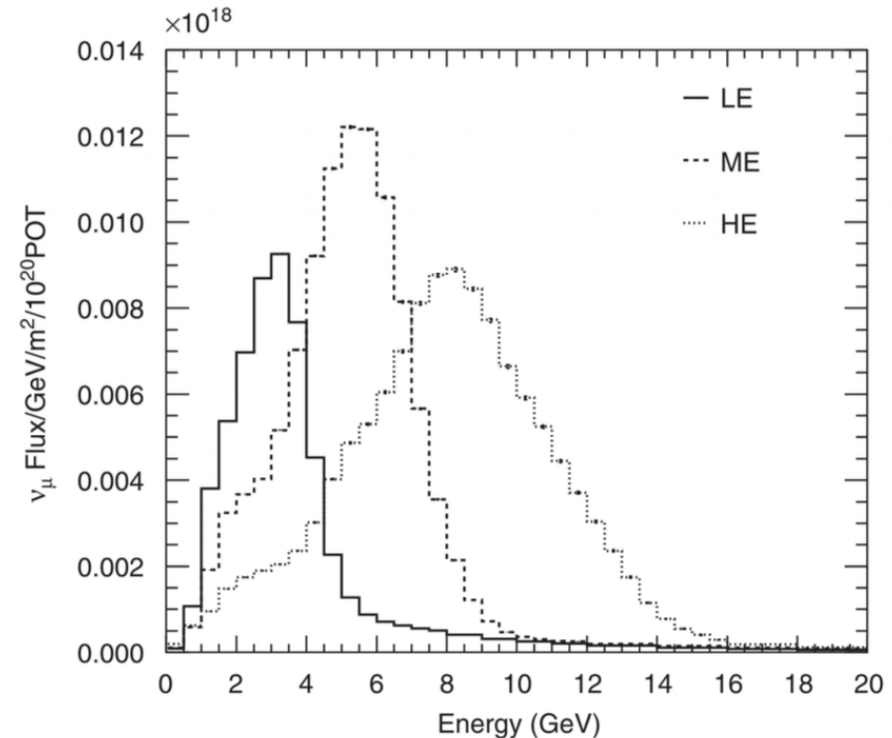


NuMI Adjustable Beamline Configuration



- A movable target in the NuMI beamline allows for control of the neutrino flux distribution
- Moving the target upstream directs smaller-angle, higher-momentum particles into the horn field, resulting in a higher energy neutrino beam

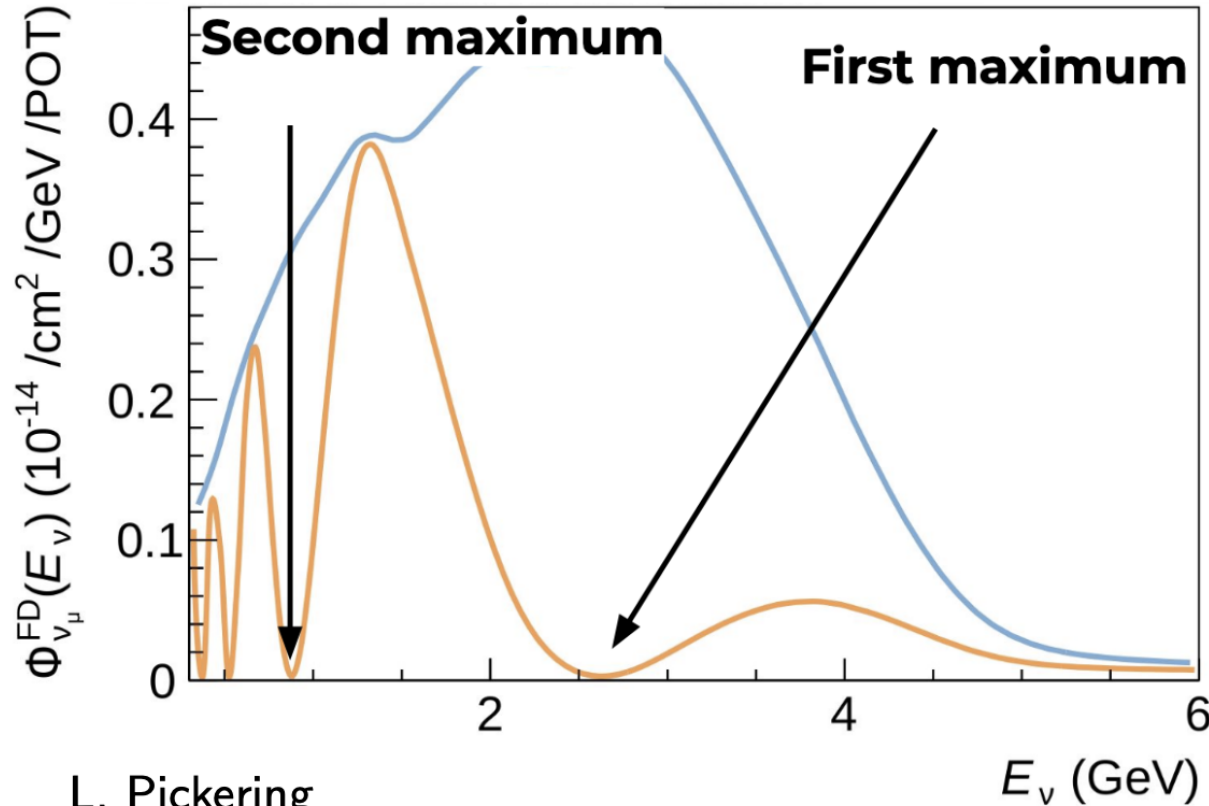
Flux at NuMI Near Detector



Nucl. Instrum.
Meth. A 568 (2006)

LBNF On-Axis Flux

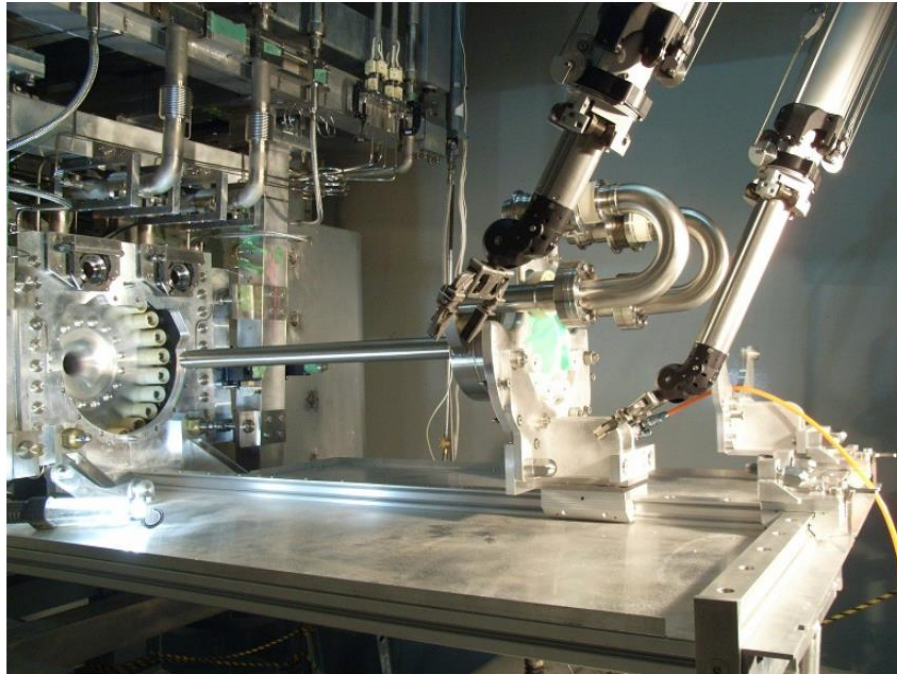
LBNF/DUNE flux and oscillation probability



- LBNF/DUNE uses an on-axis beam for wide energy range
- Wide energy spectrum allows DUNE experiment to observe multiple oscillation maxima

J-PARC Neutrino Production Target

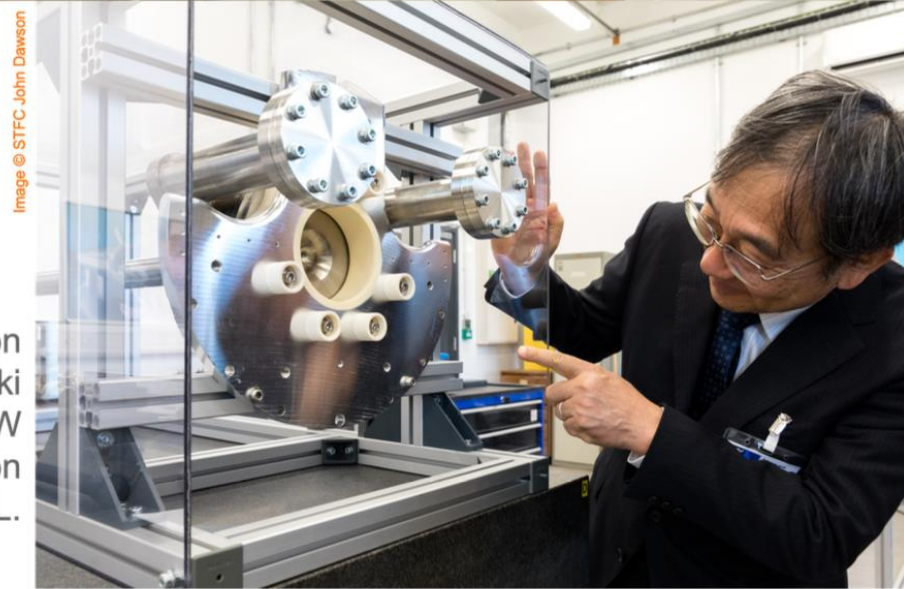
- J-PARC neutrino production target consists of a 91.4cm long (1.9 interaction length) monolithic carbon target installed in the 1st horn
- Cooled by He gas – increase of cooling capacity (He flow rate) for higher power underway now
- New J-PARC target for 1.3MW developed and ready for installation in summer 2026 (RAL)



- Studies to establish new target types to further maximize number of produced neutrinos are also ongoing
 - Possible to decrease forward-going wrong-sign component by new target design
 - Higher-density and/or hybrid materials, longer targets

New targets produced here at RAL by TD!

J-PARC 1.3MW Target



SuperK Spokesperson
Professor Nakahata Masayuki
inspects the first 1.3 MW
capable neutrino production
target manufactured at RAL.

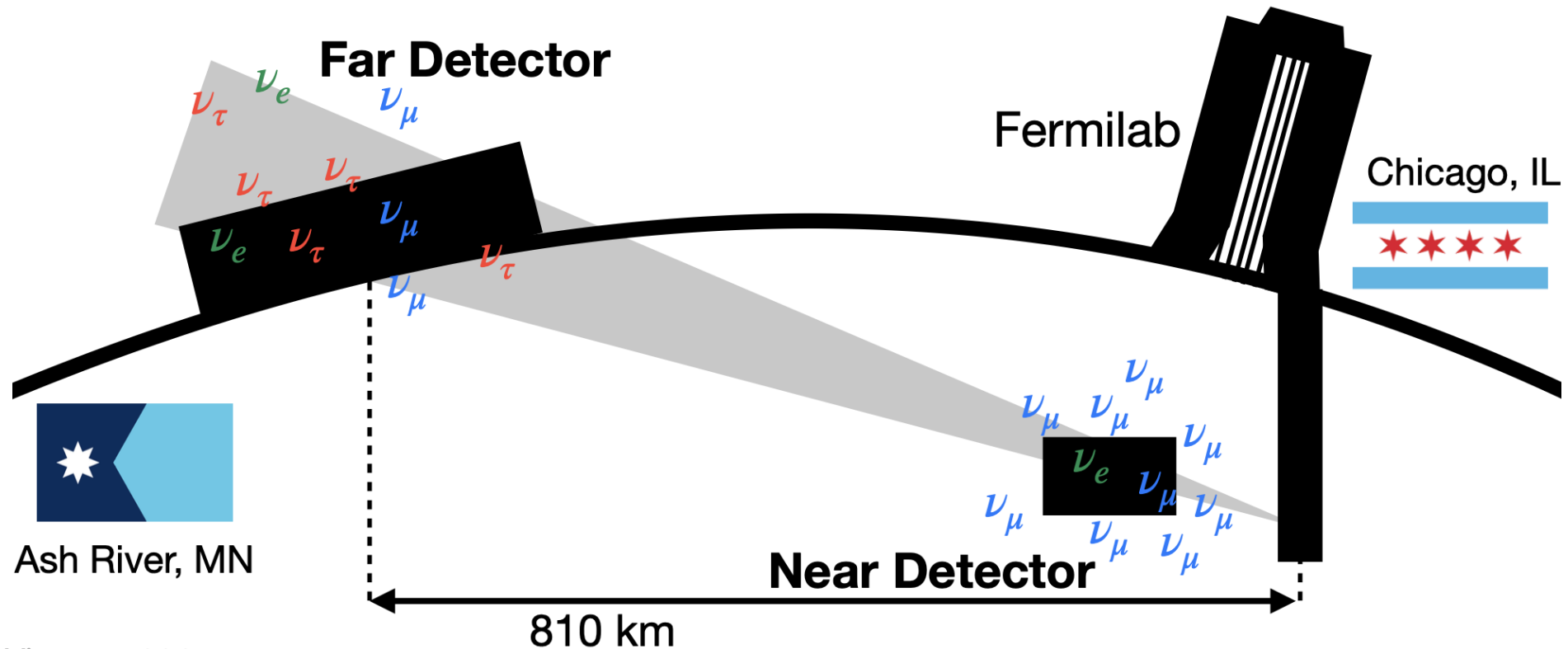
NBI2024

- T2K 1.3MW target developed and built at RAL, to be installed in summer 2026



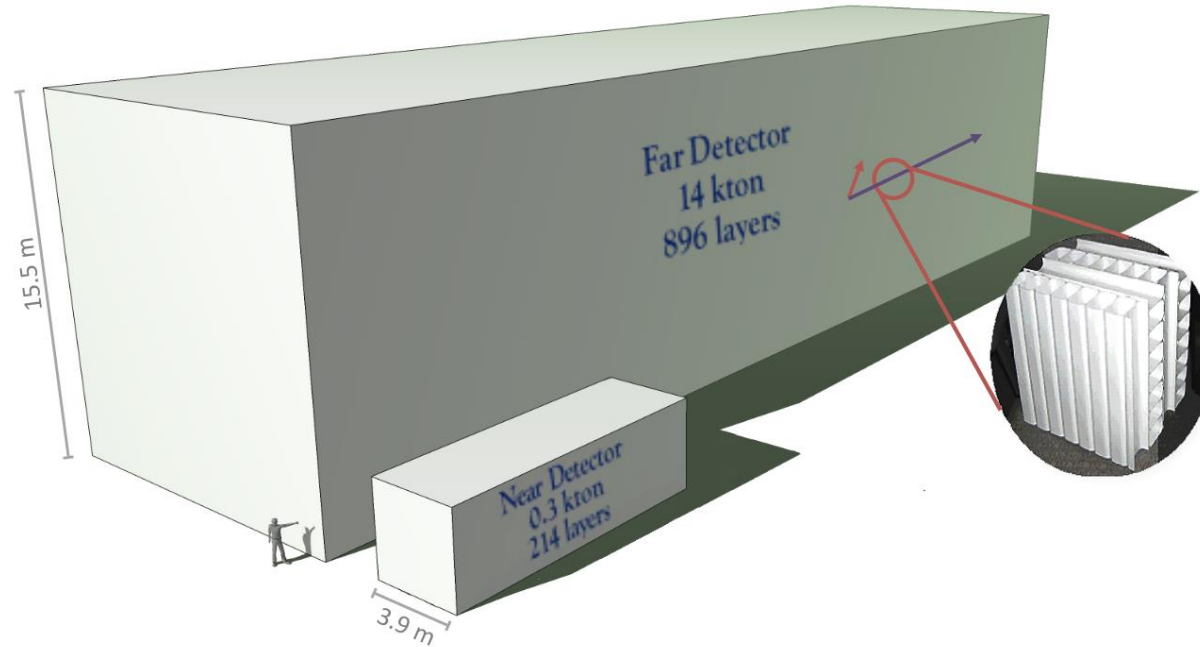
NOvA Experimental Setup

- Long-baseline neutrino oscillation experiment.
 - NuMI **neutrino beam** at Fermilab.
 - **Near detector** to measure beam before oscillations.
 - **Far detector** measures the oscillated spectrum.
- **Primary goal is to study 3-flavour oscillations via:**
 - $\nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e$
 - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Other goals include:
 - Search for sterile neutrinos.
 - Neutrino cross sections.
 - Supernova neutrinos.
 - Cosmic ray physics.



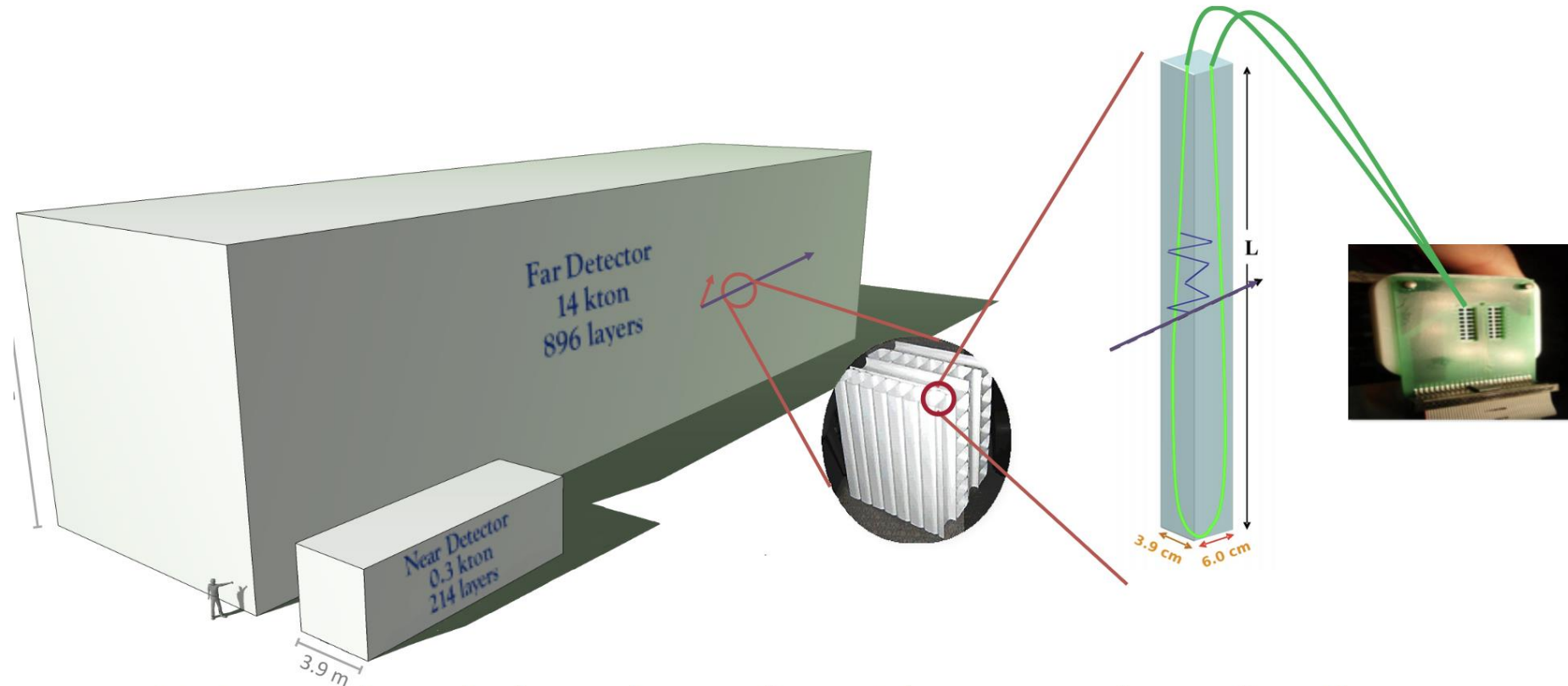


The NOvA Detectors



- Both are large, (FD 60 m long).
- Functionally identical: consist of extruded PVC cells filled with 11 million litres of liquid scintillator.
- Arranged in alternating directions for 3D reconstruction.

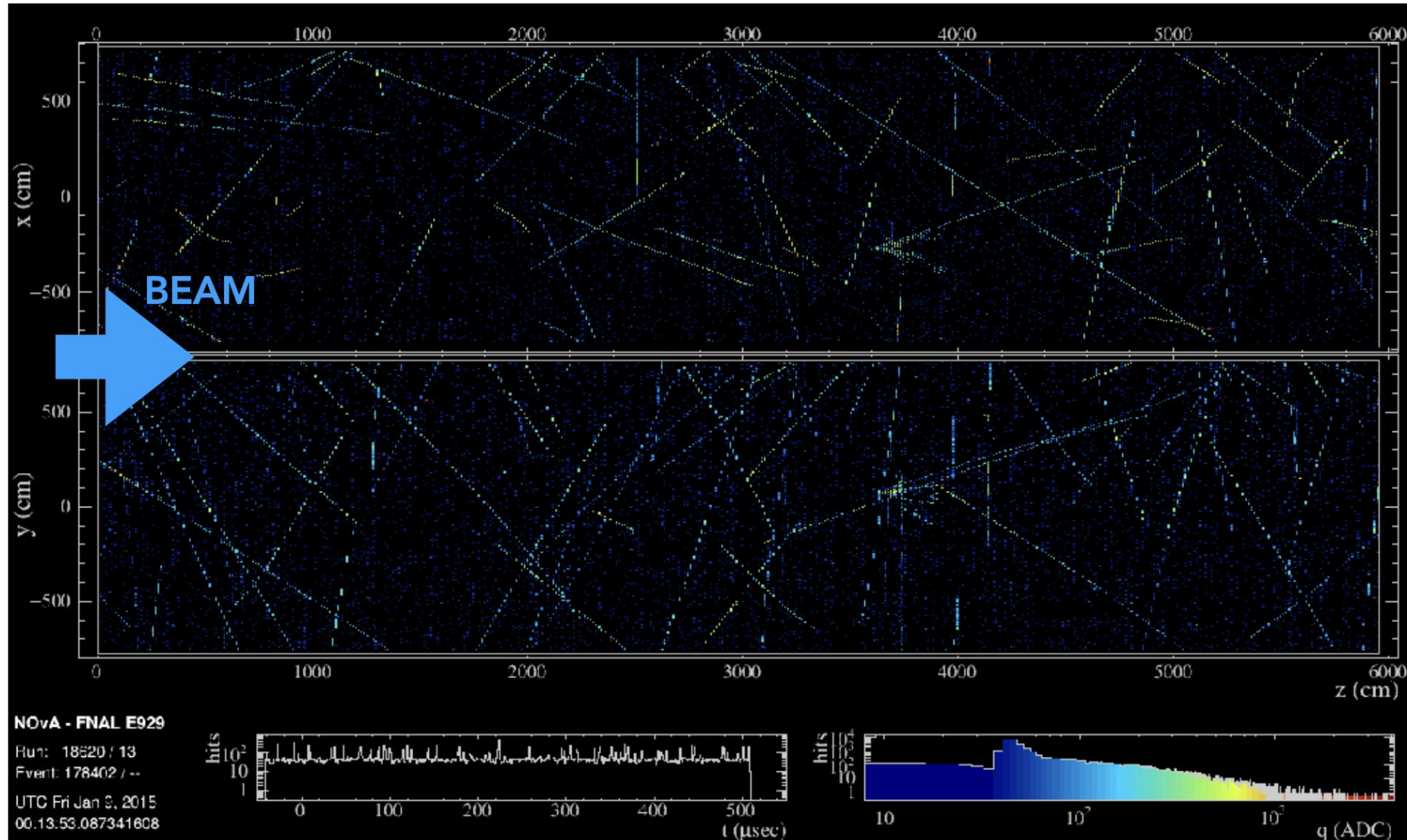
The NOvA Detectors



- Light produced when charged particle passes through cells.
- The light is picked up by wavelength shifting fibre. Transported to an Avalanche PhotoDiode - light collected and amplified.
- Good timing resolution. $\sim$ few ns.



Selection: Cosmic Rejection



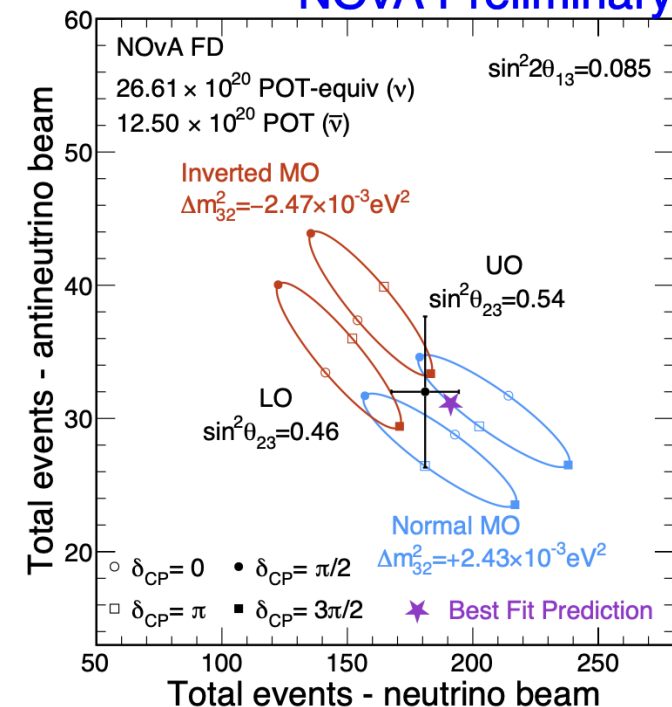
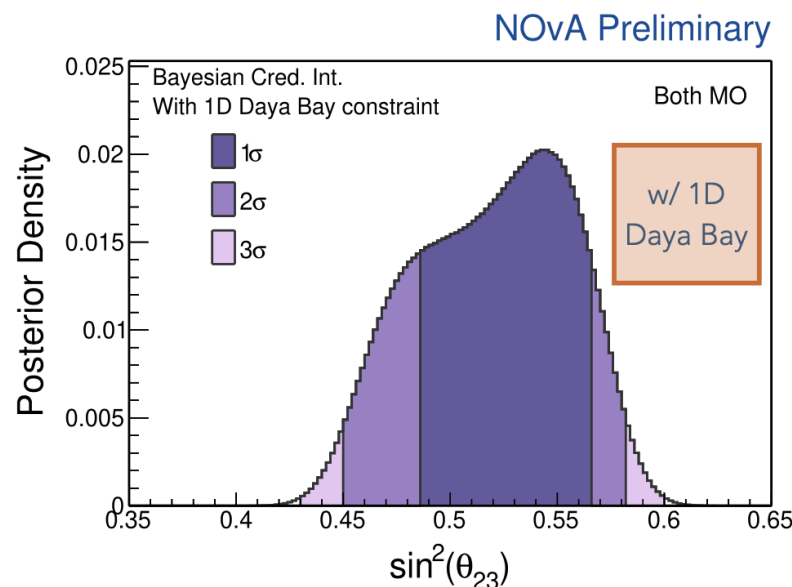
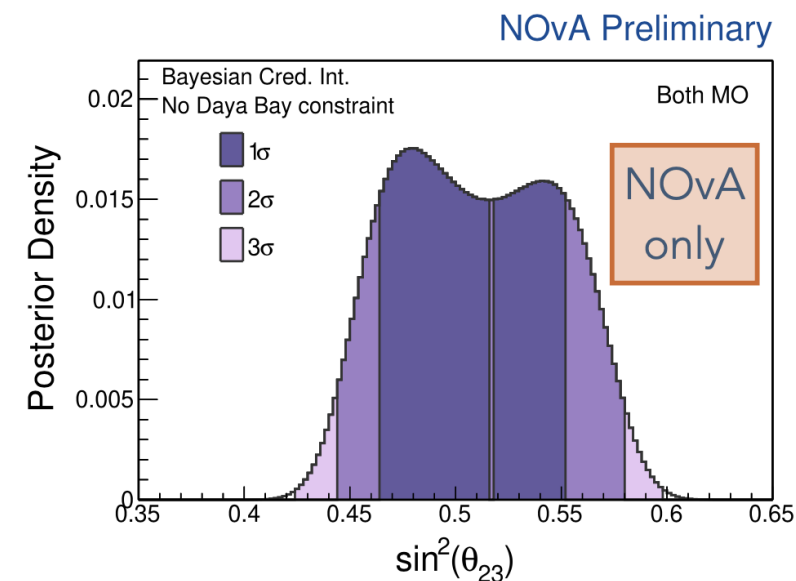
Cosmic rejection critical for FD: 11 billion cosmic rays/day

$\nu_2 - \nu_3$ Sector

NOvA



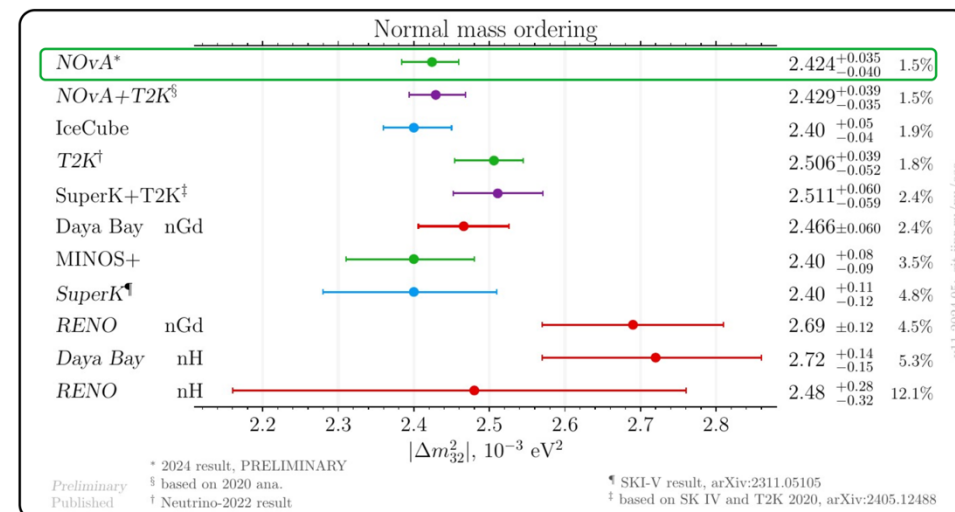
NOvA Preliminary



Maximal mixing is allowed at $< 1\sigma$ in both cases.

Mild upper octant preference w/ 1D constraint (Bayes Factor 2.2, 69% odds).

Most precise single experiment measurement of Δm_{32}^2 .



Tokai-to-Kamioka (T2K) Experiment

International collaboration: 565 members from 75 institutions in 15 countries (as of 1 July 2025)

295 km baseline for neutrino oscillations

Far detector “measures” the oscillated beam composition

Super-Kamiokande

Upgrade completed in May 2024! (More in this talk)

Near Detector Complex aka ND280 (280 m from production) “measures” the initial beam composition

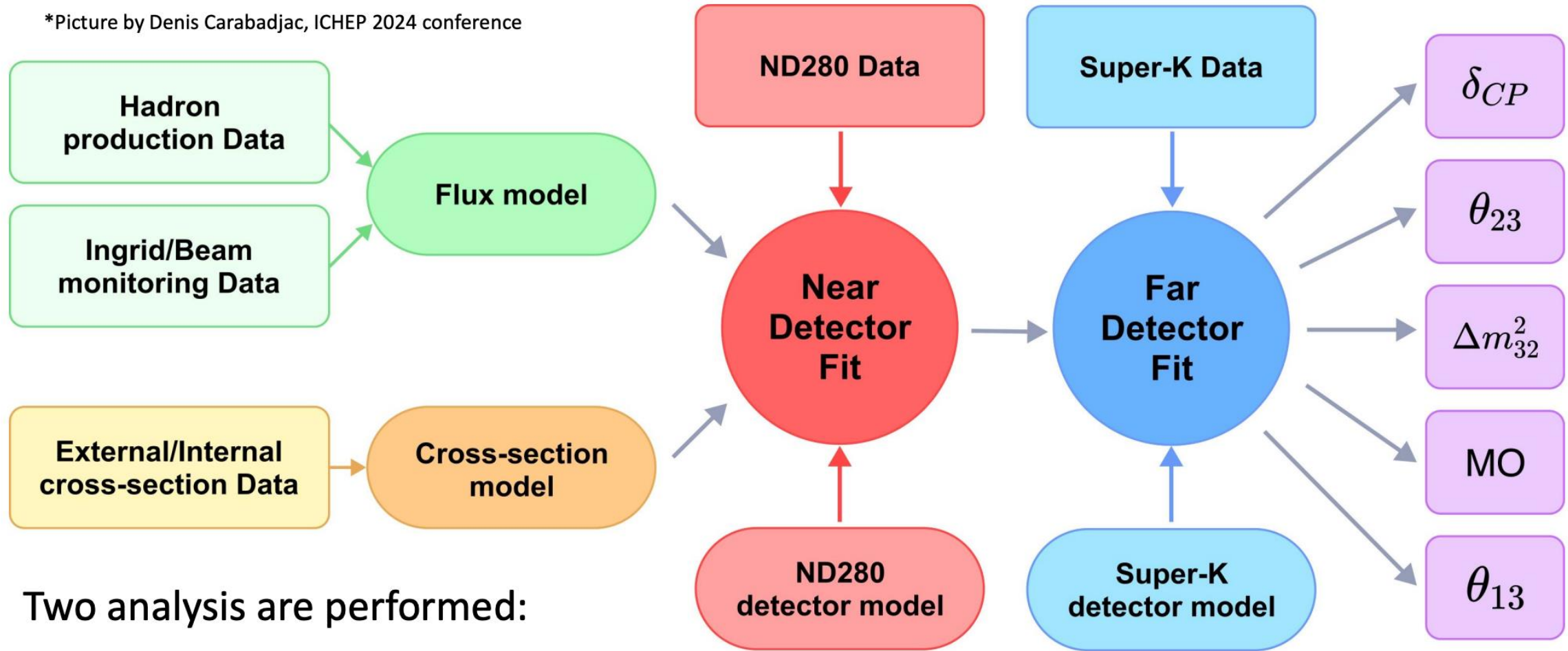
(Anti-)neutrino beam (~600 MeV) produced at J-PARC

T2K

T2K [Japan, 2010-]

T2K OSCILLATION ANALYSIS STRATEGY

*Picture by Denis Carabadjac, ICHEP 2024 conference



Two analysis are performed:

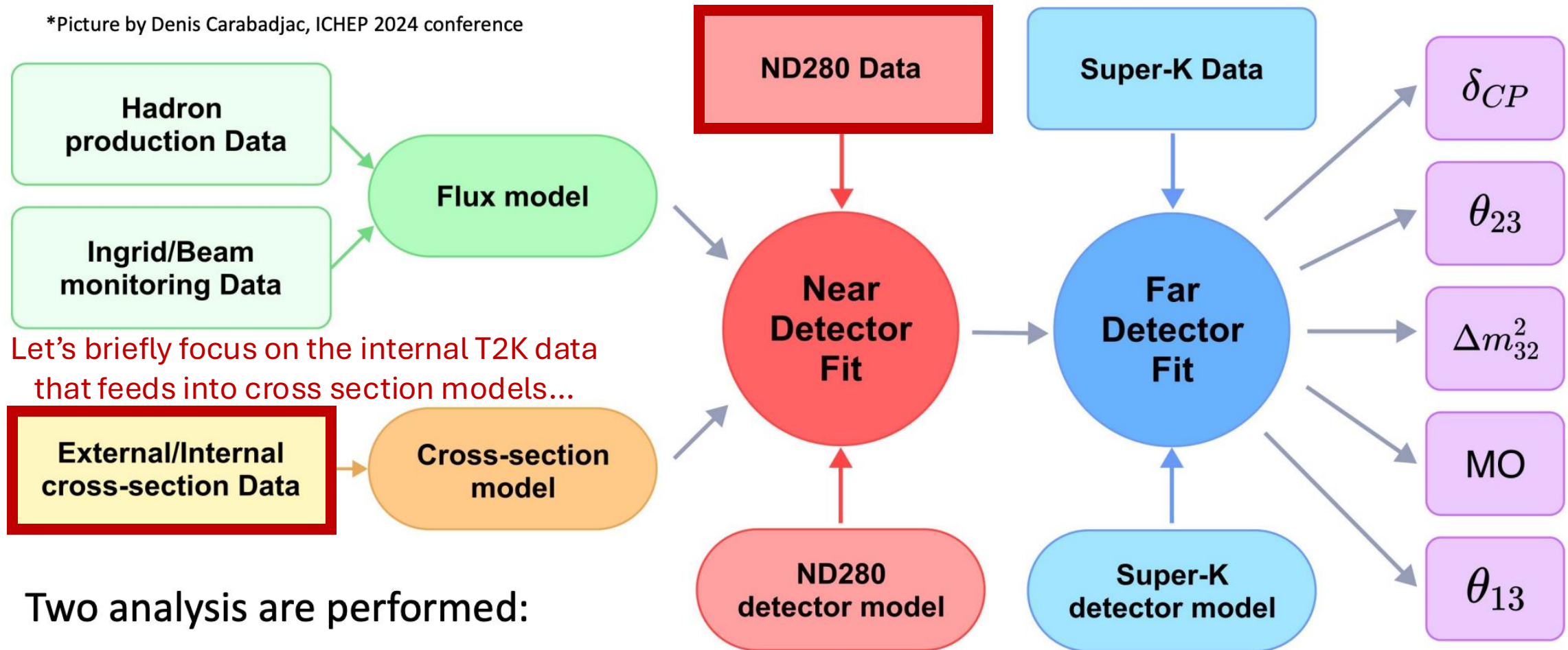
- **Frequentist analysis:** Feldman-Cousins method for **confidence intervals**, fitting sequentially ND and FD
- **Bayesian analysis:** Metropolis-Hastings algorithm for **credible intervals**, fitting simultaneously ND and FD

Fake data studies are made to test the robustness of the results to variations of the model



T2K OSCILLATION ANALYSIS STRATEGY

*Picture by Denis Carabadjac, ICHEP 2024 conference



Let's briefly focus on the internal T2K data that feeds into cross section models...

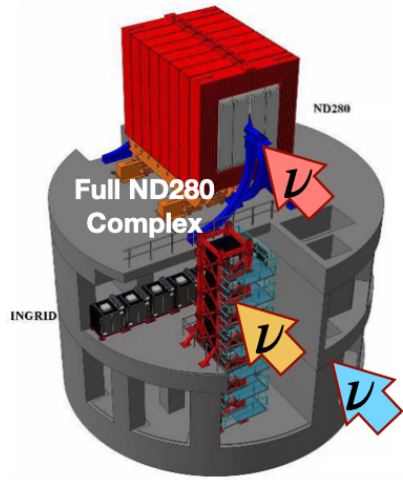
Two analysis are performed:

- **Frequentist analysis:** Feldman-Cousins method for **confidence intervals**, fitting sequentially ND and FD
- **Bayesian analysis:** Metropolis-Hastings algorithm for **credible intervals**, fitting simultaneously ND and FD

Fake data studies are made to test the robustness of the results to variations of the model

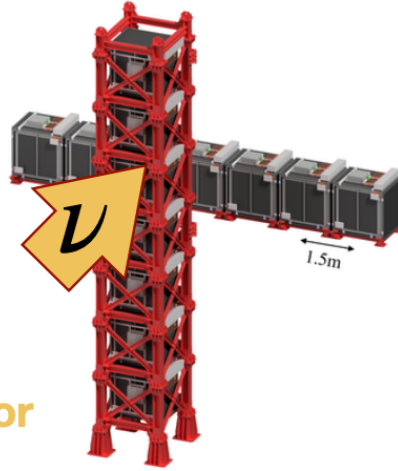


T2K's near detector physics programme



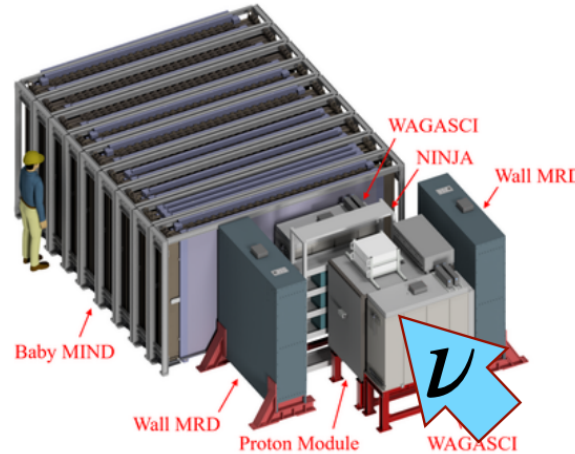
**INGRID detector
(on-axis)**

- Unmagnetised detector, consisting of 16 identical modules, each made of alternating iron (Fe) and plastic (CH) layers
- Used to constrain non-hadronic beam systematics (e.g. off-axis angle on a run-by-run basis), and to monitor beam profile stability
- Also measures cross sections for neutrino interaction models

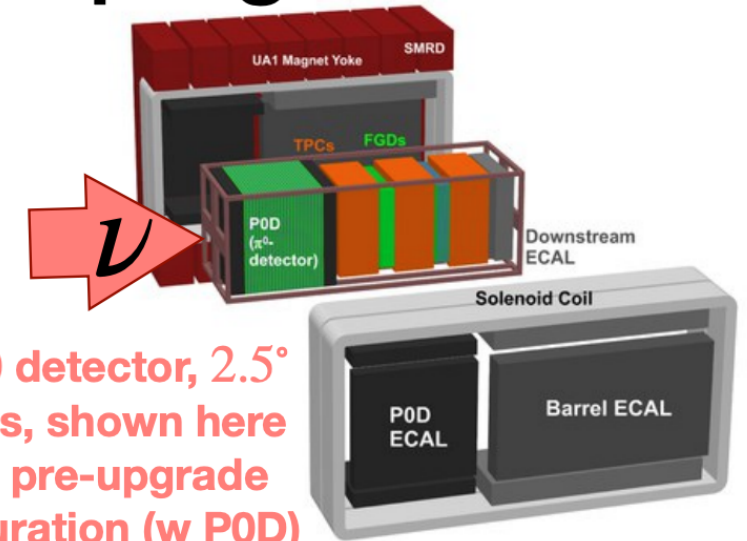


**WAGASCI and BabyMIND
detectors, 1.5° off-axis**

- Water/CH lattice neutrino target (WAGASCI) with a magnetised (1.5 T) iron and scintillator (BabyMIND) muon range tracking detector
- Plans to start using in oscillation analyses, and already producing cross section results



**ND280 detector, 2.5°
off-axis, shown here
is the pre-upgrade
configuration (w P0D)**



- Magnetised (0.2 T) composite detector: 2 Fine Grained Detectors (2x 0.8 t target mass, mostly C_8H_8 and water) sandwiched between 3 vertical Time Projection Chambers (PID and momentum measurements) + P0D (mostly carbon alternating with water target, lead foil or brass foil) + ECAL + SMRD (high energy muon range)
- Main constraint of flux and cross section model parameters in the oscillation analysis + rich suite of cross section measurements

SELECTIONS AT NEAR DETECTOR

T2K

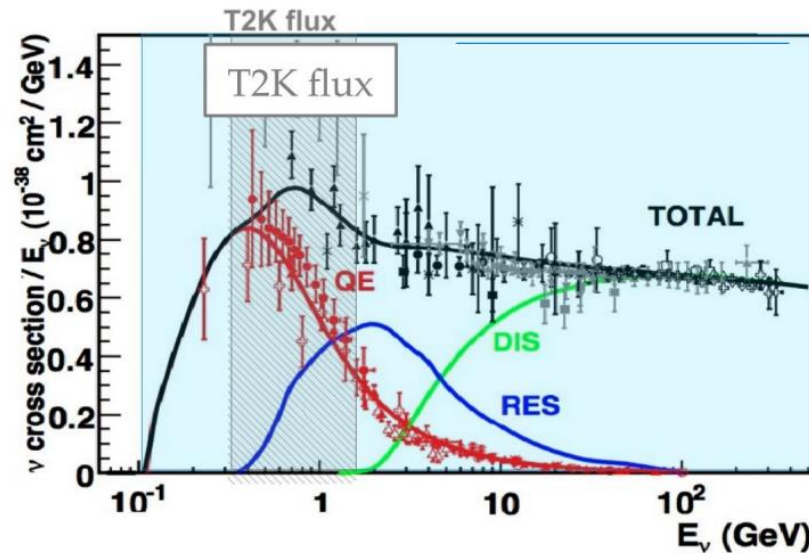
Samples based on the **event topology**

→ **Target different ν interactions**

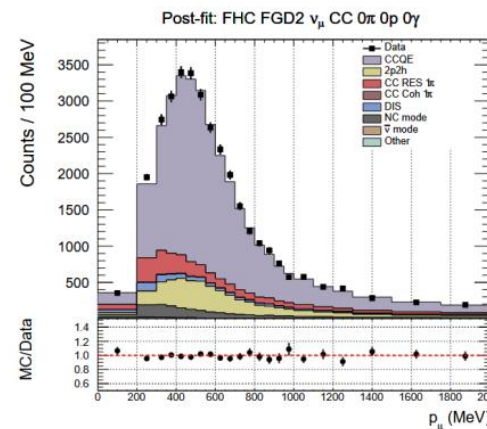
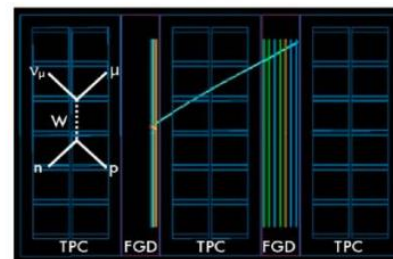
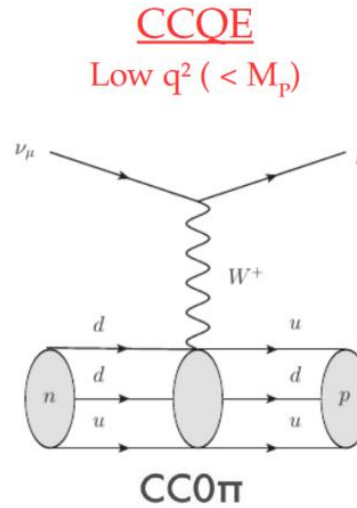
CCQE: Charged Current Quasi-Elastic

CCRes: Charged Current Resonant Pion production

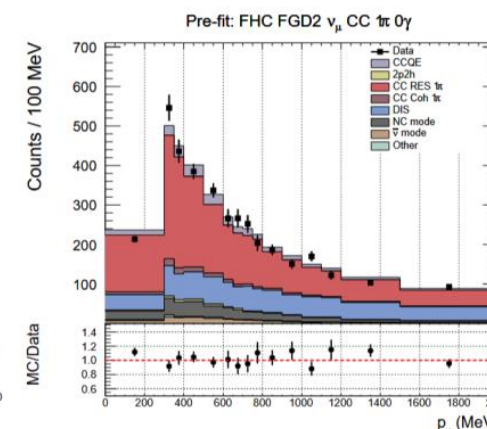
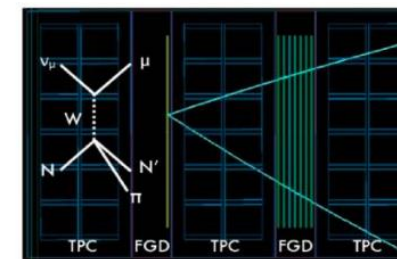
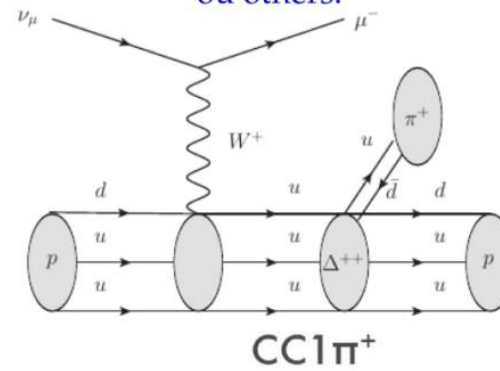
CCDIS: Charged Current Deep Inelastic Scattering



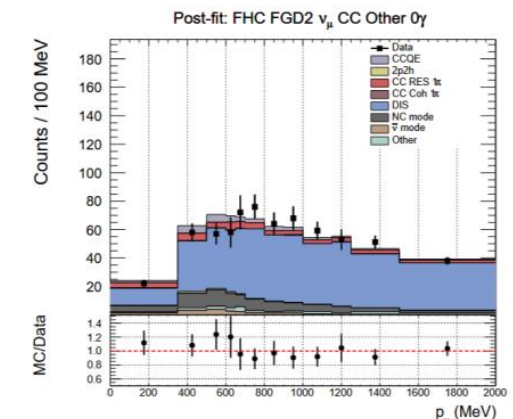
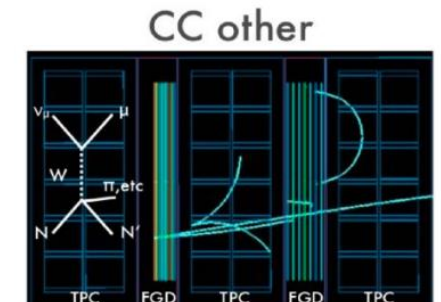
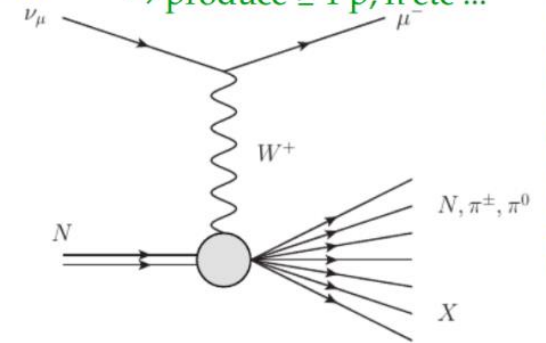
Each event topology is enriched with a specific interaction



CCResonant
Large enough q^2 to produce Δ (1230 MeV), ou others.



CCDIS
Large enough q^2 to see quarks
→ produce ≥ 1 p, n etc ...



INTERACTIONS

TOPOLOGIES

DATA FIT

Cross section measurement history with the T2K beam

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
$\sigma_{\nu_{\mu}}^{CC-inc(-)}$	On C (FGD1)	On Fe, CH (INGRID)		On Fe (INGRID)	On C, O, H, Cu (P0D)	2D on C (FGD1)	On water, C, Fe (INGRID)					Inclusive $\nu_{\mu}^{(-)}$ charged-current
$\sigma_{\nu_e}^{CC-inc(-)}$		On C (FGD1)	On water (P0D)				nu+anti-nu, on CH (FGD1)					Inclusive $\nu_e^{(-)}$ charged-current
$\sigma_{\nu_{\mu}}^{CC0\pi(-)}$ $\nu_{\mu}^{(-)}$ charged-current pionless		QE on C (INGRID)	QE on C (FGD1)	On CH (FGD1)	On water (P0D)	TKI, On CH (FGD1)	nu+anti-nu, on CH (FGD1)	On O, C (FGDs)	Anti-nu, on water (P0D)	On water, CH (WAGASCI+PM)	On CH (ND280+INGRID)	On water, CH (WAGASCI-BabyMIND)
$\sigma_{\nu}^{NC0\pi(-)}$		On O (Super-K)					QE on O, nu+anti-nu (Super-K)					$\nu^{(-)}$ neutral-current pionless
$\sigma_{\nu_{\mu}}^{CC1\pi(-)}$ $\nu_{\mu}^{(-)}$ charged-current with a pion in the final state				COH on C (FGD1)	On water (FGD2)			1 pi+, on CH (FGD1)	1 pi+, TKI, on C (FGD1)		COH on C, nu+anti-nu	
$\sigma_{\nu_e}^{CC\pi(-)}$ $\nu_e^{(-)}$ charged-current with a pion in the final state												Pion(s), on CH (FGD1)
$\sigma_{\nu}^{NC1\pi(-)}$ $\nu^{(-)}$ neutral-current with a pion in the final state						1 pi0, on water (P0D)						1 pi+, on CH (FGD1), <u>PRL</u> & <u>PRD</u>

SELECTIONS AT FAR DETECTOR

Reconstructed ν_μ

Reconstructed ν_e

Six samples at far detector

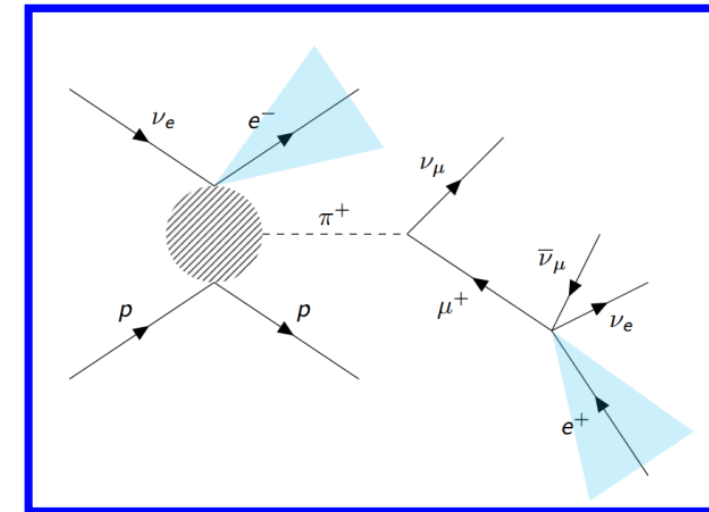
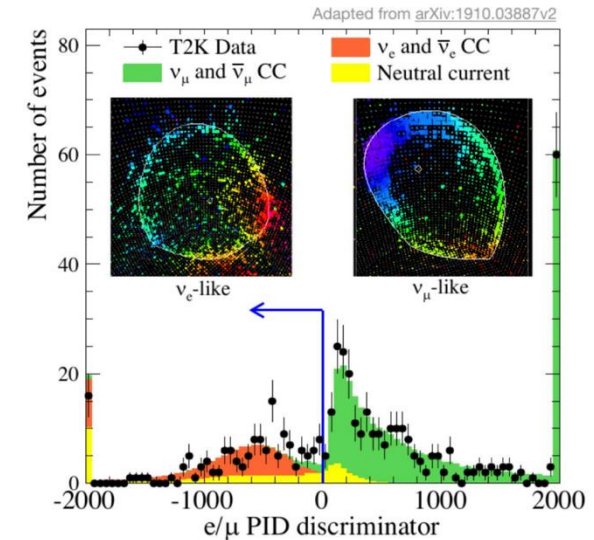
Binning in reconstructed lepton momentum & angle



Target ν CCQE
1 ring topology in « ν beam mode »

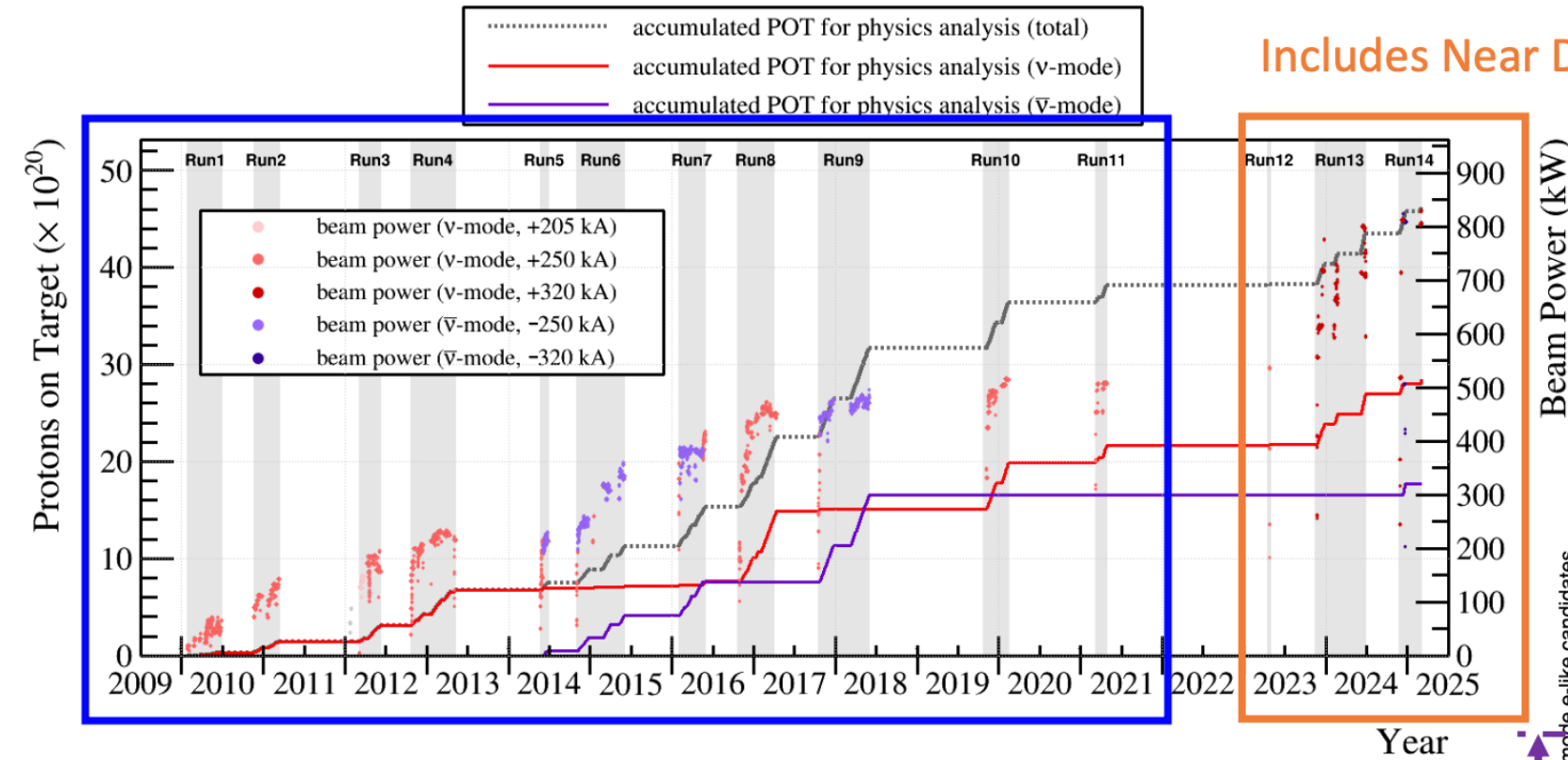
Target $\bar{\nu}$ CCQE
1 ring topology in « $\bar{\nu}$ beam mode »

Target ν CC1 π
1 main ring + 1 decay electron



ANALYZED DATA FOR LATEST RESULTS

Includes Near Detector Upgrade & Flux Upgrade!

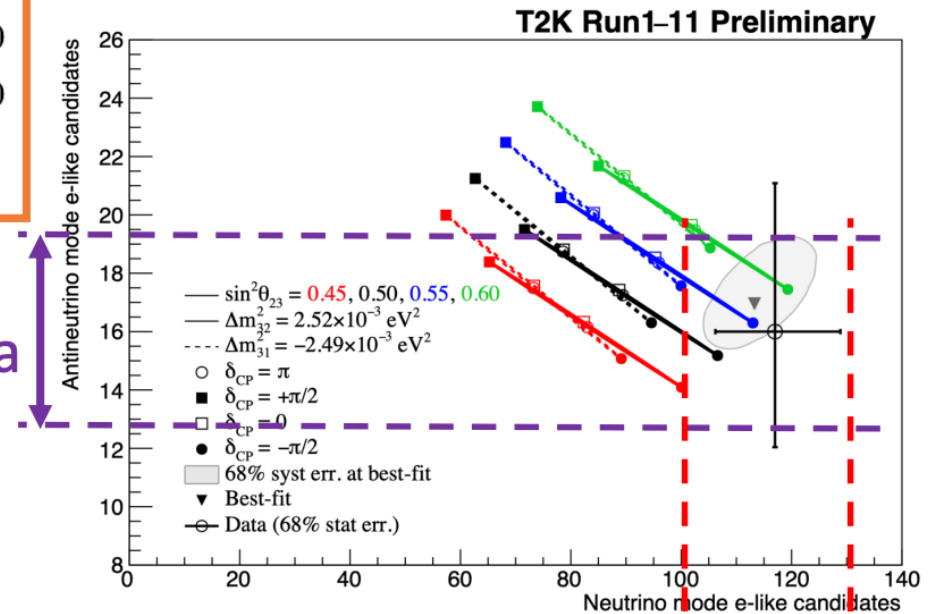


Latest analysed data: Runs 1-11

FHC: 2.1423×10^{21} POT

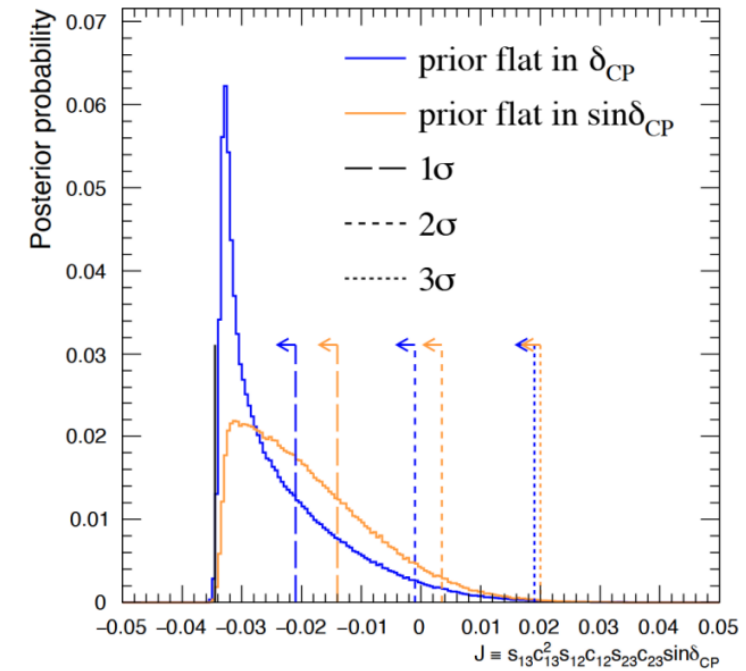
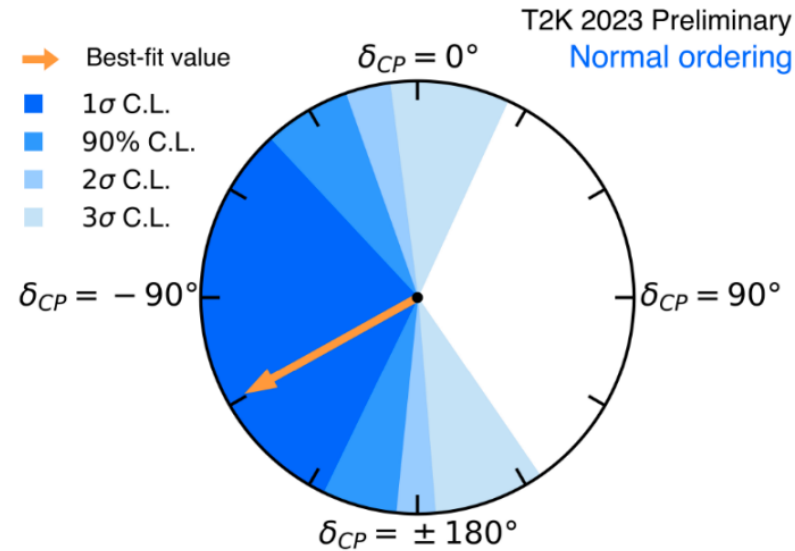
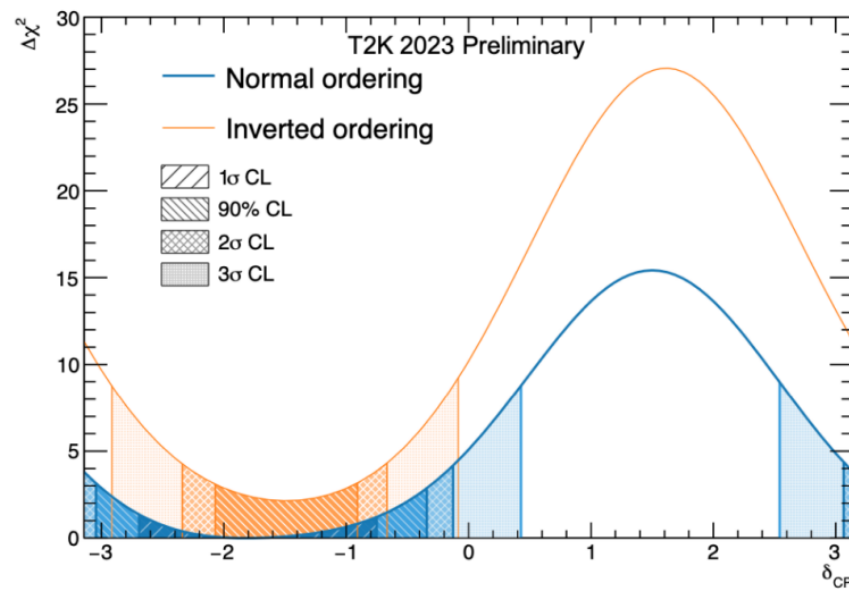
RHC: 1.6344×10^{21} POT

$\bar{\nu}$ mode data



ν mode data

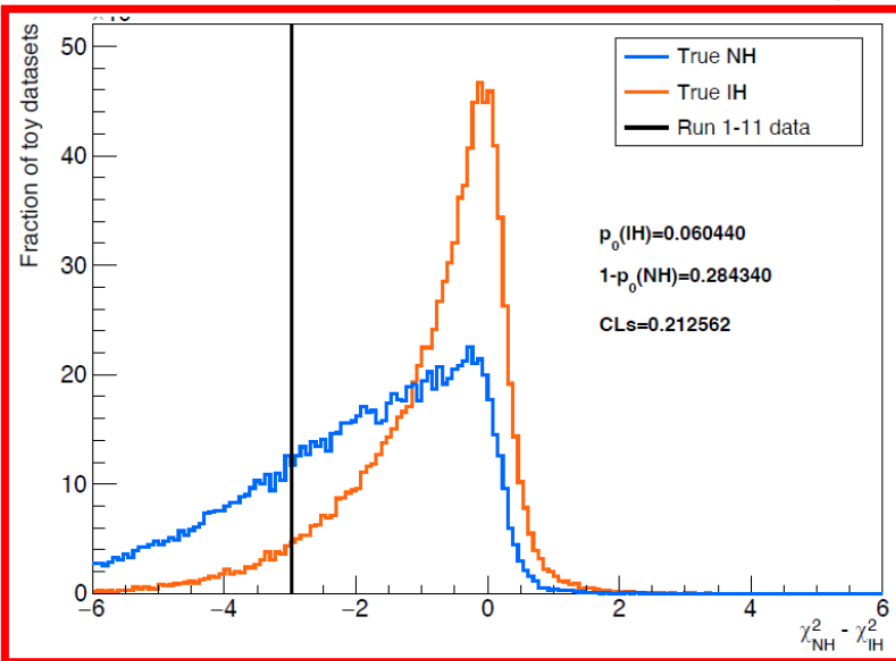
LATEST T2K RESULTS: CP VIOLATION AND MASS HIERARCHY



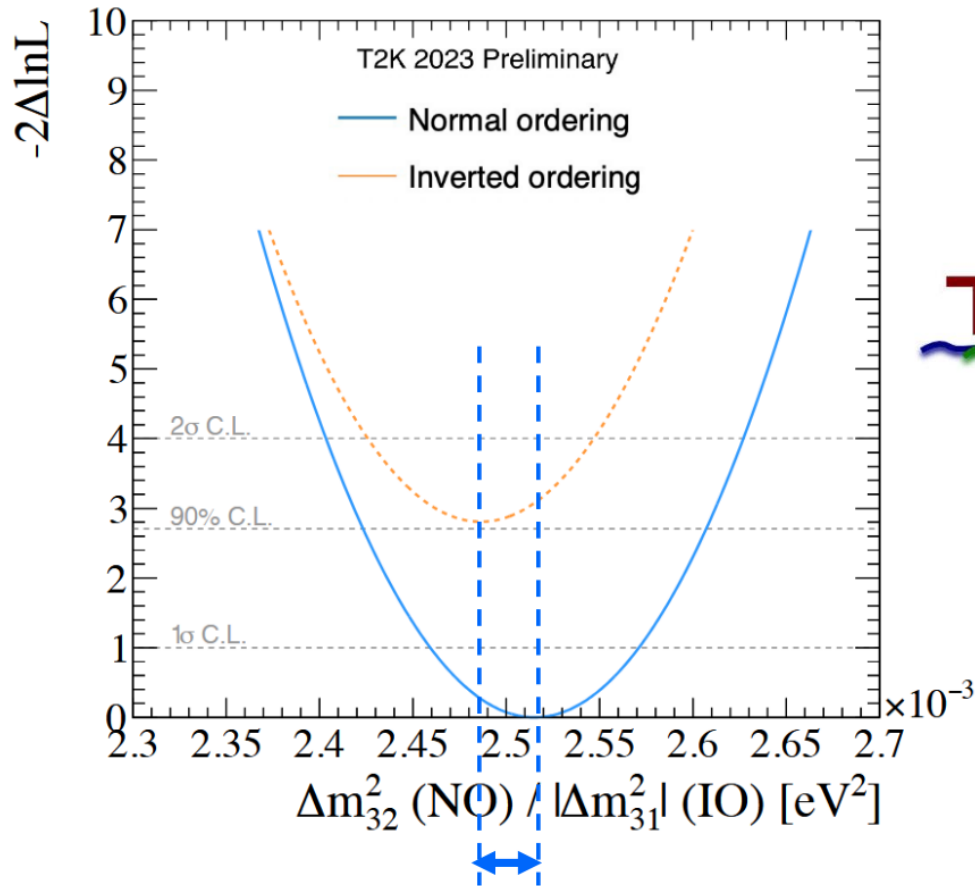
$$\delta_{CP} = -2.08^{+1.33}_{-0.61}$$

CP Conservation is excluded with 90% confidence level!

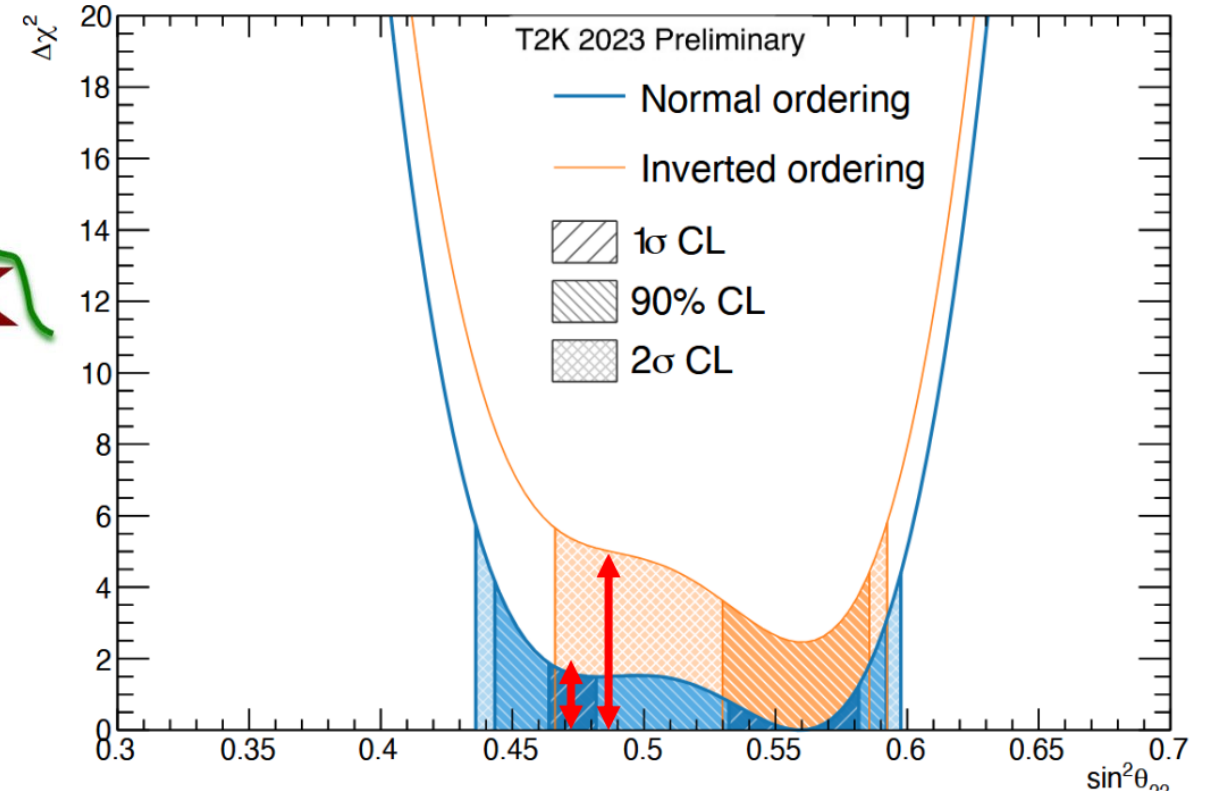
Exclusion of inverted ordering by 1.25σ (CLs method)



LATEST T2K RESULTS: Δm_{ATM}^2 AND $\sin^2 \theta_{23}$



T2K



Lower octant exclusion from appearance channel

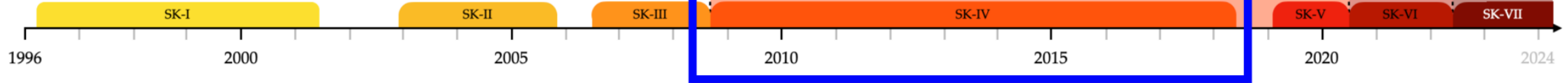
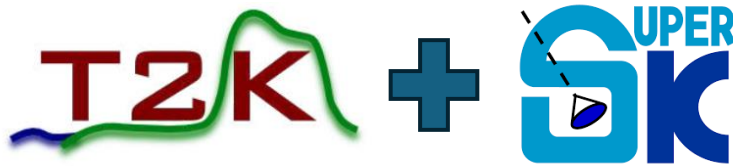
MO Bias from disappearance channel

$$|\Delta m_{\text{atm}}^2| = 2.521_{-0.050}^{+0.037} \times 10^{-3} \text{ eV}^2$$

(mass hierarchy treated as nuisance)

$$\sin^2 \theta_{23} = \begin{cases} 0.568_{-0.036}^{+0.014} & \text{Upper Octant} \\ 0.475_{-0.011}^{+0.007} & \text{Lower Octant} \end{cases}$$

JOINT FIT WITH SUPER-KAMIOKANDE ATMOSPHERICS



First iteration of the T2K+SK Joint Fit

Phys.Rev.Lett. 134 (2025) 1, 011801

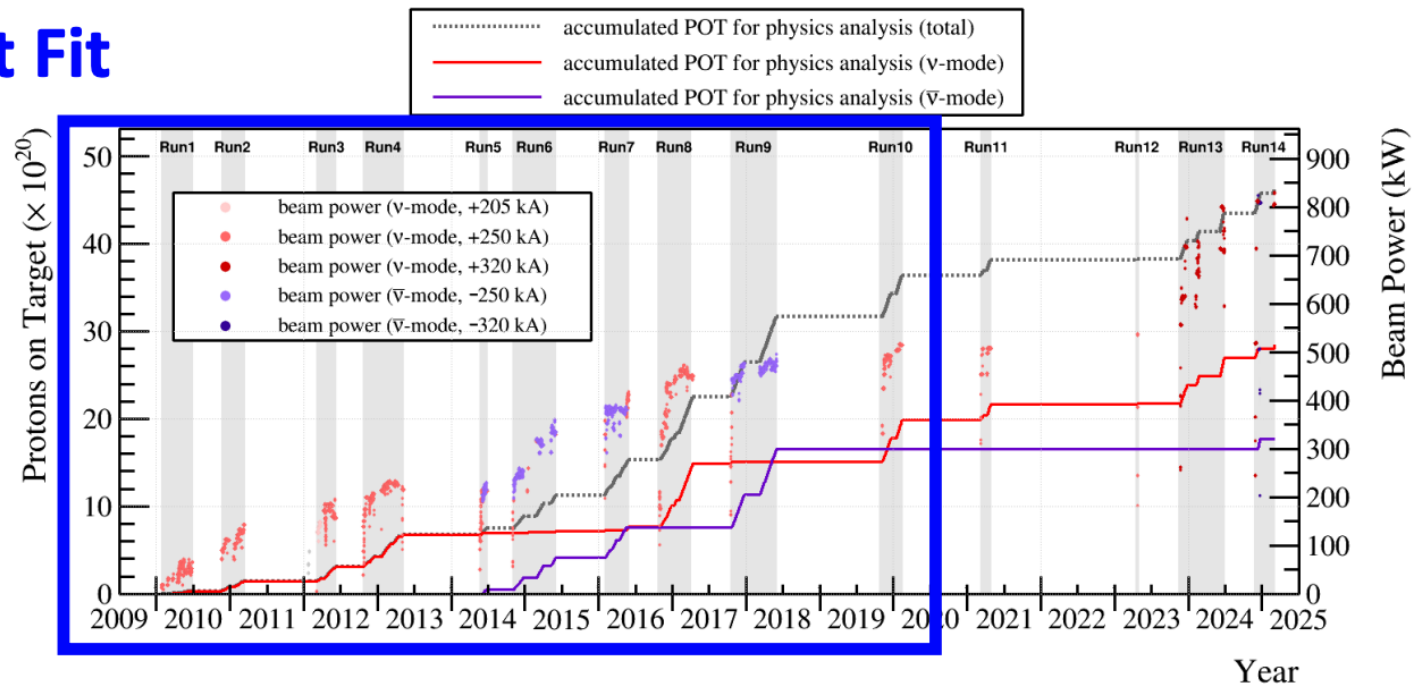
Why a joint fit?

- More data
- Common systematics
- **Resolve degeneracies**

- δ_{CP} — **Mass Hierarchy** degeneracy
- δ_{CP} — θ_{23} **octant** degeneracy
- θ_{13} — δ_{CP} **degeneracy**
- θ_{13} — θ_{23} **octant** degeneracy

Joint fit with SK atmospheric!

Use constraint on θ_{13} provided by reactor experiments!



NEUTRINO INTERACTION MODELS IN THE JOINT FIT

Number of
neutrino events

=

Neutrino flux
 ν flux model

$\otimes$

Neutrino oscillation
PMNS model

$\otimes$

Neutrino interactions
 ν cross-section models

$\otimes$

Neutrino detection
SK detector model

Neutrino flux models

Hadronic models could be correlated
→ Not implemented yet

SK detector model

The systematics for atmospheric neutrinos detection and T2K neutrinos detection have been correlated

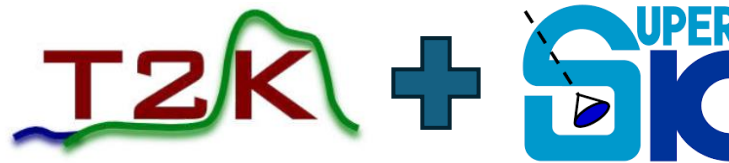
Neutrino interaction models

T2K interaction models:

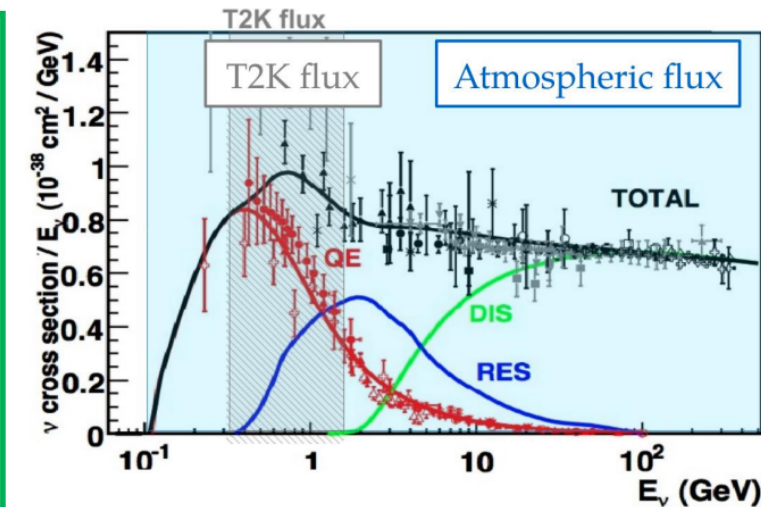
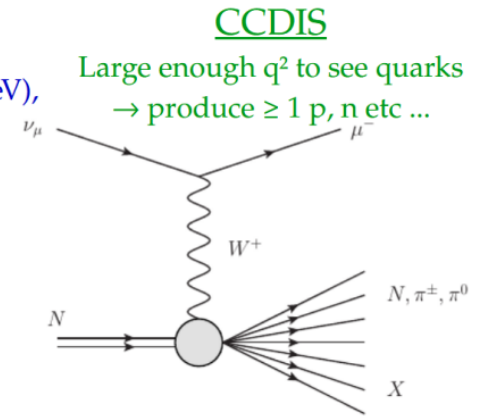
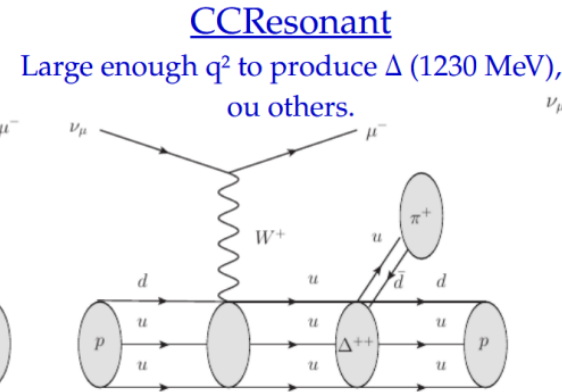
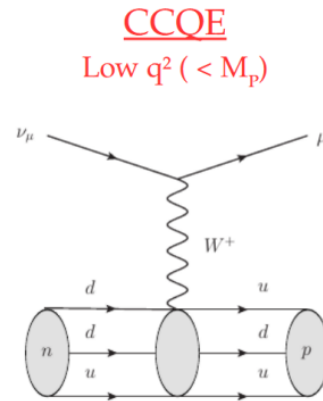
- Very well-constrained by ND
- Robust only in 0 – 2 GeV region

SK interaction models:

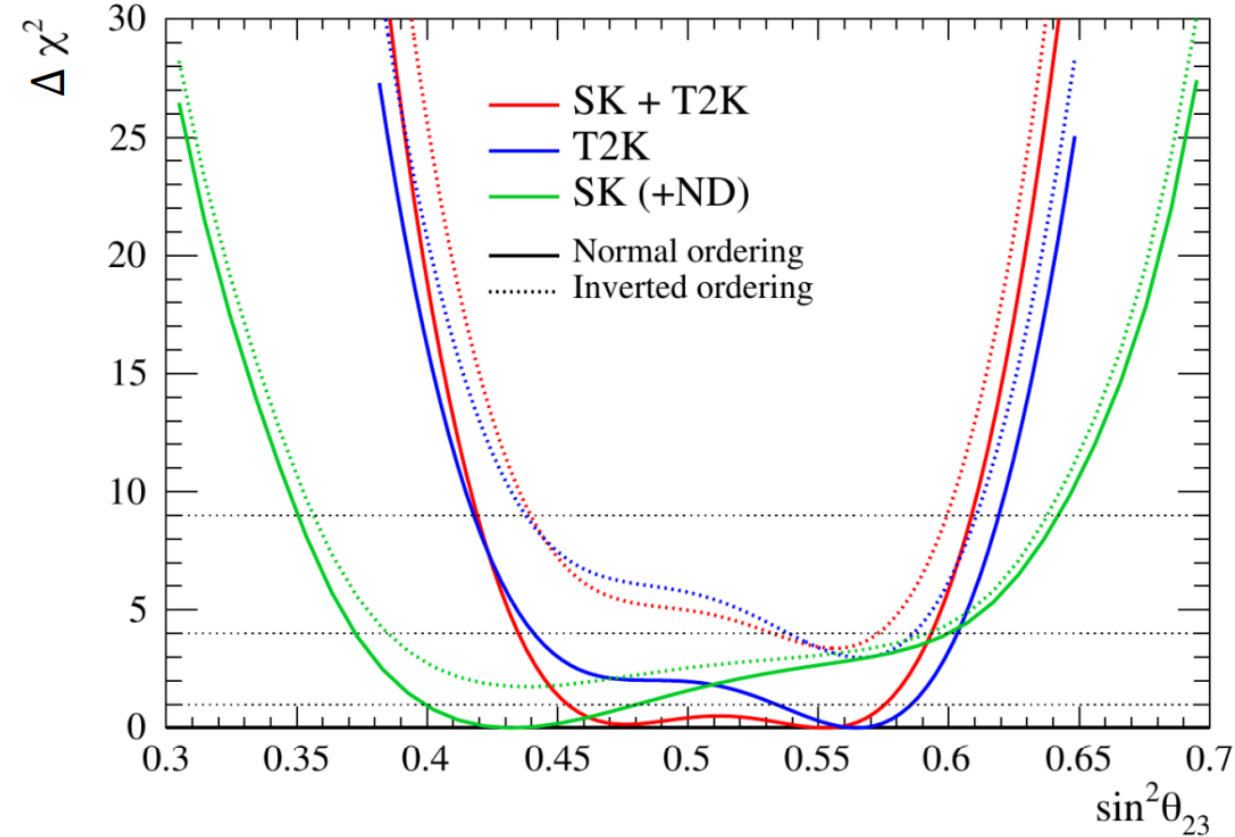
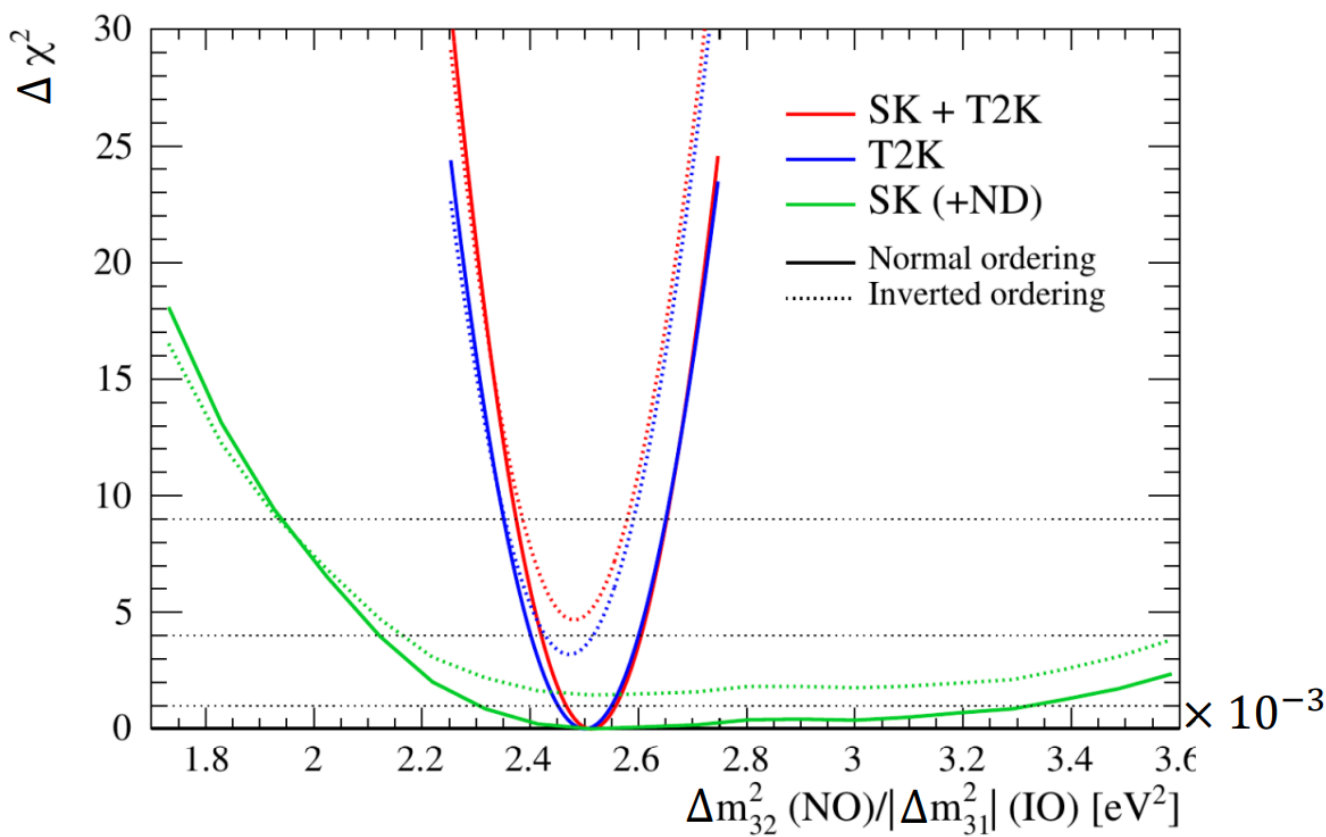
- Up to 10 TeV for atmospherics!



Correlate only T2K and Sub-GeV
atmospherics (with ND constraint)

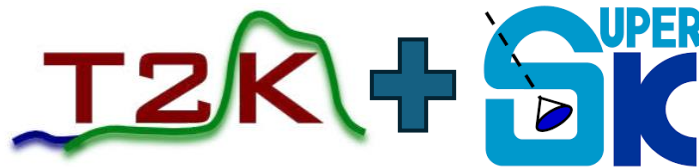


JOINT FIT RESULTS: Δm_{ATM}^2 AND $\sin^2 \theta_{23}$



$$\begin{cases} \Delta m_{32}^2 = 2.520^{+0.048}_{-0.058} \text{ eV}^2 & \text{Normal Hierarchy} \\ \Delta m_{32}^2 = -2.480^{+0.052}_{-0.048} \text{ eV}^2 & \text{Inverted Hierarchy} \end{cases}$$

→ Similar to T2K only



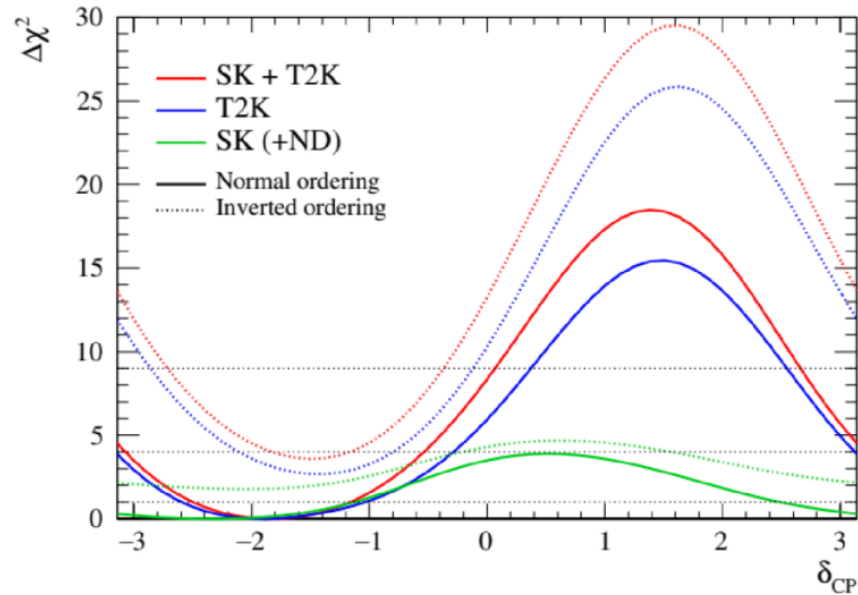
$$\sin^2 \theta_{23} = 0.468^{+0.106}_{-0.025}$$

(mass hierarchy treated as nuisance)

→ Different octant preferences for SK and T2K

→ Largely compatible with Maximal Mixing

JOINT FIT RESULTS: CP VIOLATION AND MASS HIERARCHY

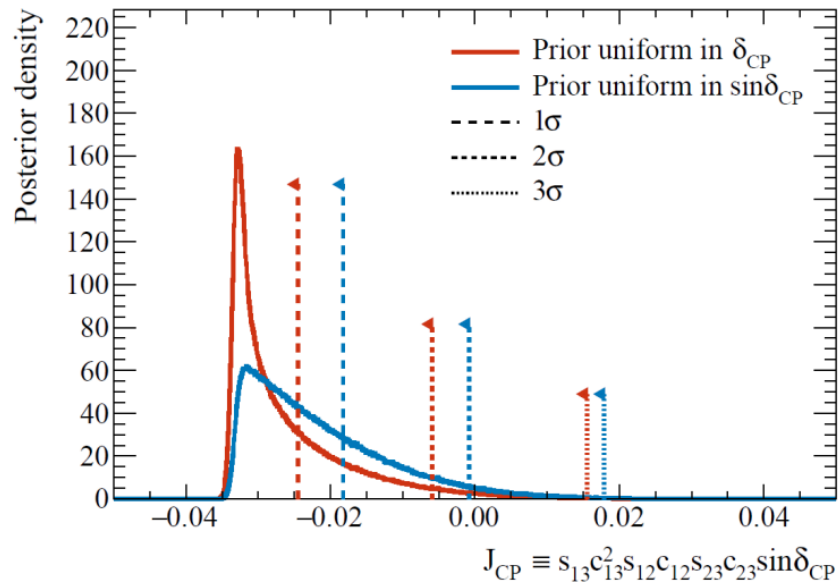
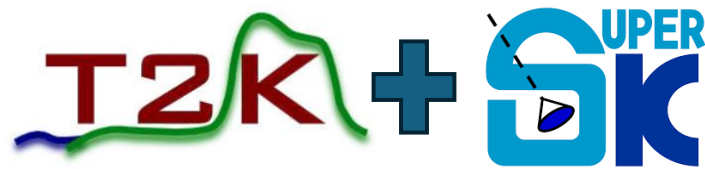


$$\delta_{CP} = -1.76^{+0.73}_{-0.95}$$

→ Both T2K and SK favor $\delta_{CP} \approx -\frac{\pi}{2}$

→ Clear enhancement in the exclusion of $\delta_{CP} = 0$: 2.5σ

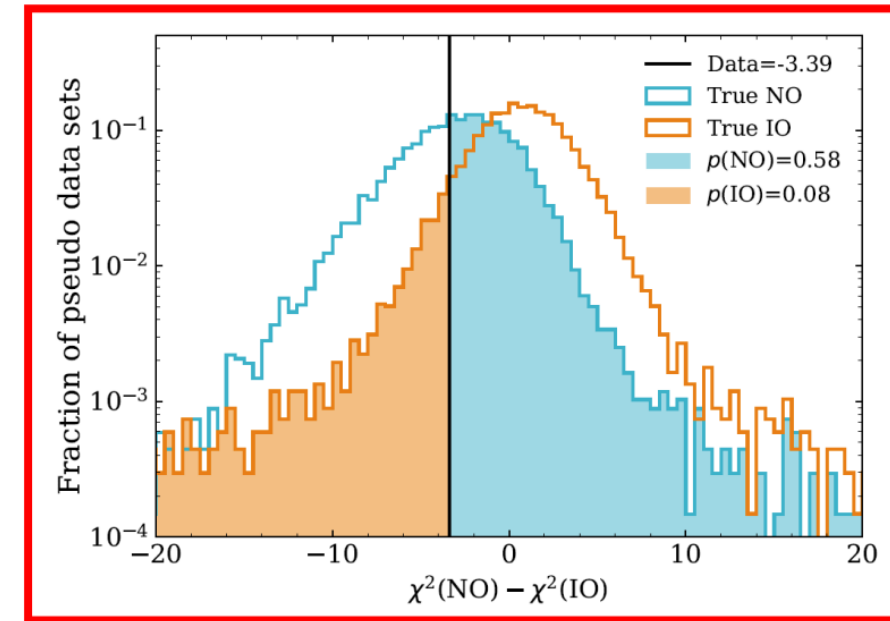
→ Overall exclusion of $J_{CP} = 0$: 1.9σ



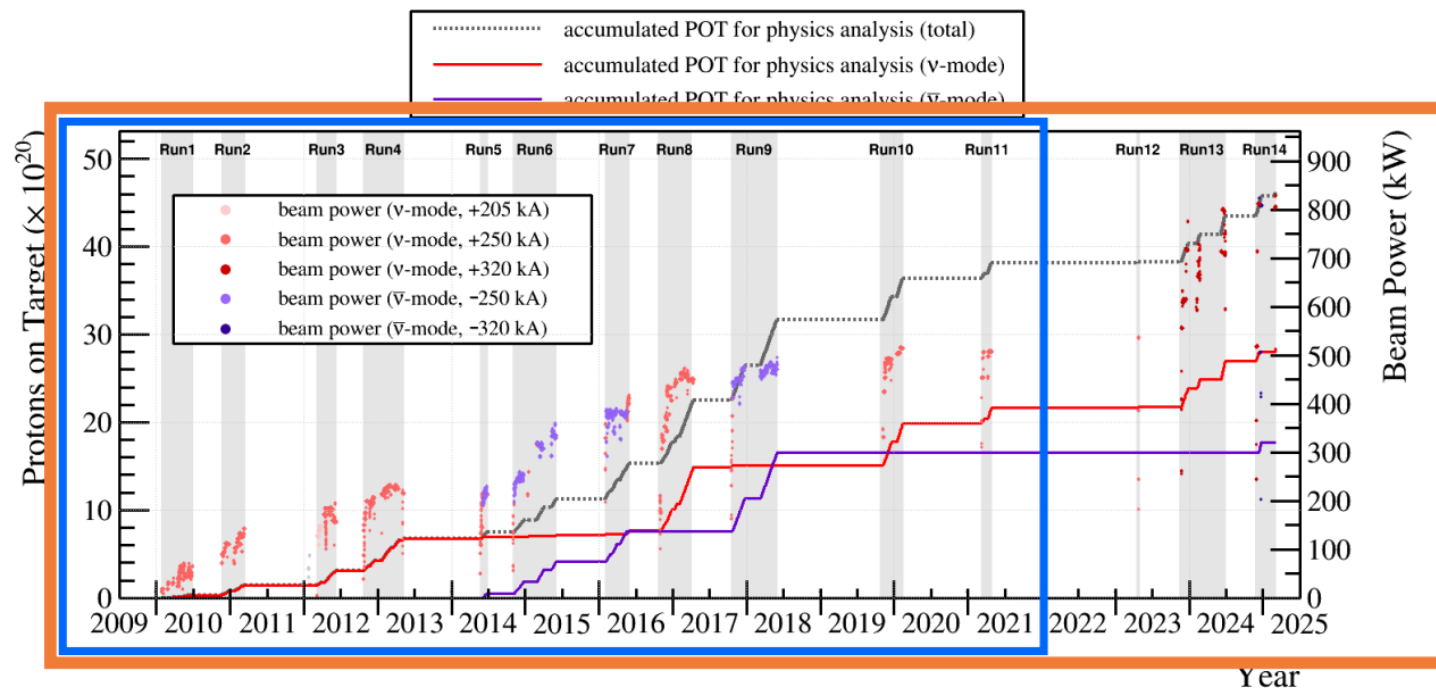
Limited preference for NO:

→ 1.2σ rejection of IO

→ Large improvement expected with all SK atmospheric data



CONCLUSION



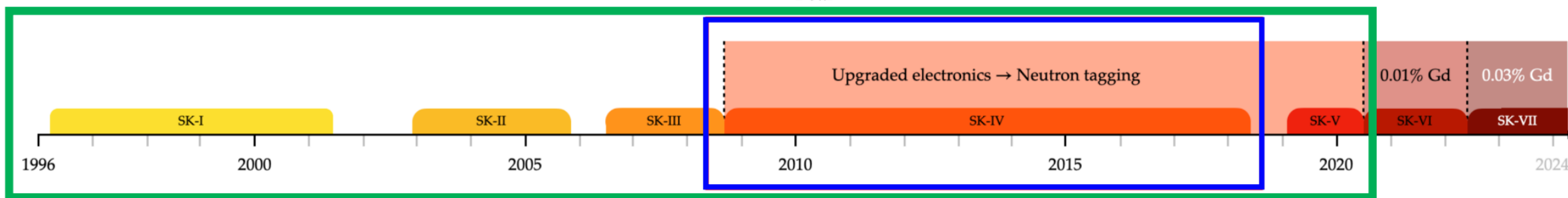
Latest analyzed data

- $\sin\delta_{CP} = 0$ excluded at 90% C.L.
- Slight preference for NO and upper octant
- Precision of $4 \times 10^{-5} \text{ eV}^2$ on Δm_{atm}^2

T2K

Future analyses

- Upgraded focusing horns: less flux contamination
- ND Upgrade: More fiducial mass, better resolution
- Increased beam power: more POT per year



First iteration of the T2K+SK Joint Fit

- $J_{CP} = 0$ excluded at 2σ
- Slight preference for NO
- No octant preference

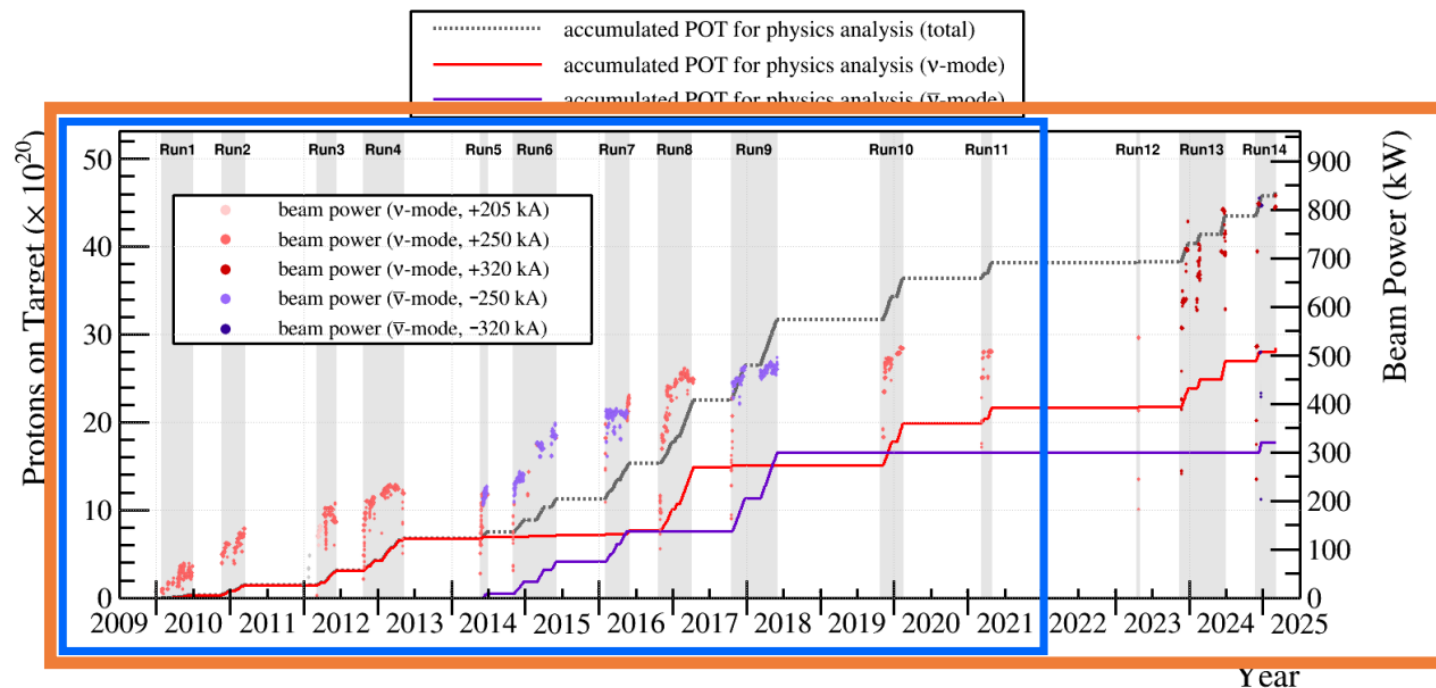


Second iteration of the T2K+SK Joint Fit

- Even more data! ($\times 2$ SK, +9% T2K)
- New accelerator samples
- New cross-section model

T2K + SK

CONCLUSION



Latest analyzed data

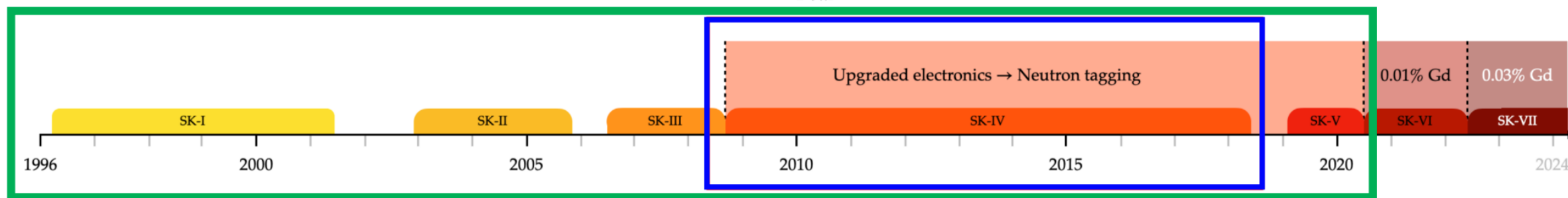
T2K

- $\sin\delta_{CP} = 0$ excluded at 90% C.L.
- Slight preference for NO and upper octant
- Precision of $4 \times 10^{-5} \text{ eV}^2$ on Δm_{atm}^2



Future analyses

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First iteration of the T2K+SK Joint Fit

- $J_{CP} = 0$ excluded at 2σ
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- No octant preference



Second iteration of the T2K+SK Joint Fit

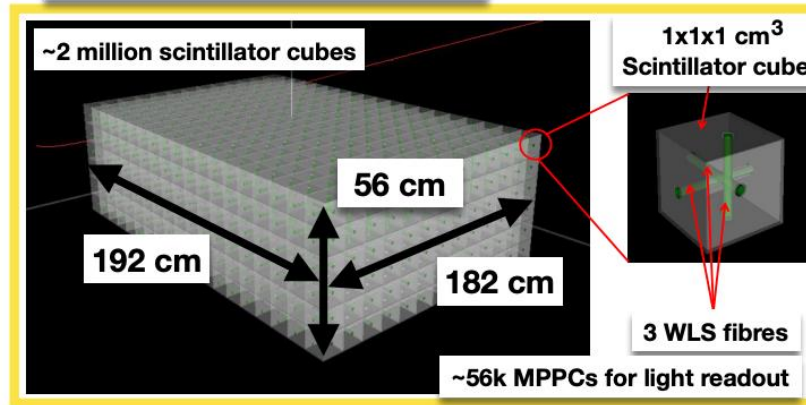
- Even more data! ($\times 2$ SK, +9% T2K)
- New accelerator samples
- New cross-section model

T2K + SK

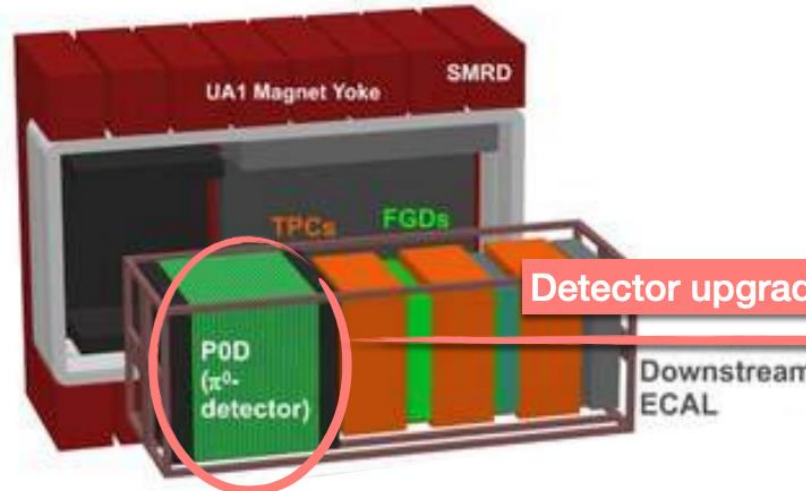
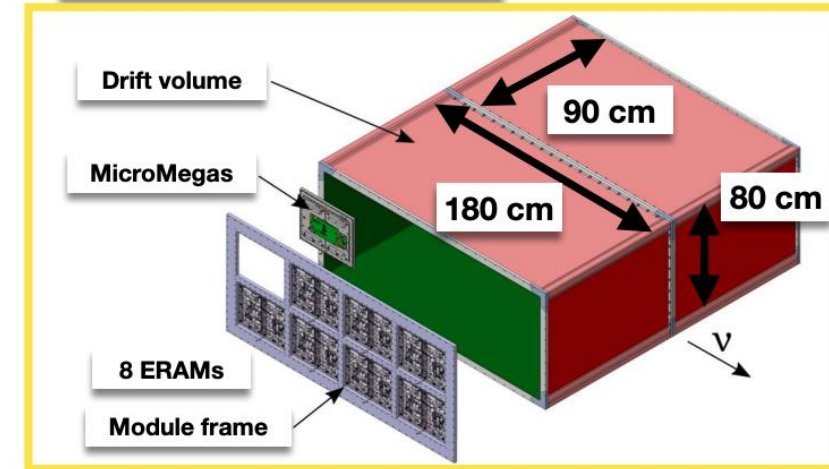
T2K Near detector upgrade

- P0D sub-detector has been replaced with:
 - a new fine grained scintillator target (Super Fine Grained Detector aka SFGD) for good low energy proton and neutron(!) reconstruction
 - two high angle TPCs (HATs) to increase the angular acceptance closer to that of Super-K
 - six time-of-flight (ToF) detector panels for directionality info of charged tracks and for veto
- Installation at J-PARC completed in May 2024

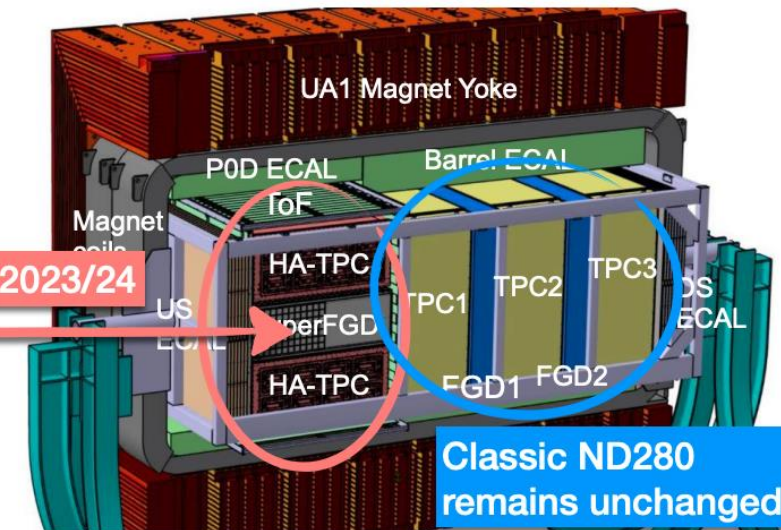
SuperFGD Design:



2 HTPCs Design:



Original ND280 detector (2010-2023)



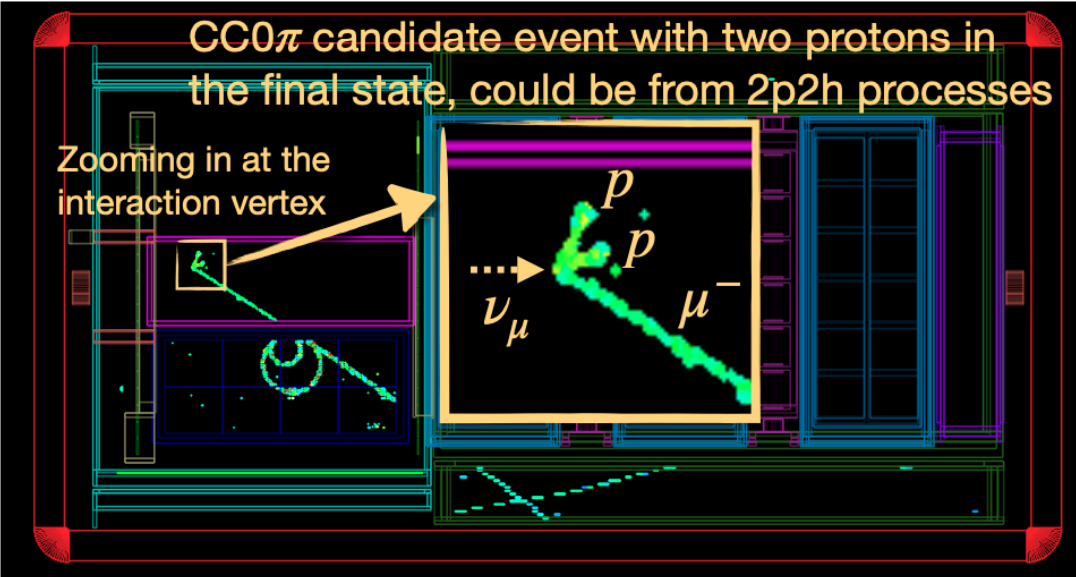
New ND280 detector (Completed in 2024)

For more details on the design, refer to the ND280 Upgrade Technical Design Report: [arXiv:1901.03750](https://arxiv.org/abs/1901.03750)

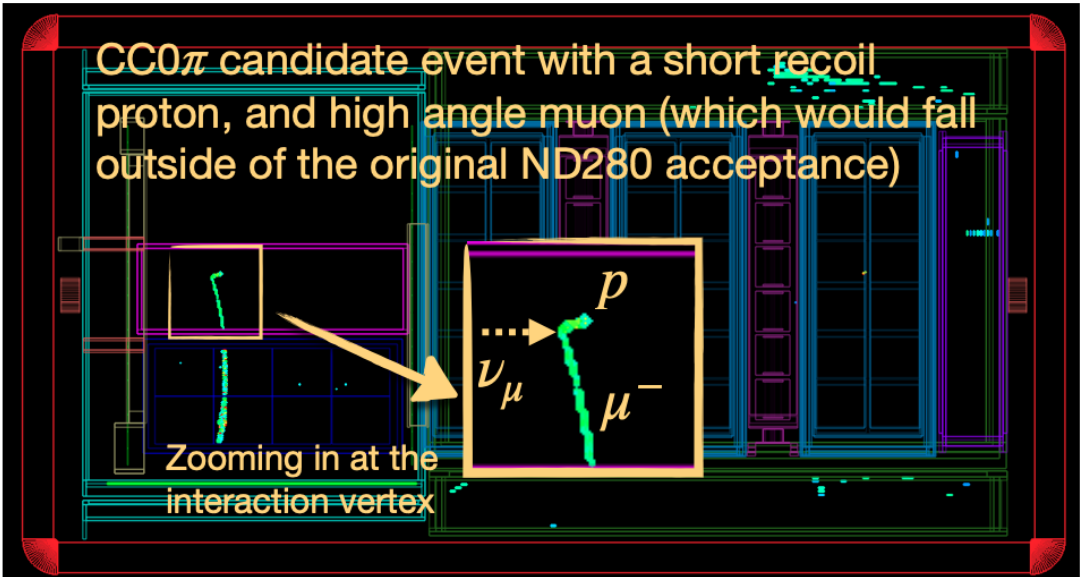
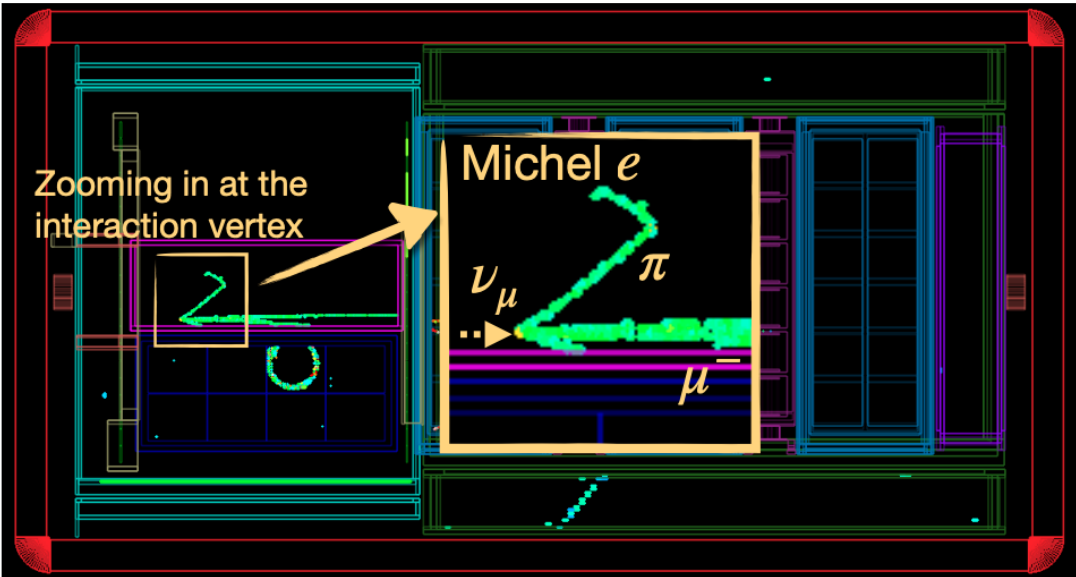
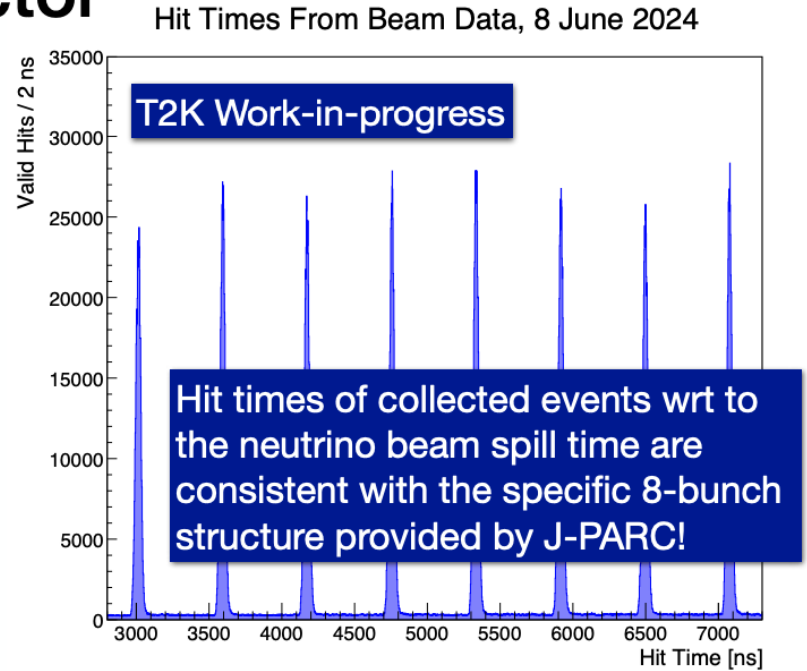
RAL neutrino group played an important part during detector

commissioning and integration in the global DAQ system in 2023/24

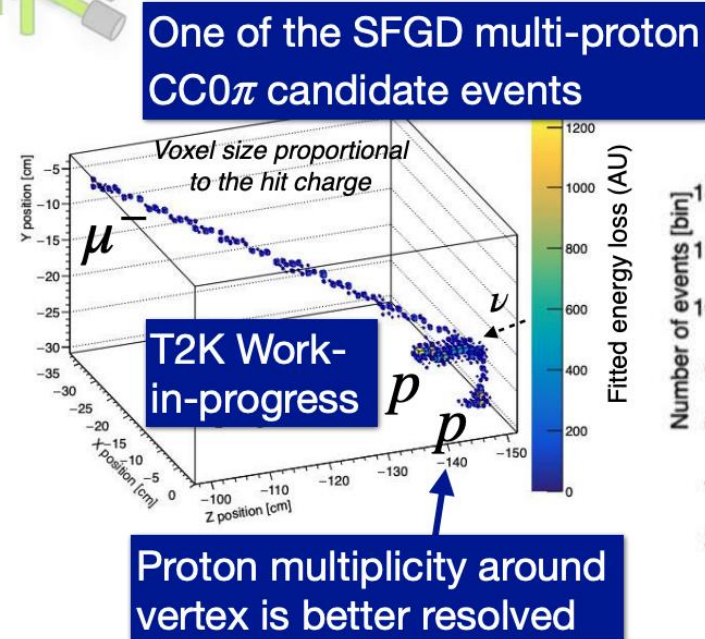
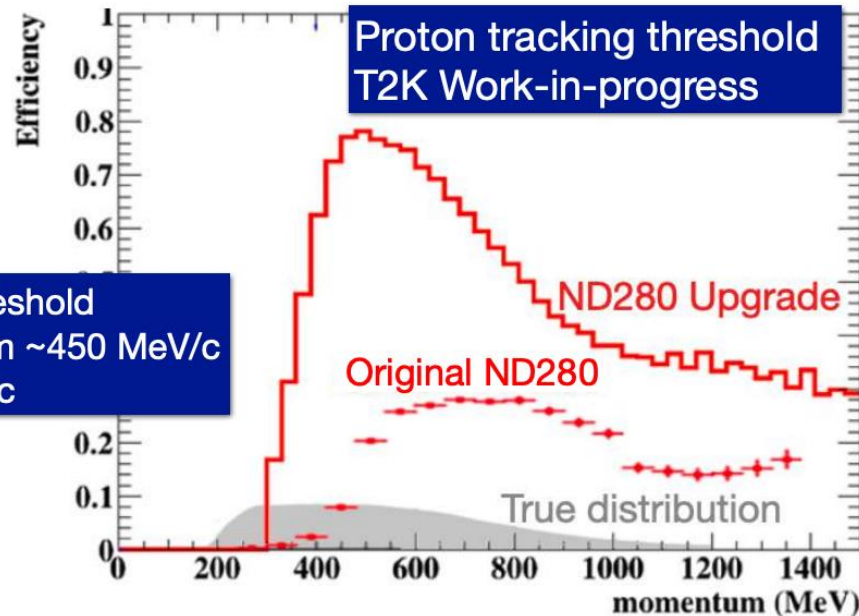
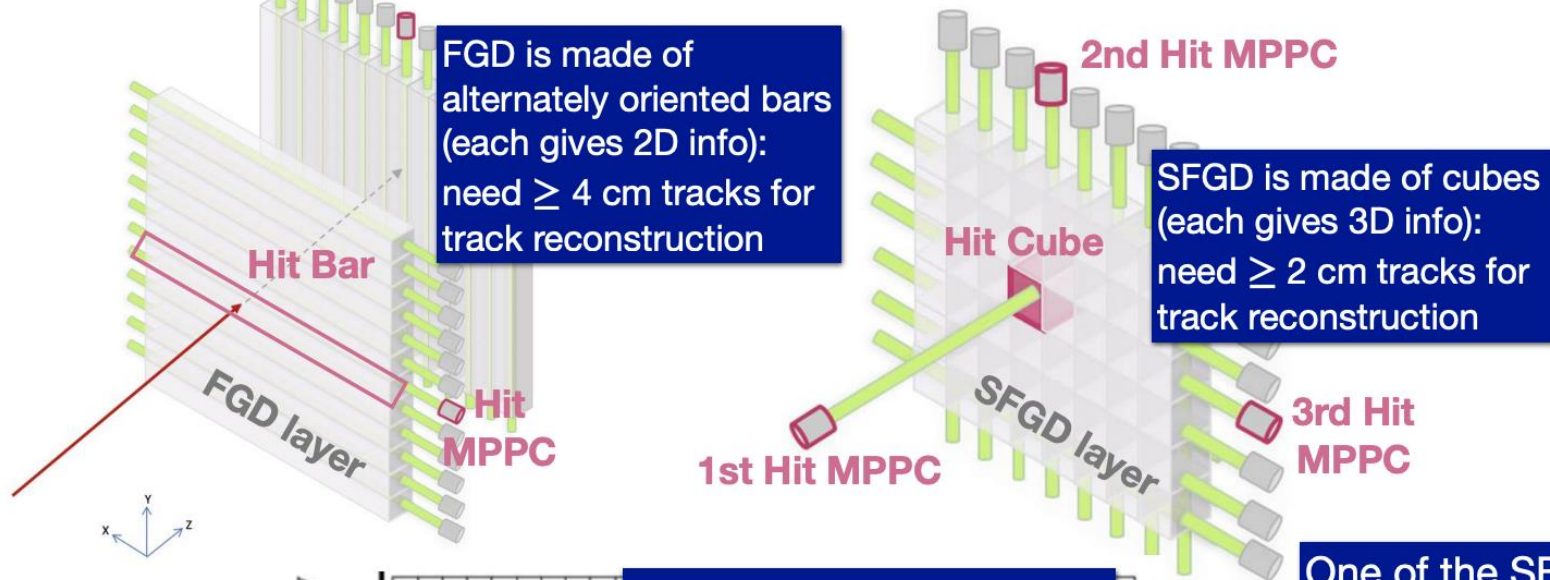
Examples of event displays with the upgraded detector



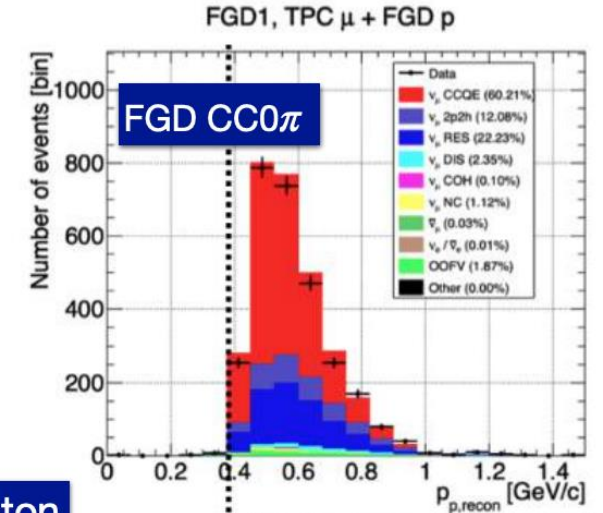
- Unprecedented resolution around the interaction vertex and level of detail for the T2K near detector has been achieved during commissioning of the upgraded ND280 with the T2K beam
- Shown here are few of the events from the June/July 2024 T2K run



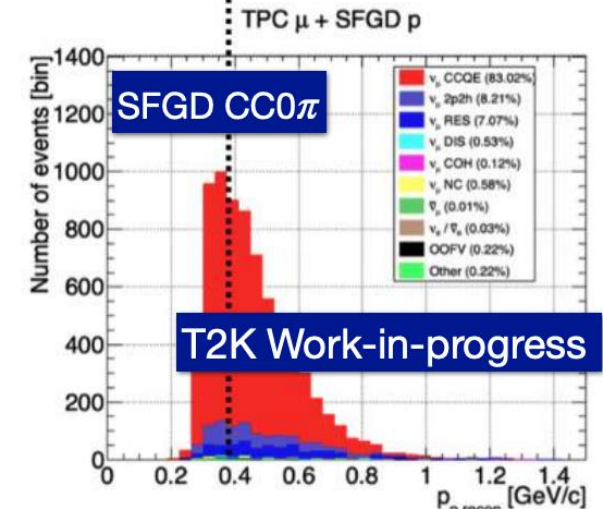
Proton threshold reduction and improved purity



Proton threshold + purity



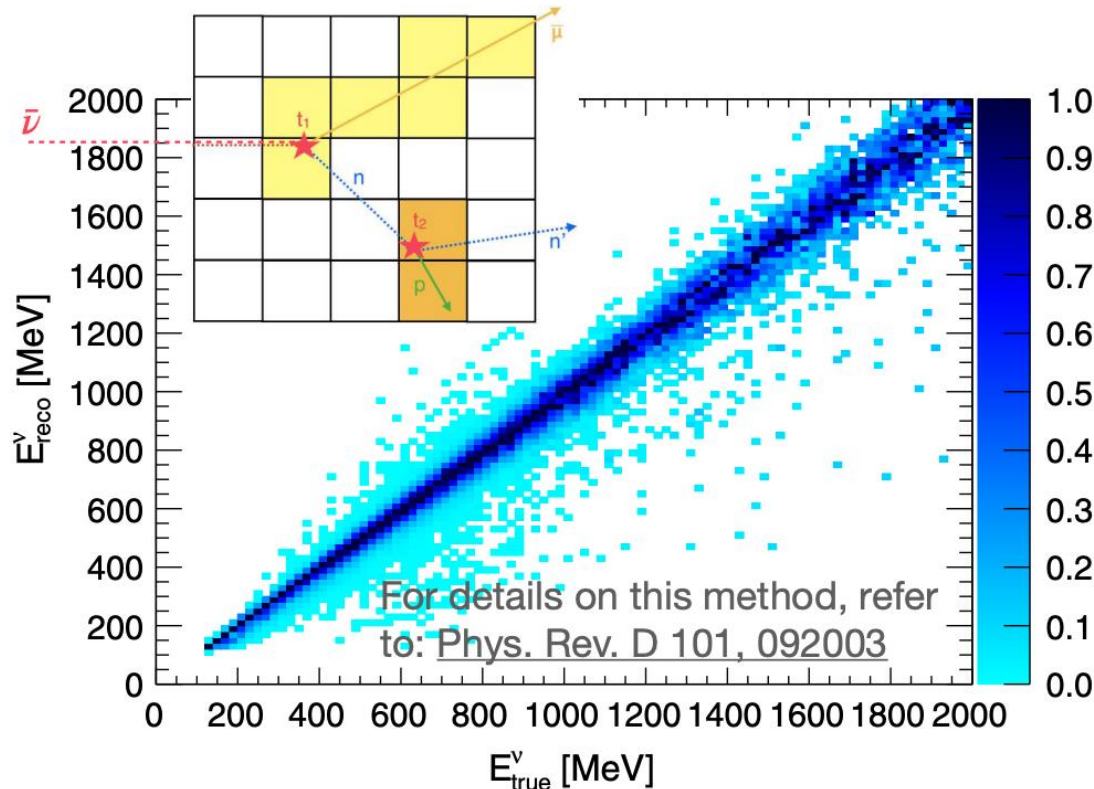
Lower proton threshold
Better CCQE purity



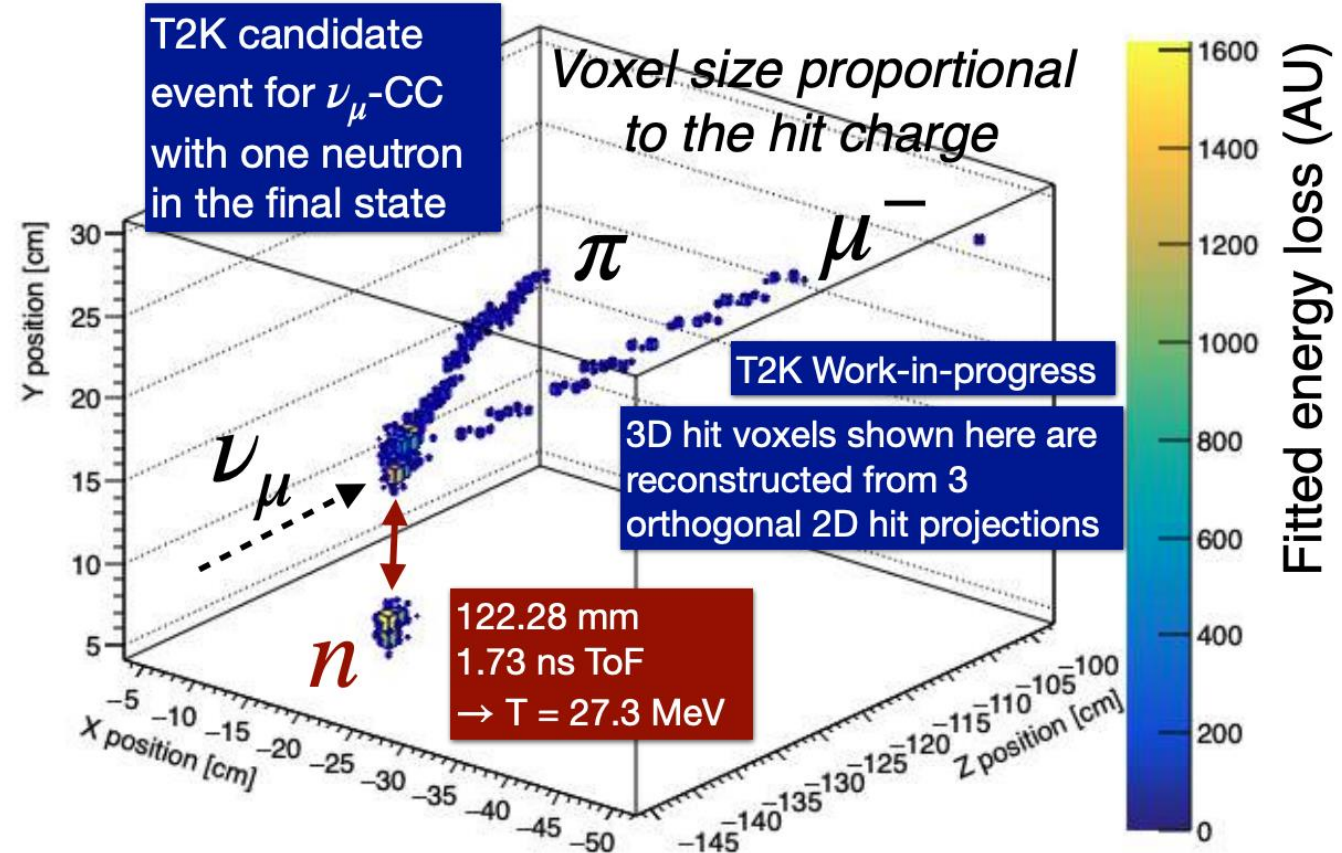
T2K Work-in-progress

Neutron detection with SFGD

- For the first time, neutron reconstruction will be possible, by identifying time of flight between the $\bar{\nu}$ interaction vertex and secondary vertex of the pre-thermalisation re-interaction of the outgoing neutron (50% tagging efficiency)
- The impact that this neutron detection will have on energy reconstruction of T2K anti-neutrino's has been assessed: resolution is reduced from $\sim 15\%$ to $\sim 7\%$

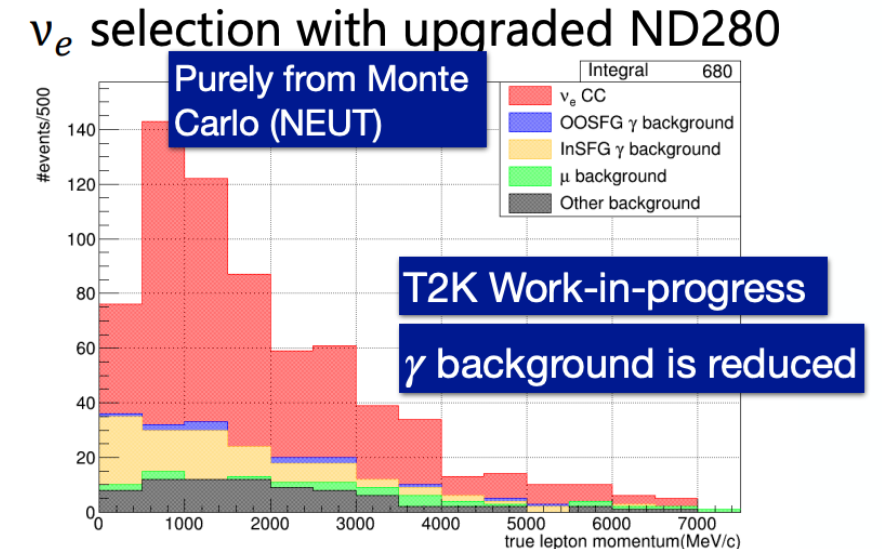
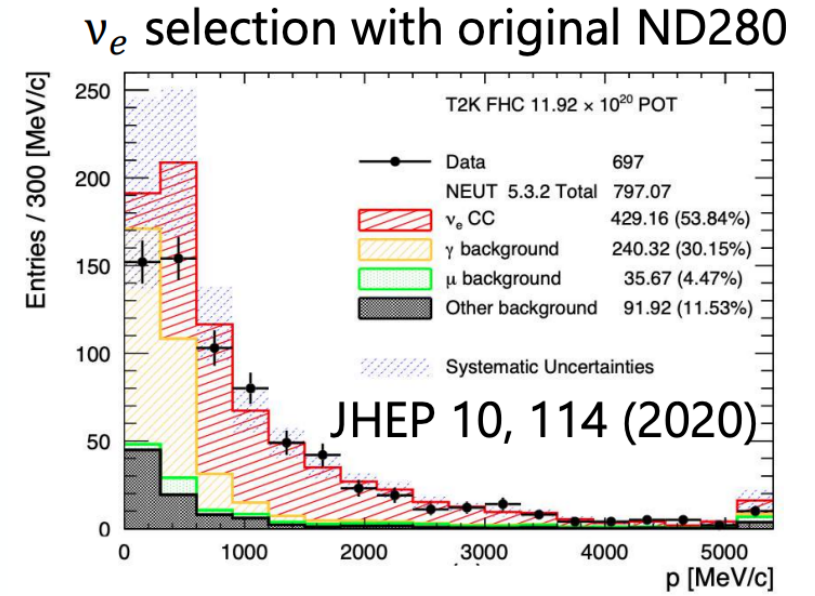
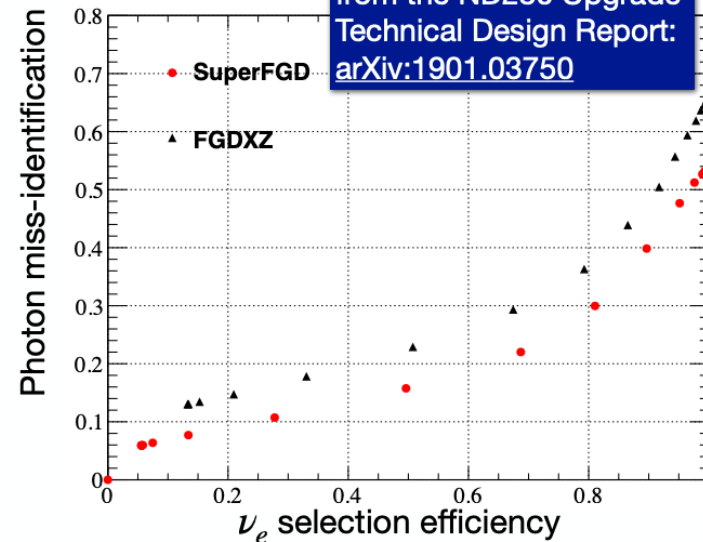
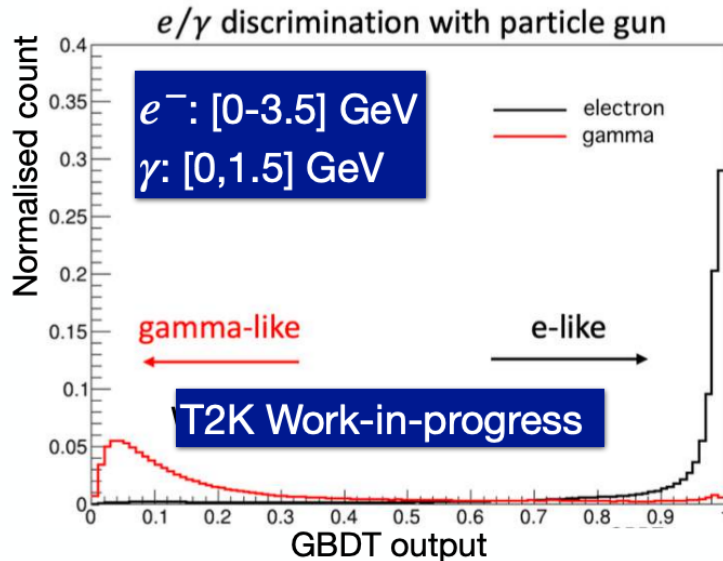
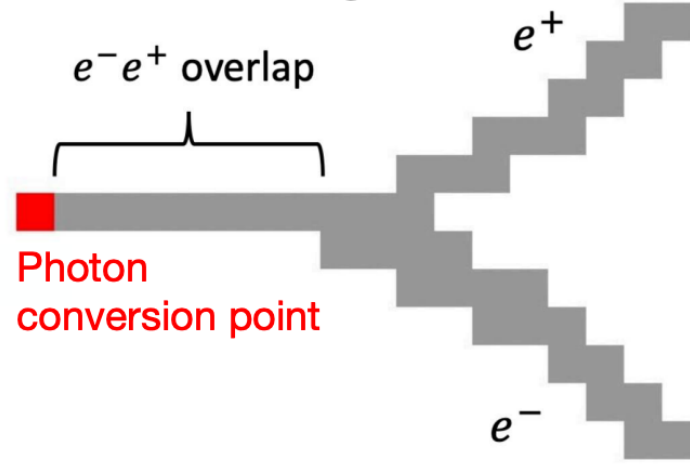


- Neutron detection has been demonstrated with the SFGD prototype exposed to the LANL neutron beamline
- For the measured total neutron cross section refer to [Phys. Lett. B 840 \(2023\) 137843](#)

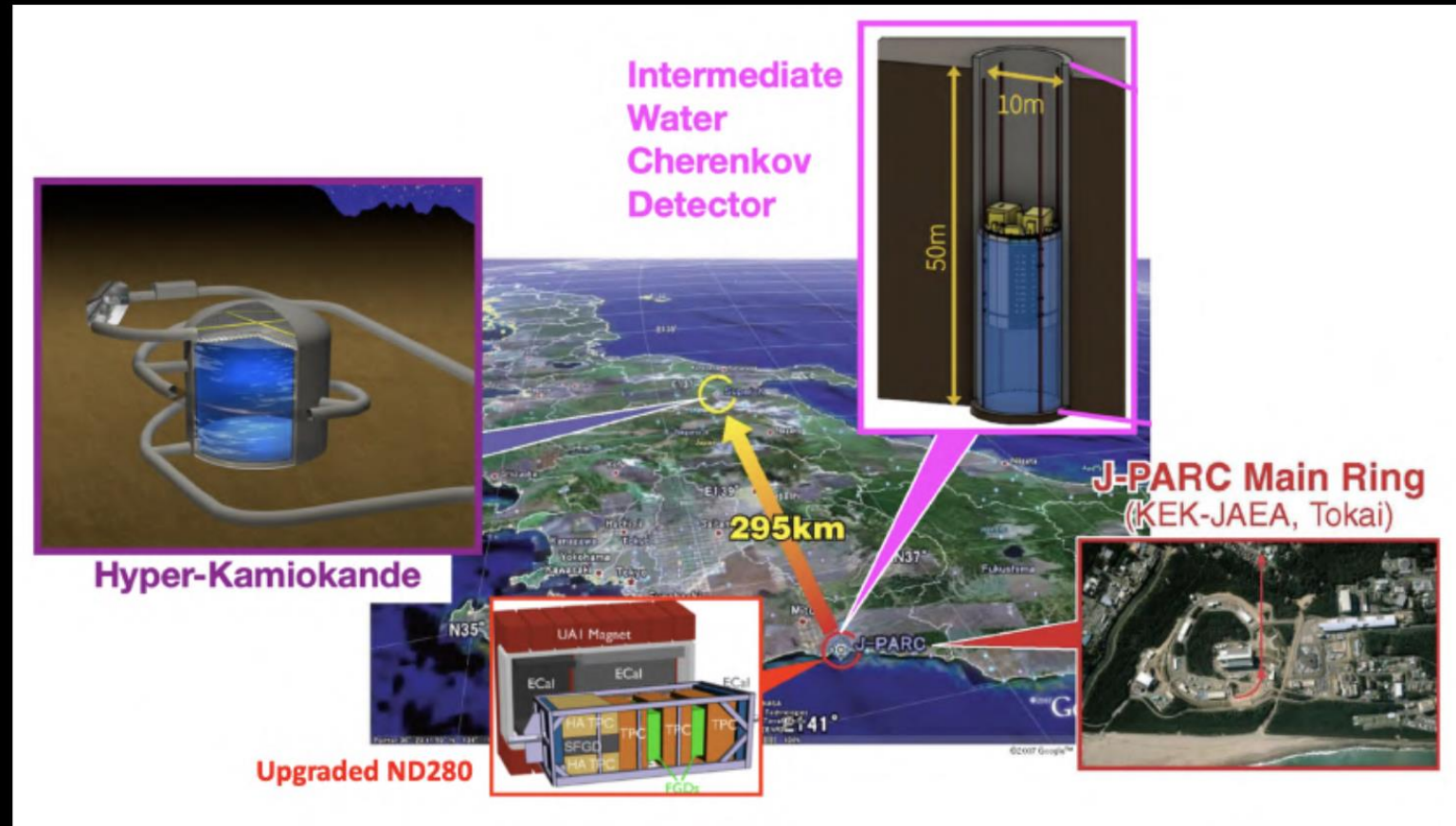


Improved ν_e selection with SFGD

- Dominant background on ν_e selection with pre-upgrade ND280 are photons from NC1Pi0
- Improved separation between single $e^\pm$ and $e^\pm$ from γ conversion enabled by the detector granularity



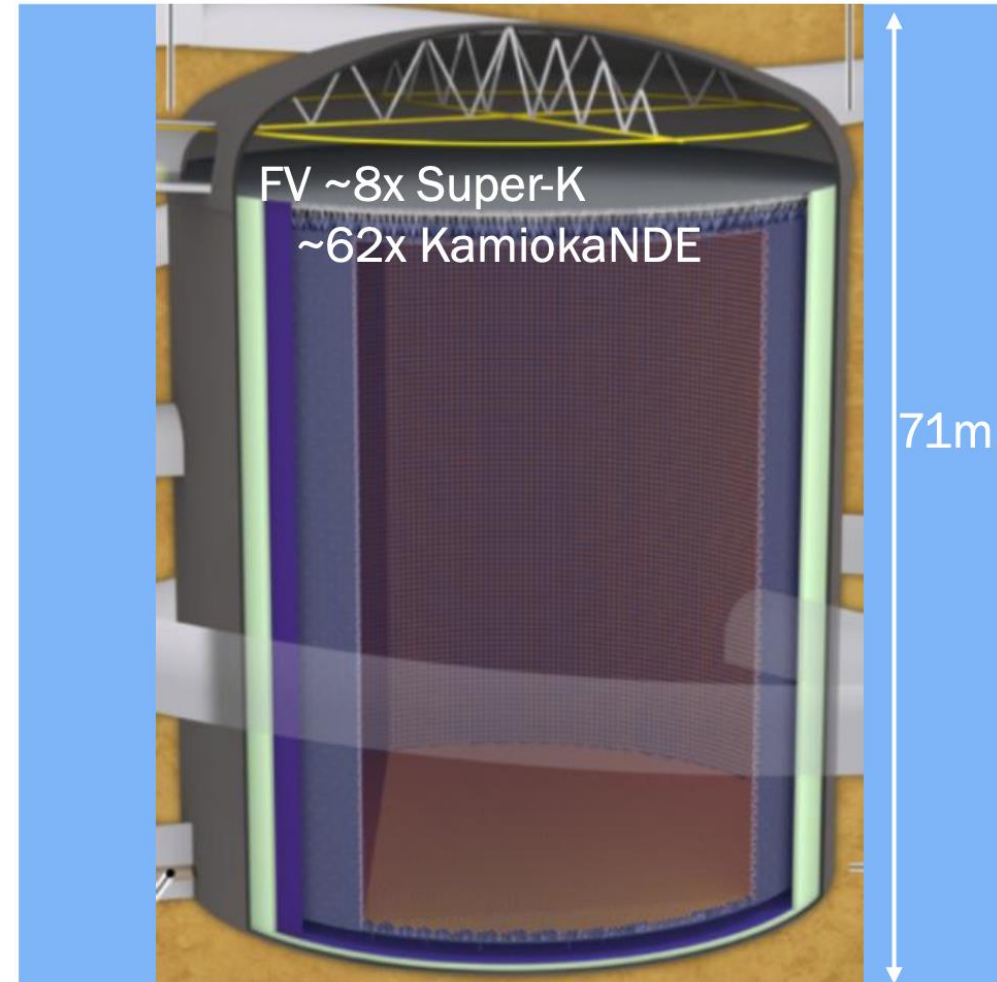
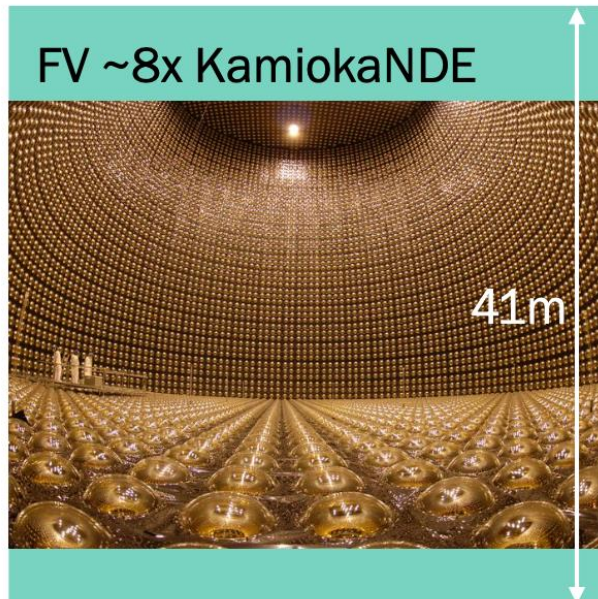
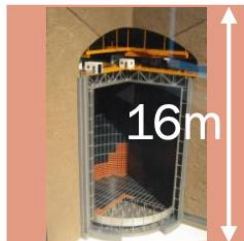
the Hyper-Kamiokande experiment



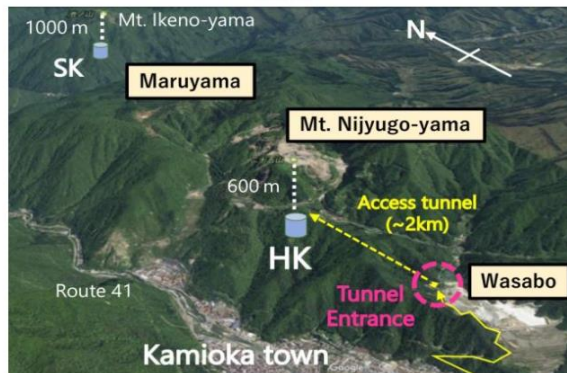
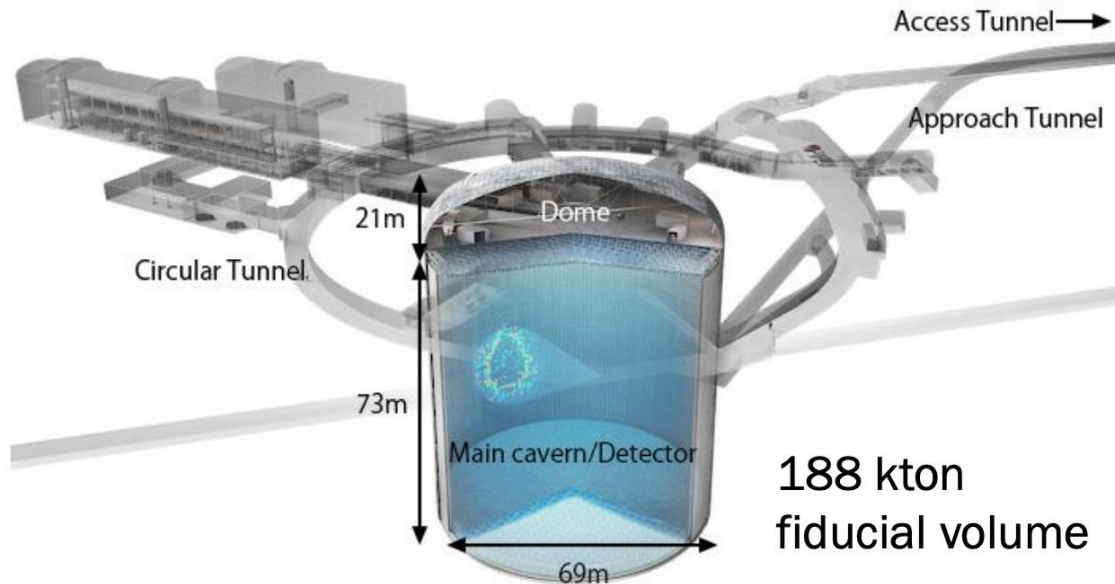
- ▶ **J-PARC beam:** ν_μ and $\bar{\nu}_\mu$ beam, 600 MeV, power upgraded to reach 1.3 MW
- ▶ **near detectors:** 280 m, measure before oscillations, tune fit, reduce systematics to 3%
- ▶ **IWCD:** 850 m downstream, water Cerenkov like far detector
- ▶ **far detector:** Hyper-Kamiokande, 295 km

Predecessors

- KamiokaNDE: 1983-96
- Super-Kamiokande: 1996-
- Hyper-Kamiokande: 2028-

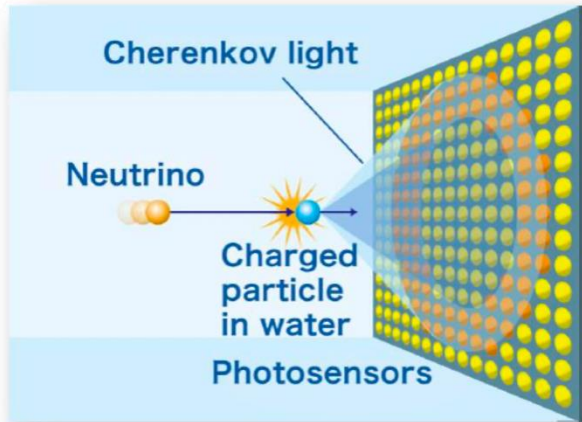


Far detector

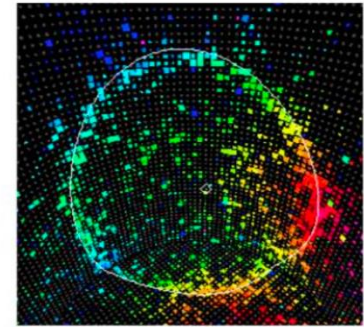
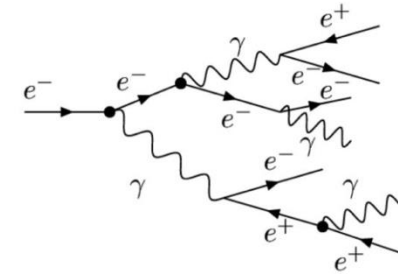
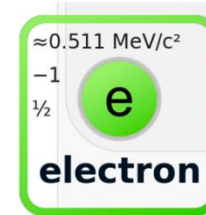
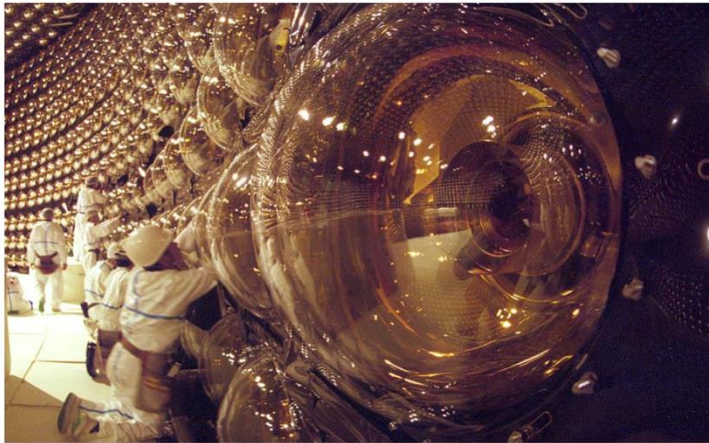
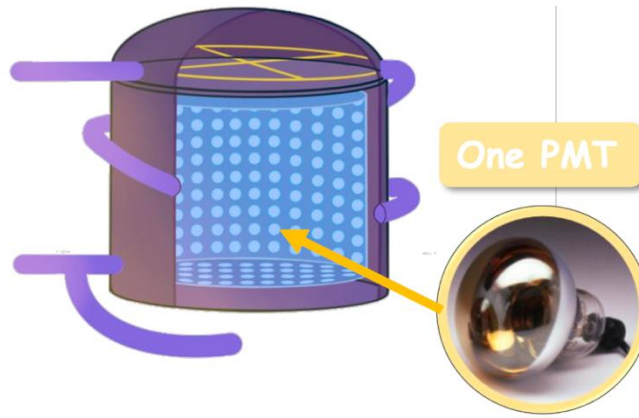


- Large water Cherenkov detector.
 - Similar conceptually to Super-Kamiokande (Super-K) -> tried and tested methods.
- Fiducial volume ~8x Super-K.
 - Larger size = more statistics.
- ~20,000 50 cm PMTs. } Located throughout the
- ~800 multi PMTs. } Inner Detector.
- ~3600 3" PMTs in the Outer Detector.
- Pure water target cheap relative to other targets.
- Located 8 km away from Super-K.
- Rock overburden of 600 m.

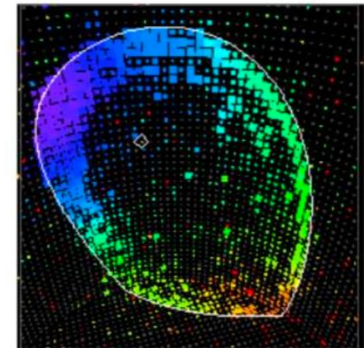
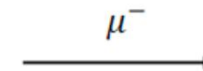
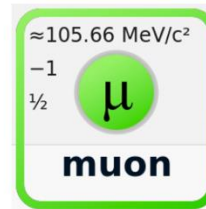
Detection Principle



Ultra-sensitive **PhotoMultiplier Tubes** (PMTs) to detect Cherenkov light from energetic charged particles.



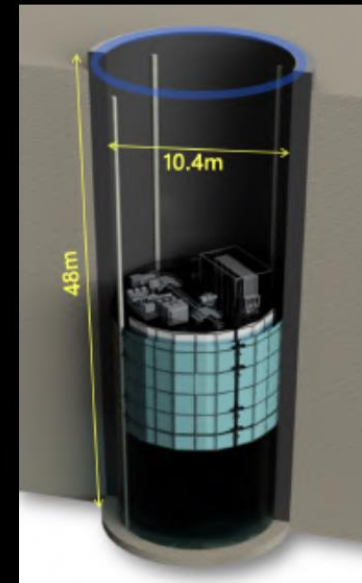
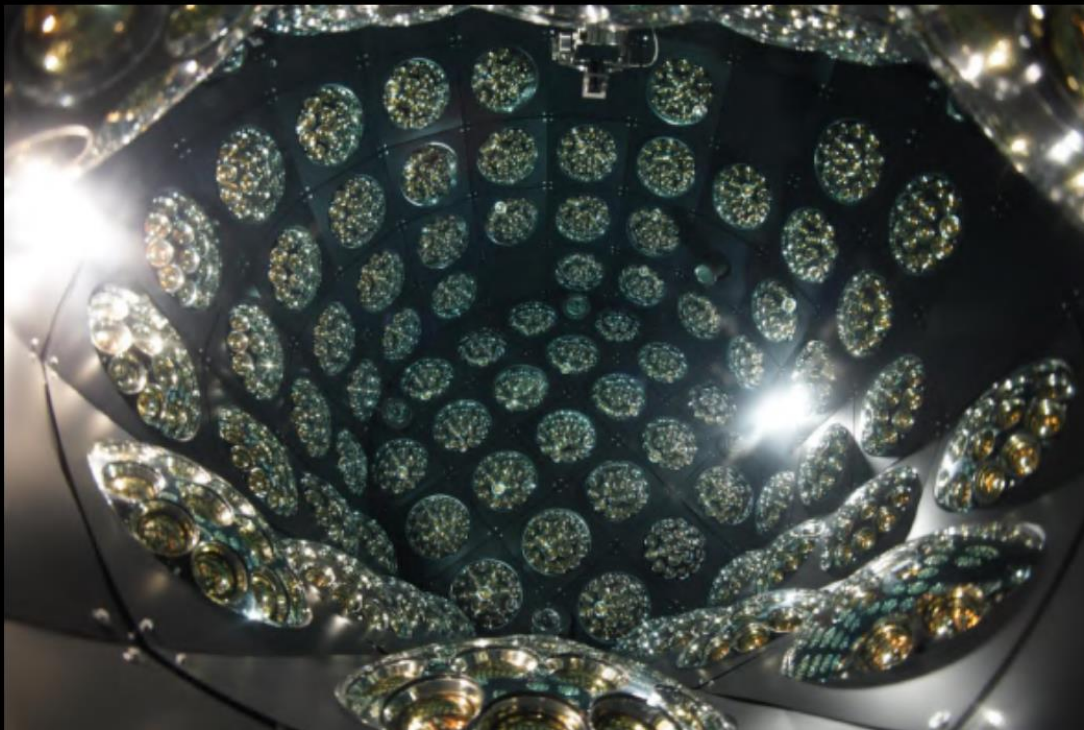
ν_e -like



ν_μ -like

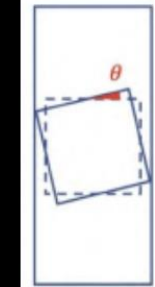
Intermediate Water Cerenkov Detector

- ▶ water Cerenkov cylinder (like FD)
- ▶ 850 m downstream
 - ▶ one more point for matching near/far fluxes
 - ▶ reduce pile-up wrt ND
- ▶ located on surface, in 50 m pit



monitor
position

$< 1 \text{ mrad}$

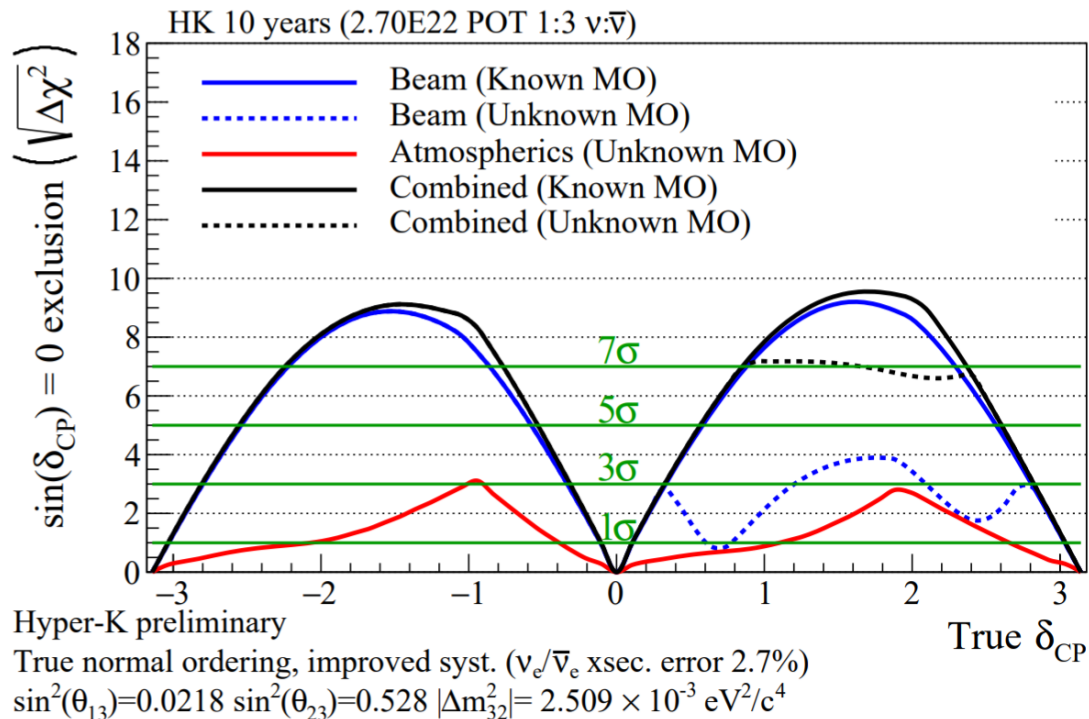


ID diameter	7 m
ID height	8 m
water mass	640 t
ID mPMTs	368
OD PMTs	368

this is a picture of the
half-sized prototype...

more on this later!

Atmospheric + Long Baseline Oscillations

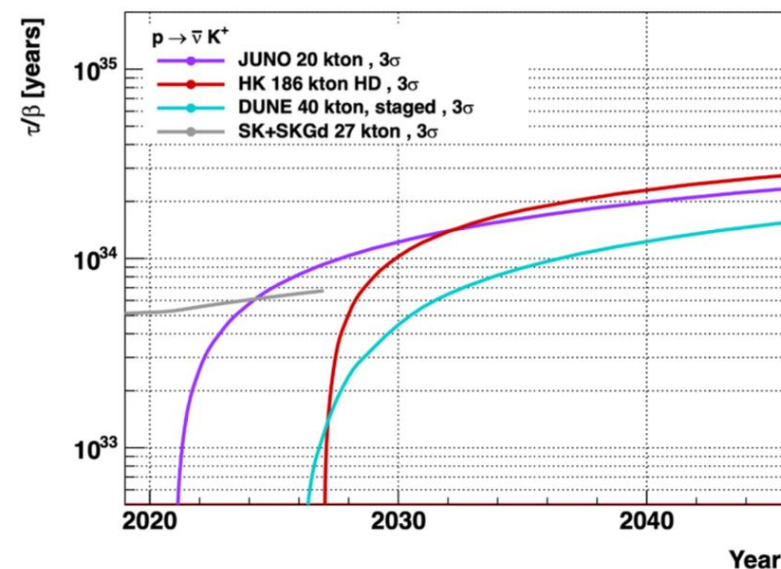
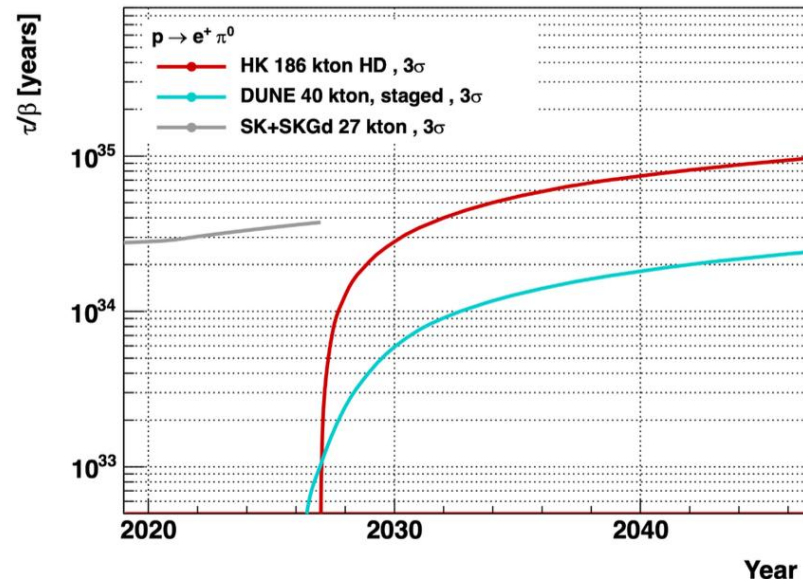


- Long baseline only fit – if MO unknown, degraded performance in degenerate regions.
- Atmospheric neutrino samples – sensitive to MO $\rightarrow$ matter effects.
- MO known $\rightarrow$ increased δ_{CP} sensitivity.
- Large improvement in δ_{CP} measurement, if MO is not known, with joint atmospheric + beam fit.

Nucleon Decay

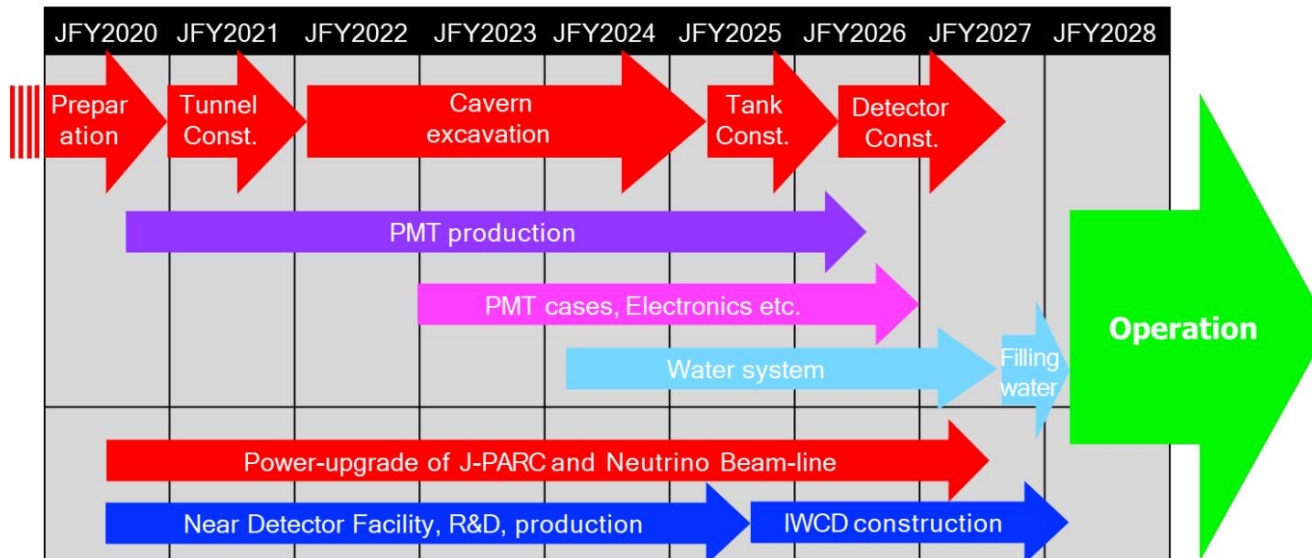


- Nucleon decay predicted in many grand unifying theories.
- Large mass, and free proton in H_2O of Hyper-K aid analysis.
- Hyper-K will probably produce world-leading sensitivity on proton decay for two channels, $p \rightarrow e^+ \pi^0$, $p \rightarrow \bar{\nu} K^+$.





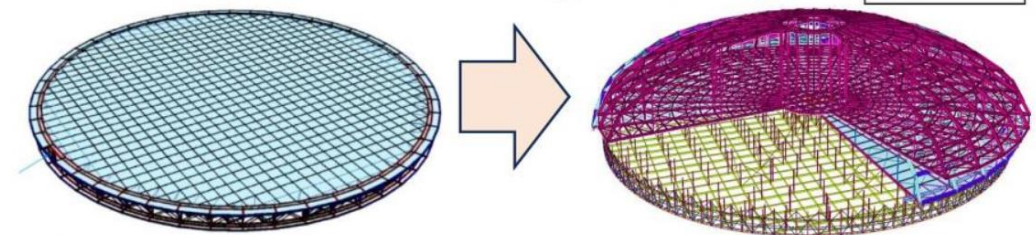
Timeline



- Data taking will begin in 2028.
- Cavern Excavation – additional support added for safety -> cavern excavation extended by 6 months.
- Tank design change – changes to the roof design -> construction period extended by 5 months.

- Original design – roof plate + PMT support structure made from stainless steel.
- New design – Dome-shape structure made from inexpensive iron. Roof plate and PMT-structure below (stainless steel) are simplified.

Tank Roof Design Change



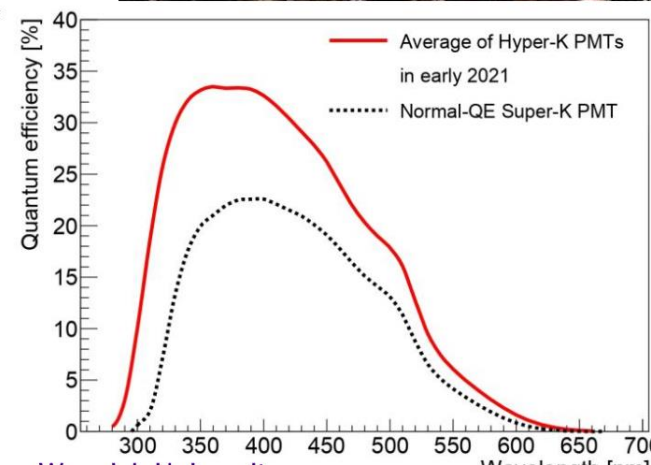
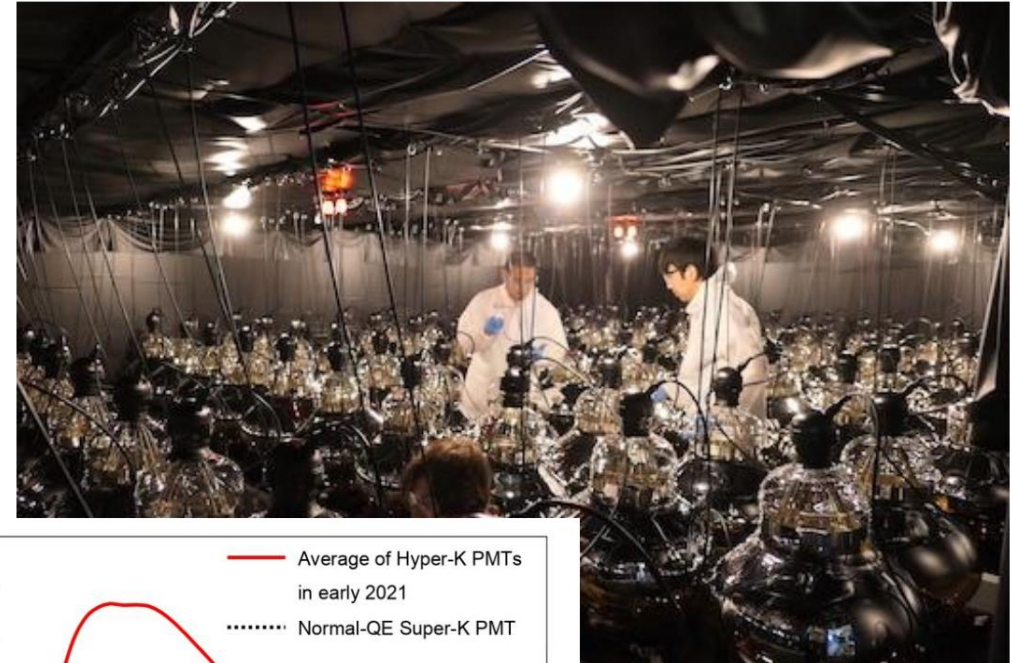
Excavation Status

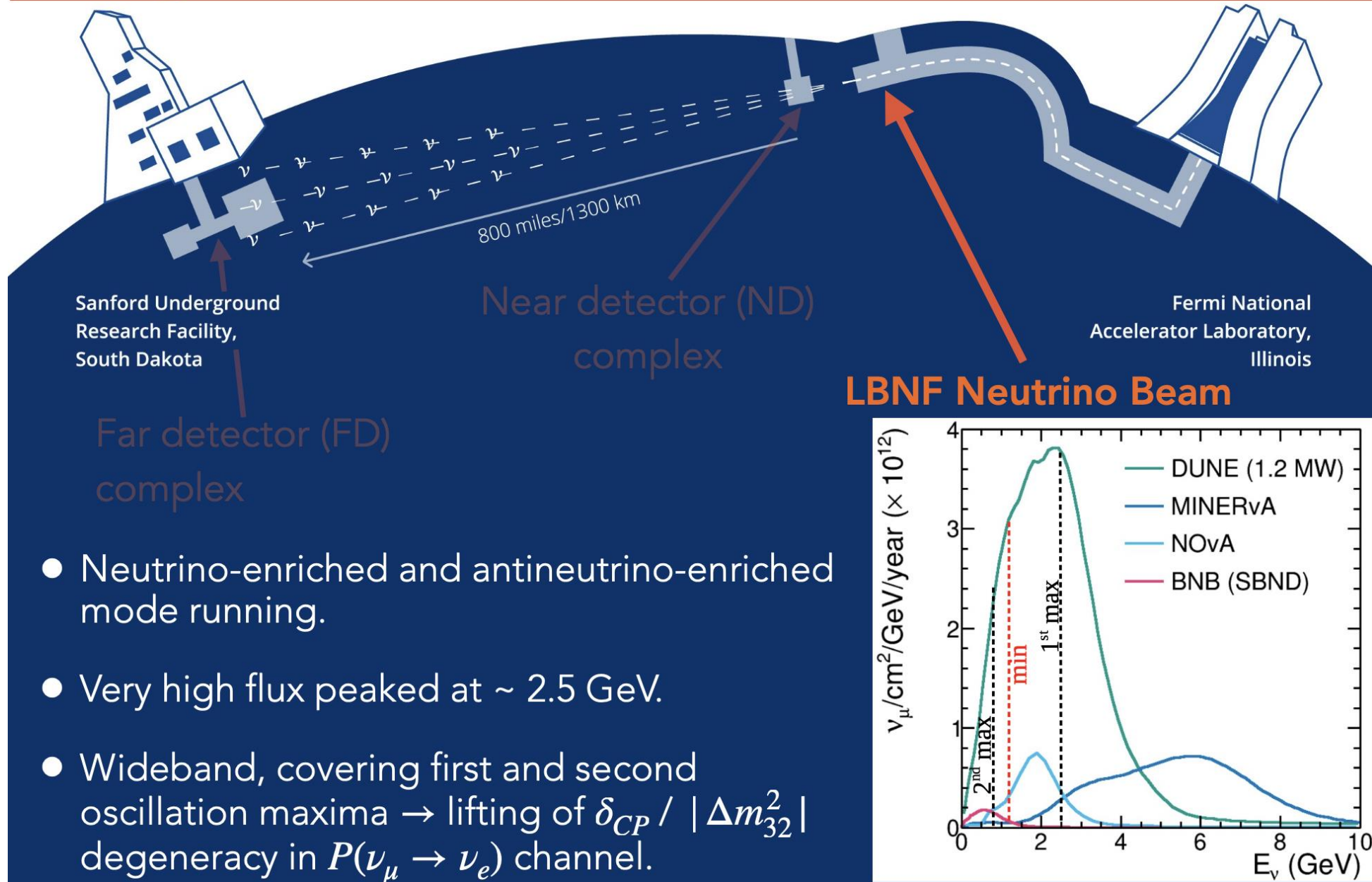
Water purification system room
02/2024

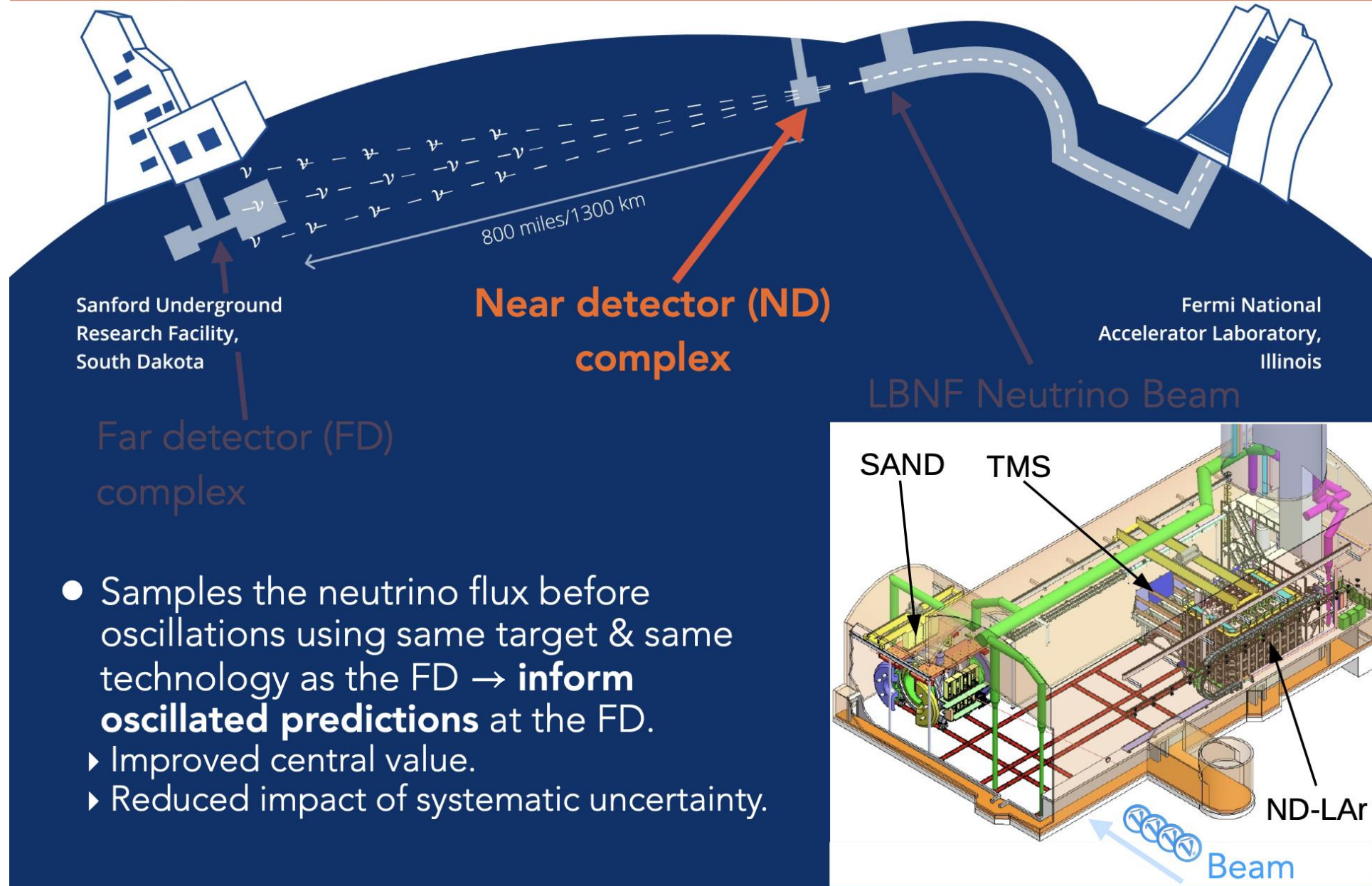


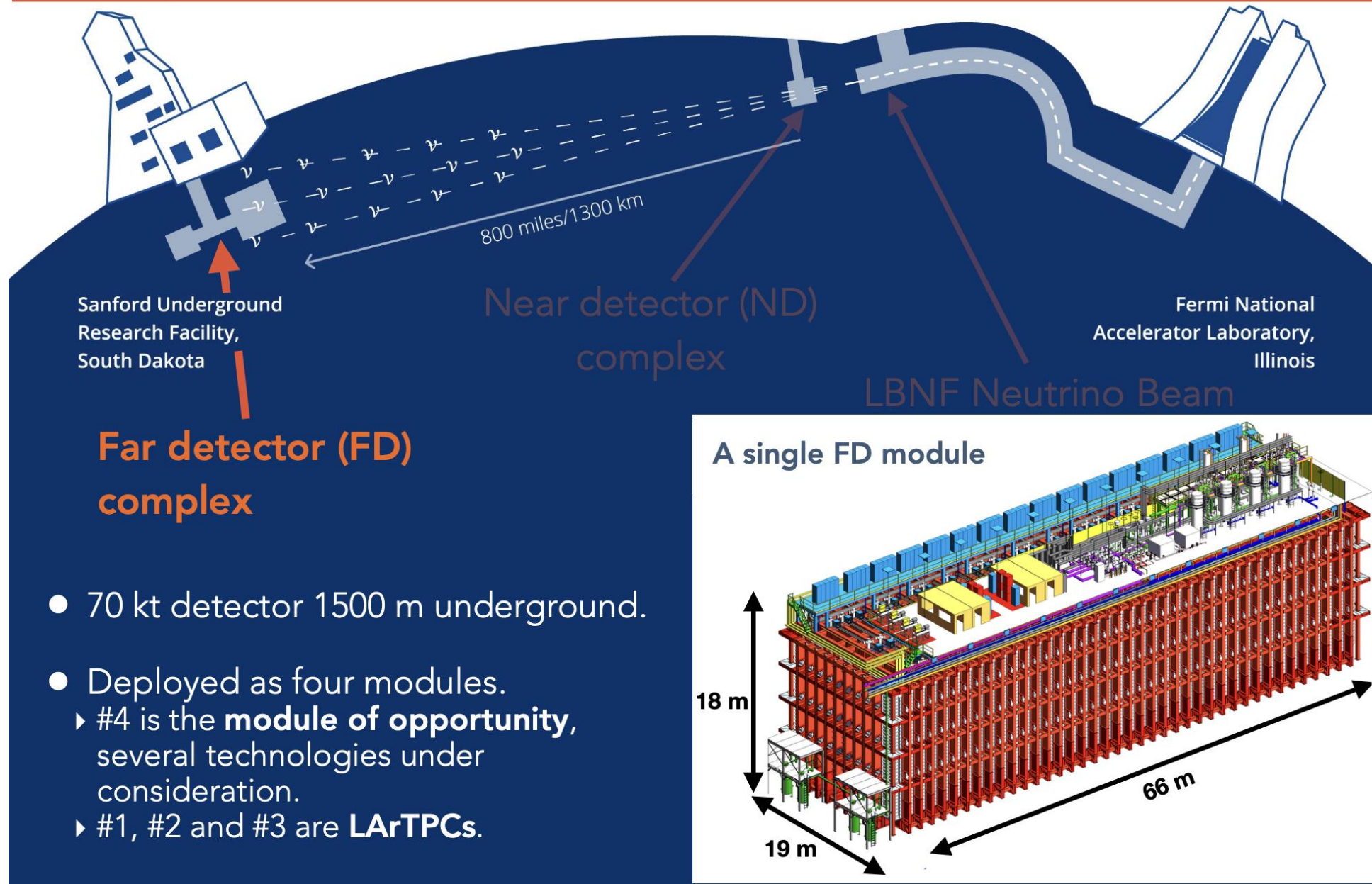
PMT Status

- Improved PMT design (Box and Line dynode) -> higher quantum efficiency (30%), timing resolution (1 ns), pressure tolerance (~ 10 bar).
- Mass production of 50 cm PMTs ongoing.
- >15,000 PMTs have been delivered. Screen testing signal and visual inspection ongoing in Kamioka and Hamamatsu.
- Dark rate stability measured on smaller batches.

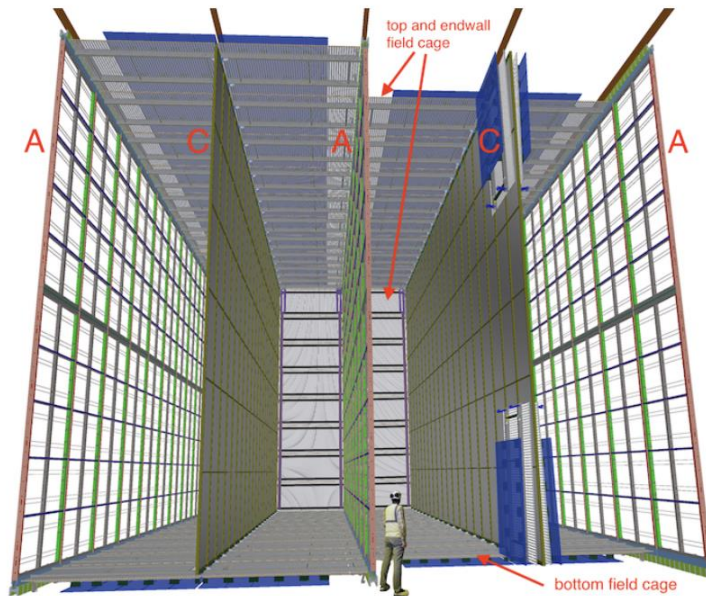




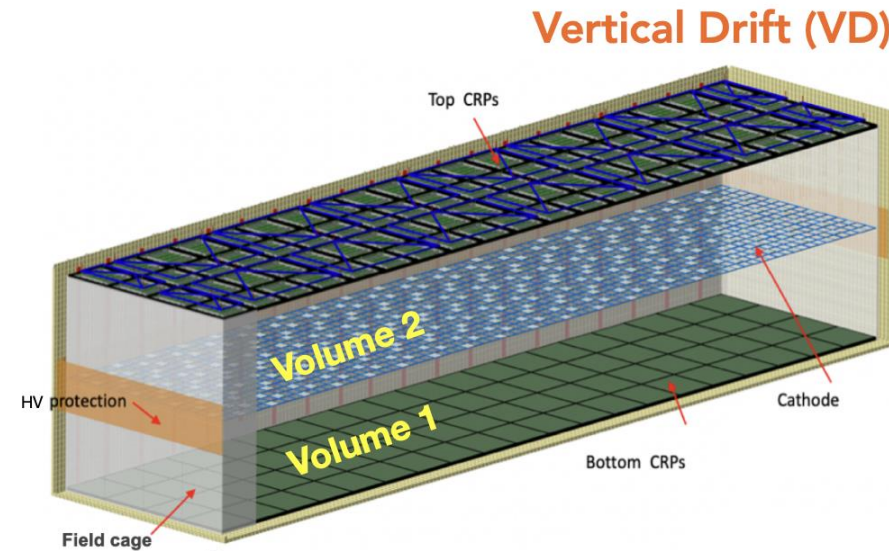




Two LArTPC Readout Technologies



Horizontal Drift (HD)



Vertical Drift (VD)

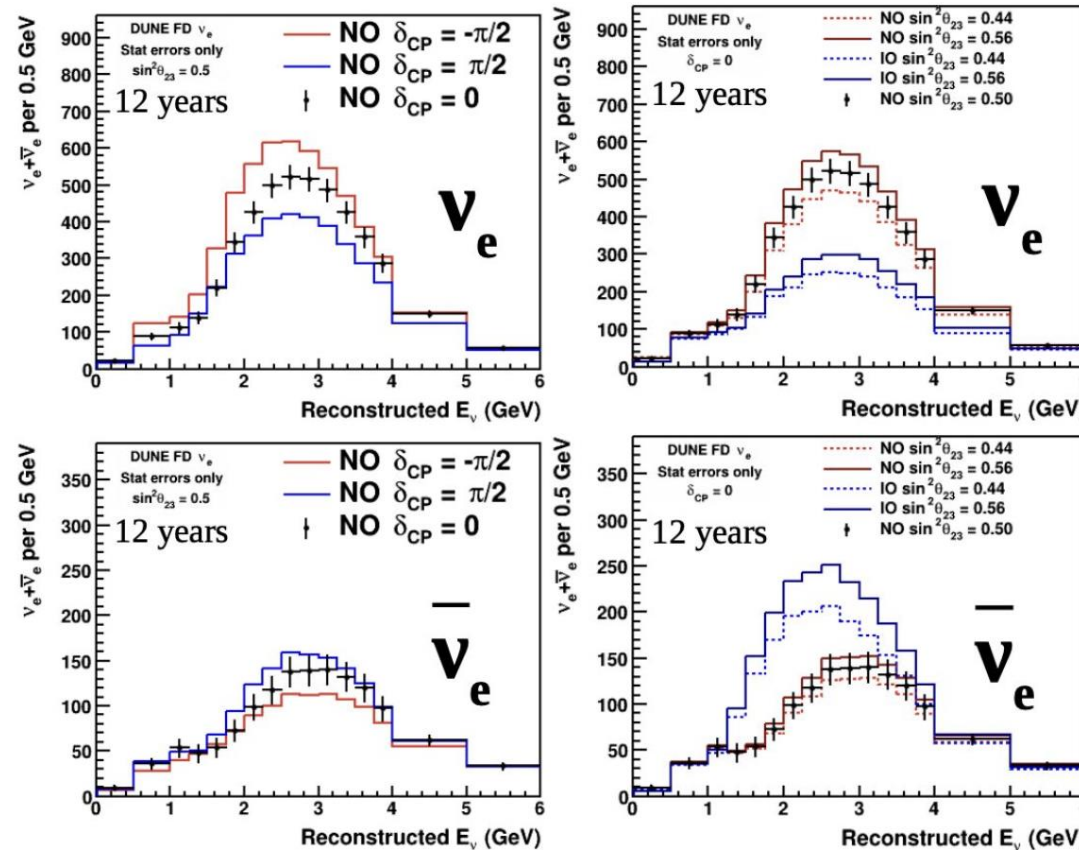
JINST 15 T08010 (2020), JINST 19 T08004 (2024)

	HD	VD
Drift Field	500 V / cm horizontally	480 V / cm vertically
Drift Regions	4, each 3.5 m long	2, each 6.5 m long
Charge Readout	Wire-based (APA)	Strip-based (CRP)
Light Readout (PDS)	X-Arapucas on anode planes	X-Arapucas on cathode plane + cryostat membrane

second

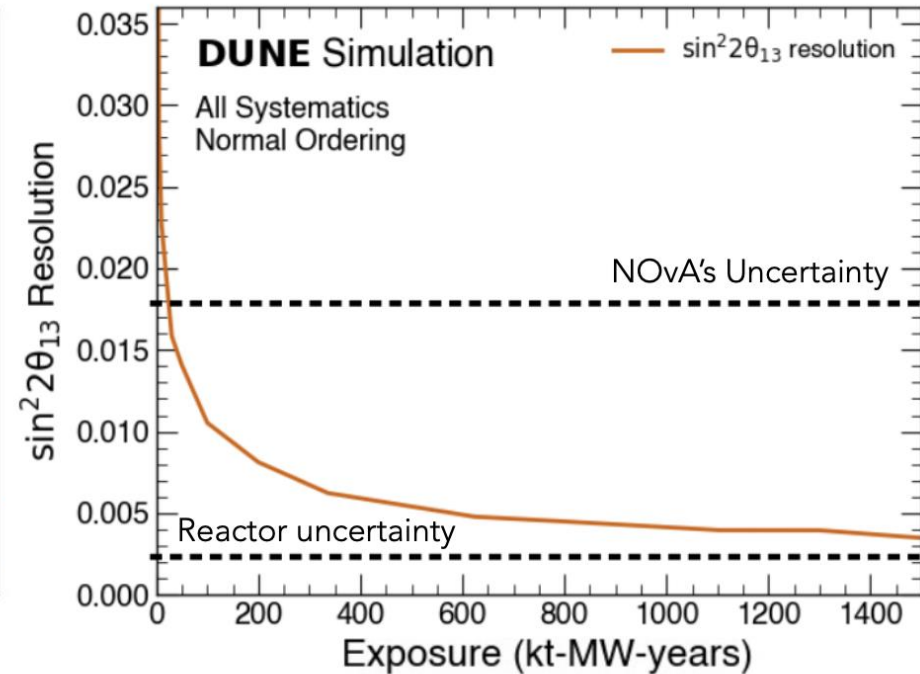
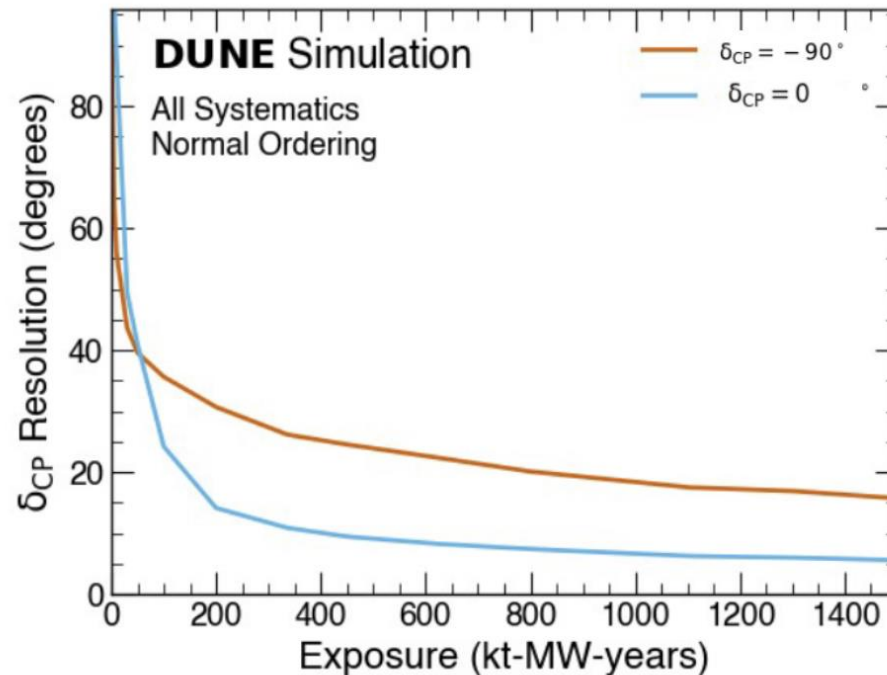
first

Oscillation Physics Reach



- DUNE probes δ_{CP} and the mass ordering (MO) by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.
- MO, δ_{CP} and θ_{23} all affect the asymmetry in the number of appearing ν_e s and $\bar{\nu}_e$ s, and spectral shapes in different ways → handle on resolving degeneracies.
- If there is new physics → may be no combination of MO, δ_{CP} and θ_{23} that fits the data!

Oscillation Physics Reach



- Ultimate precision of $6 - 16^\circ$ in δ_{CP} .
- World-leading precision among long baseline experiments on θ_{13} and Δm_{32}^2 .
 - ▶ Interesting comparison with reactor experiments → new physics!

Path to First Physics

DUNE



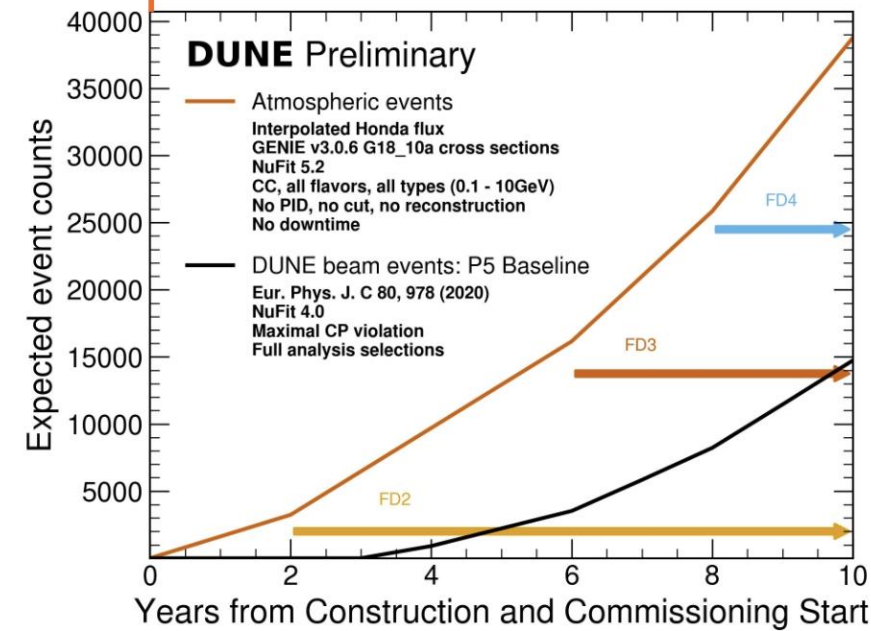
Q3, '25



You are here!



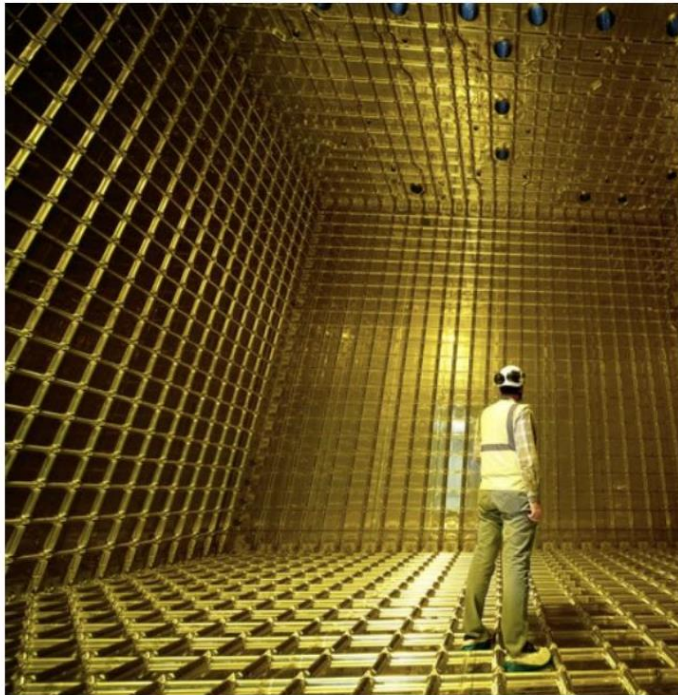
Q4, '29



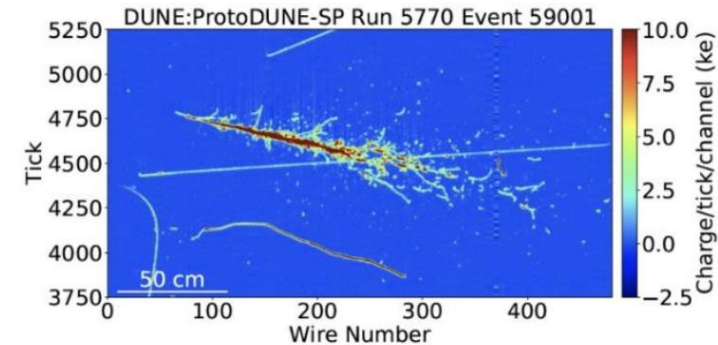
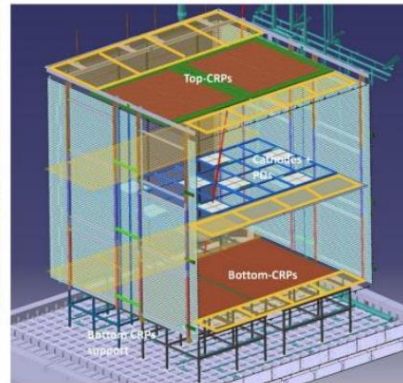
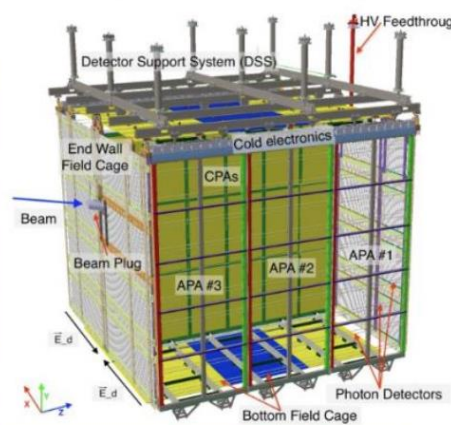
Protodunes at the Neutrino Platform

The ProtoDUNEs are 4% size prototypes for the Far Detectors (FD) of DUNE

ProtoDUNE LAr modules
($>700\text{t}$, $>200\text{m}^3$)



Horizontal and vertical drift



Xe-doping in PDSP
with dedicated sensors



ARIADNE : TPC
optical readout
(tested in the cold-box)



- Past: horizontal drift prototype results in 2018. Vertical drift is a new concept
- Now: tests with final (?) configurations of HD and VD for FD1 and FD2
- Future: new technologies on the NP for future decisions on FD3 and FD4

Jiangmen Underground Neutrino Observatory

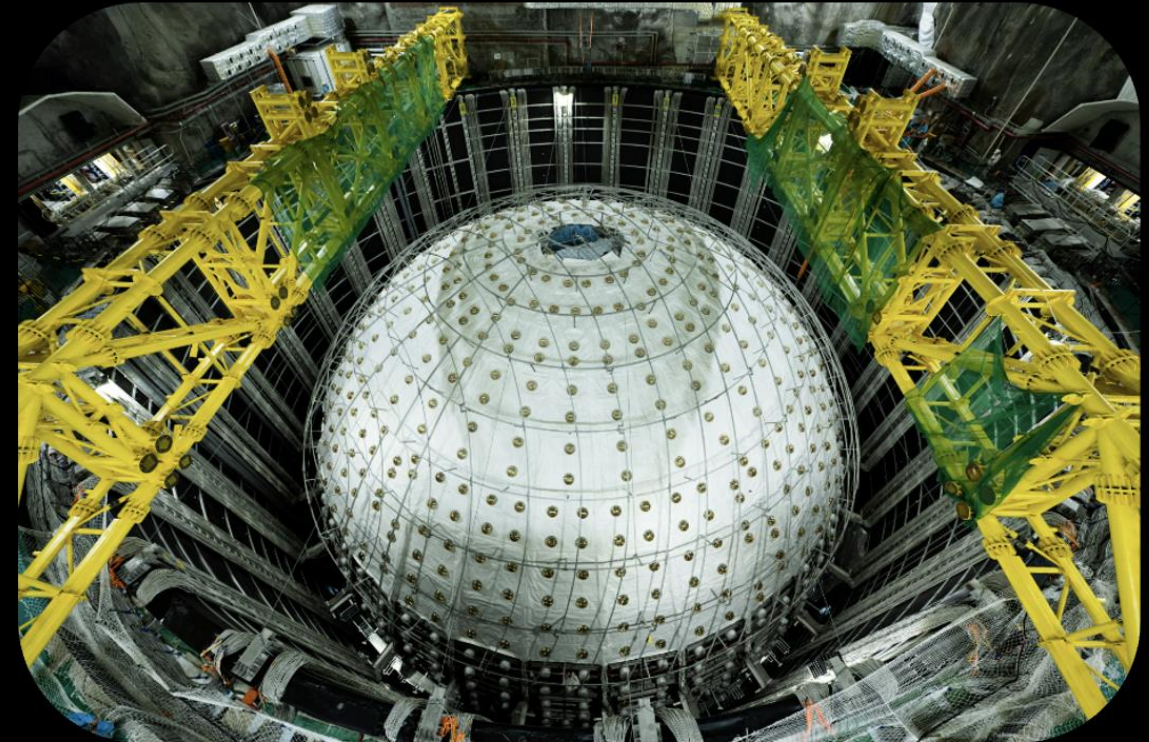
20 kiloton liquid scintillator detector



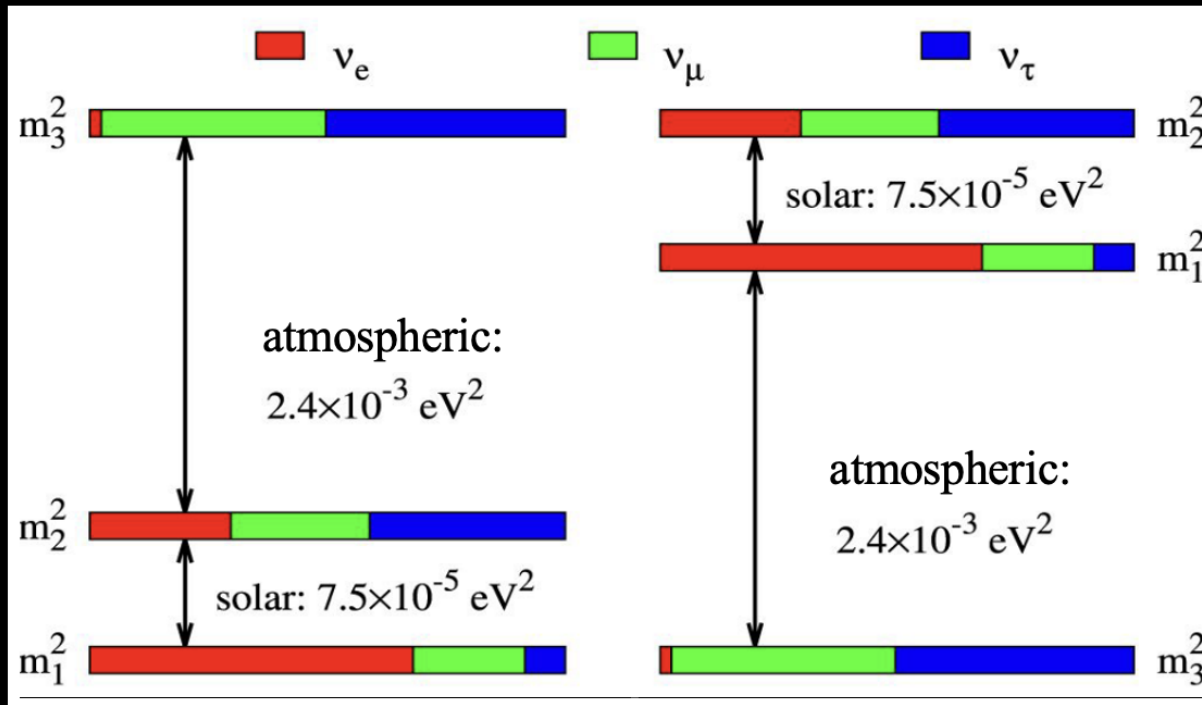
Sloped
Railway

Vertical
shaft

1.3km tunnel
~40° incline



JUNO Physics Goals



1) Determine Neutrino Mass Ordering (NMO)

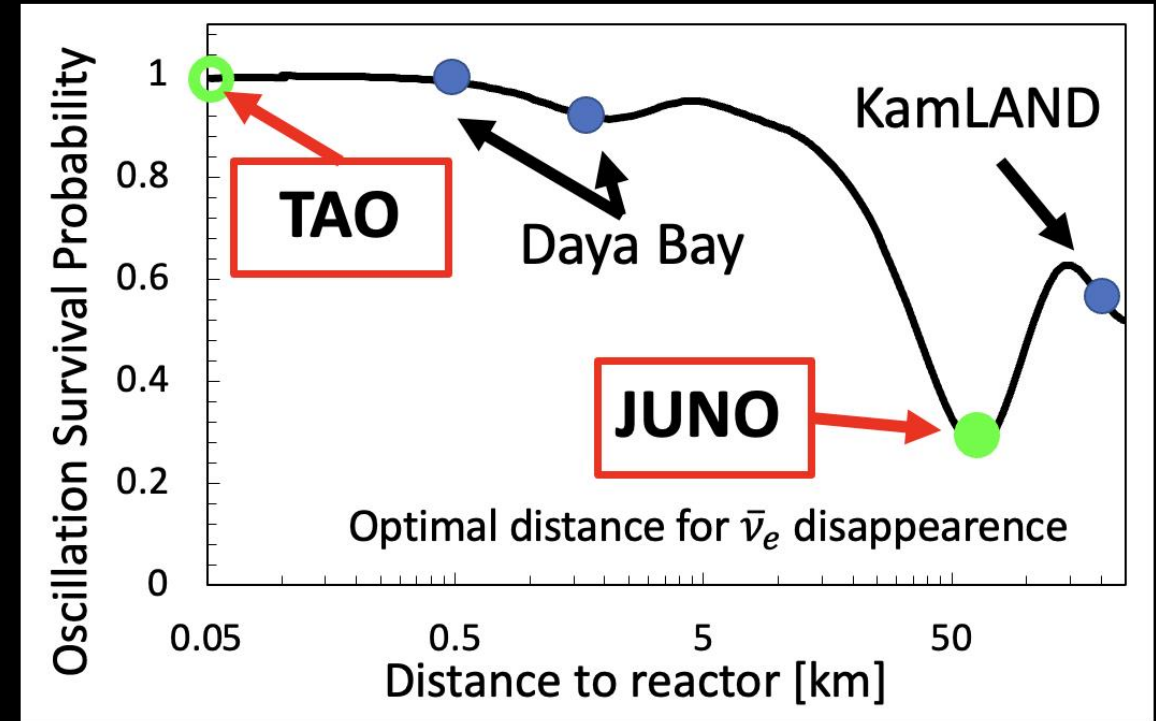
2) Precisely determine oscillation parameters Δm_{31}^2 , Δm_{21}^2 and $\sin^2\theta_{12}$

JUNO : Reactor Neutrinos

JUNO's nearest nuclear reactors



Reactor - detector baselines



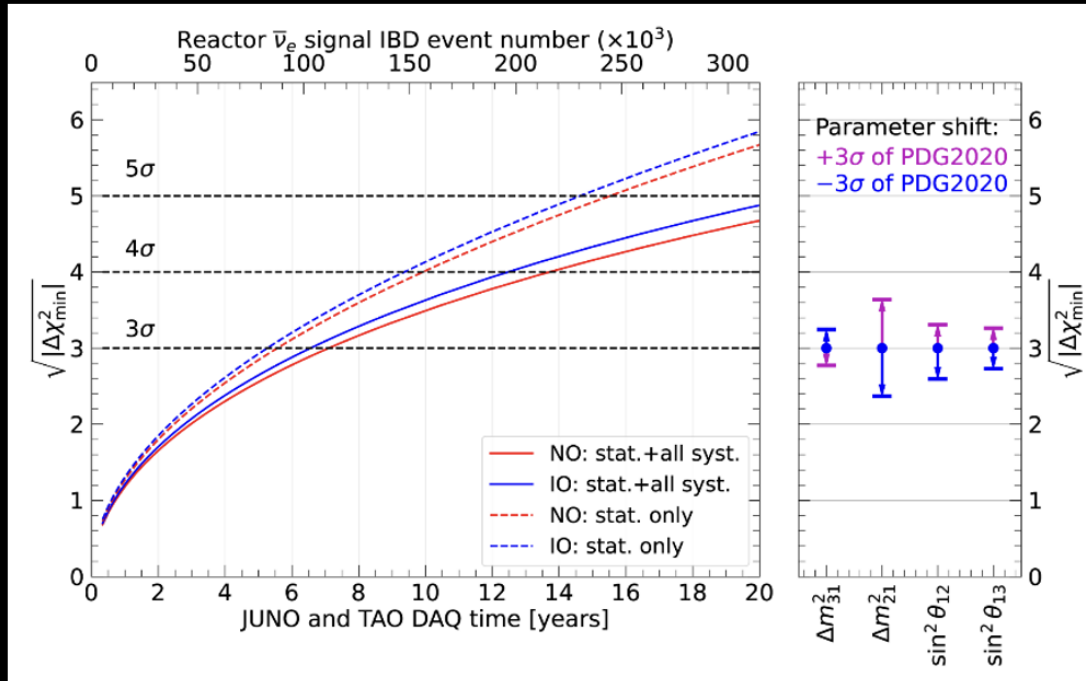
($\bar{\nu}_e$ survival averaged over reactor energy spectrum)



["Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO," arXiv:2405.18008 \(2024\)](https://arxiv.org/abs/2405.18008)

NMO with reactor neutrinos

Expected NMO sensitivity vs livetime



Expected NMO sensitivity vs livetime

Parameter	PDG 2024	JUNO 100 days	JUNO 6 years
Δm^2_{31}	1.2%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2 \theta_{12}$	4.0%	1.9%	0.5%
$\sin^2 \theta_{13}$	3.2%	47.9	12.1%

- 3 σ expected in 6.5 yrs using reactor neutrinos alone
- World-leading measurements of Δm^2_{21} , Δm^2_{31} and θ_{12} in ~ 100 days

JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking



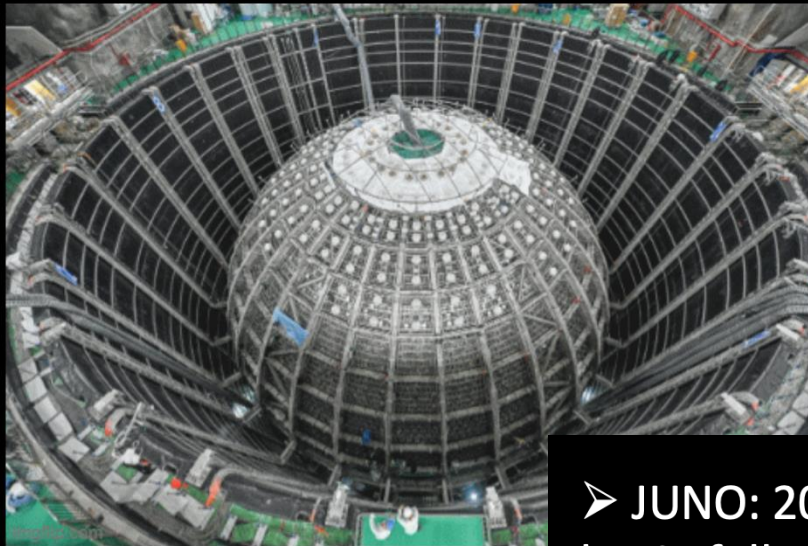
JUNO Timeline

2013 → Project begins

Jan 2015 → Ground breaking

2022 → Detector installation

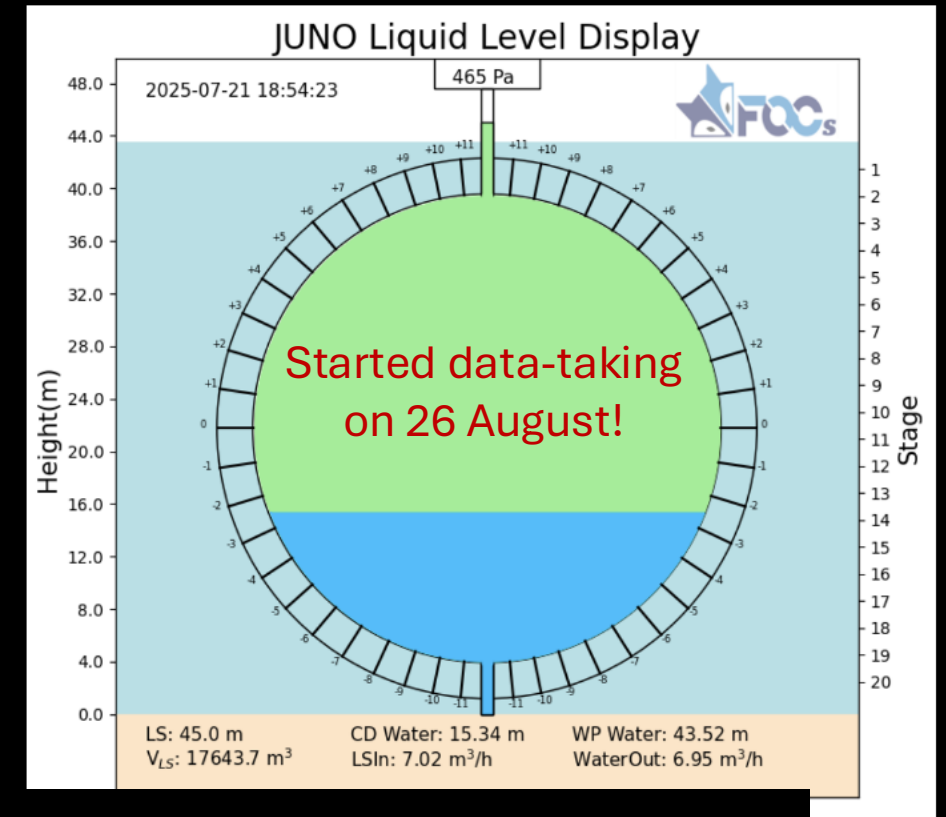
2024 → Installation complete



Dec 18 2024 → Water fill starts

Feb 1 2025 → Water filling complete

Feb 8 2025 → LS filling / Water exchange
(ongoing)



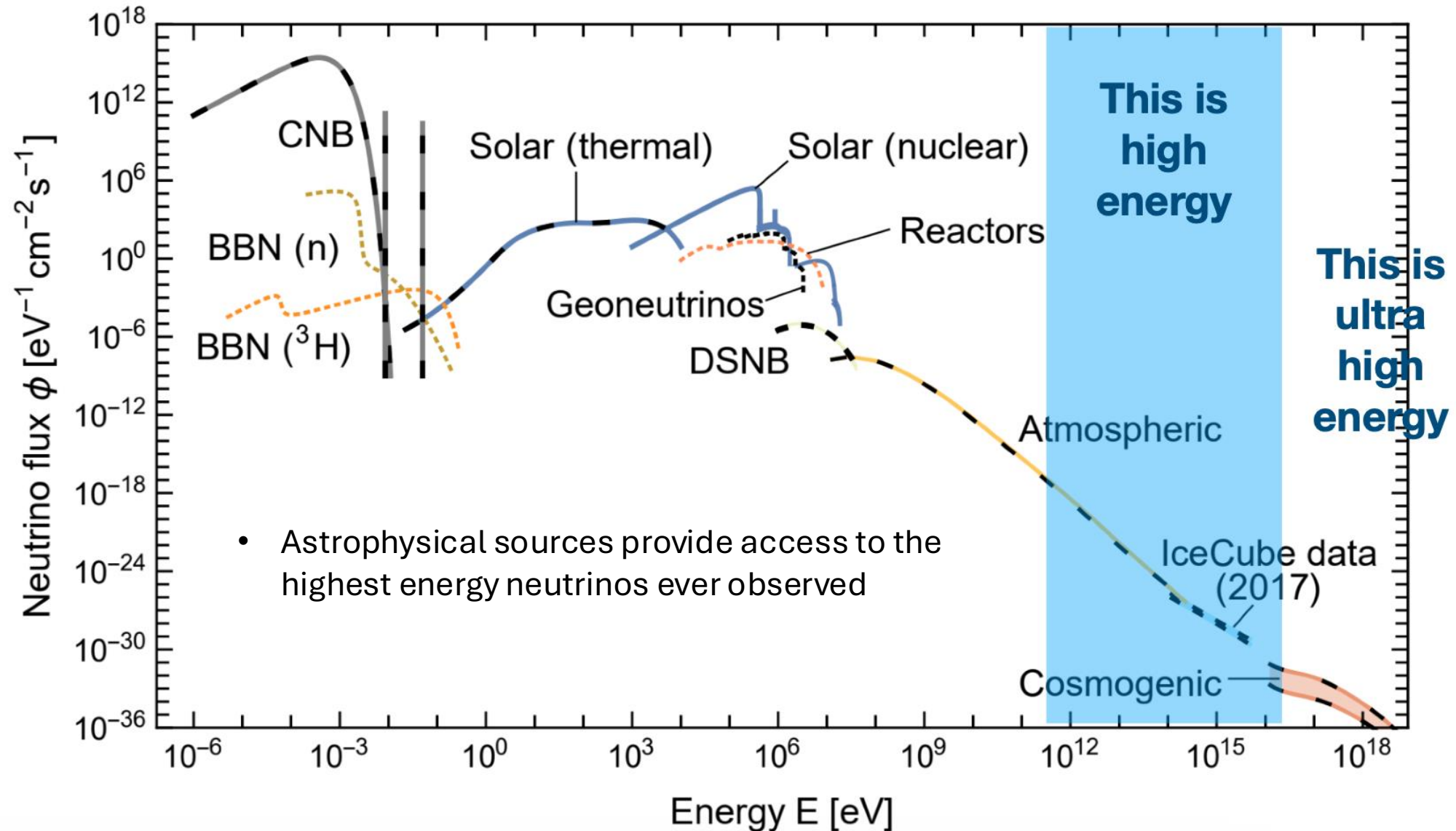
➤ JUNO: 20 kT liquid scintillator detector, expects to begin fully-filled data taking Aug 2025

astrophysical neutrinos

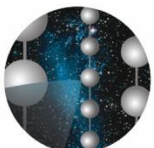
- KM3NeT-ARCA/ORCA, IceCube, GVD-Baikal
- Future projects: P-ONE, TRIDENT

the higher in energy, the less flux....

Rev. Mod. Phys. 92, 45006 (2020)



Running detectors



IceCube

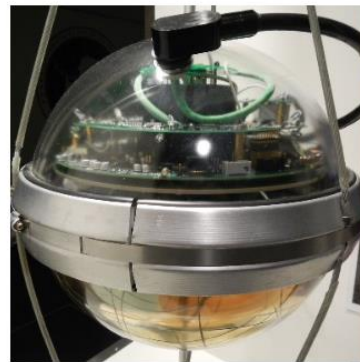


KM3NeT



Baikal

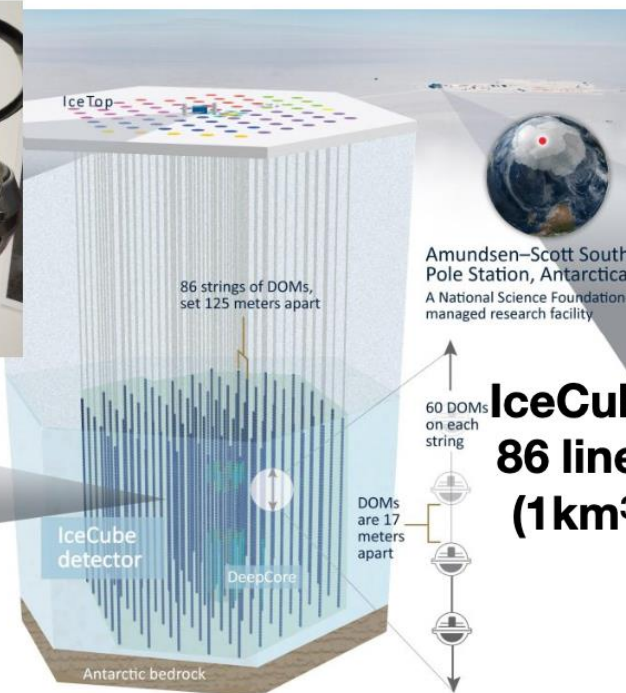
● Similar detector layout



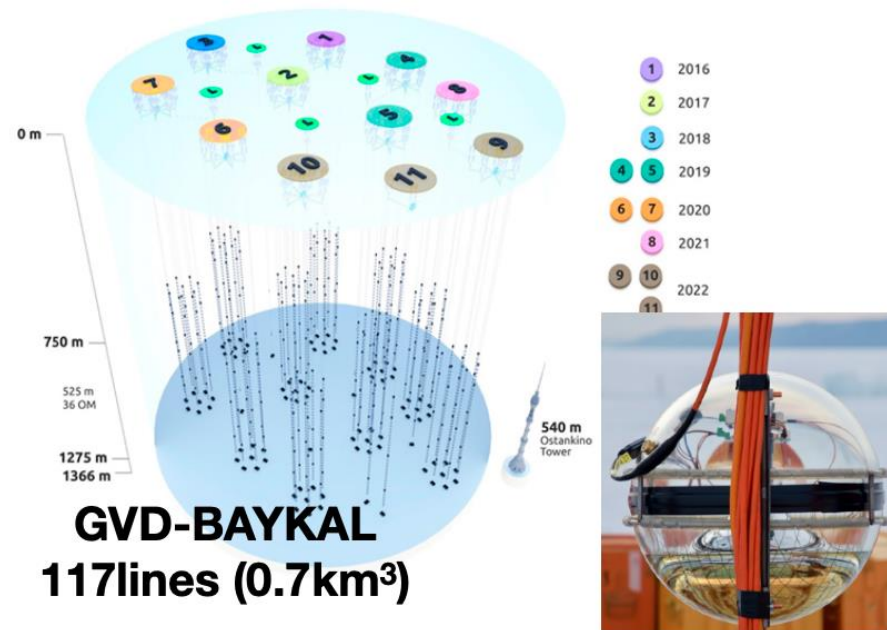
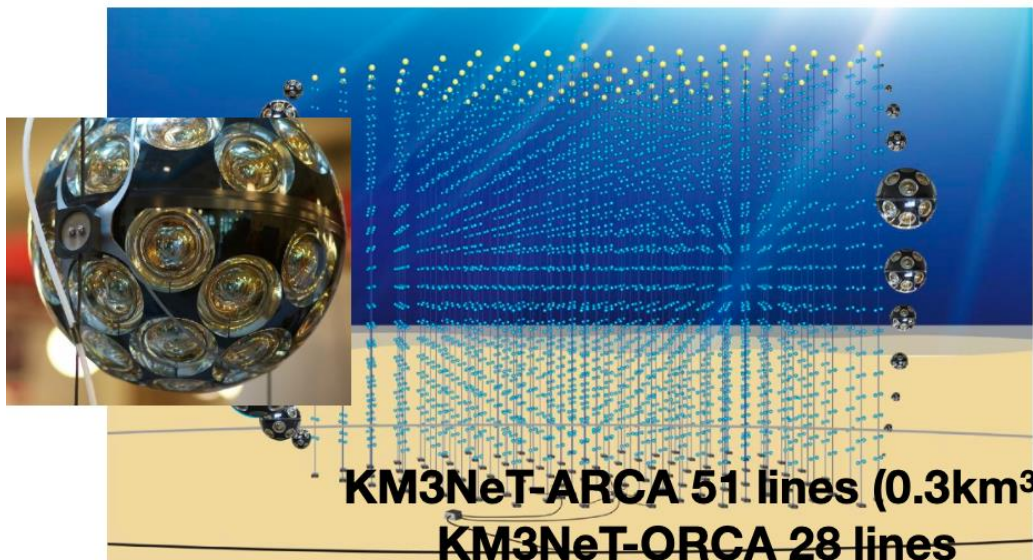
Digital Optical Module (DOM)
5,160 DOMs
deployed in the ice

1450 m

2450 m

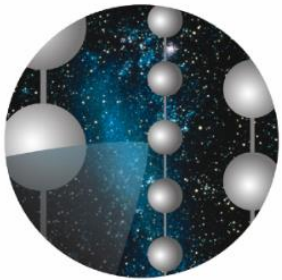


IceCube
86 lines
(1km³)

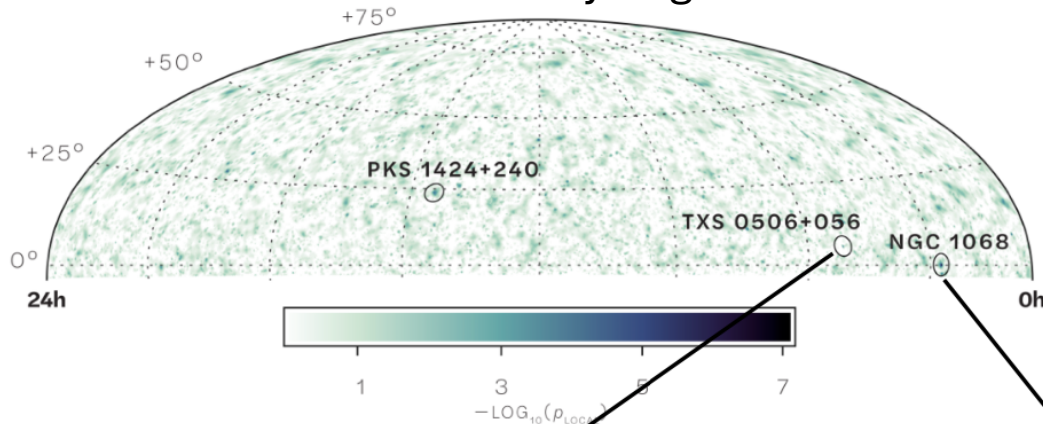


IceCube: Extragalactic ν

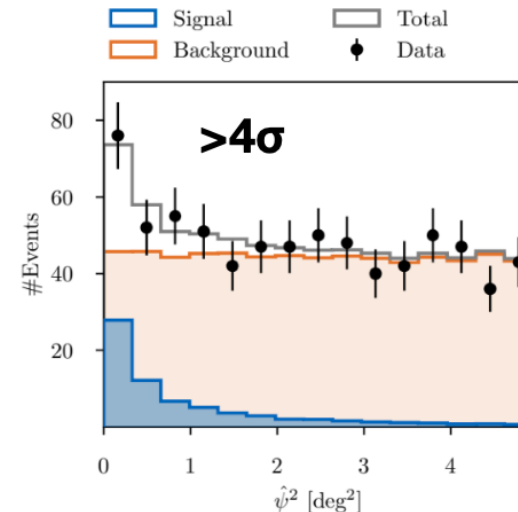
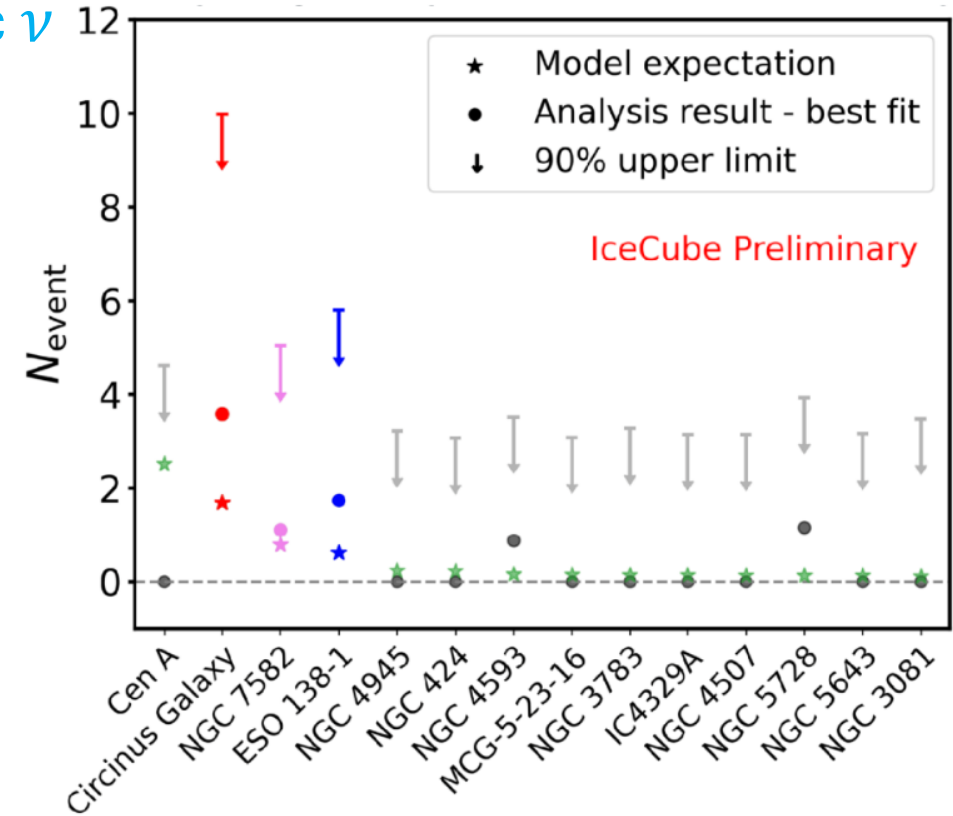
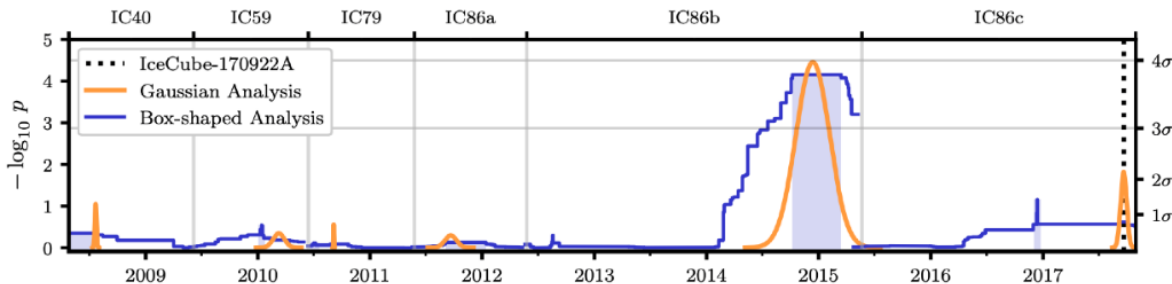
- IceCube have identified 2 point sources, neither of which is bright in high energy gammas
- Targets that efficiently attenuate high energy gammas, such as obscured Active Galactic Nuclei (AGNs) which are bright in X-rays are good target candidates
- Multiple analyses show a $\sim 3\sigma$ for these X-ray bright AGNs



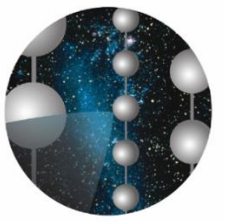
IceCube



Science 361 (2018)

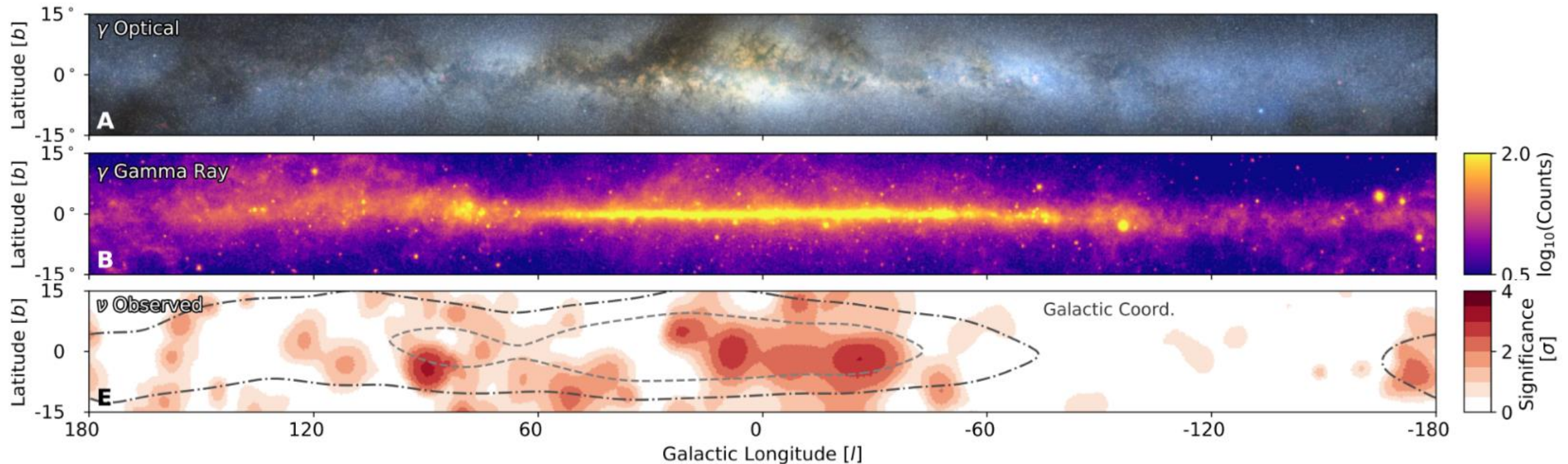


- Seyfert galaxies in the Southern Hemisphere used in the analyses



Science 380 (2023)

Galactic neutrinos



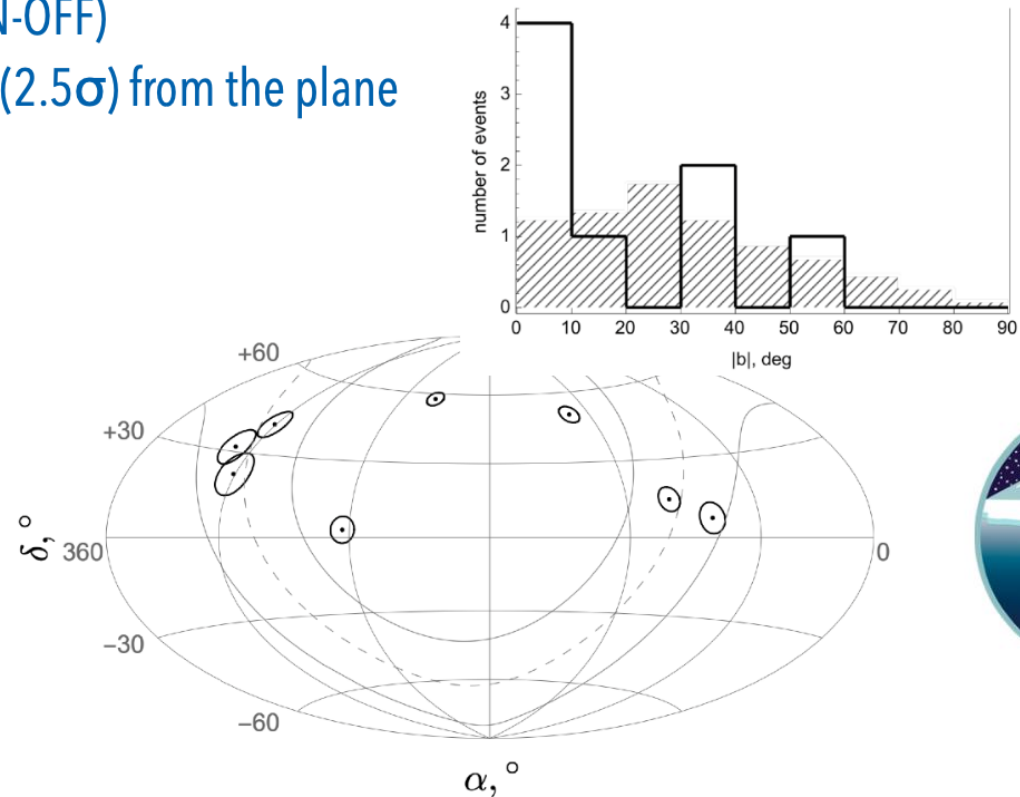
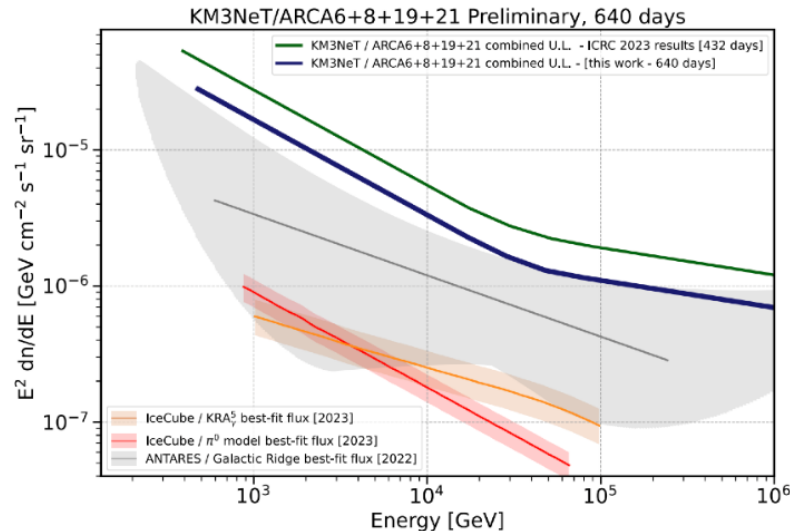
- Search for neutrino emission from within the Milky Way, along the Galaxy plane
- Comparing diffuse emission models to a background-only hypothesis identified neutrino emission at the $\sim 4.5 \sigma$ significance (see [here](#))
- Now combining cascade and track events for increased sensitivity

Other active experiments: Search for Galactic ν And the others in the North?

- ANTARES also observed a 2.2σ excess (ON-OFF technique)
 - They don't see a significant preference using templates

Model	$\hat{r}$	$\hat{TS}$	p-value ($n\sigma$)	UL	Sensitivity
DiffUSE	0.7 [8.9]	0.2	0.22 (1.23)	2.2 [28.4]	1.3 [17.3]
CRINGE	0.7 [8.1]	0.3	0.21 (1.26)	2.2 [24.8]	1.3 [15.1]
$KRA_{\gamma}^{\max}$	0.4 [6.2]	0.6	0.11 (1.59)	1.2 [20.7]	0.6 [9.6]
$KRA_{\gamma}^{\min}$	0.4 [6.4]	0.5	0.15 (1.46)	1.4 [22.5]	0.7 [11.9]
$KRA_{\gamma}^{5\text{PeV}}$	0.5 [6.4]	0.7	0.10 (1.65)	1.5 [19.5]	0.7 [9.4]
π^0	3.0 [10.3]	0.2	0.20 (1.28)	9.5 [33.2]	5.7 [19.7]

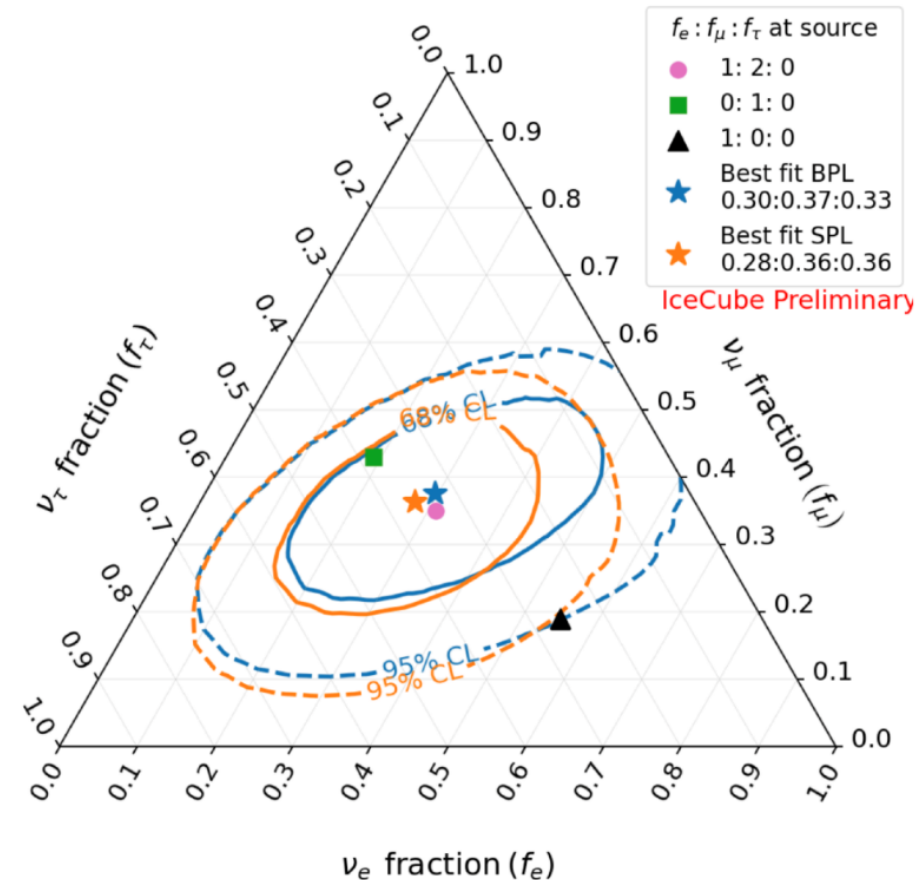
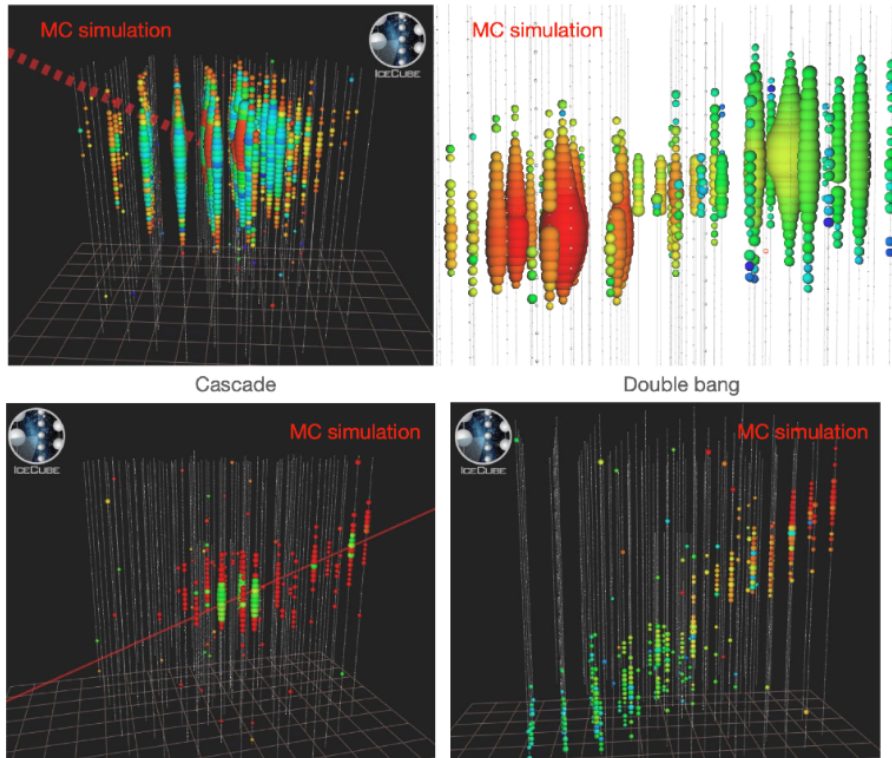
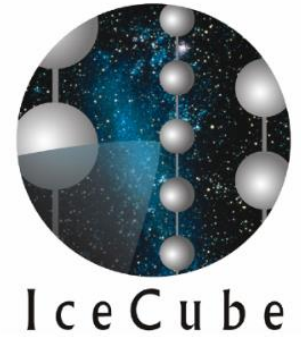
- KM3NeT/ARCA still not sensitive (also ON-OFF)
- Baykal preliminary analysis show excess (2.5σ) from the plane



IceCube: ν flavor composition

What about the flavor composition?

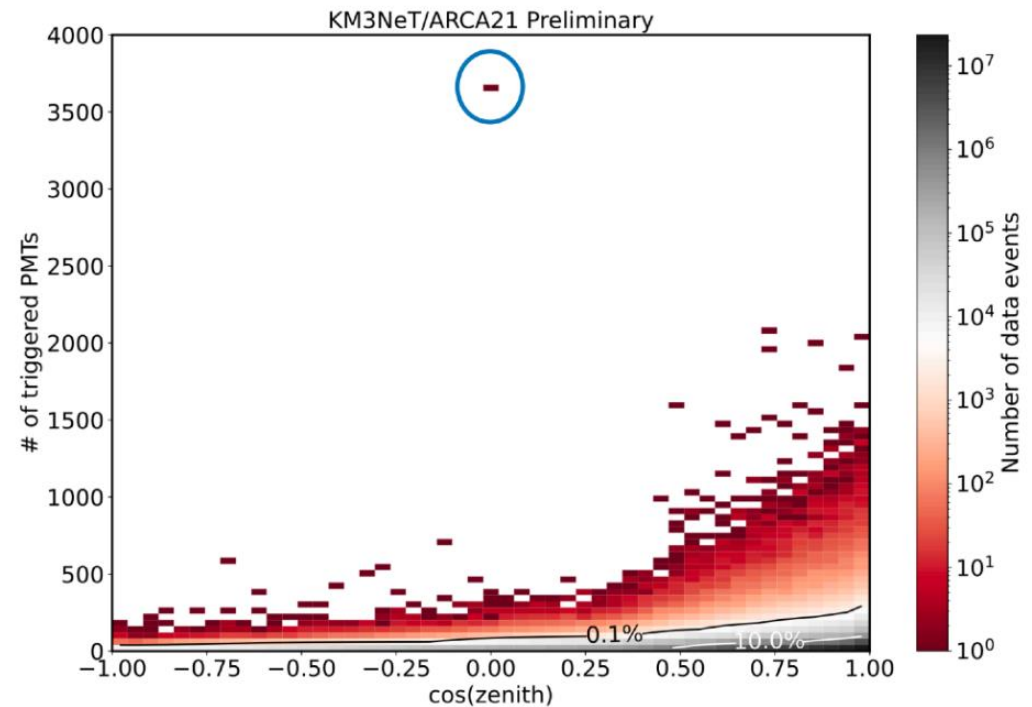
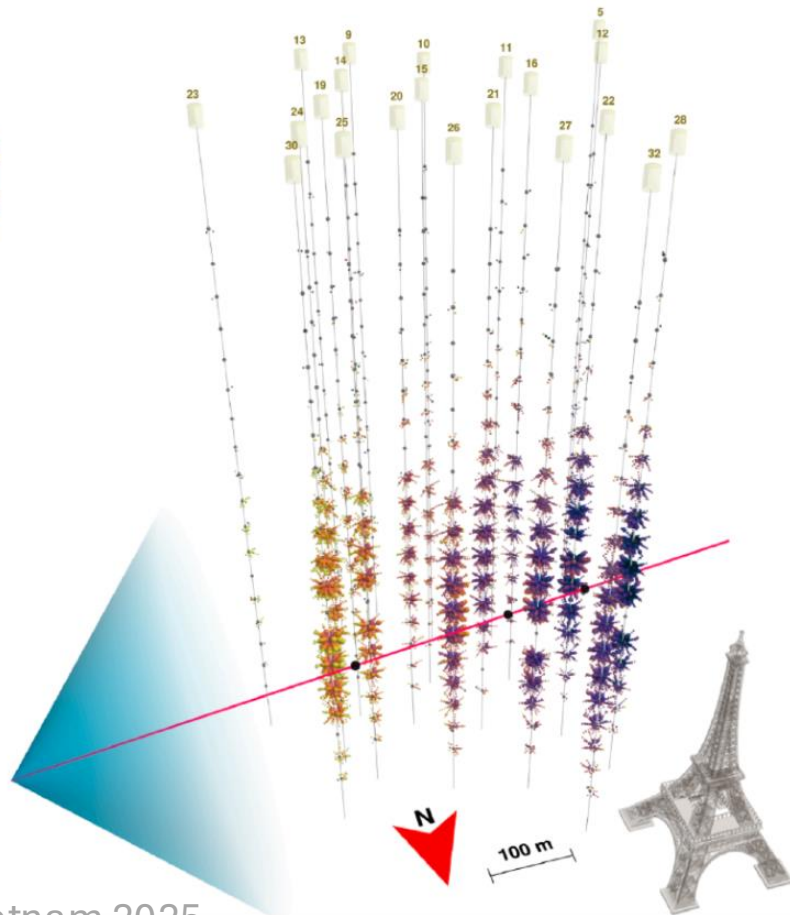
- Right now only IceCube is able to do this (access to tau-neutrino candidates).
- Latests analysis using MESE sample start disfavoring neutron production



The unexpected

KM3NeT-ARCA: New discoveries

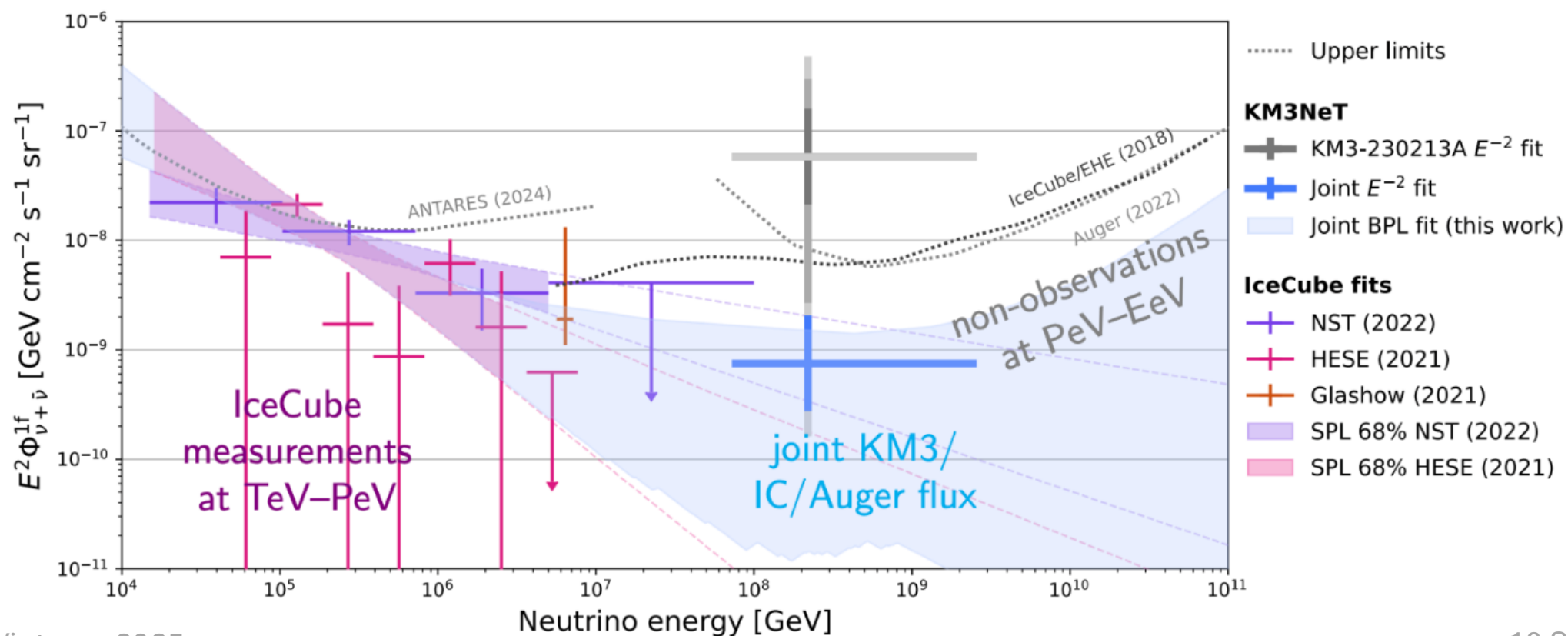
- KM3NeT observed an very bright muon crossing the detector horizontally
 - Coming from a neutrino the median energy is 220PeV -> new energy regime!
- The KM3NeT Collaboration. Observation of an ultra-high-energy cosmic neutrino with KM3NeT. *Nature* **638**, 376–382 (2025).
<https://doi.org/10.1038/s41586-024-08543-1>



The unexpected

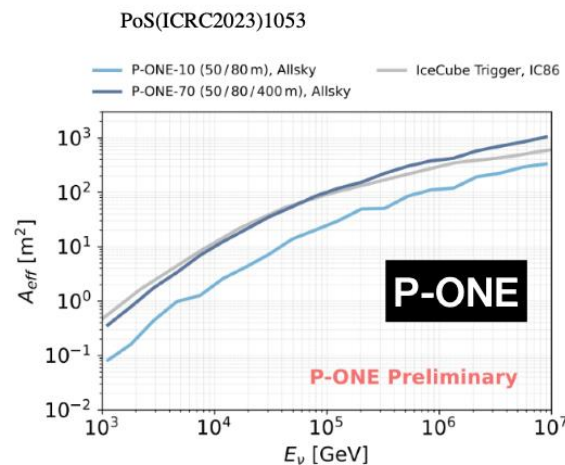
KM3NeT-ARCA: Bigger picture

- No sources identified (still large angular error).
- No observation of similar events by IC or Baykal.
 - Current tension at the level of 3σ

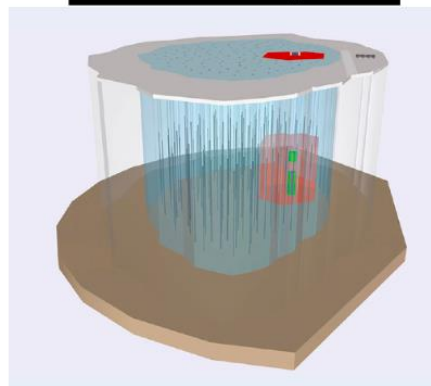


Future for Cerenkov detectors

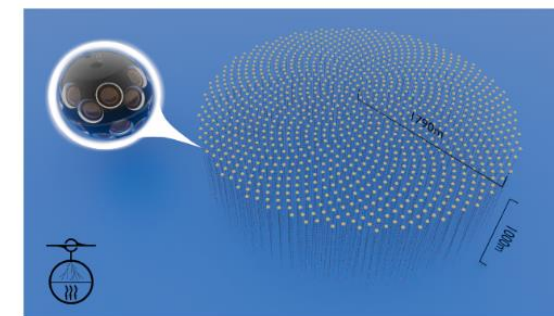
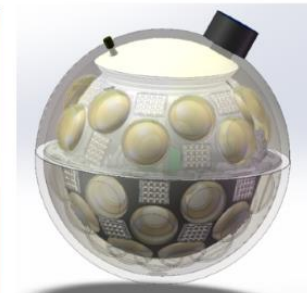
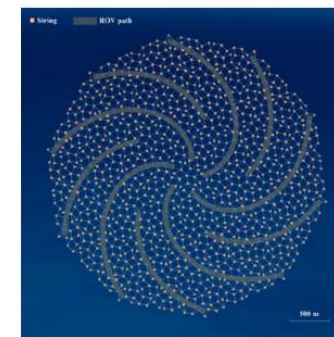
- GVD-Baykal and ARCA will be completed before the end of the decade



IC Gen2 - Optical



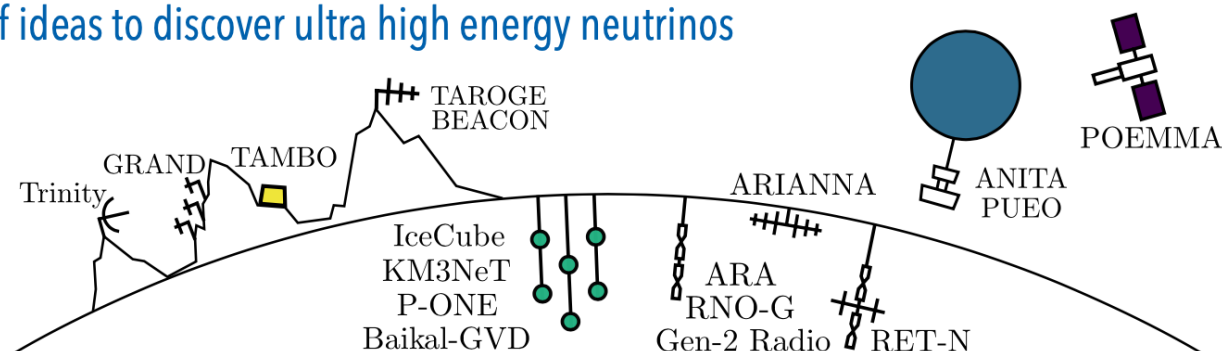
TRIDENT

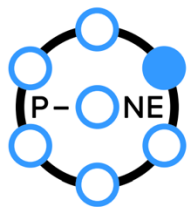


NEON

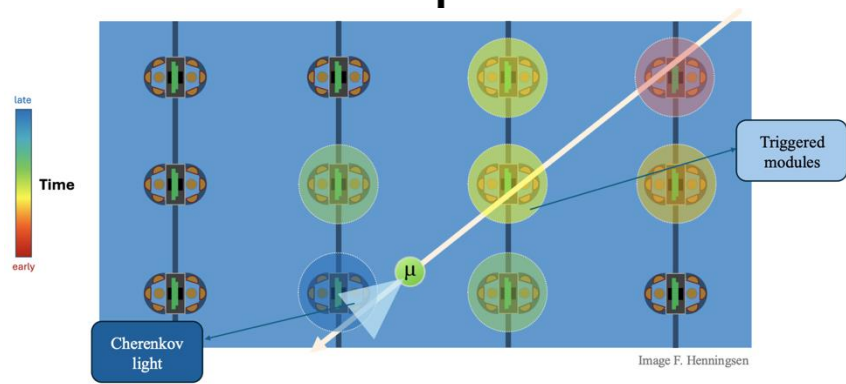
Going to even higher energies

- A plethora of ideas to discover ultra high energy neutrinos





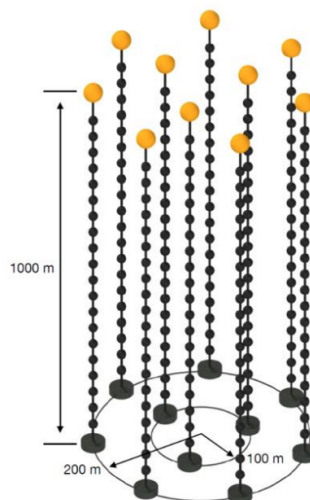
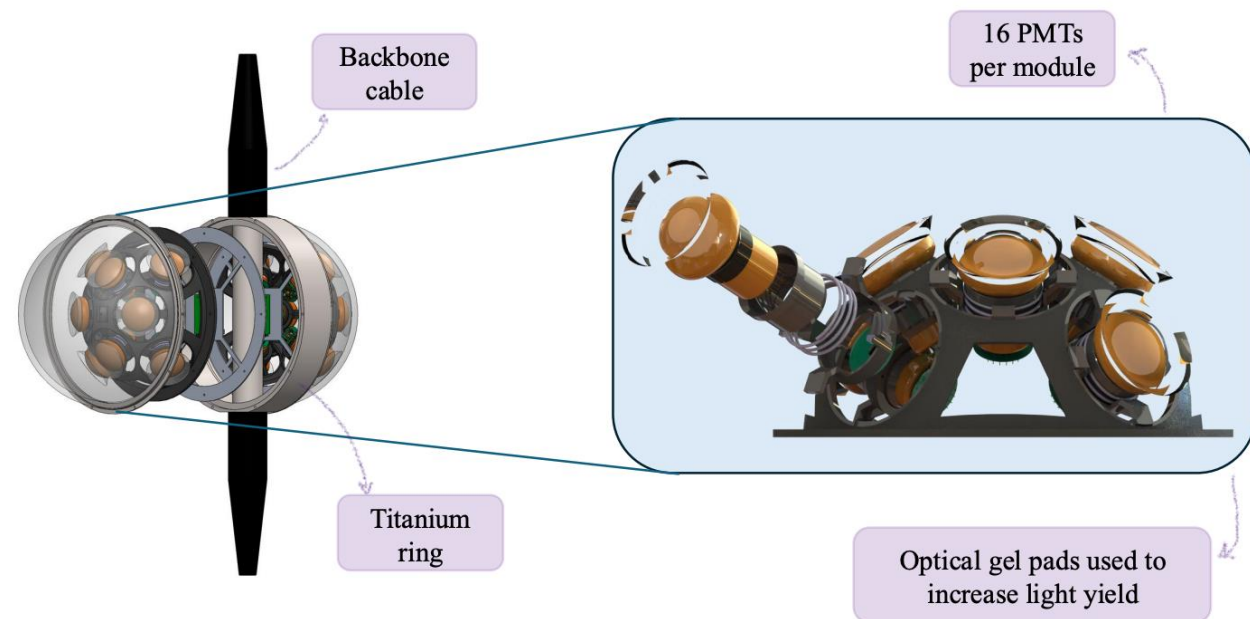
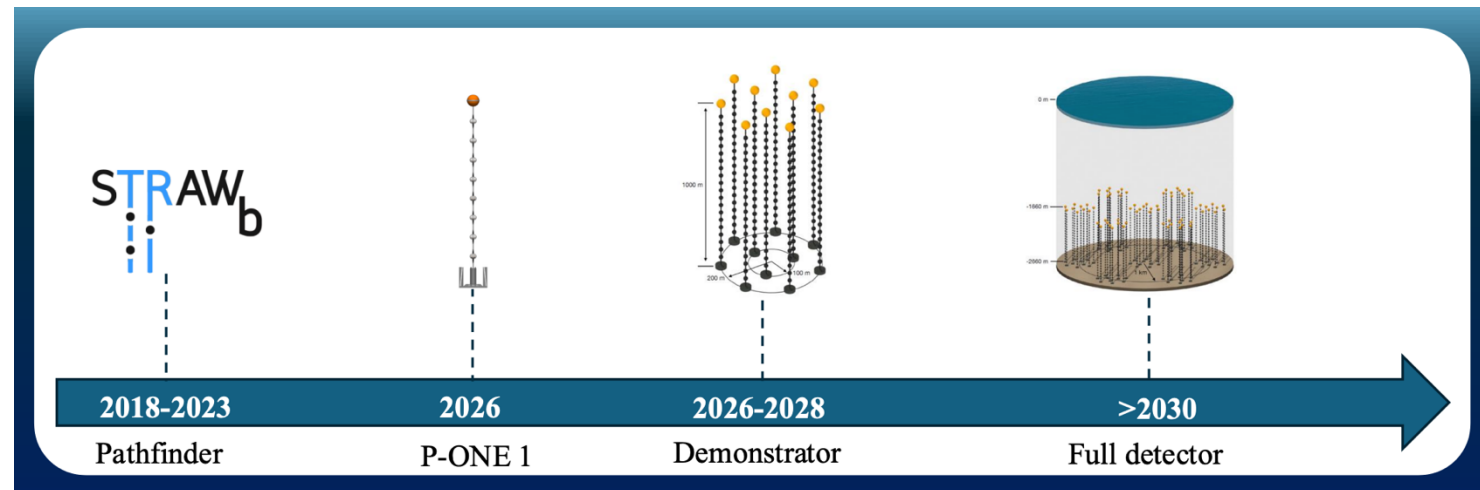
The Pacific Ocean Neutrino Experiment: Progress and Prospects

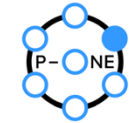


- 1 km long mooring line with 20 modules
- Connector-less design
- Optical and calibration modules
- Acoustic & optical calibration systems
- Sub-ns time synchronization between modules (0.1nsec)
- DAQ: Digitize waveform @ 210MHz

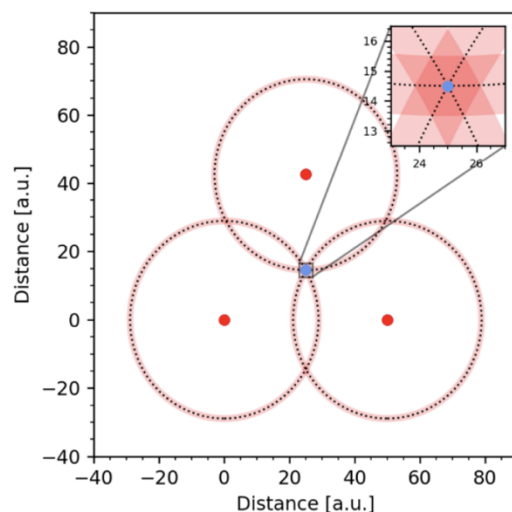
18 optical modules

2 calibration modules

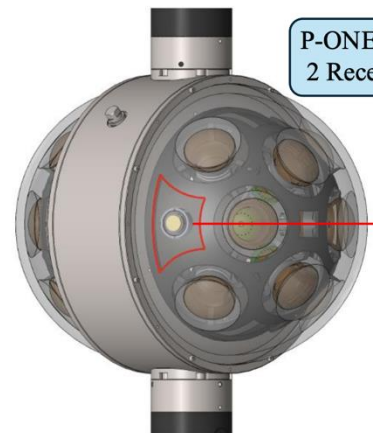
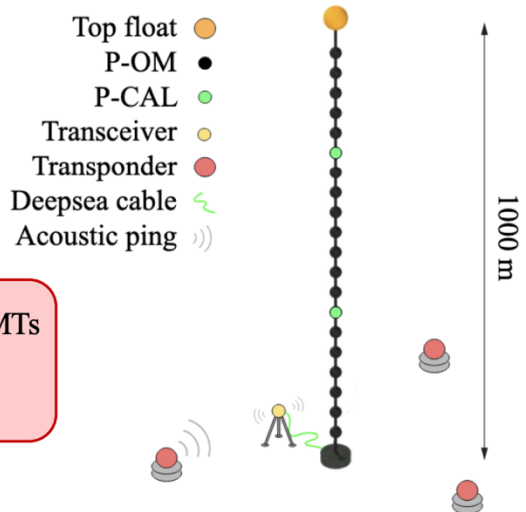




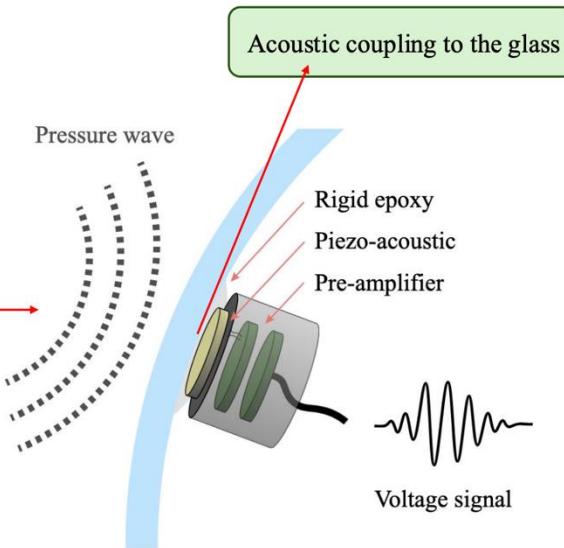
The Pacific Ocean Neutrino Experiment: Progress and Prospects



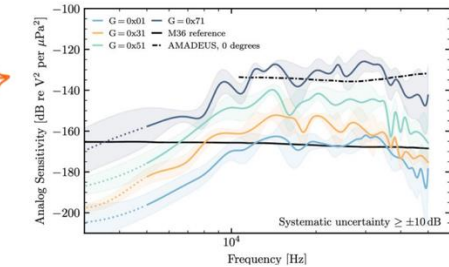
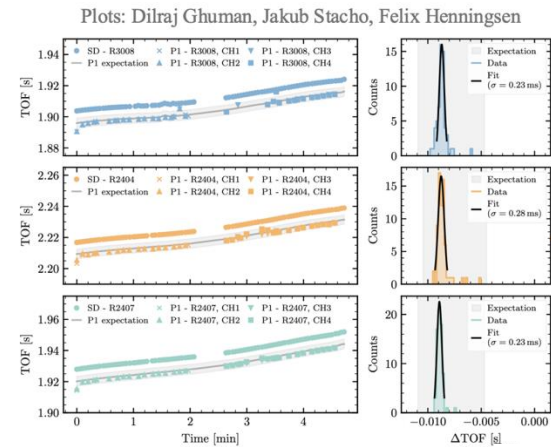
~1 ns resolution of P-ONE PMTs requires a relative positioning resolution ≥ 20 cm



P-ONE optical module:
2 Receivers per Module



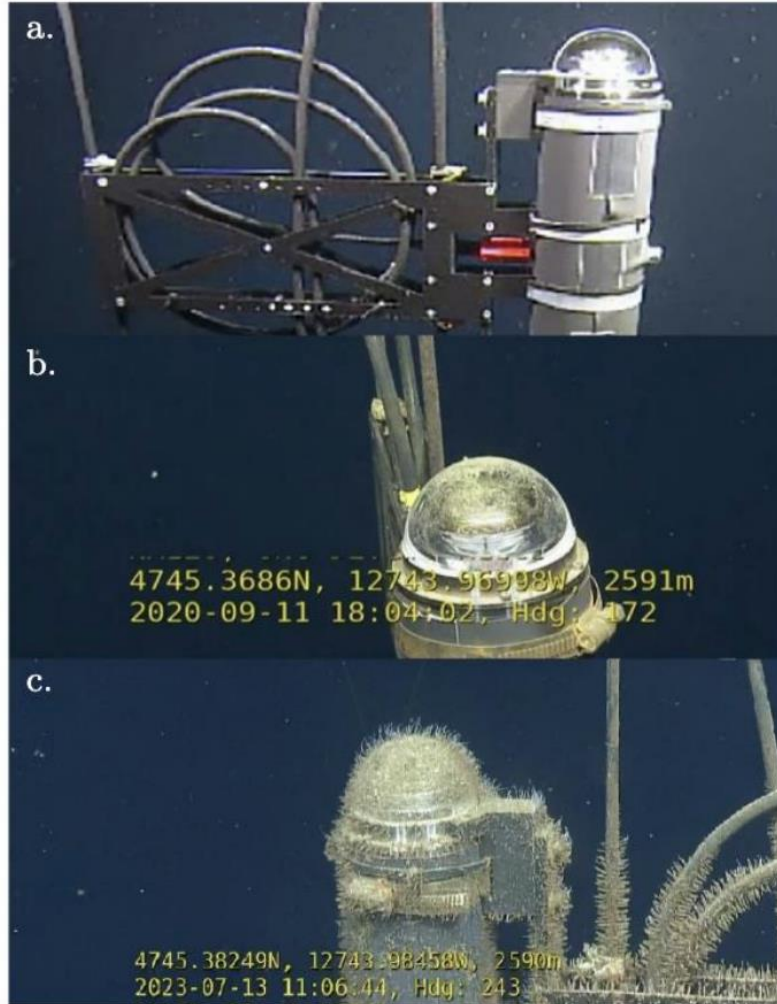
- Absolute sensitivities of up to -125 dB re $V^2/\mu Pa^2$
- Frequency range of 10–40 kHz



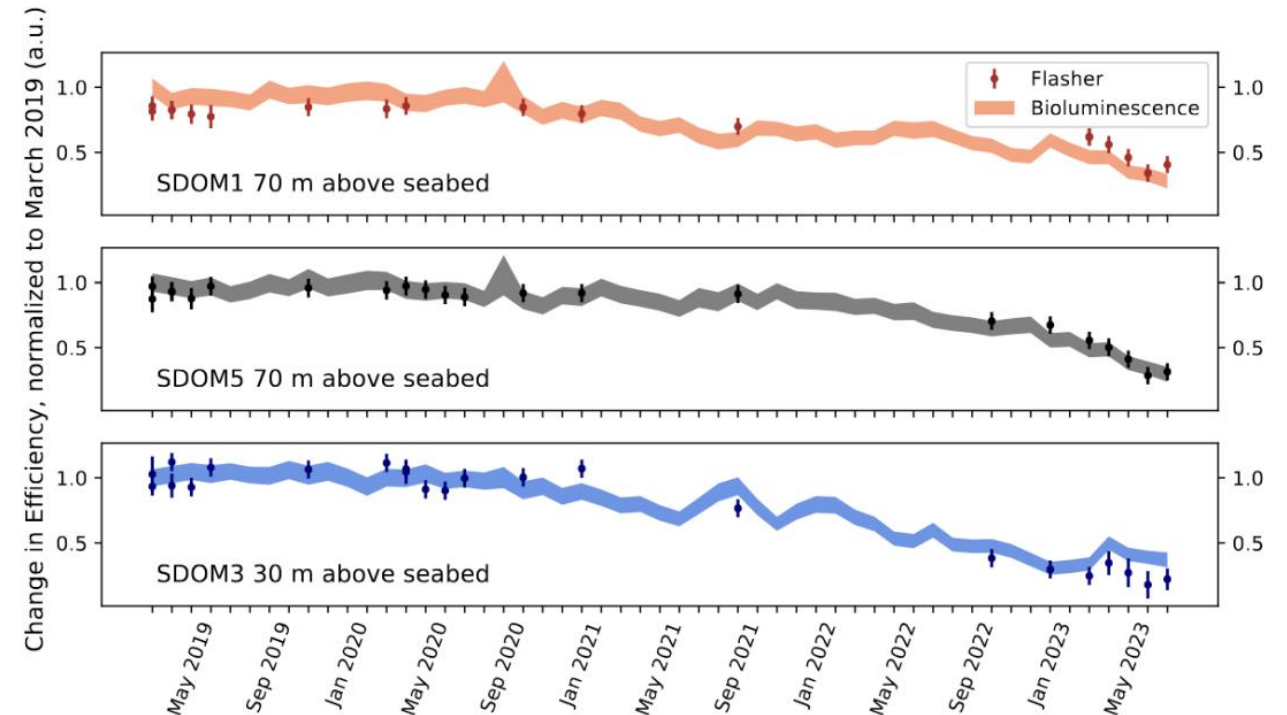
- Positioning measurement campaign in the ocean
- 3 autonomous acoustic pingers, cabled acoustic interrogator, P-ONE prototype module deployed from ship
- Peak-finding detection algorithm: high accuracy (< 30 cm) @ distances of up to 1600 m

Images: Dilraj Ghuman, Jakub Stacho, Felix Henningsen
Credit: arXiv:2504.13323

Biofouling



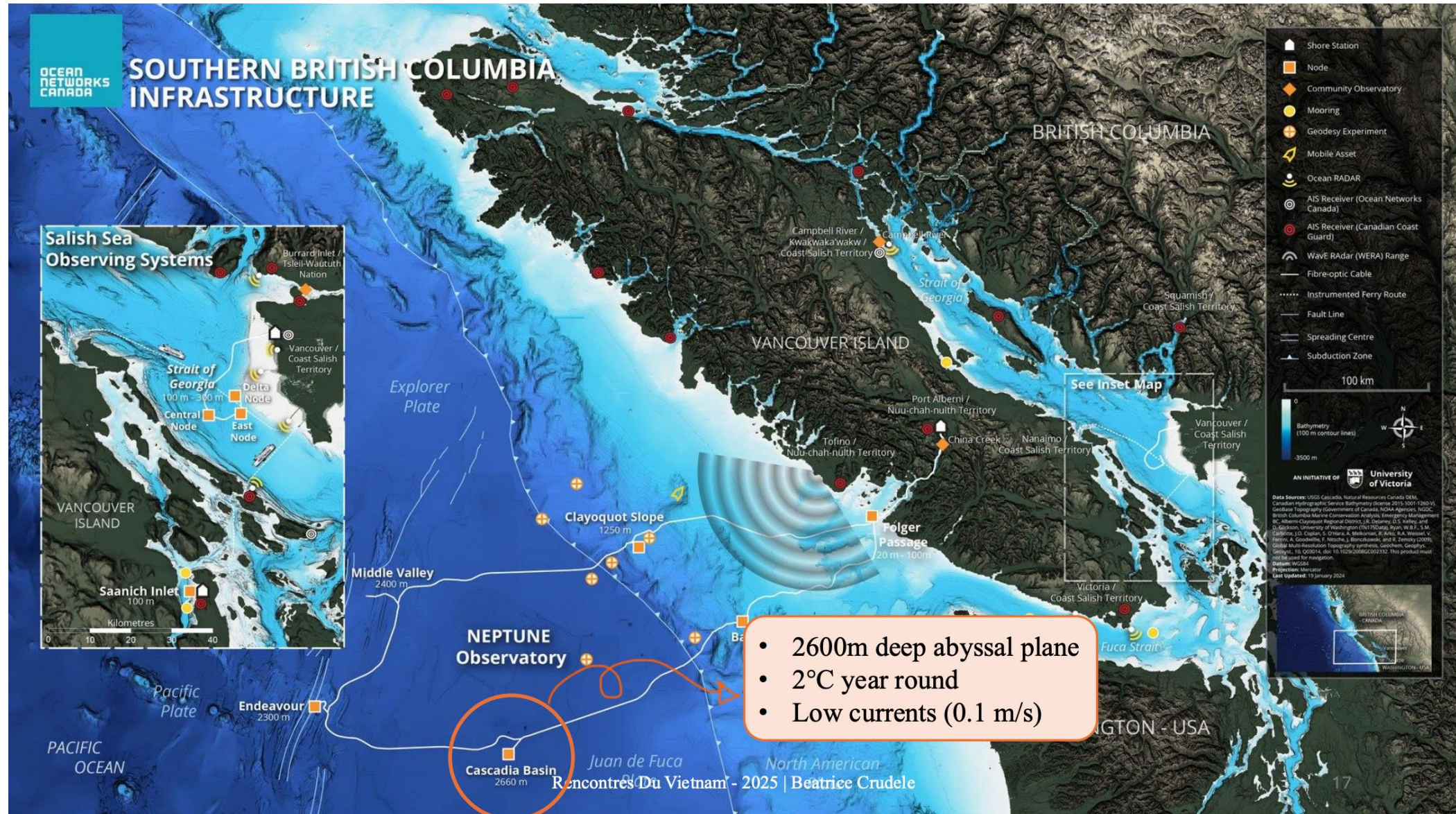
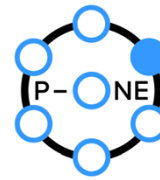
- Upward-facing optical surfaces saw around a 65% drop in efficiency.
- Downward-facing surfaces mostly clear
- Can be checked with flashers
- Mitigation with biofouling coating



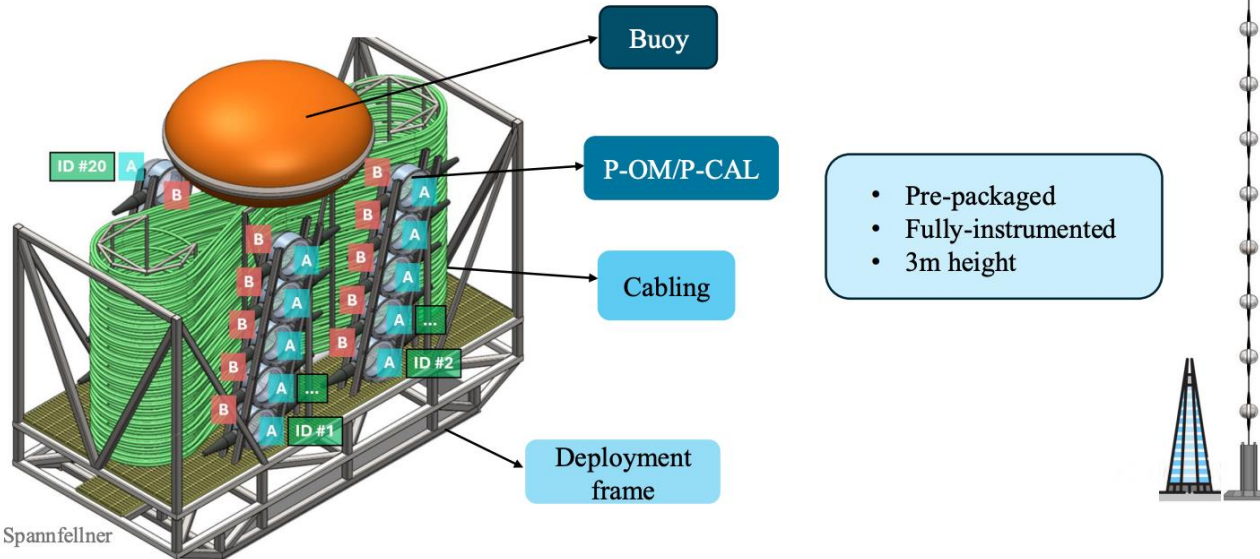
Images and plots: Braeden Veenstra et al.

Credit: arXiv:2507.09086

The Pacific Ocean Neutrino Experiment: Progress and Prospects



Deployment of first string



P-ONE 1

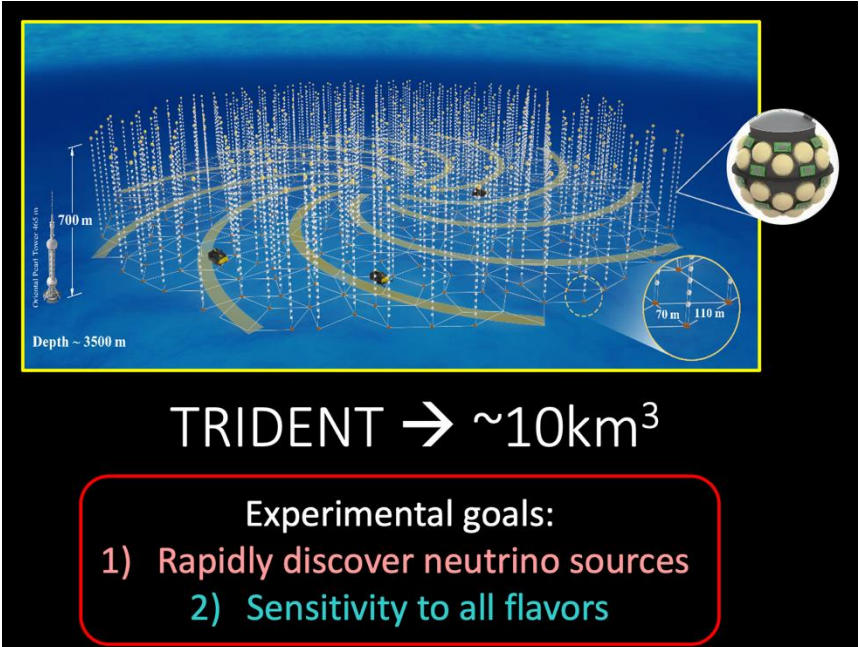
- Hemispheres have been shipped with mounted PMTs from TUM
- All modules have been received at TRIUMF
- Deployment frame has been moved into the clean room
- Backbone cable contains optical fibres which are cut and spliced, then fully spooled on frame at McCartney facilities



Conclusions

- P-ONE's goal is to search for high energy neutrinos in the southern sky
- Improved angular resolution and innovative design
- Will come online along others in the next decade
- P-ONE 1 is making great progress – deployment follows a technical driven schedule with opportunity for spring 2026
- Many discovery opportunities from our galaxy and beyond

TRIDENT [China, Future]



Detector Design – hDOM

["A Cost Effective Optimization of the hybrid-DOM Design for TRIDENT"](#)
[JINST 19 \(2024\) 06, P06011](#)
[JINST 19 \(2024\) 05, P05040](#)

Hybrid Digital Optical Module
Hybrid: PMTs + SIPMs

PMTs

- Fine timing resolution (TTS FWHM 1.3ns)
- High quantum efficiency >30% at 400nm

SIPMs

- Fine timing resolution
- Fills spaces between the PMTs, extra sensitivity
- SIPM arrays aids in calibration

Balance design with:

- Reduction of backgrounds: e.g. ⁴⁰K & PMT Dark noise
- Cost & Power consumption
- Additional low energy physics

Detector Design – Location

South China Sea

- Near the equator
- 3.5 km deep
- Large, flat plane

TRIDENT sensitive viewing region:

Low seacurrents, bioactivity

10 x 10 strings
800 doms

1:25 scale string models in SJTU Ship-towing tank

Low atmospheric muon rate

"MuonLab: A plastic scintillator based detector for muon measurement in the deep ocean"

["A Cost Effective Optimization of the hybrid-DOM Design for TRIDENT"](#)

Detector Design – hDOM

["A Cost Effective Optimization of the hybrid-DOM Design for TRIDENT"](#)
[JINST 19 \(2024\) 06, P06011](#)
[JINST 19 \(2024\) 05, P05040](#)

3-inch PMT hDOM design

- 31 3" PMTs
- 24 SIPMs (4x8 array)

4-inch PMT hDOM design

- 31 4" PMTs
- 5 SIPMs (8x8 array)

Check / compare performances for various designs:
e.g. neutrino detection efficiency + angular resolution

Effective Area ($\nu_\mu - CC$)

Angular Resolution ($\nu_e - CC$)

Efficient light collection is important (as expected)