report from Neutrino 2024

Federico Nova
25 Sept 2024

neutrino 2024

- conference held every 2 years since 1972
- 2024 edition in Milan (Italy)
- 71 plenary talks
- 460 posters
- 828 participants

neutrino oscillations

flavor states

mass states

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

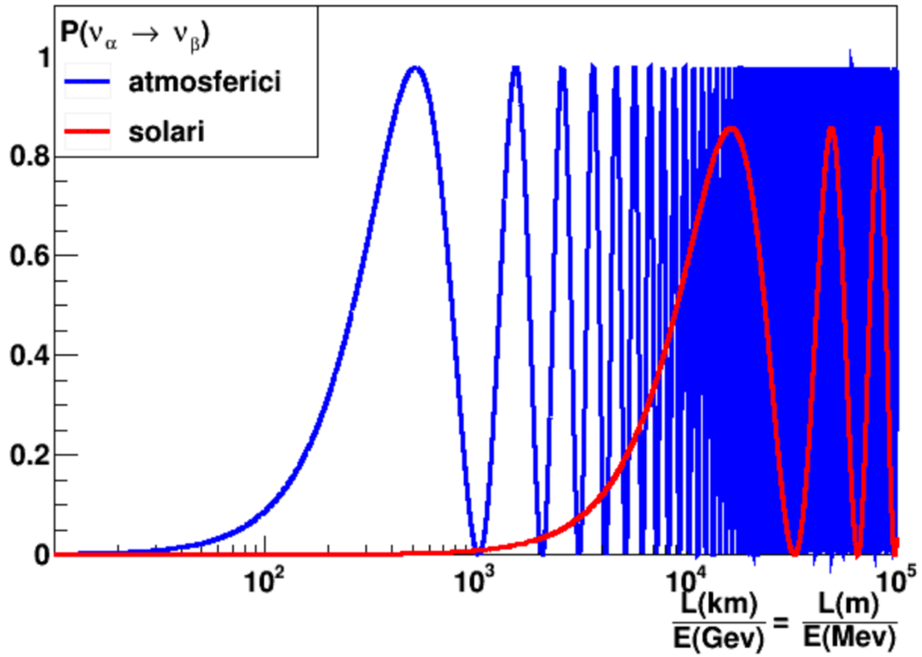
Atmospherics and LBL
$\theta_{23} \sim 45°$
$|\Delta m^2_{32}| \sim 2.5\text{x}10^{-3}\ eV^2$

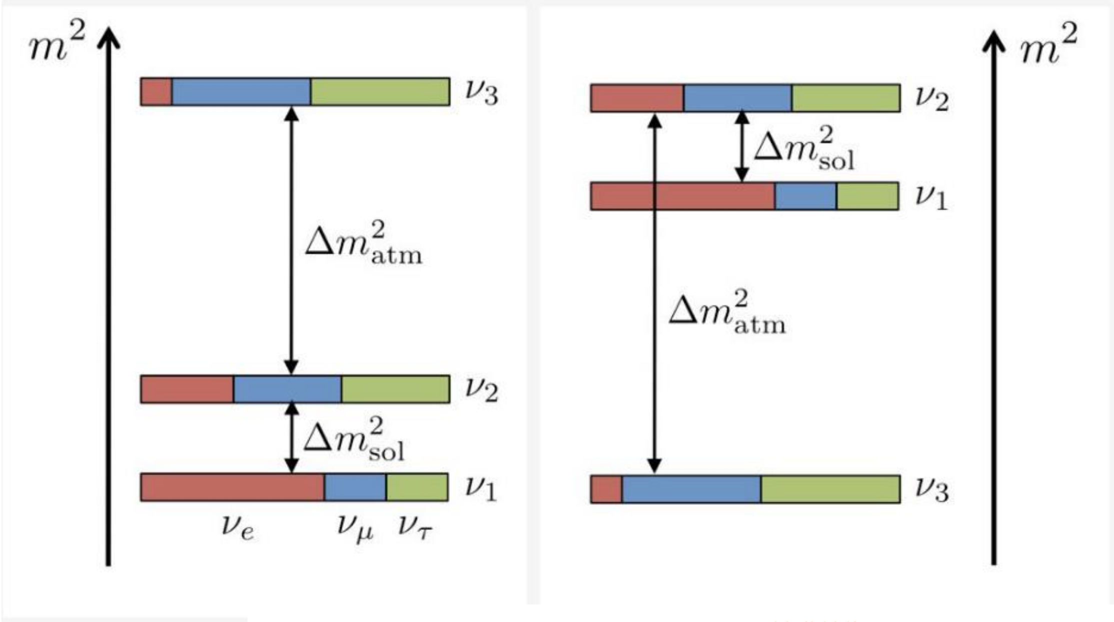
Reactors
$\theta_{13} \sim 10°$
LBL
θ_{13} and δ_{CP}

Solar and reactors
$\theta_{12} \sim 35°$
$\Delta m^2_{21} \sim 7.5\text{x}10^{-5}\ eV^2$

two-flavors approximation

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





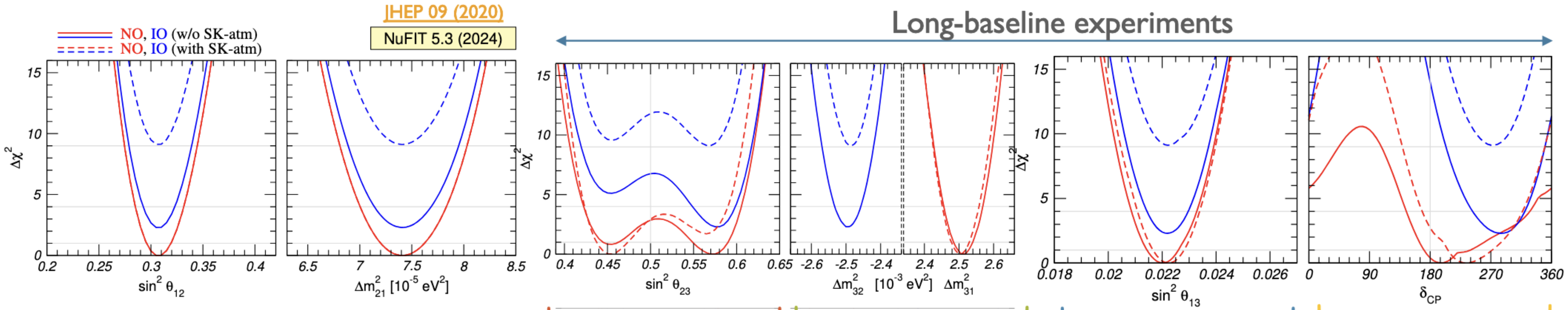
Future objectives:

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

δ_{CP}, θ_{23} max?, Hierarchy? → Accelerator, Reactor, Atmospheric

Hierarchy?, Majorana ν?, Absolute mass → 0νββ, Cosmology, Electron spectrometers,

Sterile ν? → Accelerator, Reactor, Atmospheric



"Solar" parameters – expect very precise measurements from JUNO

Octant unknown

Mass ordering unknown

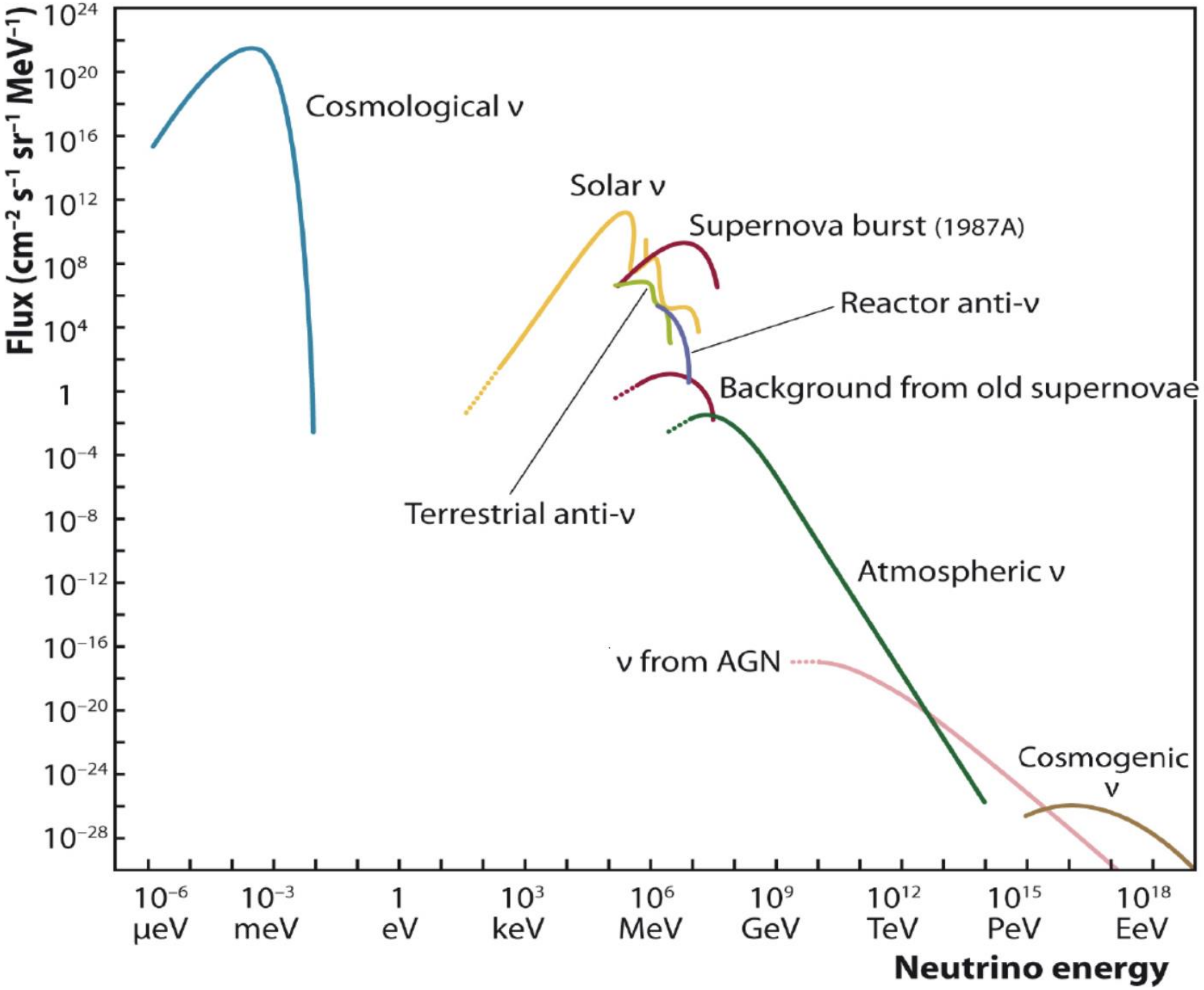
Precise measurement from reactor experiments

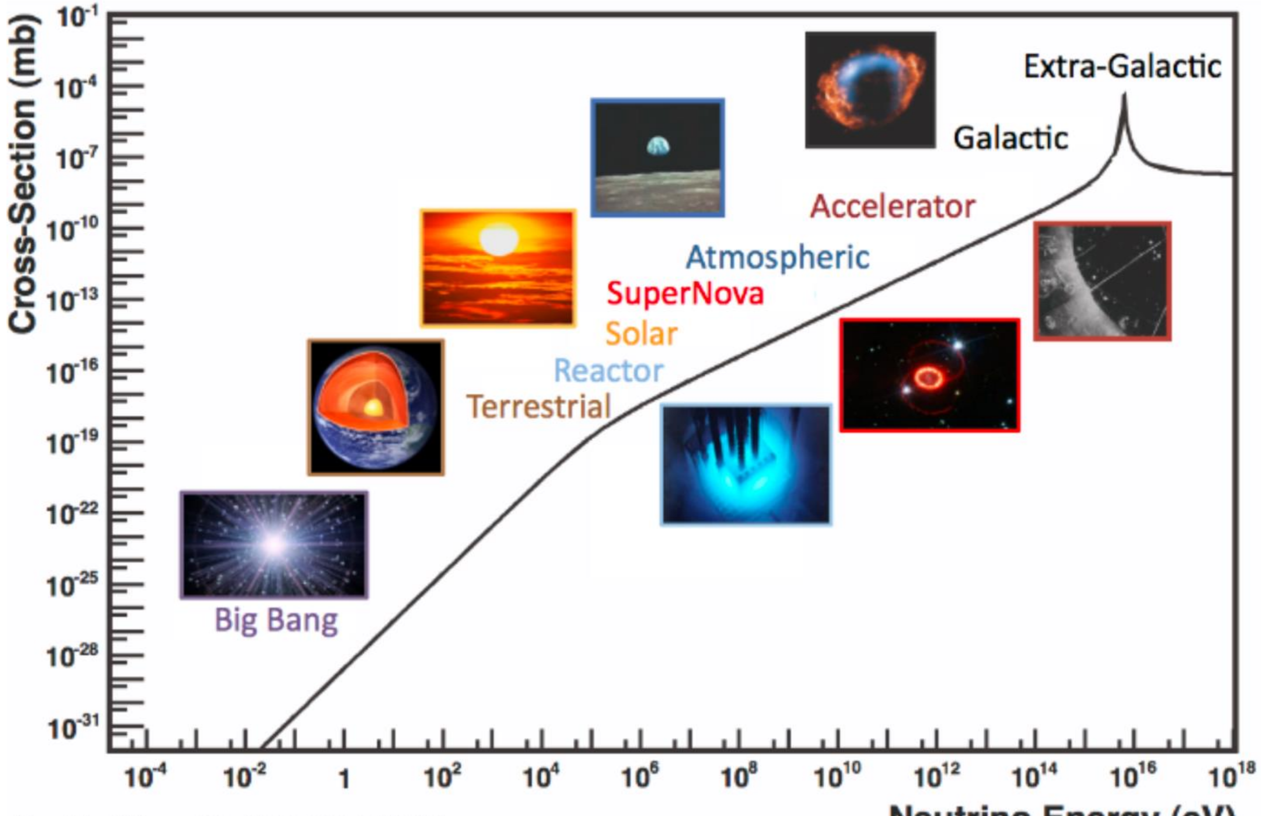
CP Violation?

LBL PHENOMENOLOGY, ETW, NEUTRINO 2024

7

Neutrinos Reaching the Earth



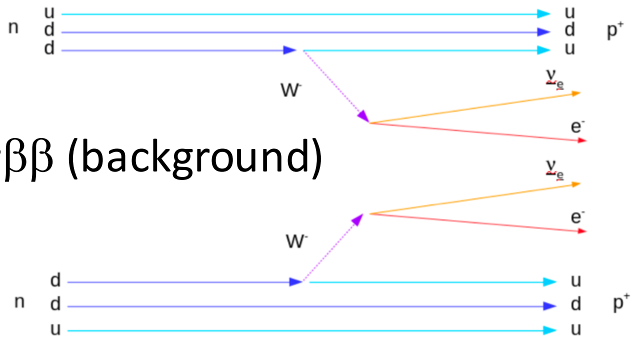


Rev.Mod.Phys. 84, 1307-1341 (2012)

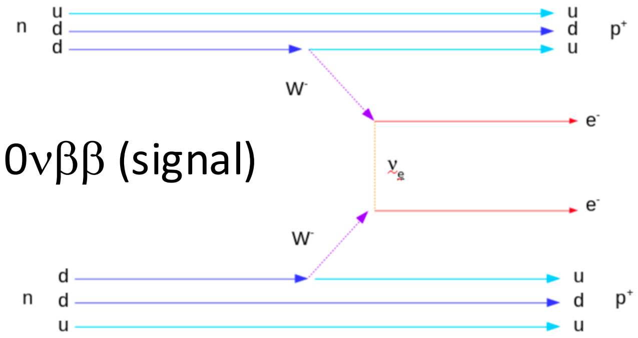
double beta decay

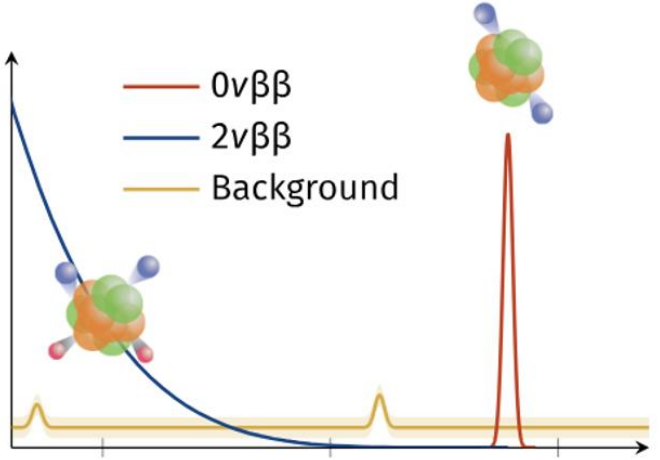
- LEGEND
- KamLAND-Zen
- CUORE

2νββ (background)



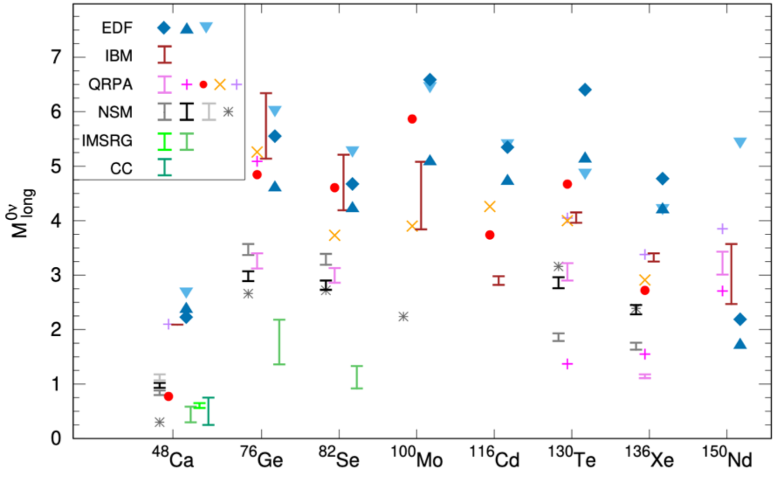
0νββ (signal)





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

Large difference in nuclear matrix element calculations

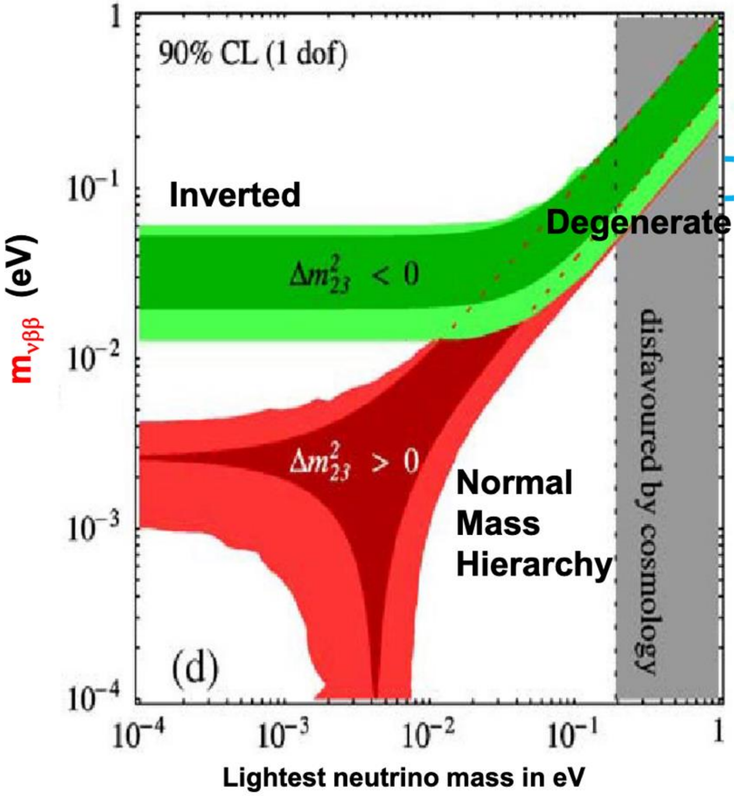


Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

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

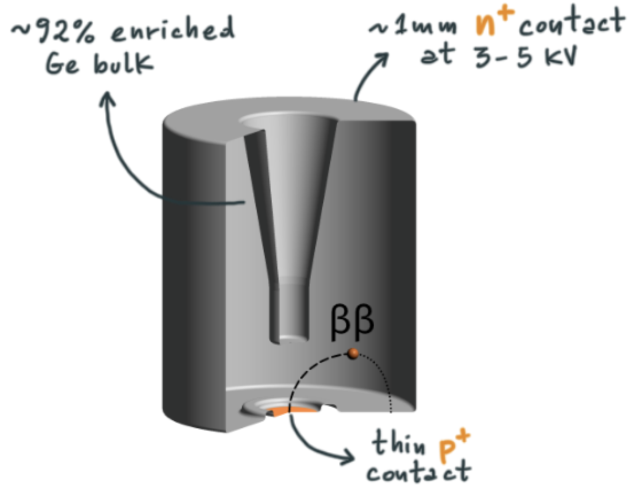
$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

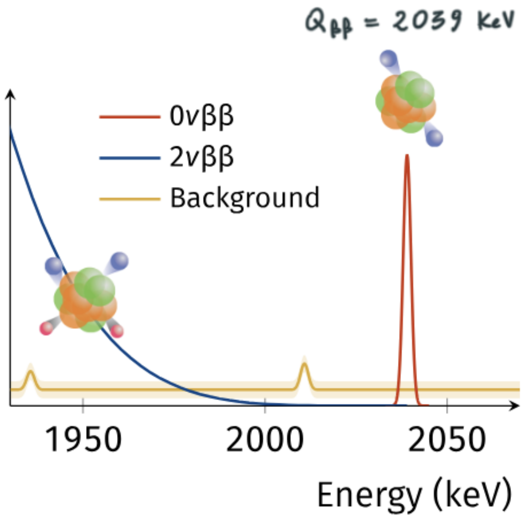
- uncertainty in nuclear matrix element



LEGEND [Italy, 2023-]

Searching for 0νββ with Germanium: concept

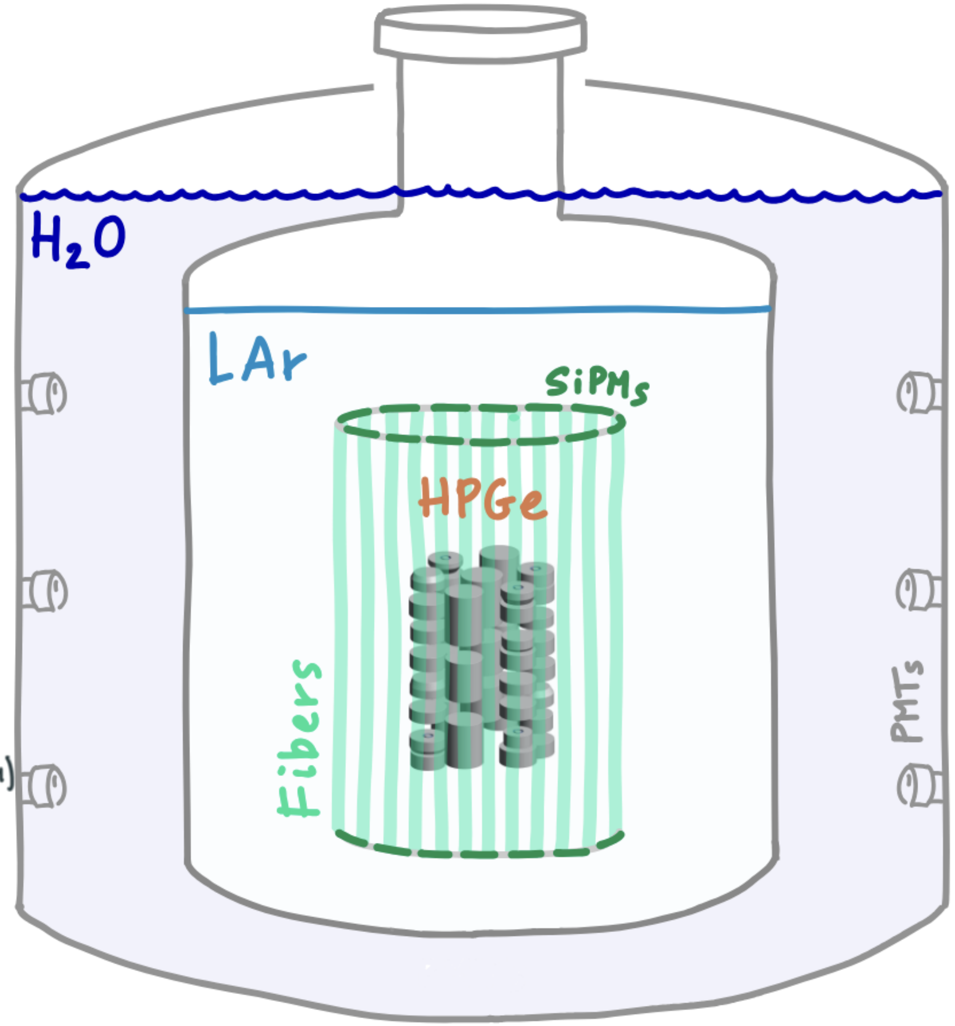


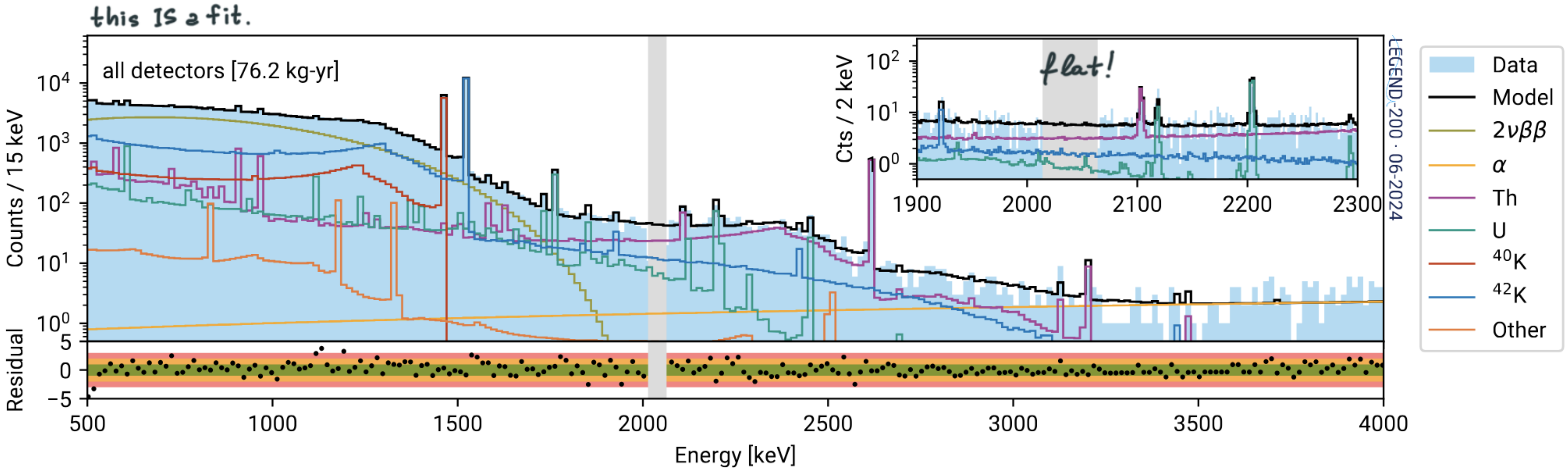


High-Purity Germanium detectors enriched in ^{76}Ge

- source = detector ⟼ *high efficiency*
- pure ⟼ *low intrinsic background*
- Ge crystal ⟼ *outstanding energy resolution* 0.1% @ $Q_{\beta\beta}$ (FWHM)
- "solid-state TPC" ⟼ *topological discrimination* Pulse Shape Analysis

GERDA and MAJORANA constraints among the most stringent





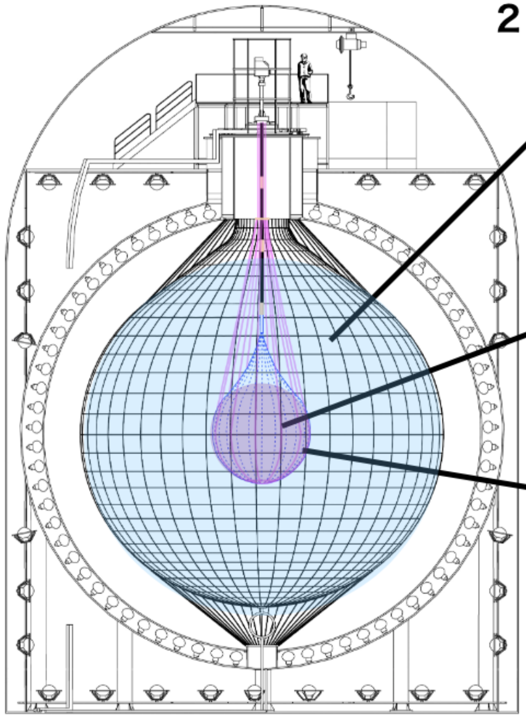
- Bayesian background model using data before analysis cuts [SILVER]
  - *Includes 10.2 kg yr from special "background characterization" runs*
- Data well reproduced, model is flat at $Q_{\beta\beta}$
  - *No "hotspot" or significant asymmetry observed in data*
  - *Model can test hypotheses on the origin of ^{228}Th*

KamLAND-Zen [Japan, 2011-]

KamLAND-Zen

Kamioka underground KamLAND detector

Zero Neutrino Double Beta



2-type of liquid scintillator

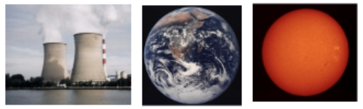
1000-ton pure liquid scintillator

U, Th < 10^{-17} g/g

745 kg Xe-loaded liquid scintillator (91% enrichment)

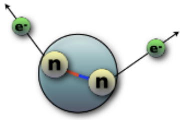
inner balloon (IB)

2002– KamLAND



reactor, geo, solar neutrino observation

2011– KamLAND-Zen



double beta decay measurement ($0\nu\beta\beta$ search)

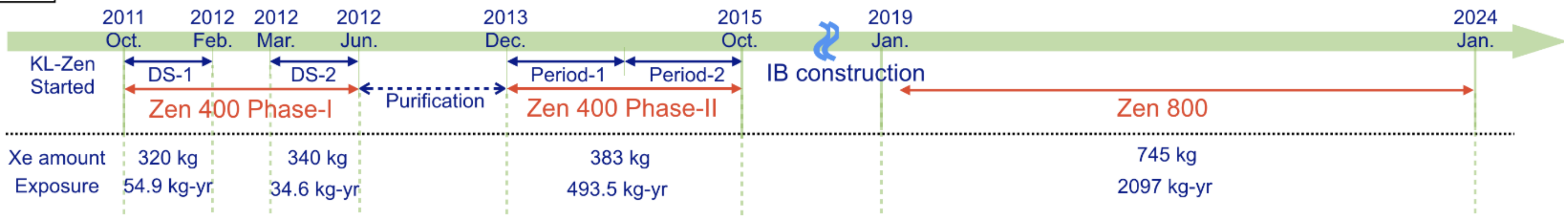
2019– Xe increase, cleaner balloon

big and pure : no background from external gamma-rays

purification of LS, replacement of mini-balloon are possible

→ **high scalability**

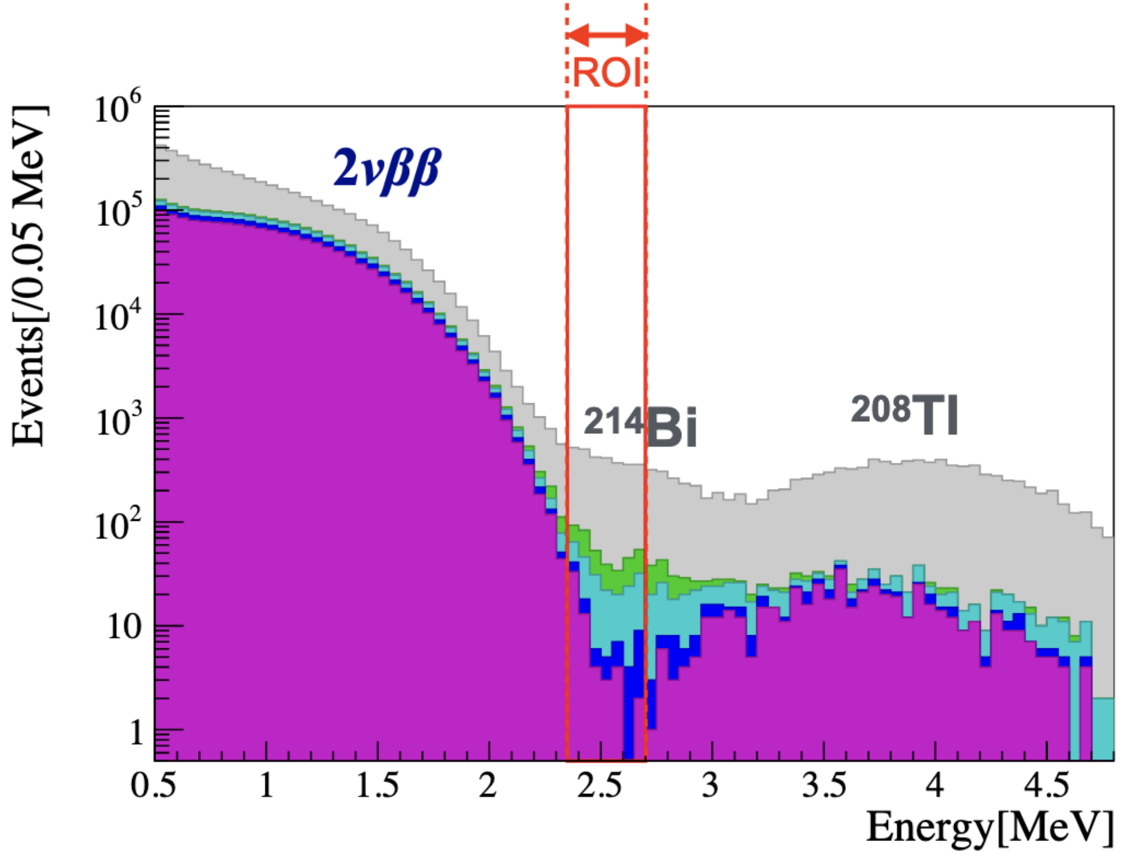
Xe **320 kg** **340 kg** **383 kg** **745 kg** **largest ^{136}Xe !!**



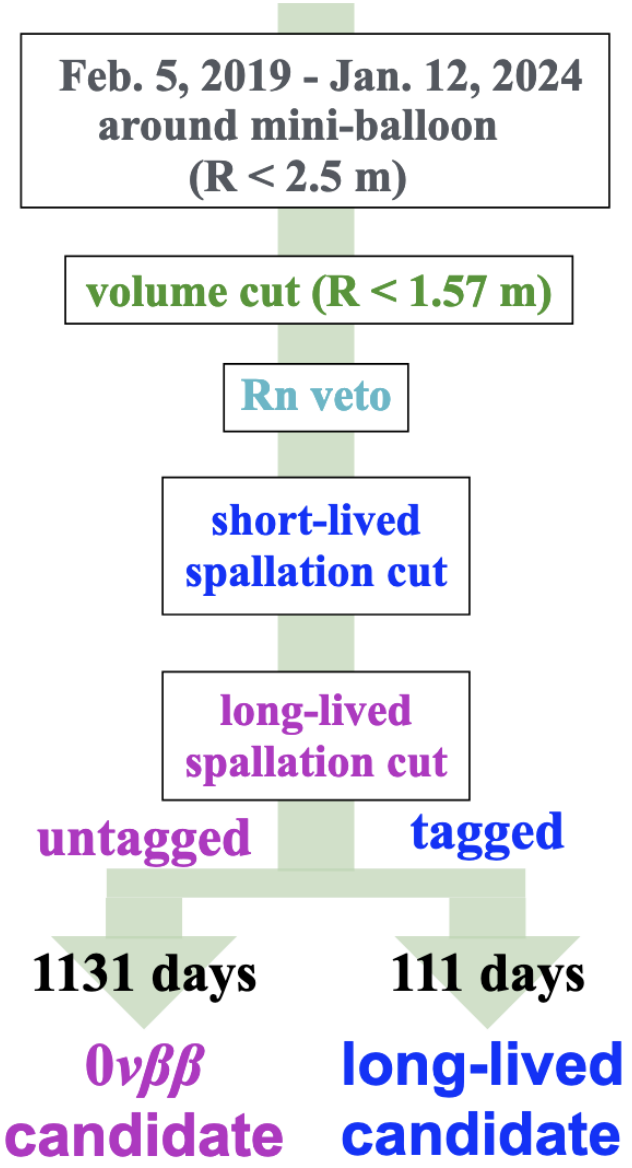
Event Selection

ββ isotope ^{136}Xe **90.85% enriched** $Q_{\beta\beta}$ = 2458 keV

745 kg Xe in all volume Feb. 5, 2019 - Jan. 12, 2024



Two energy spectra (0νββ, long-lived) are fitted simultaneously



$0\nu\beta\beta$ candidate

(sensitive to $0\nu\beta\beta$ signal)

1131 days livetime

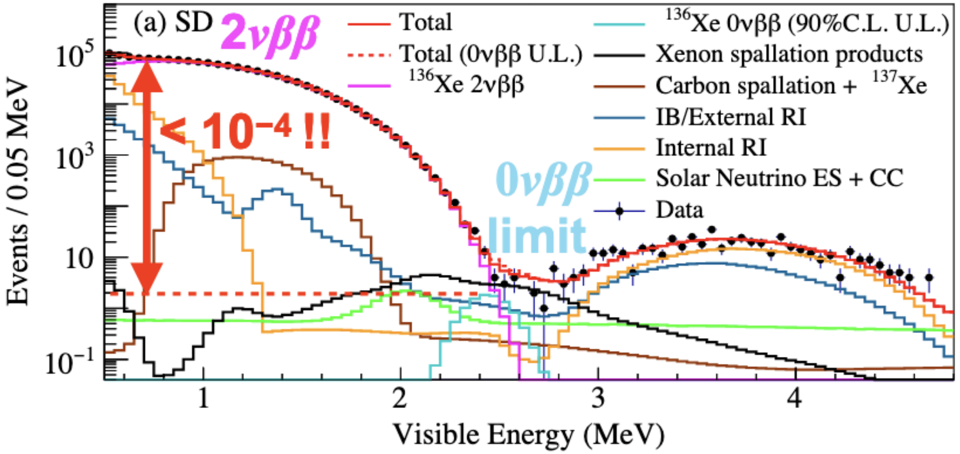
R < 1.57 m

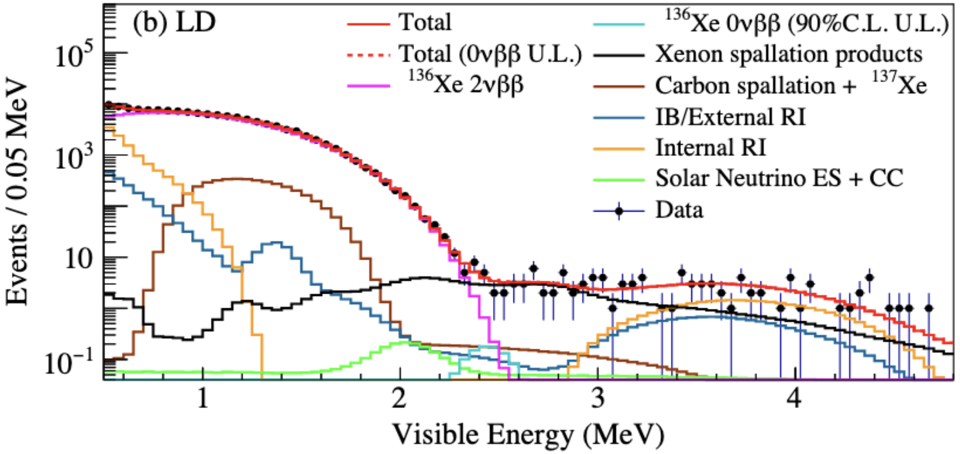
long-lived candidate

(Long-lived BG constraint)

111 days livetime

R < 1.57 m





$0\nu\beta\beta$ best-fit : **0 event**

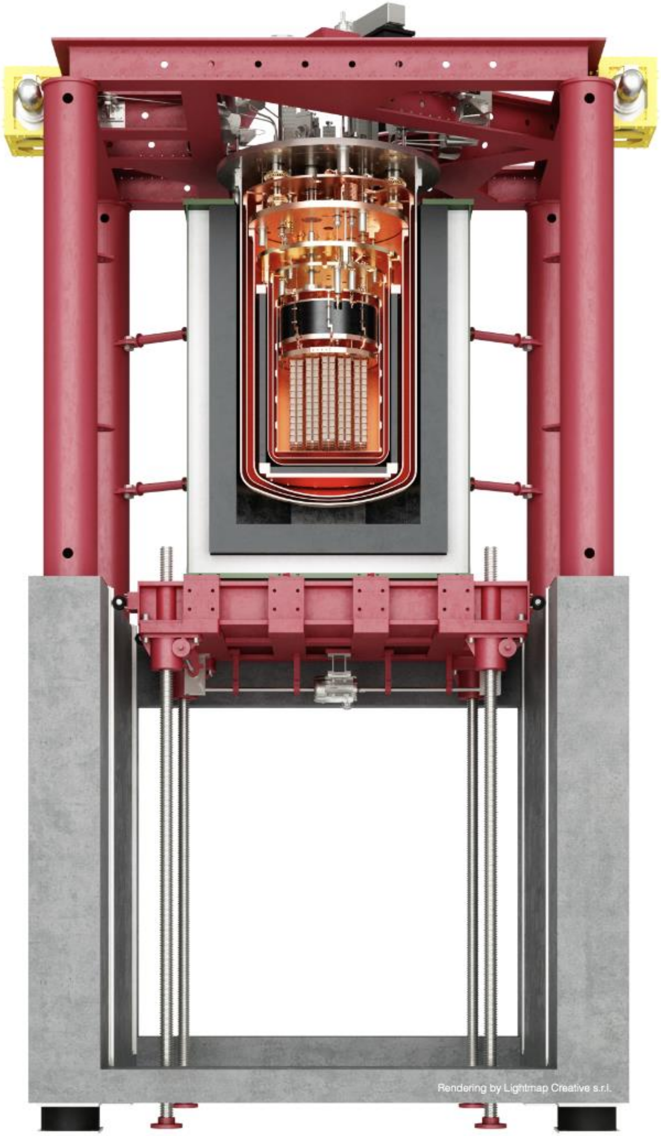
upper limit : **< 10.0 event** at 90% C.L.

in R < 1.57 m

No positive signal, but we obtained a stringent upper limit

Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO_2 crystals (750 g each) working as cryogenic calorimeters
- Total mass of TeO_2: 742 kg (~206 kg of ^{130}Te)
- Operating temperature: ~10 mK
- Main goal: assess the Majorana nature of neutrinos by searching for $0\nu\beta\beta$ in ^{130}Te



Build a cryogenic system with an experimental volume of ~1 m^3 in which to operate for several years a huge Low Temperature Detector array in a low-radioactivity and low-vibrations environment

- Cryogenics
  - Mass cooled below 4K : ~ 15 tons
  - Mass cooled below 50 mK : ~ 3 tons
  - Lowest operating temperature: 7 mK
  - Continuously operating at mK temperature: > 5 years
- Low-background
  - Deep underground location
  - Strict radio-purity controls on materials and assembly
  - Passive shields outside and inside the cryostat

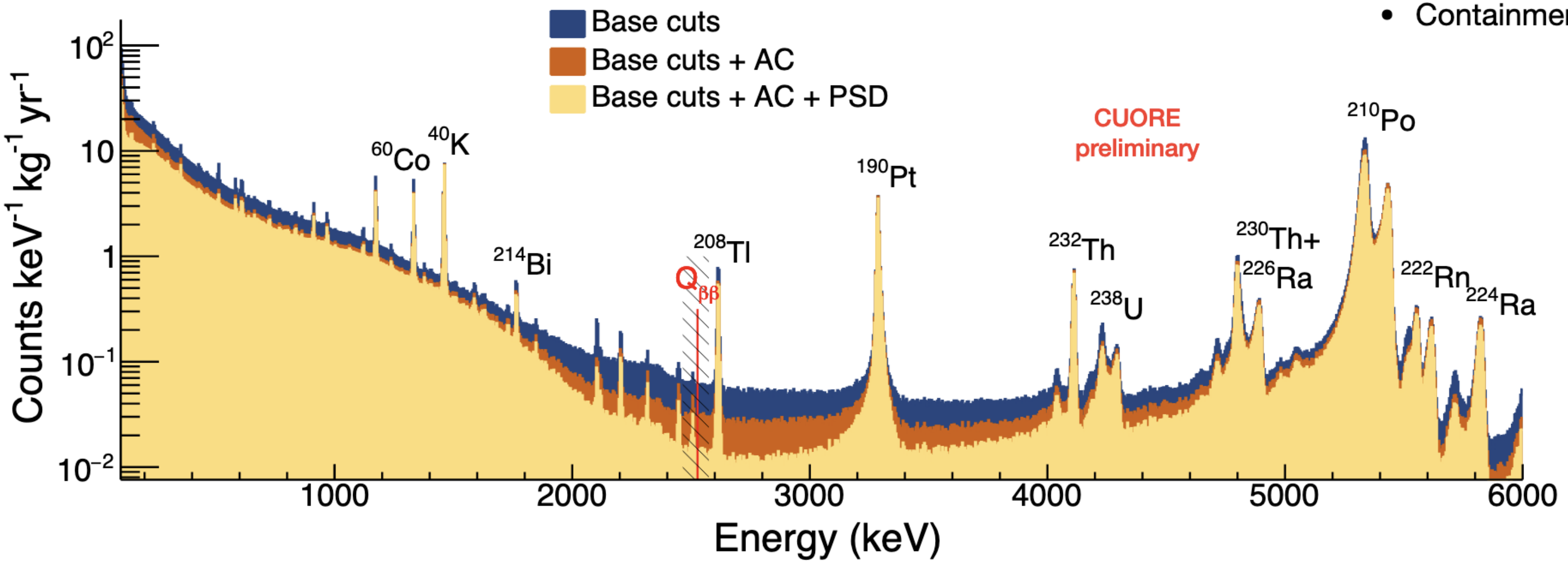
Ancient roman lead

Latest results on the ^{130}Te $0\nu\beta\beta$ search

- 28 datasets analyzed from May 2017 to April 2023
- Total analysed exposure: 2039.0 kg·yr TeO_2 (567.0 kg·yr ^{130}Te)

Efficiencies

- Total analysis efficiency 93.4 %
  - Reconstruction: 95.6 %
  - Anti-coincidence (M1): 99.8 %
  - PSD: 97.9 %
- Containment efficiency: 88.4 %



Noise reduction

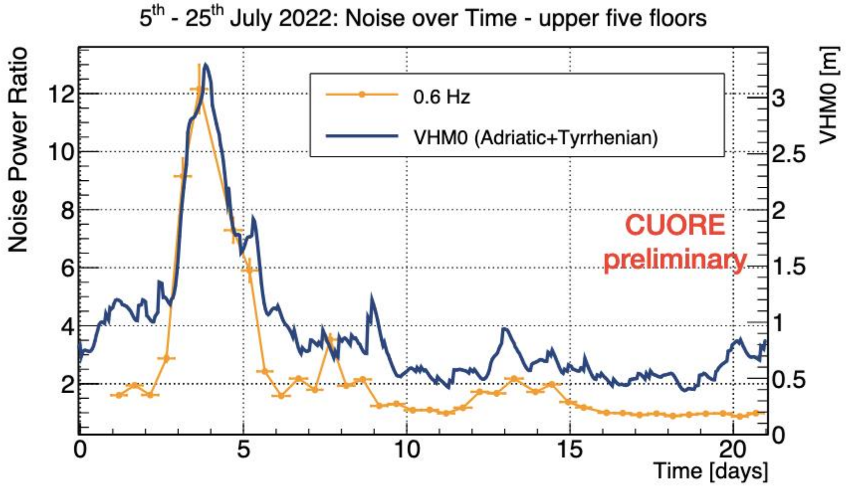
Quite unexpectedly we discovered that CUORE is sensitive to the faint microseismic activity induced by the sea waves

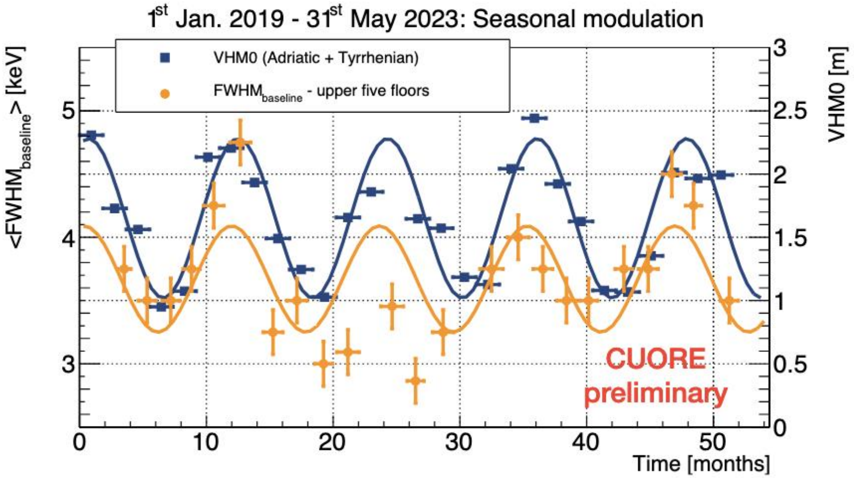
- Strong correlation between storms and low frequency noise in CUORE
- Sea waves characteristic frequency: 0.2 - 0.3 Hz
- Resonance frequency in the cryogenic apparatus

Neutrino 2024, 17-22 June, Milan

- Seasonal modulation of detectors energy resolution
- Solutions under study to improve cryostat seismic decoupling

ArXiv:2404.13602





tritium beta decay

- KATRIN

tritium β decay

why tritium?

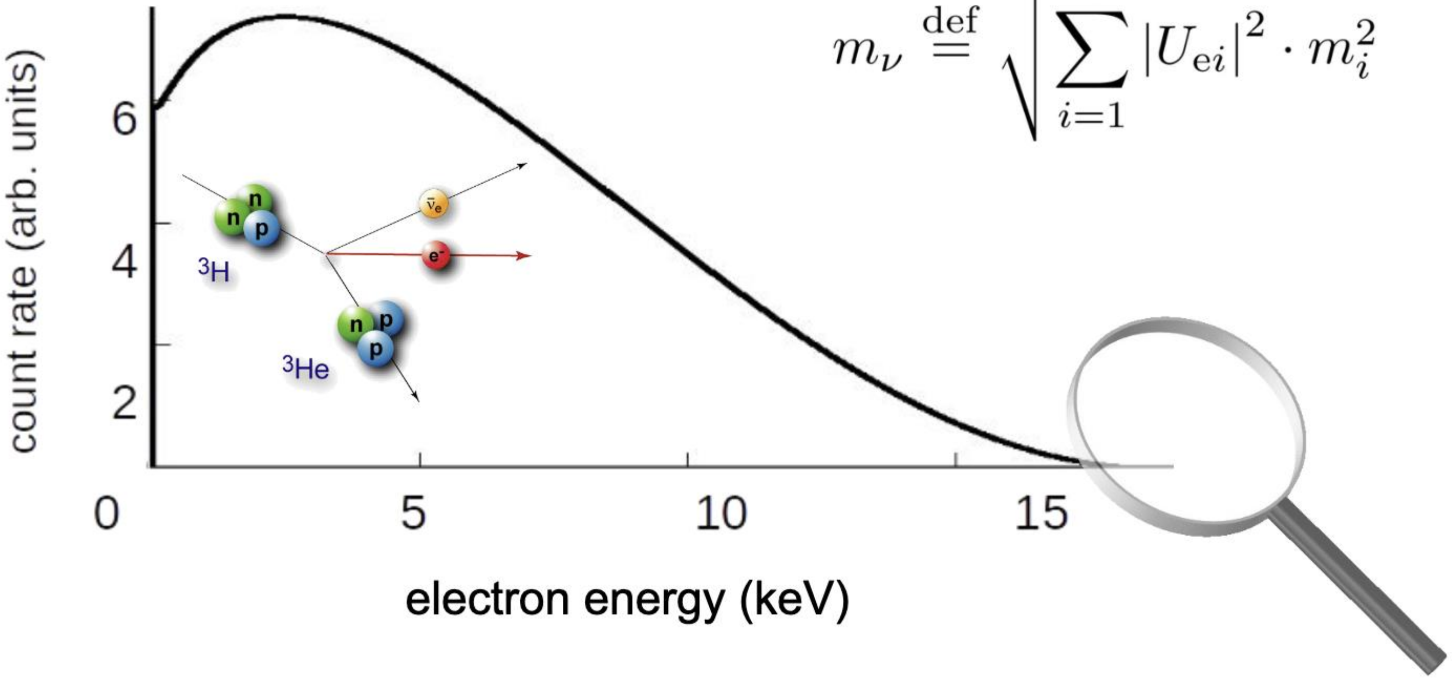
- small Q-value (~19 keV)
- short mean life (18 y) -> small mass -> small inelastic scattering
- simple atom and nucleus

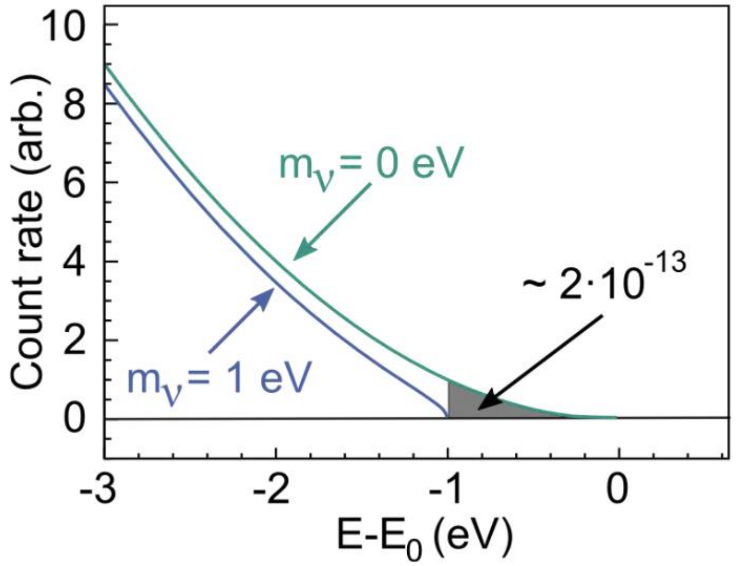
Neutrino mass in tritium β-decay

Measurement of effective mass m_ν based on **kinematic parameters & energy conservation**

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

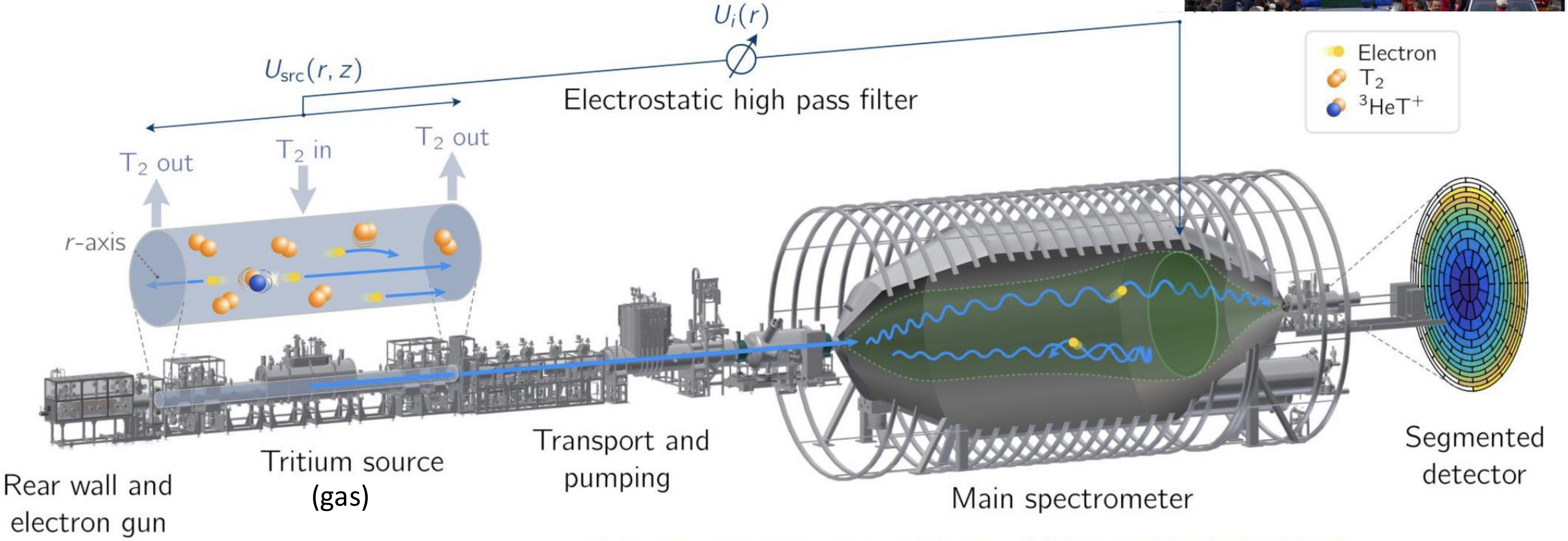
$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$





The KATRIN experiment

KATRIN:
Karlsruhe
Tritium
Neutrino
Experiment



Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

Preprint →
https://www.katrin.kit.edu/130.php#Anker0

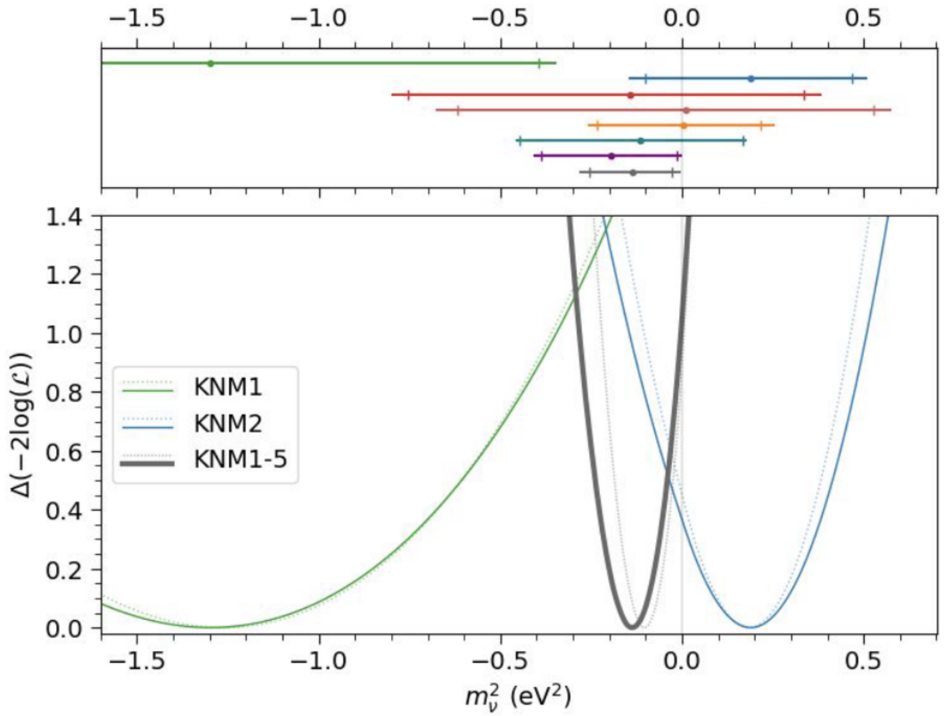
Fit result

- Best-fit value

$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$

- Negative m^2 estimates allowed by the spectrum model to accommodate statistical fluctuations

- Post-unblinding a data-combination mistake was uncovered →
  - Resolved by splitting **KNM4** into **two** data sets
  - ~ 0.1 eV^2 impact on m^2



Q-value: (18 575.0 ± 0.3) eV

18

Preprint →
https://www.katrin.kit.edu/130.php#Anker0

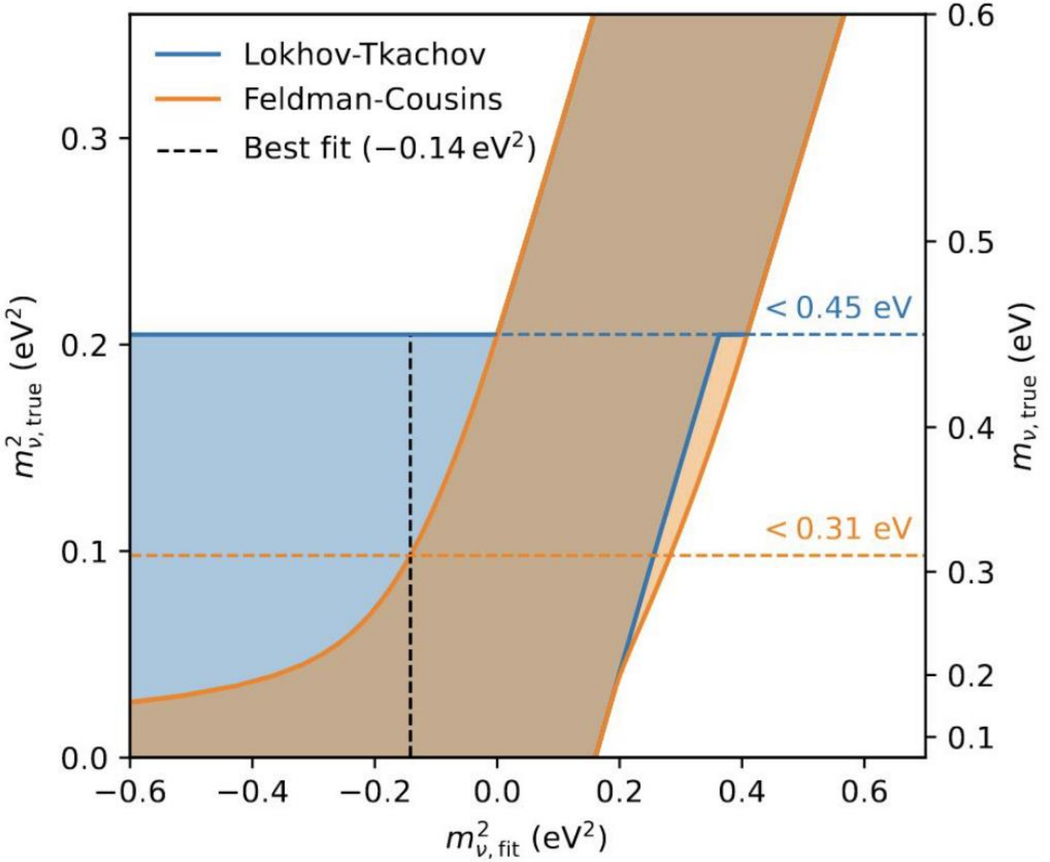
Confidence interval

- KATRIN's **new** upper limit

$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

  using **Lokhov-Tkachov** construction
- Feldman-Cousins limit:
  - m_ν < 0.31 eV at 90 % CL
  - Shrinking upper limit for negative m_ν^2
- Bayesian analysis in preparation

Poster by W. Xu

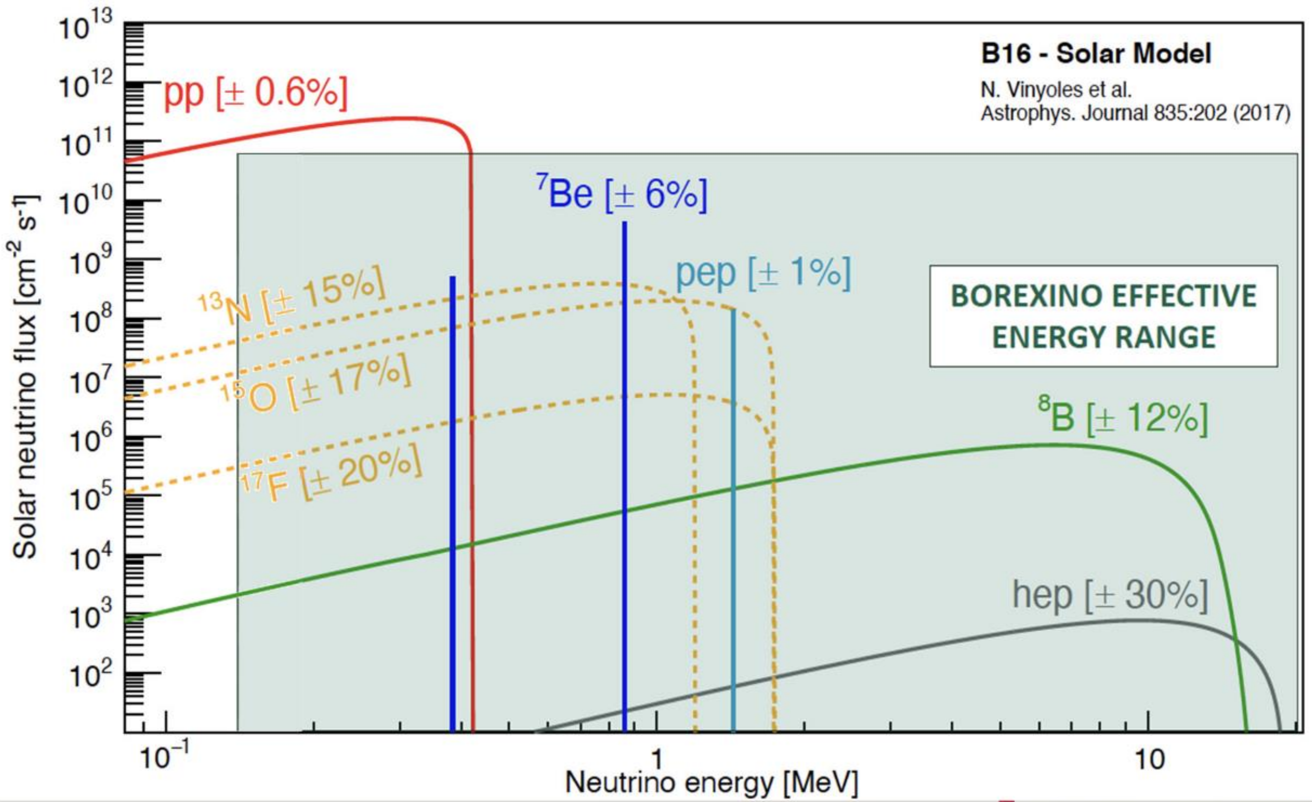


Lokhov, Tkachov, Phys. Part. Nucl. 46 (2015) 3, 347-365
Feldman, Cousins, Phys. Rev. D 57 (1998) 3873-3889

1

solar neutrinos

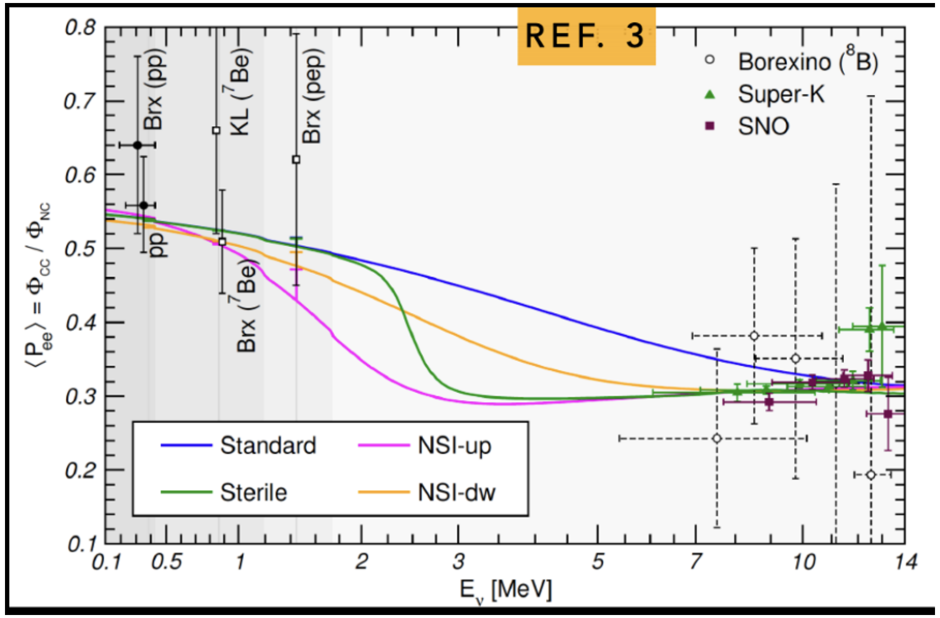
- Borexino
- Super-Kamiokande
- SNO+
- JUNO



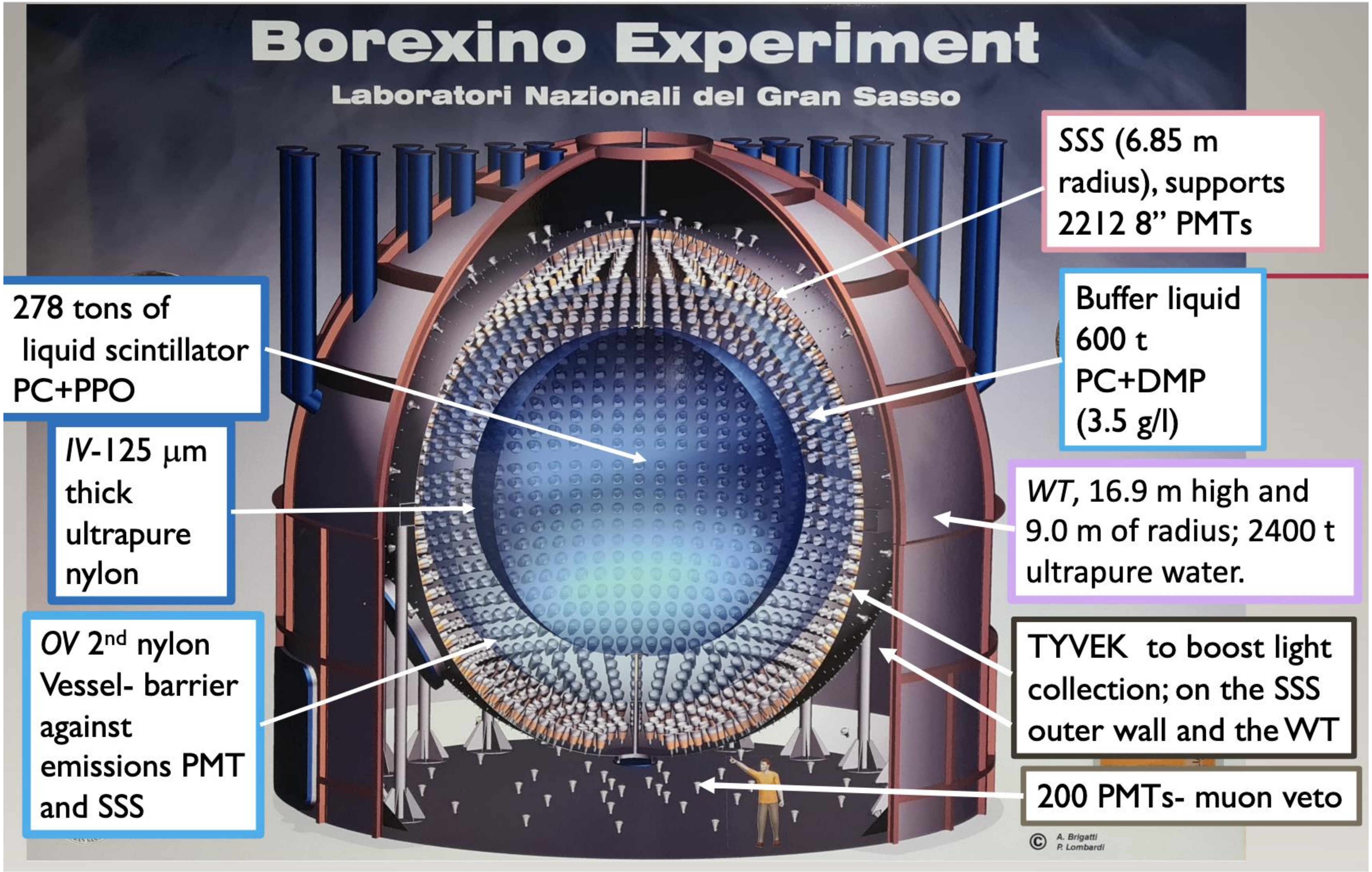
- ν_e emitted by sun
- total flux directly constrained by luminosity
- on the way oscillations happen

$$\nu_e \leftrightarrow \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$$

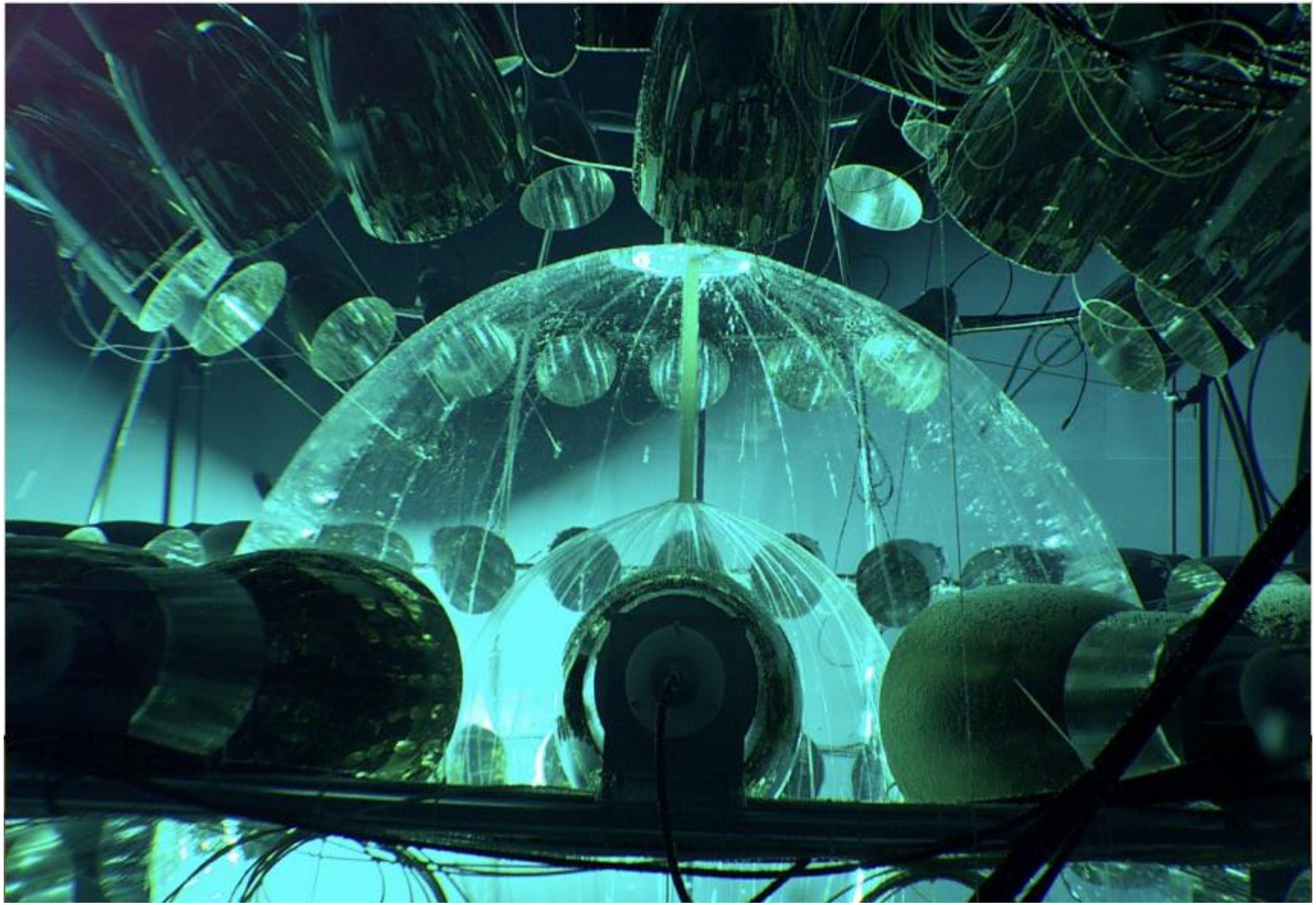
- enhanced by matter effects in the sun
- oscillation profile at 3 MeV chooses between models (but as yet unknown)



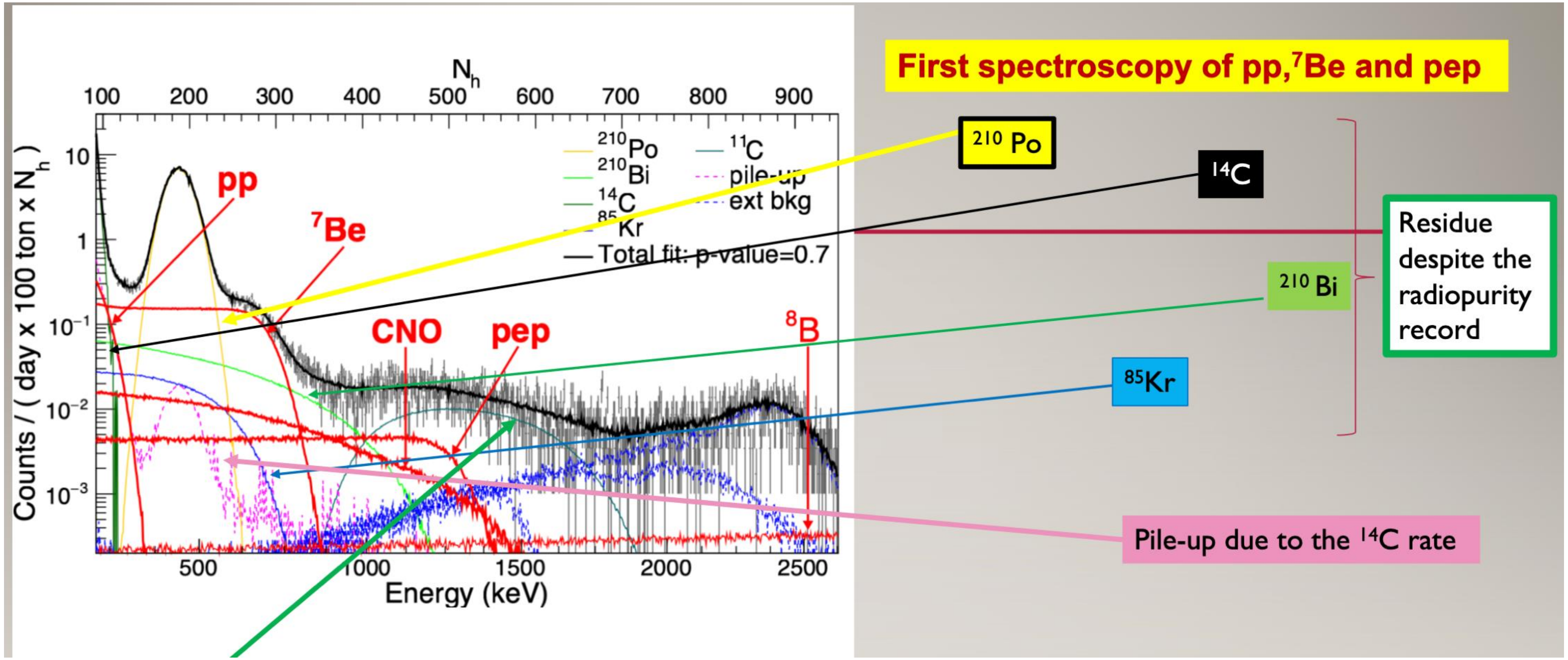
Borexino [Italy, 2007-21]

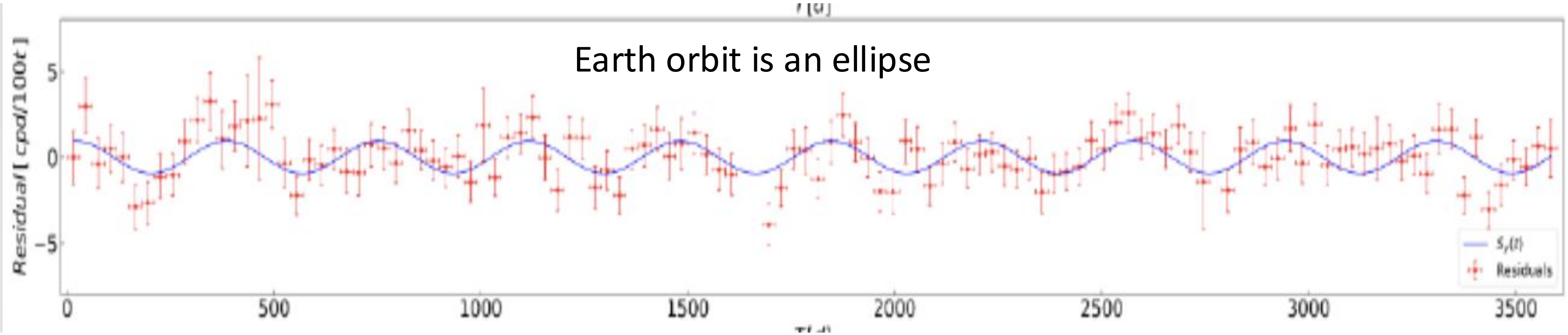


Borexino



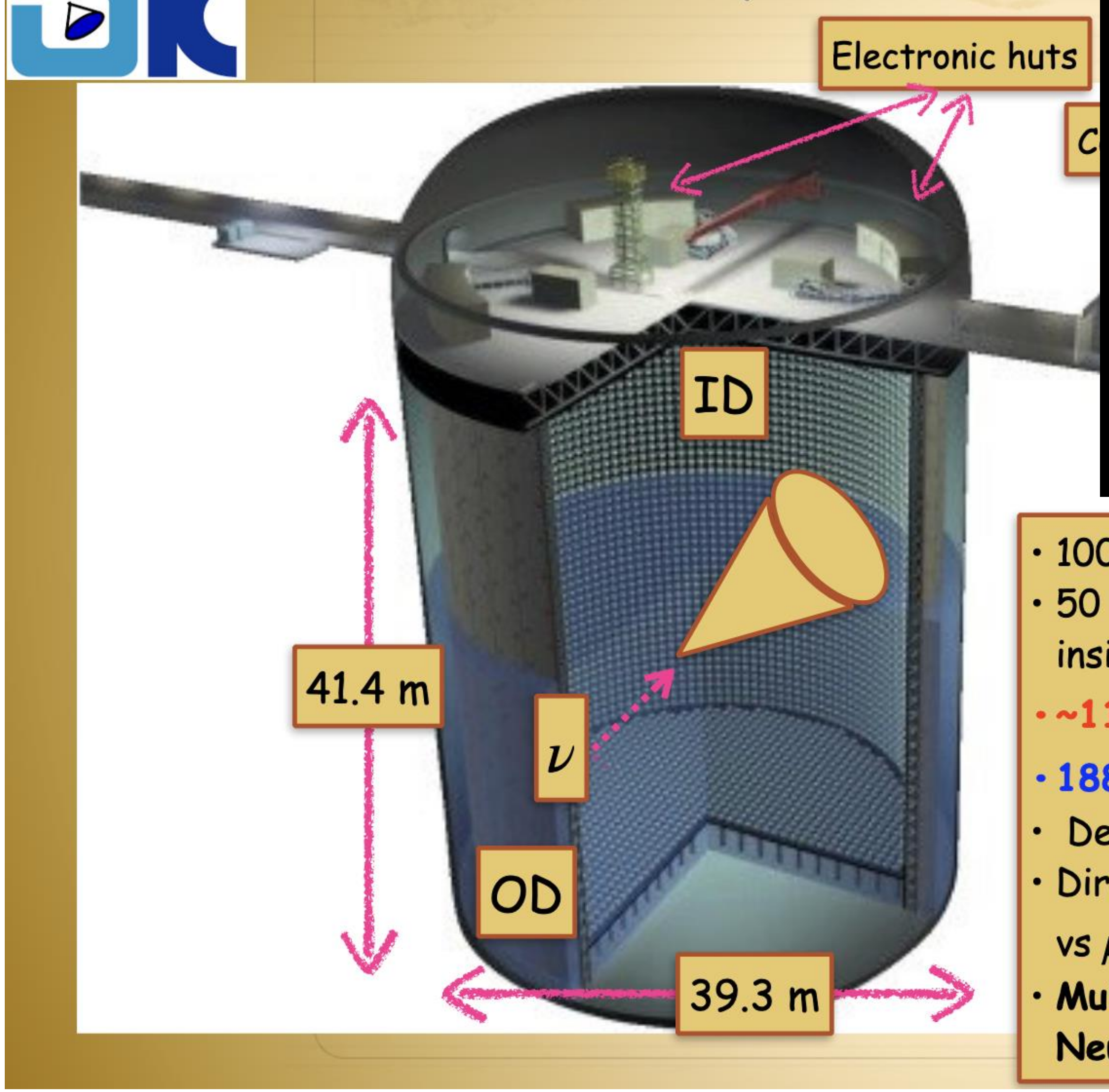
Borexino

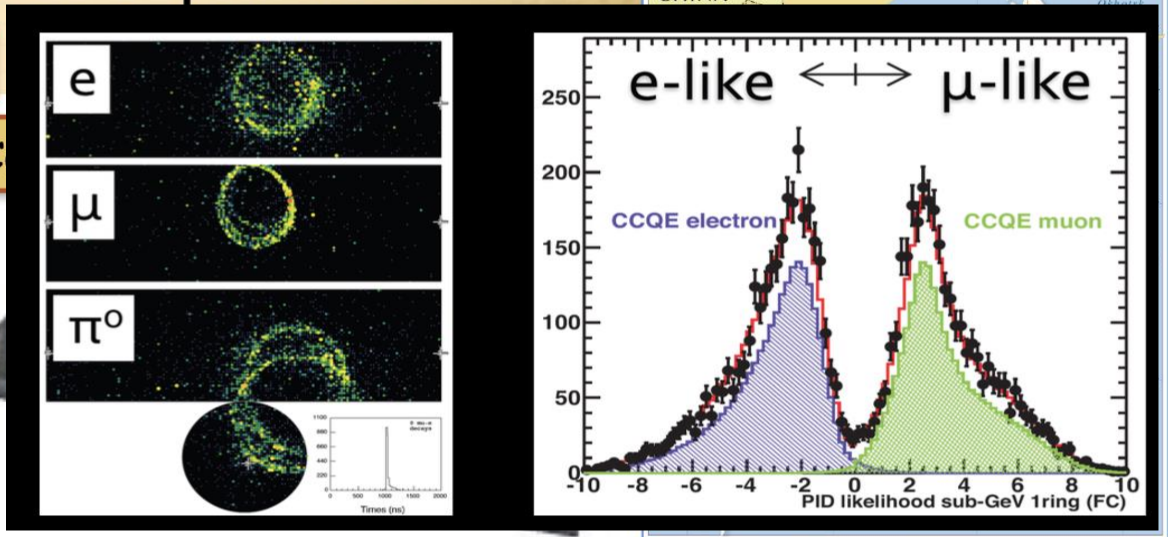

First spectroscopy of pp,7Be and pep
N h
100 200 300 400 500 600 700 800 900
Counts / (day x 100 ton x N h)
10
1
10−1
10−2
10−3
210Po
210Bi
14C
85Kr
11C
pile-up
ext bkg
Total fit: p-value=0.7
pp
7Be
CNO
pep
8B
500 1000 1500 2000 2500
Energy (keV)
210 Po
14C
210 Bi
85Kr
Residue despite the radiopurity record
Pile-up due to the 14C rate


Earth orbit is an ellipse
Residual [cpd/100t]
5
0
−5
0 500 1000 1500 2000 2500 3000 3500
Residuals

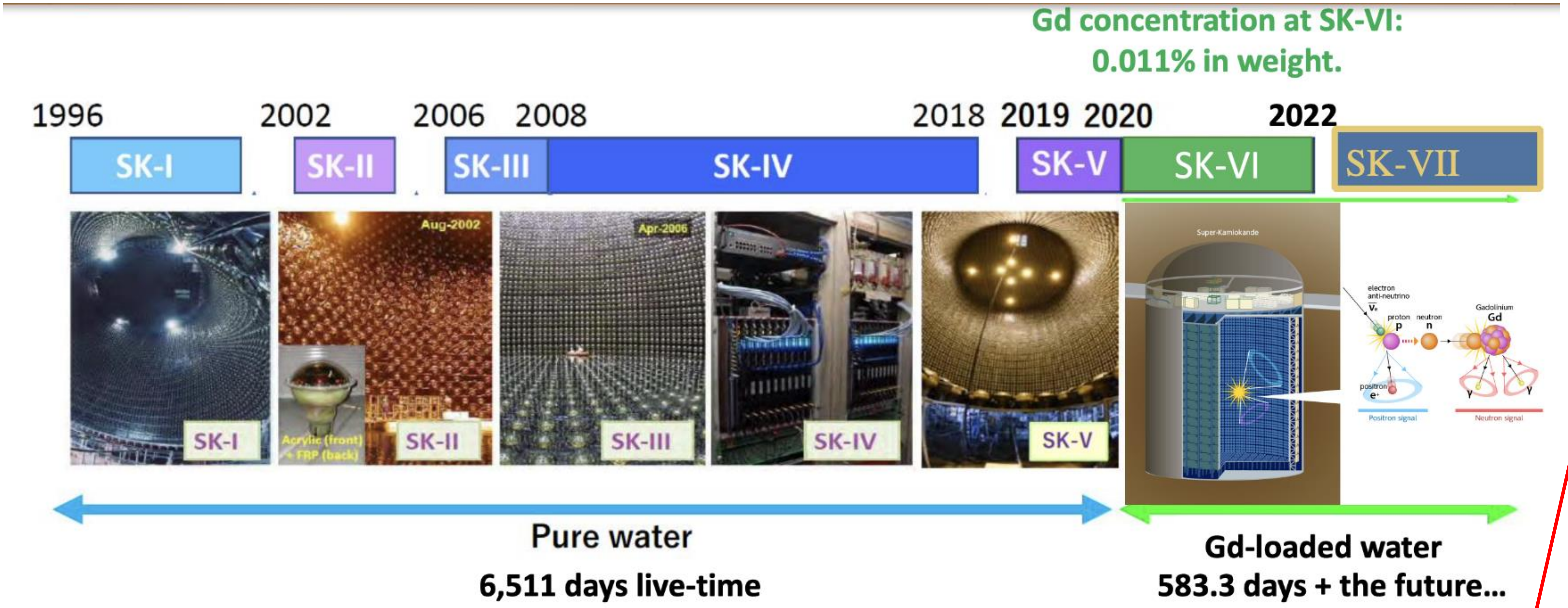
Super-Kamiokande [Japan, 1996-]

The Super-Kamiokande experiment





- 1000 m under the Ikenoyama-Mt
- 50 kton of pure water (until 2020 when Gd sulfate was added inside)
- **~11100 inner detector (ID) PMT's (~50cm ϕ)**
- **1885 outer detector (OD) PMT's (~20cm ϕ)**
- Detection technique based on the Cherenkov radiation
- Direction and particle ID determined from the ring pattern: e-like vs μ-like
- **Multipurpose machine: Nucleon Decay, Solar and Supernova Neutrinos, Atmospheric Neutrinos, Far detector for T2K**

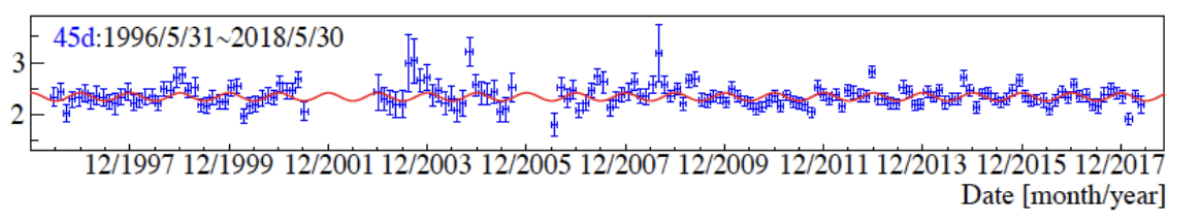


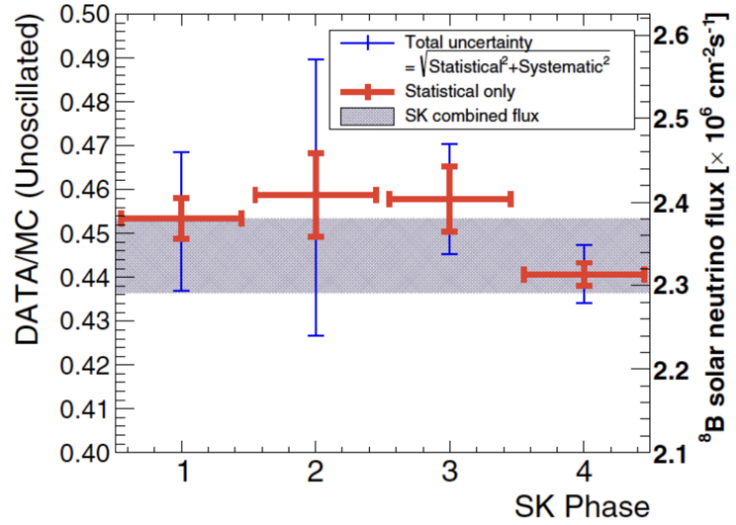
SK VIII
last week

TIME VARIATIONS OF ^{8}B FLUX

REF. 4,5

Very precise rate measurement, consistent among various phases

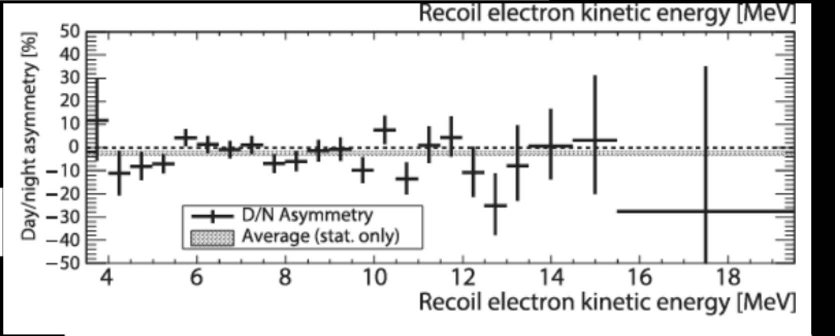




Day/night Asymmetry

SK-IV only, calc.

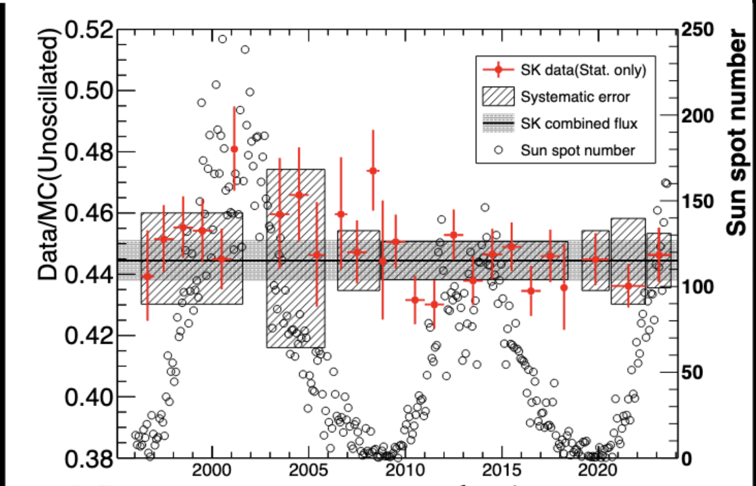
$$A_{D/N}^{\text{SK-IV, calc}} = -0.025 \pm 0.012(\text{stat.}) \pm 0.014(\text{syst.}).$$



SK I-IV combined fit, > 3 σ

$$A_{D/N}^{\text{SK, fit}} = -0.0286 \pm 0.0085\,(\text{stat.}) \pm 0.0032\,(\text{syst.}).$$

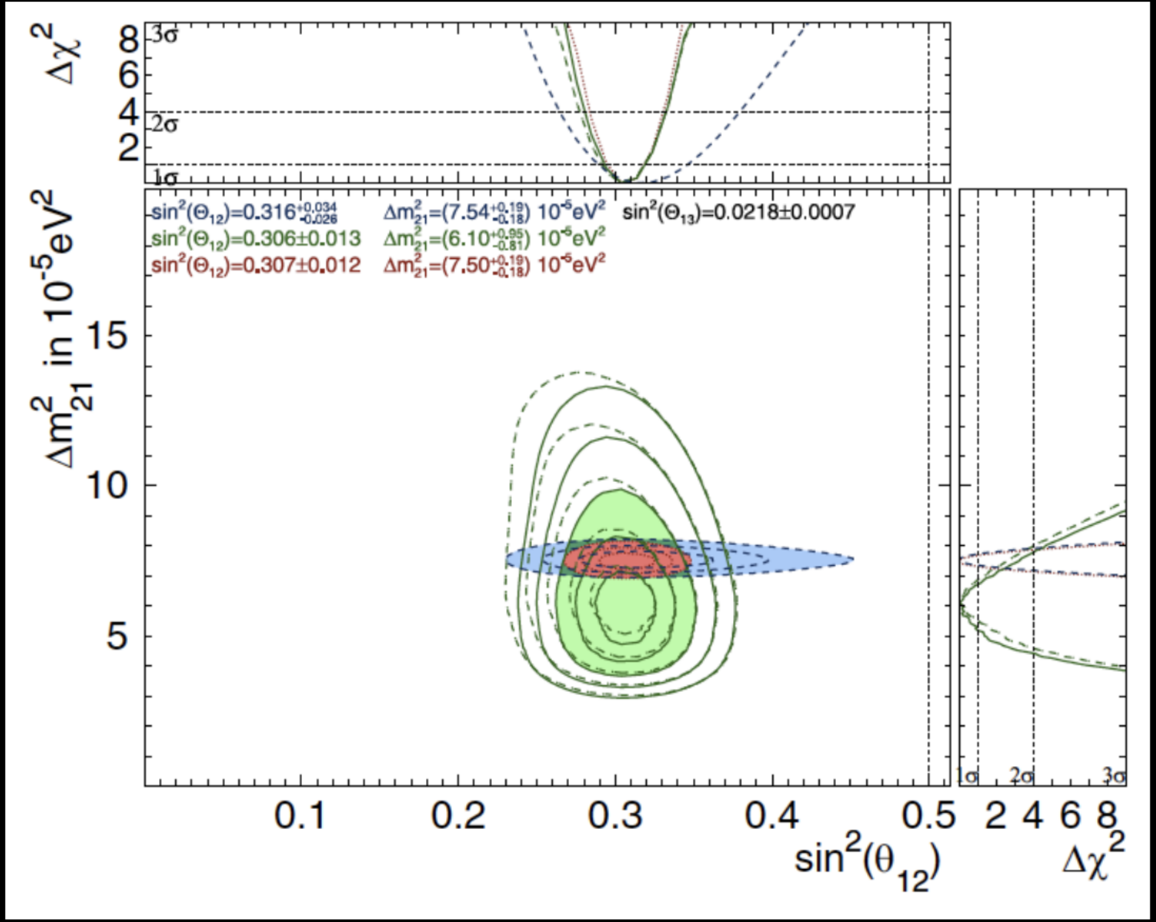
No statistically signicant time variations beyond eccentricity and day/night (compatible with MSW oscillations)



No sunspot correlation

SK OSCILLATIONS GLOBAL FIT

REF. 4



SK fit, fixed θ_{13}

- Solar best-fit value updated to:

$$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5} eV^2$$

- ~1.5 σ away from KamLAND

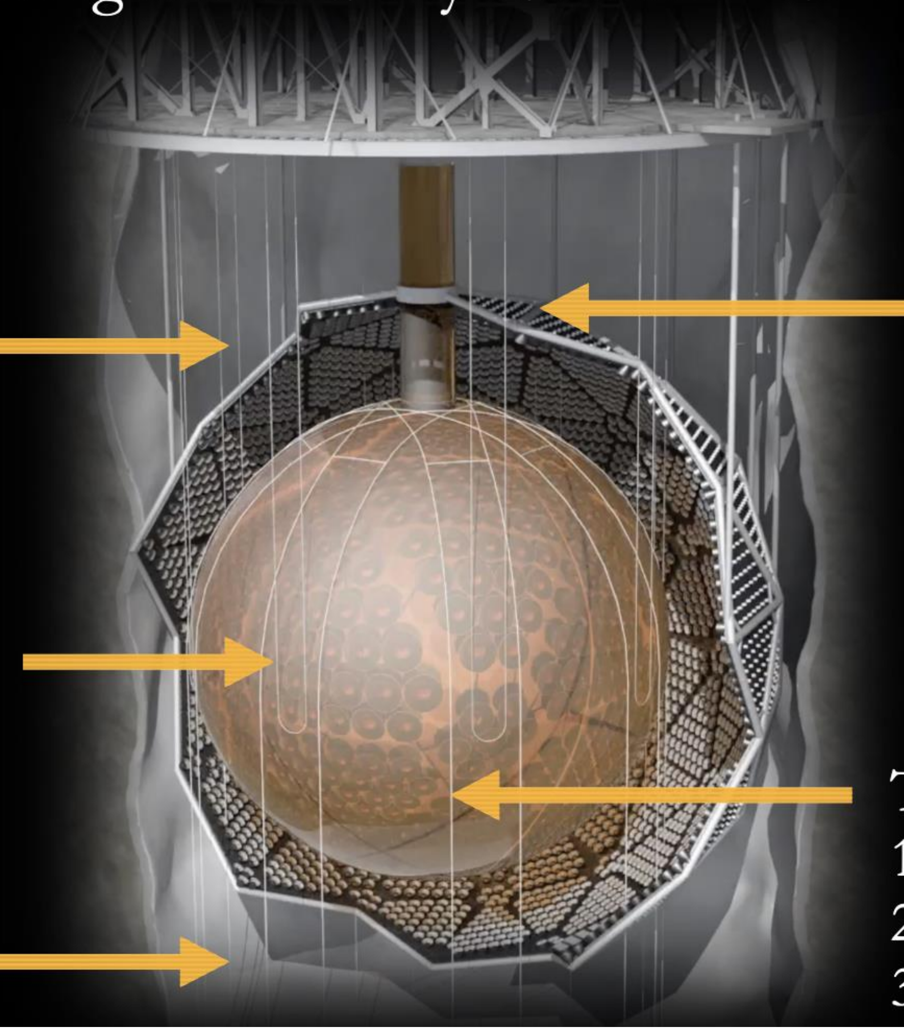
SNO+ [Canada, 2017-]

THE SNO+ EXPERIMENT

REF. 6

Repurposing the Sudbury Neutrino Observatory (SNO) detector

2 km underground
~70 muons/day



Rope system
Hold-up and -down
Low Radioactivity

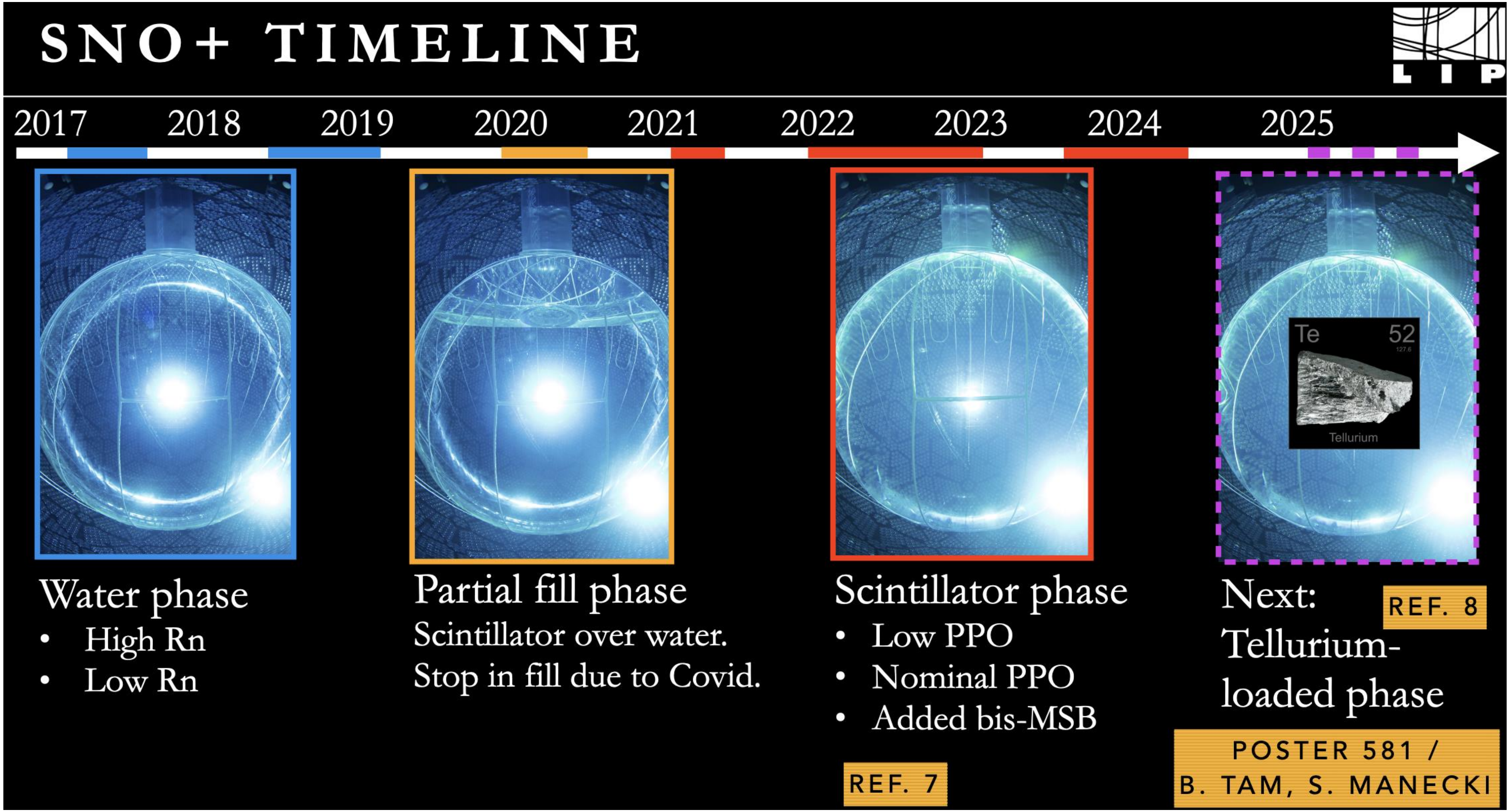
~9300 PMTs

Acrylic Vessel (AV)
12 m diameter

Ultra-Pure
Water

Purification plant

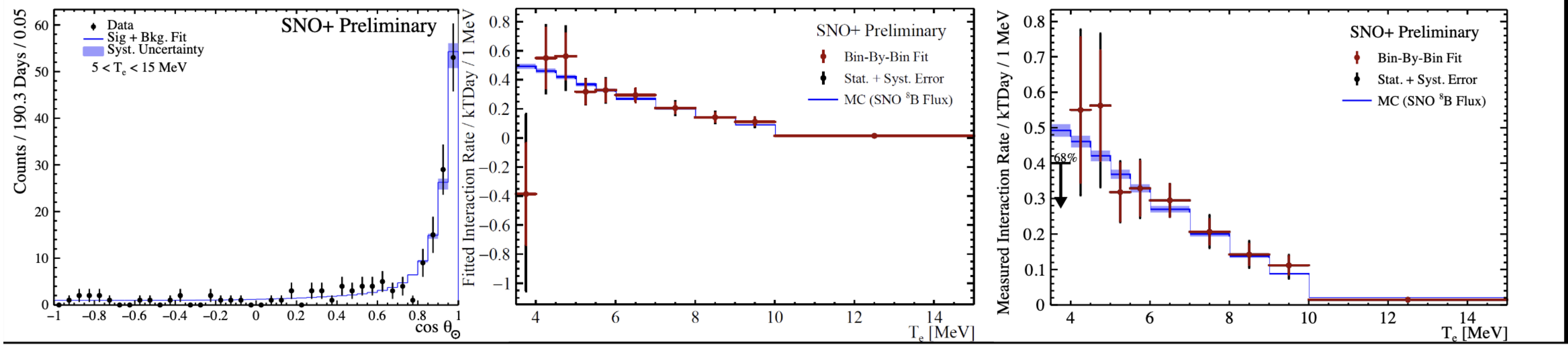
Target Material
1. Water: 905 tonnes
2. LAB Scintillator: 780 tonnes
3. Tellurium loading: +3.9 tonnes


SNO+ TIMELINE
LIP
2017
2018
2019
2020
2021
2022
2023
2024
2025
Te
52
Tellurium
Water phase
• High Rn
• Low Rn
Partial fill phase
Scintillator over water.
Stop in fill due to Covid.
Scintillator phase
• Low PPO
• Nominal PPO
• Added bis-MSB
REF. 7
Next:
Tellurium-
loaded phase
REF. 8
POSTER 581 /
B. TAM, S. MANECKI

SOLAR NEUTRINOS, WATER PHASE

- New analysis of 126.6 kt.days, including 190.3 days of low background data
  - Radon in water ~6×10^{-15} gU/g
  - Lowest background for water Cherenkov detectors > 5 MeV: 0.32 ± 0.07 ev/kt.days
- Results
  - 3.5 MeV threshold, but large uncertainties in first bins
  - Best-fit flux consistent (inc. oscillations) with other experiments, and HZ and LZ solar models

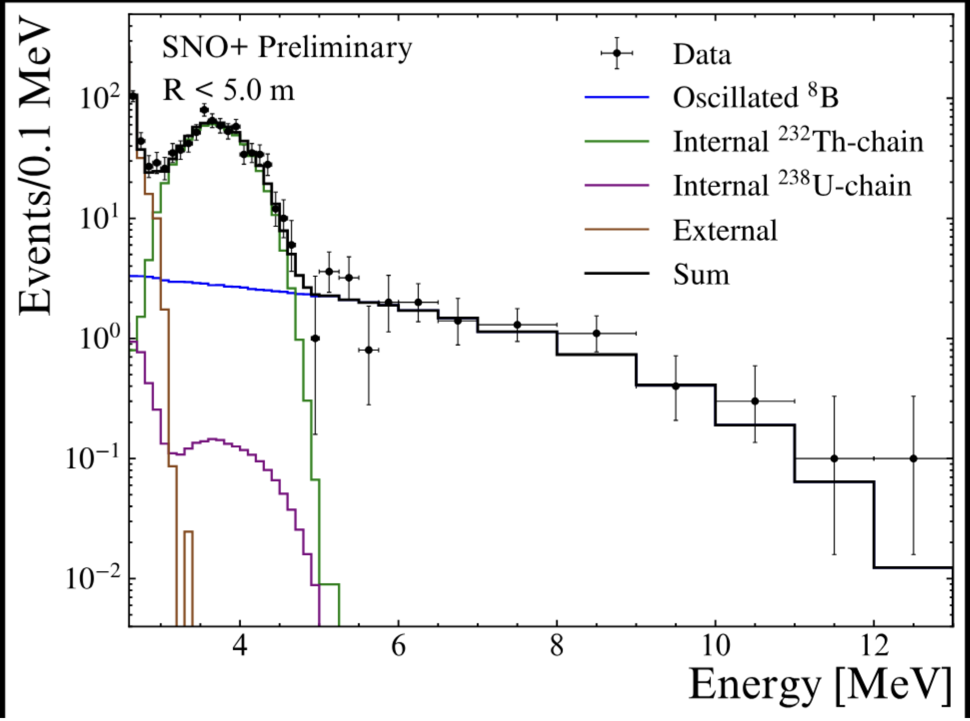
$$\left(5.36^{+0.41}_{-0.39}(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})\right) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

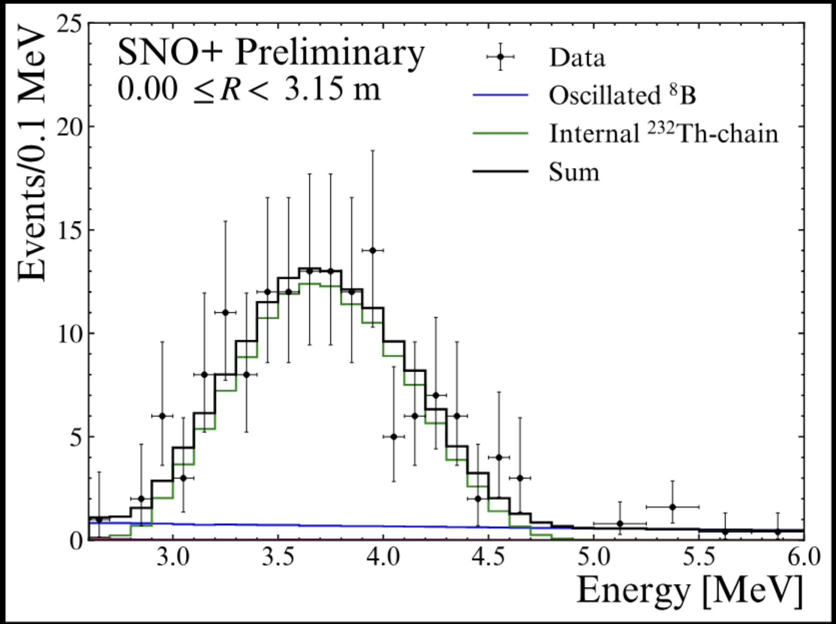


SOLAR NEUTRINOS, SCINT. PHASE

POSTER 544 / D. COOKMAN

- Analysis of ^8B ES interactions in 138.9 live days of scint. data
- Fitted oscillation parameters compatible with global fits



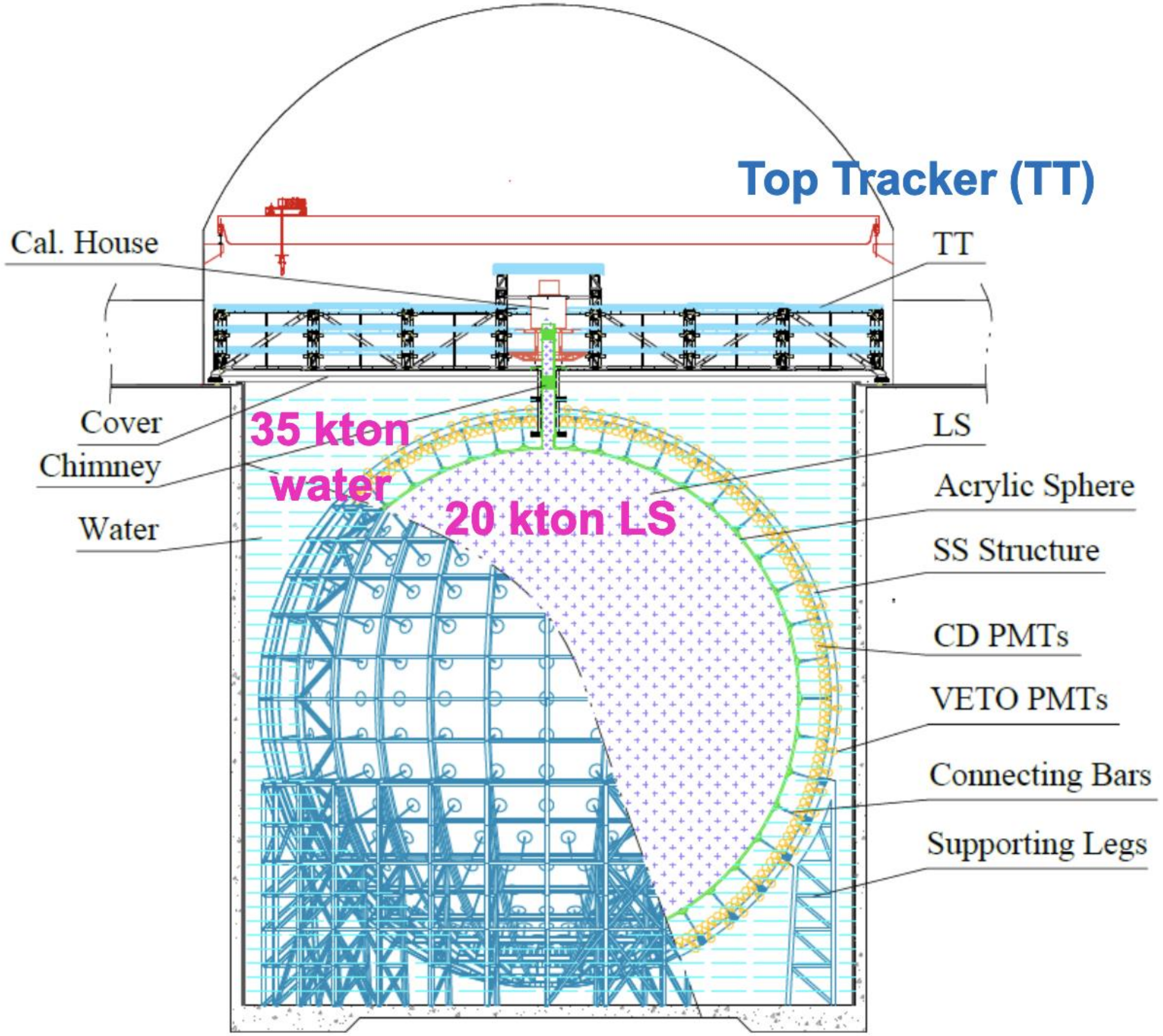


- Strict fiducial volume cut opens prospects for future sensitivity < 3 MeV !
- ^{232}Th still dominates 3-5 MeV regions, but multisite discriminant will help

POSTER 255 /A. INÁCIO, R. HUNT-STOKES

JUNO Detector

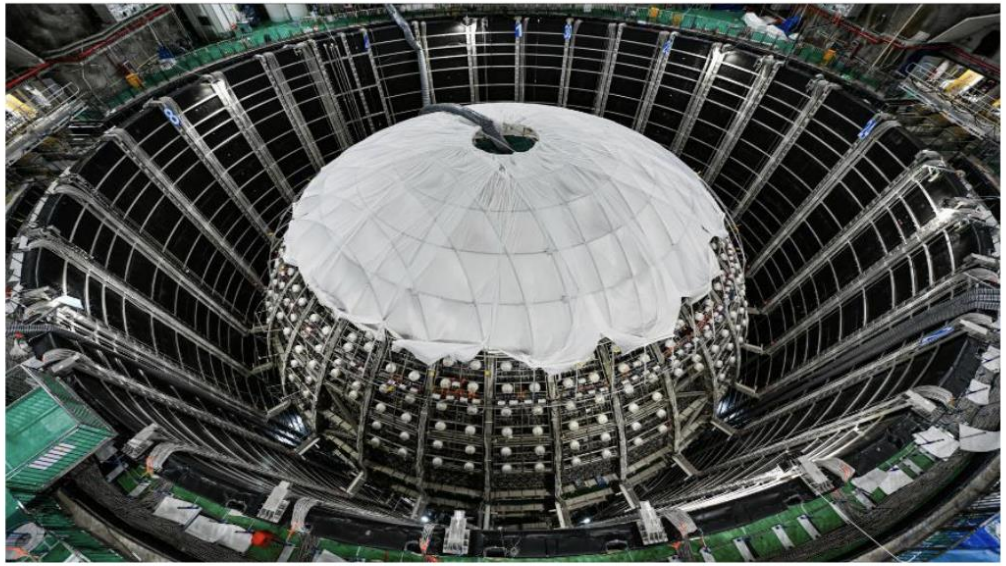
Largest liquid scintillator detector, starting this year

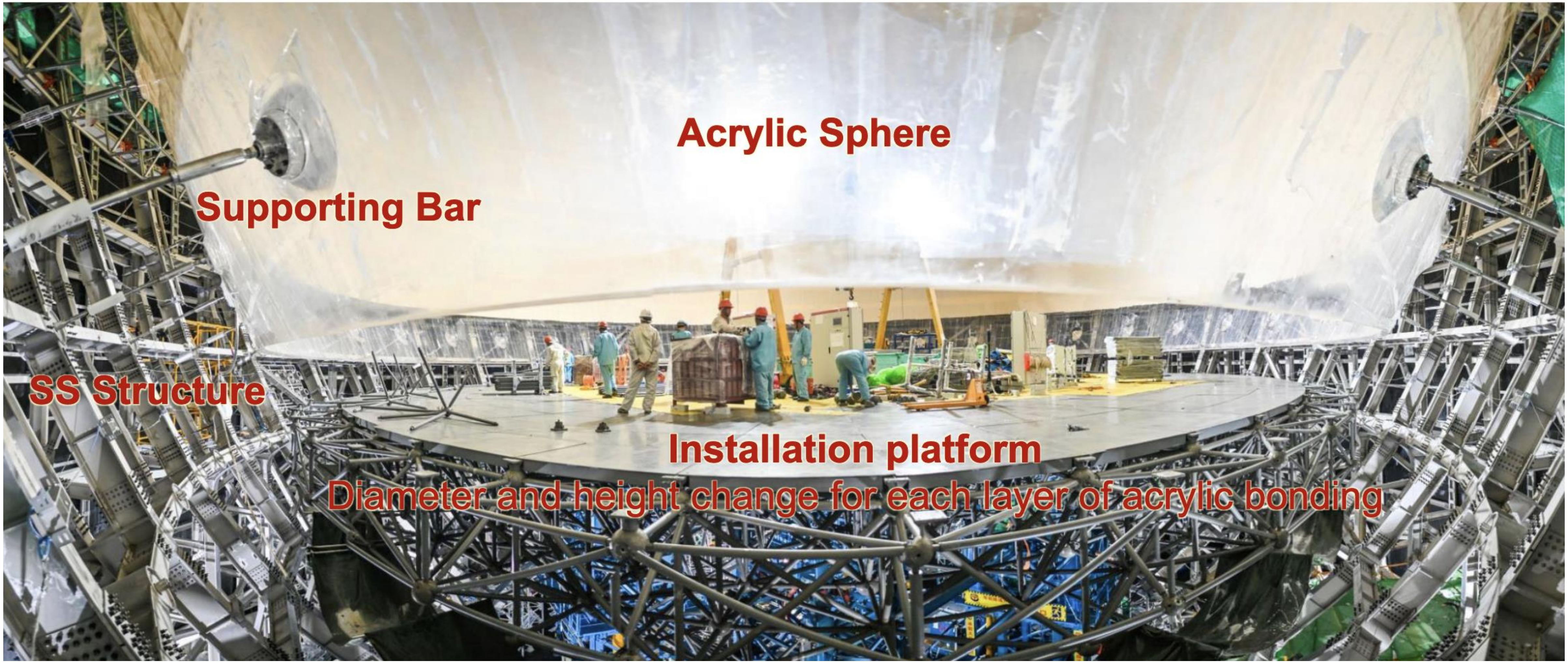


Acrylic Sphere:
- Inner Diameter (ID): 35.4 m
- Thickness:12 cm

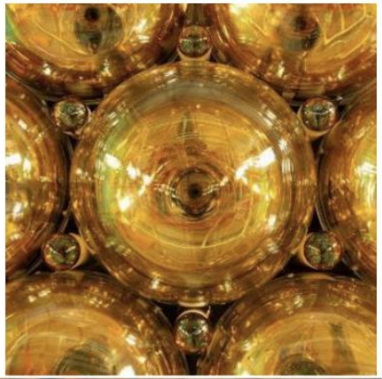
Stainless Steel (SS) Structure:
- ID: 40.1 m, Outer Diameter (OD): 41.1 m
- **17612** 20-inch PMTs, **25600** 3-inch PMTs

Water pool:
- ID: 43.5 m, Height: 44 m, Depth: 43.5 m
- **2400** 20-inch PMTs




Acrylic Sphere
Supporting Bar
SS Structure
Installation platform
Diameter and height change for each layer of acrylic bonding

PMT



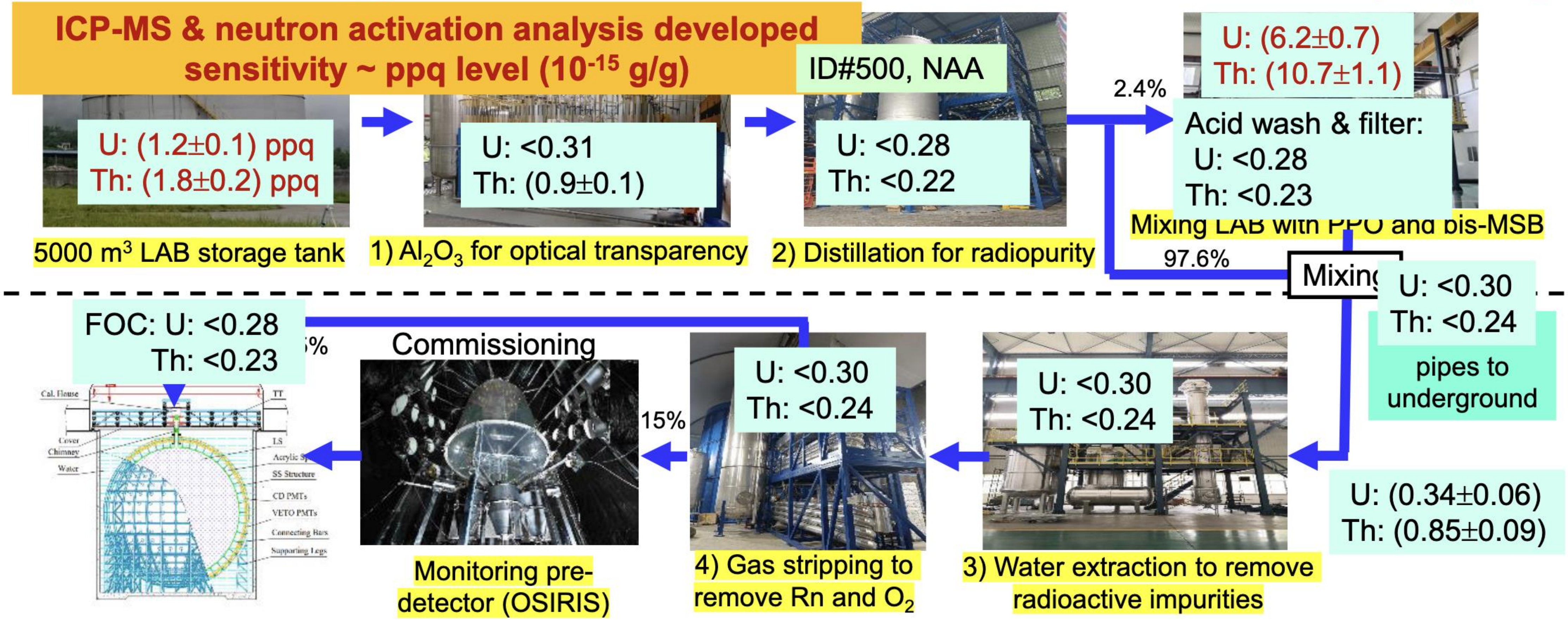
- **20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu)**
  3.1-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
  - ⇨ All PMTs delivered and their performance tested OK
- **Water proof potting** done: **failure rate < 0.5%/6 years**
- **Implosion protection: acrylic top & SS bottom** (JINST 18 (2023), P02013)
  - ⇨ Mass production completed

	LPMT (20-in)		SPMT (3-in)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Charge Collection	Dynode	MCP	Dynode
Photon Det. Eff.	**28.5%**	**30.1%**	**25%**
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	**75%**		**3%**
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

Liquid Scintillator

ID#235, LS Purification | ID# 238, Optical charactr
ID#472, OSIRIS | ID#618, OSIRIS hardware

- **LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
  - ➩ Attenuation length: LAB > 24m, LS > 20 m
  - ➩ Minimum U/Th requirement (for NMO) < 1e-15 g/g, aiming at 1e-17 g/g for solar and future 0νββ
- **All 60 ton PPO delivered, U/Th < 0.1 ppt**
- **Bis-MSB complete production soon (< 5 ppt)**
- **20 kton LAB to be delivered, U/Th ~ 1 ppq**
- **Plants commissioned individually and jointly**

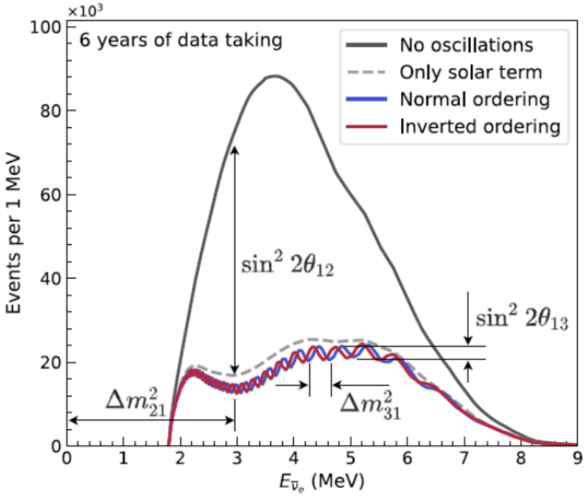


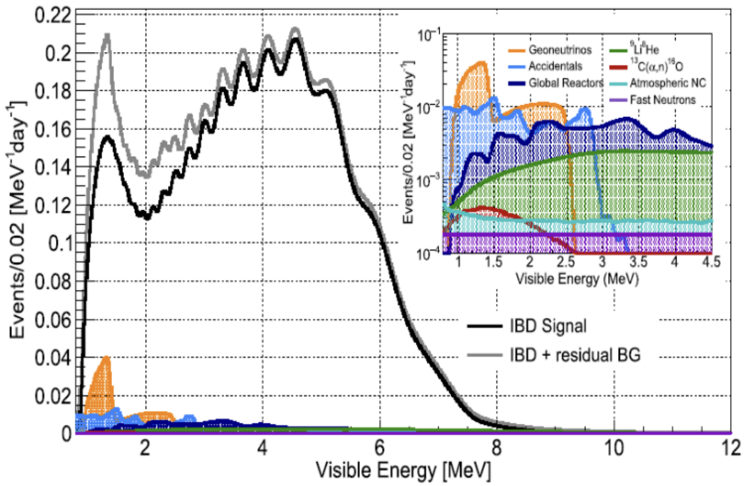
Precision Measurement of oscillation parameters

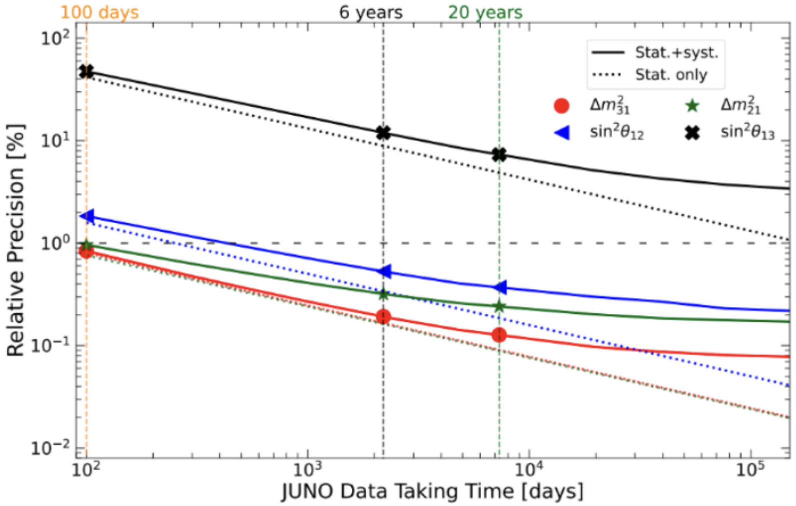
$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

ID#223, Precision Measurement

Chin. Phys. C46 (2022) 12, 123001







	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

$\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, leading measurements in 100 days; precision <0.5% in 6 years

reactor neutrinos

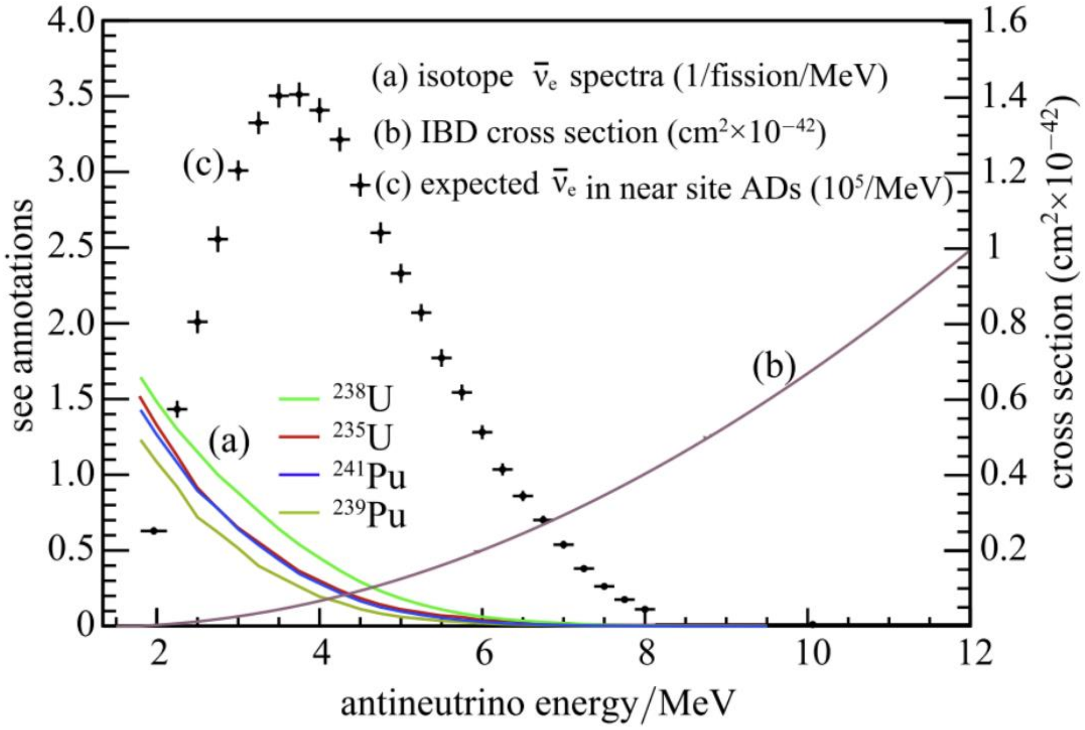
- Daya Bay

Reactor neutrinos

The strongest artificial neutrino source on the Earth

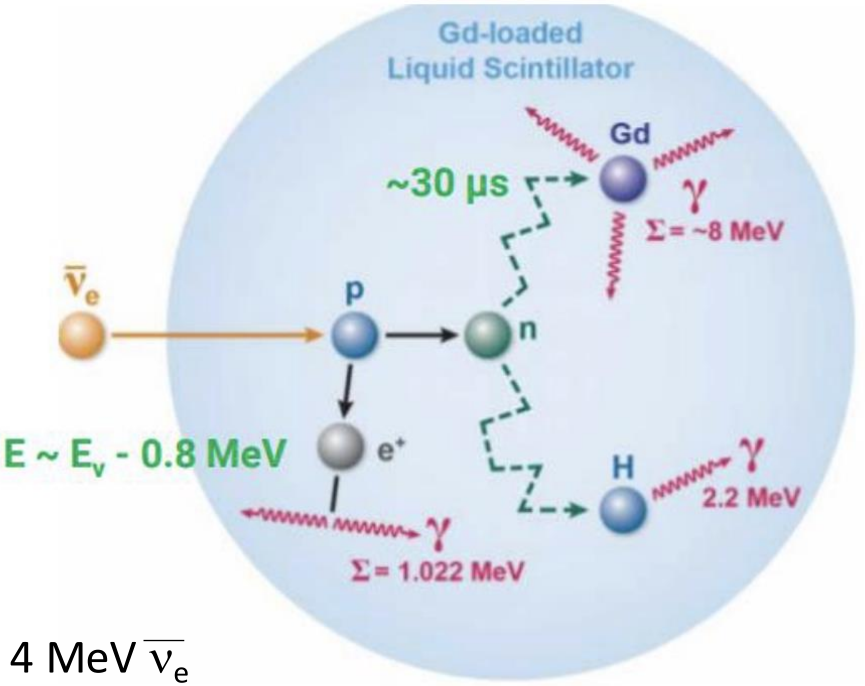
2×10^{20} ν's per second per GW thermal power, >99.7% from $^{235,238}U$ and $^{239,241}Pu$

Easy to detect via the Inverse Beta Decays (IBD)



Daya Bay, Chinese Physics C Vol. 41, No. 1 (2017) 013002

Correlated signals from e^+/neutron captures



- 4 MeV $\bar{\nu}_e$
- disappearence experiments

3

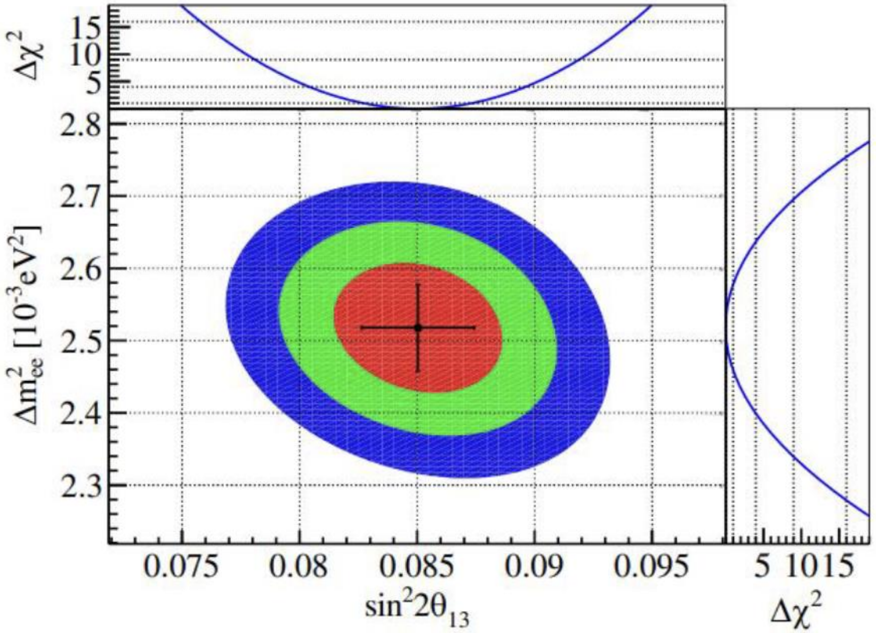
θ_{13} with nGd -- Daya Bay

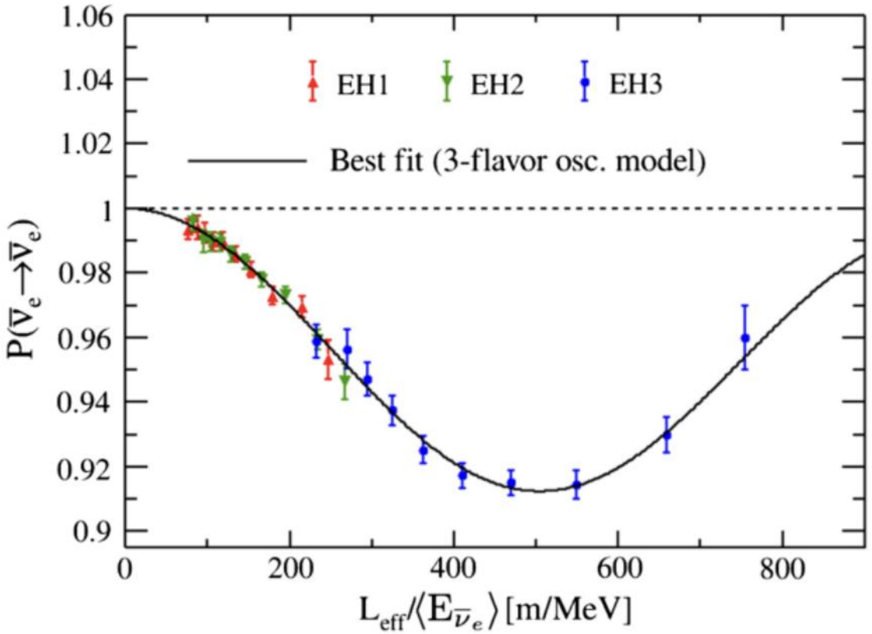
Daya Bay reported the precision measurement with 3158-days full dataset in 2022

$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ — precision 2.8%

$\Delta m^2_{32} = 2.466 \pm_{NO} 0.060\ (-2.571 \pm_{IO} 0.060) \times 10^{-3}\ eV^2$ — precision 2.4%

Systematics, mainly detector differences, contributed about 50% in the total error





Global comparison θ_{13}

Daya Bay leads the precision measurement, nGd+nH gives 2.6% precision

By combining all reactor results, ultimate precision of $\sin^2 2\theta_{13}$: 2.5%

Consistent results from reactor and accelerator experiments

Note: average is error weighted average assuming no correlation

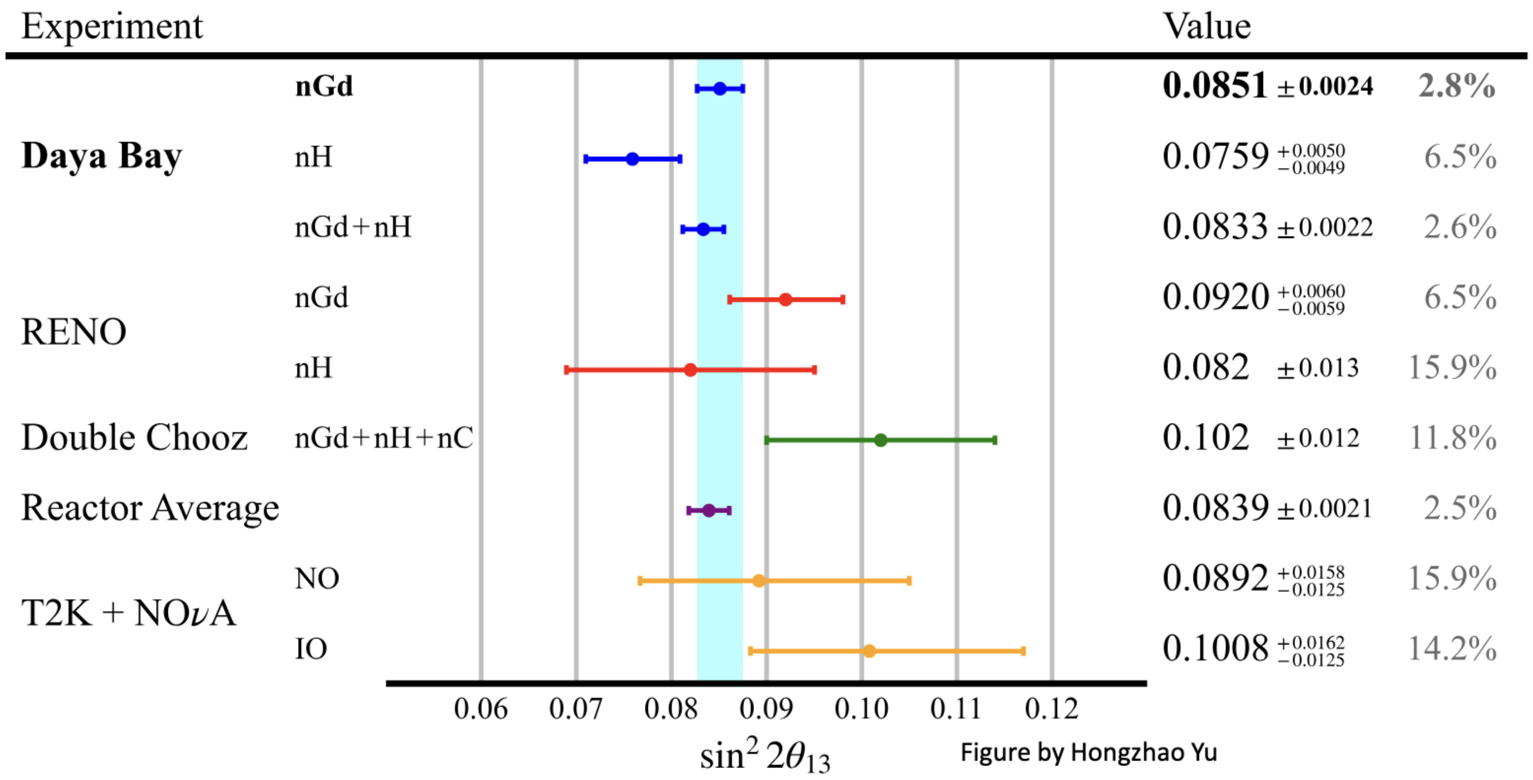


Figure by Hongzhao Yu

Global comparison Δm^2

Consistent results from reactor and accelerator experiments

Reactor weighted average 2% dominated by Daya Bay

Accelerator weighted average 1.5% (SK+T2K) + NOvA + MINOS + IceCube

Note: average is error weighted average assuming no correlation

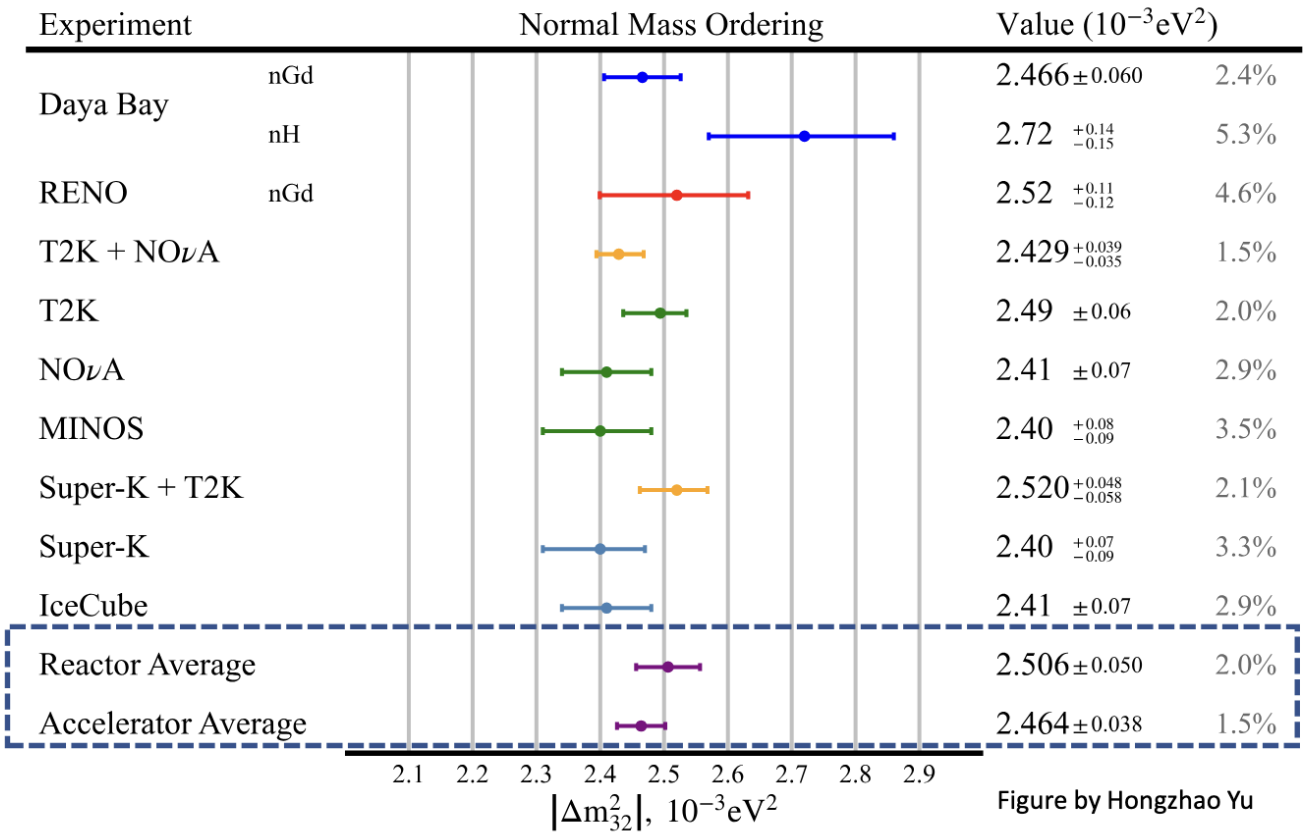
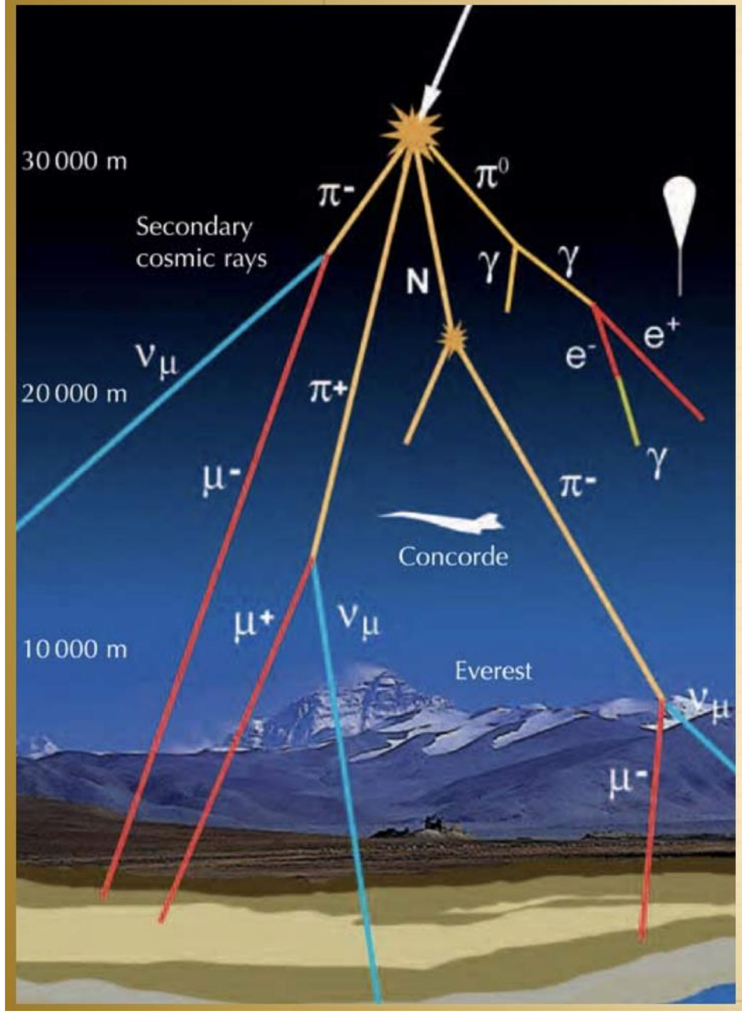


Figure by Hongzhao Yu

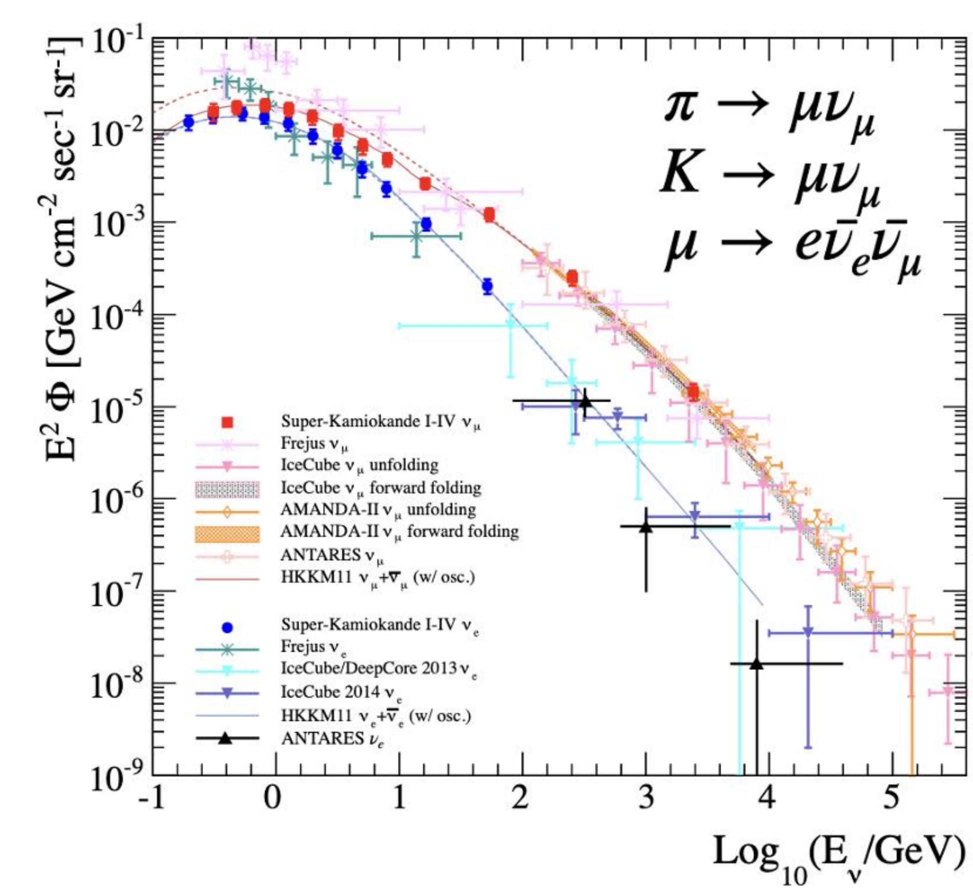
atmospheric neutrinos

- Super-Kamiokande

Atmospheric neutrinos

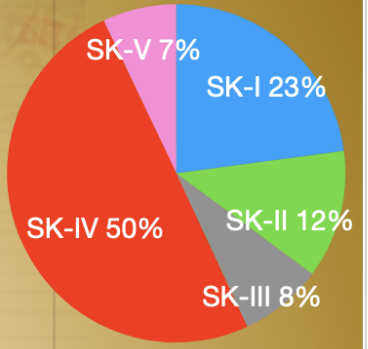


- Neutrinos are produced when cosmic particles, mainly protons, interact with the nuclei in the atmosphere:
  - **with wide range of energy MeV- TeV produced isotropically about the Earth atmosphere**
  - **travel length varies 10km ~13000 km**



E. Richard et al. (SK), PRD 94 (2016) 5

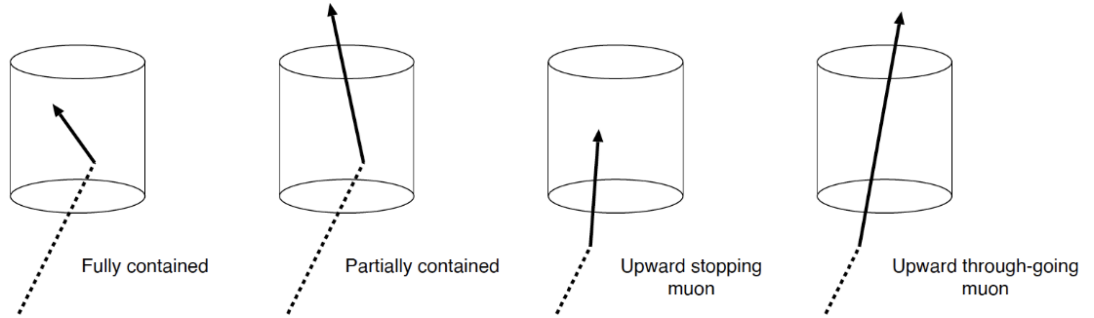
Zenith angle atmospheric neutrino oscillation analysis

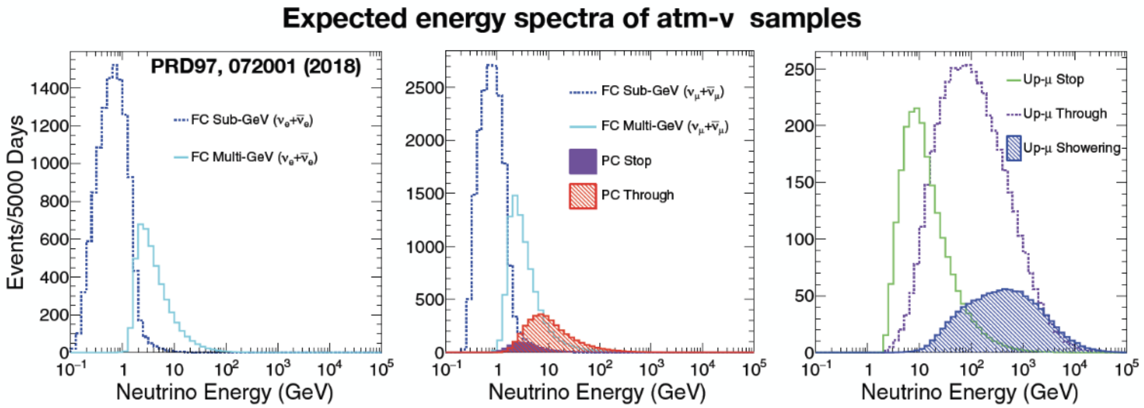


- Latest results with **full SK pure water phase (SK1-5)**:
  - Latest publication - Phys. Rev. D 109, 072014 - Published on 24 April 2024
  - Previously published results: Phys. Rev. D97, 072001 (2018)

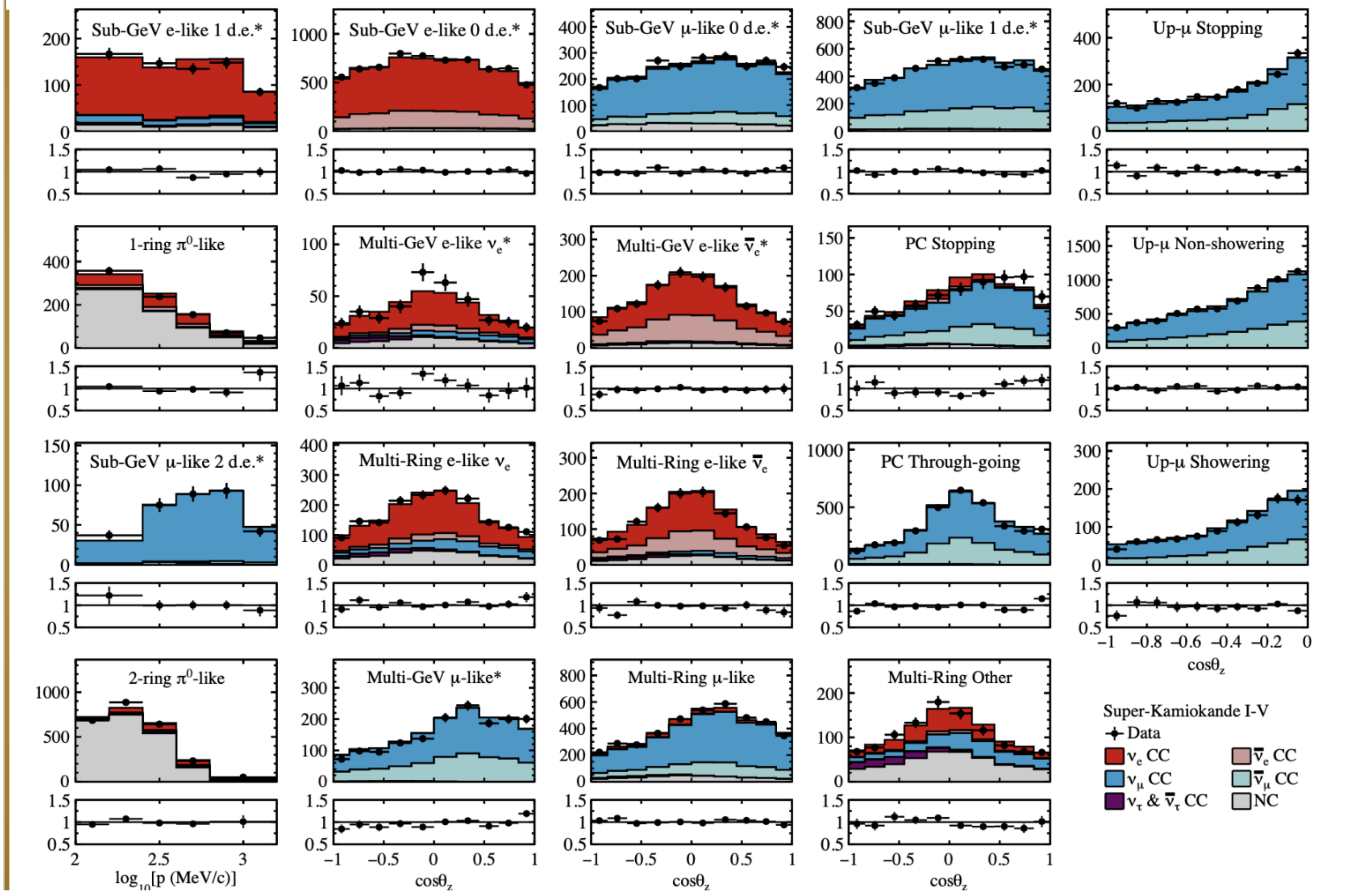
- Updates since the previous analysis:
  - **Expansion of fiducial volume and more lifetime: 6511 days, 484 kt·yr in total +50% of statistics**
  - **Event selection with neutron tagging on hydrogen (SK4-5)**
  - New multi-ring event classification using a Boosted Decision Tree (BDT)
    - Improved charged current/neutral current separation
- Atmospheric ν oscillation fit with external constrains
  - θ_{13} from reactors

★Atmospheric neutrino events at Super-K are classified into several categories:





Zenith angle or momentum distributions

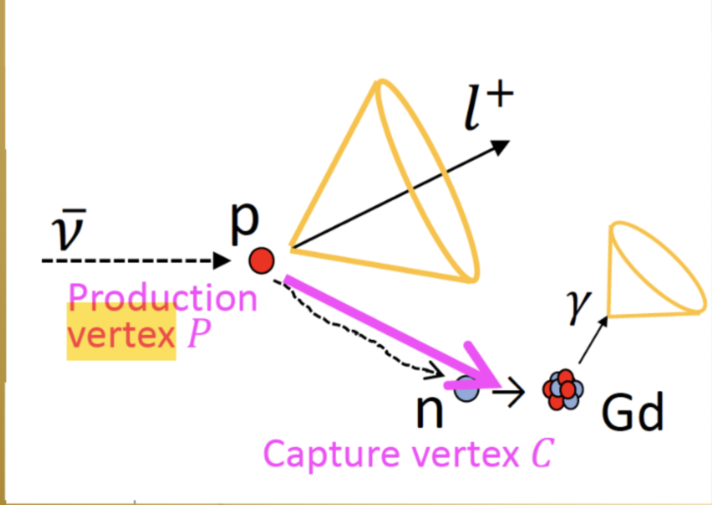


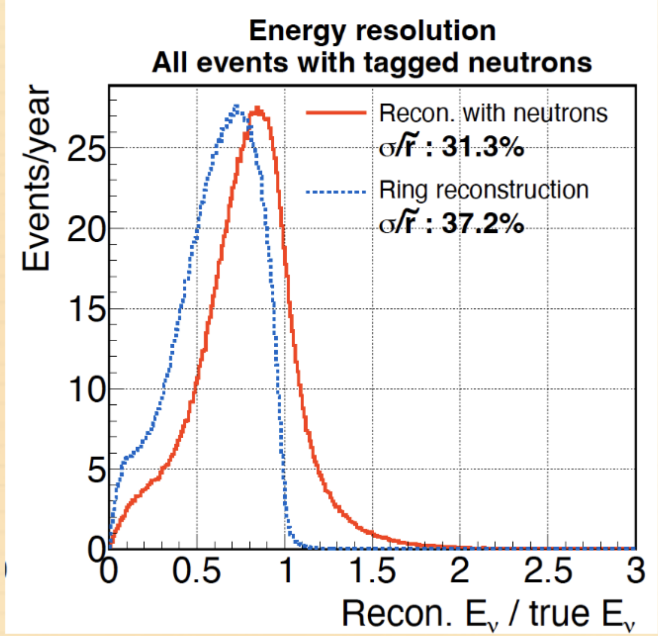
- Zenith angle or momentum distributions for the **19 analysis samples without neutron tagging.**
- FC: Sub-GeV and Multi-GeV samples with SK-I~III data, no neutron tagging included*
- PC, UPMU, FC π^0, FC Multi-Ring samples use SK-I~V data,

8

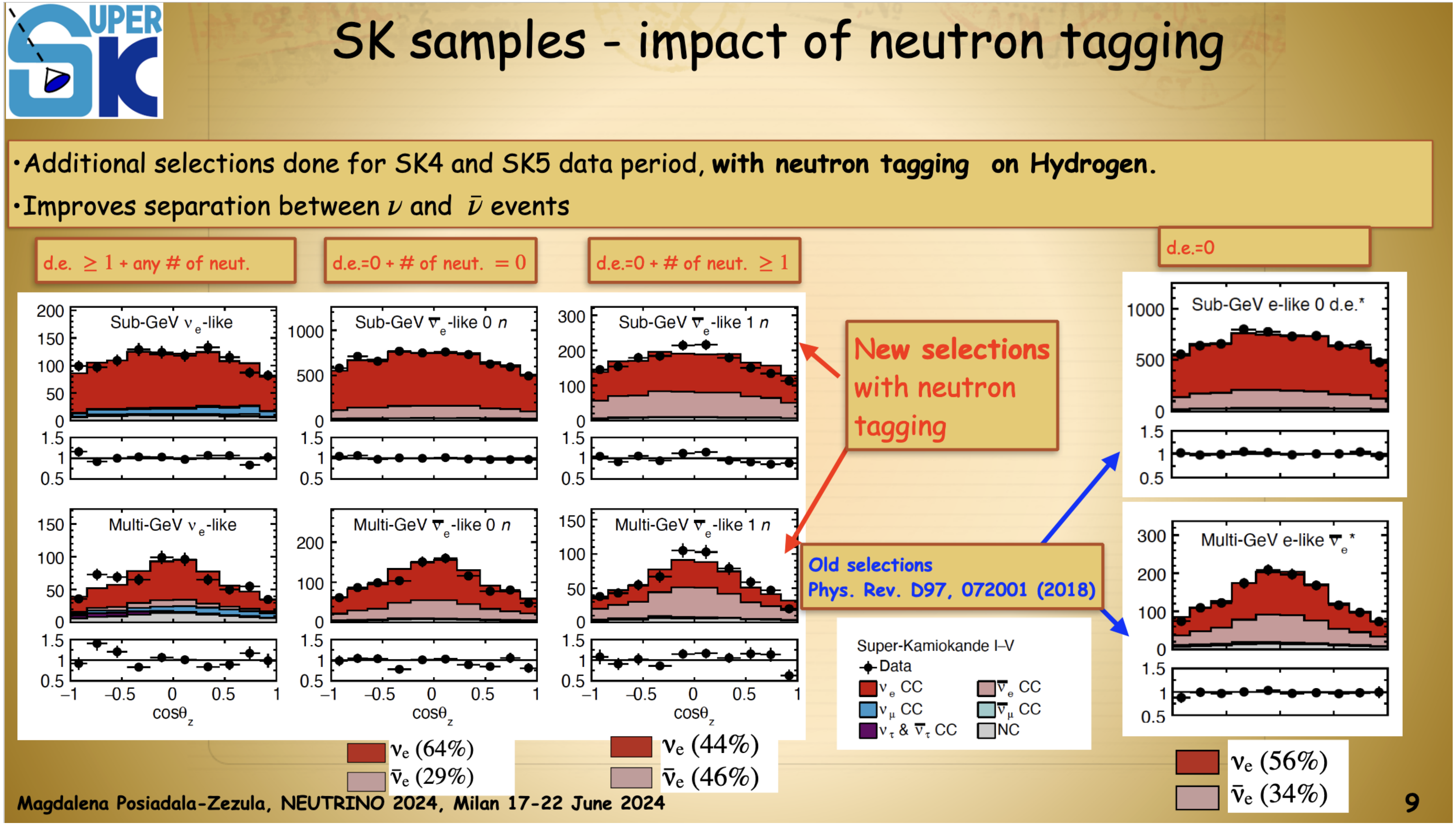
SK6 oscillation analysis with neutron tagging

- Why neutrons are useful in the atmospheric oscillation analysis?
  - they **improve the $\nu/\bar{\nu}$ separation,**
  - they **improve the reconstruction of E_ν and neutrino direction $\vec{d_\nu}$** with information on neutron momentum $\vec{p_n}$ (estimated from neutron travel distance @ the SK- assuming $\vec{p_n} \propto |\overrightarrow{PC}|$)



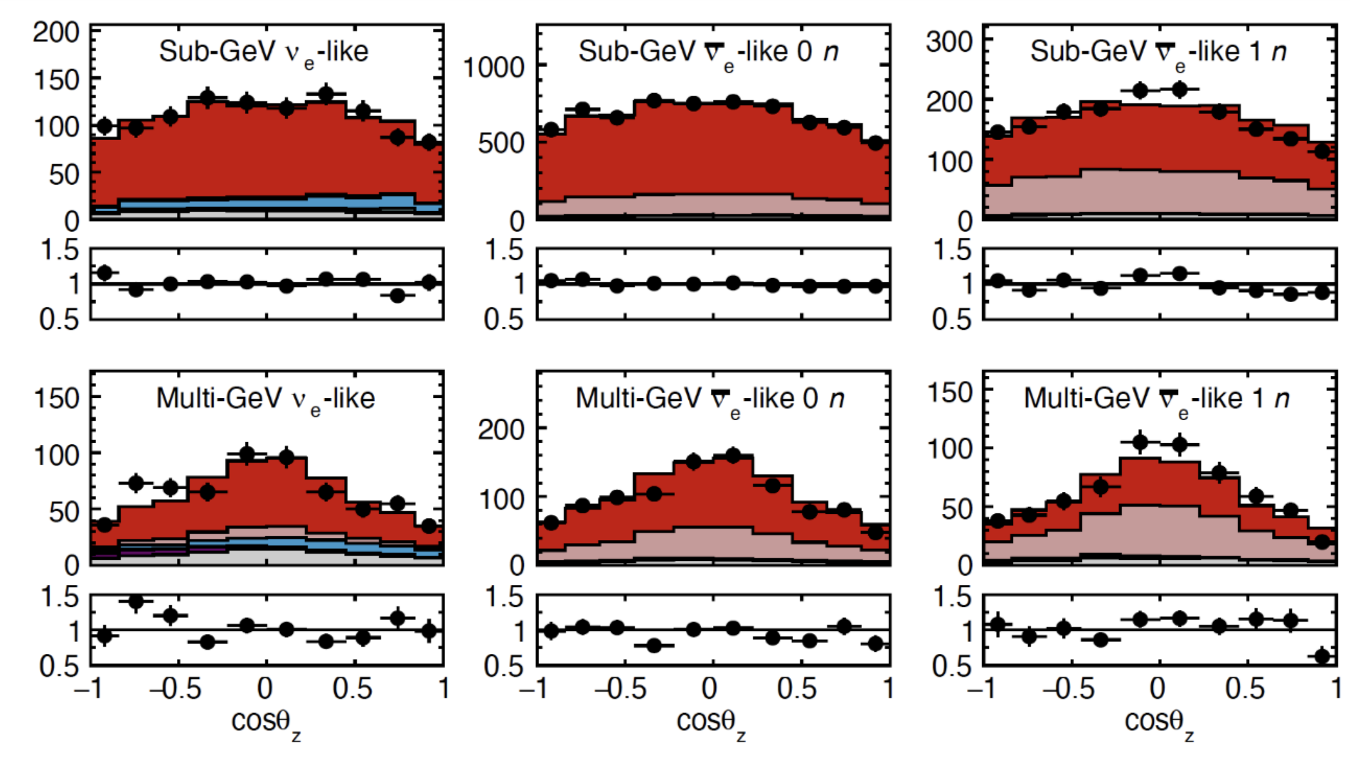


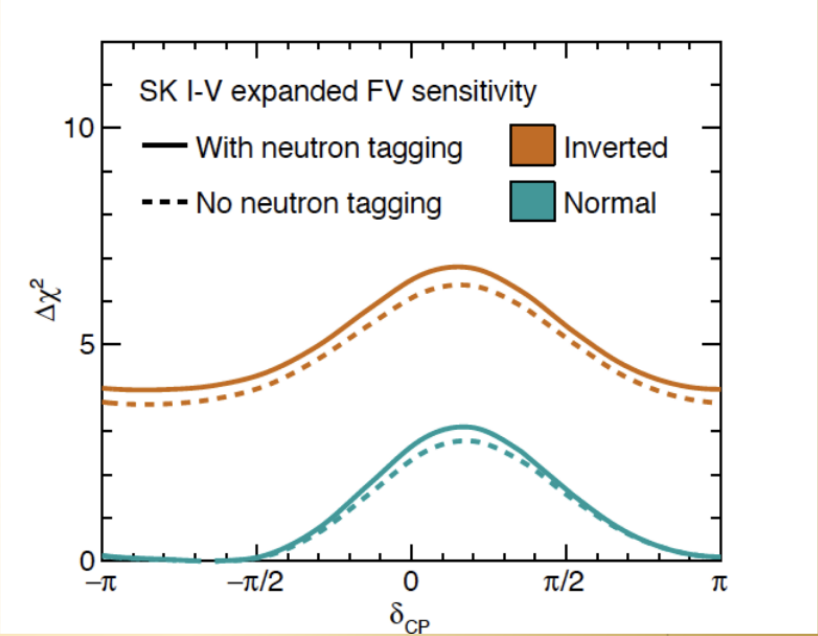
- **See the poster #112 by Shintaro Miki: Atmospheric Neutrino Oscillations in SK-Gd**


SK samples - impact of neutron tagging
•Additional selections done for SK4 and SK5 data period, with neutron tagging on Hydrogen.
•Improves separation between ν and ν̄ events
d.e. ≥ 1 + any # of neut.
d.e.=0 + # of neut. = 0
d.e.=0 + # of neut. ≥ 1
d.e.=0
Sub-GeV ν_e-like
Sub-GeV ν̄_e-like 0 n
Sub-GeV ν̄_e-like 1 n
Multi-GeV ν_e-like
Multi-GeV ν̄_e-like 0 n
Multi-GeV ν̄_e-like 1 n
cosθ_z
Sub-GeV e-like 0 d.e.*
Multi-GeV e-like ν̄_e*
New selections with neutron tagging
Old selections
Phys. Rev. D97, 072001 (2018)
Super-Kamiokande I–V
Data
ν_e CC
ν̄_e CC
ν_μ CC
ν̄_μ CC
ν_τ & ν̄_τ CC
NC
ν_e (64%)
ν̄_e (29%)
ν_e (44%)
ν̄_e (46%)
ν_e (56%)
ν̄_e (34%)
Magdalena Posiadala-Zezula, NEUTRINO 2024, Milan 17-22 June 2024
9

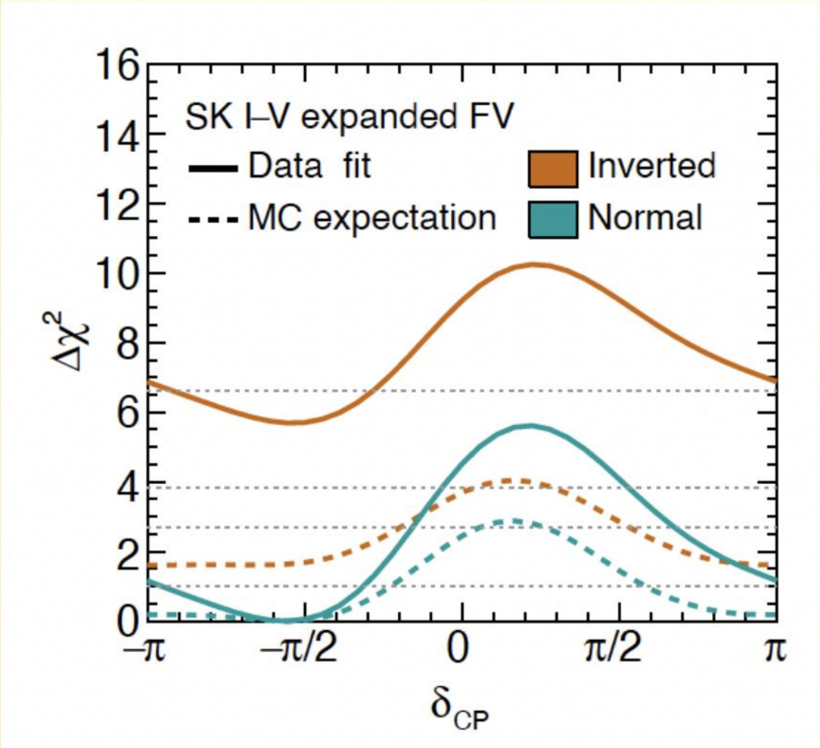
SK samples - impact of neutron tagging

- Additional selections done for SK4 and SK5 data period, **with neutron tagging on Hydrogen**.
- Improves separation between ν and $\bar{\nu}$ events





SK atmospheric ν results

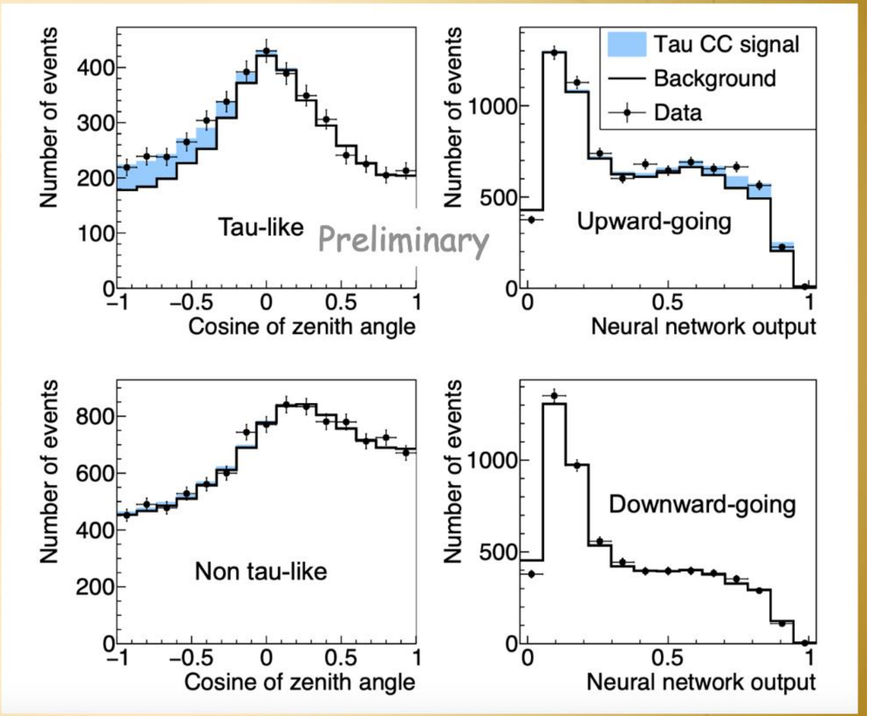


Full SK pure water phase (SK1-5) best fit results:

- Normal ordering, $\delta_{CP} \simeq -\pi/2$,
- $\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3}\mathrm{eV}^2$, $\sin^2\theta_{23} \simeq 0.45$ (Lower octant)
- Mass ordering: $\Delta\chi^2_{I.O-N.O} \simeq 5.69$

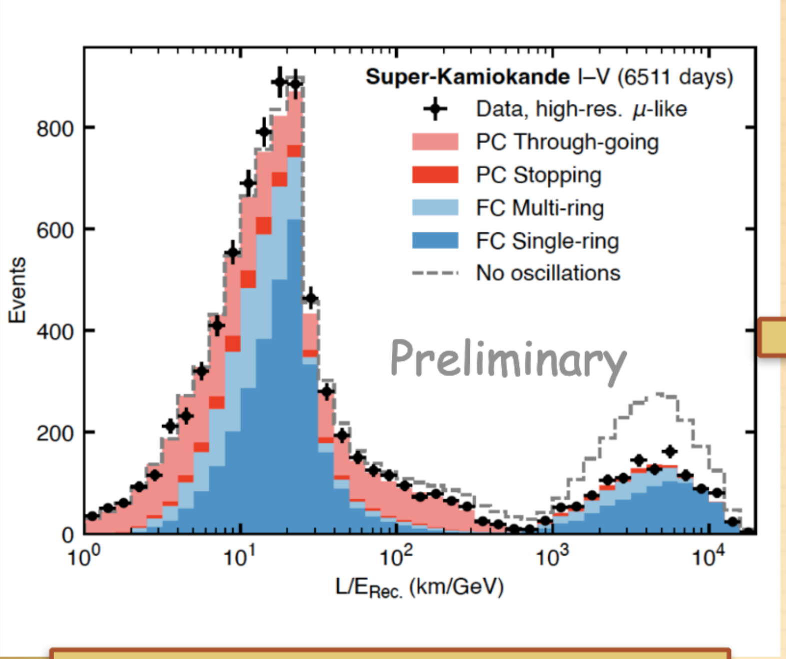
ν_τ appearance searches

- Updates since the last publication in Phys. Rev. D 98 052006 (2018)
  - Full SK pure water phases (SK1-5 data)
    - Additional 2 years of SK-IV and SK-V data added
  - Expanded fiducial volume - overall 50% more data added
- Best fit of ν_τ normalisation parameter: $\alpha = 1.359 \pm 0.289$
- Excluding no ν_τ appearance ($\alpha = 0$) at 4.8σ significance, p-value= $7.5 \cdot 10^{-7}$
- Observed # of ν_τ CC events: 428 ± 92 (normal MO)

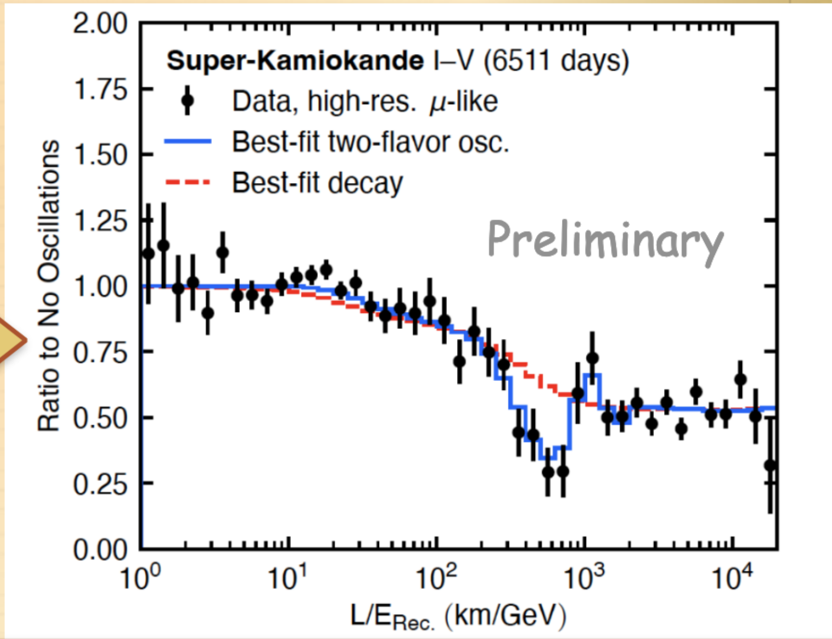


L/E analysis @ Super - Kamiokande

- Atmospheric neutrinos at SK span ~4 orders of magnitude in L/E, possible to see a complete oscillation of ν_μ **survival probability**
- Updates since the last published results in **2004 Phys. Rev. Lett. 93, 101801, SK1:**
  - Full SK pure water phases (SK-I~V data - 6511 days- $\sqrt{(\Delta\chi^2(\text{decay, 2 fl. osc.}) = 6.0\sigma)}$)
  - New L/E estimator, high- and low-resolution samples



High - resolution data/MC sample



High resolution data: best fit for two flavour oscillations vs. neutrino decay

Magdalena Posiadala-Zezula, NEUTRINO 2024, Milan 17-22 June 2024

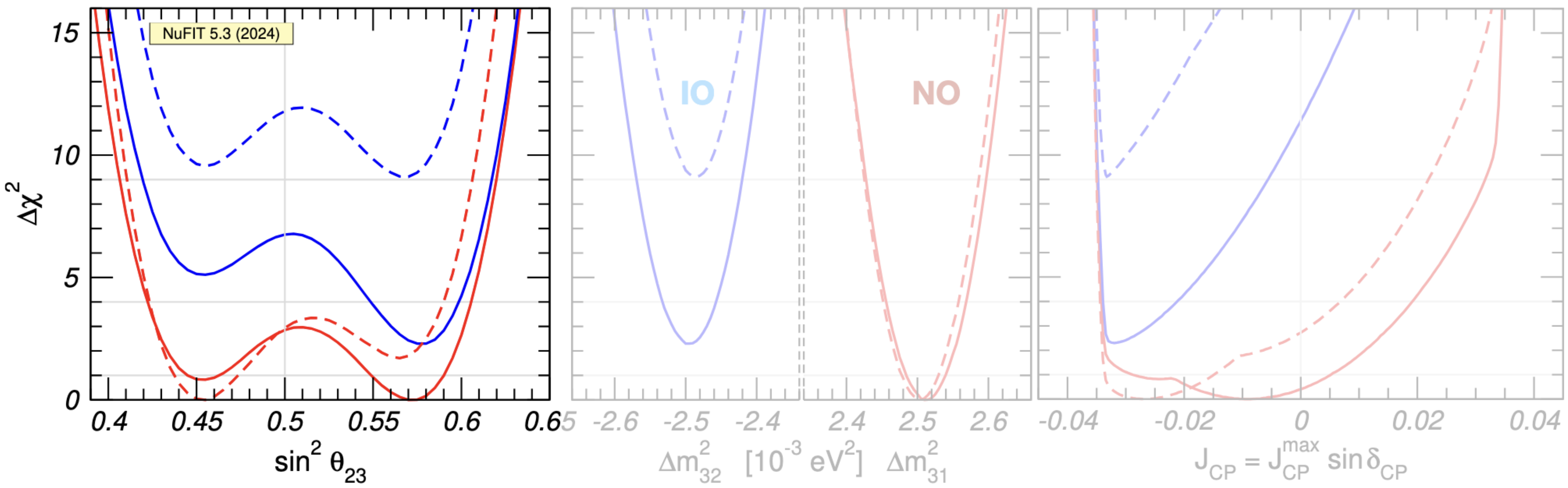
13

3ν Mixing

The **less constrained parameters** are:

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP 09 (2020)

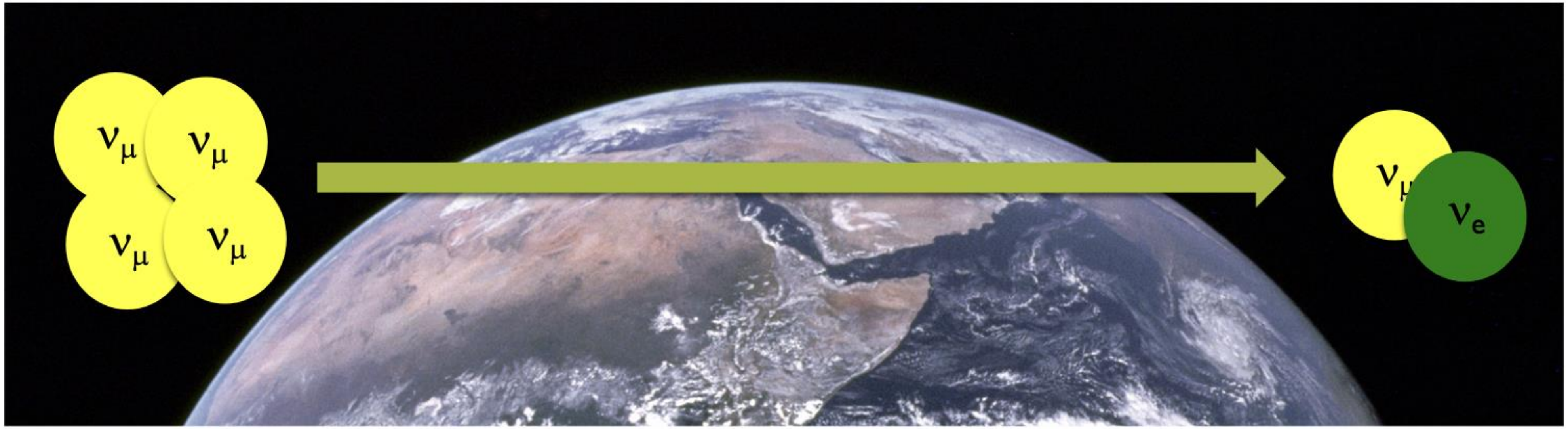
Preference for $\theta_{23} < 45$ | Preference for NO at 2σ | Preference for CP-violation

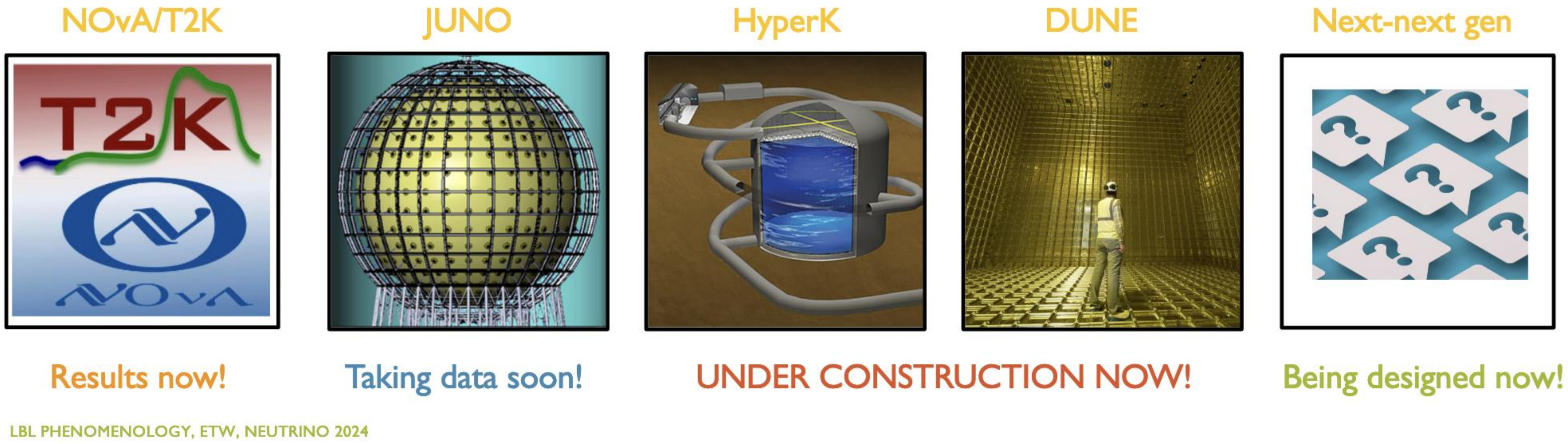


long baseline

- T2K
- NOvA
- DUNE
- Hyper-Kamiokande

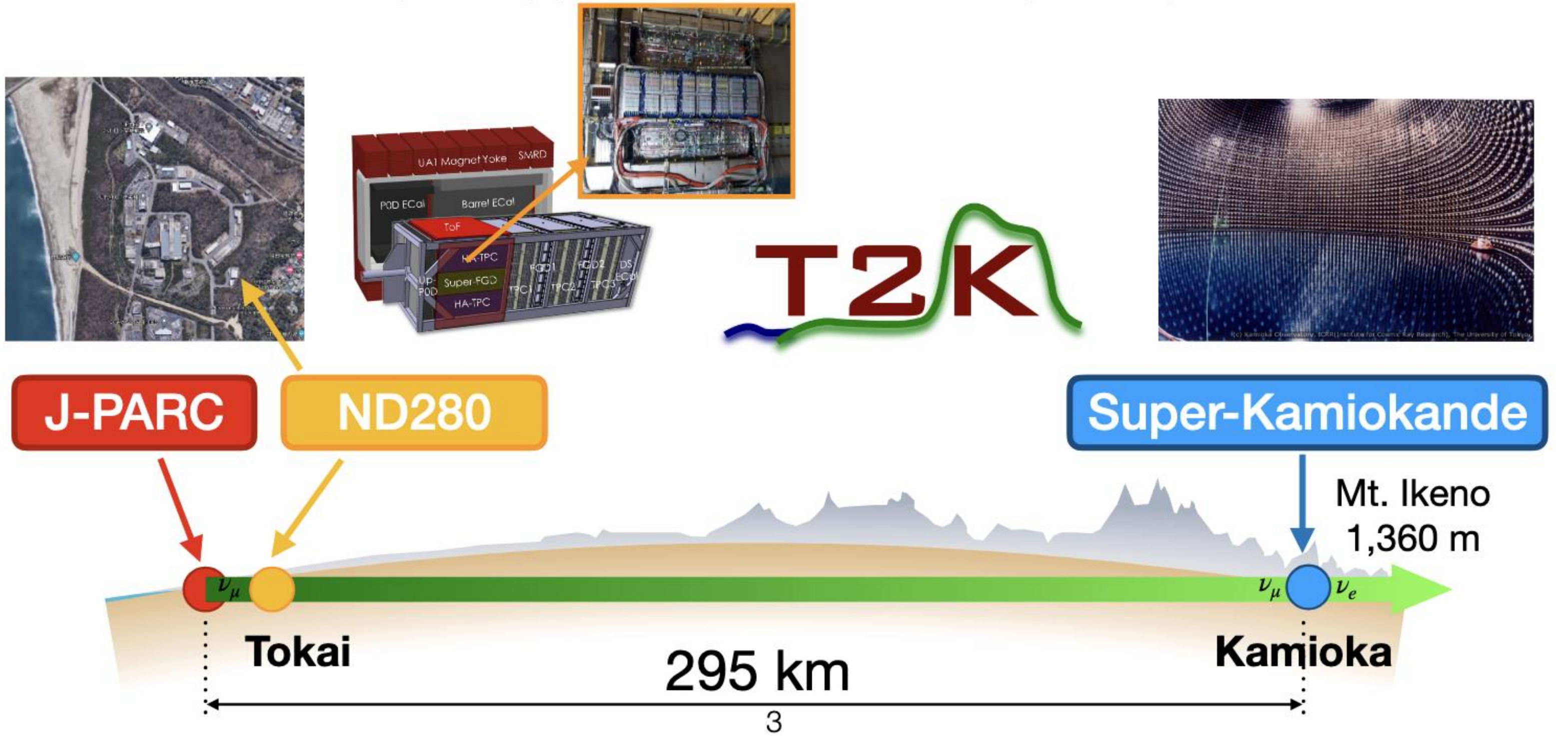
long baseline





T2K experiment

- High intensity ~600 MeV ν_μ or $\bar{\nu}_\mu$ beam produced at J-PARC (Tokai)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande)
  - ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and $|\Delta m^2_{32}|$



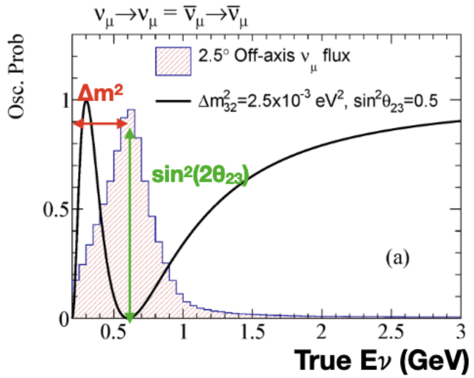
Physics case

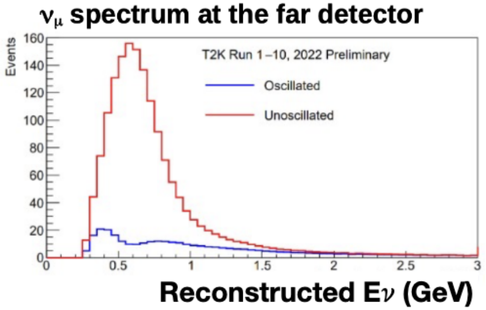
ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

Same oscillation probability for ν and $\bar{\nu}$

Sensitive to $|\Delta m^2_{32}|$ and to $\sin^2(2\theta_{23})$ → no sensitivity to mass ordering and δ_{CP}





ν_e and $\bar{\nu}_e$ appearance

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}]$$

$$(\mp)\alpha\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}]$$

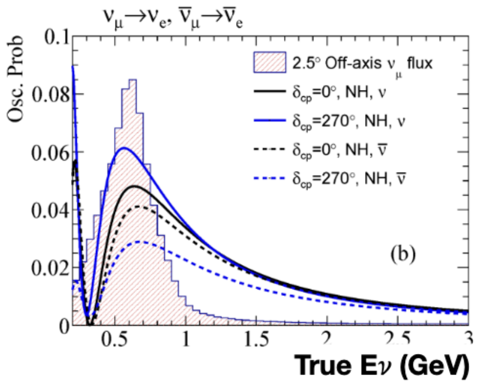
$$+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

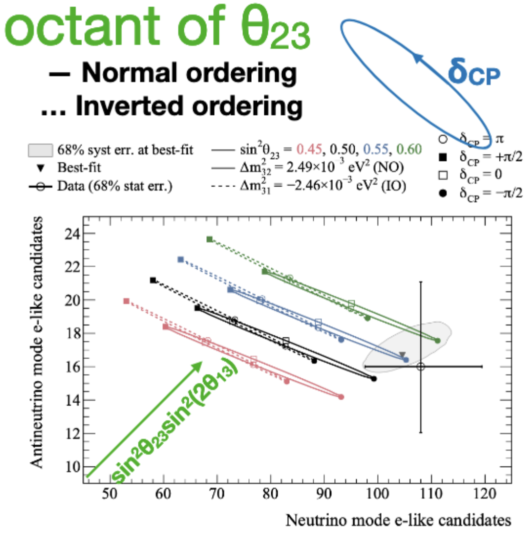
$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$

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

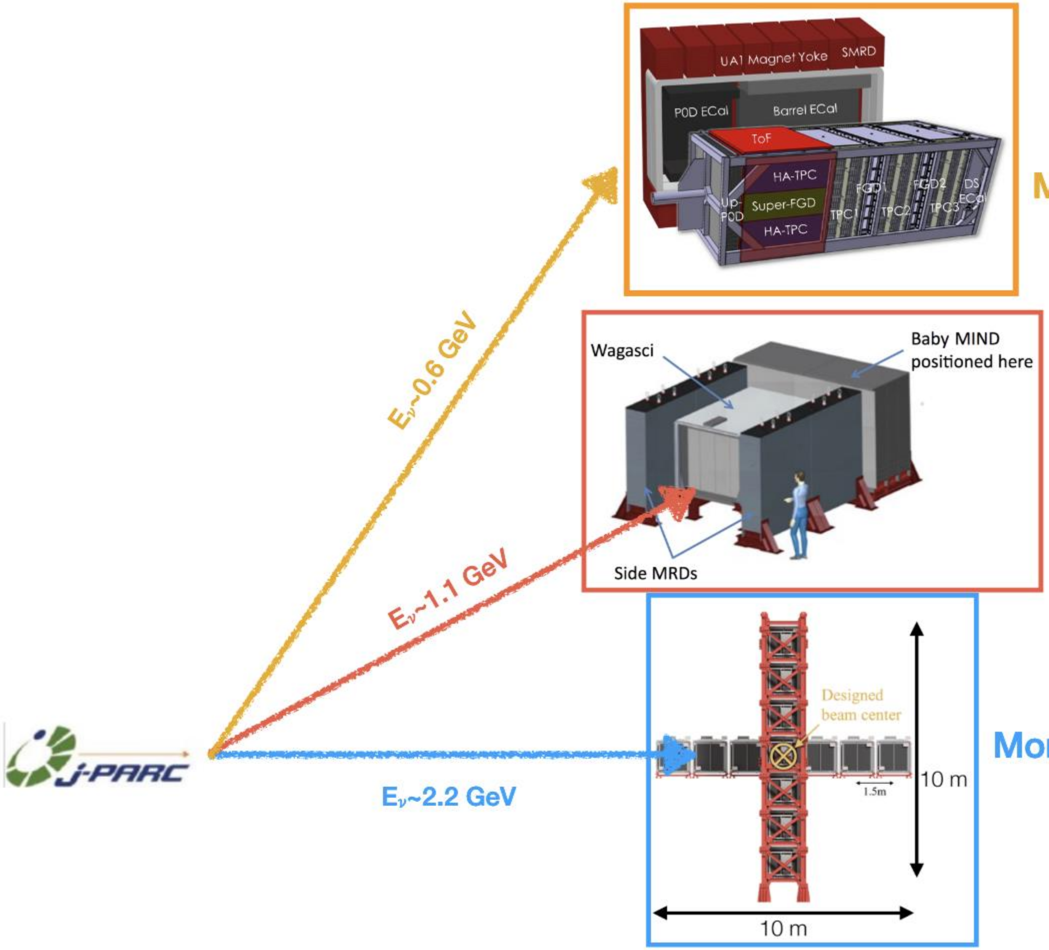
$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$

Sensitivity to δ_{CP}, to the mass ordering and to the octant of θ_{23}





Near Detector complex



Off-Axis ND280
Constrain systematics in T2K oscillation analyses
Measure neutrino cross-sections
In operation since 2010 and upgraded in 2023

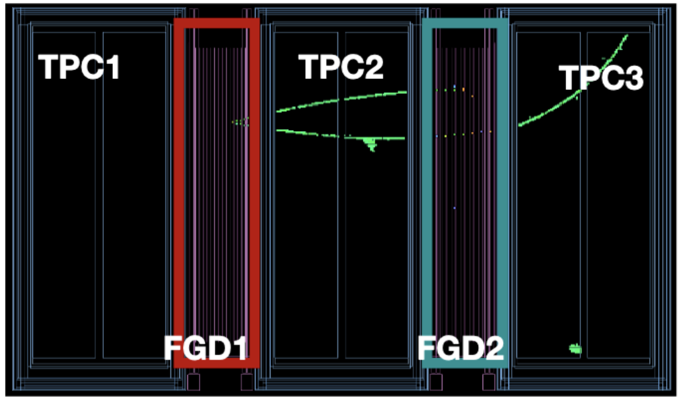
WAGASCI/BabyMIND
Installed in 2019
Cross-sections on water

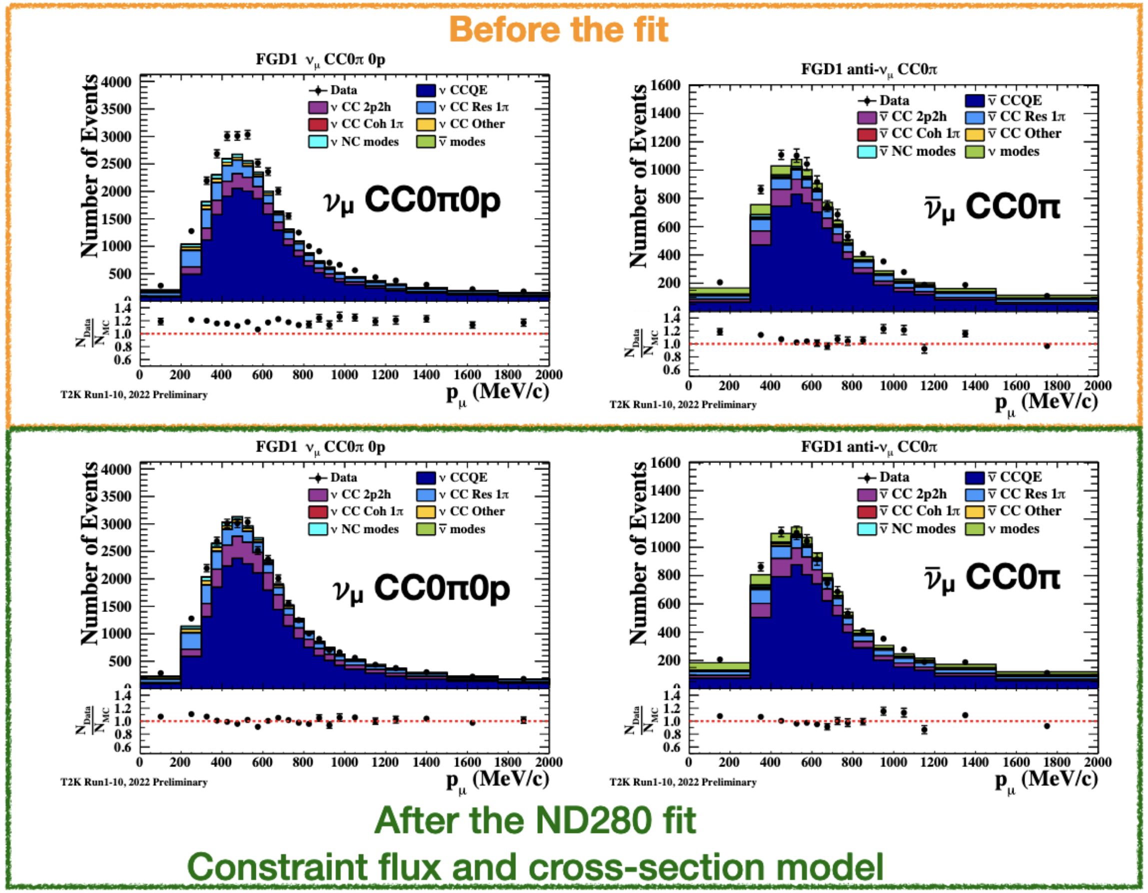
C. Valls poster

INGRID: on-axis detector
Monitoring ν beam profile day-by-day
Cross-section measurements
In operation since 2009

- Near Detector complex at 280 m from the target
- Several detectors installed to monitor the beam, reduce systematic uncertainties in oscillation analyses, and measure ν and $\bar{\nu}$ cross-sections

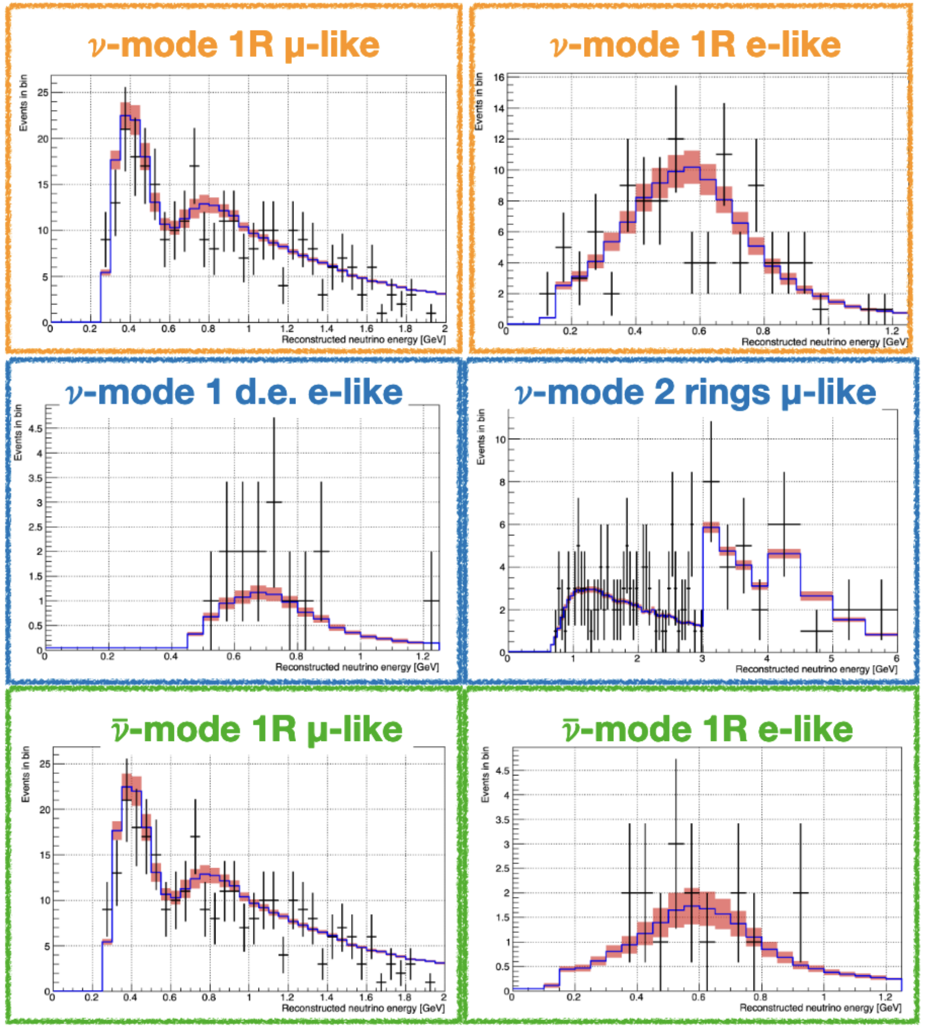
ND280 selections





- ND280 magnetized detector
- Select interactions on CH (FGD1) and CH/Water (FGD2)
- Precise measurement of P_μ and θ_μ with the TPCs
- Distinguish ν from $\bar{\nu}$ interactions thanks to the reconstruction of the charge of the lepton
- Separate samples based on number of reconstructed pions (CC0π, CC1π, CCNπ), protons, photons, etc → 22 samples in total are used in the fit

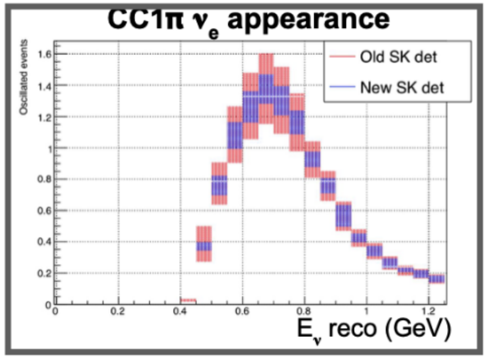
Super-K selections



- 6 samples are selected at SK
  - 2 samples 1R μ-like/e-like in ν-mode → CCQE enhanced
  - 2 samples CC1π enhanced (2 rings or with an additional decay electrons)
  - 2 samples 1R μ-like/e-like in ν̄-mode → CCQE enhanced
- New detector covariance matrix at SK → significantly reduce systematics in the 1 Re+d.e. sample

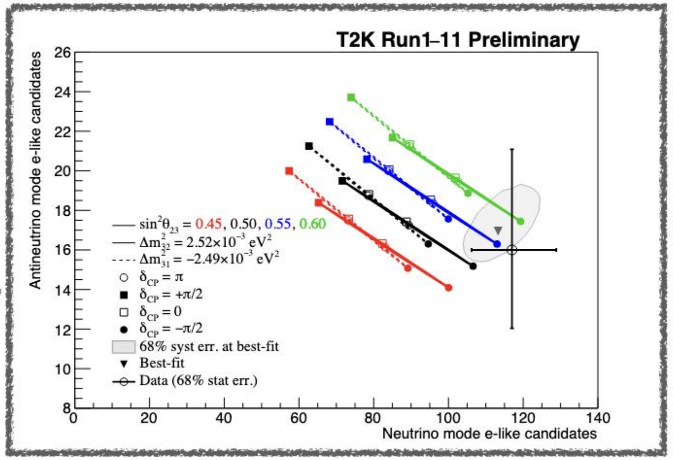
Sample	OA22	New results
ν-mode 1Rμ	3.4%	3.2%
ν-mode 1Re	5.2%	4.9%
ν-mode MR	4.9%	3.9%
ν-mode 1Re+d.e.	14.3%	6.3%
ν̄-mode 1Rμ	3.9%	5.0%
ν̄-mode 1Re	5.8%	6.7%

17



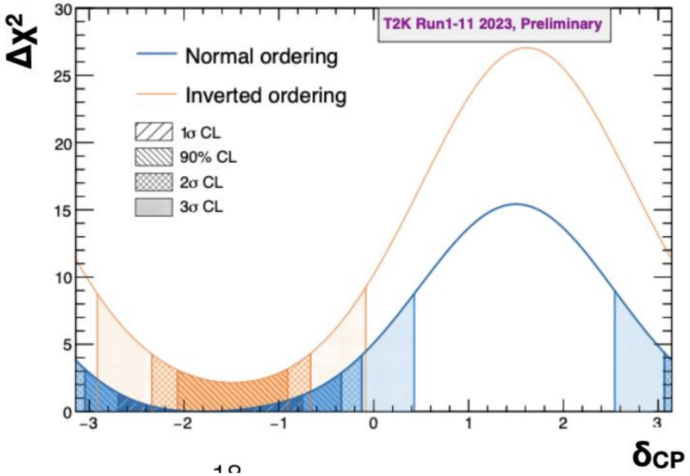
Oscillation analysis results

Sample	δCP=-π/2	δCP=0	δCP=π/2	δCP=π	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
ν̄-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
ν̄-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
ν̄-mode 1Re	17.6	20.0	22.2	19.7	16

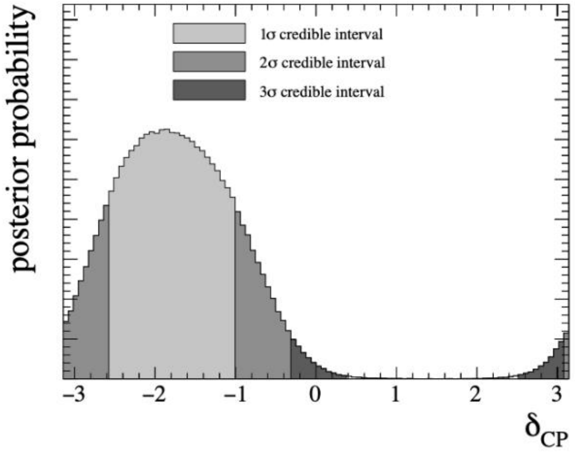


- Preference for δ_{CP}~-π/2 but CP conserving values are within the 2σ interval

D. Carabadjac poster

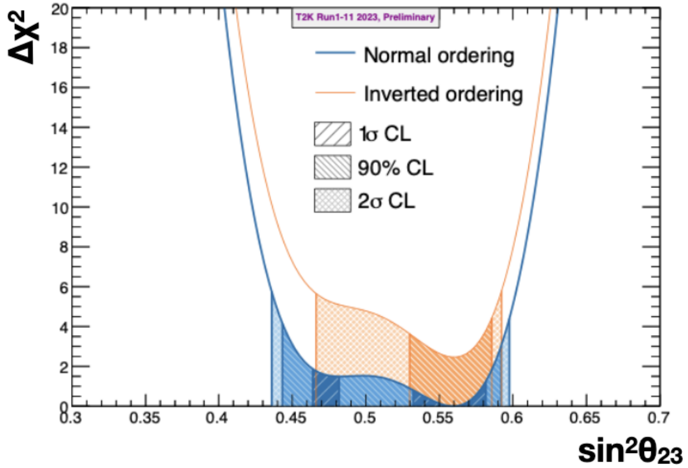


Credible intervals marginalized over both hierarchies

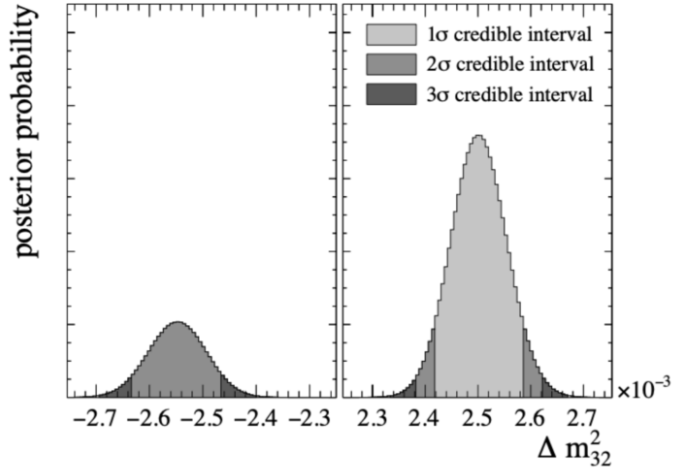


Mass ordering and θ_{23} octant

- Slight preference for normal ordering and upper octant but none of them is significant
  - Bayes factor NO/IO = 3.3
  - Bayes factor $(\theta_{23}>0.5)/(\theta_{23}<0.5) = 2.6$



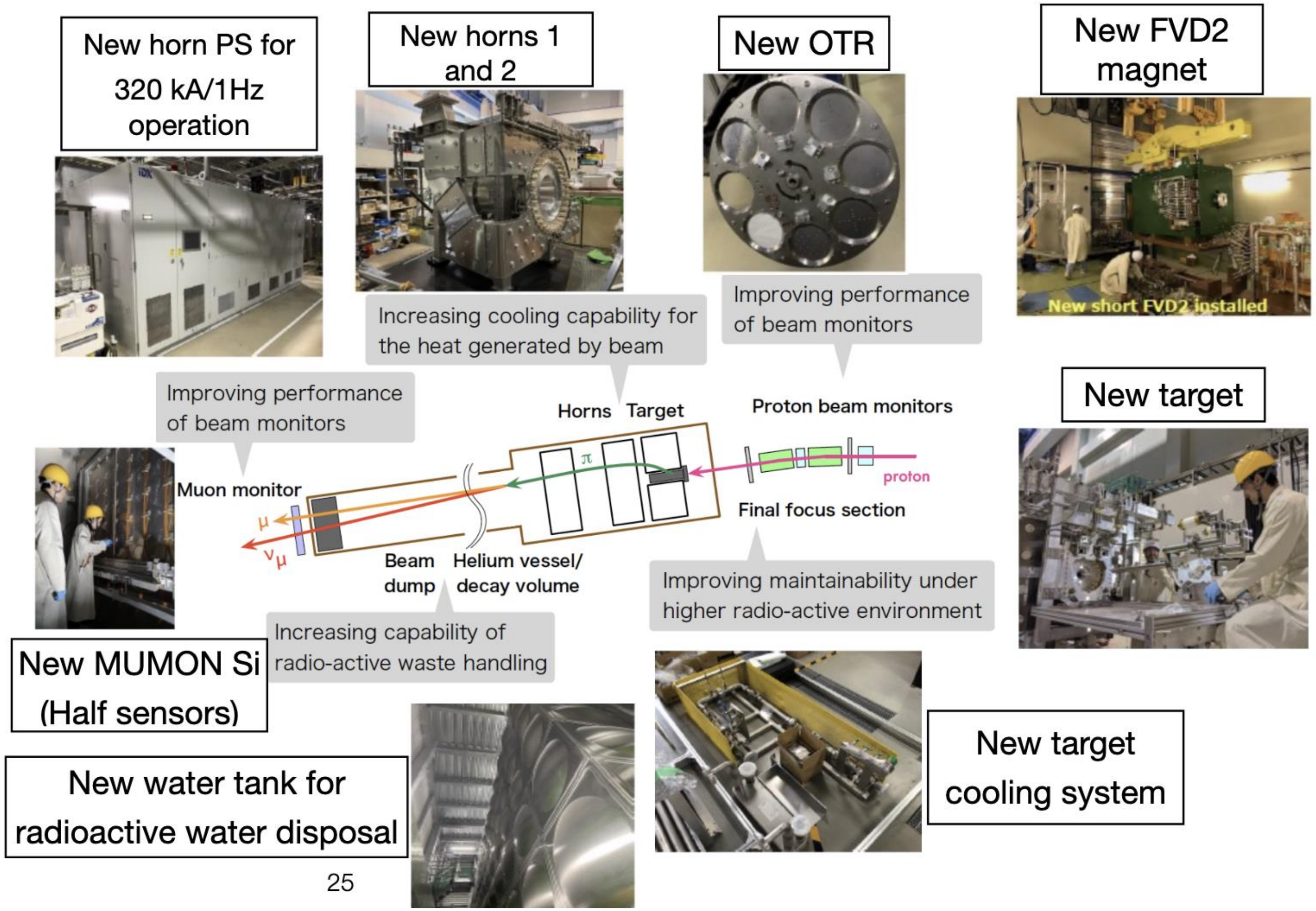
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00



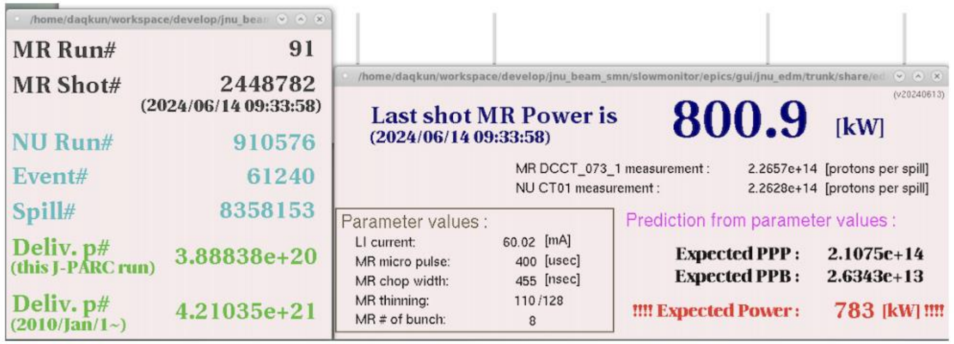
19

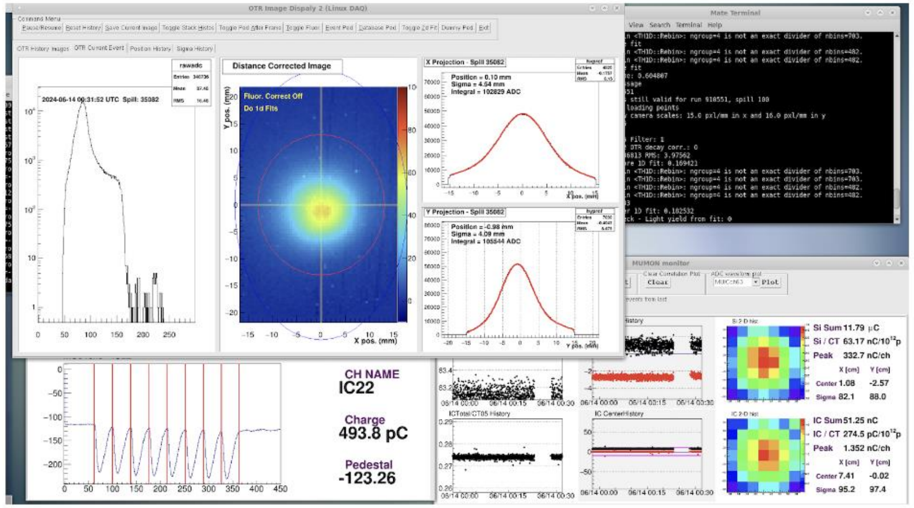
Neutrino beamline upgrades

- Replacement of Main Ring power supplies to allow for higher repetition rate from 2.48s to 1.36s
- Several upgrades done on the neutrino beamline to cope with higher beam power
- Horn being operated at 320 kA instead of 250 kA → ~10% increase in the ν flux



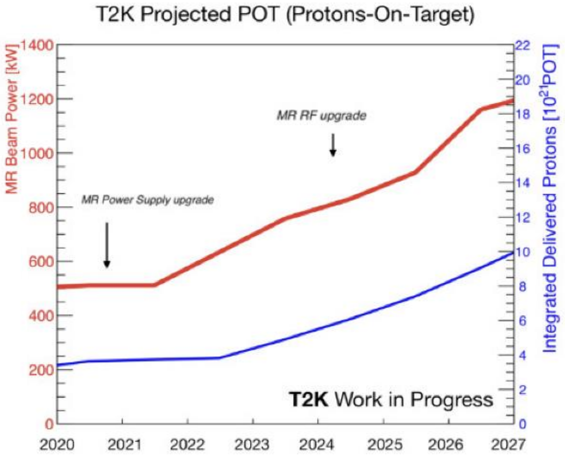
Towards higher beam power



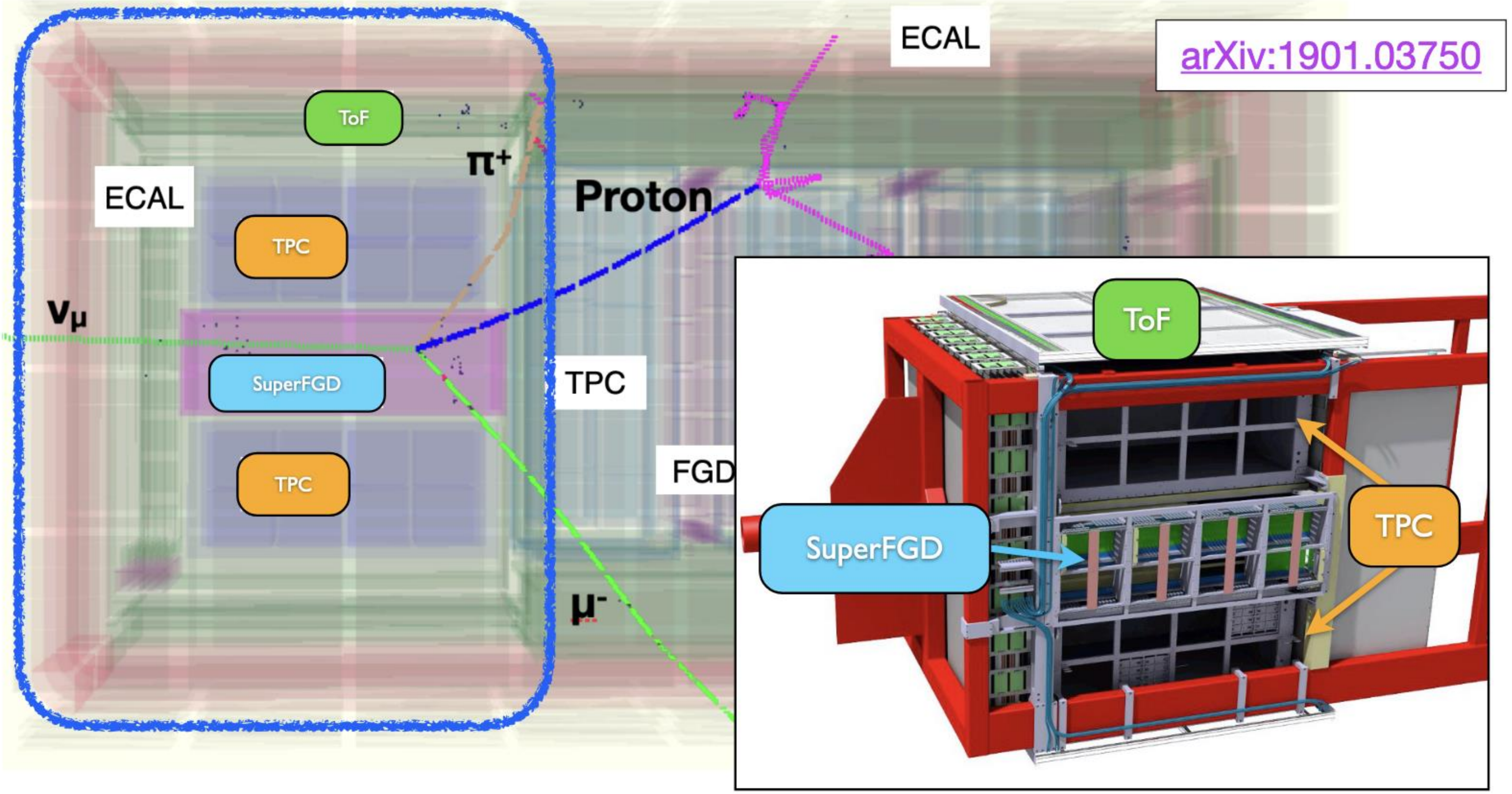


- June 2024 → Beam power increased to 800 kW since last week! (~500 kW before upgrades)
- Steady improvements to reach 1.3 MW by 2027 → increase T2K statistics by a factor of 3 by 2027
- Larger statistics → need to reduce systematic uncertainties → ND280 upgrade

26



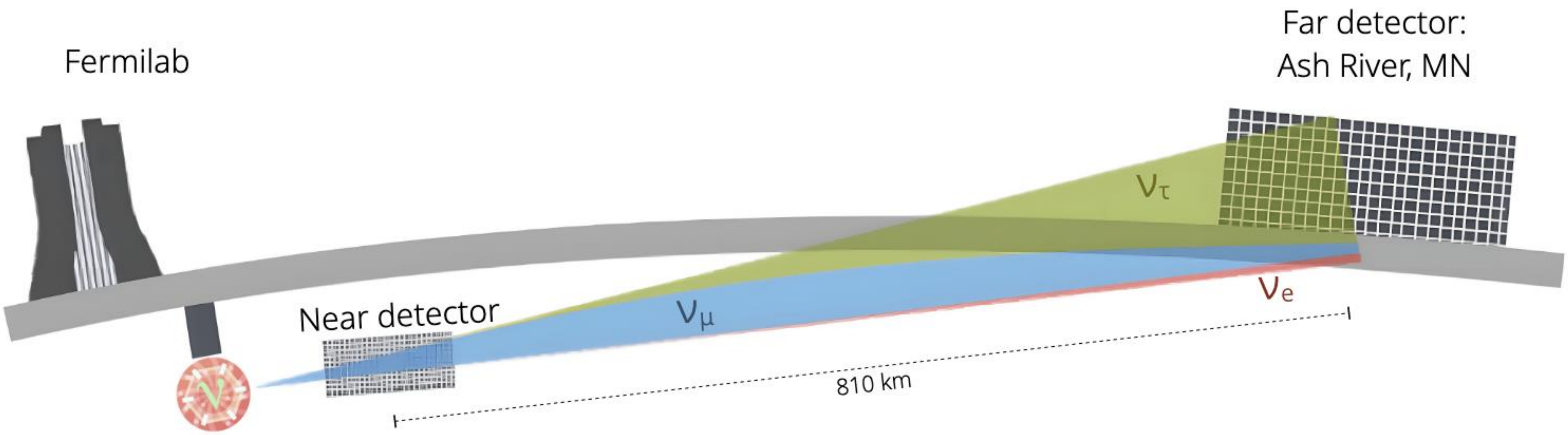
The Near Detector upgrade



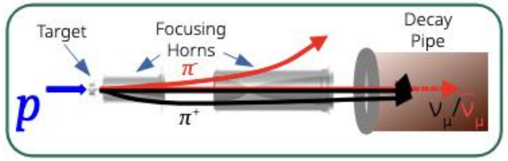
Replace part of the P0D detector (measured NC π^0 production) with a new scintillator target (SuperFGD), two High-Angle TPCs and six ToF planes

29

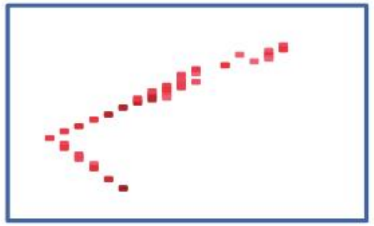
NOvA [USA, 2014-]



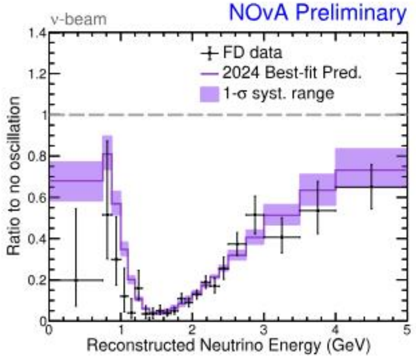
1. Make a beam of ν_μ



2. Select ν_μ and ν_e candidates at both detectors



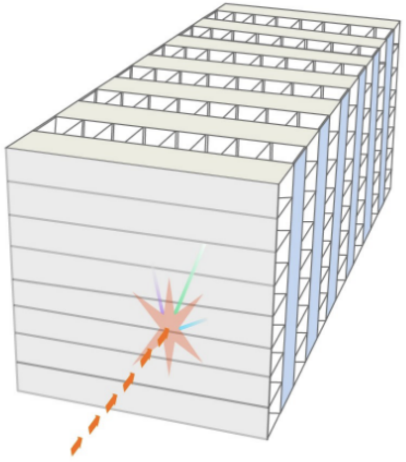
3. Interpret E_ν distributions

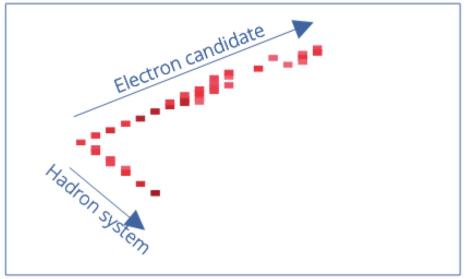


NOvA and T2K are complementary

Compared to T2K*, NOvA uses
a different experimental approach

NOvA
active scintillator calorimeters

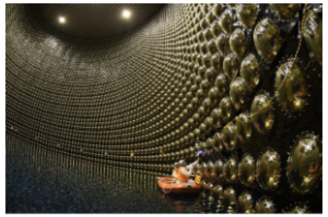


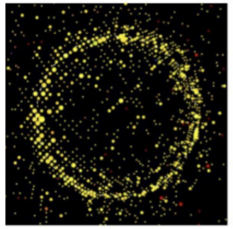


see significant energy from both lepton and hadron systems: "calorimetric" E_ν reconstruction

& functionally equivalent detectors
shared uncertainties mostly cancel

T2K
water Cherenkov FD





ν_e-like

see only lepton energy:
"kinematic" E_ν reconstruction

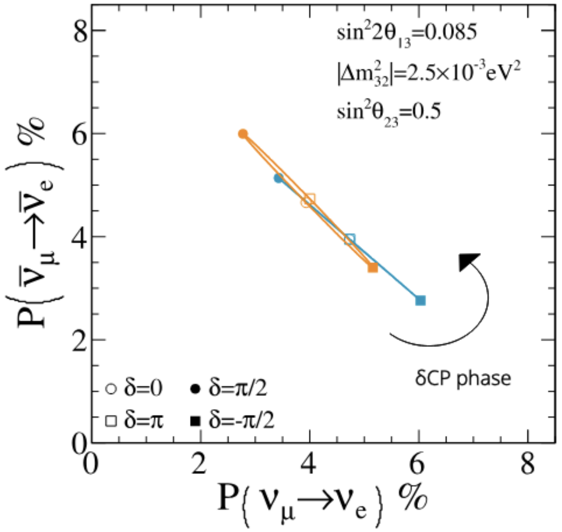
Hybrid gas TPC & scintillator tracker ND
ND+FD shared uncertainties explicitly fitted & constrained via model

NOvA and T2K are complementary

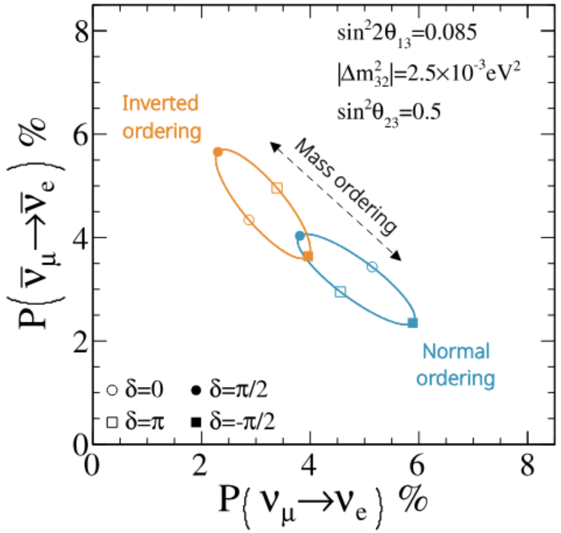
Compared to T2K*, NOvA has **Higher E_ν**

Larger matter effects

T2K: L=295 km, E=0.6 GeV



NOvA: L=810 km, E=2.0 GeV



Stronger mass ordering sensitivity;
more δ_{CP} degeneracy

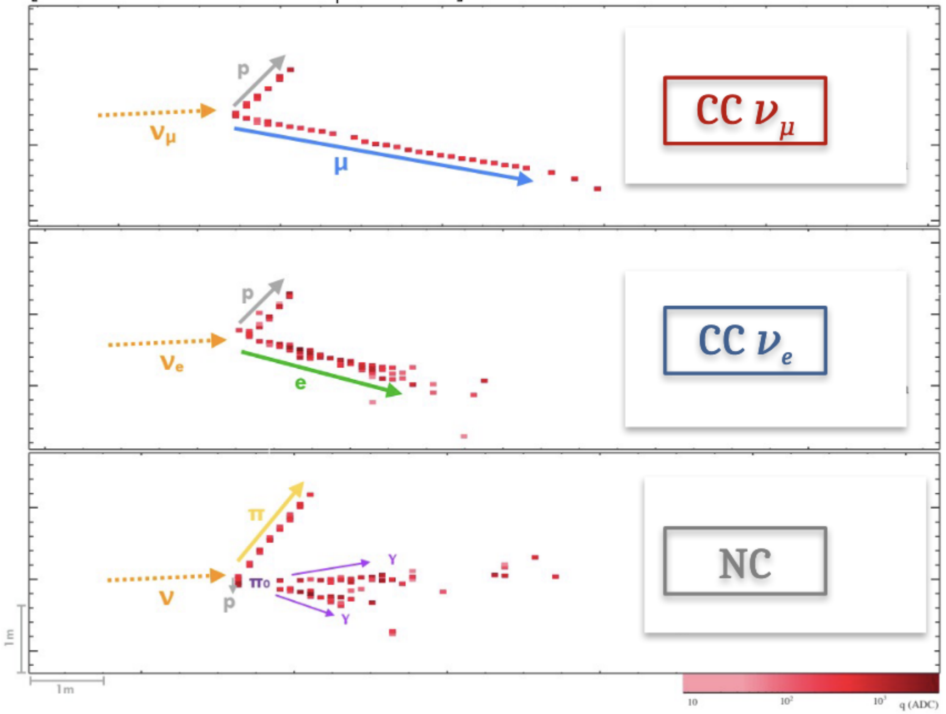
Also...

- More antineutrinos
- More final-state pions

(see overflow slides)

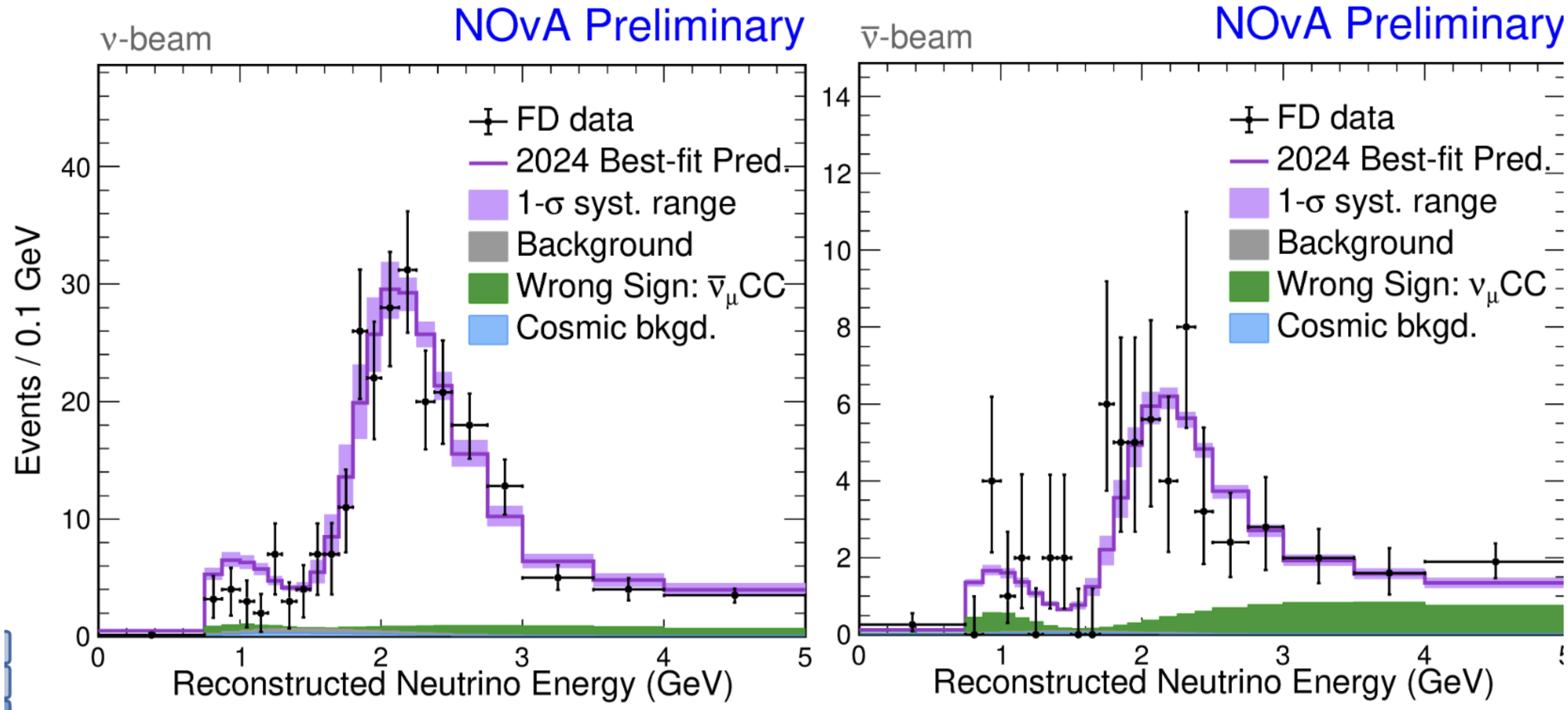
Selecting ν_μ and ν_e candidates

[Data events with candidate particle IDs]



- Make heavy use of **convolutional neural networks** (CNNs)
  - Cosmic rejection in FD
  - Neutrino interaction flavor ID
  - Particle PID
- **Performance is good;** only minor updates in 2024
- **Supplement** with other **classifiers** as needed
  - BDTs for cosmic rejection, selection of uncontained ν_es

Far detector observations: ν_μ

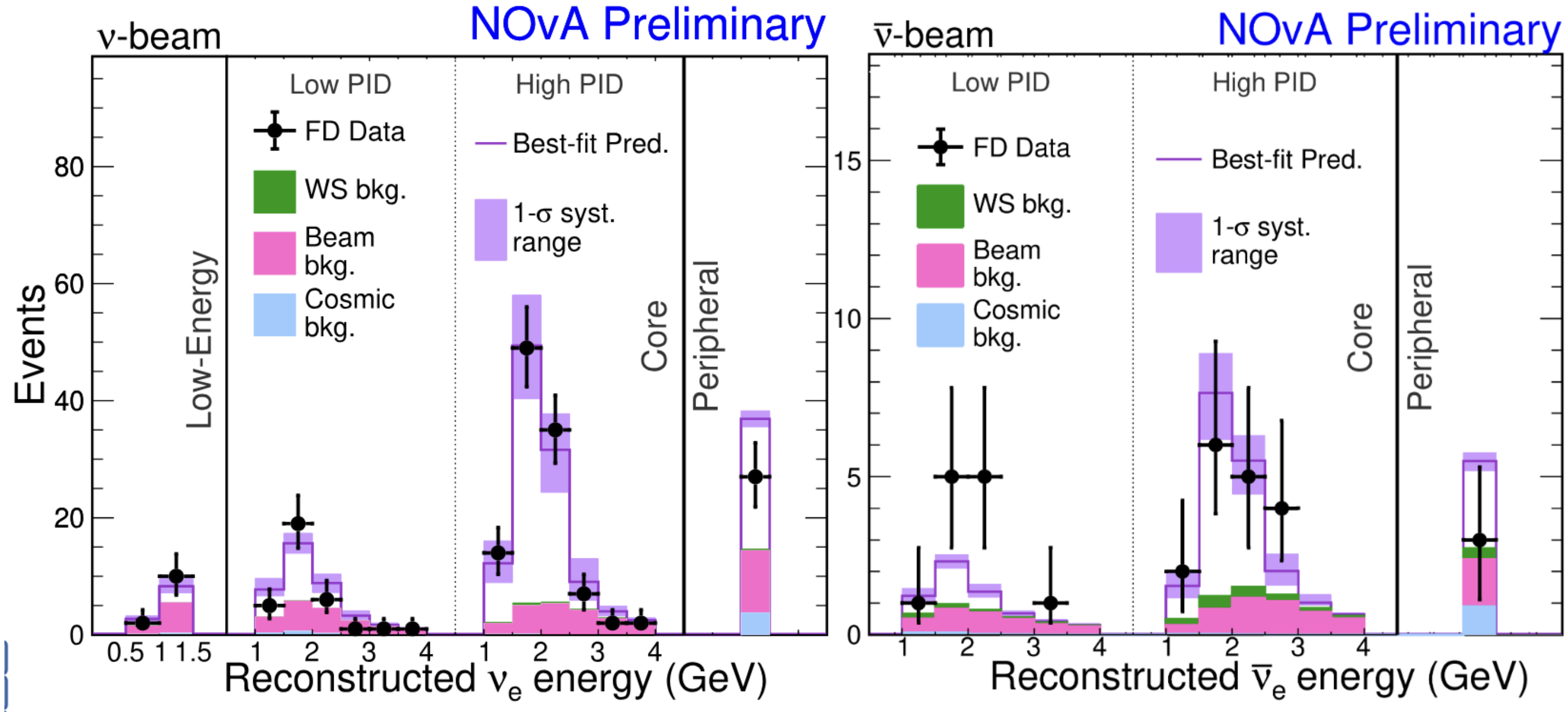


384 ν_μ data candidates
(11.3 background)

106 $\bar{\nu}_\mu$ data candidates
(1.7 background)

3-flavor oscillations describe these data well: Bayesian posterior predictive *p*-value = 0.54

Far detector observations: ν_e

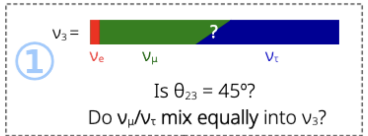


181 ν_e data candidates

	Best fit	Range
Total pred	186.2	119 – 250
Wrong-sign	1.8	1.6 – 2.8
Beam bknd.	53.7	
Cosmic bknd.	6.2	
Total bknd	61.7	61 – 63

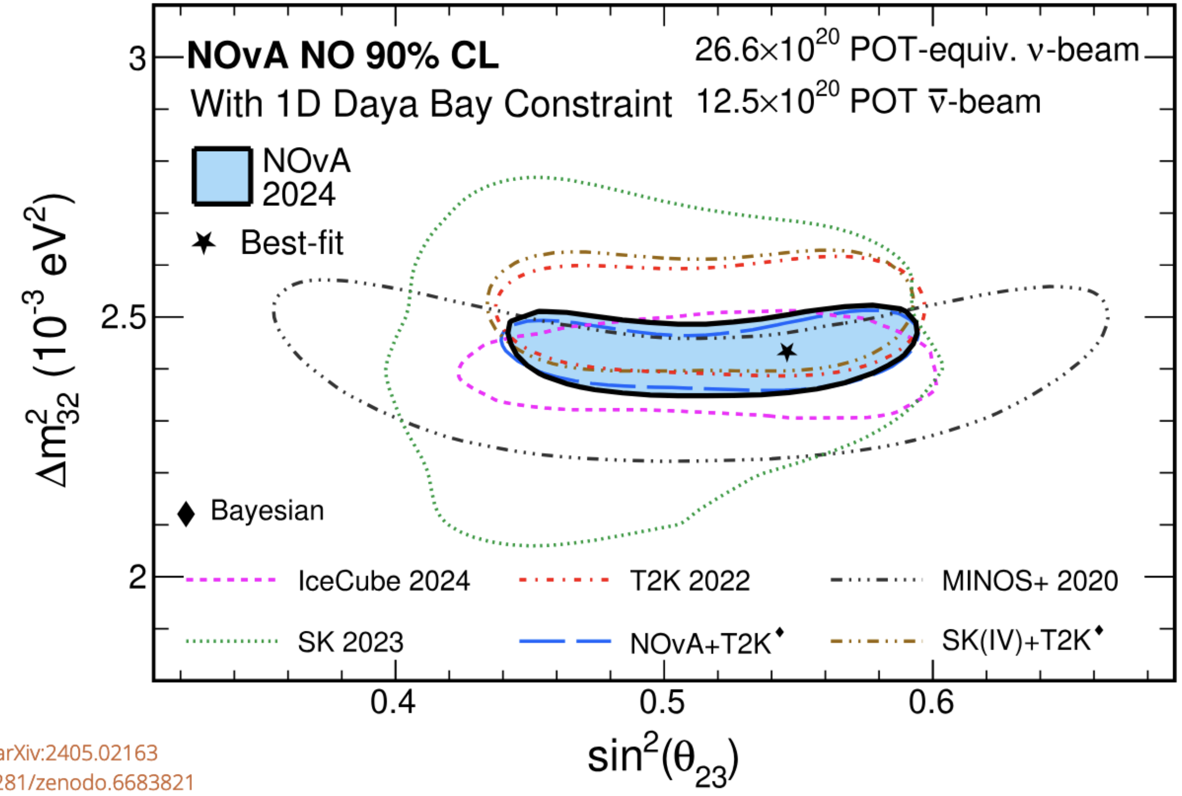
32 $\bar{\nu}_e$ data candidates

	Best fit	Range
Total pred	30.4	28 – 38
Wrong-sign	2.1	1.0 – 3.2
Beam bknd.	9.0	
Cosmic bknd.	1.1	
Total bknd	12.2	11 – 13



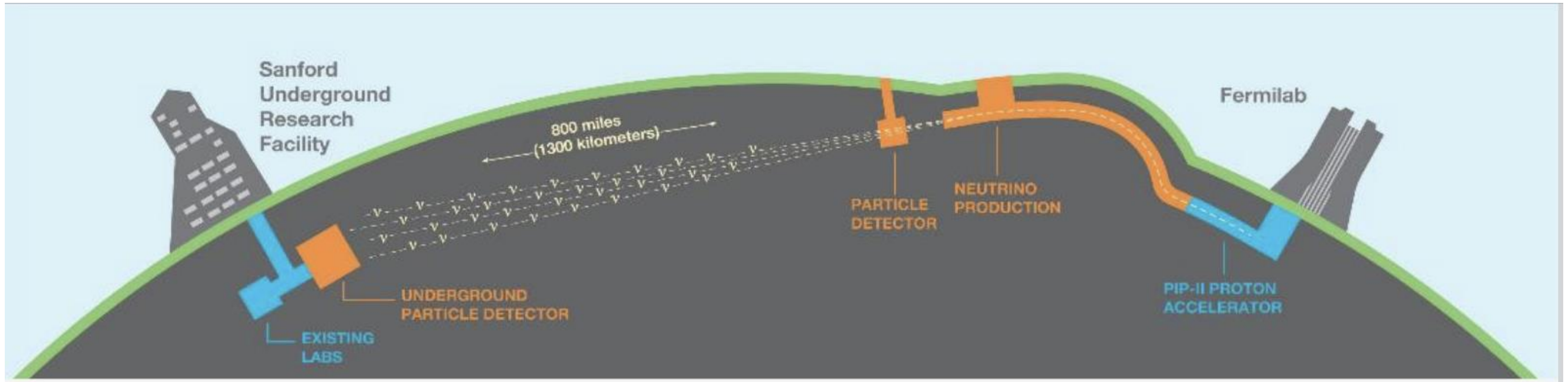
$\nu_2 - \nu_3$ sector

NOvA Preliminary

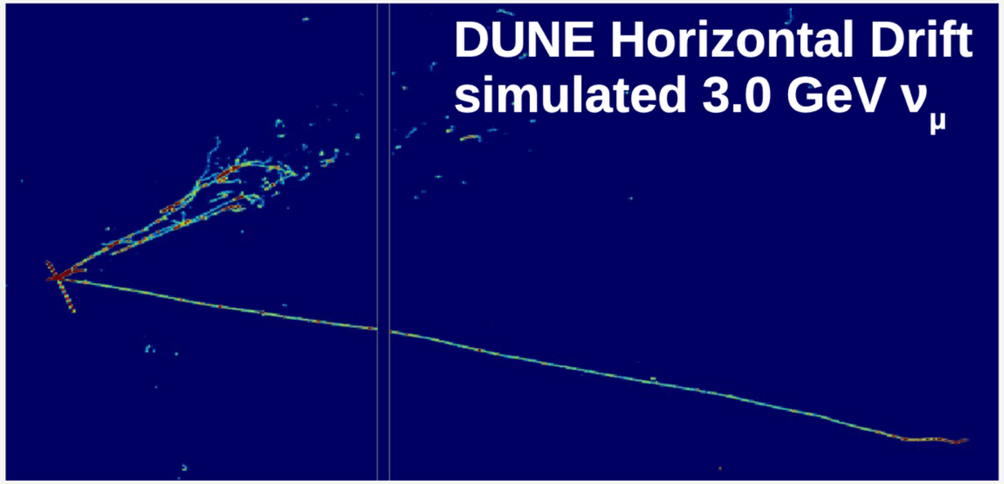


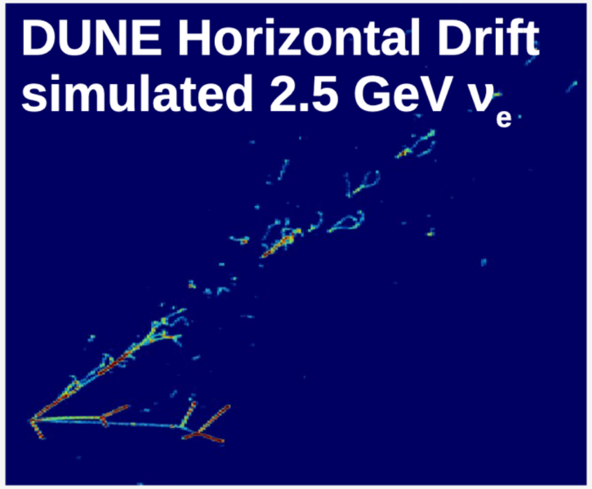
IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

(Frequentist) best fit:
$$\Delta m^2_{32} = \left(+2.433^{+0.035}_{-0.036}\right)\times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$$



LArTPC: flavor & energy reco over a broad range of topologies

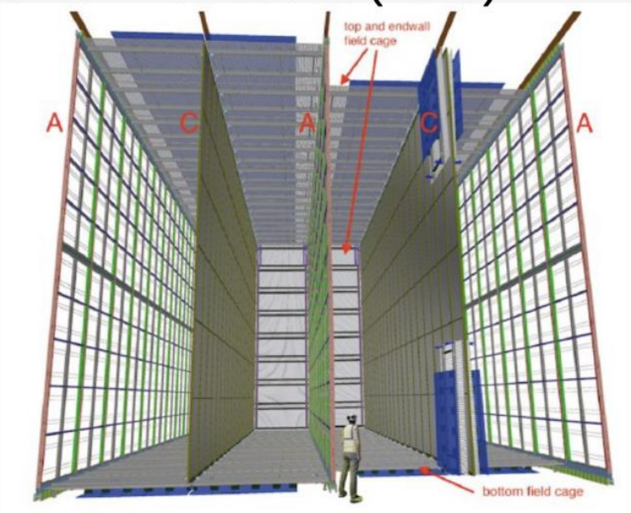




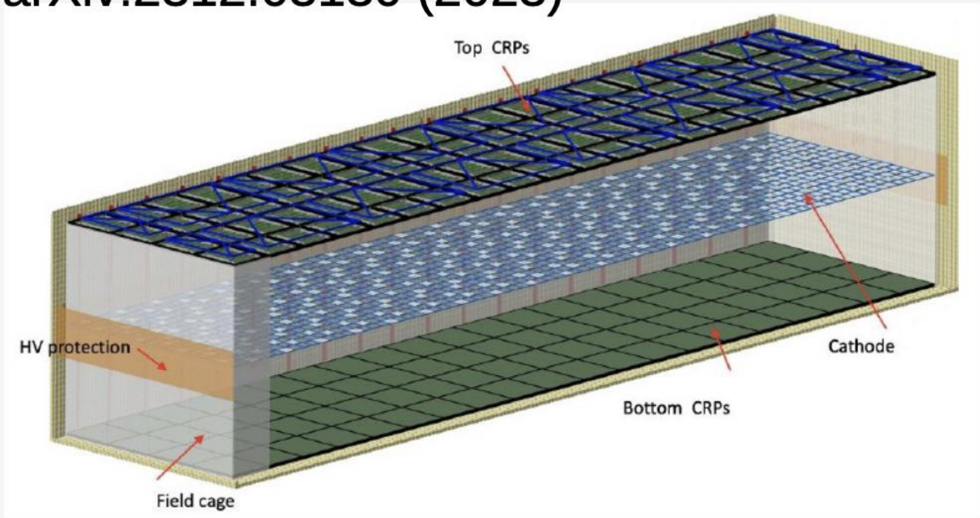
- 60% of interactions at DUNE energy have final state pions → LArTPC enables precise hadron reconstruction
- Excellent e/μ and e/γ separation

Far detector: two readout technologies

JINST 15 T08010 (2020)



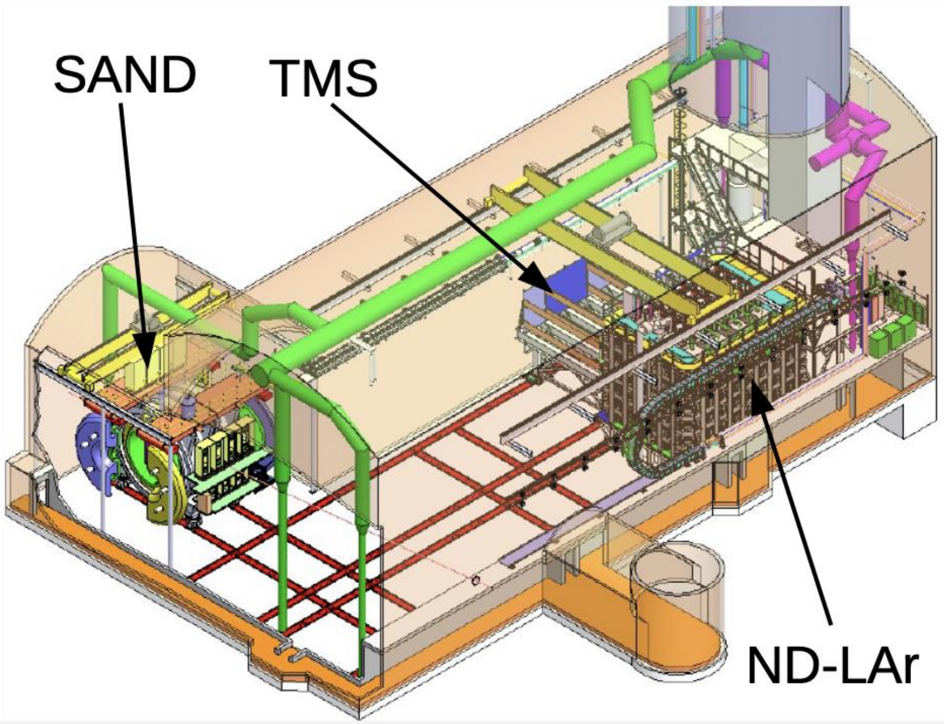
arXiv:2312.03130 (2023)



- Horizontal drift (HD, left) using wire readout planes, four drift regions
- Vertical drift (VD, right) using two 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for modules 3 and 4

Near detector: systematic constraints for precision physics

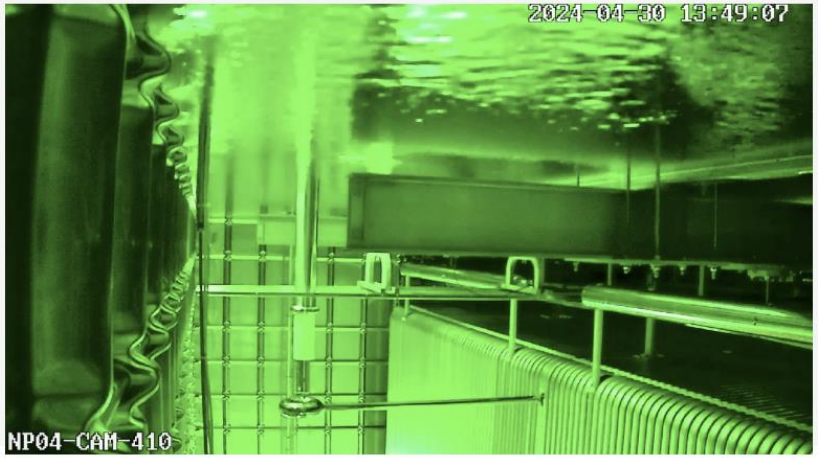
- Main purpose: enable prediction of Far Detector reconstructed spectra
- Movable detector system: LArTPC with muon spectrometer
- Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
- Same target, same technology → inform predictions of reconstructed E_ν in Far Detector

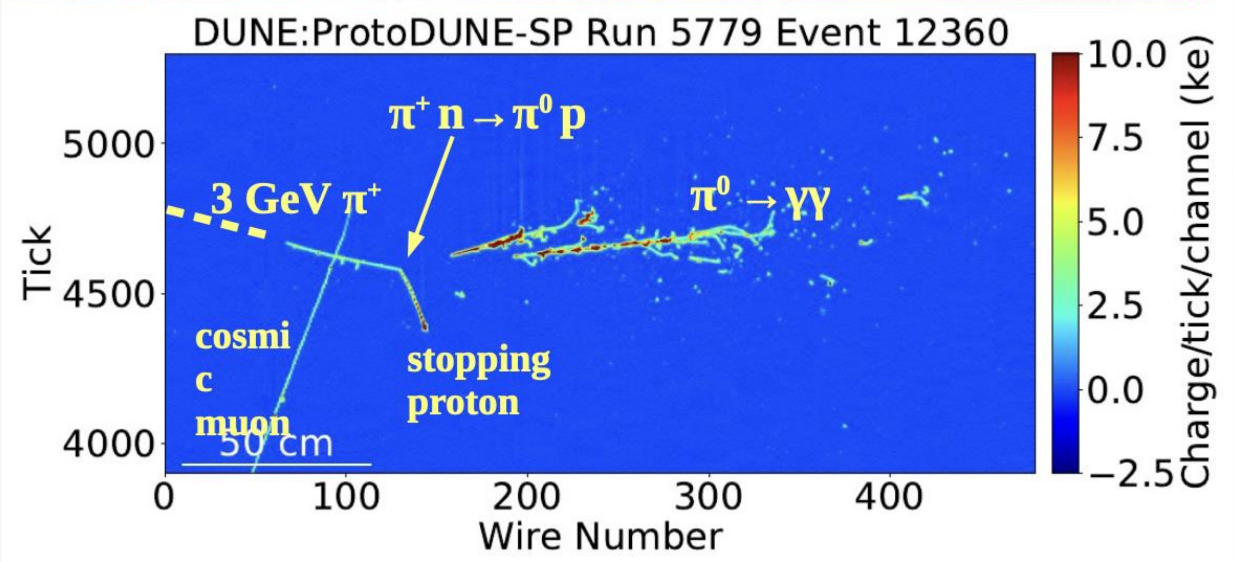


Building DUNE: construction schedule

- Far site excavation is complete
- Next: Building & Site Infrastructure work until mid-2025
- Cryostat warm structure is on its way to US from CERN to be installed in 2025-26
- Far Detector installation in 2026-27
- Purge and fill with argon in 2028
- Physics in 2028 or early 2029
- Beam physics with Near Detector 2031

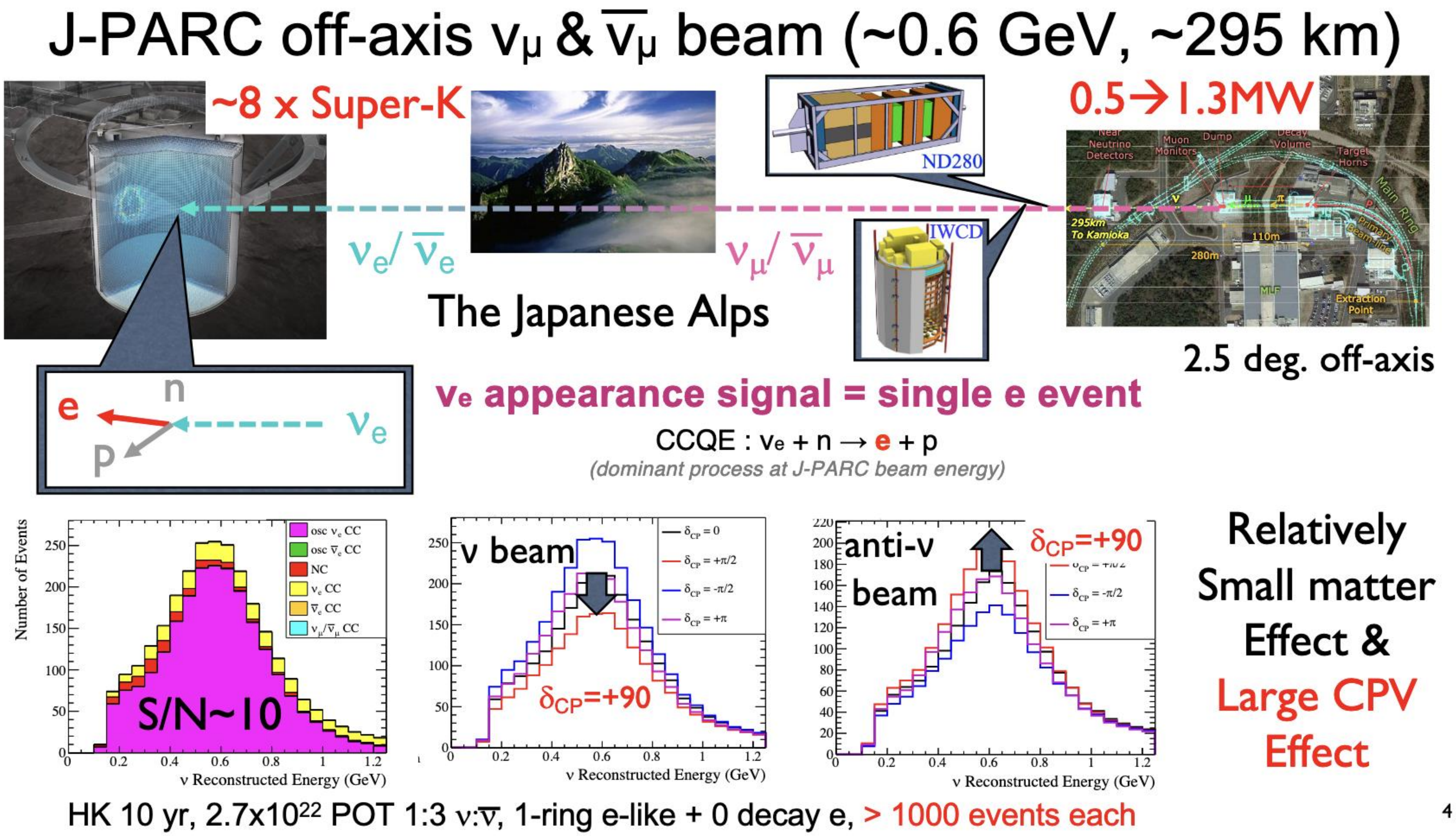
ProtoDUNE: preparing for second runs



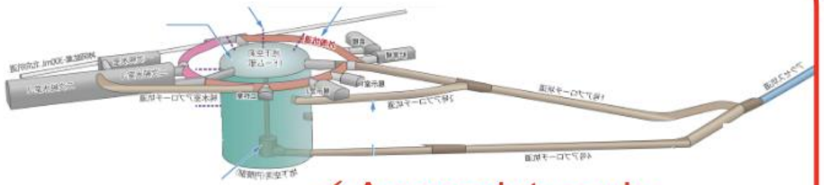


- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (ProtoDUNE-SP)
- ProtoDUNE-HD completed filling 30th April, running since May, with beam turning on at 6pm tomorrow evening
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025

Hyper-Kamiokande [Japan, future]



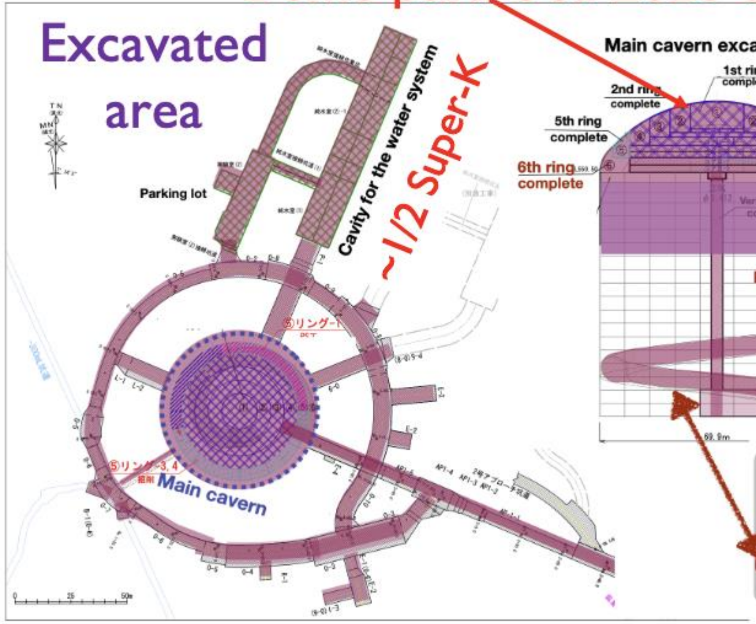
Excavating the world's largest human-made cavern

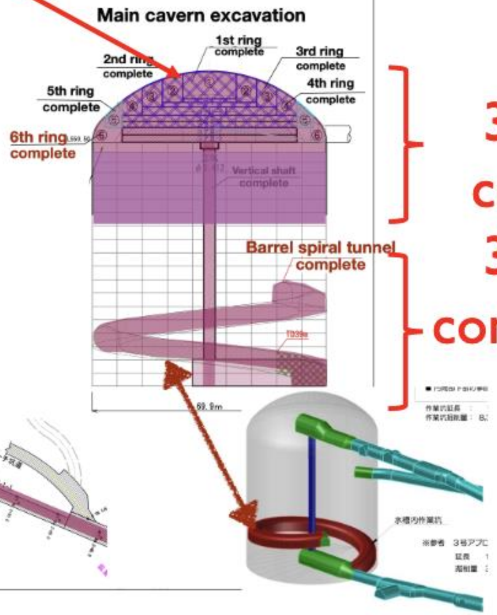


✓ Approach tunnels:
Aug. 2022 complete.

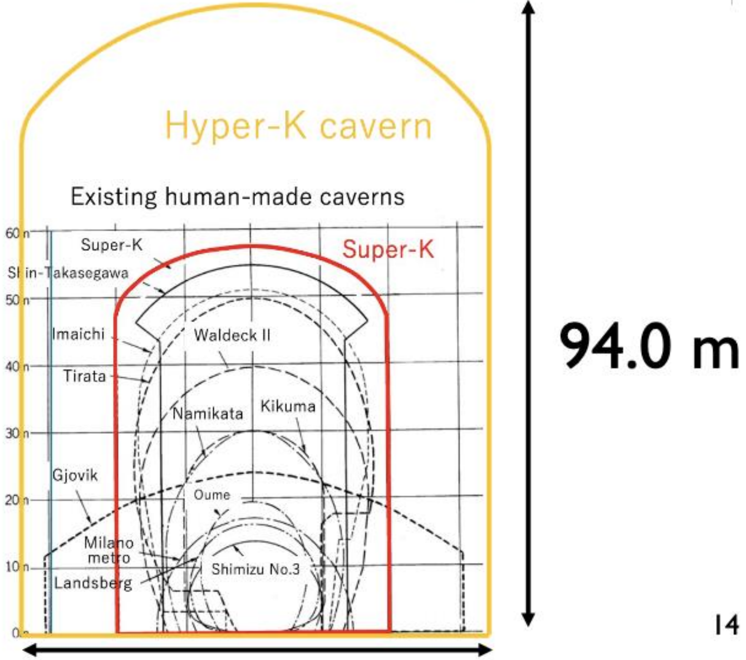
✓ Access tunnel: Feb. 2022 complete.

✓ Dome part: Oct. 2023 complete.





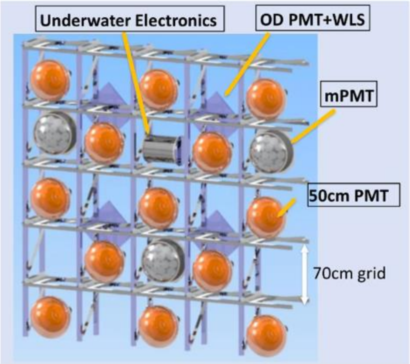
3 Super-K completed.
3 Super-K coming ~1/2yr

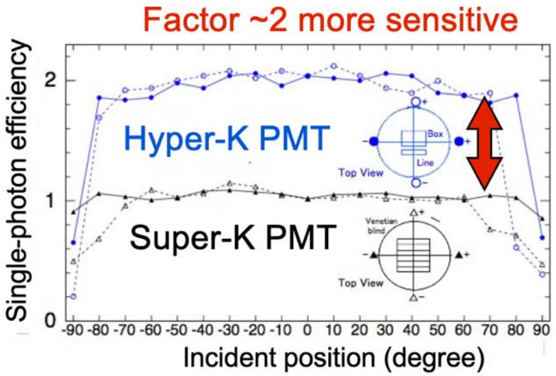



Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)

Photo-detection system

- Detailed design of the tank lining and photosensor support structure completed.



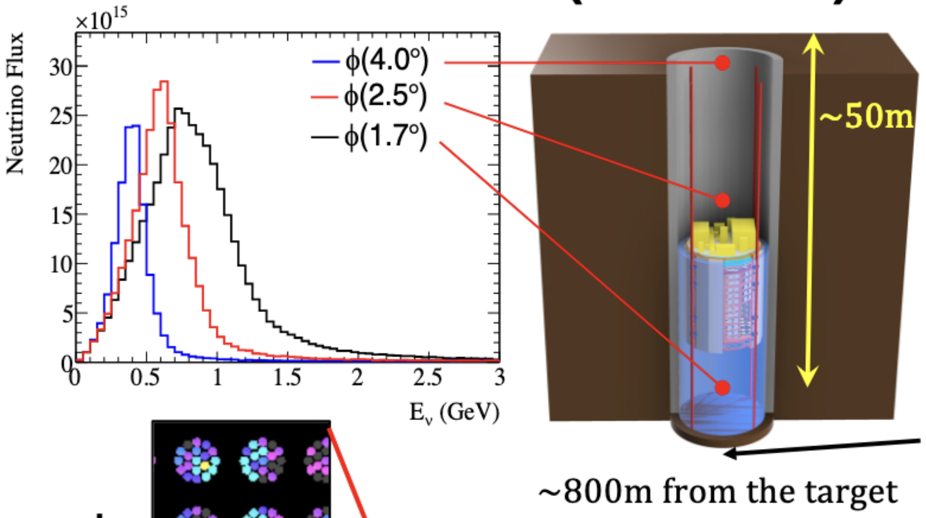


- New features of 50 cm PMT (B&L-dynode) include
  - High QE, T resolution, pressure tolerance (x2 better than Super-K)
  - dark rate reduction, low radioactivity, cover development
  - long-term performance evaluation already in Super-K
  - ➔ 20 000 of 50 cm PMTs from Japan

Intermediate Water Cherenkov Detector (IWCD)

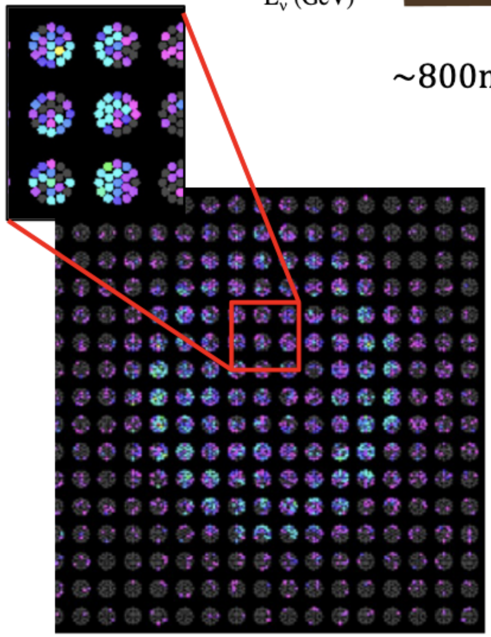
Measurements at IWCD with OAA 1.7°-4.0°

- $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$
  - 3-4% accuracy at 600 MeV (work in progress)
- Background (beam ν_e, NC) for $\nu_\mu \rightarrow \nu_e$
  - Same flux at 2.5 deg. off axis for Hyper-K
- Correlation $(p_l, \theta_l) \leftrightarrow E_\nu$
  - Combination of data with different off-axis angles



Detector site secured, depth & diameter proposed.

- 8.8 m detector diameter, and 7 m diameter for the inner volume. Entire mass ~ 600 ton.
- Multi-PMTs are useful for resolving vertices close to the wall and accurate particle identifications.
- Basic design is ongoing, and installation procedure is being considered.
- **International contributions welcome!**



22

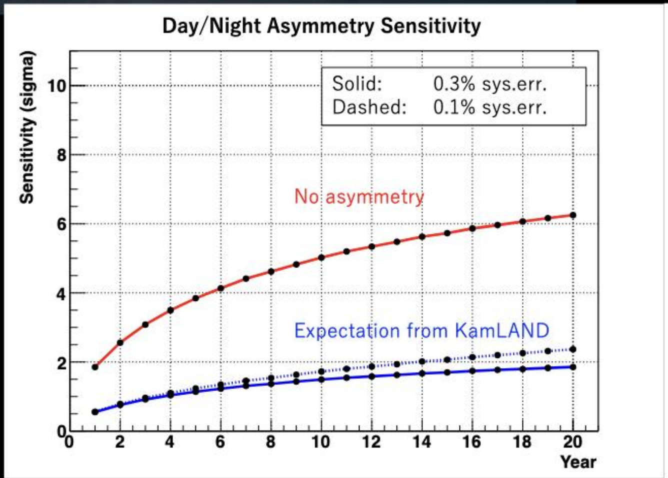
HYPER-KAMIOKANDE

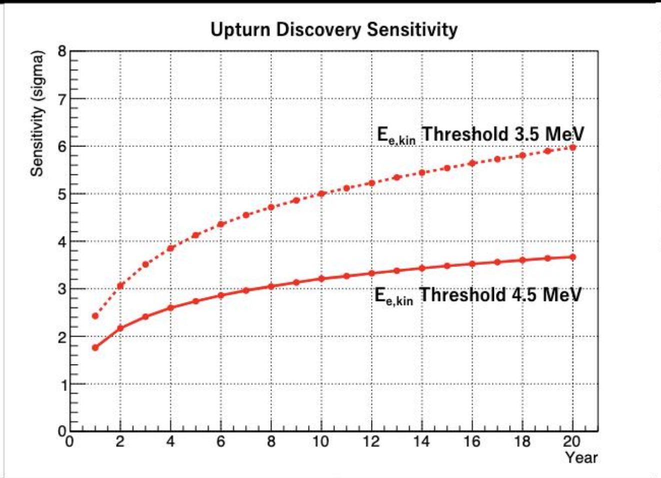
THANKS TO F. DI LODOVICO, S. MORIYAMA, T. YANO

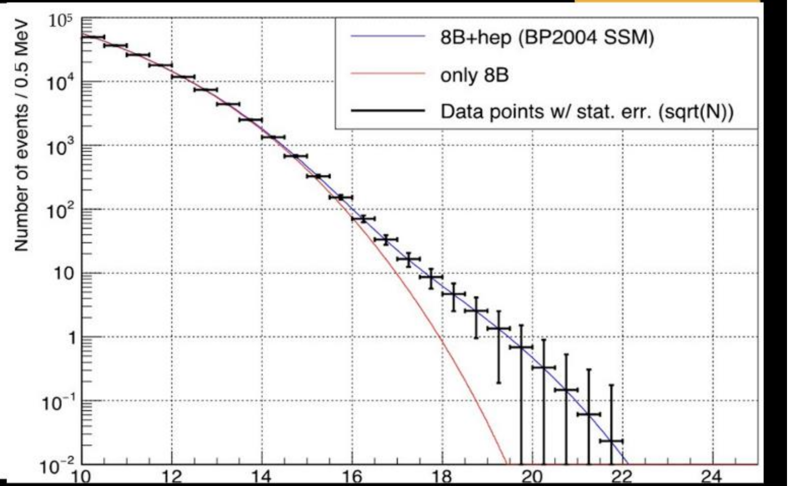
TALK 646/ S. MORIYAMA

- Largest ever (solar) neutrino detector, starting 2027
  - Less deep than SK: higher cosmogenic backgrounds, but have several methods to tag the showers
  - Huge statistics: ~5 ^{8}B ν/hour
    - If Δm^2_{21} is that of solar best fit, 5 σ on day-night effect.
    - If the threshold is 3.5 MeV, 5 σ on low energy upturn
    - 2-3 σ measurement of hep νs as well

REF. 12





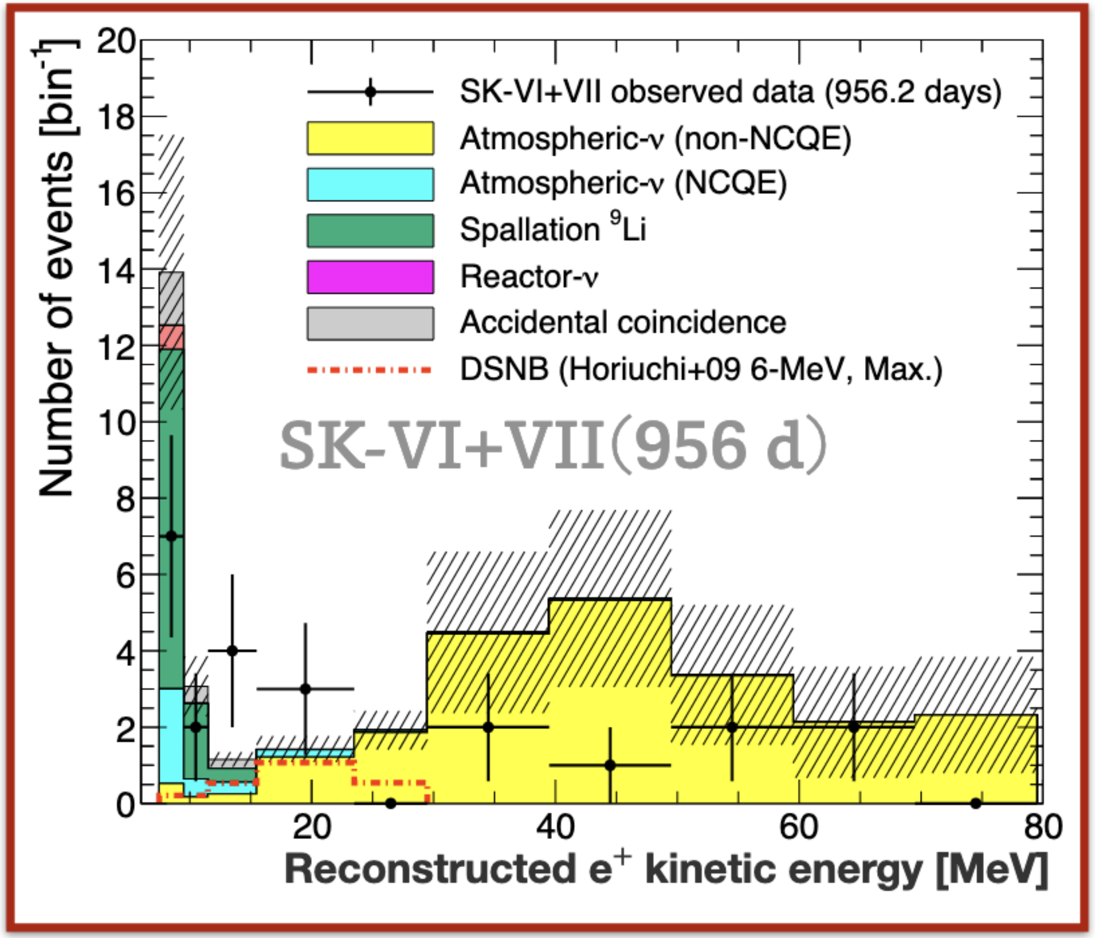


astrophysical neutrinos

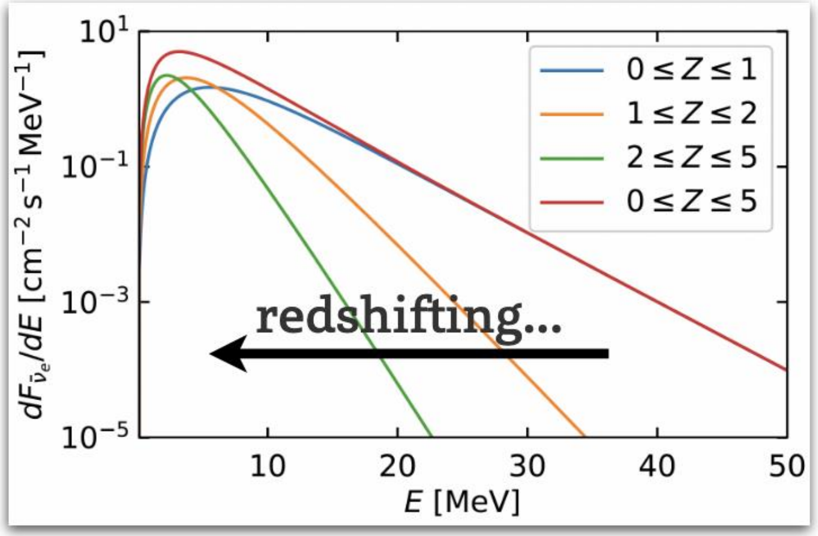
- IceCube
- KM3NeT

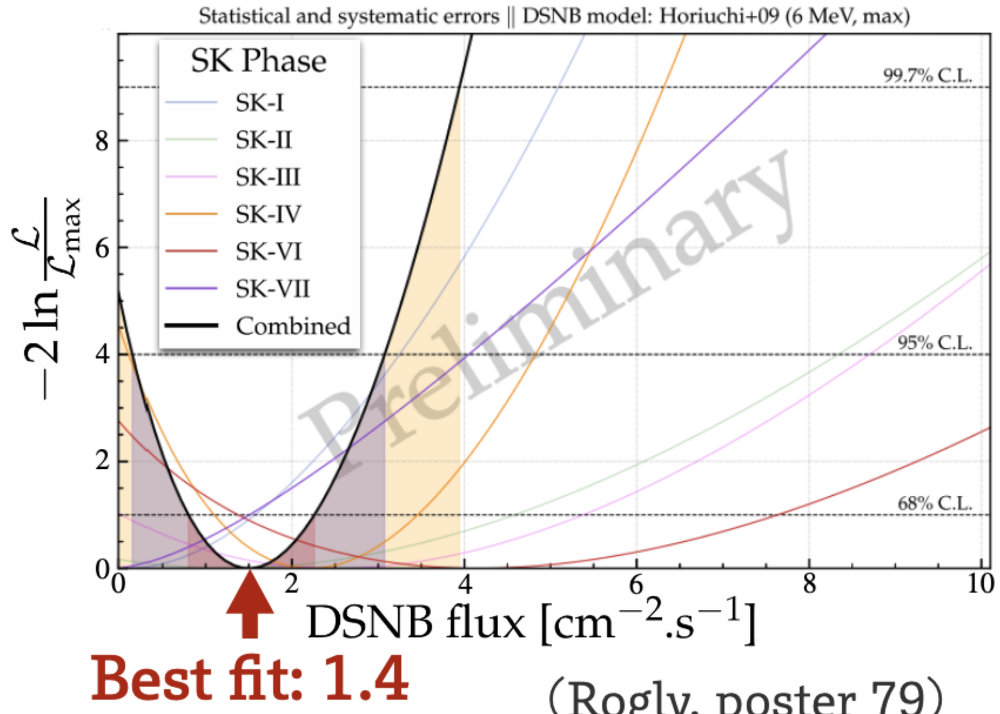
astrophysical neutrnos

- diffuse supernova neutrinos
  - remnants of all exploded supernovae
  - isotropic
  - redshifted by universe expansion (0, 20) MeV
- first hints by Super-Kamiokande with Gd
  - 2.3 σ excess



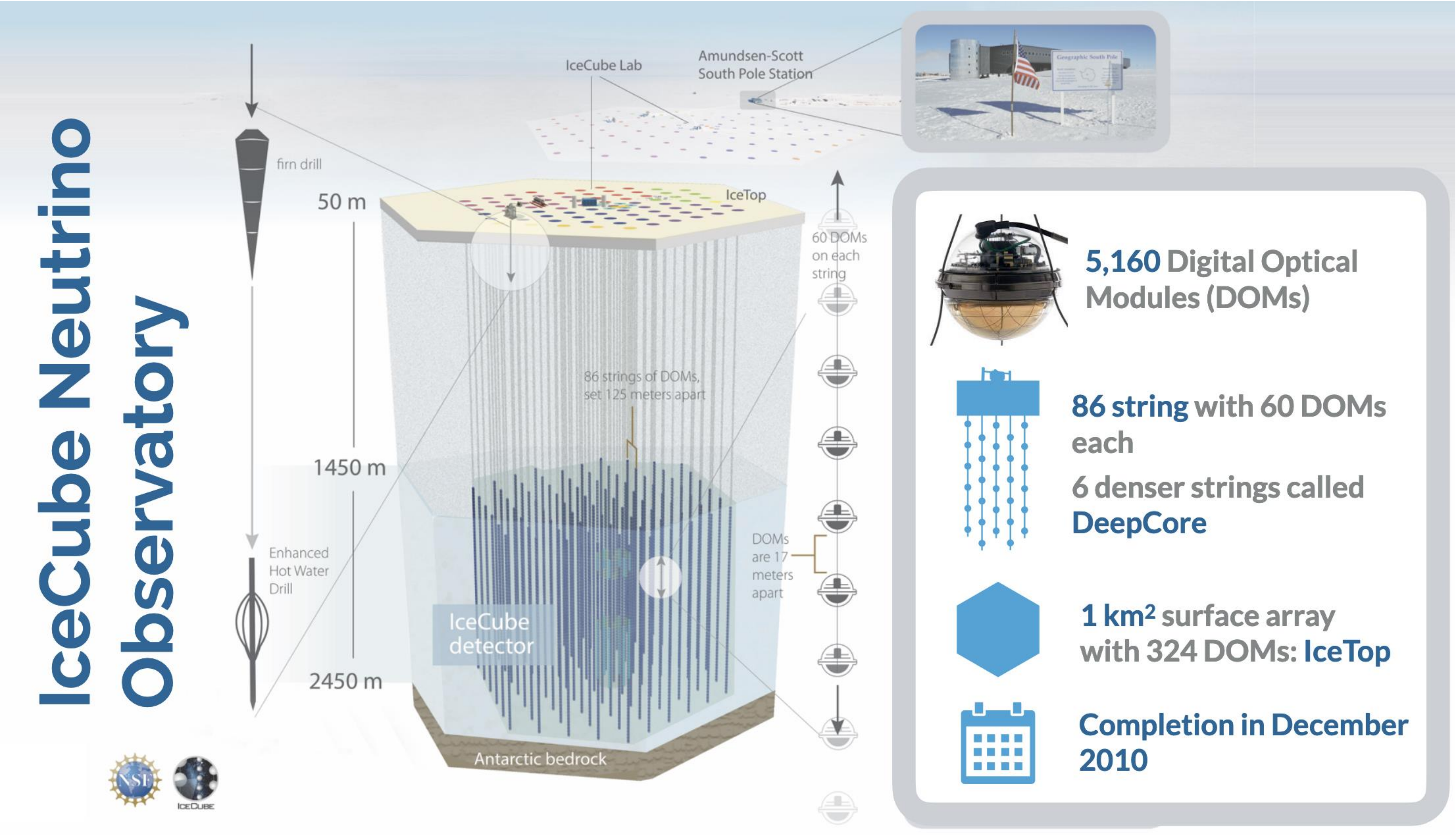
S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10





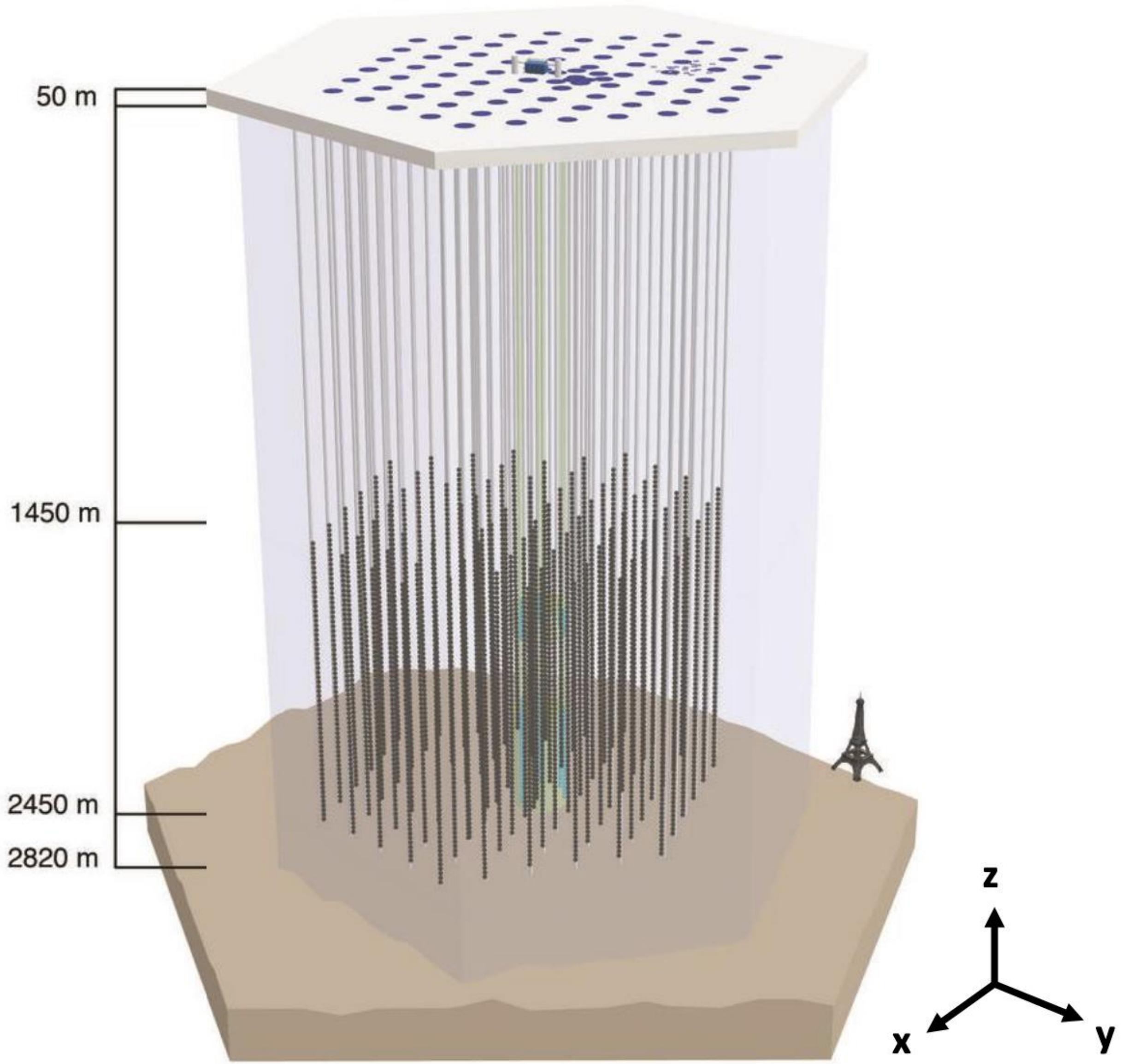
(Rogly, poster 79)

IceCube [South Pole, 2010-]



IceCube ν detector

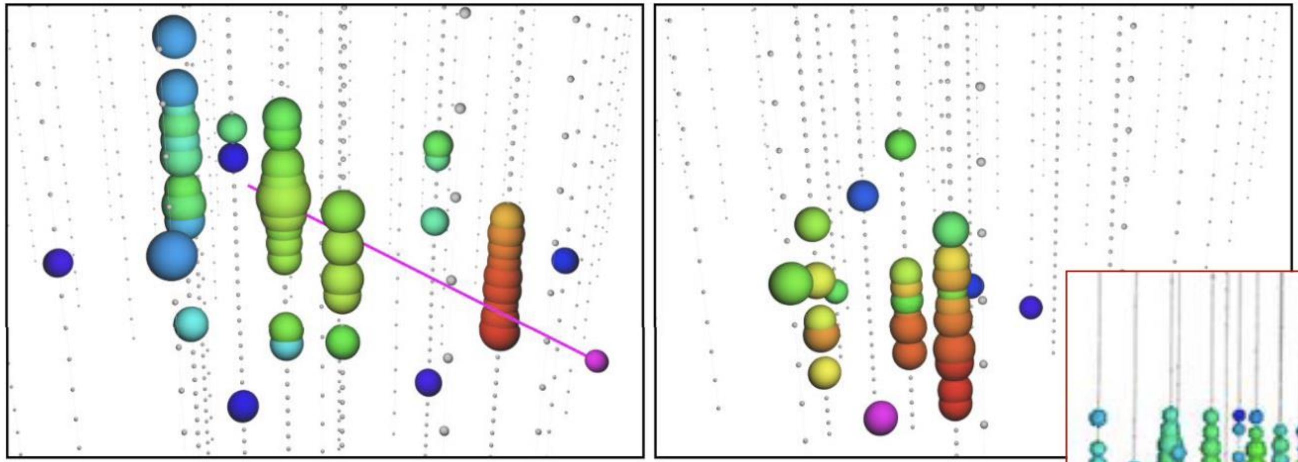
- Ice **Cherenkov ν** detector
- 1.5 – 2.5 km under ice
- 5,160 DOMs on 86 strings
- 1 km^3 volume
- High energy array spacing
  - Δz=17m
  - $\Delta(x, y)$=125m
- LE extension: DeepCore
  - Δz=7m
  - $\Delta(x, y)$=40-70m

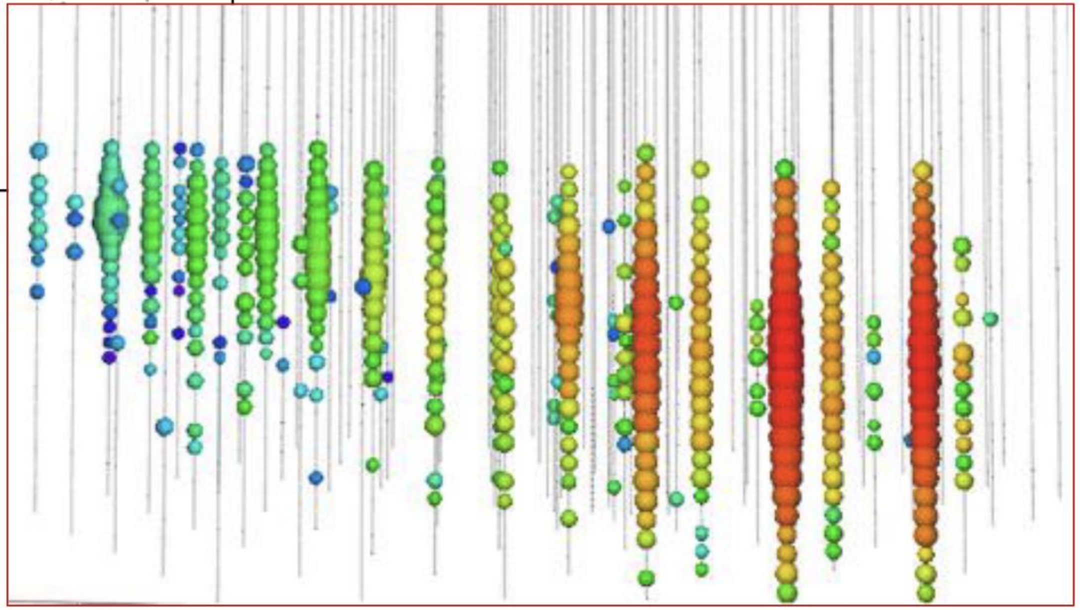


3

Events as seen by the detector

GeV events in DeepCore for ν oscillations



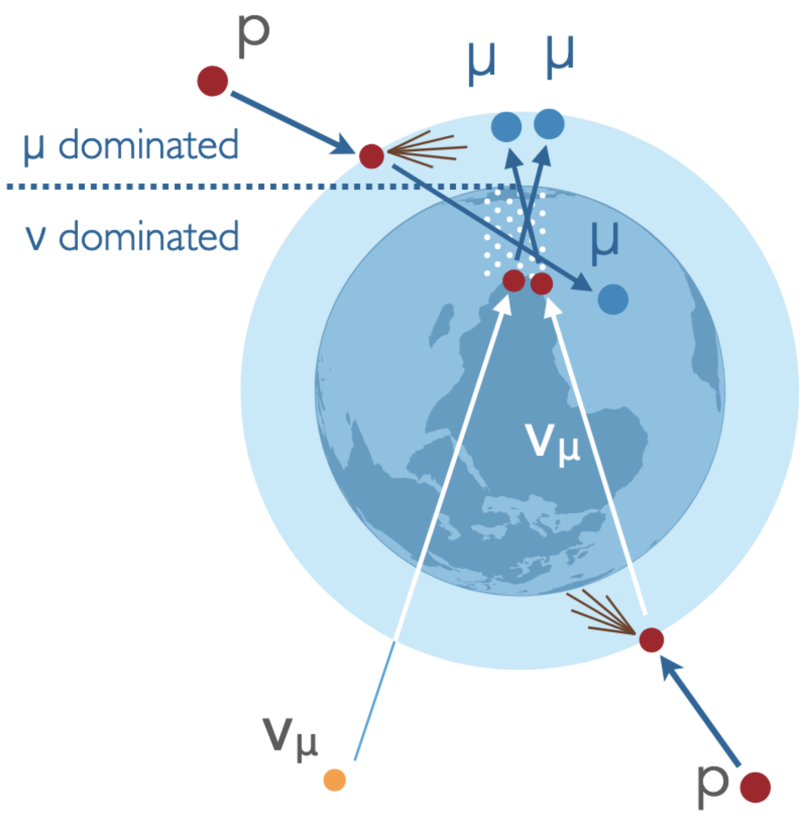


TeV event in IceCube for sterile ν searches 7

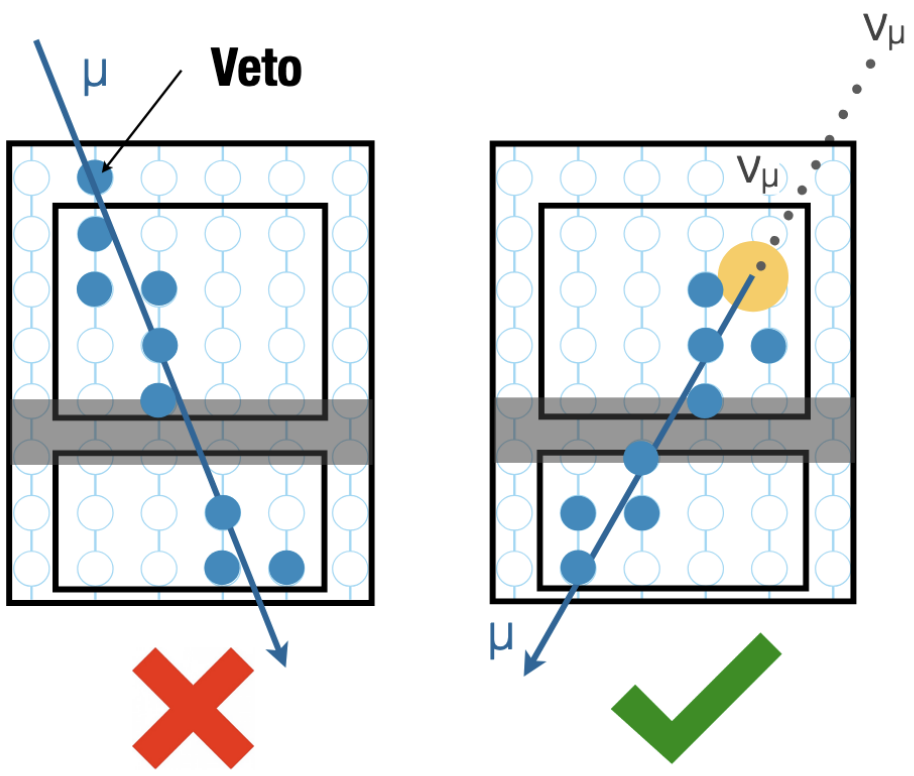
Color indicates time (red=early, blue=late).
Sphere size is proportional to number of photons observed.

Background Rejection

1. *Using up-going **through-going muon** events using Earth as a shield against atmospheric muons.*



2. *Using the outer layers as an active veto to select **starting events.***

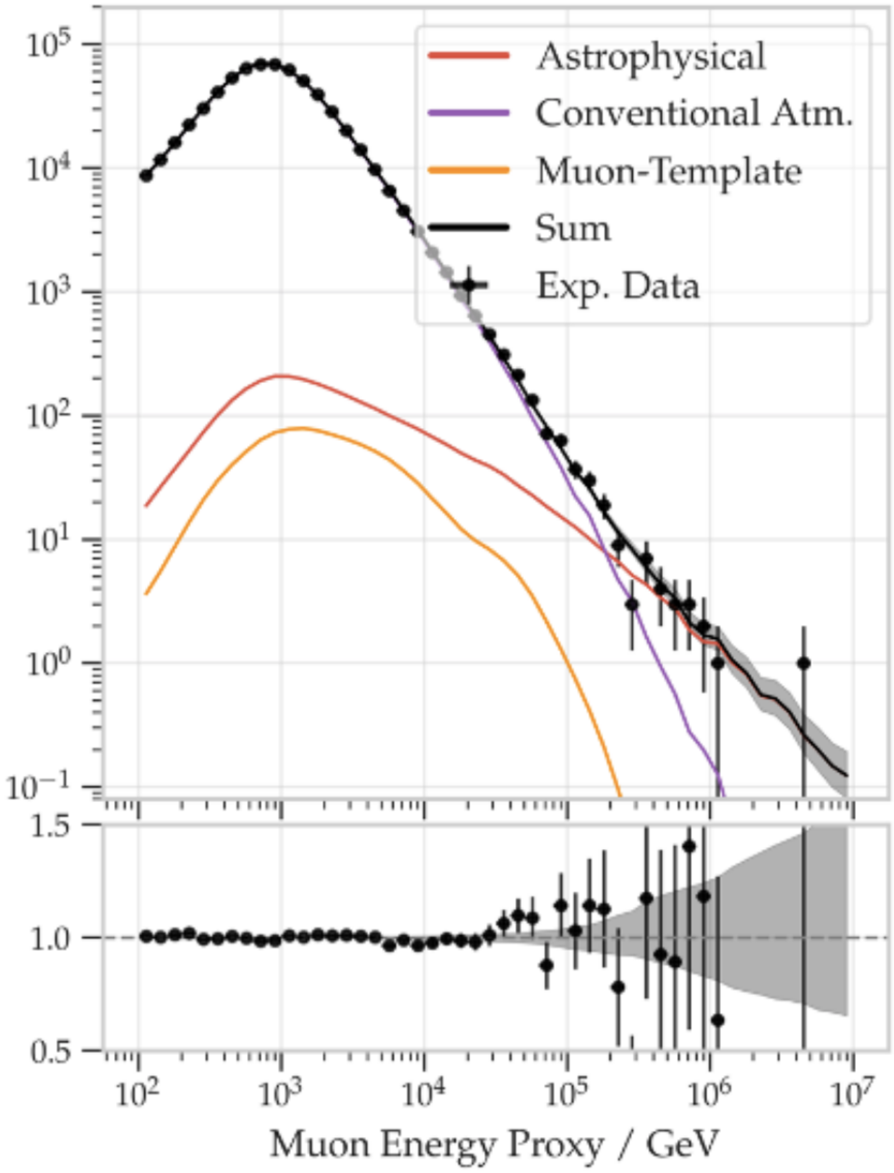


Astrophysical Journal 928 (2022) 50

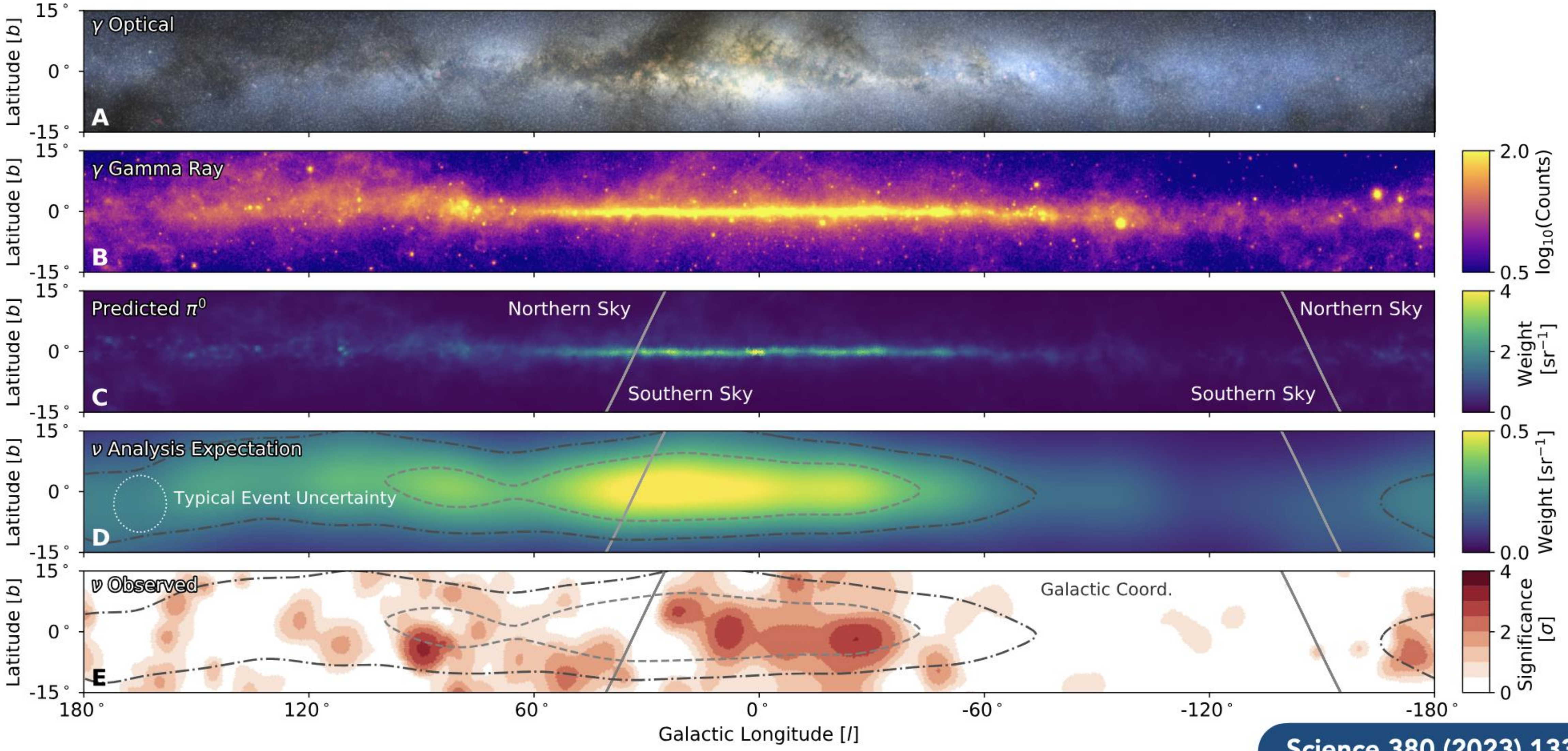
Astrophysical Neutrinos

Through-going muons

- Clear excess > 100 TeV (57 events)
- High statistics sample ~650,000 events
  - ~1000-2000 astrophysical
- Northern Sky only
- Energy range:
  - 15 TeV to 5 PeV
- Hard spectrum: $E^{-2.37}$
  - Slightly softer than previous 8yr results due to better treatment of the primary cosmic-ray flux



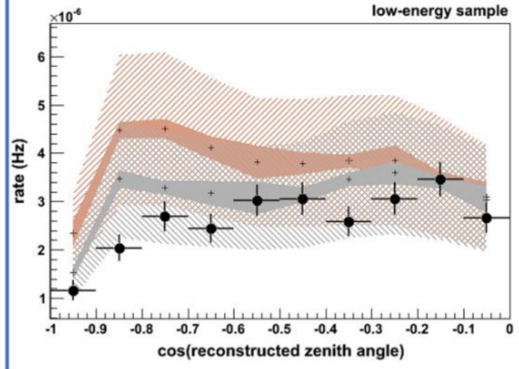
IceCube

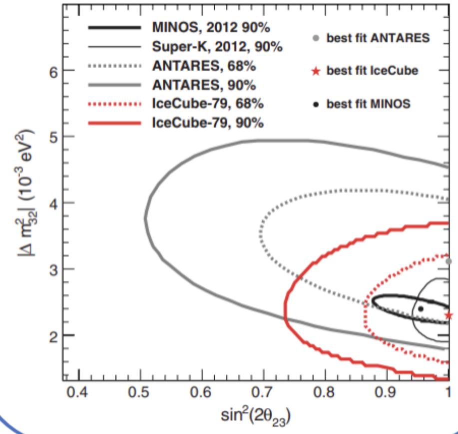


Science 380 (2023) 1338

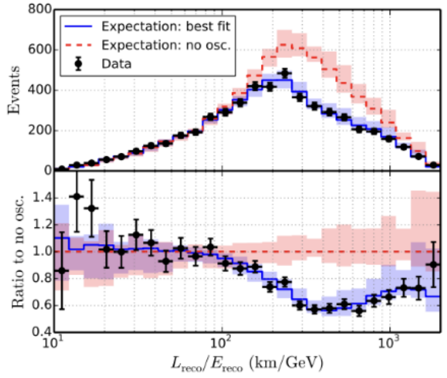
Atmospheric oscillations progression

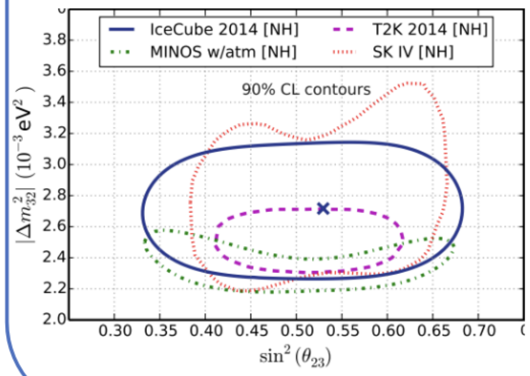
IceCube, PRL 111, 081801 **(2013)**
700 events



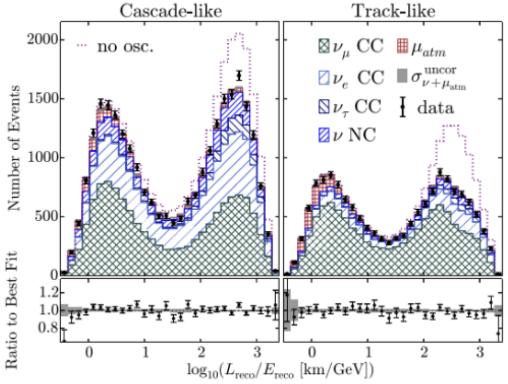


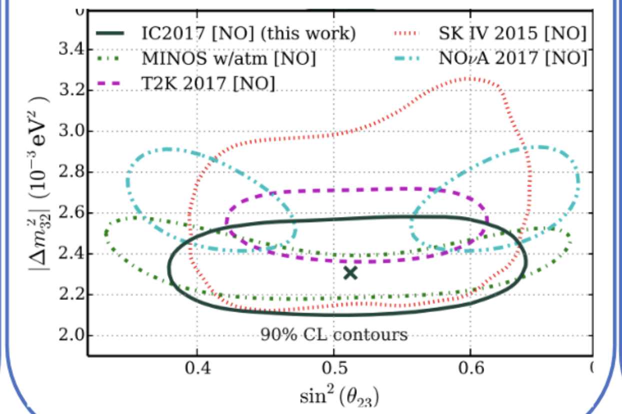
IceCube, PRD 91, 072004 **(2015)**
~5k events, "golden events"



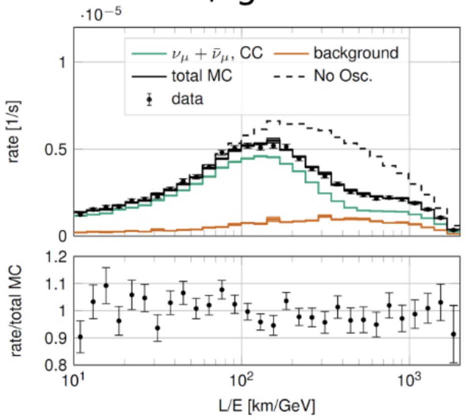


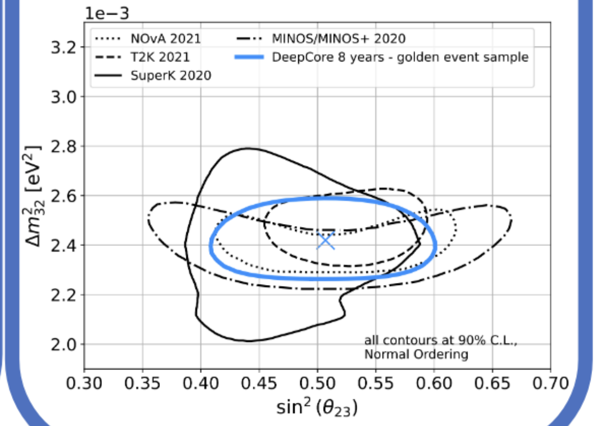
IceCube, PRL 120, 071801 **(2018)**
~35k events, inclusive sample





IceCube, PRD 108, 012014 **(2023)**
~22k events, "golden events"



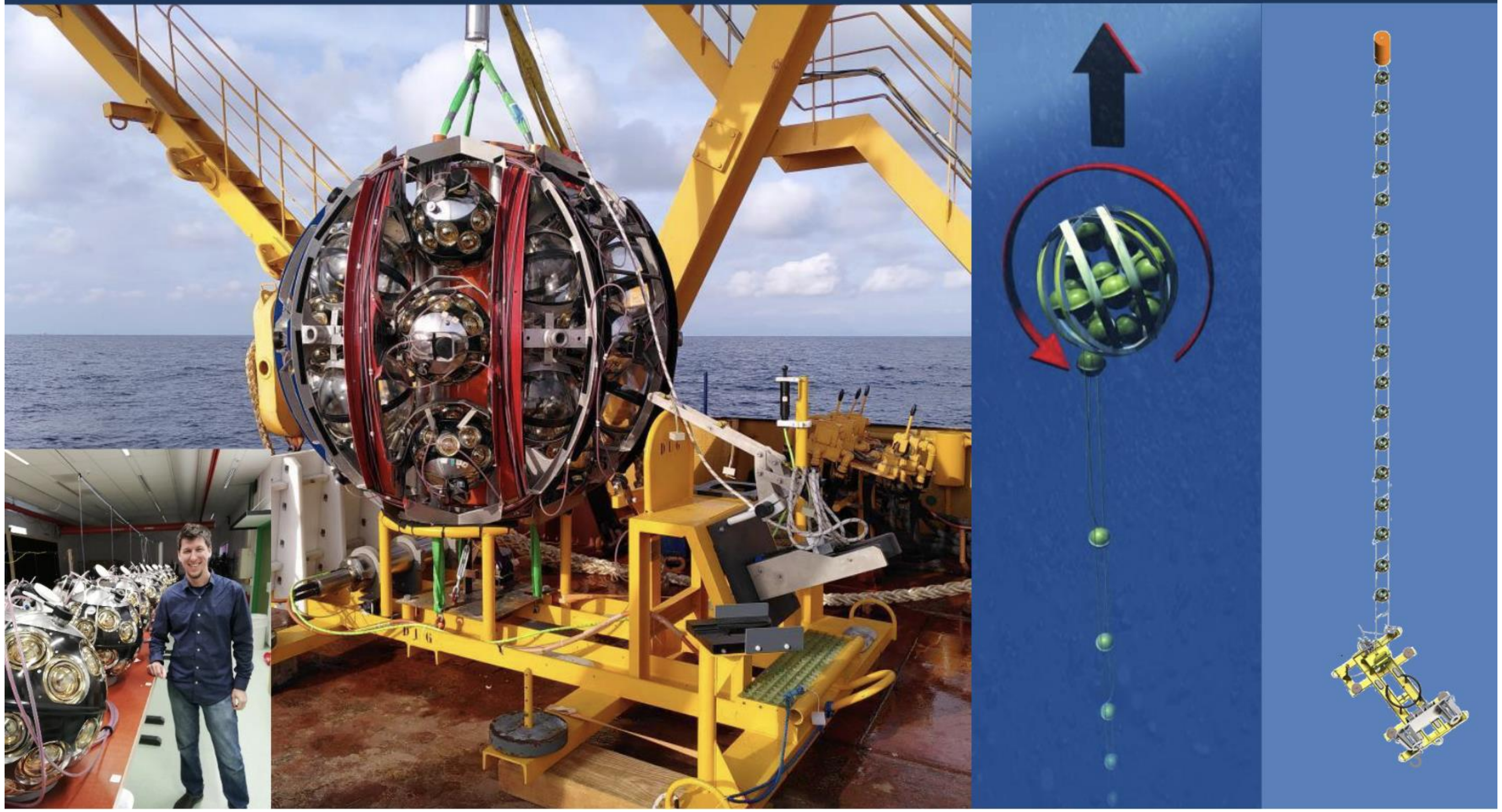


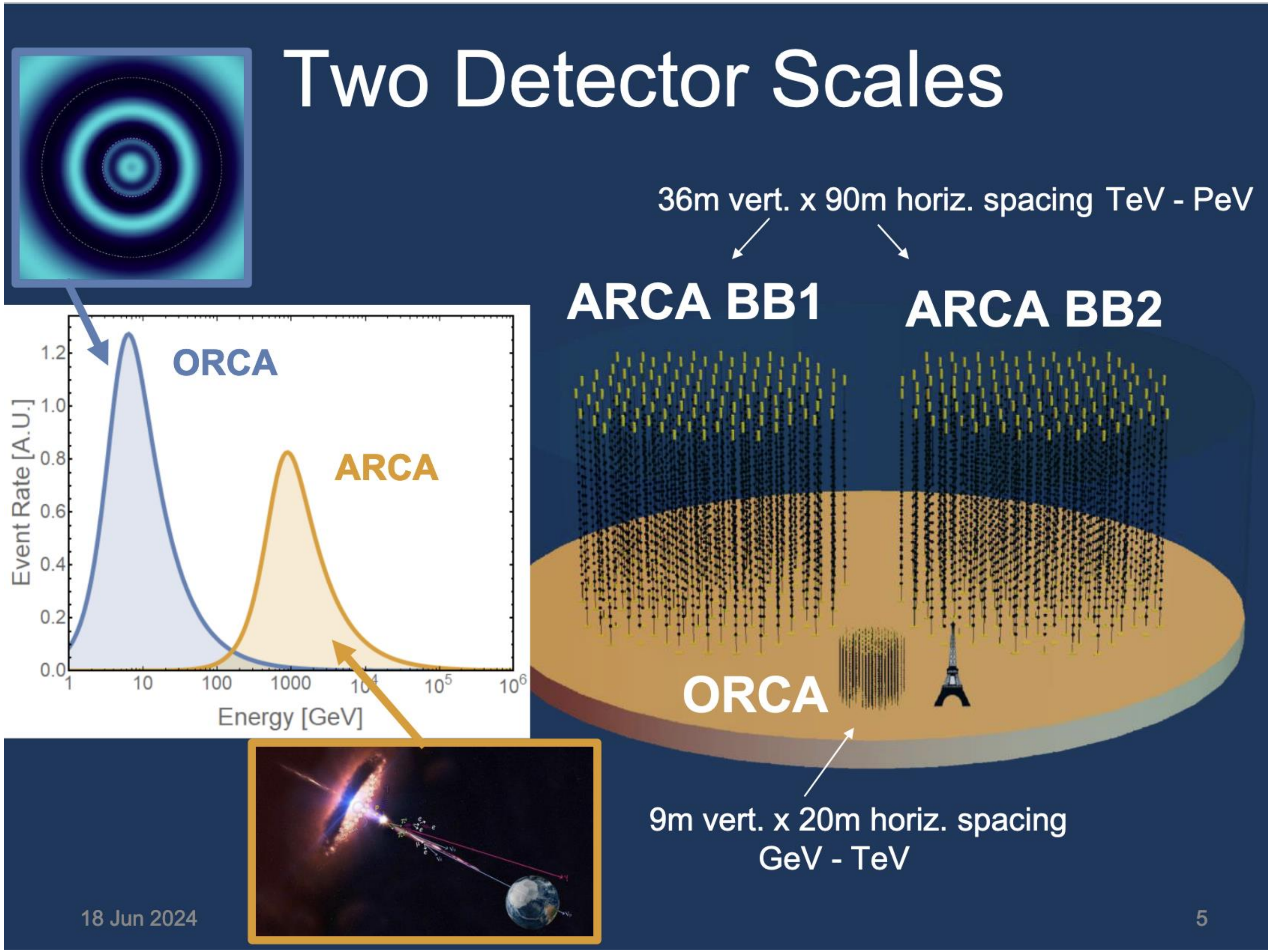
13


The KM3NeT Eyes
• KM3NeT is building a series of neutrino telescopes in the Mediterranean Sea
• The KM3NeT DOMs are the eyes of the experiment observing the light around it

The KM3NeT DU

- 18 KM3NeT DOMs are joined together in a chain to form a Detection Unit (DU)
- DUs are rolled up into a Launcher of Optical Modules (LOM) for deployment at sea
- Once at the bottom, LOM is released and unrolls the DUs into its final vertical position




Two Detector Scales
36m vert. x 90m horiz. spacing TeV - PeV
ARCA BB1
ARCA BB2
ORCA
ARCA
Event Rate [A.U.]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
10
100
1000
10^4
10^5
10^6
Energy [GeV]
ORCA
9m vert. x 20m horiz. spacing
GeV - TeV
18 Jun 2024
5

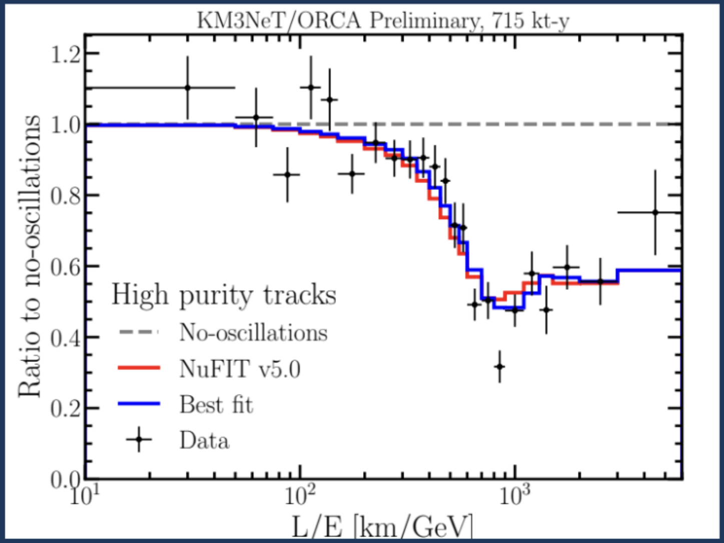
Improved Measurement

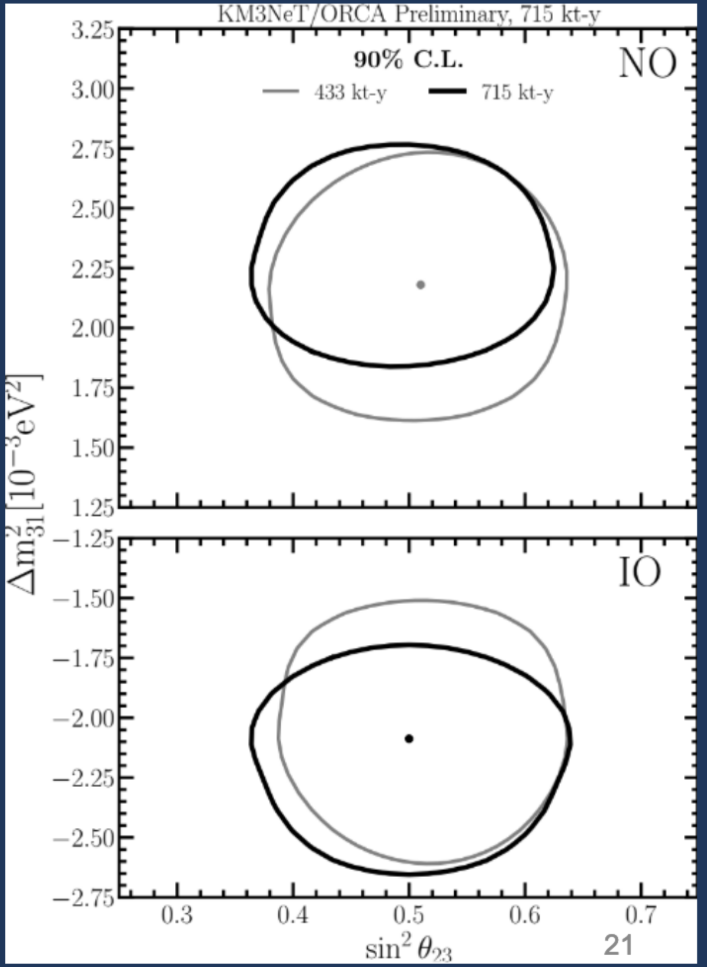
- New measurement uses 715 kt-y of data (65% increase over 2023 dataset)
- Clear oscillation pattern in L/E
- Slight preference for Inverted Ordering (IO)

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\mathrm{eV}^2, & \mathrm{IO} \\ [2.10, 2.37] \times 10^{-3}\mathrm{eV}^2, & \mathrm{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$





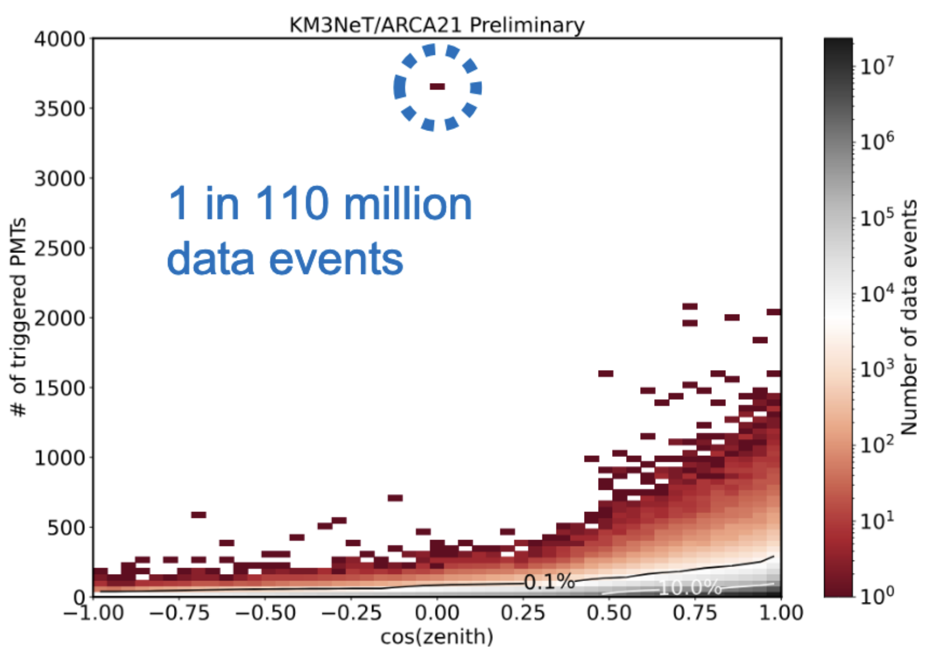
18 Jun 2024

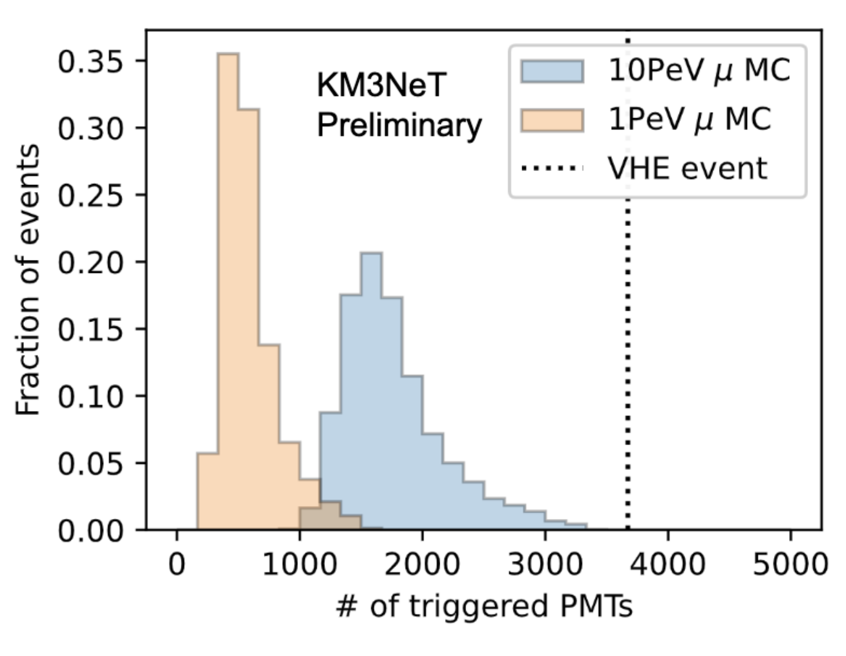
See poster 358

21

Uncharted Territory

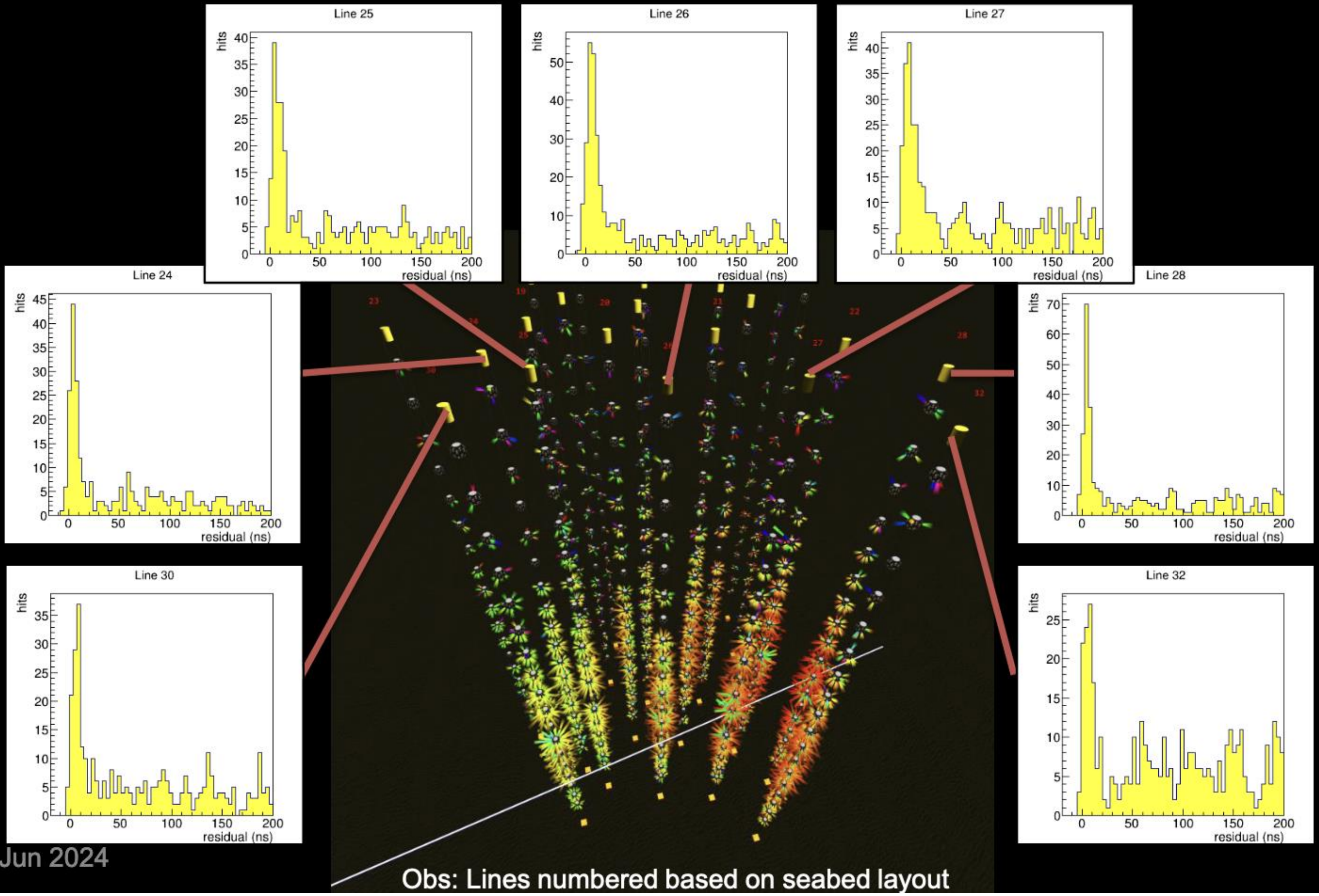
- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





Uncharted Territory

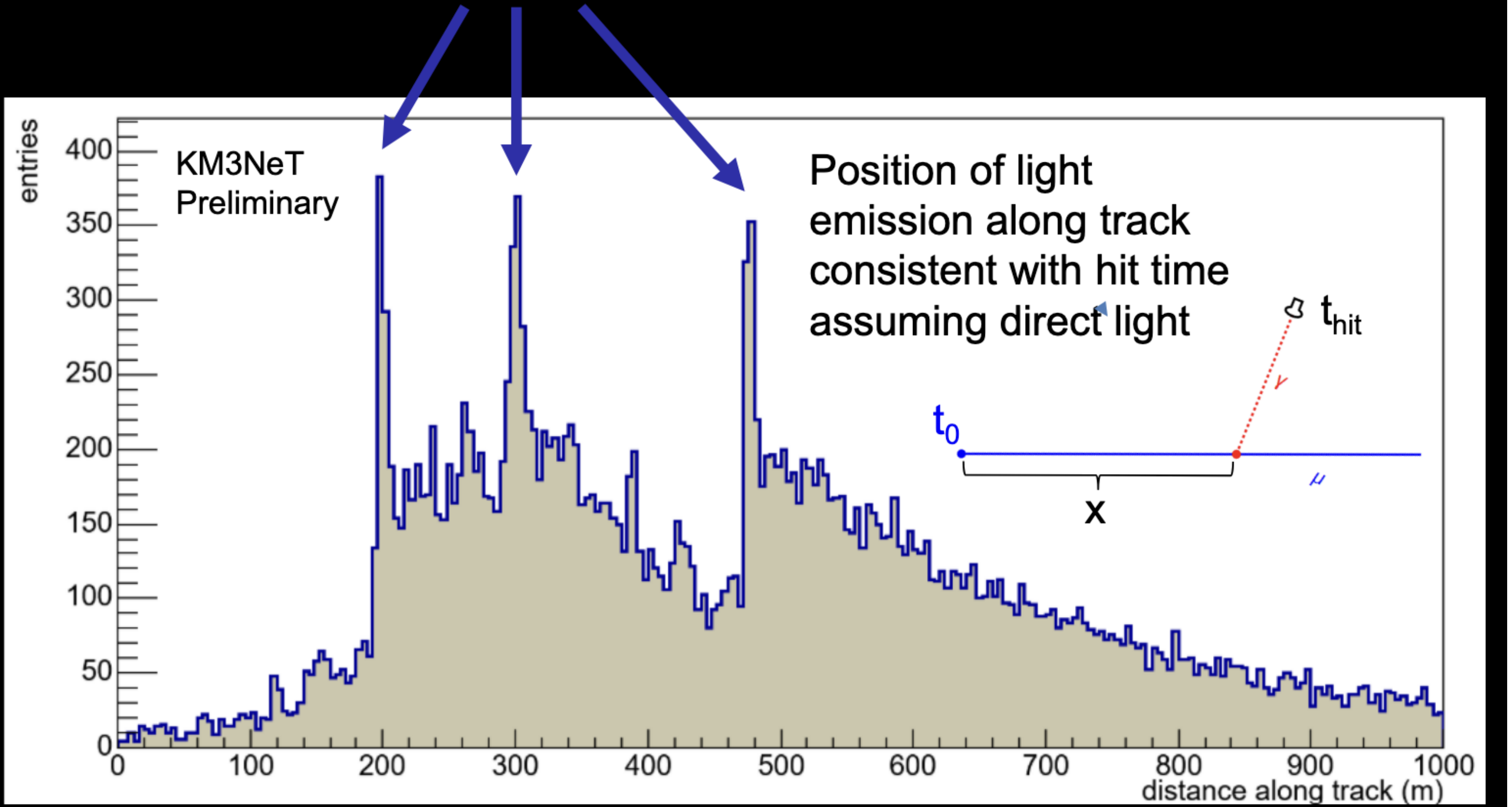
- Event is well reconstructed as a high energy muon crossing entire ARCA21 detector



18 Jun 2024 38

Uncharted Territory

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons



18 Jun 2024 39

geoneutrinos

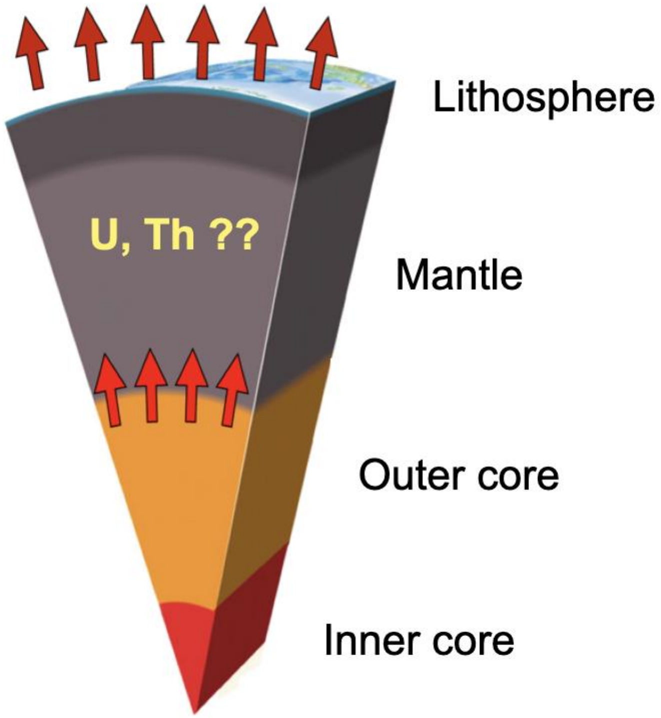
- KamLAND-Zen
- Borexino

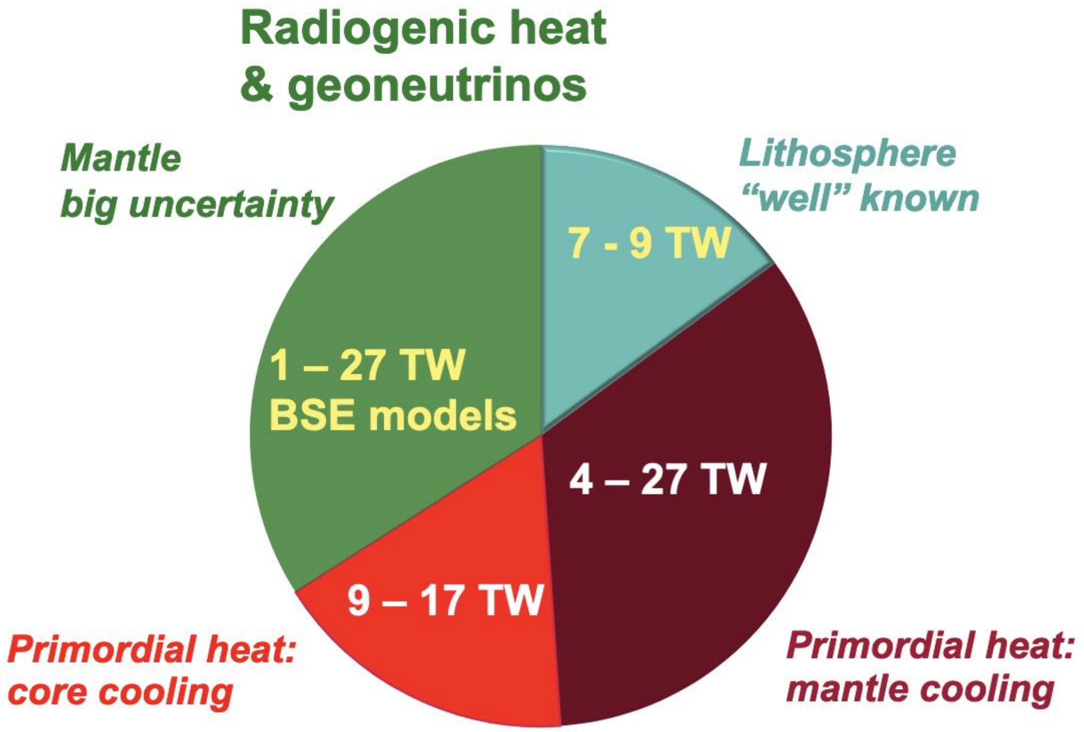
THE EARTH'S HEAT BUDGET

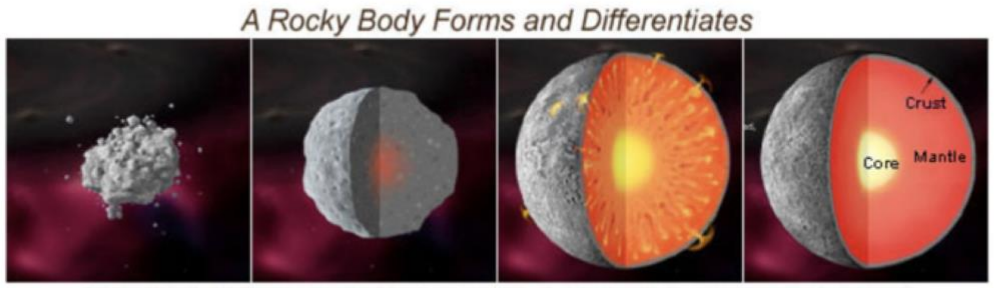
Integrated surface heat flux:

From measured T-gradients along bore-holes

$H_{tot} = 47 \pm 2$ **TW**







(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

GEONEUTRINO DETECTION

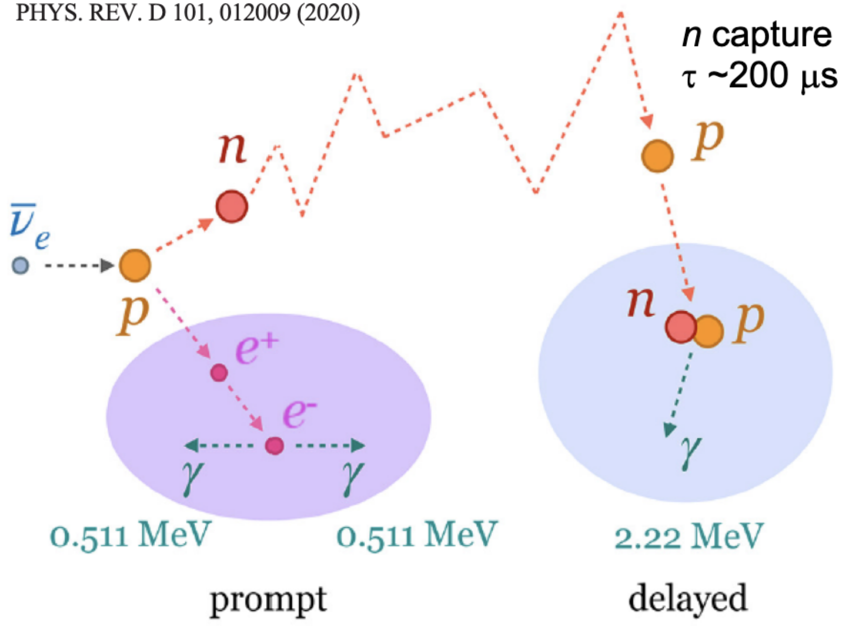
- Inverse Beta Decay on proton (IBD): **delayed coincidence.**
- Charge current interaction mediated by W bosons.
- Sensitive only to **electron flavour antineutrinos.**
- Cross section well known.
- Coincidence = powerful **background suppression** tool.
- **Reactor neutrinos – irreducible background,** with ~10 MeV end-point, geoneutrinos ~3.3 MeV.

Energy threshold = 1.8 MeV

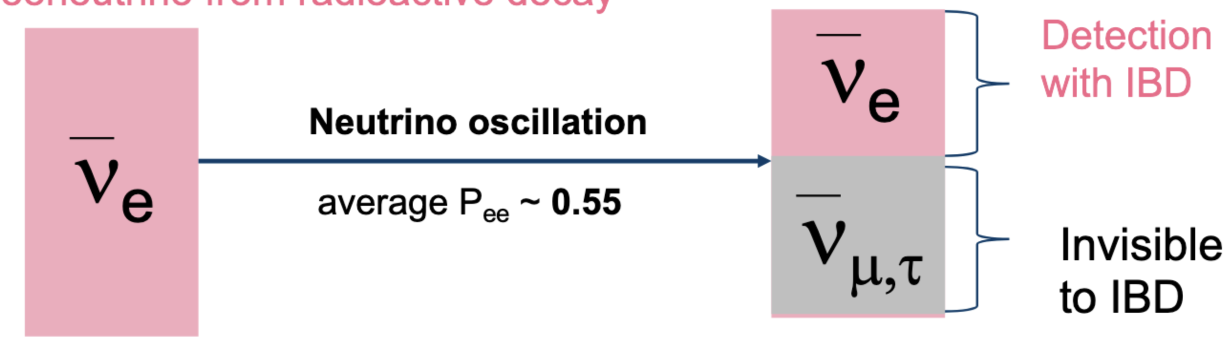
σ @ few MeV: ~10^{-42} cm^2

(~100 x more than elastic scattering on electron)

PHYS. REV. D 101, 012009 (2020)



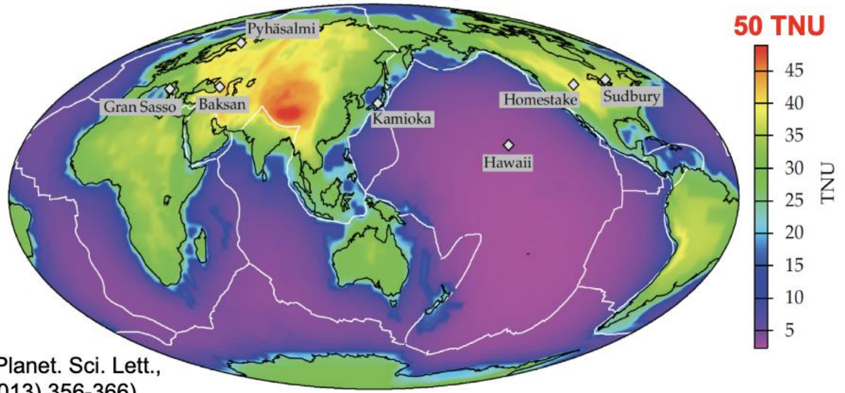
Geoneutrino from radioactive decay



$$E_{prompt} = E_{visible} = T_{e+} + 2 \times 511 \text{ keV} \sim E_{antinu} - 0.784 \text{ MeV}$$

GEONEUTRINO SIGNAL WORLDWIDE: from ϕ ~10^6 cm^{-2} s^{-1} to a handful of events

Expected crustal signal: "known" and "large".



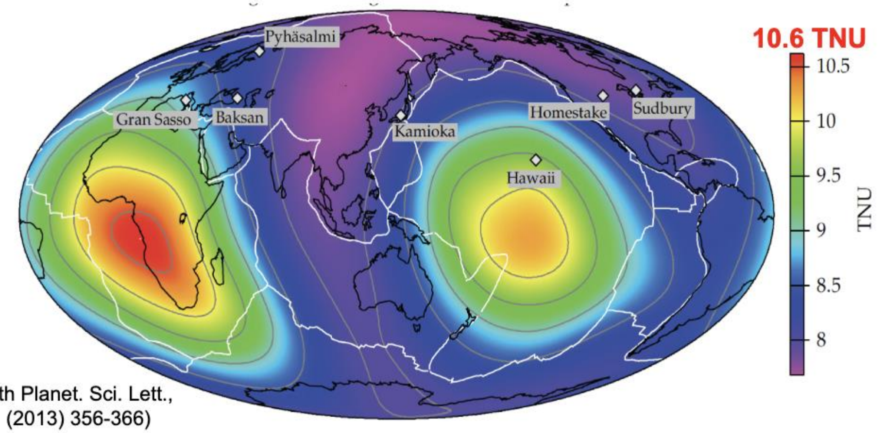
Earth Planet. Sci. Lett., 361 (2013) 356-366)

The signal is small, we need big detectors!

Terrestrial Neutrino Unit

1 TNU = 1 IBD event / 10^{32} target protons / year
(cca 1 IBD event /1 kton /1 year)
with 100% detection efficiency

Expected mantle signal: super-tiny and unknown.
Hypothesis of heterogeneous mantle composition motivated by the observed **Large Shear Velocity Provinces** at the mantle base.



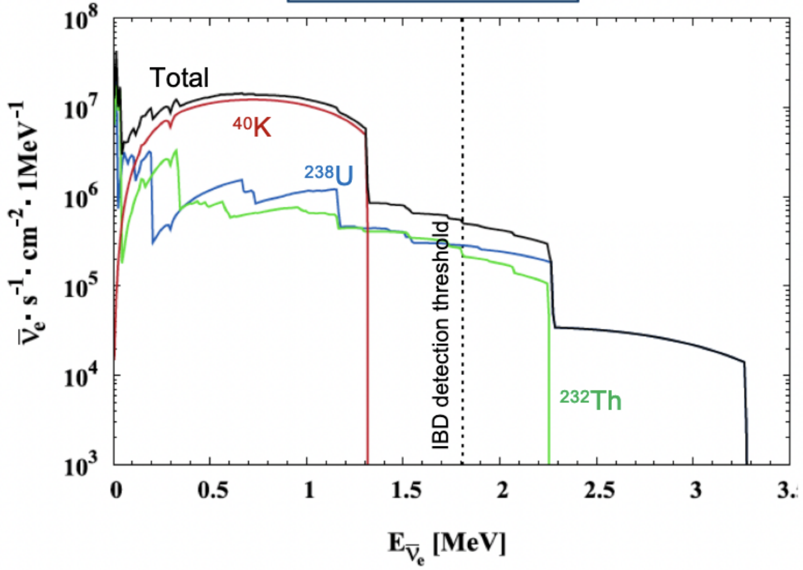
Earth Planet. Sci. Lett., 361 (2013) 356-366)

Mantle signal is even more challenging!

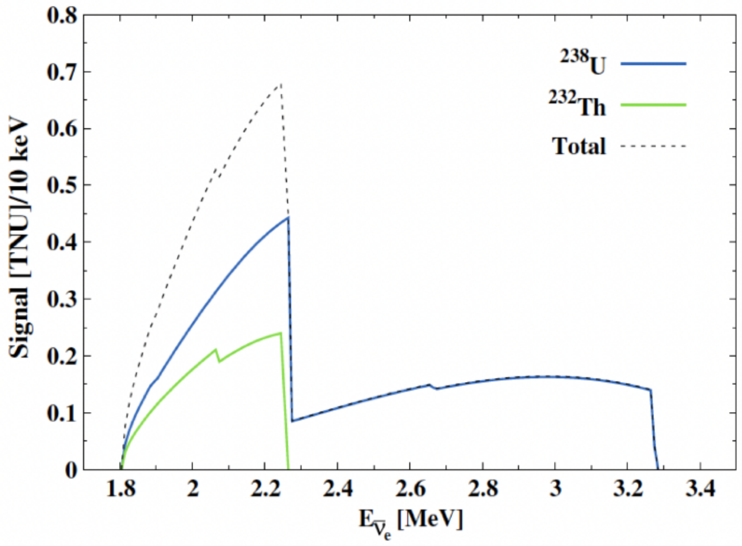
JÜLICH Forschungszentrum

GEONEUTRINO SPECTRAL SHAPE @ LNGS

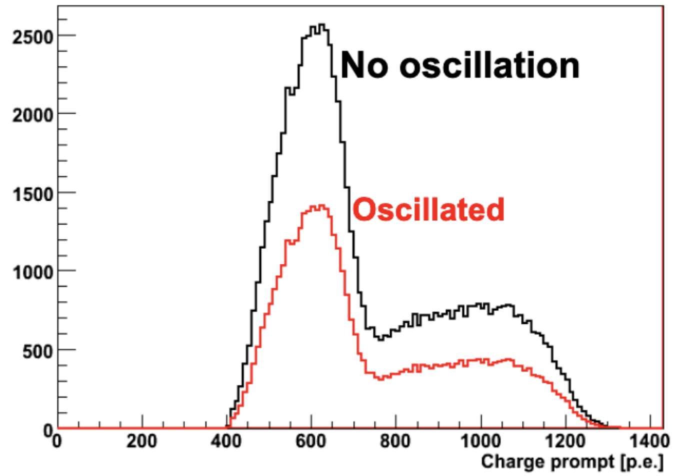
Geoneutrino flux



Geoneutrinos detected via IBD



Effect of neutrino oscillations



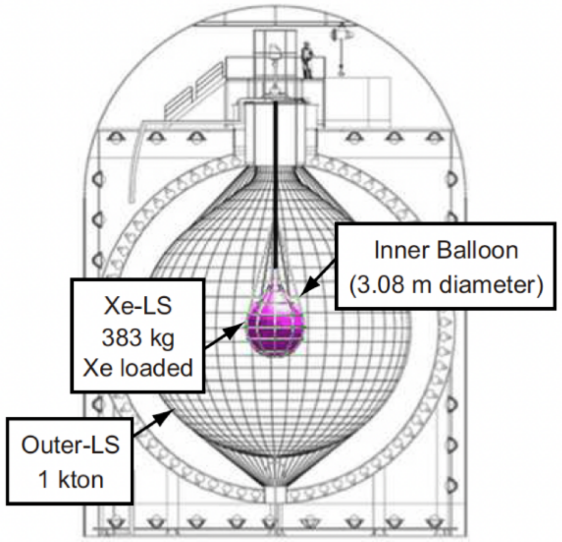
500 p.e. ~ 1 MeV

- We are able to **detect geoneutrinos only from the decay chains of ^{238}U and ^{232}Th** above 1.8 MeV.
- ^{238}U and ^{232}Th have different end points: **the key how to spectrally distinguish them**.
- **^{40}K** geoneutrinos cannot be detected.
- **Effect of neutrino oscillations**: for 3 MeV antineutrino, the oscillation length is ~100 km; considering the Earth's dimensions and continuous distribution of U and Th: for the precision of current experiments – suppression of the visible signal without spectral deformation.

JÜLICH Forschungszentrum

EXPERIMENTS THAT MEASURED GEONEUTRINOS

KamLAND(- Zen), Kamioka, Japan
Border between OCEANIC / CONTINENTAL CRUST



- Main goal: reactor neutrinos (+ since 2011 $0\nu\beta\beta$)
- Data taking: since 2002
- LS: ~1000 tons
- Depth: 2700 m.w.e.
- S(reactors) / S(geo) ~ 6.7 (up to 2010)
  ~ 0.4 (from 2011 after Fukushima)

Liquid scintillator detectors

Large target volume

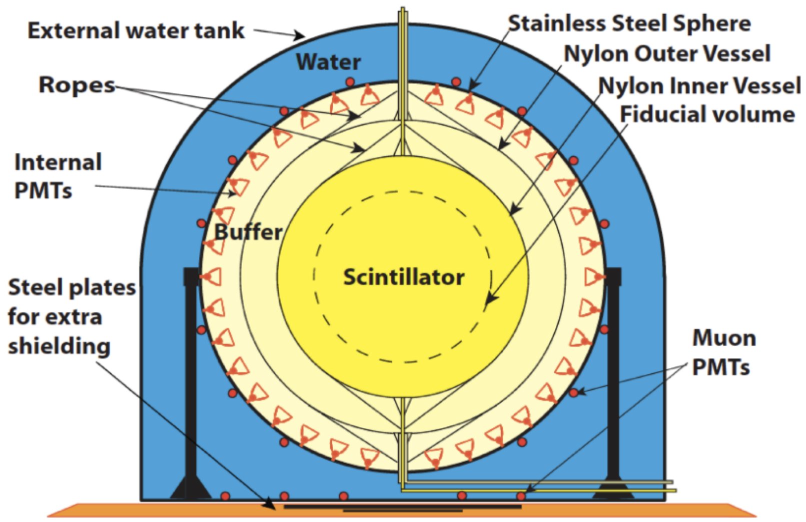
Placed underground

PMT arrays to detect scintillation light

Water Cherenkov veto

Radiopurity

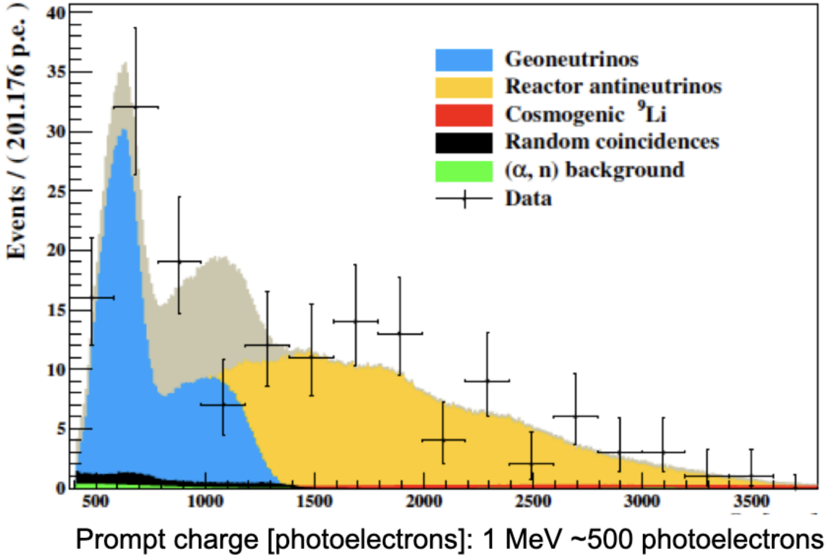
Borexino, LNGS, Italy
CONTINENTAL CRUST



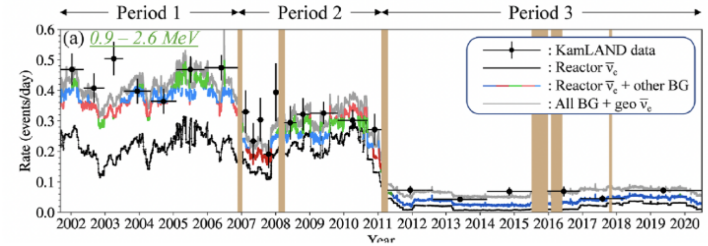
- Main goal: solar neutrinos:
  extreme radio-purity needed and achieved
- Data taking: 2007 – 2021
- LS: 280 tons
- Depth: 3800 m.w.e.
- S(reactors) / S(geo) ~ 0.3 (2010)

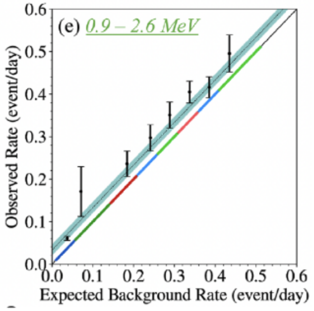
LATES RESULTS: SPECTRAL FIT with chondritic Th/U ratio

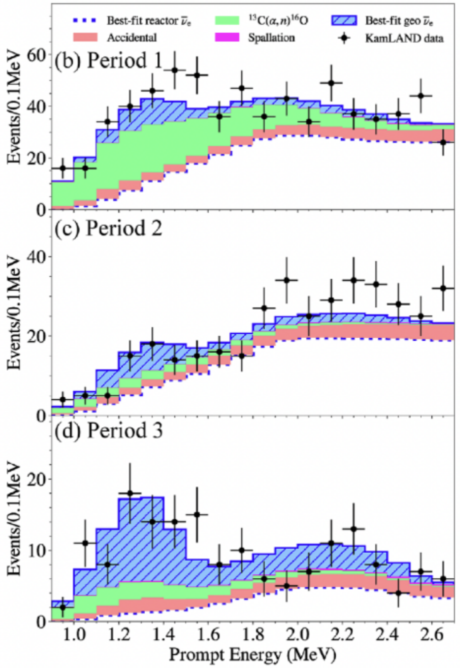
Borexino (PRD101 (2020) 012009)



KamLAND (Geophys. Res. Lett. 49 e2022GL099566)







1.29 x 10^{32} proton x years (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32} proton x years** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6\ ^{+9.4}_{-8.6}$ *(stat)* $^{+2.7}_{-2.1}(sys)$ $^{+18.3}_{-17.2}\%$	**Geoneutrinos** (mass Th/U fixed to 3.9)	$183\ ^{+29}_{-28}$ *(stat + sys)*: $^{+15.8}_{-15.3}\%$
$47.0\ ^{+8.4}_{-7.7}$ *(stat)* $^{+2.4}_{-1.9}(sys)$	**Signal [TNU]**	Not provided
Shape only, reactor-ν free – results compatible with prediction	**Analysis with** S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)	Rate + shape + time

summary

- double-beta decay
- tritium
- nuclear reactors
- accelerator neutrinos
- solar neutrinos
- atmospheric neutrinos
- astrophysical neutrinos
- geo-neutrinos