Reactor Neutrino Studies in China: an experimental review

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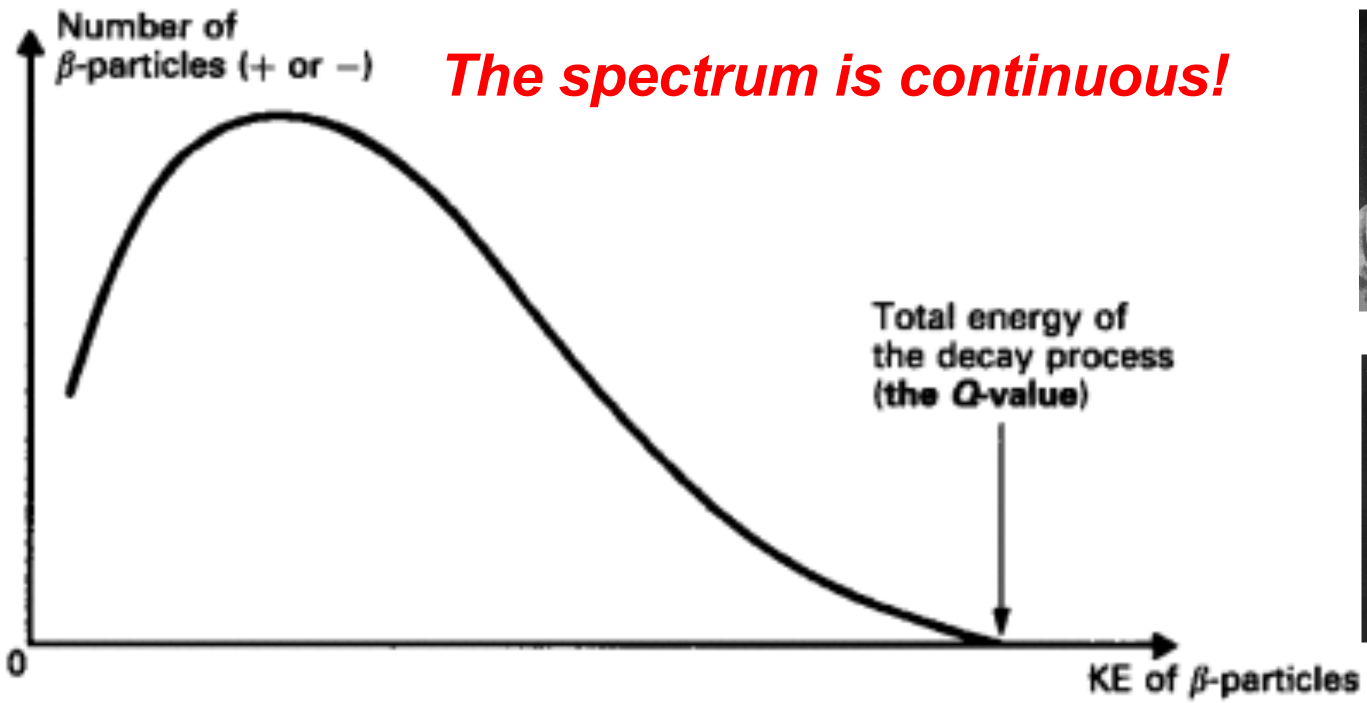
NUSYS, Beijing Normal University, 2024

Outline

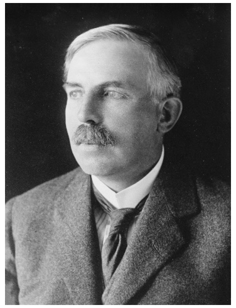
- Part I: Introduction of Neutrino
  - The need of Neutrino
  - Standard Model Neutrino and Neutrino Oscillation
- Part II: Discovery of Neutrino Oscillation, Atmospheric Neutrinos, Long-Baseline Neutrino Experiments
  - Search for neutrino oscillation signals
  - Super-Kamiokande → Hyper-Kamiokande
  - K2K → MINOS/T2K/NOvA and DUNE (extremely brief)
- **Part III: Reactor Neutrinos**
  - **Daya Bay Reactor Neutrino Experiment and Contemporaries (brief)**
  - **JUNO**

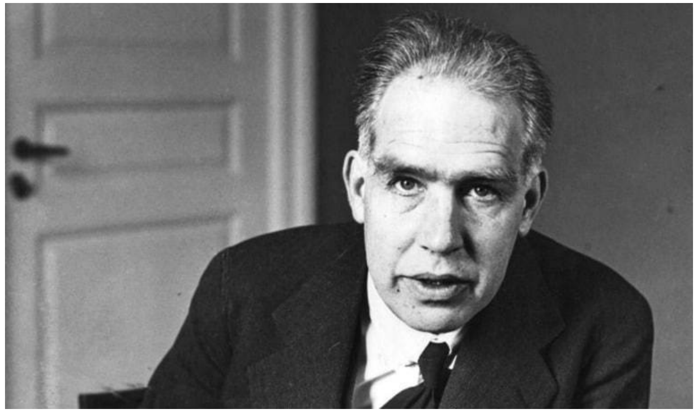
5 Campuses in 3 Major Cities

The Crisis of the beta-Spectrum in 1920s

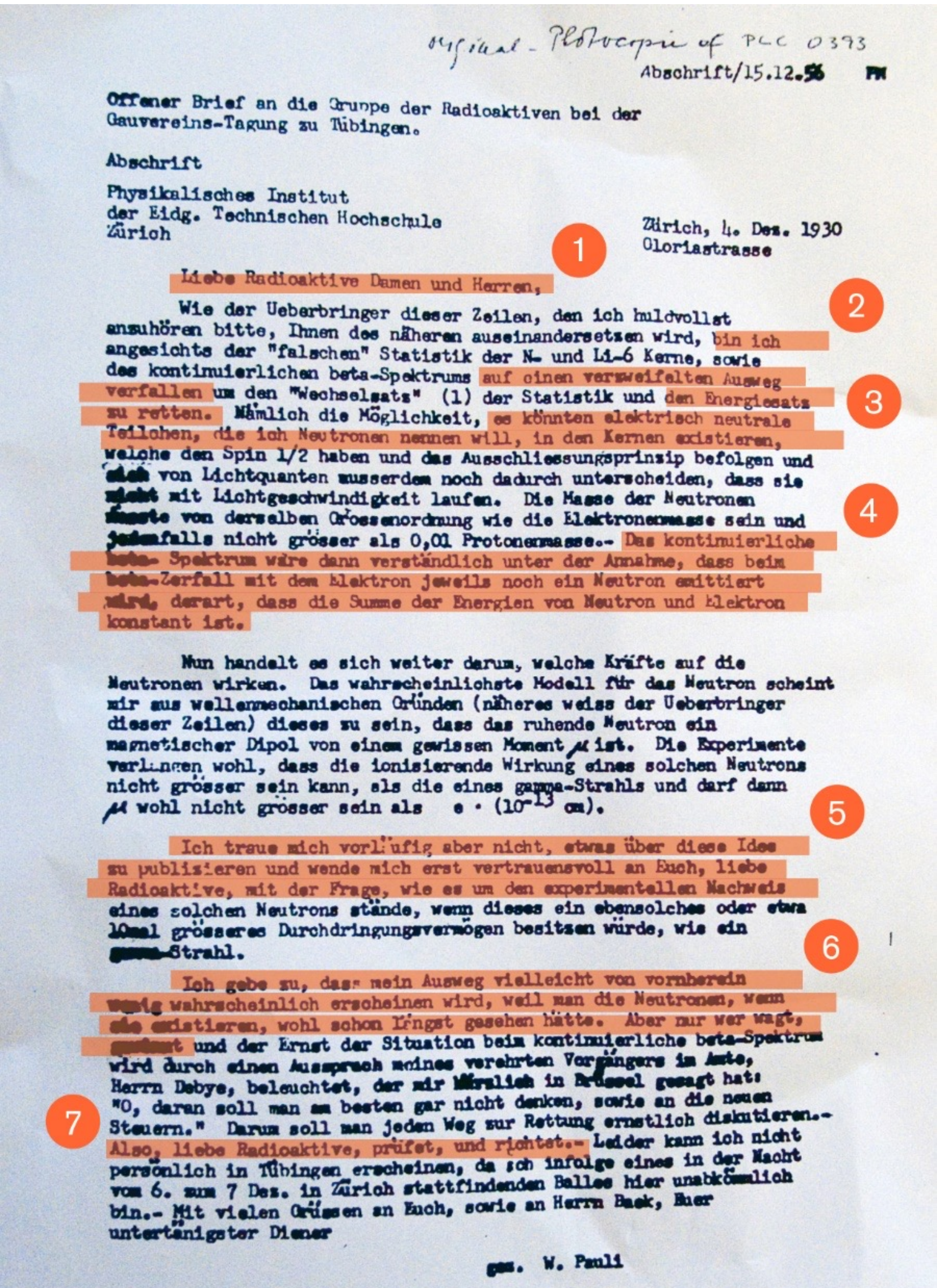


The spectrum is continuous!





- Bohr: "The energy in microworld was conserved not on an event-by-event basis, only on average"
- Pauli thought of another idea ……



original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

1 Liebe Radioaktive Damen und Herren,

2 Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. 3 Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- 4 Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

5 Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

6 Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- 7 Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

https://www.symmetrymagazine.org/article/march-2007/neutrino-invention

1. Dear Radioactive Ladies and Gentlemen!
2. I have hit upon a desperate remedy to save…the law of conservation of energy.
3. …there could exist electrically neutral particles, which I will call neutrons, in the nuclei…
4. The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, **a *neutron* is emitted such that the sum of the energies of *neutron* and electron is constant**
5. But so far **I do not dare to publish anything about this idea**, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron…
6. I admit that my remedy may seem almost improbable **because one probably would have seen those *neutrons*, if they exist, for a long time**. But nothing ventured, nothing gained…
7. Thus, dear radioactive ones, scrutinize and judge.

"I have done a terrible thing, I have postulated a particle that cannot be detected."

The First Attempts Detecting Neutrinos in 1930s-1940s

A Suggestion on the Detection of the Neutrino

KAN CHANG WANG
Department of Physics, National University of Chekiang Tsunyi, Kweichow, China
October 13, 1941

- **In 1941, Kan Chang Wang suggested a method detecting the neutrino**
- **In 1942, James S. Allen carried out the measurement, obtaining ~50 eV recoil E**

atom *alone*. Moreover, this recoil is now of the same amount for all atoms, since no continuous β-rays are emitted. We take for example the element Be^7 which decays in 43 days with K capture in two different processes:[2]

$$Be^7+e_K \rightarrow Li^7+\eta+(1\ \text{Mev})$$

and

$$Be^7+e_K \rightarrow (Li^7)^*+\eta+(0.55\ \text{Mev}),$$
$$(Li^7)^* \rightarrow Li^7+h\nu+0.45\ \text{Mev}.$$

The first process is relatively large, about 10 to 1 in comparison with the second process. The recoil energy of the first process is, by assuming the mass of neutrino to be zero, about 77 ev while that of the second process is about one-third of that amount. This recoil energy would have to be detected and measured in some way, and a correction would have to be made for the disturbances due to the γ-rays and the soft x-rays (originating from the replacement of the K electrons by outer electrons). The recoil

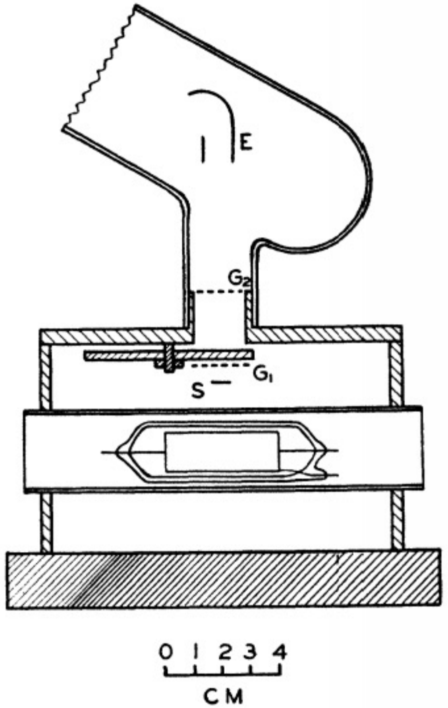


FIG. 1. Experimental arrangement of G-M and electron multiplier tubes.

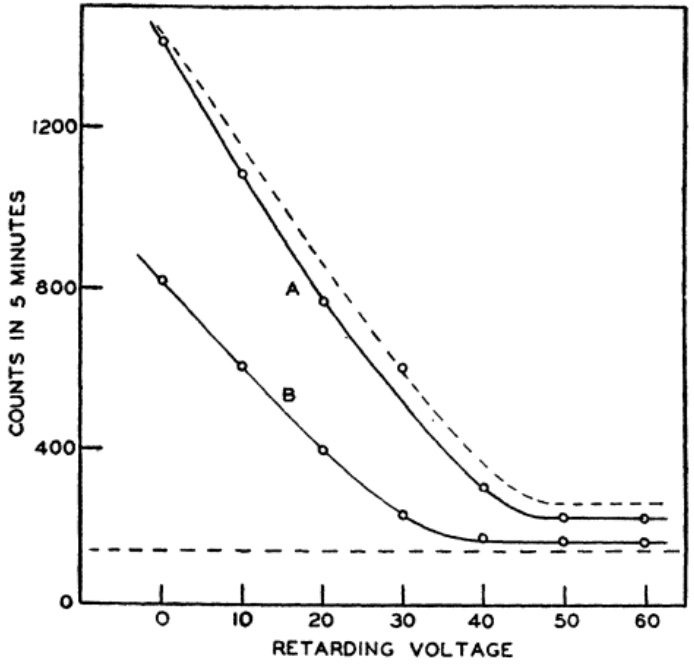
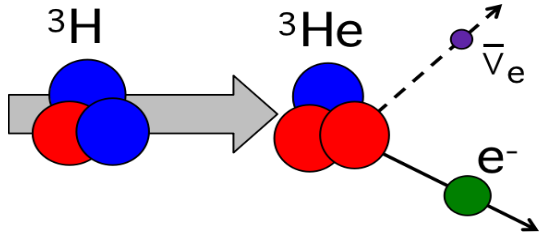


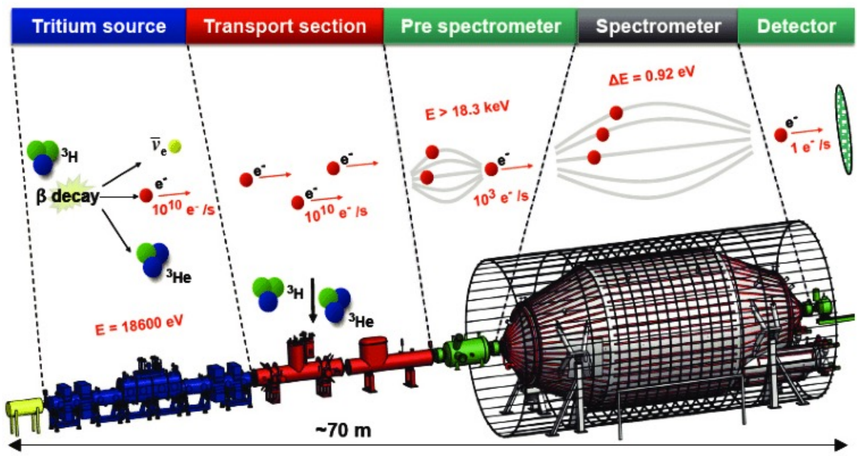
FIG. 3. Retarding potential curves for recoil ions. The horizontal dotted line represents the background counting rate.

Prof. Kan Chang Wang (1907-1998)

- PhD from Berlin Univ. under Meitner
- Vice Director of JINR 1959-1960

Latest Direct Neutrino Mass Measurement by KATRIN





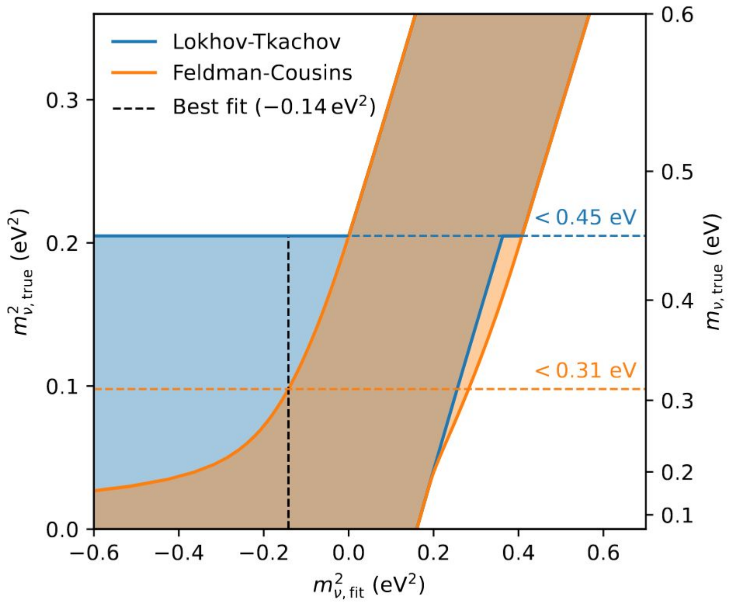
- 259 days of data released at Neutrino 2024
- 1000 days planned and eventual sensitivity 0.2eV

- KATRIN's **new** upper limit

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

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

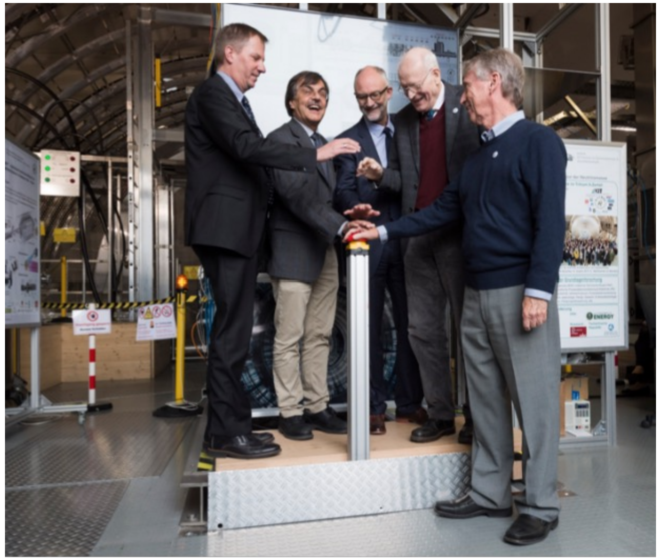
$$m_{\nu_\beta} = \sqrt{\sum_i^3 |U_{ei}|^2 m_i^2}$$



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

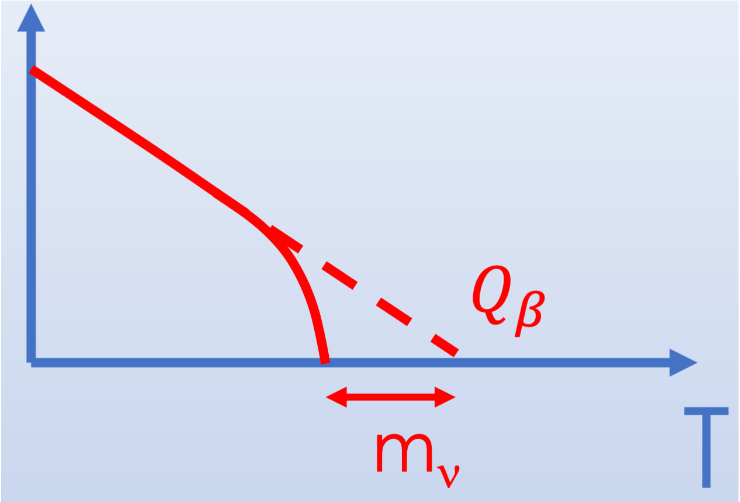
KATRIN Talk @ Neutrino 2024

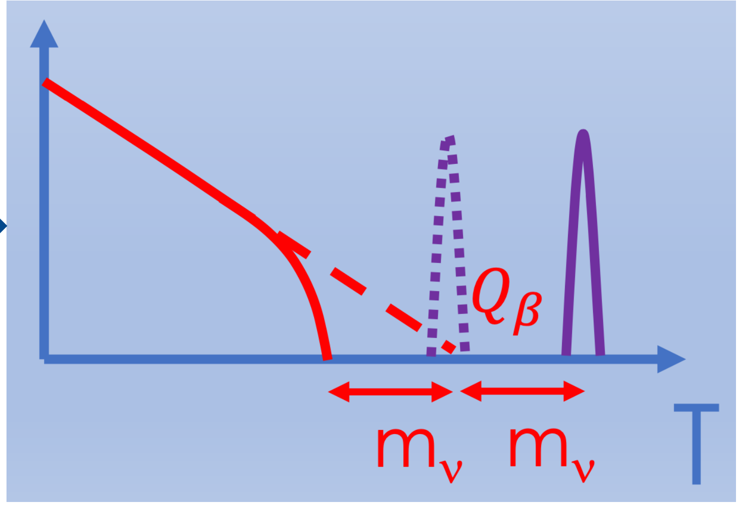
KATRIN: A Long Journey



15 Years of Hard Working and Persistence!

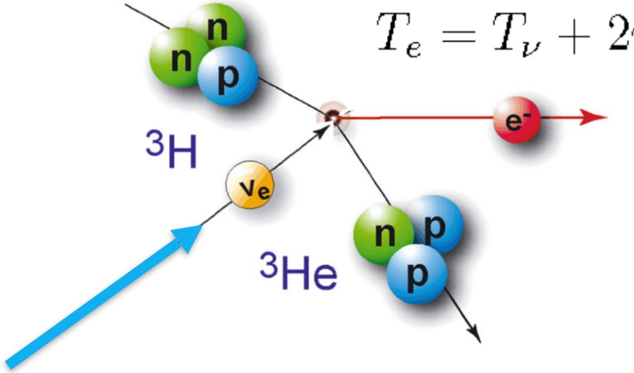
A Very Smart Approach: PTOLEMY

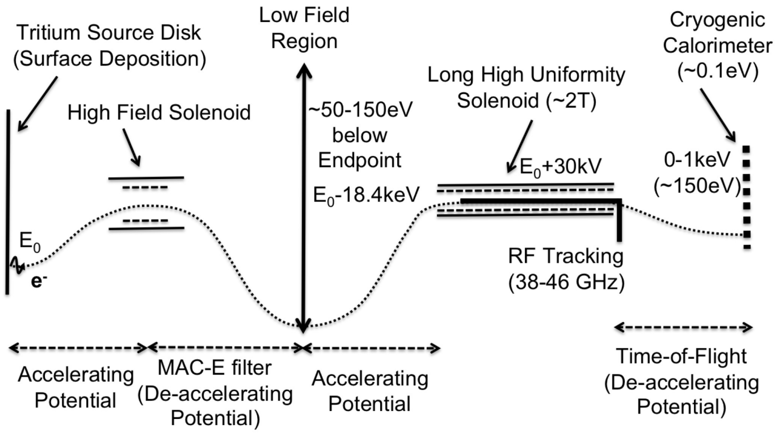


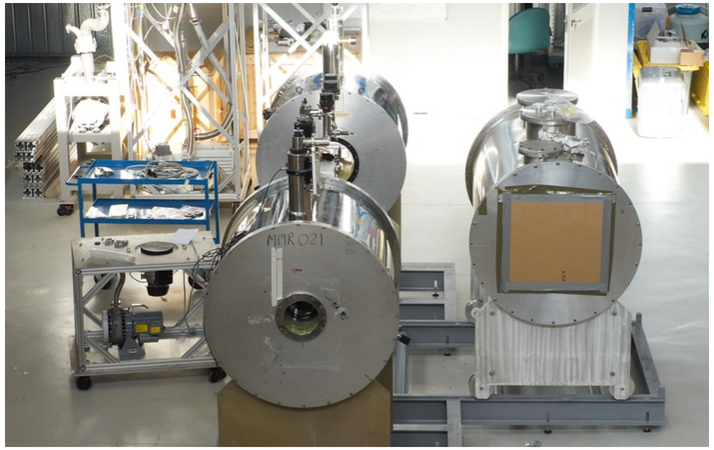


Neutrino capture on Tritium

$$T_e = T_\nu + 2m_\nu + Q$$





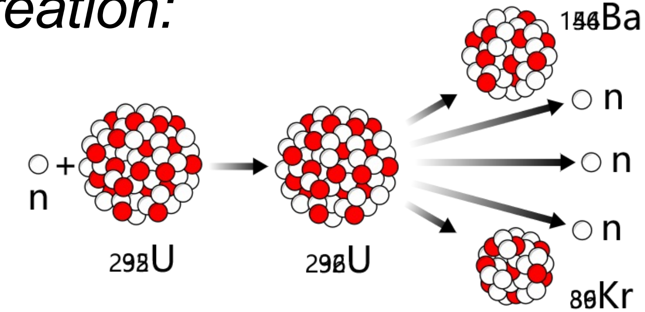


PTOLEMY Collaboration, arxiv/1307.4738, presentations etc; Planned at LNGS.

Reines&Cowan Detected Neutrinos in 1956

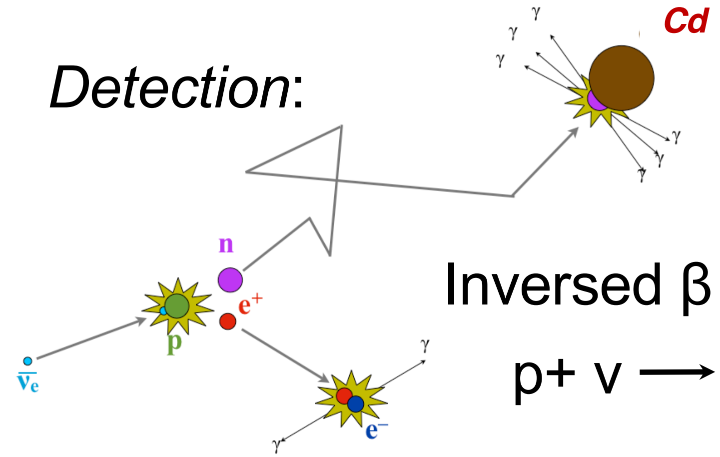
- Cowan and Reines at the Savannah River Power Plant (1956-1959)

Creation:



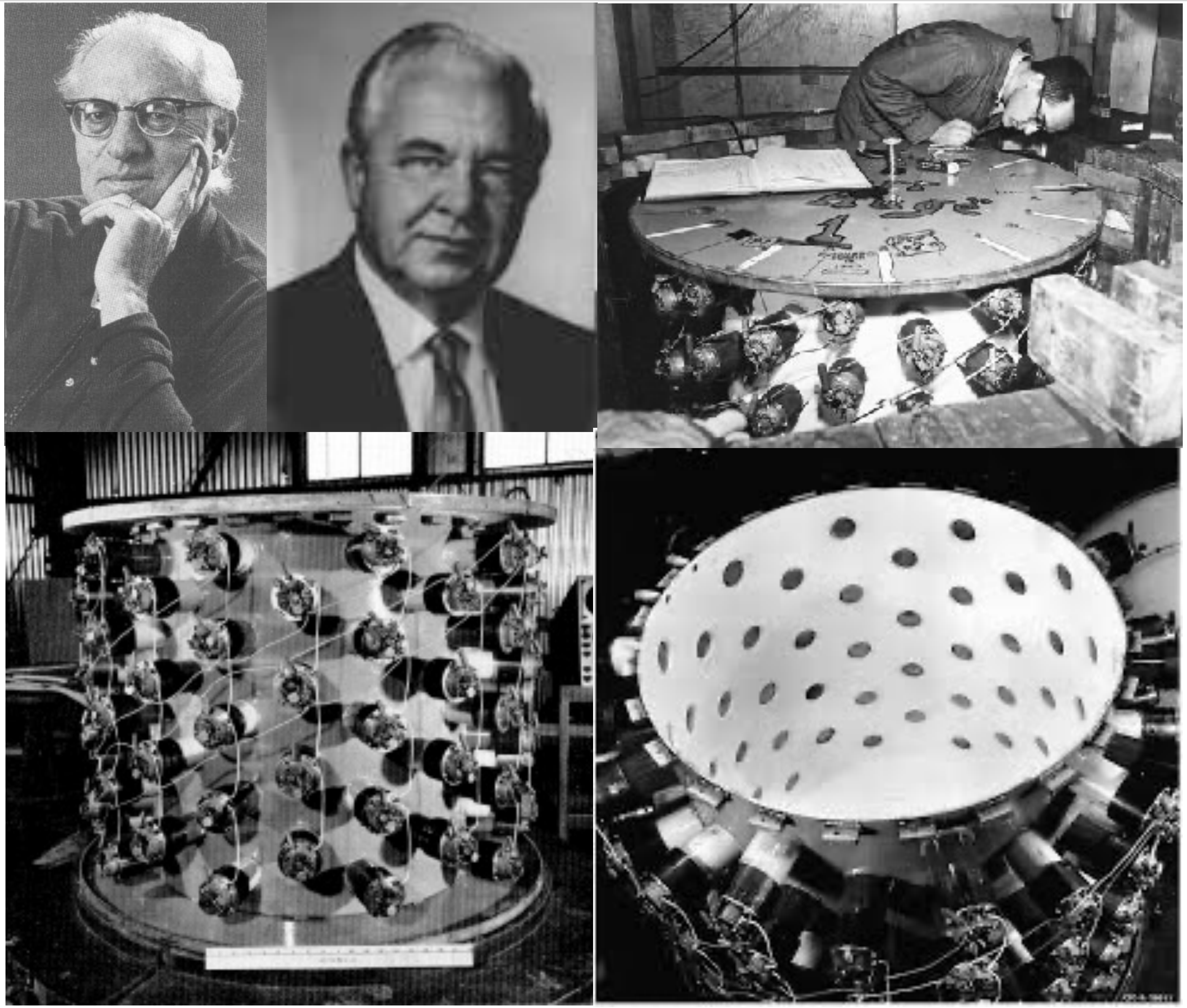
β decay: $N \rightarrow N' + e + v$

Detection:

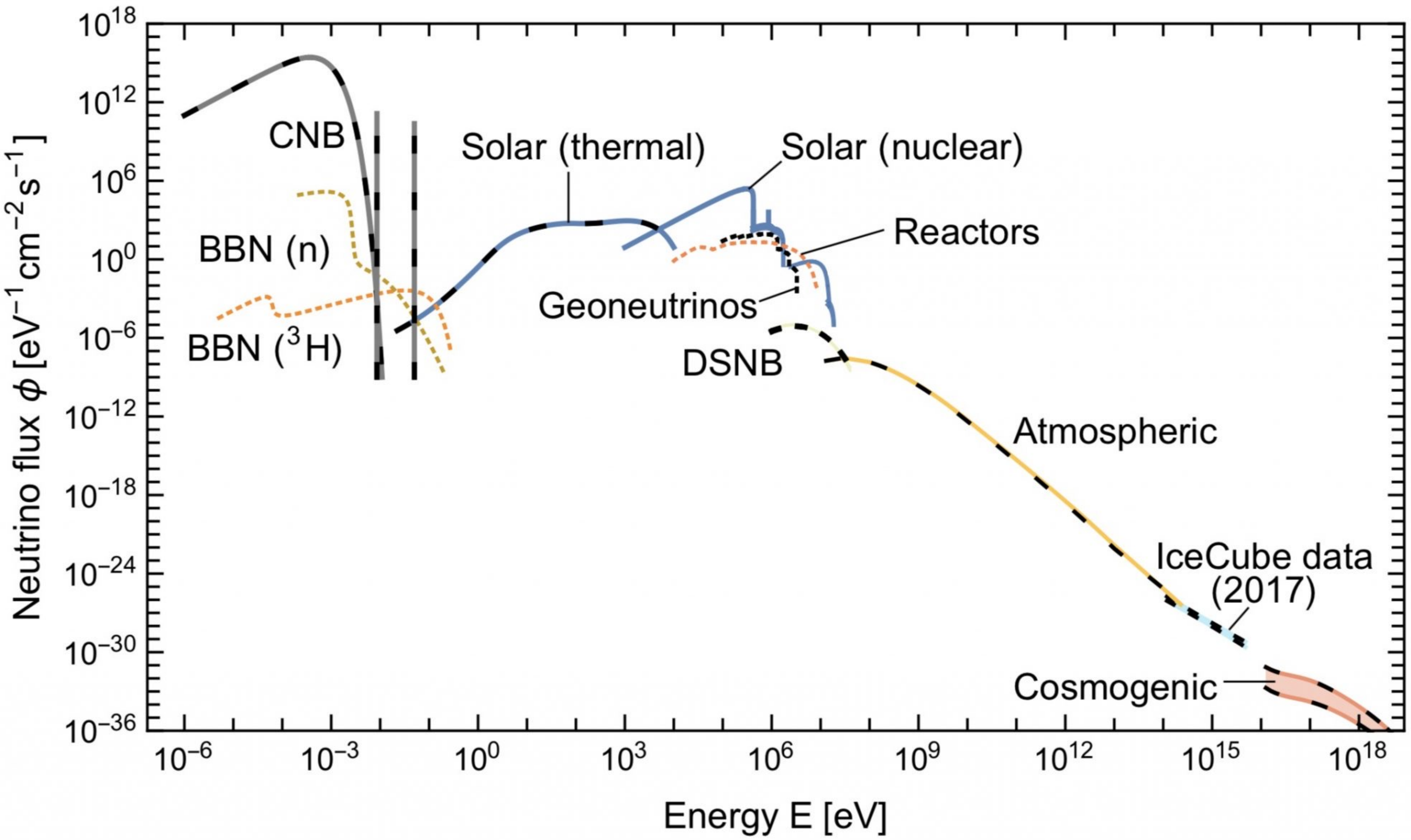


Inversed β decay

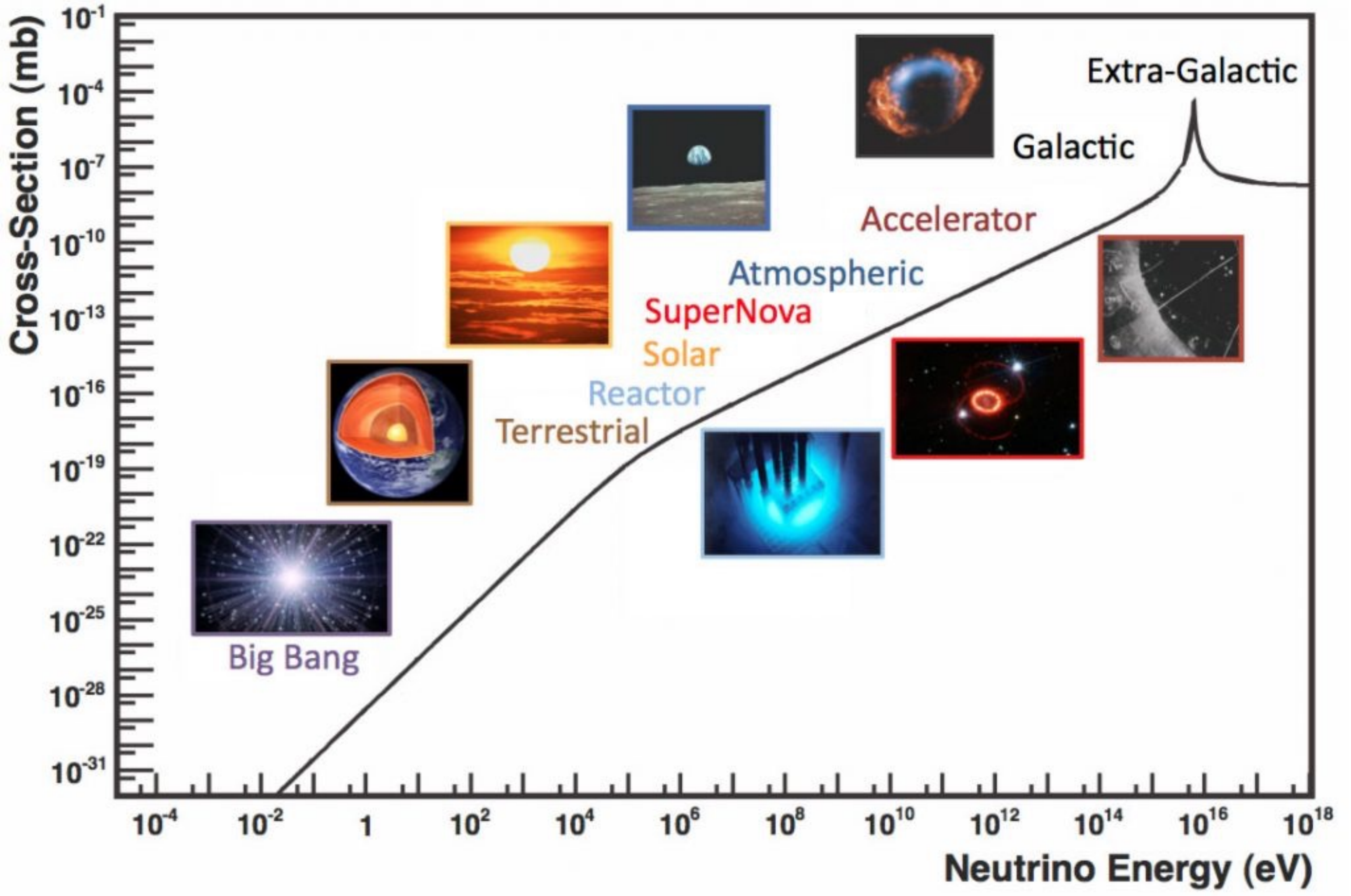
$p + v \longrightarrow e^{+} + n$



Various Neutrino Sources



Various Neutrino Sources



Neutrino Mixing & Oscillation First Proposed by Pontecorvo

- Bruno Pontecorvo in 1957:

  Interaction Eigenstates ≠ Mass Eigenstates
  → Neutrino Mixing and Oscillation

3-Flavor Neutrino Mixing & Oscillation

- Extended to 3 flavor mixing by Maki, Nakagawa and Sakata, after muon neutrino was discovered at BNL in 1962

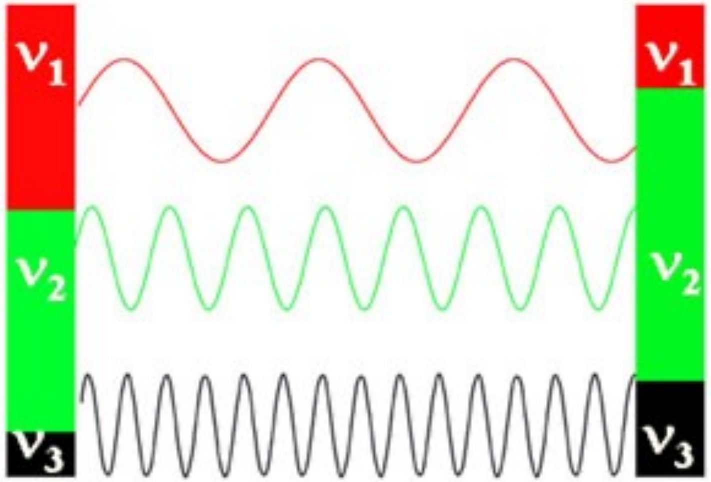
Courtesy of Sakata Memorial Archival Library

S. Sakata 1911-1970 | Z. Maki 1929-2005 | M. Nakagawa 1932-2001

Neutrino Mixing & Oscillation

➢ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

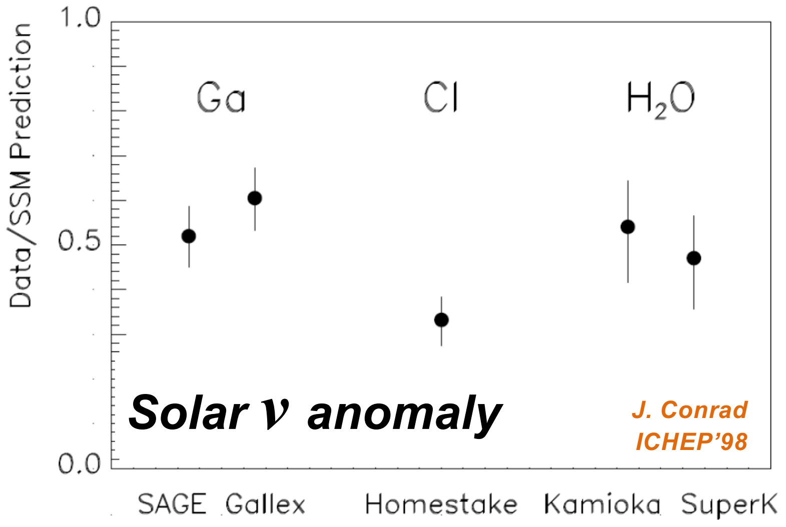
⇒ Oscillation Probability:

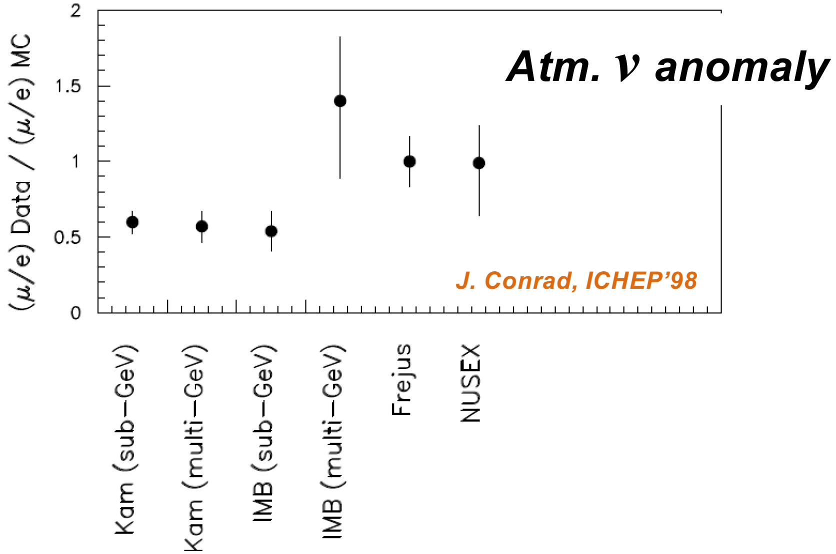
$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4\sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

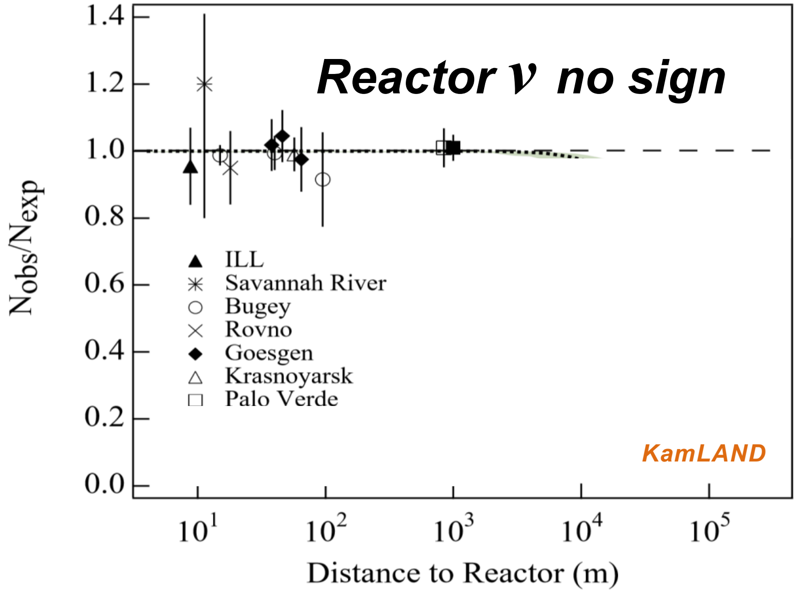
Amplitude ∝ $\sin^2 2\theta$

Frequency ∝ $\Delta m^2 L/E$

The Search for Neutrino Oscillation 1956-1998



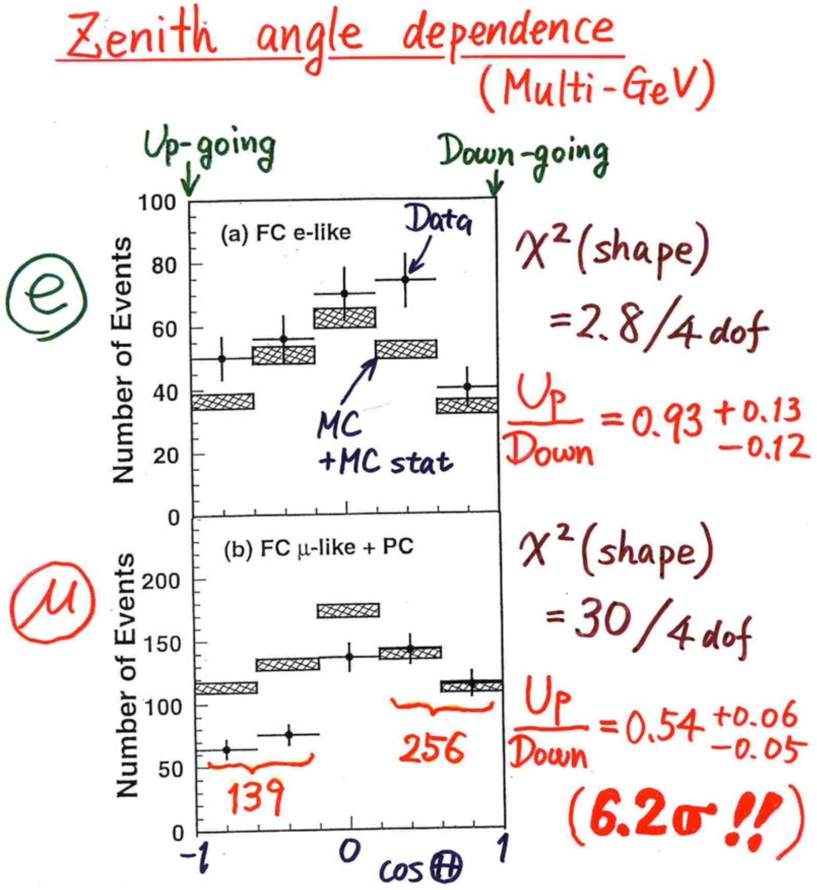




- ***The search for neutrino oscillation lasted decades but nothing conclusive***

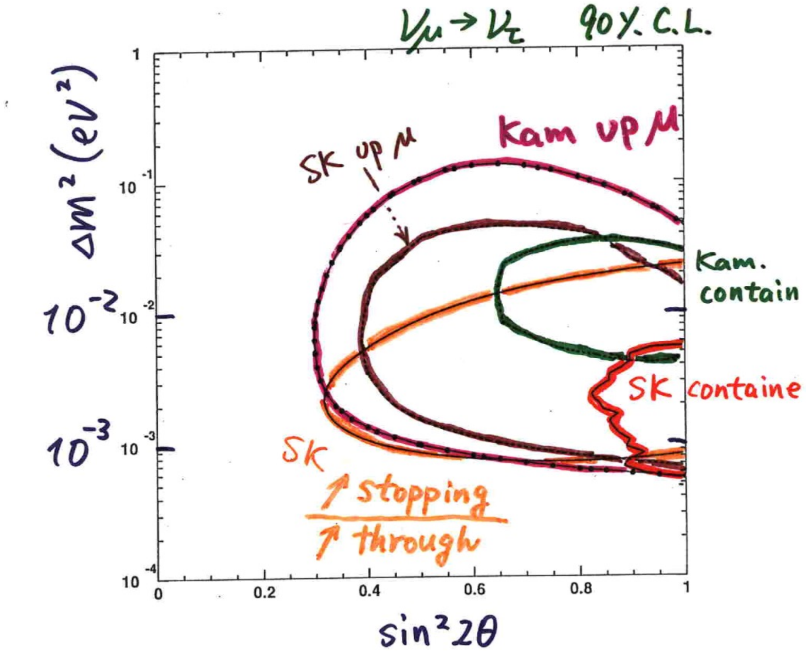
Neutrino Oscillation Discovered by Super-Kamiokande in 1998

T. Kajita, Neutrino'98



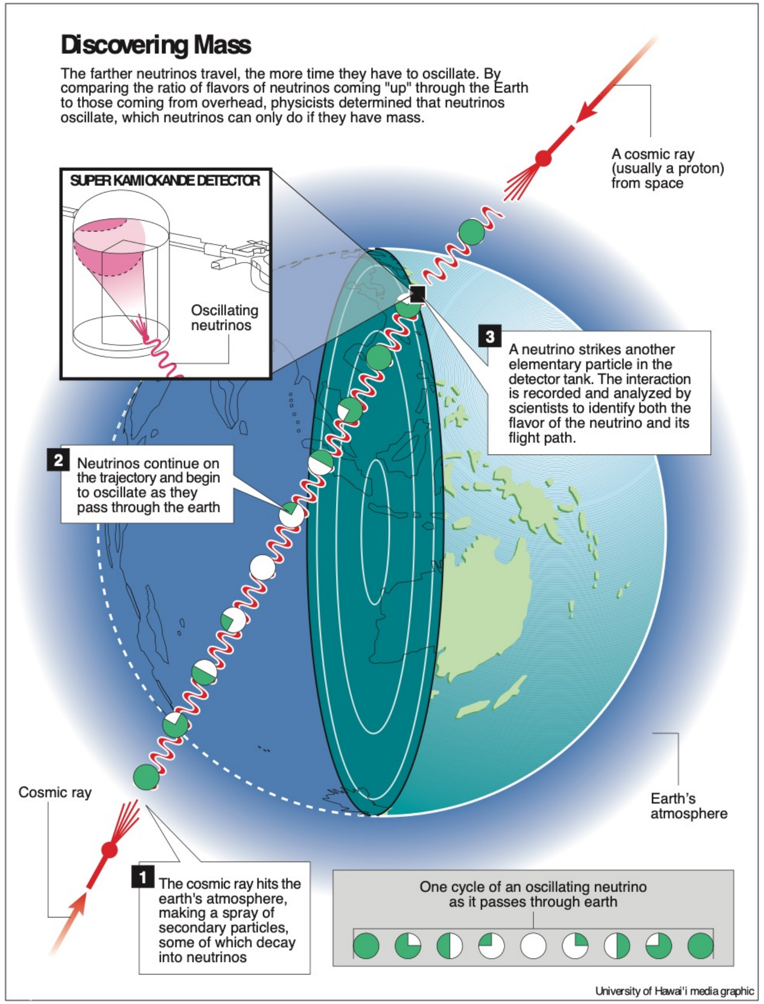
Summary

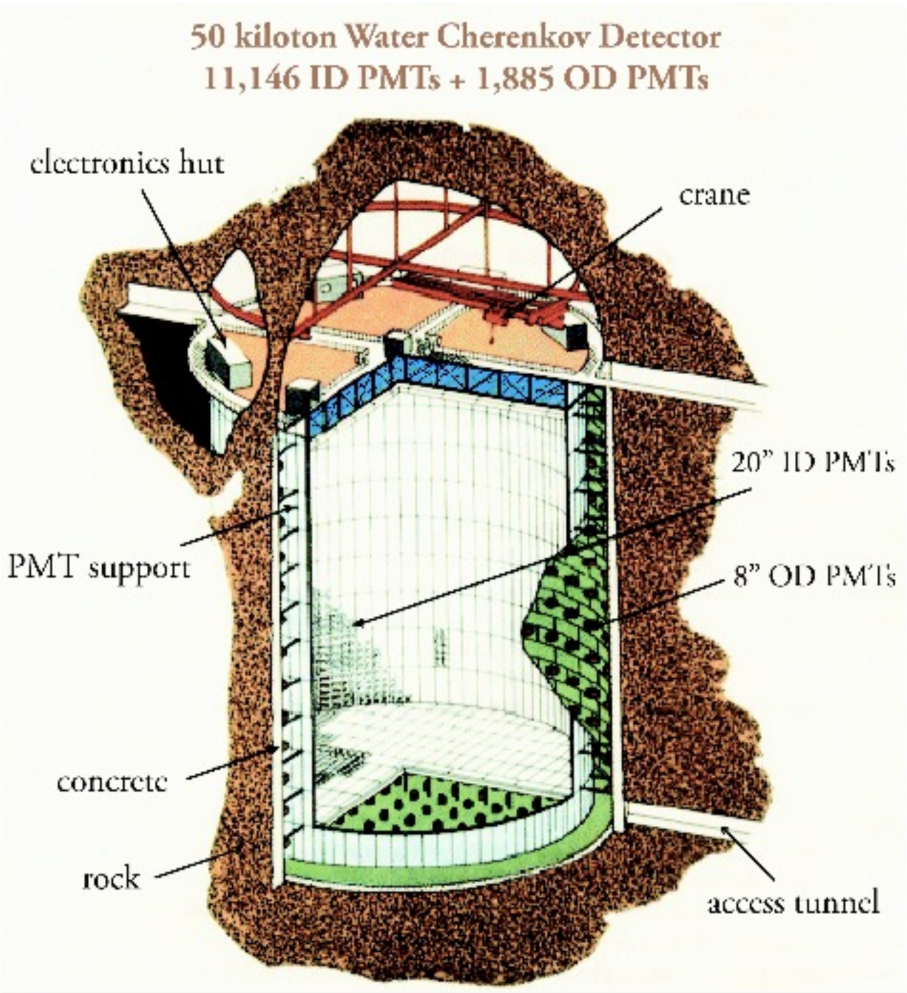
Evidence for ν_μ oscillations

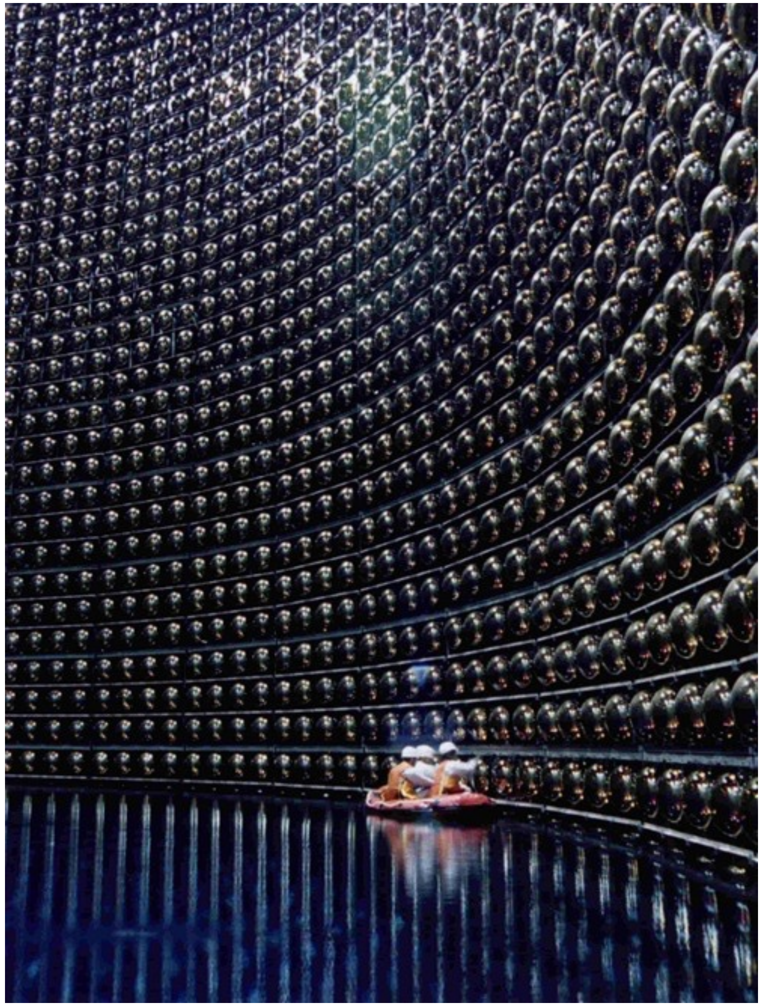


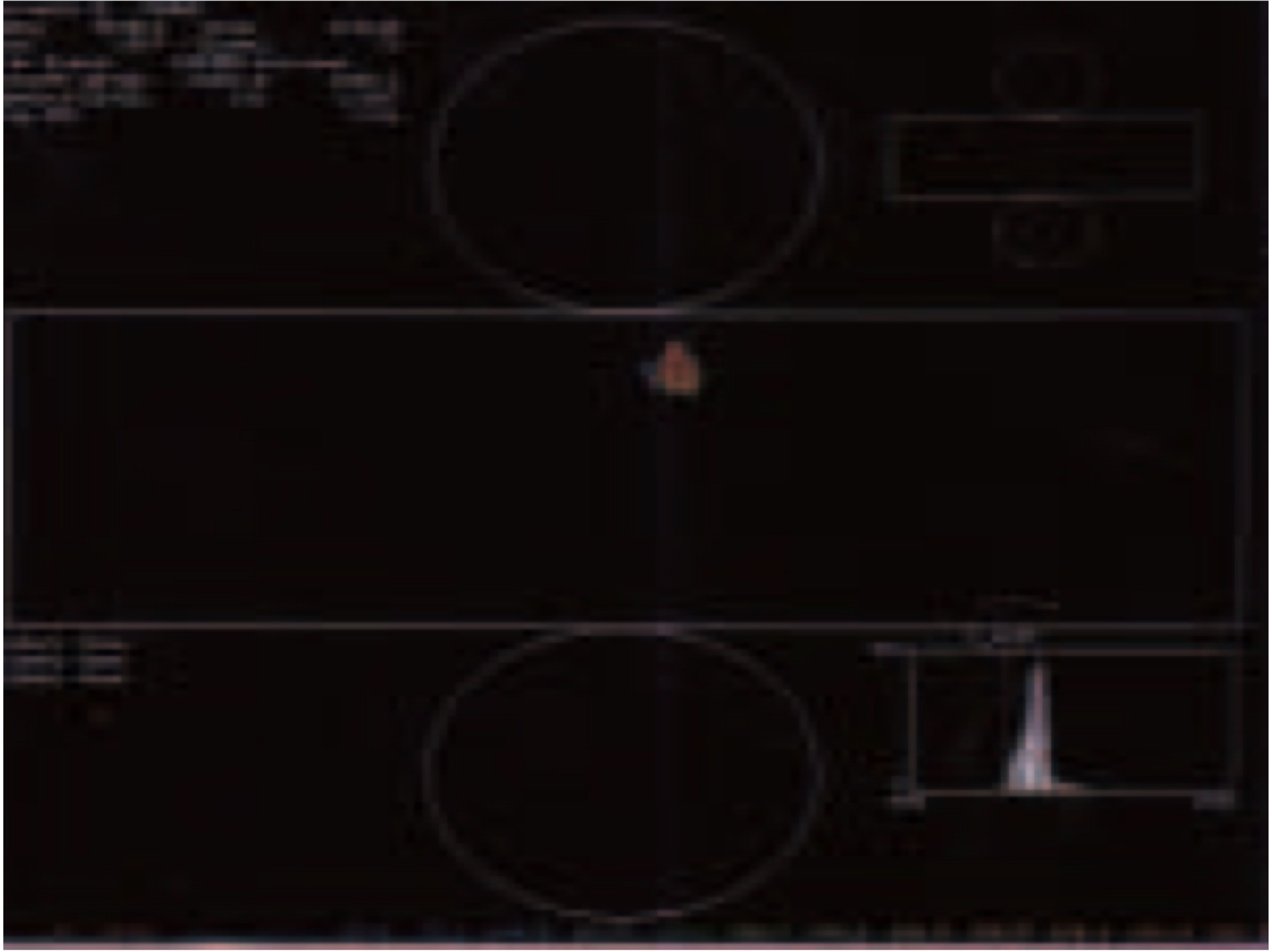
- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

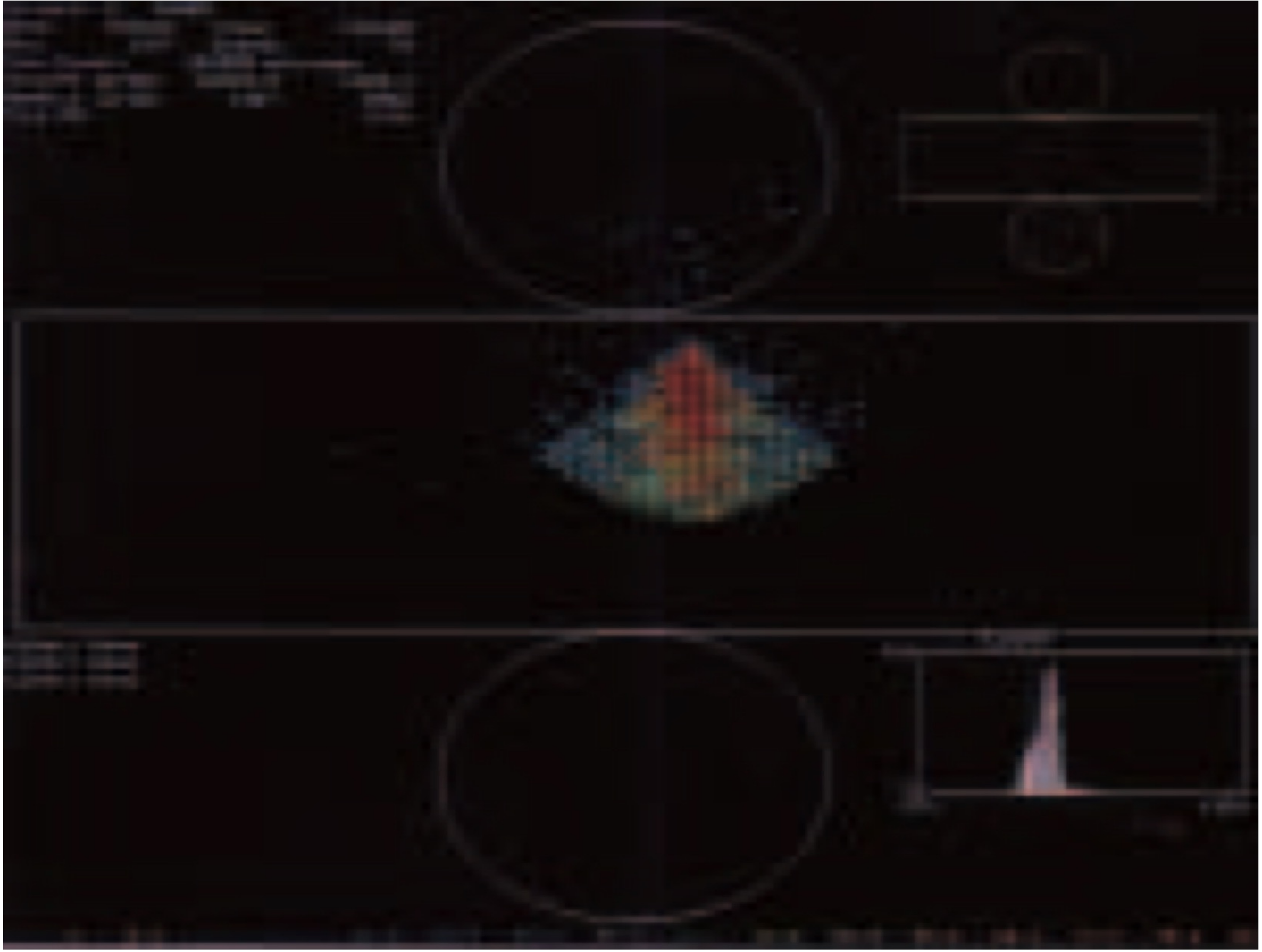
The Super-Kamiokande Experiment

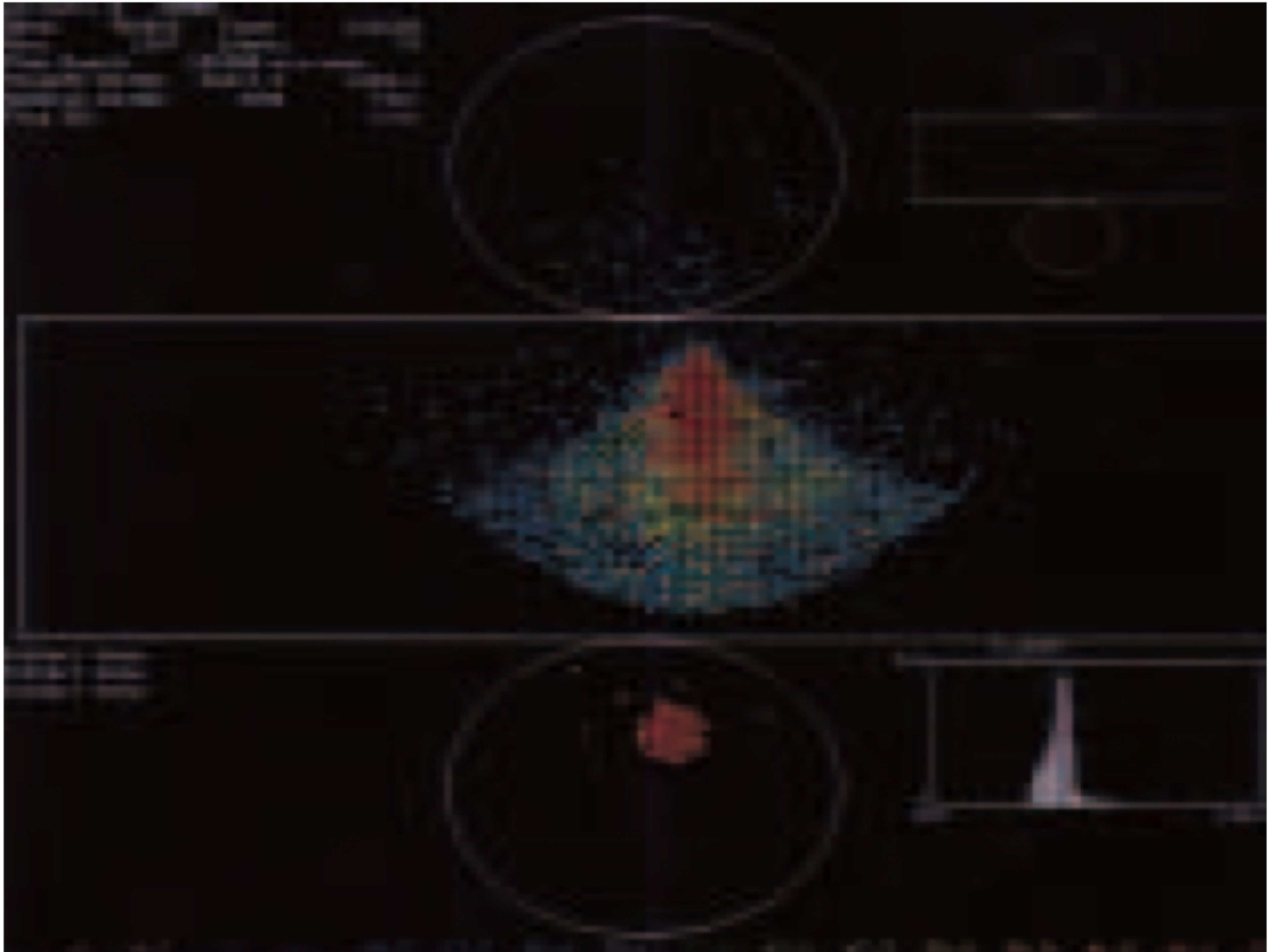


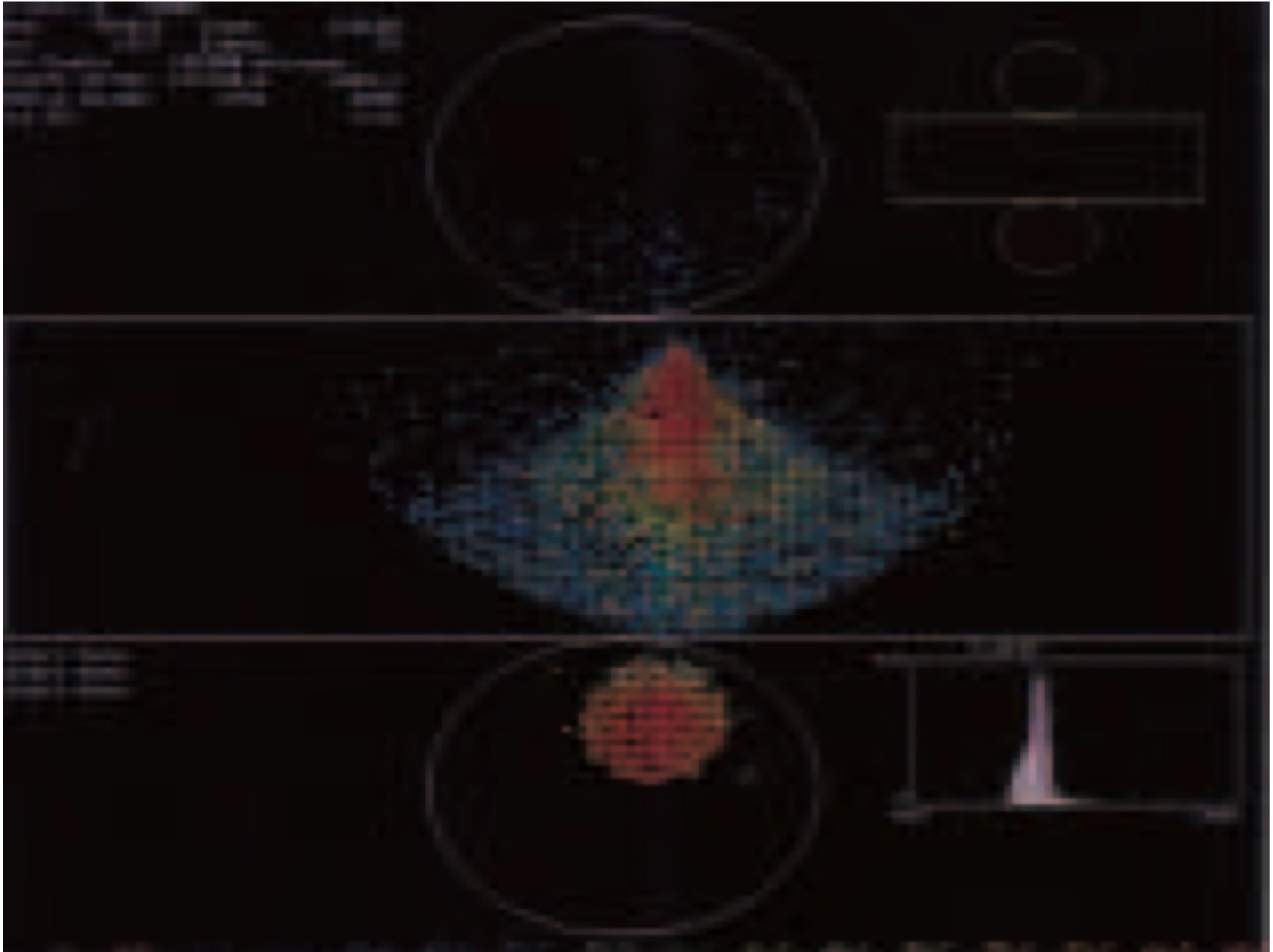


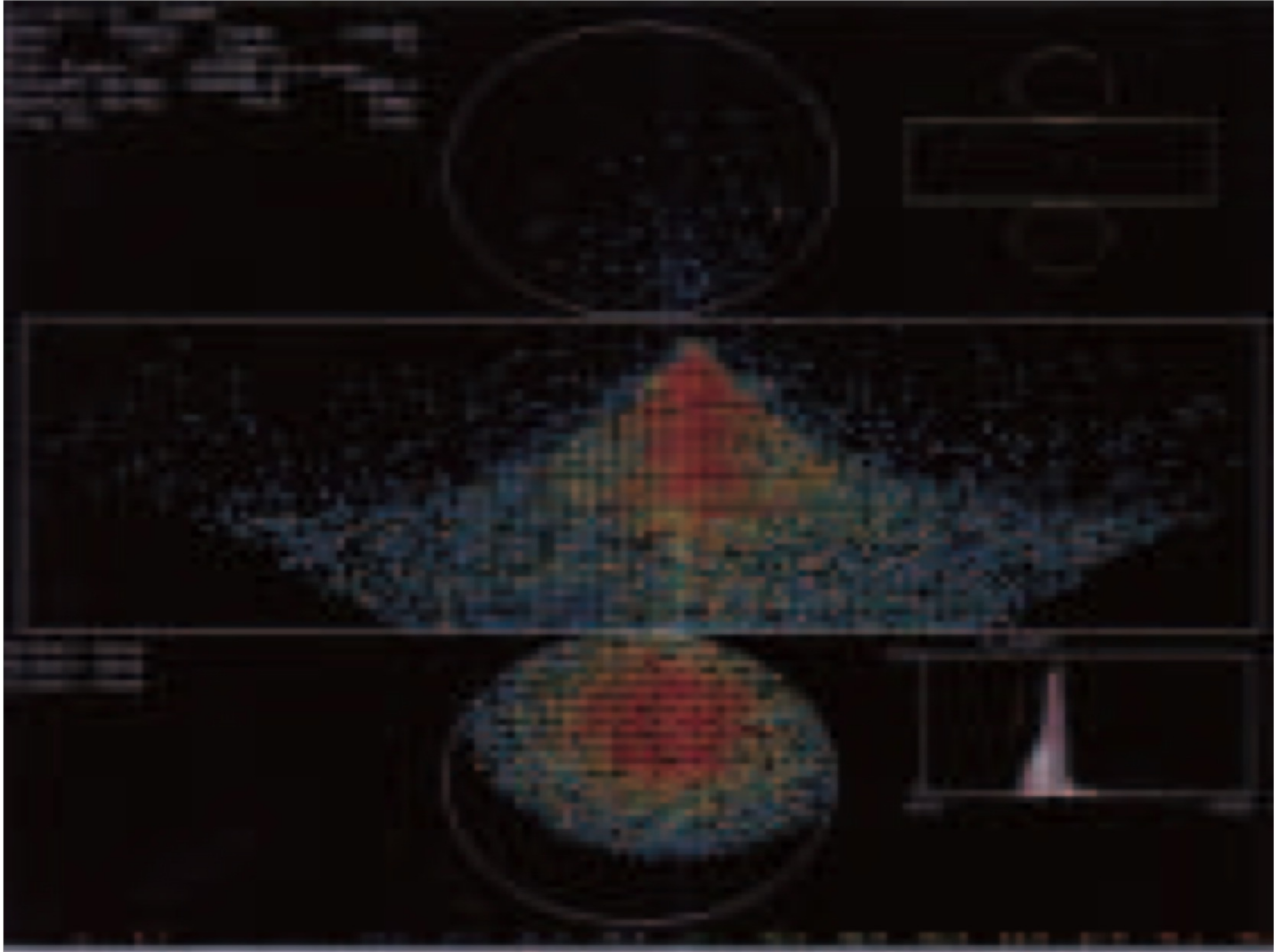


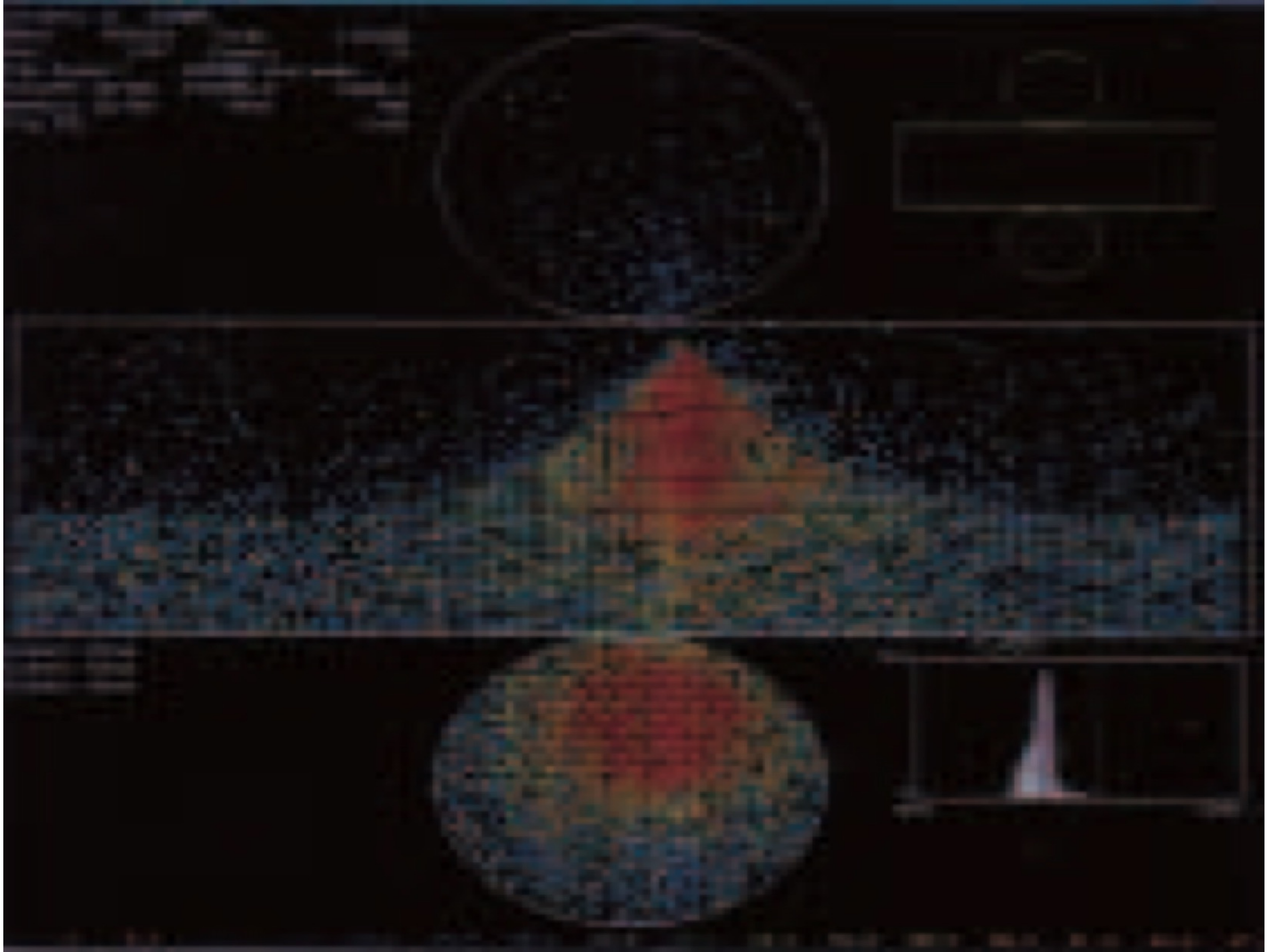






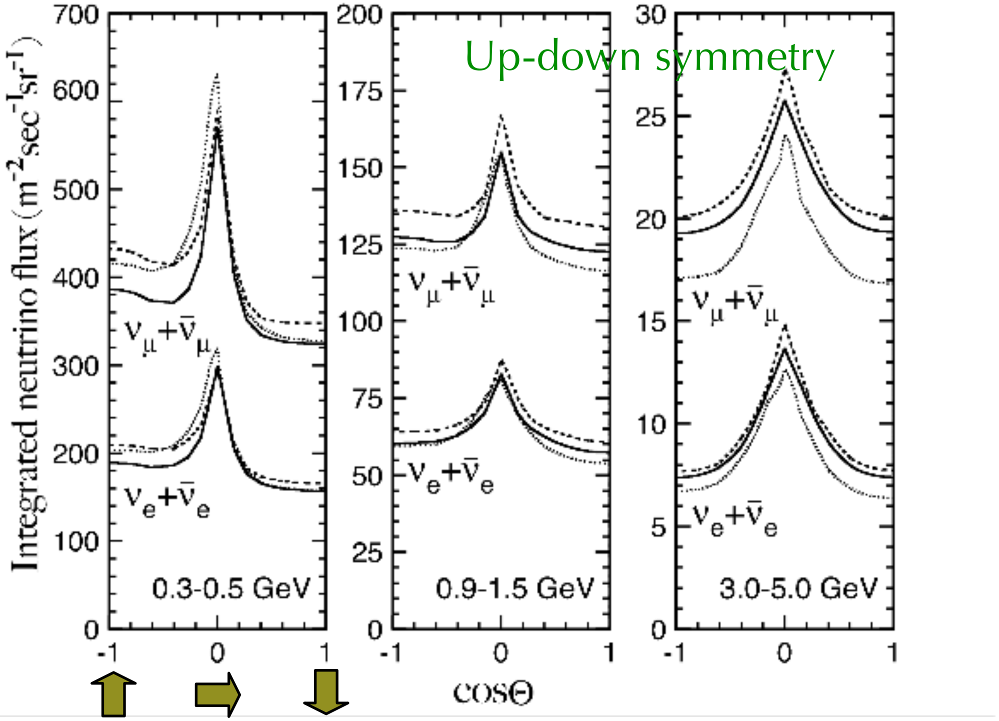


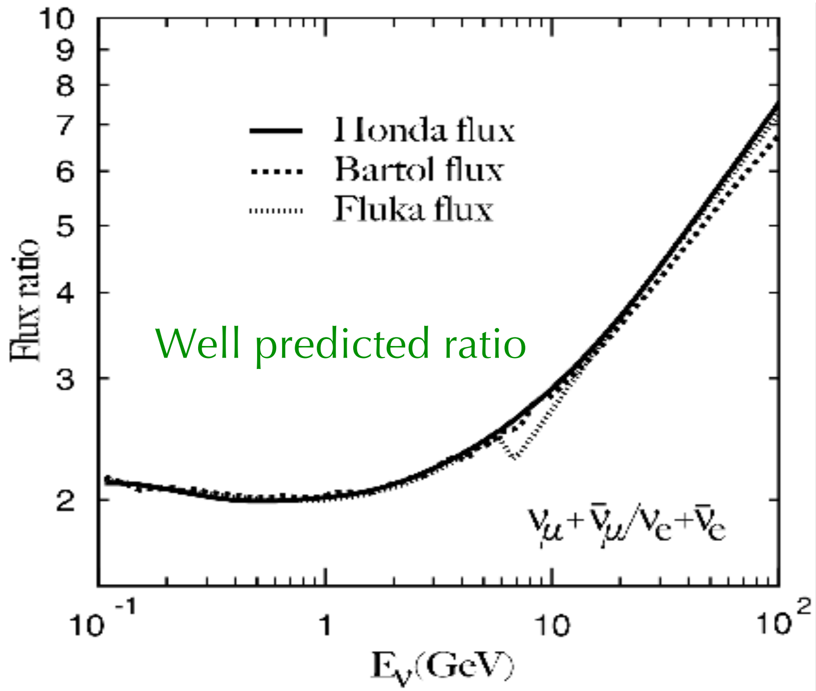


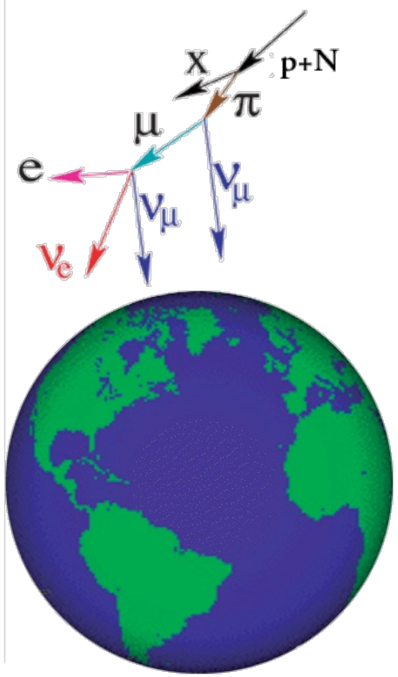


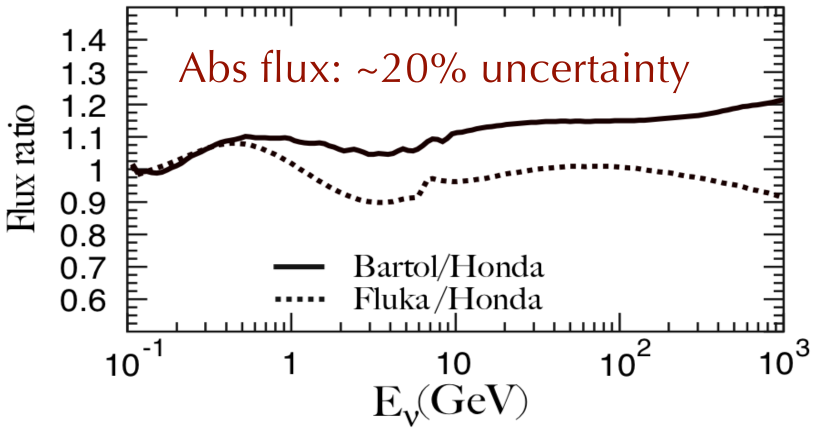
Atmospheric Neutrinos

- A large uncertainty on the absolute flux
- Good knowledge on flavor ratio
- Up-down symmetric

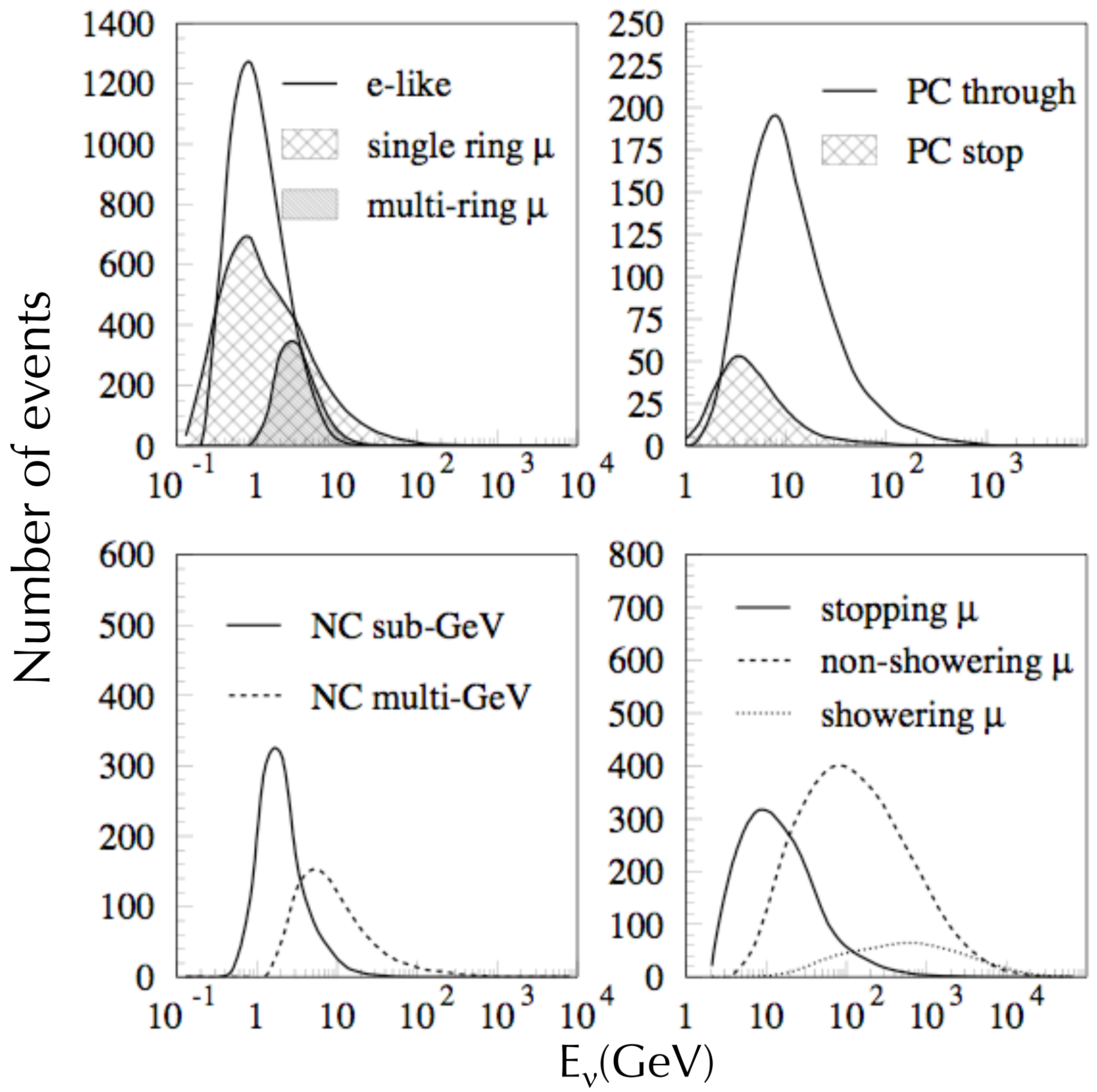


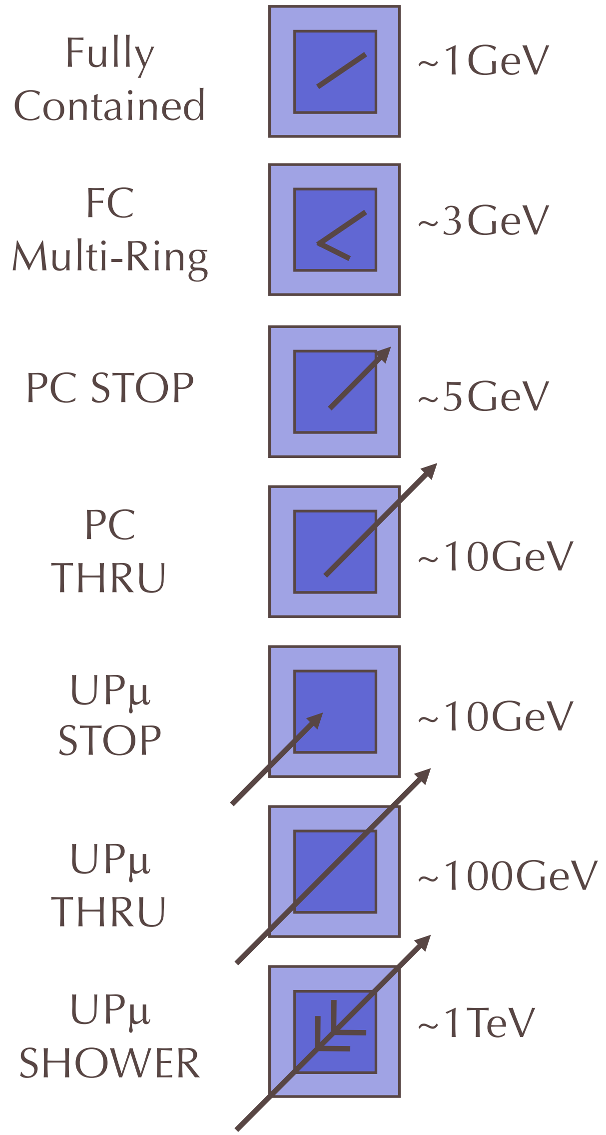






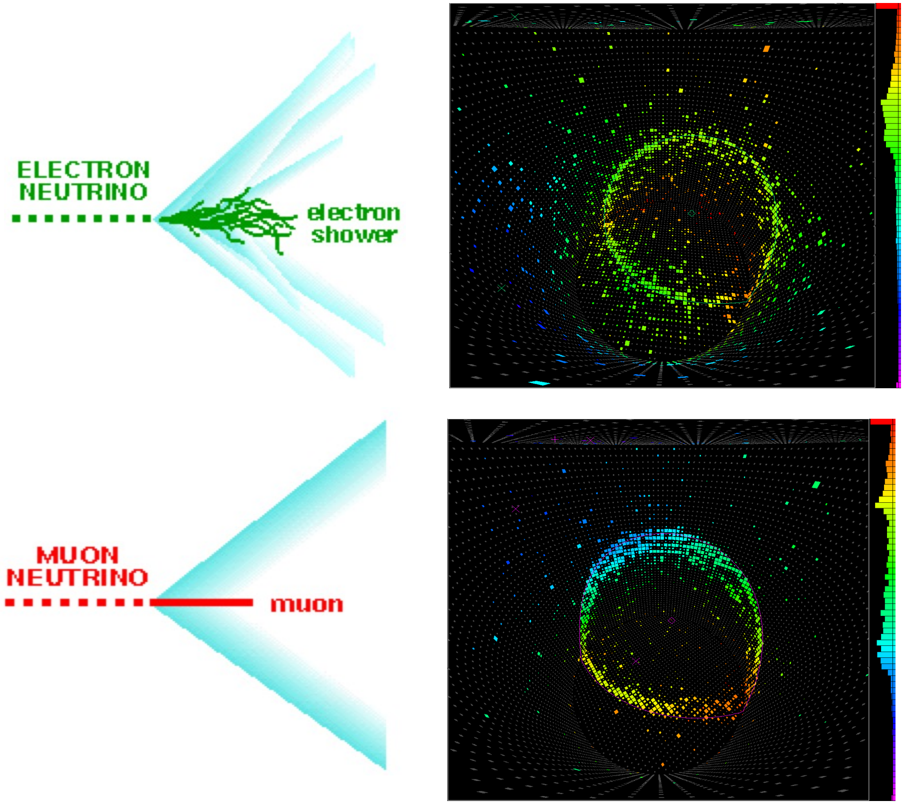
Great Advantage: Five Orders of Magnitude Energy Coverage

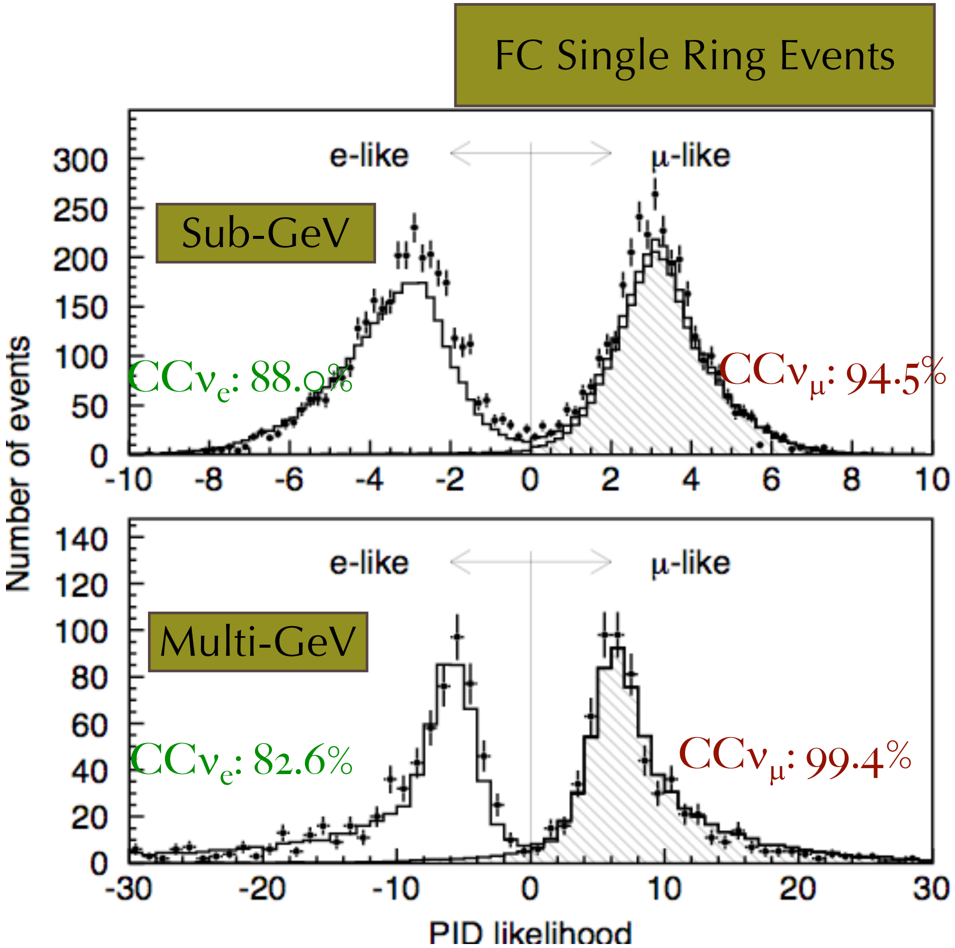




How to Identify/Reconstruct Neutrinos in the Super-K Detector?

- Vertex finding: first, PMT hit time; then more precise fitters
- Ring recognition: charge & position of hit PMTs
- PID (e-/μ-like): hit pattern
- Momentum: total number of photoelectrons



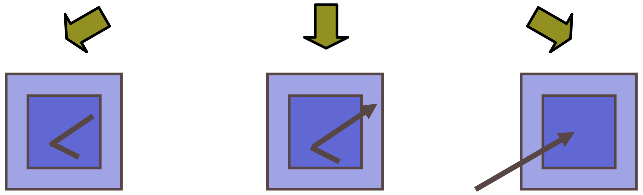


An Over-Simplified Super-K Neutrino Event Reduction Scheme

Neutrino Interactions
→ charged particles
→ Cherenkov radiation
→ recorded by PMTs

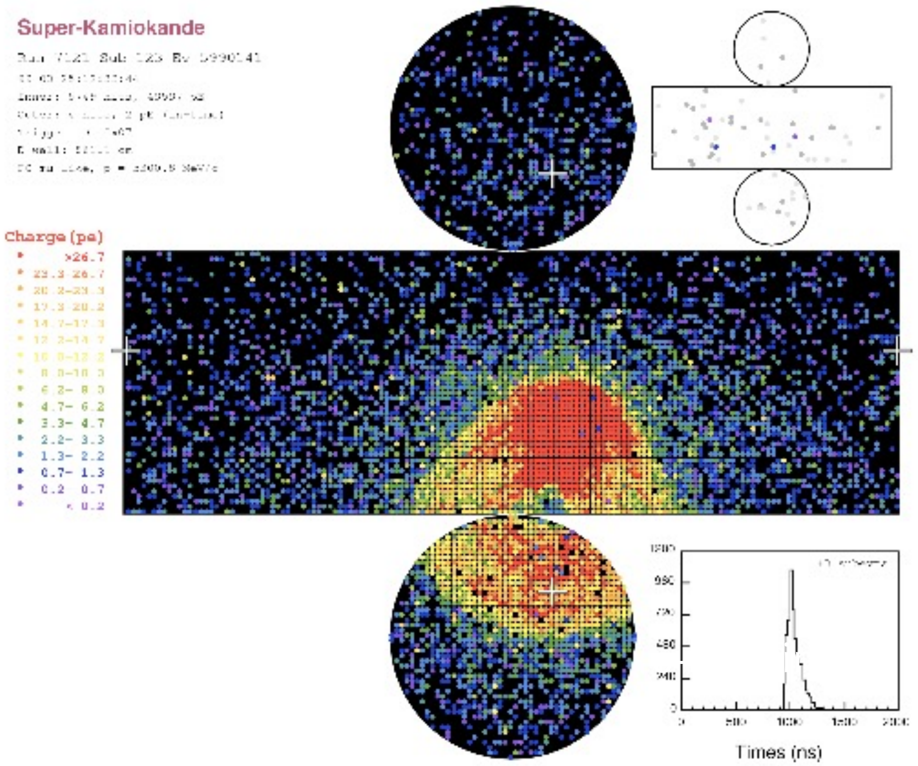
\+ Cosmic Rays + Others

Event Reduction



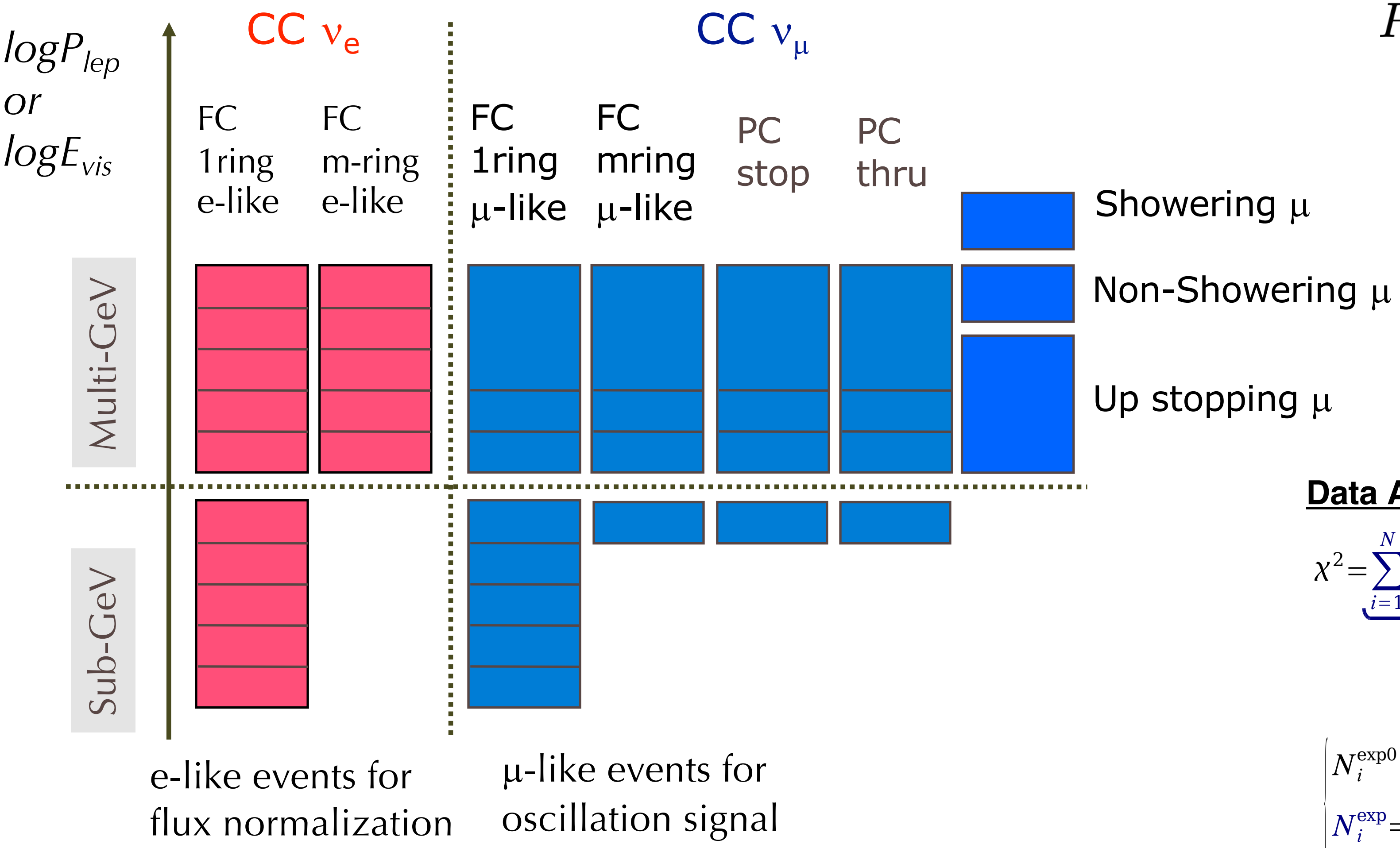
Fully Contained	Partially Contained	Upward-going μ

Event Reconstruction



Same procedures for Monte Carlo simulation events

Data Analysis: 2-Flavor Oscillation Analysis as an Example



$$P_{\nu_\alpha\to\nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Data Analysis: Pull Method

$$\chi^2 = \underbrace{\sum_{i=1}^{N} 2\left(N_i^{\mathrm{exp}} - N_i^{\mathrm{obs}} - N_i^{\mathrm{obs}} \ln\frac{N_i^{\mathrm{obs}}}{N_i^{\mathrm{exp}}}\right)}_{\text{Data bins: likelihood ratio}} + \underbrace{\sum_{j=1}^{M}\left(\frac{\epsilon_j}{\sigma_j}\right)^2}_{\text{Systematic uncertainties: Gaussian}}$$

$$N_i^{\mathrm{exp0}} = P_{\mathrm{survival}}(\text{model x with parameters } \vec{x})\, N_i^{\mathrm{nosc}}$$

$$N_i^{\mathrm{exp}} = \left(1 + \sum_{j=1}^{M} f_i^j \epsilon_j\right) N_i^{\mathrm{exp0}}$$

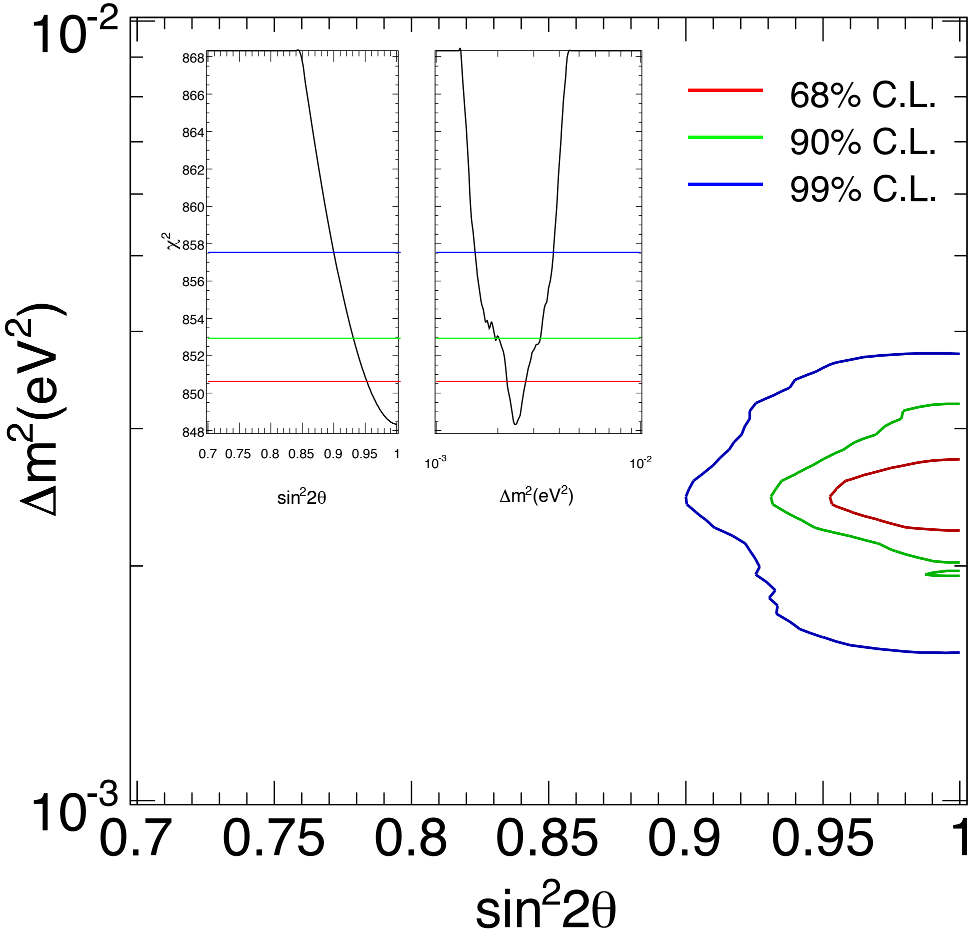
Predicted events based on ν flux

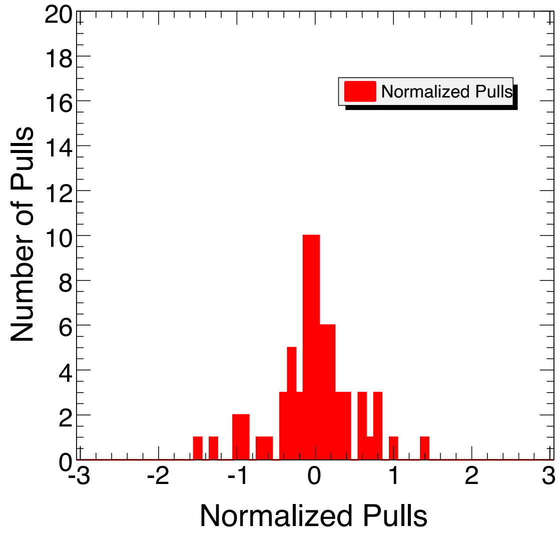
Expected number of events without considering systematics

Expected number of events

Data Analysis: 2-Flavor Oscillation Analysis as an Example

Warning: Very Much Outdated Results!





$$\nu_\mu \rightarrow \nu_\tau$$

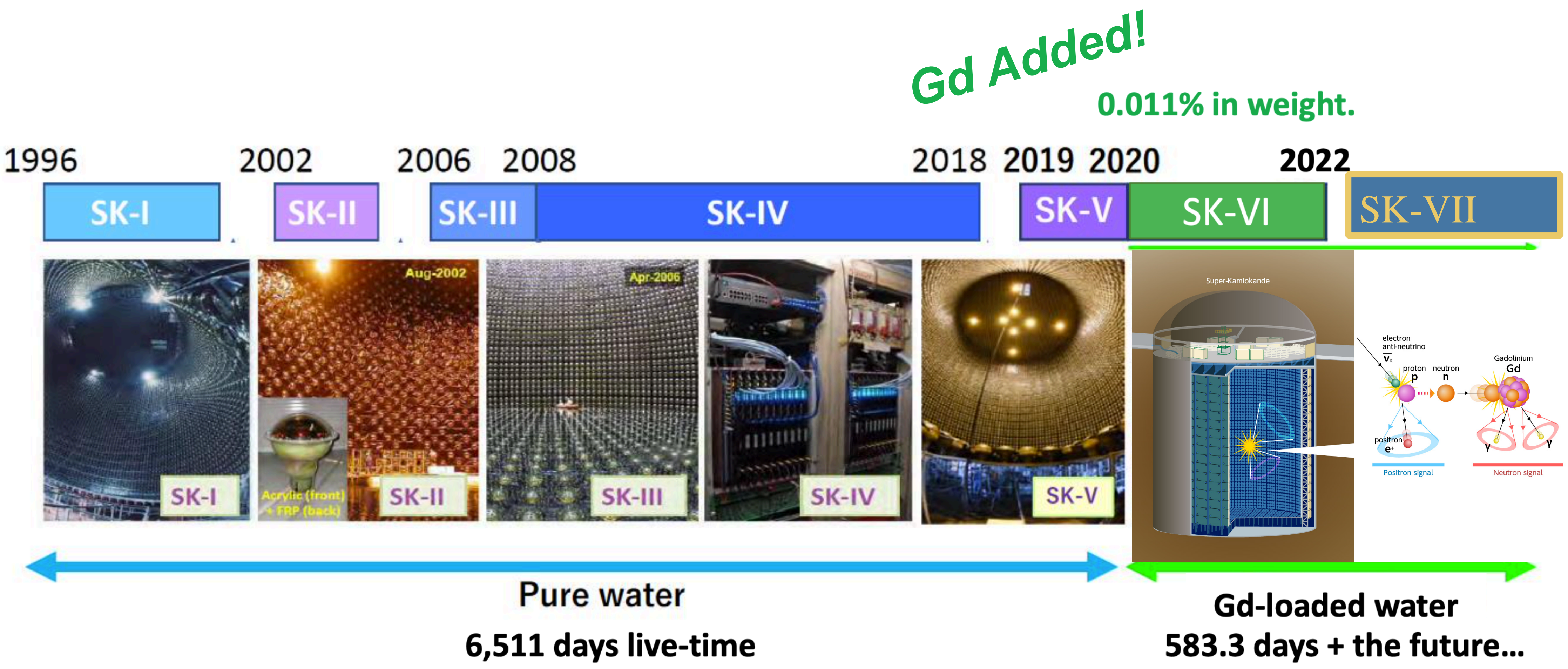
$$\sin^2 2\theta = 1$$

$$\Delta m^2 = 2.5 \times 10^{-3}\, eV^2$$

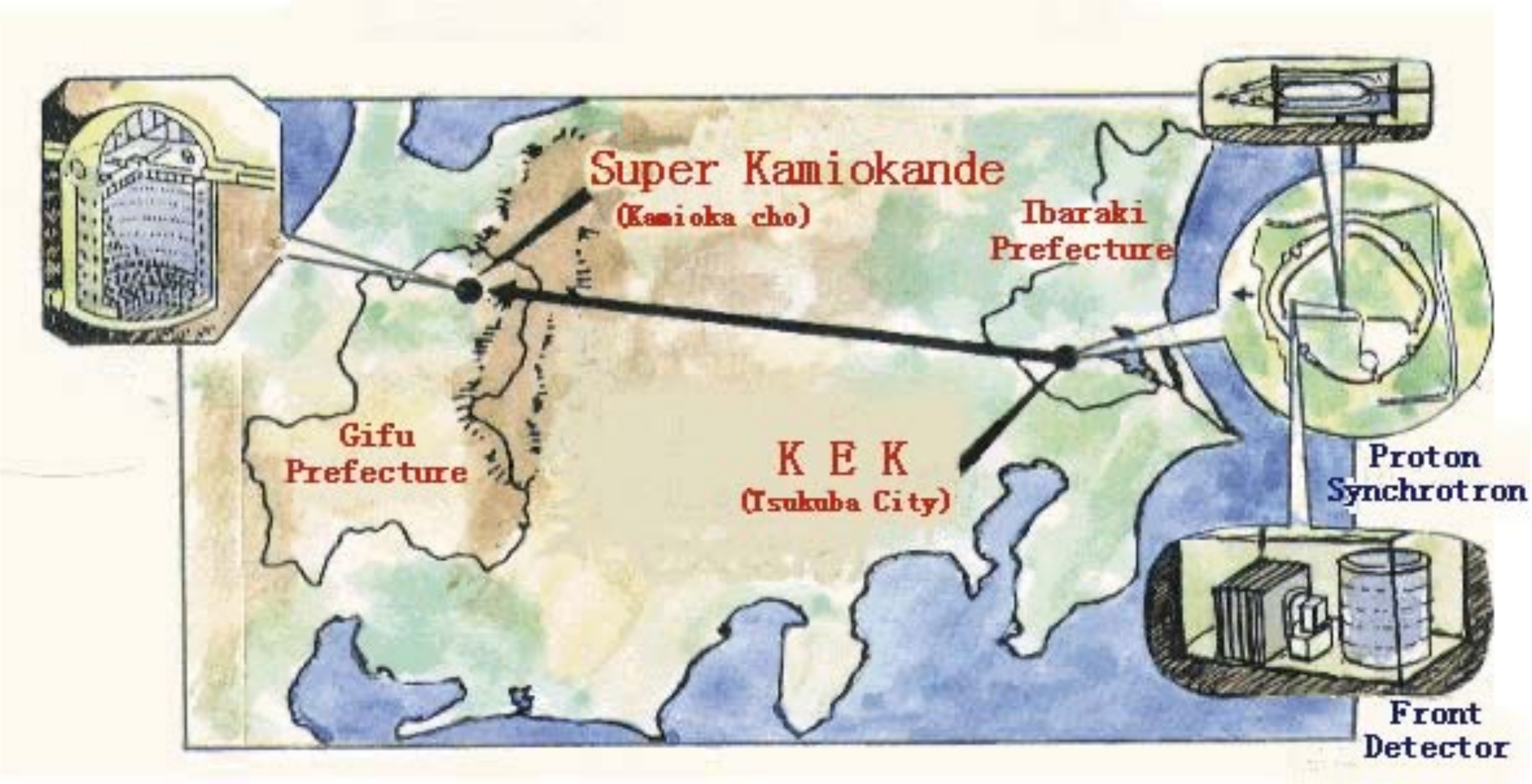
$$\chi^2 / dof = 839.7/755$$

$$p-value = 18\%$$

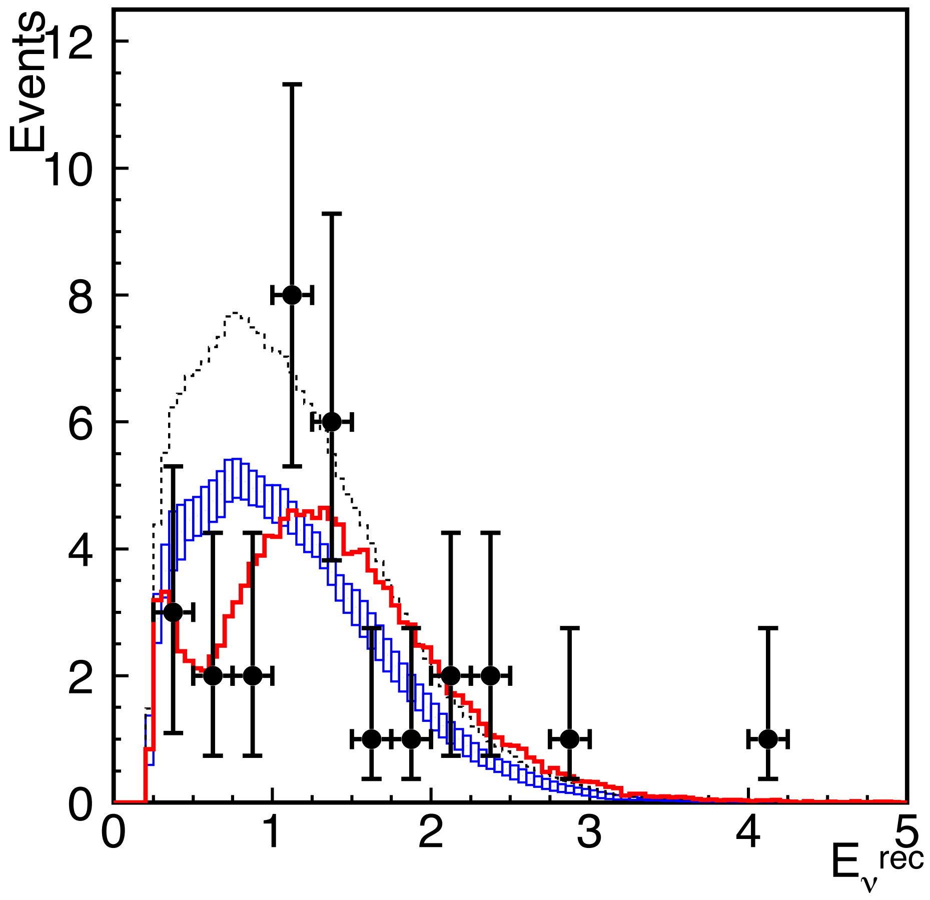
Current Super-Kamiokande Status (from Neutrino 2024 Milan)

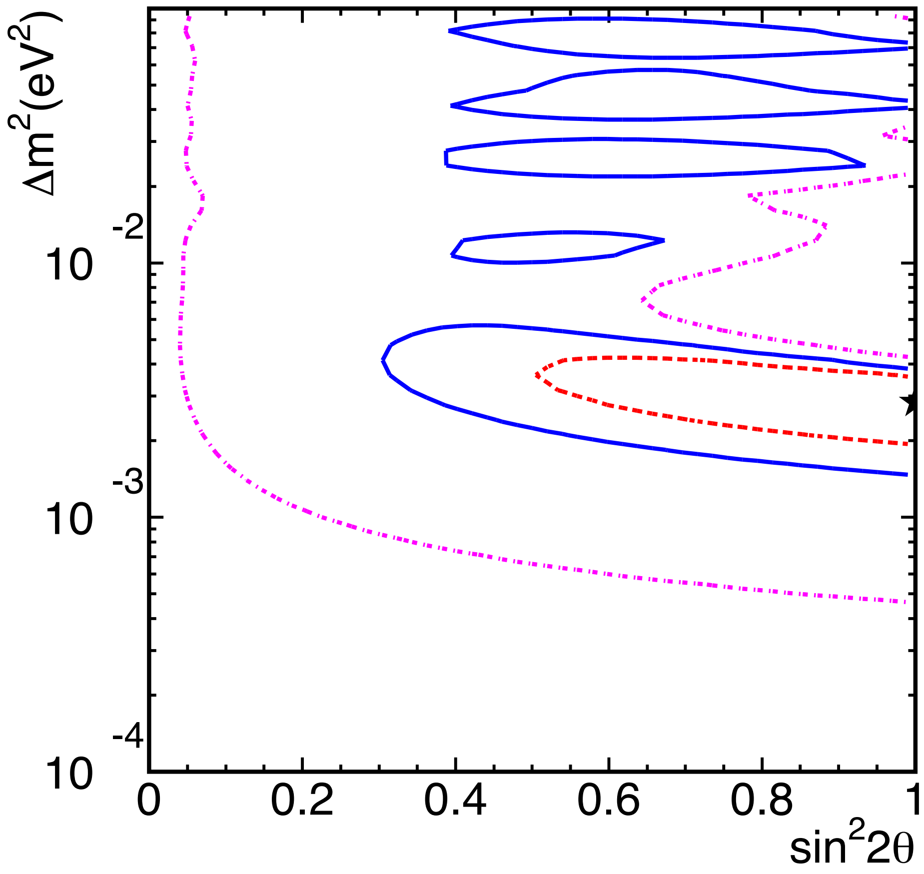


The Very First Long-Baseline Neutrino Oscillation Experiment K2K



The First Results of K2K in 2002: Indication of Neutrino Oscillation





The Final Result of K2K in 2006: Improved Results

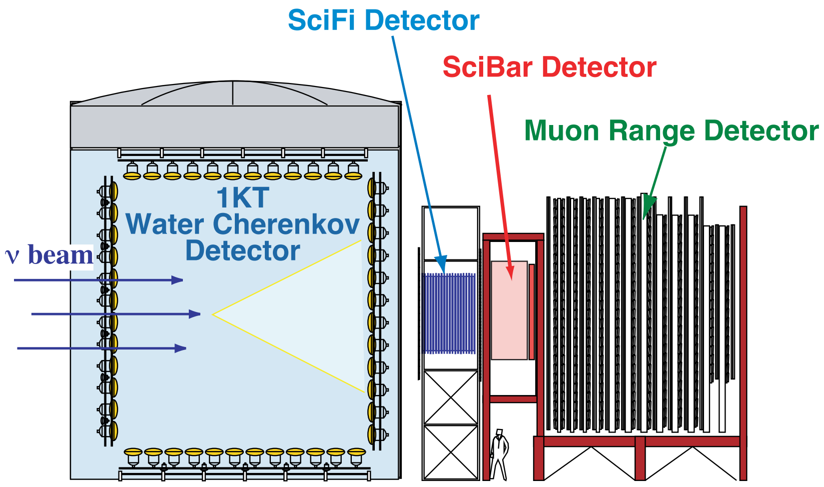
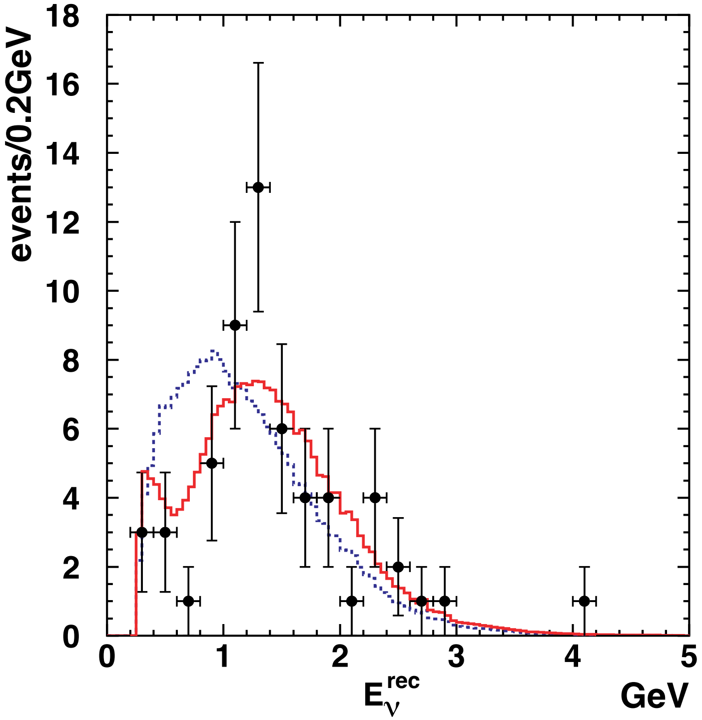
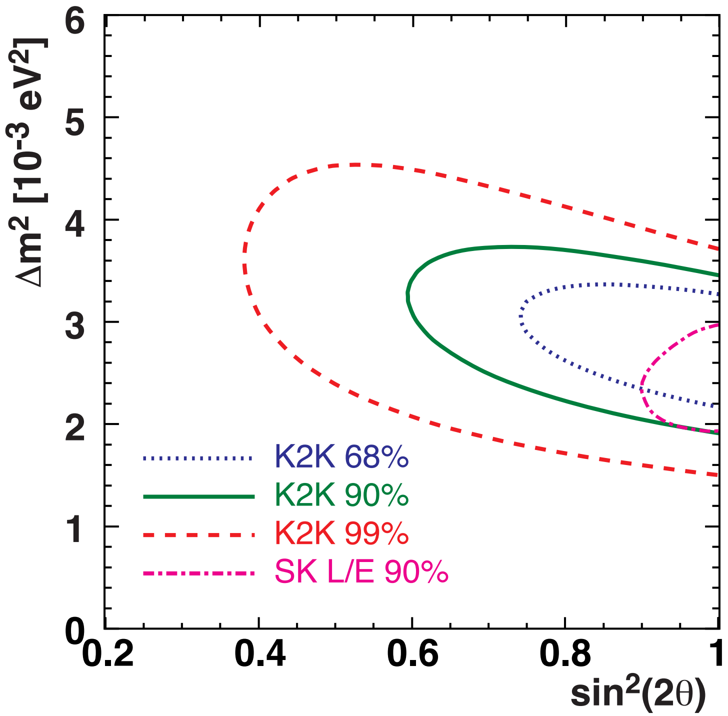


FIG. 7: The schematic view of the near neutrino detectors for K2K-IIb period. In K2K-I, the Lead-Glass calorimeter was located at the position of the SciBar detector.



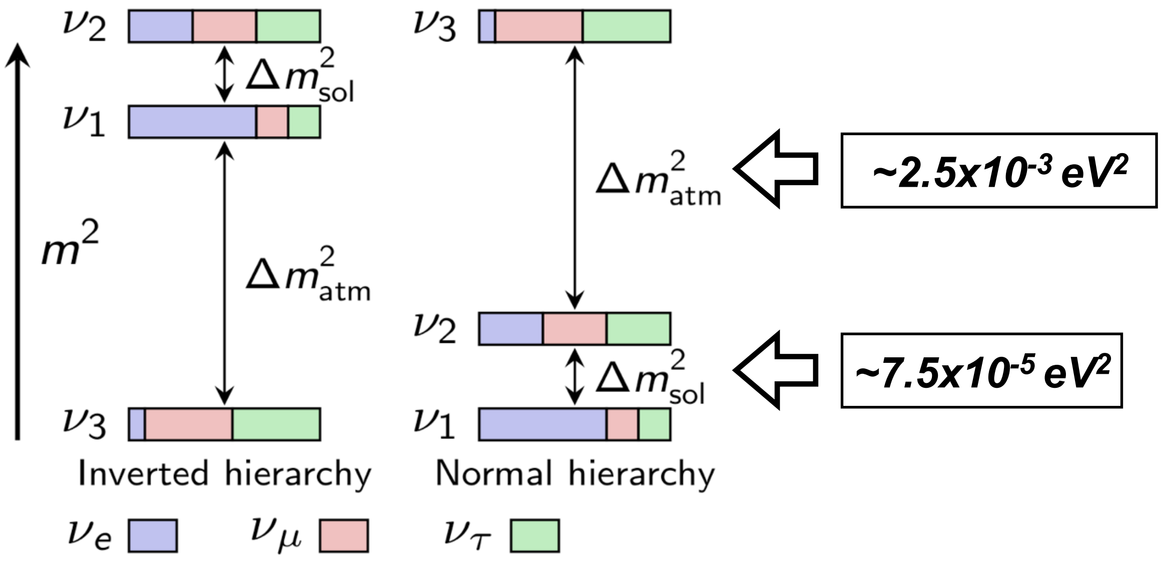


The Status of Neutrino Oscillation in 2006

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (with Majorana CP phases),

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

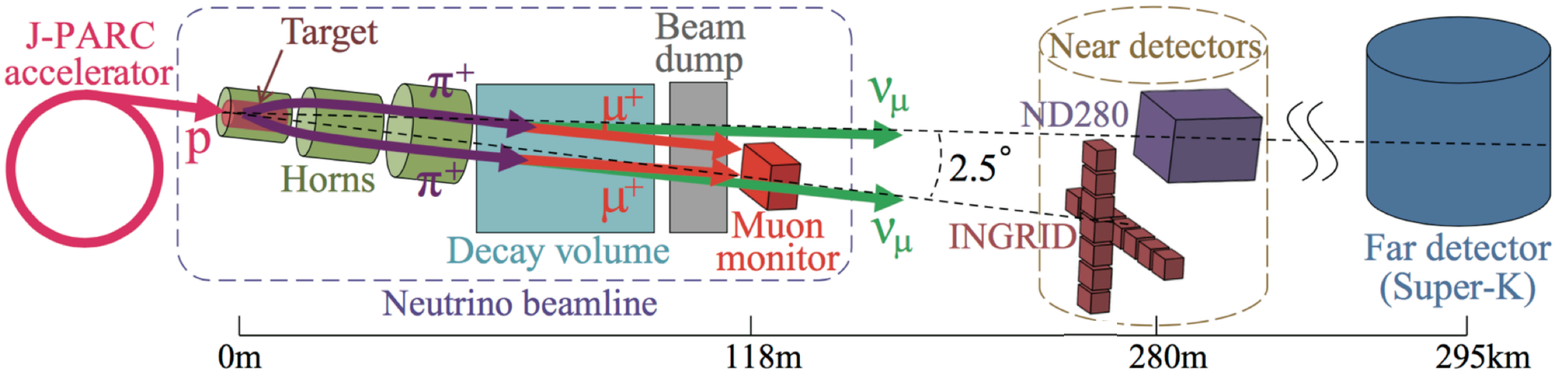


$\Rightarrow$ Neutrino Oscillation Probability:

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4\sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

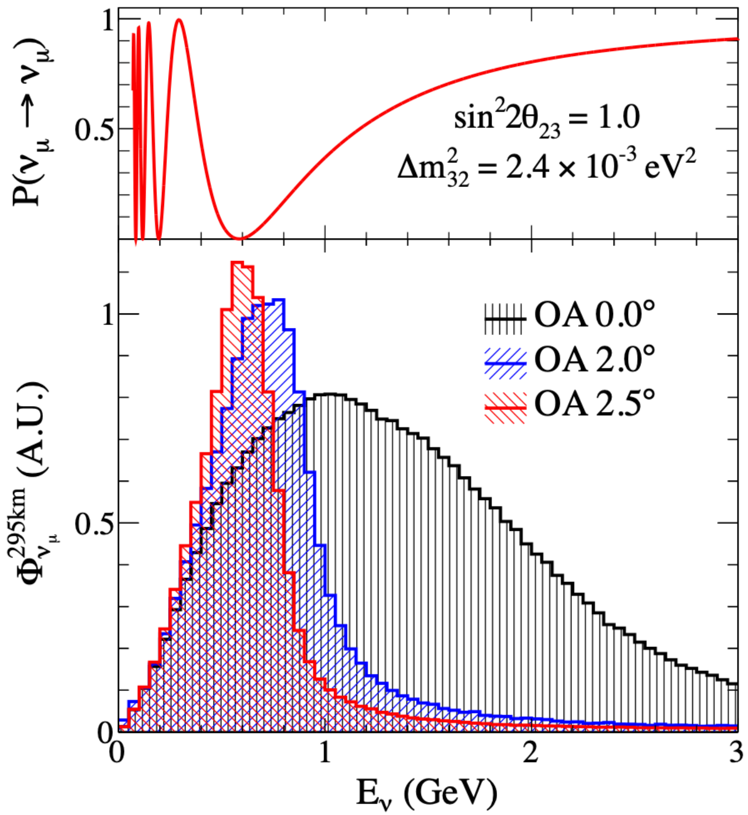
Amplitude $\propto \sin^2 2\theta$ **Frequency $\propto \Delta m^2 L/E$**

A Upgraded K2K: the T2K Experiment



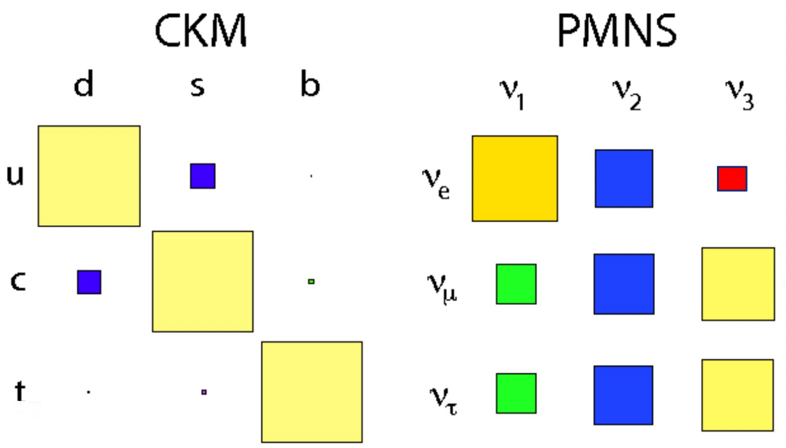
- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- p+C interactions producing hadrons (mainly pions and kaons)
- Hadrons are focused and selected in charge by 3 electromagnetic horns
  - If π^+ are focused ν_μ are produced by $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Changing the horn current we can produce $\bar{\nu}_\mu$ from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Off-axis technique → detectors intercept a narrow-band beam at the maximum of the oscillation probability

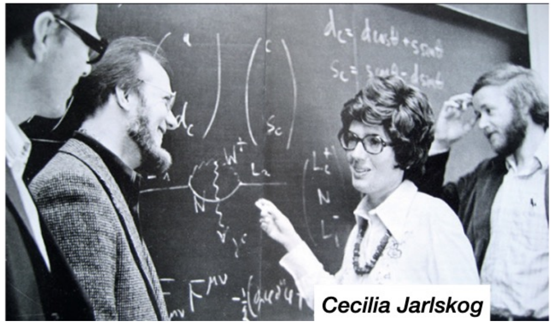
ν_μ survival probability



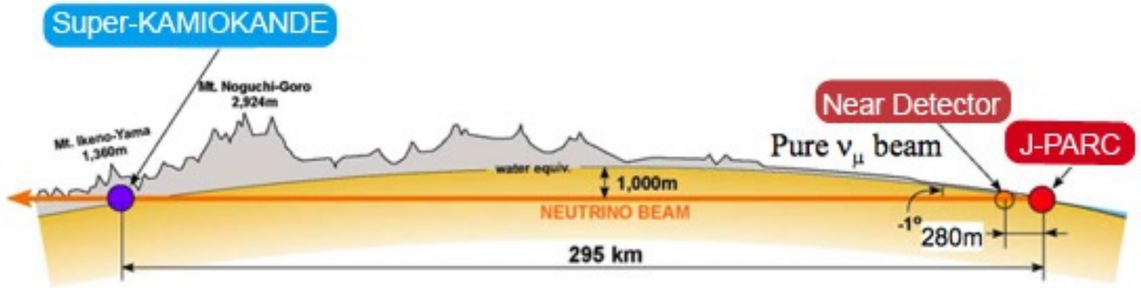
The Current Generation of Long-Baseline Experiments

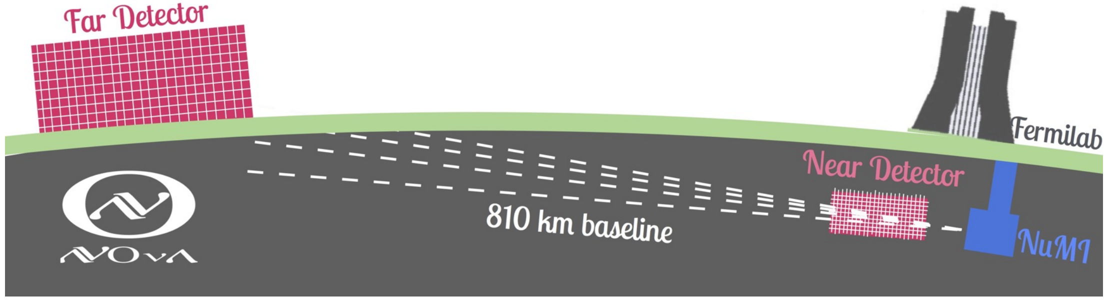
- Offaxis beam, L/E at oscillation maximal
- Disapearance for atmospheric sector
- Appearance for mass ordering and CP



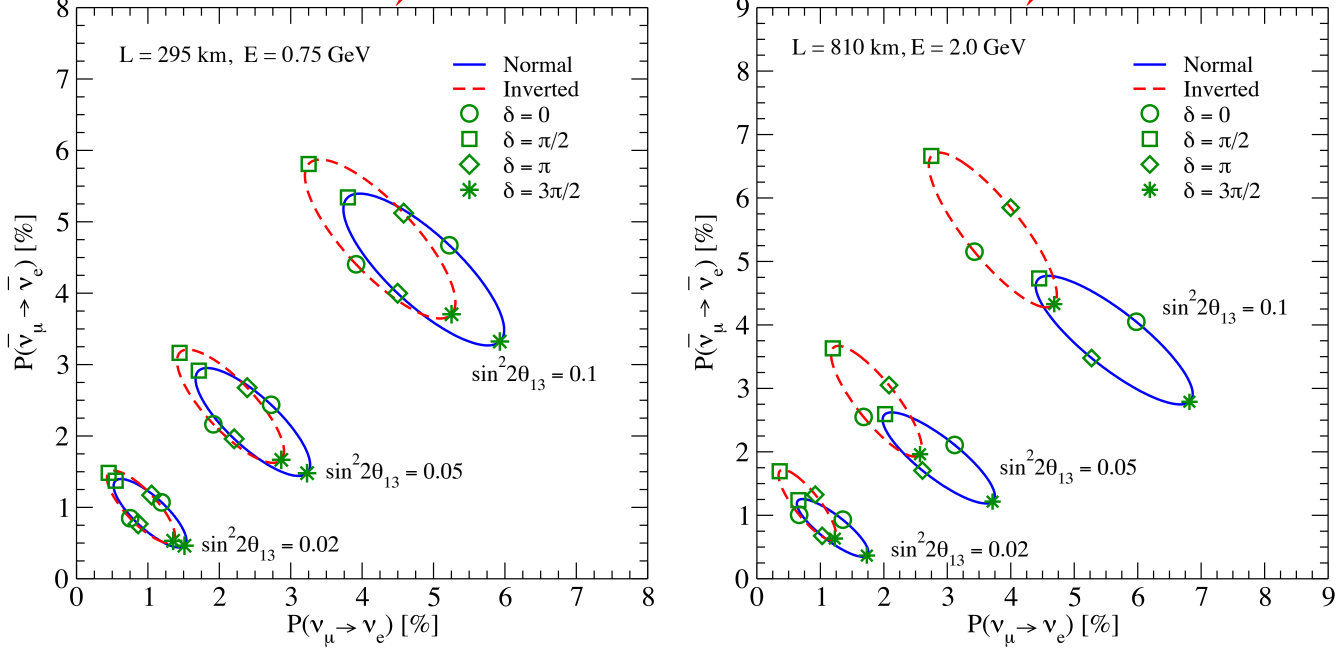


$$\frac{J_{\text{PMNS}}}{J_{\text{CKM}}} = \frac{3\times10^{-2}}{3\times10^{-5}}\sin(\delta_{\text{PMNS}})$$





Nunokawa et al, CP violation and neutrino oscillations, arXiv:07100554



The Latest Results from T2K+Super-Kamiokande

See arXiv:2405.12488

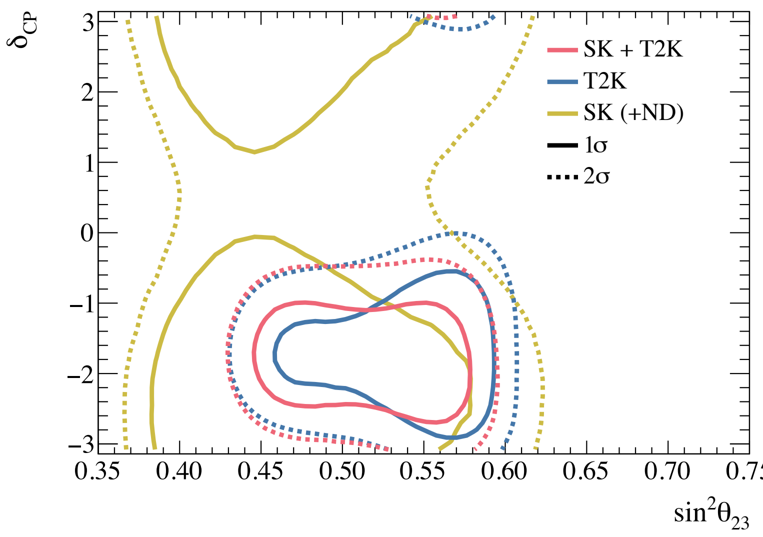


FIG. 1. The ($\sin^2\theta_{23}$, δ_{CP}) credible regions obtained with the SK, T2K, and combined datasets. The MO is marginalized over and a prior uniform in δ_{CP} is used.

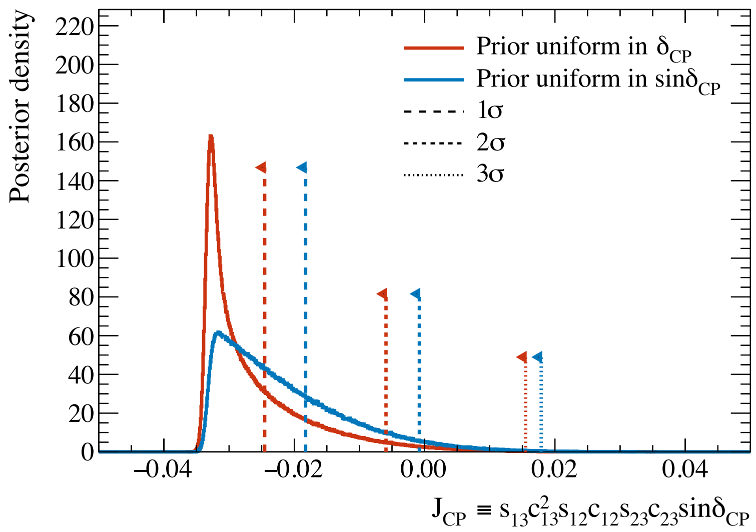


FIG. 2. The posterior density for the Jarlskog invariant with credible intervals overlaid, marginalized over both MOs, and assuming a uniform prior in either δ_{CP} or $\sin\delta_{CP}$.

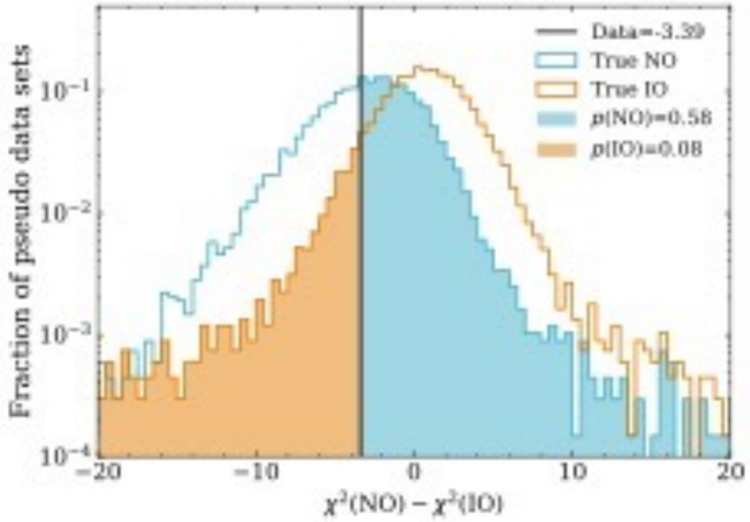


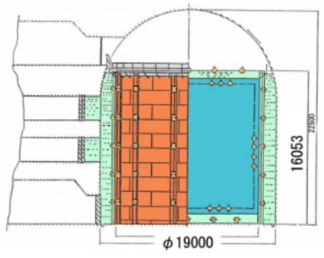
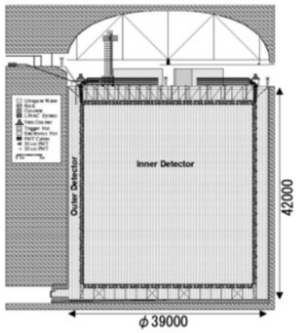
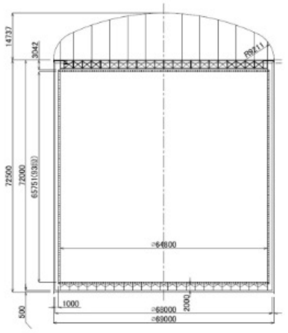
FIG. 3. Distribution of the MO test statistic under true normal and inverted ordering hypotheses. The filled areas to the left (right) of the data result indicate the p-values for the inverted (normal) hypotheses.

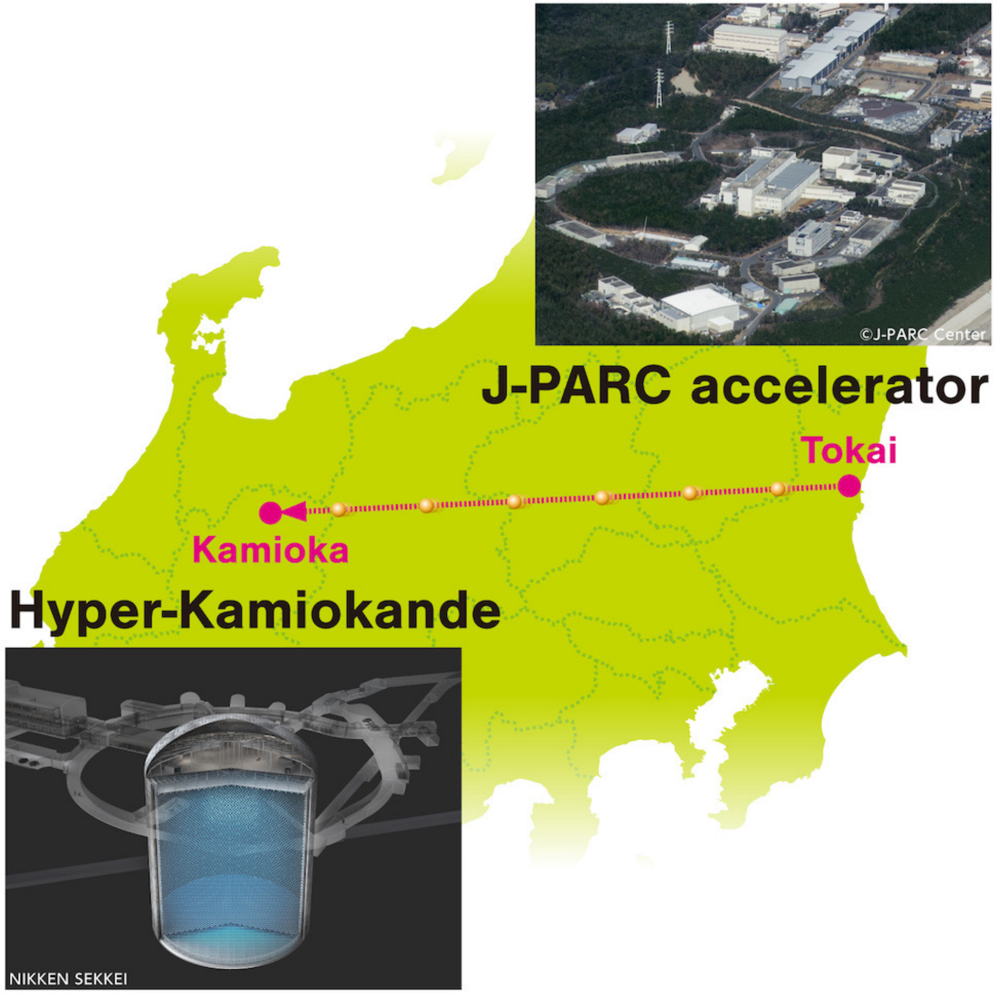
The results show an exclusion of the CP-conserving value of the Jarlskog invariant with a significance between 1.9σ and 2.0σ, a limited preference for the normal ordering, and no strong preference for the ϑ_{23} octant.

What to Do to Answer the Remaining Questions?

- **More statistics: always a good thing**
- **Better detectors: to better reconstruct events**
- **Better neutrino sources: tailored sources → stronger signals**

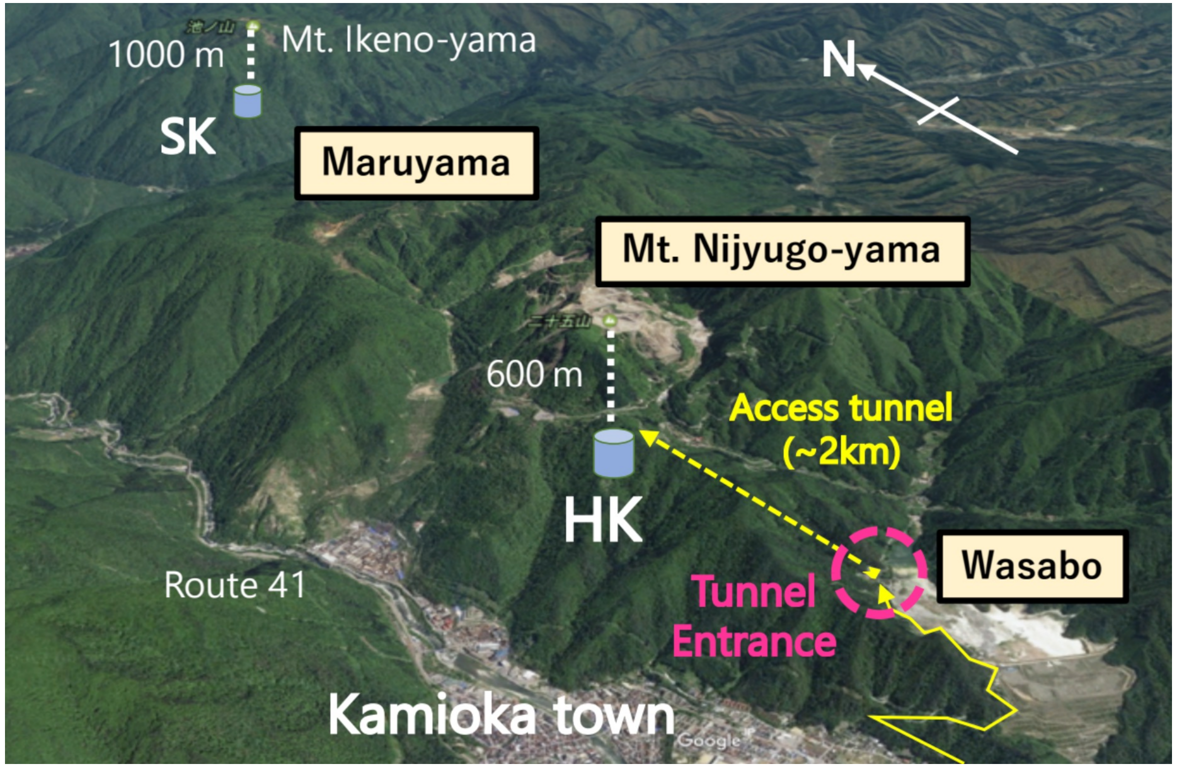
Future Long-Basline Program: Hyper-Kamiokande

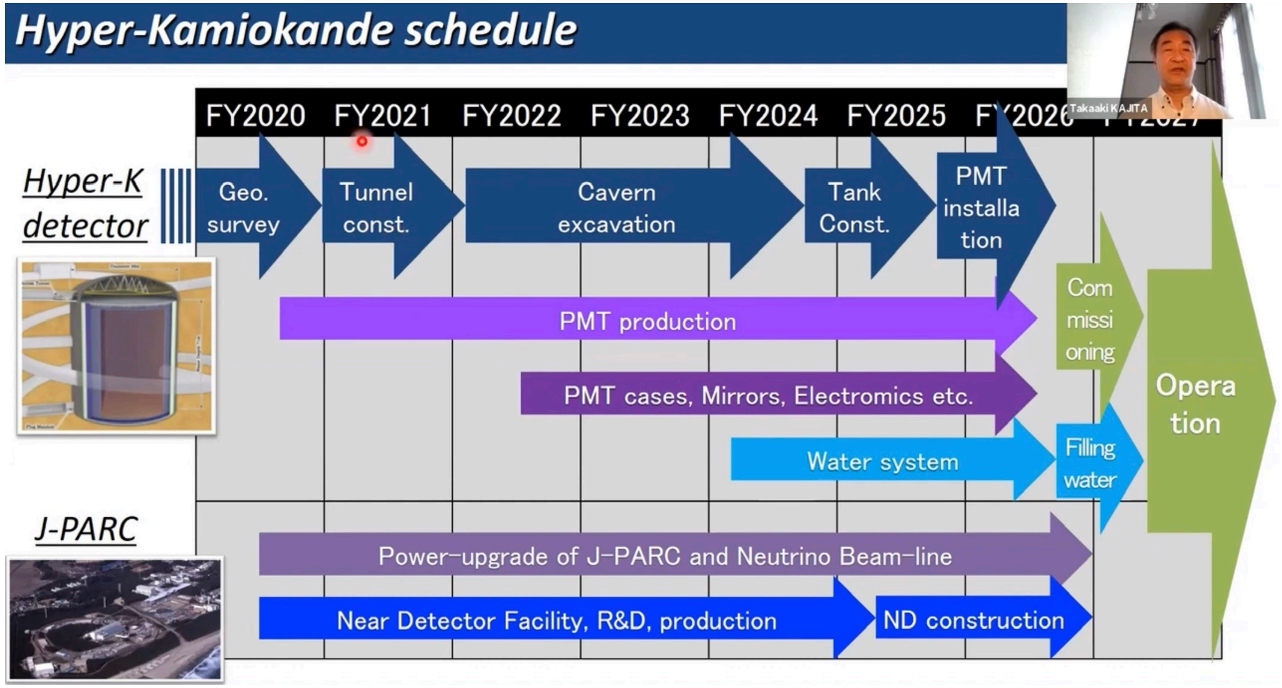
Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996-Present	Aiming to start observation in 2027
		
Size		
19m diameter x 16m hight	39m diameter x 42m hight	68m diameter x 71m hight
Water mass (Fiducial mass)		
4500 ton※ (680~1040 ton) ※The waer mass in the tank(inner tank and, upper and bottom outer tank) is 3000 ton	50000 ton (22500 ton)	260000 ton (190000 ton)
Photomultiplier Tubes		
50cm diameter / 948	50cm diameter / 11146	50cm diameter / about 40000



Future Long-Baseline Program: Hyper-Kamiokande

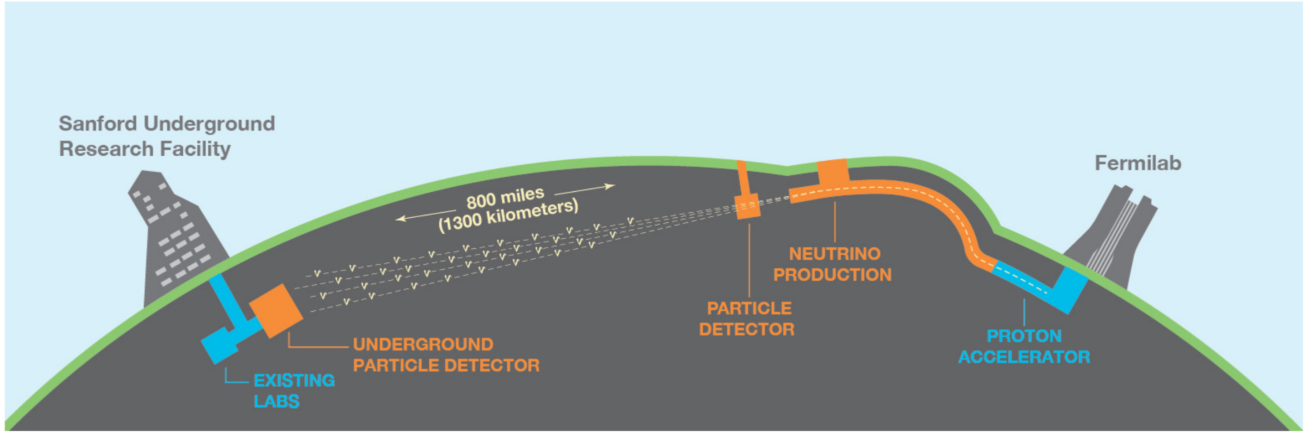
- Super-K/T2K → Hyper-K/T2HK

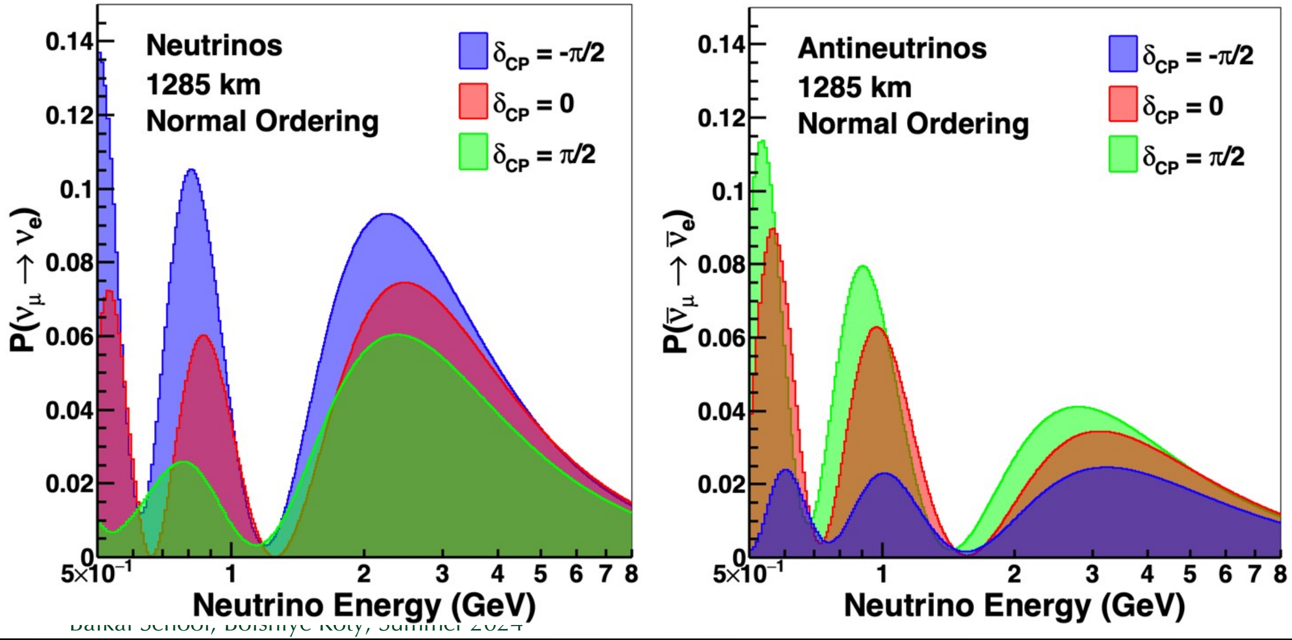


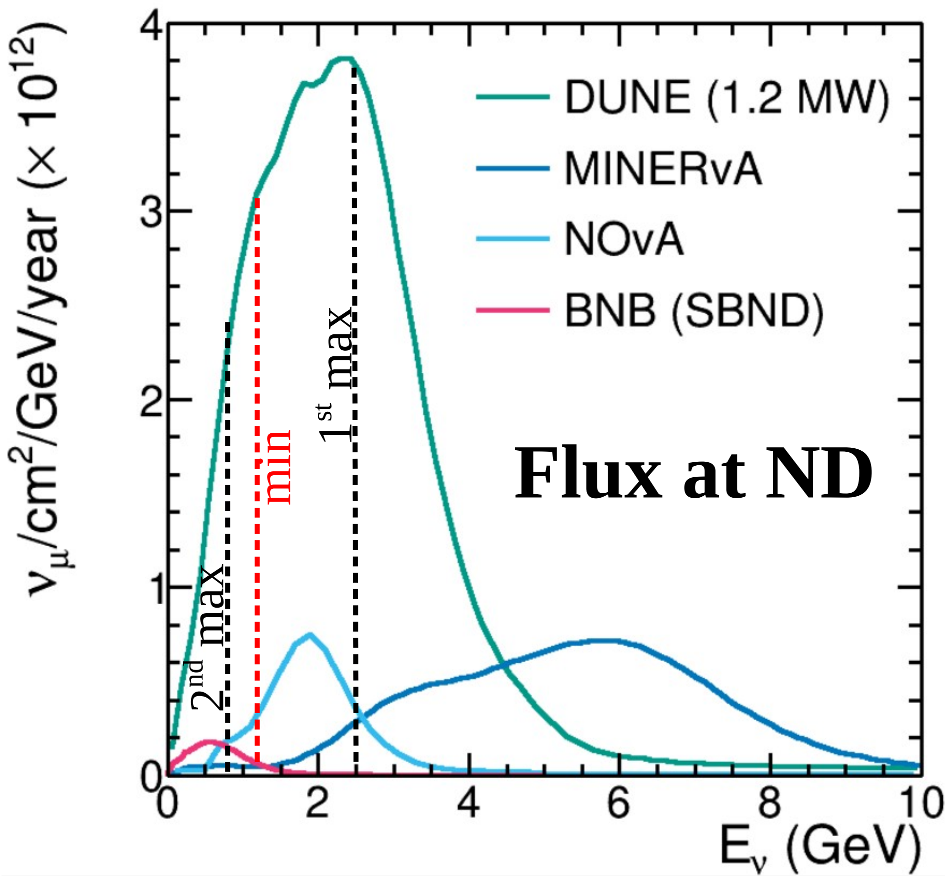


U.S. Efforts of Long-Baseline Neutrino Experiment

- **In the U.S., MINOS/MINOS+/NOvA upgrading to LBNF → DUNE**

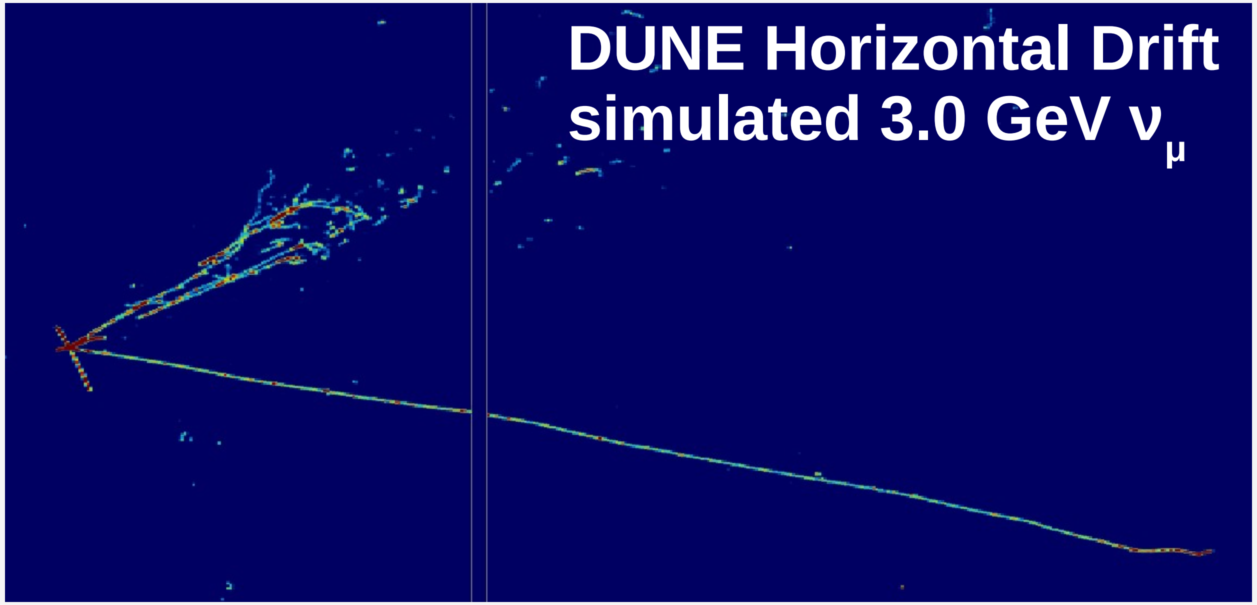


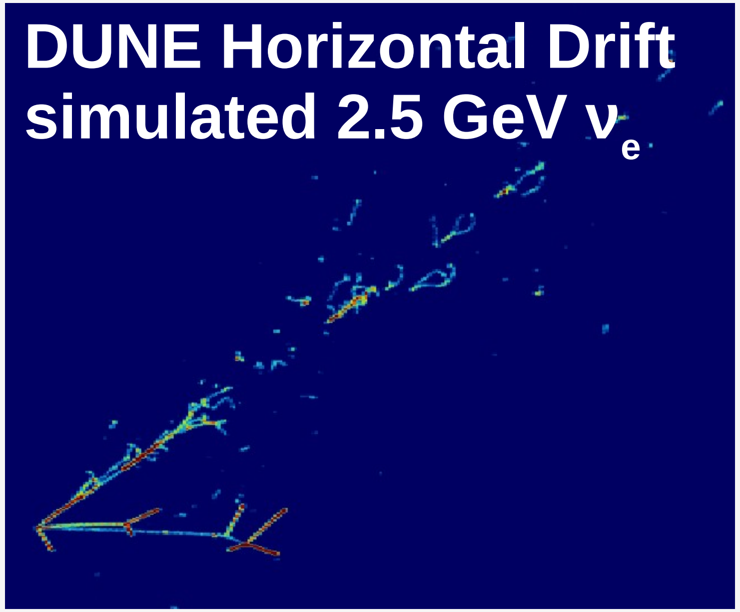




A Dream Neutrino Detector: Liquid Ar TPCs

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



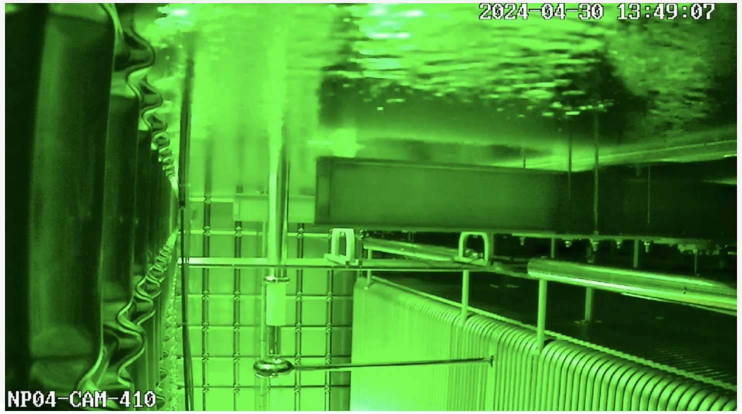


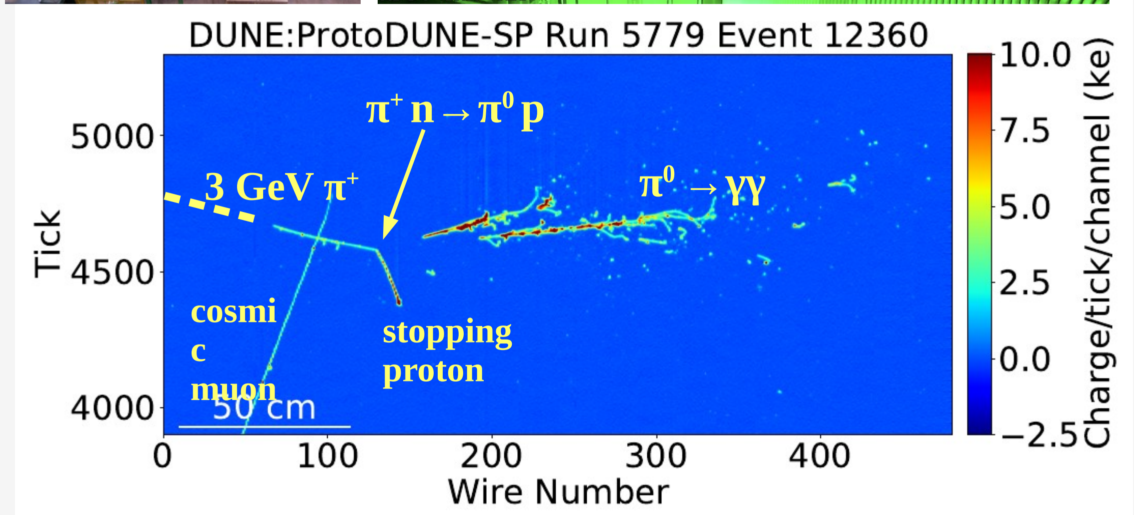
- 60% of interactions at DUNE energy have final state pions → LArTPC enables precise hadron reconstruction
- Excellent e/μ and e/γ separation

Chris Marshall for DUNE @ Neutrino'24

A Dream Neutrino Detector: Liquid Ar TPCs

ProtoDUNE: preparing for second runs

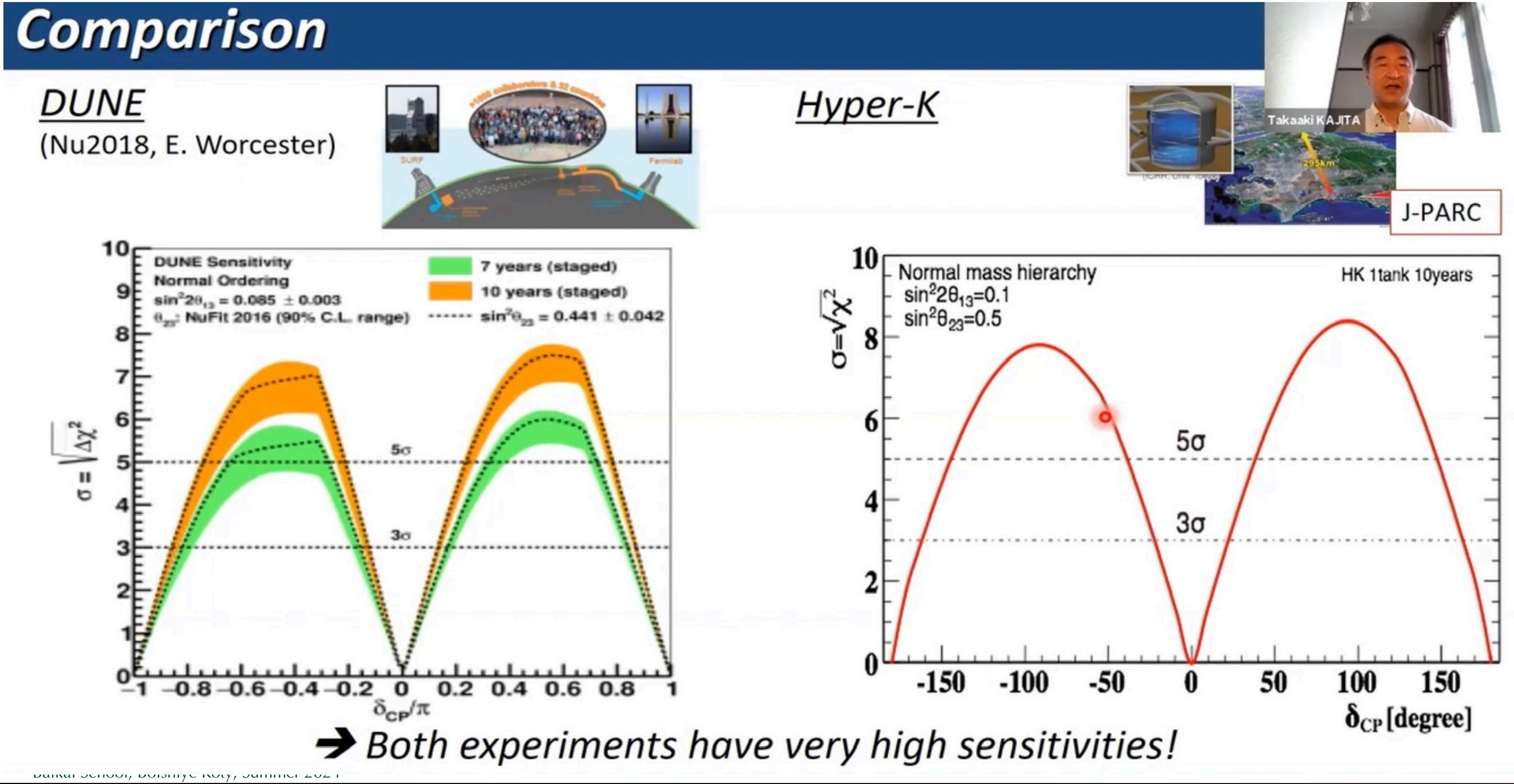




- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (ProtoDUNE-SP)
- ProtoDUNE-HD completed filling 30th April, running since May, with beam turning on at 6pm tomorrow evening
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025

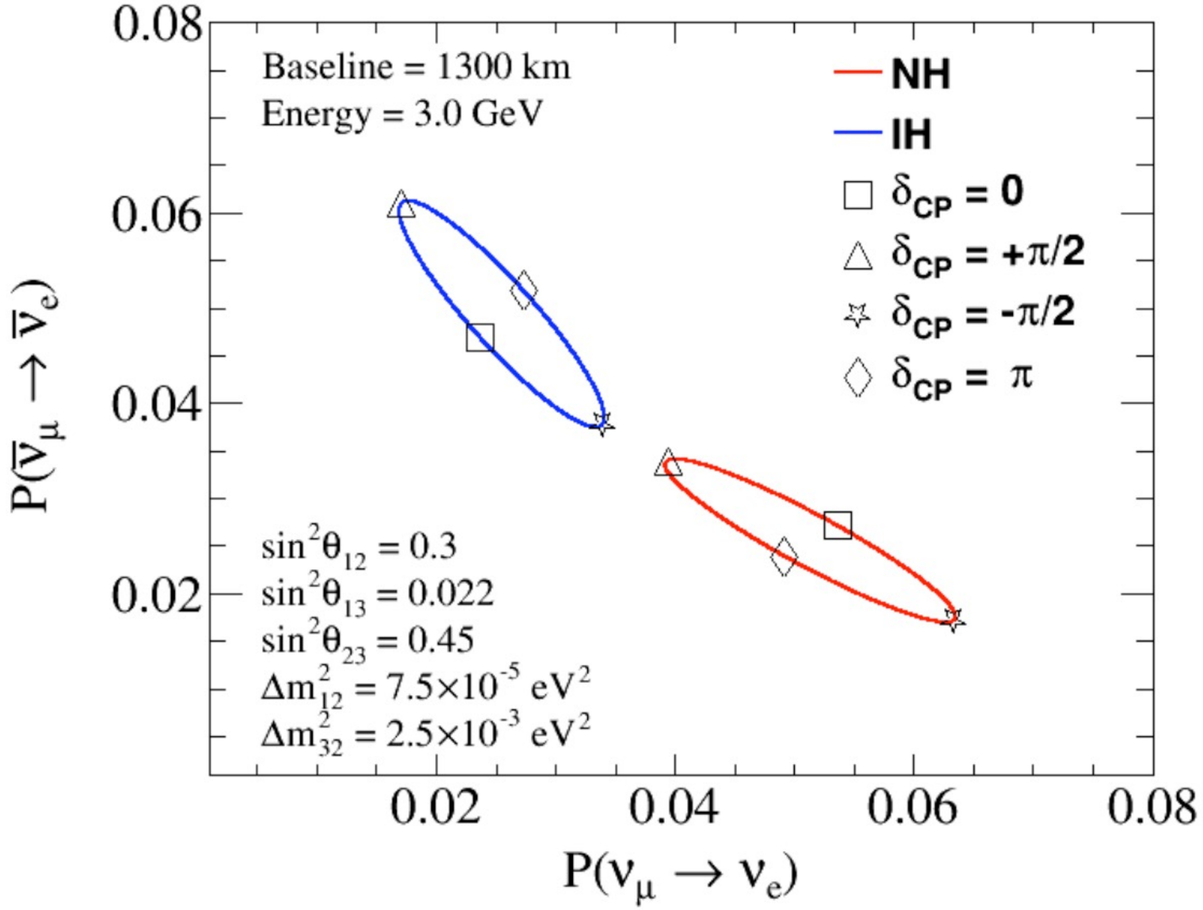
Chris Marshall for DUNE @ Neutrino'24

DUNE versus Hyper-K Comparison in CP Phase

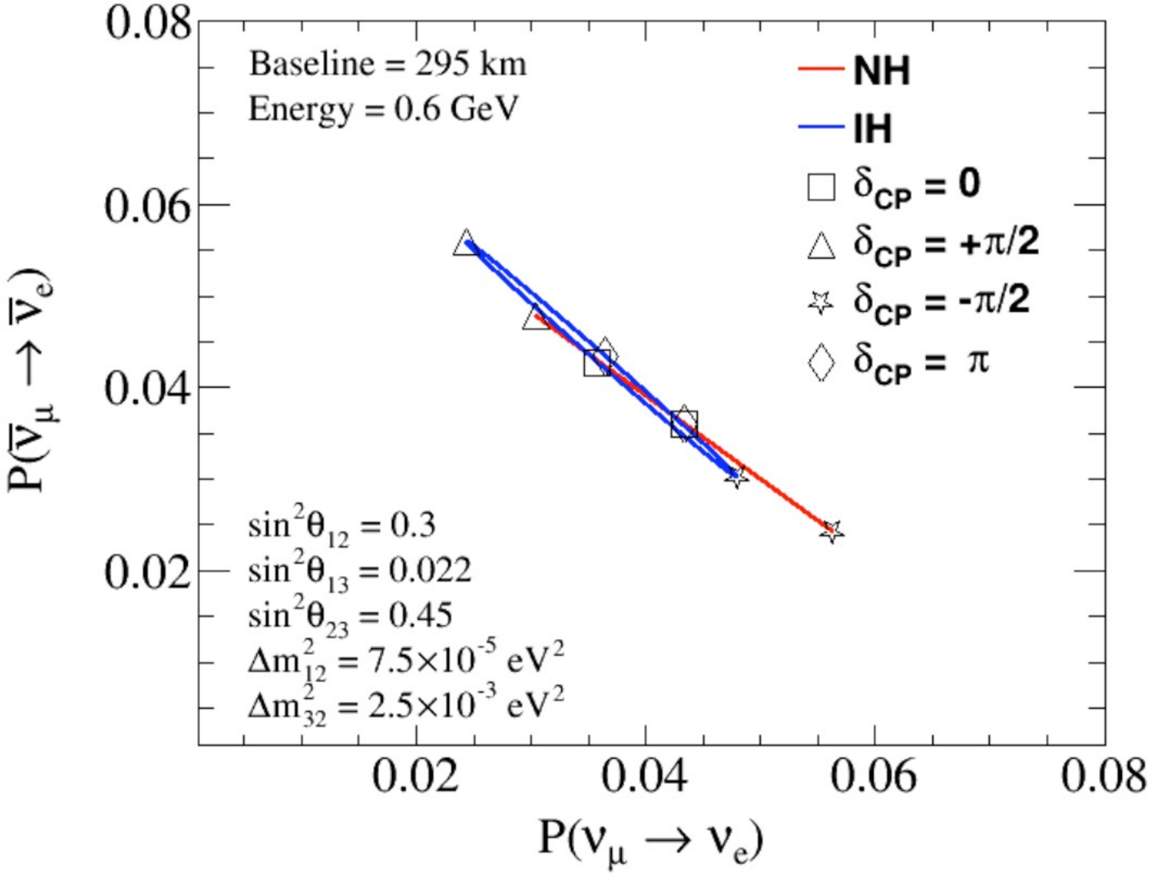


DUNE versus Hyper-K Comparison in Mass Ordering

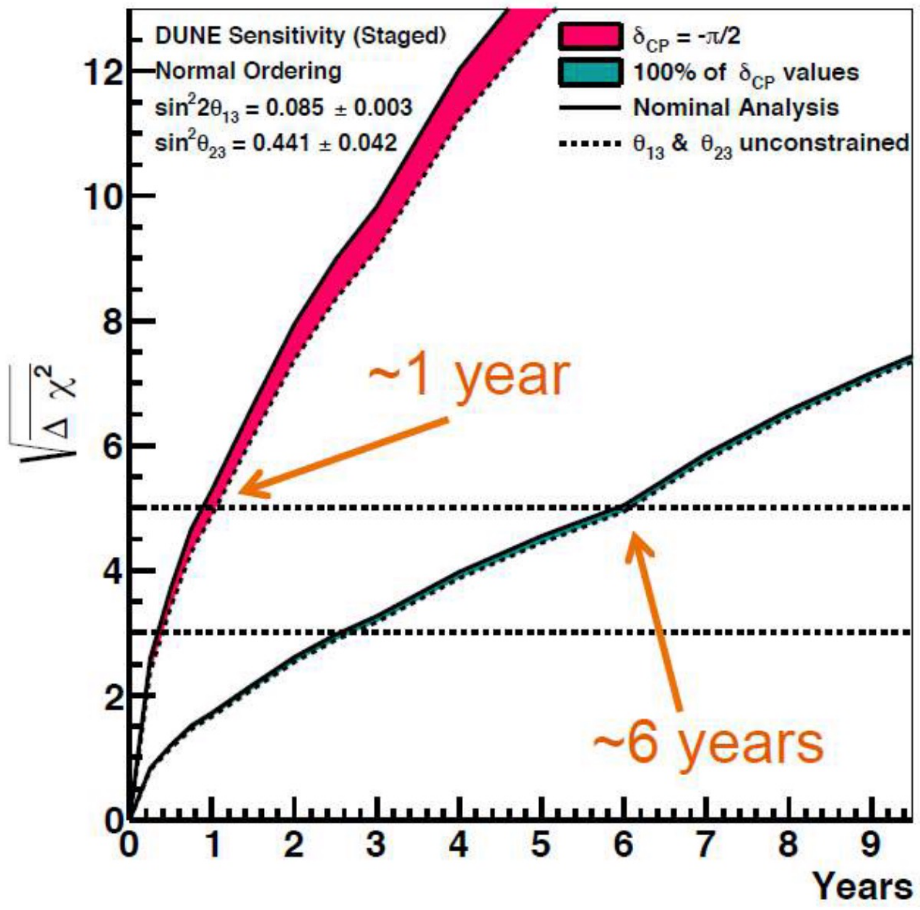
Baseline 1300 km
Energy 3.0 GeV

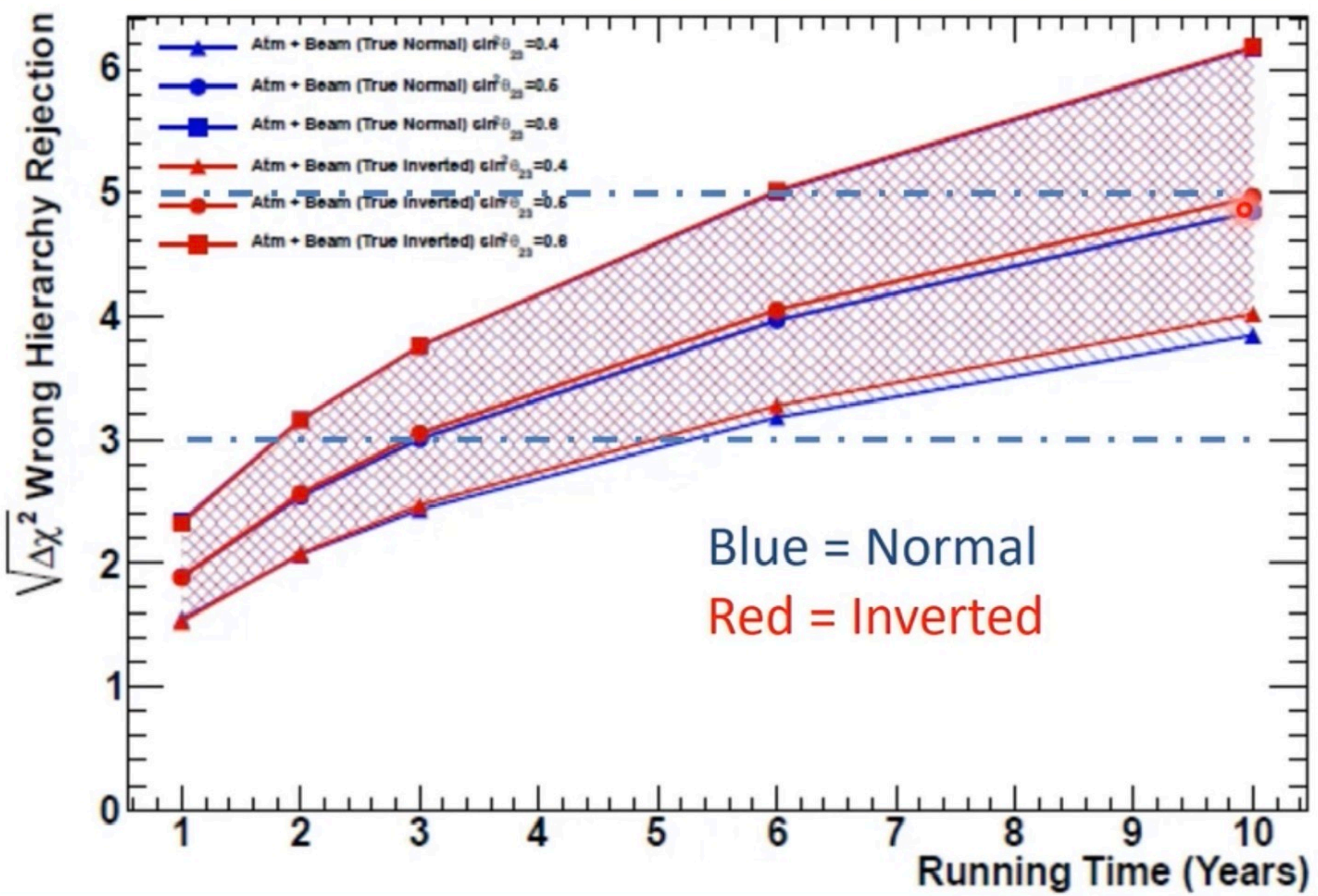


Baseline 295 km
Energy 0.6 GeV

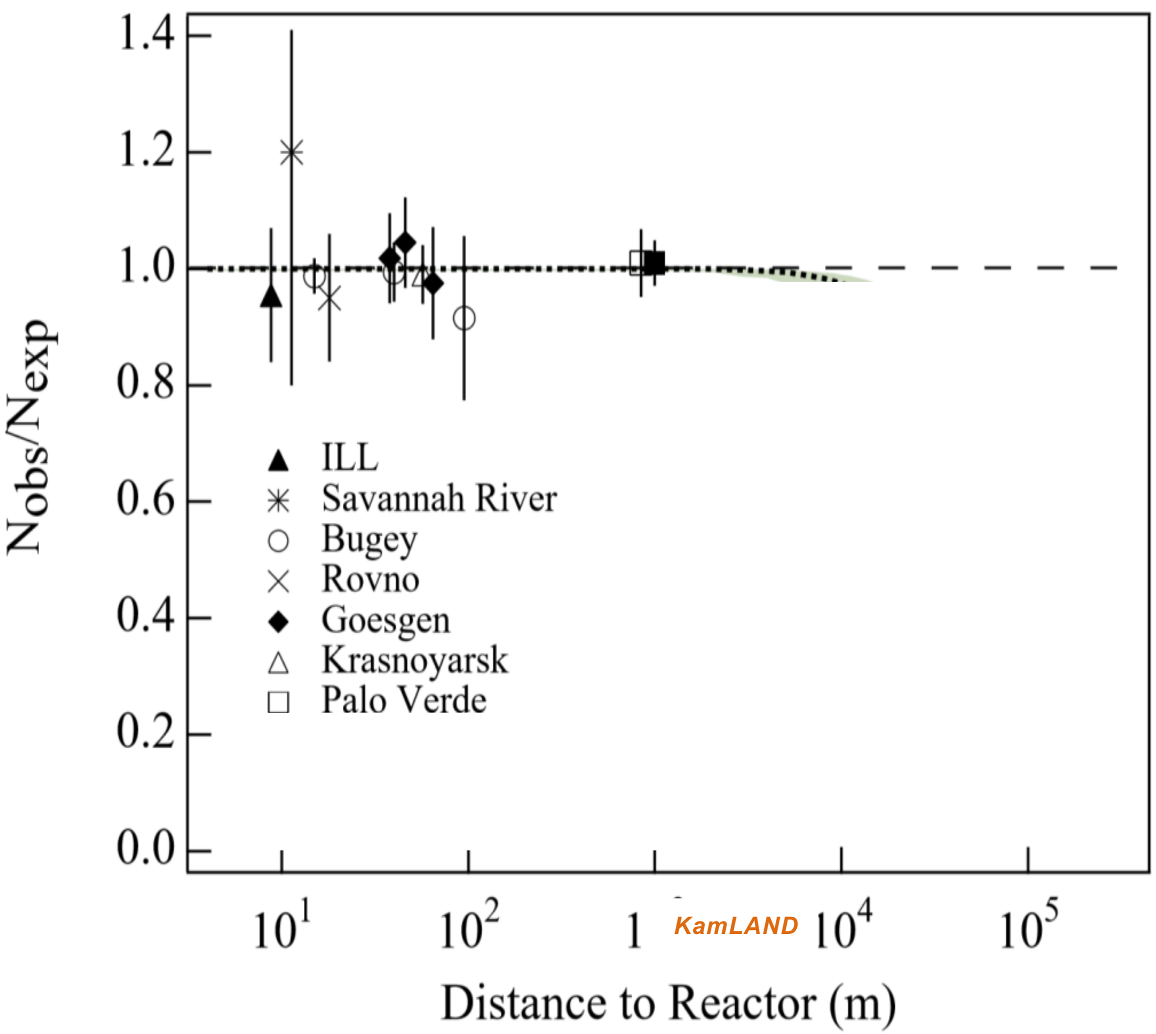


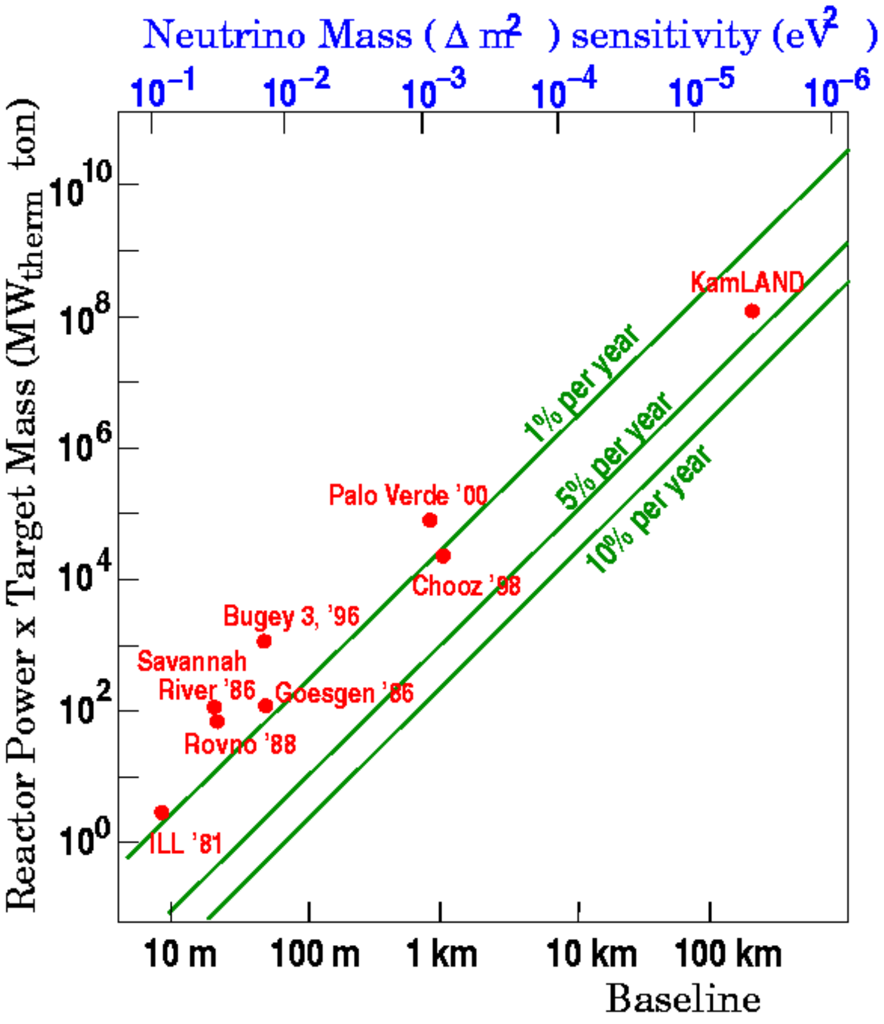
DUNE versus Hyper-K Comparison in Mass Ordering





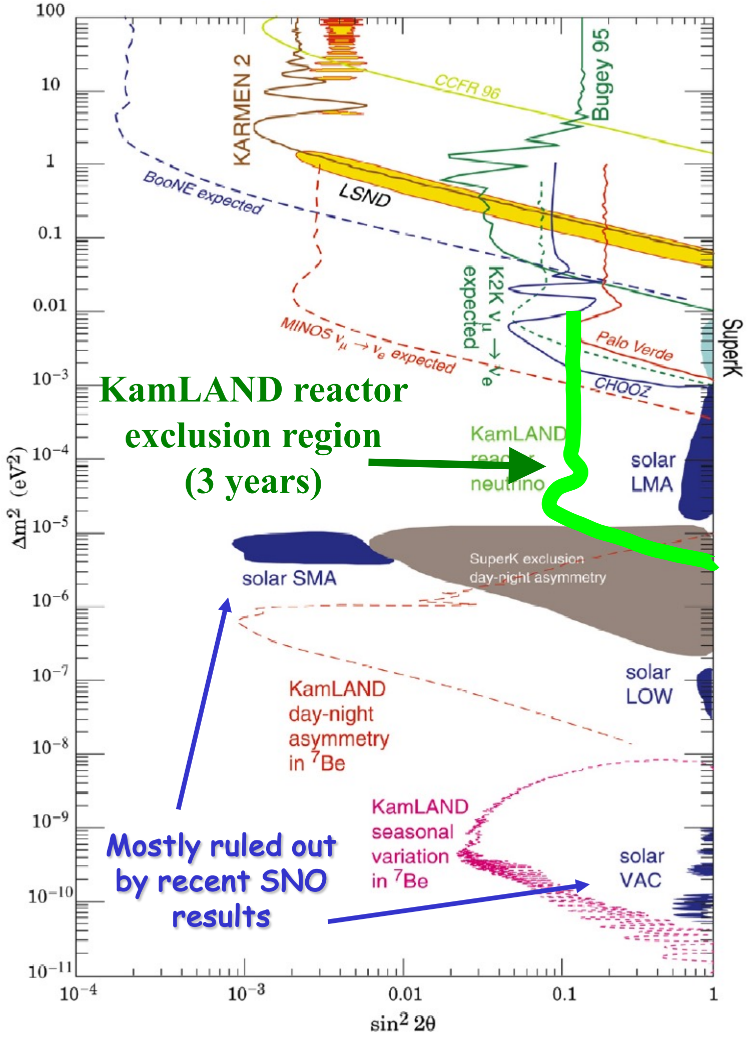
The Search for Neutrino Oscillation @ Reactors 1956-2002

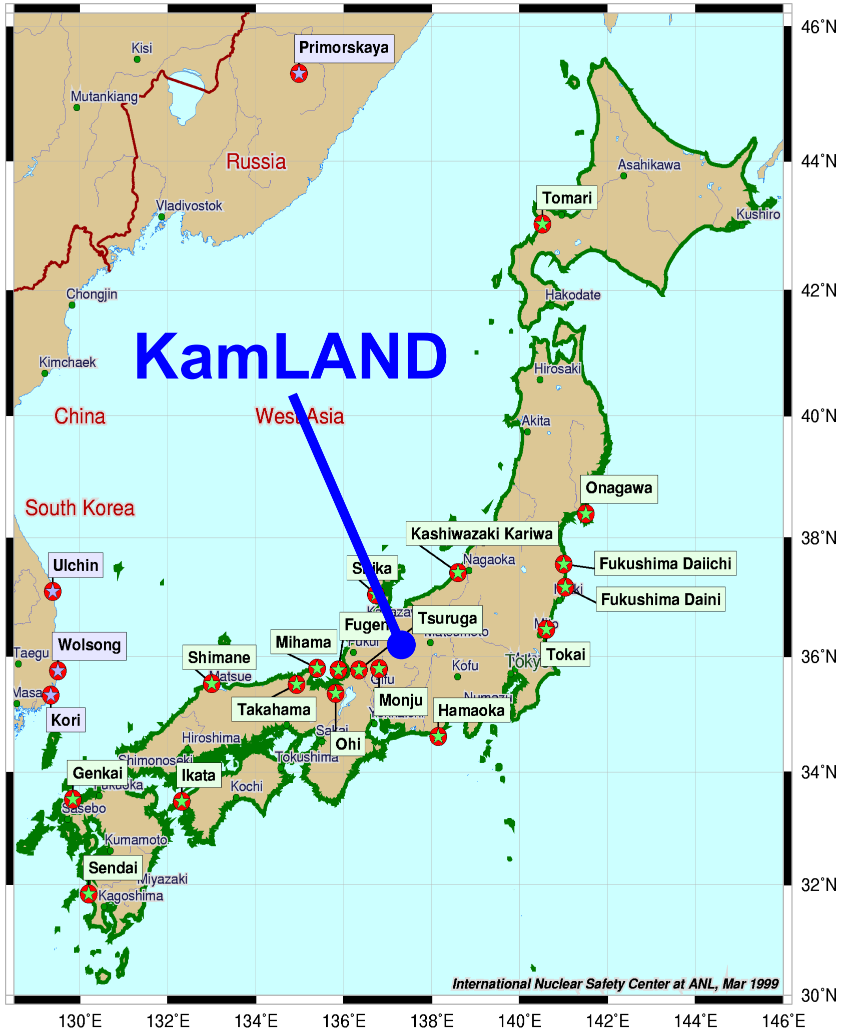


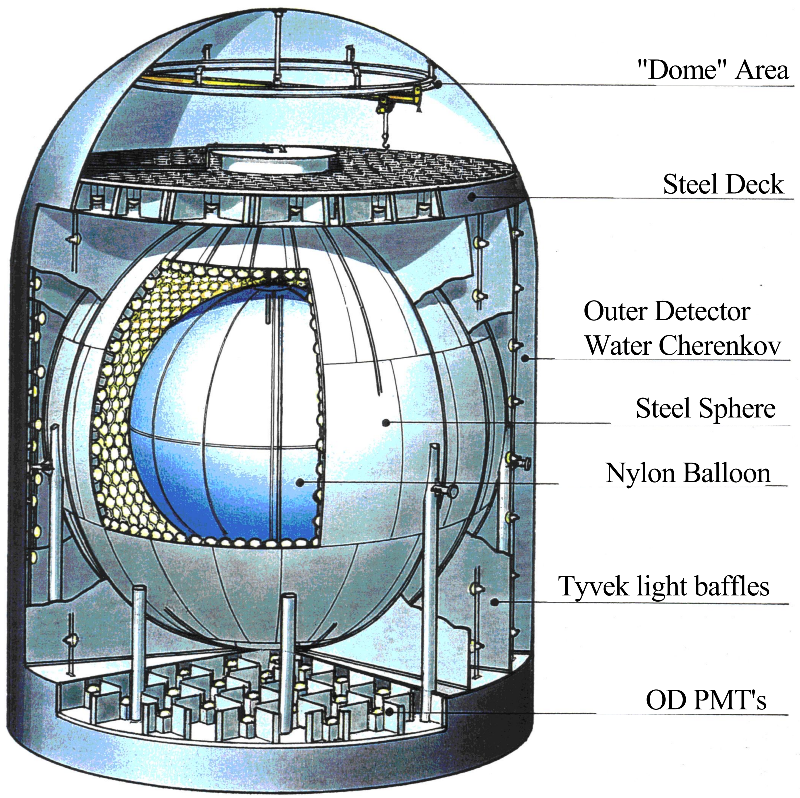


KamLAND Set Out to Discover Reactor Neutrino Oscillation

KamLAND uses the entire Japanese nuclear power industry as a longbaseline source



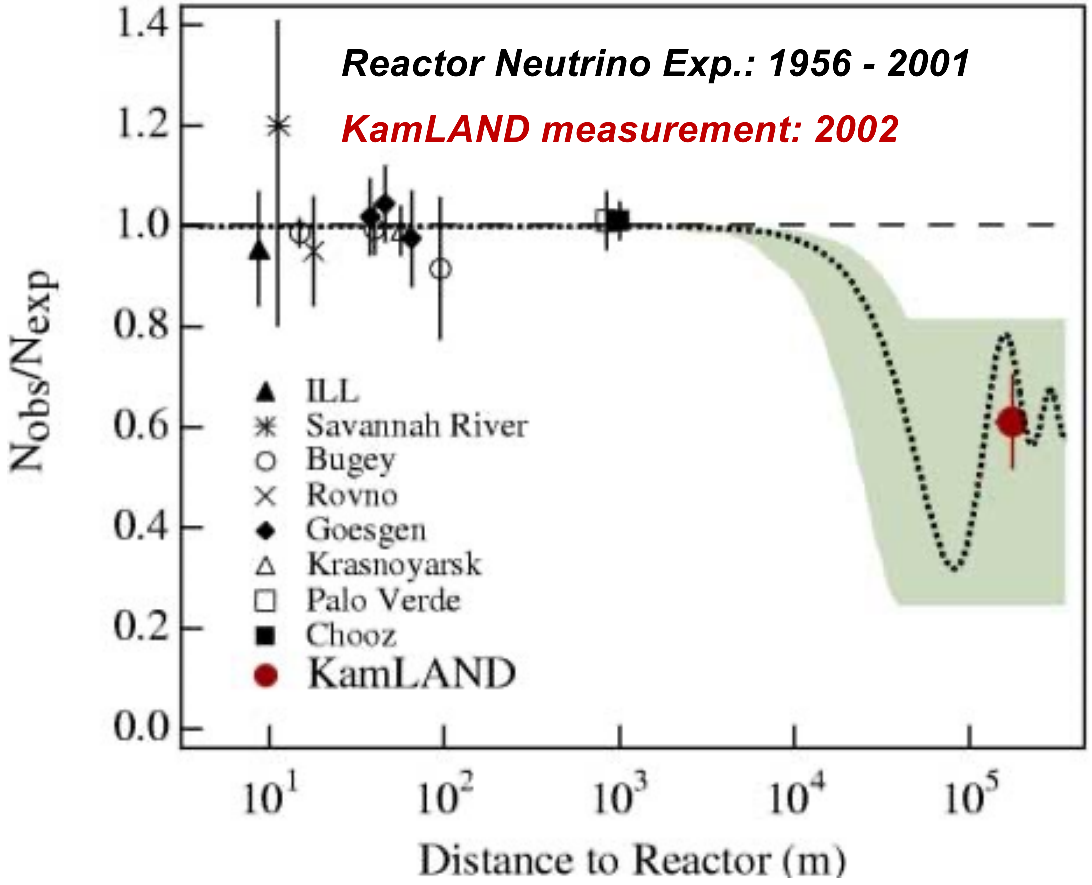


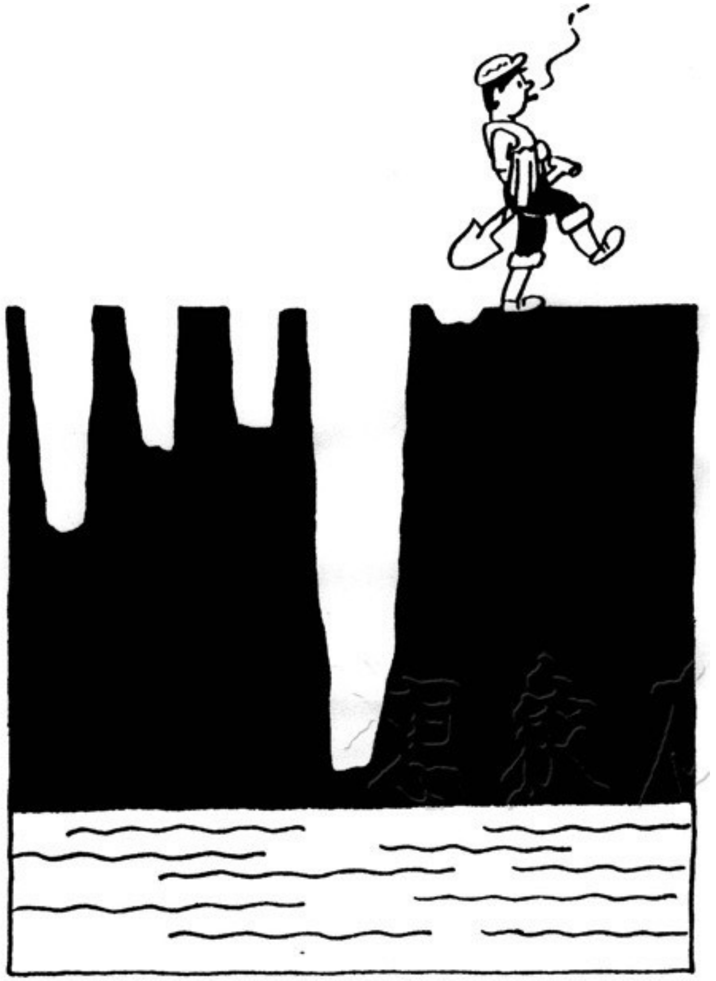


Year 2002: Reactor Neutrinos Oscillate Too!

Sometimes, we just need to push it a bit further……

from ~10m to over 100,000m





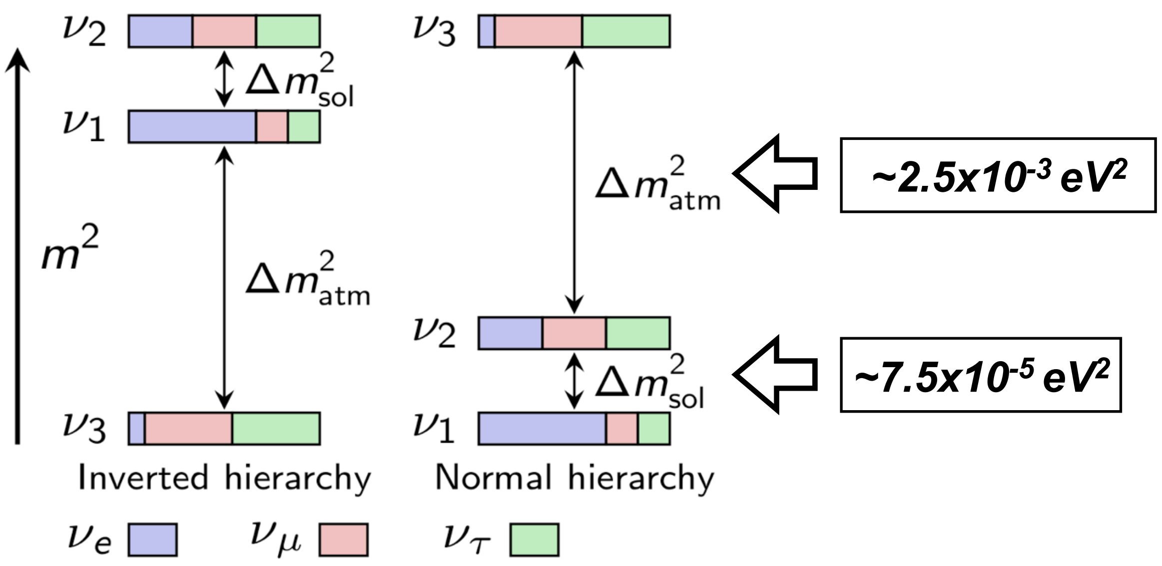
一这下面没有水，再换个地方挖　　张新华画

“No water here, try another place”

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix (with Majorana CP phases),

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

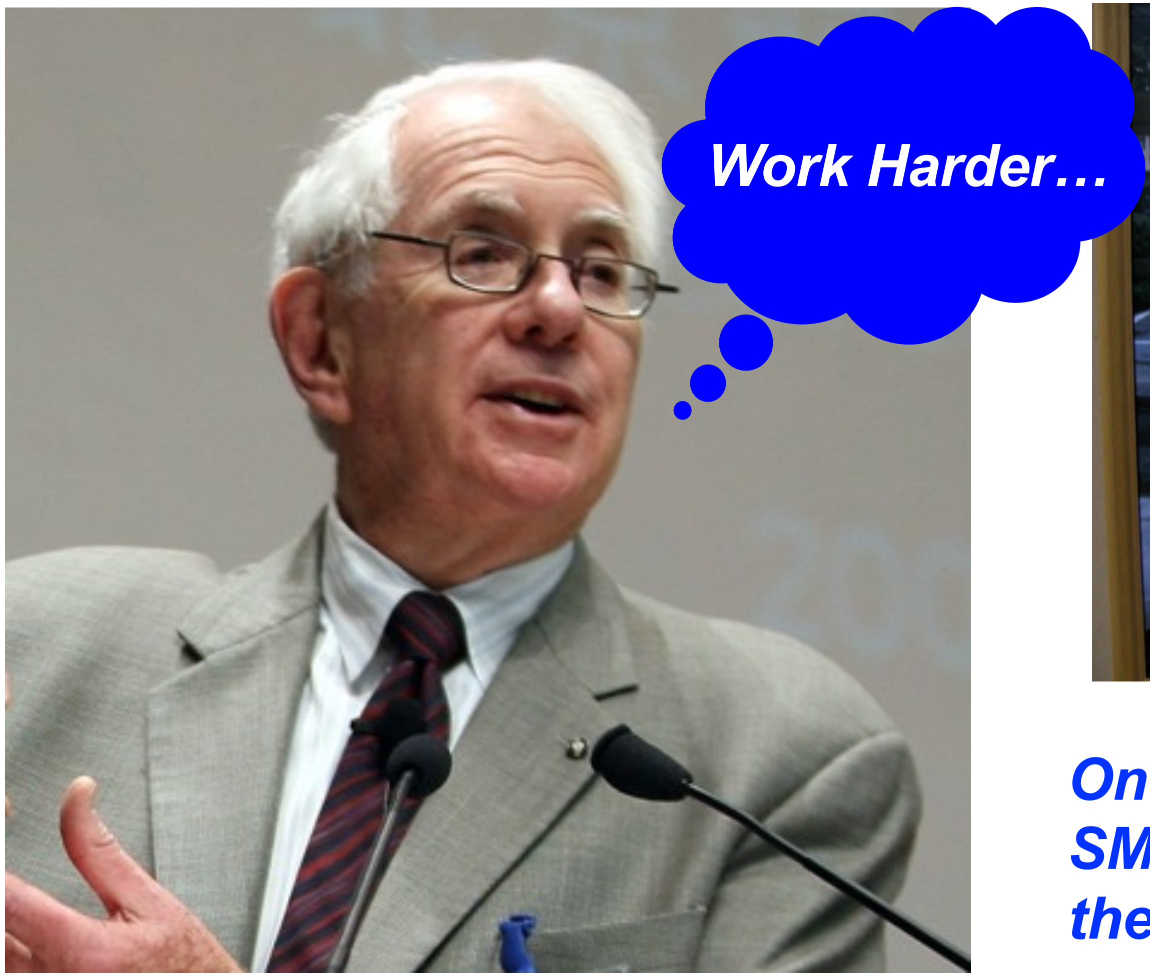


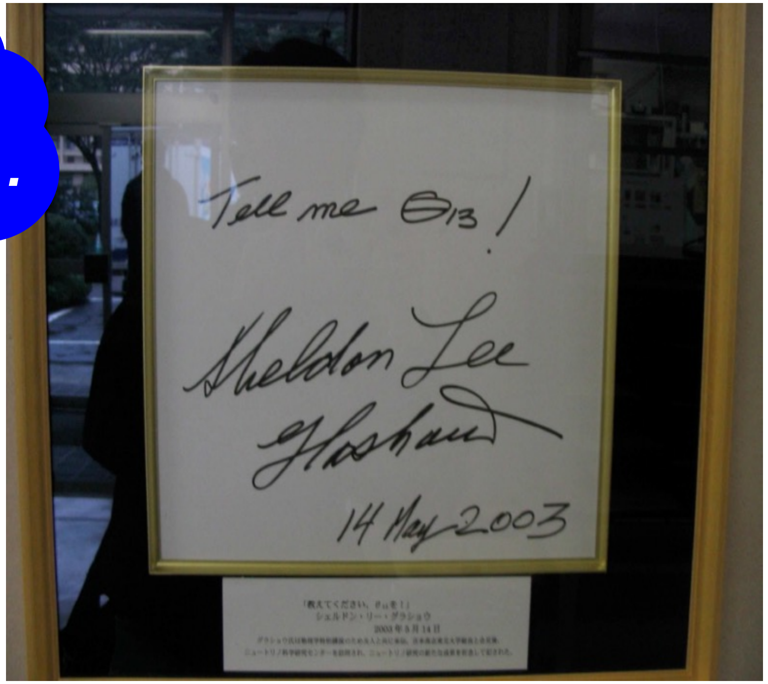
⇒ Neutrino Oscillation Probability:

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4 \sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$

Amplitude ∝ $\sin^2 2\theta$ **Frequency ∝ $\Delta m^2 L/E$**

We Were All Very Very Very **Desperate**





One of the Funders of the SM, Glashow, called for the measurement of θ_{13}

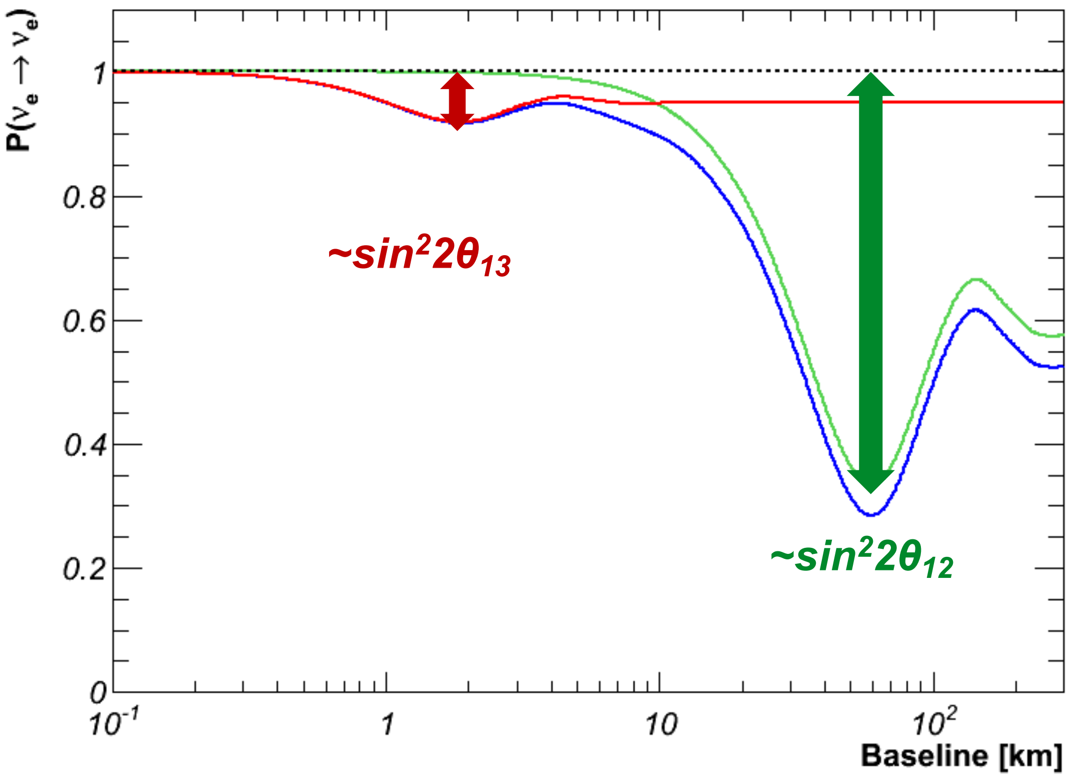
Photo by Kam-Biu Luk

What Reactor Neutrinos Can Measure

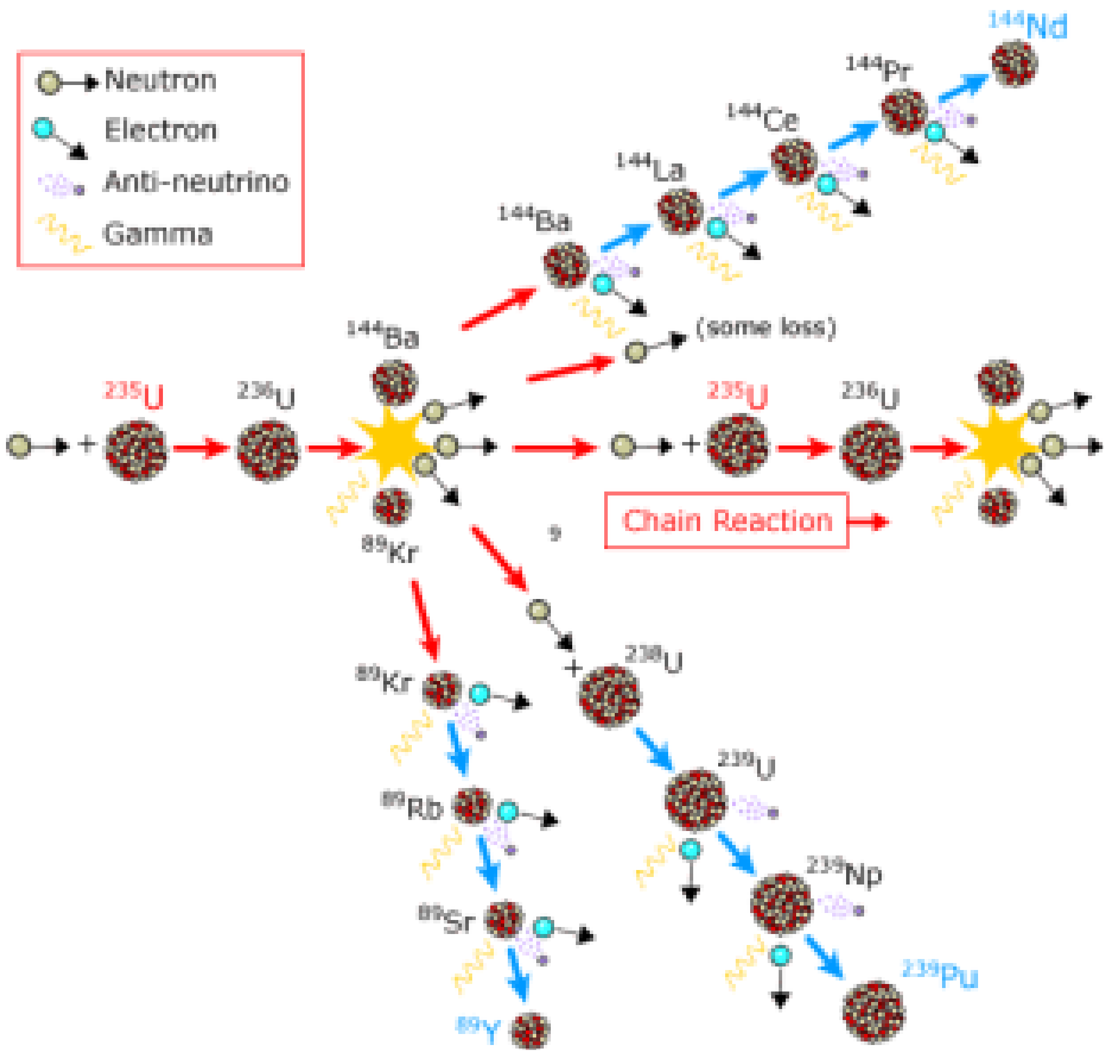
$$P\left(\bar{\nu}_e \to \bar{\nu}_e\right) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\sin^2\left(\Delta m_{ee}^2 \frac{L}{4E}\right) \equiv \cos^2\theta_{12}\sin^2\left(\Delta m_{31}^2 \frac{L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\Delta m_{32}^2 \frac{L}{4E}\right)$$

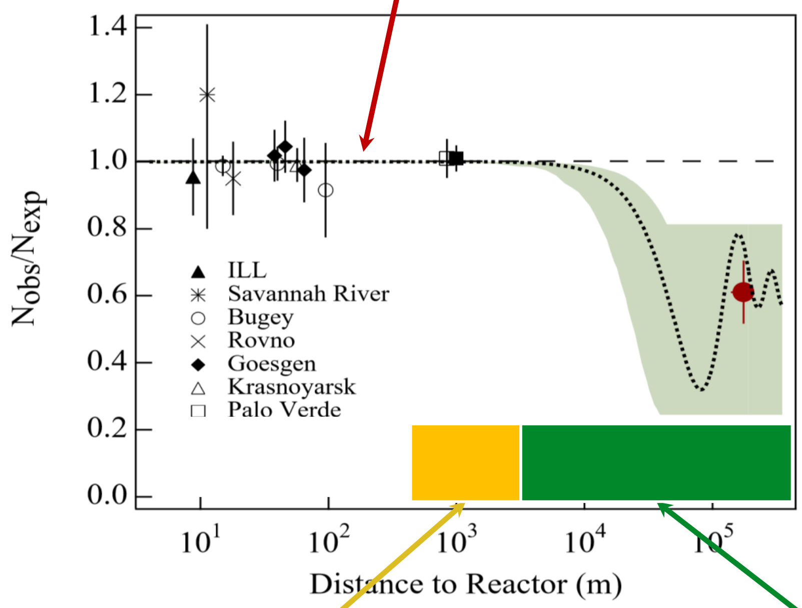
- At different distances, the survival rate is dominated by different mixing angles
- To measure θ_{13}, a baseline of ~2 km is optimal



Reactor Neutrinos for Theta13

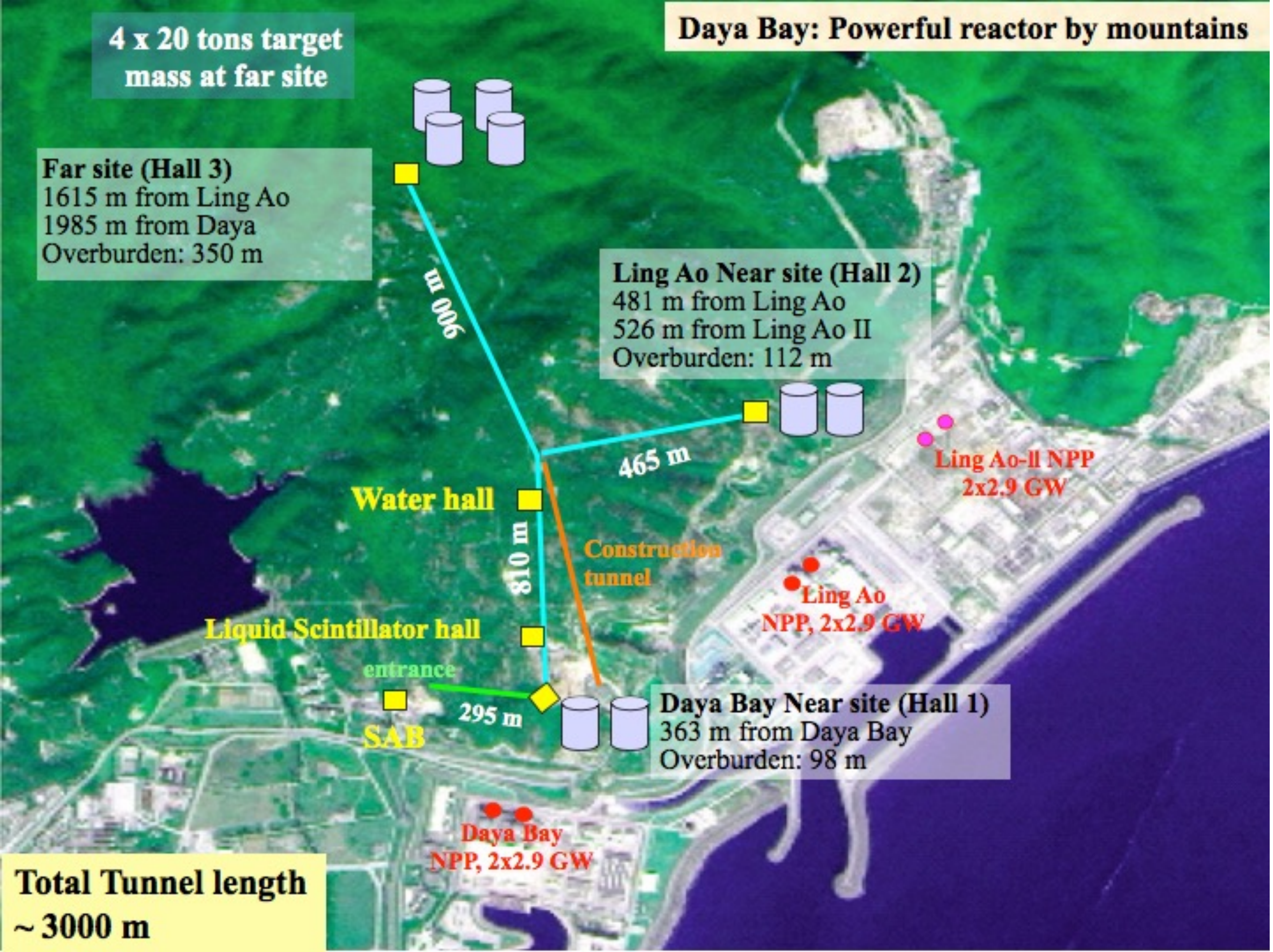


Six antineutrinos/fission: ~2-8MeV, ~5% accuracy



θ_{13} Driven

θ_{12} Driven



Mikaelyan LA, Sinev VV. , Phys. At. Nucl. 63:1002 2000.

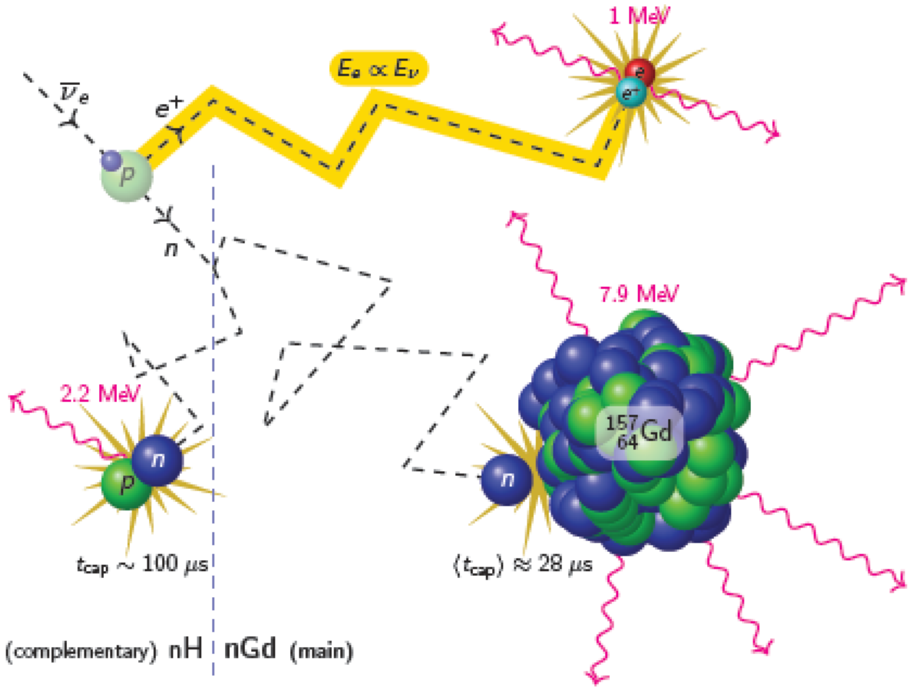
“Two identical liquid scintillation spectrometers stationed at the Krasnoyarsk underground site (600 MWE) at distances R1 = 1100 m and R2 = 250 m from the reactor source simultaneously detect (e+,n) pairs”

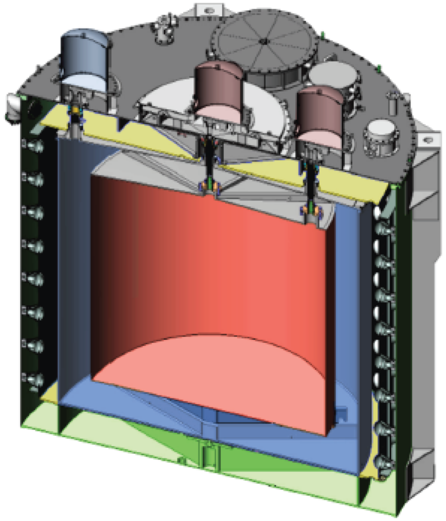
Daya Bay: A Powerful Neutrino Source at an Ideal Location

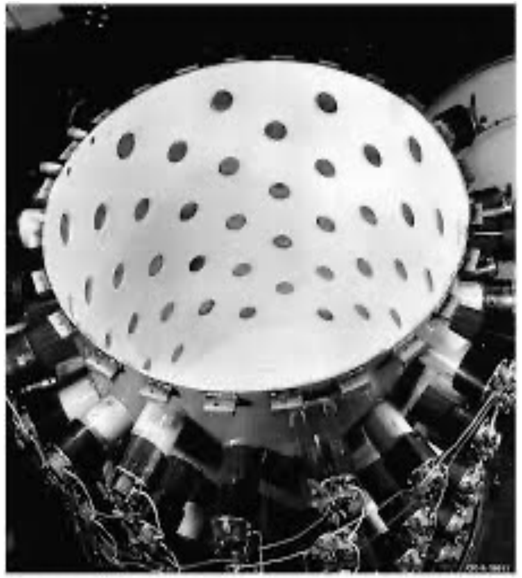
Among the top 5 most powerful reactor complexes in the world,
6 cores produce 17.4 GW_{th} power, 35×10^{20} neutrinos per second

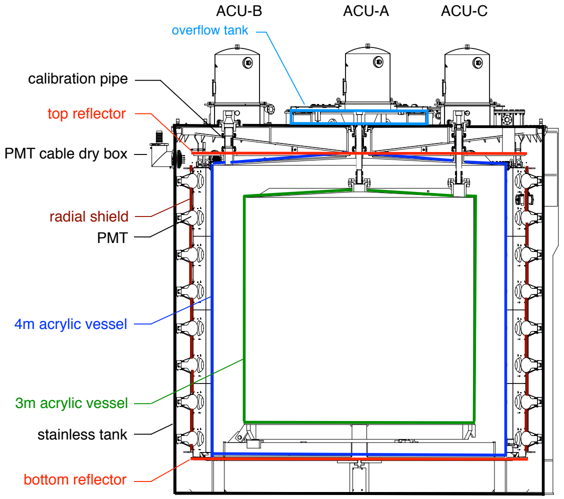
The Daya Bay Anti-neutrino Detector

3-zone antineutrino detector (AD):		
Inner zone	20 t	Gd-doped LS
Middle zone	20 t	LS
Outer zone	40 t	Mineral oil



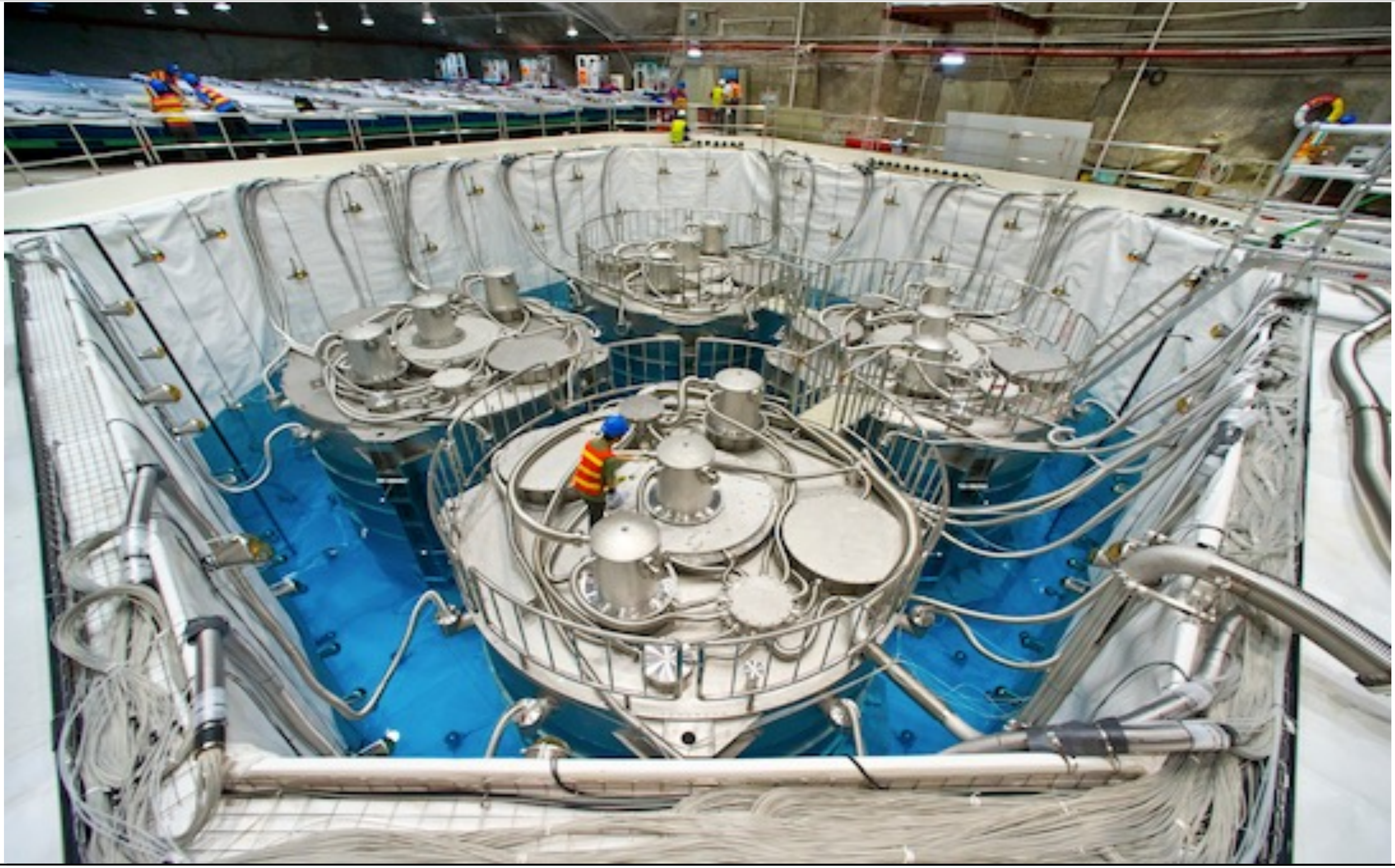




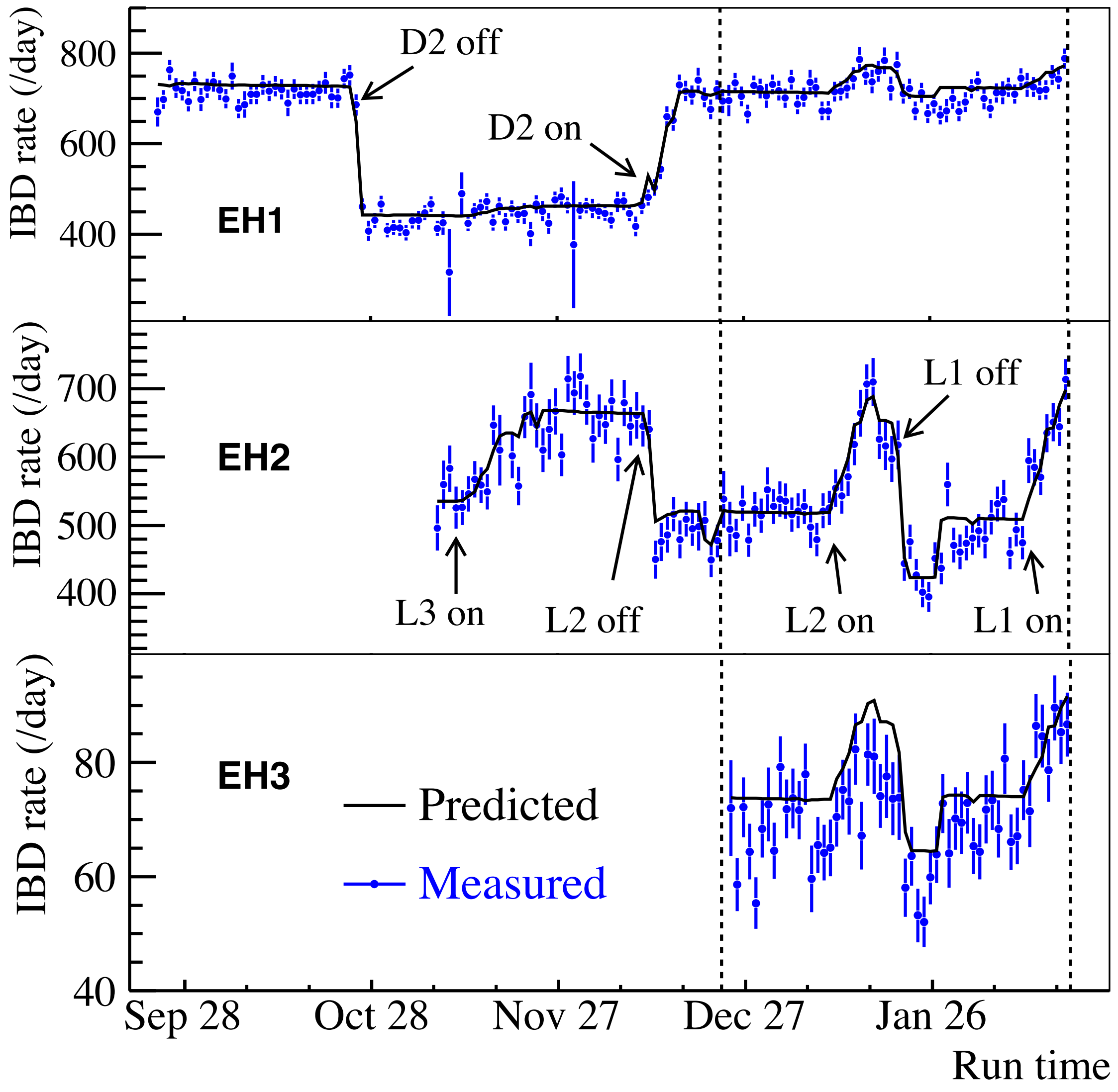


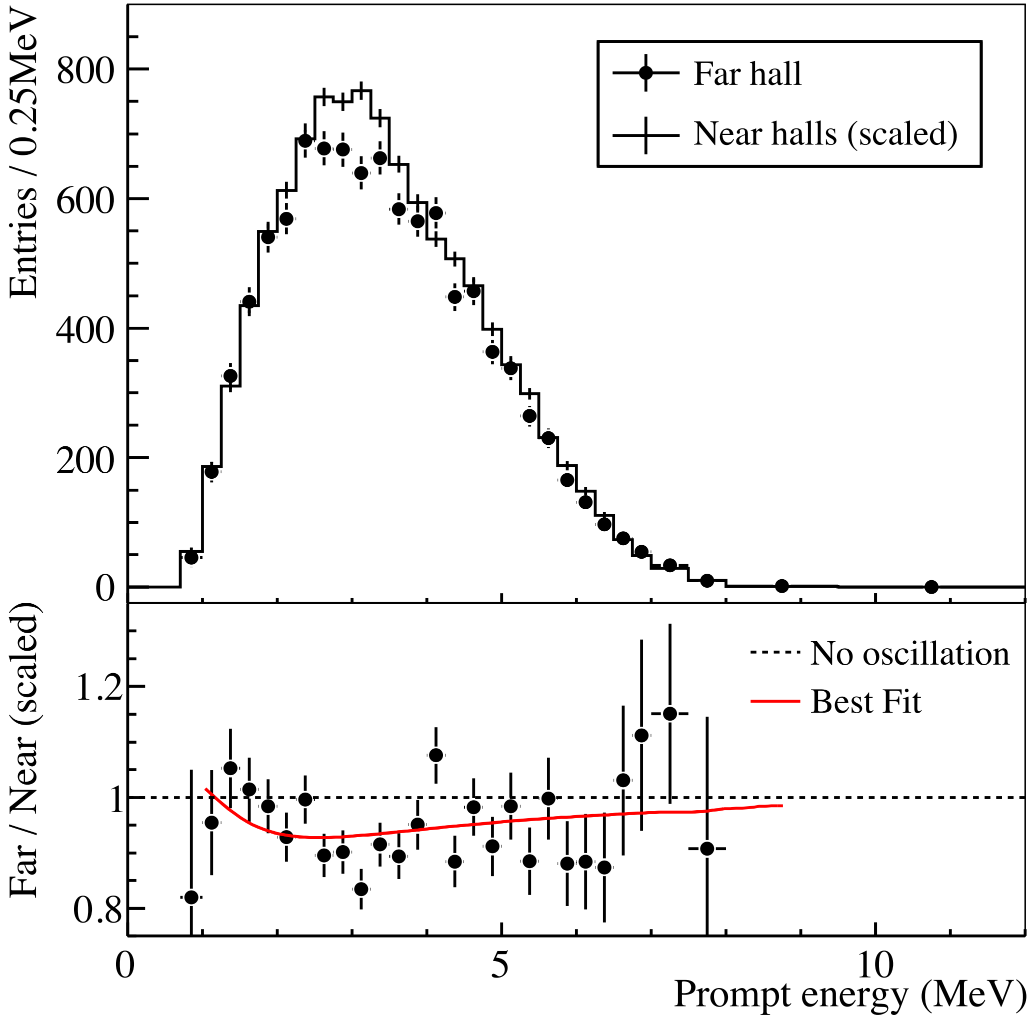
A Small Big Science Project

A Small Big Science Project

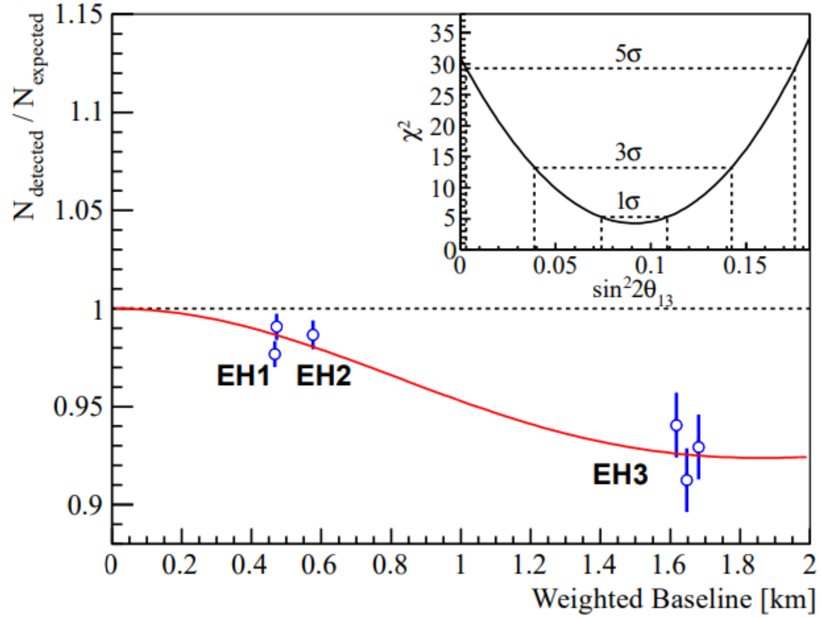


First Daya Bay Oscillation Results with 1958 Days





Daya Bay, RENO, and Double Chooz in 2012

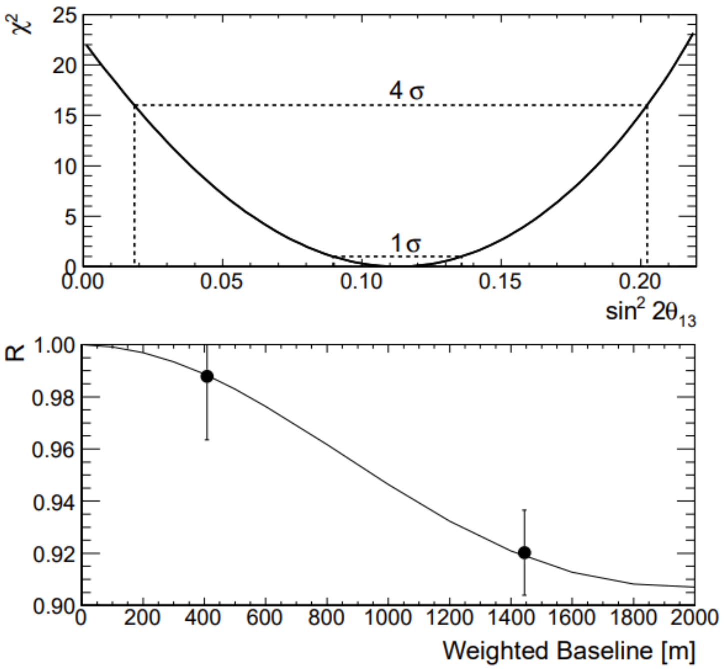


- We see a deficit through the near-far ratio: 0.94+/-0.011(stat) +/-0.004(syst) at the far site
- $\sin^2 2\theta_{13}=0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
- A 5-sigma discovery!

Daya Bay *Phys.Rev.Lett.* 108 (2012) 171803

0.113 ± 0.013(stat.) ± 0.019(syst.)

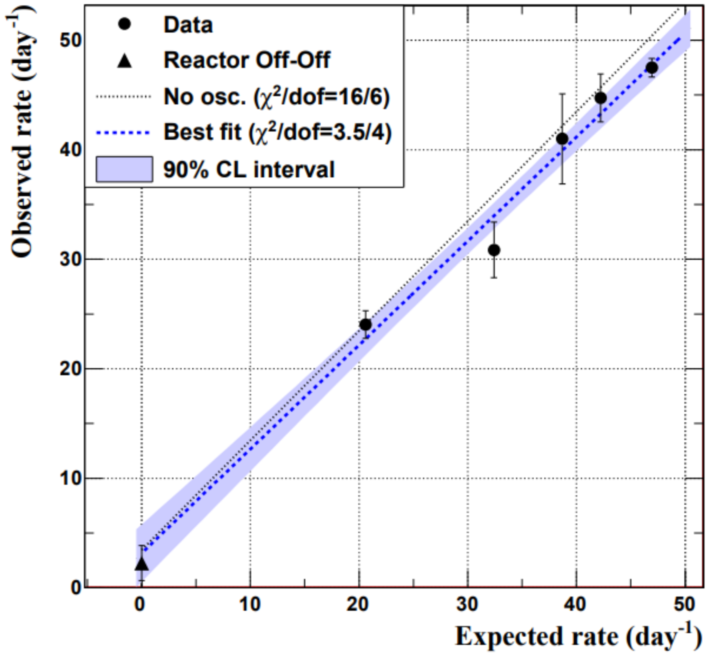
April 2012, 4.9σ



RENO *Phys.Rev.Lett.* 108 (2012) 191802

0.086 ± 0.041(stat.) ± 0.030(syst.)

Nov. 2011, 94.6% C.L.



Double Chooz far detector

Phys.Rev.Lett. 108 (2012) 131801

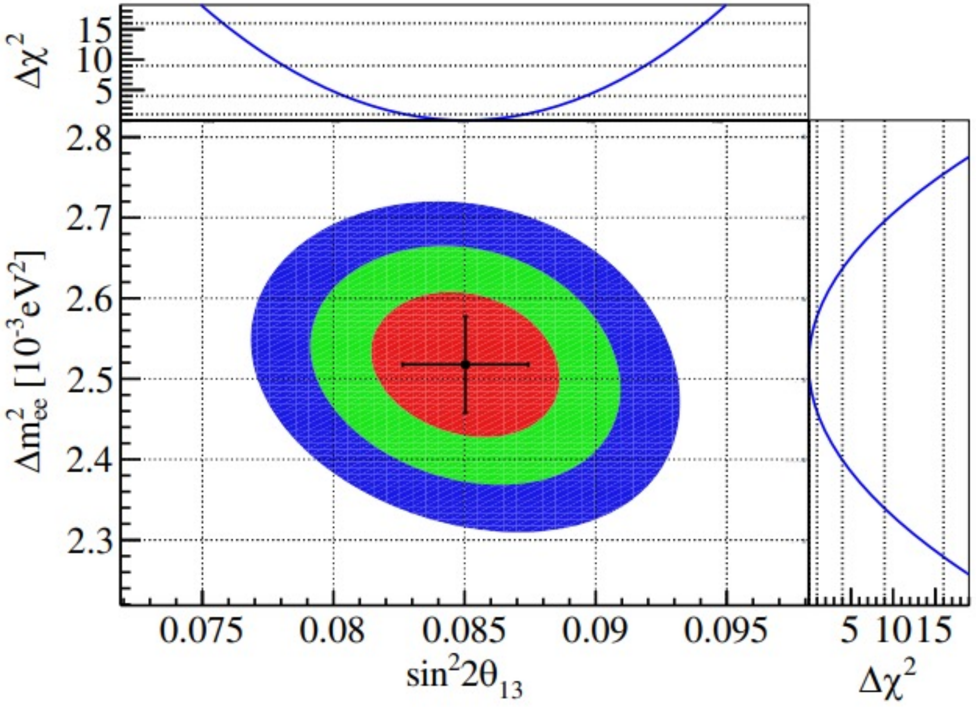
The Daya Bay Measurement with the Full Data Set (Neutrino 2024)

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

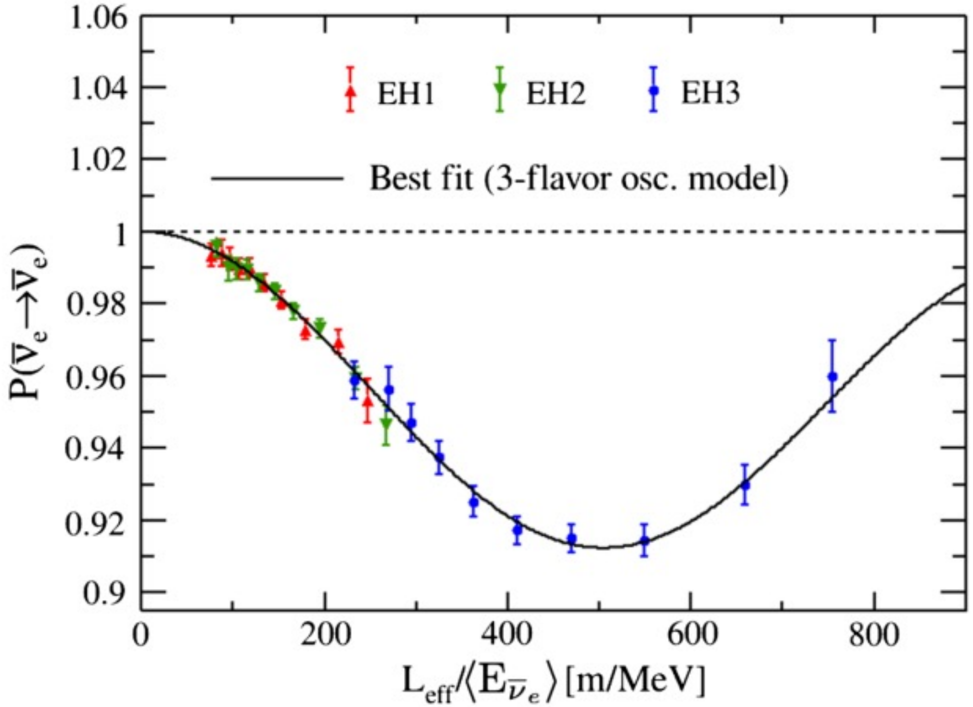
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$ precision 2.8%

$\Delta m^2_{32} = 2.466 \pm 0.060\ (-2.571 \pm 0.060) \times 10^{-3}\ \mathrm{eV}^2$ precision 2.4%

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



PhysRevLett. 130 161802



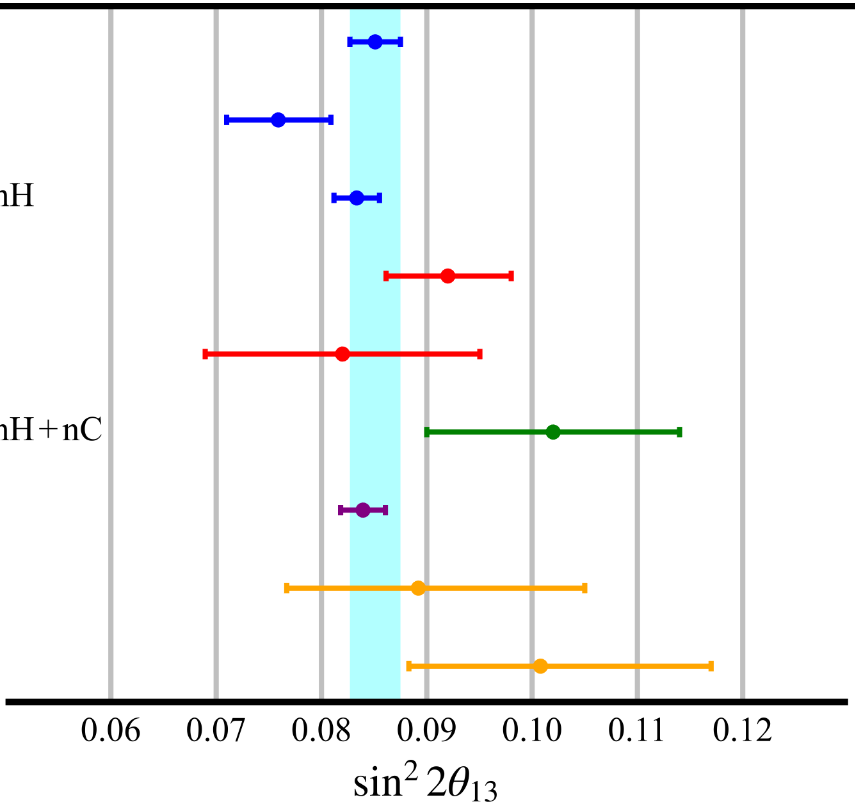
Global comparison θ_{13}

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



Experiment		Value	
Daya Bay	**nGd**	**0.0851 ± 0.0024**	2.8%
	nH	$0.0759^{+0.0050}_{-0.0049}$	6.5%
	nGd+nH	0.0833 ± 0.0022	2.6%
RENO	nGd	$0.0920^{+0.0060}_{-0.0059}$	6.5%
	nH	0.082 ± 0.013	15.9%
Double Chooz	nGd+nH+nC	0.102 ± 0.012	11.8%
Reactor Average		0.0839 ± 0.0021	2.5%
T2K + NOνA	NO	$0.0892^{+0.0158}_{-0.0125}$	15.9%
	IO	$0.1008^{+0.0162}_{-0.0125}$	14.2%

Figure by Hongzhao Yu

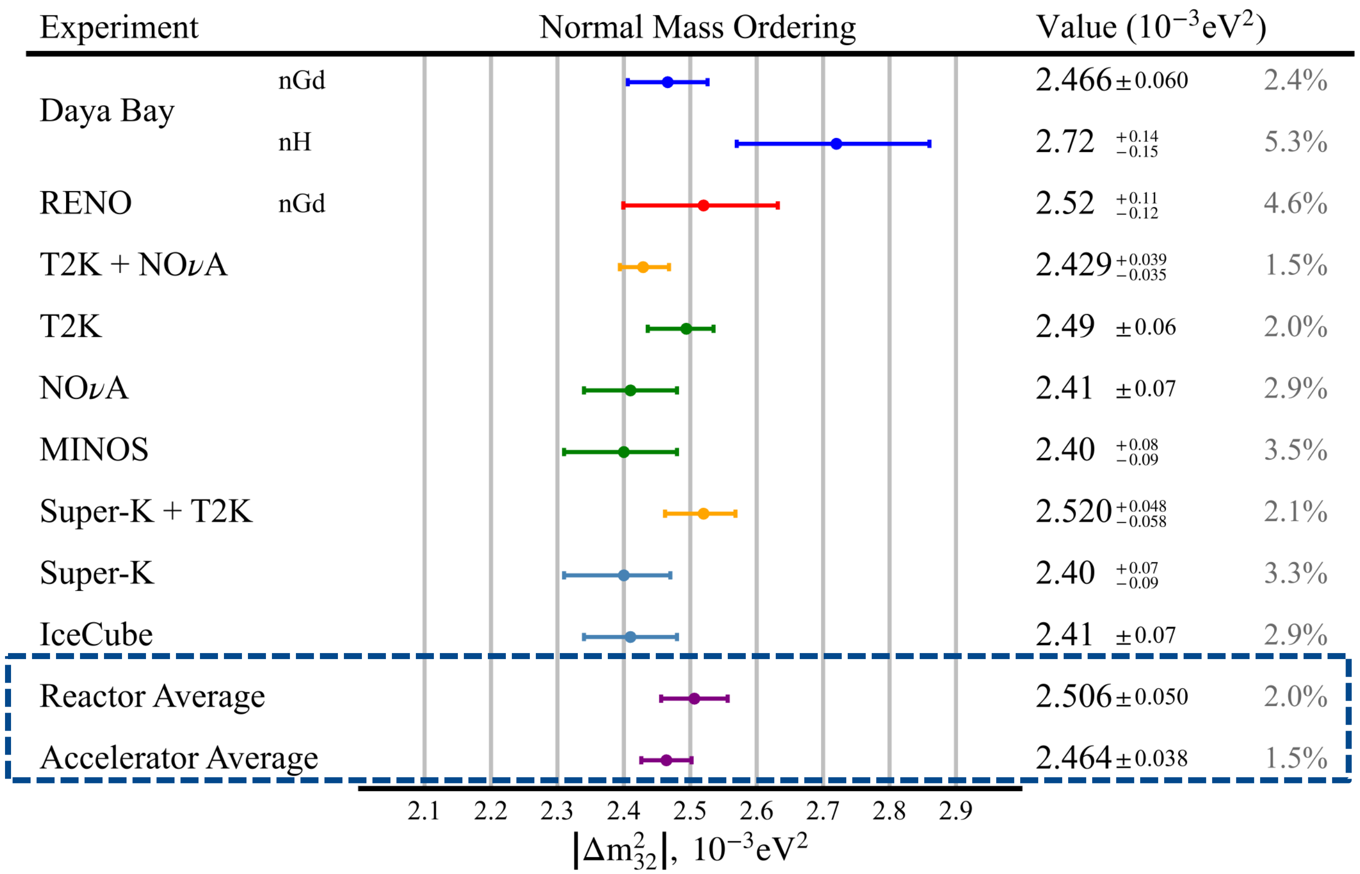
Global comparison Δm^2

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

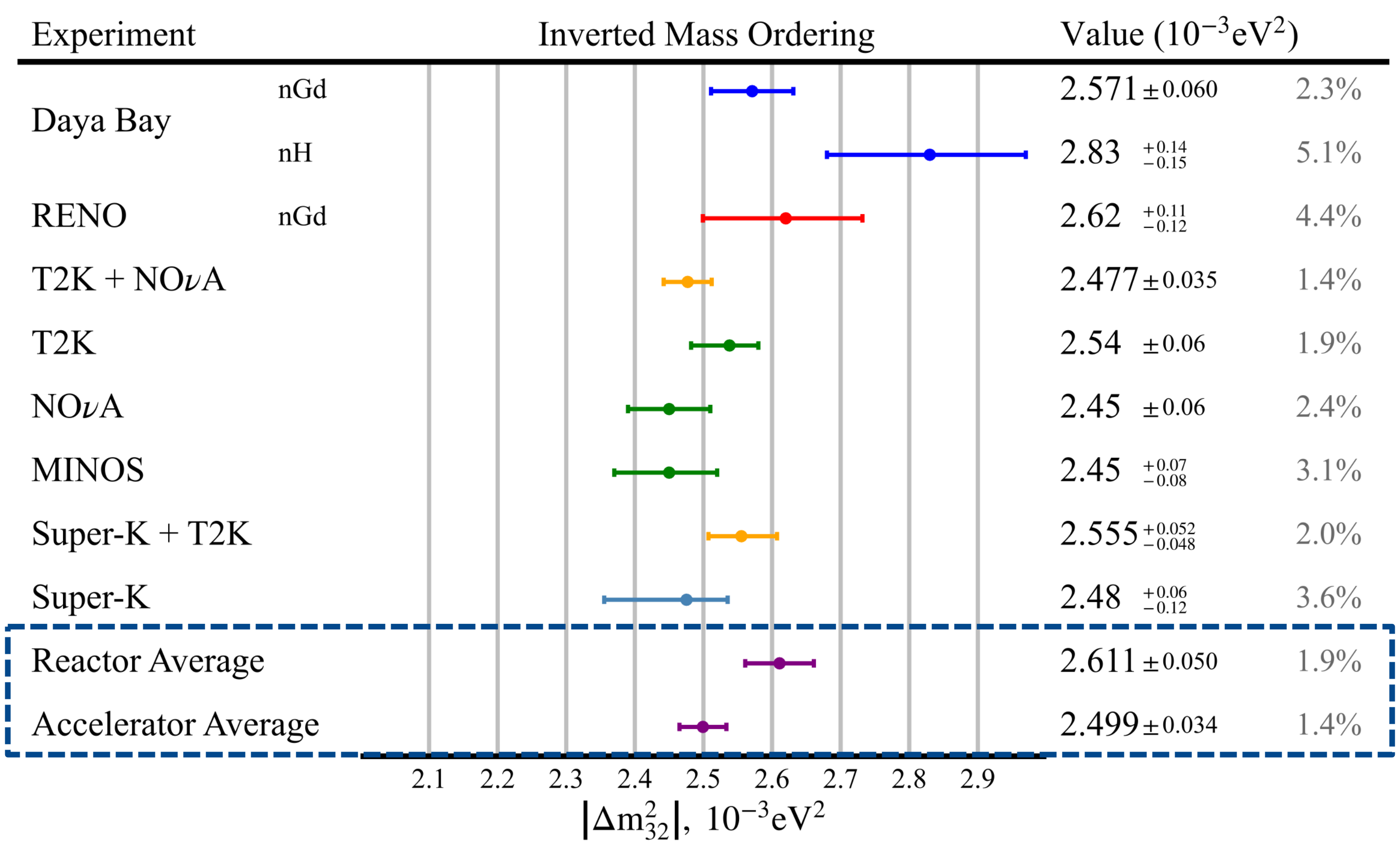
Note: average is error weighted average assuming no correlation



Global comparison Δm^2

Consistent results from reactor and accelerator experiments

Normal Ordering slightly preferred (<2σ) from reactor/accelerator averages



Note: average is error weighted average assuming no correlation

The Neutrino Decades (1996-2016) Rewarded

LAUREATES

Breakthrough Prize | Special Breakthrough Prize | New Horizons Prize | Physics Frontiers Prize

2016 | 2015 | 2014 | 2013 | 2012


Kam-Biu Luk and the Daya Bay Collaboration


Yifang Wang and the Daya Bay Collaboration


Koichiro Nishikawa and the K2K and T2K Collaboration


Atsuto Suzuki and the KamLAND Collaboration


Arthur B. McDonald and the SNO Collaboration


Takaaki Kajita and the Super K Collaboration

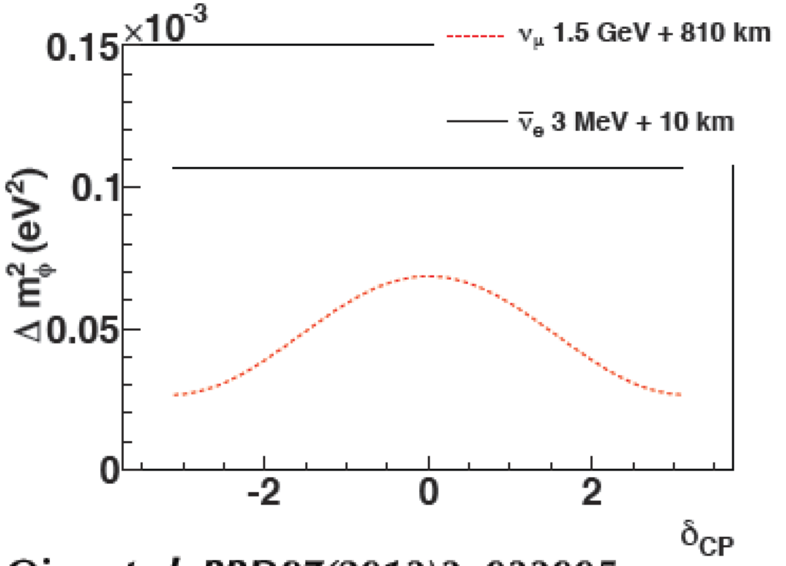

Yoichiro Suzuki and the Super K Collaboration

e- / μ-Flavor Feels Mass Ordering Differently

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

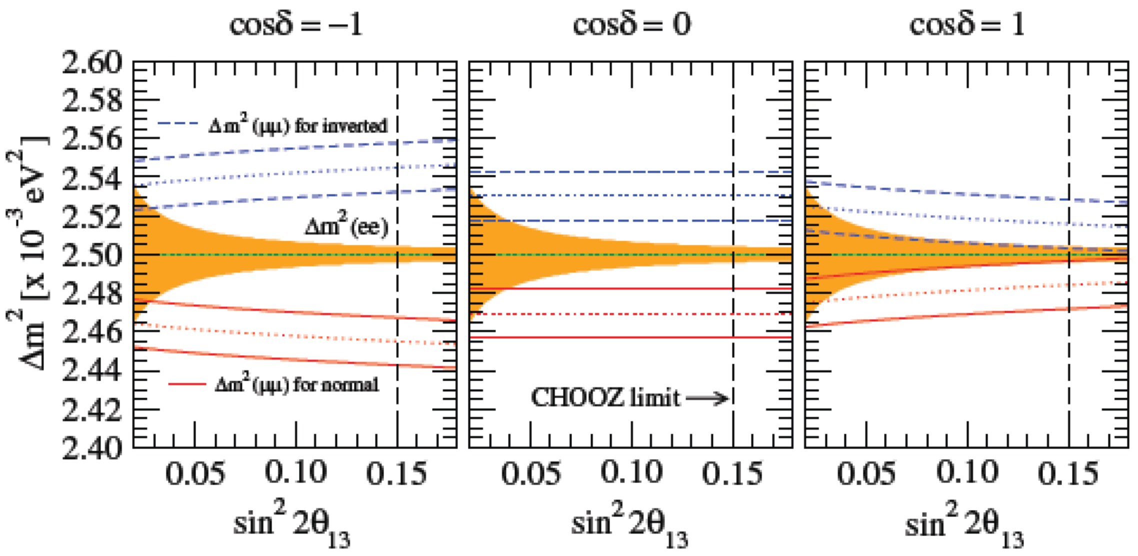
$$P_{\nu_\mu \to \nu_\mu} = 1 - P_{21}^{\mu} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m_{32}^2 \pm \phi)L}{4E}$$

- *Both reactor and long-baseline experiment measure mass-squared splitting*
- *A natural question to ask: Is this meaningful?*



Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



Minakata et al PRD74(2006), 053008

Also See: Zhang&Ma, arXiv:1310.4443/ Mod. Phys. Lett. A29 (2014) 1450096

Global Efforts Resolving ν Mass Hierarchy

Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Super-K, Hyper-K, IceCube PINGU, ICAL/INO, ORCA, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO + Atm/Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, IceCube PINGU, ORCA, DUNE, JUNO	
Interplay of Measurements				Cosmo. Data, KATRIN, Proj-8, 0νββ

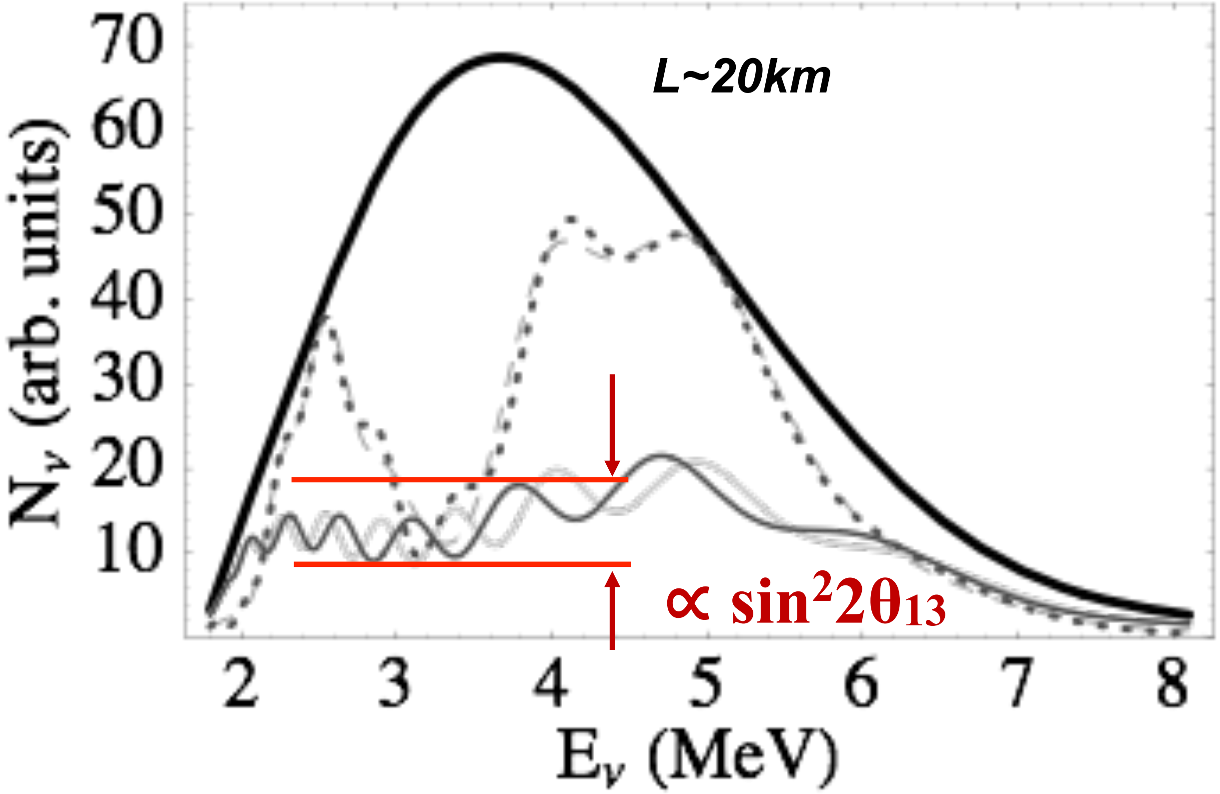
Known θ13 Enables Neutrino Mass Hierarchy at Reactors

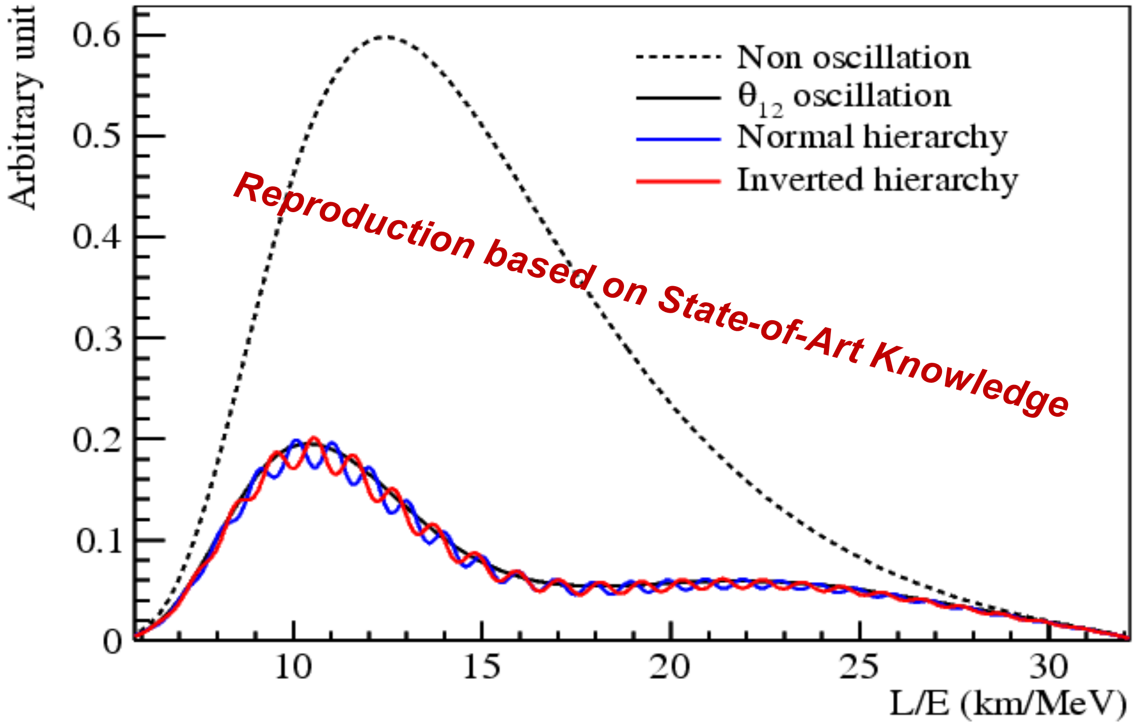
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

Petcov&Piai, Phys. Lett. B533 (2002) 94-106

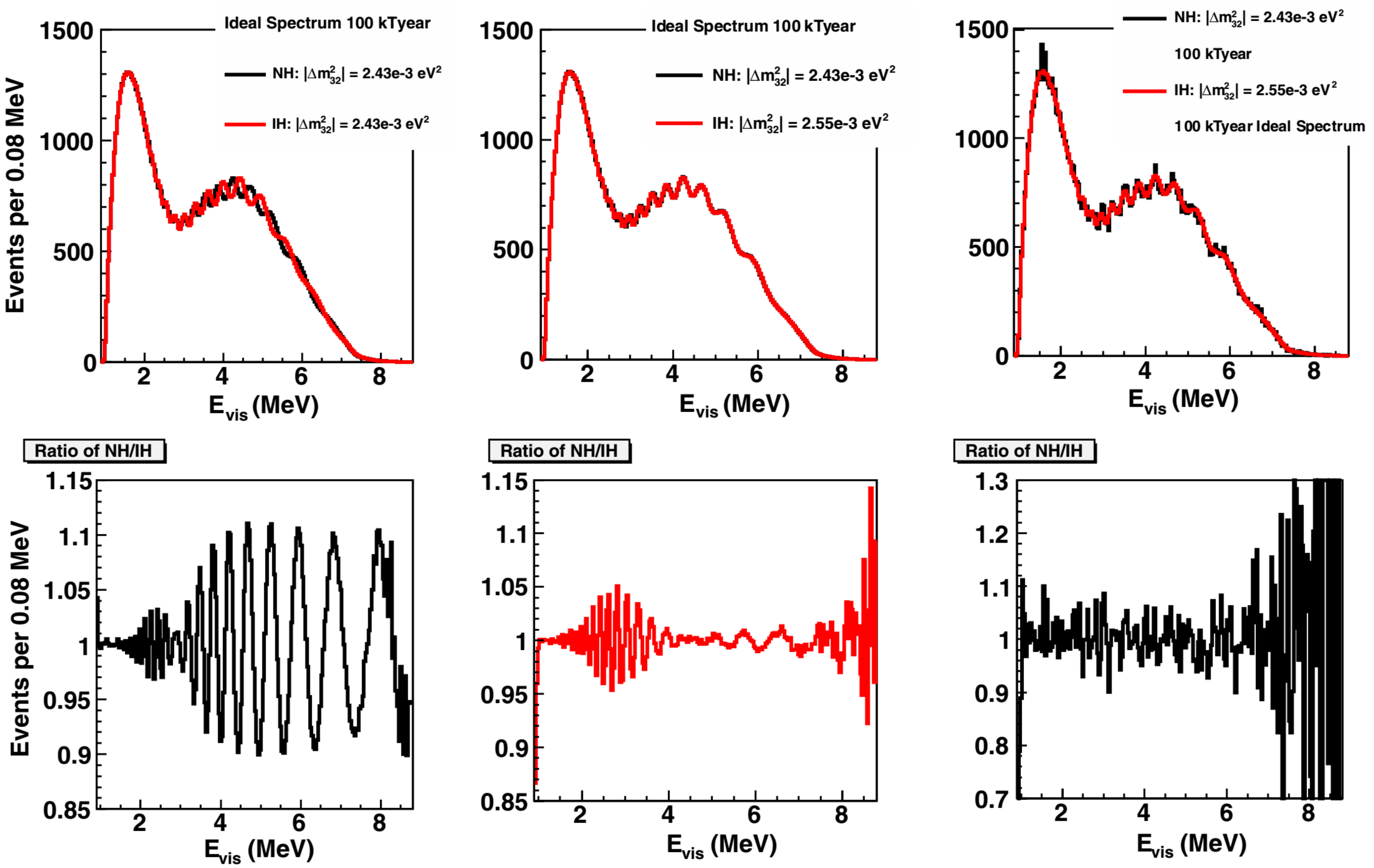
√ Mass hierarchy reflected in the spectrum

√ Independent of the unknown CP phase



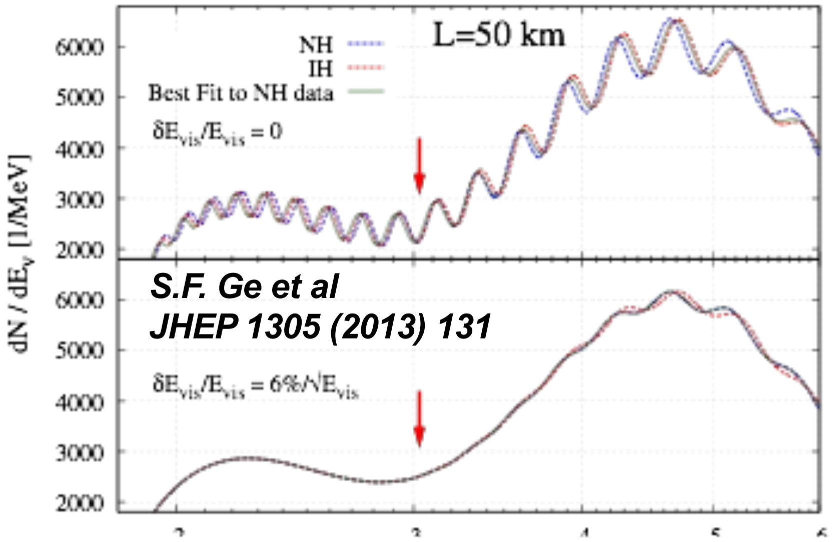


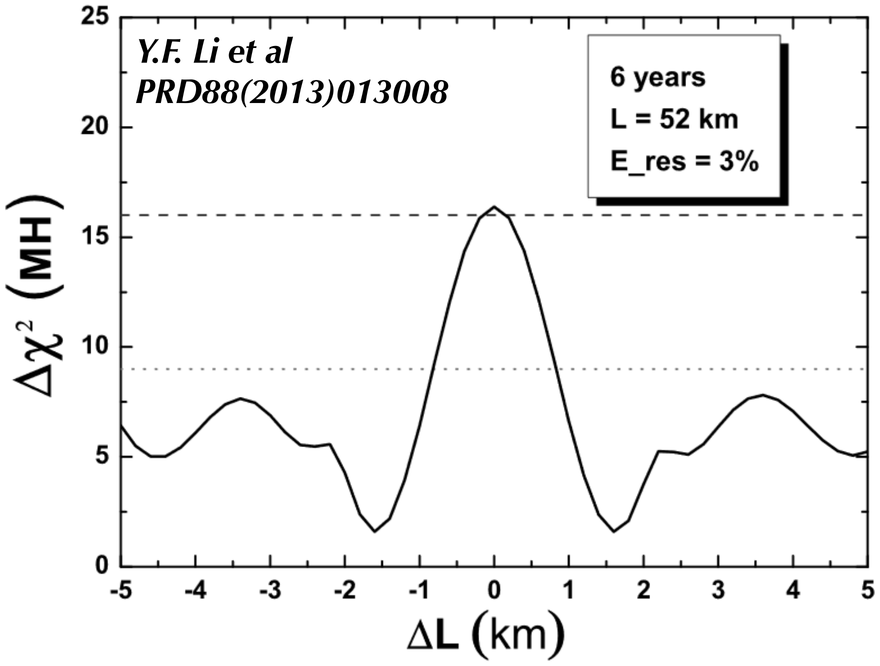
Challenges in Resolving MH using Reactor Sources

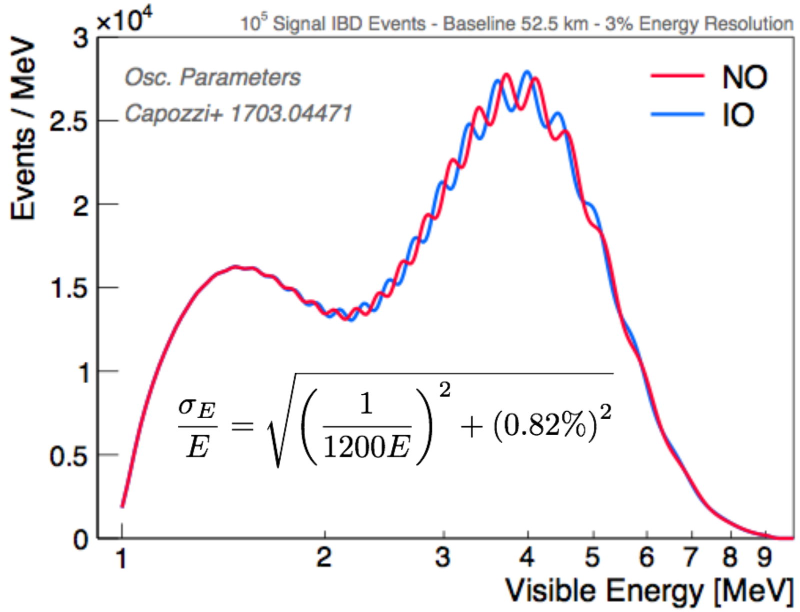


Challenges in Resolving MH using Reactors

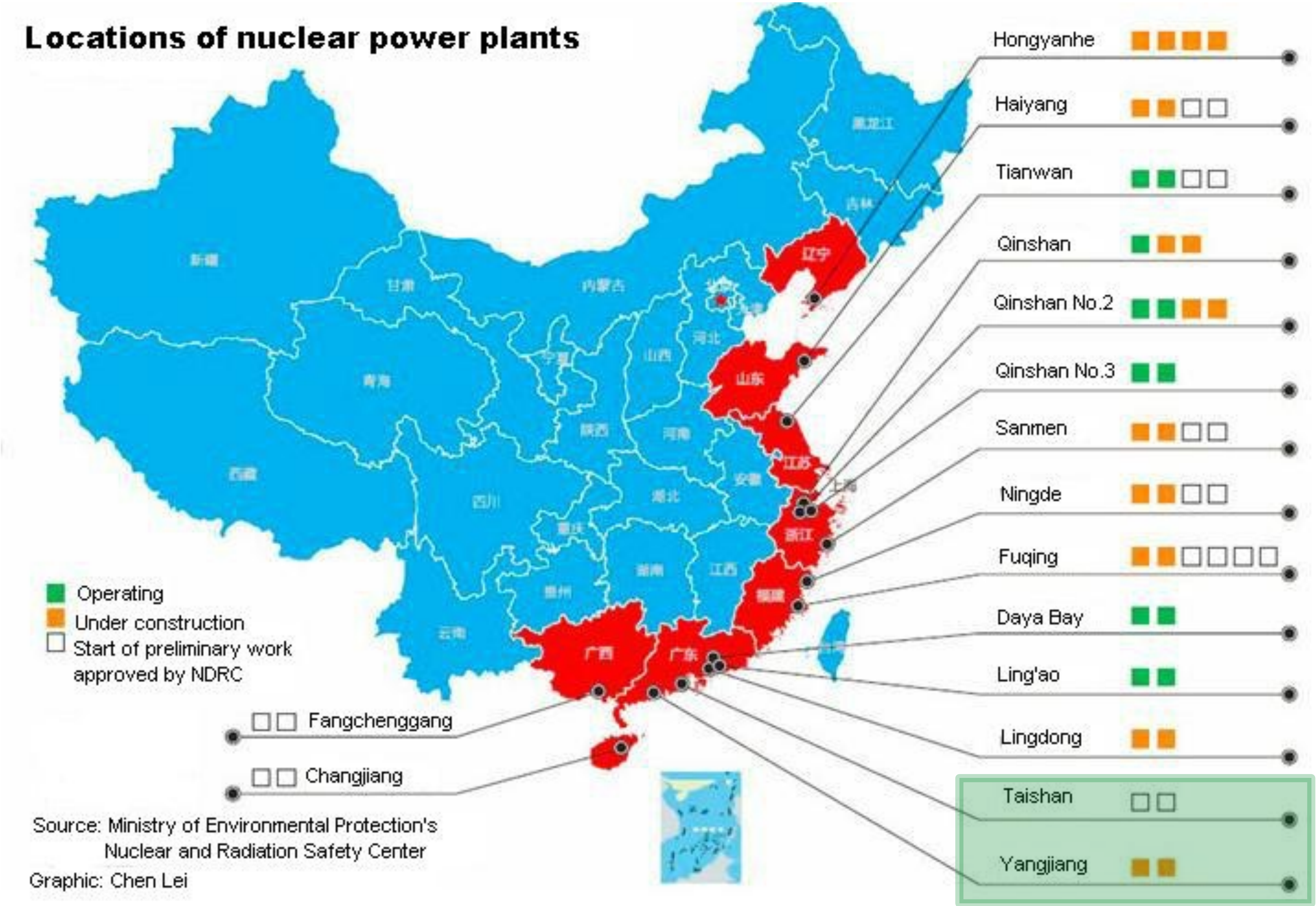
- Energy resolution: ~3%/sqrt(E)
- Energy scale uncertainty: <1%
- Statistics (the more the better)
- Reactor distribution: <~0.5km





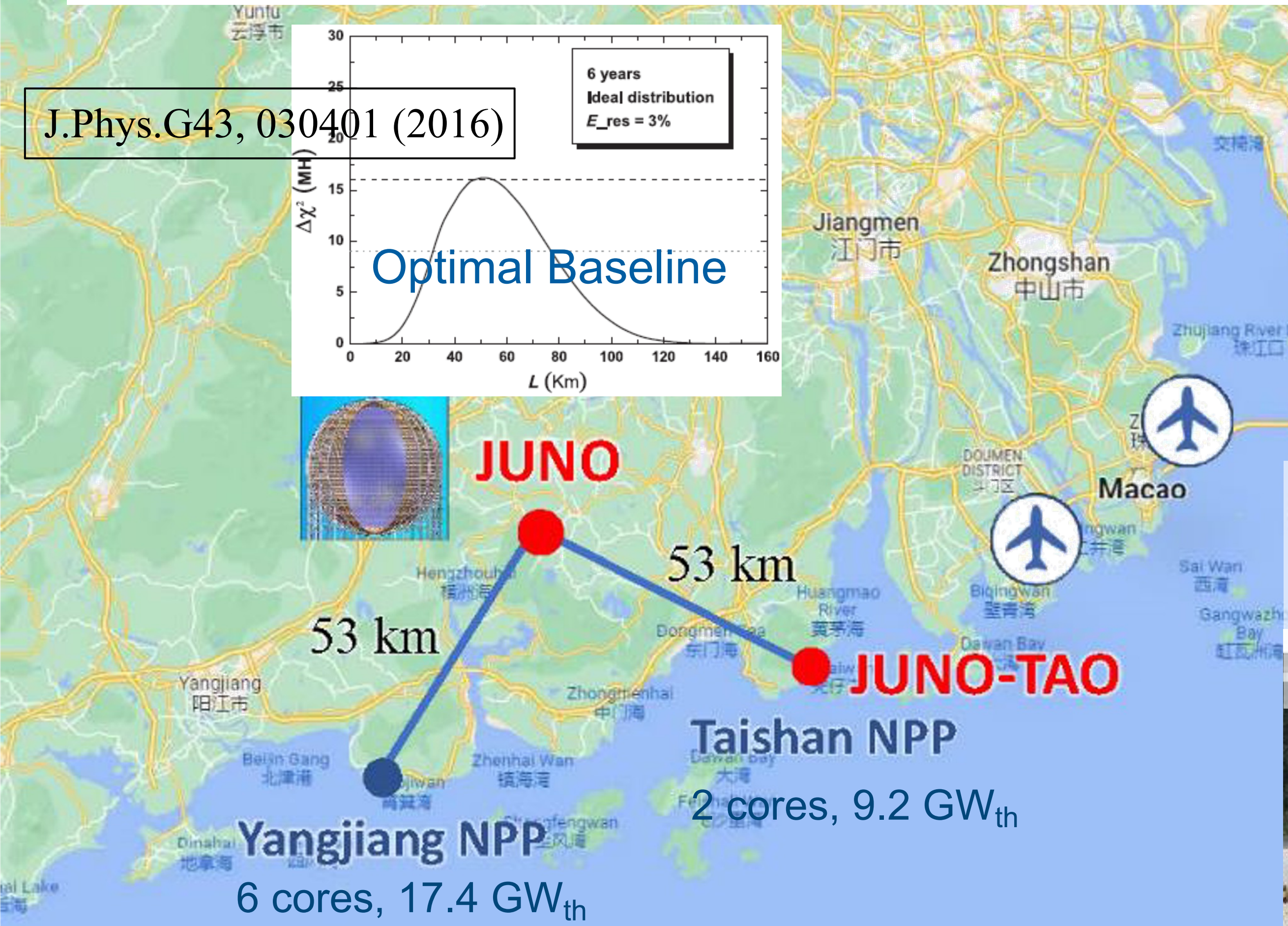


Looking for Suitable Power Plants is Easy?



Jiangmen Underground Neutrino Observatory (JUNO)

- Proposed as a reactor neutrino experiment for **mass ordering in 2008** (PRD78:111103,2008; PRD79:073007,2009)
  - ⇨ driving the design specifications: location, 20 kton LS, 3% energy resolution, 700 m underground
- Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches
- Approved in 2013. Construction in 2015-2024

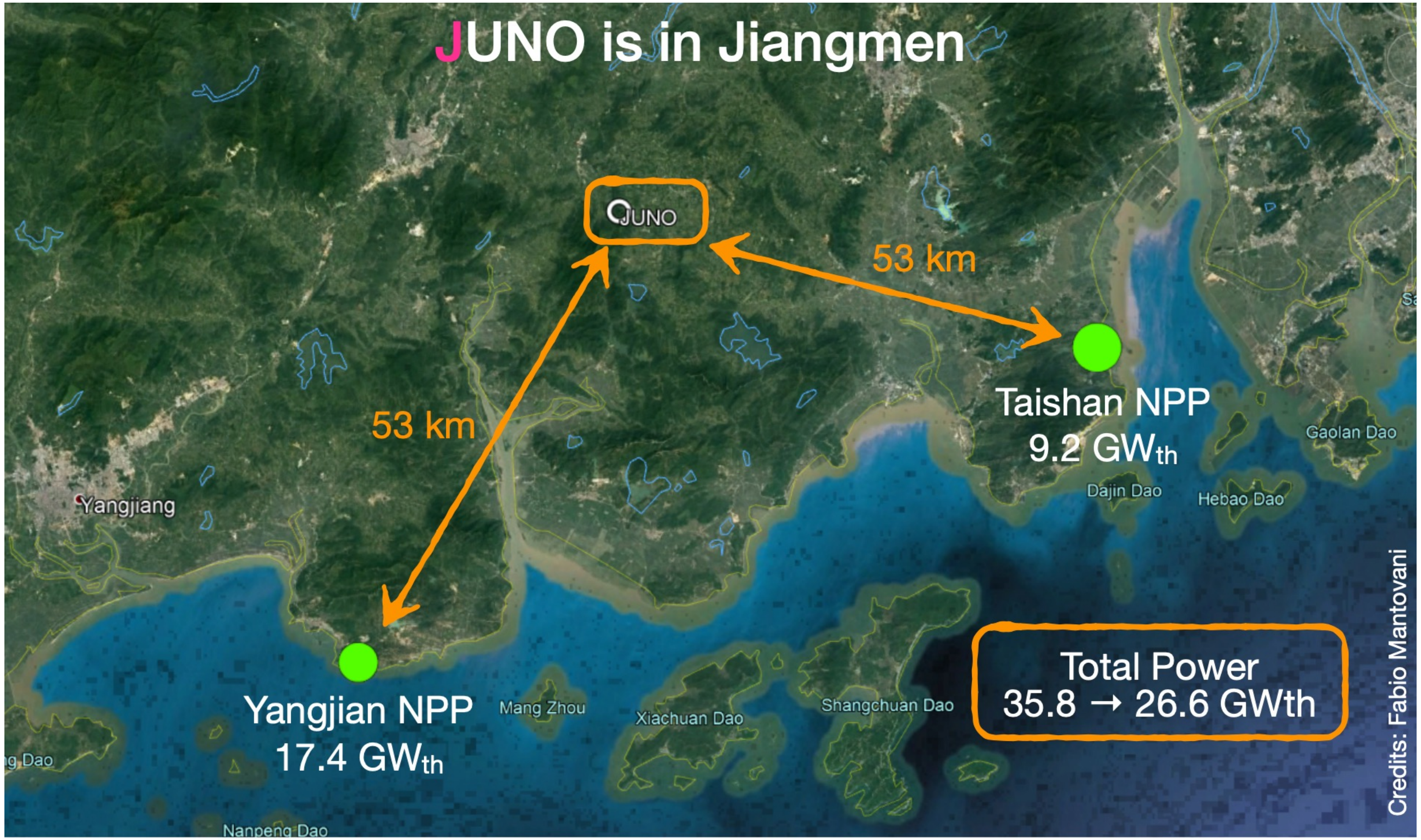


J.Phys.G43, 030401 (2016)

74 institutions, >700 collaborators

Asia: China (34), Taiwan,China (3) Thailand (3), Pakistan, Armenia
Europe: Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Latvia, Slovakia, UK
America: Brazil (2), Chile (2), USA (2)

The Jiangmen Underground Neutrino Observatory



Taishan Power Plant

Yangjiang Power Plant

Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

Only 8 Reactors Left.....

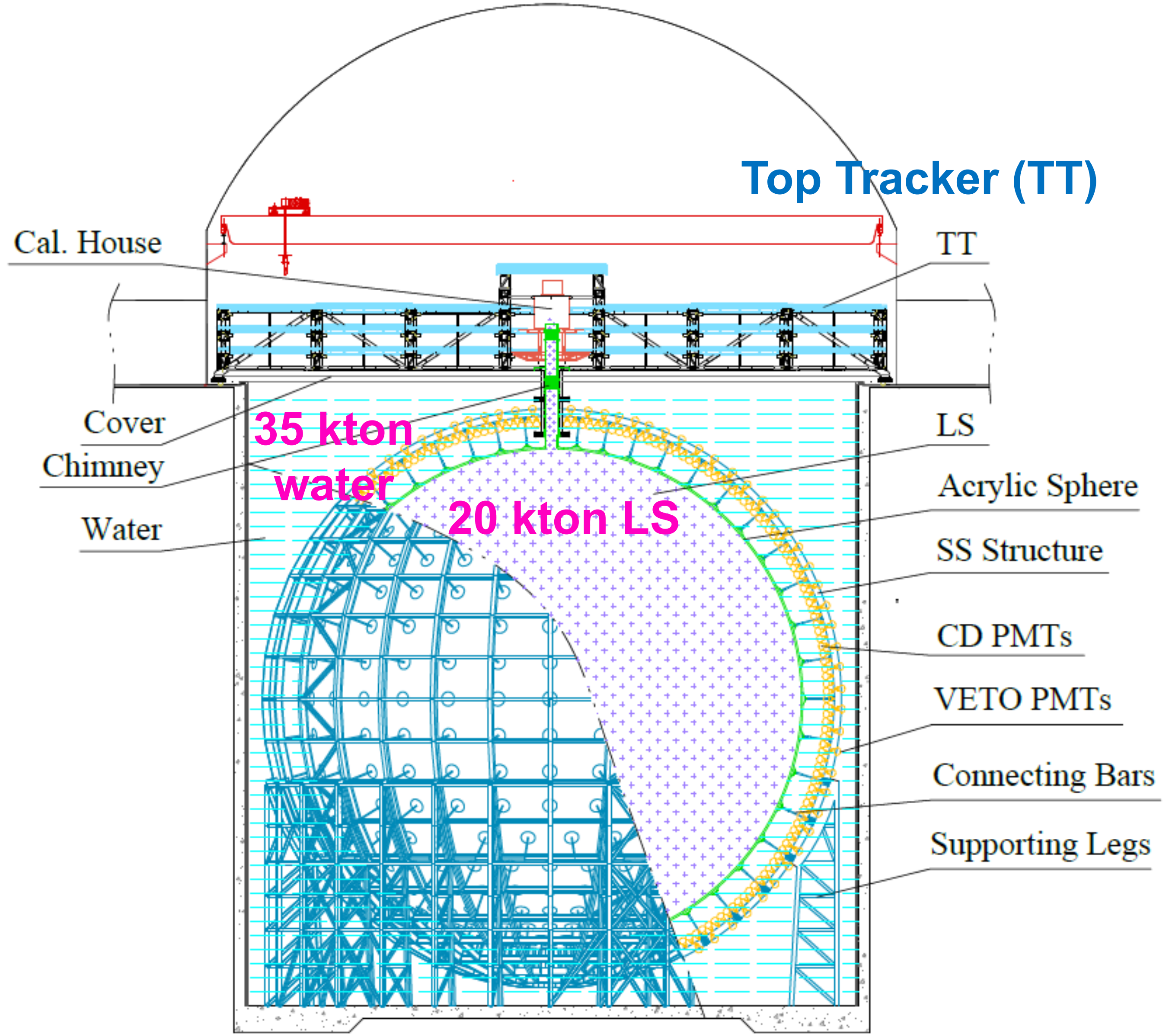
JUNO Site

Surface buildings / campus

- **Office / Dorm**
- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Computing
- Power station
- Cable train

~200 people working onsite now

JUNO Detector



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

$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

Energy leakage & non-uniformity (a); Photon statistics (b); Noise (~background) (c)

The Detector Performance Goals

	KamLAND	Daya Bay	PROSPECT	JUNO
Target Mass	**~1kt**	20t	~4t	**~20kt**
Photocathode Coverage	~34%	~12% (Effective)	ESR + PMTs	**~80%**
PE Collection	~250 PE/MeV	~160 PE/MeV	**~850 PE/MeV**	**~1200 PE/MeV**
Energy Resolution	~6%/√E	~7.5%/√E	**~4.5%/√E**	**3%/√E**
Energy Calibration	~2%	**1.5%→ 0.5%**	~1%	**<1%**

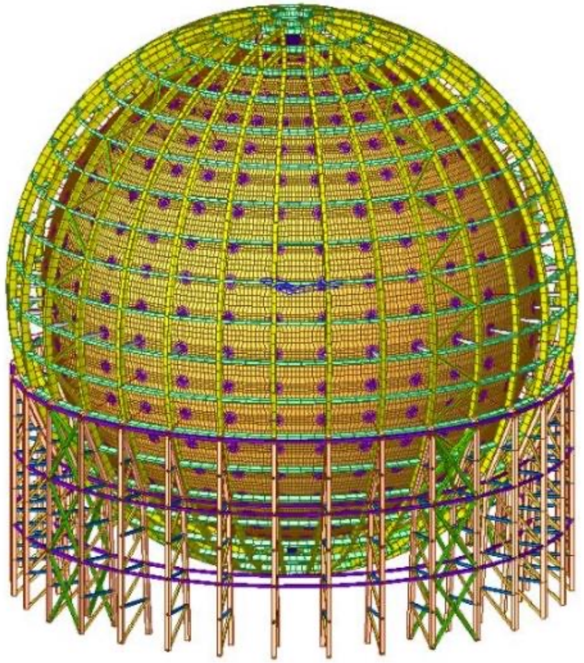
An extremely demanding detector and a challenging job

JUNO Detector

Central Detector

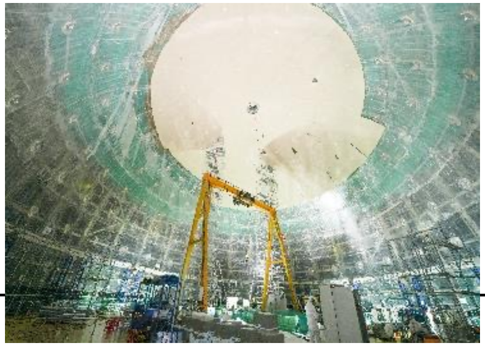
arXiv: 2311.17314 (2023)

- **35.4 m spherical acrylic vessel, containing 20 kton LS, supported by the 41.1 m Stainless Steel structure via 590 supporting bars**
- **SS structure completed except bottom 4 layers**
- **Acrylic panel production completed**
  - ⇨ A special production line for low backgrounds (< 1 ppt U/Th/K)
  - ⇨ Processed while maintaining **high transparency** (>96%) and **low surface background** (<5 ppt U/Th in 50 μm thickness): Shaping, sanding/polishing, cleaning, machining, and protection of panels by PE film
- **Acrylic vessel construction on-going (critical path)**
  - ⇨ SS structure built from bottom to top, then, acrylic built from the top to bottom, layer by layer, **17/23 layers finished**, defects repaired
  - ⇨ SS bars connecting the acrylic and SS, sensors for stress monitoring







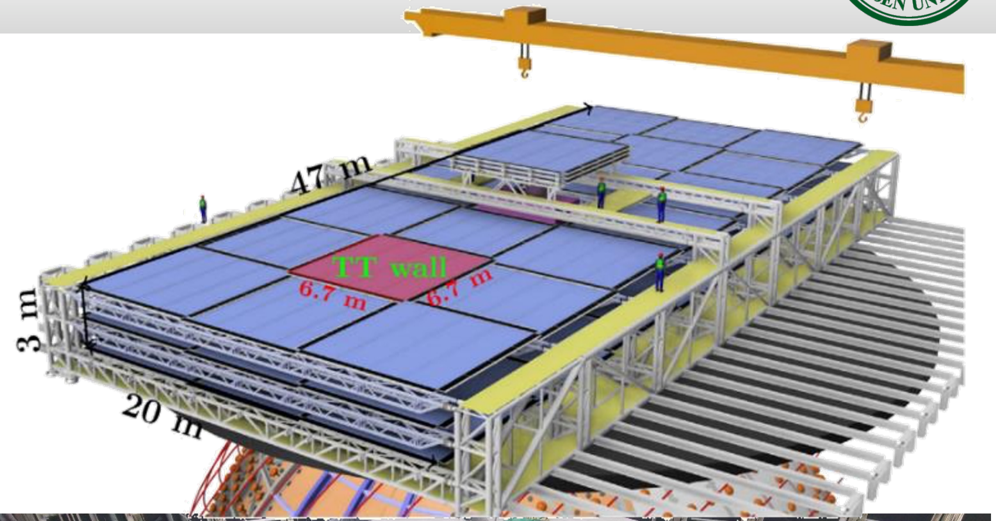


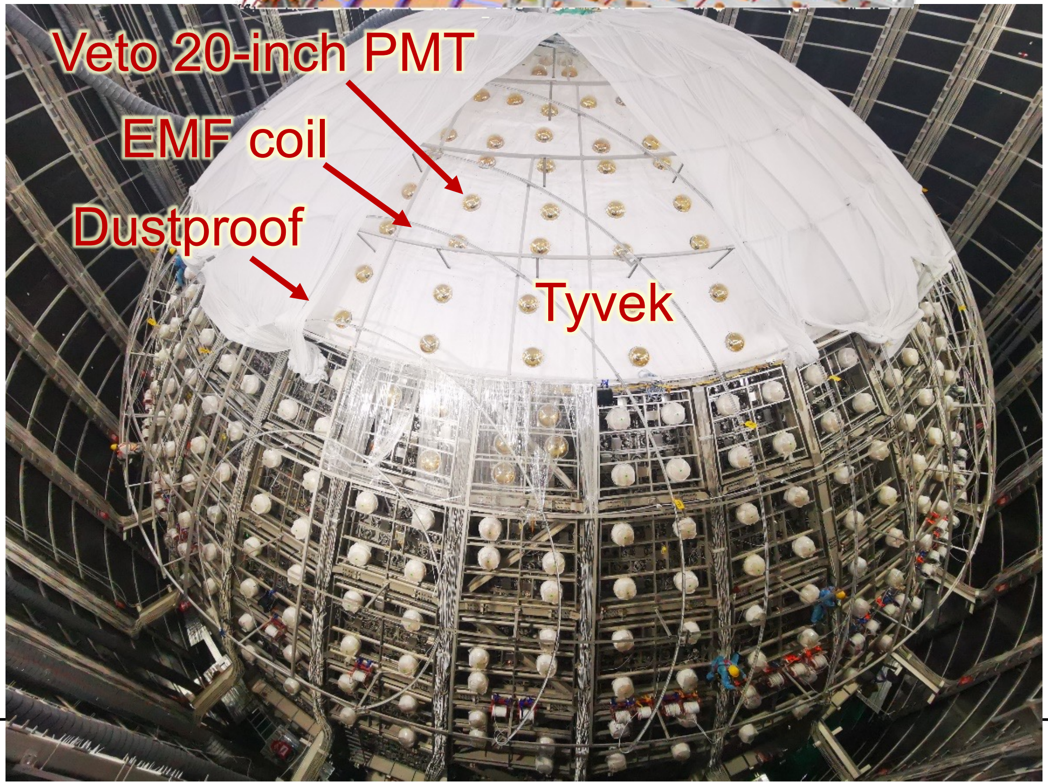
Inside the detector

Veto Detectors

- ◆ **Water Cherenkov + Top tracker**
- ◆ **Water Cherenkov detector**
  - ➪ 35 kton water to shield backgrounds from the rock
  - ➪ Instrumented w/ 2400 20-inch PMTs on SS structure
  - ➪ Water pool lining: 5 mm HDPE (black) to keep the clean water and to stop Rn from the rock, will cover w/ tyvek
  - ➪ 100 ton/h pure water system installed. Requirement: U/Th/K<10^{-14} g/g and Rn<10 mBq/m^3, attenuation length>40 m, temperature controlled to (21±1) °C
- ◆ **Top tracker (to be installed)**
  - ➪ Refurbished OPERA scintillators
  - ➪ 3 layers, ~60% coverage on the top
  - ➪ $\Delta\theta \sim 0.2°$, $\Delta D \sim 20$ cm
- ◆ **Earth Magnetic Field compensation coil**

NIMA 1057 (2023) 168680

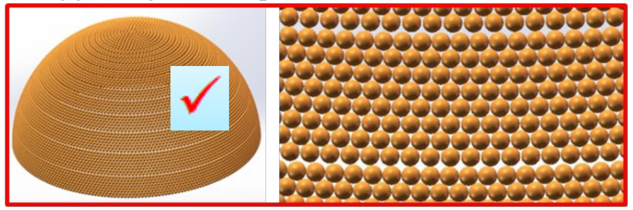




Packing PMTs as Tight as Possible

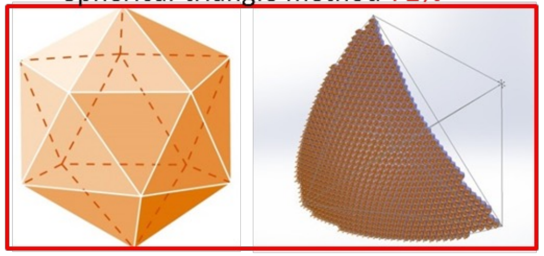
Supper layer arrangement method 77.8%

1



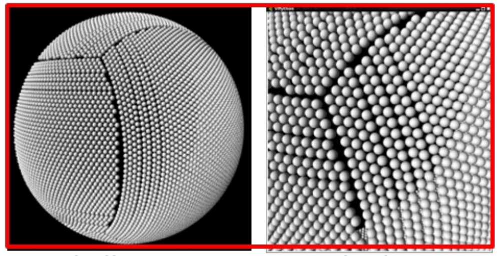
Spherical triangle method 72%

2



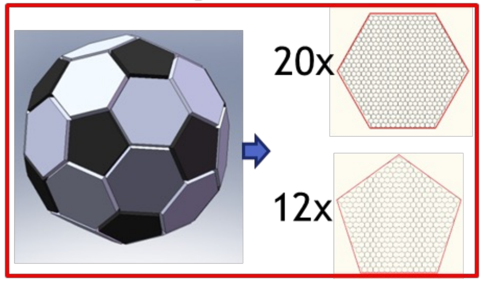
Volleyball arrangement method 75.96%

3



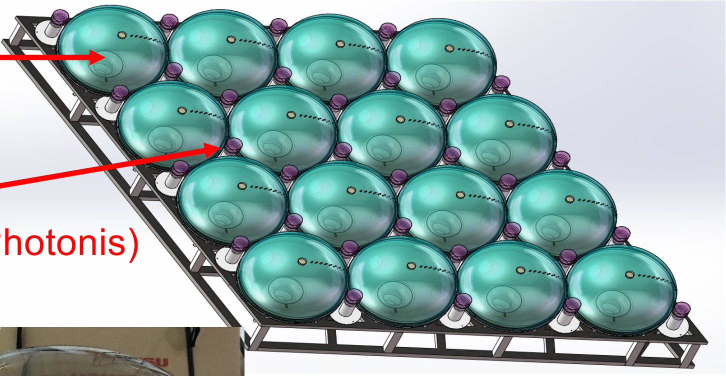
Football arrangement method 74.08%

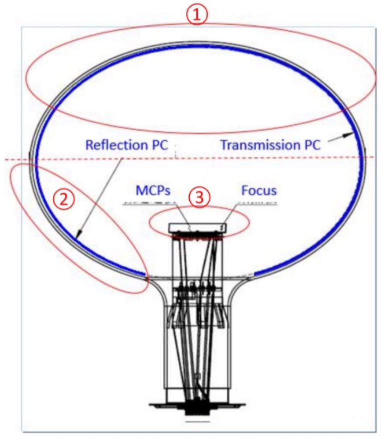
4

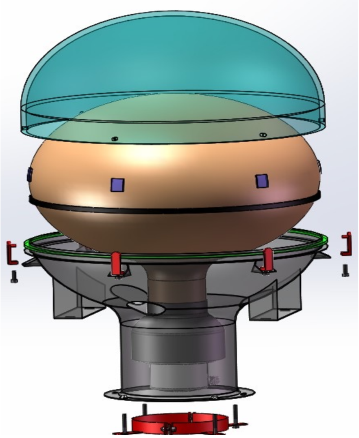


20" PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

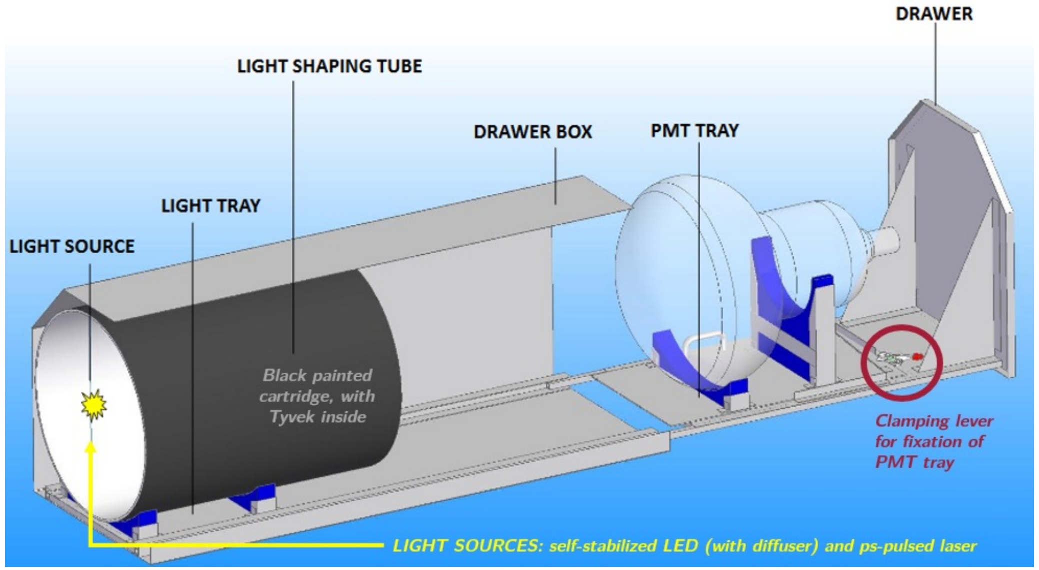
3"sPMT(~25K)
HZC XP72B22 (Photonis)

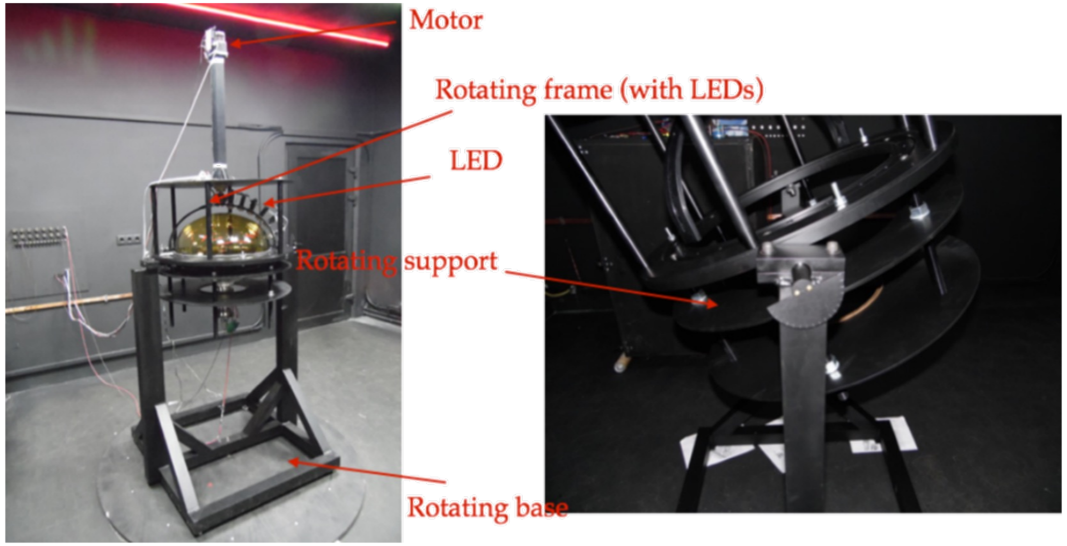


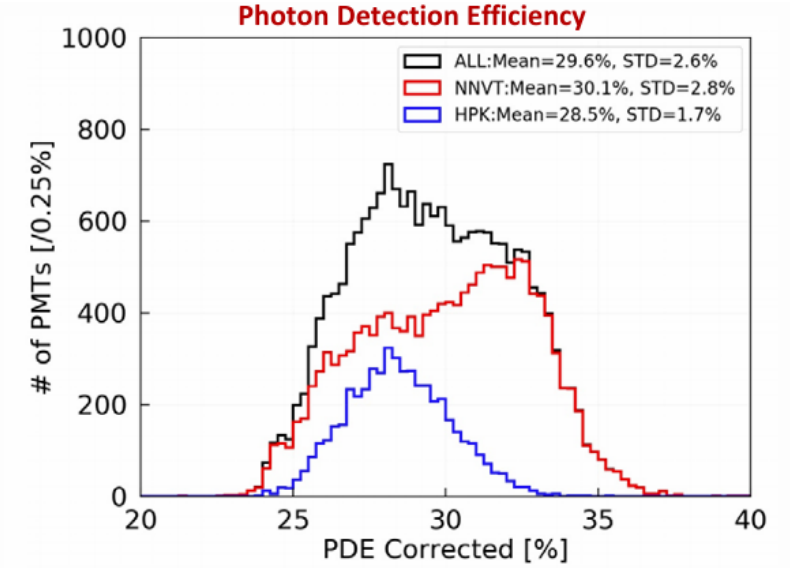


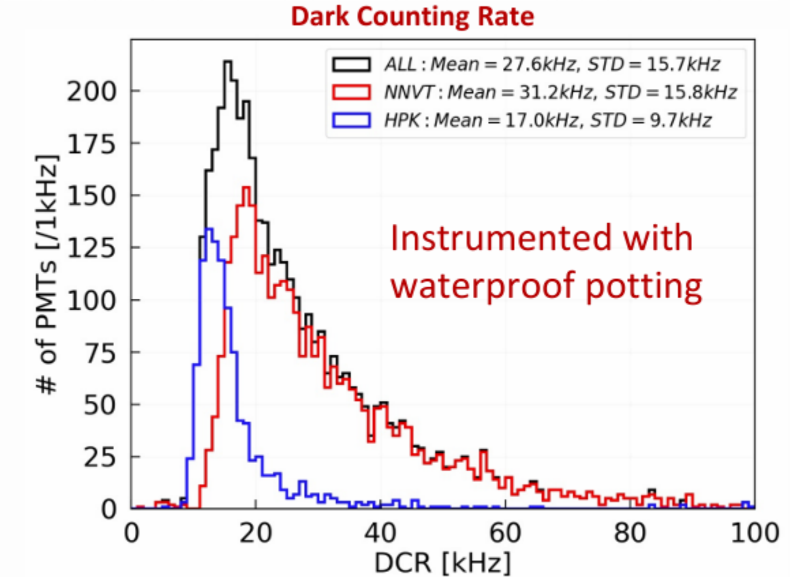


Characterizing Every Single PMT with Great Care



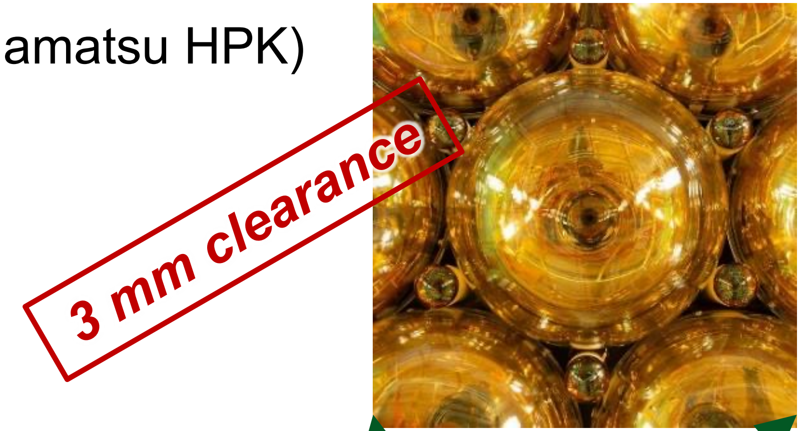




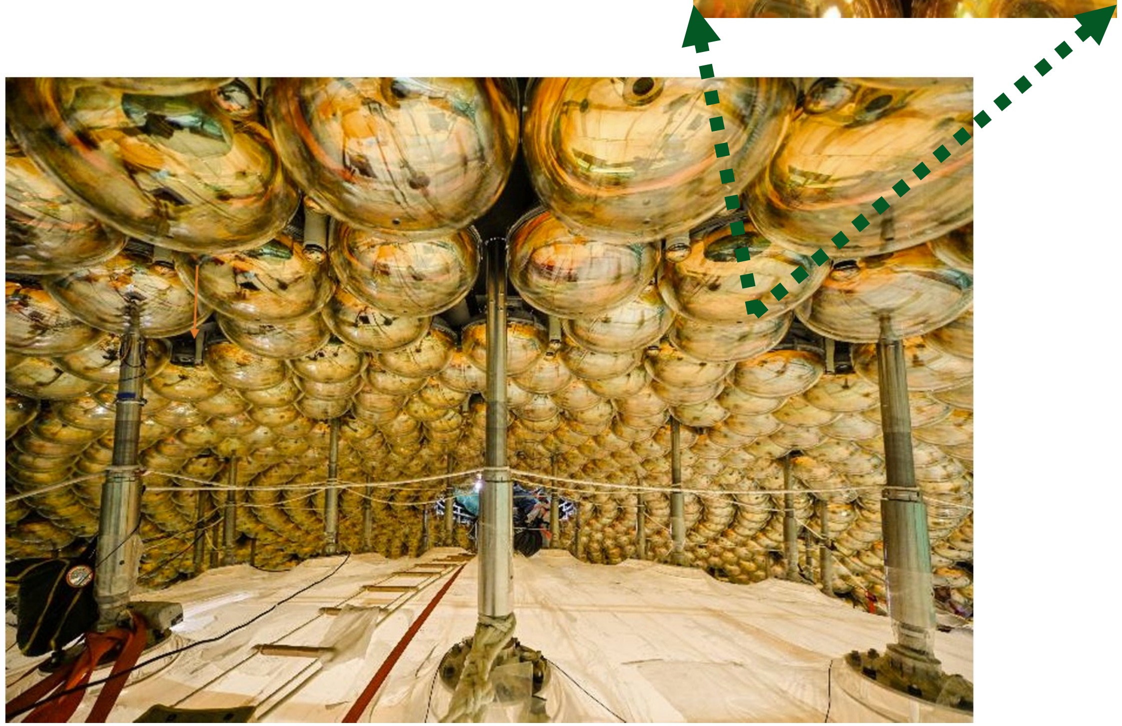


PMT Summary

- 20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu HPK)
  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

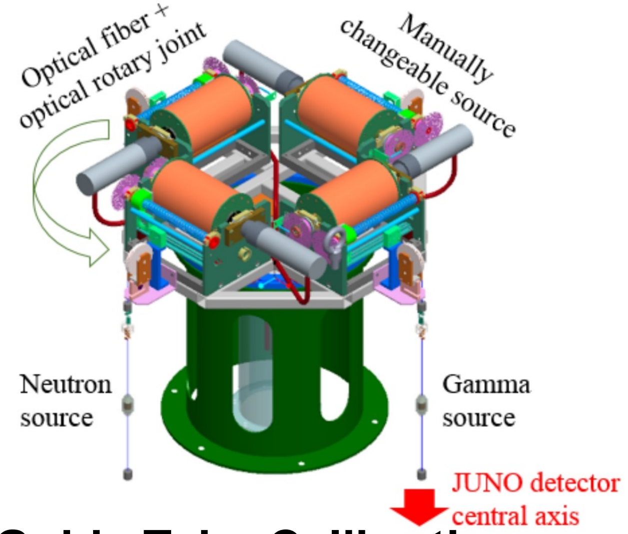


	LPMT (20-in)		SPMT (3-in)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Charge Collection	Dynode	MCP	Dynode
Photon Det. Eff.	28.5%	30.1%	25%
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

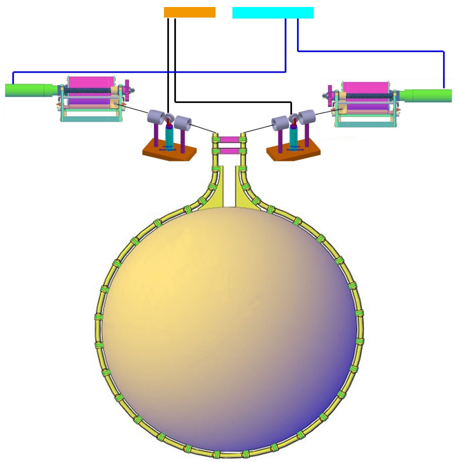


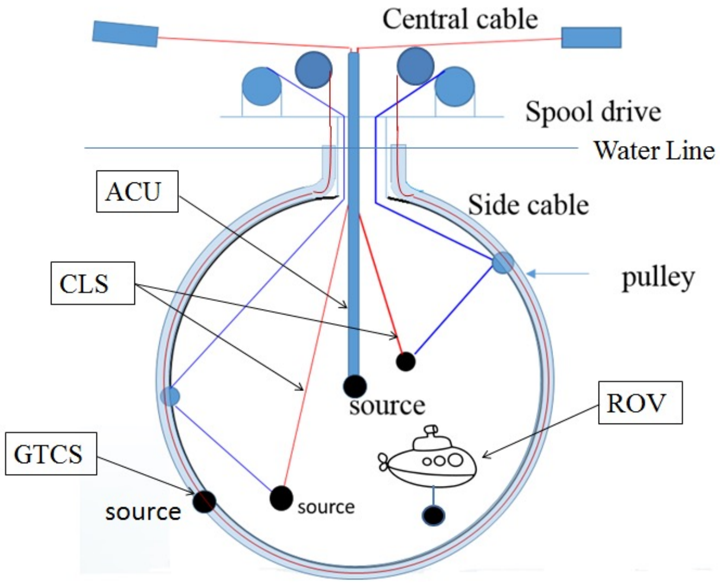
Calibration System *based on the Daya Bay experiences*

Automatic Calibration Unit (ACU)



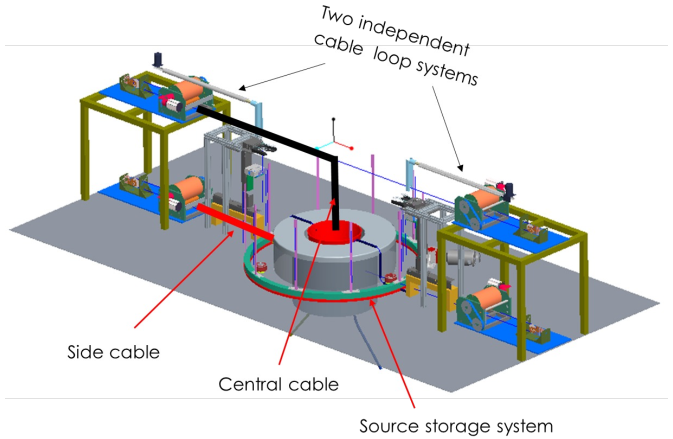
Guide Tube Calibration System(GTCS)



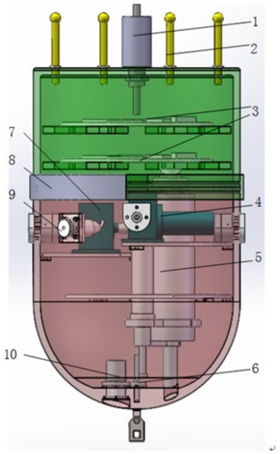


- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

Cable Loop System (CLS)



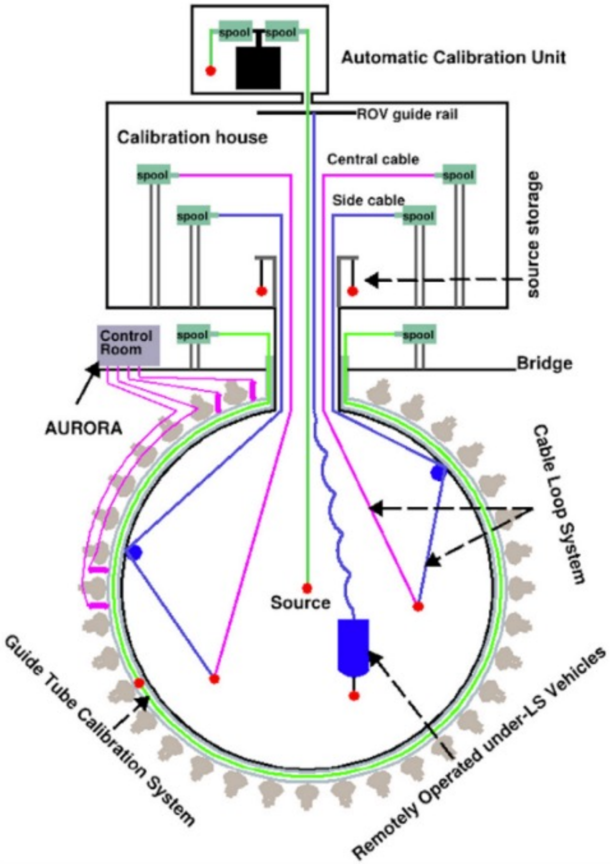
Remotely Operated under-liquid-scintillator Vehicles (ROV)



Calibration and Expected Energy Resolution

- Four systems for 1D, 2D, 3D scan with multiple sources
- Energy scale and non-linearity will be calibrated to <1% ι spectrum

JHEP 03 (2021) 004



Calibration house

All systems ready for installation

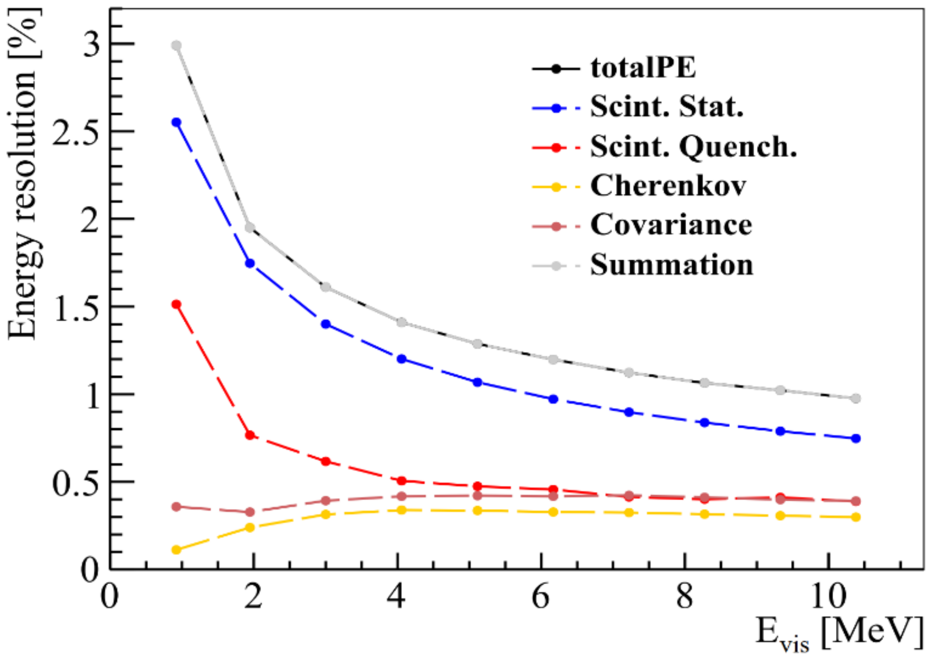
arXiv:2405.17860 (2024)

For positron

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

Photon statistics | Constant term | Dark noise, Annihilation-induced γs

Expected energy resolution: 2.95% @1MeV

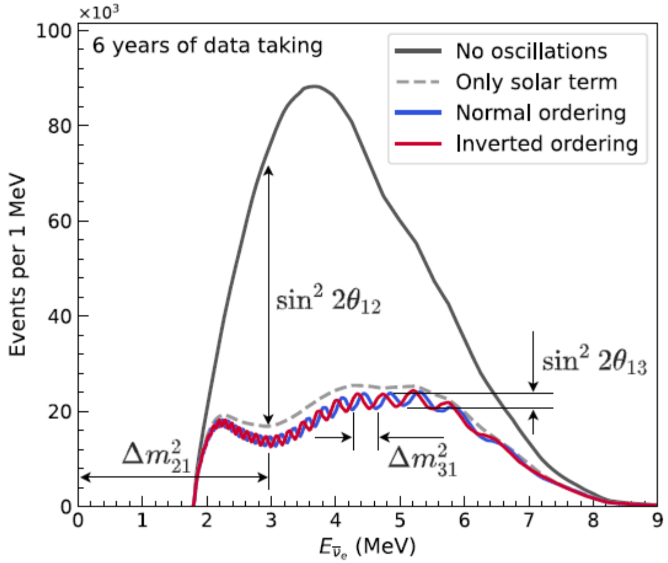


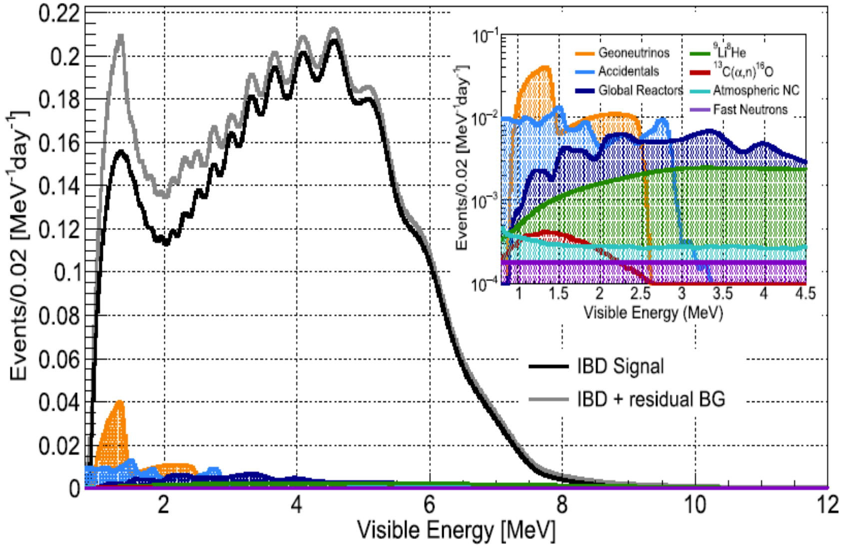
Precision Measurement of oscillation parameters

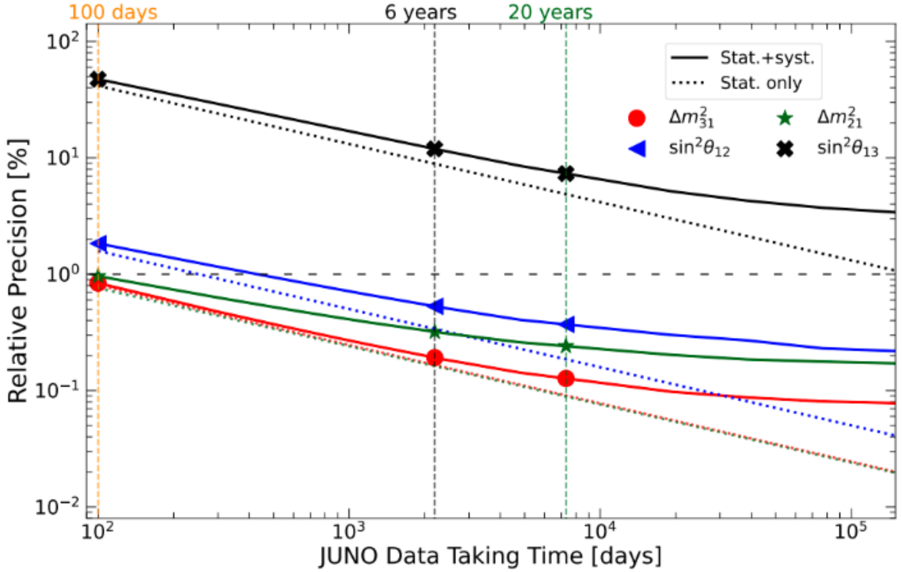
s $\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$ days; precision <0.5% in 6 years

$$- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Chin. Phys. C46 (2022) 12, 123001



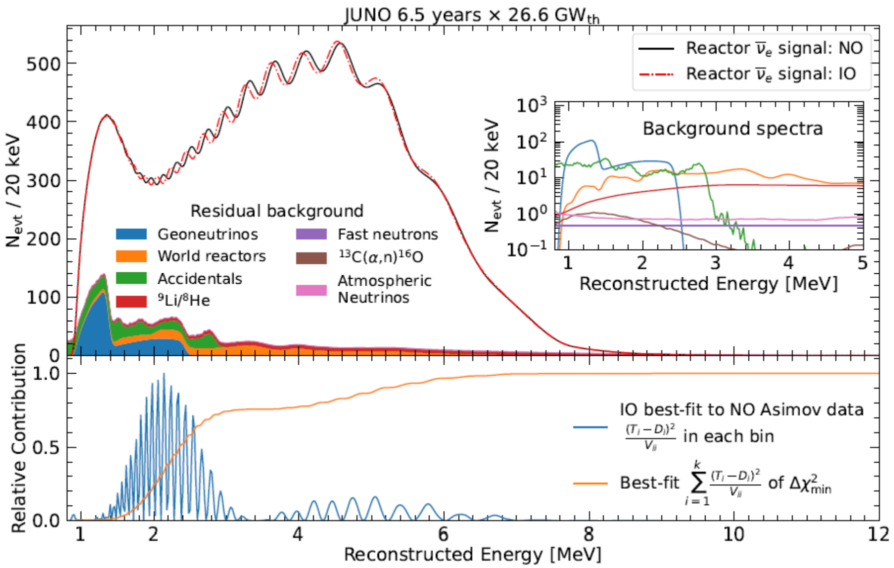




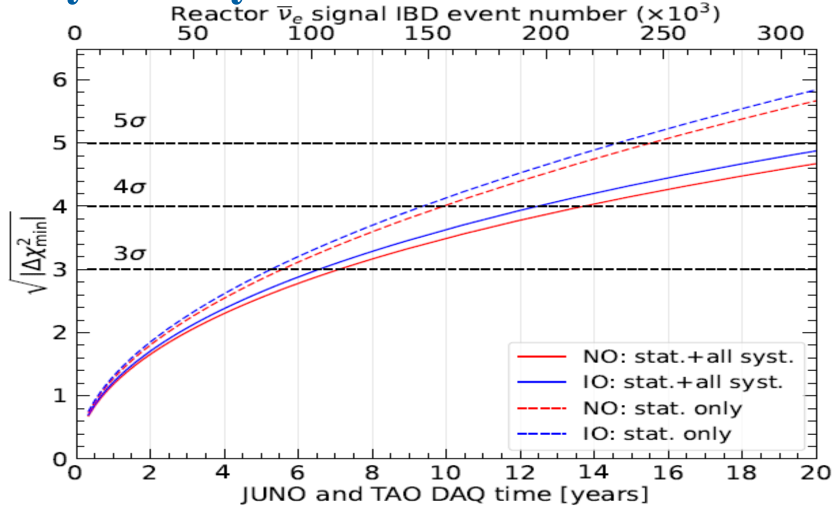
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016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

Neutrino Mass Ordering

arXiv:2405.18008 (2024)



Sensitivity mostly from 1.5-3 MeV

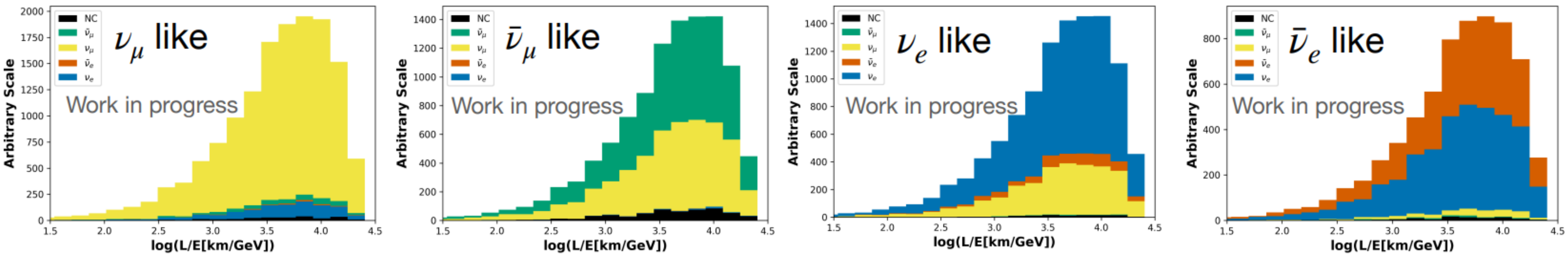


	Design	Now
Thermal Power	36 GW$_{th}$	26.6 GW$_{th}$ (**26%↓**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (**33%↑**)
Muon veto efficiency	83%	91.6% (**11%↑**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (**2%↑**)
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sens. Exposure	**<6 yrs × 35.8 GW$_{th}$**	**~6 yrs × 26.6 GW$_{th}$**

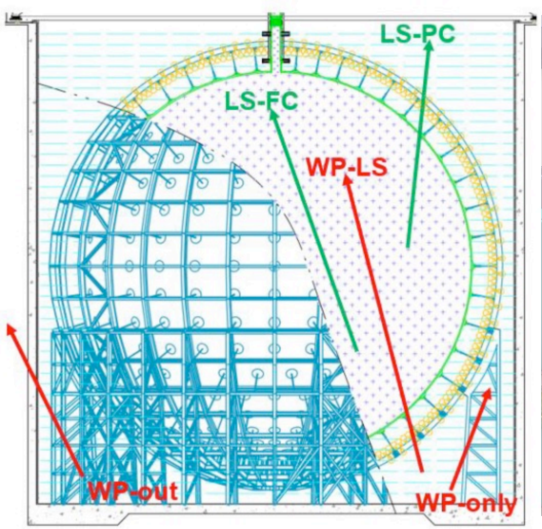
- JUNO NMO median sensitivity: 3σ (reactors only) @ ~6 yrs * 26.6 GW$_{th}$ exposure
- Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity (see next page→)

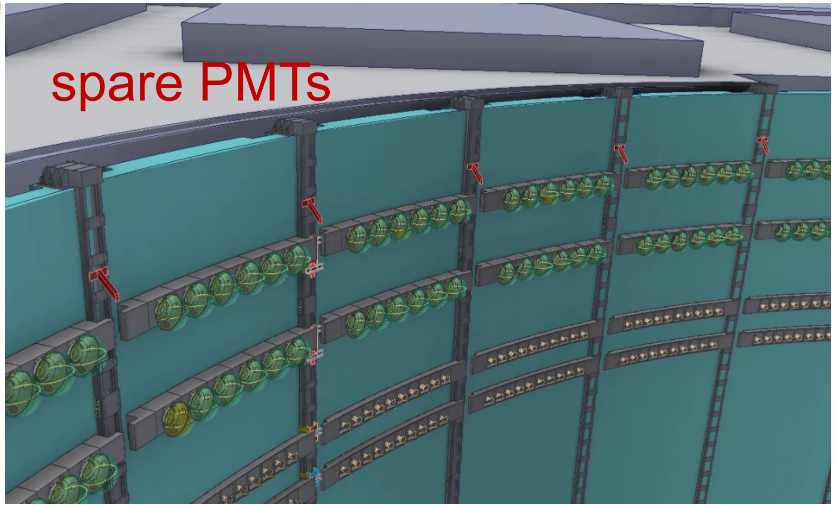
Atmospheric Neutrino

- JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator: e/μ separation, $\nu/\bar{\nu}$ separation, ν energy (instead of lepton energy), track direction in LS



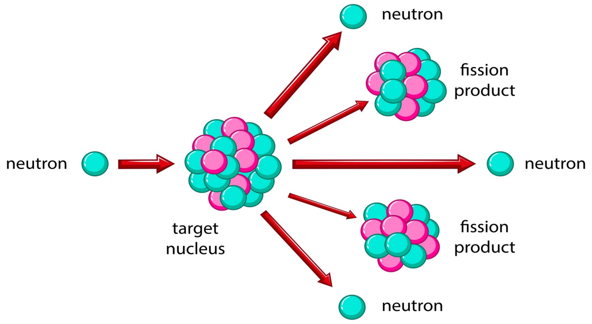
- ◆ **Improving the reconstruction and PID algorithm, as well as sensitivity**
- ◆ **Plan to install all spare PMTs on top wall of the water pool to improve PID and direction reconstruction**



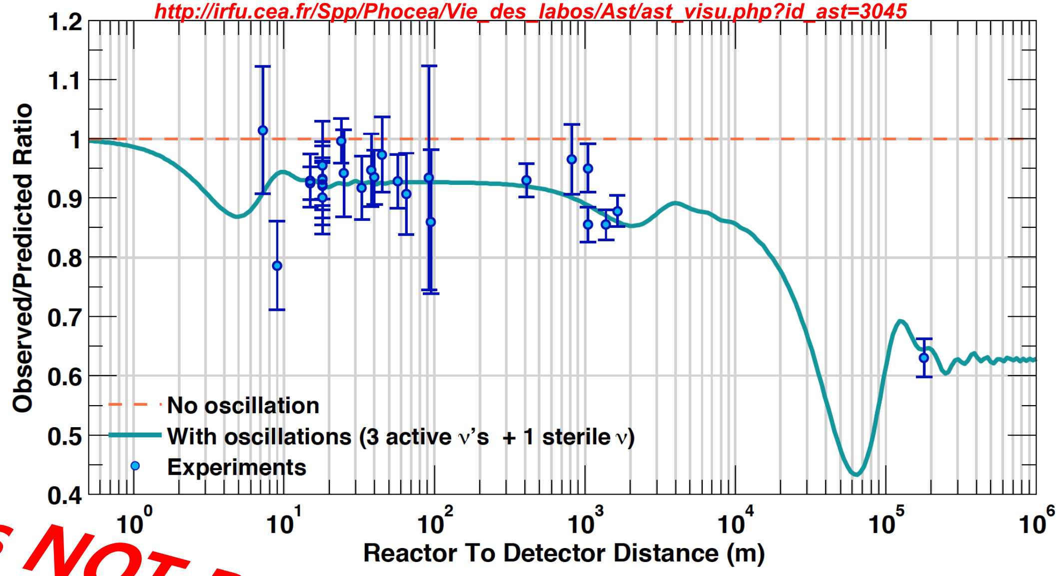


Reactor Antineutrino Anomaly (RAA)

Nuclear Fission

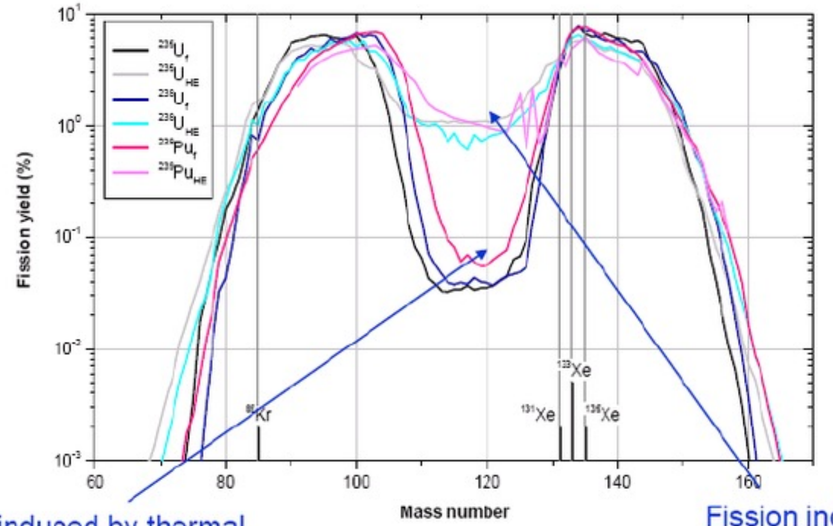


- *T. A. Mueller et al., PRC83, 054615 (2011)*
- *P. Huber, Phys. Rev.C84, 024617 (2011)*
- *Daya Bay, PRL116(2016), PRL123(2019)*
- *RENO, PRL121(2018)*
- *NEOS, PRL118(2017)*
- *Double Chooz, Nature Physics 16(2020)*



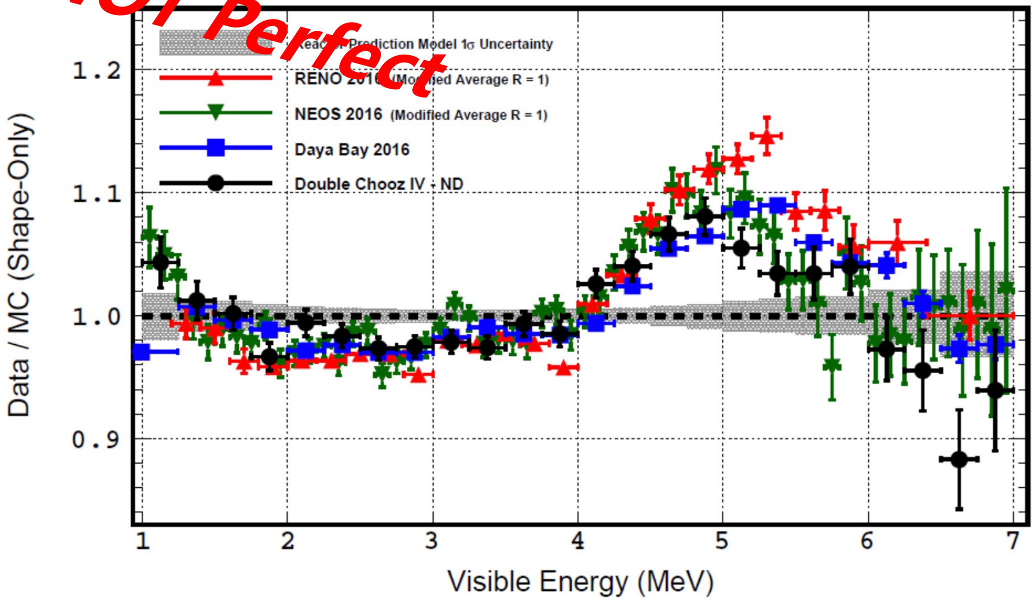
Reactor Neutrinos NOT Perfect

(Fission yield is a function of the fissioning nuclide and the incident neutron energy)



Fission induced by thermal (fission spectrum) neutrons

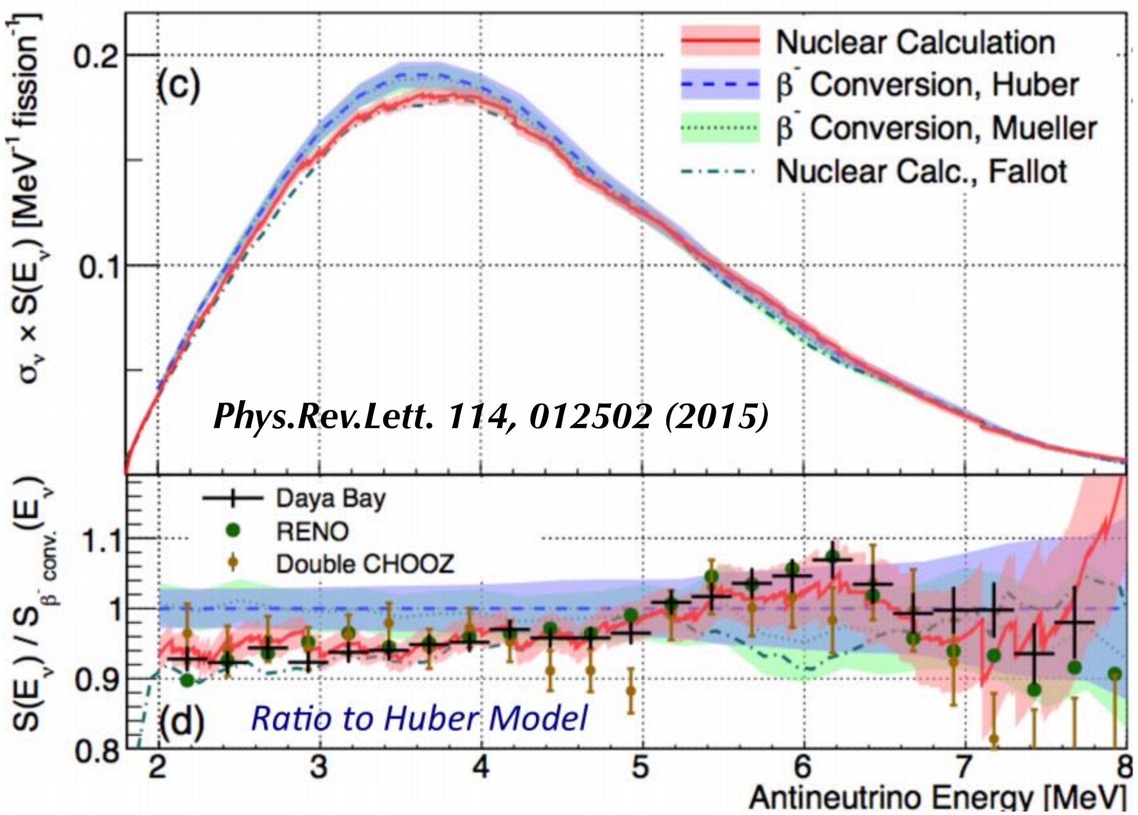
Fission induced by high energy neutrons (14.7 MeV)



The "*ab initio*" (summation) Method

$$S(E_{\bar{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\bar{\nu}})$$

f_{ij} — the branching fraction from isotope i decaying to the energy level j of daughter isotope



R_i — the equilibrium decay rate of isotope i

$$R_i \cong \sum_{p=0}^{P} R_p^f Y_{pi}^c$$

- ✓ R_p^f — the fission rate of the parent *isotope* p
- ✓ Y_{pi}^c — the cumulative yield of isotope i

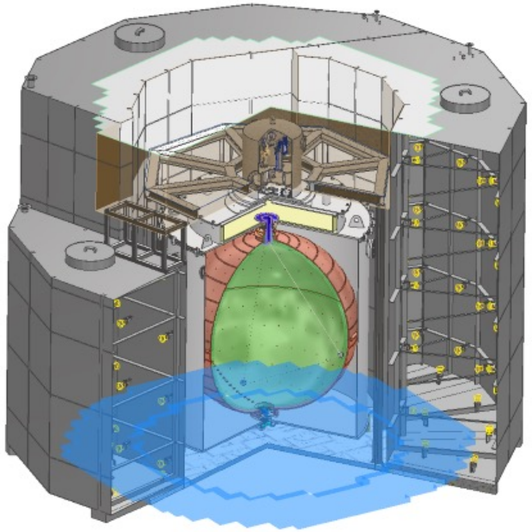
The 5 MeV bump was predicted with **a large uncertainty** from summation calculation.

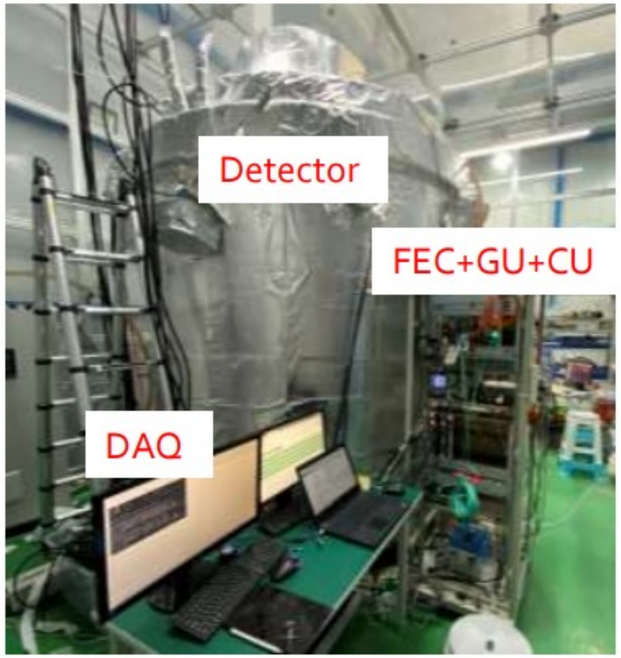
Additionally, the **saw-tooth structures** were also predicted in the summation spectrum.

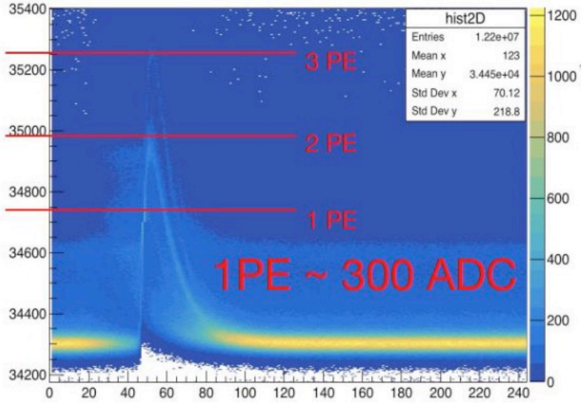
JUNO-TAO

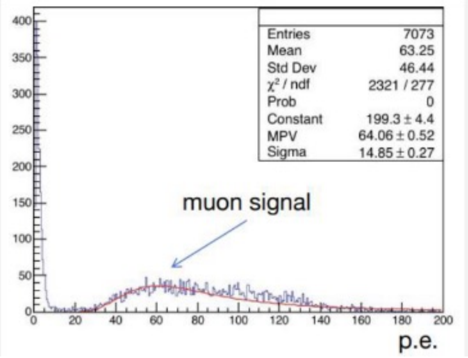
- Main goal: Measure the reactor neutrino spectrum (as a reference to JUNO)
  - better resolution to reduce fine structure effects and spectrum uncertainties
  - Improve nuclear database
- 10 m^2 SiPM + 2.8 ton Gd-loaded LS @-50℃
  - 700k/year@44m from the core (4.6 GW), ~10% bkg
  - **Energy resolution: <2%/√E, 4500 p.e./MeV**
  - SiPM (>94% coverage) w/ PDE > 50%
  - Operating at -50℃, dark rate 100k→100 Hz/mm^2
  - 2.8 ton (1-ton FV) new type of Gd-LS for -50℃
- Detector assembled at IHEP with ~100 SiPM tiles/readout (out of 4100 in total)
  - Temperature uniformity and stability OK!
  - Single PE readout
- Disassembling, to be re-installed in the Taishan Nuclear Power Plant in 2024

arXiv:2005.08745

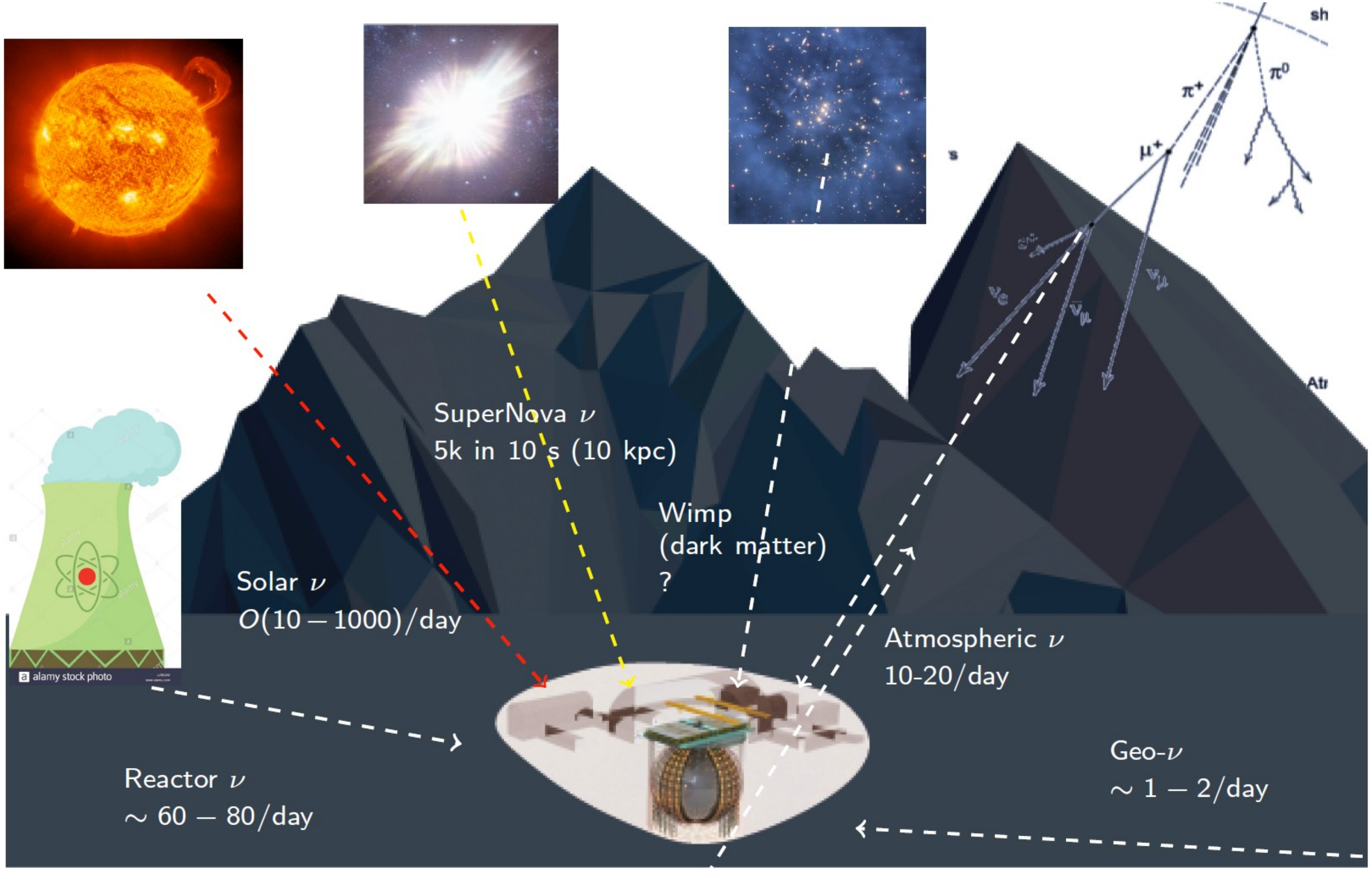






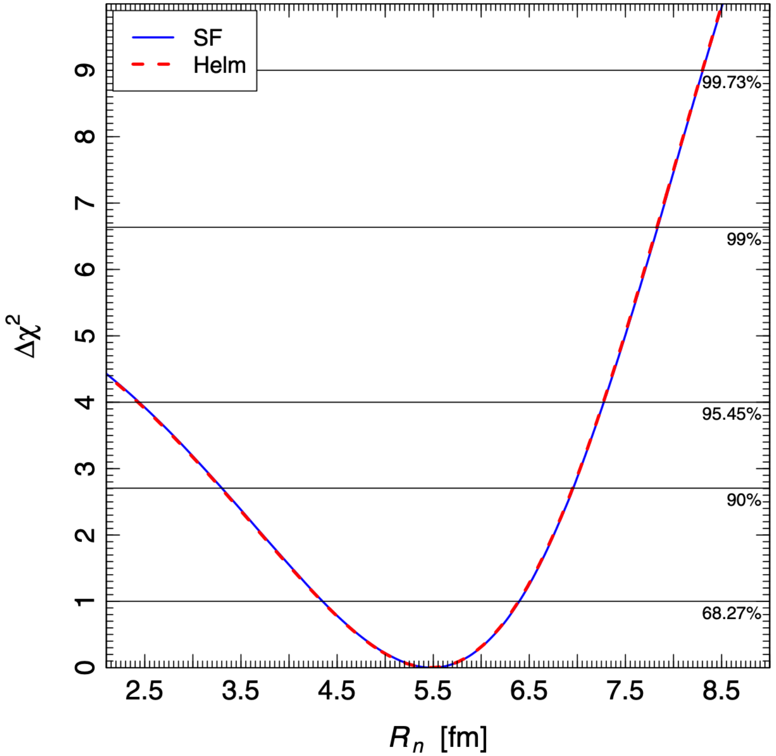


JUNO's Multi-Physics Potential



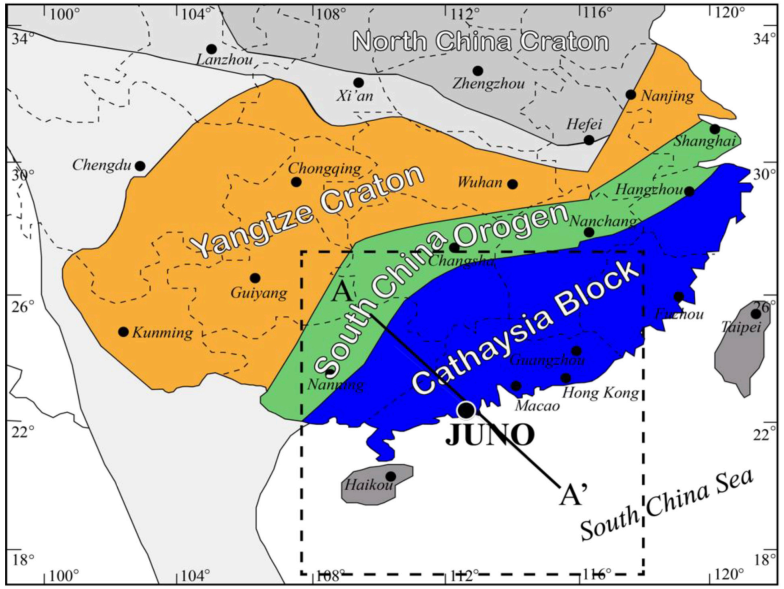
Neutrino as Probes: Nuclear and Earth Sciences

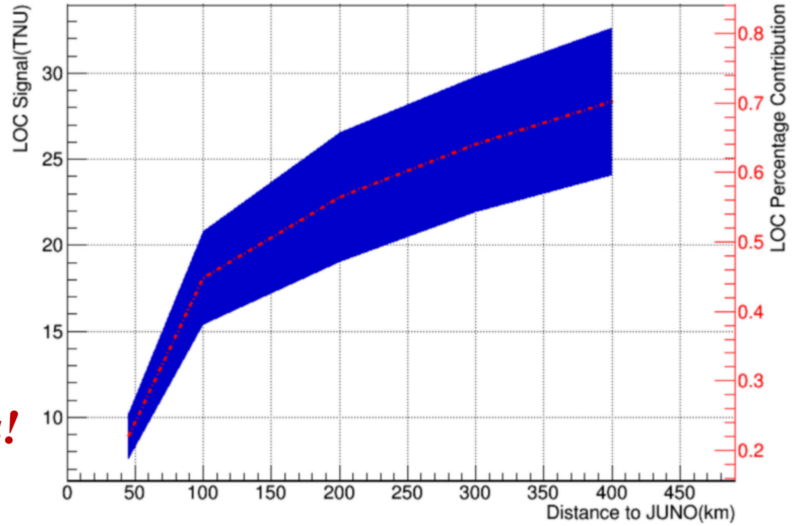
Cadeddu & Y.F. Li et al, PRL120, 072501 (2018)



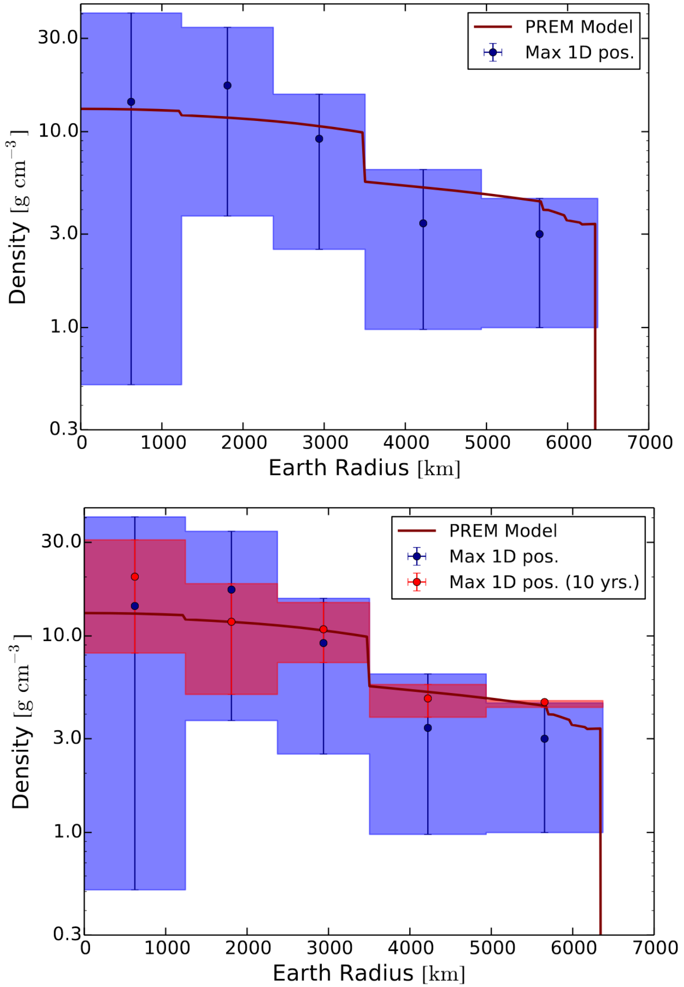
$$R_n = 5.5^{+0.9}_{-1.1}\ \text{fm}.$$

First time measuring neutron radius!





A. Donini et al, Neutrino tomography of Earth, Nature Physics 2018



Summary and Future Perspectives

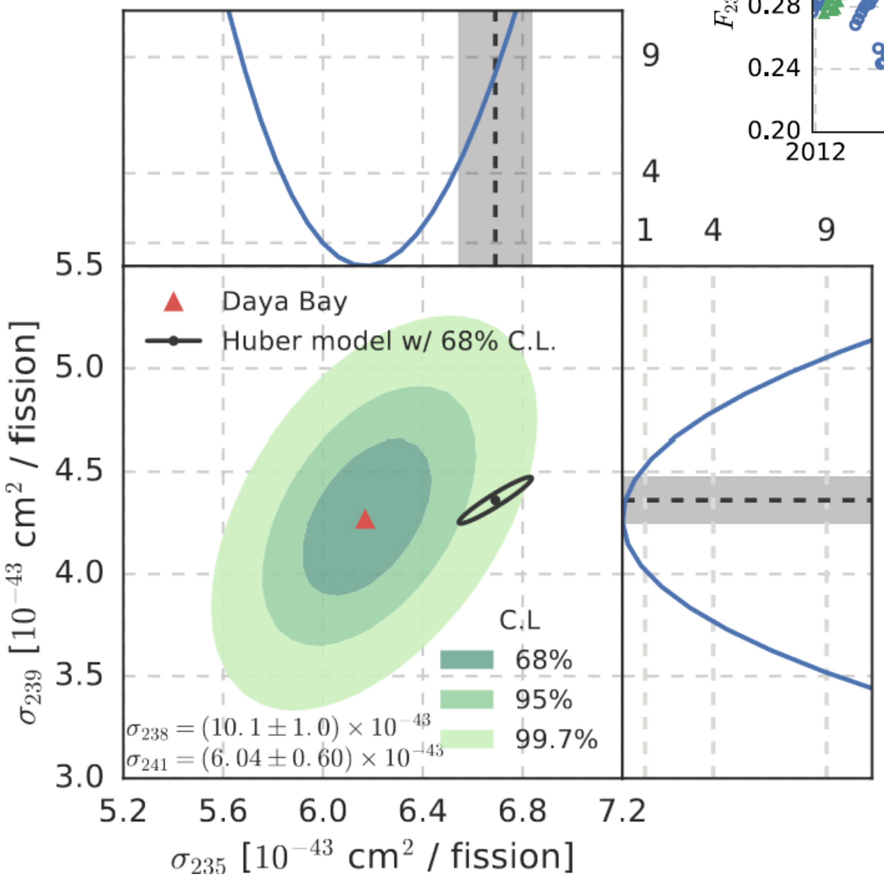
- Neutrino physics has provided the first new physics beyond the SM and it is now entering the precision phase → **Reactor Neutrinos are playing essential roles continuously**
  - **We have been using reactor neutrinos for free --- is it time for us to pay the industry back? ☺**
- **Technologies are always essential for making progresses in science**; Science always gives technologies more values and, often, leads the developments of technologies; Applications and fundamental science drive new technologies in synergy
  - **The unanswered questions in neutrino physics require new technologies**

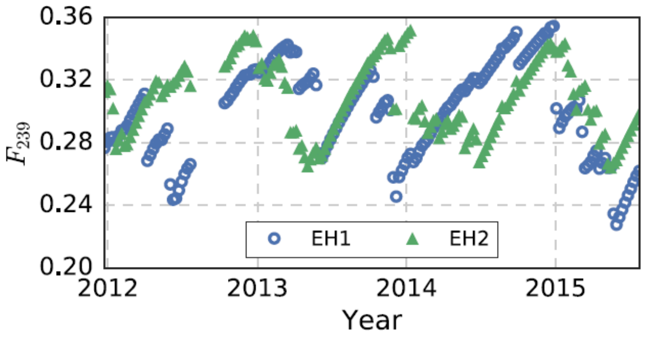
Summary and Future Perspectives

- ***Looking back to the modern history of neutrino experiments***
  - ***Important to "dream big" and dare to "dream"***
  - ***Important to be programmatic***
  - ***Important to prepare the young generations***
  - ***Important to collaborate internationally***

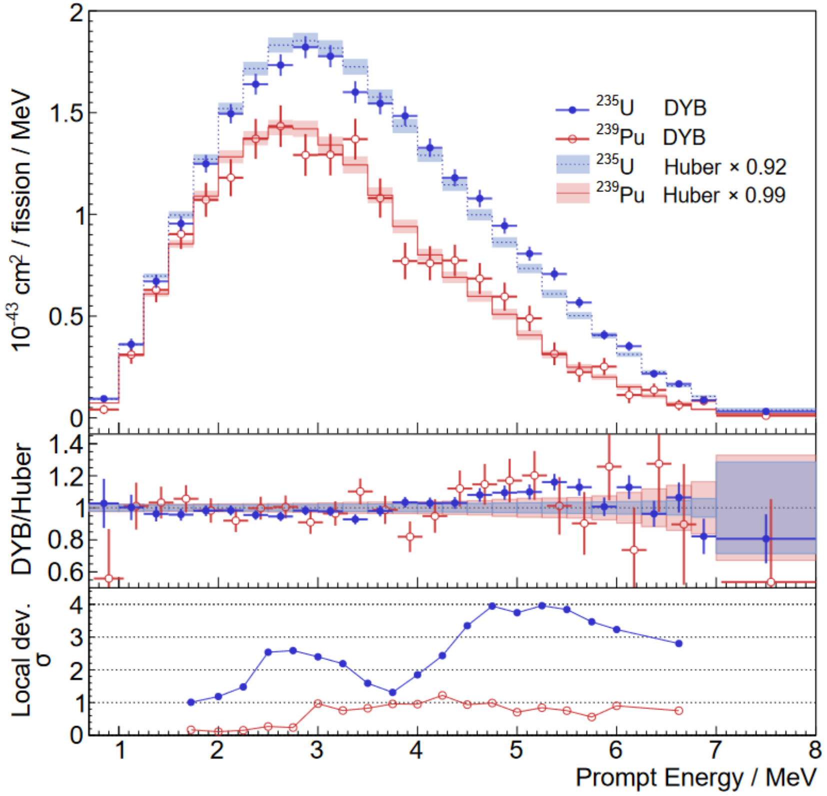
Understanding Reactor Antineutrinos

- ***Fuel evolution: Phys.Rev.Lett. 118 (2017) no.25, 251801***





- **Isotope decomposition**, *PRL 123 (2019) no.11, 111801*

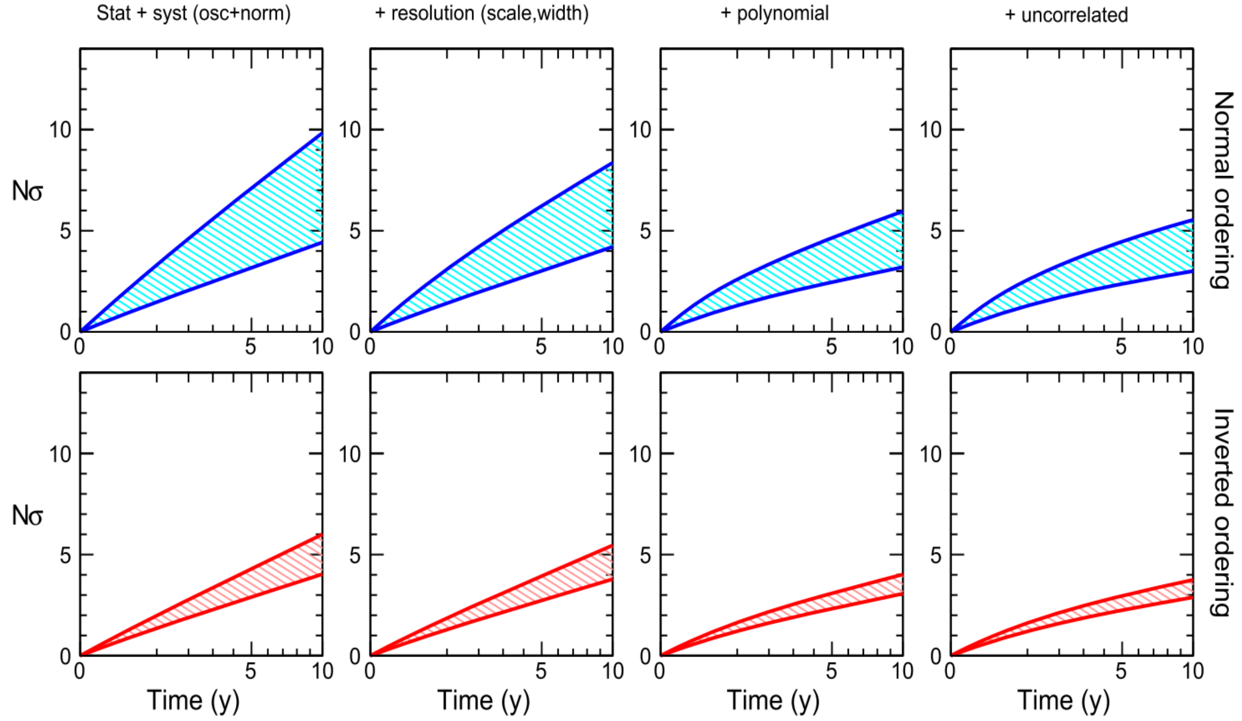


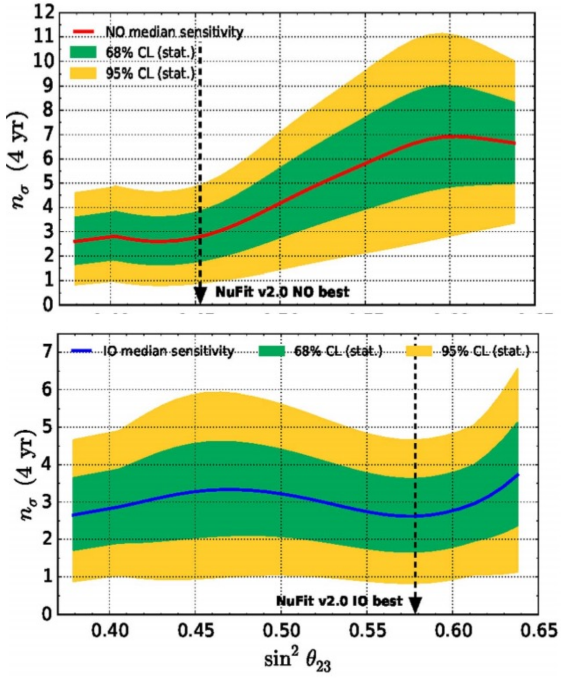
^{235}U: 4-sigma effect

^{235}Pu: 1.2-sigma effect

KM3NeT/ORCA and PINGU Sensitivities

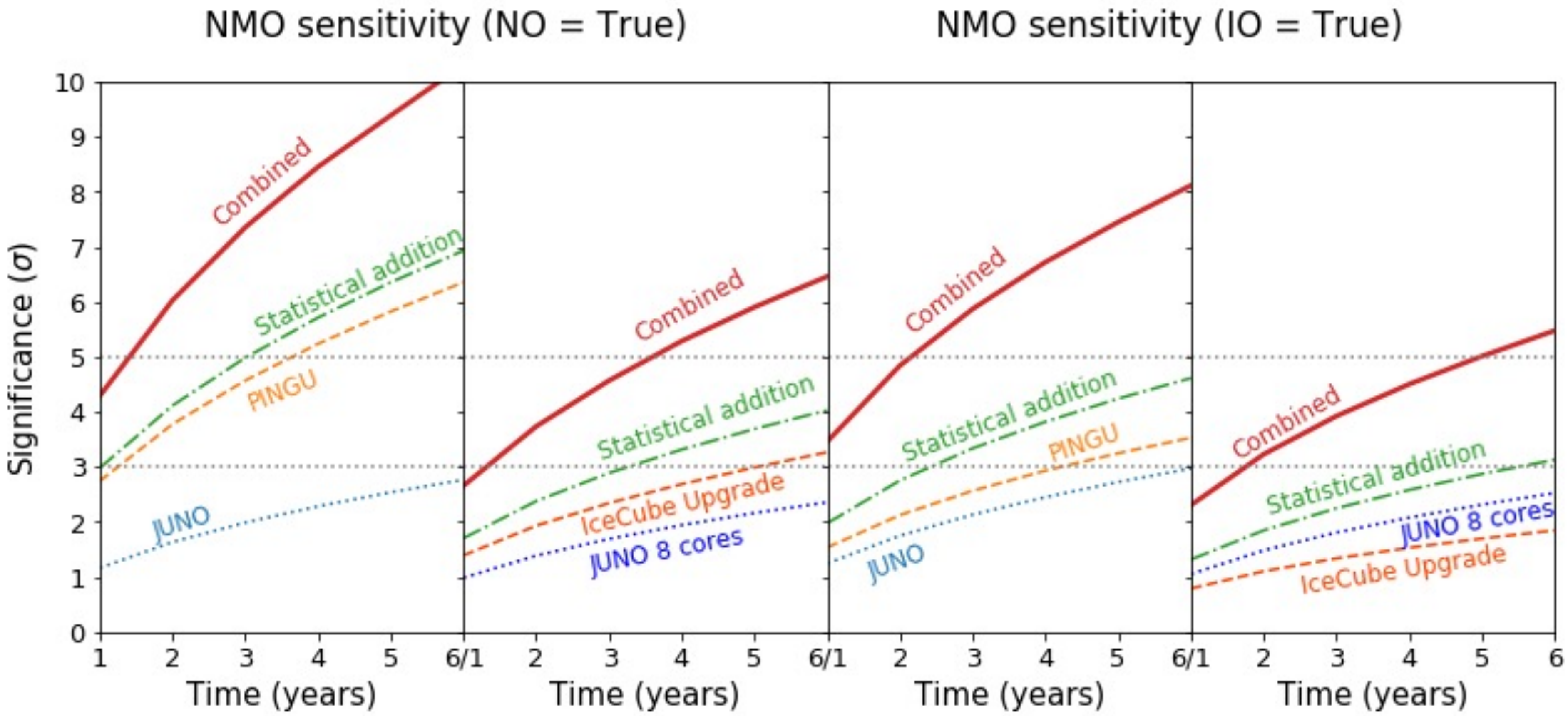
- ***F Capozzi et al for KM3NeT/ORCA, PINGU Group for PINGU J. Phys. G: Nucl. Part. Phys. 45 (2018) 024003***





- More advantageous for the normal ordering case
- Uncertain due to a different unknown parameter, the atmospheric mixing angle

Combining JUNO and PINGU/DeepCore *(courtesy of M. Wurm)*



- Nominal configuration, i.e. PINGU (26 strings) + JUNO (10 cores)
- Reduced configurations, i.e. IC Upgrade (7 str) + JUNO (8 cores)

➢ **In any case, 5σ-discovery after 5 years**