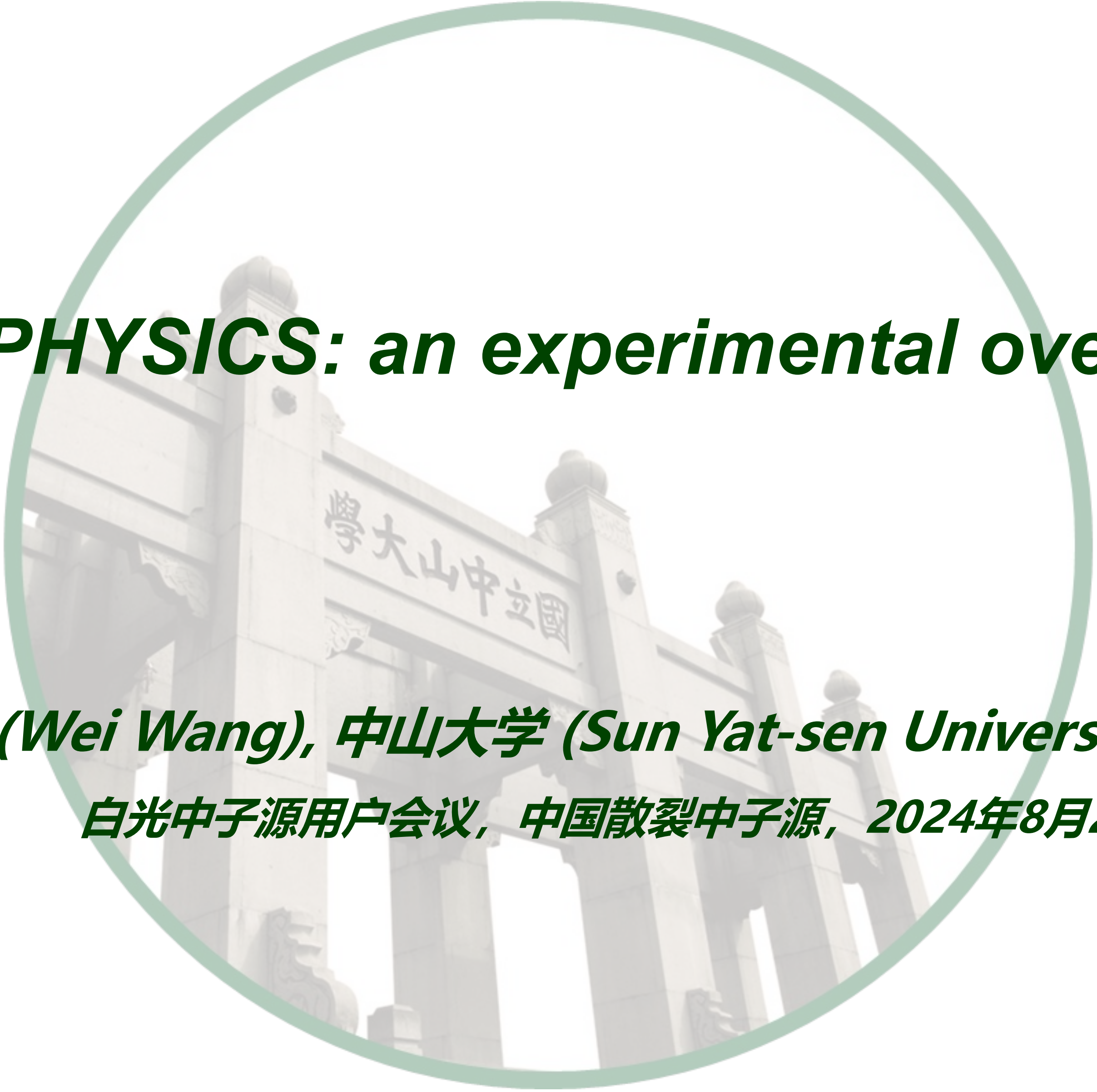


NEUTRINO PHYSICS: an experimental overview

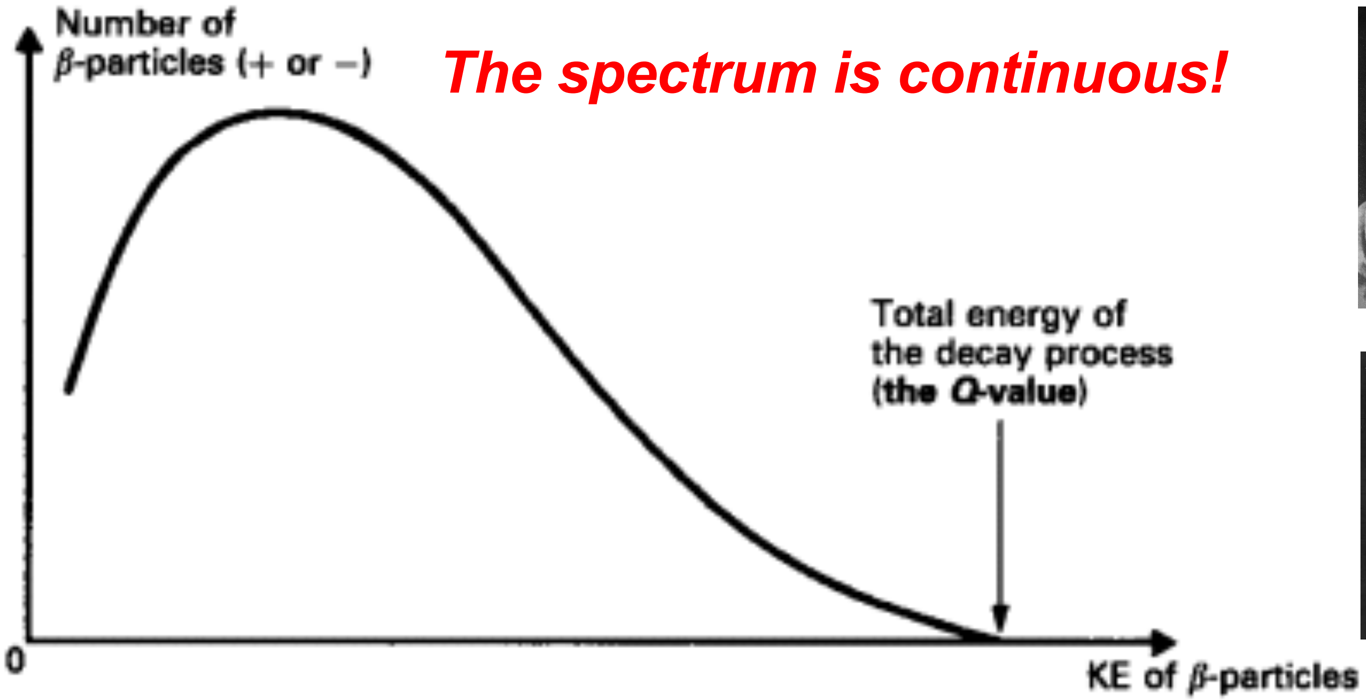
王为 (Wei Wang), 中山大学 (Sun Yat-sen University)

白光中子源用户会议，中国散裂中子源，2024年8月23日

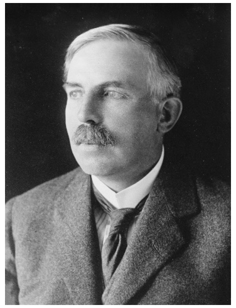
Outline

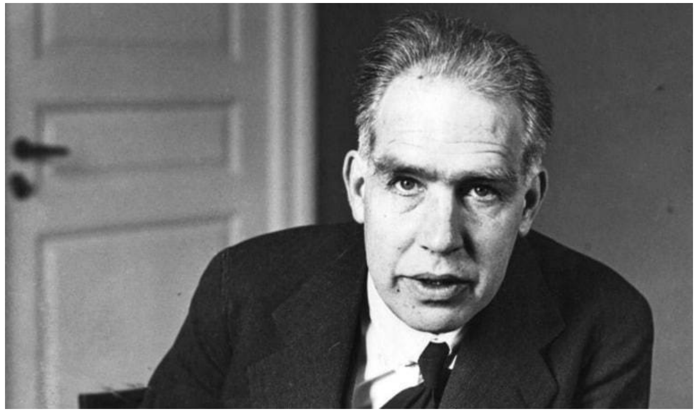
- Part I: Introduction of Neutrino
  - The need of Neutrino
  - Standard Model Neutrino and Neutrino Oscillation
- Part II: Discovery of Neutrino Oscillation, Atmospheric Neutrinos, Long-Baseline Neutrino Experiments
  - Search for neutrino oscillation signals; Super-Kamiokande, Hyper-Kamiokande (brief)
  - From K2K to MINOS/T2K/NOvA and DUNE (extremely brief)
- Part III: Reactor Neutrinos
  - Daya Bay Reactor Neutrino Experiment and Contemporaries, JUNO
- Part IV: neutrino applications and (relevant) future experiments
- Summary and Conclusion
- ***NOT covering: neutrino absolute mass experiments, neutrinoless double beta decay experiments, high energy neutrino telescopes, cosmological neutrino experiments, and many specific neutrino experiments***

The Crisis of the beta-Spectrum in 1920s

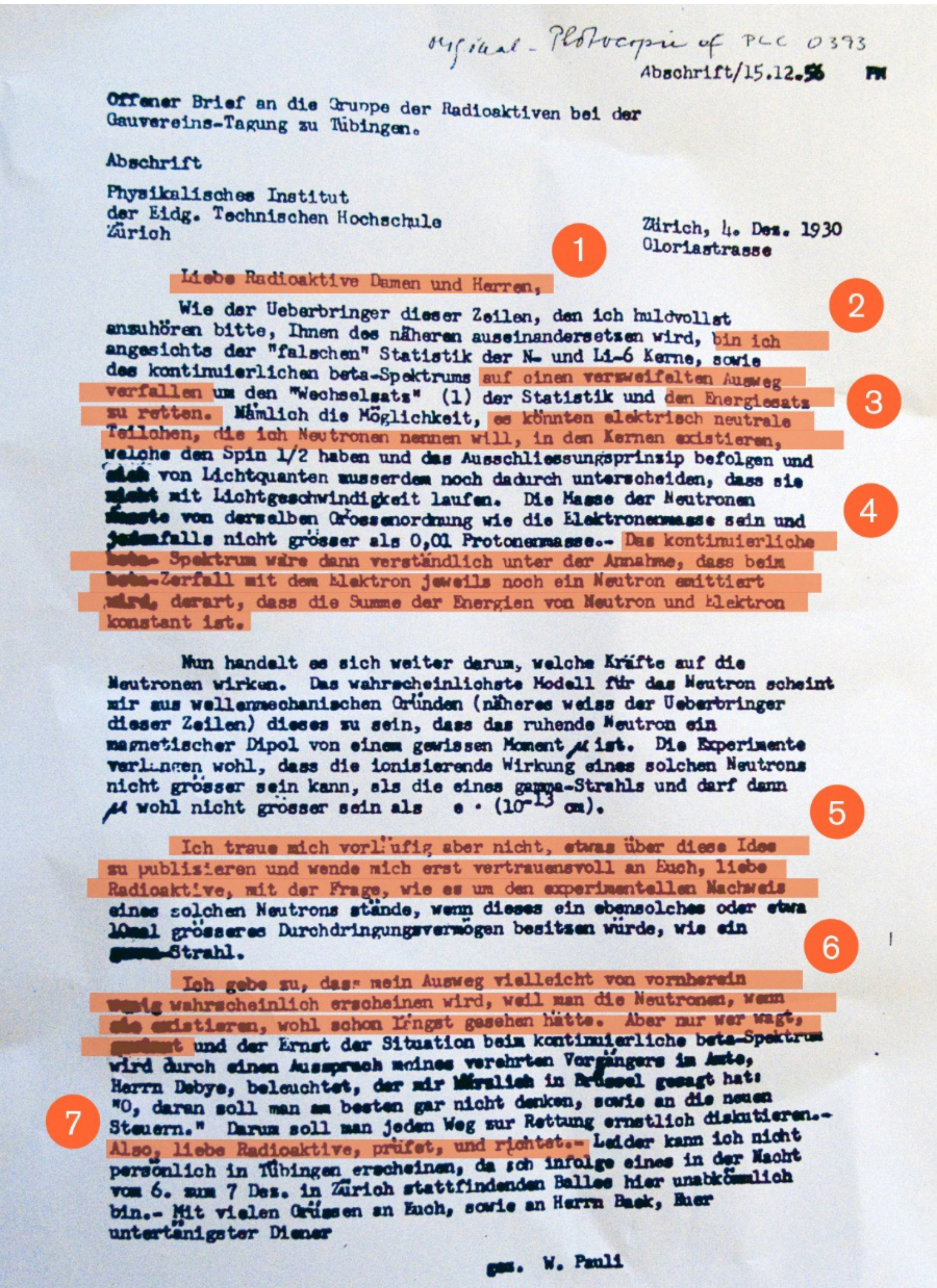


The spectrum is continuous!





- 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

Liebe Radioaktive Damen und Herren,

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. 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.- 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).

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.

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 mündlich 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.- 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…

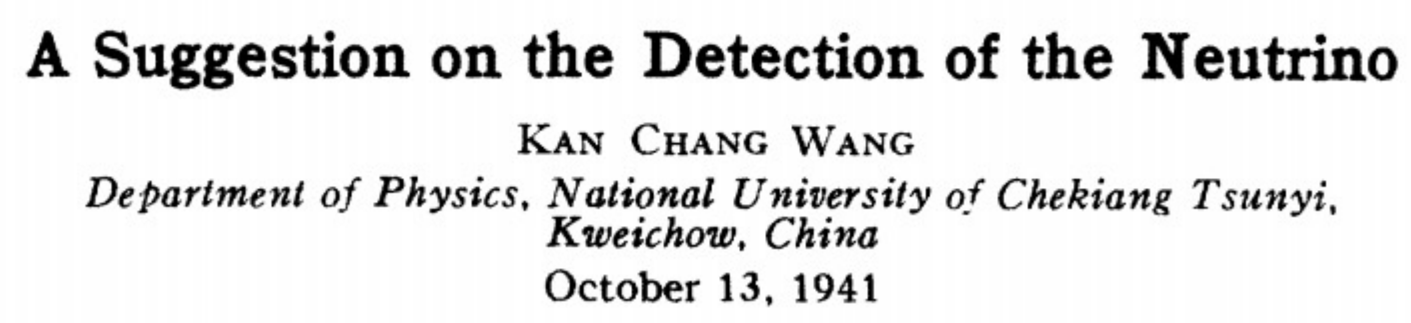
⑥ I admit that my remedy may seem almost improbable **because one probably would have seen those *neutrons*, if they exist, for a long time**. But nothing ventured, nothing gained…

⑦ Thus, dear radioactive ones, scrutinize and judge.

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

Two years later, James Chadwick discovered what we now call the neutron, but it was clear that this particle was too heavy to be the "neutron" that Pauli had predicted. Since Chadwick had taken the name "neutron" for something else, Fermi had to invent a new name. Being Italian, "neutrino" was the obvious choice: a little neutral one.

The First Attempts Detecting Neutrinos in 1930s-1940s



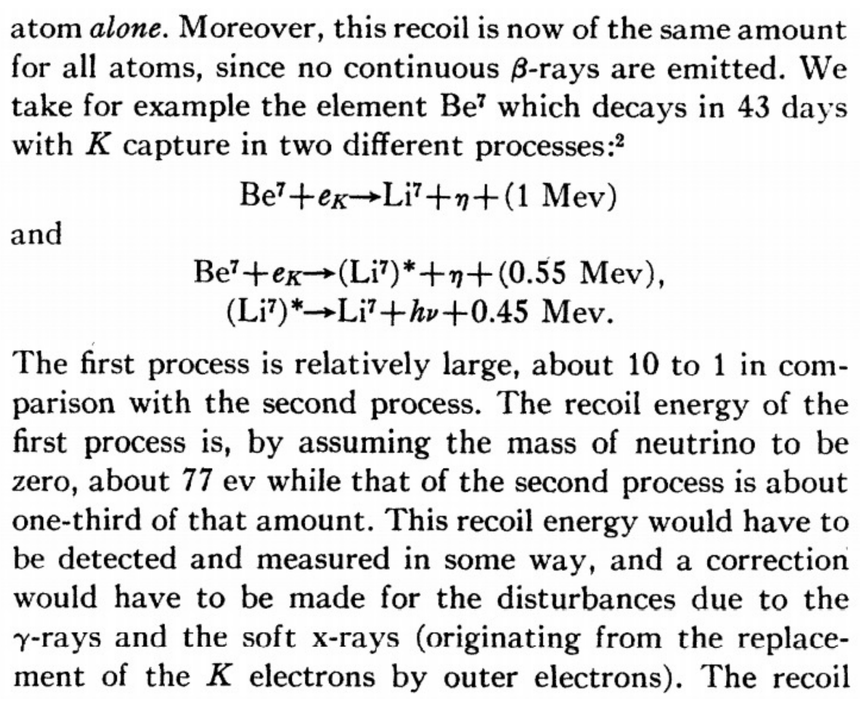
A Suggestion on the Detection of the Neutrino

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

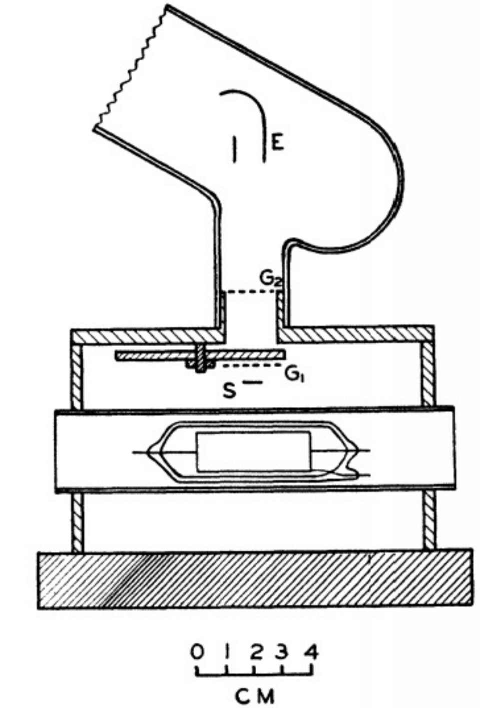


FIG. 1. Experimental arrangement of G-M and electron multiplier tubes.

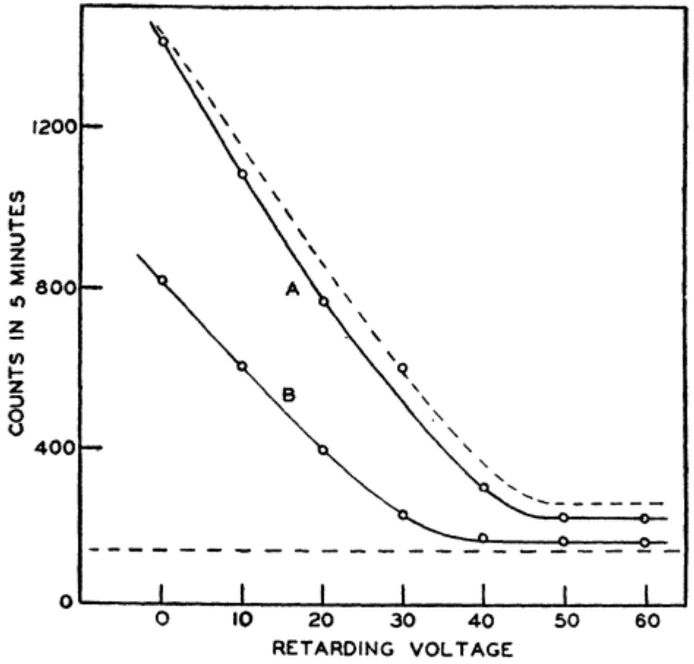


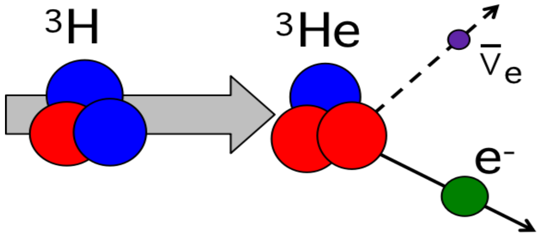
FIG. 3. Retarding potential curves for recoil ions. The horizontal dotted line represents the background counting rate.

Prof. Kan Chang Wang (1907-1998)

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


浙江大学档案馆藏

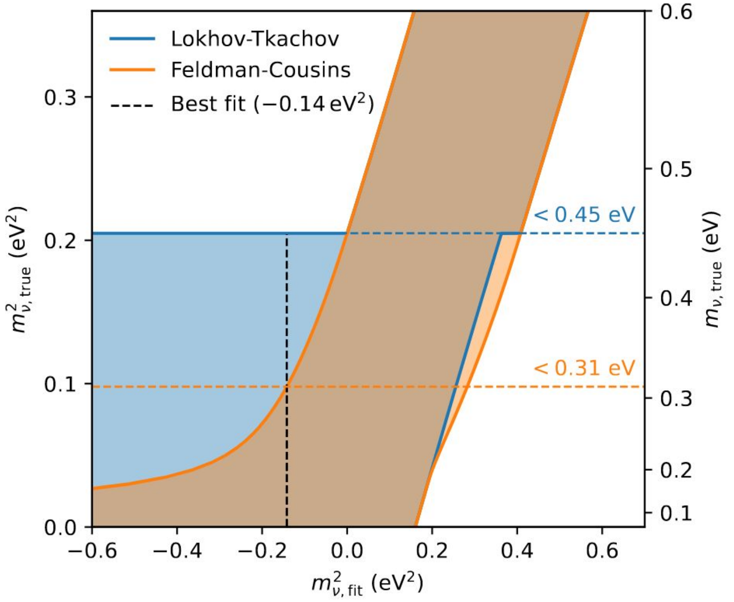
Direct Neutrino Mass Measurement by KATRIN



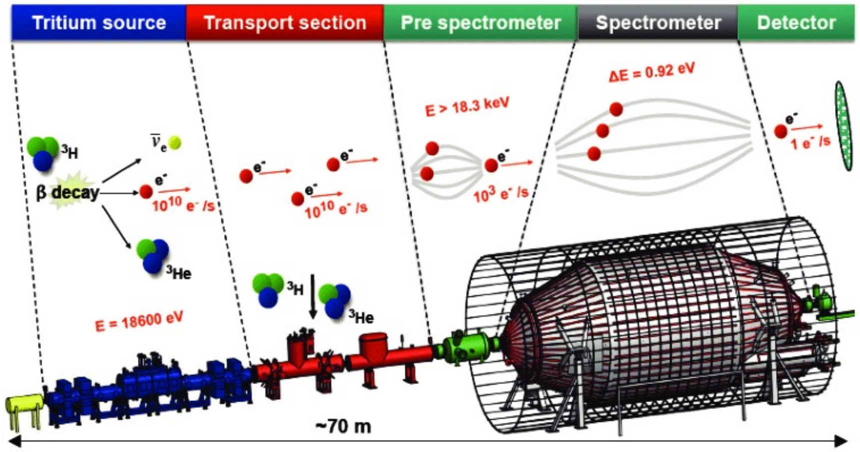
- KATRIN's **new** upper limit

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

  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



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

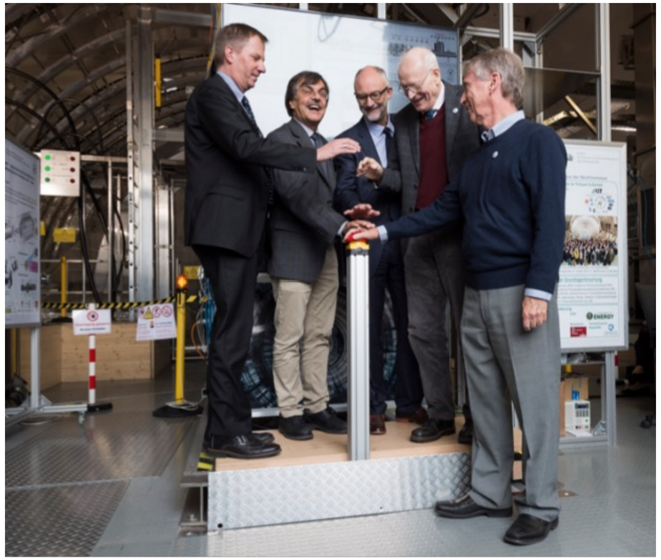


- 259 days of data released at Neutrino 2024
- 1000 days planned and eventual sensitivity 0.2eV

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

KATRIN Talk @ Neutrino 2024

KATRIN: A Long Journey

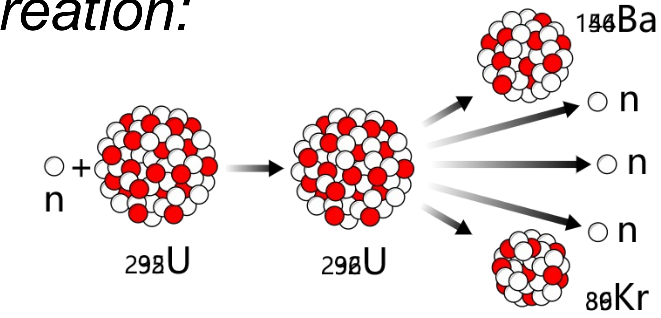


15 Years of Hard Working and Persistence!

Reines&Cowan Detected Neutrinos in 1956

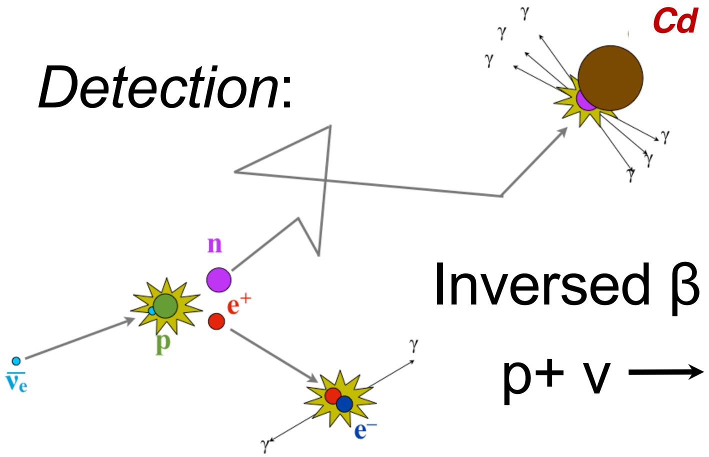
- Cowan and Reines at the Savannah River Power Plant (1956-1959)

Creation:



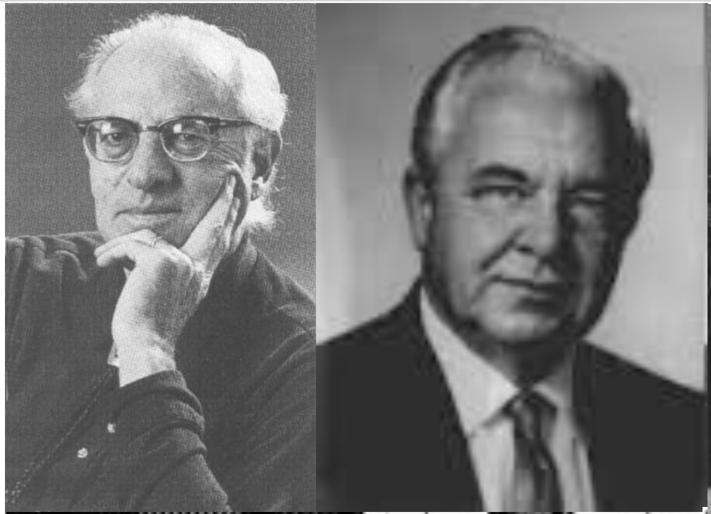
β decay：$N \rightarrow N' + e + v$

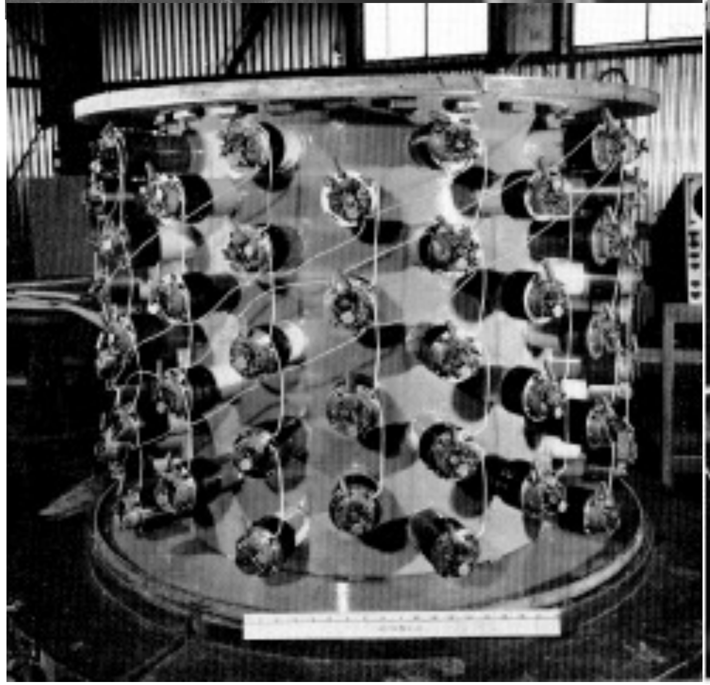
Detection:

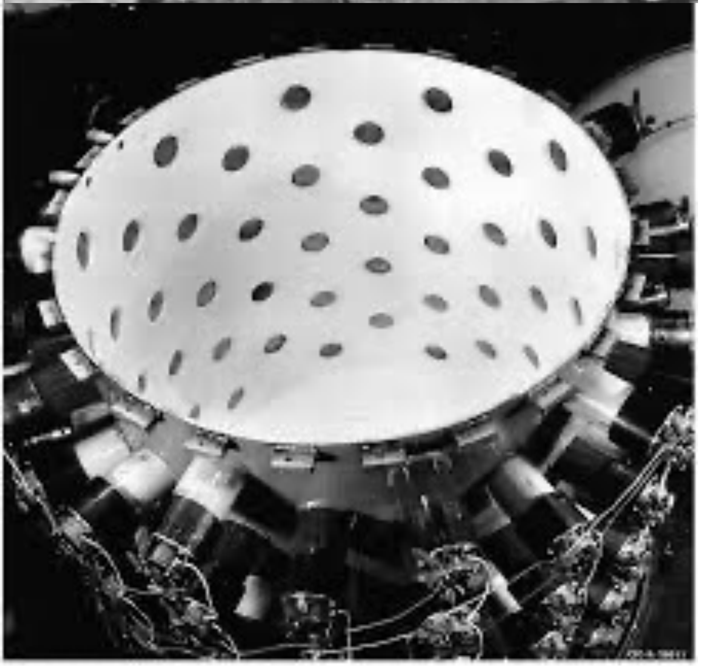


Inversed β decay

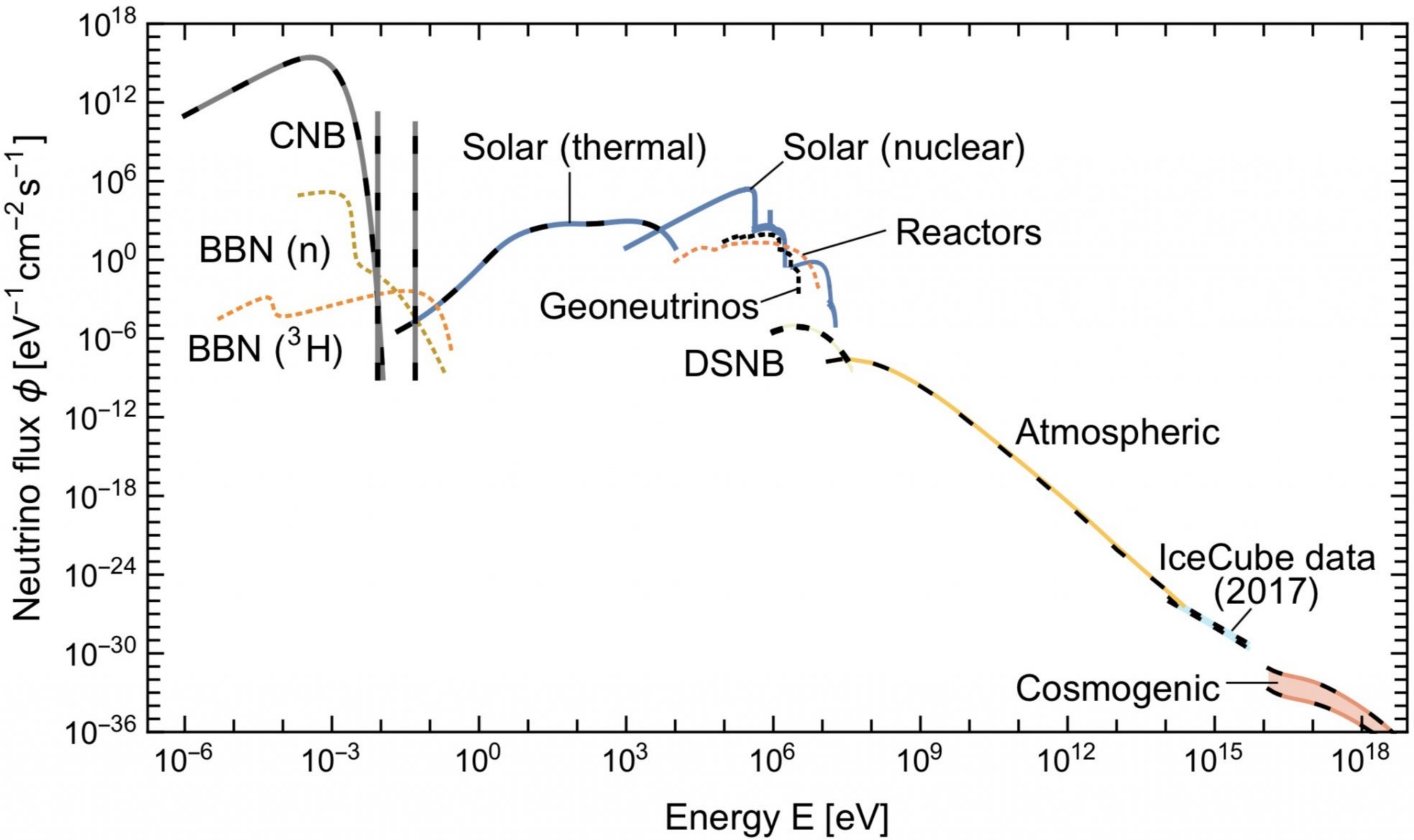
$p + v \longrightarrow e^{+} + n$







Various Neutrino Sources



Neutrino Mixing & Oscillation First Proposed by Pontecorvo

Бруно Понтекорво

- Bruno Pontecorvo proposed in 1957:

  Interaction Eigenstates ≠ Mass Eigenstates
  → Neutrino Mixing and Oscillation

Statue of Pontecorvo, JINR

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

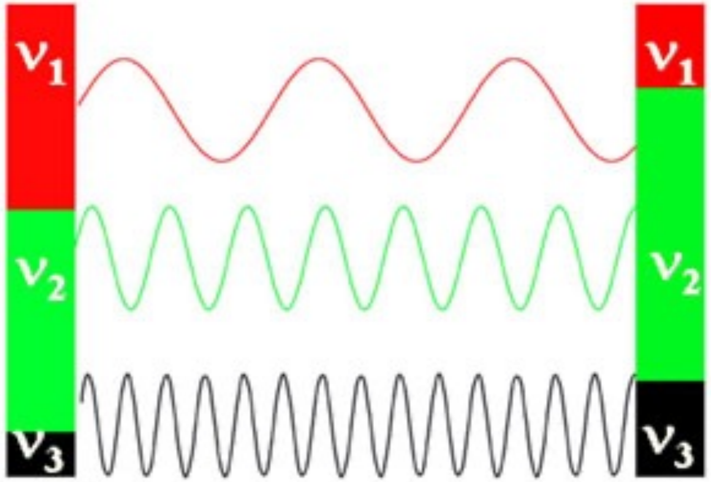
Z. Maki
1929-2005

M. Nakagawa
1932-2001

Neutrino Mixing & Oscillation

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

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



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

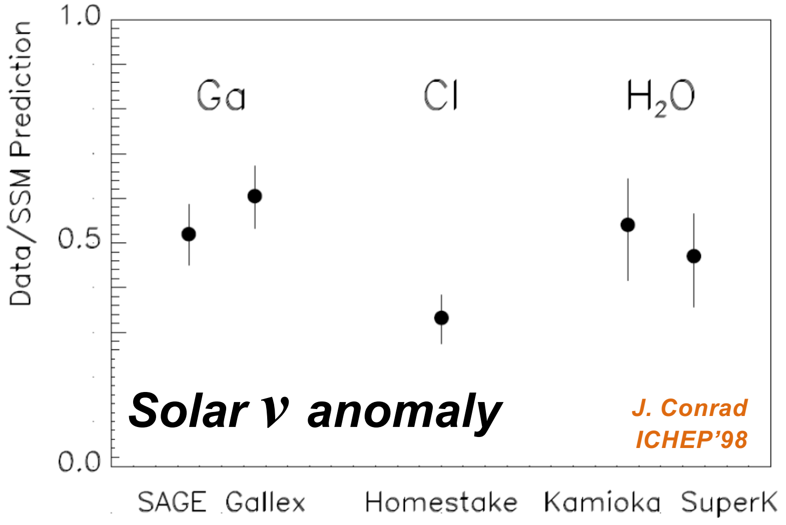
⇒ Oscillation Probability:

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

Amplitude $\propto \sin^2 2\theta$

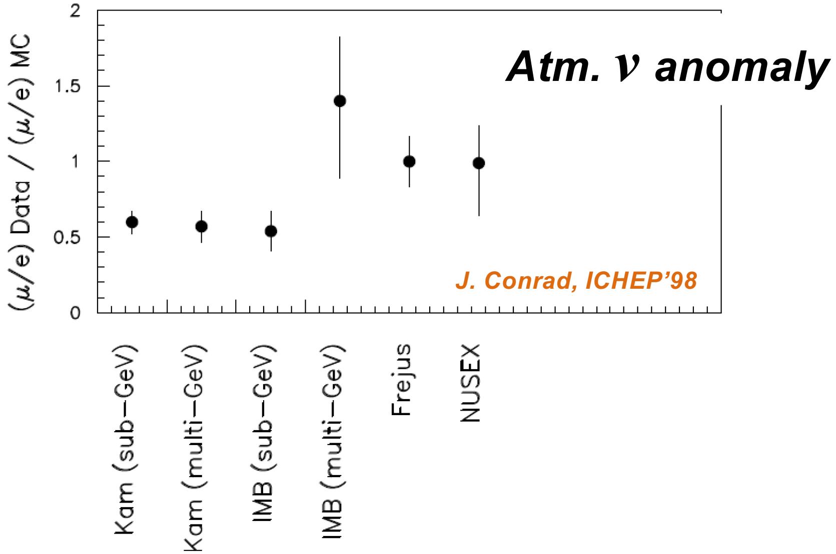
Frequency $\propto \Delta m^2 L/E$

The Search for Neutrino Oscillation 1956-1998



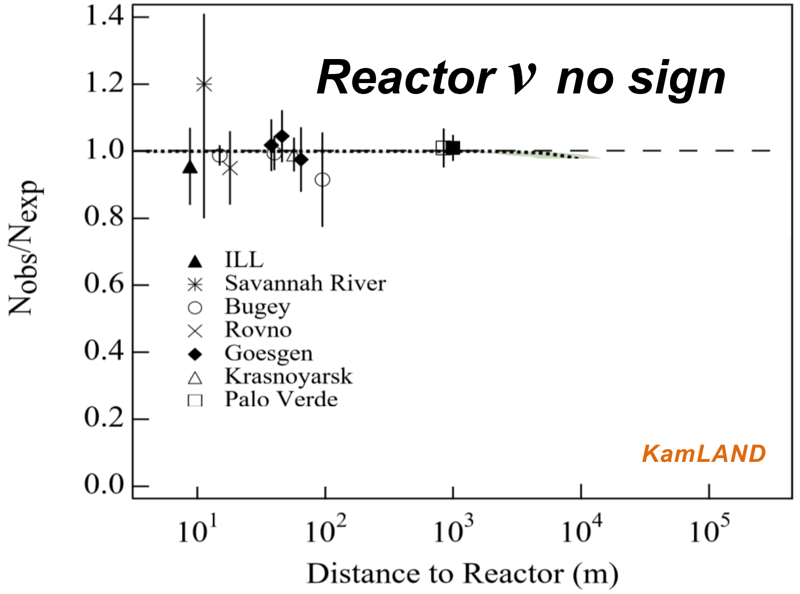
Solar ν anomaly

J. Conrad ICHEP'98



Atm. ν anomaly

J. Conrad, ICHEP'98



Reactor ν no sign

KamLAND

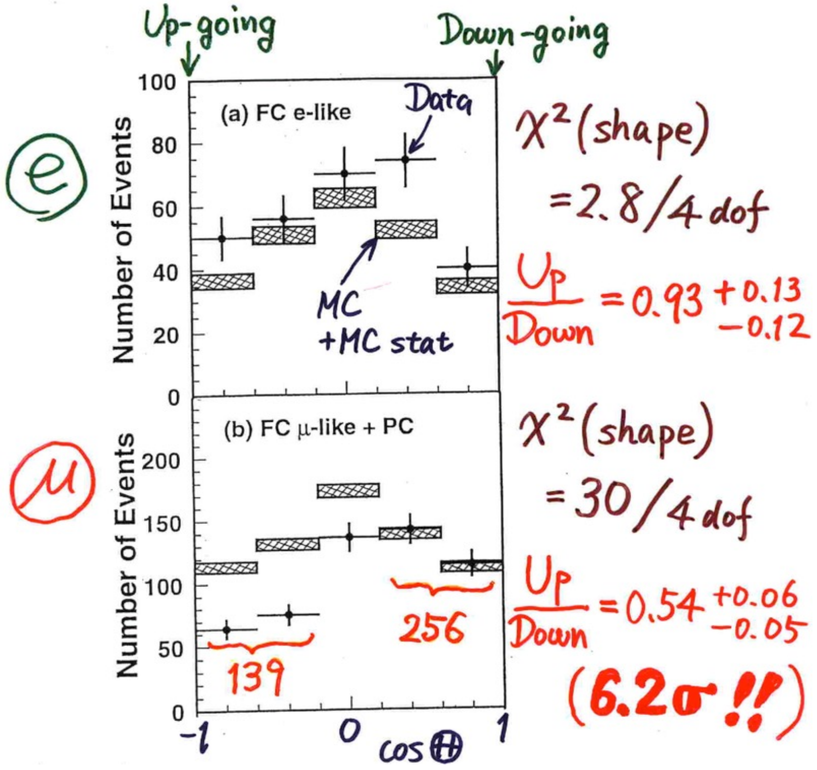
- ***The search for neutrino oscillation lasted decades but nothing conclusive until Fall 1998……***

Neutrino Oscillation Discovered by Super-Kamiokande in 1998

T. Kajita, Neutrino'98

Zenith angle dependence

(Multi-GeV)



χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

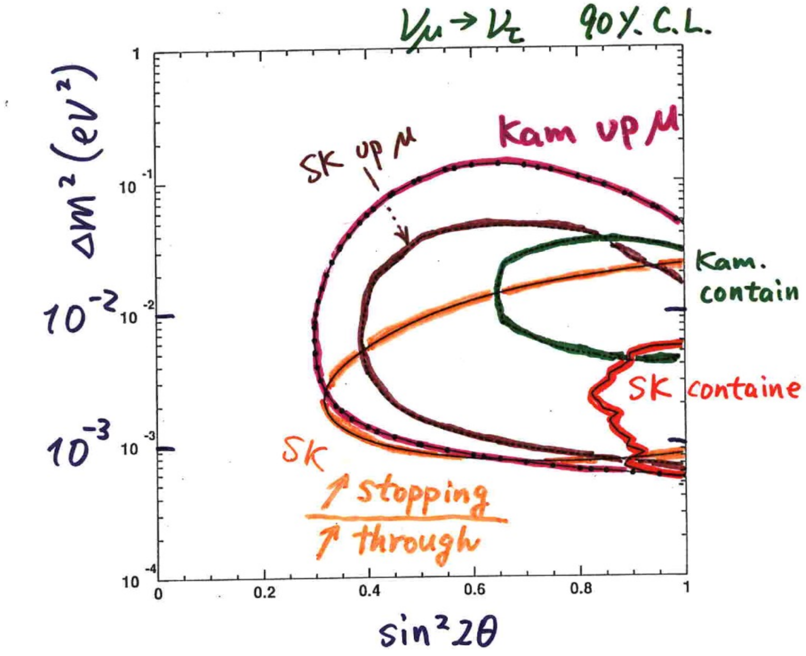
χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

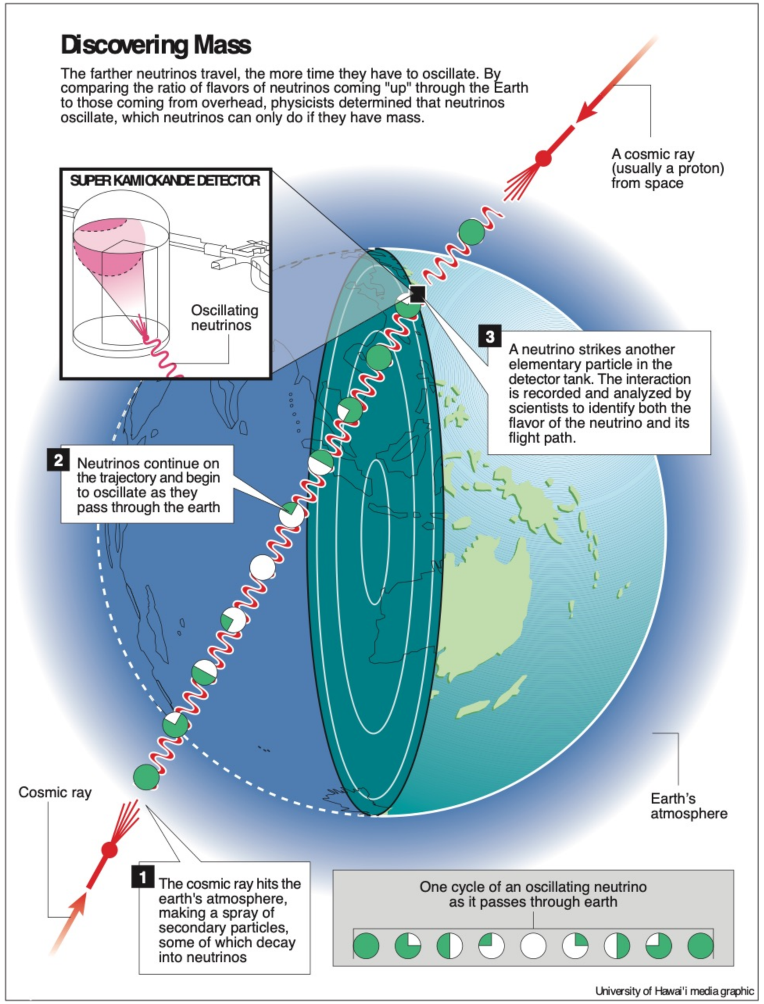
Summary

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



Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.

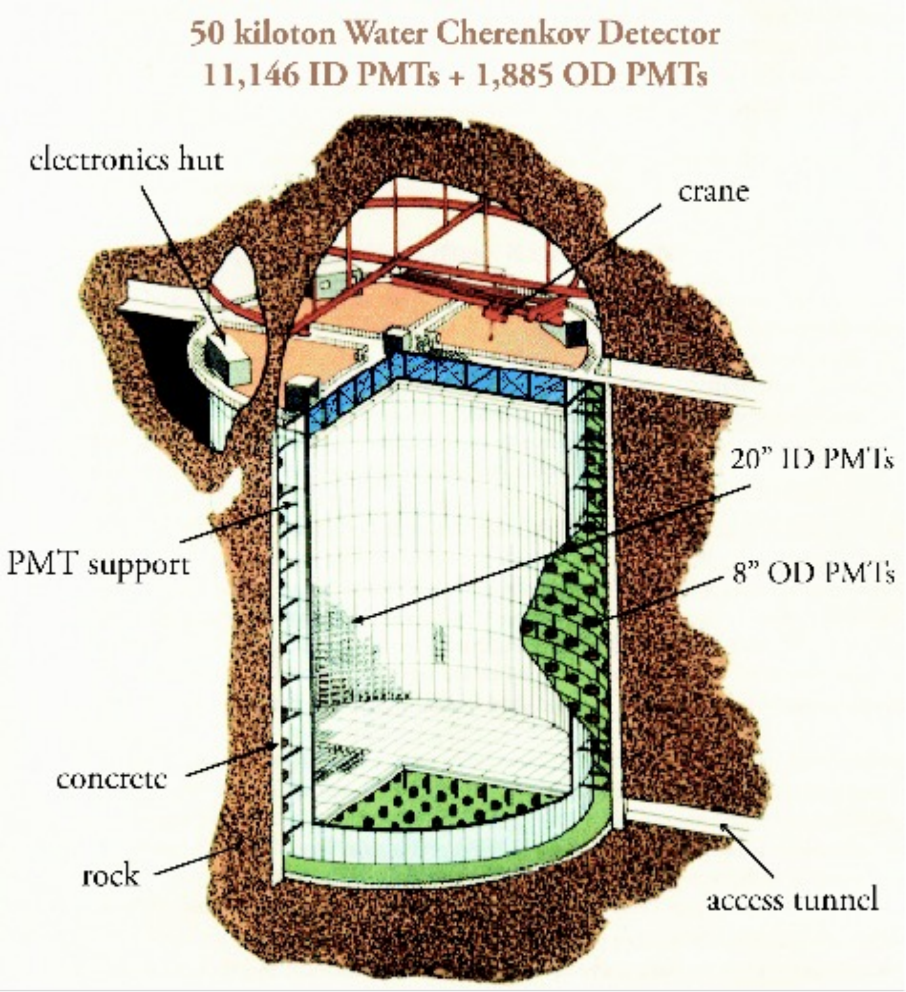
1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

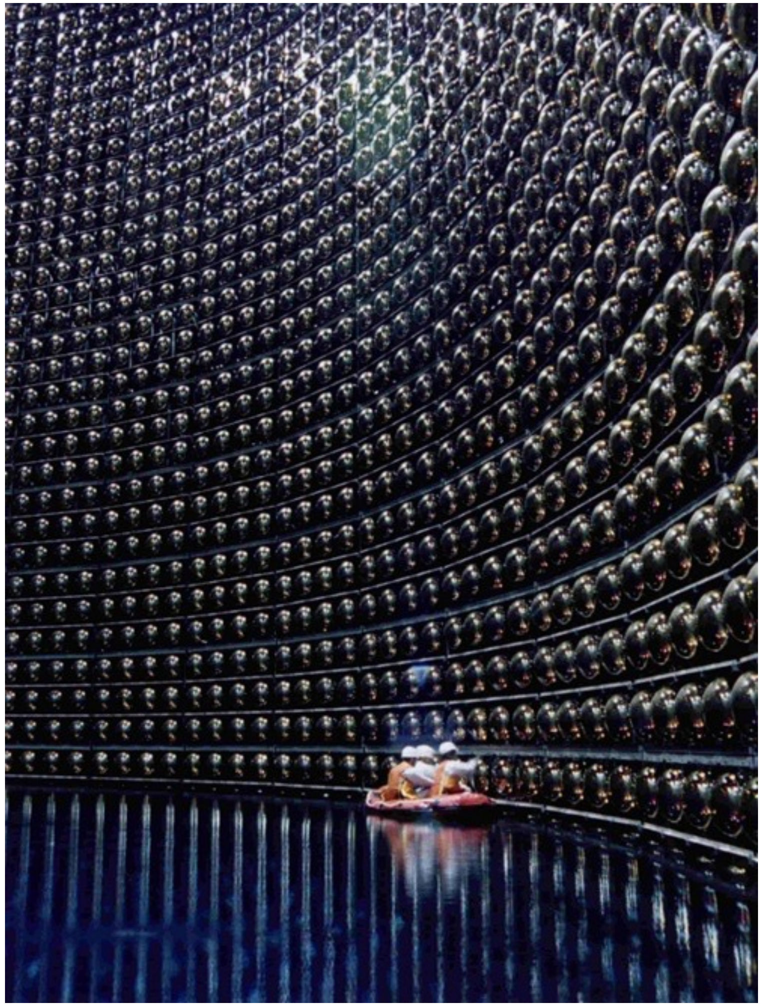
3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

One cycle of an oscillating neutrino as it passes through earth

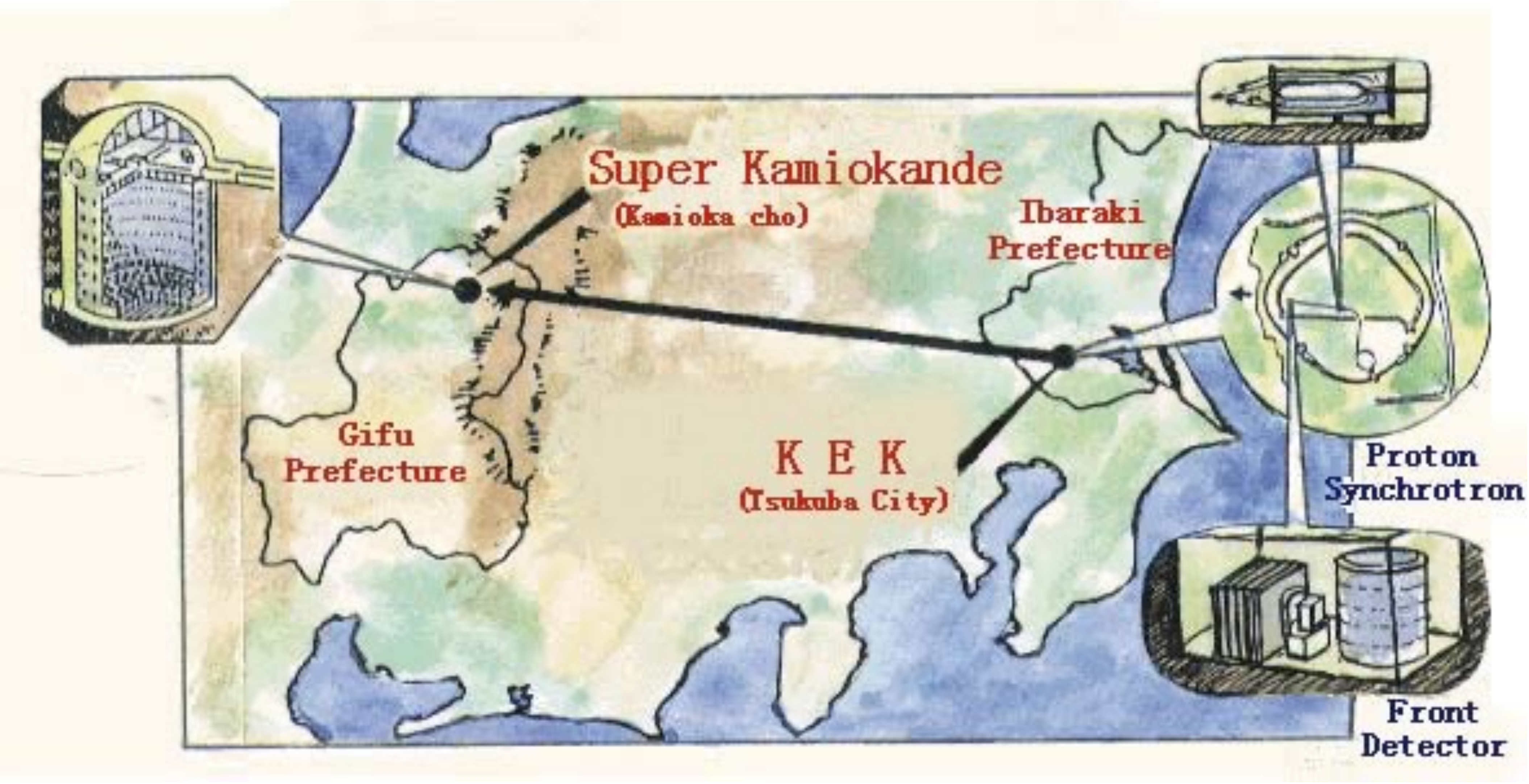
University of Hawai'i media graphic



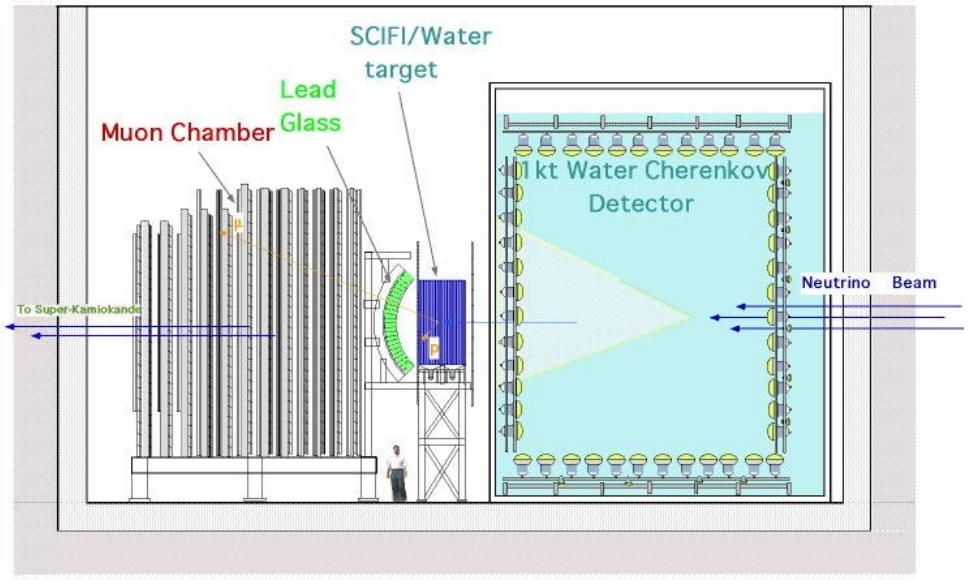
50 kiloton Water Cherenkov Detector
11,146 ID PMTs + 1,885 OD PMTs

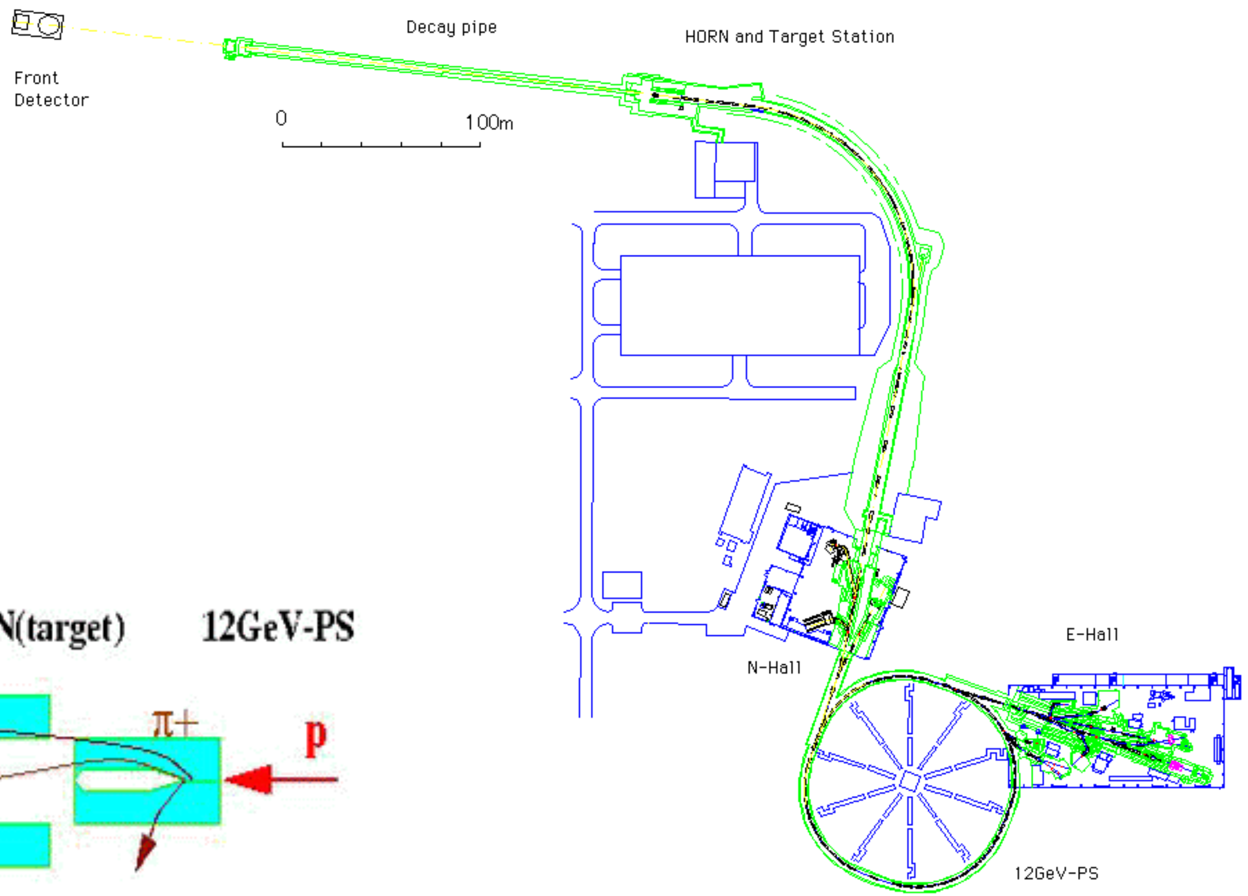


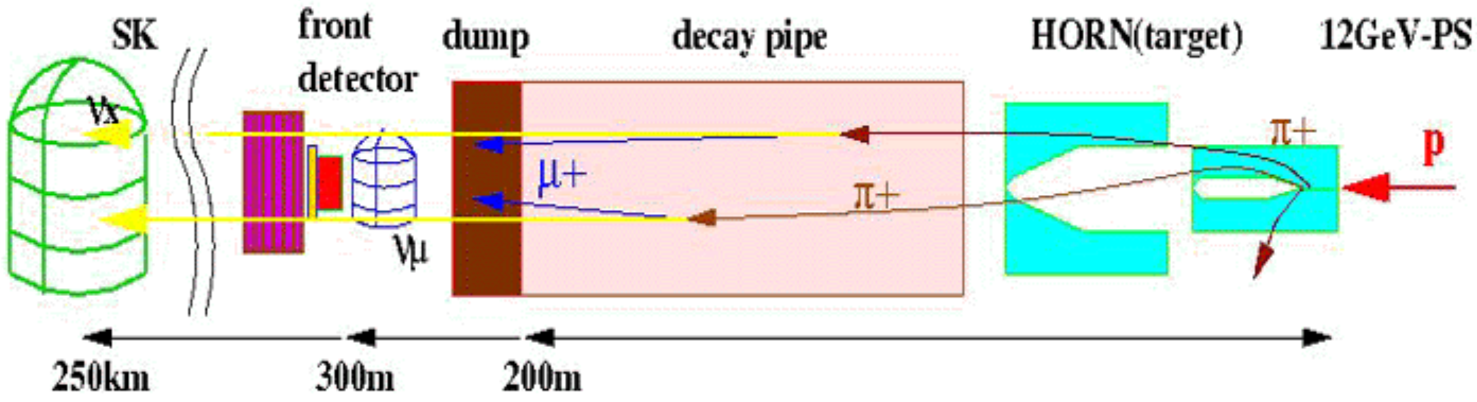
The Very First Long-Baseline Neutrino Oscillation Experiment K2K



The Very First Long-Baseline Neutrino Oscillation Experiment K2K







The Final Result of K2K in 2006

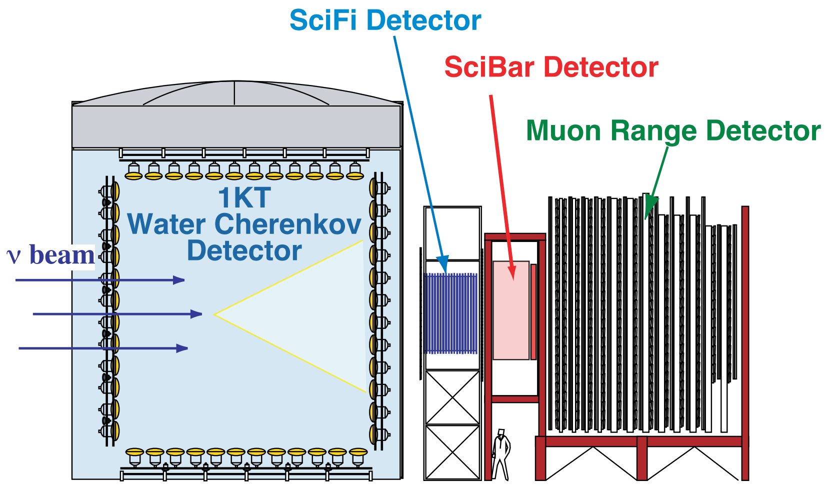
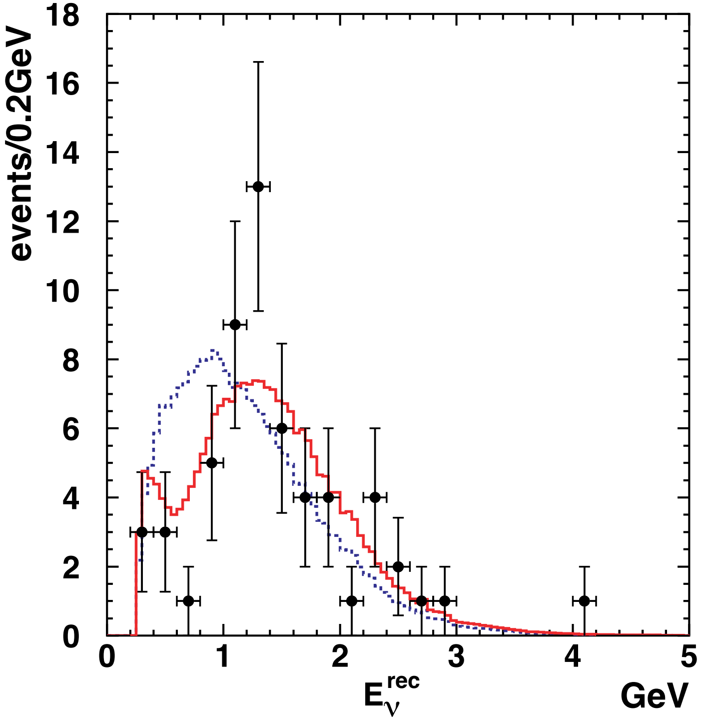
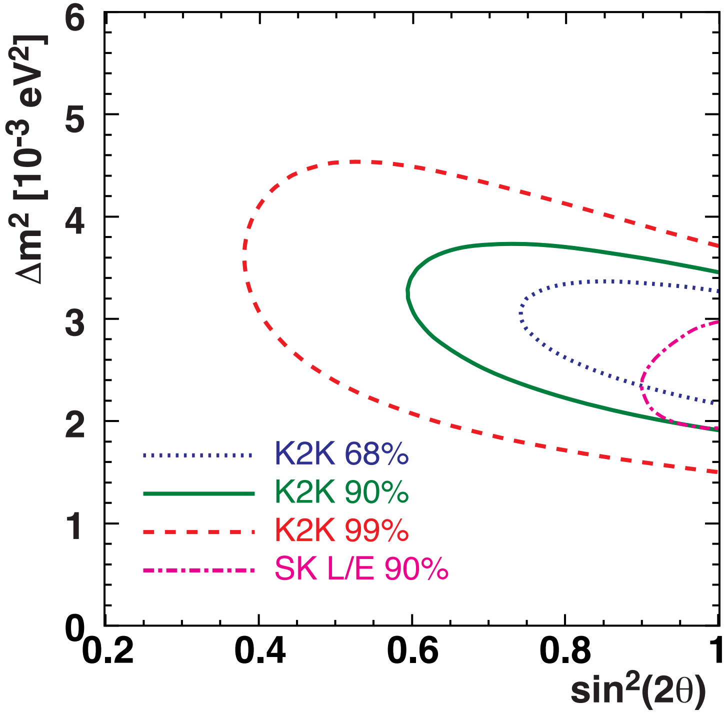


FIG. 7: The schematic view of the near neutrino detectors for K2K-IIb period. In K2K-I, the Lead-Glass calorimeter was located at the position of the SciBar detector.

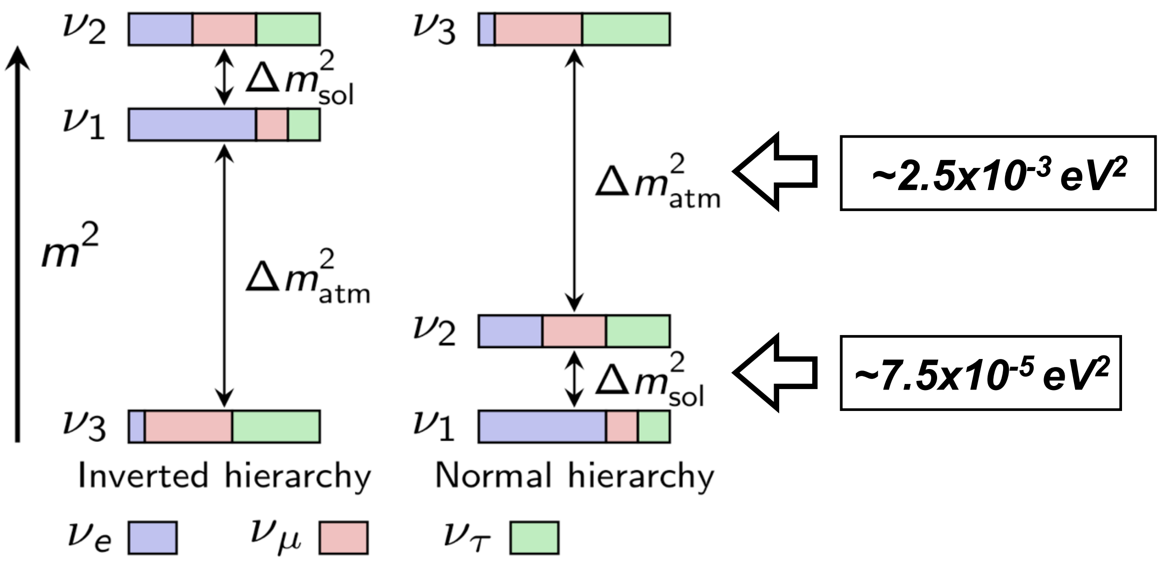




The Status of Neutrino Oscillation in 2006

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

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



Two popular ways to measure θ_{13}

- Short-baseline reactor disappearance experiments:

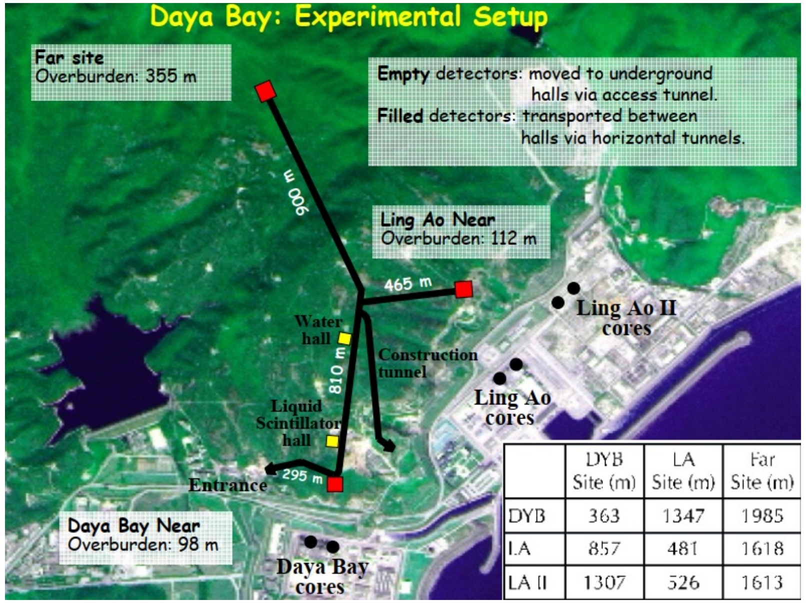
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

- Long-baseline appearance experiments

$$P_{\nu_\mu\to\nu_e} = \left|\sin\theta_{23}\sin 2\theta_{13}\left(\frac{\Delta_{31}}{\Delta_{31}-aL}\right)\sin(\Delta_{31}-aL)e^{-i(\Delta_{32}+\delta_{CP})} + \cos\theta_{23}\sin 2\theta_{12}\left(\frac{\Delta_{21}}{aL}\right)\sin(aL)\right|^2$$

θ_{13} status at Neutrino-2008

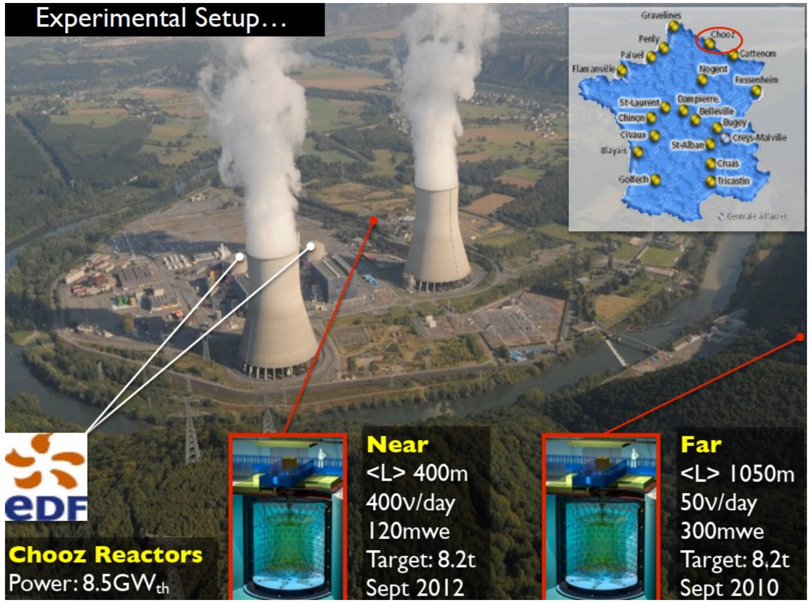
Three experiments, Daya Bay, Double Chooz and RENO started construction



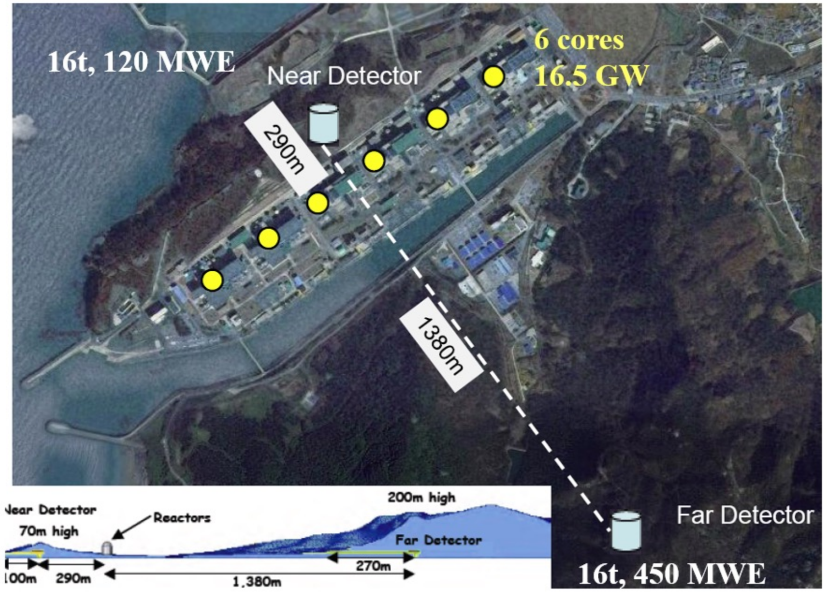
Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.

	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

- Daya Bay will reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$
- Civil construction has begun
- Subsystem prototypes exist
- Long-lead orders initiated
- Daya Bay is moving forward:
  - Surface Assembly Building - Summer 2008
  - DB Near Hall - installation activities begin early in 2009
  - Assembly of first AD pair - Spring 2009
  - Commission Daya Bay Hall by November 2009
  - LA Near and Far Hall - installation activities begin late in 2009
  - Data taking with all eight detectors in three halls by Dec. 2010



- Double Chooz Far integration Started in May 08
- First goal: measurement of θ_{13}
  - *2008-09 → Far Detector construction & integration*
  - *Middle 09 → Start of phase I : Far 1 km detector alone*
    $\sin^2(2\theta_{13}) < 0.06$ after 1,5 year (90% C.L.) if no-oscillation
  - *2008-10 → Near Lab Escavation & Near Detector Integration*
  - *2011 → Start of phase II : Both near and far detectors*
    $\sin^2(2\theta_{13}) < 0.03$ after 3 years (90% C.L.) if no-oscillation



❑ RENO is suitable for measuring θ_{13} ($\sin^2(2\theta_{13}) > 0.02$)

❑ Geological survey and design of access tunnels & detector cavities are completed. Civil construction will begin in early June, 2008.

❑ RENO is under construction phase.

❑ Data taking is expected to start in early 2010.

Asian Reactor Anti-Neutrino Experiments DAYA BAY and RENO, Christopher White at Nu-2008
Towards θ_{13}: Double Chooz and non-asian efforts, Thierry Lasserre at Nu-2008

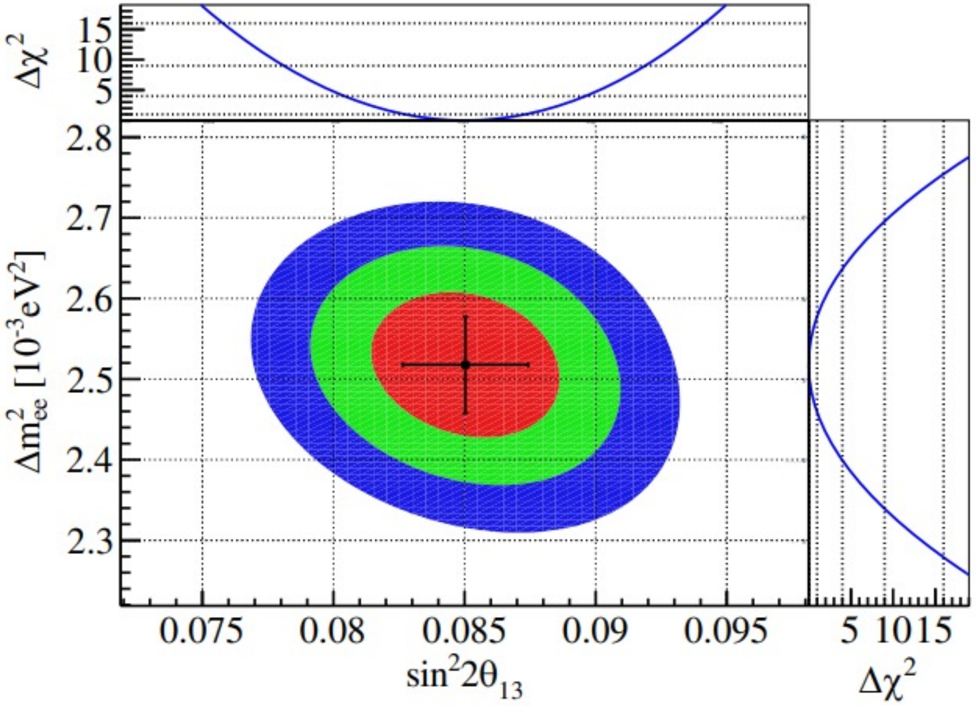
θ_{13} with nGd -- Daya Bay

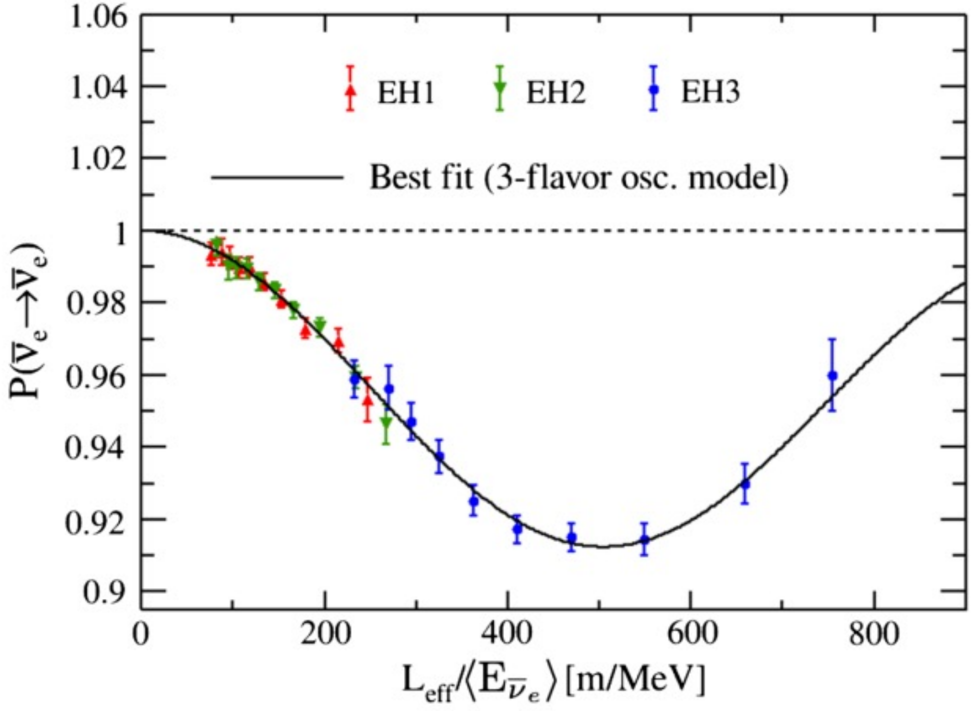
Daya Bay reported the precision measurement with 3158-days full dataset in 2022

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

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

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

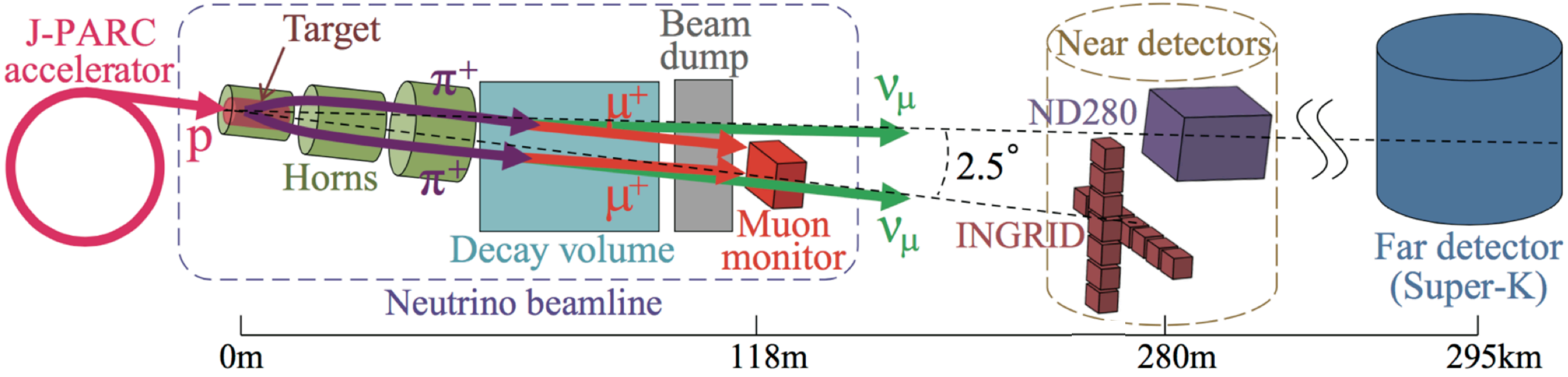




PhysRevLett. 130 161802

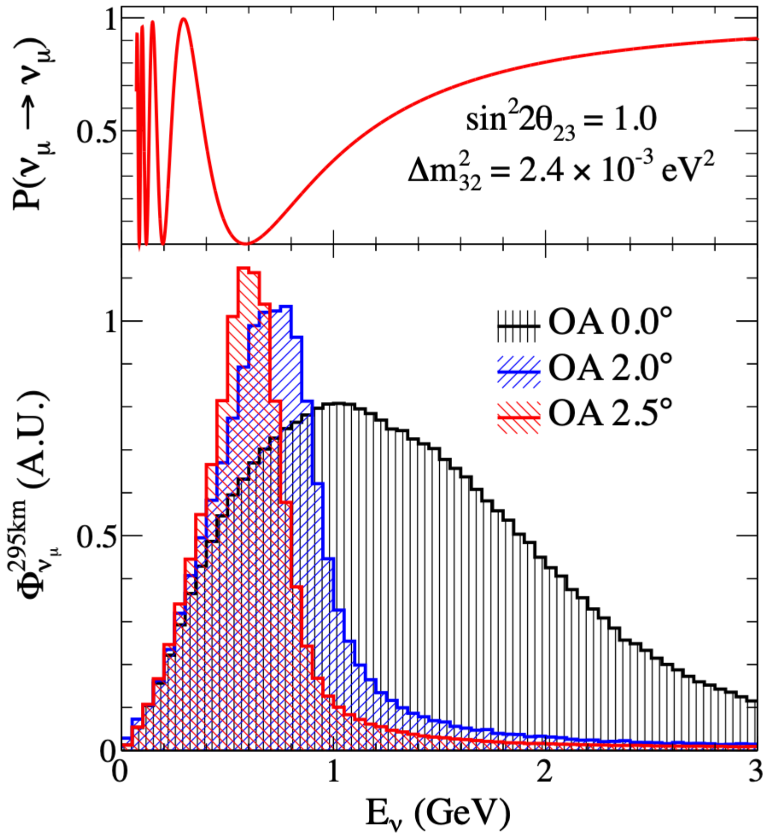
A Upgraded K2K: the T2K Experiment

Claudio Gig



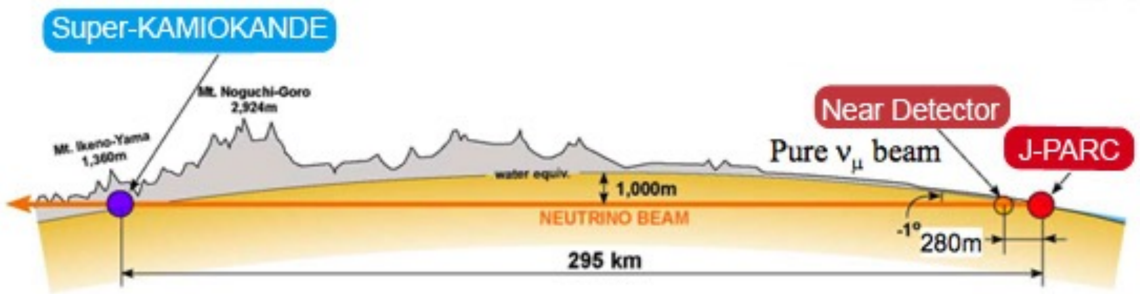
- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- p+C interactions producing hadrons (mainly pions and kaons)
- Hadrons are focused and selected in charge by 3 electromagnetic horns
  - If π^+ are focused ν_μ are produced by $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Changing 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

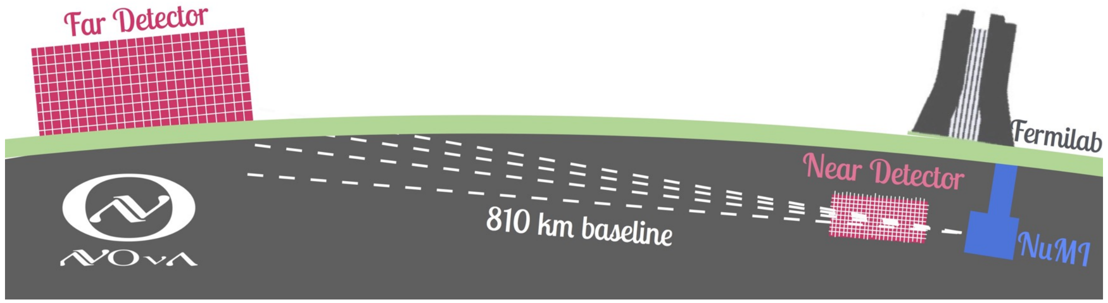
ν_μ survival probability

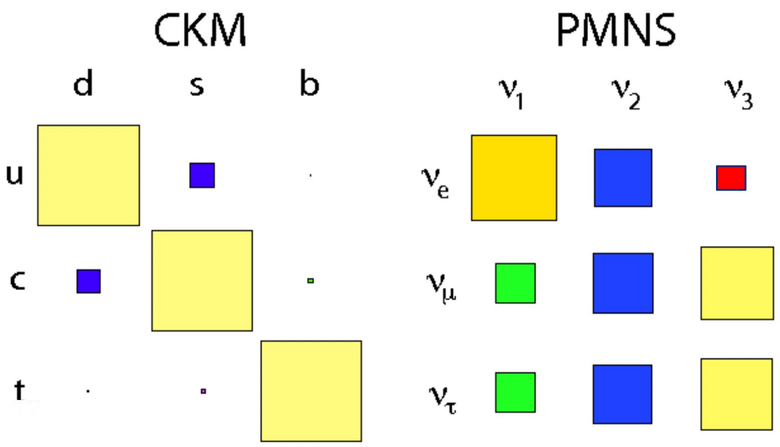


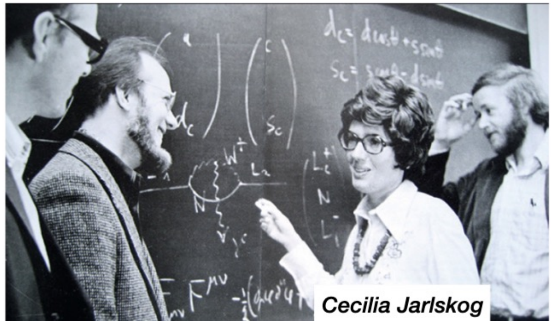
The Current Generation of Long-Baseline Experiments

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



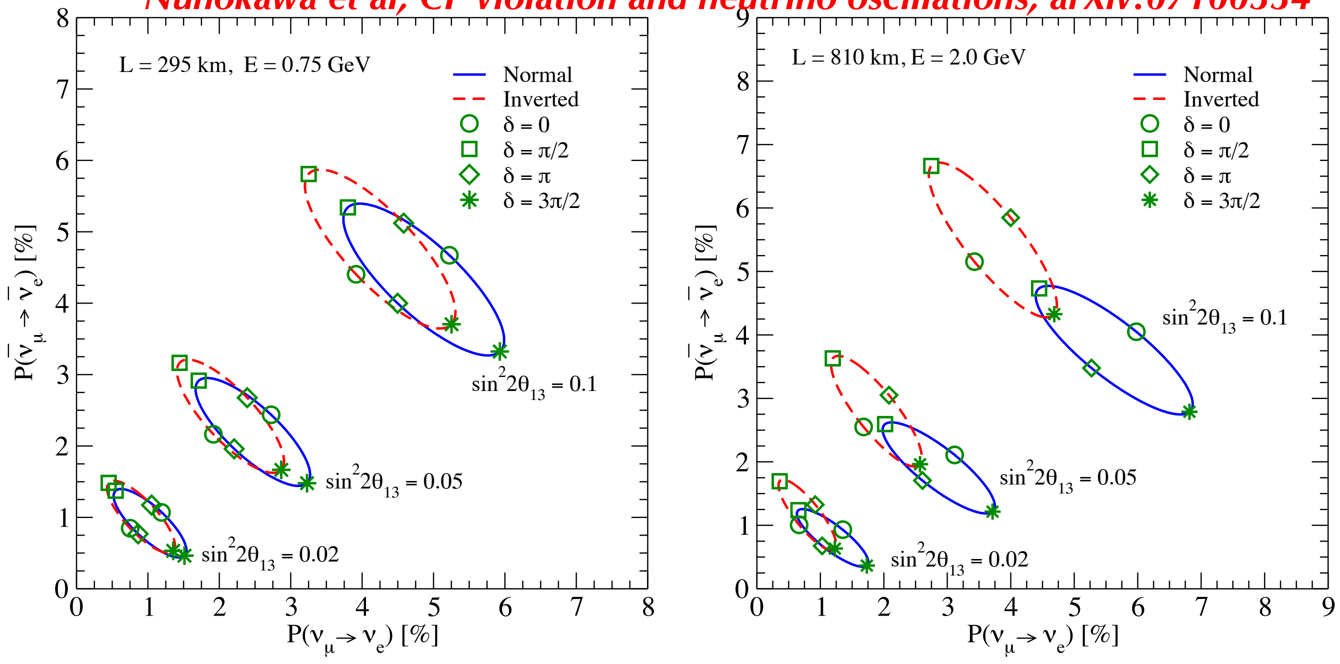




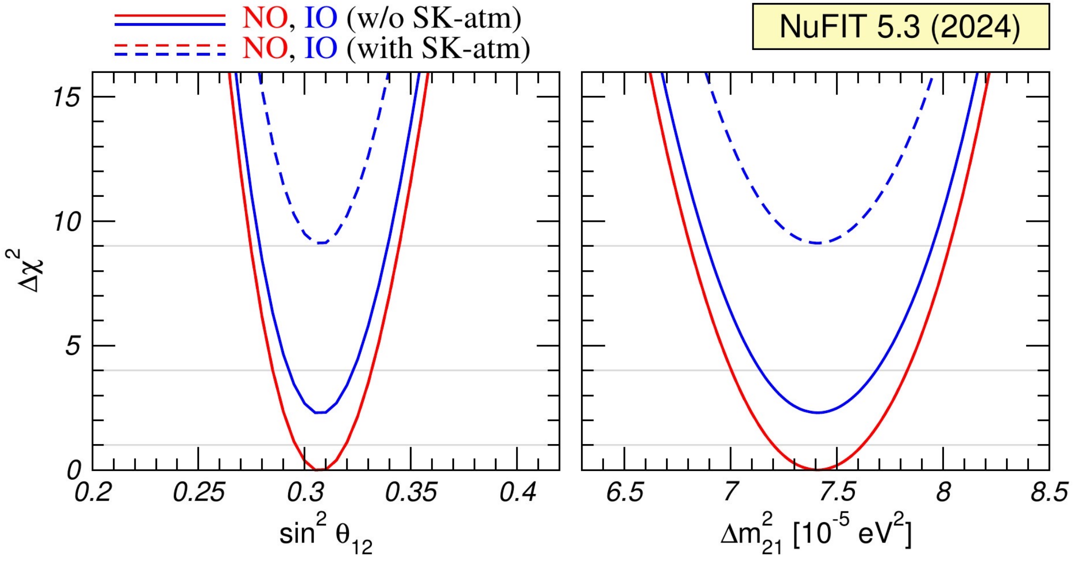


$$\frac{J_{\mathrm{PMNS}}}{J_{\mathrm{CKM}}} = \frac{3\times10^{-2}}{3\times10^{-5}}\sin(\delta_{\mathrm{PMNS}})$$

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

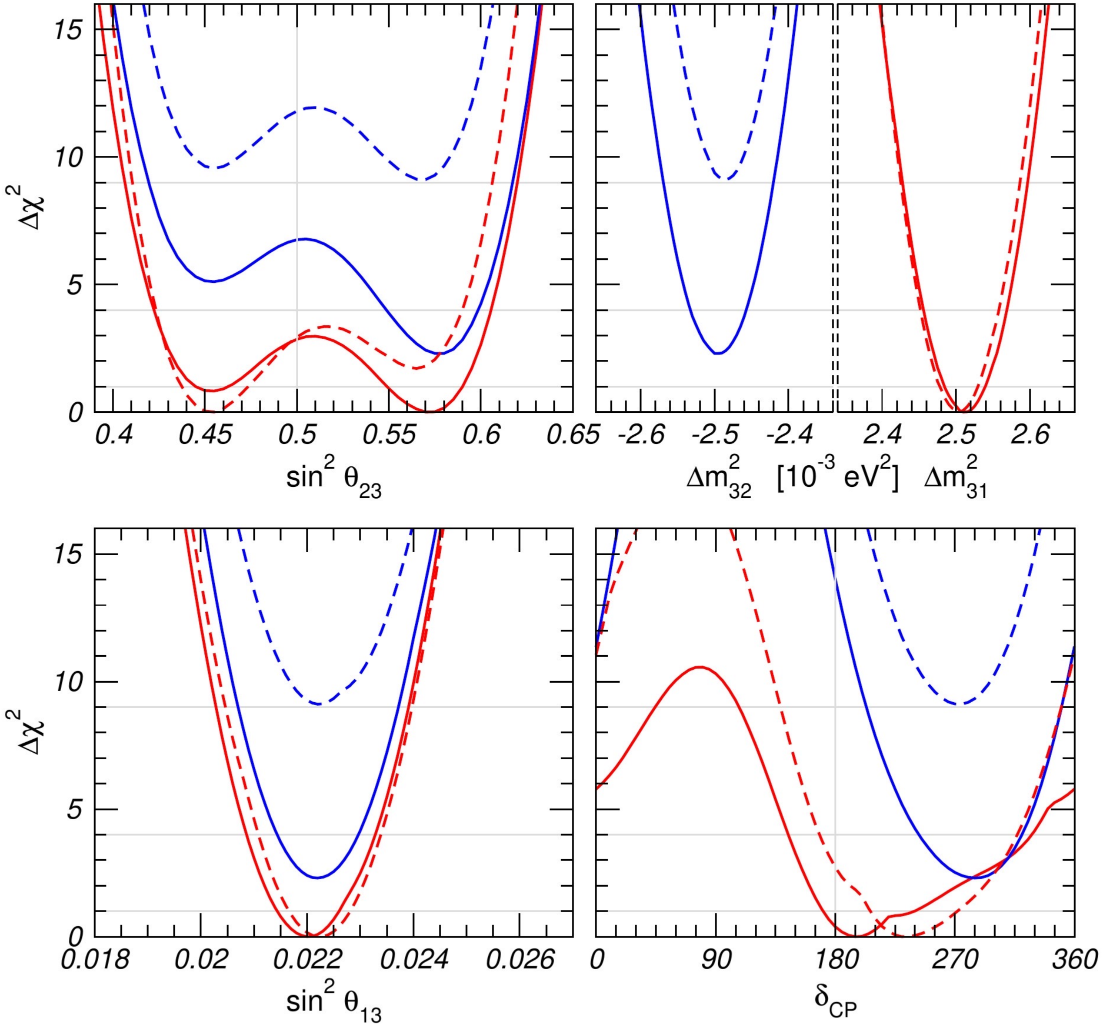


The Current Global Analysis of Neutrino Oscillation Experiments

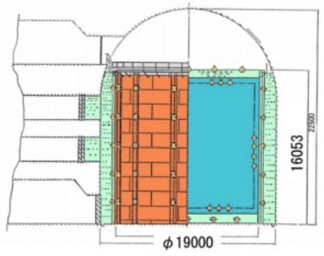
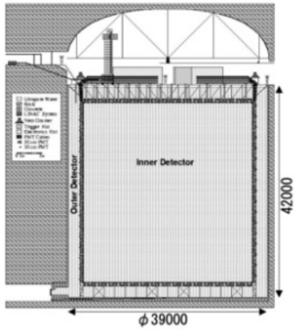
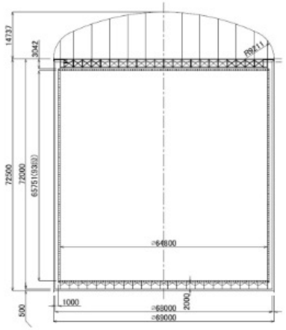


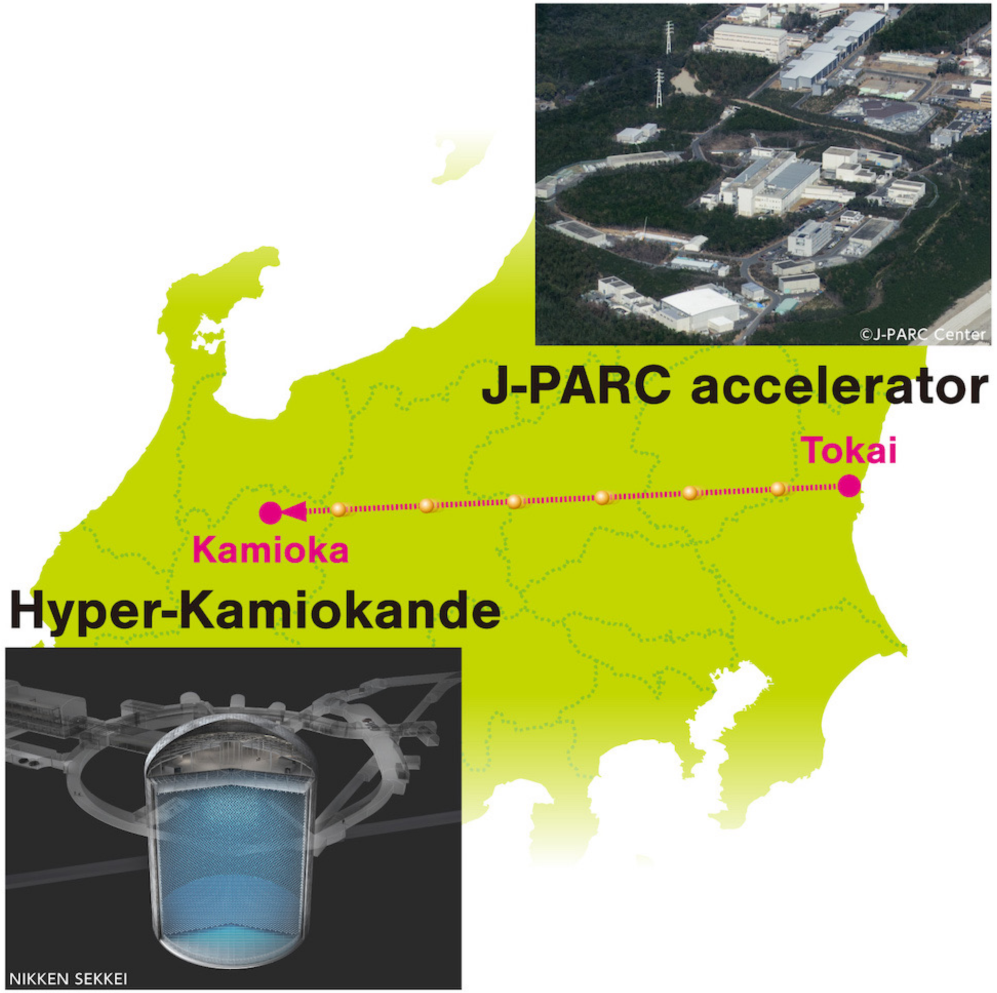
- *Global Analysis http://www.nu-fit.org, JHEP 09 (2020) 178 [arXiv:2007.14792]*

- Good or bad: Normal Ordering is preferred
- Octant: Not resolved
- CP: indication of being violated



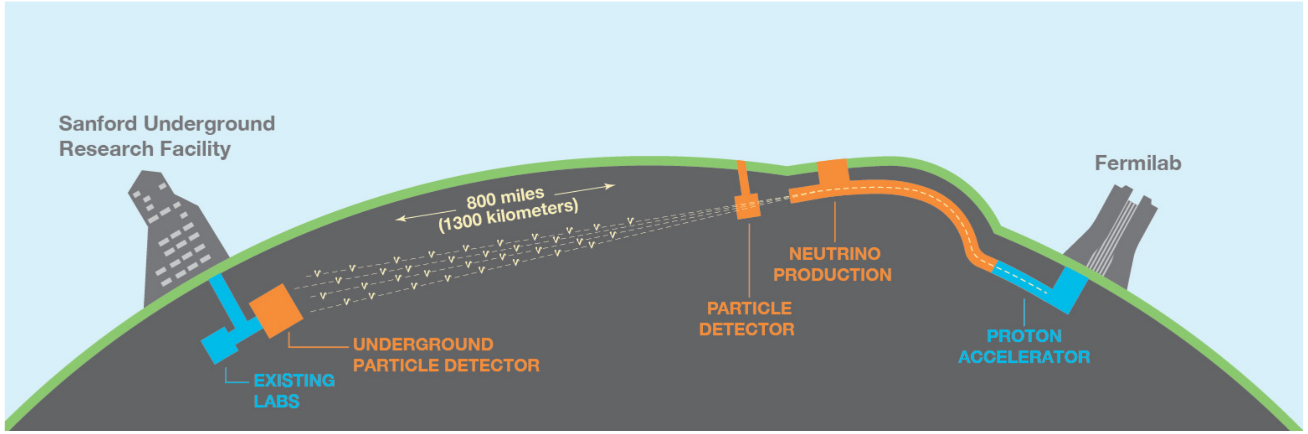
Future Long-Basline Program: Hyper-Kamiokande

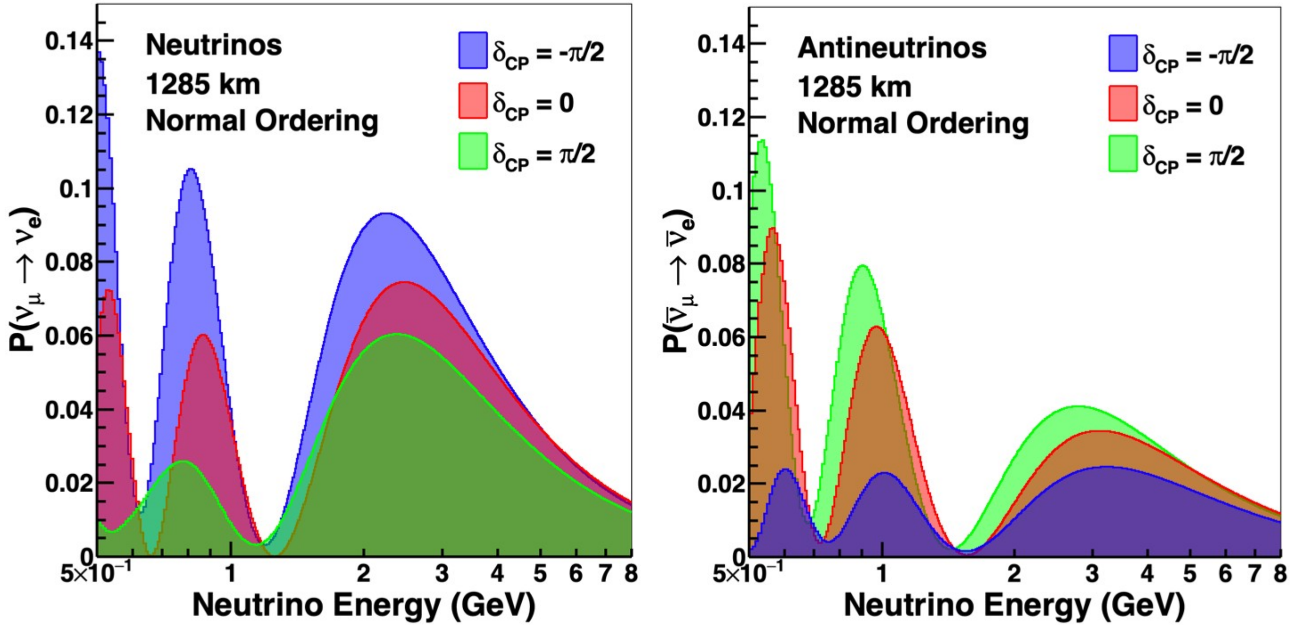
Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996-Present	Aiming to start observation in 2027
		
Size		
19m diameter x 16m hight	39m diameter x 42m hight	68m diameter x 71m hight
Water mass (Fiducial mass)		
4500 ton※ (680~1040 ton) ※The waer mass in the tank(inner tank and, upper and bottom 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

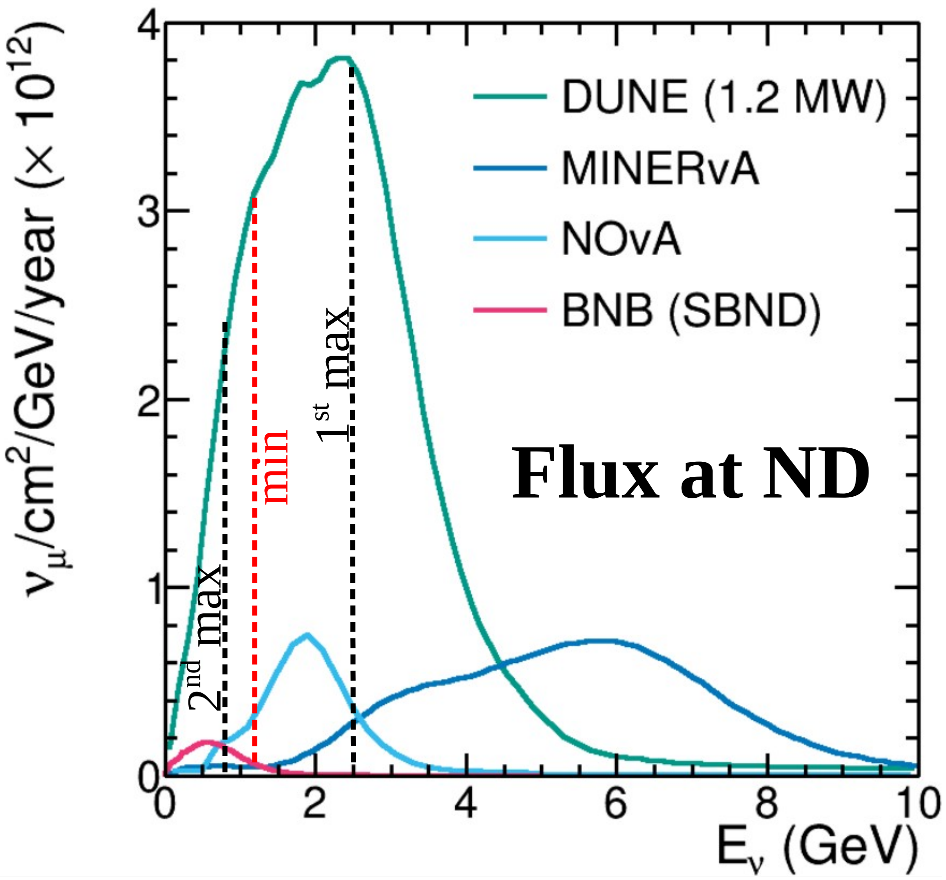


U.S. Efforts of Long-Baseline Neutrino Experiment

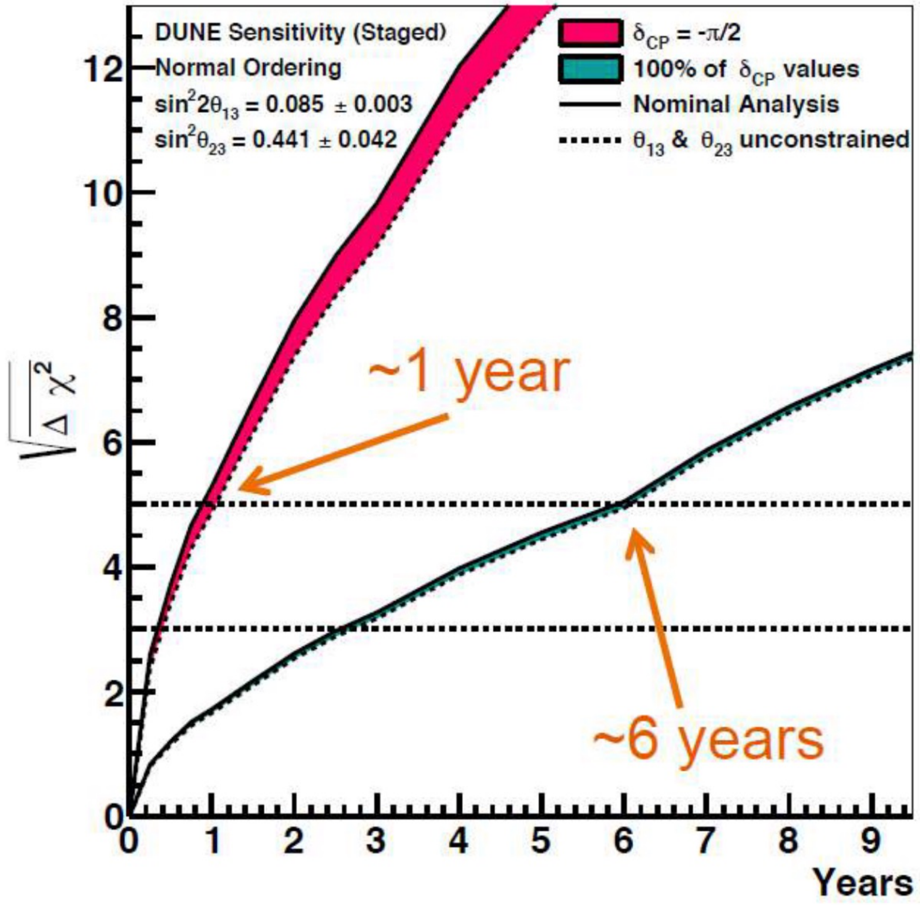
- **In the U.S., MINOS/MINOS+/NOvA upgrading to LBNF → DUNE**





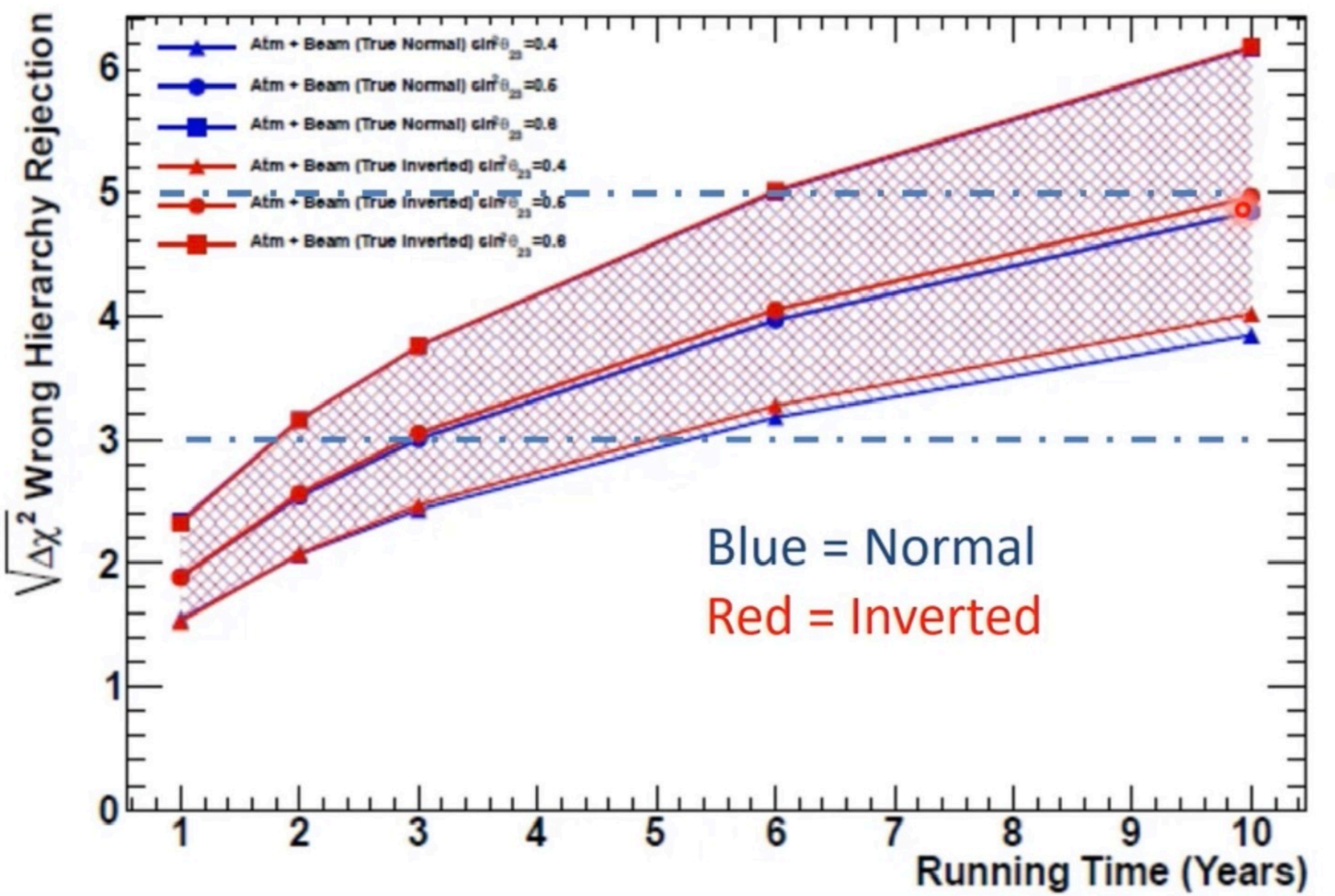


DUNE versus Hyper-K Comparison in Mass Ordering



~1 year

~6 years



Blue = Normal

Red = Inverted

Global Efforts Resolving ν Mass Hierarchy

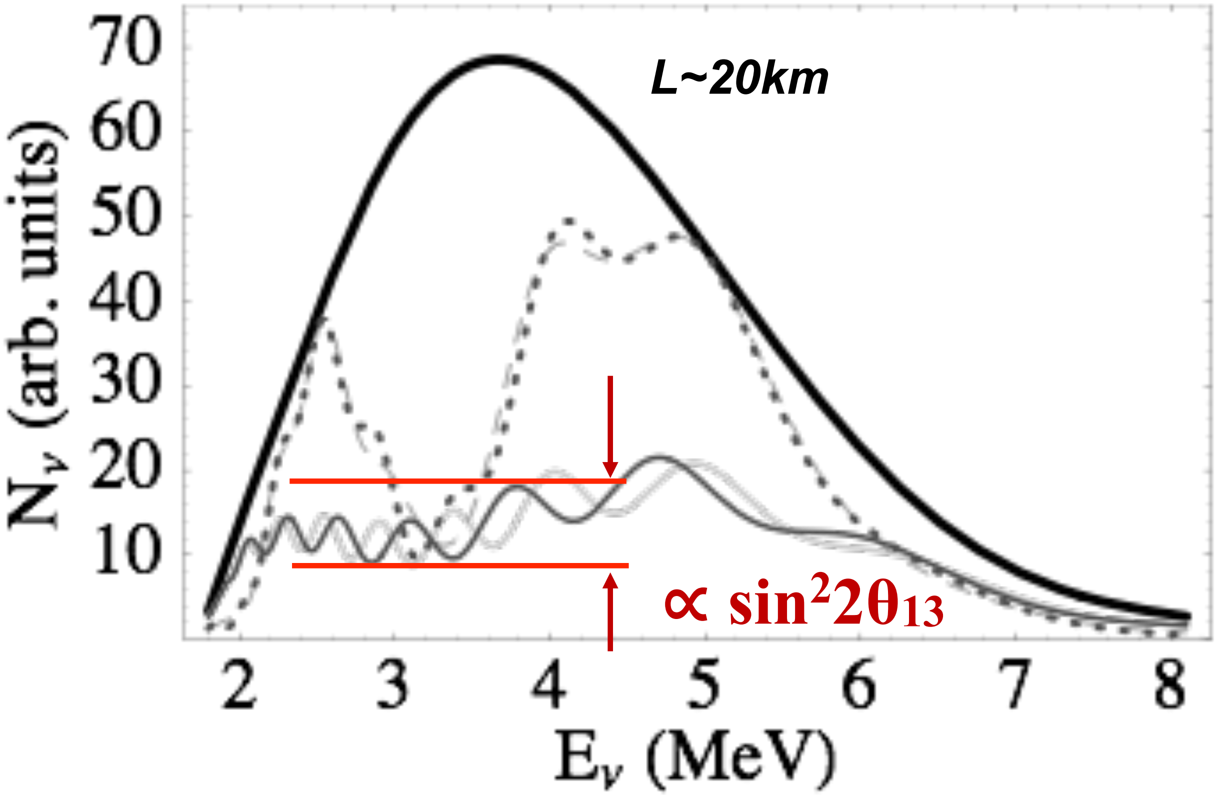
Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation	Constraining Total Mass or Effective Mass
Atmospheric ν	Super-K, Hyper-K, IceCube PINGU, ICAL/INO, ORCA, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO + Atm/Beam 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

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

$$- \boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

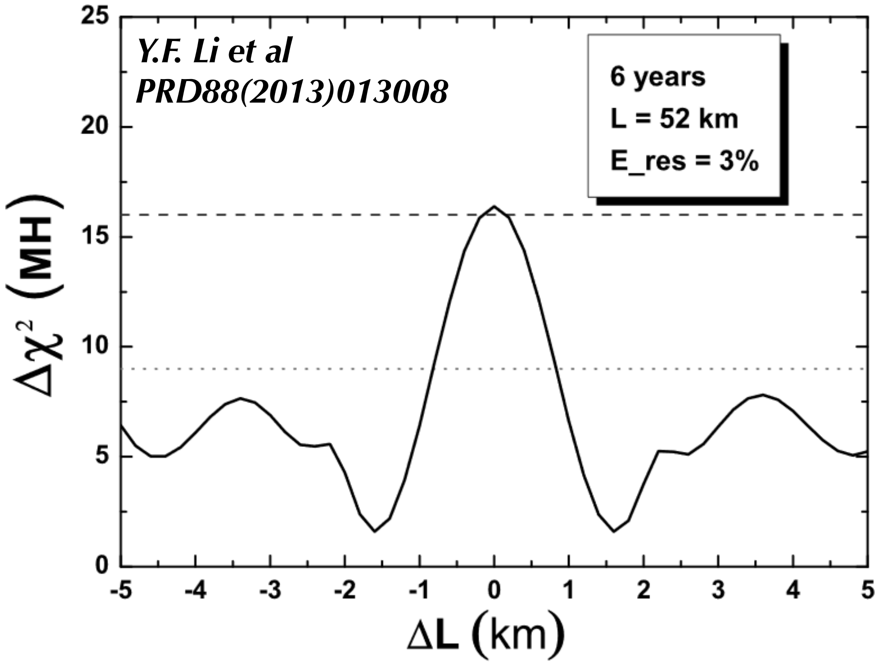
Petcov&Piai, Phys. Lett. B533 (2002) 94-106

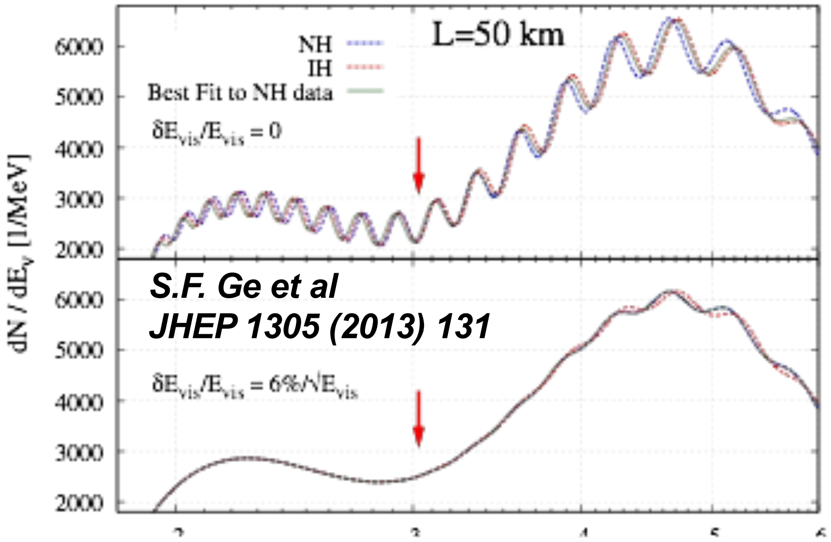


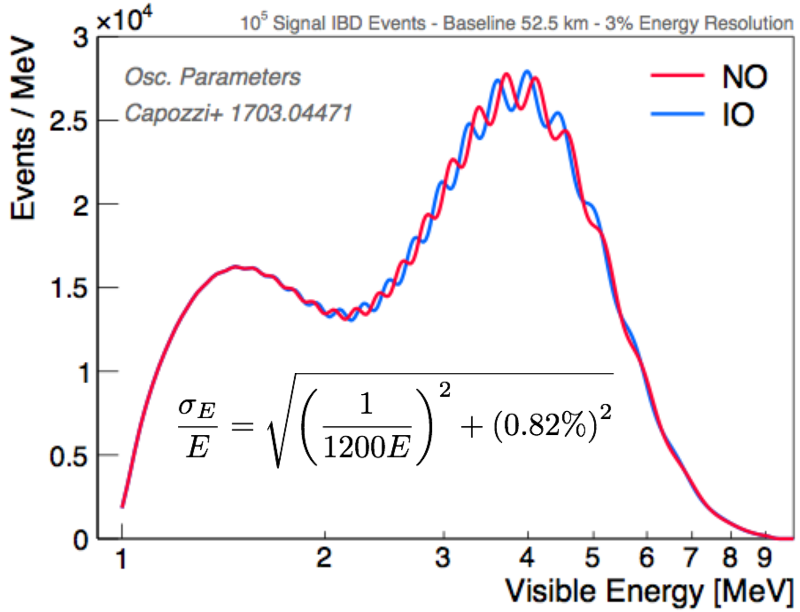
- √ **Mass hierarchy reflected in the spectrum**
- √ **Independent of the unknown CP phase**

Challenges in Resolving MH using Reactors

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







$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{1}{1200E}\right)^2 + (0.82\%)^2}$$

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**

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)

JUNO Site

Surface buildings / campus

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

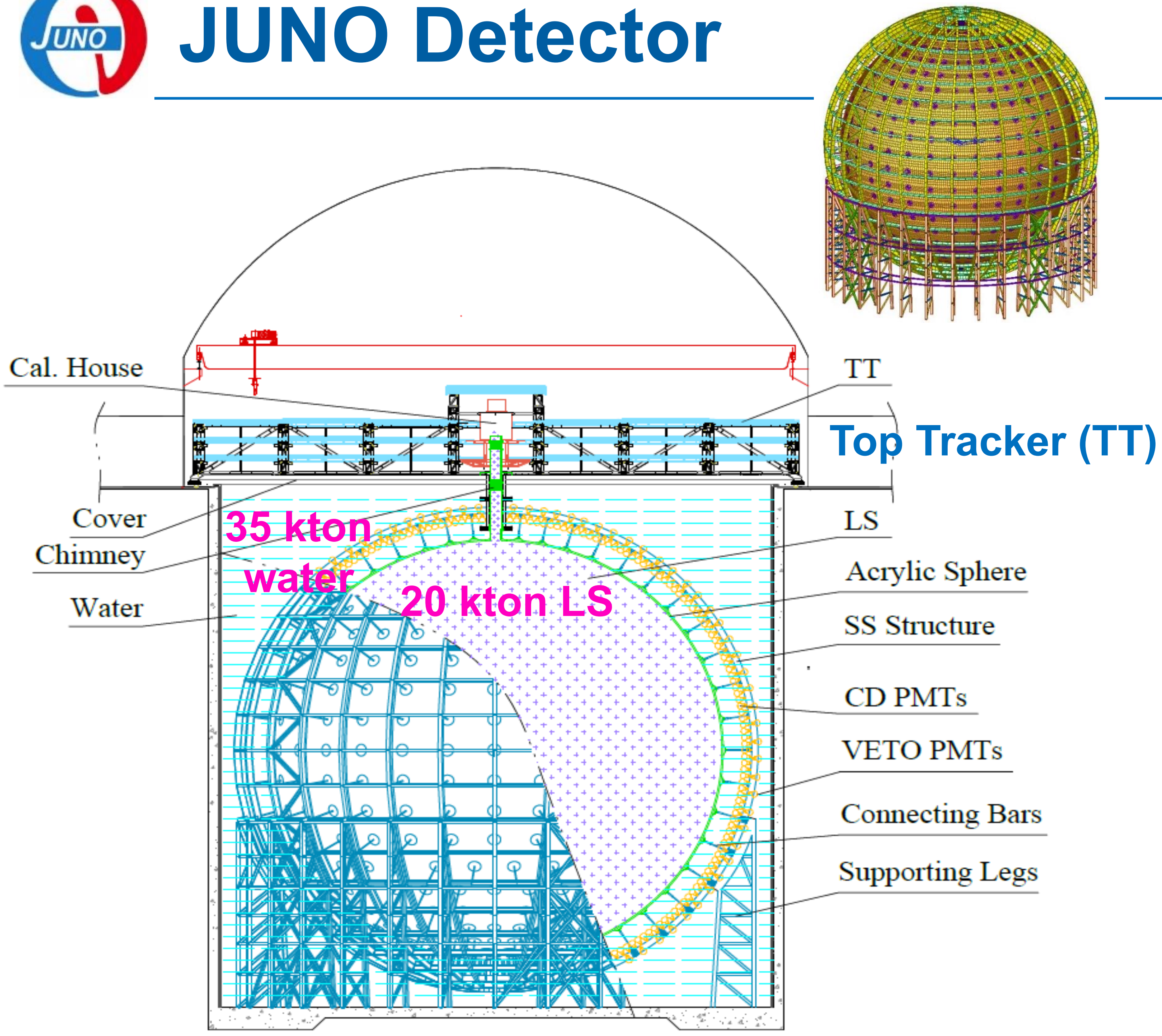
Vertical Shaft, 564 m
put into use in 2023

Slope tunnel, 1266 m

~ 650 m
$R_\mu \sim 0.004\ \mathrm{Hz/m^2}$
$\langle E_\mu \rangle \sim 207\ \mathrm{GeV}$

~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

$$\frac{\Delta E}{E} = \sqrt{\underbrace{a^2}_{\text{Energy leakage \& non-uniformity}} + \underbrace{\frac{b^2}{E}}_{\text{Photon statistics}} + \underbrace{\frac{c^2}{E^2}}_{\text{Noise (~background)}}}$$

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

Construction of the Central Detector

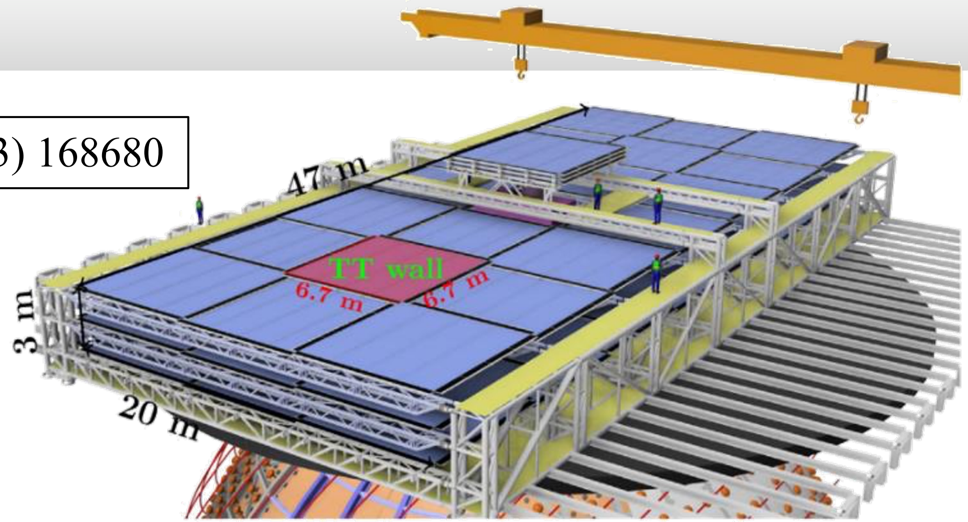
arXiv: 2311.17314 (2023)

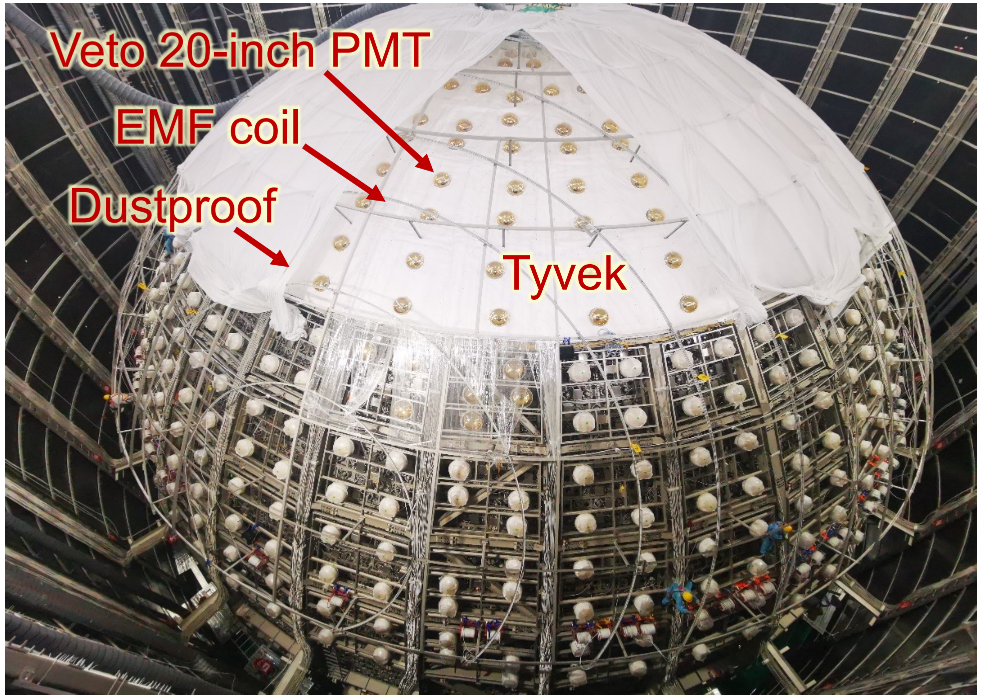
Diameter and height change for each layer of acrylic bonding

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

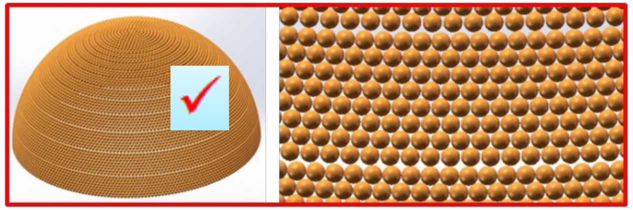




Packing PMTs as Tight as Possible

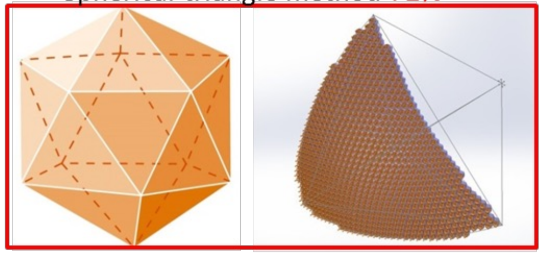
Supper layer arrangement method 77.8%

1



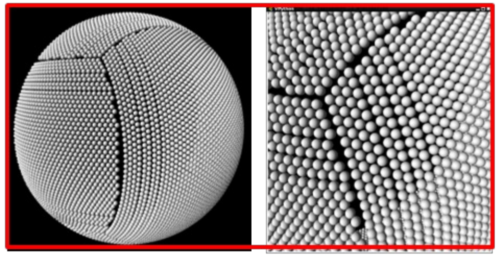
Spherical triangle method 72%

2



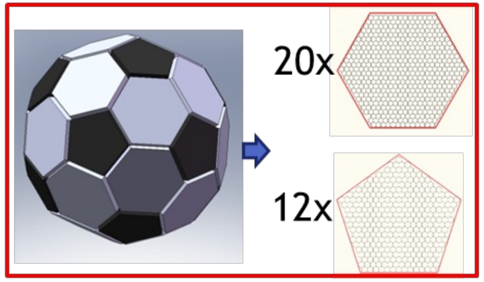
Volleyball arrangement method 75.96%

3



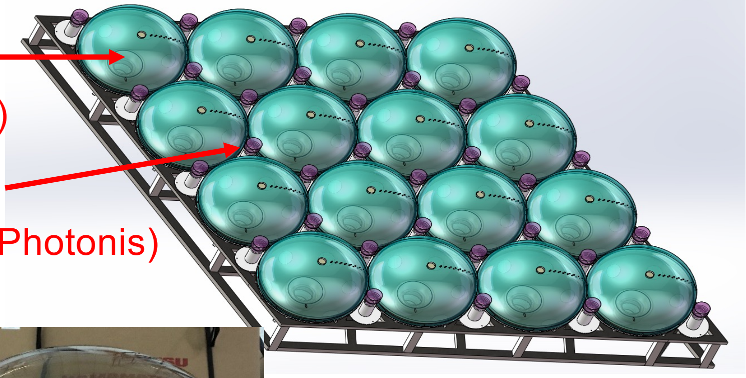
Football arrangement method 74.08%

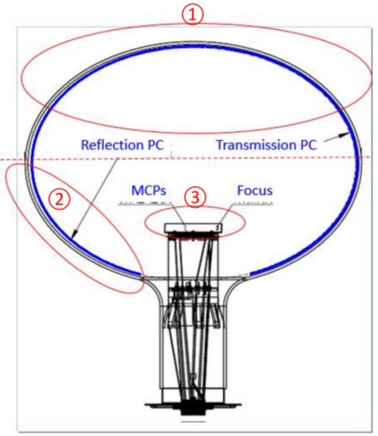
4

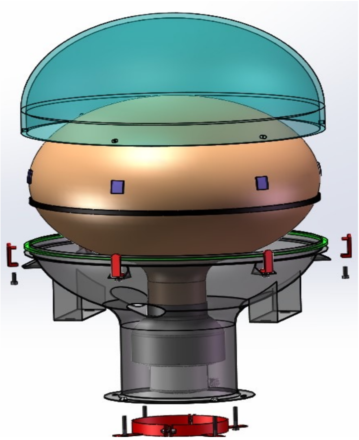


20” PMT (~18K)
MCP-PMT (~13K)
Hamamatsu HQE (5K)

3”sPMT(~25K)
HZC XP72B22 (Photonis)







PMT Summary

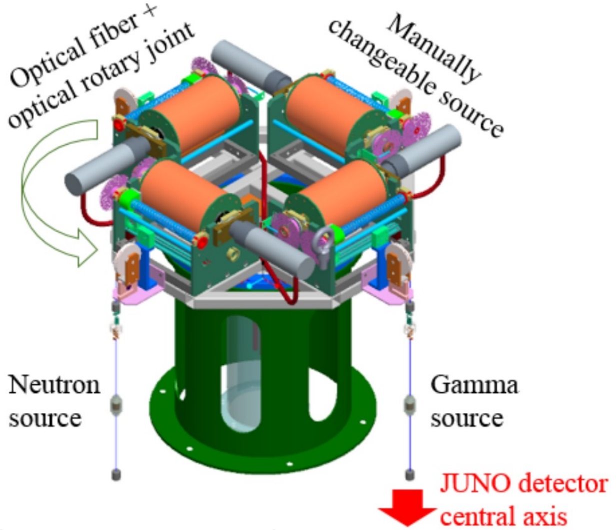
- 20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu)
  3.1-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
  - All PMTs delivered and their performance tested OK
- Water proof potting done: failure rate < 0.5%/6 years
- Implosion protection: acrylic top & SS bottom (JINST 18 (2023), P02013)
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

3 mm clearance

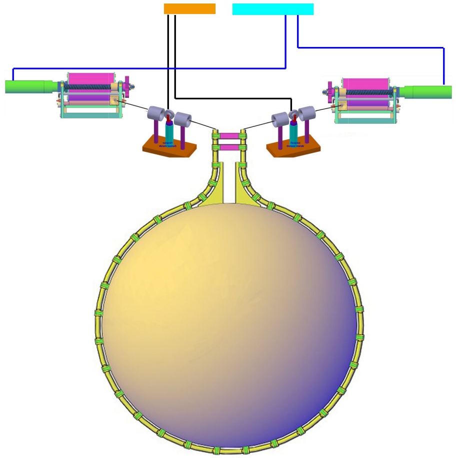
	LPMT (20-in)		SPMT (3-in)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Charge Collection	Dynode	MCP	Dynode
Photon Det. Eff.	**28.5%**	**30.1%**	**25%**
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	**75%**		**3%**
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

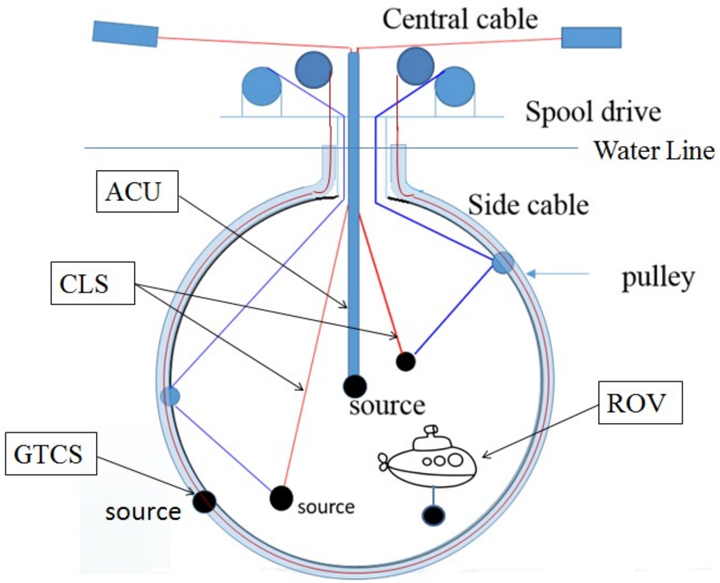
Calibration System *based on the Daya Bay experiences*

Automatic Calibration Unit (ACU)



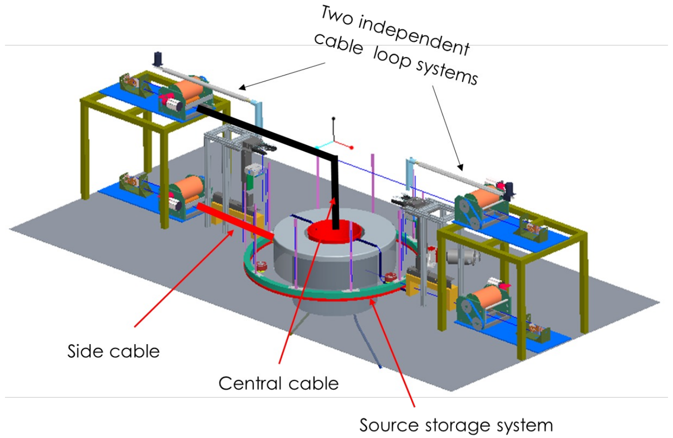
Guide Tube Calibration System(GTCS)



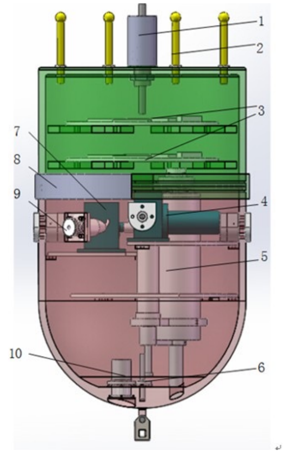


- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

Cable Loop System (CLS)



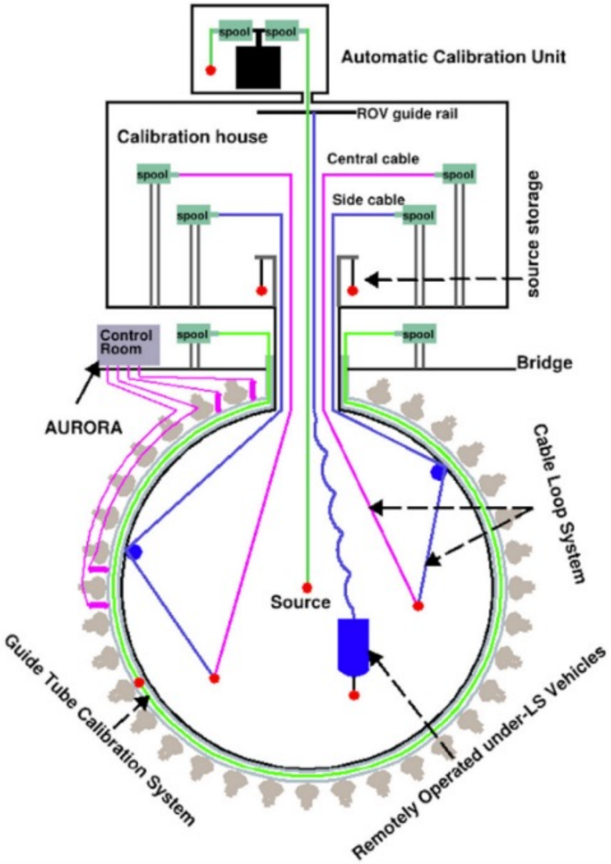
Remotely Operated under-liquid-scintillator Vehicles (ROV)



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% u spectrum

JHEP 03 (2021) 004



Calibration house

All systems ready for installation

arXiv:2405.17860 (2024)

For positron

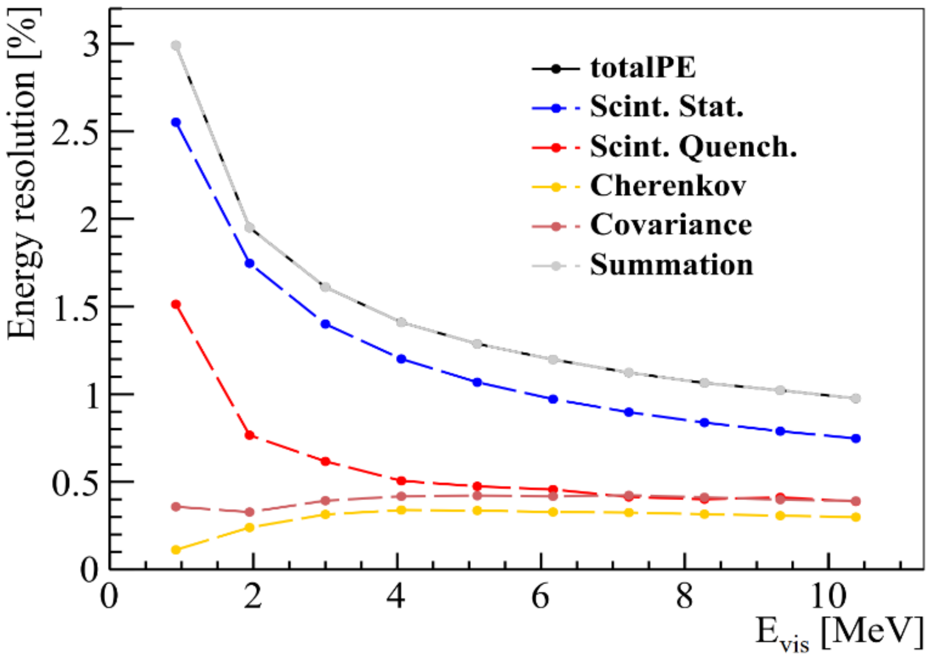
$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

Photon statistics

Constant term

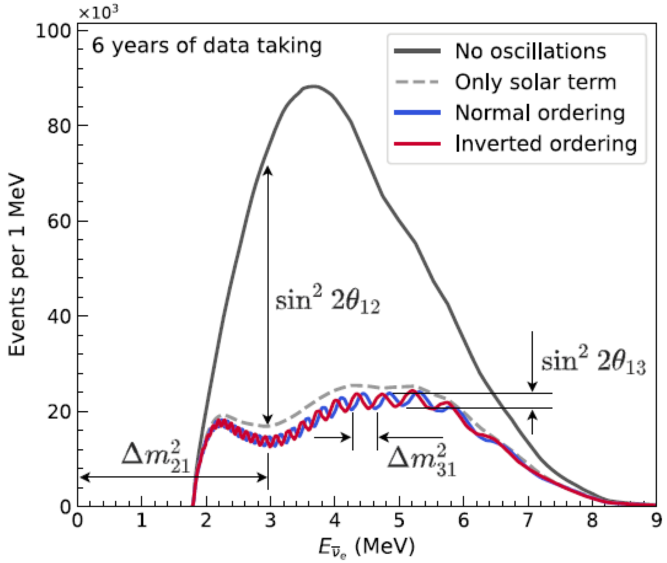
Dark noise, Annihilation -induced γs

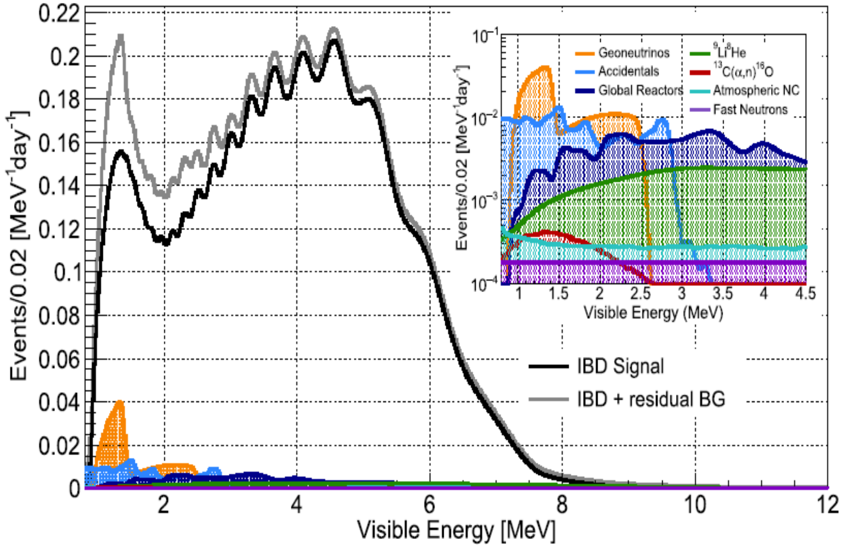
Expected energy resolution: 2.95% @1MeV



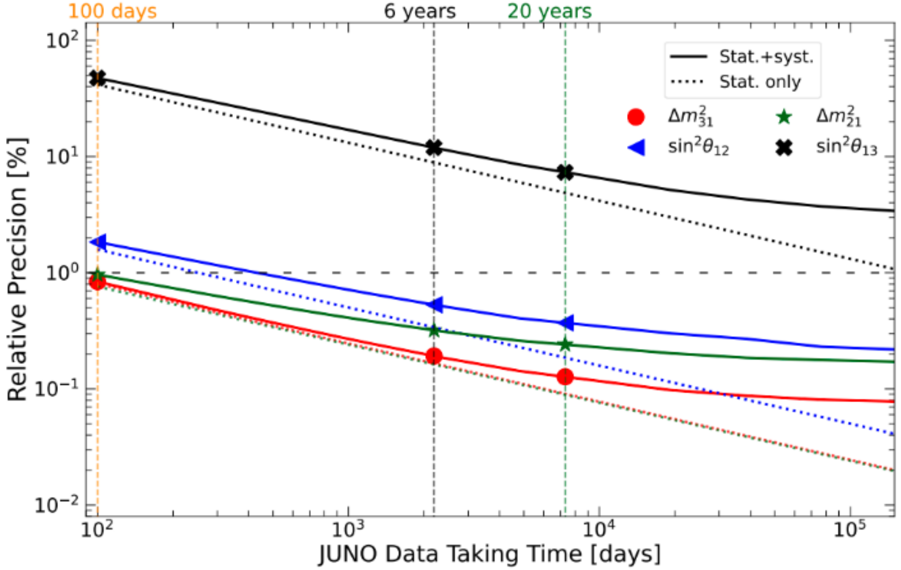
Precision Measurement of oscillation parameters

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





Chin. Phys. C46 (2022) 12, 123001

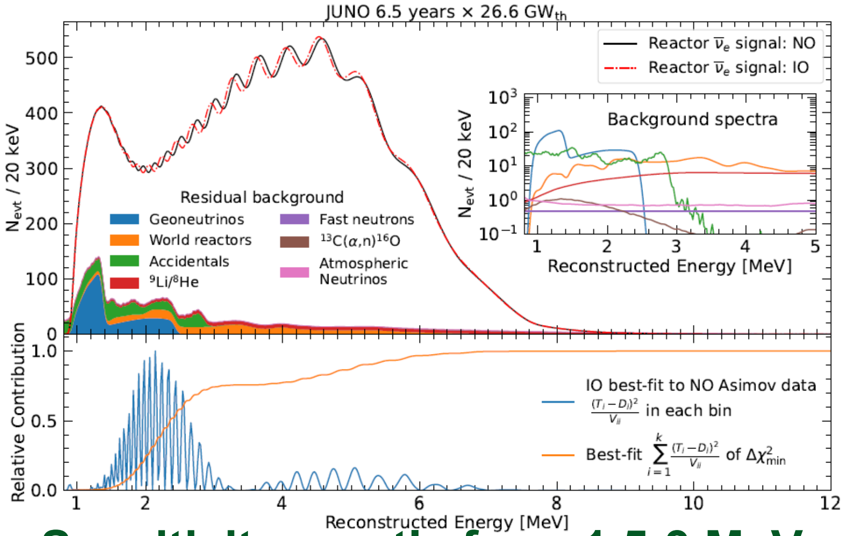


	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016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

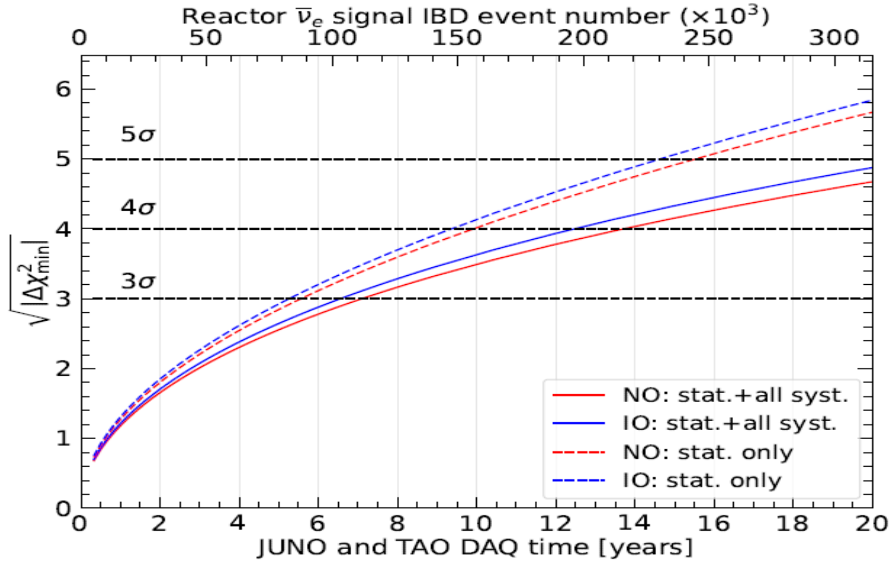
$\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, leading measurements in 100 days; precision <0.5% in 6 years

Neutrino Mass Ordering

arXiv:2405.18008 (2024)



Sensitivity mostly from 1.5-3 MeV

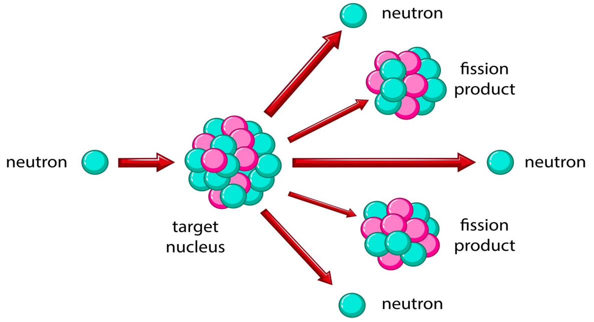


	Design	Now
Thermal Power	36 GW$_{th}$	26.6 GW$_{th}$ (**26%↓**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (**33%↑**)
Muon veto efficiency	83%	91.6% (**11%↑**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (**2%↑**)
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**

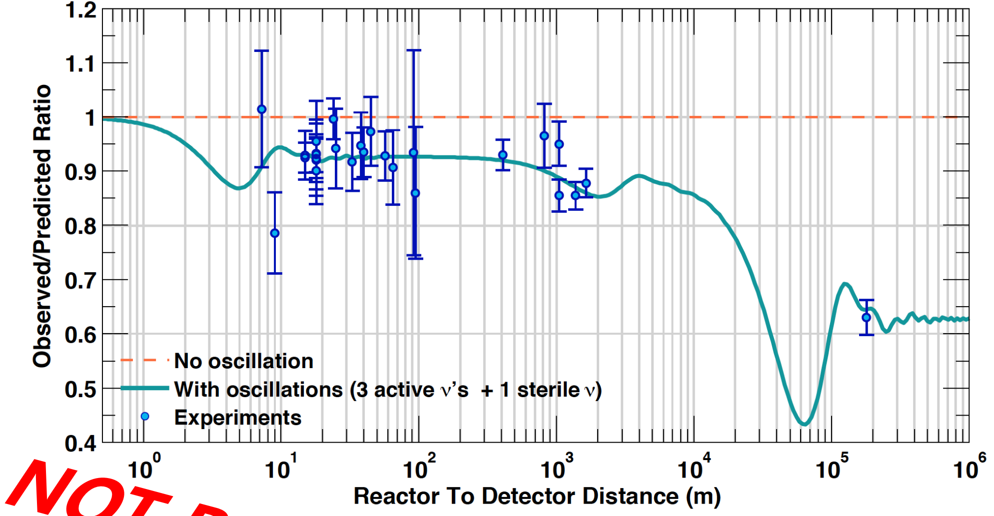
Reactor Antineutrino Anomaly (RAA)

Nuclear Fission



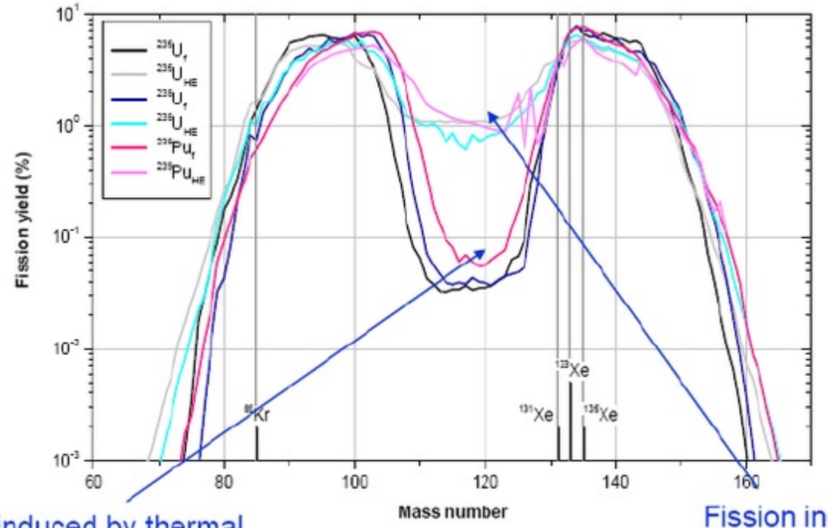
- *T. A. Mueller et al., PRC83, 054615 (2011)*
- *P. Huber, Phys. Rev.C84, 024617 (2011)*
- *Daya Bay, PRL116(2016), PRL123(2019)*
- *RENO, PRL121(2018)*
- *NEOS, PRL118(2017)*
- *Double Chooz, Nature Physics 16(2020)*

http://irfu.cea.fr/Spp/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=3045



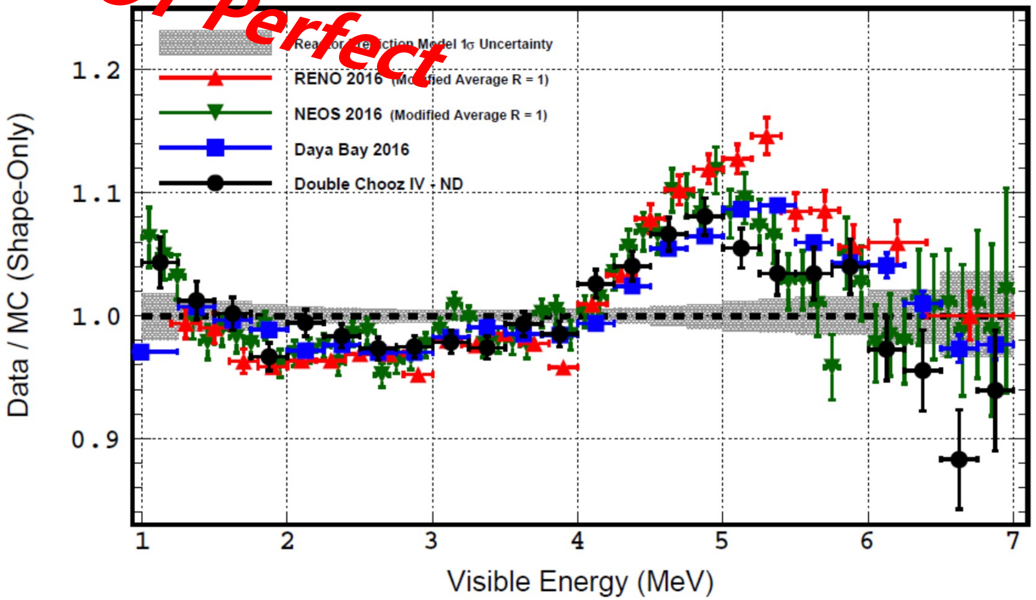
Reactor Neutrinos NOT Perfect

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



Fission induced by thermal (fission spectrum) neutrons

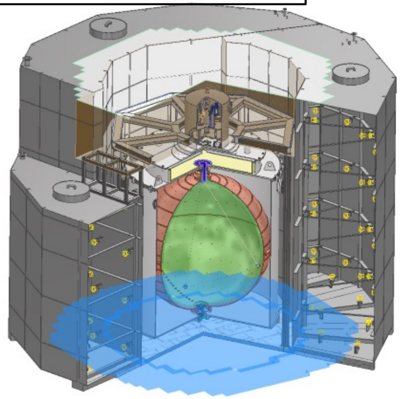
Fission induced by high energy neutrons (14.7 MeV)

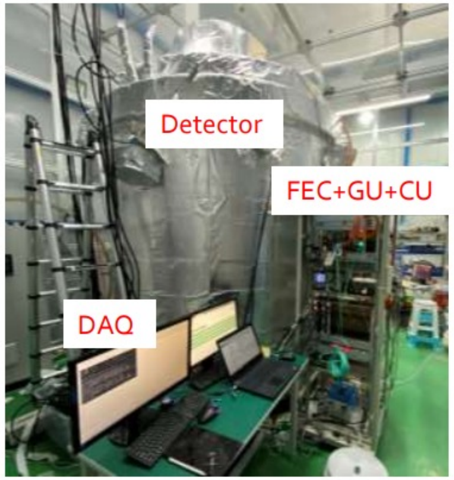


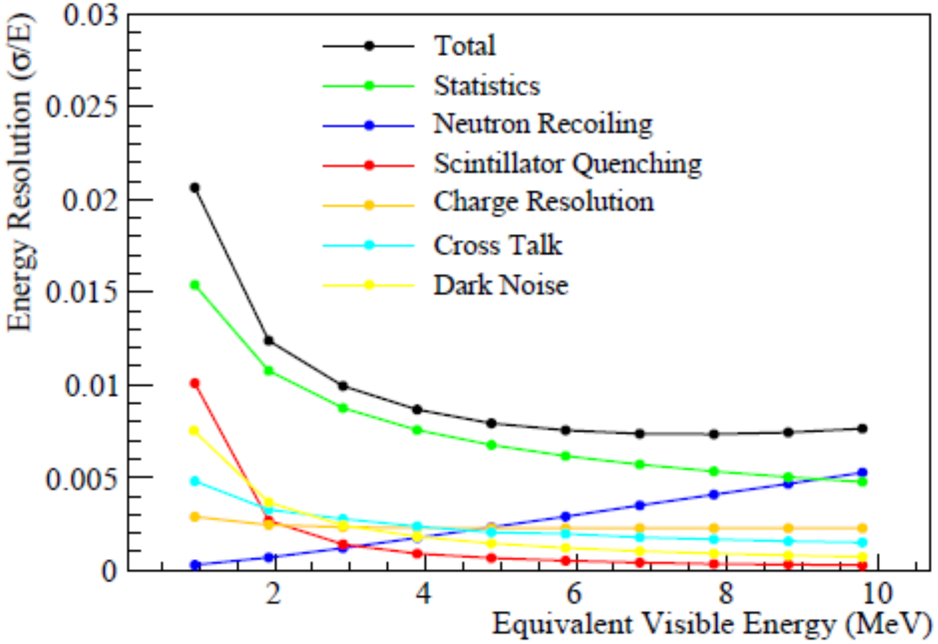
JUNO-TAO

- 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), to be re-installed in the Taishan Nuclear Power Plant in 2024

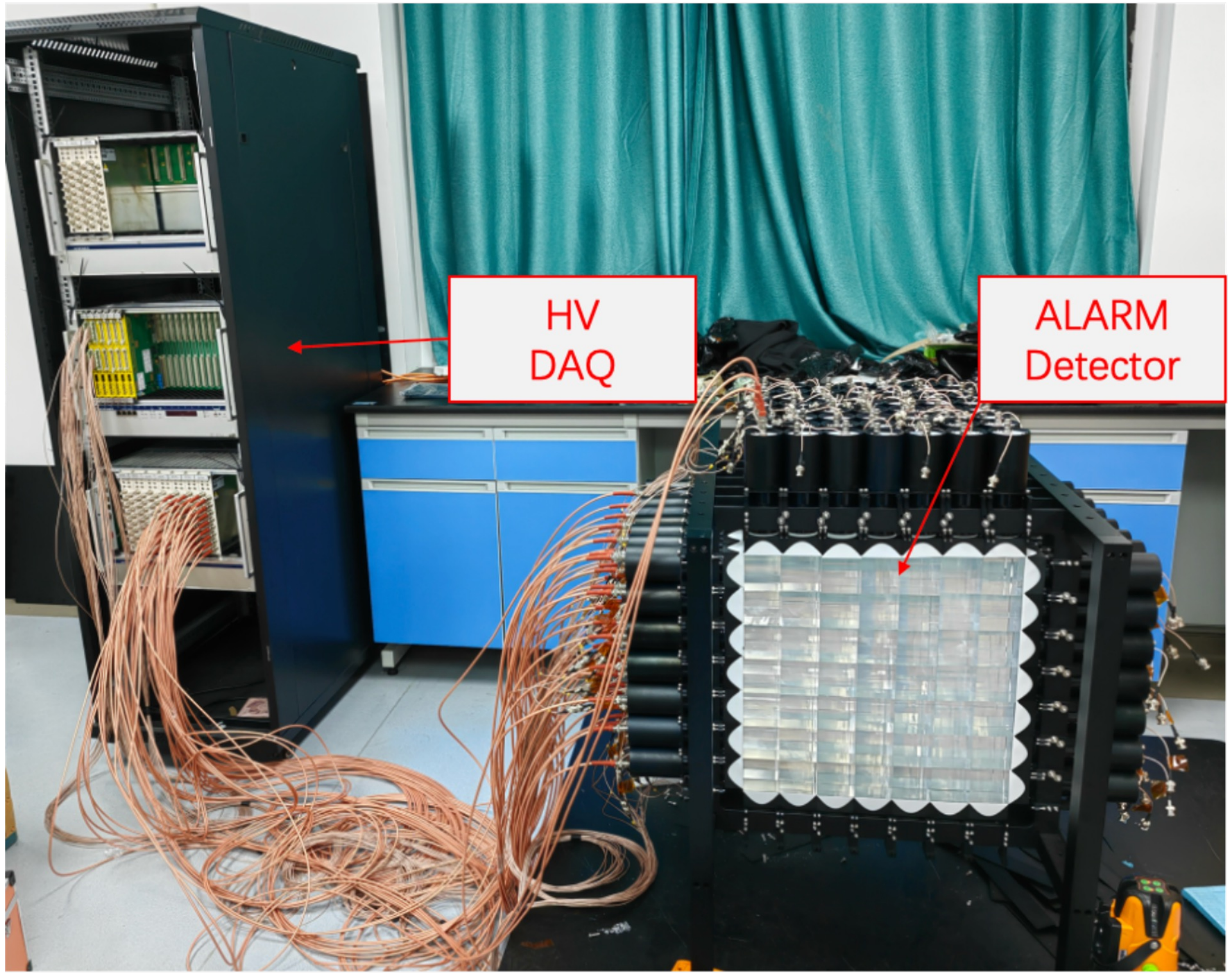
arXiv:2005.08745

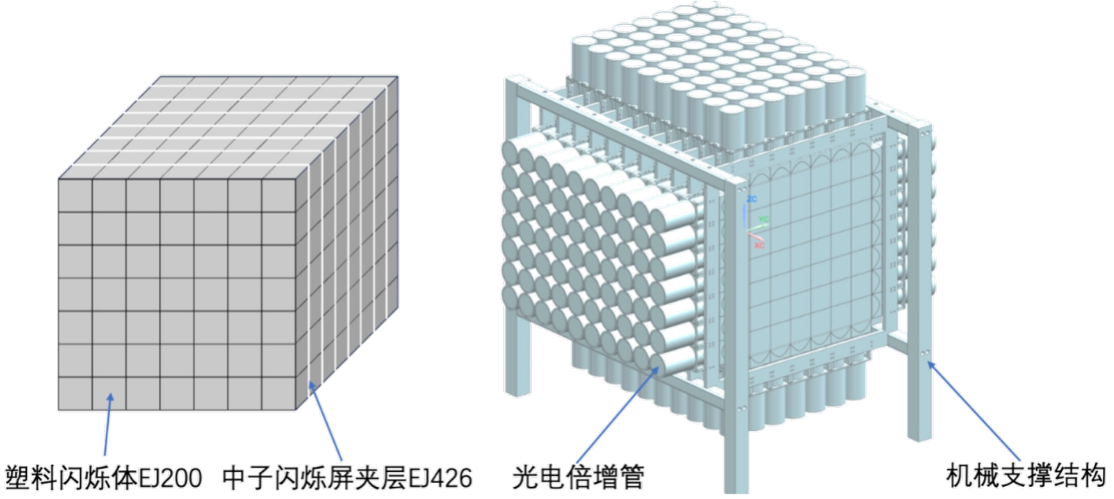






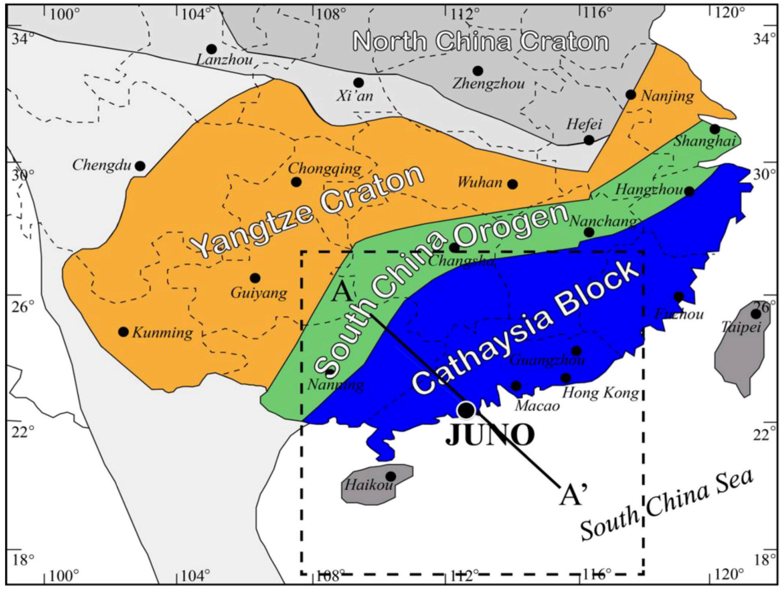
ALARM: Array of Lattice for Antineutrino Reactor Monitoring

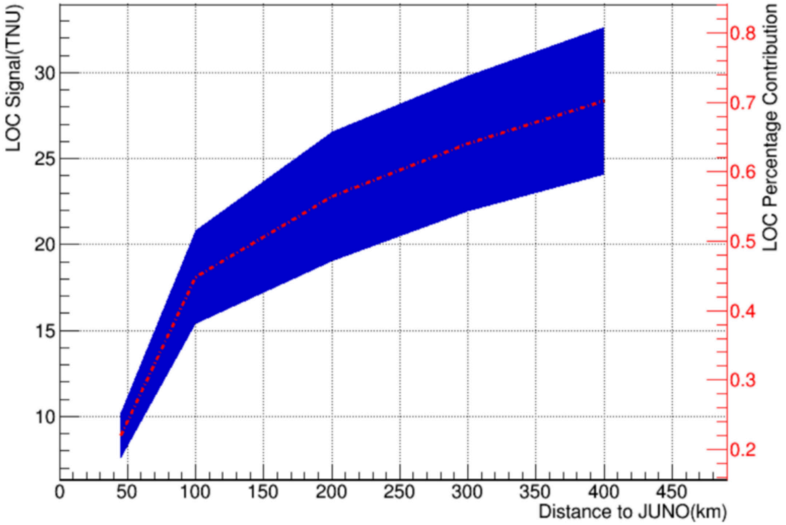


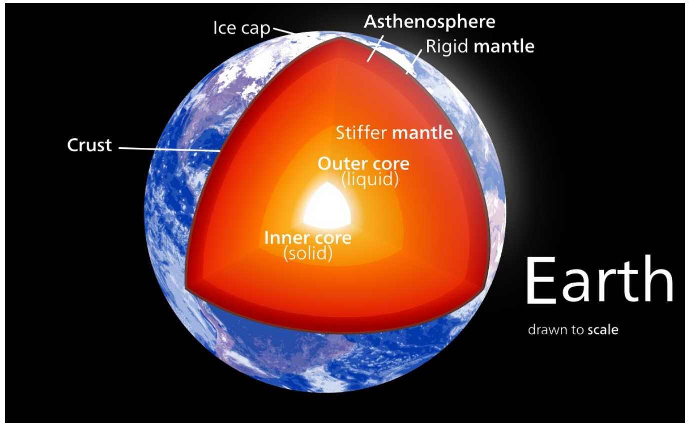


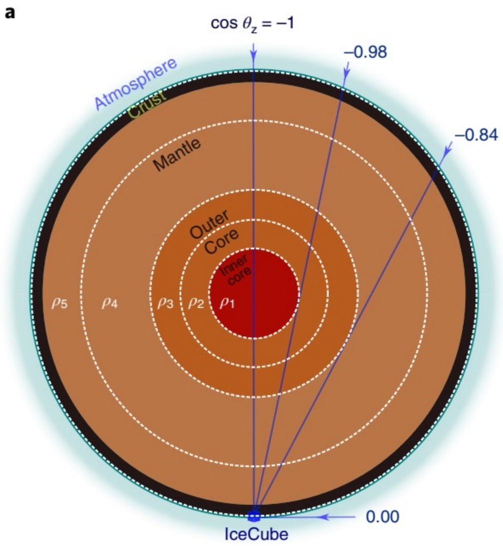
- 探测器部件到位
- PMT批量测试
- 完成小模型测试取数
- 试安装和muon取数

Neutrino as Probes: Nuclear and Earth Sciences

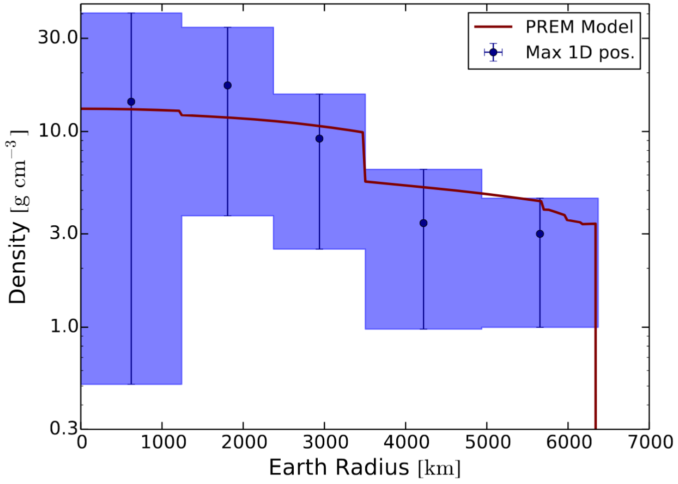


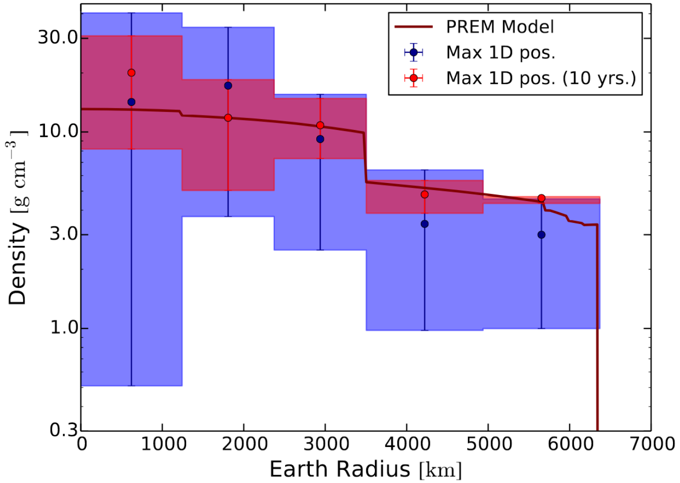






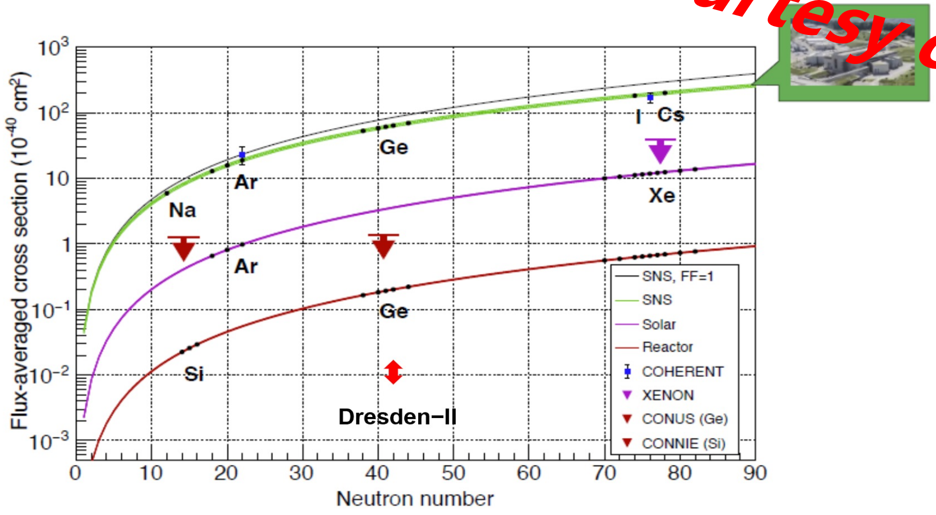
A. Donini et al, Neutrino tomography of Earth, Nature Physics 2018

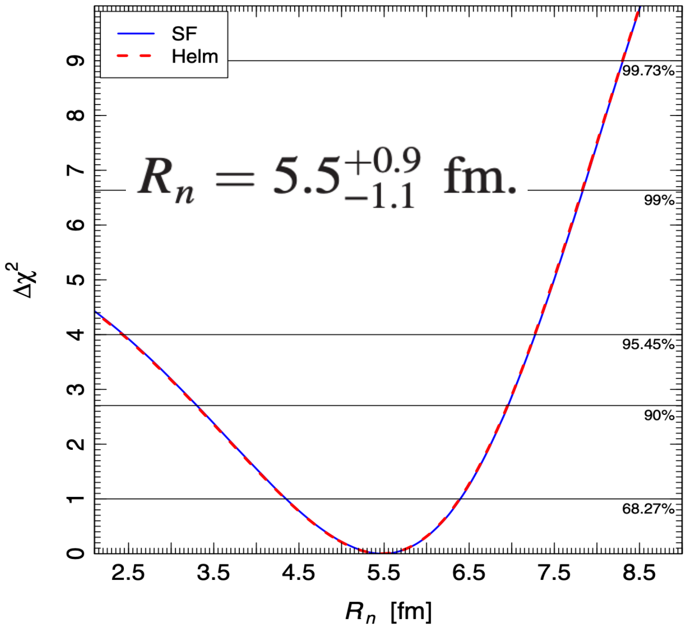


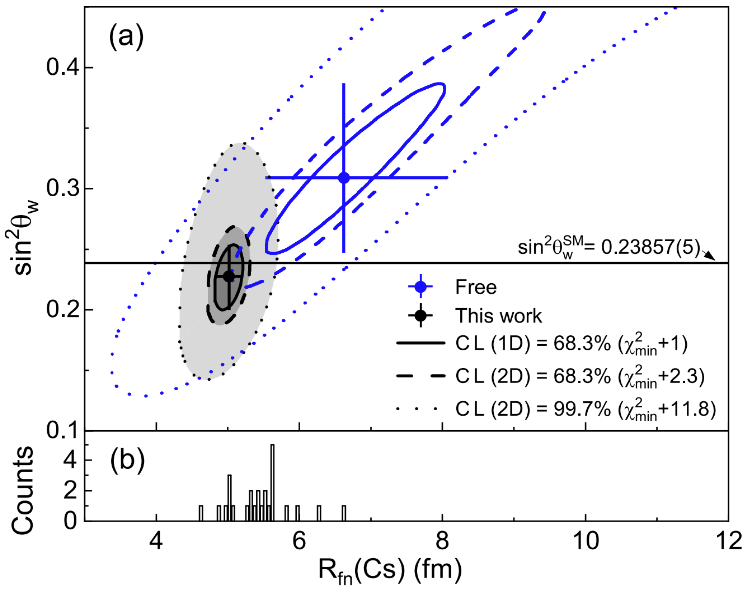


Neutrino as Probes: Neutron radius from CEvNS

Courtesy of YFL





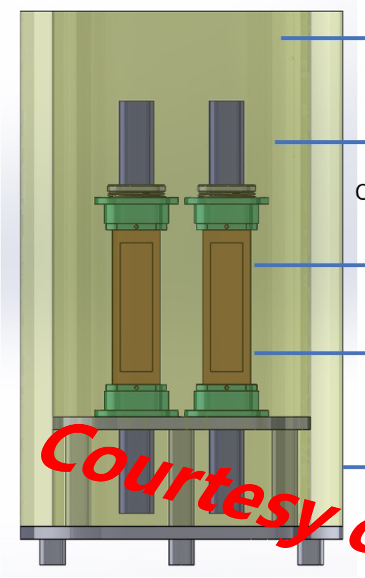


- ❖ **Neutron distribution radius can be probed via pure weak interaction of CEvNS by using neutrinos from Spallation Source**
  Science 357 (2017) 6356, 1123-1126
- ❖ **The latest results from the CsI detector present a measurement of** $\boxed{R_n(\mathrm{CsI}) = 5.55 \pm 0.44\ \mathrm{fm}}$
  PRL 120 (2018) 7, 072501, PRC 104 (2021) 6, 065502
- ❖ **It has important implications in particle physics, nuclear physics, and astrophysics.**
- ❖ **Impact on the measurement of the weak mixing angle can be aided by a direct Cs-p elastic scattering measurement at IMP.**
  PLB 856 (2024) 138902

中国科学院大学
University of Chinese Academy of Sciences

CLOVERS: Coherent eLastic neutrinO(V)-nucleus scattERing at csnS

Detector Design:
Pure CsI at 77K



LN2

R11065 PMT
double side readout

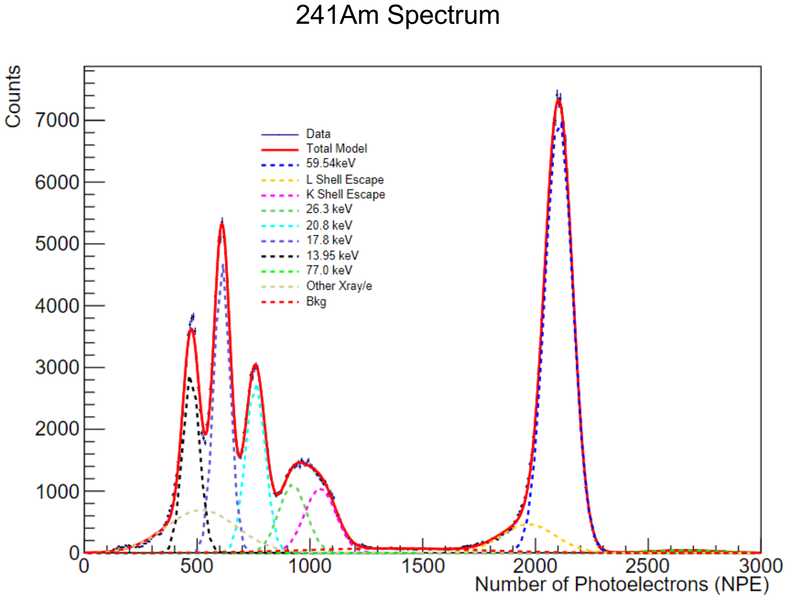
Pure CsI: 3kg × 4

OFHC (part)

Dewar

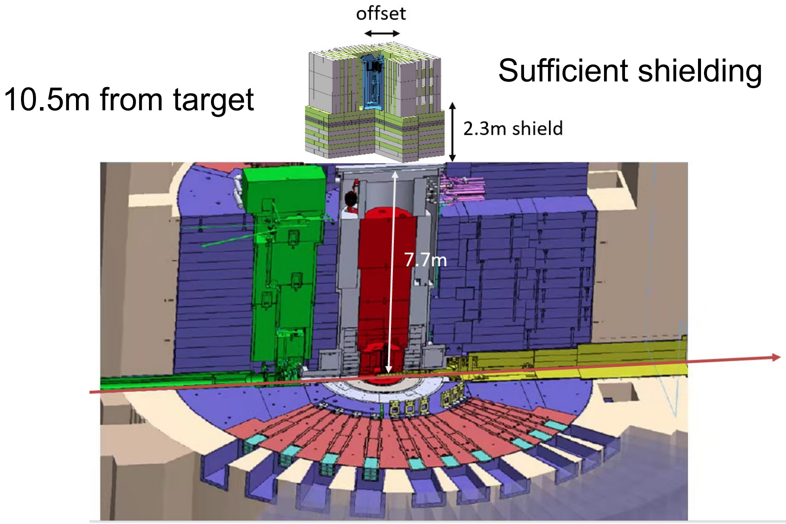
Courtesy of QL&YHZ

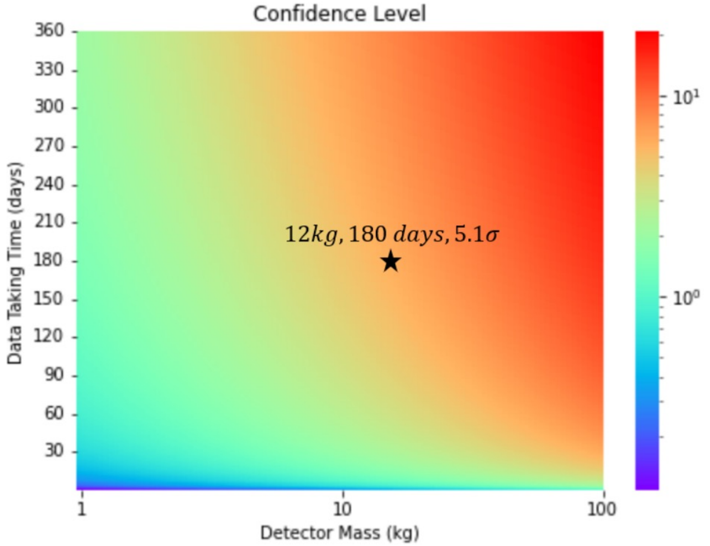
Detector Performance



Light Yield	$35.2 \pm 0.6\mathrm{PE/keV}_{ee}$
FWHM@60keV	6.9%
Expected Threshold	$1.5\mathrm{keV}_{\mathrm{nr}}$

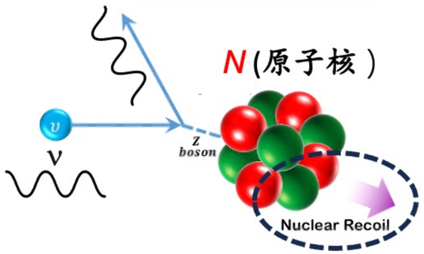
Expected Sensitivity





CICENNS experiment at CSNS

$\nu + N \rightarrow \nu + N$



“Research contents”

Development of 300kg CsI(Na) detector
For Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- Obtain sufficient CEvNS event rate with substantial target mass
- Establish a new field of studying unexplored physics using CEvNS

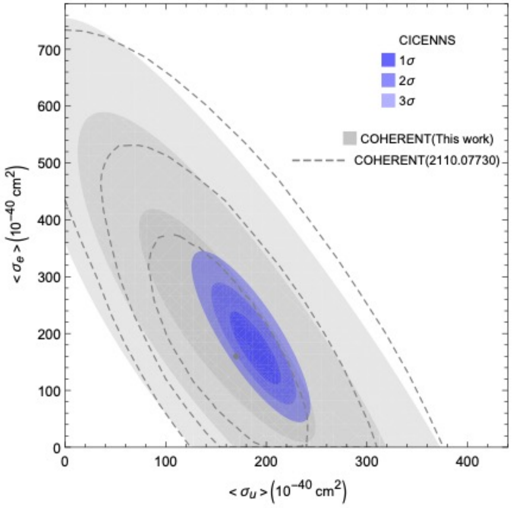
Detection of neutrinos from pion/muon decays at rest
(at China Spallation Neutron Source)

“Scientific goals”

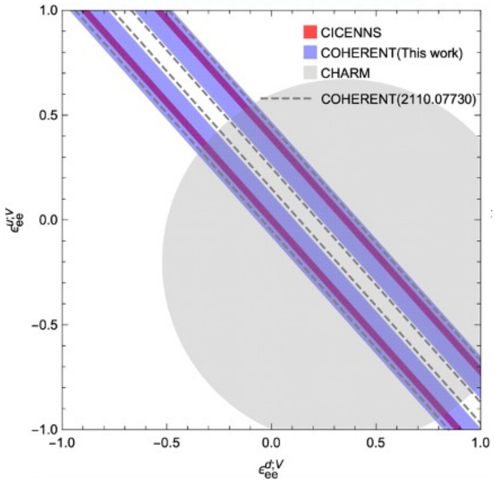
(1) *Precise measurements* (world-most accurate)
- CEvNS cross section → weak couplings at low momentum transfer (±3%)
- Mean radius of neutron distribution inside nucleus (±2%)
- Understanding of dark-matter background and detection of solar neutrinos

(2) *New physics searches*
- Non-standard (new) neutrino interactions (world-best search)
- New particle searches: dark photons or sub-GeV dark matter
- A new region of neutrino magnetic moment
- Efficient search for sterile neutrino oscillation by neutral current

CEvNS cross section



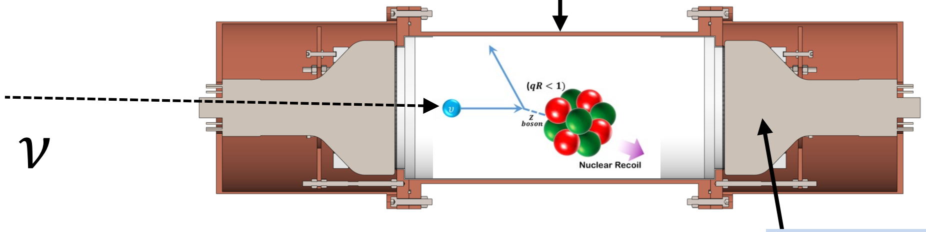
Search for NSI



[* CICENNS: CsI detector for Coherent Elastic Neutrino Nucleus Scattering]

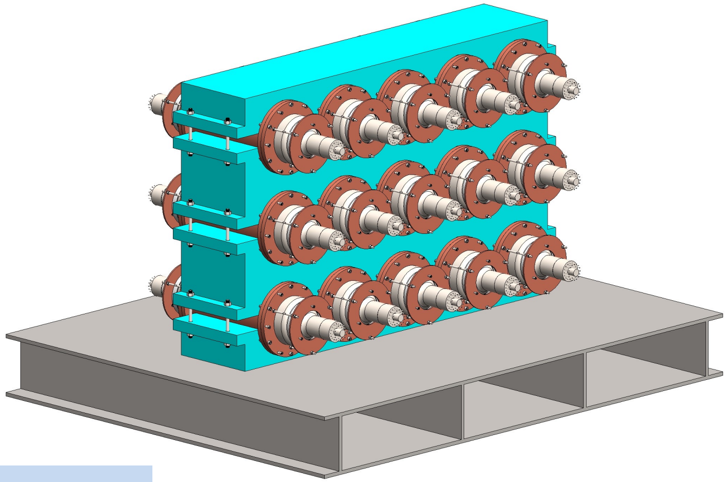
Schematic drawing of CsI(Na) crystal detector (CICENNS)

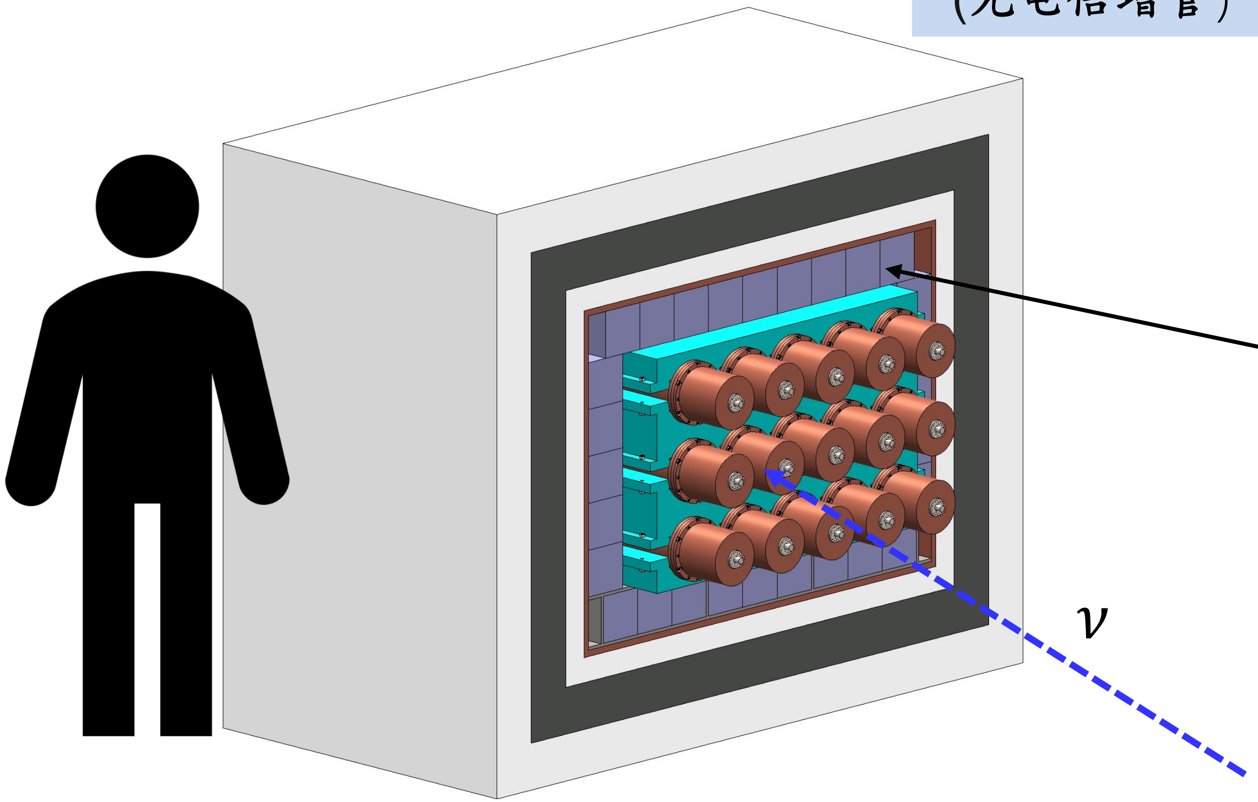
CsI crystal (闪烁晶体)



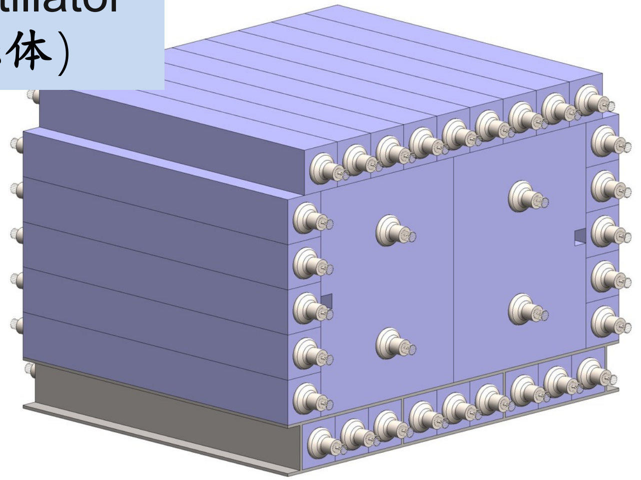
- 20 kg CsI x 15
- 14 cm (ϕ) x 28.7 cm each

5-inch PMT
(光电倍增管)





Plastic scintillator
(塑料闪烁体)



Innovative ideas on improved detector design

"Major improvement from COHERENT detector"

- **Sufficient signal events** for precise measurement: 300 → **6500**
  - Increase of **neutrino target mass**: 14.6 → **300** kg
  - Lowering **energy threshold**: 7 → **3** keV$_{nr}$

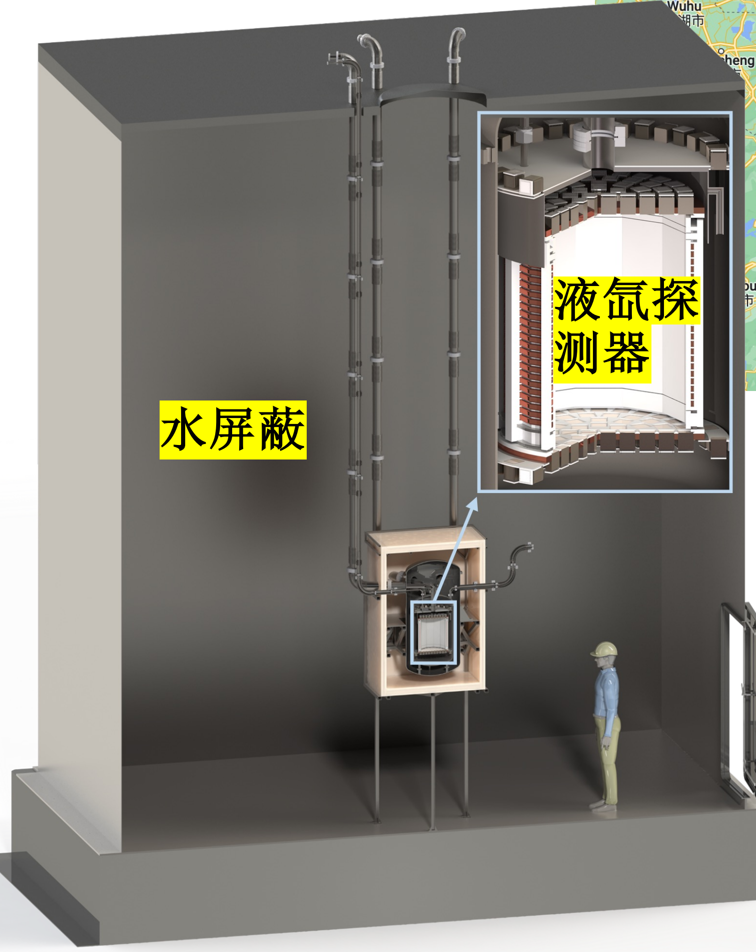
- Significantly (**20** times) lower **radioactivity contamination of CsI crystal by purification** (in collaboration with中国科学院上海硅酸盐研究所)

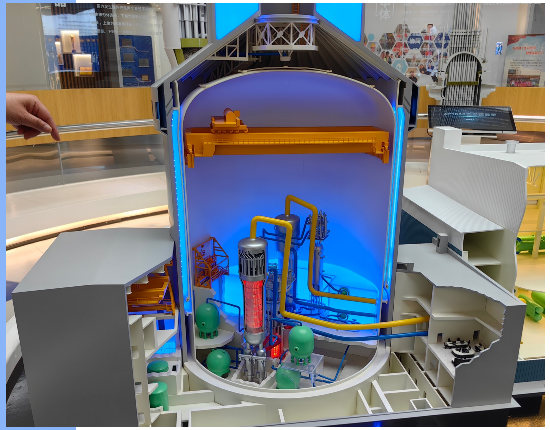
- Significant (**3 orders** of magnitude) reduction of **PMT dark rate by coincidence** between two PMTS of each crystal

- Rejection of most **beam neutron backgrounds with plastic scintillator veto component**

RELICS 中微子相干散射实验

感谢高飞提供!





热功率 3.4 GW
堆芯距离 25m
中微子流强 >1e13 $\nu/cm^2/s$

High Energy Physics – Experiment

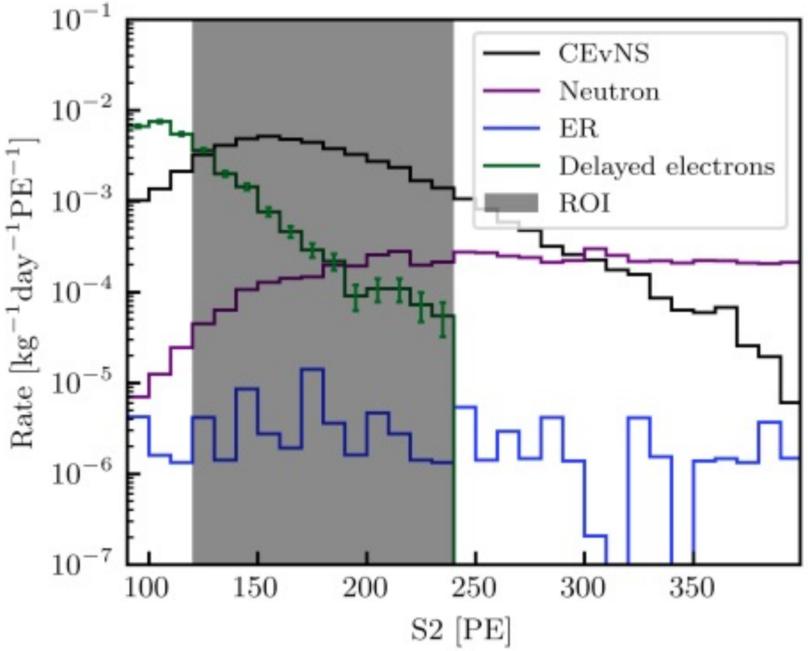
arXiv:2405.05554 (hep-ex)

[Submitted on 9 May 2024]

RELICS: a REactor neutrino LIquid xenon Coherent elastic Scattering experiment

Chang Cai, Guocai Chen, Jiangyu Chen, Fei Gao, Xiaoran Guo, Tingyi He, Chengjie Jia, Gaojun Jin, Yipin Jing, Gaojun Ju, Yang Lei, Jiayi Li, Kaihang Li, Meng Li, Minhua Li, Shengchao Li, Siyin Li, Tao Li, Qing Lin, Jiajun Liu, Minghao Liu, Sheng Lv, Guang Luo, Jian Ma, Chuanping Shen, Mingzhuo Song, Lijun Tong, Xiaoyu Wang, Wei Wang, Zihu Wang, Yuehuan Wei, Liming Weng, Xiang Xiao, Lingfeng Xie, Dacheng Xu, Jijun Yang, Litao Yang, Long Yang, Jingqiang Ye, Jiachen Yu, Qian Yue, Yuyong Yue, Bingwei Zhang, Shuhao Zhang, Yifei Zhao

	Events/($32kg \cdot year$)
CEvNS	**4902**
宇宙线中子	**230**
μ 致中子	**1.5**
电子反冲	**5.7**
延迟电子	**1081**

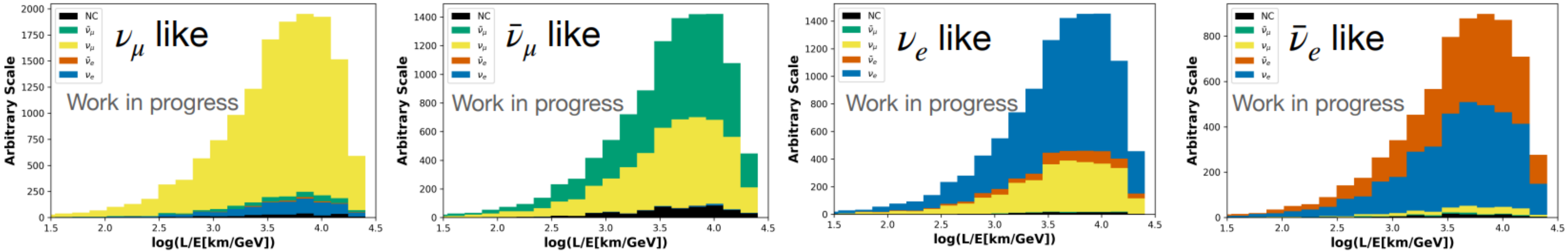


Summary and Outlook

- ❖Neutrino physics has provided the first new physics beyond the SM and it is now entering the precision phase → **we might get disappointed; but we need to finish the job** --- hopefully, oscillation parameters by 2035
- ❖**Reactor neutrinos** played irreplaceable role and are playing even more essential roles → **China leads in this field**
- ❖**After the success of Daya Bay,** non-collider HEP experiments are booming in China
- ❖Technologies are always essential for making progresses in science; Science always gives technologies more values and, often, leads the developments of technologies → **Neutrino is becoming promising new technologies/tooles in various fields.**

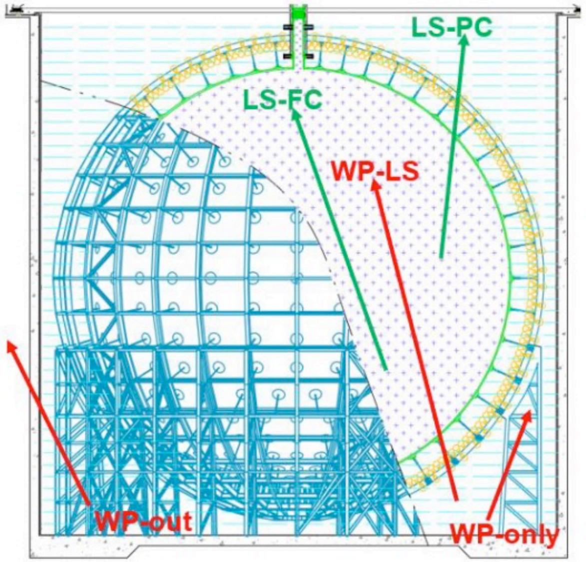
Atmospheric Neutrino

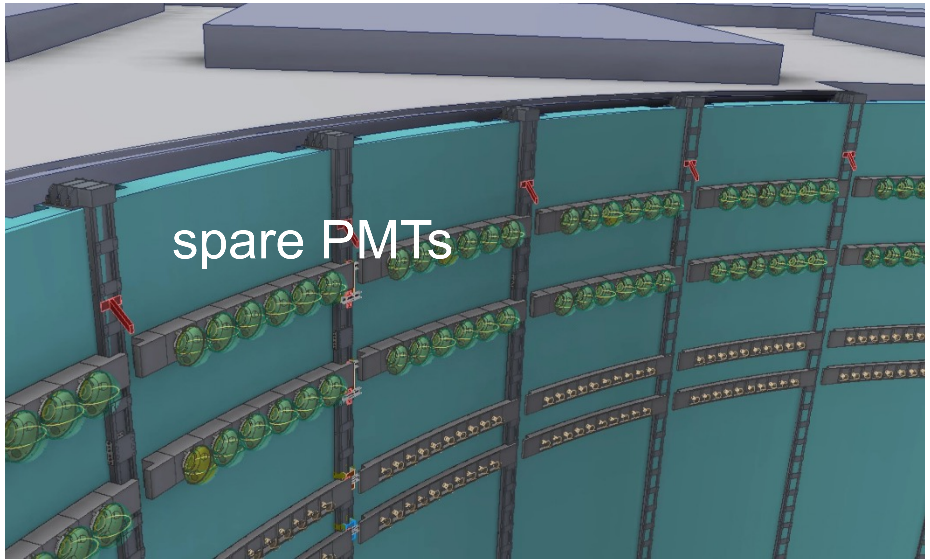
- JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator: e/μ separation, $\nu/\bar{\nu}$ separation, ν energy (instead of lepton energy), track direction in LS



◆ **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**

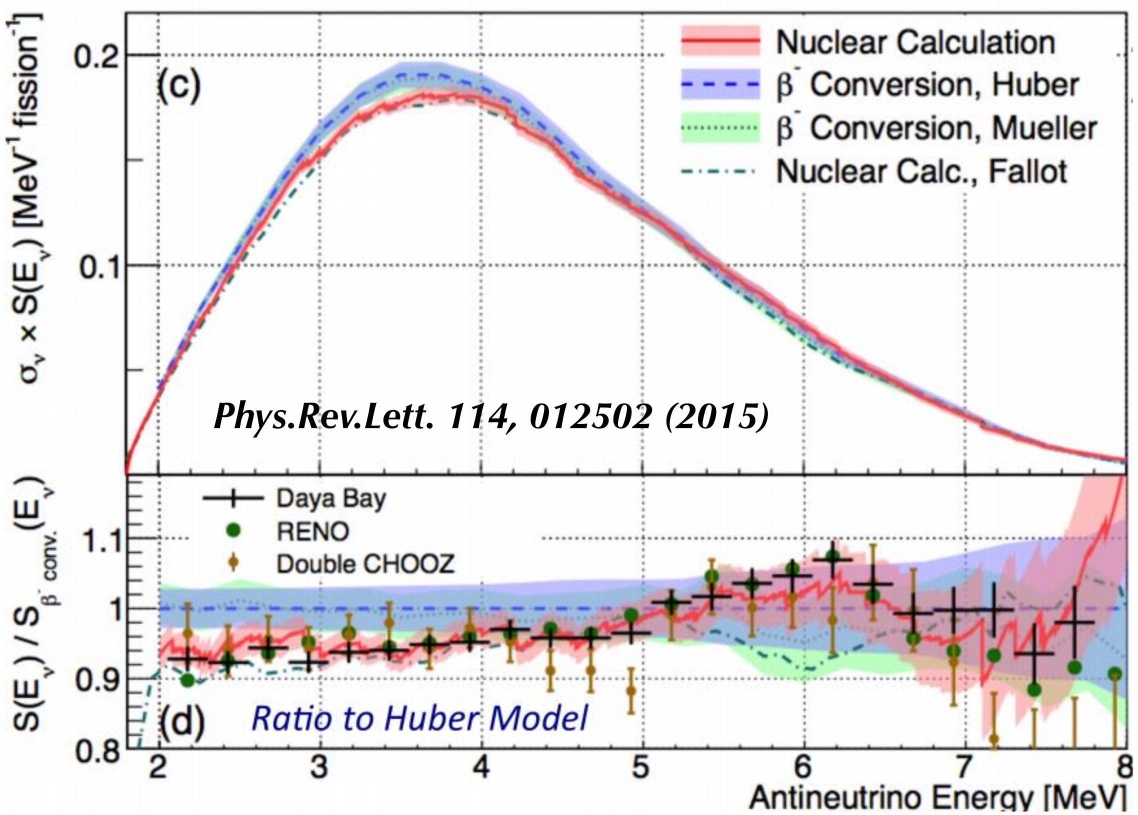




The "*ab initio*" (summation) Method

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

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



Phys.Rev.Lett. 114, 012502 (2015)

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.