Physics with Reactor Neutrinos

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Neutrino Sources

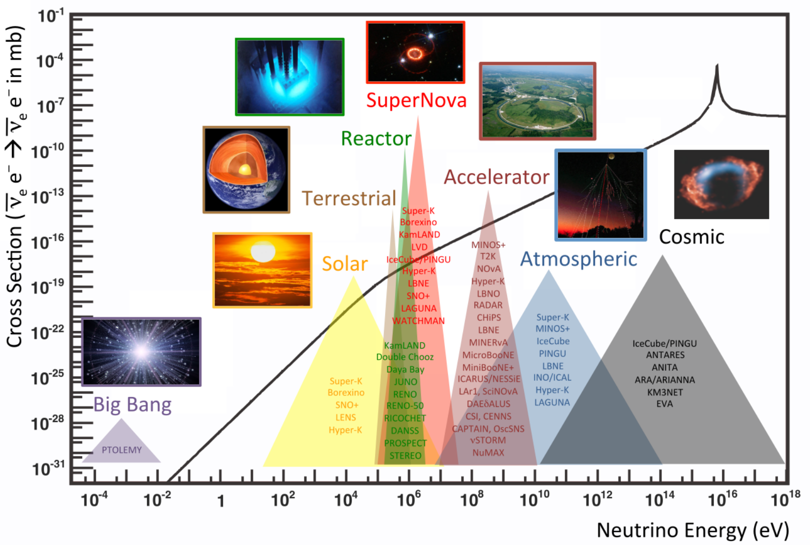
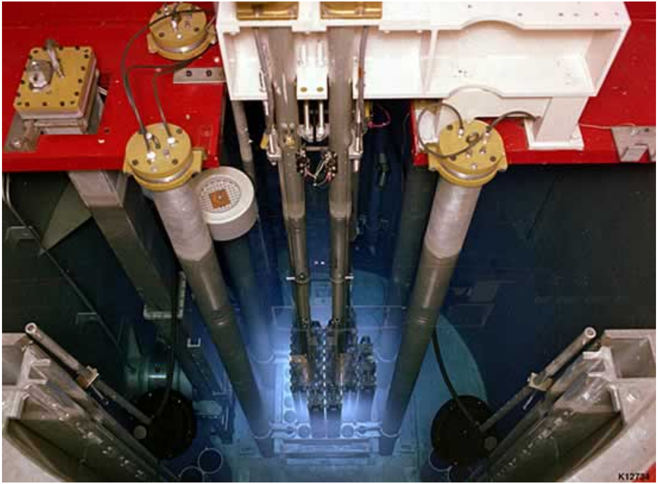


Figure 1: Neutrino sources and their energies. Figure taken from [1].

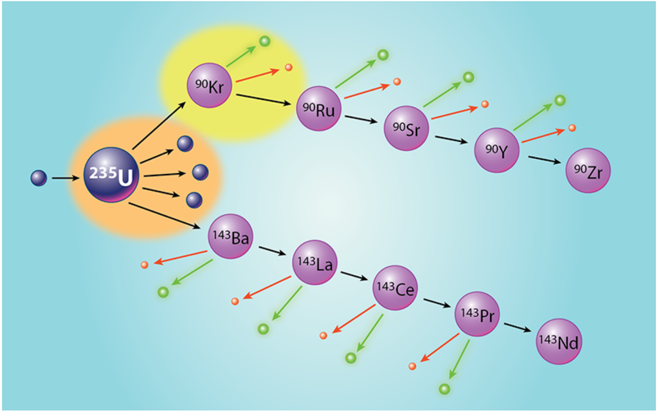
Nuclear Reactor

- nuclear fission, first reactor is Chicago Pile-1, Fermi, 1942
- a typical nuclear reactor produces $\mathcal{O}(1\,\mathrm{GW})$ of electricity

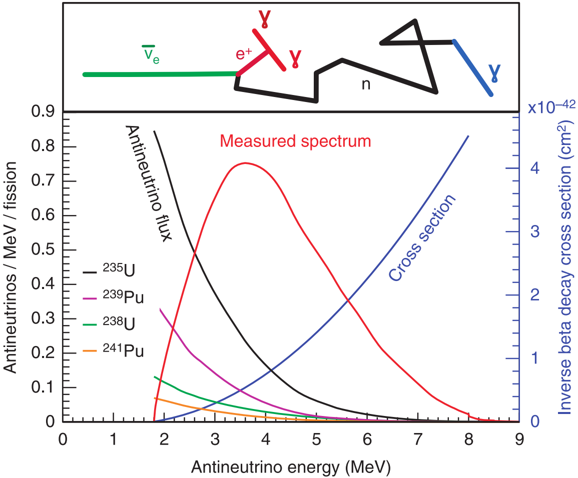


Reactor Neutrinos

- 99.9% of $\overline{\nu}_e$ from fission isotopes of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- per fission decay chain: 200 MeV, 6 neutrinos, pure $\overline{\nu}_e$
- $2 \times 10^{20}\,\mathrm{GW}^{-1}\,\mathrm{s}^{-1}$ reactor neutrinos



Neutrino Flux and Neutrino Detection



- inverse-beta decay (IBD): prompt signal, $E_{e^+} = E_\nu - 0.8\,\text{MeV}$
- neutron capture: delayed signal

Fuel Evolution

- evolution of reactor core fuel
- antineutrino flux depends on fission fraction

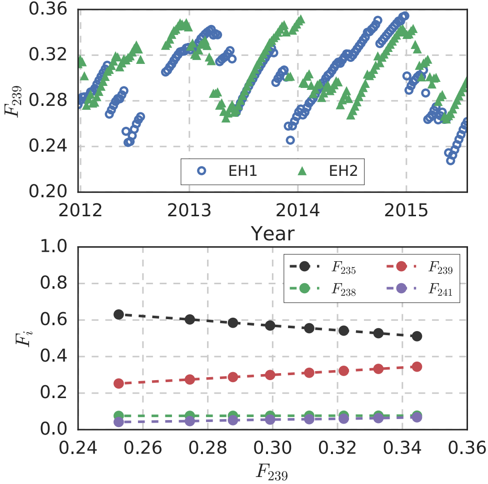


Figure 2: Evolution of reactor core fuel in Daya Bay [2].

Discovery of Neutrinos: Cowan and Reines Experiment

Original Plan of Cowan and Reines to Detect Neutrinos

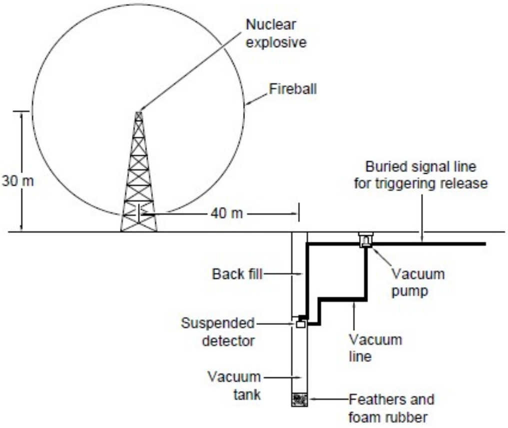


Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

Early Reactor Neutrino Measurement

- neutrino rate: from $10^{18}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ near atomic bomb site, to $10^{14}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at a reactor
- initial measurement using the nuclear reactors at Hanford (Washington State) in 1953
- inverse beta decay

$$\overline{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

- liquid scintillator (LS) with cadmium dissolved in it

$$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109m}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd} + \gamma \tag{2}$$

- coincidence of positron annihilation and neutron capture

Detector at Hanford

- 28 inches in diameter, 30 inches in height, 300-liter capacity
- 90 2-inch PMTs, "Herr Auge"

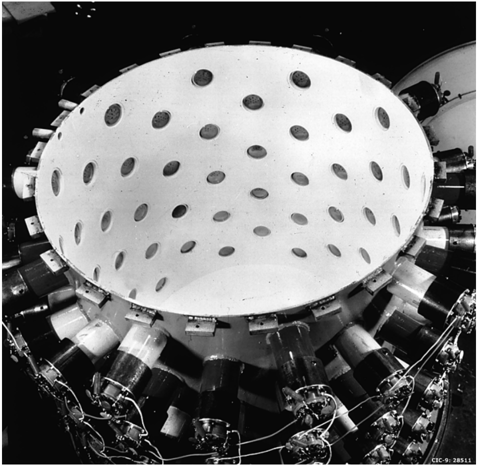
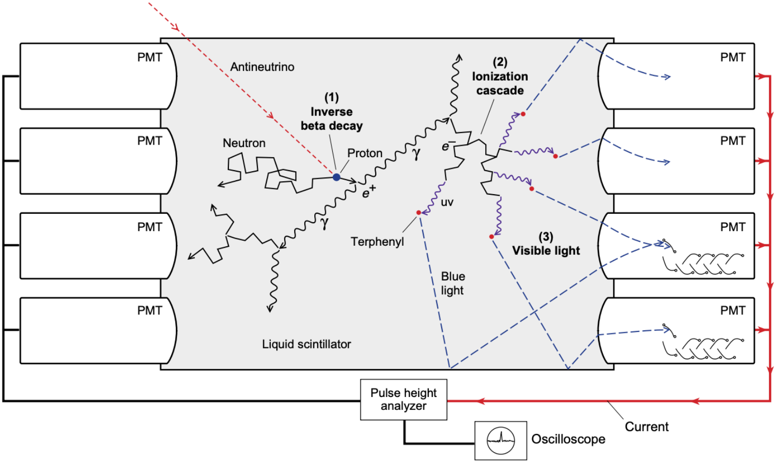


Figure 3: The scintillation detector for the 1953 neutrino detection experiment at Hanford.

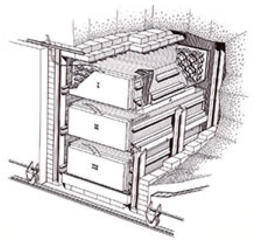
Detecting IBD

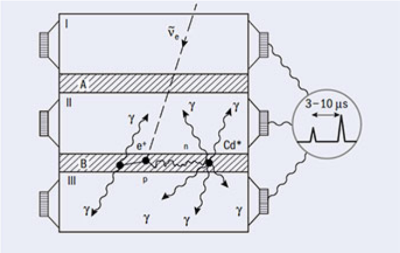


Moving to Savannah River

- “it was felt that an identification of the free neutrino had probably been made.”
- moved experiment to Savannah River Plant (South Carolina)
- a detector tank containing more than 1 ton of scintillation fluid in a crawling convoy of 5 over-sized trucks

Experimental Setup at Savannah River

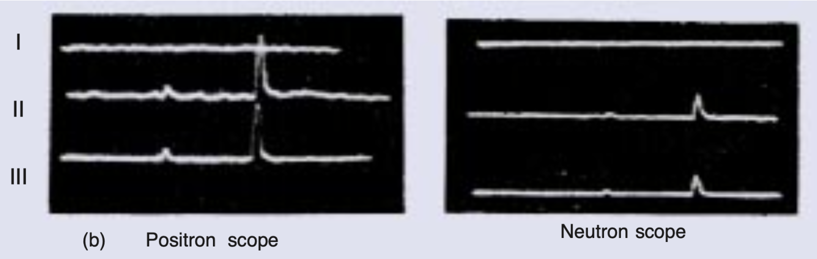




- club-sandwich setup
- bread layers: 0.6 m thick, 1.9 m long, 1.4 m wide
  - triethylbenzene solution of terphenyl (scintillator $C_{18}H_{14}$) and POPOP (wavelength shifter)
  - 110 5-inch PMTs in total, res. at 0.5 MeV is 30% FWHM
- meat layers: water solution of cadmium chloride
- parafin and lead shield, underground room

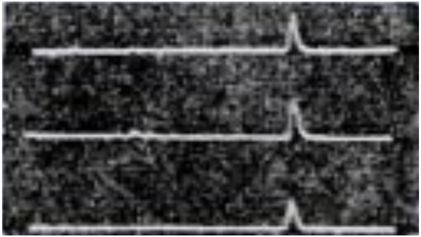
Data Acquisition

- trigger on pulse amplitudes and coincidences
- pulses on the triple-beam oscilloscopes were recorded photographically
- short delay (up to 17 μs): good signal-to-background ratio
- calibrations: copper-64 positron source, plutonium-beryllium neutron source, and cosmic ray

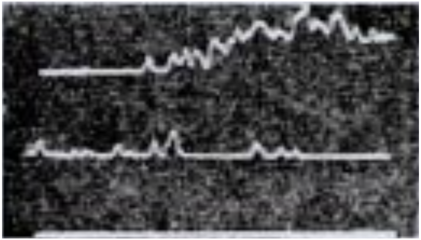


Background

- pulses in all three traces

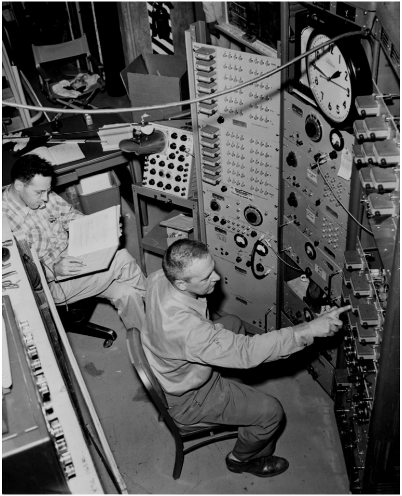


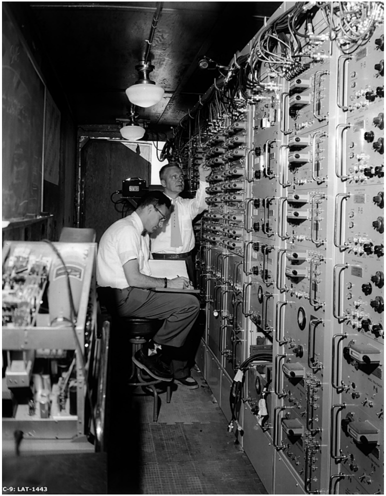
- strange signals



- accidental background: radio-activities from materials

Cowan and Reines



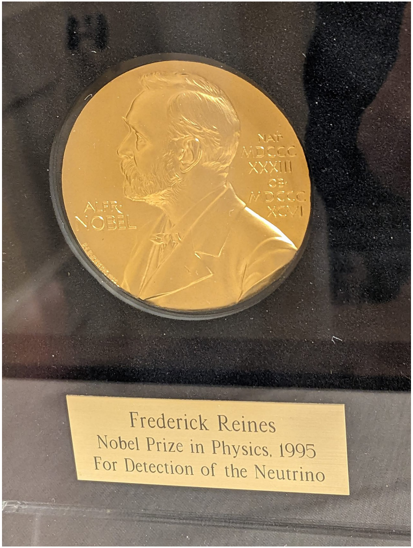


Experimental Results

- total running time: 1371 hours = 57 days
- cross section $6.3 \times 10^{-44}\,\text{cm}^2$ (about right)
- in one run, neutrino signal rate was 0.6 counts per hour, signal is 20 times the accidental background due to reactor

1995 Nobel Prize

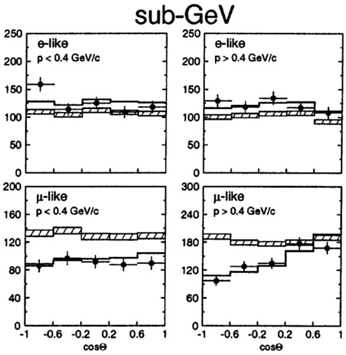
- Cowan passed way at 54 in 1974. Reines received Nobel price in 1995 in both their names.
- "for pioneering experimental contributions to lepton physics" jointly with one half to Martin L. Perl "for the discovery of the tau lepton" and with one half to Frederick Reines "for the detection of the neutrino"
- among 79 / 116 Nobel Prizes in particle physics (1901—2024)



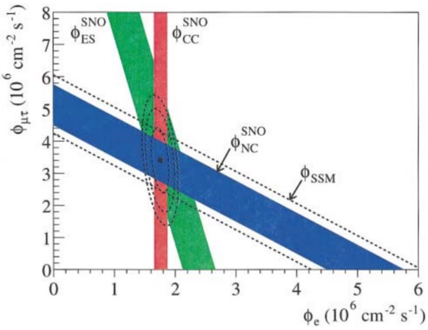
θ_{12} and Δm^2_{21} Measurement: KamLAND Experiment

Discovery of Neutrino Oscillations

- Super-Kamiokande: atmospheric ν_μ disappearance
- SNO: ν_e flux and total neutrino $\nu_{e,\mu,\tau}$ flux from the Sun
- neutrinos can change flavor as they travel
- non-zero masses, 2015 Nobel Prize



(a) Super-Kamiokande, 1998 [3]



(b) SNO, 2002 [4]

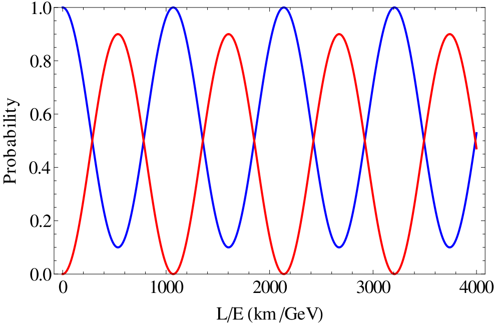
Standard Neutrino Oscillation Model

- ν_α: state with specific flavor (ν_e, ν_μ, ν_τ)
- ν_i: state with specific mass (m_1, m_2, m_3)
- $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$, matrix U is unitary, called PMNS matrix

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13}e^{i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

- 2-flavor example: $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left[\Delta m^2_{ij}(L/4E)\right]$

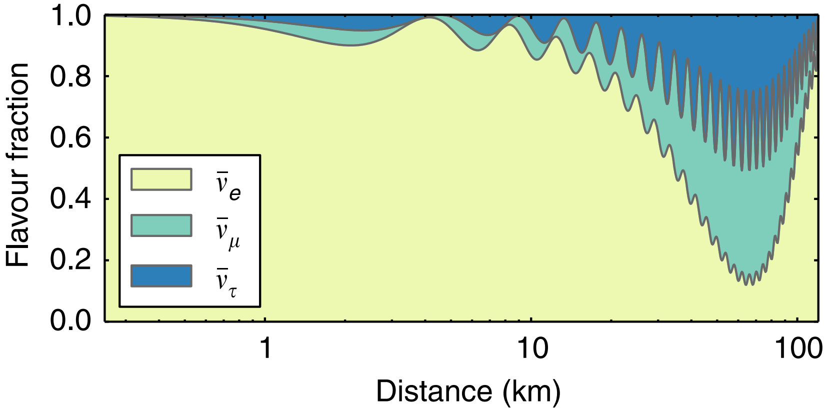
  $\Delta m^2_{ij} = m^2_i - m^2_j$, L is baseline, E is energy



Reactor Neutrino Oscillations

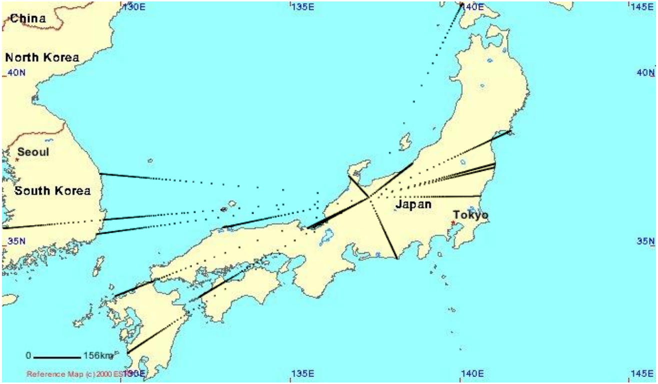
- for reactor neutrinos: $\overline{\nu}_e \to \overline{\nu}_\mu$ or $\overline{\nu}_\tau$
- oscillations depend on θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31}

$$P(\nu_e \to \nu_e) \approx 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



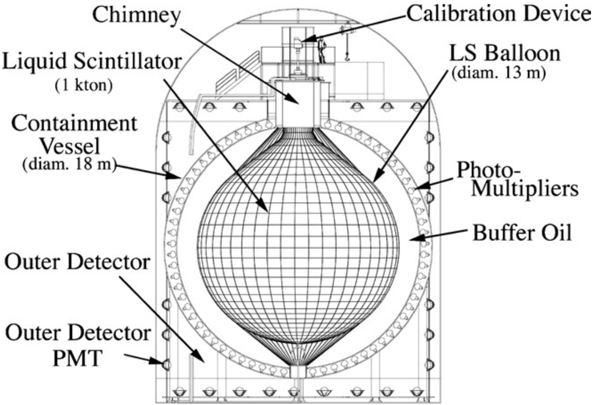
KamLAND Experiment

- KamLAND: Kamioka Liquid Scintillator Anti-Neutrino Detector, proposed in 1994, started taking data in 2002
- average baseline of 180 km



- first oscillation observation from man-made neutrino
- Δm^2_{21} was determined to a high precision

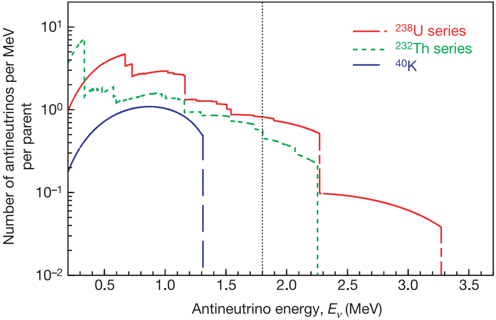
KamLAND Detector



- about 2000 PMTs, 34% photocathode coverage
- 18 m diameter vessel, 13 m diameter, 1 kton LS
- energy resolution: $6.4\%/\sqrt{E(\mathrm{MeV})}$, position resolution $12\,\mathrm{cm}/\sqrt{E(\mathrm{MeV})}$

Backgrounds in KamLAND Experiment

- unexpected: $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$, liquid scintillator purification
- geo-$\overline{\nu}_e$: cut on 2.6 MeV prompt signal



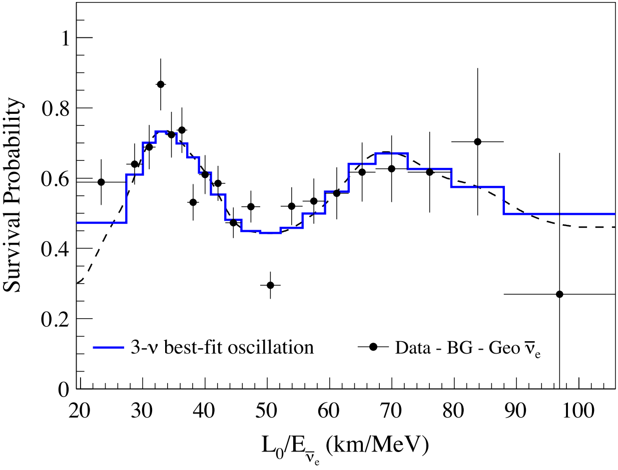
- ^{9}Li and ^{8}He: 2 s veto of entire volume for showering muon or a 2 s veto of a 3-m-radius volume around a muon track.

$$^9\mathrm{Li} \xrightarrow{\beta^-} e^- + {}^9\mathrm{Be}^* \rightarrow e^- + \alpha + \alpha + n,$$

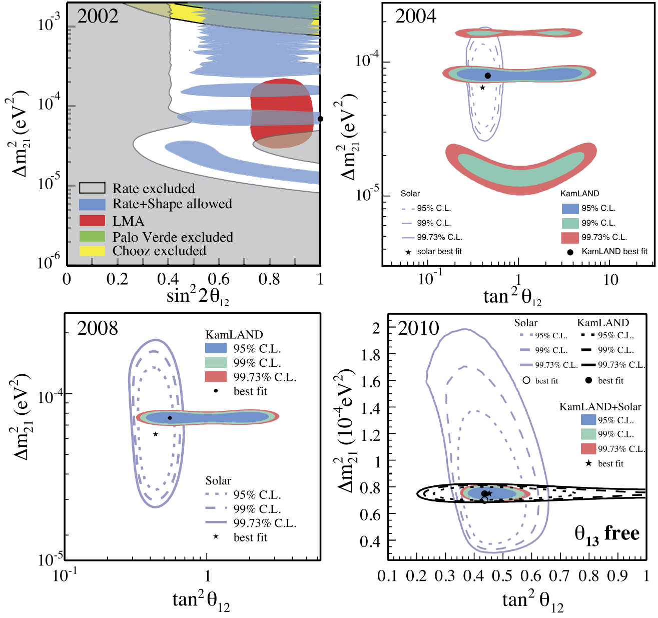
$$^8\mathrm{He} \xrightarrow{\beta^-} e^- + {}^8\mathrm{Li}^* \rightarrow e^- + {}^7\mathrm{Li} + n.$$

KamLAND Data in L/E

- ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation as a function of L/E [5]
- three flavor fit, strong constraint on Δm^2_{21}

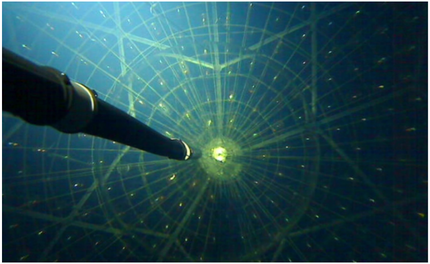


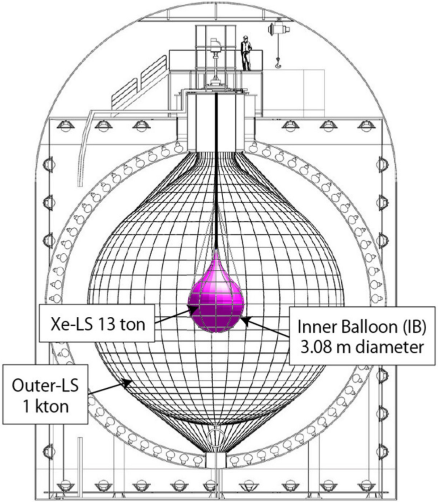
Oscillation Results from KamLAND



KamLAND-Zen

- in 2011, $>$ 300 kg ^{136}Xe loaded in 13 ton liquid scintillator
- KamLAND-800: 745 kg Xe, 91% enriched, loaded with 3.1%
- ^{110m}Ag from Fukushima (2011)
- 270 keV FWHM





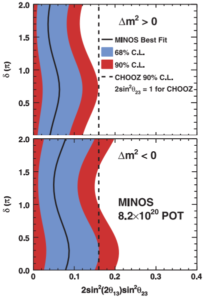
θ_{13} Measurement: Daya Bay, RENO and Double CHOOZ

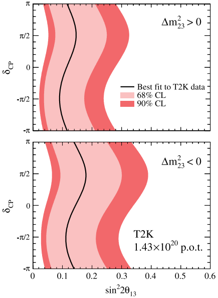
Significance of θ_{13} Measurement

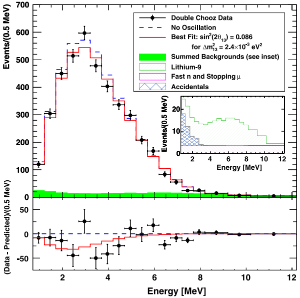
- non-zero value of θ_{13} allows the measurement of δ_{CP}, matter-antimatter asymmetry of the universe

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13}e^{i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

- indications of a nonzero θ_{13} in 2011: T2K [6], MINOS [7], Double Chooz [8]



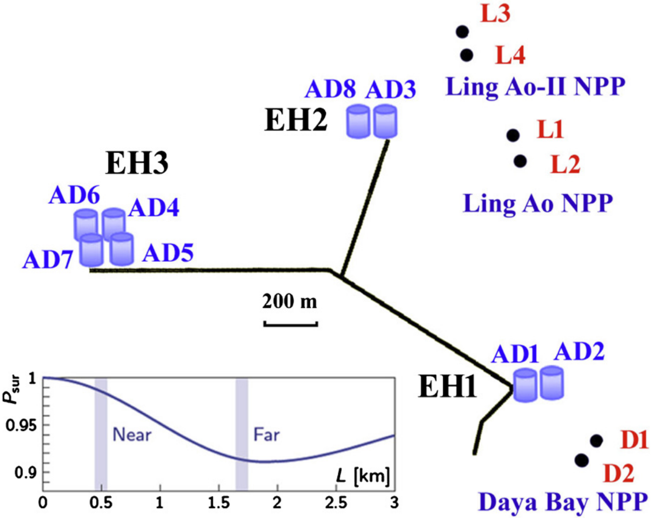




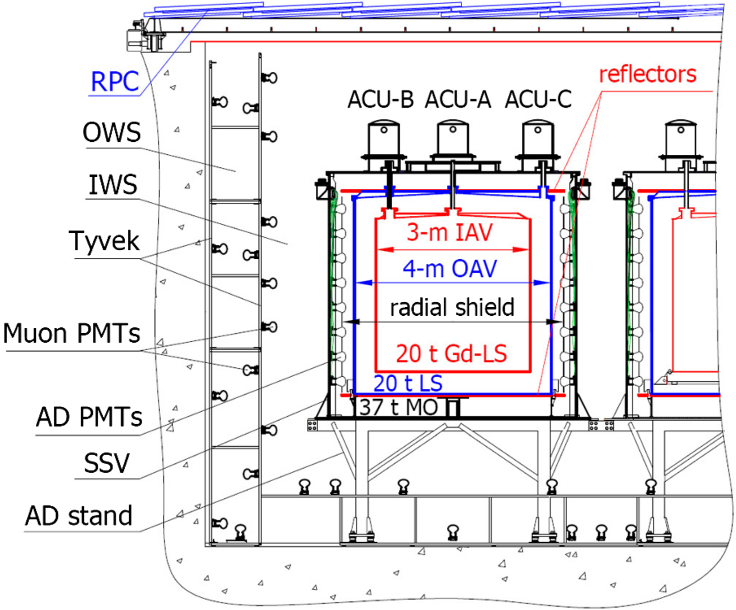
- excluded non-zero θ_{13} above 5σ in 2012: Daya Bay and RENO

Near and Far Detectors of Daya Bay Experiment

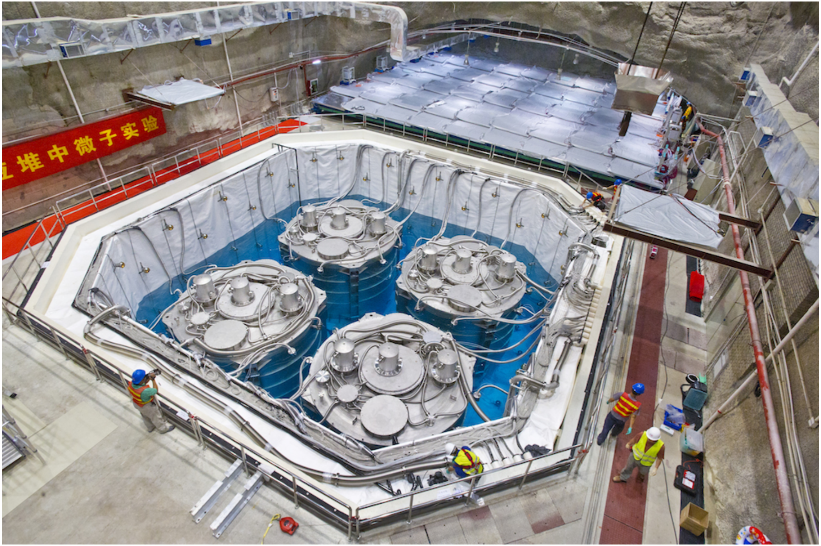
- 2 nuclear power plants (NPP), 6 reactor cores
- 4 far detectors (EH3) and 4 near detectors (EH1 and EH2)



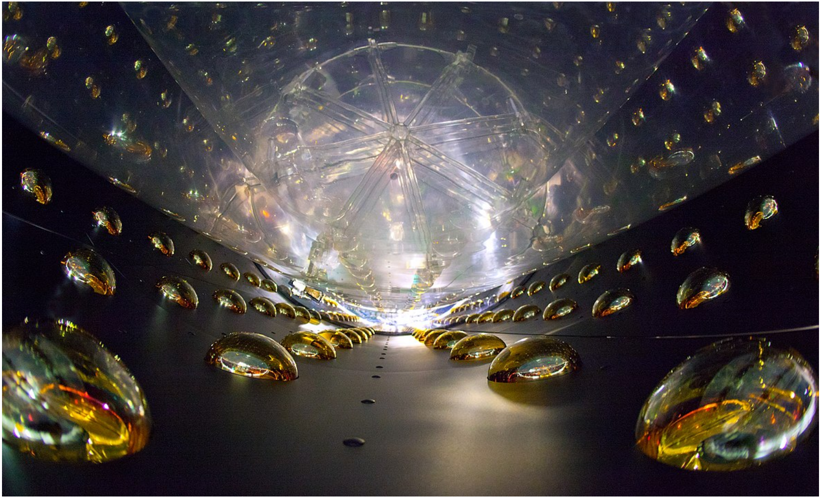
Detector Design



Daya Bay Detectors in EH3



Interior of a Daya Bay Detector



Daya Bay Results in 2012 [9]

- exposure of 55 days, rate measurement
- determine non-zero θ_{13} above 5 sigma level

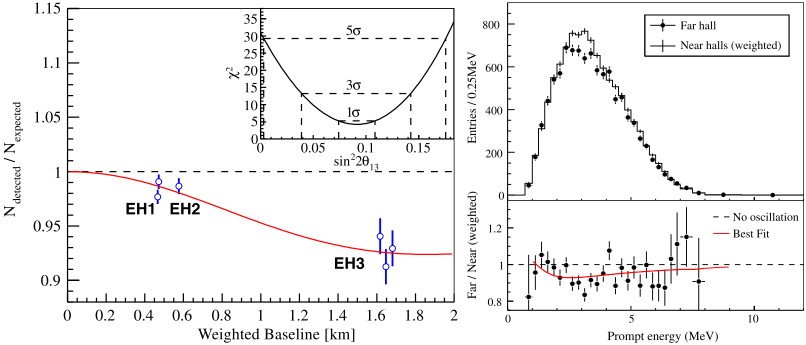


Figure 5: Daya Bay experimental results in 2012 [9].

Daya Bay Results in 2023 [10]

- $\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$,
- "The reported $\sin^2 2\theta_{13}$ will likely remain the most precise measurement of θ_{13} in the foreseeable future"
- "crucial to the investigation of the mass hierarchy and CP violation in neutrino oscillation"

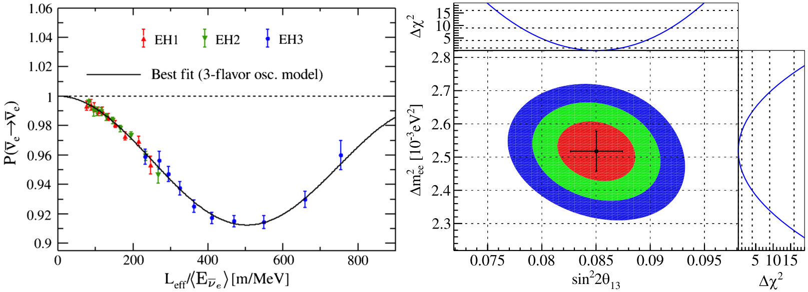
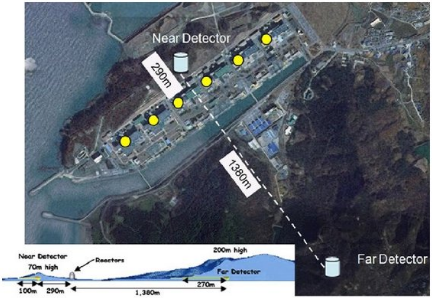


Figure 6: Daya Bay experimental results in 2023 [10].

RENO Experiment

- two detectors: near (290 m) and far detectors (1380 m)
- 16.5 t, 0.1% Gd-doped liquid scintillator
- pure LS (γ catcher), mineral oil (shielding), water
- 229 days exposure, first results in 2012 at $> 4\sigma$



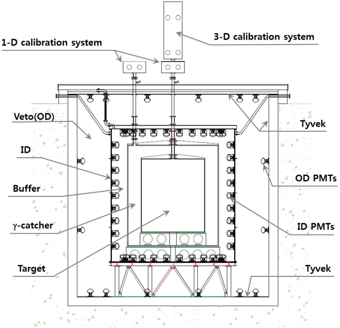


Figure 7: Detector locations and design in RENO experiment [11].

Double CHOOZ Experiment

- single detector operation: April 2011 until January 2013
- both detectors FD and ND: January 2015 until April 2016

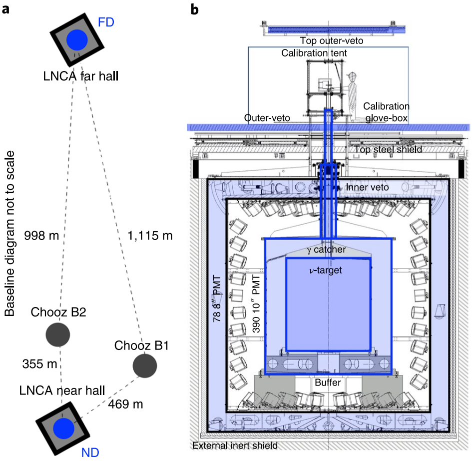


Figure 8: Baseline and detectors of Double CHOOZ experiment [12].

A Comparison of θ_{13} Measurements

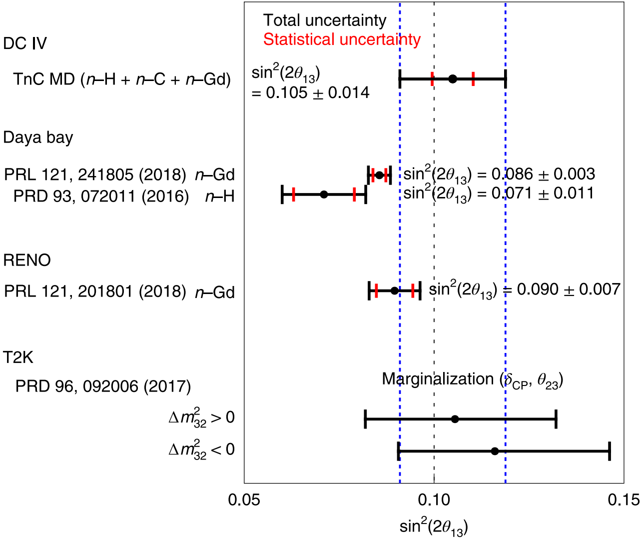
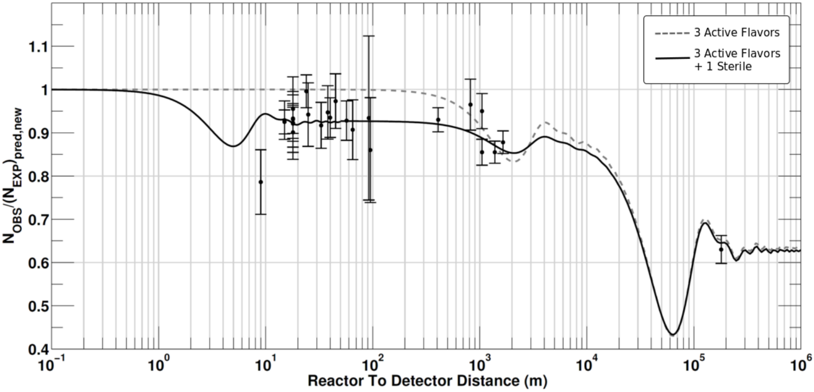


Figure 9: A comparison on θ_{13} measurements in 2020 [12]. Double CHOOZ 2021 [13] and Daya Bay 2023 results [10] not included.

Sterile Neutrino Searches: STEREO, etc.

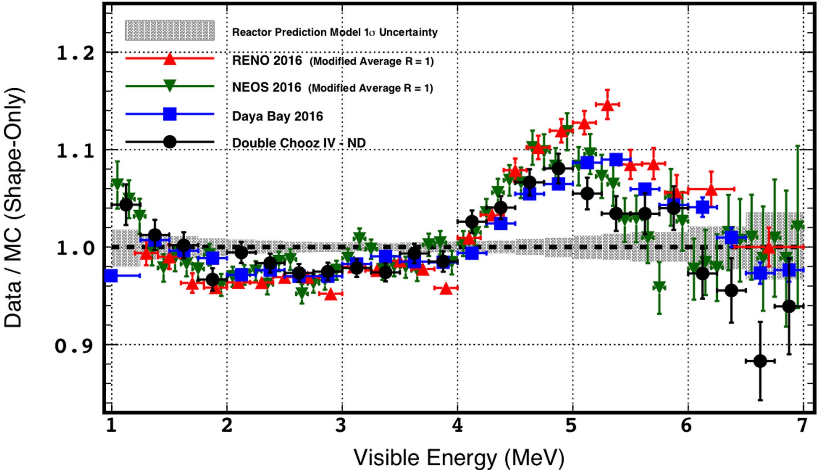
Reactor Antineutrino Anomaly

- predicting $\overline{\nu}_e$ flux from beta spectra for ^{235}U, ^{239}Th and ^{241}Th
- Huber-Mueller (HM) model in 2011, measured rates about 5% below prediction, reactor antineutrino anomaly
- sterile neutrinos: $P = 1 - \sin^2(2\theta)\sin^2\left(\Delta m^2_{41} L/4E\right)$



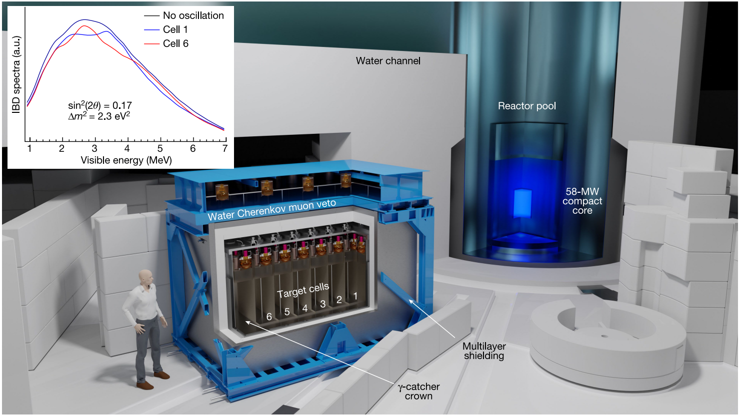
5 MeV "Bump"

- a "bump" at 5–6 MeV, with an amplitude of about 10% [12]
- seen in the data of Daya Bay, RENO, Double CHOOZ, and NEOS experiments



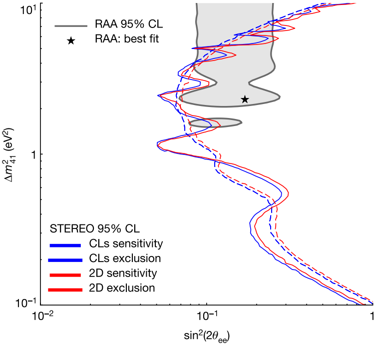
STEREO Experiment [14]

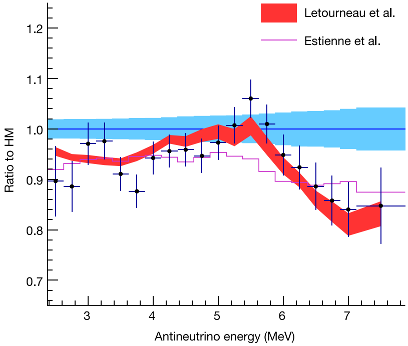
- highly enriched ^{235}U fuel, 10 m baseline, 58 MW research reactor at ILL, France
- shielding: lead, borated polystyrene, mu-metal
- started taking data in 2016, 400 neutrino events per day



STEREO Results

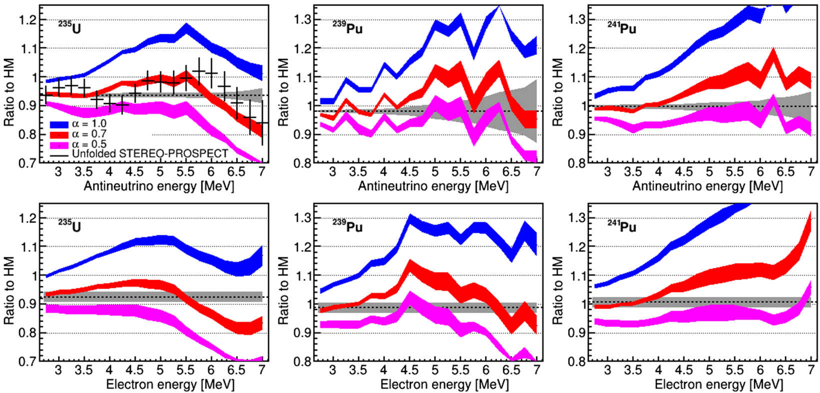
- Nature 613, 257–261 (2023), excluded most of the reactor anomaly parameter space
- agree with the prediction of Letourneau et al. [15]





Calculations by Letourneau et al. in 2022

- Phys. Rev. Lett. 130, 021801 (2023) [15], summation model
- with a single parameter, can reproduce both norm and shape
- suspect that the anomalous feature could be from a shape bias in the β^- energy spectra measured at ILL



Other Very Short Baseline Experiments

- NEOS: Yeonggwang, Korea, 24 m [16]
- PROSPECT: Oak Ridge, ^{235}U fissions, 8 m, ^{6}Li-doped LS
- Neutrino-4, DANSS, SoLid etc. [17, 18]

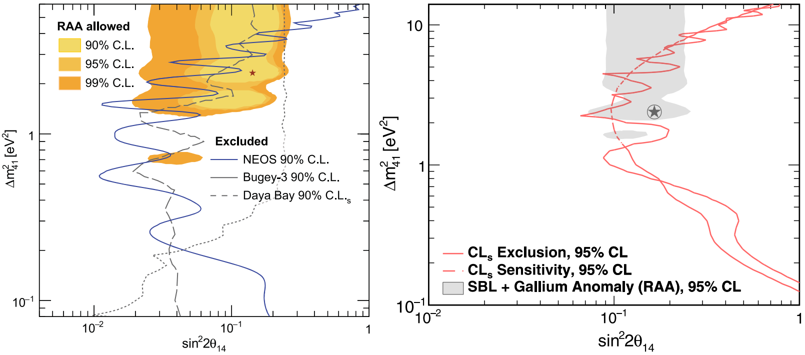
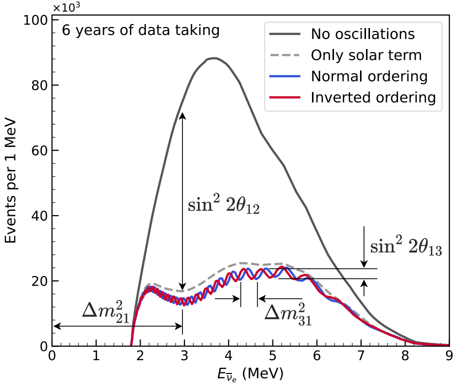


Figure 10: NEOS (left plot, 2017, [16]) and PROSPECT (right plot, 2021, [19]) results on sterile neutrinos.

Mass Ordering Measurement: JUNO Experiment

JUNO Experiment

- JUNO: Jiangmen Underground Neutrino Observatory
- reactor $\overline{\nu}_e \to \overline{\nu}_e$: neutrino mass ordering



- sub-percent measurement of θ_{12}, Δm^2_{21} and $\left|\Delta m^2_{31}\right|$
- multi-purpose detector: geoneutrinos, atmospheric neutrinos, solar neutrinos, supernova neutrinos

Detector Location and Baseline

- located at southern China, near Kaiping, Guangdong province
- two nuclear power plants (NPP), 53 km baseline

Summary of the thermal power and baseline to the JUNO detector for the Yangjiang (YJ) and Taishan (TS) reactor cores, as well as the remote reactors of Daya Bay (DYB) and Huizhou (HZ).

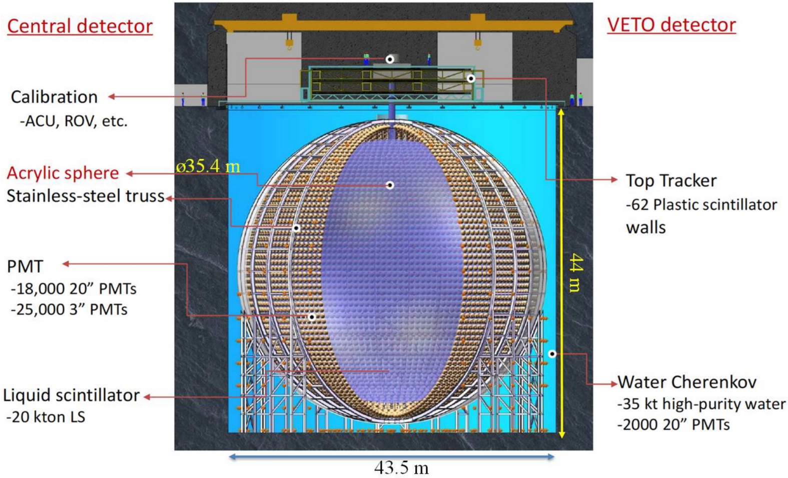
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

JUNO Experimental Site

- vertical tunnel and slope tunnel (42°)
- overburdens 650 m (1800 w.m.e.), about 4 Hz muons rate

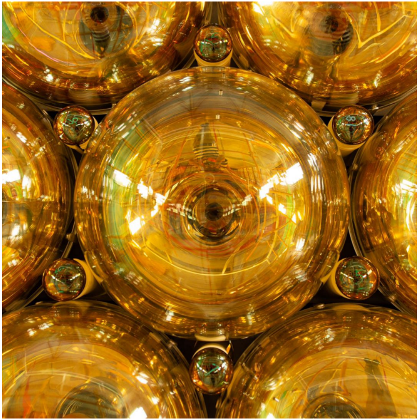
JUNO Detector

- 20 kton liquid scintillator: LAB + PPO + bis-MSB
- top tracker and water pool for muon veto

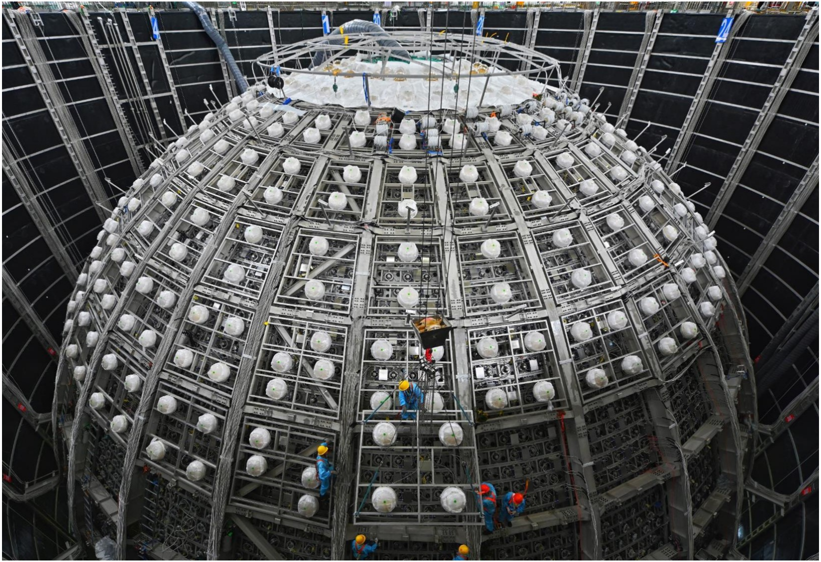


JUNO PMTs

- 3% energy resolution at 1 MeV, 78% photocathode coverage
- 17612 20 in PMTs: NNVT and Hamamatsu
- 25600 3 in PMTs: for large PMT non-linearity correction



Detector Frame

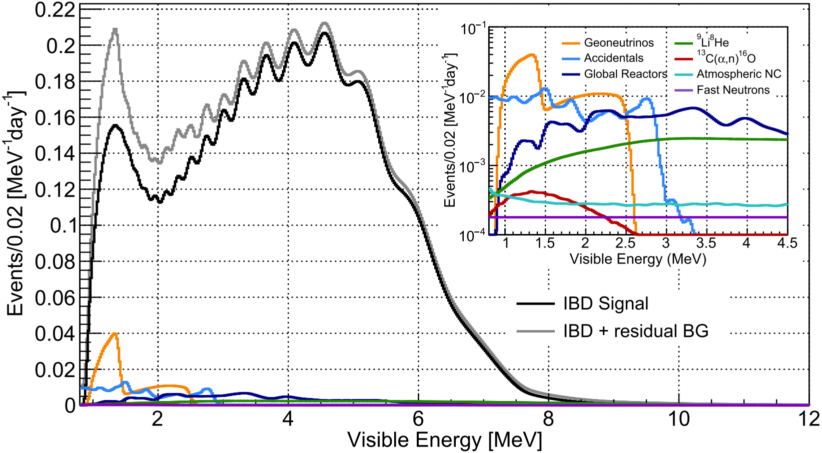


Acrylic Sphere

PMT Array

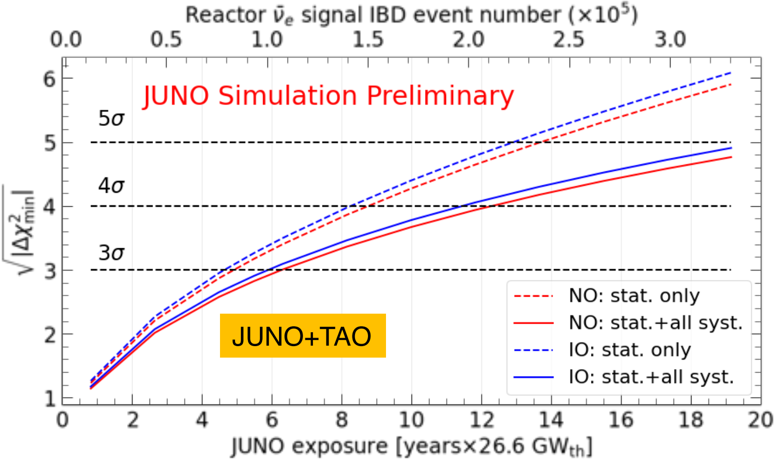
Energy Spectra

- signal: about 42 events per day
- major background: accidentals, geoneutrinos, $^{9}Li/^{8}He$, global reactors, with about 1 event per day each



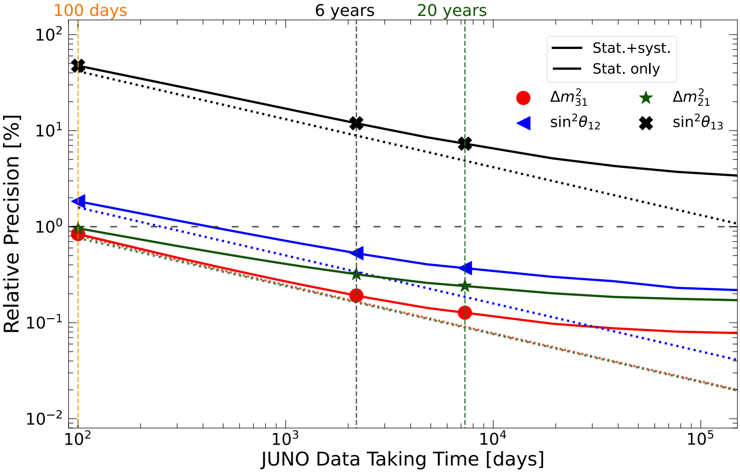
Mass Ordering Sensitivity

- data taking will start in 2025
- TAO, satellite detector by Taishan reactors, flux constraint
- 3σ (reactors only) with about 6 years $\times$ 26.6 GW exposure



Precision Measurement of Oscillation Parameters

- precision of $\sin^2\theta_{12}$, Δm^2_{21} and $\left|\Delta m^2_{31}\right| < 0.5\%$ in 6 years [20]
- current uncertainty from PDG 2024 (roughly): 4.0% for $\sin^2\theta_{12}$, 2.8% for Δm^2_{21} and 1.1% for $\left|\Delta m^2_{31}\right|$ [18]



Summary

- reactor neutrinos: $\overline{\nu}_e$ from ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu, inverse beta decay, Cd/Gd/Li for neutron capture
- discovery of neutrinos: Cowan-Reines experiment, 1956
- θ_{12} and Δm^2_{21}: KamLAND experiment 2002–2011
- θ_{13}: Daya Bay, RENO, Double CHOOZ
- sterile neutrinos: reactor anomaly remains unclear, in both theory and experiment
- mass ordering: JUNO, 3σ after 6 years starting 2025
- other topics not discussed: nuclear security, etc.

References I

[1] J. L. Hewett et al., "Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 2: Intensity Frontier", in Community Summer Study 2013: Snowmass on the Mississippi (Jan. 2014).

[2] F. P. An et al., "Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay", Phys. Rev. Lett. **118**, 251801 (2017).

[3] Y. Fukuda et al., "Evidence for oscillation of atmospheric neutrinos", Phys.Rev.Lett. **81**, 1562–1567 (1998).

[4] Q. Ahmad et al., "Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory", Phys.Rev.Lett. **89**, 011301 (2002).

[5] M. P. Decowski, "KamLAND's precision neutrino oscillation measurements", Nucl. Phys. B **908**, 52–61 (2016).

References II

[6] K. Abe et al., "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam", Phys. Rev. Lett. **107**, 041801 (2011).

[7] P. Adamson et al., "Improved search for muon-neutrino to electron-neutrino oscillations in MINOS", Phys. Rev. Lett. **107**, 181802 (2011).

[8] Y. Abe et al., "Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment", Phys.Rev.Lett. **108**, 131801 (2012).

[9] F. An et al., "Observation of electron-antineutrino disappearance at Daya Bay", Phys.Rev.Lett. **108**, 171803 (2012).

[10] F. P. An et al., "Precision Measurement of Reactor Antineutrino Oscillation at Kilometer-Scale Baselines by Daya Bay", Phys. Rev. Lett. **130**, 161802 (2023).

References III

[11] J. Ahn et al., "Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment", Phys.Rev.Lett. **108**, 191802 (2012).

[12] H. de Kerret et al., "Double Chooz θ_{13} measurement via total neutron capture detection", Nature Phys. **16**, 558–564 (2020).

[13] T. Abrahão et al., "Reactor rate modulation oscillation analysis with two detectors in Double Chooz", JHEP **01**, 190 (2021).

[14] H. Almazán et al., "STEREO neutrino spectrum of ^{235}U fission rejects sterile neutrino hypothesis", Nature **613**, 257–261 (2023).

[15] A. Letourneau, V. Savu, D. Lhuillier, T. Lasserre, T. Materna, G. Mention, X. Mougeot, A. Onillon, L. Perisse, and M. Vivier, "Origin of the Reactor Antineutrino Anomalies in Light of a New Summation Model with Parametrized β- Transitions", Phys. Rev. Lett. **130**, 021801 (2023).

References IV

[16] Y. J. Ko et al., "Sterile Neutrino Search at the NEOS Experiment", Phys. Rev. Lett. **118**, 121802 (2017).

[17] C. Awe et al., "High Energy Physics Opportunities Using Reactor Antineutrinos", (2022).

[18] *Pdg 2024: neutrino masses, mixing, and oscillations*, https://pdg.lbl.gov/2024/reviews/rpp2024-rev-neutrino-mixing.pdf.

[19] M. Andriamirado et al., "Improved short-baseline neutrino oscillation search and energy spectrum measurement with the PROSPECT experiment at HFIR", Phys. Rev. D **103**, 032001 (2021).

[20] A. Abusleme et al., "Sub-percent precision measurement of neutrino oscillation parameters with JUNO", Chin. Phys. C **46**, 123001 (2022).

$\overline{\nu}_e$ Disappearance

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12})\cos^4\theta_{13}\sin^2\left(\frac{\Delta_{21}}{2}\right)$$

$$- \sin^2(2\theta_{13})\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta_{31}}{2}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta_{32}}{2}\right)\right]$$

$$\approx 1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta_{21}}{2}\right) - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta_{31}}{2}\right)$$