Reactor Neutrinos

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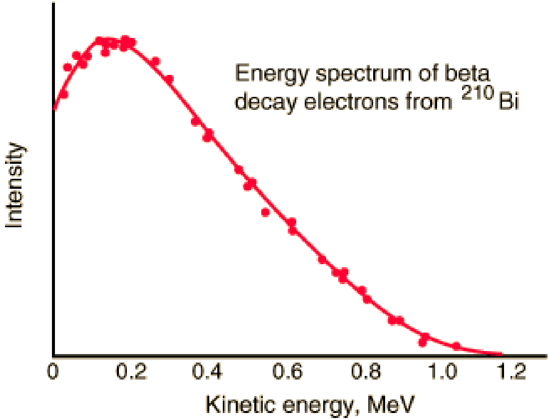
A Historical Introduction

- 1914: Chadwick observed continuous electron spectra from β decay



- 1930: Pauli proposes “neutron” to solve issue with β spectrum
- Pauli’s particle would need to be a neutron fermion with low mass and low cross-section
- 1934: Fermi incorporates this particle in electroweak theory
- Very low cross-section makes neutrino very hard to detect
  - Needs large detectors & very intense sources!

Producing a neutrinos with nuclear fission

1938 Discovery of nuclear fission. Eg:

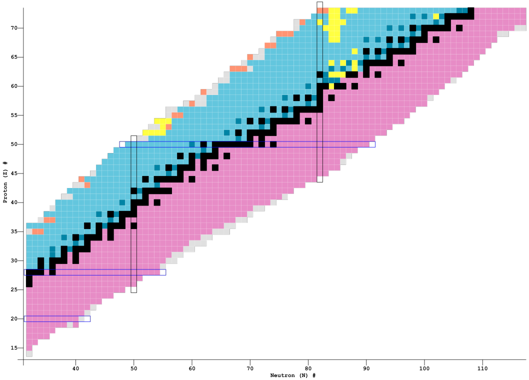
$$^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\mathrm{n}$$

- $\sim$170 MeV energy released in this fission
- Chain reaction $\rightarrow$ energy production (for bomb or nuclear power plant...)
  - Difference in those cases from how efficient/fast is chain reaction
- Produced isotopes are unstable:
  - $^{141}_{56}\mathrm{Ba} \xrightarrow{\beta} {}^{141}\mathrm{La} \xrightarrow{\beta} {}^{141}\mathrm{Ce} \xrightarrow{\beta} {}^{141}\mathrm{Pr}$
  - $^{92}_{36}\mathrm{Kr} \xrightarrow{\beta} {}^{92}\mathrm{Rb} \xrightarrow{\beta} {}^{92}\mathrm{Sr} \xrightarrow{\beta} {}^{92}\mathrm{Y} \xrightarrow{\beta} {}^{92}\mathrm{Zr}$
- Each β decay produces an electron anti-neutrino!

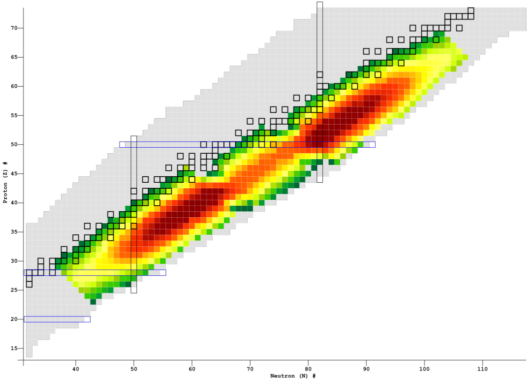
NB: many possible combinations of daughter nuclei, not fission with those exact isotopes!

Producing a neutrinos with nuclear fission: nuclear charts

Decay Modes



Fission products of ^{235}U



- Black: stable
- Rose: β^- decay

- $\sim$200 MeV/fission and $\sim$6 ν/fission
- 1 GW produced energy $\Rightarrow \sim 2 \cdot 10^{20}$ ν/s

Figures from `https://www.nndc.bnl.gov/nudat3/`

First measurement of neutrinos: “Project Poltergeist”

- First step: find adequate ν emitter…

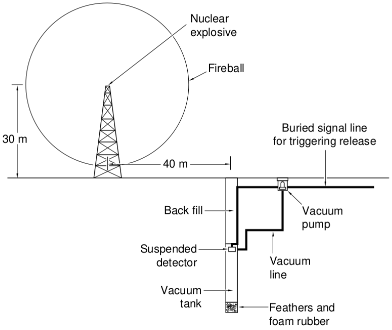
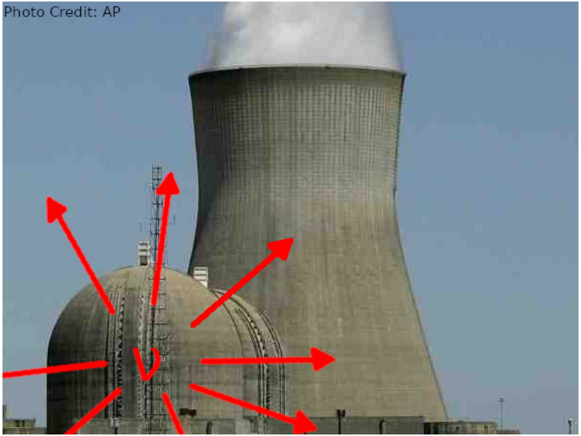


Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, 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.

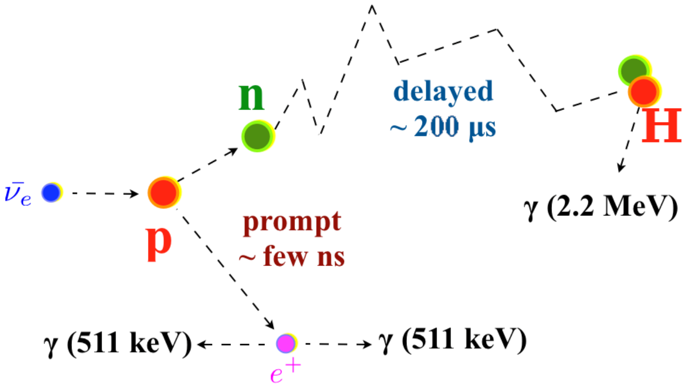
Los Alamos Science Number 25 1997



http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02

Measuring reactor $\bar{\nu}_e$: Inverse Beta Decay (IBD)

- To detect β produced neutrinos invert reaction: $\bar{\nu}_e + p \rightarrow n + e^+$
  - Reaction named Inverse Beta Decay
  - Detection method for reactor neturinos used in most experiments
  - Prompt+delayed signal $\Rightarrow$ large background suppression



NB Capture time and energy of delayed signal depend on detector used!

First measurement of neutrinos

1995

1956 Reines and Cowan detected ν from Savannah River reactors

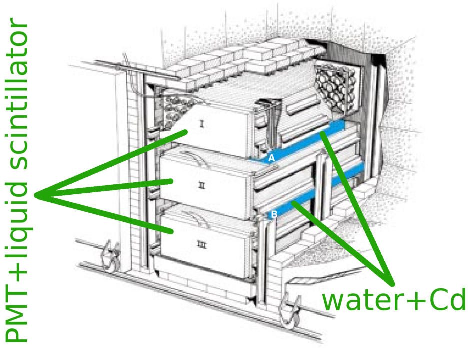


Figure 4. The Savannah River Neutrino Detector—A New Design
The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water. The protons in the water provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons. The target tanks were sandwiched between three scintillation detectors (I, II, and III). Each detector contained 1,400 liters of liquid scintillator that was viewed by 110 photomultiplier tubes. Without its shield, the assembled detector weighed about 10 tons.

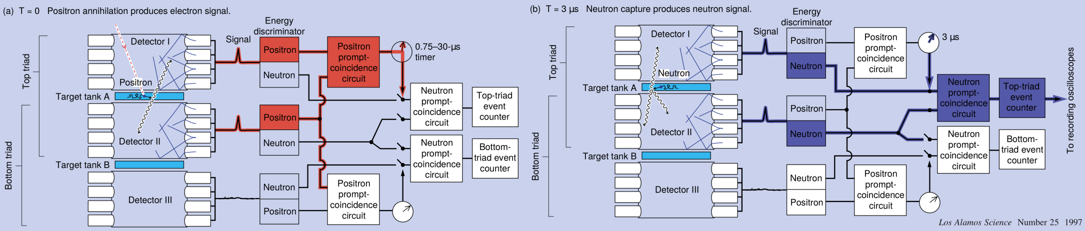
Los Alamos Science Number 25 1997

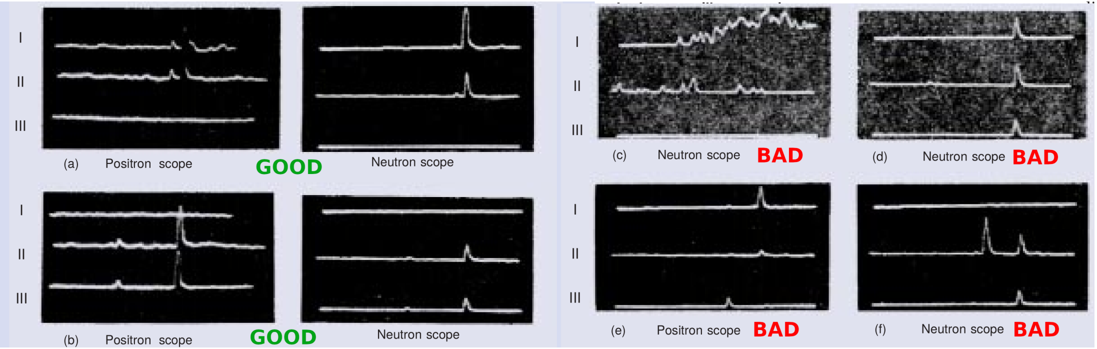
- $\bar{\nu}_e$ target: p in water
  - 2×200 tons of water
  - $\mathcal{O}(10^{31})$ H atoms
- Prompt signal from positron anihilation @ water tank
- Delayed signal from neutron capture in Cd @ water tank:

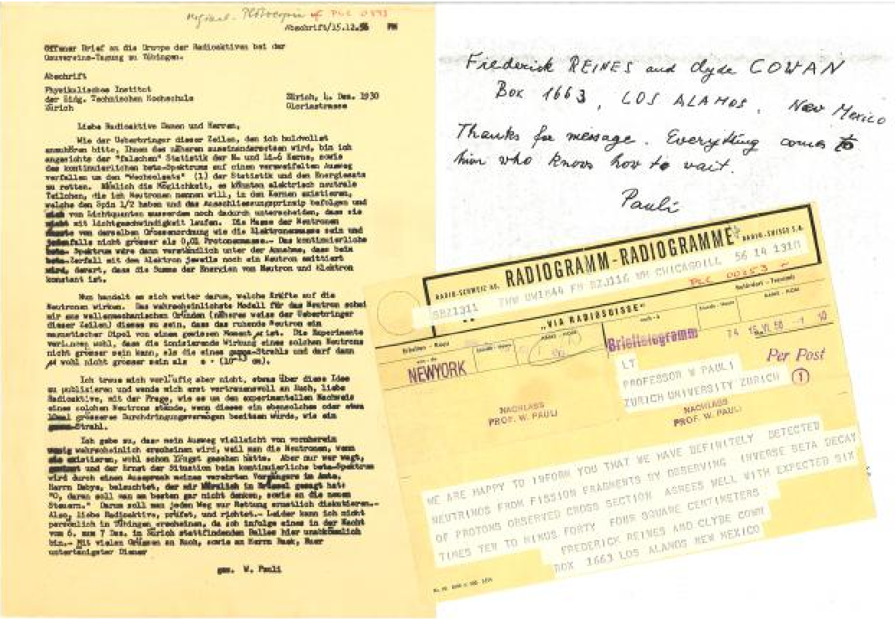
$$^{108}\text{Cd} + \text{n} \rightarrow ^{109m}\text{Cd} \rightarrow ^{109}\text{Cd} + \gamma$$

- γ emissions separated by 3 – 10 μs

Delayed-Coincidence Signals from Inverse Beta Decay







https://timeline.web.cern.ch/neutrinos-detected-last

The neutrino flux from nuclear reactors

- Up to now mainly discussed nuclear reactors produce copius amounts of $\bar{\nu}_e$...
- ...but these neutrinos don't all have same energy...
- ...important to also understand spectrum S_{tot} of those neutrinos!

$$S_{\text{tot}}(E,t) = \sum_k F_k(t) S_k(E)$$

- F_k: fraction of each fissile element k in the reactor
- S_k: neutrino spectrum of fissile element k
  - two main techniques to determine S_k:

Summation method

- Start from individual β spectrum
- Add them to get final spectrum

Conversion method

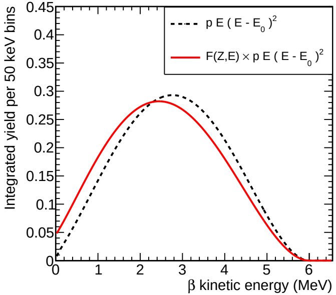
- Measure β spectra of fissile products
- Transform electron spectra in neutrino spectra

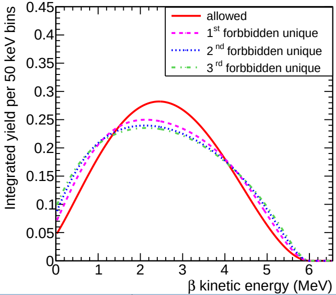
The neutrino flux from nuclear reactors: summation method

$$S_k(E) = \sum_n Y_n^k \sum_b \mathrm{BR}_n^b S_n^b(E)$$

$$S_n^b(E) \propto \mathcal{F}(Z_n, E) p E (E - E_{0,n}^b)^2 C_n^b(E)(1 + \ldots)$$

- Y_n^k: fission yield of given element n
- BR_n^b: branching ratio
- S_n^b: beta spectrum (with integral 1)
- $\mathcal{F}$: fermi function accounting for Coulomb potential
- $E_{0,n}^b$: end-point energy
- C_n^b: form factor depending on transition (allowed, 1st forbidden unique, ...)
- ...: additional 2nd order correction terms

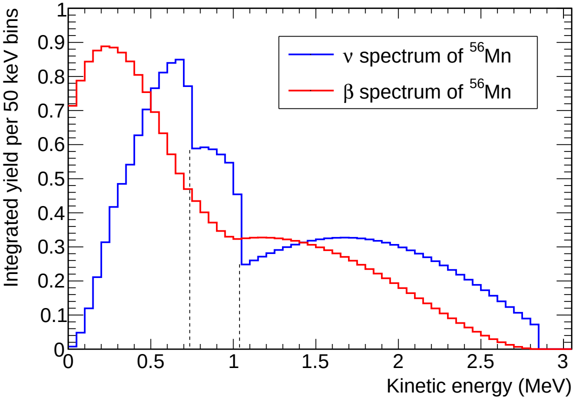




Ref.: T. Mueller PhD (2010)

The neutrino flux from nuclear reactors: summation method

Applying summation method for ^{56}Mn:



for 3 β branches, from T. Mueller PhD (2010)

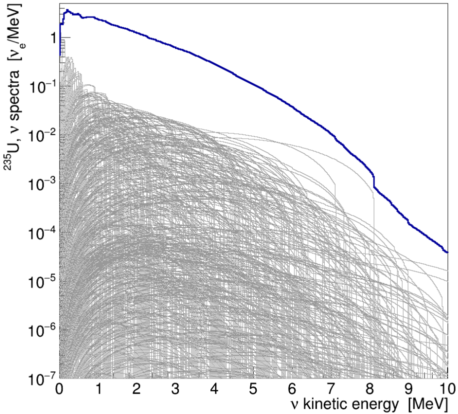
$^{56}\text{Mn} \xrightarrow{\beta} {}^{56}\text{Fe}$

- $E_0 = 2.849$ MeV with BR=56.6 (7) %
- $E_0 = 1.038$ MeV with BR=27.5 (4) %
- $E_0 = 0.736$ MeV with BR=14.5 (3) %
- $E_0 = 0.326$ MeV with BR=1.20 (3) %

The neutrino flux from nuclear reactors: summation method

		Isotope	Number of FP	Emitted particle s	$\beta^-/\bar{\nu}_e$	ν_e	α	n	p	IT
Independent	Number of emitters	^{235}U	873	85	771	7	2	192	0	59
		^{238}U	771	45	722	1	0	193	0	44
		^{239}Pu	1006	127	832	19	1	191	1	69
		^{241}Pu	958	101	834	9	0	197	0	63
	Number of particle emitted per fission	^{235}U	873	-	1.93	7.08e-11	7.30e-7	1.41e-2	-	-
		^{238}U	771	-	1.96	5.01e-14	-	3.20e-2	-	-
		^{239}Pu	1006	-	1.89	5.92e-7	2.48e-8	6.08e-3	9.78e-12	-
		^{241}Pu	958	-	1.94	6.69e-11	-	1.23e-2	-	-
Cumulative	Number of emitters	^{235}U	983	150	793	7	2	192	0	60
		^{238}U	935	130	778	2	0	193	0	55
		^{239}Pu	1093	176	851	19	3	191	1	70
		^{241}Pu	1071	163	860	9	0	197	0	66
	Number of particle emitted per fission	^{235}U	983	-	6.06	2.35e-10	7.31e-7	1.56e-2	-	-
		^{238}U	935	-	7.15	1.69e-13	-	3.83e-2	-	-
		^{239}Pu	1093	-	5.49	5.98e-7	6.32e-7	6.43e-3	9.78e-12	-
		^{241}Pu	1071	-	6.25	9.41e-11	-	1.39e-2	-	-

Table 2.3: Types of emitters and associated fluxes of particle for thermal FP of ^{235}U, ^{239}Pu and ^{241}Pu, and for fast FP of ^{238}U. The data are given right after a fission (Independent) or after reaching an equilibrium state in the rate of production of FP (Cumulative), and the fluxes are obtained respectively from IFY and CFY. Stable nuclei are reported in the column s. Decays listed in Tab. 2.2 that produce two types of particle are accounted for both types of emitter and fluxes. As most of the B^+ decays are actually EC, only the ν_e fluxes are reported. The data are obtained from the NUBASE2020 database [155] and from the JEFF-3.3 database [136].

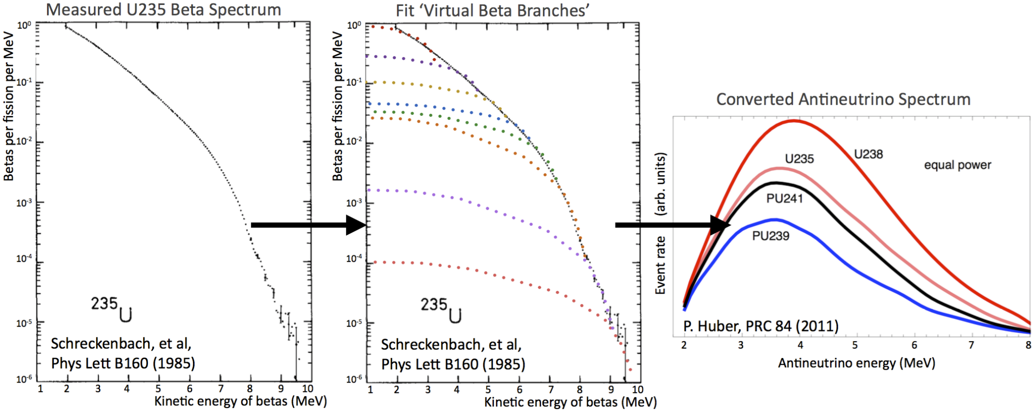


(a) Summation model of ^{235}U.

from L Périssé PhD (2021)

- Many possible fission configurations & many decay chains of fragments
- Depends on our knowledge of nuclear data bases…

The neutrino flux from nuclear reactors: conversion method



from `https://prospect.yale.edu/science`

- Assume there are N branches
- Fit amplitude of each branch with β spectrum
- Calculate ν spectrum

Inverse Beta Decay cross-section

- Vogel and Beacom, PRD 60 053003 (1999)
  - 1st order on E_ν/M, with $M = (m_\text{n} + m_\text{p})/2$
  - Reliable for $E_\nu < 60$ MeV
- Strumia and Vissani, PLB 564 42 (2003)
  - Fully relativistic

Using notation from J Formaggio et al, Rev.Mod.Phys. 84 (2012) 1307-1341, Vogel x-sec:

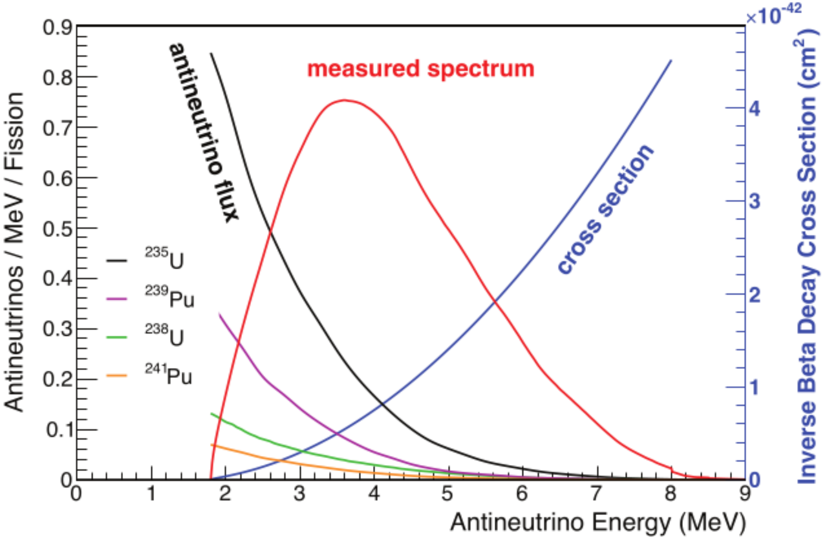
$$\frac{d\sigma(\bar{\nu}_e p \to e^+ n)}{d\cos\theta} = \frac{G_F^2 |V_{ud}|^2 E_e p_e}{2\pi}\left[f_V^2(0)(1+\beta_e\cos\theta) + 3f_A^2(0)(1-\frac{\beta_e}{3}\cos\theta)\right]$$ or

$$\frac{d\sigma(\bar{\nu}_e p \to e^+ n)}{d\cos\theta} = \frac{2\pi^2}{2m_e^5 f(1+\delta_R)\tau_n} E_e p_e \left[(1+\beta_e\cos\theta) + 3\lambda^2(1-\frac{\beta_e}{3}\cos\theta)\right]$$

which highlights relation with neutron livetime τ_n; λ is axial/vector coupling ratio.

- IBD well predicted with uncertainties around $\pm 0.5\%$ (from Formaggio et al)
- Neutrino energy threshold: $\frac{(M_n+m_e)^2 - M_p^2}{2M_p} = 1.806$ MeV (lab-frame)

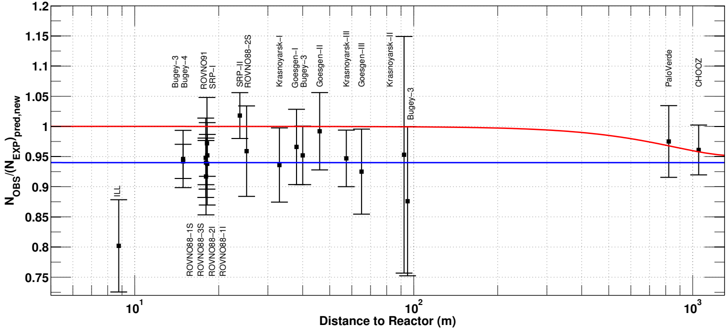
Measured $\bar{\nu}_e$ flux: flux $\times$ IBD x-sec



From [1507.05613]

Measuring reactor neutrino fluxes: a historical take

- First prediction in the 1980s by Schreckenbach et al et Vogel et al
  - using conversion method of ILL β spectra for ^{235}U, ^{239}Pu and ^{241}Pu
  - using summation method for ^{238}U
  - overall good agreement with data
- 2011: Mueller et al & Huber et al updated predictions from new spectra
  - Neutrino flux increased by 5–6%
  - Reactor Antineutrino Anomaly?

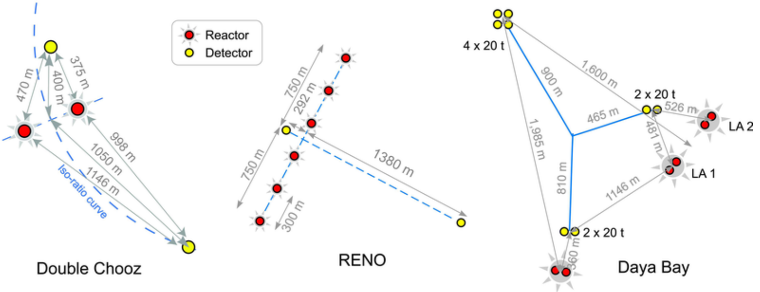


G. Mention et al, Phys.Rev.D 83 (2011) 073006 [1101.2755]

Reactor experimental program since the 2010s

- Timing of new predictions correlated to new experiments turning on to measure θ_{13}
  - Double Chooz, Reno, Daya-Bay started circa 2011
  - Very similar setups in these 3 experiments
  - Although main goal was measuring θ_{13} can also contribute to understanding ν flux
- The Reactor Antineutrino Anomaly also span a flurry of experiments to probe possible very short-baseline oscillations
  - NEOS, STEREO, Prospect, DANSS, Neutrino-4, ...

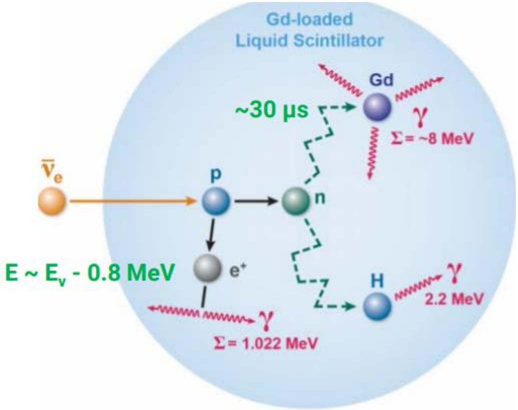
Differences and similarities between DC, RENO, and DYB

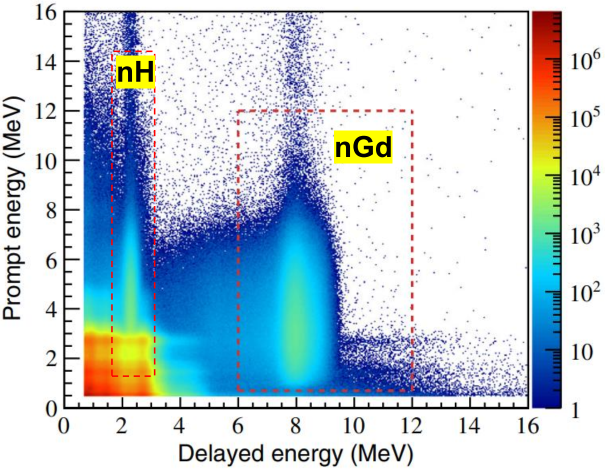


From M. Mezzetto et al J. Phys. G: Nucl. Part. Phys. 37 103001 (2010)

- Differences:
  - Double Chooz (DC): simpler geometry, less total reactor power (ie, less flux)
  - Daya Bay (DYB): more detetectors, flux from multiple reactors, more complex
- In all cases far detector at about 1–2 km
- Near detectors to reduce flux systematics in θ_{13} determination
- Gd+LS used for $\bar{\nu}_e$ target

IBDs in GdLS detector

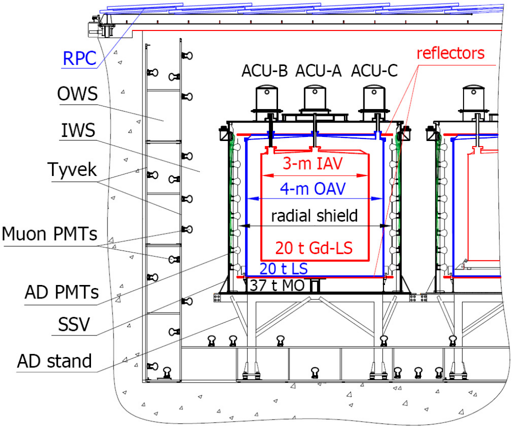




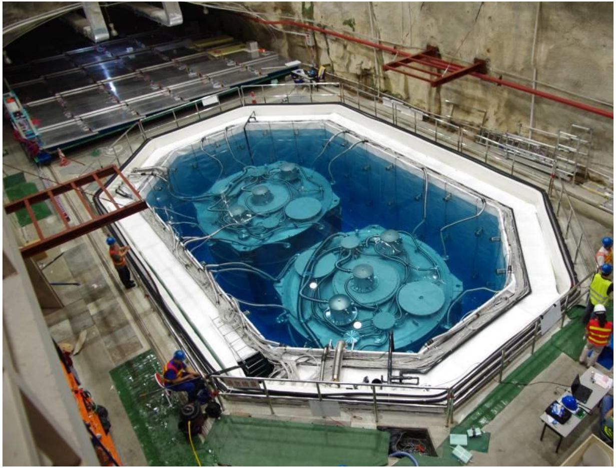
Daya Bay, PHYSICAL REVIEW D 95, 072006 (2017)

- Gd $\rightarrow$ larger neutron capture x-sec
- Prompt energy is proxy for neutrino energy

Daya Bay detector

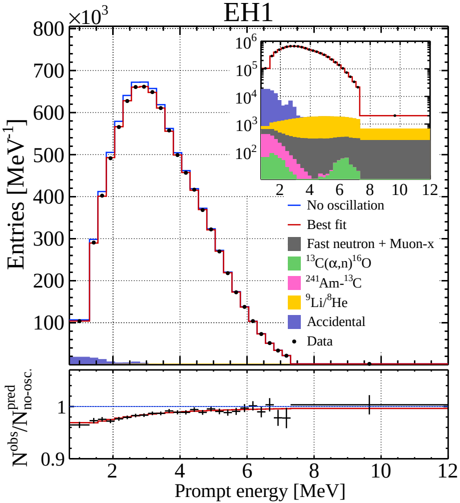


Daya-Bay, Phys.Rev.Lett. 108 (2012) 171803



from Z. Yu talk @ Neutrino 2024

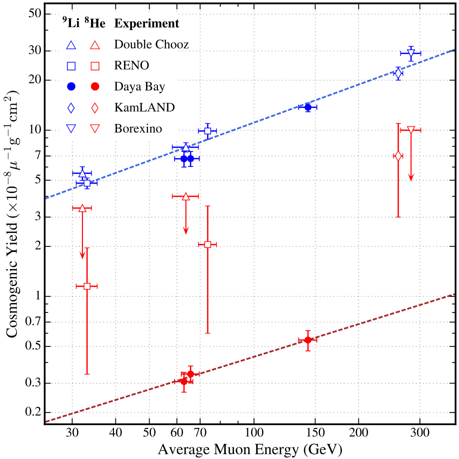
Daya Bay detector: backgrounds



Daya-Bay, Phys.Rev.Lett. 130 (2023) 16, 161802

- Clean detectors help reduce intrinsic backgrounds
- Accidental backgrounds: IBD coincidence suppresses it, remaining measured with off-time window
- Cosmogenics (^{9}Li/^{8}He), fast-n: harder to estimate; μ veto + overburden help

Daya Bay detector: cosmogenic



Phys.Rev.D 110 (2024) 1, L011101

- μ passing through LS produce lighter elements by spallation…most concerning for IBDs: ^{9}Li and ^{8}He
  - 51% of ^{9}Li decays: $^9\text{Li} \to ^9\text{Be}^* e^- \bar{\nu}$; $^9\text{Be}^* \to n + \alpha + \alpha$
  - 16% of ^{8}He decays: $^8\text{He} \to ^8\text{Li}^* e^- \bar{\nu}$; $^8\text{Li}^* \to ^7\text{Li} + n$

  NB these are not the only cosmogenic decays that can mime IBD
- Use almost similar selection for IBDs but want correlated signal with μ
- Detection of ^{9}Li by several experiments: rate depends on overburden
- First detection of ^{8}He by several Daya-Bay!

Backgrounds – radiogenic neutrons

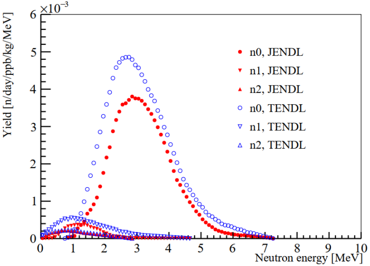
Neutrons from (α,n) reactions and spontaneous fissions

→ **Gd-LS, LS and acrylic:** clean, ^{238}U and ^{232}Th < 0.1 ppb, 1.1% ^{13}C, *O*(0.05) n's/day

→ **PMT glass:** *O*(100) ppb ^{238}U/^{232}Th and 20% boron, *O*(100) n's/day/100kg glass

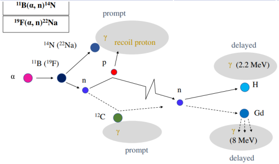
→ **Negligible for nGd but not for nH** if PMTs not well shielded from LS

- → Five Daya Bay PMTs were broken to measure the Boron fraction in glass
- → Also investigated the material screening results, no other non-negligible neutron source



Phys. Rev. D **104**, 092006

Distance from PMT to LS		Residual bkg in nH
Daya Bay	20 cm	0.2/day/AD
RENO	~50 cm	<10^{-4}/day
Double Chooz	~45 cm	<10^{-4}/day



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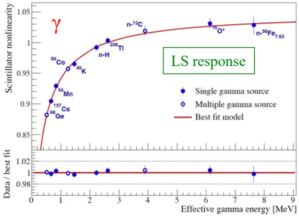
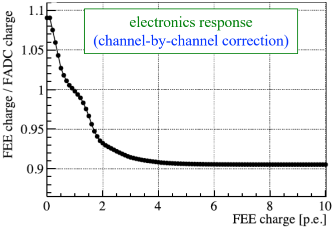
from Z. Yu talk @ Neutrino 2024

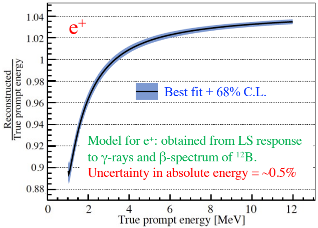
Non-linear Energy Response

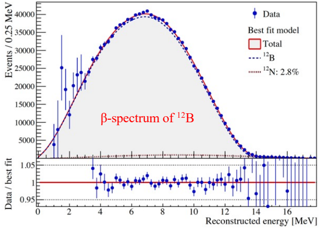
Due to nature of liquid scintillator (LS) and charge measurement of electronics

NIM A**940** (2019) 230





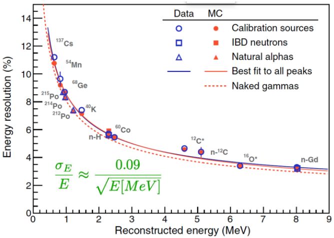


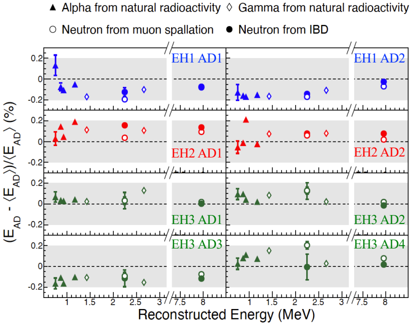


K-B Luk talk @ Neutrino 2022

Energy Scale

- Gain of photomultiplier tubes
  - Single-photoelectron dark noise
  - Weekly LED monitoring
- Energy calibration
  - Weekly ^{68}Ge, ^{60}Co, ^{241}Am-^{13}C
  - Spallation neutrons
  - Natural radioactivity

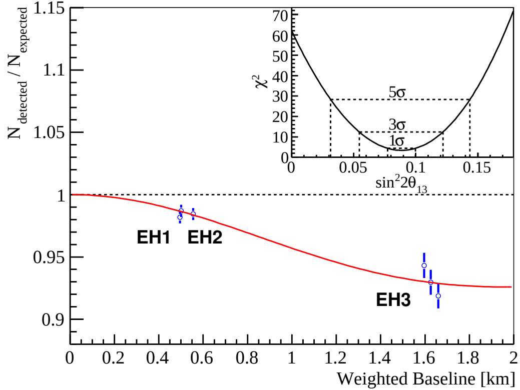




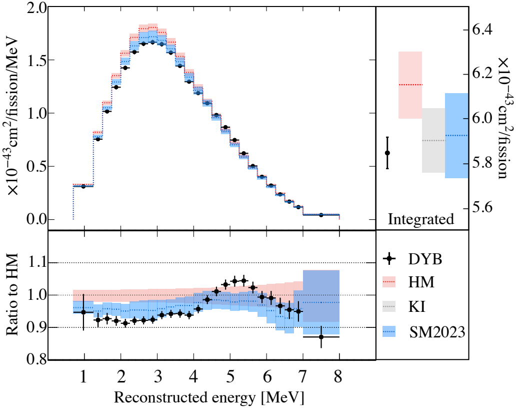
Relative uncertainty in energy scale: ~0.2%

K-B Luk talk @ Neutrino 2022

Measuring the reactor flux with Daya-Bay



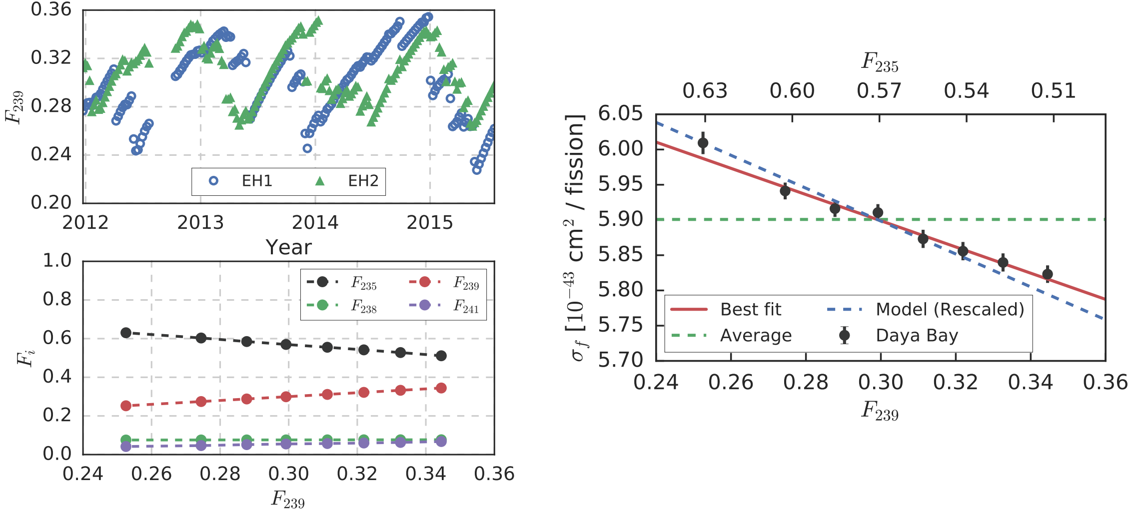
Daya-Bay, Chin.Phys.C 37 (2013) 011001



Daya-Bay, Phys.Rev.Lett. 134 (2025) 20, 201802

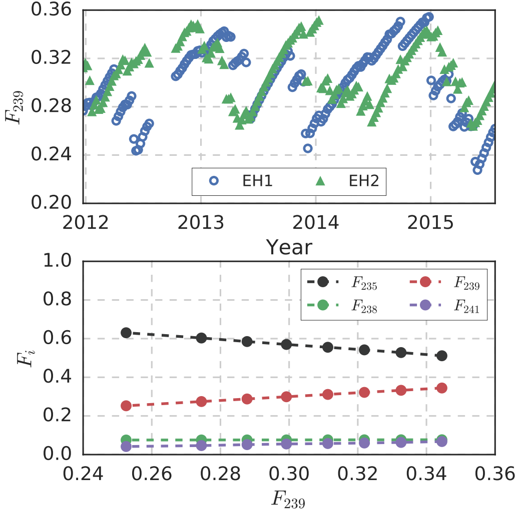
- Oscillation effects non-negligible, need to be corrected
- Similar deficit from RAA with respect to H-M prediction
- 5 MeV bump (first seen on RENO & Double Chooz data)

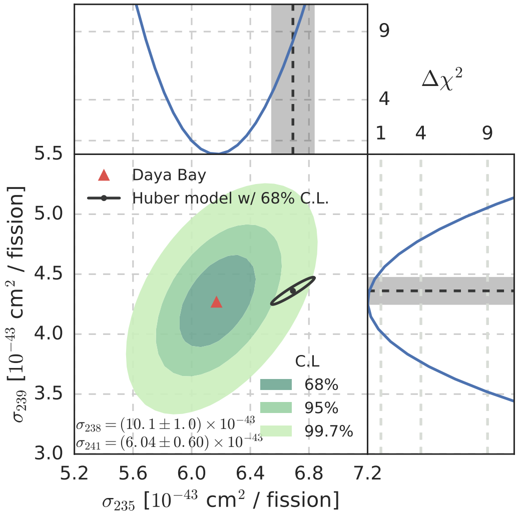
Daya Bay: Evolution of the reactor antineutrino flux



Daya Bay, Phys.Rev.Lett. 118 (2017) 25, 251801

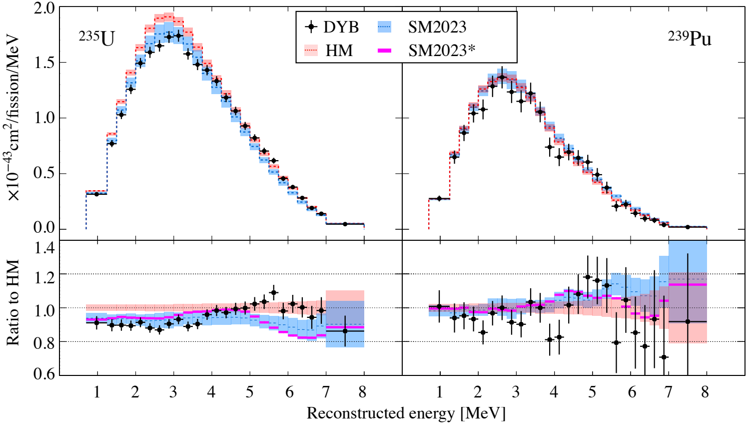
Daya Bay: Evolution of the reactor antineutrino flux

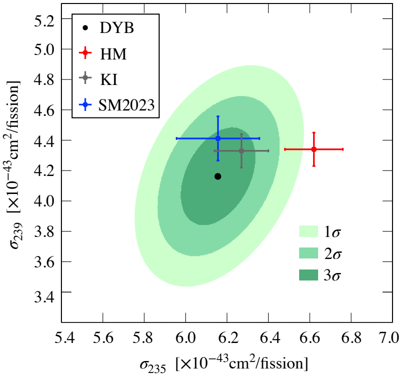




Daya Bay, Phys.Rev.Lett. 118 (2017) 25, 251801

Daya Bay: Evolution of the reactor antineutrino flux – 2025 update

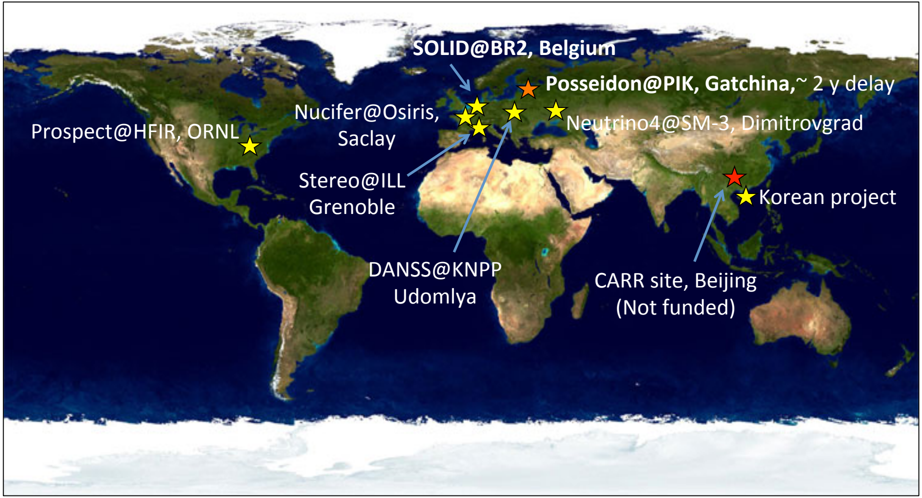




Daya-Bay, Phys.Rev.Lett. 134 (2025) 20, 201802

Newer generation of very short baseline experiments

From D. Lhuillier talk @ Neutrino 2014



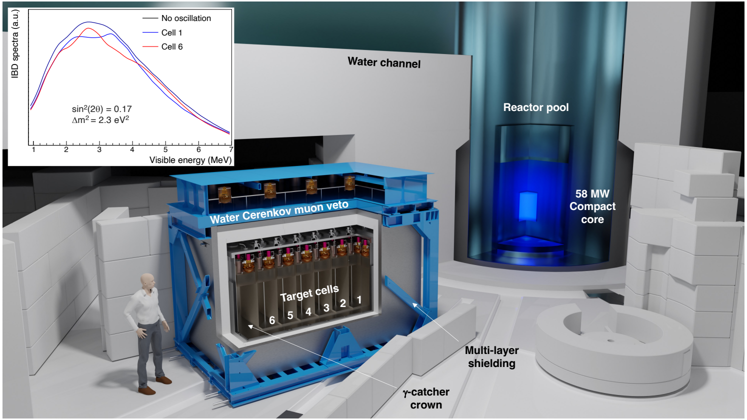
Newer generation of very short baseline experiments

From D. Lhuillier talk @ Neutrino 2014

	Gd	^{6}Li	Highly Segmented	Moving detector	2 det.
Nucifer (FRA)	■				
Poseidon (RU)	■				
Stéréo (FRA)	■			■	
Neutrino 4 (RU)	■			■	
Hanaro (KO)	◣	◥	■	■	
DANSS (RU)	■		■		
Prospect (USA)	◣	◥	■		■
SoLid (UK)		■	■		

	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
Nucifer (FRA)	70	0.8	7	13
Poseidon (RU)	100	~ 3	5-8	~ 15
Stéréo (FRA)	57	1.75	8.8-11.2	18
Neutrino 4 (RU)	100	1.5	6-12	~ 10
Hanaro (KO)	30-2800	~ 1	6	few
DANSS (RU)	3000	0.9	9.7-12.2	50
Prospect (USA)	85	1 & 10	7-18	few
SoLid (UK)	45-80	2.9	6-8	10

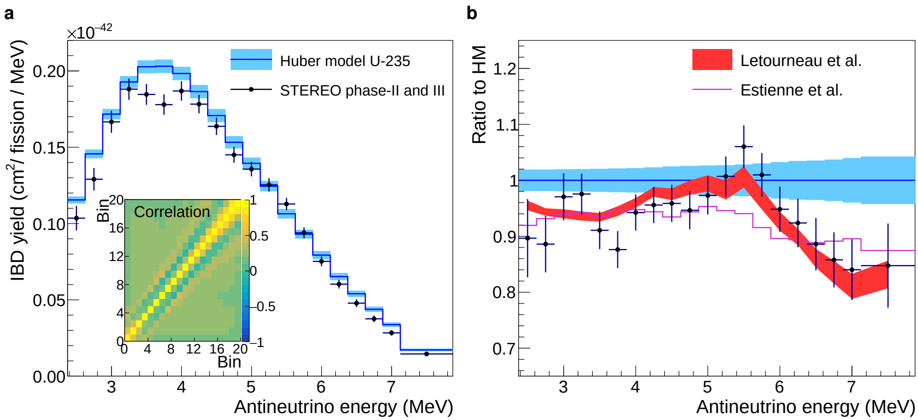
STEREO



STEREO, Nature 613 (2023) 7943, 257-261

- Reactor: ILL $\rightarrow$ Highly enriched ^{235}U fuel (HEU)
- Target cells with Gd LS
- Spectra measured independently in each cell $\rightarrow$ different if ν osc with $\Delta m^2 \sim 1$ eV^2

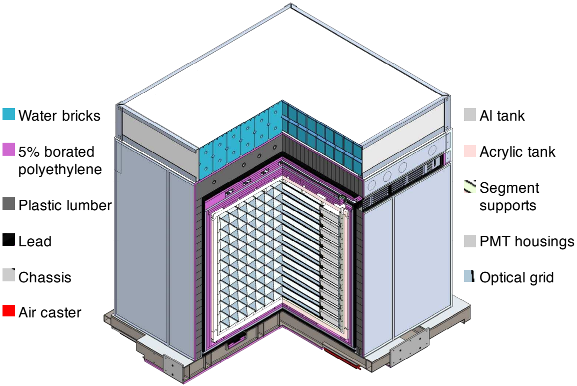
STEREO



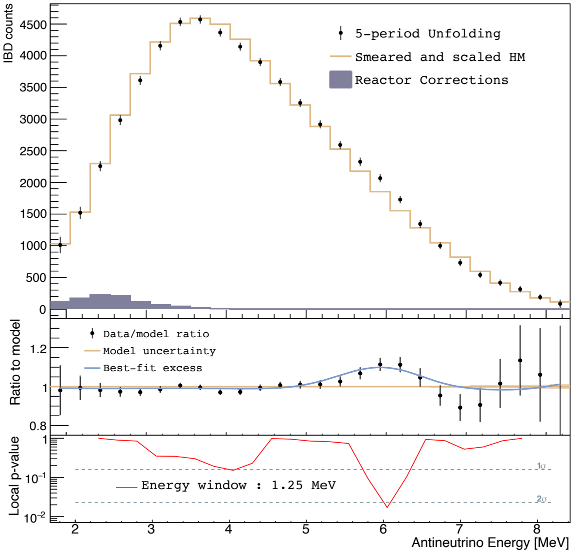
STEREO, Nature 613 (2023) 7943, 257-261

- No significant distortion found between data and no-oscillation prediction

PROSPECT



PROSPECT, Nucl.Instrum.Meth.A 922 (2019) 287-309

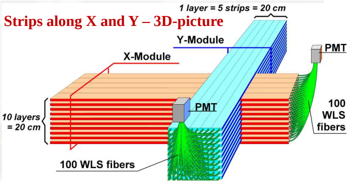


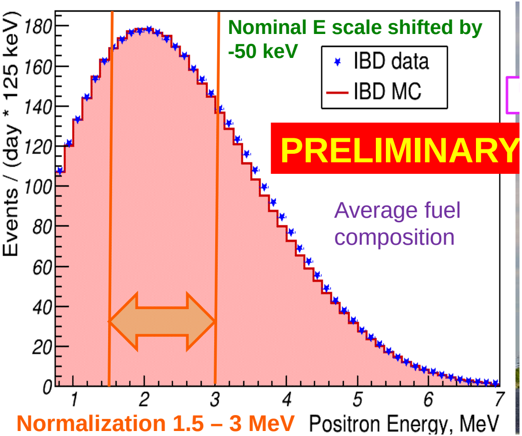
PROSPECT, Phys.Rev.Lett. 131 (2023) 2, 021802

- Also next to reactor with HEU fuel

DANSS

DANSS on a lifting platform
A week cycle of
up/middle/down position



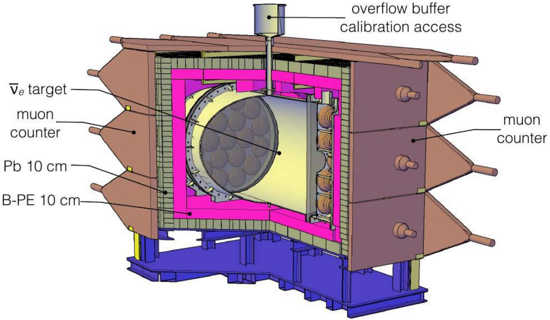


- Closer to H-M than other experiments
- Bump still clearly visible

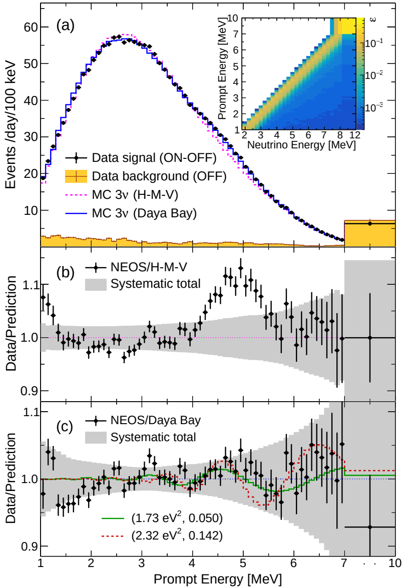
- Next to commercial (LEU) reactor

I. Alekseev talk @ NOW 2022

NEOS



- Non-segmented detector
- Next to commercial (LEU) reactor @ Korea
- Baseline: 24 m



NEOS, Phys.Rev.Lett. 118 (2017) 12, 121802

Neutrino-4

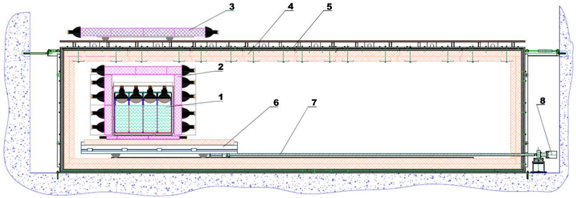
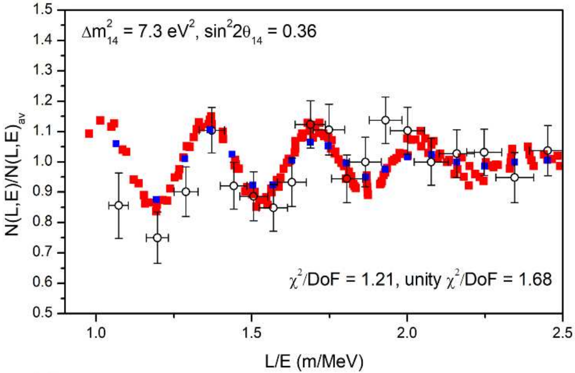


FIG. 14. General scheme of an experimental setup: 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – borated polyethylene passive shielding, 5 – steel and lead passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor.



Neutrino4, Phys.Rev.D 104 (2021) 3, 032003

- Neutrino-4 claims 2.7 σ observation of sterile neutrino oscillations
- Sterile neutrino parameters in region strongly disfavored by other experiments
- Lots of discussion about their analysis in community (Danilov talk @ Neutrino 2024)
- Upgrade of Neutrino4 under preparation

Recent progress on flux calculation: summation method

- Lots of work to account for missing data in nuclear database
- And for data with some biases in measurements of some of that...
- Also lots of progress in quantizing and propagating uncertainties from nuclear data to the neutrino spectra!
- A few highlights in next slides...for more see:
  - M. Estienne et al, Phys.Rev.Lett. 123 (2019) 2, 022502
  - L. Perissé et al, Phys.Rev.C 108 (2023) 5, 055501
  - Sonzogni talk at Neutrino-2024

Limitations from nuclear databases

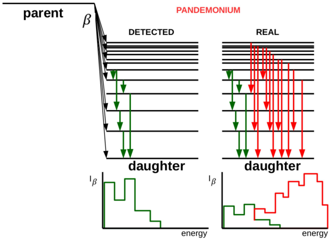
- About 70% of fissile products in ENSDF
- Uncertainties about nuclear data not always well defined

Data provided in ENSDF	Associated distribution in BESTIOLE	Number of transitions
BR $\pm \sigma$(BR)	$\mathcal{N}(\mathrm{BR}, \sigma(\mathrm{BR})^2)$	10 084
BR $\pm$ 0	$\mathcal{N}(\mathrm{BR}, (\mathrm{BR}/10)^2)$	533
BR AP	$\mathcal{N}(\mathrm{BR}, (\mathrm{BR}/10)^2)$	297
BR LE	$\mathrm{Unif}(0, \mathrm{BR})$	} 809
BR LT	$\mathrm{Unif}(0, \mathrm{BR})$	
BR GE	$\mathrm{Unif}(\mathrm{BR}, I_\beta - \sum_{B \neq BR} B)$	} 14
BR GT	$\mathrm{Unif}(\mathrm{BR}, I_\beta - \sum_{B \neq BR} B)$	

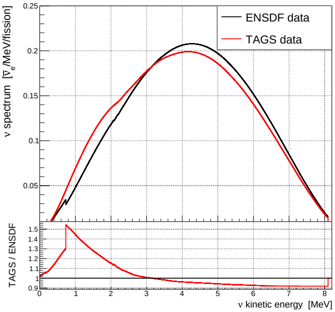
Table 4.1: Branching ratio information as provided in the ENSDF and BESTIOLE databases. In the 2021 BESTIOLE database, branching ratios and the corresponding uncertainties are respectively equal to the central values and the standard deviations of the distributions listed in the second column. There are 11 737 β^- transitions read from ENSDF [161]. The number of β^- transitions concerned by each case is reported in the third column.

from L Périssé PhD (2021)

Limitations from nuclear databases: the pandemonium effect



(a) Illustration of the Pandemonium effect.



(b) Pandemonium effect in ^{92}Rb.

Figure 4.2: (a) Schematic representation of the Pandemonium effect and how it can affect the measured β-feedings of a daughter nucleus. The γ-rays emitted from high energy levels (in red) are hidden to HPGe detectors, resulting in an overestimation of the β-feedings of low energy levels (in green). The figure is taken from [283]. **(b)** Impact of the Pandemonium effect on the ^{92}Rb neutrino spectrum, where the TAGS spectrum is corrected from Pandemonium.

from L Périssé PhD (2021)

- Issue can be fixed with different/more data

Recent progress on flux calculation: convertion method

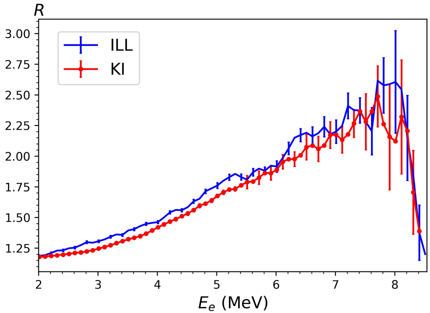
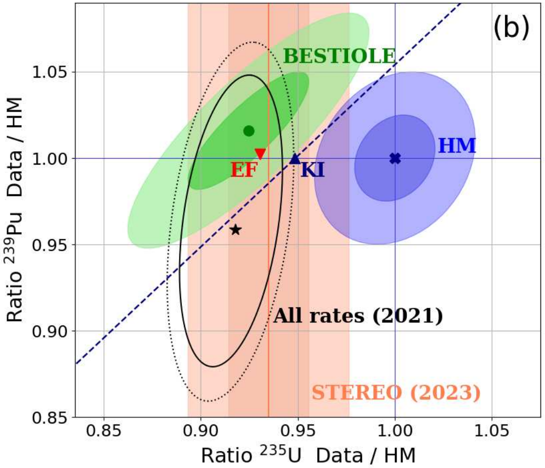


FIG. 1. Ratios $R = {}^eS_5/{}^eS_9$ between cumulative β spectra from ^{235}U and ^{239}Pu from ILL data [11] (the upper curve, blue) and KI data [10] (the lower curve, red). Total electron energies are given. Only statistical errors are shown.

Kopeikin et al, Phys.Rev.D 104 (2021) 7, L071301

- New ^{235}U/^{239}Pu electron spectra ratio at Kurchatov Institute
- Ratio $\sim$ 5% lower than ILL
  - ILL data basis for previous $\bar{\nu}_e$ spectrum calculation!
- Issue with ILL normalisation due to ^{207}Pb neutron capture xsec
  - See A. Sonzogni et al, Phys.Rev.C 108 (2023) 2, 024617 (also ν-2024 talk)
  - Old ORNL data in better agreement with KI (though only reliable up to 4.5 MeV)
- More high-quality e spectra data needed

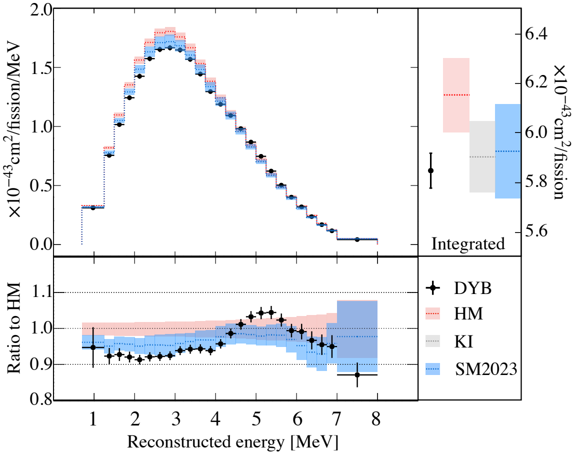
Current Status of understanding of reactor fluxes



L. Perissé et al, Phys.Rev.C 108 (2023) 5, 055501

- Estimating reactor $\bar{\nu}_e$ flux is quite complicated
- Significant recent progress both on conversion & summation methods
- Reactor Antineutrino Anomaly mostly understood to come from reactor flux prediction
- However still no clear understanding of 5 MeV bump for now
- Generally speaking: more/better data needed to help with conversion/summation methods

Current Status of understanding of reactor fluxes



Daya-Bay, Phys.Rev.Lett. 134 (2025) 20, 201802

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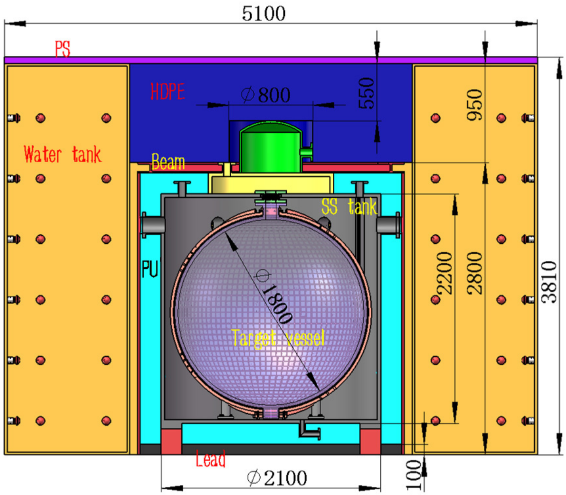
Future experimental program

- Several very short baseline detectors have proposed upgrades
  - PROSPECT-II
  - DANSS Upgrade
  - Neutrino-4 upgrade
- Updates should help clarify situation with Neutrino-4 claim given current tensions
- In additon to that JUNO-TAO should be coming online this year

JUNO-TAO

"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

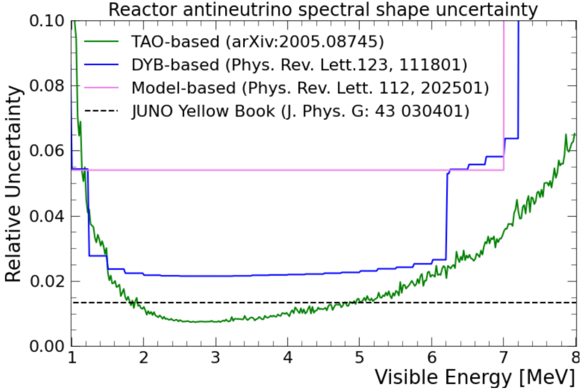
- JUNO-TAO provides reference for reactor spectrum for JUNO
- 44 m from one of Taishan's 4.6 GW_{th} reactor core
- 1 ton fiducial volume Gd-LS detector
- 10 m^2 SiPM of 50% photon detection efficiency (PDE) operated at $-50^{\circ}C$
  - >95% photo-coverage
- TAO energy resolution <2% @ 1 MeV



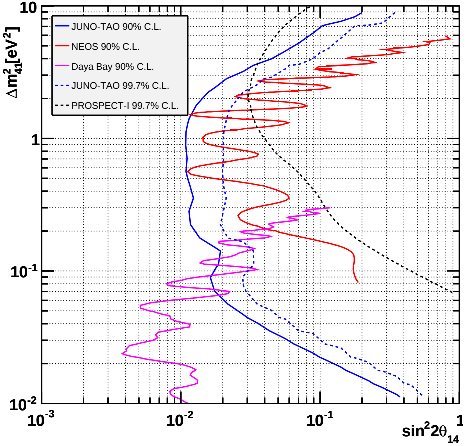
JUNO-TAO – Physics potential

"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

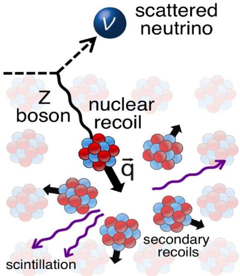
Precise measurement of $\bar{\nu}_e$ spectra

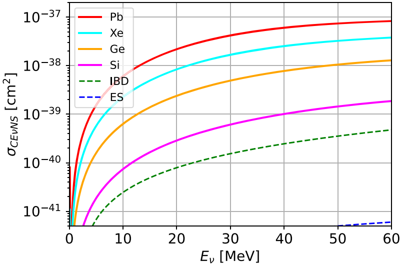


Sterile Neutrino searches



Coherent Elastic Neutrino Nucleus Scattering: CEνNS

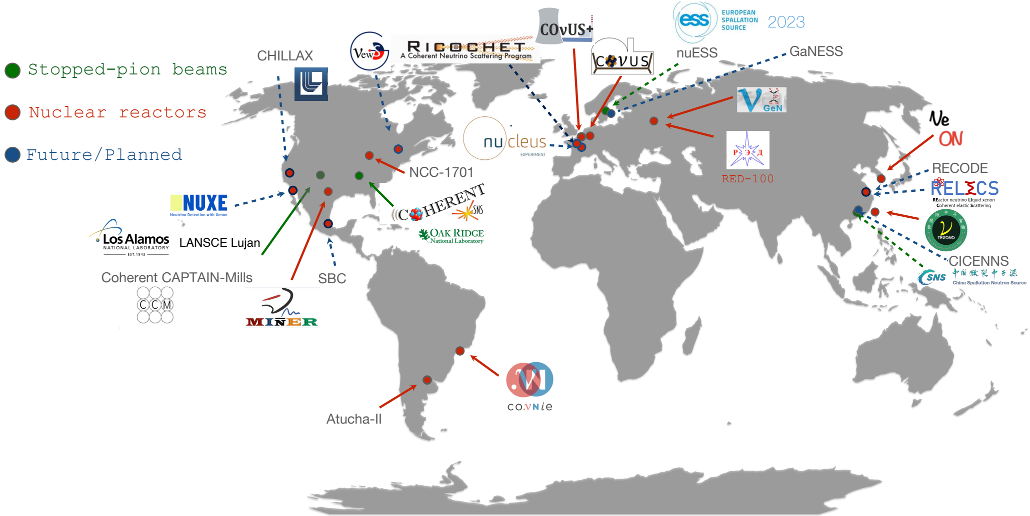




Beeman et al, EPJC (2022) 82:692

- Neutrino scattering off whole nucleus
- No threshold, large cross-section
- But small recoil energy $\rightarrow$ hard to detect
- Neutral current $\rightarrow$ insenstive to ν flavor
- Predicted in 1974
  Freedman, PRD 9 1389 (1974) &
  Kopeliovich et al, JETP Lett 19 4 236 (1974)
- First detected in 2017 from π decay at rest
  COHERENT, Science 357, 1123 (2017)

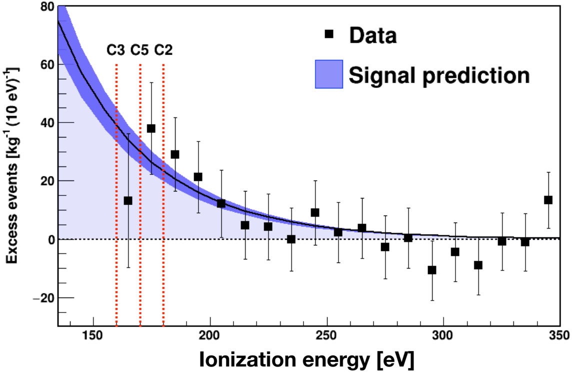
Coherent Elastic Neutrino Nucleus Scattering: CEνNS



Updated from C. Bonifazi, Neutrino 2022

I. Nasteva talk @ Neutrino 2024

First observation of CEνNS in reactors: CONUS+

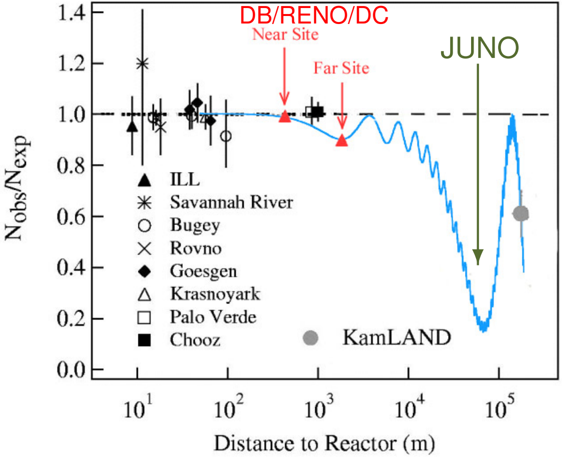


N Ackermann et al, [2501.05206]

- Detector with high-purity Ge crystals
  - Extremely low energy threshold: 160–180 eV
- Detector 20.7 m from core
- Significance of 3.7 σ
- Good agreement with SM prediction

- CONUS+ continuing data taking & many other experiments ramping up!
- Experiments using many different detector types
- Keep posted for more news!

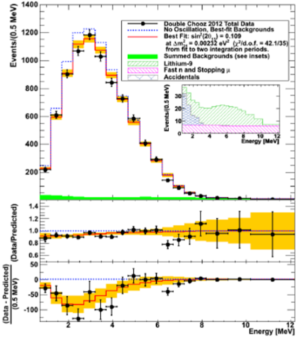
Reactor Neutrinos as a probe for neutrino oscillations



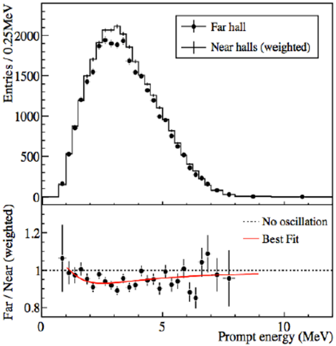
- Measuring only $P(\bar{\nu}_e \to \bar{\nu}_e)$
  - No effect from δ_{CP} or θ_{23} in oscillation pattern
- At very-short baselines: 'sterile neutrino' oscillations (if any)
  - Reactor Antineutrino Anomaly had a possible sterile neutrino interpretation
- At short baselines (1 km): Δm^2_{31} effects $\Rightarrow$ sensitive to θ_{13}
- At medium baselines (50 km): Δm^2_{21} effects dominate $\Rightarrow$ sensitive to θ_{12}

Measuring θ_{13}: situation circa 2012

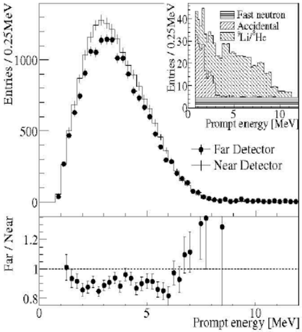
Double Chooz (Oct. 2011)



Daya Bay (March 2012)



RENO (April 2012)



From `https://neutrino-history.in2p3.fr/historical-plots/`

- Figures from when first reached 5 σ discovery of $\theta_{13} \neq 0$

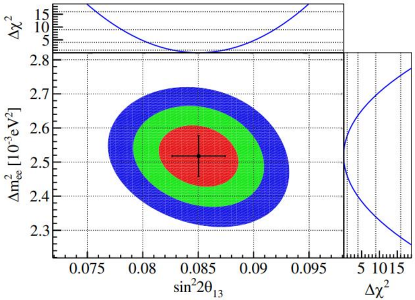
Measuring θ_{13}: latest results from Daya-Bay (nGd)

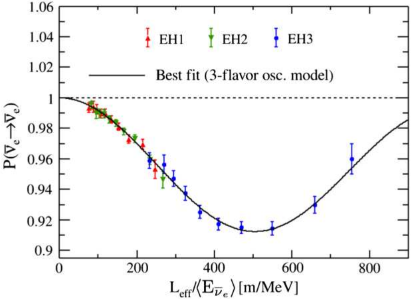
Daya Bay reported the precision measurement with 3158-days full dataset in 2022

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

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

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





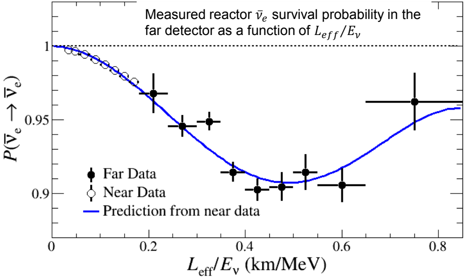
PhysRevLett. 130 161802

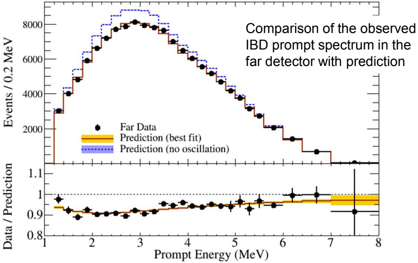
From Z. Yu @ Neutrino 2024

Measuring θ_{13}: latest results from RENO (nGd)

- $\boldsymbol{sin^2 2\theta_{13} = 0.0920\,^{+0.0044}_{-0.0042}\,(stat.)\,^{+0.0041}_{-0.0041}\,(syst.)}$ **precision 6.5%**
- $\boldsymbol{\Delta m^2_{ee} = 2.57\,^{+0.10}_{-0.11}\,(stat.)\,^{+0.05}_{-0.05}\,(syst.)[\times 10^{-3} eV^2]}$ **precision 4.6%**

- (reference) 2200[d] result published at **2018**
  - $sin^2 2\theta_{13} = 0.0896 \pm 0.0048(stat.) \pm 0.0047(syst.)$ precision 7.5%
  - $\Delta m^2_{ee} = 2.68 \pm 0.12(stat.) \pm 0.07(syst.)[\times 10^{-3} eV^2]$ precision 5.2%





From Z. Yu @ Neutrino 2024

Measuring θ_{13}: latest results from Double-Chooz (nH+nGd)

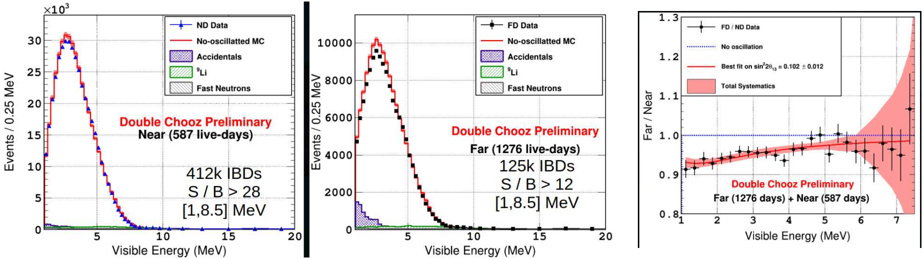
Double Chooz preliminary results with full data set, presented at Nu-2020

Using ANN to suppress accidental background

Total neutron capture enhanced the detection efficiency for n-Gd

Plan to finalize by end of 2024

$\sin^2 2\theta_{13} = 0.102 \pm 0.004(\text{stat.}) \pm 0.011(\text{syst.})$ **precision 11.8%**

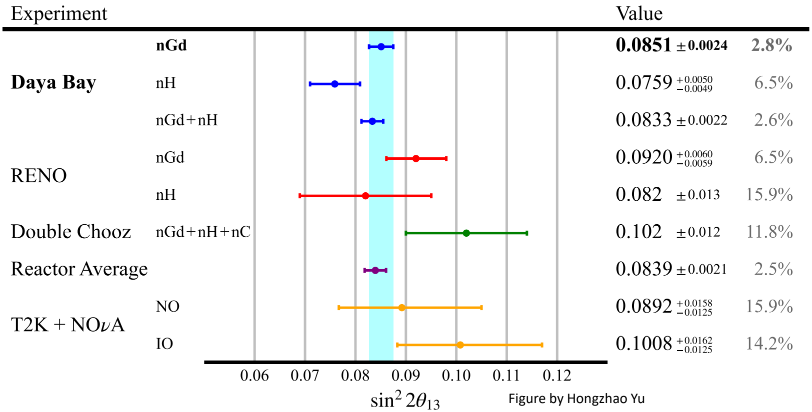


Plots from Thiago Bezerra's Double Chooz talk at Nu-2020

From Z. Yu @ Neutrino 2024

Measuring θ_{13}: summary

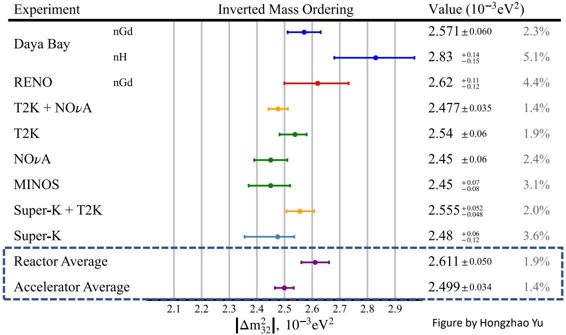
Note: average is error weighted average assuming no correlation

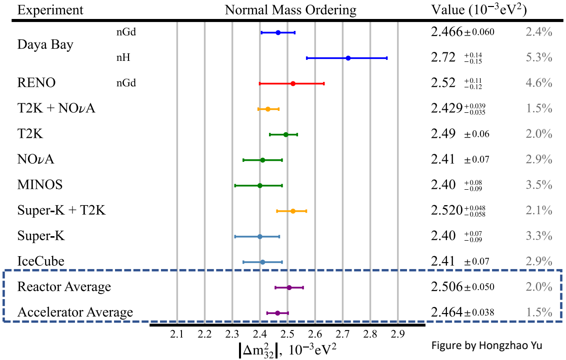


From Z. Yu @ Neutrino 2024

- Reactor experiments don't have δ_{CP} sensitivity
- but accelerator experiments gains sensitivity to δ_{CP} thanks to precise value of θ_{13}

Measuring Δm^2_{32}: summary



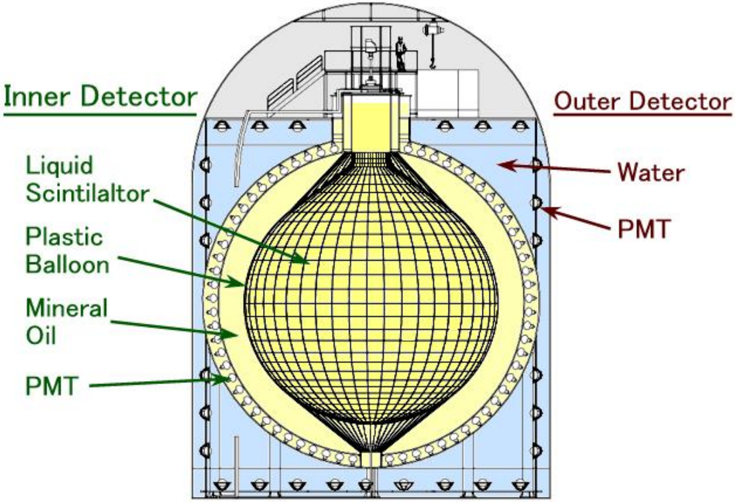


From Z. Yu @ Neutrino 2024

- Daya-Bay/RENO have no sensitivity to neutrino mass ordering. . .
- but slight (2 σ) preference to normal ordering to to tension reactor/acceleratori

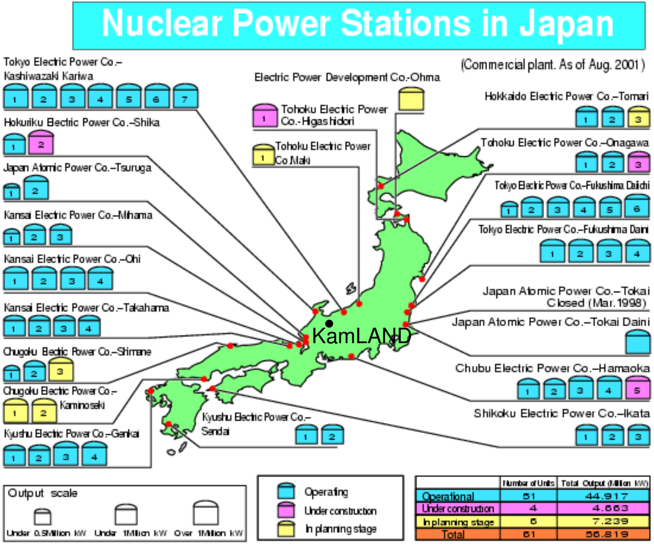
Note: average error weighted assuming no correlation

Kamioka Liquid Scintillator Antineutrino Detector (KamLAND)

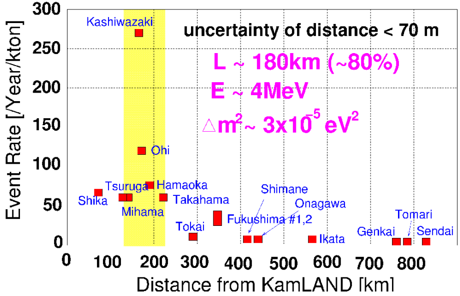


- Located in Kamioka mine, Japan
- ν target: liquid scintillator
- Measure $\bar{\nu}$ produced by nuclear reactor
- Many baselines (L), but well placed to study $\Delta m^2_{\odot}$ (Δm^2_{21})
- Very complementary to Solar experiments

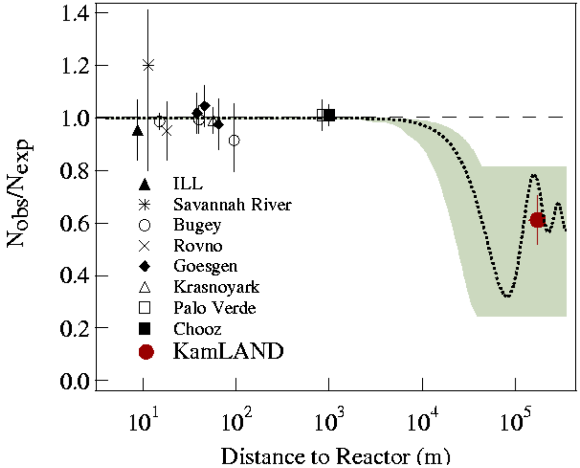
Map of nuclear reactors “close” to Kamioka mine

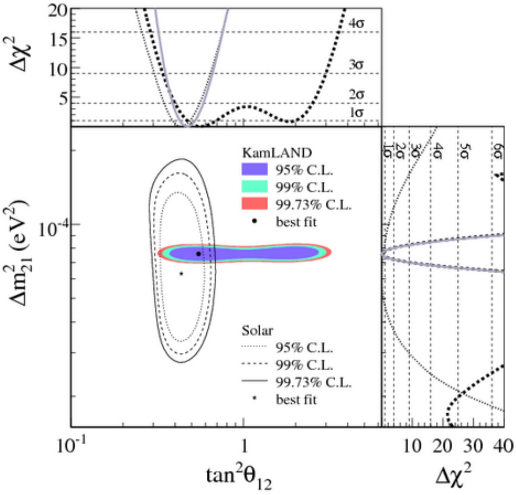


	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	6	7.239
Total	61	56.819

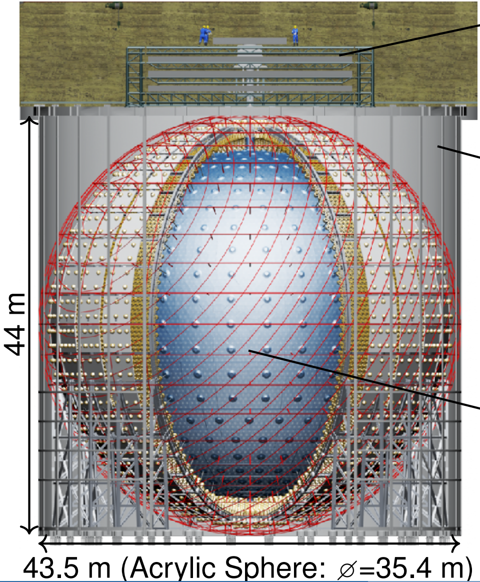


KamLAND & Solar results





Jiangmen Underground Neutrino Observatory (JUNO)



Top Tracker (TT)

- Precise μ tracker
- 3 layers of plastic scintillator
- $\sim$ 60% of area above WCD

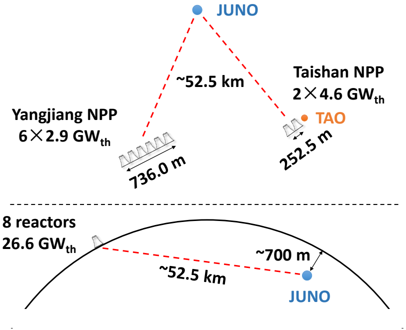
Water Cherenkov Detector (WCD)

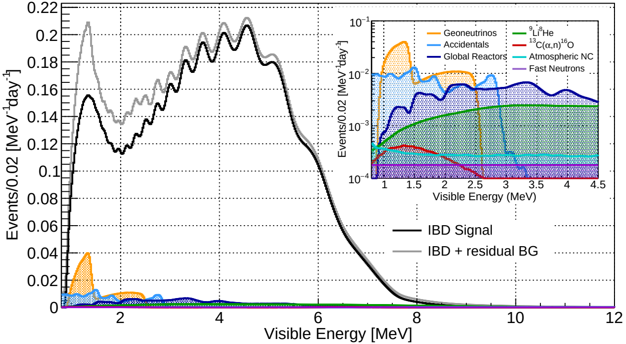
- 35 kton ultra-pure water
- 2.4k 20” PMTs
- High μ detection efficiency
- Protects CD from external radioactivity & neutrons from cosmic-rays

Central Detector (CD) – $\bar{\nu}$ target

- Acrylic sphere with 20 kton liquid scint.
- 17.6k 20” PMTs + 25.6k 3” PMTs
- 3% energy resolution @ 1 MeV

JUNO: layout and spectra





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- Medium baseline (53 km) from reactors, built for excellent energy resolution
- First time expected to see both 12 & 13 oscillations at same time
- Data taking to start in 2nd semester 2025!

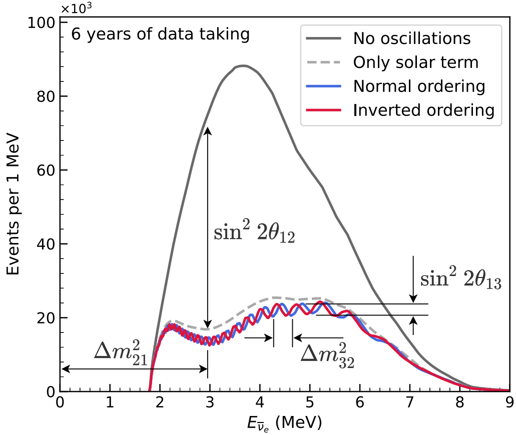
JUNO: Neutrino Mass Ordering signature

method: S. T. Petcov, M. Piai, Phys. Lett. B **533** (2002) 94; formulas: S. F. Ge, *et al.* JHEP **1305** (2013) 131

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i\frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$
$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31})$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32}),$$

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$



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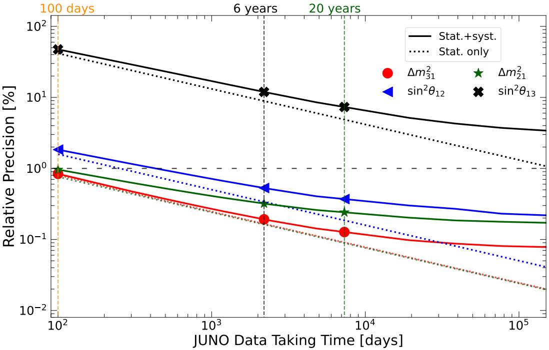
- Normal(+)/Inverted(−) Ordering
- Need excellent energy resolution to distinguish fast oscillation

JUNO: Main neutrino oscillation results using reactor $\bar{\nu}_e$



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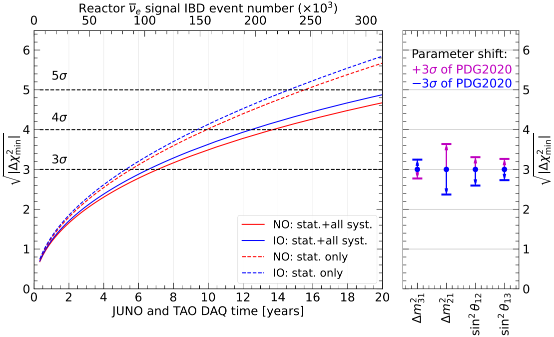
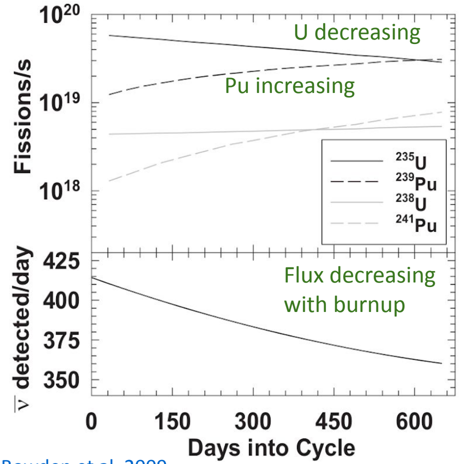


JUNO, Chin. Phys. C **49** (2025) no.3, 033104

- $< 0.5\%$ precision on θ_{12}, Δm^2_{31} and Δm^2_{32}
- NMO @ 3 σ with $\sim$7 years of data

Reactor monitoring and non proliferation



Bowden et al, 2009

L Kneale talk @ Neutrino 2024

- Rate of ν detected depend on fuel composition
- ν: continuous & non intrusive means to monitor reactors
- can also be used to monitor fuel storage sites/nuclear waste
- Various techniques under study
  - water based: scalable to very large size
  - mobile detectors

Summary

- Reactor neutrinos have been a crucial source of neutrinos since their discovery
  - High rate of neutrinos produced $\mathcal{O}(10^{20})/\mathrm{GW}$
  - Golden detection channel: inverse beta decay
- Modeling of reactor flux complicated
  - Lots of progress in recent years in summation & conversion methods
  - Lots of new reactor $\bar{\nu}_e$ data from recent experiments
  - But some unknowns remain...potential for more news for next years
- Reactor neutrinos provide clean probe of neutrino oscillations
  - limited to only $\bar{\nu}_e \to \bar{\nu}_e$ channel: no θ_{23} and δ_{CP} dependency
  - best measurements of θ_{13} (Daya Bay) and Δm^2_{21} (KamLAND)
  - JUNO expected to get sub-percent precision on θ_{12}, Δm^2_{21} and Δm^2_{31} soon
- Rapid progress on experiments using CEνNS interactions @ reactors
  - First observation done this year!
  - Further progress expected soon!
- Possible direct application on non-proliferation efforts