Review on Reactor Neutrino Experiments



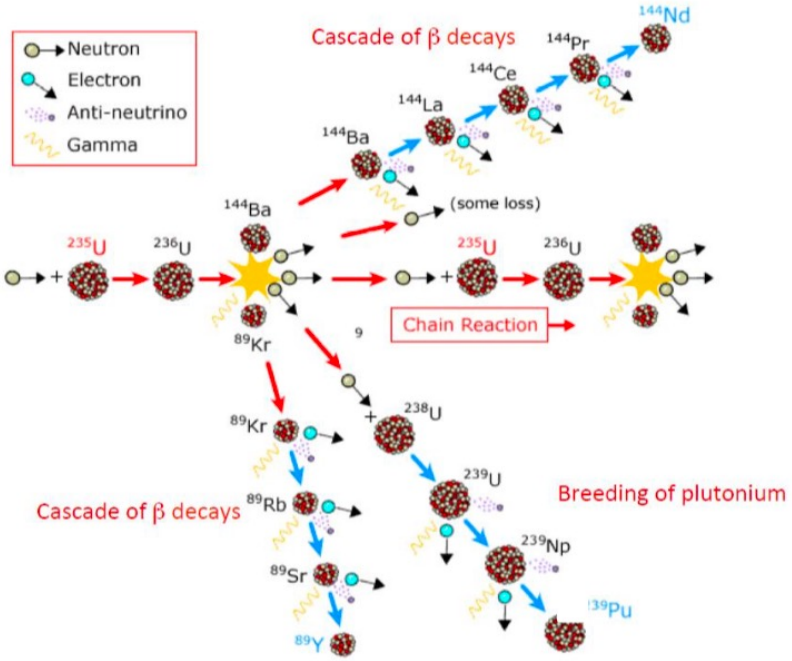
Jiajie Ling
Sun Yat-sen University

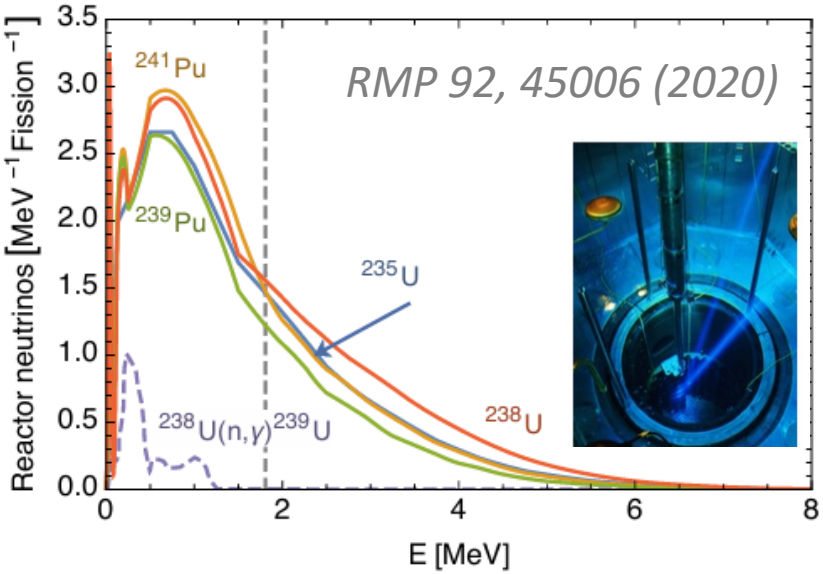
NNN26, Chung-Ang University, Seoul, Korea

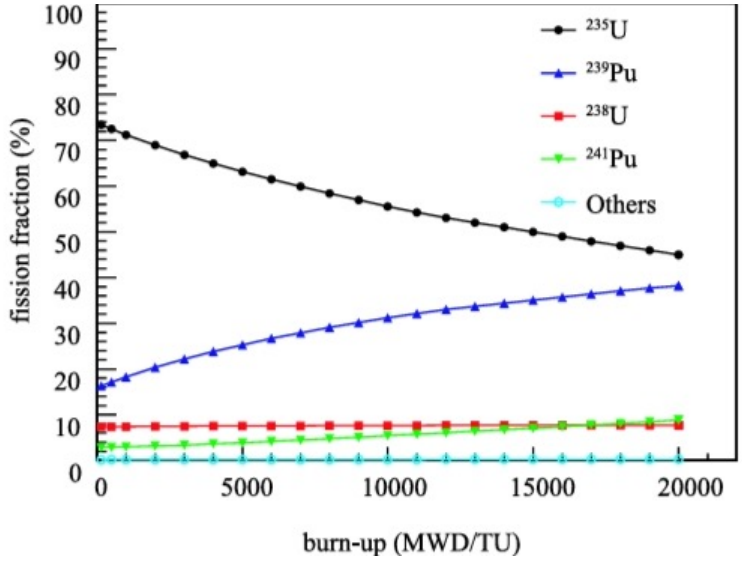
Reactor $\bar{\nu}_e$ Production

Source: Pure $\bar{\nu}_e$ from cascade of beta decays

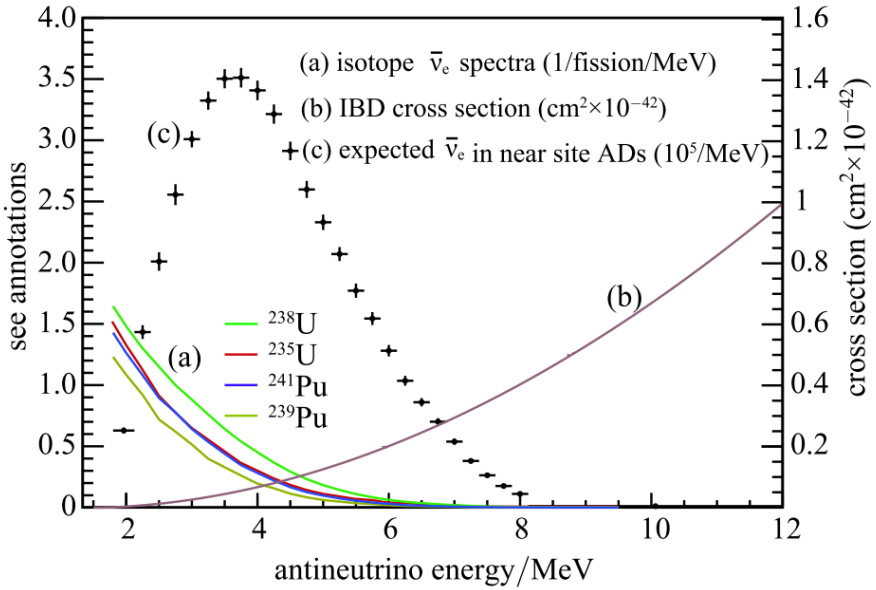
- ~ 200 MeV / fission
- ~ 6 $\bar{\nu}_e$/ fission (1/3 above IBD threshold)
- ~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}/sec

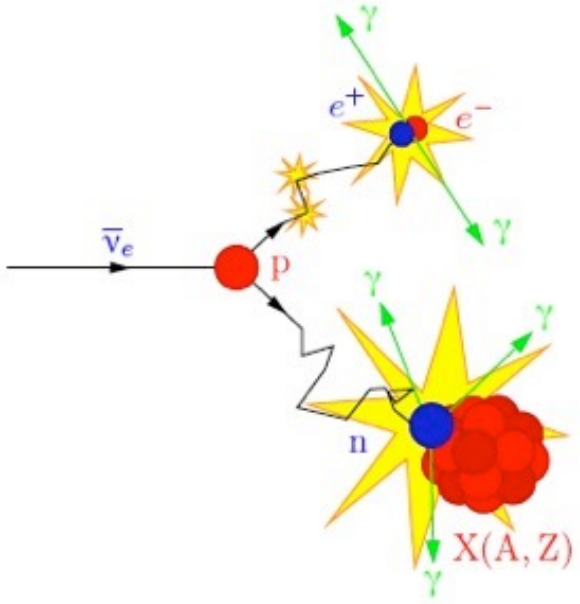






Reactor $\bar{\nu}_e$ Detection





$$S(E_\nu) \approx c \cdot \sum_i f_i \cdot S_i(E_\nu) \cdot \sigma(E_\nu)$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Observed $\bar{\nu}_e$ spectrum

Isotope fission fraction

Isotope neutrino spectra

IBD Xsec

Inverse Beta decay (IBD)

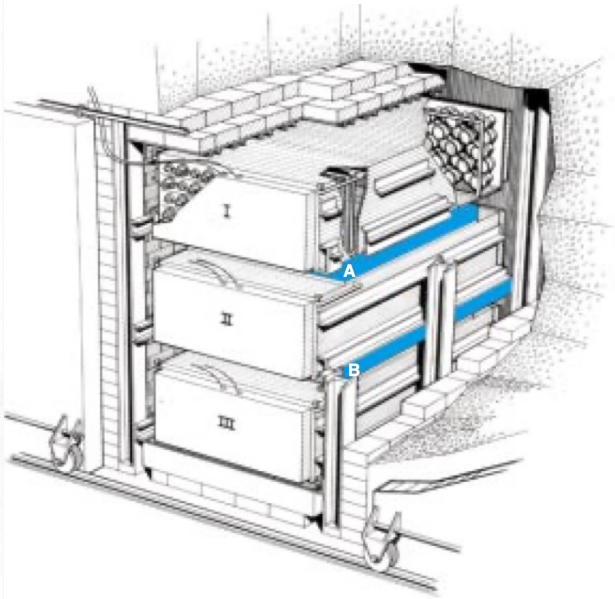
Coincidence signals to suppress background

- Prompt: $E_{\text{prompt}} \approx E_\nu - 0.8$ MeV
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)
- Temporal and spatial correlation

Savannah River Experiment



Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the (anti) neutrino was performed at Savannah River, Georgia, three years later. (Courtesy General Electric Co.)



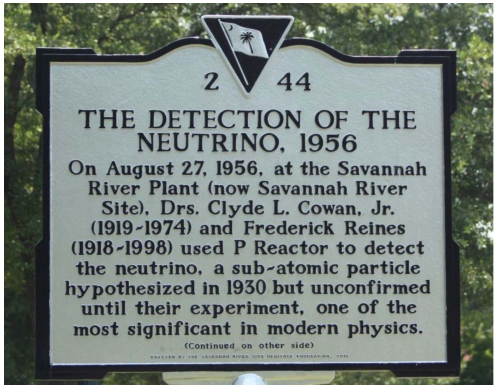
Science 124, 3212 (1956)

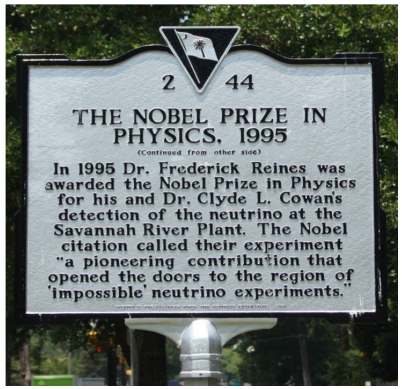
F. Reines and C. L. Cowan

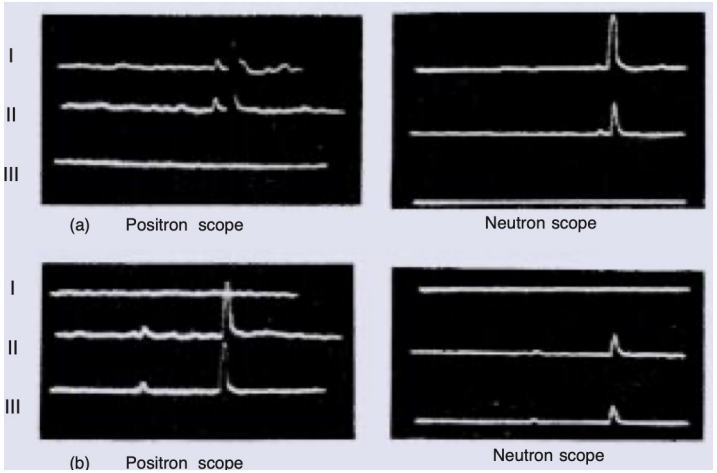
ϕ ~ 10^{13} /s/cm^2
400 L of water tank
80 kg of $CdCL_2$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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

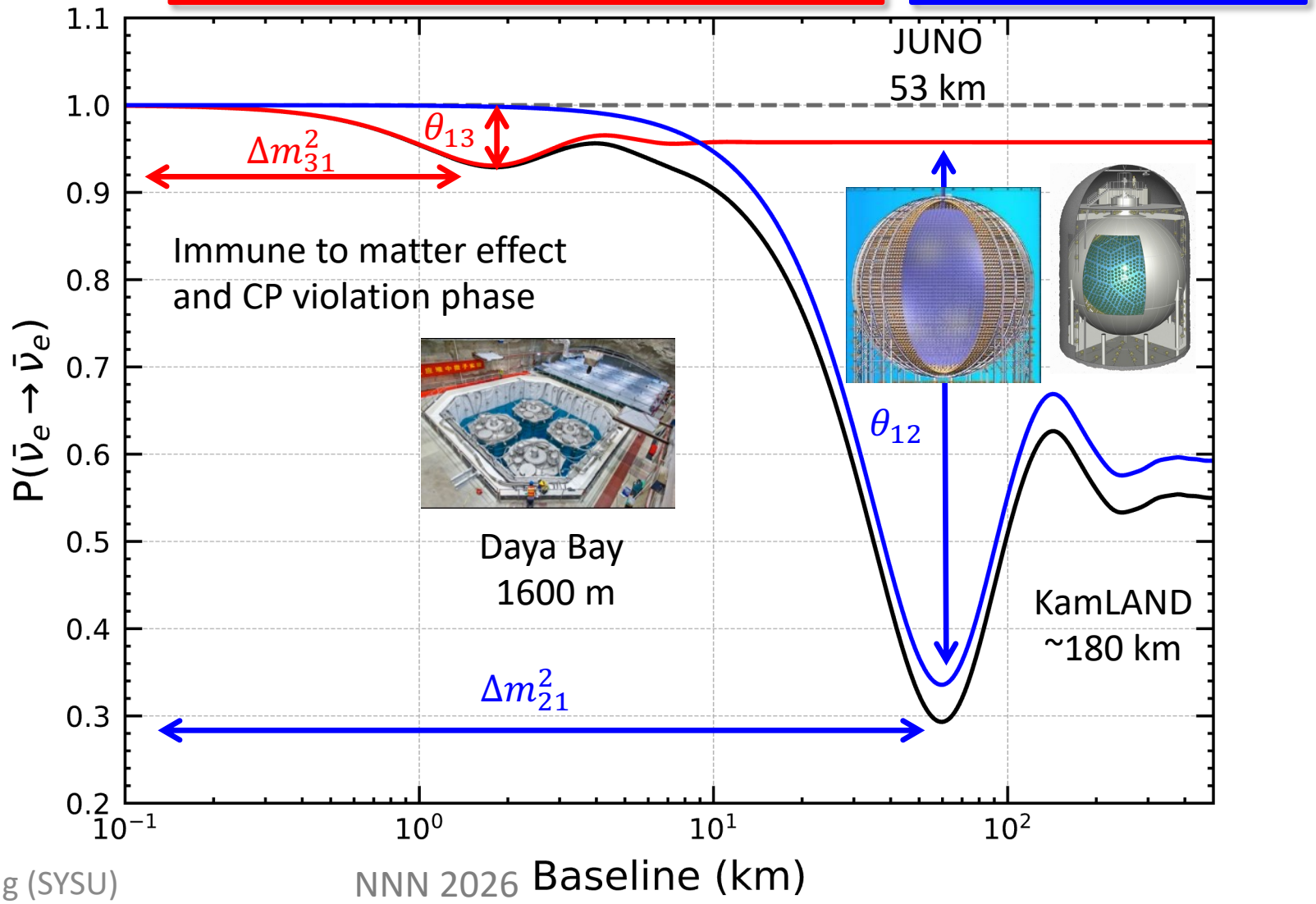




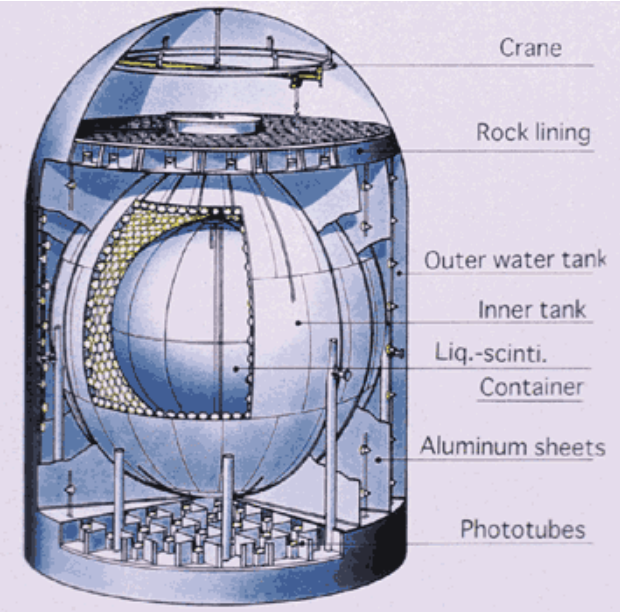


Reactor Neutrinos Oscillation

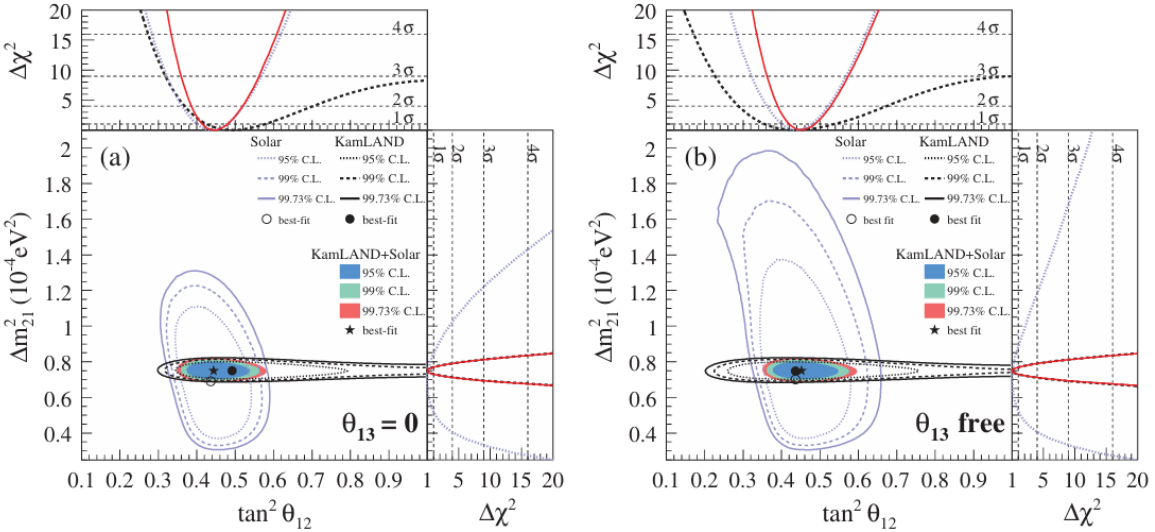
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

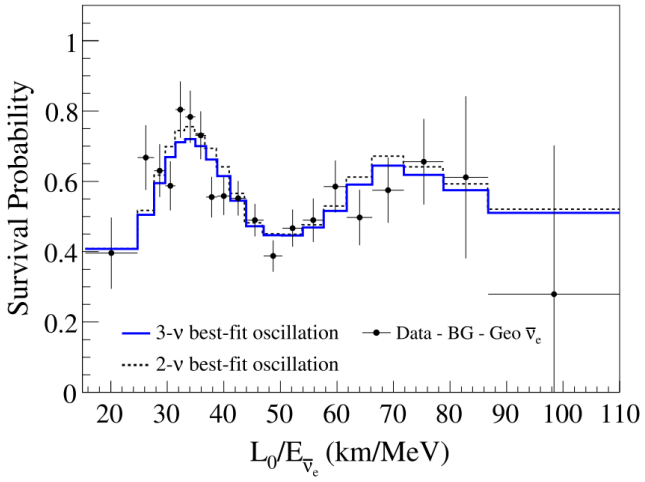


KamLAND Experiment



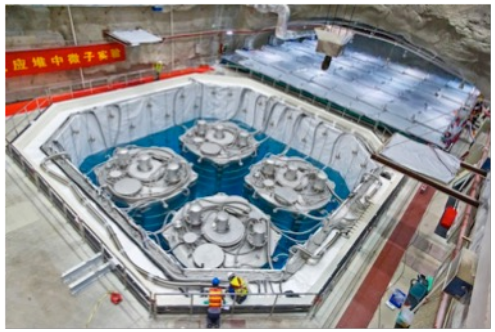
PRD 83, 052002 (2011)



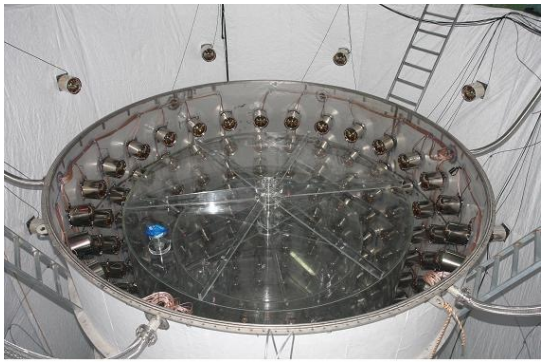


- 1-kton liquid scintillator detector
- Determine the large mixing angle solution with solar measurement from SNO
- First observation of neutrino's multiple oscillation structure in L/E
- hint of non-zero θ_{13} angle in 2011

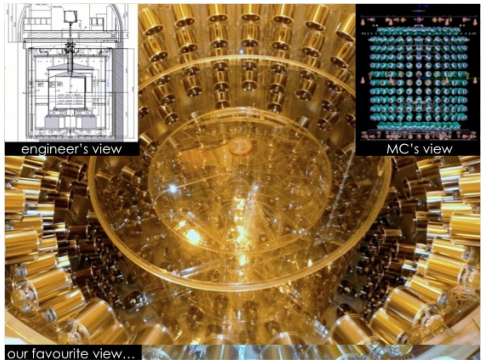
Discovery of θ_{13} in 2012



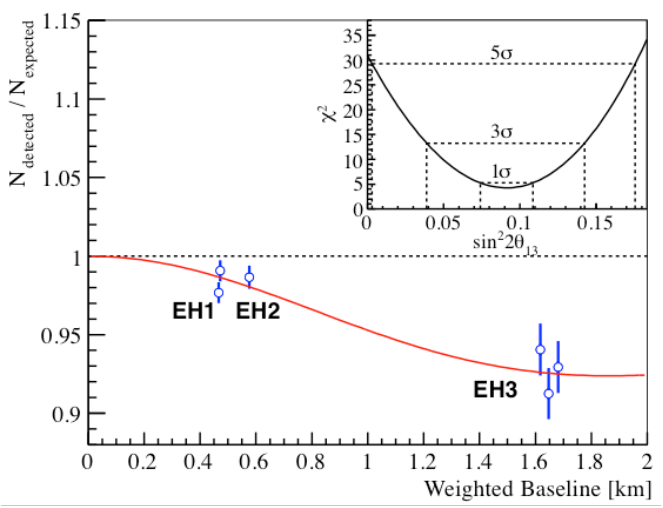
Daya Bay



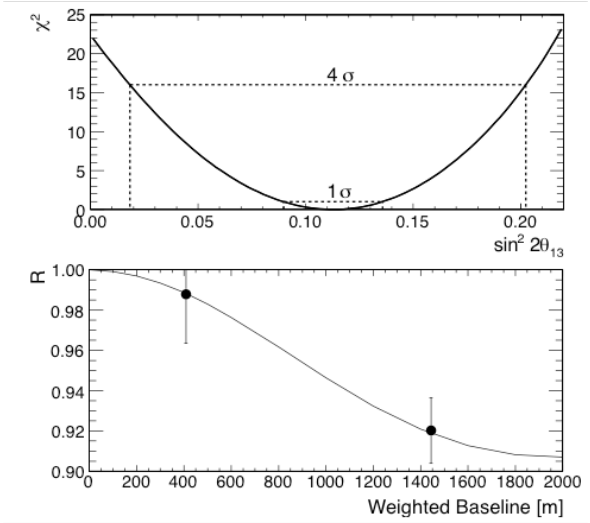
RENO



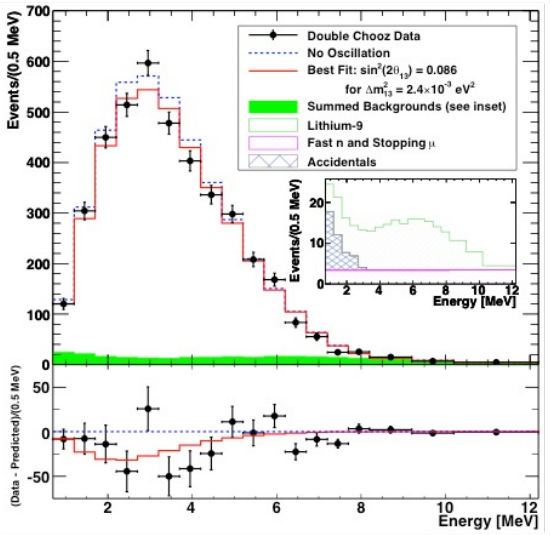
Double Chooz



5.2σ

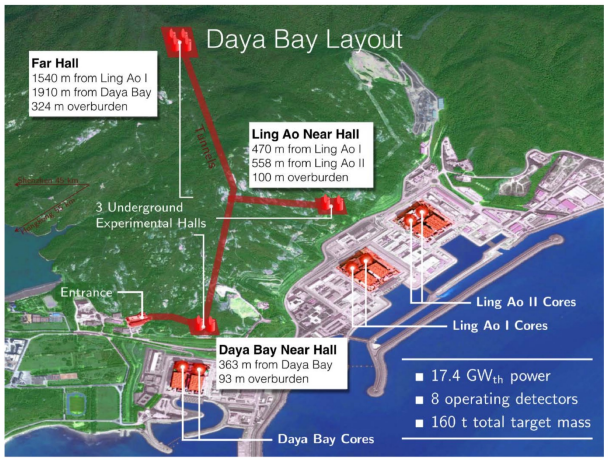


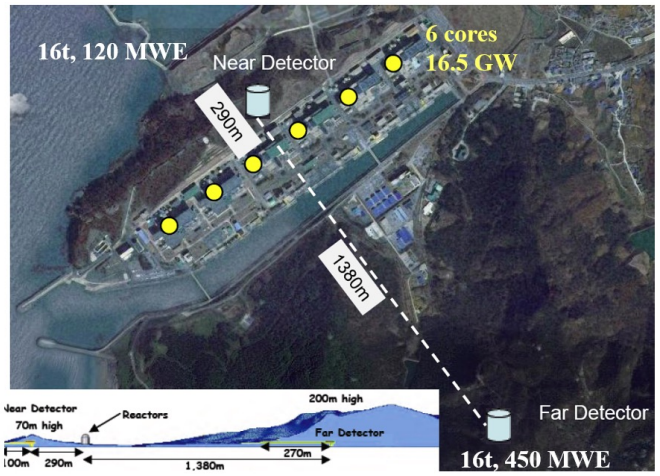
4.9σ

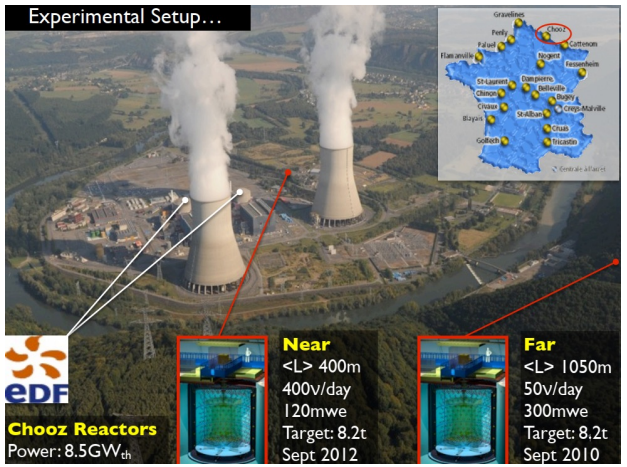


1.7σ

Multi-Detector Experimental Setup

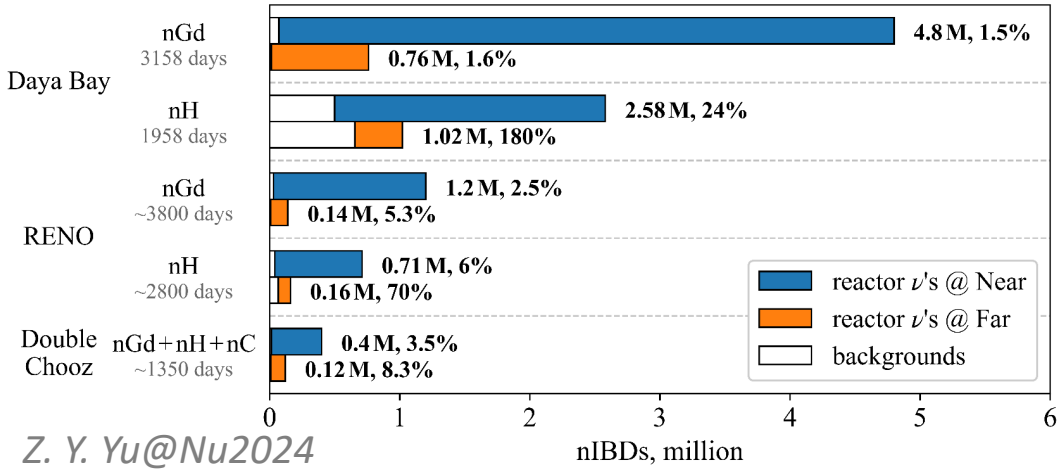






Near-Far systematic cancellation

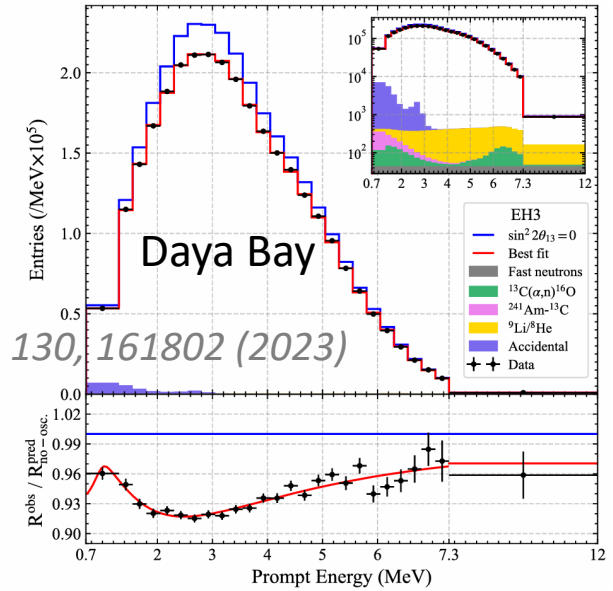
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E_\nu, L_f)}{P_{sur}(E_\nu, L_n)}\right]$$



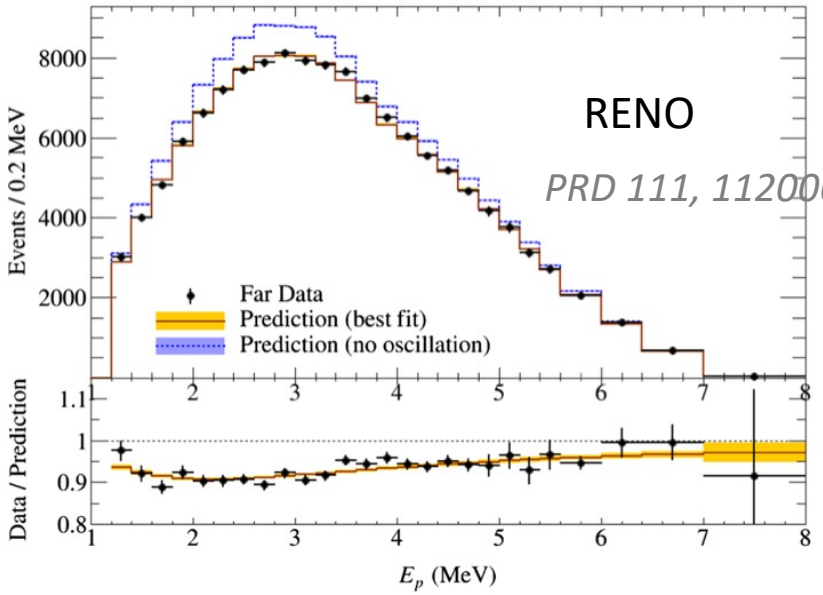
Z. Y. Yu@Nu2024

Daya Bay	Dec. 2011 to Dec. 2020
RENO	Aug. 2011 to Mar. 2023
Double Chooz	Apr. 2011 to Dec. 2017

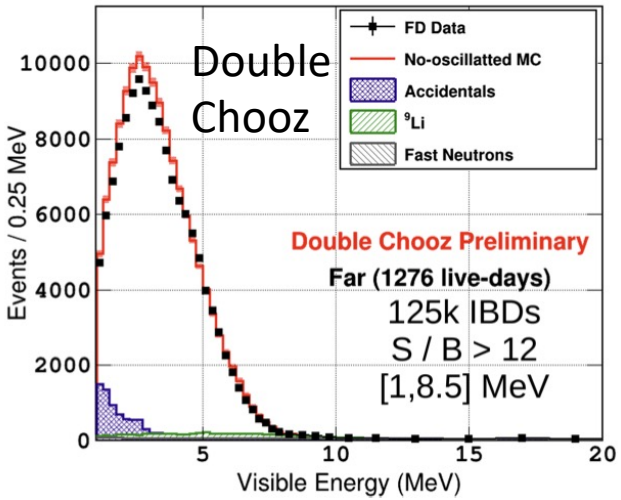
Oscillated Spectrum Distortion

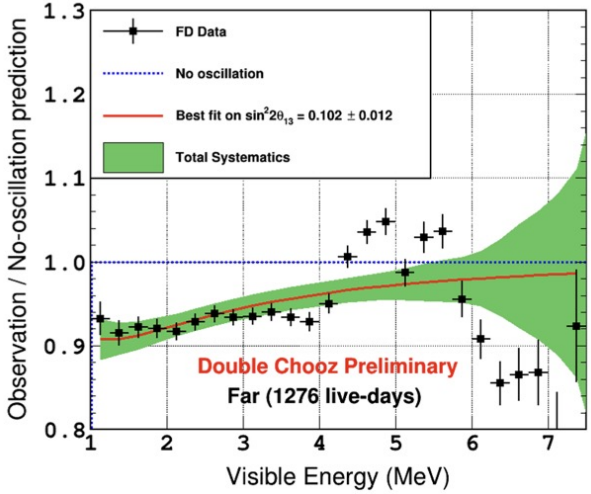


PRL 130, 161802 (2023)

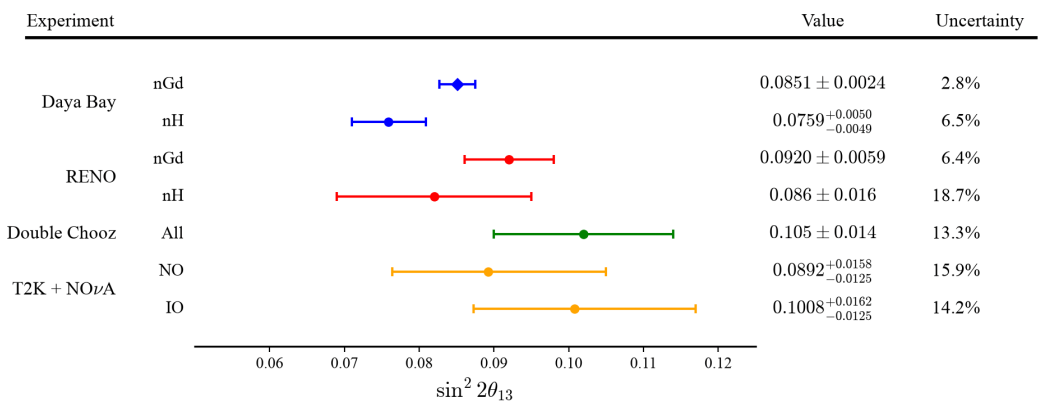


PRD 111, 112006 (2025)

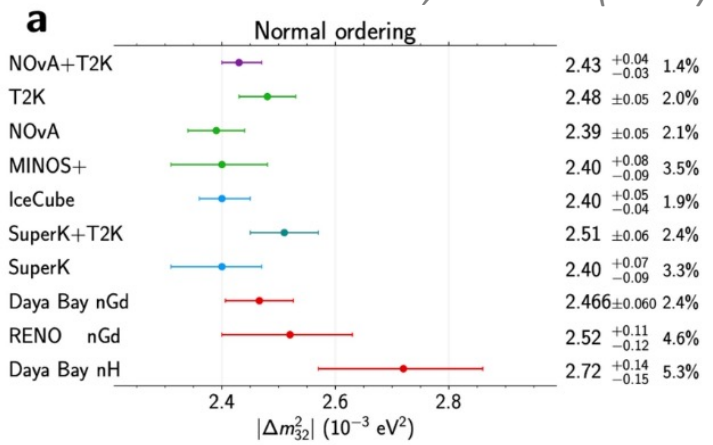


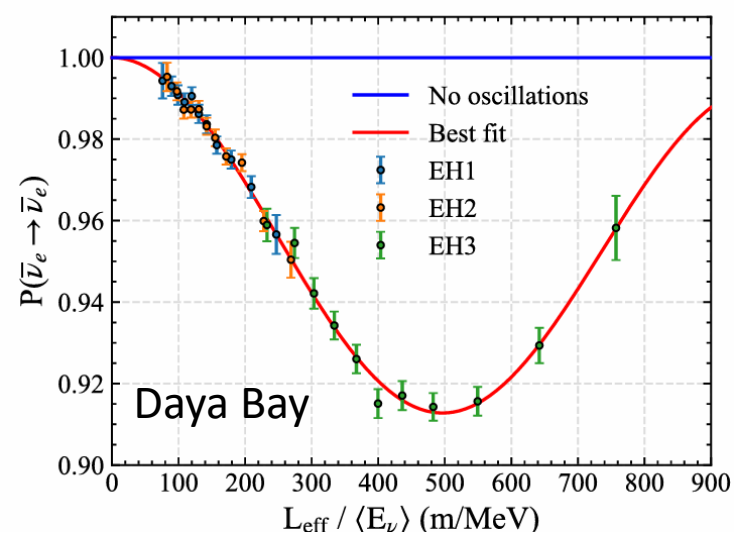


Precision Measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$

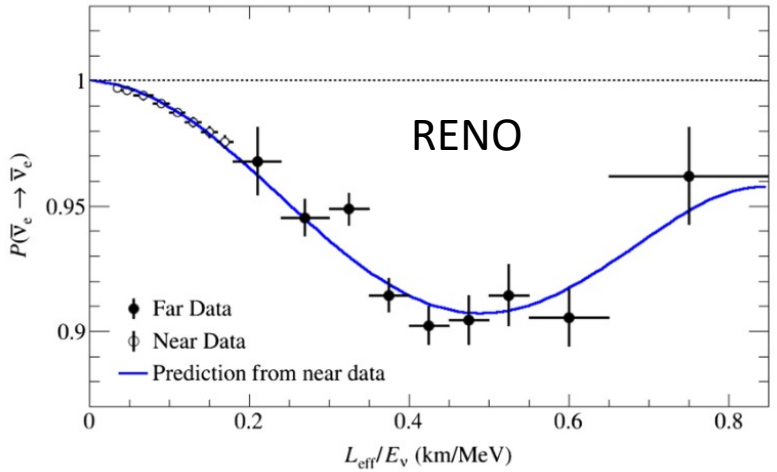


Nature 646, 818-824 (2025)





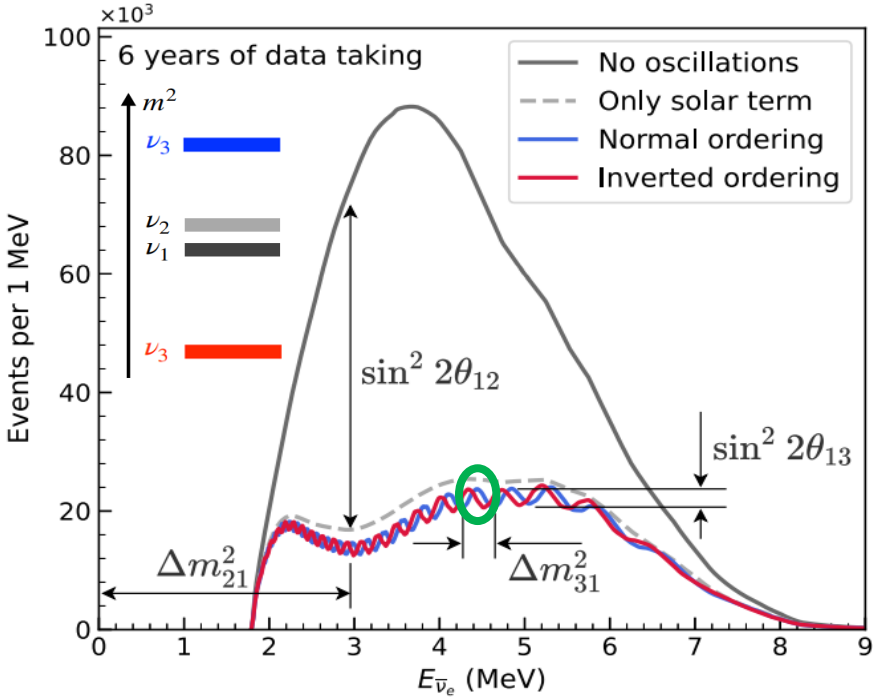
PRL 130, 161802 (2023)



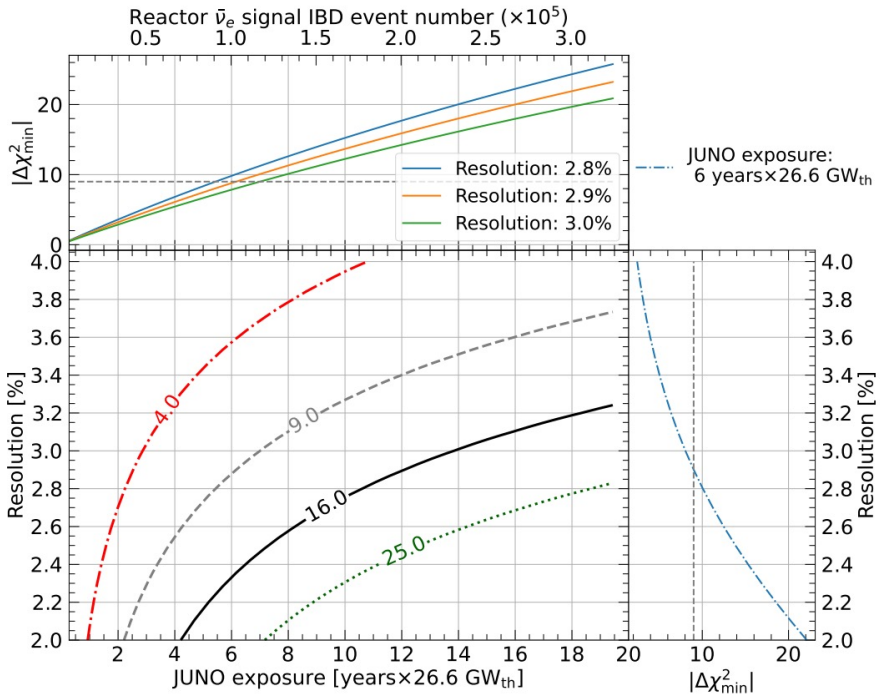
PRD 111, 112006 (2025)

Neutrino Mass Ordering from Reactors

Chin.Phys.C 46, 123001 (2022)



Chin.Phys.C 49, 033104 (2025)



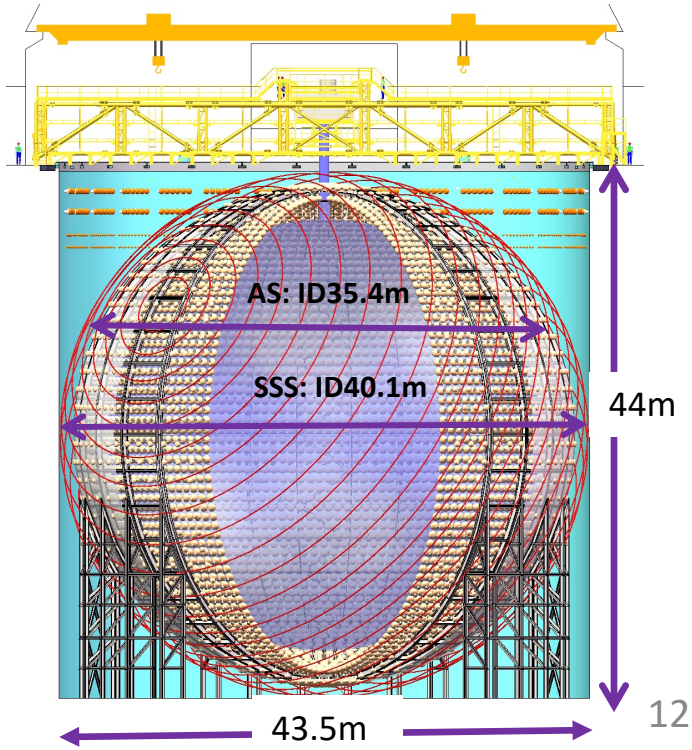
- Δm^2_{21} oscillation maximal: 50-60 km away from reactors
- fast oscillation frequency of Δm^2_{32} and Δm^2_{31} interference for NMO separation
- High energy resolution (3%)
- Large liquid scintillator detector (20 kton)
- JUNO and RENO-50
- Aiming 3-4 σ NMO sensitivity in 6 years

The JUNO Experiment

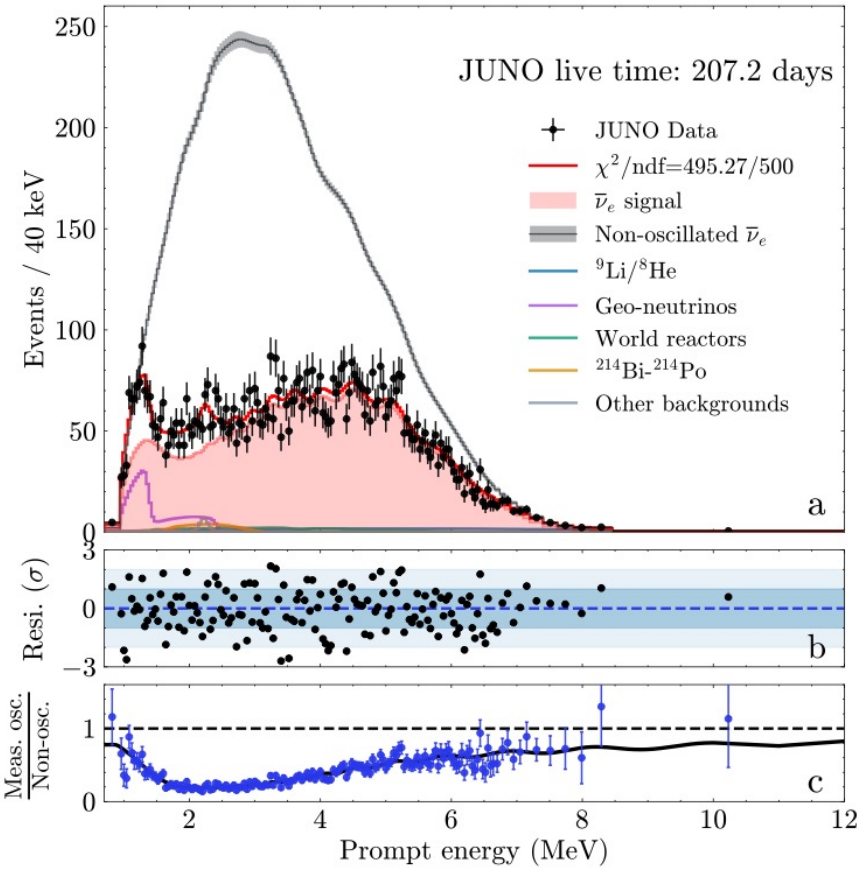
	Daya Bay	BOREXINO	SNO+	KamLAND	JUNO
Target Mass	8* 20 ton	300 ton	780 ton	1 kton	**20 kton**
Number of PMTs	8 *192 8-in.	2212 8-in.	~10000 8-in.	1325 20-in. + 554 17-in.	**20012 20-in.+ 25600 3-in.**
Photoelectron Yield (p.e./MeV)	160	450	520	250	**>1300**
Photocathode Coverage	12%	30%	50%	34%	**78%**
Energy Resolution@1MeV	7.5%	5%	6%	6%	**3%**
Energy calibration	<1%	1%	⩽ 1%	2%	**≤ 1%**

More details in C. Guo's JUNO talk on Friday

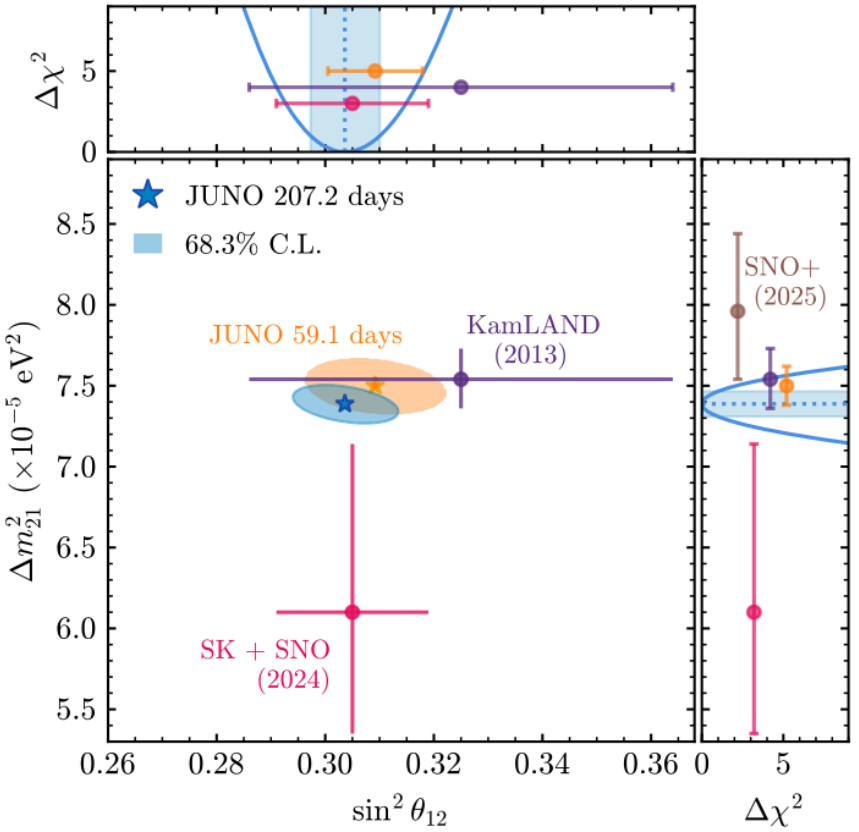




Recent Oscillation Results from JUNO



arXiv: 2609. 37895



Δm^2_{21}	$(7.388 \pm 0.078) \times 10^{-5}\ eV^2$ (1.06%)
$\sin^2\theta_{12}$	0.3036 ± 0.0064 (2.1%)

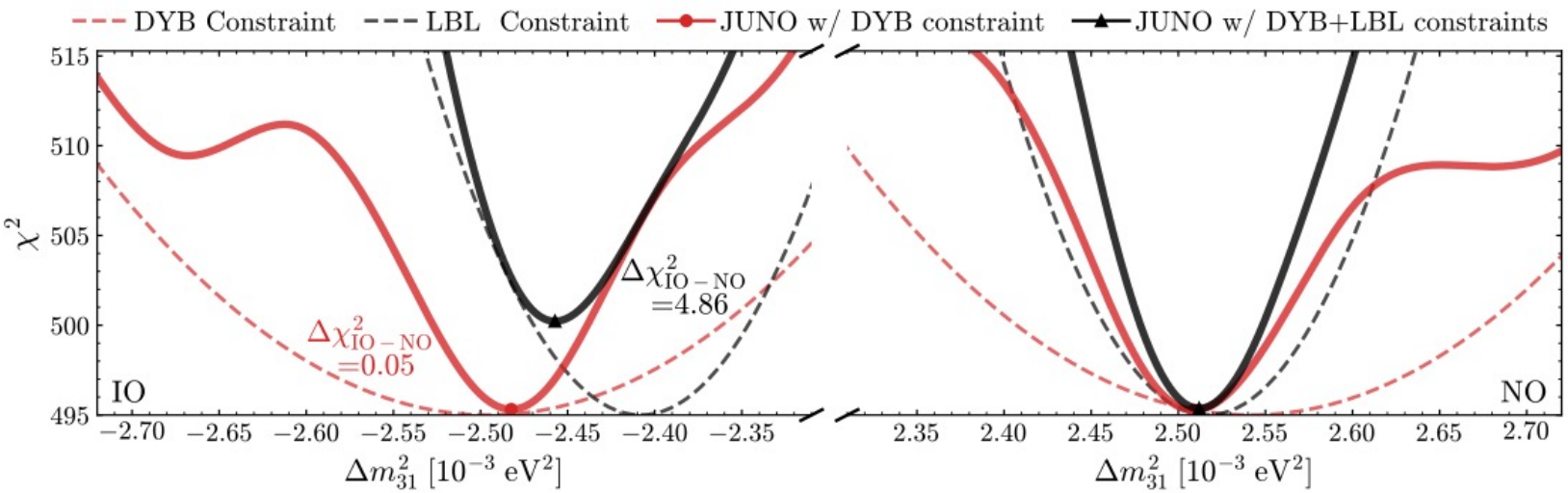
- 207.2 days (08/30/2025 – 05/18/2026)
- 8294 IBD candidates
- 74% detection efficiency
- Sig:Bg = 9:1

ν_e and ν_μ Complimentary

$$\Delta m^2_{ee} = cos^2\theta_{12}\Delta m^2_{31} + sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = sin^2\theta_{12}\Delta m^2_{31} + cos^2\theta_{12}\Delta m^2_{32} + cos\delta_{CP}sin\theta_{13}sin2\theta_{12}tan\theta_{23}\Delta m^2_{21}$$

Minakata, Hunokawa, Parke, Funchal, PRD 74, 053008 (2006) *arXiv: 2609. 37895*



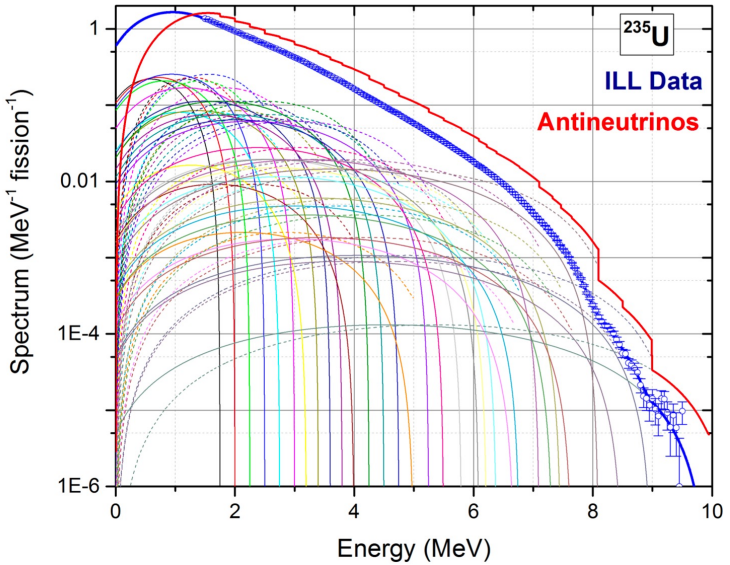
Δm^2_{31}	JUNO + Daya Bay	LBL-Comb （NuFit 6.0）
NO	$(2.509 \pm 0.026)\times 10^{-3}\ eV^2$	$(2.517 \pm 0.027)\times 10^{-3}\ eV^2$
IO	$-(2.482 \pm 0.026))\times 10^{-3}\ eV^2$	$-(2.408 \pm 0.028))\times 10^{-3}\ eV^2$

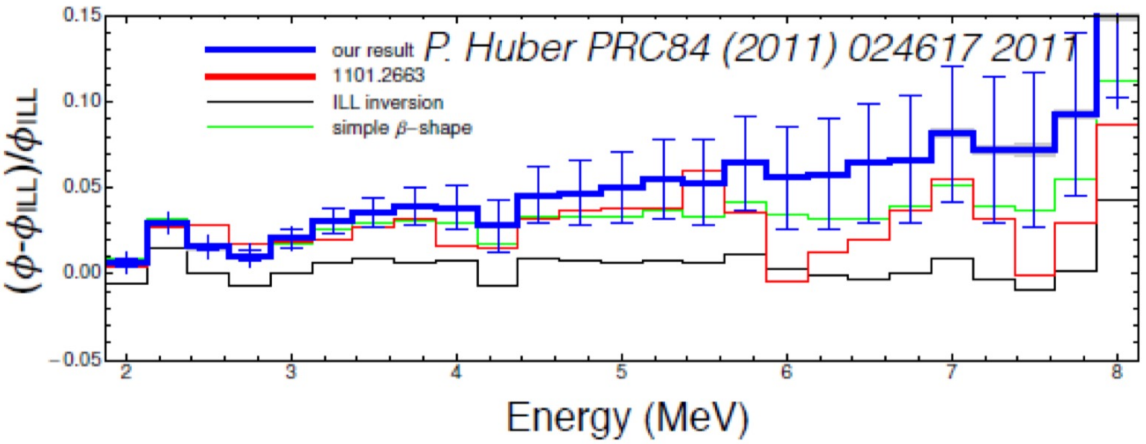
Δm^2_{31} from reactor and accelerator neutrinos align at Normal Ordering

Combine with the NuFit-LBL results: normal mass ordering is favored at $\Delta\chi^2 = 4.86$ (2.1σ 1-side)

Reactor $\bar{\nu}_e$ Flux Evaluation

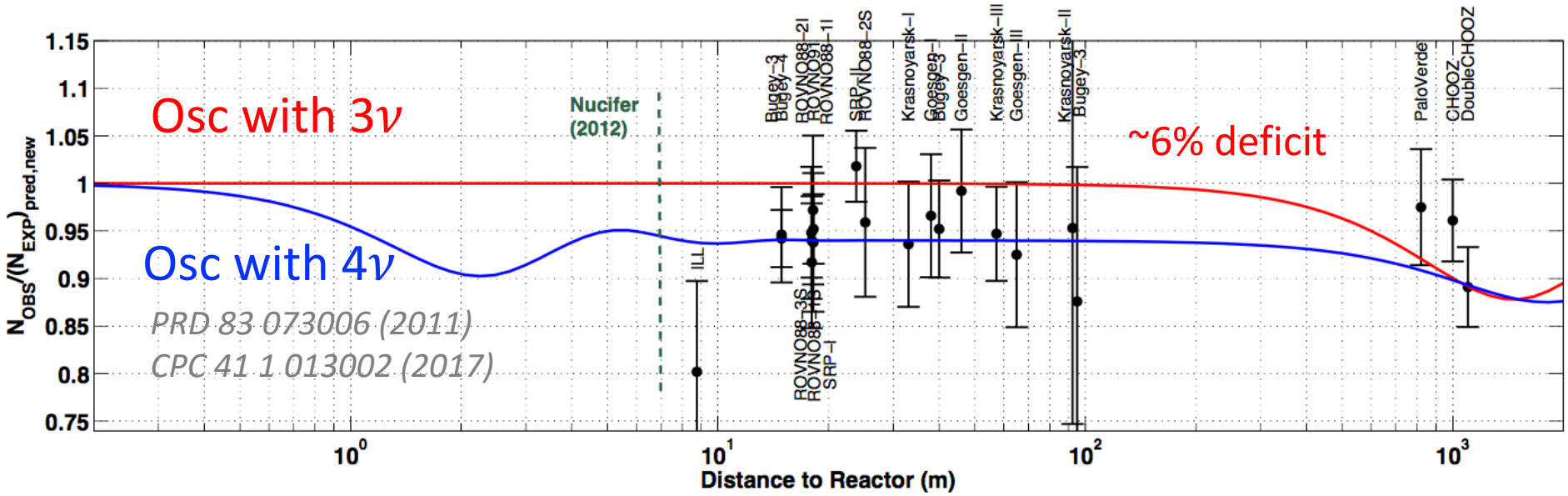
A. Sonzogni @ Neutrino 2024



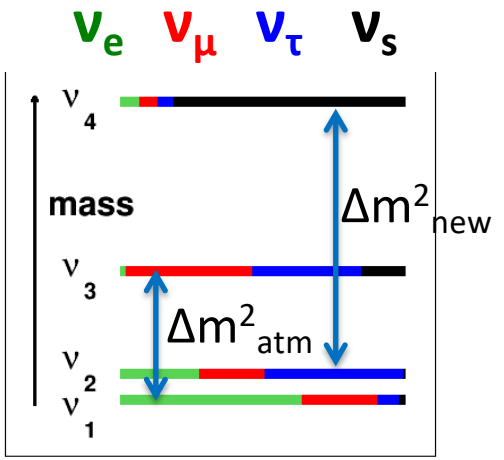


- Conversion method
  - Convert ILL measured ^{235}U, ^{239}Pu and ^{241}Pu β spectra to $\bar{\nu}_e$ with >30 virtual β-decay branches
  - Original: ILL + Vogel (^{238}U) model (1980s)
  - New: Huber + Mueller model (2011)
  - ~ 2.4% uncertainty

Reactor Antineutrino Anomaly (RAA)



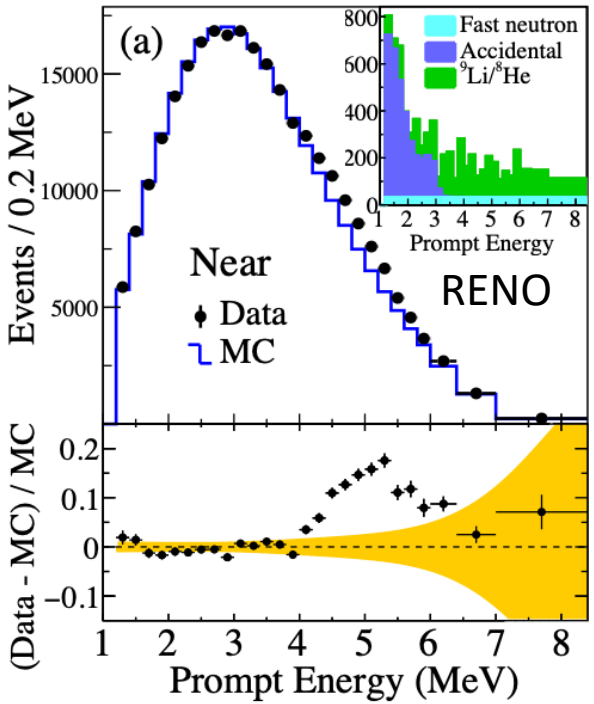
- The measured $\bar{\nu}_e$ flux at 10-100 m from reactor cores is ~6% below the theoretical calculation
- Sterile neutrinos ($\bar{\nu}_e \rightarrow \bar{\nu}_s$)?
  - High frequency oscillation (Δm^2_{new}~ 1-10 eV^2) with baseline of few meters
- Theoretical reactor $\bar{\nu}_e$ flux modelling?
  - Underestimate the systematic uncertainties



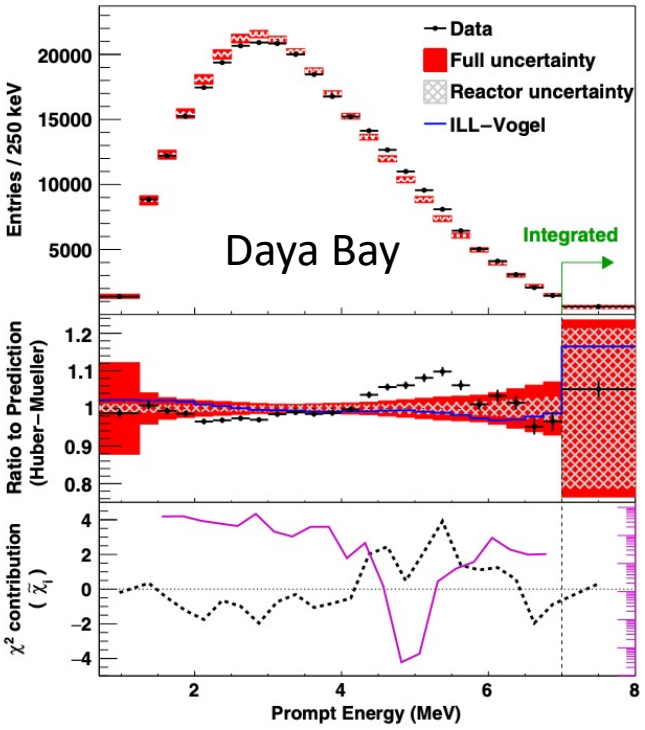
3 (active)+1(sterile)-υ model

5 MeV Bump in Reactor $\bar{\nu}_e$ Spectrum

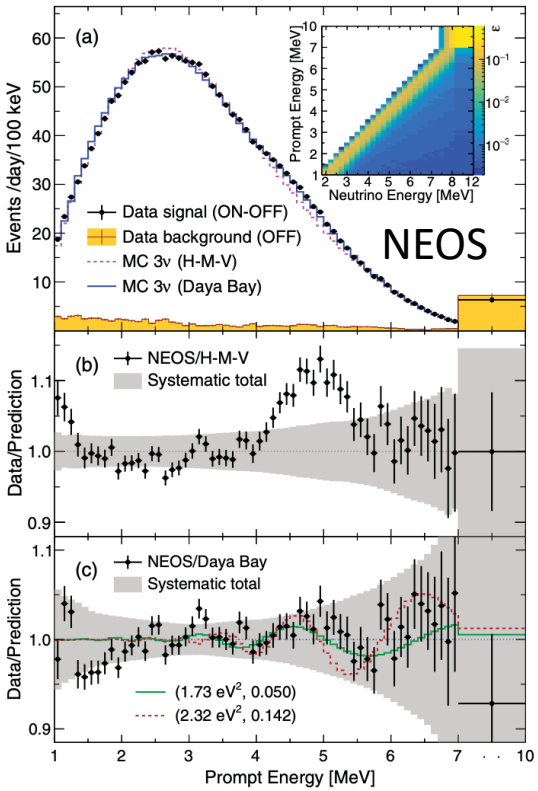
PRL 116, 211801 (2016)



PRL 116, 061801 (2016)



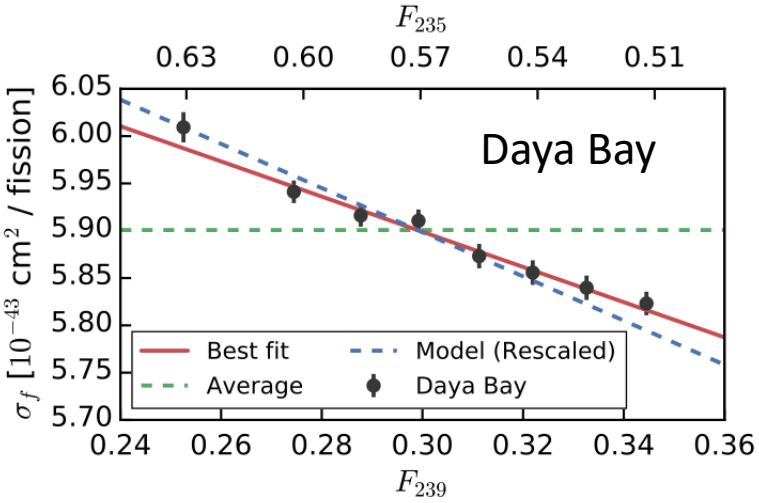
PRL 118, 121802 (2017)



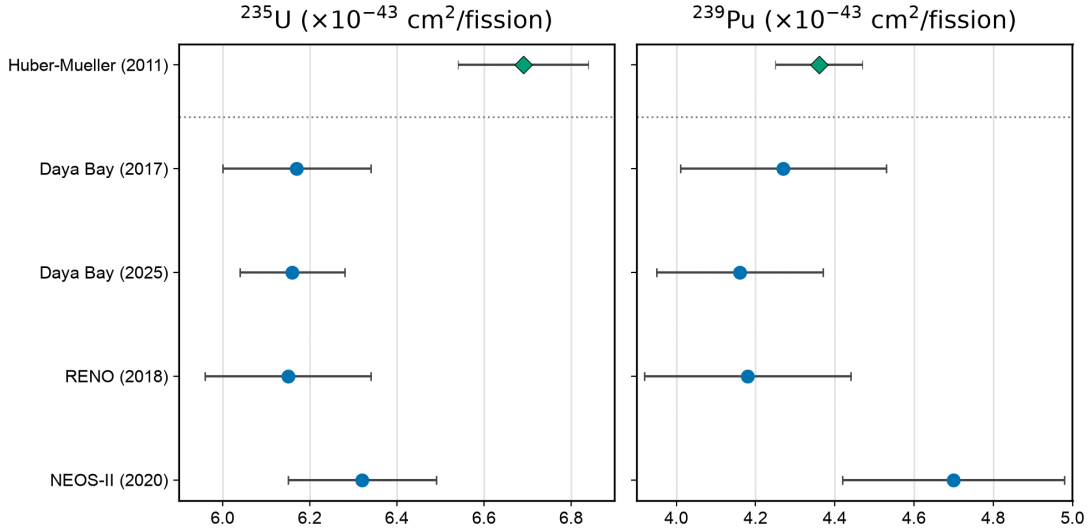
- Data/prediction spectrum shows significant deviation, especially at 4-6 MeV region for > 10 experiments (RENO, Double Chooz, Daya Bay, NEOS, PRSPECT, STEREO, etc.)
- This phenomena can not be explained by sterile neutrino.

U and Pu Separation by Fuel Evolution

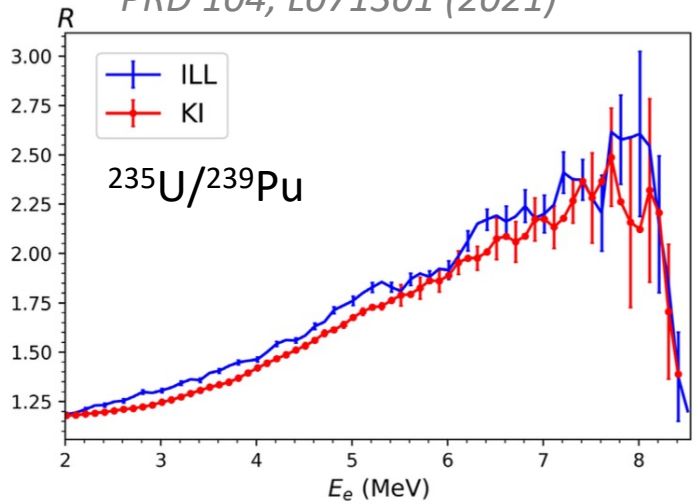
PRL 118, 251801 (2017)



C. Zhang @ Neutrino 2024



PRD 104, L071301 (2021)

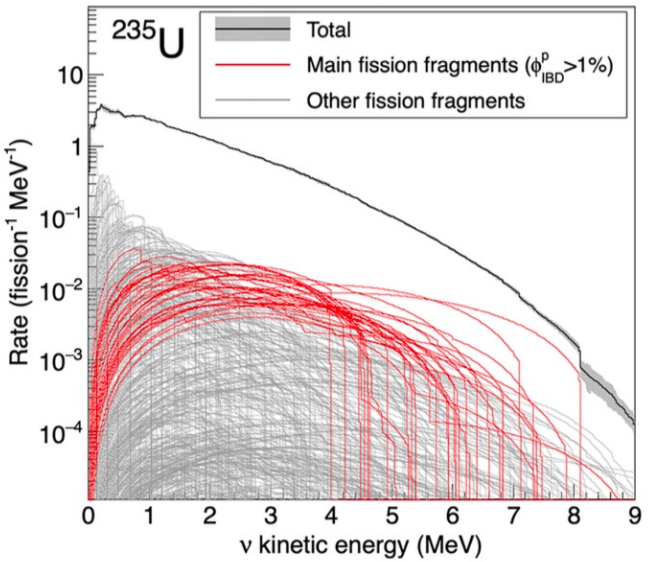


- In 2017, Daya Bay used fuel evolution to separate ^{235}U and ^{239}Pu flux contribution. ^{235}U has larger deficit than ^{239}Pu.
- It was also confirmed by RENO, NEOS-II.
- KI reevaluates the ratio of ^{235}U/^{239}Pu beta spectra, which also indicate lower ^{235}U contribution.
- The uncertainty of H-M model is certainly unestimated. (It should be ~5% by A. Hayes etc.)

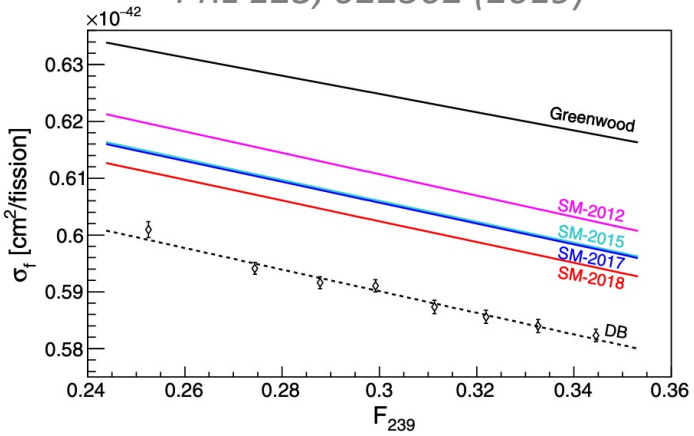
Improvement of Summation Approach

- Summation (ab initio) method
  - > 6000 decay branches
  - ~10% missing data in the nuclear database
  - ~30% forbidden decays
  - Pandemonium effect
  - ~ 10% uncertainty
- Total Absorption Gamma-ray Spectroscopy (TAGS)
  - High gamma detection efficiency
  - Free of pandemonium effect
- The agreement between Daya Bay data and summation model is keep improving

PRC 108, 055501 (2023)

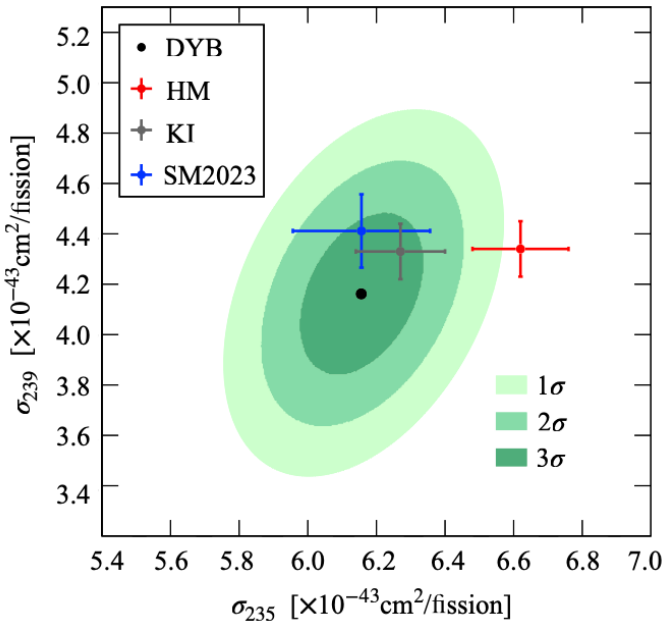


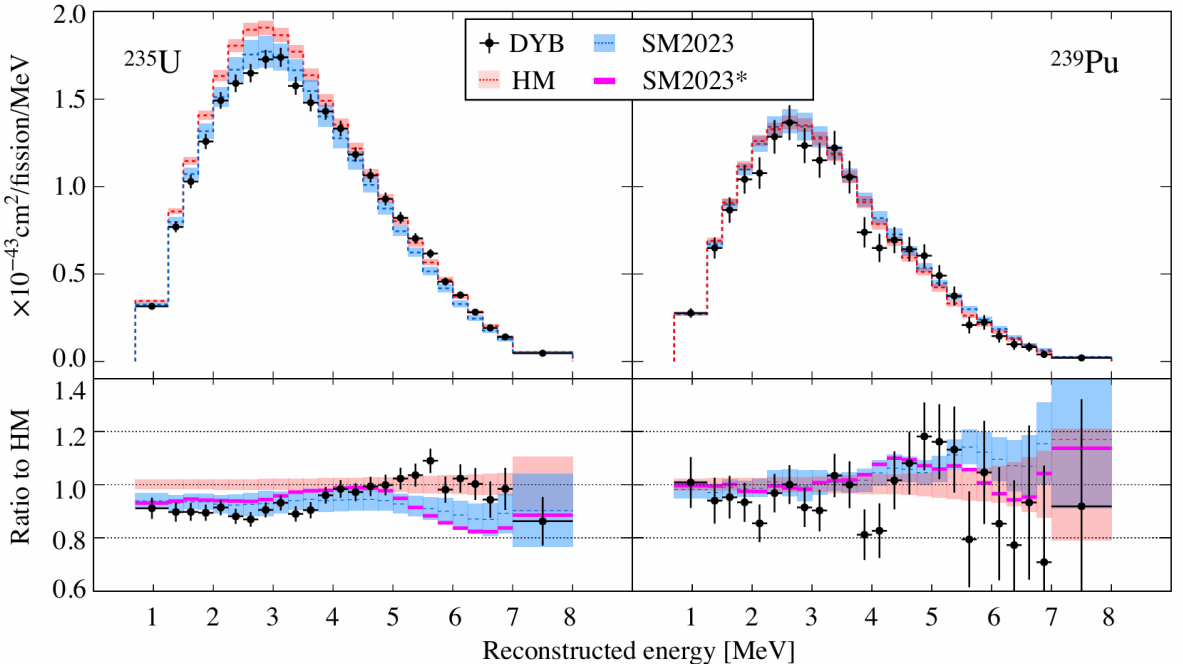
PRL 123, 022502 (2019)



Antineutrino Spectra Comparison

PRL 134, 201802 (2025)



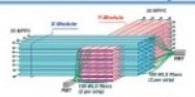
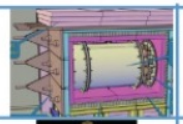
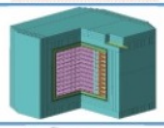
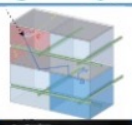
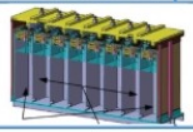


- The agreement of reactor antineutrino fluxes is improved.
- The tension between Daya Bay neutrino spectra (2025) and Conversion (H-M) or Summation models (SM2023) still exist.

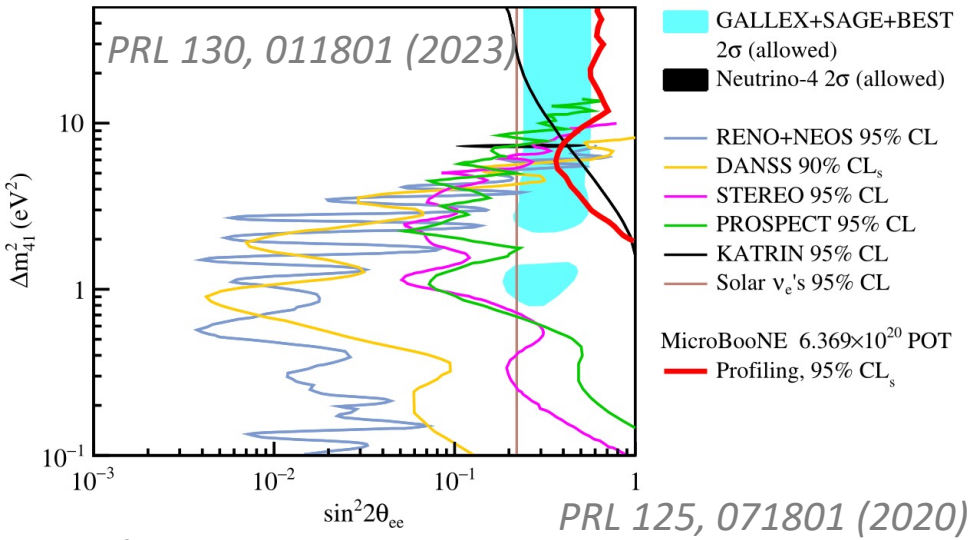
SBL Reactor Experiments

Scintillator with doping and PSD capability

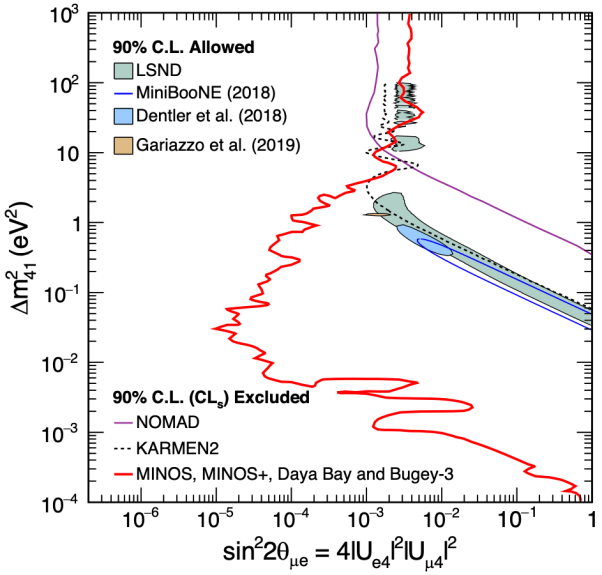
M. Mezzetto@neutrino 2016

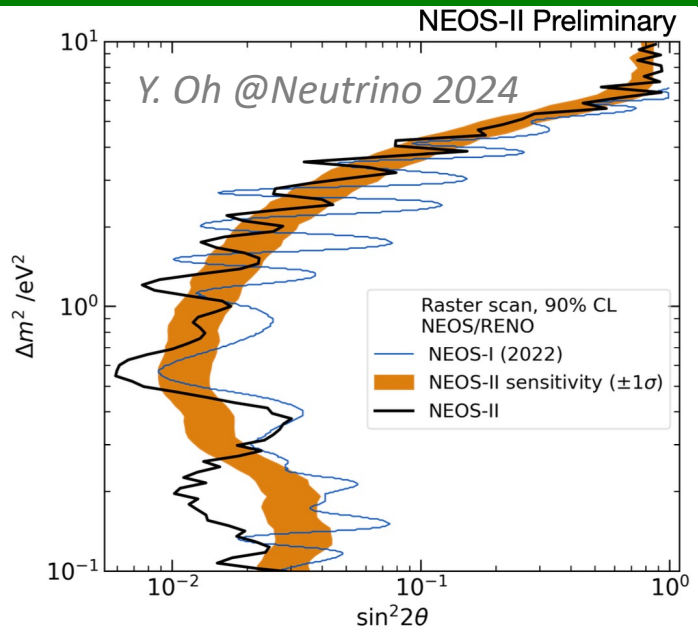
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Null Results on Light Sterile Neutrinos



PRL 125, 071801 (2020)



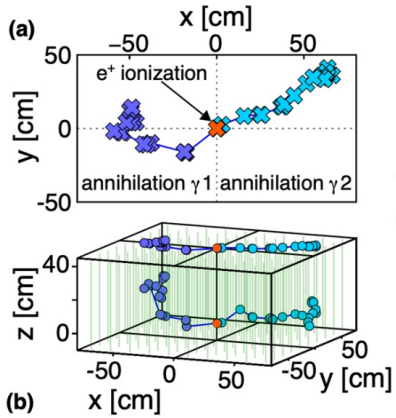


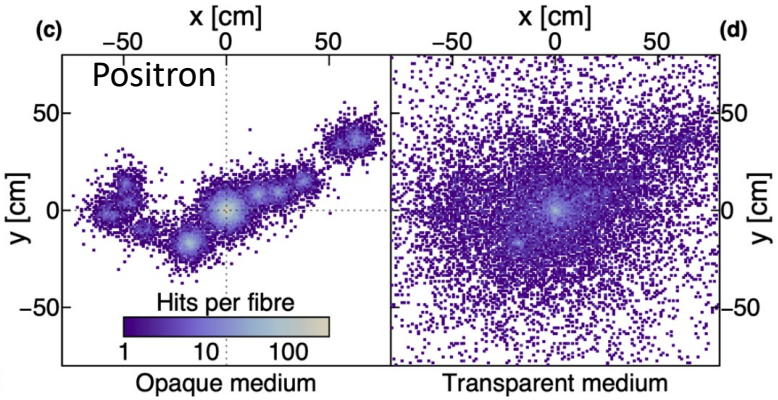
- Null light sterile neutrino signal ($0.01\ \mathrm{eV}^2 < \Delta m^2_{41} < 10\ \mathrm{eV}^2$) is observed by the SBL reactor experiments through neutrino spectrum distortion
- Neutrino-4 result has not been confirmed by other experiments.

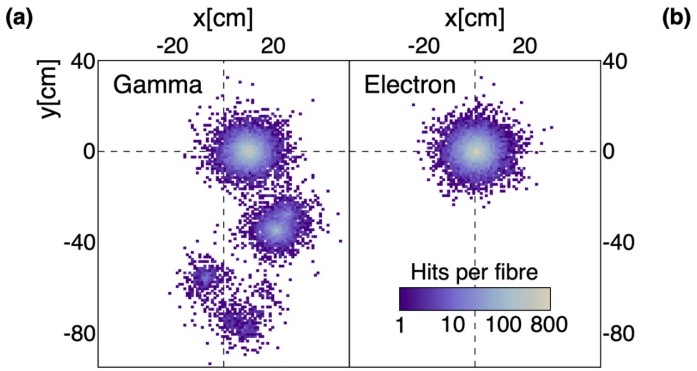
LiquidO Technology



$\lambda \geq 10\ m$ **(JUNO)** *Communications Physics 4, 273 (2021)* $\lambda \leq 1\ cm$ **(LiquidO)**





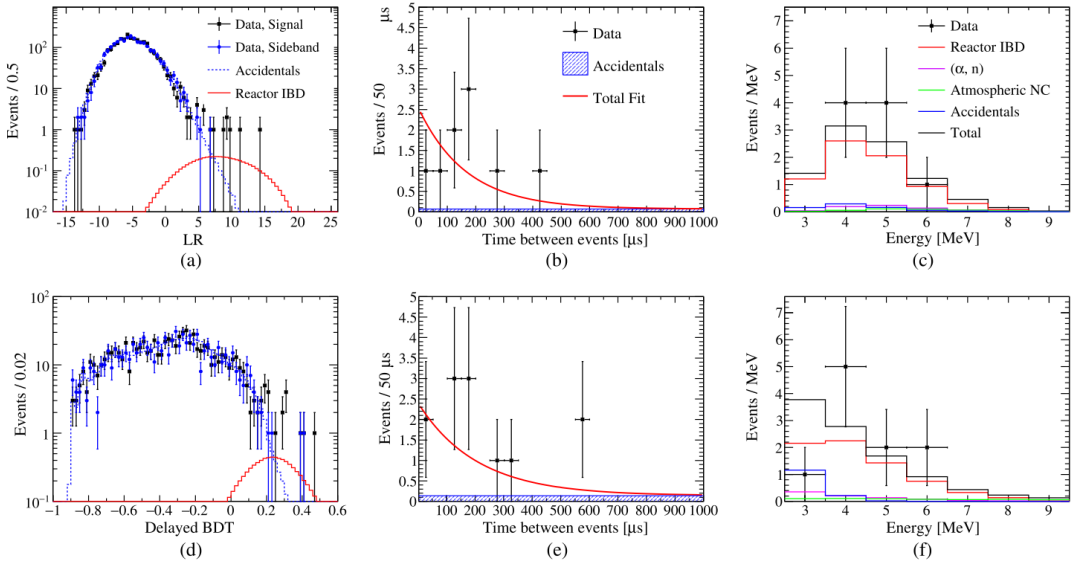


- LiquidO: Light detector with opaque medium
- Light-based “TPC”
- Uniform calorimeter
- PID capability
- Doping capability
- Detector R&D ongoing: Cloud, superChooz, LiquidO …

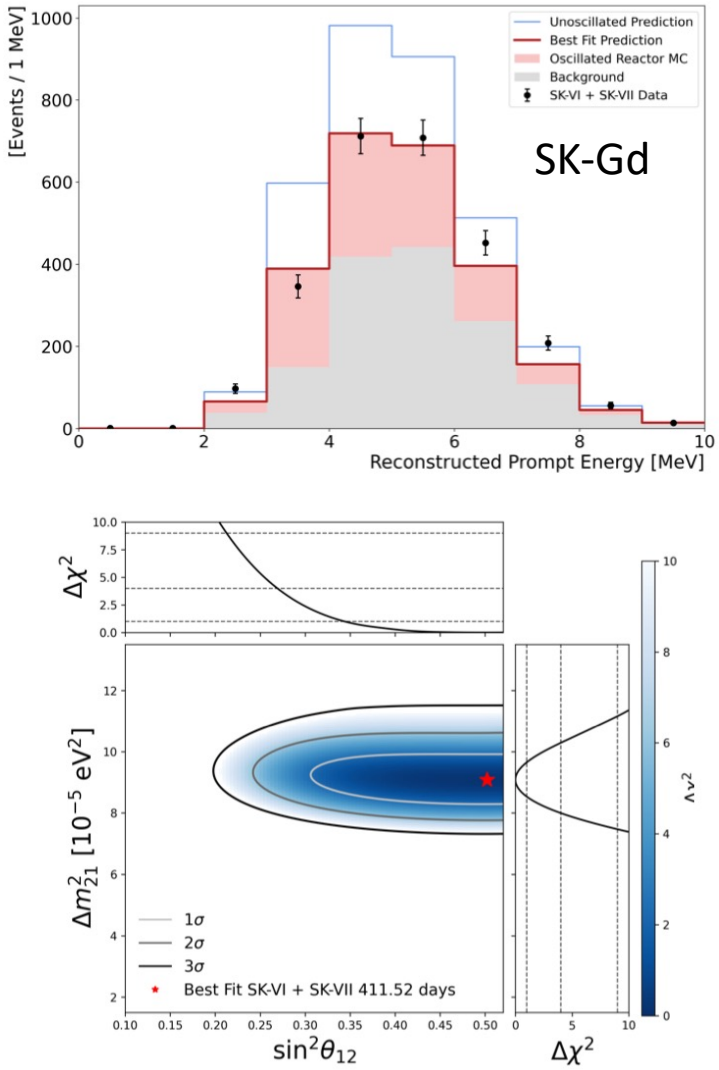
Water Cherenkov Technology

PRL 130, 091801 (2023)

SNO+ Water

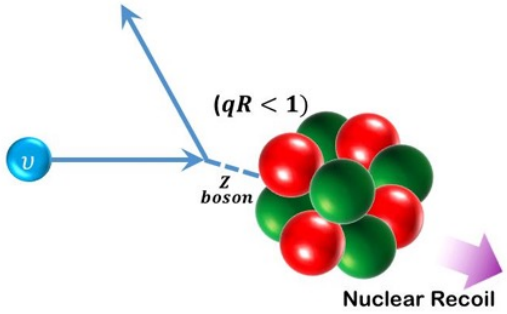


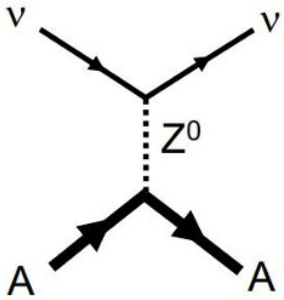
arXiv: 2610. 03143



- Both SNO+ (3.5σ) and SuperK-Gd (6σ) demonstrate their reactor antineutrino detection capability with water cherenkov technology
- Water-based Liquid Scintillator (WBLS) technology hybrid both scintillation and Cherenkov lights (*NIMA 660 (2011), JINST 21 (2026)*)

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



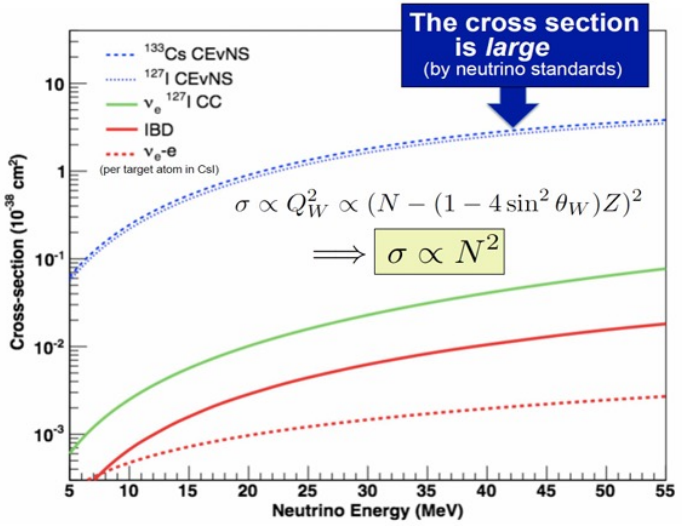


$$\left(\frac{d\sigma}{dT}\right)_{\text{coh}} = \frac{G_F^2 M}{4\pi} Q_W^2 F^2(Q) \left[1 - \frac{MT}{2E_\nu^2}\right]$$

Predicted in 1974 and discovered in 2017

New way to detect Neutrino!

- qR < 1
- Z-exchange between neutrino and nucleus
- Nucleus recoils as a whole
- Coherent up to $E_\nu \sim 50$ MeV



Many reactor CEνNS experiments: CONUS+ (3.7 σ), nuGeN, TEXONO, CONNIE, NEON, RED-100, RICOCHET, NUCLEUS, RECODE, RELICS ……

Summary

- Reactor Neutrino is an important tool for neutrino property research.
  - Oscillation Parameter Δm^2_{21} , $\Delta m^2_{31}$and θ_{13} are accurately measured.
  - A hint of normal mass ordering from JUNO and accelerator experiments
  - No undisputable evidence for light sterile neutrino signal yet
- Scintillator technology is one of the most widespread and successful neutrino detection technologies for 70 years.
  - New technology may open another window for the reactor neutrino