Status Report for RENE experiment

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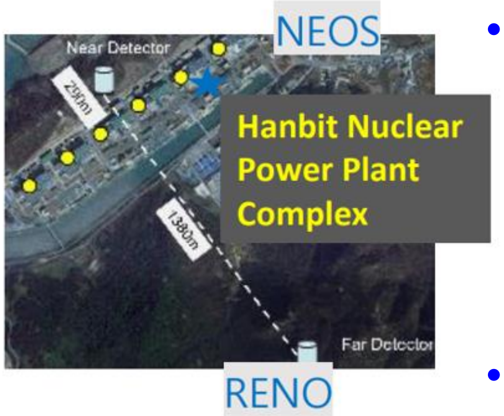
on behalf of RENE collaboration

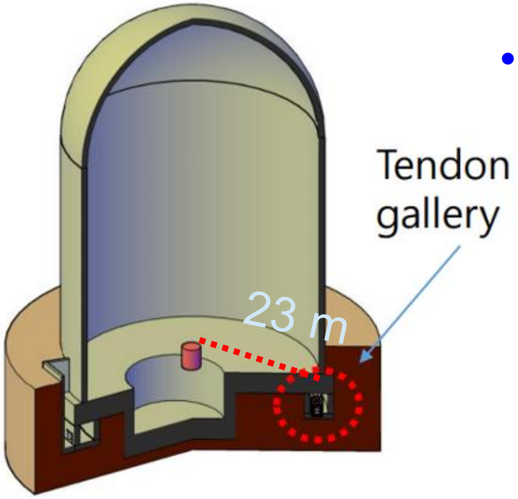
2024/07/26 K-Neutrino Symposium

Center for Precision Neutrino Research
중성미자정밀연구센터

Introduction

- RENE : Reactor Experiment for Neutrino and Exotics (started at 2022)



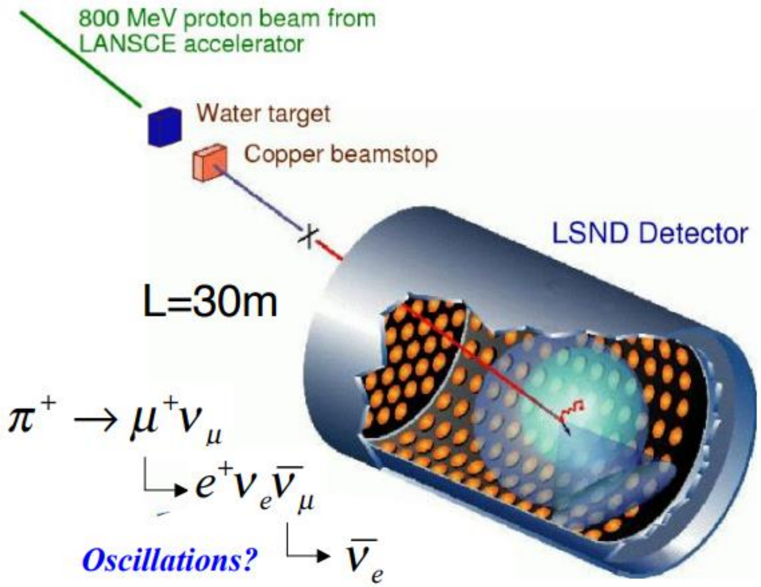


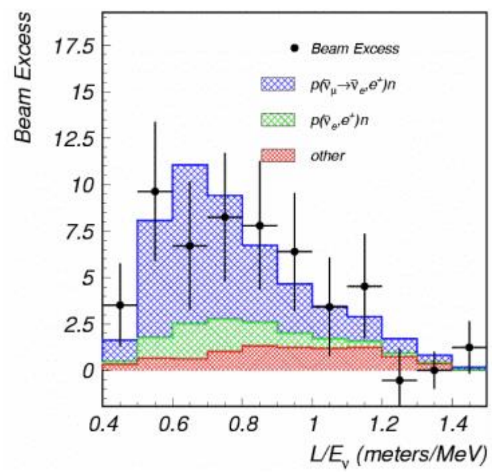
- Plan to install the liquid scintillator based neutrino detector in the tendon gallery of the reactor in Yeonggwang
- Baseline : ~ 23 m
- Physics goals
  - ✓ Sterile neutrino search for $\Delta m^2_{41} \sim 2\ eV^2$
  - ✓ Precise measurements of the flux and spectrum of reactor electrons and antineutrinos (5 MeV bump)
  - ✓ Decomposition of the neutrino spectrum of ^{235}U and ^{239}Pu

LSND proposed the 4th neutrino hypothesis

- LSND (Liquid Scintillator Neutrino Detector) reported observation of excess

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Signal Appearance





Possibility of new type of neutrino (4th neutrino ?)

Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

Los Alamos Meson Physics Facility, LANL 1993-1998

3.8σ evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Observed $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ with baseline of 30 m ($\Delta m^2 \approx 1 eV^2$ > known other Δm^2)

Existence of 4th neutrino ?

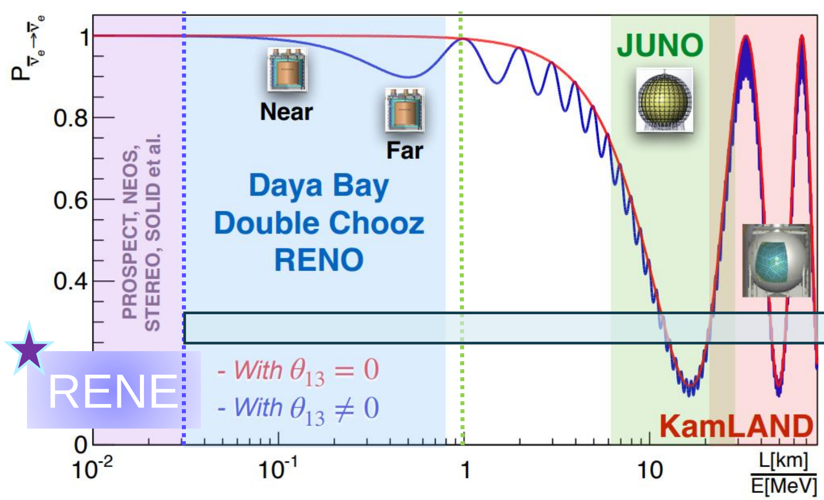
Experiments	Neutrino source	signal	type	Significance σ
LSND	μ Decay-At-Rest	$\bar{\nu}_\mu \to \bar{\nu}_e$	appearance	3.8
MiniBooNE	π Decay-In-Flight	$\nu_\mu \to \nu_e$	appearance	4.5
		$\bar{\nu}_\mu \to \bar{\nu}_e$	appearance	2.8
		combined		4.7
Ga(calibration)	e capture	$\nu_e \to \nu_X$	disappearance	2.7
Reactors	Beta decay	$\bar{\nu}_e \to \bar{\nu}_X$	disappearance	3.0

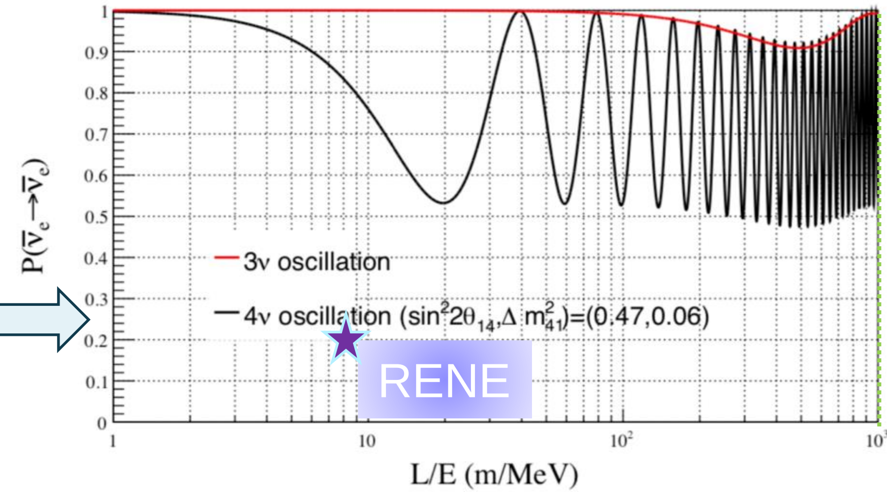
Still room for 5 σ discovery

Neutrino 2023 J. Ochoa-Ricoux

(3+1) Neutrino Model

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m^2_{31} \frac{L}{E_\nu}\right) - \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{41} \frac{L}{E_\nu}\right)$$



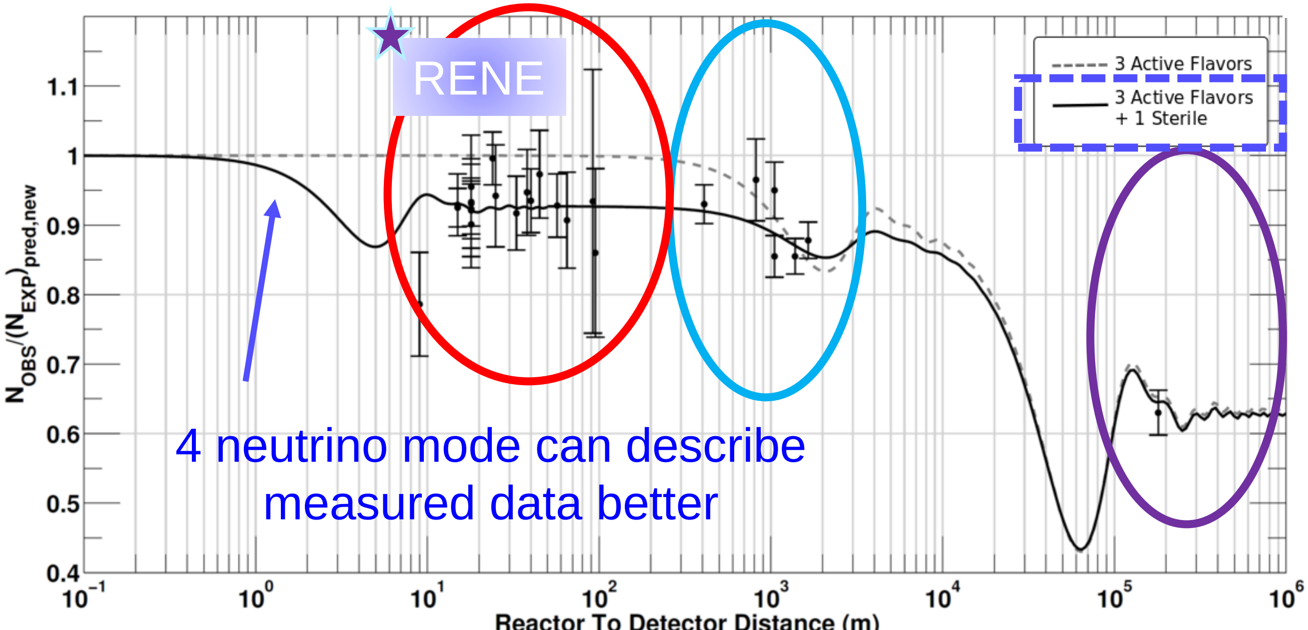


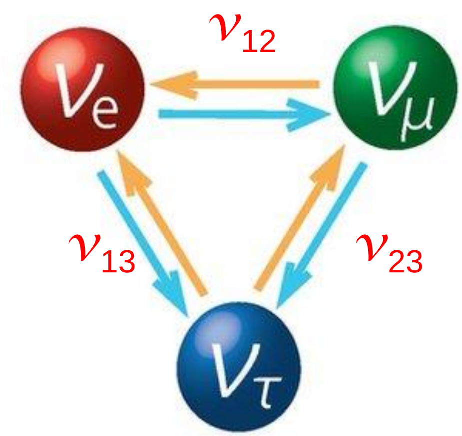
Reactor Neutrino Anomaly

- Neutrino anomaly observations were reported $P(\nu_e \to \nu_\mu) = 1 - 2\sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$

PLB 829 (2022) 137054, PRD 83 (2011) 073006

$$\Delta m^2 = m_2^2 - m_1^2$$





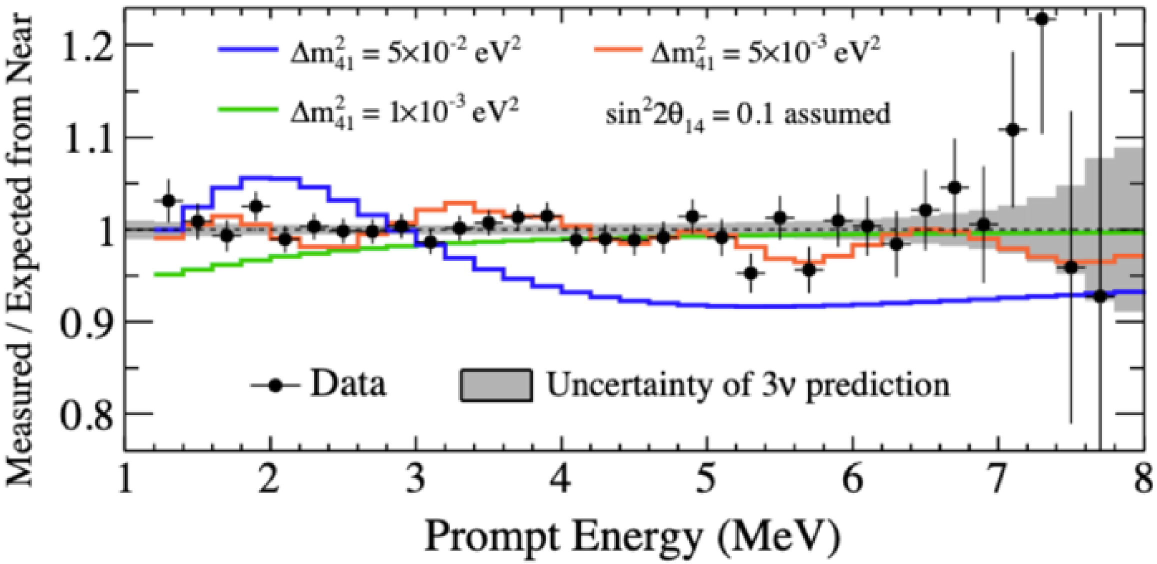
Anti neutrino anomaly in reactors (2011 ~)
ν_{13}-oscillation
($\Delta m^2 \approx 2.7\text{x}10^{-3}\text{eV}^2$)

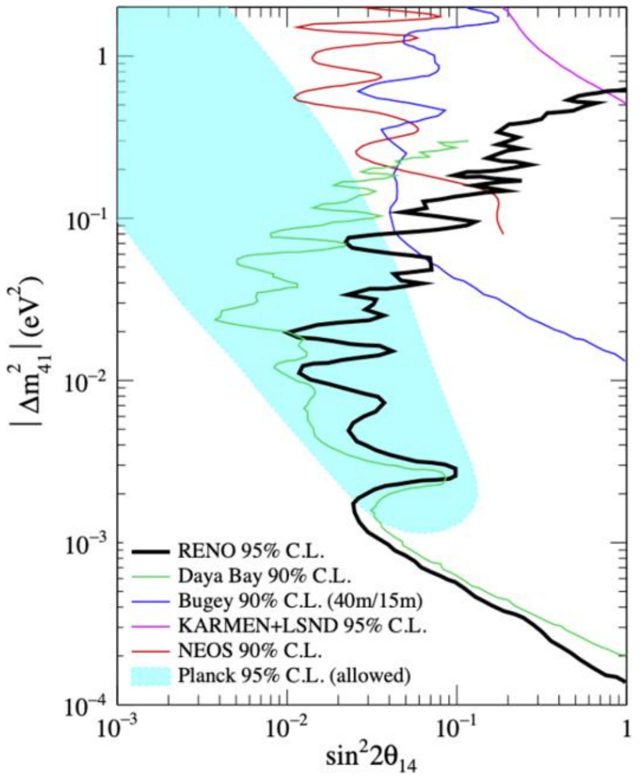
Solar neutrino anomaly (1968 ~ 2001)
ν_{12}-oscillation
($\Delta m^2 \approx 8\text{x}10^{-5}\text{eV}^2$)

Atmospheric neutrino anomaly (1986 ~ 1998)
ν_{23}-oscillation
($\Delta m^2 \approx 2.5\text{x}10^{-3}\text{eV}^2$)

Sterile neutrino at RENO

PRL 125 (2020) 191801

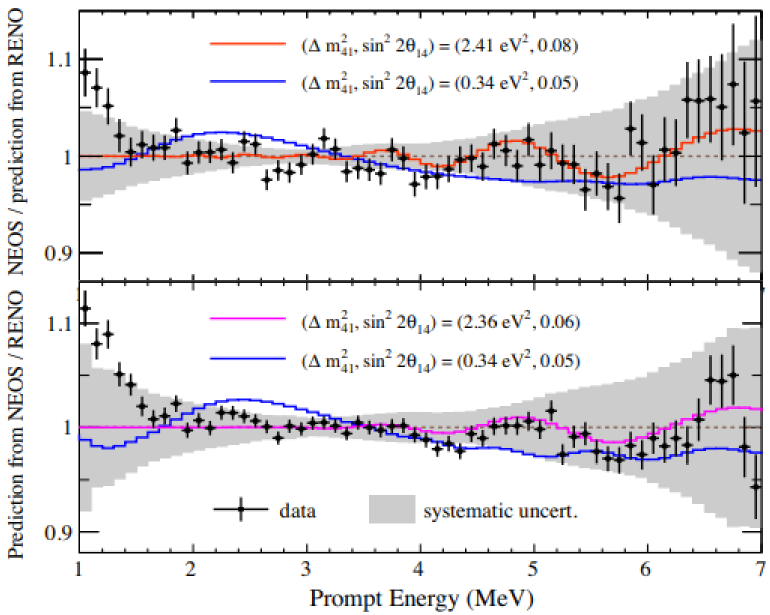


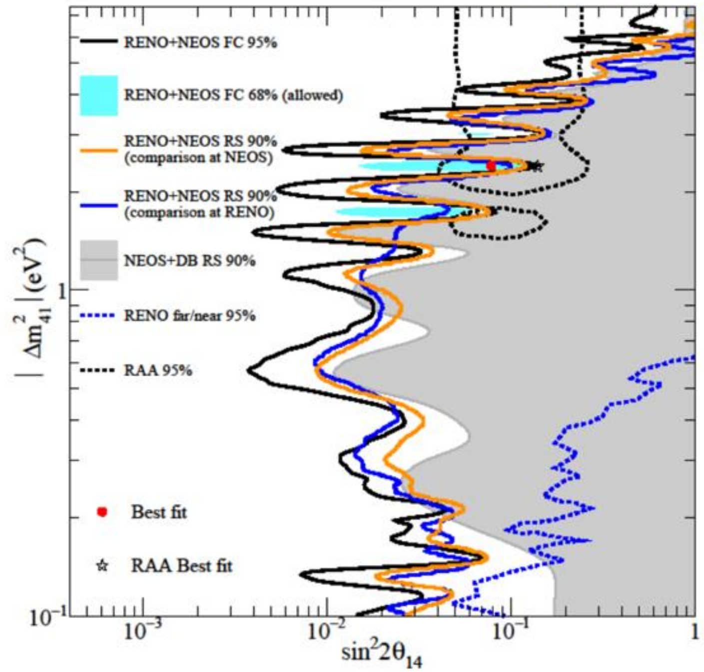


- Search for Sub-eV sterile neutrino in the 4 ν framework
- Orange line describes well data ($\Delta m^2_{41} = 5\text{x}10^{-3}$ eV^2)

RENO + NEOS joint analysis

PRL 125 (2020) 191801



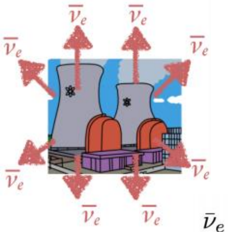


- Hint for the sterile neutrino at $\Delta m^2 \sim 2$ eV^2
- Need to improve systematics for confirmation of $\sin^2\theta_{14}$
- p-value of inconsistency of 3 and 4 neutrino modes is 8.2 %

RENE collaboration

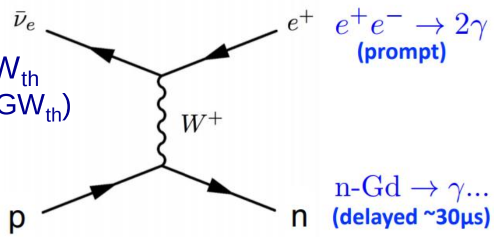
12 institutions and ~ 40 members

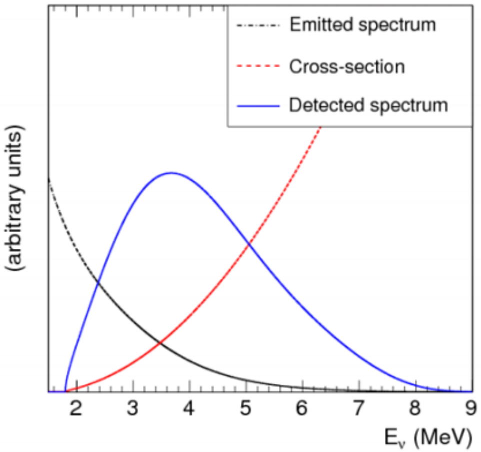
Neutrino detection (IBD)

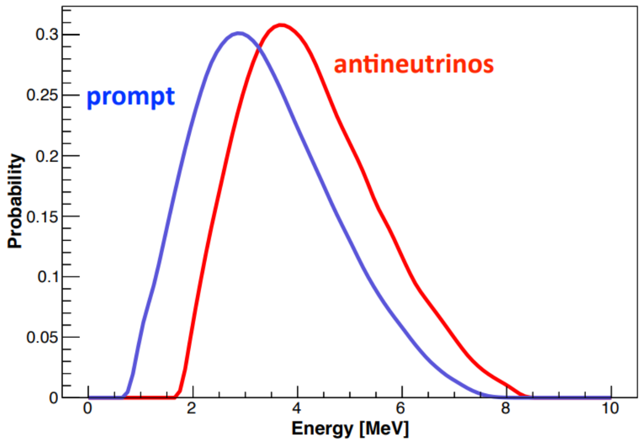


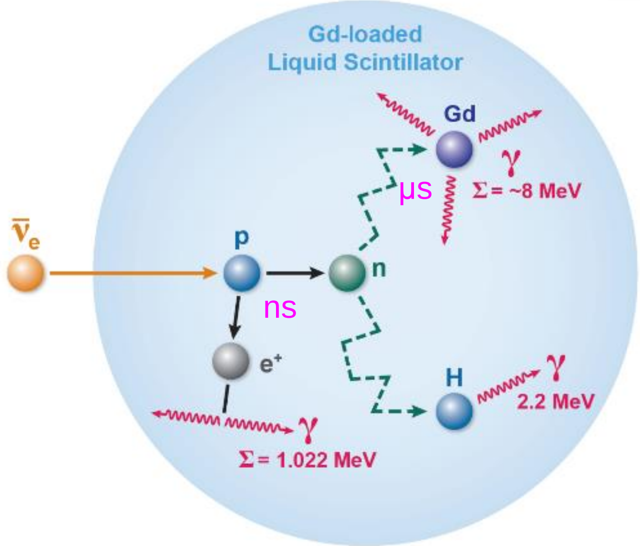
$\overline{\nu_e}$ + p → n + e$^+$

~10^{20} $\overline{\nu_e}$ /GW_{th}
(Hanbit : 2.8GW_{th})









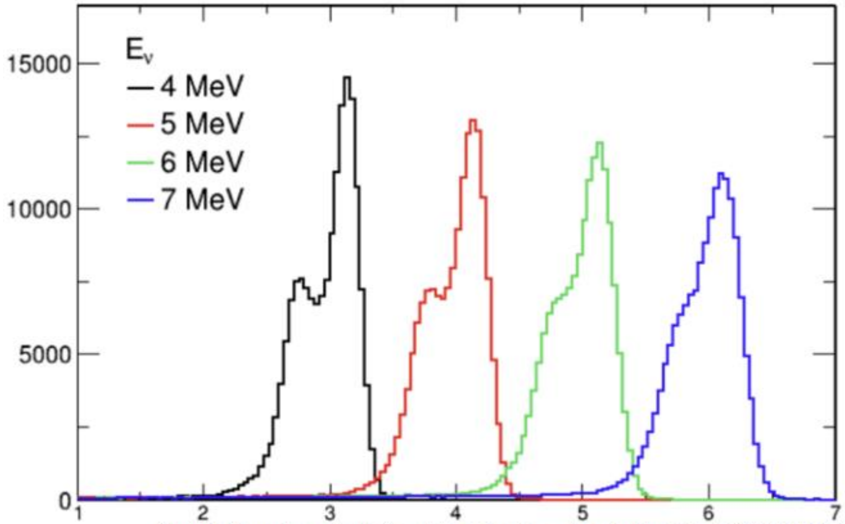
$$E_\nu^{thr} = \frac{(m_n + m_p)^2 - m_p^2}{2m_p} = 1.806\,\mathrm{MeV}$$

$$E_{\mathrm{prompt}} = K.E.(e^+) + 2 \times (0.511)\,\mathrm{MeV}$$
$$\simeq E_\nu - 0.78\,\mathrm{MeV}$$

- Prompt signal : electron positron annihilation in ns
- Delay : n-Gd capture in μs
- Timing constraints help to reject the background events

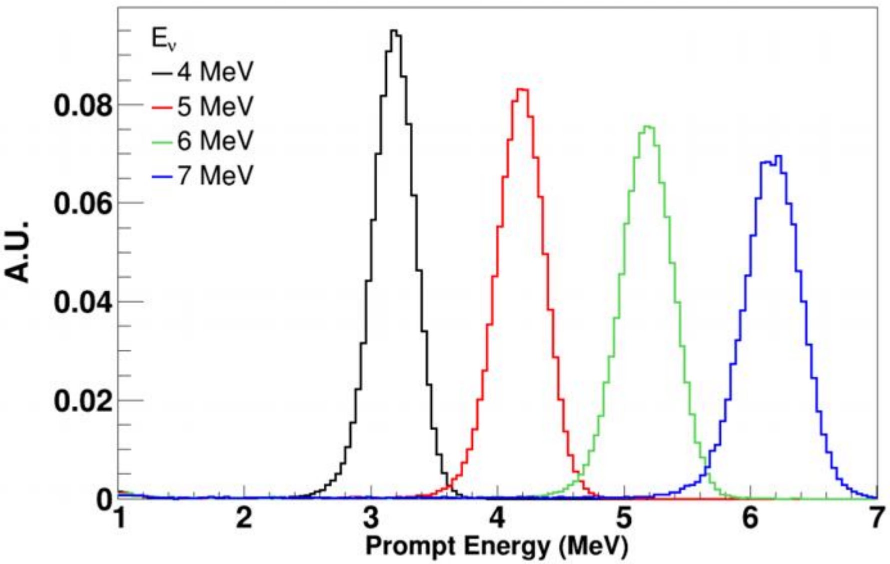
Detector response simulation

- **NEOS**



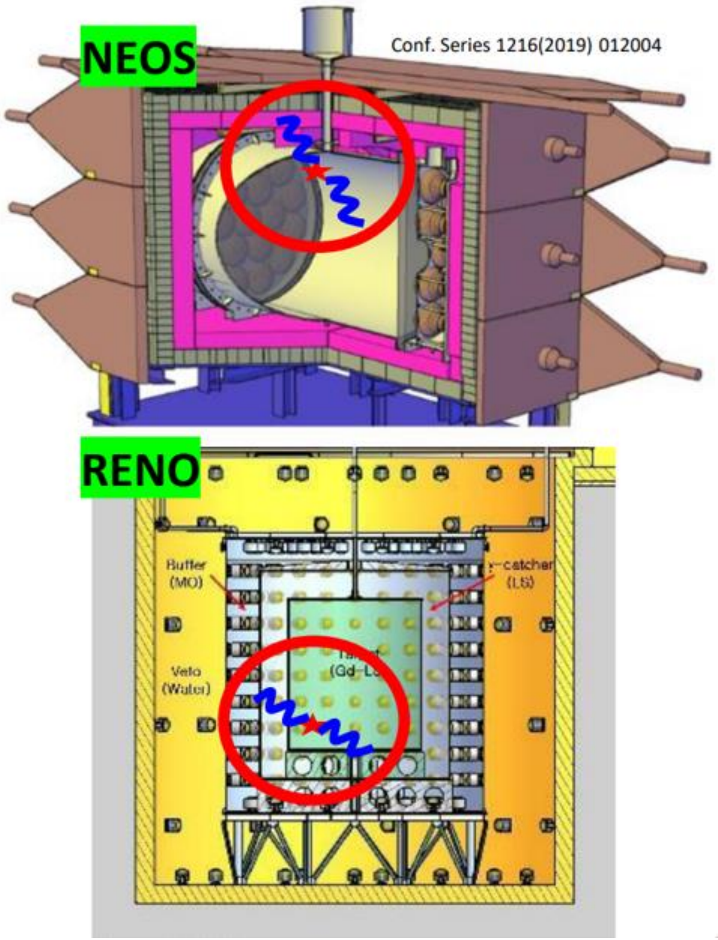
Neutrino Experiment Oscillation at Short Baseline – Yoomin Oh, @The 39th ISNP (2017)

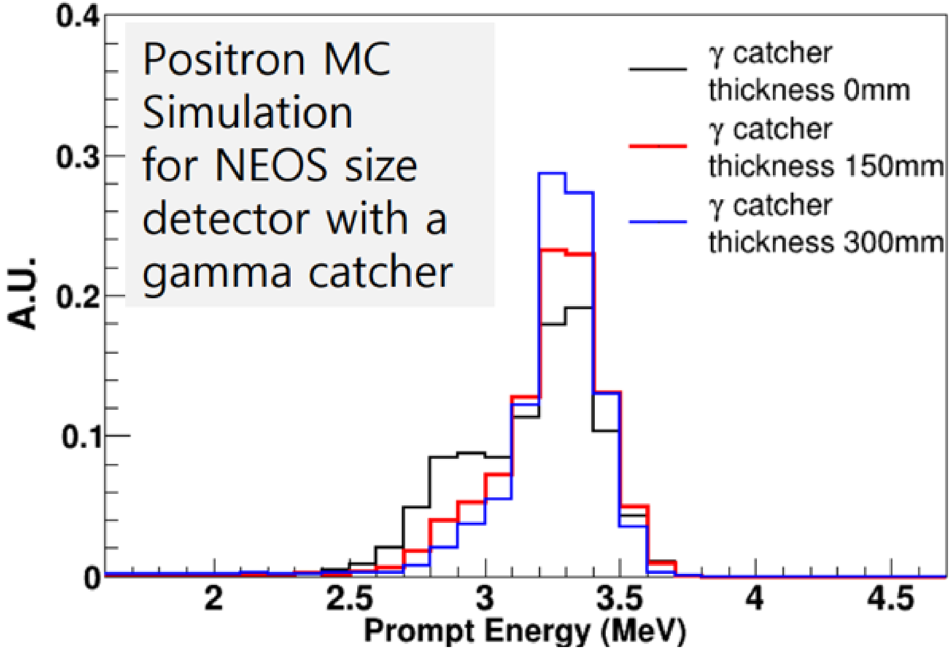
- **RENO**



- Energy distributions of prompt signal for NEOS and RENO
- 2nd peaks appear below the main peaks

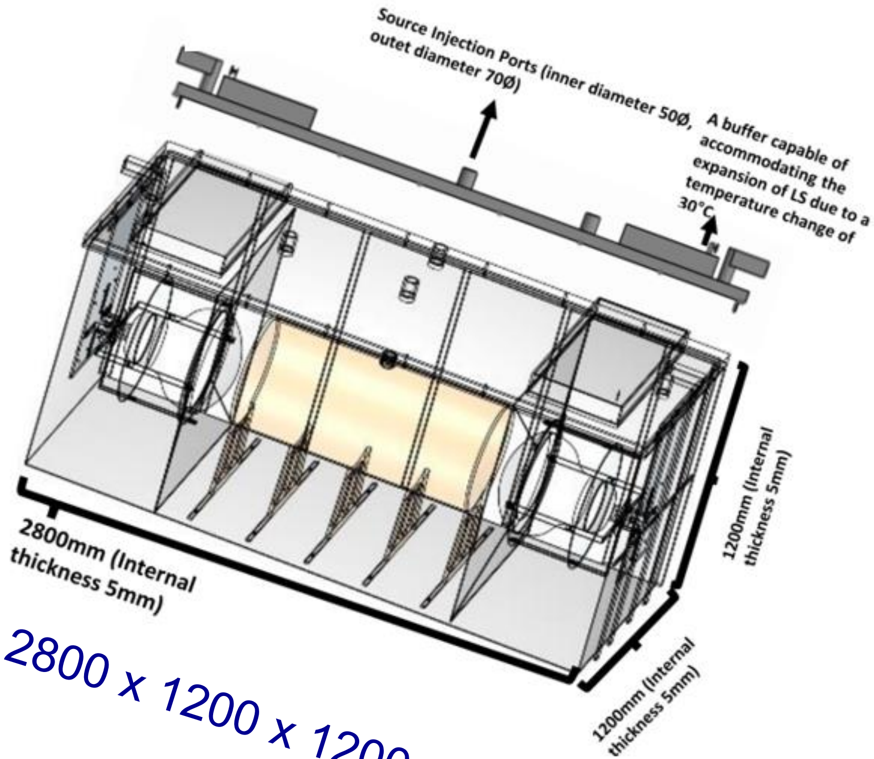
Significance of gamma catcher





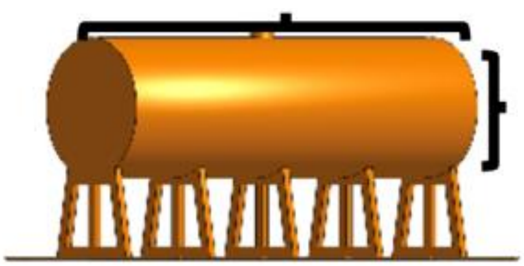
- Escaping gammas induce the 2nd peak of energy distributions
- Gamma catcher can play an important role to smear the 2nd peak and get better resolution

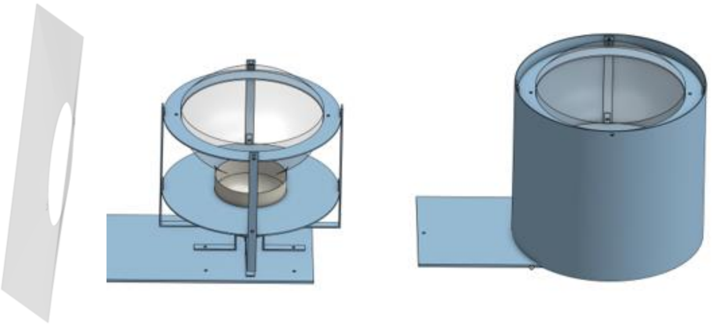
Detector design for the prototype



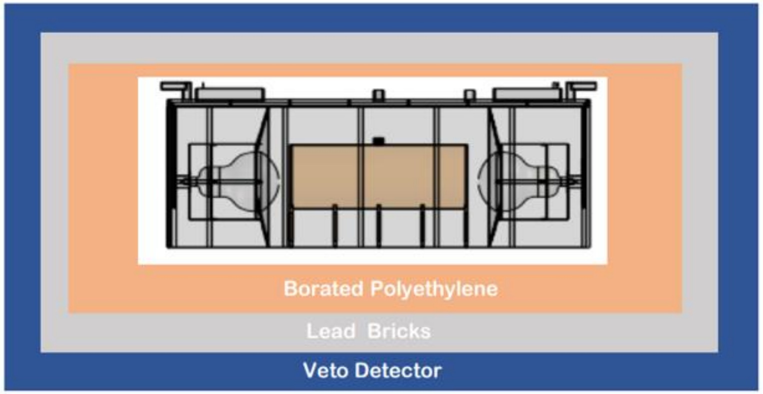
2800 x 1200 x 1200 mm³

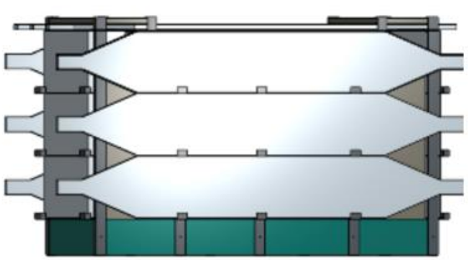
- Detector inner structure
  - ✓ Cylindrical shape acrylic target filled with 0.5 % Gd-LS
  - ✓ Box type stainless steel gamma catcher filled with LS
  - ✓ Cone structure for efficient optical photon collection
  - ✓ Two 20-inch PMTs on left and right
  - ✓ PMT holder with Mu-metal shield

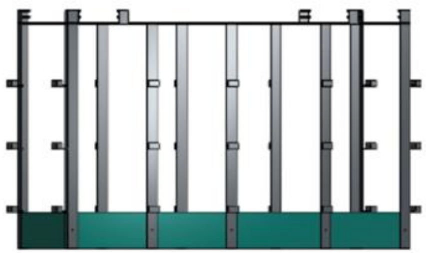




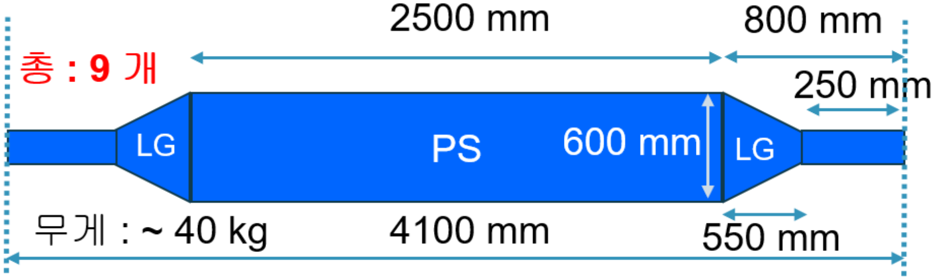
Shielding and outer VETO detector

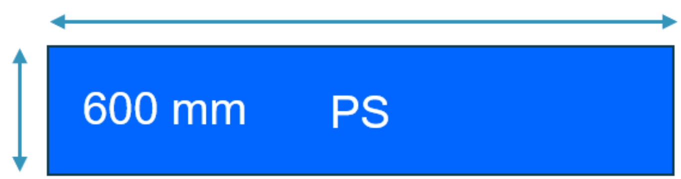






- Shielding
  - ✓ Six borated PE plates with 100 mm thickness
- Veto detector
  - ✓ 15 plastic scintillator panels donated from the NEOS collaboration
  - ✓ 32 2-inch PMTs





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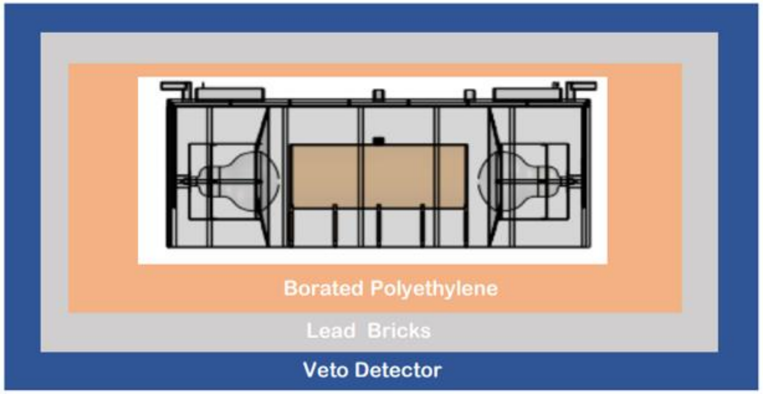
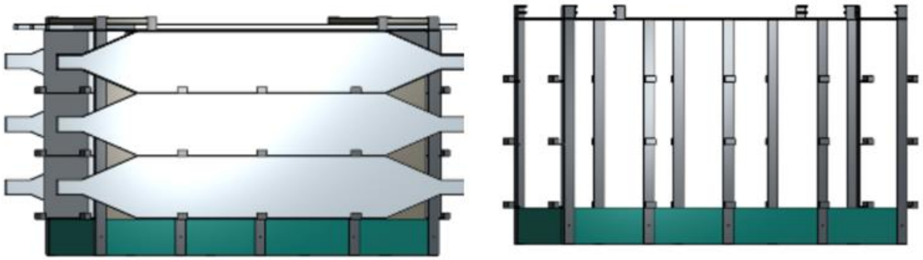
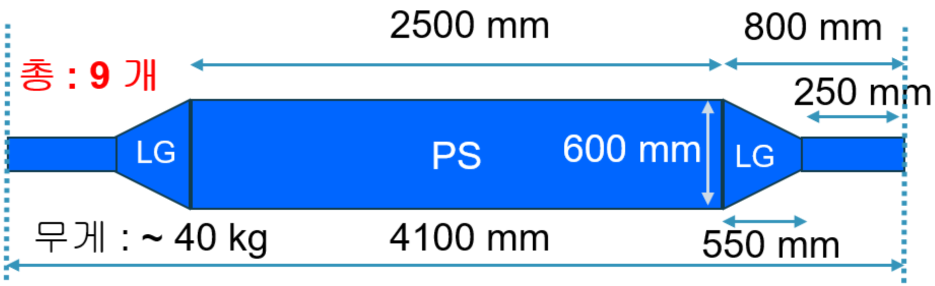
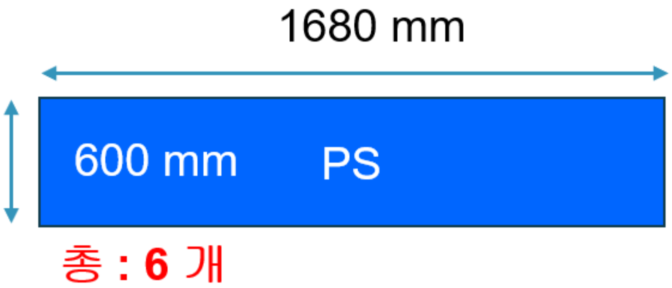




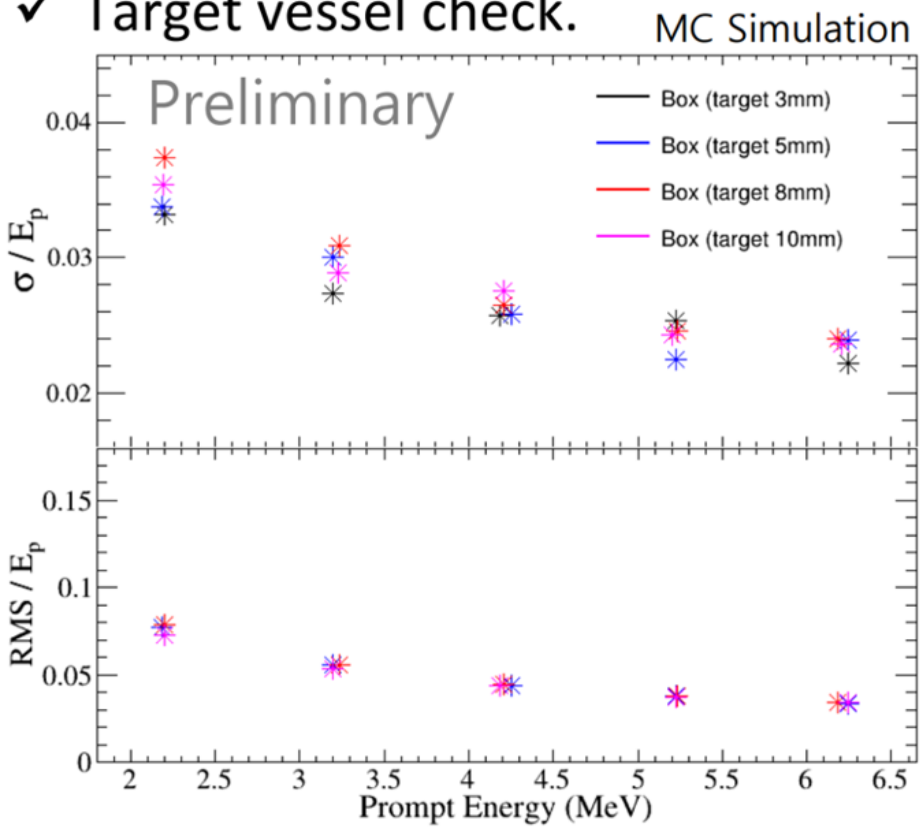




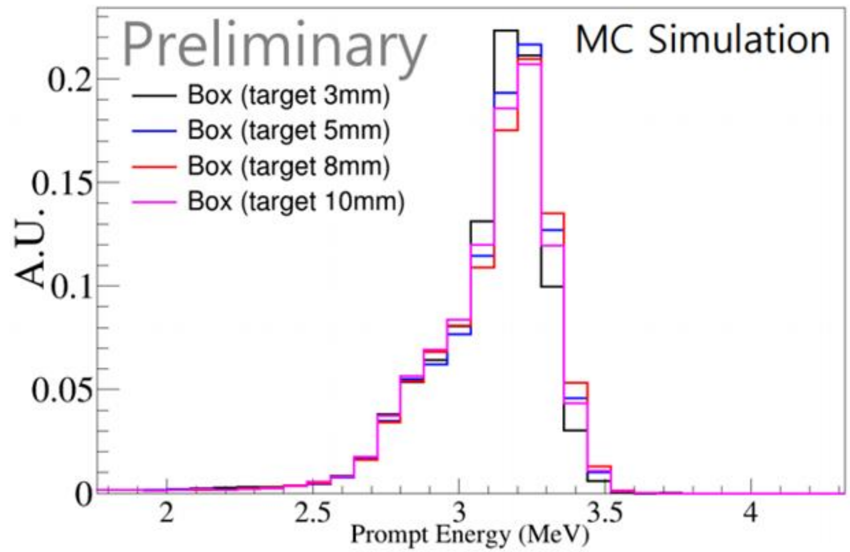
Target detector simulation

See poster
W. Hwang

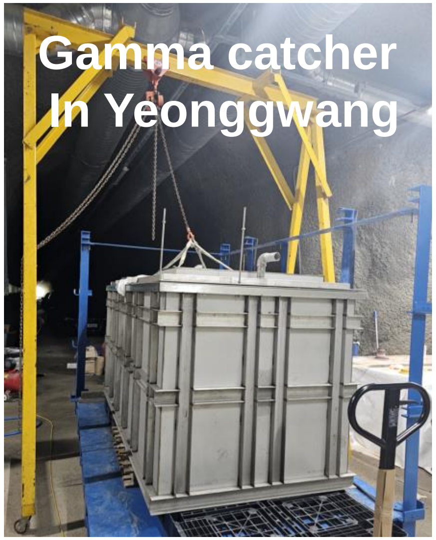
✓ Target vessel check.

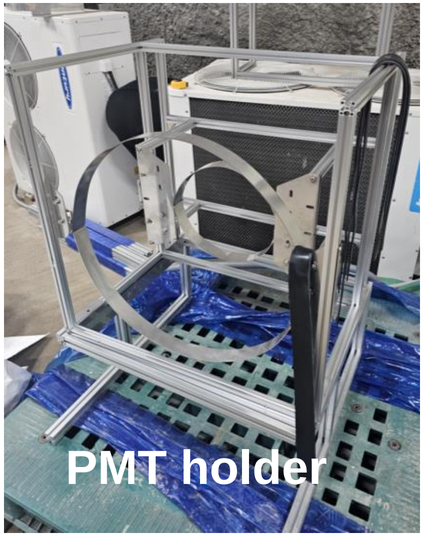


- The thickness of the target acrylic vessel is not significant
- 8 mm-thick target was selected



Detector construction

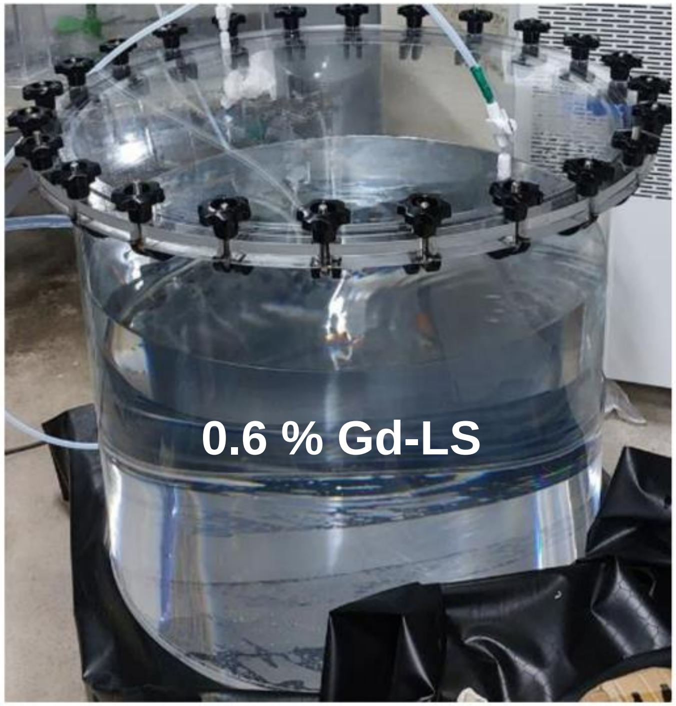




- Manufactured gamma catcher and PMT holder with the stainless steel in 2024.04.15

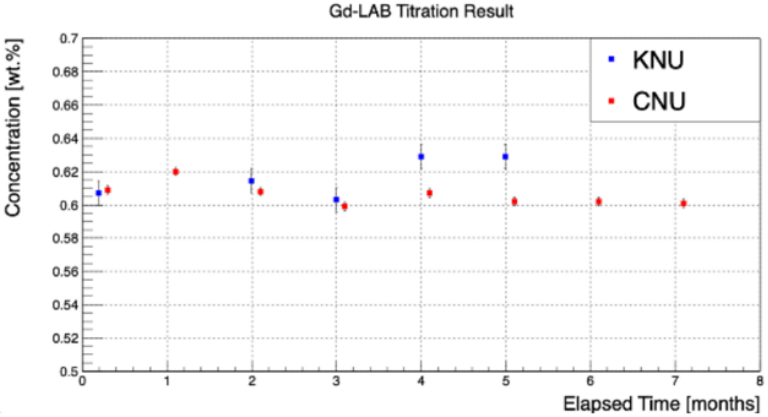
- All components are delivered into Yeonggwang.

Liquid scintillator



- The target will be filled with 0.5 % Gd-LS
- DIN will be added for PSD later (Pulse Shape Discrimination) : ~ 210 L 0.6 % Gd-LS is ready
- The gamma catcher will be filled with LS
- Stability check in KNU and CNU

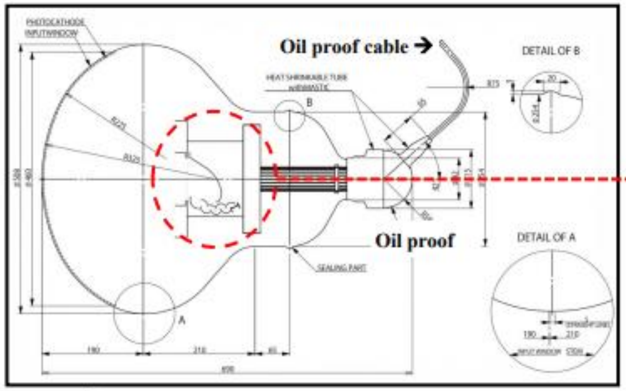
- At RENO far site

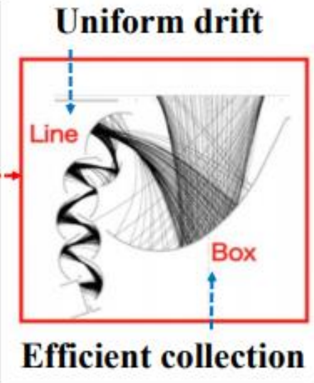


Concentration is stable for over 7 months

20-inch PMT

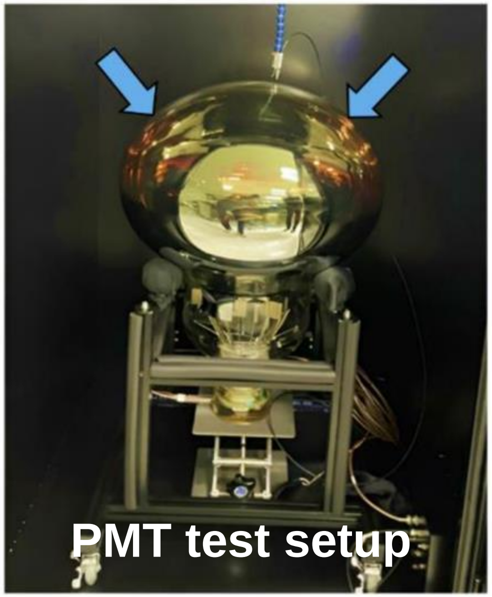
See poster
J. Oh





Features	
1. Fast time response	
2. High stability	
3. Low dark count	Reference from Hamamatsu handbook
Specifications (typical)	
Quantum Efficiency	30 % (390 nm), λ_{peak}: 420 nm
Gain (➔ Charge)	1×10^7 ➔ 1.6 pC (@Single Photoelectron, SPE)
Peak to Valley	1.5 ~ 2.8
Dynode structure	
Box (efficient collection) & Line (uniform drift path)	

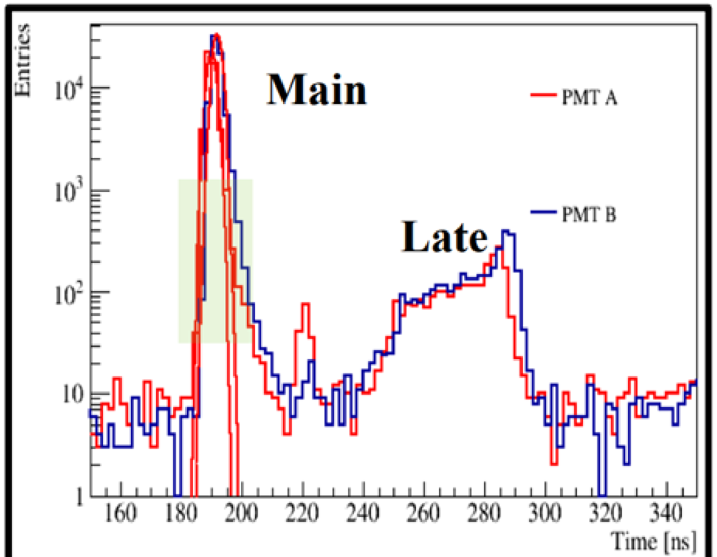
- Hamamatsu R12860



20-inch PMT

See poster
J. Oh

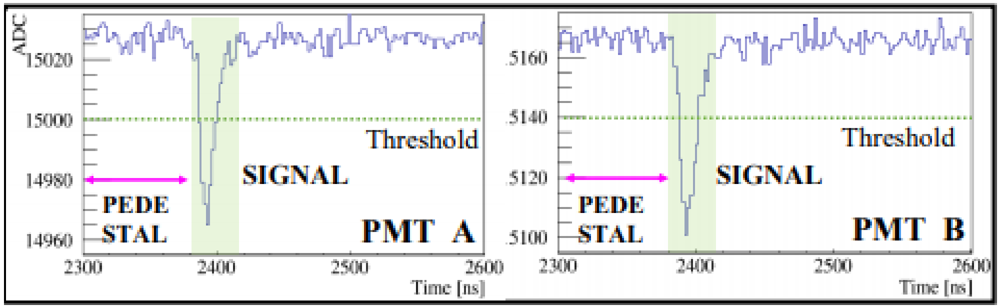
Time response



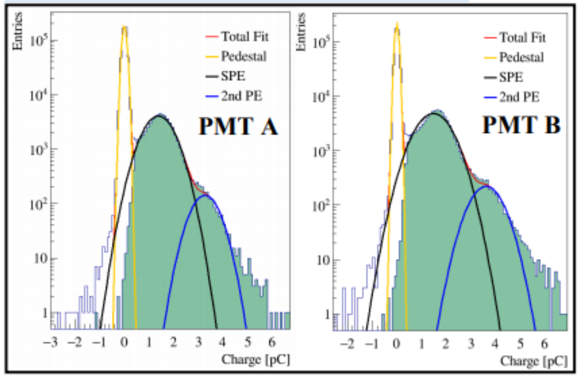
- Main Time response (A): **189 ± 0.0078 ns**
- Main Time response (B): **191 ± 0.0072 ns**
- Late Time response: **Main + 100 ns**
- Transit Time Spread (**TTS**) ≈ **2 ns**

*Time response: Trigger time – PMT falling time

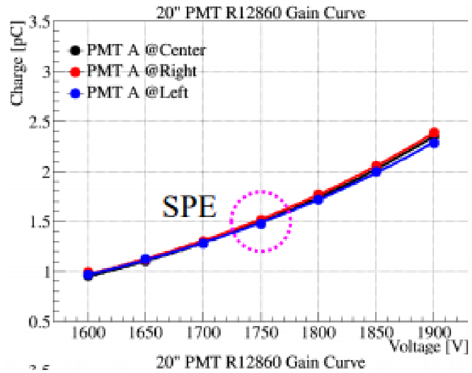
Wave form



Charge distribution



Gain measurement



- Single photo electron : 1.48 (A), 1.51 (B) pC
- Peak to valley : ~ 3
- Acting voltage : 1750 V
- Gain, position dependence and after pulse study are done

DAQ system

DAQ equipment

20-inch

PMT signal

Notice NKFADC500
- 4 + 4 channels
- ADC resolution = 12 bit
- 2.5 V_{pp} dynamic range
- Sampling rate = 500 MS/ch/s
- 4+4 GB DRAM

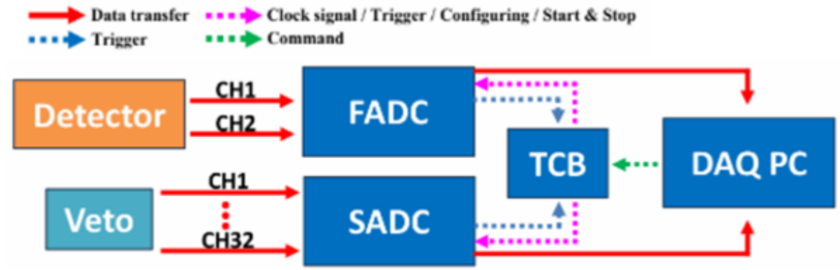
VETO signal

Notice M64ADC (SADC)
- 32 channels
- ADC resolution = 12 bit
- 2 V_{pp} dynamic range
- Sampling rate = 62.5 MS/ch/s
- 4 GB DRAM

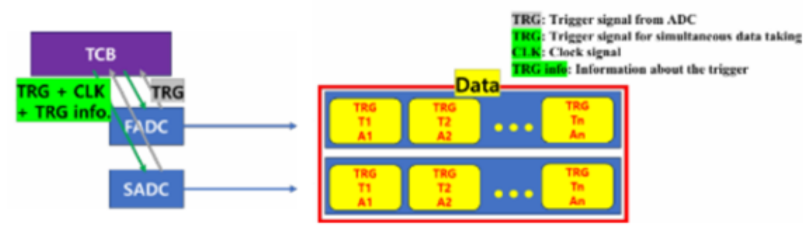
Trigger control

Notice TCB (Trigger Control Board)
- Make trigger and clock signals
- 40 ADCs available
- RJ-45 port

DAQ schematic view



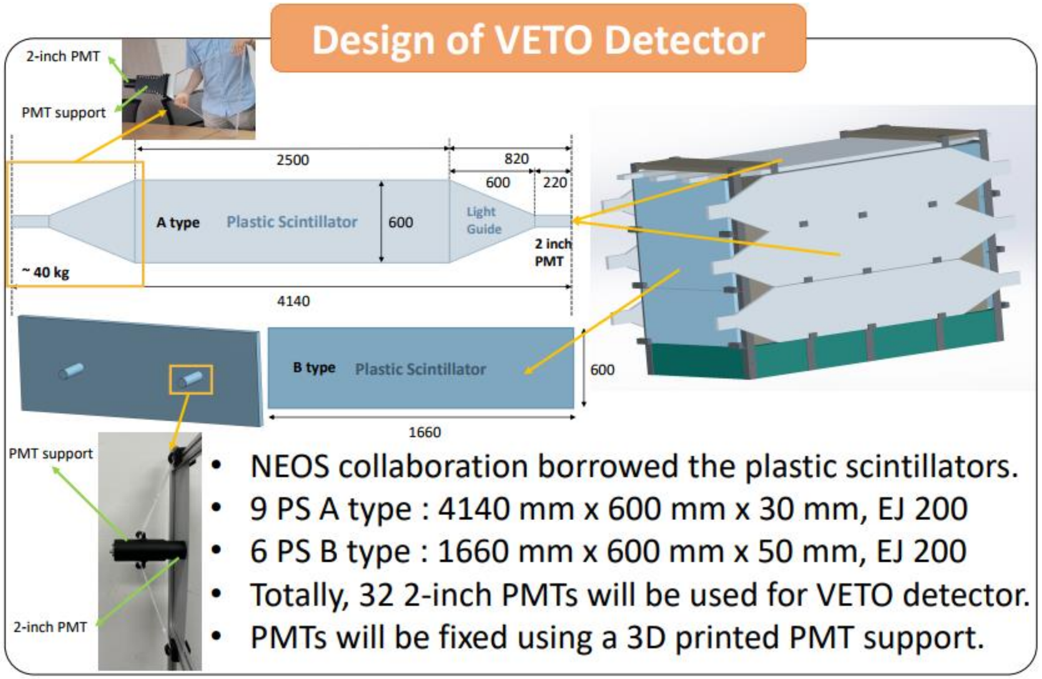
DAQ synchronization



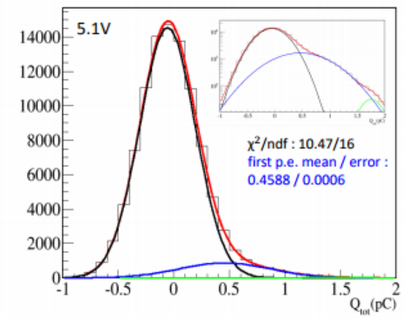
- PSD (pulse shape discrimination) will be performed by using FADC 500 at offline
- SADC will be used to control VETO signal

VETO detector performance

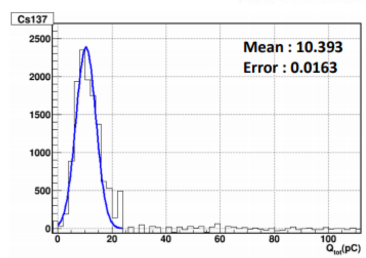
See poster
J. Park

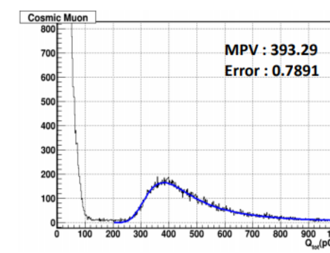


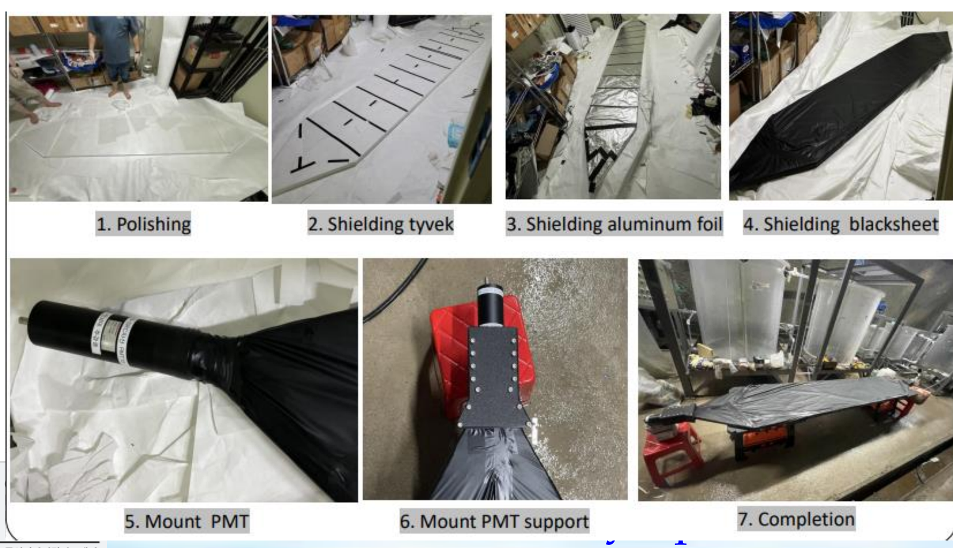
PMT model number : H7195
PMT diameter : 60.0 mm



Coincidence test







- Ongoing to work in Yeonggwang
- Coincidence test with Cs137 and cosmic muons

Short baseline (SBL) experiments

Neutrino 2023 J. Ochoa-Ricoux

2) Short-Baseline (SBL) Experiments

Hope to join in the world race soon !!!

- Primary goal: search for a sterile neutrino with O(10 m) baselines

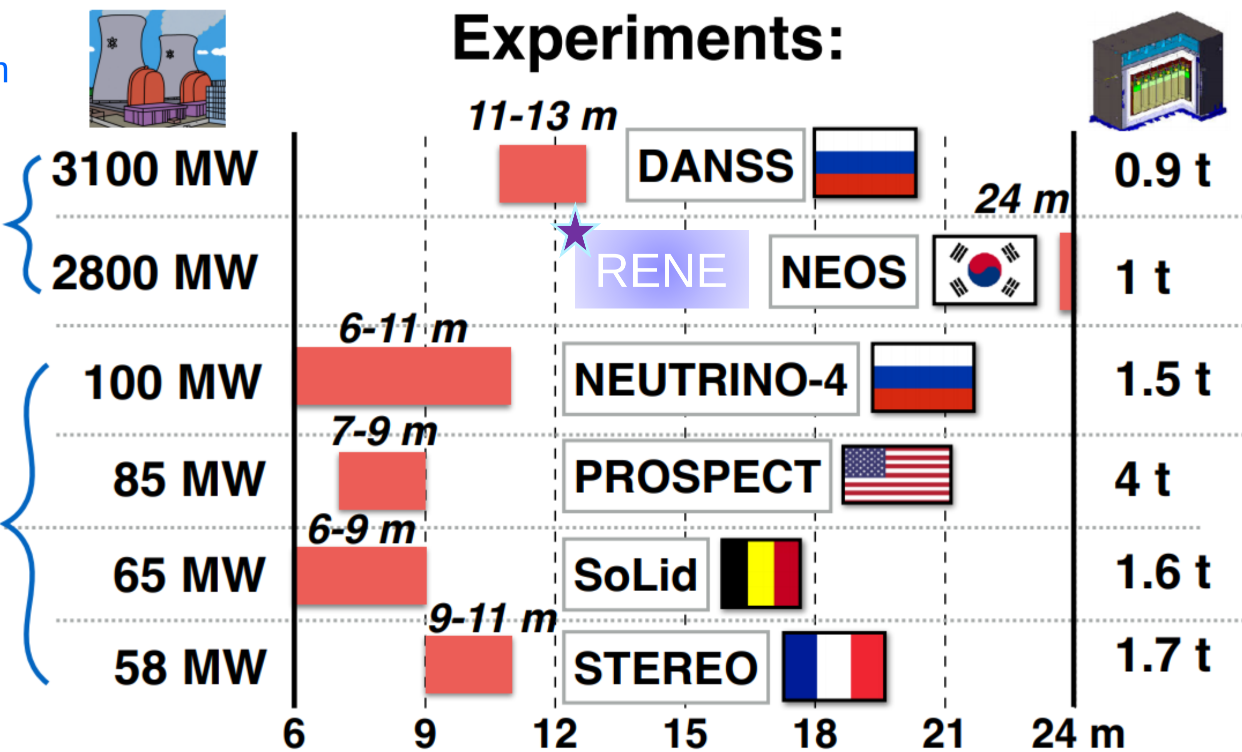
Motivation: anomalies in neutrino physics that can be explained by sterile neutrino mixing with $\Delta m^2_{41} \sim 1 \text{ ev}^2$, including the reactor antineutrino anomaly

Low-Enriched Uranium (LEU)

LEU Reactors
Fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

HEU Reactors
Fission of ^{235}U

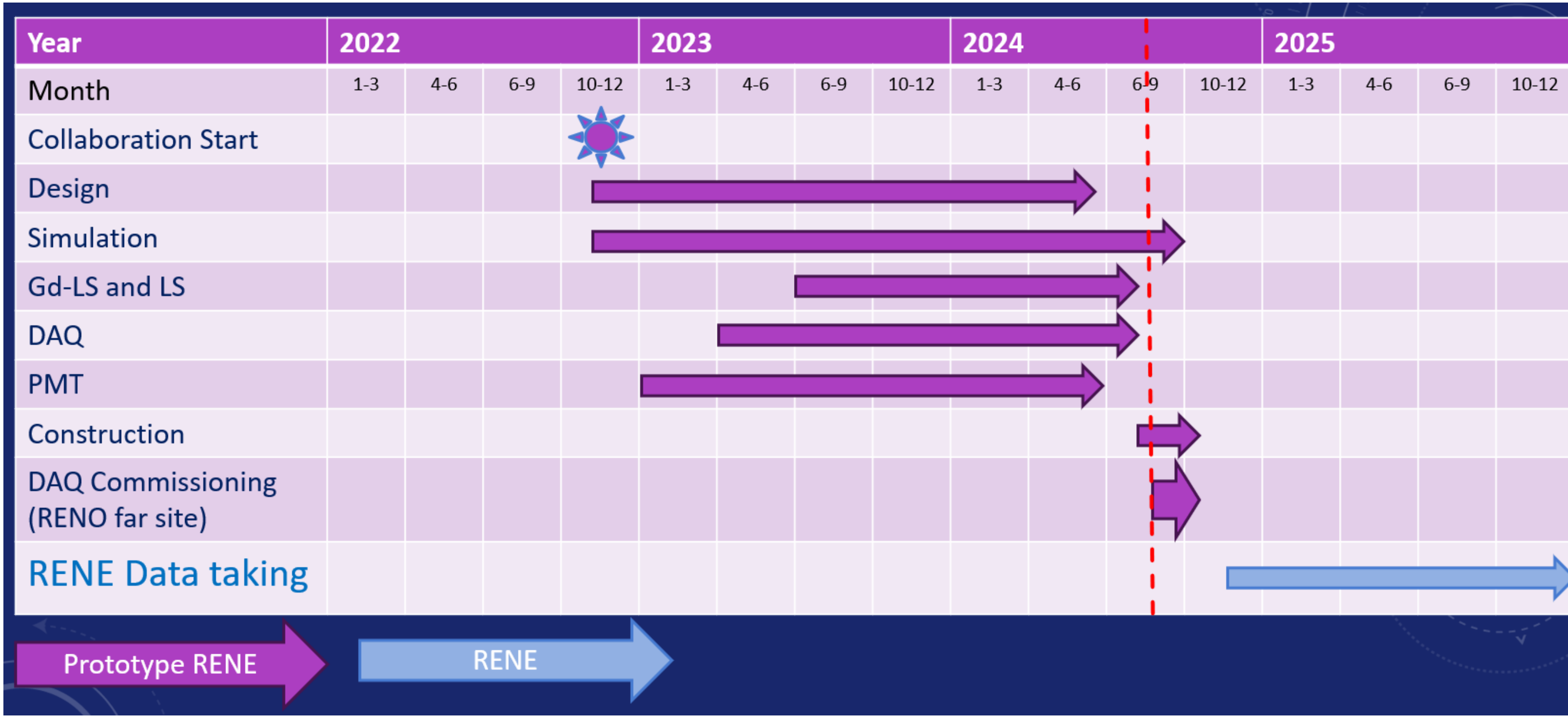
High-Enriched Uranium (LEU)



(chart courtesy of B. Roskovec)

+ (mini-)CHANDLER, NuLAT

Schedule

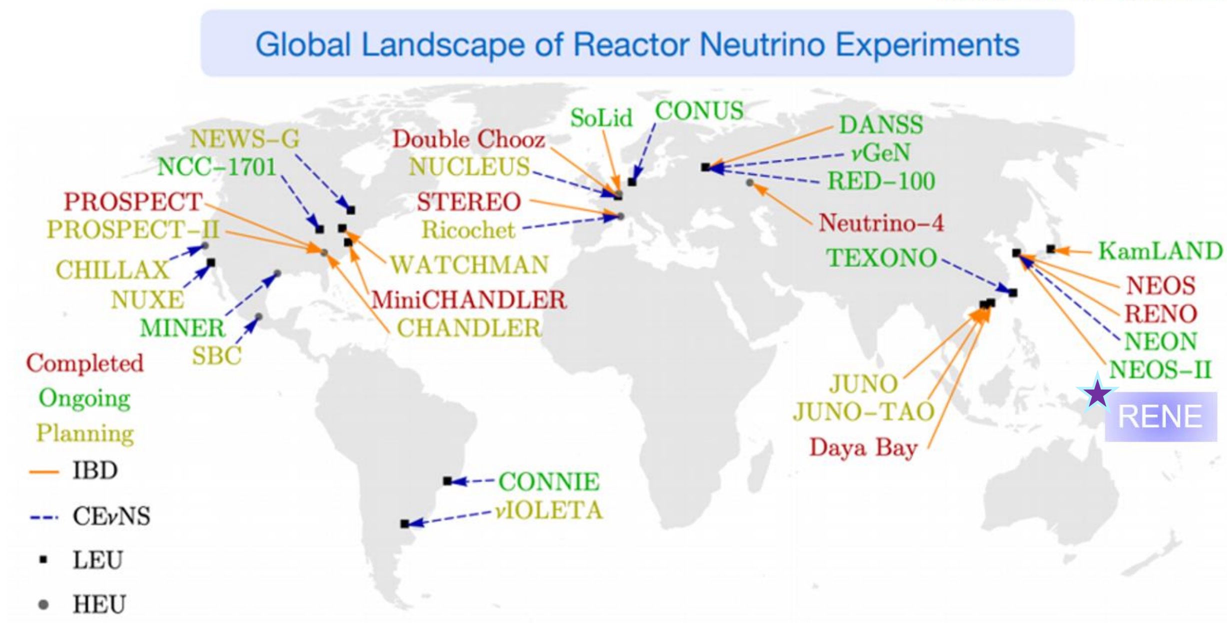


Year
2022
2023
2024
2025
Month
1-3
4-6
6-9
10-12
1-3
4-6
6-9
10-12
1-3
4-6
6-9
10-12
1-3
4-6
6-9
10-12
Collaboration Start
Design
Simulation
Gd-LS and LS
DAQ
PMT
Construction
DAQ Commissioning (RENO far site)
RENE Data taking
Prototype RENE
RENE

Summary and outlook

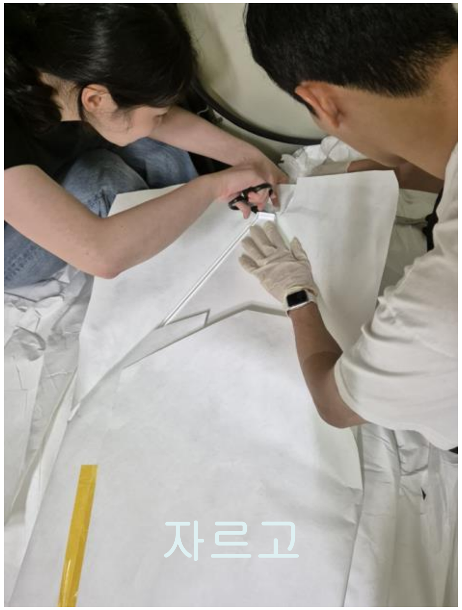
- Inspired by the hint of RENO-NEOS joint analysis, RENE has begun to search for the sterile neutrino around $\Delta m^2 \sim 2\ eV^2$
- Detector constructions are ongoing
- Expecting timeline to install in tendon gallery is set to middle of October
- Please stay tuned to the RENE experiment

Neutrino 2023 J. Ochoa-Ricoux



arXiv:2203.07214 and arXiv:2203.07361

체험 삶의 현장 영광 편


자르고


갈고


붙이고


옮기고


KBS
ENGLISH
시각장애인
LOGOUT
정보수정
채널별 편성표 보기
TV
RADIO
뉴스 | 스포츠 | 드라마 | 시사교양 | 연예오락 | 1FM | 2FM | 1R | 2R | 3R
체험
삶의 현장
편성표
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WE ARE
OPEN
24/7


THANK YOU.

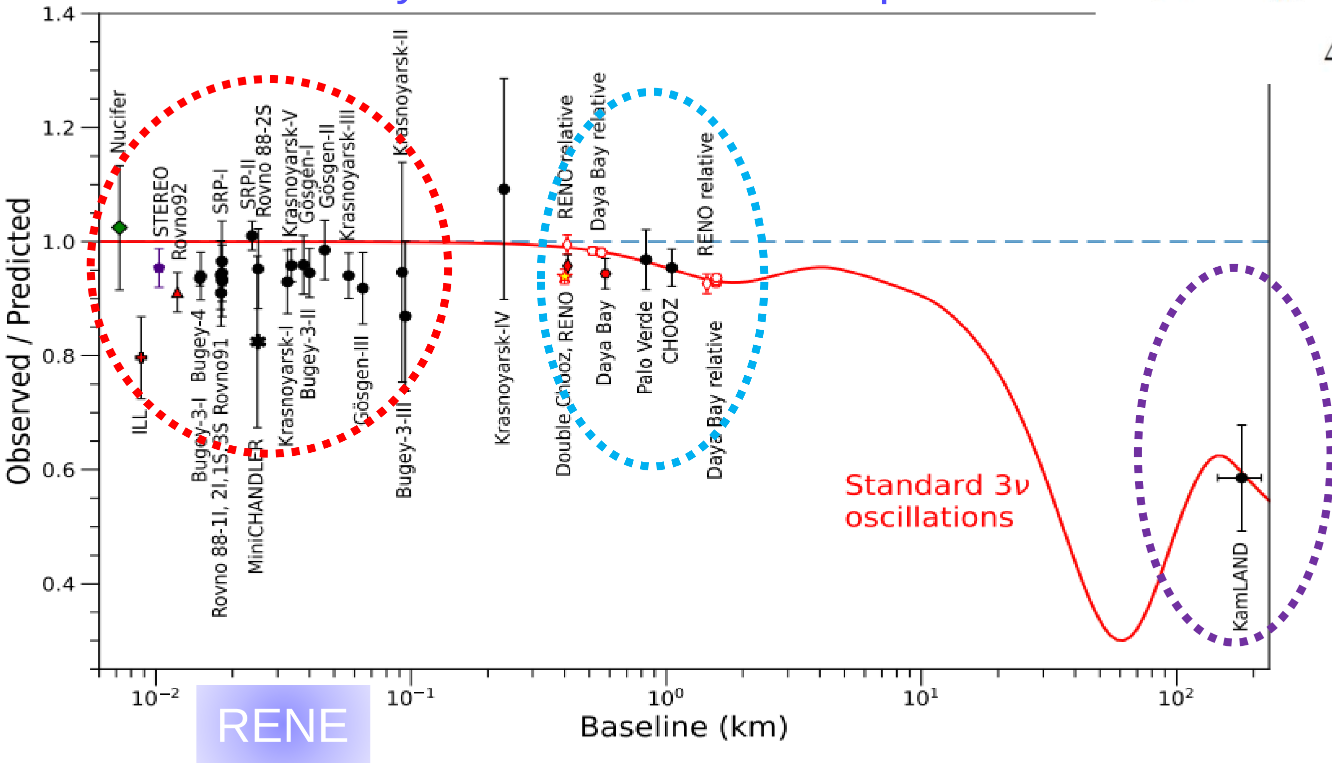
Back Up

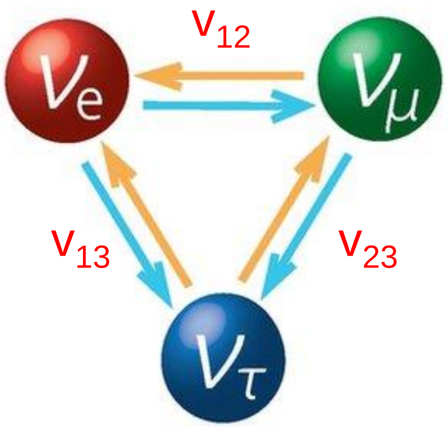
Reactor Neutrino Anomaly

- Neutrino anomaly observations were reported

$$P(\nu_e \rightarrow \nu_\mu) = 2\sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$



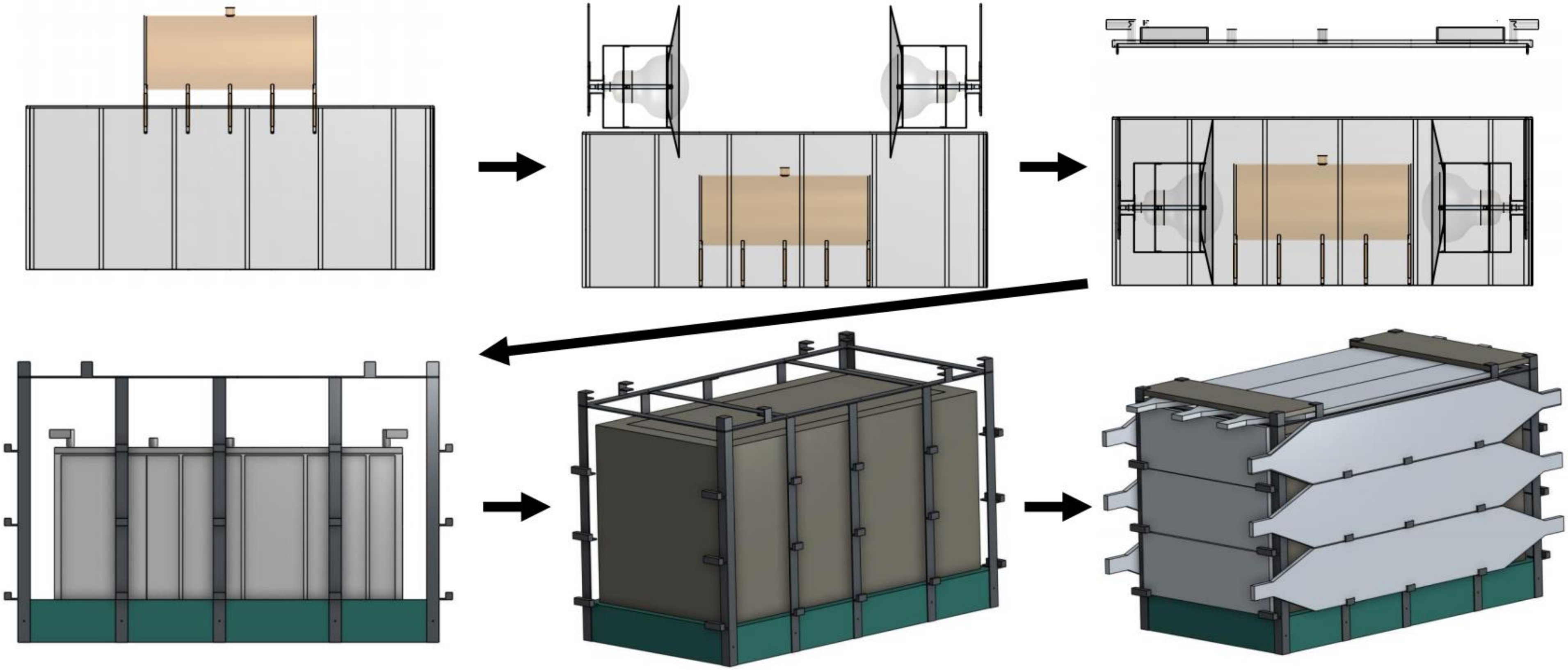


Anti neutrino anomaly in reactors (2011 ~) ν_{13}-oscillation

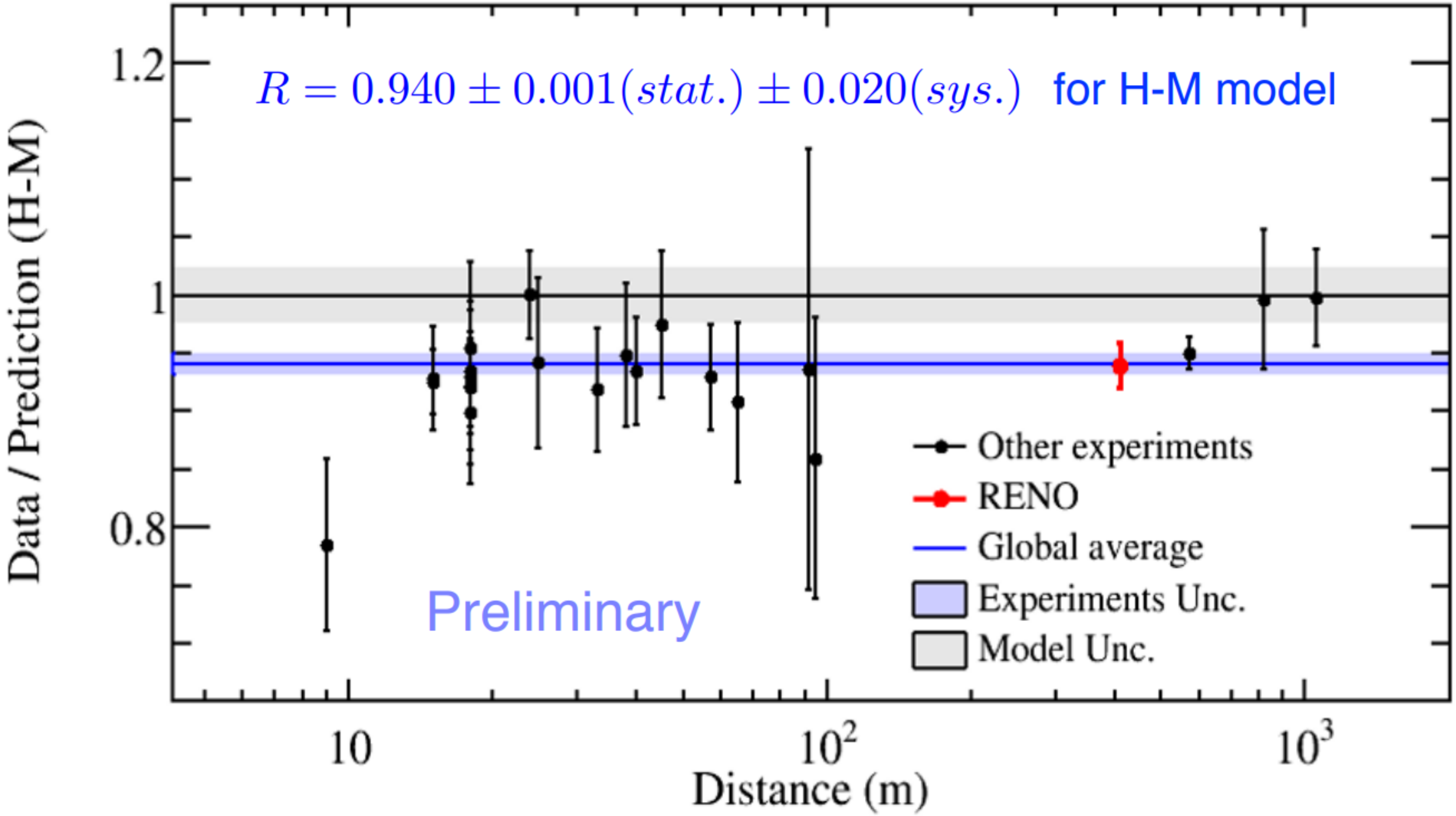
Atmospheric neutrino anomaly (1986 ~ 1998) ν_{23}-oscillation ($\Delta m^2 \approx 2.5\text{x}10^{-3}eV^2$)

Solar neutrino anomaly (1968 ~ 2001) ν_{12}-oscillation ($\Delta m^2 \approx 8\text{x}10^{-5}eV^2$)

Detector Assembly



Reactor Antineutrino Anomaly (RAA)



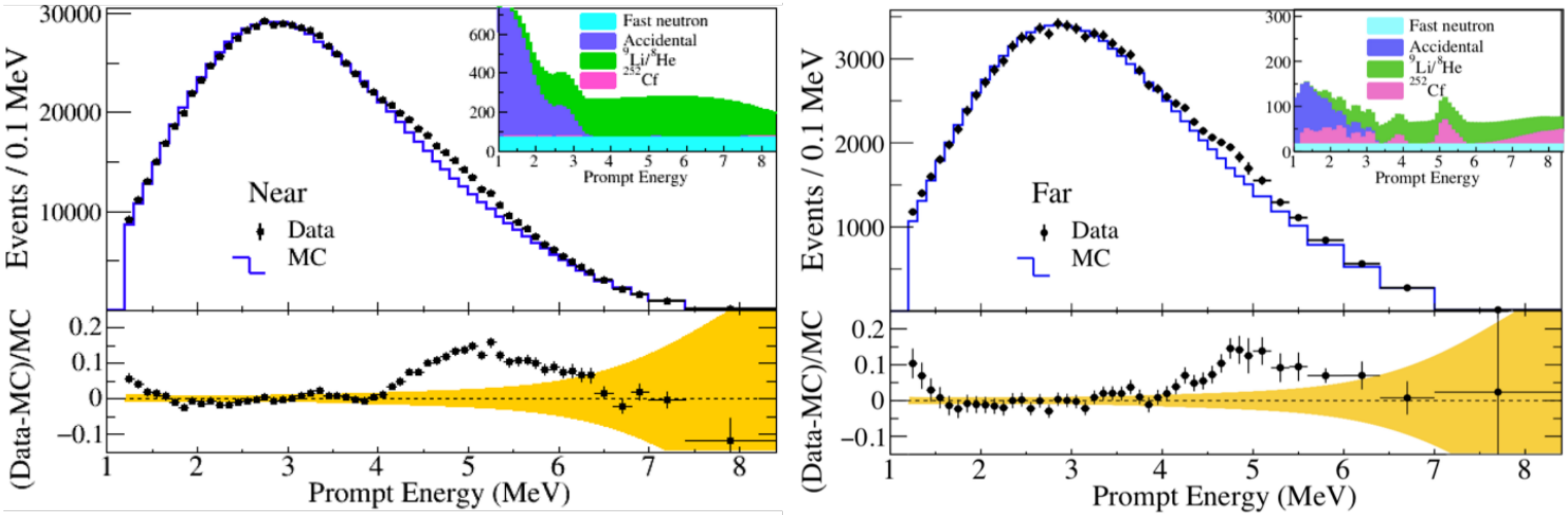
IBD yield: $\bar{y}_f = 5.8303 \pm 0.1249(\times 10^{-43}\,\mathrm{cm}^2/\mathrm{fission})$

Data / Prediction: $R = 0.983 \pm 0.001(stat.) \pm 0.021(sys.)$ for ILL+Vogel model

Average fission fraction: $\overline{F}_{235} : \overline{F}_{238} : \overline{F}_{239} : \overline{F}_{241} = 0.571 : 0.073 : 0.300 : 0.056$

Measured Spectra of IBD Prompt Signal

RENO 2900 days (2200 + 700 days) : Aug. 2011 — Feb. 2020
- Clear excess at 5MeV compared to the Huber-Mueller prediction

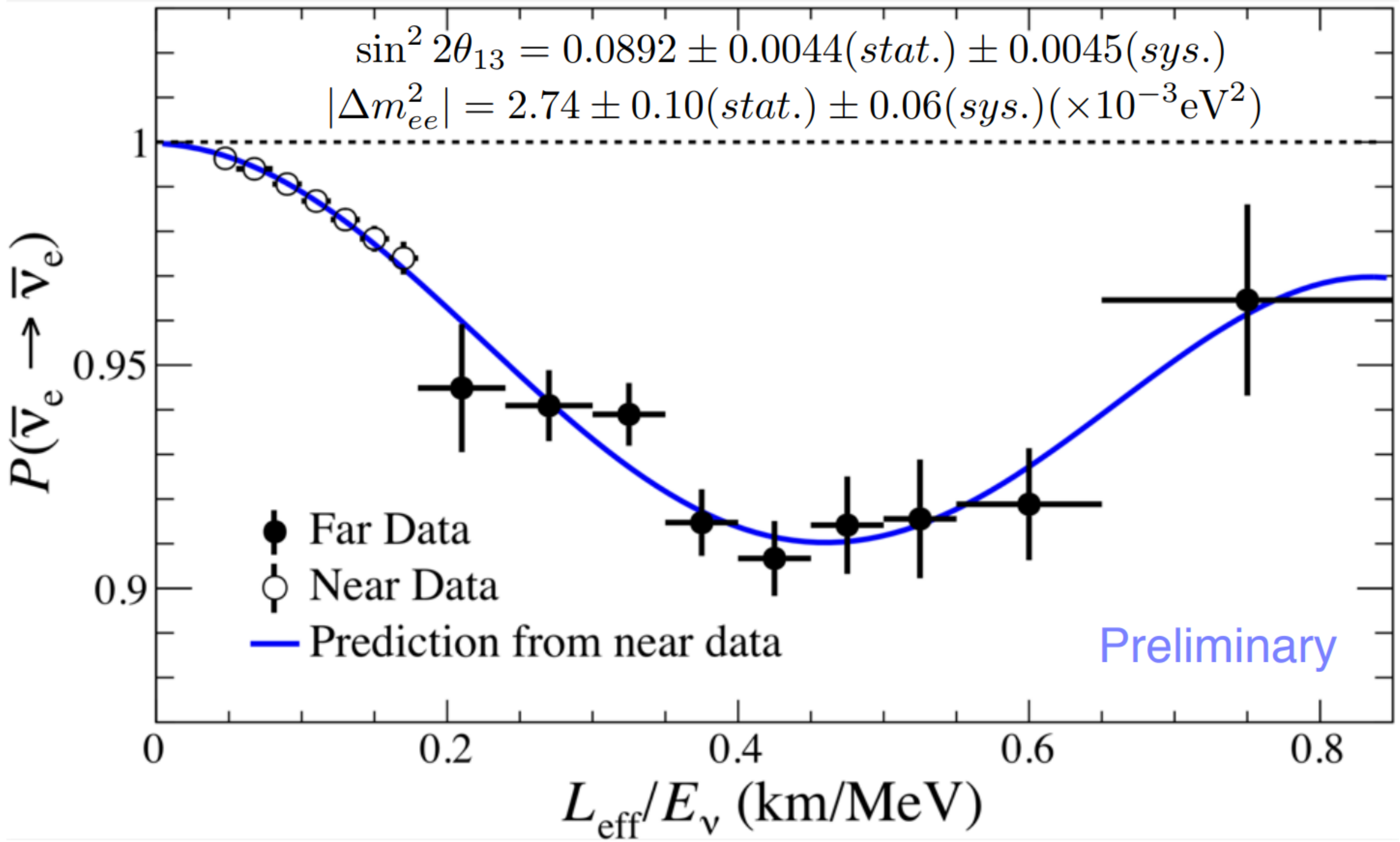


Near detector live time: 2509 days
#IBD candidates: 989,736
Background rate: 2.26 ± 0.05 %
5 MeV excess rate: 2.50 ± 0.06 %

Far detector live time: 2908 days
IBD candidates: 120,383
Background rate: 4.77 ± 0.19 %
5 MeV excess rate: 2.26 ± 0.18 %

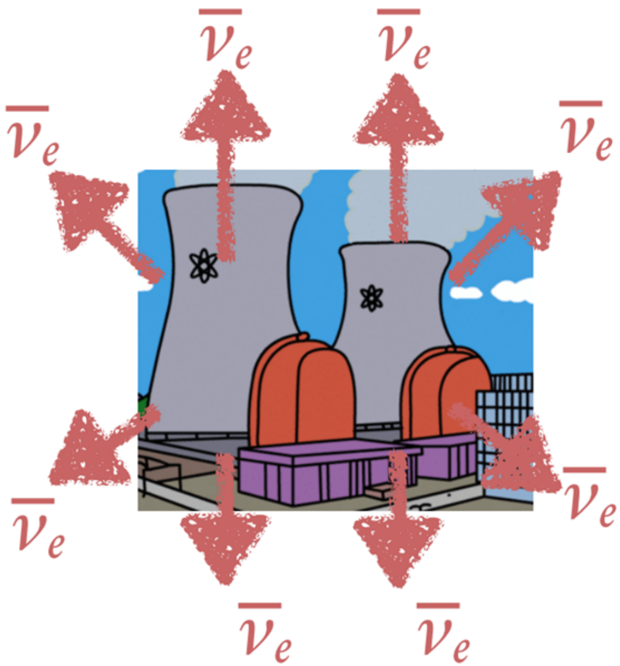
Neutrino Oscillation: L/E Dependence

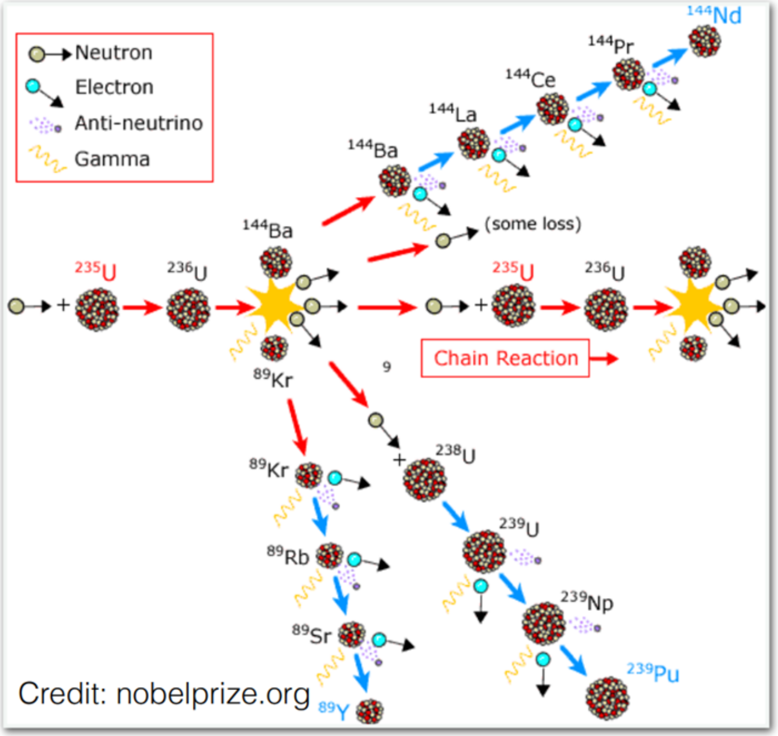
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \Delta m^2_{ee} \frac{L}{E_\nu} \right)$$

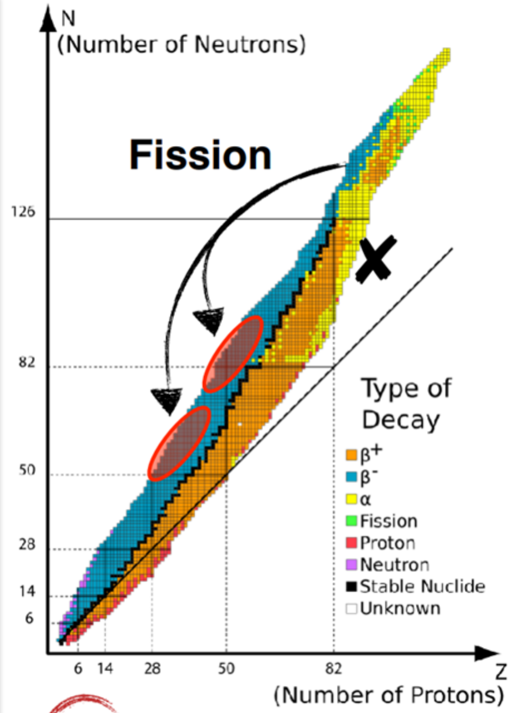


Reactor Antineutrinos

- Nuclear reactors are a flavor-pure, widely available, cost-effective, **extremely intense** and well-understood source of electron antineutrinos:







$\sim 10^{20}\ \bar{\nu}_e/\mathrm{GW_{th}}$

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

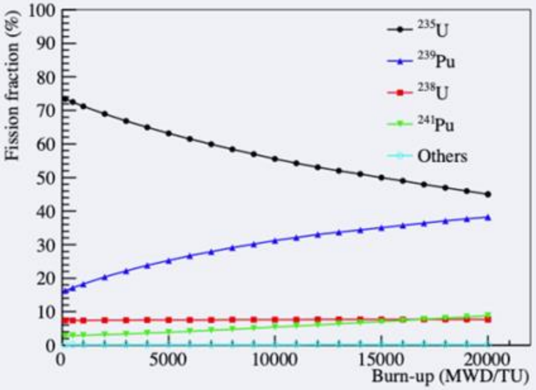
– A 1 $\mathrm{GW_{th}}$ core produces in one minute more neutrinos than the NuMI and BNB beams produced in a typical year

Types of Nuclear Reactors

- Nuclear reactors fall into two main categories:

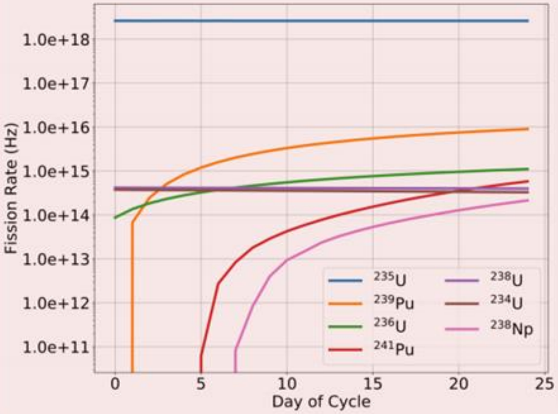
Low-Enriched Uranium (**LEU**)-fueled power reactors

- Commercial reactors
- Several GW of thermal power
- $\bar{\nu}_e$'s originate from fission products of 4 isotopes: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U
- Fuel evolves as ^{235}U is consumed and $^{239,241}Pu$ is produced



Highly-Enriched Uranium (**HEU**)-fueled reactors

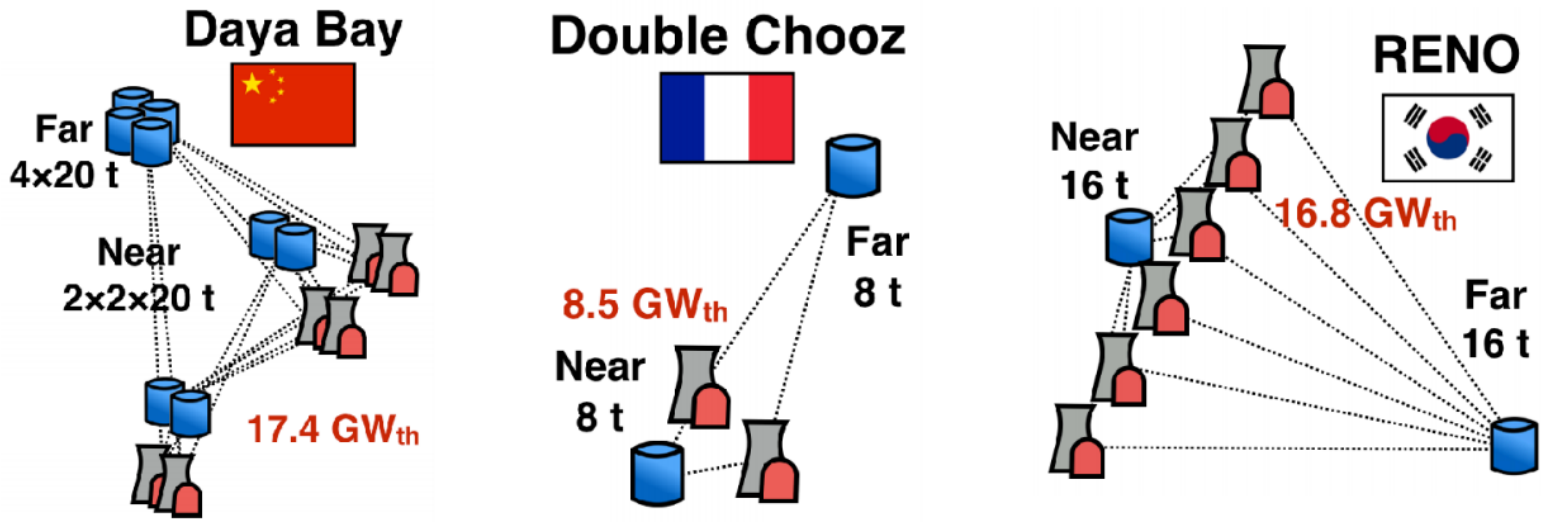
- Research reactors
- 50-100 MW of thermal power
- Almost all fissions are ^{235}U



θ_{13} Experiments

- The current generation of reactor experiments fall roughly into two categories:

1) Experiments designed to measure the θ_{13} mixing angle:



Data taking: 2011 - 2020 | Data taking: 2011 - 2017 | Data taking: 2011 - present

Notes: all reactors are LEU; flags indicate location of experiment, not composition of collaboration

- < 2 km baseline means only need "small" detectors (tens or hundreds of tons)
- Looking for small (<10%) disappearance, so **key is keeping systematics under control**
- Near/far **relative** comparison allows to essentially cancel uncertainties in flux prediction and correlated detection efficiencies

SBL Experiments

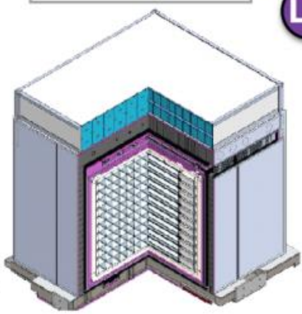
- Wide range of detection media and approaches:

Segmentation:
S Segmented
U Unsegmented

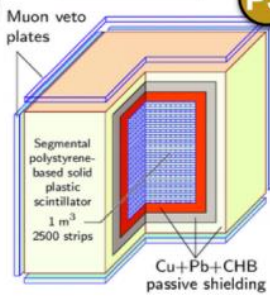
Doping:
Gd Gadolinium
Li Lithium

Scintillator:
LS Liquid
PS Plastic

PROSPECT S Li LS

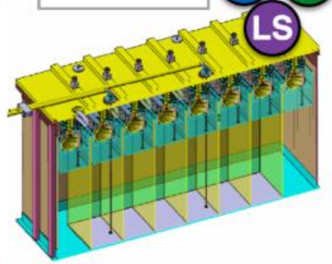


DANSS S Gd PS

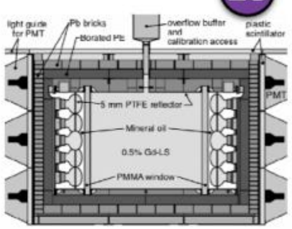


SoLid S Li PS

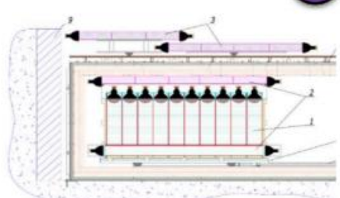
STEREO S Gd LS



NEOS U Gd LS

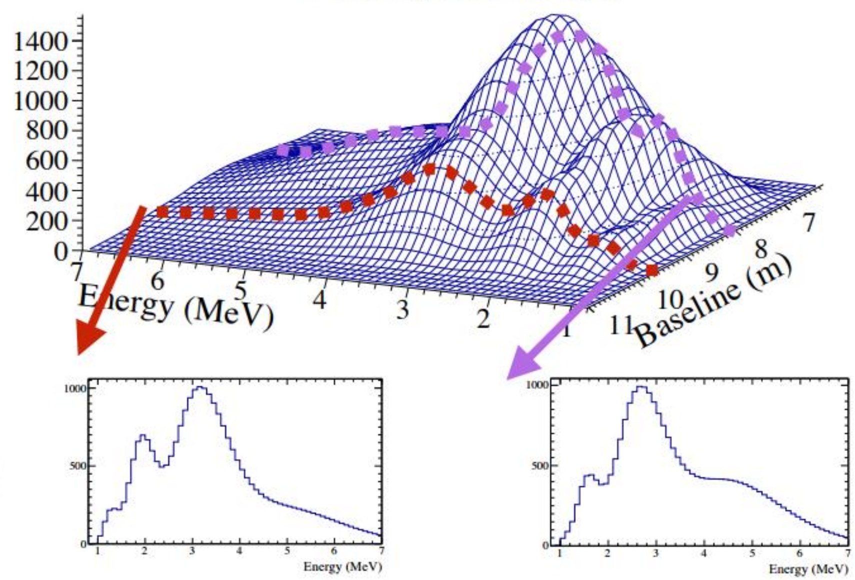


NEUTRINO-4 S Gd LS



Segmentation/movability allows to make a **relative** measurement within/with the same detector

L vs E, oscillated



(from B. Littlejohn's seminar at FNAL)

Makes measurement largely independent of reactor prediction models!

Non-Standard Flavor Mixing Landscape

- Almost all SBL experiments have released results by now
- In general, no significant evidence so far for non-standard flavor mixing

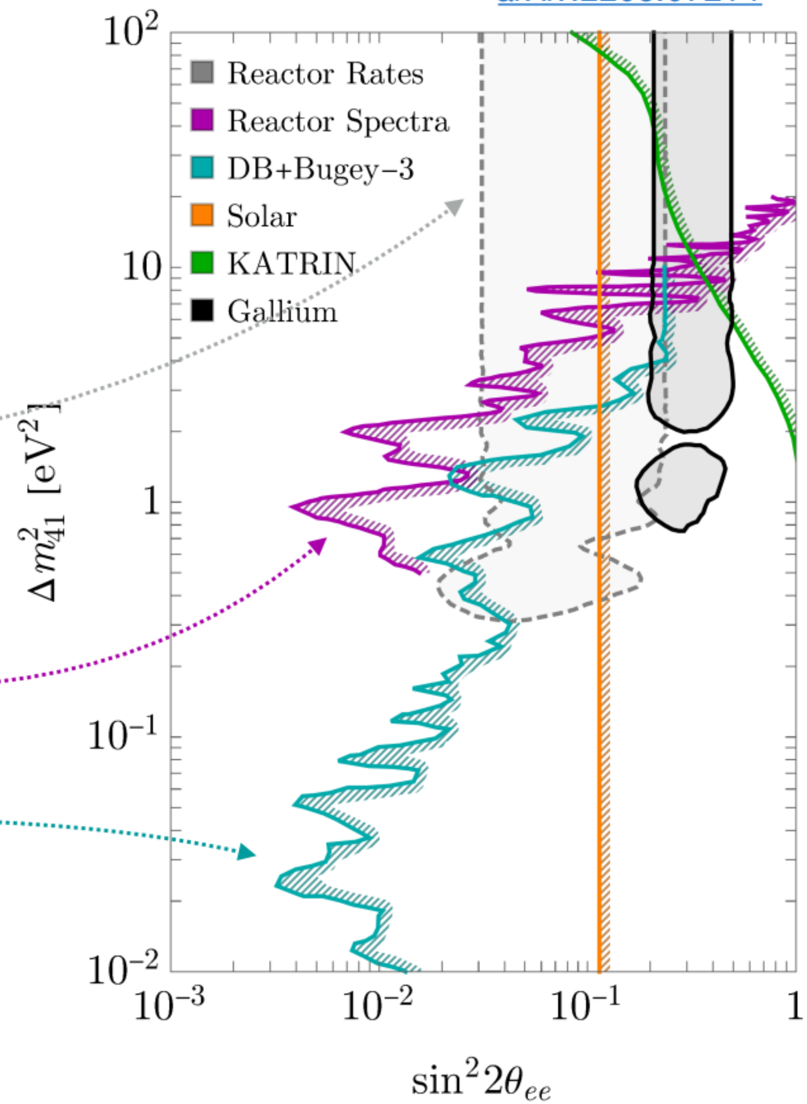
Parameter space motivated by the reactor antineutrino anomaly (see next section)

Exclusion curve from global fit of SBL spectral measurements (DANSS, NEOS, Neutrino-4, PROSPECT, STEREO)

Exclusion limit from combination of Daya Bay and Bugey-3

(Daya Bay's longer baseline of ~2 km makes it sensitive to lower values of Δm^2_{41}; Bugey-3 operated at several <100 m baselines)

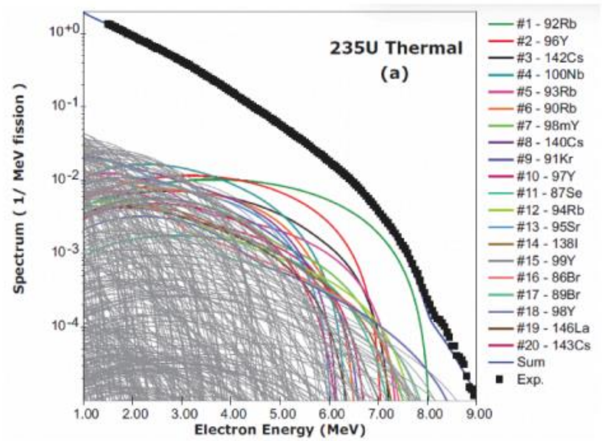
arXiv:2203.07214

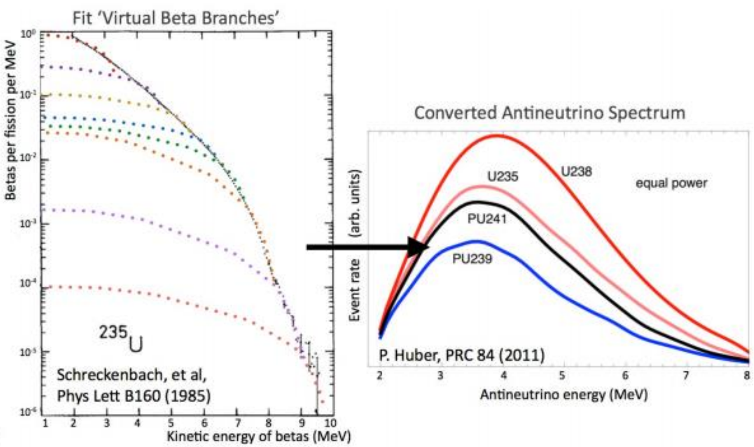


Characterizing $\bar{\nu}_e$ emission

- Existing data can be also be used to characterize the emission of antineutrinos from nuclear reactors and to compare with prediction models:
  - Important for fundamental physics, non-proliferation applications, and as a stringent test of nuclear data inputs

- Two approaches to predict the reactor $\bar{\nu}_e$ rate and spectral shape:
  - Ab-initio method:
    - Bottom-up calculation using fission yields, Q values and decay branching ratios from nuclear data bases
  - Conversion method:
    - Converting measured beta spectra from thermal-neutron induced fission (^{235}U, ^{239}Pu, ^{241}Pu) at ILL in the 1980s to $\bar{\nu}_e$ spectra
    - Smaller estimated uncertainties (few %)
    - Latest implementation is the so-called Huber+Mueller (HM) model

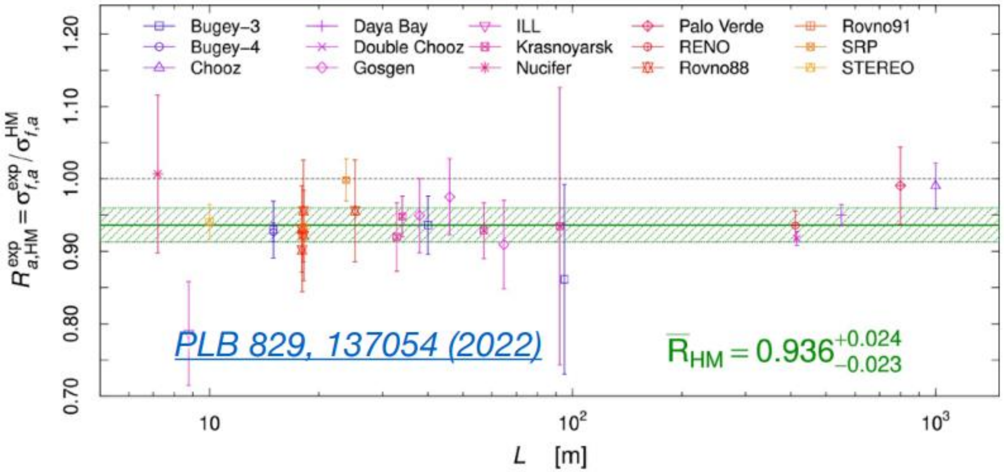




Disagreements with Predictions

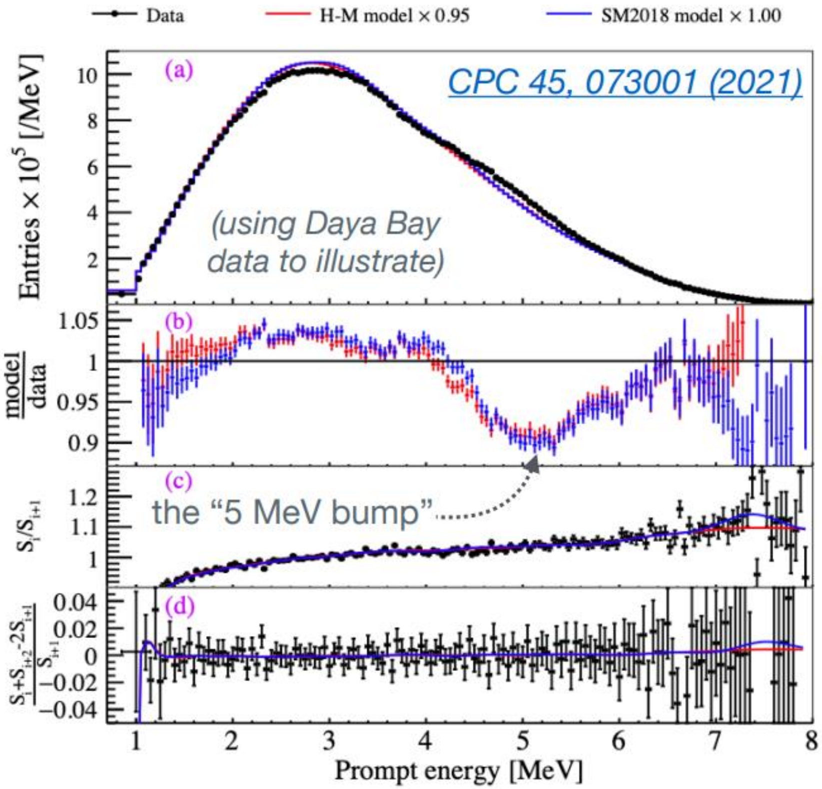
- Some disagreements with prediction models came to light during the last decade:

Rate



- ~6% deficit in total flux with respect to the HM model at short baselines is known as the "**reactor antineutrino anomaly**" (RAA)
- Primary motivation for SBL sterile neutrino searches
- Not seen with recent summation models

Shape



- Main disagreement is often referred to as "the 5 MeV bump"
- Seen with both summation and conversion models

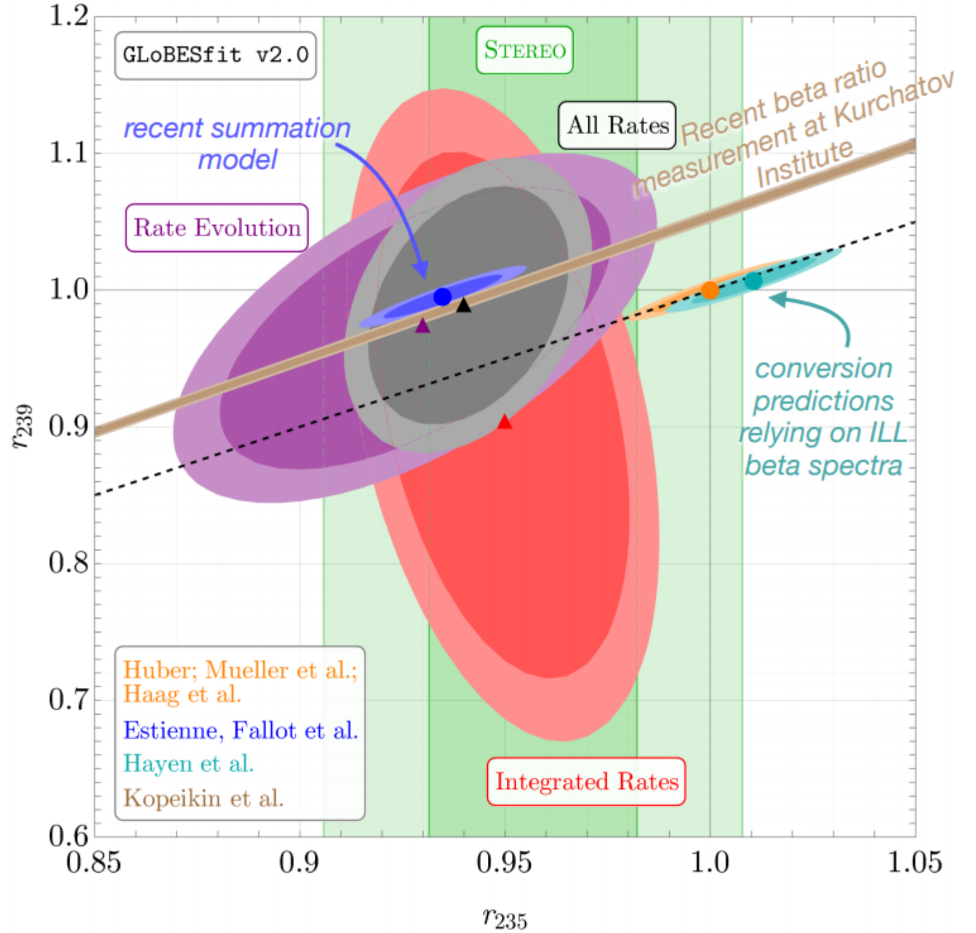
Current Status

- Good progress in understanding the reactor antineutrino anomaly:
  - New data* suggests that ^{235}U beta spectrum from ILL underlying all conversion predictions is largely responsible for reactor antineutrino anomaly
  - Shape anomaly remains unexplained and is caused by a yet unknown issue affecting both conversion and summation predictions
  - All in all, sterile neutrino hypothesis **not ruled out, but weakened**

See arXiv:2203.07214 for a detailed description

**new data = fuel evolution in LEU experiments, measurements in HEU experiments, measurement of $^{235}U/^{239}Pu$ beta spectra ratio at Kurchatov Institute*

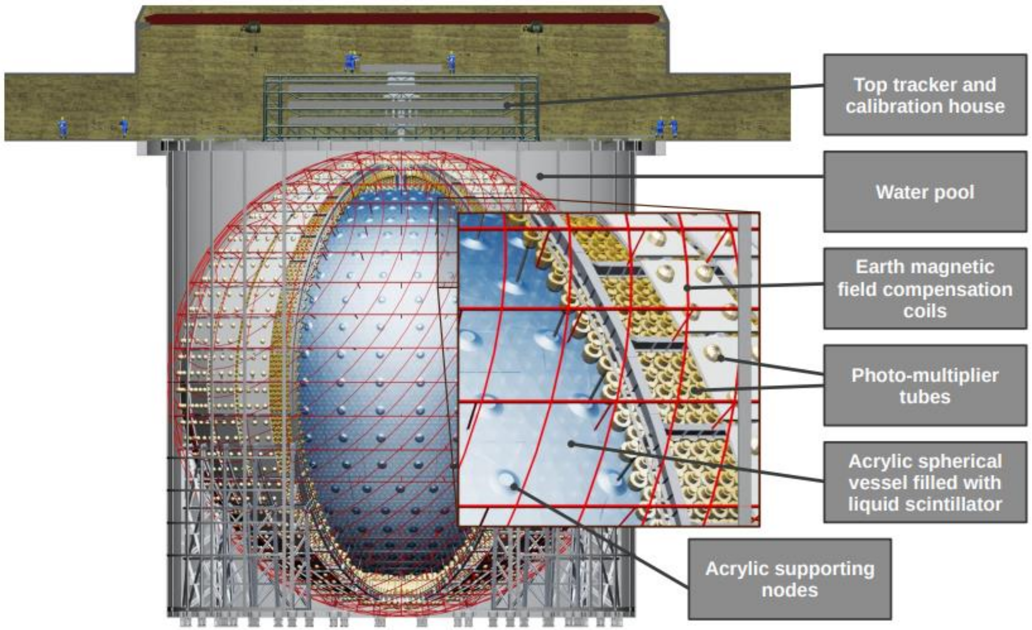
r_X = ratio of measured over predicted rate for isotope X with respect to the HM prediction

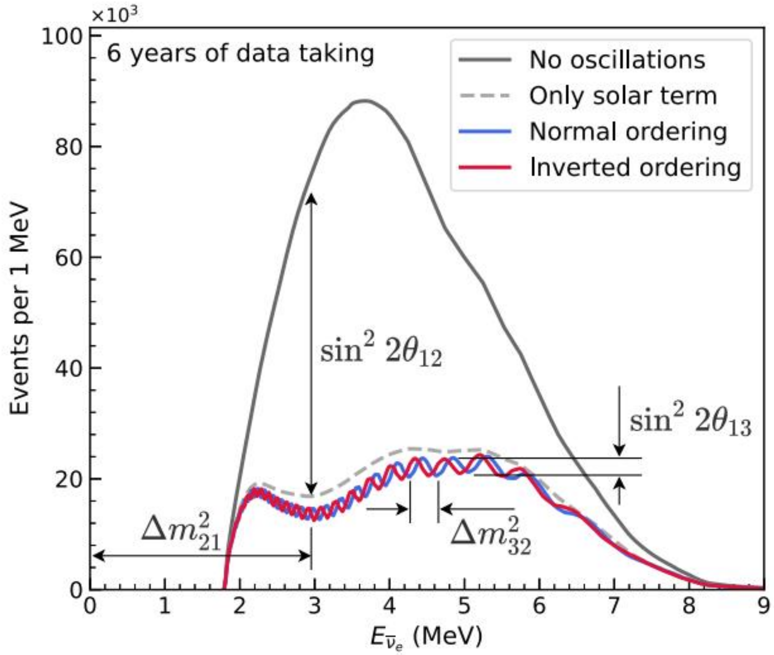


JUNO

See Yang Han's plenary talk on Thursday!

- JUNO is a large, next-generation reactor neutrino experiment under construction in China





  - 53 km from 8 reactors
  - Energy resolution of 3% at 1 MeV

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	Δm^2_{32}
Current Precision*	4.2%	2.4%	3.2%	1.5%
JUNO 6 years	0.5%	0.3%	12.1%	0.2%

* from PDG 2020

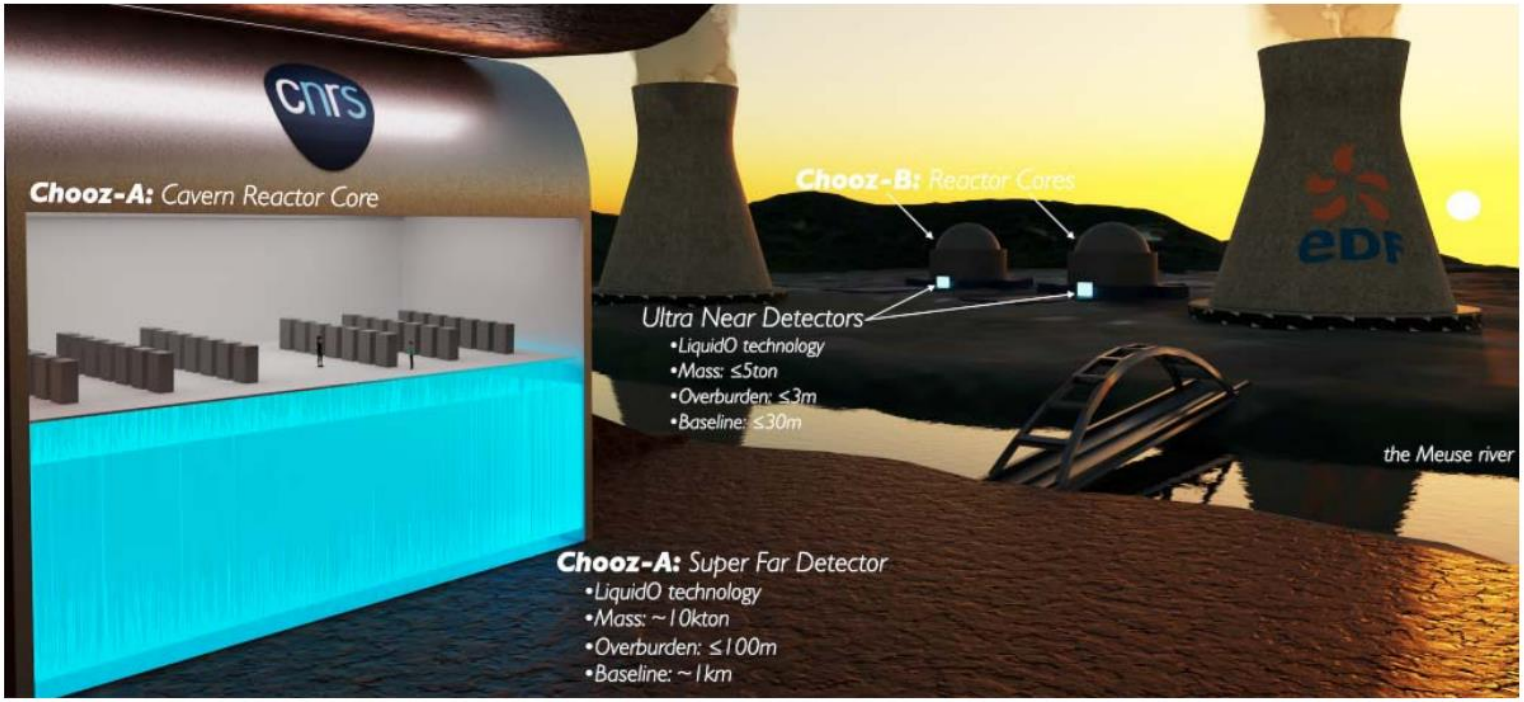
CPC 46, 123001 (2022)

- Rich physics program:
  - Neutrino mass ordering to 3σ in ~6 years
  - Sub-percent precision in oscillation parameters
  - Supernova, geo, atmospheric, solar neutrinos + searches for new physics

SuperChooz

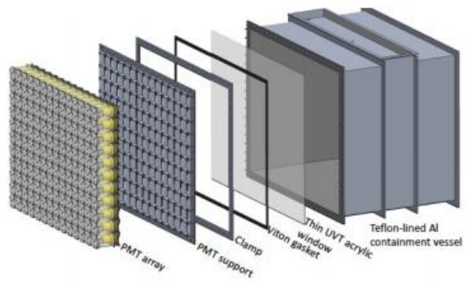
- Proposal for next-generation θ_{13} reactor experiment
  - Soon to become the most poorly known mixing angle
- Far detector in existing cavern of old Chooz-A reactor (under decommissioning)
- Based on the new LiquidO detection technology
  - Opaque scintillator volume traversed by dense array of fibers
- In exploratory phase, demonstrator approved and under development

See Comms. Phys. 4, 273 (2021) for more information on LiquidO, and this seminar for more details on the project

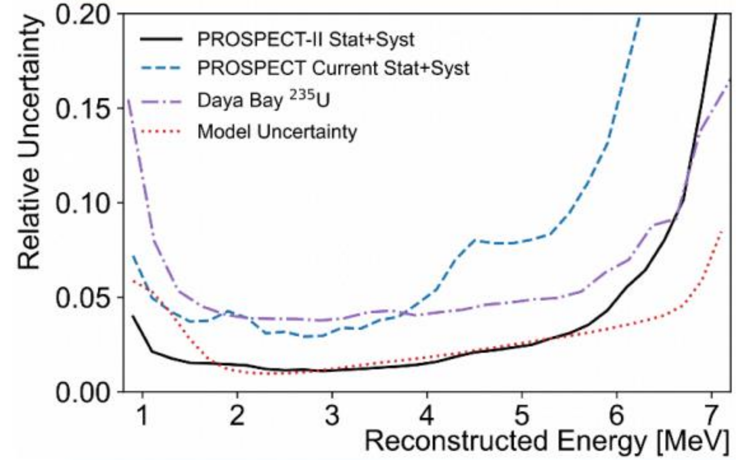


Future SBL Experiments?

- There are also at least four new SBL experiments/upgrades in preparation:
  - DANSS and Neutrino-4 are being upgraded
  - There is a proposal for a PROSPECT-II detector:
    - Address technical challenges of PROSPECT-I
    - Able to relocate between HEU and LEU reactors

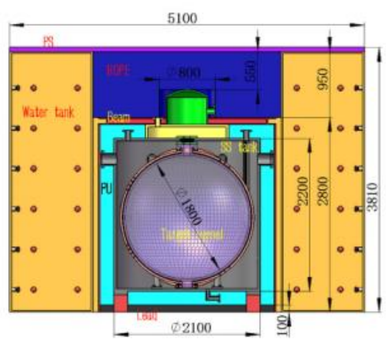


PROSPECT-II ^{235}U spectrum uncertainty

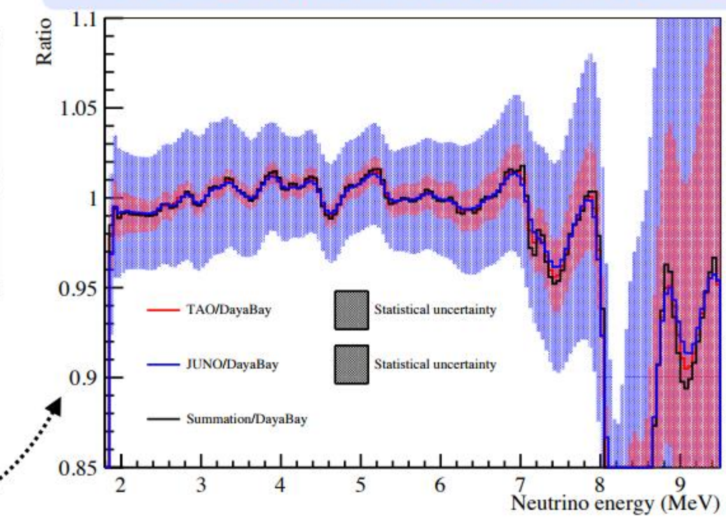


arXiv:2107.03934

  - JUNO will deploy a satellite detector called "TAO" at 30 m from one of the 4.6 GWth Taishan reactors
    - <2% energy resolution @ 1 MeV



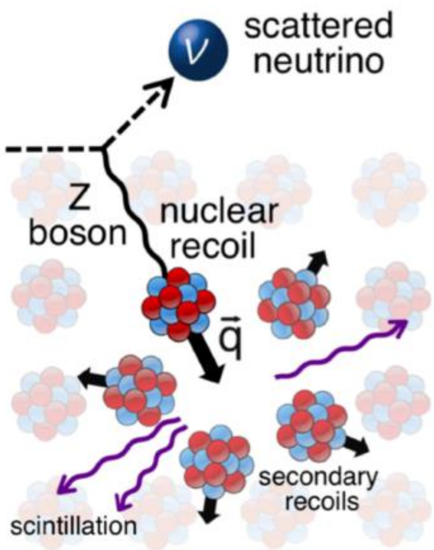
TAO's sensitivity to fine structure in spectrum



arXiv:2005.08745

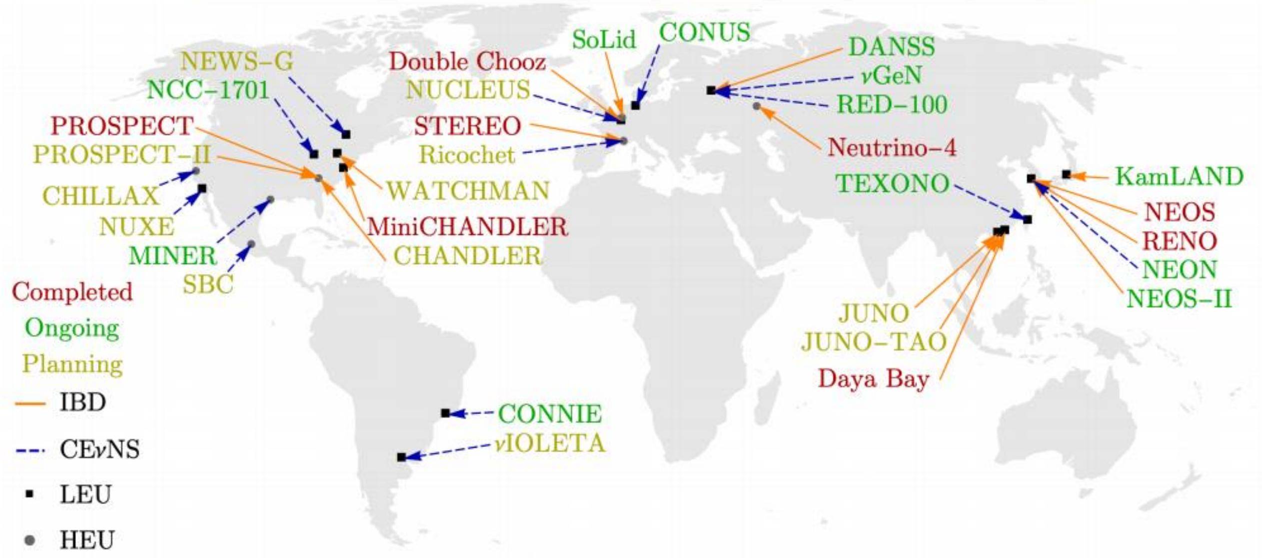
  - All these experiments will search for sterile ν's
    - TAO and PROSPECT-II will also improve our knowledge of the isotopic yields and spectra
    - TAO will see the fine structure for the first time

CEvNS at Reactors



- An exciting new program using CEvNS at reactors is in its first stages
  - Pro: very high cross-section (can be orders of magnitude higher than IBD)
  - Con: very difficult to detect (only signal is low-energy recoiling nucleus)
- Search for deviations from Standard Model, hidden sector particles & interactions
- The race is on!
  - Vibrant effort in many reactors throughout the world with different technologies
  - First definitive detection of CEvNS from reactors expected soon

Global Landscape of Reactor Neutrino Experiments



arXiv:2203.07214 and arXiv:2203.07361

3+1 Neutrino Oscillation Framework

- The PMNS matrix is extended to 4x4 unitary matrix, and is parameterized as following

$$U_{PMNS} = R_{34}(\theta_{34}, \delta_{34})\ R_{24}(\theta_{24}, \delta_{24})\ R_{14}(\theta_{14}, 0)\ R_{23}(\theta_{23}, 0)\ R_{13}(\theta_{13}, \delta_{13})\ R_{12}(\theta_{12}, 0)$$

- The effective mixing angles $\theta_{\alpha\beta}$ for short-baseline oscillations are defined below

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} + (-1)^{\delta_{\alpha\beta}} \cdot \sin^2 2\theta_{\alpha\beta} \cdot \sin^2\left(1.267 \frac{\Delta m^2_{41}(\mathrm{eV}^2) L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$

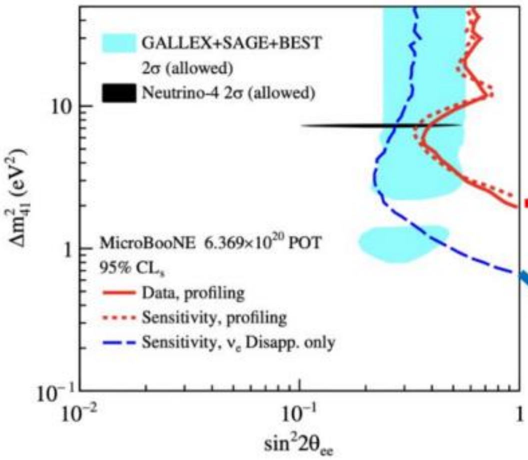
ν_e disappearance ($\nu_e \to \nu_e$): $\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$

ν_μ disappearance ($\nu_\mu \to \nu_\mu$): $\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}(1 - \cos^2\theta_{14}\sin^2\theta_{24})$

ν_e appearance ($\nu_\mu \to \nu_e$): $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$

- In MicroBooNE analysis, the above three oscillation effects are applied to all ν_e and ν_μ events; the ν_μ appearance ($\nu_e \to \nu_\mu$) is ignored because of tiny $\frac{\nu_e \text{ flux rate}}{\nu_\mu \text{ flux rate}} \sim 0.005$

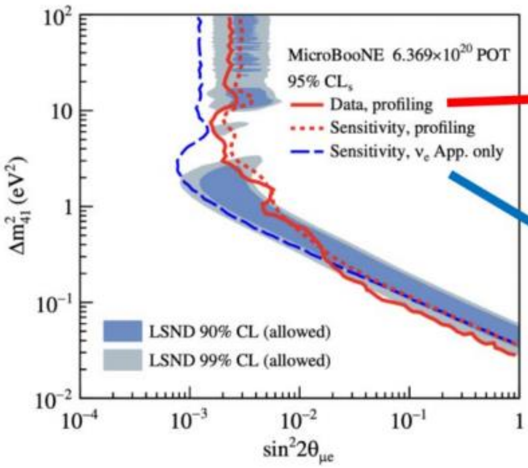
Fermilab



Sterile Neutrinos: 3+1 Framework

2D profiled result, full 3+1 analysis considering ν_μ to $\nu_{e,}$ ν_e to ν_e and ν_μ to ν_μ at each point in the parameter space.

ν_e disappearance-only (only ν_e to ν_e), more stringent limit corresponding to a fixed $\sin^2\theta_{24} = 0$.



2D profiled result, full 3+1 analysis considering ν_μ to $\nu_{e,}$ ν_e to ν_e and ν_μ to ν_μ at each point in the parameter space.

ν_e appearance-only (only ν_μ to ν_e), more stringent limit However, it is physically not allowed in the 3+1 framework. (non-zero ν_e appearance requires both ν_e and ν_μ disappearance)

Fermilab

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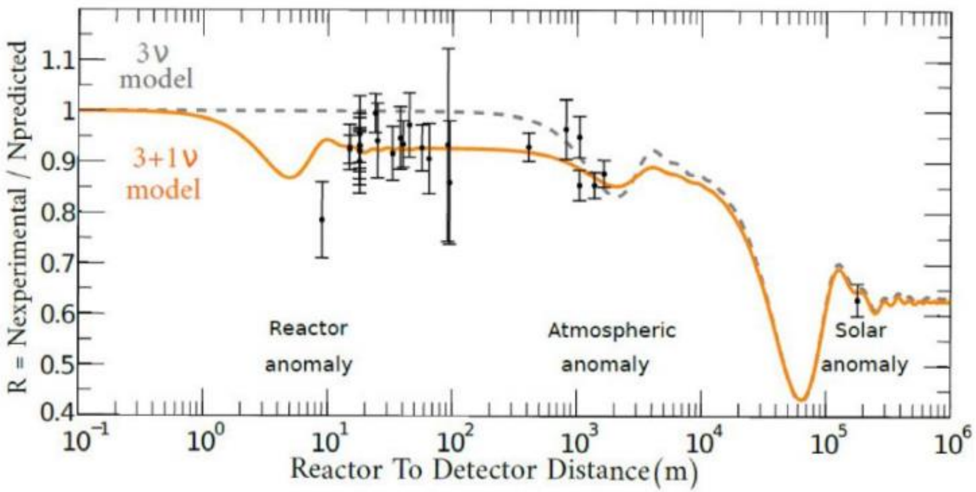
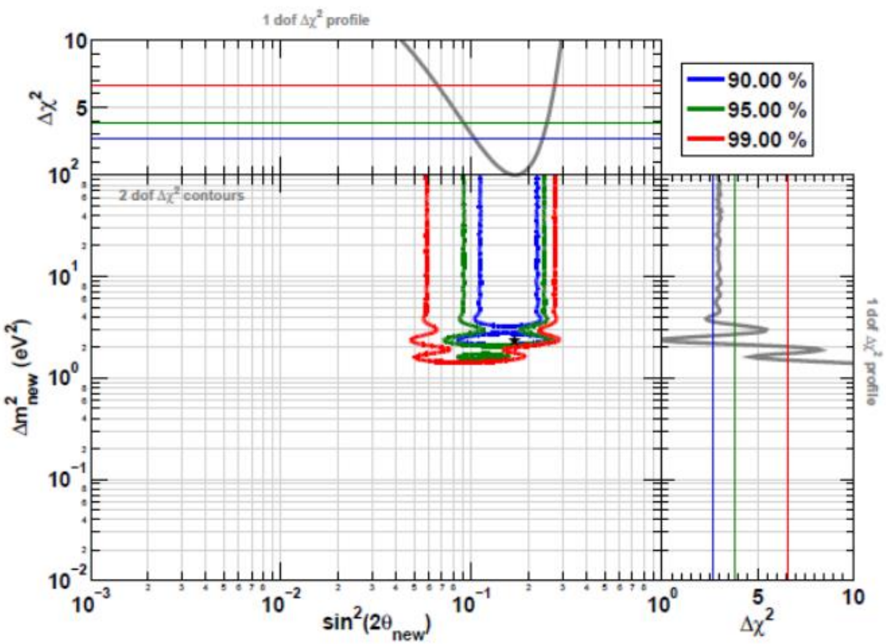
The Reactor Antineutrino Anomaly (RAA)

2011: **Re-evaluation of the predicted flux of antineutrinos coming from a reactor** **(PRC 83:054615)**

→ ~6% deficit measured compared to the prediction: **Reactor Antineutrino Anomaly** (RAA) (PRD 83:073006)



⋆ RAA best fit point:
Δm^2_{new} = 2.3 eV²; $\sin^2(2\theta_{new})$ =0.17

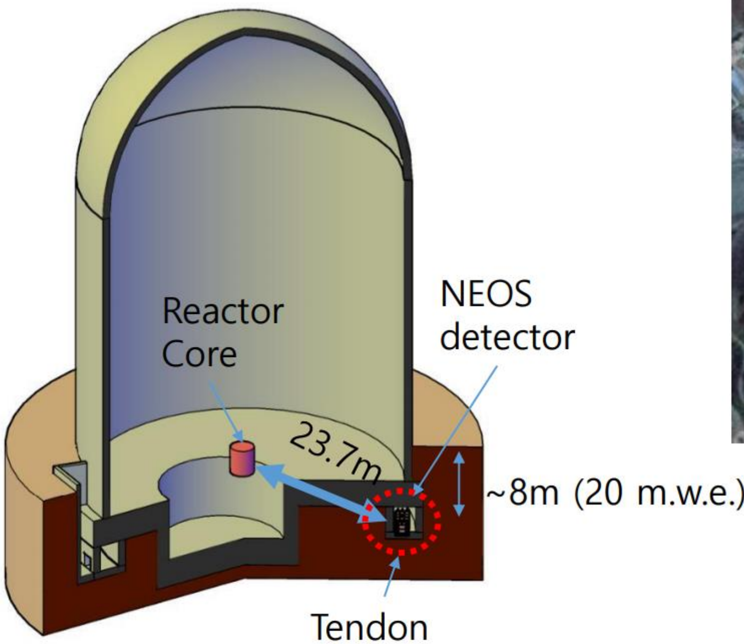


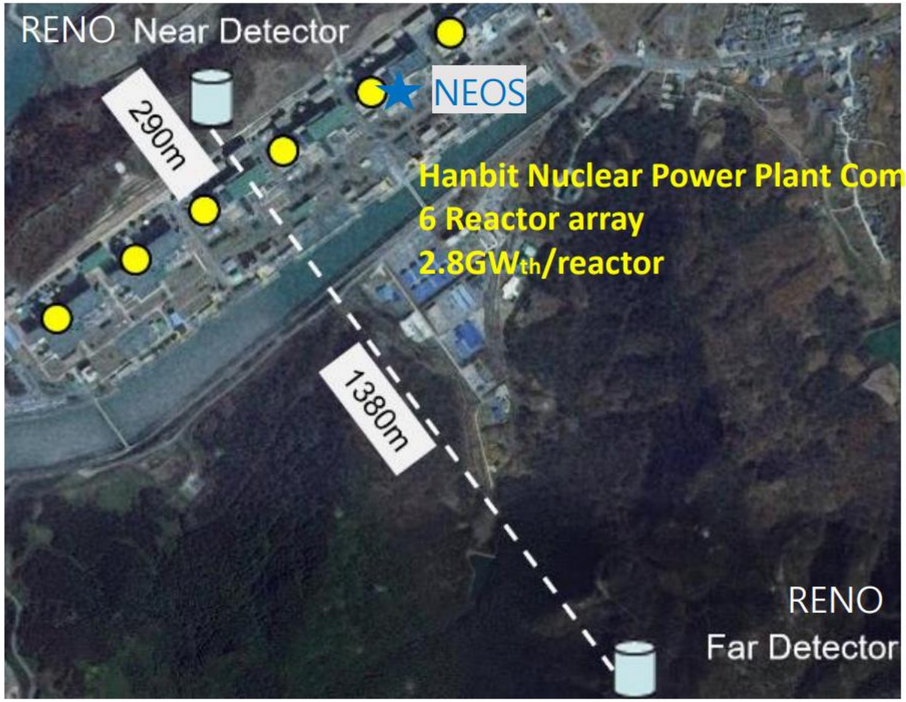
Unpredicted disappearance at short distance -> New sterile neutrino?

arXiv:1204.5379

NEOS

(Neutrino Experiment for Oscillation at Short baseline)

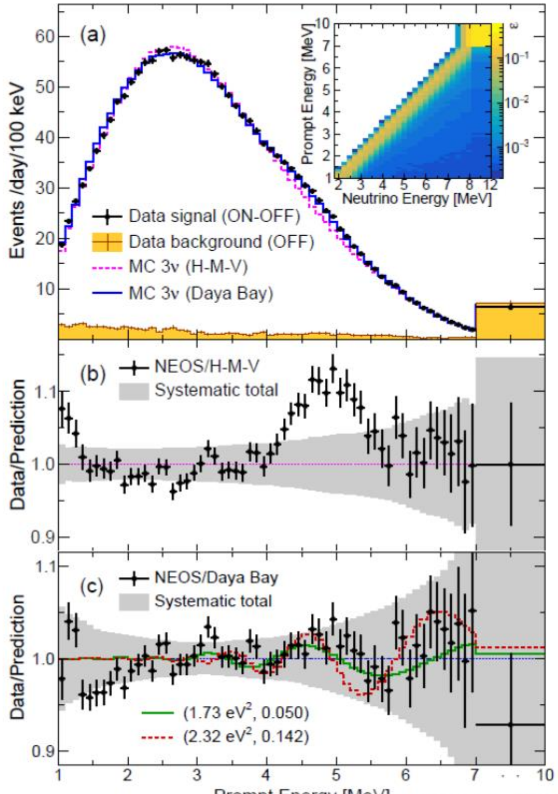


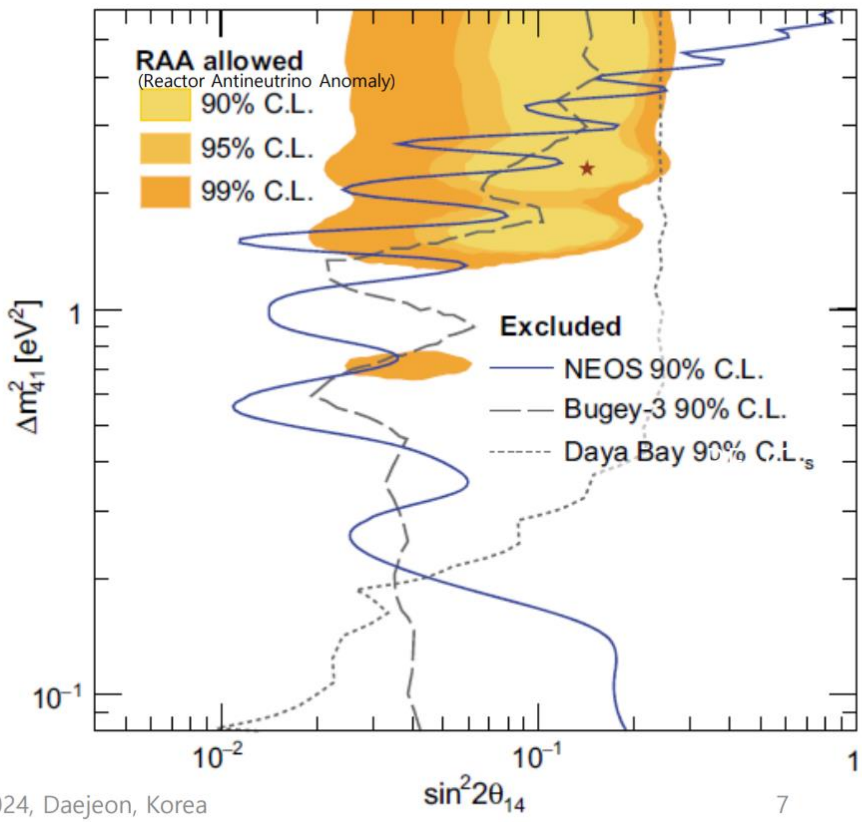


- Primary goal: search for eV scale sterile neutrino in the 4 ν framework.
- NEOS-1: Aug. 2015 - May 2016
- NEOS-2: Sep. 2018 ~ Oct. 2020

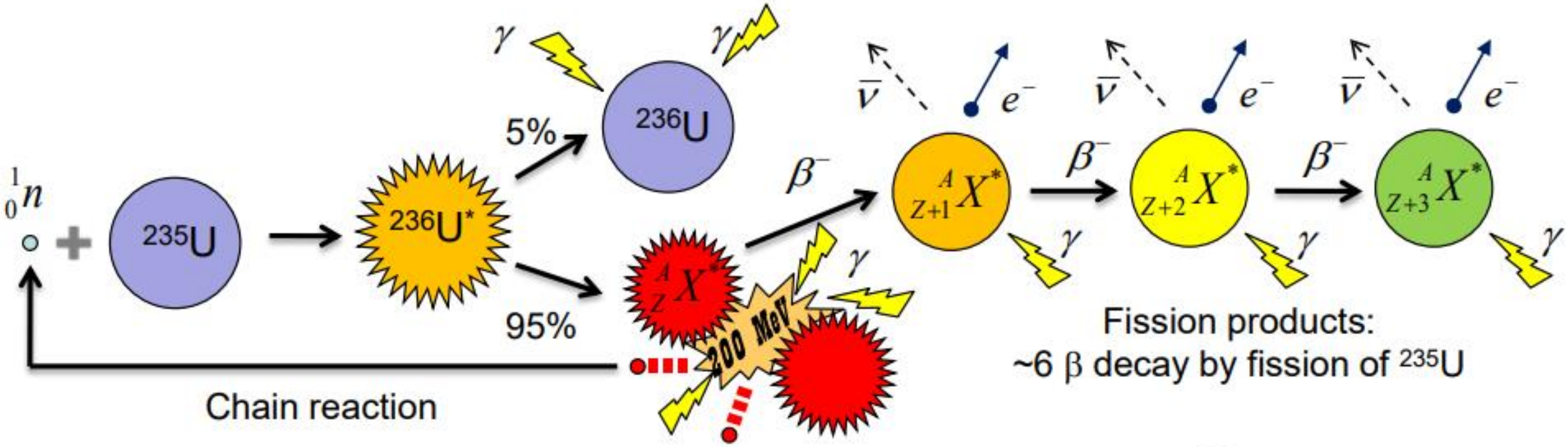
NEOS Result for sterile neutrino

PRL 118 (2017) 121802

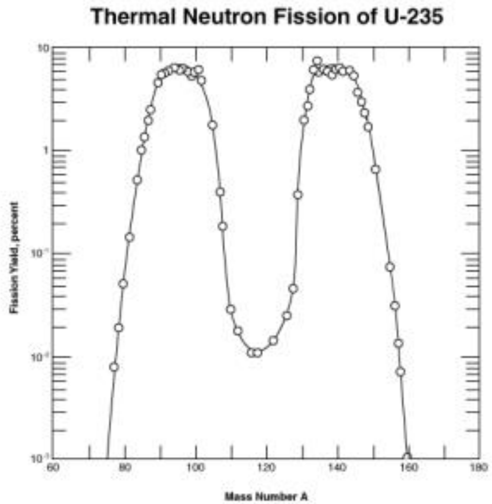


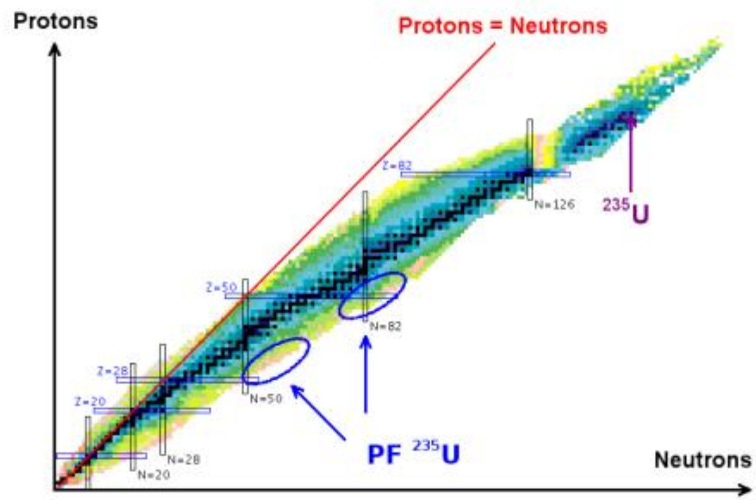


Reactor Neutrinos



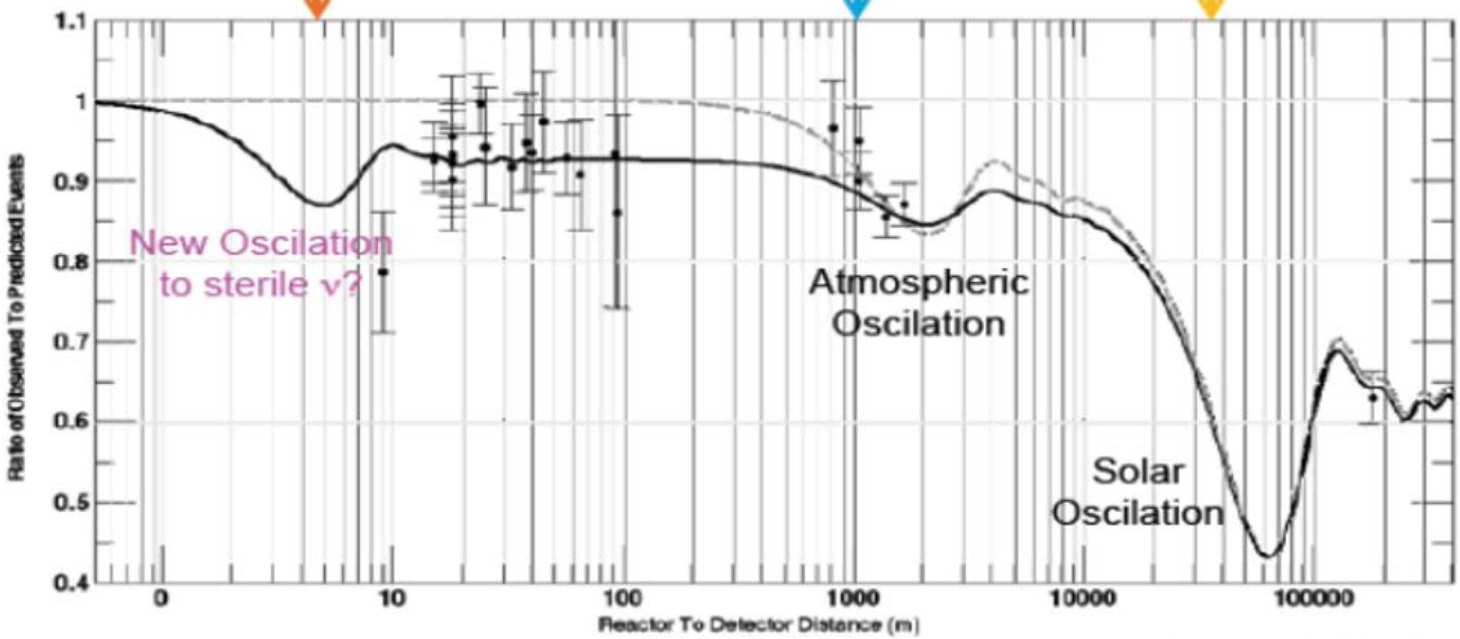
$\Rightarrow$ Proportionnality with power: $1\ \mathrm{GW_{th}} \Leftrightarrow 2.10^{20}\bar{\nu}/\mathrm{s}$





Existence of 4th neutrino ?

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\Theta_{14}\sin^2(1.27\Delta m^2_{41}\frac{L}{E}) - c^4_{14}\sin^2 2\Theta_{13}\sin^2(1.27\Delta m^2_{31}\frac{L}{E}) - c^4_{14}c^4_{13}\sin^2 2\Theta_{12}\sin^2(1.27\Delta m^2_{21}\frac{L}{E})$$



G. Mention et al. Phys Rev D 83 073006 (2011)

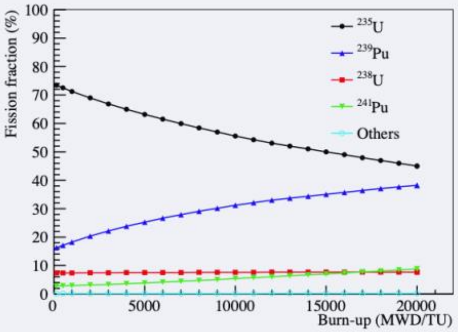
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\Theta_{14}\sin^2(1.27\Delta m^2_{41}\frac{L}{E}) - c^4_{14}\sin^2 2\Theta_{13}\sin^2(1.27\Delta m^2_{31}\frac{L}{E}) - c^4_{14}c^4_{13}\sin^2 2\Theta_{12}\sin^2(1.27\Delta m^2_{21}\frac{L}{E})$$

Types of Nuclear Reactors

- Nuclear reactors fall into two main categories:

Low-Enriched Uranium (LEU)-fueled power reactors

- Commercial reactors
- Several GW of thermal power
- $\bar{\nu}_e$'s originate from fission products of 4 isotopes: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U
- Fuel evolves as ^{235}U is consumed and $^{239,241}Pu$ is produced



Highly-Enriched Uranium (HEU)-fueled reactors

- Research reactors
- 50-100 MW of thermal power
- Almost all fissions are ^{235}U