Sterile neutrino search with research reactor and its impact on neutrino-less double beta decay

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NEWS Colloquium 2023/Apr/14

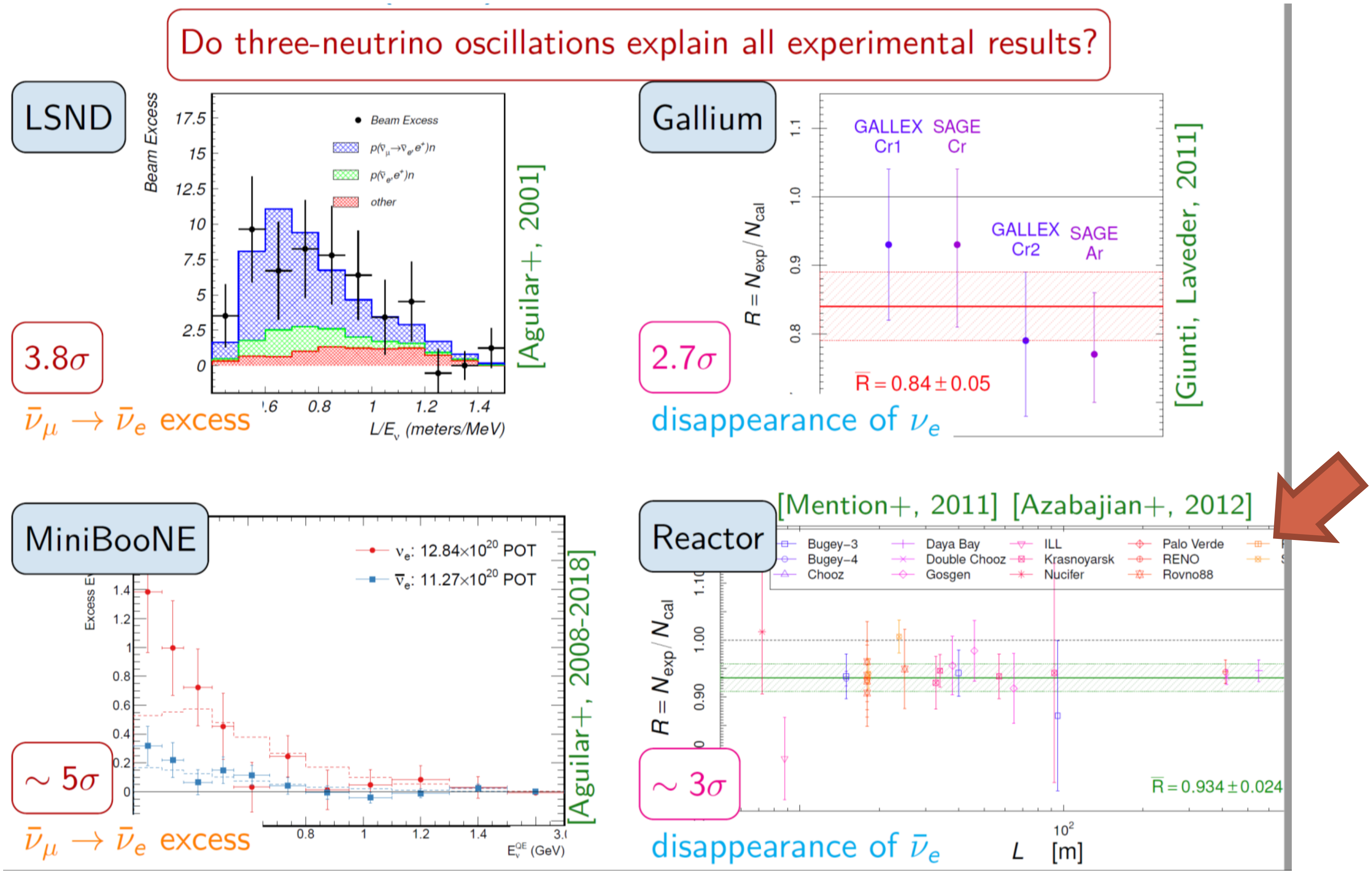
Contents

- Reactor Anti-neutrino Anomaly(RAA)
  - RAA and sterile neutrino hypothesis
  - Recent status of RAA research
    - STEREO/PROSPECT
- Short notice ; sterile neutrino and neutrino-less double beta decay
- Sterile search with new research reactor
  - Advantage for new research reactor

S. Gariazzo, Talk at TAUP2021

Short Baseline (SBL) anomalies

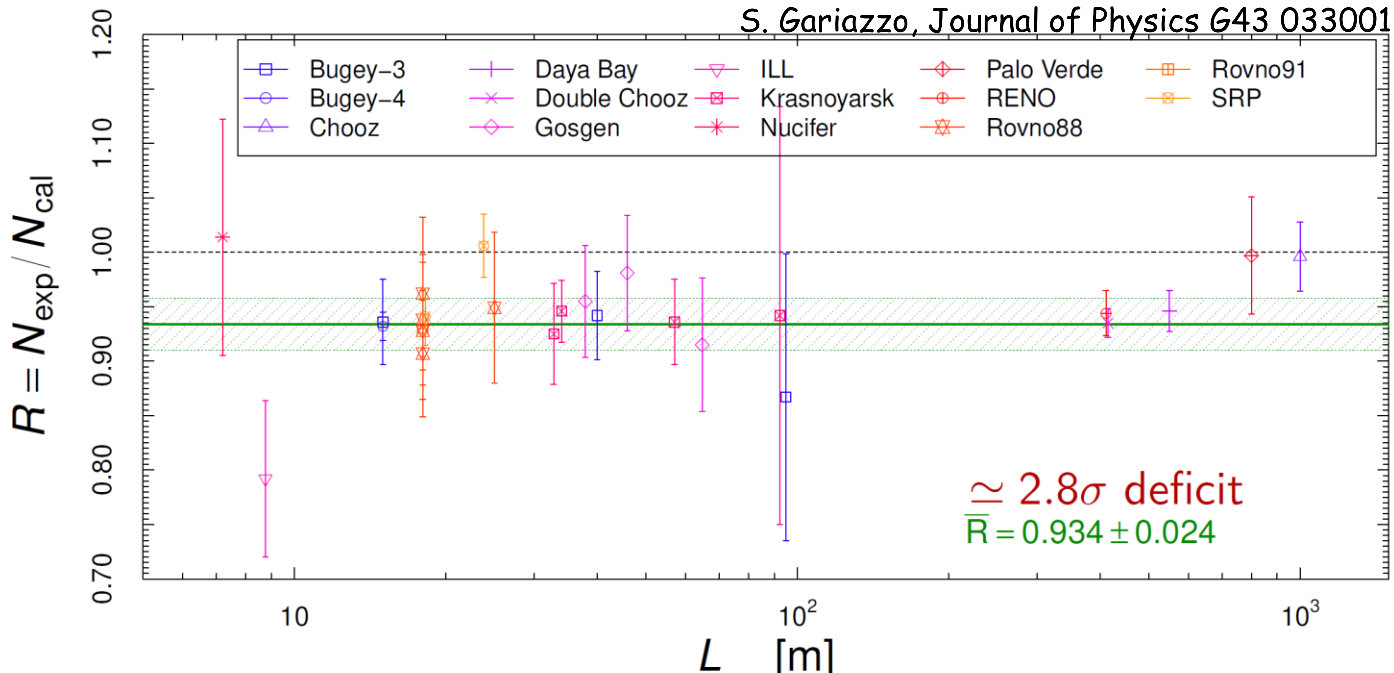
- Experimental results not interpretable in 3-generation neutrinos



Reactor Anti-ν Anomalies (RAA)

- Short-baseline Reactor Antineutrino Anomalies (RAA)

S. Gariazzo, Journal of Physics G43 033001 (2016)

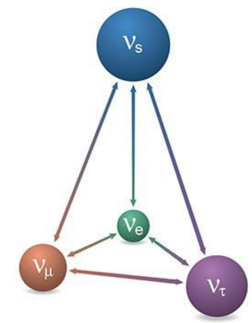


- Could be explained by additional short-distance oscillation to a sterile state
- There are systematic errors (not taken into account)
  - Detector performance
  - Reactor neutrino energy spectrum
    - 2011: new reactor $\bar{\nu}_e$ fluxes by Huber and Mueller （HM-Model）
    - [Huber, PRC 84 (2011) 024617] [Mueller+, PRC 83 (2011) 054615]

Rate Anomalies and Sterile-ν

- 3+1 generation neutrino mixing
  - 3 weakly interacting light neutrinos (from LEP experiment) + sterile neutrinos

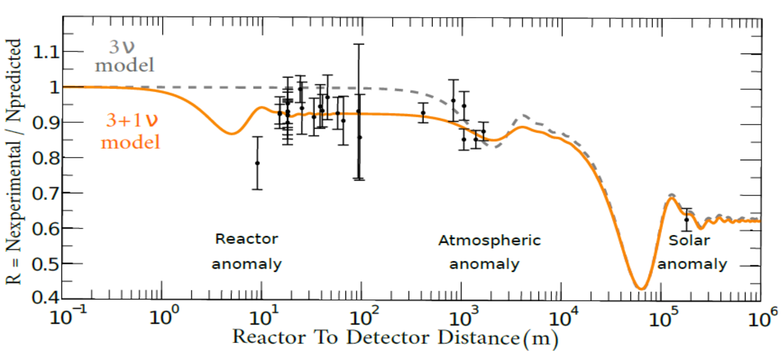
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$



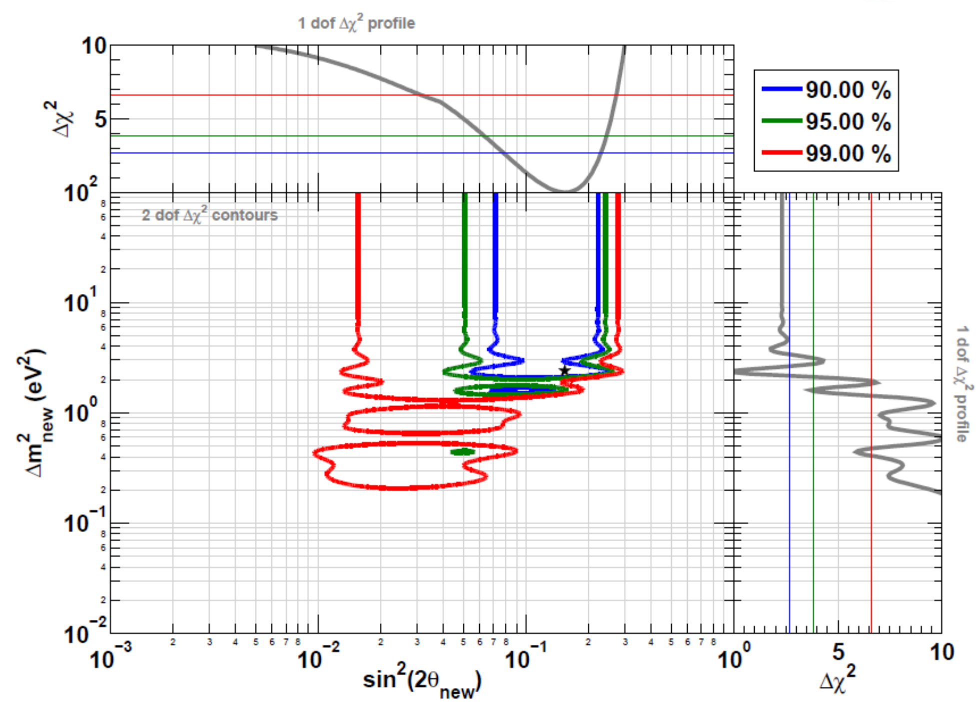
- Indication from RAA

$$\sin^2 2\theta_{\text{new}} \sim 0.1$$

$$\Delta m^2_{\text{new}} \sim 2\ \text{eV}^2$$



Electron anti-ν survival probability



A world-wide effort with reactors

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - \sin^2(2\theta_{ee})\sin^2\left(\Delta m^2_{41}\frac{L}{4E}\right)$$

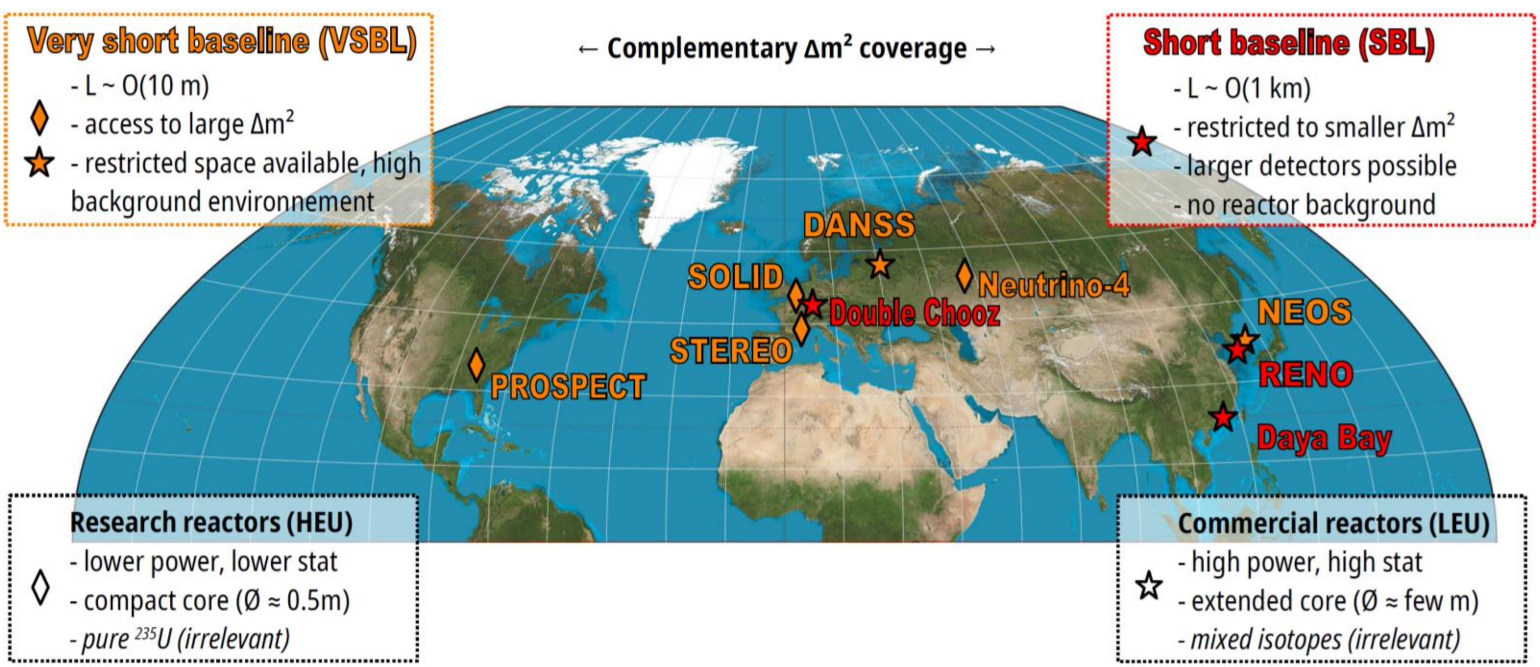
- Short baseline (SBL) experiment ← (~ km)
  - main target was θ_{13} ← can only access to $\Delta m^2 \sim 0.1 - 10^{-2}\ eV^2$
  - use (mainly) several commercial power plants
  - Detector : relatively large
  - Site : in shallow depth → No reactor BG & modest background from cosmic ray

A world-wide effort with reactors

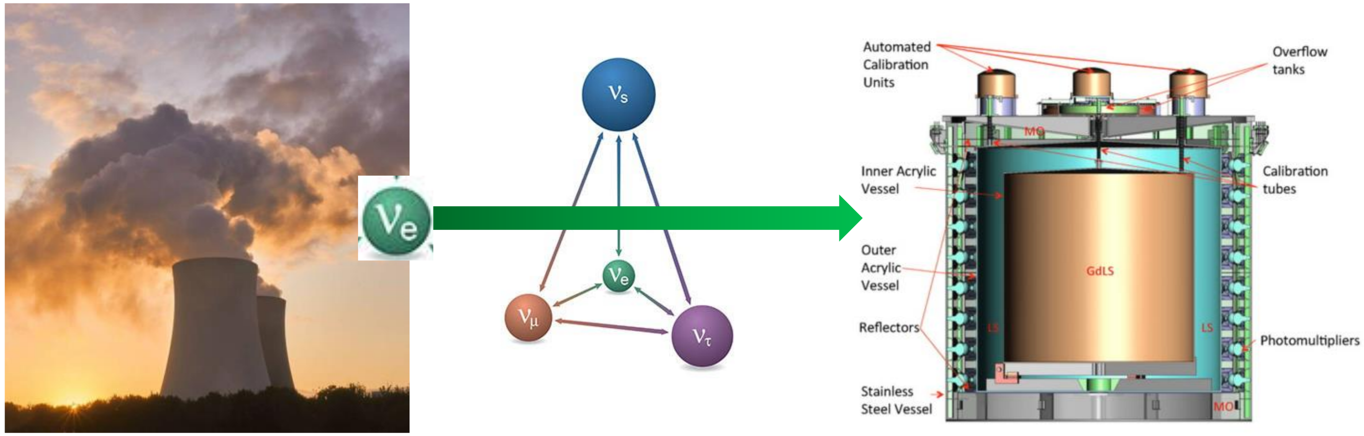
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) = 1 - \sin^2(2\theta_{ee}) \sin^2\left(\Delta m^2_{41} \frac{L}{4E}\right)$$

- VERY Short baseline (VSBL) experiment ← (~ 10 m)
  - main target was θ_{13} ← can access to $\Delta m^2 \sim 1\ eV^2$ (indicated by RAA)
  - use (mainly) research reactors → low output power.
  - Detector : relatively small
  - Site : very close to the reactor core

➔ low event rates is expected due to low anti-neutrino flux and small detector

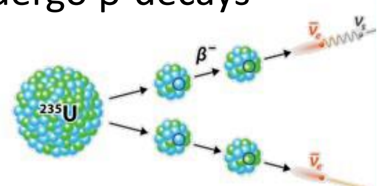


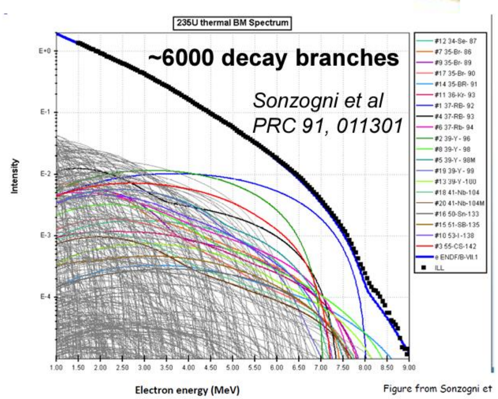
Reactor anti-neutrinos



Antineutrino flux

Fission fragments of U, Pu undergo β-decays





Oscillation

Survival probability

$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}L}{4E_{\bar{\nu}_e}}\right)$$

only required for L ~ 1km

Sensitivity Δm^2

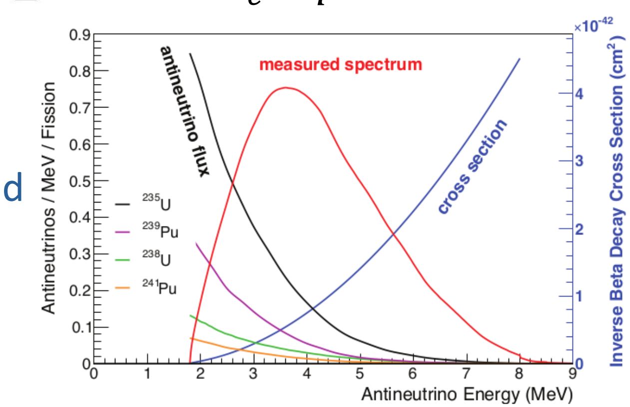
10^{-1} — 10^{-2} eV^2 @ 1km

1 — 10 eV^2 @ 10m

Detection

Inverse β-decay

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



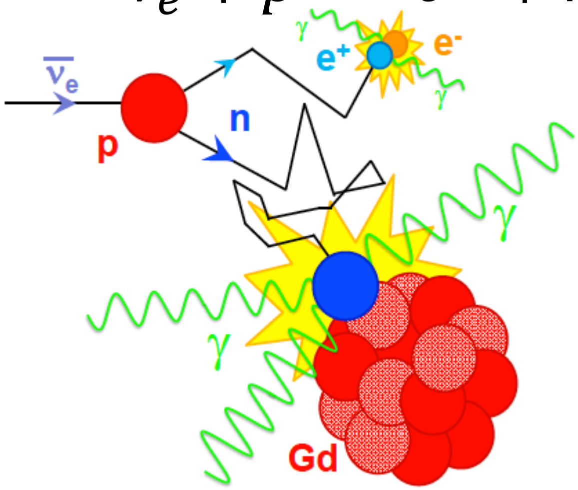
Observable energy range

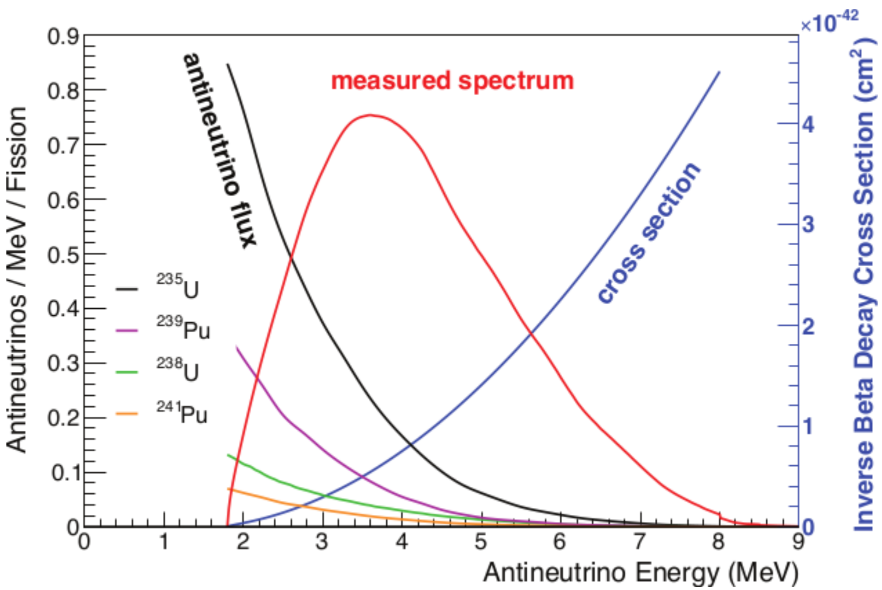
E_ν ; 2-8 MeV

Reactor $\bar{\nu}_e$ Detection

Inverse beta decay

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





- Usually use metal-loaded liquid scintillator (Gd, ^{6}Li)
  - Uniformity of detector performance
  - However, flammable hazardous material

- Signal ; Delayed coincidence
  - Prompt signal : e^+ +2γ (1.02 ~ 8MeV).
  - Delayed signal : neutron capture
    - γ-ray; Gd (~ 8MeV) , H (2.2 MeV)
    - ^{6}Li (triton & α).
  - Time correlation:
    - Δt ~30 μs (Gd) ~200 μs(H).
  - Spatial correlation :
    - Δr < ~ 1 m. (depends on detector)

Short Baseline Reactor Experiments

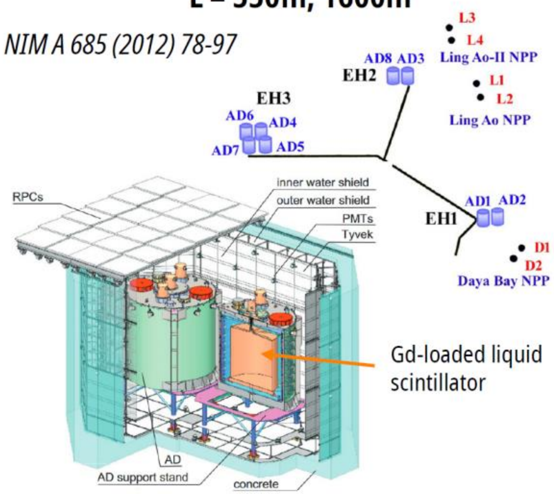
- Very similar setup

Daya Bay

Daya Bay and Ling Ao (II) NPPs

L = 550m, 1600m

NIM A 685 (2012) 78-97



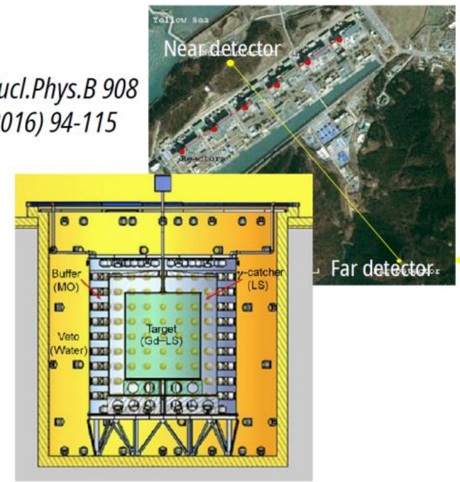
- 8 identical detectors (4 NDs + 4 FDs)
- Each 20t of Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

RENO

Hanbit NPP, Korea

L ≈ 300m, 1380m

Nucl.Phys.B 908 (2016) 94-115

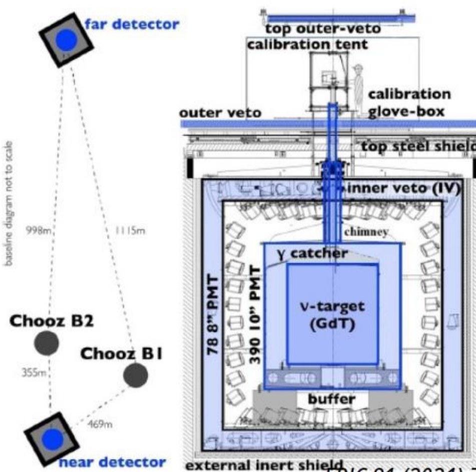


- Identical ND and FD
- 16t Gd-loaded liquid scintillator
- Energy resolution 8% @1MeV

Double Chooz

Chooz-B NPP, France

L = 400m, 1050m

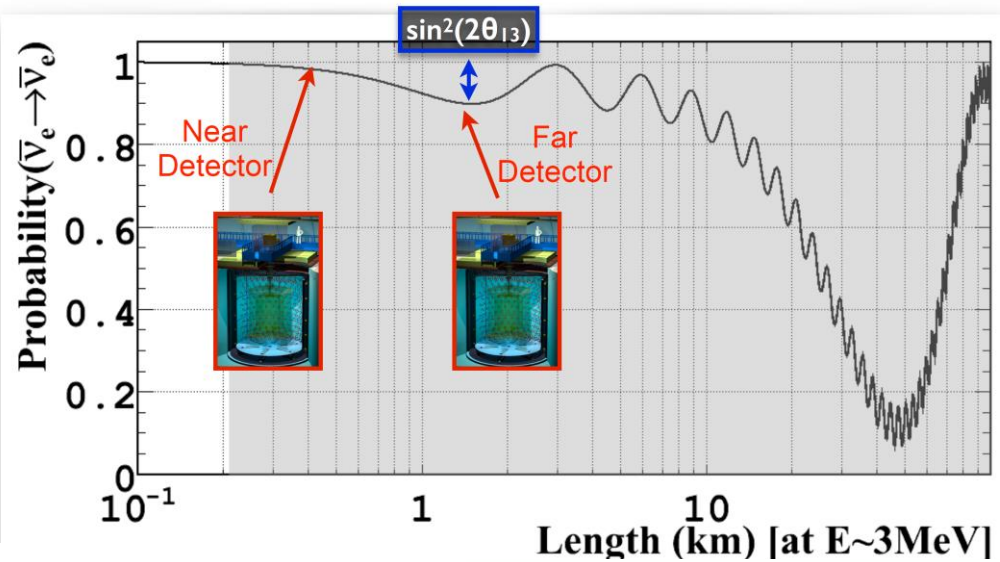


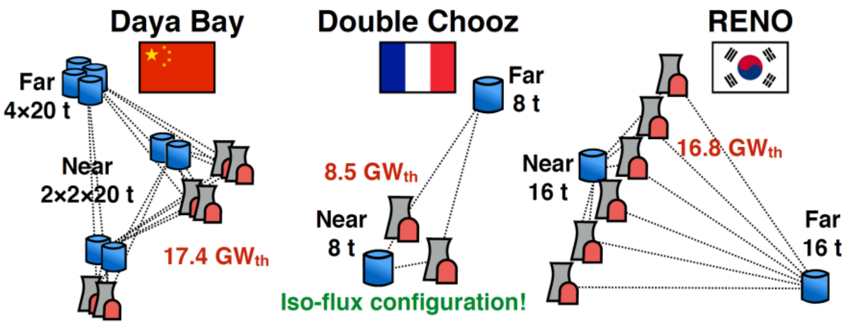
EPJC 81 (2021) 775

- Identical ND and FD
- Gd-loaded liquid scintillator (GdT, $10m^3$)
- Energy resolution 7% @1MeV

θ_{13} Experiments and Spectrum Anomaly

- The importance of relative measurements
- θ_{13} expriments ? → Successful discovery & precise measurement
  - Daya Bay, RENO, Double Chooz
  - Why ? → Near&Far detectors measurement and compare spectra



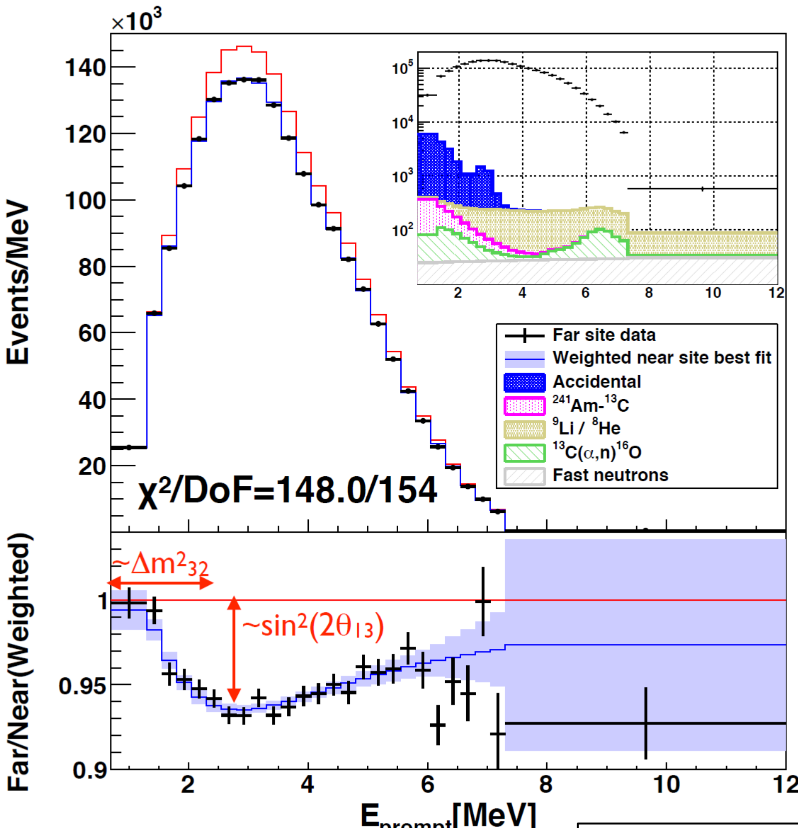


	Power [GWth]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]
Daya Bay	17.4	2x2x20 4x20	365,490 1650	250 860
Double Chooz	8.5	8 8	400 1050	120 300
RENO	16.8	16 16	290 1380	120 450

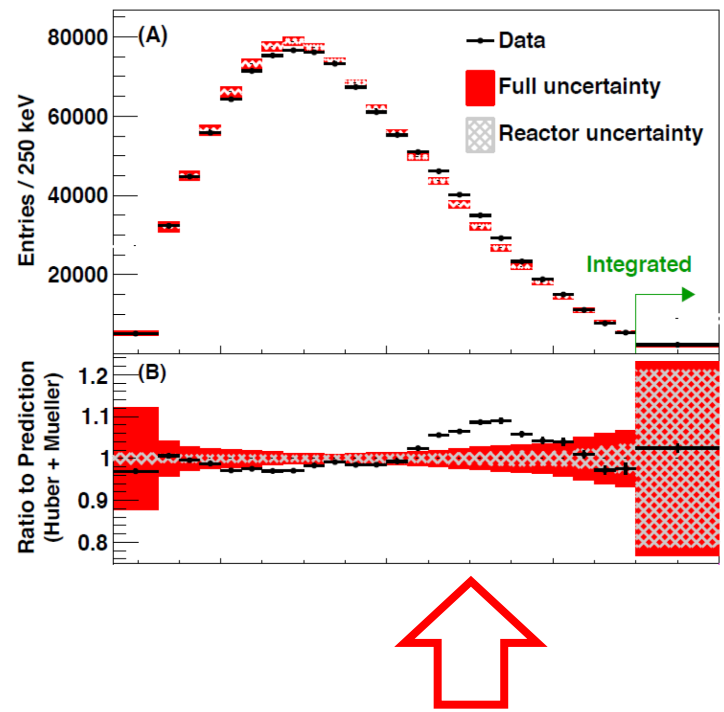
θ_{13} measurement experiments

- A shape distortion with respect to predicted spectrum has been observed
- Both at near and far sites ; bump at ~ 4-6 MeV is observed.

Daya Bay
Phys.Rev.Lett. 121 (2018) 24, 241805



Daya Bay
Chin.Phys.C 41 (2017) 1, 013002



- Near/Far → reduce systematic uncertainties
- Spectral shape was not consistent with the Model

Results from SBL Experiments

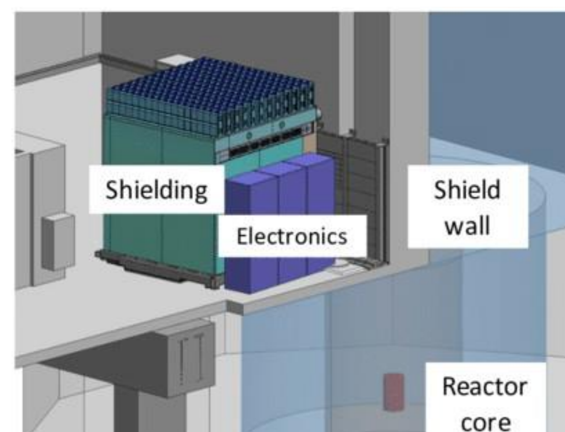
- Short baseline reactor anti-neutrino experiments have **extended their study** of $\sin^2\theta_{13}$ in 3-flavor model to search for ($\sin^2\theta_{14}$, Δm_{14}^2) in 3+1 model
- **Very large anti-neutrino samples** (~ 10^6 events), with well-known detectors
- **Relative measurements** are performed using Near- and Far-Detectors, in order to be independent from flux model predictions
- They provide **leading constraints** for Δm_{14}^2 ranging **from Δm_{31}^2 to 0.1 eV²**
- **RENO-NEOS** observe the positive results for sterile-ν, but with **low significance (2.8σ)**, needs confirmation

VERY Short Baseline (VSBL)

- **L~10m → vicinity of reactor core**
  - Design constraints
    - Limited space, limited floor load in the reactor building
    - Constraints : size of detector, amount of shielding
  - **(Relatively) Large backgrounds**
    - Cosmogenic : surface level → shallow overburden (~ 10 m.w.e.)
    - Ambient fast neutron & gamma-ray flux (from reactor & cosmic-ray)
  - Resolution on L/E
    - Extended cores (LEU) : size ~3m → σ_L/L up to 15%
    - Small cores (HEU) : size ~0.5m → σ_L/L down to 3%
    - E-resolution is also important !

STEREO

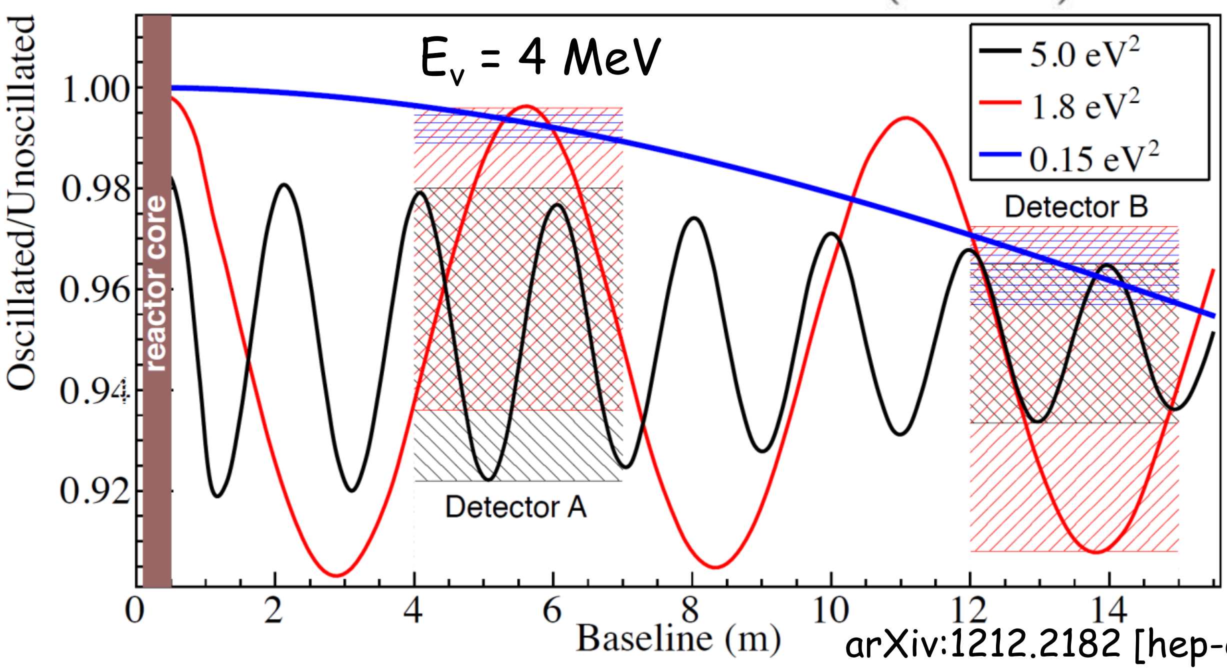
PROSPECT



Sterile-ν Oscillation

- Important characteristics for oscillation observation
  - Reduce the systematics
    - Place two identical detectors (Detector A & B in Fig.)
    - Mechanisms that allow observation by moving the detector
    - Long detector in the direction of the reactor core,
  - There is position resolution, oscillation patterns can be observed without moving the detector

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E) = 1 - \sin^2(2\theta_{ee}) \sin^2\left(\Delta m^2_{41} \frac{L}{4E}\right)$$



arXiv:1212.2182 [hep-ex]

Oscillation parameter and Exp. Setup

- Reactor & Detector characteristics .vs. Oscillation parameters
  - **Small reactor core** → Possible to search for **large Δm^2**

arXiv:1212.2182 [hep-ex]

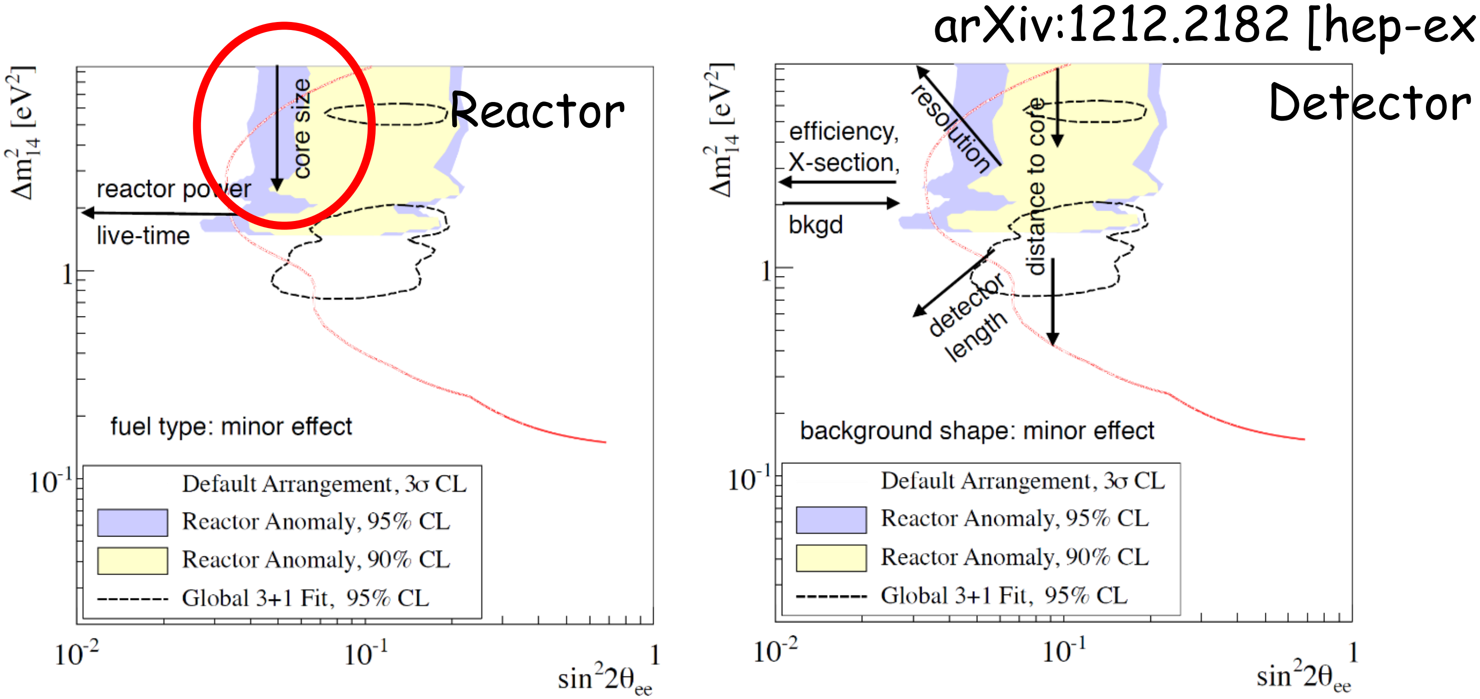


FIG. 17: Reactor and detector parameters relevant for covering the suggested parameter space. These graphs indicate the direction in which the sensitivity curve moved when reactor (left) and detector (right) parameters are improved or adjusted.

Very-Short Baseline (VSBL) Experiments

Positive results for sterile-ν

Experiment	Reactor [power in MW_{th}]	Baseline [m]	Target material and mass	Segmentation	Signal/ Background	Status
NEOS	LEU [2800]	24	GdLS ~1 m^3	No	21	2018-2020 180(46) days On(Off)
DANSS	LEU [3100]	10-12	PS (Gd layer) 1 m^3	quasi-3D	0.6	2016-2020 (~ 3M events)
Neutrino-4	HEU [100]	6-12	GdLS 1.8 ton	2D	0.3	720(417) days On(Off) data
PROSPECT	HEU [85]	7-12	^{6}LiLS 4 ton	2D	0.8	96(73) days On(Off) data
STEREO	HEU [58]	9-11	GdLS 2.4 m^3	2D	0.9	data taking finished (>300 days data)
SOLID	HEU [72]	6-9	PS (^{6}Li layer) 1.6 ton	3D	1.0 (expected)	196(146) days On(Off) data
NuLAT	any	any	^{6}LiPS 0.9 ton	3D	3 (expected)	R&D
CHANDLER	any	any	PS (^{6}Li layer) 1m^3	3D	3 (expected)	R&D

Very CLOSE to reactor core

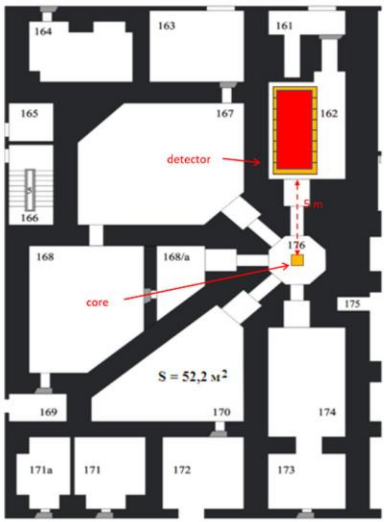
C.Jollet, Talk at TAUP2021

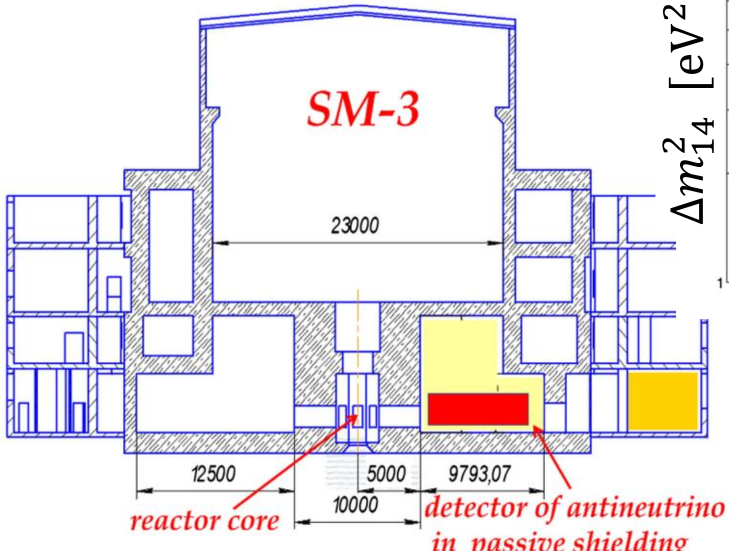
Neutrino-4 Experiment

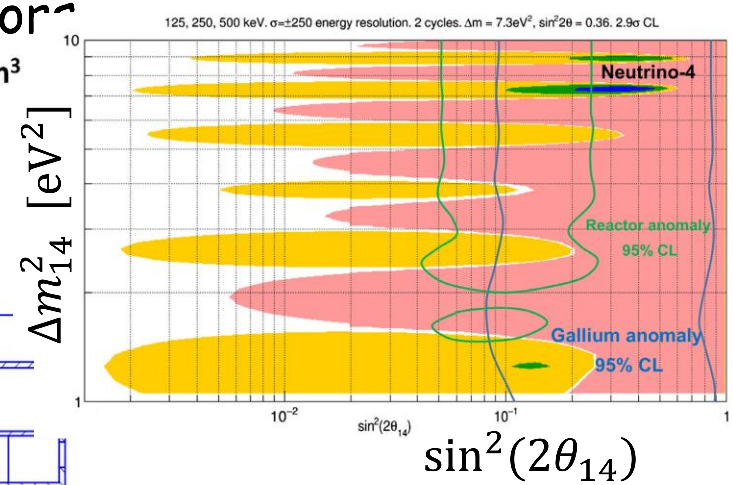
A. P. Serebrov et al., PHYSICAL REVIEW D 104, 032003 (2021)

- Neutrino-4 Experiment ; Site & Detector

Reactor: SM-3 reactor in Dimitrovgrad (Russia): 100 MW compact core 35x42x42 cm^3







- Vicinity of the reactor core
- Movable （6 - 12 m）
- Gd-LS（1.8 tons, Segmented）
- Shields（Active+Passive）
-

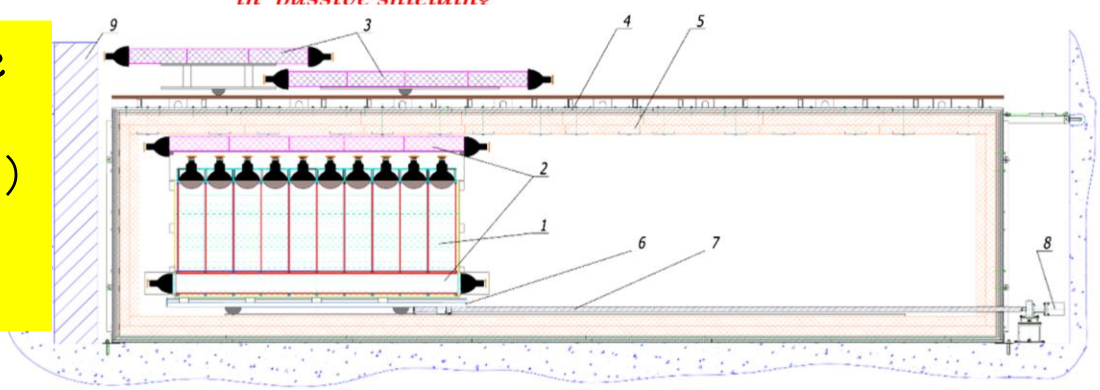
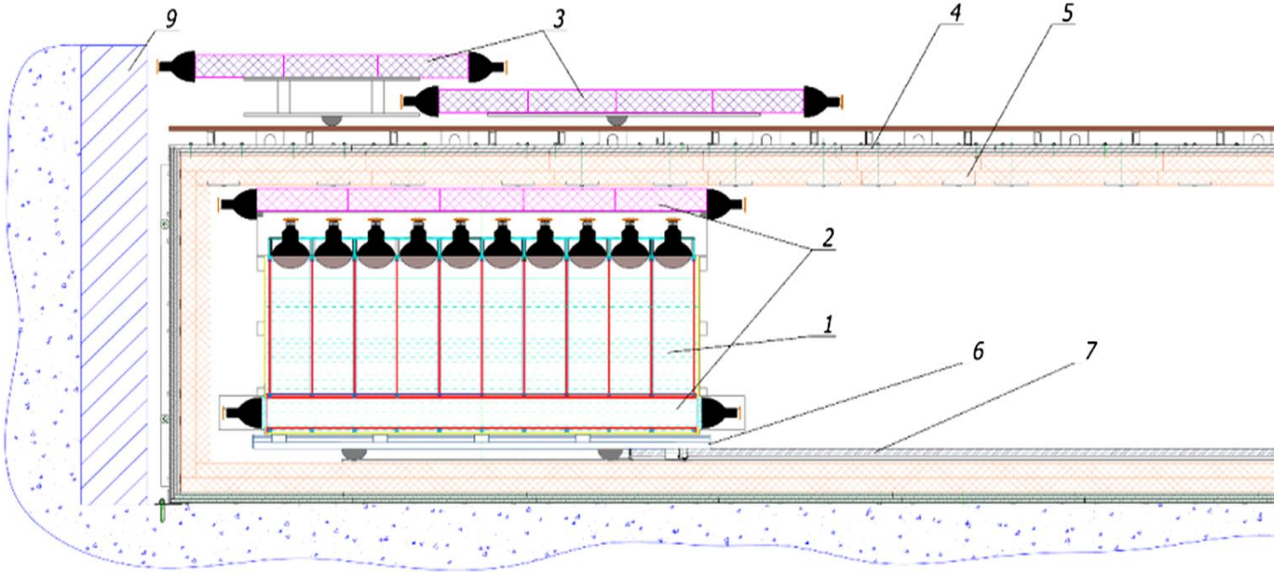
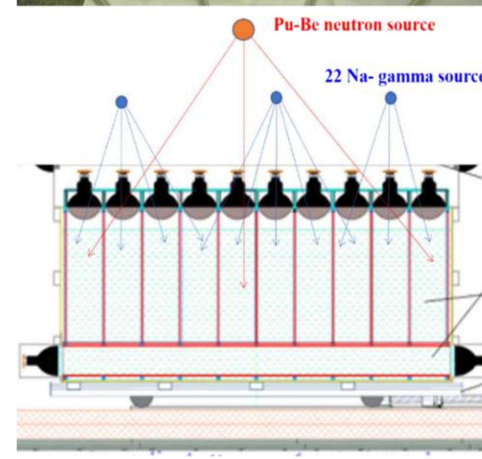


FIG. 18. General scheme of an experimental setup. 1—detector of reactor antineutrino, 2—internal active shielding, 3—external active shielding (umbrella), 4—steel and lead passive shielding, 5—borated polyethylene passive shielding, 6—moveable platform, 7—feed screw, 8—step motor, 9—shielding against fast neutrons made of iron shot.

Neutrino-4 Detector





1—detector of reactor antineutrino,
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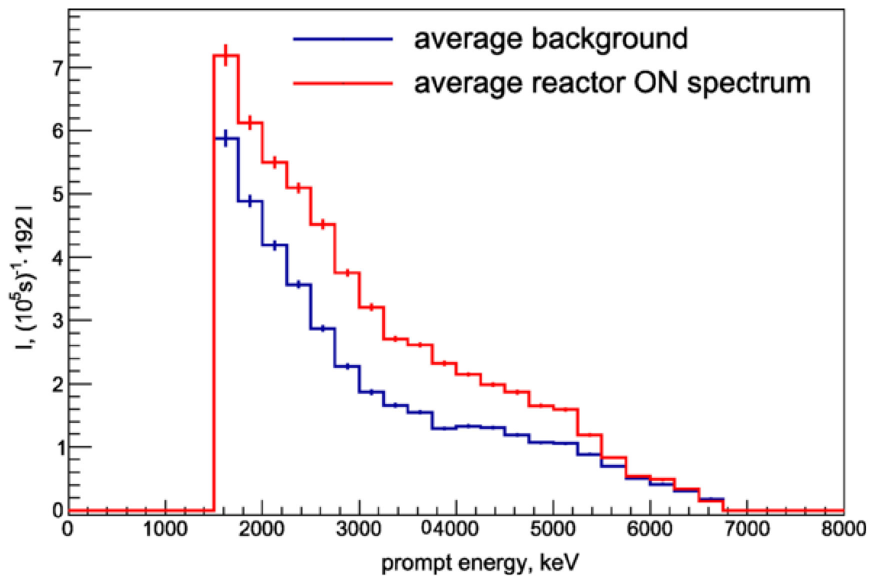
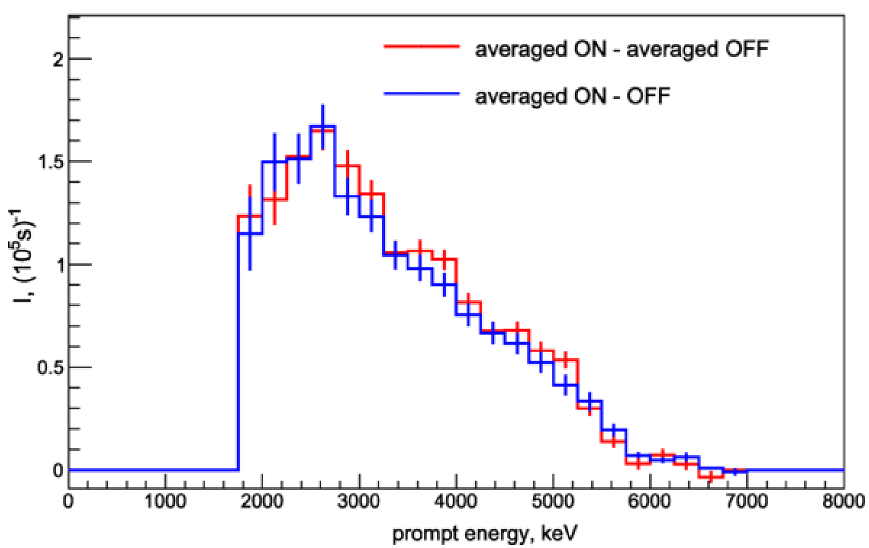
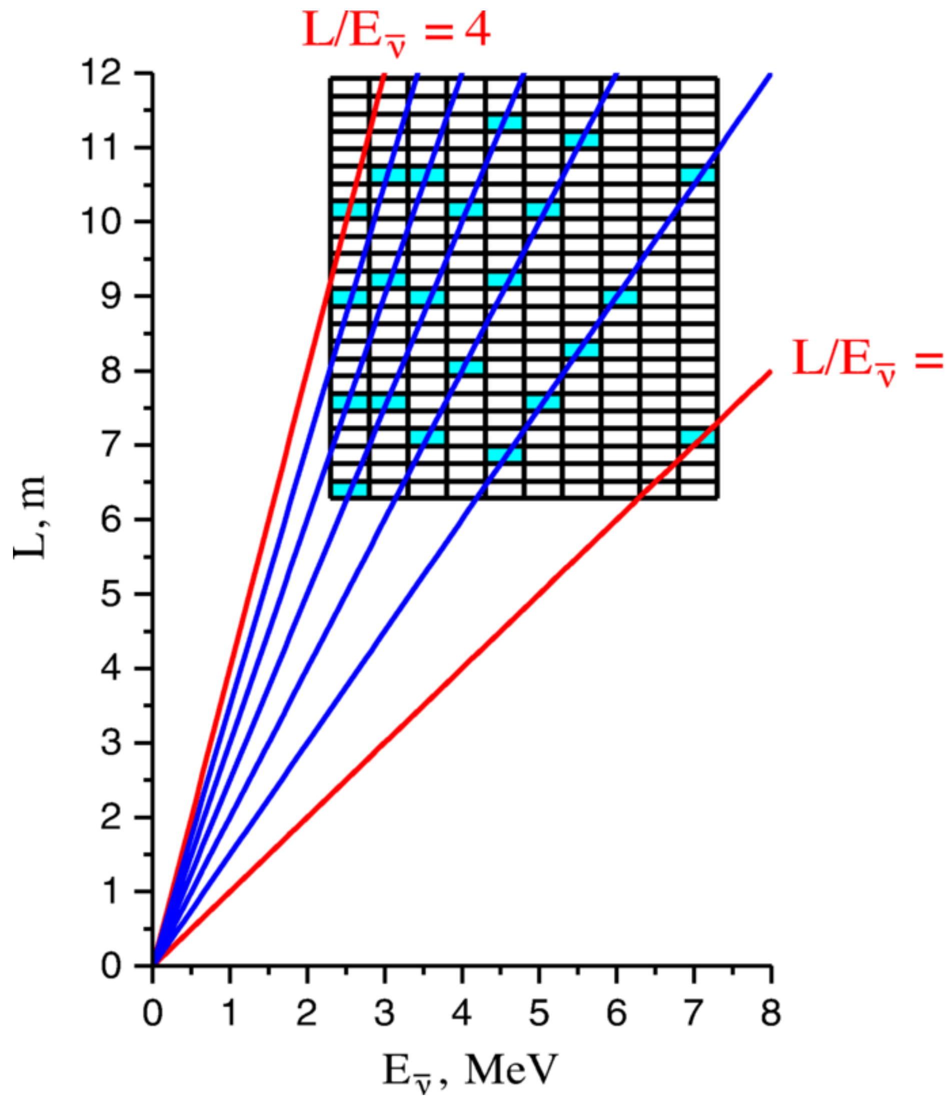
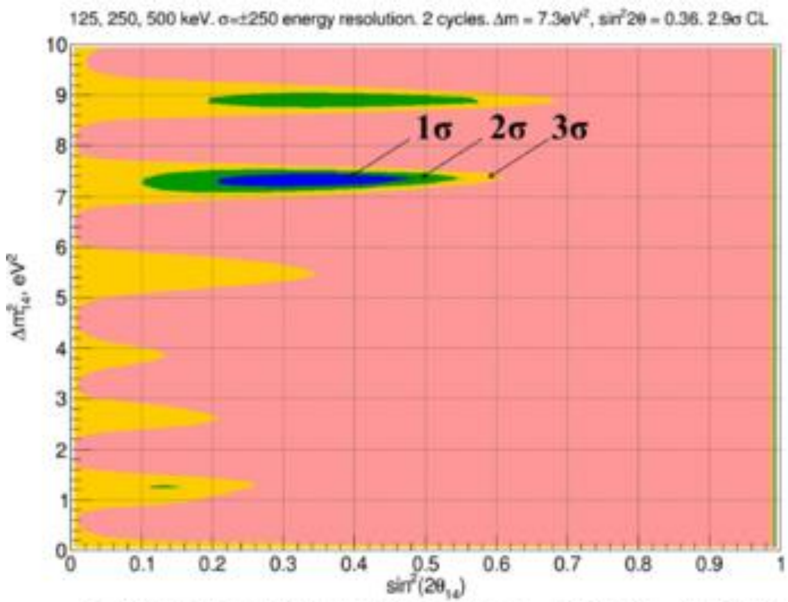
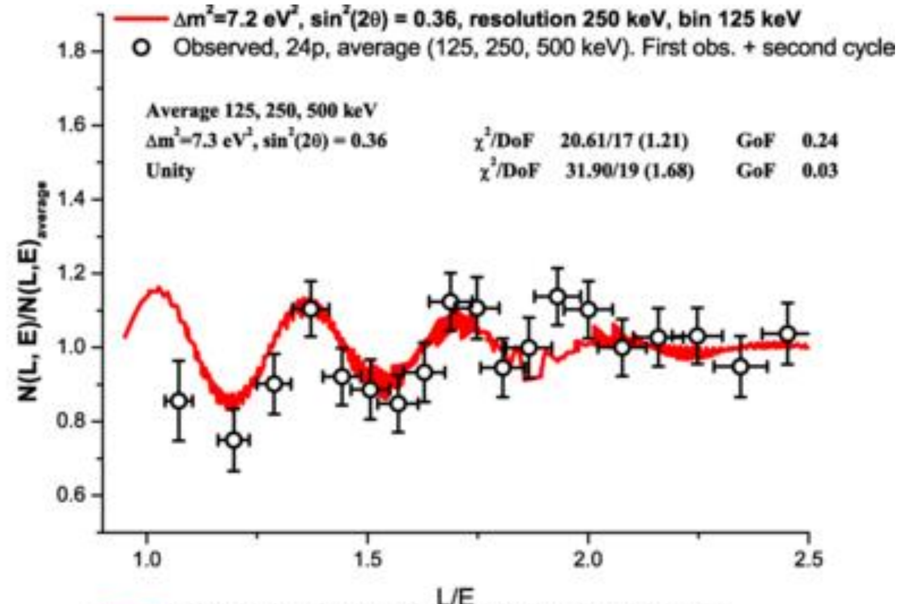

average background
average reactor ON spectrum
I, (10^5s)^-1 192 l
prompt energy, keV

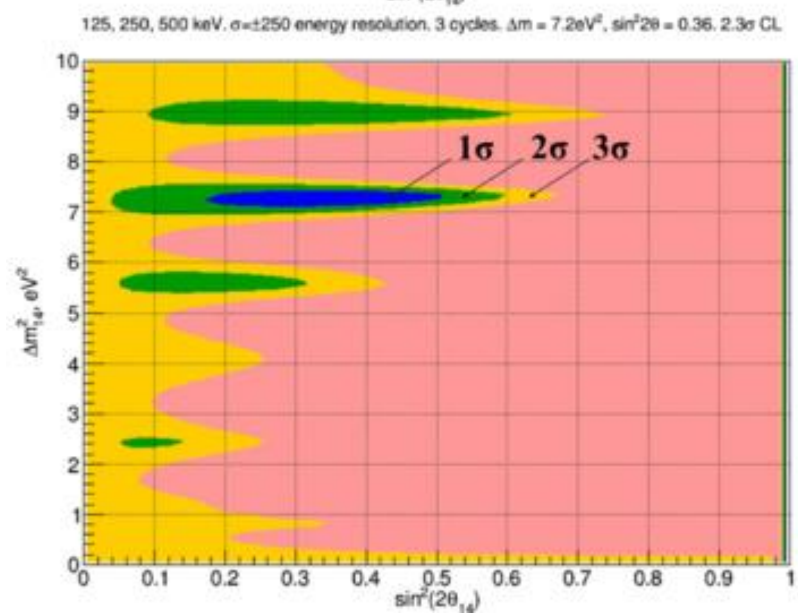

averaged ON - averaged OFF
averaged ON - OFF
I, (10^5s)^-1
prompt energy, keV

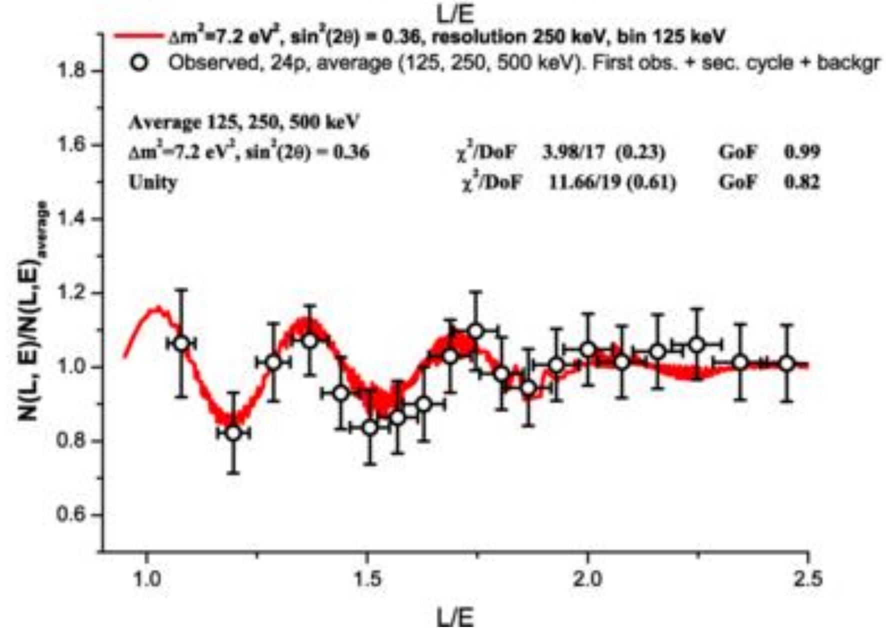

L/E$_{\bar{\nu}}$ = 4
L/E$_{\bar{\nu}}$ =
L, m
E$_{\bar{\nu}}$, MeV

NEUTRINO-4 result









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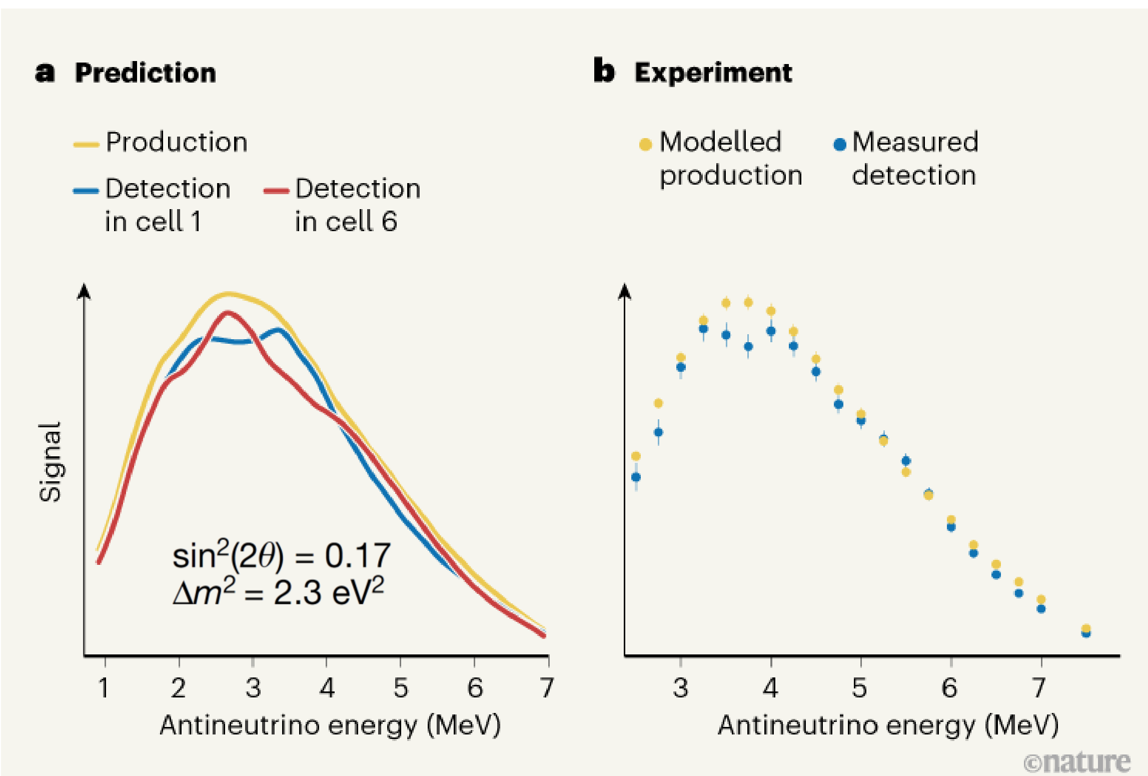
Nature News artilces
https://www.nature.com/articles/d41586-022-04581-9

NEWS AND VIEWS | 11 January 2023

Nuclear reaction rules out sterile-neutrino hypothesis

An anomalous measurement from a nuclear reactor triggered a three-year campaign to find an elusive particle called the sterile neutrino. The search shows definitively that sterile neutrinos don't exist – but the anomaly persists.



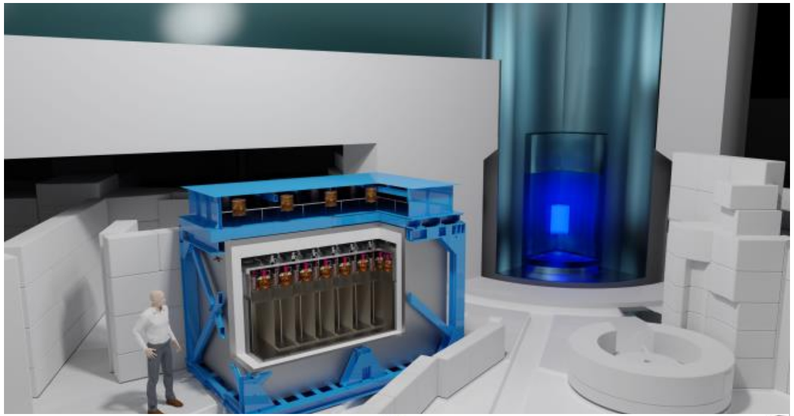
(a) Reactor antineutrino energy Spectrum deforms in dependence on distance from the core.

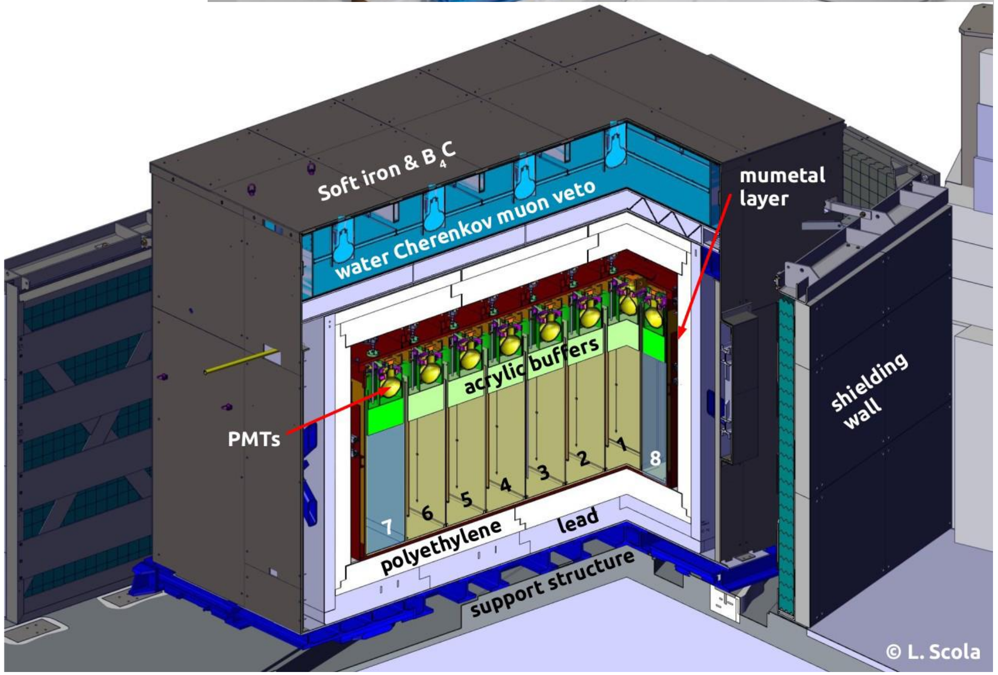
(b) No distance dependence in the spectrum was observed. The observed event rate is less than predicted!

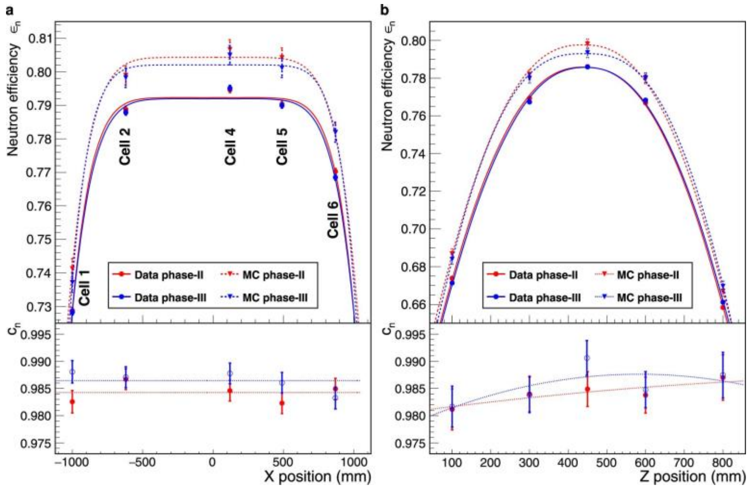
STEREO Experiment

Nature **volume 613**, 257–261 (2023)

- STEREO
  - Experimental site ; ILL
    - 58 MW Highly Enriched ^{235}U reactor (99%以上 of flux ← ^{235}U fissions)
    - Compact core → Ø 40cm, h=80cm
  - Detector
    - 6 cells @ L = 9.4 – 11.2 m
    - Liq. Scintillator + Gd
    - ~ 360 ν's/day, S/B = 0.8
    - Surrounding γ-catcher





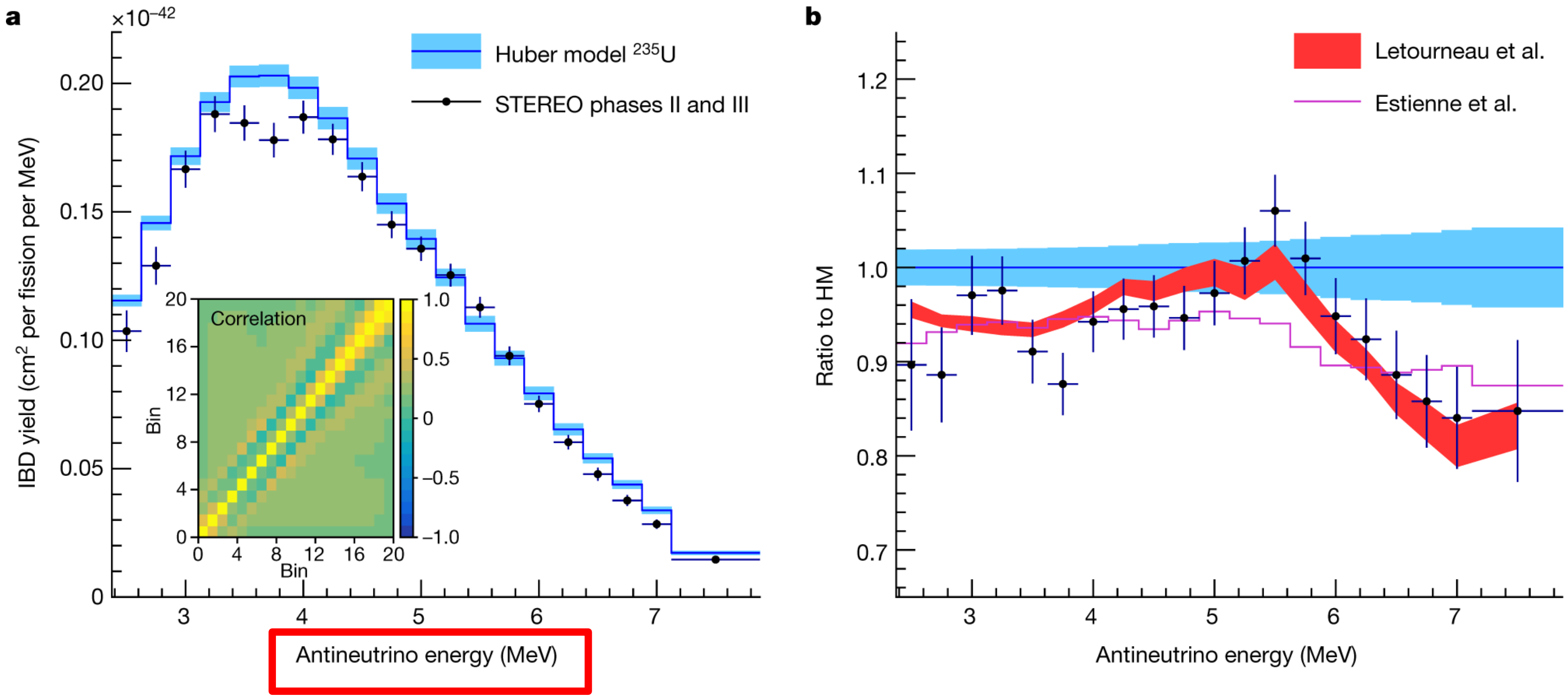


Gamma-Catcher: unloaded liquid scintillator
Target: Gd-loaded liquid scintillator

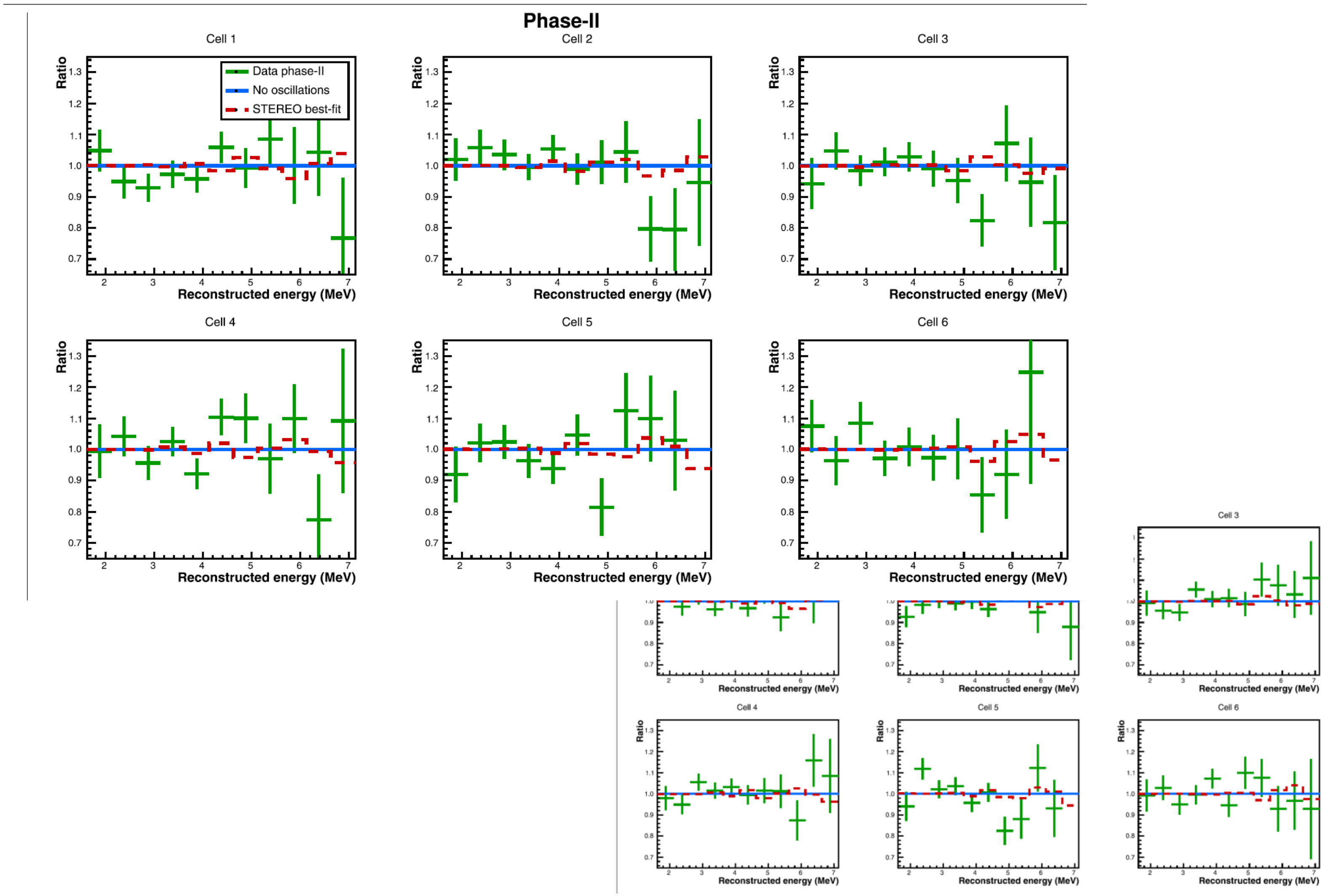
STEREO ; Results

Nature **volume 613**, 257–261 (2023)

- Results
  - Anti-ν energy spectra do not change with distance
  - Spectrum comparison for each cell is not listed (next page)
  - Only from the left figure, it looks that there is oscillation. The shape of the spectrum does not match HM-Model (there is also a bump at ~ 5MeV).
    - Maybe the HM-Model needs correction



- Ratio Obserbed/Model per CELL (dipendence on distance)

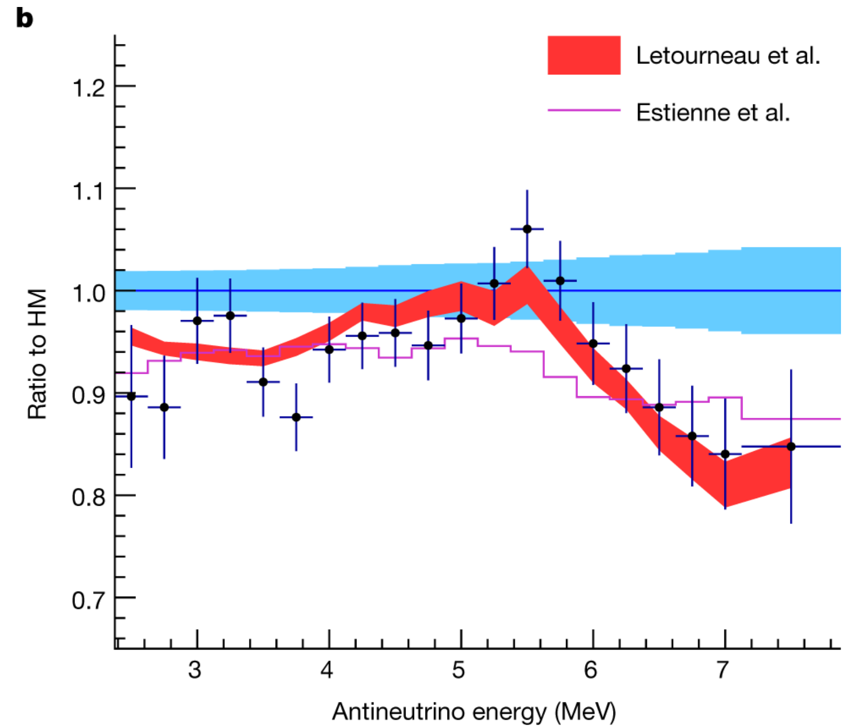


STEREO ; Results

- Results
  - Spectrum shape does not match HM-Model (with Bump)
    - ➔ HM-Model needs correction
  - Model by Estienne *et al.*
    - Correction of the evaluated nuclear data by including the most **recent measurements of the β-strengths** of the main fission products.
    - well consistent with rate deficit (~ 5.5%)

Nature **volume 613**, 257-261 (2023)

- Model by Letourneau *et al.*
  - Correction of the β-spectra **to all nuclei by completing the β-decay schemes** of the ENSDF nuclear database.
  - with a simple phenomenological Gamow-Teller β-decay strength model.
  - Very well-reproduce the spectrum shape

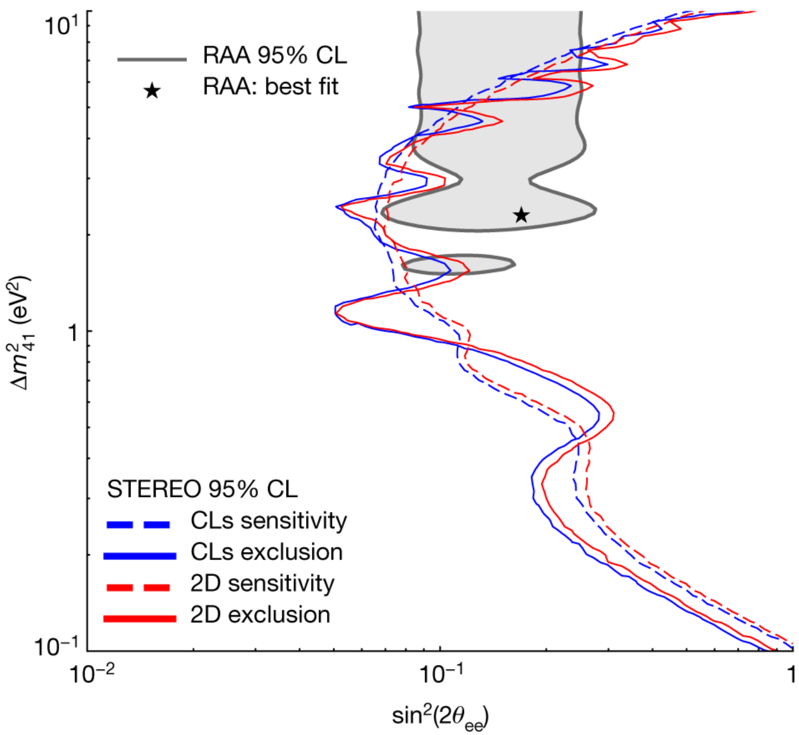


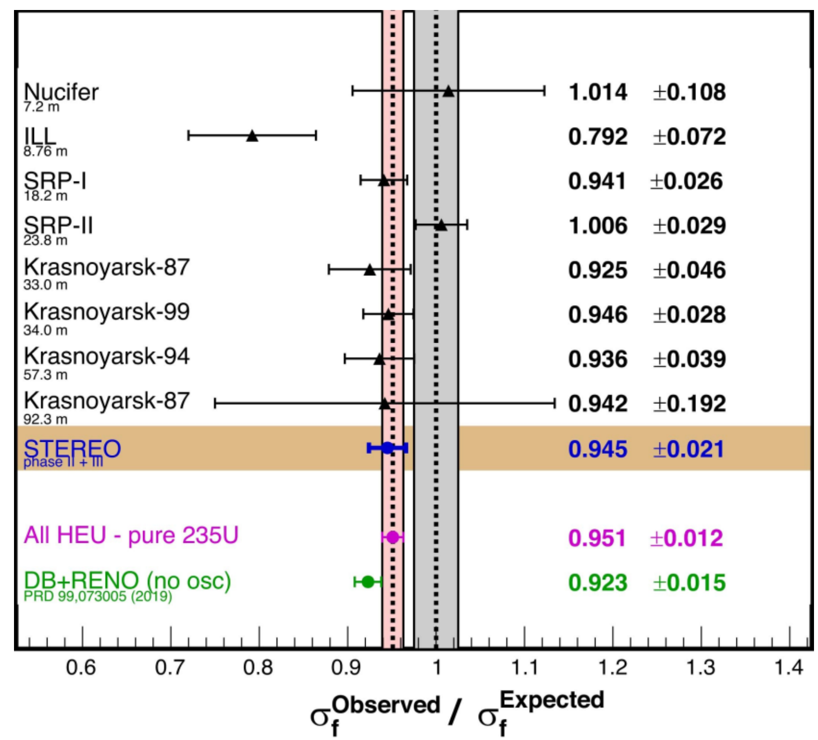
STEREO ; results

- Constraints on sterile-ν

Nature **volume 613**, 257–261 (2023)

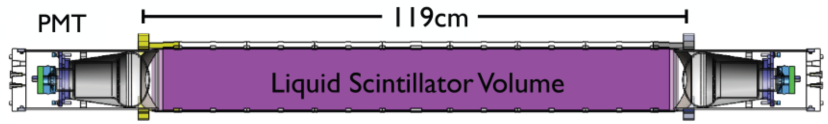
  - Parameter space favored by the RAA (a few eV^2) was excludes
  - Exclude the **Best Fit Point of** Neutrino-4 (3.3σ), NEOS-RENO (2.8σ)



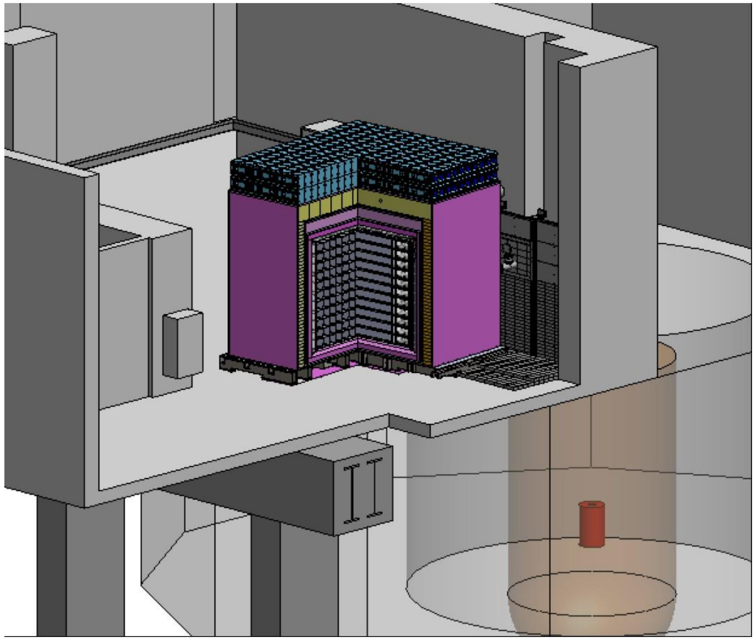


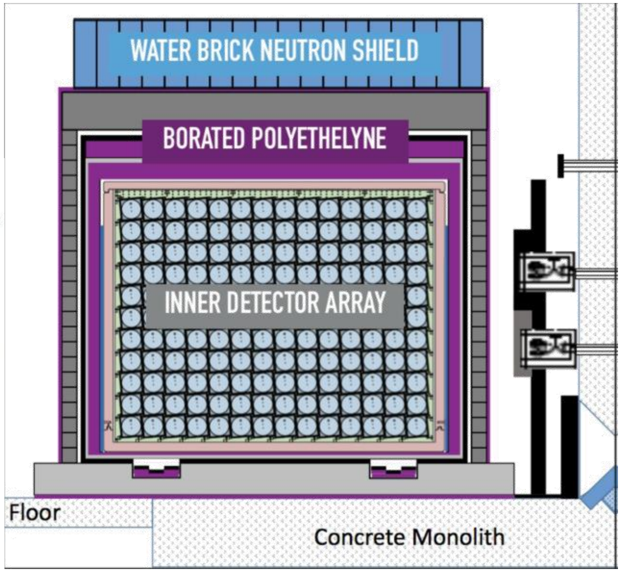
The explanation of the RAA by a few-eV-mass sterile neutrino is strongly disfavored by STEREO data.

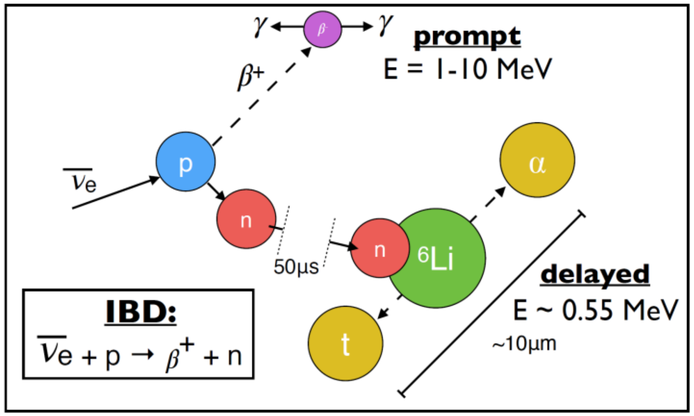
PROSPECT

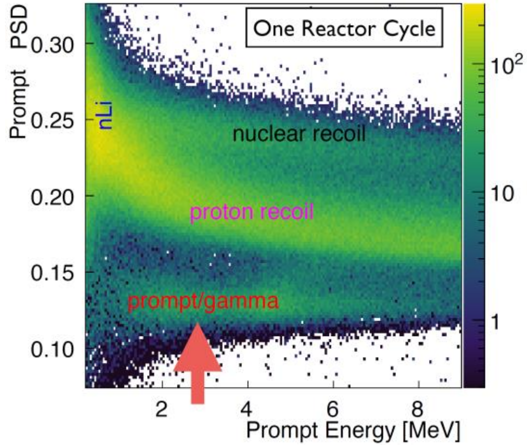


- PROSPECT
  - Experimental site: ORNL
    - 85 MW HEU reactor core
    - Compact core: < 50cm height, diameter
    - 99%以上 of flux ← ^{235}U fissions
  - Detector design
    - Segmented, L = 6.7 – 9.3m
    - 4 tons of Liq. Scintillator + ^{6}Li
    - Optimized for BG suppression
    - (no overburden, S/B = 1.4)
    - ~ 500 events/day









Joint Analysis by STEREO & PROSPECT

H. Almazán et al. (PROSPECT Collaboration, STEREO Collaboration)
Phys. Rev. Lett. 128, 081802

- Anti-ν Energy Spectrum
  - Well consistent
    - Different detectors, sites
  - Bump@~5MeV (HM-Model比)
    - Significance ; 2.4 σ

- Spectrum Anomalies (Bump structure)
  - Observed w/o distance dependence
    - θ_{13} experiments (Baseline~1 km)
    - VSBL (~10 m)
    - ➔ Problem with the spectrum model.

  - Observed both HEU and LEU (Commercial) reactors
    - Cannot be explained by contributions other than ^{235}U

Need more statistics !

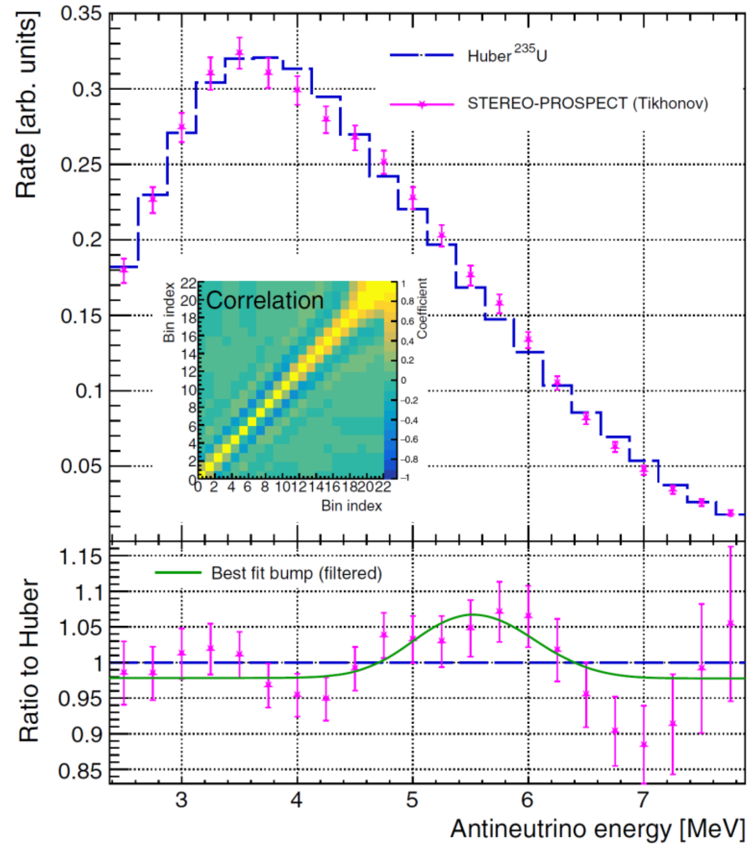
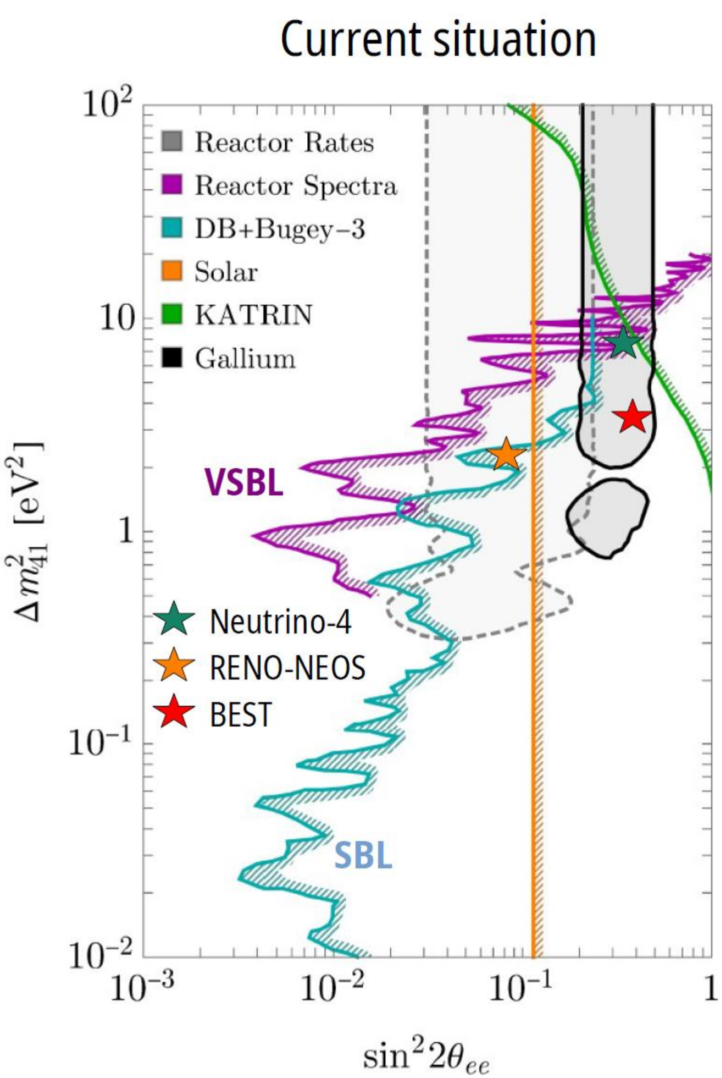


FIG. 3. (Top) Jointly unfolded ^{235}U spectrum with diagonal errors and Huber prediction normalized to unit area. The non-trivial correlation matrix is displayed. (Bottom) Jointly unfolded ^{235}U spectrum, as a ratio to Huber. The filtered best-fit bump is displayed.

Global picture of sterile-ν search

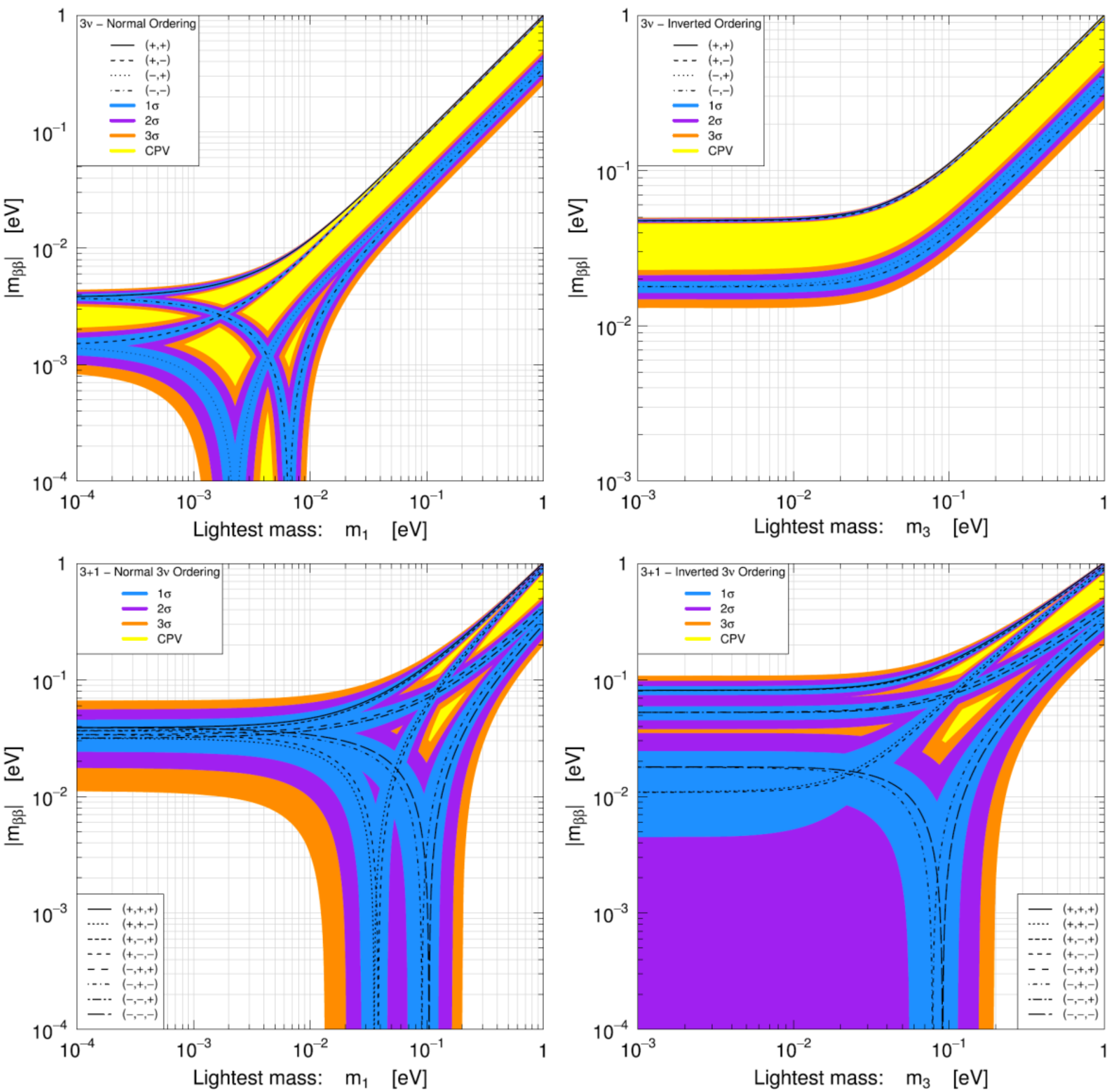


Snowmass 2021 white paper 2203.07214

- **Complementary constraints** from SBL and VSBL allow to probe a large range of Δm^2.
- **Reactor Anomaly** strength ($\sin^2\theta_{ee}$) still **depends on flux modelling** : not fully solved yet but need to be modified
- Large Δm^2 region of RAA will be covered by KATRIN
- KATRIN + Reactor constraints already **cover most of Gallium Anomaly parameters**
- Positive observations (BEST, Neutrino-4, RENO-NEOS) **in (strong) tension** with other experiments, to be confirmed in future experiments.
- The situation remains as chaotic.

Impacts on 0ν-DBD

J. Phys. G: Nucl. Part. Phys. **43** (2016) 033001 Topical Review

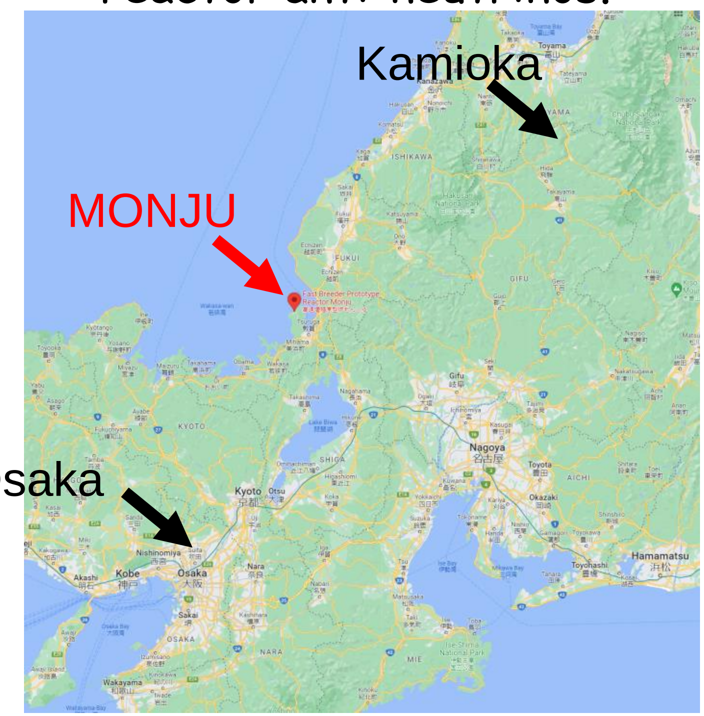


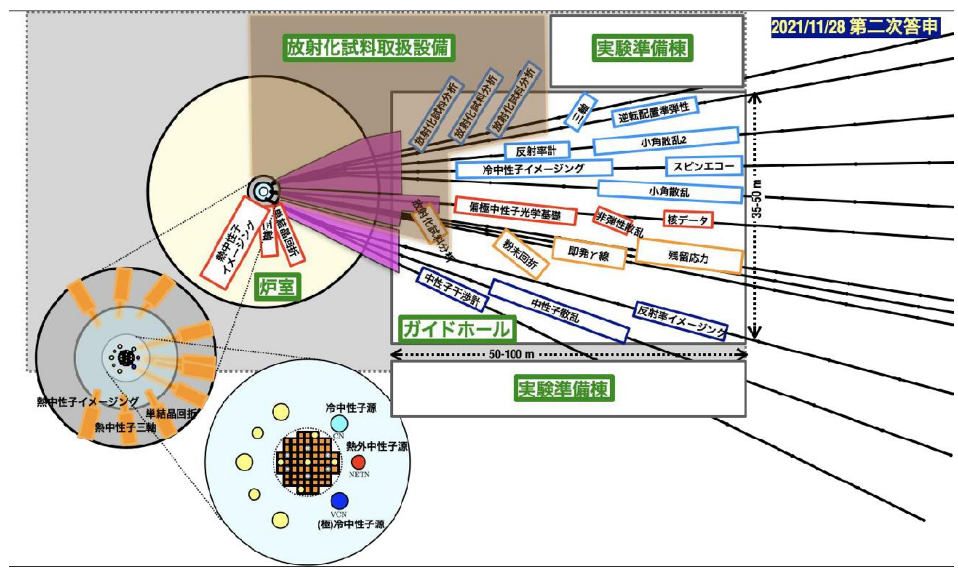
		LOW	HIG	noMB	noLSND
No Osc.	χ^2	339.2	308.0	283.2	286.7
	NDF	259	253	221	255
	GoF	0.06%	1%	0.3%	8%
3+1 Osc.	χ^2_{min}	291.7	261.8	236.1	278.4
	NDF	256	250	218	252
	GoF	6%	29%	19%	12%
	$\Delta m^2_{41}\,[\text{eV}^2]$	1.6	1.6	1.6	1.7
	$\lvert U_{e4}\rvert^2$	0.033	0.03	0.03	0.024
	$\lvert U_{\mu 4}\rvert^2$	0.012	0.013	0.014	0.0073
	$\sin^2 2\vartheta_{e\mu}$	0.0016	0.0015	0.0017	0.0007
	$\sin^2 2\vartheta_{ee}$	0.13	0.11	0.12	0.093
	$\sin^2 2\vartheta_{\mu\mu}$	0.048	0.049	0.054	0.03
	$(\chi^2_{\text{min}})_{\text{APP}}$	99.3	77.0	50.9	91.8
	$(\chi^2_{\text{min}})_{\text{DIS}}$	180.1	180.1	180.1	180.1
	$\Delta\chi^2_{\text{PG}}$	12.7	4.8	5.1	6.4
	NDF_{PG}	2	2	2	2
	GoF_{PG}	0.2%	9%	8%	4%
	$\text{p-val}_{\text{No Osc.}}$	3×10^{-10}	5×10^{-10}	3×10^{-10}	4×10^{-2}
	$n\sigma_{\text{No Osc.}}$	6.3σ	6.2σ	6.3σ	2.1σ

TABLE I. Results of the fit of short-baseline data taking into account all MiniBooNE data (LOW), only the MiniBooNE data above 475 MeV (HIG), without MiniBooNE data (noMB) and without LSND data (noLSND). The results of the fit without neutrino oscillations are given in the first three lines, whereas the other lines refer to the 3+1 fit. We list the χ^2, the number of degrees of freedom (NDF), the goodness-of-fit (GoF), the best-fit values of the 3+1 oscillation parameters and the quantities relevant for the appearance-disappearance (APP-DIS) parameter goodness-of-fit (PG) [61]. In the last

New research reactor in Japan

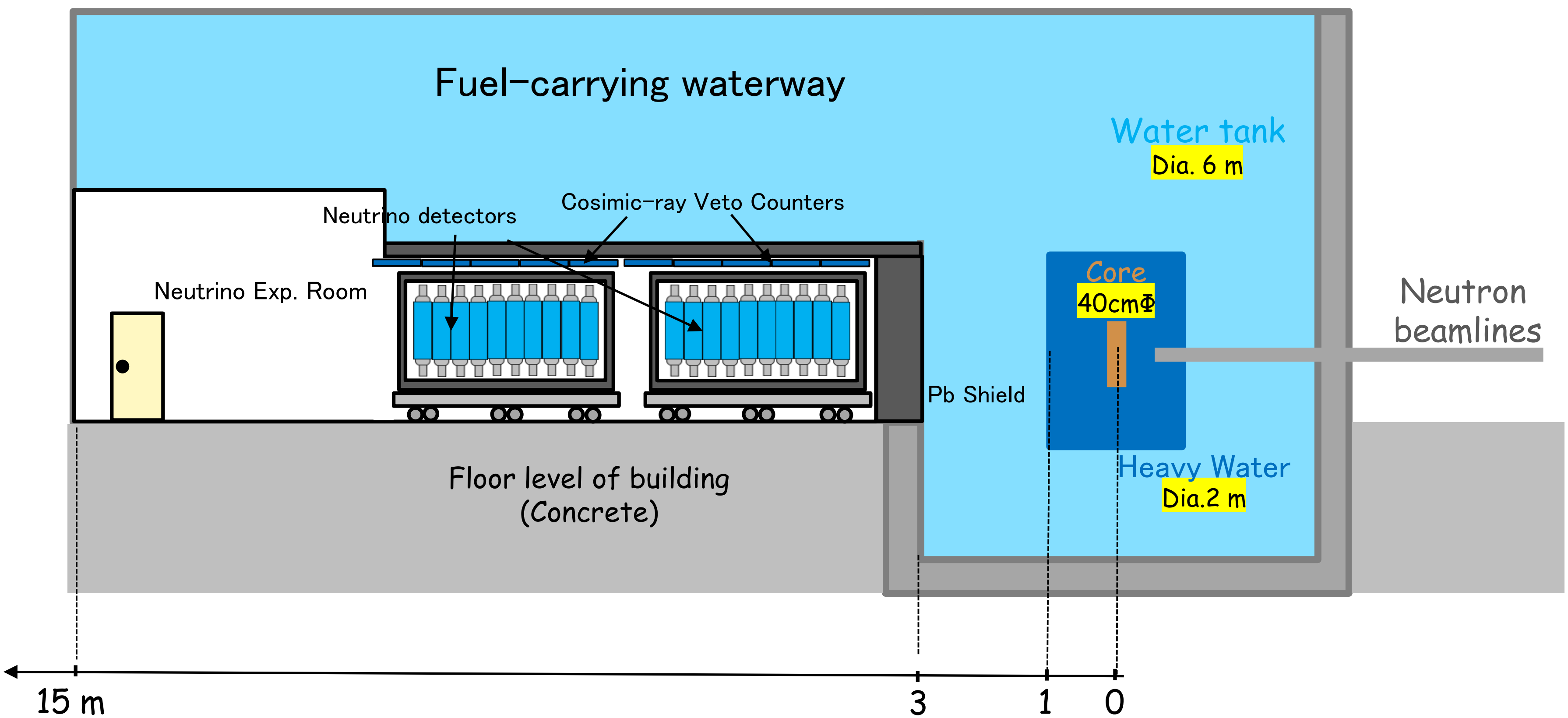
- A new research reactor is planned at the site of Monju/Fukui Pref..
  - Currently, the design of the reactor core is in progress.
  - Various research and industrial applications are planned.
  - These design will be done in the near future in the vicinity of the reactor core.
  - This is an excellent opportunity to propose a site for research using reactor anti-neutrinos.





Conceptual Design

- Proposed facility (Laboratory room)
  - Realize a low background laboratory (high SN)
    - γ-rays, neutrons → environmental level at sea level lab.
  - Shield the inner walls of the laboratory and around the detector to achieve an extremely low radioactivity environment
  - Cosmic ray induced BG → Tag all passing events around the detector



Potential in new research reactor

- What is the advantage ? ➔ Newly constructed
- What can be done with "some" degree of freedom in design?
  - To improve SN, BG reduction (for ex., shielding)
  - Requested at the designing stage ➔ possibly taken into account

- Detection method
  - Initial design → organic scintillator + Gd, Li^6
  - Need options for detector replacement to ensure variety in research
  - Need to be "**as close as possible**" since studying with neutrinos.

Topic of nuclear and particle physics research

- ✓ Neutrino oscillation (sterile neutrino search)
- ✓ Precise measurement of reactor neutrinos
  - ✓ Spectrum, flux (time-dependent)
- ✓ Neutrino nuclear reactions
- ✓ Magnetic moment search for neutrinos (low energy)
- ✓ Coherent scattering with nuclei, elastic scattering with electrons

Summary

- Many experimental data suggest RAA at short baseline, and searches for sterile neutrinos are active.

- Why conduct neutrino research in a new research reactor?
  - Design flexibility
  - Close to the reactor core
  - The detector
  - BG reduction (shields) are important to improve SN → Need to be considered at the design stage. Possible !