Testing the Gallium Anomaly Using Liquid Scintillators

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Based on **EC** *et al.*, **JHEP 07 (2025) 017**

Gallium Anomaly: disappearance channel $\nu_e \rightarrow \nu_e$

- Neutrino flux from the Sun was considerably lower than the prediction (50-70% deficit) $\rightarrow$ **solar neutrino problem**, solved in 2002 (Nobel Prize for Physics in 2015)
- Issue: most of solar neutrinos have very low energies $\rightarrow$ difficult to detect

W.-M. Yao et al. [PDG], JPG 33, 1 (2006)
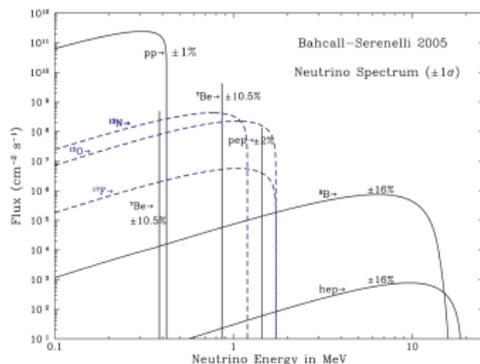
- GALLEX and SAGE: detect ν_e from Sun using neutrino capture on ^{71}Ga

$$^{71}Ga + \nu_e \rightarrow^{71} Ge + e^-$$

thres.: 234 keV

- ^{71}Ge is unstable (half-life: 11.5 days) $\rightarrow$ extracted and activity measured

Gallium Anomaly: disappearance channel $\nu_e \to \nu_e$

- To exclude that the deficit was due to detector systematic, calibration using radioactive sources (mostly ^{51}Cr), late 1990's - early 2000's

- However, observed flux was 20% less that expected $\to$ **Gallium anomaly**

- Recently confirmed by the BEST experiment (2022) using an upgraded version of SAGE detector and an intense ^{51}Cr source
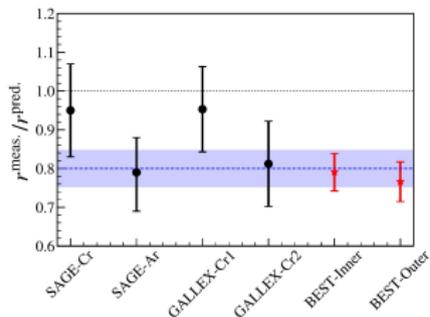
$R = 0.82 \pm 0.03$

S.R. Elliott, V.N. Gavrin, W.C. Haxton, Prog.Part.Nucl.Phys. 134 (2024) 104082

- Significance of the anomaly, depending on the model used, ranges from 5 to 6 σ's (for example, **C. Giunti** *et al.*, **Phys.Lett.B 842 (2023) 137983; M. Cadeddu** *et al.*, **arXiv: 2507.13103 [hep-ph]**)

Possible Explanations

Status of the Gallium anomaly: **unsolved!**
Any explanation of the Gallium Anomaly is **either in tension with other experimental results, requires new physics, or both**.
Possible explanations:
(see **V. Brdar, J. Gehrlein, J. Kopp, JHEP 05 (2023) 143** for a review)

- Source (estimation of source activity, etc...)
- Detector (cross section of ν capture, ^{71}Ge extraction efficiency, etc...)
- Sterile Neutrinos
- Other BSM explanations (ν_s coupled with DM/DE, decaying ν_s, CPT violation, etc...)

Source

^{51}Cr has 2 decay modes

10% $^{51}\text{Cr} \rightarrow ^{51}\text{V} + \nu_e + \gamma$ $E_{\nu,1} = 430$ keV $E_\gamma = 320$ keV
90% $^{51}\text{Cr} \rightarrow ^{51}\text{V} + \nu_e$ $E_{\nu,2} = 750$ keV

Source activity estimated by measuring the 320 keV γ's → even a small error in the BR could explain the anomaly
However, these BR have been measured separately by 4 different collaborations, with great precision

TABLE XVIII. A summary of the branching ratio of the 320 keV emission from ^{51}Cr.

Branching ratio	Reference	Method
0.1030(19)	[70]	Ge(Li)
0.0990(8)	[71]	NaI
0.1008(11)	[71]	HPGe
0.099(1)	[72]	HPGe (Beta-gamma coincidence)
0.0987(3)	[73]	Si(Li) with fixed activity

Table from V.V. Barinov *et al.*, Phys.Rev.C 105 (2022) 6, 065502
[70] S. Fisher and R. Hershberger, Nucl.Phys.A 423 (1984) 121-129
[71] A. Konstantinov *et al.*, Nucl.Inst.Metho.Phys.Res.A, 339, 200 (1994)
[72] P. Yalcin and Y. Kurucu, Appl.Radiat.Isot. 62, 63 (2005)
[73] D. S. Moreira *et al.*, Appl.Radiat.Isot. 68, 596 (2010)

Detector

- Different models give different prediction for the cross section
 $\rightarrow$ change the significance of the anomaly, but not drastically

Model	$R^{\mathrm{HR}}_{\mathrm{GALLEX\text{-}1}}$	$R^{\mathrm{HR}}_{\mathrm{GALLEX\text{-}2}}$	$R^{\mathrm{HR}}_{\mathrm{SAGE\text{-}Cr}}$	$R^{\mathrm{HR}}_{\mathrm{SAGE\text{-}Ar}}$	$R^{\mathrm{HR}}_{\mathrm{BEST\text{-}in}}$	$R^{\mathrm{HR}}_{\mathrm{BEST\text{-}out}}$	$\overline{R}^{\mathrm{HR}}$	GA
Ground State [33]	1.00 ± 0.12	0.85 ± 0.12	1.00 ± 0.13	0.83 ± 0.10	0.83 ± 0.05	0.80 ± 0.05	$0.845^{+0.031}_{-0.031}$	5.0
Bahcall [10]	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.09	0.79 ± 0.05	0.77 ± 0.05	$0.804^{+0.037}_{-0.036}$	5.2
Haxton [30]	0.86 ± 0.10	0.74 ± 0.10	0.86 ± 0.11	0.72 ± 0.08	0.72 ± 0.05	0.70 ± 0.05	$0.731^{+0.088}_{-0.072}$	5.1
Frekers et al. [31]	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.09	0.78 ± 0.05	0.75 ± 0.05	$0.789^{+0.033}_{-0.032}$	6.1
Kostensalo et al. [32]	0.97 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.09	0.81 ± 0.05	0.78 ± 0.05	$0.825^{+0.031}_{-0.031}$	5.5
Semenov [33]	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.09	0.77 ± 0.05	0.75 ± 0.05	$0.787^{+0.033}_{-0.032}$	6.1

Table from **C. Giunti** *et al.*, **Phys.Lett.B 842 (2023) 137983**

- Efficiency in the extraction of ^{71}Ge and/or activity estimation
  also considered

Detector

However, in 2024, comparison of solar neutrino fluxes measured at
GALLEX and SAGE with the ones measured at Borexino (electron
neutrino scattering) **found no tension** (**M.C. Gonzalez-Garcia** *et al.*,
JHEP 02 (2024) 064): if the issue was in the detection process, we
would expect a deficit in solar neutrinos as well
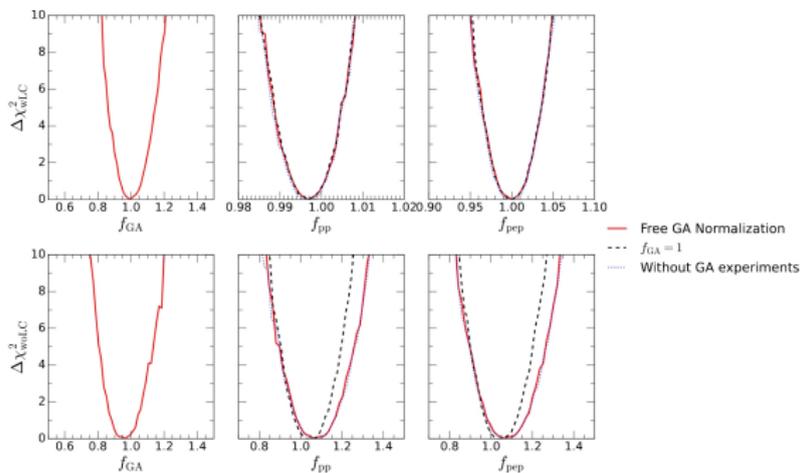
Plot from **M.C. Gonzalez-Garcia** *et al.*, **JHEP 02 (2024) 064**

Sterile Neutrinos

Until a few years ago, it seems that most of the anomalies can be explained with just 1 family of sterile neutrinos, $\Delta m^2 \sim 1$ eV^2. However

- **Reactor anomaly** due to errors in the theoretical predictions
- Sterile neutrinos would not be able to explain **MiniBOONE**'s LEE.
- **More important**, severe tension with the **negative results** obtained by several experiments
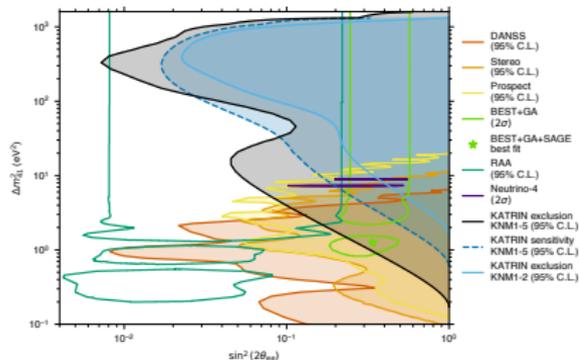
Plot from **KATRIN, arXiv: 2503.1866**

Focus of the community is now on trying to find a "local" explanation for each anomaly separately, rather than find a global solution (**M. Maltoni, Neutrino2024**)

Testing Ga Anomaly Without Ga Detectors

Testing Ga Anomaly
Without Ga Detectors

Electron Neutrino Scattering

No simple solutions seems available for this anomaly
Very difficult to solve it without new data

Our Idea

- Study the anomaly using the same source but a different method, namely electron-neutrino scattering
- Cross section of the process is known with excellent precision
- If the anomaly is still present, we can exclude any explanation related to the detection method. Otherwise, we will know exactly where the issue is
- Liquid scintillators would give us additional information, such as space distribution of the events, energy distribution, etc... which were difficult to get in Ga experiments

EC *et al.*, **JHEP 07 (2025) 017**

Other similar proposals: **P. Huber, Phys.Rev.D 107 (2023) 9, 096011; G. Chauhan, P. Huber, arXiv:2507.07397 [hep-ph], G. Benato, TAUP2025**

SOX

This is similar to the set-up proposed by the SOX experiment

SOX: Short distance neutrino Oscillations with BoreXino

ABSTRACT:

The very low radioactive background of the Borexino detector, its large size, and the well proved capability to detect both low energy electron neutrinos and anti-neutrinos make an ideal case for the study of short distance neutrino oscillations with artificial sources at Gran Sasso.

This paper describes the possible layouts of ^{51}Cr (ν_e) and ^{144}Ce–^{144}Pr ($\bar{\nu}_e$) source experiments in Borexino and shows the expected sensitivity to eV mass sterile neutrinos for three possible different phases of the experiment. Expected results on neutrino magnetic moment, electroweak mixing angle, and couplings to axial and vector currents are shown too.

They were planning to use also a different radioactive source, ^{144}Ce, to search for sterile neutrinos. There were issues with the production of ^{144}Ce, however, and the experiment was canceled. To avoid these issues, in our study we assumed only the use of ^{51}Cr, and a **source activity** of **3 MCi** (comparable to the one used in BEST).
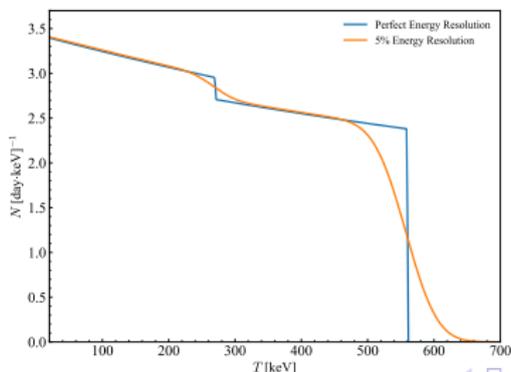
Electron-Neutrino Scattering

Maximum recoil energy:

$$T_{max}(E_\nu) = \frac{2E_\nu^2}{2E_\nu^2 + m_e} \qquad T_{max}(E_{\nu,1}) \sim 270 \text{ keV} \qquad T_{max}(E_{\nu,2}) \sim 560 \text{ keV}$$

Energy spectrum

$$\frac{d\sigma}{dT}(T, E_\nu) = \frac{2G_F^2 Z m_e}{\pi}\left(C_L^2 + C_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - C_L C_R \frac{m}{E_\nu}\frac{T}{E_\nu}\right)$$

$C_L = \mathrm{Sin}^2(\theta_W) + 1/2$ and $C_R = \mathrm{Sin}^2(\theta_W)$

Detector Requirements

- **Extremely low background** : using radioactive source event rate is quite low, very low background required
- **keV-scale low-energy threshold**, at least 200 keV
- **Ton-scale detector**.

Note: if we increase the size R of the detector, the signal grows like R, while usually the bg grows like R^3: if detector is very large, it might be useful to consider only part of it.
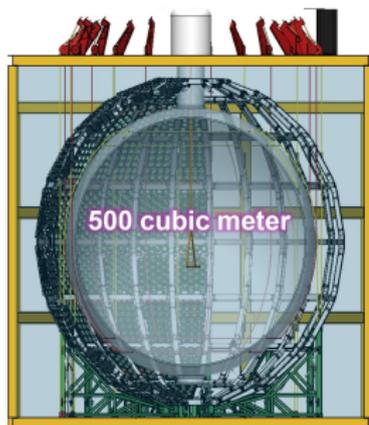

$$L_{eff} = \frac{R}{3}$$
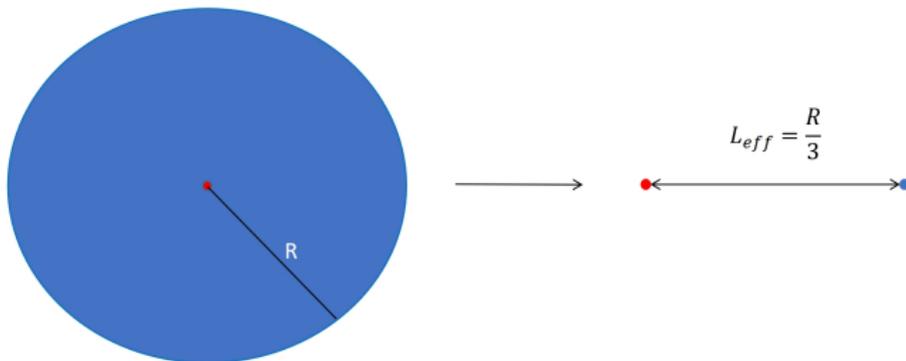
Possible Locations

We considered two possible location for the experiment, both
liquid scintillators

**JUNO**, 20 kton 700 m overbuden

JNE, 2,400 m overbudern (CJPL)

For JNE, both the 1-ton prototype (LAB scintillator, already
operative) and the 500 ton detector (under construction, expected
to be operative in 2027)

Background

- **JNE**, 500 ton, if LAB is used $\rightarrow$ ^{14}C main source of bg; nat. abundance: $f_C \sim 10^{-12}$, in Borexino (for example), $f_C \sim 2 \times 10^{-18} \rightarrow \sim 2 \times 10^7$ evts/day
- However, Q-value of ^{14}C is 156 keV $\rightarrow$ rejection via low-energy veto or looking for Cherenkov light
- No such issue if pure water is used
- ^{7}Be solar neutrino: < 700 evts/day
- **JUNO** $\rightarrow$ ^{11}C (37,000 evts/day), . Possible solution: only part of the detector is used

Data from **F. An** *et al.*, **J. Phys. G 43, no.3, 030401 (2016);**

J. F. Beacom *et al.*, **Chin. Phys. C 41, no.2, 023002 (2017)**
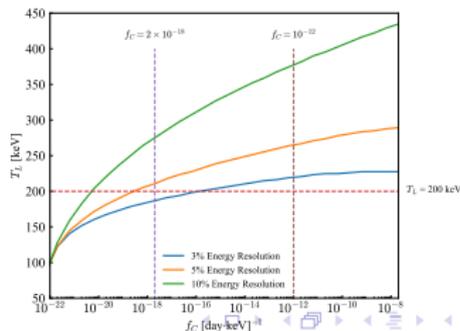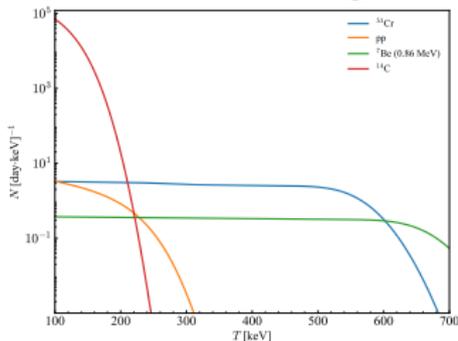
Expected Signal

Runtime is limited by half-life of ^{51}Cr, ~ 28 days

Expected number of events (3 MCi source activity), 200 keV low-energy threshold

Detector	D (m)	Events/day	10 days	30 days
JNE 1 ton	1	71.0	628.1	1,497.86
JNE 1 ton	0	315.9	2,794.7	6,664.9
JNE 500 ton	6	1,080.3	9,557.5	22,793.3
JNE 500 ton	0	3,701.4	32,745.9	78,094.5
JUNO	19	4,566.6	40,400.5	96,349.9
JUNO	0	12,881.1	113,959.1	271,777.2

$\sigma \simeq 1/\sqrt{N_{tot}}$, to exclude 20% anomaly at 5 σ's we need at least 625 events if **bg is negligible**

Requirements on Source Activity

If the expected number of events is very large, we can relax the requirements on the source activity.

Weaker source $\rightarrow$ bg more relevant. If $N \sim B$, we need 1250 events for $5\sigma' s$. Rough estimation:

$$N(R, A) = B(R) \qquad B(R) = N(R, A) = 1250$$

N= number of events, B= background, A=activity, R=dimension of the part of the detector considered

Detector	10 days		30 days	
	A (MCi)	R (m)	A (MCi)	R (m)
JNE - Center	0.23	2.5	0.14	1.73
JNE - Outside	0.92	3.2	0.68	2.0
JUNO - Center	0.24	2.4	0.14	1.7
JUNO - Outside	1.4	2.5	1.2	1.6

Branching Ratio

Possible (in principle!) to measure the BR of ^{51}Cr decay as well. Very challenging, and the precision that can be achieved is significantly lower than the current one, however it would be an independent check of a possible cause of the anomaly
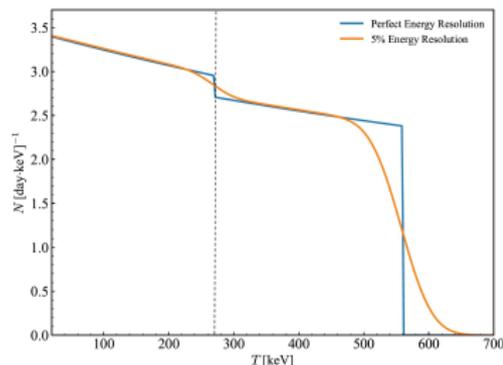
Two possible ways too measure the BR:

- **"Brute Force"**: measure the discontinuity in the recoil spectrum at 270 keV
- **Neutrino Energy**: from θ (via Cherenkov) and T $\to E_\nu$

With the "brute force" method, we would need at least 10^5 events (challenging), if we want to reconstruct the neutrino energy, we would need an angular resolution $< 13°$ (very challenging: for comparison, at JNE expected angular resolution $\sim 46°$ at 2 MeV)

Summary

- Gallium Anomaly still a puzzle after 30 years, confirmed in 2022 and currently at $> 5\sigma$'s significance

- Every possible explanation is either in tension with experimental results, requires new physics, or both

- Possible to test it using electron-neutrino scattering: in this way we would know for sure if the cause is related to the detection process, or if it lies somewhere else

- Very low-background environment required, ton-scale detector. Possible to run at JUNO and JNE

Backup Slides

Backup
Slides

# LSND Anomaly: appearance ch. $\bar{\nu}_\mu \to \bar{\nu}_e$

- First one to be detected (1990's)
- Excess observed in the appearance channel, $\bar{\nu}_\mu \to \bar{\nu}_e$
- ν via μ Decay At Rest, $E_\nu \sim 30$ MeV, $L \sim 35$ m
- L/E **not compatible** with oscillations in the 3-flavor model, requires $\Delta m^2 \geq 0.1\text{eV}^2$ (significance: 3.8σ's) $\to$ new (sterile) neutrino flavor?
- KARMEN did not confirm, but was not able to completely exclude
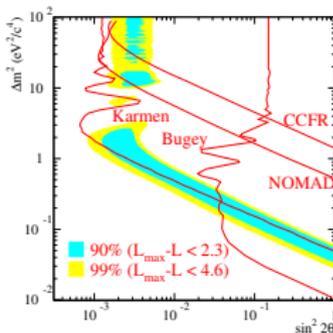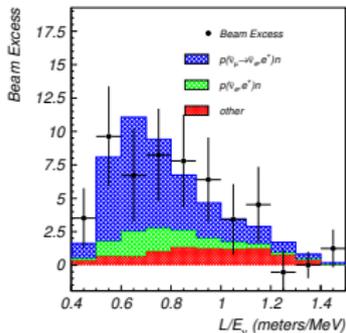
A. Aguilar-Arevalo et al. [LSND], PRD 64 (2001) 112007

MiniBooNE Anomaly: appearance ch. $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

- ν via μ Decay In Flight, higher E and larger L, but same L/E: $E_\nu = 200 - 1250$ MeV, $L \sim 540$ m
- Both $\bar\nu$ and ν
- Excess in the appearance channel consistent with LSND (4.8σ's) **BUT** also a Low Energy Excess (LEE) that cannot be explained with oscillations
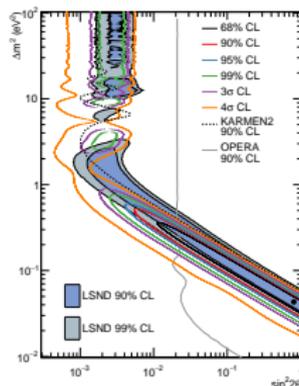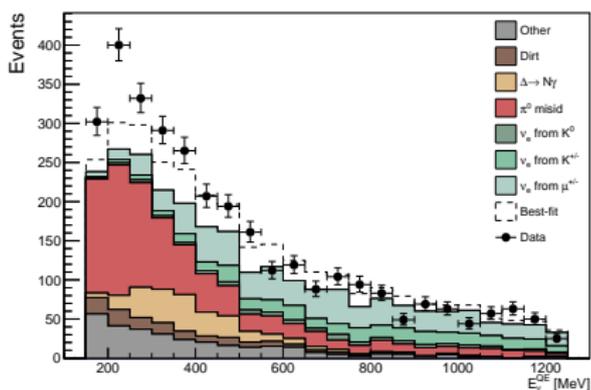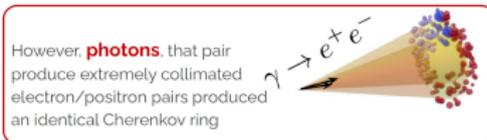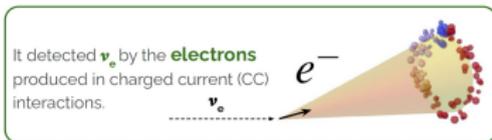

Left: **A. Aguilar-Arevalo et al. [MiniBooNE] PRD 103 (2021), 052002**,
Right: **P. Abratenko et al. [MiniBooNE] PRL 130, 011801 (2023)**

MicroBooNE

- Same beam as MiniBooNE, slightly different baseline (~ 70 m shorter)
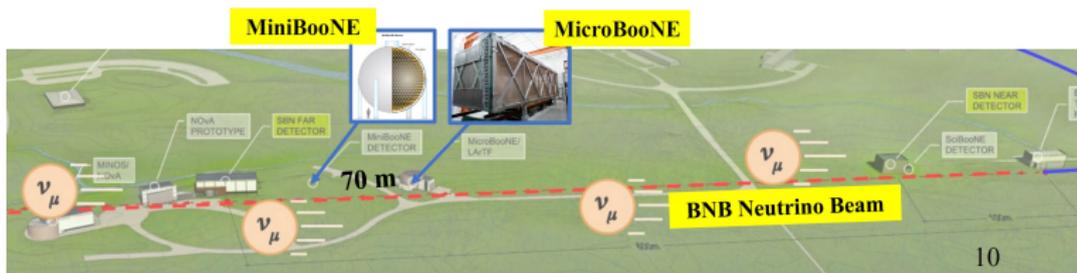
- Using LArTPC instead of Cherenkov detector $\rightarrow$ better tracking capabilities
- In particular, it was able to discriminate between CC events $\nu_e \rightarrow e^-$ and $\gamma \rightarrow e^- + e^+$ events

It detected ν_e by the **electrons** produced in charged current (CC) interactions.

However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring

Pictures from **X.P. Ji, TAUP2025**

MicroBooNE

- No sign of MiniBooNE-like excess (no ν_e nor γ)
- MicroBooNE disfavors sterile explanation, but does not exclude it completely
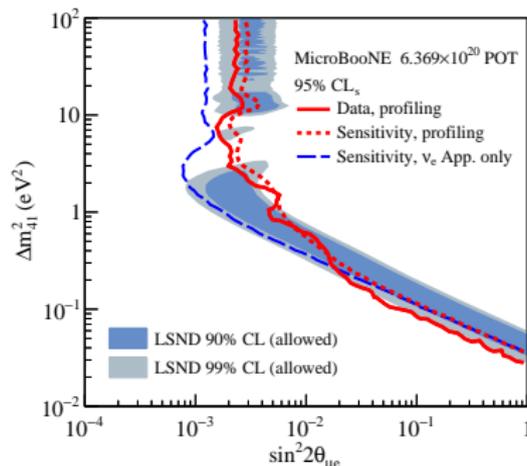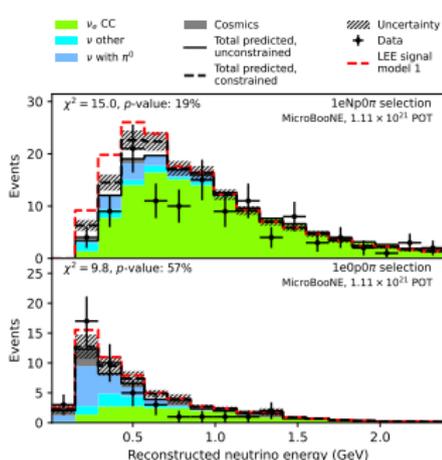
Left: **P. Abratenko et al. [MicroBooNE] PRL 135, 081802 (2025)**,

Right: **P. Abratenko et al. [MicroBooNE] PRL 130 (2023) 011801**

Status of LSND/MiniBooNE anomaly: **not clear!**

JSSN[2], in Japan, will be able to test LSND/MiniBooNE anomaly

Reactor Neutrino Anomaly: disappearance channel $\bar{\nu}_e \rightarrow \bar{\nu}_e$

- In 2011, re-evaluation of reactor neutrino flux up of $\rightarrow \sim 3.5\%$
- Hence, all the short baseline experiments (which were in agreement with the predictions) now were detecting a deficit
- Again, if oscillations were responsible for the deficit, $\Delta m^2 \geq 1 \text{ eV}^2$
- Also, difference in energy spectrum observed at 4-6 MeV ("5 MeV bump")
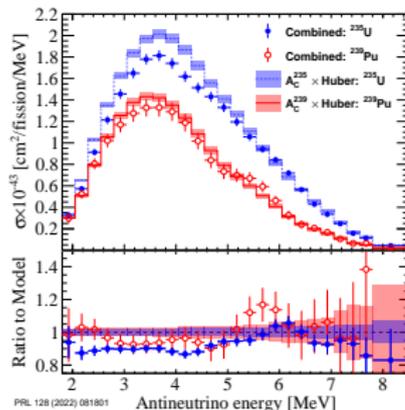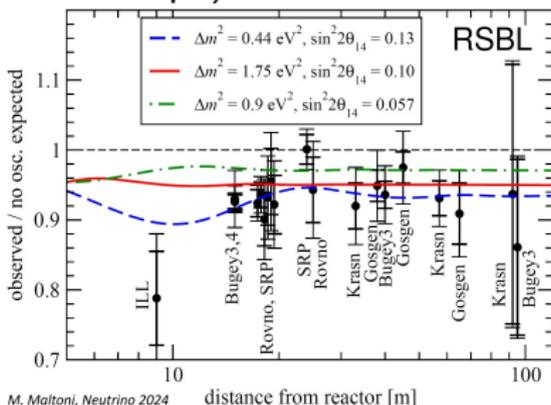
Left: **M. Maltoni, Neutrino2024**,
Right: **F.P. An et al. [DayaBay], [PROSPECT], PRL 128 (2022) 8, 081801**

Flux Re-Evaluation

- RAA **NOT** fuel-independent (which would be expected if due to sterile ν)
- ^{239}Pu flux in agreement with models, ^{235}U not *(PRL 118 (2017) 251801)*, *PRL. 122 (2019) 232501, Nature 613 (2023) 257-261*
- Neutrino flux re-evaluated *(EF: PRL 123 (2019) 022502, HKSS: PRC 100 (2019) 054323, KI: PRD 104 (2021) 7 L071301)*, EF and KI in agreement with ex. data (sign. 0.8 and 1.4σ's), HKSS not (3.0 σ's), see also *PLB 829 (2022) 137054*
- 5 MeV bump accounted by HKSS but not KI and EF
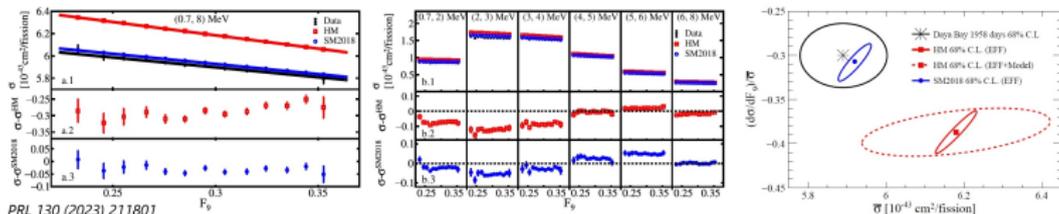
PRL 130 (2023) 211801

F.P. An et al. [DayaBay], PRL. 130 (2023) 21, 211801

Status of RAA: considered **solved** (bump still in tension with models, but no baseline dependence $\rightarrow$ no sterile ν)

Reactor Neutrino Models

Two approaches

- **Ab initio calculations** (also called **summation** models): compute the spectrum for each β decay individually, then sum them, weighted by their BR
  - Main issue: very large number of isotopes involved ($\sim 10^2$) and BR ($\sim 10^3$)
- **Conversion** method: starts with the β spectrum, then use a conversion matrix to to calculate the

Two issues seems to cause the RAA and 5 MeV bump

1. Error in the β spectrum for ^{235}U (RAA), **V. I. Kopeikin et al, Phys. At. Nucl. 84, 1 (2021).**, see also Pandemonium effect **J. C. Hardy et al., Phys. Lett. B 71, 307 (1977).** Taken into account in EF and KI

2. First-forbidden decays (5 MeV bump), taken into account in HKSS

Source Production

In Ga experiments, source was produced via $^{50}Cr+n\rightarrow^{51}Cr$ Possible alternatives:

- Produce it locally
  - Requires a research reactor $\rightarrow$ present in China!
  - Bureaucracy for producing and moving the source will be a nightmare
- Produce it outside China (ex: Russia).
  - Bureaucracy even more complicated
  - SOX tried this way, and they had to cancel the experiment
  - On The other hand, we could use benefit from the expertise of people who already worked on this kind of experiments

Sterile Neutrino

Finite size of the detector $\rightarrow$ range of baseline that can be explored.

In Ga detector it is very difficult to reconstruct the position where the neutrino was observed; this was only partially achieved in BEST by dividing the detector in two parts, inner and outer (no significant difference were observed, however).

In liquid scintillators it would be possible to reconstruct precisely the interaction point: if some dependence on the baseline is observed, this would be a strong evidence in favor of sterile neutrinos
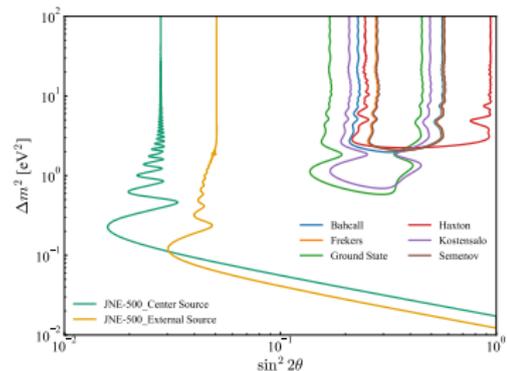
Plot from **EC** *et al.*, **JHEP 07 (2025) 017**