Testing the Gallium Anomaly Without Using Gallium Detectors

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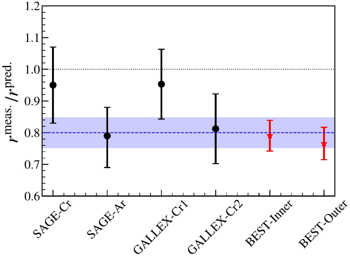
Based on EC *et al.*, JHEP 07 (2025) 017

Gallium Anomaly

- First observed during calibration of GALLEX and SAGE (solar neutrino) using radioactive sources (mostly, ^{51}Cr). Neutrino rate was only ∼80% of the expected value (1990's-2000's)
- Recently confirmed by the BEST experiment (2022) using an upgraded version of SAGE detector and 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]**)
- Ga detectors: $^{71}Ga + \nu_e \rightarrow ^{71} Ge + e^-$

Possible Explanations

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

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

Source activity estimated by measuring the 320 keV γ's $\rightarrow$ 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.MethodsPhys.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

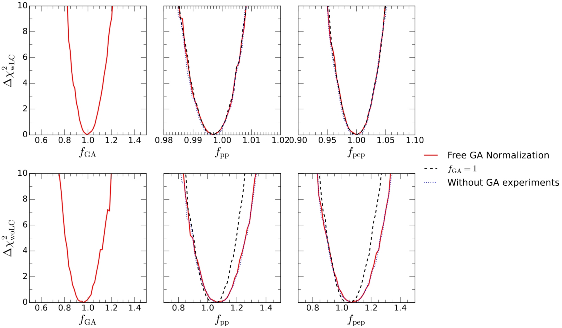
- Different models give different prediction for the cross section $\rightarrow$ change the significance of the anomaly, but not drastically

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

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

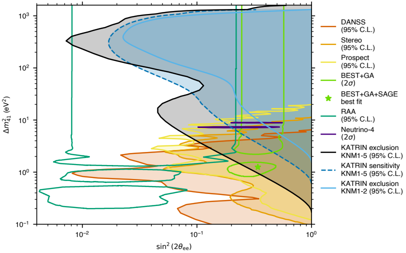


Plot from **M.C. Gonzalez-Garcia** *et al.*, **JHEP 02 (2024) 064**

Sterile Neutrinos

A few years ago this hypothesis gained a lot of traction, because it seemed that it could explain several anomalies (**Reactor, LSND/MiniBOONE**) with just 1 family of sterile neutrinos, $\Delta m^2 \sim 1$ eV^2. However (see also talks by Schwetz, Lindner, etc...)

- **Reactor anomaly** (mostly?) due to errors in the theoretical predictions
- Sterile neutrinos would not be able to explain the low-energy excess observed in **MiniBOONE**.
- 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**)

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

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]**
See also G. Benato's talk on Thursday

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

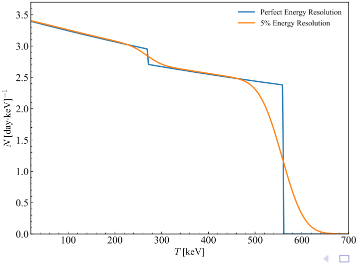
Maximum recoil energy:

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

Energy spectrum

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

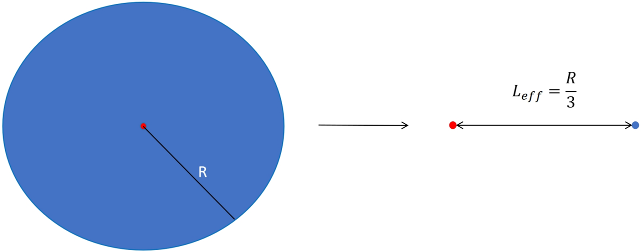
$C_L = \mathrm{Sin}^2(\theta_W) + 1/2$ and $C_R = \mathrm{Sin}^2(\theta_W)$



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**.

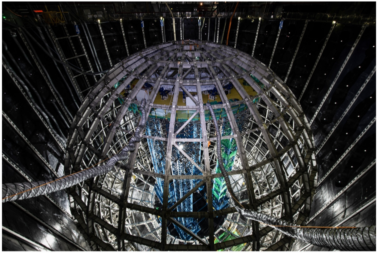
Note: if we increase the size R of the detector, the signal grows like R, while usually the bg grows like R^3: if detector is very large, it might be useful to consider only part of it.



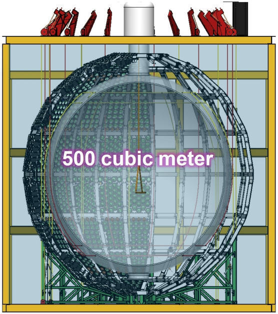
Possible Locations

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

JUNO, 20 kton 700 m overbuden



JNE, 2,400 m overbudern (CJPL)



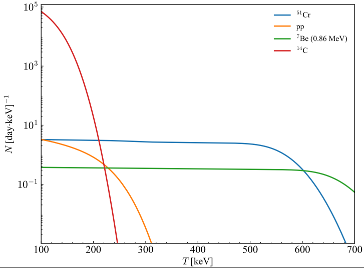
For JNE, both the 1-ton prototype (LAB scintillator, already operative) and the 500 ton detector (under construction, expected to be operative in 2027, see W. Lou talk earlier today)

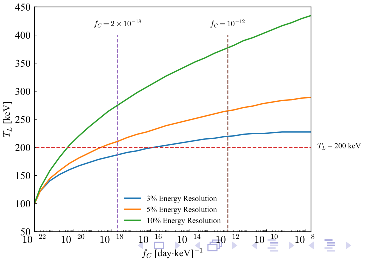
Background

- **JNE**, 500 ton, if LAB is used → ^{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 → rejection via low-energy veto or looking for Cherenkov light
- No such an issue if pure water is used
- ^{7}B solar neutrino: < 700 evts/day
- **JUNO** → ^{11}C (37,000 evts/day), ^{7}B (10,000 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, $\sim$ 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

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

Gallium Experiments

GALLEX and SAGE were solar neutrino experiments, they detected ν_e via the reaction

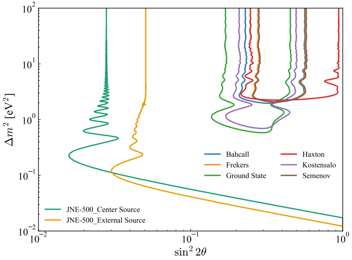
$$^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^-$$

- Main advantage: low energy threshold, 234 keV
- ^{71}Ge is unstable, event rate was obtained by collecting Ge and measuring its activity
- ^{71}Ge half-life: $\sim$ 11.5 days

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).

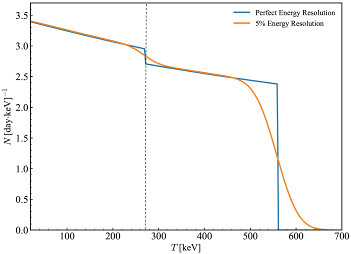
In liquid scintillators it would be possible to reconstruct precisely the interaction point: if some dependence on the baseline is observed, this would be a strong evidence in favor of sterile neutrinos



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

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 $\rightarrow E_\nu$

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)