The Gallium Anomaly

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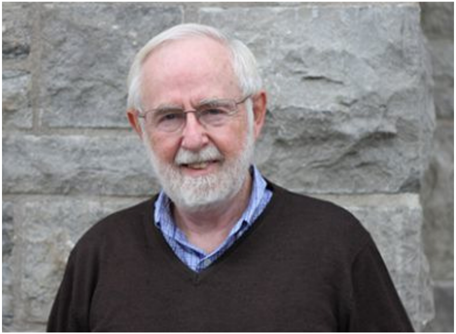
MOSCOW STATE UNIVERSITY

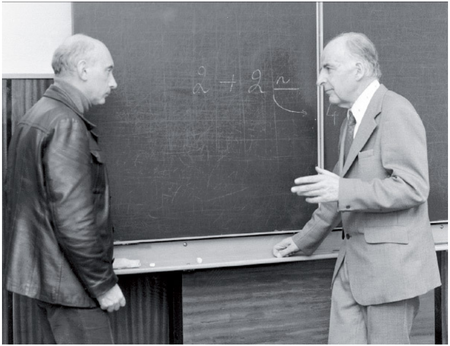
10^{th} Anniversary of the 2015 Nobel Prize



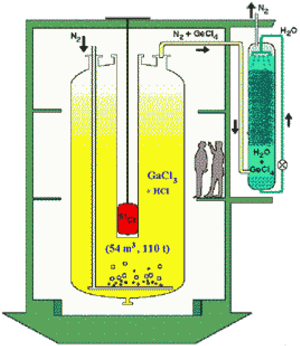
- The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".
- The 17th International School on Neutrino Physics and Astrophysics is dedicated to the 10th anniversary of the 2015 Nobel Prize.

Founders of the Theory of Neutrino Oscillations

Bruno Pontecorvo and Samoil Bilenky



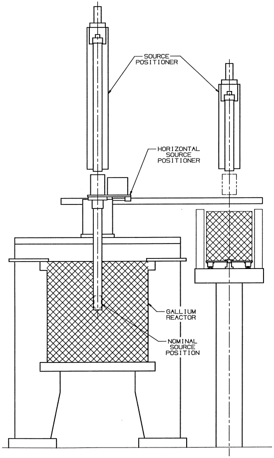
Gallium Radioactive Source Experiments



GALLEX

1995 & 1998

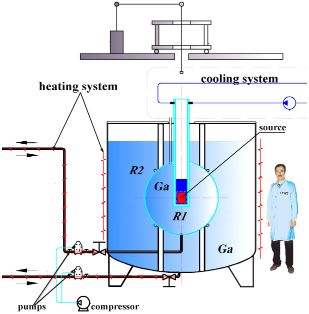
$\langle L \rangle_{\text{GALLEX}} \simeq 1.9\,\text{m}$



SAGE

1999 & 2006

$\langle L \rangle_{\text{SAGE}} \simeq 0.6\,\text{m}$



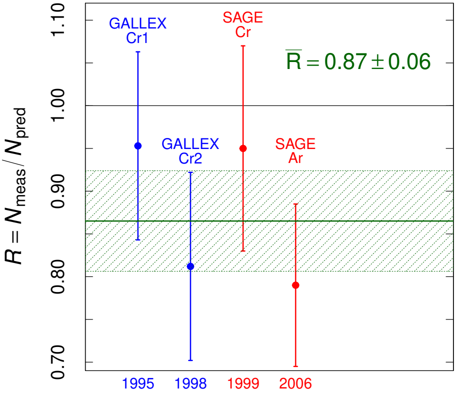
BEST

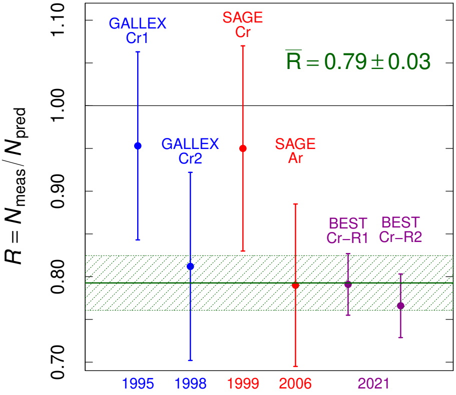
2021

$\langle L \rangle^{\text{R1}}_{\text{BEST}} \simeq 0.7\,\text{m}$

$\langle L \rangle^{\text{R2}}_{\text{BEST}} \simeq 1.1\,\text{m}$

Gallium Anomaly (Bahcall Cross Sections)





Before BEST: $\approx 2.3\sigma$ deficit

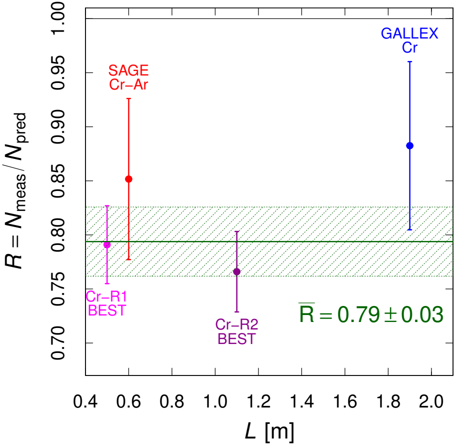
Mild Anomaly!

After BEST: $\approx 5.9\sigma$ deficit

Strong Anomaly!

SAGE: nucl-ex/0512041, 0901.2200;
Laveder et al: NPPS 168 (2007) 344, hep-ph/0610352, 0711.4222, 1006.3244, 1507.08204;
Kostensalo et al, 1906.10980

BEST: 2109.11482, 2109.14654, 2201.07364;
Barinov and Gorbunov: 2109.14654;
Huber et al: 2111.12530, 2209.02885;
Brdar et al: 2303.05528; Banks et al: 2311.06352;
Schwetz et al: 2303.15524, 306.09422;
Elliott et al: 2303.13623, 2306.03299;
CG et al: 2209.00916, 2212.09722, 2312.00565, 2507.13103



- No clear model-independent anomaly from different path lengths.
- A constant suppression can fit all data.
- After the BEST measurements, the Gallium Anomaly is still an anomaly based on the absolute comparison of observed and predicted rates.

The Ingredients of the Gallium Anomaly

- The ν_e flux.
- The ν_e propagation probability.
- The $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ detection cross section.
- The radiochemical ${}^{71}\text{Ge}$ extraction efficiency.

The ν_e Sources

$e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$

$E \simeq 0.75\,\text{MeV}$ and $E \simeq 0.43\,\text{MeV}$

$e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

$E \simeq 0.81\,\text{MeV}$

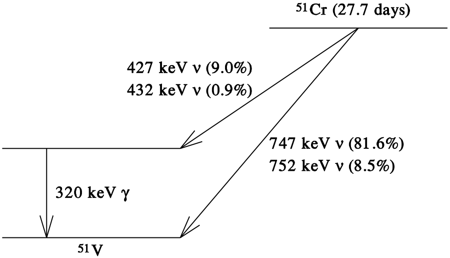
$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Detection

The ν_e Flux

The neutrino flux is evaluated by calorimetric measurements of the activity of the sources:

^{51}Cr Source [SAGE, hep-ph/9803418]



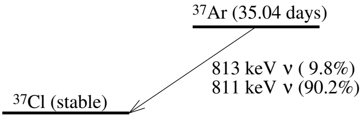
γ energy release per decay:

$320\,\text{keV} \times 0.099 \simeq 31.7\,\text{keV}$

Atomic energy release:

$36.750 \pm 0.084\,\text{keV}$ [BEST, 2015]

^{37}Ar Source [SAGE, nucl-ex/0512041]

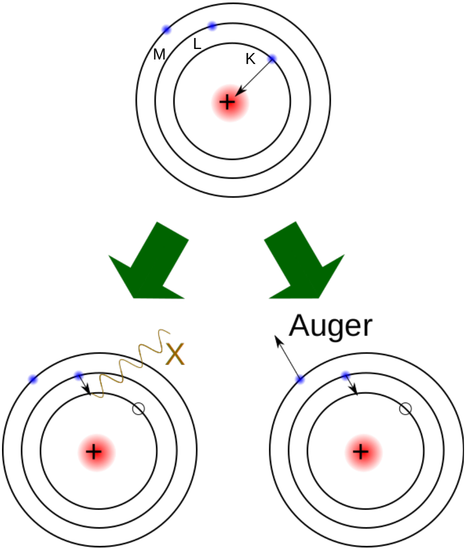


Atomic energy release:

$2.751 \pm 0.021\,\text{keV}$

[SAGE, nucl-ex/0512041]

Atomic Energy Release

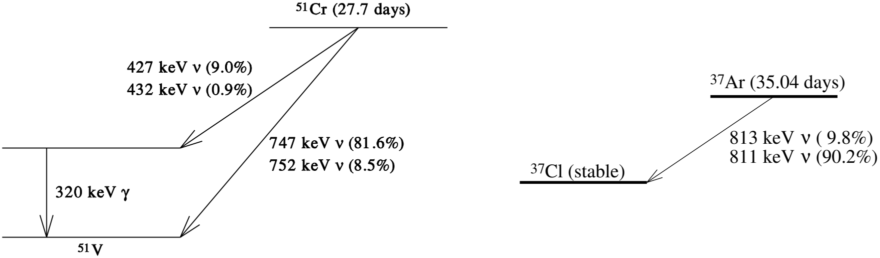


Well measured radioactivity of the sources

- GALLEX Cr1 [PLB 1995] : $1.714^{+0.030}_{-0.043}\,\text{MCi} = 63.4^{+1.1}_{-1.6}\,\text{PBq}$ ($\approx 2.5\%$ unc.)
- GALLEX Cr2 [PLB 1998] : $1.868^{+0.090}_{-0.057}\,\text{MCi} = 69.1^{+3.3}_{-2.1}\,\text{PBq}$ ($\approx 3\%$ unc.)
- SAGE Cr [hep-ph/9803418] : $0.5166 \pm 0.0060\,\text{MCi} = 19.11 \pm 0.22\,\text{PBq}$ ($\approx 1.2\%$ unc.)
- SAGE Ar [nucl-ex/0512041] : $0.409 \pm 0.002\,\text{MCi} = 15.1 \pm 0.7\,\text{PBq}$ ($\approx 4.6\%$ unc.)
- BEST Cr [arXiv:2109.11482] : $3.414 \pm 0.008\,\text{MCi} = 12.632 \pm 0.030\,\text{PBq}$ ($\approx 0.3\%$ unc.)

$(1\,\text{Ci} = 3.7 \times 10^{10}\,\text{Bq})$

The ν_e Propagation Probability



	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.00930	0.9020	0.098
σ [10^{-46} cm^2]	62.58	63.22	26.72	27.14	71.35	71.63

[Barinov, Cleveland, Gavrin, Gorbunov, Ibragimova, arXiv:1710.06326]

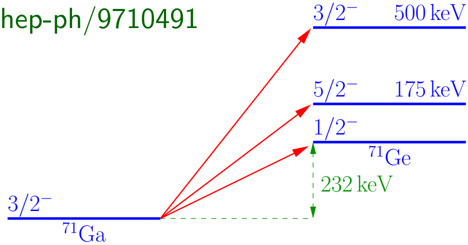
$$\langle P_{\nu_e\to\nu_e}\rangle = \frac{\int \mathrm{d}V\, L^{-2} \sum_i (\mathrm{B.R.})_i\, \sigma_i\, P_{\nu_e\to\nu_e}(L, E_i)}{\sum_i (\mathrm{B.R.})_i\, \sigma_i \int \mathrm{d}V\, L^{-2}}$$

[Acero, CG, Laveder, arXiv:0711.4222]

The detection cross section

- Deficit could be due to an overestimate of
$$\sigma(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-)$$

- First calculation: Bahcall, hep-ph/9710491



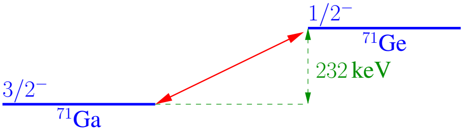
- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03\,\text{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45}\,\text{cm}^2$$ [Bahcall, hep-ph/9710491]

- $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}\right)$

- The contribution of excited states is only $\sim 5\%$! [Bahcall, hep-ph/9710491]

The Ground State Cross Section



$$\sigma_{G.S.}(^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}) \propto \mathrm{BGT}_{G.S.}(^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}) \propto \Gamma(^{71}\mathrm{Ge}) \propto \frac{1}{T_{1/2}(^{71}\mathrm{Ge})}$$

- The Gallium Anomaly could be explained with a decrease of the Ground State Cross Section through an increase of the ^{71}Ge half life.

[CG, Li, Ternes, Xin, arXiv:2212.09722]

- Recent measurements of the ^{71}Ge half life:

$$T_{1/2}^{\mathrm{CY}}(^{71}\mathrm{Ge}) = 11.46 \pm 0.04\,\mathrm{d}$$ [Collar and Yoon, 2023]

$$T_{1/2}^{\mathrm{LLNL}}(^{71}\mathrm{Ge}) = 11.468 \pm 0.008\,\mathrm{d}$$ [Norman et al. (LLNL), 2024]

- Confirm the 1985 Hampel and Remsberg measurement

$$T_{1/2}^{\mathrm{HR}}(^{71}\mathrm{Ge}) = 11.43 \pm 0.03\,\mathrm{d}$$ [Hampel, Remsberg, PRC 31 (1985) 666]

- Exclude the explanation of the Gallium Anomaly with a decrease of the Ground State Cross Section through an increase of the ^{71}Ge half life.

The $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$ Cross Section

Model	Method	^{51}Cr $\sigma_{\mathrm{g.s.}}$	^{51}Cr σ_{tot}	^{51}Cr δ_{exc}	^{37}Ar $\sigma_{\mathrm{g.s.}}$	^{37}Ar σ_{tot}	^{37}Ar δ_{exc}
Bahcall (1997) [hep-ph/9710491]	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	5.53 ± 0.01	$5.81^{+0.21}_{-0.16}$	4.8%	6.62 ± 0.02	$7.00^{+0.49}_{-0.21}$	5.4%
Elliott et al. (2023) [arXiv:2303.13623] (p,n)	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	$5.39^{+0.04}_{-0.04}$	$5.69^{+0.28}_{-0.06}$	5.3%	$6.45^{+0.05}_{-0.05}$	$6.85^{+0.35}_{-0.08}$	5.8%
Cadeddu et al. (2025) [arXiv:2507.13103] (p,n)		$5.41^{+0.07}_{-0.07}$	$5.71^{+0.27}_{-0.08}$	5.3%	$6.47^{+0.08}_{-0.08}$	$6.87^{+0.34}_{-0.10}$	5.8%
Elliott et al. (2023) [arXiv:2303.13623] $(^3\mathrm{He}, {}^3\mathrm{H})$	$^{71}\mathrm{Ga}(^3\mathrm{He},{}^3\mathrm{H})^{71}\mathrm{Ge}$	$5.39^{+0.04}_{-0.04}$	$5.85^{+0.18}_{-0.10}$	7.9%	$6.45^{+0.05}_{-0.05}$	$7.02^{+0.19}_{-0.14}$	8.1%
Cadeddu et al. (2025) [arXiv:2507.13103] $(^3\mathrm{He}, {}^3\mathrm{H})$		$5.41^{+0.07}_{-0.07}$	$5.83^{+0.16}_{-0.16}$	7.2%	$6.47^{+0.08}_{-0.08}$	$7.05^{+0.21}_{-0.21}$	8.2%

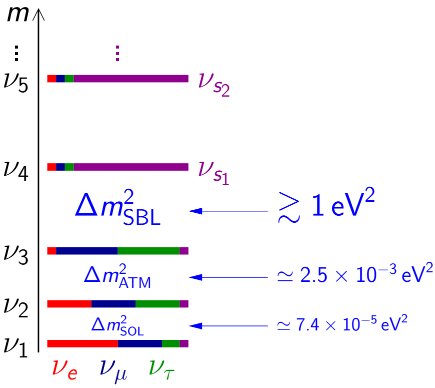
Units of $10^{-45}\,\mathrm{cm}^2$

Size of the Gallium Anomaly

Model	$\overline{R}$	GA
Bahcall (1997) [hep-ph/9710491]	$0.800^{+0.035}_{-0.038}$	5.9σ
Elliott et al. (2023) [arXiv:2303.13623] (p, n)	$0.817^{+0.028}_{-0.047}$	6.3σ
Cadeddu et al. (2025) [arXiv:2507.13103] (p, n)	$0.814^{+0.029}_{-0.045}$	6.1σ
Elliott et al. (2023) [arXiv:2303.13623] $(^3\mathrm{He}, ^3\mathrm{H})$	$0.795^{+0.030}_{-0.033}$	6.5σ
Cadeddu et al. (2025) [arXiv:2507.13103] $(^3\mathrm{He}, ^3\mathrm{H})$	$0.797^{+0.035}_{-0.034}$	5.3σ

- Large anomaly with all cross section calculations!
- Even neglecting the excited states contribution, the anomaly is larger than 5σ.

Light Sterile Neutrinos



Active-Sterile
Neutrino Mixing

$$\nu_\alpha = \sum_{k=1}^{N} U_{\alpha k} \nu_k$$

where $N \geq 3$ and

$$\alpha = e, \mu, \tau, s_1, s_2, \ldots$$

$$\boxed{L_{kj}^{\text{osc}} = \frac{4\pi E}{\Delta m_{kj}^2}}$$

Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

- Minimal perturbation of successful 3ν mixing:
  effective 4ν mixing with $|U_{e4}|, |U_{\mu4}|, |U_{\tau4}| \ll 1$

Effective 3+1 Active-Sterile Neutrino Oscillations

Effective short-baseline survival probability of ν_e (Gallium experiments) and $\bar{\nu}_e$ (SBL reactor experiments):

$$P_{ee}^{\text{SBL}} \simeq 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

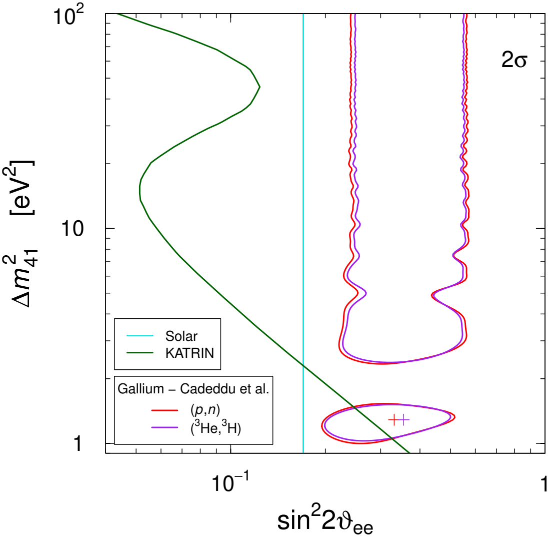
with different notations in the literature:

$$\vartheta_{ee} = \vartheta_{14} = \vartheta_{\text{new}} = \vartheta$$

and

$$\Delta m^2_{41} = \Delta m^2_{\text{SBL}} = \Delta m^2_{\text{new}} = \Delta m^2$$

3+1: Gallium Tension with Solar ν and KATRIN



[Cadeddu et al., arXiv:2507.13103]

- Gallium and Solar neutrinos are ν_e.
- KATRIN and reactor neutrinos are $\bar{\nu}_e$.
- There is a tension also with SBL reactor antineutrinos.
- A very exotic CPT violation could remove the tensions with reactor and KATRIN antineutrinos.

  [CG, Laveder, arXiv:1008.4750]
- There is no CPT-violating solution of the Gallium-Solar neutrino tension!

[Solar ν: arXiv:2411.16840; KATRIN: arXiv:2503.18667]

Tentative Alternative Explanations of the Gallium Anomaly

- Four-Neutrino Mixing (effective 3+1 Active-Sterile Neutrino Oscillations) is a general possibility which can be tested in many experiments and was not invented for the Gallium Anomaly.
- Typical Alternative Explanations of the Gallium Anomaly are invented ad hoc for the Gallium Anomaly.

scenario	comments	our rating
Explanations within the Standard Model		
increased ^{71}Ge half-life (section 2.1 and ref. [39])	would lead to smaller matrix element for $\nu + {}^{71}$Ga; but the ^{71}Ge half-life has been measured many times with different methods in [38], all of which yield consistent results. So it is hard to imagine a bias in these measurements.	★★☆☆☆
new ^{71}Ga excited state (section 2.2)	would imply a bias in the extraction of the $\nu + {}^{71}$Ga matrix element from the measured ^{71}Ge half-life. Some very old experiments claim the existence of such a state, but this has not been confirmed in more recent observations.	★★☆☆☆
increased BR(^{51}Cr $\to$ ^{51}V*) (section 3)	would cause a bias in translating the heat output of the source to a neutrino production rate. Measurements of BR(^{51}Cr $\to$ ^{51}V*) show some tension, but it is far less than the shift required to explain the gallium anomaly.	★★★☆☆
^{71}Ge extraction efficiency (section 4)	one of SAGE's calibration runs has revealed a large bias. Could a small, unnoticed, bias have been present in all gallium experiments?	★★★★☆

[Brdar, Gehrlein, Kopp, arXiv:2303.05528]

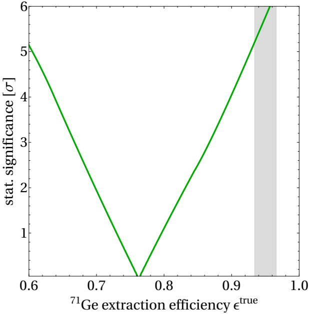
Explanations beyond the Standard Model

ν_s coupled to ultralight DM (MSW resonance, section 5.1.1)	several exotic ingredients; somewhat tuned MSW resonance; new ν_4 decay channel required for cosmology.	★★★★☆
ν_s coupled to dark energy (MSW resonance, section 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, section 5.1.3)	several exotic ingredients; somewhat tuned parametric resonance; cosmology requires post-BBN DM production via misalignment.	★★★★☆
decaying ν_s (section 5.2)	difficult to reconcile with reactor and solar data; regeneration of active neutrinos in ν_s decays alleviates tension, but does not resolve it.	★★☆☆☆
vanilla eV-scale ν_s (refs. [17, 18])	preferred parameter space is strongly disfavored by solar and reactor data.	★☆☆☆☆
ν_s with CPT violation (ref. [130])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (refs. [131–133])	neutrinos oscillate into sterile Kaluza-Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (ref. [134])	based on a difference between sterile neutrino mixing angles at production and detection (see also [135, 136]); fit worse than for vanilla ν_s.	
decoherence (refs. [137, 138])	non-standard source of decoherence needed; known experimental energy resolutions constrain wave packet length, making an explanation by wave packet separation alone challenging.	
ν_s coupled to ultralight scalar (ref. [139])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	

Radiochemical ^{71}Ge Extraction Efficiency

- BEST outer volume:
  10 extractions of $\sim 100\ {}^{71}\mathrm{Ge}$ atoms in $\sim 40\,\mathrm{t} \sim 3 \times 10^{29}$ atoms
- For each experiment, the ^{71}Ge extraction efficiency ϵ^{cal} was obtained with special calibration measurements.
- An overestimate of the extraction efficiency can obviously explain the Gallium Anomaly:

$$\epsilon^{\mathrm{true}} < \epsilon^{\mathrm{cal}} \quad \Longrightarrow \quad R^{\mathrm{true}} = \frac{N_{\mathrm{meas}}}{N_{\mathrm{pred}}} \frac{\epsilon_{\mathrm{cal}}}{\epsilon_{\mathrm{true}}} > \frac{N_{\mathrm{meas}}}{N_{\mathrm{pred}}} = R$$



"resolving the anomaly would require the calibration to be off by around 20%"

[Brdar, Gehrlein, Kopp, arXiv:2303.05528]

Checks of the ^{71}Ge Extraction Efficiency

- GALLEX performed a hot-atom chemistry* test introducing ^{71}As and counting the ^{71}Ge atoms produced in $e^- + {}^{71}\text{As} \to {}^{71}\text{Ge} + \nu_e$:

  $100 \pm 1\%$ recovery [GALLEX, PLB 436 (1998) 158]

- SAGE introduced about $700\,\mu g \sim 6 \times 10^{18}$ atoms of stable natural Ge carrier at the beginning of each of the 8 exposures:

  $95 \pm 3\%$ recovery [SAGE, arXiv:0901.2200]

- BEST introduced about $175\,\mu g \sim 1.5 \times 10^{18}$ atoms of stable natural Ge carrier at the beginning of each of the 10+10 exposures:

  $95 \pm 1.6\%$ recovery [BEST,arXiv:2109.11482]

- More: see the experimental papers and the review

  Elliott, Gavrin, Haxton, arXiv:2306.03299

- Conclusion: a 20% calibration overestimate seems very unlikely

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* The ^{71}Ge recoil energy is close to that in $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ for a ^{51}Cr source and comparable to the $\sim 3 - 4\,\text{eV}$ chemical binding energy of the extracted $GeCl_4$.

Decoherence Explanation of the Gallium Anomaly

[Farzan, Schwetz, arXiv:2306.09422]

- "Our proposal does not require the presence of sterile neutrinos but implies a modification of the standard quantum mechanical evolution equations for active neutrinos"
- However, "the decoherence that we postulate here requires exotic new physics"
- "conventional decoherence based on particle localisation leads only to tiny effects which are negligible for all oscillation experiments considered here"
- $P_{ee} = \sum_{i=1}^{3} |U_{ei}|^4 + \sum_{i \neq j} |U_{ei}|^2 |U_{ej}|^2 e^{-i\phi_{ij}} e^{-\gamma_{ij} L}$ with $\phi_{ij} = \dfrac{\Delta m^2_{ji} L}{2E_\nu}$ and

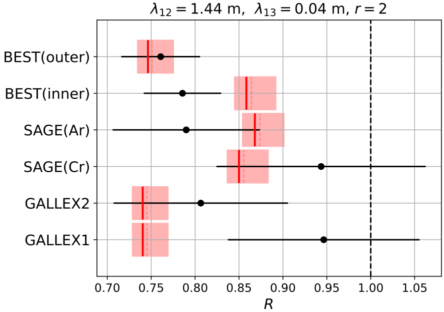
$$\gamma_{ij} = \frac{1}{\lambda_{ij}} \left(\frac{0.75\,\mathrm{MeV}}{E_\nu} \right)^r \quad \text{with} \quad \gamma_{23} = \gamma_{12} + \gamma_{13} \pm 2\sqrt{\gamma_{12}\gamma_{13}}$$

- In Gallium experiments $\phi_{ij} \ll 1 \Rightarrow e^{-i\phi_{ij}} \approx 1$. Best fit: $\lambda_{13} \to 0 \Rightarrow \gamma_{23} = \gamma_{12}$

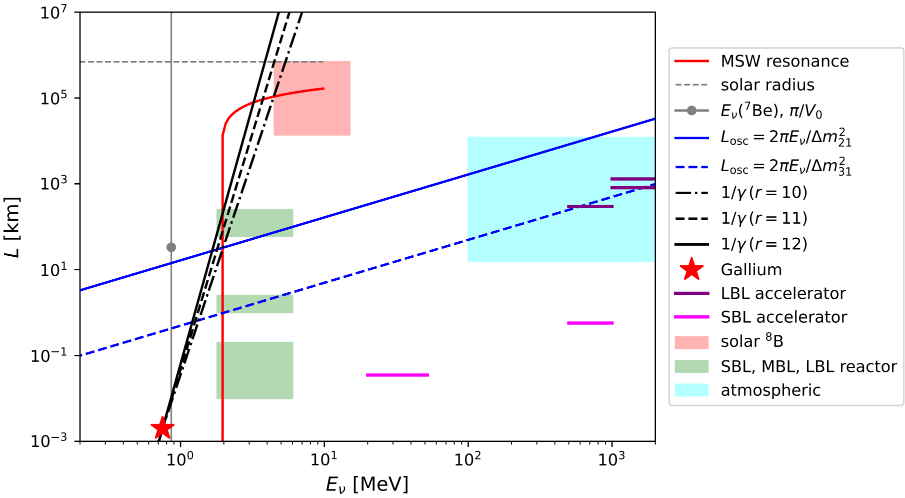
$$P_{ee}^{\mathrm{gal}} \approx 1 - \frac{1}{2}\sin^2 2\theta_{13} - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_{12}\left(1 - e^{-\gamma_{12} L}\right)$$

- "Numerically we have $0.5\cos^4\theta_{13}\sin^2 2\theta_{12} \approx 0.404$. Hence, we need partial decoherence in the 12 sector to obtain $P_{ee}^{\mathrm{gal}} \simeq 0.8$"

	$r=2$					$r=12$				
	$\chi^2_{\min}$/dof	p-val.	$\Delta\chi^2$	$\#\sigma$	λ_{12} [m]	$\chi^2_{\min}$/dof	p-val.	$\Delta\chi^2$	$\#\sigma$	λ_{12} [m]
CS1, BEST	2.0/1	0.16	30.1	5.1	1.44	1.7/1	0.19	30.4	5.2	1.44
CS1, all	7.7/5	0.17	28.6	5.0	1.74	8.3/5	0.14	28.0	4.9	2.10
CS2, BEST	2.6/1	0.11	32.1	5.3	1.19	2.2/1	0.14	32.5	5.4	1.44
CS2, all	8.4/5	0.14	30.0	5.1	1.44	9.2/5	0.10	29.2	5.0	1.74



- "While this is a huge improvement compared to the p-values of the null hypothesis the fit is not perfect"
- "This is related to the partial decoherence in the 12 sector"
- "It leads to a distance dependence on the scale of gallium experiments which in particular predicts different event ratios in the inner and outer detector volumes of the BEST experiment"



- Solar and KamLAND oscillations $\Longrightarrow$ $r \gtrsim 10$ Extreme!
- SBL reactor antineutrino data $\Longrightarrow$ $r \gtrsim 7$ [CG, Ternes, arXiv:2312.00565]
- "A testable prediction of our scenario is a distance dependent deficit at the radioactive source experiments" [Farzan, Schwetz, arXiv:2306.09422]

Other Proposed Solutions of the Gallium Anomaly

- Active-sterile mixing with wavepacket-induced decoherence

  [Arguelles, Bertolez-Martinez, Salvado, arXiv:2201.05108, Hardin et al, arXiv:2211.02610]

  Extremely small wave packet size $\sigma \approx 6.7 \times 10^{-5}\,\text{nm}$ in tension with:

  - a theoretical estimation: $\approx (2 - 14) \times 10^{2}\,\text{nm}$ [Akhmedov, Smirnov, arXiv:2208.03736]

  - phenomenological bounds: $\sigma > 2.1 \times 10^{-4}\,\text{nm}$ at 90% C.L.

    [de Gouvea, De Romeri, Ternes, arXiv:2005.03022, 2104.05806]

  In tension with the reactor antineutrino rates [CG, Ternes, arXiv:2312.00565]

- ν_4 decay [Hardin et al, arXiv:2211.02610; Brdar, Gehrlein, Kopp, arXiv:2303.05528]

  In tension with the reactor antineutrino rates [CG, Ternes, arXiv:2312.00565]

- Broad ν_4 mass distribution [Banks, Kelly, McCullough, Zhou, arXiv:2311.06352]

  In tension with the reactor antineutrino rates [CG, Ternes, arXiv:2312.00565]

Compatibility with Solar Neutrinos

- The Gallium experiments SAGE and GALLEX/GNO measured the solar neutrino flux with about 5% uncertainty $(66.1 \pm 3.1\,\text{SNU})$
- Taking into account the results of other solar neutrino experiments and neutrino oscillations [SAGE, arXiv:0901.2200]

$$\Phi_{pp}^{\text{Gallium}} = (6.0 \pm 0.8) \times 10^{10}\,\text{cm}^{-2}\,\text{s}^{-1}\text{: about } 13\% \text{ uncertainty}$$

- In agreement with the Borexino measurement [Borexino, Nature 562 (2018) 505]

$$\Phi_{pp}^{\text{Borexino}} = (6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}\,\text{cm}^{-2}\,\text{s}^{-1}\text{: about } 12\% \text{ uncertainty}$$

and with the Standard Solar Model (SSM) predictions

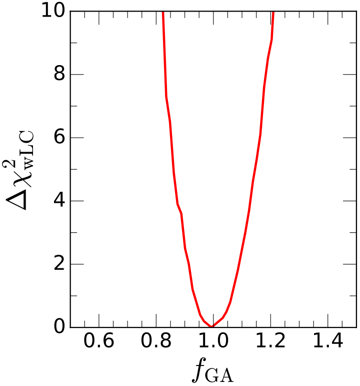
$$\Phi_{pp}^{\text{HZ}} = 5.98(1 \pm 0.006) \times 10^{10}\,\text{cm}^{-2}\,\text{s}^{-1}$$
$$\Phi_{pp}^{\text{LZ}} = 6.03(1 \pm 0.005) \times 10^{10}\,\text{cm}^{-2}\,\text{s}^{-1}$$

[Vinyoles et al, arXiv:1611.09867]

- The $\sim 20\%$ reduction of the detection efficiency of the Gallium experiments indicated by the Gallium Anomaly, which implies a $\sim 20\%$ increase of $\Phi_{pp}^{\text{Gallium}}$, would be in tension with Borexino and SSM

Global Fit of Solar Neutrino Data

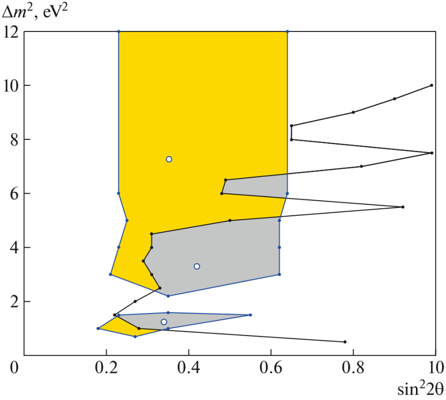
[Gonzalez-Garcia, Maltoni, Pinheiro, Serenelli, arXiv:2311.16226]



- f_{GA} multiplies the predicted event rates of all solar fluxes in the Gallium experiments
- "the global analysis of the solar experiments do not support a modification of the neutrino capture cross section in Gallium (or any other effect inducing an energy-independent reduction of the detection efficiency in the Gallium experiments)"
- "This is so because the global fit implies a rate of *pp* and ^{7}Be neutrinos in the Gallium experiment which is in good agreement with the luminosity constraint as well as with the rates observed in Borexino"

Future Experimental Proposals

- Perform another high-intensity experiment with ^{51}Cr or another source
- BEST-2: 50 tons of ^{71}Ga divided into 3 zones, irradiated with a ^{65}Zn (Zinc) EC source [Gorbachev, Gavrin, Ibragimova, Phys.Atom.Nucl. 86 (2023) 1385]



Sensitivity for a 0.5 Mci ^{65}Zn source

- Longer half life: $244.01 \pm 0.09\,\mathrm{d}$
  Allows more extractions
- Higher ν_e energy: 1350 keV
  Probes larger values of Δm^2_{41}
- Larger detection cross section
  Bigger event rate
- Problem: larger contribution of model-dependent transitions to higher energy excited states of ^{71}Ge

- Real-time detection of ν_e from a ^{51}Cr source with a Cerium-doped Gadolinium Aluminum Gallium Garnet (Ce:GAGG) crystal scintillator detector: [Huber, arXiv:2209.02885]
  - $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ and $\nu_e + e^- \to \nu_e + e^-$
  - "With 1.5 tons of scintillator and 10 source runs of 3.4 MCi, each, we obtain about 1700 gallium capture events with a purity of 90% and 680,000 neutrino electron scattering events"
  - "this configuration would allow us to test the gallium anomaly at more than 5σ in an independent way"

- A strong ν_e or $\bar{\nu}_e$ source inside or near a liquid scintillator detector as in the cancelled projects SOX with the Borexino detector [SOX, arXiv:1304.7721] and CeLAND with the KamLAND detector [arXiv:1312.0896] :
  - JUNO: [arXiv:1507.05613]
    - A monochromatic ^{51}Cr or ^{37}Ar source of ν_e detected with $\nu_e + e^- \to \nu_e + e^-$
    - A ^{144}Ce-^{144}Pr source of $\bar{\nu}_e$ with a continuous β spectrum detected with the Inverse Beta Decay (IBD) reaction $\bar{\nu}_e + p \to n + e^+$
    - A cyclotron-produced ^{8}Li source (IsoDAR) of $\bar{\nu}_e$ with a continuous β spectrum detected with the IBD reaction
    - A ^{51}Cr source in JUNO or JNE [Ciuffoli, Evslin, Gao, Lin, Tang, arXiv:2504.16590]

- Real-time detection of ν_e from a ^{51}Cr source with a ^{115}In (Indium) target (as in the old LENS project) dissolved in a liquid scintillator detector (as LiquidO): [Chauhan and Huber, arXiv:2507.07397]
  - $\nu_e + {}^{115}\text{In} \to {}^{115}\text{Sn}^* + e^-$ and ${}^{115}\text{Sn}^* \to {}^{115}\text{Sn} + 2\gamma$
  - "a 100 ton indium target combined with 2 source runs of a 3.4 MCi ^{51}Cr source can probe the complete parameter space of the gallium anomaly"

Conclusions

- Light Sterile Neutrinos can be powerful messengers of BSM New Physics.
- Historically, the existence of light sterile neutrinos is motivated by the LSND, Gallium, and Reactor Short-Baseline Anomalies.
- The Reactor Antineutrino Anomaly, discovered in 2011, is fading away.
- The Gallium Neutrino Anomaly, discovered in 2007, has been revived by the BEST results. It is now the most significant anomaly in neutrino physics.
- The Active-Sterile neutrino oscillation explanation of the Gallium Anomaly is in tension with the results of the solar neutrino experiments and the results of the reactor and KATRIN antineutrino experiment (assuming CPT).
- No convincing SM explanation of the Gallium Anomaly has been found.
- Difficulty: known BSM explanations of the Gallium Anomaly affect also solar and reactor neutrinos if not fine-tuned with ad-hoc assumptions.