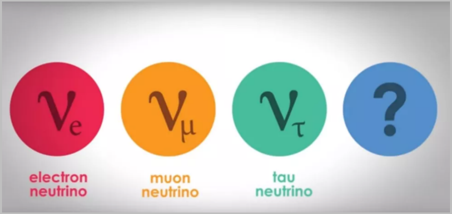
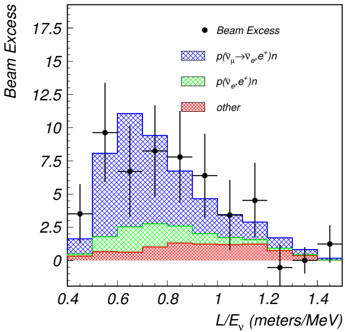
Short Baseline Oscillations and the Gallium Mystery

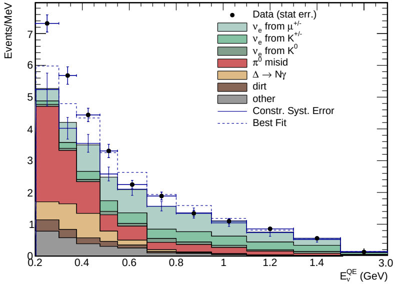


Vedran Brdar (CERN–TH)

The Fall of the Standard Three Flavor Picture?

Anomalies: LSND and MiniBooNE





- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\mathrm{km\,GeV}^{-1}$ (arXiv:hep-ex/0104049)
- MiniBooNE: reports electron-like event excess (4.8σ) (arXiv:0812.2243, 1805.12028, 2006.16883)
- in combination with LSND 6.1σ

3+1 Model with eV-scale Sterile Neutrino

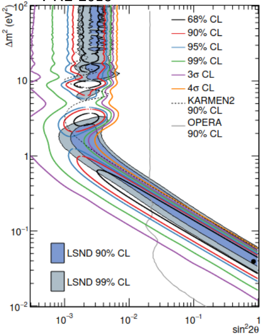
$$U^{4\text{flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \color{red}{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \color{red}{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

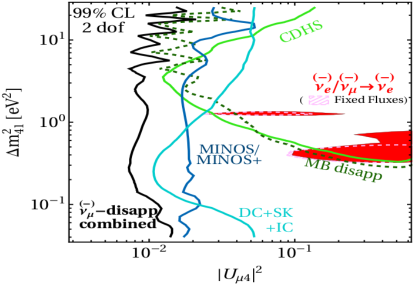
$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

$$P_{\mu e} = 4|U_{\mu 4} U_{e4}|^2 \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

PRL 2018



Dentler et al, JHEP 2018

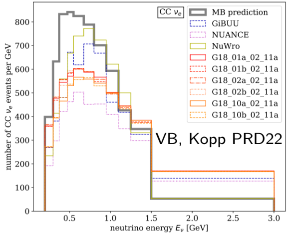


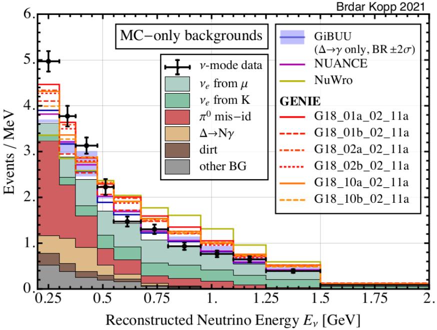
Nuclear Physics Uncertainties

$\nu_e + N \to e^- + N'$

$\nu + N \to \nu + N + \pi^0(\gamma\gamma)$

$\nu + N \to \nu + \Delta \to \nu + N\gamma$





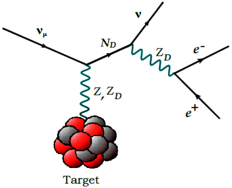
Generator	Tune	Δm^2_{41} [eV^2]	$\sin^2 2\theta_{\mu e}$	Significance
MB official		0.25	0.01	4.0σ
GiBUU	default	0.25	0.01	4.6σ
	$\mathrm{BR}(\Delta \to \gamma) - 2\sigma$	0.32	0.0063	4.9σ
	$\mathrm{BR}(\Delta \to \gamma) + 2\sigma$	0.32	0.0050	4.2σ
NUANCE	–	0.32	0.0079	4.0σ
NuWro	–	3.2	0.0020	3.5σ
GENIE	G18_01a_02_11a	0.13	0.079	4.3σ
	G18_01b_02_11a	0.79	0.0001	3.6σ
	G18_02a_02_11a	0.13	0.050	3.5σ
	G18_02b_02_11a	0.13	0.050	3.5σ
	G18_10a_02_11a	0.25	0.016	2.9σ
	G18_10b_02_11a	0.40	0.013	3.8σ

Non-oscillatory BSM Explanations of MiniBooNE Anomaly

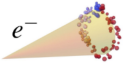
slide from MicroBooNE presentations

Evolving Theory Landscape

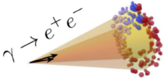
- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
  - [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
  - [4] Gninenko, Phys.Rev.D83:015015,2011
  - [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
  - [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
  - [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
  - [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
  - [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
  - [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
  - [6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
  - [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)
- A model-independent approach to any new particle
  - [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)



Produces true **electrons**

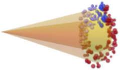


Produces true **photons**



Produces e^+e^- pairs

Overlapping e^+e^-



Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

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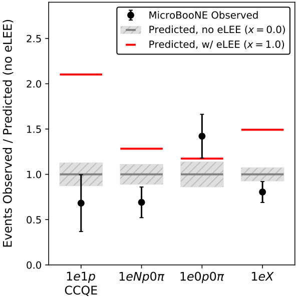
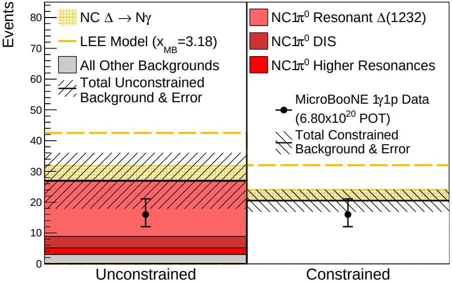
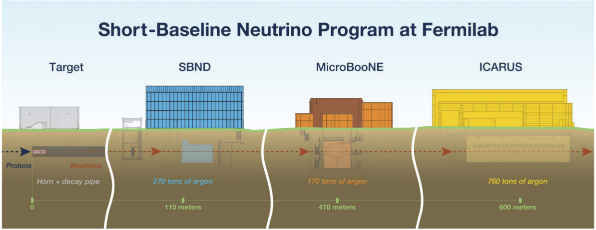
First Results from Short-Baseline Neutrino Program

2110.14054



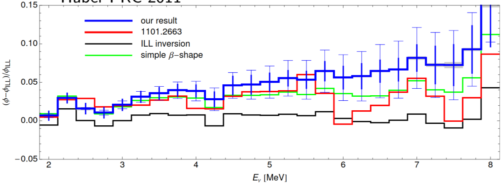
PRL 2022

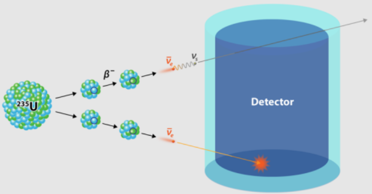




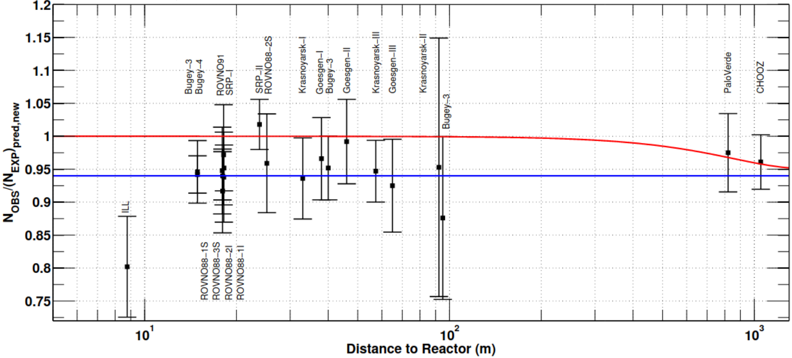
Reactor Anomaly 2011: sterile neutrino?

Huber PRC 2011



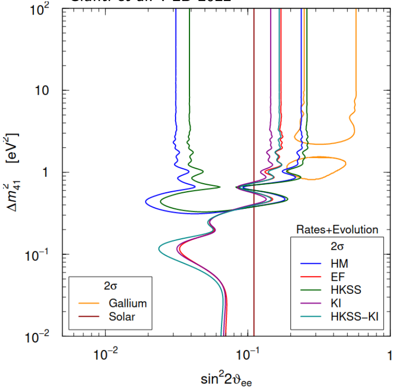


Mention et al., PRD 2011

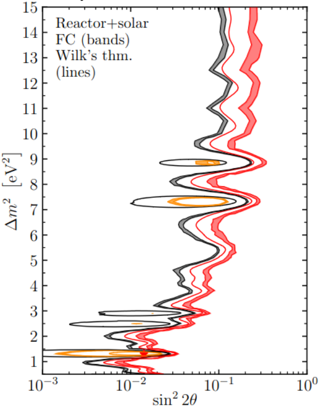


Reactor Anomaly 2023

Giunti et al. PLB 2022

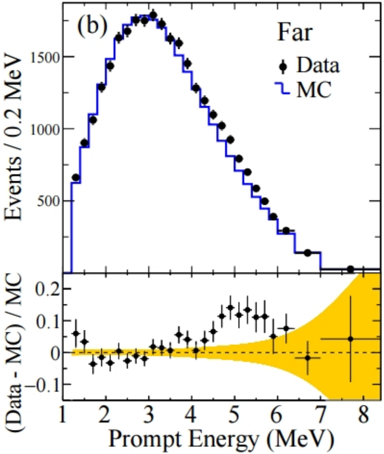


Berryman et al. JHEP 2022



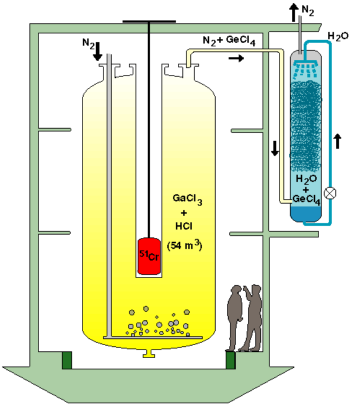
Honorable Mention: 5 MeV Bump

Reno collaboration, PRL 2016

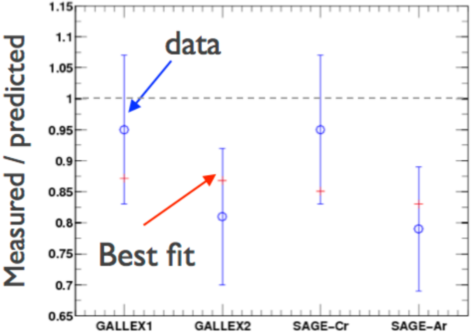


Gallium Anomaly 2020

- GALLEX, GNO, SAGE
- solar experiments
- radioactive source

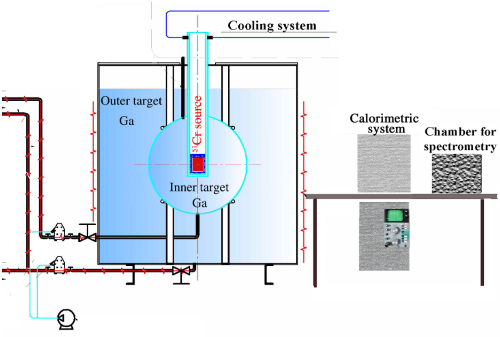


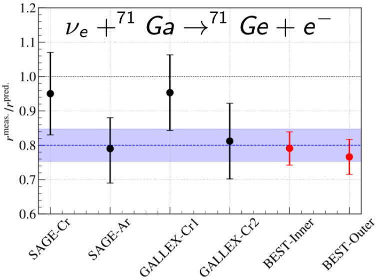
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$$



$$R = \frac{\text{measured}}{\text{predicted}} = 0.87 \pm 0.05$$

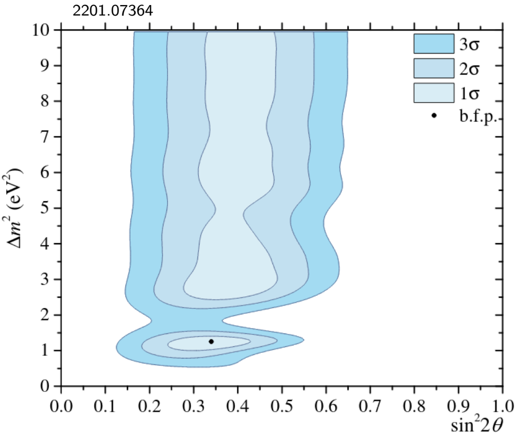
Baksan Experiment on Sterile Transitions (BEST)





$$R = \frac{\text{measured}}{\text{predicted}} = 0.803 \pm 0.035 \implies \gtrsim 5\sigma \text{ effect}$$

Sterile Neutrino?



SM or BSM explanation?

High Energy Physics - Phenomenology

[Submitted on 9 Mar 2023]

Towards Resolving the Gallium Anomaly

Vedran Brdar, Julia Gehrlein, Joachim Kopp

A series of experiments studying neutrinos from intense radioactive sources have reported a deficit in the measured event rate which, in combination, has reached a statistical significance of $\sim 5\sigma$. In this paper, we explore avenues for explaining this anomaly, both within the Standard Model and beyond. First, we discuss possible biases in the predicted cross section for the detection reaction $\nu_e +^{71}\mathrm{Ga} \to e^- +^{71}\mathrm{Ge}$, which could arise from mismeasurement of the inverse process, $^{71}\mathrm{Ge}$ decay, or from the presence of as yet unknown low-lying excited states of $^{71}\mathrm{Ga}$. The latter would imply that not all $^{71}\mathrm{Ge}$ decays go to the ground state of $^{71}\mathrm{Ga}$, so the extraction of the ground state-to-ground state matrix element relevant for neutrino capture on gallium would be incorrect. Second, we scrutinize the measurement of the source intensity in gallium experiments, and we point out that a $\sim 2\%$ error in the branching ratios for $^{51}\mathrm{Cr}$ decay would be enough to explain the anomaly. Third, we investigate the calibration of the radiochemical germanium extraction efficiency as a possible origin of anomaly. Finally, we outline several new explanations beyond the Standard Model, including scenarios with sterile neutrinos coupled to fuzzy dark matter or to dark energy, as well as a model with decaying sterile neutrinos. We critically assess the viability of these scenarios, and others that have been proposed, in a summary table.

SM Explanation: Cross Section

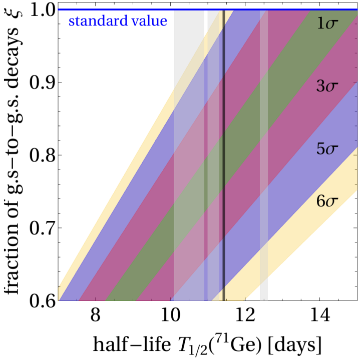
$$\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge}$$

- transition to g.s. of ^{71}Ge
- transition to exctited states of ^{71}Ge
  $\to$ anomaly at 5σ even when set to 0

(A) $T_{1/2}({}^{71}Ge)$

(B) new states of ${}^{71}Ga$?

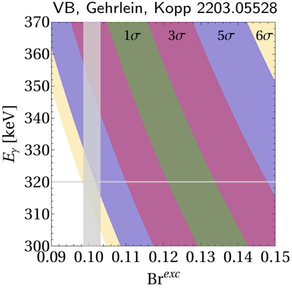
VB, Gehrlein, Kopp 2203.05528



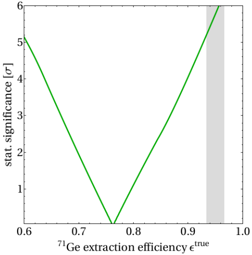
Flux. Ge Extraction Efficiency.

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

- source intensity measured calorimetrically
- $\sim$ 10% of all ^{51}Cr decays goes to the excited state of ^{51}V



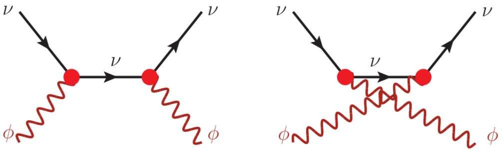
- Ge extraction efficiency is reported to be $\approx$ 95%
- 20% smaller value would explain the anomaly
- route for Ge to enter the detector?



BSM Explanations

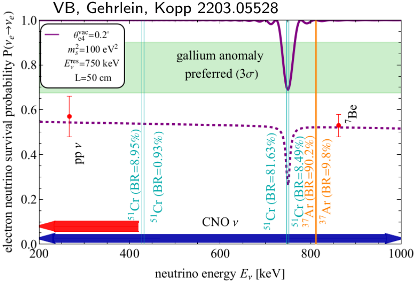
$$\mathcal{L} \supset g_s \phi^\mu \overline{\nu}_s \gamma_\mu \nu_s$$

$$\sin 2\theta_{e4}^{\text{eff}} = \frac{\frac{\Delta m^2}{2E_\nu} \sin 2\theta_{e4}^{\text{vac}}}{\sqrt{(V - \frac{\Delta m^2}{2E_\nu} \cos 2\theta_{e4}^{\text{vac}})^2 + (\frac{\Delta m^2}{2E_\nu})^2 \sin^2 2\theta_{e4}^{\text{vac}}}}$$



- solar and reactor constraints are strong
- avoid by employing a sharp resonance

VB, Gehrlein, Kopp 2203.05528



VB, Gehrlein, Kopp 2203.05528

Explanations beyond the Standard Model		
ν_s coupled to ultralight DM (MSW resonance, Sec. 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, Sec. 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, Sec. 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 (Refs. [132])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (Refs. [133–135])	neutrinos oscillate into sterile Kaluza–Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (Ref. [136])	based on a difference between sterile neutrino mixing angles at production and detection (see also [137, 138]); fit worse than for vanilla ν_s.	
decoherence (Refs. [139, 140])	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. [141])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	

Summary

- recent reevaluations of reactor and MiniBooNE anomalies imply reduction in their statistical significance
- gallium anomaly takes the central stage with $\gtrsim 5\sigma$ effect
- vanilla eV-scale sterile neutrino is disfavored
- SM or BSM explanation?
- can be tested with different radioactive source (e.g. ^{37}Ar or ^{65}Zn) or detector material (e.g. ^{37}Cl), or with a gallium doped scintillation experiment