Status of the reactor and gallium anomalies and implications for active-sterile neutrino mixing

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Standard Three Neutrino Mixing Paradigm

- Supported by robust, abundant, and consistent solar, atmospheric and long-baseline (accelerator and reactor) neutrino oscillation data.
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions.
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector.
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^* \\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^* \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- U is the 3×3 unitary Neutrino Mixing Matrix.
- $$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right) \qquad (\alpha, \beta = e, \mu, \tau)$$
- The oscillation probabilities depend on:

$$U \text{ (osc. amplitude)} \quad \text{and} \quad \Delta m_{kj}^2 \equiv m_k^2 - m_j^2 \text{ (osc. phase)}$$

Three-Neutrino Mixing Parameters

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \le \vartheta_{ab} \le \frac{\pi}{2}$ $\quad 0 \le \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS

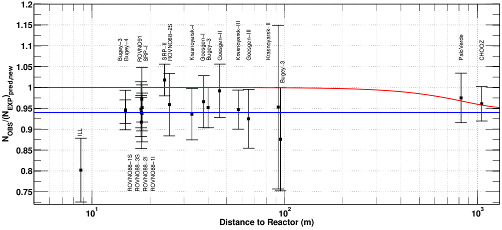
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

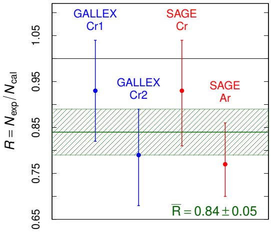
- In the standard 3ν mixing paradigm there are two independent Δm^2's:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$ Solar Mass Splitting
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$ Atmospheric Mass Splitting
- The solar and atmospheric mass splittings generate oscillations that are detectable at the distances
  - $L^{\text{osc}}_{\text{SOL}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{SOL}}} \approx 50\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
  - $L^{\text{osc}}_{\text{ATM}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{ATM}}} \approx 1\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
- The solar and atmospheric mass splittings cannot explain neutrino oscillations at shorter distances.
- A neutrino oscillation explanation of short-baseline anomalies needs the existence of larger Δm^2's.

Historical Short-Baseline Anomalies

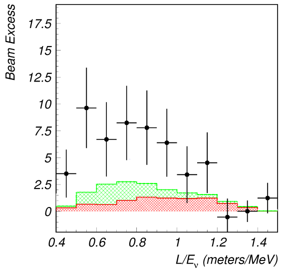
2011 Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ ($\approx 2.5\sigma$)



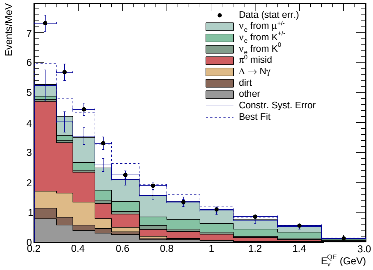
2005 Gallium Anomaly: $\nu_e \to \nu_x$ ($\approx 2.9\sigma$)



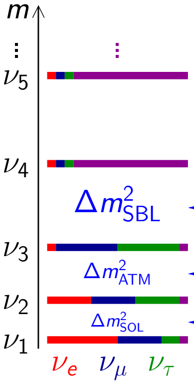
1995 LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ ($\sim 4\sigma$)



2008 MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



Beyond Three-Neutrino Mixing: Sterile Neutrinos

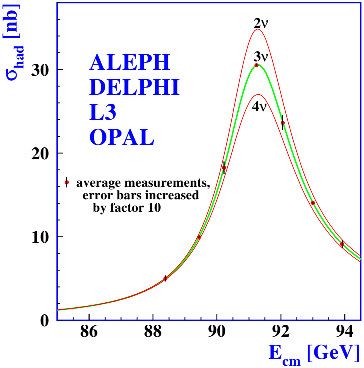


$$L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$

Δm^2_{SBL} ← $\gtrsim 1\,\text{eV}^2$

Δm^2_{ATM} ← $\simeq 2.5 \times 10^{-3}\,\text{eV}^2$

Δm^2_{SOL} ← $\simeq 7.4 \times 10^{-5}\,\text{eV}^2$



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

$$N^{\text{LEP}}_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

$$\boxed{N_{\nu_{\text{active}}} = 2.9963 \pm 0.0074}$$

[Janot, Jadach, arXiv:1912.02067]

Terminology: a eV-scale sterile neutrino

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

Effective 3+1 SBL Oscillation Probabilities

Appearance $(\alpha \neq \beta)$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_{\alpha} \to \overset{(-)}{\nu}_{\beta}} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_{\alpha} \to \overset{(-)}{\nu}_{\alpha}} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

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

SBL

$$\boxed{\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}}$$

Common Parameterization of 4ν Mixing

$$U = \left[W^{34} R^{24} W^{14} R^{23} W^{13} R^{12}\right] \text{diag}\left(1, e^{i\lambda_{21}}, e^{i\lambda_{31}}, e^{i\lambda_{41}}\right)$$

$$= \begin{pmatrix} c_{12} c_{13} c_{14} & s_{12} c_{13} c_{14} & c_{14} s_{13} e^{-i\delta_{13}} & s_{14} e^{-i\delta_{14}} \\ \cdots & \cdots & \cdots & c_{14} s_{24} \\ \cdots & \cdots & \cdots & c_{14} c_{24} s_{34} e^{-i\delta_{34}} \\ \cdots & \cdots & \cdots & c_{14} c_{24} c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 & 0 \\ 0 & 0 & e^{i\lambda_{31}} & 0 \\ 0 & 0 & 0 & e^{i\lambda_{41}} \end{pmatrix}$$

$$|U_{e4}|^2 = \sin^2\vartheta_{14} \quad \Rightarrow \quad \sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) = \sin^2 2\vartheta_{14}$$

$$|U_{\mu4}|^2 = \cos^2\vartheta_{14}\sin^2\vartheta_{24} \simeq \sin^2\vartheta_{24} \Rightarrow \sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2\left(1 - |U_{\mu4}|^2\right) \simeq \sin^2 2\vartheta_{24}$$

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

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

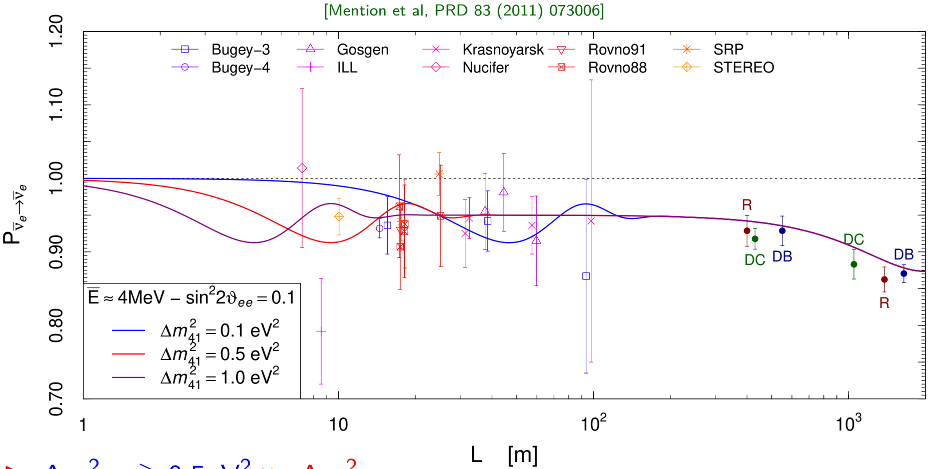
with different notations in the literature:

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

and

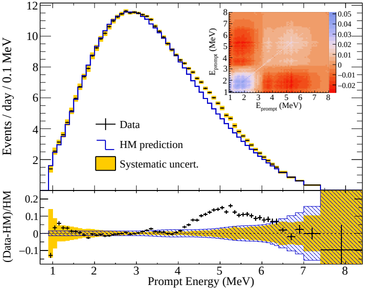
$$\Delta m^2_{41} = \Delta m^2_{\mathrm{SBL}} = \Delta m^2_{\mathrm{new}} = \Delta m^2$$

Reactor Electron Antineutrino Anomaly

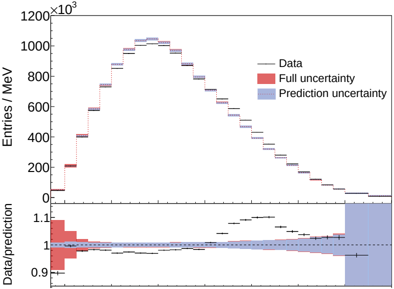


- $\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$
- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion
- The Reactor Antineutrino Anomaly is model dependent; it depends on the Huber-Mueller (HM) reactor neutrino flux calculation; is it reliable?

Reactor Antineutrino 5 MeV Bump (Shoulder)



[RENO, arXiv:2010.14989]



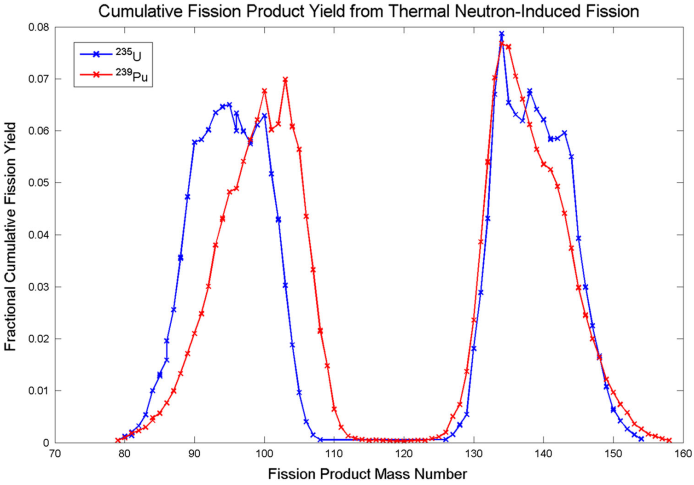
[Daya Bay, arXiv:1904.07812]

- Discovered in 2014 by RENO, Double Chooz, Daya Bay.
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).
- Most likely it is due to a theoretical miscalculation of the spectrum.
- A recalculation of the spectrum can have opposite effects on the anomaly:
  - A 4-6 MeV increase of the predicted flux which explains the bump increases the anomaly.
  - A 1-4 MeV decrease of the predicted flux decreases the anomaly.

Reactor $\bar{\nu}_e$ Flux Calculation

Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

^{235}U ^{238}U ^{239}Pu ^{241}Pu



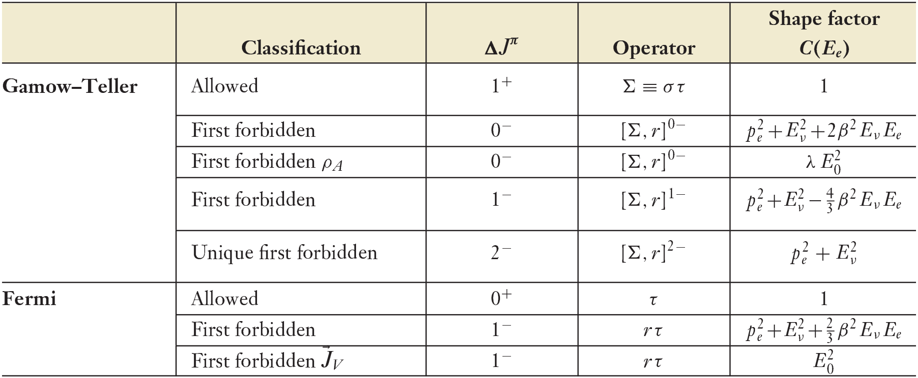
[Dayman, Biegalski, Haas, Rad. Nucl. Chem. 305 (2015) 213]

- For each allowed β decay $(\Delta J = 0, \pm 1;\ \pi_i \pi_f = 1)$:

$$S_e(E_e) = K p_e E_e \left(E_e - E_0\right)^2 F(Z, E_e)$$

$$(E_\nu = E_0 - E_e)$$

$$S_\nu(E_\nu) = K \sqrt{(E_0 - E_e)^2 - m_e^2}\,(E_0 - E_e)\, E_\nu^2\, F(Z, E_e)$$



	Classification	**ΔJ^π**	**Operator**	**Shape factor $C(E_e)$**
Gamow–Teller	Allowed	1^+	$\Sigma \equiv \sigma\tau$	1
	First forbidden	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$
	First forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	$\lambda\, E_0^2$
	First forbidden	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$
	Unique first forbidden	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$
Fermi	Allowed	0^+	τ	1
	First forbidden	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$
	First forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2

[Hayes, Vogel, arXiv:1605.02047]

Summation (*ab initio*) Method

- Aggregate reactor spectrum (electron or neutrino):

$$S_{\text{tot}}(E,t) = \sum_k \underset{\substack{\uparrow \\ \text{fission fractions}}}{F_k(t)}\, S_k(E) \qquad (k = 235, 238, 239, 241)$$

$$S_k(E) = \sum_n \underset{\substack{\uparrow \\ \text{cumulative} \\ \text{fission} \\ \text{yield}}}{Y_n^k} \quad \sum_b \underset{\substack{\uparrow \\ \text{branching} \\ \text{ratio}}}{\mathrm{BR}_n^b} \quad S_n^b(E) \leftarrow \begin{array}{c} \text{allowed or} \\ \text{forbidden} \\ \text{decay} \\ \text{spectrum} \end{array}$$

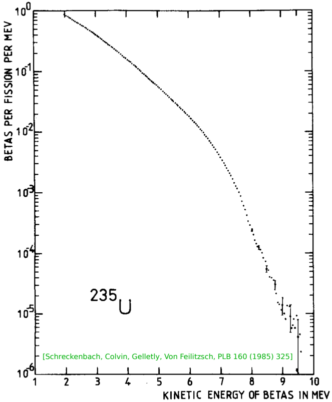
- The calculation of each $S_k(E)$ requires knowledge of about 1000 spectra and branching ratios.

- Large uncertainties, because nuclear databases are incomplete and sometimes inexact.

Conversion Method

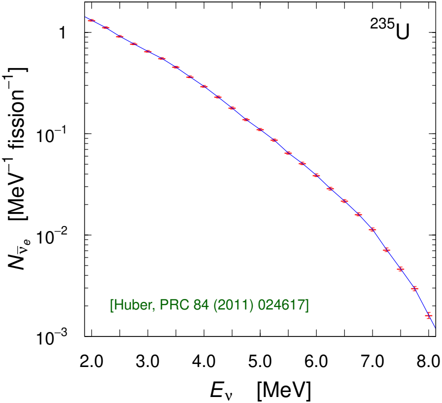
- In the 80's Schreckenbach et al. measured the aggregate β spectra of ^{235}U, ^{239}Pu, and ^{241}Pu exposing thin foils to the thermal neutron flux of the ILL reactor in Grenoble.

- Semi-empirical method: conversion $S^{e}_{k}(E_e) \to S^{\nu}_{k}(E_\nu)$ considering ~ 30 virtual allowed β decay spectra. $(k = 235, 239, 241)$



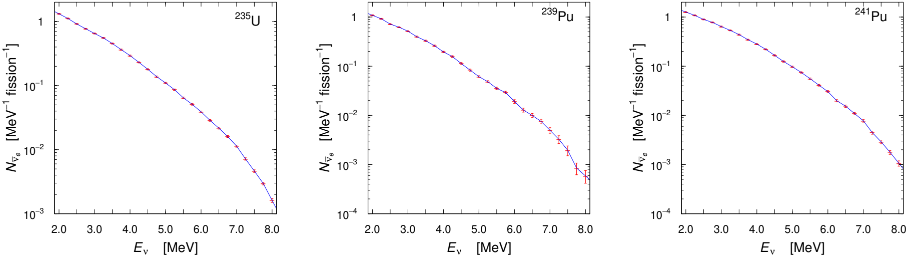
[Schreckenbach, Colvin, Gelletly, Von Feilitzsch, PLB 160 (1985) 325]

$\Longrightarrow$



[Huber, PRC 84 (2011) 024617]

- The standard reactor $\bar{\nu}_e$ fluxes and spectra from ^{235}U, ^{239}Pu, and ^{241}Pu were obtained with the conversion method:



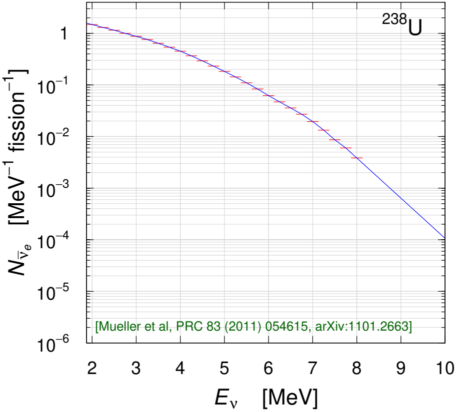
[Huber, PRC 84 (2011) 024617]

- The uncertainty induced by the conversion method was estimated to be about 1%. [Vogel, PRC 76 (2007) 025504]

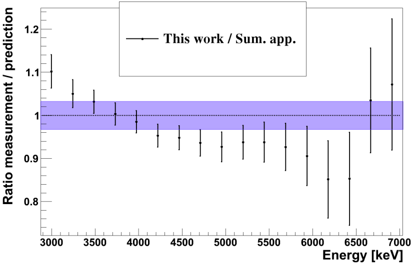
- Estimated total uncertainties on the neutrino detection rates:

2.4% (^{235}U) 2.9% (^{239}Pu) 2.6% (^{241}Pu)

- The HM ^{238}U $\bar{\nu}_e$ flux was calculated with the summation method with estimated 8% uncertainty. [Mueller et al, PRC 83 (2011) 054615]
- Approximate agreement with the 2014 β spectrum measurement at FRM II in Garching using a fast neutron beam. [Haag et al, PRL 112 (2014) 122501]



[Mueller et al, PRC 83 (2011) 054615]



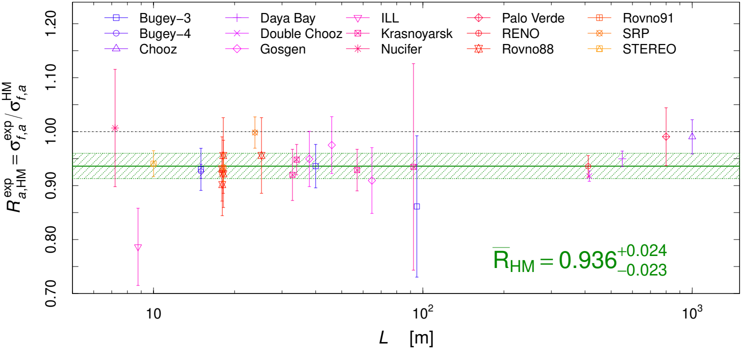
[Haag et al, PRL 112 (2014) 122501]

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

2011: new reactor $\bar{\nu}_e$ fluxes: Huber-Mueller (HM)

[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]

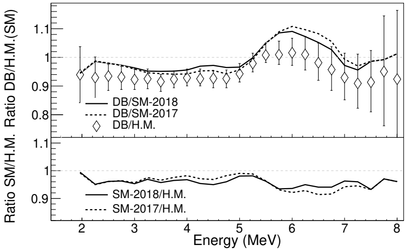


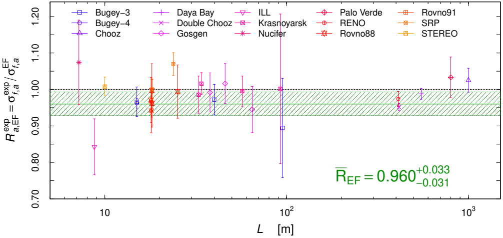
$\approx 2.5\,\sigma$ deficit $\Longrightarrow$ Anomaly!

[CG, Li, Ternes, Xin, arXiv:2110.06820]

2019: new summation reactor $\bar{\nu}_e$ fluxes: EF

[Estienne, Fallot, et al, arXiv:1904.09358]





[CG, Li, Ternes, Xin, arXiv:2110.06820]

$\approx 1.2\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

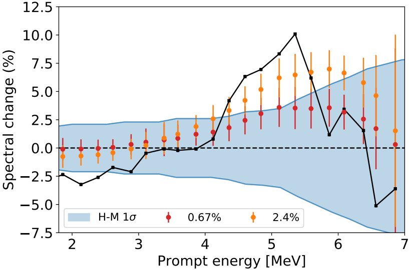
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

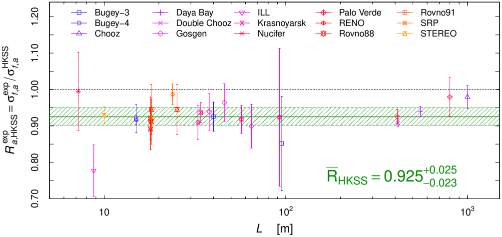
- UNKNOWN UNCERTAINTIES!
- Rough estimation used in our calculations: 5% for ^{235}U, ^{239}Pu, ^{241}Pu and 10% for ^{238}U.

[Hayes, Jungman, McCutchan, Sonzogni, Garvey, Wang, arXiv:1707.07728]

2019: new converted reactor $\bar{\nu}_e$ fluxes: HKSS

[Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302]





[CG, Li, Ternes, Xin, arXiv:2110.06820]

$\approx 2.9\,\sigma$ deficit $\Longrightarrow$ Anomaly larger than the $\approx 2.5\,\sigma$ HM anomaly!

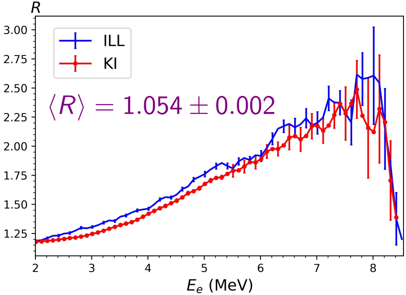
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

- HM + HKSS uncertainties.

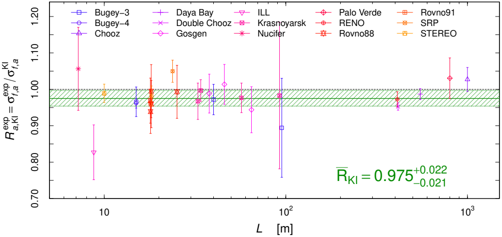
2021: new converted reactor $\bar{\nu}_e$ fluxes: KI

[Kurchatov Institute: Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]

$$R = S^{(e)}_{235}/S^{(e)}_{239}$$



$$\langle R \rangle = 1.054 \pm 0.002$$



[CG, Li, Ternes, Xin, arXiv:2110.06820]

$\approx 1.1\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

Approximate agreement with ab initio EF fluxes!

- HM + KI uncertainties.

Reactor Fuel Evolution

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

  $^{235}\mathrm{U}$ $^{238}\mathrm{U}$ $^{239}\mathrm{Pu}$ $^{241}\mathrm{Pu}$

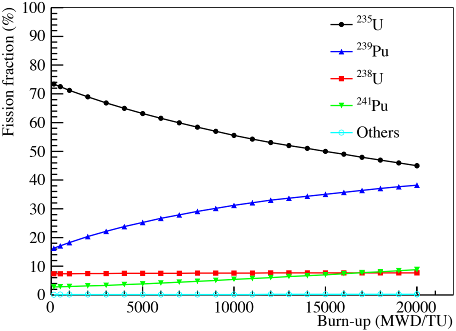
- Effective fission fractions:

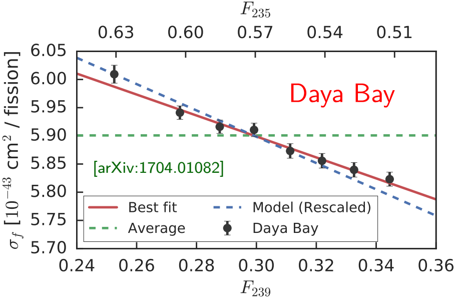
  F_{235} F_{238} F_{239} F_{241}

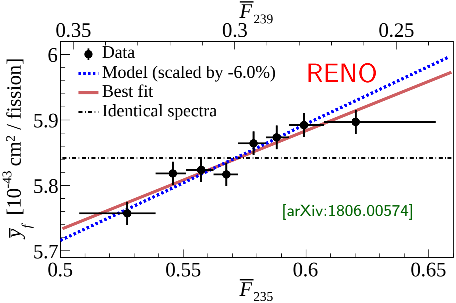
- Cross section per fission (IBD yield):

$$\sigma_f = \sum_k F_k \, \sigma_{f,k}$$

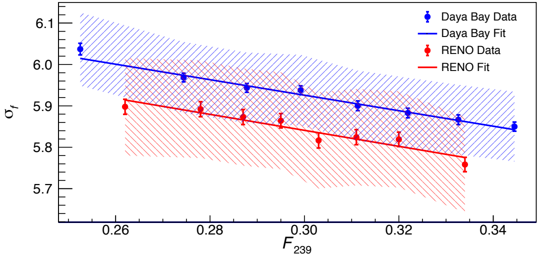
for $k = 235, 238, 239, 241$

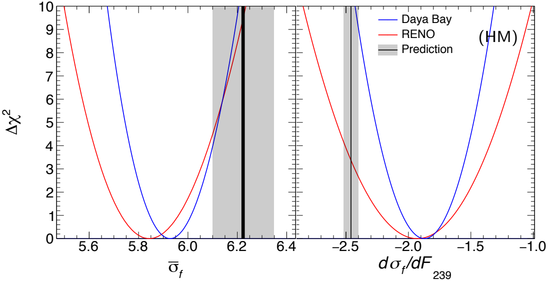






Approximate linear fit: $\sigma_f(F_{239}) = \overline{\sigma}_f + \dfrac{d\sigma_f}{dF_{239}}\left(F_{239} - \overline{F}_{239}\right)$





[CG, Li, Littlejohn, Surukuchi, arXiv:1901.01807]

- Rate anomaly:

$$\overline{\sigma}_f^{\text{exp}} \neq \overline{\sigma}_f^{\text{HM}} = \sum_k \overline{F}_k\, \sigma_{f,k}^{\text{HM}}$$

- Evolution anomaly:

$$\frac{d\sigma_f^{\text{exp}}}{dF_{239}} \neq \frac{d\sigma_f^{\text{HM}}}{dF_{239}} = \sum_k \frac{dF_k}{dF_{239}}\, \sigma_{f,k}^{\text{HM}}$$

- Oscillations: $\overline{\sigma}_f = P_{ee}\overline{\sigma}_f^{\text{HM}}$

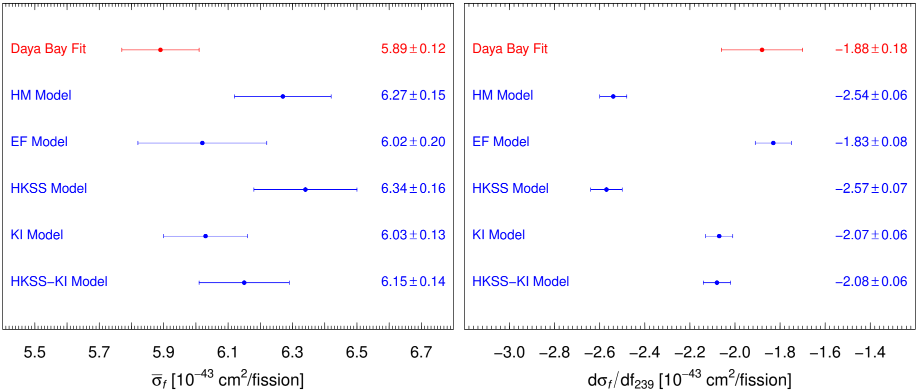
and $\dfrac{d\sigma_f}{dF_{239}} = P_{ee}\dfrac{d\sigma_f^{\text{HM}}}{dF_{239}}$

$$\boxed{\frac{1}{\overline{\sigma}_f}\,\frac{d\sigma_f}{dF_{239}} = \frac{1}{\overline{\sigma}_f^{\text{HM}}}\,\frac{d\sigma_f\text{HM}}{dF_{239}}}$$

$$\frac{1}{\overline{\sigma}_f^{\text{DB}}}\,\frac{d\sigma_f^{\text{DB}}}{dF_{239}} = -0.31 \pm 0.03$$

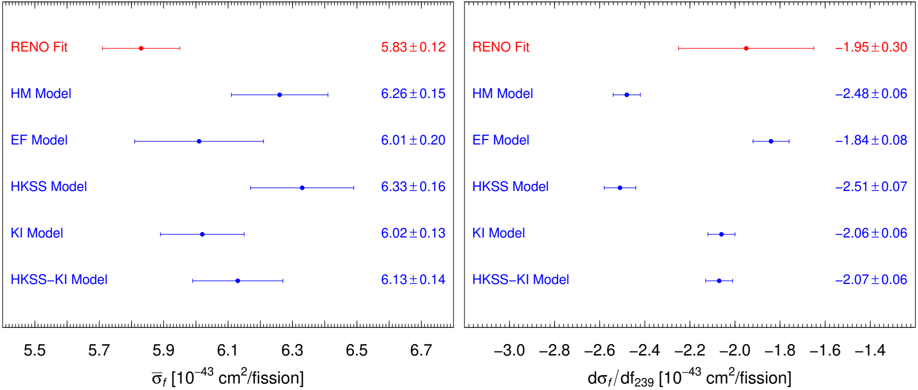
2.6σ

$$\frac{1}{\overline{\sigma}_f^{\text{HM}}}\,\frac{d\sigma_f^{\text{HM}}}{dF_{239}} = -0.39 \pm 0.01$$



[CG, Li, Ternes, Xin, arXiv:2110.06820]

- Tension with HM $(2.6\,\sigma)$, HKSS $(2.8\,\sigma)$, and HKSS-KI $(1.9\,\sigma)$.
- Agreement with EF $(0.8\,\sigma)$ and KI $(1.2\,\sigma)$.



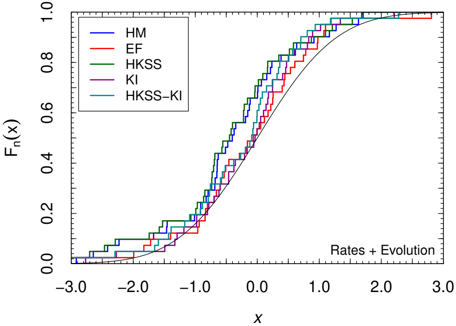
[CG, Li, Ternes, Xin, arXiv:2110.06820]

- Tension with HM $(2.6\,\sigma)$, HKSS $(2.8\,\sigma)$, and HKSS-KI $(1.9\,\sigma)$.
- Agreement with EF $(0.8\,\sigma)$ and KI $(1.2\,\sigma)$.

Best-fit reactor flux model

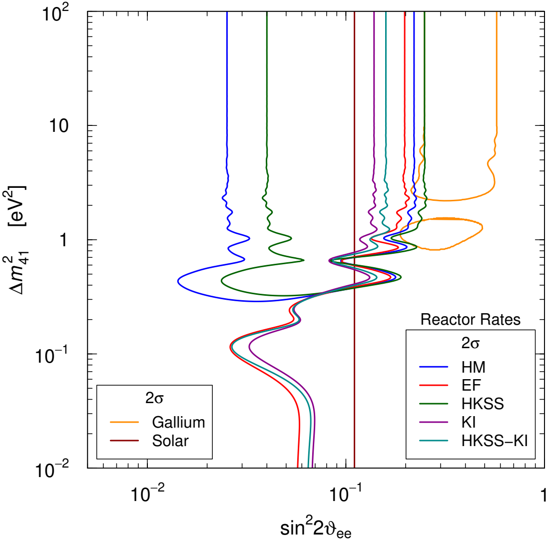
Goodness of fit tests assuming no (or negligible) SBL oscillations

Test	HM	EF	HKSS	KI	HKSS-KI
χ^2	0.13	0.22	0.08	0.68	0.44
SW	0.32	0.13	0.35	0.59	0.41
sign	0.03	0.38	0.006	0.38	0.11
KS	0.04	0.84	0.02	0.39	0.20
CVM	0.02	0.67	0.006	0.38	0.14
AD	0.02	0.57	0.006	0.40	0.13
Z_K	$< 10^{-3}$	0.05	$< 10^{-3}$	0.05	0.008
Z_C	0.02	0.11	0.005	0.55	0.15
Z_A	0.03	0.20	0.01	0.41	0.12
weighted average	0.05	0.35	0.03	0.42	0.16



[CG, Li, Ternes, Xin, arXiv:2110.06820]

- The KI model is the best among the conversion models.
- The summation EF model is approximately equally good.
  But the uncertainties are guessed!



- The favored KI and EF models are compatible with the absence of SBL oscillations and give only 2σ upper bounds on the effective mixing parameter $\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$.
- Independently from the reactor neutrino flux model, we have $\sin^2 2\vartheta_{ee} \lesssim 0.25$ at 2σ.

- There is agreement with the solar neutrino bound on $\sin^2 2\vartheta_{ee}$.

[Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898]

- There is a tension with the Gallium anomaly region.

[BEST, arXiv:2109.11482]

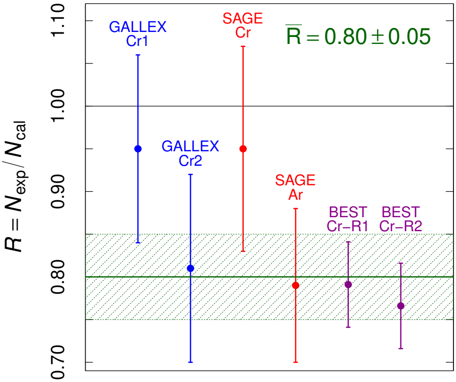
Gallium Anomaly

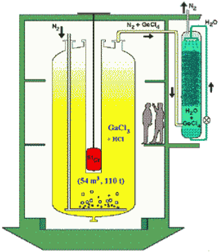
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

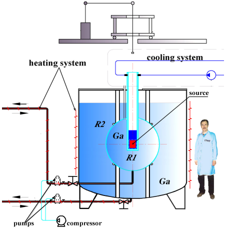
$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

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





GALLEX



BEST

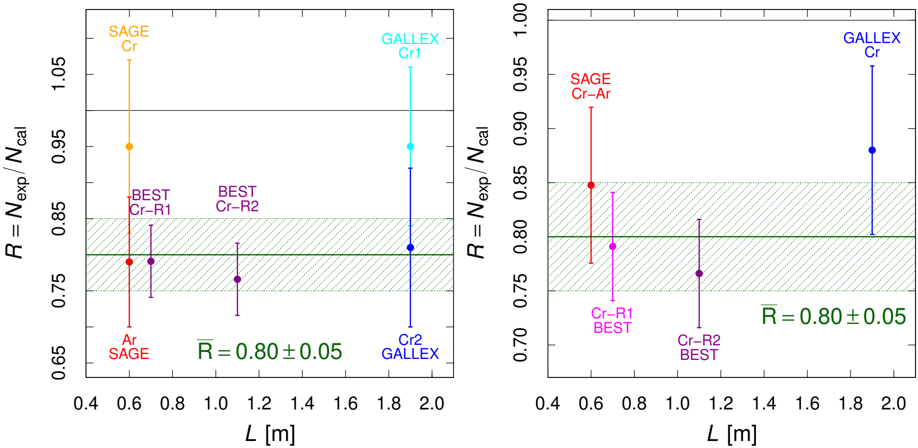
$\approx 4\sigma$ deficit $\Longrightarrow$ Anomaly!

$\langle L \rangle_{\text{GALLEX}} \simeq 1.9\,\text{m}$ $\quad \langle L \rangle_{\text{SAGE}} \simeq 0.6\,\text{m}$

$\langle L \rangle^{\text{R1}}_{\text{BEST}} \simeq 0.7\,\text{m}$ $\quad \langle L \rangle^{\text{R2}}_{\text{BEST}} \simeq 1.1\,\text{m}$

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

[SAGE, arXiv:nucl-ex/0512041, arXiv:0901.2200; Laveder et al, NPPS 168 (2007) 344, arXiv:hep-ph/0610352, arXiv:0711.4222, arXiv:1006.3244; Kostensalo et al, arXiv:1906.10980; BEST, arXiv:2109.11482, arXiv:2109.14654; Berryman et al, arXiv:2111.12530]

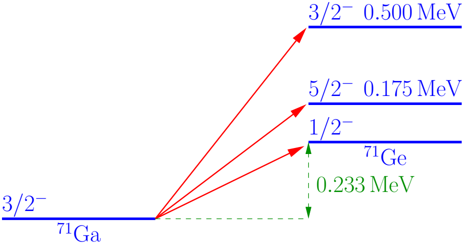


No clear model-independent anomaly from different path lengths

- Deficit could be due to an overestimate of

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

- First calculation: Bahcall, PRC 56 (1997) 3391, 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]

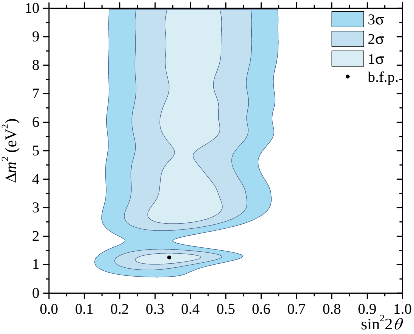
$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45}\,\text{cm}^2$$

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

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

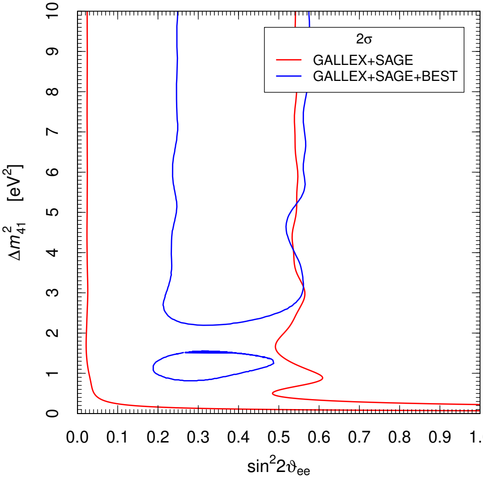
$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$ cross sections in units of $10^{-45}\,\mathrm{cm}^2$:

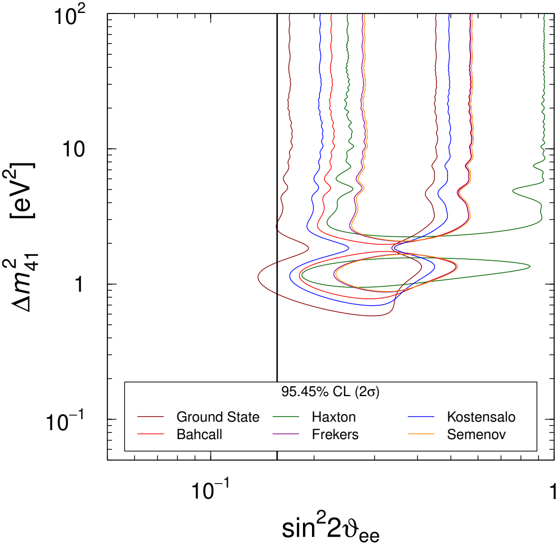
		^{51}Cr		^{37}Ar	
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State [Semenov, Phys.Atom.Nucl. 83 (2020) 1549]	$T_{1/2}({}^{71}\mathrm{Ge})$	5.539 ± 0.019	—	6.625 ± 0.023	—
Bahcall (1997) [hep-ph/9710491]	${}^{71}\mathrm{Ga}(p,n){}^{71}\mathrm{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998) [nucl-th/9804011]	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015) [PRC 91 (2015) 034608]	${}^{71}\mathrm{Ga}({}^{3}\mathrm{He},{}^{3}\mathrm{H}){}^{71}\mathrm{Ge}$	5.92 ± 0.11	6.4%	7.15 ± 0.14	7.3%
Kostensalo et al. (2019) [arXiv:1906.10980]	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
Semenov (2020) [Phys.Atom.Nucl. 83 (2020) 1549]	${}^{71}\mathrm{Ga}({}^{3}\mathrm{He},{}^{3}\mathrm{H}){}^{71}\mathrm{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%



[BEST, arXiv:2109.11482]

GALLEX+SAGE+BEST
with Bahcall cross section





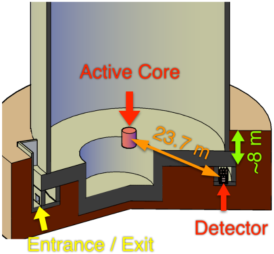
- Strong tension with the solar bound! [Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898]

[see also: Berryman, Coloma, Huber, Schwetz, Zhou, arXiv:2111.12530]

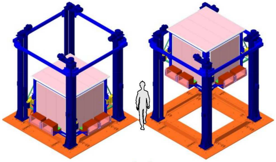
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

NEOS

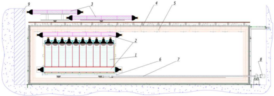


DANSS

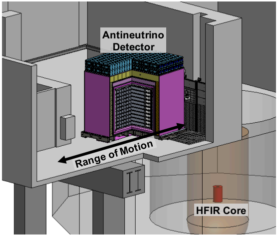


DANSS on a lifting platform

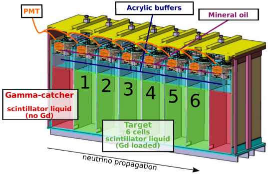
Neutrino-4



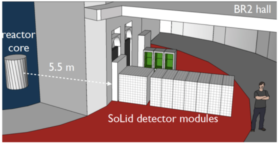
PROSPECT

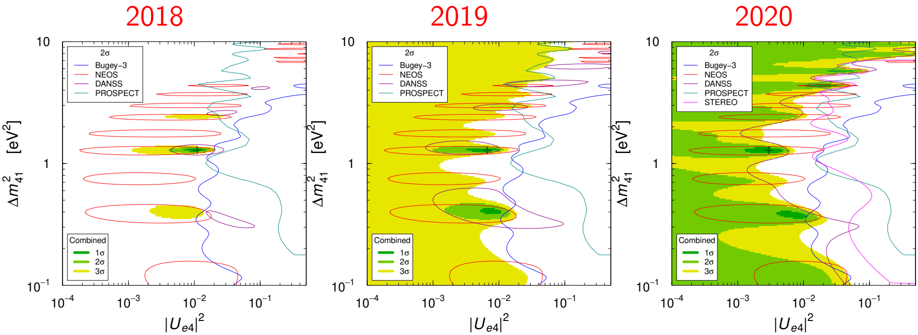


STEREO



SoLid

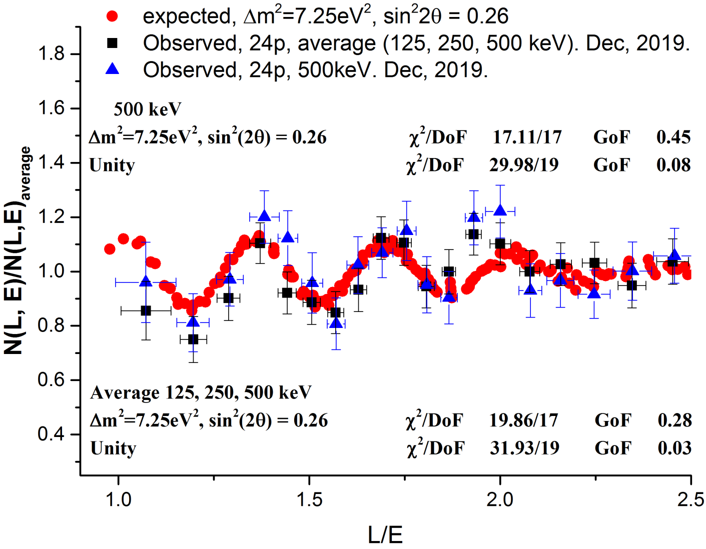


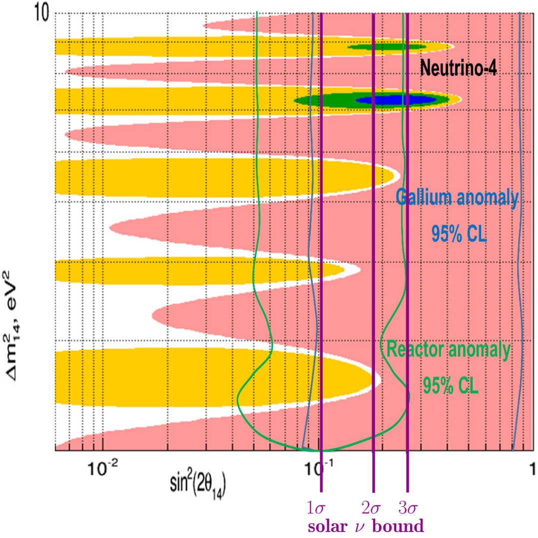


- 2018: remarkable agreement of the DANSS and NEOS best-fit regions at $\Delta m^2_{41} \approx 1.3\,\text{eV}^2 \Longrightarrow$ model independent indication in favor of SBL oscillations. [Gariazzo, CG, Laveder, Li, arXiv:1801.06467]
  [Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]
- 2019: decreased agreement between NEOS and DANSS allowed regions. [CG, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]
- 2020: No 2σ DANSS allowed regions (exclusion curve).
  No compelling indication of oscillations.
  In practice these reactor experiments exclude large values of $|U_{e4}|^2$ for
  $$0.1 \lesssim \Delta m^2_{41} \lesssim 10\,\text{eV}^2$$

Neutrino-4

[arXiv:1708.00421, arXiv:1809.10561, arXiv:2003.03199, arXiv:2005.05301, arXiv:2006.13639]





- Neutrino-4 best fit:

$$\sin^2 2\vartheta_{ee} = 0.26$$

$$\Delta m^2_{41} = 7.25\,\text{eV}^2$$

- Very large mixing!

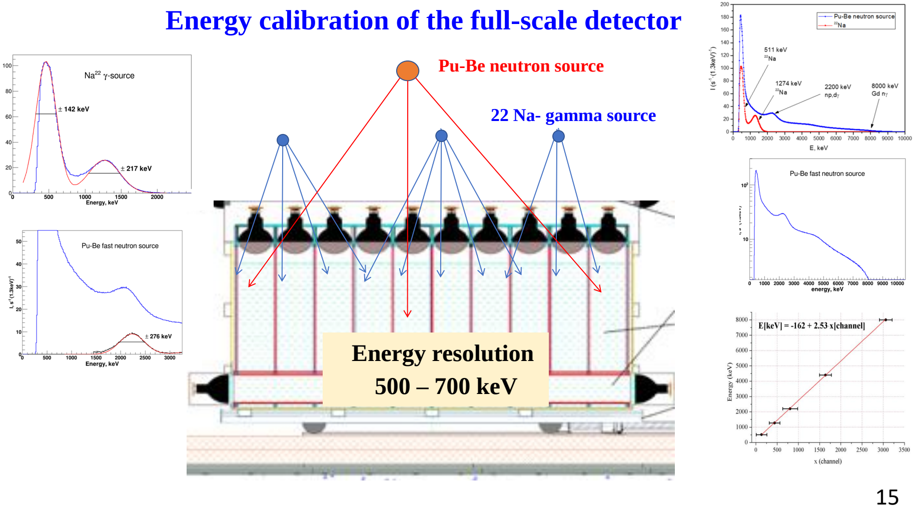
- Not a small perturbation of 3ν mixing.

- Tension with solar neutrino bound.

[Palazzo, arXiv:1105.1705, arXiv:1201.4280]
[CG, Laveder, Li, Liu, Long, arXiv:1210.5715]
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]
[Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898]

- No energy resolution!

[Danilov, arXiv:1812.04085]
[Danilov, Skrobova, JETP Lett. 112 (2020) 7]
[CG, Li, Ternes, Zhang, arXiv:2101.06785]



Energy calibration of the full-scale detector

Pu-Be neutron source

22 Na- gamma source

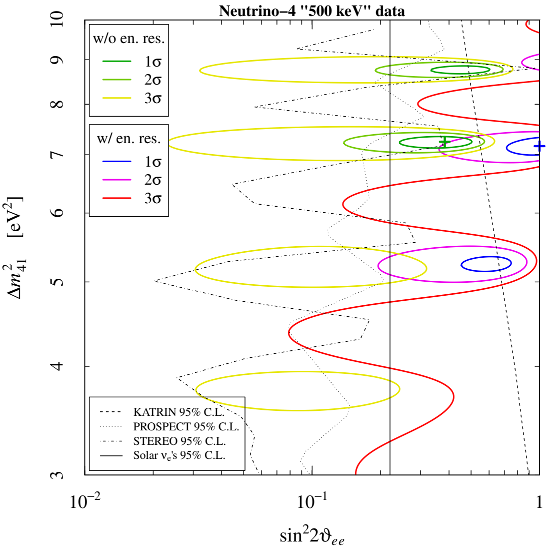
Energy resolution

500 – 700 keV

15

- We approximate the energy resolution with the function

$$R(E_{\rm p}, E'_{\rm p}) = \frac{1}{\sqrt{2\pi}\sigma_{E_p}} \exp\left(-\frac{(E_{\rm p} - E'_{\rm p})^2}{2\sigma^2_{E_p}}\right) \quad \text{with} \quad \sigma_{E_p} = 0.19\sqrt{\frac{E_p}{\text{MeV}}}\,\text{MeV}$$



$$\chi^2 = \sum_{j=1}^{19} \left(\frac{R_j^{\text{the}} - R_j^{\text{exp}}}{\Delta R_j^{\text{exp}}} \right)^2$$

	without en. res.	with en. res.
χ^2_{min}	14.9	18.2
GoF	60%	37%
$(\sin^2 2\vartheta_{ee})_{\text{bf}}$	0.38	1.0
$(\Delta m^2_{41})_{\text{bf}}$	7.2	7.2
$\Delta\chi^2_{\text{NO}}$	13.1	9.8
p-value	0.0014	0.0075
σ-value	3.2	2.7

[CG, Li, Ternes, Zhang, arXiv:2101.06785]

- Disconcerting comment in arXiv:2005.05301v7, published in PRD 104 (2021) 032003: The simultaneous usage of energy interval $\Delta E = 500\,\mathrm{keV}$ and energy resolution $\sigma = 250\,\mathrm{keV}$ is incorrect, because it includes into the analysis the resolution of the detector twice as it was done in the work [CG, Li, Ternes, Zhang, arXiv:2101.06785].

- The Neutrino-4 collaboration thinks that energy binning takes into account the energy resolution.

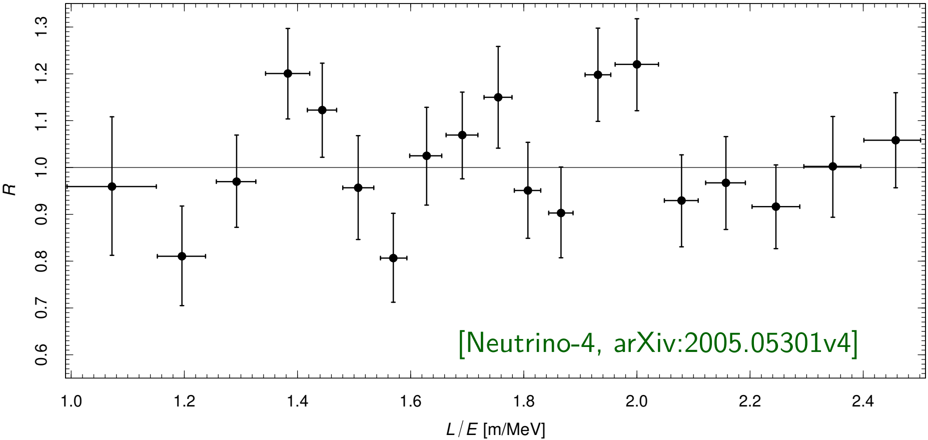
- It is obvious that an event with an unknown true energy in an unknown energy bin can be counted in another bin because of the energy resolution.

- This effect is obviously not taken into account by the binning.

- This effect can be neglected if the energy resolution is much smaller than the bin width.

- This effect cannot be neglected in the Neutrino-4 experiment, where the the bin width is only twice of the energy resolution.

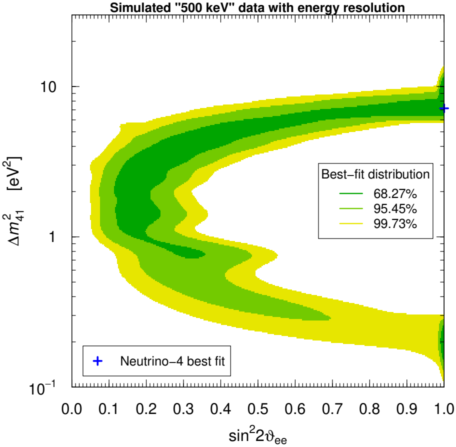
Neutrino-4: Oscillations or Fluctuations?



Deviations from χ^2 Distribution (Wilks' Theorem)

[Agostini, Neumair, arXiv:1906.11854; Silaeva, Sinev, arXiv:2001.10752; CG, arXiv:2004.07577]
[PROSPECT+STEREO, arXiv:2006.13147; Coloma, Huber, Schwetz, arXiv:2008.06083]

Even in the absence of real oscillations, binned data can often be fitted better by oscillations that reproduce the statistical fluctuations of the bins.



Distribution of best-fit points in a large set of random data generated without oscillations

	probability
$\sin^2 2\vartheta_{ee} < 0.1$	0.008
$0.1 < \sin^2 2\vartheta_{ee} < 0.5$	0.625
$0.5 < \sin^2 2\vartheta_{ee} < 0.9$	0.184
$\sin^2 2\vartheta_{ee} > 0.9$	0.183

[CG, Li, Ternes, Zhang, arXiv:2101.06785]

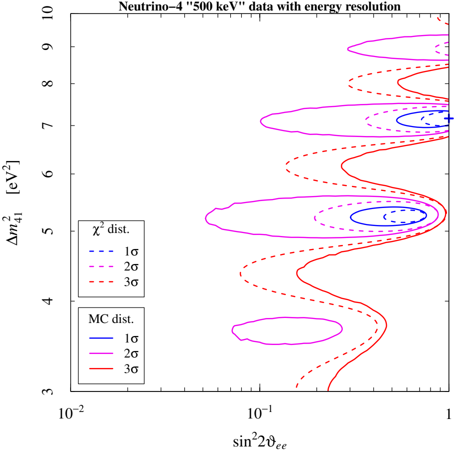
Monte Carlo confidence intervals

- For each point on a grid in the $(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ plane we generated a large number of random data sets (of the order of 10^5) with the uncertainties of the Neutrino-4 data set.

- For each random data set:
  - We calculated the value of χ^2 corresponding to the generating values of $\sin^2 2\vartheta_{ee}$ and Δm^2_{41}: $\chi^2_{\text{MC}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$.
  - We found the minimum value of χ^2 in the $(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ plane: $\chi^2_{\text{MC,min}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$.

- In this way, we obtained the distribution of $\Delta\chi^2_{\text{MC}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) = \chi^2_{\text{MC}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) - \chi^2_{\text{MC,min}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$.

- This distribution allows us to determine if the value of $\Delta\chi^2(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) = \chi^2(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) - \chi^2_{\text{min}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ obtained with the analysis of the actual Neutrino-4 data is included or not in a region with a fixed confidence level.



	χ^2 dist.	MC dist.
p-value	0.0075	0.028
σ-value	2.7	2.2

[CG, Li, Ternes, Zhang, arXiv:2101.06785]

Conclusion on Neutrino-4: the claimed indication in favor of short-baseline neutrino oscillations with very large mixing is rather doubtful.

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.
- We are back by 10 years, when there was a Gallium-Reactor tension, before the Reactor Antineutrino Anomaly.
- CPT violation explanation of the Reactor Antineutrino–Gallium Neutrino tension? [CG, Laveder, arXiv:1008.4750]
  - Theoretically challenging.
  - Cannot resolve the tension between the the Gallium Neutrino Anomaly and the solar neutrino bound.
- Even more confusing status of appearance data (MicroBooNE vs MiniBooNE vs LSND) and the appearance-disappearance tension.