

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.
- ▶ $P_{\nu_\alpha \rightarrow \nu_\beta}(L) = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right)$ ($\alpha, \beta = e, \mu, \tau$)
- ▶ 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)

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

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

OSCILLATION
PARAMETERS

$$\left\{ \begin{array}{l} 3 \text{ Mixing Angles: } \vartheta_{12}, \vartheta_{23}, \vartheta_{13} \\ 1 \text{ CPV Dirac Phase: } \delta_{13} \\ 2 \text{ independent } \Delta m_{kj}^2 \equiv m_k^2 - m_j^2: \Delta m_{21}^2, \Delta m_{31}^2 \end{array} \right.$$

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

- ▶ In the standard 3ν mixing paradigm there are **two independent Δm^2 's**:
 - ▶ $\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2$ Solar Mass Splitting
 - ▶ $\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2$ Atmospheric Mass Splitting

- ▶ The **solar and atmospheric mass splittings generate oscillations that are detectable at the distances**
 - ▶ $L_{\text{SOL}}^{\text{osc}} \gtrsim \frac{E_\nu}{\Delta m_{\text{SOL}}^2} \approx 50 \text{ km} \frac{E_\nu}{\text{MeV}}$
 - ▶ $L_{\text{ATM}}^{\text{osc}} \gtrsim \frac{E_\nu}{\Delta m_{\text{ATM}}^2} \approx 1 \text{ km} \frac{E_\nu}{\text{MeV}}$

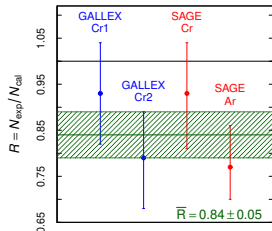
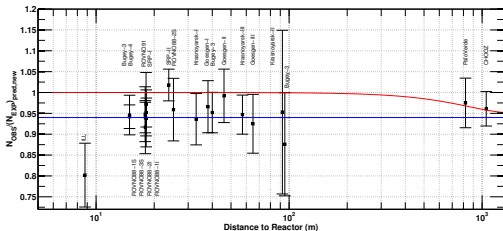
- ▶ The **solar and atmospheric mass splittings cannot explain neutrino oscillations at shorter distances.**

- ▶ A neutrino oscillation explanation of short-baseline anomalies needs the **existence of larger Δm^2 's.**

Historical Short-Baseline Anomalies

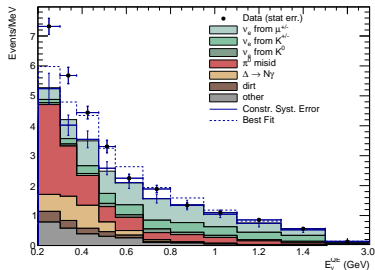
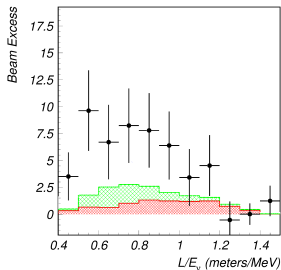
2011 Reactor Anomaly: $\bar{\nu}_e \rightarrow \bar{\nu}_x$ ($\approx 2.5\sigma$)

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

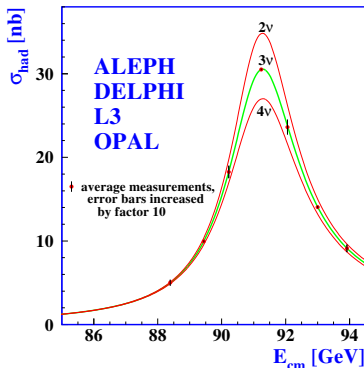
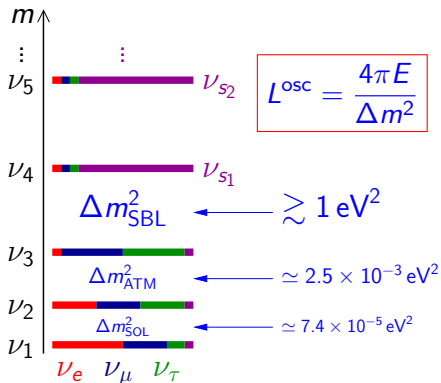


1995 LSND Anomaly: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ($\sim 4\sigma$)

2008 MiniBooNE Anomaly: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (4.8σ)



Beyond Three-Neutrino Mixing: Sterile Neutrinos



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

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

[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 ($\alpha \neq \beta$)

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SBL}(-)(-)} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

Disappearance

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}(-)(-)} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

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

SBL

$$\Delta m_{\text{SBL}}^2 = \Delta m_{41}^2 \simeq \Delta m_{42}^2 \simeq \Delta m_{43}^2$$

Common Parameterization of 4ν Mixing

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

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

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

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

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

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

with different notations in the literature:

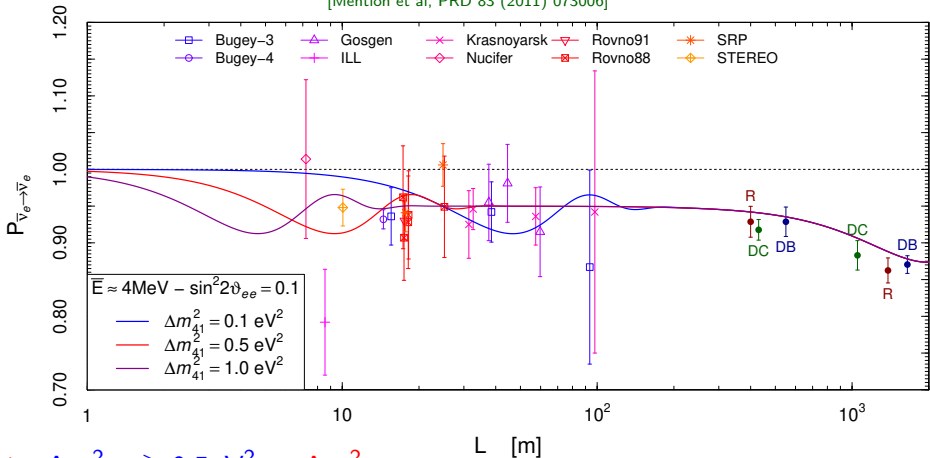
$$\vartheta_{ee} = \vartheta_{14} = \vartheta_{\text{new}} = \vartheta$$

and

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

Reactor Electron Antineutrino Anomaly

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

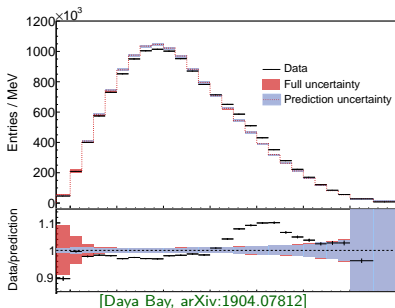
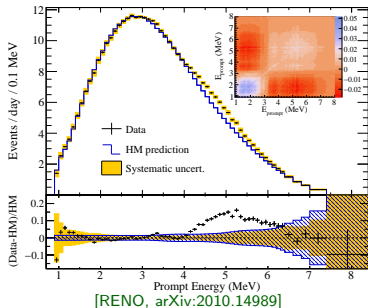


▶ $\Delta m_{\text{SBL}}^2 \gtrsim 0.5 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$

▶ SBL oscillations are **averaged** at the Daya Bay, RENO, and Double Chooz near detectors \implies **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)



- ▶ 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

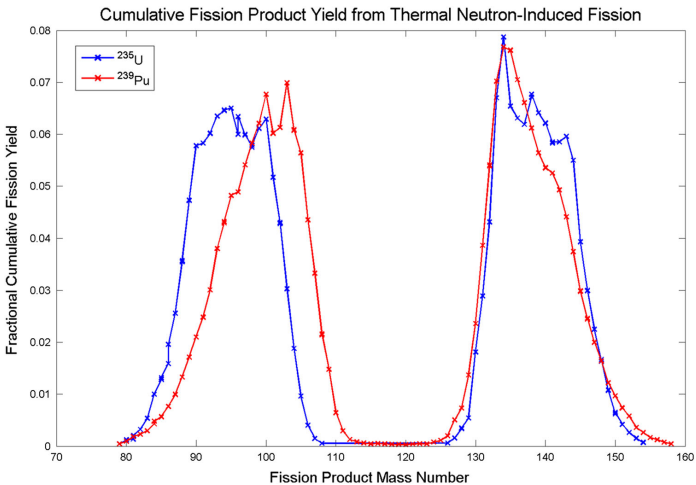
Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

^{235}U

^{238}U

^{239}Pu

^{241}Pu



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

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

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

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

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

	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^-	$[\Sigma, r]^{0-}$	λE_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):

$$S_{\text{tot}}(E, t) = \sum_k F_k(t) S_k(E) \quad (k = 235, 238, 239, 241)$$

↑
fission fractions

$$S_k(E) = \sum_n Y_n^k \sum_b \text{BR}_n^b S_n^b(E)$$

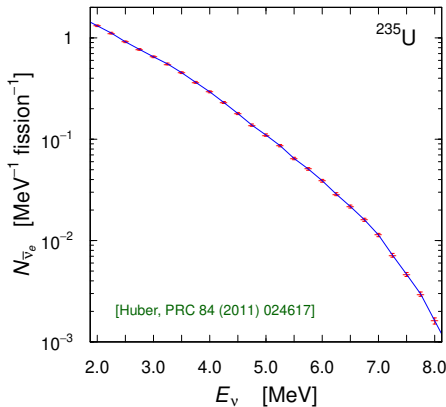
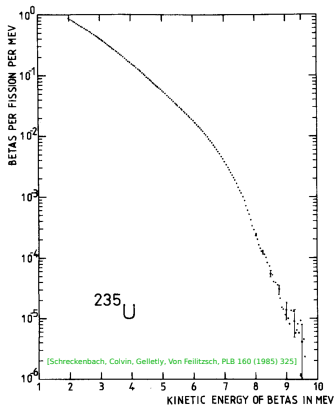
↑ ↑
cumulative branching
fission ratio
yield

allowed or
forbidden
decay
spectrum

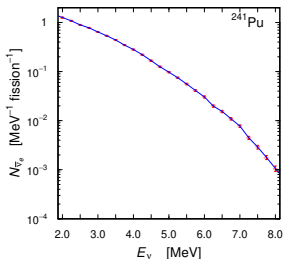
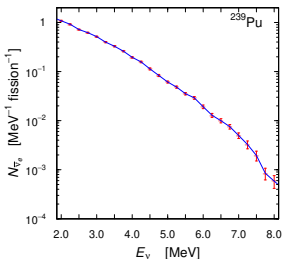
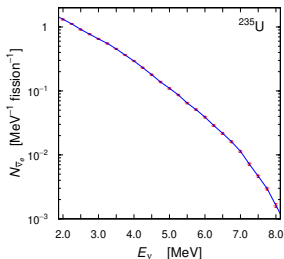
- ▶ The calculation of each $S_k(E)$ requires knowledge of about 1000 spectra and branching ratios.
- ▶ Large uncertainties, because nuclear databases are incomplete and sometimes inexact.

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 $S_k^e(E_e) \rightarrow S_k^\nu(E_\nu)$ considering ~ 30 virtual allowed β decay spectra. ($k = 235, 239, 241$)



- ▶ 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:

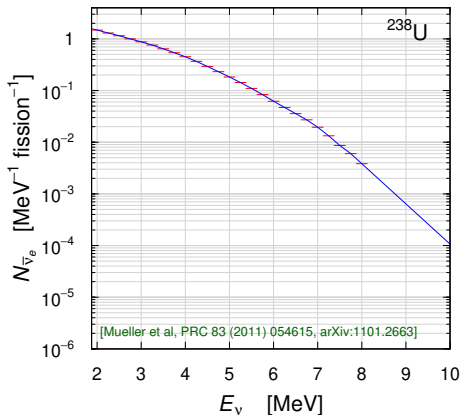
2.4% (^{235}U)

2.9% (^{239}Pu)

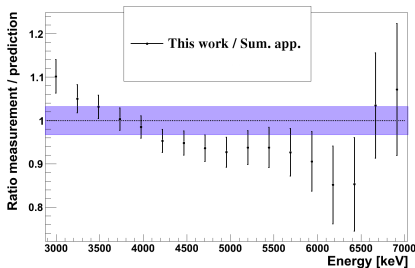
2.6% (^{241}Pu)

▶ 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]



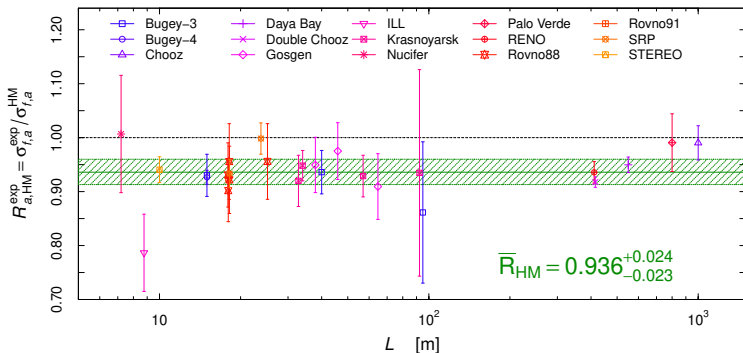
[Haag et al, PRL 112 (2014) 122501]

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]

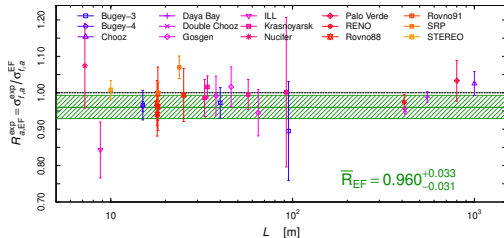
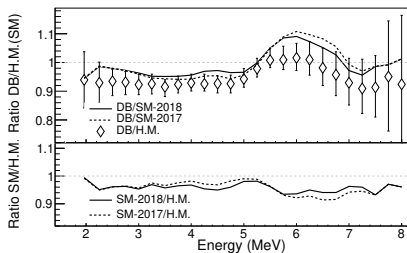


$\approx 2.5 \sigma$ deficit \implies Anomaly!

[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 \implies No Anomaly!

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

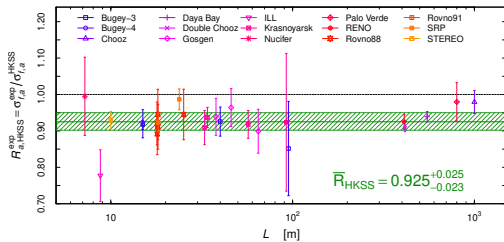
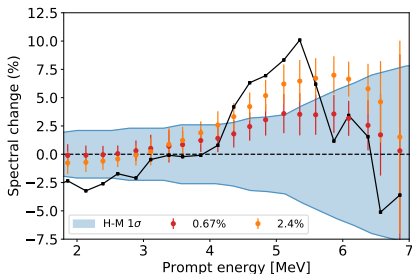
▶ UNKNOWN UNCERTAINTIES!

▶ 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 \implies Anomaly larger than the $\approx 2.5 \sigma$ HM anomaly!

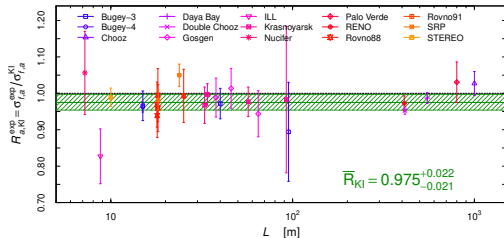
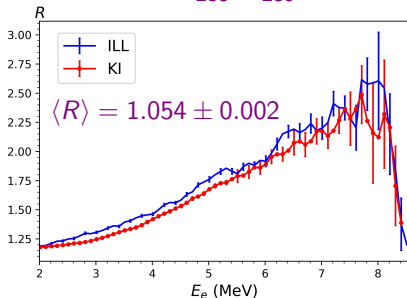
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

► HM + HKSS uncertainties.

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

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

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



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

$\approx 1.1 \sigma$ deficit \implies 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



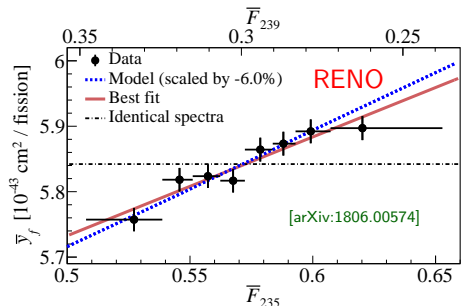
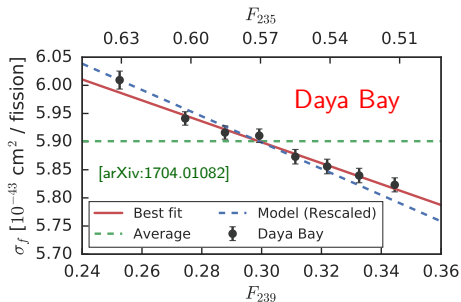
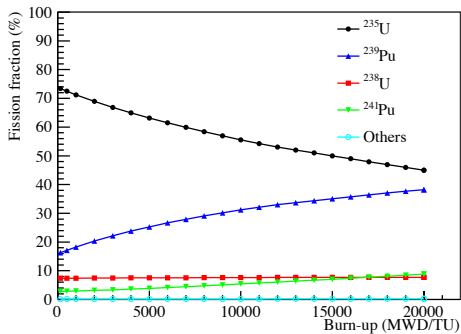
- ▶ Effective fission fractions:

$$F_{235} \quad F_{238} \quad F_{239} \quad F_{241}$$

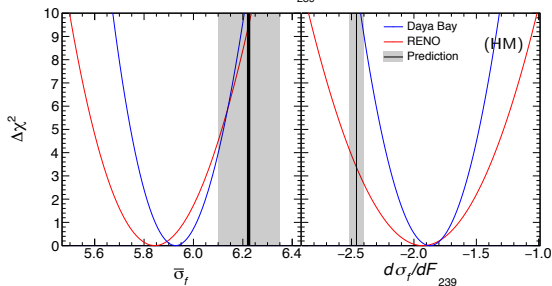
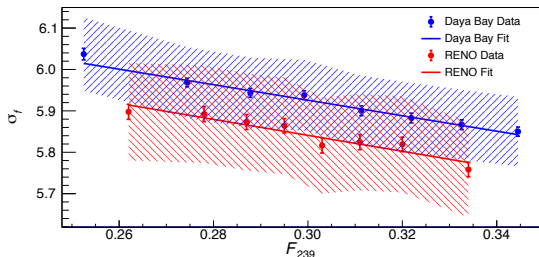
- ▶ Cross section per fission (IBD yield):

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

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



Approximate linear fit: $\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}} (F_{239} - \bar{F}_{239})$



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

► Rate anomaly:

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

► 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: $\bar{\sigma}_f = P_{ee} \bar{\sigma}_f^{\text{HM}}$

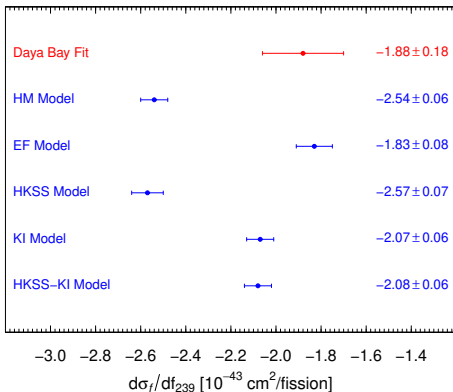
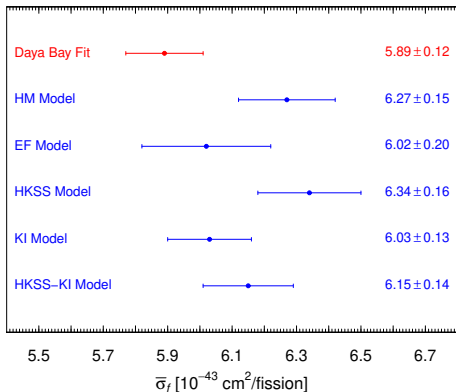
and
$$\frac{d\sigma_f}{dF_{239}} = P_{ee} \frac{d\sigma_f^{\text{HM}}}{dF_{239}}$$

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

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

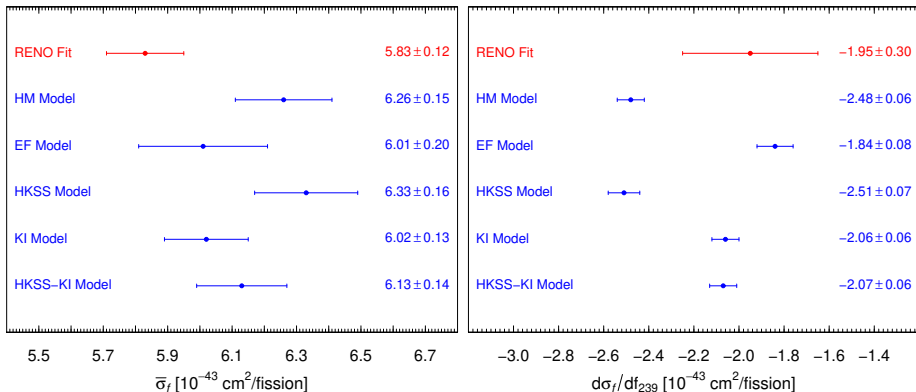
2.6σ

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



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

- ▶ Tension with HM (2.6σ), HKSS (2.8σ), and HKSS-KI (1.9σ).
- ▶ Agreement with EF (0.8σ) and KI (1.2σ).



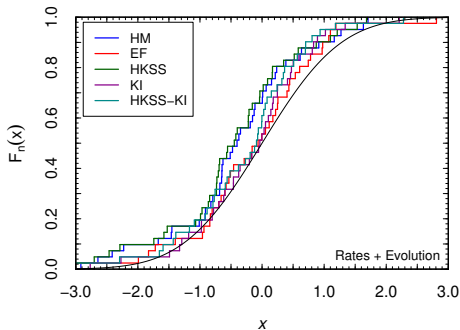
[CG, Li, Ternes, Xin, arXiv:2110.06820]

- ▶ Tension with HM (2.6σ), HKSS (2.8σ), and HKSS-KI (1.9σ).
- ▶ Agreement with EF (0.8σ) and KI (1.2σ).

Best-fit reactor flux model

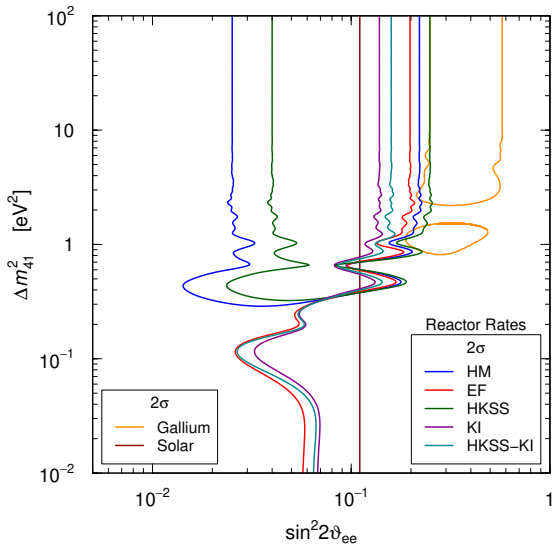
Goodness of fit tests assuming no (or negligible) SBL oscillations

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 $\sin^2 2\vartheta_{ee}$.

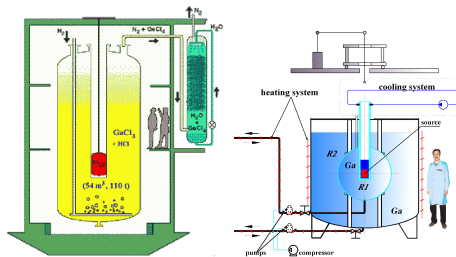
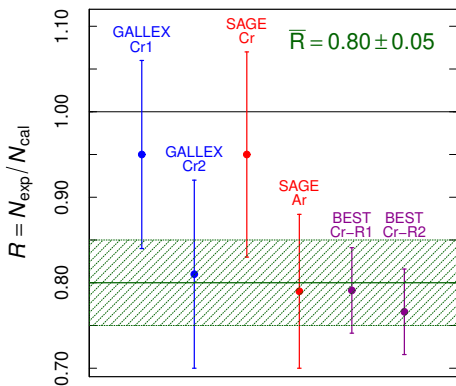
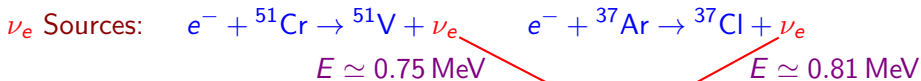
[Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898]

▶ There is a **tension** with the **Gallium anomaly** region.

[BEST, arXiv:2109.11482]

Gallium Anomaly

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



GALLEX

BEST

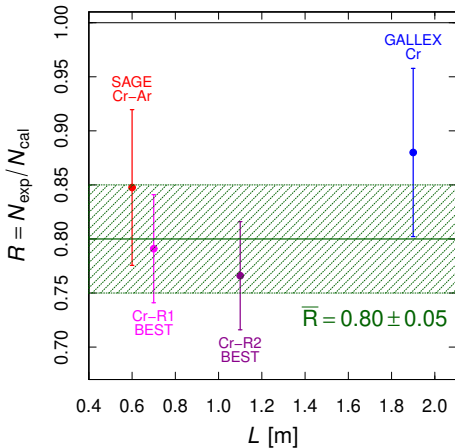
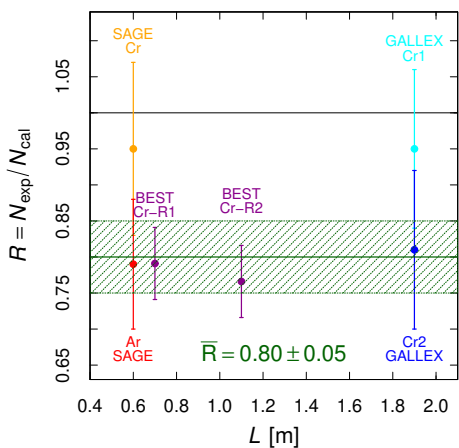
$\approx 4\sigma$ deficit \Rightarrow Anomaly!

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

$\langle L \rangle_{\text{BEST}}^{\text{R1}} \simeq 0.7 \text{ m}$ $\langle L \rangle_{\text{BEST}}^{\text{R2}} \simeq 1.1 \text{ m}$

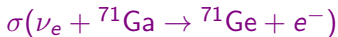
$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$

[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]

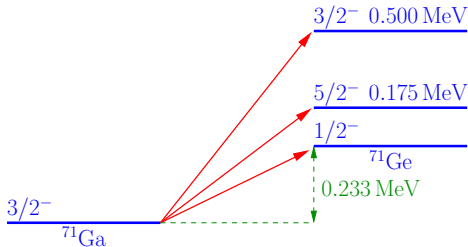


No clear model-independent anomaly from different path lengths

- ▶ Deficit could be due to an **overestimate** of



- ▶ First calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



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

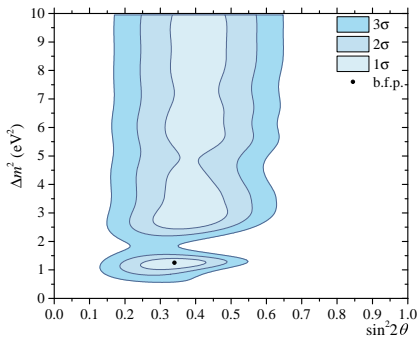
$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45} \text{ cm}^2$$

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

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

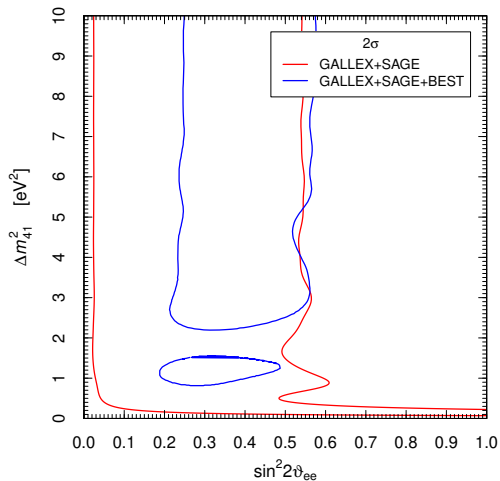
$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$ cross sections in units of 10^{-45} cm^2 :

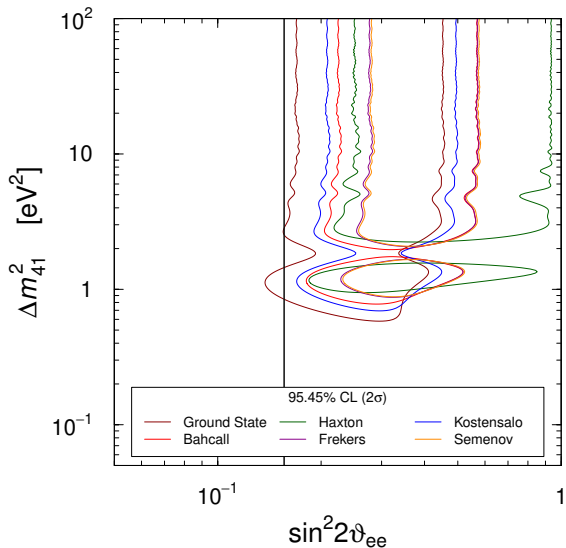
		${}^{51}\text{Cr}$		${}^{37}\text{Ar}$	
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State	$T_{1/2}({}^{71}\text{Ge})$	5.539 ± 0.019	—	6.625 ± 0.023	—
[Semenov, Phys.Atom.Nucl. 83 (2020) 1549]					
Bahcall (1997)	${}^{71}\text{Ga}(p, n){}^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
[hep-ph/9710491]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



[BEST, arXiv:2109.11482]

GALLEX+SAGE+BEST
with Bahcall cross section





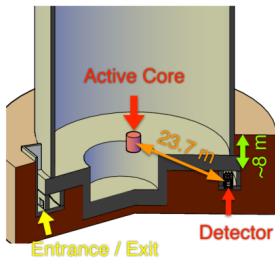
► Strong tension with the solar bound! [Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898]

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

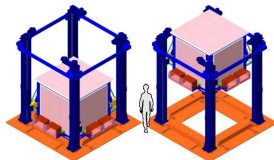
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

NEOS

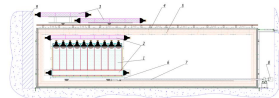


DANSS

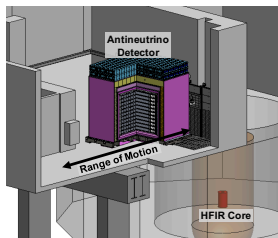


DANSS on a lifting platform

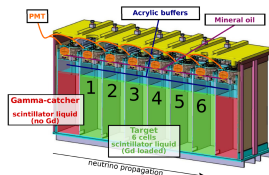
Neutrino-4



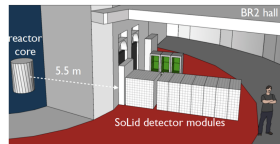
PROSPECT



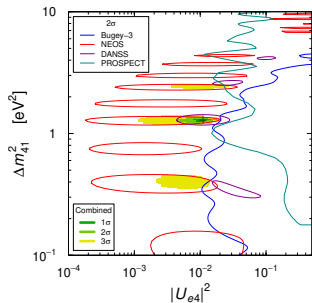
STEREO



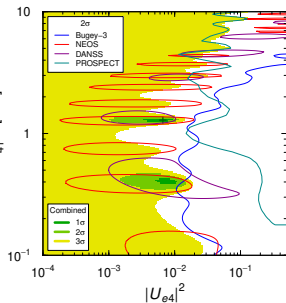
SoLid



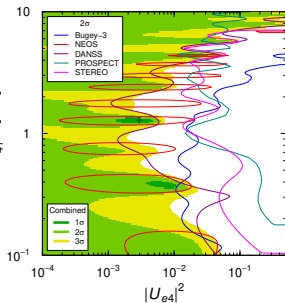
2018



2019



2020



- ▶ **2018:** remarkable agreement of the DANSS and NEOS best-fit regions at $\Delta m_{41}^2 \approx 1.3$ eV² \implies 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.

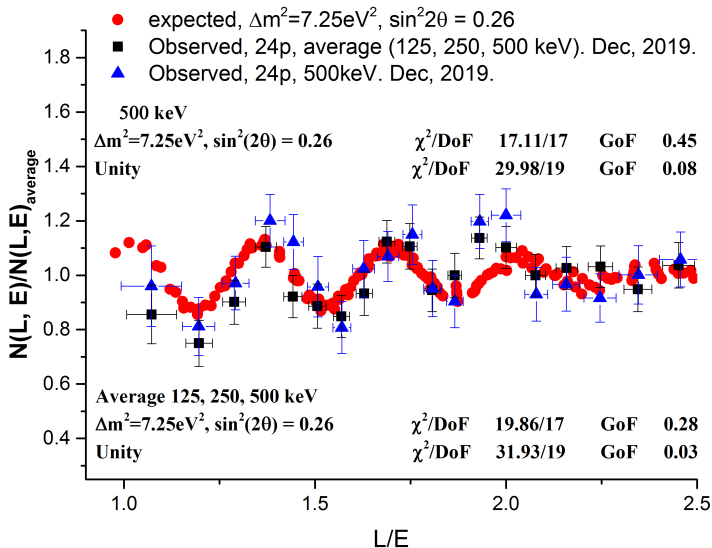
[CG, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

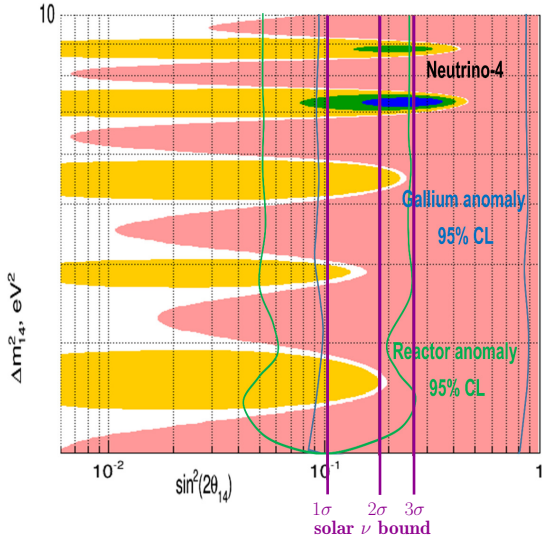
- ▶ **2020:** No 2σ DANSS allowed regions (exclusion curve).
No compelling indication of oscillations.

In practice these reactor experiments exclude large values of $|U_{e4}|^2$ for $0.1 \lesssim \Delta m_{41}^2 \lesssim 10$ eV²

Neutrino-4

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





► Neutrino-4 best fit:

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

$$\Delta m_{41}^2 = 7.25 \text{ eV}^2$$

► 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]

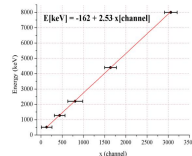
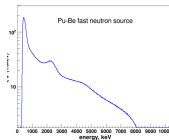
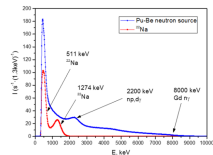
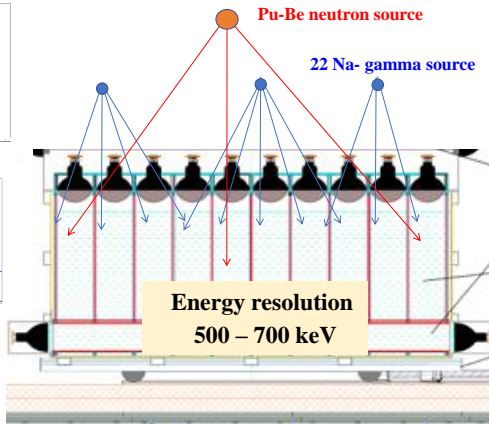
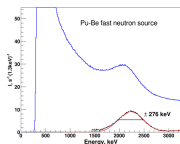
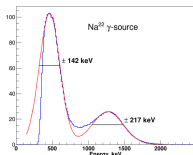
► No energy resolution!

[Danilov, arXiv:1812.04085]

[Danilov, Skrobova, JETP Lett. 112 (2020) 7]

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

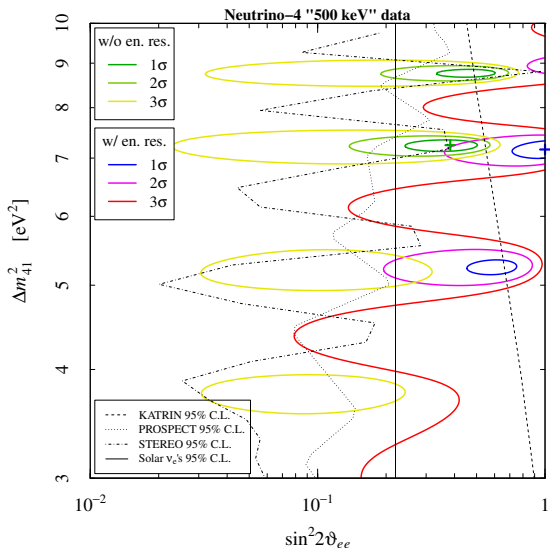
Energy calibration of the full-scale detector



15

- ▶ We approximate the energy resolution with the function

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



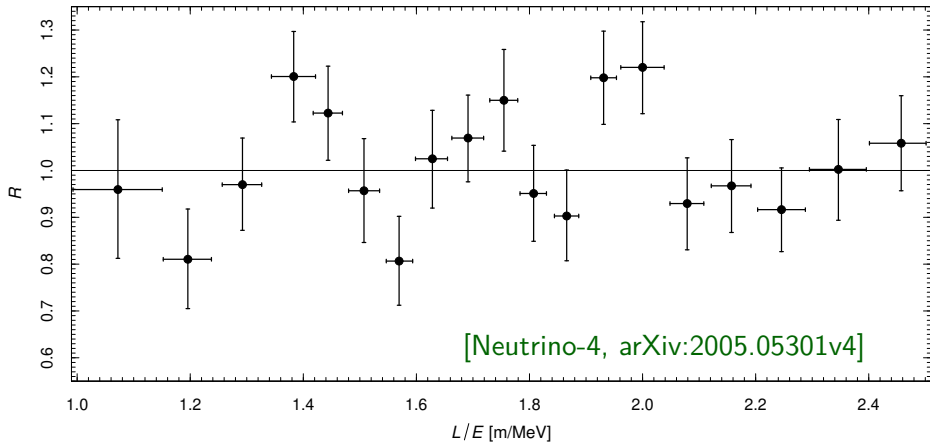
$$\chi^2 = \sum_{j=1}^{19} \left(\frac{R_j^{\text{the}} - R_j^{\text{exp}}}{\Delta R_j^{\text{exp}}} \right)^2$$

	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
$(\Delta m_{41}^2)_{\text{bf}}$	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](https://arxiv.org/abs/2005.05301v7), published in PRD 104 (2021) 032003: [The simultaneous usage of energy interval \$\Delta E = 500\$ keV and energy resolution \$\sigma = 250\$ 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.

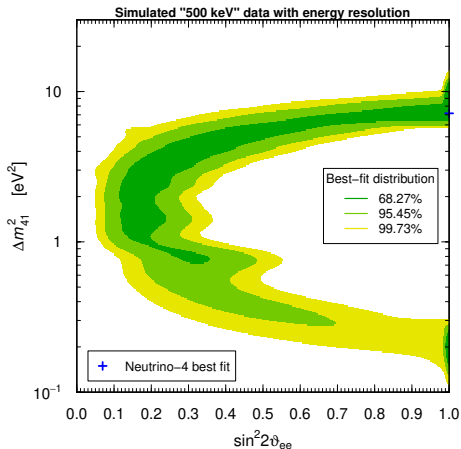
Neutrino-4: Oscillations or Fluctuations?



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.



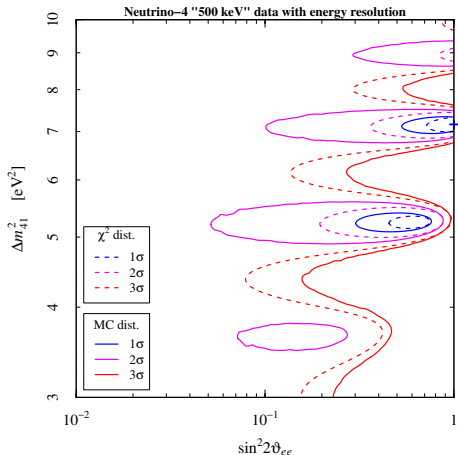
Distribution of best-fit points in a large set of random data generated without oscillations

	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 $(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2)$ 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_{41}^2 : $\chi_{\text{MC}}^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2)$.
 - ▶ We found the minimum value of χ^2 in the $(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2)$ plane: $\chi_{\text{MC,min}}^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2)$.
- ▶ In this way, we obtained the distribution of $\Delta\chi_{\text{MC}}^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2) = \chi_{\text{MC}}^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2) - \chi_{\text{MC,min}}^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2)$.
- ▶ This distribution allows us to determine if the value of $\Delta\chi^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2) = \chi^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2) - \chi_{\text{min}}^2(\sin^2 2\vartheta_{ee}, \Delta m_{41}^2)$ 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 12 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.