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:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- 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)

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

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

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

OSCILLATION PARAMETERS

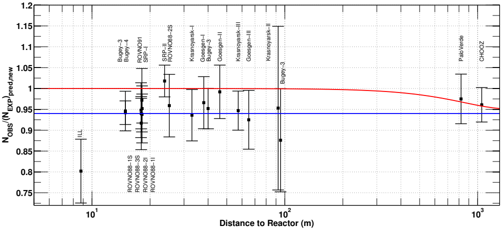
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

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

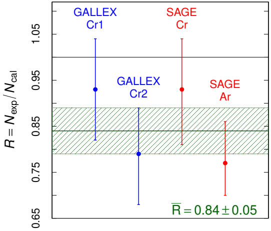
- In the standard 3ν mixing paradigm there are two independent Δm^2's:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$ Solar Mass Splitting
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$ Atmospheric Mass Splitting
-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

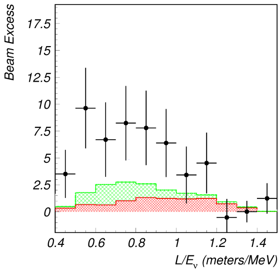
2011 Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ ($\approx 2.5\sigma$)



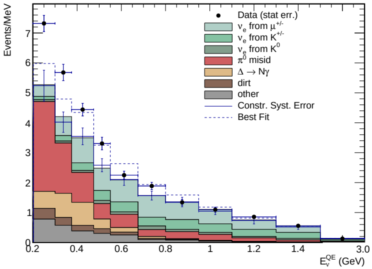
2005 Gallium Anomaly: $\nu_e \to \nu_x$ ($\approx 2.9\sigma$)



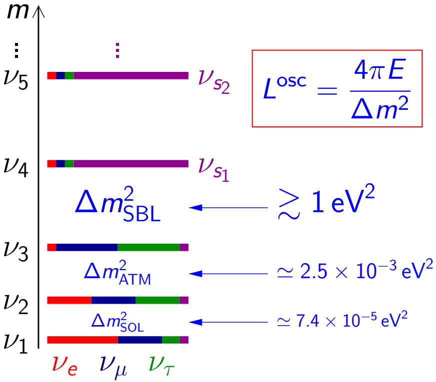
1995 LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ ($\sim 4\sigma$)



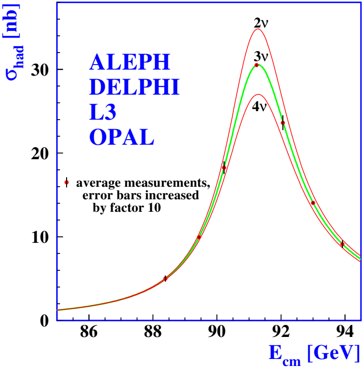
2008 MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



Beyond Three-Neutrino Mixing: Sterile Neutrinos



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



Minimal perturbation of successful 3ν mixing: effective 4ν mixing with

$$|U_{e4}|,\ |U_{\mu4}|,\ |U_{\tau4}| \ll 1$$

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

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

[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

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

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

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

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

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

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

with different notations in the literature:

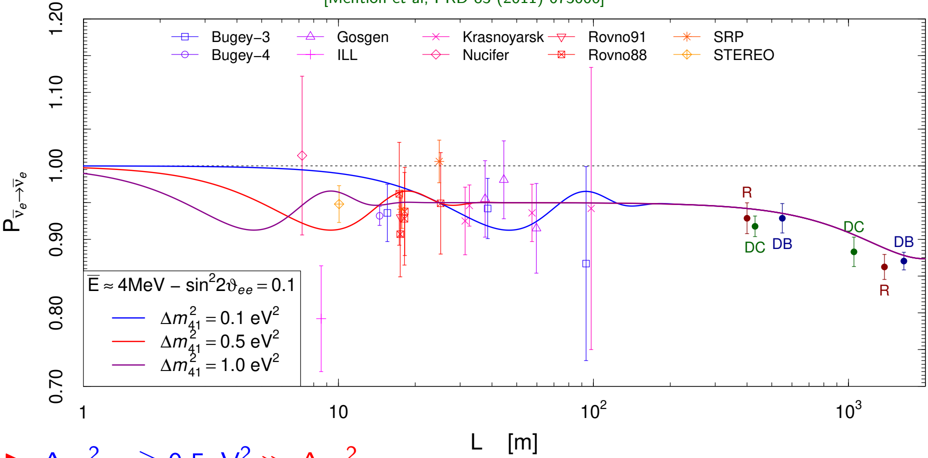
$$\vartheta_{ee} = \vartheta_{14} = \vartheta_{\text{new}} = \vartheta$$

and

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

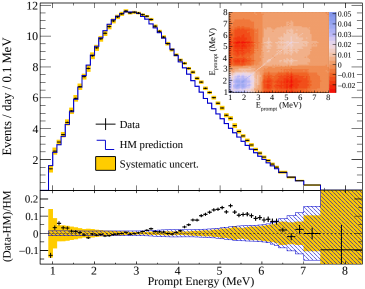
Reactor Electron Antineutrino Anomaly

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

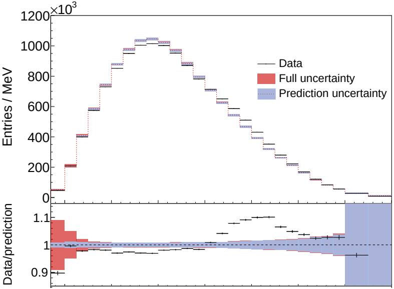


- $\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$
- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion
- The Reactor Antineutrino Anomaly is model dependent (depends on the theoretical reactor neutrino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

Reactor Antineutrino 5 MeV Bump (Shoulder)



[RENO, arXiv:2010.14989]



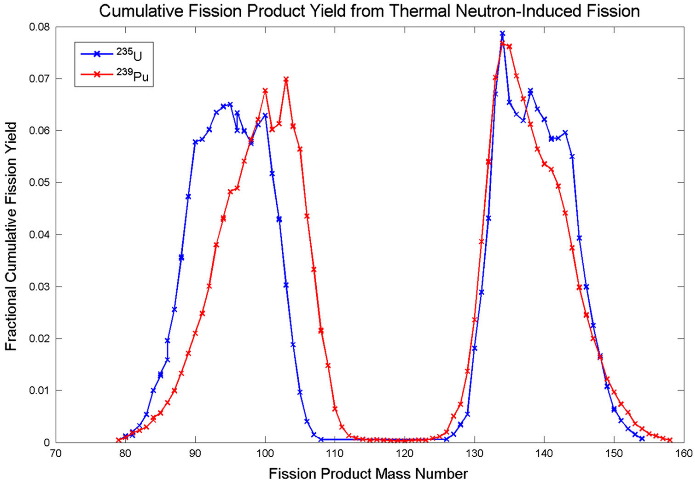
[Daya Bay, arXiv:1904.07812]

- Discovered in 2014 by RENO, Double Chooz, Daya Bay.
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).
- If it is due to a theoretical miscalculation of the spectrum, it can have opposite effects on the anomaly: [see: Berryman, Huber, arXiv:1909.09267]
  - If it is a 4-6 MeV excess it increases the anomaly: recent HKSS flux calculation [Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302]
  - If it is a 1-4 MeV suppression it decreases the anomaly: recent EF flux calculation [Estienne, Fallot, et al, arXiv:1904.09358] new KI ^{235}U flux renormalization [Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]

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 the electron spectrum is

$$S_\beta(E_e) = K p_e E_e \left(E_e - E_0\right)^2 F(Z, E_e) \qquad (E_\nu = E_0 - E_e)$$

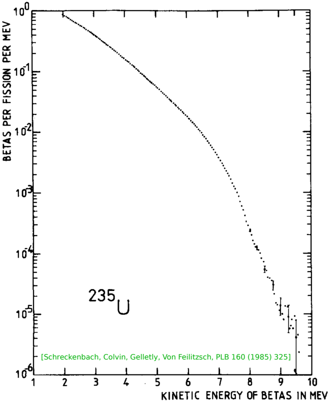
$$S_\nu(E_\nu) = K \sqrt{(E_0 - E_e)^2 - m_e^2}\,(E_0 - E_e)\, E_\nu^2 F(Z, E_e)$$

- Aggregate reactor spectrum (electron or neutrino):

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

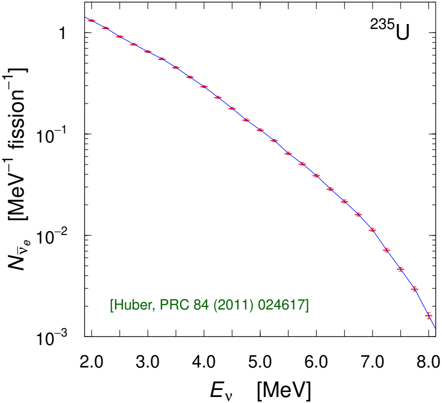
$$S_k(E) = \sum_n \underset{\substack{\uparrow \\ \text{cumulative} \\ \text{fission} \\ \text{yield}}}{Y_n^k} \sum_b \underset{\substack{\uparrow \\ \text{branching} \\ \text{ratio}}}{\text{BR}_n^b}\; S_n^b(E) \leftarrow \begin{array}{c}\text{allowed or} \\ \text{forbidden} \\ \text{decay} \\ \text{spectrum}\end{array}$$

- The *ab initio* calculation of each $S_k^{\nu}(E_{\nu})$ requires knowledge of about 1000 spectra and branching ratios $(k = 235, 238, 239, 241)$.
- Nuclear data tables are incomplete and sometimes inexact.
- Semi-empirical method: conversion of the aggregate β spectra $S_k^{\beta}(E_e)$ measured at ILL in the 80's with $\sim$ 30 virtual β branches.



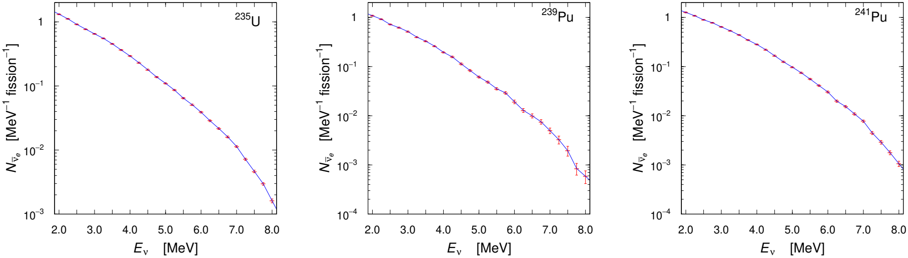
[Schreckenbach, Colvin, Gelletly, Von Feilitzsch, PLB 160 (1985) 325]

$\Longrightarrow$



[Huber, PRC 84 (2011) 024617]

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



[Huber, PRC 84 (2011) 024617]

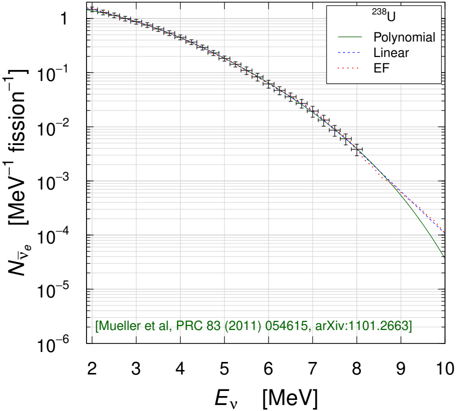
- The conversion method was estimated to have about 1% uncertainty.

[Vogel, PRC 76 (2007) 025504]

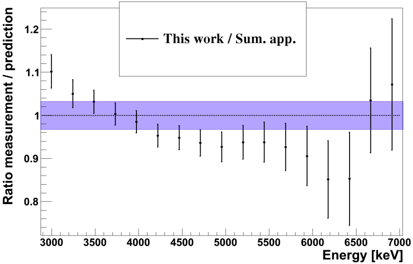
- Estimated total uncertainties on the neutrino detection rates:

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

- The ^{238}U $\bar{\nu}_e$ flux was calculated ab initio 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]



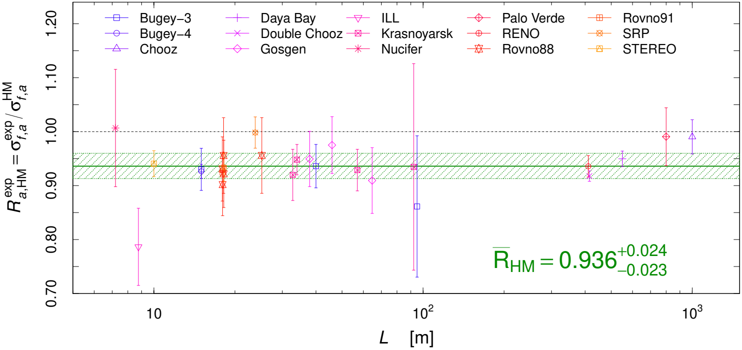
[Haag et al, PRL 112 (2014) 122501]

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]

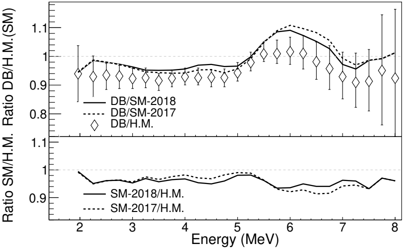


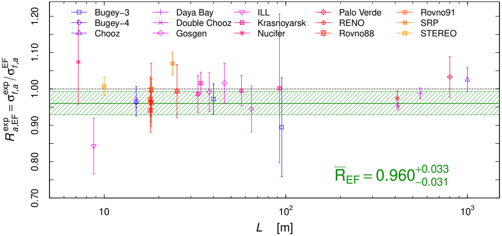
$\approx 2.5\,\sigma$ deficit $\Longrightarrow$ Anomaly!

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

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

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





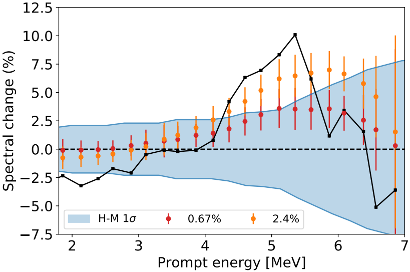
[CG, Li, Ternes, Xin, arXiv:2110.06820]

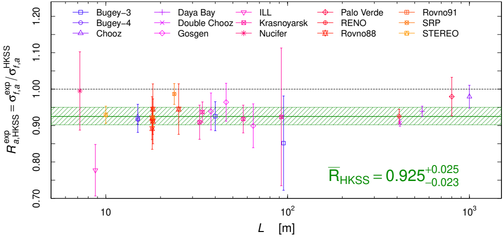
$\approx 1.2\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

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

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

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





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

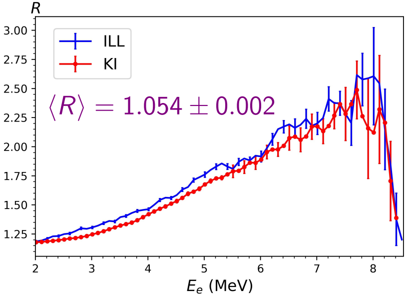
$\approx 2.9\,\sigma$ deficit $\Longrightarrow$ Anomaly larger than the $\approx 2.5\,\sigma$ HM anomaly!

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

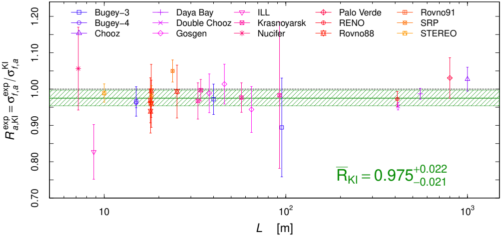
2021: new converted reactor $\bar{\nu}_e$ fluxes: KI

[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!

Reactor Fuel Evolution

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

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

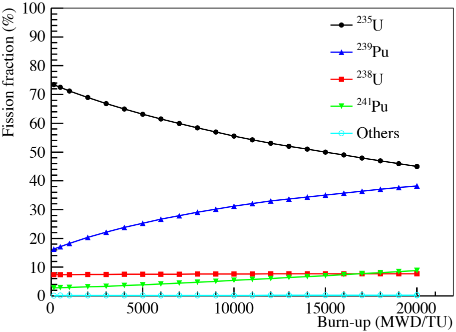
- Effective fission fractions:

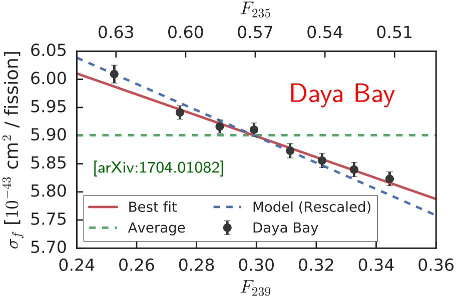
  F_{235} F_{238} F_{239} F_{241}

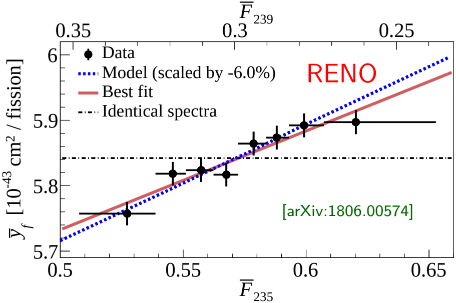
- Cross section per fission (IBD yield):

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

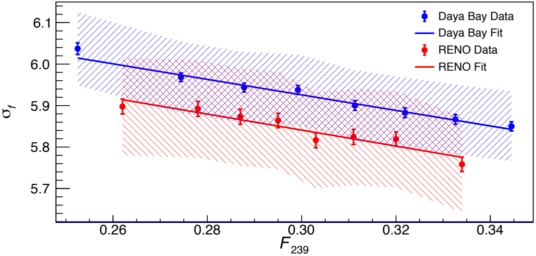
for $k = 235, 238, 239, 241$

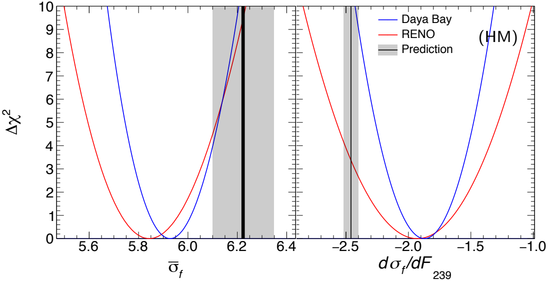






Approximate linear fit: $\sigma_f(F_{239}) = \overline{\sigma}_f + \frac{d\sigma_f}{dF_{239}} \left(F_{239} - \overline{F}_{239}\right)$





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

- Rate anomaly:

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

- Evolution anomaly:

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

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

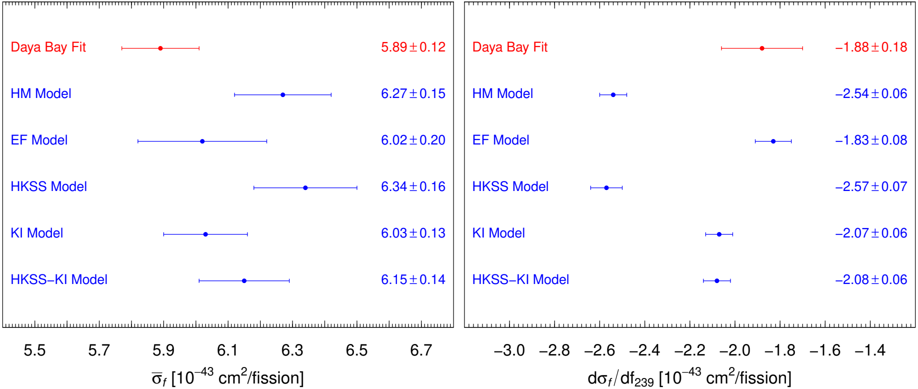
and $\frac{d\sigma_f}{dF_{239}} = P_{ee} \frac{d\sigma_f^{\mathrm{HM}}}{dF_{239}}$

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

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

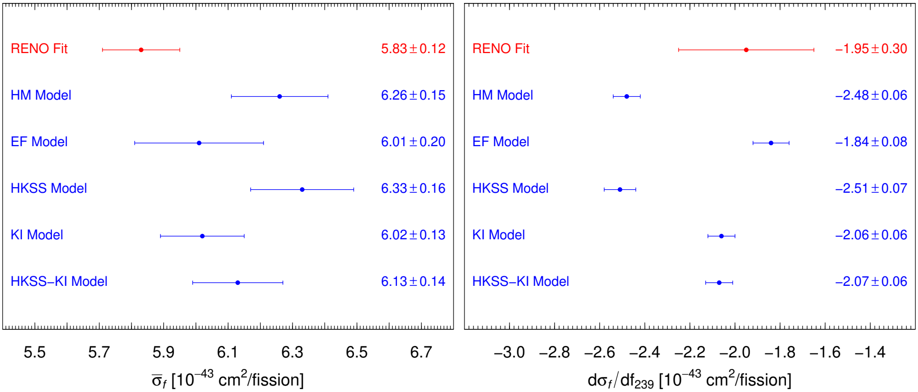
2.6σ

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



[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 $(1.2\,\sigma)$.



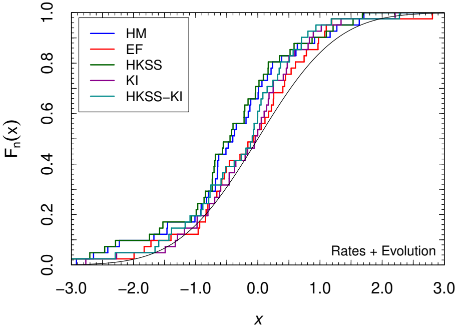
[CG, Li, Ternes, Xin, arXiv:2110.06820]

- 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

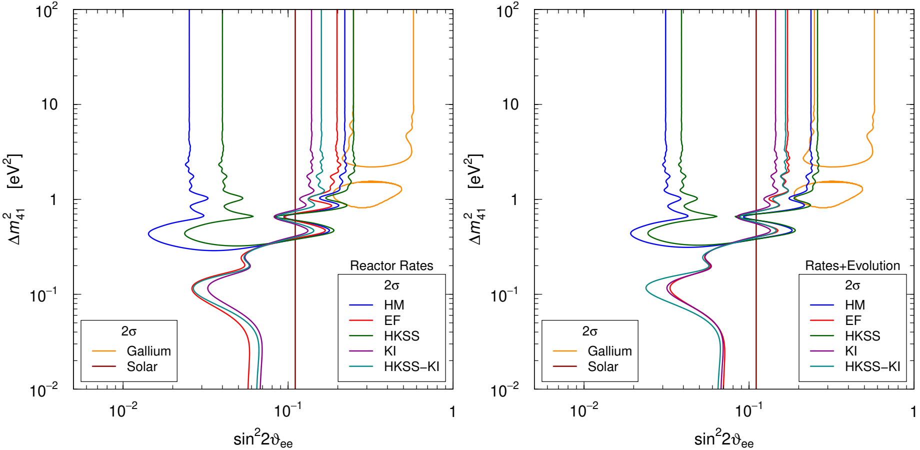


[CG, Li, Ternes, Xin, arXiv:2110.06820]

- The KI model is the best among the conversion models.
- The summation EF model is approximately equally good.

Implications for oscillations

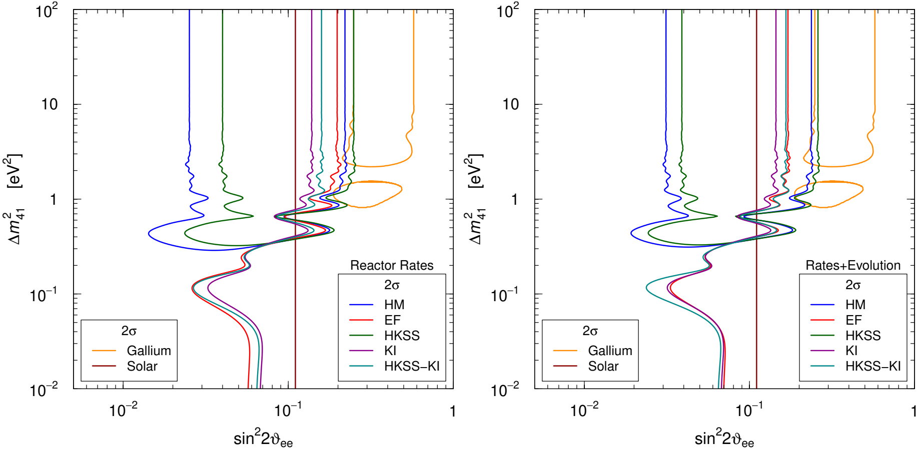
[CG, Li, Ternes, Xin, arXiv:2110.06820]



- 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, $\sin^2 2\vartheta_{ee} \lesssim 0.25$ at 2σ.

Implications for oscillations

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



- 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 BEST Gallium anomaly region. [BEST, arXiv:2109.11482]

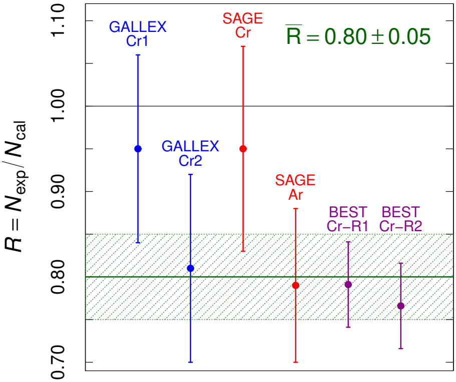
Gallium Anomaly

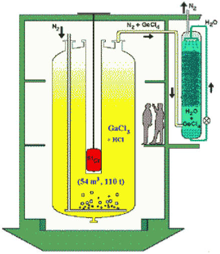
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

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

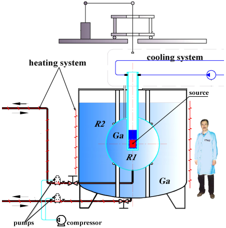
$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

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





GALLEX



BEST

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

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

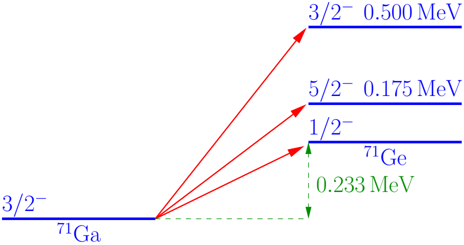
$\langle L \rangle_{\text{BEST}}^{\text{R1}} \simeq 0.7\,\text{m}$ $\quad \langle L \rangle_{\text{BEST}}^{\text{R2}} \simeq 1.1\,\text{m}$

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

[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]

- 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]

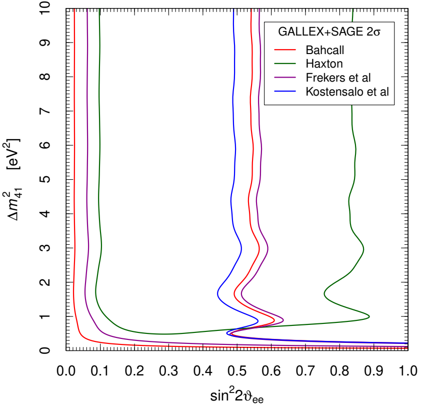
$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45}\,\text{cm}^2$$

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

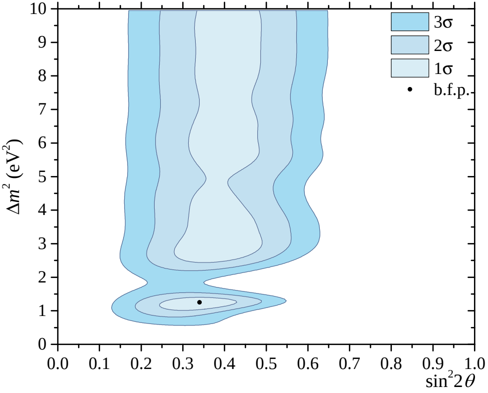
- The contribution of excited states is only $\sim 5\%$! [Bahcall, hep-ph/9710491]

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

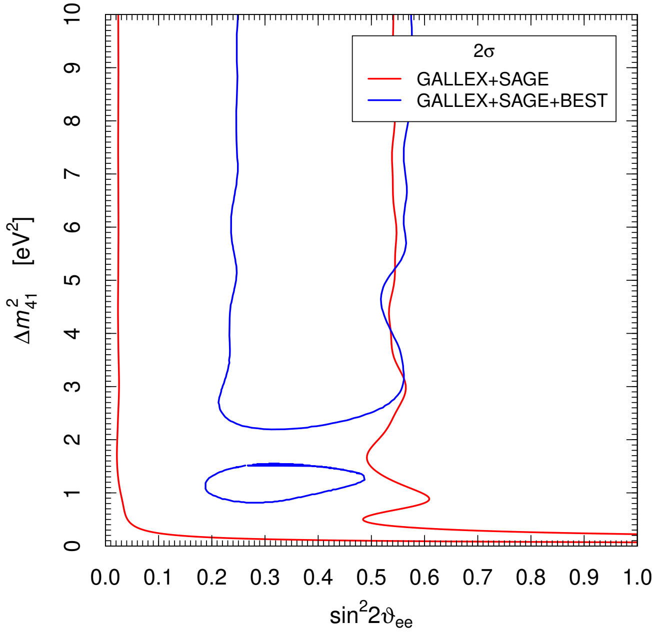


[Kostensalo, Suhonen, CG, Srivastava, arXiv:1906.10980]

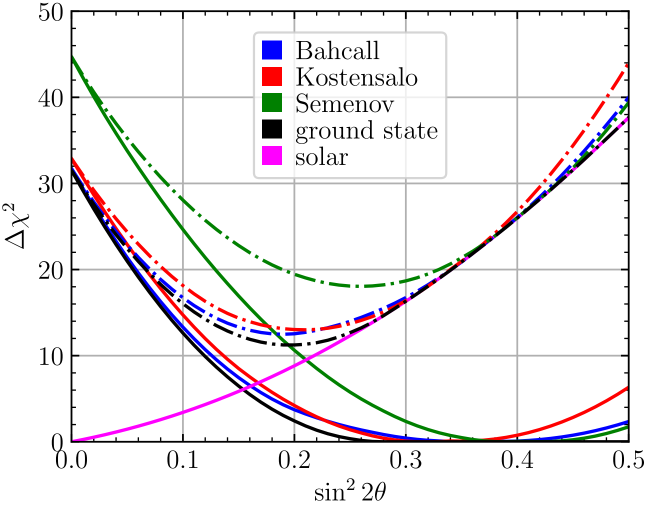


[BEST, arXiv:2109.11482]

GALLEX+SAGE+BEST
with Bahcall cross section

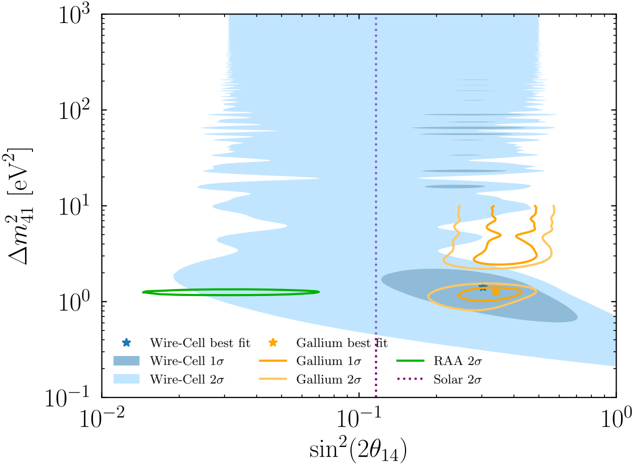

2σ
GALLEX+SAGE
GALLEX+SAGE+BEST
Δm^2_{41} [eV^2]
0
1
2
3
4
5
6
7
8
9
10
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\sin^2 2\vartheta_{ee}$

BEST tension with solar bound



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

BEST agreement with hypothetical MicroBooNE ν_e disappearance

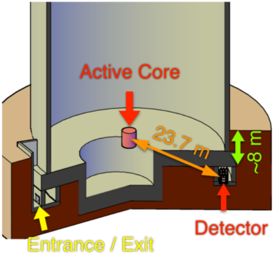


[Denton, arXiv:2111.05793]

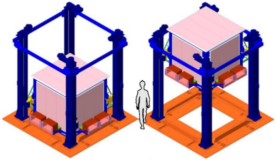
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

NEOS

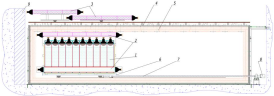


DANSS

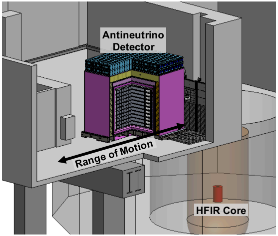


DANSS on a lifting platform

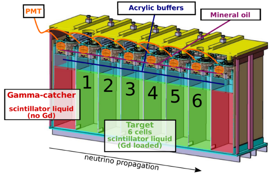
Neutrino-4



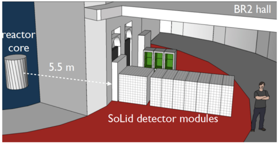
PROSPECT

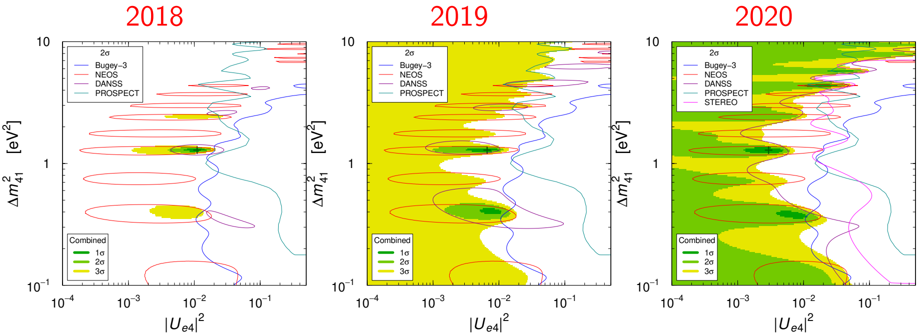


STEREO



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.

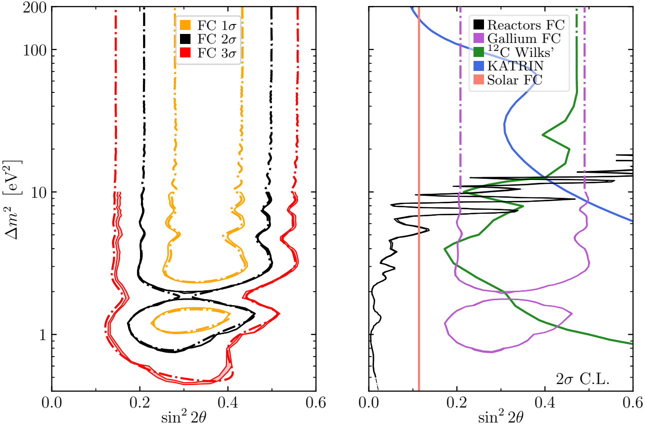
  [CG, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

- 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

  $$0.1 \lesssim \Delta m^2_{41} \lesssim 10\,\text{eV}^2$$



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

Kostensalo et al. Gallium cross section [arXiv:1906.10980]

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.
- Topic for another seminar (by somebody else): even more confusing status of appearance data (MicroBooNE vs MiniBooNE), global fits, and the appearance-disappearance tension.