Overview of Light Sterile Neutrinos

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NOW 2022

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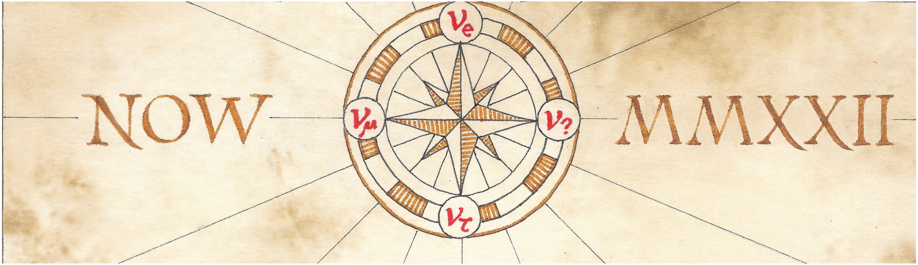
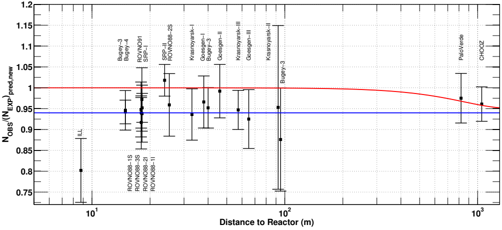
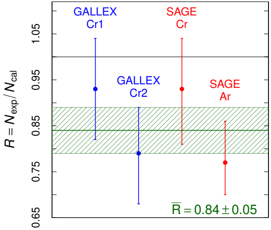


Historical Short-Baseline Anomalies

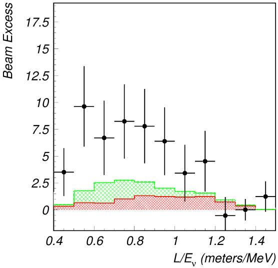
2011 Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ (2.5σ)



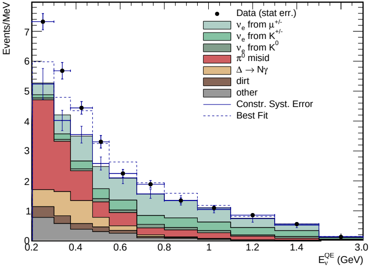
2005 Gallium Anomaly: $\nu_e \to \nu_x$ (2.9σ)



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

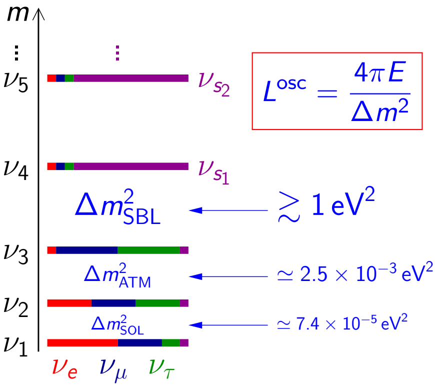


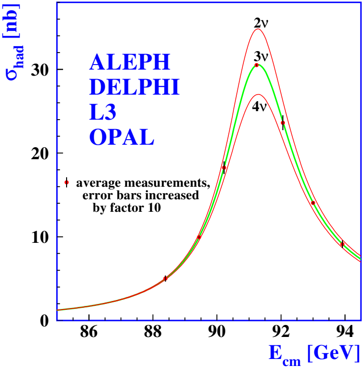
2008 MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



Beyond Three-Neutrino Mixing: Sterile Neutrinos

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





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

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

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

[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 ($\alpha \neq \beta$)

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

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

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

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

Common Parameterization of 4ν Mixing

$$U = \Big[W^{34} R^{24} W^{14} \underbrace{R^{23} W^{13} R^{12}}_{\text{standard } 3\nu} \Big] \, \mathrm{diag}\left(1, e^{i\lambda_{21}}, e^{i\lambda_{31}}, e^{i\lambda_{41}}\right)$$

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

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

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

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

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

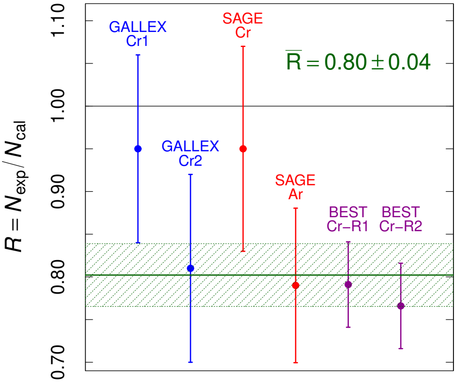
Gallium Anomaly

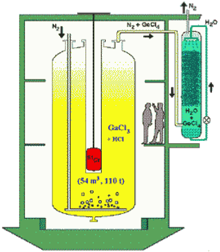
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

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

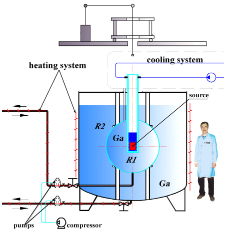
$E \simeq 0.75\,\text{MeV}$ $\quad$ $E \simeq 0.81\,\text{MeV}$

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





GALLEX



BEST

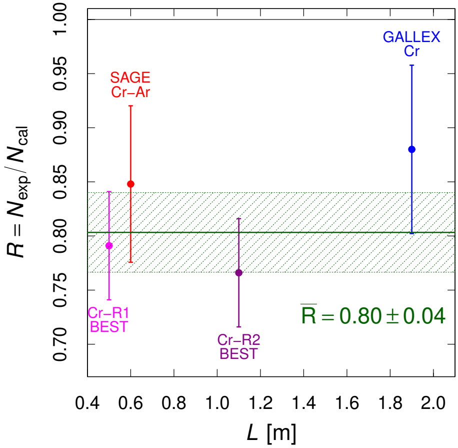
$\approx$ 5-6σ deficit $\Longrightarrow$ Anomaly!

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

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

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

[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]

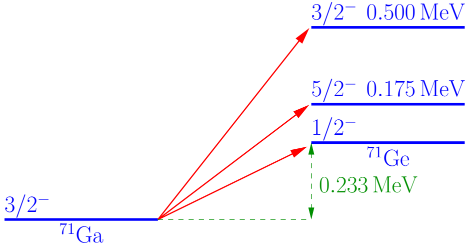


- No clear model-independent anomaly from different path lengths.
- Puzzling quasi-equality of the two BEST measurements at different distances.
- After the BEST measurements, the Gallium Anomaly is still an anomaly based on the absolute comparison of observed and predicted rates.

- A 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]

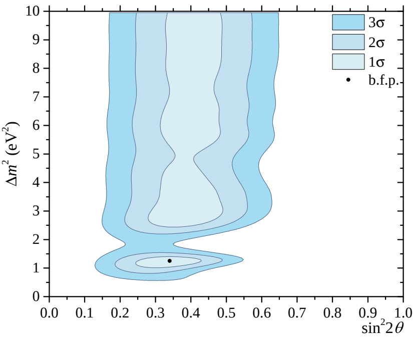
$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45}\,\text{cm}^2$$

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

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

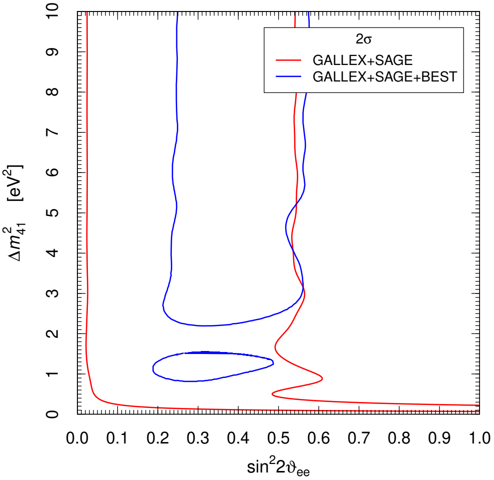
$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ cross sections in units of $10^{-45}\,\text{cm}^2$:

		^{51}Cr		^{37}Ar			
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}	$\overline{R}$	GA
Ground State [Phys.Atom.Nucl. 83 (2020) 1549]	$T_{1/2}({}^{71}\text{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–	0.844 ± 0.031	5.0σ
Bahcall [hep-ph/9710491]	${}^{71}\text{Ga}(p,n){}^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%	0.802 ± 0.037	5.4σ
Kostensalo et al. [arXiv:1906.10980]	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%	0.824 ± 0.031	5.6σ
Semenov [Phys.Atom.Nucl. 83 (2020) 1549]	${}^{71}\text{Ga}({}^{3}\text{He},{}^{3}\text{H}){}^{71}\text{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%	0.786 ± 0.033	6.6σ

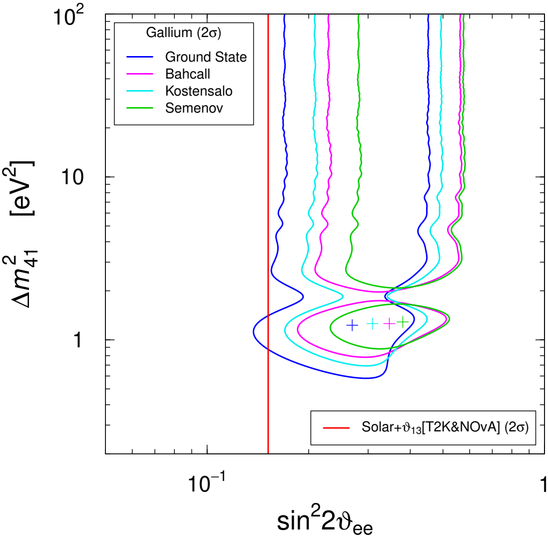


[BEST, arXiv:2109.11482]

GALLEX+SAGE+BEST
with Bahcall cross section



Strong tension with the solar neutrino bound



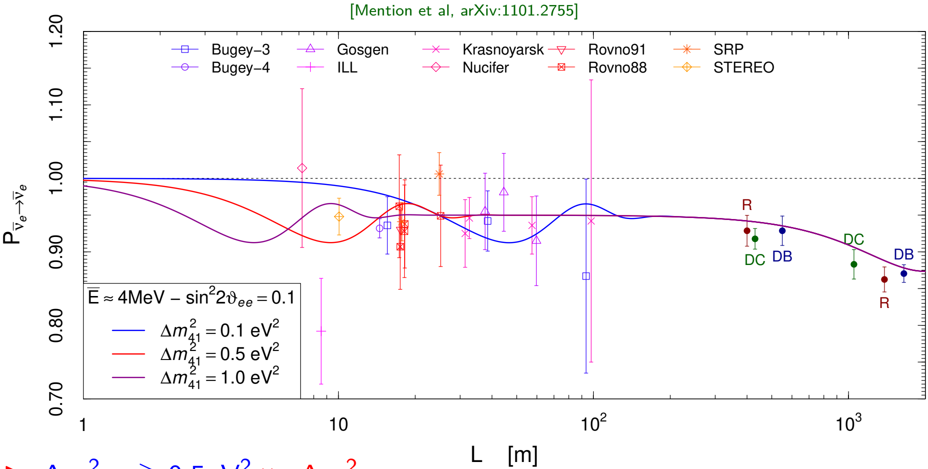
	Solar neutrinos + ϑ_{13}[T2K&NOvA]	
	$\Delta\chi^2_{\text{PG}}$	GoF_{PG}
Ground State	10.65	0.49%
Bahcall	14.14	0.085%
Kostensalo	12.79	0.17%
Semenov	17.24	0.018%

[CG, Li ,Ternes, Tyagi, Xin, arXiv:2209.00916]

- Both Gallium and solar experiments detect neutrinos.
- No CPT-violating solution of the tension!

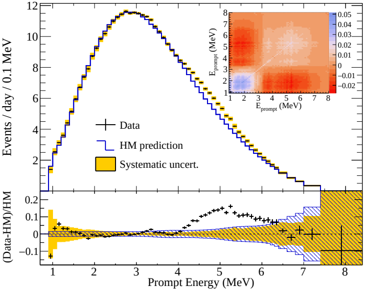
[see also: Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898; Berryman, Coloma, Huber, Schwetz, Zhou, arXiv:2111.12530]

Reactor Electron Antineutrino Anomaly

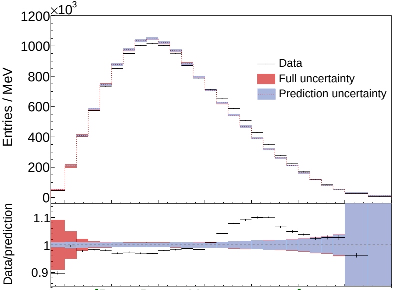


- $\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$
- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion
- The Reactor Antineutrino Anomaly is model dependent; it depends on the Huber-Mueller (HM)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

Reactor Antineutrino 5 MeV Bump (Shoulder)



[RENO, arXiv:2010.14989]



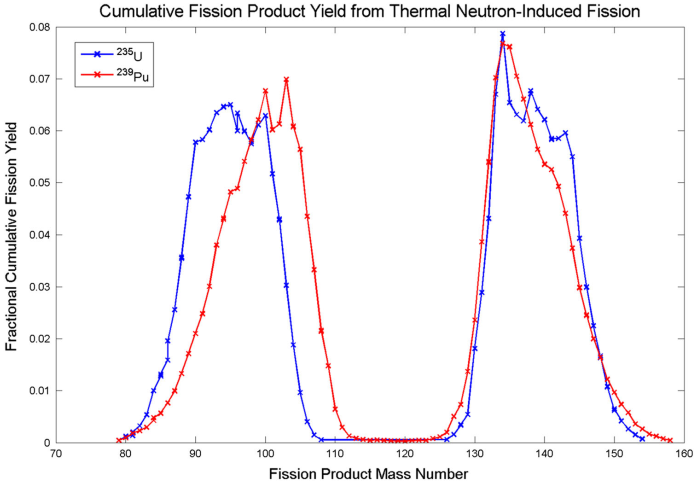
[Daya Bay, arXiv:1904.07812]

- 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 Calculations

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]

Two methods:

- Summation method (*ab initio*)
- Conversion method

Summation (*ab initio*) Method

- Aggregate reactor spectrum (electron or neutrino):

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

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

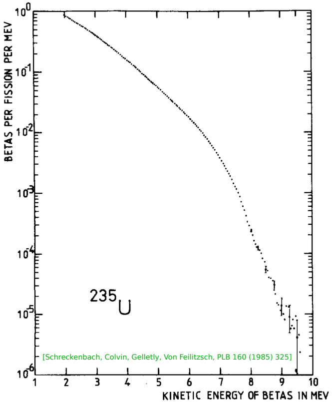
- The calculation of each $S_k(E)$ requires knowledge of about 1000 spectra and branching ratios.

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

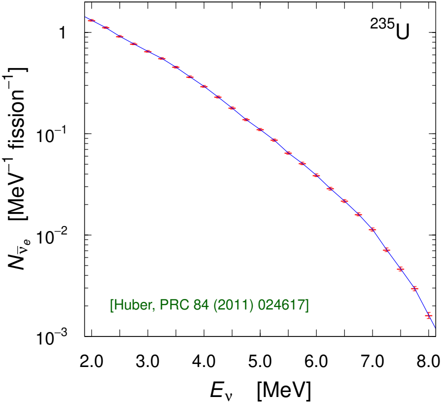
Conversion Method

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

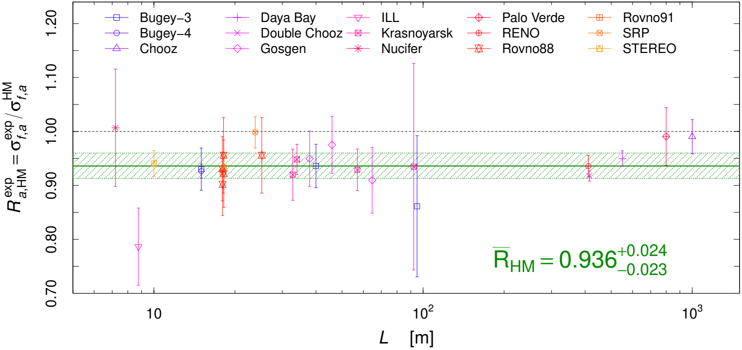


$\Longrightarrow$



2011: HM fluxes (conversion method)

[Mueller et al, arXiv:1101.2663], Huber, arXiv:1106.0687]



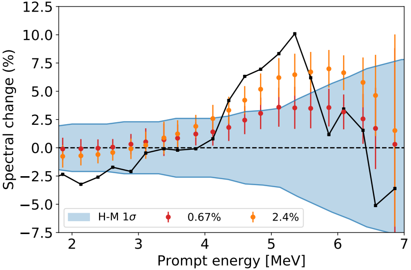
$2.5\,\sigma$ deficit $\Longrightarrow$ Anomaly!

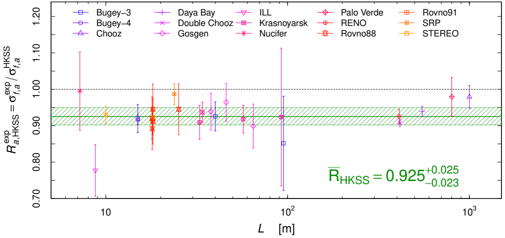
[CG, Li, Ternes, Xin, arXiv:2110.06820]

- Original 2011 Reactor Antineutrino Anomaly: 2.5σ [Mention et al, arXiv:1101.2755]

2019: HKSS fluxes (conversion method)

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





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

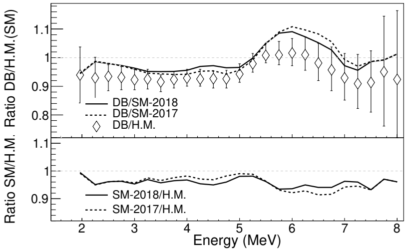
$2.9\,\sigma$ deficit $\Longrightarrow$ Anomaly larger than the $2.5\,\sigma$ HM anomaly!

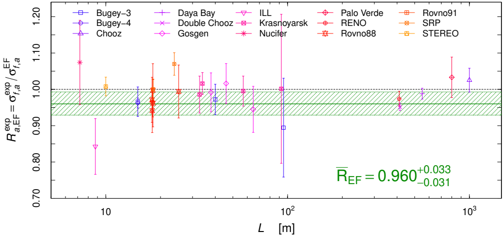
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

- HM + HKSS uncertainties.

2019: EF fluxes (summation method)

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





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

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

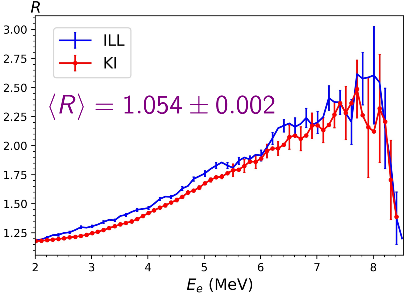
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

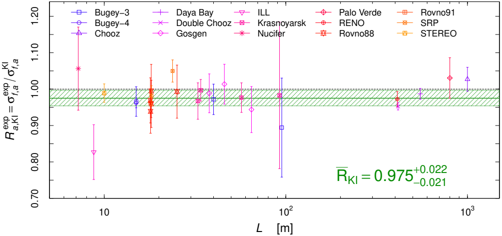
- UNKNOWN UNCERTAINTIES!
- Rough estimation used in our calculations: 5% for ^{235}U, ^{239}Pu, ^{241}Pu and 10% for ^{238}U. [Hayes, Jungman, McCutchan, Sonzogni, Garvey, Wang, arXiv:1707.07728]

2021: KI fluxes (conversion method)

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

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





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

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

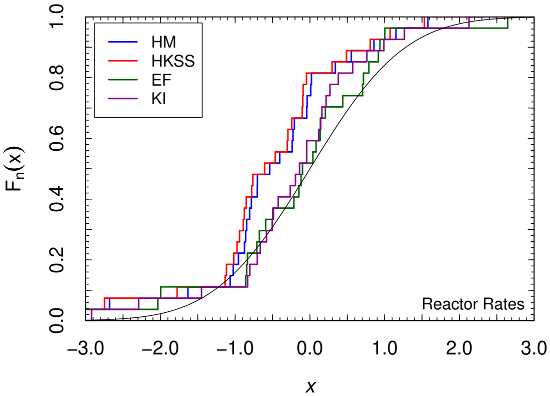
Approximate agreement with ab initio EF fluxes!

- HM + KI uncertainties.

Best-fit reactor flux model

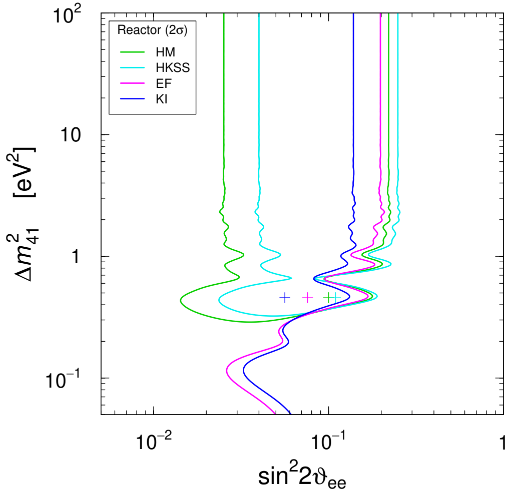
Goodness of fit tests assuming no (or negligible) SBL oscillations

Test	HM	HKSS	EF	KI
χ^2	0.21	0.12	0.08	0.43
SW	0.14	0.13	0.04	0.20
sign	0	$< 10^{-3}$	0.50	0.22
KS	0	0	0.77	0.36
CVM	0.01	0	0.74	0.37
AD	0.02	0	0.50	0.39
Z_K	$< 10^{-3}$	$< 10^{-3}$	0	0.06
Z_C	0.01	0	0.02	0.42
Z_A	0.02	0	0.12	0.38
weighted average	0.06	0.04	0.40	0.50



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

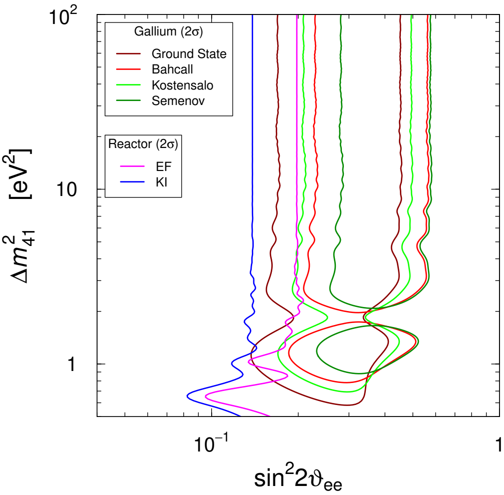
- The KI model is the best among the conversion models.
- The summation EF model is approximately equally good.
  But the uncertainties are guessed!



- 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

$$\sin^2 2\vartheta_{ee} \lesssim 0.25 \text{ at } 2\sigma.$$

Gallium – Reactor Rates tension



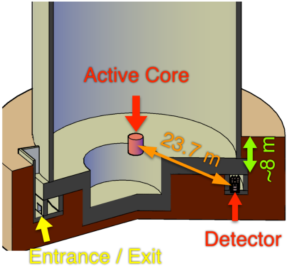
	EF		KI	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
Ground State	9.1	1.1%	11.9	0.26%
Bahcall	12.9	0.16%	16.3	0.029%
Kostensalo	11.5	0.31%	15.3	0.049%
Semenov	17.0	0.02%	22.5	0.0013%

[CG, Li ,Ternes, Tyagi, Xin, arXiv:2209.00916]

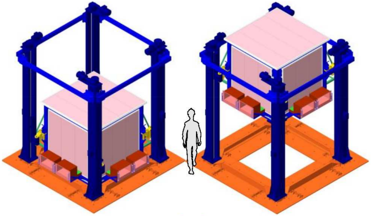
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

NEOS

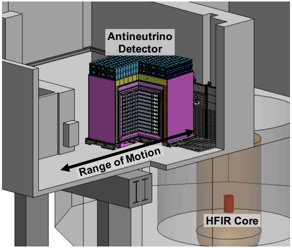


DANSS [Alekseev @ NOW 2022]

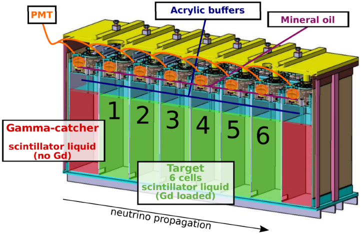


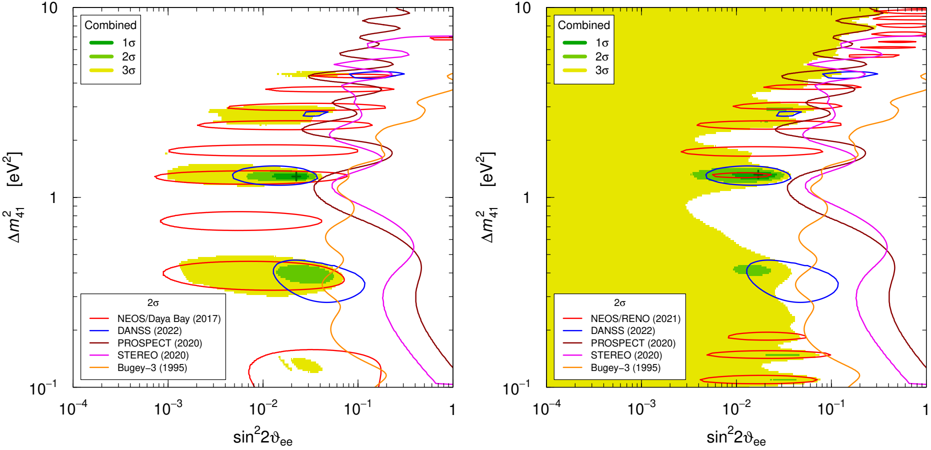
DANSS on a lifting platform

PROSPECT [Roca Catala @ NOW 2022]



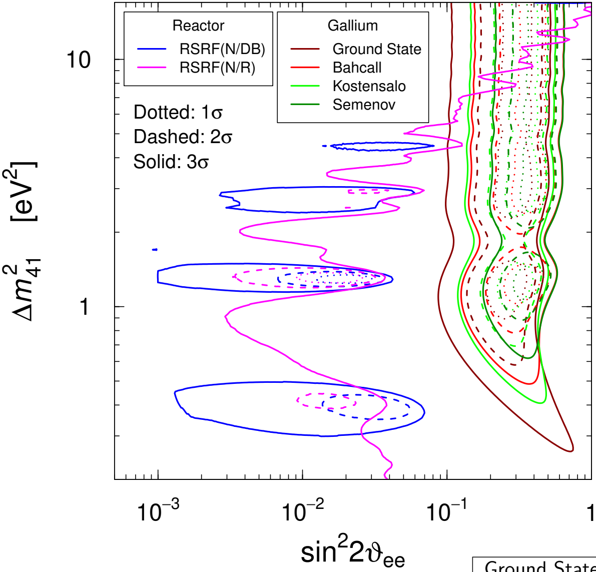
STEREO [del Amo Sanchez @ NOW 2022]





[CG, Li ,Ternes, Tyagi, Xin, arXiv:2209.00916]

- Fit with NEOS/Daya Bay: $\Delta\chi^2_{3\nu-4\nu} = 12.6 \Longrightarrow 3.1\ \sigma$
- Fit with NEOS/RENO: $\Delta\chi^2_{3\nu-4\nu} = 9.1 \Longrightarrow 2.6\ \sigma$



- The Reactor Spectral Ratio Fits (RSRF) prefer SBL oscillations with small mixing ($\sin^2 2\vartheta_{ee} \approx 0.02$).
- Tension with the Gallium Anomaly!

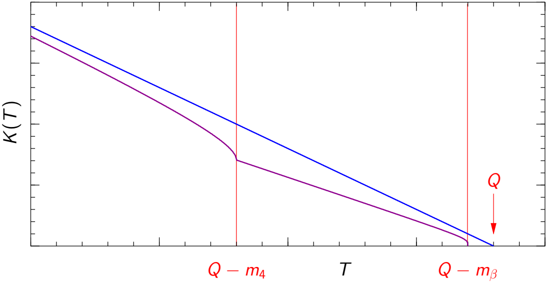
	RSRF(N/DB)		RSRF(N/R)	
	$\Delta\chi^2_{PG}$	GoF_{PG}	$\Delta\chi^2_{PG}$	GoF_{PG}
Ground State	12.95	0.15%	8.91	1.2%
Bahcall	12.86	0.16%	8.74	1.3%
Kostensalo	12.91	0.16%	8.89	1.2%
Semenov	12.88	0.16%	8.70	1.3%

Robust kinematical probe of $\nu_e - \nu_s$ mixing

$$\frac{K^2(T)}{Q-T} = \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2}\,\theta(Q-T-m_k)$$

$$m_4 \gg m_{1,2,3} \Rightarrow \simeq \left(1-|U_{e4}|^2\right)\sqrt{(Q-T)^2 - m_\beta^2}\,\theta(Q-T-m_\beta)$$

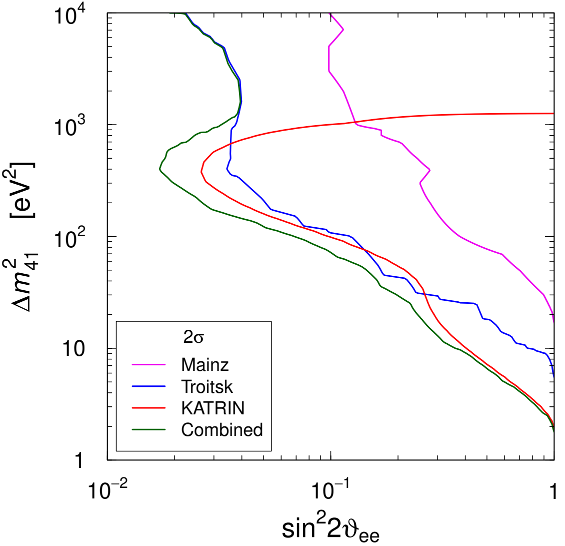
$$+|U_{e4}|^2 \sqrt{(Q-T)^2 - m_4^2}\,\theta(Q-T-m_4)$$



$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

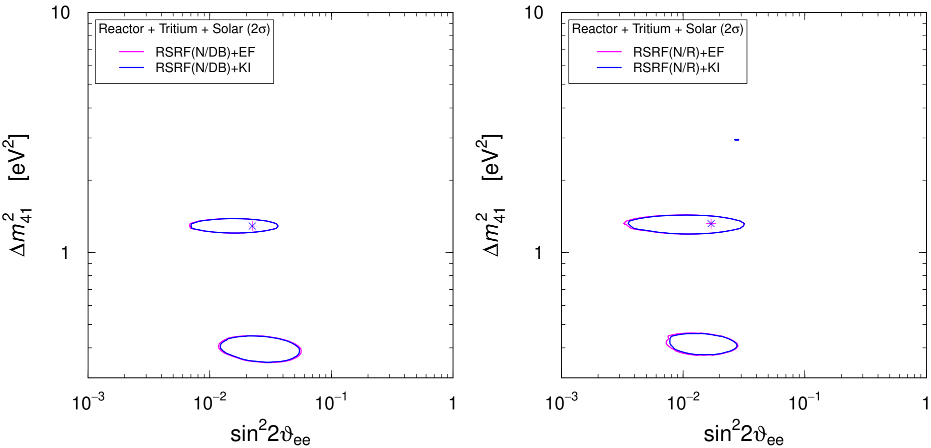
$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

Tritium Neutrino Mass Bound



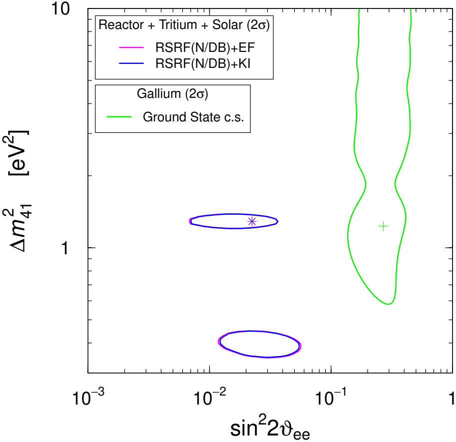
$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

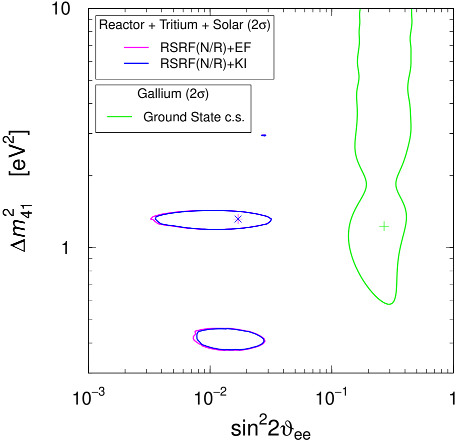
Global ν_e and $\bar{\nu}_e$ Disappearance



- Fit with NEOS/Daya Bay:
  $\Delta\chi^2_{3\nu-4\nu} = 12.6$ (EF), 12.9 (KI) $\Longrightarrow$ $3.1\,\sigma$ (EF), $3.2\,\sigma$ (KI)
- Fit with NEOS/RENO:
  $\Delta\chi^2_{3\nu-4\nu} = 9.1$ (EF), 9.3 (KI) $\Longrightarrow$ $2.6\,\sigma$ (EF), $2.6\,\sigma$ (KI)

Strong tension with the Gallium Anomaly!





- Fit with NEOS/Daya Bay:

$\Delta\chi^2_{\text{PG}} = 21.92$ (EF), 21.90 (KI) $\Longrightarrow$ GoF$_{\text{PG}} = 0.0017\%$ (EF), 0.0018% (KI)

- Fit with NEOS/RENO:

$\Delta\chi^2_{\text{PG}} = 22.56$ (EF), 22.66 (KI) $\Longrightarrow$ GoF$_{\text{PG}} = 0.0013\%$ (EF), 0.0012% (KI)

3+1 Appearance vs Disappearance

- SBL Oscillation parameters: Δm^2_{41} $|U_{e4}|^2$ $|U_{\mu4}|^2$ $(|U_{\tau4}|^2)$
- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

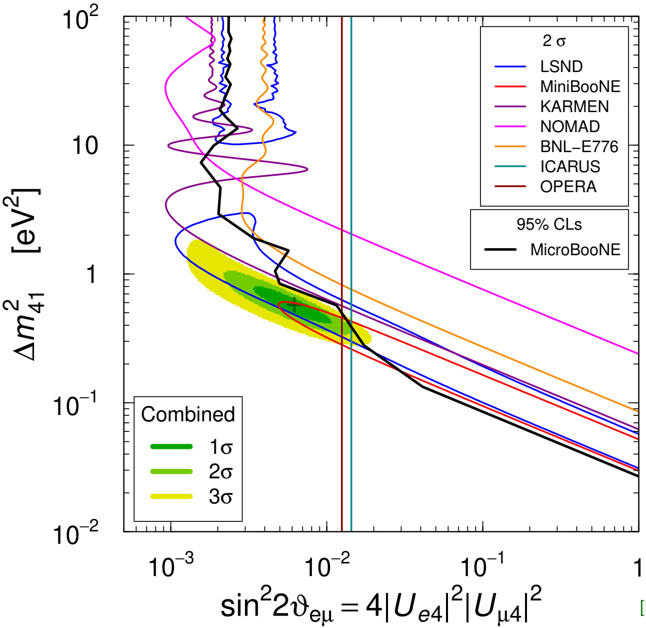
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

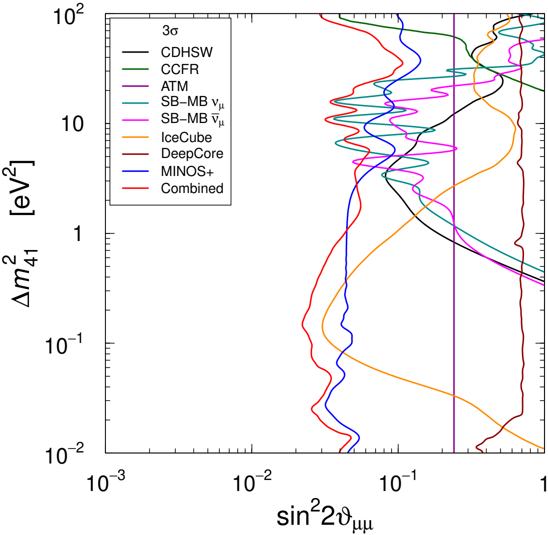
[Okada, Yasuda, arXiv:hep-ph/9606411] [Bilenky, CG, Grimus, arXiv:hep-ph/9607372]

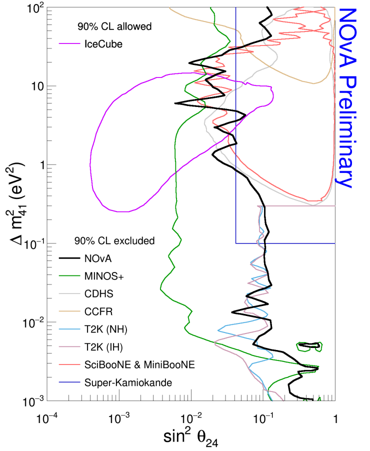
$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



[MicroBooNE: Karagiorgi @ NOW 2022]

ν_μ and $\bar{\nu}_\mu$ Disappearance





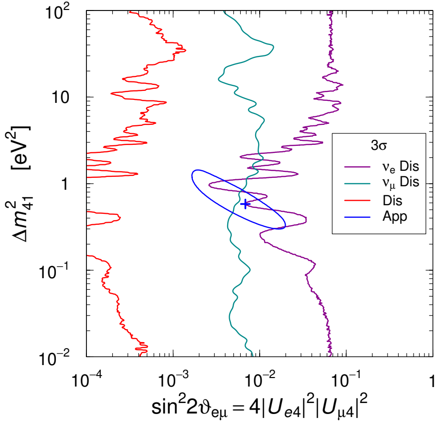
[Aurisano @ NOW 2022]

Global Appearance-Disappearance Tension

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- 2019 Global Fit:

  $\chi^2/\text{NDF} = 843.6/794$

  $\text{GoF} = 11\%$

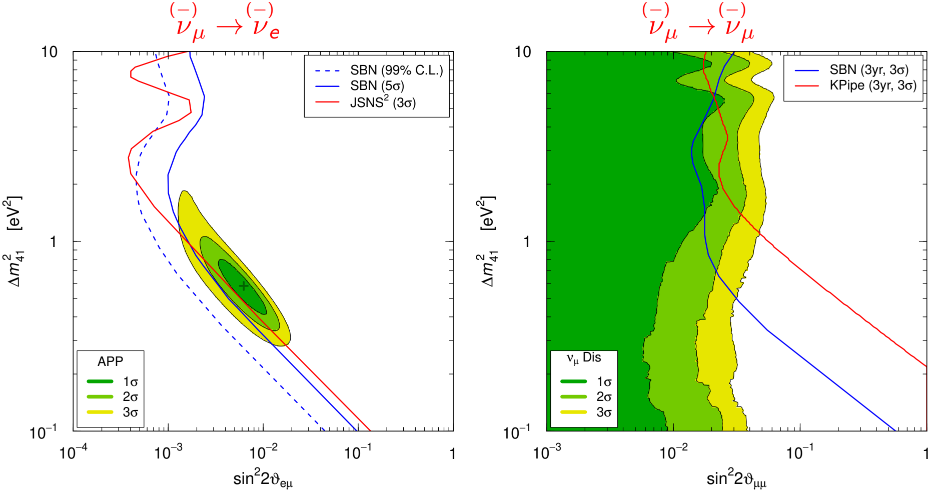
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 46.7/2$

  $\text{GoF}_{\text{PG}} = 7 \times 10^{-11}$ ← ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[CG, Zavanin, arXiv:1508.03172]

New Dedicated Experiments

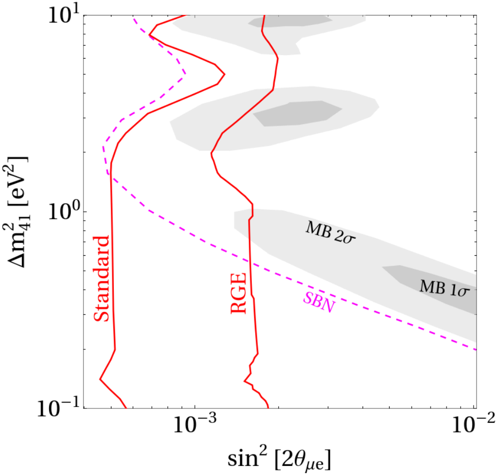


- SBN: Stanco @ NOW 2022 and Karagiorgi @ NOW 2022.
- JSNS^2 : August 2022 Long-Baseline Neutrino News: They are working on the blind analysis of the 1.45×10^{22} POT data taken until June 2021.

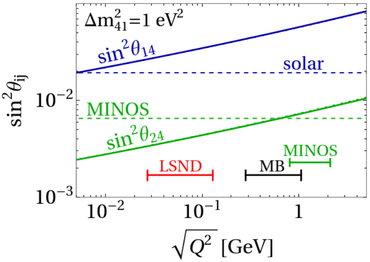
A way to alleviate the APP–DIS tension?

Energy-Dependent Active-Sterile Mixing

[Babu, Brdar, de Gouvea, Machado, arXiv:2209.00031]



- Model: secret interactions between the sterile neutrino and a light U(1) gauge boson.
- Renormalization Group Effects (RGE).



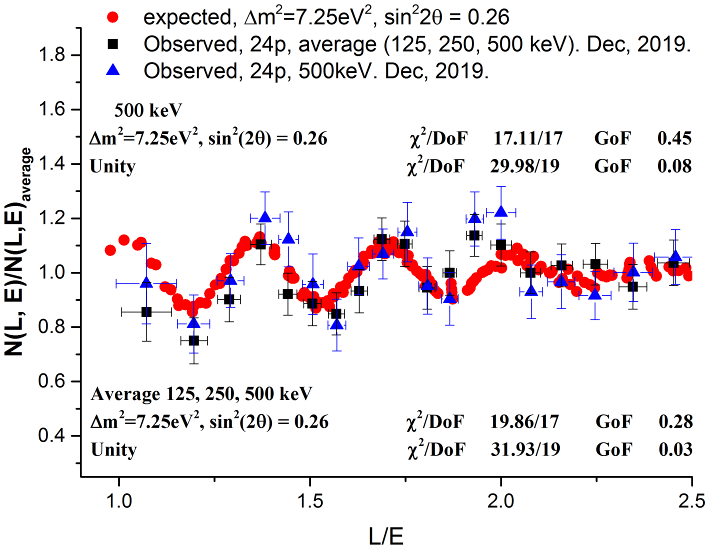
Conclusions

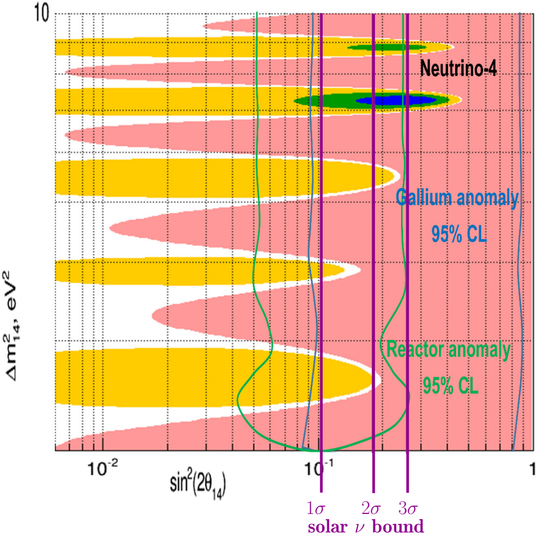
- Light Sterile Neutrinos can be powerful messengers of BSM New Physics.
- Historically, the existence of light sterile neutrinos is motivated by the LSND, Gallium, and Reactor Short-Baseline Anomalies.
- The Reactor Antineutrino Anomaly, discovered in 2011, is fading away.
- The Gallium Neutrino Anomaly, 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.
- Difficulty: probably any new physics explanation of the Gallium Anomaly should have a similar effect on solar and reactor neutrinos.
- Even more confusing status of appearance data (MicroBooNE vs MiniBooNE vs LSND) and the appearance-disappearance tension.

Backup Slides

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!

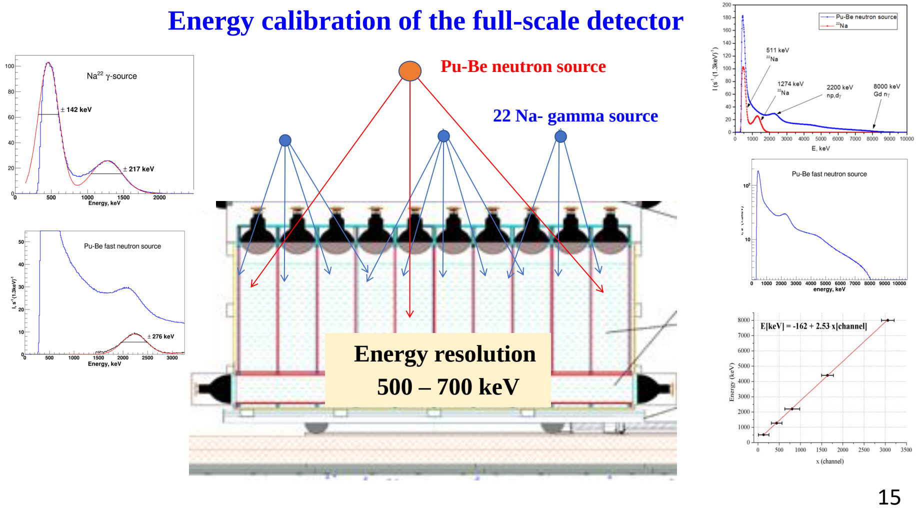
- Not a small perturbation of 3ν mixing.

- 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]

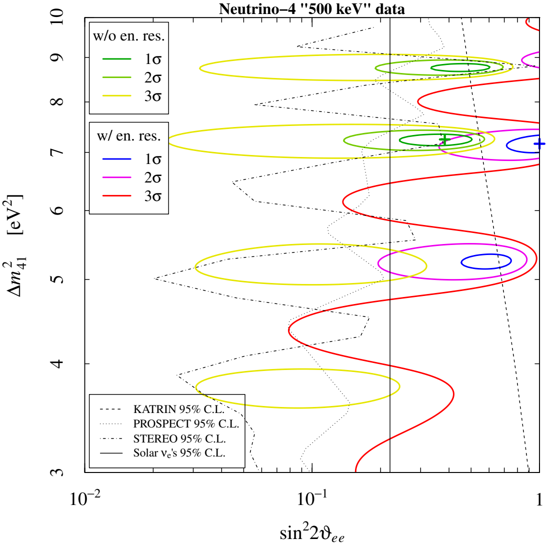
- No energy resolution!

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



- We approximate the energy resolution with the function

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



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

	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 $\Delta E = 500\,\text{keV}$ and energy resolution $\sigma = 250\,\text{keV}$ 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.

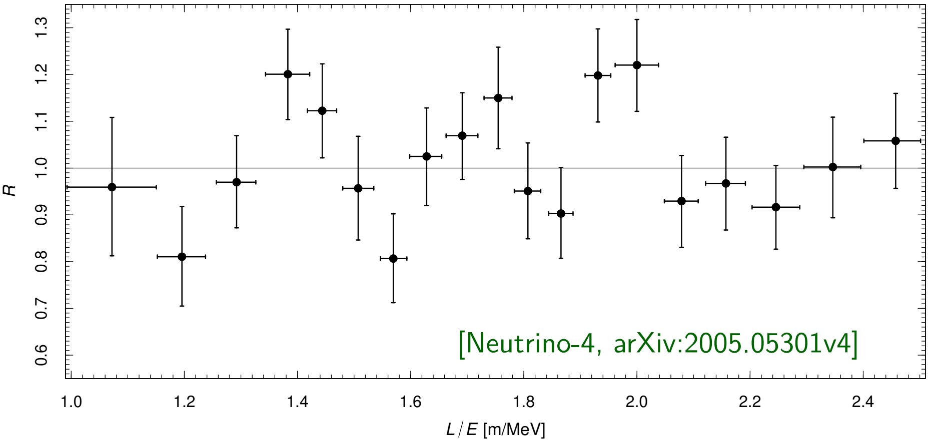
- It is obvious that an event with an unknown true energy in an unknown energy bin can be counted in another bin because of the energy resolution.

- 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.

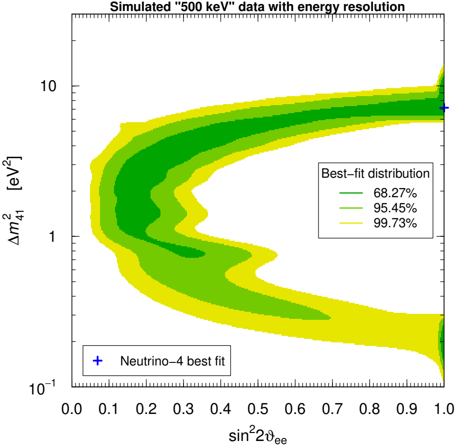
Neutrino-4: Oscillations or Fluctuations?



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.



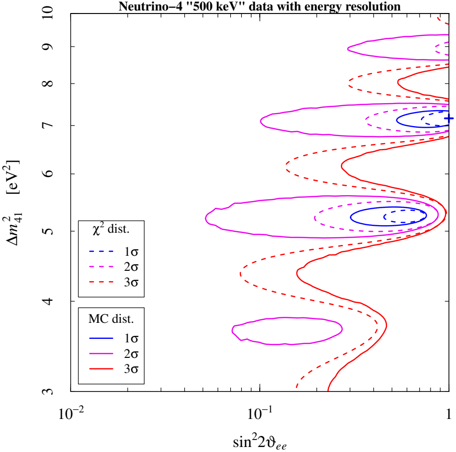
Distribution of best-fit points in a large set of random data generated without oscillations

	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

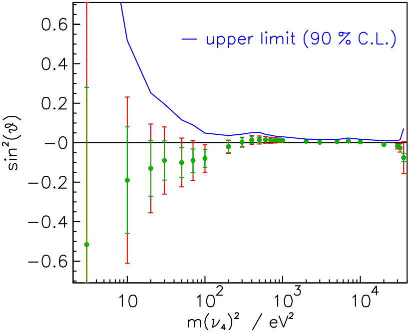
[CG, Li, Ternes, Zhang, arXiv:2101.06785]

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

Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

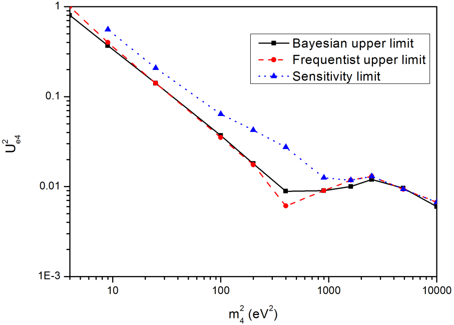
$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

Mainz



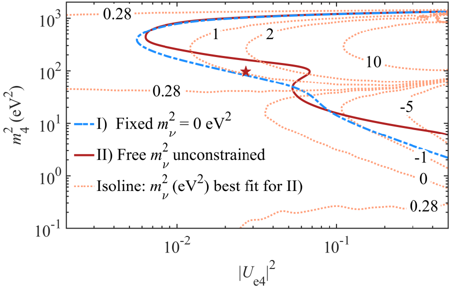
[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

Troitsk

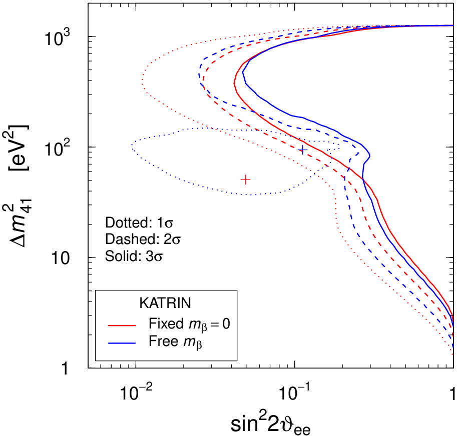


[Belesev et al, arXiv:1307.5687]

KATRIN Bounds



[KATRIN, arXiv:2201.11593]



[CG, Li ,Ternes, Tyagi, Xin, arXiv:2209.00916]

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4|U_{e4}|^2 \quad \text{for} \quad |U_{e4}|^2 \ll 1$$

Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- $\chi^2_{\rm min}$ has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF} = N_\text{D} - N_\text{P}$$

N_D = Number of Data $\qquad$ N_P = Number of Fitted Parameters

- $\langle \chi^2_{\rm min} \rangle = \text{NDF}$ $\qquad$ $\text{Var}(\chi^2_{\rm min}) = 2\text{NDF}$
- $\text{GoF} = \int_{\chi^2_{\rm min}}^{\infty} p_{\chi^2}(z, \text{NDF})\, dz$ $\qquad$ $p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

Parameter Goodness of Fit

Maltoni, Schwetz, PRD 68 (2003) 033020 (arXiv:hep-ph/0304176)

- Measure compatibility of two (or more) sets of data points A and B under fitting model
- $\chi^2_{\rm PGoF} = (\chi^2_{\rm min})_{\rm A+B} - [(\chi^2_{\rm min})_{\rm A} + (\chi^2_{\rm min})_{\rm B}]$
- $\chi^2_{\rm PGoF}$ has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF}_\text{PGoF} = N_\text{P}^\text{A} + N_\text{P}^\text{B} - N_\text{P}^\text{A+B}$$

- $\text{PGoF} = \int_{\chi^2_{\rm PGoF}}^{\infty} p_{\chi^2}(z, \text{NDF}_\text{PGoF})\, dz$