

Current status of the Gallium and reactor anomalies

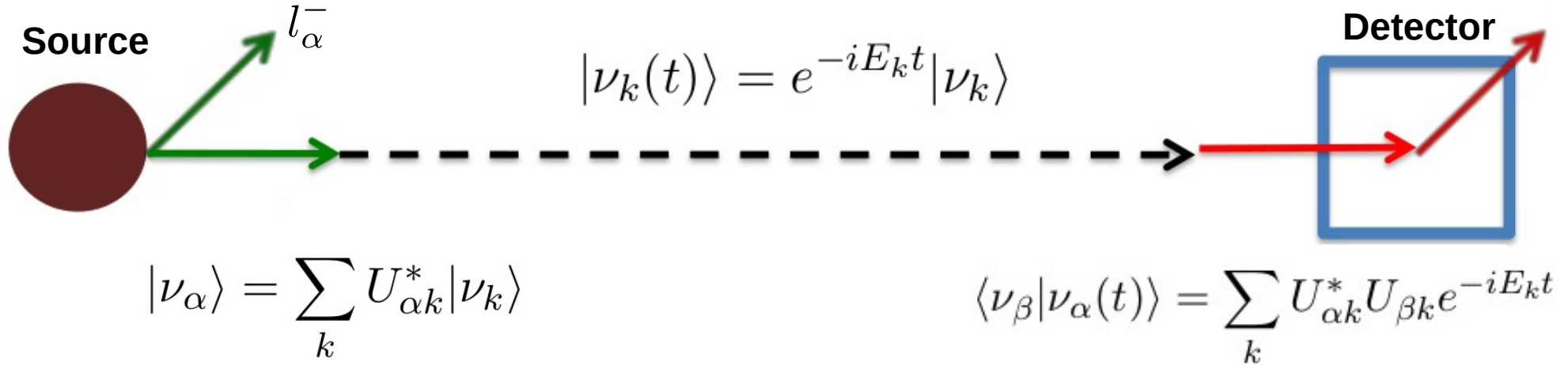


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Fermilab Theory Seminar
May 16th 2024



Neutrino oscillations



$$P(\alpha \rightarrow \beta; E, L) = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* e^{i \frac{\Delta m_{kj}^2}{2E} L}$$

Neutrino oscillations

Neutrino mixing matrix

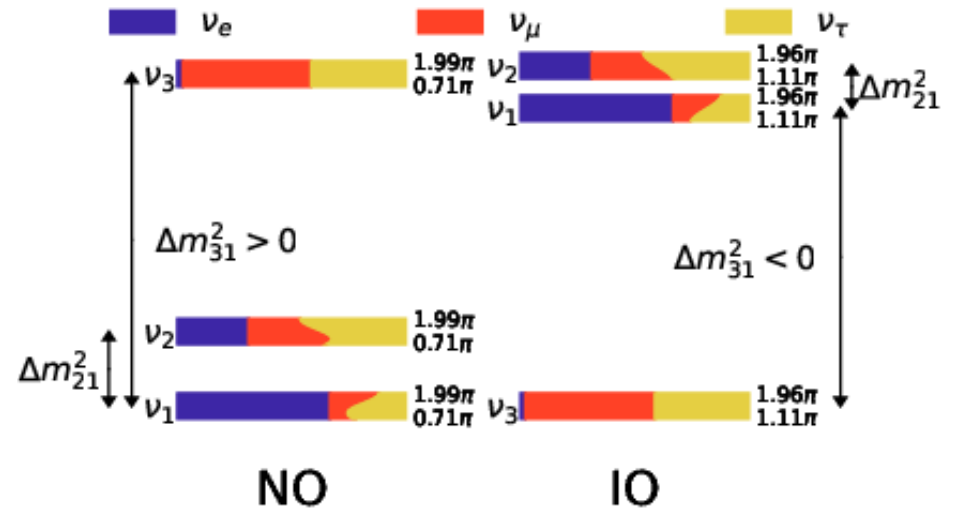
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 Dirac + 2 Majorana CP-phases

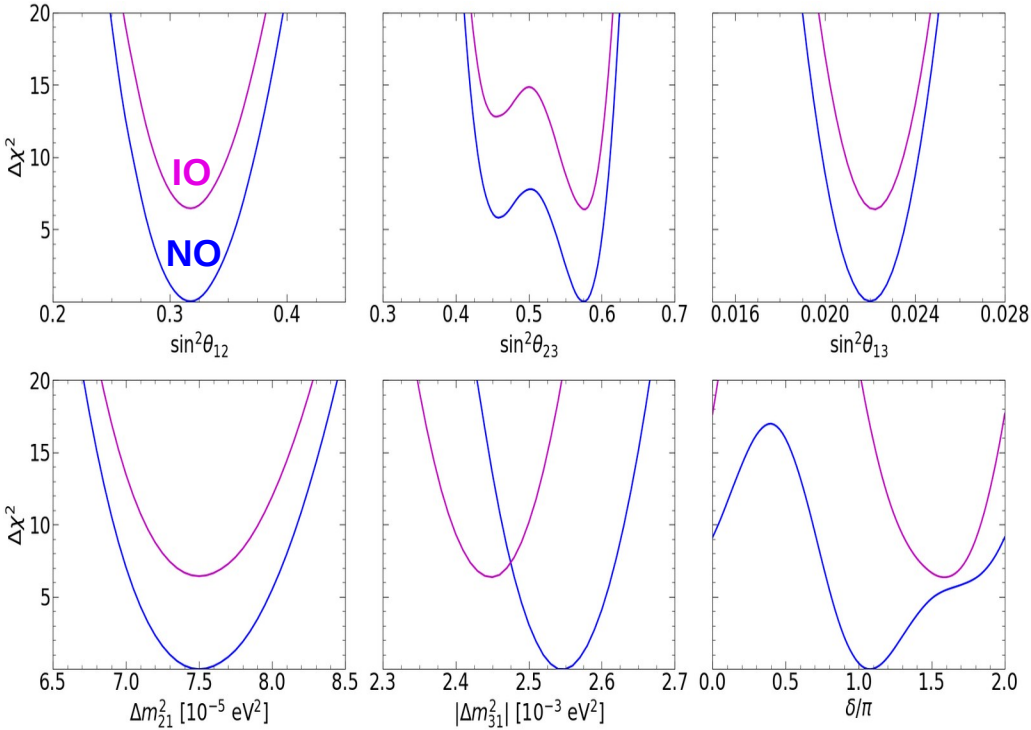
Three masses m_1, m_2, m_3 for which two orderings are possible

Oscillations are only sensitive to mass splittings



Neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



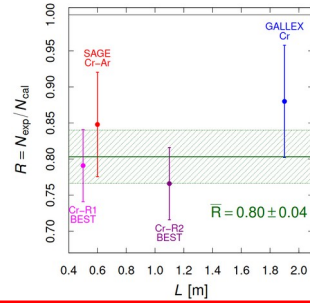
parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2 \theta_{12} / 10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2 \theta_{23} / 10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2 \theta_{23} / 10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2 \theta_{13} / 10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2 \theta_{13} / 10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

See also:
Bari - 2107.00532, PRD 2021

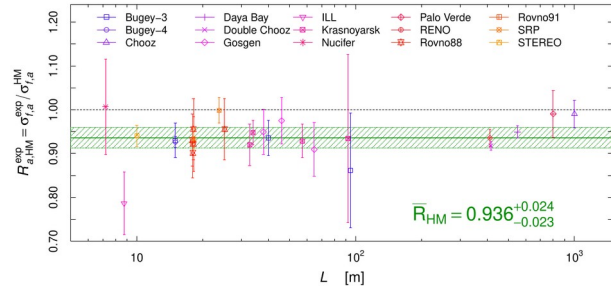
See also:
NuFit - 2111.03086, Universe 2021

Anomalies

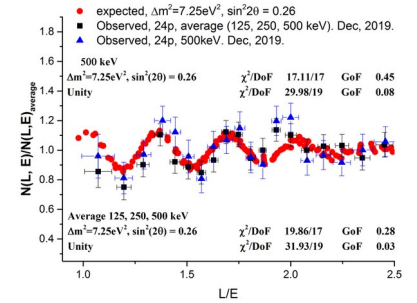
Gallium



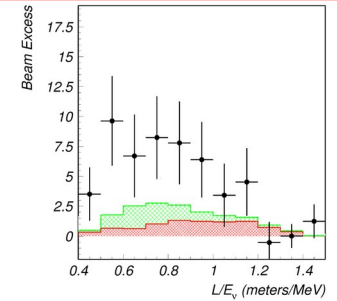
RAA



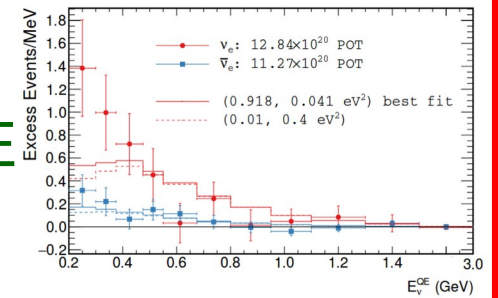
Neutrino-4



LSND



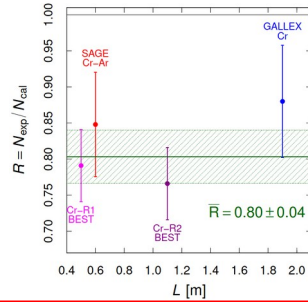
MiniBooNE



Anomalies

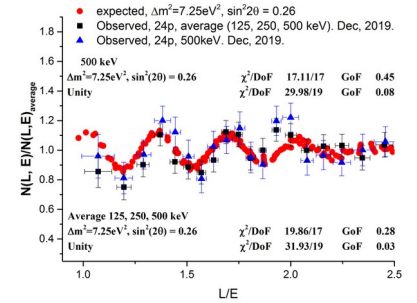
5-6 σ

Gallium



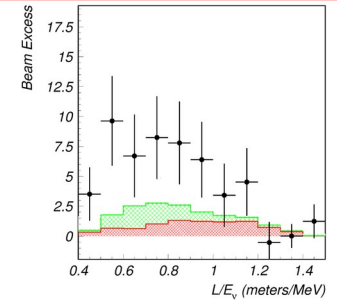
2-3 σ

Neutrino-4



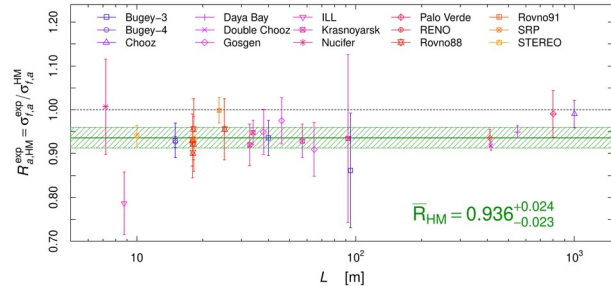
$\sim 4\sigma$

LSND



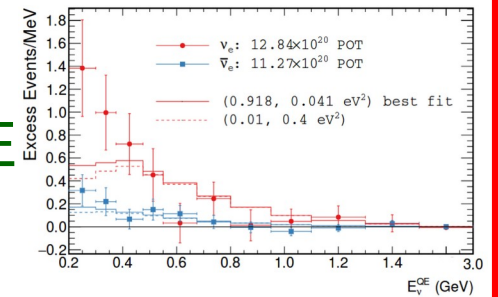
1-3 σ

RAA



$\sim 5\sigma$

MiniBooNE



Anomalies

Three-neutrino oscillations can not account for short baseline anomalies

$$L_{kj}^{\text{osc}} = \frac{4\pi E}{\Delta m_{kj}^2}$$
$$L_{21}^{\text{osc}} \gtrsim 50 \text{ km} \frac{E}{\text{MeV}}$$
$$L_{31}^{\text{osc}} \gtrsim 1 \text{ km} \frac{E}{\text{MeV}}$$



Short baseline oscillations require:

$$\frac{L}{E} \lesssim 10 \text{ m/MeV} \quad \Longrightarrow \quad \Delta m^2 \gtrsim 0.1 \text{ eV}^2$$

3+1 neutrino oscillations

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \Rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Appearance

$$P_{\alpha\beta}^{\text{SBL}} \approx \sin^2(2\theta_{\alpha\beta}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

@LSND, Karmen, MiniBooNE,
Opera

Disappearance

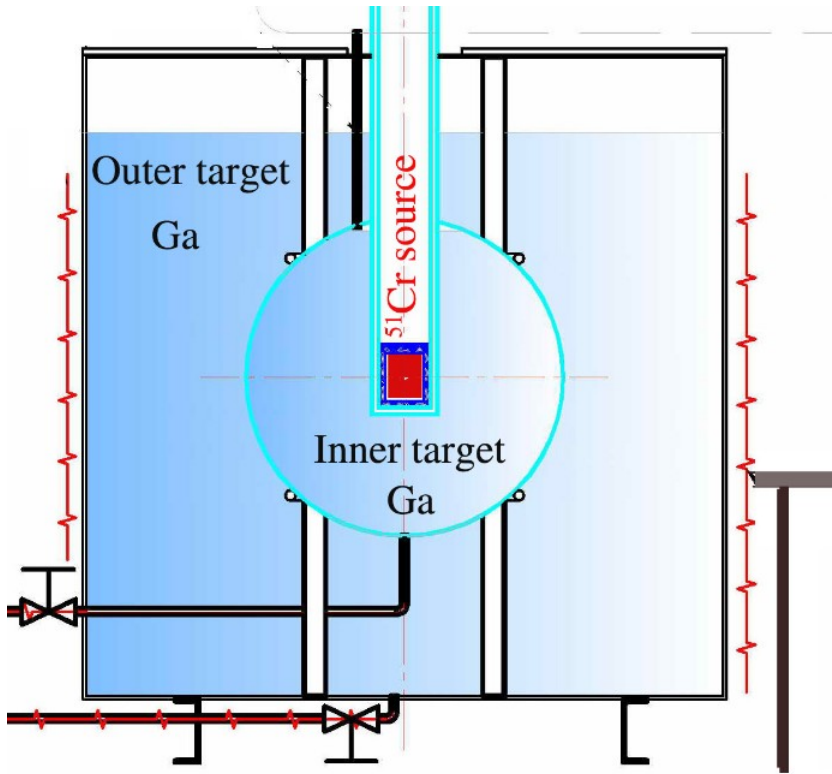
$$P_{\alpha\alpha}^{\text{SBL}} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2)$$

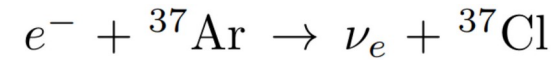
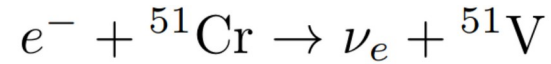
@Reactors and Gallium
@atmospherics and accelerators

The Gallium anomaly

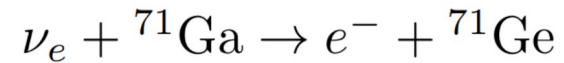
BEST, 2109.11482, PRL 2022



Intense sources of electron neutrinos are placed into the detector volume



The neutrinos interact with the detector material



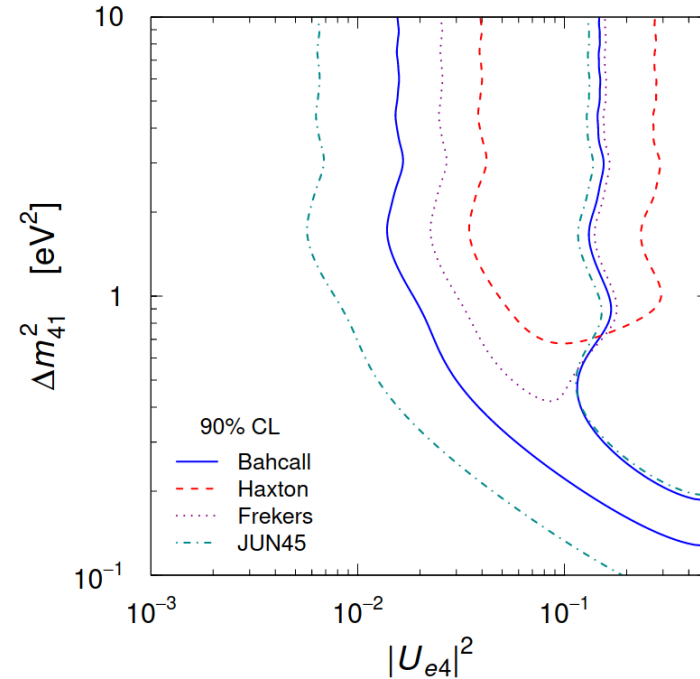
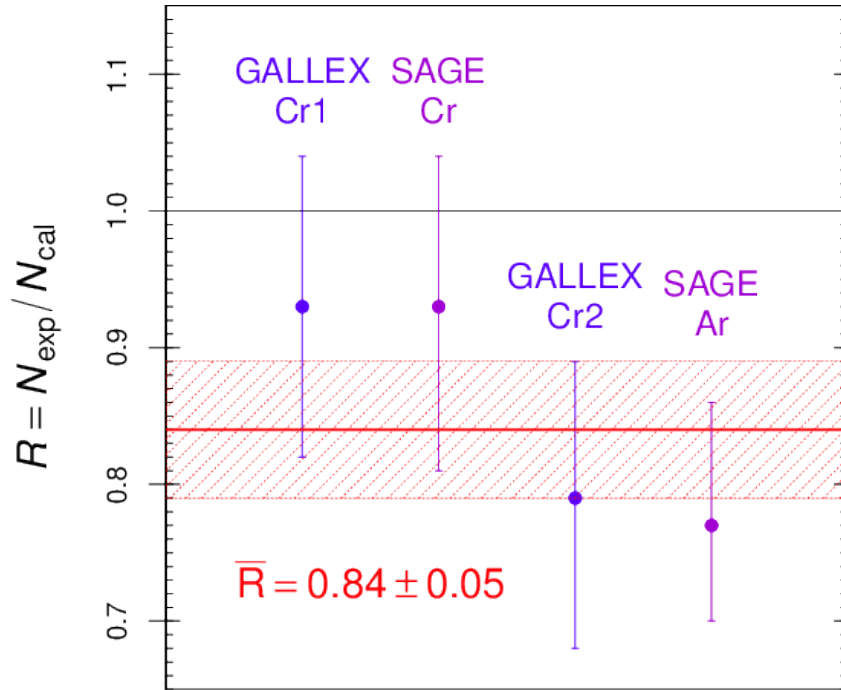
The Gallium anomaly

Model	Method	^{51}Cr		^{37}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	—
Bahcall (1997)	$^{71}\text{Ga}(p, n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
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%
Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
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%

Slightly different values for the different cross section models

The Gallium anomaly

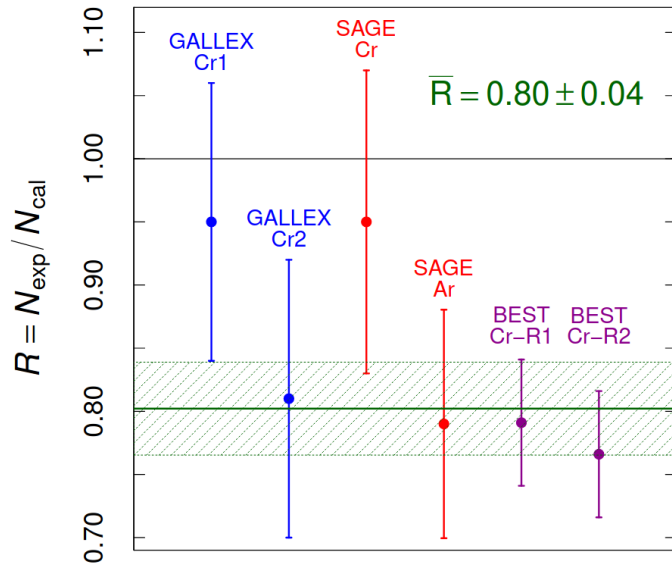
Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980, PLB 2019



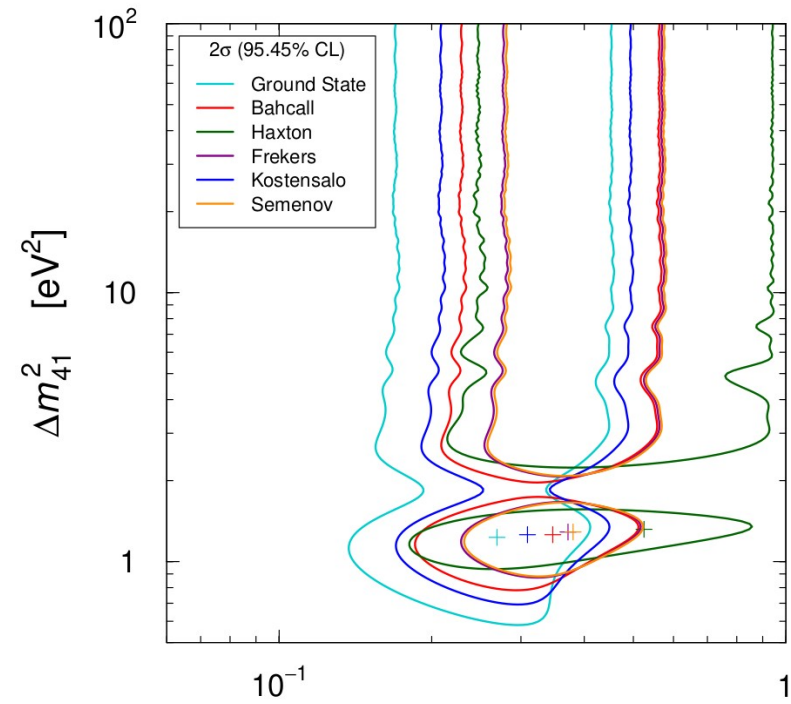
The significance of the “old” Gallium anomaly varied between 2.3 and 3.0 σ , depending on the cross section model

The Gallium anomaly

Giunti, Li, Ternes, Tyagi, Zhao,
2209.00916, JHEP 2022



Strong indication for short
baseline (SBL) oscillations?



Model	Method	\bar{R}	GA
Ground State	$T_{1/2}(^{71}\text{Ge})$	$0.845^{+0.031}_{-0.031}$	5.0
Bahcall (1997)	$^{71}\text{Ga}(p, n)^{71}\text{Ge}$	$0.804^{+0.037}_{-0.036}$	5.2
Haxton (1998)	Shell Model	$0.731^{+0.088}_{-0.072}$	5.1
Frekers et al. (2015)	$^{71}\text{Ga}(^3\text{He}, ^3\text{H})^{71}\text{Ge}$	$0.789^{+0.033}_{-0.032}$	6.1
Kostensalo et al. (2019)	Shell Model	$0.825^{+0.031}_{-0.031}$	5.5
Semenov (2020)	$^{71}\text{Ga}(^3\text{He}, ^3\text{H})^{71}\text{Ge}$	$0.787^{+0.033}_{-0.032}$	6.1

See also:

Barinov, Gorbunov, 2109.14654, PRD2022

Berryman, Coloma, Huber, Schwetz, Zhao, 2111.12530, JHEP 2022

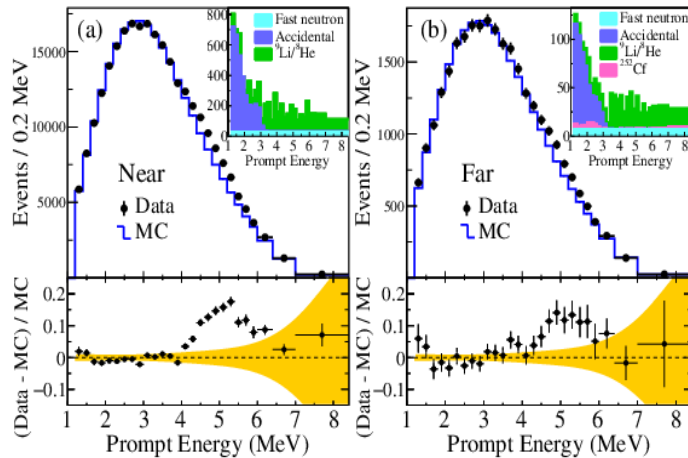
5 MeV bump

5 MeV bump discovered in 2014

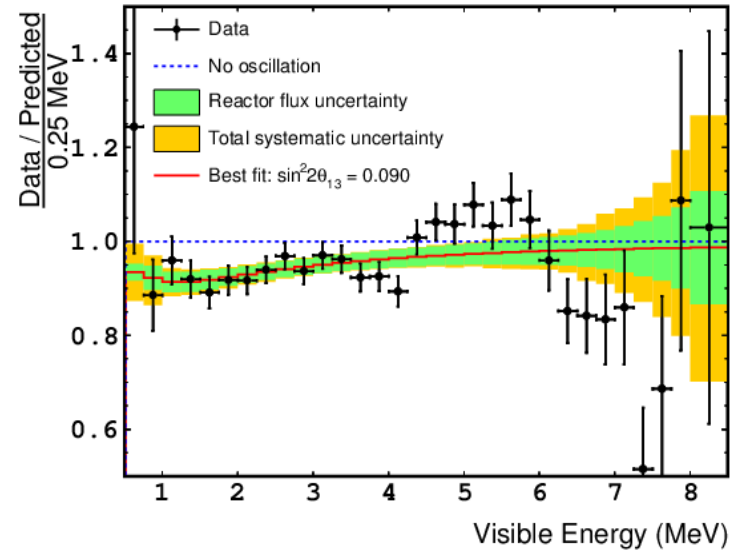
Can not be explained with short baseline oscillations

Proof of our incomplete understanding of nuclear reactor fluxes

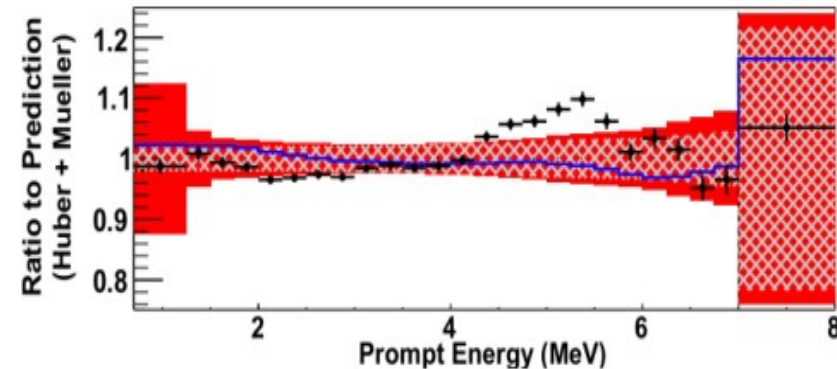
RENO, 1511.05849, PRL 2016



Double Chooz, 1406.7763, JHEP 2015



Daya Bay, 1508.04233, PRL 2016



Rate calculation

New cross section calculation produces the same reactor rates,

Calculate inverse beta yields for each isotope

See Ricciardi, Vignaroli, Vissani, 2206.05567, JHEP 2022

We use the Strumia-Vissani IBD cross section

Strumia, Vissani, astro-ph/0302055, PLB 2003

$$\sigma_i = \int_{E_\nu^{\text{thr}}}^{E_\nu^{\text{max}}} dE_\nu \Phi_i(E_\nu) \sigma_{\text{IBD}}(E_\nu)$$

Yields depend on the neutrino flux

$$\sigma_{f,a} = \sum_i f_i^a \sigma_i$$

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.74 ± 0.17	10.19 ± 0.83	4.40 ± 0.13	6.10 ± 0.16
EF	6.29 ± 0.31	10.16 ± 1.02	4.42 ± 0.22	6.23 ± 0.31
HKSS	6.82 ± 0.18	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16
KI	6.41 ± 0.14	9.53 ± 0.48	4.40 ± 0.13	6.10 ± 0.16

Berryman, Huber, 2005.01756, JHEP 2021

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.60 ± 0.14	10.00 ± 1.12	4.33 ± 0.11	6.01 ± 0.13
EF	6.17 ± 0.13	9.94 ± 1.09	4.32 ± 0.11	6.10 ± 0.13
HKSS	6.67 ± 0.15	10.08 ± 1.14	4.37 ± 0.12	6.06 ± 0.14

Compare against measurements

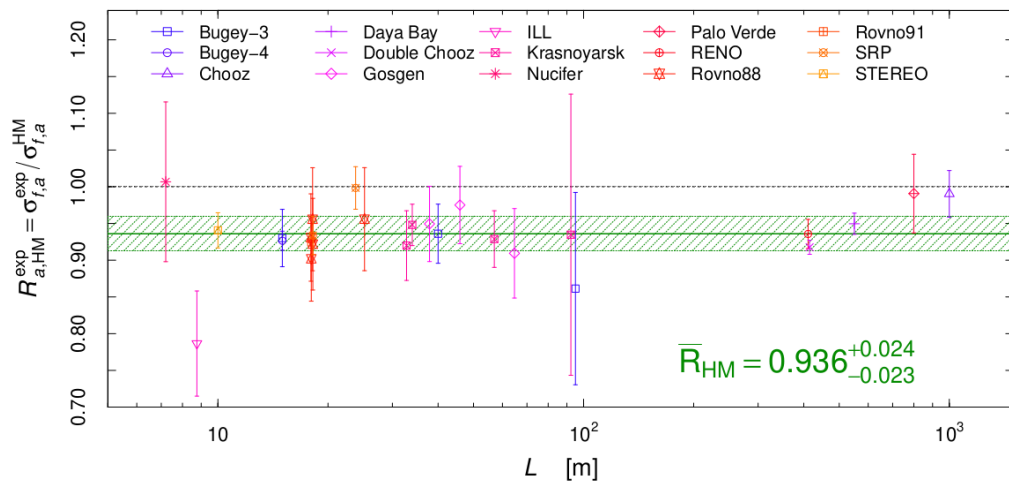
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

a	Experiment	f_{235}^a	f_{238}^a	f_{239}^a	f_{241}^a	$\sigma_{f,a}^{\text{exp}}$	$R_{a,\text{HM}}^{\text{exp}}$	$R_{a,\text{EF}}^{\text{exp}}$	$R_{a,\text{HKSS}}^{\text{exp}}$	$R_{a,\text{KI}}^{\text{exp}}$	$R_{a,\text{HKSS-KI}}^{\text{exp}}$	δ_a^{exp} [%]	δ_a^{cor} [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	5.75	0.927	0.962	0.916	0.962	0.944	1.4	}1.4	15
2	Rovno91	0.614	0.074	0.274	0.038	5.85	0.924	0.965	0.914	0.962	0.945	2.8		18
3	Rovno88-II	0.607	0.074	0.277	0.042	5.70	0.902	0.941	0.892	0.939	0.921	6.4	}3.1	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	5.89	0.931	0.971	0.920	0.969	0.951	6.4		17.96
5	Rovno88-1S	0.606	0.074	0.277	0.043	6.04	0.956	0.997	0.945	0.995	0.976	7.3	}2.2	18.15
6	Rovno88-2S	0.557	0.076	0.313	0.054	5.96	0.956	0.994	0.945	0.993	0.974	7.3		25.17
7	Rovno88-3S	0.606	0.074	0.274	0.046	5.83	0.922	0.962	0.911	0.960	0.942	6.8	}3.1	18.18
8	Bugey-3-15	0.538	0.078	0.328	0.056	5.77	0.930	0.966	0.920	0.966	0.947	4.2	}4.0	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	5.81	0.936	0.972	0.926	0.972	0.953	4.3		40
10	Bugey-3-95	0.538	0.078	0.328	0.056	5.35	0.861	0.895	0.852	0.894	0.877	15.2		95
11	Gosgen-38	0.619	0.067	0.272	0.042	5.99	0.949	0.992	0.939	0.988	0.971	5.4	}2.0	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	6.09	0.975	1.016	0.964	1.014	0.995	5.4		45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	5.62	0.909	0.945	0.899	0.944	0.927	6.7	}3.8	64.7
14	ILL	1.000	0.000	0.000	0.000	5.30	0.787	0.843	0.777	0.827	0.818	9.1	}4.1	8.76
15	Krasnoyarsk87-33	1	0	0	0	6.20	0.920	0.986	0.909	0.967	0.957	5.2	}4.1	32.8
16	Krasnoyarsk87-92	1	0	0	0	6.30	0.935	1.002	0.924	0.983	0.972	20.5		92.3
17	Krasnoyarsk94-57	1	0	0	0	6.26	0.929	0.995	0.918	0.977	0.966	4.2		0
18	Krasnoyarsk99-34	1	0	0	0	6.39	0.948	1.016	0.937	0.997	0.986	3.0	0	34
19	SRP-18	1	0	0	0	6.29	0.934	1.000	0.923	0.982	0.971	2.8	0	18.2
20	SRP-24	1	0	0	0	6.73	0.998	1.070	0.987	1.050	1.038	2.9	0	23.8
21	Nucifer	0.926	0.008	0.061	0.005	6.67	1.007	1.074	0.995	1.056	1.044	10.8	0	7.2
22	Chooz	0.496	0.087	0.351	0.066	6.12	0.990	1.025	0.979	1.027	1.007	3.2	0	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	6.25	0.991	1.033	0.980	1.031	1.012	5.4	0	≈ 800
24	Daya Bay	0.564	0.076	0.304	0.056	5.94	0.950	0.988	0.939	0.987	0.968	1.5	0	≈ 550
25	RENO	0.571	0.073	0.300	0.056	5.85	0.936	0.974	0.925	0.973	0.954	2.1	0	≈ 411
26	Double Chooz	0.520	0.087	0.333	0.060	5.71	0.918	0.952	0.907	0.953	0.934	1.1	0	≈ 415
27	STEREO	1	0	0	0	6.34	0.941	1.008	0.930	0.989	0.978	2.5	0	9 – 11

2011 Huber Mueller fluxes

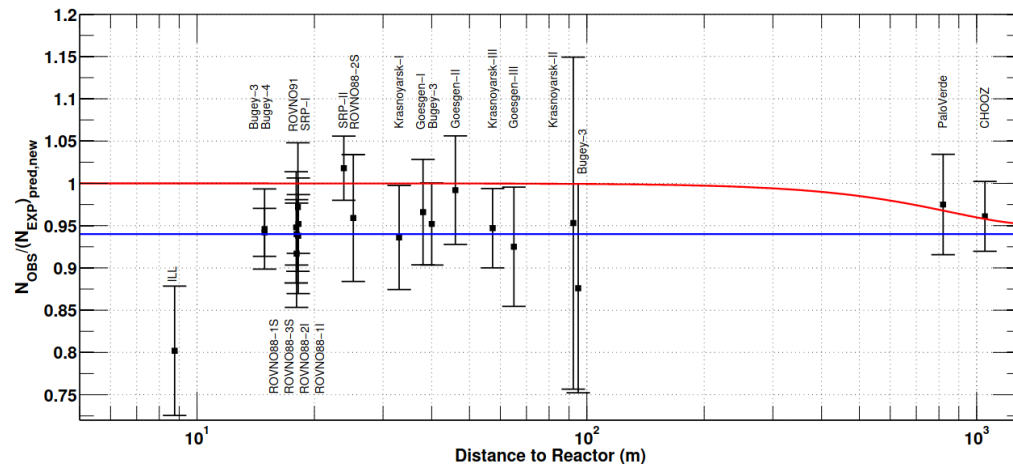
Huber, 1106.0687, PRC 2012

Mueller, Lhuillier, Fallot, Letourneau, Cormon, 1101.2663, PRC 2012



HM flux gives 2.5σ anomaly

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

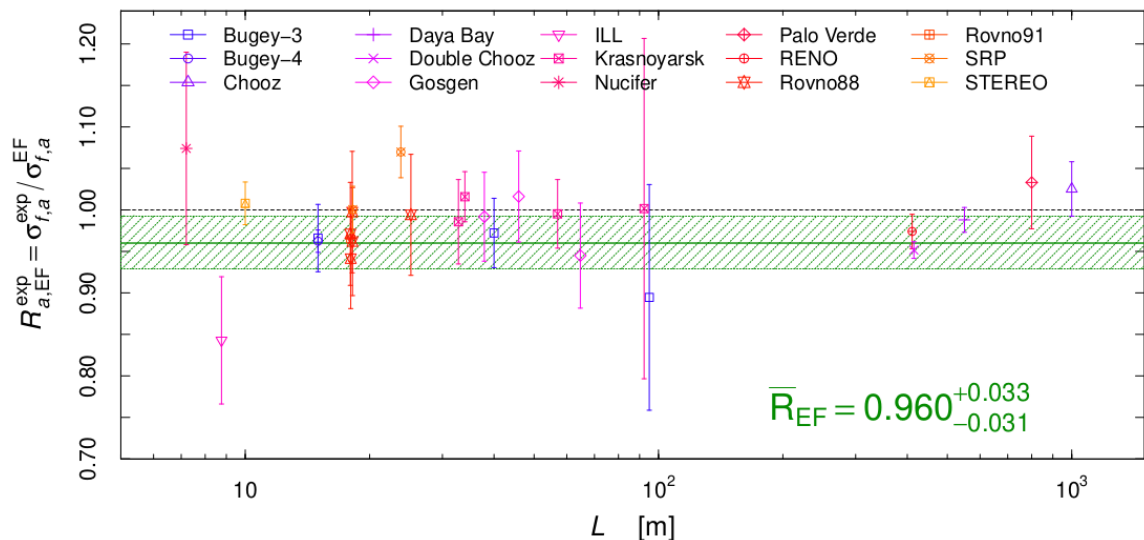


Original RAA was also 2.5σ

Mention, Fechner, Lasserre, Mueller, Lhuillier, 1101.2755, PRD 2011

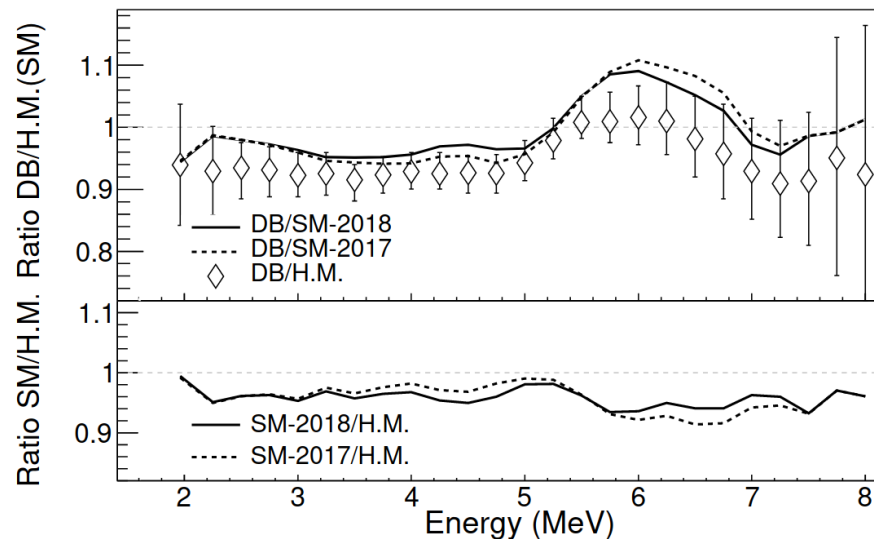
2019 summation method fluxes

Estienne, Fallot, et al, 1904.09358, PRL 2019



1.2 σ deficit, no anomaly!

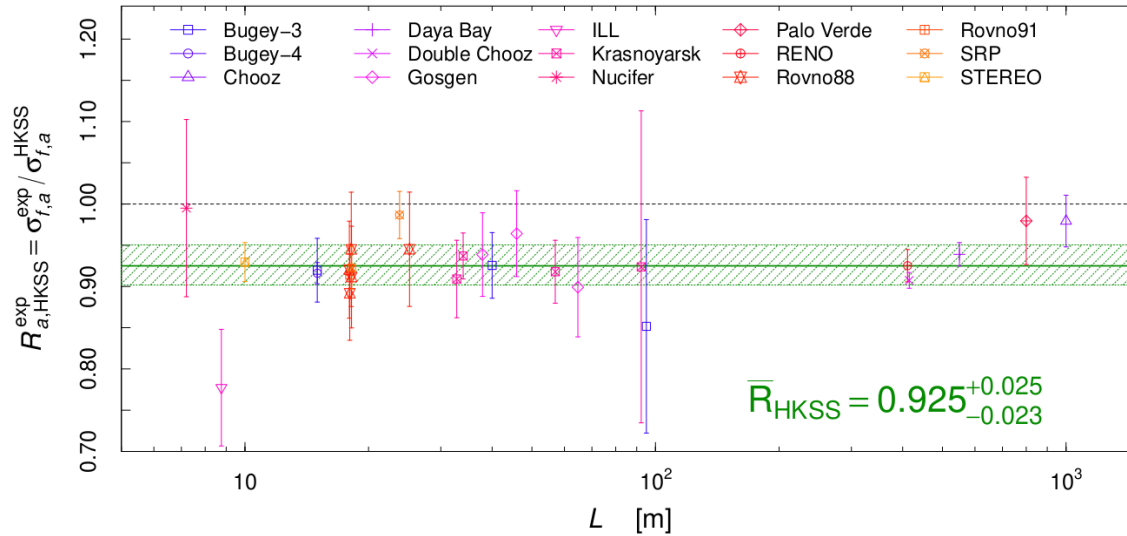
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



Ratio reduced with respect to HM for all energies!

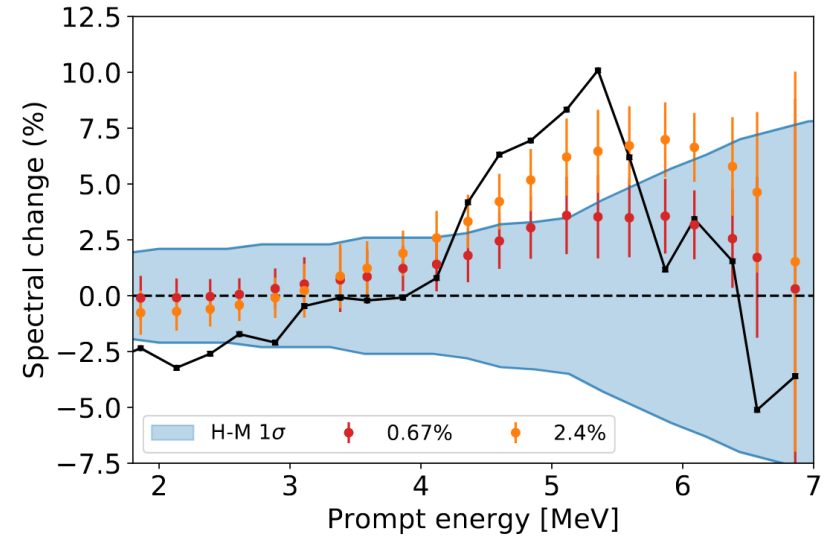
2019 new converted fluxes

Hayen, Kostensalo, Severijns, Suhonen, 1908.08302, PRC 2019



HKSS flux results in 2.9σ anomaly!

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

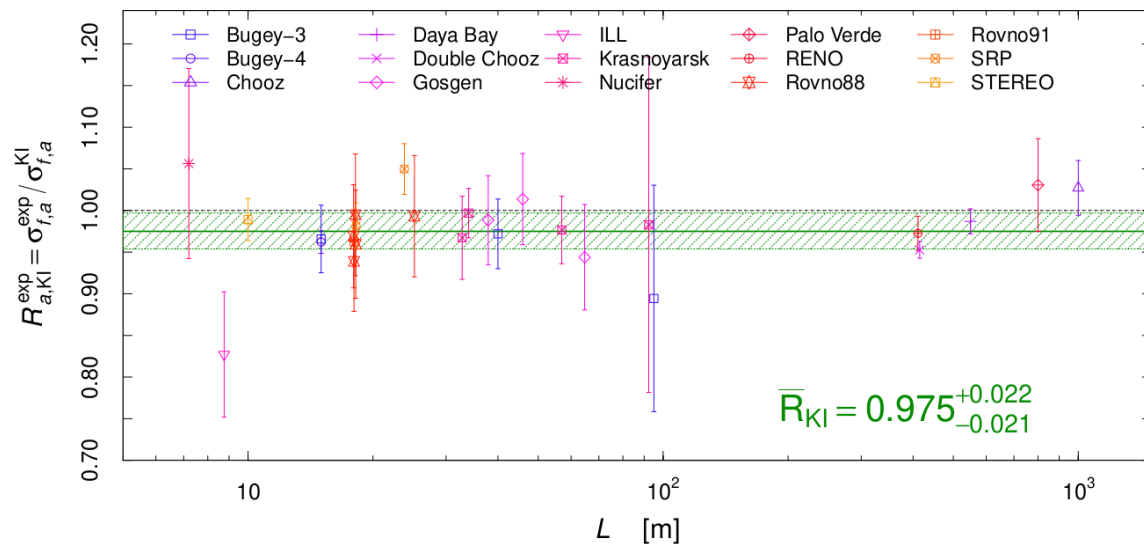


Better prediction for the energies of the bump!

2021 new converted fluxes

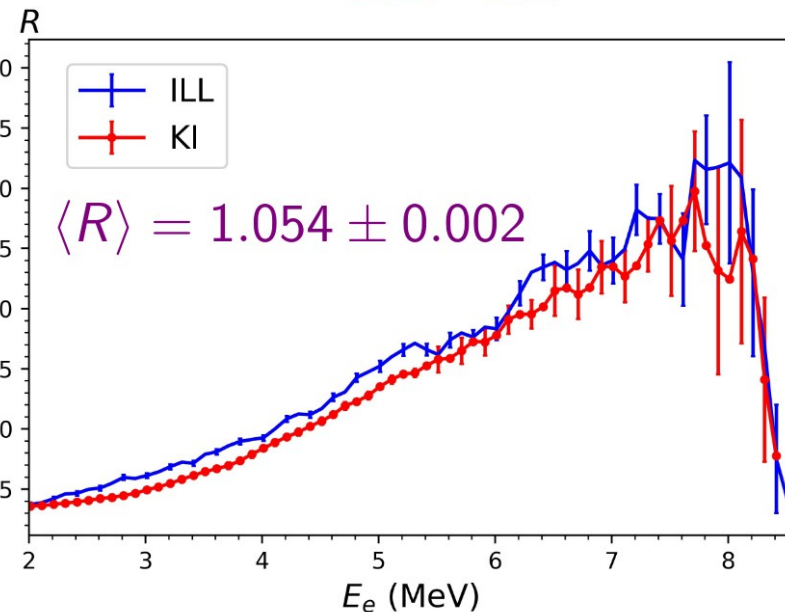
Kurchatov Institute: Kopeikin, Skorokhvatov, Titov, 2103.01684, PRD 2021

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



No anomaly (1.1σ) with KI flux!

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



New measurement suggests a reduction in the flux of ^{235}U

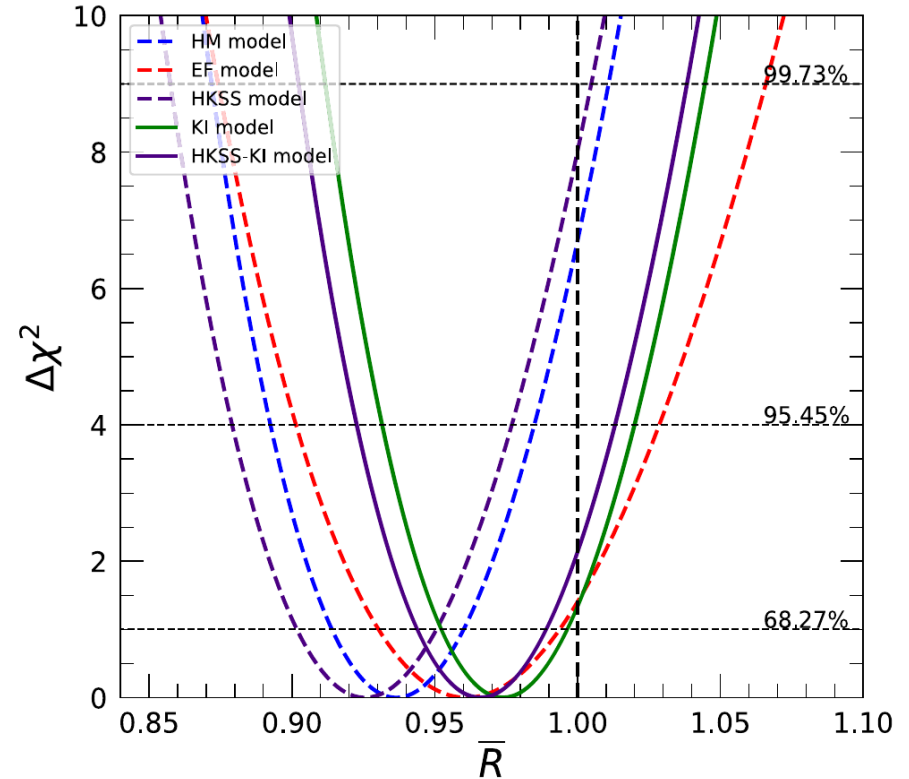
The reactor rate anomaly

The significance of the RAA depends on the input flux model

The EF and KI models have no anomaly

Mention, Fechner, Lasserre, Mueller, Lhuillier, 1101.2755, PRD 2011
Huber, 1106.0687, PRC 2012
Mueller, Lhuillier, Fallot, Letourneau, Cormon, 1101.2663, PRC 2012
Estienne, Fallot, et al, 1904.09358, PRL 2019
Hayen, Kostensalo, Severijns, Suhonen, 1908.08302, PRC 2019
Kurchatov Institute: Kopeikin, Skorokhvatov, Titov, 2103.01684, PRD 2021

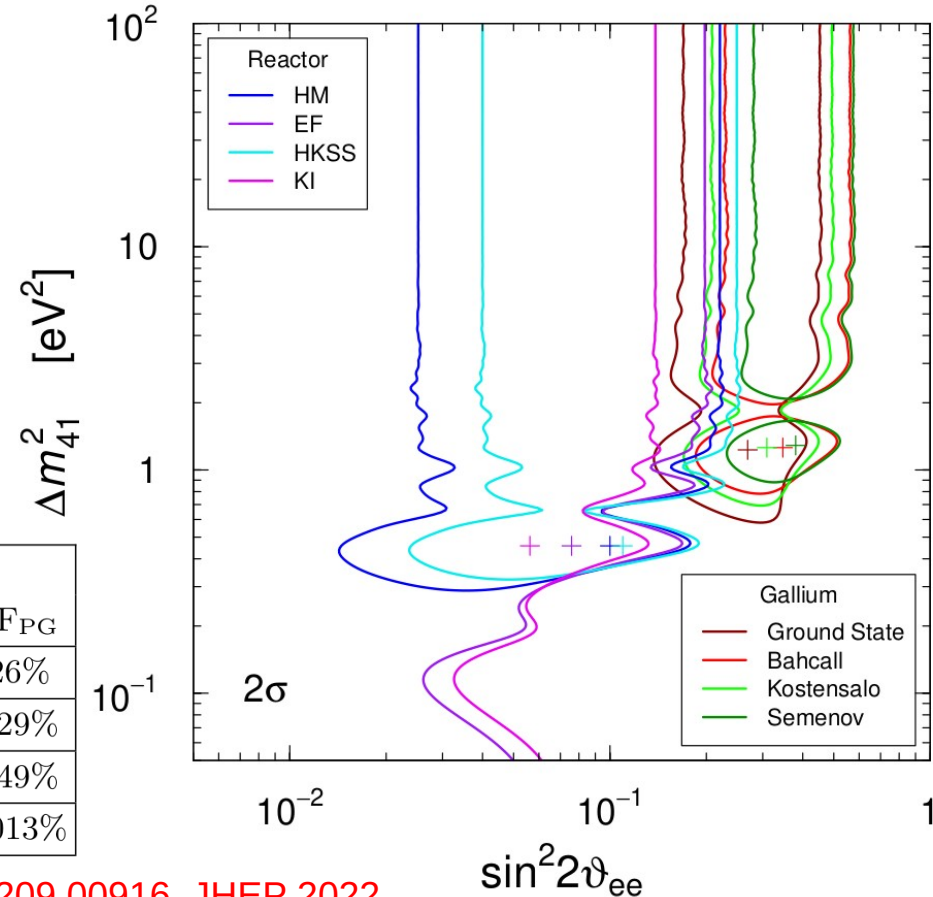
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



Tension between RAA and Gallium

Severe tension between reactor rate and Gallium data!

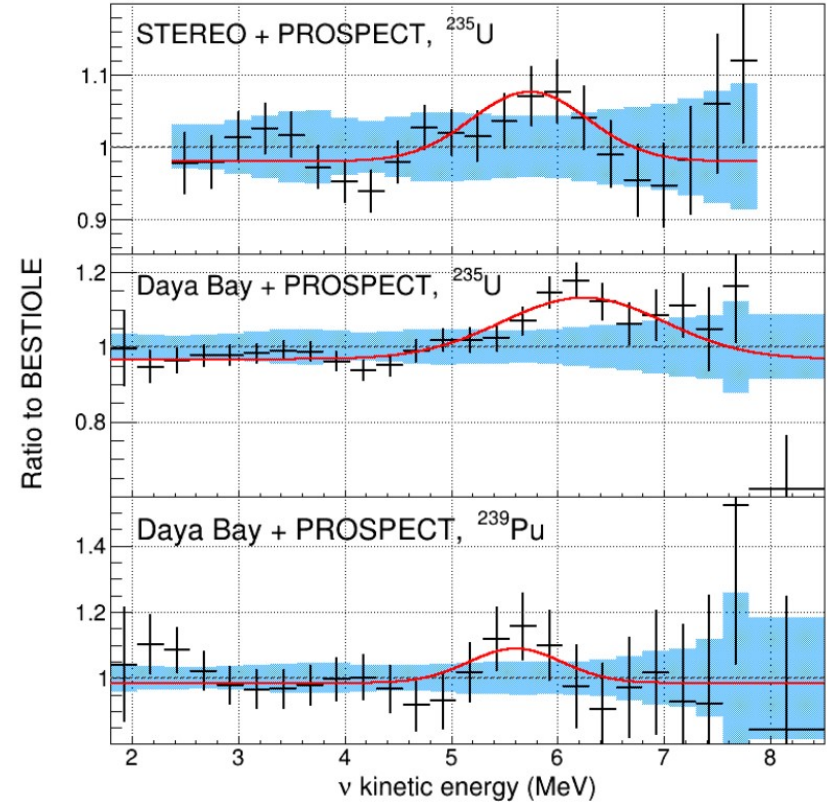
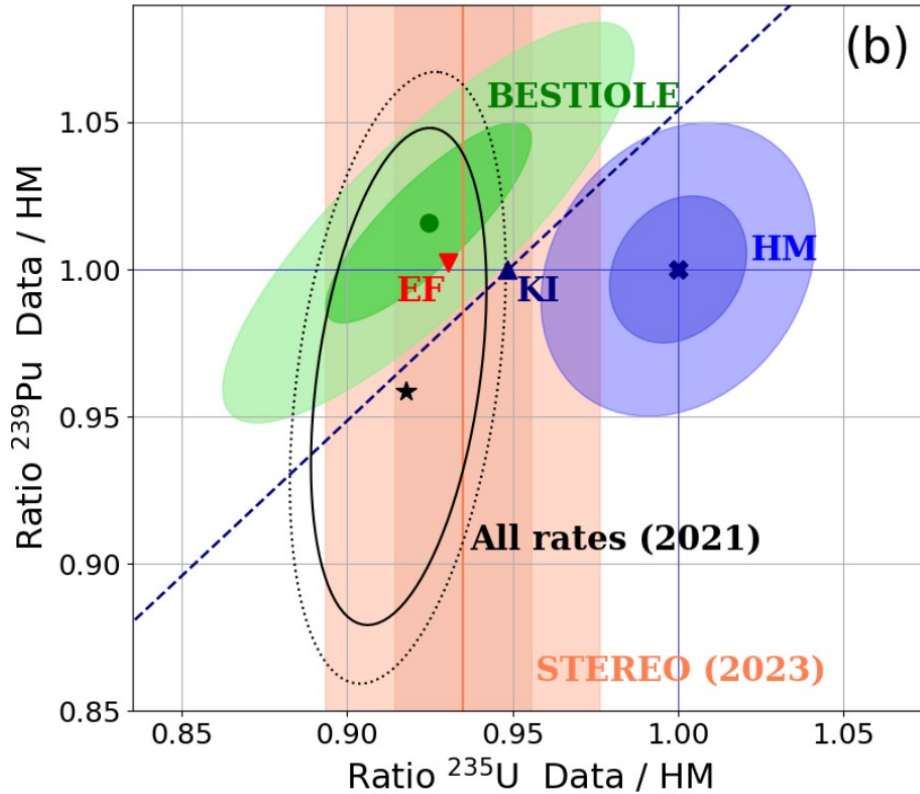
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}
Ground State	7.2	2.8%	5.4	6.8%	9.1	1.1%	11.9	0.26%
Bahcall	10.9	0.42%	8.9	1.2%	12.9	0.16%	16.3	0.029%
Kostensalo	9.6	0.83%	7.5	2.4%	11.5	0.31%	15.3	0.049%
Semenov	15.1	0.052%	12.6	0.18%	17.0	0.02%	22.5	0.0013%



Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

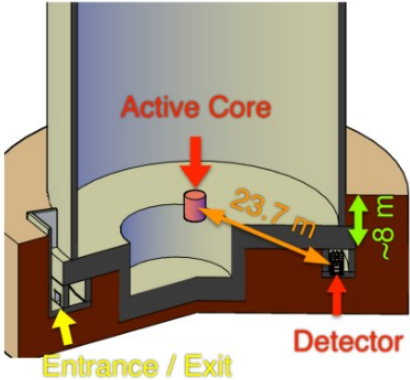
BESTIOLE: 2023 new flux from summation method

BESTIOLE: Périssé, et al, 2304.14992, PRC 2023

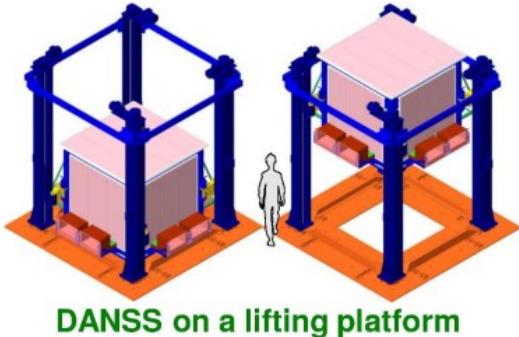


Ratio analysis

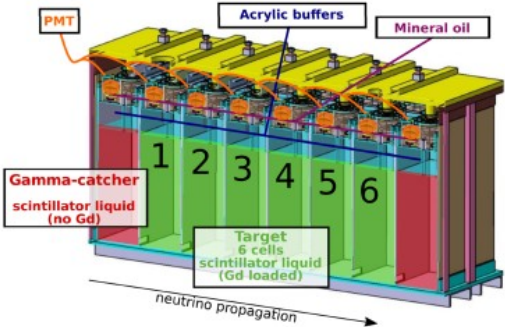
NEOS



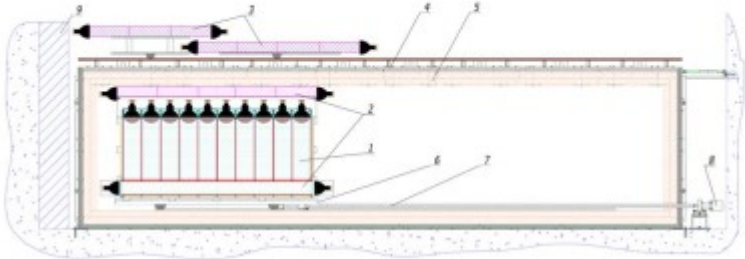
DANSS



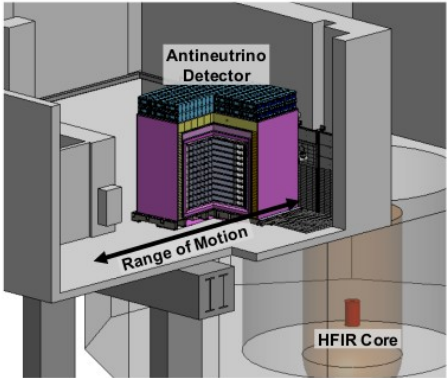
STEREO



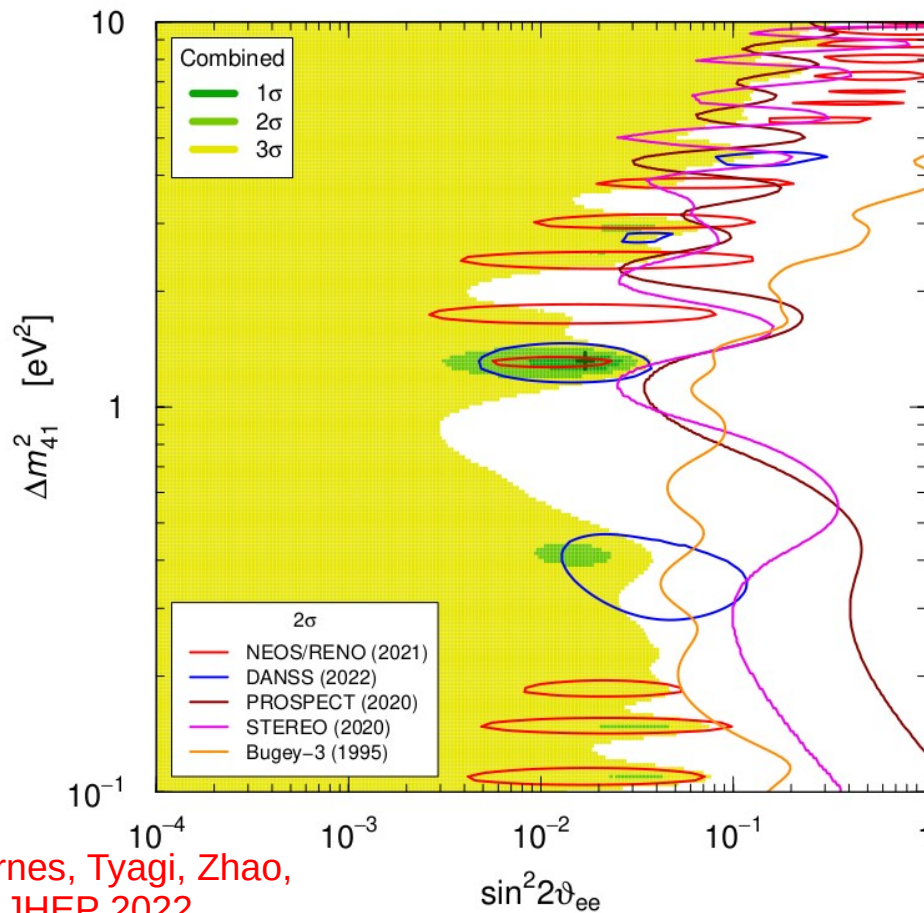
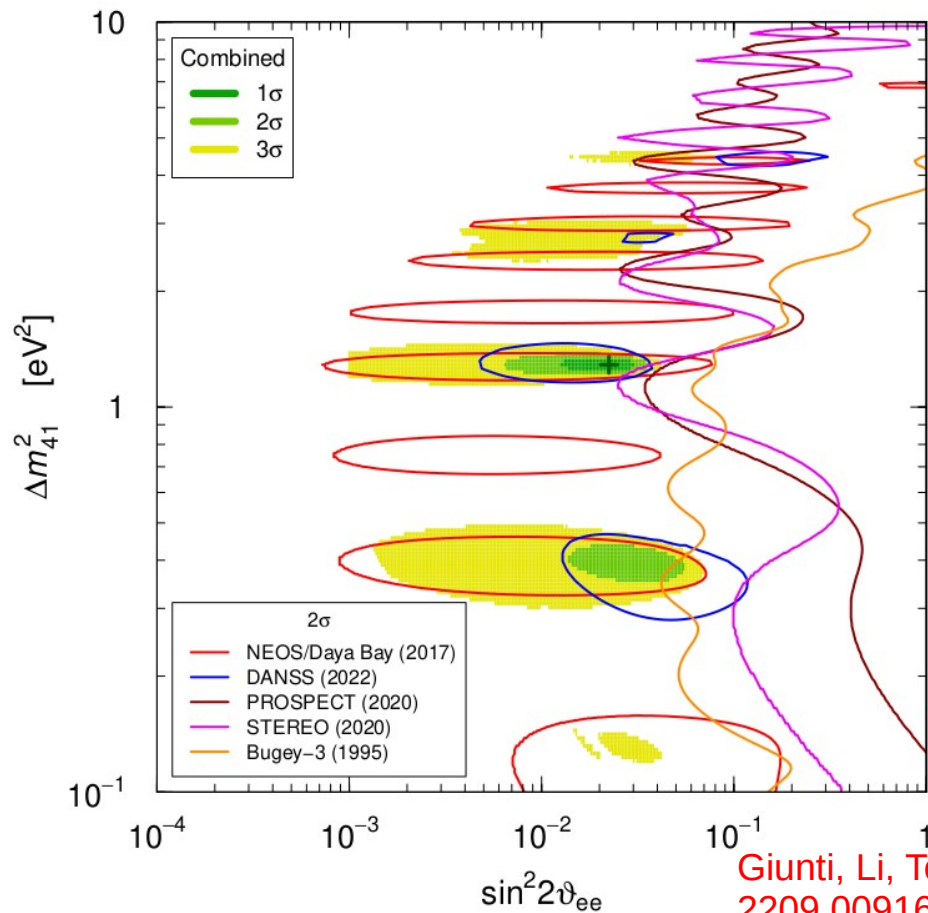
Neutrino-4



PROSPECT

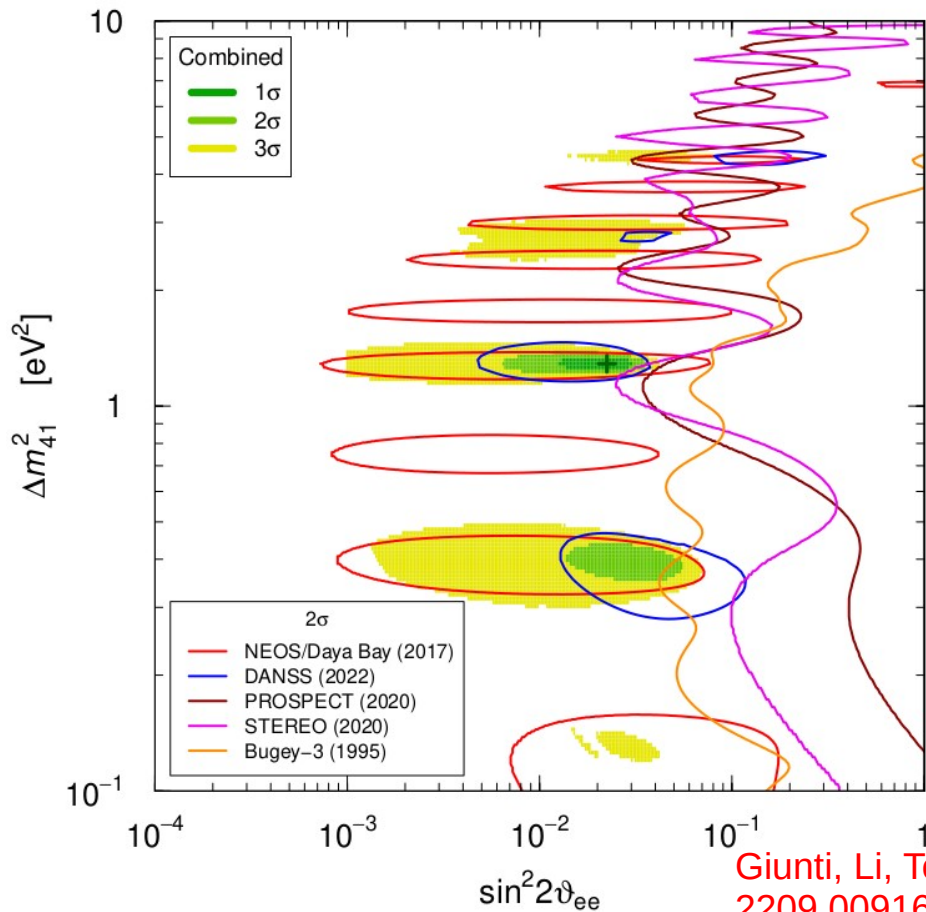


Ratio analysis



Giunti, Li, Ternes, Tyagi, Zhao,
2209.00916, JHEP 2022

Ratio analysis



The NEOS collaboration performed an analysis using the Daya Bay spectrum as a reference spectrum

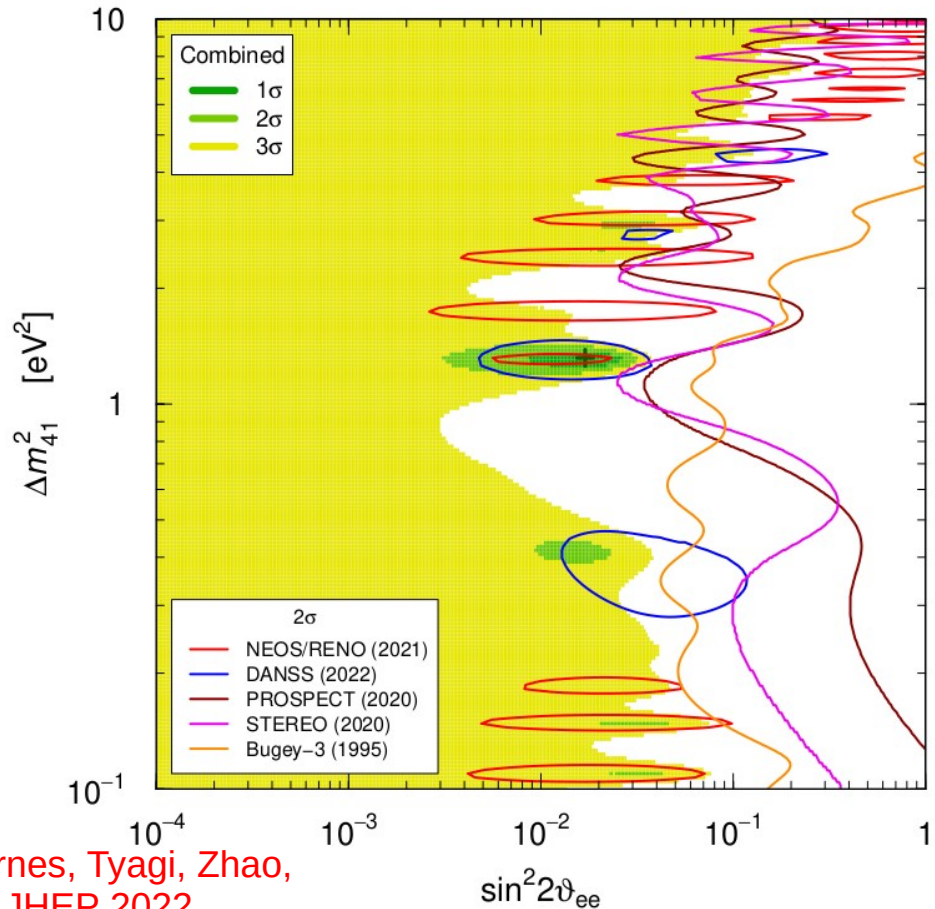
Many many events at Daya Bay!

Giunti, Li, Ternes, Tyagi, Zhao,
2209.00916, JHEP 2022

Ratio analysis

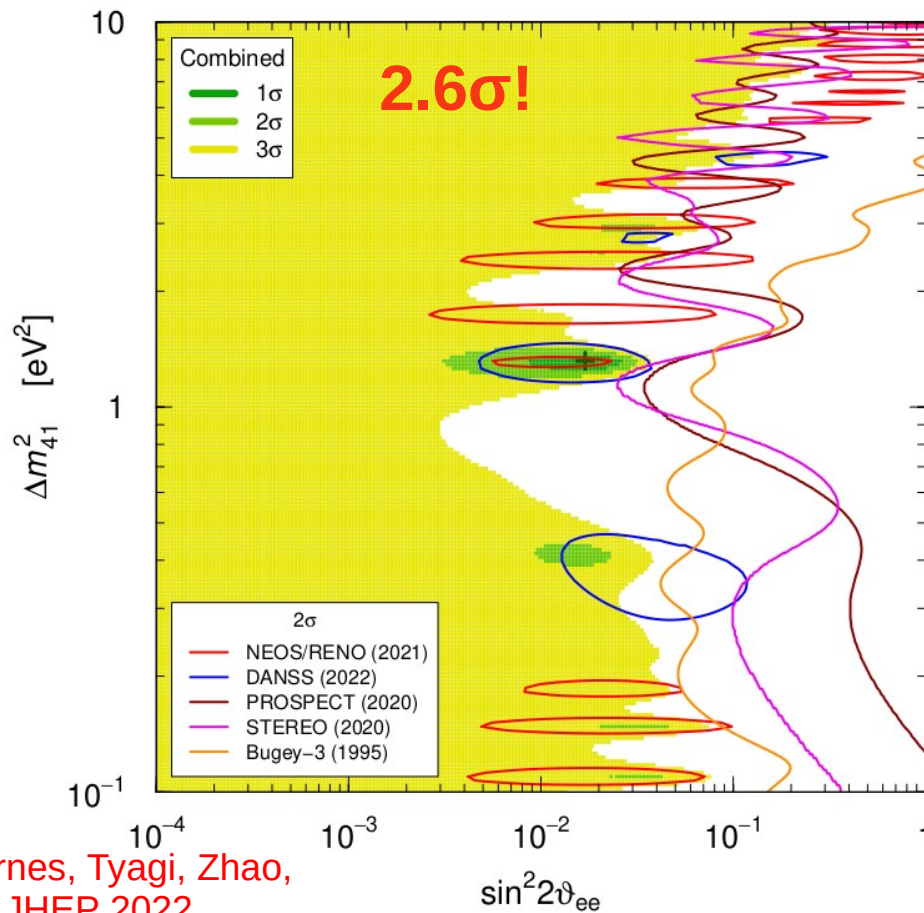
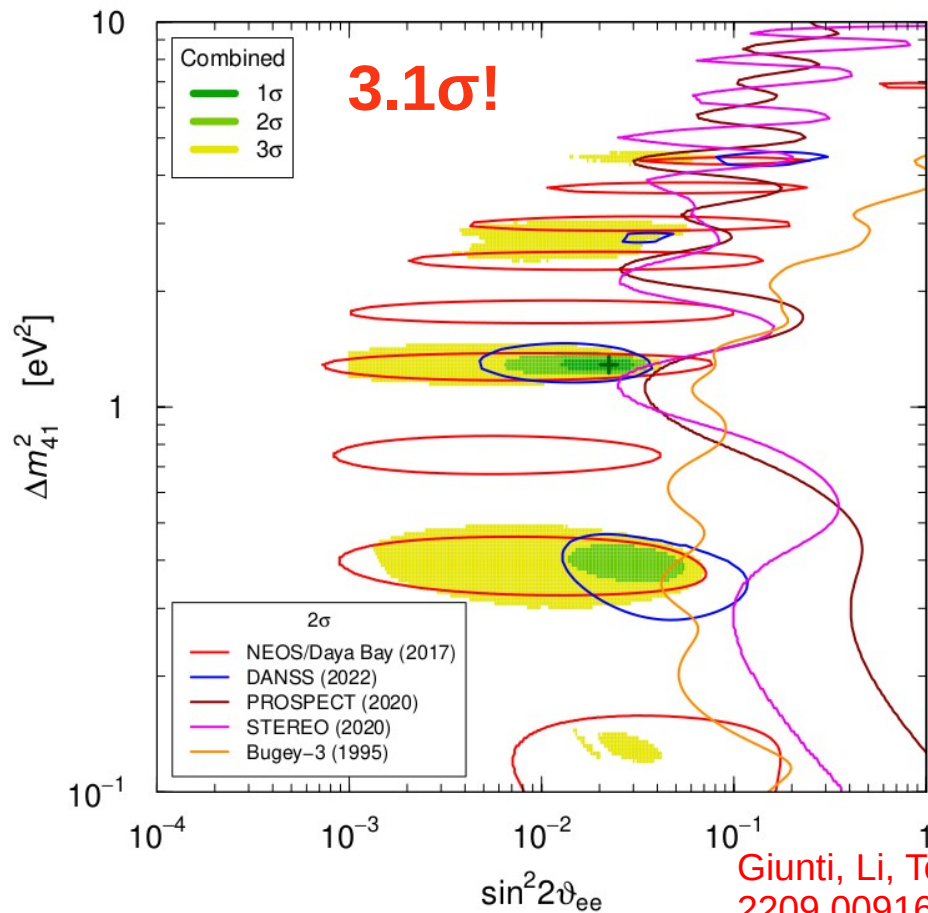
The NEOS collaboration also performed an analysis using the RENO spectrum as a reference spectrum

Same reactor complex, better control of systematic uncertainties!



Giunti, Li, Ternes, Tyagi, Zhao,
2209.00916, JHEP 2022

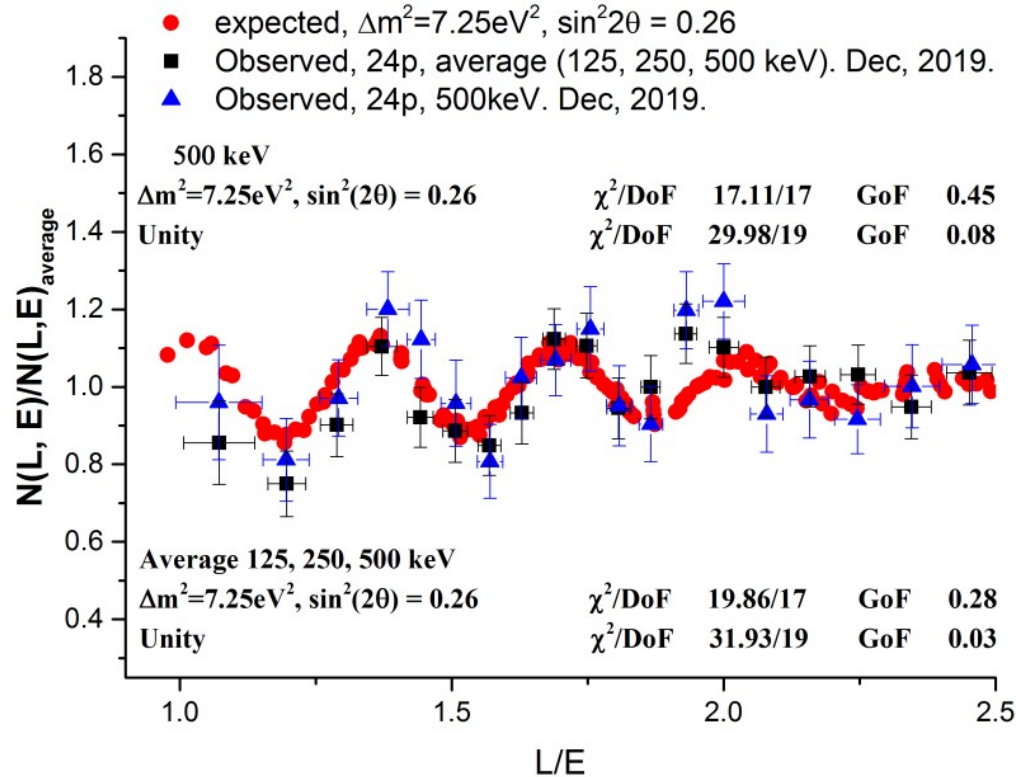
Ratio analysis



Giunti, Li, Ternes, Tyagi, Zhao,
2209.00916, JHEP 2022

Neutrino-4

Neutrino-4, 2005.05301, PRD 2021



Neutrino-4 observes
sterile oscillations
at about 3σ

Very large mixing

In tension with solar
data

Neutrino-4

Neutrino-4, 2005.05301, PRD 2021

- [v1] Sat, 9 May 2020 08:02:58 UTC (4,608 KB)
- [v2] Thu, 18 Jun 2020 19:22:37 UTC (4,634 KB)
- [v3] Fri, 31 Jul 2020 15:14:06 UTC (5,803 KB)
- [v4] Sun, 16 Aug 2020 19:05:32 UTC (5,849 KB)
- [v5] Sun, 14 Feb 2021 10:27:34 UTC (4,406 KB)
- [v6] Sun, 21 Feb 2021 07:51:12 UTC (4,405 KB)
- [v7] Mon, 5 Apr 2021 15:21:56 UTC (5,488 KB)
- [v8] Tue, 25 May 2021 15:21:59 UTC (5,479 KB)

Neutrino-4

Neutrino-4, 2005.05301, PRD 2021



[v1] Sat, 9 May 2020 08:02:58 UTC (4,608 KB)	2.8 σ
[v2] Thu, 18 Jun 2020 19:22:37 UTC (4,634 KB)	2.8 σ
[v3] Fri, 31 Jul 2020 15:14:06 UTC (5,803 KB)	4.6 σ (added Gallium data)
[v4] Sun, 16 Aug 2020 19:05:32 UTC (5,849 KB)	4.6 σ
[v5] Sun, 14 Feb 2021 10:27:34 UTC (4,406 KB)	2.4 σ (removed Gallium data)
[v6] Sun, 21 Feb 2021 07:51:12 UTC (4,405 KB)	3.2 σ (?????)
[v7] Mon, 5 Apr 2021 15:21:56 UTC (5,488 KB)	2.9 σ
[v8] Tue, 25 May 2021 15:21:59 UTC (5,479 KB)	2.7 σ -2.9 σ

Neutrino-4

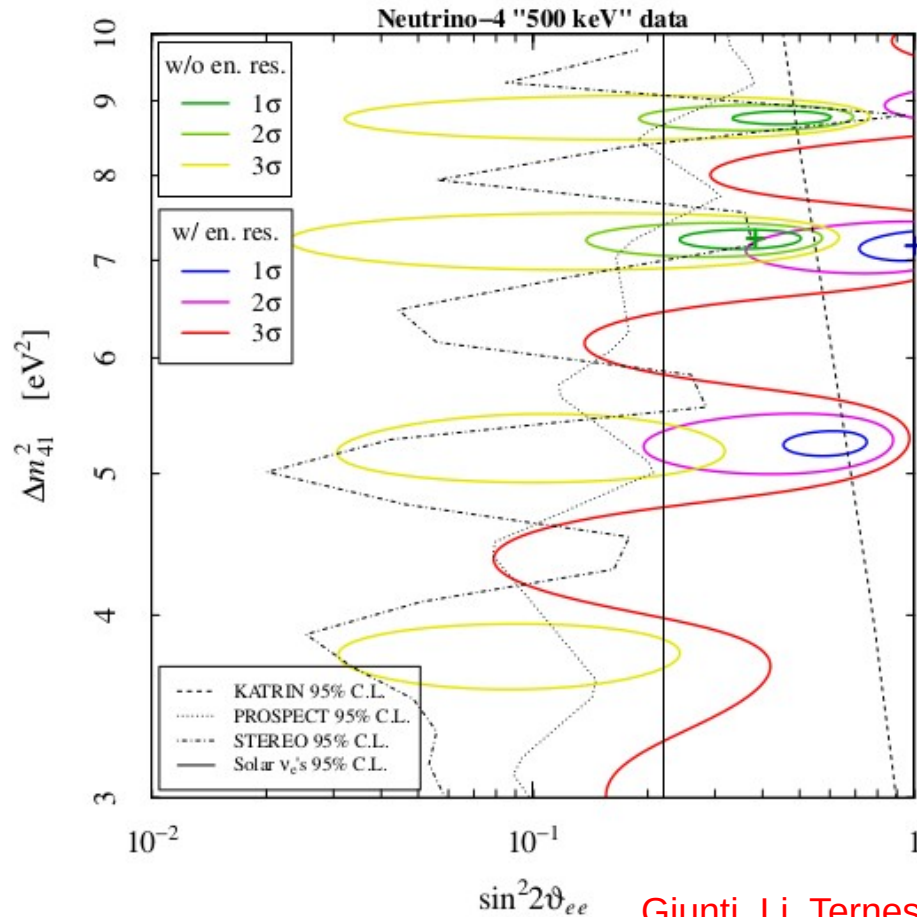
Averaging contains integration over flux, distance, detector resolution

$$\left\langle \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \right\rangle_{ik} = \frac{\int_{L_k^{\min}}^{L_k^{\max}} dL L^{-2} \int_{E_i^{\min}}^{E_i^{\max}} dE'_p \int dE_p R(E_p, E'_p) \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right) \phi_{\bar{\nu}_e}(E) \sigma_{\bar{\nu}_e p}(E)}{\int_{L_k^{\min}}^{L_k^{\max}} dL L^{-2} \int_{E_i^{\min}}^{E_i^{\max}} dE'_p \int dE_p R(E_p, E'_p) \phi_{\bar{\nu}_e}(E) \sigma_{\bar{\nu}_e p}(E)}$$

Using energy calibration information from 2005.05301 we extract the approximate energy resolution function

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

Neutrino-4



We can only reproduce Neutrino-4 confidence regions when not including energy resolution

Inclusion shifts the best fit to even larger values, but reduces the preference for sterile oscillations

Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

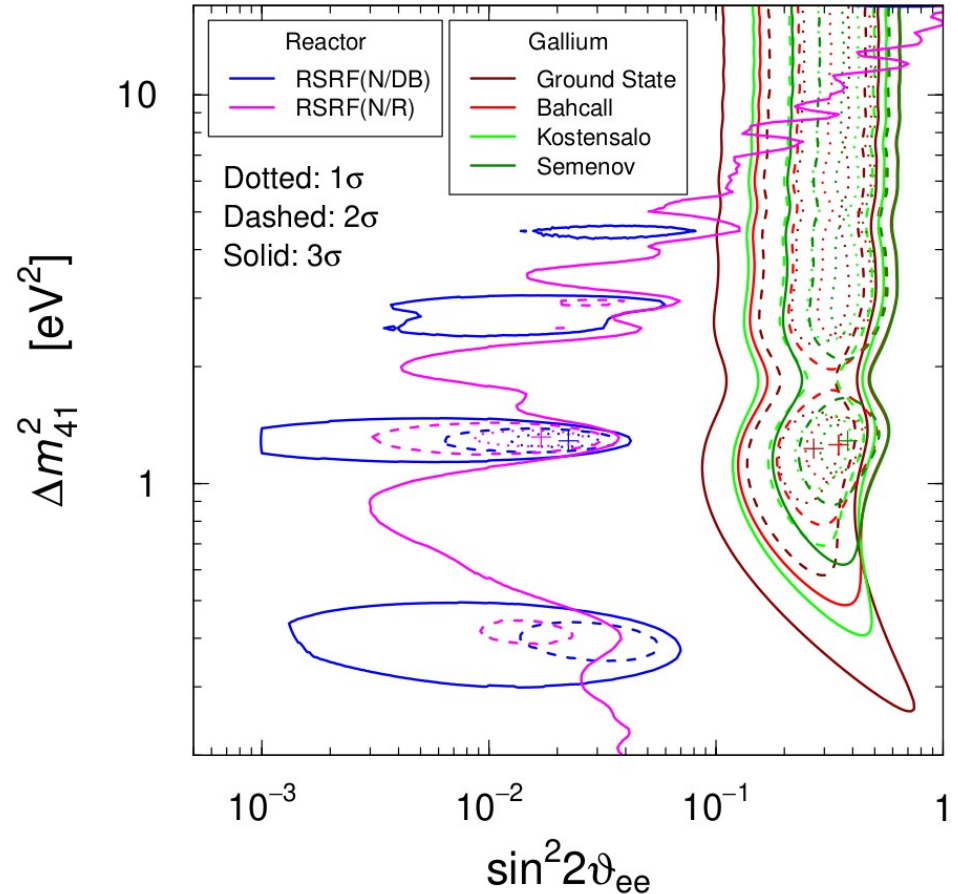
Ratio analysis

Giunti, Li, Ternes, Tyagi, Zhao,
2209.00916, JHEP 2022

Severe tension between
RSRF(N/DB) and Gallium
data!

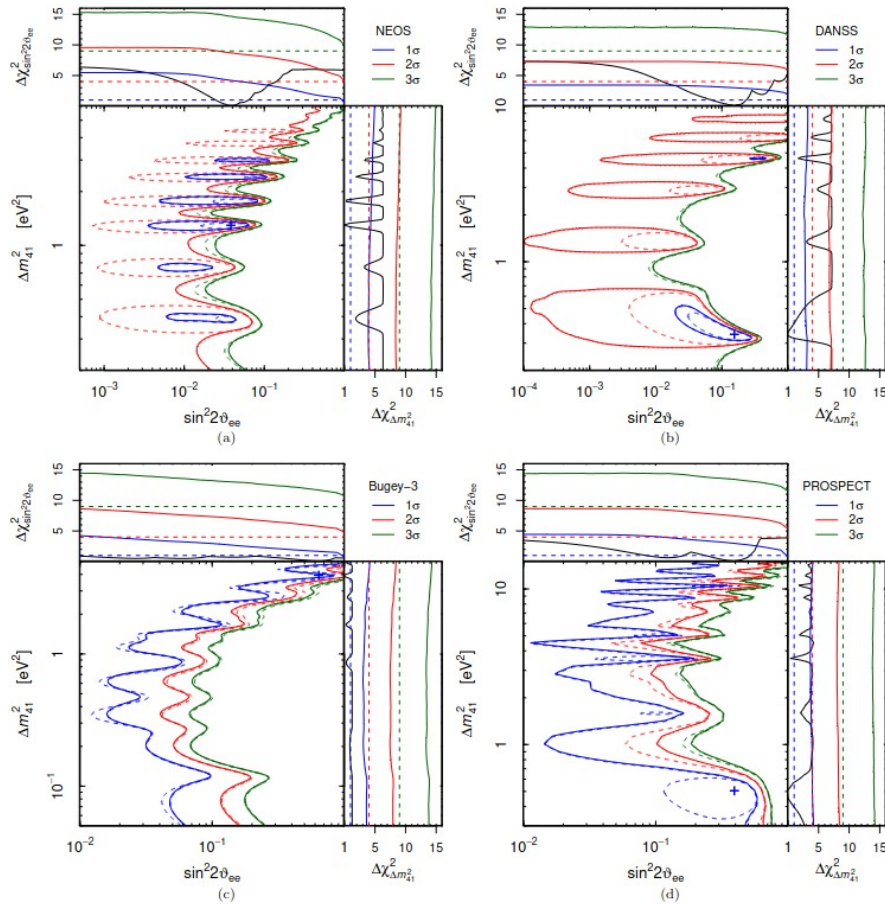
No good fit for RSRF(N/R)
either.

	RSRF(N/DB)		RSRF(N/R)	
	$\Delta\chi_{PG}^2$	GoF _{PG}	$\Delta\chi_{PG}^2$	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%



For a combined analysis including Neutrino-4 see:
Berryman, Coloma, Huber, Schwetz, Zhao, 2111.12530, JHEP 2022

Caution!

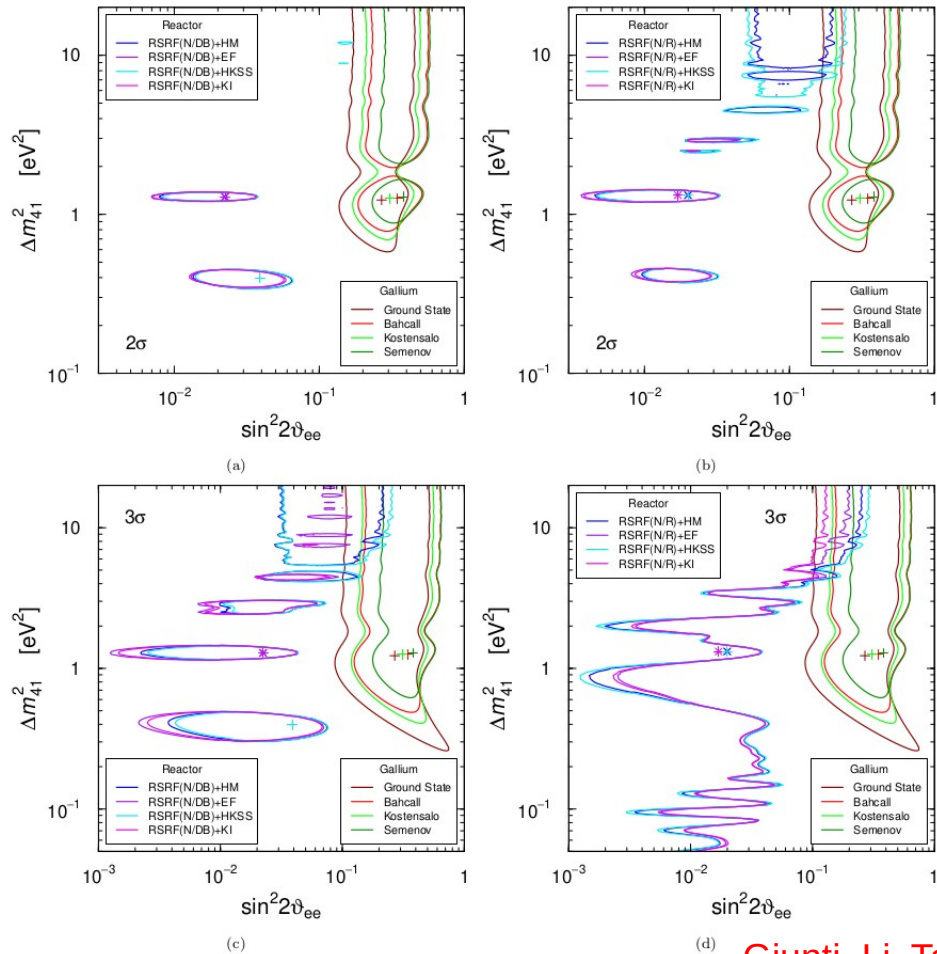


We performed simple χ^2 analyses

If one takes into account statistical fluctuation of the data the significance can be reduced

Giunti, 2004.07577, PRD 2020

Combined ratio and rate data



Combining ratio and rate data leads to better localization of allowed regions.

Severe tension for any combination with Gallium data!

	RSRF(N/DB) + Reactor Rates							
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}
Ground State	14.30	0.078%	11.36	0.34%	19.57	0.0056%	21.81	0.0018%
Bahcall	18.33	0.01%	15.16	0.051%	23.60	0.00075%	26.02	0.00022%
Kostensalo	17.04	0.02%	13.80	0.1%	22.30	0.0014%	27.51	0.00011%
Semenov	23.22	0.00091%	19.39	0.0061%	28.28	0.000072%	36.85	0.00000099%
	RSRF(N/R) + Reactor Rates							
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}
Ground State	10.12	0.63%	6.94	3.1%	15.59	0.041%	21.04	0.0027%
Bahcall	14.14	0.085%	10.72	0.47%	19.61	0.0055%	25.63	0.00027%
Kostensalo	12.84	0.16%	9.36	0.93%	18.30	0.011%	24.89	0.00039%
Semenov	19.04	0.0073%	15.00	0.055%	24.29	0.00053%	32.99	0.0000068%

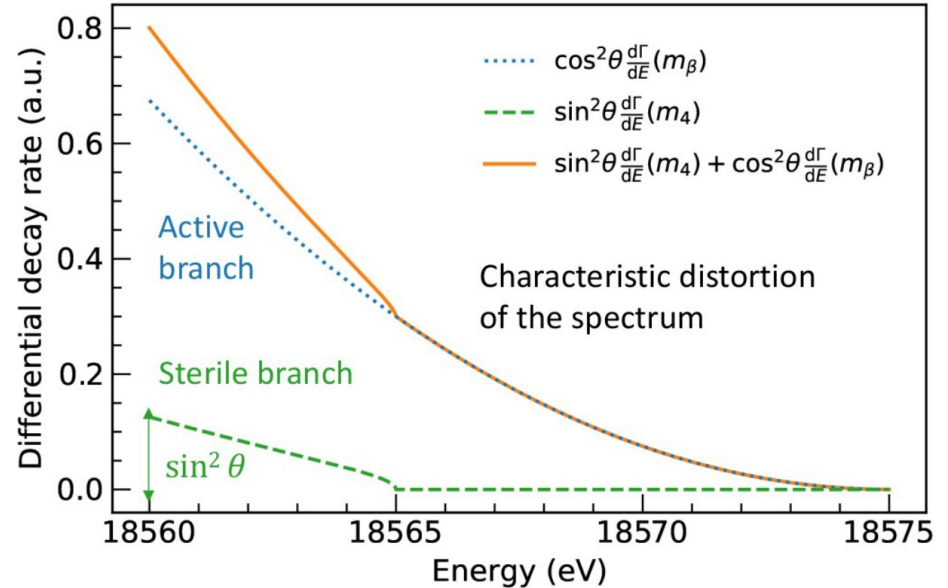
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Tritium data

Tritium experiments measure the beta-decay spectrum

$$R_\beta(E) \simeq \frac{G_F^2 \cos^2 \theta_C}{2\pi^3} |\mathcal{M}|^2 F(E, Z+1) \\ \times (E + m_e) \sqrt{(E + m_e)^2 - m_e^2} \\ \times \sum_j \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2} \Theta(\varepsilon_j - m_\beta)$$

$$\frac{d\Gamma}{dE} = \underbrace{(1 - |U_{e4}|^2) \frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$



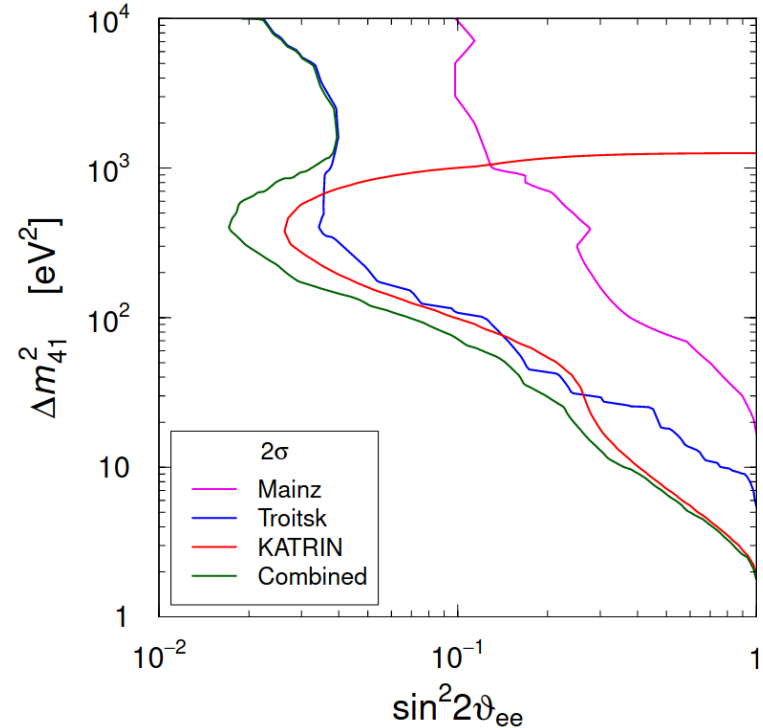
Lokhov @ NuMass 2022, Milano

Tritium data

Tritium experiments measure the beta-decay spectrum

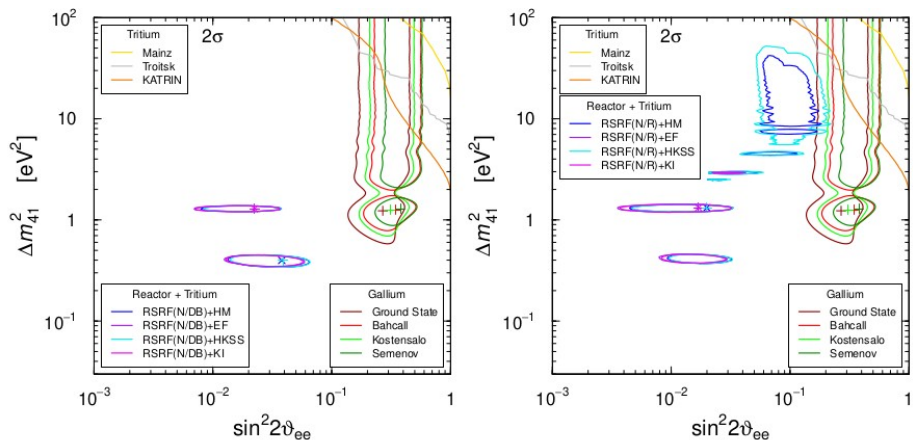
$$R_\beta(E) \simeq \frac{G_F^2 \cos^2 \theta_C}{2\pi^3} |\mathcal{M}|^2 F(E, Z + 1) \\ \times (E + m_e) \sqrt{(E + m_e)^2 - m_e^2} \\ \times \sum_j \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2} \Theta(\varepsilon_j - m_\beta)$$

$$\frac{d\Gamma}{dE} = \underbrace{(1 - |U_{e4}|^2)}_{\text{light neutrino}} \frac{d\Gamma}{dE}(m_\beta^2) + \underbrace{|U_{e4}|^2}_{\text{heavy neutrino}} \frac{d\Gamma}{dE}(m_4^2)$$



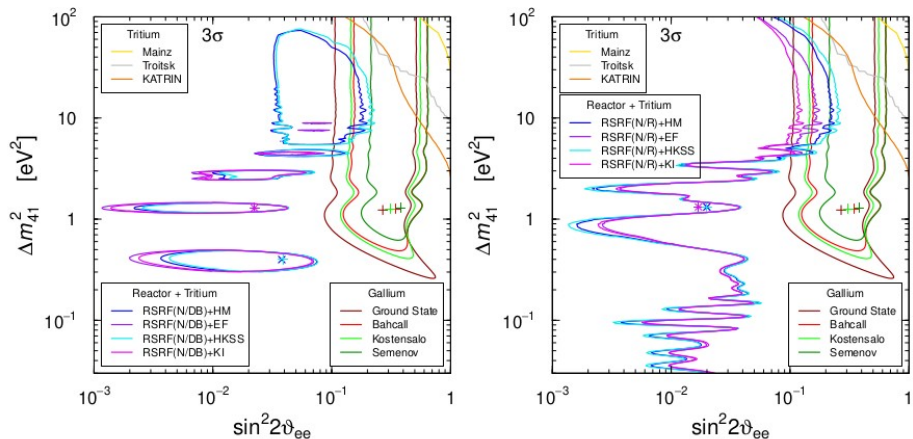
Giunti @ NOW 2022, Ostuni

Combined reactor and Tritium data



(a)

(b)



(c)

(d)

Tritium data removes the regions at large values of the mass splitting.

Severe tension for any combination with Gallium data!

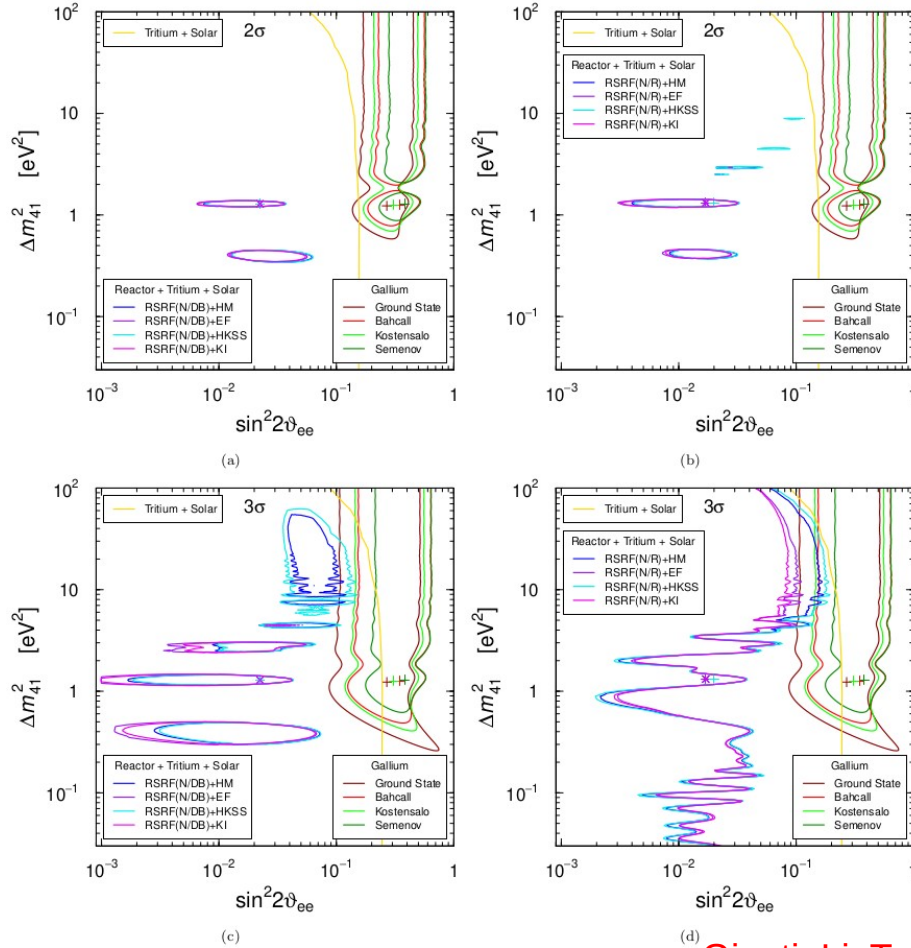
RSRF(N/DB) + Reactor Rates + Tritium									
		HM		HKSS		EF		KI	
		$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}
Ground State		15.69	0.039%	13.17	0.14%	20.82	0.003%	21.82	0.0018%
Bahcall		19.86	0.0049%	17.19	0.019%	25.06	0.00036%	26.03	0.00022%
Kostensalo		18.63	0.009%	15.87	0.036%	23.83	0.00067%	27.52	0.00011%
Semenov		25.22	0.00033%	21.94	0.0017%	30.42	0.000025%	37.42	0.00000075%
RSRF(N/R) + Reactor Rates + Tritium									
		HM		HKSS		EF		KI	
		$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}
Ground State		11.56	0.31%	8.72	1.3%	16.96	0.021%	21.49	0.0022%
Bahcall		15.76	0.038%	12.74	0.17%	21.19	0.0025%	26.08	0.00022%
Kostensalo		14.49	0.071%	11.40	0.33%	19.97	0.0046%	25.37	0.00031%
Semenov		21.04	0.0027%	17.45	0.016%	26.45	0.00018%	33.56	0.0000052%

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Combined reactor, Tritium, and solar data

Combination of all data!

Severe and unacceptable tension for any combination with Gallium data!



Global Fit: RSRF(N/DB) + Reactor Rates + Tritium + Solar									
		HM		HKSS		EF		KI	
		$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	
Ground State		21.54	0.0021%	19.51	0.0058%	21.92	0.0017%	21.90	0.0018%
Bahcall		25.99	0.00023%	23.88	0.00065%	26.13	0.00021%	26.11	0.00021%
Kostensalo		25.05	0.00036%	22.77	0.0011%	27.62	0.0001%	27.60	0.0001%
Semenov		32.52	0.0000087%	29.93	0.000032%	37.69	0.00000065%	38.81	0.00000037%
Global Fit: RSRF(N/R) + Reactor Rates + Tritium + Solar									
		HM		HKSS		EF		KI	
		$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	GoF _{PG}	$\Delta\chi^2_{PG}$	
Ground State		17.61	0.015%	15.53	0.042%	22.56	0.0013%	22.66	0.0012%
Bahcall		22.07	0.0016%	19.90	0.0048%	26.82	0.00015%	26.80	0.00015%
Kostensalo		21.11	0.0026%	18.77	0.0084%	26.27	0.0002%	28.45	0.000066%
Semenov		28.57	0.000062%	25.93	0.00023%	34.00	0.0000041%	38.24	0.0000005%

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

More on the Gallium anomaly

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Model	Method	^{51}Cr		^{37}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	—
Bahcall (1997)	$^{71}\text{Ga}(p, n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
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%
Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
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%

More on the Gallium anomaly

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Model	Method	^{51}Cr		^{37}Ar	
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Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
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%

Small

More on the Gallium anomaly

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Model	Method	^{51}Cr		^{37}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	—
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Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
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%

Large

More on the Gallium anomaly

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Model	Method	^{51}Cr		^{37}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	—
Bahcall (1997)	$^{71}\text{Ga}(p, n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
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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%
Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
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%

$$\sigma_{\text{tot}} = \sigma_{\text{gs}} \left(\overset{\text{Main contribution}}{1 + \xi_{5/2^-} \frac{\text{BGT}_{5/2^-}}{\text{BGT}_{\text{gs}}}} + \overset{\text{Corrections}}{\xi_{3/2^-} \frac{\text{BGT}_{3/2^-}}{\text{BGT}_{\text{gs}}}} + \xi_{5/2^+} \frac{\text{BGT}_{5/2^+}}{\text{BGT}_{\text{gs}}} \right)$$

More on the Gallium anomaly

The ground-state cross section is obtained from the half life measurement

$$\sigma_{\text{gs}} = \frac{G_{\text{F}}^2 \cos^2 \vartheta_{\text{C}}}{\pi} g_{\text{A}}^2 \text{BGT}_{\text{gs}} \langle p_e E_e F(Z_{\text{Ge}}, E_e) \rangle = \frac{\pi^2 \ln 2}{m_e^5 f t_{1/2}({}^{71}\text{Ge})} \langle p_e E_e F(Z_{\text{Ge}}, E_e) \rangle$$

Different results obtained in the past

$$T_{1/2}^{\text{BGZZ}}({}^{71}\text{Ge}) = 12.5 \pm 0.1 \text{ d} \quad (\text{Bisi, Germagnoli, Zappa, and Zimmer, 1955})$$

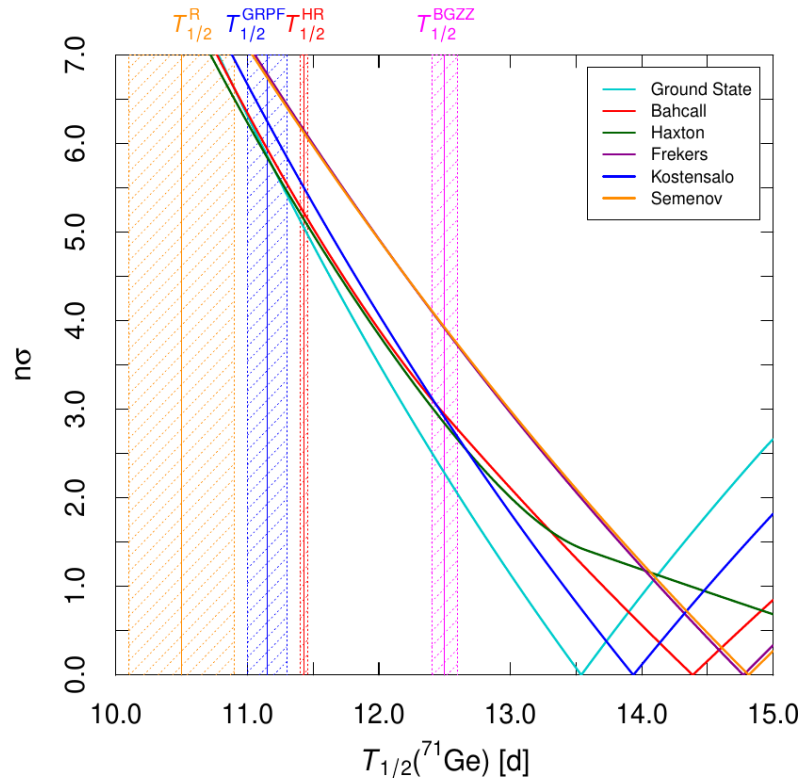
$$T_{1/2}^{\text{R}}({}^{71}\text{Ge}) = 10.5 \pm 0.4 \text{ d} \quad (\text{Rudstam, 1956})$$

$$T_{1/2}^{\text{GRPF}}({}^{71}\text{Ge}) = 11.15 \pm 0.15 \text{ d} \quad (\text{Genz, Renier, Pengra, and Fink, 1971})$$

$$T_{1/2}^{\text{HR}}({}^{71}\text{Ge}) = 11.43 \pm 0.03 \text{ d} \quad (\text{Hampel and Remsberg, 1985})$$

More on the Gallium anomaly

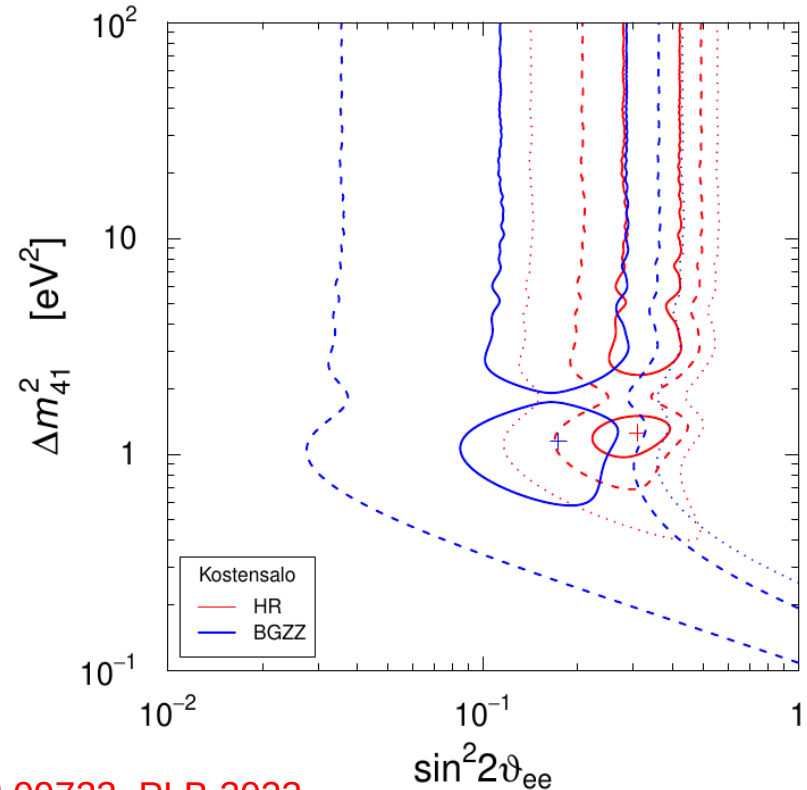
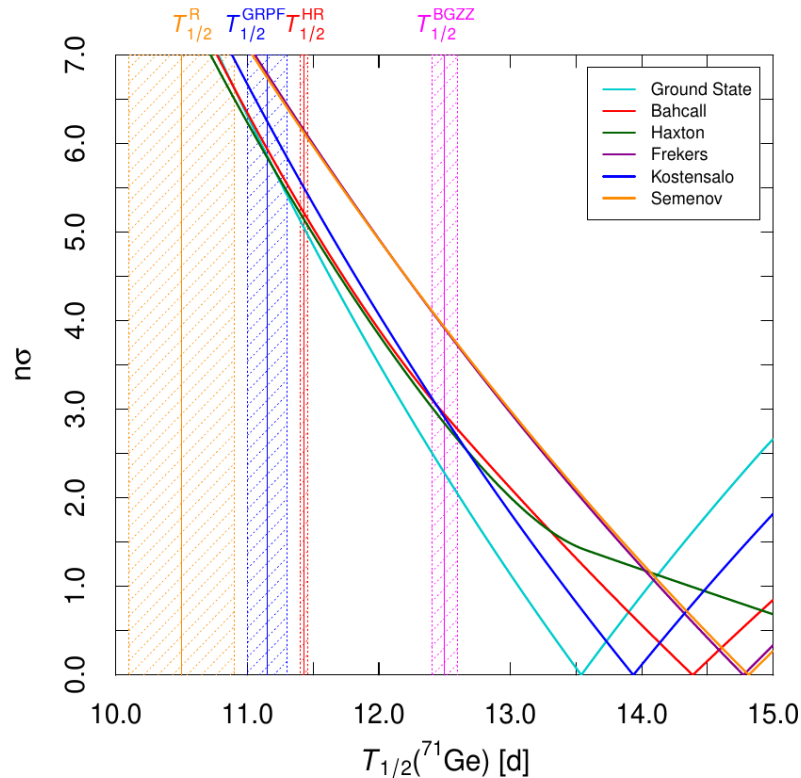
Fit the Germanium half life using data from Gallium experiments



Giunti, Li, Ternes, Zhao, 2212.09722, PLB 2023

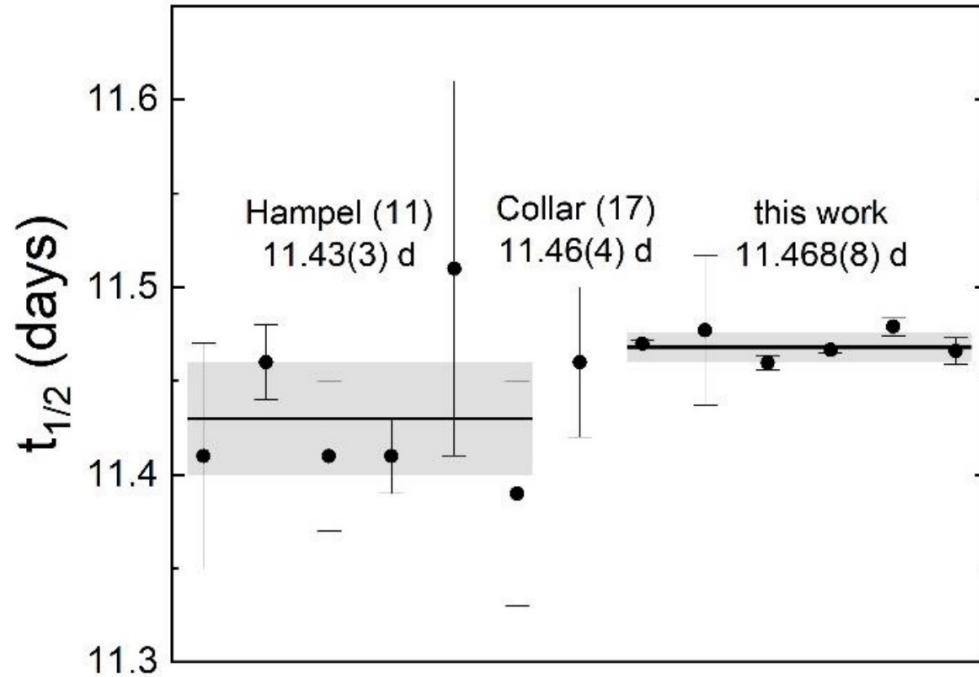
More on the Gallium anomaly

Fit the Germanium half life using data from Gallium experiments



Giunti, Li, Ternes, Zhao, 2212.09722, PLB 2023

More on the Gallium anomaly



Dedicated experiments have been performed since then!

The 1984 measurement was confirmed!

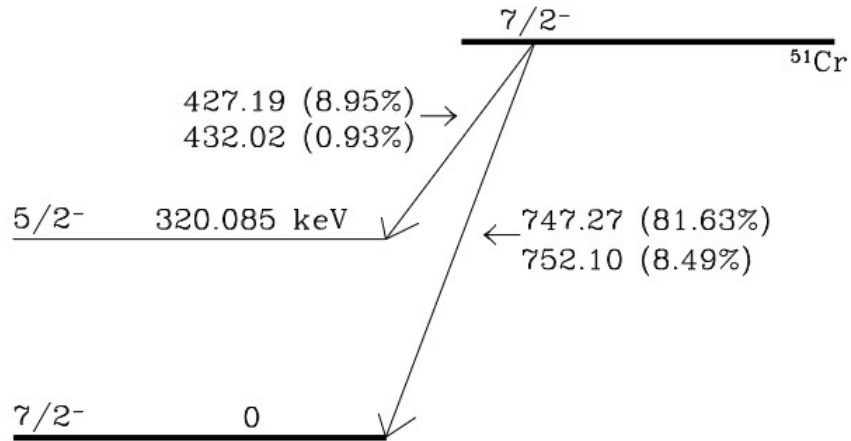
Norman, et al, 2401.15286

Collar, Yoon, 2307.05353, PRC 2023

More on the Gallium anomaly

Different branching ratios in Chromium decays?

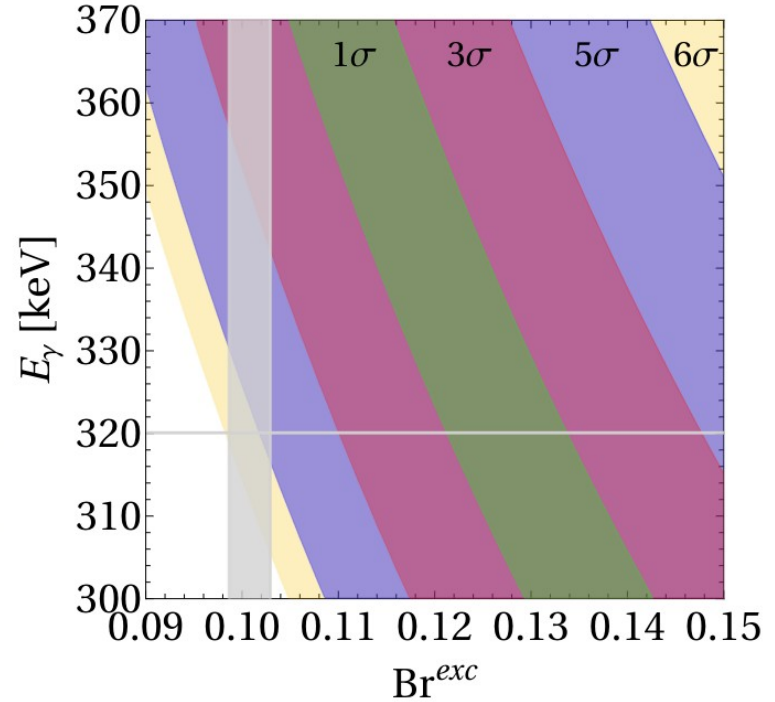
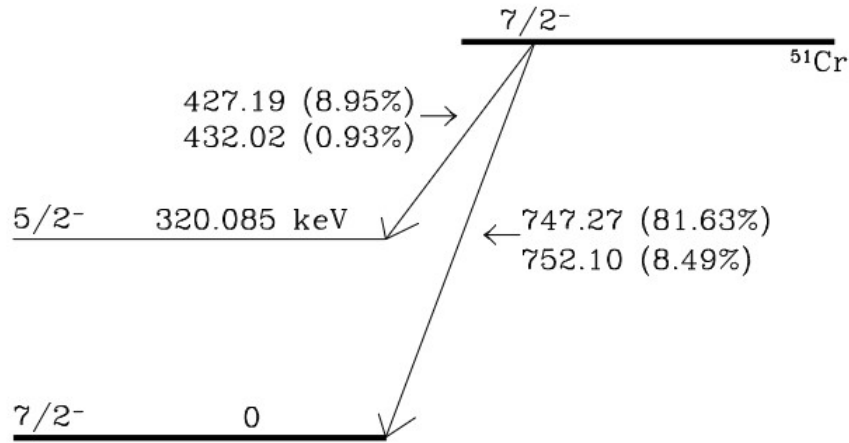
^{51}Cr Neutrino Decay



More on the Gallium anomaly

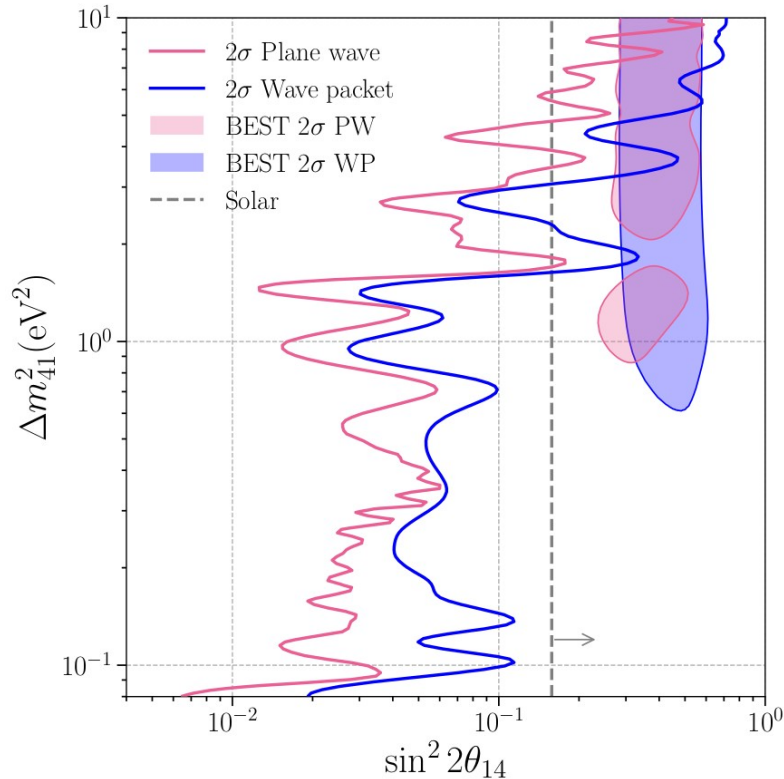
Different branching ratios in Chromium decays?

^{51}Cr Neutrino Decay



Brdar, Gehrlein, Kopp, 2303.05528, JHEP 2023

Wavepackets



Argüelles, Bertólez-Martínez, Salvado,
2201.05108, PRD 2023

It was argued that if the size of the neutrino wavepacket is small the tension is reduced

$$P_{ee}^{\text{WP}} = 1 - \frac{1}{2} \sin^2 2\vartheta_{ee} \left[1 - \cos \left(\frac{\Delta m_{41}^2 L}{2E} \right) e^{-\left(\frac{L}{L_{\text{coh}}} \right)^2} \right]$$

$$L_{\text{coh}} = \frac{4\sqrt{2}E^2}{|\Delta m_{41}^2|} \sigma$$

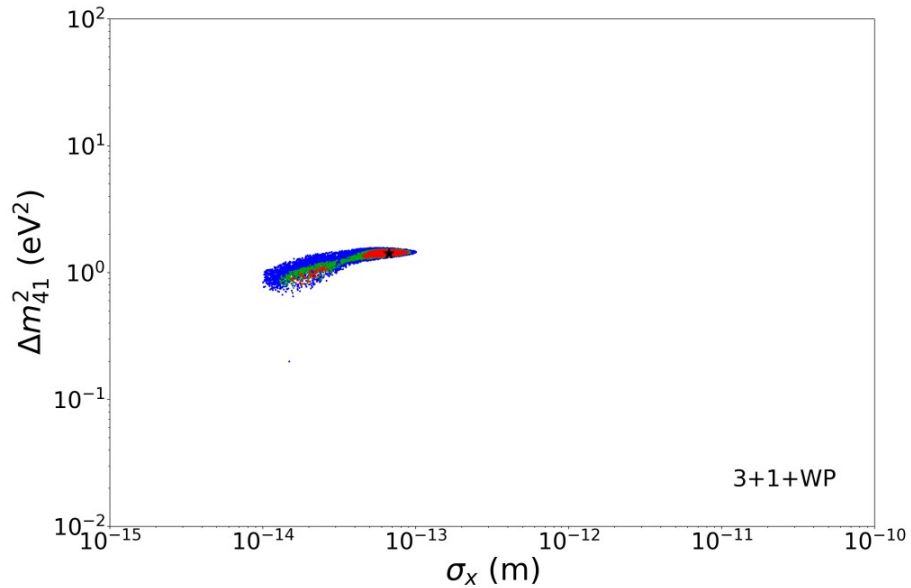
But: The estimated size of the wavepacket is very large

$$\sigma_x = (2 \times 10^{-5} - 1.4 \times 10^{-4}) \text{ cm}$$

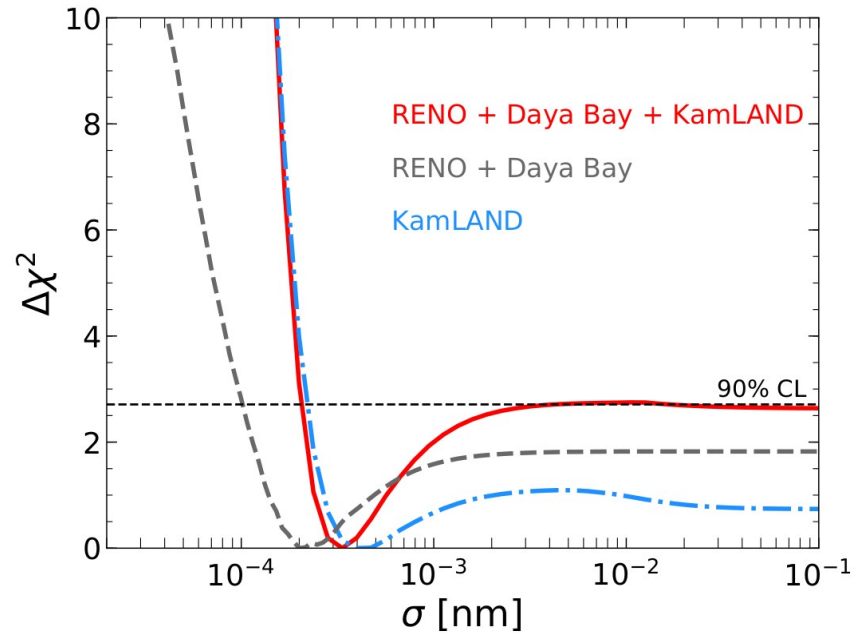
Akhmedov, Smirnov, 2208.03736, JHEP 2022

Wavepackets

Hardin, et al, 2211.02610, JHEP 2023



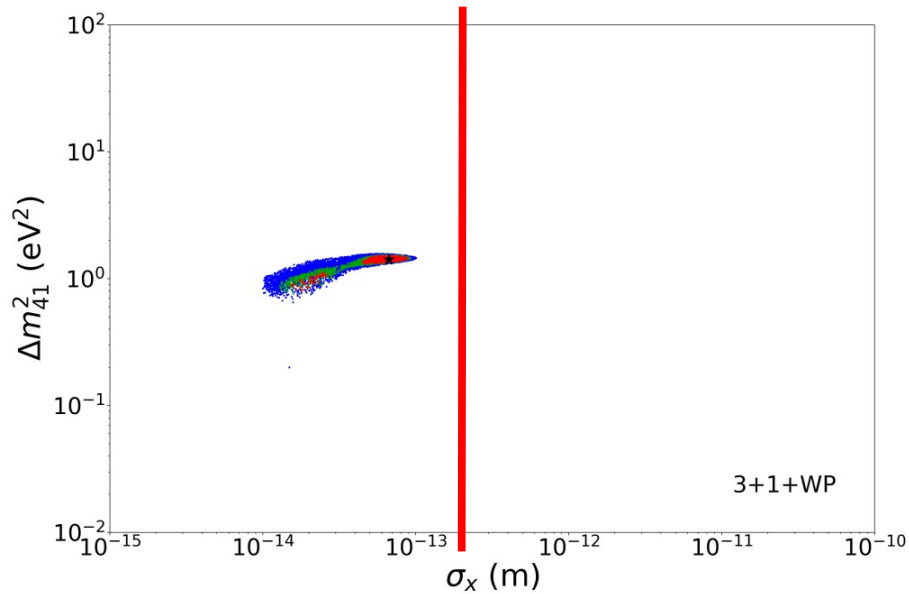
de Gouvêa, De Romeri, Ternes, 2104.05806, JHEP 2021



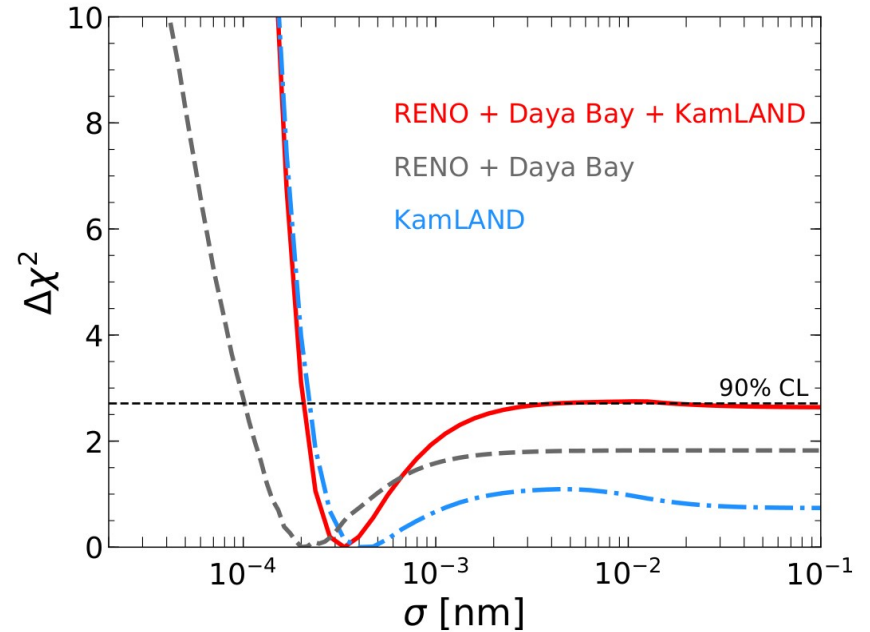
The required size of the wavepacket is in tension with other bounds

Wavepackets

Hardin, et al, 2211.02610, JHEP 2023



de Gouvêa, De Romeri, Ternes, 2104.05806, JHEP 2021



The required size of the wavepacket is in tension with other bounds

Neutrino decay or broad neutrinos?

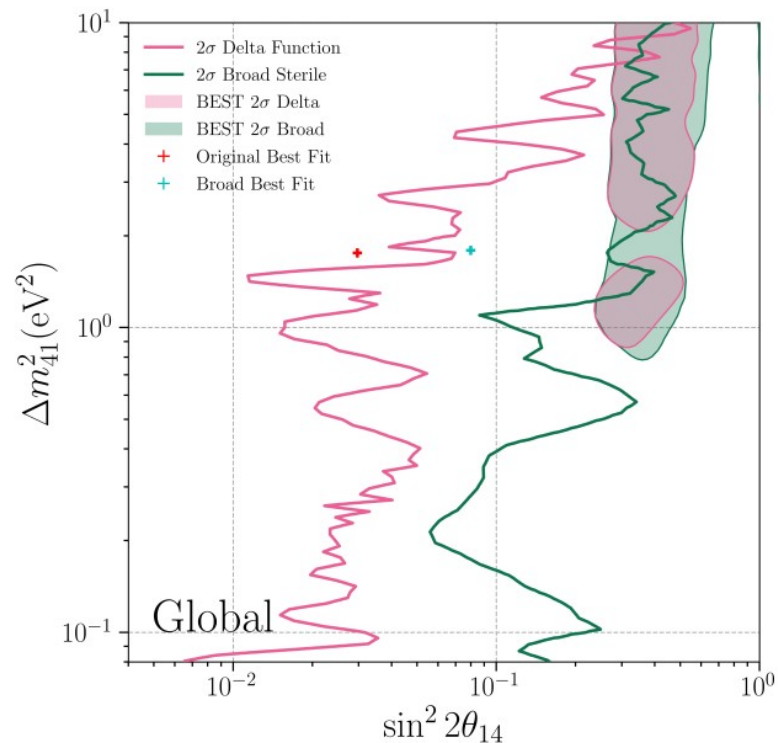
Hardin, et al, 2211.02610, JHEP 2023

Banks, Kelly, McCullough, Zhou,
2311.06352, JHEP 2024

$$P_{ee}^{\text{dec.}} = 2|U_{e4}|^2(1 - |U_{e4}|^2)e^{-\frac{\Gamma m_4 L}{2E}} \cos\left(\frac{\Delta m_{41}^2 L}{2E}\right) + |U_{e4}|^4 e^{-\frac{\Gamma m_4 L}{E}} + (1 - |U_{e4}|^2)^2$$

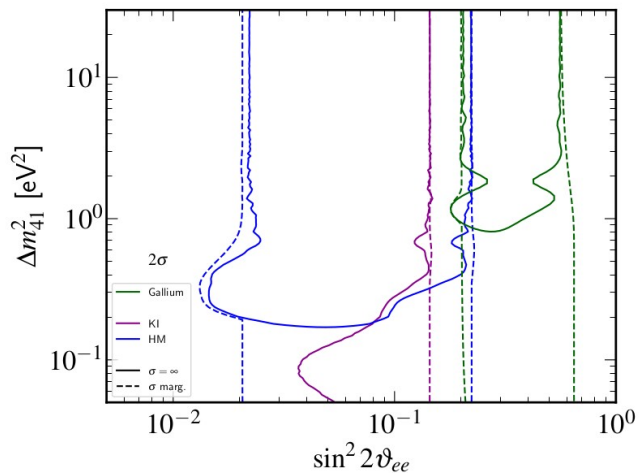
$$P_{ee}^b = \left(1 + \left(\text{sinc}\left(\frac{bL}{4E}\right) - 1\right) |U_{e4}|^2\right)^2 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \text{sinc}\left(\frac{bL}{4E}\right)$$

Alternatively, the neutrino decay or broad neutrino mass distributions have been suggested to alleviate the tension

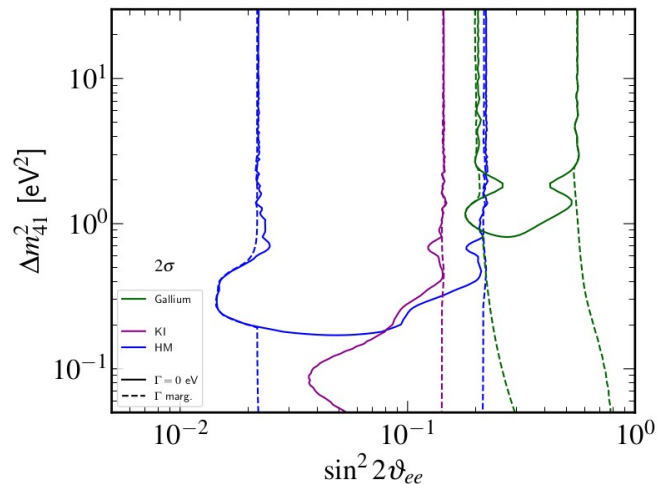


Gallium-Reactor tension

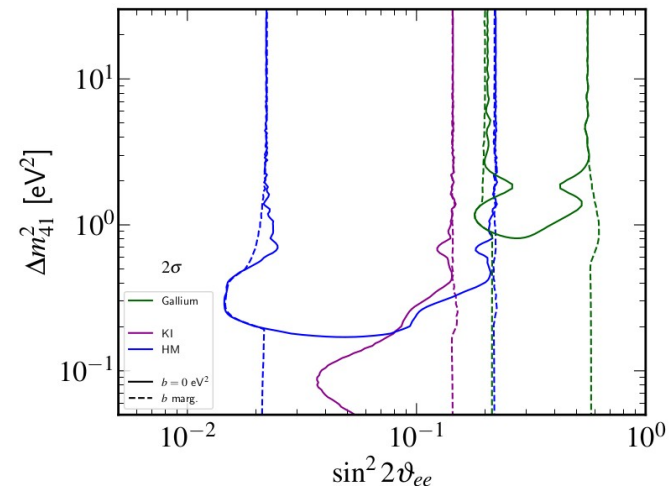
Reactor rate data was not considered in any of the previously discussed analyses



Wavepacket!



Decay!

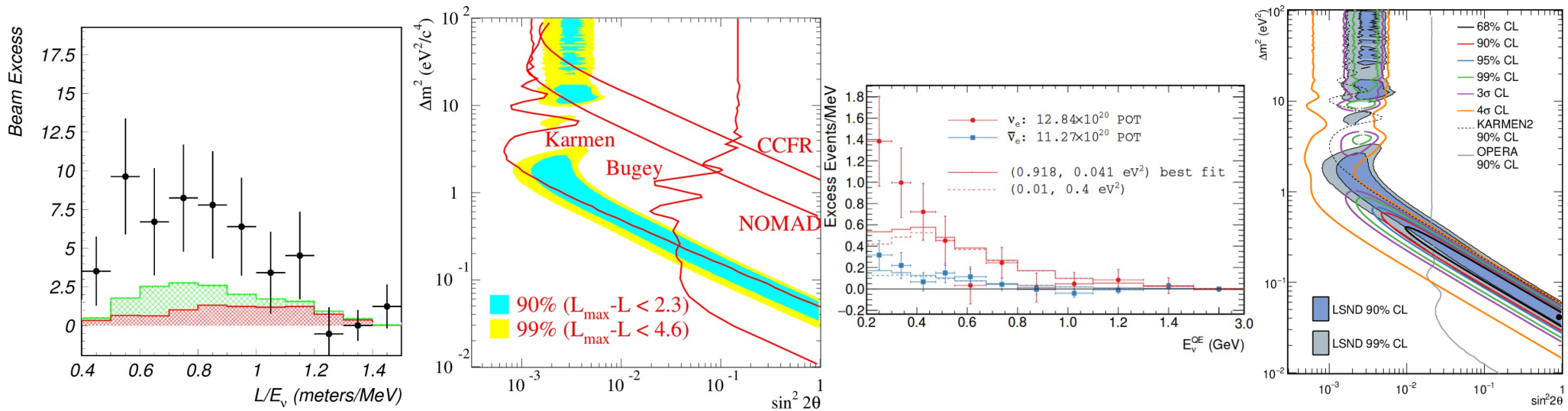


Broad neutrinos!

Giunti, Ternes, 2312.00565, PLB 2024

LSND and MiniBooNE

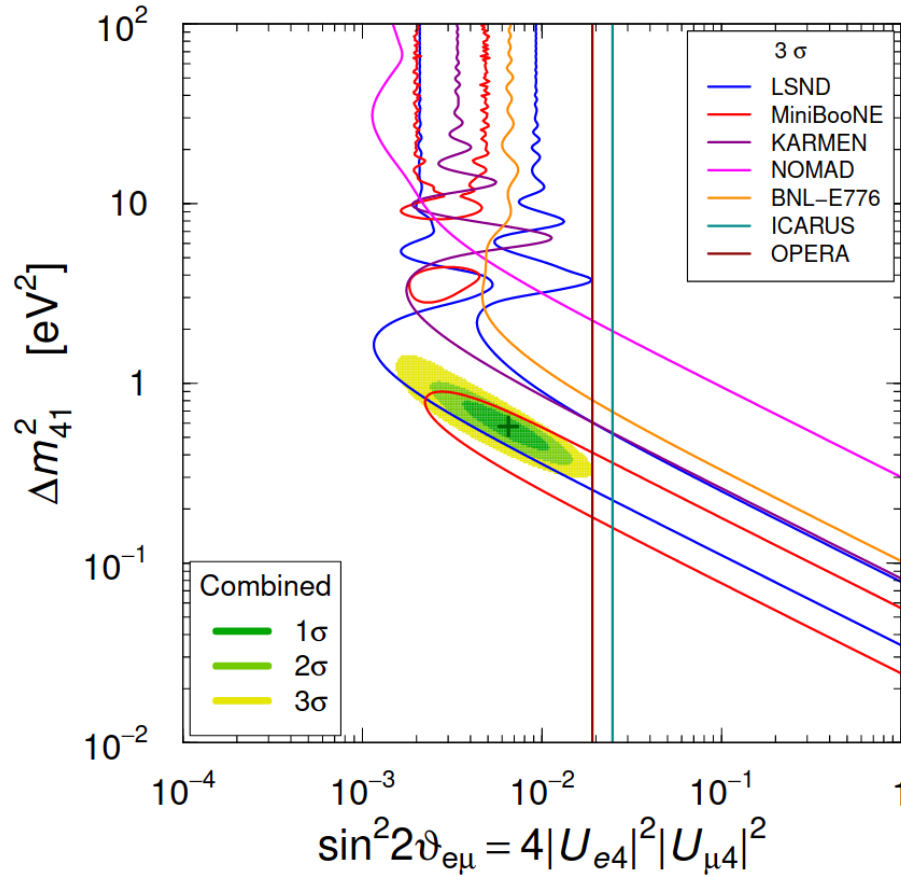
LSND saw an excess of electron neutrinos in an muon neutrino beam
MiniBooNE confirmed this observation!



LSND, hep-ex/0104049, PRD 2001

MiniBooNE, 1805.12028, PRL 2018

Appearance results



Strong preference in appearance channel

The best fit value of MiniBooNE is excluded by Icarus and Opera

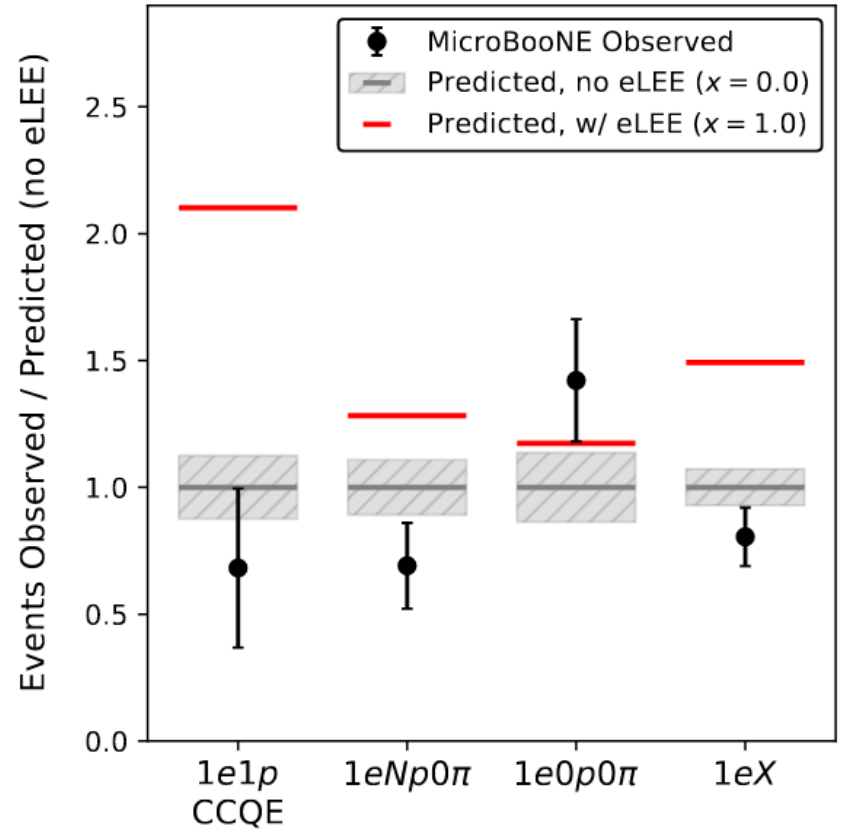
LSND and MiniBooNE only partially agree

Giunti, Lasserre, 1901.08330, Ann.Rev. 2019

MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels



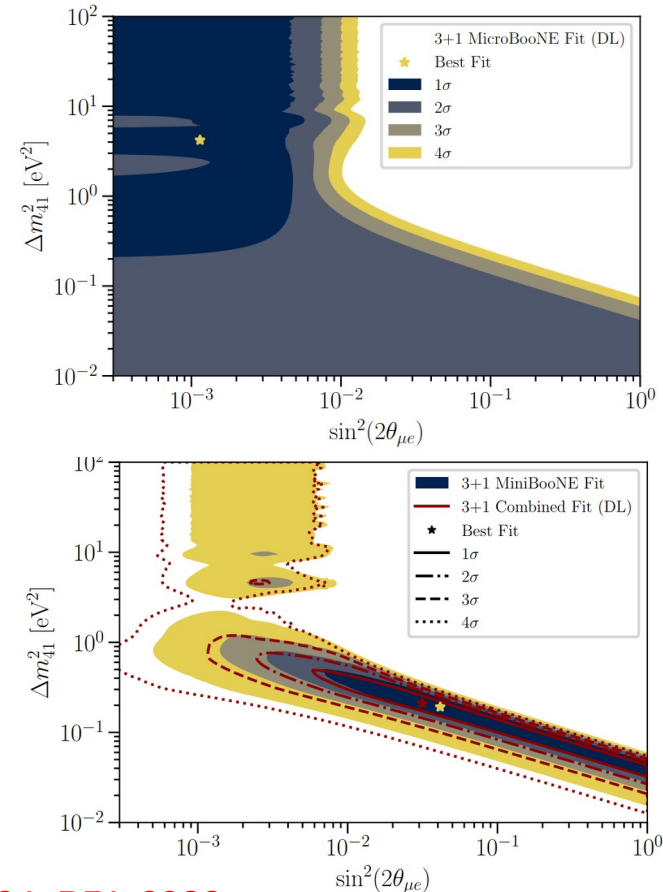
MicroBooNE, 2110.14054, PRL 2022

MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels

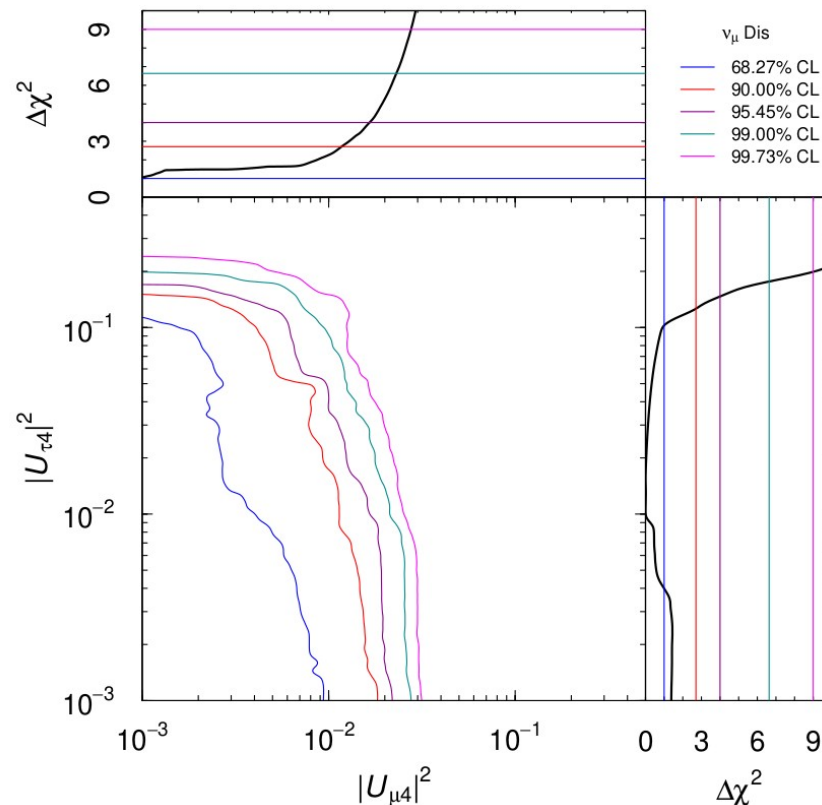
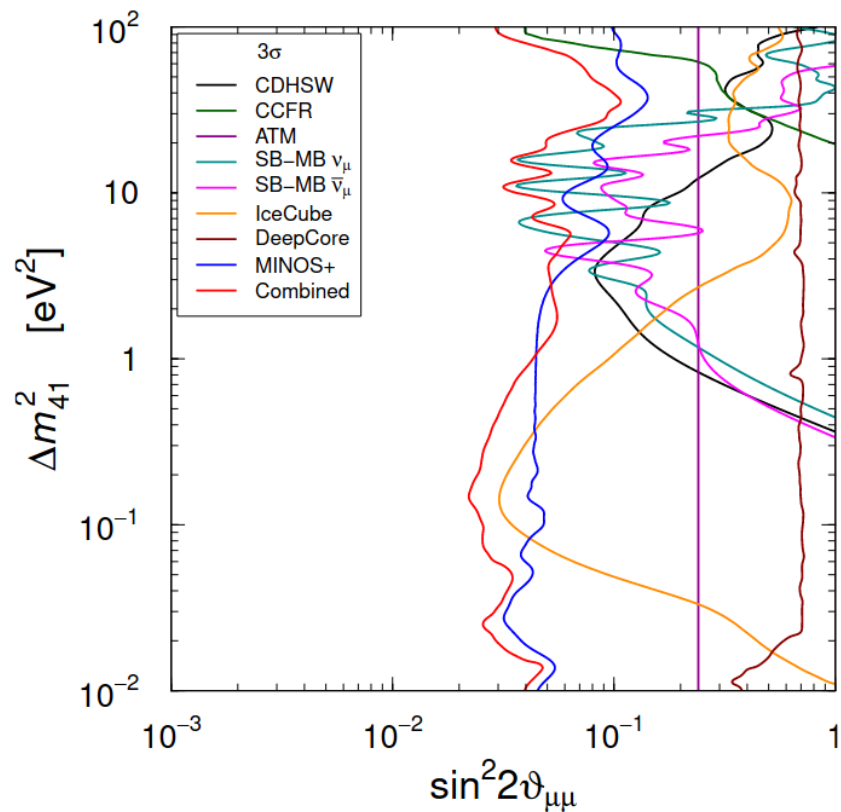
A combined analysis shows that MicroBooNE can not exclude the region of parameter space preferred by MiniBooNE



MiniBooNE, 2201.01724, PRL 2022

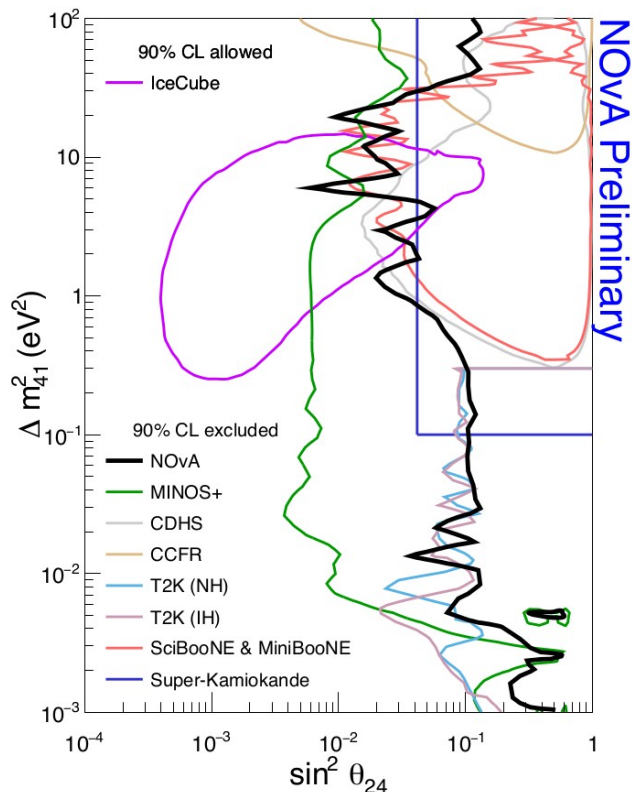
Accelerator and atmospheric experiments

No evidence in muon disappearance

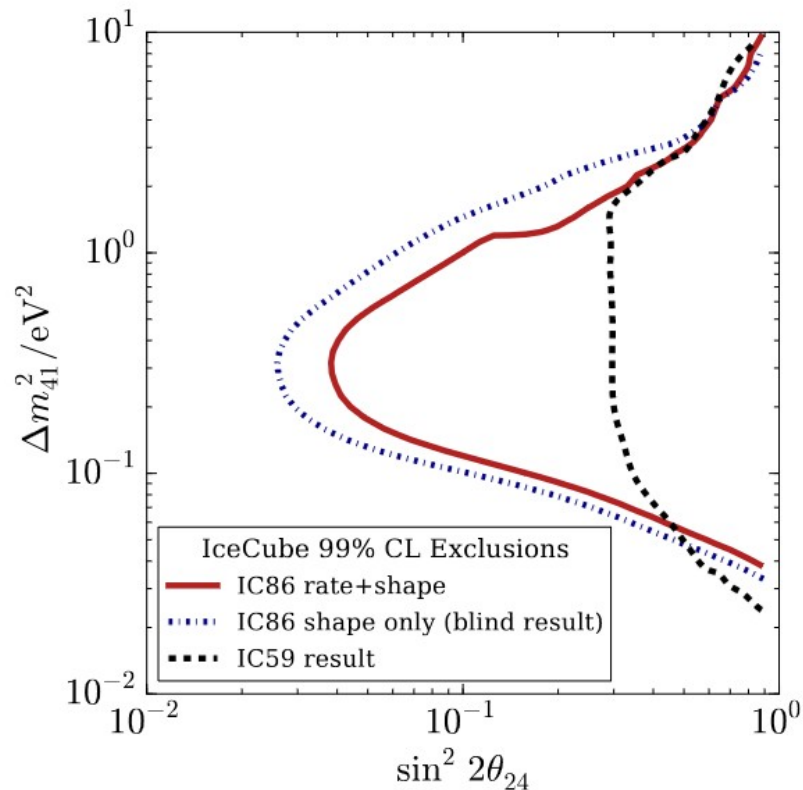


Accelerator and atmospheric experiments

No evidence in muon disappearance



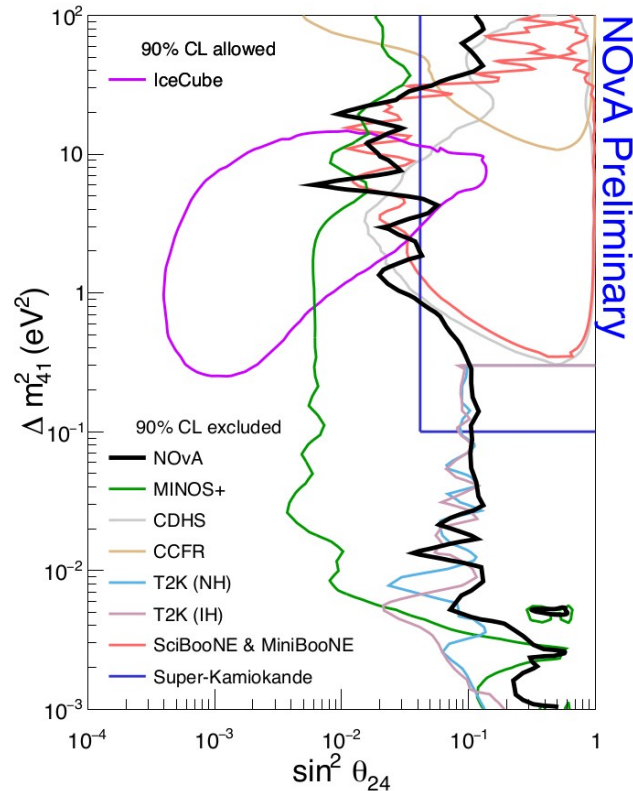
NOvA, Talk by Jeff Hartnell, Neutrino 2022



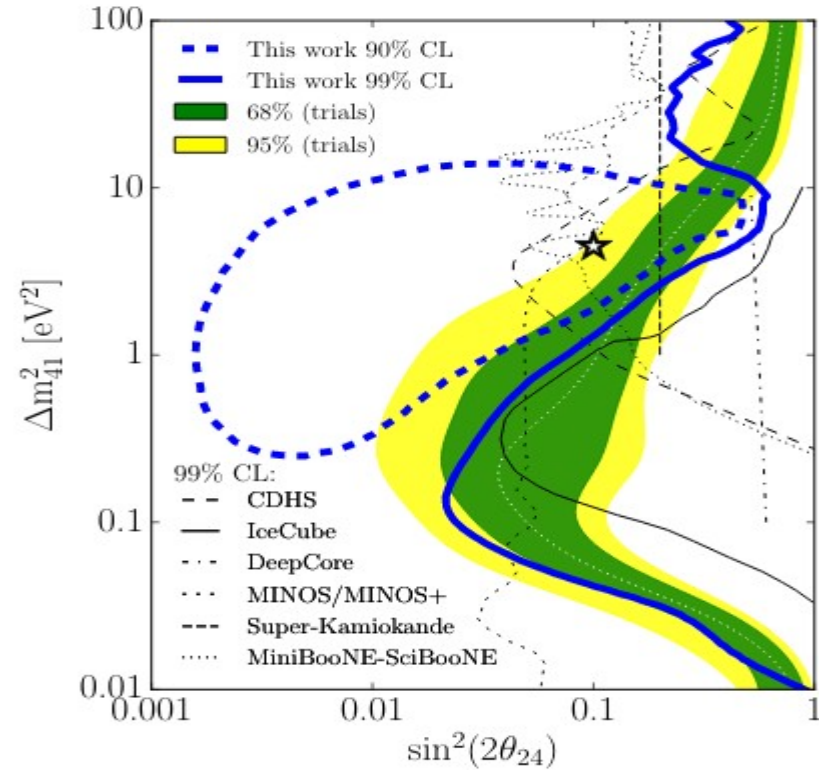
IceCube, 1605.01990, PRL 2016

Accelerator and atmospheric experiments

No evidence in muon disappearance



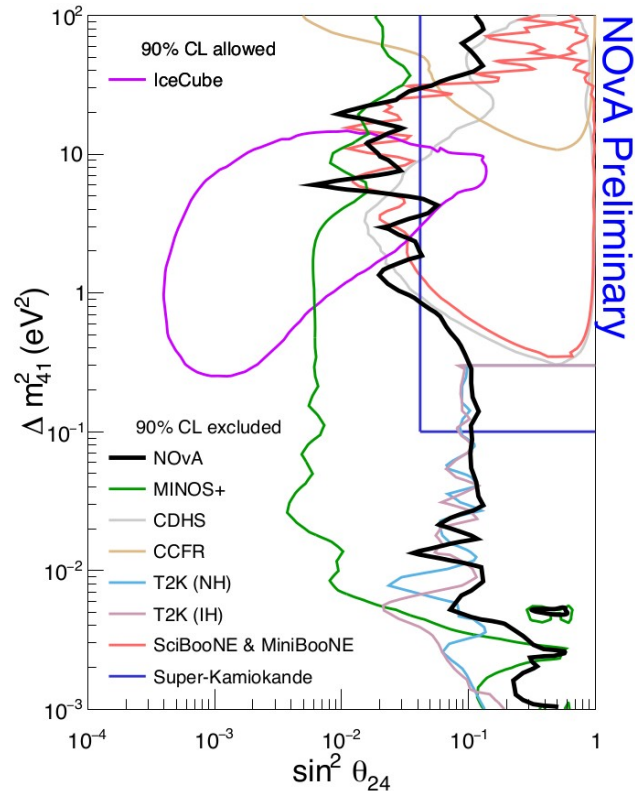
NOvA, Talk by Jeff Hartnell, Neutrino 2022



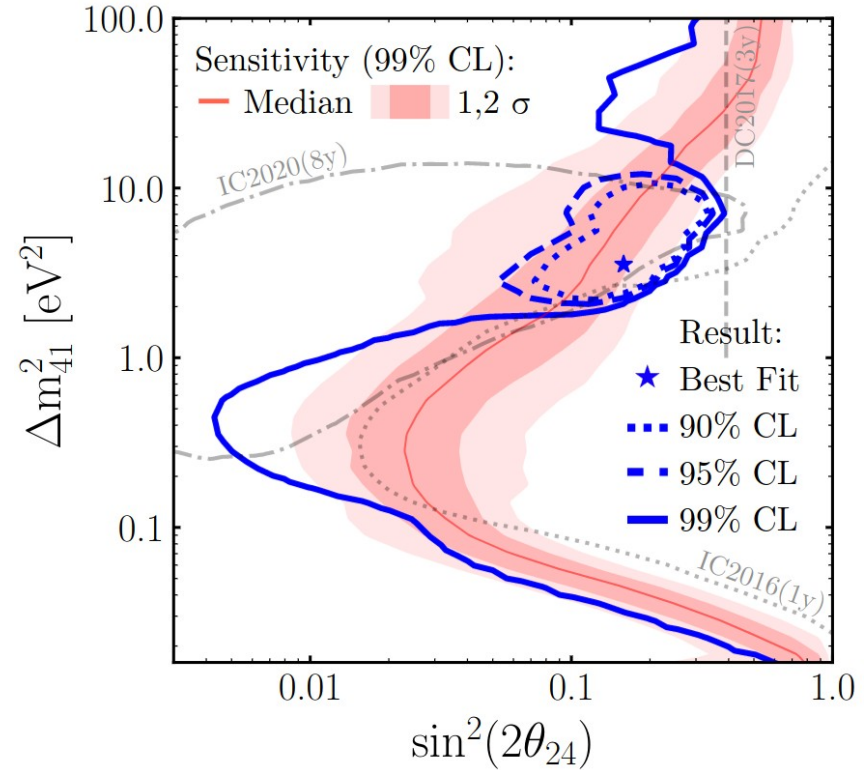
IceCube, 2005.12942, PRL 2020

Accelerator and atmospheric experiments

Hmm....

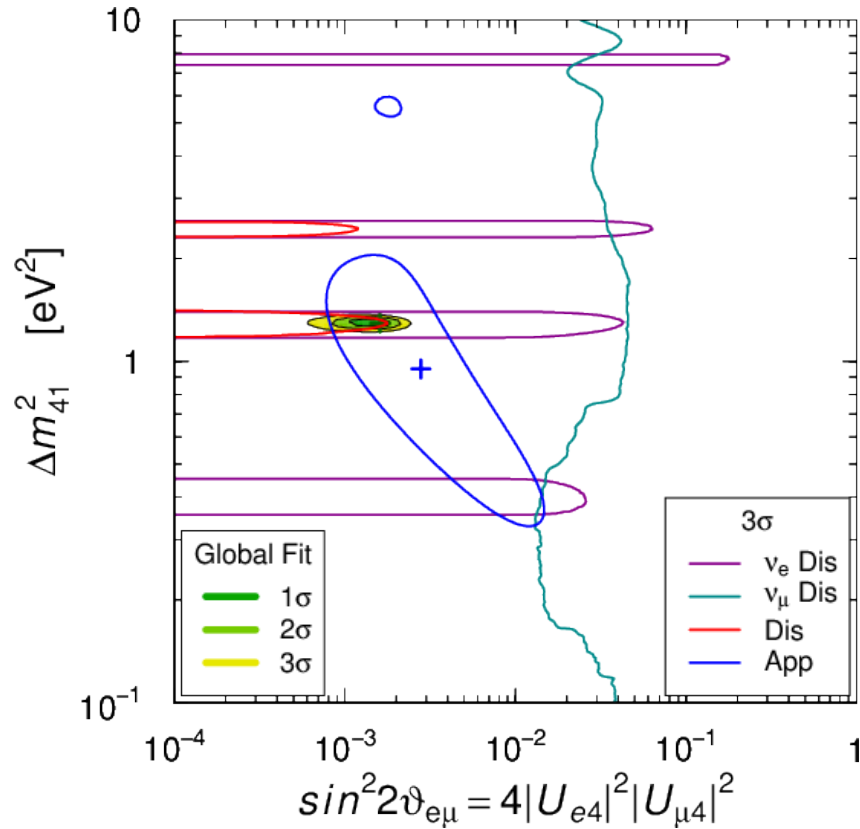


NOvA, Talk by Jeff Hartnell, Neutrino 2022



IceCube, 2405.08070

Global fit?



$$\nu_e \rightarrow \nu_e : |U_{e4}|^2 = \sin^2 \theta_{14}$$

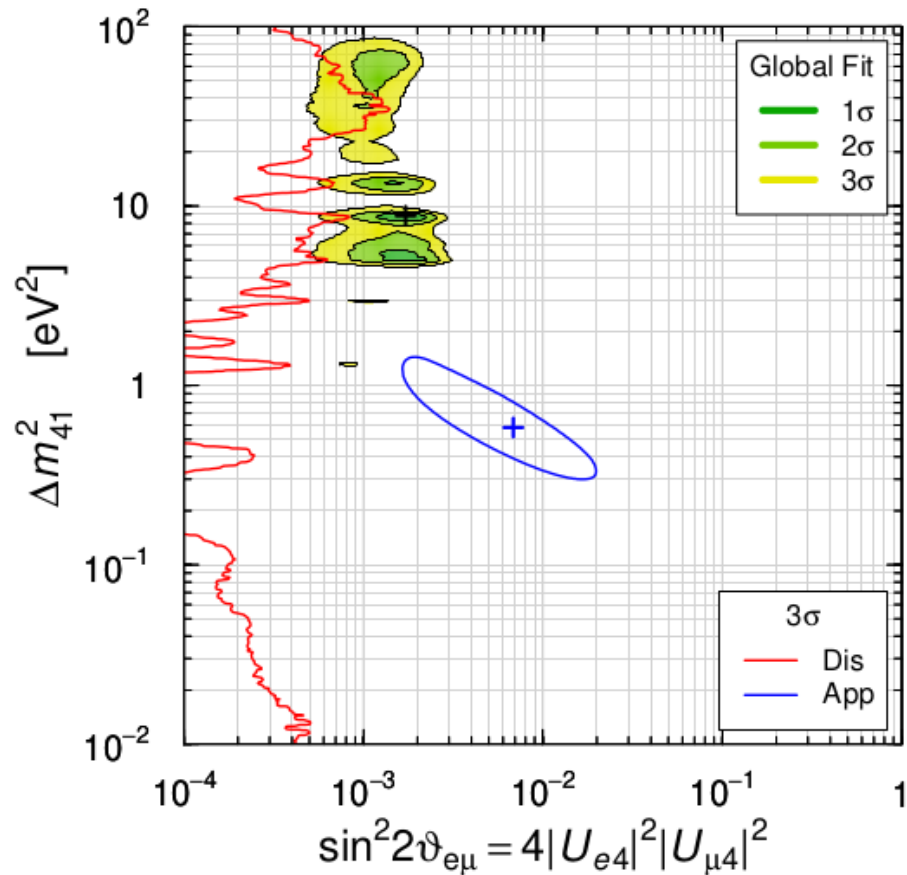
$$\nu_\mu \rightarrow \nu_\mu : |U_{\mu4}|^2 = \sin^2 \theta_{24} \cos^2 \theta_{14}$$

$$\nu_\mu \rightarrow \nu_e : \sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2|U_{\mu4}|^2$$

Gariazzo, Giunti, Laveder, Li, 1703.00860, JHEP 2017

See also: Dentler, et al,
1803.10661, JHEP 1808

Global fit?



NOT most up-to-date data here!

No overlap anymore!

$$\text{GoF}_{\text{PG}} = 7 \times 10^{-11}$$

Global 3+1 fit is unacceptable!

Conclusions

The 3+1 explanation to the Gallium anomaly is in strong tension with the analysis of data of all other classes of experiments

RAA might be resolved for newer flux models

Neutrino-4 preference doubtful, but other ratio experiment find a preference for SBL oscillations, too

First MicroBooNE data do not confirm the MiniBooNE excess (but can not rule it out either)

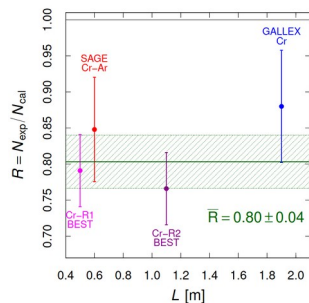
No (significant) signal in atmospheric or accelerator experiments

A global 3+1 fit is statistically not acceptable

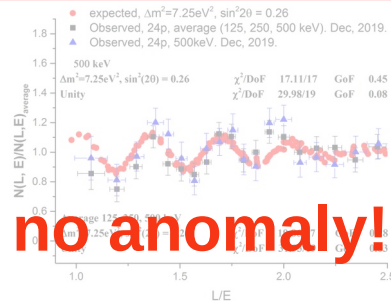
More data is needed to clarify open issues

Anomalous AND also Null results have to be checked

Gallium
UNSOLVED!



Neutrino-4
Possibly no anomaly!

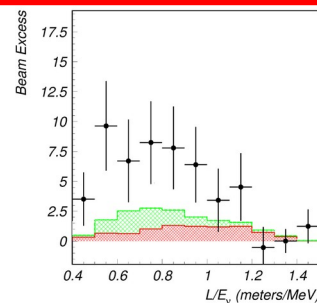


RAA

Possibly solved!

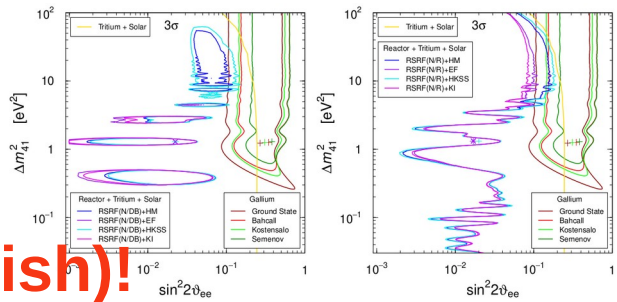


LSND
UNSOLVED!

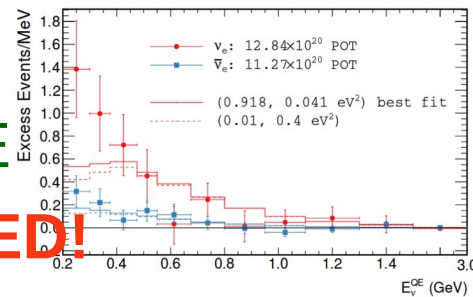


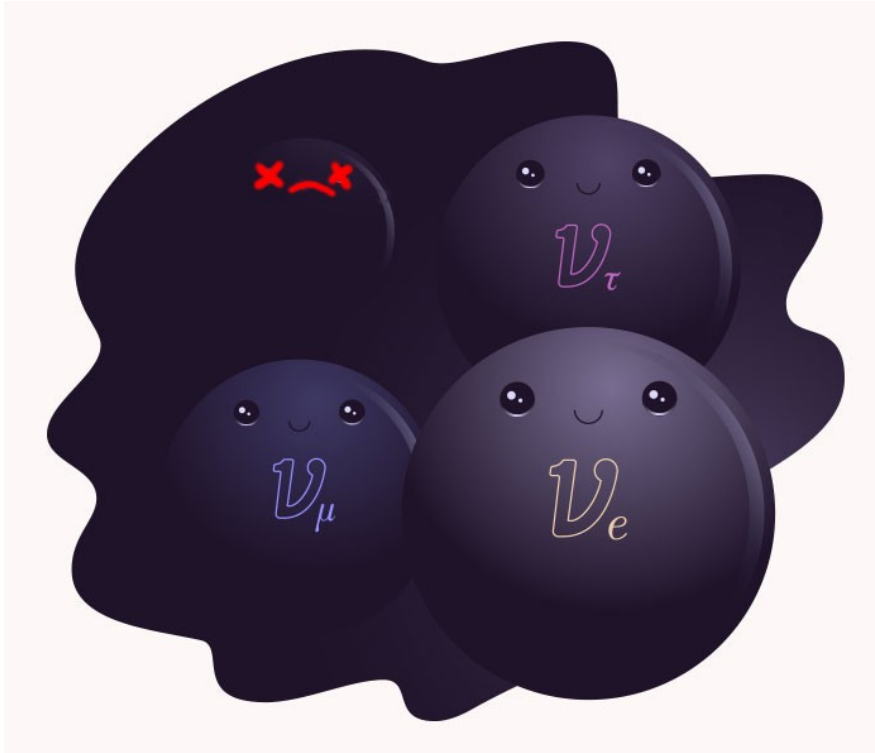
Ratio

NEW(ish)!



MiniBooNE
UNSOLVED!

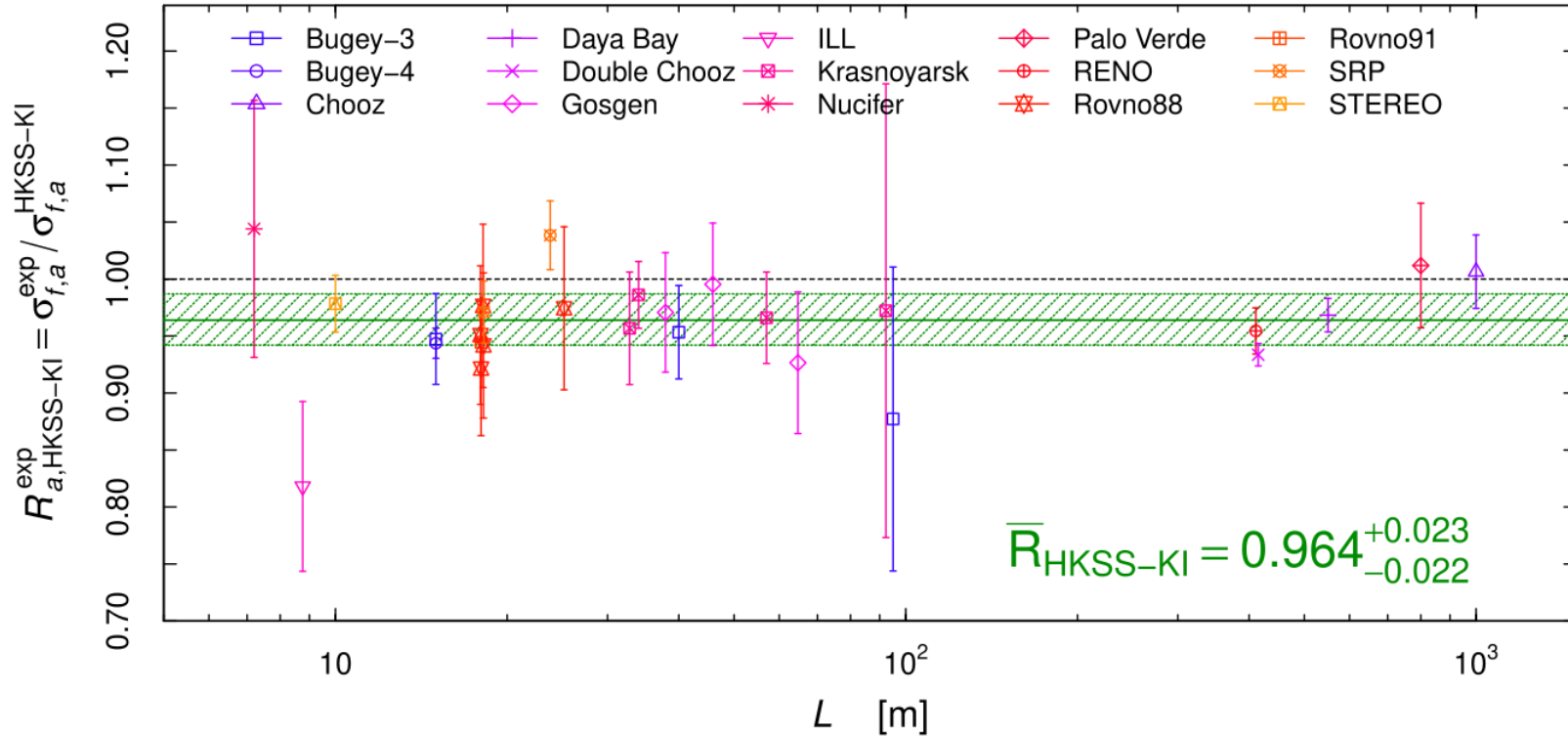




Thanks!

2021 combining HKSS and KI

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

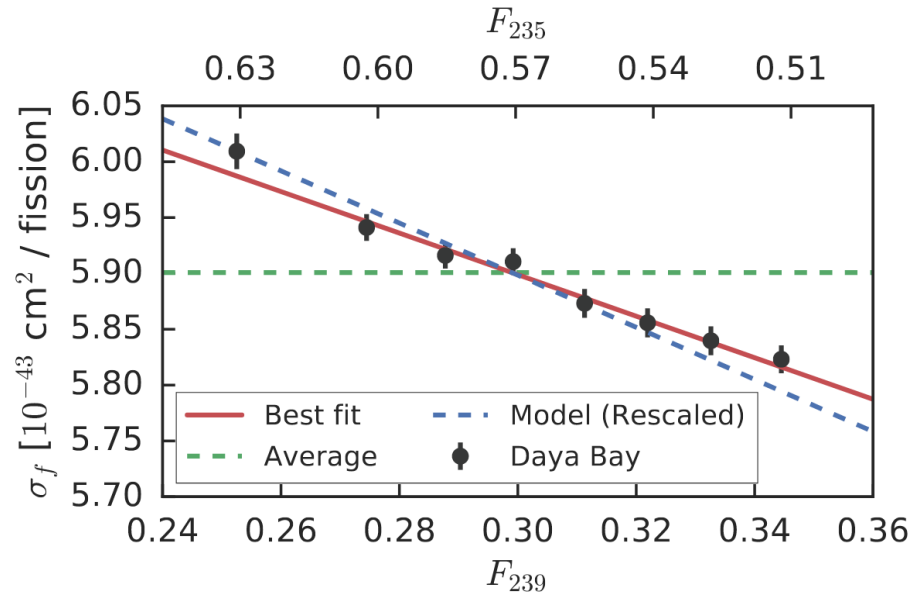


No anomaly (1.5σ) with HKSS-KI flux!

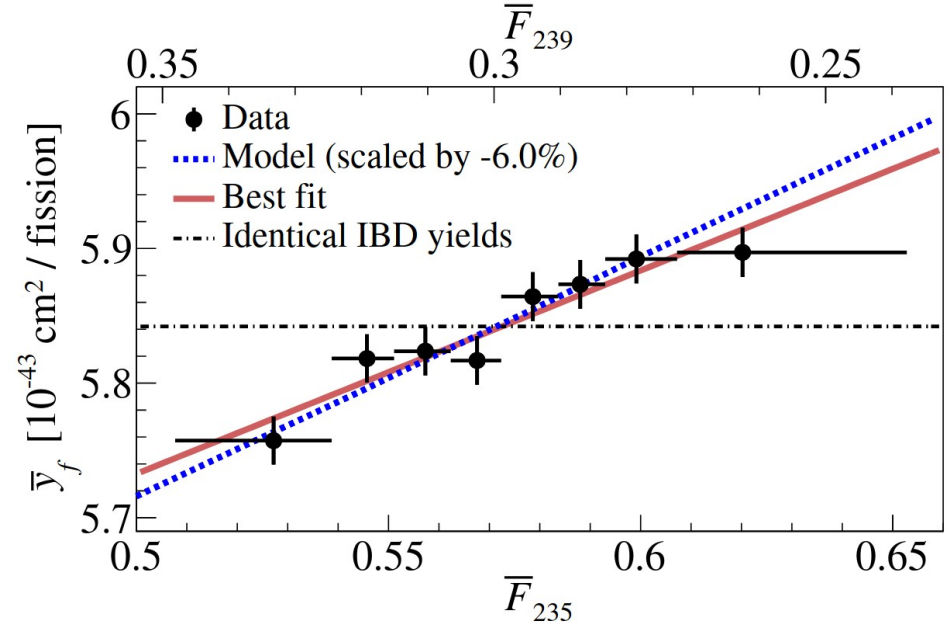
Evolution data

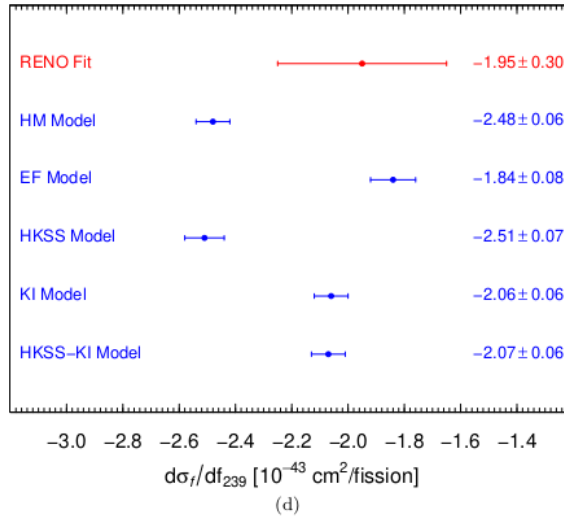
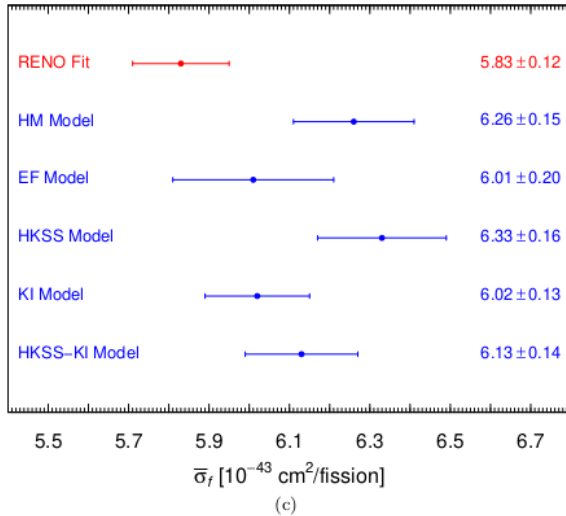
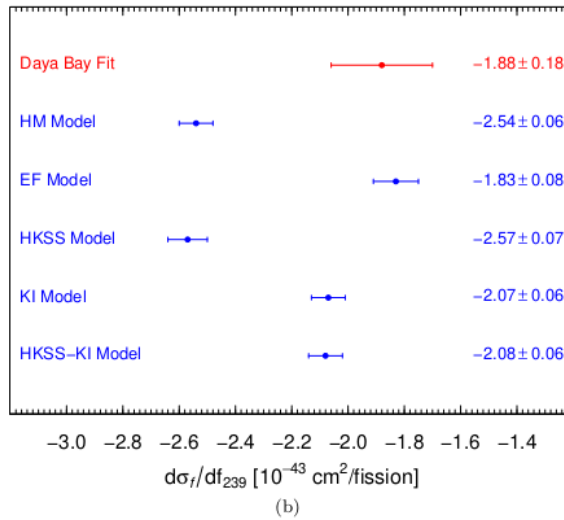
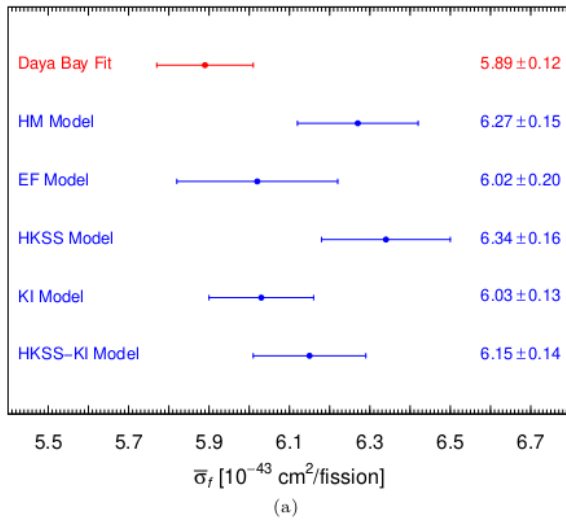
Measure rates at different stages of reactor cycle

Daya Bay, 1704.01082, PRL 2017



RENO, 1806.00574, PRL 2019





Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

We get additional information from the measurement of the slope parameter

Evolution data

Effect of evolution data on RAA

Model	Rates		Evolution		Rates + Evolution	
	\bar{R}_{mod}	RAA	\bar{R}_{mod}	RAA	\bar{R}_{mod}	RAA
HM	$0.936^{+0.024}_{-0.023}$	2.5σ	$0.933^{+0.025}_{-0.024}$	2.6σ	$0.930^{+0.024}_{-0.023}$	2.8σ
EF	$0.960^{+0.033}_{-0.031}$	1.2σ	$0.975^{+0.032}_{-0.030}$	0.8σ	$0.975^{+0.032}_{-0.030}$	0.8σ
HKSS	$0.925^{+0.025}_{-0.023}$	2.9σ	$0.925^{+0.026}_{-0.024}$	2.8σ	$0.922^{+0.024}_{-0.023}$	3.0σ
KI	$0.975^{+0.022}_{-0.021}$	1.1σ	$0.973^{+0.023}_{-0.022}$	1.2σ	0.970 ± 0.021	1.4σ
HKSS-KI	$0.964^{+0.023}_{-0.022}$	1.5σ	$0.955^{+0.024}_{-0.023}$	1.9σ	$0.960^{+0.022}_{-0.021}$	1.8σ

Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

Best fit reactor flux model

We perform several statistical tests for the best fit flux model

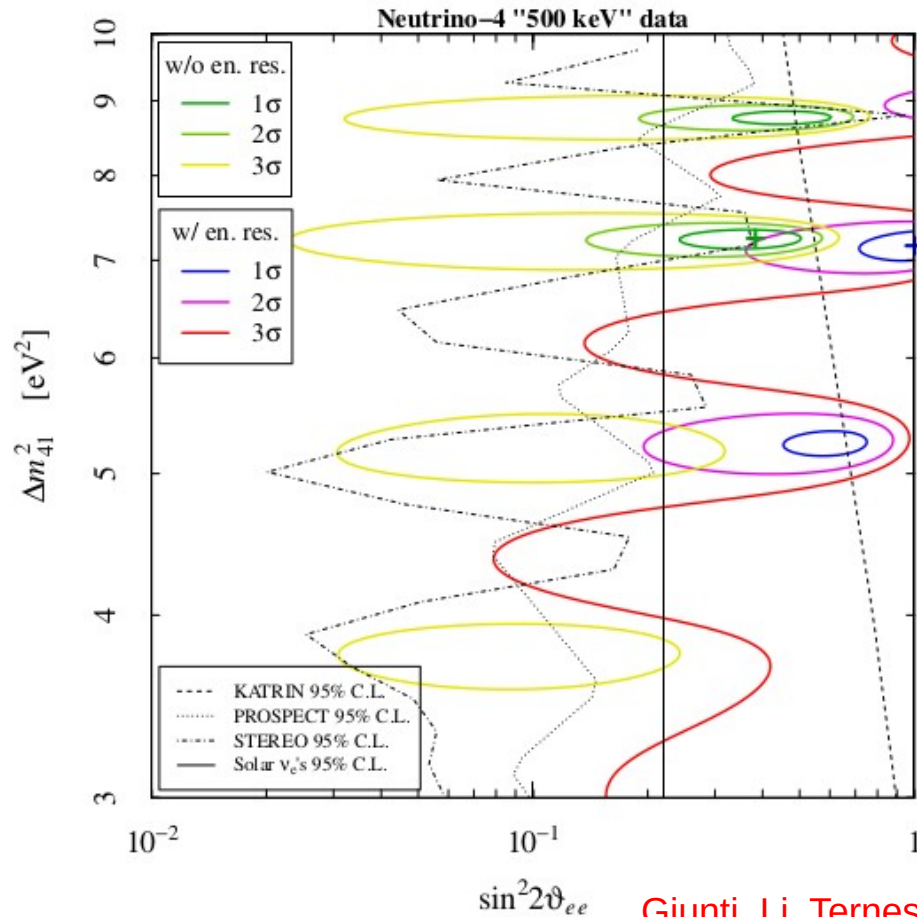
We find that the recent KI model is the best among the conversion models

The EF model is equally good as the KI model

	Rates + Evolution				
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

HM EF HKSS KI HKSS-KI

Neutrino-4



We can only reproduce Neutrino-4 confidence regions when not including energy resolution

Inclusion shifts the best fit to even larger values, but reduces the preference for sterile oscillations

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

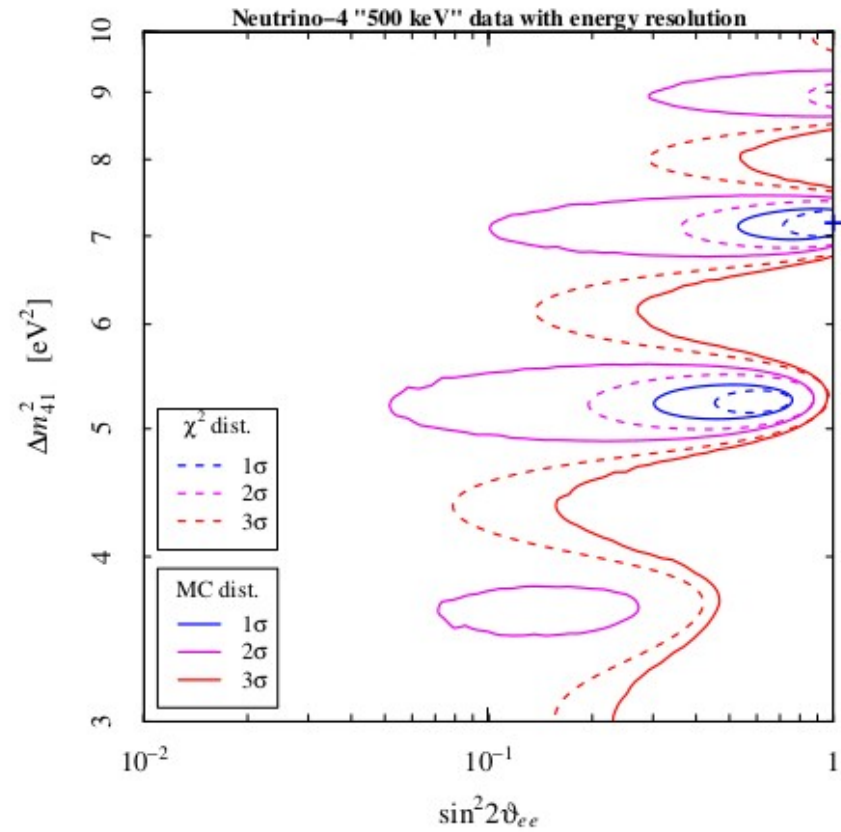
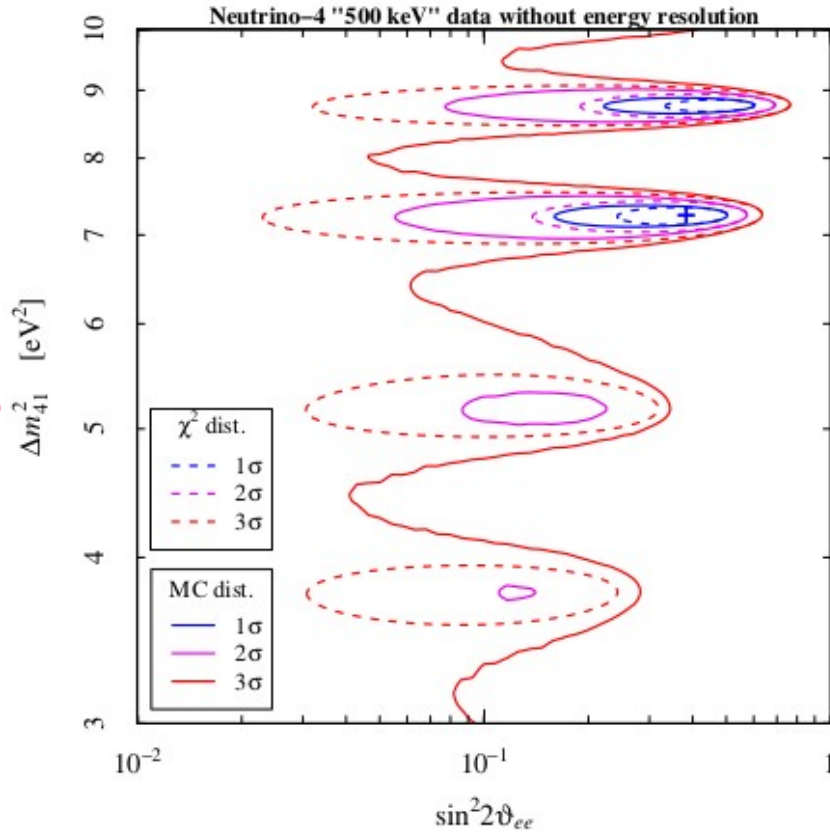
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Neutrino-4

See also: Coloma, Huber, Schwetz,
2008.06083, EPJC 2021

Monte Carlo analysis

Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021



Neutrino-4

Summary

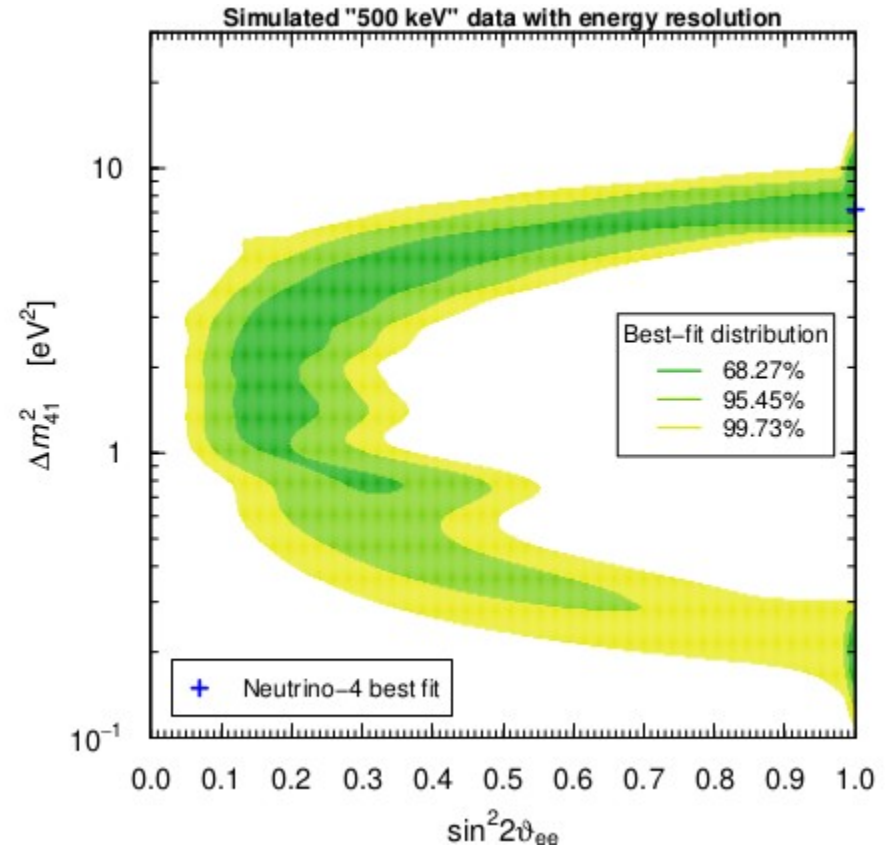
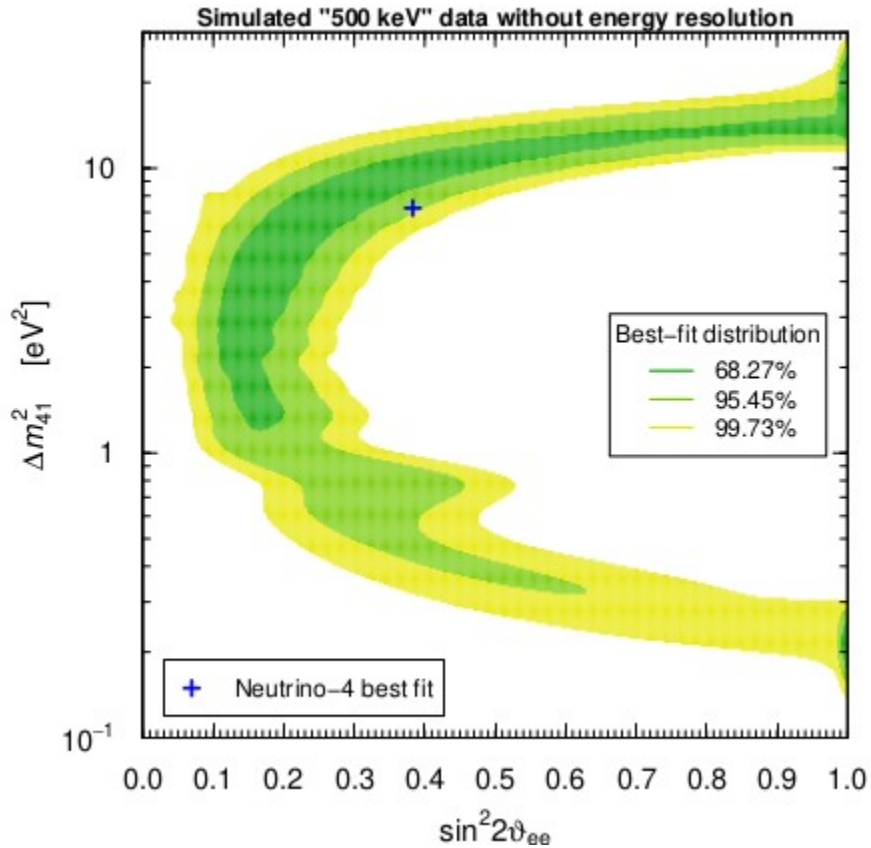
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Neutrino-4	"500 keV" data		"125-250-500 keV" data	
	without en. res.	with en. res.	without en. res.	with en. res.
χ_{\min}^2	14.9	18.2	21.9	21.1
GoF	60%	37%	19%	22%
$(\sin^2 2\vartheta_{ee})_{\text{bf}}$	0.38	1.0	0.27	0.93
$(\Delta m_{41}^2)_{\text{bf}}$	7.2	7.2	8.8	7.2
$\Delta\chi_{\text{NO}}^2$	13.1	9.8	9.9	10.7
χ^2 distribution				
p -value	0.0014	0.0075	0.0072	0.0048
σ -value	3.2	2.7	2.7	2.8
Monte Carlo distribution				
p -value	0.011	0.028	0.087	0.026
σ -value	2.5	2.2	1.7	2.2

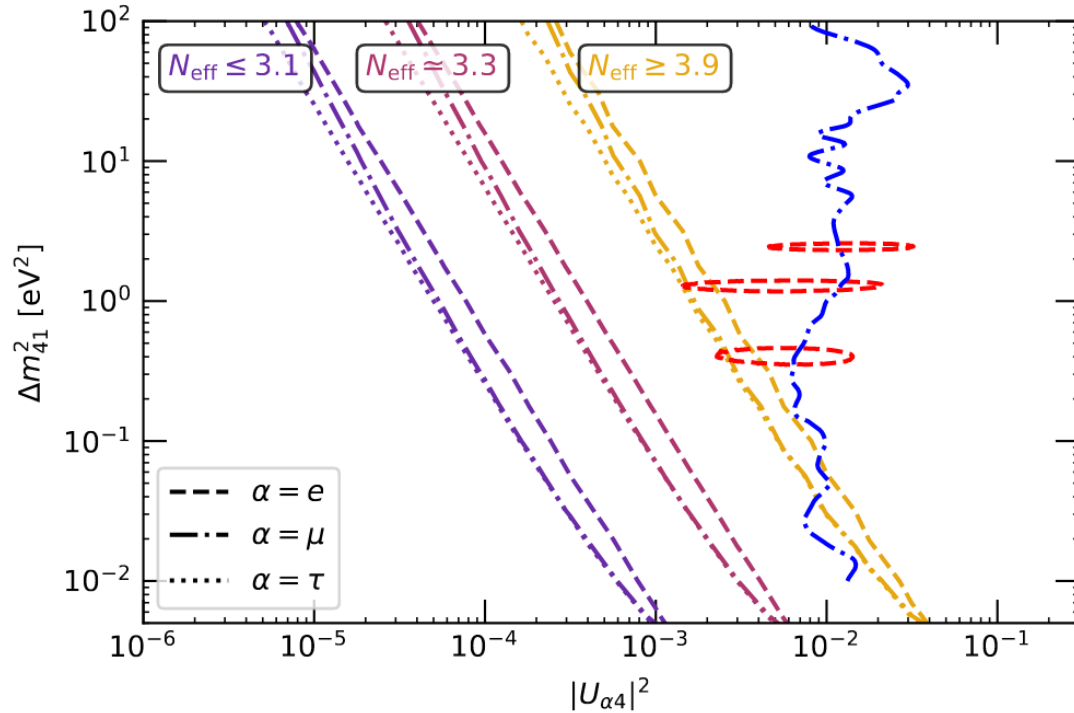
Neutrino-4

Distribution of best fit points without oscillations

Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021



Cosmology

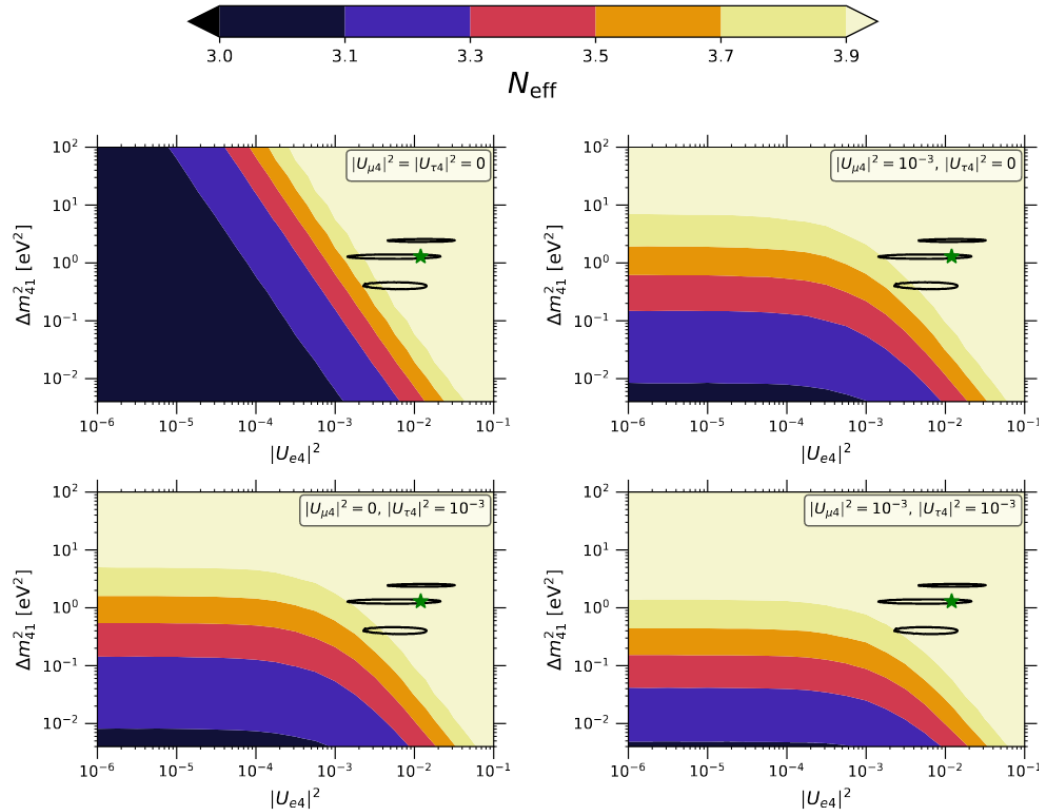


Cosmology can set strong bounds on sterile parameter space

Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

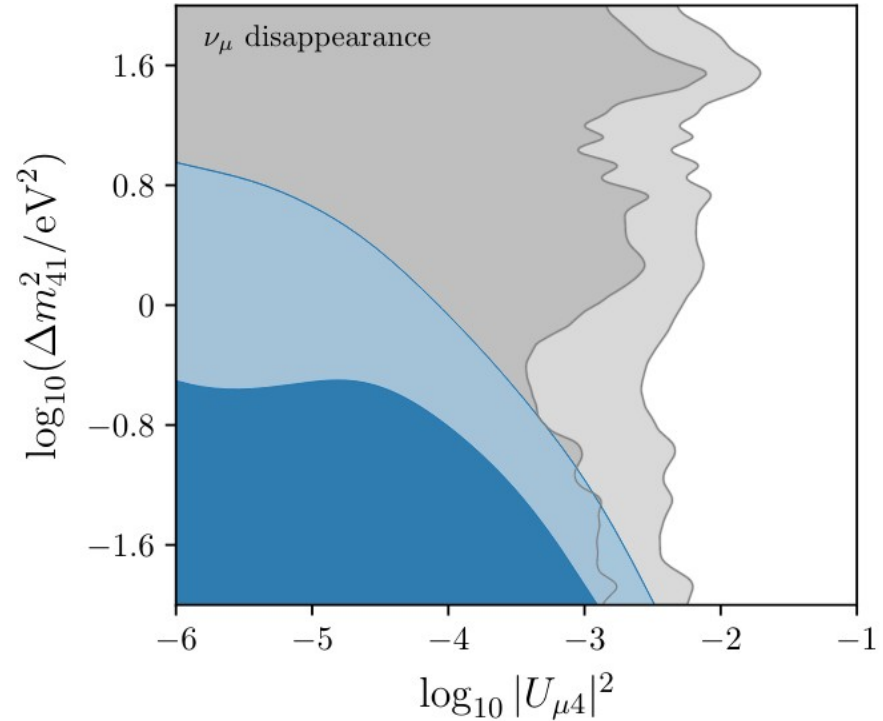
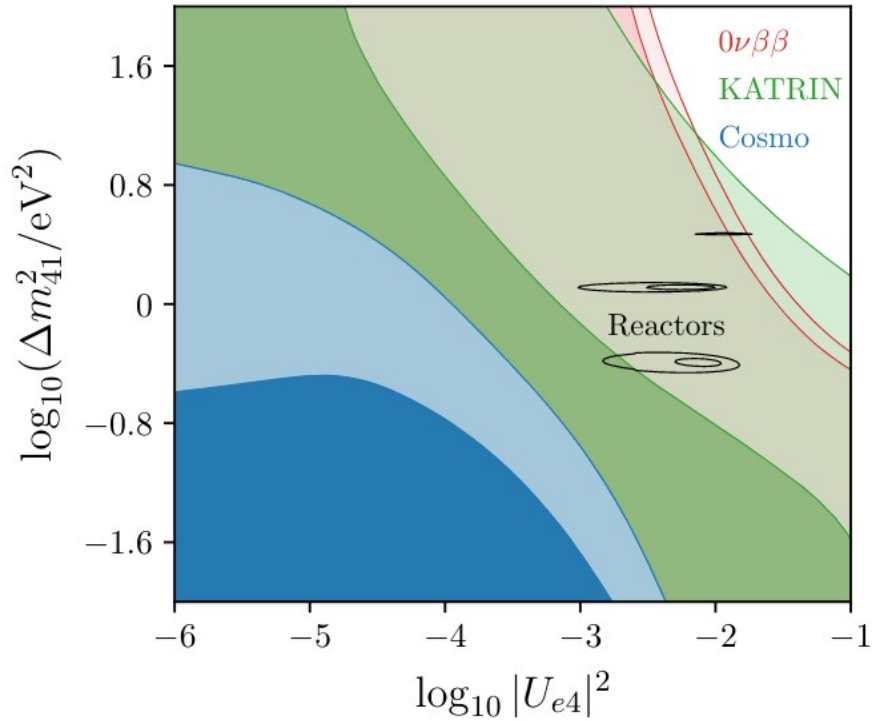
Cosmology

Cosmology can set strong bounds on sterile parameter space
Which become even stronger when considering more than one angle



Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

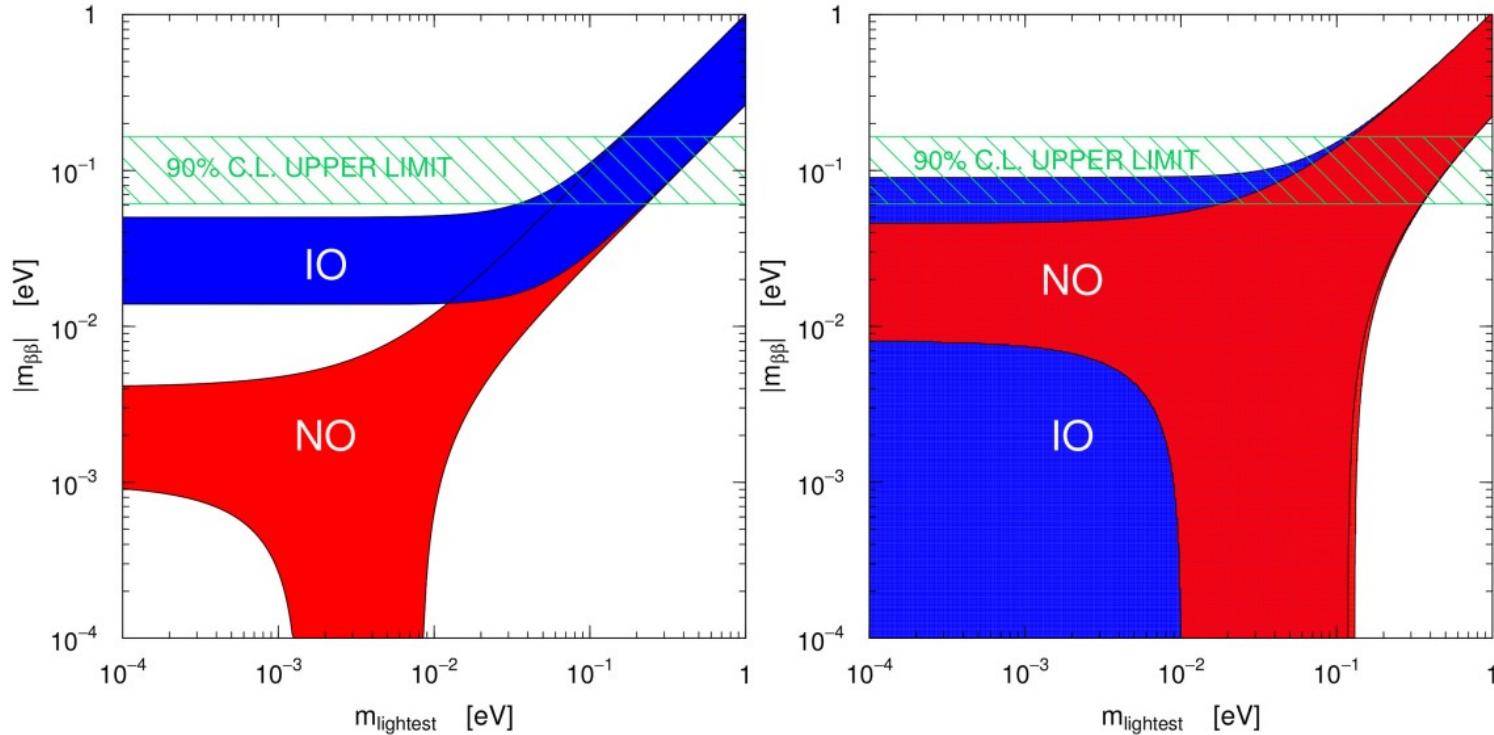
Cosmology



Complementary between Cosmology and terrestrial experiments

Hagstotz, et al, 2003.02289, PRD 2021

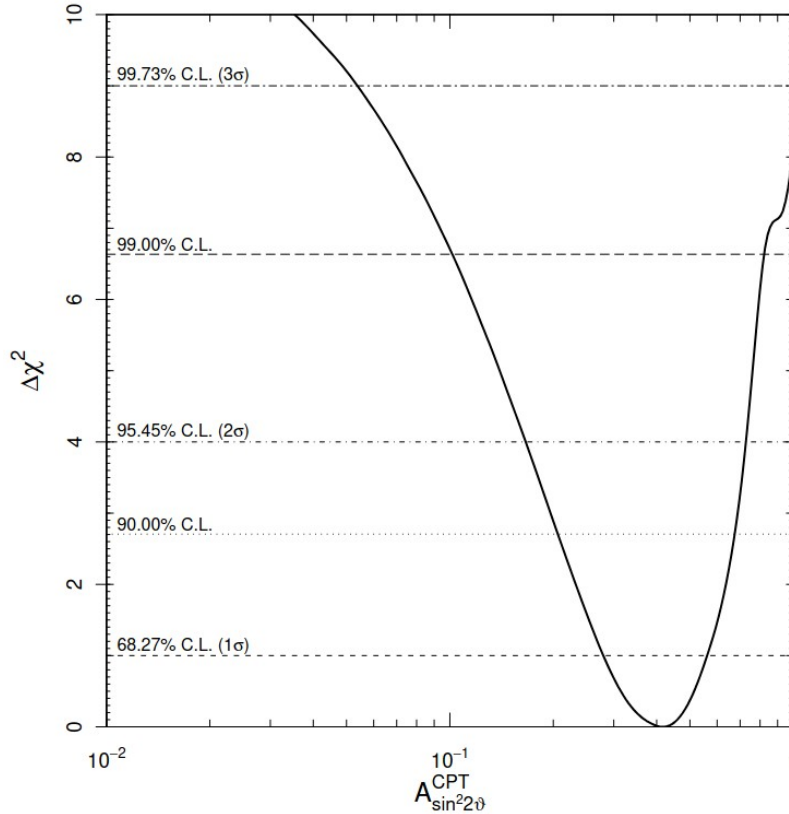
Neutrinoless $\beta\beta$ decay



De Salas, Gariazzo, Mena, Ternes, Tortola, 1806.11051, Frontiers 2018

FIGURE 7 | Effective Majorana mass as a function of the lightest neutrino mass in the three neutrino (Left) and 3+1 neutrino (Right) scenarios, at 99.7% CL, comparing normal (red) and inverted (blue) ordering of the three active neutrinos. Adapted from Giunti (2017). The green band represents the 90% CL bounds from KamLAND-Zen Gando et al. (2016), given the uncertainty on the NME.

CPT violating neutrinos?

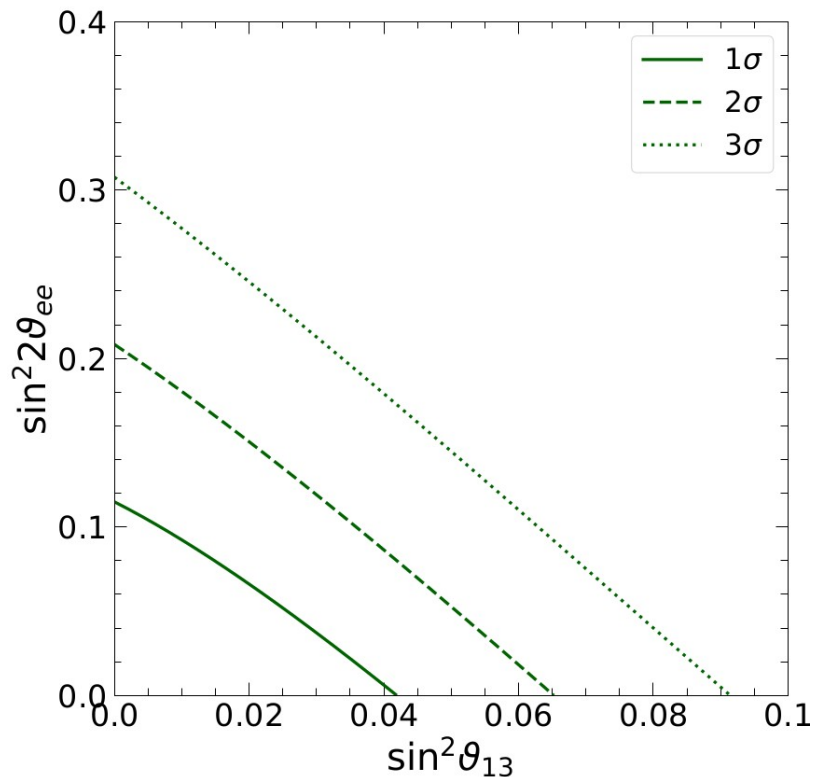


Allowing for different neutrino and antineutrino oscillation parameters could solve the tension between Reactor+Tritium data and Gallium data

$$A_{\Delta m^2}^{\text{CPT}} = \Delta m_\nu^2 - \Delta m_{\bar{\nu}}^2,$$
$$A_{\sin^2 2\theta}^{\text{CPT}} = \sin^2 2\theta_\nu - \sin^2 2\theta_{\bar{\nu}}$$

Giunti, Laveder, 1008.4750, PRD 2010

CPT violating neutrinos?



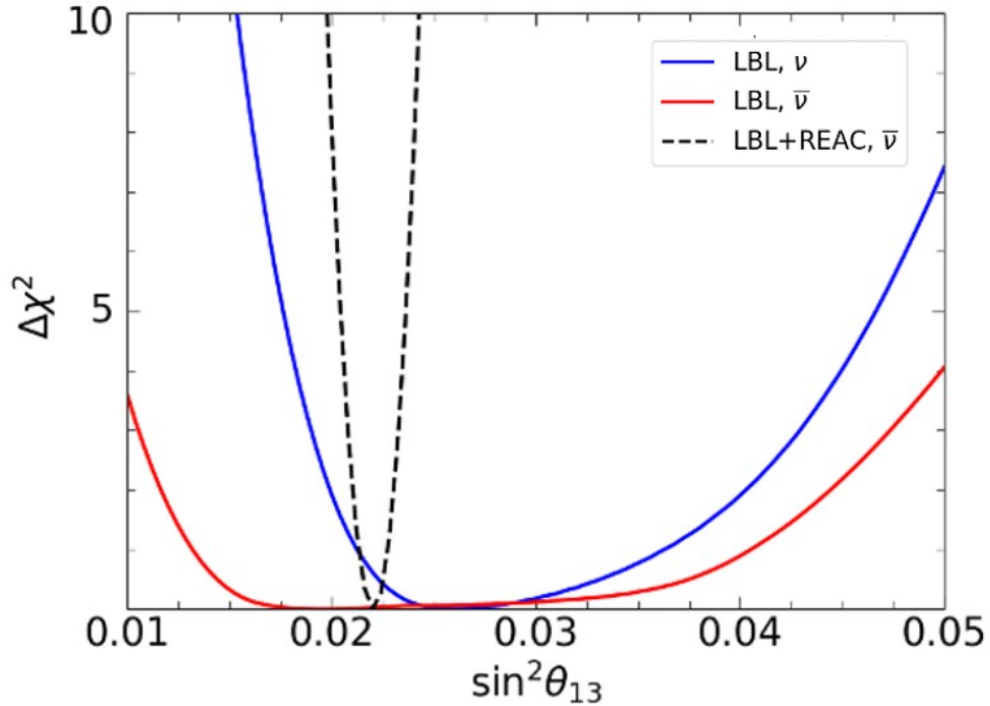
Solar experiments measure neutrinos, not antineutrinos!

Solar bound is relaxed when leaving reactor angle free!

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

See also: Goldhagen, Maltoni, Reichert, Schwetz, 2109.14898, EPJC 2022

CPT violating neutrinos?



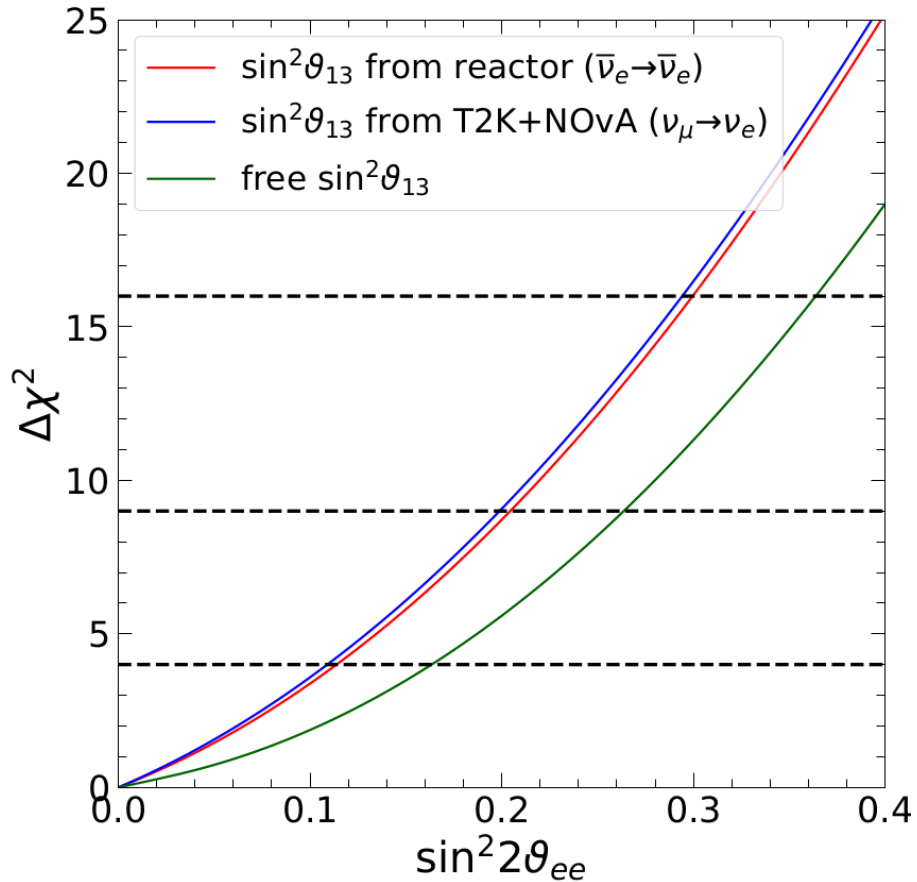
Solar experiments measure neutrinos, not antineutrinos!

Solar bound is relaxed when leaving reactor angle free!

However, data from NOvA and T2K are able to bound the neutrino angle now, too.

Barenboim, Ternes, Tortola, 2005.05975, JHEP 2020

No CPT violating neutrinos

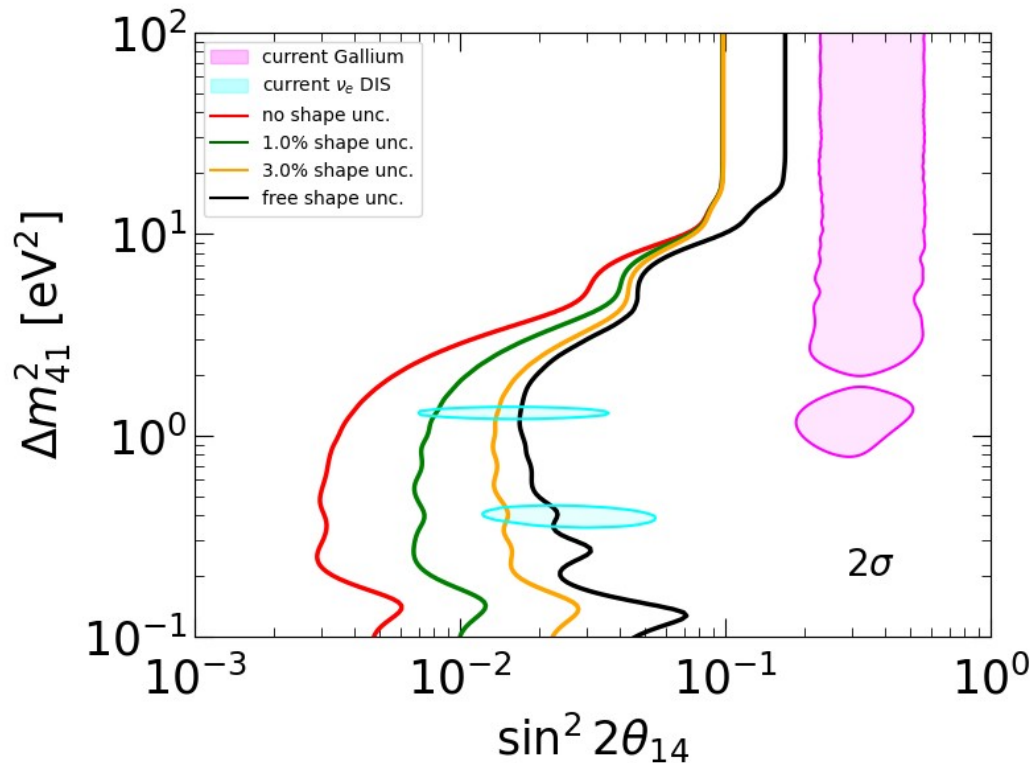


Using the newest solar data the CPT violating explanation is not viable anymore

	Solar-only		S+ ϑ_{13} (T&N)		S+ ϑ_{13} (R)	
	$\Delta\chi_{\text{PG}}^2$	GoF _{PG}	$\Delta\chi_{\text{PG}}^2$	GoF _{PG}	$\Delta\chi_{\text{PG}}^2$	GoF _{PG}
Ground State	7.31	2.6%	10.65	0.49%	10.32	0.57%
Bahcall	10.30	0.58%	14.14	0.085%	13.78	0.1%
Kostensalo	9.03	1.1%	12.79	0.17%	12.43	0.2%
Semenov	12.70	0.17%	17.24	0.018%	16.83	0.022%

Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Anomalies can be tested in future experiments



Next generation reactor
JUNO+TAO

Depending on the uncertainty of the shape of the flux JUNO and TAO would be able to fully test the preferred regions from current ratio analyses

Figure adapted from
Basto-Gonzalez, Forero, Giunti, Quiroga, Ternes,
2112.00379, PRD 2022

Anomalies can be tested in future experiments

Uncertainty	Opt.	Def.	Con.
Fiducial volume ND	0.2%	0.5%	1%
Fiducial volume FD	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%
Flux error background ν	10%	15%	20%
Flux error signal $\bar{\nu}$	10%	15%	20%
Flux error background $\bar{\nu}$	20%	30%	40%
NC background	5%	7.5%	10%
CC cross section	10%	15%	20%
NC cross section	10%	15%	20%
ν_e/ν_μ ratio	3.5%	11%	22%
$\nu/\bar{\nu}$ ratio	3.5%	11%	22%

We also studied the sensitivity at the European Spallation Source Neutrino Super Beam experiment for several choices of uncertainties

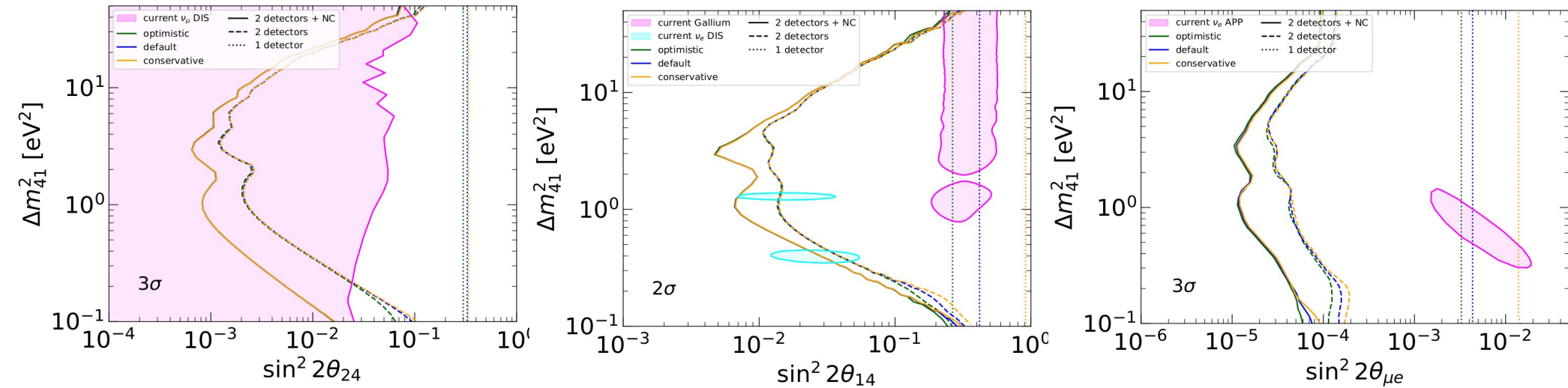
Advantage: All channels can be testes simultaneously at ESSvSB

See also: Dieminger, et al, 2301.08065

Capozzi, Giunti, Ternes, 2302.07154, JHEP 2023

Anomalies can be tested in future experiments

Capozzi, Giunti, Ternes, 2302.07154, JHEP 2023



Sterile neutrino explanation can be tested at ESSvSB