Neutrino anomalies and future prospects in neutrino physics

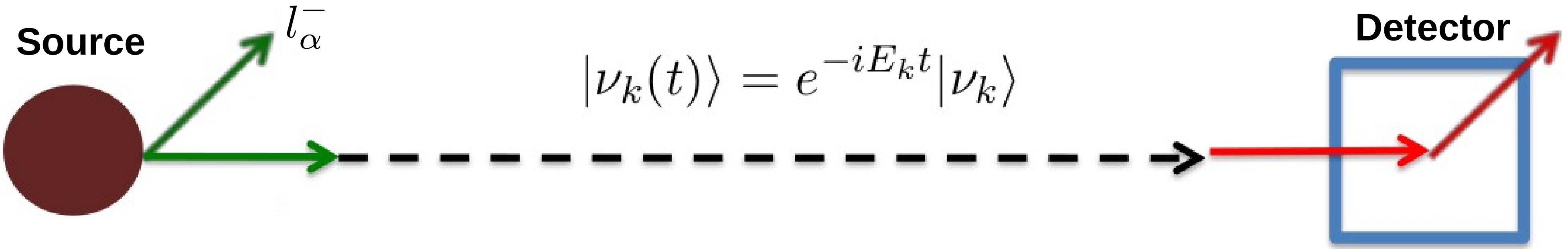
Christoph Andreas Ternes

La Thuile 2023
Les Rencontres de Physique de la Vallée d'Aoste
March 7th 2023

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

UNIVERSITÀ DI TORINO

Neutrino oscillations



$$|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$$

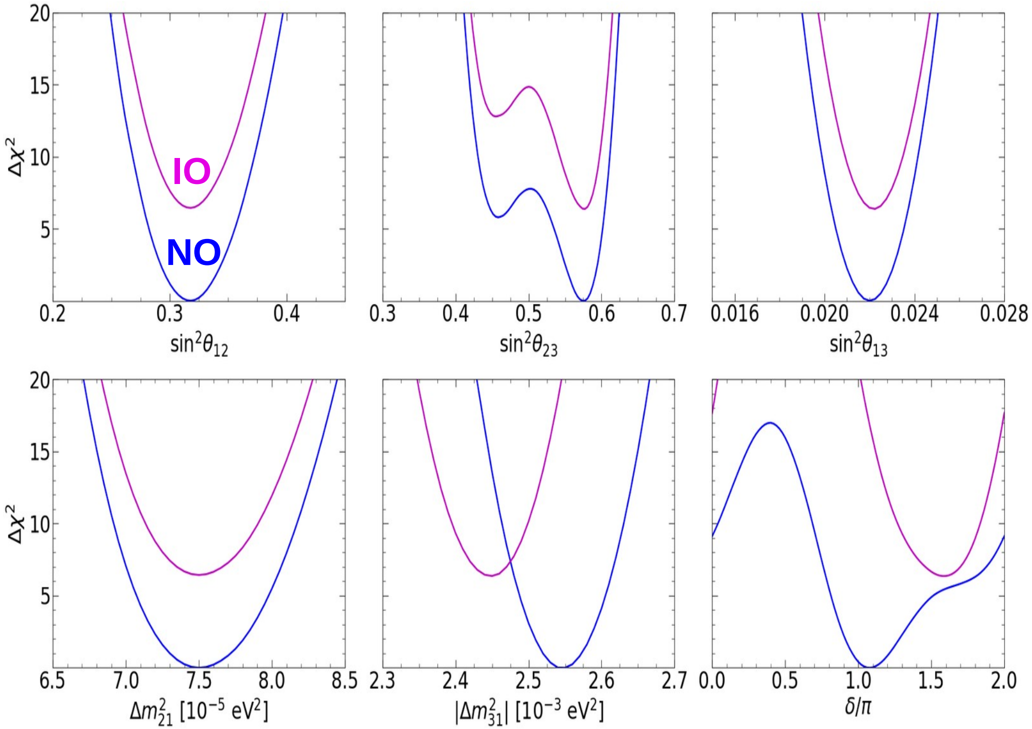
$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle$$

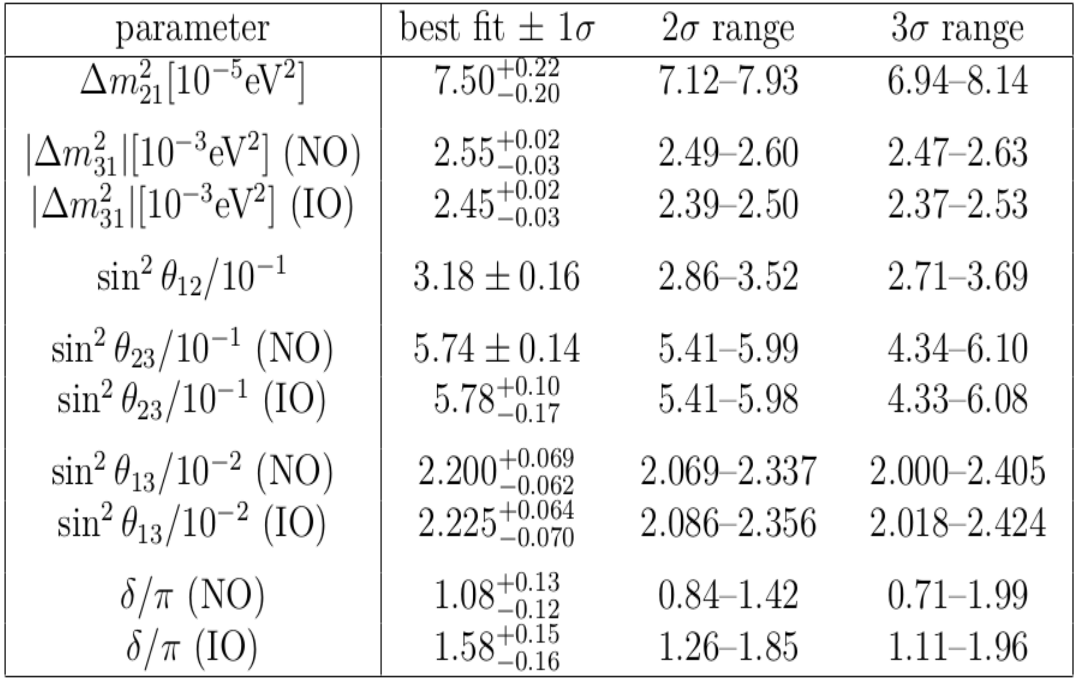
$$\langle\nu_\beta|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^* U_{\beta k} e^{-iE_k t}$$

$$P_{\nu_\alpha\to\nu_\beta}(t) = \left|A_{\nu_\alpha\to\nu_\beta}(t)\right|^2 = \sum_{k,j} U_{\alpha k}^*\, U_{\beta k}\, U_{\alpha j}\, U_{\beta j}^*\, e^{-i(E_k-E_j)t}$$

Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021





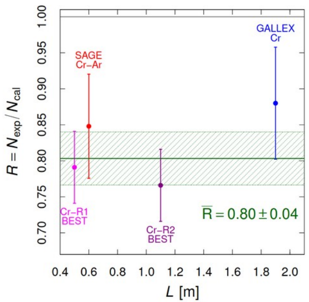
parameter	best fit ± 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	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

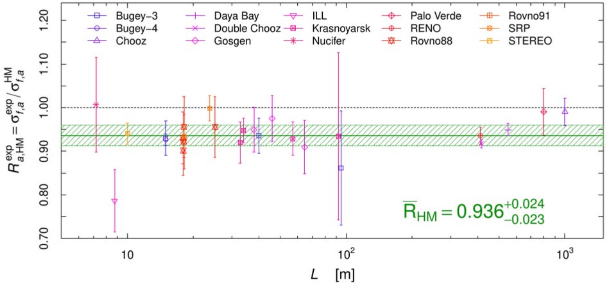
See also:
NuFit - 2111.03086, Universe 2021

Anomalies

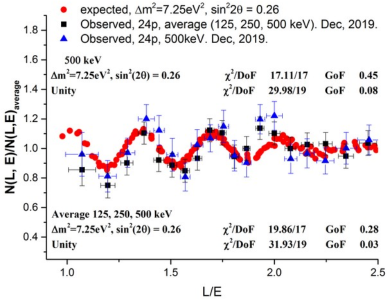
Gallium



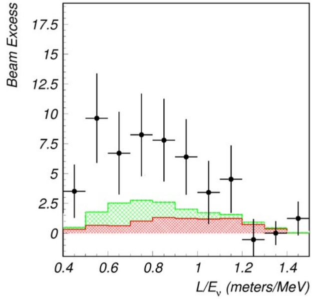
RAA



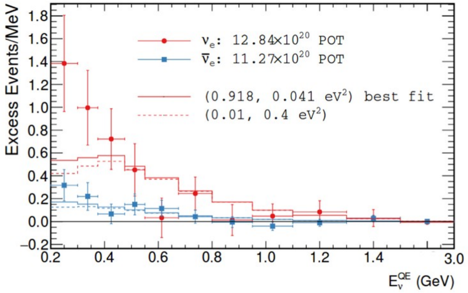
Neutrino-4



LSND



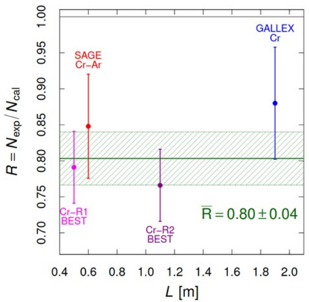
MiniBooNE



Anomalies

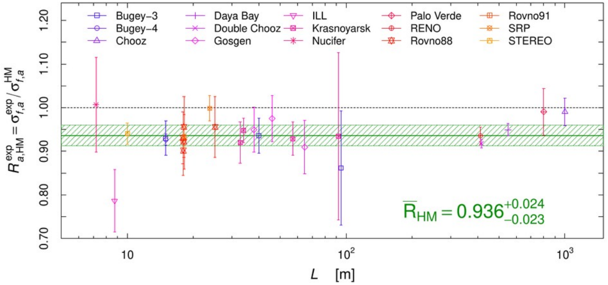
5-6σ

Gallium



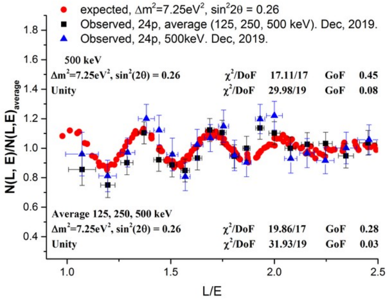
1-3σ

RAA



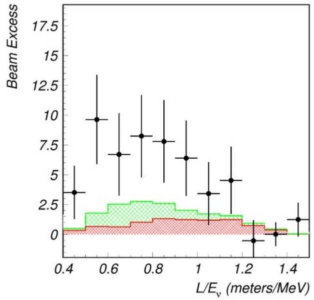
2-3σ

Neutrino-4



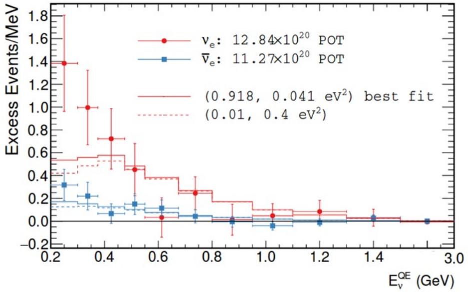
~4σ

LSND



~5σ

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:

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

3+1 neutrino oscillations

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

Appearance

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

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

@LSND, Karmen, MiniBooNE, Opera

Disappearance

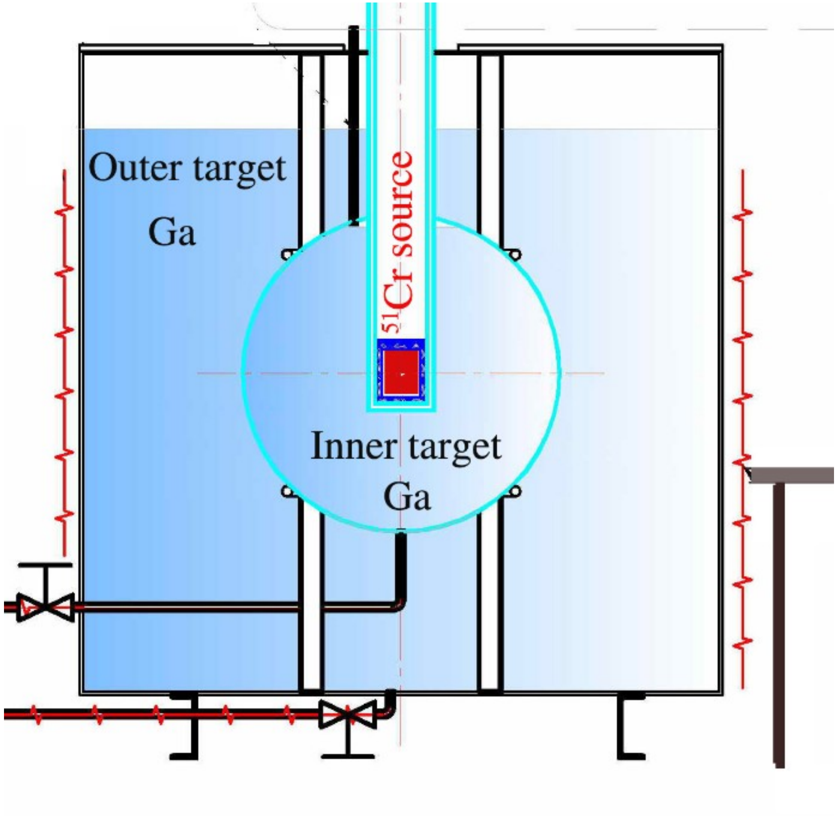
$$P_{\alpha\alpha}^{\rm SBL} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

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

@Reactors and Gallium
@atmospherics and accelerators

The Gallium anomaly

BEST coll., 2109.11482, PRL 2022



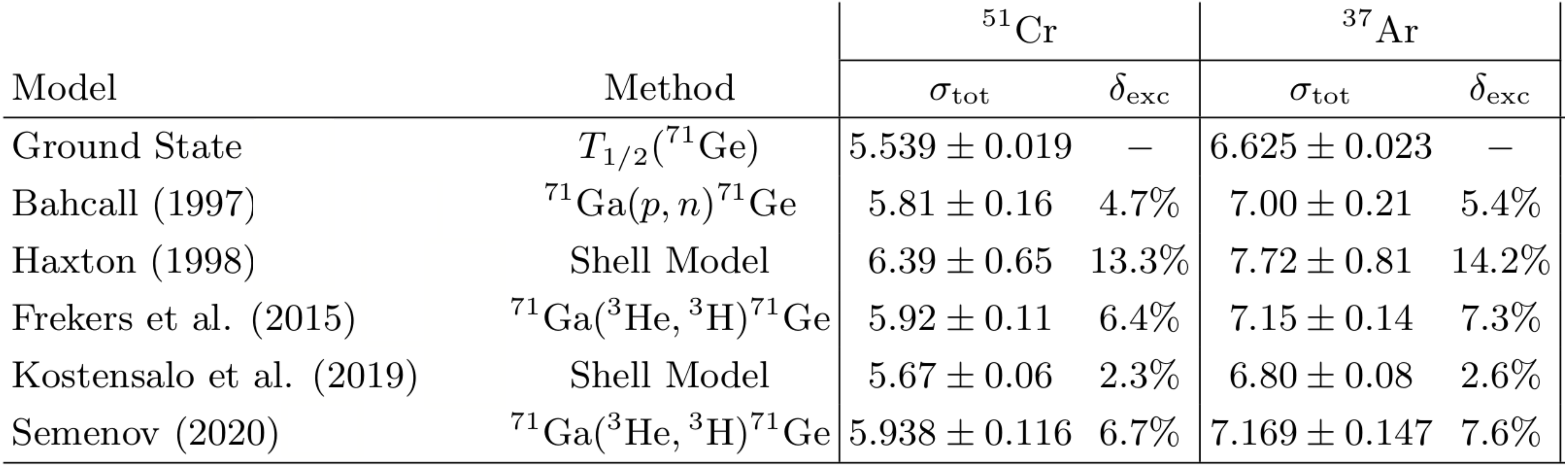
Intense sources of electron neutrinos are placed into the detector volume

$$e^- + {}^{51}\mathrm{Cr} \to \nu_e + {}^{51}\mathrm{V}$$
$$e^- + {}^{37}\mathrm{Ar} \to \nu_e + {}^{37}\mathrm{Cl}$$

The neutrino interact with the detector material

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

The Gallium anomaly



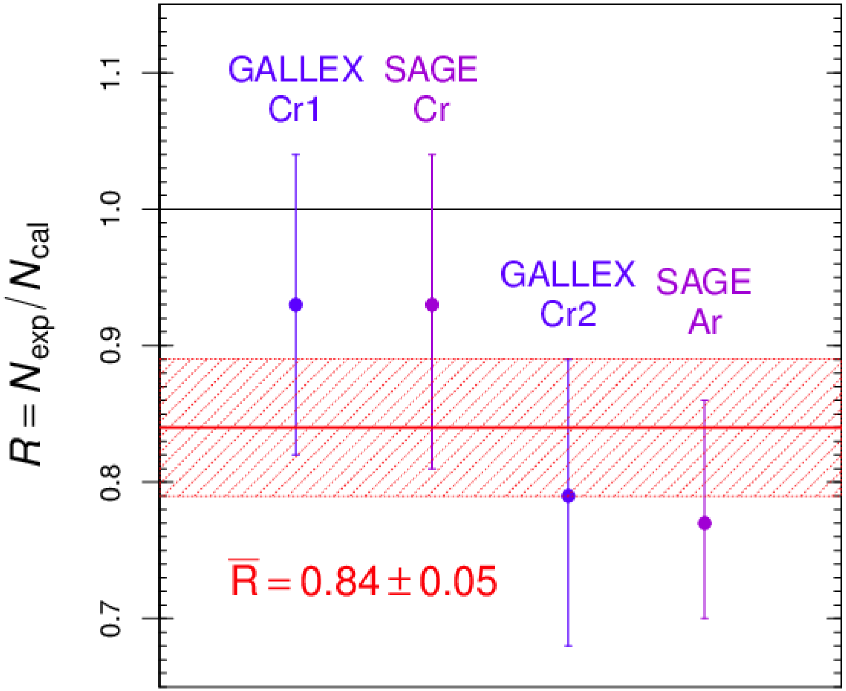
		$^{51}\mathrm{Cr}$		$^{37}\mathrm{Ar}$	
Model	Method	σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State	$T_{1/2}(^{71}\mathrm{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997)	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015)	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	5.92 ± 0.11	6.4%	7.15 ± 0.14	7.3%
Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
Semenov (2020)	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%

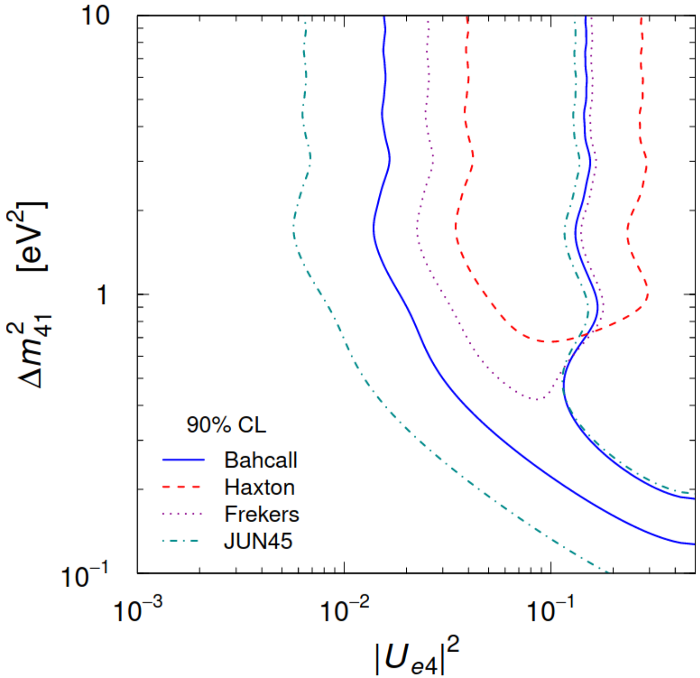
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Slightly different values for the different cross section models

The Gallium anomaly

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

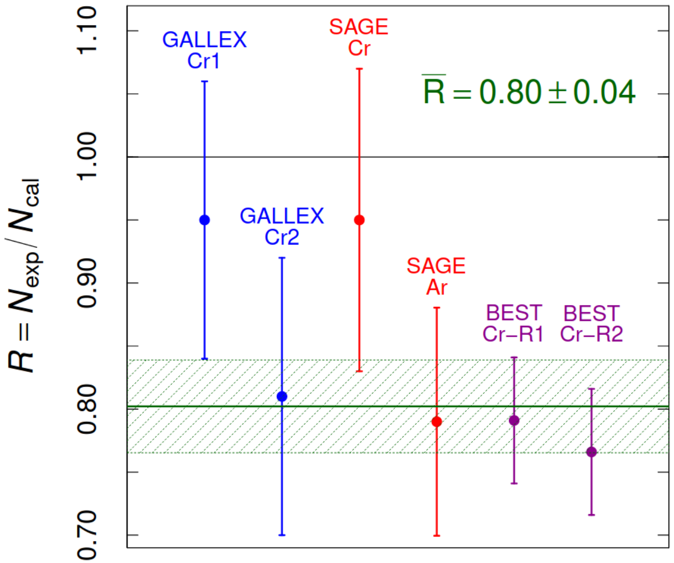


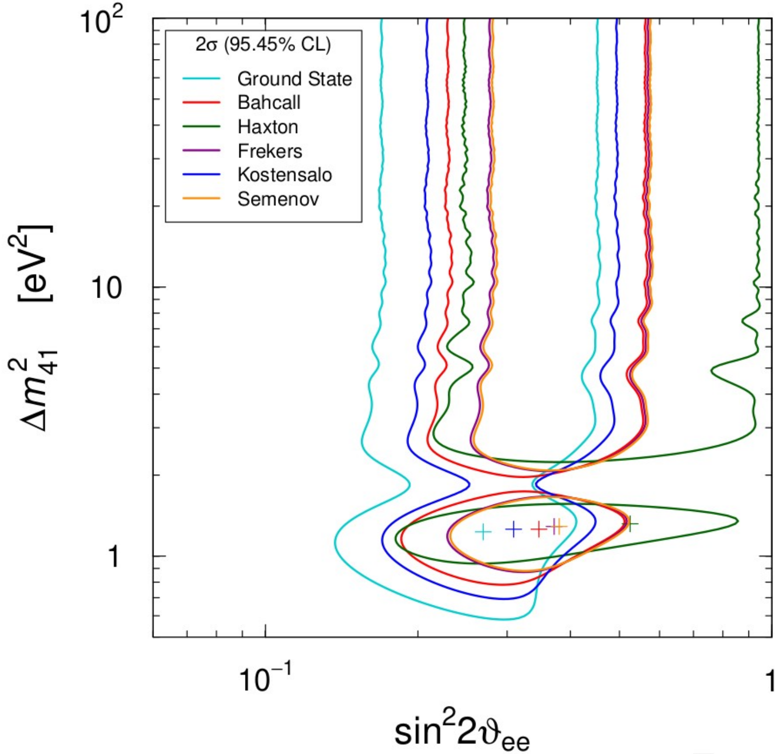


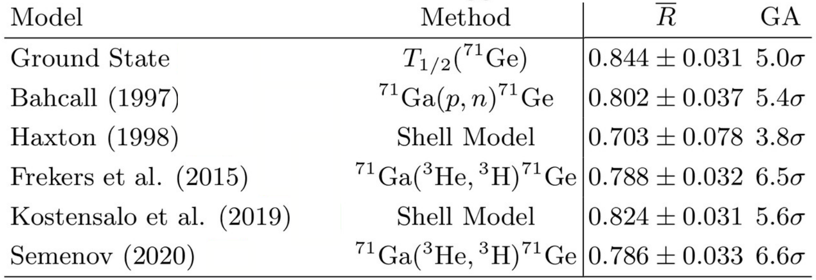
The significance of the “old” Gallium anomaly varied between 2.3 and 3.0σ, depending on the cross section model

The Gallium anomaly

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







Model	Method	$\overline{R}$	GA
Ground State	$T_{1/2}(^{71}\mathrm{Ge})$	0.844 ± 0.031	5.0σ
Bahcall (1997)	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	0.802 ± 0.037	5.4σ
Haxton (1998)	Shell Model	0.703 ± 0.078	3.8σ
Frekers et al. (2015)	$^{71}\mathrm{Ga}(^3\mathrm{He}, ^3\mathrm{H})^{71}\mathrm{Ge}$	0.788 ± 0.032	6.5σ
Kostensalo et al. (2019)	Shell Model	0.824 ± 0.031	5.6σ
Semenov (2020)	$^{71}\mathrm{Ga}(^3\mathrm{He}, ^3\mathrm{H})^{71}\mathrm{Ge}$	0.786 ± 0.033	6.6σ

Strong indication for short baseline (SBL) oscillations!

See also:
Berryman, Coloma, Huber, Schwetz, Zhao, 2111.12530, JHEP 2022

The reactor rate anomaly

Calculate inverse beta yields for each isotope

We use the Strumia-Vissani IBD cross section

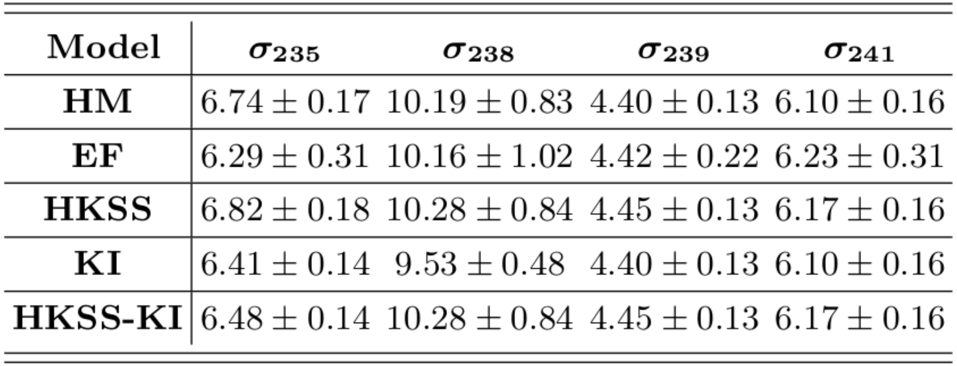
Strumia, Vissani, astro-ph/0302055, PLB 2003

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

Yields depend on the neutrino flux

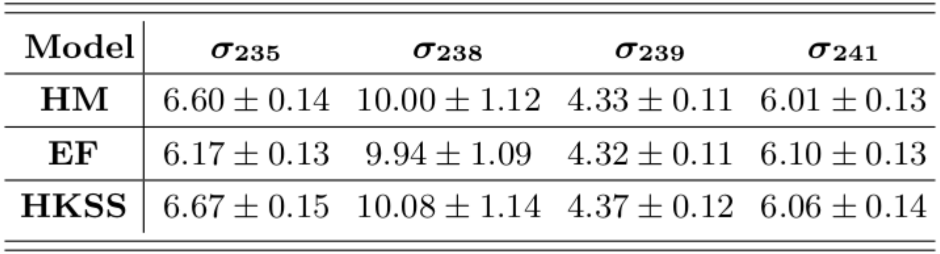
$$\sigma_{f,a} = \sum_i f_i^a \sigma_i$$

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
HKSS-KI	6.48 ± 0.14	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 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

The reactor rate anomaly

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

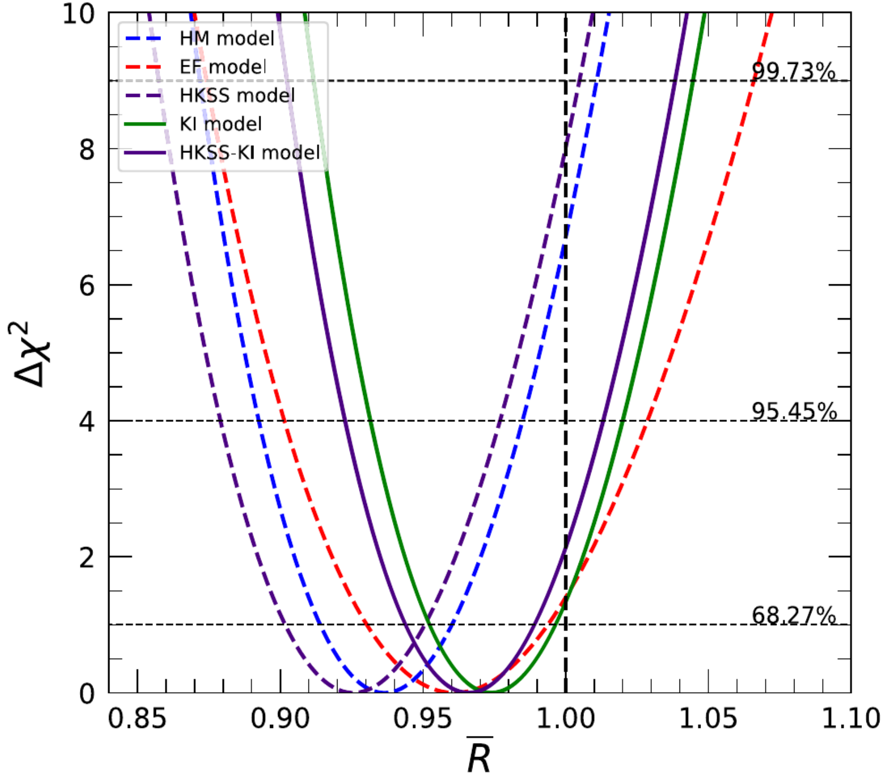
a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$\sigma^{\rm exp}_{f,a}$	$R^{\rm exp}_{a,\rm HM}$	$R^{\rm exp}_{a,\rm EF}$	$R^{\rm exp}_{a,\rm HKSS}$	$R^{\rm exp}_{a,\rm KI}$	$R^{\rm exp}_{a,\rm HKSS\text{-}KI}$	$\delta^{\rm exp}_a$ [%]	$\delta^{\rm cor}_a$ [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	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	Rovno88-1I	0.607	0.074	0.277	0.042	5.70	0.902	0.941	0.892	0.939	0.921	6.4	3.1 2.2	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	3.1	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		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 3.8	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		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		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	57
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	$9-11$

The reactor rate anomaly

The significance of the RAA depends on the input flux model

The EF and KI models have no anomaly

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

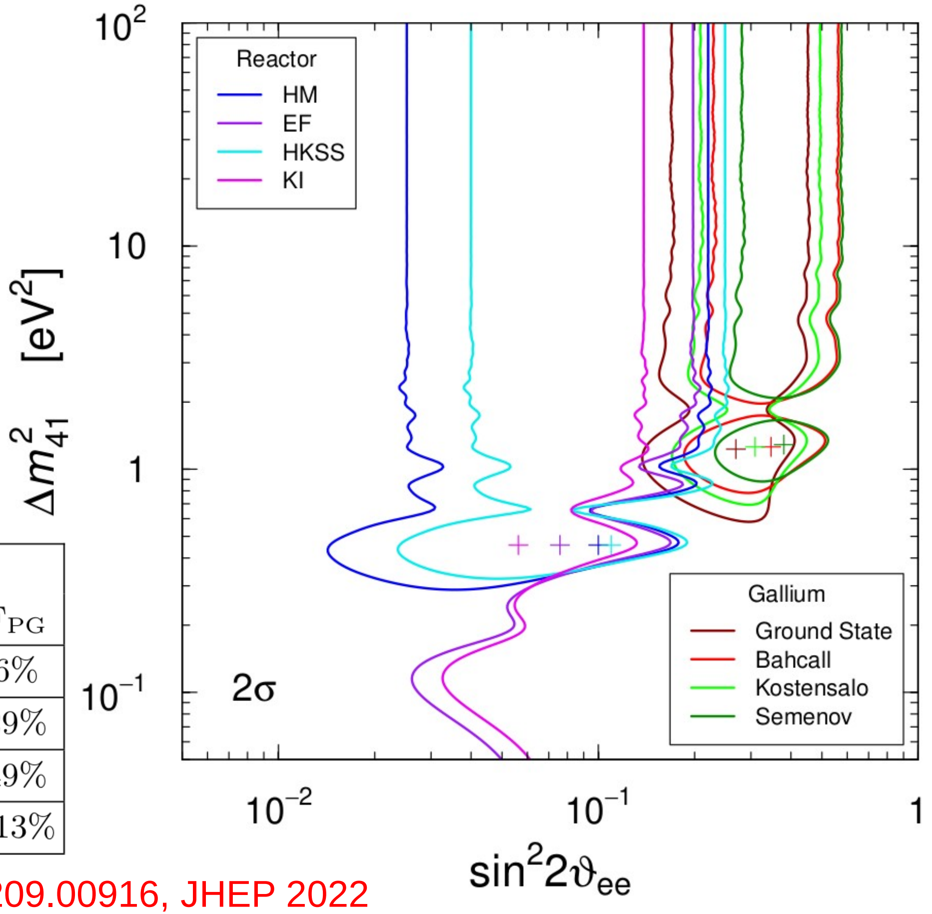


Mention, Fechner, Lasserre, Mueller, Lhuillier,
1101.2755, PRD 2011Huber, 1106.0687, PRC 2012
Mueller, Lhuillier, Fallot, Letourneau, Cormon, 1101.2663, PRC 2012
Estienne, Fallot, et al, 1904.09358, PRL 2019
Hayen, Kostensalo, Severijns, Suhonen, 1908.08302, PRC 2019
Kurchatov Institute: Kopeikin, Skorokhvatov,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

Tension between RAA and Gallium

Severe tension between reactor rate and Gallium data!

	HM		HKSS		EF		KI	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
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%

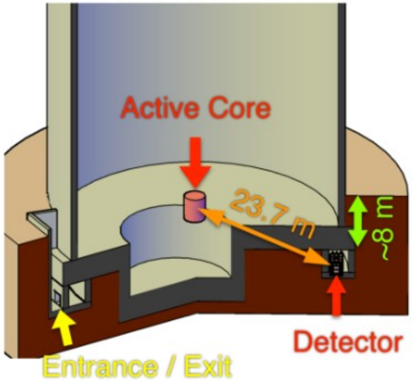


Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

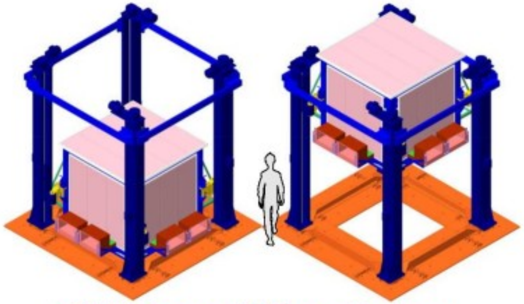
Ratio analysis

Talk by Nataliya Skrobova!

NEOS

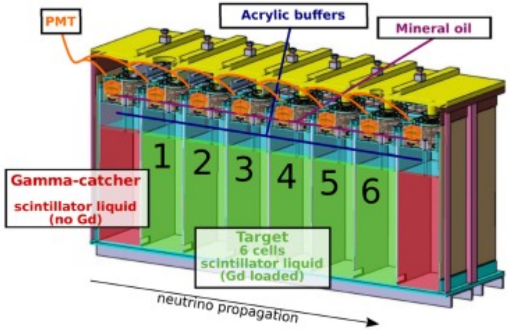


DANSS

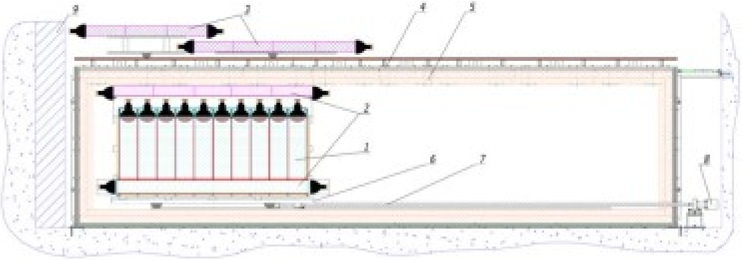


DANSS on a lifting platform

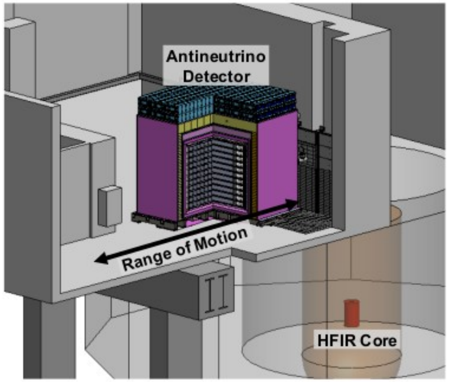
STEREO



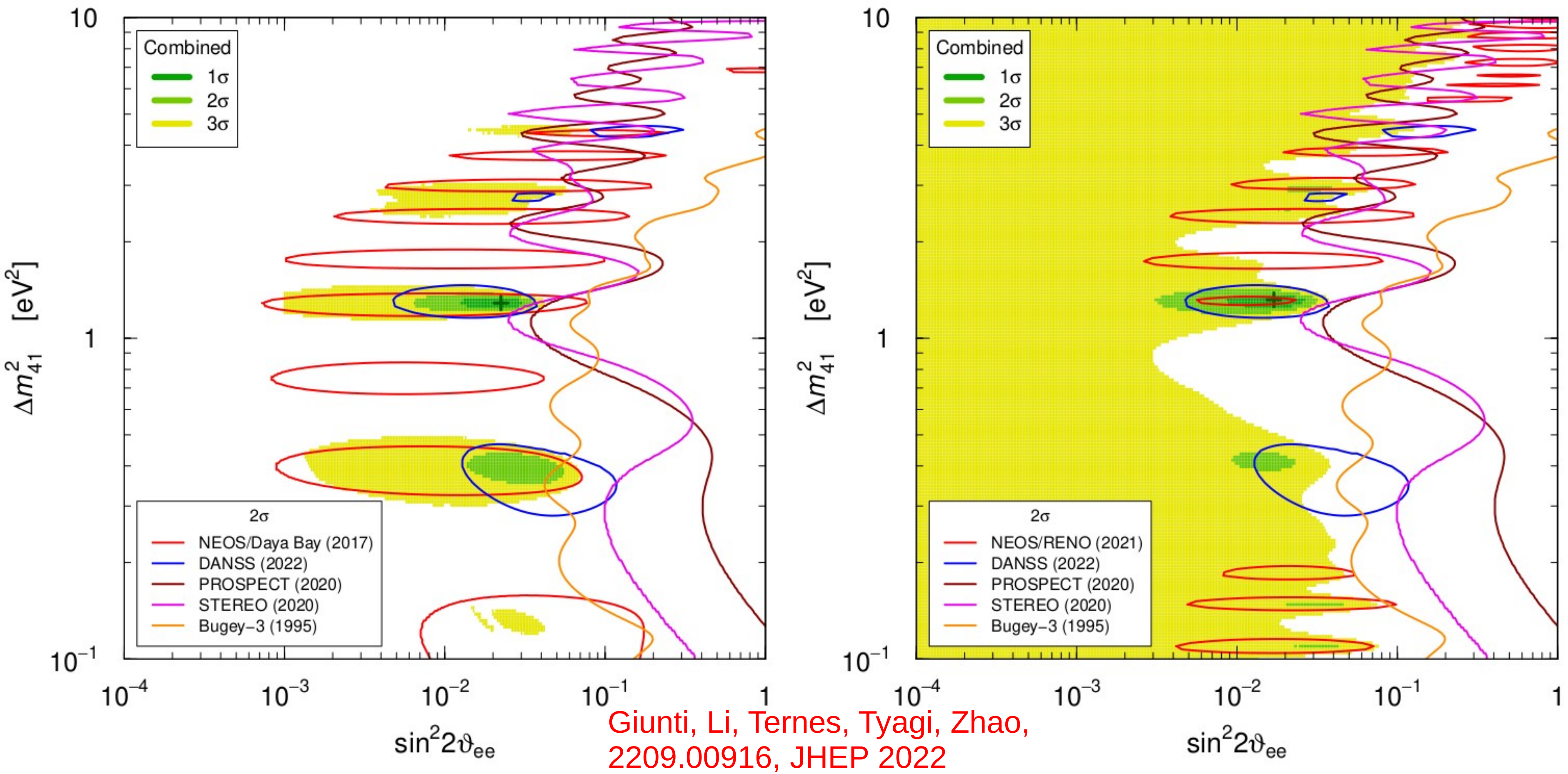
Neutrino-4



PROSPECT

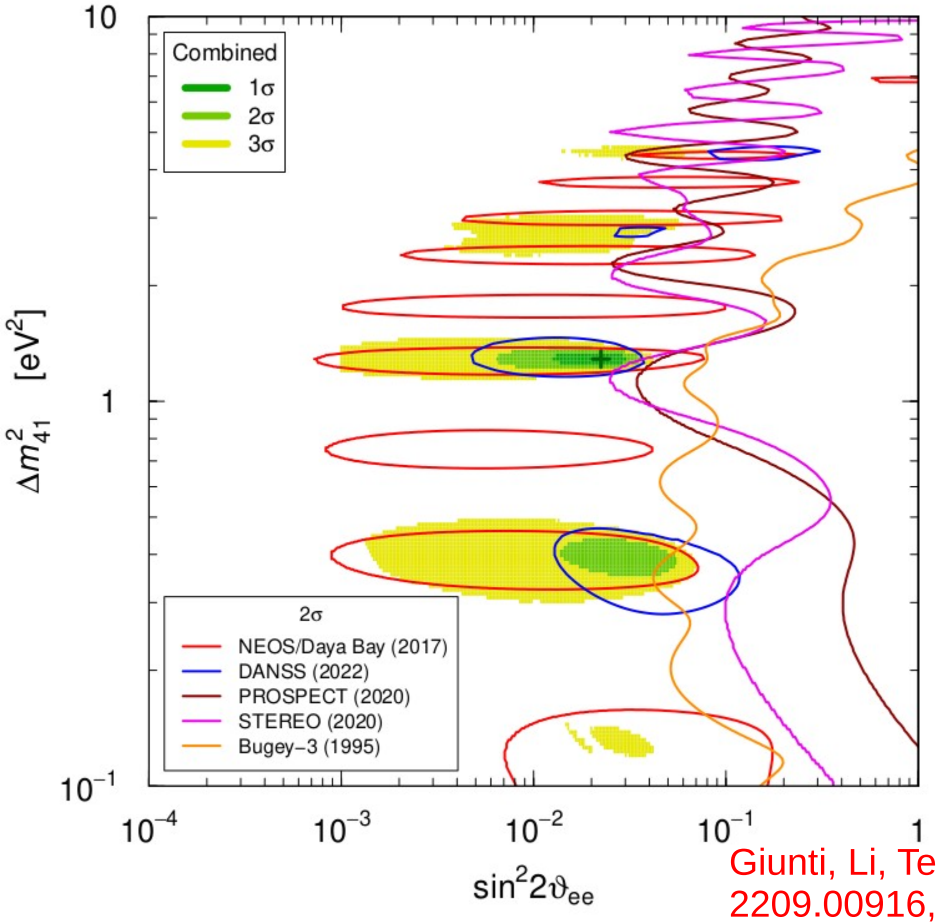


Ratio analysis



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

Ratio analysis



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

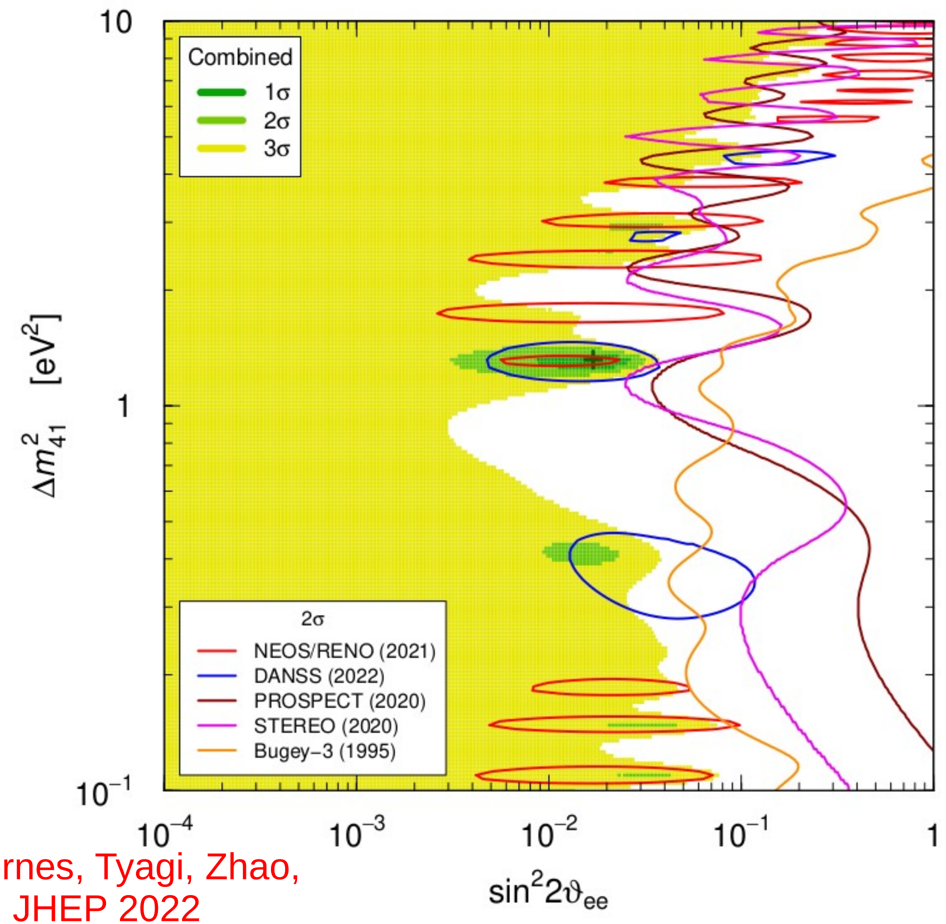
The NEOS collaboration performed an analysis using the Daya Bay spectrum as a reference spectrum

Many many events at Daya Bay!

Ratio analysis

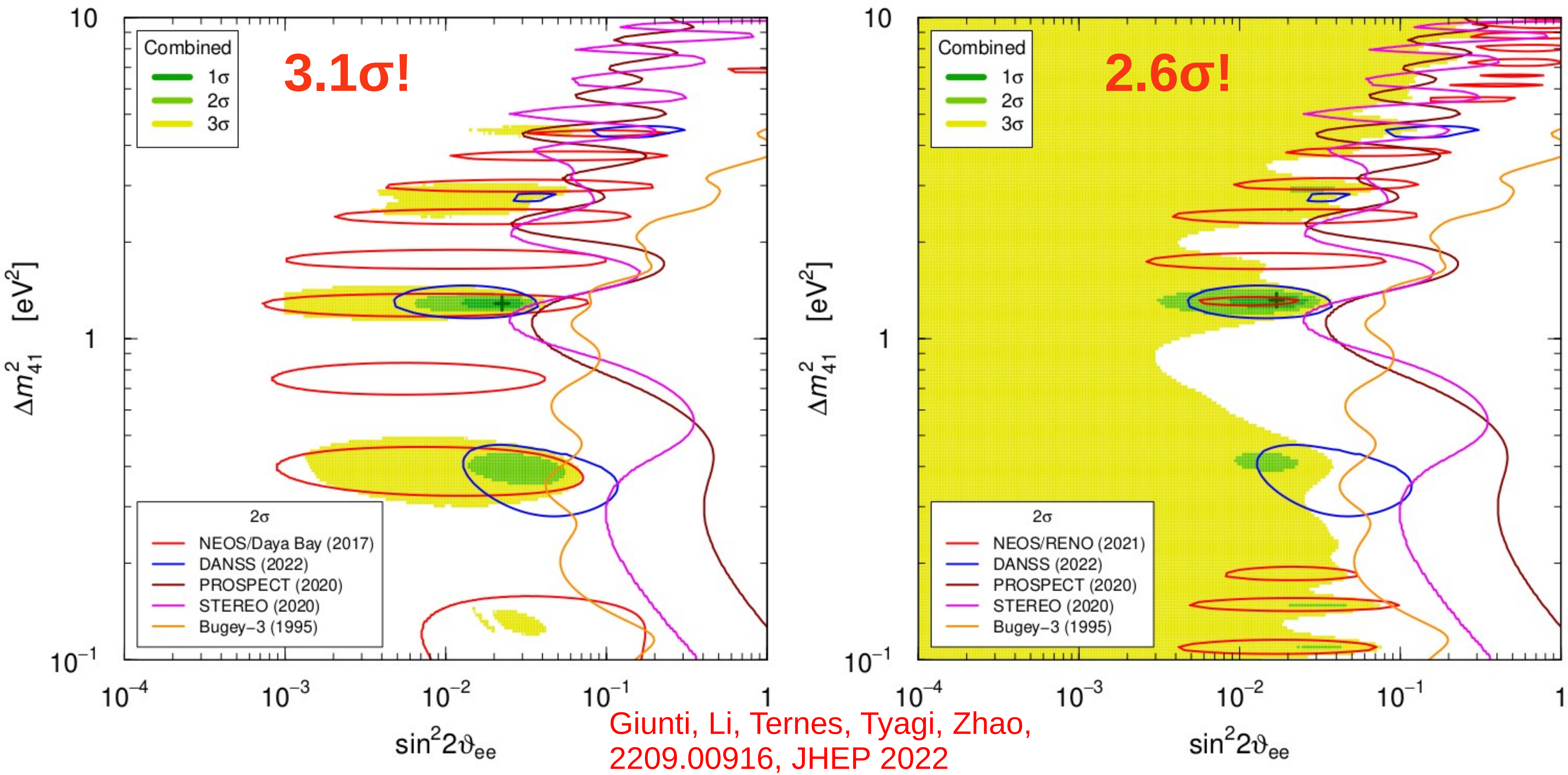
The NEOS collaboration also performed an analysis using the RENO spectrum as a reference spectrum

Same reactor complex, better control of systematic uncertainties!



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

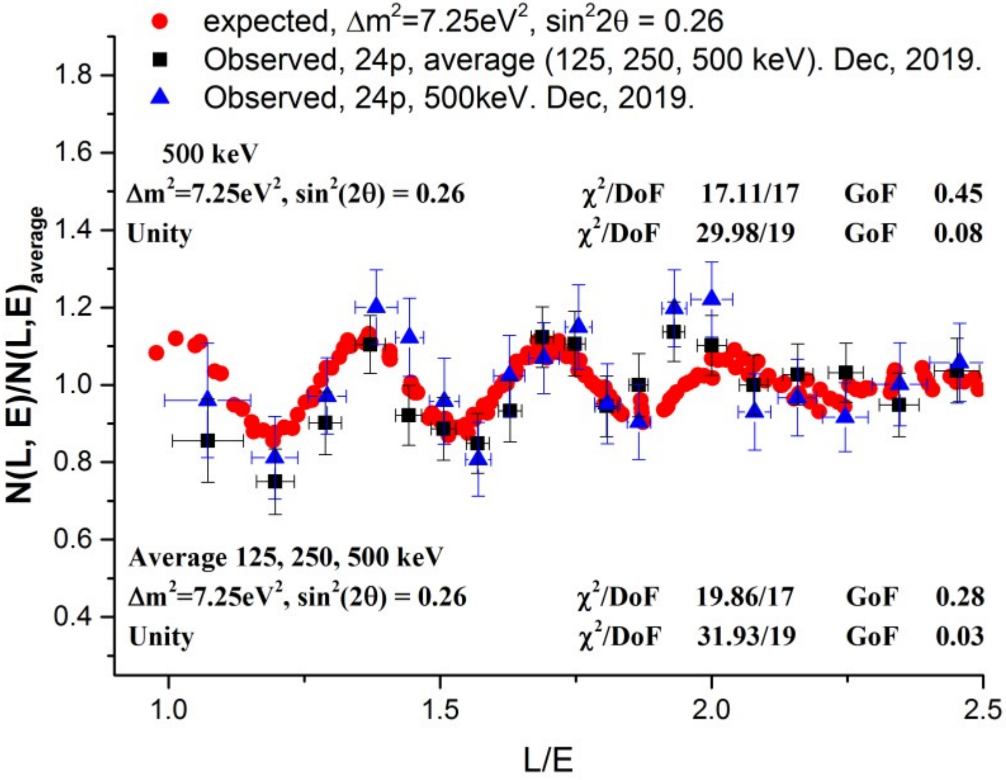
Ratio analysis



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

Neutrino-4

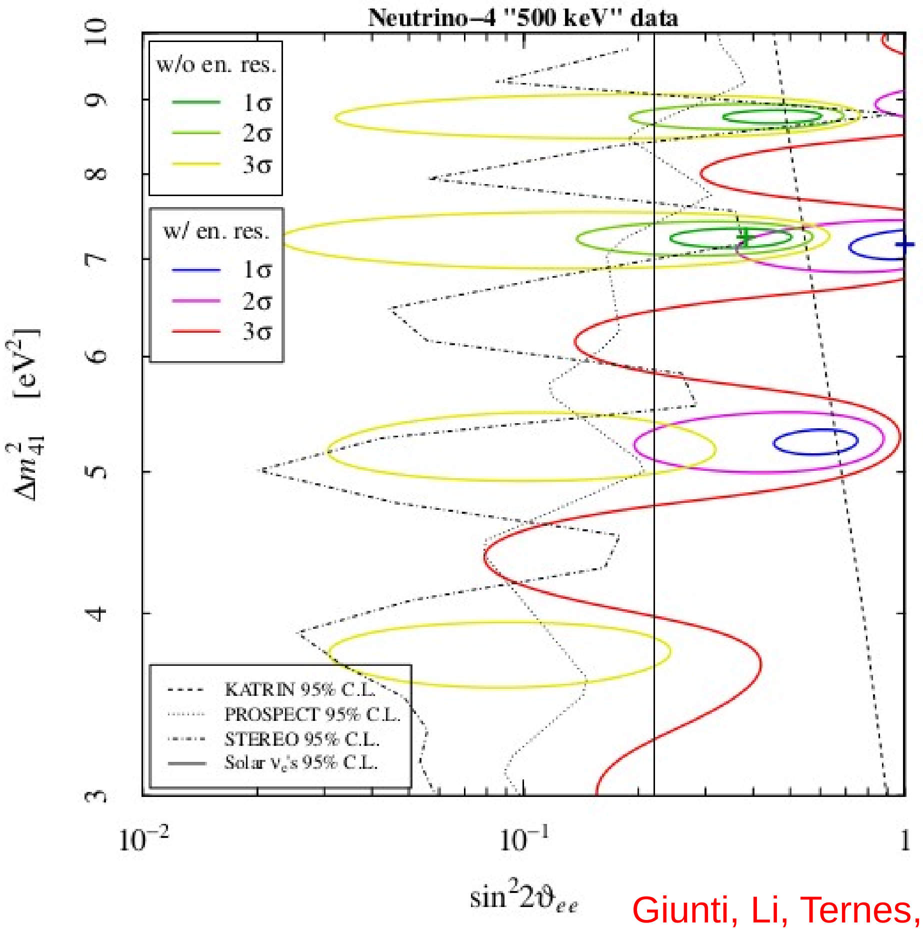
Averaging contains integration over flux, distance, detector resolution

$$\left\langle \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)\right\rangle_{ik} = \frac{\int_{L_k^{\rm min}}^{L_k^{\rm max}} dL\, L^{-2} \int_{E_i^{\rm min}}^{E_i^{\rm max}} dE'_{\rm p} \int dE_{\rm p}\, \boxed{R(E_{\rm p}, E'_{\rm p})} \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \phi_{\bar{\nu}_e}(E)\, \sigma_{\bar{\nu}_e p}(E)}{\int_{L_k^{\rm min}}^{L_k^{\rm max}} dL\, L^{-2} \int_{E_i^{\rm min}}^{E_i^{\rm max}} dE'_{\rm p} \int dE_{\rm p}\, \boxed{R(E_{\rm p}, E'_{\rm p})}\, \phi_{\bar{\nu}_e}(E)\, \sigma_{\bar{\nu}_e p}(E)}$$

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

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

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

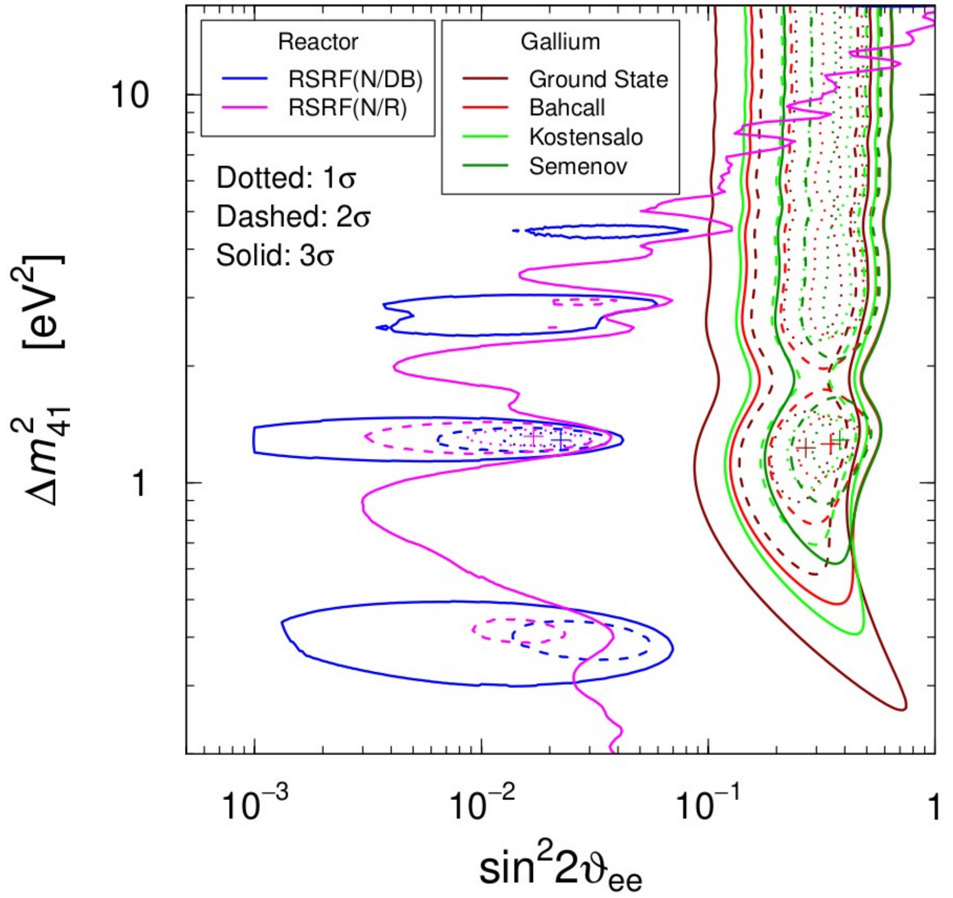
Ratio analysis

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

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

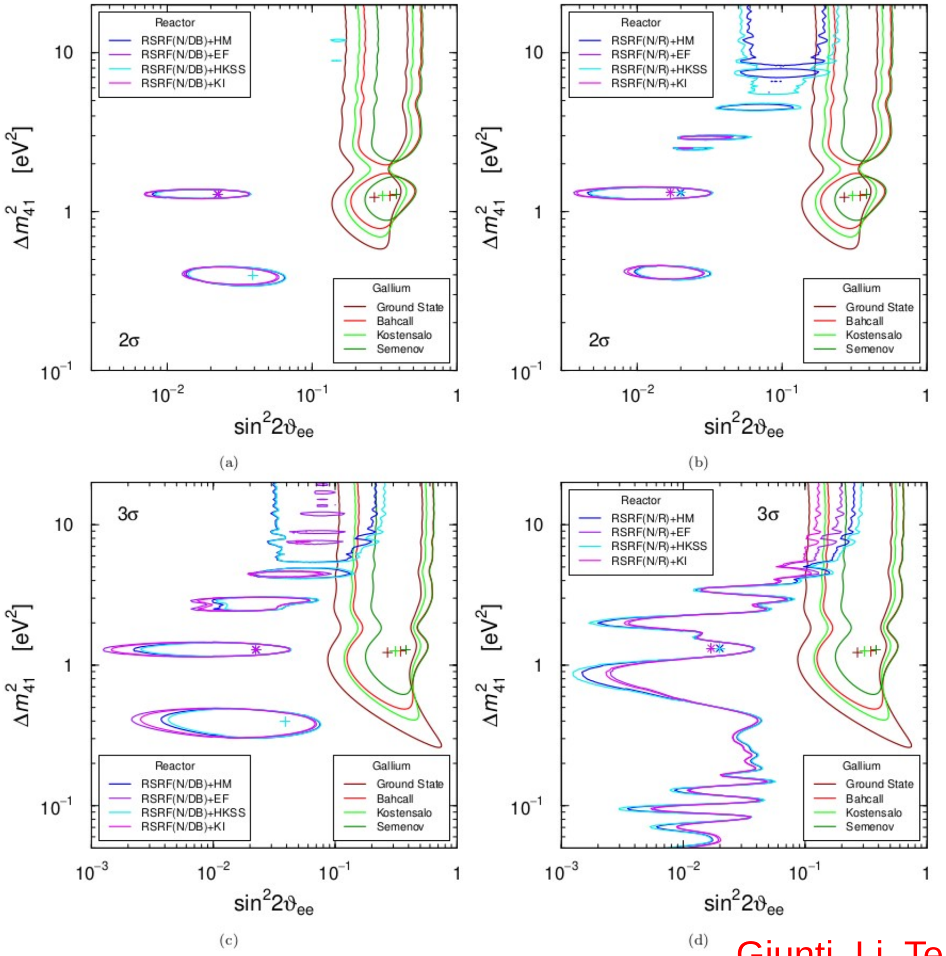
No good fit for RSRF(N/R) either.

	RSRF(N/DB)		RSRF(N/R)	
	$\Delta\chi^2_{\text{PG}}$	GoF_{PG}	$\Delta\chi^2_{\text{PG}}$	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%



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

Combined ratio and rate data



(a) (b) (c) (d)

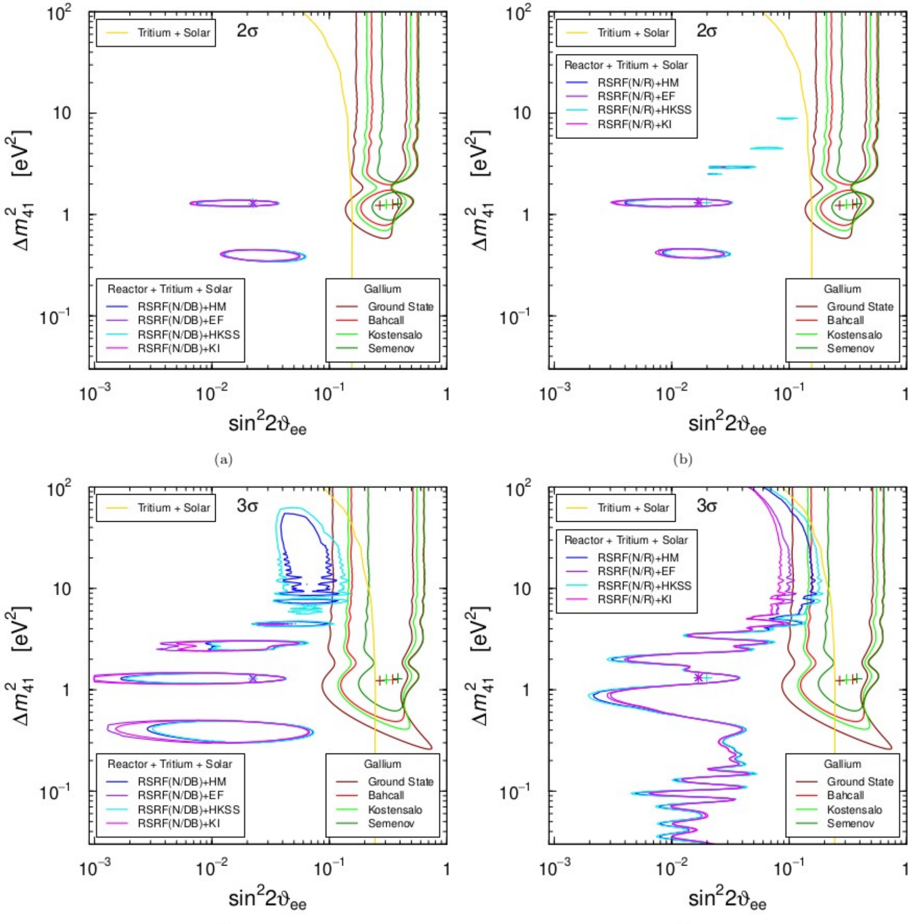
Combing ratio and rate data leads to better localization of allowed regions.

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

Combined reactor, Tritium, and solar data



(a) (b)

(c) (d)

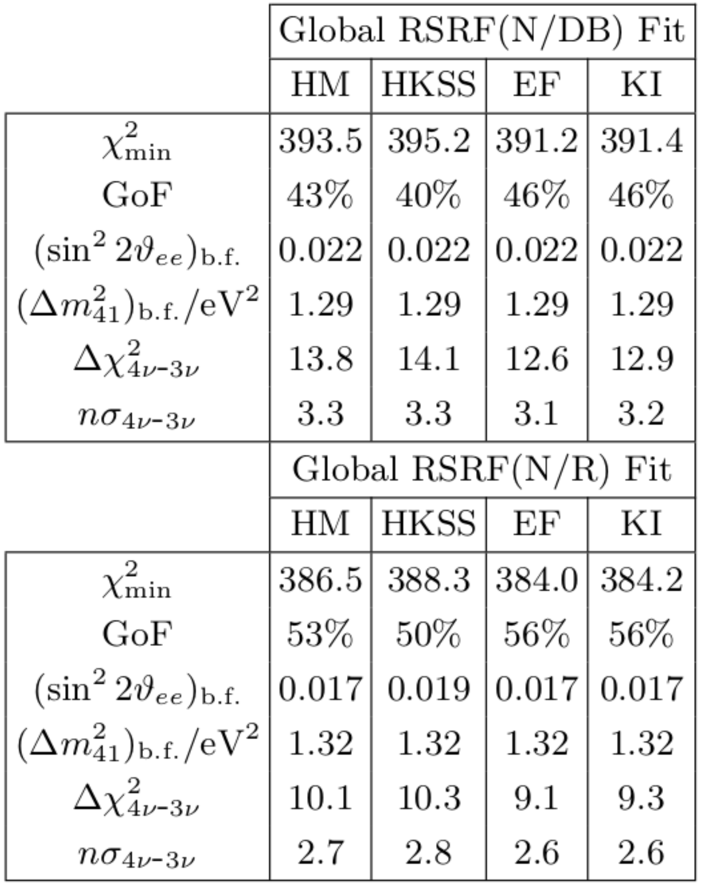
Combination of all data!

Severe and unacceptable tension for any combination with Gallium data!

	Global Fit: RSRF(N/DB) + Reactor Rates + Tritium + Solar							
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
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	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
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

Combined reactor, Tritium, and solar data



	Global RSRF(N/DB) Fit			
	HM	HKSS	EF	KI
χ^2_{min}	393.5	395.2	391.2	391.4
GoF	43%	40%	46%	46%
$(\sin^2 2\vartheta_{ee})_{\text{b.f.}}$	0.022	0.022	0.022	0.022
$(\Delta m^2_{41})_{\text{b.f.}}/\text{eV}^2$	1.29	1.29	1.29	1.29
$\Delta\chi^2_{4\nu\text{-}3\nu}$	13.8	14.1	12.6	12.9
$n\sigma_{4\nu\text{-}3\nu}$	3.3	3.3	3.1	3.2
	Global RSRF(N/R) Fit			
	HM	HKSS	EF	KI
χ^2_{min}	386.5	388.3	384.0	384.2
GoF	53%	50%	56%	56%
$(\sin^2 2\vartheta_{ee})_{\text{b.f.}}$	0.017	0.019	0.017	0.017
$(\Delta m^2_{41})_{\text{b.f.}}/\text{eV}^2$	1.32	1.32	1.32	1.32
$\Delta\chi^2_{4\nu\text{-}3\nu}$	10.1	10.3	9.1	9.3
$n\sigma_{4\nu\text{-}3\nu}$	2.7	2.8	2.6	2.6

Global fit (without Gallium data) has a preference between 2.6σ and 3.3σ in favor of 3+1 oscillations!

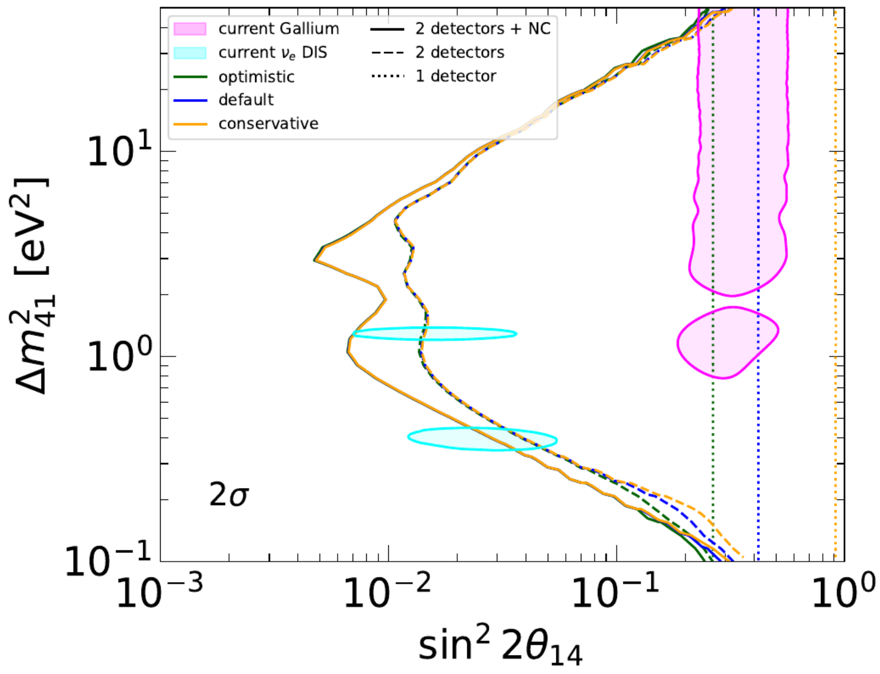
Due to new reactor ratio data

Another new (or revived) anomaly!

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

Anomalies can be tested in future experiments

ESSνSB sensitivity



Capozzi, Giunti, Ternes,
2302.07154

JUNO+TAO sensitivity

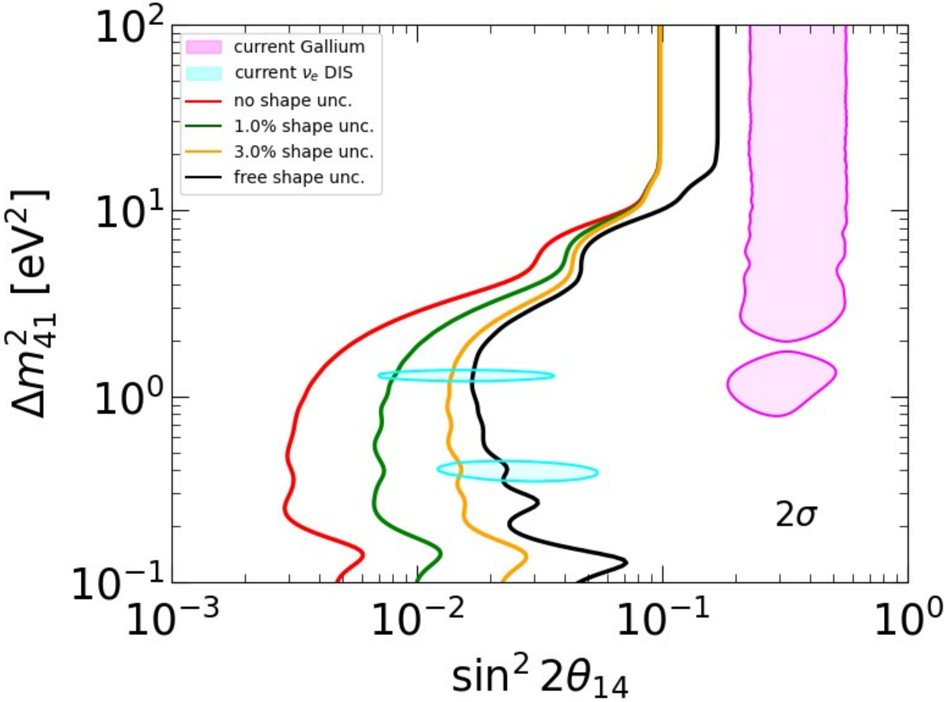
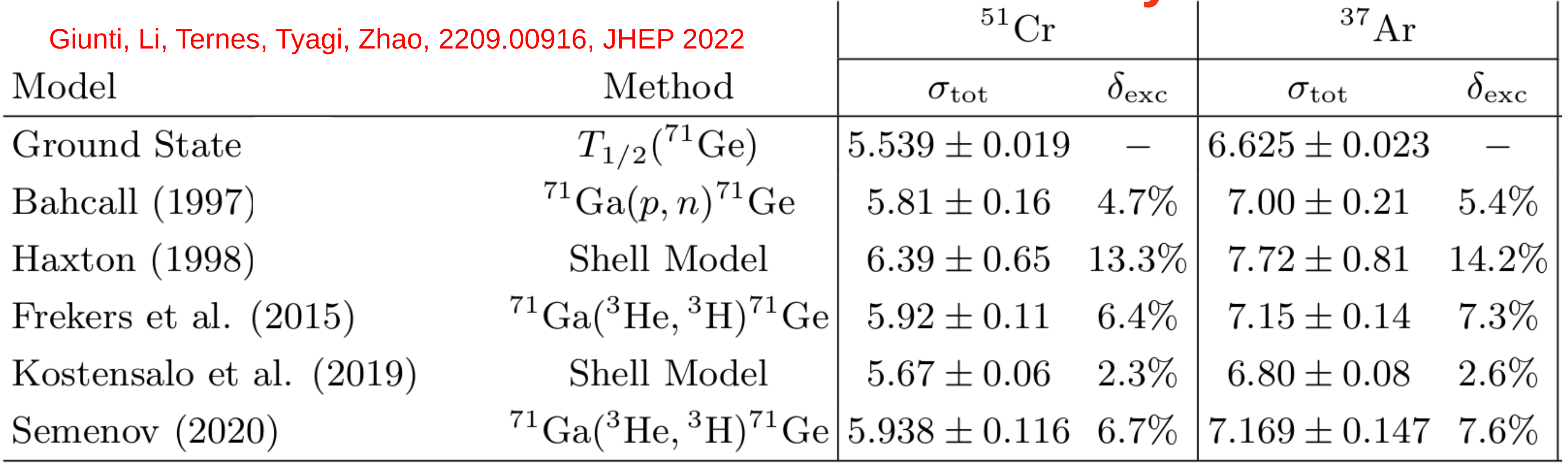


Figure adapted from
Basto-Gonzalez, Forero, Giunti, Quiroga, Ternes,
2112.00379, PRD 2022

More on the Gallium anomaly

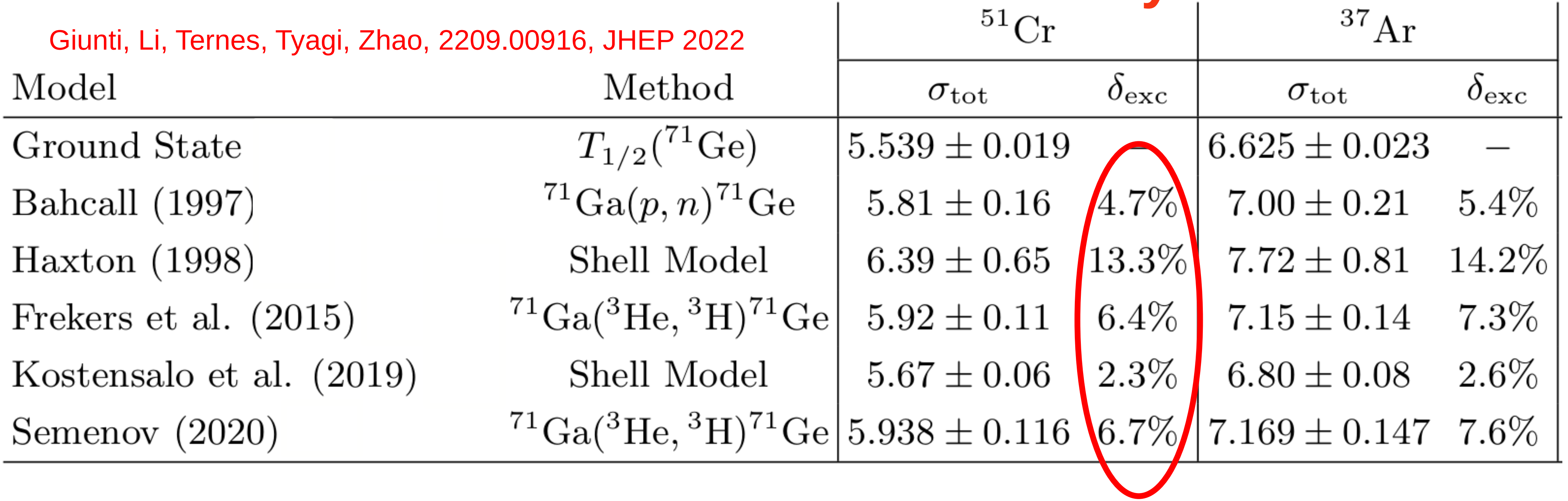
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022



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

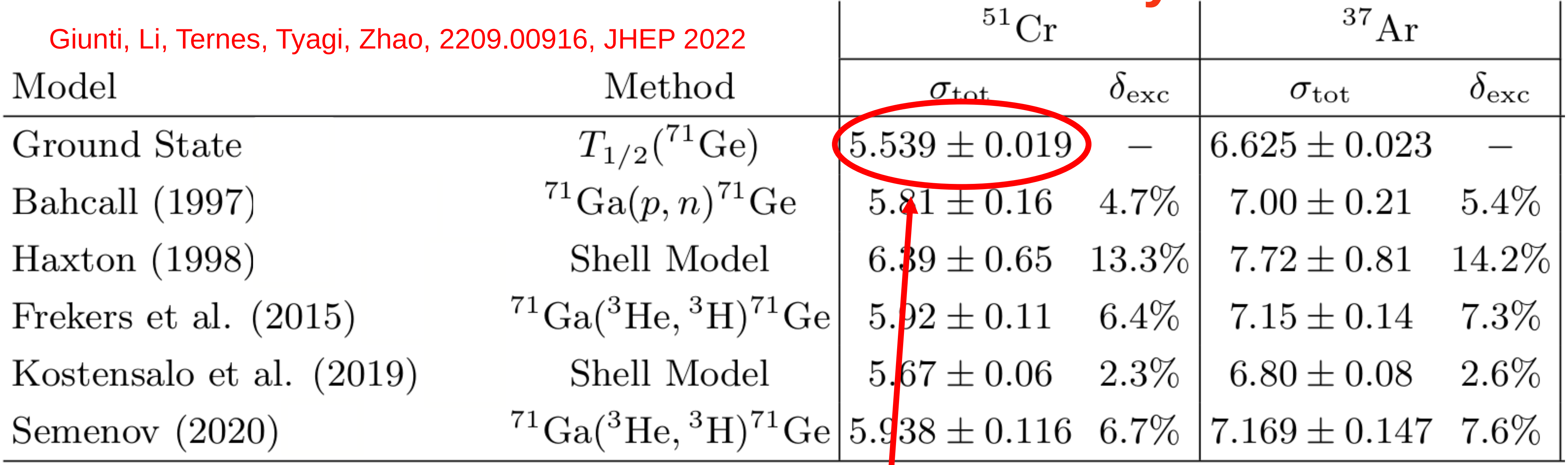


Model	Method	^{51}Cr		^{37}Ar	
		$\sigma_{\rm tot}$	$\delta_{\rm exc}$	$\sigma_{\rm tot}$	$\delta_{\rm exc}$
Ground State	$T_{1/2}(^{71}\mathrm{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997)	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015)	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	5.92 ± 0.11	6.4%	7.15 ± 0.14	7.3%
Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
Semenov (2020)	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	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

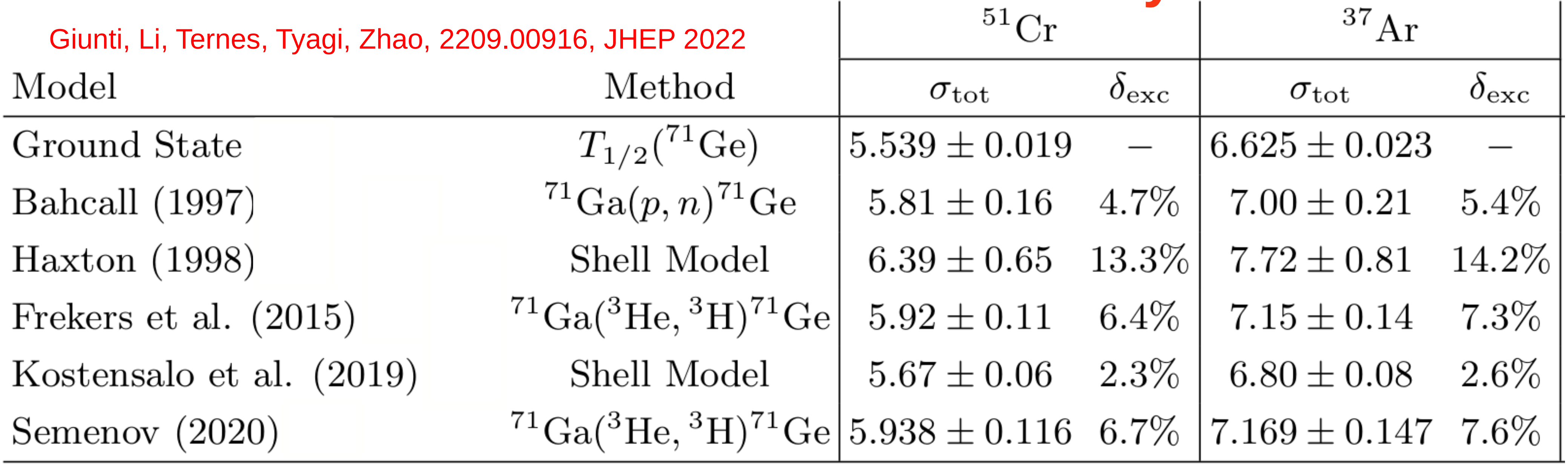


Model	Method	^{51}Cr		^{37}Ar	
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State	$T_{1/2}(^{71}\text{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997)	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015)	$^{71}\text{Ga}(^3\text{He},^3\text{H})^{71}\text{Ge}$	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%

Large

More on the Gallium anomaly

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



		^{51}Cr		^{37}Ar	
Model	Method	$\sigma_{\rm tot}$	$\delta_{\rm exc}$	$\sigma_{\rm tot}$	$\delta_{\rm exc}$
Ground State	$T_{1/2}(^{71}\mathrm{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997)	$^{71}\mathrm{Ga}(p,n)^{71}\mathrm{Ge}$	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)	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	5.92 ± 0.11	6.4%	7.15 ± 0.14	7.3%
Kostensalo et al. (2019)	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%
Semenov (2020)	$^{71}\mathrm{Ga}(^{3}\mathrm{He},{}^{3}\mathrm{H})^{71}\mathrm{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%

Main contribution

Corrections

$$\sigma_{\rm tot} = \sigma_{\rm gs}\left(1 + \xi_{5/2^-}\frac{\mathrm{BGT}_{5/2^-}}{\mathrm{BGT}_{\rm gs}} + \xi_{3/2^-}\frac{\mathrm{BGT}_{3/2^-}}{\mathrm{BGT}_{\rm gs}} + \xi_{5/2^+}\frac{\mathrm{BGT}_{5/2^+}}{\mathrm{BGT}_{\rm gs}}\right)$$

More on the Gallium anomaly

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

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

Different results obtained in the past

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

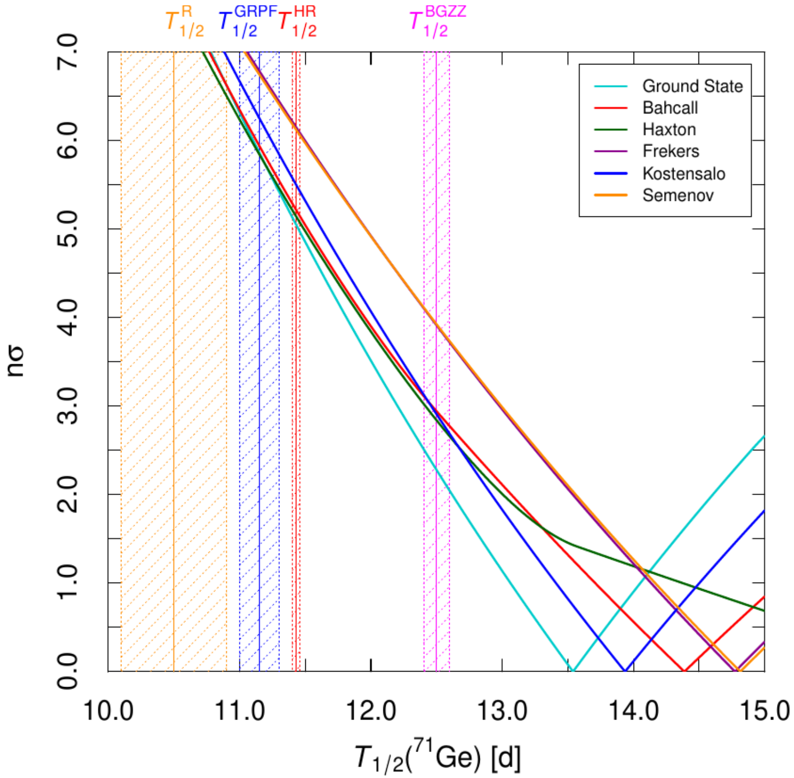
$$T_{1/2}^{\mathrm{R}}(^{71}\mathrm{Ge}) = 10.5 \pm 0.4\,\mathrm{d} \quad \text{(Rudstam, 1956)}$$

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

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

More on the Gallium anomaly

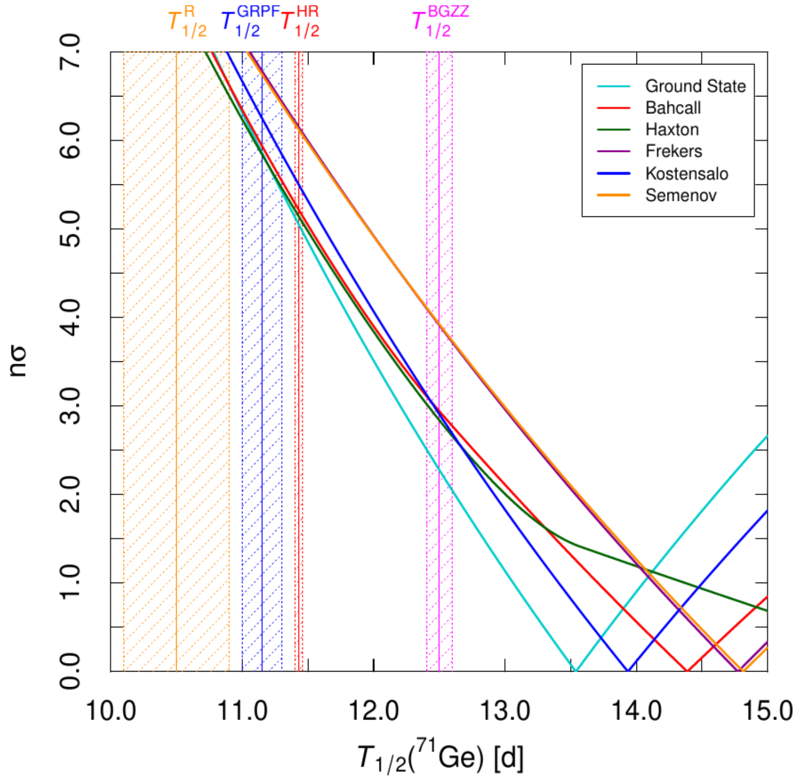
Fit the Germanium half life using data from Gallium experiments

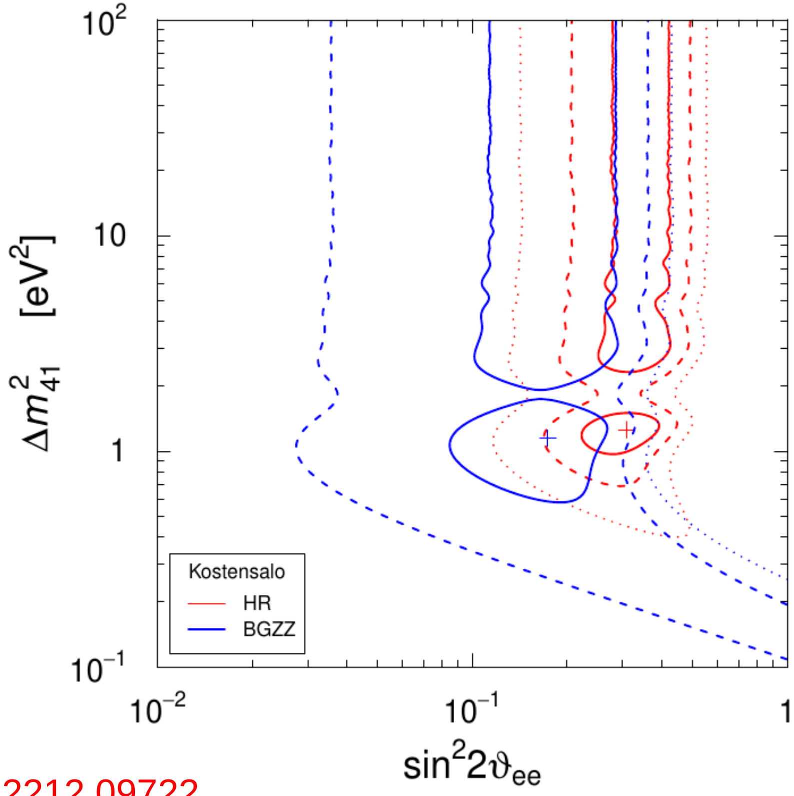


Giunti, Li, Ternes, Zhao, 2212.09722

More on the Gallium anomaly

Fit the Germanium half life using data from Gallium experiments





Giunti, Li, Ternes, Zhao, 2212.09722

Conclusions

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

Shall we perform a new measurement of the Germanium half life?

RAA might be solved for newer flux models

New (revived) preference for SBL oscillations from ratio experiments

Neutrino-4 preference doubtful

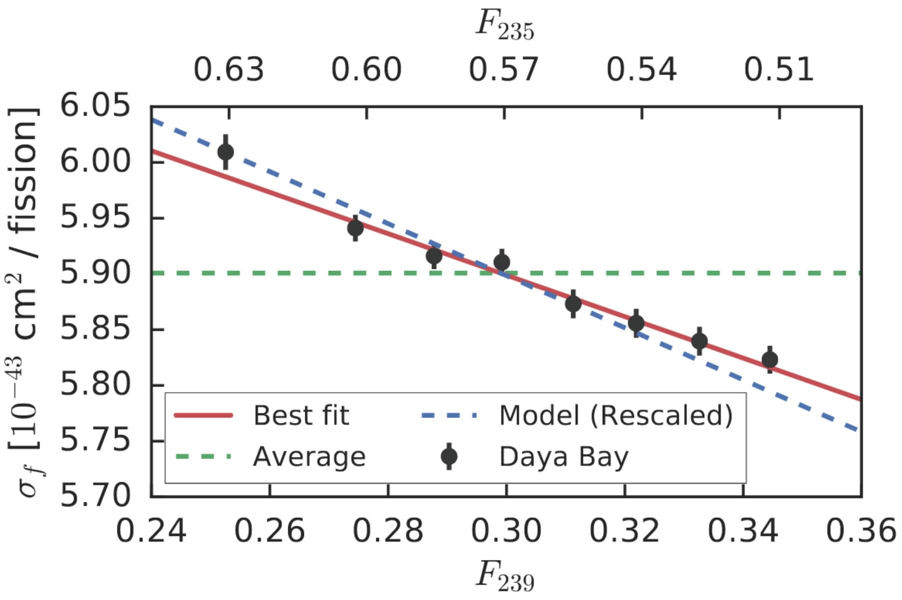
Anomalous AND also Null results have to be checked

Grazie!

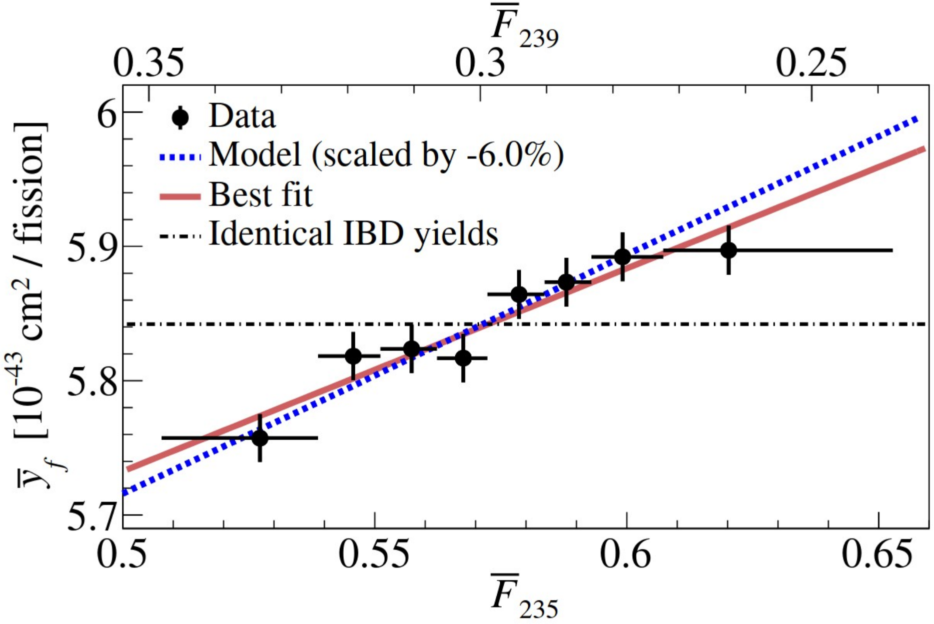
Evolution data

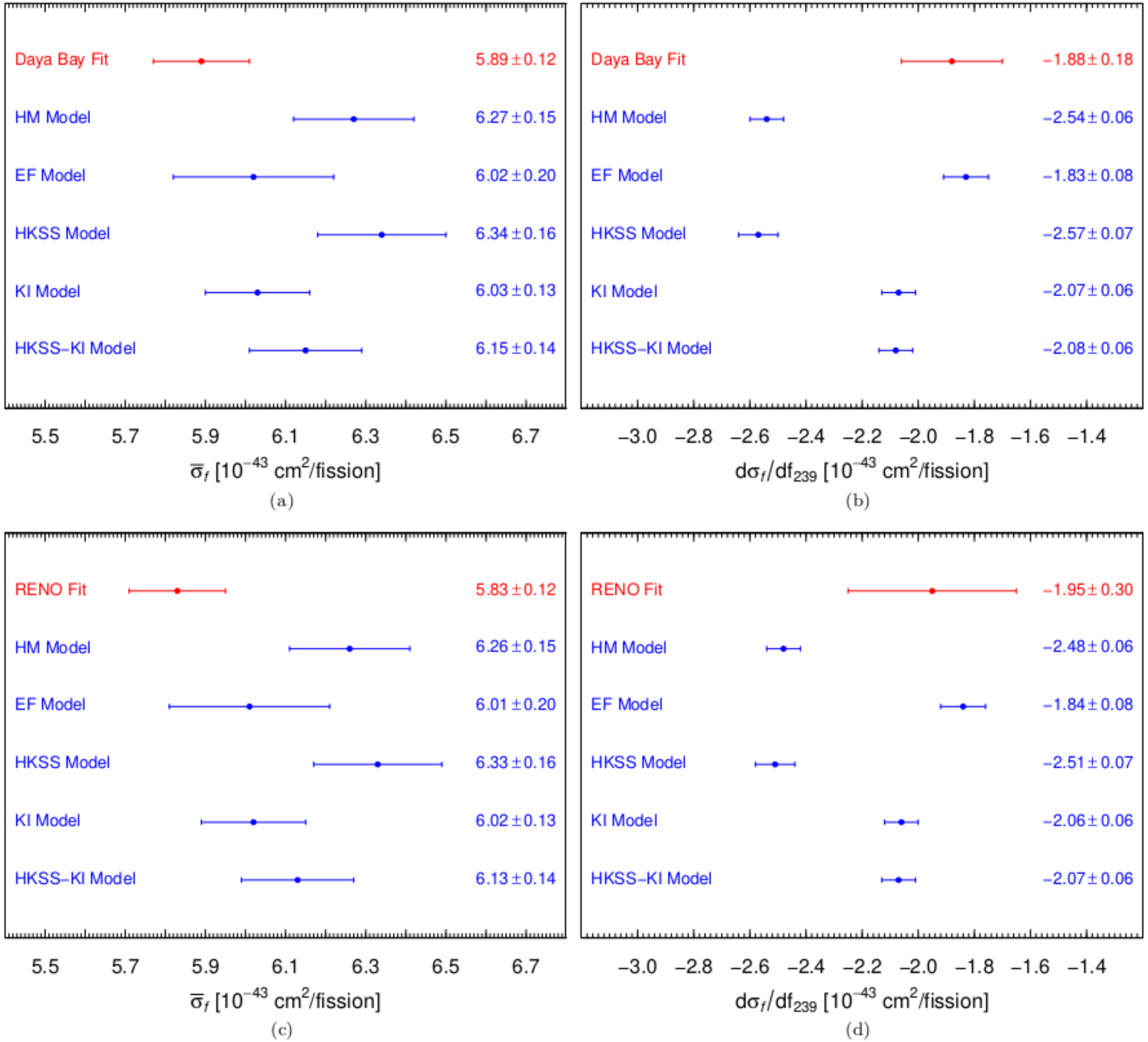
Measure rates at different stages of reactor cycle

Daya Bay, 1704.01082, PRL 2017



RENO, 1806.00574, PRL 2019





(a) (b)

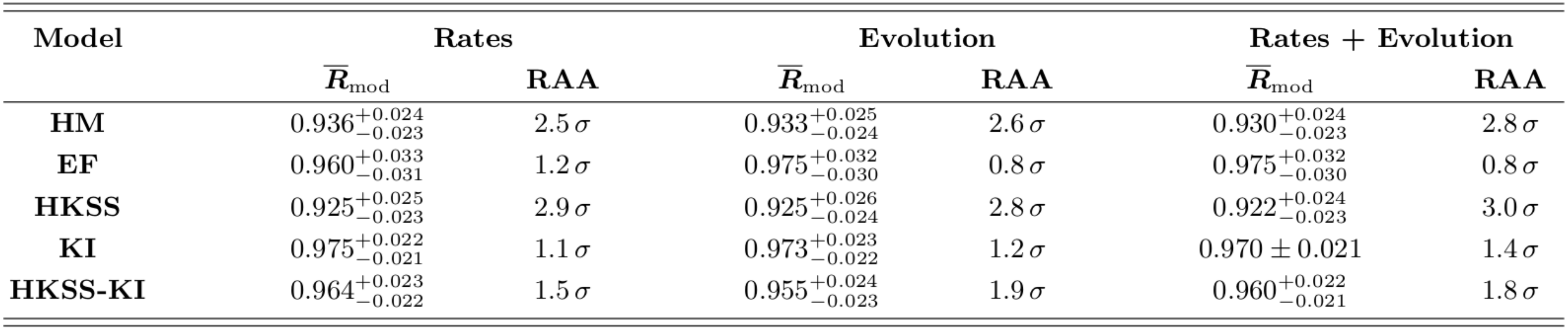
(c) (d)

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

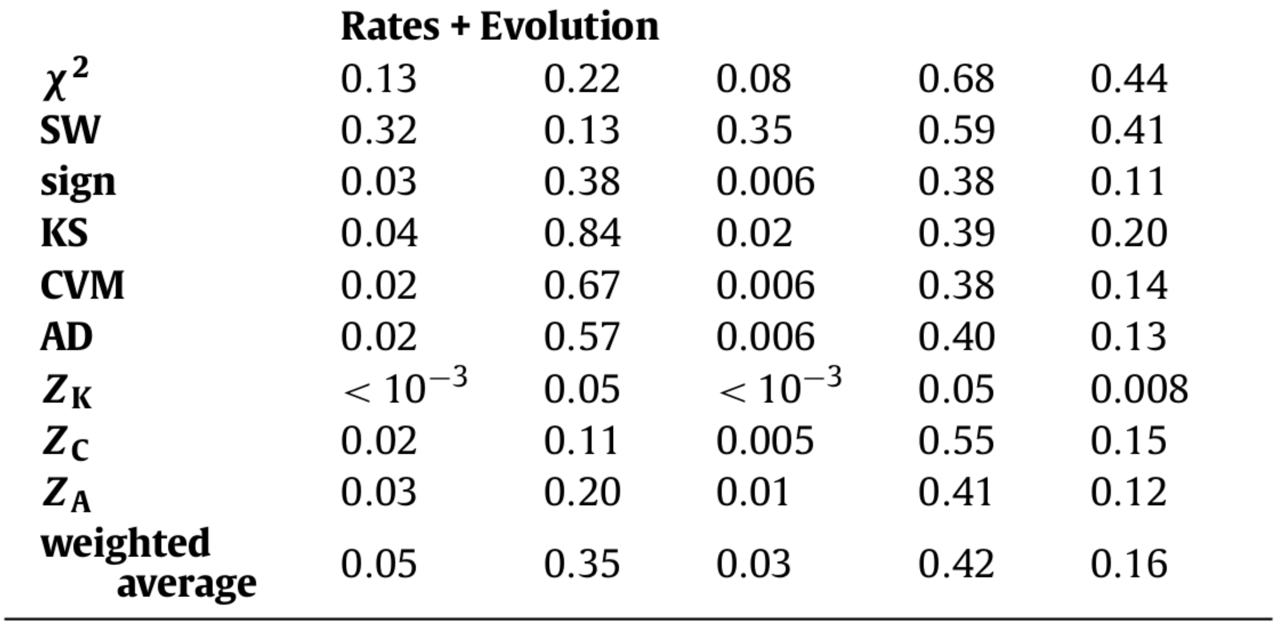
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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

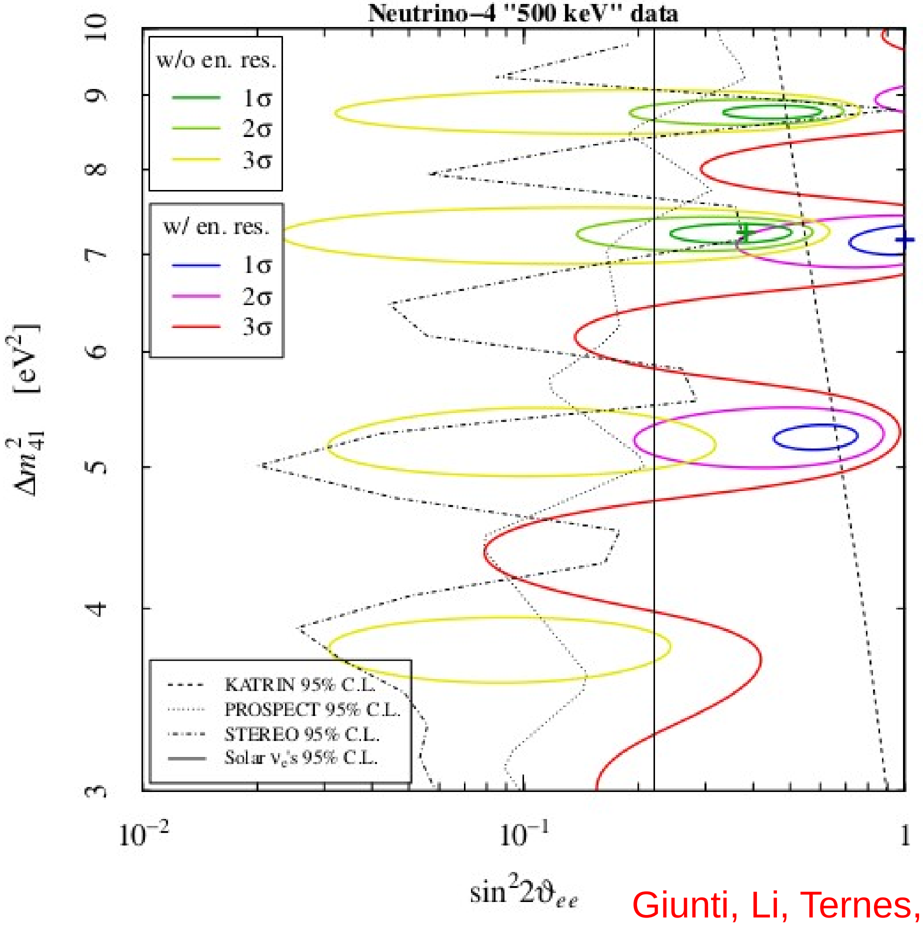
The EF model is equally good as the KI model



Rates + Evolution

	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

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

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

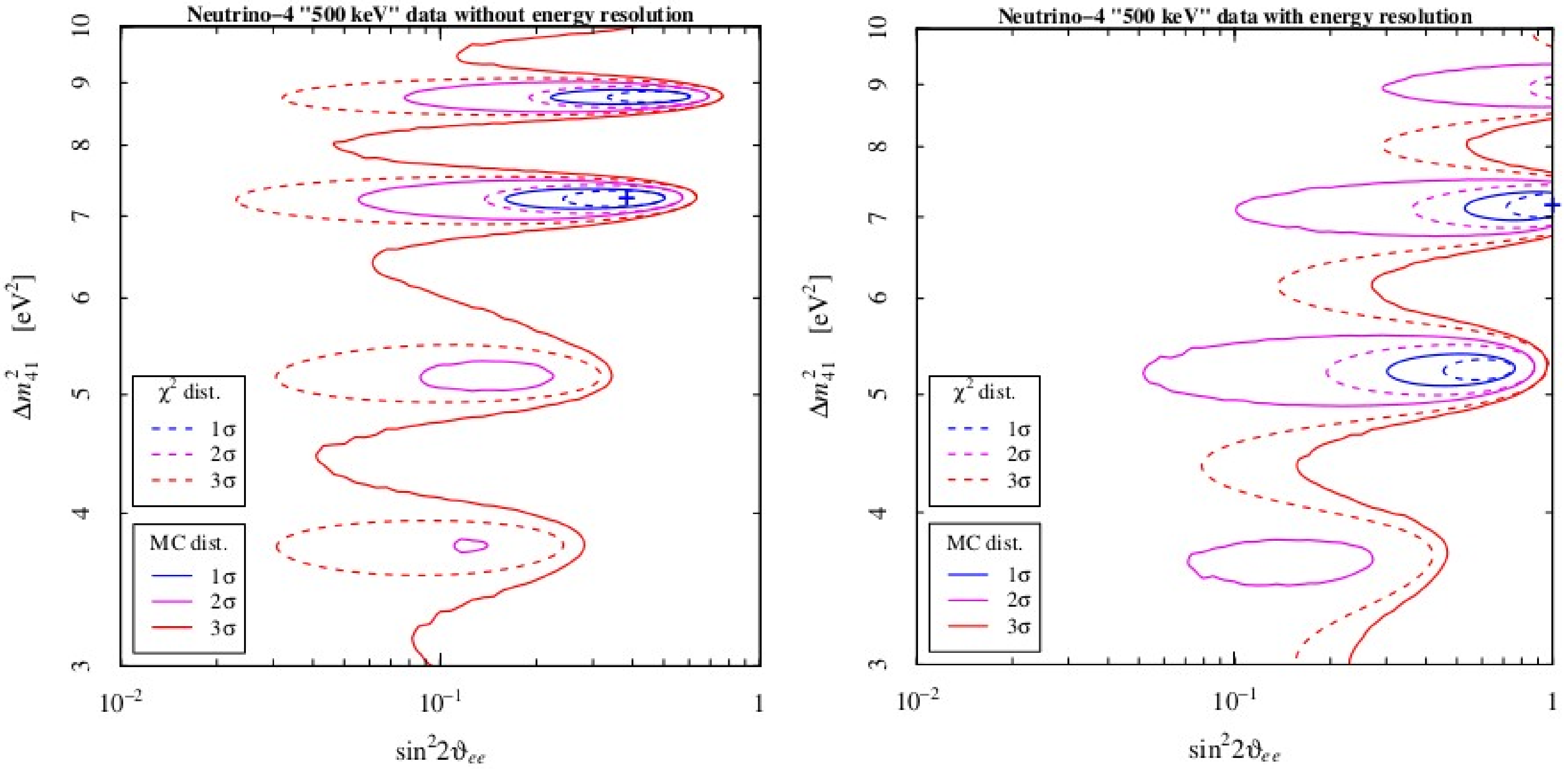
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Neutrino-4

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

Monte Carlo analysis

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

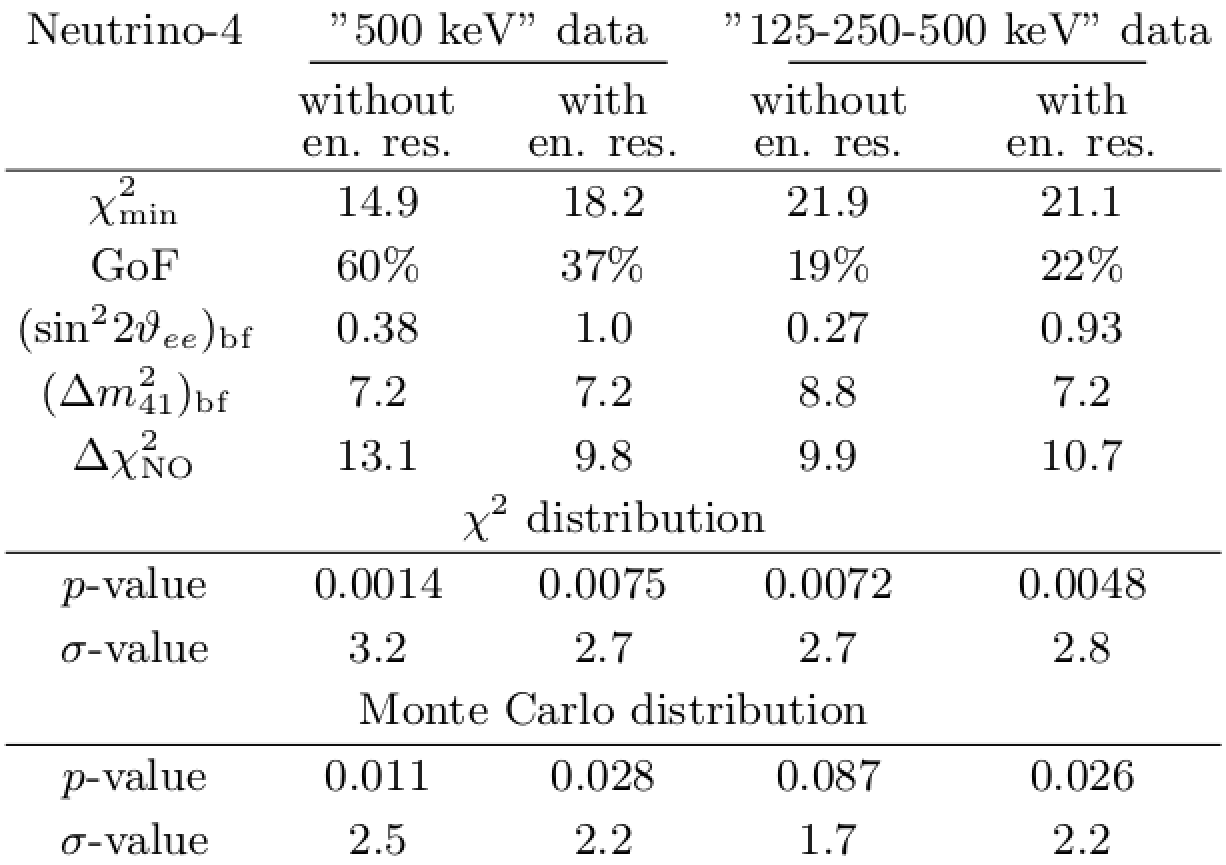


Christoph Ternes

Neutrino-4

Summary

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

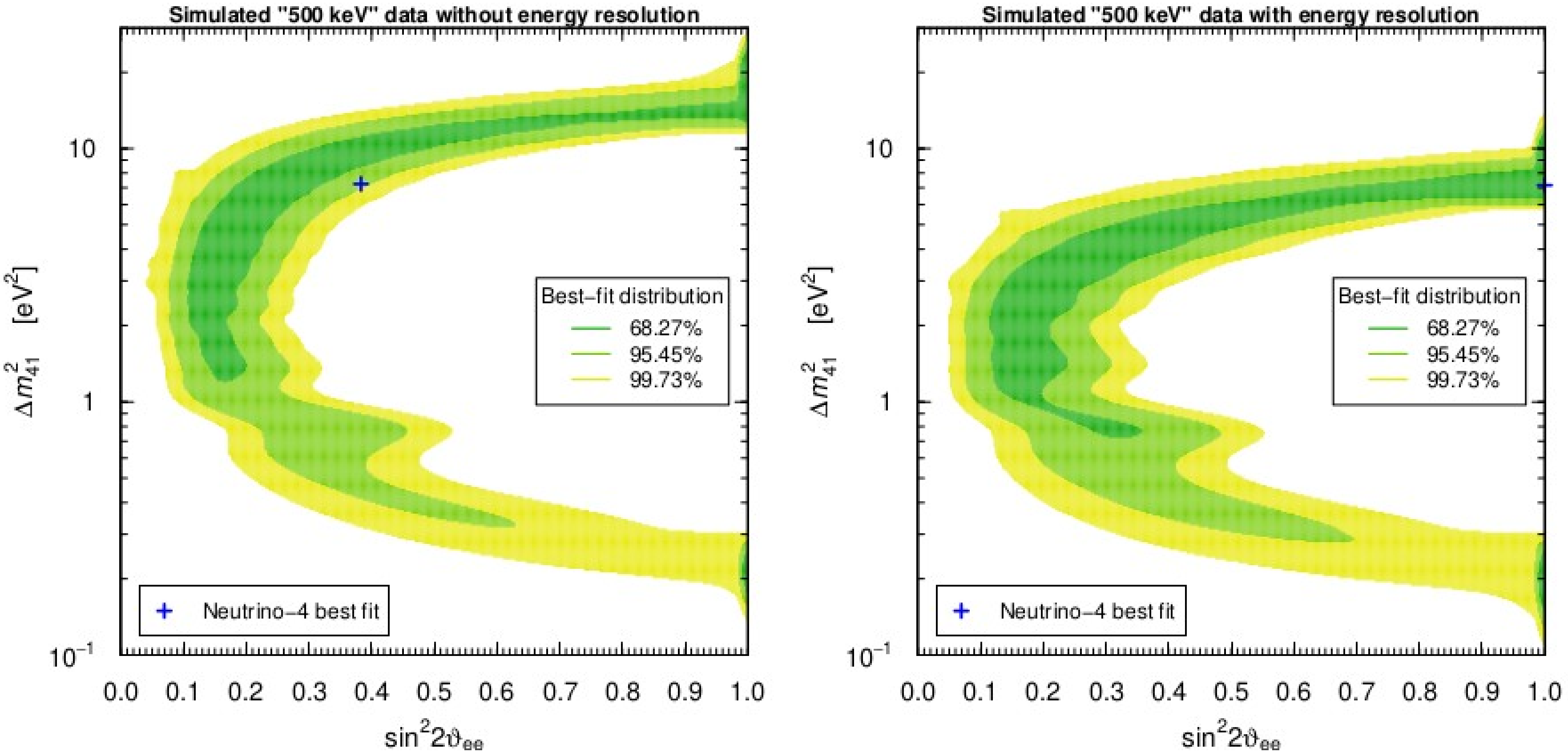


Neutrino-4	"500 keV" data		"125-250-500 keV" data	
	without en. res.	with en. res.	without en. res.	with en. res.
$\chi^2_{\rm min}$	14.9	18.2	21.9	21.1
GoF	60%	37%	19%	22%
$(\sin^2 2\vartheta_{ee})_{\rm bf}$	0.38	1.0	0.27	0.93
$(\Delta m^2_{41})_{\rm bf}$	7.2	7.2	8.8	7.2
$\Delta\chi^2_{\rm NO}$	13.1	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



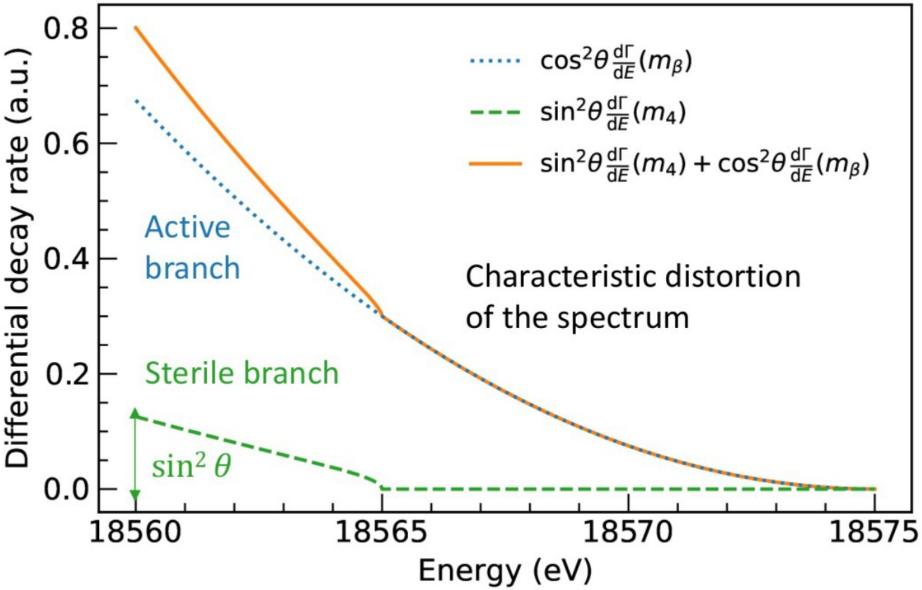
Christoph Ternes

Tritium data

Tritium experiments measure the beta-decay spectrum

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

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



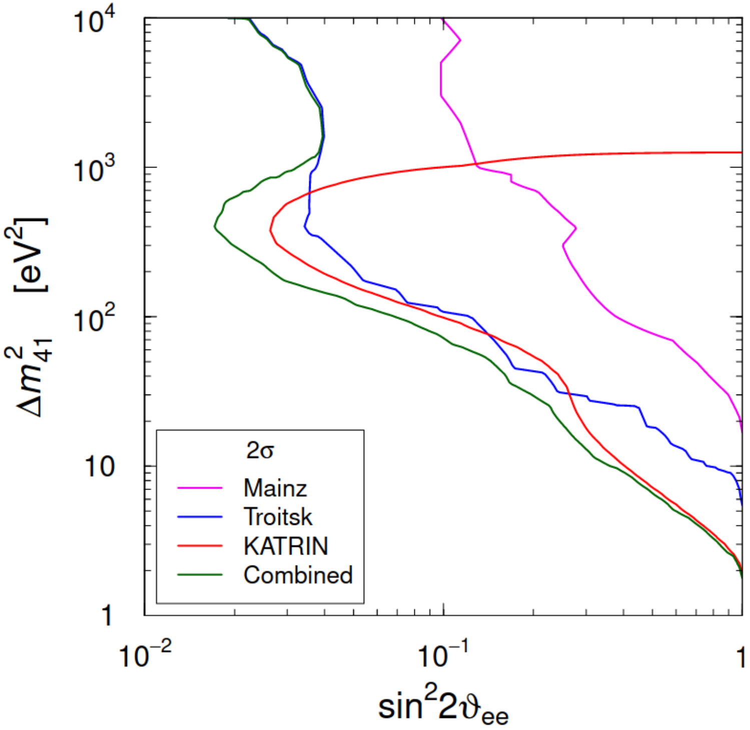
Lokhov @ NuMass 2022, Milano

Tritium data

Tritium experiments measure the beta-decay spectrum

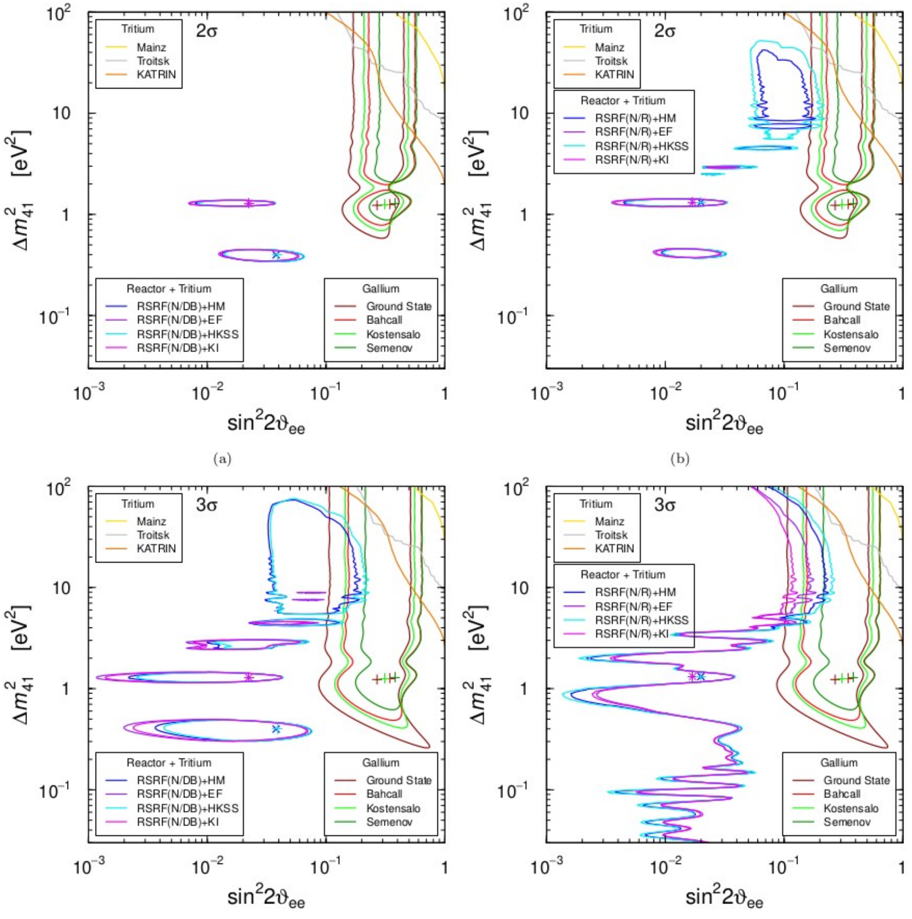
$$R_\beta(E) \simeq \frac{G_F^2 \cos^2\theta_C}{2\pi^3} \, |\mathcal{M}|^2 \, F(E, Z+1)$$
$$\times \, (E + m_e) \sqrt{(E+m_e)^2 - m_e^2}$$
$$\times \sum_j \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_\beta^2} \, \Theta(\varepsilon_j - m_\beta)$$

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



Giunti @ NOW 2022, Ostuni

Combined reactor and Tritium data



(a) (b) (c) (d)

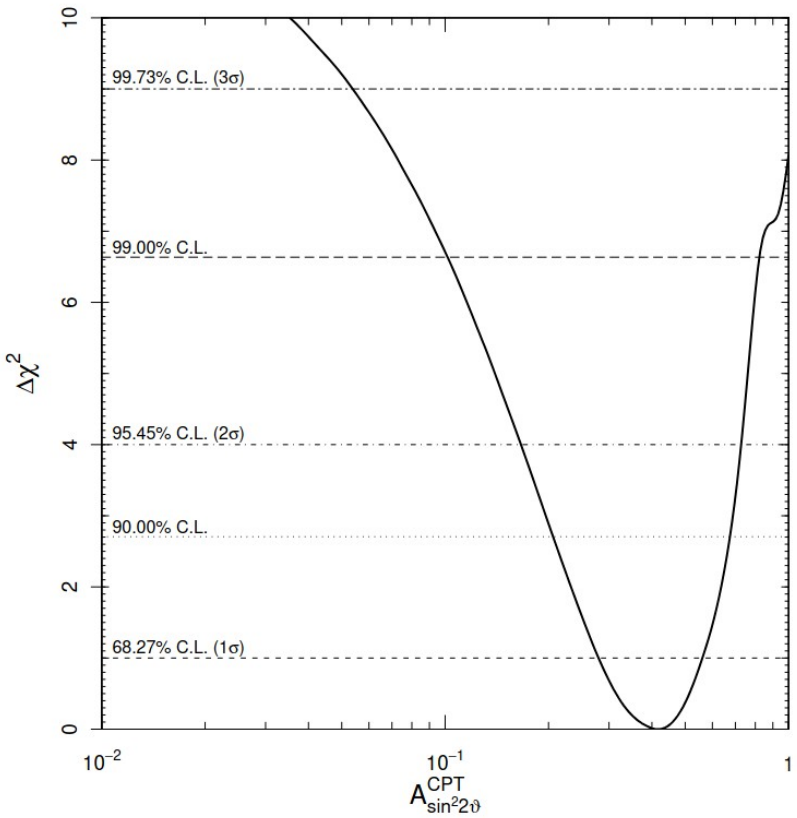
Tritium data removes the regions at large values of the mass splitting.

Severe tension for any combination with Gallium data!

	RSRF(N/DB) + Reactor Rates + Tritium							
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
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	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
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

CPT violating neutrinos?

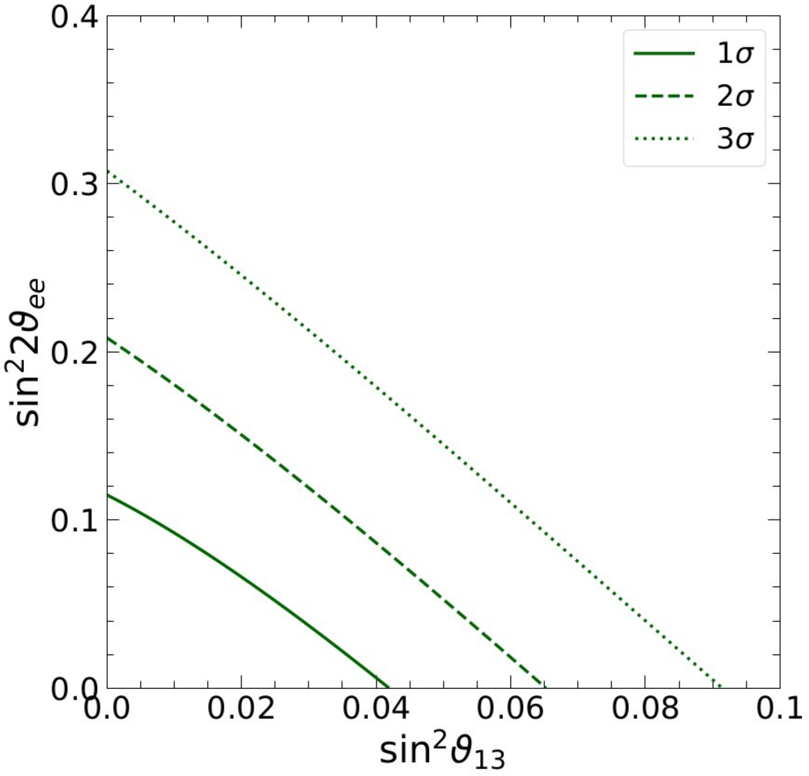


Allowing for different neutrino and antineutrino oscillation parameters could solve the tension between Reactor+Tritium data and Gallium data

$$A^{\mathrm{CPT}}_{\Delta m^2} = \Delta m^2_{\nu} - \Delta m^2_{\bar{\nu}} \,,$$
$$A^{\mathrm{CPT}}_{\sin^2 2\vartheta} = \sin^2 2\vartheta_{\nu} - \sin^2 2\vartheta_{\bar{\nu}}$$

Giunti, Laveder, 1008.4750, PRD 2010

CPT violating neutrinos?



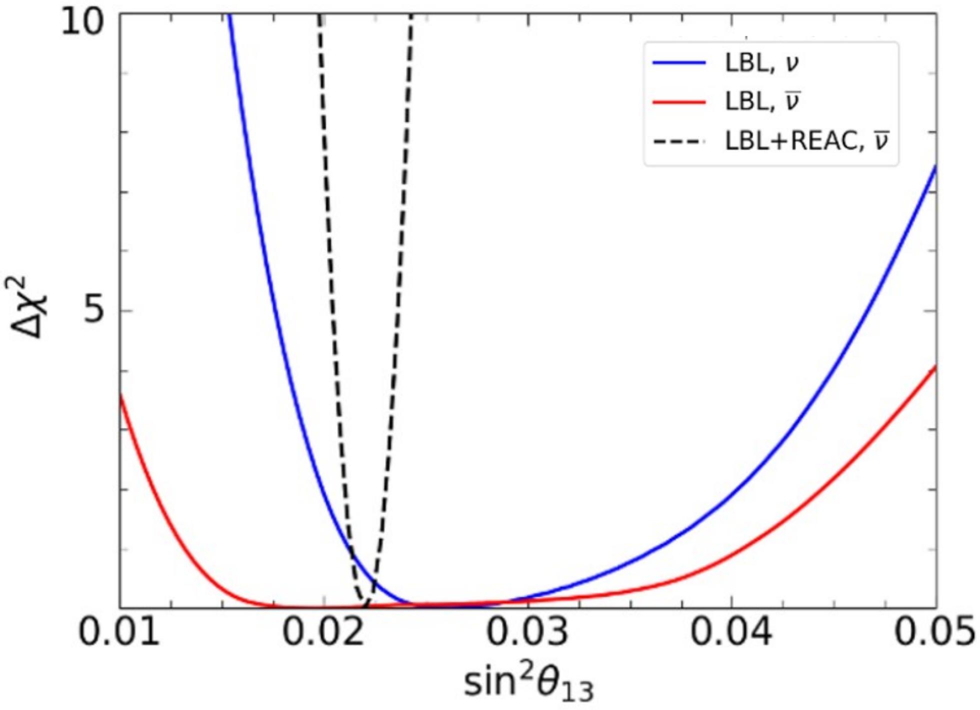
Solar experiments measure neutrinos, not antineutrinos!

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?



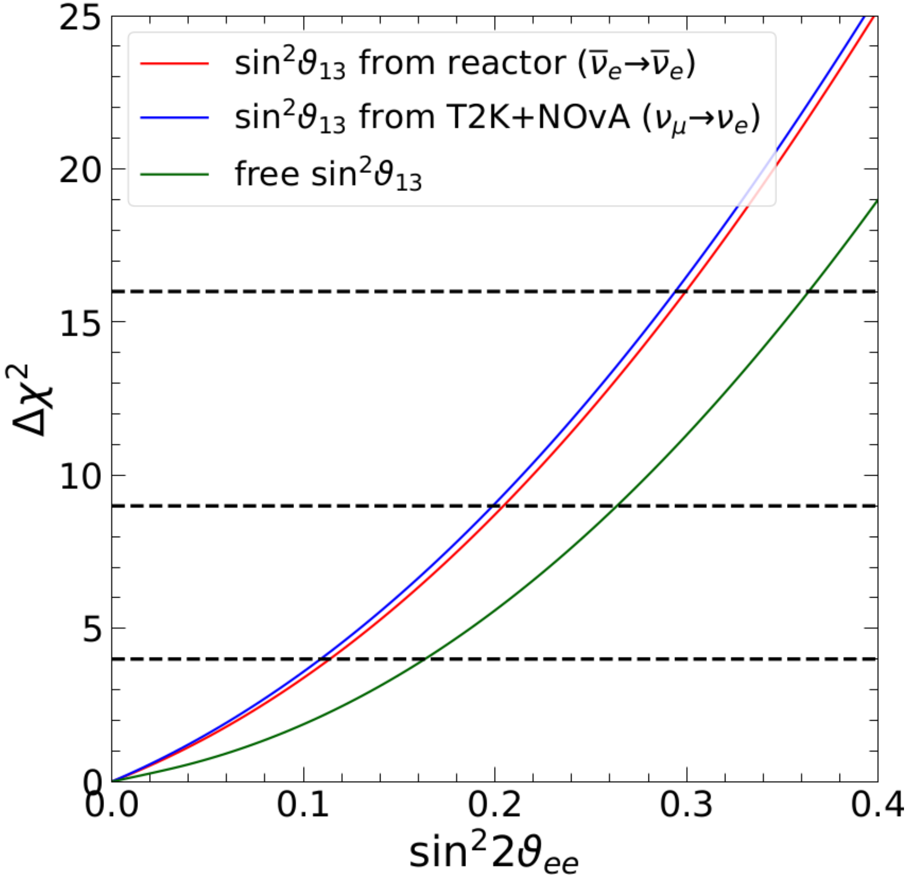
Solar experiments measure neutrinos, not antineutrinos!

Solar bound is relaxed when leaving reactor angle free!

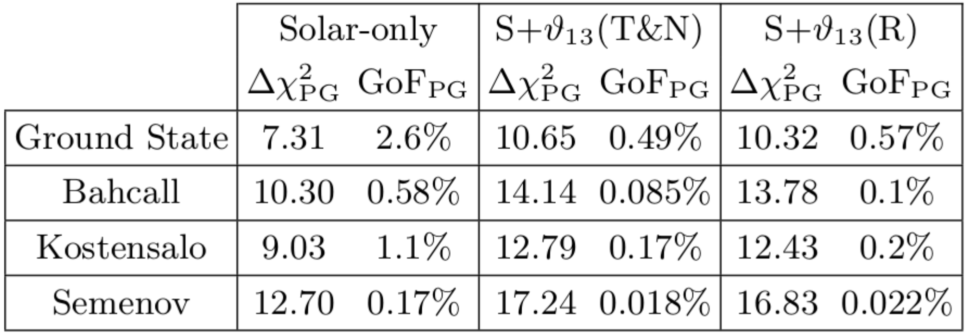
However, data from NOvA and T2K are able to bound the neutrino angle now, too.

Barenboim, Ternes, Tortola, 2005.05975, JHEP 2020

No CPT violating neutrinos



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



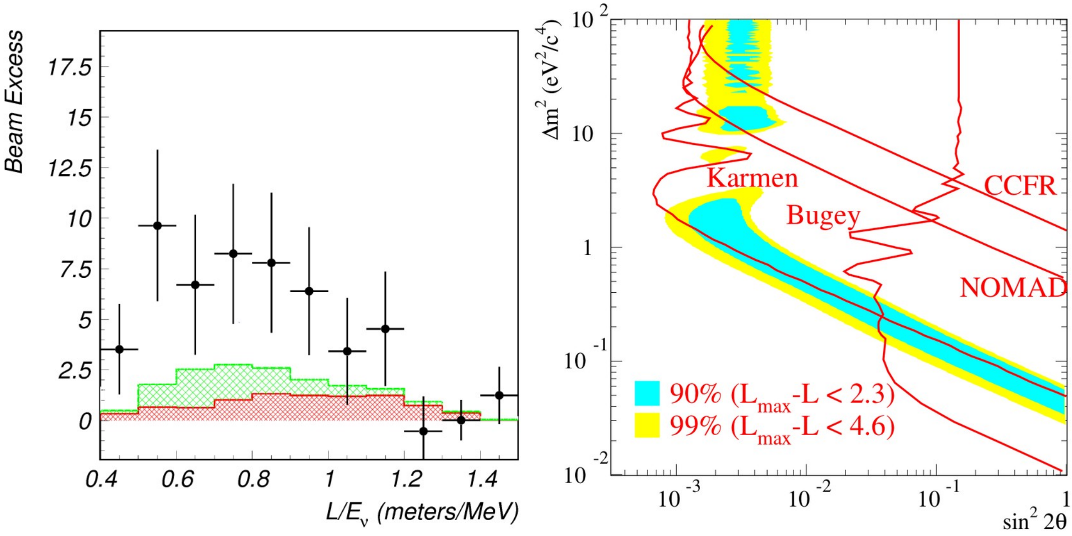
	Solar-only		S+ϑ_{13}(T&N)		S+ϑ_{13}(R)	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
Ground State	7.31	2.6%	10.65	0.49%	10.32	0.57%
Bahcall	10.30	0.58%	14.14	0.085%	13.78	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

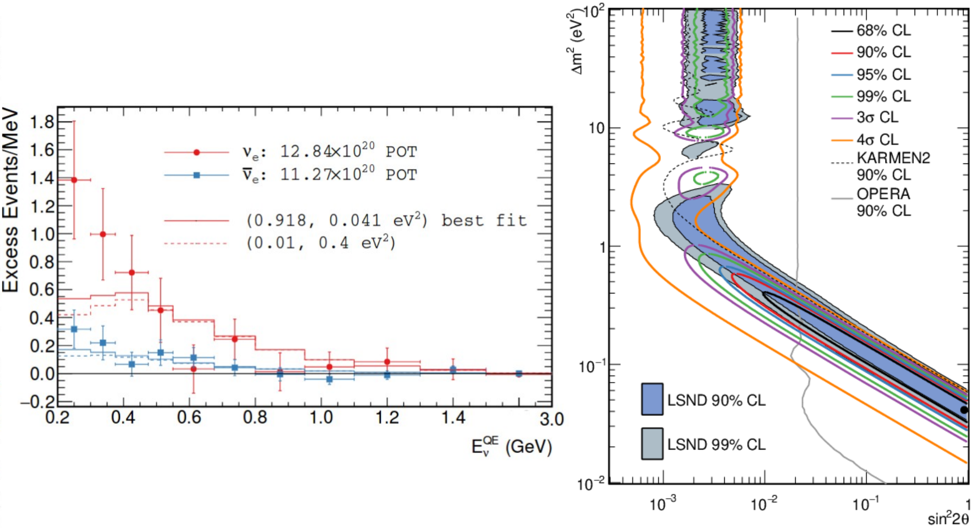
LSND and MiniBooNE

LSND saw an excess of electron neutrinos in an muon neutrino beam

MiniBooNE confirmed this observation!

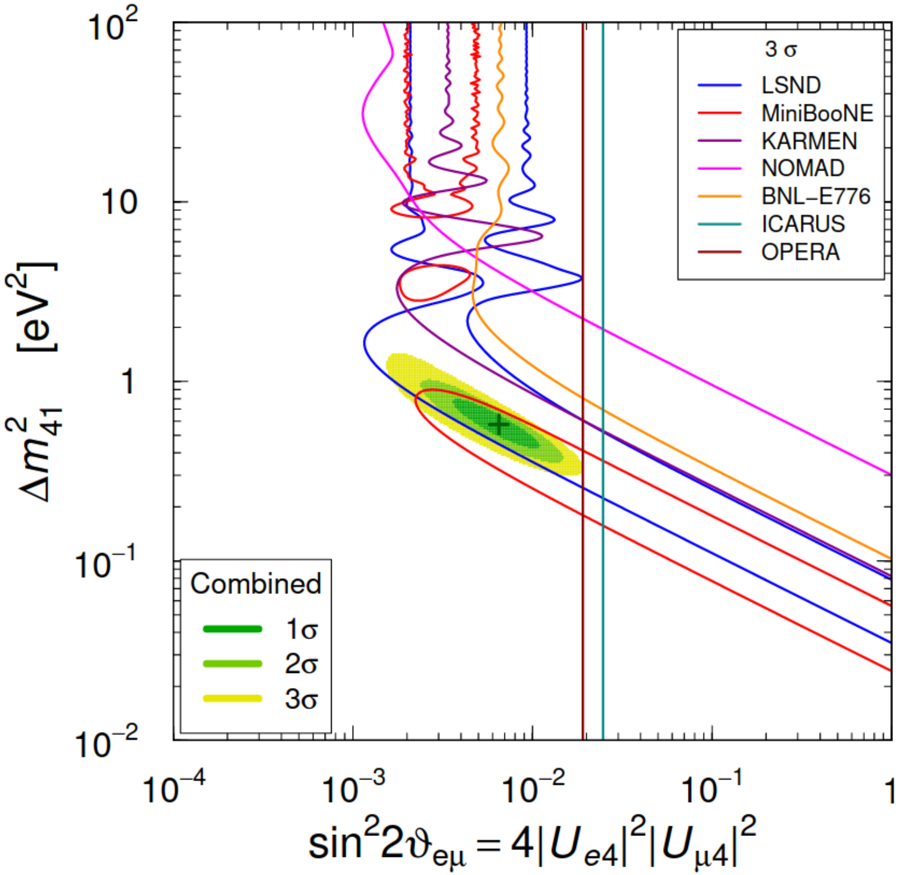


LSND, hep-ex/0104049, PRD 2001



MiniBooNE, 1805.12028, PRL 2018

Appearance results



Strong preference in appearance channel

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

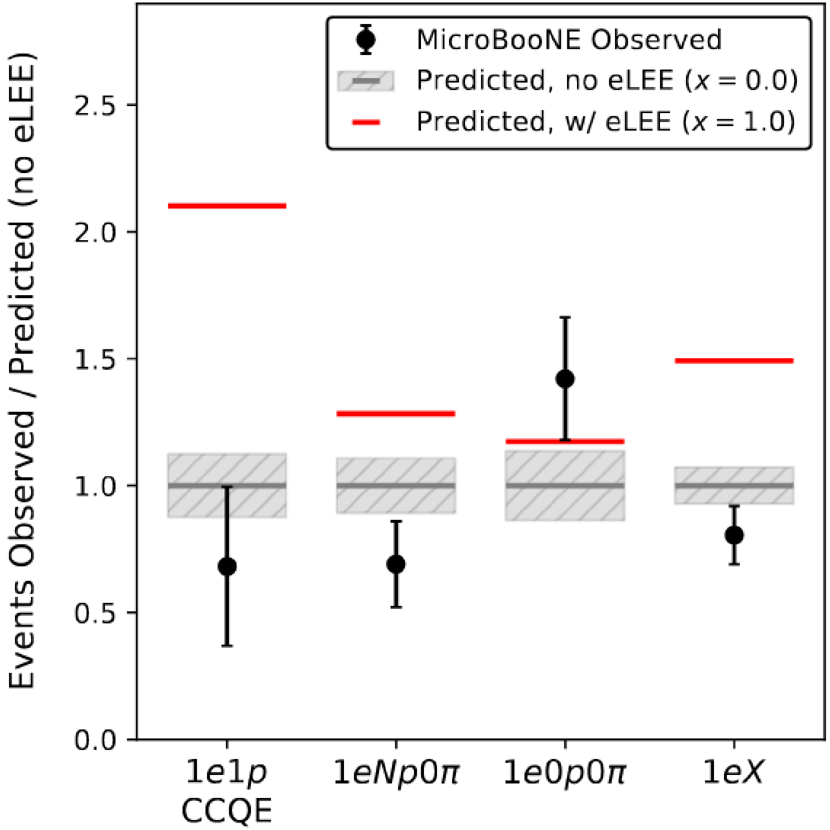
LSND and MiniBooNE only partially agree

Giunti, Lasserre, 1901.08330, Ann.Rev. 2019

MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels



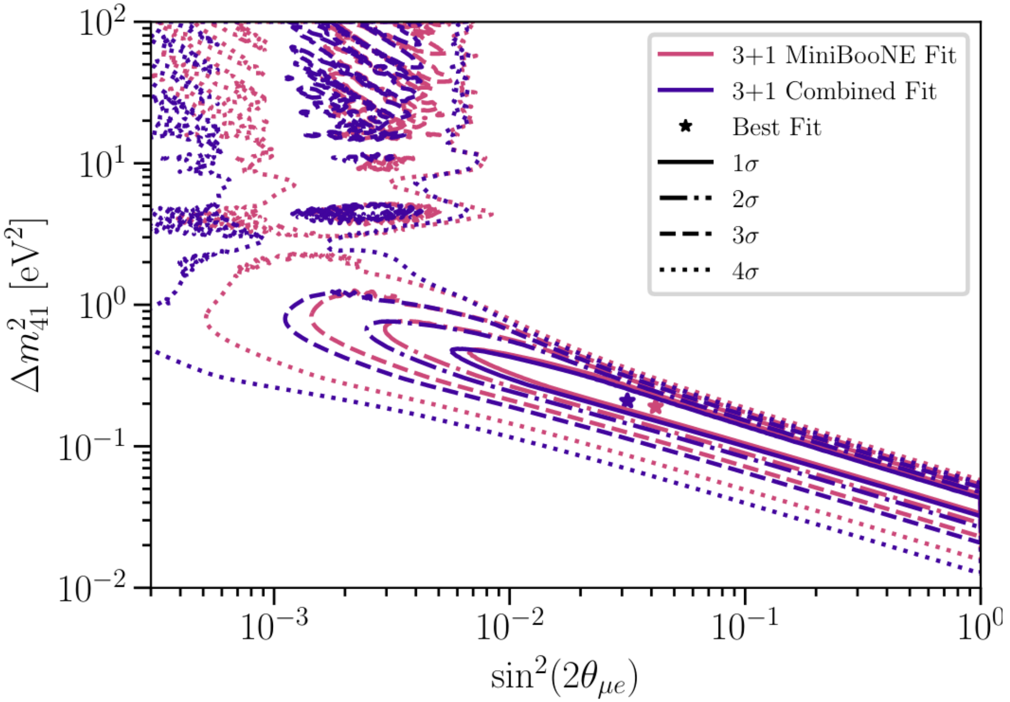
MicroBooNE, 2110.14054, PRL 2022

MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels

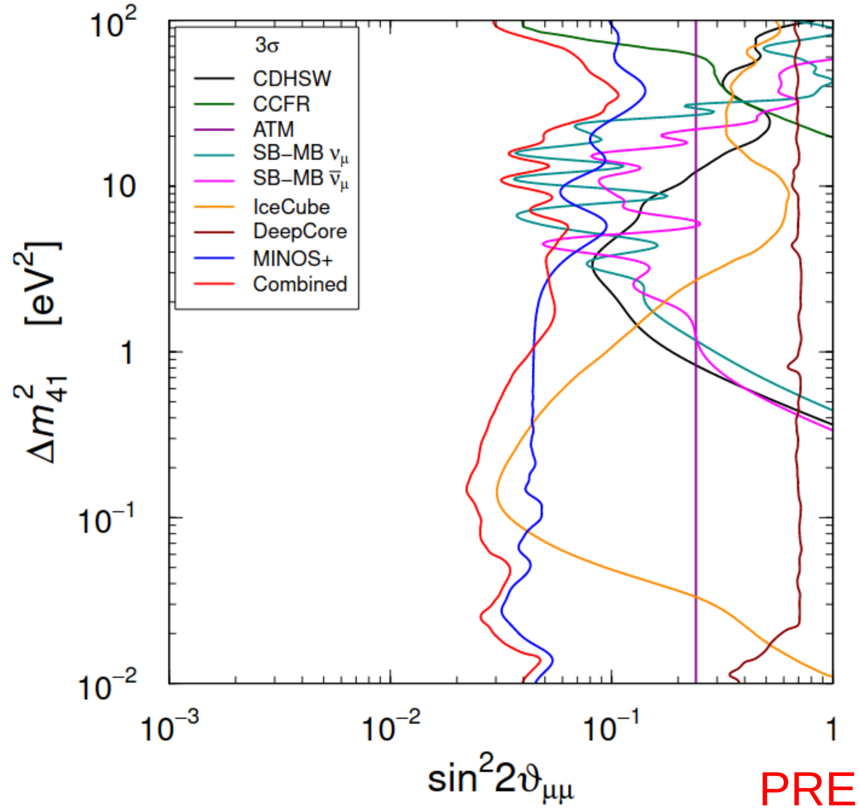
A combined analysis shows that MicroBooNE can not exclude the region of parameter space preferred by MiniBooNE

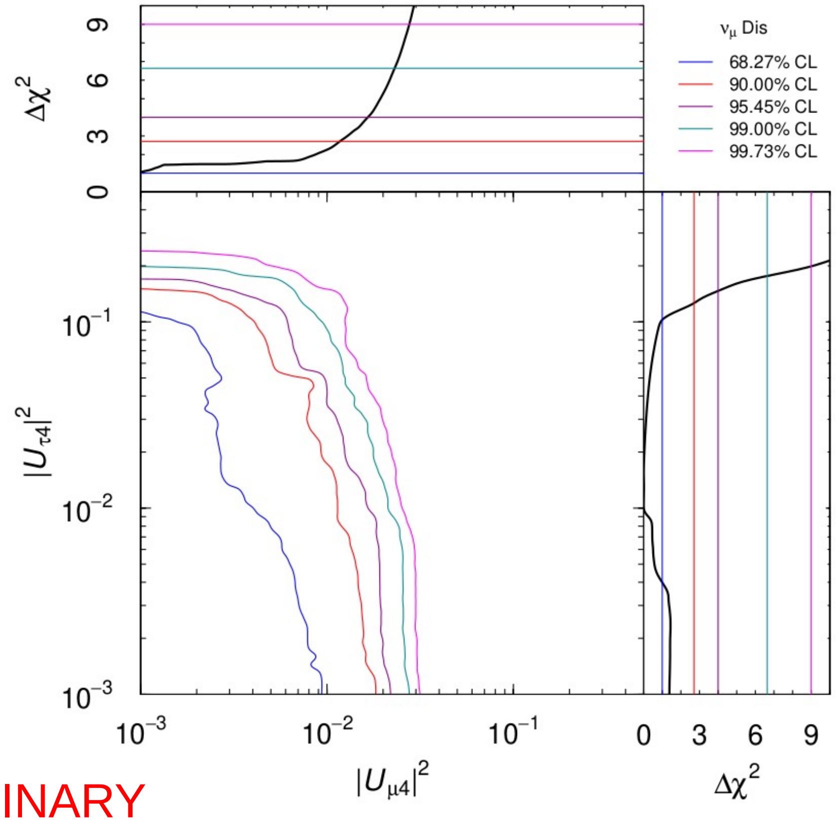


MiniBooNE, 2201.01724

Accelerator and atmospheric experiments

No evidence in muon disappearance

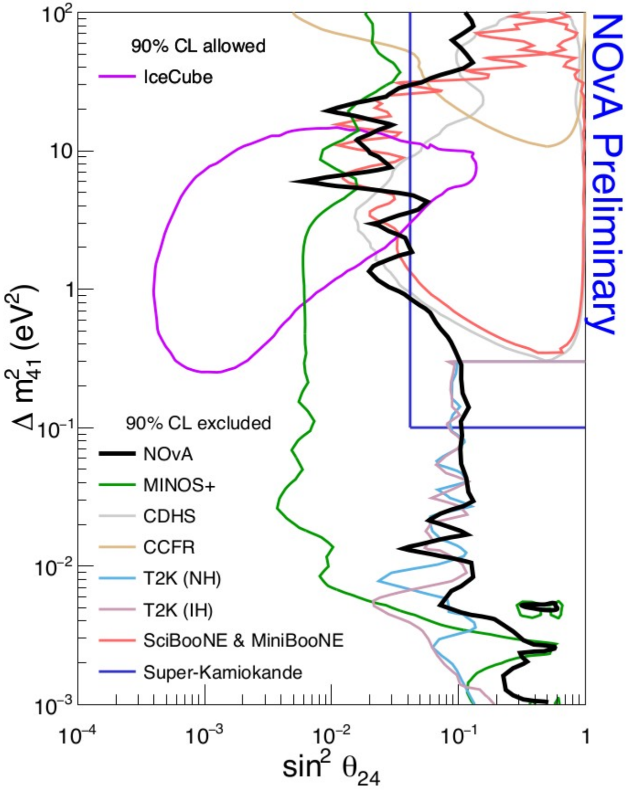




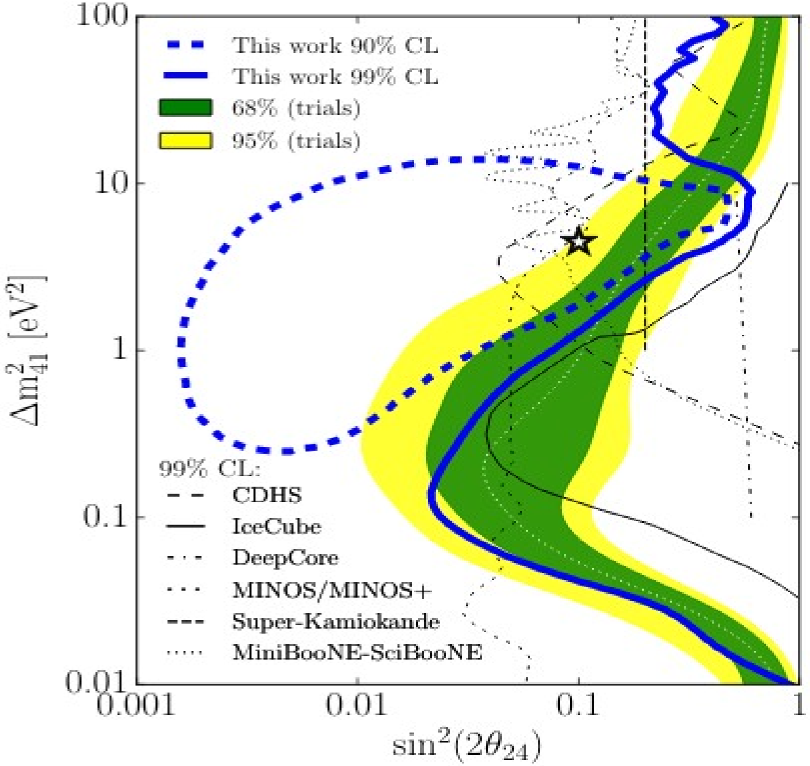
PRELIMINARY

Accelerator and atmospheric experiments

No evidence in muon disappearance

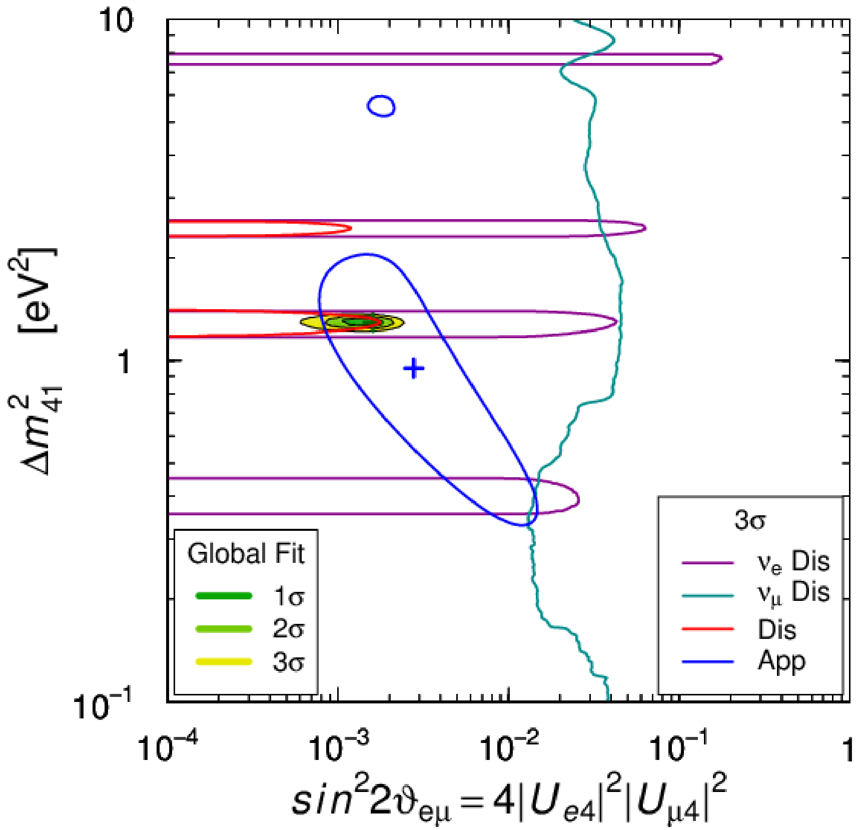


NOvA, Talk by Jeff Hartnell, Neutrino 2022



IceCube, 2005.12942, PRL 2020

Global fit?



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

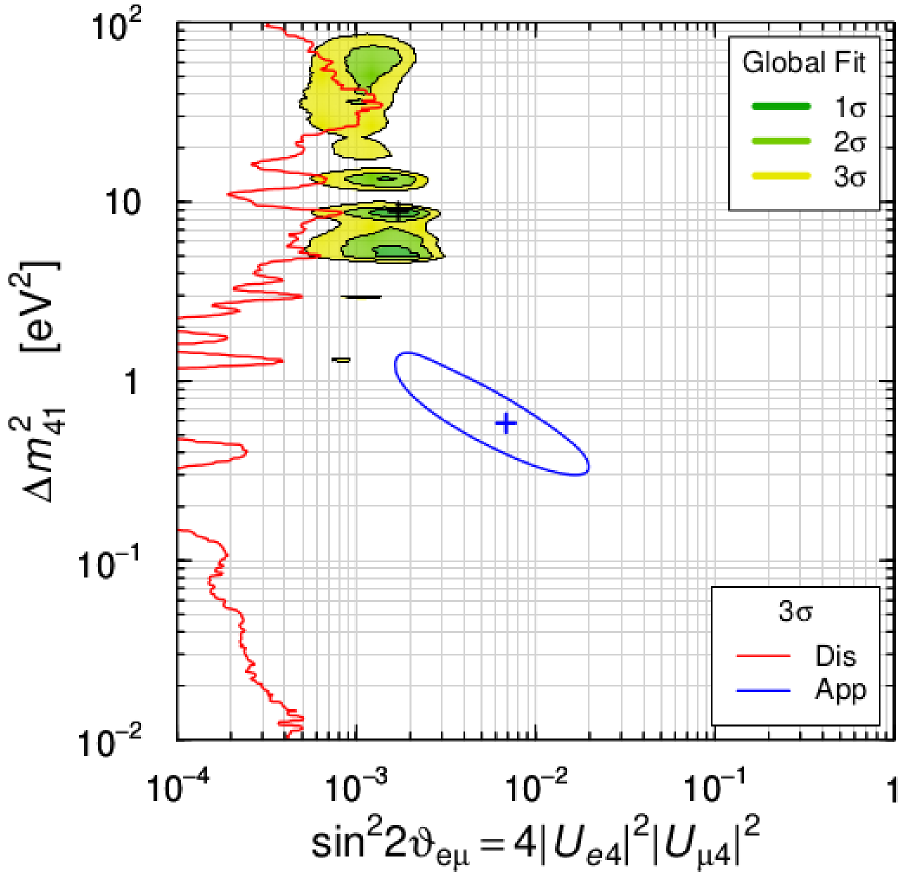
$$\nu_\mu \to \nu_\mu : |U_{\mu4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

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

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

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

Global fit?



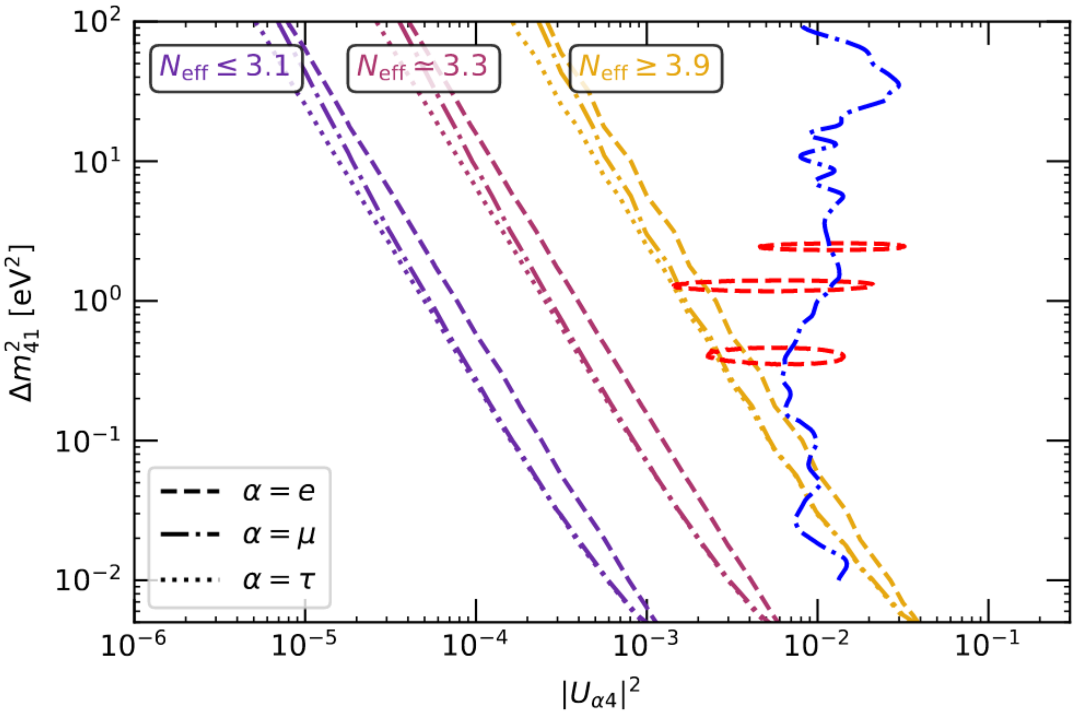
NOT most up-to-date data here!

No overlap anymore!

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

Global 3+1 fit is unacceptable!

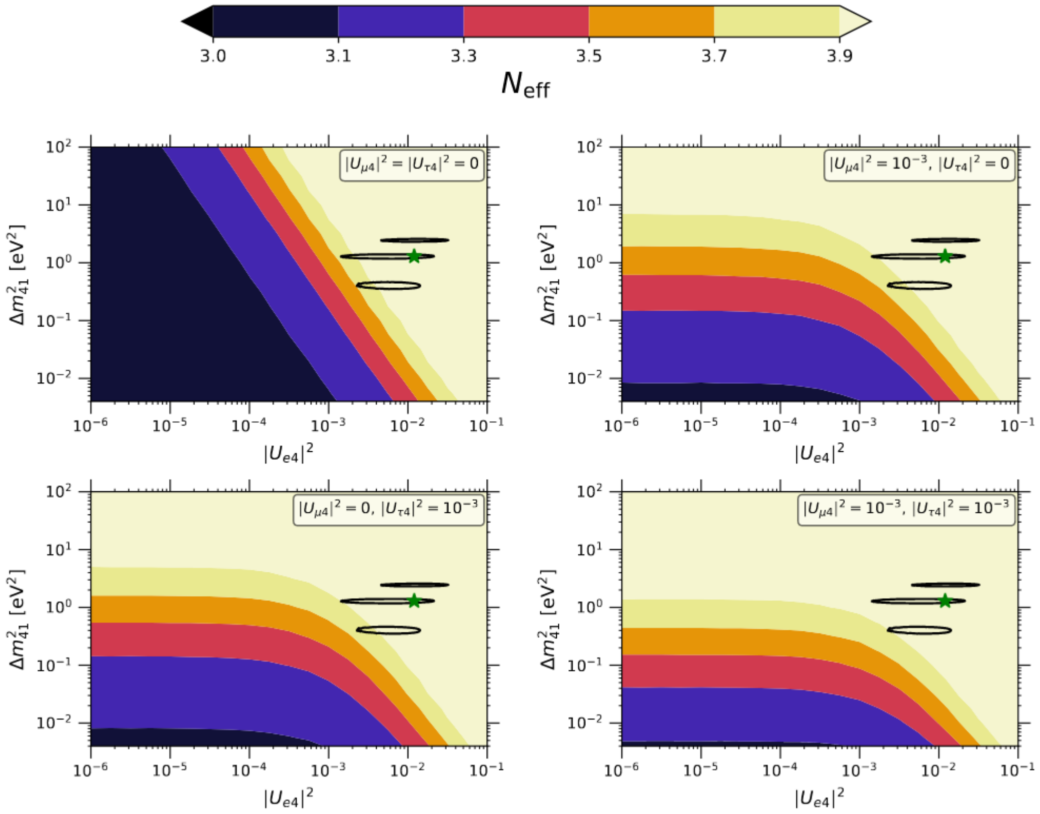
Cosmology



Cosmology can set strong bounds on sterile parameter space

Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

Cosmology

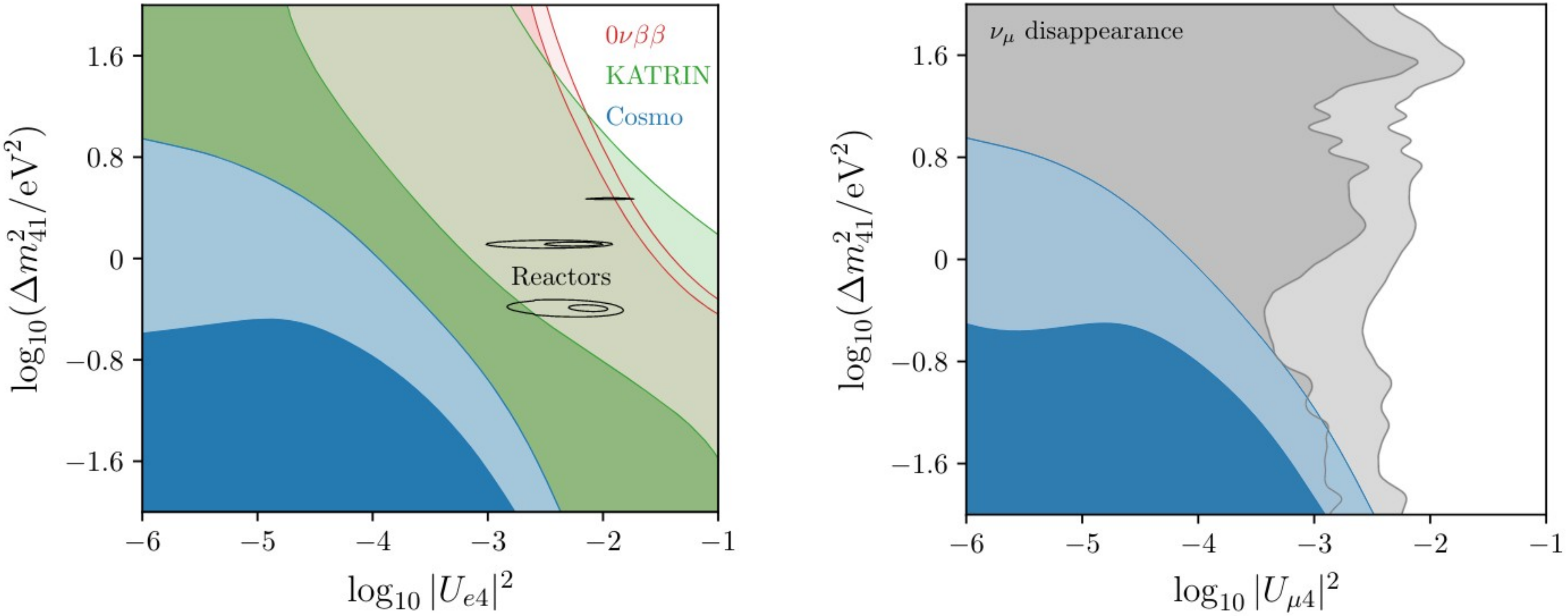


Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

Cosmology can set strong bounds on sterile parameter space

Which become even stronger when considering more than one angle

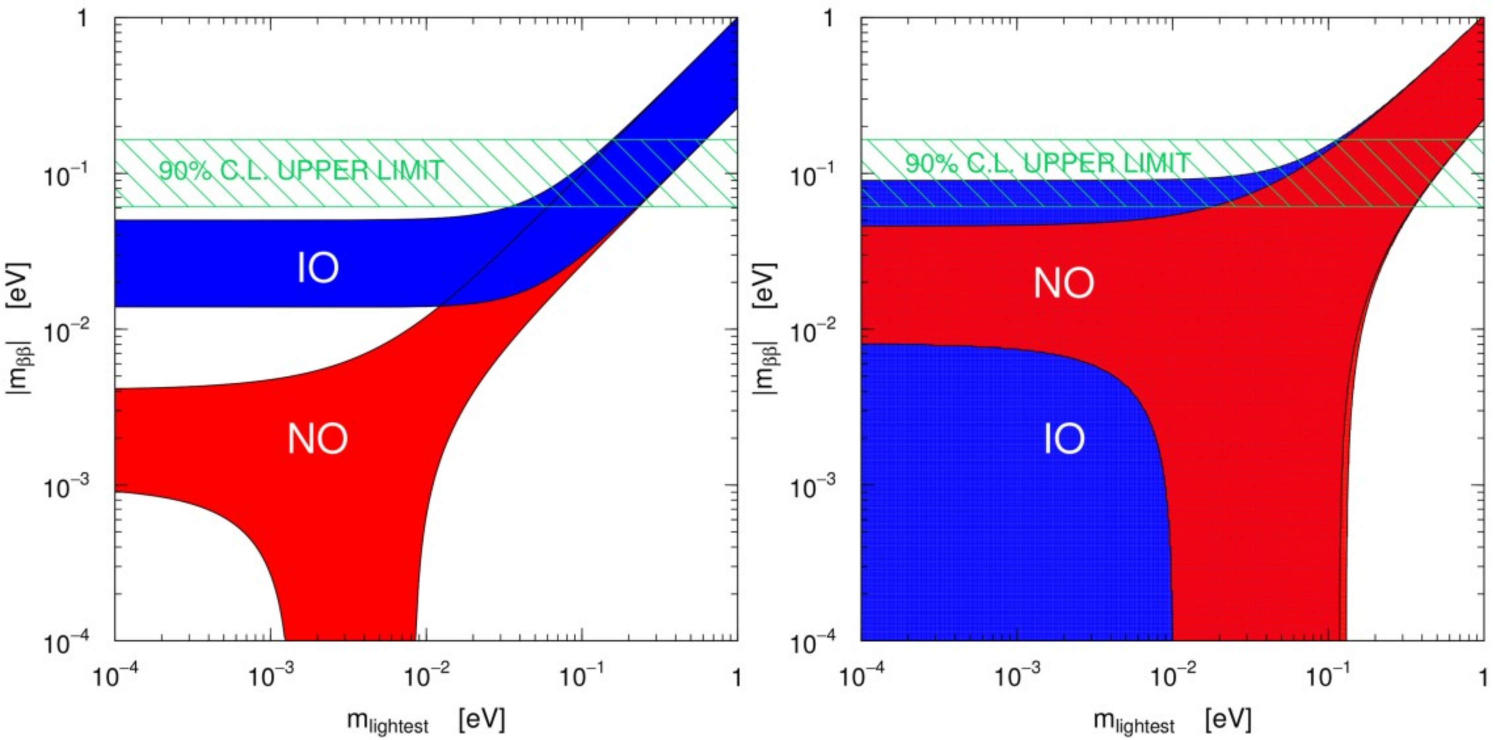
Cosmology



Complementary between Cosmology and terrestrial experiments

Hagstotz, et al, 2003.02289, PRD 2021

Neutrinoless ββ 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.