Development in reactor neutrino models

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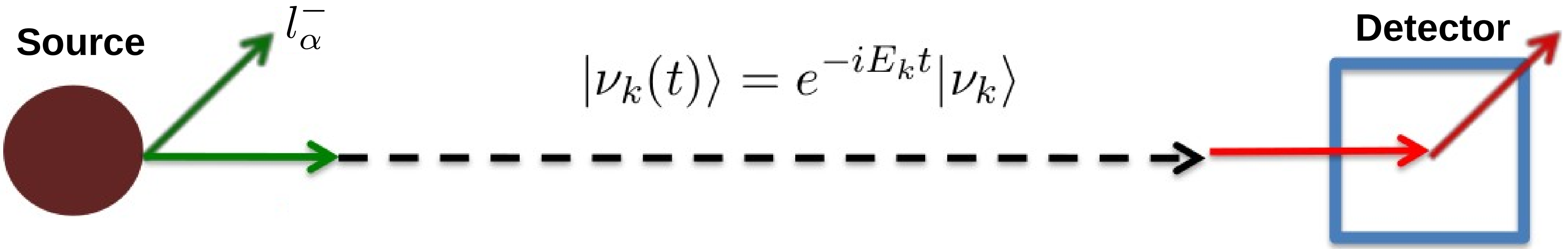
Neutrino oscillations



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

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

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

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

Three-neutrino oscillations

Neutrino mixing matrix

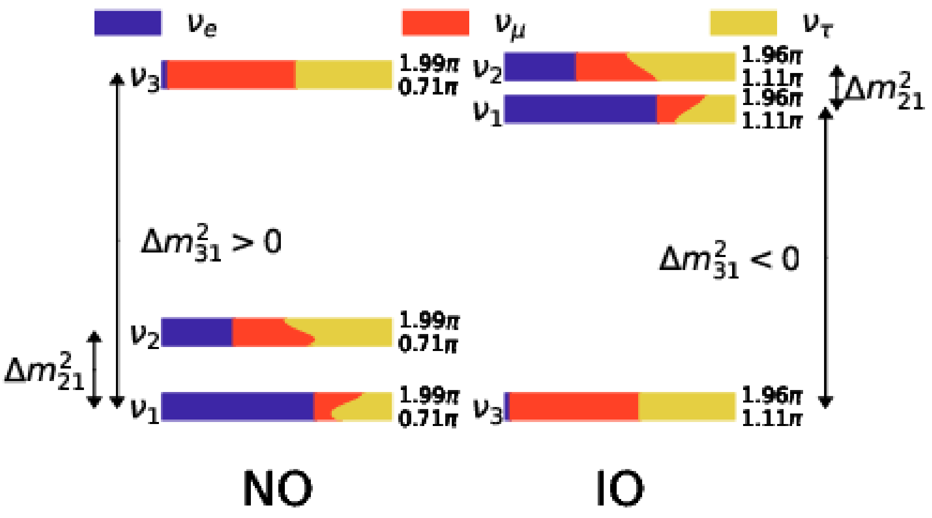
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

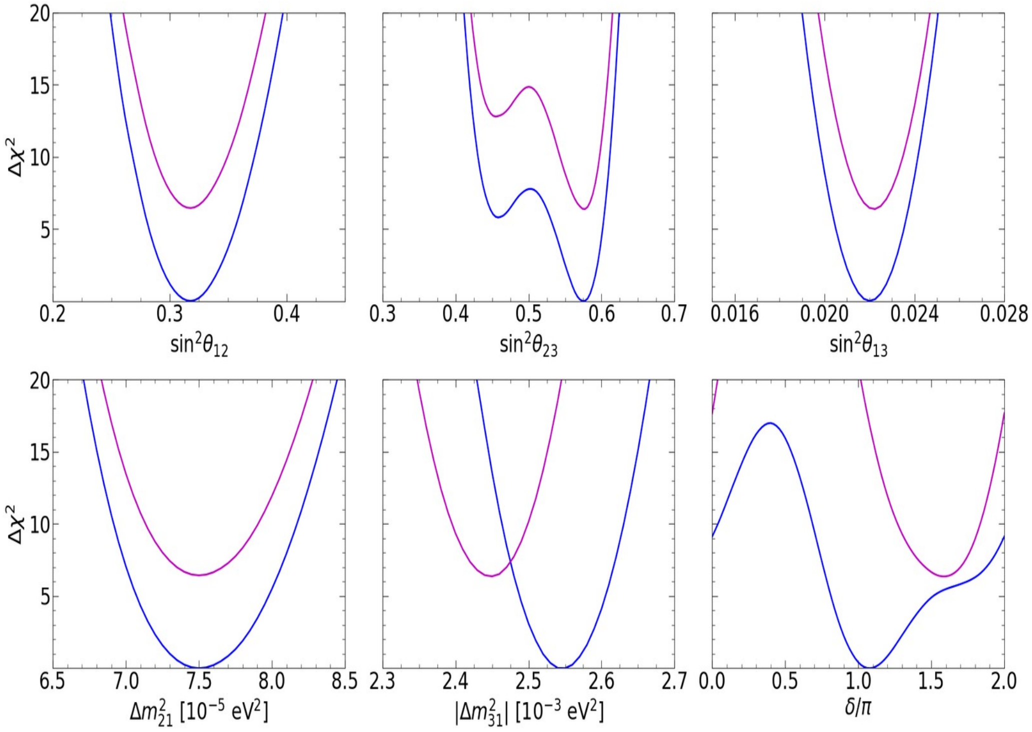
Oscillations are only sensitive to mass splittings



Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021

Talk by Mariam Tortola!



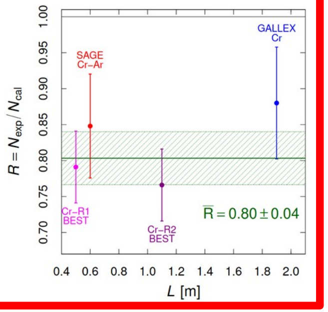
parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50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

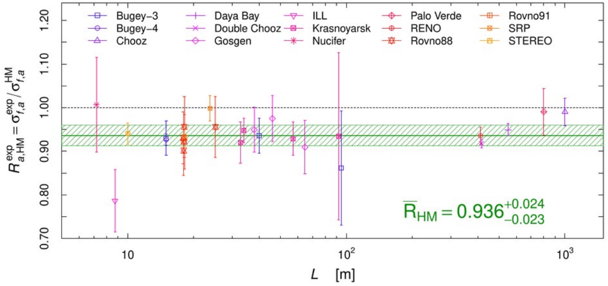
See also:
NuFit - 2111.03086 , Universe 2021

Anomalies

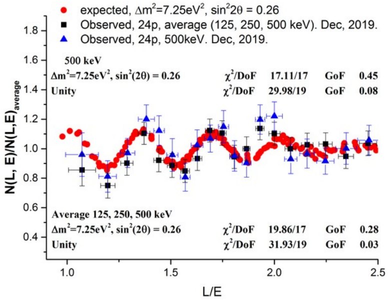
Gallium



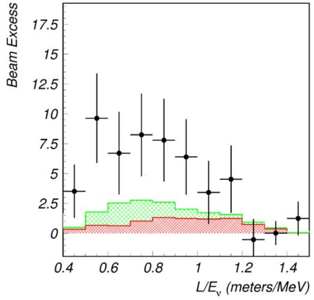
RAA



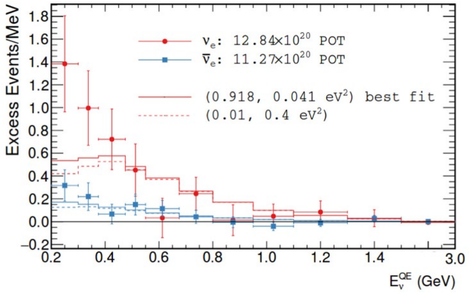
Neutrino-4



LSND

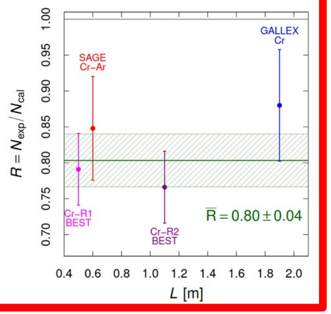


MiniBooNE

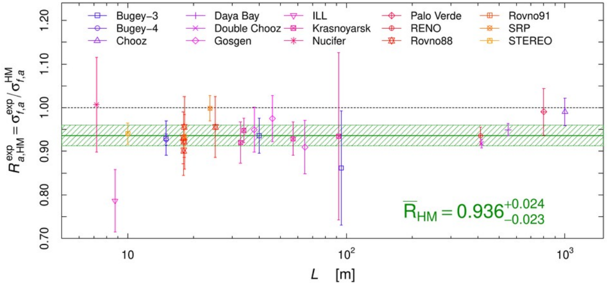


Anomalies

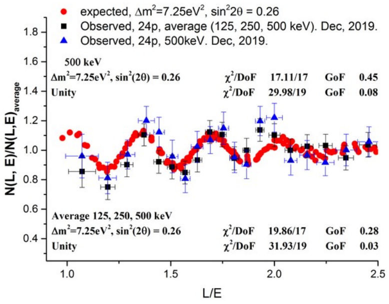
5-6σ Gallium



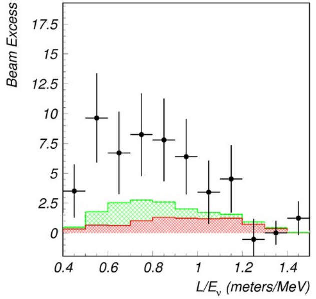
1-3σ RAA



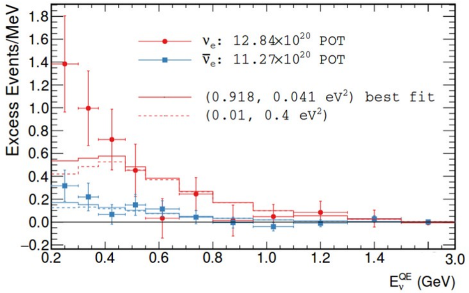
2-3σ Neutrino-4



~4σ LSND



~5σ MiniBooNE



Anomalies

Three-neutrino oscillations can not account for short baseline anomalies

$$L_{kj}^{\rm osc} = \frac{4\pi E}{\Delta m_{kj}^2}$$

$$L_{21}^{\rm osc} \gtrsim 50 \text{ km} \frac{E}{\rm MeV}$$

$$L_{31}^{\rm osc} \gtrsim 1 \text{ km} \frac{E}{\rm MeV}$$

Short baseline oscillations require:

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

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

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

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

@LSND, Karmen, MiniBooNE, Opera

Disappearance

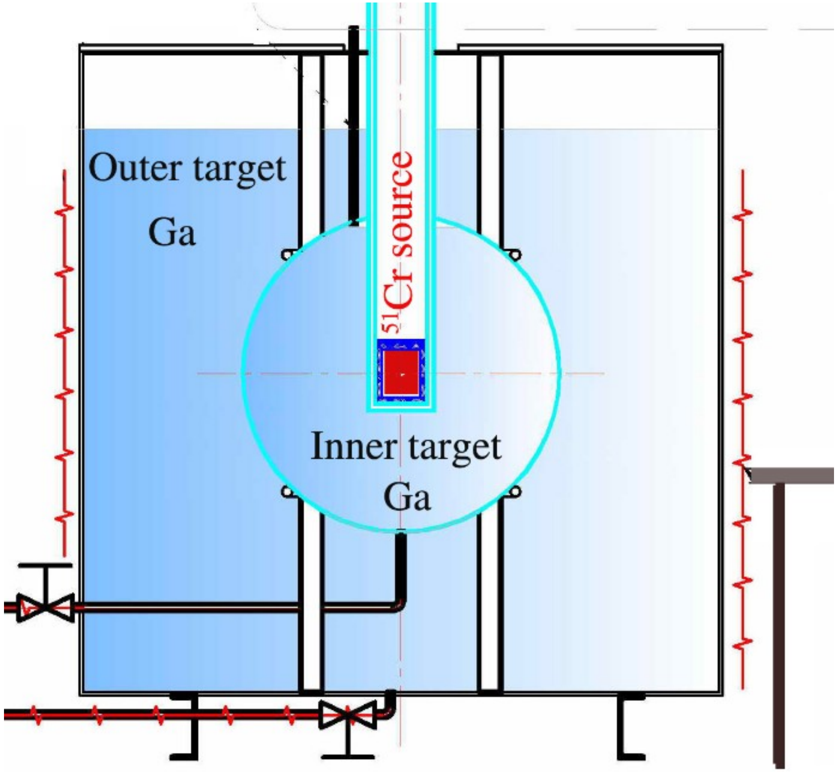
$$P_{\alpha\alpha}^{\mathrm{SBL}} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

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

@Reactors and Gallium
@atmospherics and accelerators

The Gallium anomaly

BEST, 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

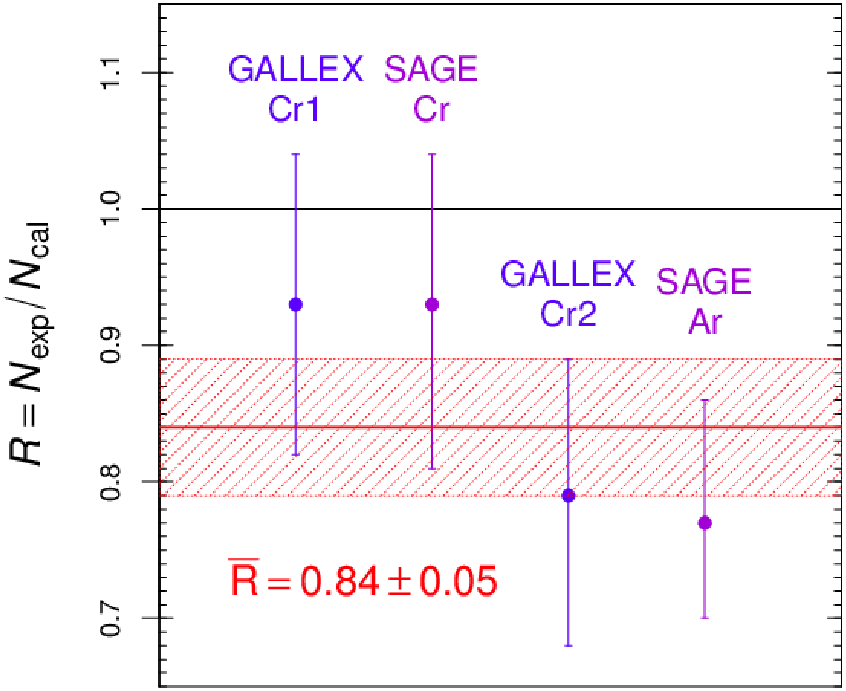
Model	Method	^{51}Cr		^{37}Ar	
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State	$T_{1/2}(^{71}\text{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997)	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015)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

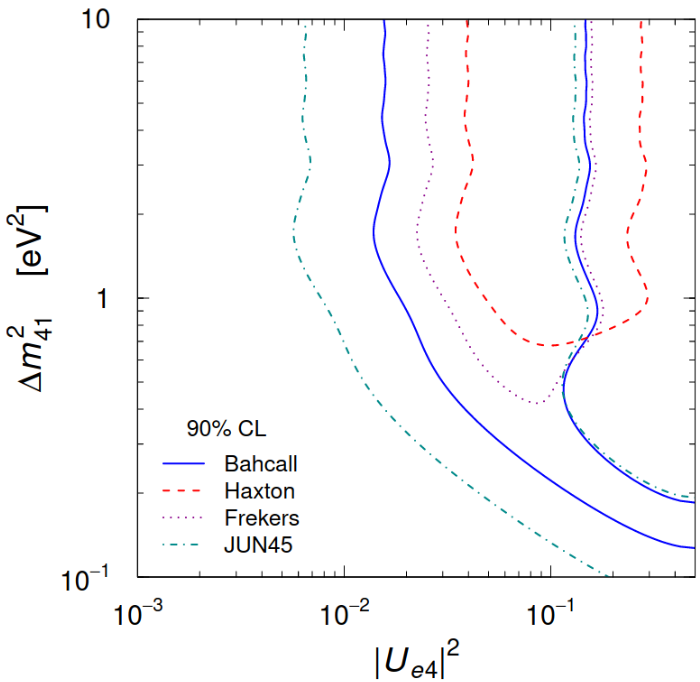
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Slightly different values for the different cross section models

The Gallium anomaly

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

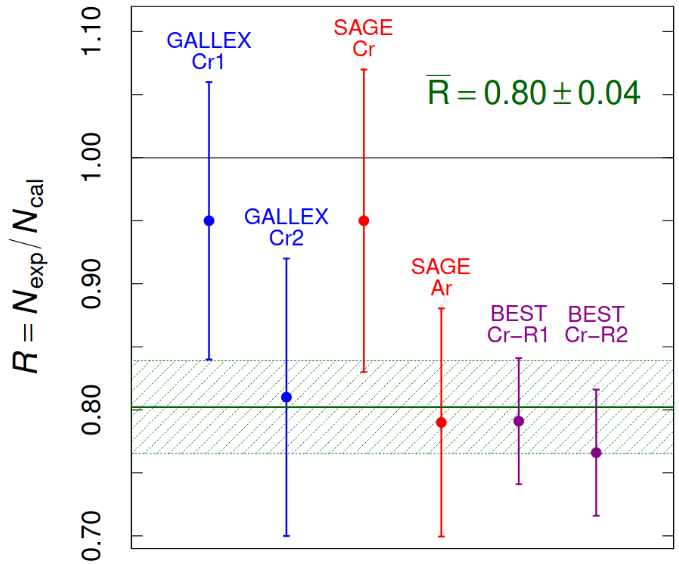


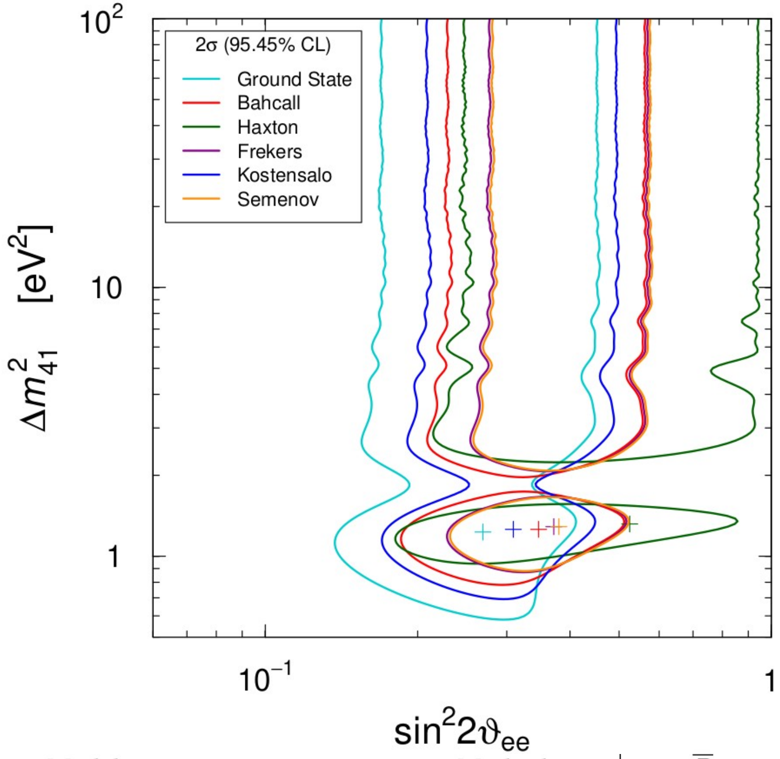


The significance of the "old" Gallium anomaly varied between 2.3 and 3.0σ, depending on the cross section model

The Gallium anomaly

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





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

Strong indication for short baseline (SBL) oscillations?

See also:
Barinov, Gorbunov, 2109.14654, PRD2022
Berryman, Coloma, Huber, Schwetz, Zhao, 2111.12530, JHEP 2022

The reactor antineutrino anomaly: Flux calculations

The neutrino spectrum is produced from the beta decays of the fission products of $^{235}\mathrm{U}$, $^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, and $^{241}\mathrm{Pu}$

Summation method

$$S_{\mathrm{tot}}(E,t) = \sum_k F_k(t)\, S_k(E)$$

↑ fission fractions

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

↑ cumulative fission yield; ↑ branching ratio; ← allowed or forbidden decay spectrum

There are more than 1000 beta spectra and branching ratios

Nuclear data bases might be incomplete or inaccurate

Conversion method

Measure beta spectra of

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

and use empirical method to get

$$S_k^e(E_e) \rightarrow S_k^\nu(E_\nu)$$

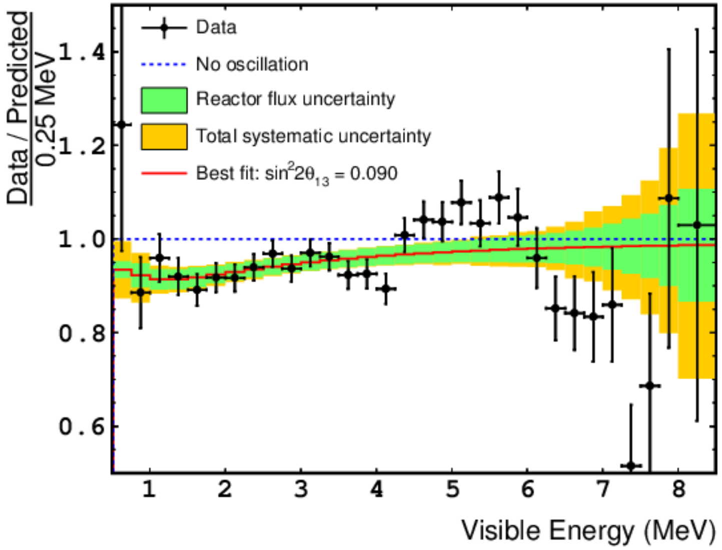
5 MeV bumb

5 MeV bump discovered in 2014

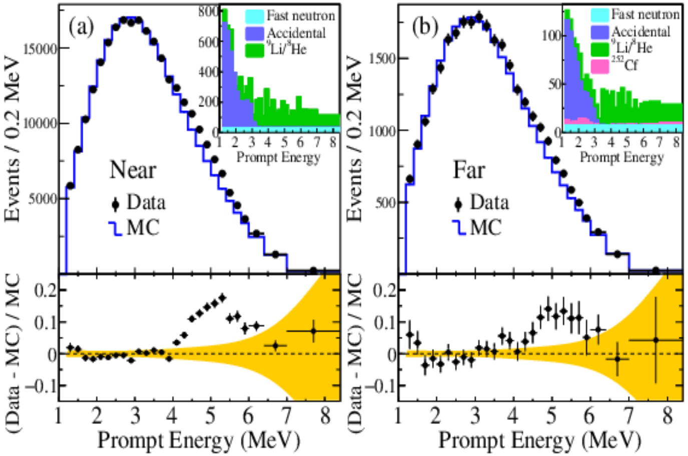
Can not been explained with SBL oscillations

Proof of our incomplete understanding of nuclear reactor fluxes

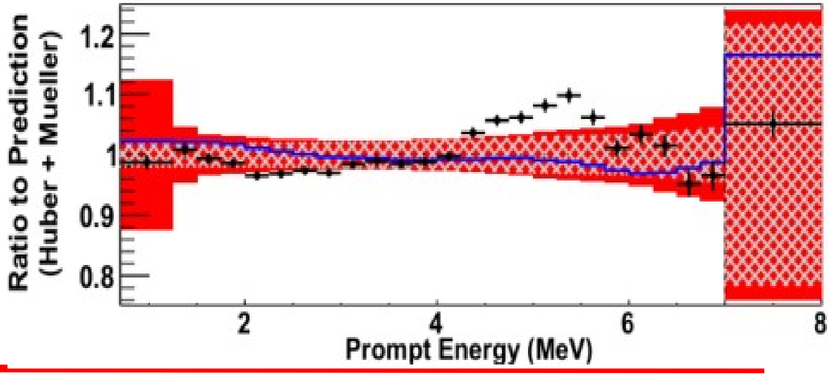
Double Chooz, 1406.7763, JHEP 2015



RENO, 1511.05849, PRL 2016



Daya Bay, 1508.04233, PRL 2016



Rate calculation

New cross section calculation produces the same reactor rates,

See
Ricciardi, Vignaroli, Vissani, 2206.05567, JHEP 2022

Talk by Giulia Ricciardi!

Calculate inverse beta yields for each isotope

We use the Strumia-Vissani IBD cross section

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

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

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

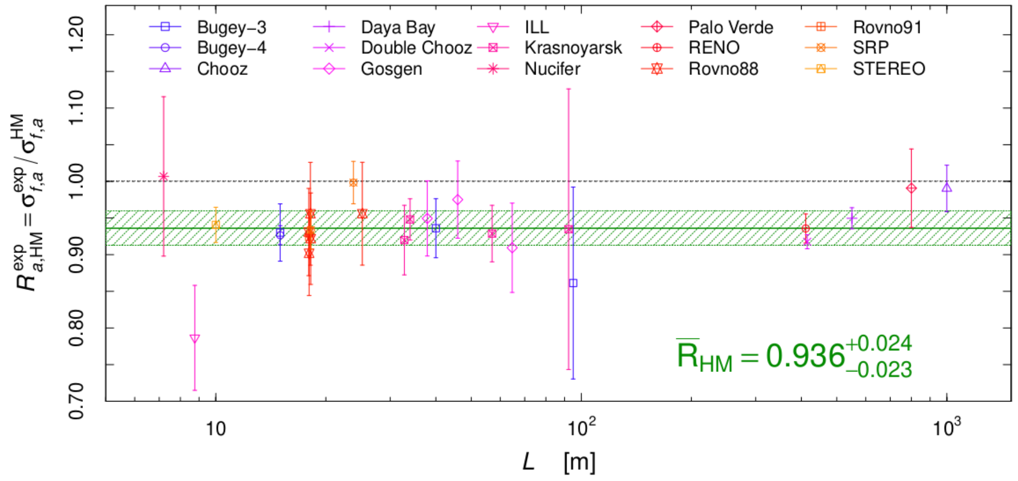
Compare against measurements

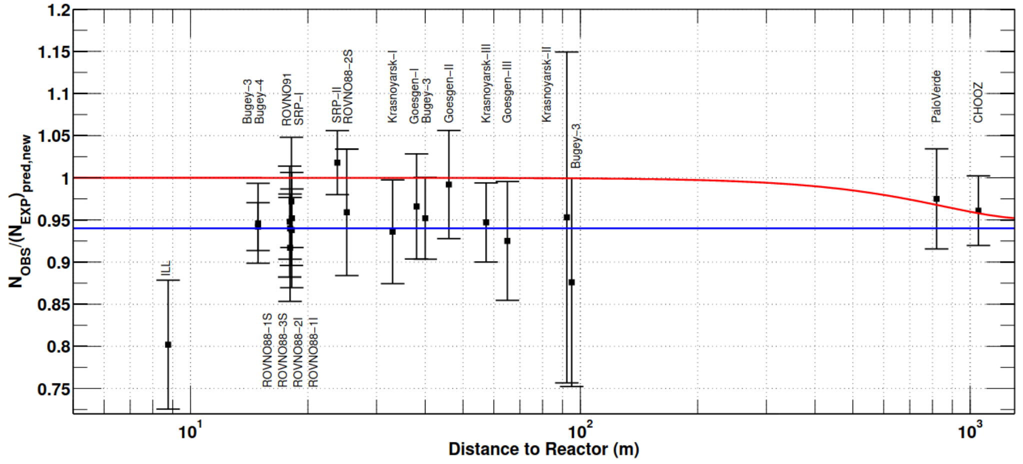
Giunti, Li, Ternes, Xin, 2110.06820

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 (rows 1–2)		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 (rows 3–4)	2.2 (rows 3–7)	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 (rows 5–7)		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 (rows 8–10)		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 (rows 11–13)	3.8 (rows 11–14)	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 (rows 15–16)		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

2011 Huber Mueller fluxes

Huber, 1106.0687, PRC 2012
Mueller, Lhuillier, Fallot, Letourneau, Cormon, 1101.2663, PRC 2012





HM flux gives 2.5σ anomaly

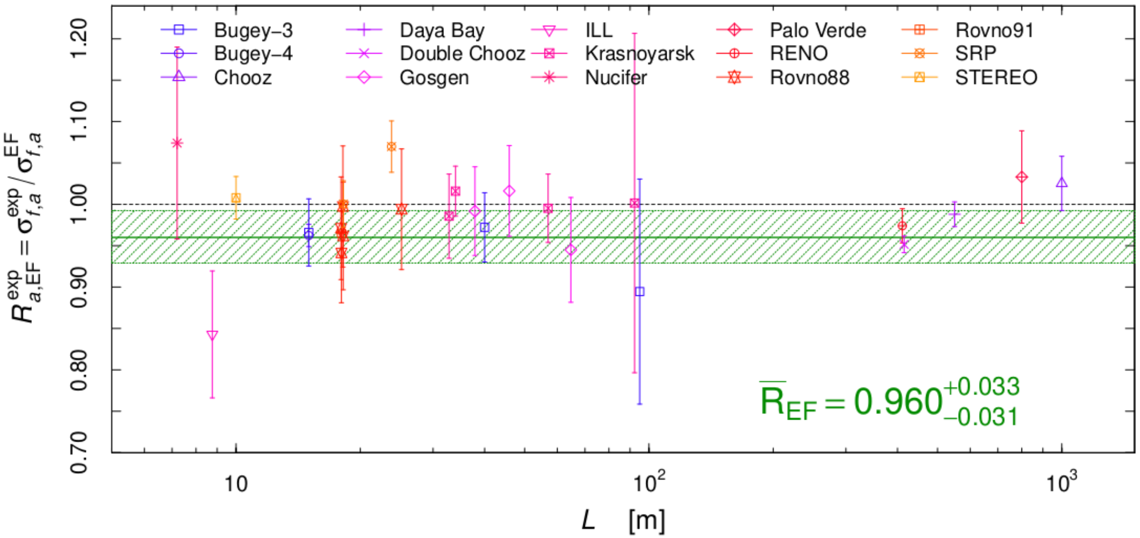
Original RAA was also 2.5σ

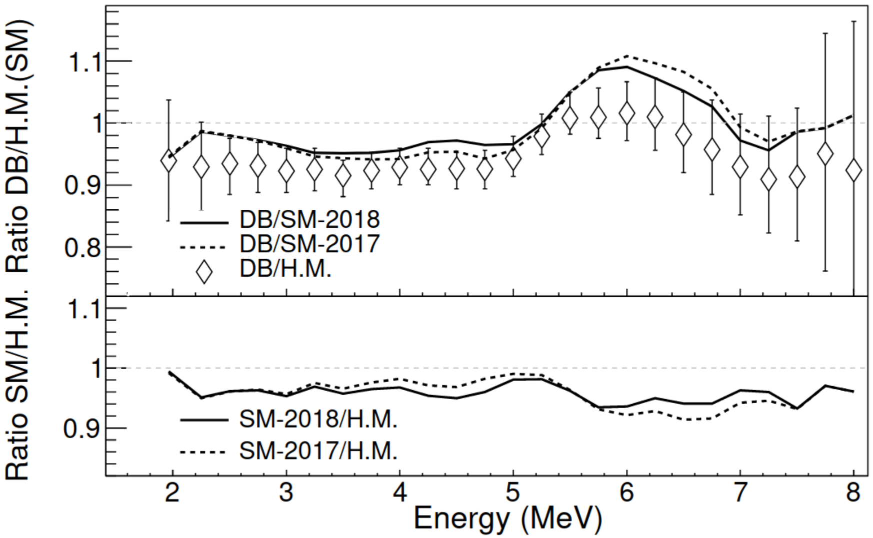
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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

2019 summation method fluxes

Estienne, Fallot, et al, 1904.09358, PRL 2019





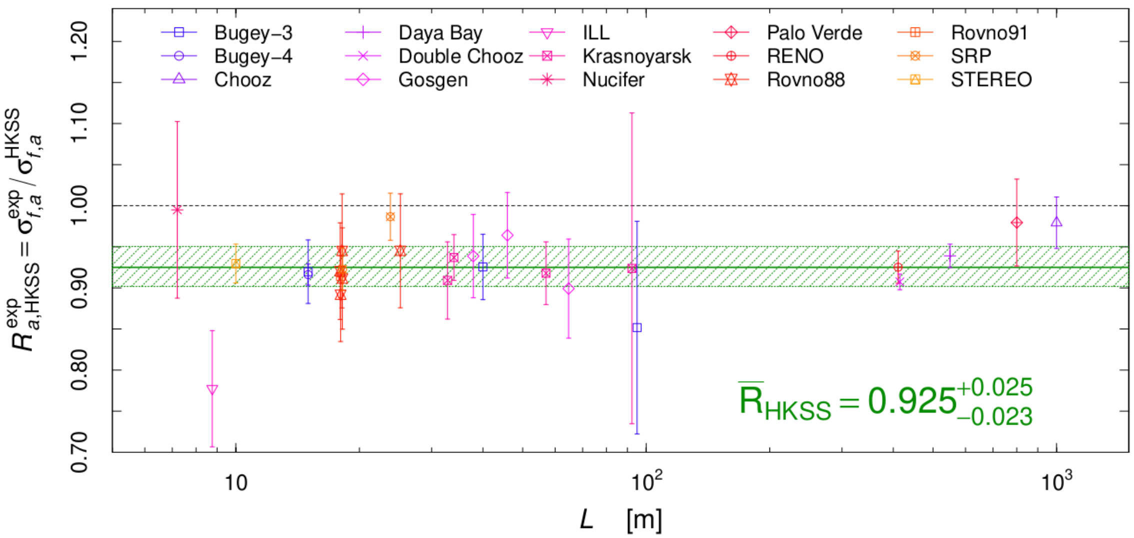
1.2σ deficit, no anomaly!

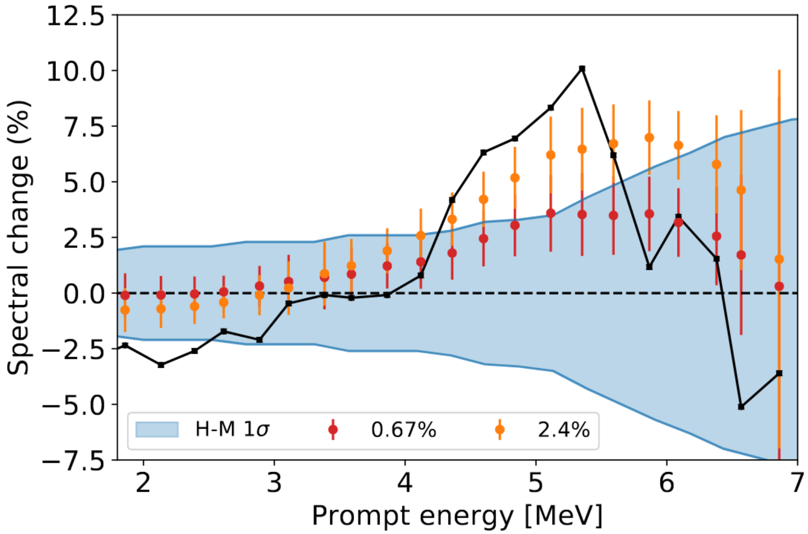
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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!

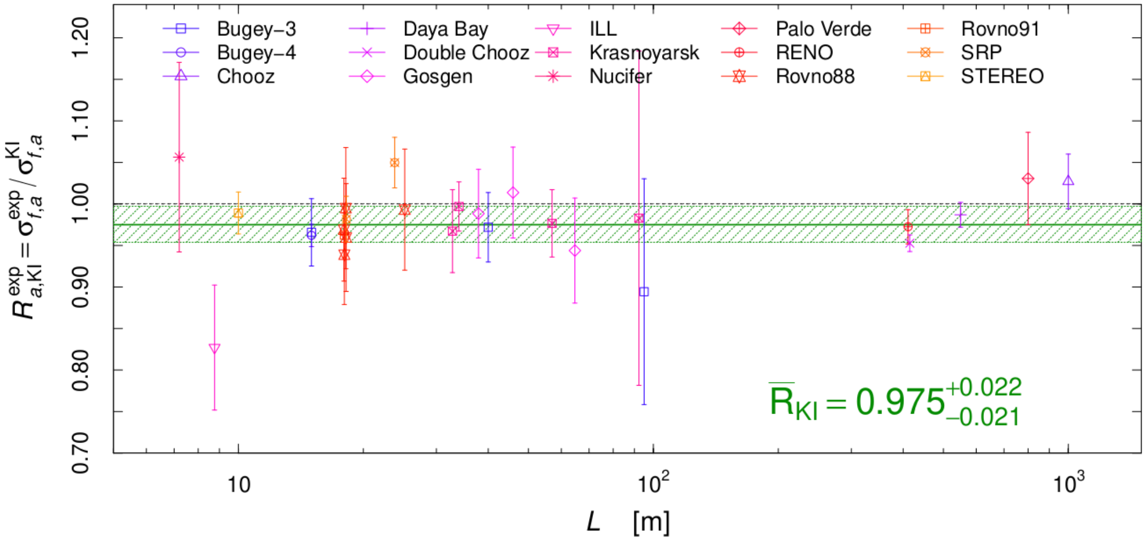
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

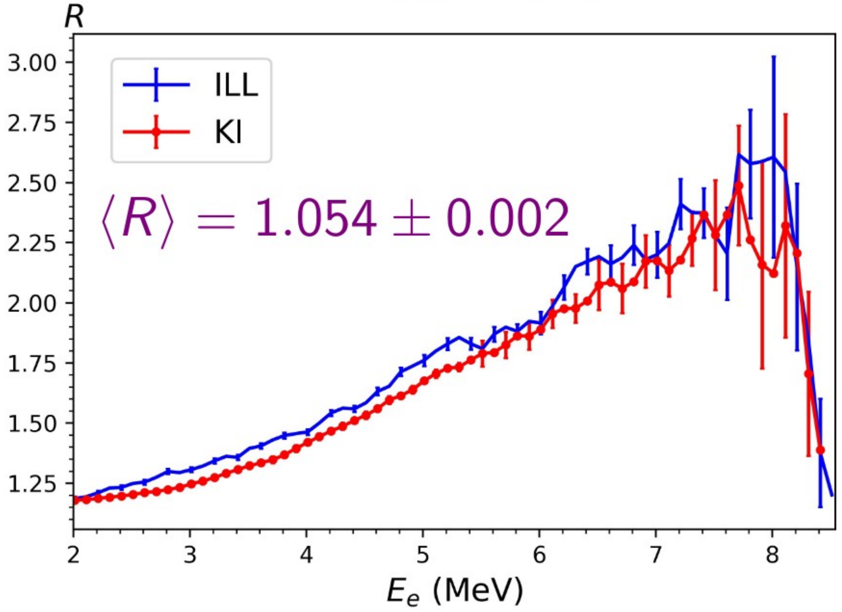
Better prediction for the energies of the bump!

2021 new converted fluxes

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

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





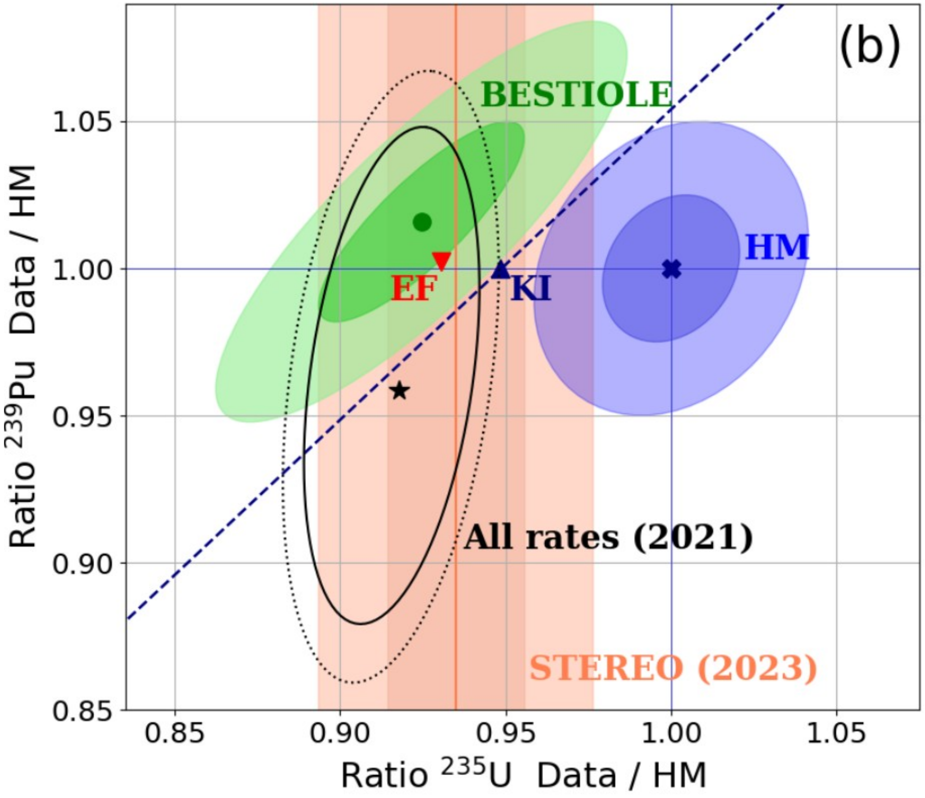
No anomaly (1.1σ) with KI flux!

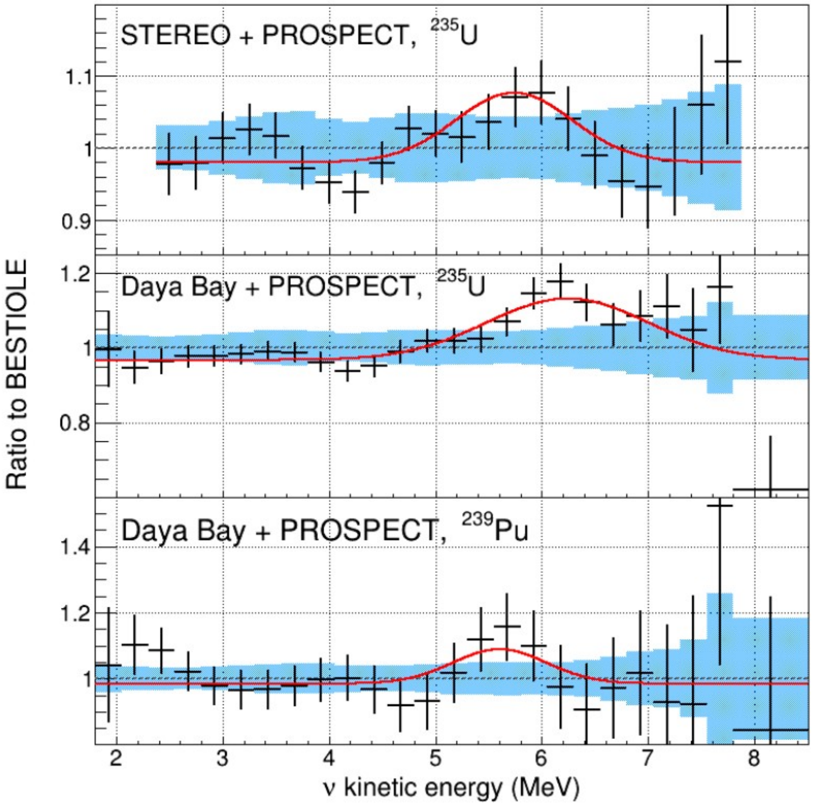
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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

BESTIOLE: 2023 new flux from summation method

BESTIOLE: Périssé, el al, 2304.14992

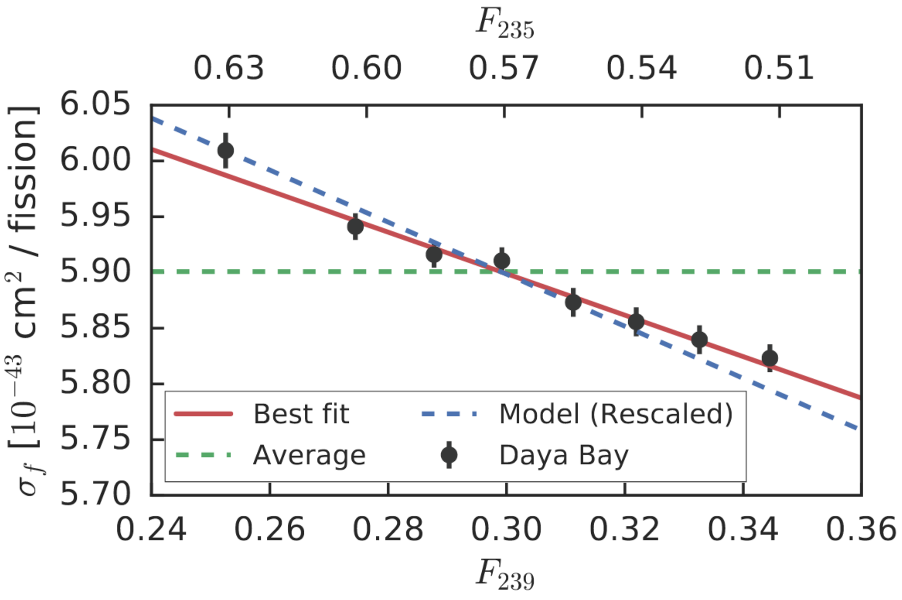




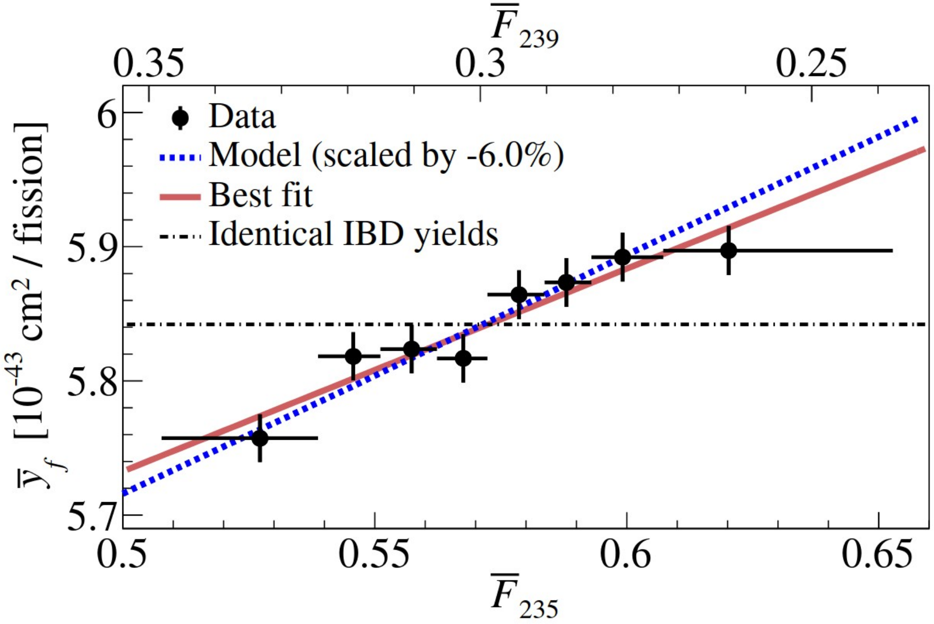
Evolution data

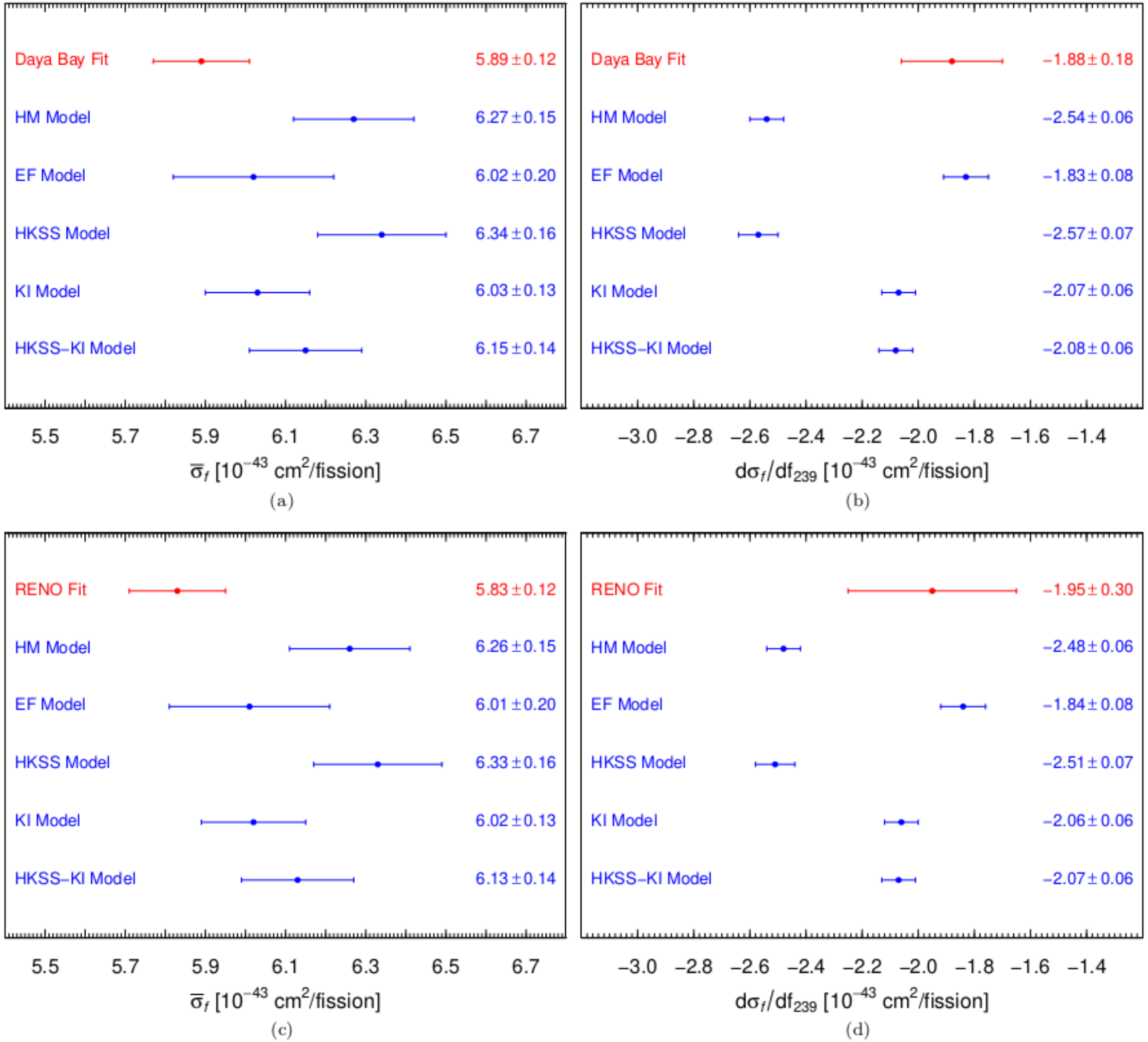
Measure rates at different stages of reactor cycle

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	
	$\overline{R}_{\mathrm{mod}}$	RAA	$\overline{R}_{\mathrm{mod}}$	RAA	$\overline{R}_{\mathrm{mod}}$	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				
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

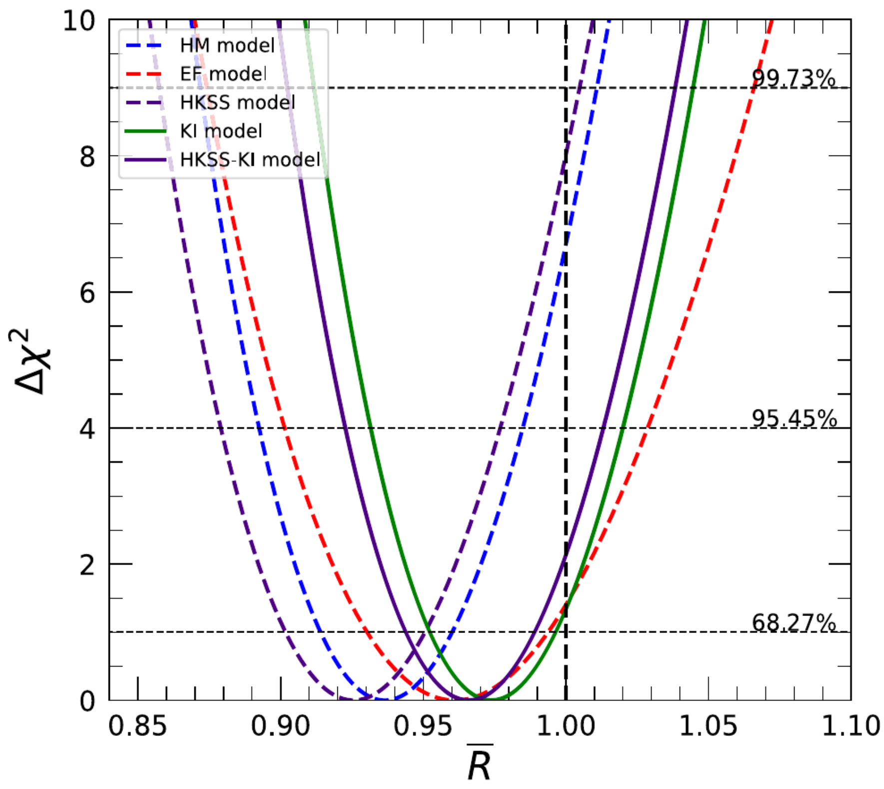
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

The reactor rate anomaly

The significance of the RAA depends on the input flux model

The EF and KI models have no anomaly

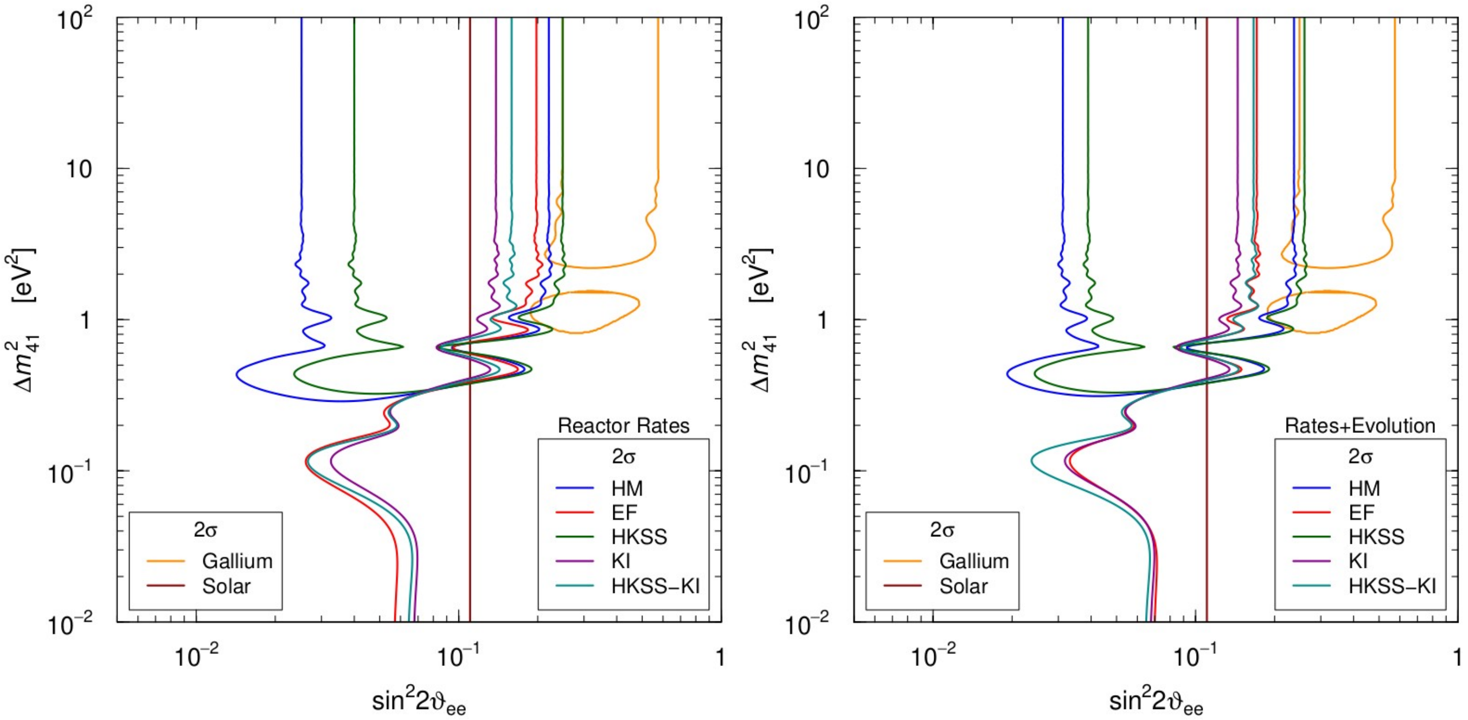
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



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

Impact on neutrino oscillations

Giunti, Li, Ternes, Xin, 2110.06820



Rate data are (for any flux model) in tension with Gallium data

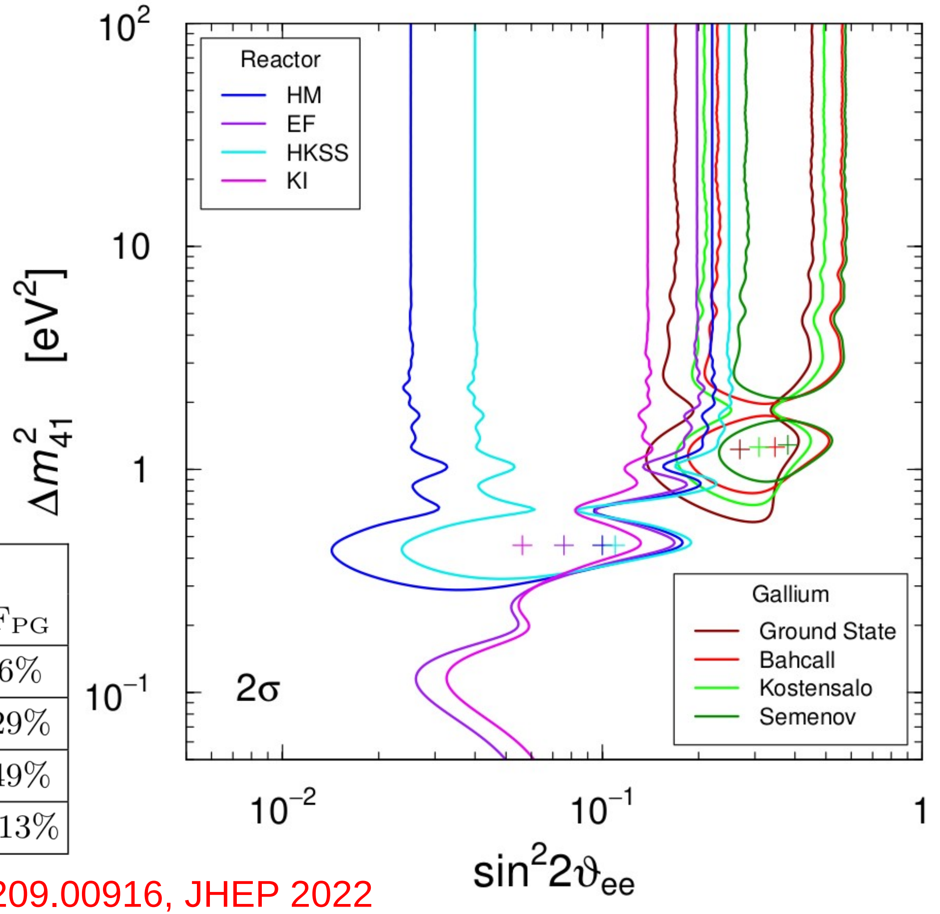
BEST coll., 2109.11482

Rate data are in agreement with solar neutrino bounds

Goldhagen, et al., 2109.14898, EPJC 2022

Tension between reactor rate and Gallium data

Severe tension between reactor rate and Gallium data!



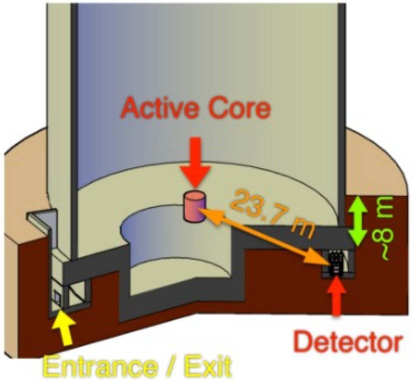
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{PG}$	GoF_{PG}	$\Delta\chi^2_{PG}$	GoF_{PG}	$\Delta\chi^2_{PG}$	GoF_{PG}	$\Delta\chi^2_{PG}$	GoF_{PG}
Ground State	7.2	2.8%	5.4	6.8%	9.1	1.1%	11.9	0.26%
Bahcall	10.9	0.42%	8.9	1.2%	12.9	0.16%	16.3	0.029%
Kostensalo	9.6	0.83%	7.5	2.4%	11.5	0.31%	15.3	0.049%
Semenov	15.1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

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

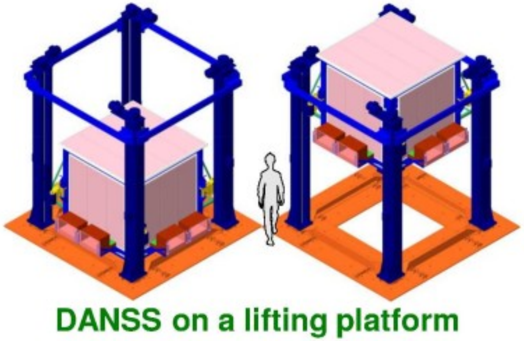
Ratio analysis

Talk by Bryce Littlejohn!

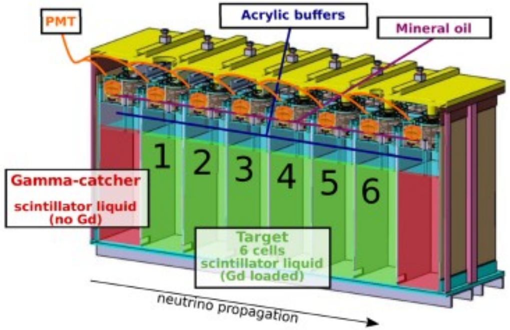
NEOS



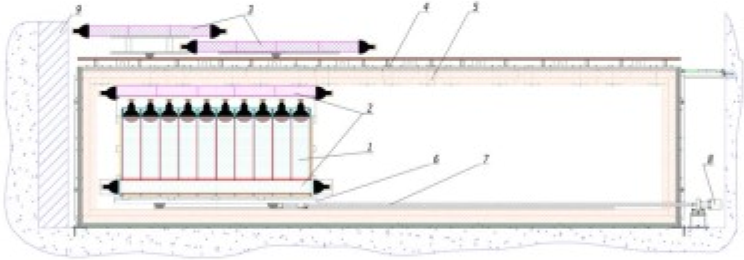
DANSS



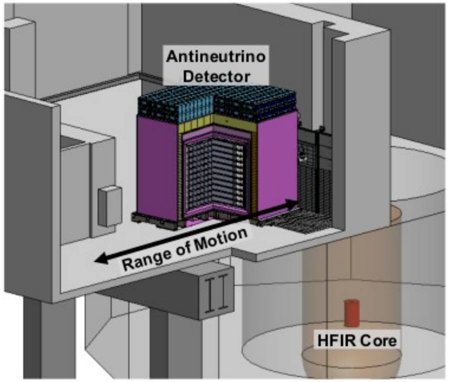
STEREO



Neutrino-4



PROSPECT



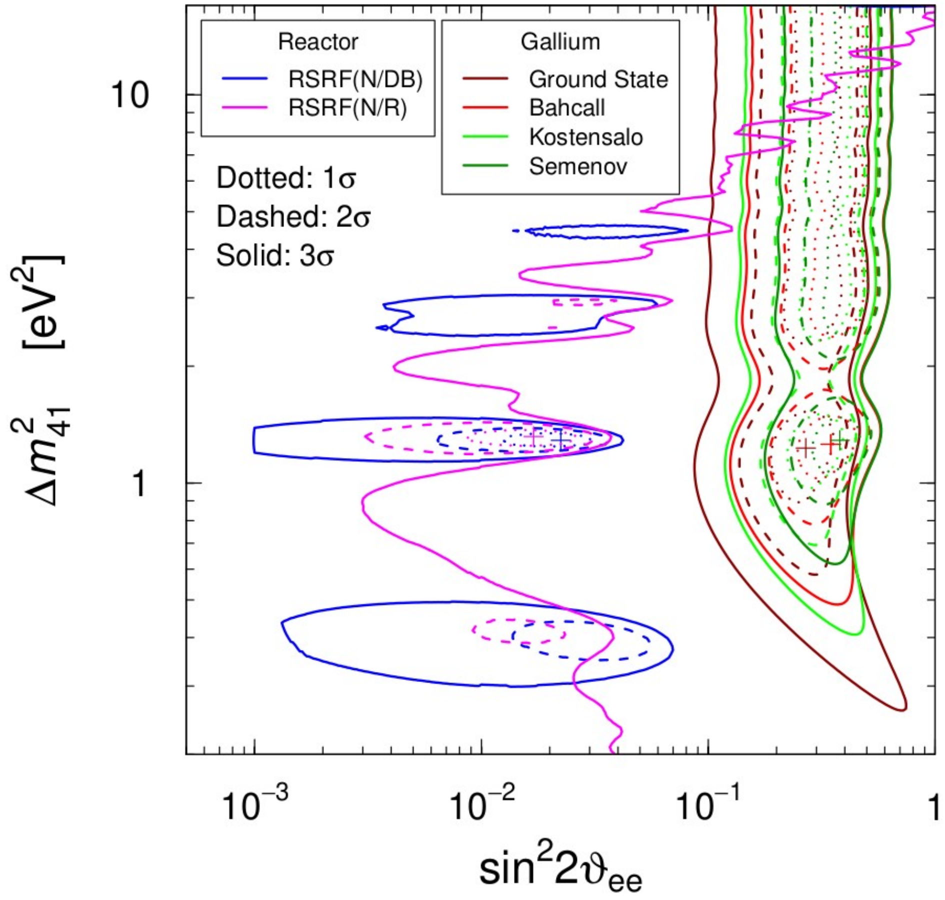
Ratio analysis

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

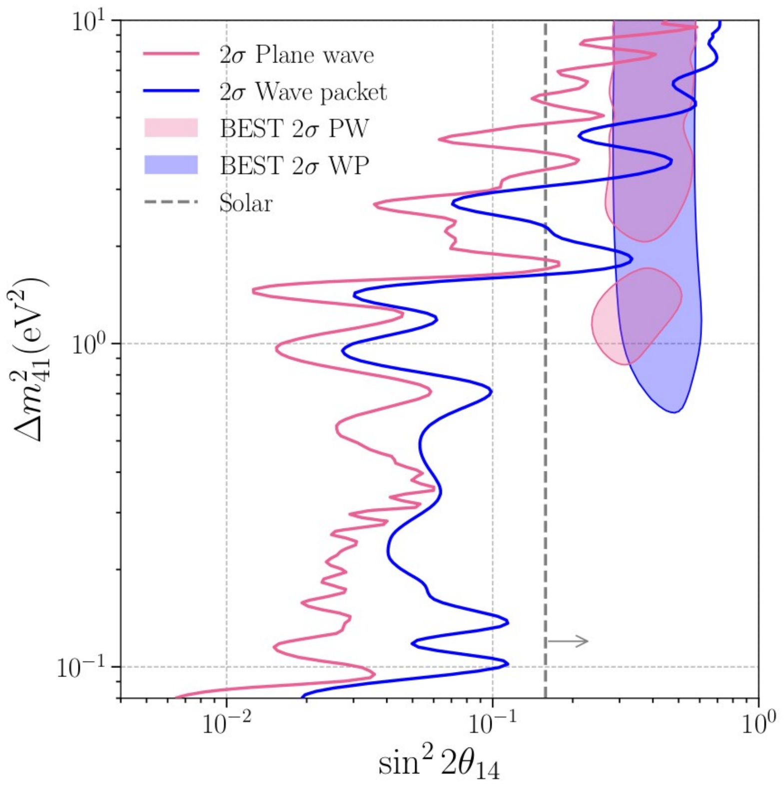
Severe tension between RSRF(N/DB) and Gallium data!

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

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



Wavepackets



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

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

$$L_{\mathrm{coh}} = \frac{4\sqrt{2}E^2}{|\Delta m^2_{41}|}\sigma$$

But: The estimated size of the wavepacket is very large

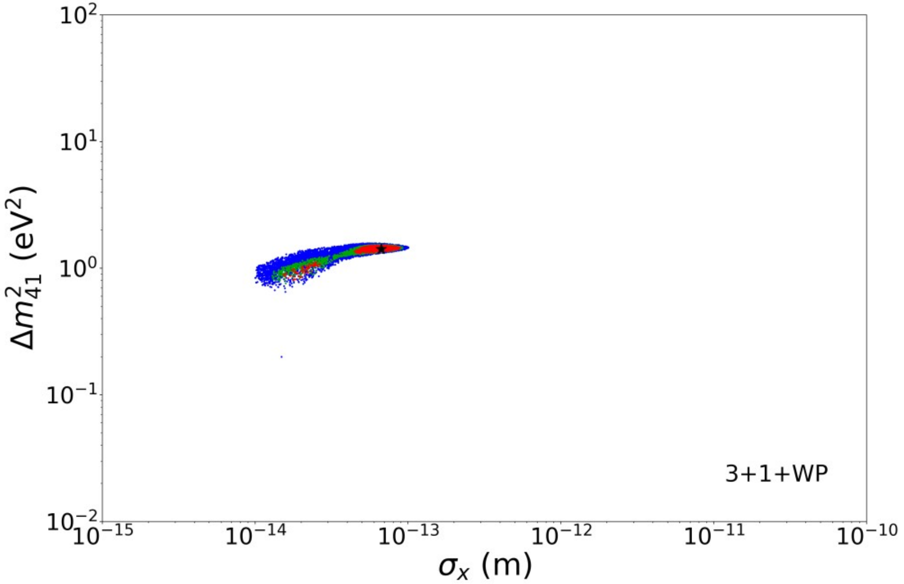
$$\sigma_x = (2\times 10^{-5} - 1.4\times 10^{-4})\ \mathrm{cm}$$

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

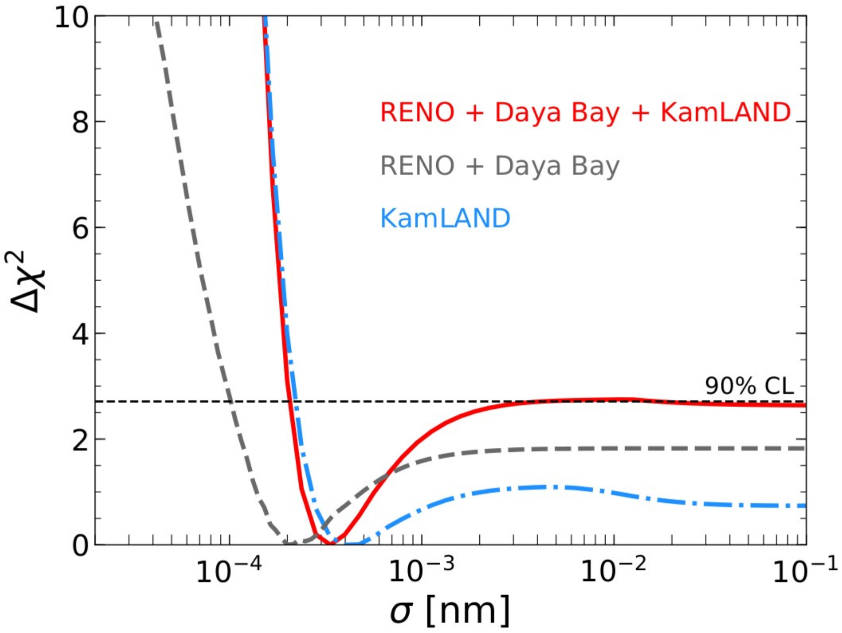
Akhmedov, Smirnov, 2208.03736, JHEP 2022

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

Neutrino decay or broad neutrinos?

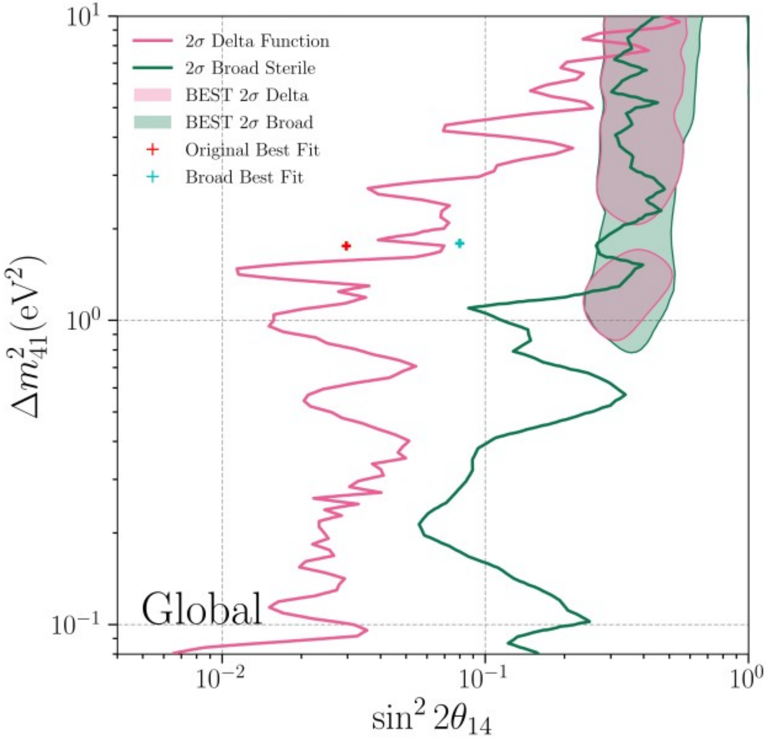
Hardin, et al, 2211.02610, JHEP 2023

Banks, Kelly, McCullough, Zhou, 2311.06352

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

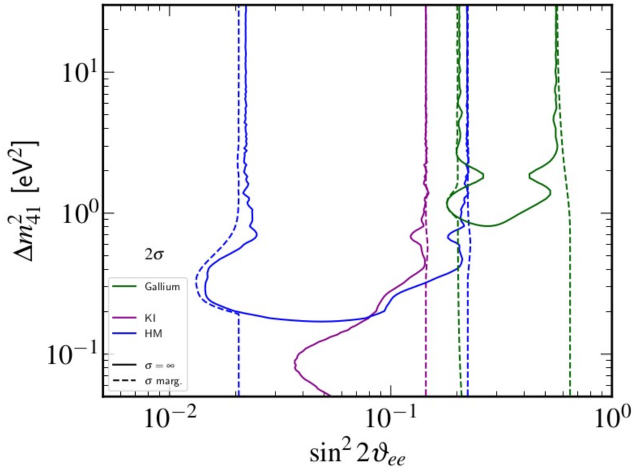
$$P_{ee}^{b} = \left(1+\left(\text{sinc}\left(\frac{bL}{4E}\right)-1\right)|U_{e4}|^2\right)^2 - 4|U_{e4}|^2\left(1-|U_{e4}|^2\right)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)\text{sinc}\left(\frac{bL}{4E}\right)$$

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

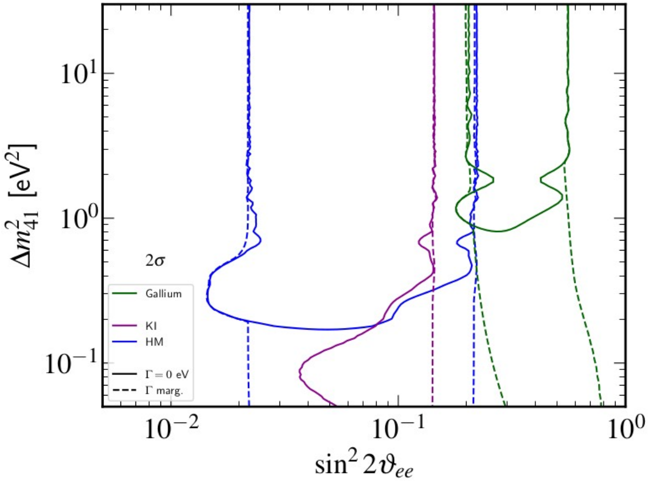


Gallium-Reactor tension

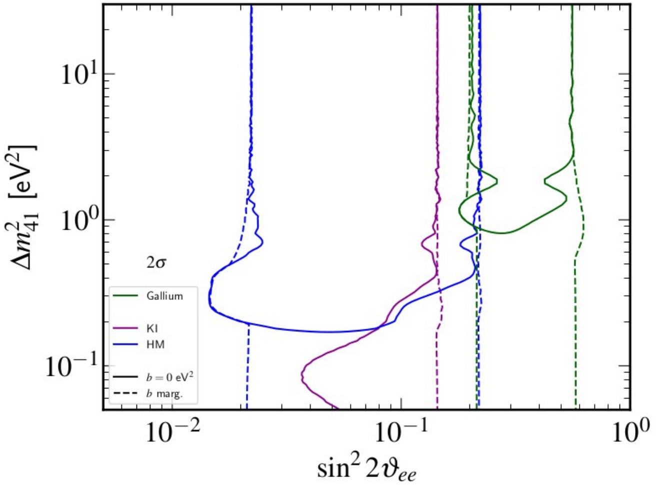
Reactor rate data was not considered in any of the previously discussed analyses



Wavepacket!



Decay!



Broad neutrinos!

Giunti, Ternes, 2312.00565

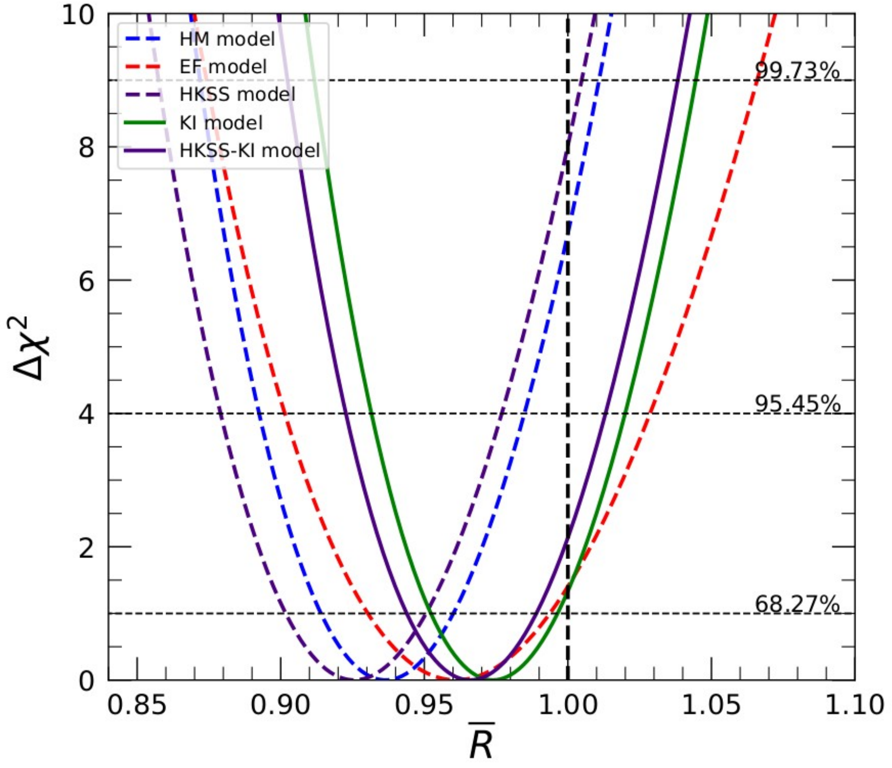
Conclusions

RAA mostly resolved for some flux models

Good agreement between KI and EF predictions! The argument that reactor rate data is not reliable is outdated!

Reactor rate data excludes the sterile neutrino explanation of the Gallium anomaly

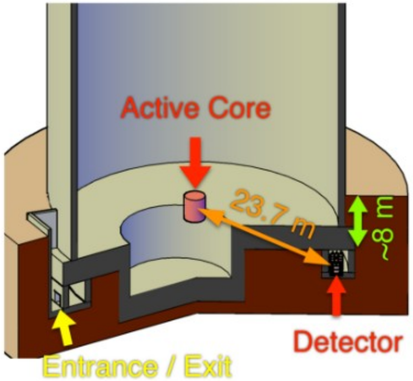
Reactor rate data eliminates several models proposed to alleviate tensions among data sets



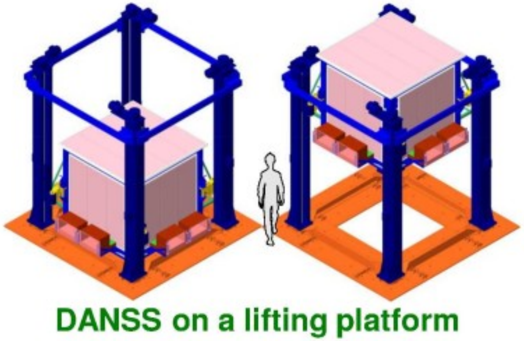

Thanks!
electron-neutrino
muon neutrino
tau-neutrino

Ratio analysis

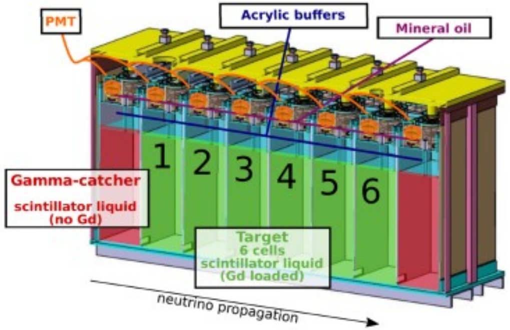
NEOS



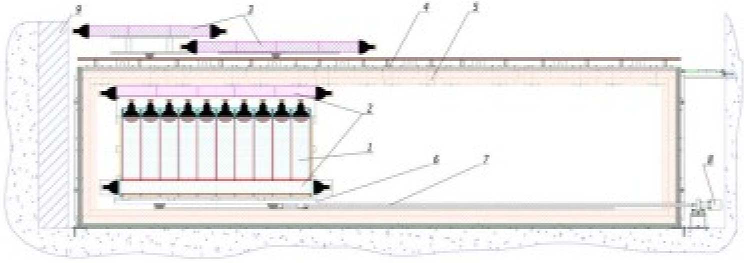
DANSS



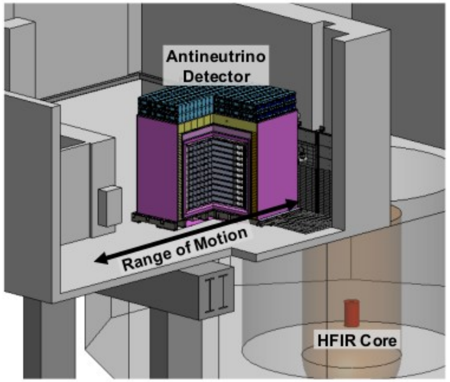
STEREO



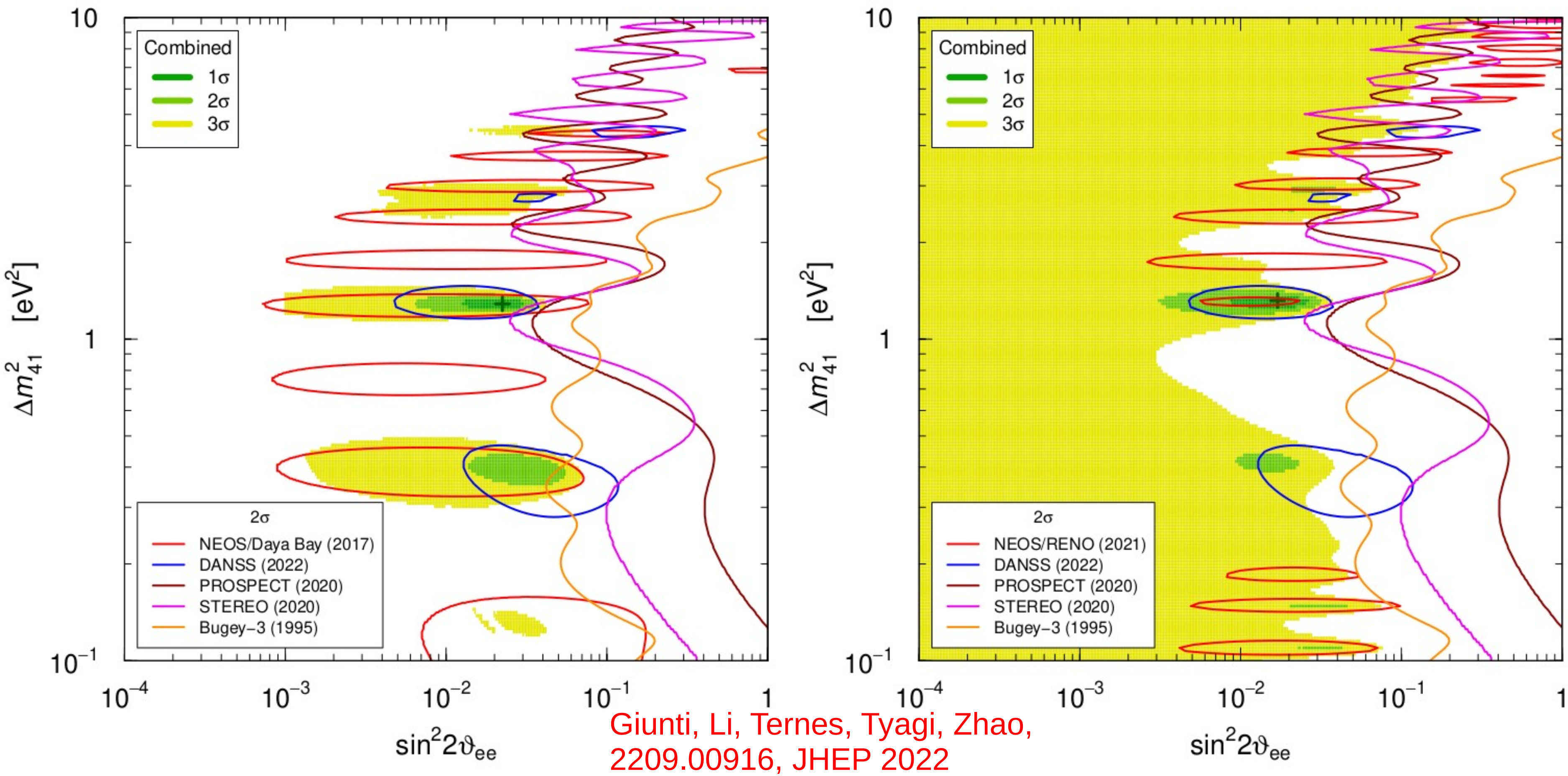
Neutrino-4



PROSPECT

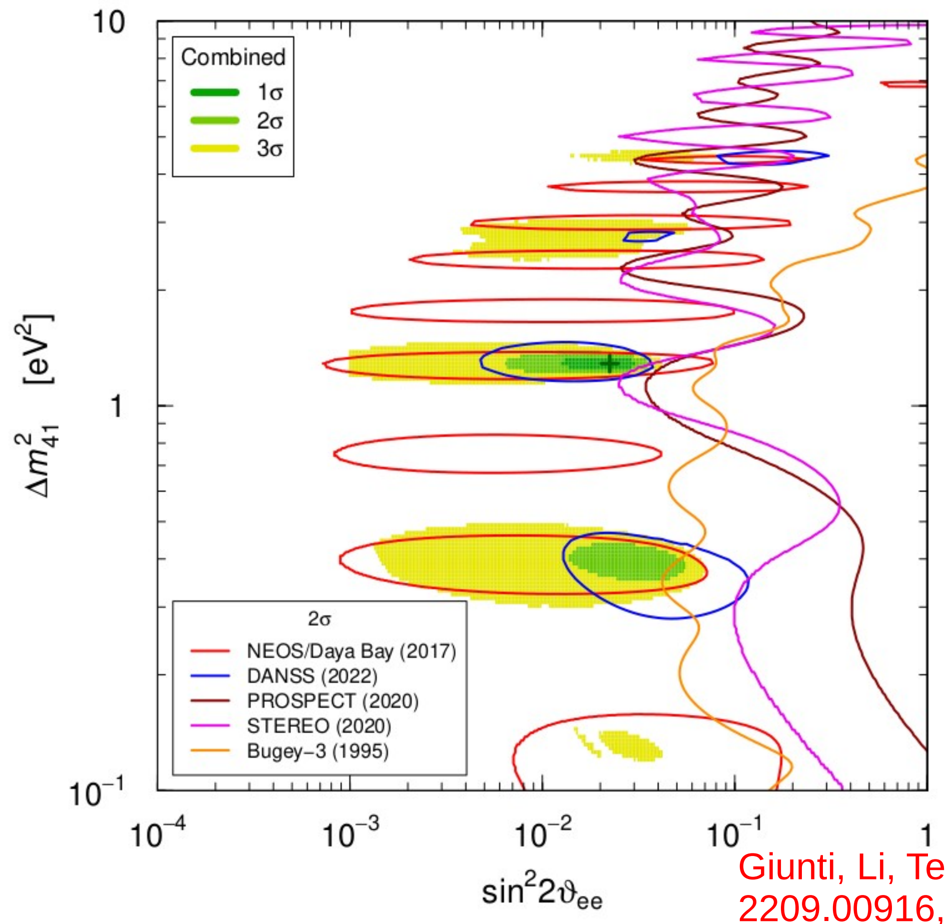


Ratio analysis



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

Ratio analysis



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

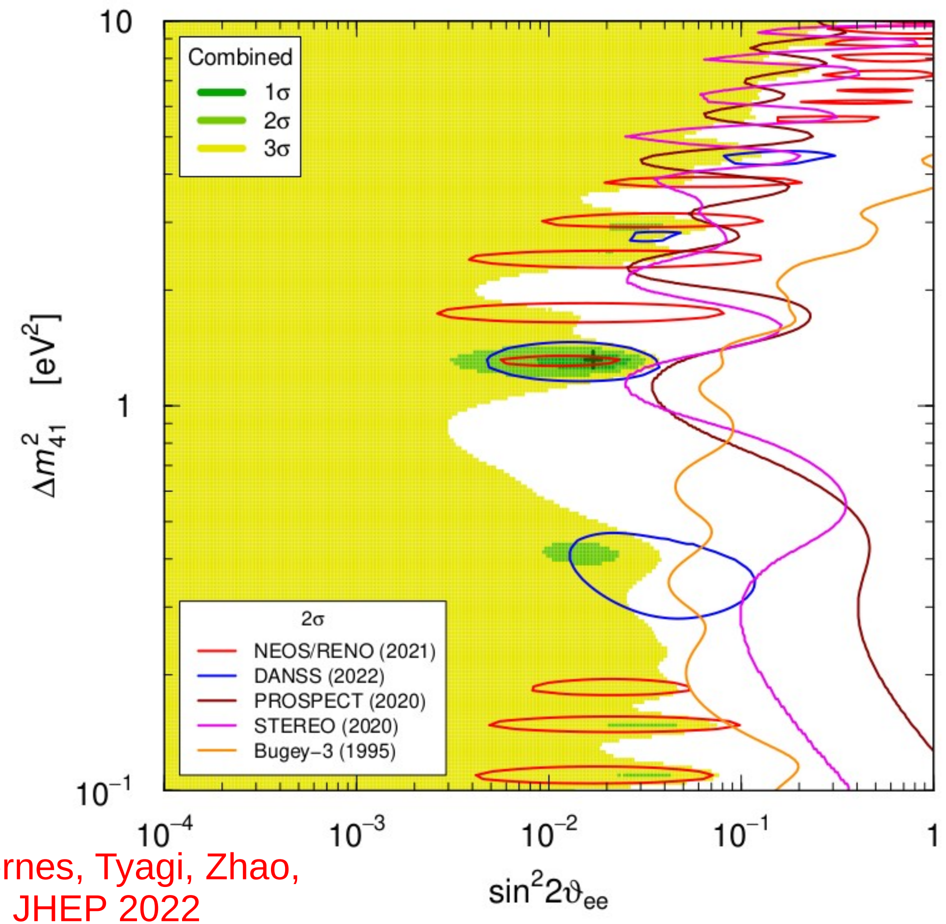
The NEOS collaboration performed an analysis using the Daya Bay spectrum as a reference spectrum

Many many events at Daya Bay!

Ratio analysis

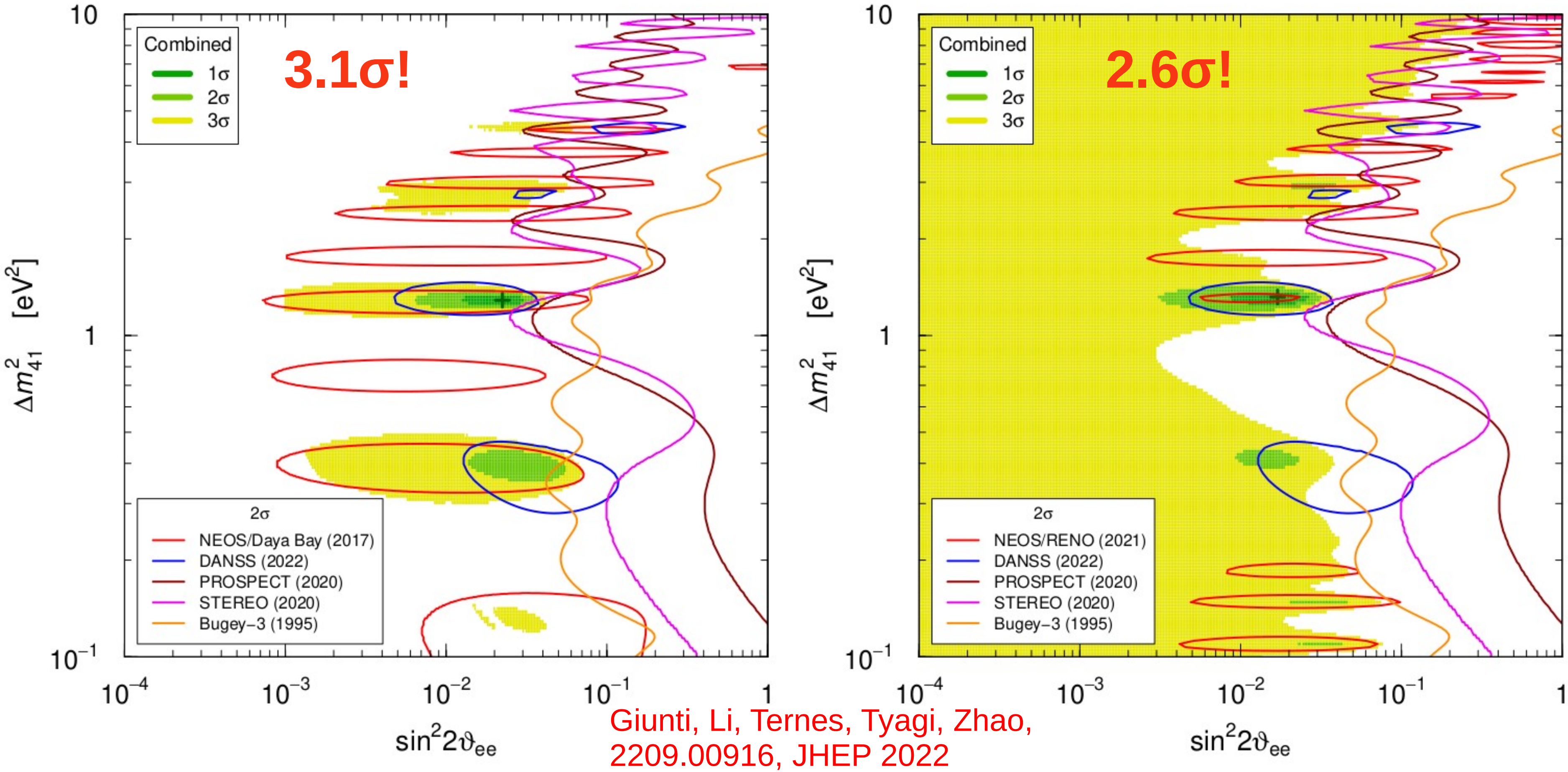
The NEOS collaboration also performed an analysis using the RENO spectrum as a reference spectrum

Same reactor complex, better control of systematic uncertainties!



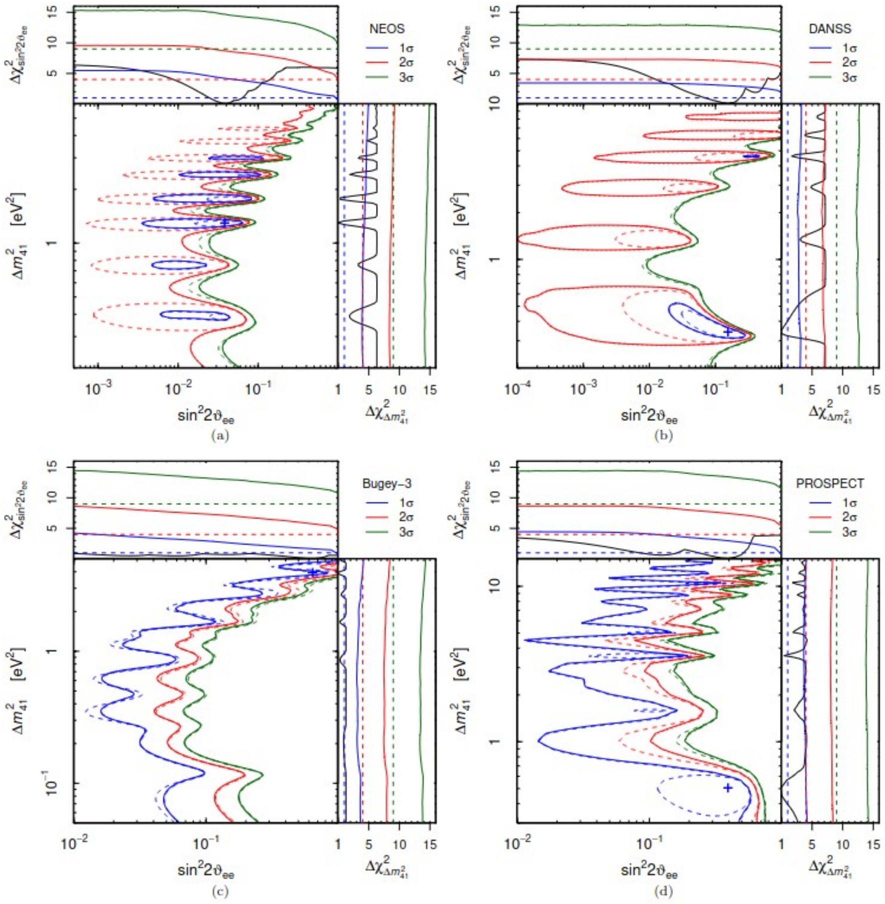
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Ratio analysis



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

Caution!



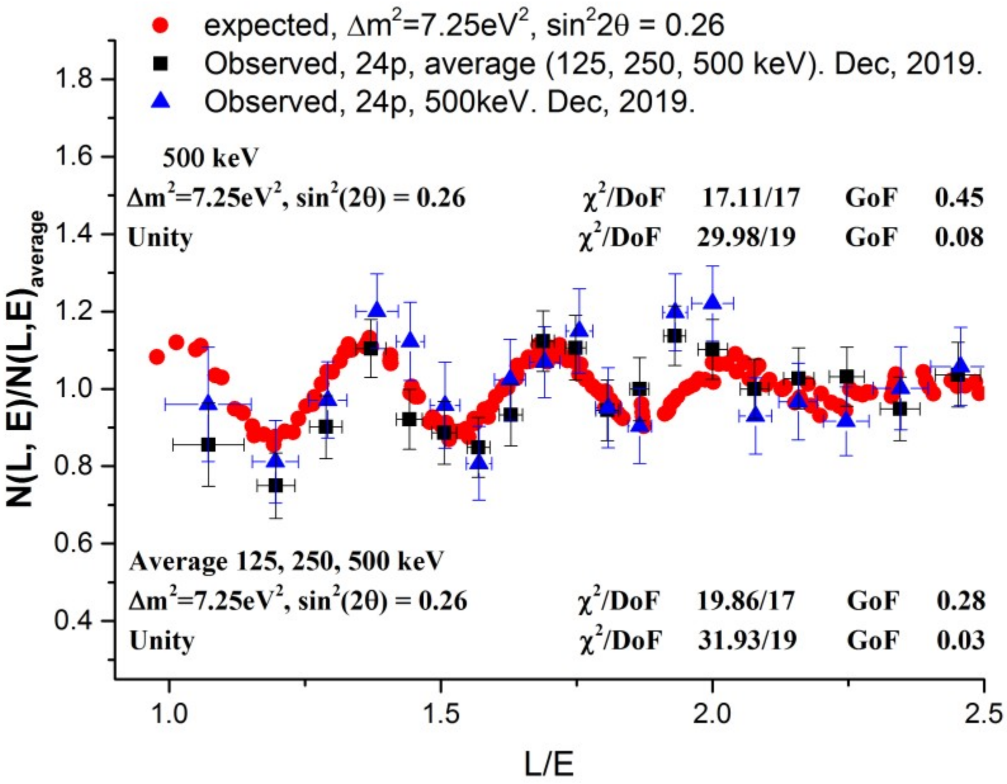
We performed simple χ^2 analyses

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

Giunti, 2004.07577, PRD 2020

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

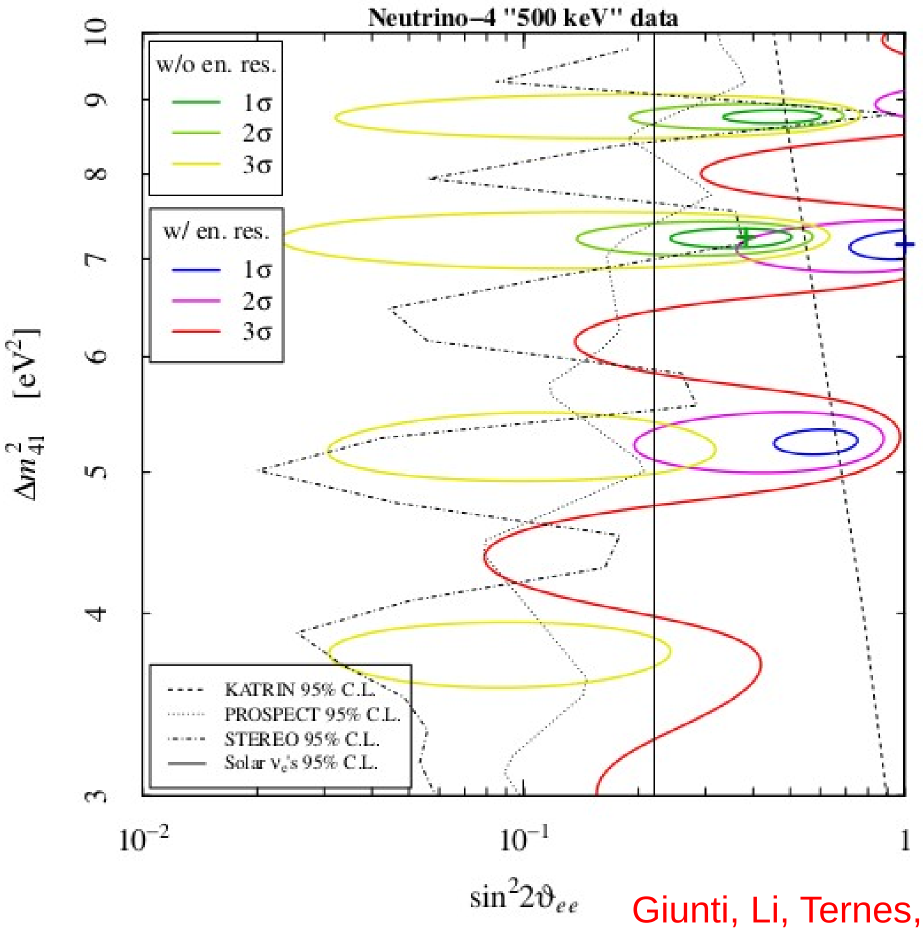
Averaging contains integration over flux, distance, detector resolution

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

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

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

Neutrino-4

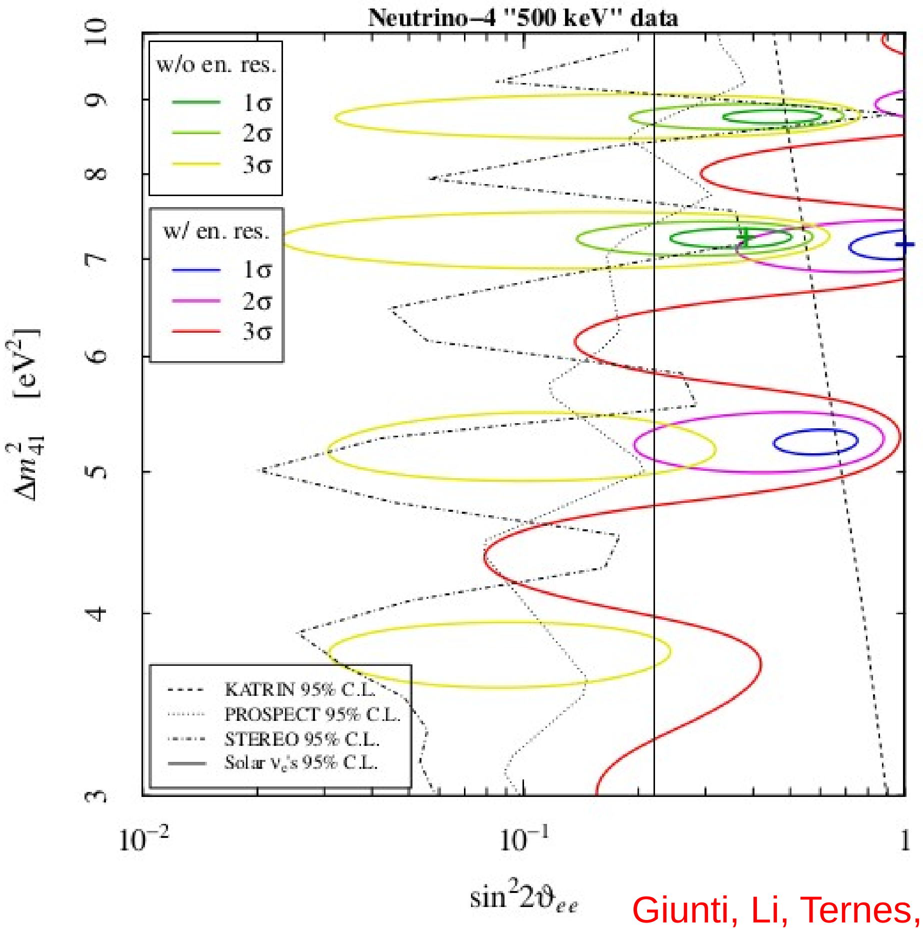


We can only reproduce Neutrino-4 confidence regions when not including energy resolution

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

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

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

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

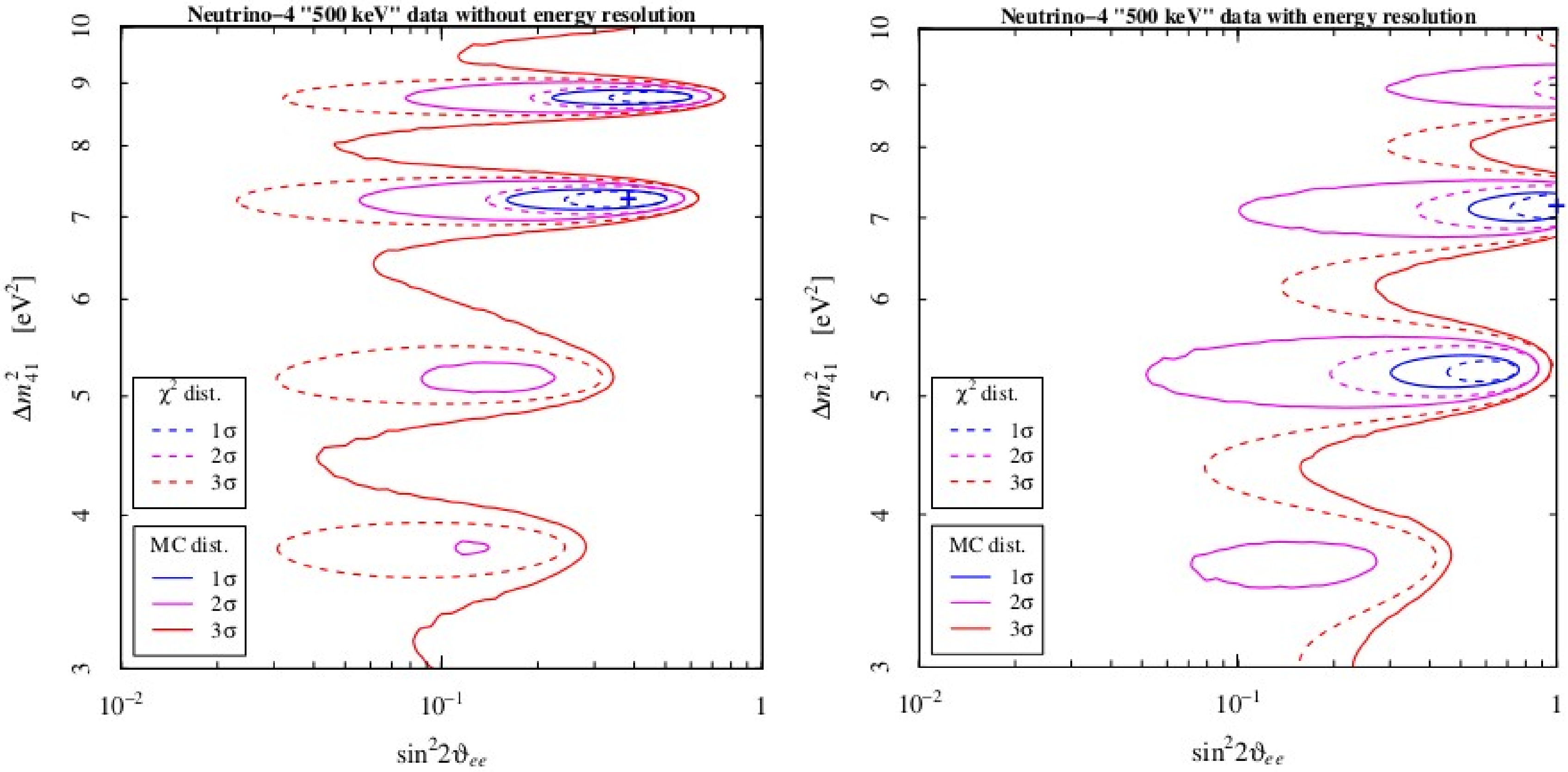
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

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

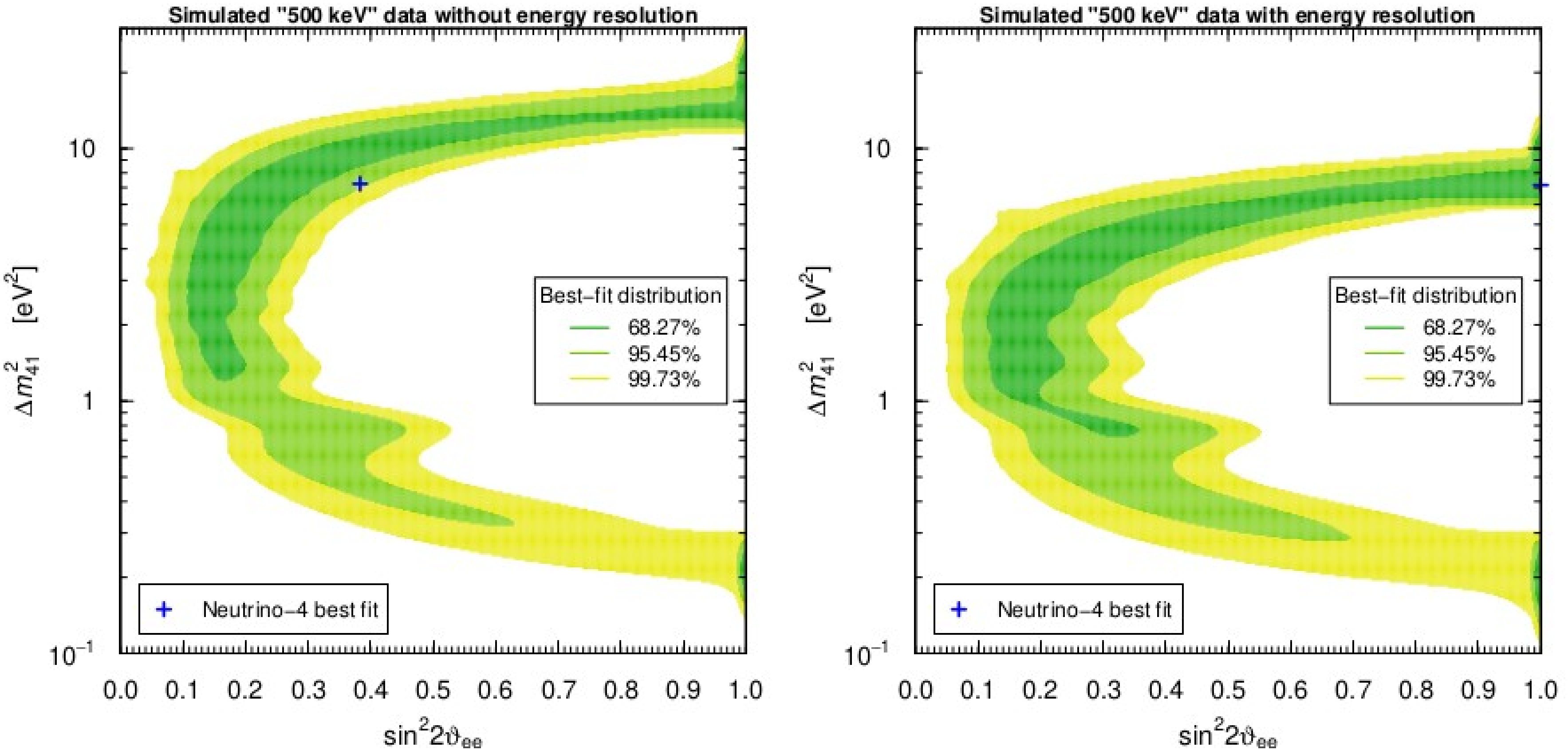
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Neutrino-4	"500 keV" data		"125-250-500 keV" data	
	without en. res.	with en. res.	without en. res.	with en. res.
χ^2_{min}	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
$(\Delta m^2_{41})_{\text{bf}}$	7.2	7.2	8.8	7.2
$\Delta\chi^2_{\text{NO}}$	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

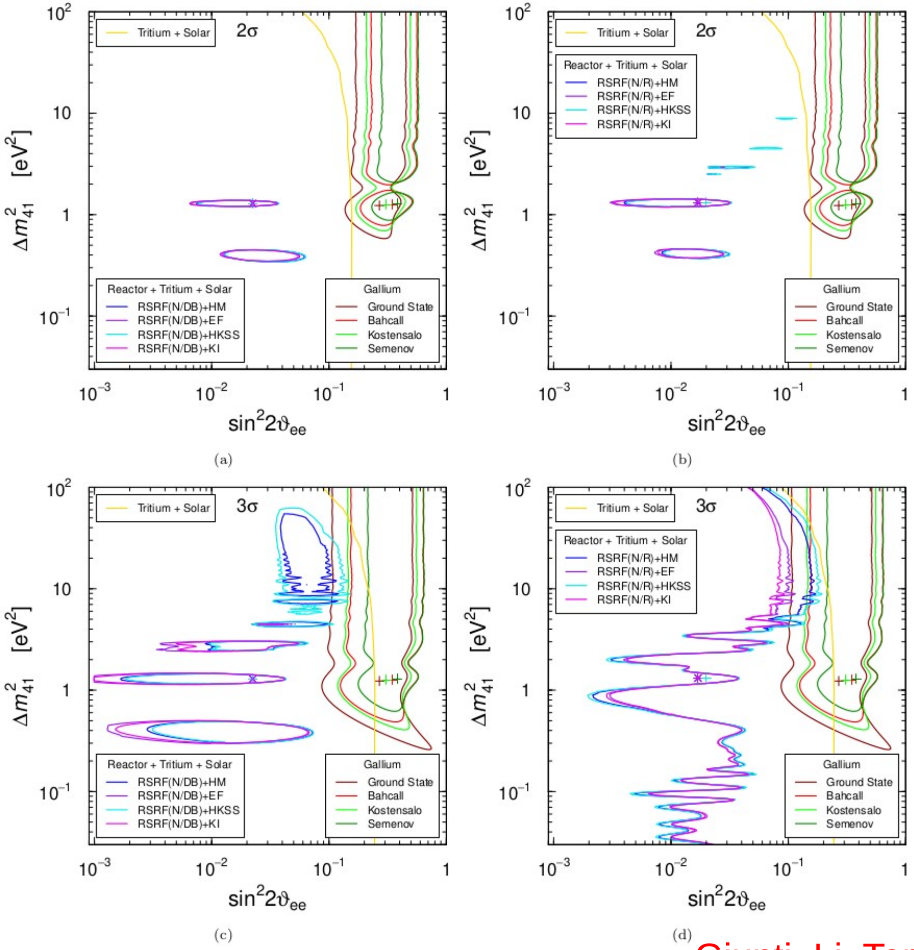
Distribution of best fit points without oscillations

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



Christoph Ternes

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	
	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$
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	
	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$	$\Delta\chi^2_{\rm PG}$	GoF$_{\rm PG}$
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

	HM	HKSS	EF	KI
Global RSRF(N/DB) Fit				
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
$\Delta\chi^2_{4\nu-3\nu}$	13.8	14.1	12.6	12.9
$n\sigma_{4\nu-3\nu}$	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
$\Delta\chi^2_{4\nu-3\nu}$	10.1	10.3	9.1	9.3
$n\sigma_{4\nu-3\nu}$	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

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 σ_{tot}	^{51}Cr δ_{exc}	^{37}Ar σ_{tot}	^{37}Ar 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

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Small

More on the Gallium anomaly

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

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		$\sigma_{\rm tot}$	$\delta_{\rm exc}$	$\sigma_{\rm tot}$	$\delta_{\rm exc}$
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Large

More on the Gallium anomaly

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

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		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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Main contribution

Corrections

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

More on the Gallium anomaly

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

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

Different results obtained in the past

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

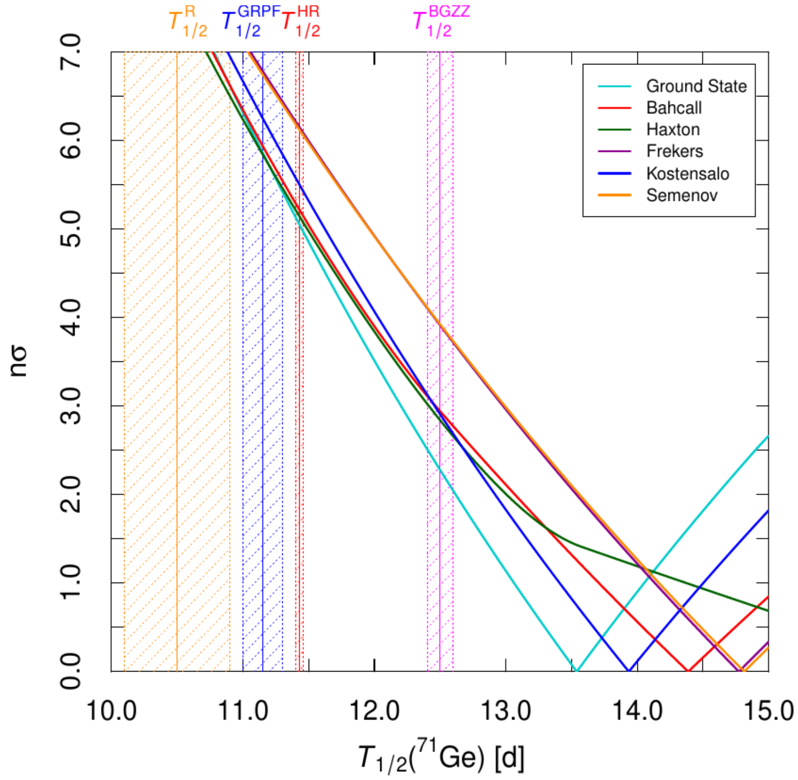
$$T_{1/2}^{\rm R}(^{71}{\rm Ge}) = 10.5 \pm 0.4\,{\rm d} \quad \text{(Rudstam, 1956)}$$

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

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

More on the Gallium anomaly

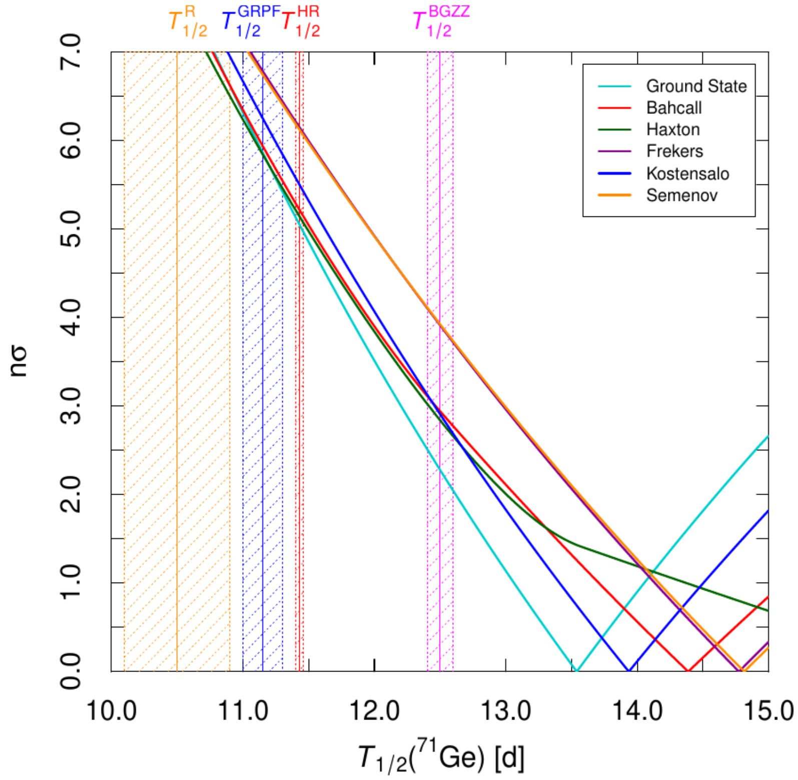
Fit the Germanium half life using data from Gallium experiments

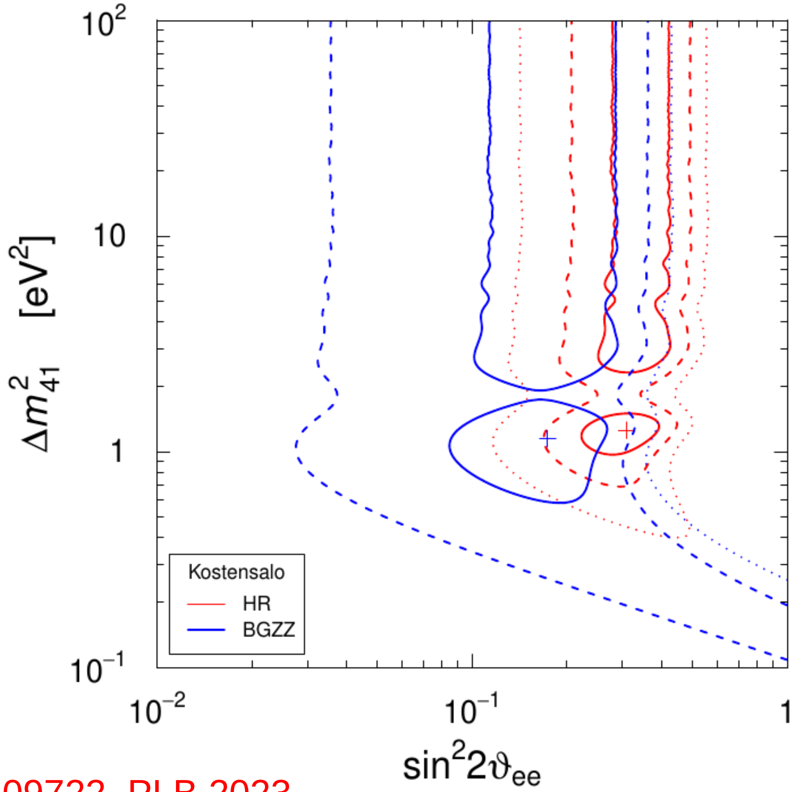


Giunti, Li, Ternes, Zhao, 2212.09722, PLB 2023

More on the Gallium anomaly

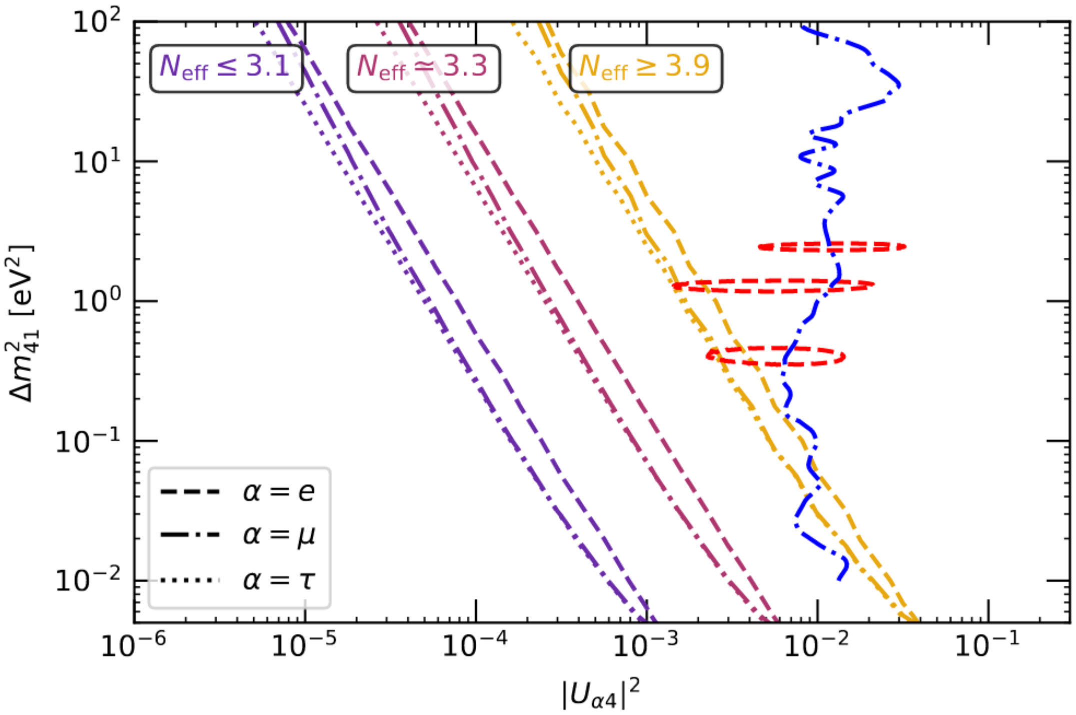
Fit the Germanium half life using data from Gallium experiments





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

Cosmology



Cosmology can set strong bounds on sterile parameter space

Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019