Global neutrino oscillation fits and neutrino anomalies

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INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

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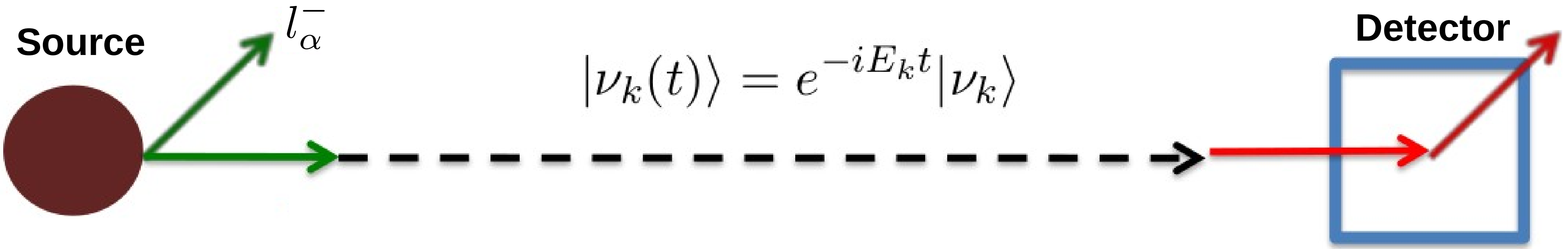
Neutrino oscillations



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

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

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

$$E_k = E + \frac{m_k^2}{2E}, \quad t = L$$

$$P_{\nu_\alpha\to\nu_\beta}(L,E) = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, \exp\left(-i\,\frac{\Delta m^2_{kj} L}{2E}\right)$$

Three-neutrino oscillations

Neutrino mixing matrix

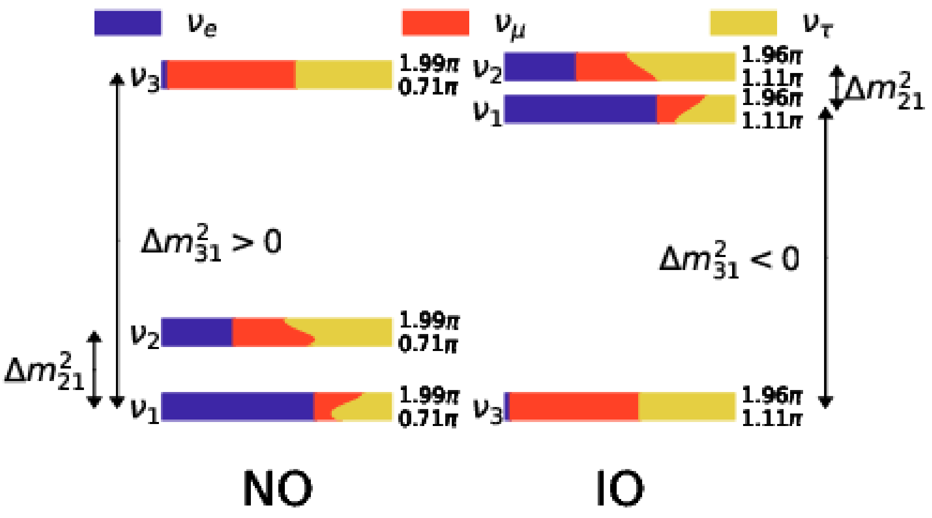
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

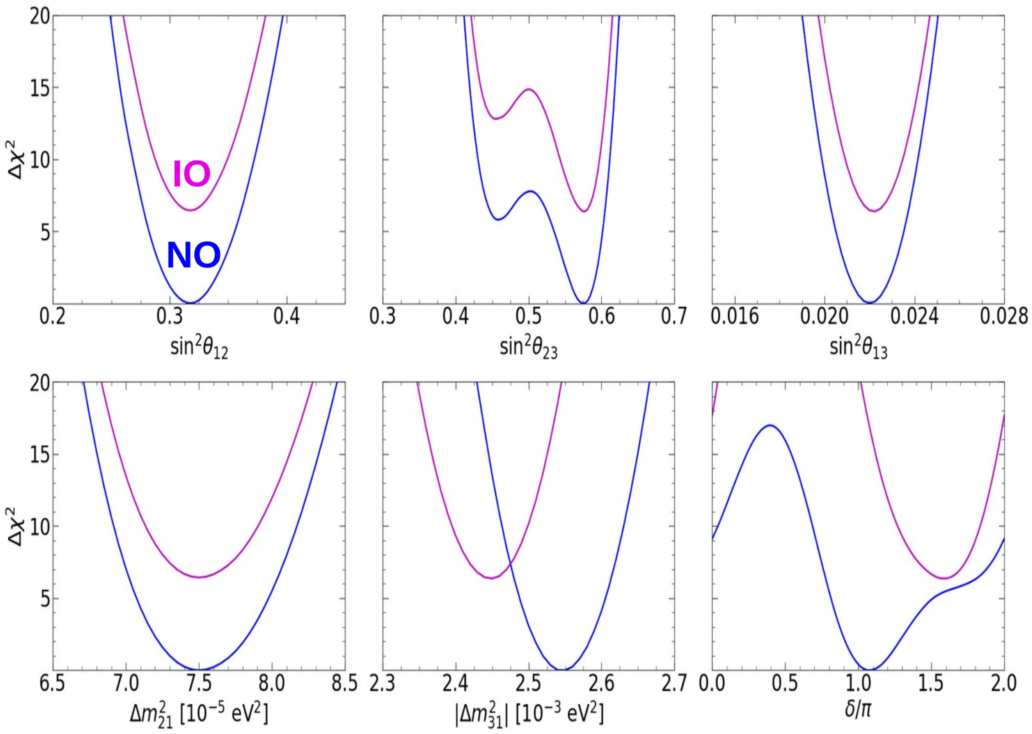
Common sensitivities from different types of experiments

Combination of data sets can enhance sensitivities to oscillation parameters

=> Perform a global fit to neutrino oscillation data!

Three-neutrino Global Fit

Valencia - Global Fit, 2006.11237, JHEP 2021



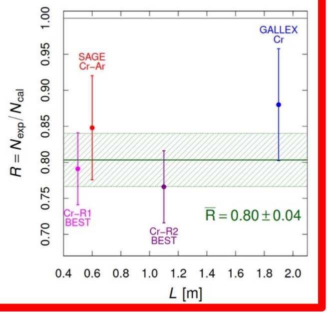
parameter	best fit $\pm$ 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	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

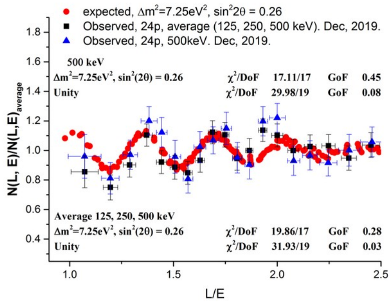
See also:
NuFit - 2111.03086, Universe 2021

Anomalies

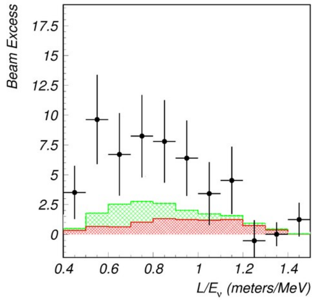
Gallium



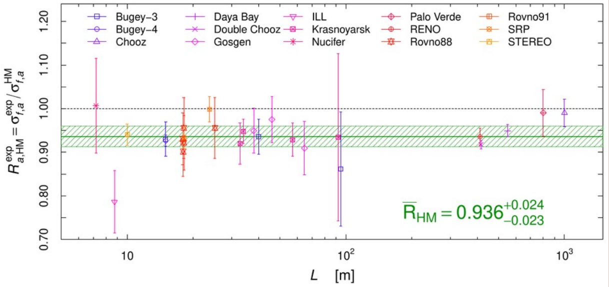
Neutrino-4



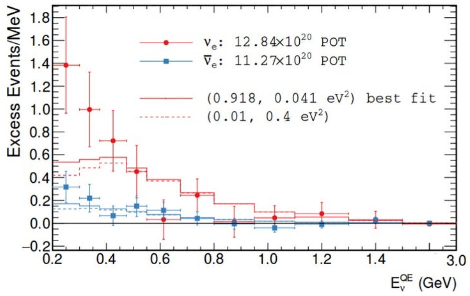
LSND



RAA

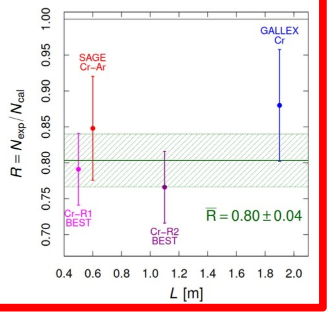


MiniBooNE

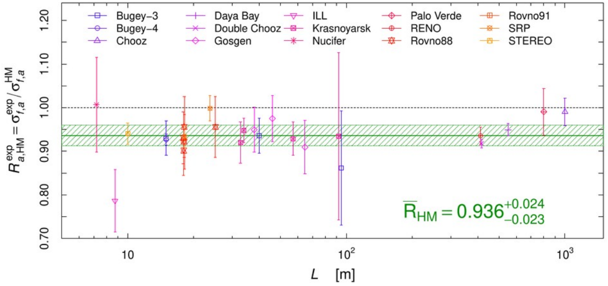


Anomalies

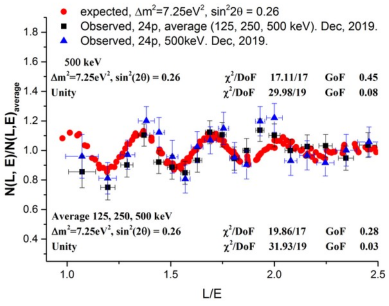
5-6σ Gallium



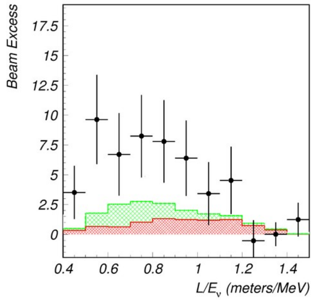
1-3σ RAA



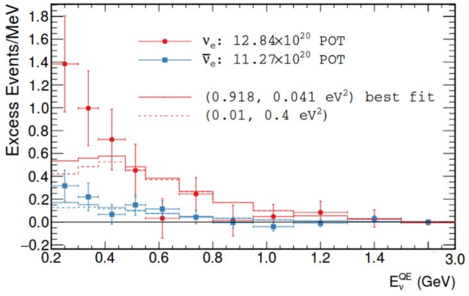
2-3σ Neutrino-4



~4σ LSND



~5σ MiniBooNE



Anomalies

Three-neutrino oscillations can not account for short baseline anomalies

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

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

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

Short baseline oscillations require:

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

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

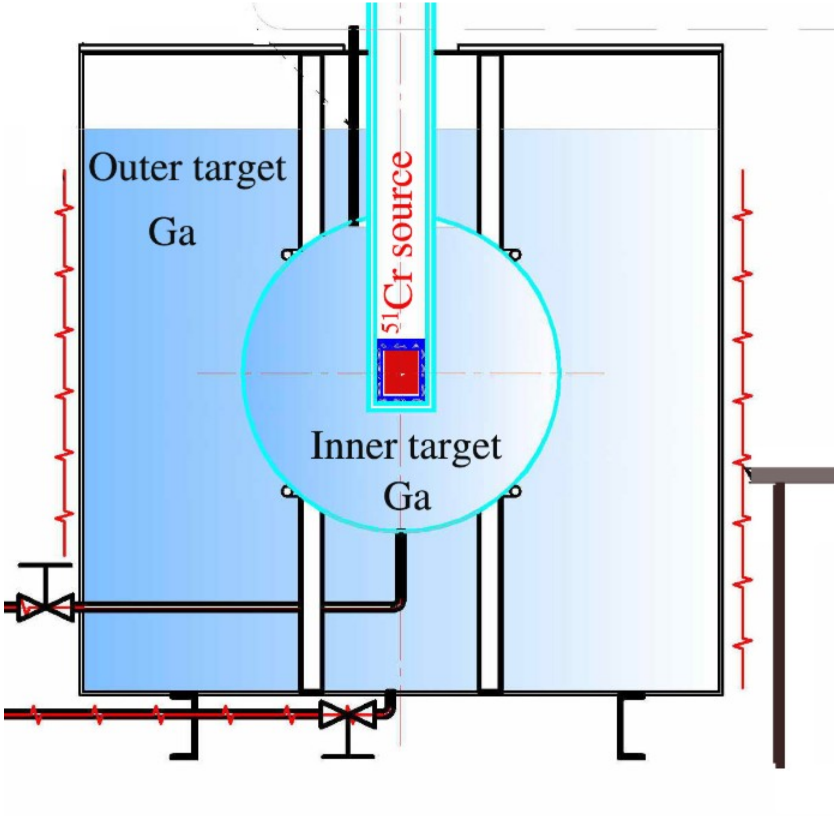
$$P_{\alpha\alpha}^{\mathrm{SBL}} \approx 1 - \sin^2(2\theta_{\alpha\alpha}) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

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

@Reactors and Gallium
@atmospherics and accelerators

The Gallium anomaly

BEST 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

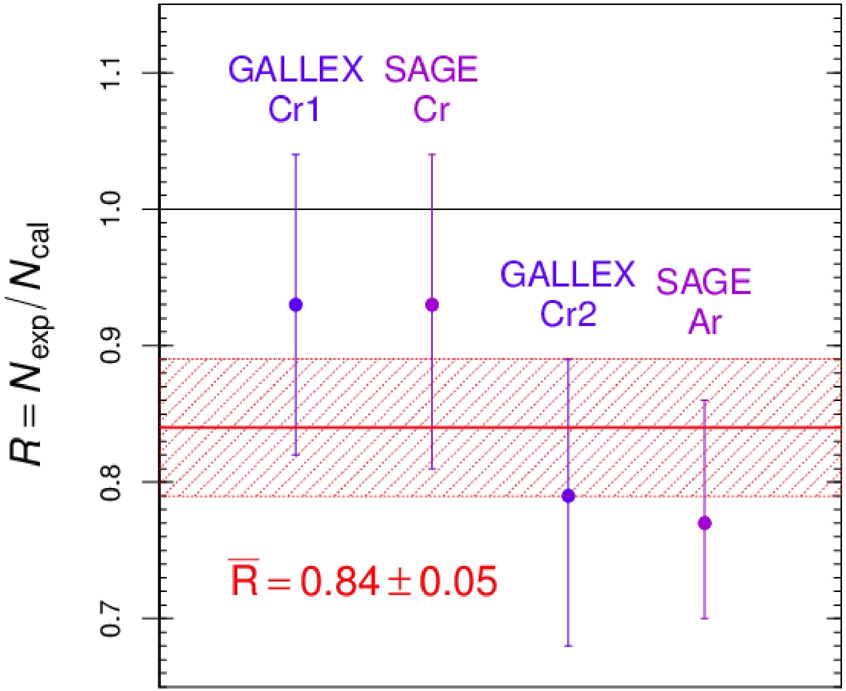
Model	Method	^{51}Cr		^{37}Ar	
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}
Ground State	$T_{1/2}(^{71}\text{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–
Bahcall (1997)	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%
Haxton (1998)	Shell Model	6.39 ± 0.65	13.3%	7.72 ± 0.81	14.2%
Frekers et al. (2015)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

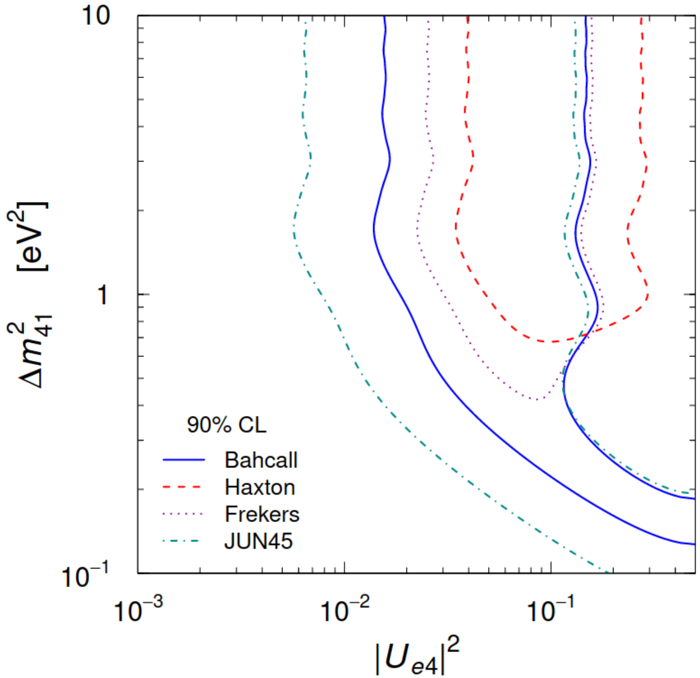
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Slightly different values for the different cross section models

The Gallium anomaly

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

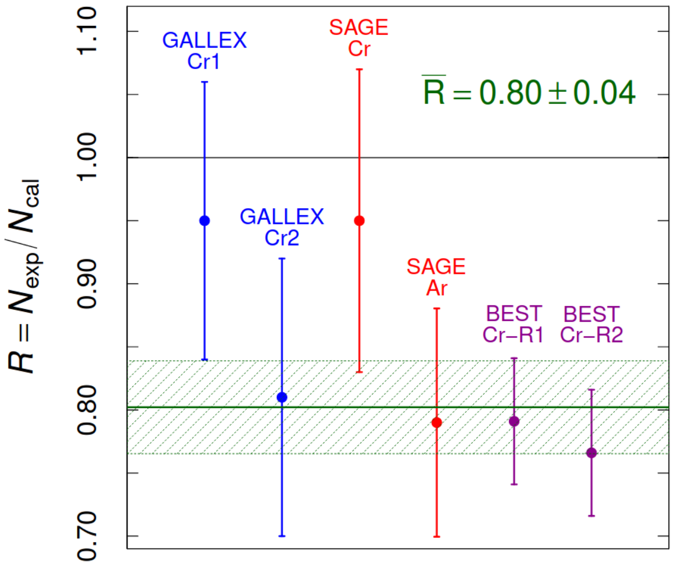


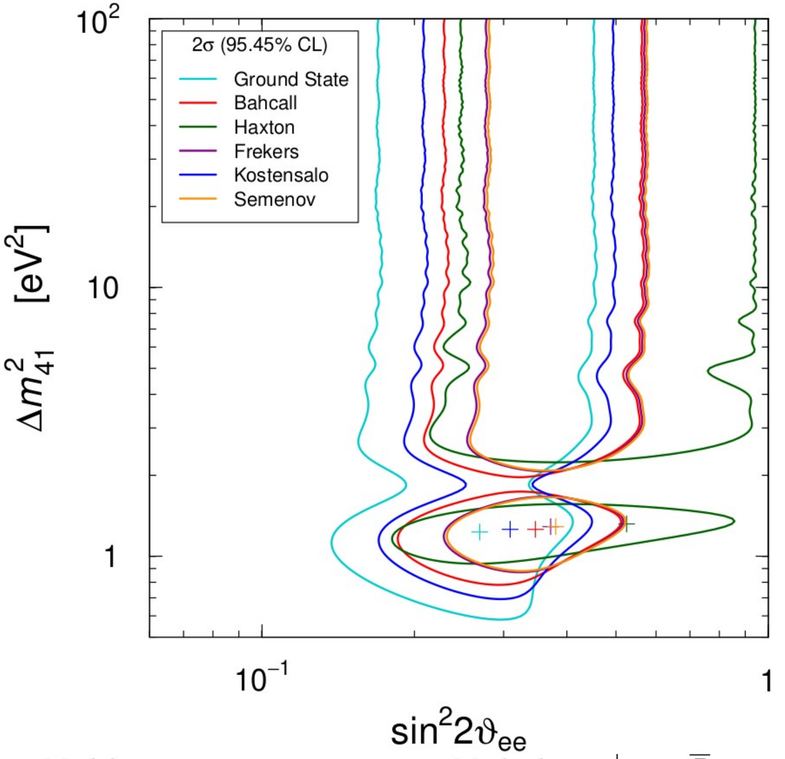


The significance of the “old” Gallium anomaly varied between 2.3 and 3.0σ, depending on the cross section model

The Gallium anomaly

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





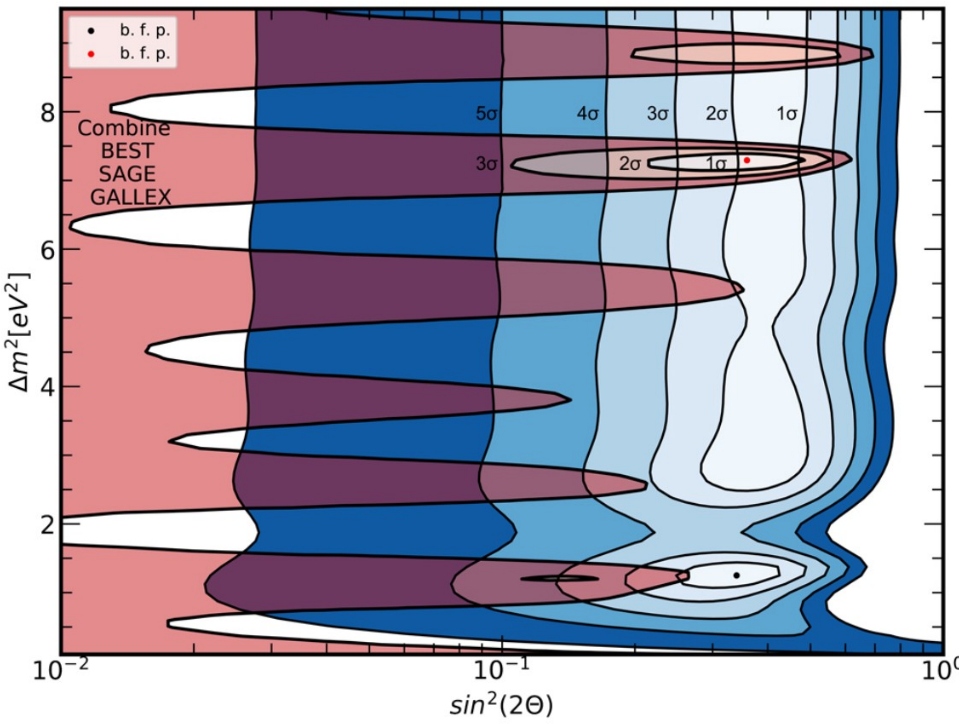
Model	Method	$\overline{R}$	GA
Ground State	$T_{1/2}(^{71}\text{Ge})$	$0.845^{+0.031}_{-0.031}$	5.0
Bahcall (1997)	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	$0.804^{+0.037}_{-0.036}$	5.2
Haxton (1998)	Shell Model	$0.731^{+0.088}_{-0.072}$	5.1
Frekers et al. (2015)	$^{71}\text{Ga}(^{3}\text{He},^{3}\text{H})^{71}\text{Ge}$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

Strong indication for short baseline (SBL) oscillations?

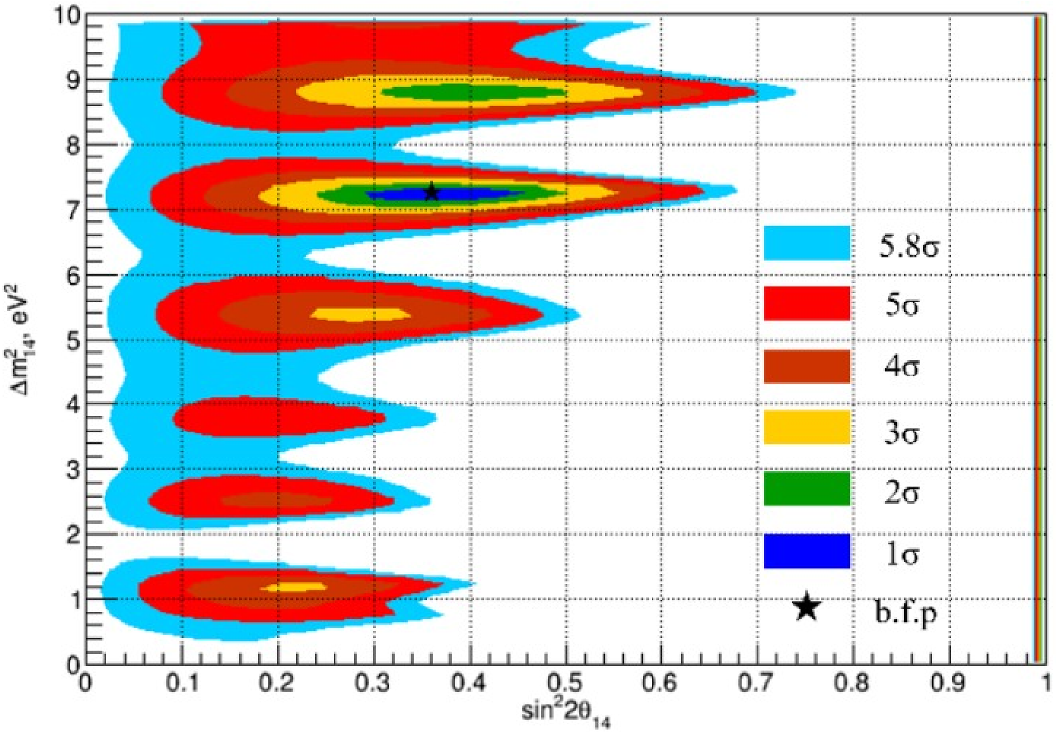
See also:
Barinov, Gorbunov, 2109.14654, PRD2022
Berryman, Coloma, Huber, Schwetz, Zhao, 2111.12530, JHEP 2022

Gallium and Neutrino-4

Barinov, Gorbunov, 2109.14654, PRD2022



Serebrov, Samoilov, Zherebtsov, 2306.09962



Gallium and Neutrino-4 results are compatible

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

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

Yields depend on the neutrino flux

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

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

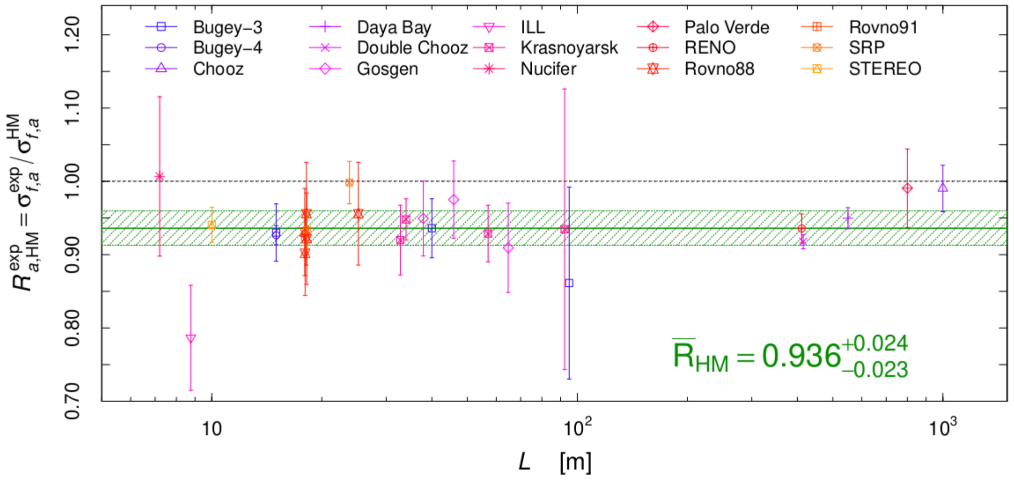
Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.74 ± 0.17	10.19 ± 0.83	4.40 ± 0.13	6.10 ± 0.16
EF	6.29 ± 0.31	10.16 ± 1.02	4.42 ± 0.22	6.23 ± 0.31
HKSS	6.82 ± 0.18	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16
KI	6.41 ± 0.14	9.53 ± 0.48	4.40 ± 0.13	6.10 ± 0.16
HKSS-KI	6.48 ± 0.14	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16

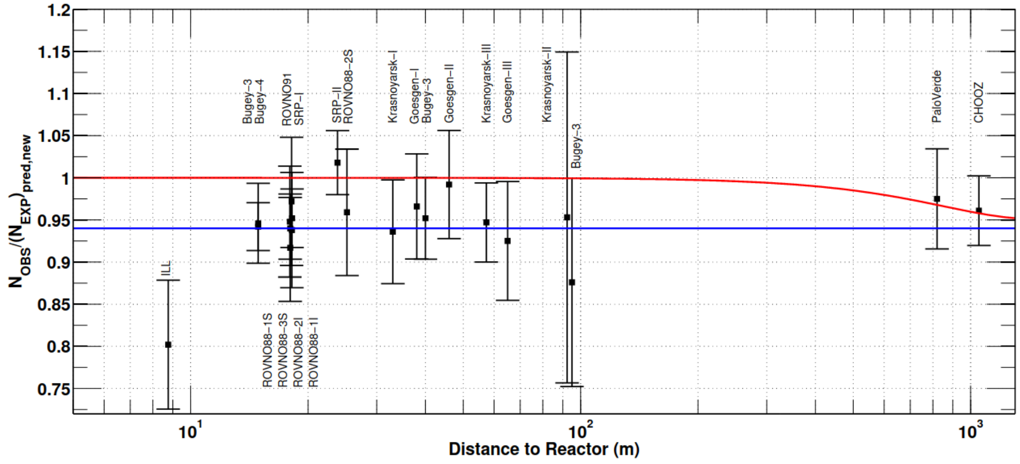
Berryman, Huber, 2005.01756, JHEP 2021

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

2011 Huber Mueller fluxes

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





HM flux gives 2.5σ anomaly

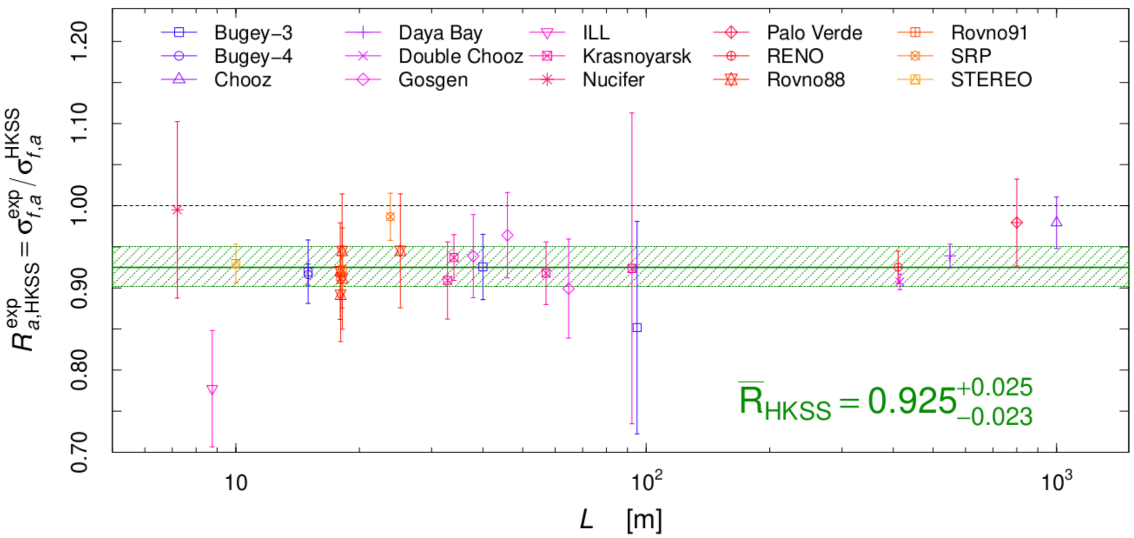
Original RAA was also 2.5σ

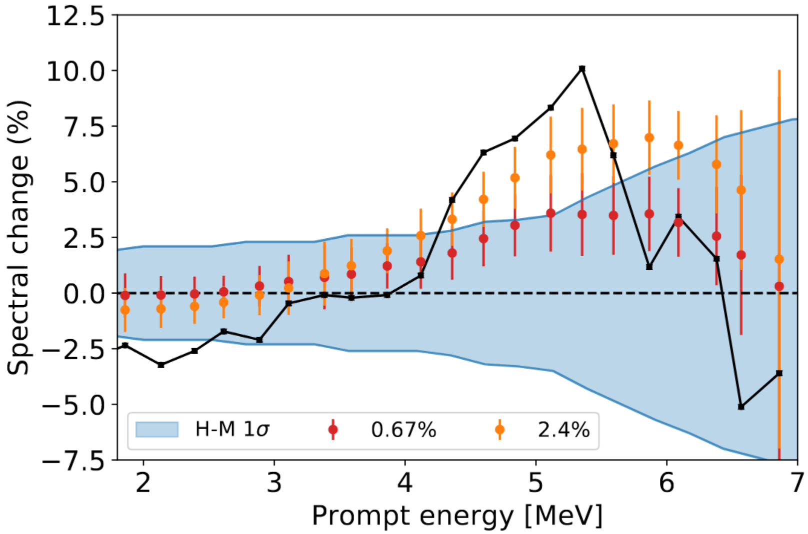
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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

2019 new converted fluxes

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





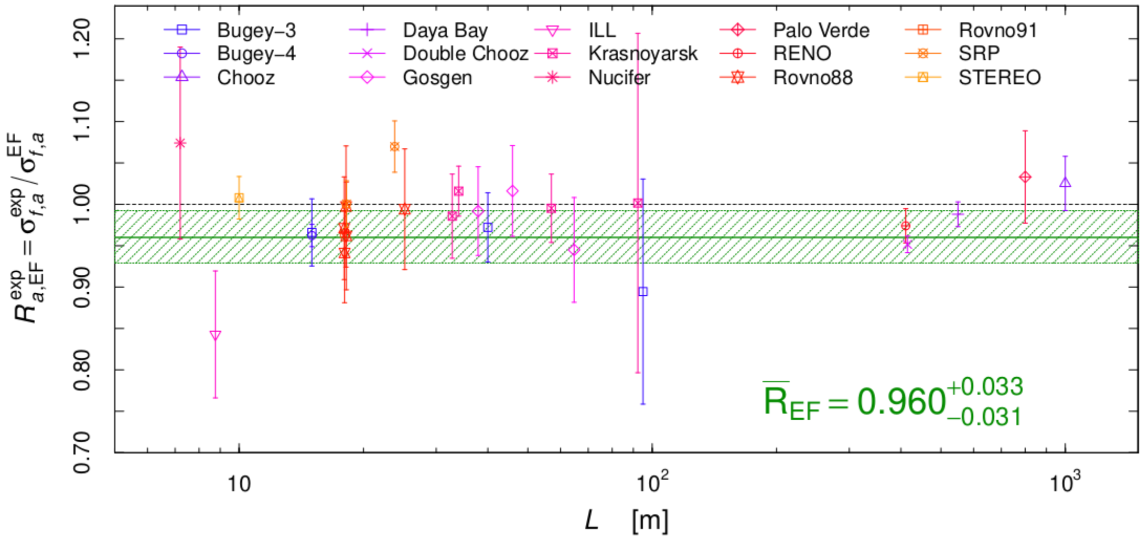
HKSS flux results in 2.9σ anomaly!

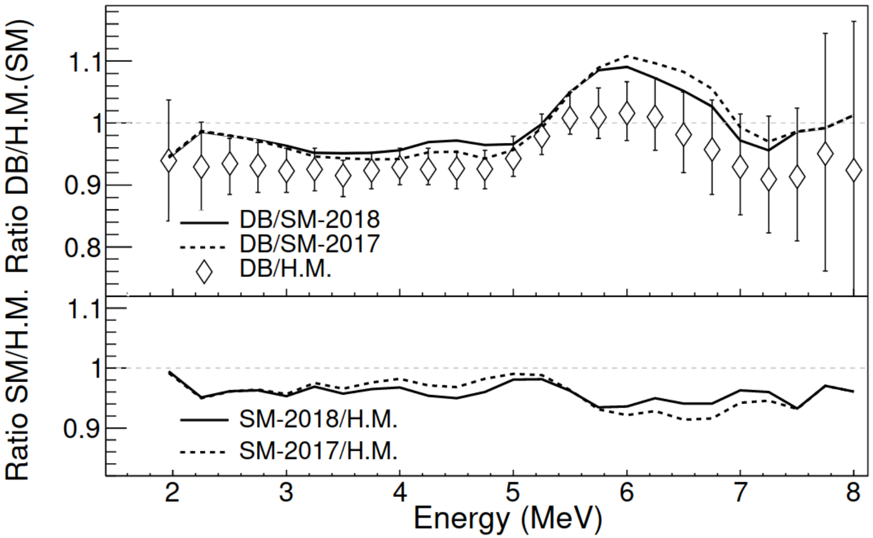
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

Better prediction for the energies of the bump!

2019 summation method fluxes

Estienne, Fallot, et al, 1904.09358, PRL 2019





1.2σ deficit, no anomaly!

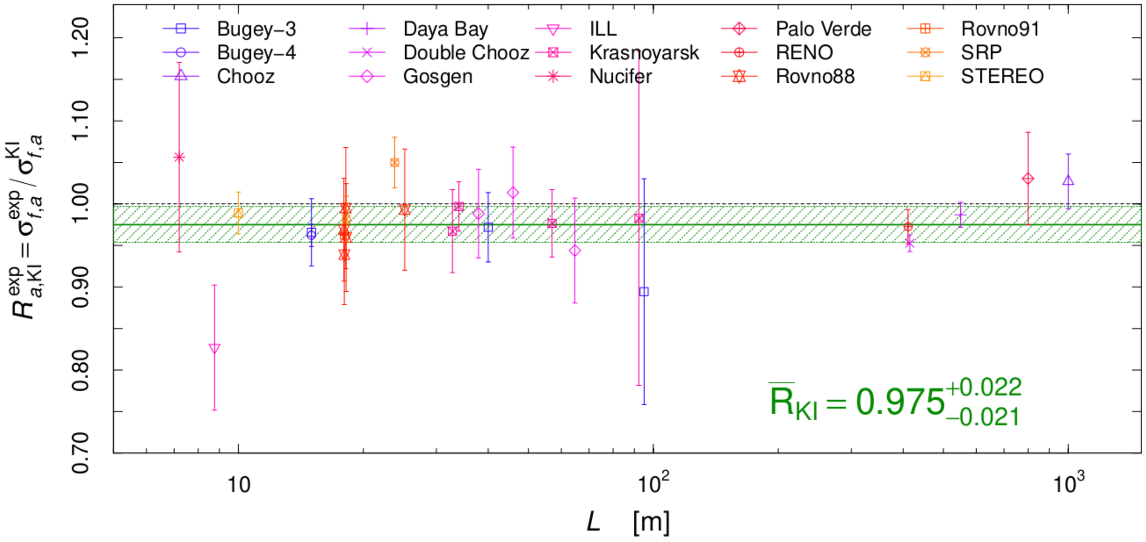
Ratio reduced with respect to HM for all energies!

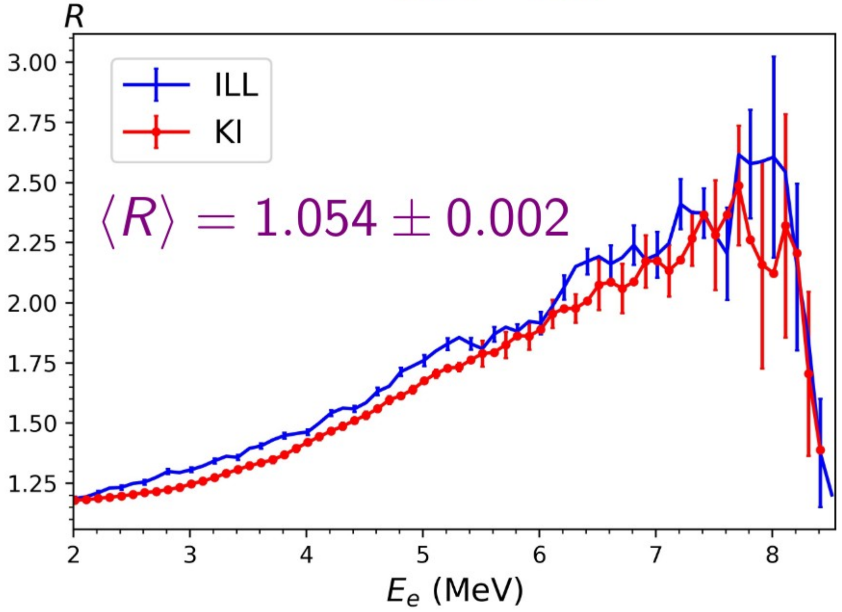
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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

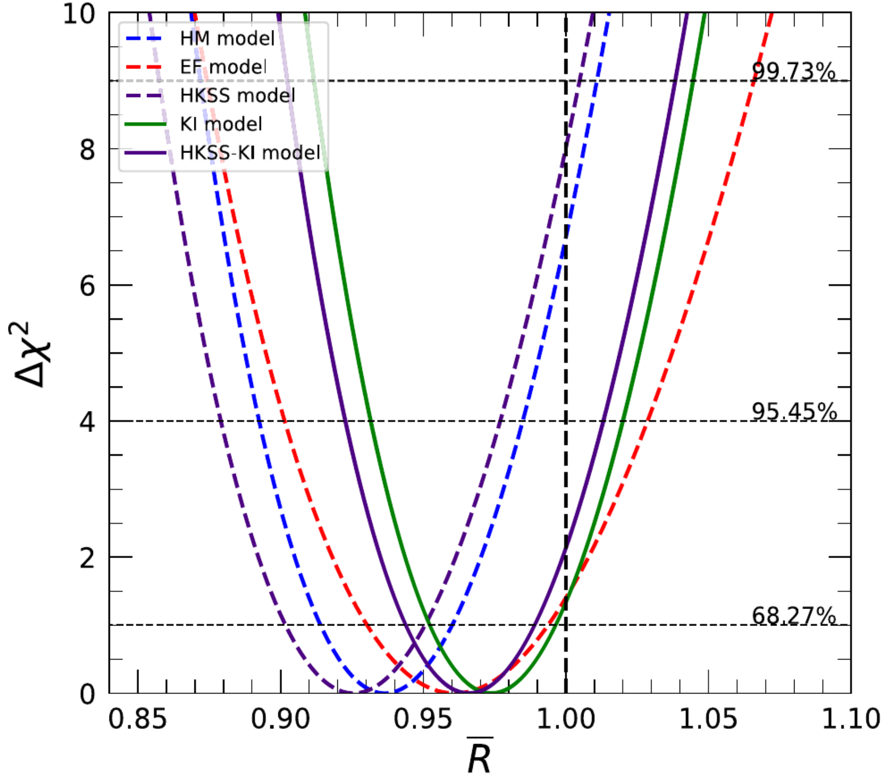
New measurement suggests a reduction in the flux of $^{235}\mathrm{U}$

The reactor rate anomaly

The significance of the RAA depends on the input flux model

The EF and KI models have no anomaly

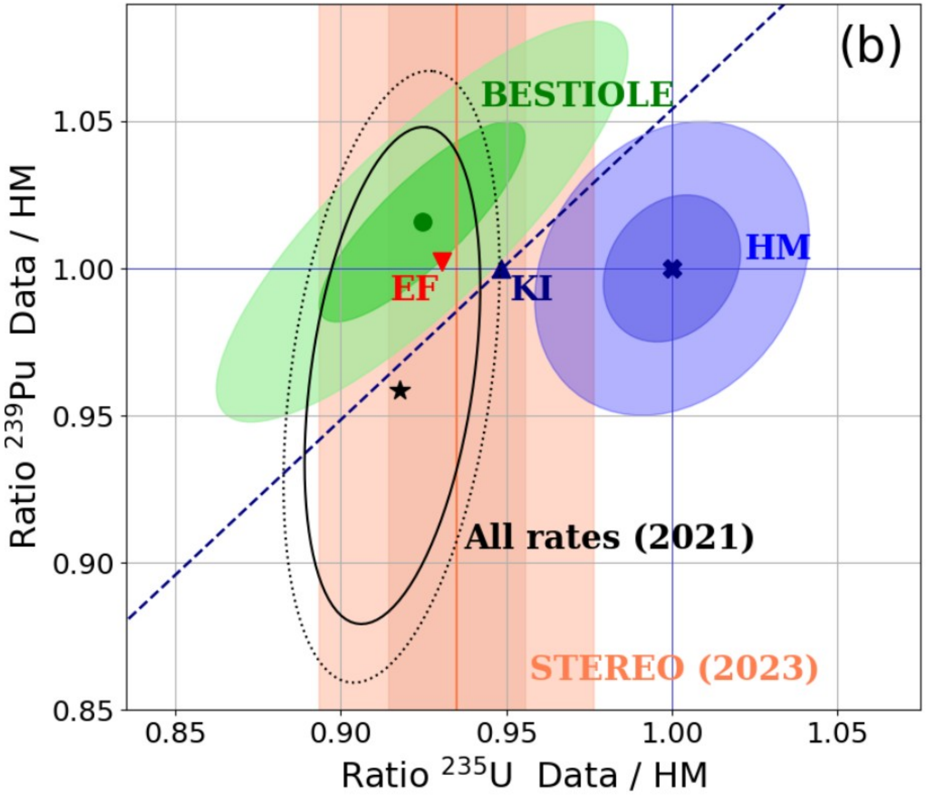
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

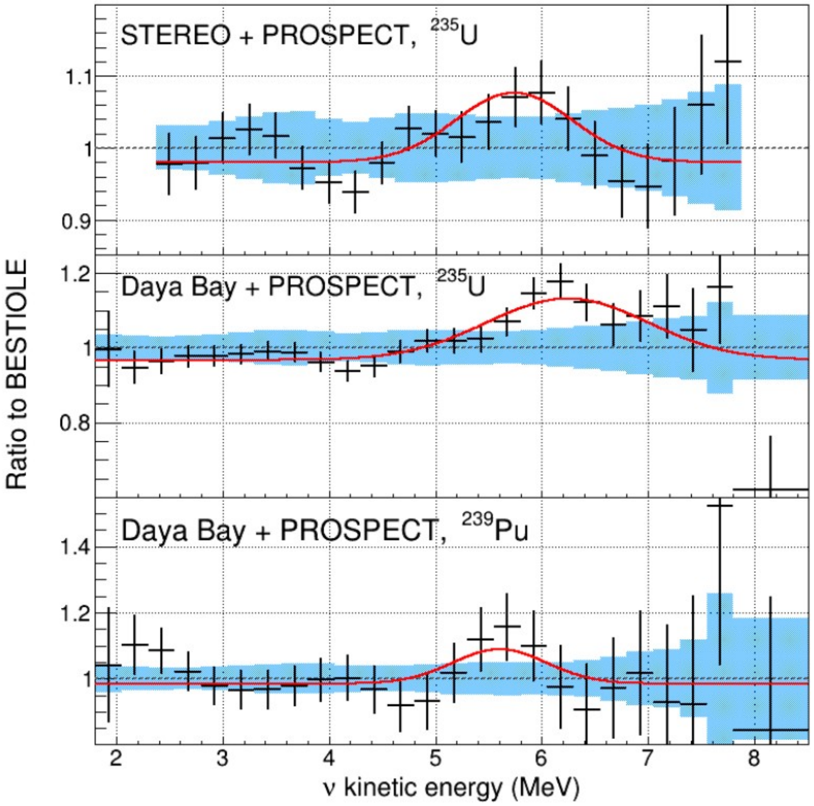


Mention, Fechner, Lasserre, Mueller, Lhuillier, 1101.2755, PRD 2011Huber, 1106.0687, PRC 2012
Mueller, Lhuillier, Fallot, Letourneau, Cormon, 1101.2663, PRC 2012
Estienne, Fallot, et al, 1904.09358, PRL 2019
Hayen, Kostensalo, Severijns, Suhonen, 1908.08302, PRC 2019
Kurchatov Institute: Kopeikin, Skorokhvatov,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

BESTIOLE: 2023 new flux from summation method

BESTIOLE: Périssé, el al, 2304.14992

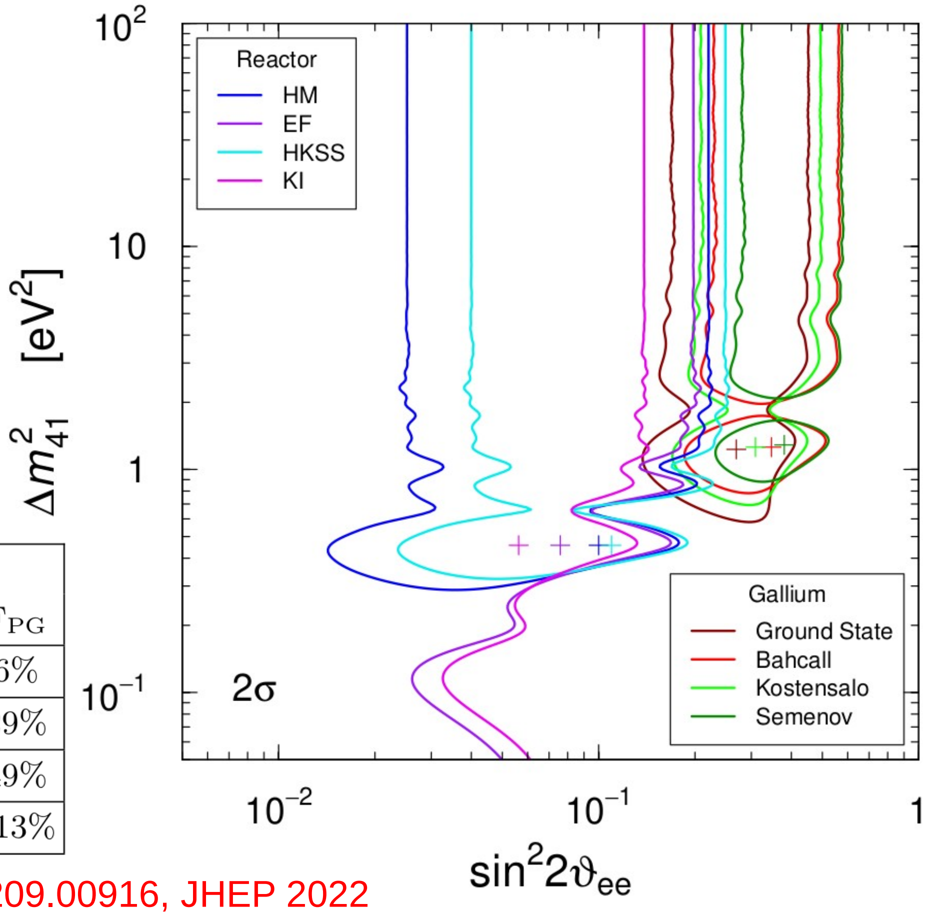




Tension between RAA and Gallium

Severe tension between reactor rate and Gallium data!

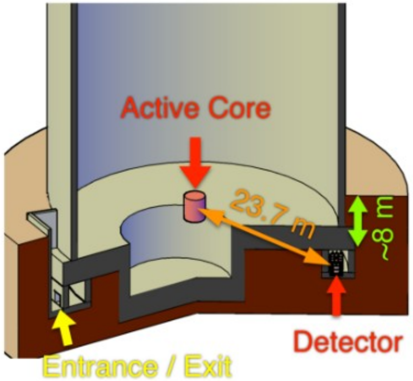
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$	$\Delta\chi^2_{\mathrm{PG}}$	$\mathrm{GoF}_{\mathrm{PG}}$
Ground State	7.2	2.8%	5.4	6.8%	9.1	1.1%	11.9	0.26%
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%



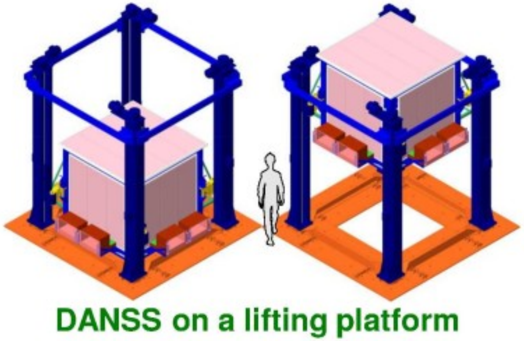
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Ratio analysis

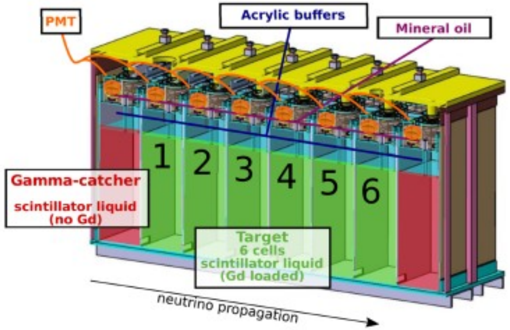
NEOS



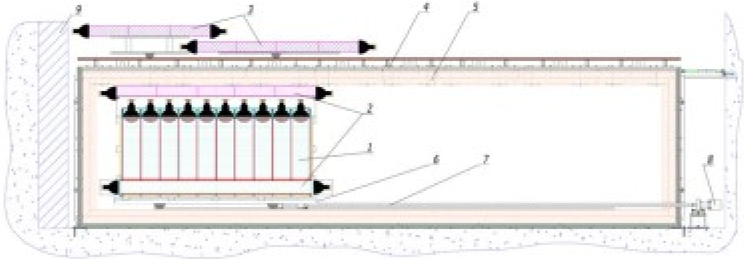
DANSS



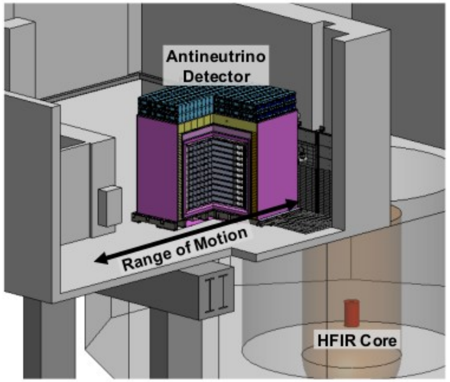
STEREO



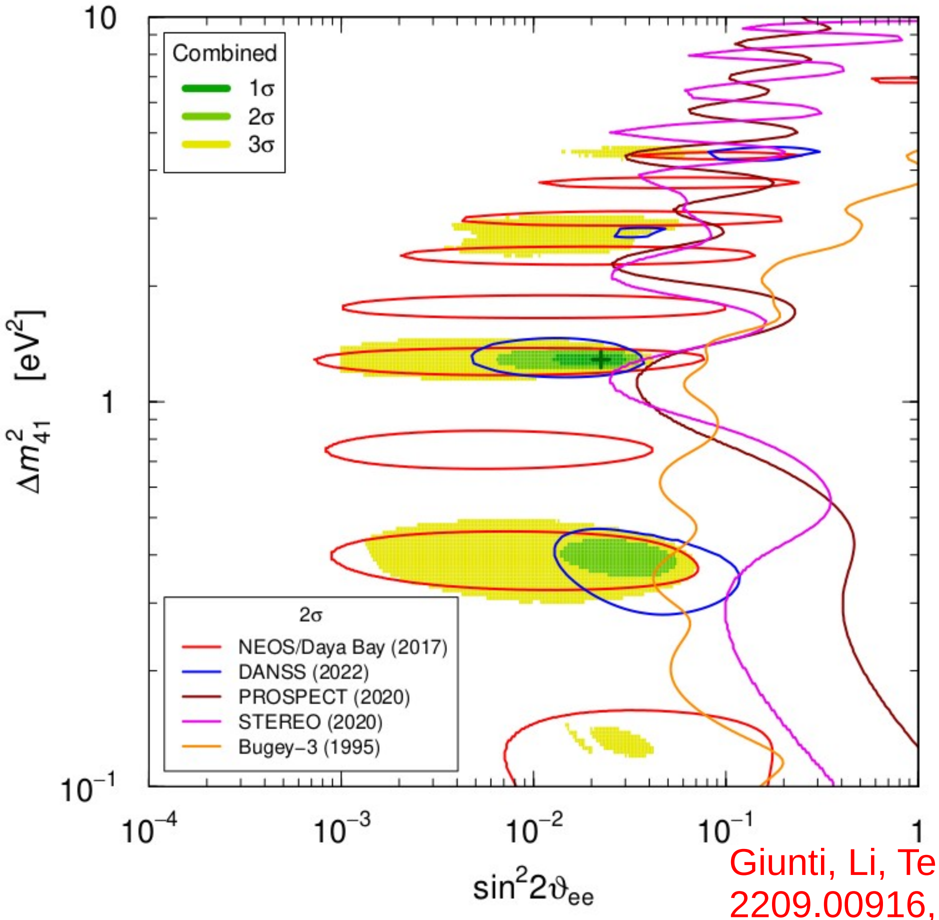
Neutrino-4

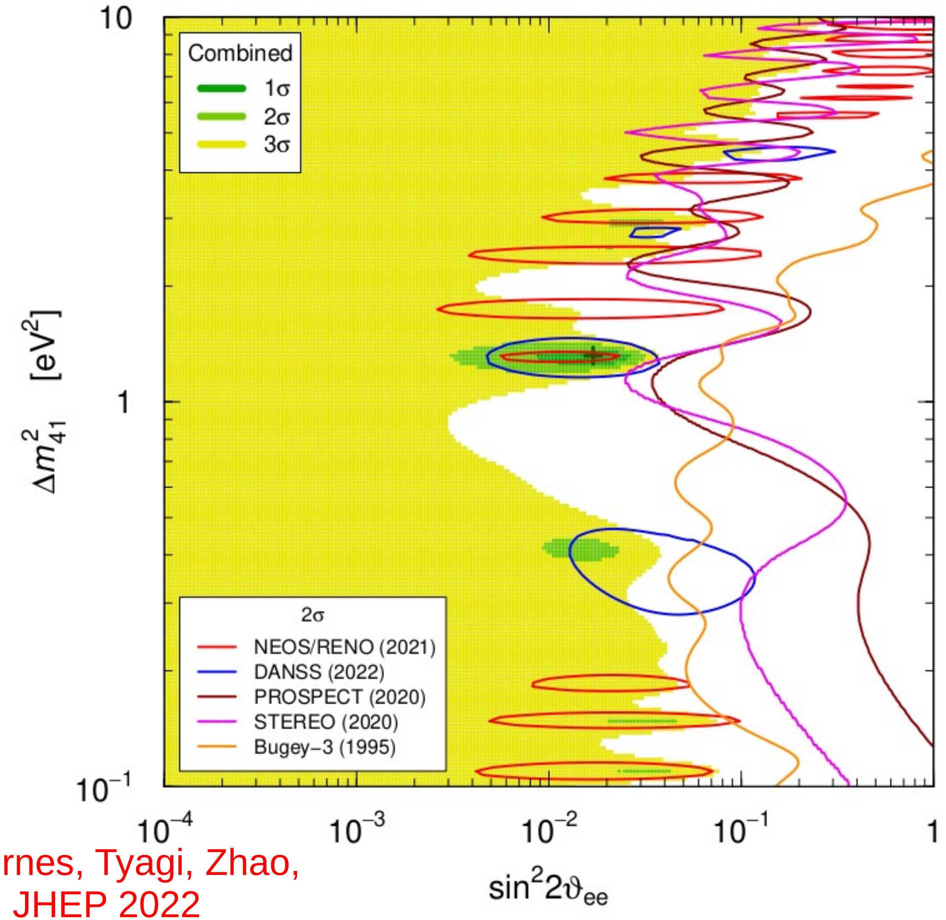


PROSPECT



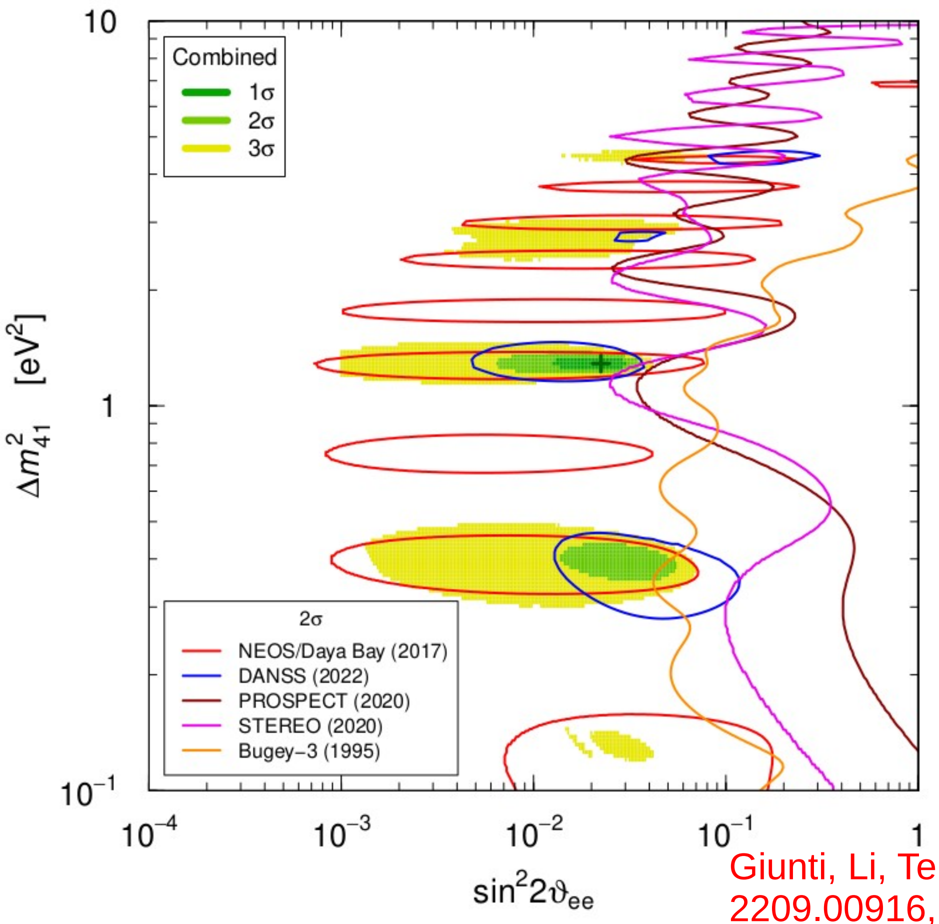
Ratio analysis





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

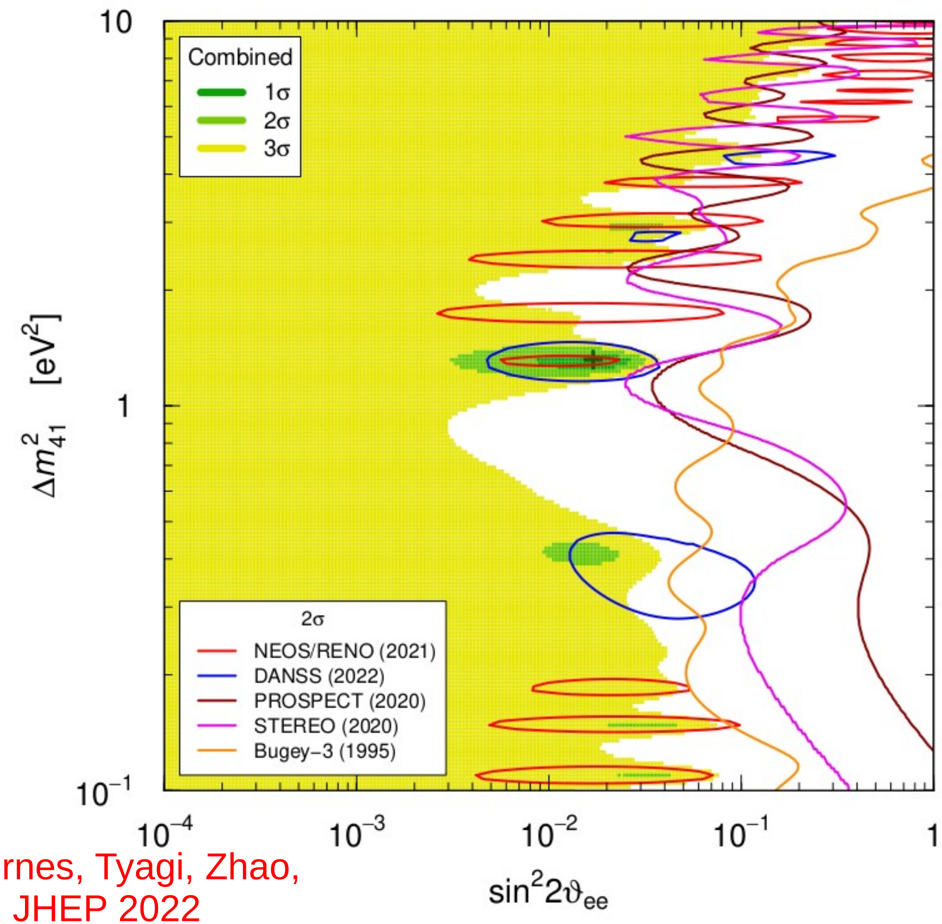
Many many events at Daya Bay!

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

Ratio analysis

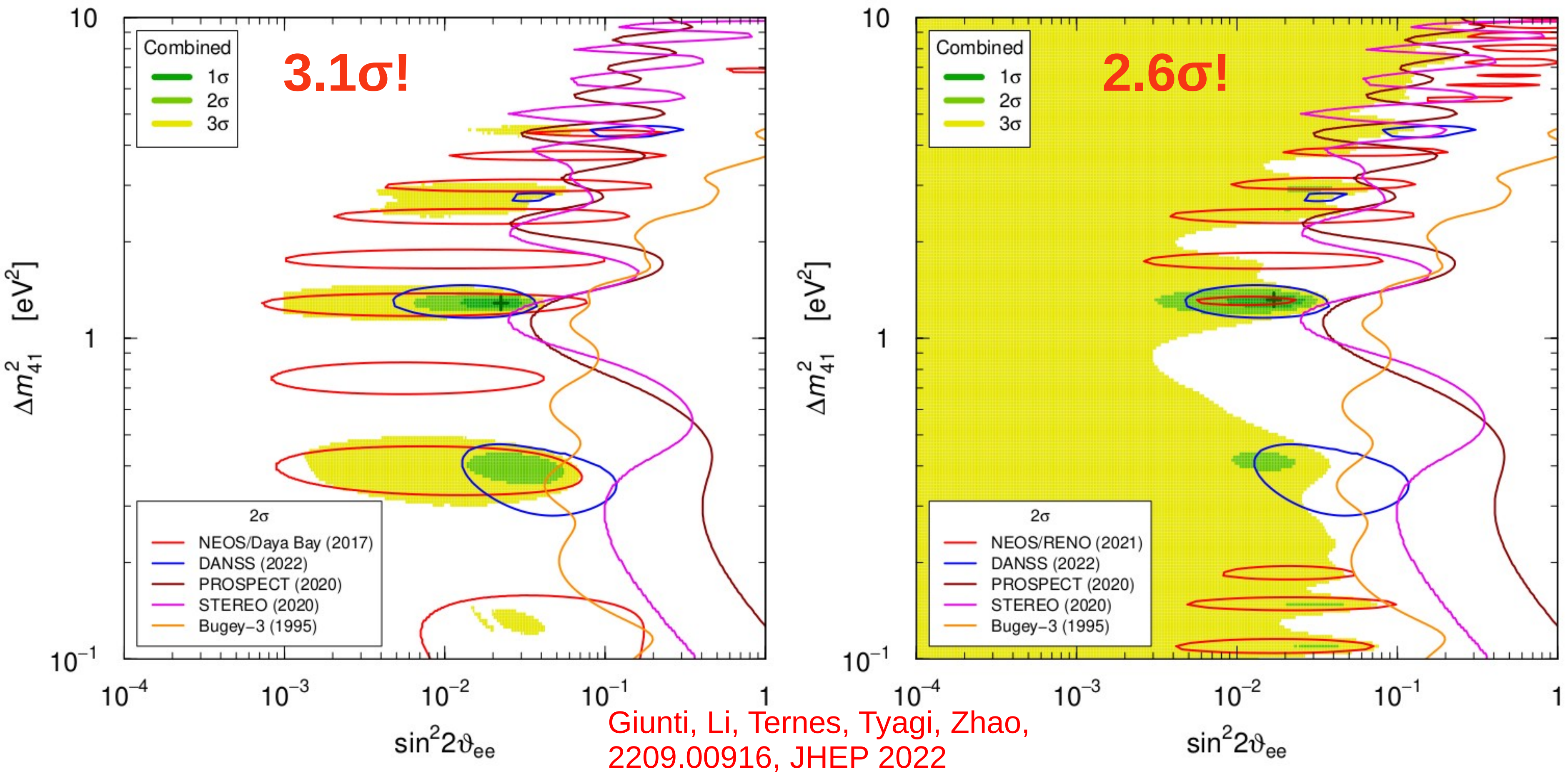
The NEOS collaboration also performed an analysis using the RENO spectrum as a reference spectrum

Same reactor complex, better control of systematic uncertainties!



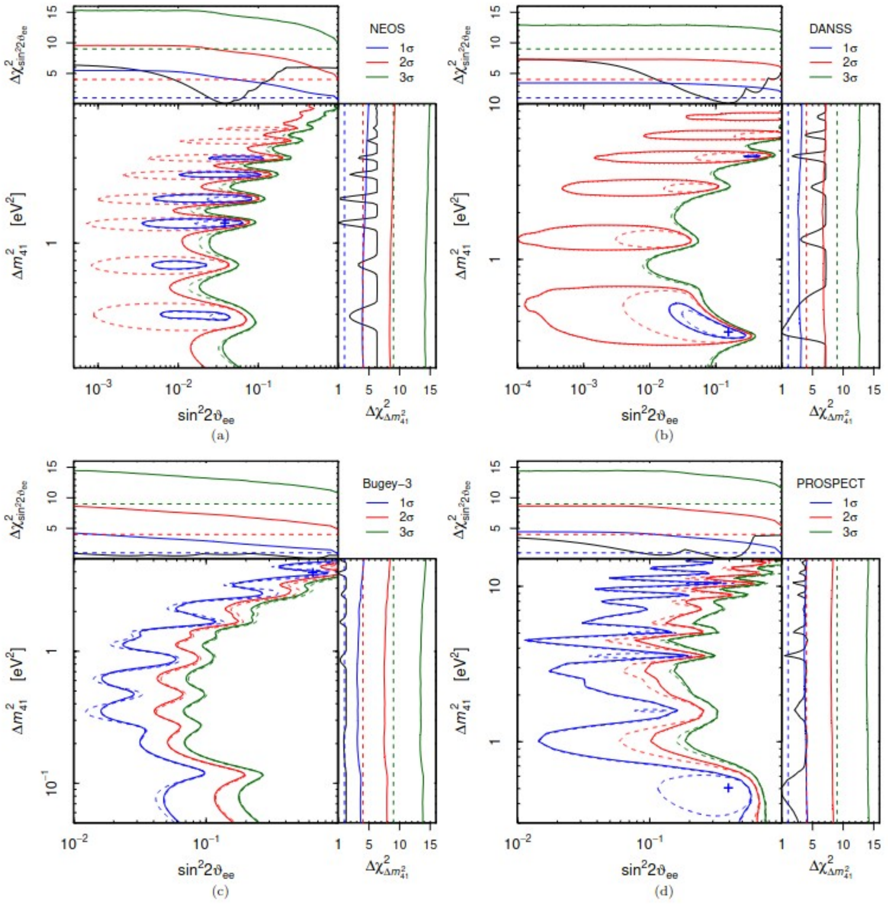
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

Ratio analysis



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

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

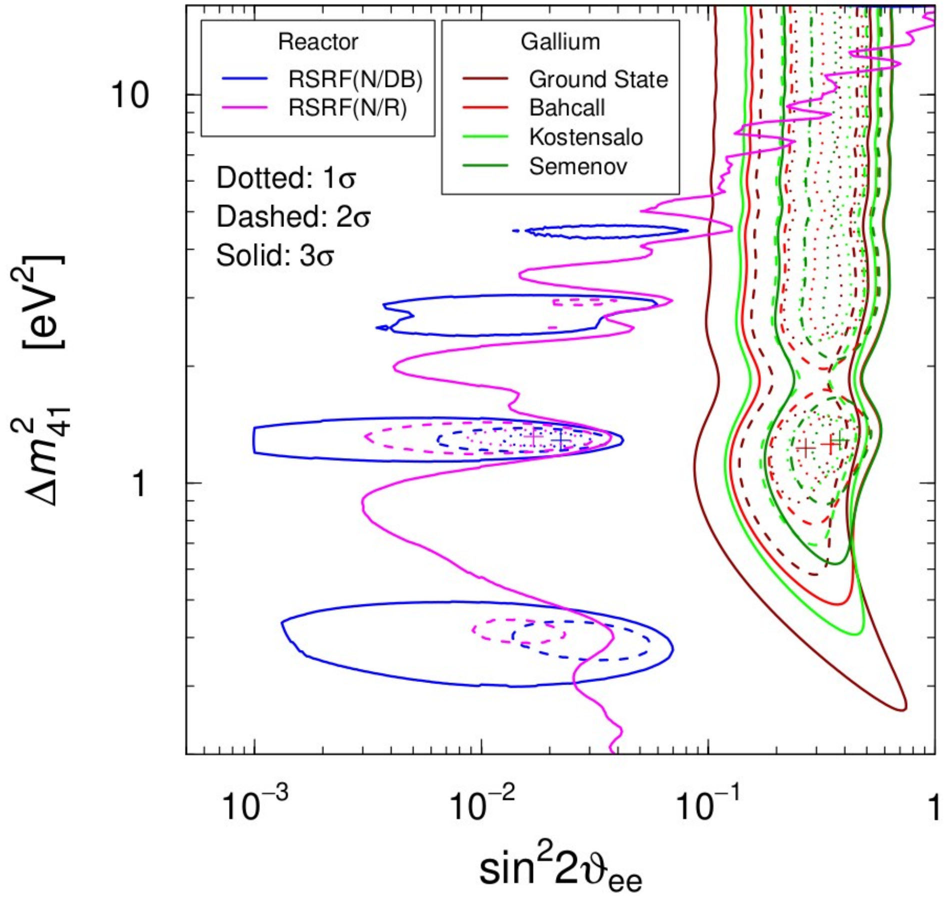
Ratio analysis

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%

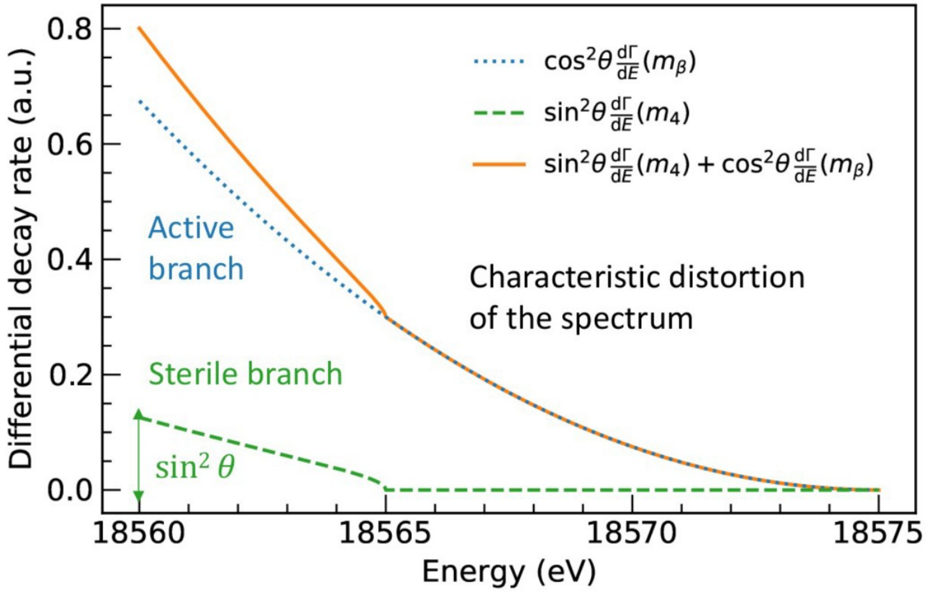


Tritium data

Tritium experiments measure the beta-decay spectrum

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

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



Lokhov @ NuMass 2022, Milano

Tritium data

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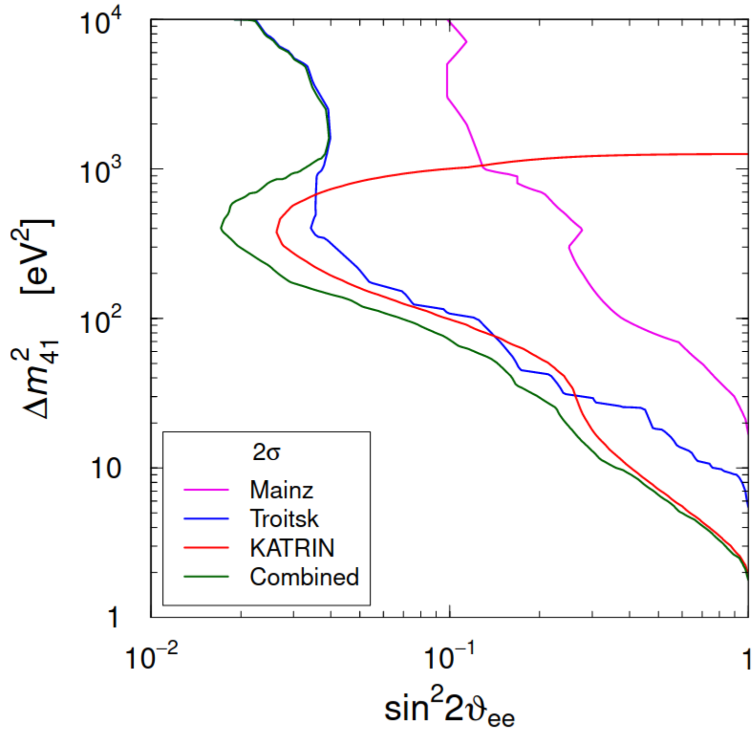
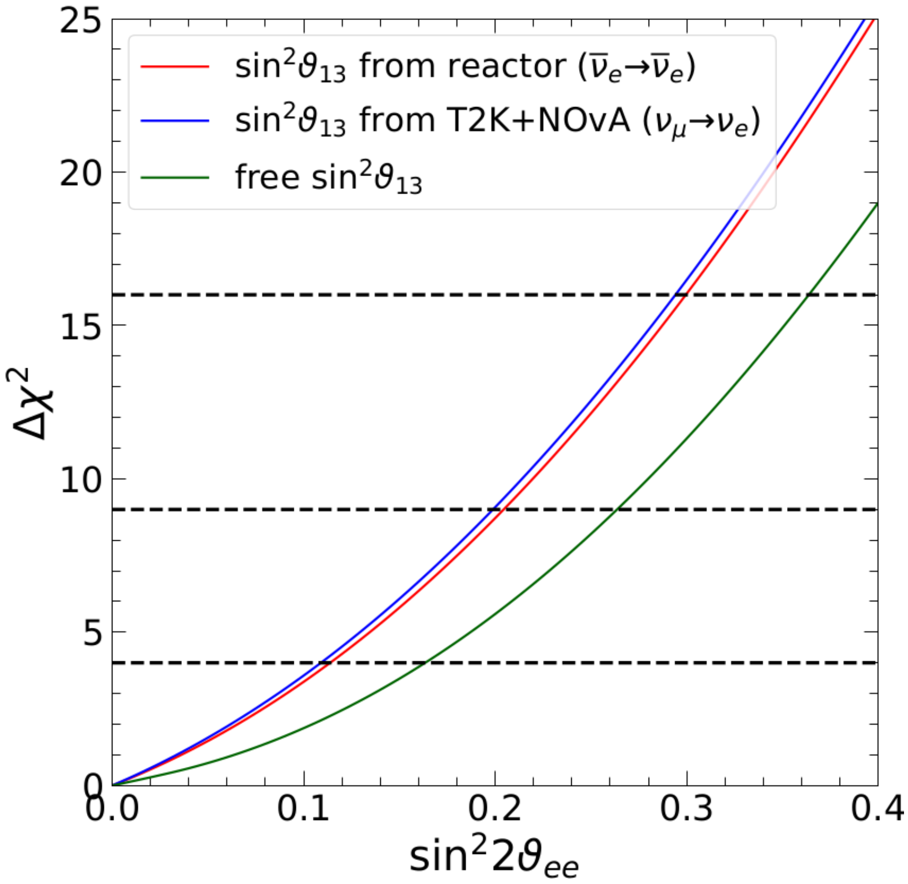


Giunti @ NOW 2022, Ostuni

Solar data

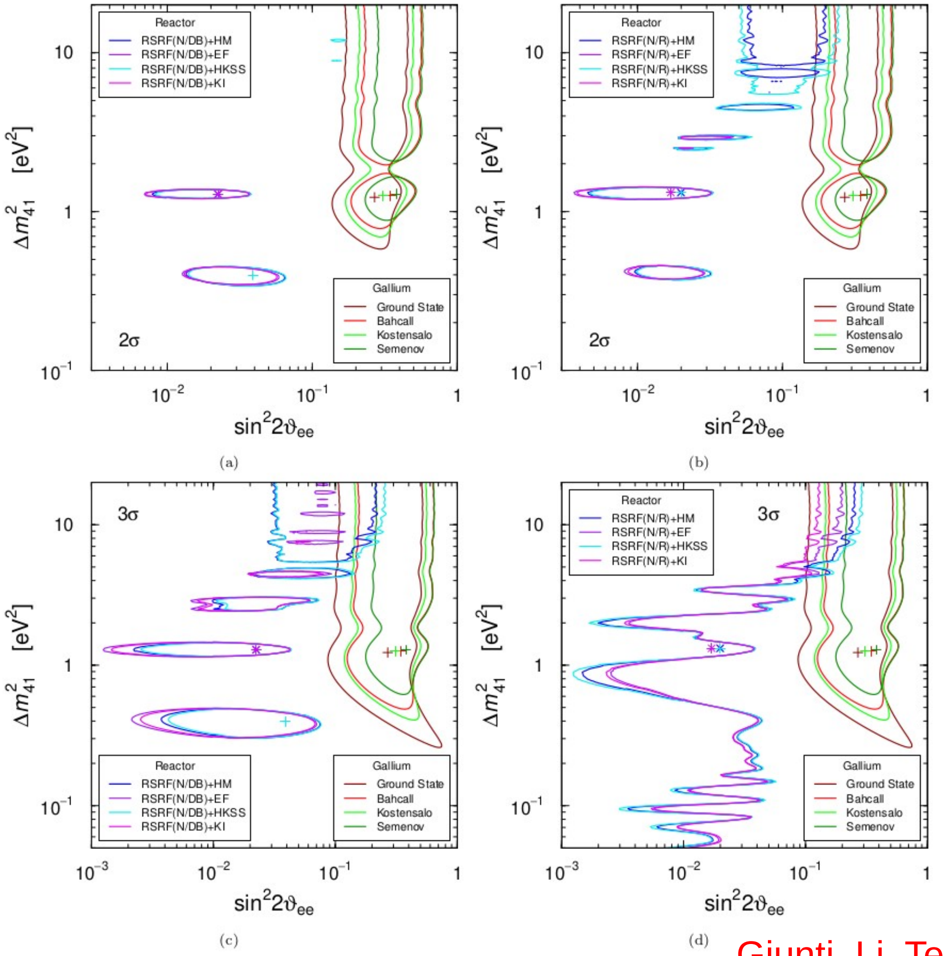


Using the newest solar data we can get additional bounds on the sterile mixing angle

	Solar-only		S+ϑ_{13}(T&N)		S+ϑ_{13}(R)	
	$\Delta\chi^2_{\text{PG}}$	GoF$_{\text{PG}}$	$\Delta\chi^2_{\text{PG}}$	GoF$_{\text{PG}}$	$\Delta\chi^2_{\text{PG}}$	GoF$_{\text{PG}}$
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

Combined ratio and rate data



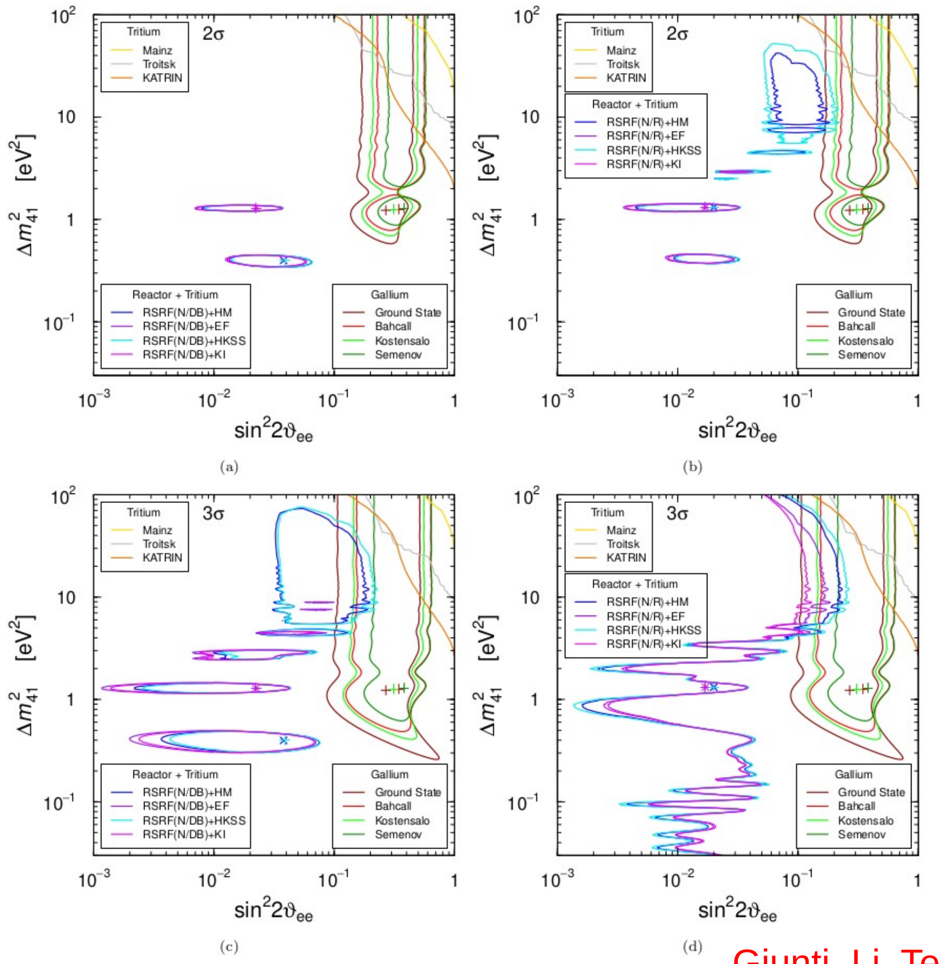
Combing ratio and rate data leads to better localization of allowed regions.

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 and Tritium data



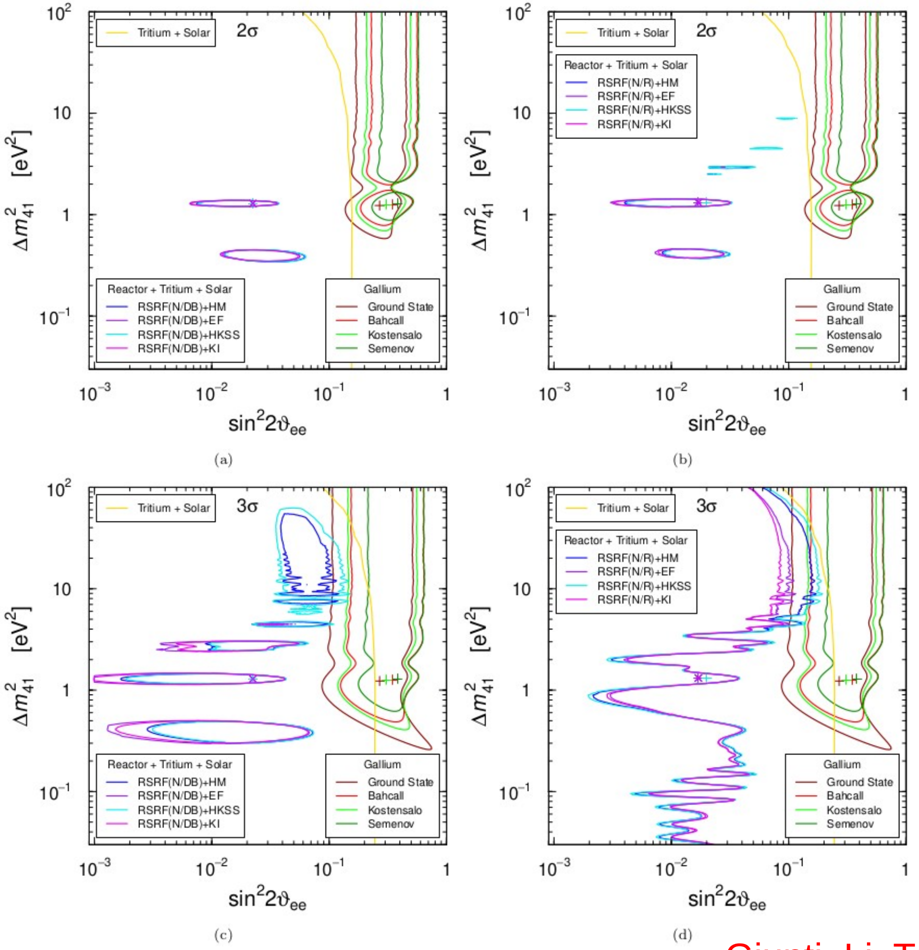
Tritium data removes the regions at large values of the mass splitting.

Severe tension for any combination with Gallium data!

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

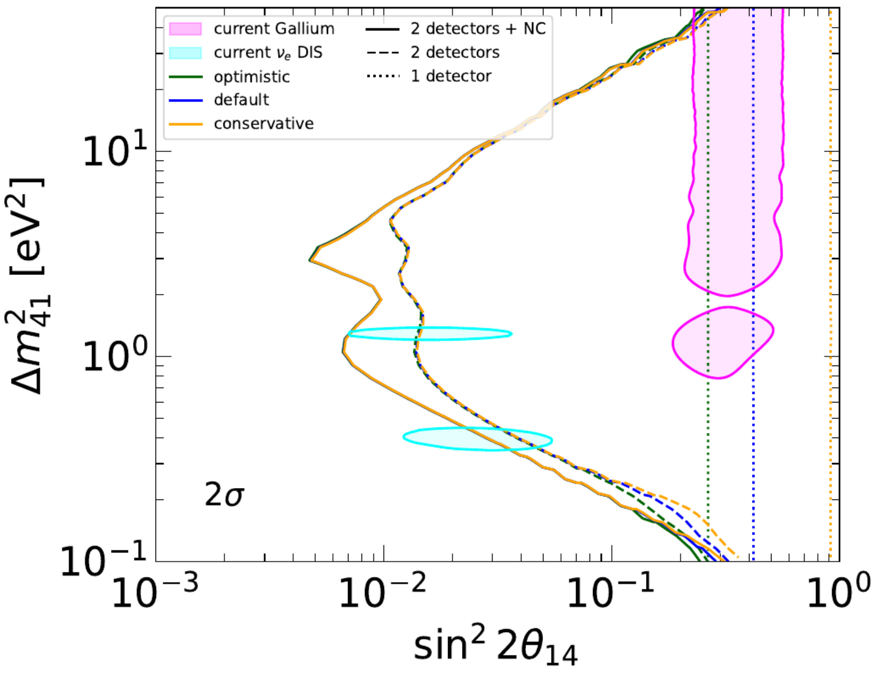
Due to new reactor ratio data

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, JHEP 2023

JUNO+TAO sensitivity

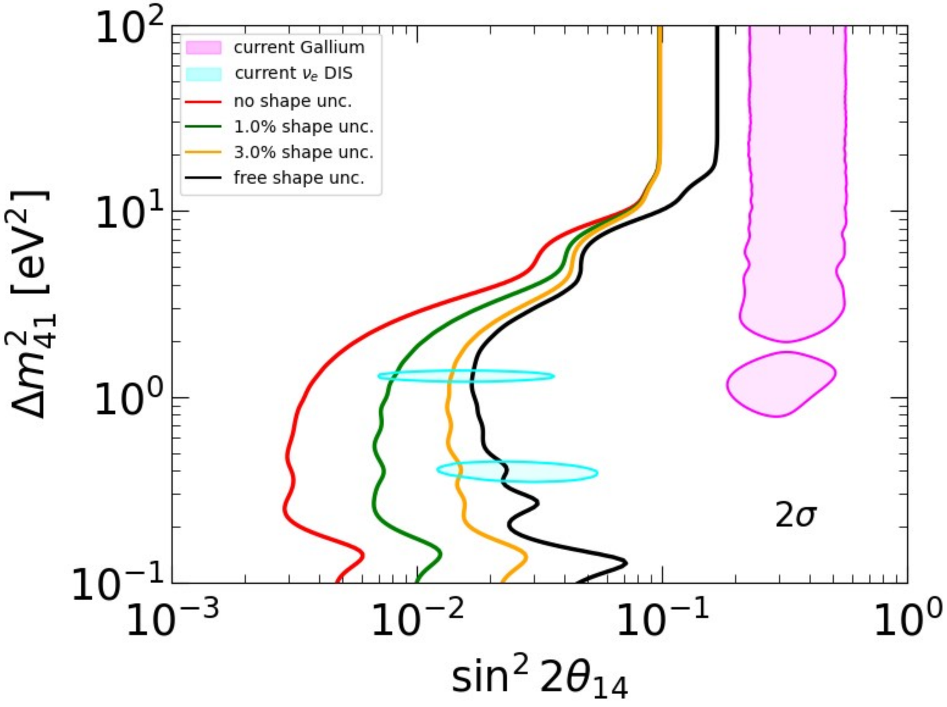


Figure adapted from
Basto-Gonzalez, Forero, Giunti, Quiroga, Ternes,
2112.00379, PRD 2022

Conclusions

The 3+1 explanation to the Gallium and Neutrino-4 anomalies is in severely strong tension with the analysis of data of all other classes of experiments

RAA might be solved due to updated reactor flux models (EF and KI)

New (revived) preference for SBL oscillations from ratio experiments

However, significance would be reduced if statistical fluctuation of data were included in the fit


Thanks!
electron-neutrino
muon neutrino
tau-neutrino

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

$$S_k(E) = \sum_n Y_n^k \sum_b \mathrm{BR}_n^b \; S_n^b(E) \leftarrow \text{allowed or forbidden decay spectrum}$$

Y_n^k ↑ cumulative fission yield

BR_n^b ↑ branching ratio

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

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

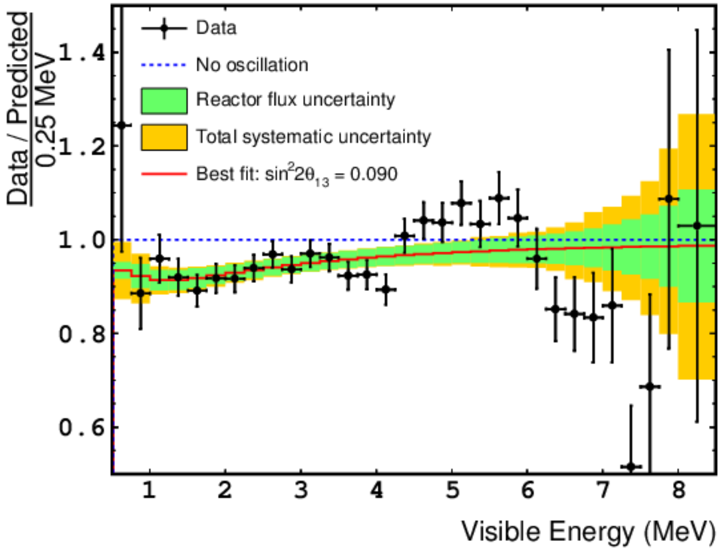
5 MeV bumb

5 MeV bump discovered in 2014

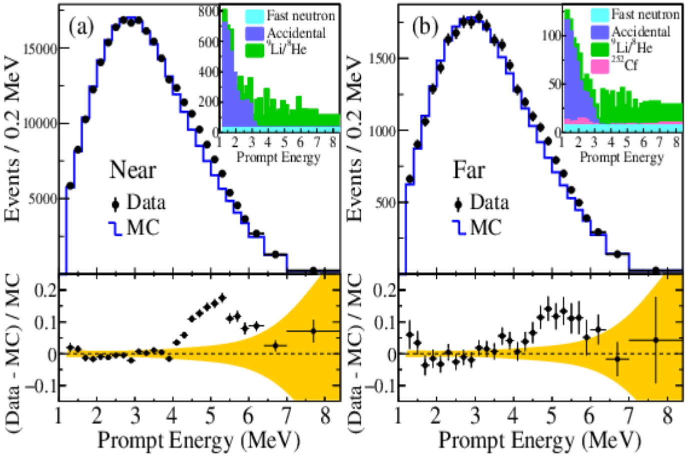
Can not been explained with short baseline oscillations

Proof of our incomplete understanding of nuclear reactor fluxes

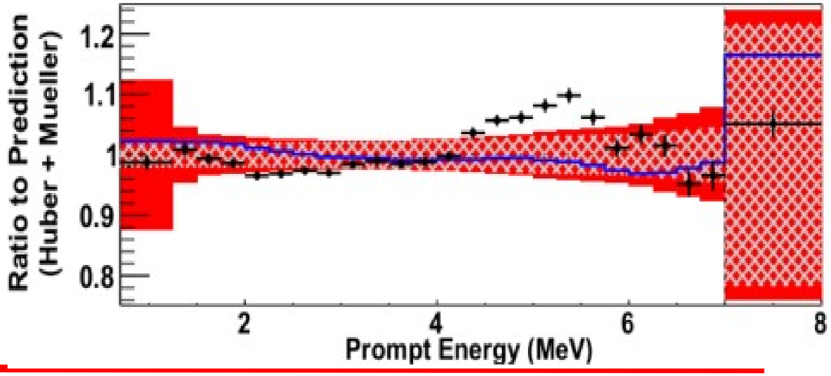
Double Chooz, 1406.7763, JHEP 2015



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

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

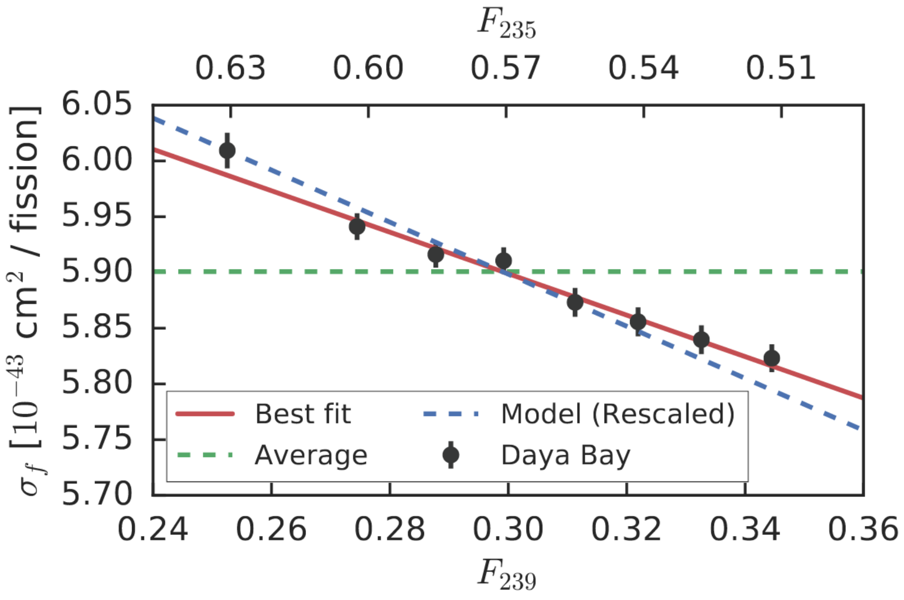
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022

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	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	3.1	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		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	4.0	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		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	2.0 3.8	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	$\approx$ 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	$\approx$ 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	$\approx$ 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	$\approx$ 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	$\approx$ 415
27	STEREO	1	0	0	0	6.34	0.941	1.008	0.930	0.989	0.978	2.5	0	9 – 11

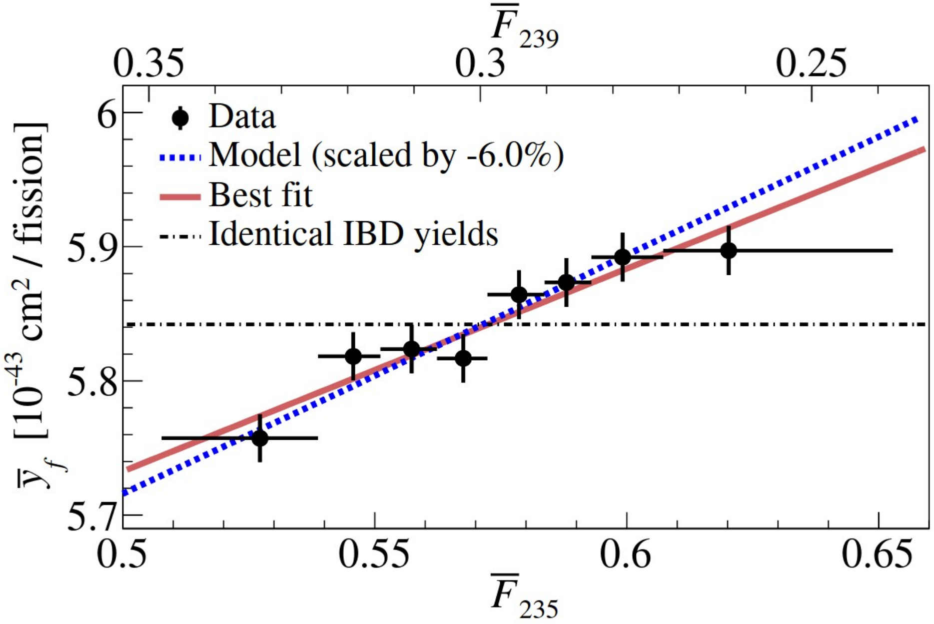
Evolution data

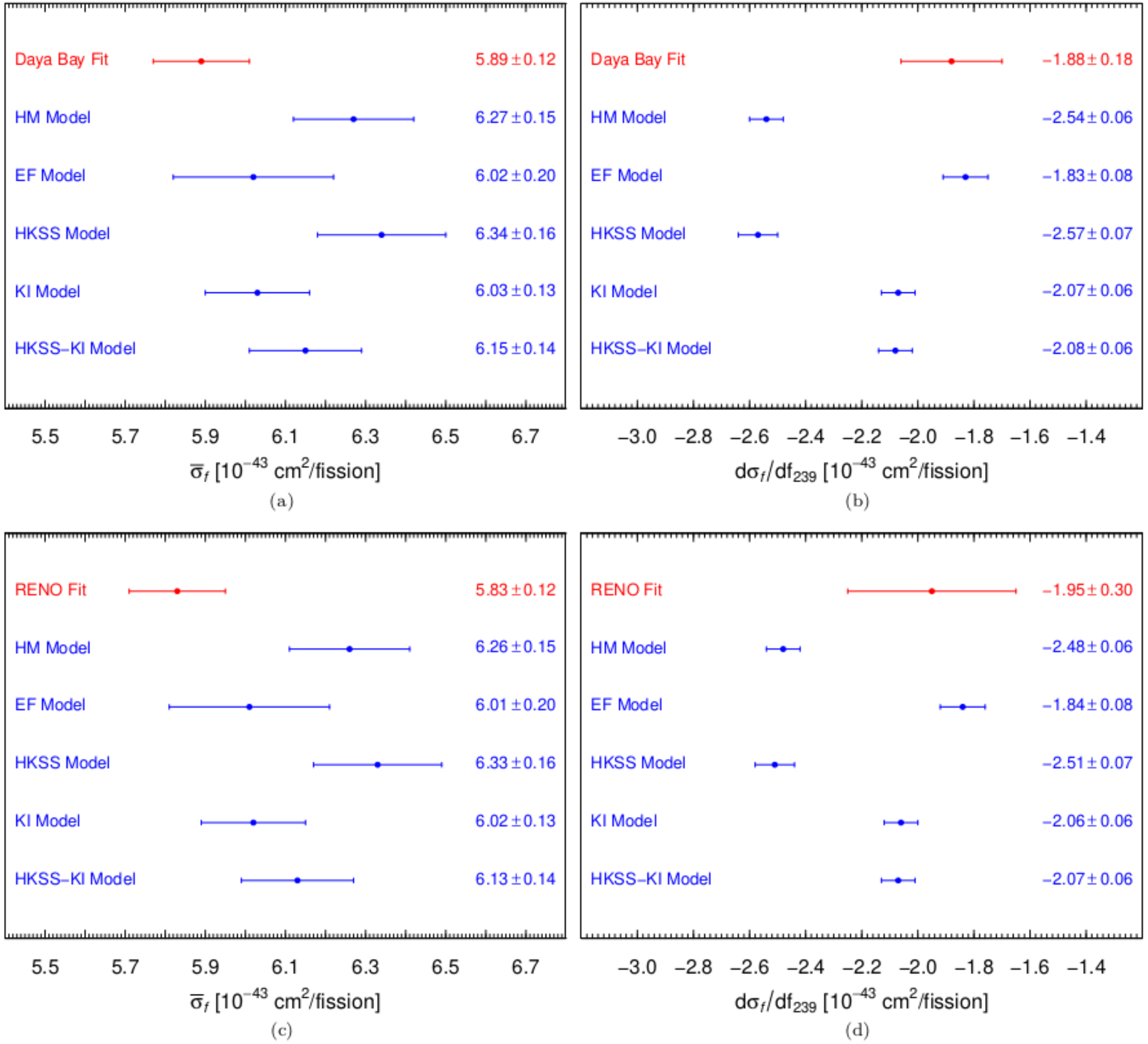
Measure rates at different stages of reactor cycle

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

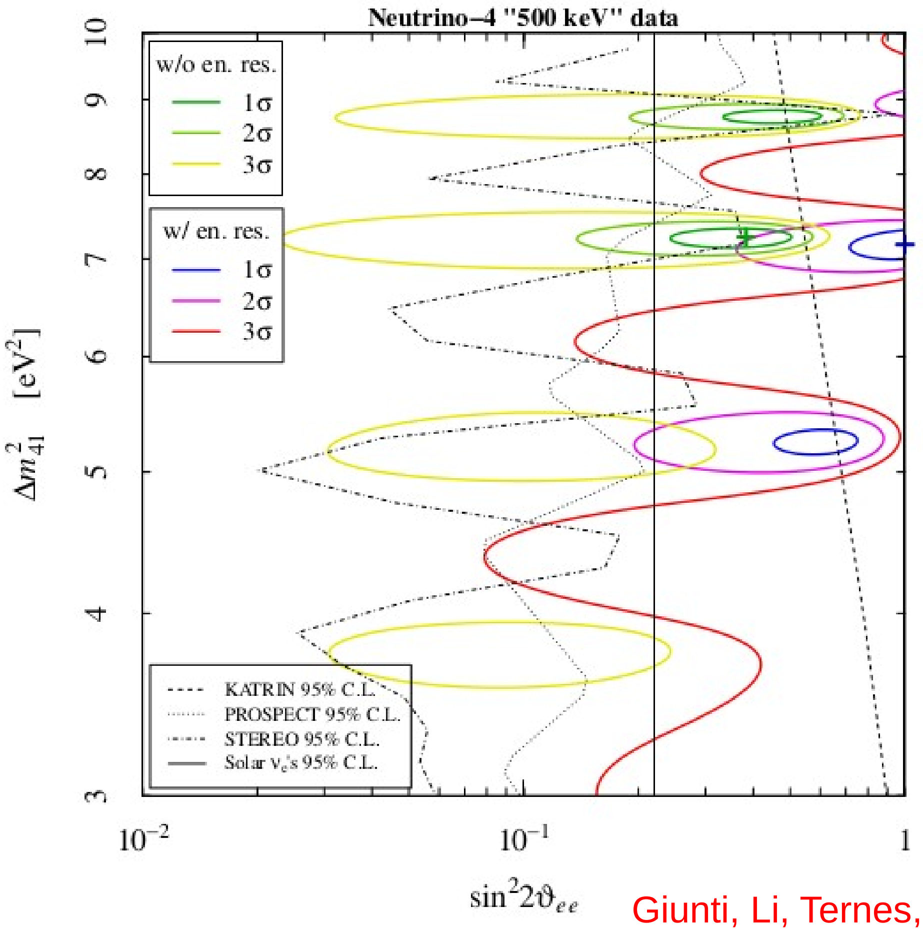
We perform several statistical tests for the best fit flux model

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
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

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

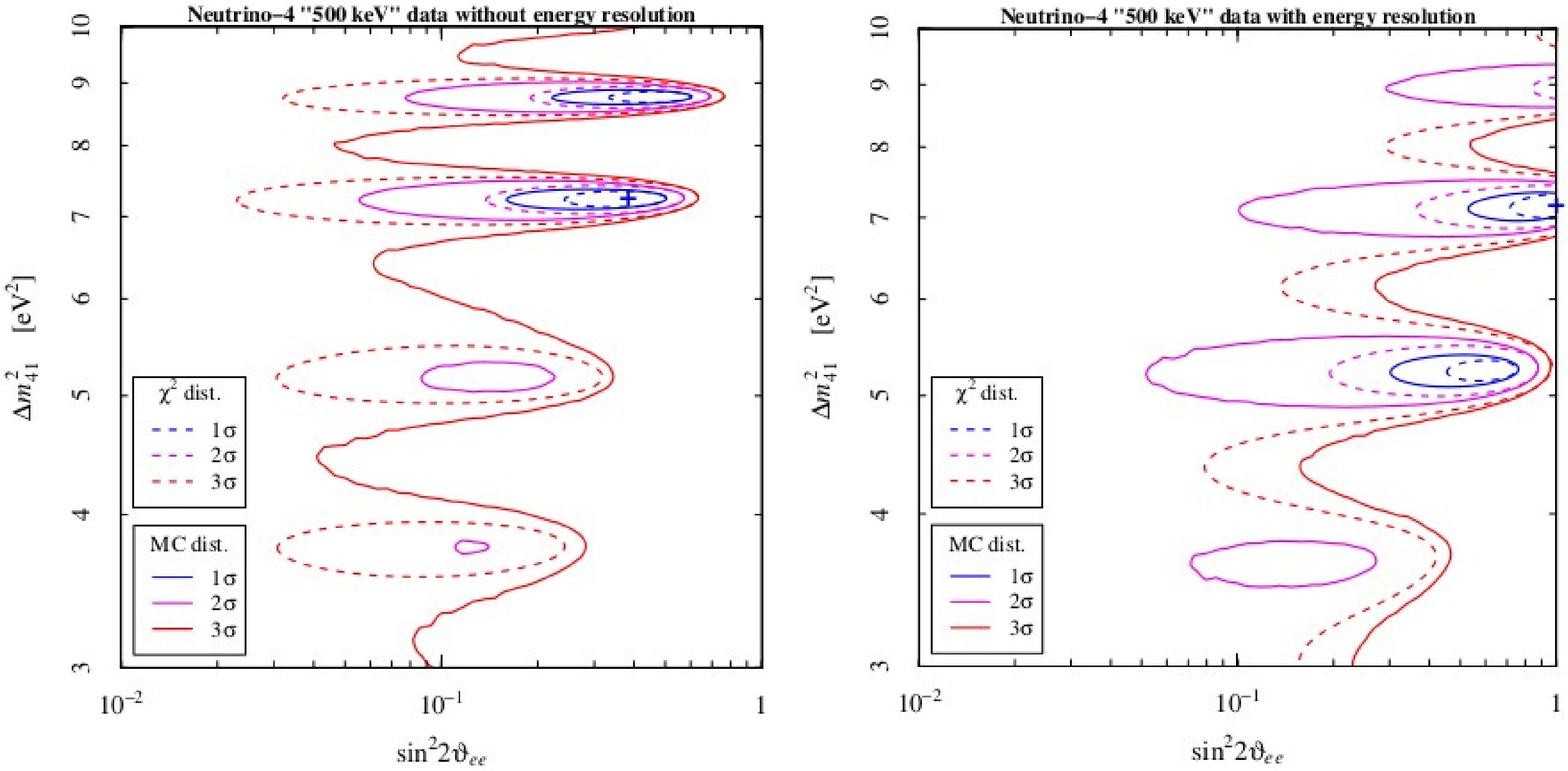
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

Neutrino-4

Monte Carlo analysis

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

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



Neutrino-4

Summary

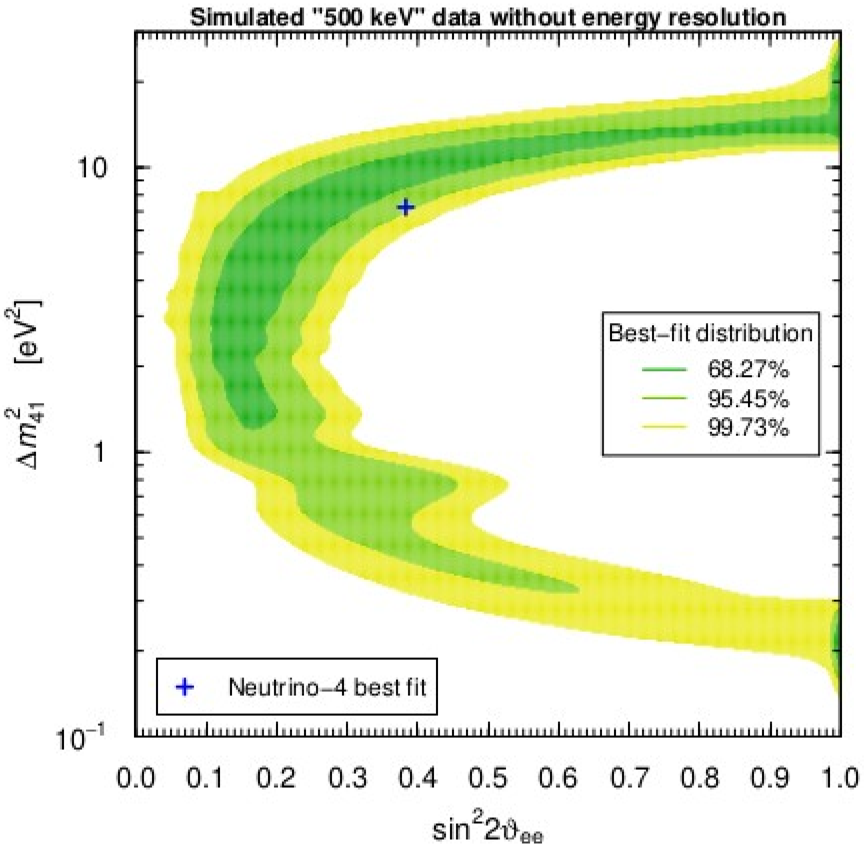
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

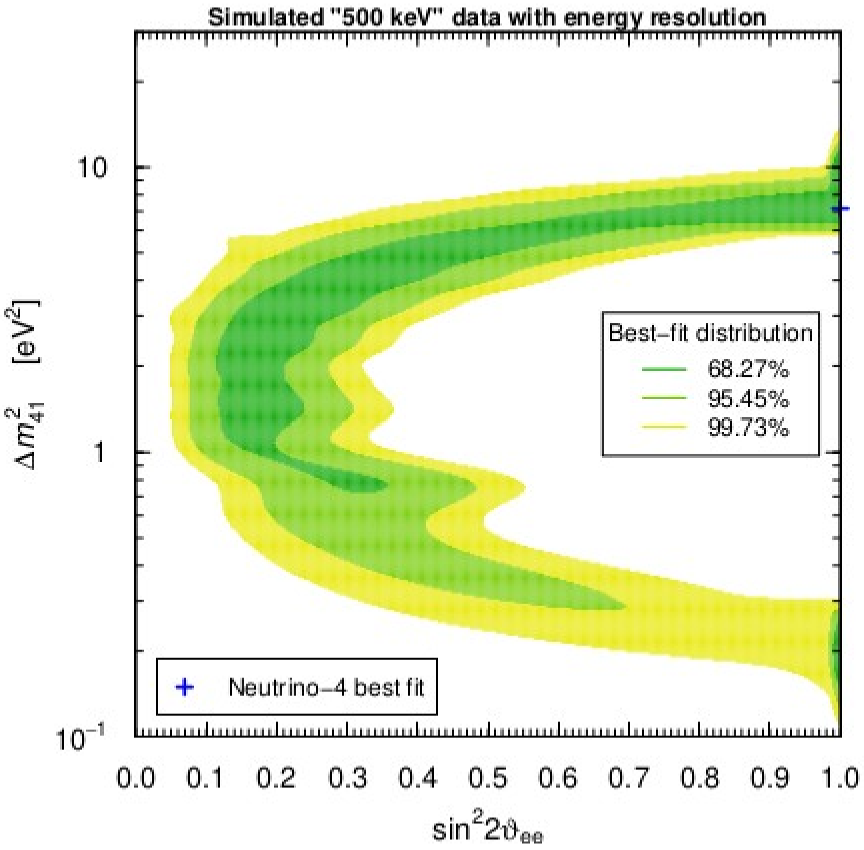
Neutrino-4	"500 keV" data		"125-250-500 keV" data	
	without en. res.	with en. res.	without en. res.	with en. res.
$\chi^2_{\rm min}$	14.9	18.2	21.9	21.1
GoF	60%	37%	19%	22%
$(\sin^2 2\vartheta_{ee})_{\rm bf}$	0.38	1.0	0.27	0.93
$(\Delta m^2_{41})_{\rm bf}$	7.2	7.2	8.8	7.2
$\Delta\chi^2_{\rm NO}$	13.1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

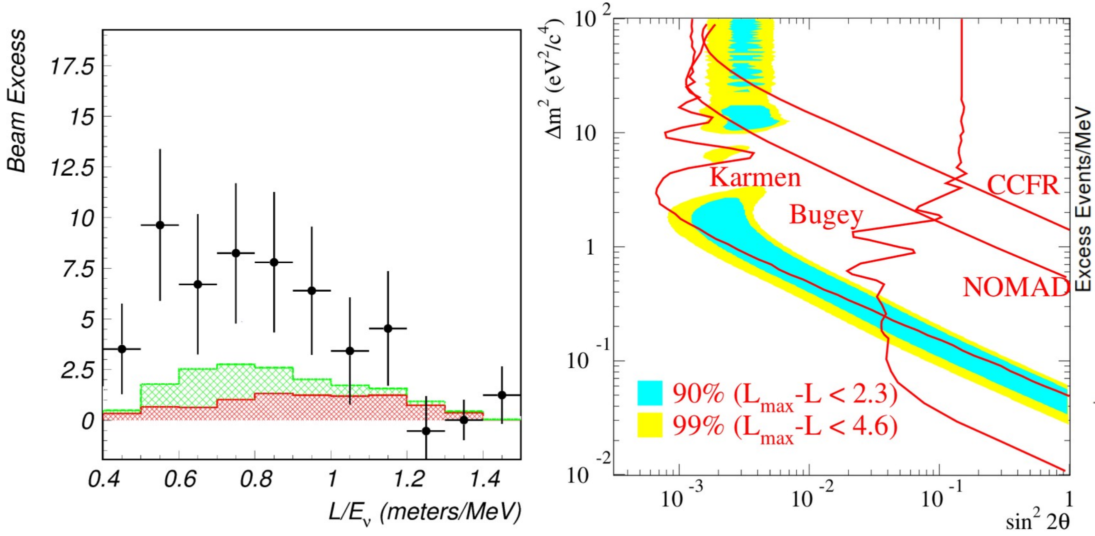




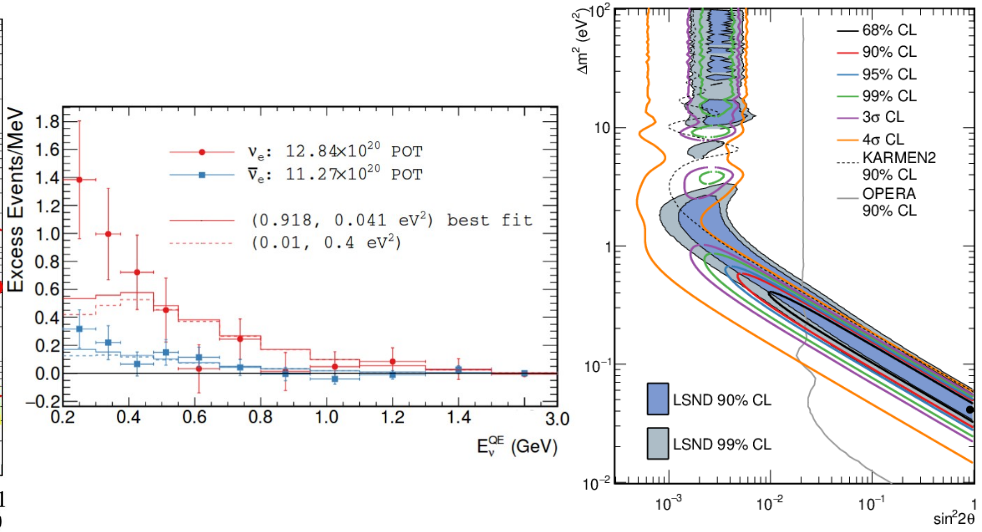
LSND and MiniBooNE

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

MiniBooNE confirmed this observation!

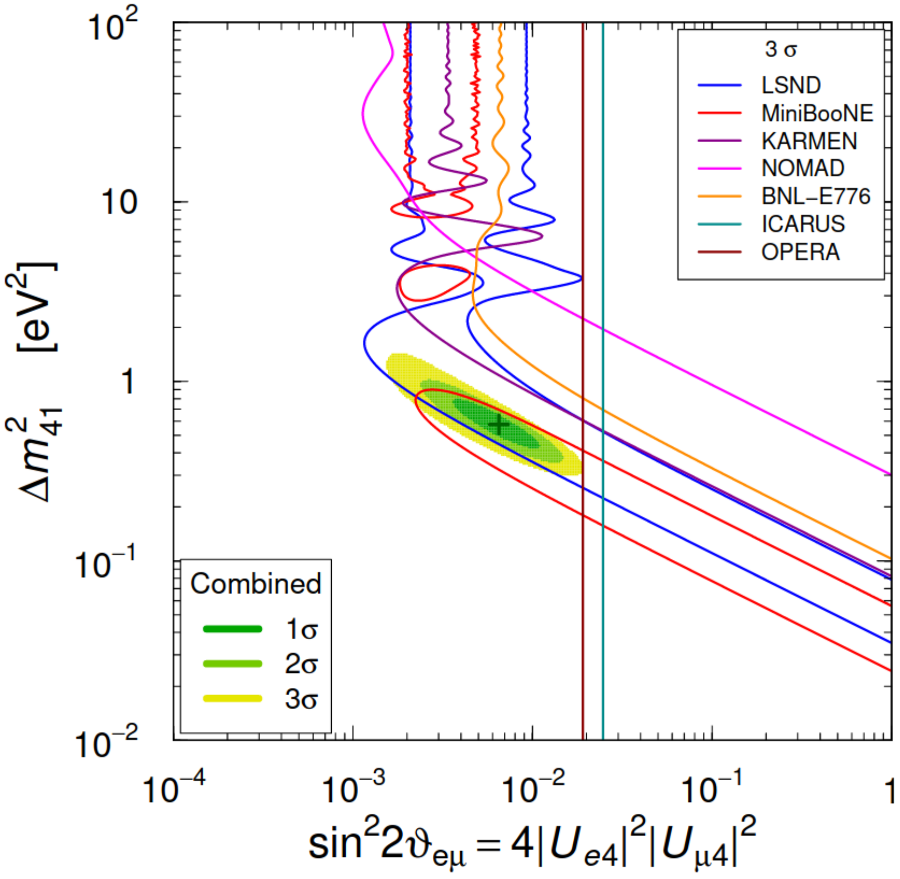


LSND, hep-ex/0104049, PRD 2001



MiniBooNE, 1805.12028, PRL 2018

Appearance results



Strong preference in appearance channel

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

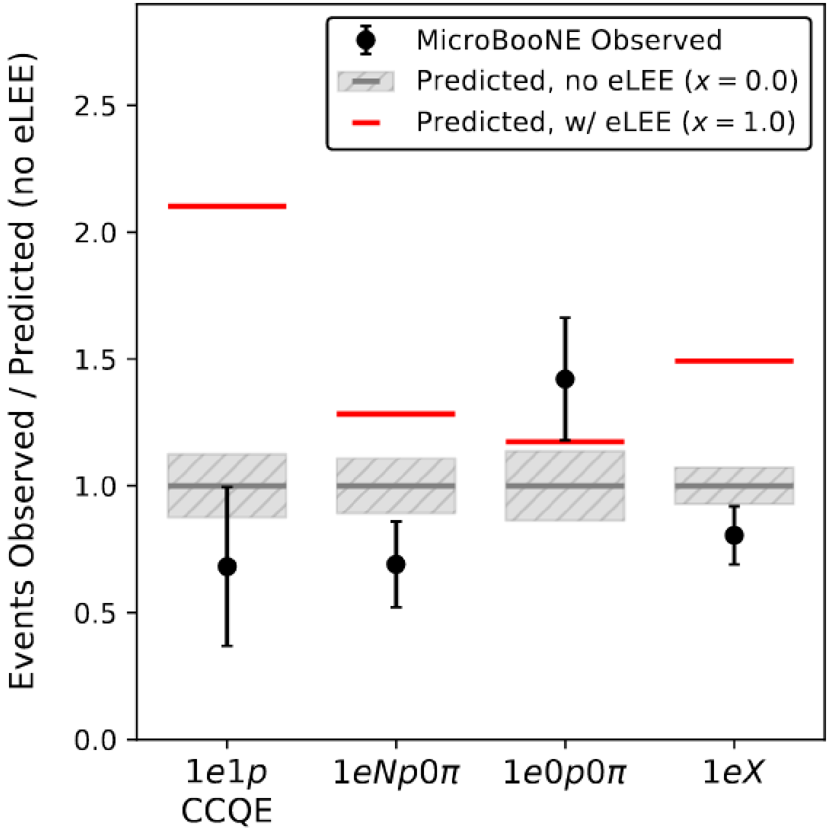
LSND and MiniBooNE only partially agree

Giunti, Lasserre, 1901.08330, Ann.Rev. 2019

MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels



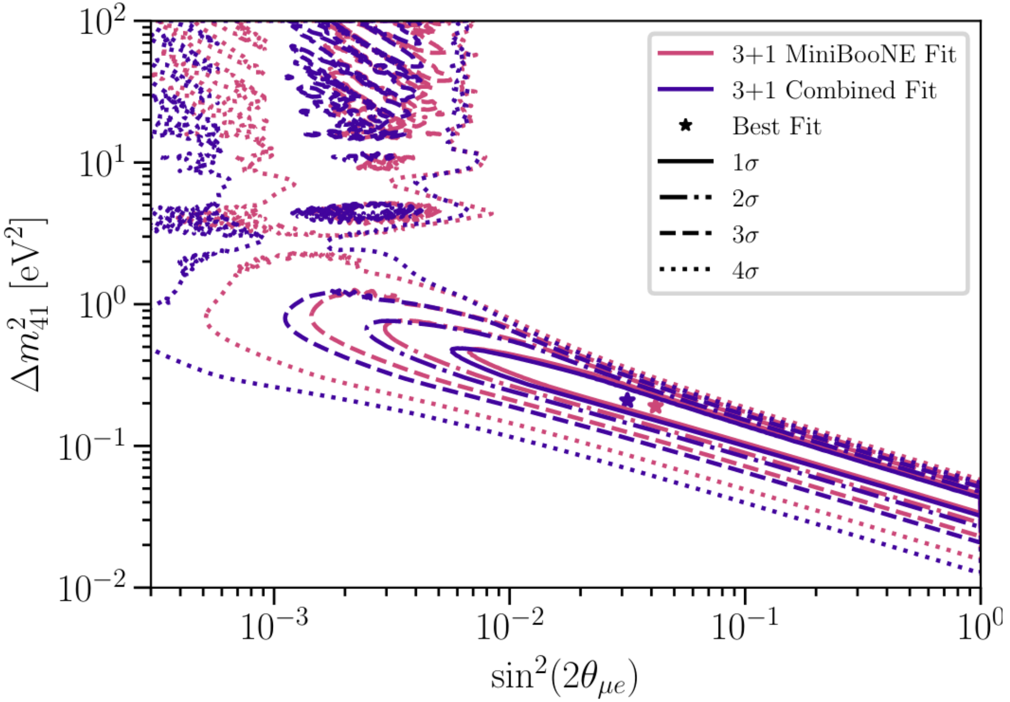
MicroBooNE, 2110.14054, PRL 2022

MicroBooNE

MicroBooNE was built to check the MiniBooNE results!

Looking for signals using several final state channels

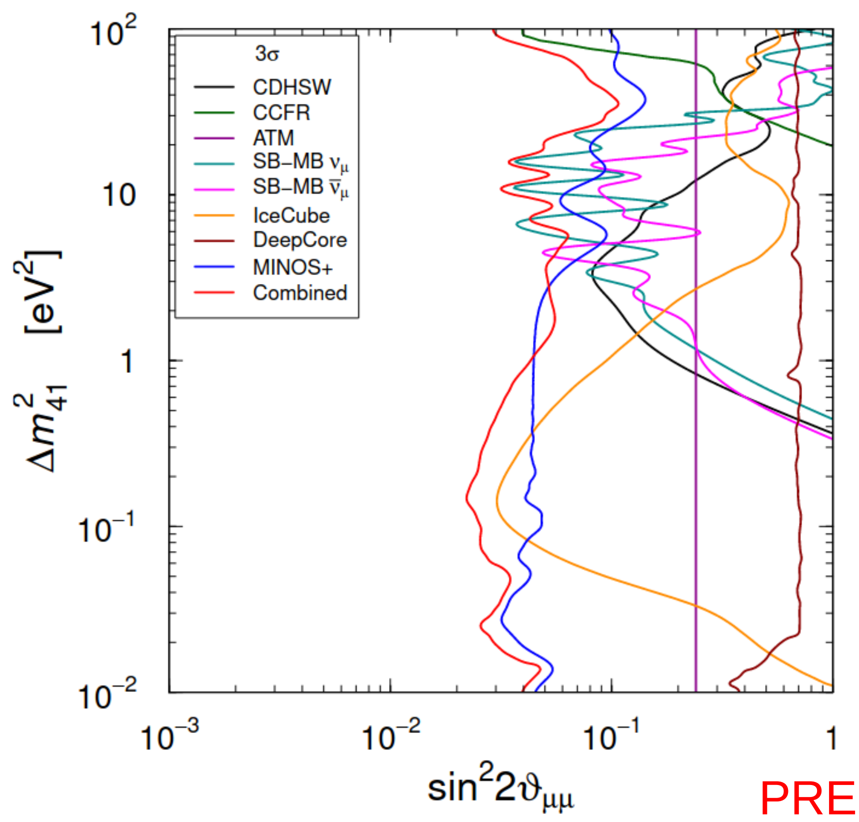
A combined analysis shows that MicroBooNE can not exclude the region of parameter space preferred by MiniBooNE

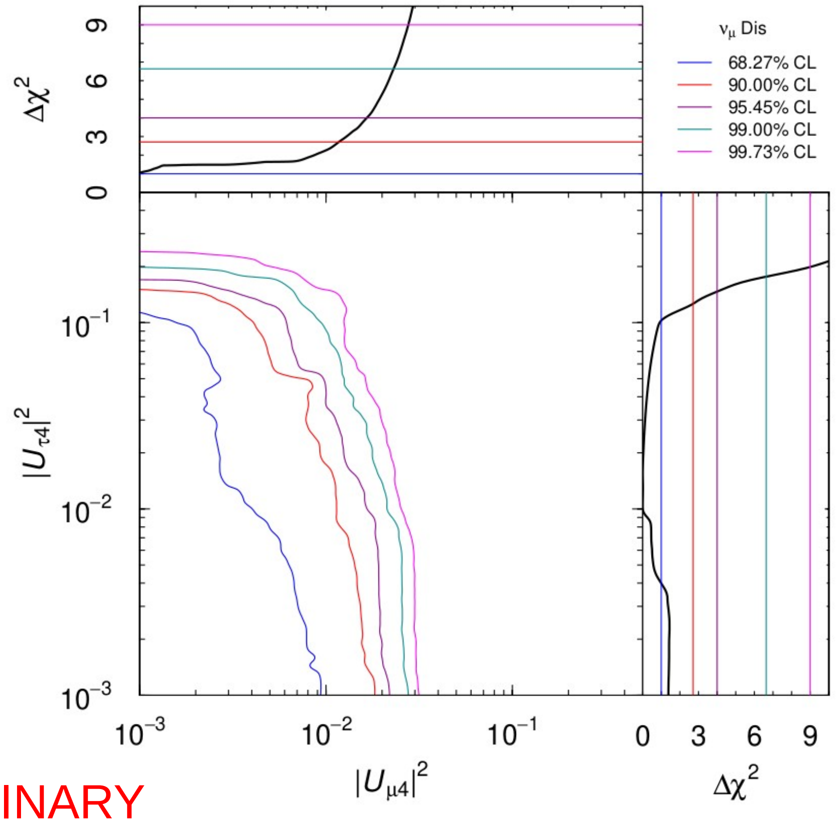


MiniBooNE, 2201.01724

Accelerator and atmospheric experiments

No evidence in muon disappearance

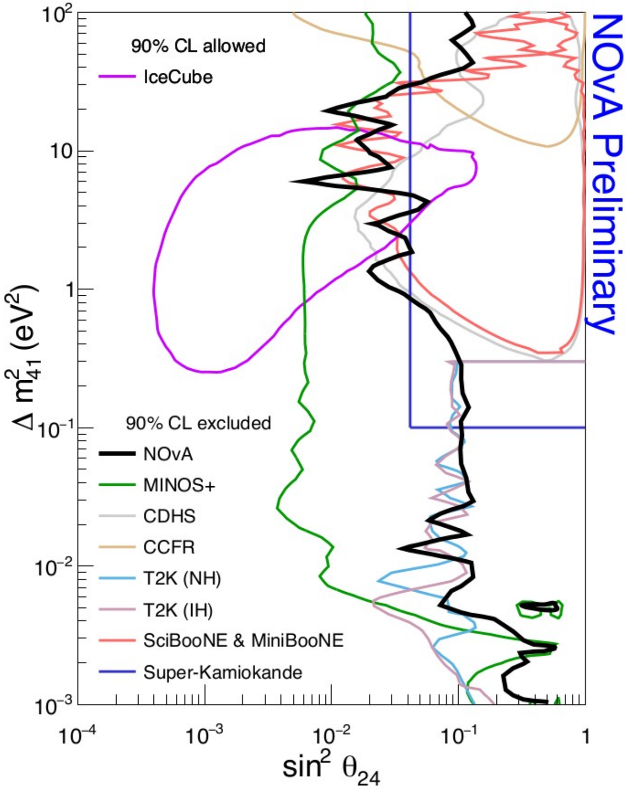




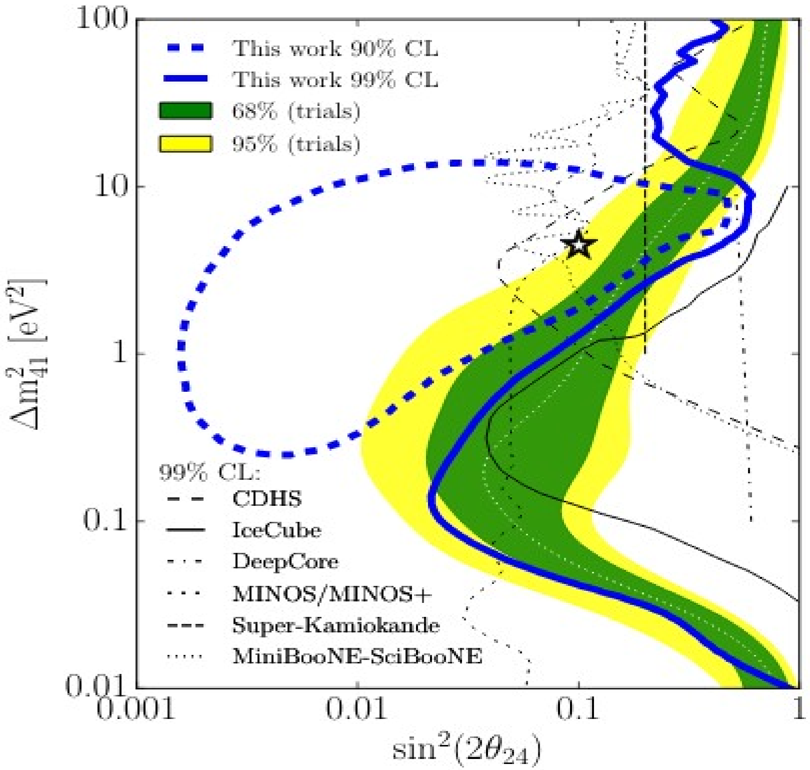
PRELIMINARY

Accelerator and atmospheric experiments

No evidence in muon disappearance

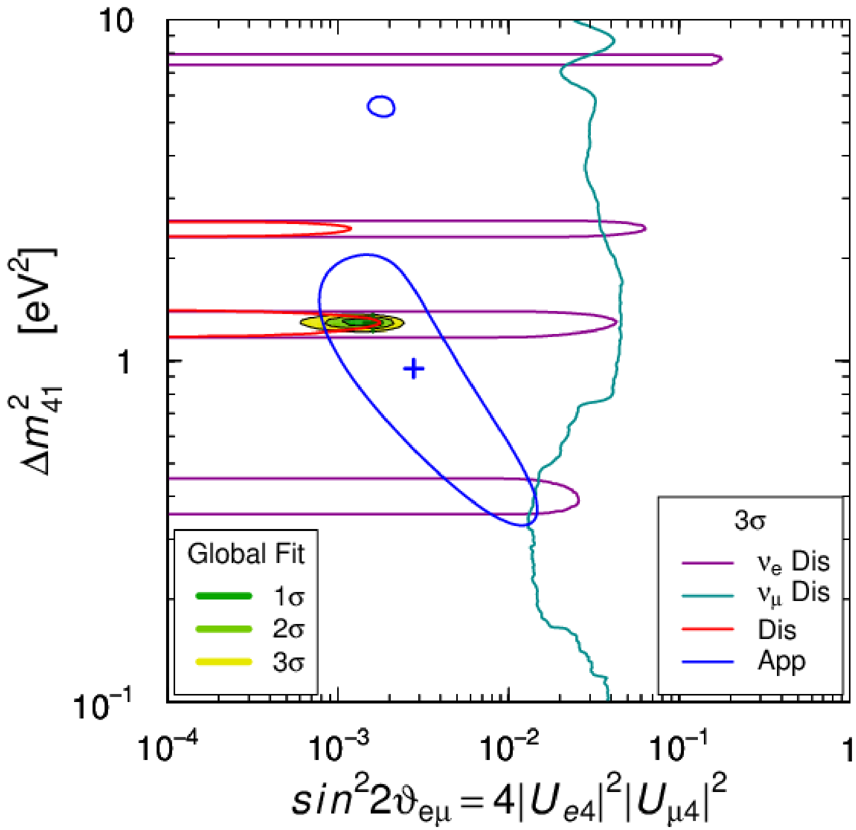


NOvA, Talk by Jeff Hartnell, Neutrino 2022



IceCube, 2005.12942, PRL 2020

Global fit?



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

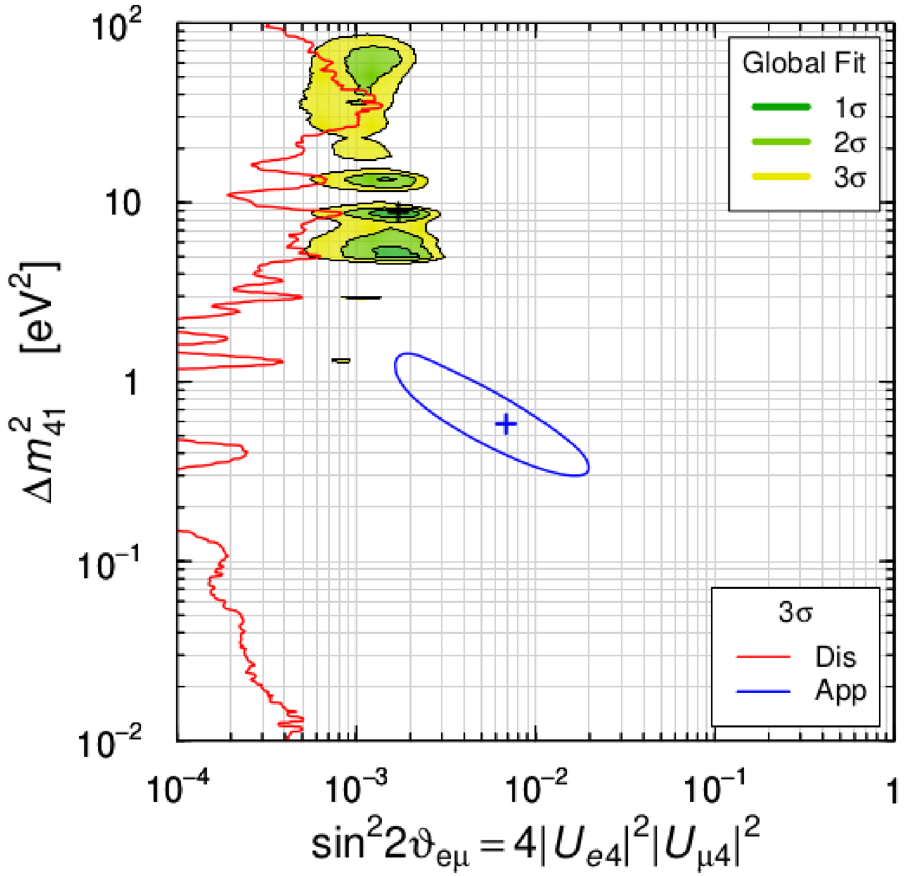
$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

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

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

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

Global fit?



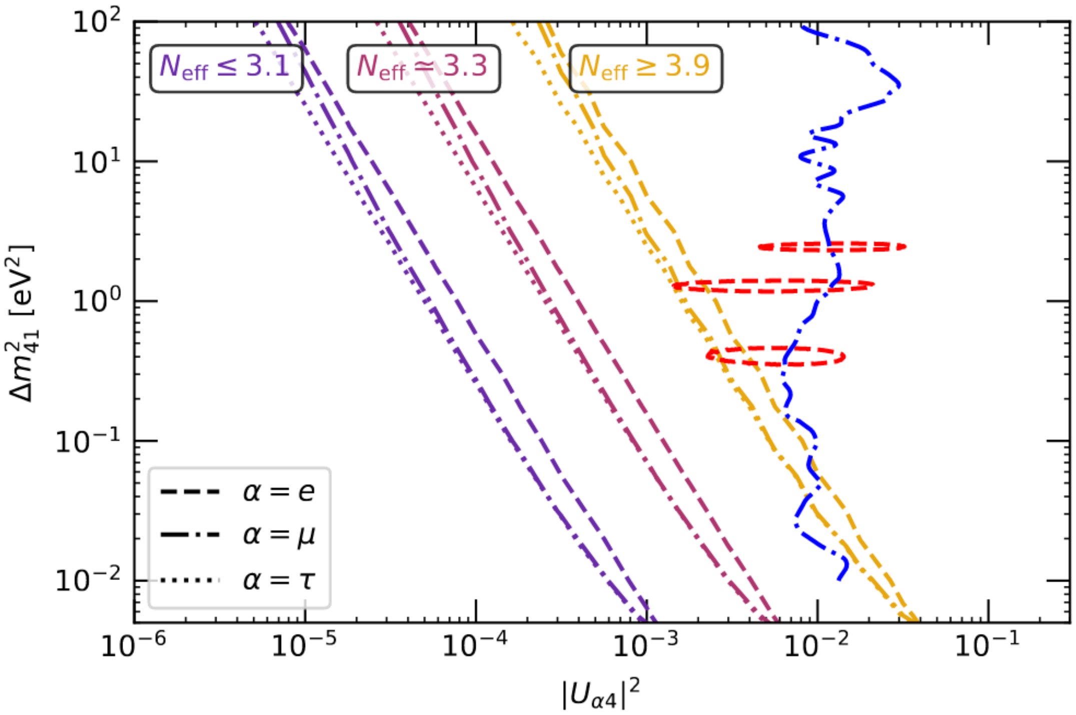
NOT most up-to-date data here!

No overlap anymore!

GoF_{PG}= 7 x 10^{-11}

Global 3+1 fit is unacceptable!

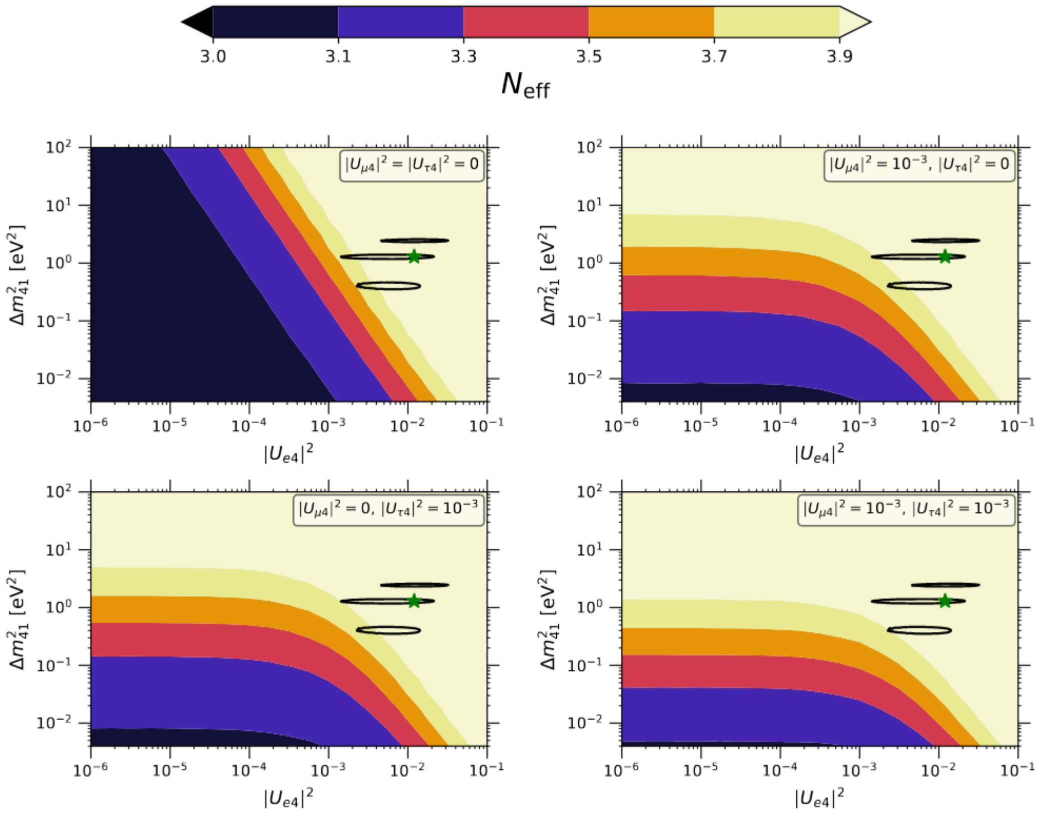
Cosmology



Cosmology can set strong bounds on sterile parameter space

Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

Cosmology

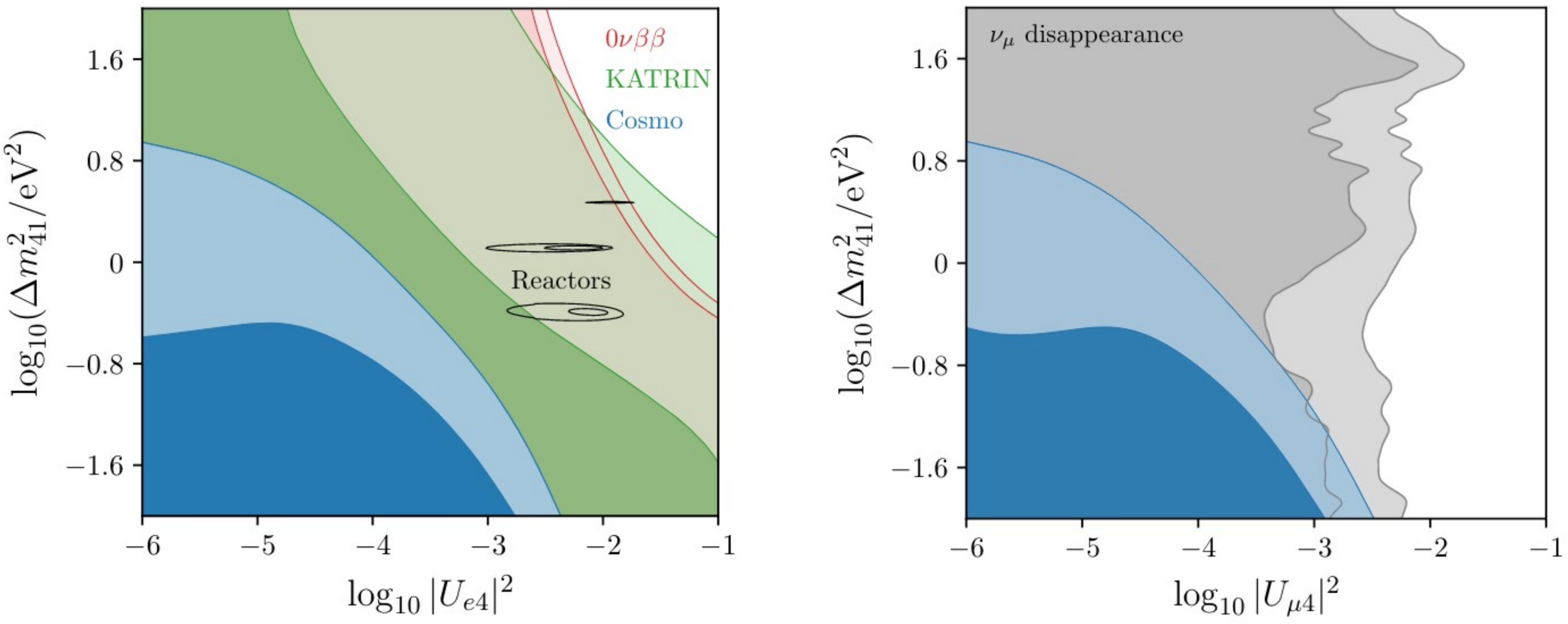


Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

Cosmology can set strong bounds on sterile parameter space

Which become even stronger when considering more than one angle

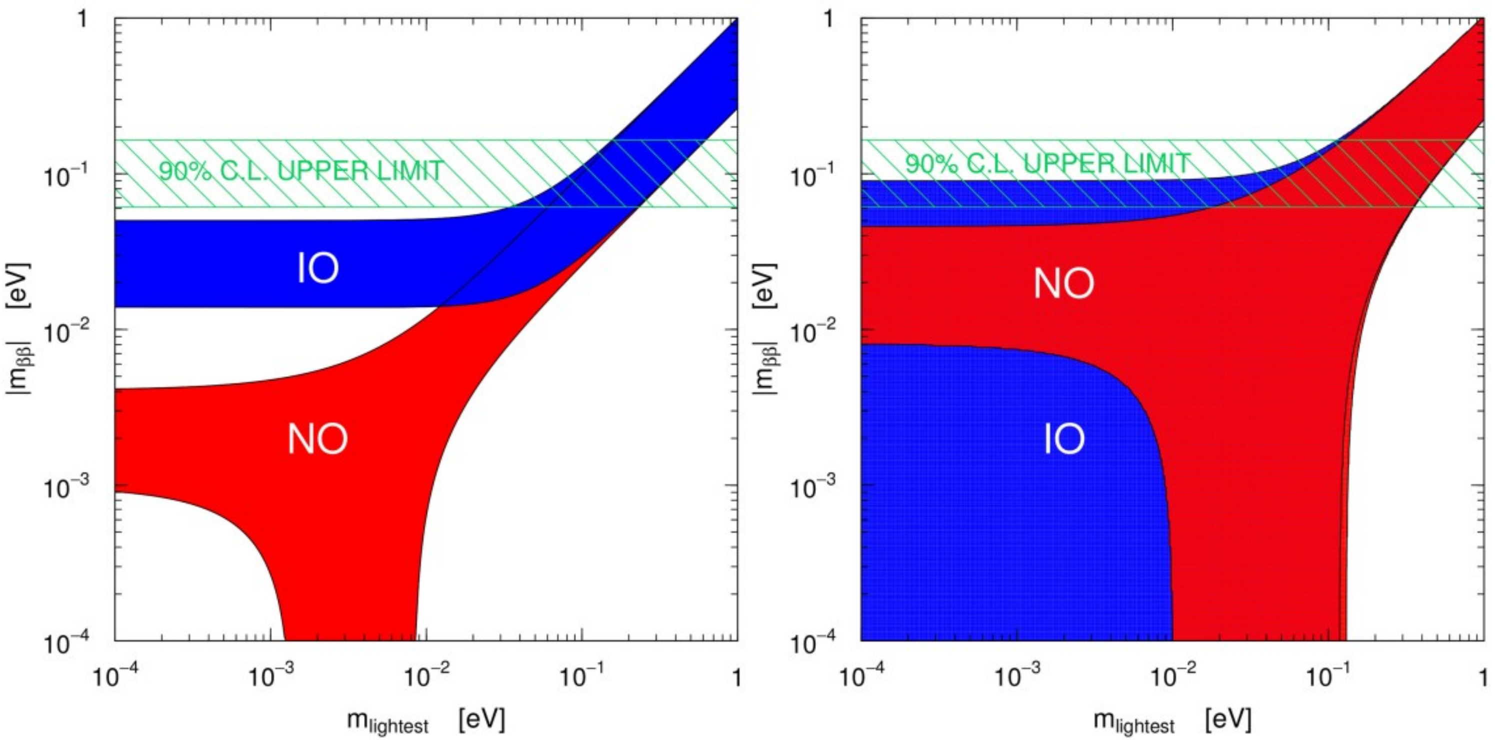
Cosmology



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.