

# Neutrino oscillation anomalies

or

Where we are with searches for light sterile neutrinos



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European Nuclear Physics Conference  
October 26<sup>th</sup> 2022

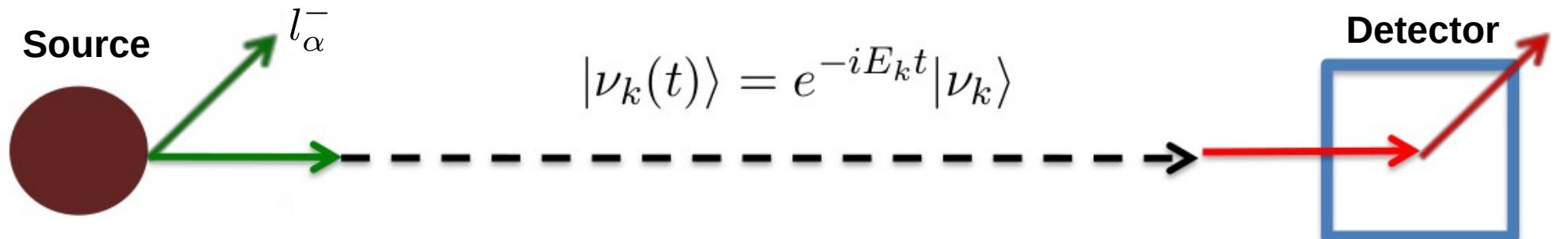


Istituto Nazionale di Fisica Nucleare  
SEZIONE DI TORINO



UNIVERSITÀ  
DI TORINO

# Neutrino oscillations



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

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

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

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

# Three-neutrino oscillations

Neutrino mixing matrix

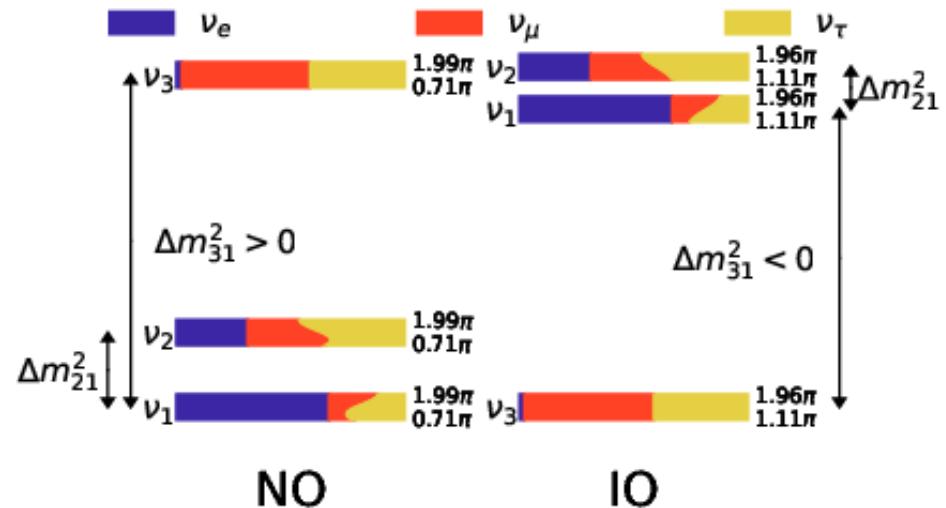
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Parameter	Main contribution from	Other contributions from
$\Delta m_{21}^2$	KamLAND	SOL
$ \Delta m_{31}^2 $	LBL+ATM+REAC	-
$\theta_{12}$	SOL	KamLAND
$\theta_{23}$	LBL+ATM	-
$\theta_{13}$	REAC	(LBL+ATM) and (SOL+KamLAND)
$\delta$	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

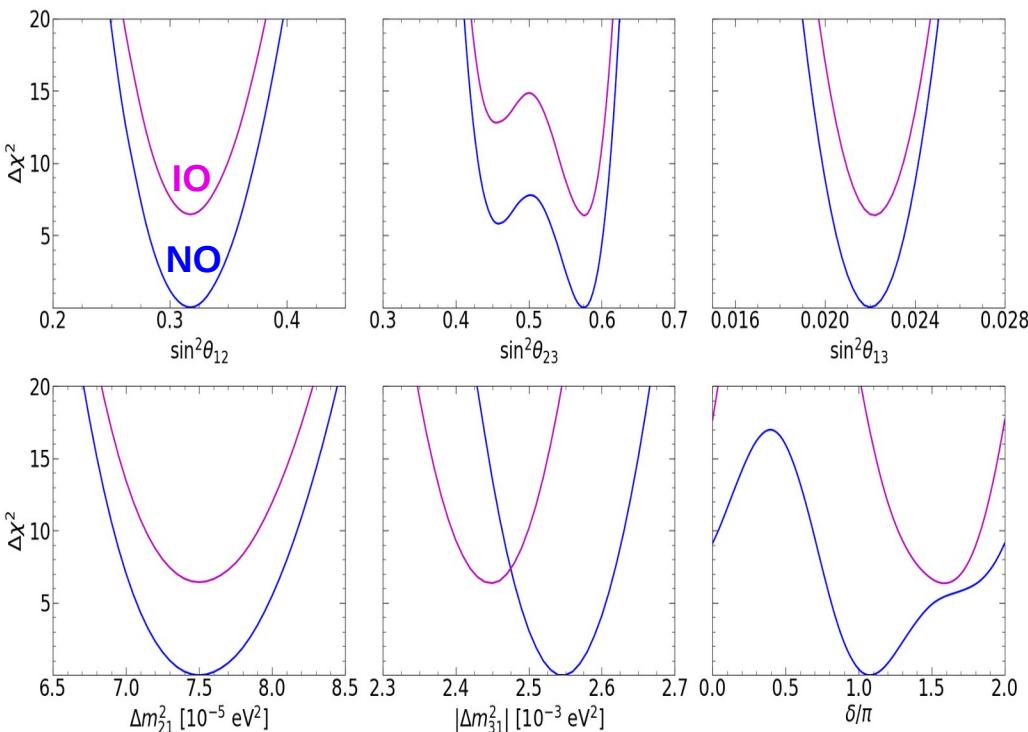
Common sensitivities from different types of experiments

Combination of data sets can enhance sensitivities to oscillation parameters

=> Perform a global fit to neutrino oscillation data!

# Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



parameter	best fit $\pm 1\sigma$	$2\sigma$ range	$3\sigma$ 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
$\sin^2 \theta_{12}/10^{-1}$	$3.18 \pm 0.16$	2.86–3.52	2.71–3.69
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.74 \pm 0.14$	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
$\delta/\pi$ (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/\pi$ (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

See also:

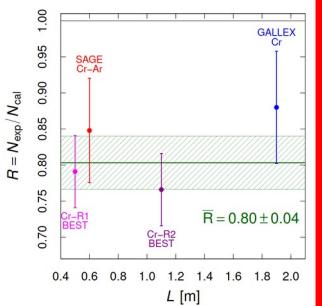
Bari – 2107.00532, PRD 2021

See also:

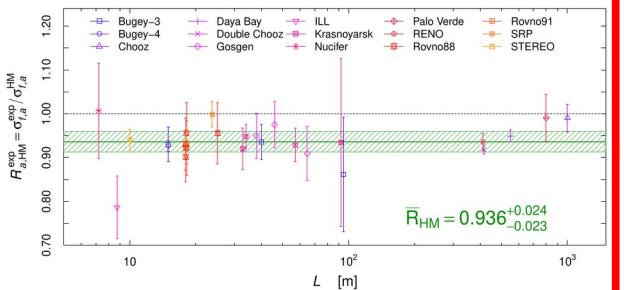
NuFit - 2111.03086 , Universe 2021

# Anomalies

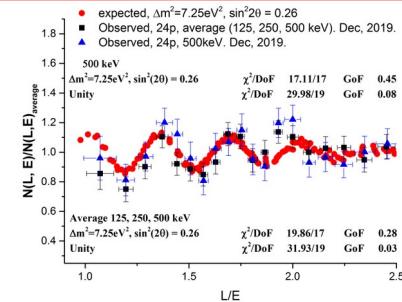
Gallium



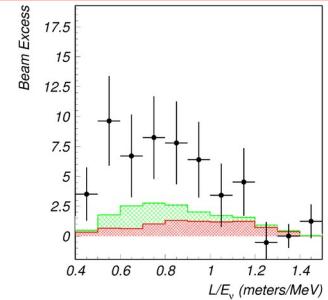
RAA



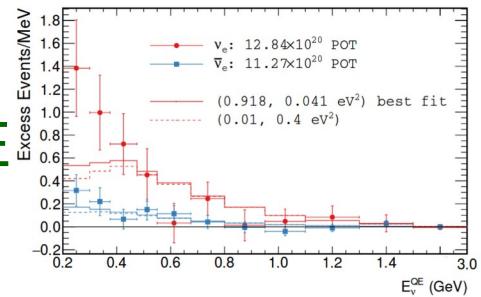
Neutrino-4



LSND



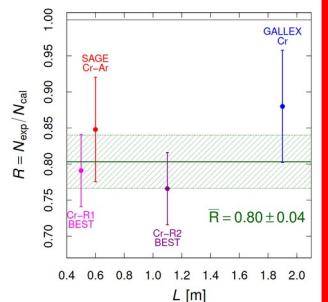
MiniBooNE



# Anomalies

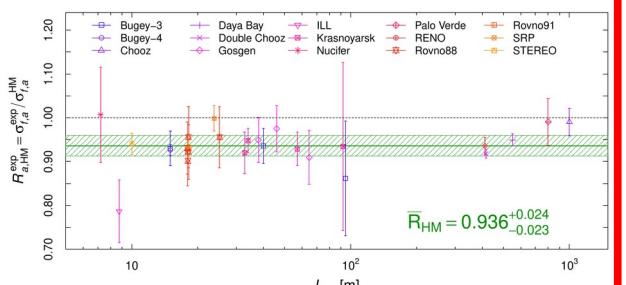
$5\text{-}6\sigma$

Gallium



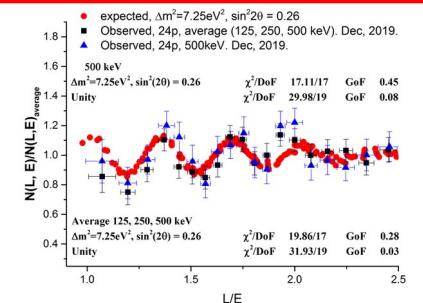
$1\text{-}3\sigma$

RAA



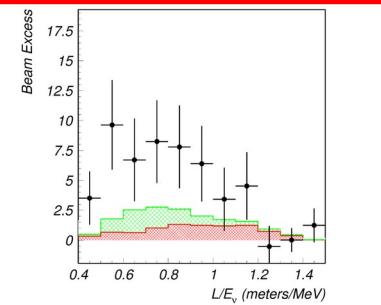
$2\text{-}3\sigma$

Neutrino-4



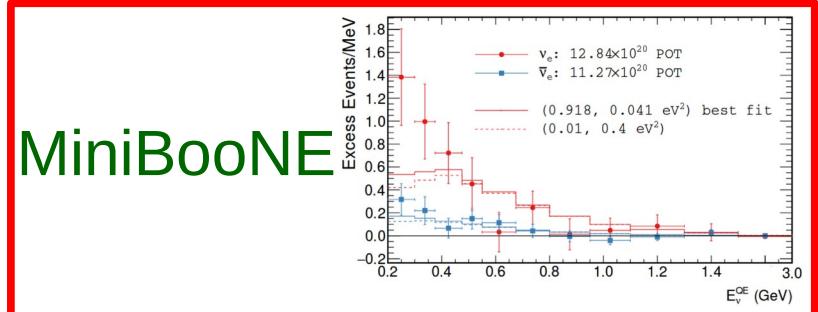
$\sim 4\sigma$

LSND



$\sim 5\sigma$

MiniBooNE



# Anomalies

Three-neutrino oscillations can not account for short baseline anomalies

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

Short baseline oscillations require:

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

# 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

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

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

Disappearance

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

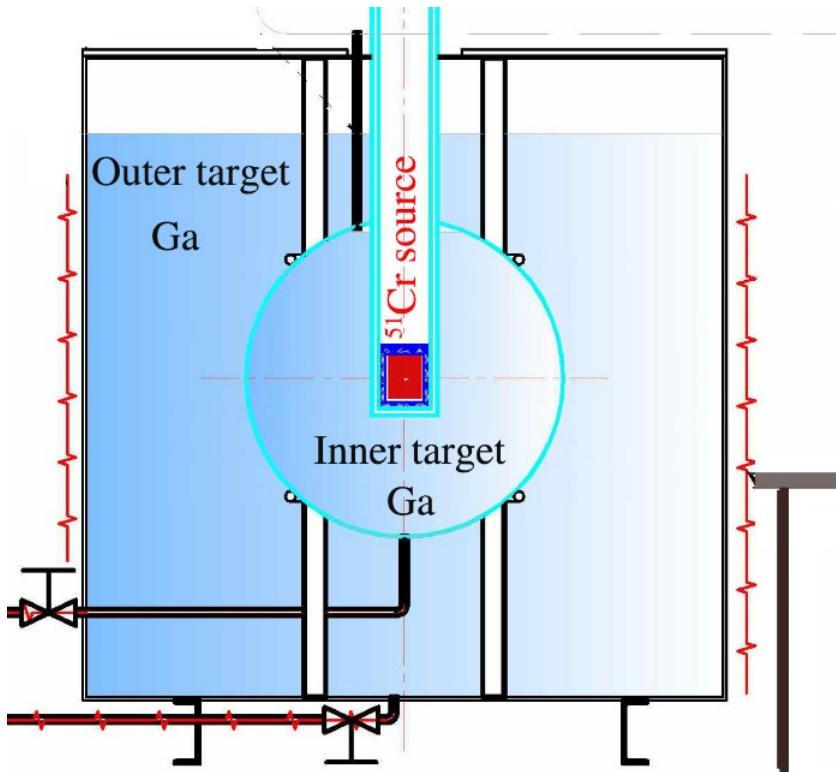
$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

@LSND, Karmen, MiniBooNE,  
Opera

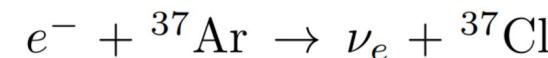
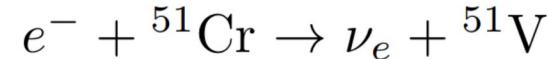
@Reactors and Gallium  
@atmospherics and accelerators

# The Gallium anomaly

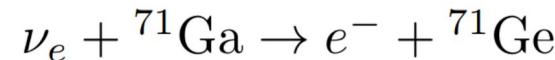
BEST coll., 2109.11482, PRL 2022



Intense sources of electron neutrinos are placed into the detector volume



The neutrino interact with the detector material



# The Gallium anomaly

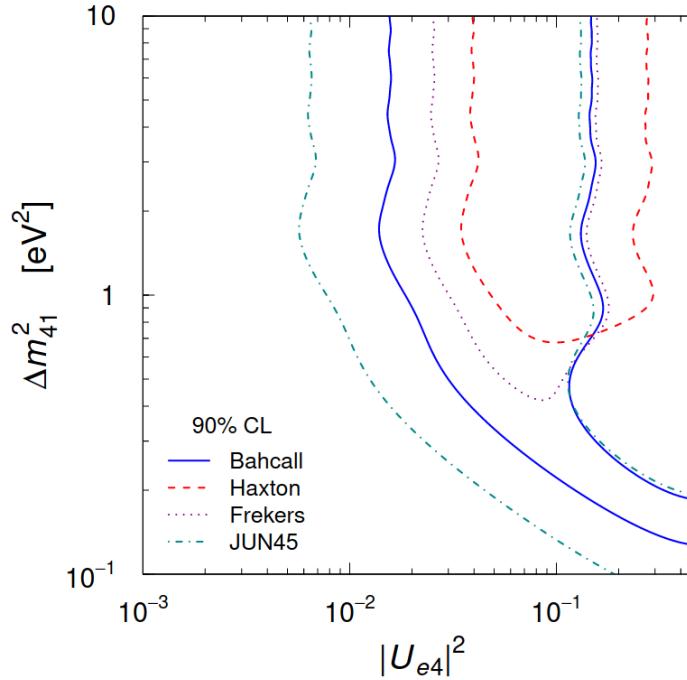
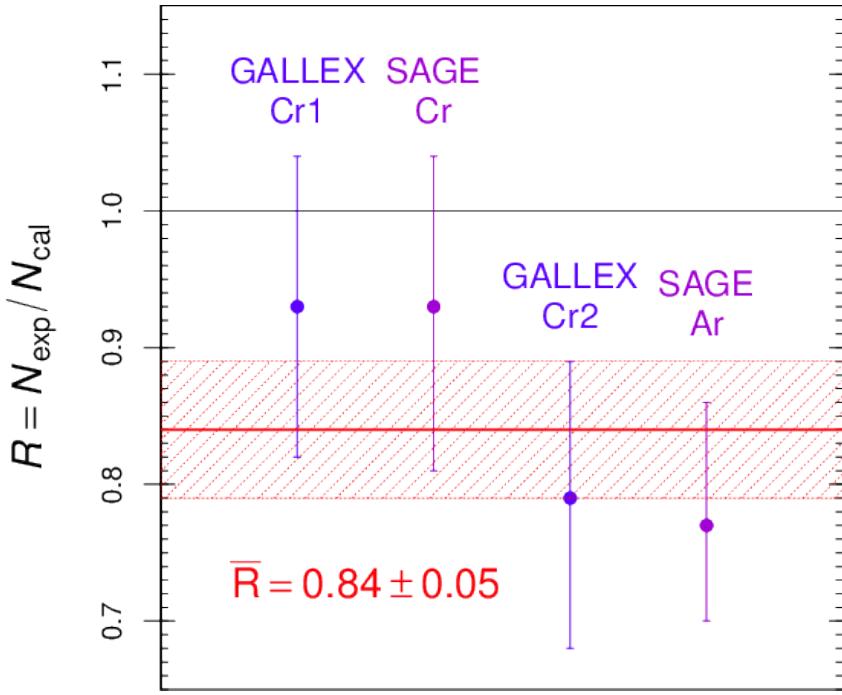
Model	Method	$^{51}\text{Cr}$		$^{37}\text{Ar}$	
		$\sigma_{\text{tot}}$	$\delta_{\text{exc}}$	$\sigma_{\text{tot}}$	$\delta_{\text{exc}}$
Ground State	$T_{1/2}(^{71}\text{Ge})$	$5.539 \pm 0.019$	–	$6.625 \pm 0.023$	–
Bahcall (1997)	$^{71}\text{Ga}(p, n)^{71}\text{Ge}$	$5.81 \pm 0.16$	4.7%	$7.00 \pm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

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

Slightly different values for the different cross section models

# The Gallium anomaly

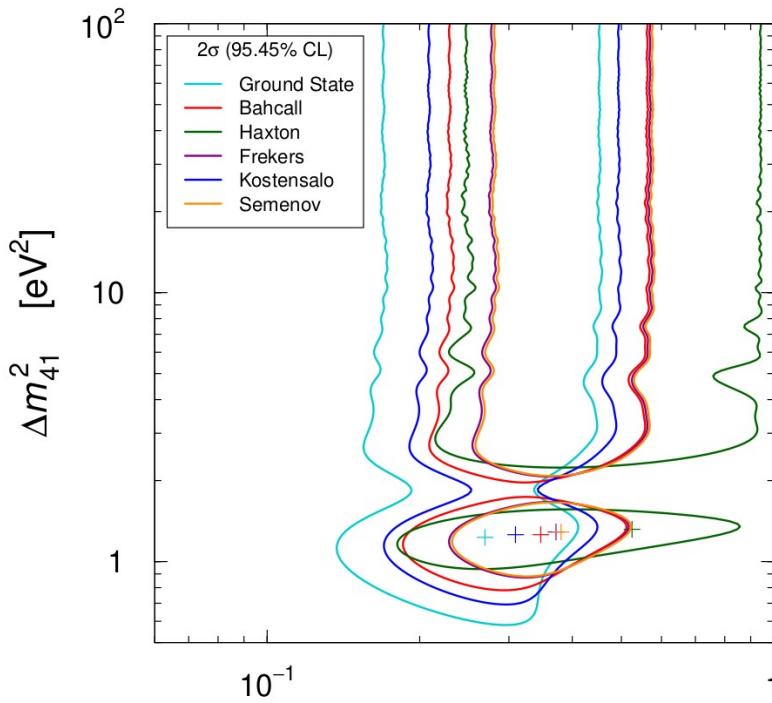
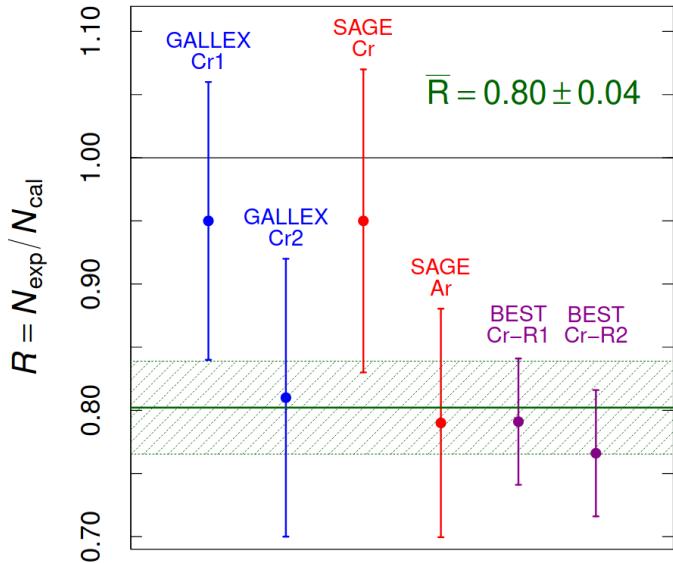
Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980, PLB 2019



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

# The Gallium anomaly

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



Strong indication for short baseline (SBL) oscillations!

See also:

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

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

# The reactor antineutrino anomaly: Flux calculations

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

In the summation method one needs to sum over all beta branches

There are more than 1000 beta spectra and branching ratios

Nuclear data bases might be incomplete or inaccurate

In the conversion method one converts the observed beta spectra into neutrino spectra

$^{235}\text{U}$ ,  $^{239}\text{Pu}$ , and  $^{241}\text{Pu}$  are inferred from measurements at Institut Laue-Langevin (ILL)

$^{238}\text{U}$  is inferred from measurements at a neutron source at Garching

# 5 MeV bump

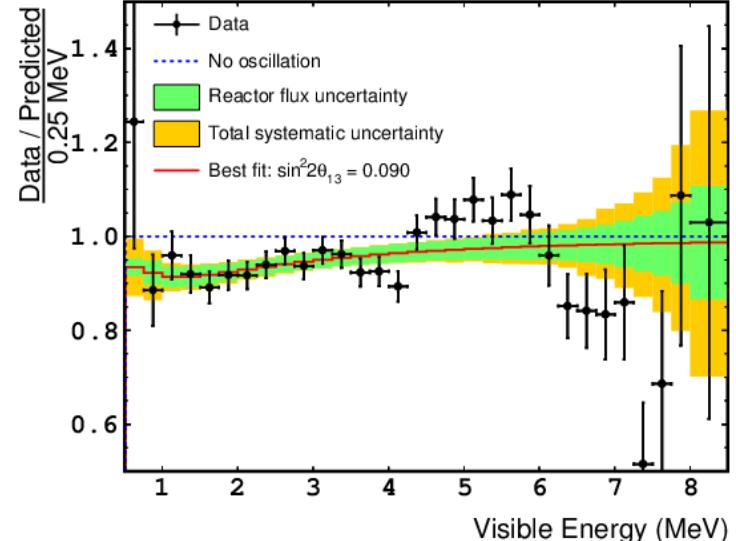
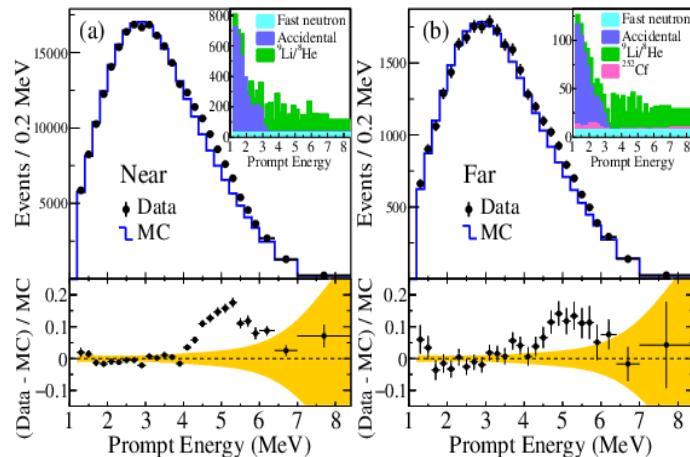
Double Chooz, 1406.7763, JHEP 2015

5 MeV bump discovered in 2014

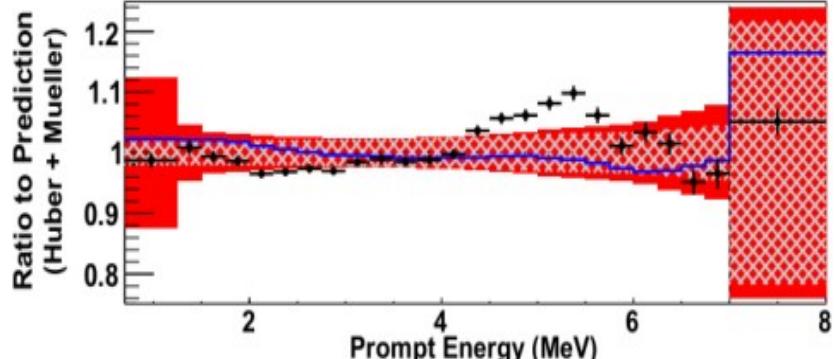
Can not been explained with SBL oscillations

Proof of our incomplete understanding of nuclear reactor fluxes

RENO, 1511.05849, PRL 2016



Daya Bay, 1508.04233, PRL 2016



# Rate calculation

Calculate inverse beta yields for each isotope

We use the Strumia-Vissani IBD cross section

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

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

Yields depend on  
the neutrino flux

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

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

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

Berryman, Huber, 2005.01756, JHEP 2021

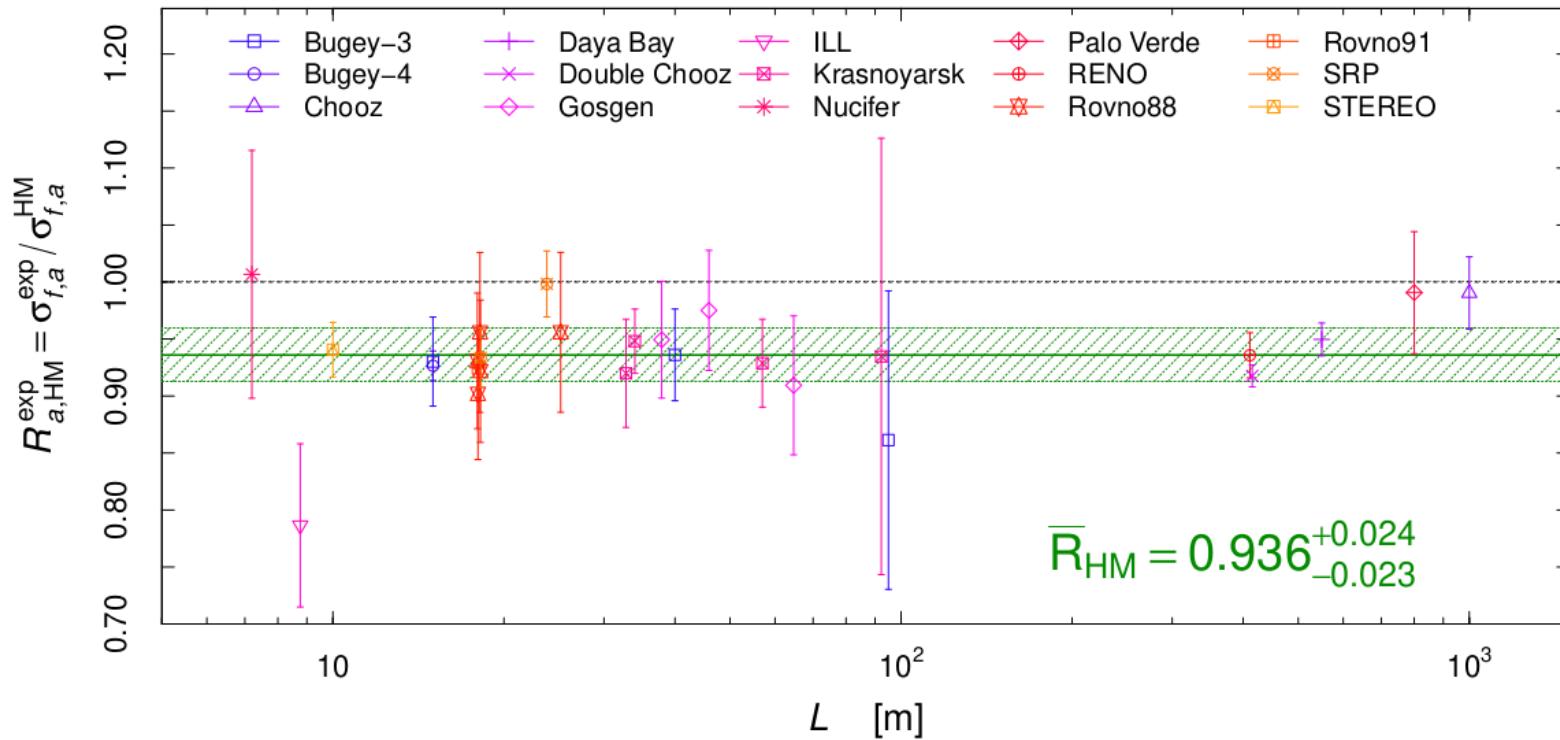
Model	$\sigma_{235}$	$\sigma_{238}$	$\sigma_{239}$	$\sigma_{241}$
HM	$6.60 \pm 0.14$	$10.00 \pm 1.12$	$4.33 \pm 0.11$	$6.01 \pm 0.13$
EF	$6.17 \pm 0.13$	$9.94 \pm 1.09$	$4.32 \pm 0.11$	$6.10 \pm 0.13$
HKSS	$6.67 \pm 0.15$	$10.08 \pm 1.14$	$4.37 \pm 0.12$	$6.06 \pm 0.14$

# Compare against measurements

$a$	Experiment	$f_{235}^a$	$f_{238}^a$	$f_{239}^a$	$f_{241}^a$	$\sigma_{f,a}^{\text{exp}}$	$R_{a,\text{HM}}^{\text{exp}}$	$R_{a,\text{EF}}^{\text{exp}}$	$R_{a,\text{HKSS}}^{\text{exp}}$	$R_{a,\text{KI}}^{\text{exp}}$	$R_{a,\text{HKSS-KI}}^{\text{exp}}$	$\delta_a^{\text{exp}} [\%]$	$\delta_a^{\text{cor}} [\%]$	$L_a [\text{m}]$
1	Bugey-4	0.538	0.078	0.328	0.056	5.75	0.927	0.962	0.916	0.962	0.944	1.4	1.4	15
2	Rovno91	0.614	0.074	0.274	0.038	5.85	0.924	0.965	0.914	0.962	0.945	2.8		18
3	Rovno88-II	0.607	0.074	0.277	0.042	5.70	0.902	0.941	0.892	0.939	0.921	6.4	3.1	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	5.89	0.931	0.971	0.920	0.969	0.951	6.4		17.96
5	Rovno88-1S	0.606	0.074	0.277	0.043	6.04	0.956	0.997	0.945	0.995	0.976	7.3	2.2	18.15
6	Rovno88-2S	0.557	0.076	0.313	0.054	5.96	0.956	0.994	0.945	0.993	0.974	7.3		25.17
7	Rovno88-3S	0.606	0.074	0.274	0.046	5.83	0.922	0.962	0.911	0.960	0.942	6.8	3.1	18.18
8	Bugey-3-15	0.538	0.078	0.328	0.056	5.77	0.930	0.966	0.920	0.966	0.947	4.2		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	2.0	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	6.09	0.975	1.016	0.964	1.014	0.995	5.4		45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	5.62	0.909	0.945	0.899	0.944	0.927	6.7	3.8	64.7
14	ILL	1.000	0.000	0.000	0.000	5.30	0.787	0.843	0.777	0.827	0.818	9.1		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

# 2011 Huber Mueller fluxes

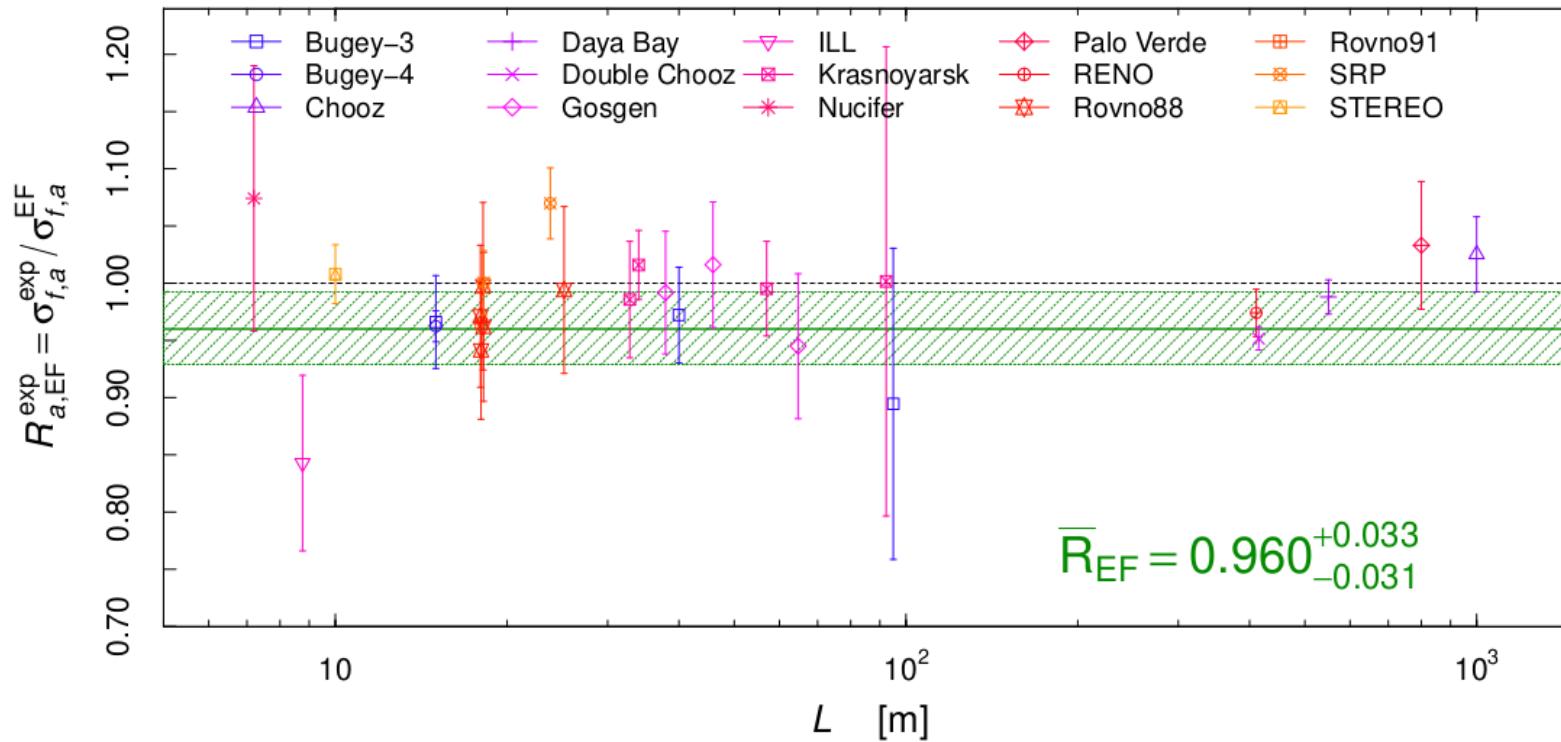
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



HM flux gives  $2.5\sigma$  anomaly

# 2019 summation method fluxes

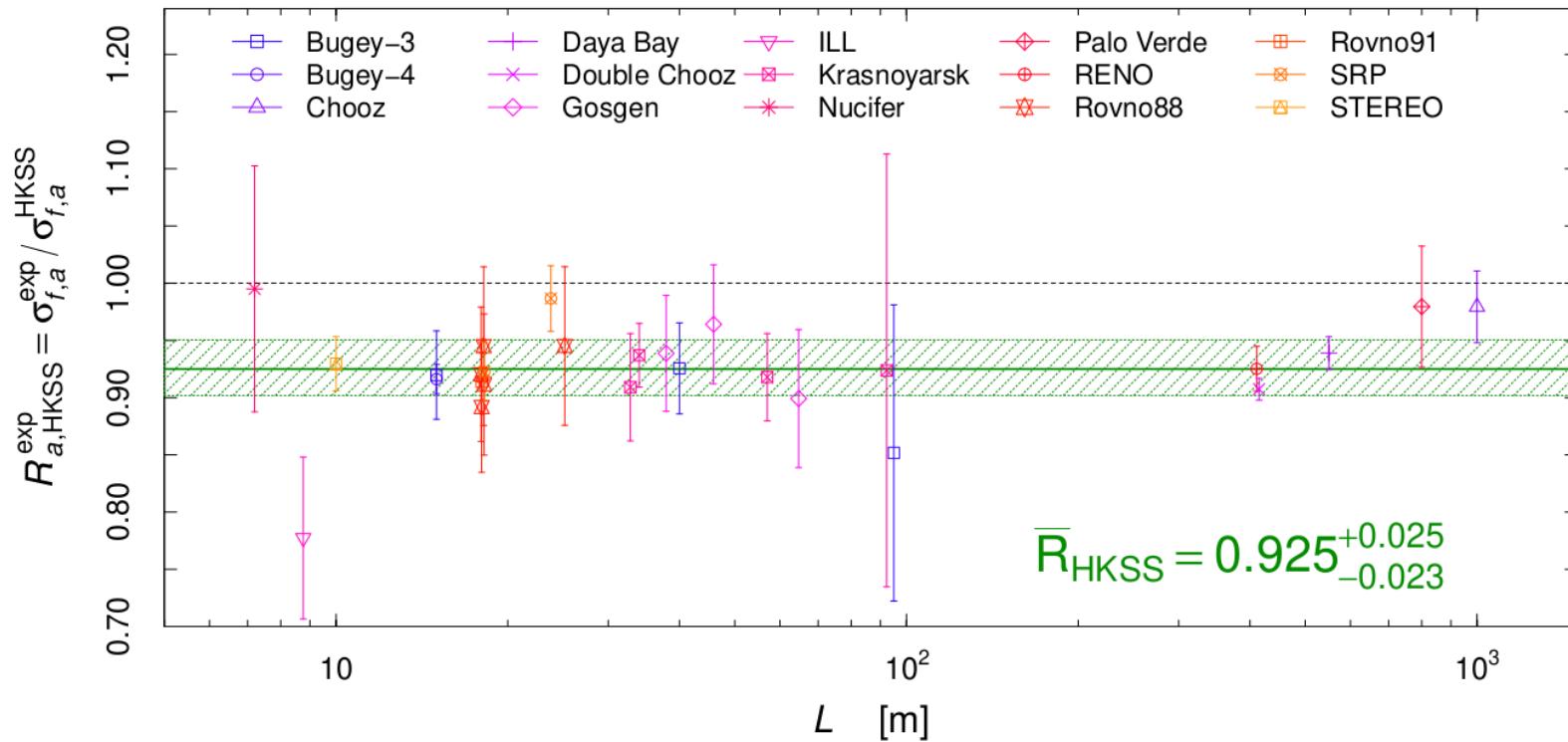
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



1.2 $\sigma$  deficit, no anomaly!

# 2019 new converted fluxes

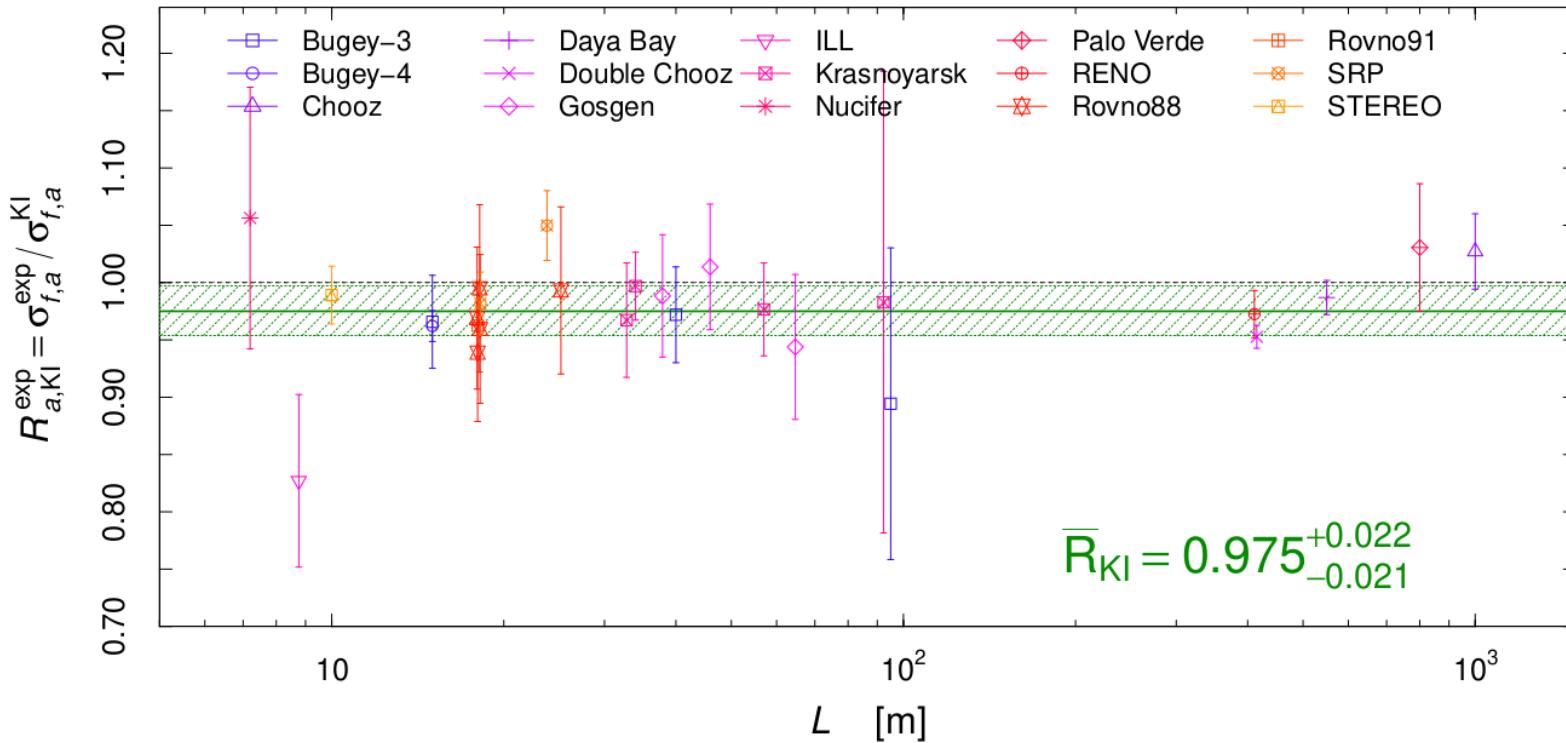
Giunti, Li, Ternes, Xin, 2110.06820, PLB 2022



HKSS flux results in  $2.9\sigma$  anomaly!

# 2021 new converted fluxes

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

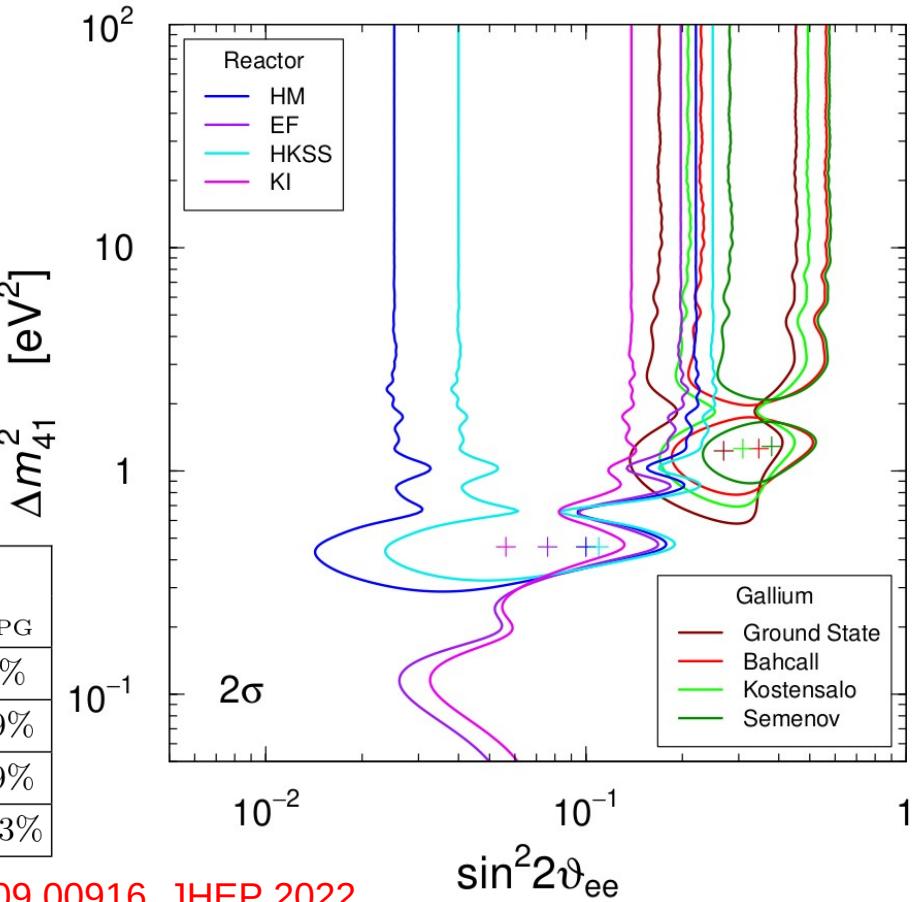


No anomaly ( $1.1\sigma$ ) with KI flux!

# Tension between RAA and Gallium

Severe tension between reactor rate and Gallium data!

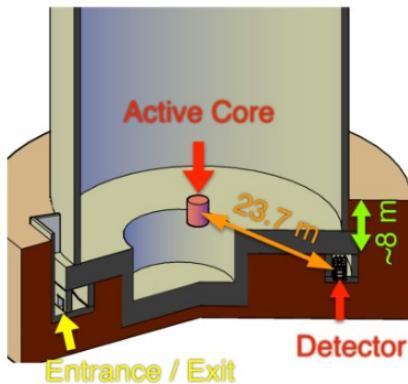
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>						
Ground State	7.2	2.8%	5.4	6.8%	9.1	1.1%	11.9	0.26%
Bahcall	10.9	0.42%	8.9	1.2%	12.9	0.16%	16.3	0.029%
Kostensalo	9.6	0.83%	7.5	2.4%	11.5	0.31%	15.3	0.049%
Semenov	15.1	0.052%	12.6	0.18%	17.0	0.02%	22.5	0.0013%



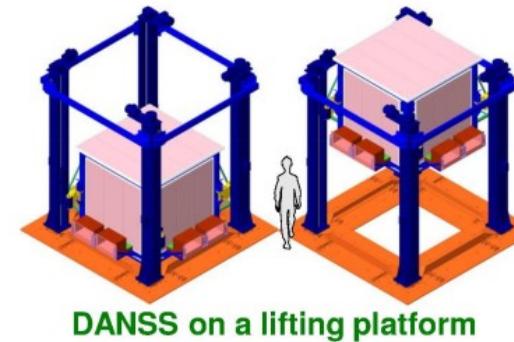
Giunti, Li, Ternes, Tyagi, Zhao, 2209.00916, JHEP 2022

# Ratio analysis

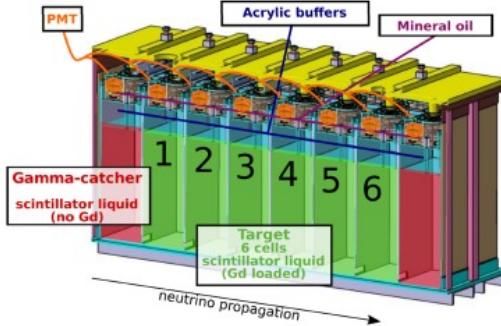
NEOS



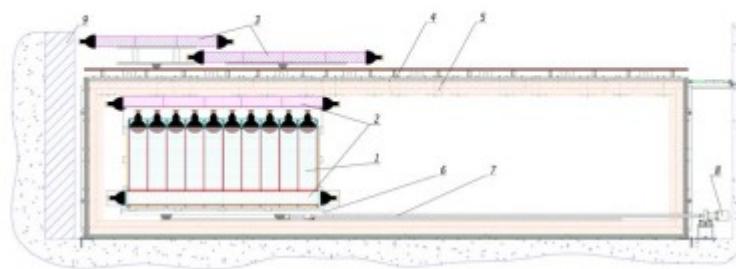
DANSS



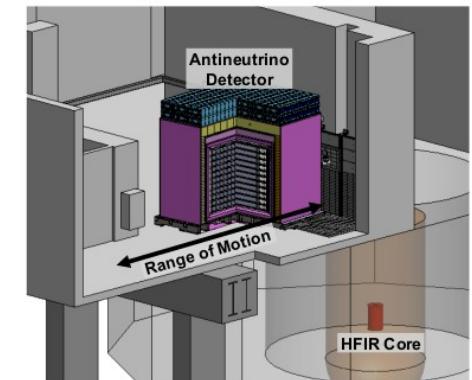
STEREO



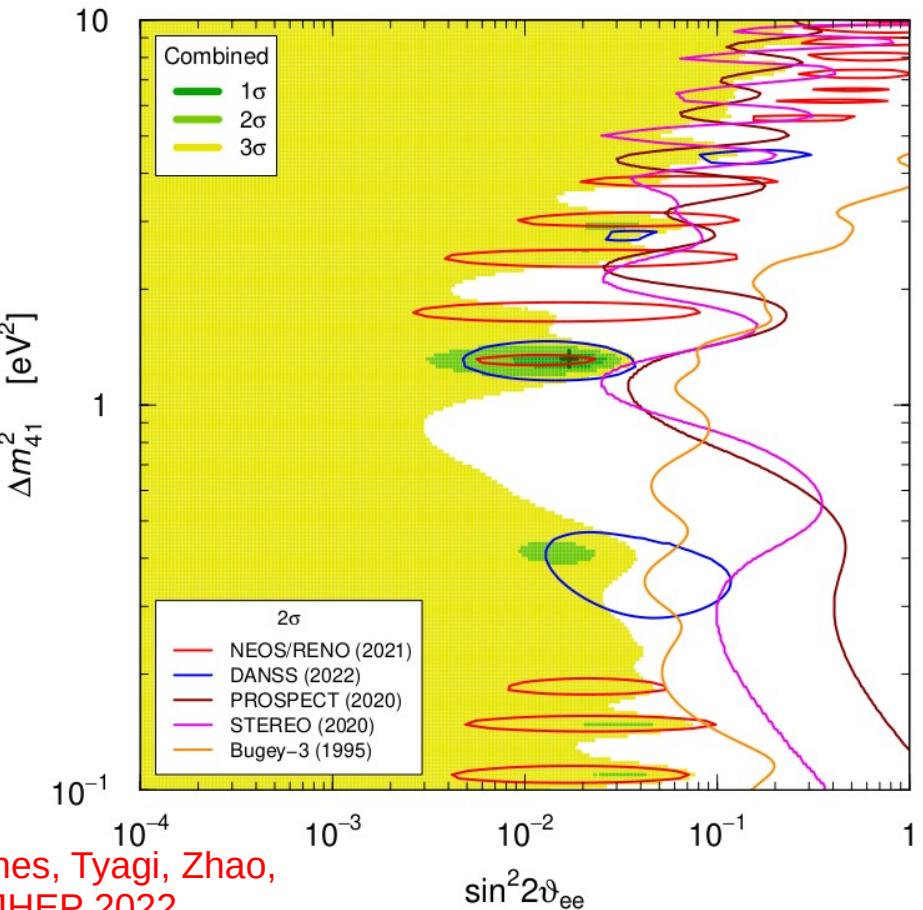
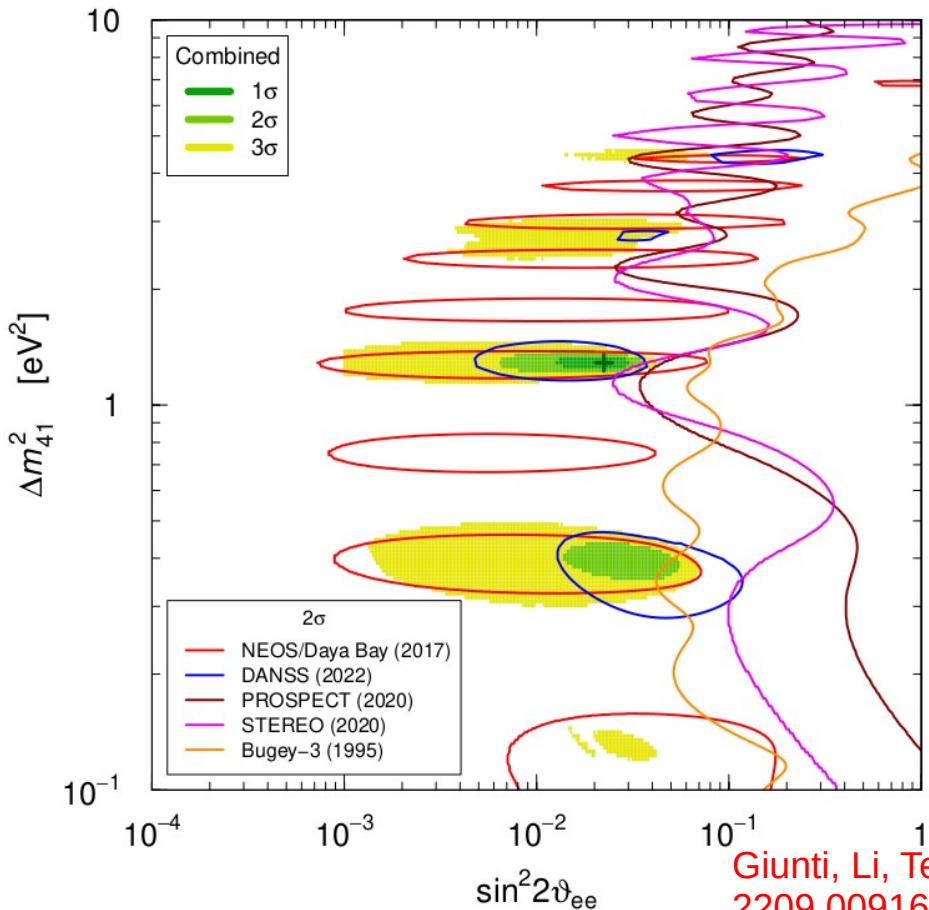
Neutrino-4



PROSPECT

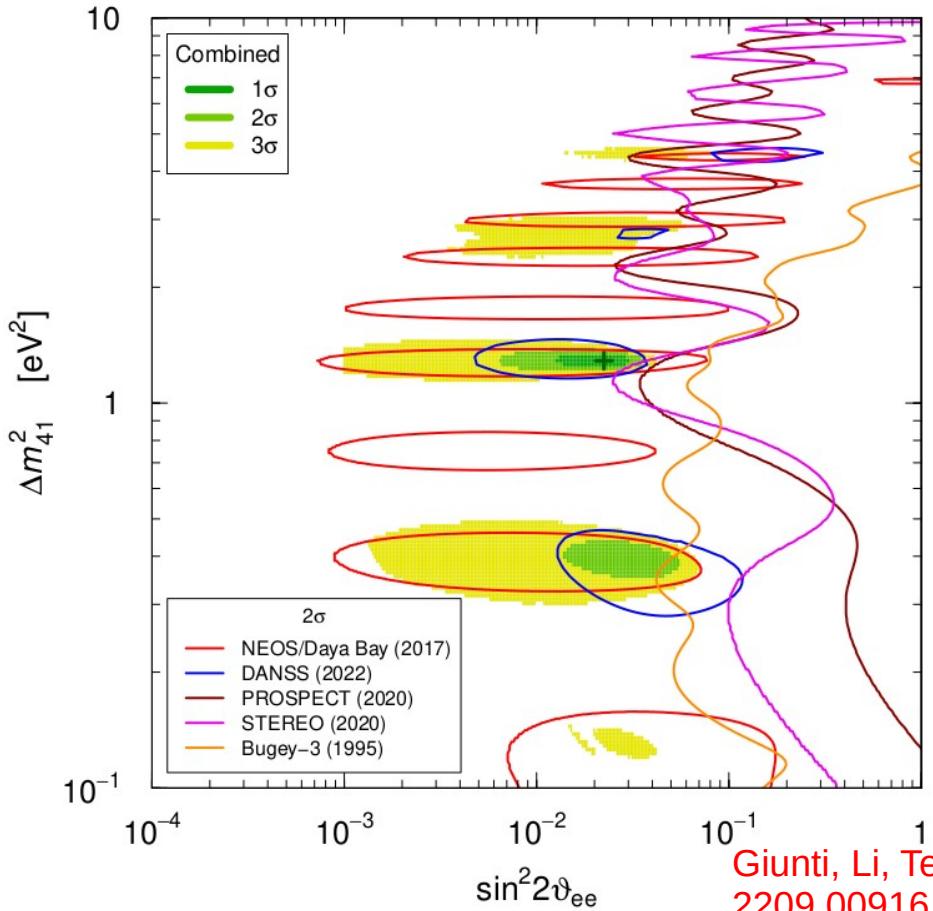


# Ratio analysis



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

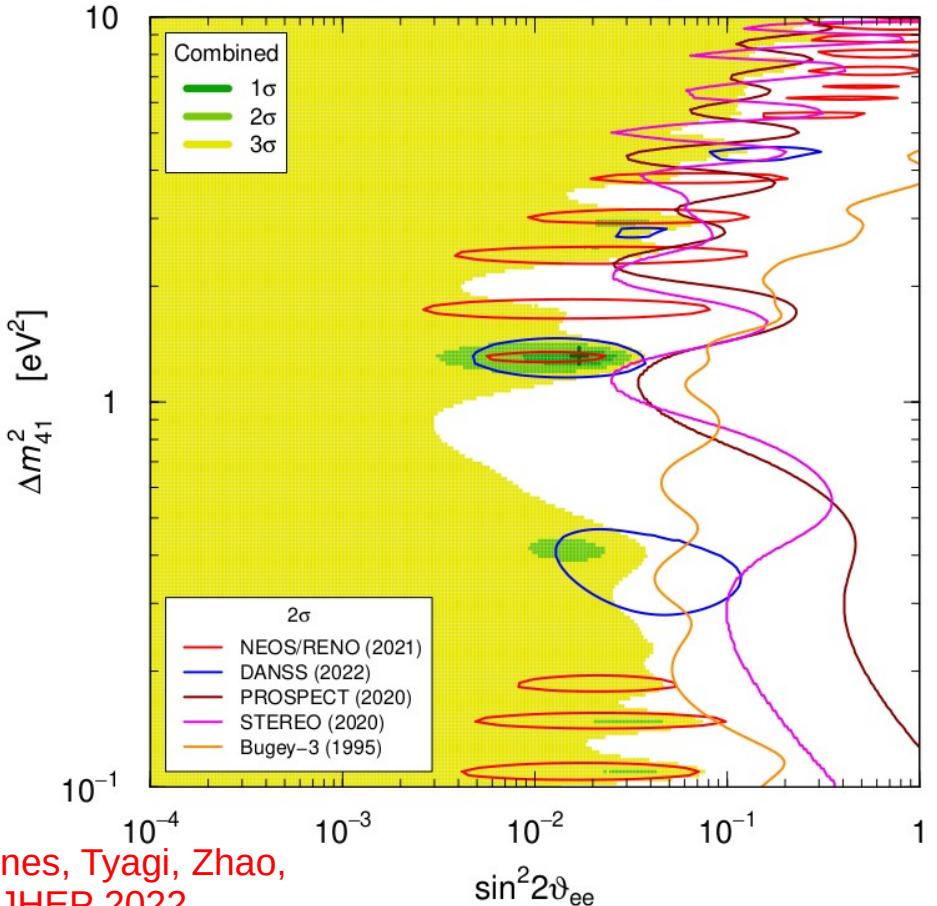
Many many events at Daya Bay!

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

# Ratio analysis

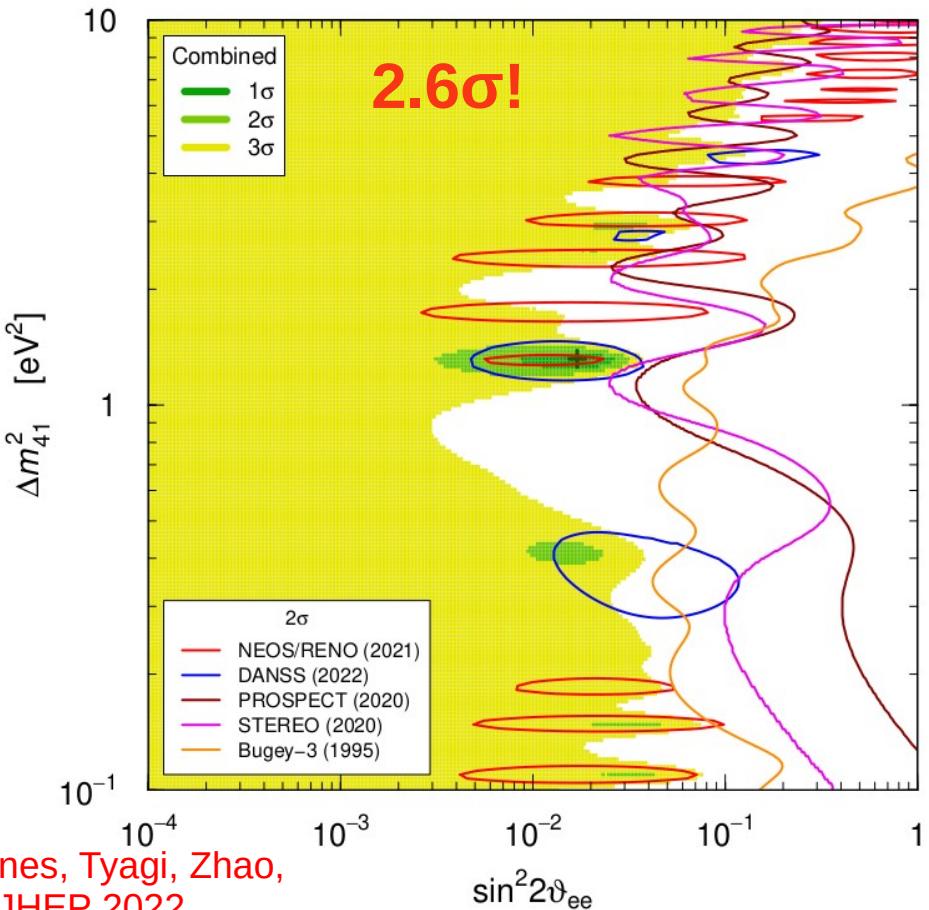
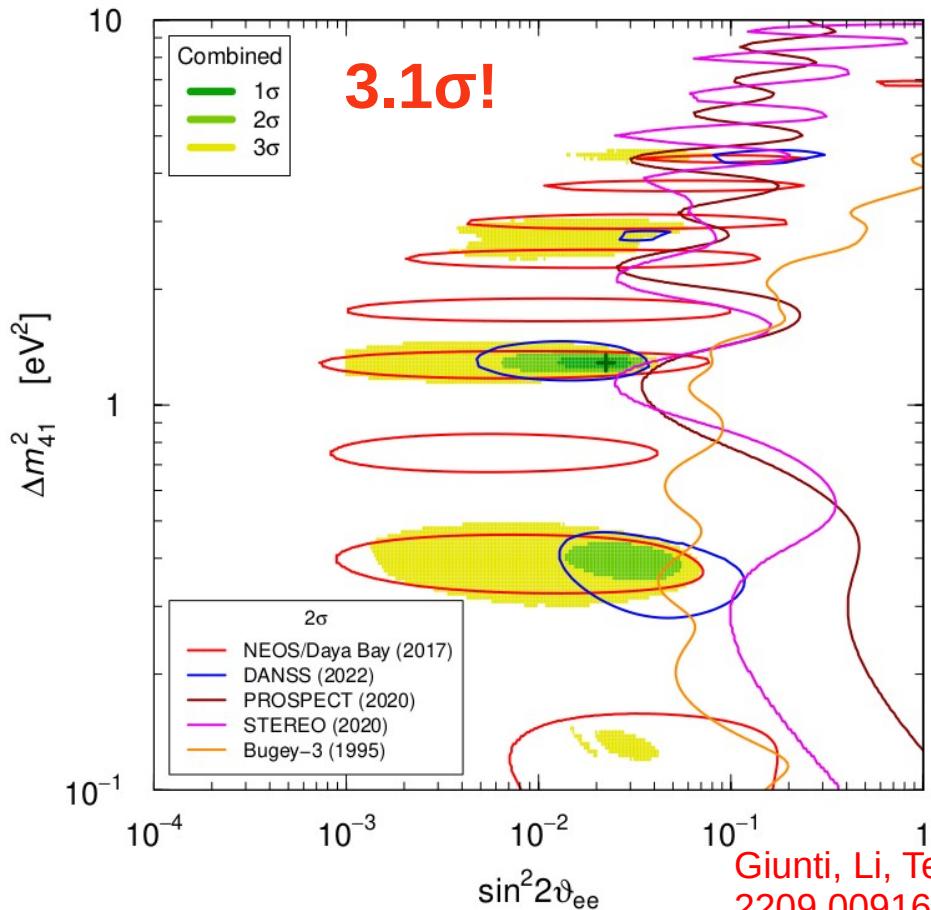
The NEOS collaboration also performed an analysis using the RENO spectrum as a reference spectrum

Same reactor complex,  
better control of systematic  
uncertainties!



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

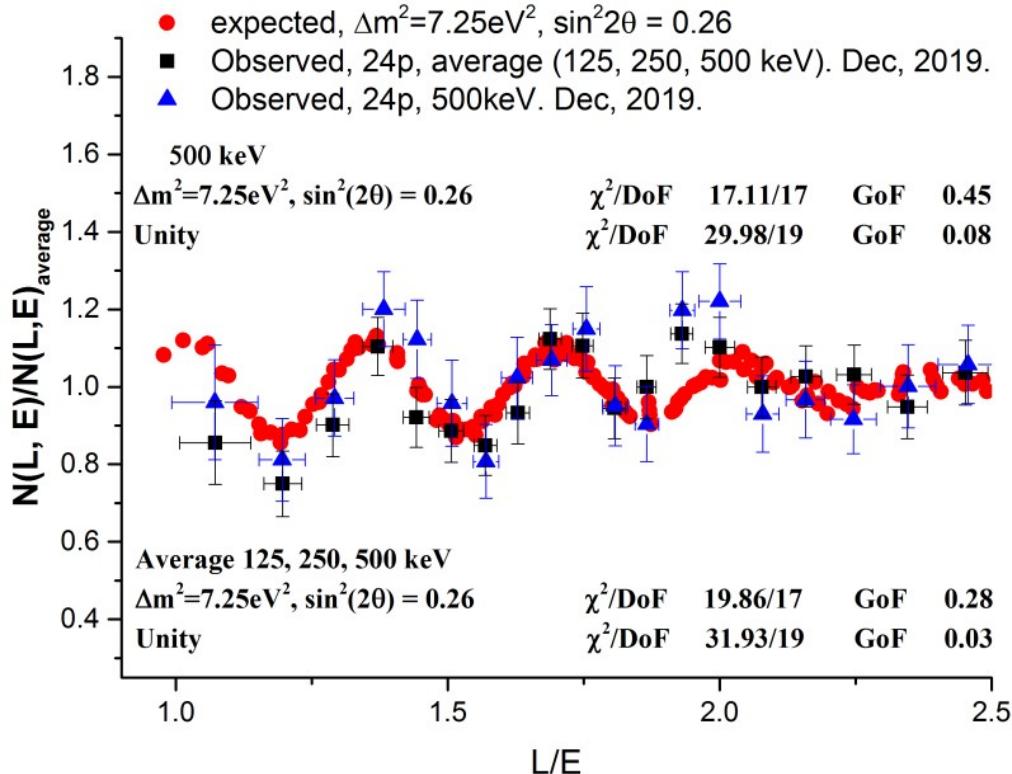
# Ratio analysis



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

# Neutrino-4

Neutrino-4, 2005.05301, PRD 2021



Neutrino-4 observes sterile oscillations at about  $3\sigma$   
Very large mixing  
In tension with solar data

# Neutrino-4

Neutrino-4, 2005.05301, PRD 2021

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

# Neutrino-4



Neutrino-4, 2005.05301, PRD 2021

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

# Neutrino-4

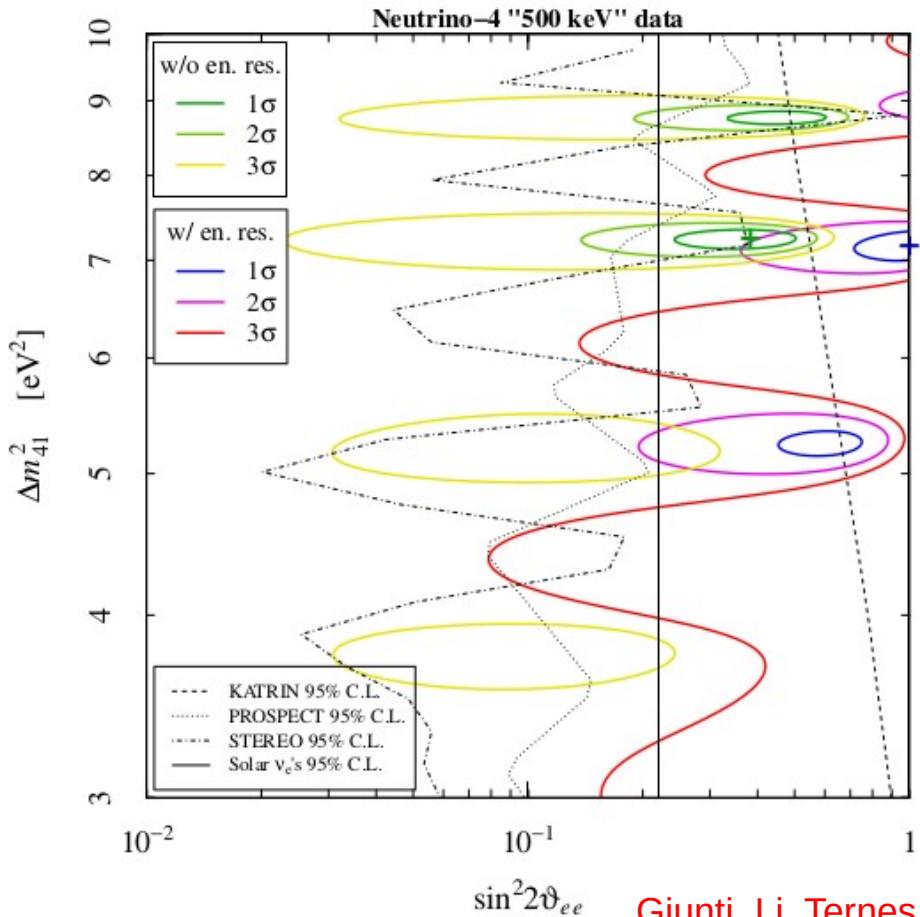
Averaging contains integration over flux, distance, detector resolution

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

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

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

# Neutrino-4



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

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

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

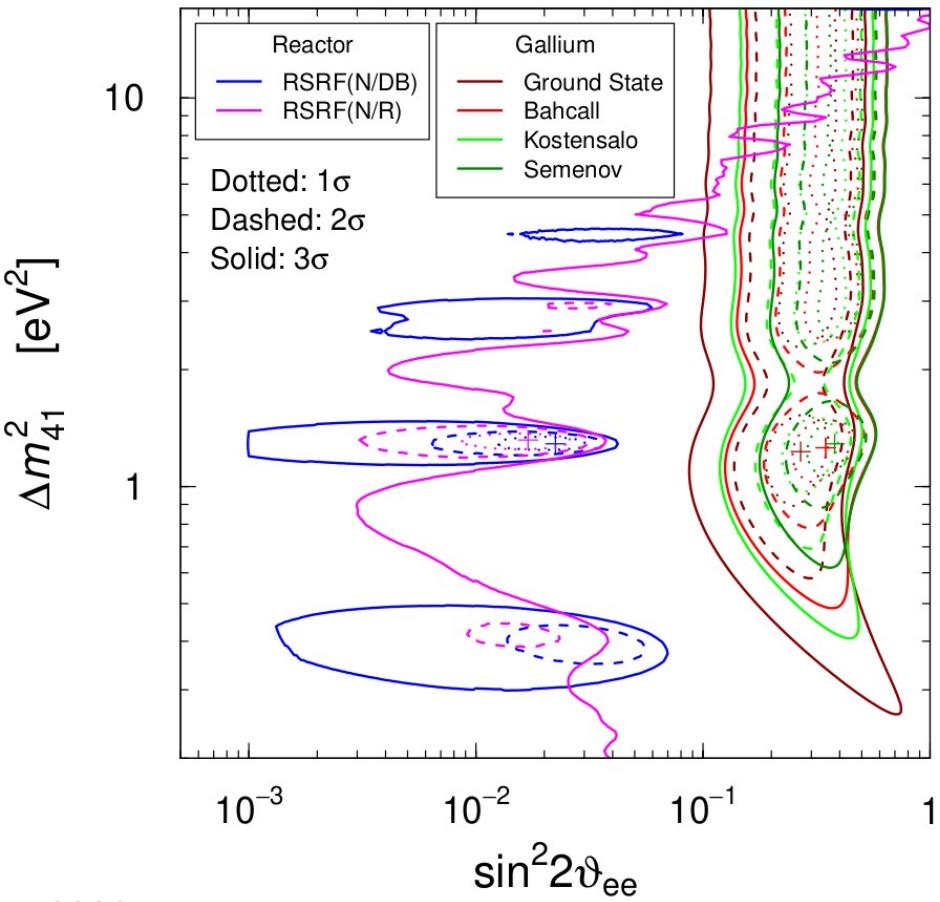
# Ratio analysis

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

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

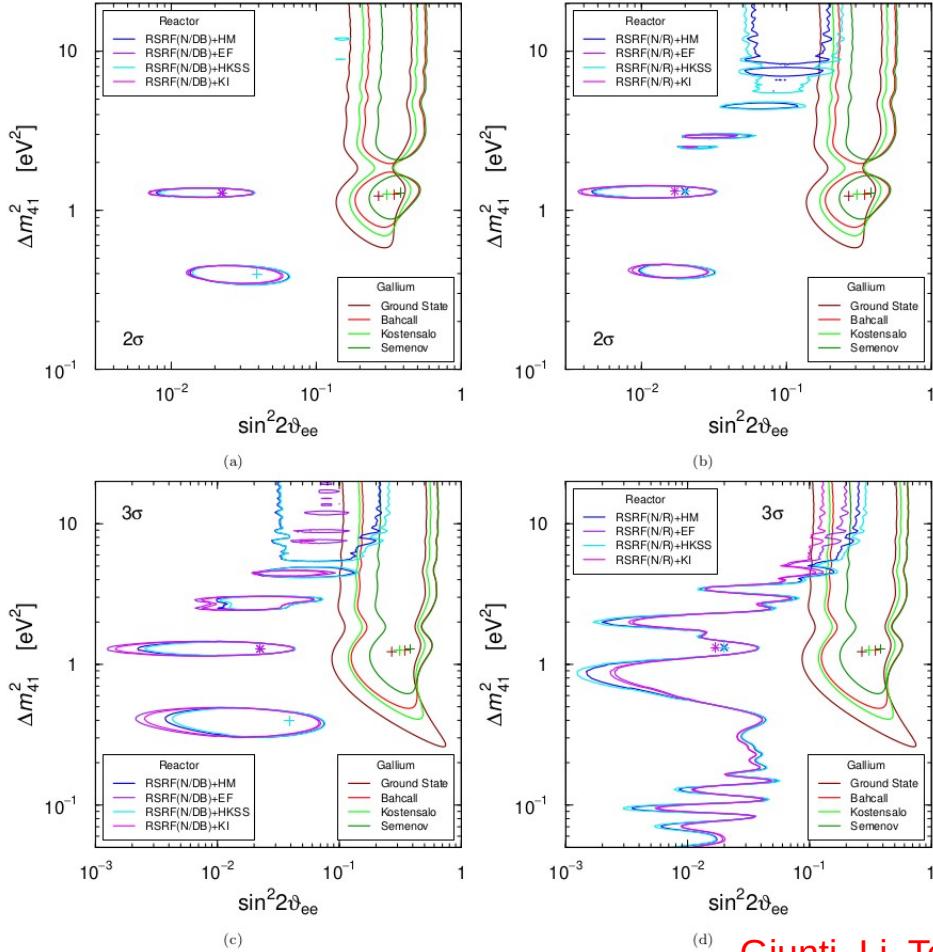
No good fit for RSRF(N/R)  
either.

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



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

Severe tension for any combination with Gallium data!

RSRF(N/DB) + Reactor Rates								
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{PG}$	GoF <sub>PG</sub>						
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	0.0000099%
RSRF(N/R) + Reactor Rates								
	HM		HKSS		EF		KI	
	$\Delta\chi^2_{PG}$	GoF <sub>PG</sub>						
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	0.000068%

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

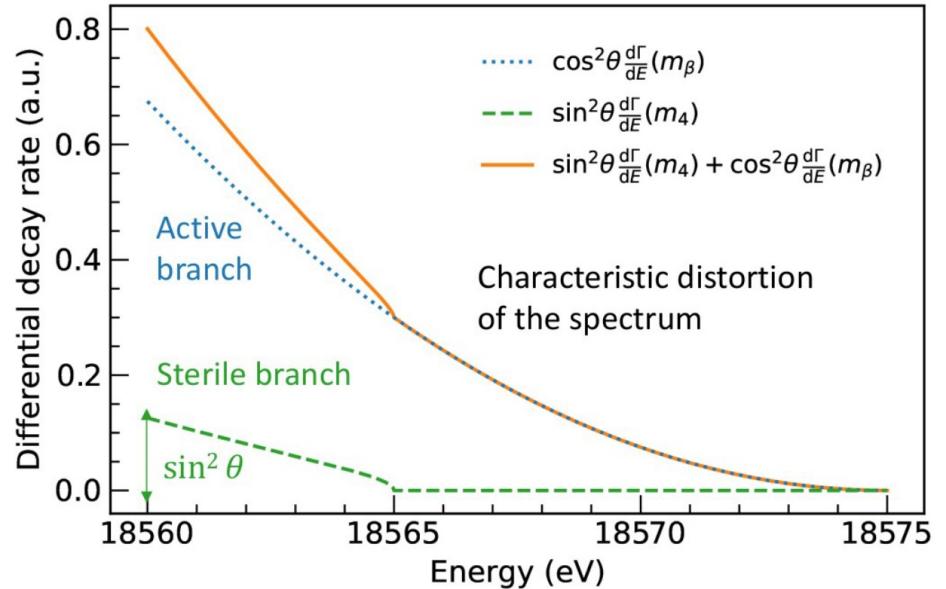
# Tritium data

Tritium experiments measure the beta-decay spectrum

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

$$\frac{d\Gamma}{dE} = (1 - |U_{e4}|^2) \frac{d\Gamma}{dE}(m_\beta^2) + |U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)$$

light neutrino                          heavy neutrino



Lokhov @ NuMass 2022, Milano

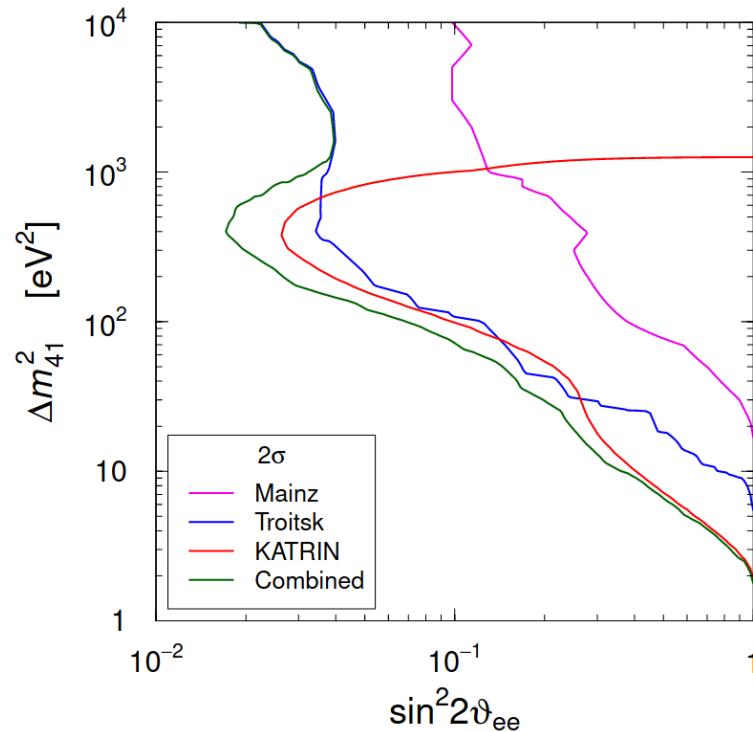
# Tritium data

Tritium experiments measure the beta-decay spectrum

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

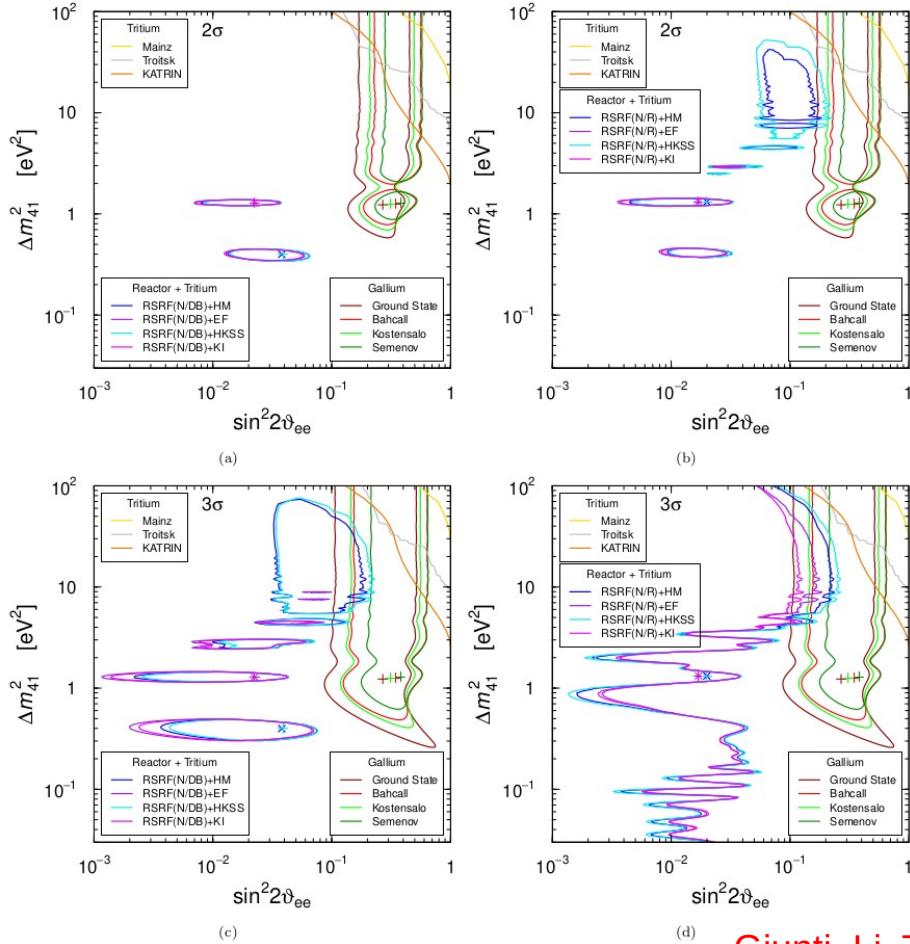
$$\frac{d\Gamma}{dE} = (1 - |U_{e4}|^2) \frac{d\Gamma}{dE}(m_\beta^2) + |U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)$$

light neutrino                  heavy neutrino



Giunti @ NOW 2022, Ostuni

# Combined reactor and Tritium data



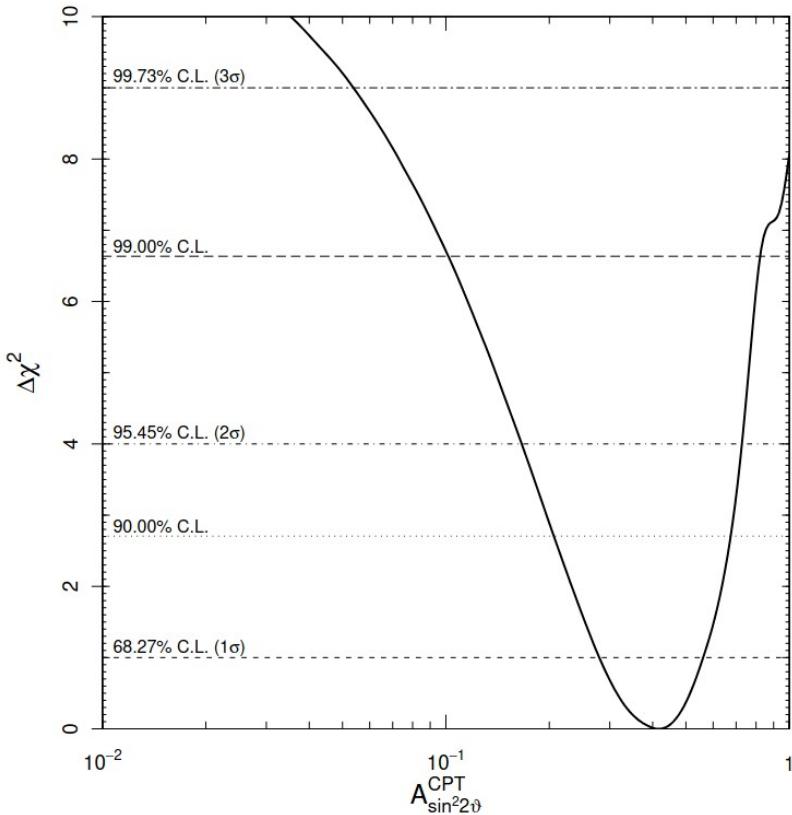
Tritium data removes the regions at large values of the mass splitting.

Severe tension for any combination with Gallium data!

RSRF(N/DB) + Reactor Rates + Tritium						
	HM		HKSS		EF	
	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>
Ground State	15.69	0.039%	13.17	0.14%	20.82	0.003%
Bahcall	19.86	0.0049%	17.19	0.019%	25.06	0.00036%
Kostensalo	18.63	0.009%	15.87	0.036%	23.83	0.00067%
Semenov	25.22	0.00033%	21.94	0.0017%	30.42	0.000025%
RSRF(N/R) + Reactor Rates + Tritium						
	HM		HKSS		EF	
	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>	$\Delta\chi^2_{\text{PG}}$	GoF <sub>PG</sub>
Ground State	11.56	0.31%	8.72	1.3%	16.96	0.021%
Bahcall	15.76	0.038%	12.74	0.17%	21.19	0.0025%
Kostensalo	14.49	0.071%	11.40	0.33%	19.97	0.0046%
Semenov	21.04	0.0027%	17.45	0.016%	26.45	0.00018%

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

# CPT violating neutrinos?

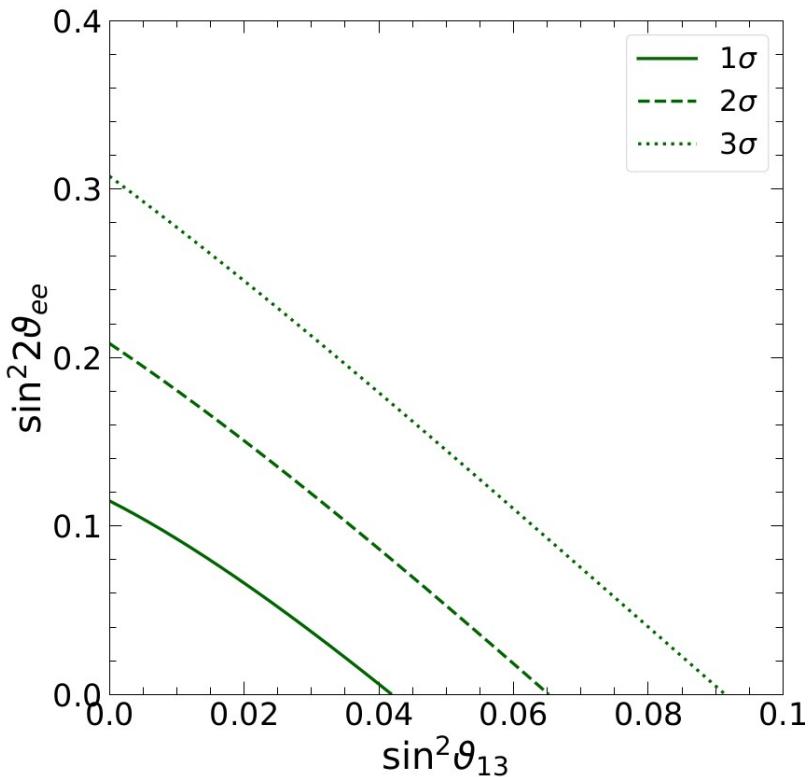


Allowing for different neutrino and antineutrino oscillation parameters could solve the tension between Reactor+Tritium data and Gallium data

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

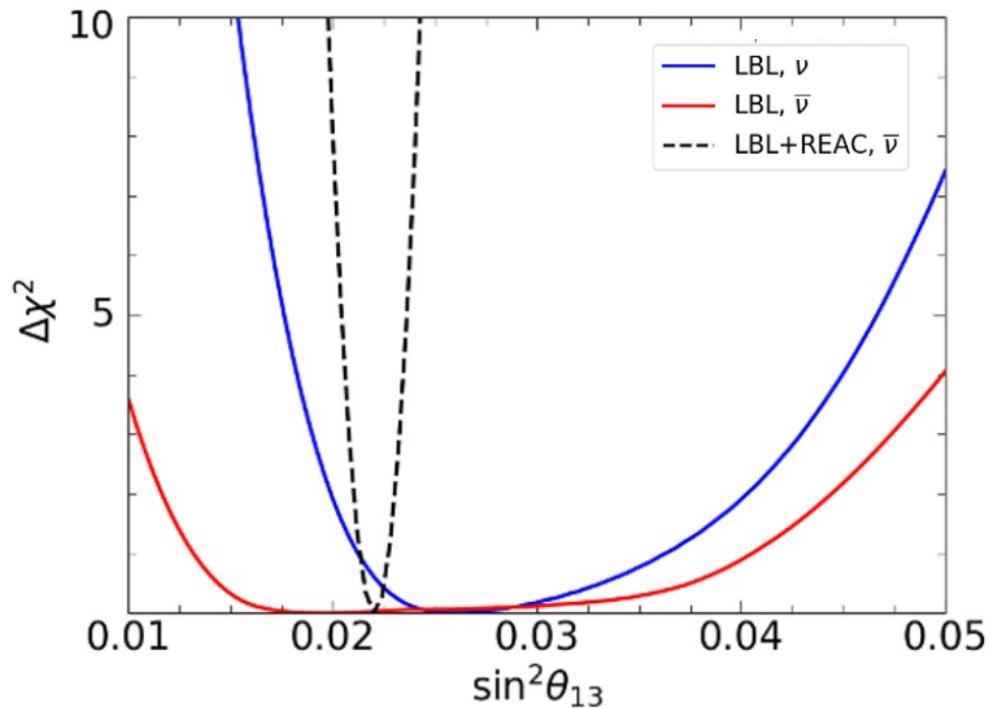
Giunti, Laveder, 1008.4750, PRD 2010

# CPT violating neutrinos?



Solar experiments measure neutrinos, not antineutrinos!  
Solar bound is relaxed when leaving reactor angle free!

# CPT violating neutrinos?



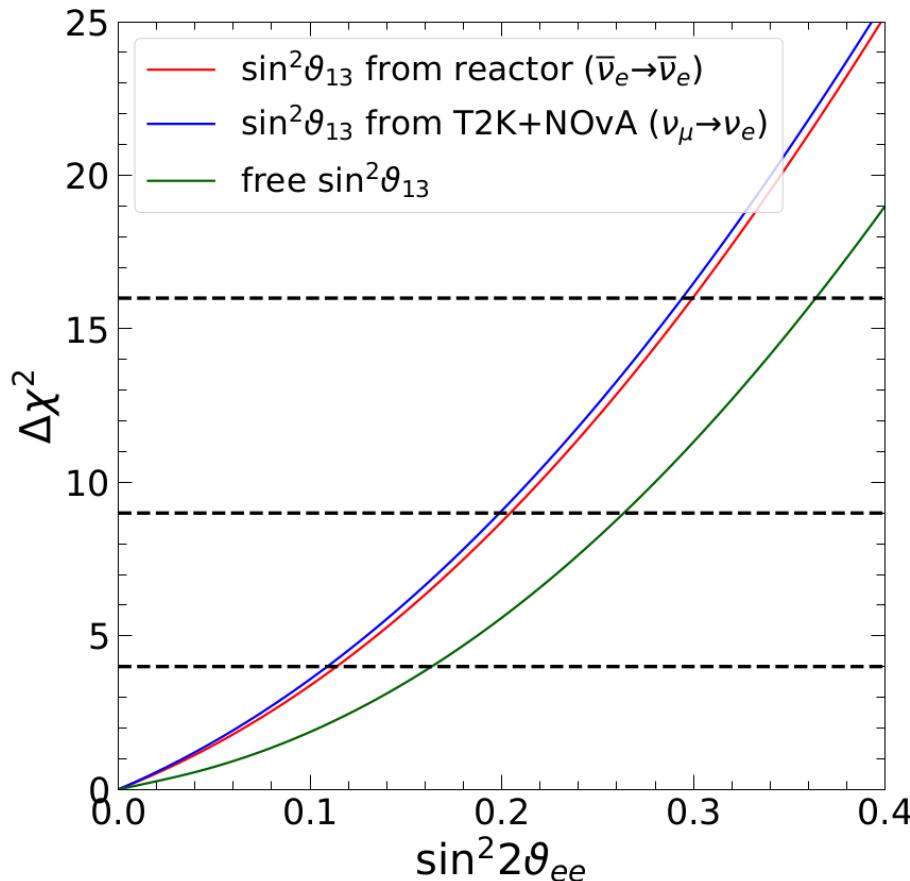
Solar experiments measure neutrinos, not antineutrinos!

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

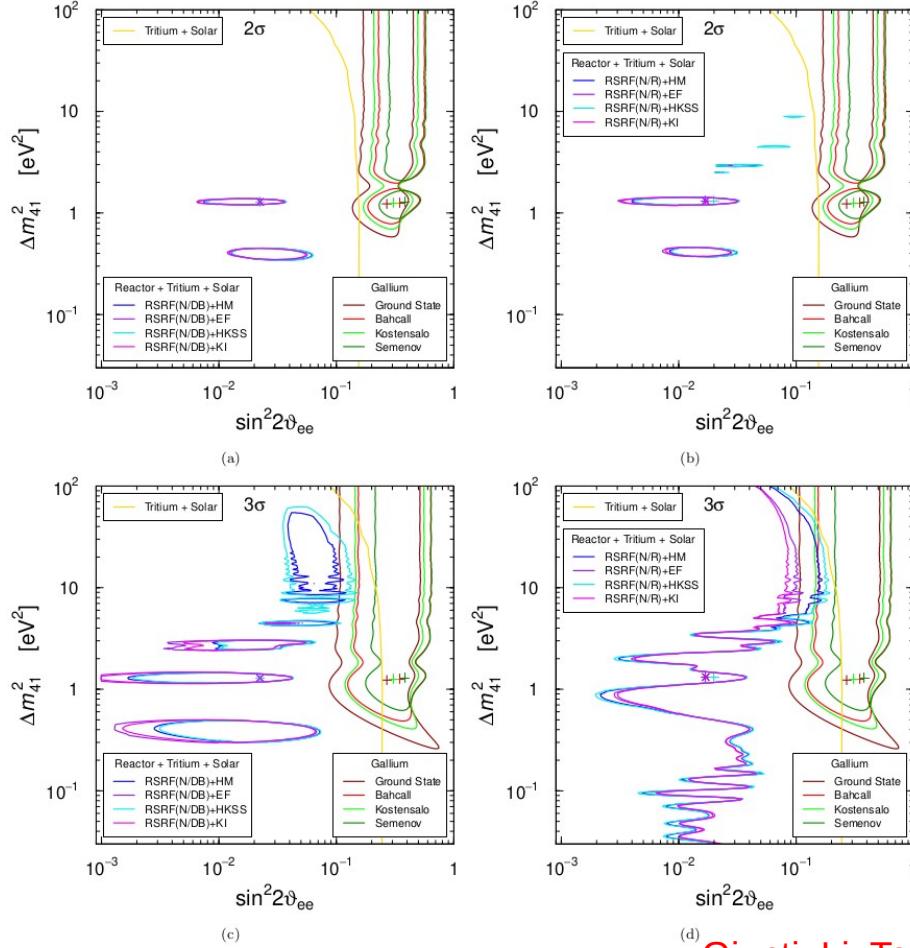


Using the newest solar data the CPT violating explanation is not viable anymore

	Solar-only $\Delta\chi^2_{PG}$ GoF <sub>PG</sub>		S+ $\vartheta_{13}$ (T&N) $\Delta\chi^2_{PG}$ GoF <sub>PG</sub>		S+ $\vartheta_{13}$ (R) $\Delta\chi^2_{PG}$ GoF <sub>PG</sub>	
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 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 <sub>PG</sub>						
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 <sub>PG</sub>						
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
$\chi^2_{\text{min}}$	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
$\chi^2_{\text{min}}$	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

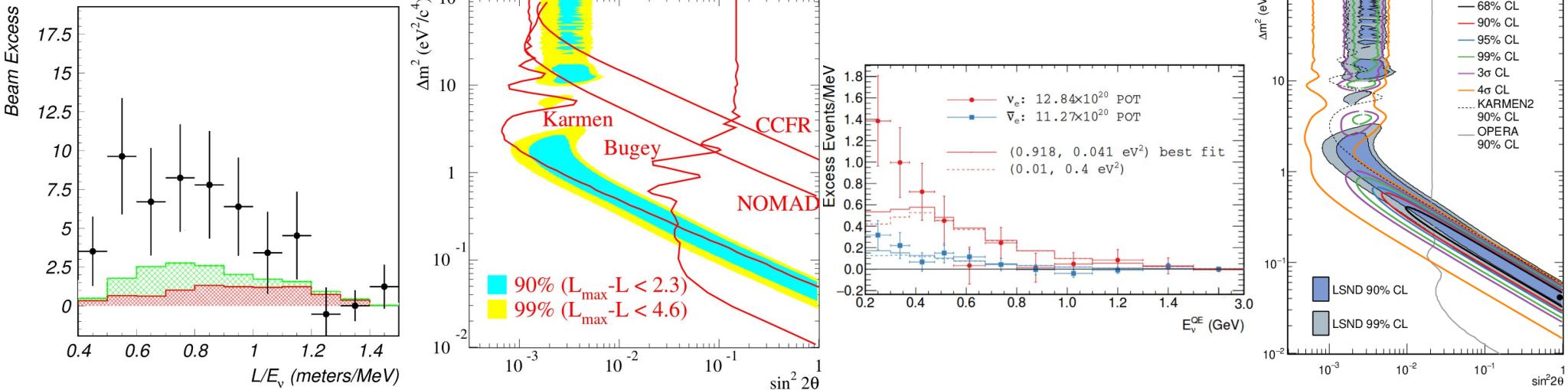
Global fit (without Gallium data)  
has a preference between  $2.6\sigma$   
and  $3.3\sigma$  in favor of 3+1  
oscillations!

Due to new reactor ratio data

Another new (or revived)  
anomaly!

# LSND and MiniBooNE

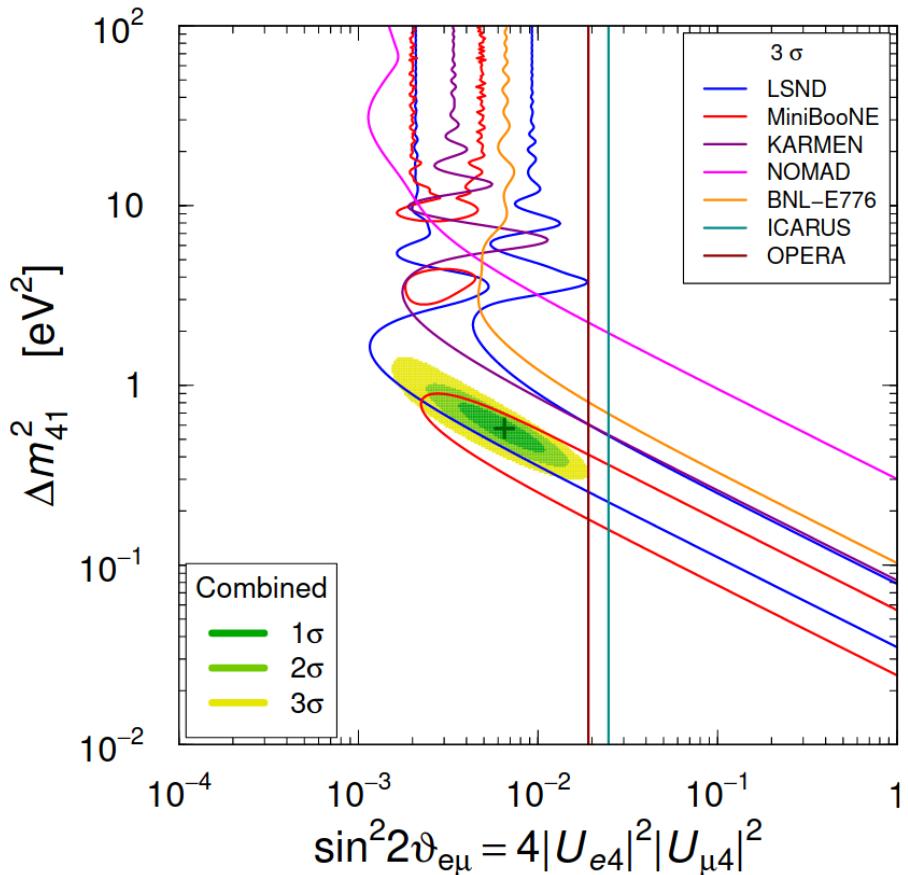
LSND saw an excess of electron neutrinos in an muon neutrino beam  
MiniBooNE confirmed this observation!



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

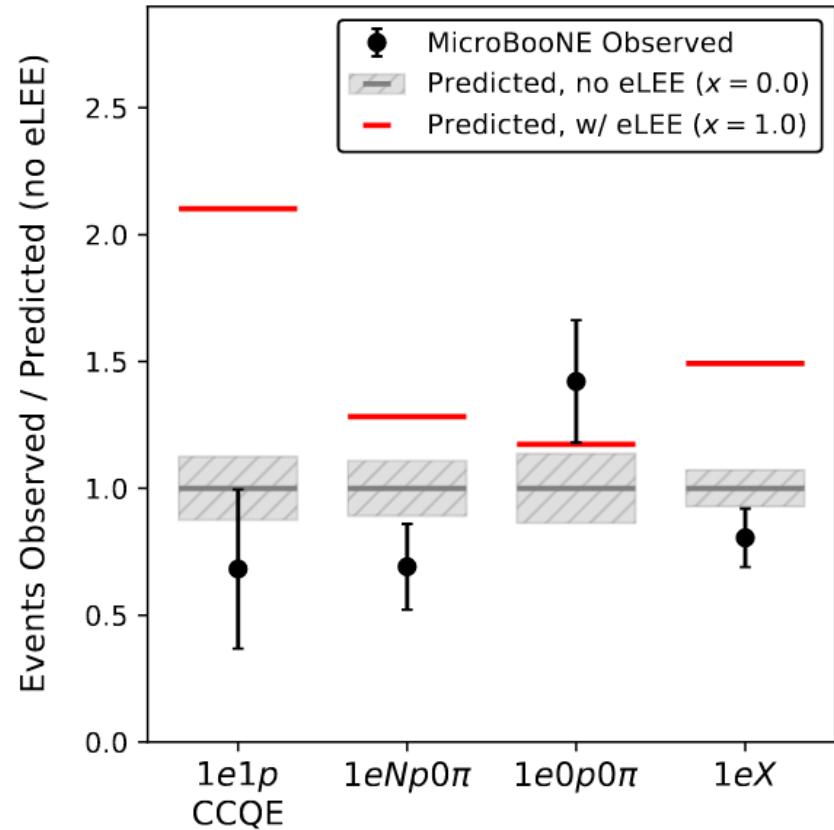
LSND and MiniBooNE only partially agree

Giunti, Lasserre, 1901.08330, Ann.Rev. 2019

# MicroBooNE

MicroBooNE was built to check  
the MiniBooNE results!

Looking for signals using several  
final state channels



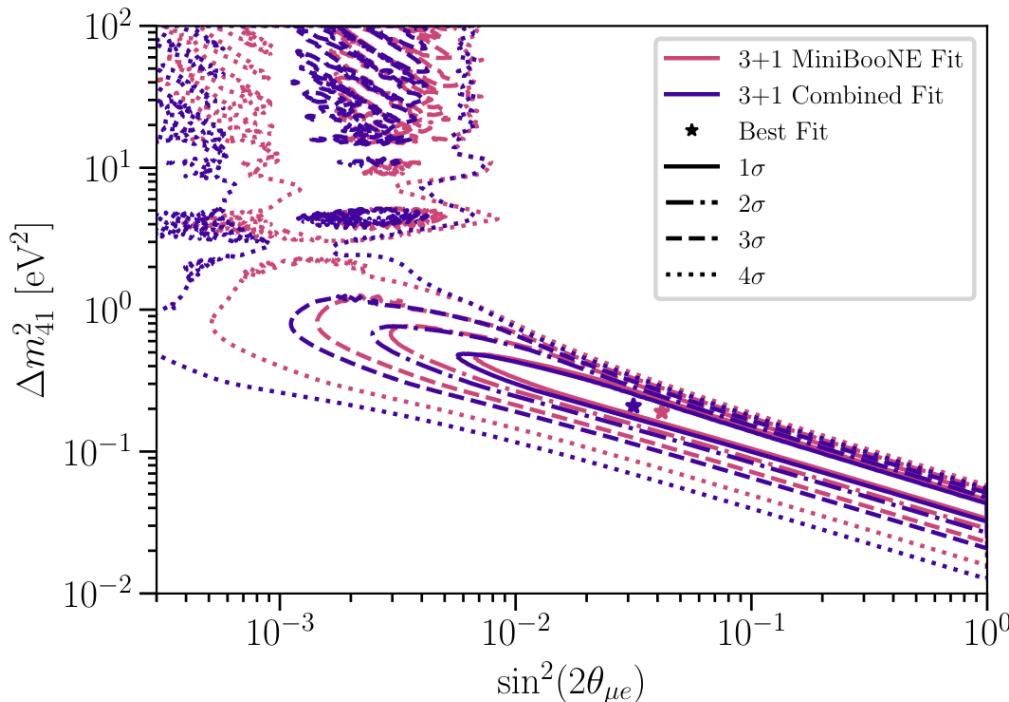
MicroBooNE, 2110.14054, PRL 2022

# MicroBooNE

MicroBooNE was built to check  
the MiniBooNE results!

Looking for signals using several  
final state channels

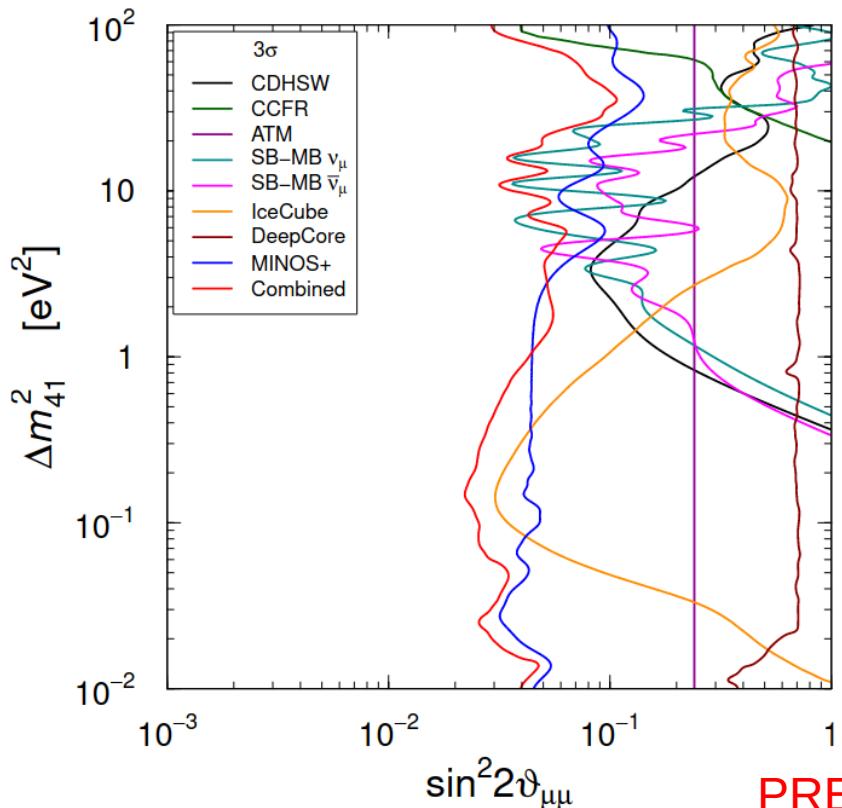
A combined analysis shows that  
MicroBooNE can not exclude the  
region of parameter space  
preferred by MiniBooNE



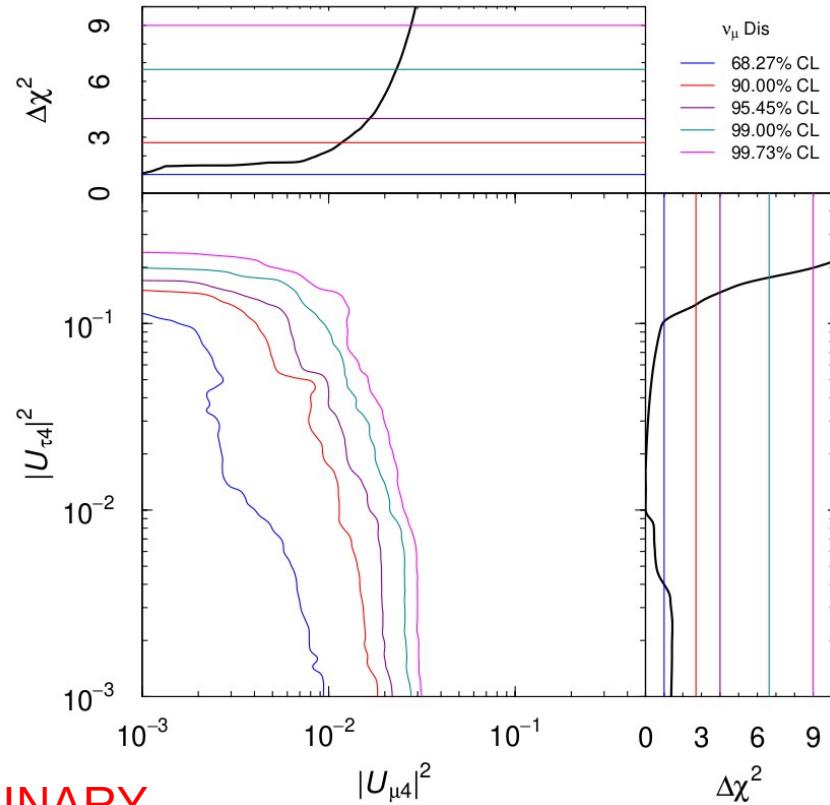
MiniBooNE, 2201.01724

# Accelerator and atmospheric experiments

No evidence in muon disappearance

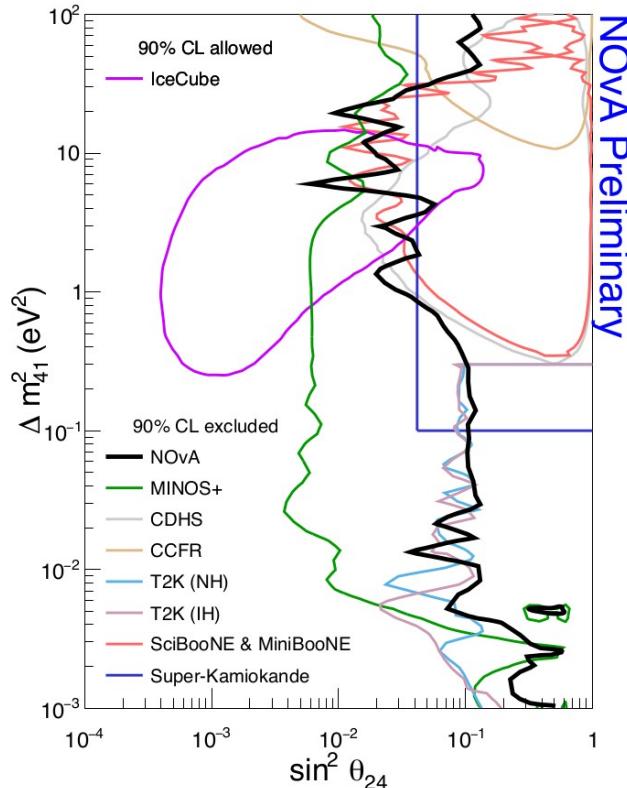


PRELIMINARY

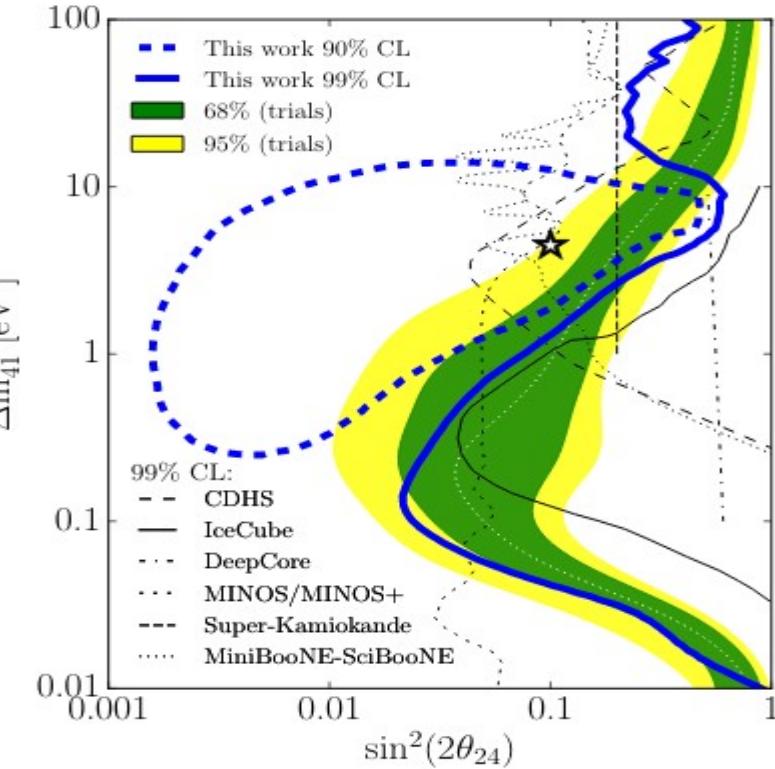


# Accelerator and atmospheric experiments

No evidence in muon disappearance

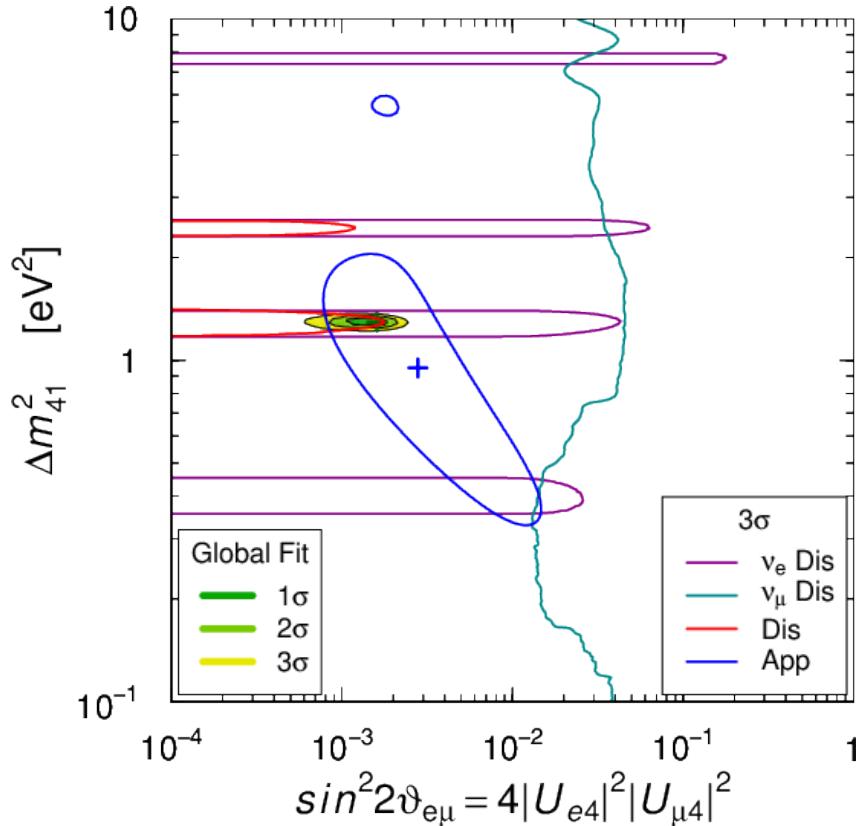


NOvA, Talk by Jeff Hartnell, Neutrino 2022



IceCube, 2005.12942, PRL 2020

# Global fit?



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

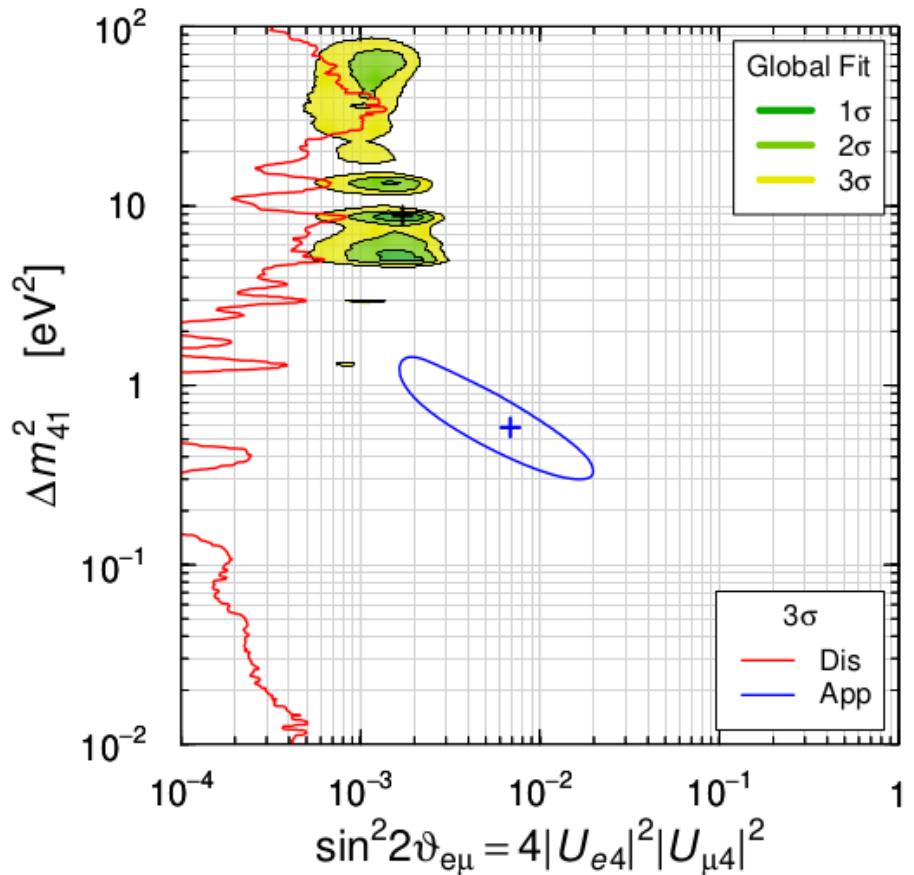
$$\nu_\mu \rightarrow \nu_\mu : |U_{\mu 4}|^2 = \sin^2 \theta_{24} \cos^2 \theta_{14}$$

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

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!

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

Global 3+1 fit is  
unacceptable!

# Conclusions

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

RAA might be resolved for newer flux models

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

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

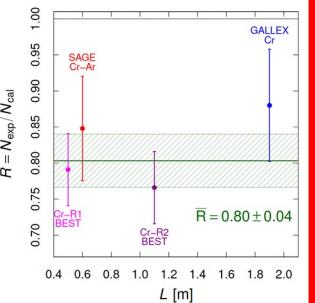
No (significant) signal in atmospheric or accelerator experiments

A global 3+1 fit is statistically not acceptable

More data is needed to clarify open issues

Anomalous AND also Null results have to be checked

# Gallium UNSOLVED!

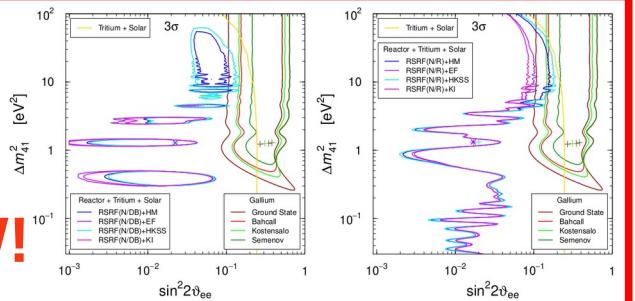


RAA

Possibly solved!

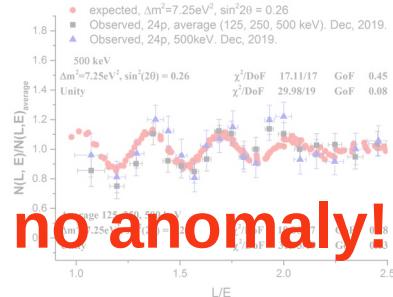


Ratio  
NEW!



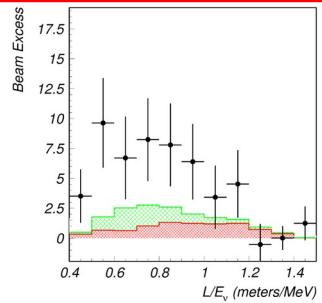
Neutrino-4

Possibly no anomaly!

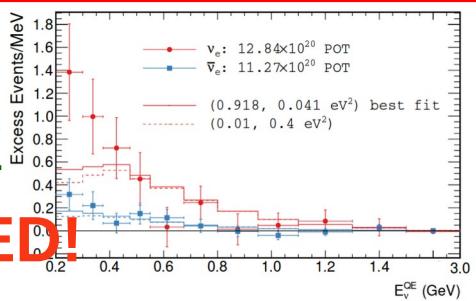


LSND

UNSOLVED!



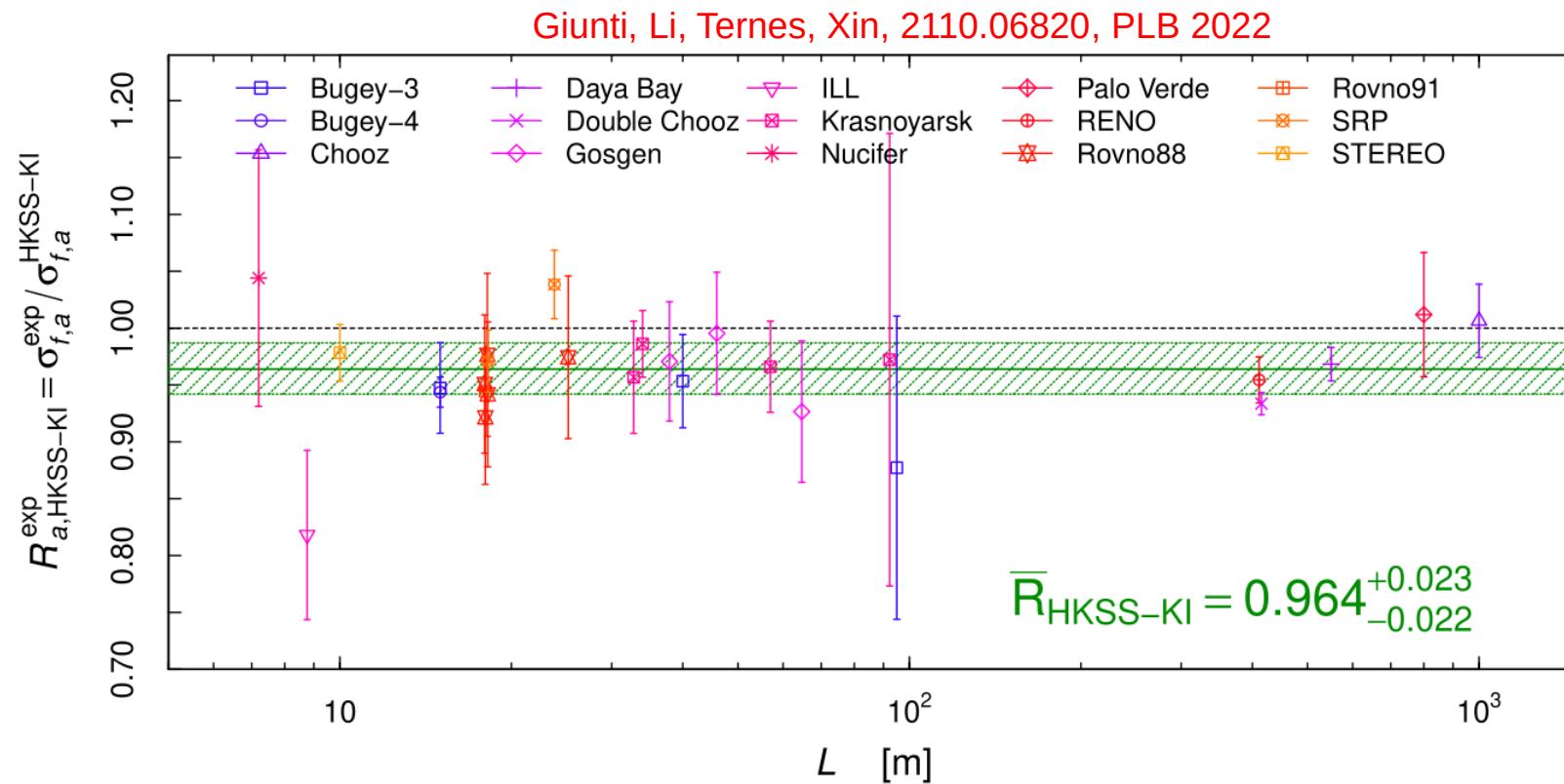
MiniBooNE  
UNSOLVED!





**Gracias!**

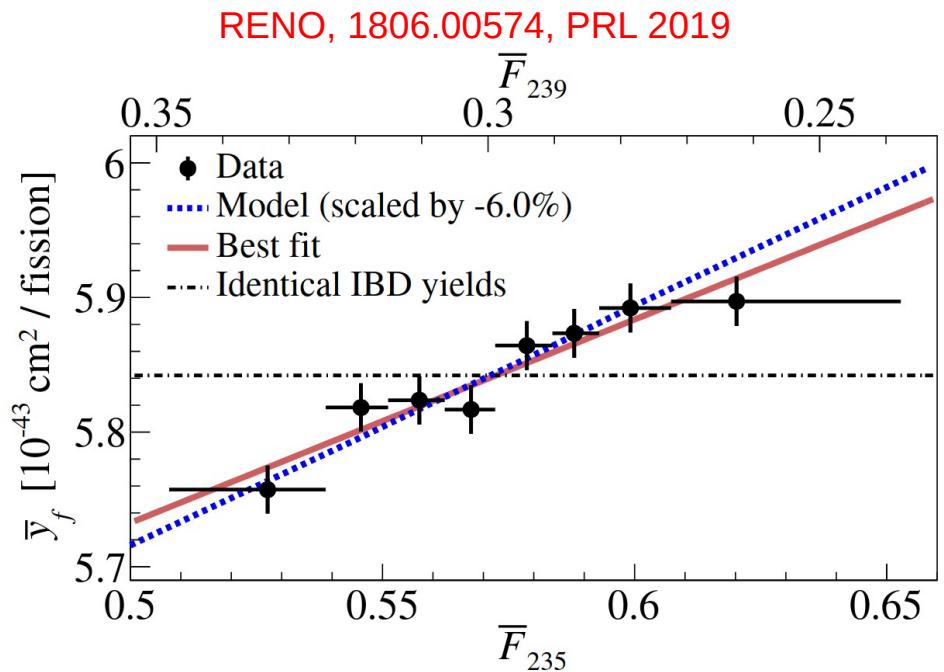
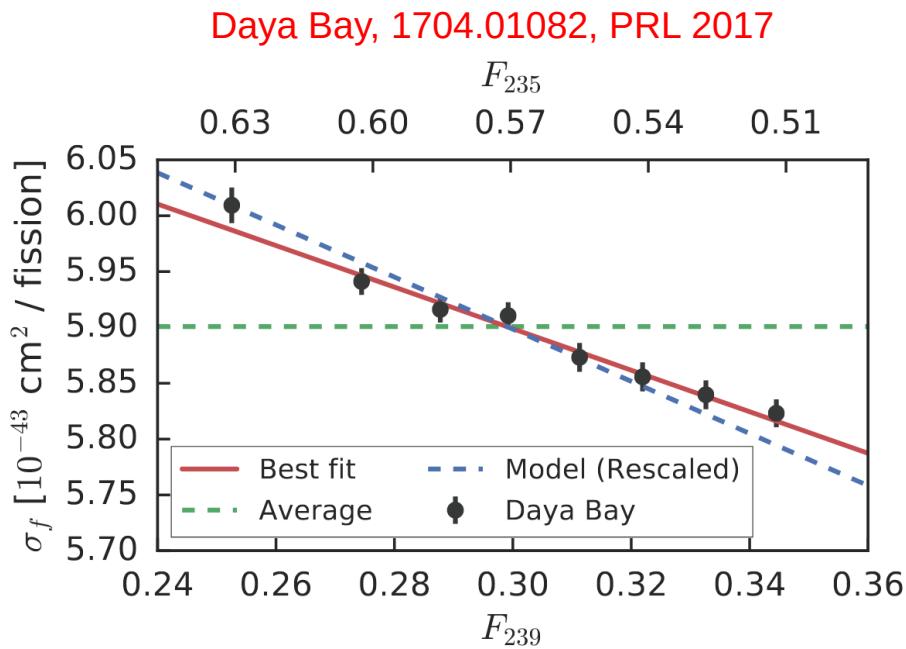
# 2021 combining HKSS and KI

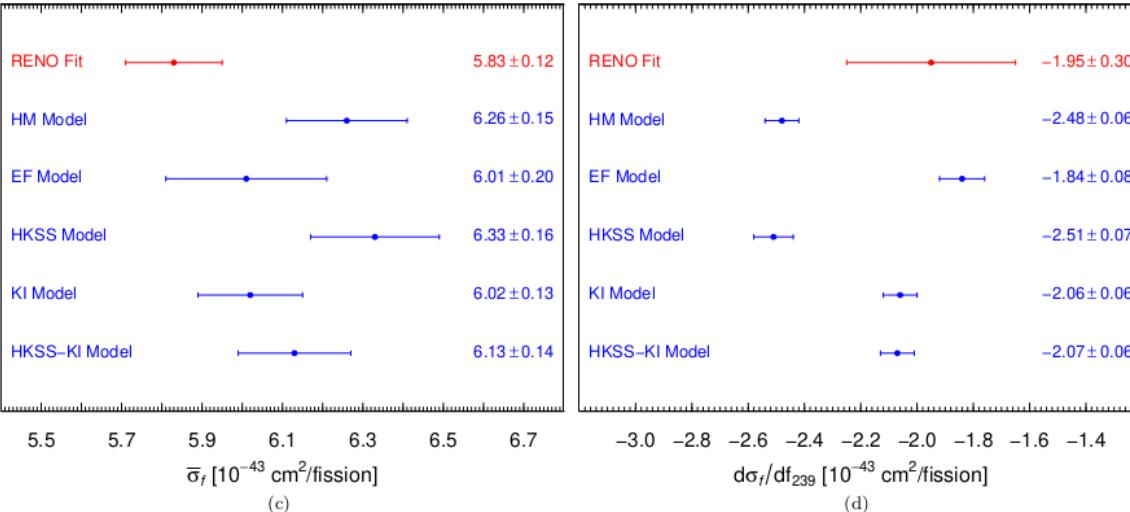
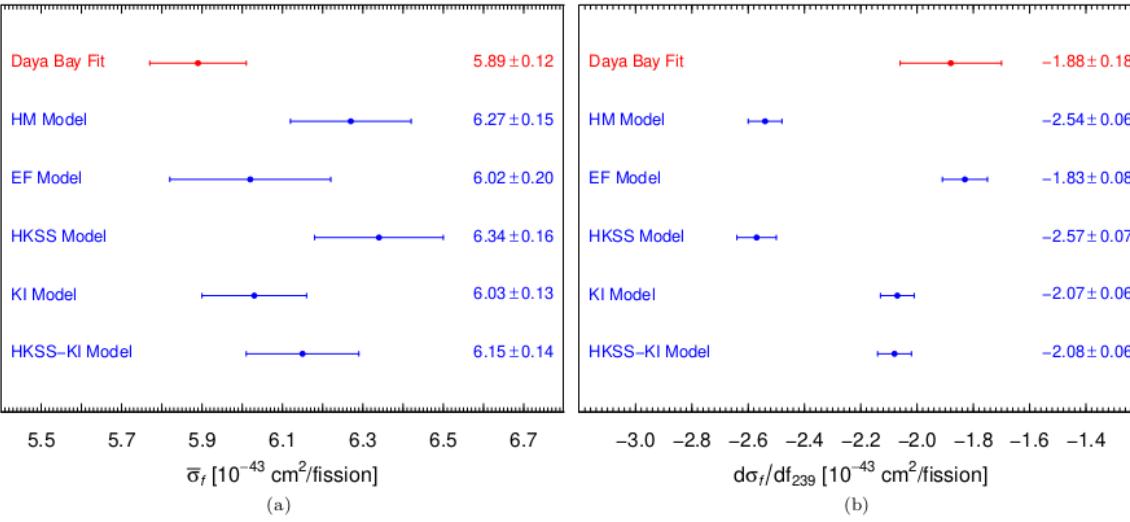


No anomaly ( $1.5\sigma$ ) with HKSS-KI flux!

# Evolution data

Measure rates at different stages of reactor cycle





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

We get additional information from the measurement of the slope parameter

# Evolution data

## Effect of evolution data on RAA

Model	Rates		Evolution		Rates + Evolution	
	$\bar{R}_{\text{mod}}$	RAA	$\bar{R}_{\text{mod}}$	RAA	$\bar{R}_{\text{mod}}$	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	$0.975^{+0.022}_{-0.021}$	$1.1\sigma$	$0.973^{+0.023}_{-0.022}$	$1.2\sigma$	$0.970 \pm 0.021$	$1.4\sigma$
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

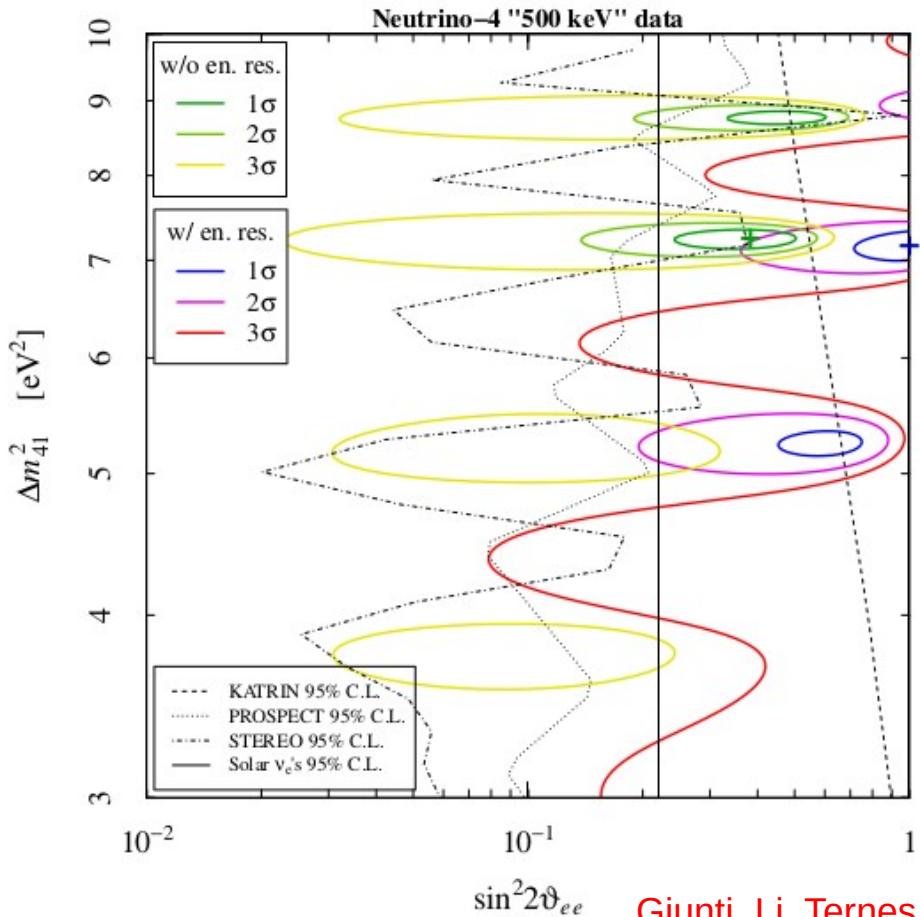
We find that the recent KI model is the best among the conversion models

The EF model is equally good as the KI model

	Rates + Evolution				
$\chi^2$	0.13	0.22	0.08	0.68	0.44
<b>SW</b>	0.32	0.13	0.35	0.59	0.41
<b>sign</b>	0.03	0.38	0.006	0.38	0.11
<b>KS</b>	0.04	0.84	0.02	0.39	0.20
<b>CVM</b>	0.02	0.67	0.006	0.38	0.14
<b>AD</b>	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
<b>weighted average</b>	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

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

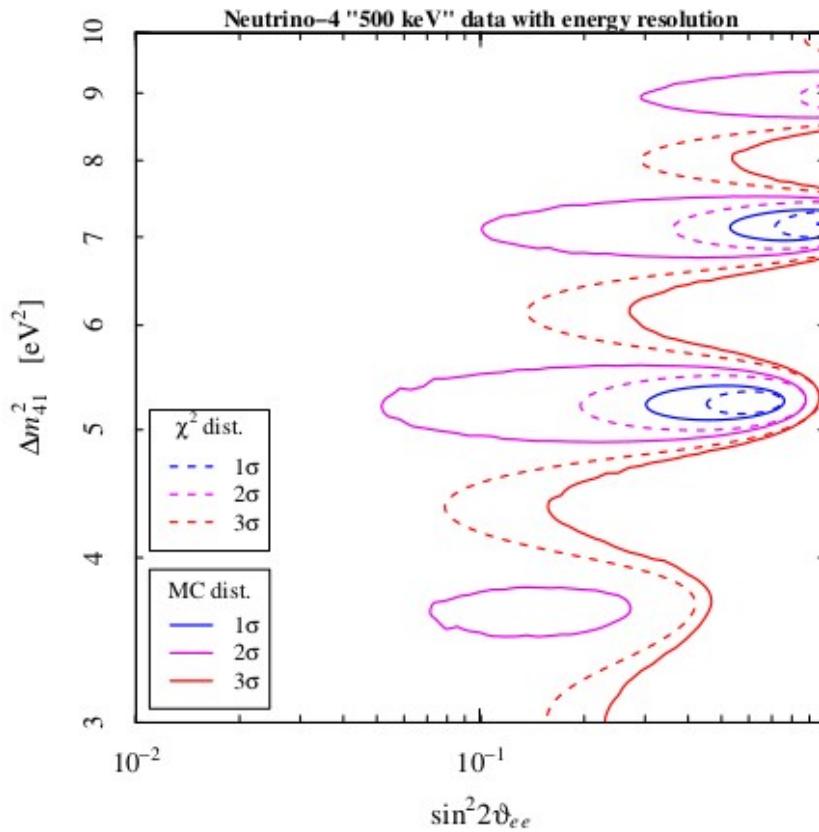
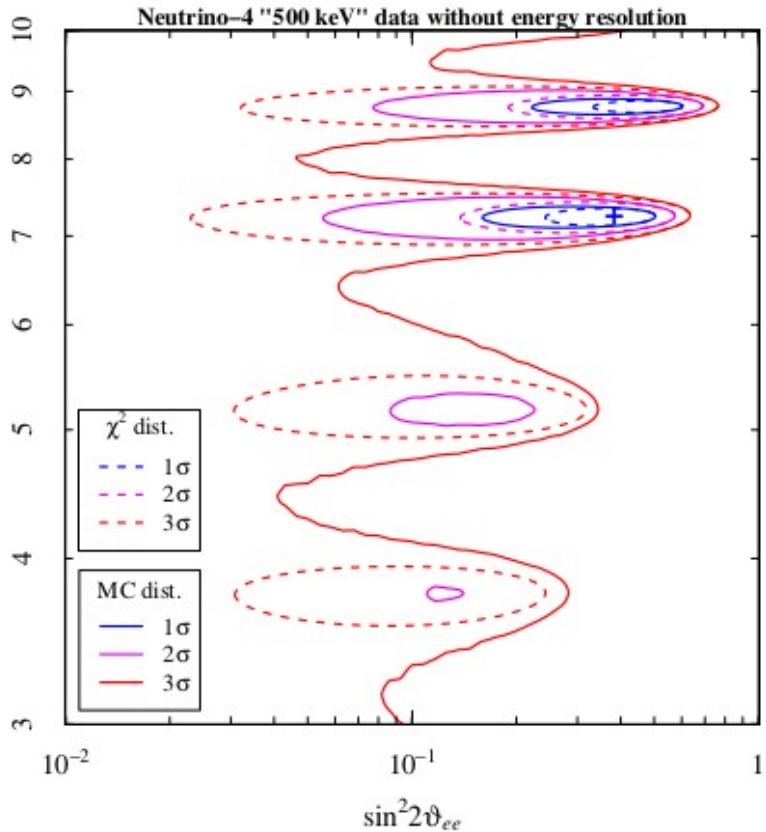
Giunti, Li, Ternes, Zhang, 2101.06785, PLB 2021

# Monte Carlo analysis

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

# Neutrino-4

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



# Neutrino-4

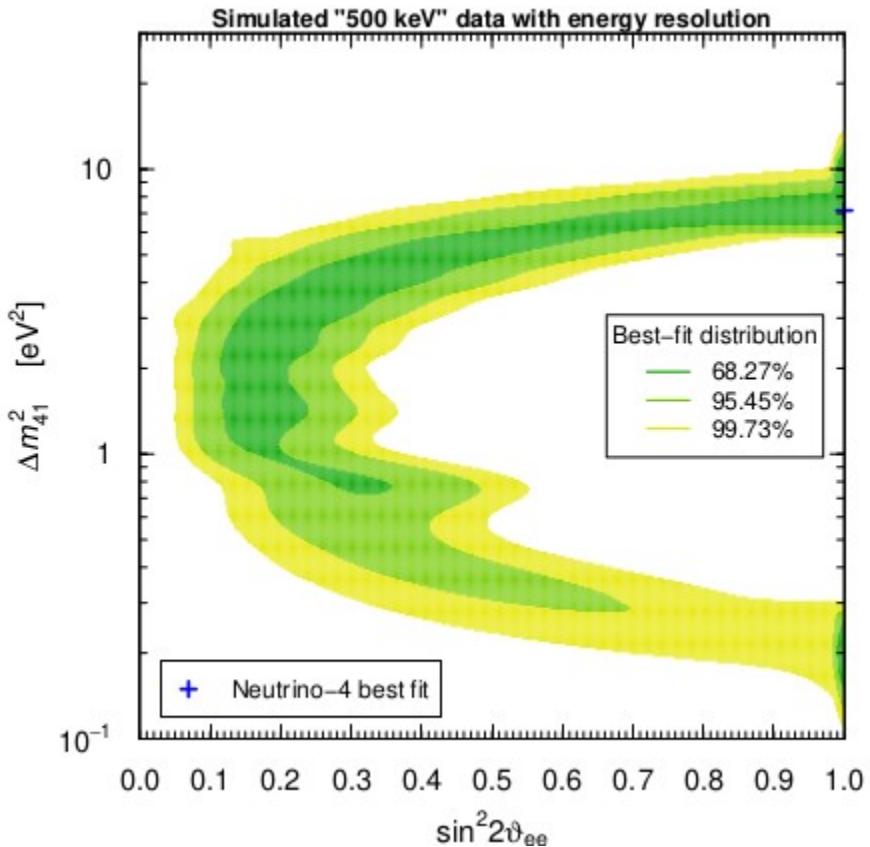
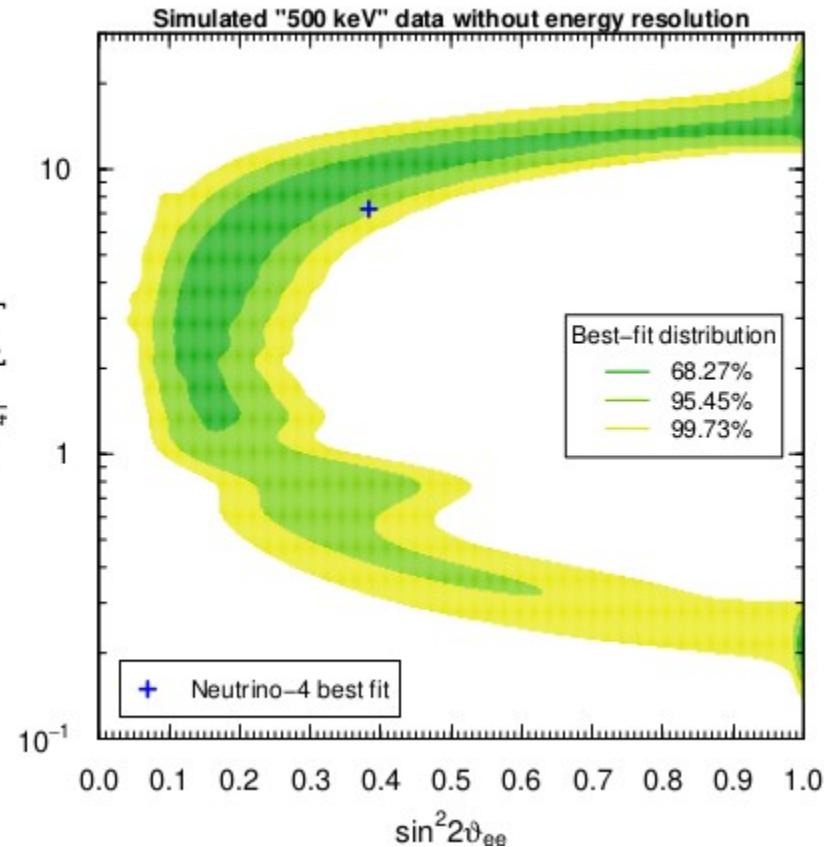
## Summary

Neutrino-4	"500 keV" data		"125-250-500 keV" data	
	without en. res.	with en. res.	without en. res.	with en. res.
$\chi^2_{\text{min}}$	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
$\chi^2$ distribution				
$p$ -value	0.0014	0.0075	0.0072	0.0048
$\sigma$ -value	3.2	2.7	2.7	2.8
Monte Carlo distribution				
$p$ -value	0.011	0.028	0.087	0.026
$\sigma$ -value	2.5	2.2	1.7	2.2

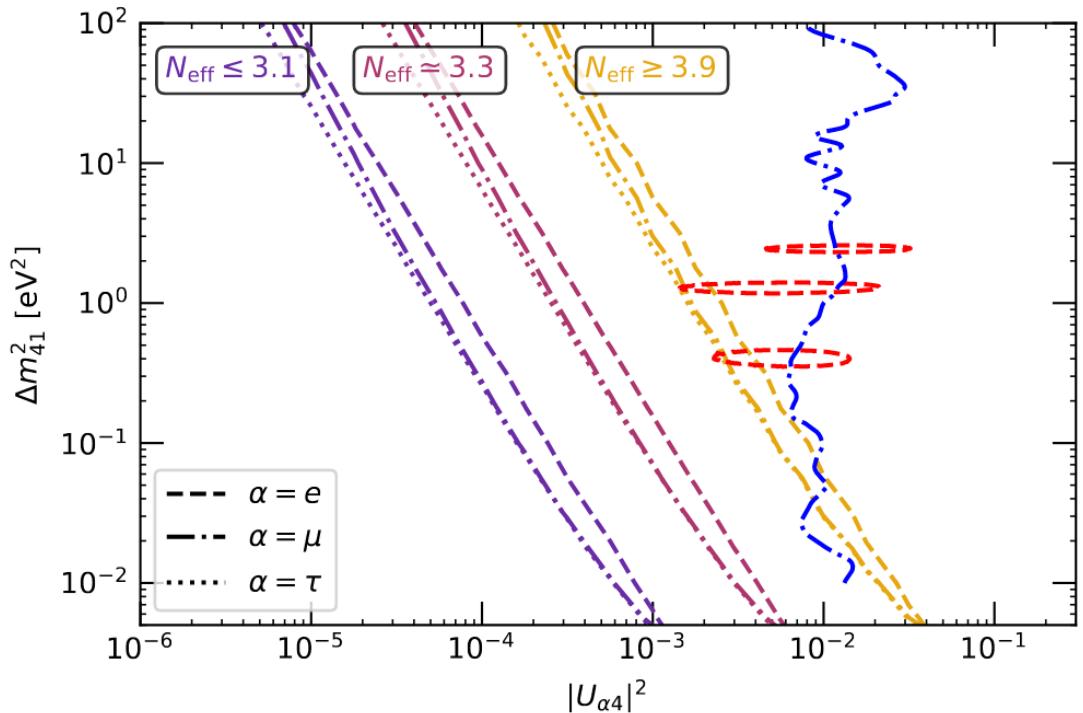
# Neutrino-4

## Distribution of best fit points without oscillations

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



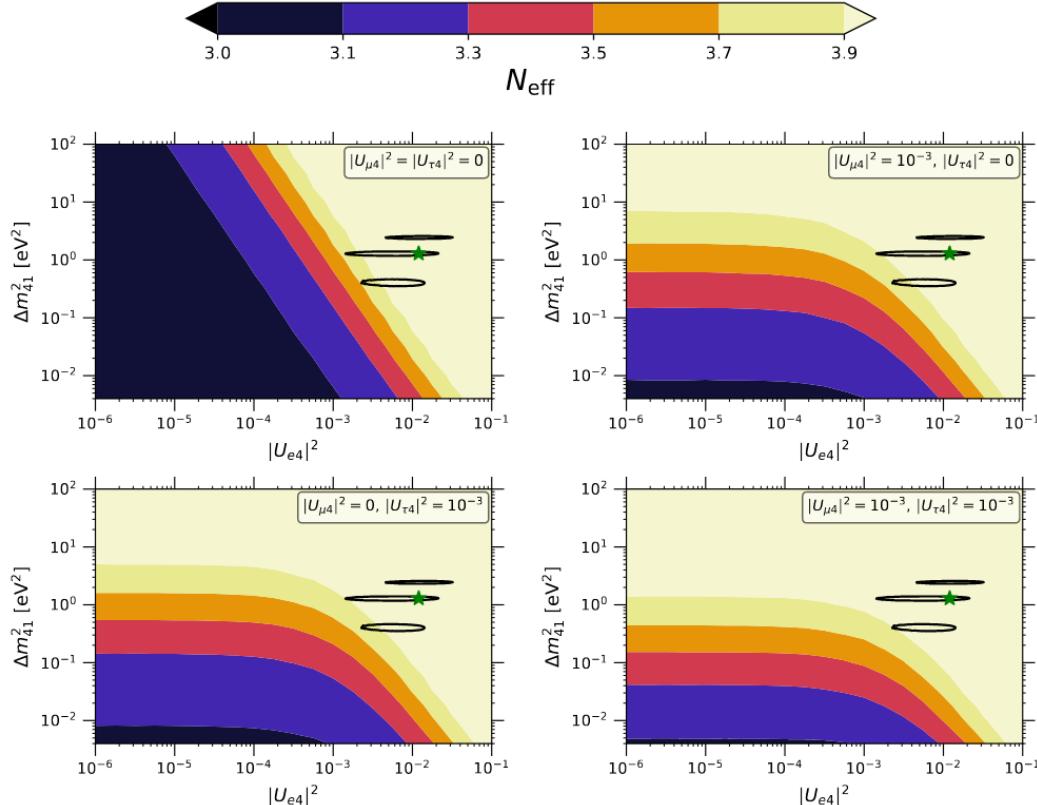
# Cosmology



Cosmology can set strong bounds on sterile parameter space

Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

# Cosmology

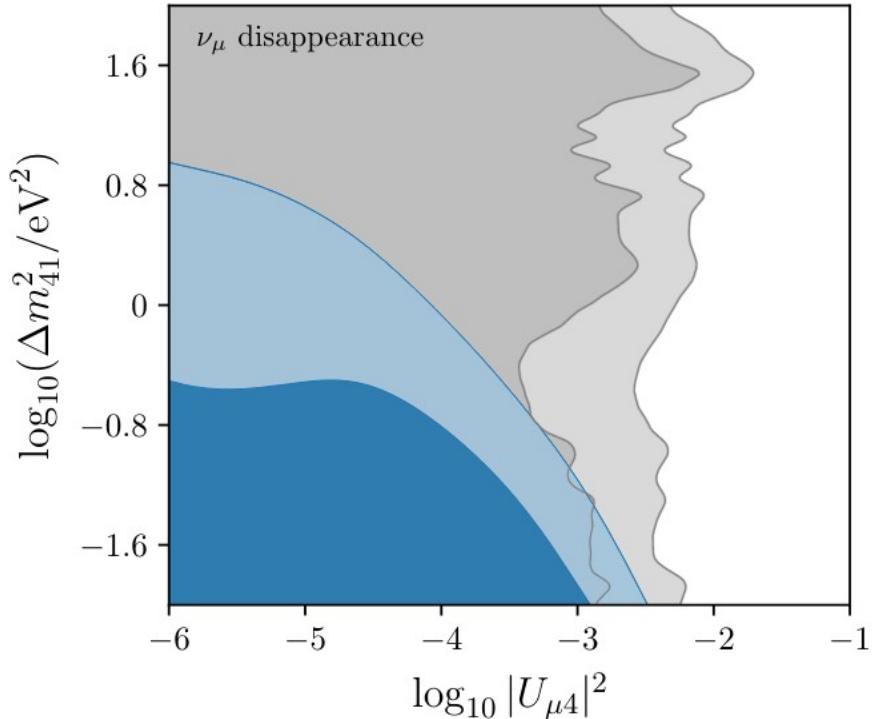
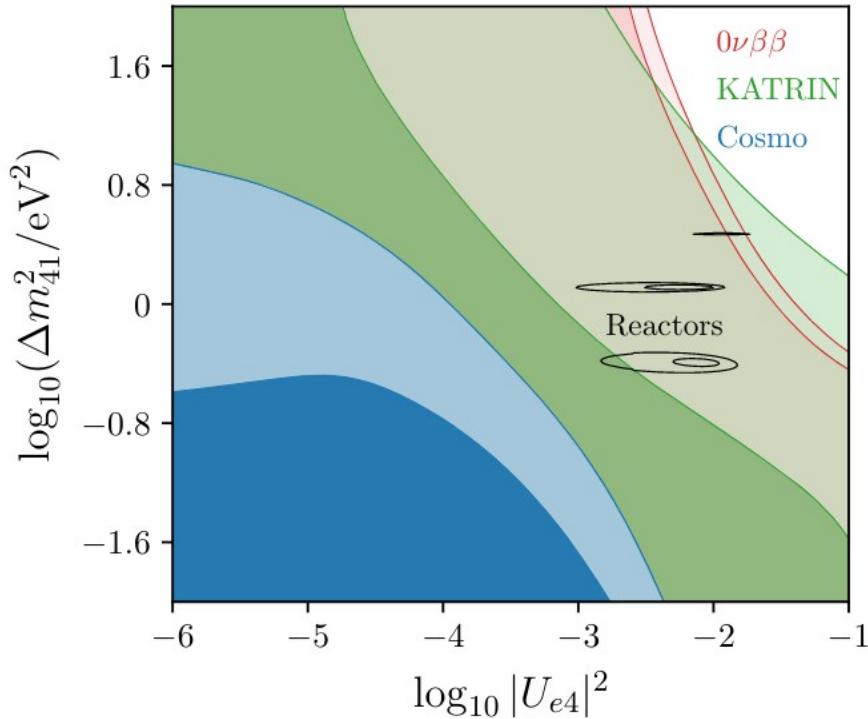


Cosmology can set strong bounds on sterile parameter space

Which become even stronger when considering more than one angle

Gariazzo, de Salas, Pastor, 1905.11290, JCAP 2019

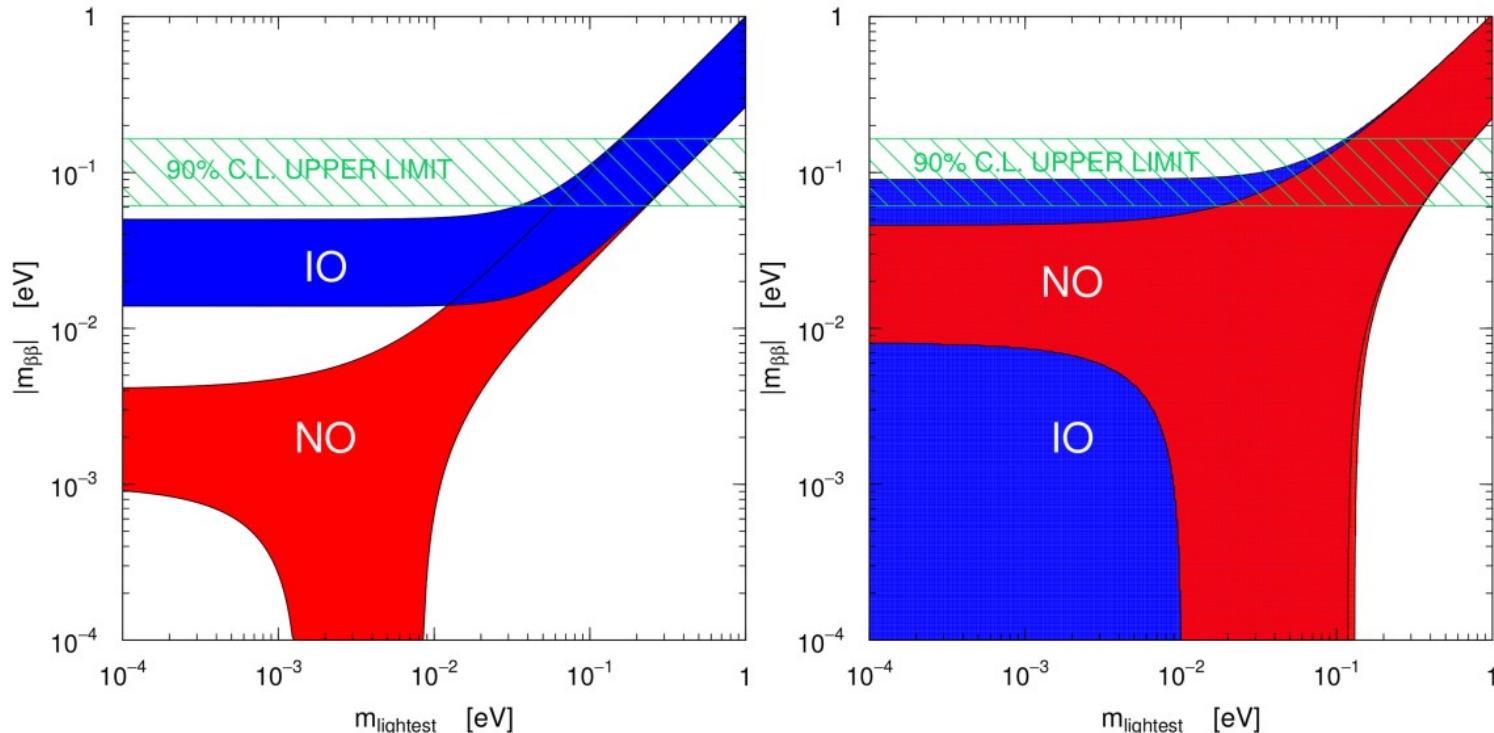
# Cosmology



Complementary between Cosmology and terrestrial experiments

Hagstotz, et al, 2003.02289, PRD 2021

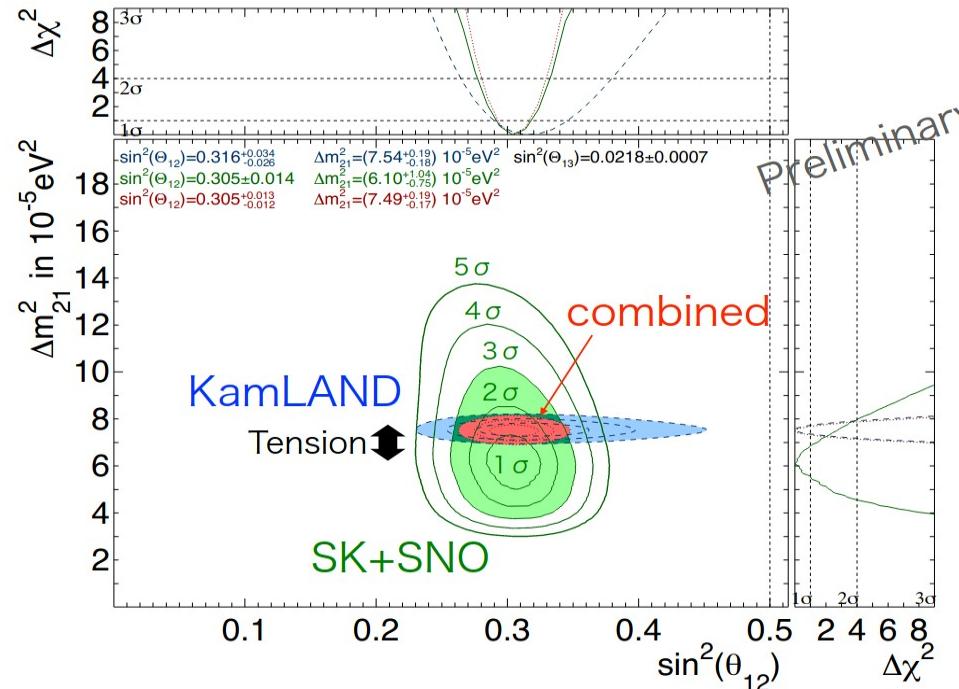
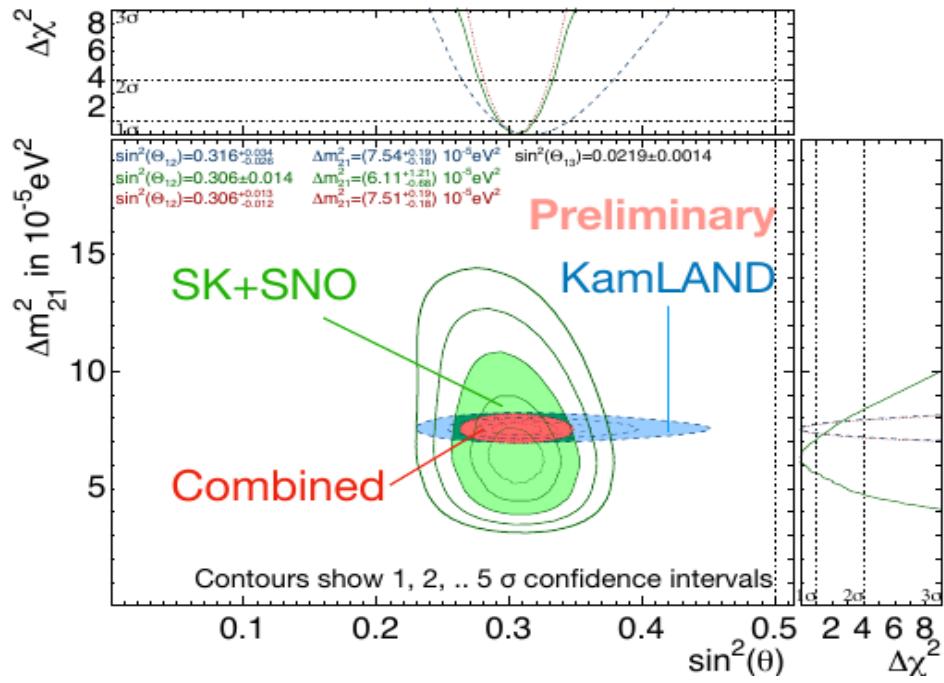
# Neutrinoless $\beta\beta$ decay



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

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

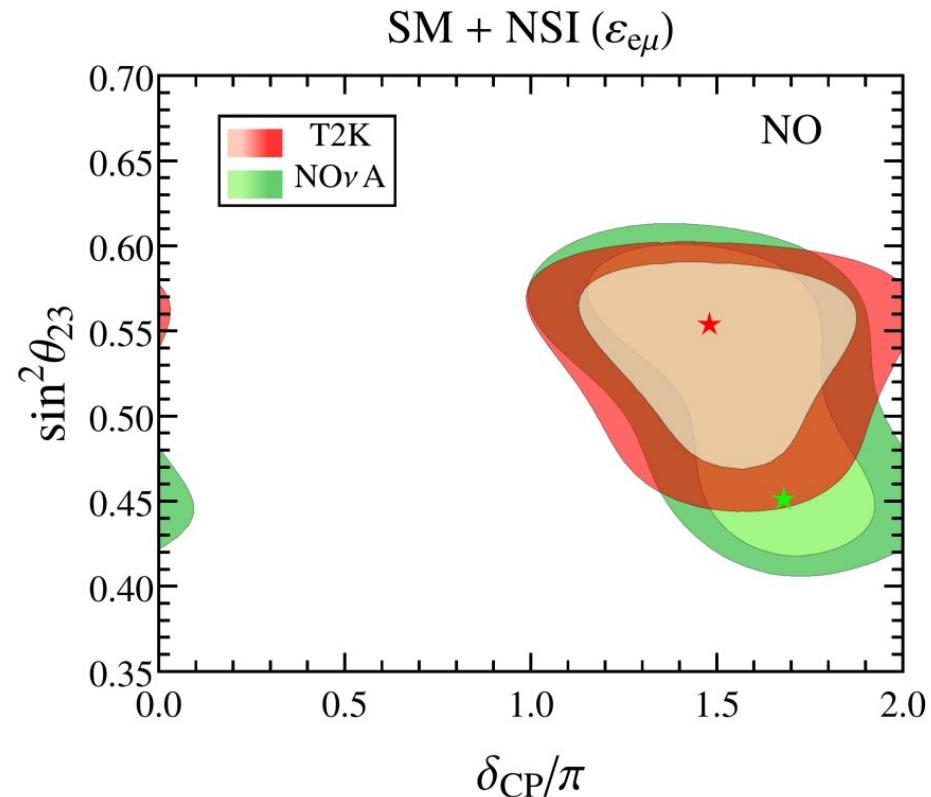
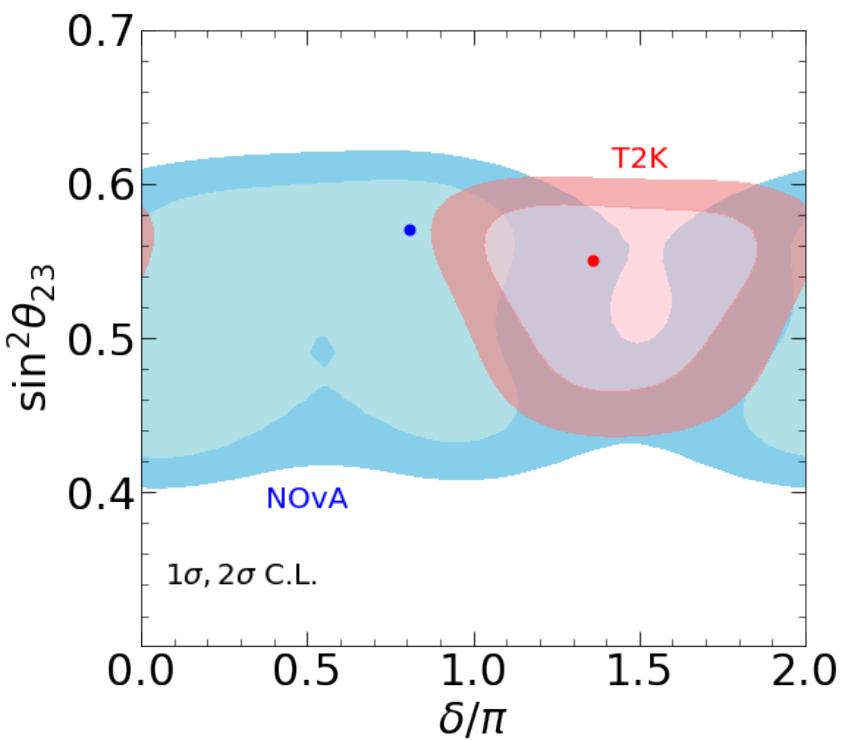
# Solar sector



Discrepancy at  $1.5\sigma$  in 2022

Takeuchi @ NOW 2022

# CP violation



Discrepancy in T2K and NOvA measurements; Hint of NSI?

Valencia - Global Fit, 2006.11237, JHEP 2021

Chatterjee, Palazzo, 2008.04161, PRL 2021  
See also: Denton, Gehrlein, Pestes, 2008.01110, PRL 2021