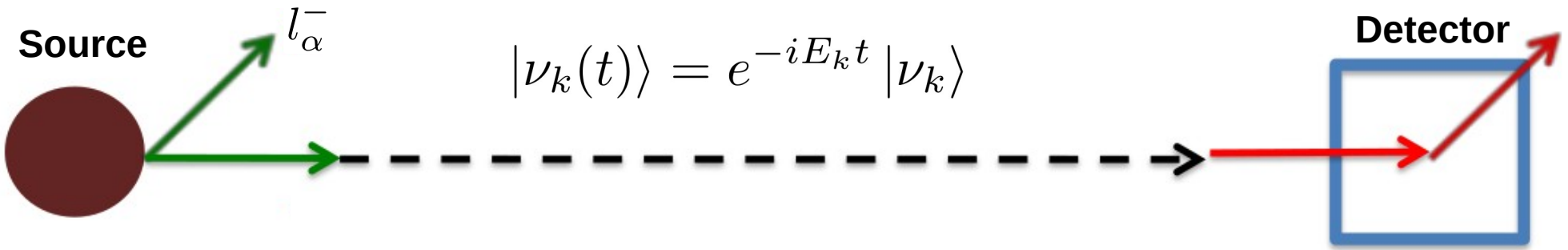
Light sterile neutrinos and reactor experiments

Christoph Andreas Ternes

NuCo 2021: Neutrinos en Colombia, July 28th 2021

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Neutrino oscillations



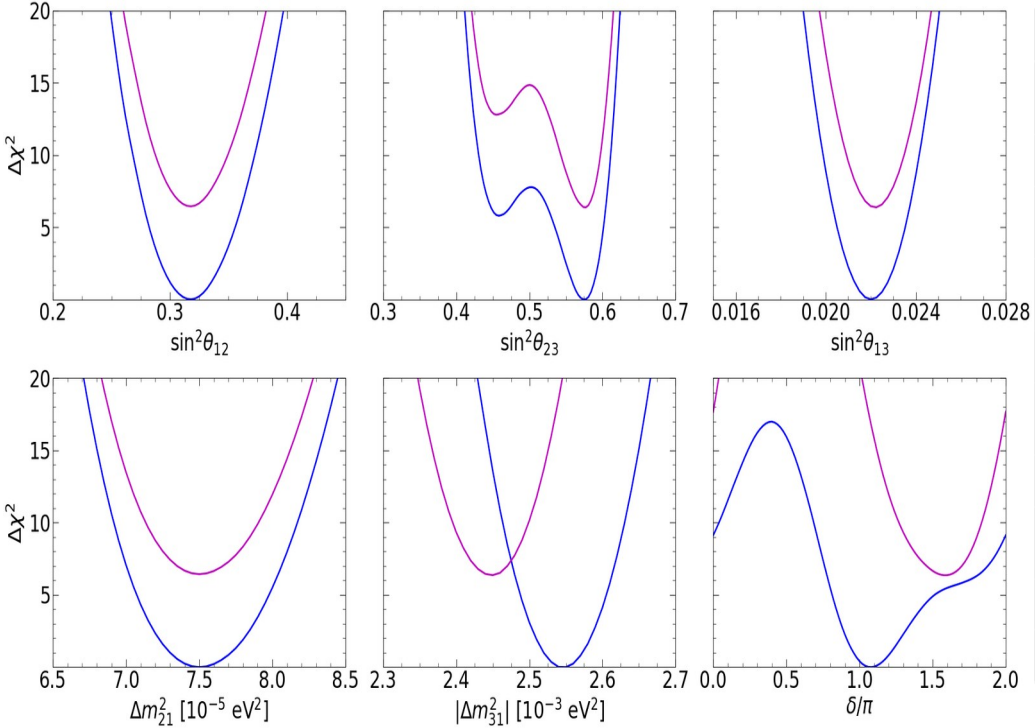
$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle$$

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

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

Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



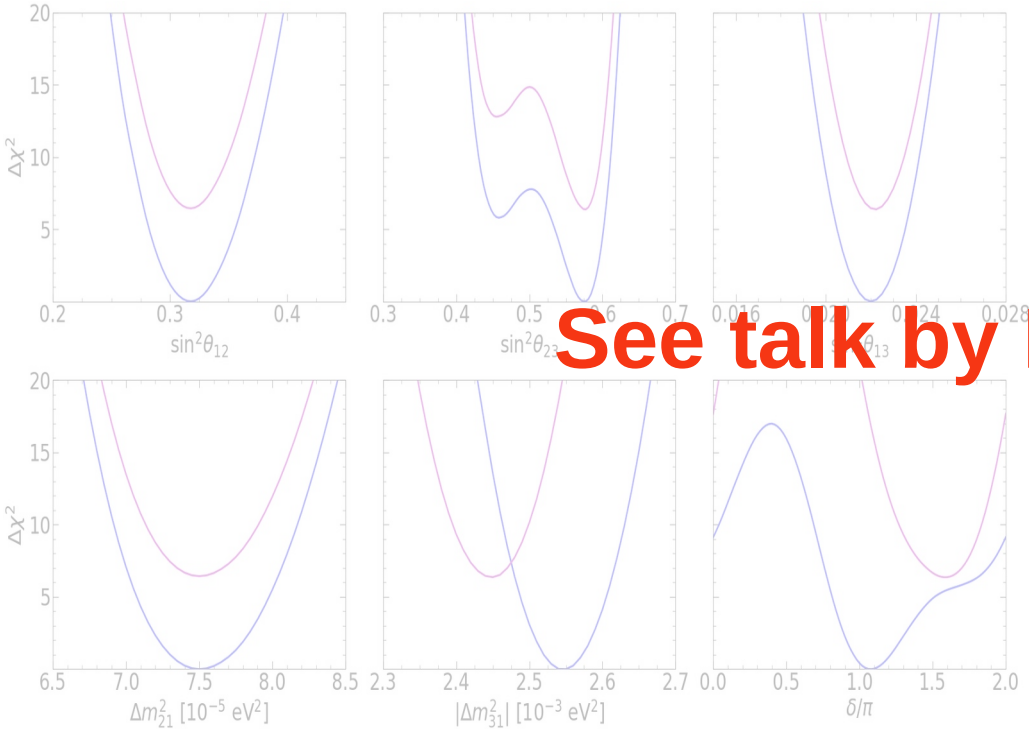
parameter	best fit ± 1σ	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$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

See also:
NuFit - 2007.14792, JHEP 2020

Three-neutrino oscillations

Valencia - Global Fit, 2006.11237, JHEP 2021



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
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.74^{+0.14}_{-0.26}$	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

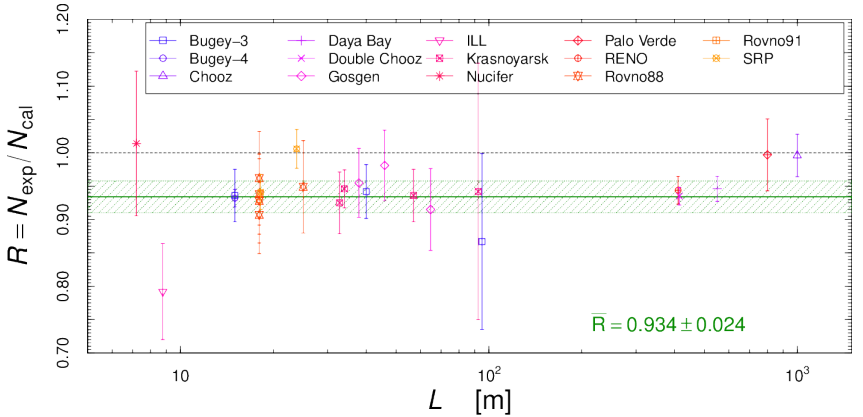
See talk by Mariam Tórtola

See also:
Bari – 2107.00532

See also:
NuFit - 2007.14792, JHEP 2020

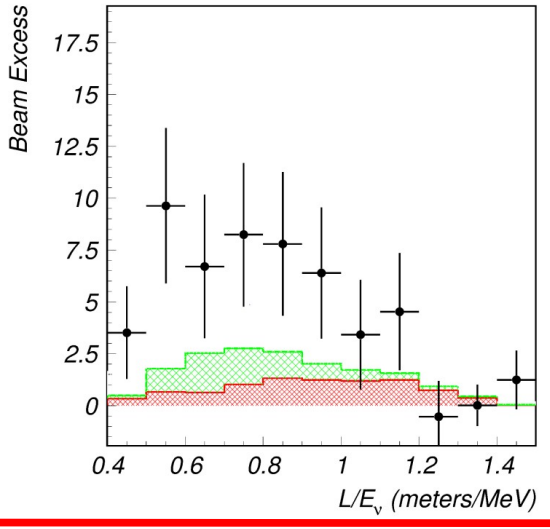
Anomalies

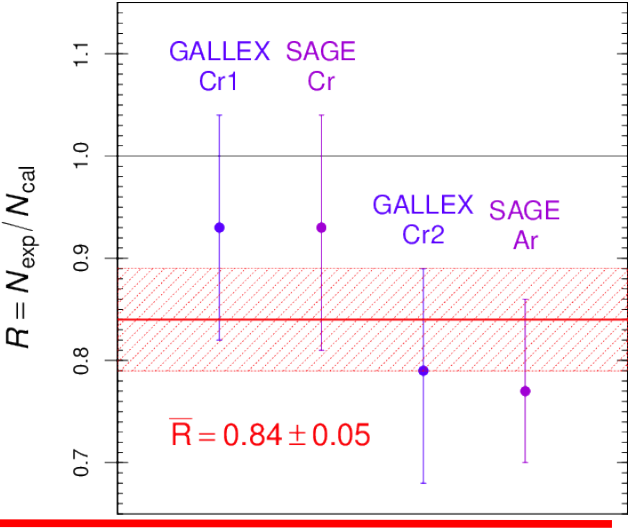
Deficit of events in reactor rates -> ~3σ



Excess of events in LSND -> ~4σ

Deficit of events in Gallium -> ~3σ





Anomalies

Three neutrino oscillations can not account for short baseline anomalies

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

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

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

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

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

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

@LSND, Karmen, MiniBooNE, Opera

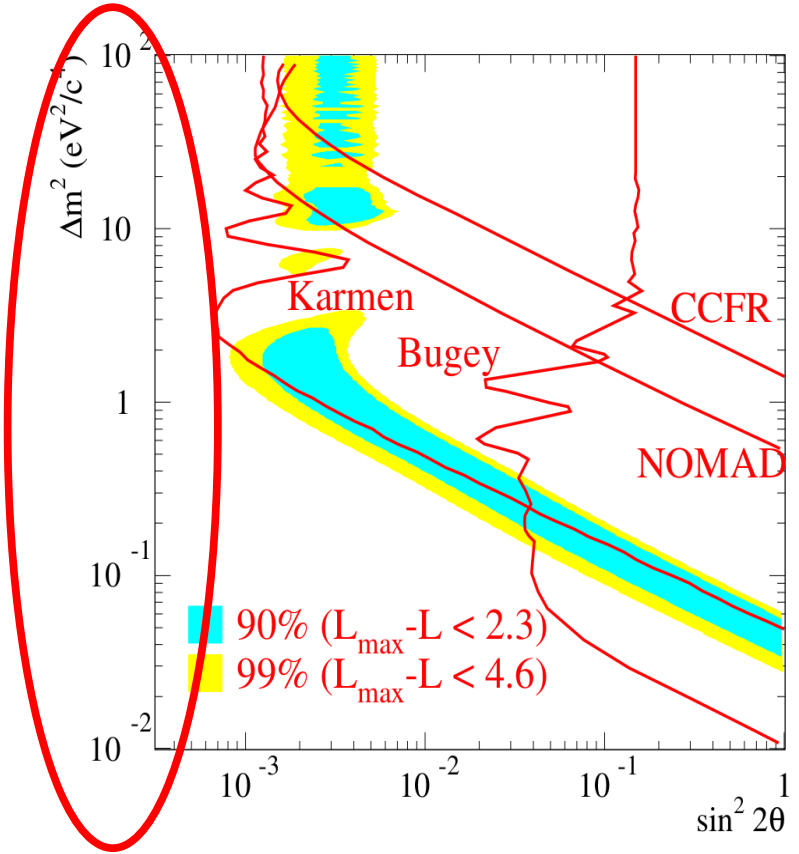
Disappearance

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

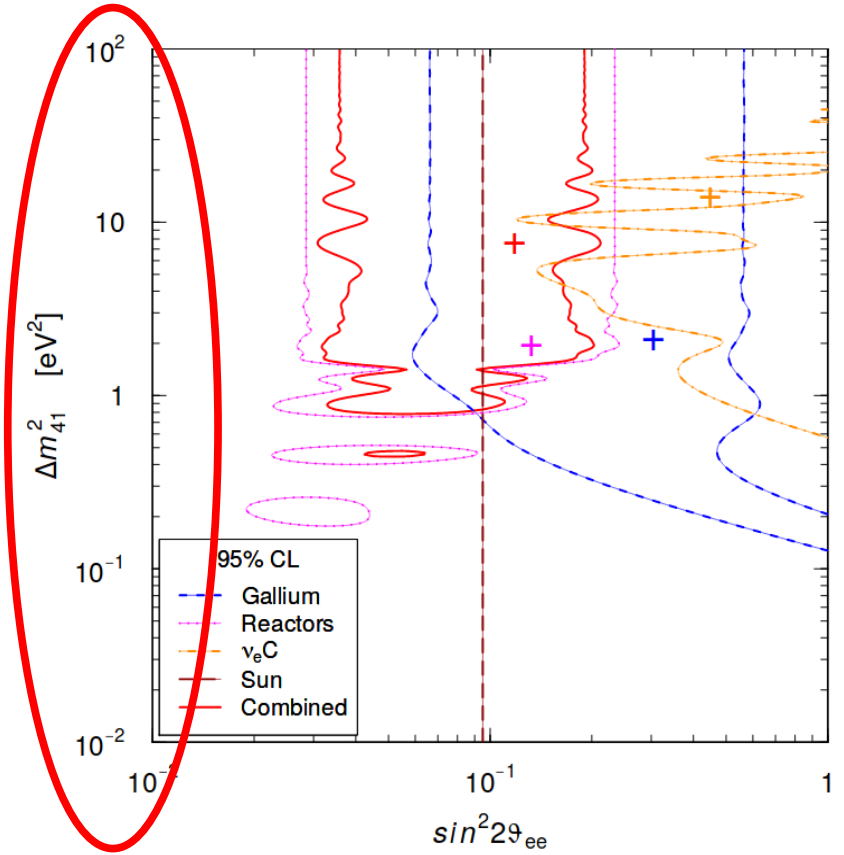
$$\sin^2(2\theta_{\alpha\alpha}) = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

@Reactors and Gallium
@atmospherics and accelerators

3+1 neutrino oscillations

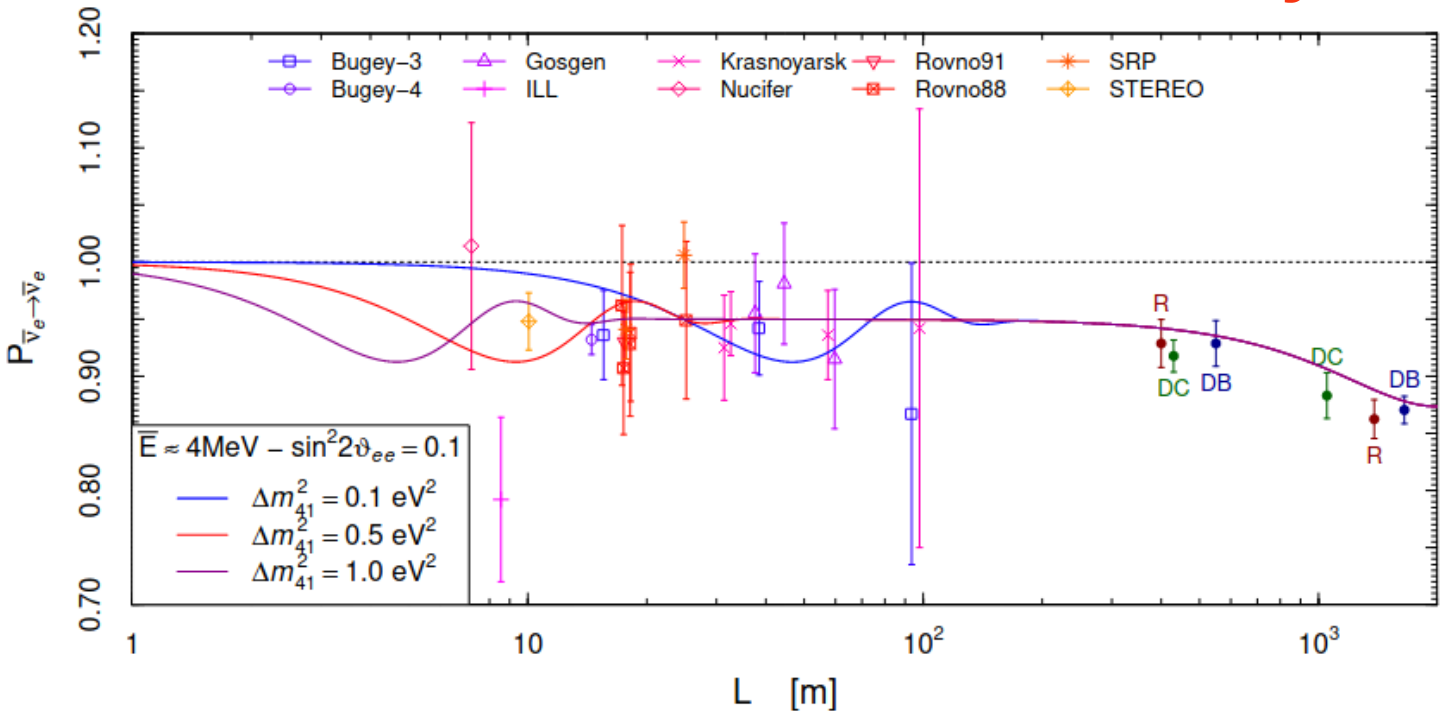


LSND collaboration
hep-ex/0104049, PRD 2001



Giunti, Laveder, Li, Liu, Long
1210.5715, PRD 2012

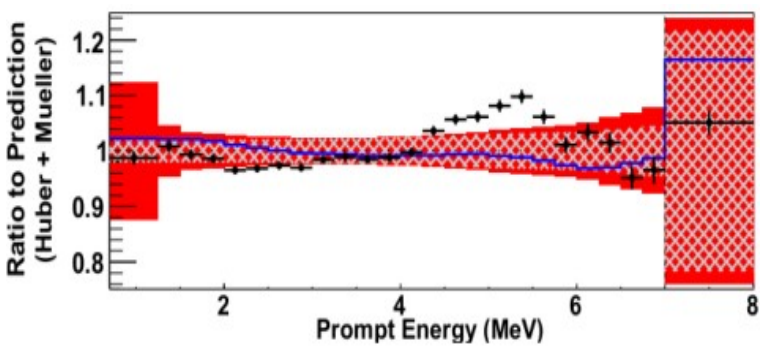
The reactor antineutrino anomaly

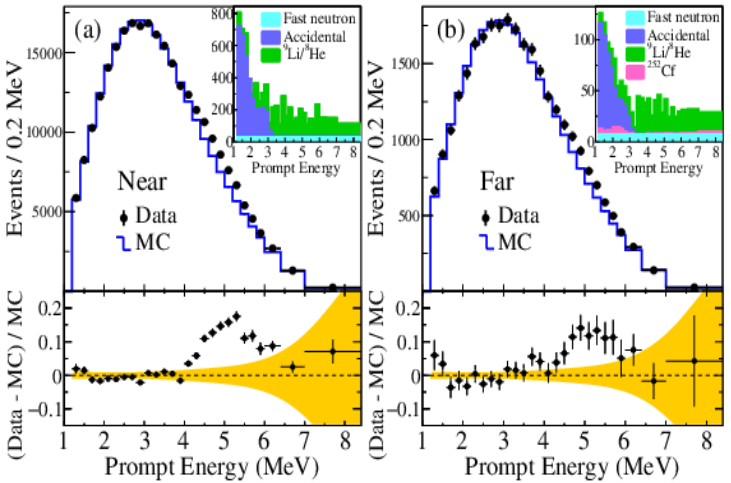


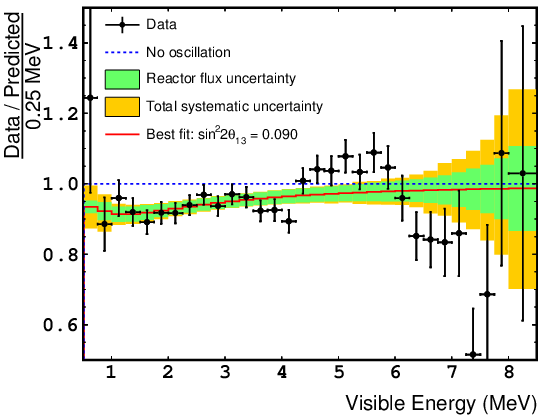
Sterile oscillations are averaged out at larger distances

The reactor anomaly is model dependent

The reactor antineutrino anomaly



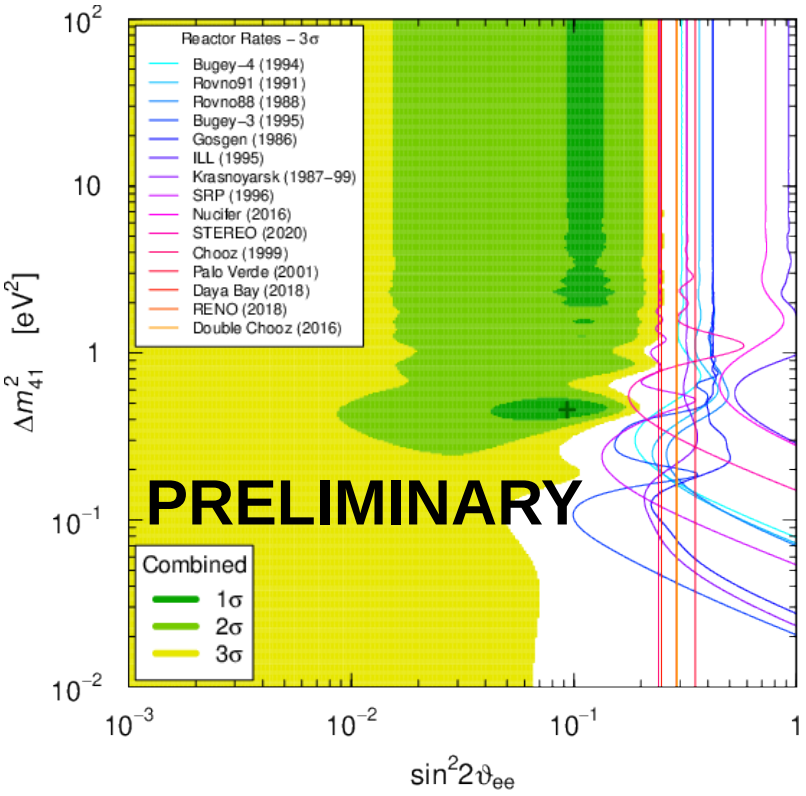


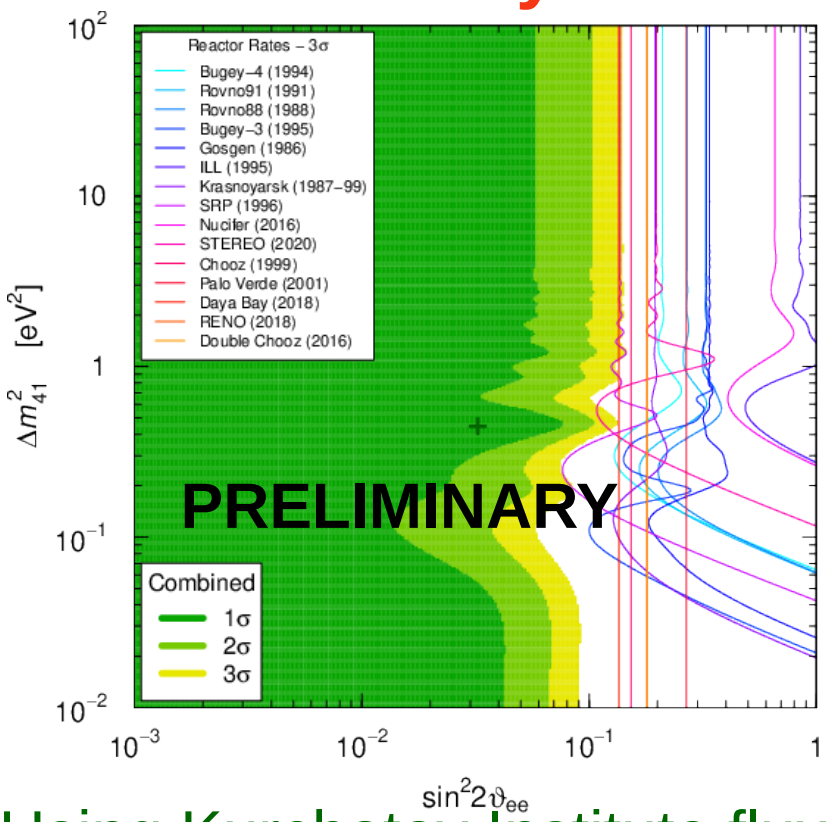


Double Chooz, 1406.7763 JHEP 2014
Daya Bay, 1511.05849, PRL 2016
RENO, 1505.03456 , PRL 2015

The “bump” cannot be explained with sterile neutrino oscillations, because there are no spectral distortions at large distances

The reactor antineutrino anomaly





Using Huber Mueller flux model

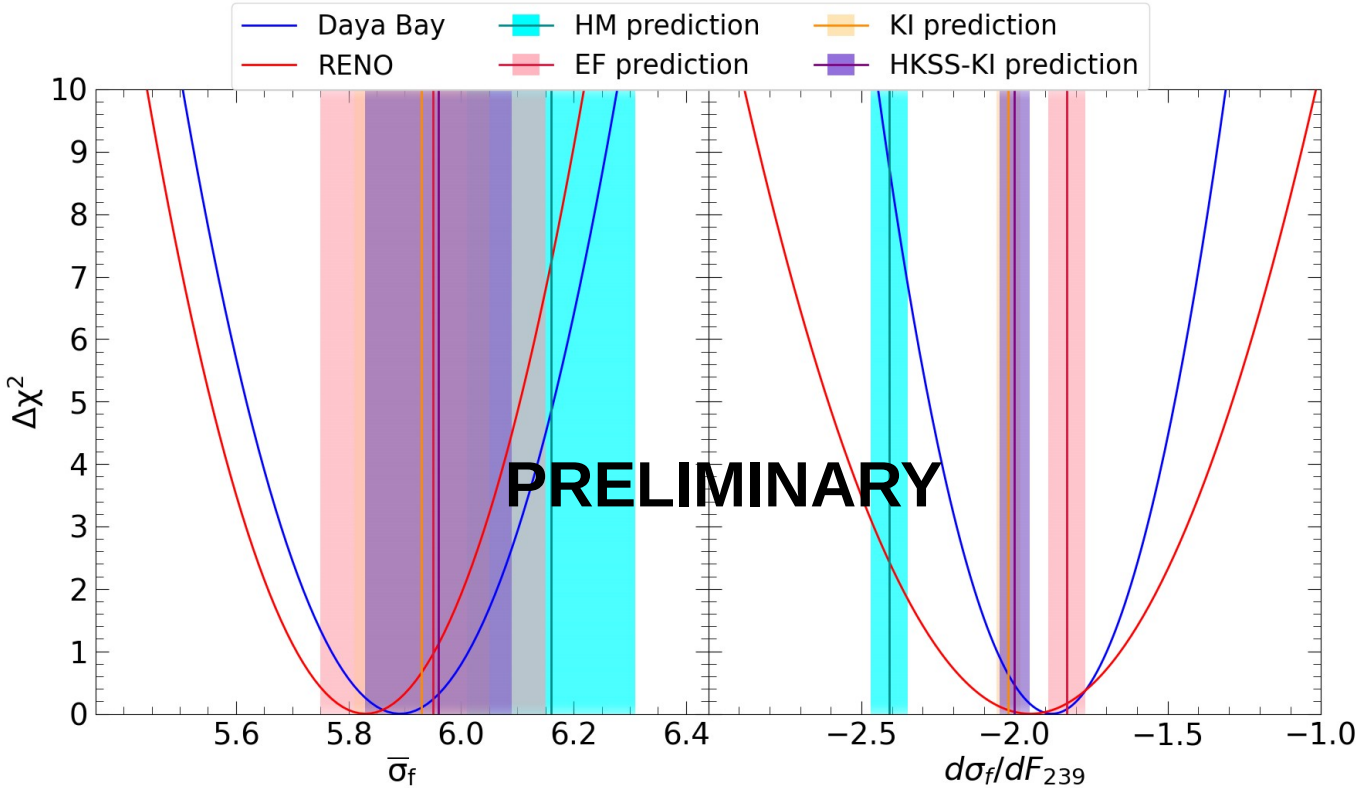
P. Huber, 1106.0687, PRC 2012

Th. Mueller, et al 1101.2663, PRC 2012

Using Kurchatov Institute flux model

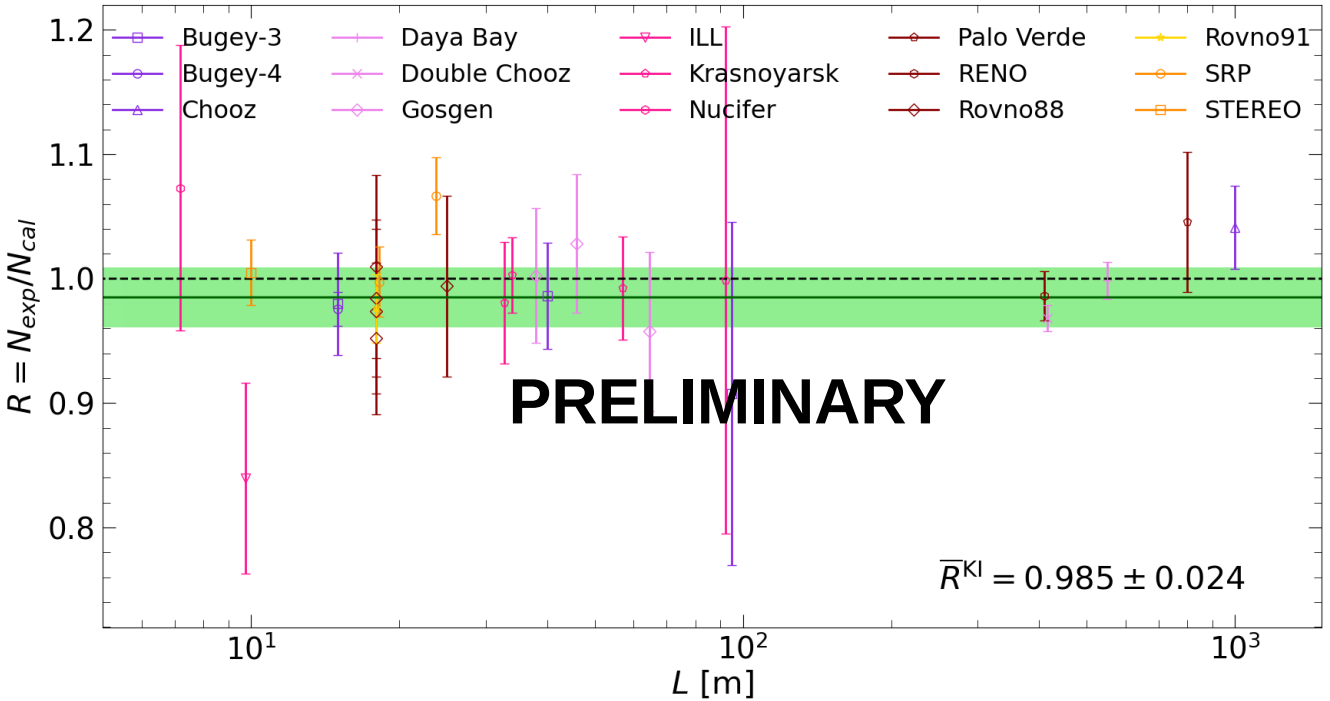
V. Kopeikin, et al, 2103.01684

The reactor antineutrino anomaly



Good agreement between measured and predicted IBD yields!

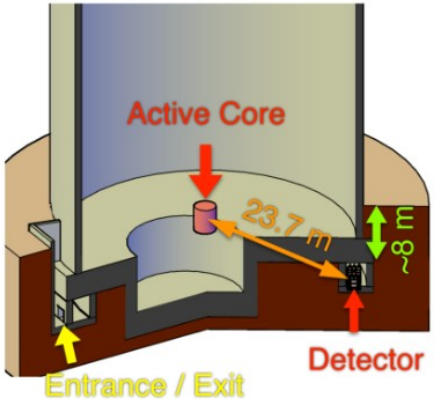
The reactor antineutrino anomaly



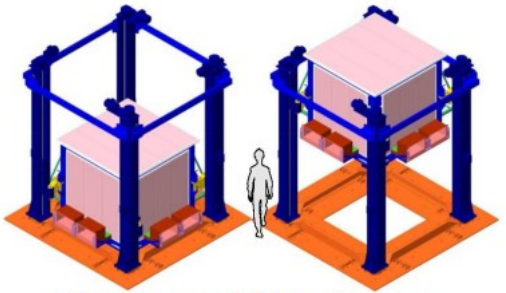
There is NO reactor antineutrino anomaly using the latest flux calculations!

Ratio analysis

NEOS

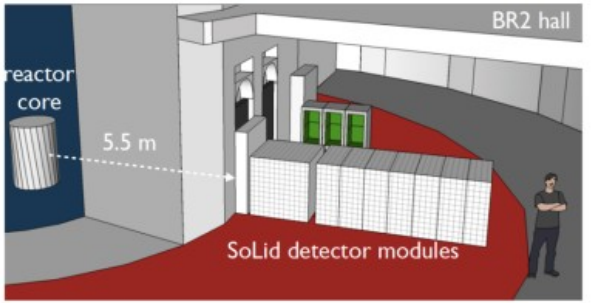


DANSS

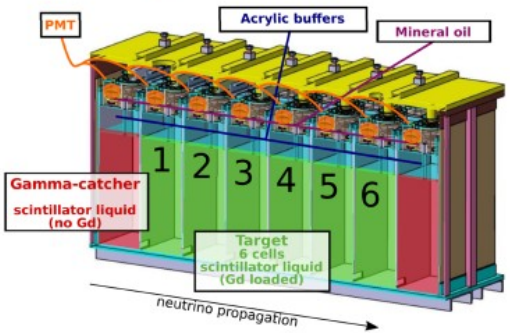


DANSS on a lifting platform

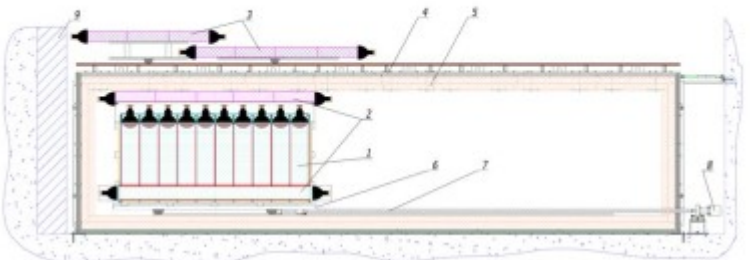
SoLid



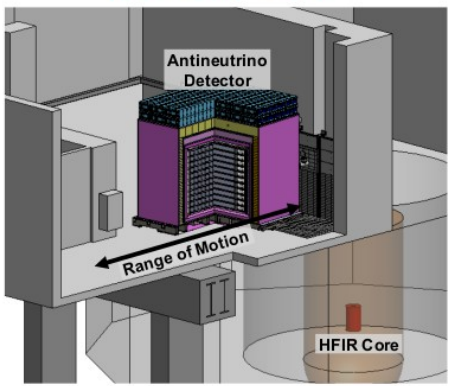
STEREO



Neutrino-4

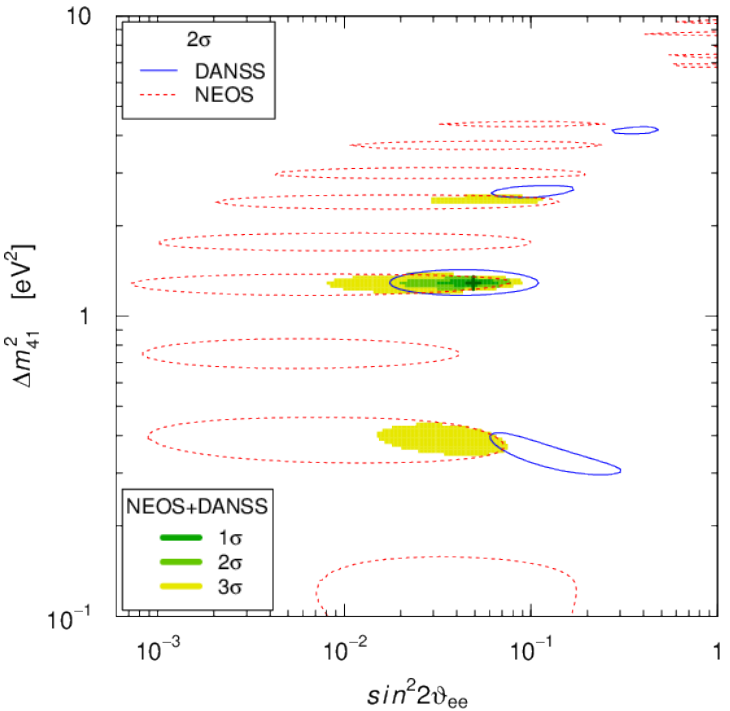


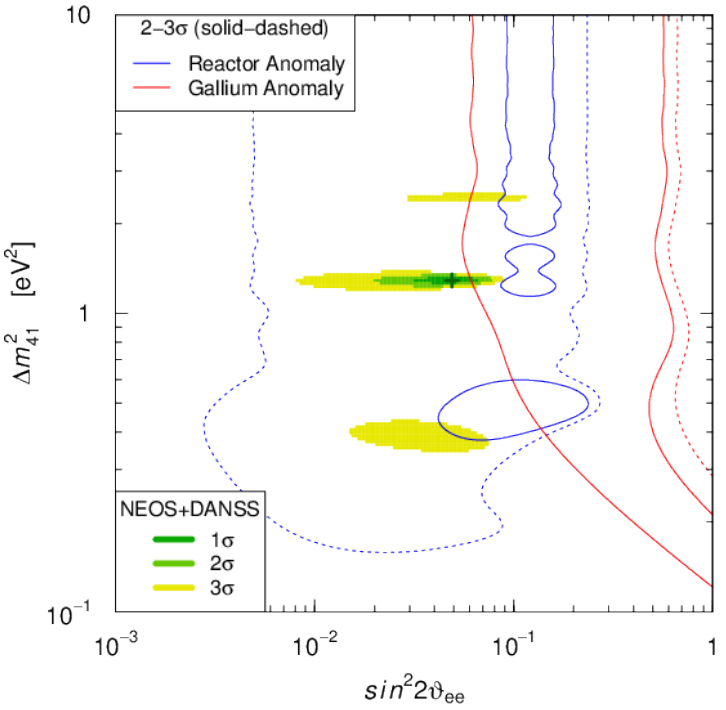
PROSPECT



Ratio analysis 2018

Gariazzo, Giunti, Laveder, Li, 1801.06467, PLB 2018



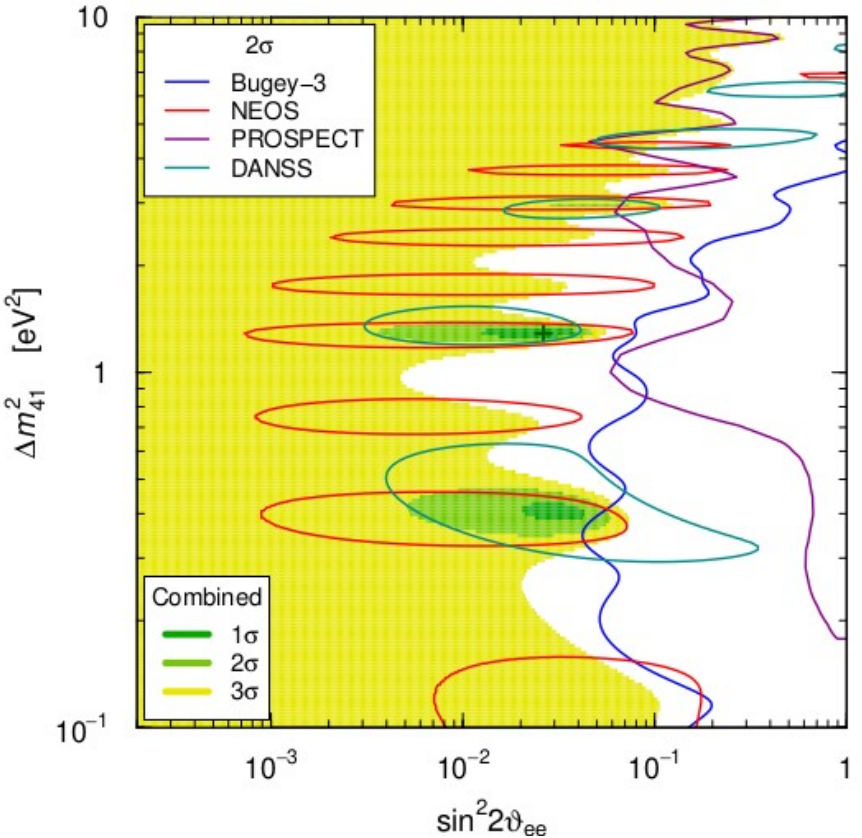


~2σ individual preference from DANSS and NEOS

>3σ combined preference

Ratio analysis 2019/2020

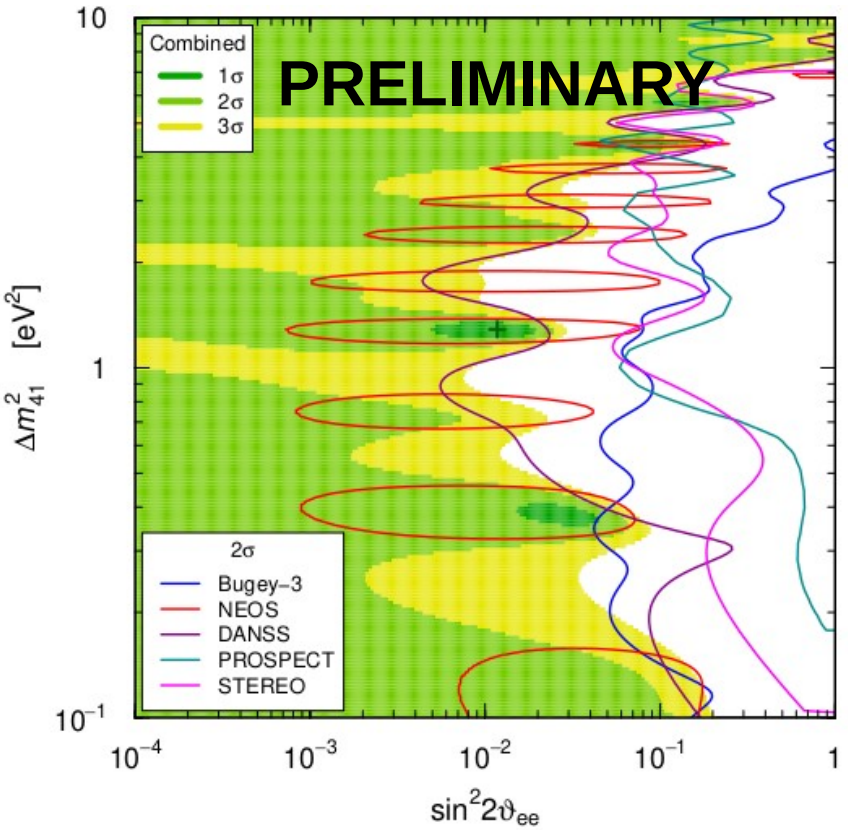
Giunti, Li, Zhang, 1912.12956, JHEP 2020



Less agreement between DANSS and NEOS

still >2σ combined preference

Ratio analysis 2021

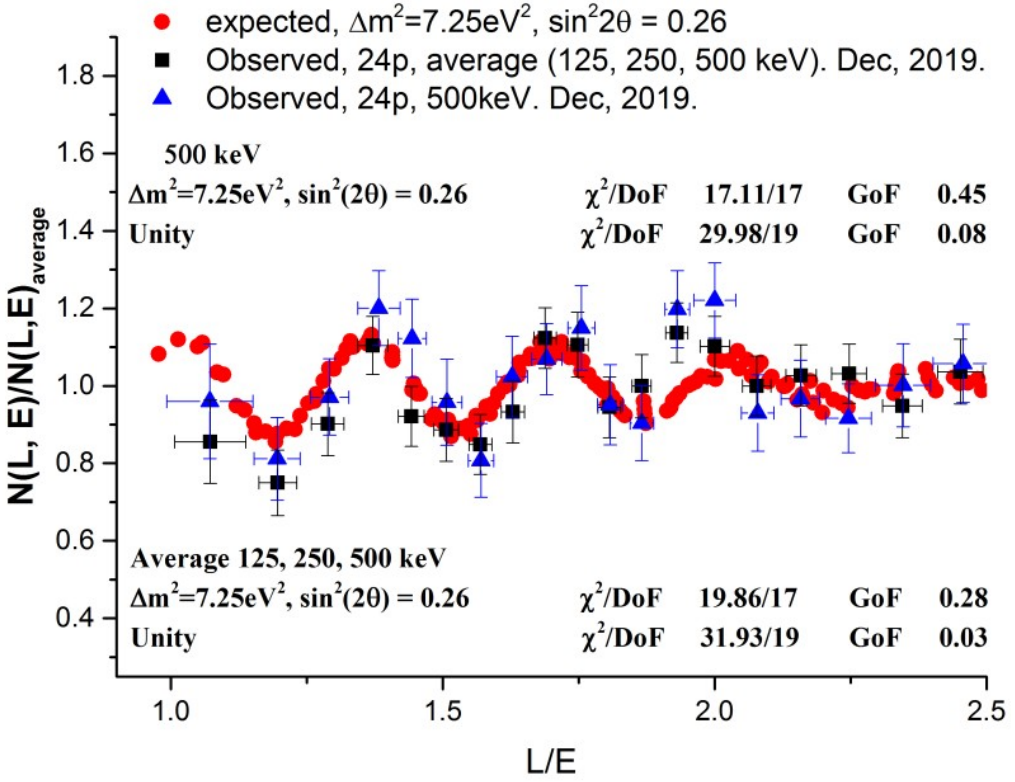


No preference at all for oscillations in DANSS data

no closed contours at 2σ

we can only set upper limits on $|U_{e4}|^2 = \sin^2\theta_{14}$

Neutrino-4

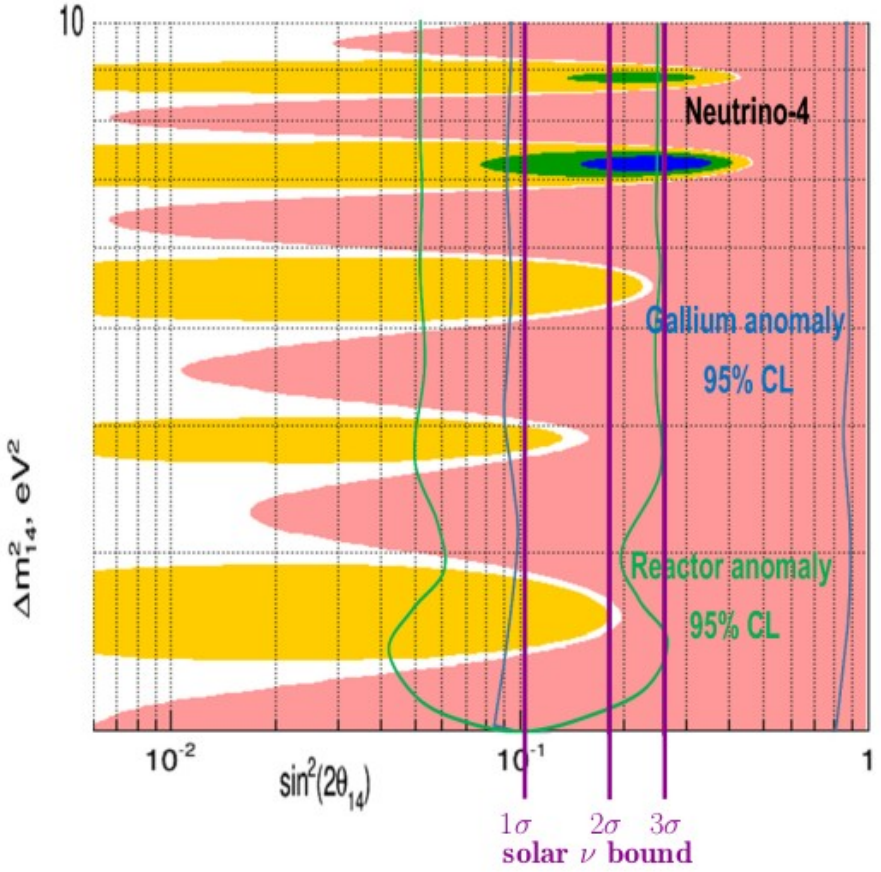


Neutrino-4 observes sterile oscillations at > 3σ

Very large mixing

In tension with solar data

Neutrino-4



Neutrino-4 observes sterile oscillations at > 3σ

Very large mixing

In tension with solar data

Neutrino-4

$$R_{ik}^{\rm the} = \frac{1 - \sin^2 2\vartheta_{ee} \left\langle \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\right\rangle_{ik}}{1 - \sin^2 2\vartheta_{ee}\, n_L^{-1} \sum_{k'=1}^{n_L} \left\langle \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\right\rangle_{ik'}}$$

For the predicted number of events one needs to average over the oscillation term

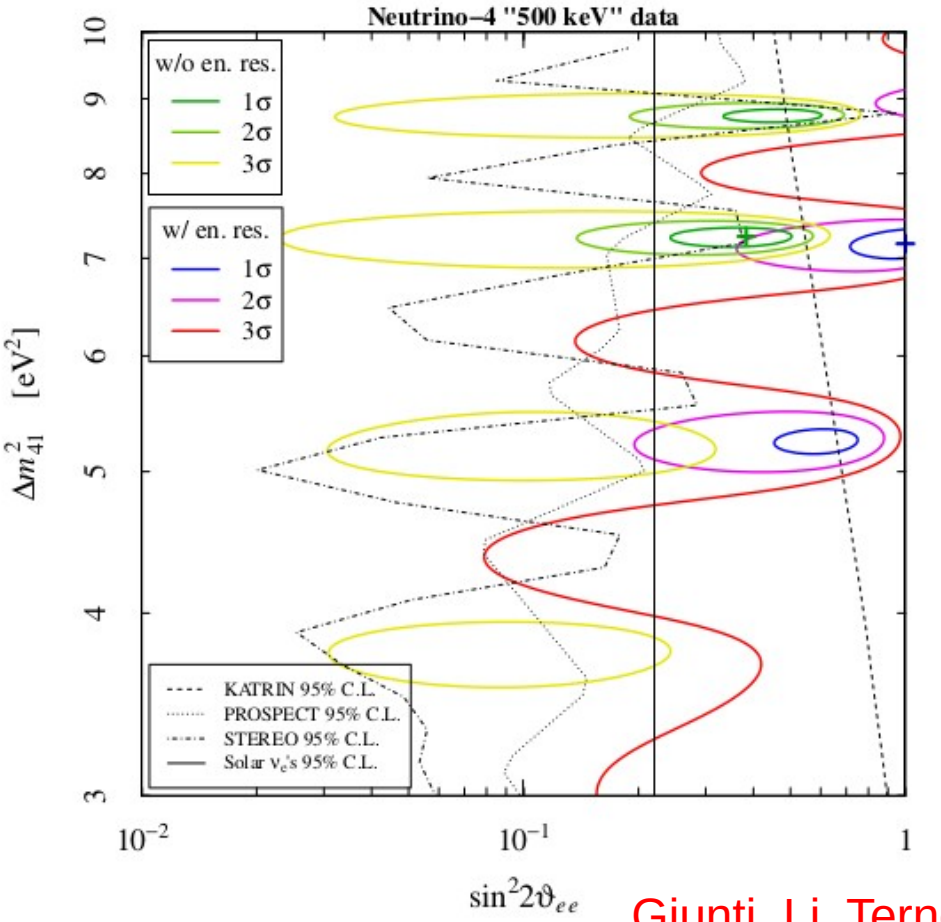
Averaging contains integration over flux, distance, detector resolution

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

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

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

Neutrino-4



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

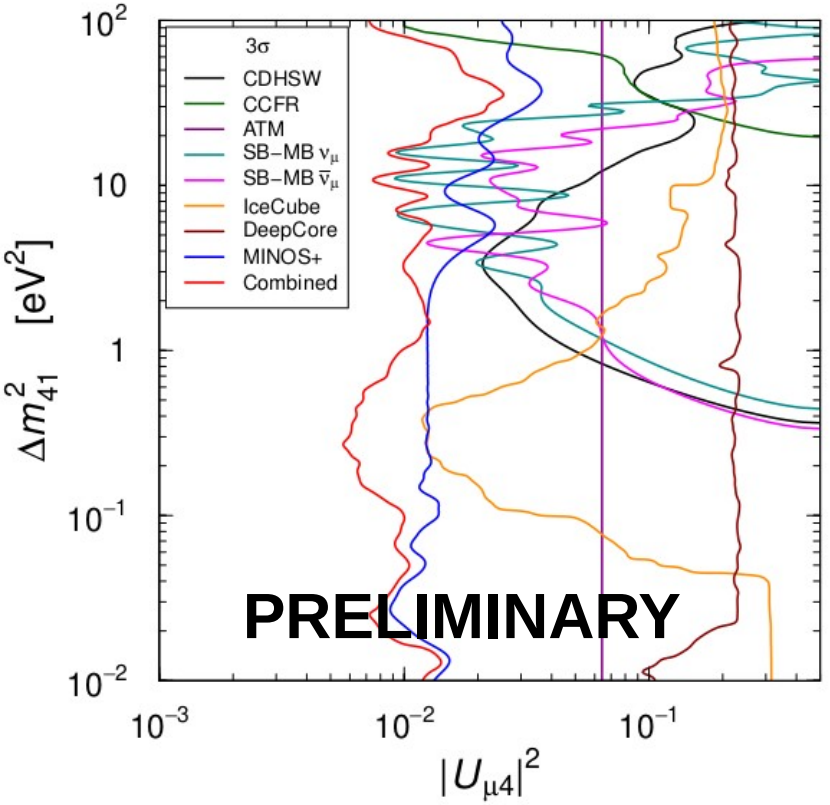
Inclusion shifts the best fit to even larger values, but reduces the preference for sterile oscillations

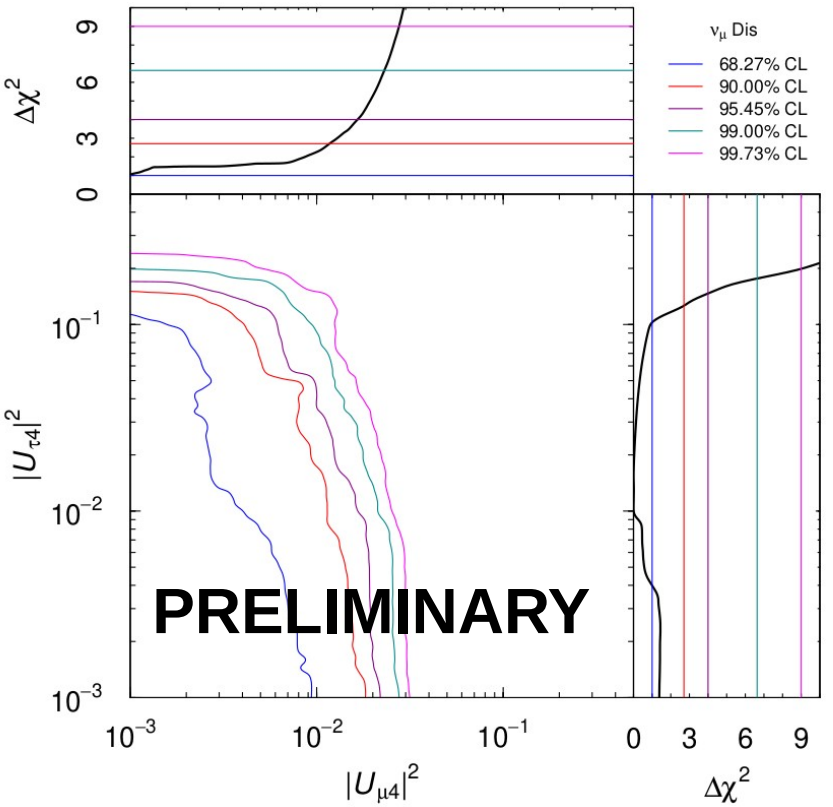
$$\chi^2 = \sum_{j=1}^{19} \left(\frac{R_j^{\rm the} - R_j^{\rm exp}}{\Delta R_j^{\rm exp}} \right)^2$$

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

Other channels

No evidence in muon disappearance

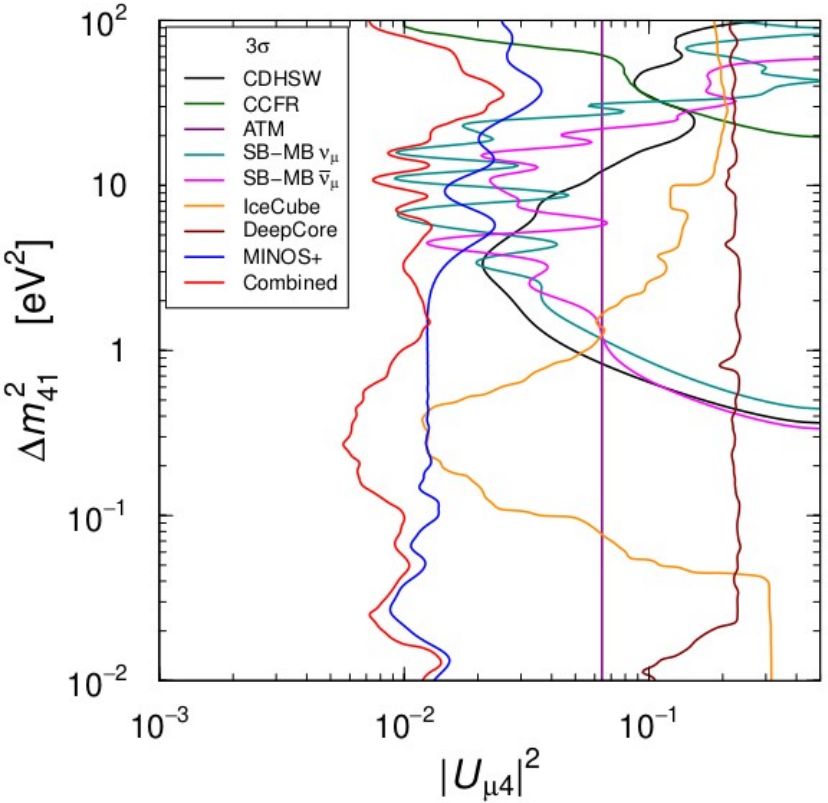


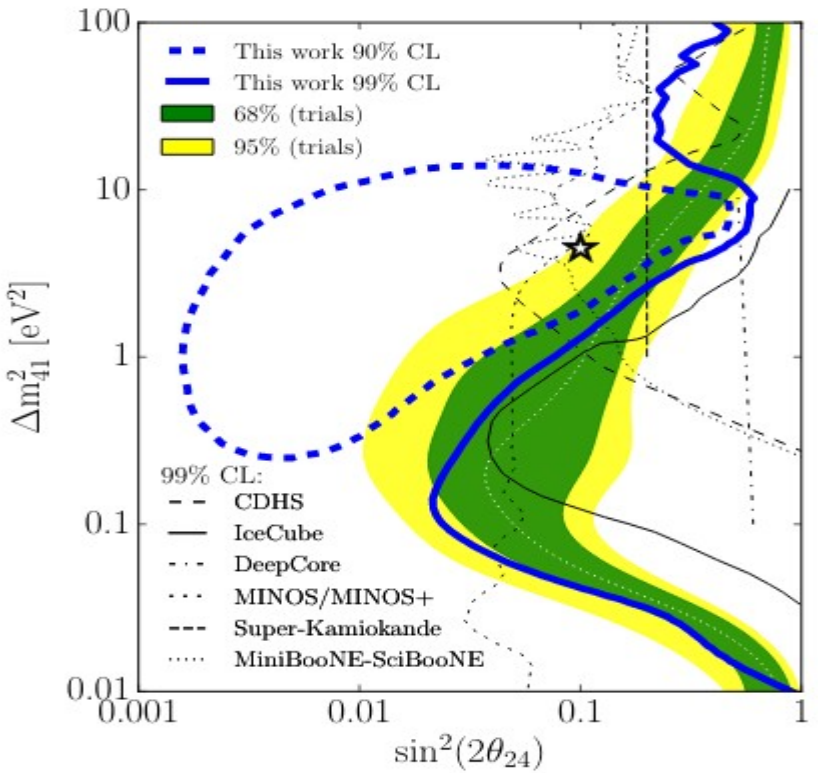


Other channels

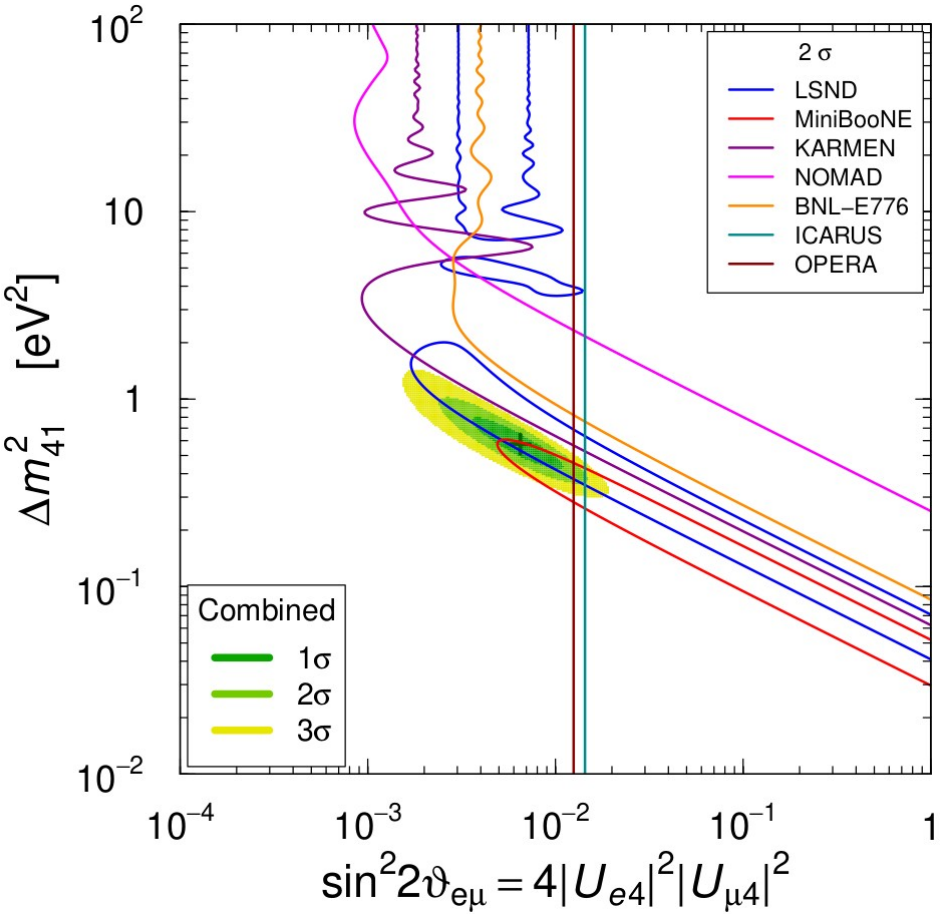
No evidence in muon disappearance

IceCube, 2005.12942, PRL 2020





Other channels

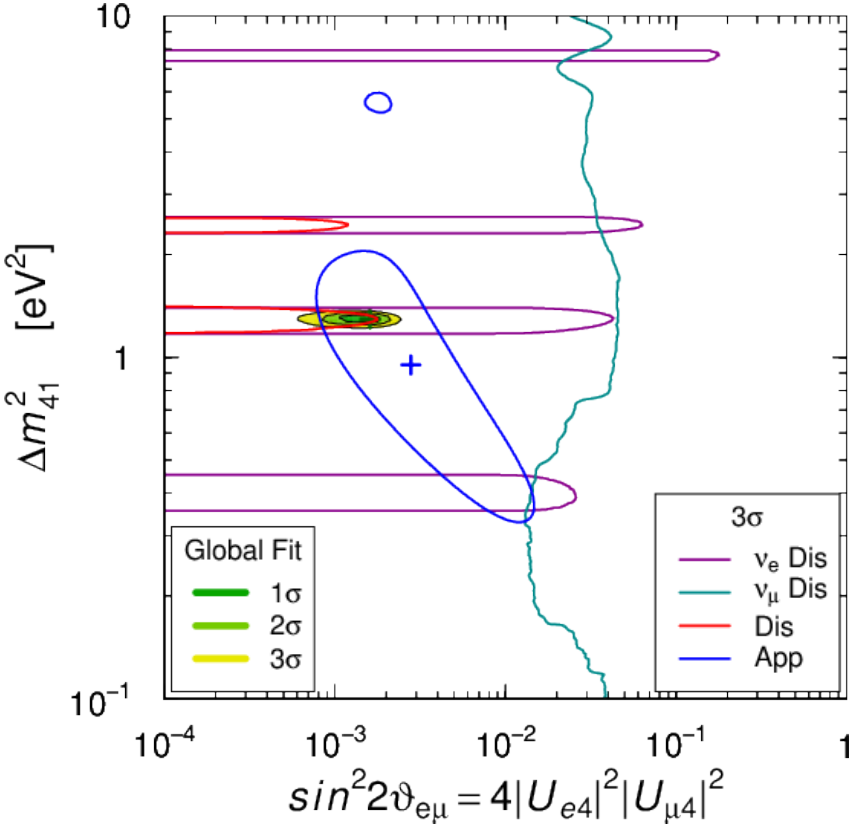


Strong preference in appearance channel

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

LSND and MiniBooNE only partially agree

Global fit?



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

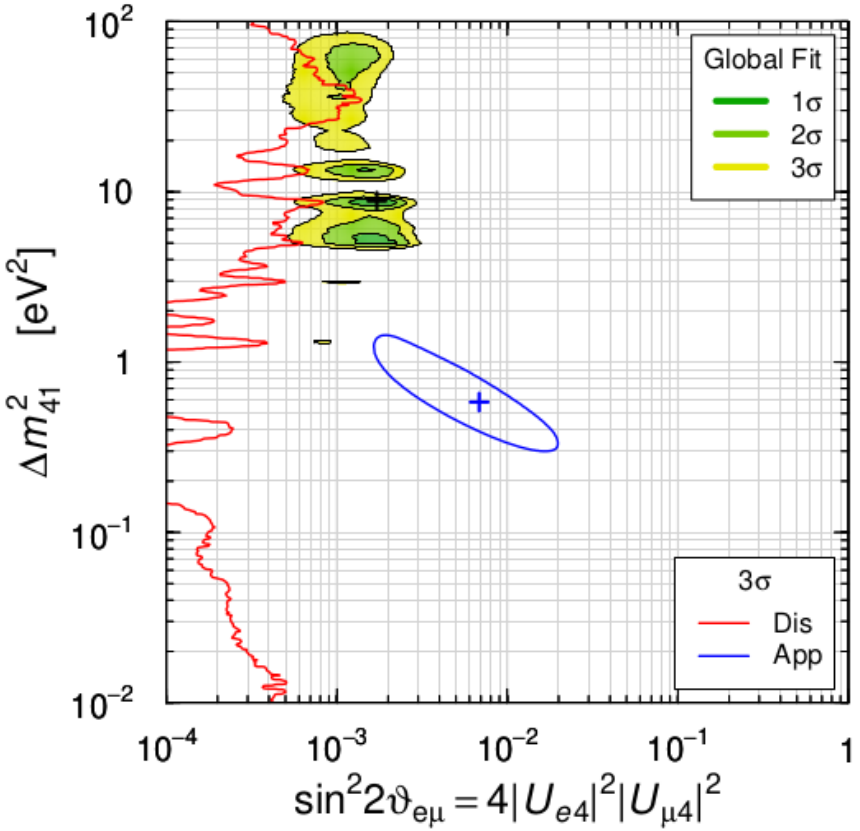
$$\nu_\mu \to \nu_\mu : |U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14}$$

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

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

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

Global fit?



No overlap anymore!

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

Global 3+1 fit is unacceptable!

NOT most up-to-date data included in this figure!

Conclusions

Short baseline anomalies can not be explained with 3-neutrino oscillations

There is no reactor antineutrino anomaly using the newest flux calculations

The preference for 3+1 mixing from ratio experiments is fading away, the Neutrino-4 result is doubtful

No significant preference for sterile neutrinos from disappearance experiments!

A global 3+1 fit is statistically unacceptable

What were LSND and MiniBooNE observing?

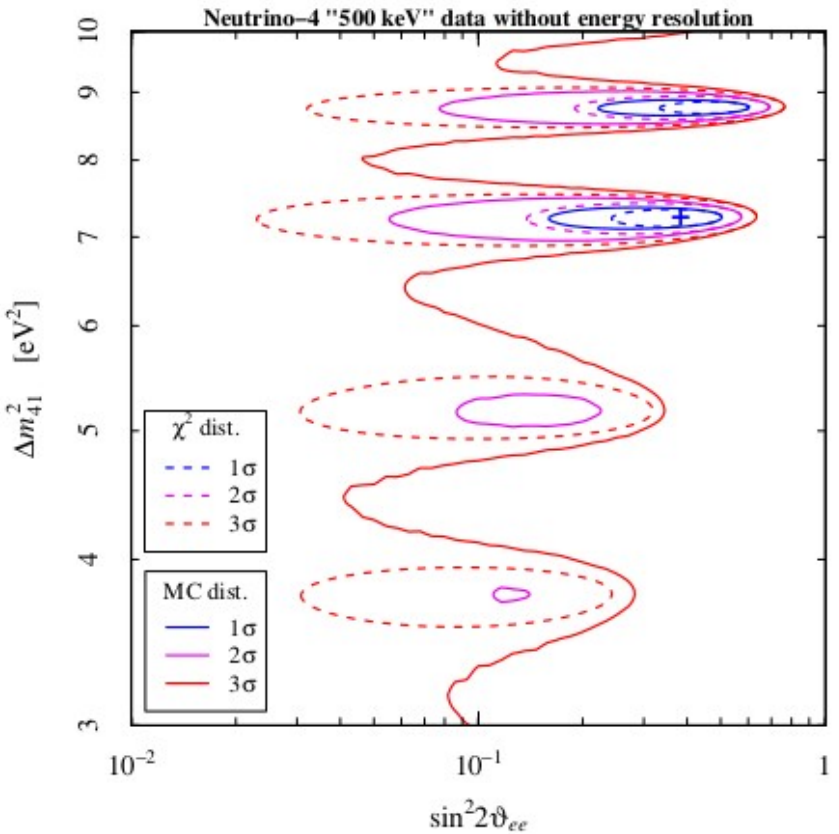
Gracias

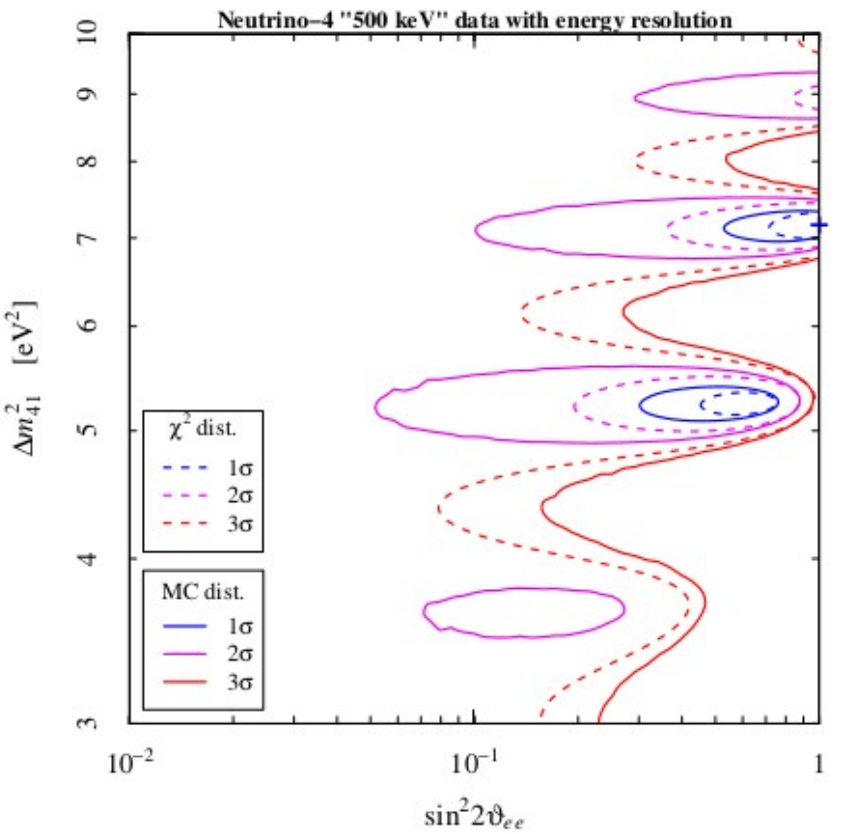
Backup

Neutrino-4

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

Monte Carlo analysis





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

Neutrino-4

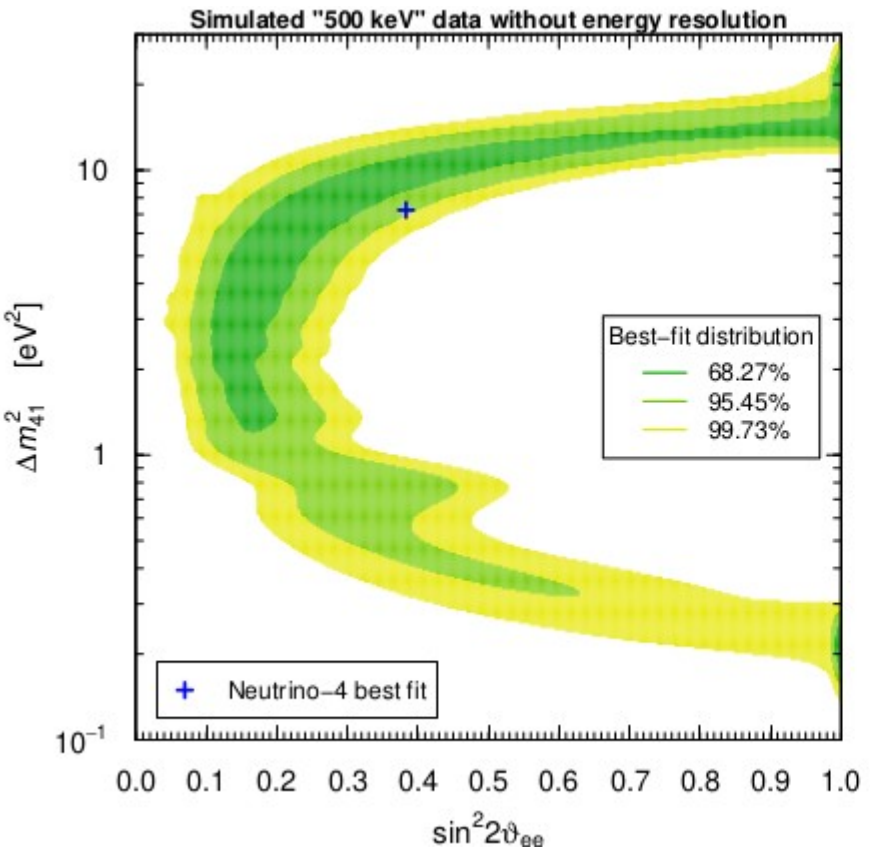
Summary

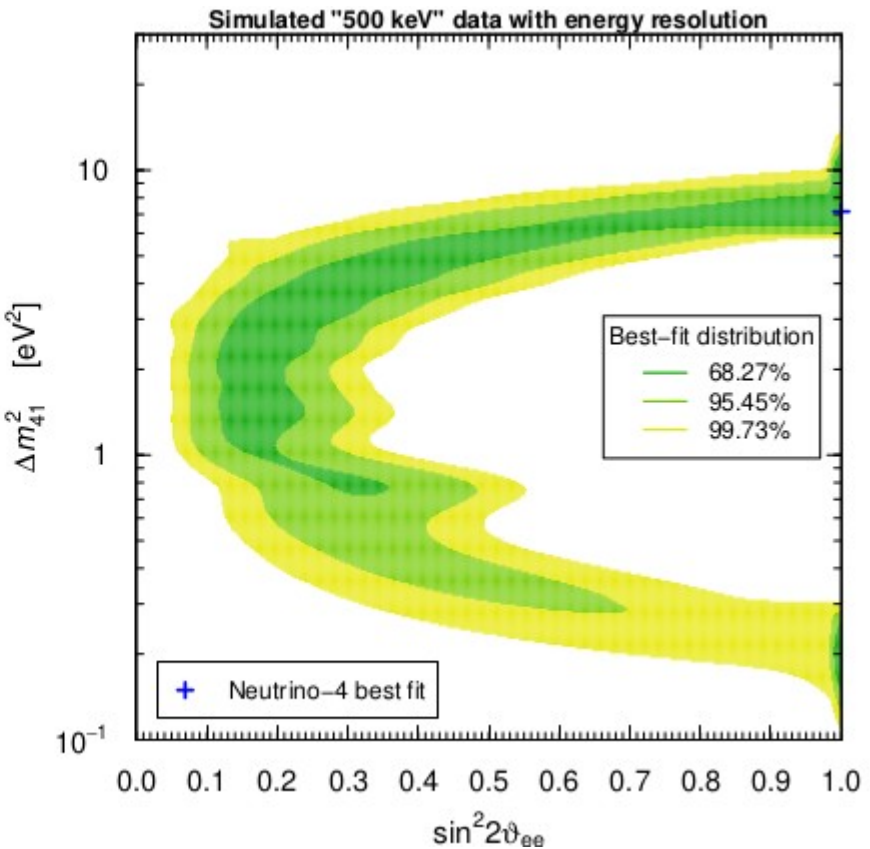
Neutrino-4	"500 keV" data		"125-250-500 keV" data	
	without en. res.	with en. res.	without en. res.	with en. res.
$\chi^2_{\rm min}$	14.9	18.2	21.9	21.1
GoF	60%	37%	19%	22%
$(\sin^2 2\vartheta_{ee})_{\rm bf}$	0.38	1.0	0.27	0.93
$(\Delta m^2_{41})_{\rm bf}$	7.2	7.2	8.8	7.2
$\Delta\chi^2_{\rm NO}$	13.1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

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

Neutrino-4

Distribution of best fit points without oscillations





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