Phenomenology of light sterile neutrinos

Yu-Feng Li

liyufeng@ihep.ac.cn

Institute of High Energy Physics, Beijing

XVIII International Workshop on Neutrino Telescopes

18-22 March 2019, Venice, Italy

Three Neutrino Paradigm

Standard Parameterization of Mixing Matrix

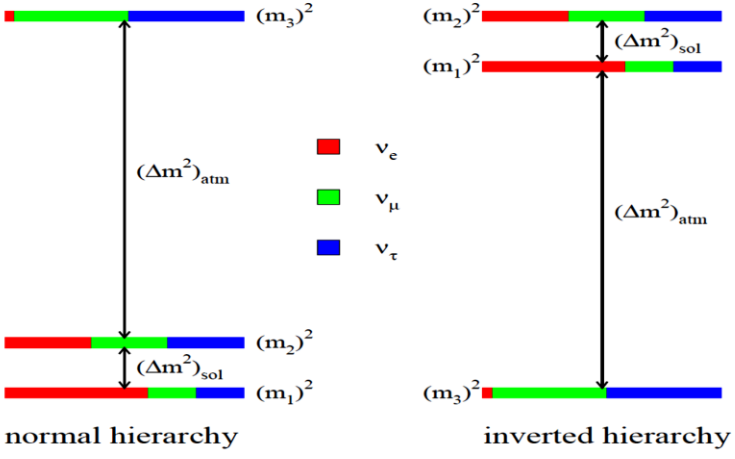
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

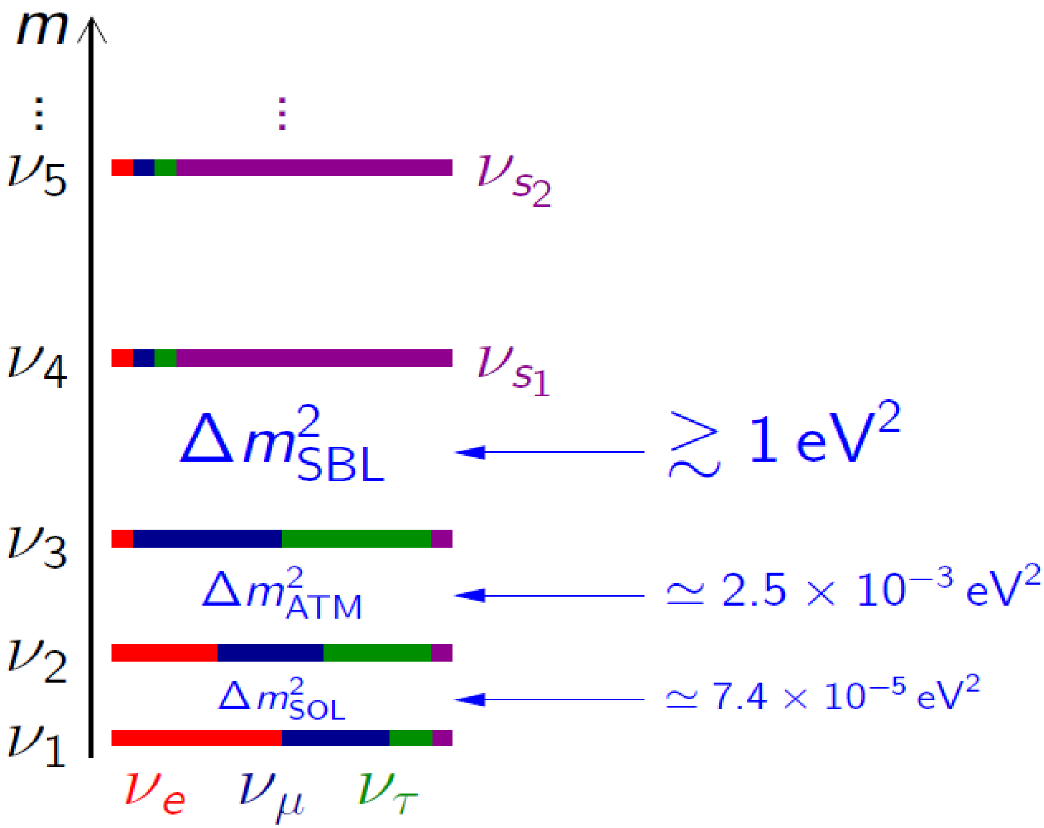
$$c_{ab} \equiv \cos\vartheta_{ab} \qquad s_{ab} \equiv \sin\vartheta_{ab} \qquad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \qquad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$$

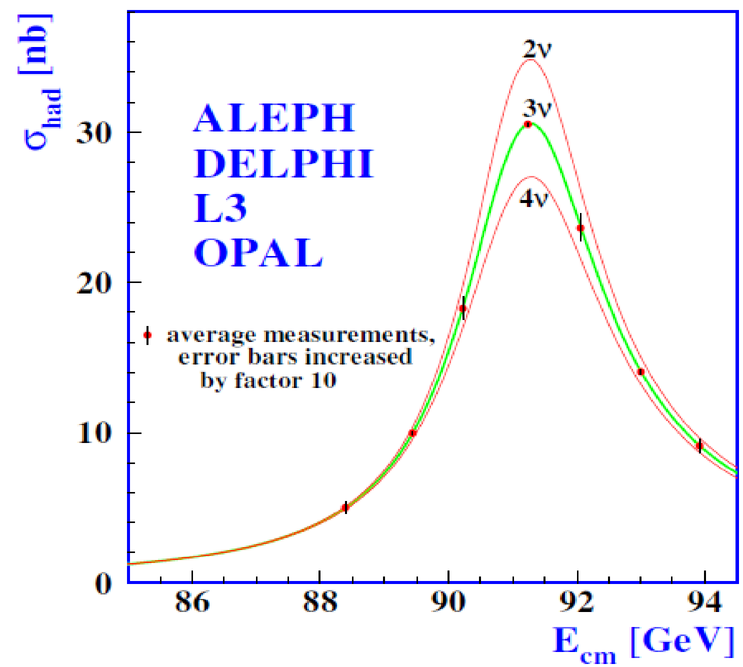
3 Mixing Angles: $\vartheta_{12}, \vartheta_{23}, \vartheta_{13}$
1 CPV Dirac Phase: δ_{13}
2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: $\Delta m^2_{21}, \Delta m^2_{31}$

- **Absolute Neutrino Masses**
- **Two CPV Majorana Phases**



Beyond 3-ν oscillations: sterile neutrinos





$$N_{\nu_{\text{active}}}^{\text{LEP}} = 2.9840 \pm 0.0082$$

Explanation of short baseline oscillations:

eV-scale sterile neutrinos (which have mixing with active mass eigenstates)

Status of short baseline oscillations in nu-e(bar) disappearance channels

Gallium anomaly

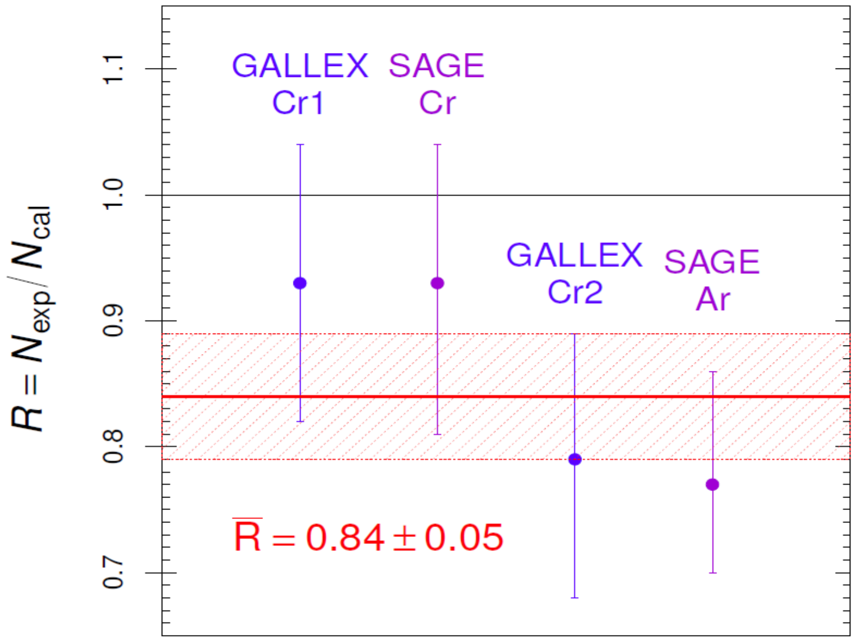
SAGE, PRC (2006); PRC (2009); Laveder et al. (2007), etc.

Gallium Radioactive Source Experiments: GALLEX and SAGE

Test of Solar Neutrino Detection

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

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



$\langle L \rangle_{GALLEX} = 1.9\ \mathrm{m}$ $\quad \langle L \rangle_{SAGE} = 0.6\ \mathrm{m}$

- **~2.9σ deficit**

Neutrino energies: ~0.8 MeV

$\Delta m^2_{SBL} \gtrsim 1\ \mathrm{eV}^2 \gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL}$

- **Anomaly supported by the new cross section measurement**

${}^{3}\mathrm{He} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + {}^{3}\mathrm{H}$

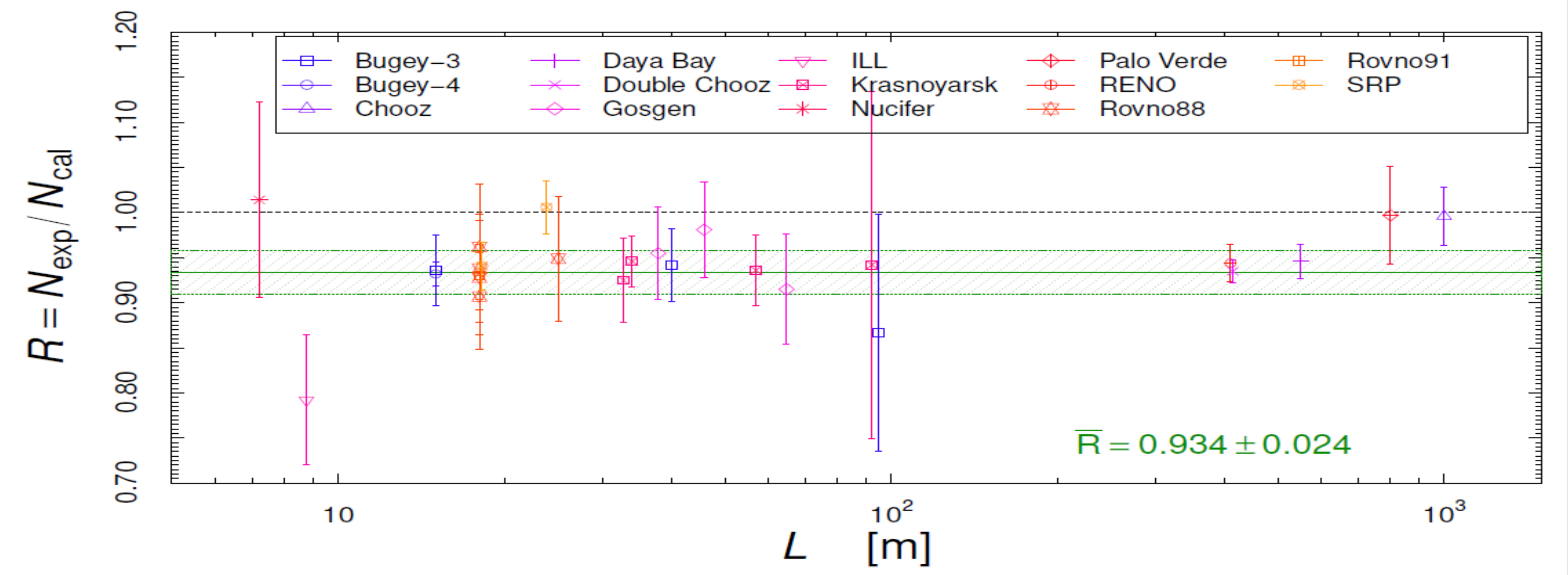
Frekers et al., PLB 706 (2011) 134

- **Contributions from excited states verified** ***Giunti et. al. 1210.5715***

Reactor Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

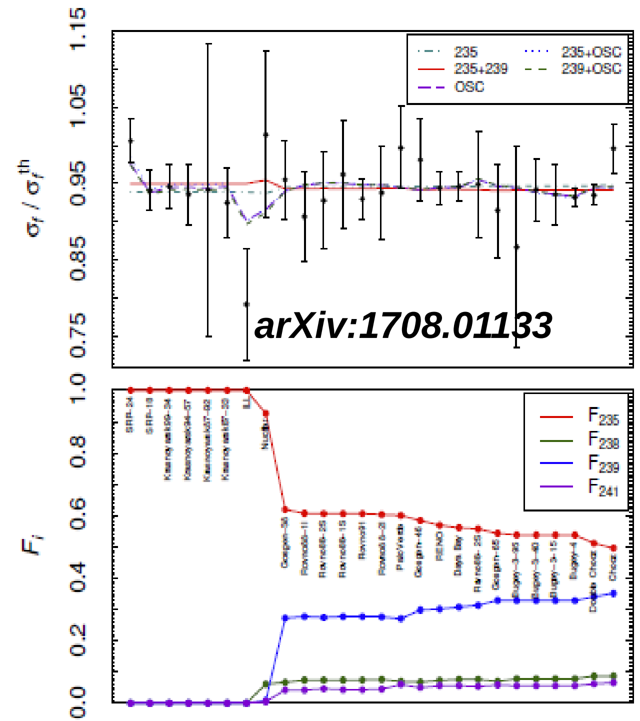
New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



- **Discrepancy between theory and measurements**
- **~2.8σ deficit (depending on the theoretical flux uncertainty)**
- **Nominal theoretical uncertainty from the Mueller+Huber model ~ 2.5%**

A closer look at reactor rates data

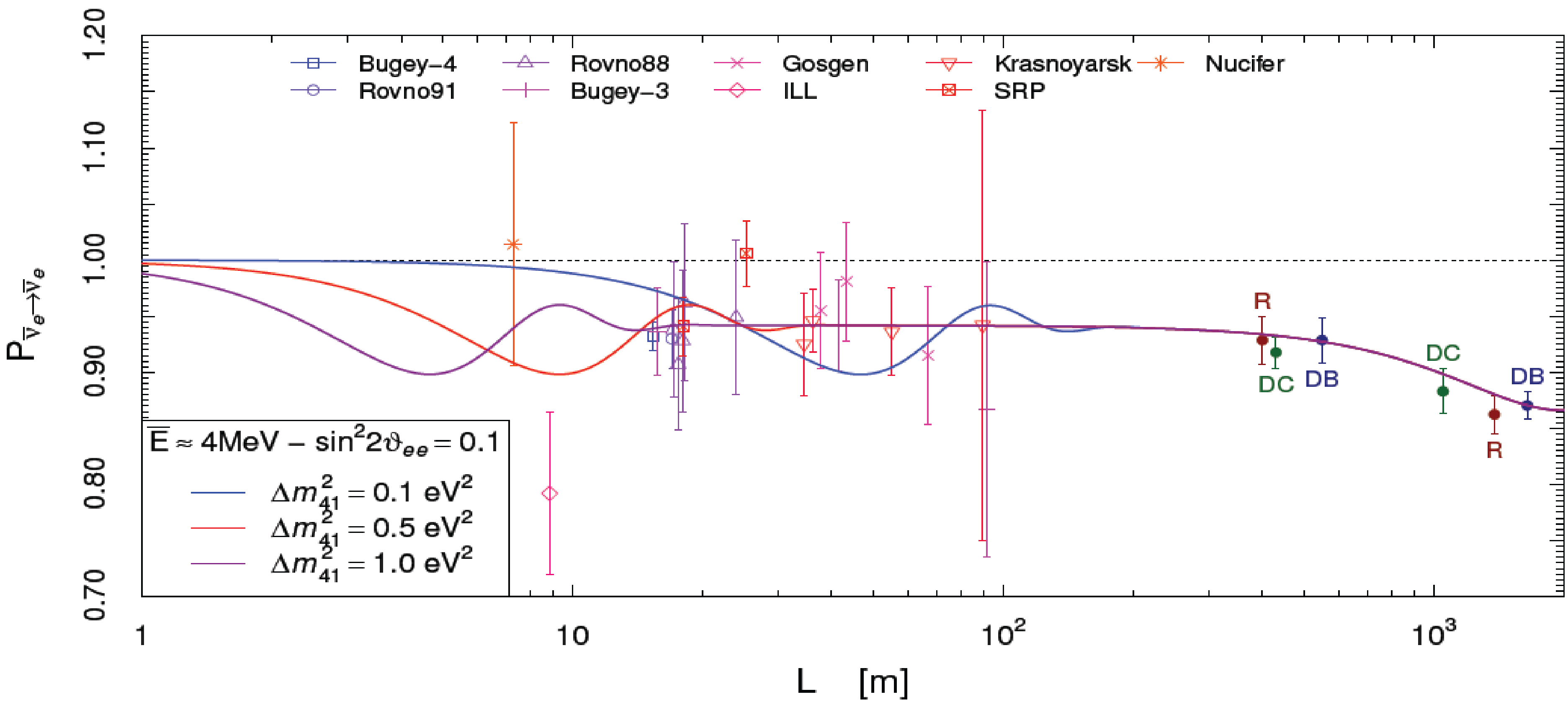
a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	R^{exp}_a	σ^{exp}_a [%]	σ^{cor}_a [%]	σ^{the}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	2.5	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		2.4	18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.1	2.4	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		2.4	18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	2.2	2.4	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.1	2.5	25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		2.4	18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2		2.5	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	2.5	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		2.5	95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4		2.4	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	2.4	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	2.4	64.7
14	ILL	1	0	0	0	0.792	9.1		2.4	8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	2.4	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		2.4	92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	2.4	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	2.4	34
19	SRP-18	1	0	0	0	0.941	2.8	0	2.4	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	2.4	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	2.3	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	2.5	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	2.4	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	2.5	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.944	2.2	0	2.4	≈ 411
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	2.5	≈ 415



All Reactors	^{235}U	OSC
χ^2_{min}	25.3	23.0
NDF	32	31
GoF	79%	85%

MC: ^{235}U disfavored at 1.7σ

RAA: oscillation-based explanation



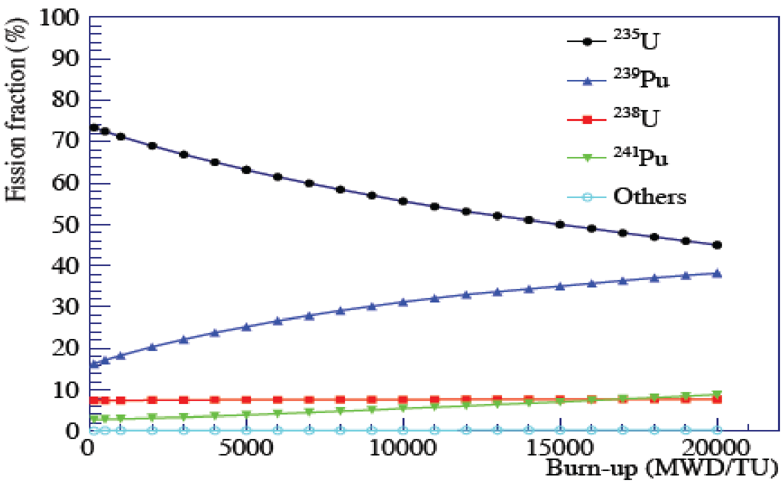
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion

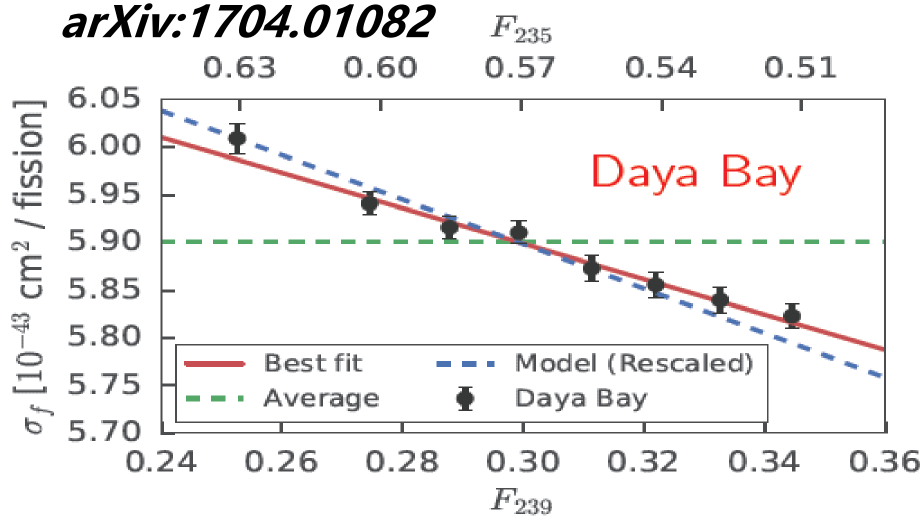
Burn-up Feature @ Reactors

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of
  ^{235}U ^{238}U ^{239}Pu ^{241}Pu
- Effective fission fractions:
  F_{235} F_{238} F_{239} F_{241}
- Cross section per fission:

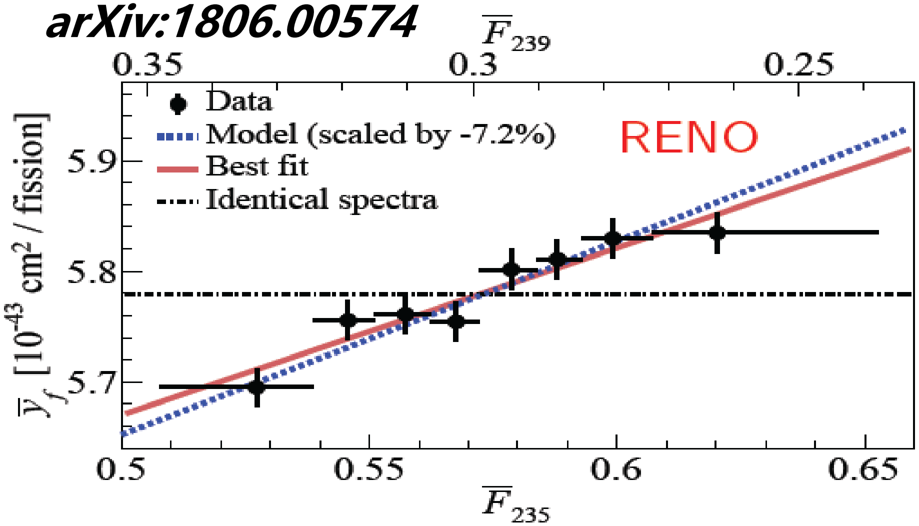
$$\sigma_f = \sum_{k=235,238,239,241} F_k \, \sigma_{f,k}$$



arXiv:1704.01082

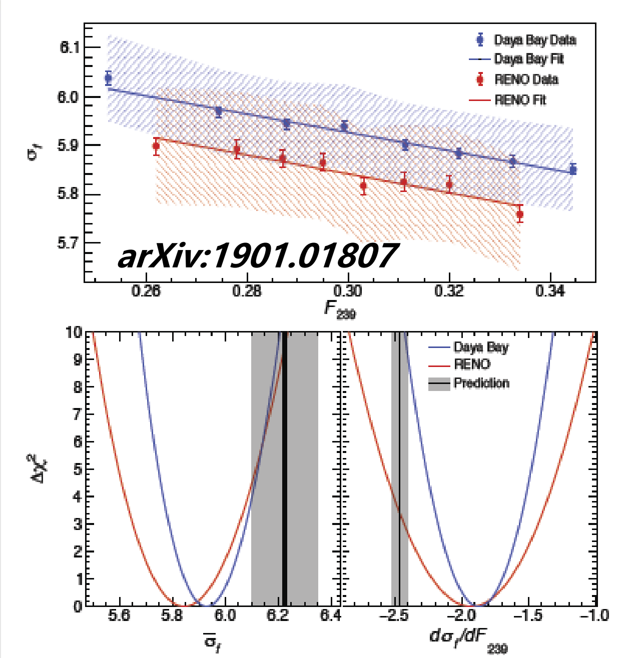


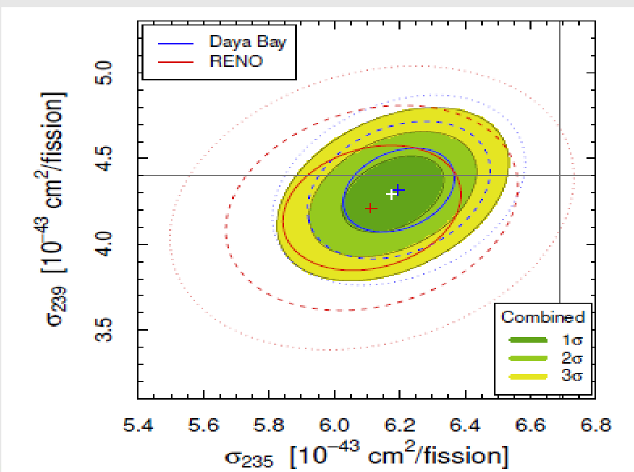
arXiv:1806.00574



Both experiments disfavor the equal suppression at around 3-sigma!

A Global Analysis of Reactor Flux Data





	235	239	235+239	235+238+239	235=239=241+238	OSC	235+OSC	239+OSC
χ^2_{min}	34.6	41.6	34.1	29.9	38.6	33.1	29.5	26.9
NDF	39	39	38	37	38	38	37	37
GoF	67%	36%	65%	79%	44%	69%	80%	89%
r_5	0.933 ± 0.010	(0.941)	0.932 ± 0.009	0.952 ± 0.014	0.941 ± 0.013	(1.014)	0.984 ± 0.025	(1.014)
r_8	(0.890)	(0.868)	(0.914)	0.672 ± 0.135	0.926 ± 0.096	(1.021)	(0.969)	(0.956)
r_9	(0.987)	0.997 ± 0.029	0.969 ± 0.030	1.042 ± 0.046	0.944 ± 0.015	(1.019)	(1.026)	1.099 ± 0.040
r_1	(0.989)	(0.938)	(1.003)	(1.001)	0.942 ± 0.013	(1.015)	(1.024)	(1.015)
Δm^2_{41}						$0.49^{+0.02}_{-0.03}$	$0.48^{+0.05}_{-0.03}$	0.49 ± 0.02
$\sin^2 2\vartheta_{ee}$						0.15 ± 0.04	$0.10^{+0.05}_{-0.04}$	0.16 ± 0.04

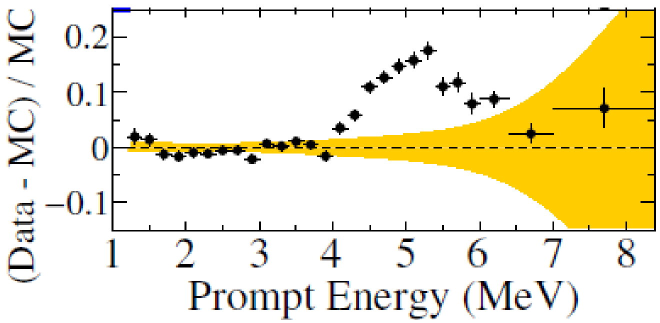
DYB+RENO joint data:
2.9σ preference of U235 over oscillation-only

Global Flux Data (evolution+rates):

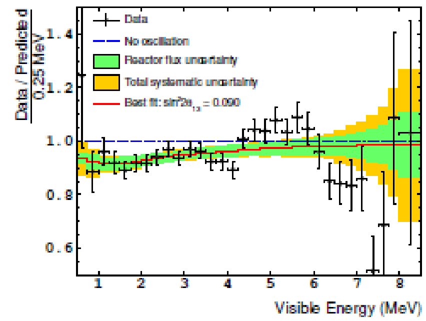
a) A common inaccuracy of all beta conversion predictions: disfavored at 2.9σ

b) Oscillation-including hypothesis is favored over the oscillation-including one: at 1-2σ

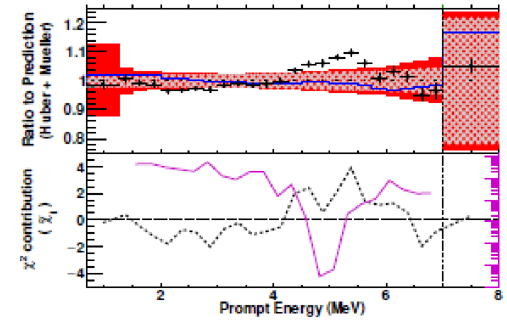
New Spectral Feature @ Reactors



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

(1) The "5 MeV bump" cannot be explained by neutrino oscillations
(averaged in RENO, Double CHOOZ and Daya Bay)

(2) Theoretical miscalculation of both the rate and spectrum?

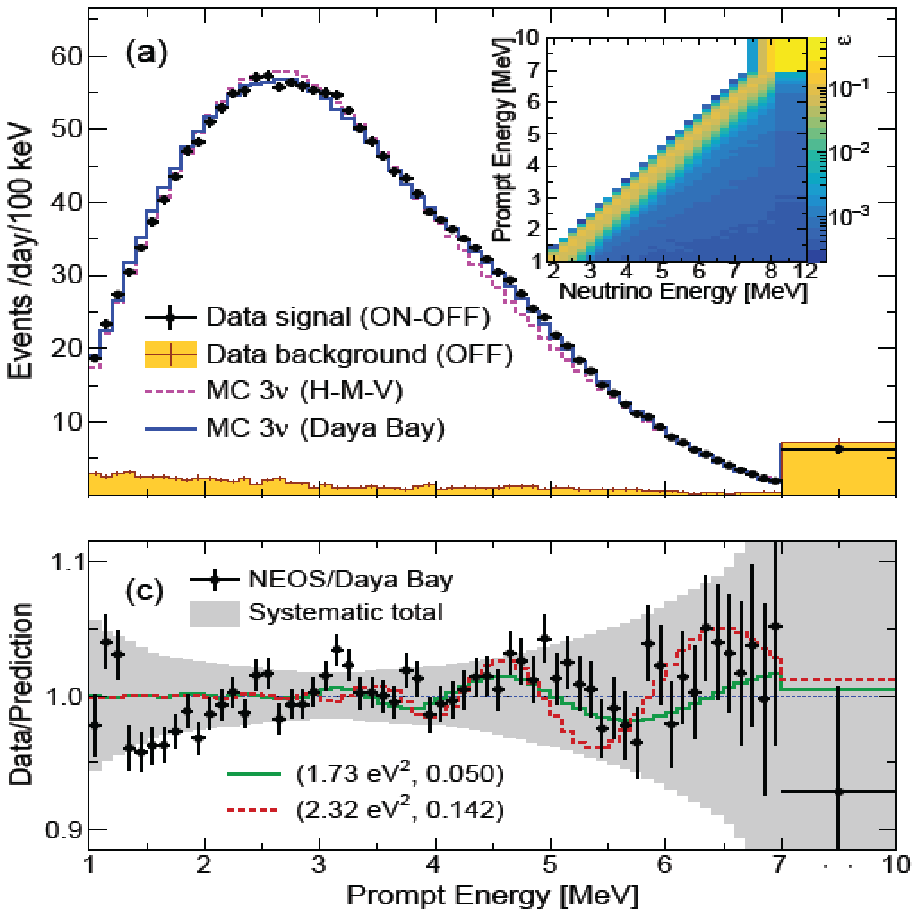
(3) Detector energy nonlinearity? ***[Mention et al, PLB 773 (2017) 307]***
(DYB/DC achieved better than 1% precision → see the talk by Jiajie Ling)

(4) One may need to increase the uncertainty: e.g. about 4%-5%.
[Hayes and Vogel, 2016]

Spectral ratio result@NEOS

NEOS

[PRL 118 (2017) 121802 (arXiv:1610.05134)]



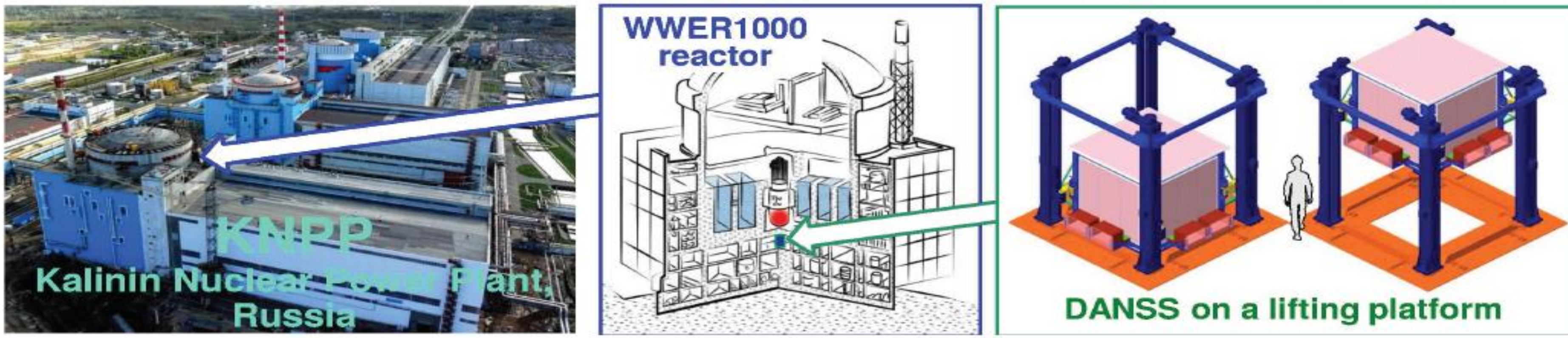
- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

Spectral ratio result@DANSS

DANSS

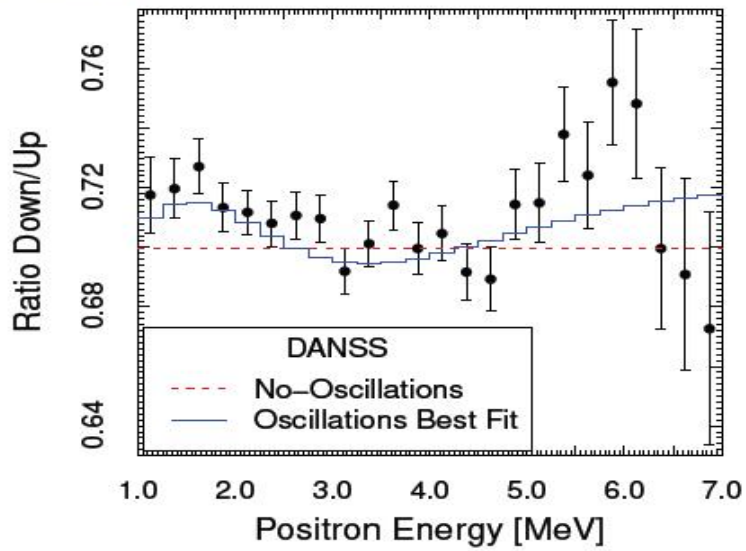
[Solvay Workshop, 1 December 2017; La Thuile 2018, 3 March 2018; Neutrino 2018, 8 June 2018]

Detector of reactor AntiNeutrino based on Solid Scintillator



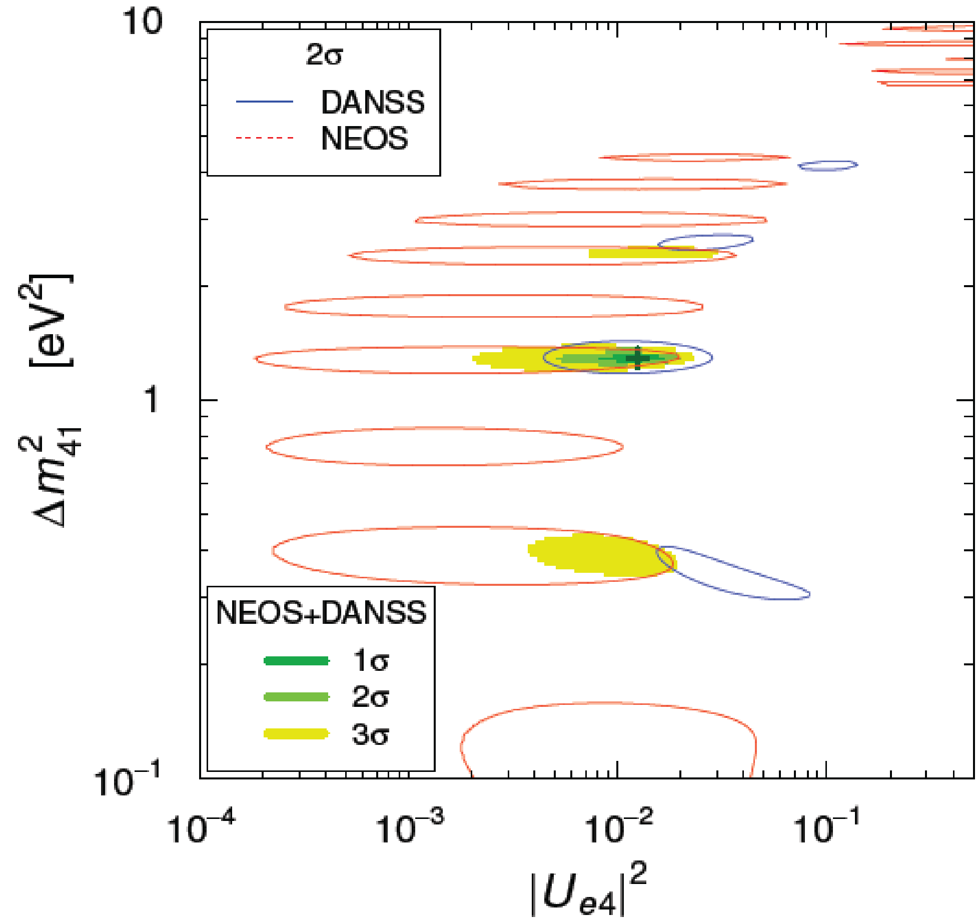
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

$$\text{Down} = 12.7\,\text{m}$$
$$\text{Up} = 10.7\,\text{m}$$



Model independent SBL oscillations

Gariazzo et. al., PLB 782 (2018) 13



$\sim 3.7\sigma$

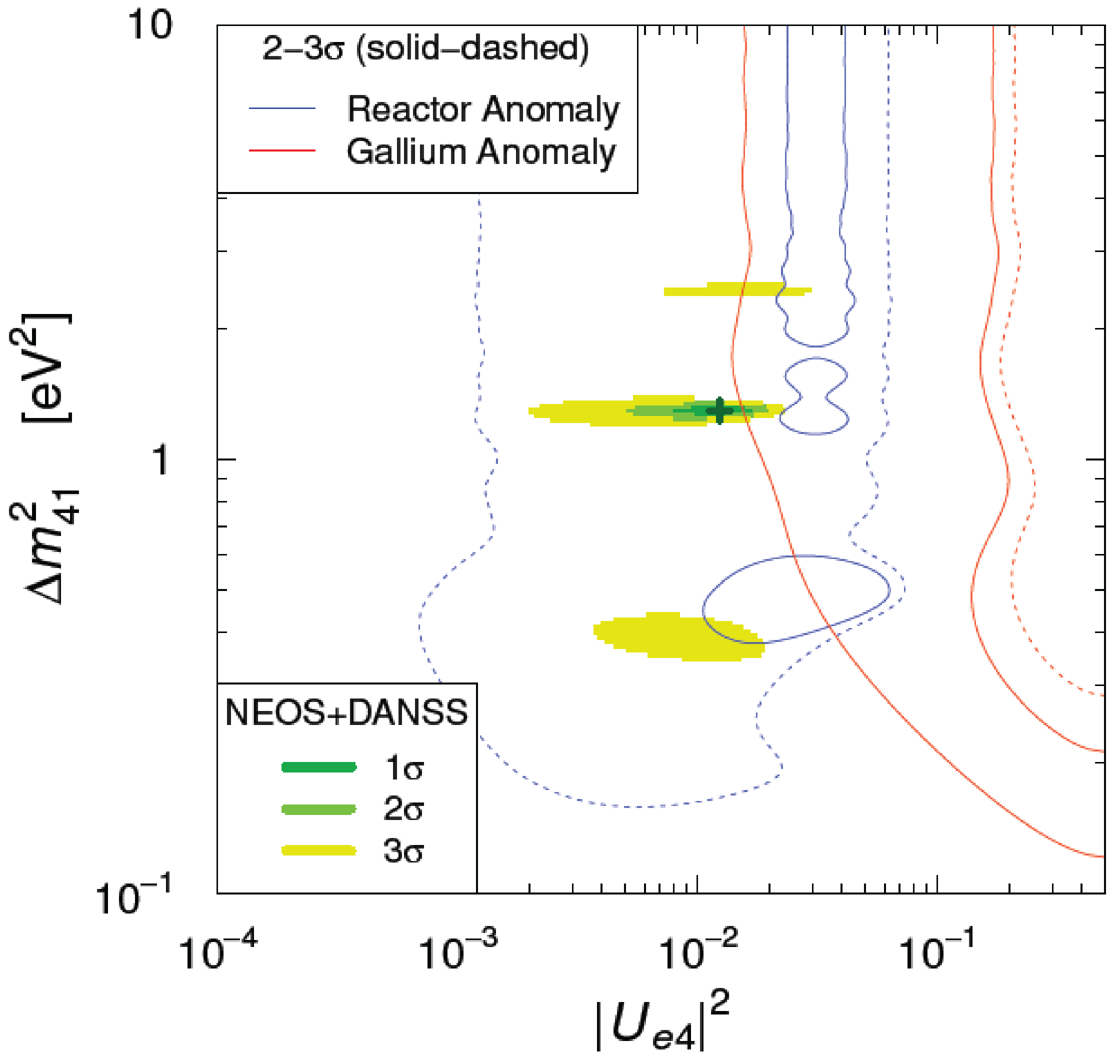
$\Delta m^2_{41} = 1.29 \pm 0.03$

$|U_{e4}|^2 = 0.012 \pm 0.003$

$|U_{e3}|^2 = 0.022 \pm 0.001$

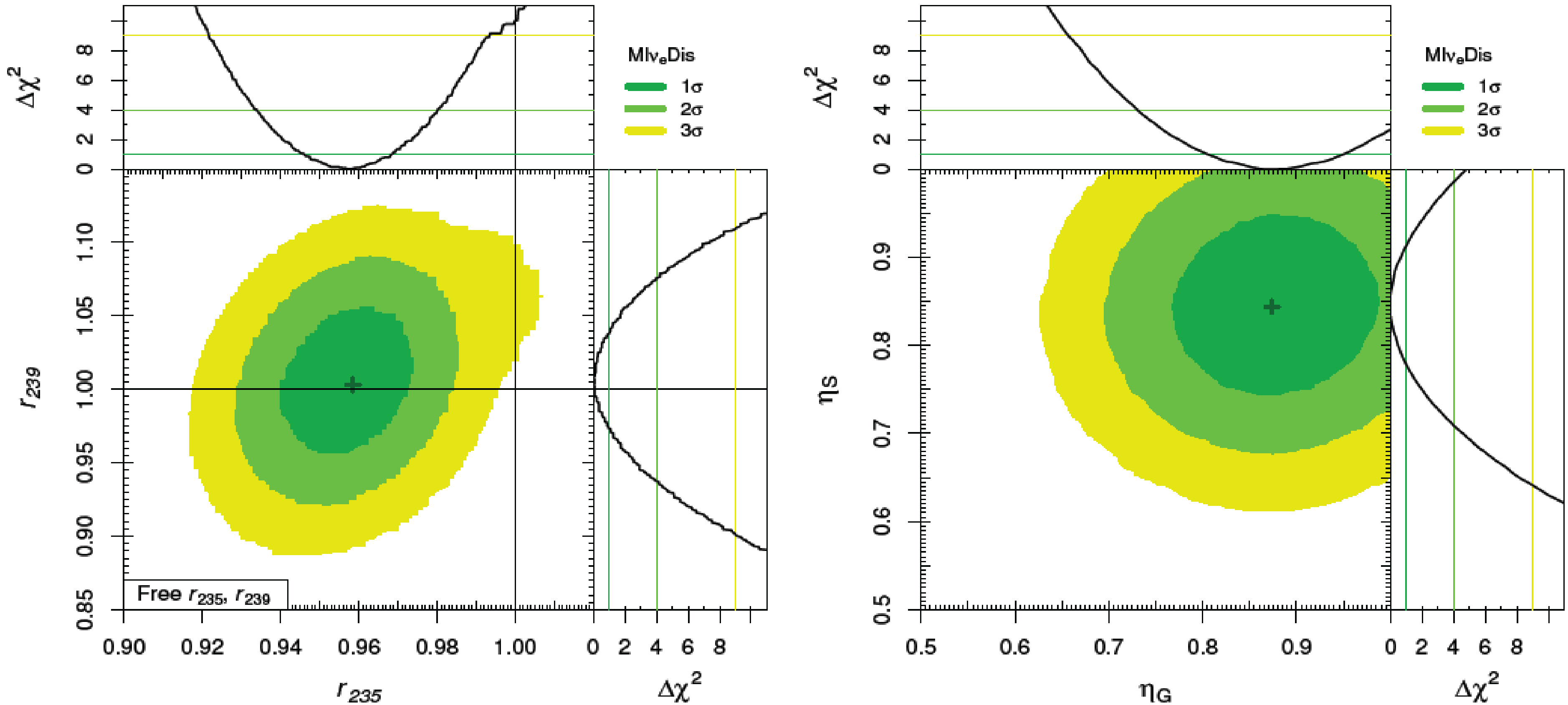
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Implications for Reactor and Gallium anomalies



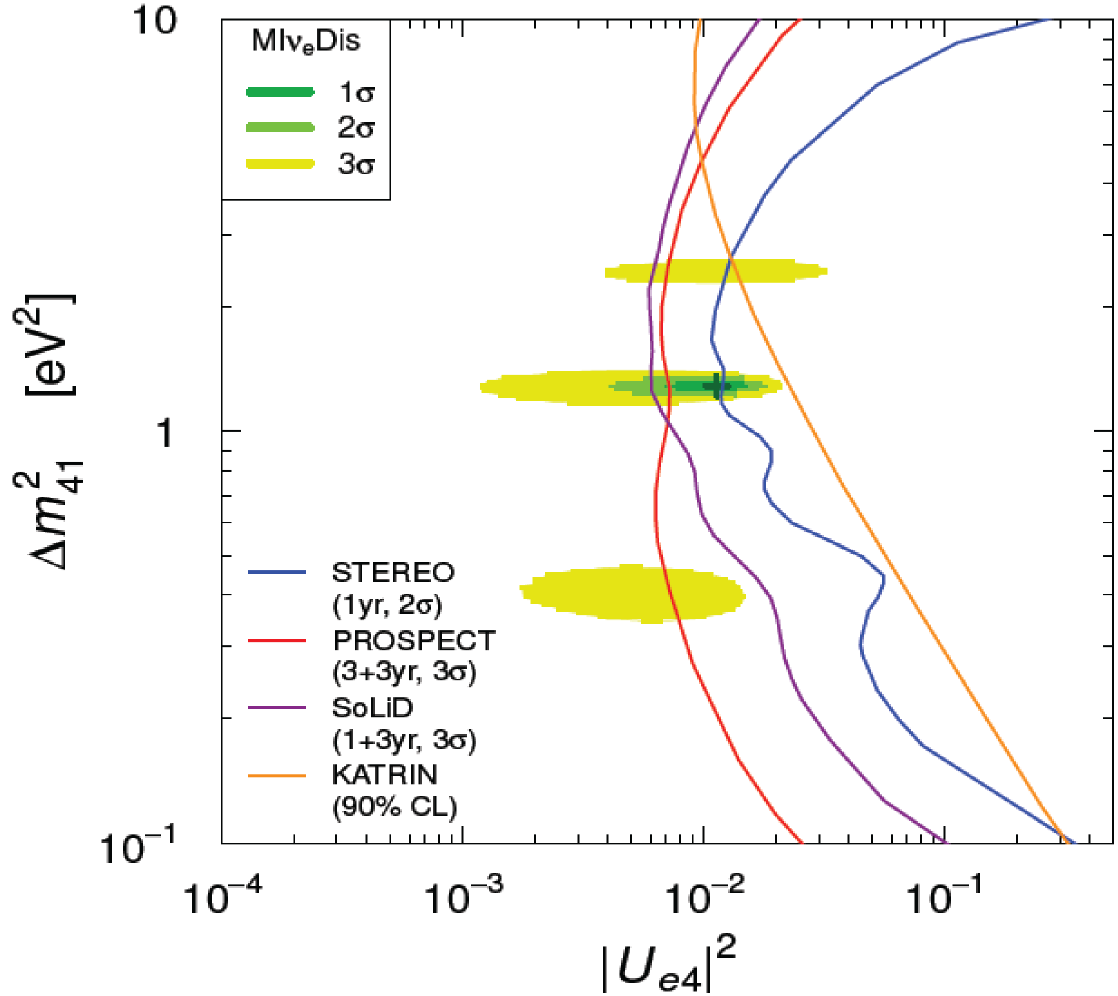
- 3σ agreement.
- 2σ tension.
- Small overestimate of the reactor fluxes.
- Small overestimate of the GALLEX and SAGE efficiencies.

Implications for Reactor and Gallium anomalies



- Indication of $r_{235} < 1$.
- Likely small overestimate of the GALLEX and SAGE efficiencies.

Model independent fit and the future tests

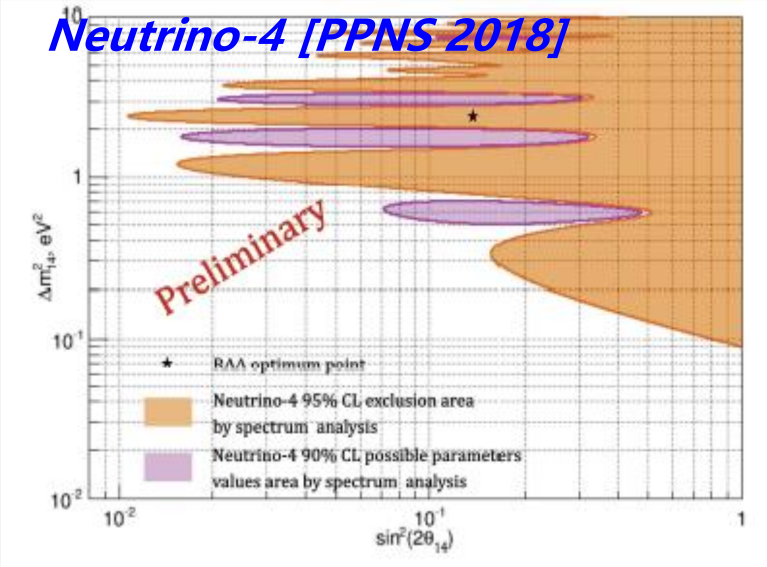


- NEOS and DANSS.
- Reactor rates with free ^{235}U and ^{239}Pu fluxes: r_{235} and r_{239}.
- Gallium data with free GALLEX and SAGE efficiencies: η_G and η_S.
- New reactor experiments: STEREO, Neutrino-4, SoLiD, PROSPECT
- Kinematic ν_4 mass measurement: KATRIN

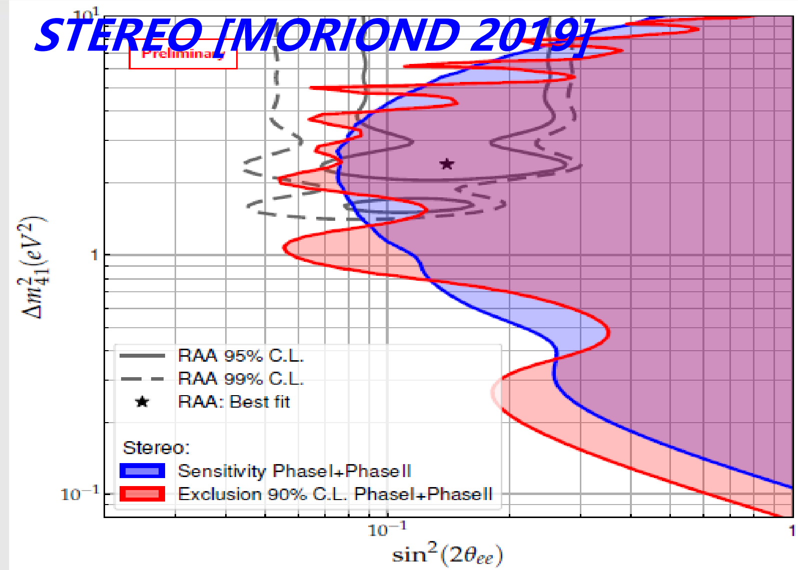
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Latest results from spectral ratios

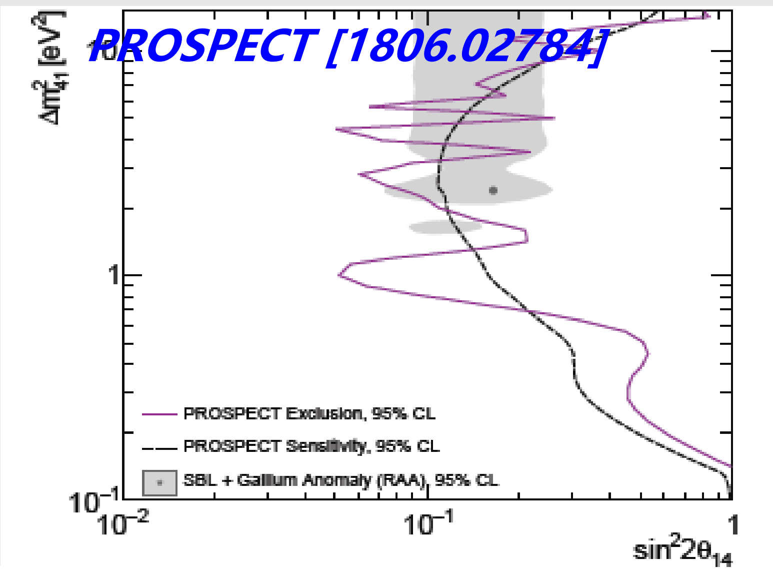
Neutrino-4 [PPNS 2018]

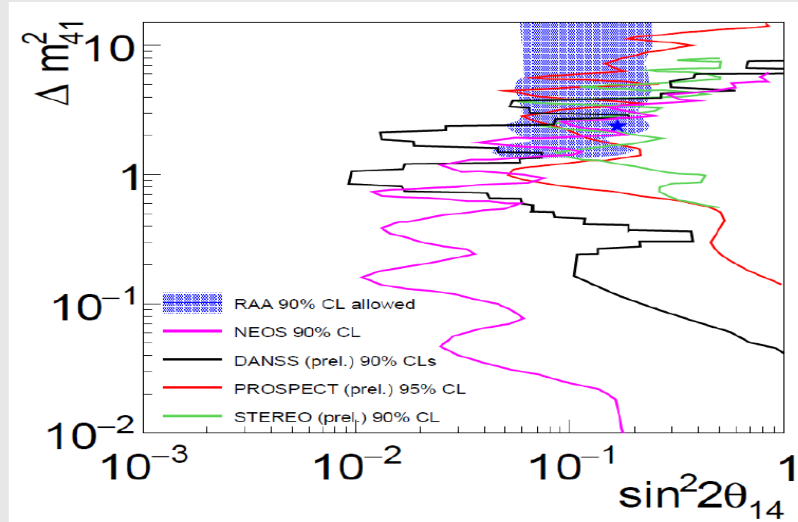


STEREO [MORIOND 2019]



PROSPECT [1806.02784]





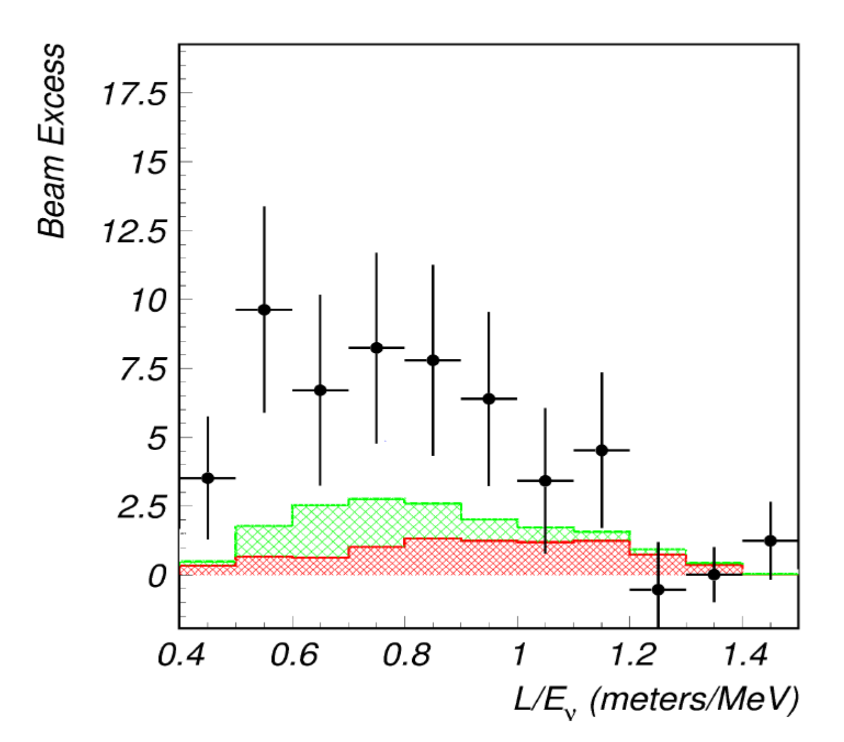
X. Qian and J-C Peng, arXiv:1801.05386

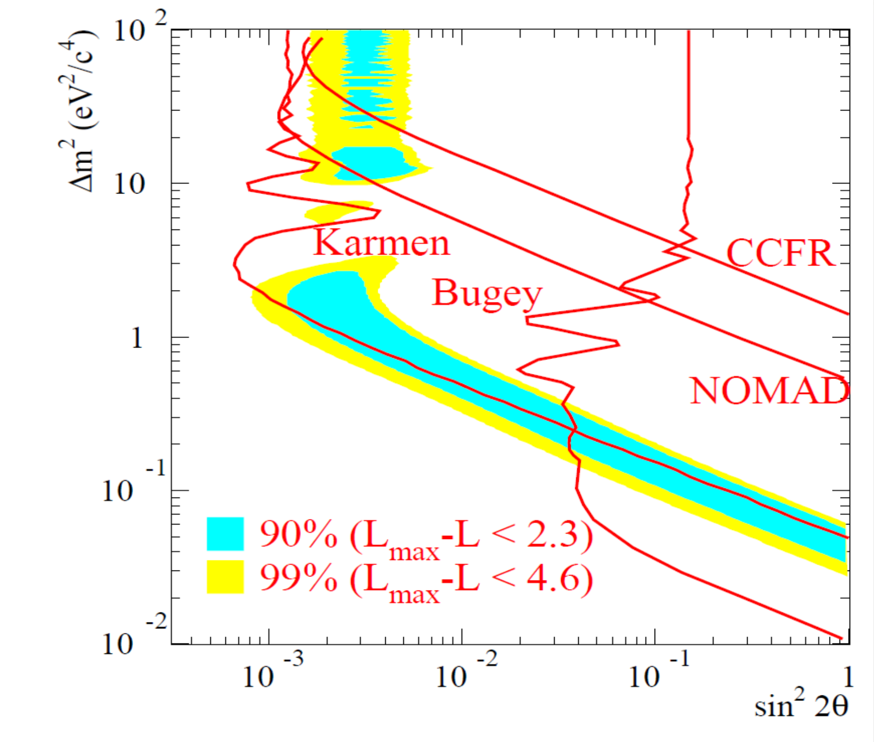
See the talk by Seon-Hee Seo

Status of short baseline oscillations in nu-mu(bar)→nu-e(bar) and nu-mu(bar) disappearance channels

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]





- **Muon decay-at-rest beam:**

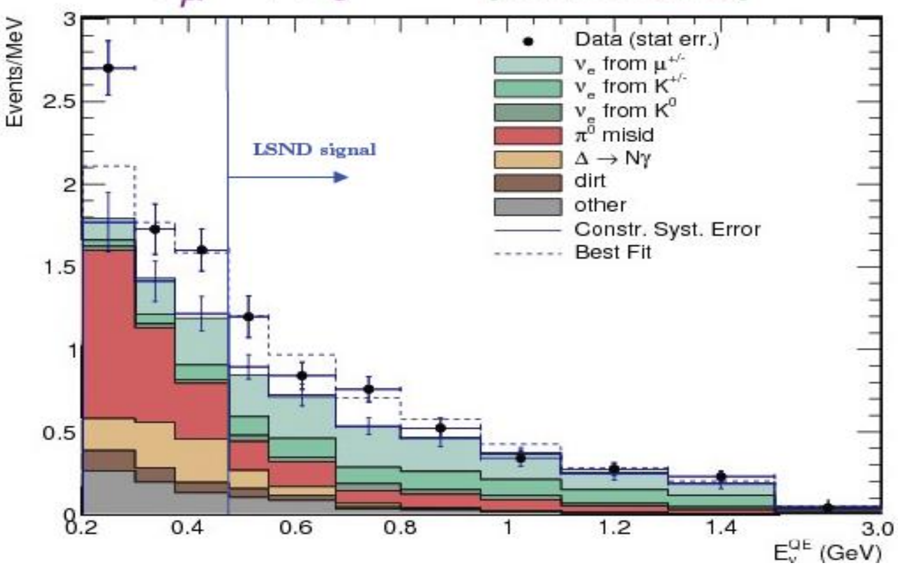
$\bar{\nu}_\mu \to \bar{\nu}_e \qquad L \simeq 30\,\mathrm{m} \qquad 20\,\mathrm{MeV} \le E \le 200\,\mathrm{MeV}$

3.8σ excess $\qquad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_A \gg \Delta m^2_S)$

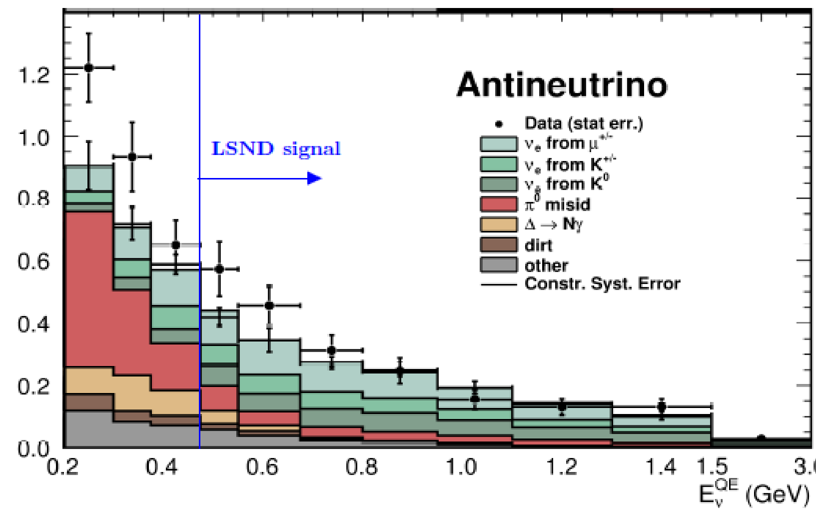
MiniBooNE

$L \simeq 541\,\mathrm{m}$ $200\,\mathrm{MeV} \leq E \lesssim 3\,\mathrm{GeV}$

$\nu_\mu \to \nu_e$ [arXiv:1805.12028]



$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]

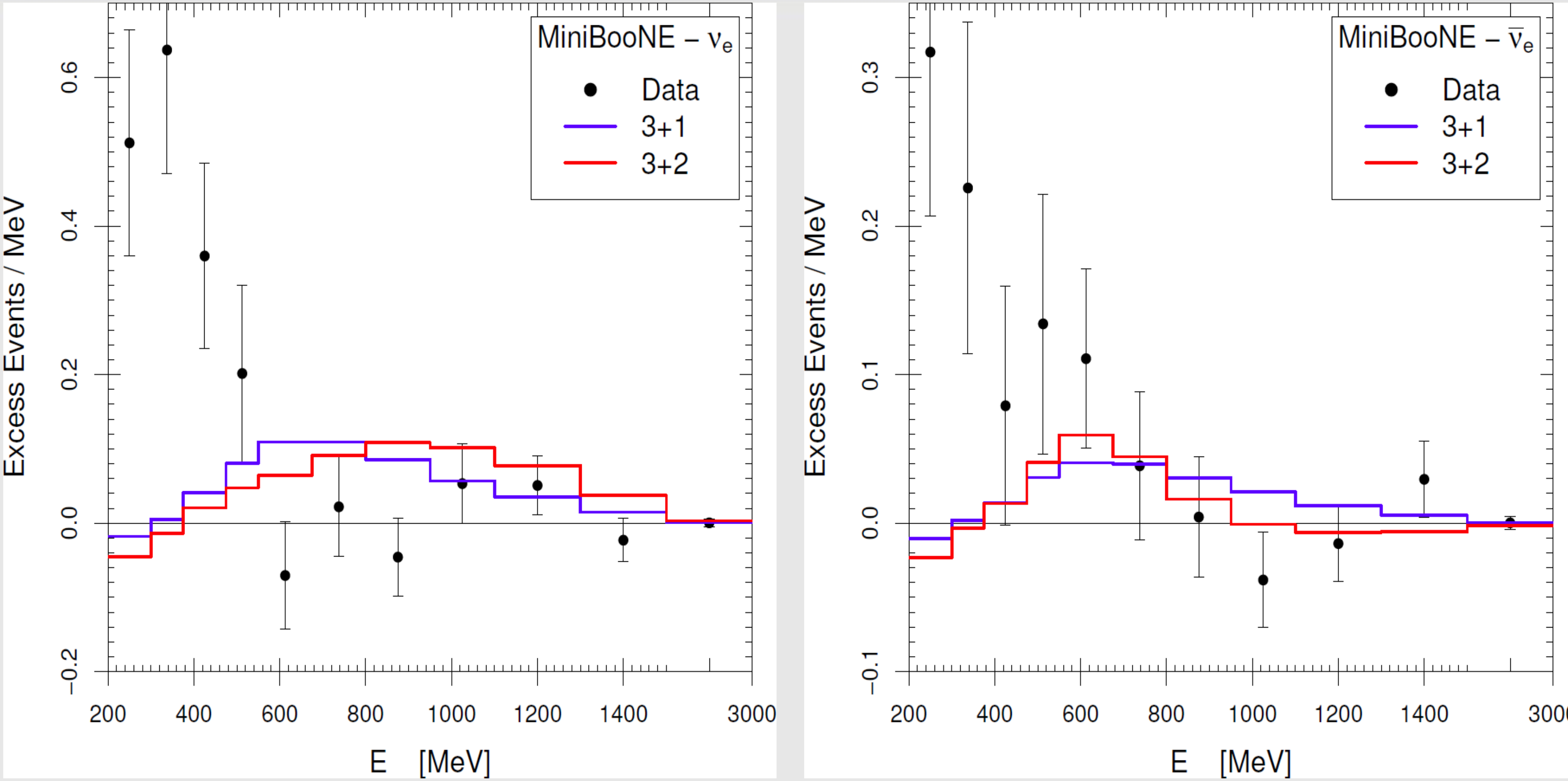


Purpose: **check LSND signal with different L&E, but the same L/E (>475 MeV)**

~4.5σ (2.8σ) excess: unidentified backgrounds in low energy ranges?
→ MicroBooNE.

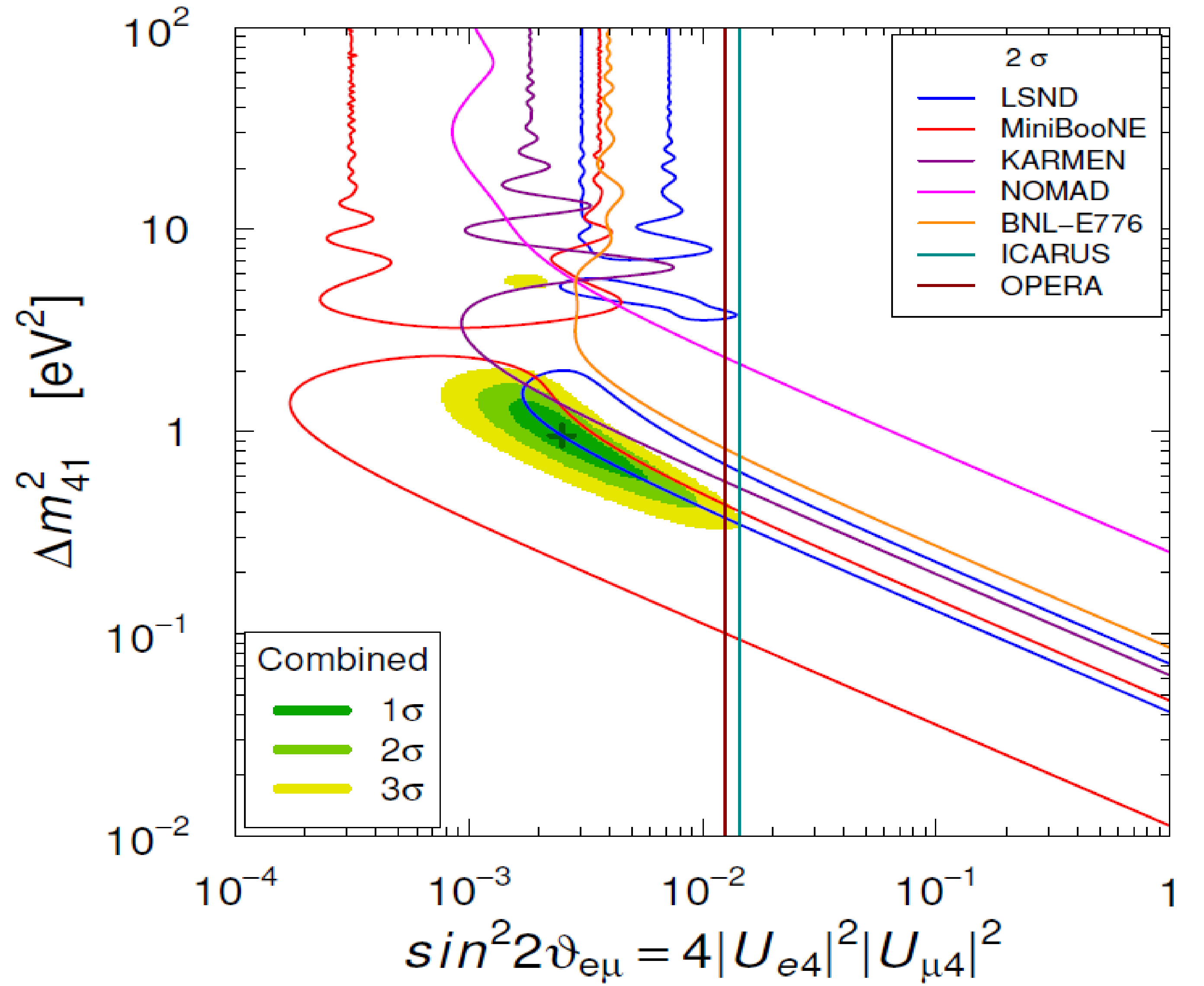
A pragmatic approach: (E>475 MeV) ***[arXiv: 1308.5288]***

MiniBooNE low energy bins

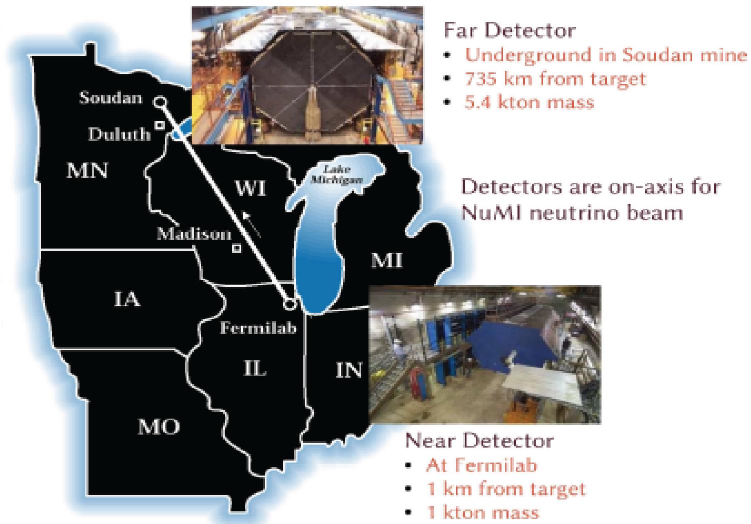


Fit of MB Low-Energy Excess requires small mass splitting and large mixing angle, which are in contradiction with ICARUS/OPERA and the disappearance data.

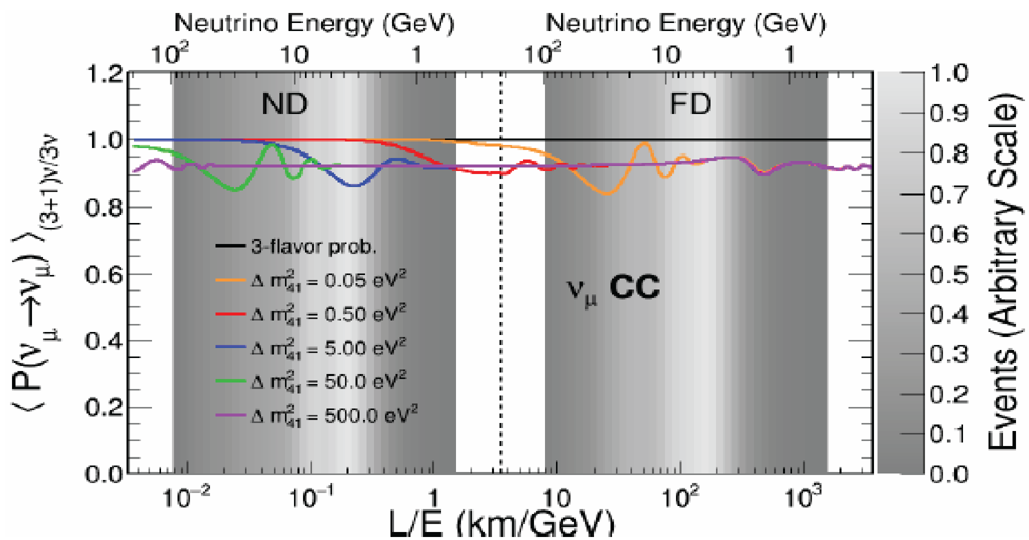
Appearance data

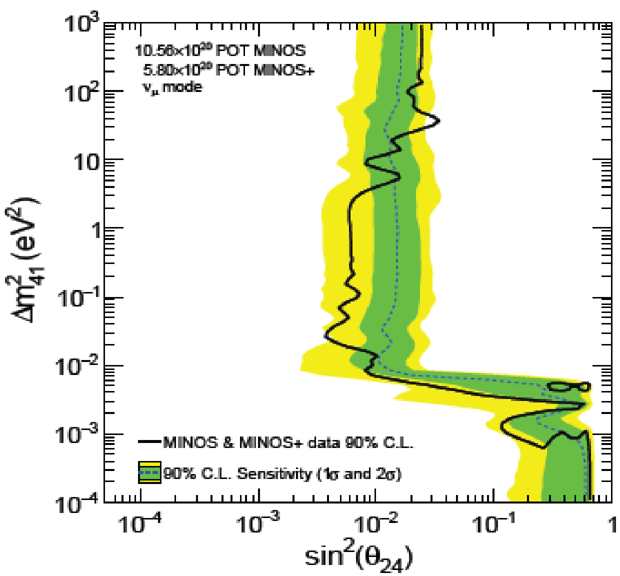


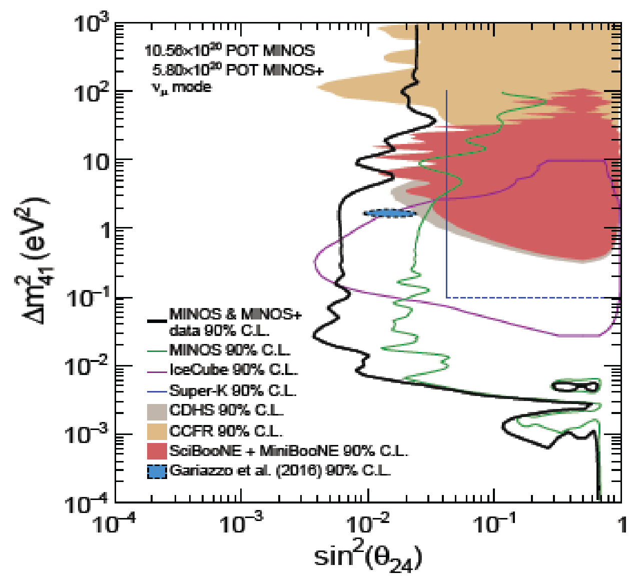
MINOS+



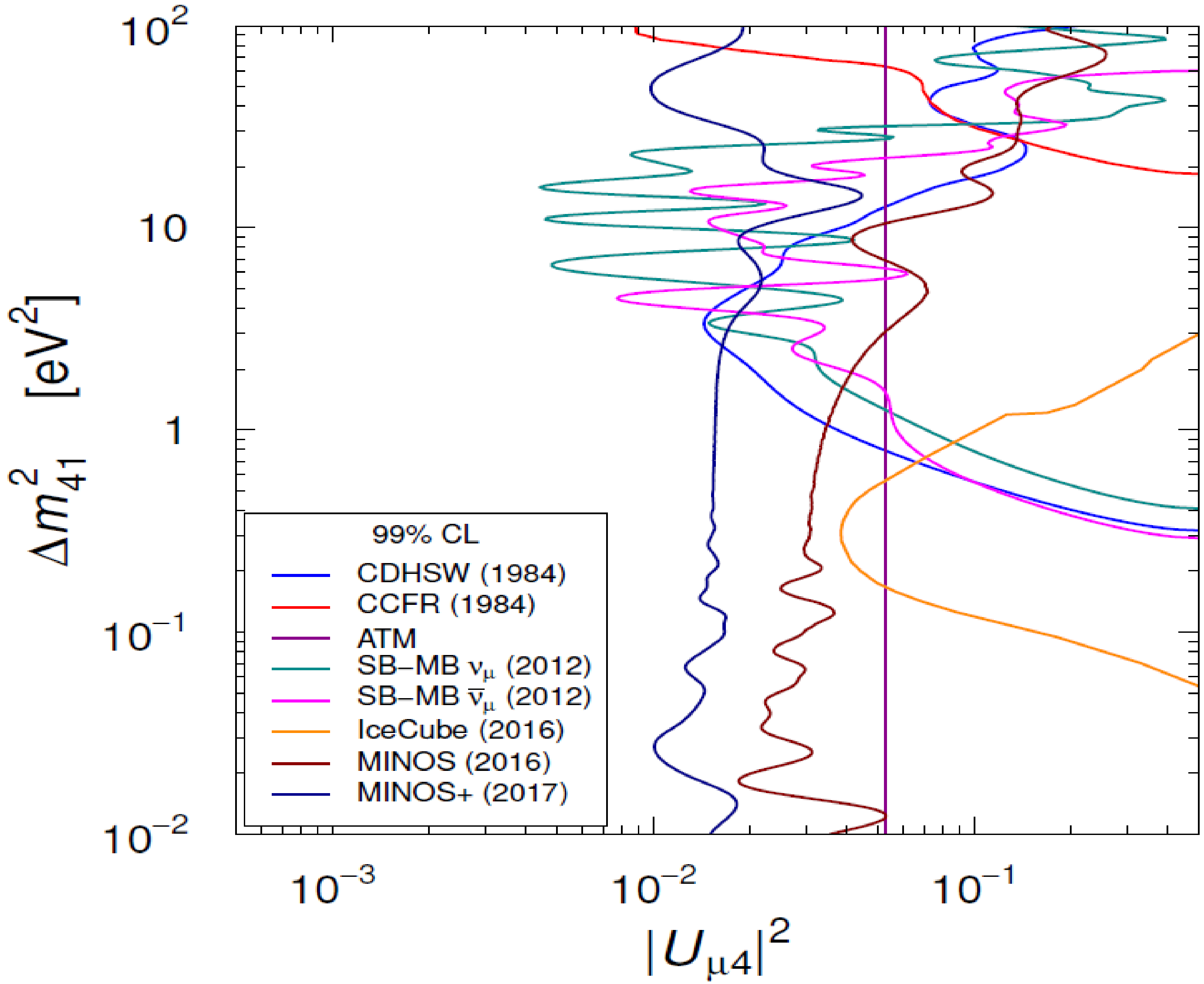
[arXiv:1710.06488]







All the results in (anti)ν_μ disappearance



Global fit of nu-e(bar) disappearance, nu-mu(bar)→nu-e(bar) and nu-mu(bar) disappearance data

Based on the latest update of

Gariazzo, Giunti, Laveder, YFL, arXiv:1703.00860

SBL oscillations in the 3+1 scheme

In SBL experiments $\Delta_{21} \ll \Delta_{31} \ll 1$.

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha4}|^2\left(1-|U_{\alpha4}|^2\right)$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

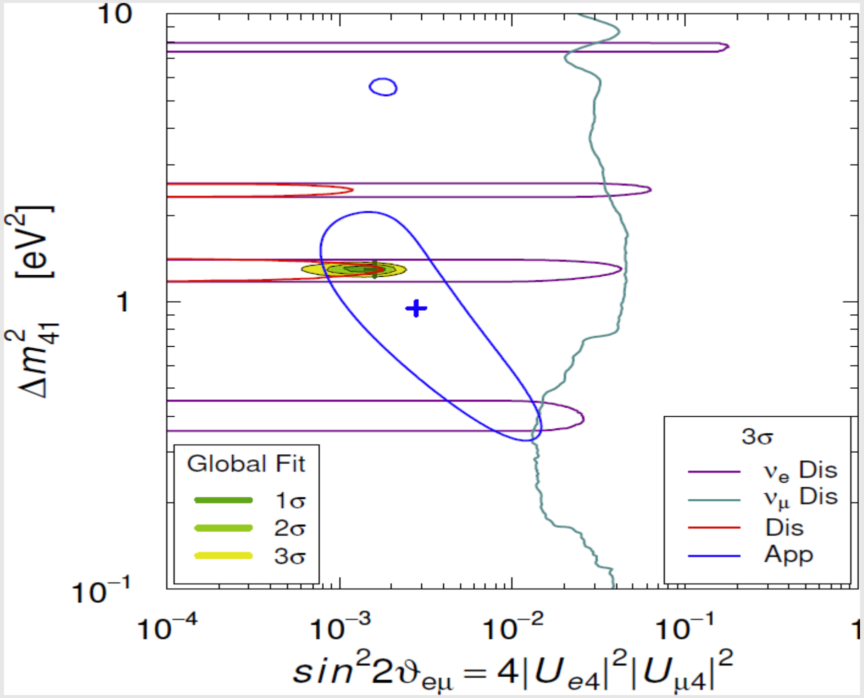
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

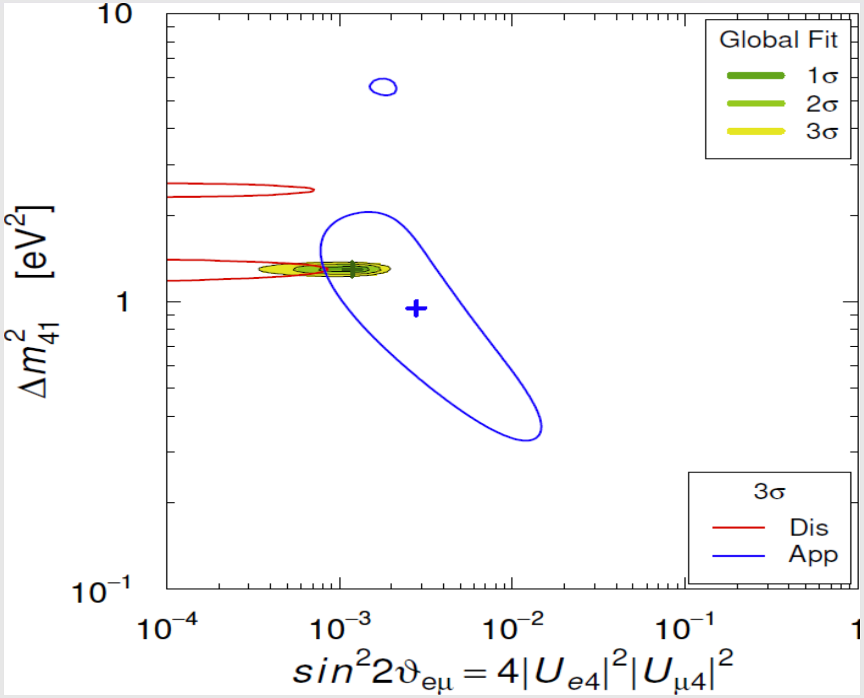
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, ..., 3+N_s! [Giunti, Zavanin, MPLA 31 (2015) 1650003]

Appearance-Disappearance Tension



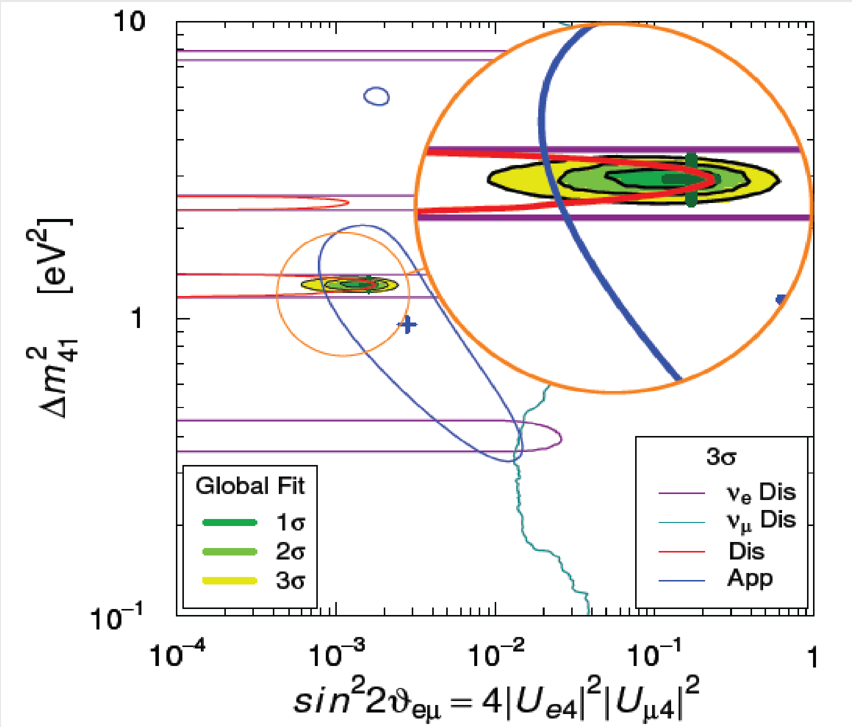


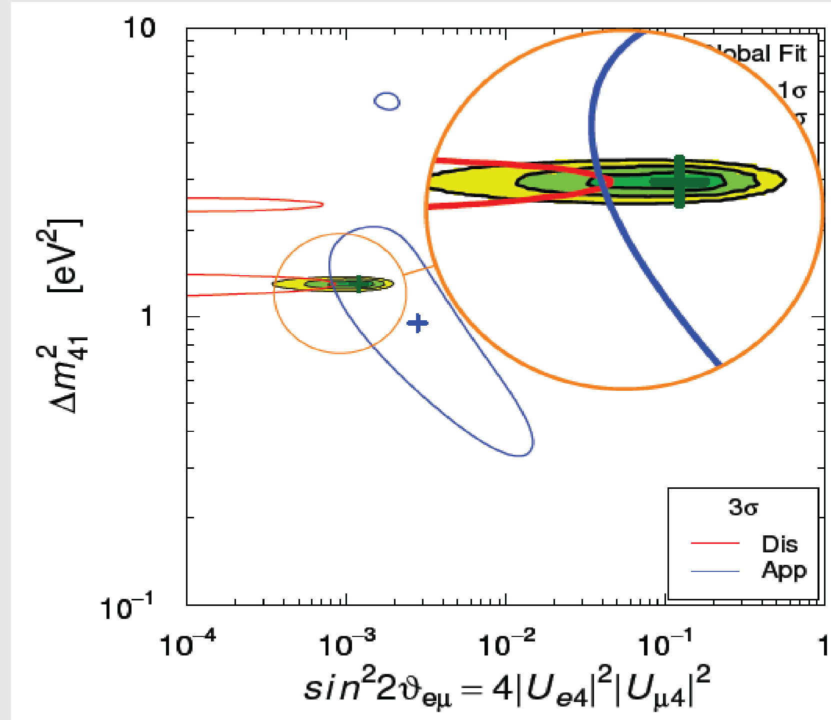
- **Without (left) and with (right) MINOS+ data (both without the MB low energy bins)**

$\chi^2_{PG}/\mathrm{NDF}_{PG} = 7.8/2 \Rightarrow \mathrm{GoF}_{PG} = 2\%$

$\chi^2_{PG}/\mathrm{NDF}_{PG} = 18.3/2 \Rightarrow \mathrm{GoF}_{PG} = 0.01\%$

Appearance-Disappearance Tension





- **Without (left) and with (right) MINOS+ data (both without the MB low energy bins)**

$\chi^2_{PG}/NDF_{PG} = 7.8/2 \Rightarrow GoF_{PG} = 2\%$

$\chi^2_{PG}/NDF_{PG} = 18.3/2 \Rightarrow GoF_{PG} = 0.01\%$

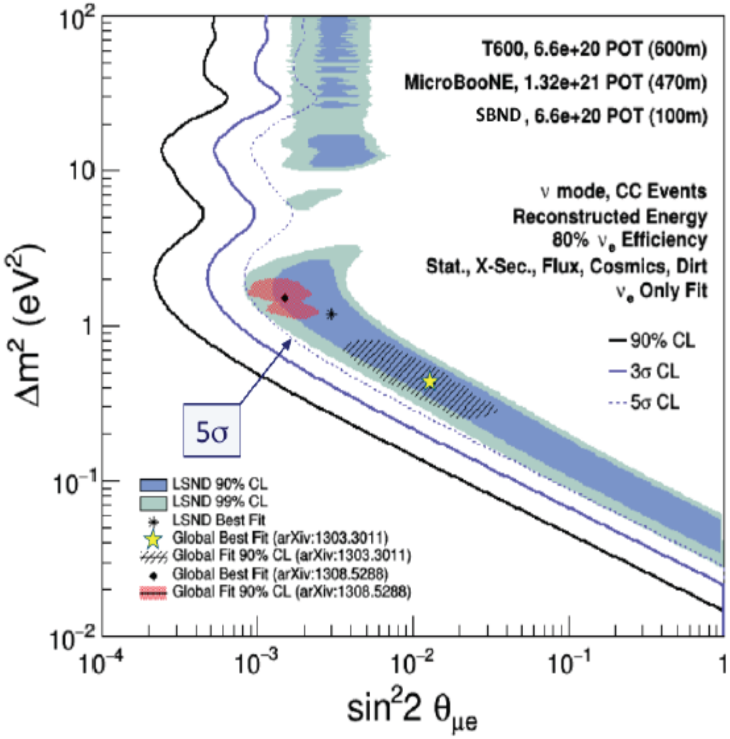
- **From Mild to Strong tension → New physics beyond 3+1 (3+N) vacuum mixing ??**

See also Dentler et. al., arXiv:1803.10661

Future test of the appearance channel

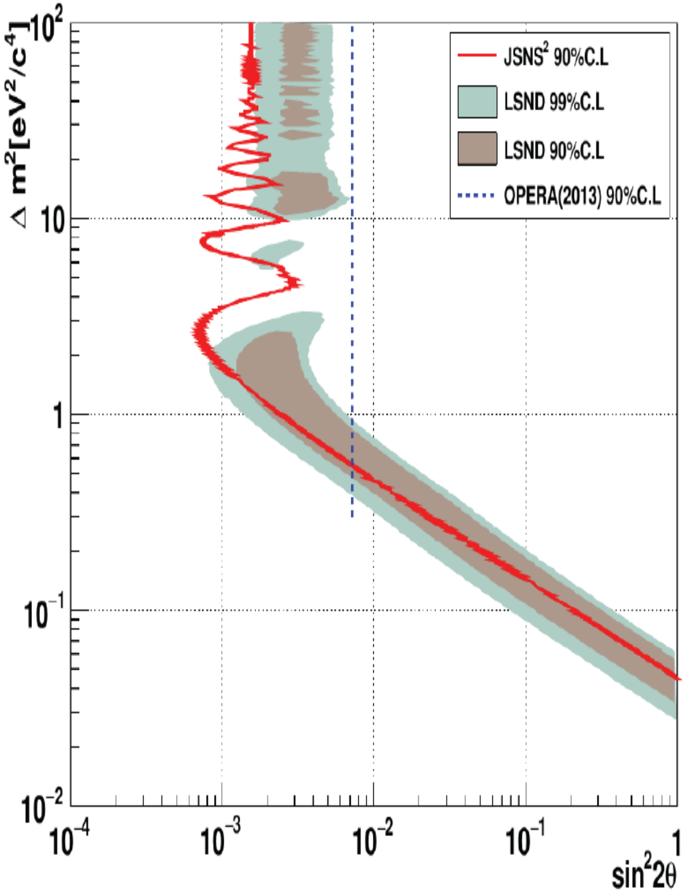
SBN PROGRAM @ FERMILAB

Definitive program to address LSND/MiniBoone anomalies in next ~5 years.



JSNS2 @ J-PARK

Sensitivity of the JSNS2 experiment with the latest configuration (1 MW × 3years × 1 detector).



Conclusion

a) Interesting model-independent indications of short baseline oscillations from reactors (DANSS & NEOS)

b) Reactor and Gallium Anomalies → Need revision of the U235 calculation and small decrease of the GALLEX and SAGE efficiencies. → consistent with the fuel evolution data

c) Many on-going experiments will check the indication in the next several years:

DANSS, NEOS, STEREO, Neutrino-4, PROSPECT, SoLid, CHANDLER, …

d) The MINOS+ result disfavors the LSND signal in the 3+1 (3+N) vacuum mixing scheme

→ future direct test at SBN@Fermi Lab and JSNS2@J-PARC

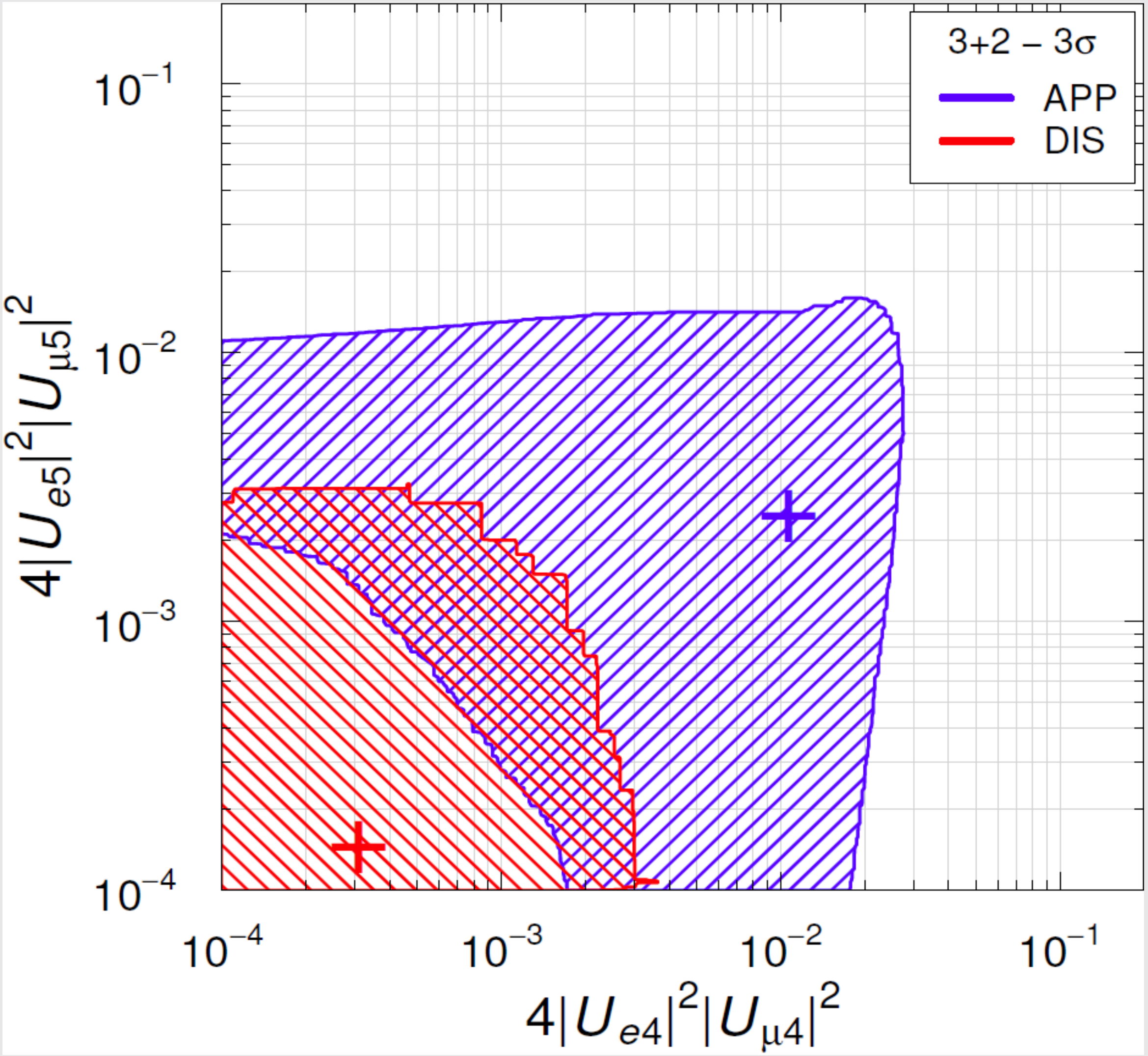
Thanks!

Backup

The 3+2 scheme and more

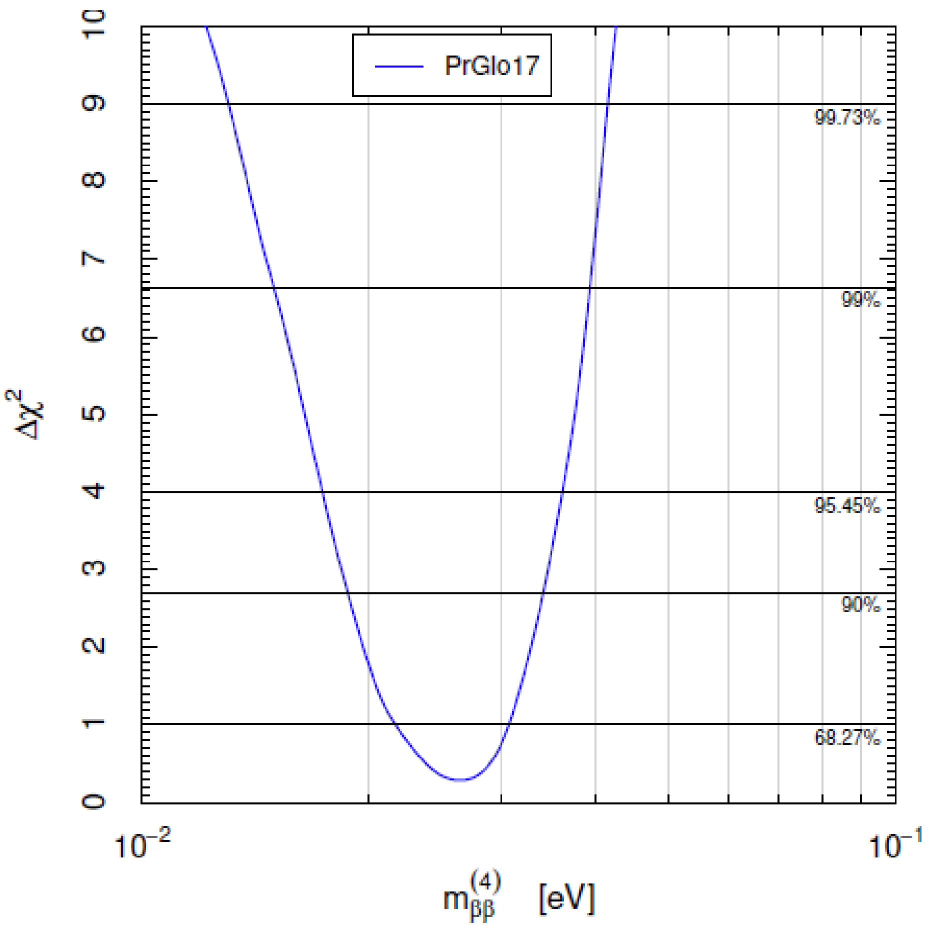
$$\sin^2 2\vartheta_{\alpha\beta}^{(k)} \simeq \frac{1}{4} \sin^2 2\vartheta_{\alpha\alpha}^{(k)} \sin^2 2\vartheta_{\beta\beta}^{(k)},$$

arXiv:1508.03172



Light Sterile Neutrinos@0νββ

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 + |U_{e4}|^2 e^{i\alpha_{41}} m_4$$



$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

warning:
possible cancellation
with $m_{\beta\beta}^{(3\nu)}$

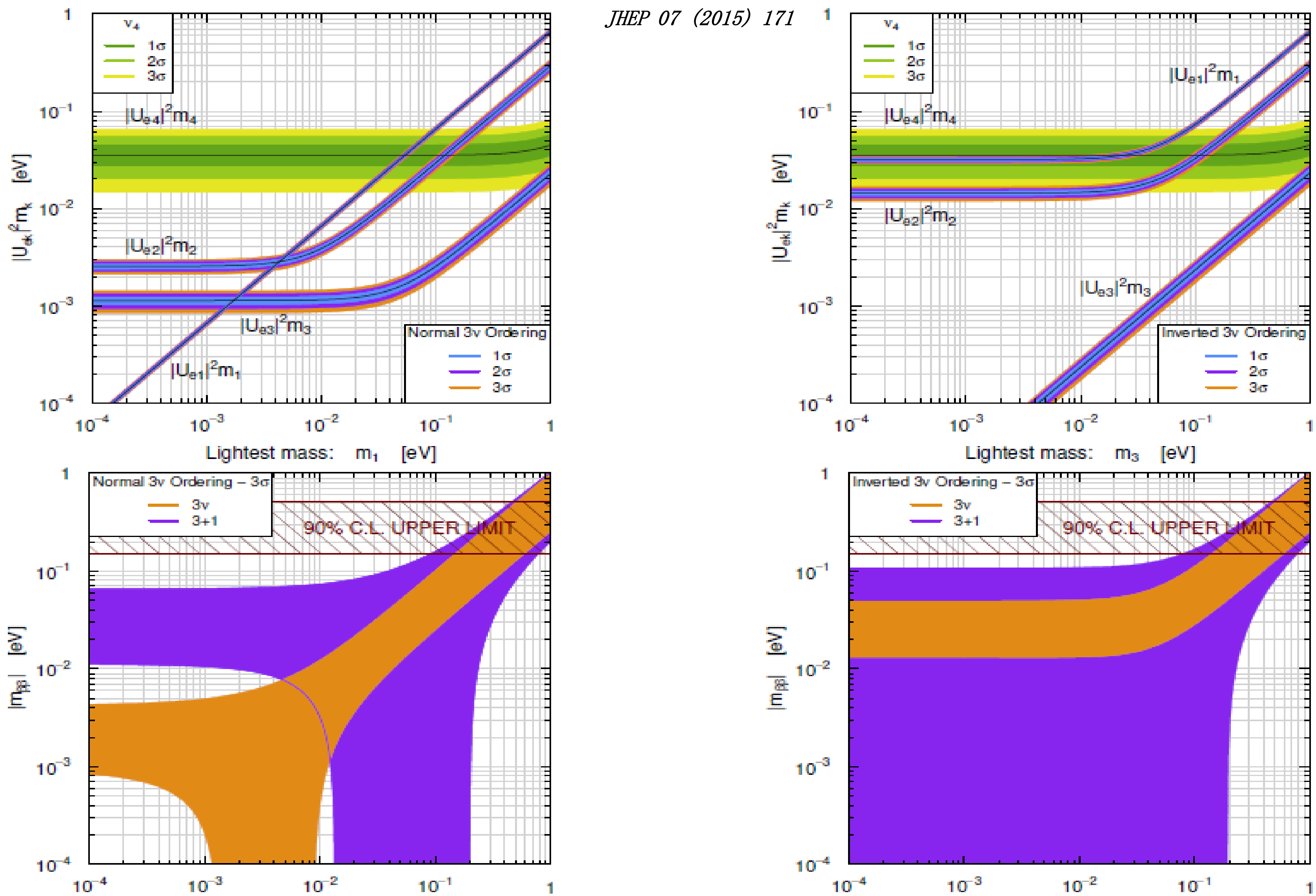
[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

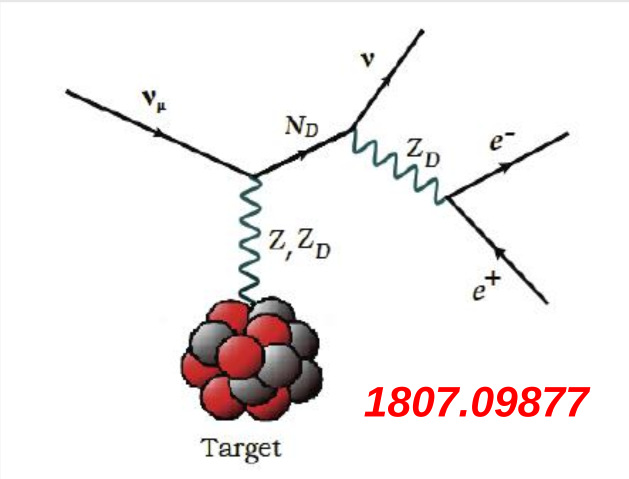
[Rodejohann, JPG 39 (2012) 124008]

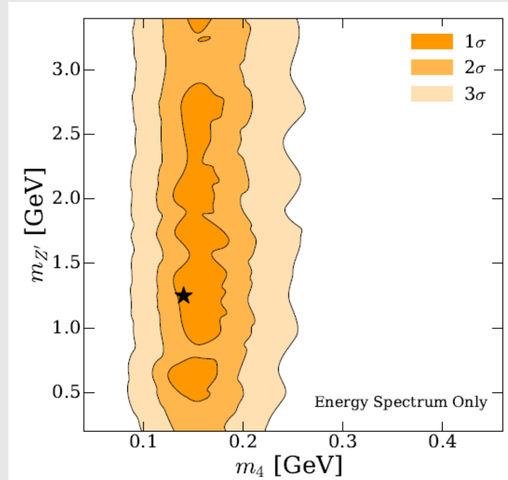
[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

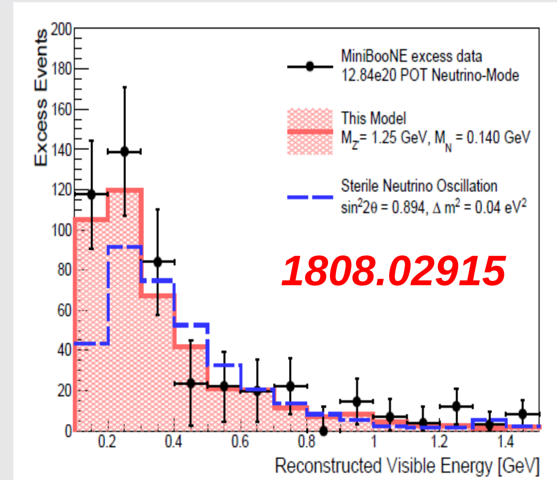
[CG, Zavanin, JHEP 07 (2015) 171]

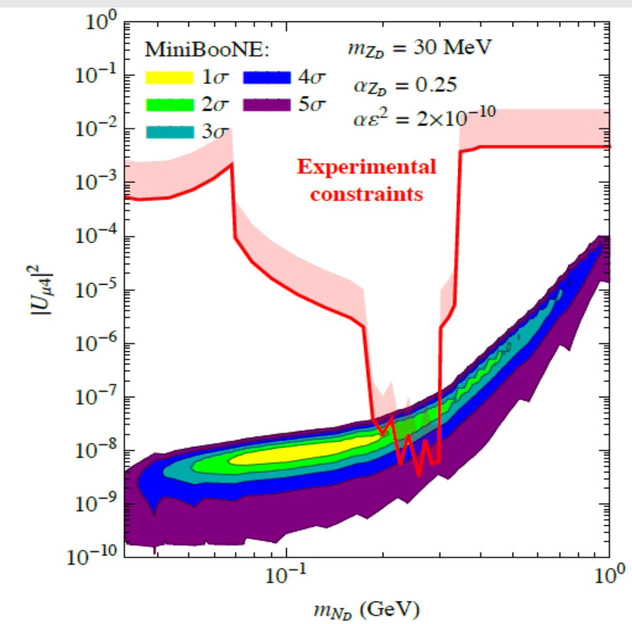

JHEP 07 (2015) 171
ν_4
1σ
2σ
3σ
$|U_{e4}|^2 m_4$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{e1}|^2 m_1$
Normal 3ν Ordering
Inverted 3ν Ordering
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_1 [eV]
Lightest mass: m_3 [eV]
Normal 3ν Ordering – 3σ
Inverted 3ν Ordering – 3σ
3ν
3+1
90% C.L. UPPER LIMIT
$|m_{\beta\beta}|$ [eV]

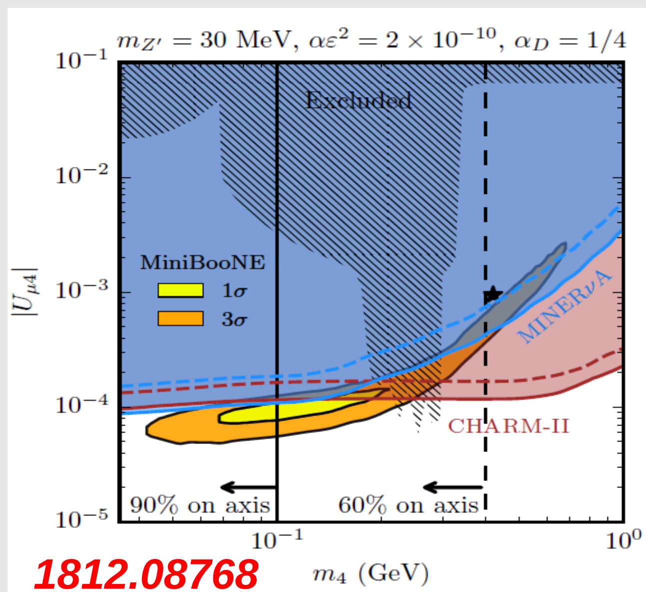
Examples of New Physics for the MB Excess











See also other models and constraints: 1810.07185; 1810.01000; 1808.07460