Global status of eV-scale sterile neutrinos

Yu-Feng Li

liyufeng@ihep.ac.cn

Institute of High Energy Physics, Beijing

Neutrino Oscillation Workshop 2018

9-16 September 2018, Rosa Marina, Ostuni, Italy

Three Neutrino Paradigm

Standard Parameterization of Mixing Matrix

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

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

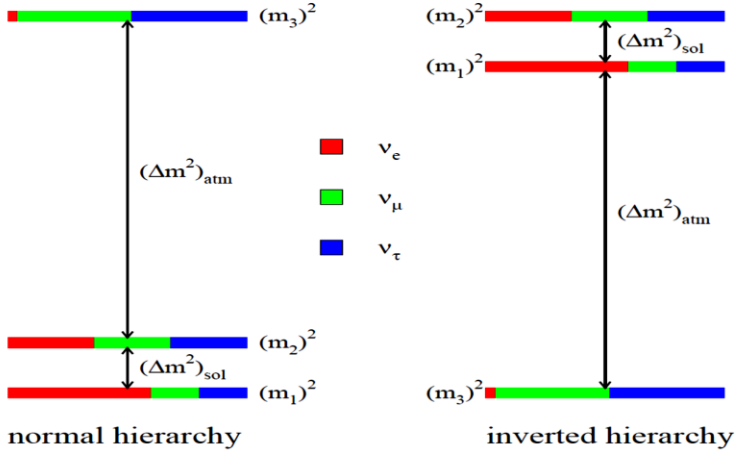
$$c_{ab} \equiv \cos\vartheta_{ab} \qquad s_{ab} \equiv \sin\vartheta_{ab} \qquad 0 \le \vartheta_{ab} \le \frac{\pi}{2} \qquad 0 \le \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$$

3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}

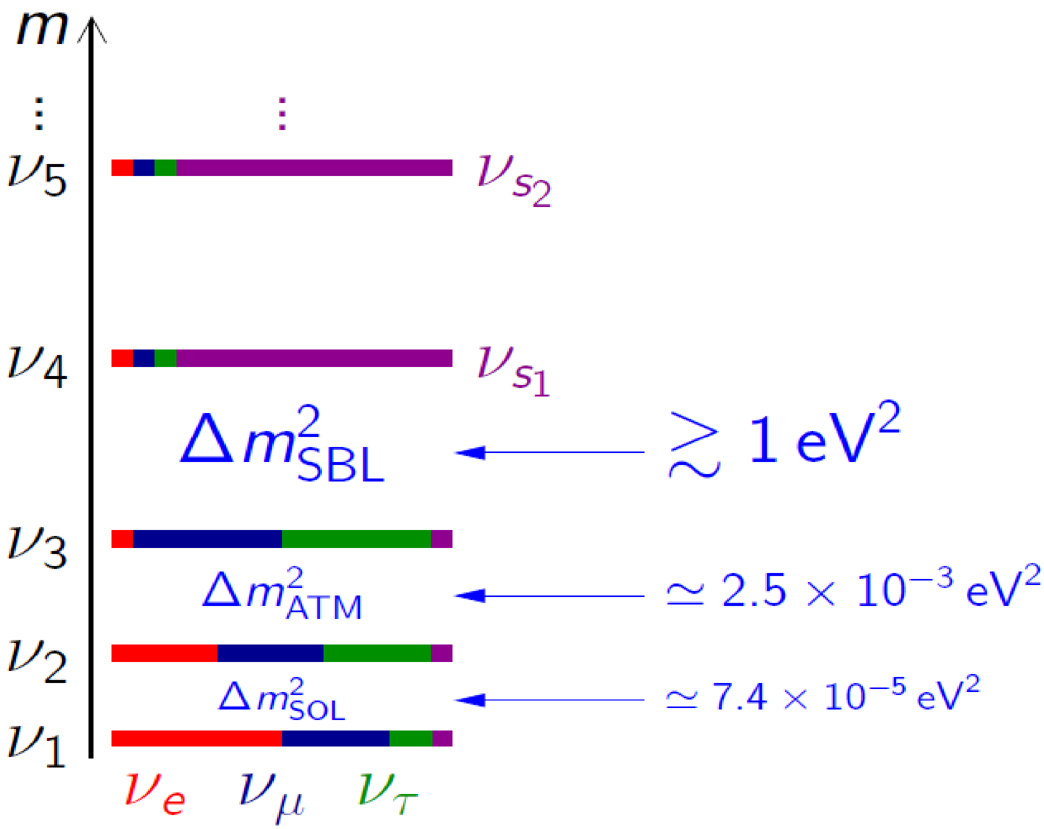
1 CPV Dirac Phase: δ_{13}

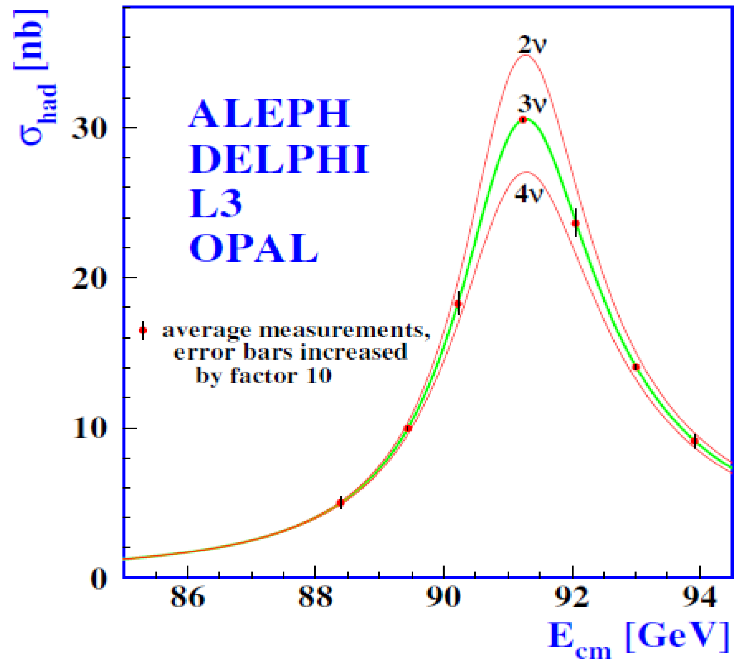
2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

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



Beyond 3-ν oscillations: sterile neutrinos





$$N^{LEP}_{\nu_{active}} = 2.9840 \pm 0.0082$$

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

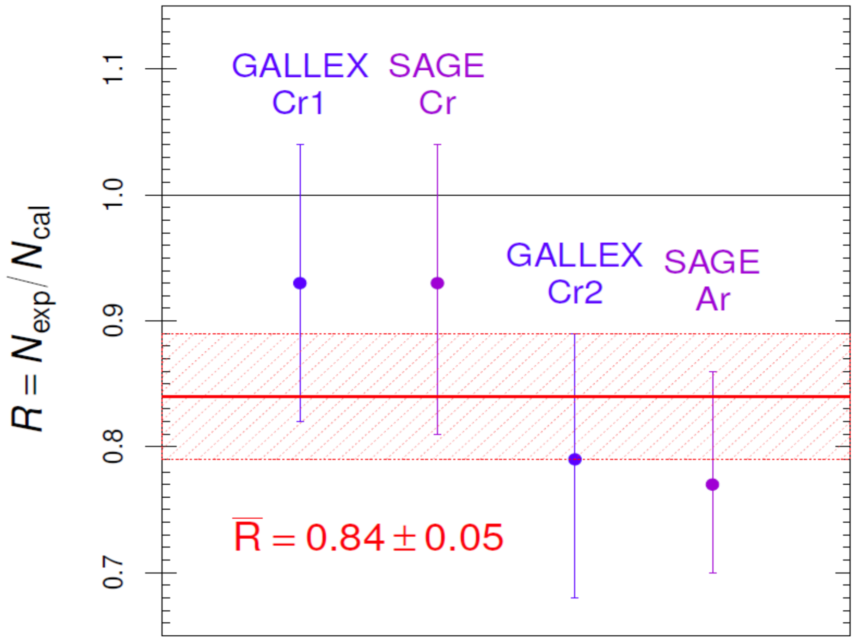
SAGE, PRC (2006); PRC (2009); Laveder et al. (2007), etc.

Gallium Radioactive Source Experiments: GALLEX and SAGE

Test of Solar Neutrino Detection

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

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



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

- **~2.9σ deficit**

Neutrino energies: ~0.8 MeV

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

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

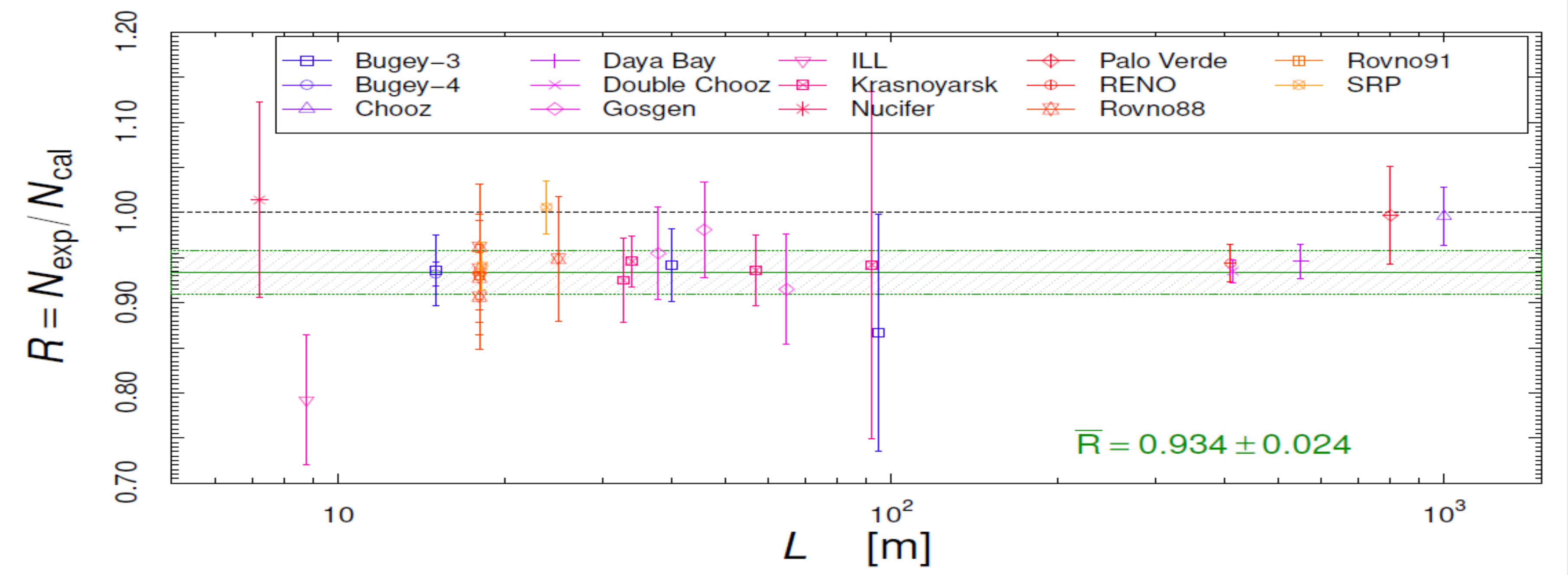
$${}^{3}\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^{3}\text{H}$$

Frekers et al., PLB 706 (2011) 134

Reactor Antineutrino Anomaly

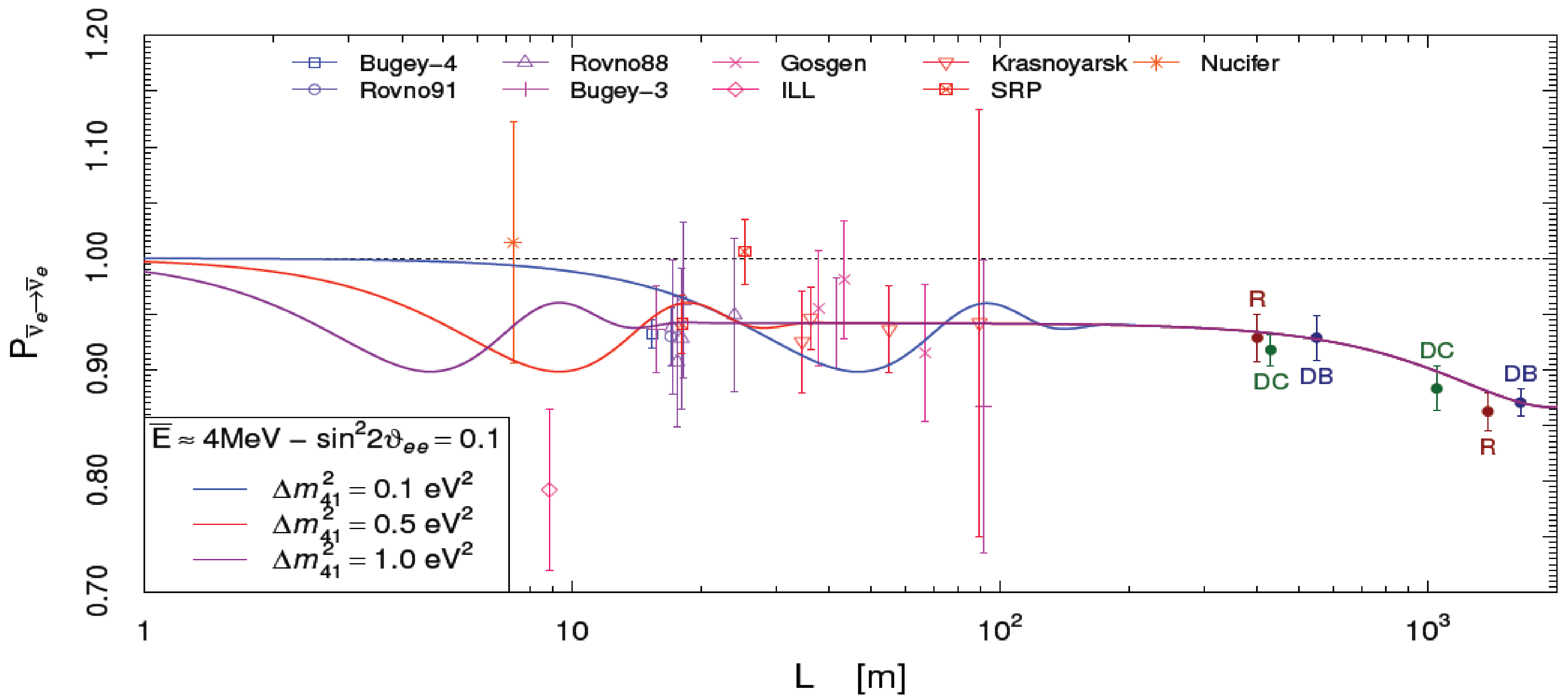
[Mention et al, PRD 83 (2011) 073006]

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%**

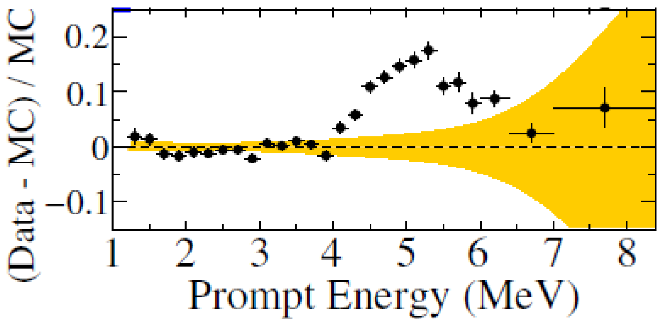
Reactor Antineutrino Anomaly



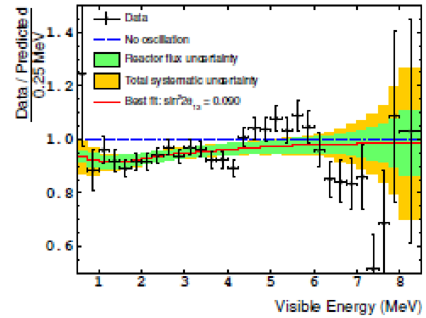
$$\Delta m^2_{\mathrm{SBL}} \gtrsim 0.5\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$$

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

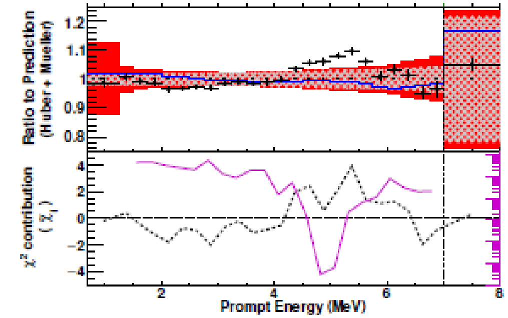
New spectral feature @ reactors



[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 the rate and spectrum?

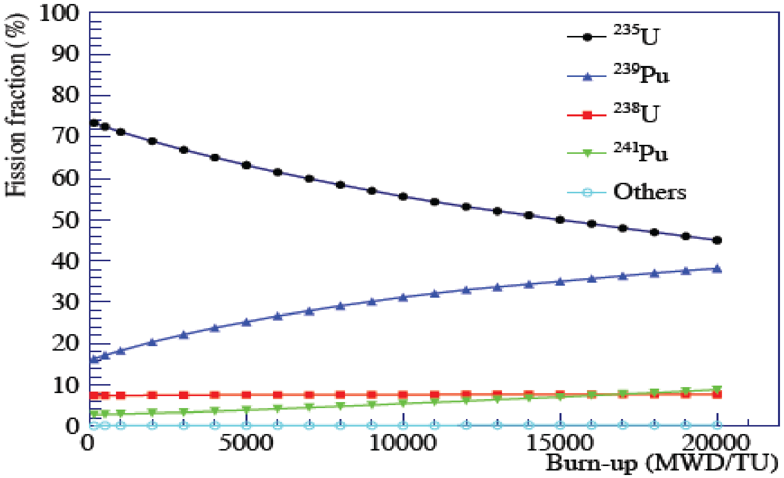
(3) Detector energy nonlinearity? ***[Mention et al, PLB 773 (2017) 307]***
(Daya Bay and Double CHOOZ already achieved the 0.5% precision)

(4) Some guess to increase the uncertainty: e.g. about 5%.
[Hayes and Vogel, 2016]

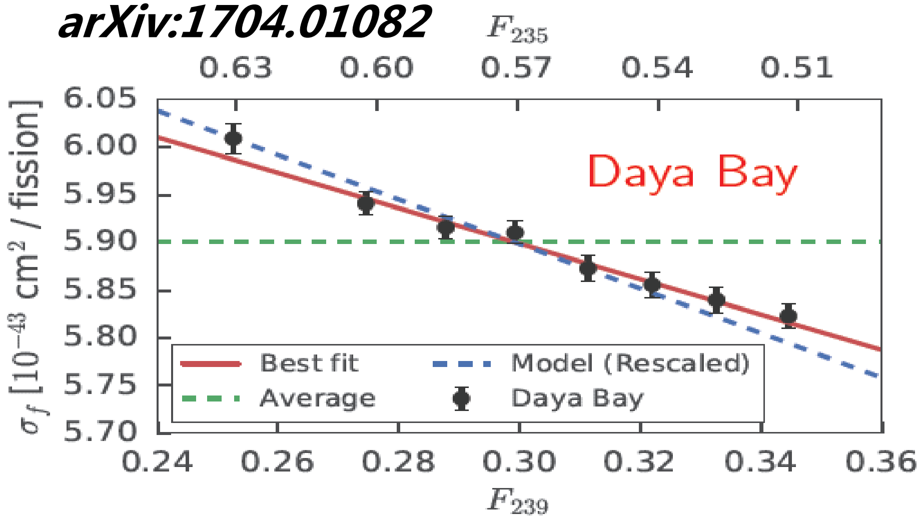
New burn-up feature @ reactors

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

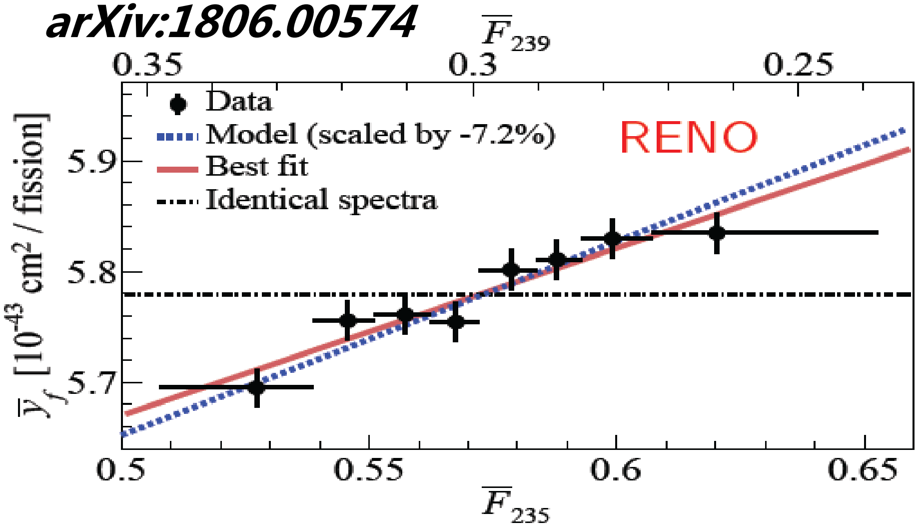
$$\sigma_f = \sum_{k=235,238,239,241} F_k \, \sigma_{f,k}$$



arXiv:1704.01082

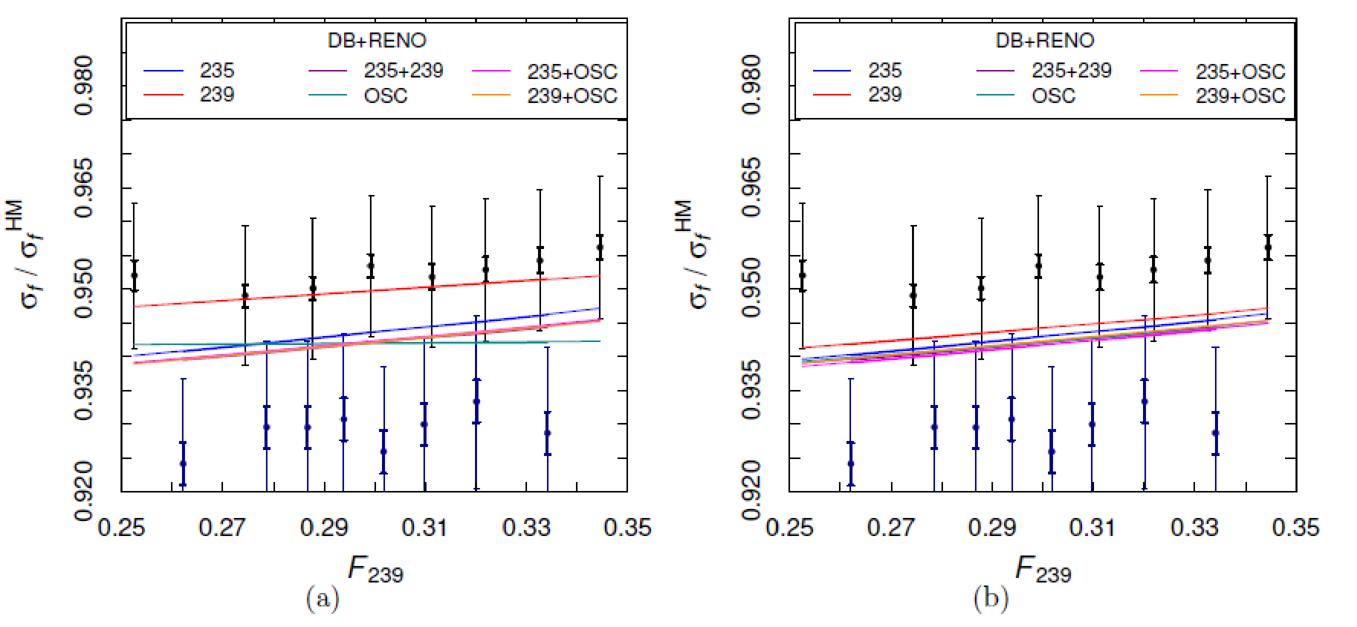


arXiv:1806.00574



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

Comparison and combination of DYB and RENO



	HM	HM uncertainties	extended uncertainties
$\sigma_{f,235}$	6.69	2.44%	5%
$\sigma_{f,238}$	10.10	8.15%	10%
$\sigma_{f,239}$	4.40	2.88%	5%
$\sigma_{f,241}$	6.03	2.60%	5%

	235	239	235+239	OSC	235+OSC	239+OSC
$\chi^2_{\min}$	10.2	12.4	9.9	10.9	10.0	10.1
NDF	15	15	14	15	14	14
GoF	80%	65%	77%	76%	76%	76%
P_{ee}	–	–	–	0.958 ± 0.031	0.979 ± 0.029	0.926 ± 0.045
r_{235}	0.919 ± 0.016	(0.925)	0.917 ± 0.016	(0.963)	0.937 ± 0.037	(0.998)
r_{238}	(0.979)	(0.966)	(1.001)	(1.007)	(1.003)	(1.000)
r_{239}	(0.978)	0.972 ± 0.038	0.965 ± 0.038	(1.023)	(0.998)	1.090 ± 0.085
r_{241}	(0.995)	(1.004)	(1.002)	(1.010)	(1.001)	(1.002)
$\Delta\chi^2_{\rm PG}$	1.5	-0.5	1.9	1.5	2.0	2.0
$\mathrm{GoF_{PG}}$	35%	11%	39%	21%	35%	35%

Extended uncertainties

work in progress (2018) (Giunti, YFL, et. al)

(1) The 2% rate difference may be compensated by the systematic uncertainties of the Daya Bay (1.44%) and RENO (1.36%)

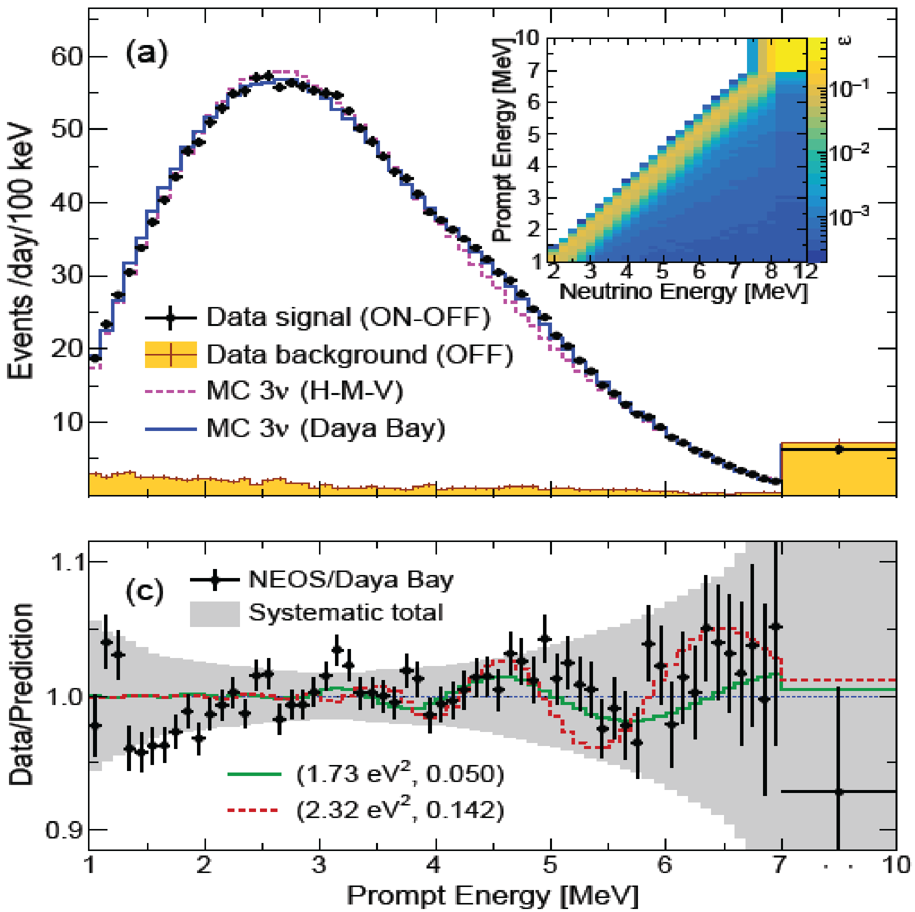
(2) Hybrid solutions fit better →

Model independent spectral-ratio method!

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.

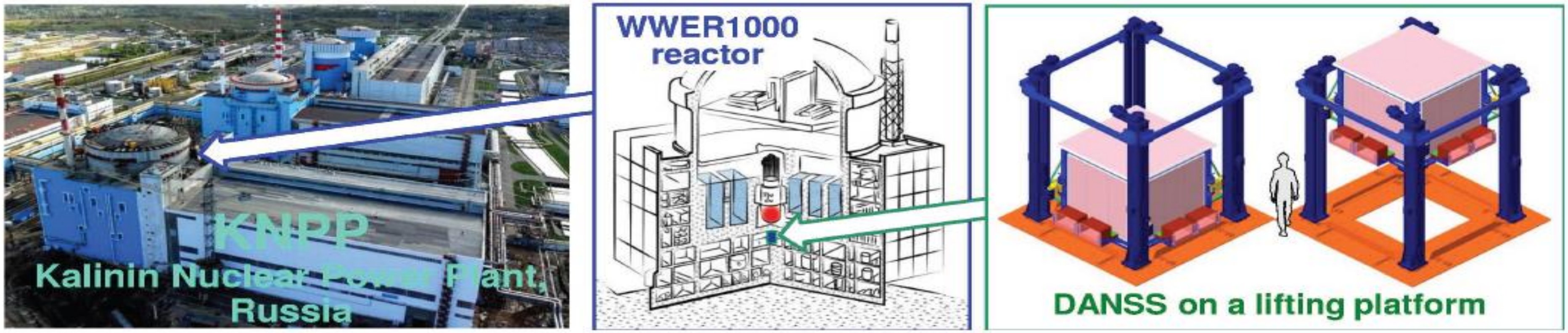
Spectral ratio result@DANSS

talk by Dmitry Svirida

DANSS

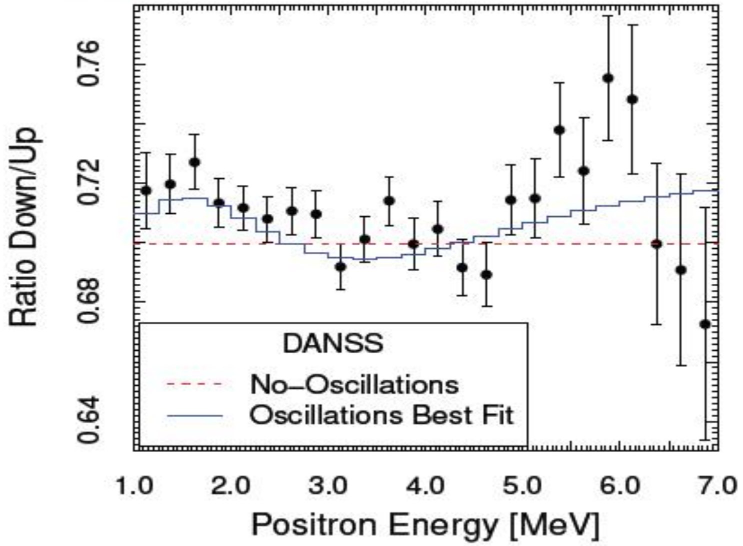
[Solvay Workshop, 1 December 2017; La Thuile 2018, 3 March 2018; Neutrino 2018, 8 June 2018]

Detector of reactor AntiNeutrino based on Solid Scintillator



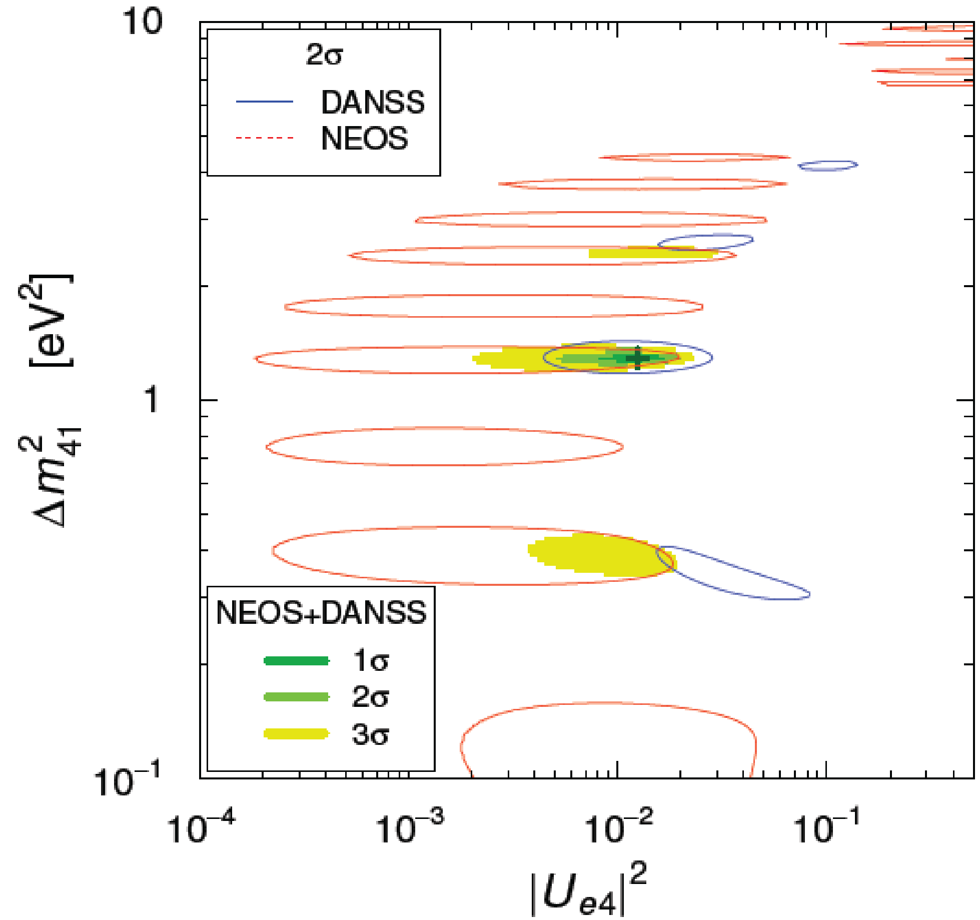
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

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



Model independent SBL oscillations

Gariazzo, Giunti, Laveder, YFL, PLB 782 (2018) 13, arXiv:1801.06467



$\sim 3.7\sigma$

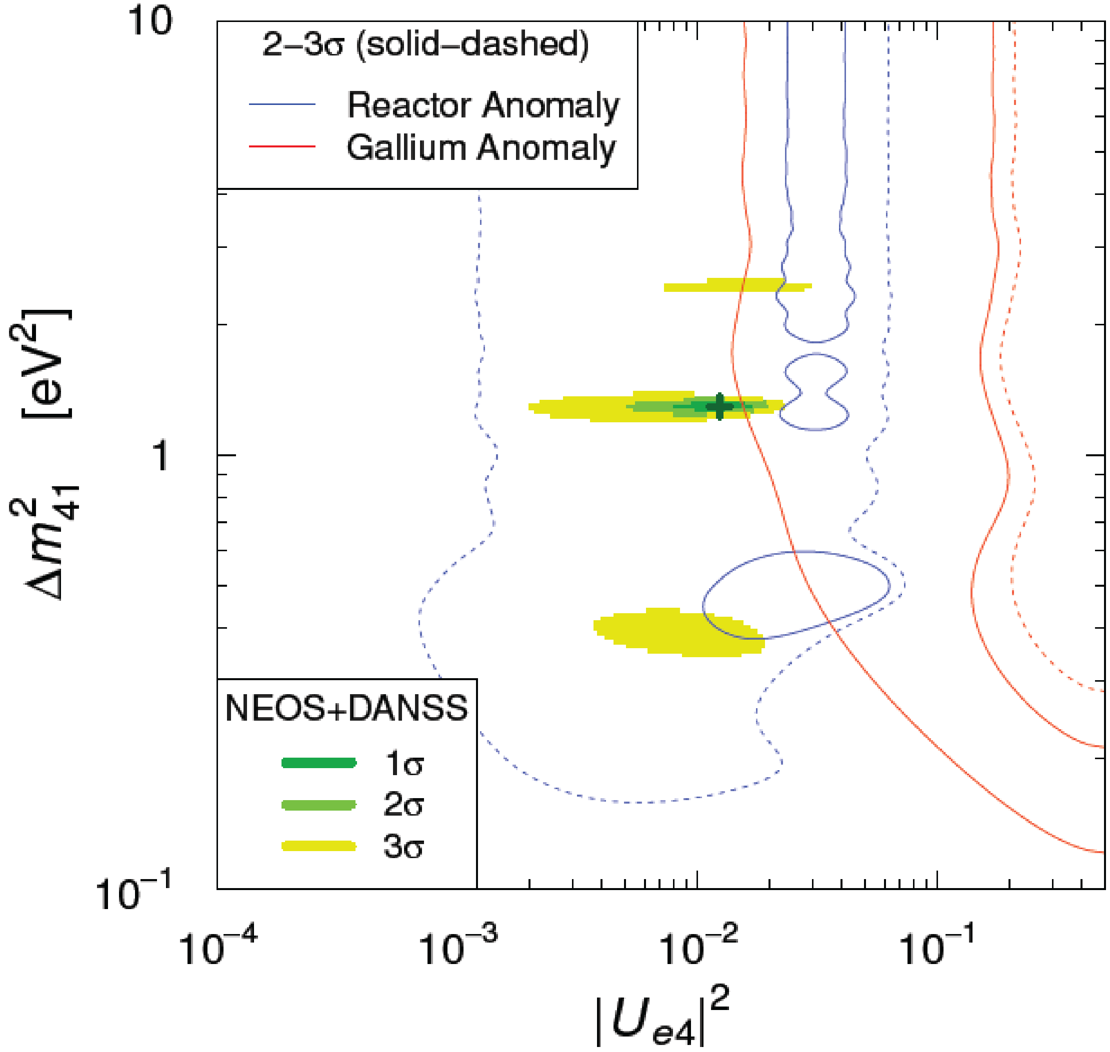
$$\Delta m^2_{41} = 1.29 \pm 0.03$$

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

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

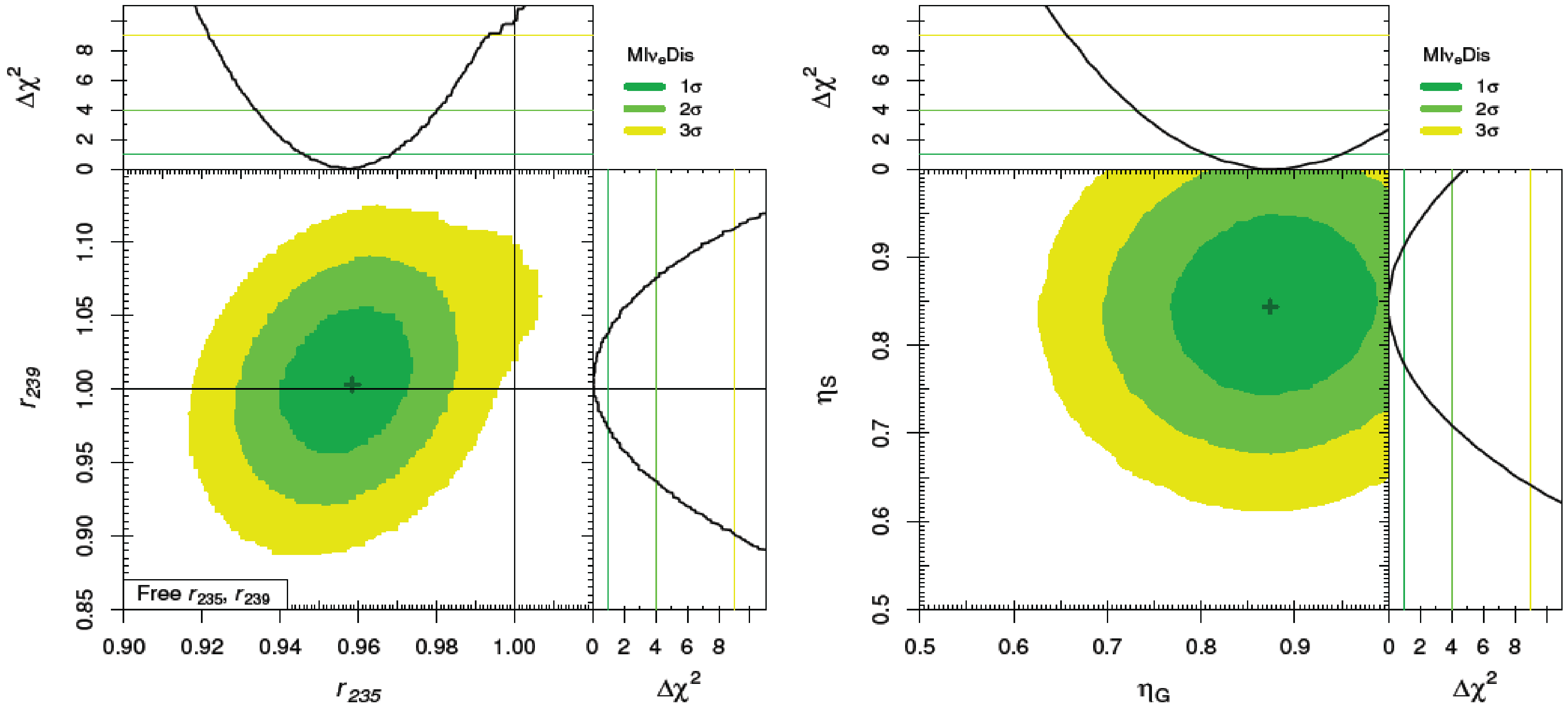
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Implications for Reactor and Gallium anomalies



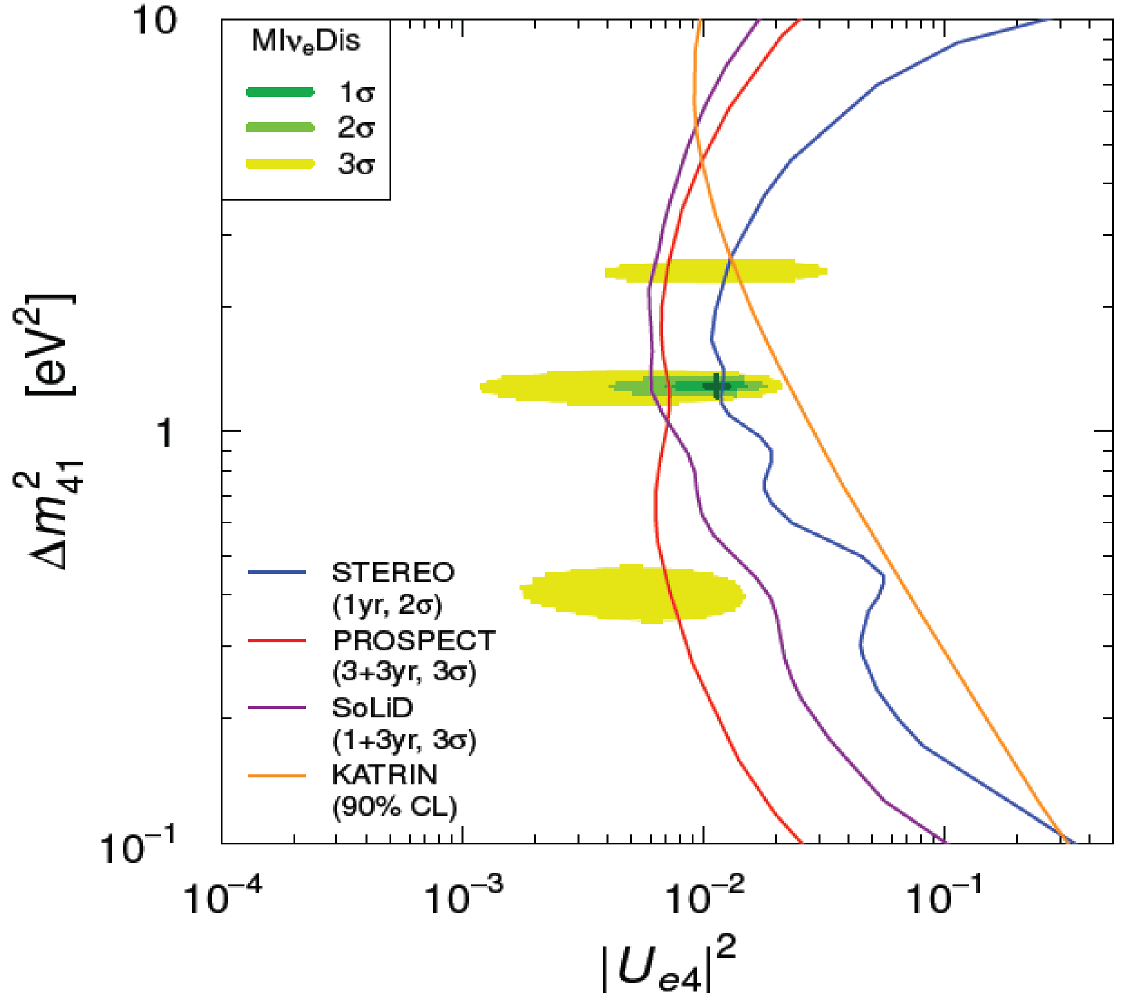
- 3σ agreement.
- 2σ tension.
- Small overestimate of the reactor fluxes.
- Small overestimate of the GALLEX and SAGE efficiencies.

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



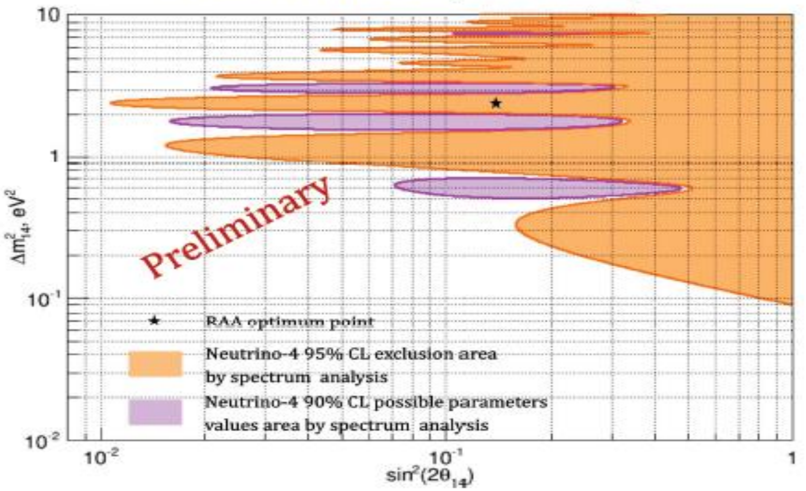
- NEOS and DANSS.
- Reactor rates with free ^{235}U and ^{239}Pu fluxes: r_{235} and r_{239}.
- Gallium data with free GALLEX and SAGE efficiencies: η_G and η_S.
- New reactor experiments: STEREO, Neutrino-4, SoLiD, PROSPECT
- Kinematic ν_4 mass measurement: KATRIN

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

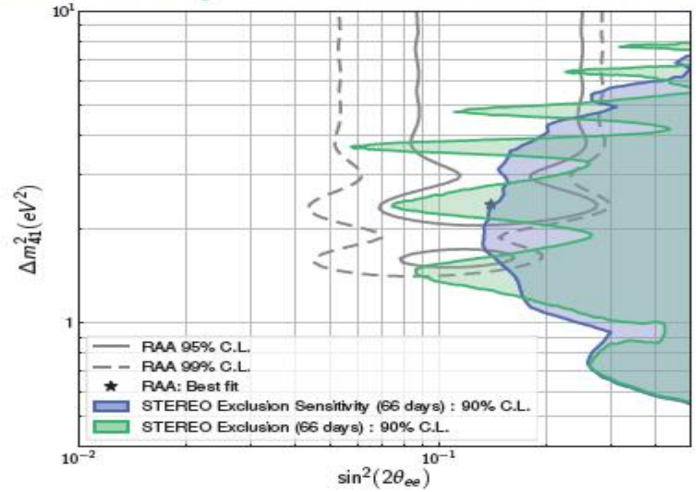
Latest spectral ratio results

talk by Victoriya Sergeyeva

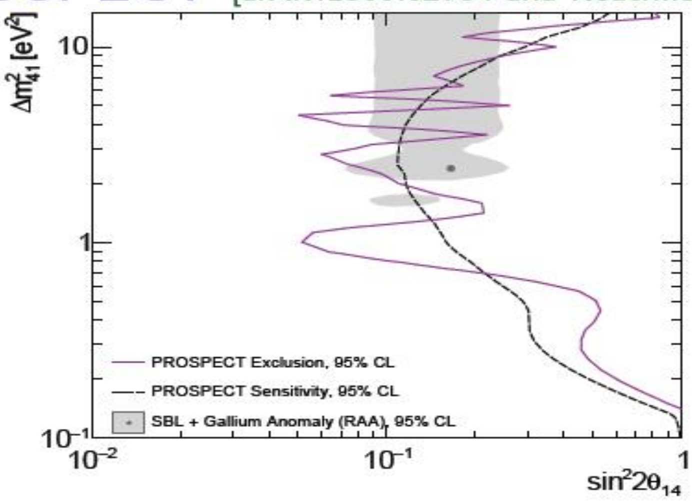
Neutrino-4 [PPNS 2018]

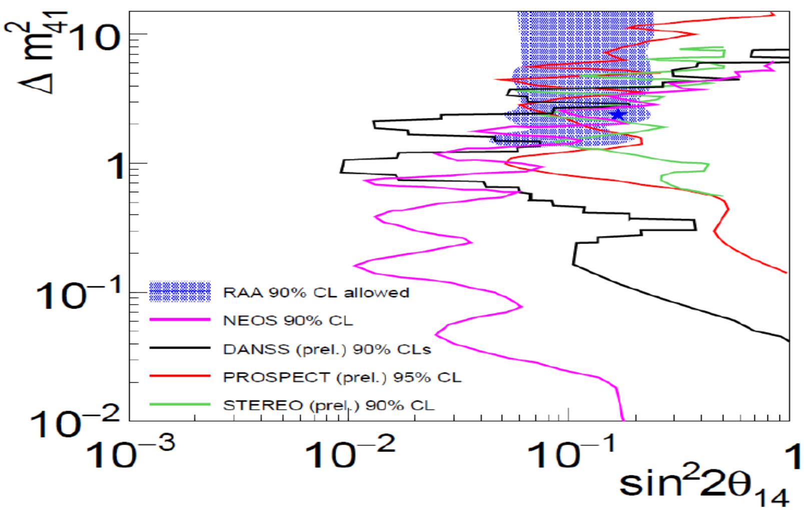


STEREO [arXiv:1806.02096 and Neutrino 2018]



PROSPECT [arXiv:1806.02784 and Neutrino 2018]





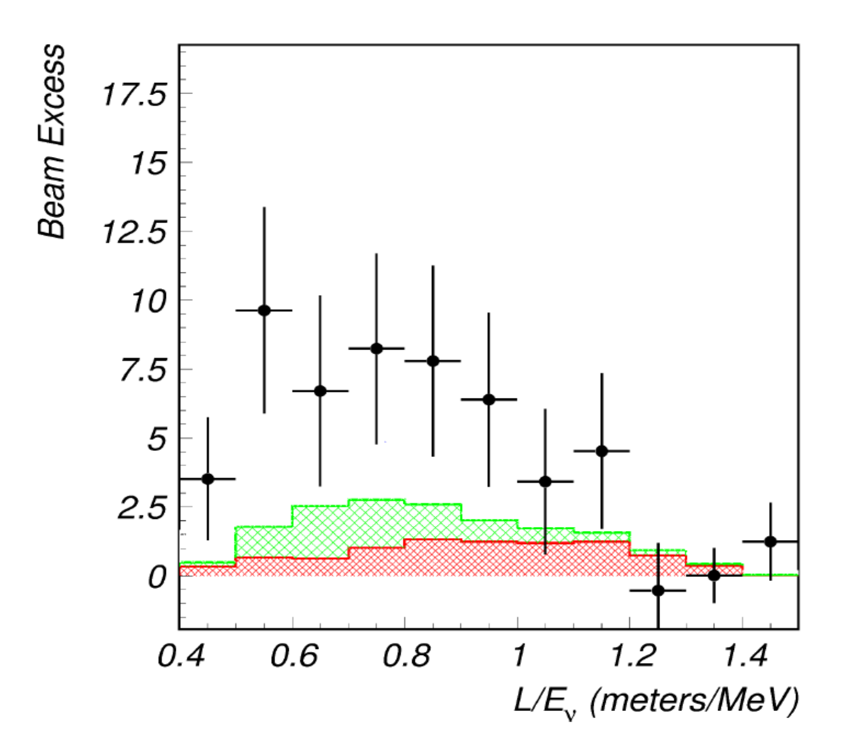
X. Qian and J-C Peng, arXiv:1801.05386

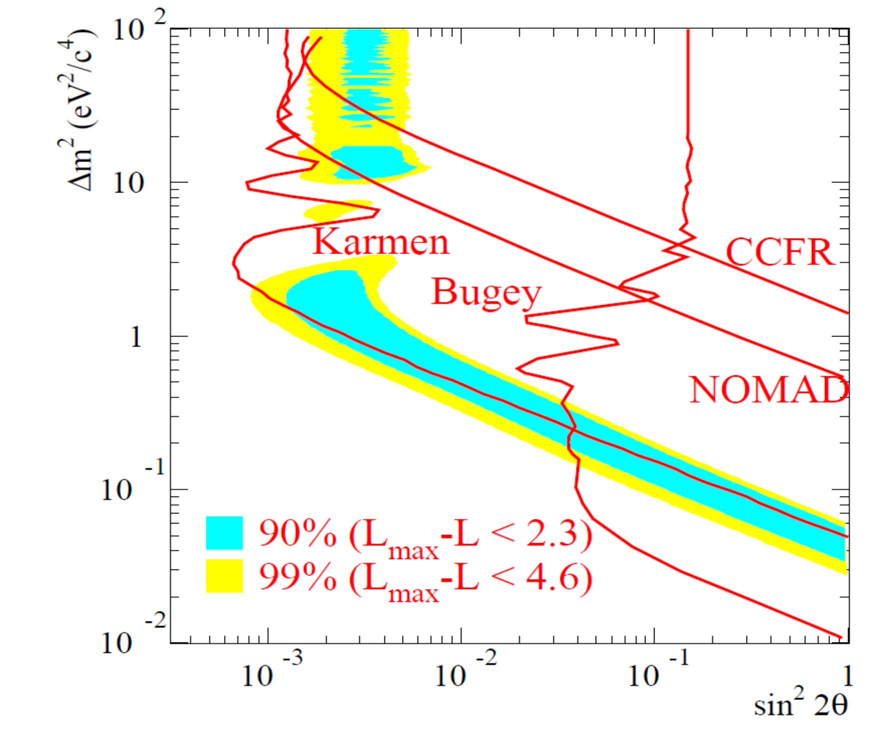
From Chao Zhang @Nufact2018

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:**

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

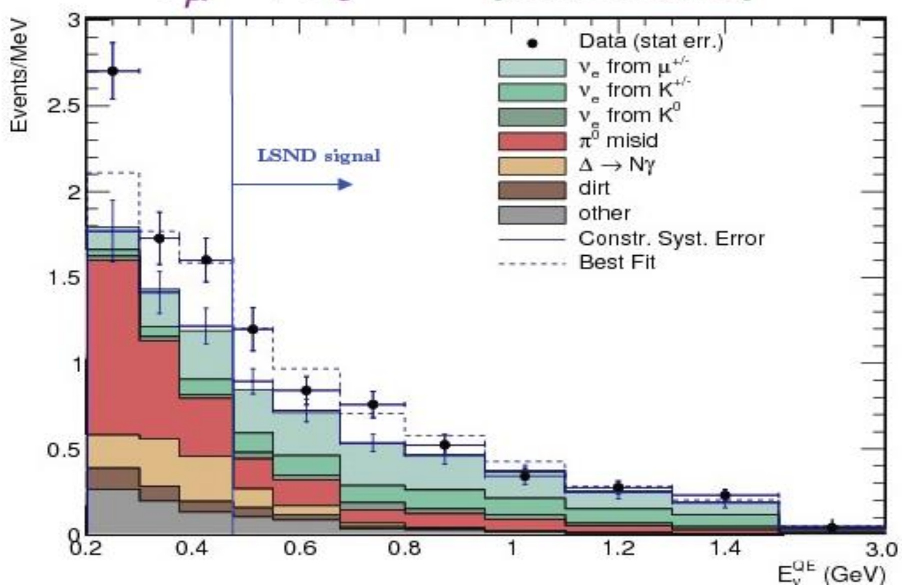
3.8σ excess $\qquad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

MiniBooNE

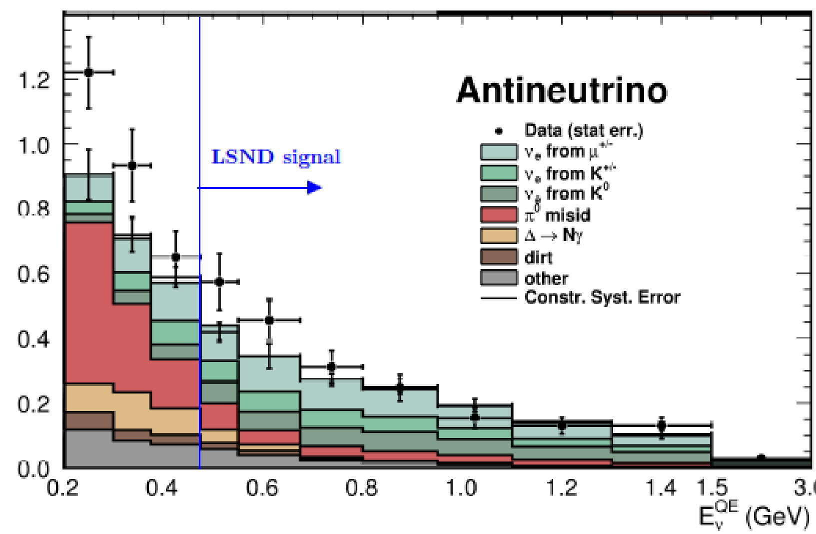
See the talk by Prof. Michael Shaevitz

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

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



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

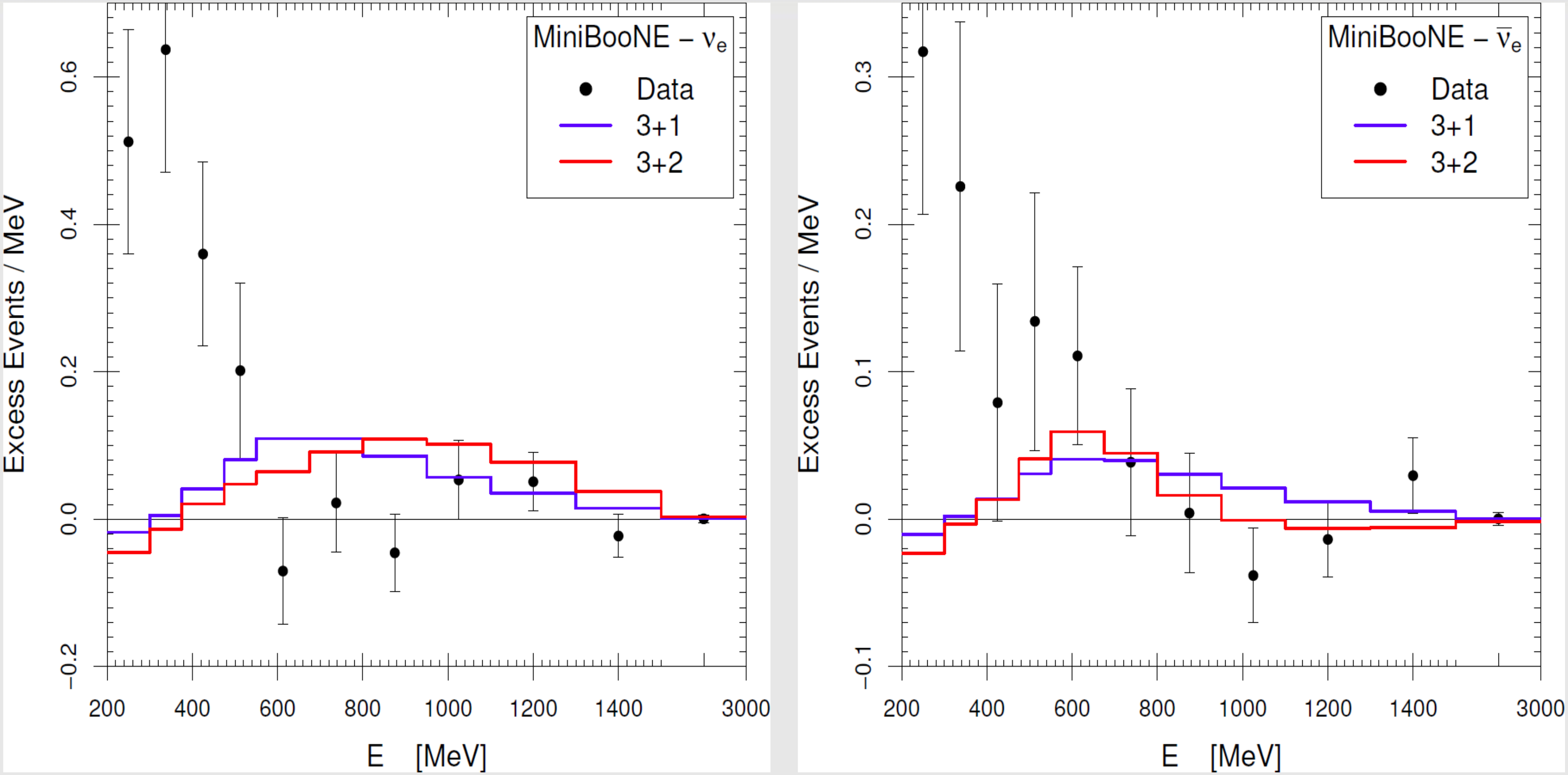


Purpose: check LSND signal with different L&E, but the same L/E (>475 MeV)

~3σ excess in the Low energy range: unidentified backgrounds?
→ MicroBooNE.

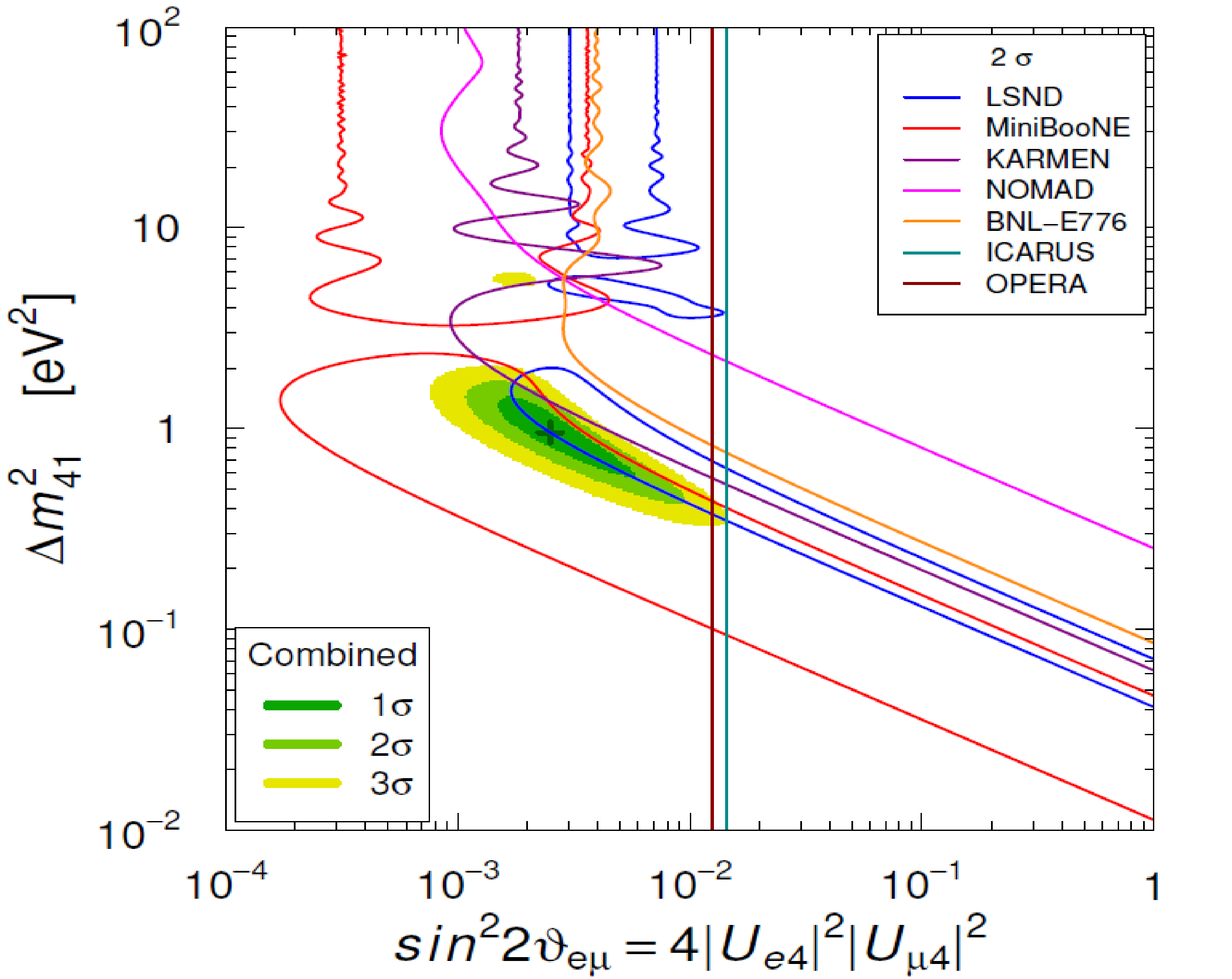
A pragmatic approach: (E>475 MeV) *[arXiv: 1308.5288]*

MiniBooNE low energy bins



Fit of MB Low-Energy Excess requires
small mass splitting and large mixing angle, which are in contradiction with the disappearance data (and solar & atmospheric data).

Appearance data



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

Based on the 2018 update of

Gariazzo, Giunti, Laveder, YFL, arXiv:1703.00860

Effective SBL oscillation in 3+1 schemes

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

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

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

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

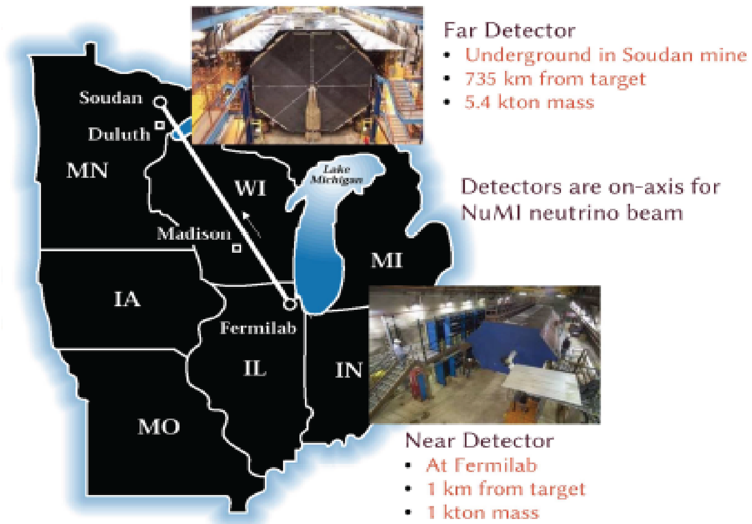
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

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

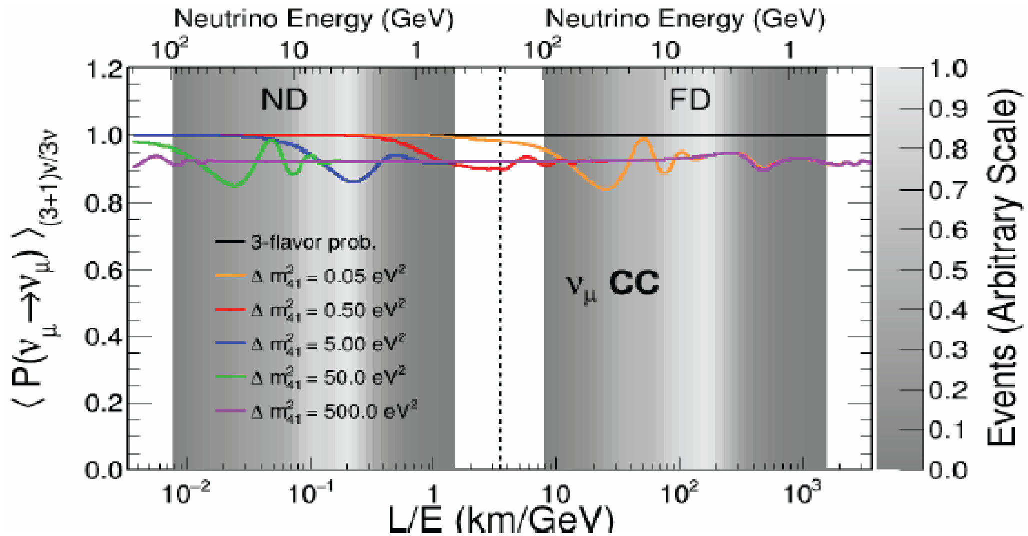
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

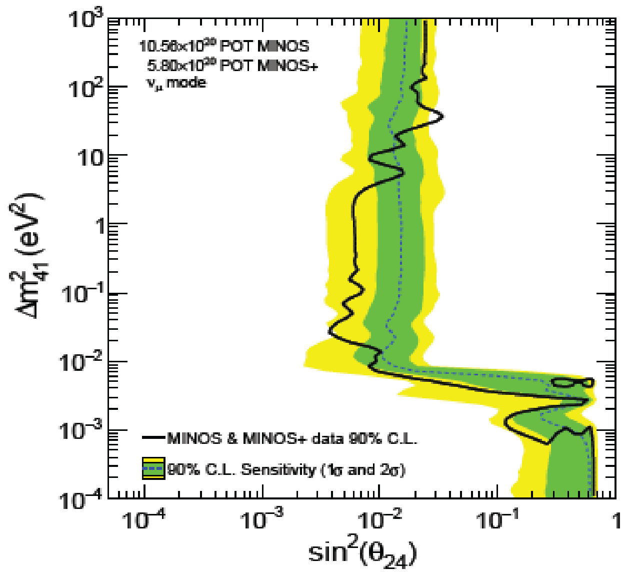
- Similar constraint in 3+2, 3+3, ..., 3+N_s! [Giunti, Zavanin, MPLA 31 (2015) 1650003]

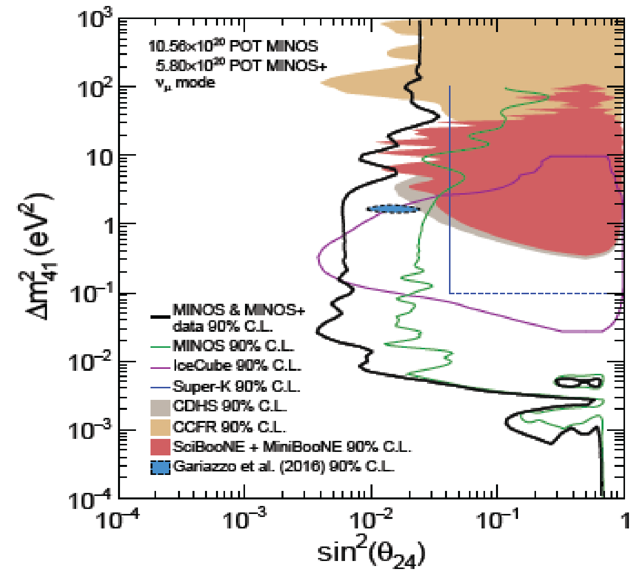
MINOS+



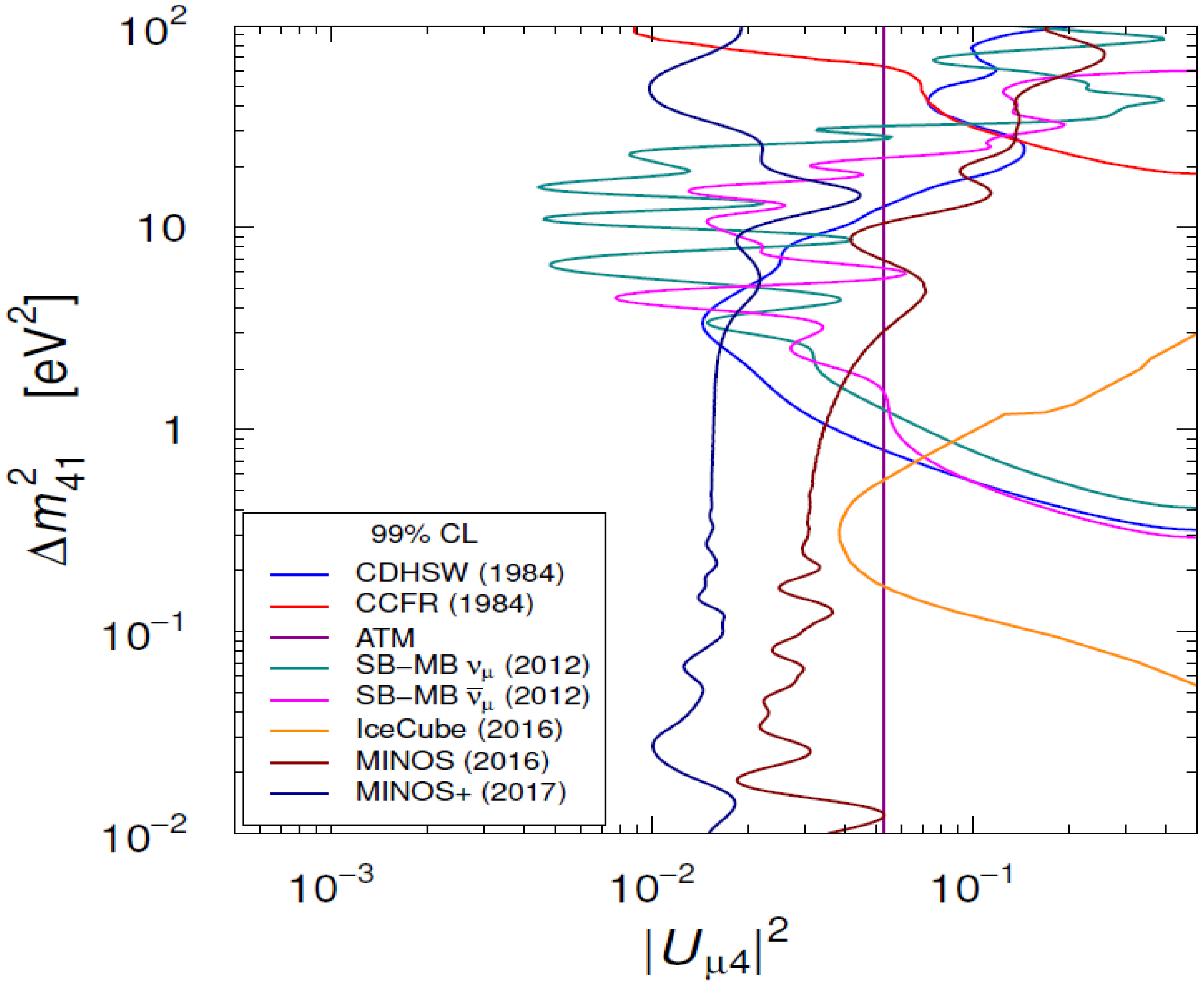
[arXiv:1710.06488]



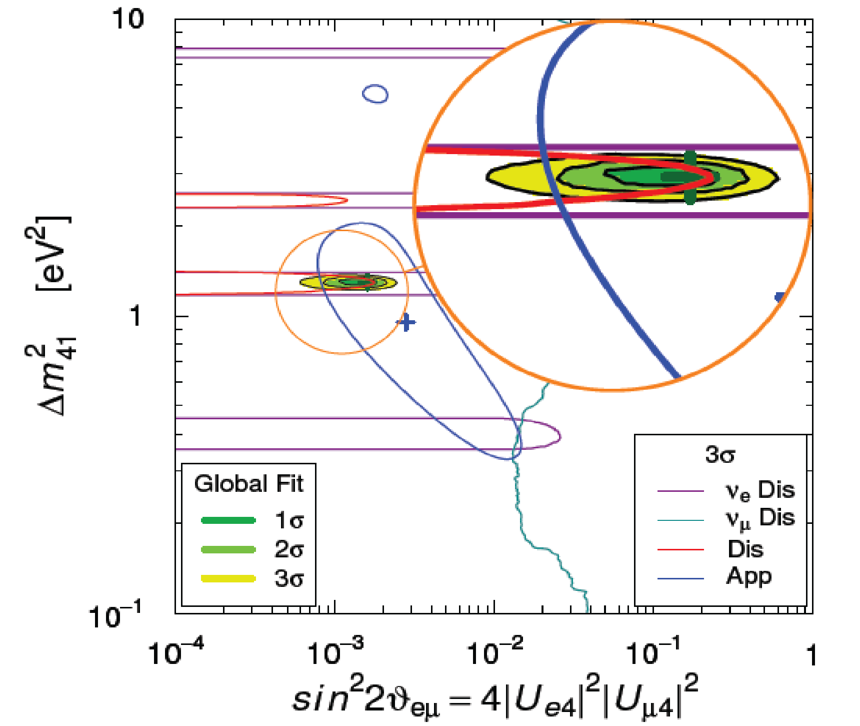


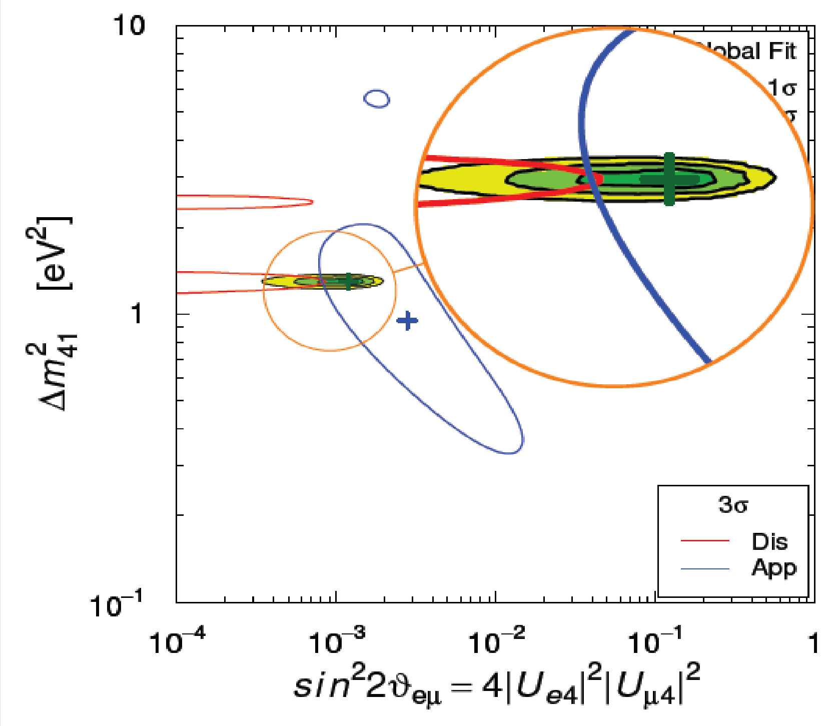


All the results in (anti)ν_μ disappearance



Appearance-Disappearance Tension





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

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

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

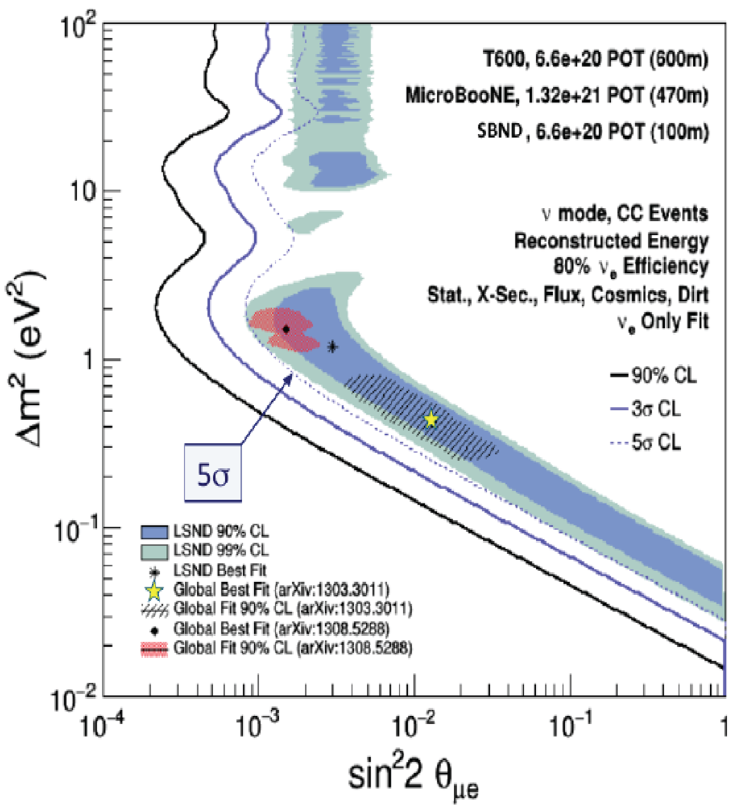
- **From Mild to very Strong tensions**

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

Future test of the appearance channel

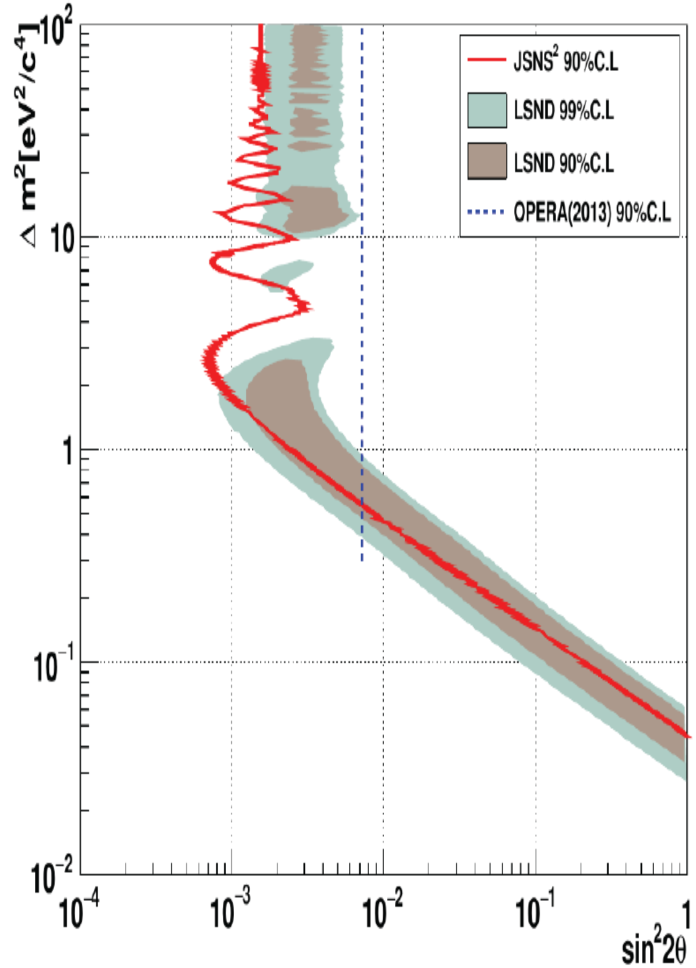
SBN PROGRAM @ FERMILAB

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 (talk by Dmitry Svirida), NEOS, STEREO, Neutrino-4, SoLid (talk by Leonidas Kalousis), PROSPECT, CHANDLER, … …

d) The MINOS+ result (if correct) disfavors the LSND signal. → future test at SBN and JSNS2

Thanks!