# Status of Light Sterile Neutrinos

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# Three Neutrino Paradigm

## Standard Parameterization of Mixing Matrix

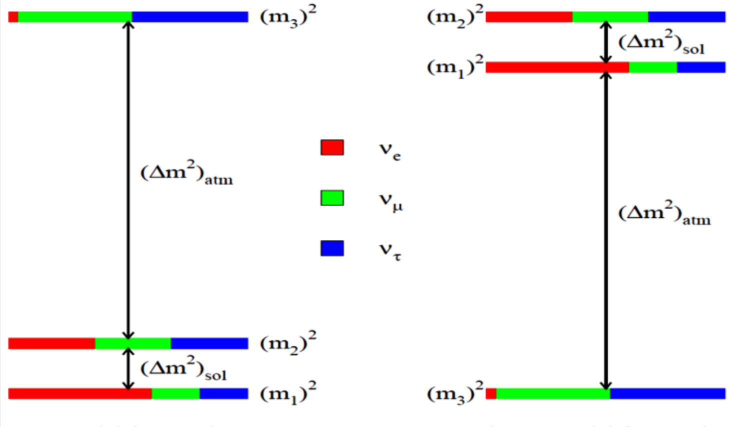
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}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

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

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

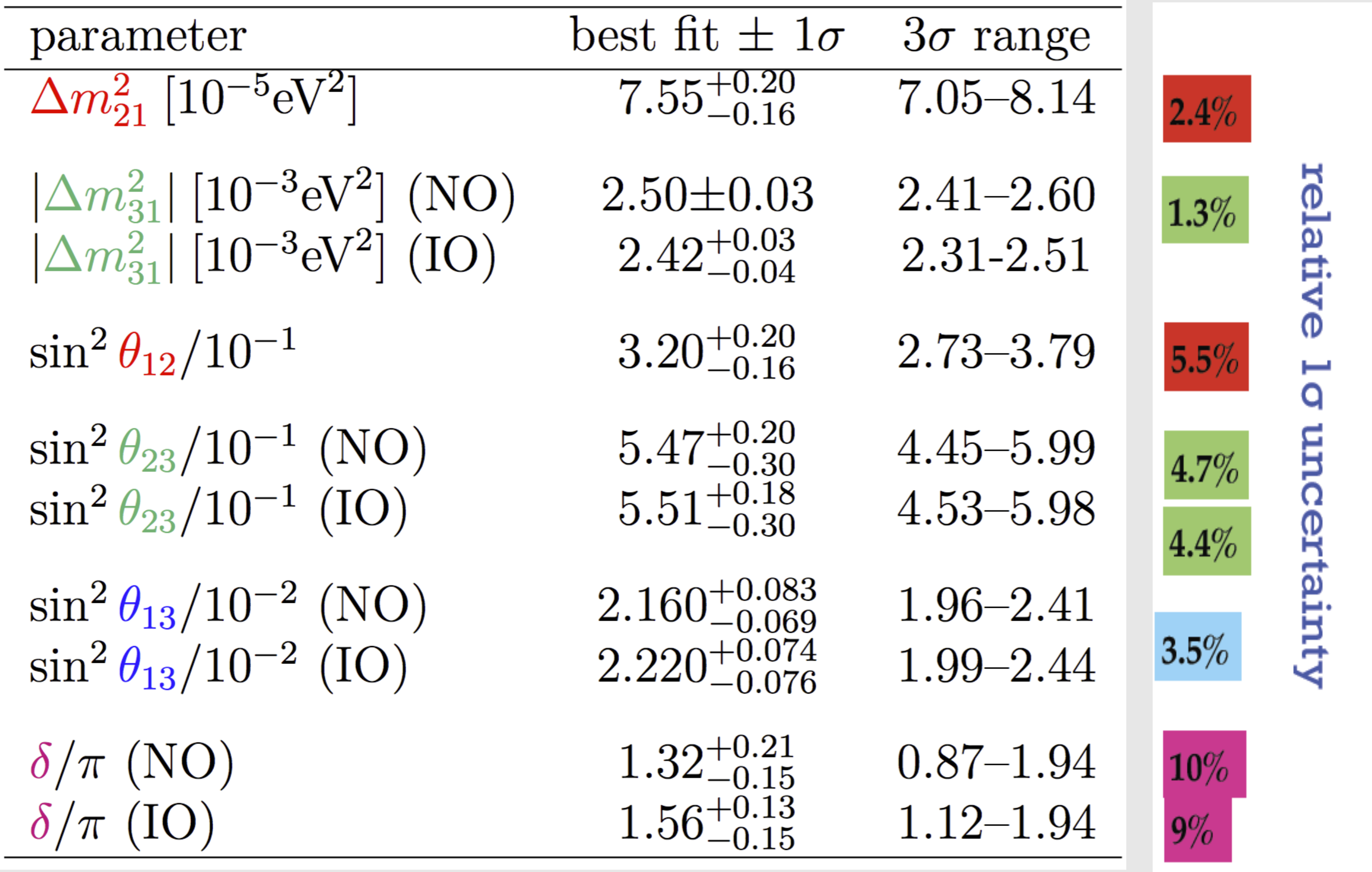
3 Mixing Angles: $\vartheta_{12}$, $\vartheta_{23}$, $\vartheta_{13}$
1 CPV Dirac Phase: $\delta_{13}$
2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: $\Delta m^2_{21}$, $\Delta m^2_{31}$

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



# Current Status: 3-ν oscillations

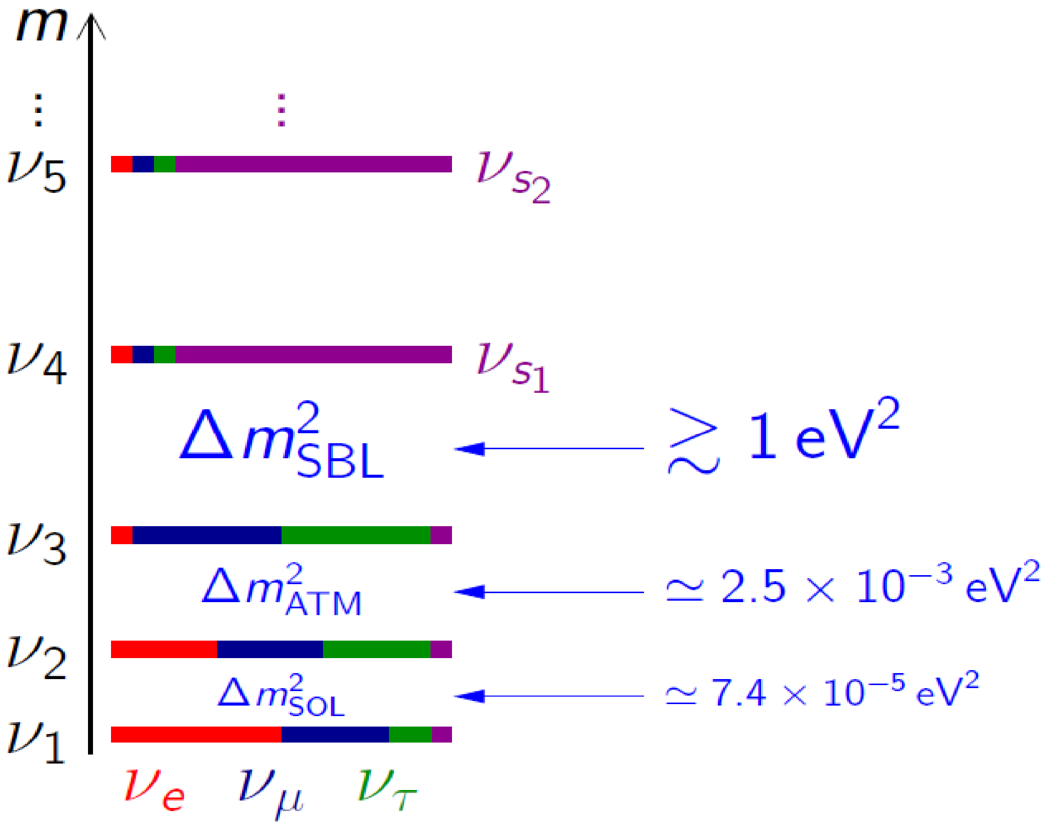
***de Salas et al, PLB782 (2018) 633***, *see also results from the Bari group & Nu-fit group*

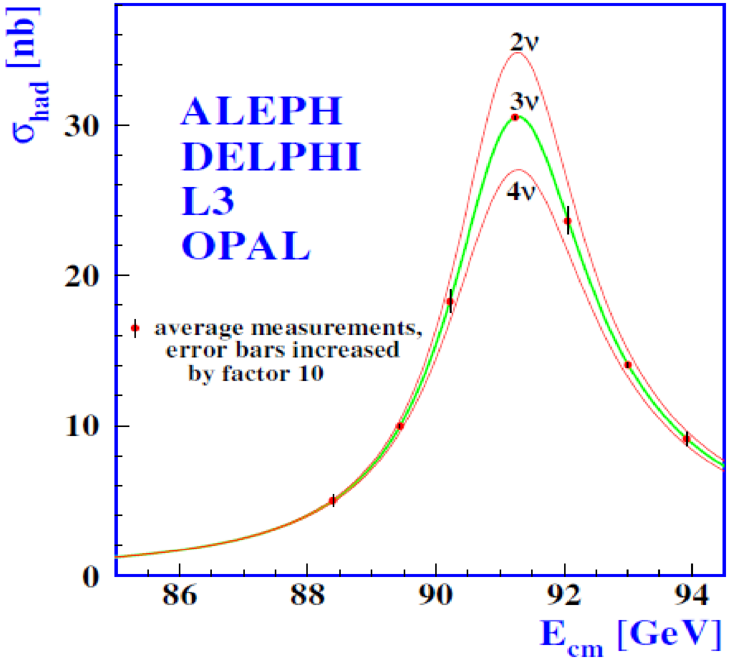


| parameter | best fit ± 1$\sigma$ | 3$\sigma$ range | relative 1σ uncertainty |
|---|---|---|---|
| $\Delta m^2_{21}$ $[10^{-5}\mathrm{eV}^2]$ | $7.55^{+0.20}_{-0.16}$ | 7.05–8.14 | 2.4% |
| $\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NO) | 2.50±0.03 | 2.41–2.60 | 1.3% |
| $\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IO) | $2.42^{+0.03}_{-0.04}$ | 2.31-2.51 | |
| $\sin^2\theta_{12}/10^{-1}$ | $3.20^{+0.20}_{-0.16}$ | 2.73–3.79 | 5.5% |
| $\sin^2\theta_{23}/10^{-1}$ (NO) | $5.47^{+0.20}_{-0.30}$ | 4.45–5.99 | 4.7% |
| $\sin^2\theta_{23}/10^{-1}$ (IO) | $5.51^{+0.18}_{-0.30}$ | 4.53–5.98 | 4.4% |
| $\sin^2\theta_{13}/10^{-2}$ (NO) | $2.160^{+0.083}_{-0.069}$ | 1.96–2.41 | 3.5% |
| $\sin^2\theta_{13}/10^{-2}$ (IO) | $2.220^{+0.074}_{-0.076}$ | 1.99–2.44 | |
| $\delta/\pi$ (NO) | $1.32^{+0.21}_{-0.15}$ | 0.87–1.94 | 10% |
| $\delta/\pi$ (IO) | $1.56^{+0.13}_{-0.15}$ | 1.12–1.94 | 9% |

**Are there any new neutrino states, new interactions or new paradigm ?**

# 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

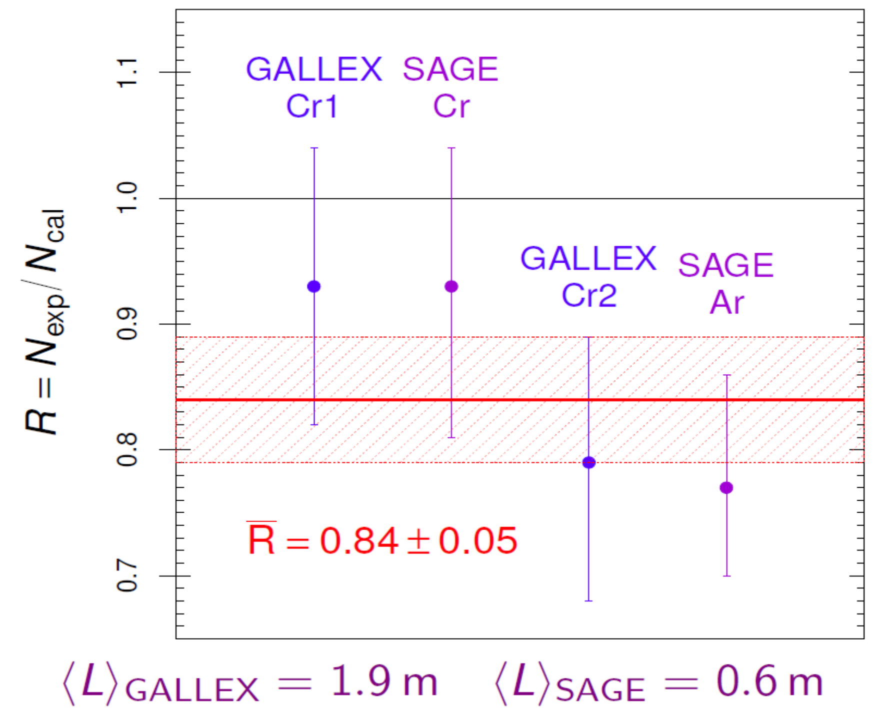
SAGE, PRC (2006); PRC (2009); Laveder et al. (2007)

## Gallium Radioactive Source Experiments: GALLEX and SAGE

## Test of Solar Neutrino Detection

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

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



- **~2.9σ deficit**

**Neutrino energies: ~0.8 MeV**

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

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

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

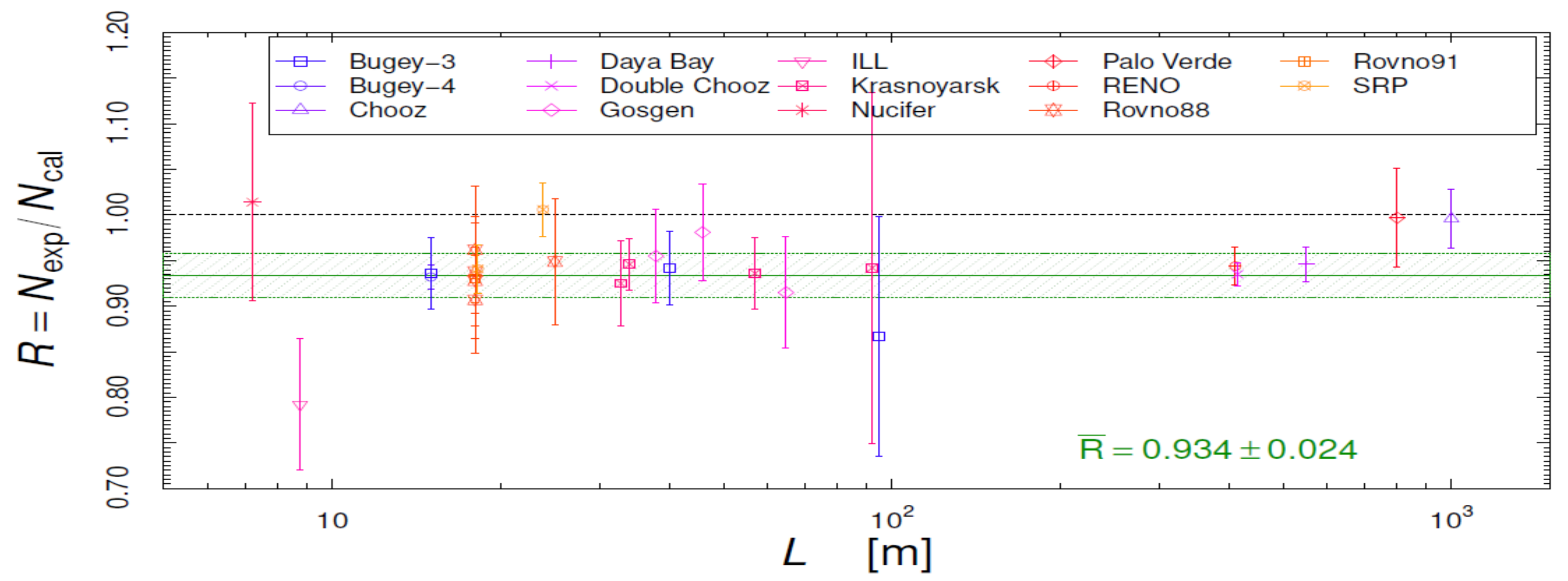
*Frekers et al., PLB 706 (2011) 134*

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

# Reactor Antineutrino Anomaly

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

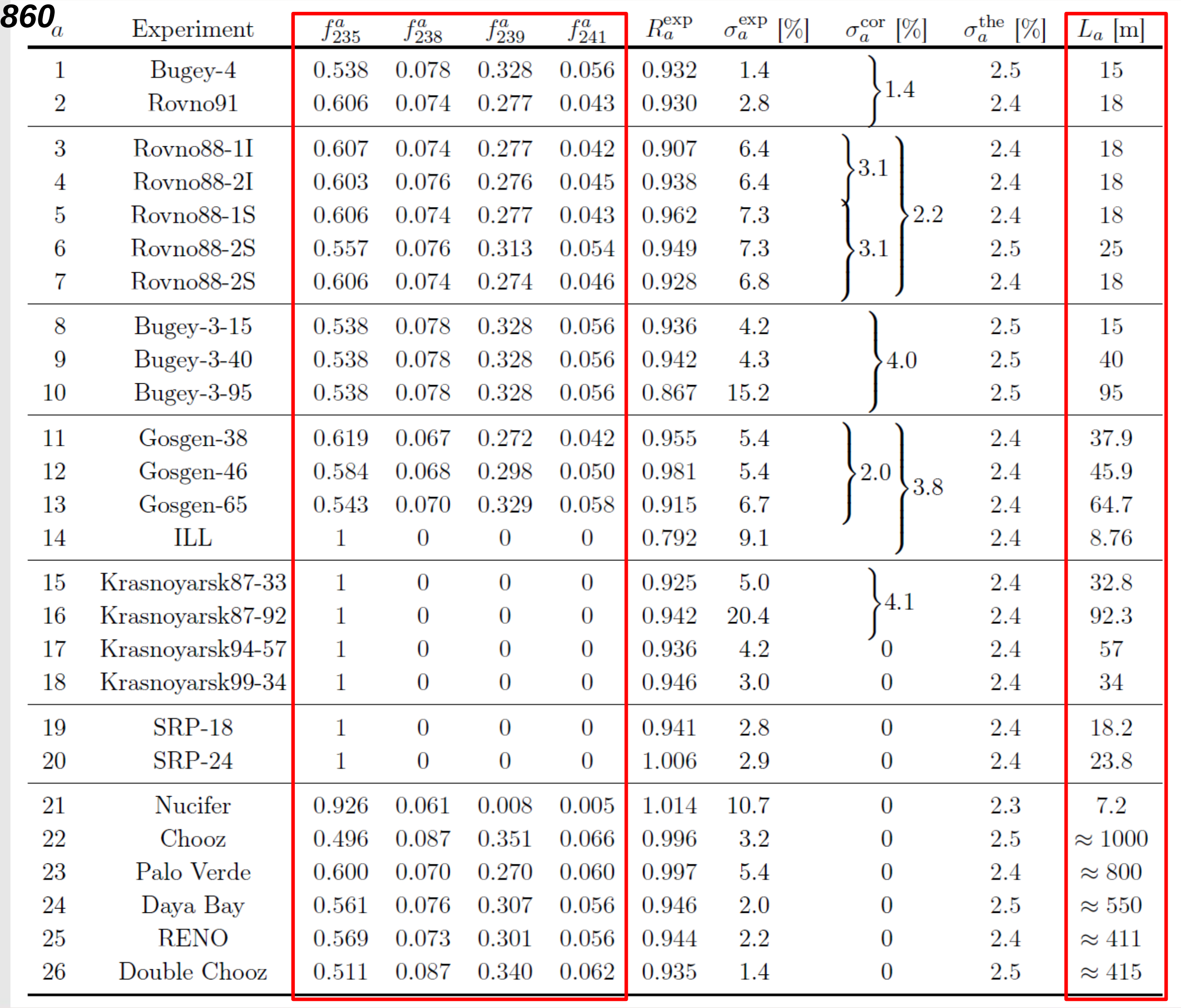
New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



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

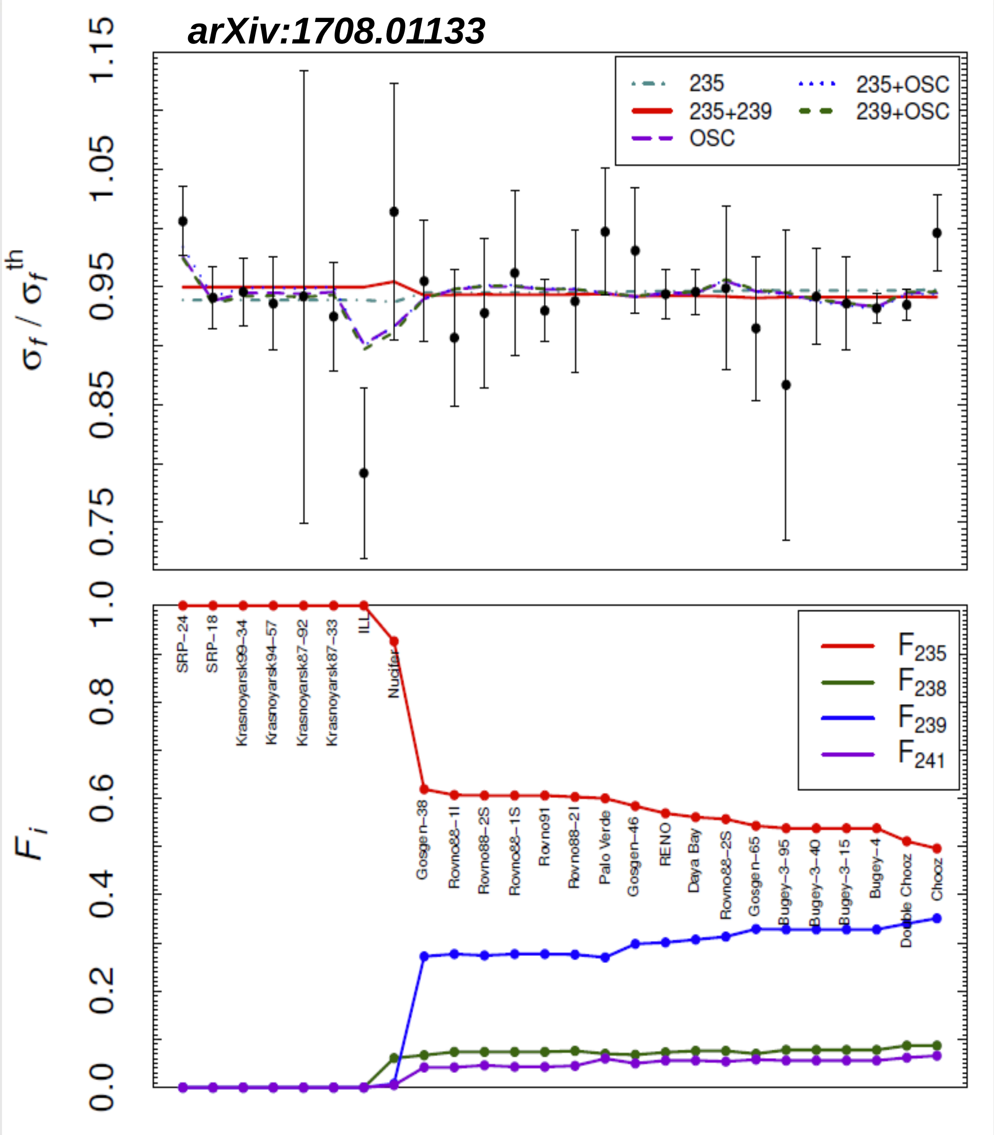
# A closer look at reactor rates data

arXiv:1703.00860

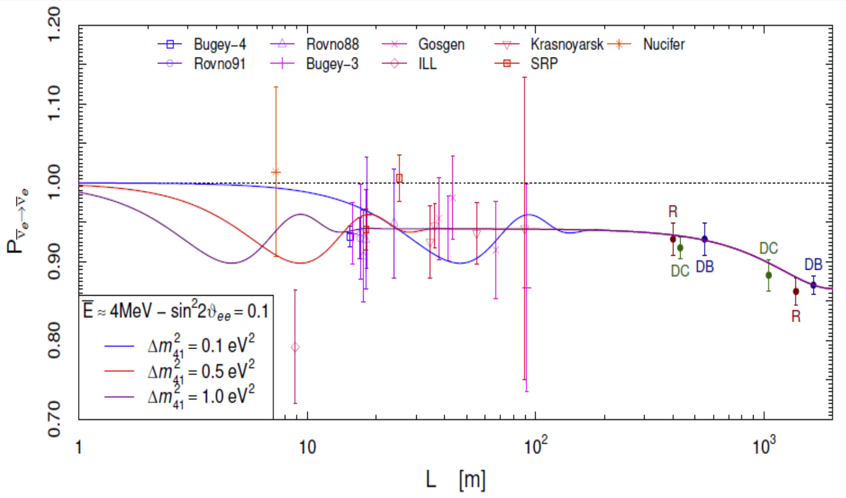


| $a$ | Experiment | $f^a_{235}$ | $f^a_{238}$ | $f^a_{239}$ | $f^a_{241}$ | $R^{\text{exp}}_a$ | $\sigma^{\text{exp}}_a$ [%] | $\sigma^{\text{cor}}_a$ [%] | $\sigma^{\text{the}}_a$ [%] | $L_a$ [m] |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bugey-4 | 0.538 | 0.078 | 0.328 | 0.056 | 0.932 | 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<br>2.2 | 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 | 3.1 | 2.4 | 18 |
| 6 | Rovno88-2S | 0.557 | 0.076 | 0.313 | 0.054 | 0.949 | 7.3 | | 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 | 4.0 | 2.5 | 15 |
| 9 | Bugey-3-40 | 0.538 | 0.078 | 0.328 | 0.056 | 0.942 | 4.3 | | 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 | 2.0<br>3.8 | 2.4 | 37.9 |
| 12 | Gosgen-46 | 0.584 | 0.068 | 0.298 | 0.050 | 0.981 | 5.4 | | 2.4 | 45.9 |
| 13 | Gosgen-65 | 0.543 | 0.070 | 0.329 | 0.058 | 0.915 | 6.7 | | 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 |

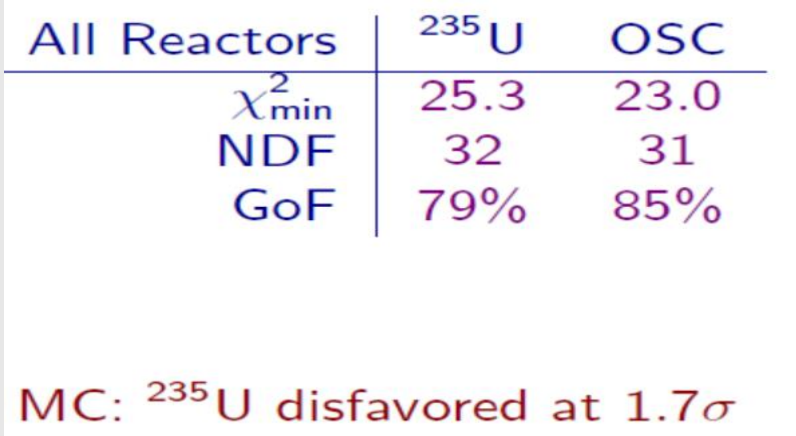
# Two alternative solutions



arXiv:1708.01133



**Oscillation-based solution or fuel-based solution, or both?**



| All Reactors | $^{235}$U | OSC |
|---|---|---|
| $\chi^2_{\min}$ | 25.3 | 23.0 |
| NDF | 32 | 31 |
| GoF | 79% | 85% |

MC: $^{235}$U disfavored at 1.7$\sigma$

# New burn-up Feature @ Reactors

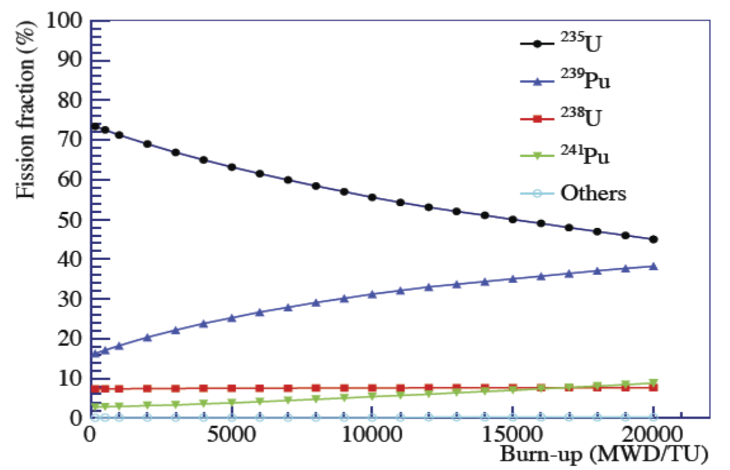
**Reactor antineutrinos: produced by beta decays the fission products**

$^{235}\mathrm{U}$ $^{238}\mathrm{U}$ $^{239}\mathrm{Pu}$ $^{241}\mathrm{Pu}$

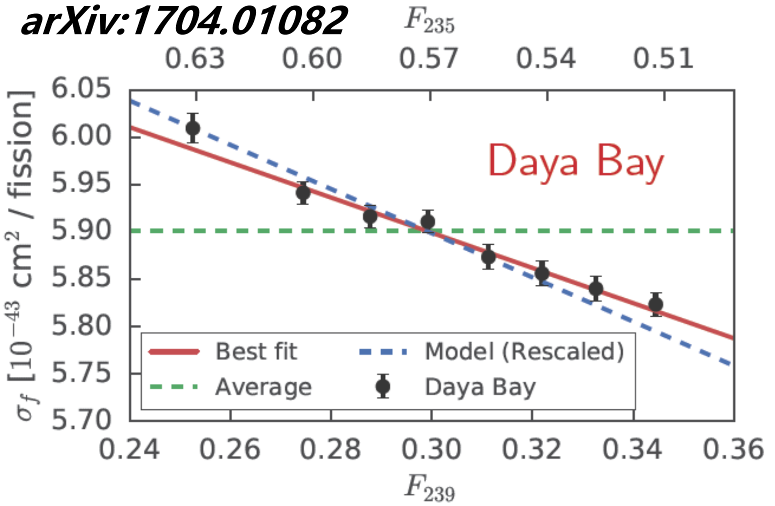
**The fission fractions are changing along with the burn-up:**

$F_{235}$ $F_{238}$ $F_{239}$ $F_{241}$

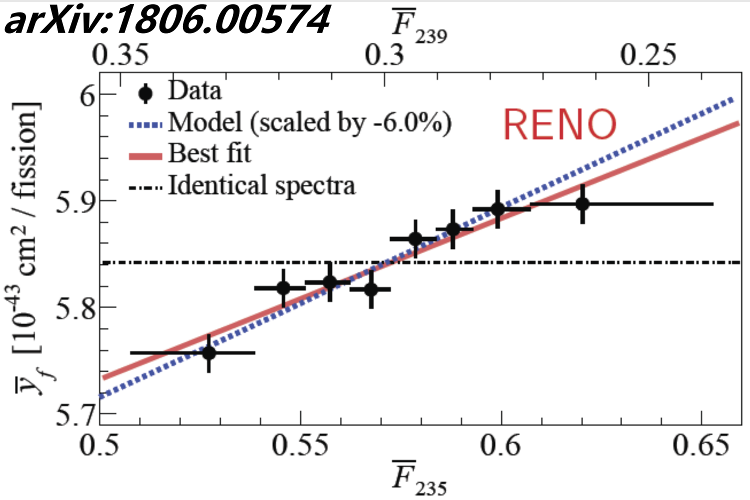
**The IBD yields are measured as the cross sections per fission**



arXiv:1704.01082

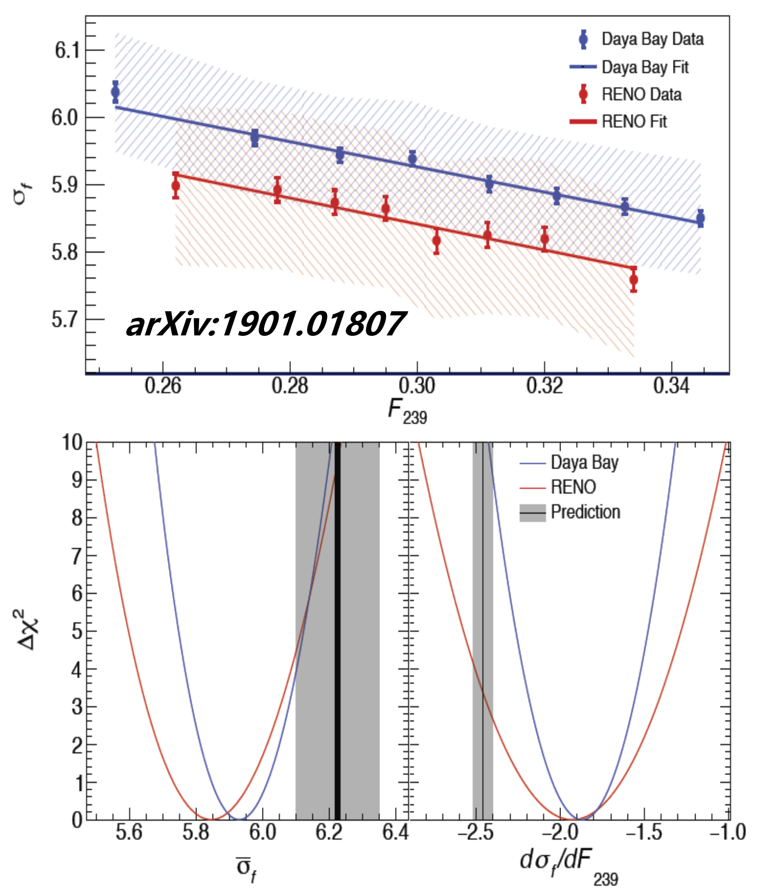


arXiv:1806.00574



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

# Global Analysis of Reactor Flux Data



$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}\left(F_{239} - \overline{F}_{239}\right)$$

**DYB+RENO joint data:**

**disagree with both rates and slopes, 2.9σ preference of U235 over oscillation-only**

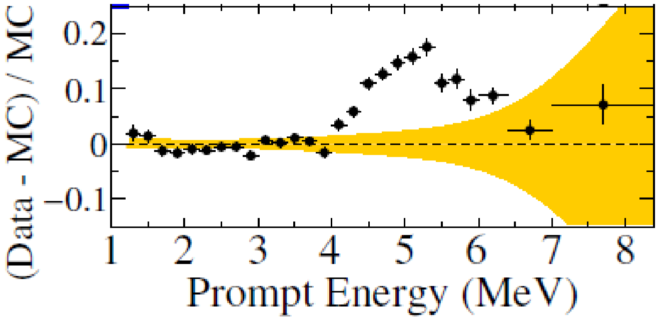
**Global Flux Data (DYB+RENO+rates):**

**a) A common inaccuracy of all beta conversion predictions: disfavored at 2.9σ → question on the ILL data**

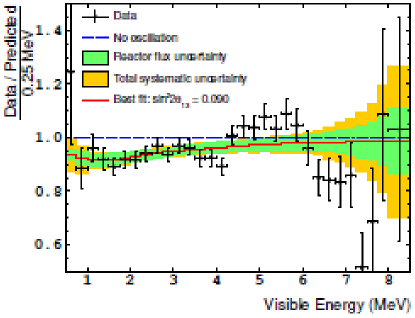
**b) Oscillation-including hypothesis is favored over the oscillation-including one: at 1-2σ**

**Needs future results from highly-enriched uranium (HEU) reactors !**

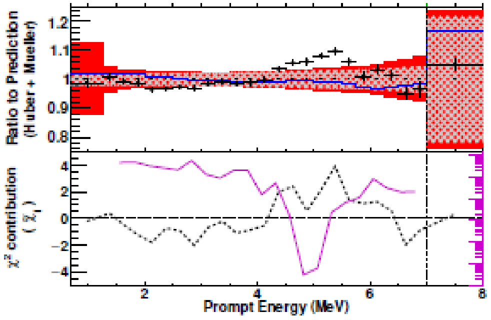
# New Spectral Feature @ Reactors



[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?**

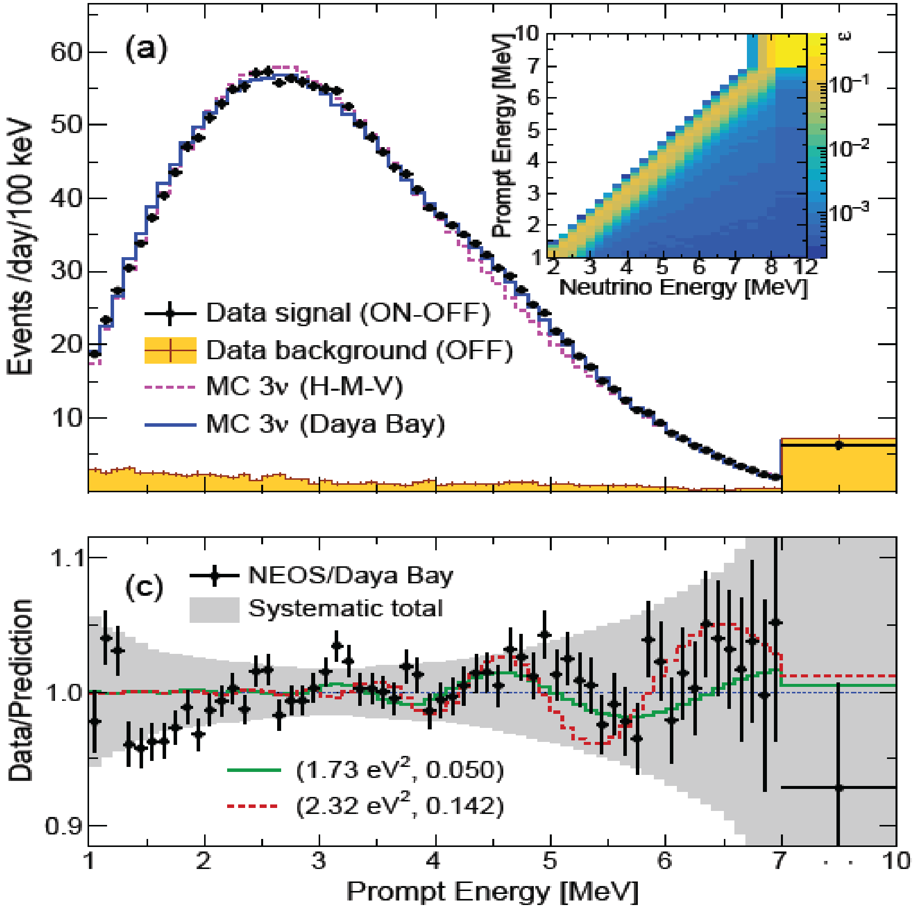
**(3) Detector energy nonlinearity?** ***[Mention et al, PLB 773 (2017) 307]***
**(DYB/DC achieved better than 1% precision)**

**(4) One may need to increase the uncertainty: e.g. 5% or larger.**
***[Hayes and Vogel, 2016, YFL, Zhang 2019]***

# Spectral ratio result@NEOS

## NEOS

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



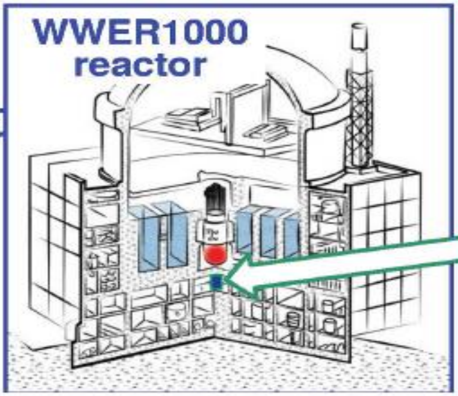
- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

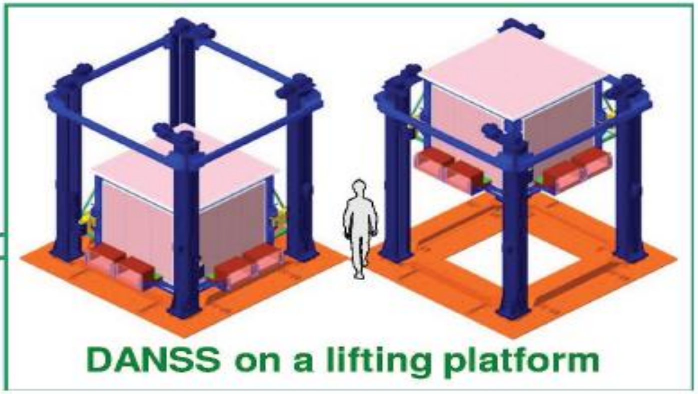
# Spectral ratio result@DANSS

## DANSS

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

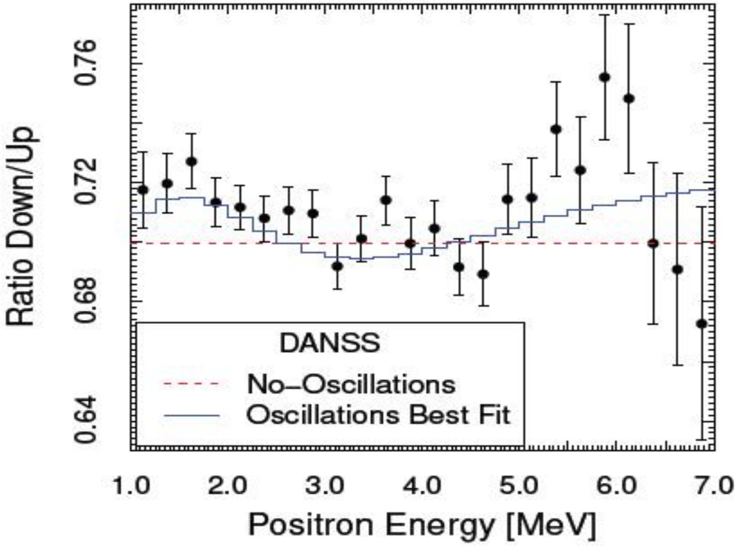
**Detector of reactor AntiNeutrino based on Solid Scintillator**





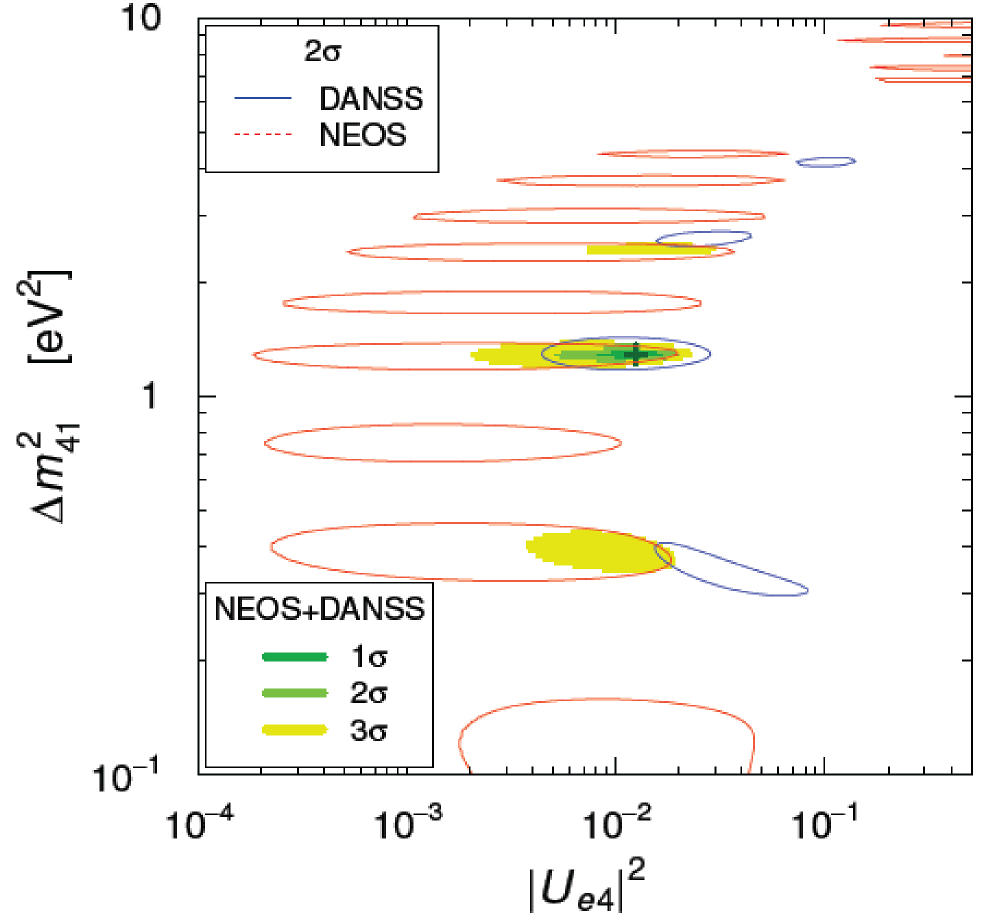
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

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



# Model independent SBL oscillations

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



$$\sim 3.7\sigma$$

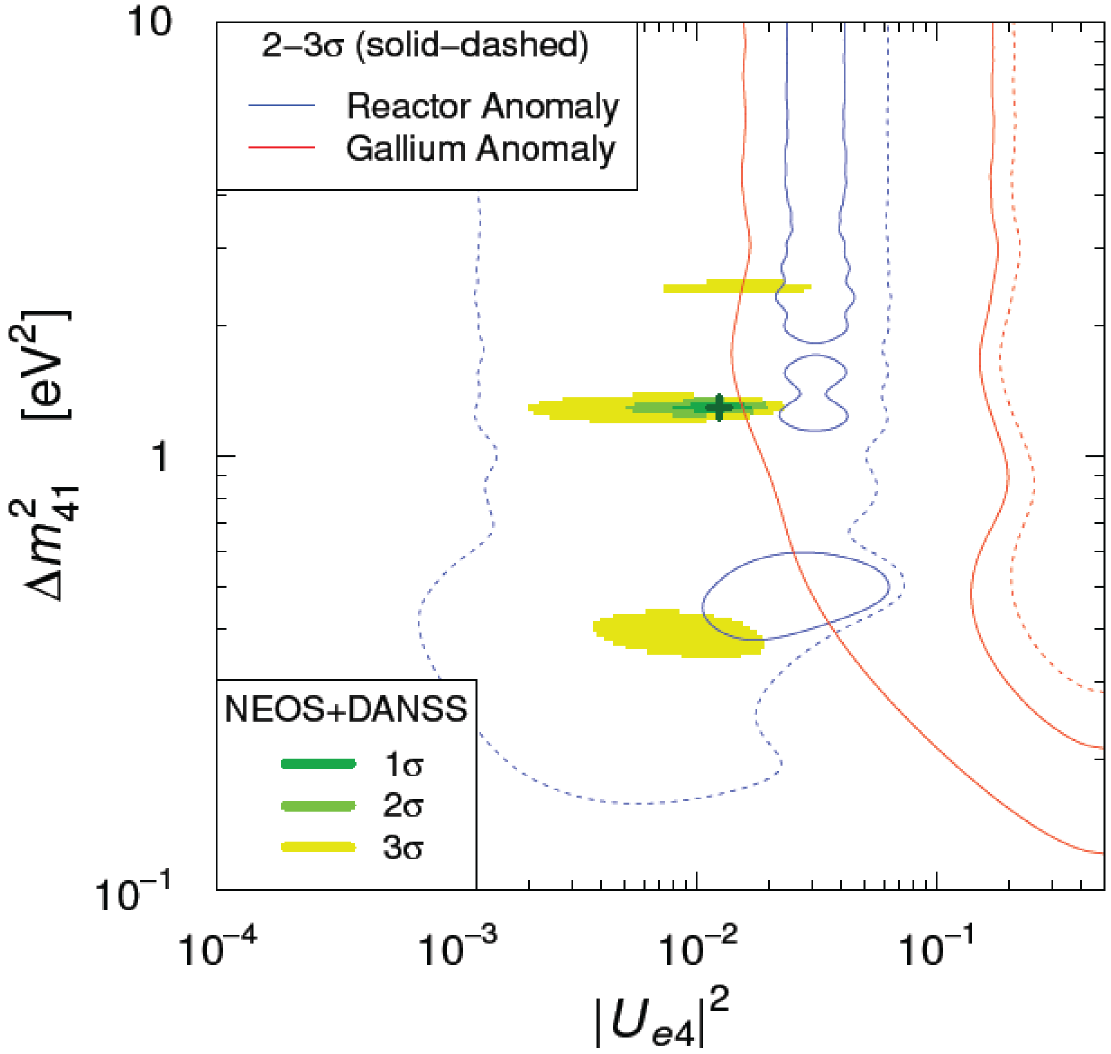
$$\Delta m^2_{41} = 1.29 \pm 0.03$$

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

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

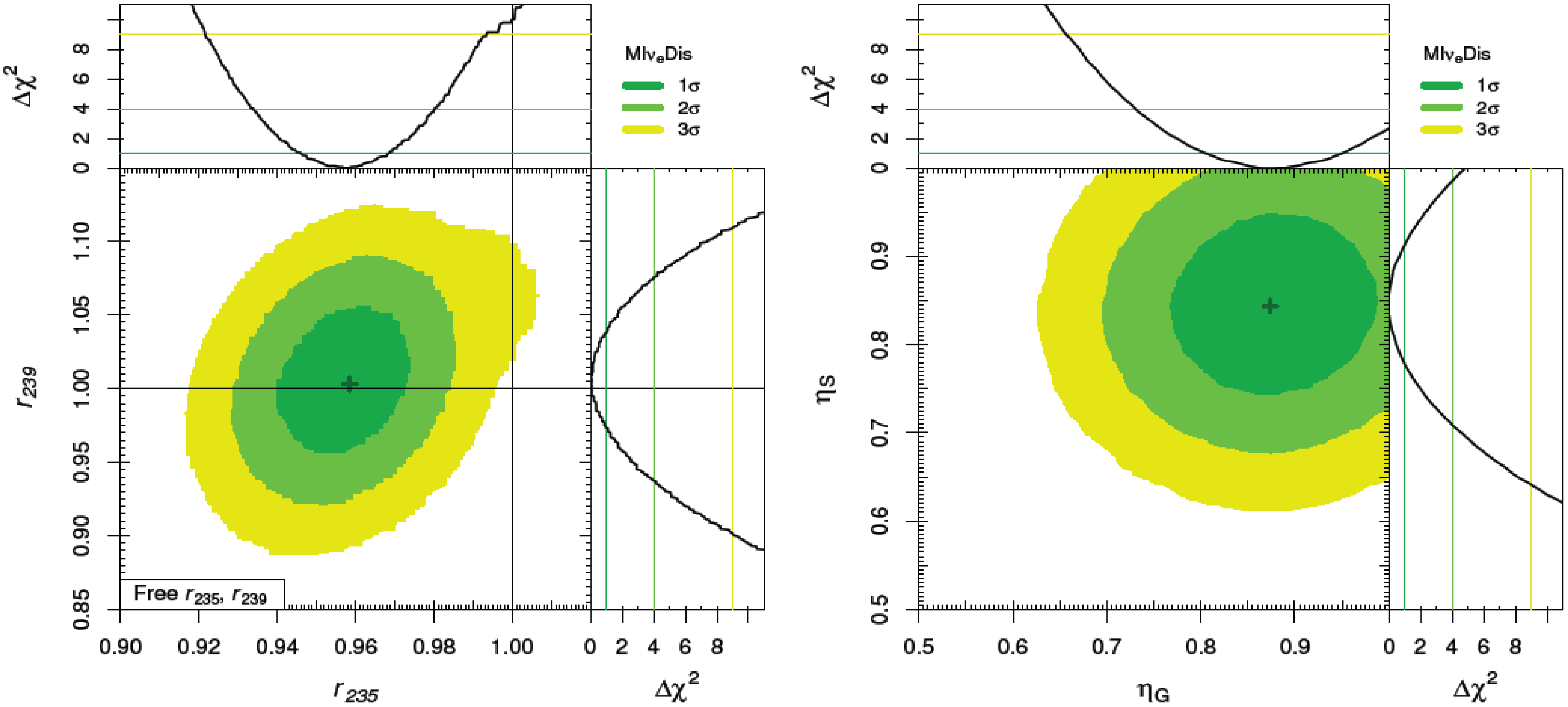
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

# Implications for Reactor and Gallium anomalies



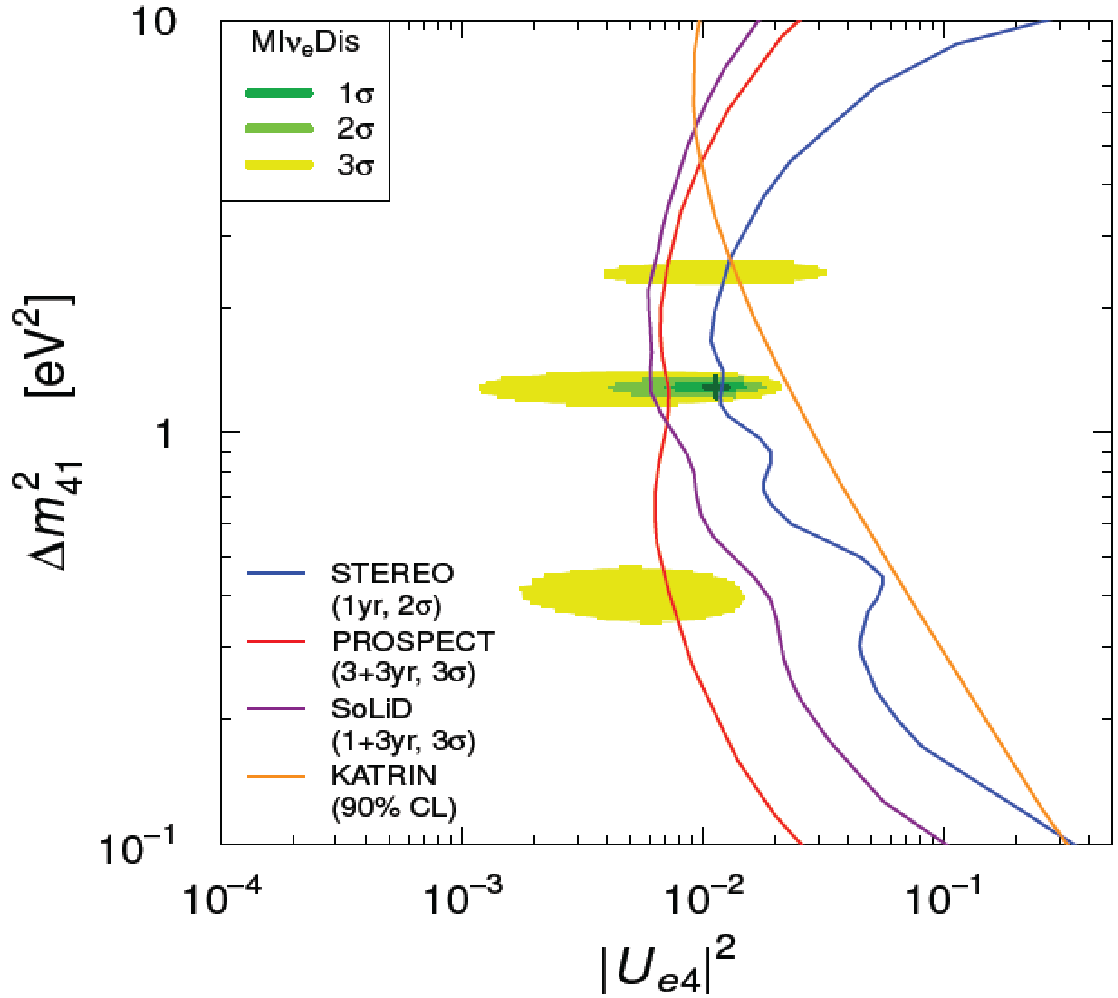
- $3\sigma$ agreement.
- $2\sigma$ tension.
- Small overestimate of the reactor fluxes.
- Small overestimate of the GALLEX and SAGE efficiencies.

# Implications for Reactor and Gallium anomalies



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

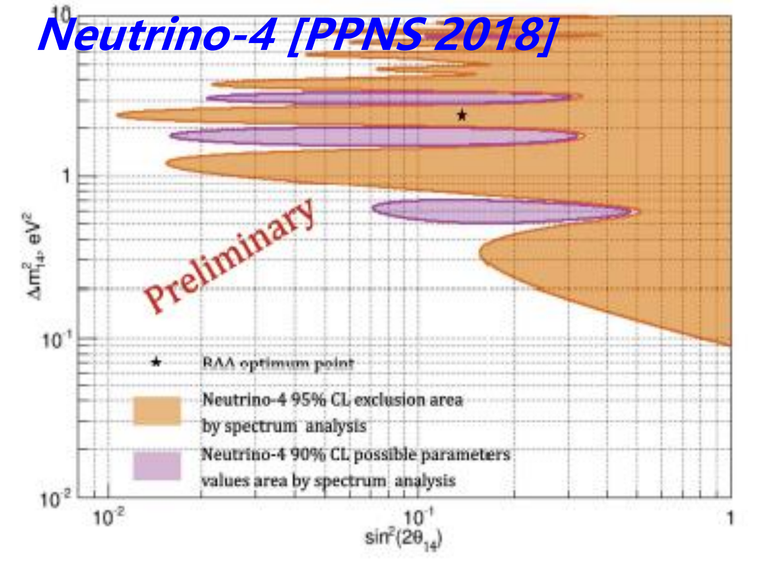
# Model independent fit and the future tests



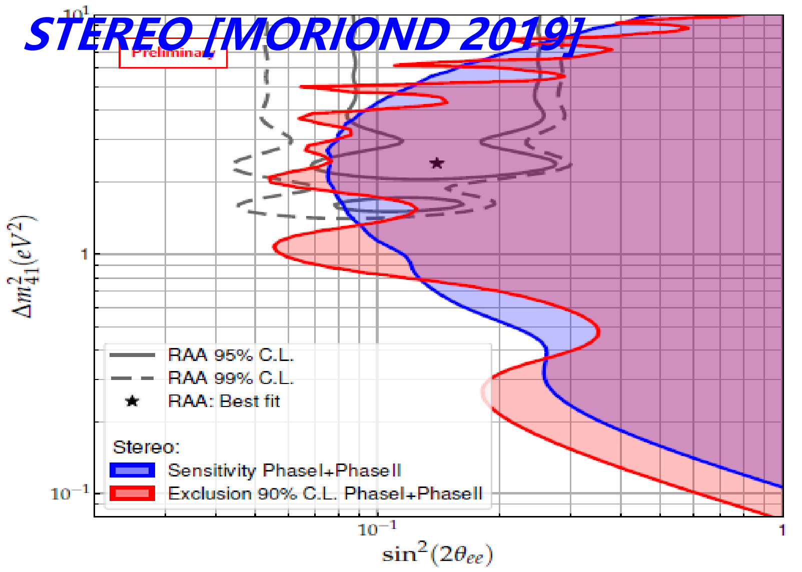
- NEOS and DANSS.
- Reactor rates with free $^{235}$U and $^{239}$Pu fluxes: $r_{235}$ and $r_{239}$.
- Gallium data with free GALLEX and SAGE efficiencies: $\eta_G$ and $\eta_S$.
- New reactor experiments: STEREO, Neutrino-4, SoLiD, PROSPECT
- Kinematic $\nu_4$ mass measurement: KATRIN

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

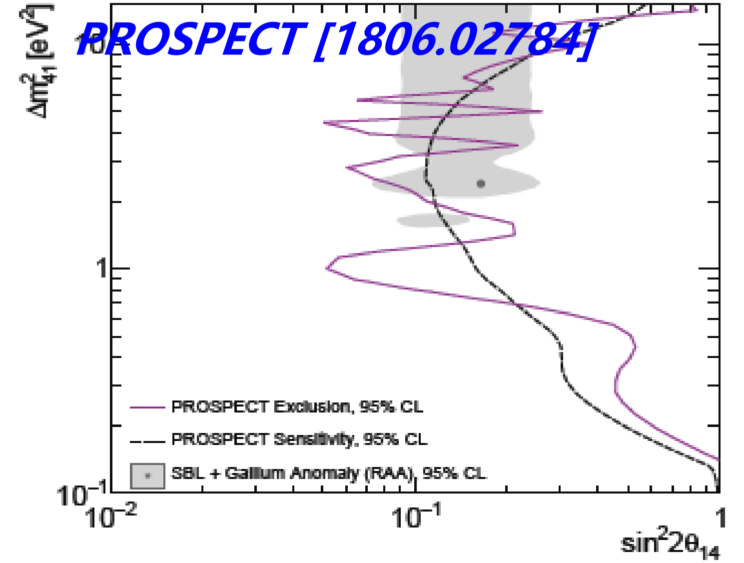
# Latest results from Spectral Ratios



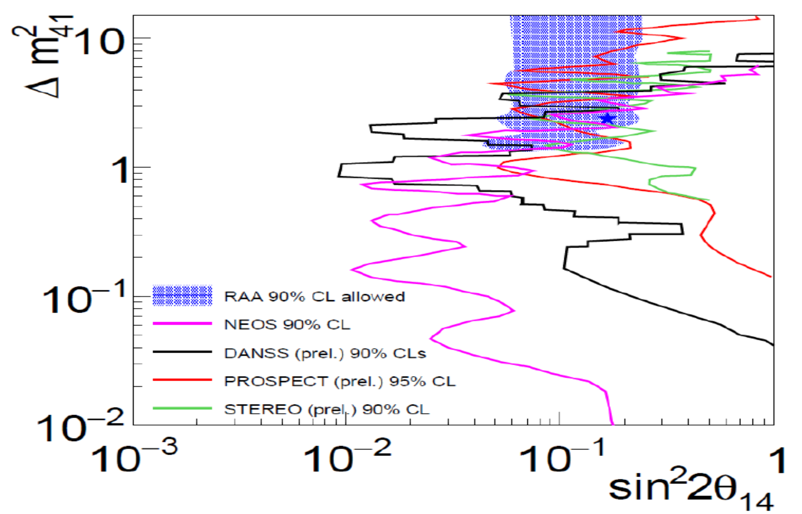
*Neutrino-4 [PPNS 2018]*



*STEREO [MORIOND 2019]*



*PROSPECT [1806.02784]*

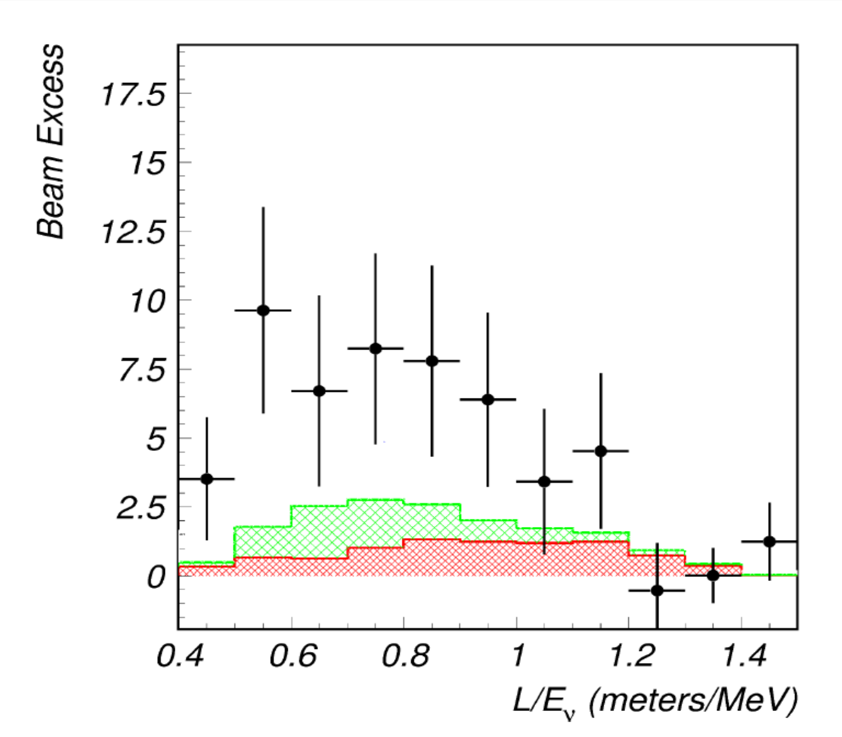


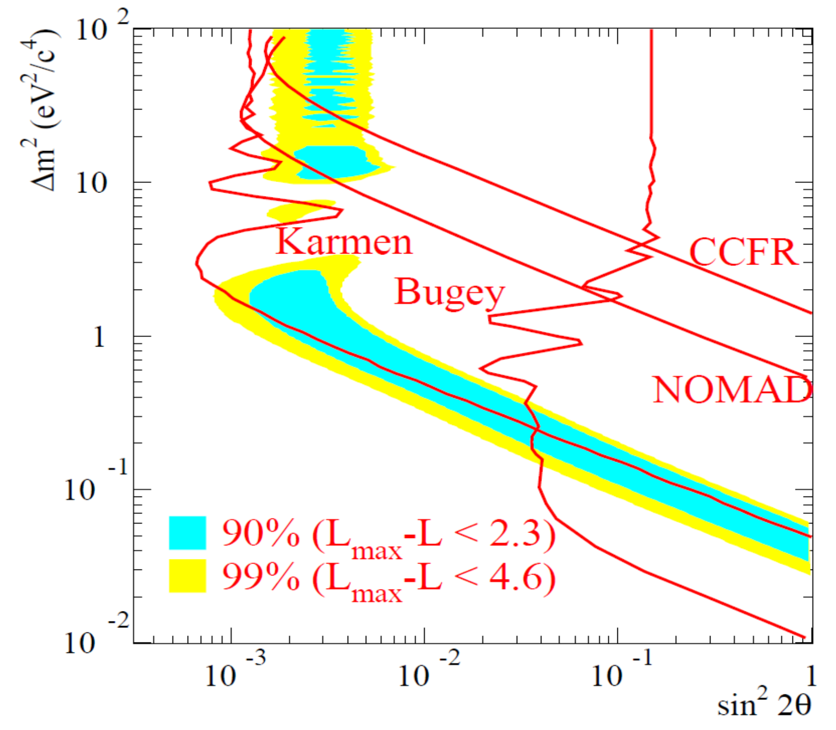
*X. Qian and J-C Peng, arXiv:1801.05386*

# 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:**

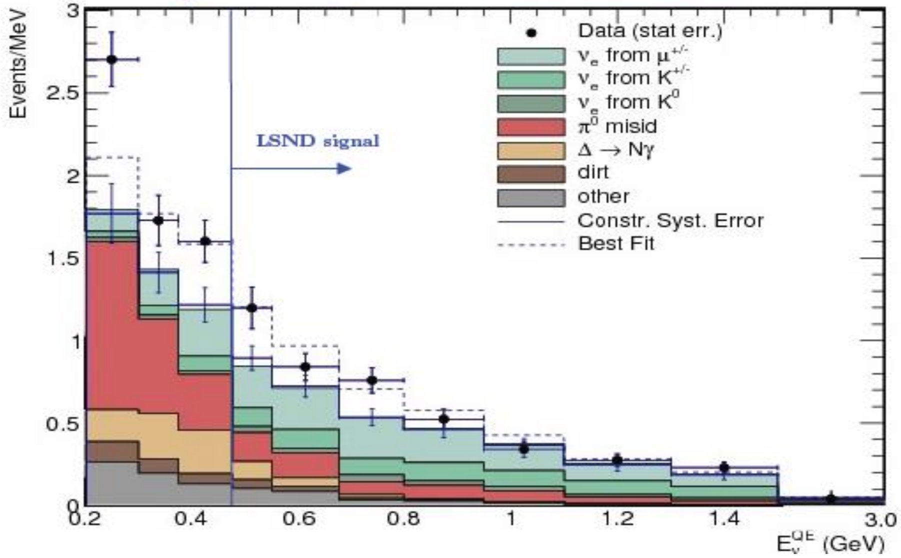
$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \leq E \leq 200\,\text{MeV}$

$3.8\sigma$ excess $\quad \Delta m^2 \gtrsim 0.2\,\text{eV}^2$ $\quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

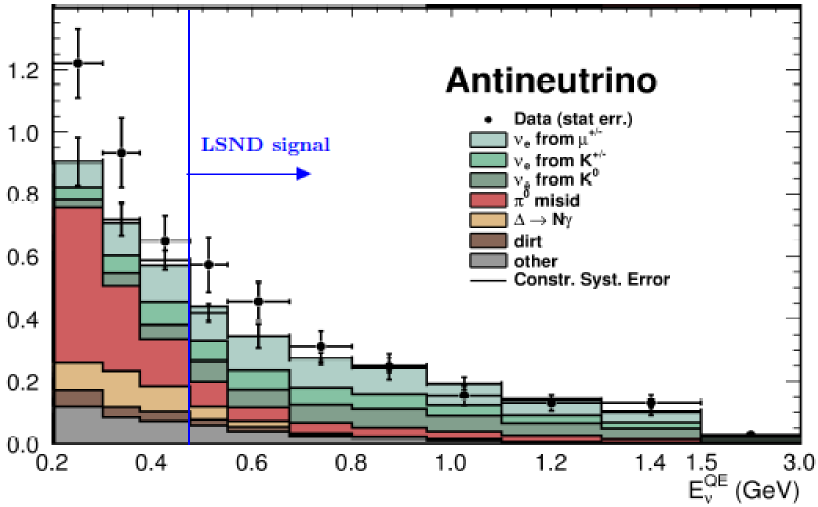
# MiniBooNE

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

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



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



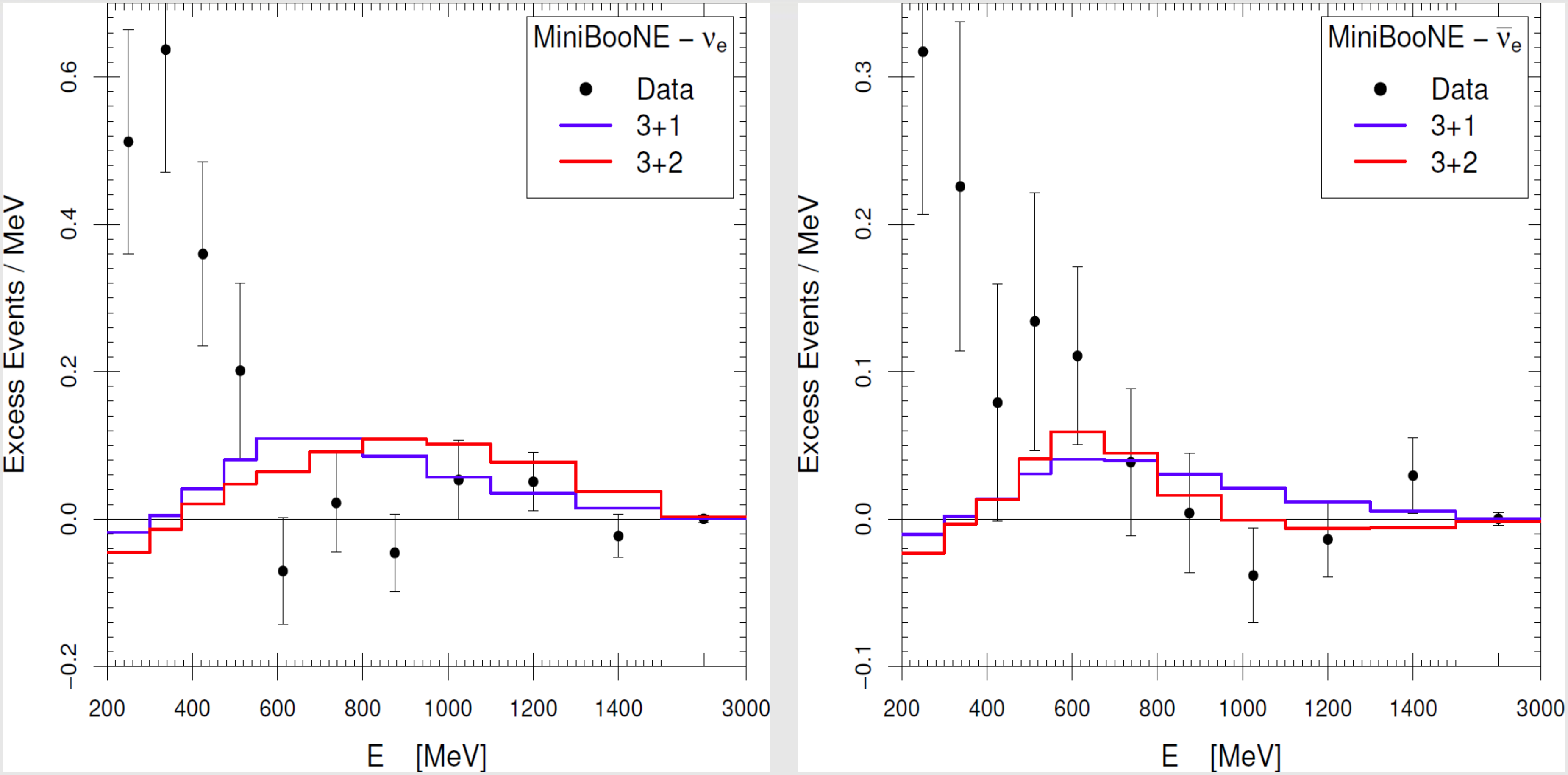
**Purpose:** check LSND signal with different L&E, but the same L/E (>475 MeV)

**~4.5σ (2.8σ) excess: unidentified backgrounds in low energy ranges?**

**→ further test at MicroBooNE.**

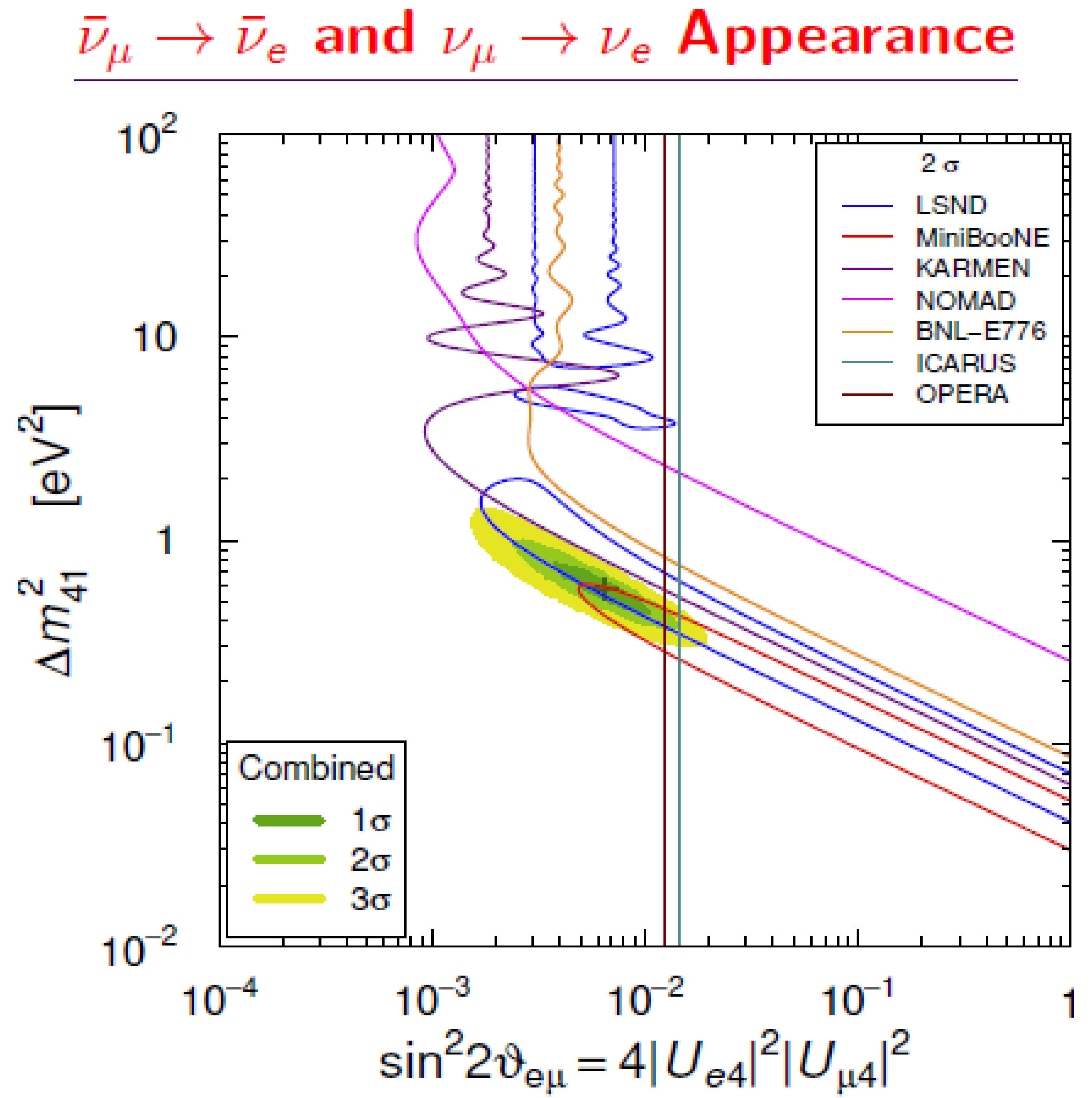
**A pragmatic approach: (E > 475 MeV)** ***[arXiv: 1308.5288]***

# MiniBooNE low energy bins

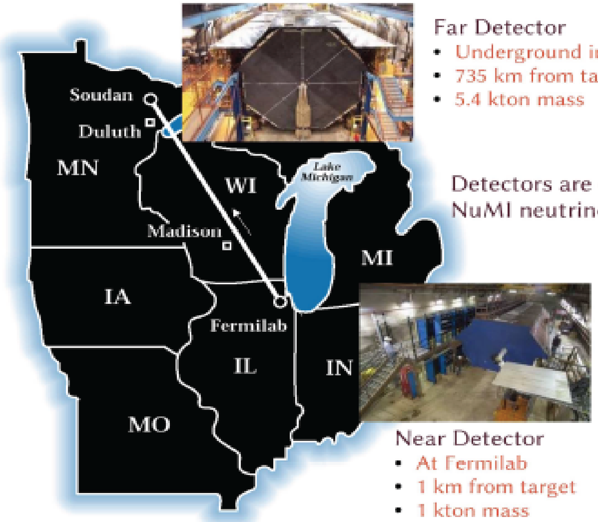


**Fit of MB Low-Energy Excess requires**
**small mass splitting and large mixing angle, which are in contradiction with ICARUS/OPERA and the disappearance data.**

# Appearance data



# MINOS+

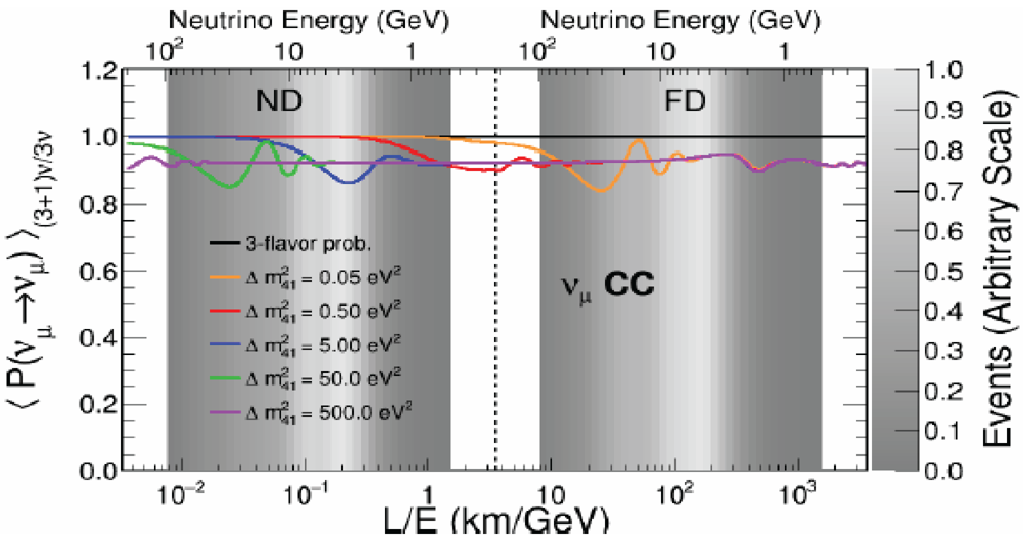


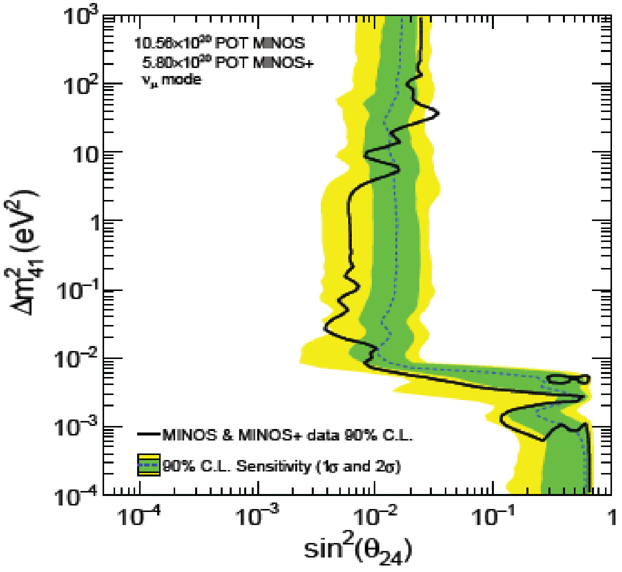
Far Detector
- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass

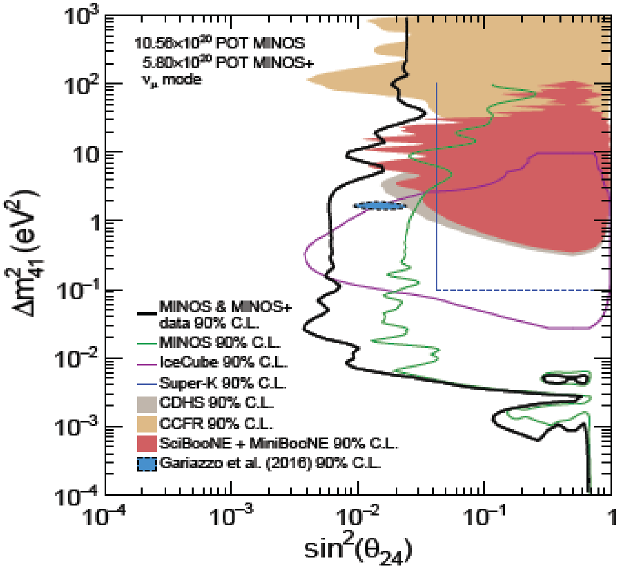
Detectors are on-axis for NuMI neutrino beam

Near Detector
- At Fermilab
- 1 km from target
- 1 kton mass

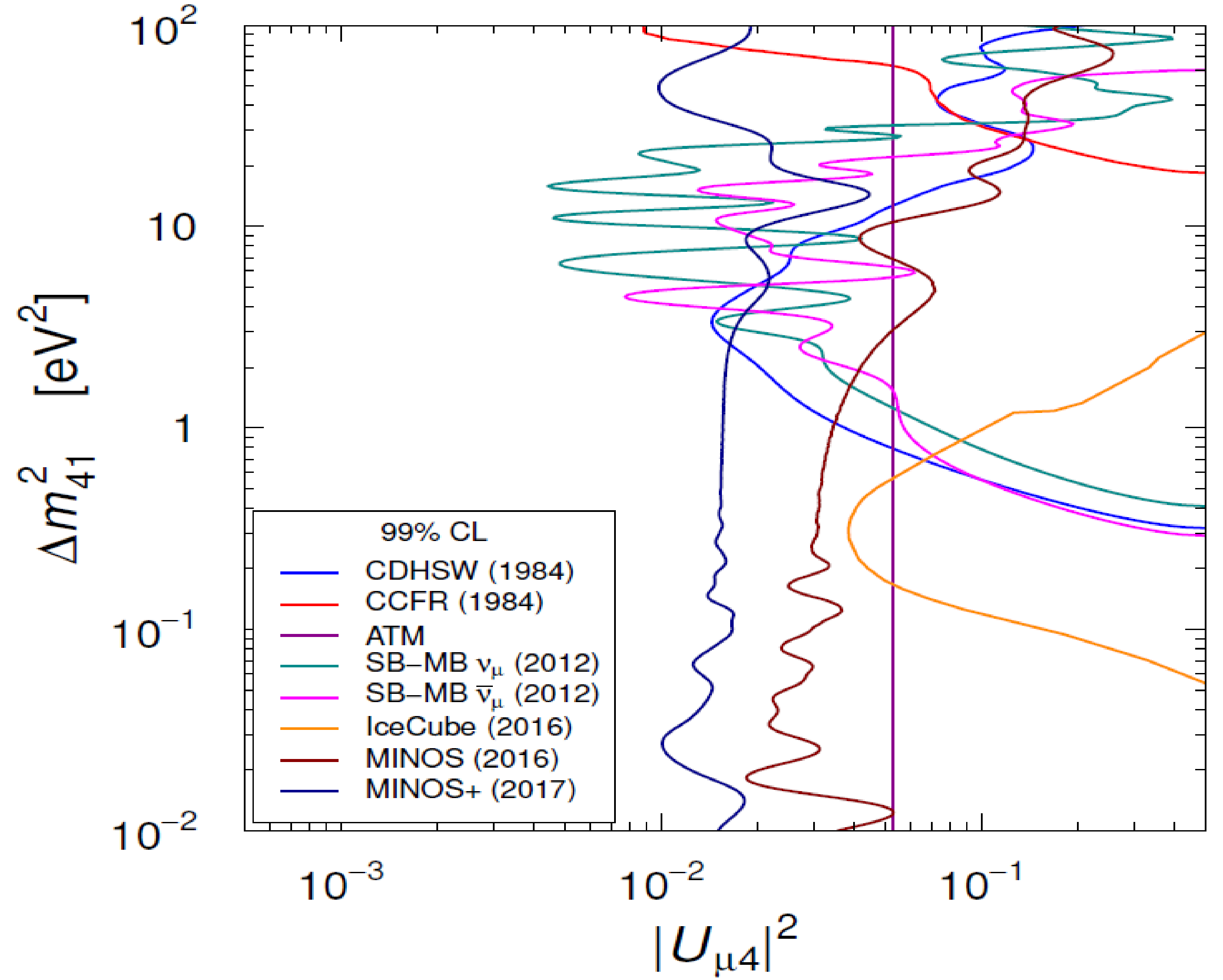
[arXiv:1710.06488]







# All the results in (anti)$\nu_\mu$ disappearance



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

**Based on the 2019 update of**

**Gariazzo, Giunti, Laveder, YFL, arXiv:1703.00860**

# Oscillations in the 3+1 scheme

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

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

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

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

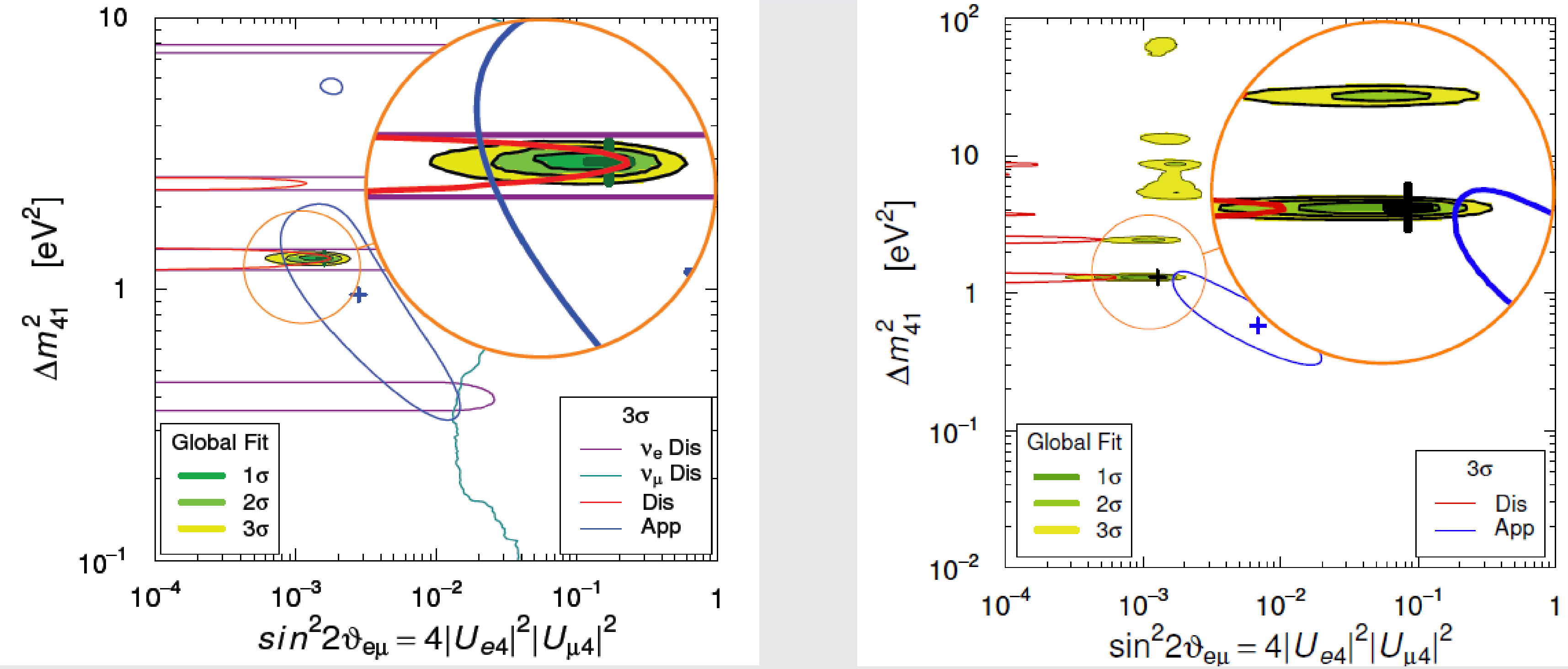
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

- Upper bounds on $\nu_e$ and $\nu_\mu$ 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

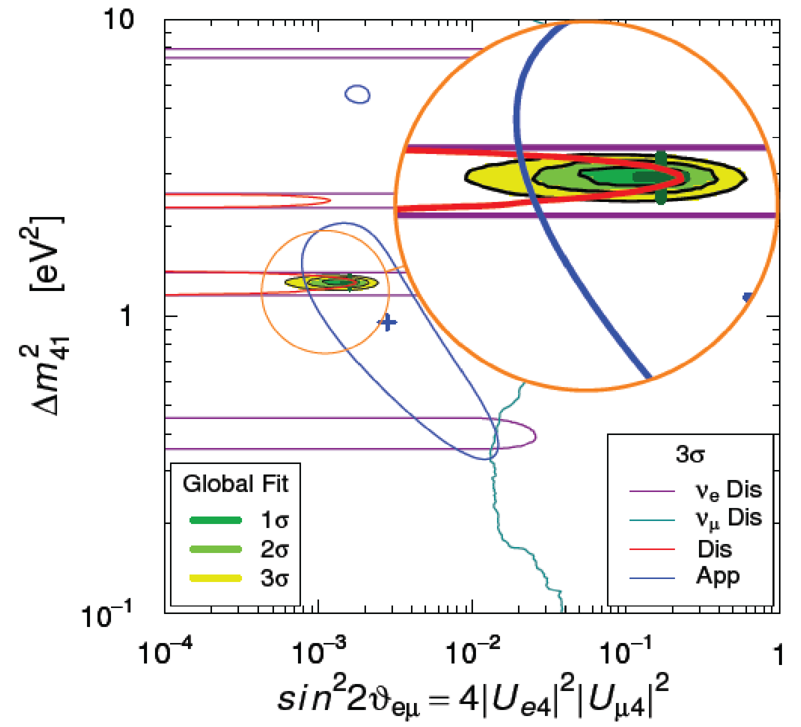


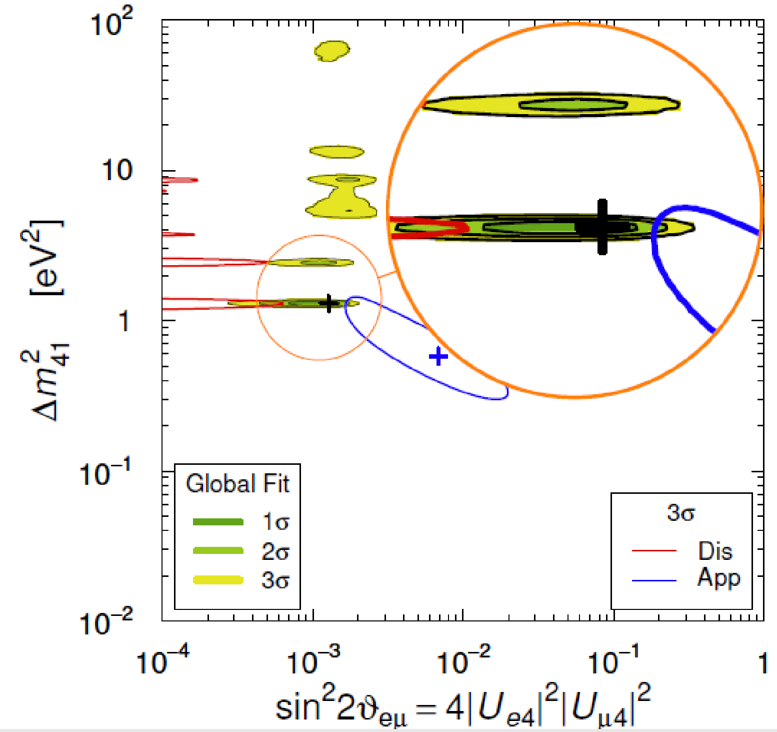
- **Without (left) and with (right) MINOS+ data (both without the MB low energy bins)**

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

$$\chi^2_{\rm PG}/{\rm NDF_{PG}} = 42.8/2 \Rightarrow {\rm GOF_{PG}} = 5 \times 10^{-10}$$

# Appearance-Disappearance Tension





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

$$\chi^2_{\rm PG}/{\rm NDF}_{\rm PG} = 7.8/2 \Rightarrow {\rm GOF}_{\rm PG} = 2\%$$

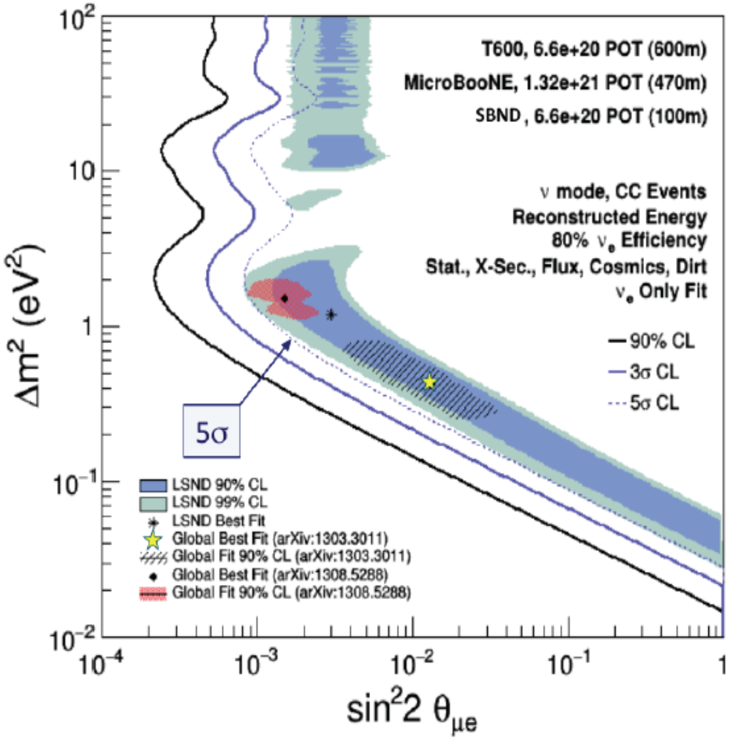
$$\chi^2_{\rm PG}/{\rm NDF}_{\rm PG} = 42.8/2 \Rightarrow {\rm GOF}_{\rm PG} = 5 \times 10^{-10}$$

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

# Future test of the appearance channel

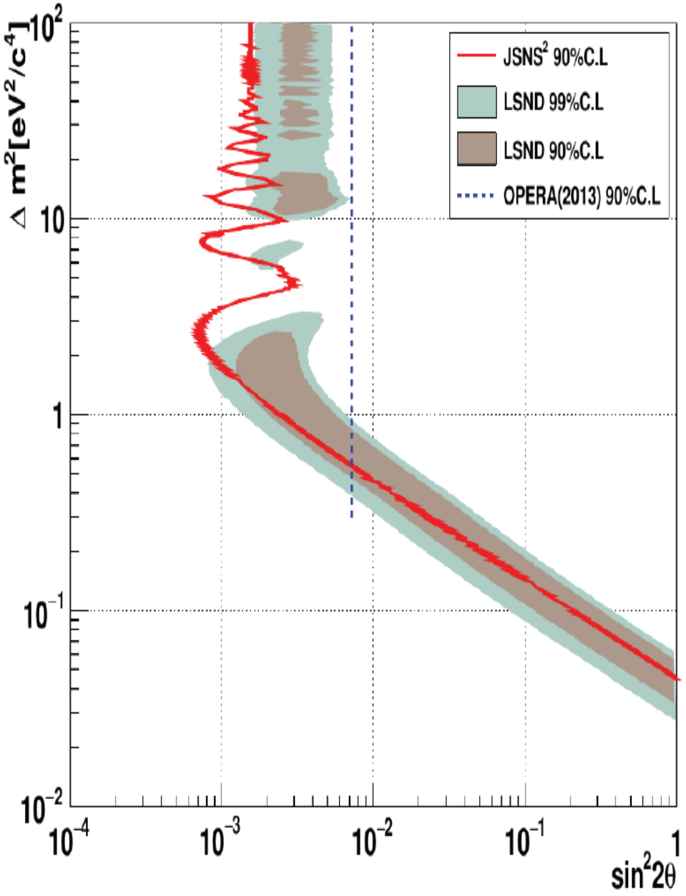
## SBN PROGRAM @ FERMILAB

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) Model-independent indications of short baseline oscillations (SBL) from reactors (DANSS & NEOS → ~3 sigma)**

**b) Reactor and Gallium Anomalies →**

**latest analysis favors hybrid solutions with SBL and nuclear effects**

**c) Many on-going experiments will check the indications**

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

**d) The MINOS+ & LSND signals disfavors the 3+1 (3+N) vacuum mixing scheme**

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

**Status of light sterile neutrinos: They do not seem to feel well**

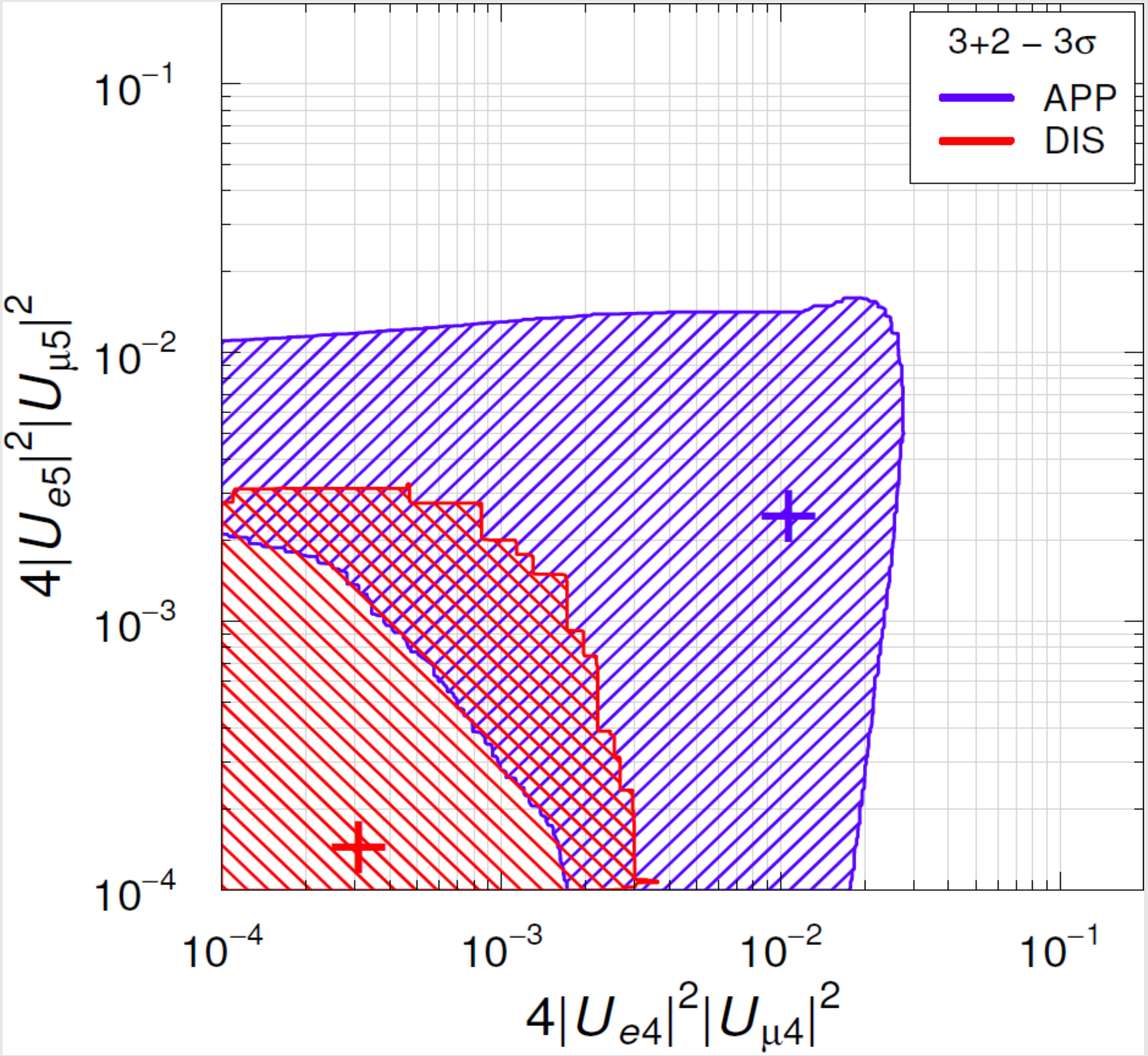
# Thanks!

# Backup

# The 3+2 scheme and more

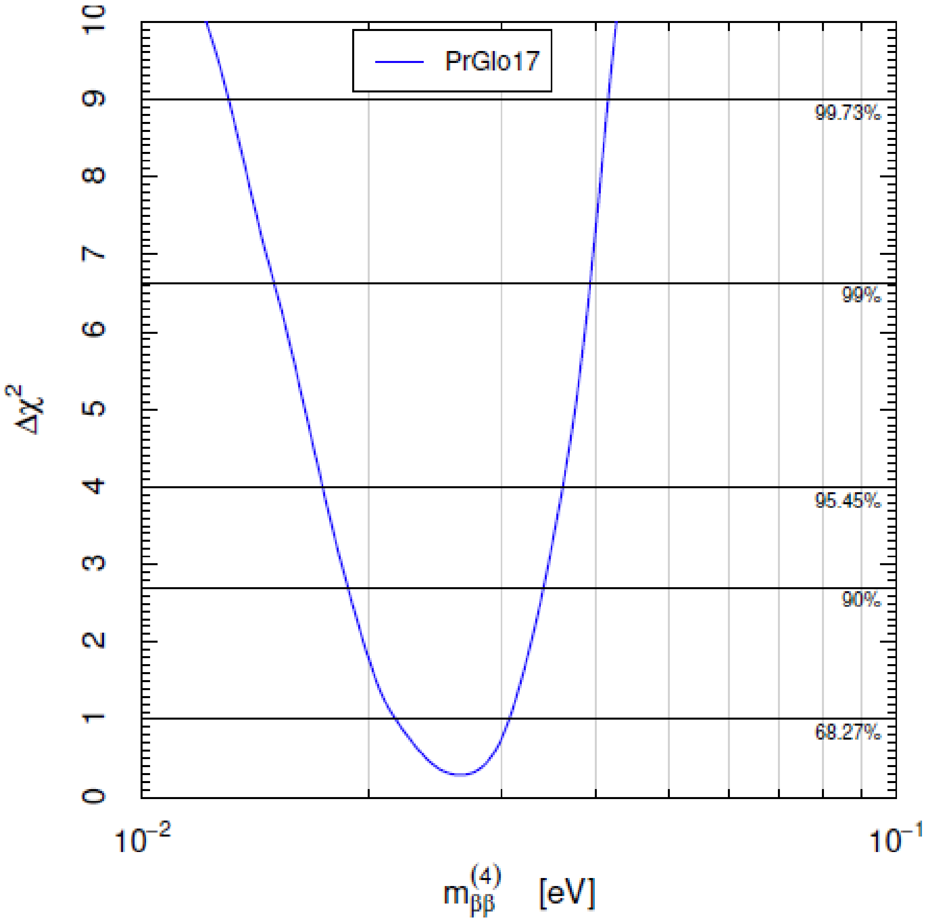
$$\sin^2 2\vartheta_{\alpha\beta}^{(k)} \simeq \frac{1}{4} \sin^2 2\vartheta_{\alpha\alpha}^{(k)} \sin^2 2\vartheta_{\beta\beta}^{(k)},$$

***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]

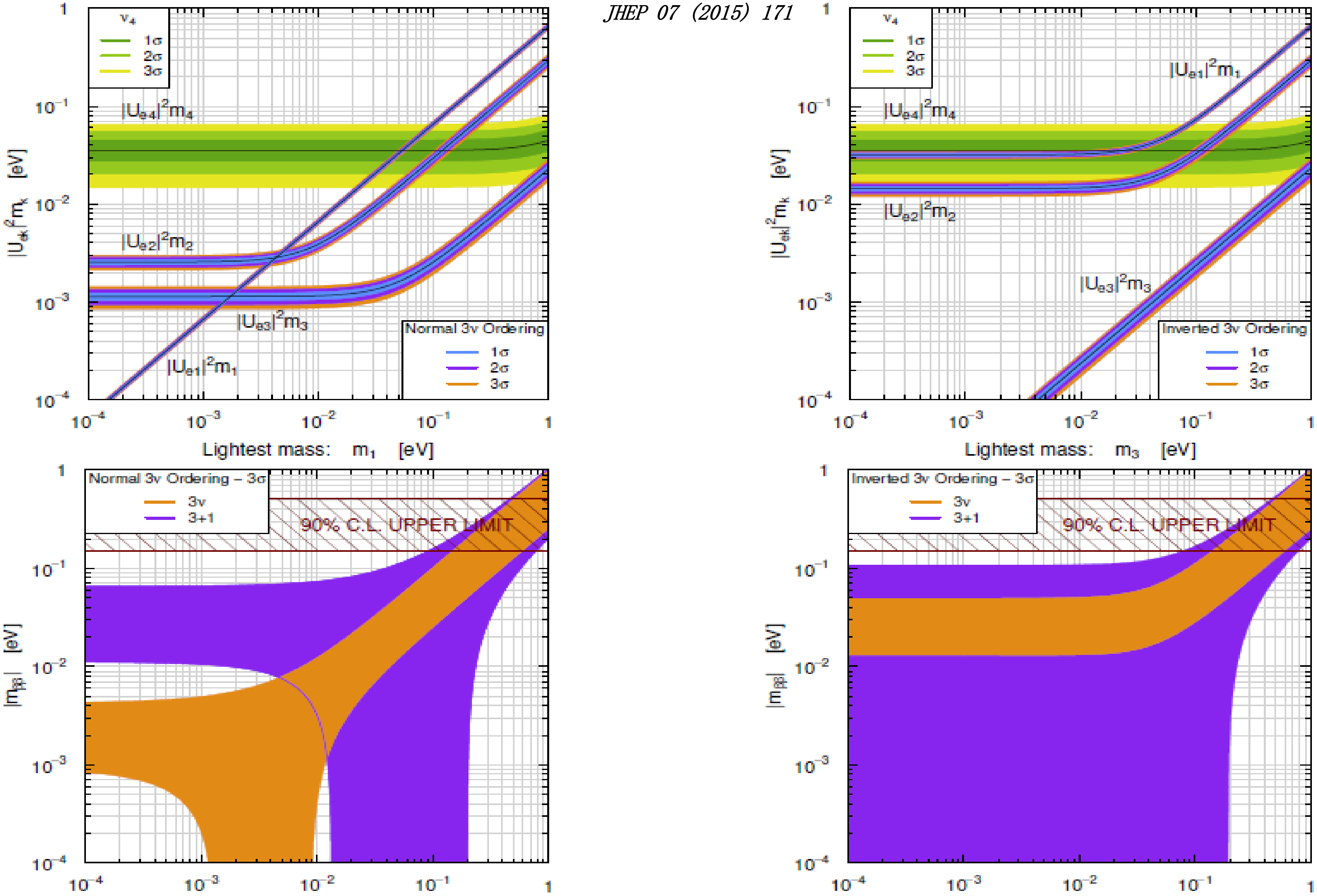
[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

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

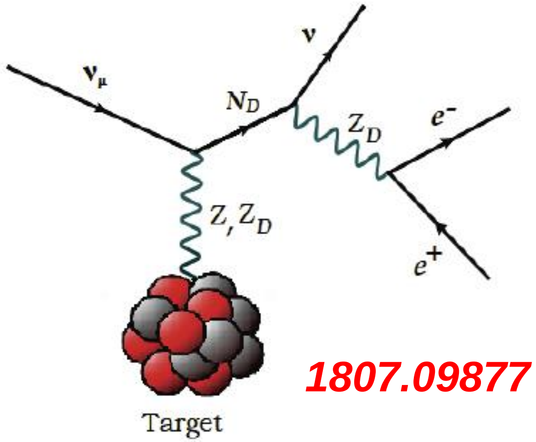
[CG, Zavanin, JHEP 07 (2015) 171]

# Light Sterile Neutrinos@0νββ

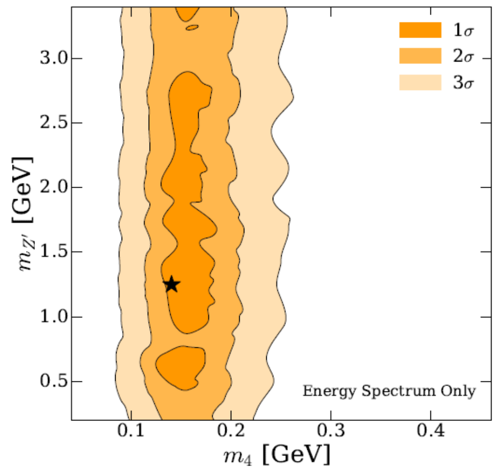


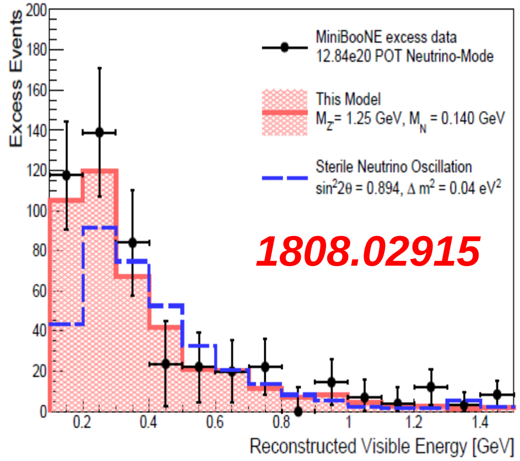
*JHEP 07 (2015) 171*

# Examples of New Physics for the MB Excess

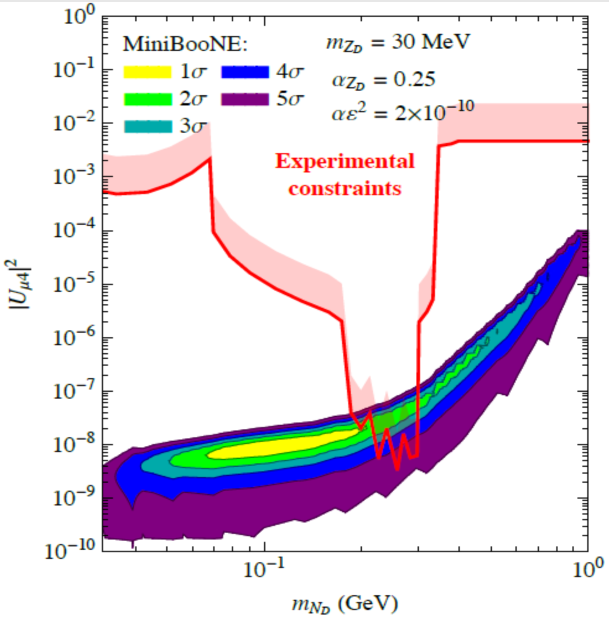


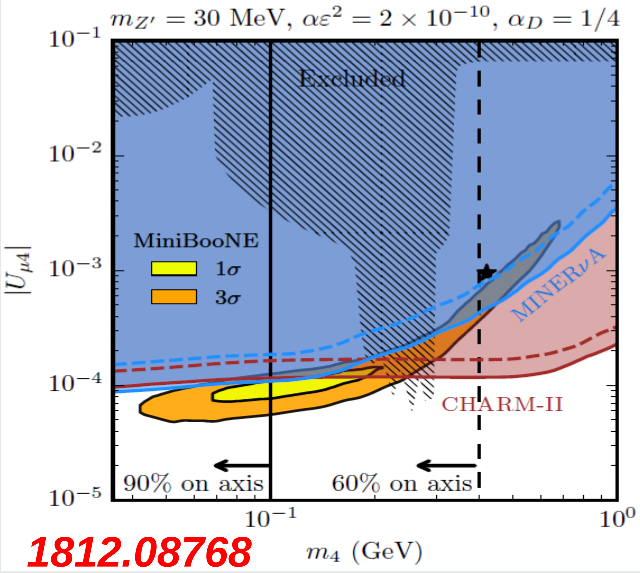
1807.09877





1808.02915





1812.08768

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