Synthesizing Data: Sterile Neutrinos

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Three Neutrino Paradigm

Standard Parameterization of Mixing Matrix

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

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

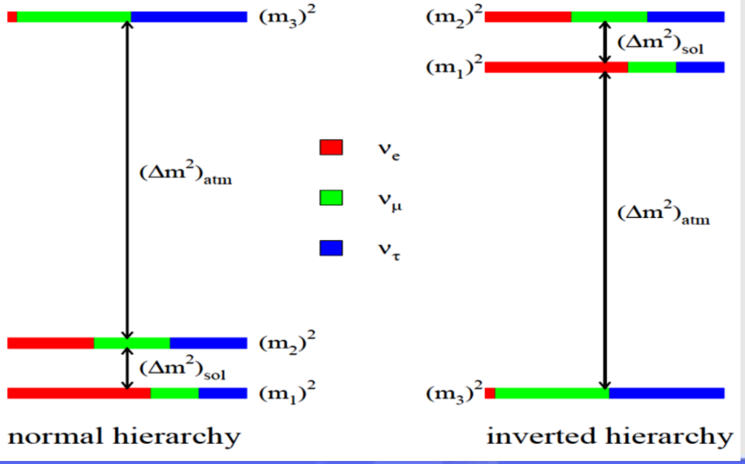
$$c_{ab} \equiv \cos\vartheta_{ab} \qquad s_{ab} \equiv \sin\vartheta_{ab} \qquad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \qquad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$$

3 Mixing Angles: 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**



Current Oscillation data

$m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH)   Gonzalez-Garcia et al.   NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix}+2.407 \to +2.643 \\ -2.629 \to -2.405\end{bmatrix}$

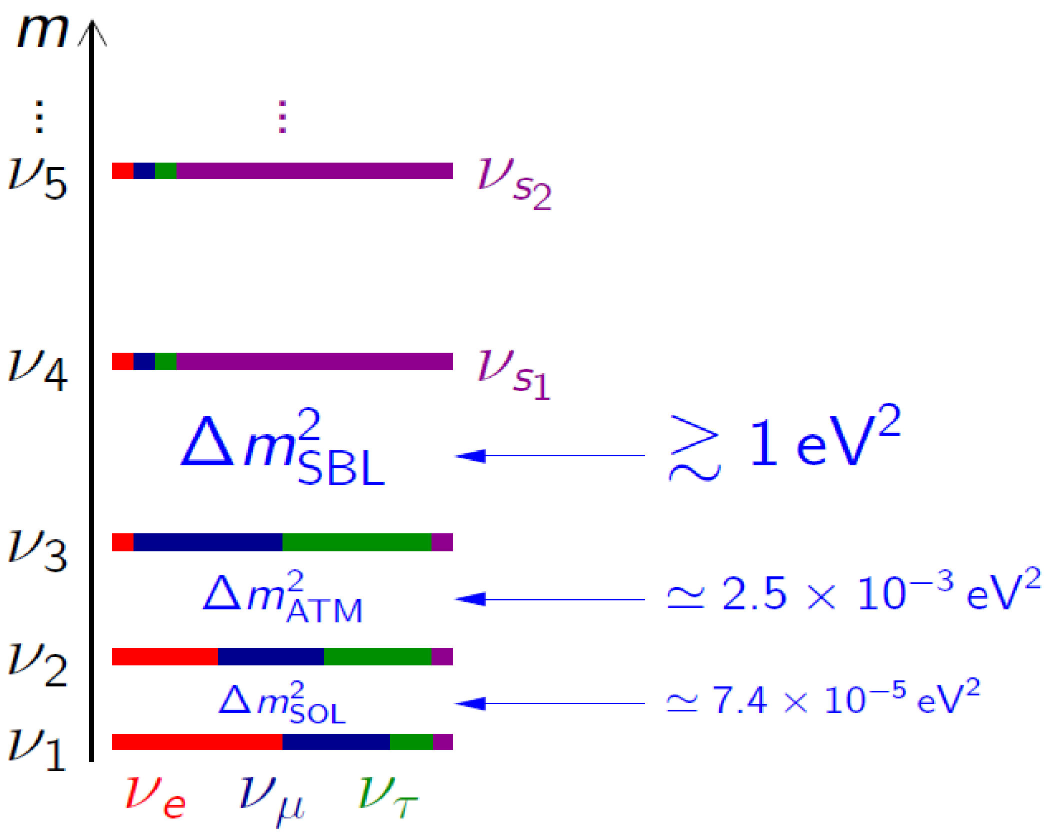
Neutrino Mass Hierarchy

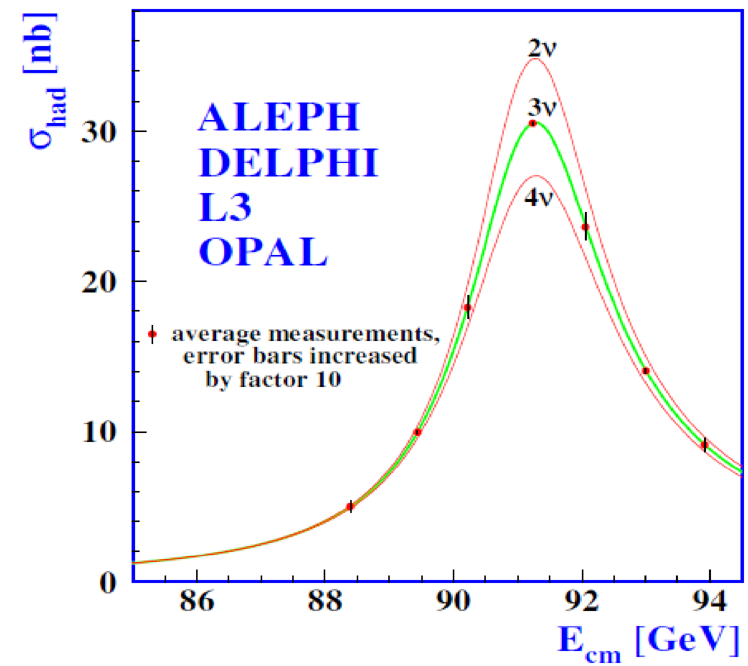
- Reactor: JUNO, RENO-50
- Acc.: T2K, NOνA, LBNF/DUNE
- Atm: PINGU, ORCA, Hyper-K, INO

Leptonic CP Violation

- LBL Acc.: T2K, NOνA
- LBL Acc.: LBNF/DUNE, T2HK

Beyond 3-ν oscillations: Sterile neutrinos





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

Explanation of short baseline oscillations:

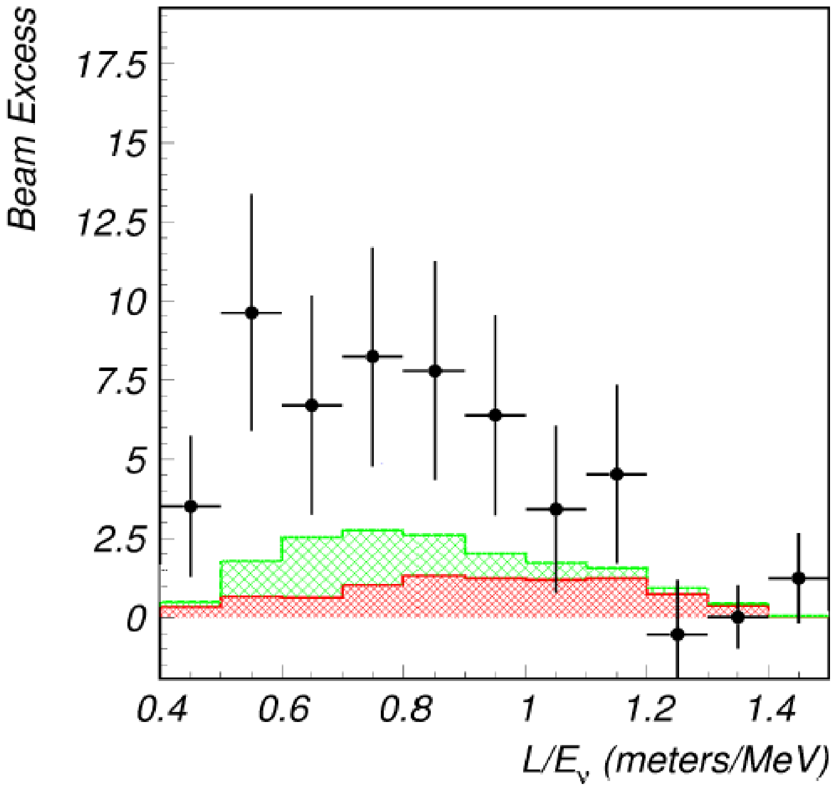
eV-scale sterile neutrinos (which have mixing with active mass eigenstates)

Indications of SBL oscillation beyond 3-νs

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad$ $20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



$\Delta m^2_{\text{SBL}} \gtrsim 0.1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

- Well-known and pure source of $\bar{\nu}_\mu$

$$\underset{800\,\text{MeV}}{p} + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30\,\text{m}$

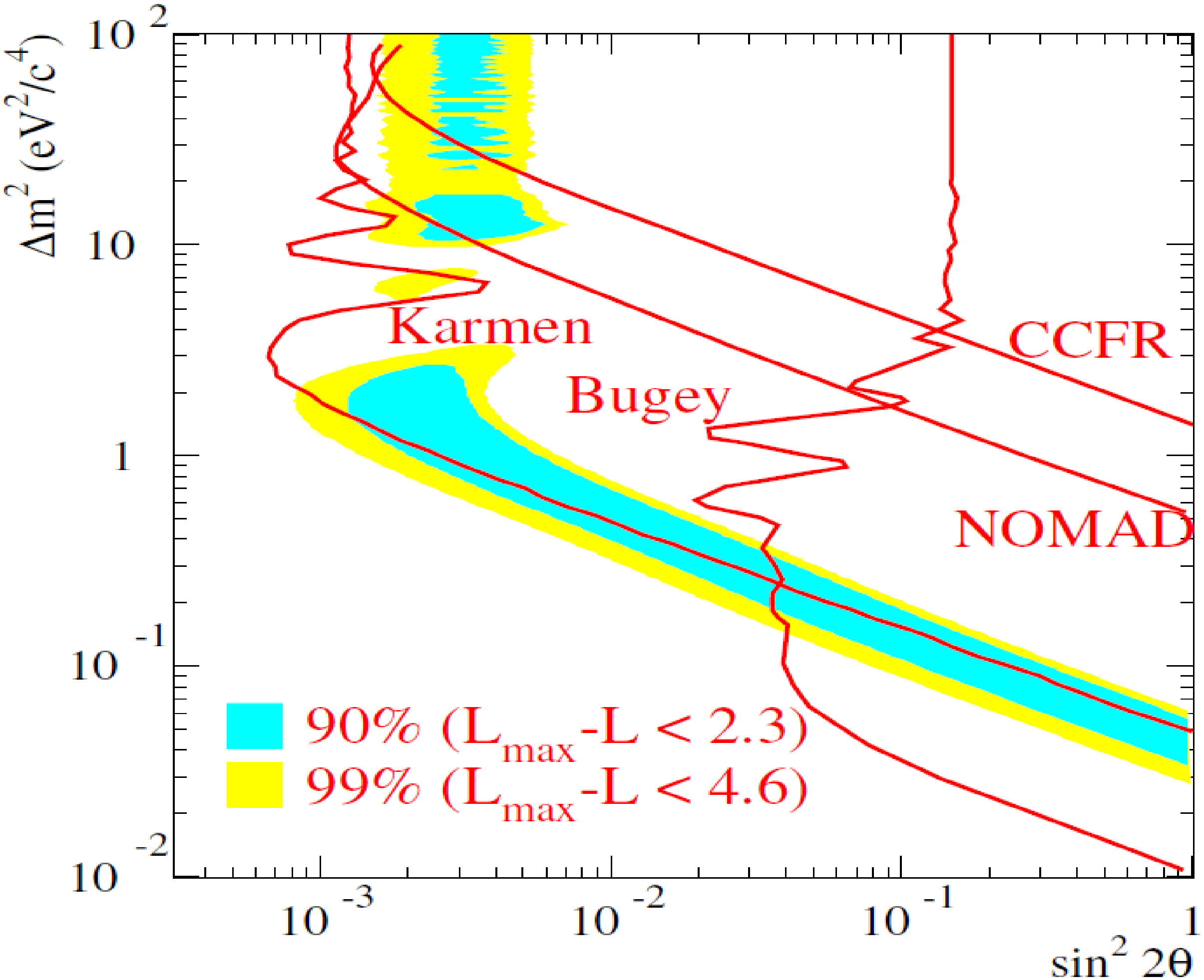
$$\bar{\nu}_e + p \to n + e^+$$

Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

Allowed parameter space



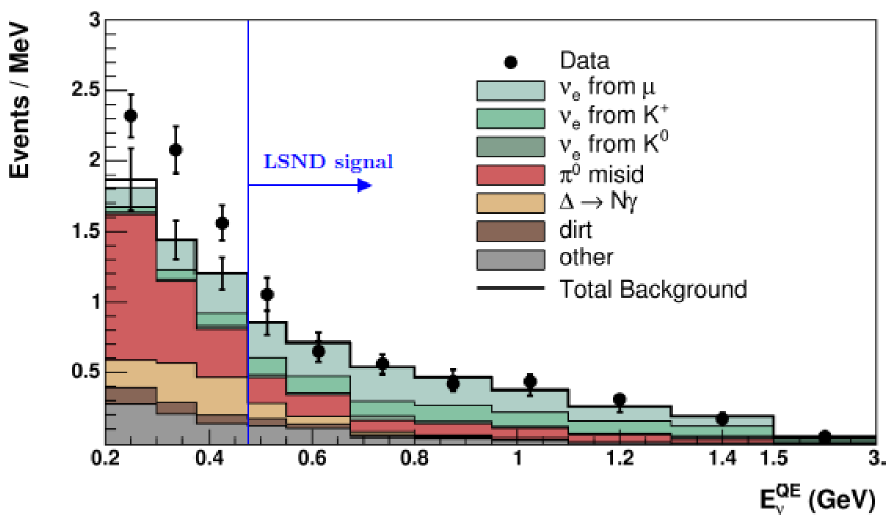
$$\Delta m^2_{\rm SBL} \gtrsim 3 \times 10^{-2}\,{\rm eV}^2 \gg \Delta m^2_{\rm ATM} \simeq 2.5 \times 10^{-3}\,{\rm eV}^2 \gg \Delta m^2_{\rm SOL}$$

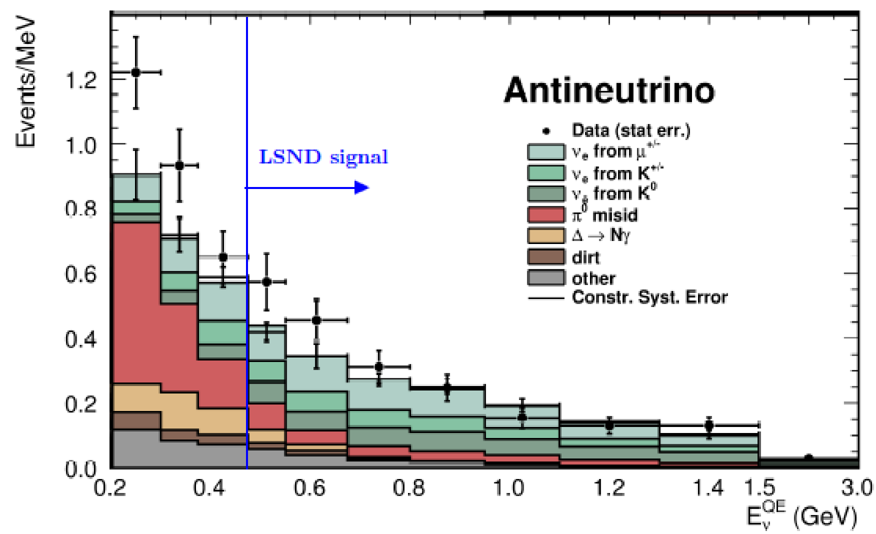
MiniBooNE

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

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]

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





Purpose: check LSND signal with different L&E, but the same L/E

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

Oscillation search is not conclusive. → no near detector!

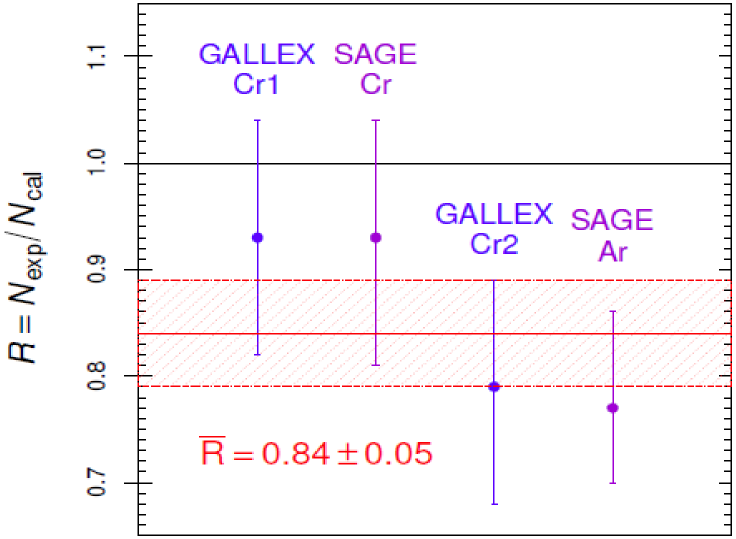
Gallium anomaly

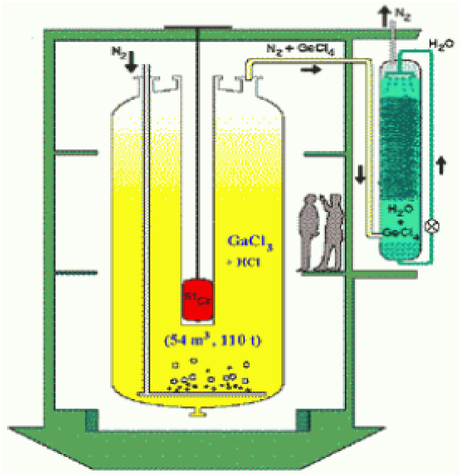
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\mathrm{MeV}$ $\quad E \simeq 0.81\,\mathrm{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$





$\approx 2.9\sigma$ deficit

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

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

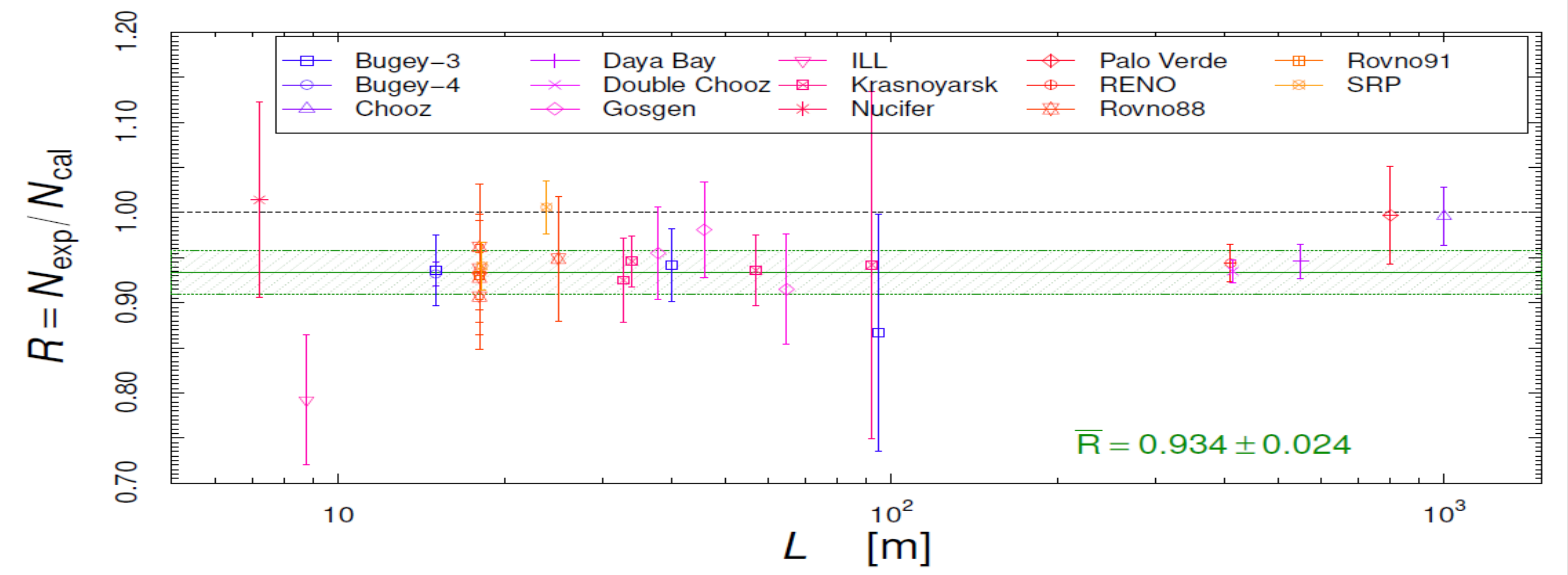
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

- ${}^{3}\mathrm{He} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + {}^{3}\mathrm{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

Reactor Antineutrino Anomaly

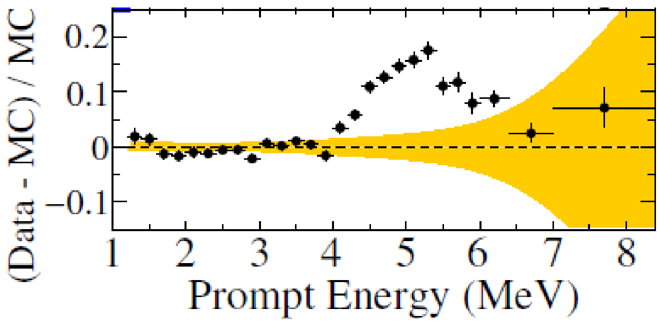
[Mention et al, PRD 83 (2011) 073006]

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

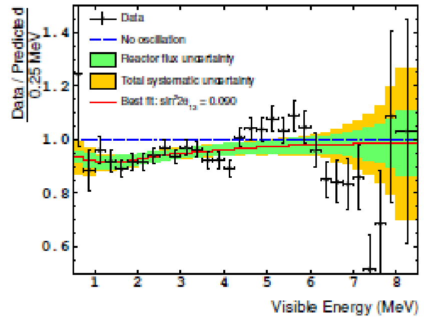


- **Discrepancy between theory and measurements**
- **~2.8σ deficit (depending on the theoretical flux uncertainty)**
- **Nominal theoretical uncertainty from the Saclay+Huber model ~ 2.5%**

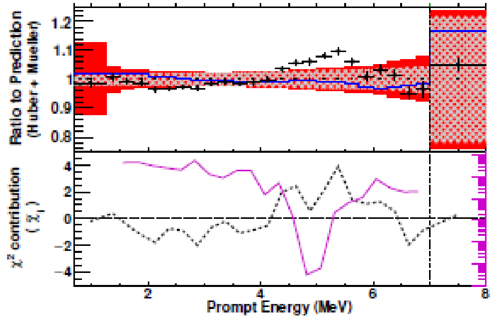
New issue on RAA: 5 MeV bump



[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 (SBL oscillations are averaged in RENO, Double Chooz and Daya Bay)

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

(3) No complete calculation of the neutrino flux and associated uncertainty after the observation of the discrepancy.

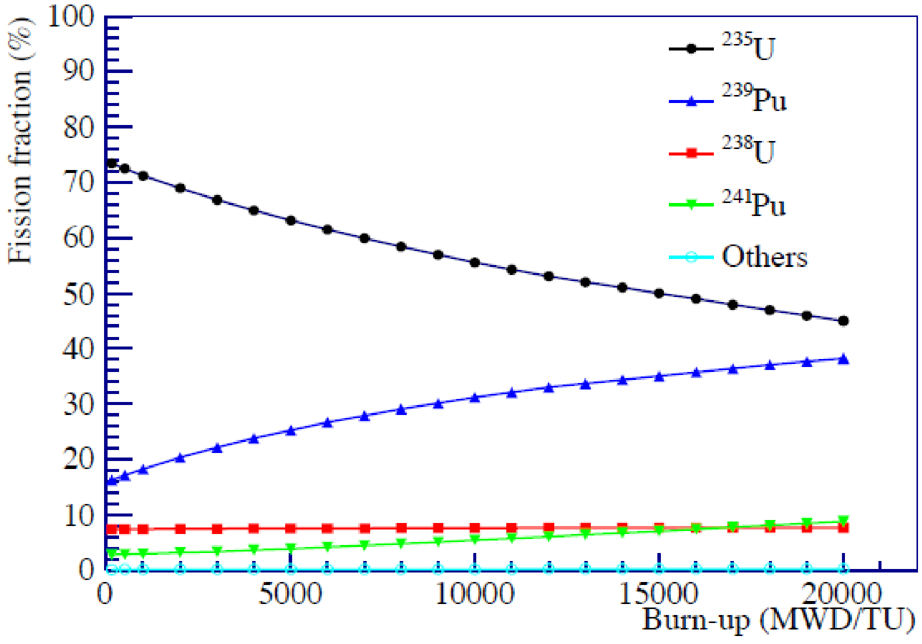
(4) Some guess to increase the uncertainty: e.g. about 5%. [Hayes and Vogel, 2016]

New issue on RAA: fuel Evolution data

Daya Bay, PRL 118 (2017) 251801

- 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:

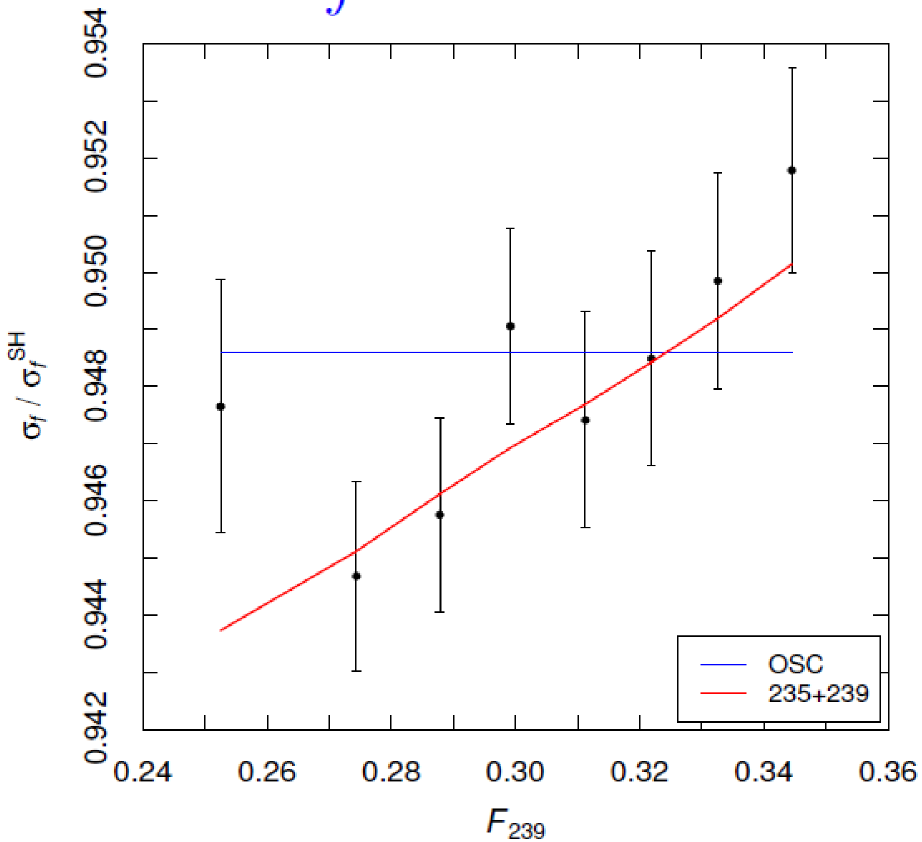
$$F_{235},\ F_{238},\ F_{239},\ F_{241}.$$



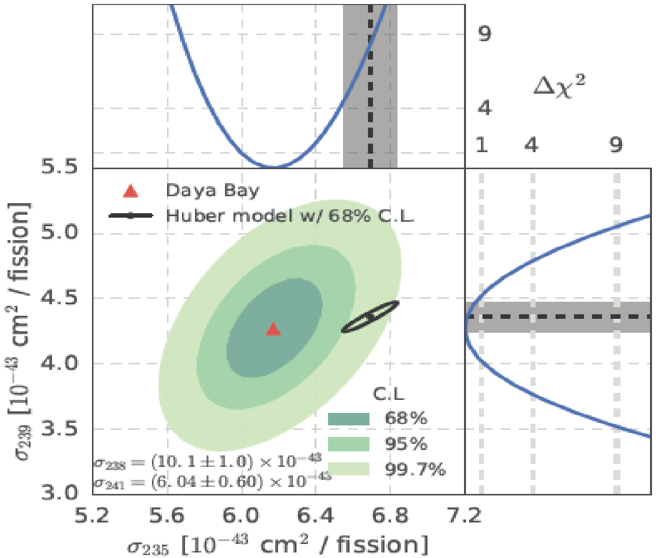
- Cross section per fission:

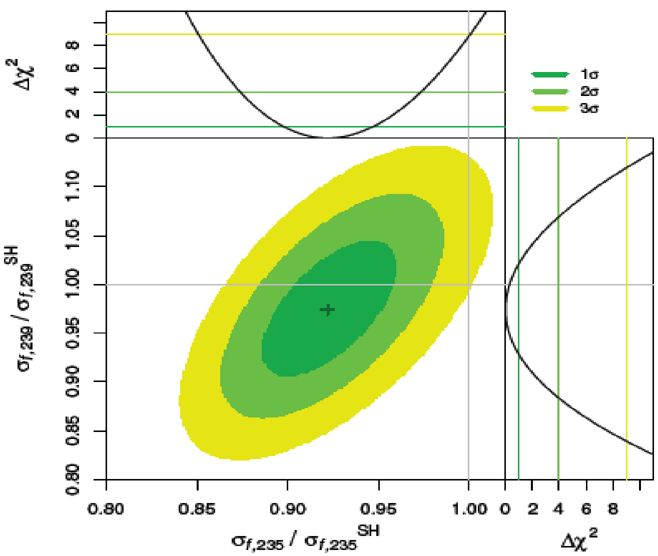
$$\sigma_f = \sum_{k=235,238,239,241} F_k\, \sigma_{f,k}$$

$$\sigma_{f,k} = \int dE_\nu\, \phi_k(E_\nu)\, \sigma(E_\nu)$$



Daya Bay fuel evolution data





- Best fit: mainly suppression of $\sigma_{f,235}$
- Equal fluxes suppression:

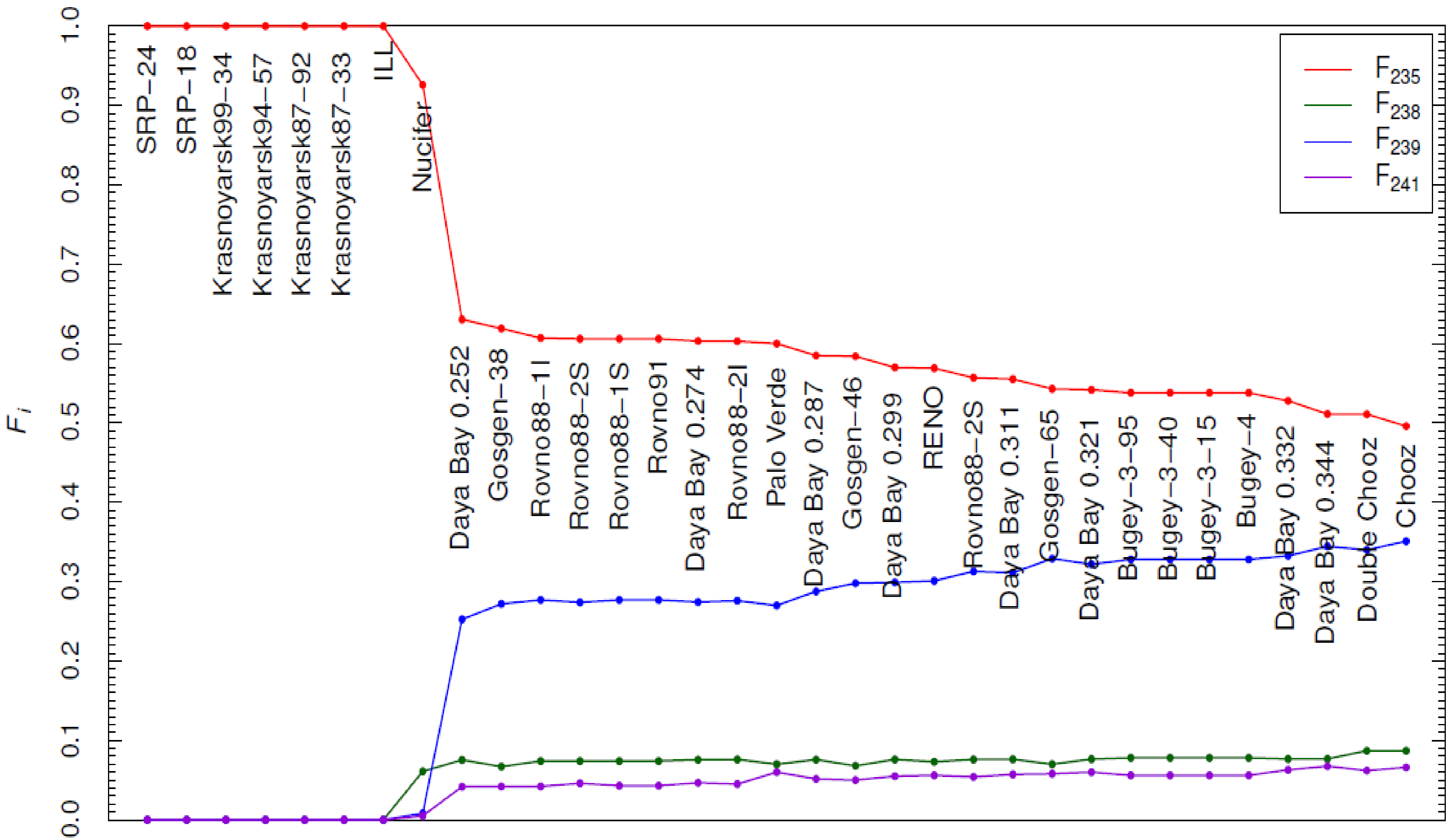
$$\Delta\chi^2/\text{NDF} = 7.9/1$$

  disfavored at 2.8σ
- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account
- With theoretical flux uncertainties:

Daya Bay	^{235}U	OSC
χ^2_{min}	3.8	9.5
NDF	7	7
GoF	80%	22%

- MC: OSC disfavored at 2.6σ

Fuel fractions of all reactor experiments

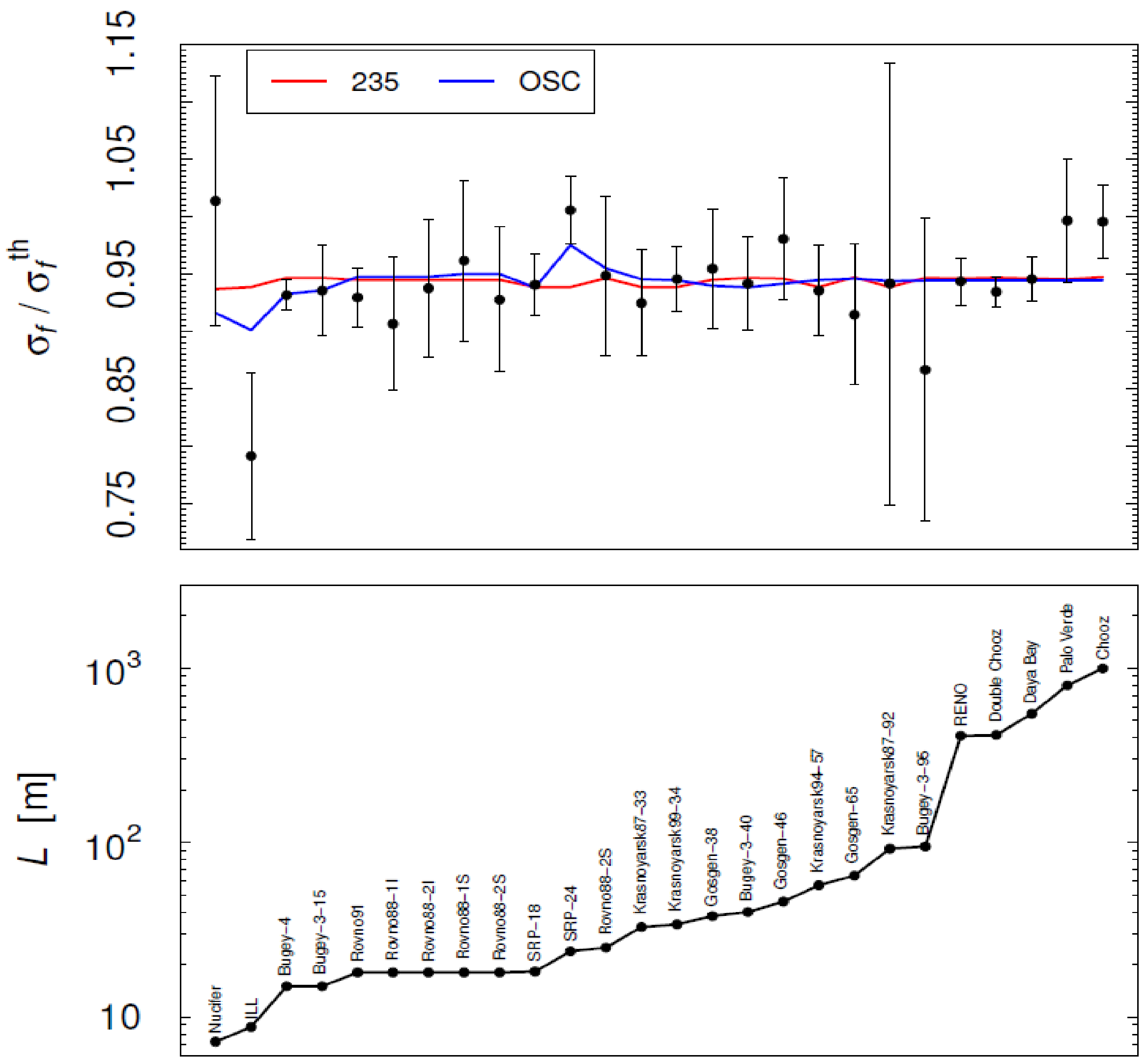


Fits of Reactor rates data

Giunti, Ji, Laveder, YFL, Littlejohn, arXiv:1708.01133

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

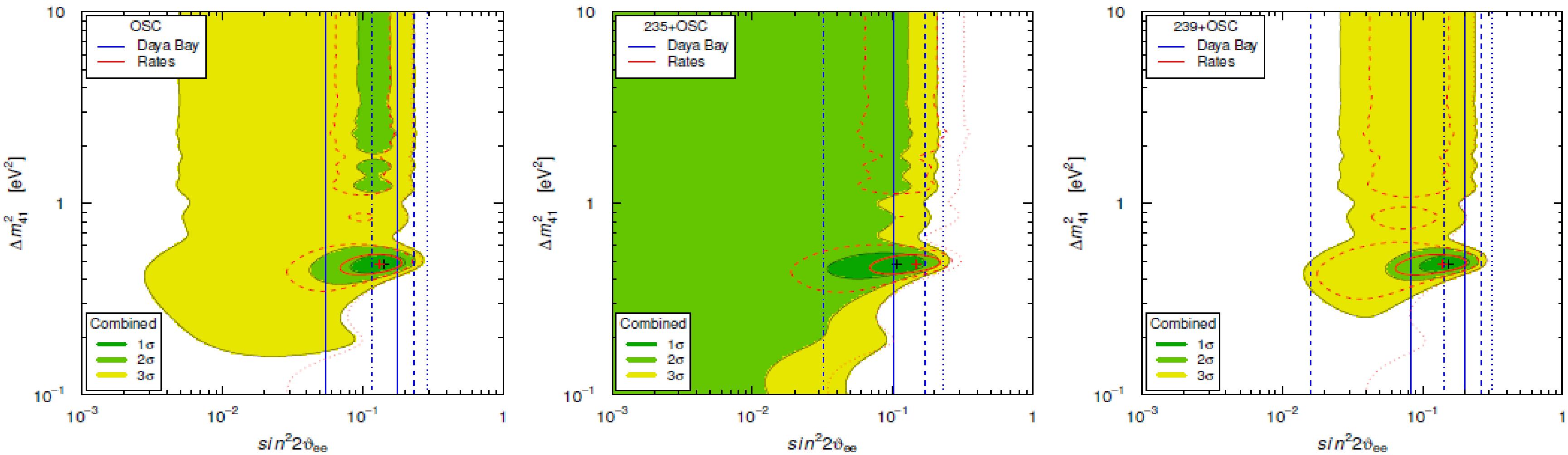
MC: ^{235}U disfavored at 1.7σ



Combining Evolution data with Reactor rates data

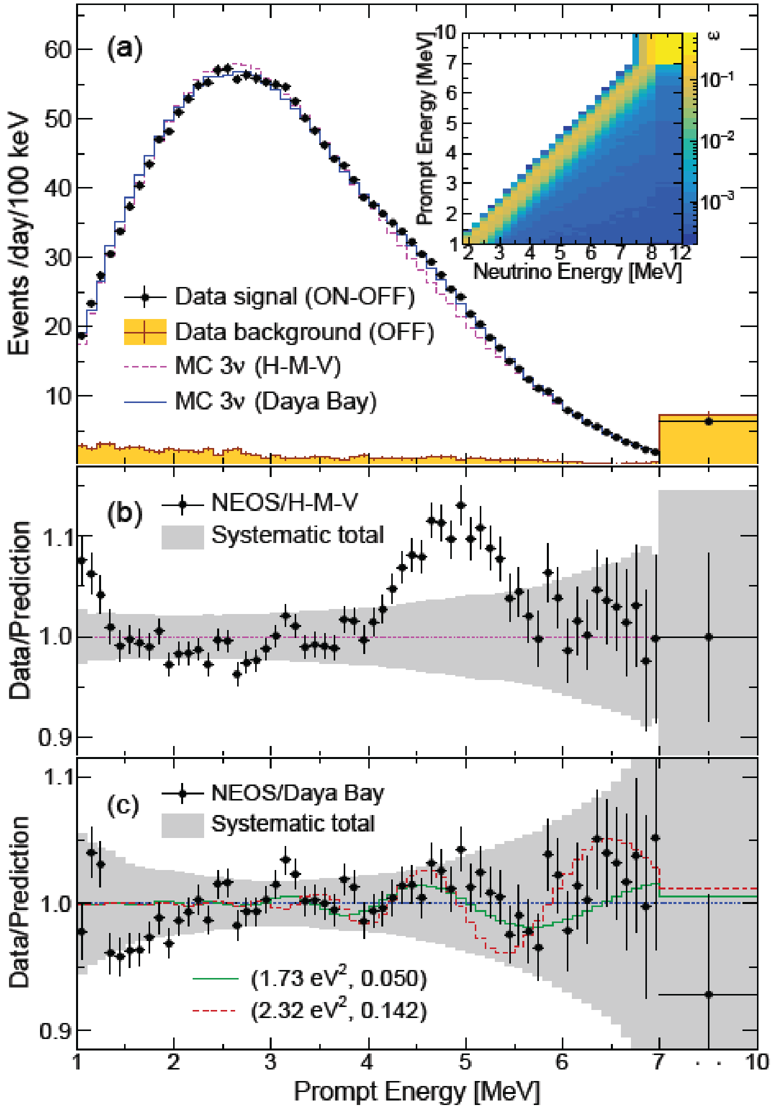
Giunti, Ji, Laveder, YFL, Littlejohn, arXiv:1708.01133

	^{235}U	$^{235}U + {}^{239}U$	OSC	^{235}U+OSC	^{239}U+OSC
χ^2_{min}	25.3	24.8	23.0	20.2	17.5
NDF	32	31	31	30	30
GoF	79%	78%	85%	91%	100%
Δm^2_{41}	—	—	0.48	0.48	0.48
$\sin^2 2\vartheta_{ee}$	—	—	0.14	0.11	0.15
r_{235}	0.934	0.934	—	0.987	—
r_{239}	—	0.970	—	—	1.099



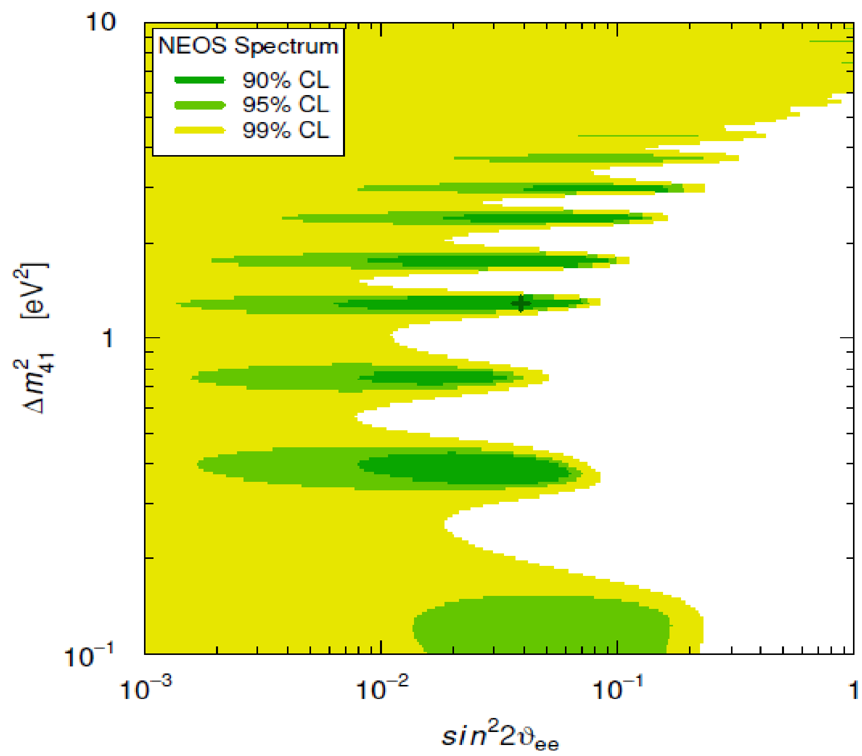
See also *Dentler, et. al. 1709.04294*

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.

NEOS fits



$$\chi^2_{\text{no osc.}} - \chi^2_{\text{min}} = 6.5$$

Best Fits:

$\Delta m^2_{41} = 1.7\,\text{eV}^2 \quad \sin^2 2\theta_{14} = 0.05$

$\Delta m^2_{41} = 1.3\,\text{eV}^2 \quad \sin^2 2\theta_{14} = 0.04$

χ^2 distribution: $\approx 2.1\sigma$ anomaly

NEOS Monte Carlo: $\approx 1.2\sigma$ anomaly

Global status of light sterile neutrinos

Based on Gariazzo, Giunti, Laveder, YFL, arXiv:1703.00860

Effective SBL oscillation in 3+1 schemes

Appearance $(\alpha \neq \beta)$

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

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

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

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

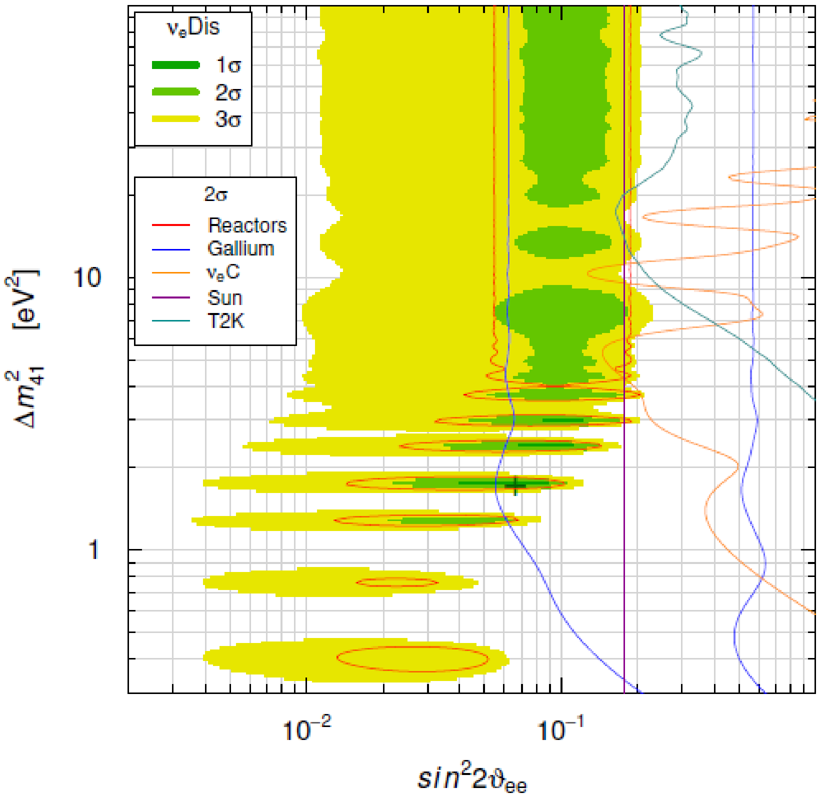
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to $\Delta m^2_{\mathrm{ATM}}$ [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to $\Delta m^2_{\mathrm{SOL}}$ [Long, Li, CG, PRD 87, 113004 (2013) 113004]

Global (anti)nu_e disappearance



- KARMEN+LSND ν_e–^{12}C
  [Conrad, Shaevitz, PRD 85 (2012) 013017]
  [CG, Laveder, PLB 706 (2011) 20]
- Solar ν_e + KamLAND $\bar{\nu}_e$
  [Li et al, PRD 80 (2009) 113007, PRD 86 (2012) 113014]
  [Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]
- T2K Near Detector ν_e disappearance
  [T2K, PRD 91 (2015) 051102]
- $\Delta\chi^2_{\text{NO}} = 14.1 \Rightarrow \approx 3.3\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \Leftrightarrow |U_{e4}|^2 = 0.017$
- $\chi^2_{\text{min}}/\text{NDF} = 163.0/174 \Rightarrow \text{GoF} = 71\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.7/7 \Rightarrow \text{GoF}_{\text{PG}} = 6\%$

Tritium Beta-Decay: $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

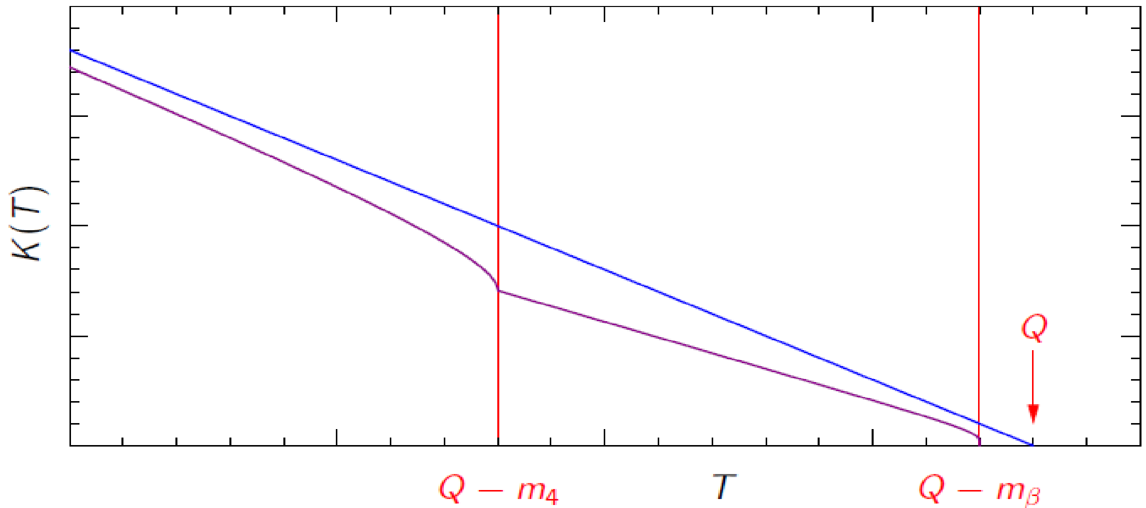
$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C\, G_F)^2}{2\pi^3}\,|\mathcal{M}|^2\, F(E)\, p\, E\, K^2(T)$$

$$\frac{K^2(T)}{Q-T} = \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2}\,\theta(Q-T-m_k)$$

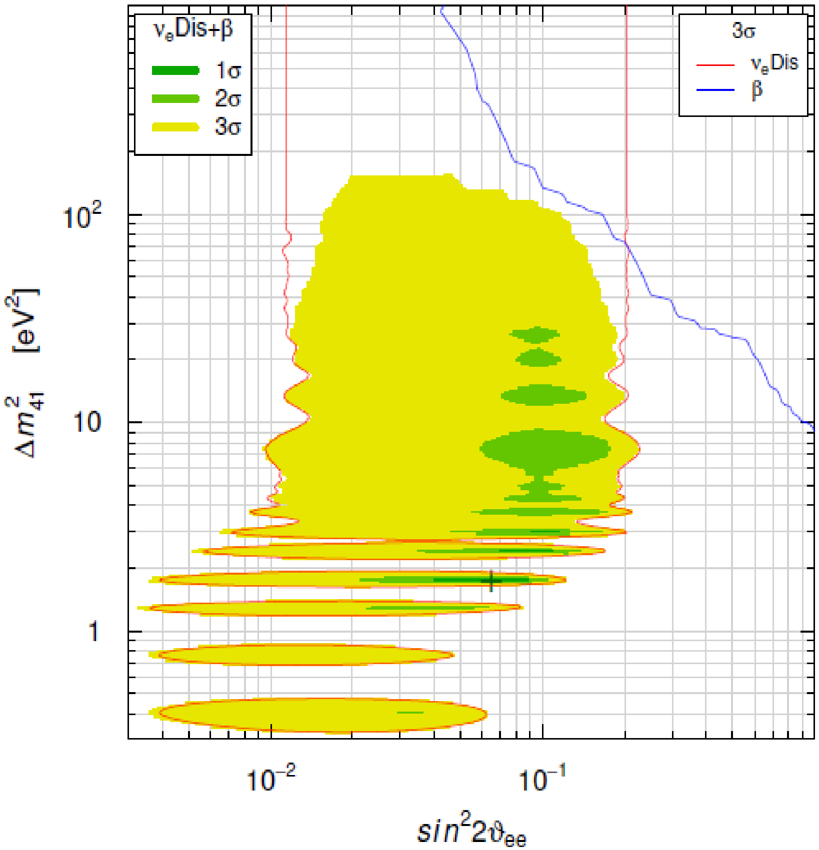
$$m_4 \gg m_{1,2,3} \Rightarrow \simeq (1-|U_{e4}|^2)\sqrt{(Q-T)^2 - m_\beta^2}\,\theta(Q-T-m_\beta)$$

$$+|U_{e4}|^2\sqrt{(Q-T)^2 - m_4^2}\,\theta(Q-T-m_4)$$



$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

Constraints from beta decay data

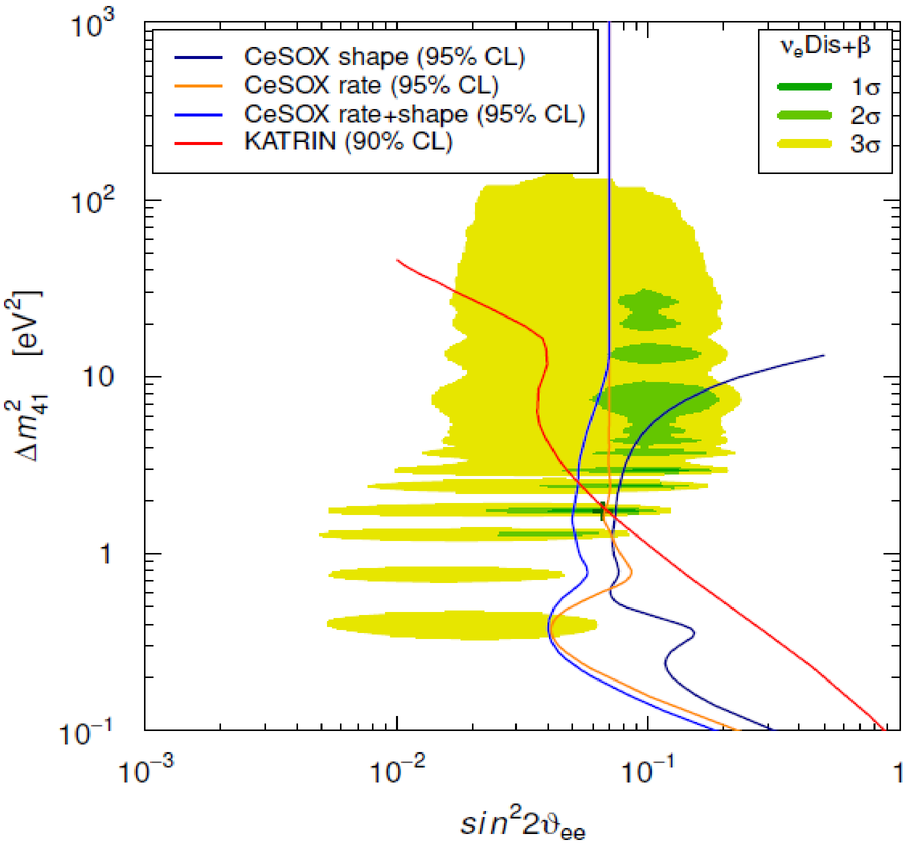


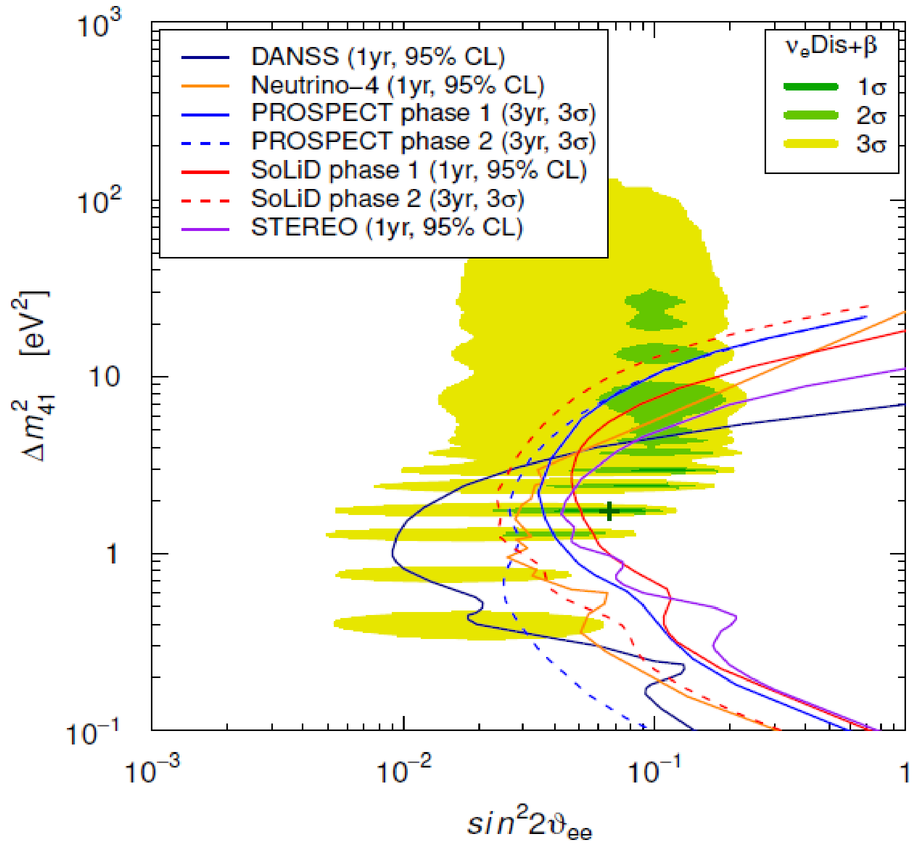
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \Leftrightarrow |U_{e4}|^2 = 0.017$
- $2\,\text{cm} \lesssim \frac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 7\,\text{m}$ at 3σ
- $0.0050 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.23$ at 3σ

Mainz + Troitsk Tritium beta decays
Mainz, EPJC (2013);
Troitsk, JETPL (2013); JPG 41 (2014)

→ ***Future Better Sensitivity of KATRIN: Formaggio,Barrett, PLB (2011), etc.***

Future search with (anti)nu_e disappearance



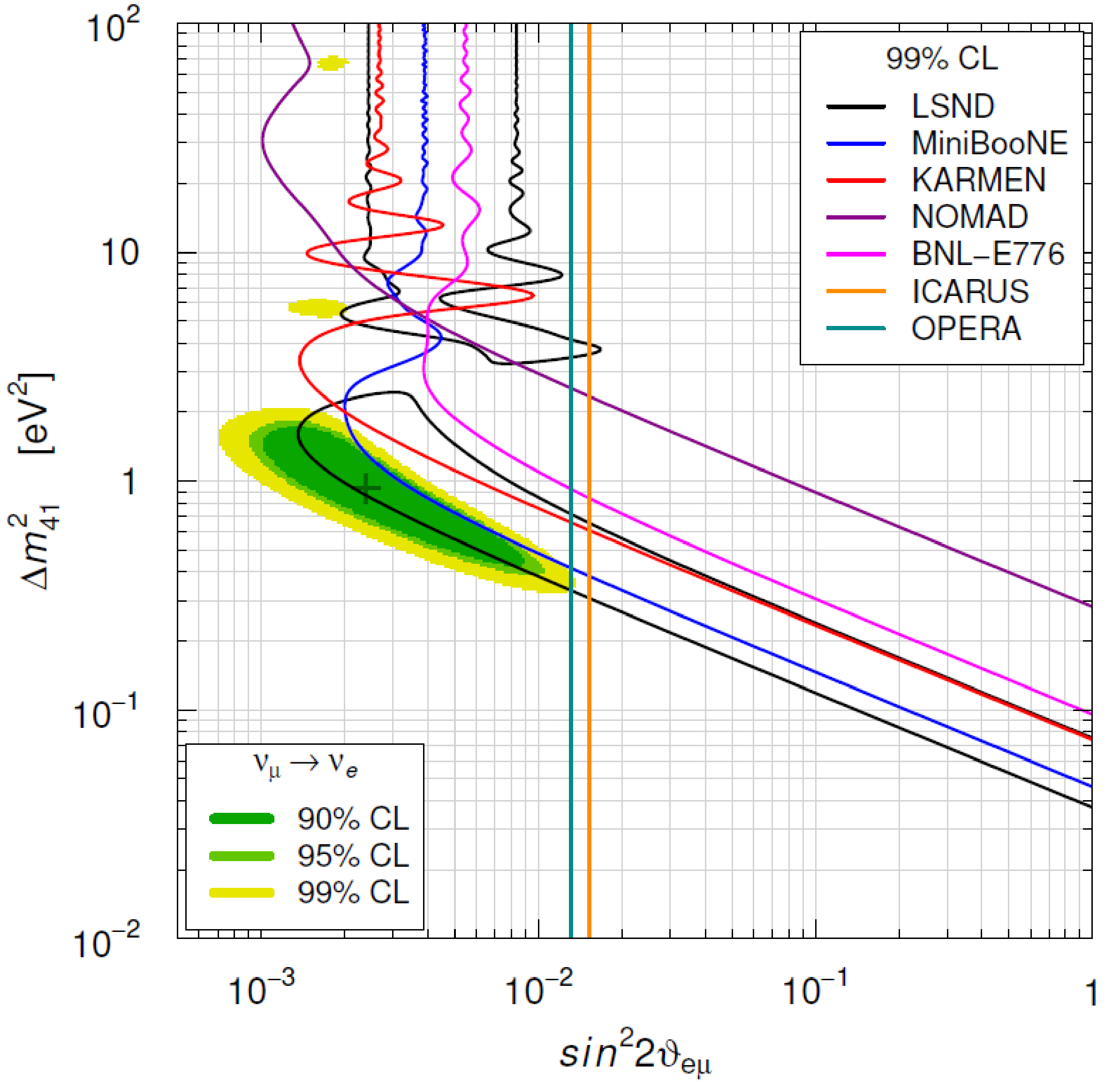


CeSOX (Gran Sasso, Italy) $^{144}\mathrm{Ce} \to \bar{\nu}_e$
BOREXINO: $L \simeq$ 5-12m [Vivier@TAUP2015]

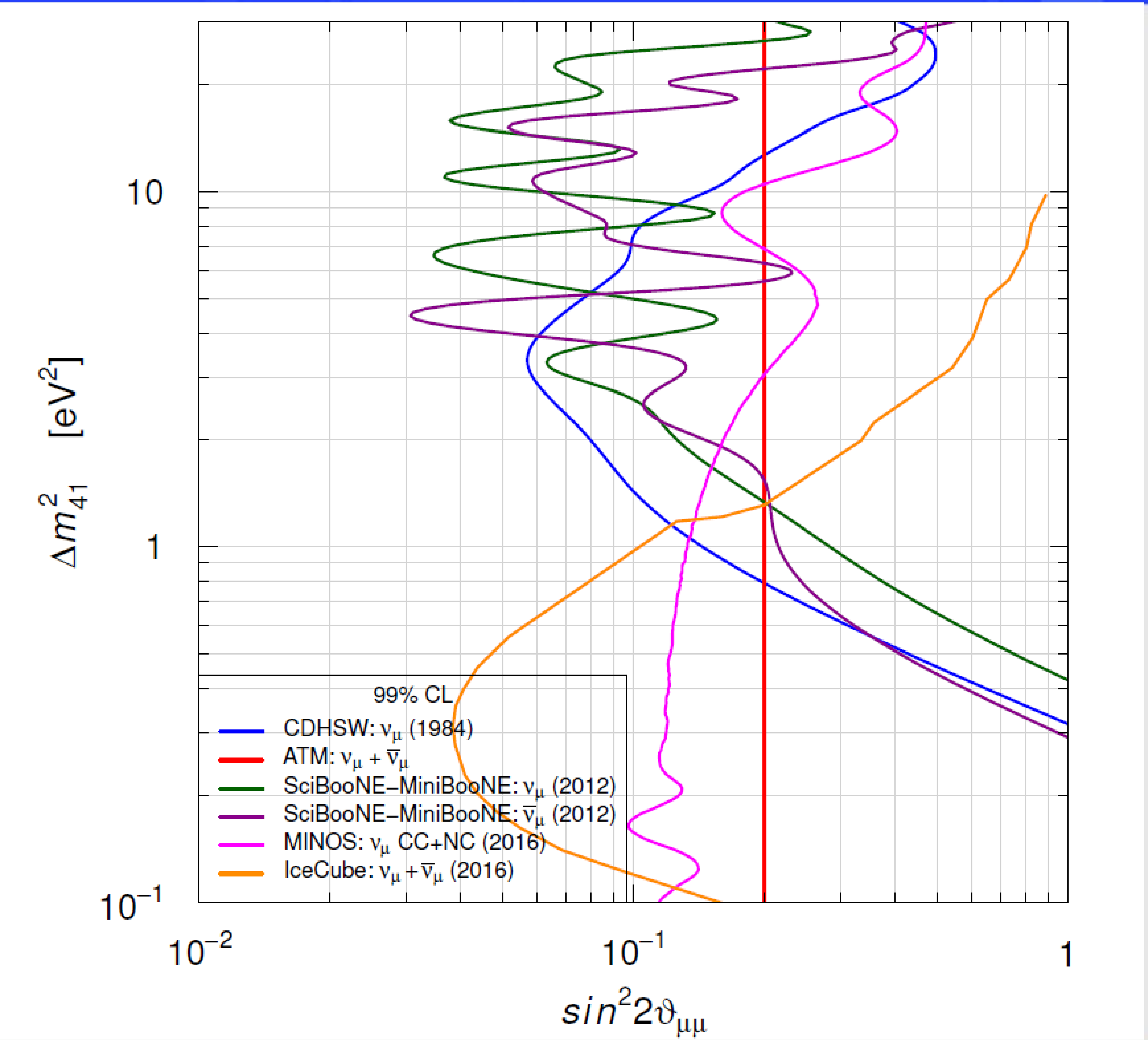
KATRIN (Karlsruhe, Germany) $^{3}\mathrm{H} \to \bar{\nu}_e$
[Drexlin@NOW2016]

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

Global (anti)nu_mu→(anti)nu_e appearance



Null results in (anti)ν_μ disappearance



Appearance-Disappearance Tension

ν_e DIS

$$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$$

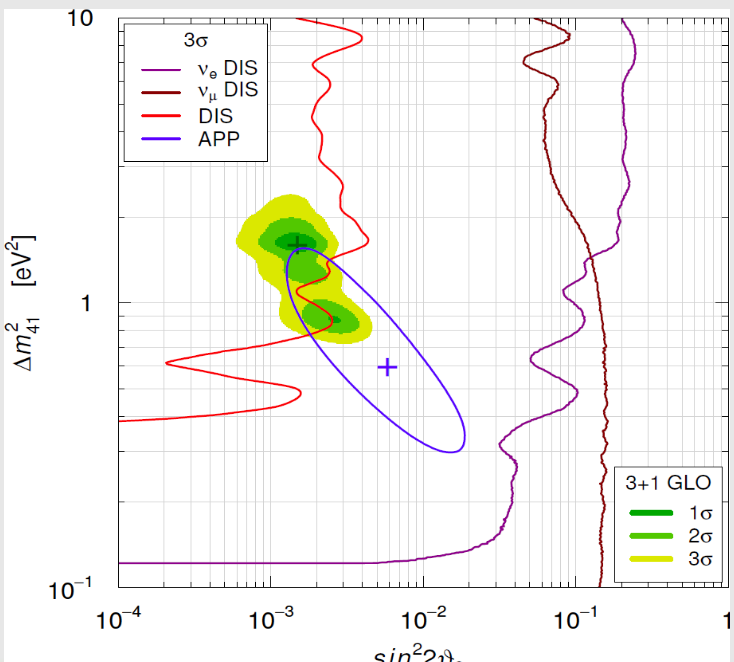
ν_μ DIS

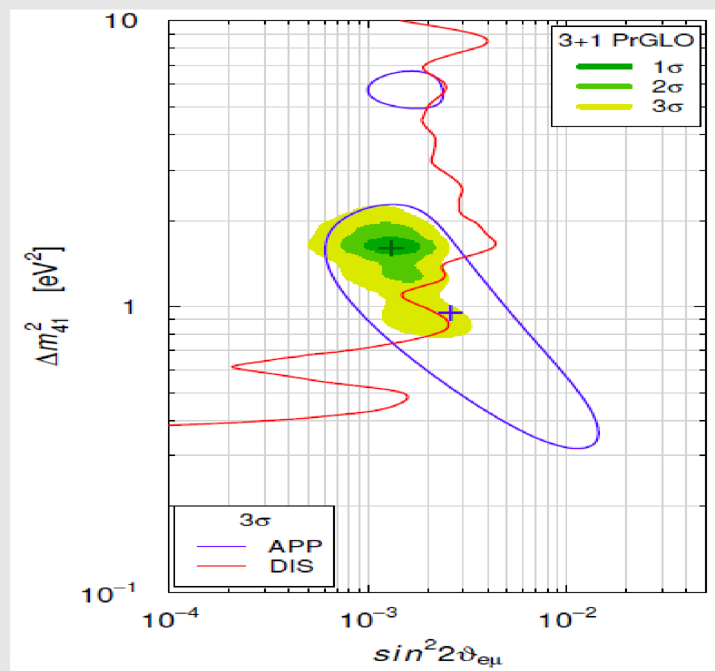
$$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$$

$\nu_\mu \to \nu_e$ APP

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

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



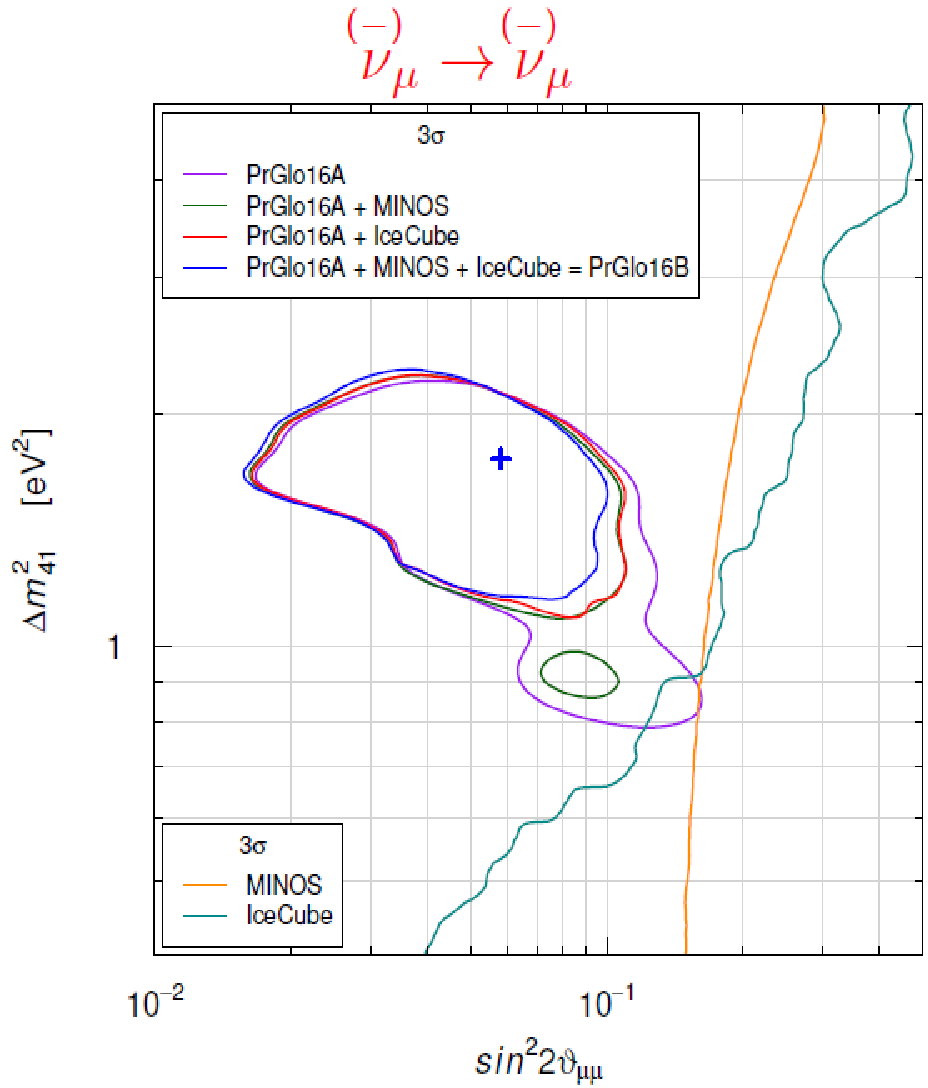


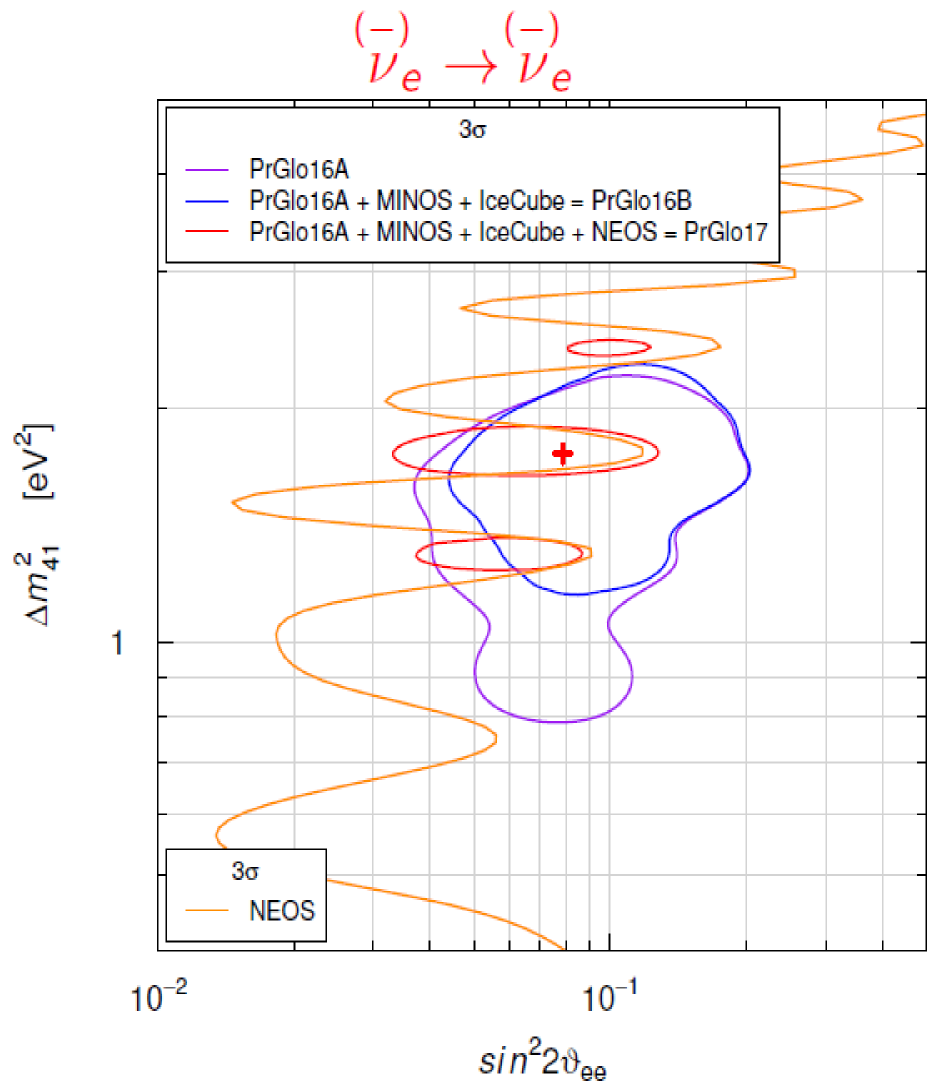
With (left) and without (right) the MiniBooNE low energy bins (<475 MeV)

(left) GoF_PG = 0.06%

(right) GoF_PG = 7%

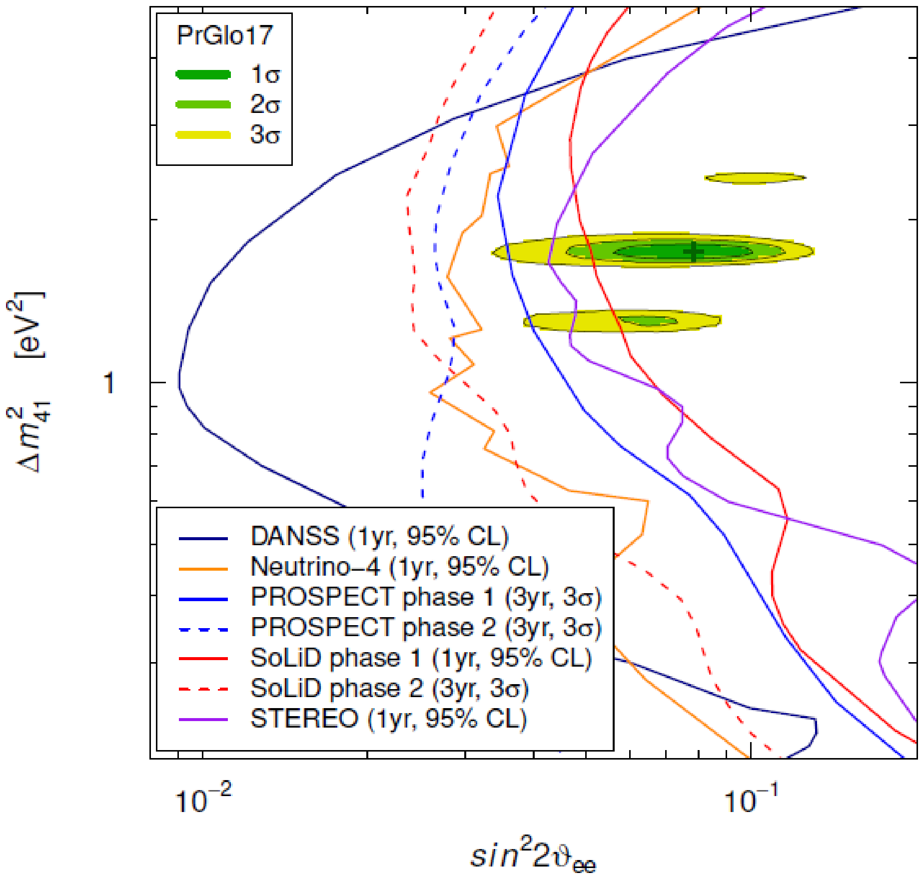
Effects of MINOS, IceCube and NEOS

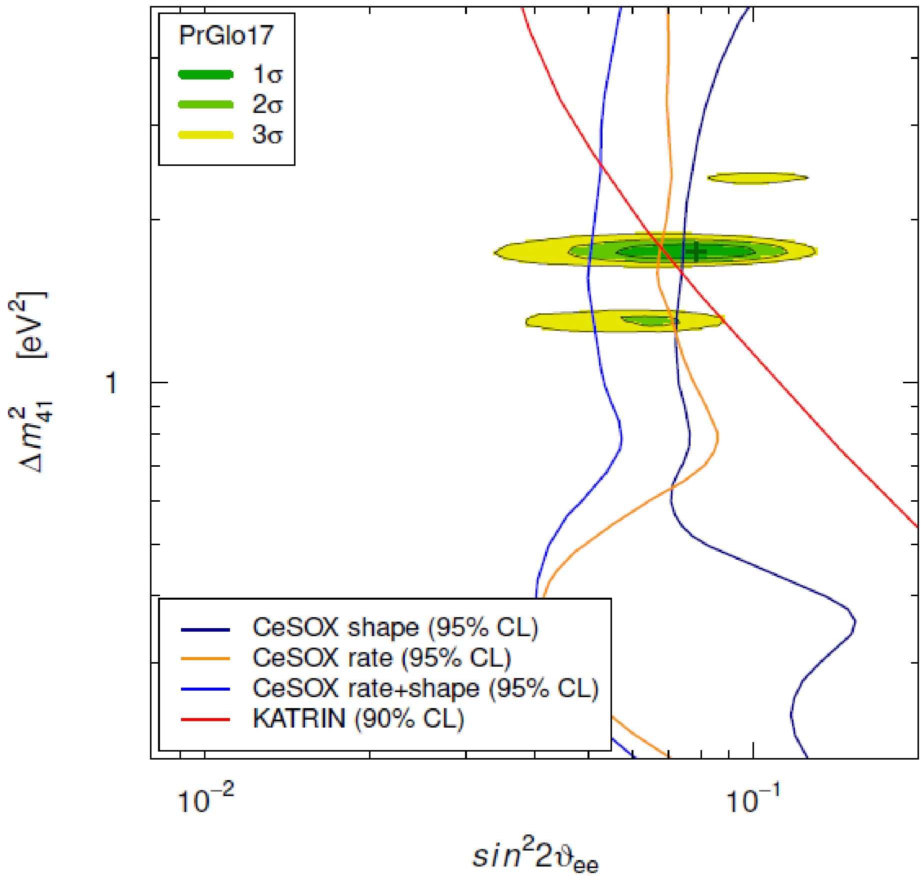




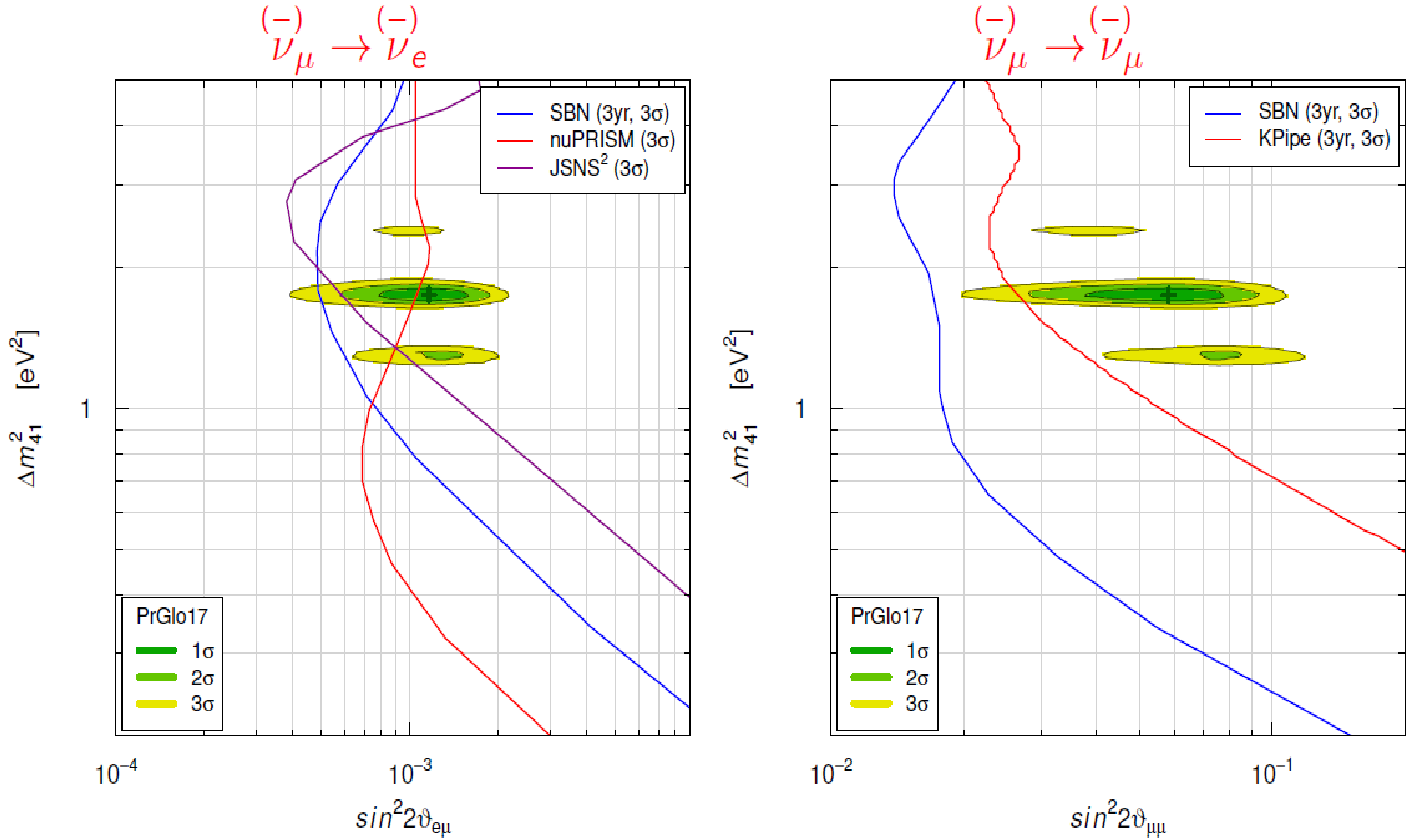
Future searches in the global region

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$





Future searches in the global region



Conclusion

Interesting indications of short baseline oscillations

(a) LSND nu_mu → nu_e signal (need confirmation)

(b) Gallium nu_e disappearance (detector efficiency)

(c) Reactor (anti)nu_e disappearance (flux calculation dependence)

Many experiments will be on-line in the next several years

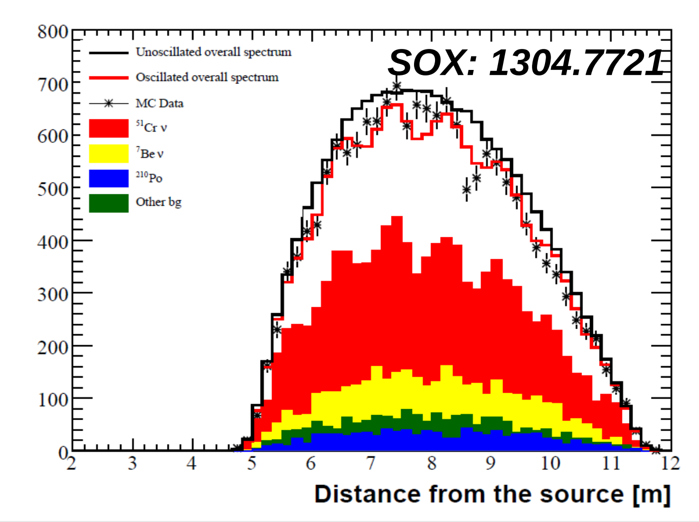
Source, Reactor & Accelerator experiments to give the decisive tests!

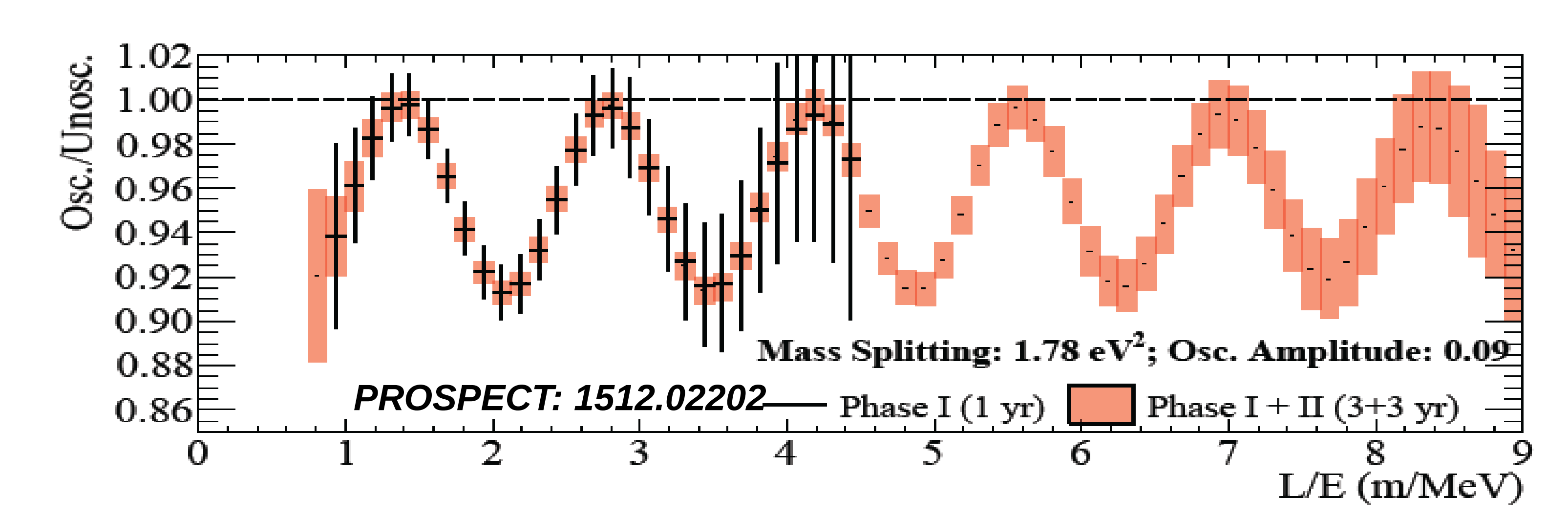
Interesting effects in the beta decay, neutrino-less double beta decay, and cosmology.

Final remarks

- The **smoking gun** for short baseline oscillations: oscillatory behavior as a function of the **energy and/or baseline.**

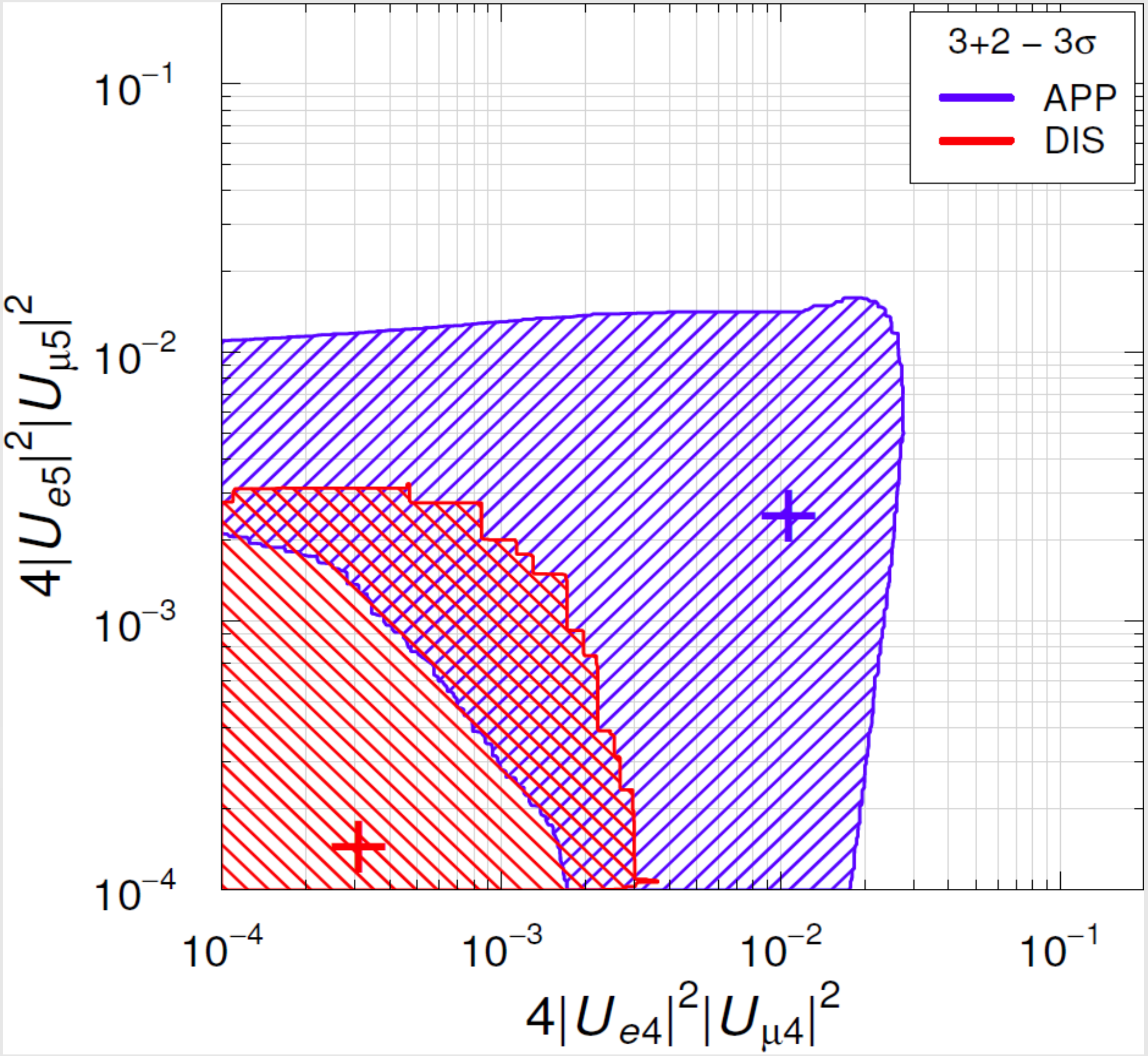
- Otherwise only marginal interest in light sterile neutrinos



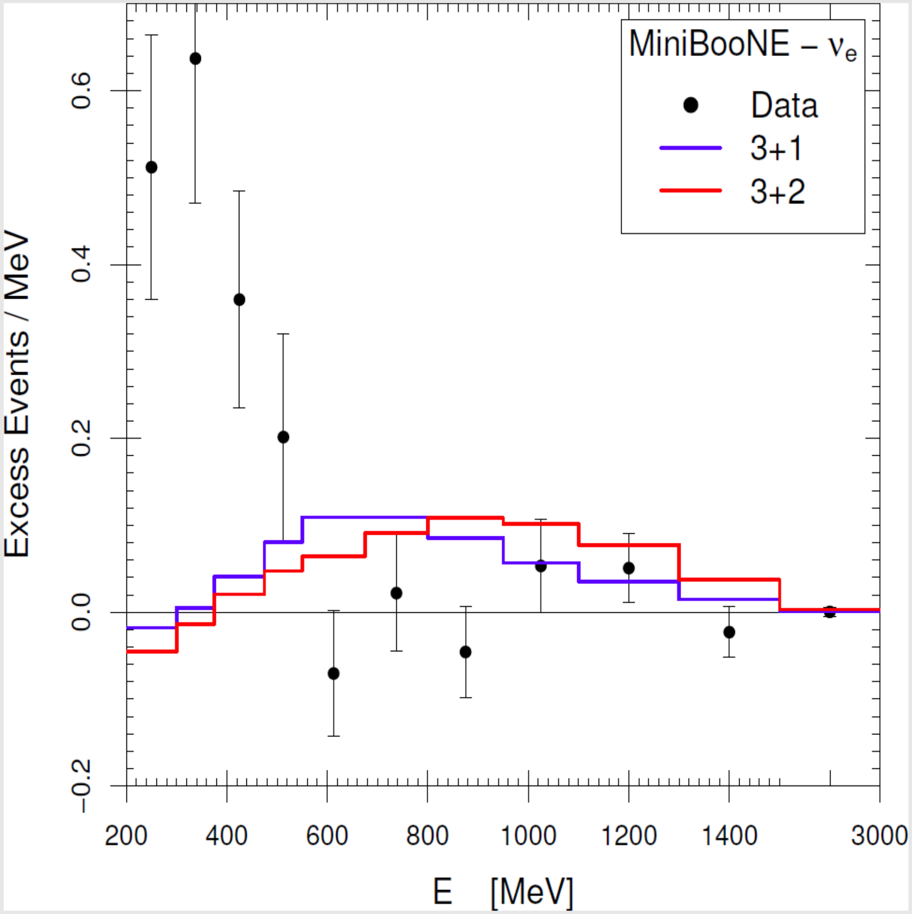


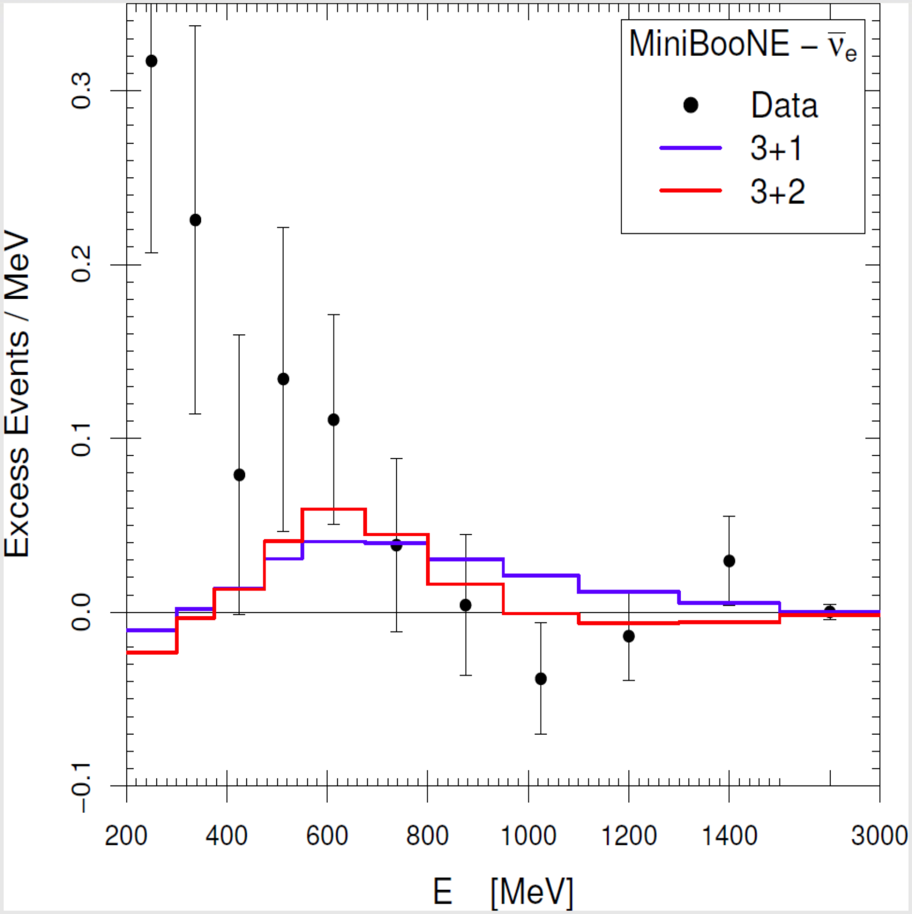
Thanks!

3+2: appearance vs. disappearance



MiniBooNE low energy bins

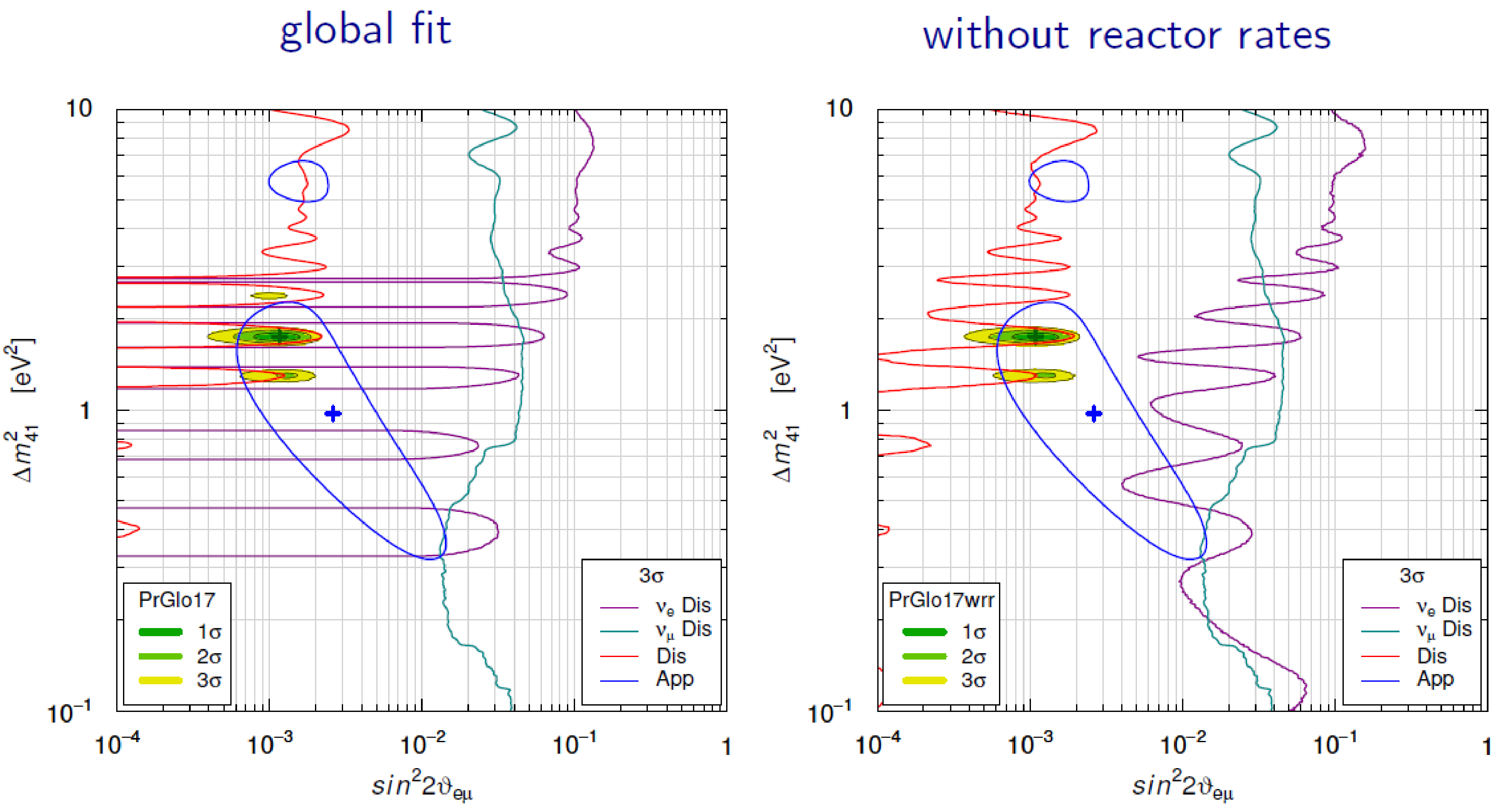




Fit of MB Low-Energy Excess requires small mass splitting and large mixing angle, in contradiction with disappearance data.

MB low-energy excess is the main cause of bad APP-DIS agreement.

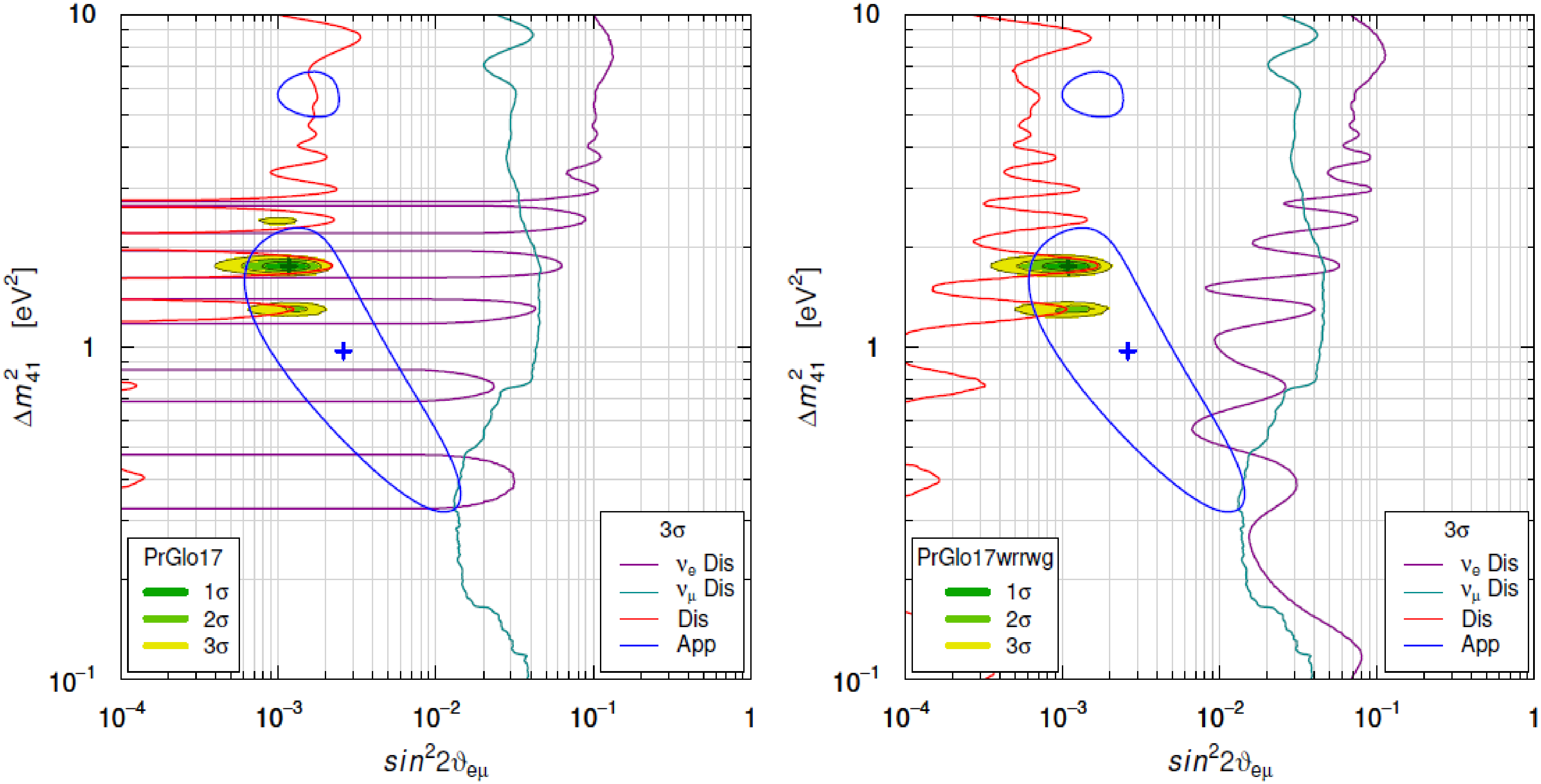
Effects of Reactor Antineutrino Anomaly



The Reactor Antineutrino Anomaly has small impact on the global fit.

Global Fit

Without Reactor Rates and Gallium Data



Given the current constraints, only the LSND signal is crucial for a positive indication in favor of active-sterile SBL oscillations.

New Bound from MINOS & MINOS+

1710.06488