Status of Light Sterile Neutrinos

Carlo Giunti

INFN, Torino, Italy

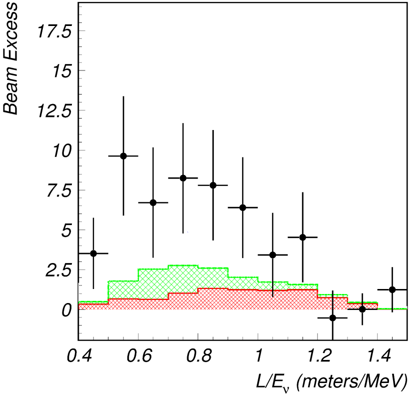
EPS-HEP 2017
2017 European Physical Society Conference on High Energy Physics
Venezia, Italy, 5-12 July 2017

Indications of SBL Oscillations Beyond 3ν

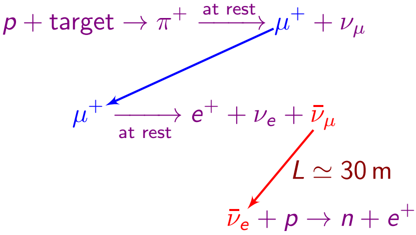
LSND

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

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



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



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

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

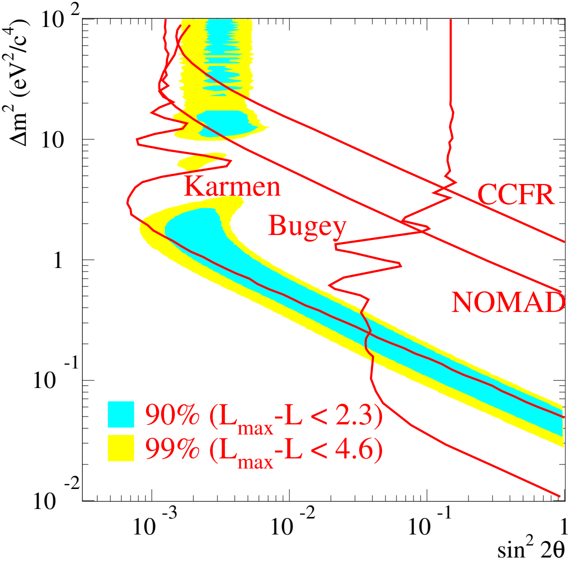
$L \simeq 30\,\text{m}$

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

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]

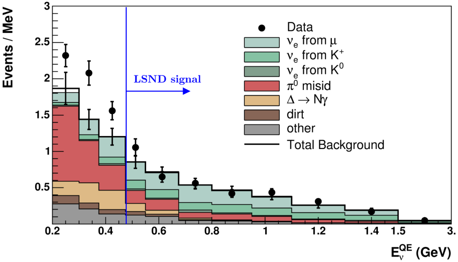


$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

MiniBooNE

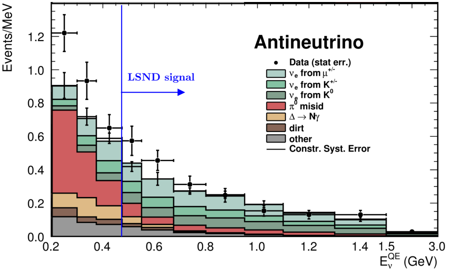
$L \simeq 541\,\text{m}$ $\qquad$ $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

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



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.

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



- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Gallium Anomaly

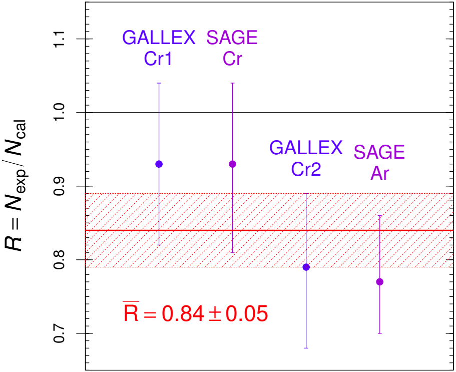
Gallium Radioactive Source Experiments: GALLEX and SAGE

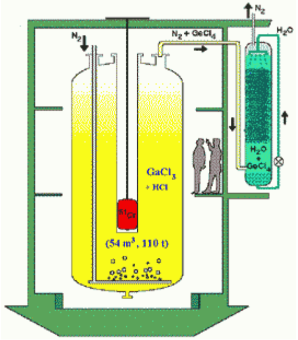
ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad$ $e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

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

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

Test of Solar ν_e Detection:





$\approx 2.9\sigma$ deficit

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

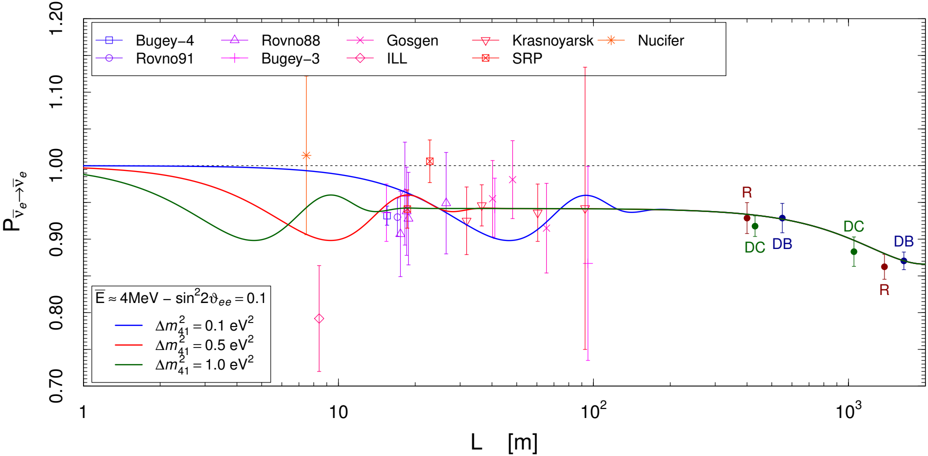
$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}}$

[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]

Reactor Electron 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]

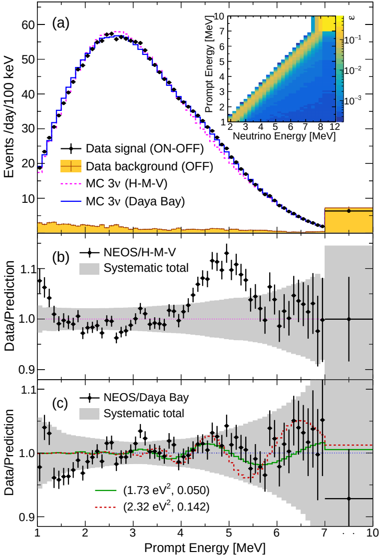


$\approx 2.8\sigma$ deficit

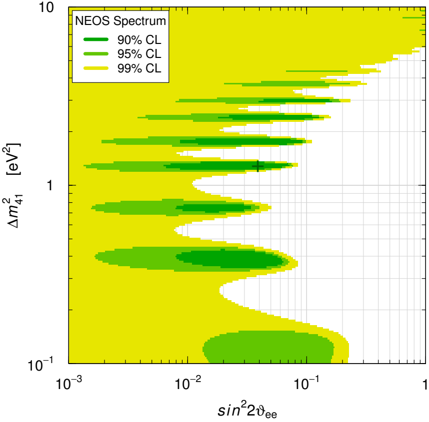
$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

NEOS

[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.



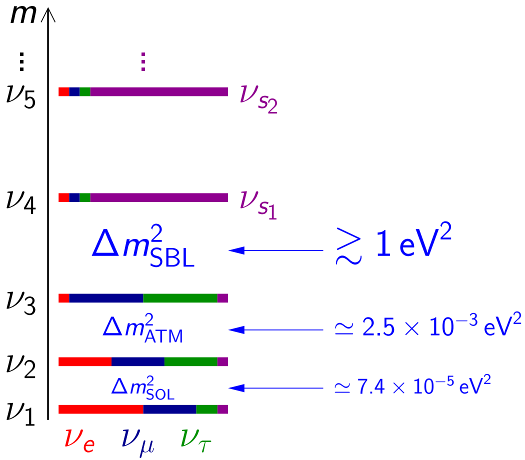
Best Fit:

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

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

$\approx 2.1\sigma$ anomaly

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Effective 3+1 SBL Oscillation Probabilities

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; Gandhi 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]

[Palazzo, EPS-HEP 2017]

3+1 Appearance-Disappearance Tension

ν_e DIS

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

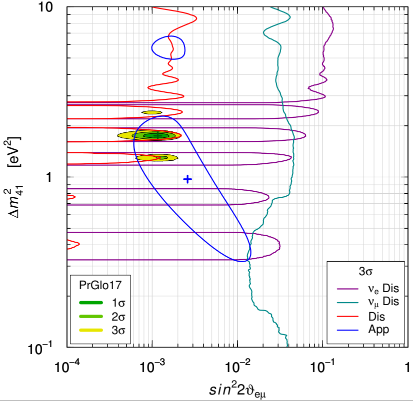
ν_μ DIS

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

$\nu_\mu \to \nu_e$ 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]



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo17 = Pragmatic Global Fit 2017

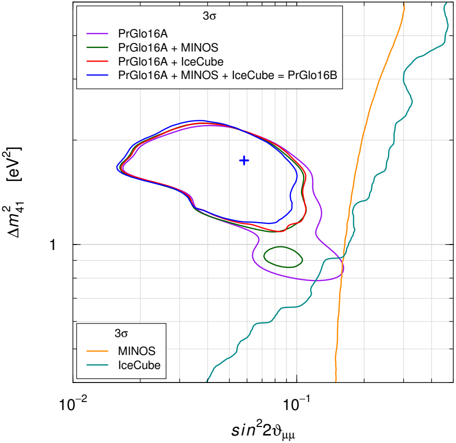
  [Gariazzo, CG, Laveder, Li, arXiv:1703.00860]
- $\Delta\chi^2_{\text{NO}} = 47.4 \Rightarrow \approx 6.1\sigma$ anomaly
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$

  $|U_{e4}|^2 = 0.020 \quad |U_{\mu4}|^2 = 0.015$
- $\chi^2_{\text{min}}/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$
- $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\%$
- Similar tension in 3+2, 3+3, . . . , $3+N_s$

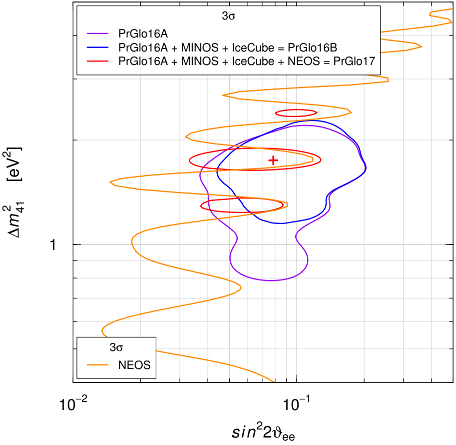
  [CG, Zavanin, MPLA 31 (2015) 1650003]

Effects of MINOS, IceCube and NEOS

$\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{\mu}$



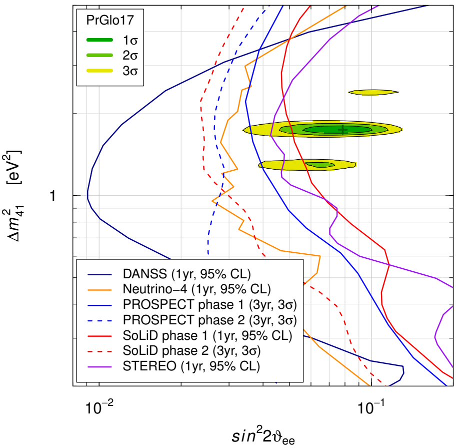
$\overset{(-)}{\nu}_{e} \to \overset{(-)}{\nu}_{e}$

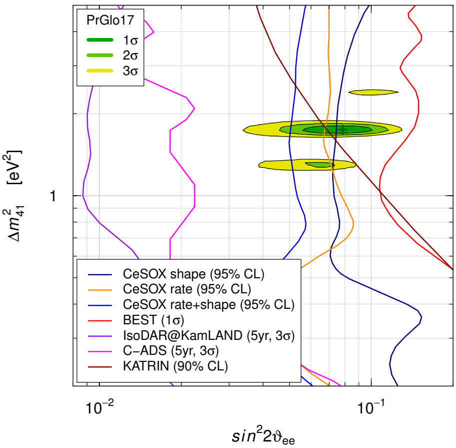


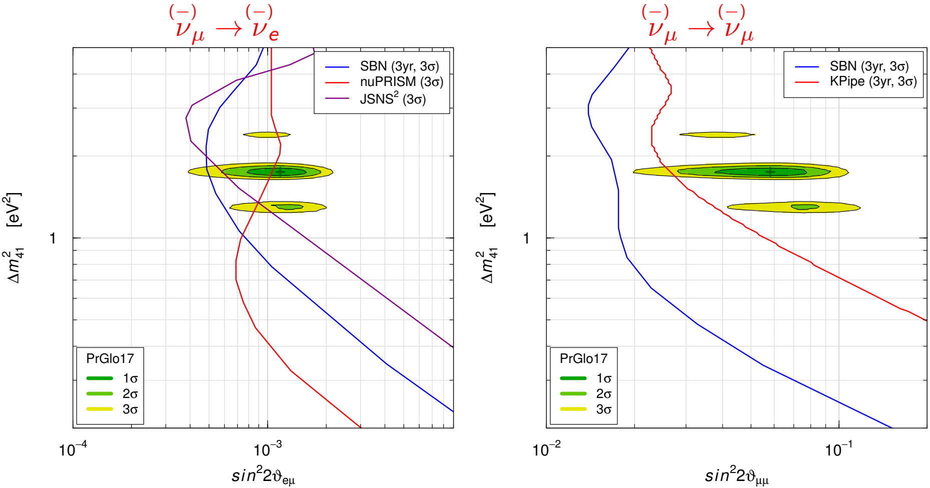
IceCube effect in agreement with
Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801

The Race for the Light Sterile

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







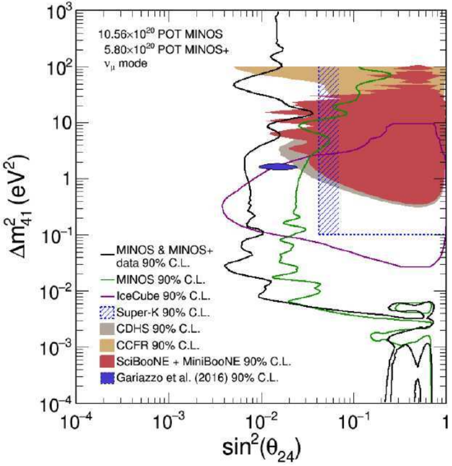
$\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}$

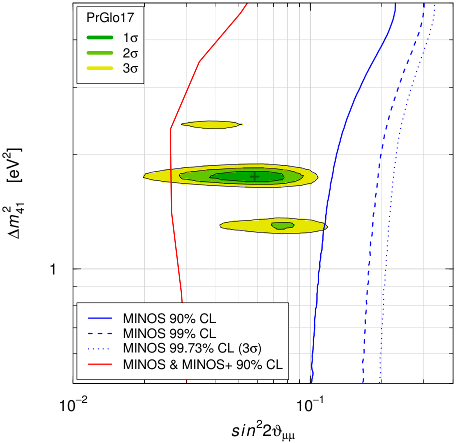
$\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{\mu}$

Preliminary Bound from MINOS & MINOS+

[Whitehead, EPS-HEP 2017]

Flanagan @ PPC2017

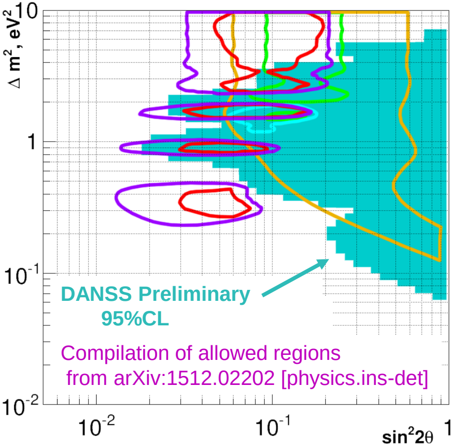




Preliminary Bound from DANSS

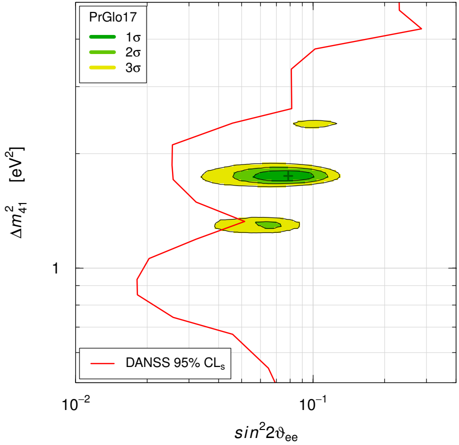
[Danilov, EPS-HEP 2017]

Svirida @ WIN2017

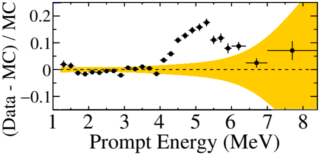


DANSS Preliminary
95%CL

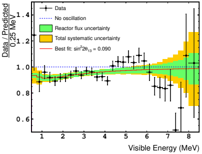
Compilation of allowed regions
from arXiv:1512.02202 [physics.ins-det]



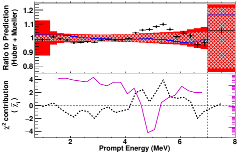
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



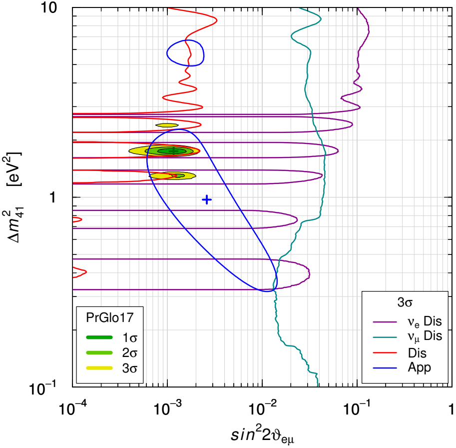
[Double Chooz, arXiv:1406.7763]



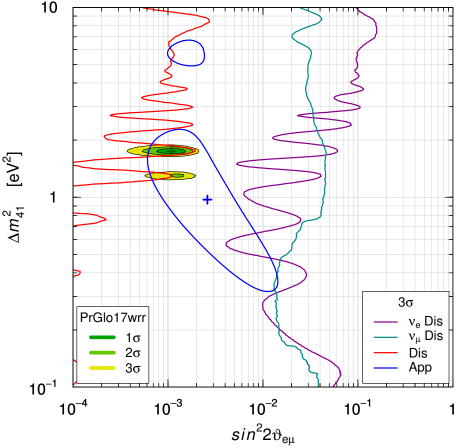
[Daya Bay, arXiv:1508.04233]

- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in Double Chooz, Daya Bay, RENO).
- Very likely due to theoretical miscalculation of the spectrum.
- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Saclay-Huber flux calculation uncertainty is about 2.5%.
- Increasing the flux uncertainty is a game that one can play, but there are only guesses, e.g. about 5%. [Hayes and Vogel, 2016]
- Better to exclude the reactor rates from the global fit. [suggestion of Pedro Machado at WIN 2017]

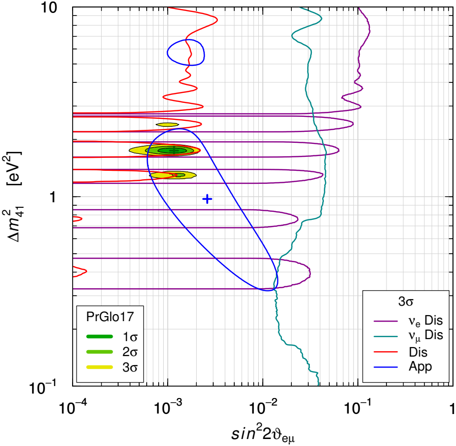
Global Fit



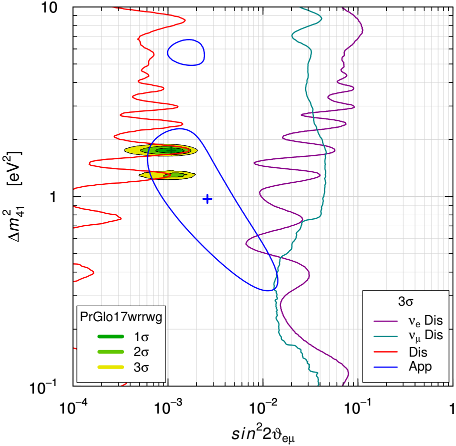
Without Reactor Rates



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



Global Fit



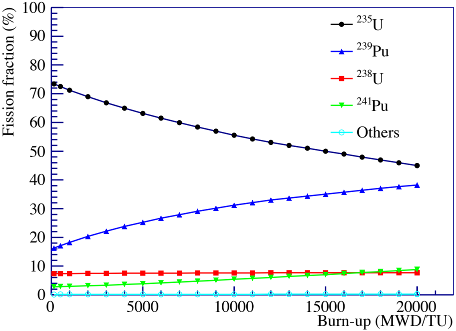
Without Reactor Rates and Gallium Data

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

Daya Bay Reactor Fuel Evolution

[Daya Bay, arXiv:1704.01082] [Tsang @ EPS-HEP 2017]

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.

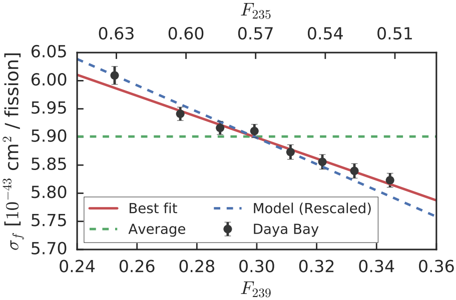


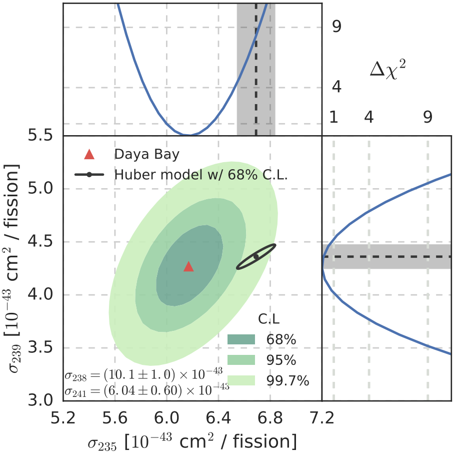
- Cross section per fission:

$$\sigma_f = \sum_{i=235,238,239,241} F_i \, \sigma_{f,i}$$

- Effective fission fractions:

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





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

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

disfavored at 2.8σ.

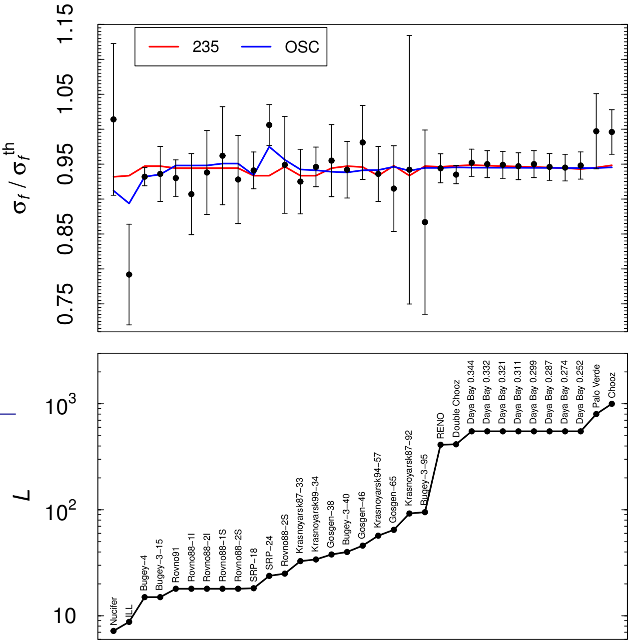
- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account.

With theoretical flux uncertainties:

Daya Bay	^{235}U	OSC
χ^2_{min}	4.6	9.6
NDF	7	7
GoF	71%	21%

All Reactors	^{235}U	OSC
χ^2_{min}	29.4	28.7
NDF	32	31
GoF	60%	58%

[CG, Laveder, Li, in preparation]



Conclusions

- Exciting indications of sterile neutrinos (new physics!) at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal (caveat: single experimental signal).
  - Gallium ν_e disappearance (caveat: overestimated detector efficiency?).
  - Reactor $\bar{\nu}_e$ disappearance (caveat: flux calculation dependence).
- Vigorous experimental program to check conclusively in a few years:
  - ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
  - $\nu_\mu \to \nu_e$ transitions with accelerator neutrinos.
  - ν_μ disappearance with accelerator neutrinos.
- Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Cosmology: strong tension with $\Delta N_{\text{eff}} = 1$ and $m_4 \approx 1\,\text{eV}$. It may be solved by a non-standard cosmological mechanism.
- Possibilities for the next years:
  - Reactor and source experiments ν_e and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Otherwise: still marginal interest to check the LSND appearance signal.
  - In any case the possibility of the existence of sterile neutrinos related to New Physics beyond the Standard Model will continue to be studied (e.g keV sterile neutrinos).