

Sterile Neutrinos

Carlo Giunti

INFN, Torino, Italy

XI International Conference on Interconnections between
Particle Physics and Cosmology

Corpus Christi, Texas, USA, 22-26 May 2017



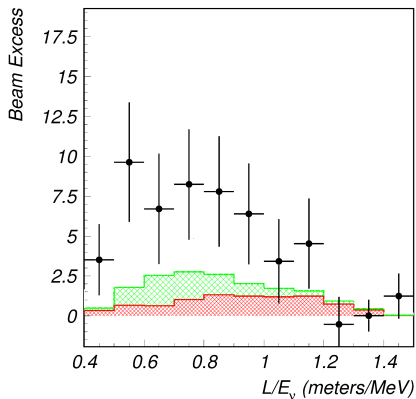
Indications of SBL Oscillations Beyond 3ν

LSND

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

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$20 \text{ MeV} \leq E \leq 52.8 \text{ MeV}$$



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

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

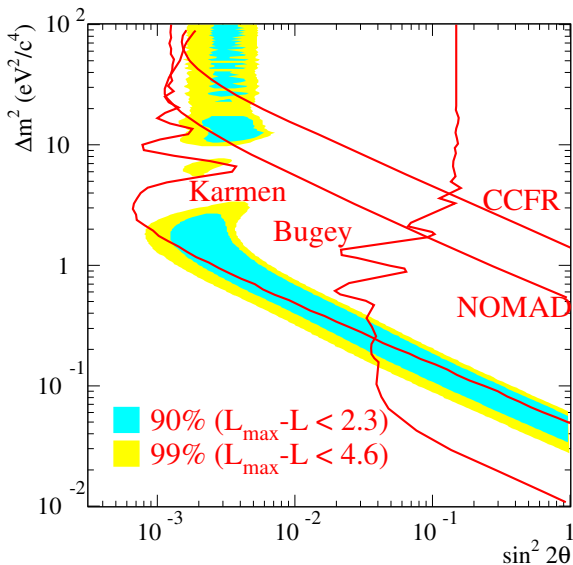
$$\mu^+ \xrightarrow{\text{at rest}} e^+ + \nu_e + \bar{\nu}_\mu$$

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad L \simeq 30 \text{ m}$$

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]



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

MiniBooNE

$L \simeq 541 \text{ m}$

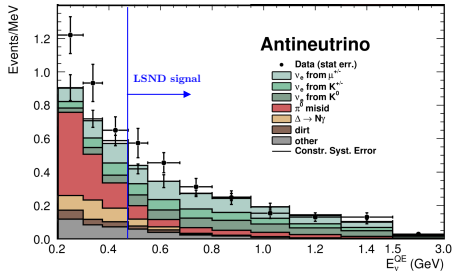
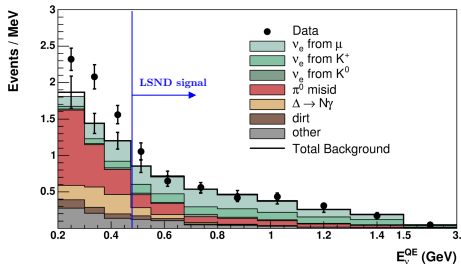
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

[PRL 110 (2013) 161801]



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

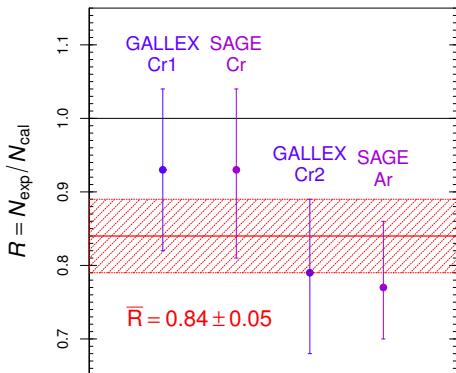
- ▶ LSND signal: $E > 475 \text{ MeV}$.
- ▶ Agreement with LSND signal?
- ▶ CP violation?
- ▶ Low-energy anomaly!

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

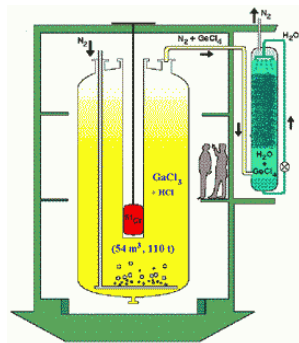


Test of Solar ν_e Detection:



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

$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2$



$\approx 2.9\sigma$ deficit

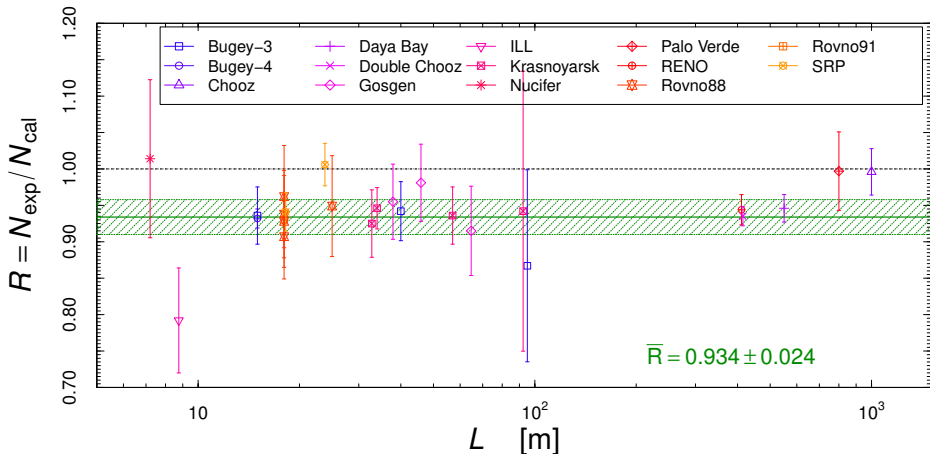
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

Reactor Electron Antineutrino Anomaly

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

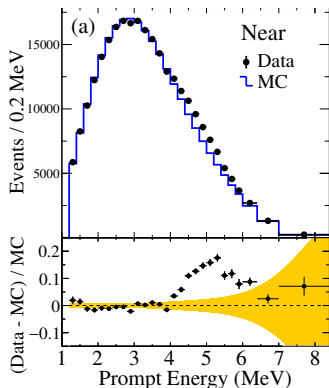
New reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]

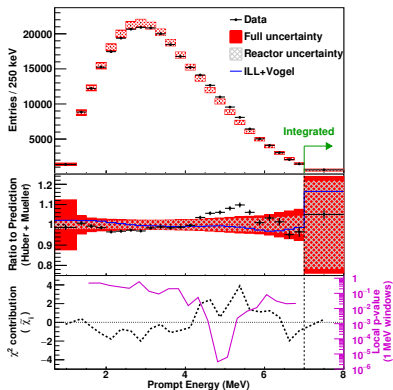


$\approx 2.8\sigma$ deficit

5 MeV Bump



[RENO, arXiv:1511.05849]



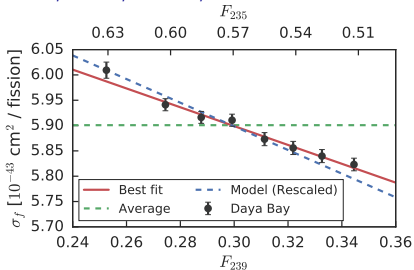
[Daya Bay, arXiv:1508.04233]

- ▶ It is correlated with the reactor activity.
- ▶ Cannot be explained by neutrino oscillations.
- ▶ Very likely due to theoretical miscalculation of the spectrum.
- ▶ $\sim 3\%$ effect on total flux.
- ▶ It seems to be an excess!

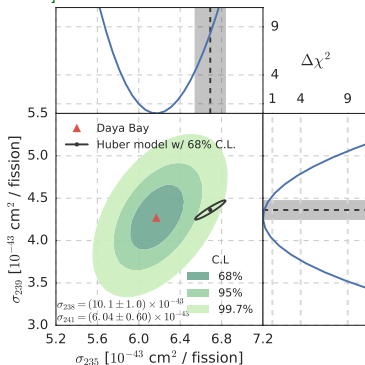
Daya Bay Reactor Fuel Evolution

[Daya Bay, arXiv:1704.01082]

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



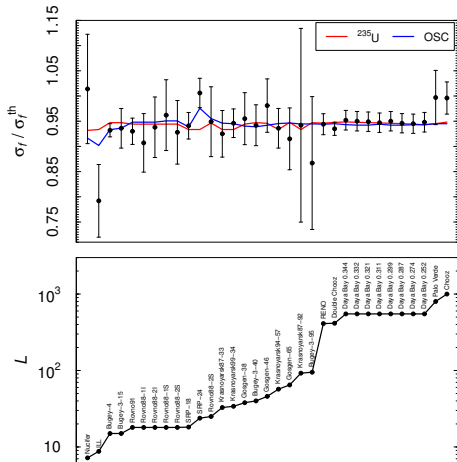
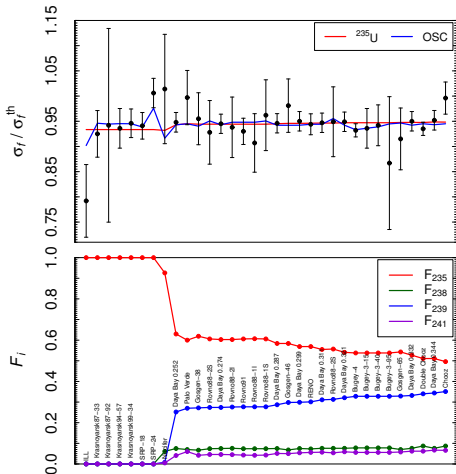
- ▶ Linear fit: equal suppression (oscillations) disfavored at 3.1σ .
- ▶ It is not clear which is the correspondence of the best linear fit with the suppression of the four fluxes.



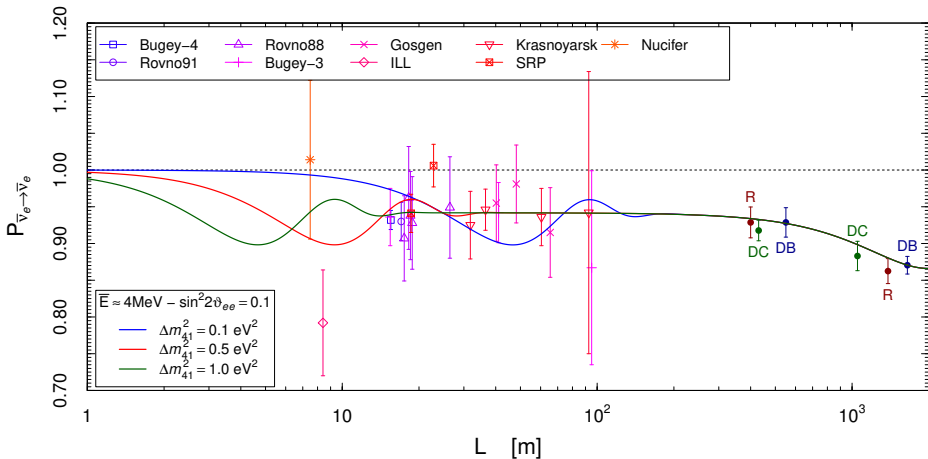
- ▶ Oscillations: $\Delta\chi^2/\text{NDF} = 7.9/1$ disfavored at 2.8σ .
- ▶ Uncertainty of theoretical fluxes in oscillation fit seems not to be taken in account because with different covariance matrices the models are not nested and one cannot apply the $\Delta\chi^2/\text{NDF}$ estimation.

Daya Bay	^{235}U	OSC
χ^2_{\min}	4.6	9.6
NDF	7	7
GoF	70%	22%

All Reactors	^{235}U	OSC
χ^2_{\min}	29.4	31.7
NDF	32	31
GoF	60%	43%



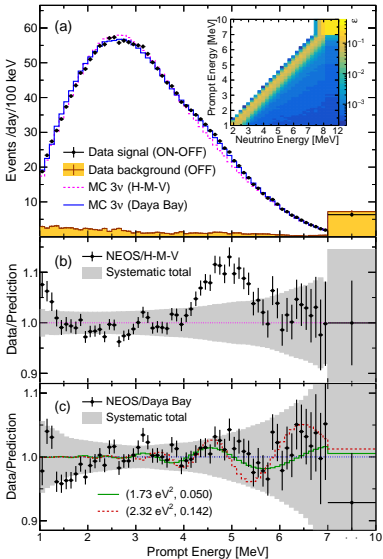
[CG, Laveder, Li, in preparation]



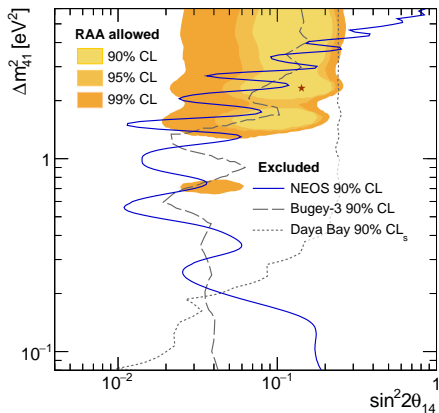
$$\Delta m_{\text{SBL}}^2 \gtrsim 0.5 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2 \gg \Delta m_{\text{SOL}}^2$$

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.

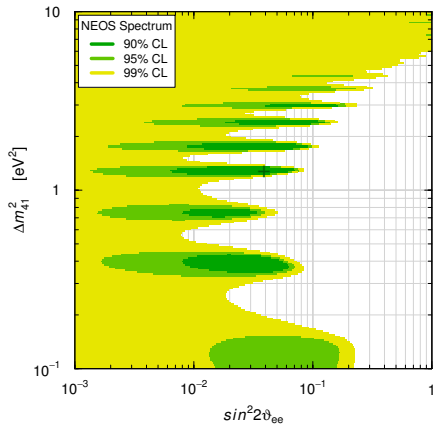


Raster Scan [NEOS, arXiv:1610.05134]

Best Fits:

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

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



2-D χ^2 Analysis

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

$\approx 2.1\sigma$ anomaly

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SBL}(-)} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

Disappearance

$$P_{\nu_\alpha \rightarrow \nu_\alpha}^{\text{SBL}(-)} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

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

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

SBL

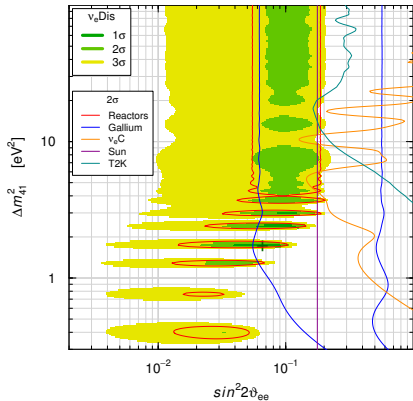
▶ CP violation is not observable in SBL experiments!

▶ Observable in LBL accelerator exp. sensitive to Δm_{ATM}^2 [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] and solar exp. sensitive to Δm_{SOL}^2 [Long, Li, CG, PRD 87, 113004 (2013) 113004]

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

Global ν_e and $\bar{\nu}_e$ Disappearance

[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



▶ 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: $\Delta m^2_{41} = 1.7 \text{ eV}^2$

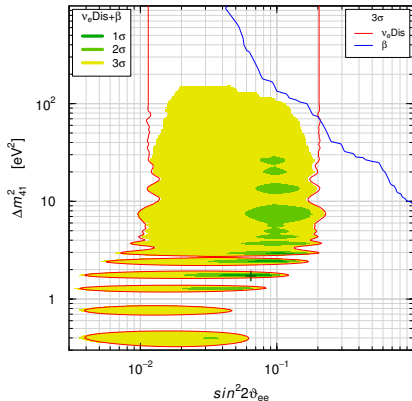
$$\sin^2 2\vartheta_{ee} = 0.066 \Leftrightarrow |U_{e4}|^2 = 0.017$$

▶ $\chi^2_{\text{min}}/\text{NDF} = 163.0/174 \Rightarrow \text{GoF} = 71\%$

▶ $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 13.7/7 \Rightarrow \text{GoF}_{\text{PG}} = 6\%$

Global ν_e and $\bar{\nu}_e$ Disappearance + β Decay

[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]

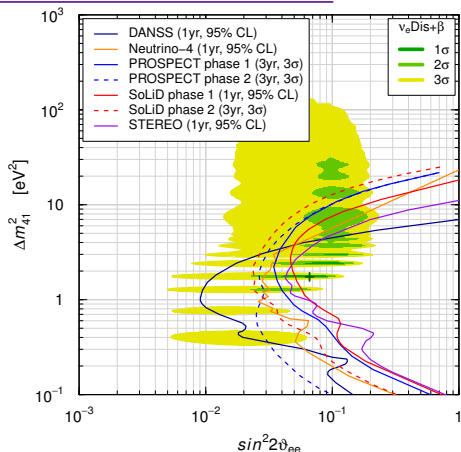
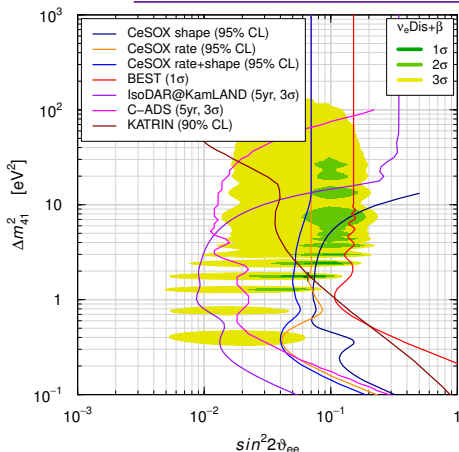


► Best Fit: $\Delta m_{41}^2 = 1.7 \text{ eV}^2$
 $\sin^2 2\vartheta_{ee} = 0.066 \Leftrightarrow |U_{e4}|^2 = 0.017$

► $2 \text{ cm} \lesssim \frac{L_{41}^{\text{osc}}}{E [\text{MeV}]} \lesssim 7 \text{ m}$ at 3σ

► $0.0050 \lesssim \sin^2 2\vartheta_{ee} \lesssim 0.23$ at 3σ

The Race for ν_e and $\bar{\nu}_e$ Disappearance



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

BEST (Baksan, Russia) $^{51}\text{Cr} \rightarrow \nu_e$
 $L \simeq 5\text{-}12\text{m}$ [PRD 93 (2016) 073002]

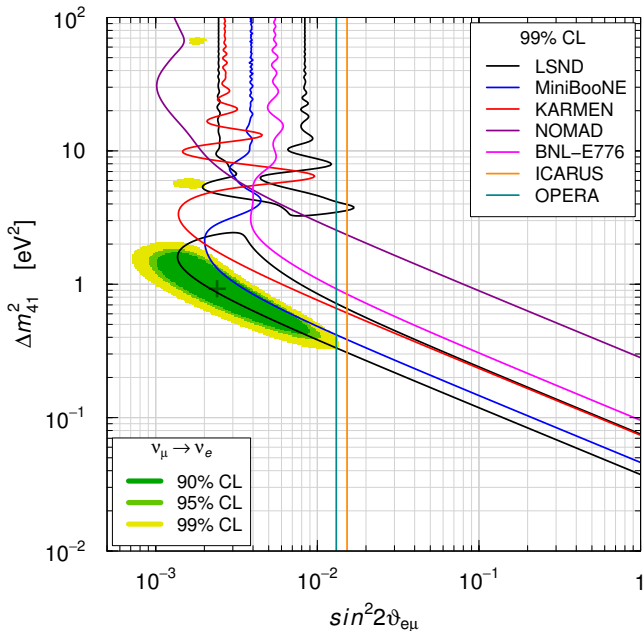
IsoDAR@KamLAND (Kamioka, Japan)
 $^8\text{Li} \rightarrow \bar{\nu}_e$ $L \simeq 16\text{m}$ [arXiv:1511.05130]

C-ADS (Guangdong, China)
 $^8\text{Li} \rightarrow \bar{\nu}_e$ $L \simeq 15\text{m}$ [JHEP 1601 (2016) 004]

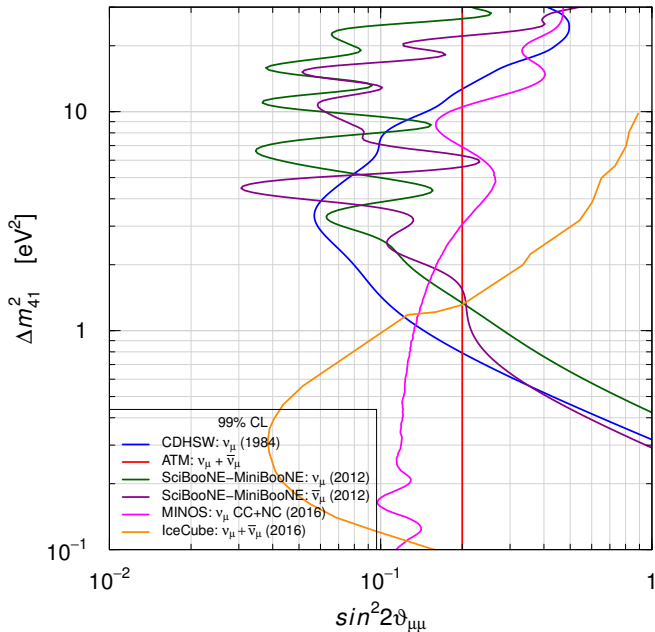
DANSS (Kalinin, Russia) $L \simeq 10\text{-}12\text{m}$ [arXiv:1606.02896]
 Neutrino-4 (RIAR, Russia) $L \simeq 6\text{-}11\text{m}$ [JETP 121 (2015) 578]
 PROSPECT (ORNL, USA) $L \simeq 7\text{-}12\text{m}$ [arXiv:1512.02202]
 SoLid (SCK-CEN, Belgium) $L \simeq 5\text{-}8\text{m}$ [arXiv:1510.07835]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

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

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



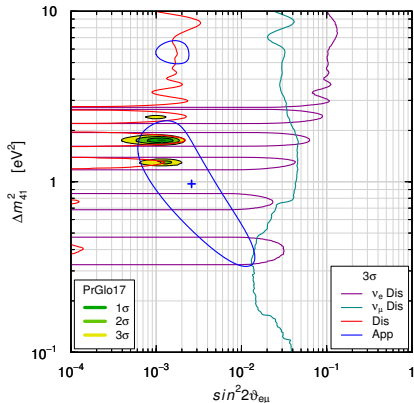
3+1 Appearance-Disappearance Tension

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

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

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

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



▶ $\nu_\mu \rightarrow \nu_e$ 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: $\Delta m_{41}^2 = 1.7 \text{ eV}^2$

$$|U_{e4}|^2 = 0.020 \quad |U_{\mu4}|^2 = 0.015$$

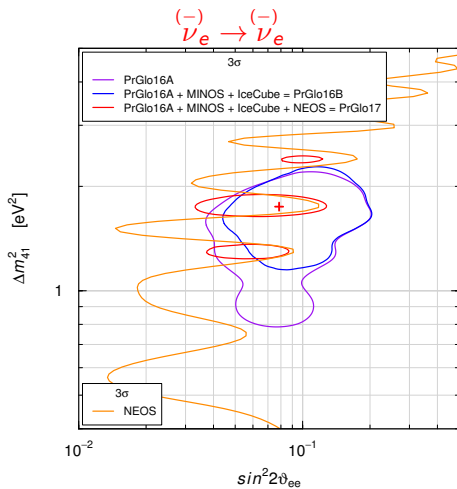
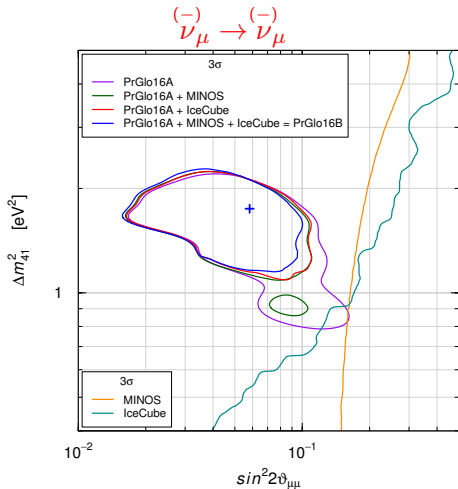
▶ $\chi^2_{\text{min}}/\text{NDF} = 595.1/579 \Rightarrow \text{GoF} = 31\%$

▶ $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.2/2 \Rightarrow \text{GoF}_{\text{PG}} = 2.7\%$

▶ Similar tension in 3+2, 3+3, ..., 3+N_s

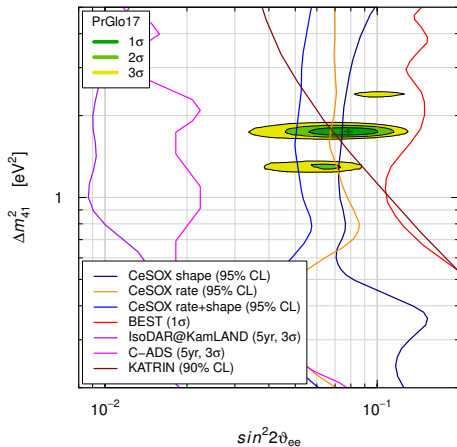
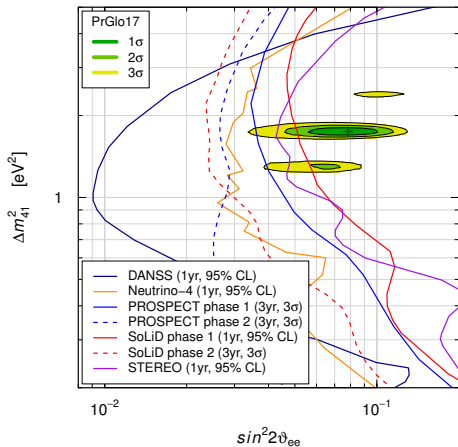
[CG, Zavanin, MPLA 31 (2015) 1650003]

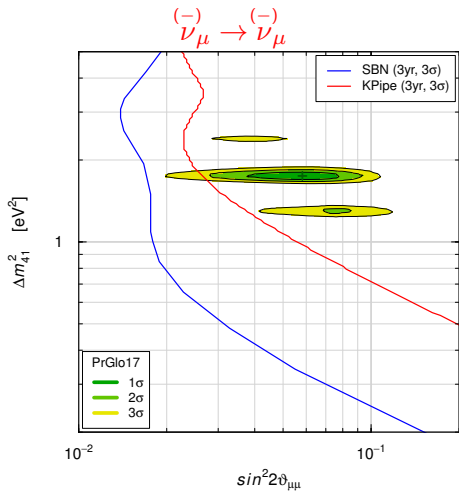
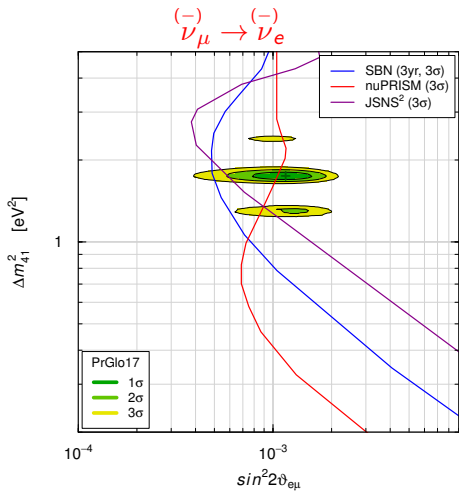
Effects of MINOS, IceCube and NEOS



The Race for the Light Sterile

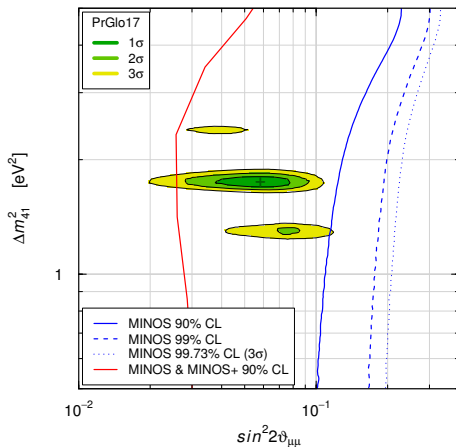
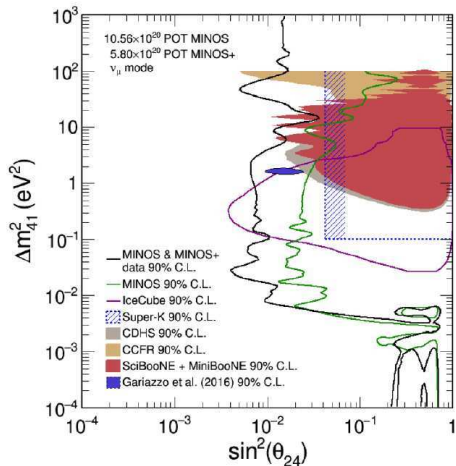
$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$





New Preliminary Bound from MINOS & MINOS+

Flanagan @ PPC2017



Conclusions

- ▶ Exciting indications of light sterile neutrinos at the eV scale:
 - ▶ LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal (caveat: single experimental signal).
 - ▶ Gallium ν_e disappearance (caveat: overestimated detector efficiency?).
 - ▶ Reactor $\bar{\nu}_e$ disappearance (caveat: Daya Bay reactor fuel evolution).
- ▶ Vigorous experimental program to check **conclusively** in a few years:
 - ▶ ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.
 - ▶ $\nu_\mu \rightarrow \nu_e$ 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 $m_4 \approx 1$ 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).