Synthesizing Data: Sterile Neutrinos

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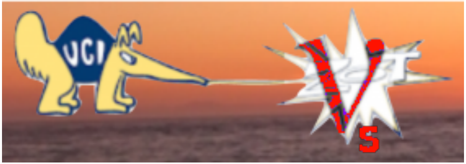
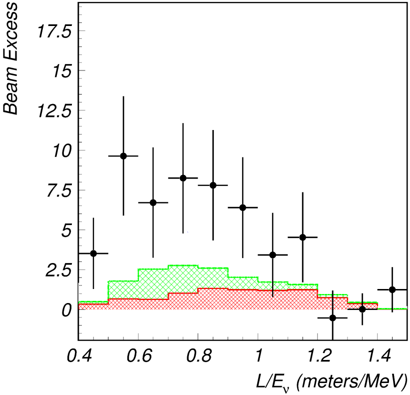


Indications of SBL Oscillations Beyond 3ν

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 $\bar{\nu}_\mu$

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

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

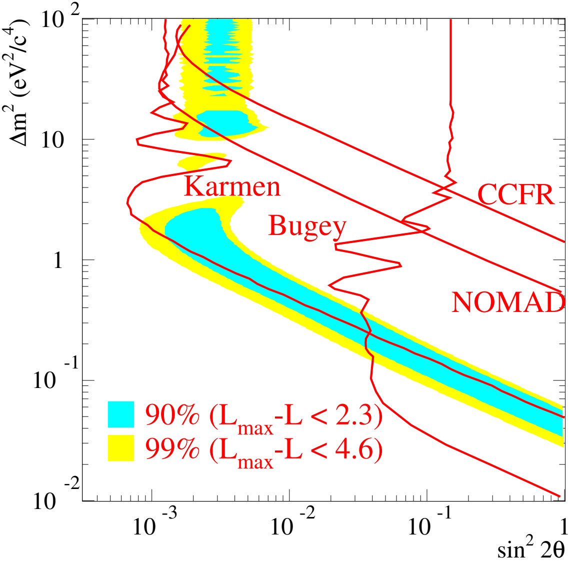
$L \simeq 30\,\text{m}$

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

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]

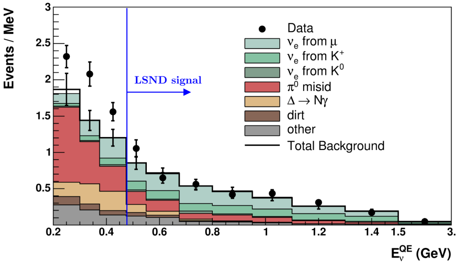


$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

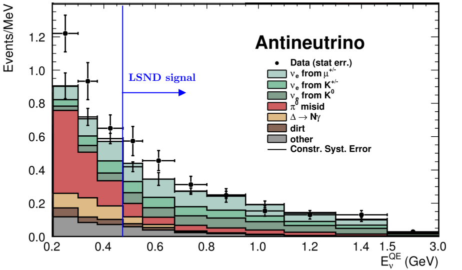
MiniBooNE

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

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



$\bar{\nu}_\mu \to \bar{\nu}_e$ [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

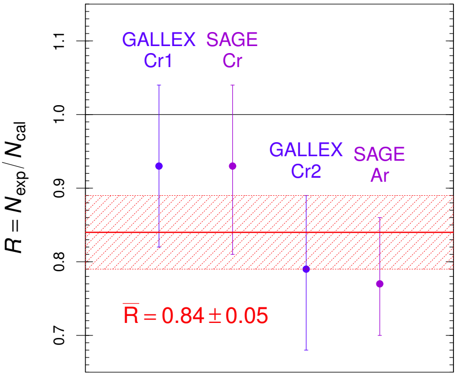
Gallium Radioactive Source Experiments: GALLEX and SAGE

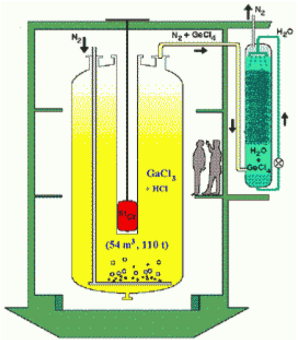
ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$

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

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

Test of Solar ν_e Detection:





$\approx 2.9\sigma$ deficit

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

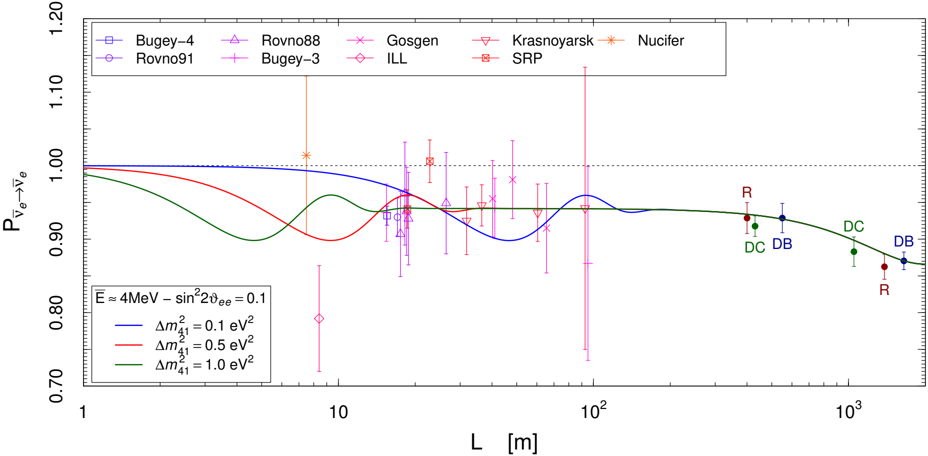
$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

[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

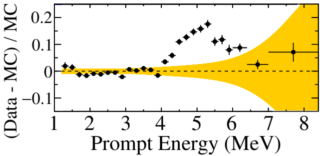
[Mention et al, PRD 83 (2011) 073006]

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

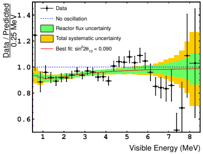


$\approx 2.8\sigma$ deficit $\Delta m^2_{SBL} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL}$

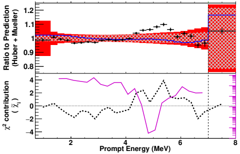
5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



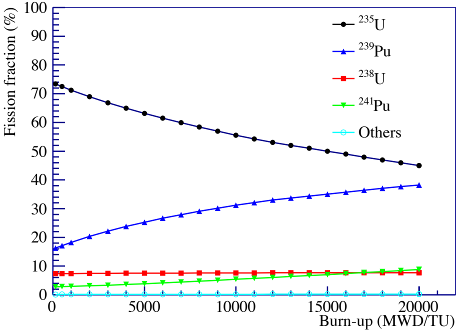
[Daya Bay, arXiv:1508.04233]

- 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]
  - Increasing the uncertainty decreases the statistical significance of the anomaly alone, but can lead to a larger anomaly when combined with the Gallium anomaly which is larger and in the global fit, because of the appearance-disappearance tension.

Daya Bay Reactor Fuel Evolution

[Daya Bay, arXiv:1704.01082; Martinez Caicedo @ WIN2017]

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

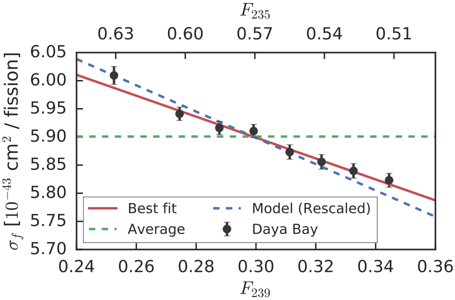


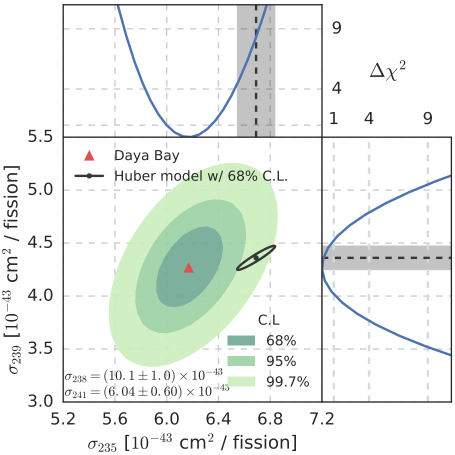
- Cross section per fission:

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

- Effective fission fractions:

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





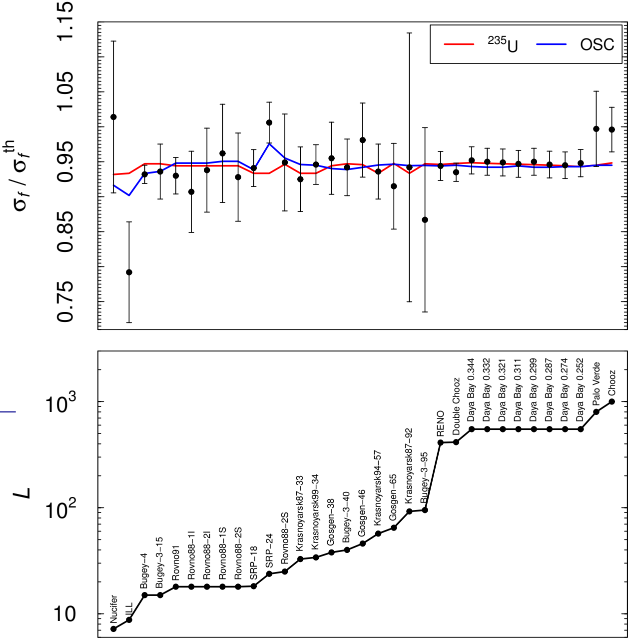
- Best fit: suppression of $\sigma_{f,235}$.
- Equal fluxes suppression:
$$\Delta\chi^2/\text{NDF} = 7.9/1$$
disfavored at 2.8σ.
- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account.

With theoretical flux uncertainties:

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

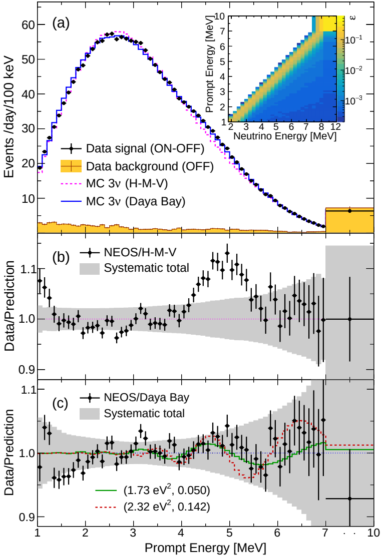
All Reactors	^{235}U	OSC
$\chi^2_{\min}$	29.4	31.7
NDF	32	31
GoF	60%	43%

[CG, Laveder, Li, in preparation]

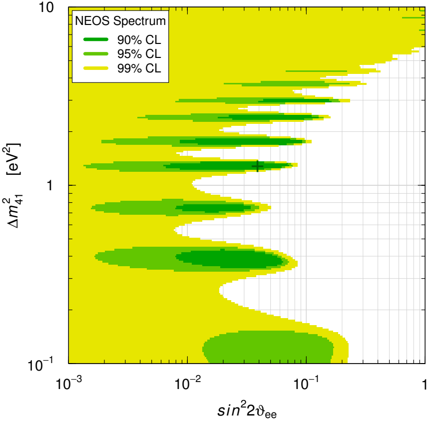


NEOS

[arXiv:1610.05134; Ho @ WIN2017]



- 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.



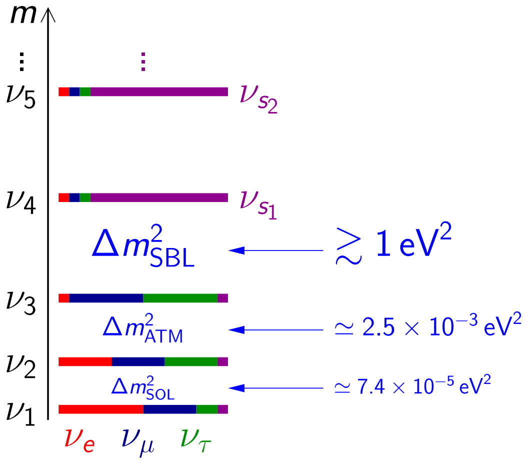
Best Fit:

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

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

$\approx 2.1\sigma$ 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 ($\alpha \neq \beta$)

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

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

Disappearance

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

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

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

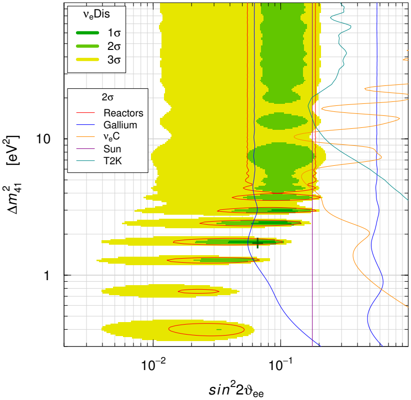
SBL

- 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 Δm^2_{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 Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

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

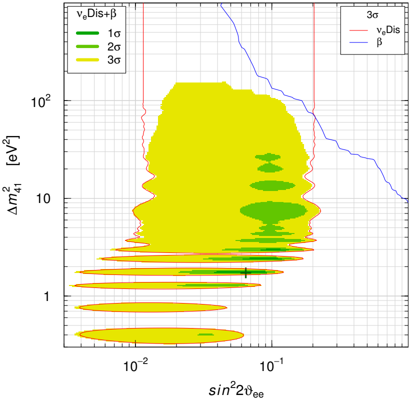
[Gariazzo, CG, Laveder, Li, arXiv:1703.00860]



- 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]

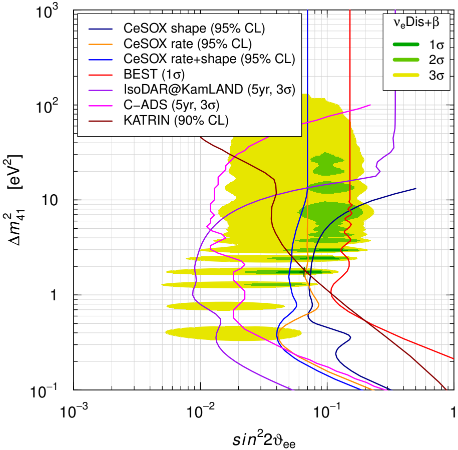


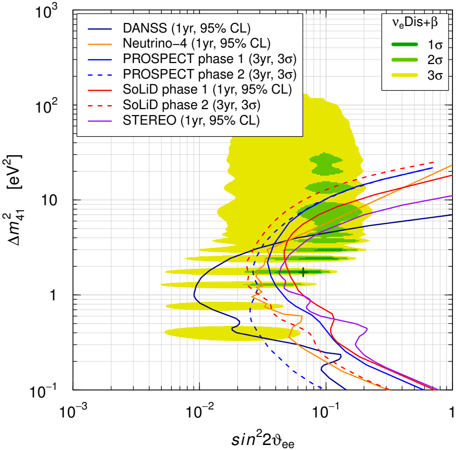
- Best Fit: $\Delta m^2_{41} = 1.7\,\text{eV}^2$
  $\sin^2 2\vartheta_{ee} = 0.066 \quad \Leftrightarrow \quad |U_{e4}|^2 = 0.017$

- $2\,\text{cm} \lesssim \dfrac{L^{\text{osc}}_{41}}{E\,[\text{MeV}]} \lesssim 7\,\text{m}$ at 3σ

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

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





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

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

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

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

DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]

Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]

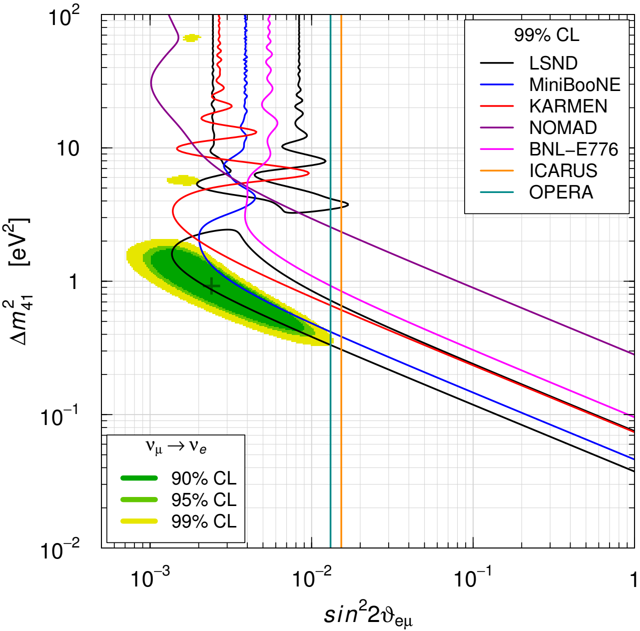
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]

SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]

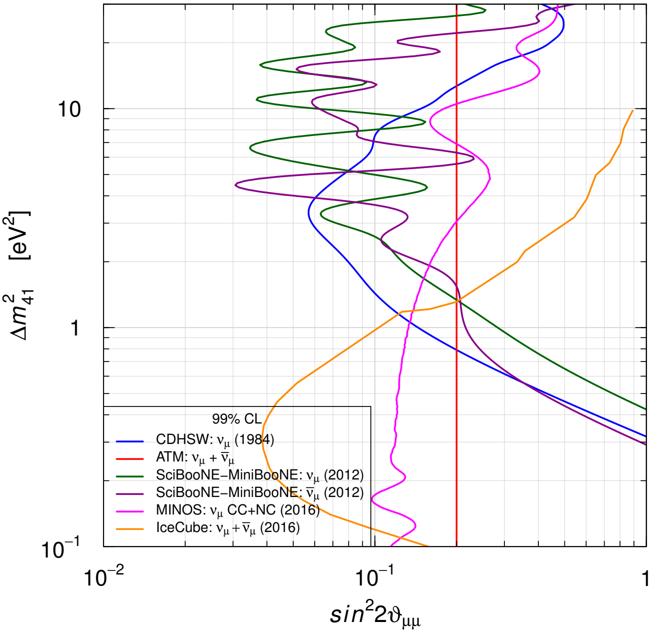
STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]

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

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



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

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

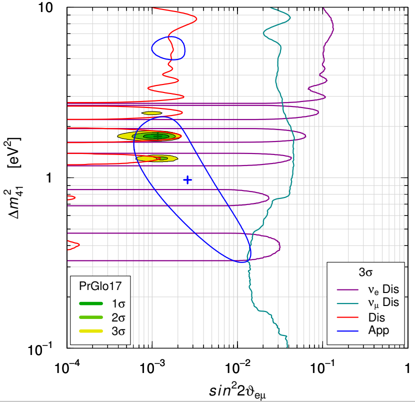
ν_μ DIS

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

$\nu_\mu \to \nu_e$ 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]



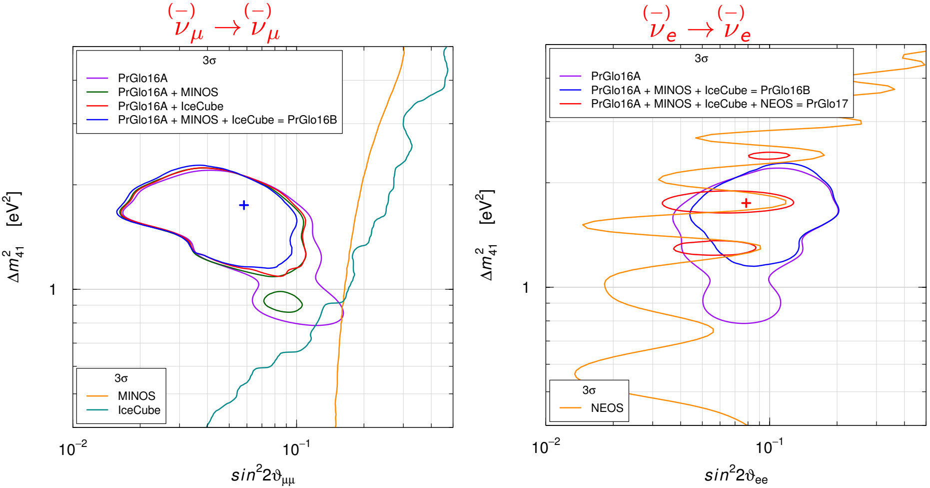
- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- PrGlo17 = Pragmatic Global Fit 2017

  [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]

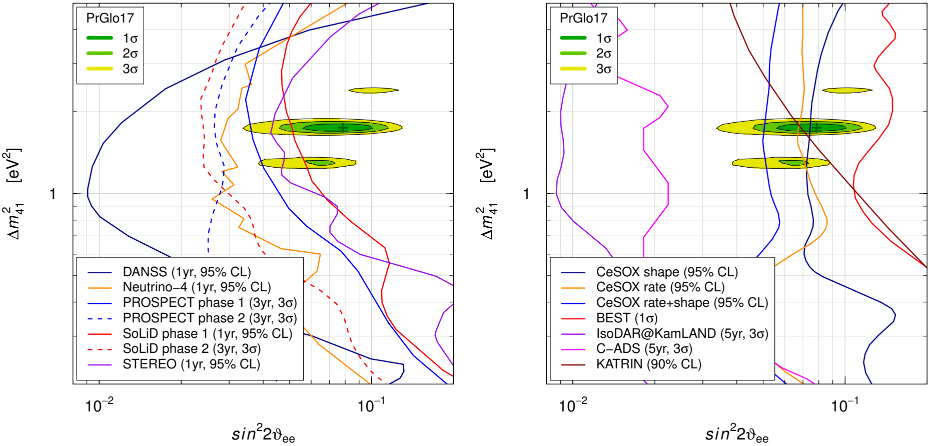
Effects of MINOS, IceCube and NEOS

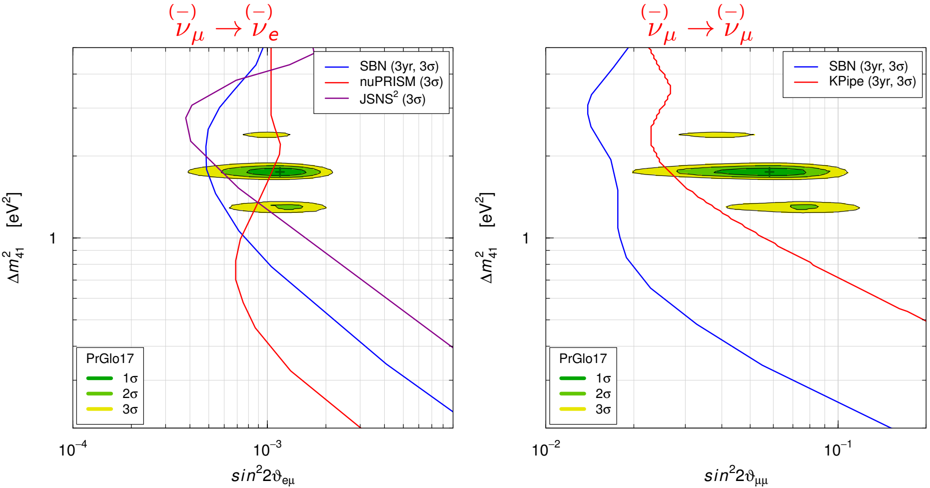


IceCube effect in agreement with
Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801

The Race for the Light Sterile

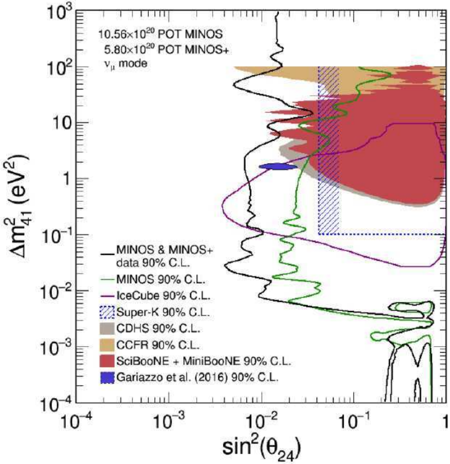
$$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$$

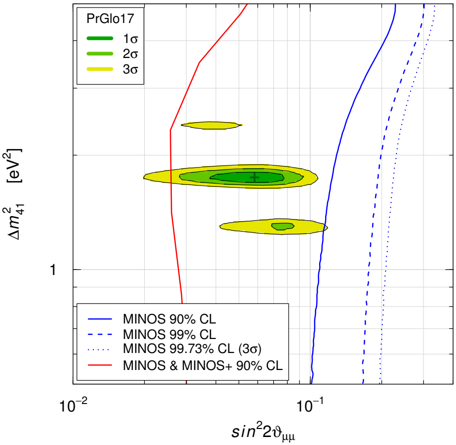



$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$
SBN (3yr, 3σ)
nuPRISM (3σ)
JSNS^2 (3σ)
PrGlo17
1σ
2σ
3σ
Δm^2_{41} [eV^2]
1
10^{-4}
10^{-3}
$sin^2 2\vartheta_{e\mu}$
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
SBN (3yr, 3σ)
KPipe (3yr, 3σ)
PrGlo17
1σ
2σ
3σ
Δm^2_{41} [eV^2]
1
10^{-2}
10^{-1}
$sin^2 2\vartheta_{\mu\mu}$

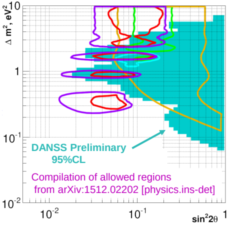
Preliminary Bound from MINOS & MINOS+

Flanagan @ PPC2017

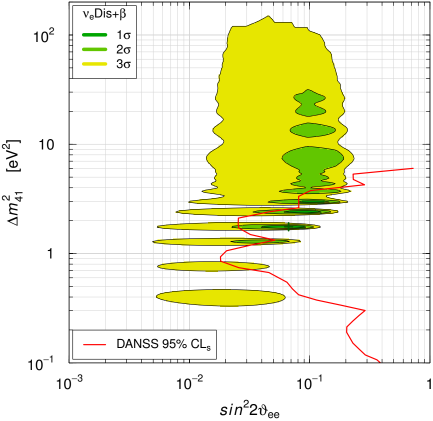


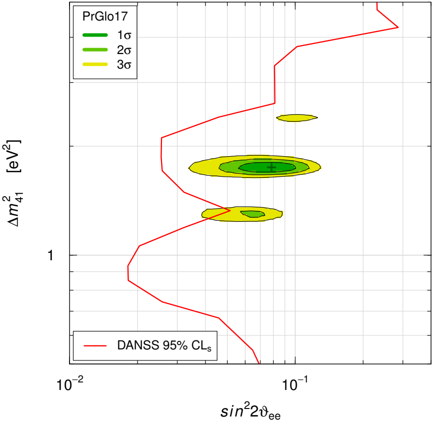


Preliminary Bound from DANSS



Svirida @ WIN2017





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).