Sterile Neutrino Mixing NOW and in the Next 10+ Years

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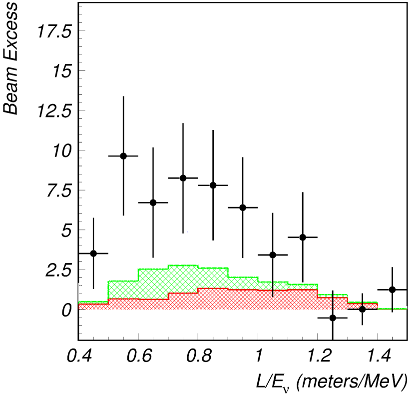
Indications of SBL Oscillations Beyond 3ν

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad$ $20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



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

μ^+ at rest $\to e^+ + \nu_e + \bar{\nu}_\mu$

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

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

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

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

[PRD 65 (2002) 112001]

$\approx 3.8\sigma$ excess $\qquad$ $\Delta m^2_{\text{SBL}} \gtrsim 0.2\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

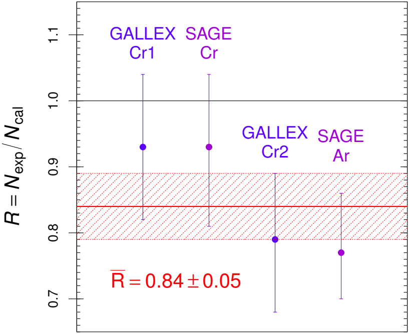
Gallium Anomaly

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



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

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

$\approx 2.9\sigma$ deficit

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

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

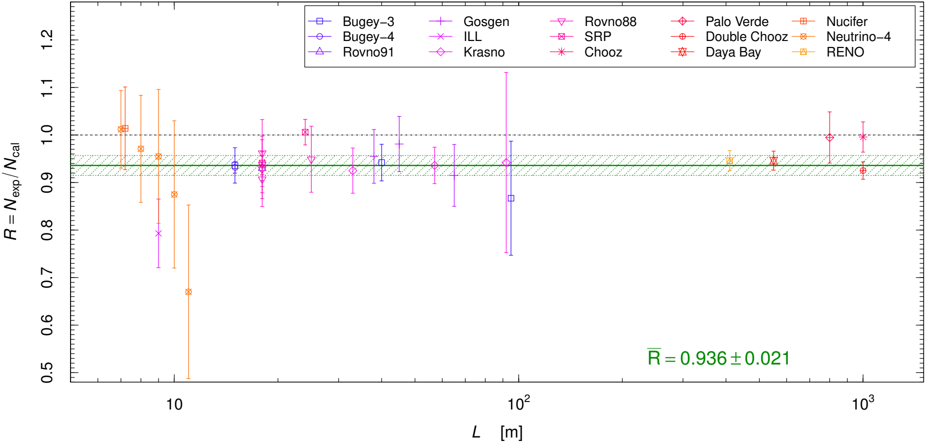
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344;
MPLA 22 (2007) 2499; PRD 78 (2008) 073009;
PRC 83 (2011) 065504]

- ${}^{3}\mathrm{He} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + {}^{3}\mathrm{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\mathrm{th}}(\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-) = 233.5 \pm 1.2\,\mathrm{keV}$ [Frekers et al., PLB 722 (2013) 233]

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]



$\approx 3.1\sigma$ deficit $\Delta m^2_{SBL} \gtrsim 0.5\,eV^2 \gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL}$

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

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

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

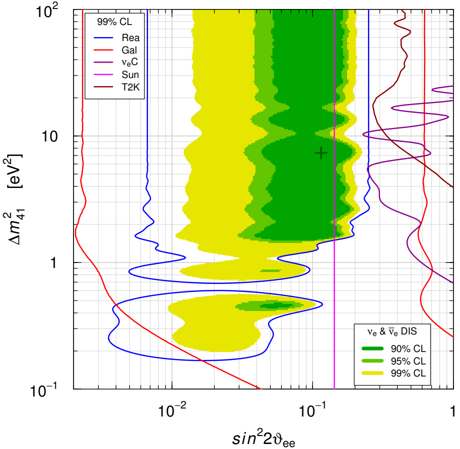
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boxed{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boxed{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}} \\ U_{s1} & U_{s2} & U_{s3} & \boxed{U_{s4}} \end{pmatrix}$$

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] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, PRD 87, 113004 (2013) 113004]

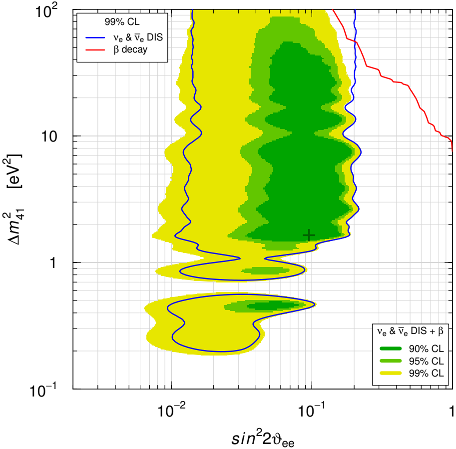
Global ν_e and $\bar{\nu}_e$ Disappearance



KARMEN + LSND $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N}_{\mathrm{g.s.}} + e^-$
[Conrad, Shaevitz, PRD 85 (2012) 013017]
[CG, Laveder, PLB 706 (2011) 200]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}
[CG, Li, PRD 80 (2009) 113007]
[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]
[CG, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

T2K Near Detector ν_e disappearance
[T2K, PRD 91 (2015) 051102]

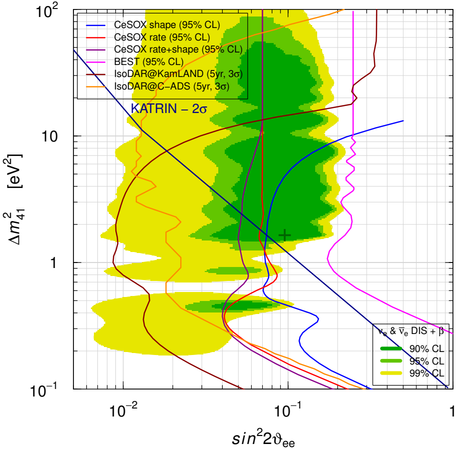


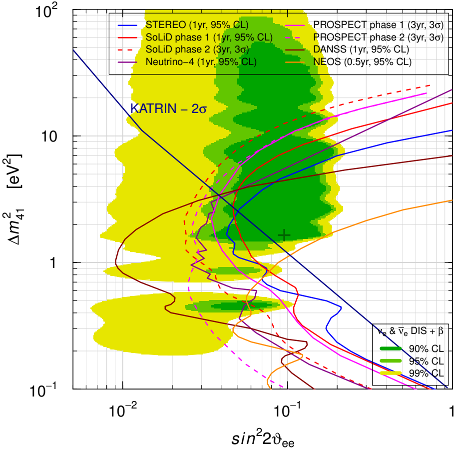
Mainz + Troitsk Tritium β decay
[Mainz, EPJC 73 (2013) 2323]
[Troitsk, JETPL 97 (2013) 67; JPG 41 (2014) 015001]

No Osc. excluded at 2.8σ
$(\Delta\chi^2/\mathrm{NDF} = 10.8/2)$

$$6\,\mathrm{cm} \lesssim \frac{L_{41}^{\mathrm{osc}}}{E\,[\mathrm{MeV}]} \lesssim 6\,\mathrm{m} \qquad (2\sigma)$$

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





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

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

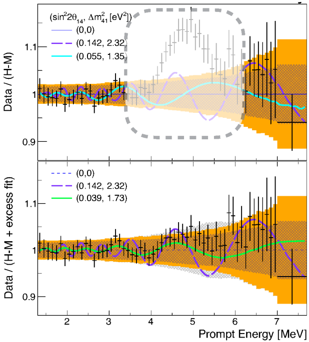
IsoDAR@KamLAND (Kamioka, Japan)
^{8}Li → $\bar{\nu}_e$ $L \simeq$ 16m [arXiv:1511.05130]

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

STEREO (ILL, France) $L \simeq$ 8-12m [arXiv:1602.00568]
SoLid (SCK-CEN, Belgium) $L \simeq$ 5-8m [arXiv:1510.07835]
Neutrino-4 (RIAR, Russia) $L \simeq$ 6-11m [JETP 121 (2015) 578]
PROSPECT (ORNL, USA) $L \simeq$ 7-12m [arXiv:1512.02202]
DANSS (Kalinin, Russia) $L \simeq$ 10-12m [arXiv:1606.02896]
NEOS (Hanbit, Korea) $L \simeq$ 24m [Oh@WIN2015]

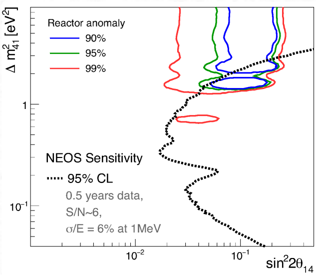
KATRIN (Karlsruhe, Germany) ^{3}H → $\bar{\nu}_e$ [Mertens@TAUP2015]

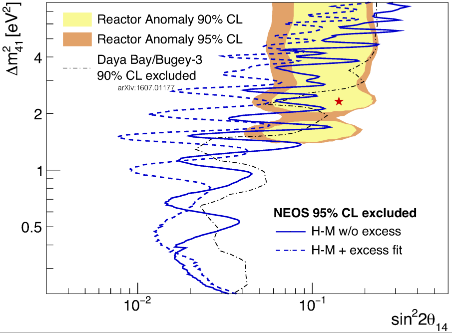
NEOS@ICHEP2016



NEOS Preliminary

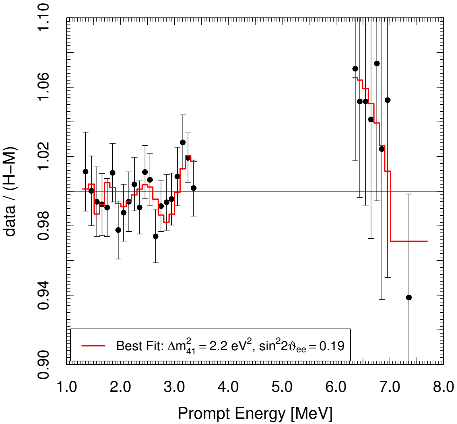
		H-M w/o bump	H-M w bump fit
χ^2	null	33.1	59.1
	minimum	25.5	47.9
	anomaly best fit	52.3	111
N_{DoF}		38	67
χ^2 minimum at		(0.055, 1.35 eV^2)	(0.039, 1.73 eV^2)
significance		2.00σ	2.68σ

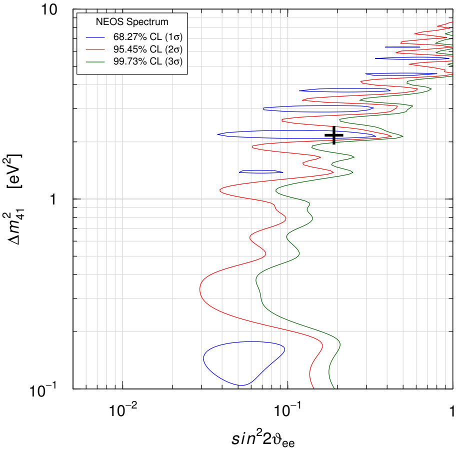




Our Analysis of NEOS@ICHEP2016 Spectrum

[CG & Marco Laveder]

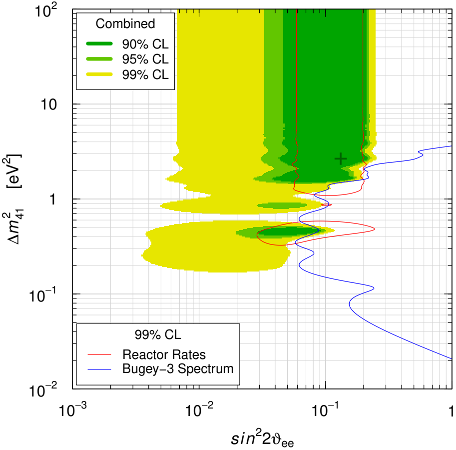




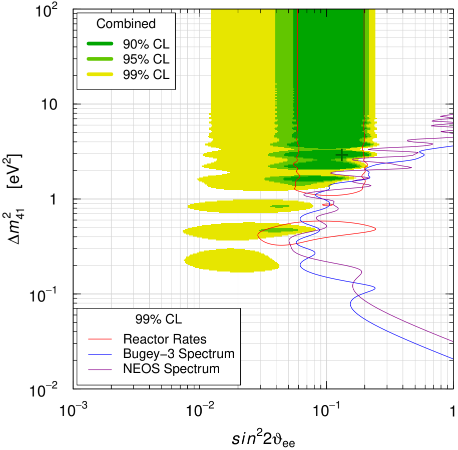
- We did not use the NEOS spectrum data in the 5 MeV bump region.
- The calculated spectrum may need corrections also elsewhere.
- To be safe we added 5% uncorrelated uncertainties to all the bins.

- We fitted the NEOS spectrum with a free normalization constant determined by the fit.
- $\chi^2_{\text{null}} - \chi^2_{\text{osc}} = 3.44 \quad (\approx 1.3\sigma)$

Reactor Rates + Bugey-3 and NEOS Spectra



Without NEOS



With NEOS

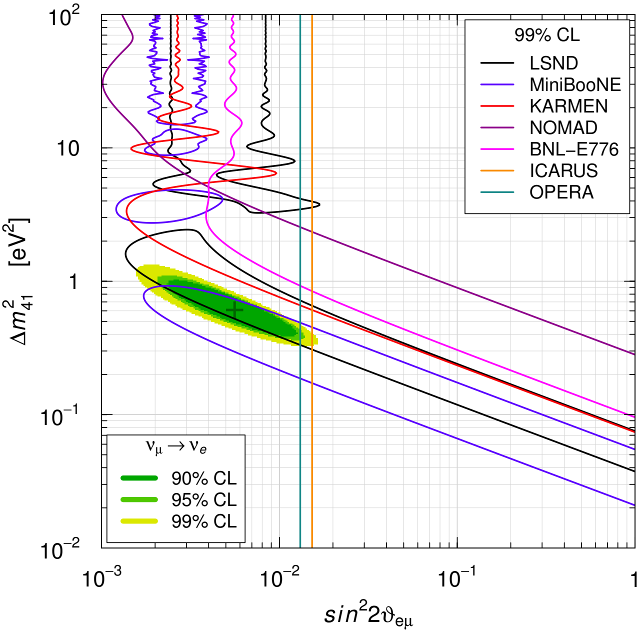
Best Fit: $$\begin{cases} \Delta m^2_{41} = 2.7\,\mathrm{eV}^2 \\ \sin^2 2\vartheta_{ee} = 0.13 \end{cases}$$

$$\chi^2_{\text{null}} - \chi^2_{\text{osc}} = 10.2 \quad (\approx 2.7\sigma)$$

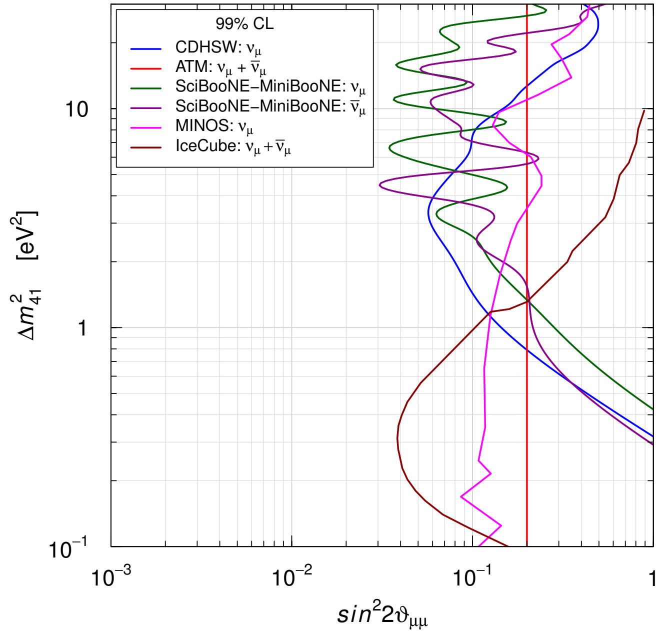
Best Fit: $$\begin{cases} \Delta m^2_{41} = 3.0\,\mathrm{eV}^2 \\ \sin^2 2\vartheta_{ee} = 0.13 \end{cases}$$

$$\chi^2_{\text{null}} - \chi^2_{\text{osc}} = 10.9 \quad (\approx 2.9\sigma)$$

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



ν_μ and $\bar{\nu}_\mu$ Disappearance



3+1 Appearance-Disappearance Tension

ν_e DIS

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

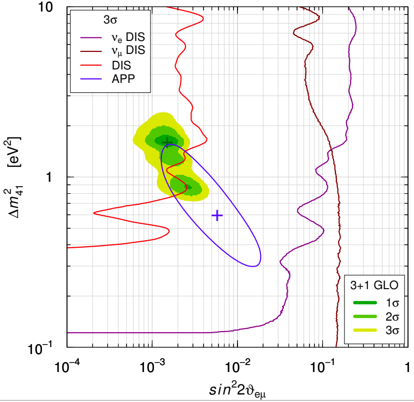
ν_μ DIS

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

$\nu_\mu \to \nu_e$ 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!
- Similar constraint in

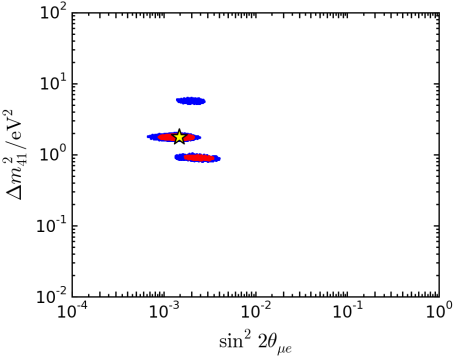
  3+2, 3+3, . . . , 3+N_s

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

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001] with improved treatment of the MiniBooNE background disappearance due to neutrino oscillations according to information from Bill Louis (thanks!)

Collin, Arguelles, Conrad, Shaevitz

[NPB 908 (2016) 354]



Best Fit: $\Delta m^2_{41} = 1.75\,\text{eV}^2$

$|U_{e4}|^2 = 0.027$ $|U_{\mu4}|^2 = 0.014$

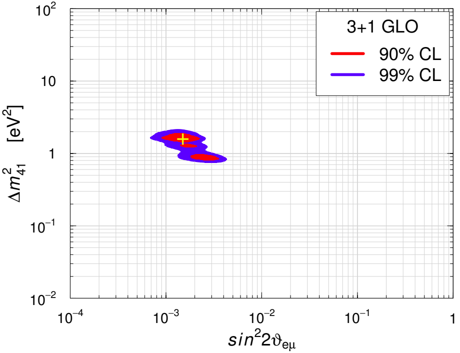
GoF = 57% (χ^2_{min}/NDF = 306.8/312)

GoF$_{\text{null}}$ = 4.4% (χ^2/NDF = 359.2/315)

$\Delta\chi^2$/NDF = 52.3/3 ($\approx 6.7\sigma$)

Our Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]



Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$

$|U_{e4}|^2 = 0.028$ $|U_{\mu4}|^2 = 0.014$

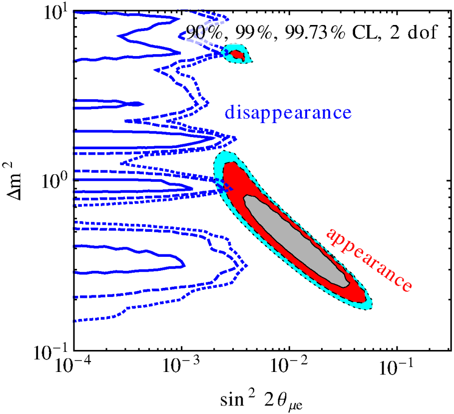
GoF = 6% (χ^2_{min}/NDF = 304.0/268)

GoF$_{\text{null}}$ = 0.04% (χ^2/NDF = 355.2/271)

$\Delta\chi^2$/NDF = 51.2/3 ($\approx 6.6\sigma$)

Kopp, Machado, Maltoni, Schwetz

[JHEP 1305 (2013) 050]



Best Fit: $\Delta m^2_{41} = 0.93\,\text{eV}^2$

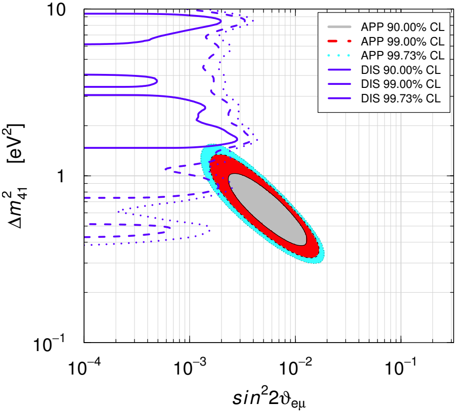
$|U_{e4}|^2 = 0.023$ $|U_{\mu 4}|^2 = 0.029$

GoF = 19% ($\chi^2_{\text{min}}/\text{NDF} = 712/680$)

GoF$_{\text{PG}}$ = 0.01% ($\chi^2_{\text{PG}}/\text{NDF} = 18.0/2$)

Our Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]



Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$

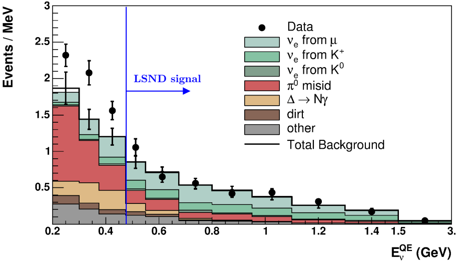
$|U_{e4}|^2 = 0.028$ $|U_{\mu 4}|^2 = 0.014$

GoF = 6% ($\chi^2_{\text{min}}/\text{NDF} = 304.0/268$)

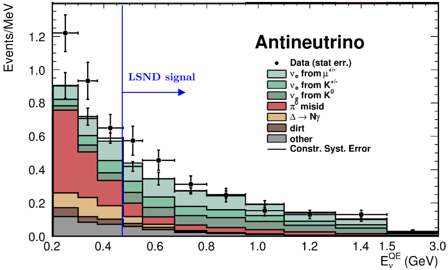
GoF$_{\text{PG}}$ = 0.06% ($\chi^2/\text{NDF} = 15.0/2$)

MiniBooNE Low-Energy Anomaly

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

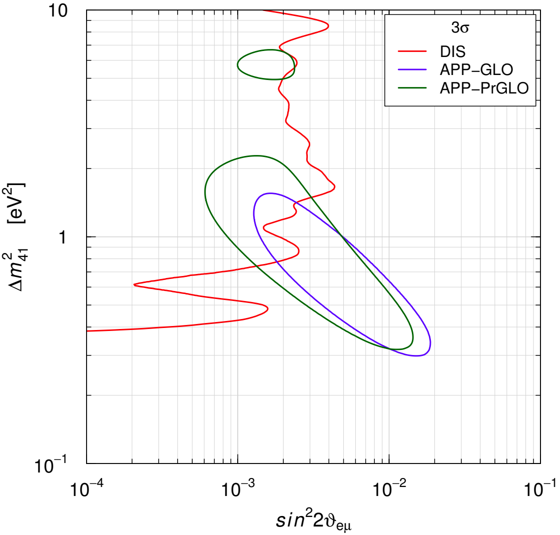


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Fit of MB Low-Energy Excess requires small Δm^2_{41} and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data
- MB low-energy excess is the main cause of bad APP-DIS $\text{GoF}_{\text{PG}} = 0.06\%$
- Multinucleon effects in neutrino energy reconstruction are not enough to solve the problem [Martini et al, PRD 85 (2012) 093012; PRD 87 (2013) 013009; PRD 93 (2016) 073008]
- Pragmatic Approach: discard the Low-Energy Excess because it is likely not due to oscillations [CG, Laveder, Li, Long, PRD 88 (2013) 073008]
- MicroBooNE is crucial for checking the MiniBooNE Low-Energy Anomaly and the consistency of different short-baseline data

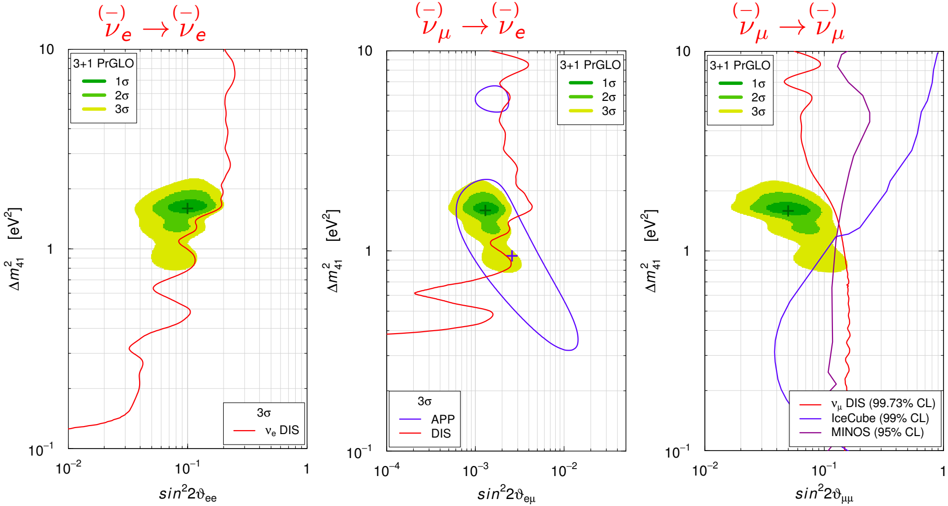
Global → Pragmatic



- APP-GLO: all MiniBooNE data
- APP-PrGLO: only MiniBooNE $E > 475\,\text{MeV}$ data (Pragmatic)

Pragmatic Global 3+1 Fit

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]



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

GoF = 24% $\qquad$ PGoF = 7%

No Osc. disfavored at $\approx 6.2\sigma$

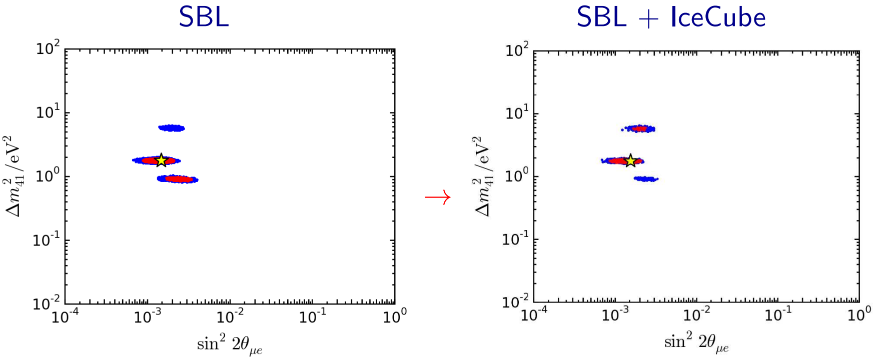
$\Delta\chi^2/\mathrm{NDF} = 46.6/3$

Not yet included:

- IceCube, arXiv:1605.01990
- MINOS, arXiv:1607.01176

SBL + IceCube

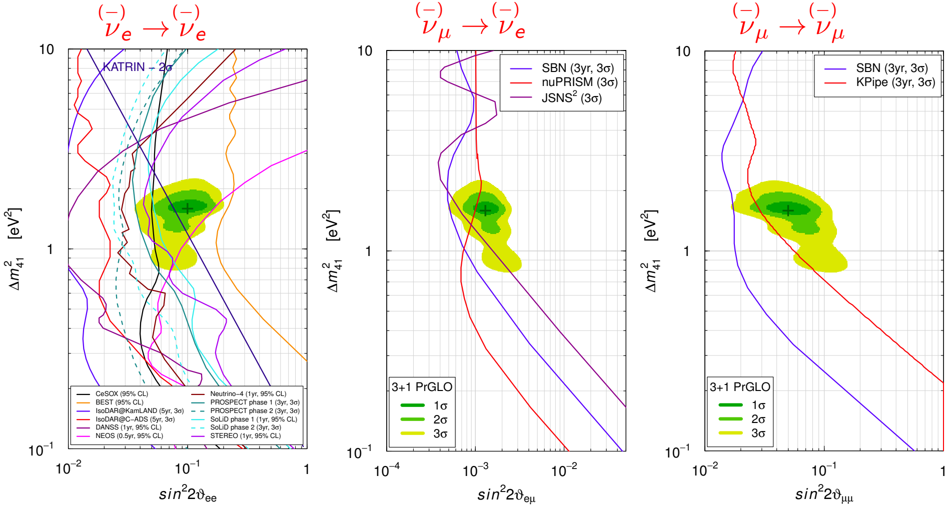
[Collin, Arguelles, Conrad, Shaevitz, arXiv:1607.00011]



Red: 90% CL Blue: 99% CL

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	$\lvert U_{\tau4}\rvert$	N_{bins}	$\chi^2_{\rm min}$	$\chi^2_{\rm null}$	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.59	568.84	50.26 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

The Race for the Light Sterile



Effects of light sterile neutrinos should also be seen in:

- β Decay Experiments
  [Hannestad et al, JCAP 1102 (2011) 011, PRC 84 (2011) 045503; Formaggio, Barrett, PLB 706 (2011) 68; Esmaili, Peres, PRD 85 (2012) 117301; Gastaldo et al, JHEP 1606 (2016) 061]
- Neutrinoless Double-β Decay Experiments
  [Rodejohann et al, JHEP 1107 (2011) 091; Li, Liu, PLB 706 (2012) 406; Meroni et al, JHEP 1311 (2013) 146, PRD 90 (2014) 053002; Pascoli et al, PRD 90 (2014) 093005; CG, Zavanin, JHEP 1507 (2015) 171; Guzowski et al, PRD 92 (2015) 012002]
- Long-baseline Neutrino Oscillation Experiments
  [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, arXiv:1601.05995, arXiv:1603.03759, arXiv:1605.04299; Gandhi et al, JHEP 1511 (2015) 039; Pant et al, arXiv:1509.04096, Choubey, Pramanik, arXiv:1604.04731]
- Solar neutrinos
  [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301; Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056; Kopp et al, JHEP 1305 (2013) 050]
- Atmospheric neutrinos
  [Goswami, PRD 55 (1997) 2931; Bilenky et al, PRD 60 (1999) 073007; Maltoni et al, NPB 643 (2002) 321, PRD 67 (2003) 013011; Choubey, JHEP 0712 (2007) 014; Razzaque, Smirnov, JHEP 1107 (2011) 084, PRD 85 (2012) 093010; Gandhi, Ghoshal, PRD 86 (2012) 037301; Barger et al, PRD 85 (2012) 011302; Esmaili et al, JCAP 1211 (2012) 041, JCAP 1307 (2013) 048, JHEP 1312 (2013) 014; Rajpoot et al, EPJC 74 (2014) 2936; Lindner et al, JHEP 1601 (2016) 124; Behera et al, arXiv:1605.08607]
- Supernova neutrinos
  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005; Peres, Smirnov, NPB 599 (2001); Sorel, Conrad, PRD 66 (2002) 033009; Tamborra et al, JCAP 1201 (2012) 013; Wu et al, PRD 89 (2014) 061303; Esmaili et al, PRD 90 (2014) 033013]
- Cosmic neutrinos
  [Cirelli et al, NPB 708 (2005) 215; Donini, Yasuda, arXiv:0806.3029; Barry et al, PRD 83 (2011) 113012]
- Indirect dark matter detection [Esmaili, Peres, JCAP 1205 (2012) 002]
- Cosmology [see: Wong, ARNPS 61 (2011) 69; Archidiacono et al, AHEP 2013 (2013) 191047]

Effective 3+1 LBL Oscillation Probabilities

[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, arXiv:1601.05995, arXiv:1603.03759, arXiv:1605.04299; Gandhi et al, JHEP 1511 (2015) 039]

$$|U_{e3}| \simeq \sin\vartheta_{13} \simeq 0.15 \sim \varepsilon \quad \Longrightarrow \quad \varepsilon^2 \sim 0.03$$

$$|U_{e4}| \simeq \sin\vartheta_{14} \simeq 0.17 \sim \varepsilon$$

$$|U_{\mu4}| \simeq \sin\vartheta_{24} \simeq 0.11 \sim \varepsilon$$

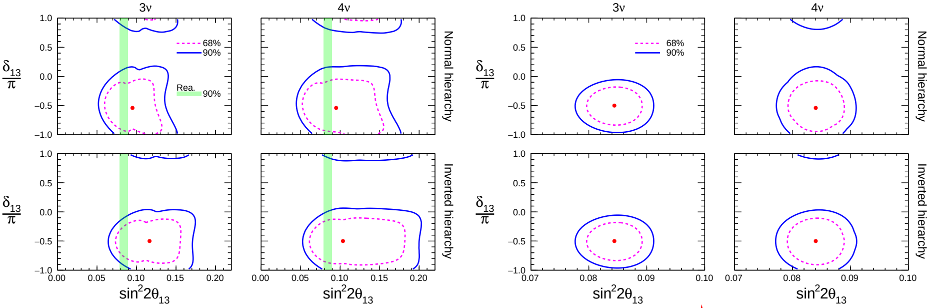
$$\alpha \equiv \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \simeq \frac{7 \times 10^{-5}}{2.4 \times 10^{-3}} \simeq 0.031 \sim \varepsilon^2$$

At order ε^3: [Klop, Palazzo, PRD 91 (2015) 073017] $\Delta_{kj} \equiv \Delta m^2_{kj} L / 4E$

$$\begin{aligned} P^{\text{LBL}}_{\nu_\mu \to \nu_e} \simeq\ & 4 \sin^2\vartheta_{13} \sin^2\vartheta_{23} \sin^2\Delta_{31} && \sim \varepsilon^2 \\ & + 2 \sin\vartheta_{13} \sin 2\vartheta_{12} \sin 2\vartheta_{23} (\alpha\Delta_{31}) \sin\Delta_{31} \cos(\Delta_{32} + \delta_{13}) && \sim \varepsilon^3 \\ & + 4 \sin\vartheta_{13} \sin\vartheta_{14} \sin\vartheta_{24} \sin\vartheta_{23} \sin\Delta_{31} \sin(\Delta_{31} + \delta_{13} - \delta_{14}) && \sim \varepsilon^3 \end{aligned}$$

CP Violation in T2K and NOνA

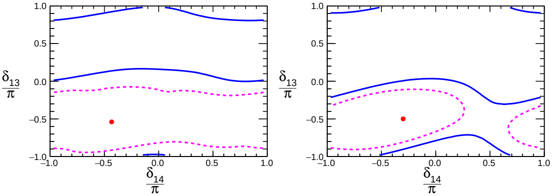
[Capozzi, CG, Laveder, Palazzo, in preparation, with T2K and NOνA data presented at Neutrino 2016]



LBL + Reactors

Normal Ordering

Inverted Ordering



Inverted Ordering: Better agreement of LBL & Reactors for $\delta_{14} \approx -\pi/2$

Conclusions

- Exciting indications of light sterile neutrinos at the eV scale:
  - LSND $\bar{\nu}_{\mu} \to \bar{\nu}_{e}$ signal.
  - Gallium ν_e disappearance.
  - Reactor $\bar{\nu}_e$ disappearance.
- 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.
- Possibilities for the next 10+ years:
  - Reactor and source experiments ν_e and $\bar{\nu}_e$ observe SBL oscillations: big excitement and explosion of the field.
  - Because of 5 MeV bump we know that the calculated spectrum must be corrected: oscillations must be observed as a function of distance!
  - 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: see the talk by A. Merle).
  - Sterile neutrinos will always be allowed at all mass scales below the existing mixing bounds.