Oscillations Beyond Three-Neutrino Mixing

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Neutrino 2016
XXVII International Conference on Neutrino Physics and Astrophysics

4-9 July 2016 – London, UK

Oscillations Beyond Three-Neutrino Mixing

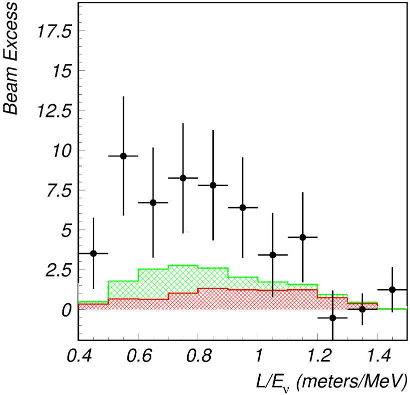
- Light Sterile Neutrinos.
- Non-Unitarity of Mixing Matrix.
- Non-Standard Interactions.
- Magnetic Moments.

Indications of SBL Oscillations Beyond 3ν

LSND

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

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



- 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 $\qquad \Delta m^2_{\text{SBL}} \gtrsim 0.2\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

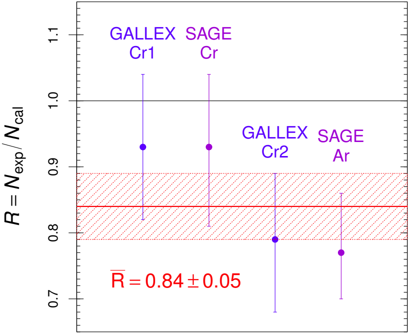
Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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]

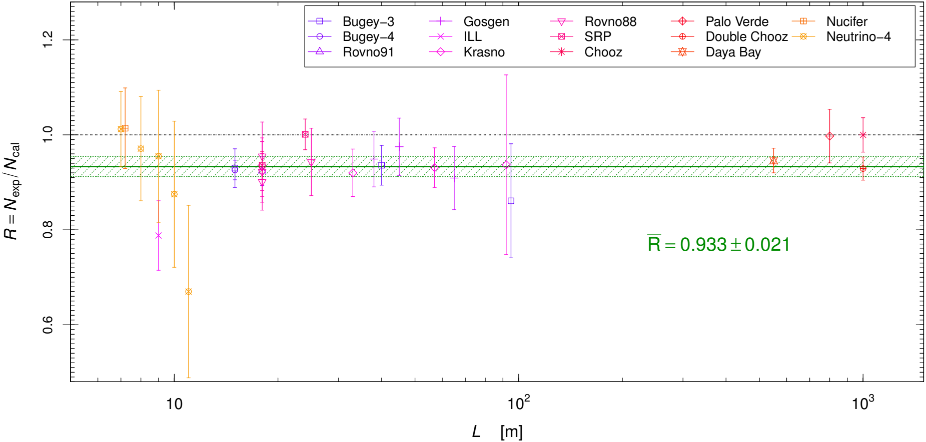
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344;
MPLA 22 (2007) 2499; PRD 78 (2008) 073009;
PRC 83 (2011) 065504]

- ${}^{3}\mathrm{He} + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + {}^{3}\mathrm{H}$ 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

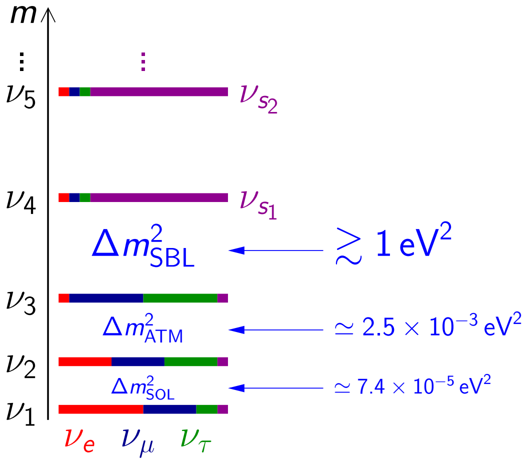
[Mention et al, PRD 83 (2011) 073006; updated in White Paper, arXiv:1204.5379]

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



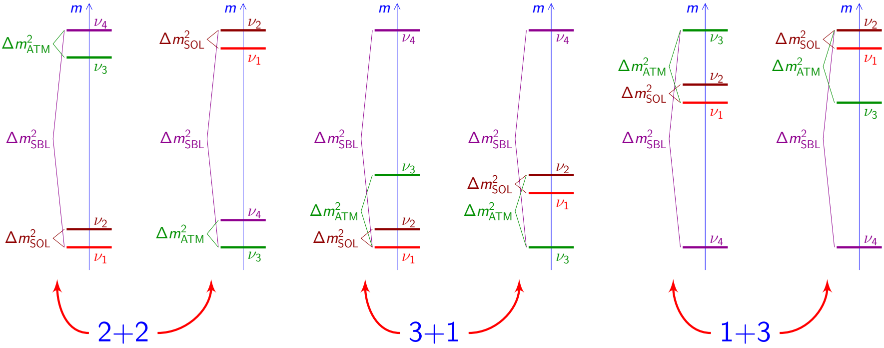
$\approx 3.2\sigma$ deficit $\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$

Beyond Three-Neutrino Mixing: Sterile Neutrinos

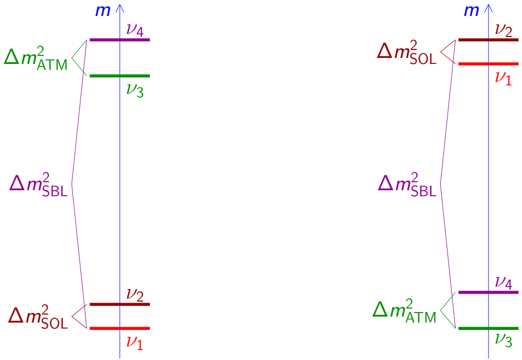


Terminology: a eV-scale sterile neutrino
means: a eV-scale massive neutrino which is mainly sterile

Four-Neutrino Schemes: 2+2, 3+1 and 1+3



2+2 Four-Neutrino Schemes

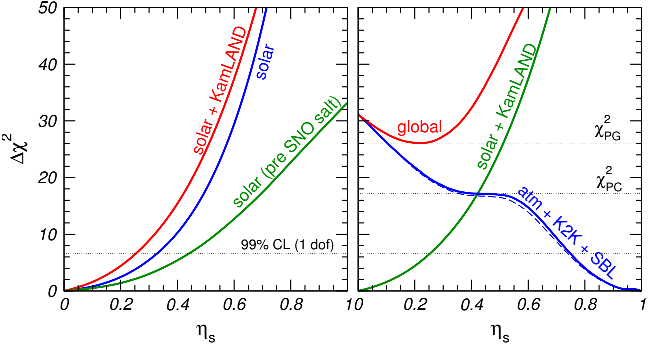


- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

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

- This is not a perturbation of 3-ν Mixing $\Longrightarrow$ Large active–sterile oscillations for solar or atmospheric neutrinos!

2+2 Schemes are Strongly Disfavored



Solar: Matter Effects + SNO NC

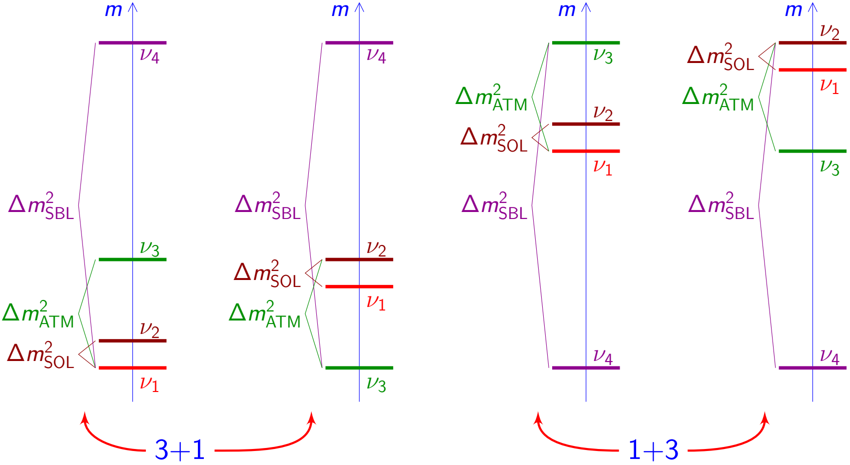
Atmospheric: Matter Effects

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2 = 1 - |U_{s3}|^2 + |U_{s4}|^2$$

$$99\%\ \text{CL:} \quad \begin{cases} \eta_s < 0.25 & \text{(Solar + KamLAND)} \\ \eta_s > 0.75 & \text{(Atmospheric + K2K)} \end{cases}$$

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122]

3+1 and 1+3 Four-Neutrino Schemes



- Perturbation of 3-ν Mixing: $|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 \ll 1 \quad |U_{s4}|^2 \simeq 1$
- 1+3 schemes are disfavored by cosmology (ΛCDM):

$$\sum_{k=1}^{3} m_k < 0.21\,\text{eV} \text{ (95\%, Planck TT + lowP + BAO)}$$ [arXiv:1502.01589]

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]

3+1 Appearance-Disappearance Tension

ν_e DIS

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

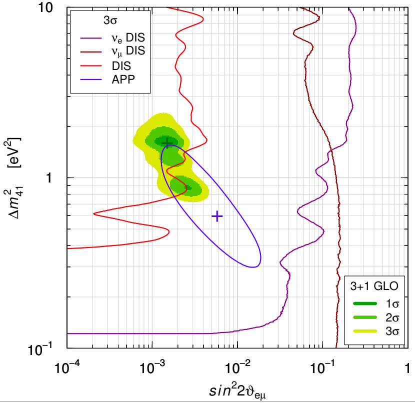
ν_μ DIS

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

$\nu_\mu \to \nu_e$ 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

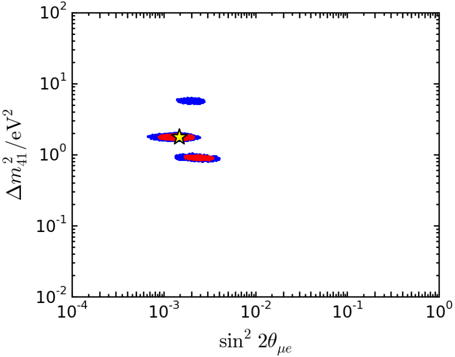
  3+2, 3+3, . . . , 3+N_s

  [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: $\Delta m^2_{41} = 1.75\,\mathrm{eV}^2$

$|U_{e4}|^2 = 0.027 \qquad |U_{\mu 4}|^2 = 0.014$

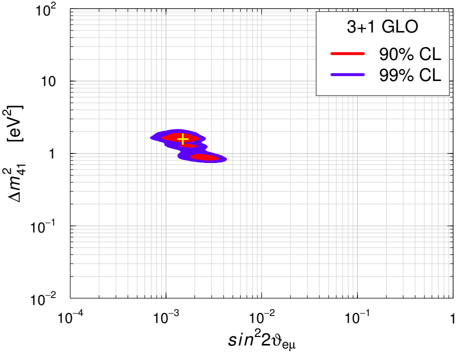
GoF $= 57\%$ $(\chi^2_{\mathrm{min}}/\mathrm{NDF} = 306.8/312)$

$\mathrm{GoF_{null}} = 4.4\%$ $(\chi^2/\mathrm{NDF} = 359.2/315)$

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

Our Fit

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



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

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

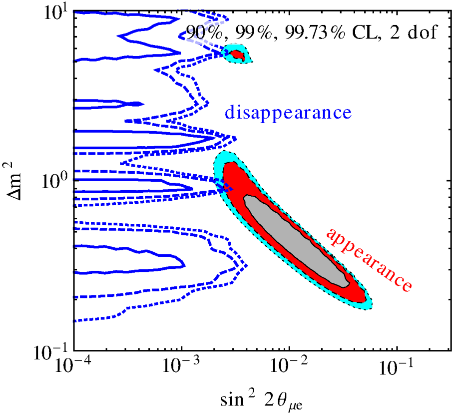
GoF $= 6\%$ $(\chi^2_{\mathrm{min}}/\mathrm{NDF} = 304.0/268)$

$\mathrm{GoF_{null}} = 0.04\%$ $(\chi^2/\mathrm{NDF} = 355.2/271)$

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

Kopp, Machado, Maltoni, Schwetz

[JHEP 1305 (2013) 050]



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

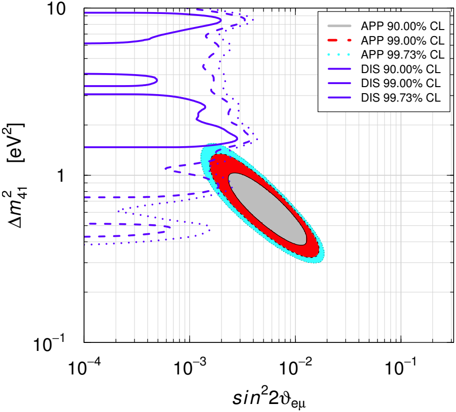
$|U_{e4}|^2 = 0.023$ $|U_{\mu 4}|^2 = 0.029$

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

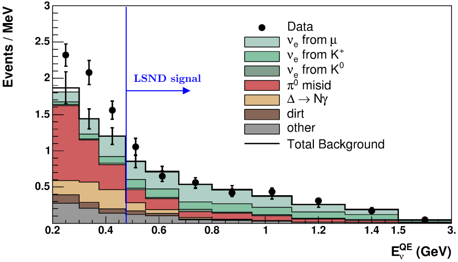
$|U_{e4}|^2 = 0.028$ $|U_{\mu 4}|^2 = 0.014$

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

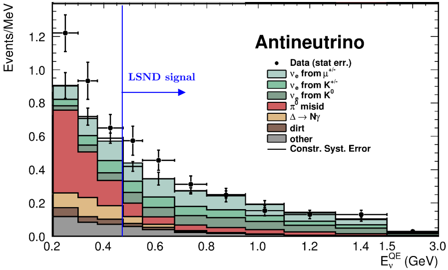
GoF$_{\text{PG}} = 0.06\%\,(\chi^2/\text{NDF} = 15.0/2)$

MiniBooNE Low-Energy Anomaly

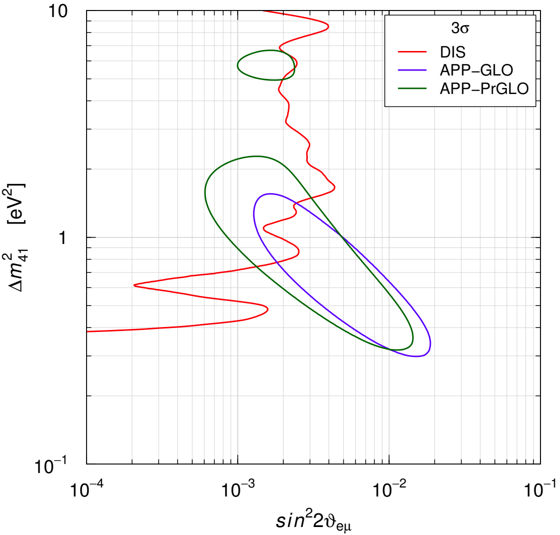
$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]



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



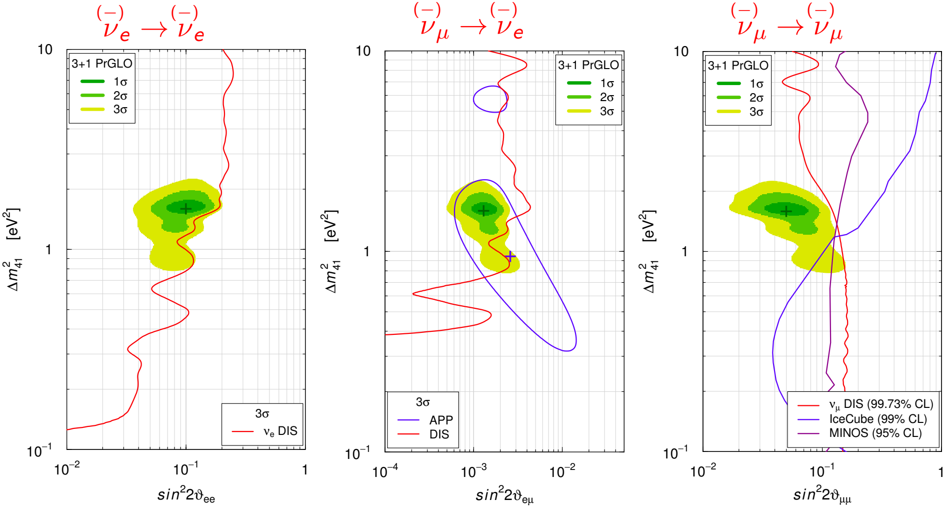
- Fit of MB Low-Energy Excess requires small Δm^2_{41} and large $\sin^2 2\vartheta_{e\mu}$, in contradiction with disappearance data
- MB low-energy excess is the main cause of bad APP-DIS $\text{GoF}_{\text{PG}} = 0.06\%$
- Multinucleon effects in neutrino energy reconstruction are not enough to solve 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



- APP-GLO: all MiniBooNE data
- APP-PrGLO: only MiniBooNE $E > 475\,\mathrm{MeV}$ 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 $\approx 6.2\sigma$

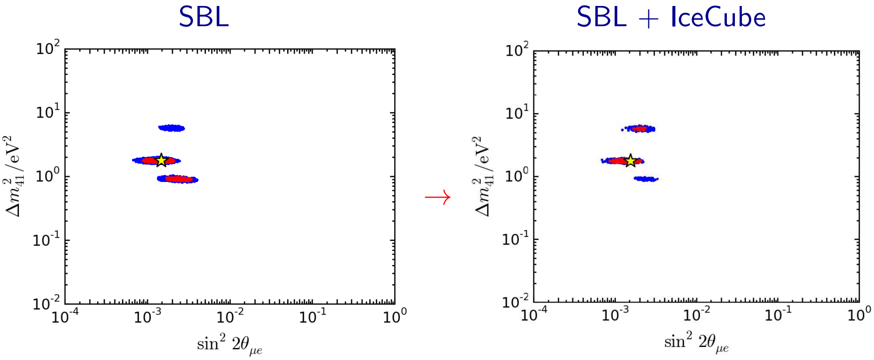
$\Delta\chi^2/\text{NDF} = 46.6/3$

Not yet included:

- IceCube, arXiv:1605.01990
- MINOS Preliminary, arXiv:1605.04544

SBL + IceCube

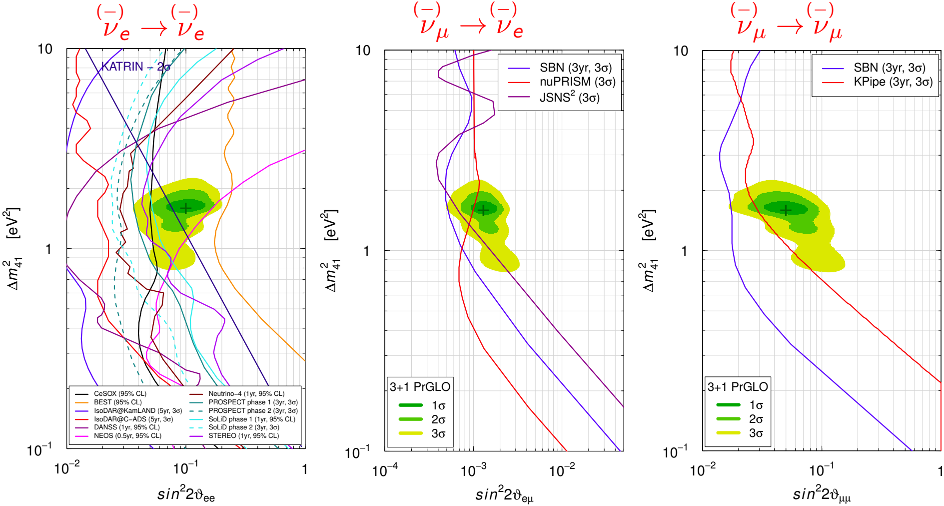
[Collin, Arguelles, Conrad, Shaevitz, arXiv:1607.00011]



Red: 90% CL Blue: 99% CL

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	χ^2_{min}	χ^2_{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



Effective 3+2 SBL Oscillation Probabilities

[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004]

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\Delta_{41} + 4|U_{e5}|^2|U_{\mu5}|^2\sin^2\Delta_{51}$$

$$+8|U_{\mu4}U_{e4}U_{\mu5}U_{e5}|\sin\Delta_{41}\sin\Delta_{51}\cos(\Delta_{54}\overset{(+)}{-}\eta)$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1-|U_{\alpha4}|^2-|U_{\alpha5}|^2)(|U_{\alpha4}|^2\sin^2\Delta_{41}+|U_{\alpha5}|^2\sin^2\Delta_{51})$$

$$-4|U_{\alpha4}|^2|U_{\alpha5}|^2\sin^2\Delta_{54}$$

$$\Delta_{kj} = \Delta m^2_{kj}L/4E \qquad \eta = \arg[U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5}]$$

- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

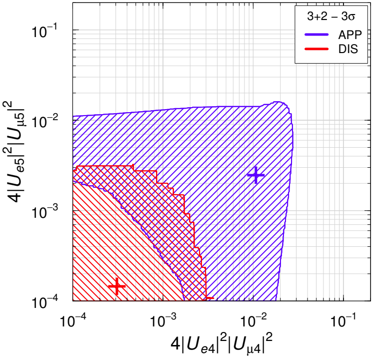
4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu5}|^2, \eta$

[Conrad, Shaevitz et al, PRD 75 (2007) 013011, PRD 80 (2009) 073001, AHEP 2013 (2013) 163897, NPB 908 (2016) 354; Maltoni, Schwetz, et al, PRD 76 (2007) 093005, PRL 107 (2011) 091801, JHEP 1305 (2013) 050; Bandyopadhyay, Choubey, arXiv:0707.2481; Akhmedov, Schwetz, JHEP 1010 (2010) 115; Laveder et al, PRD 84 (2011) 073008, PRD 88 (2013) 073008, JPG 43 (2016) 033001; Donini et al, JHEP 1107 (2011) 105, JHEP 1207 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028, PRD 87 (2013) 125034; Jacques, Krauss, Lunardini, PRD 87 (2013) 083515; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

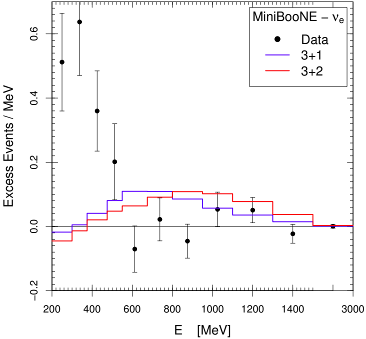
3+2 Appearance-Disappearance Tension

Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	6%	10%	19%	23%
PGoF	0.06%	0.3%	0.01%	0.003%

- Our Fit: Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]
- KMMS: [Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]



3+2 cannot fit MiniBooNE Low-Energy Excess



- Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data
- Conclusion: with current data 3+2 is not needed

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]

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

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

$$|U_{\mu 4}| \simeq \sin\vartheta_{24} \simeq 0.11 \sim \varepsilon$$

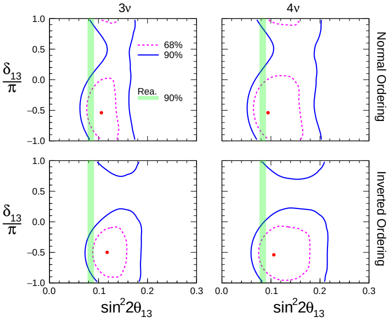
$$\alpha \equiv \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \simeq \frac{7 \times 10^{-5}}{2.4 \times 10^{-3}} \simeq 0.031 \sim \varepsilon^2$$

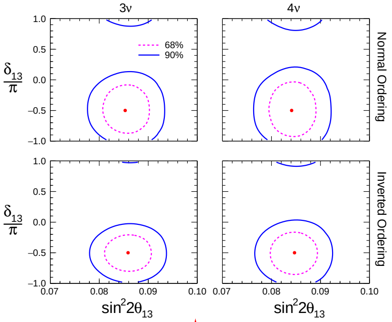
At order ε^3: [Klop, Palazzo, PRD 91 (2015) 073017] $\Delta_{kj} \equiv \Delta m^2_{kj} L/4E$

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

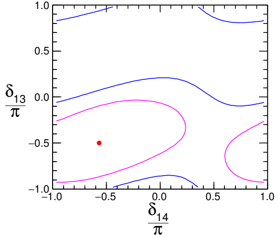
CP Violation in T2K and NOνA

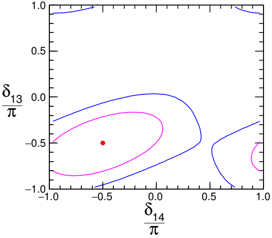
[Capozzi, CG, Laveder, Palazzo, in preparation]





LBL + Reactors

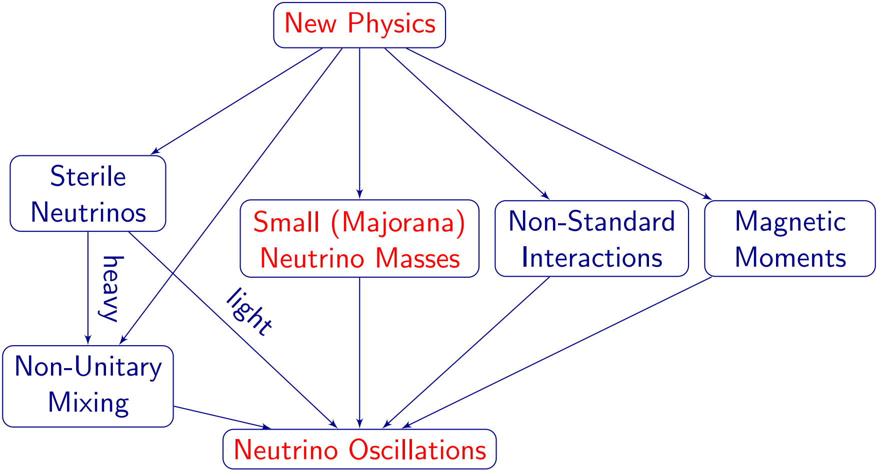




Normal Ordering →

← Inverted Ordering

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


New Physics

Sterile Neutrinos

Small (Majorana) Neutrino Masses

Non-Standard Interactions

Magnetic Moments

heavy

light

Non-Unitary Mixing

Neutrino Oscillations

Non-Unitary Mixing

Standard Light Massive Neutrinos

ν_1, ν_3, ν_3

Heavy Neutral Leptons ($m_k \gtrsim 100\,\text{GeV}$)

$\nu_4, \ldots, \nu_N$

$N_s = N - 3$ Heavy Sterile Neutrinos

$\nu_{s_1}, \ldots, \nu_{N_s}$

$$U^{N\times N} = \left(\begin{array}{cc} \overset{\widetilde{U}}{\boxed{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}} & \begin{matrix} \cdots & U_{eN} \\ \cdots & U_{\mu N} \\ \cdots & U_{\tau N} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_{N_s}1} & U_{s_{N_s}2} & U_{s_{N_s}3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_{N_s}N} \end{matrix} \end{array}\right)$$

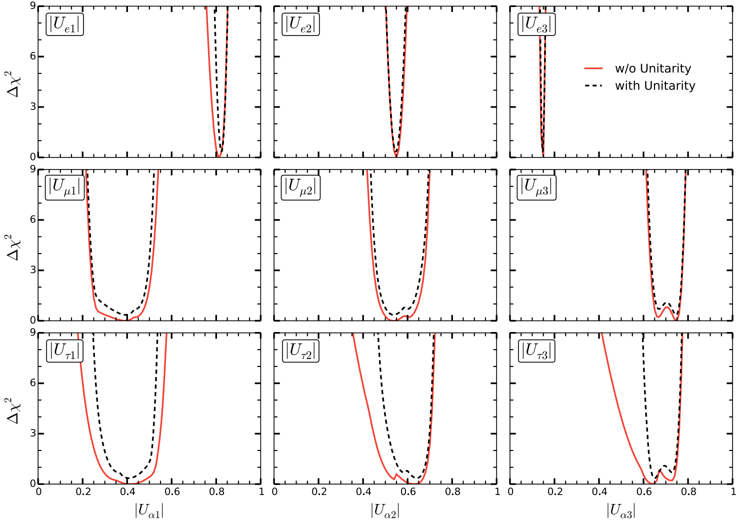
Effective Low-Energy Mixing of Active Neutrinos ($\alpha = e, \mu, \tau$)

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^{N\times N}_{\alpha k} |\nu_k\rangle = \sum_{k=1}^{3} \widetilde{U}_{\alpha k} |\nu_k\rangle$$

Non-Unitary Effective 3×3 Mixing Matrix $\widetilde{U}$

Global Non-Unitary Fit of Oscillation Data

[Parke, Ross-Lonergan, PRD 93 (2016) 113009]



Assumption: $\Delta m^2_{21} = 7.6 \times 10^{-5}\,\mathrm{eV}^2$ $|\Delta m^2_{31}| = 2.4 \times 10^{-3}\,\mathrm{eV}^2$ [PDG 2014]

See also: [Langacker, London, PRD 38 (1988) 907; Bilenky, CG, PLB 300 (1993) 137; Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP 0610 (2006) 084; Xing, PLB 718 (2013) 1447; Qian, Zhang, Diwan, Vogel, arXiv:1308.5700]

Bounds on Non-Unitarity of the Mixing Matrix

- Any matrix can be parameterized as a product of a Hermitian and a Unitary matrix: [Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, PLB 649 (2007) 427]

$$\boxed{\widetilde{U} = (\mathbb{1} - \eta)\, U} \quad \text{with} \quad \eta = \eta^\dagger$$

$$U = \text{Standard Unitary } 3 \times 3 \text{ Mixing Matrix}$$

- Since massive neutrinos are not observed in flavor neutrinos interactions observables depend on

$$\sum_k \widetilde{U}_{\alpha k} \widetilde{U}^\dagger_{k\alpha} \approx \delta_{\alpha\beta} - 2\eta_{\alpha\beta} \quad \text{for} \quad |\eta_{\alpha\beta}| \ll 1$$

- From electroweak and LFV measurements:

$$2|\eta| \leq \begin{pmatrix} 2.5 \times 10^{-3} & 2.4 \times 10^{-5} & 2.7 \times 10^{-3} \\ 2.4 \times 10^{-5} & 4.0 \times 10^{-4} & 1.2 \times 10^{-3} \\ 2.7 \times 10^{-3} & 1.2 \times 10^{-3} & 5.6 \times 10^{-3} \end{pmatrix} \quad \text{at } 2\sigma$$

[Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, arXiv:1605.08774]

See also: [Langacker, London, PRD 38 (1988) 886; Nardi, Roulet, Tommasini, PLB 327 (1994) 319; Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP 0610 (2006) 084; Rodejohann, PLB 684 (2010) 40; Alonso, Dhen, Gavela, Hambye, JHEP 1301 (2013) 118; Akhmedov, Kartavtsev, Lindner, Michaels, Smirnov, JHEP 1305 (2013) 081; Abada, Das, Teixeira, Vicente, Weiland, JHEP 1302 (2013) 048; Basso, Fischer, van der Bij, Europhys.Lett. 105 (2014) 11001; Abada, Teixeira, Vicente, Weiland, JHEP 1402 (2014) 091; Antusch, Fischer, JHEP 1410 (2014) 094, JHEP 1505 (2015) 053; Abada, De Romeri, Teixeira, JHEP 1602 (2016) 083]

Non-Unitarity CP-Violation Ambiguity

- Another parameterization: $\boxed{\widetilde{U} = T^{\mathrm{NP}} U}$ [Schechter, Valle, PRD 22 (1980) 2227; Xing, PLB 660 (2008) 515; Escrihuela, Forero, Miranda, Tortola, Valle PRD 92 (2015) 053009]

$$T^{\mathrm{NP}} = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Real: $\alpha_{ee}, \alpha_{\mu\mu}, \alpha_{\tau\tau}$

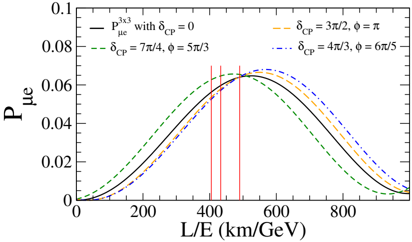
Complex: $\alpha_{\mu e}, \alpha_{\tau e}, \alpha_{\tau\mu}$

- $P_{\mu e} = \alpha_{ee}^2 \alpha_{\mu\mu}^2 P_{\mu e}^{3\times3} - \alpha_{ee}^2 \alpha_{\mu\mu} |\alpha_{\mu e}| P_{\mu e}^{I} + \boxed{\alpha_{ee}^2 |\alpha_{\mu e}|^2}$

zero-distance effect

$$P_{\mu e}^{I} = 2 \sin 2\theta_{13} \sin\theta_{23} \sin\Delta_{31} \sin\left(\Delta_{31} + \delta_{CP} + \phi\right) + \cos\theta_{13} \cos\theta_{23} \sin 2\theta_{12} \sin 2\Delta_{21} \sin\phi$$

$\phi = -\arg(\alpha_{\mu e})$



Vertical lines indicate the mean value of L/E for NOνA (405), DUNE (433) and T2K (490 km/GeV)

[Miranda, Tortola, Valle, arXiv:1604.05690]

See also: [Fernandez-Martinez, Gavela, Lopez-Pavon, Yasuda, PLB 649 (2007) 427; Antusch, Blennow, Fernandez-Martinez, Lopez-Pavon, PRD 80 (2009) 033002; Ge, Pasquini, Tortola, Valle, arXiv:1605.01670]

Non-Standard Interactions

- Observable non-renormalizable effective NSI of left-handed neutrinos:

Charged-Current-like NSI: $(\alpha, \beta = e, \mu, \tau)$

$$\mathcal{H}_{\text{NSI}}^{\text{CC}} = 2\sqrt{2} G_{\text{F}} V_{ud} \sum_{\alpha,\beta} \left(\overline{\ell_{\alpha L}} \gamma_\rho \nu_{\beta L}\right) \left[\varepsilon_{\alpha\beta}^{udL} \overline{u_L} \gamma^\rho d_L + \varepsilon_{\alpha\beta}^{udR} \overline{u_R} \gamma^\rho d_R\right] + \text{H.c.}$$

$$+ 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_\rho \nu_{\beta L}\right) \sum_{\gamma \neq \delta} \left[\varepsilon_{\alpha\beta}^{\gamma\delta L} \overline{\ell_{\gamma L}} \gamma^\rho \ell_{\delta L} + \varepsilon_{\alpha\beta}^{\gamma\delta R} \overline{\ell_{\gamma R}} \gamma^\rho \ell_{\delta R}\right]$$

Neutral-Current-like or Matter NSI: $(\varepsilon_{\alpha\beta}^{fP} = \varepsilon_{\beta\alpha}^{fP*})$

$$\mathcal{H}_{\text{NSI}}^{\text{NC}} = 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_\rho \nu_{\beta L}\right) \sum_{f=e,u,d} \left[\varepsilon_{\alpha\beta}^{fL} \overline{f_L} \gamma^\rho f_L + \varepsilon_{\alpha\beta}^{fR} \overline{f_R} \gamma^\rho f_R\right]$$

- Bounds from non-oscillation data:

[Davidson, Pena-Garay, Rius, Santamaria, JHEP 0303 (2003) 011;
Biggio, Blennow, Fernandez-Martinez, JHEP 0908 (2009) 090;
Forero, Guzzo, PRD 84 (2011) 013002; Khan, PRD 93 (2016) 093019]

- Reviews: [Ohlsson, RPP 76 (2013) 044201;
Miranda, Nunokawa, NJP 17 (2015) 095002]

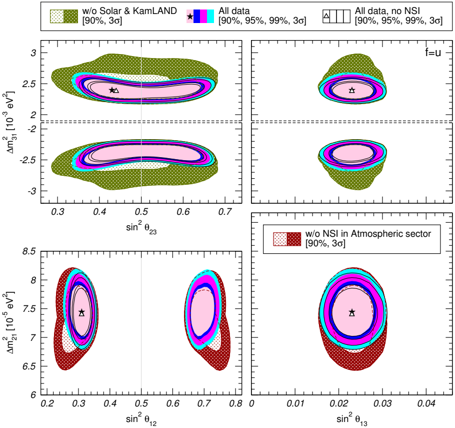
Neutrino flavor evolution equation in matter with NSI: $(\Delta_{kj} = \Delta m^2_{kj}/2E)$

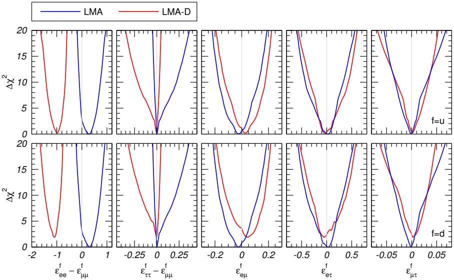
$$i\frac{\mathrm{d}}{\mathrm{d}x}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\begin{pmatrix}0&0&0\\ 0&\Delta_{21}&0\\ 0&0&\Delta_{31}\end{pmatrix}U^\dagger + \sum_{f=e,u,d} V_f \begin{pmatrix}\delta_{ef}+\varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

unpolarized matter: $\varepsilon^f_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$ vector couplings

Global Analysis of Neutrino Oscillation Data

[Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152; Gonzalez-Garcia, Maltoni, Schwetz, NPB 908 (2016) 199]



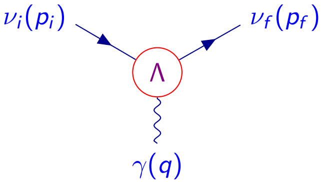


- "Dark-Side" LMA-D with $\vartheta_{12} > 45^\circ$ and large NSI. [Miranda, Tortola, Valle, JHEP 0610 (2006) 008]
- NSI have small effects on the determination of the other mixing parameters.

Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[\mathbb{f}_Q(q^2) + \mathbb{f}_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^{\nu} \left[\mathbb{f}_M(q^2) + i \mathbb{f}_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \implies$ $\mathbb{q}$, $\mathbb{a}$, $\mathbb{\mu}$, $\mathbb{\epsilon}$

- Hermitian form factor matrices $\implies$ $\mathbb{\mu} = \mathbb{\mu}^{\dagger} \quad \mathbb{\epsilon} = \mathbb{\epsilon}^{\dagger} \quad \mathbb{q} = \mathbb{q}^{\dagger} \quad \mathbb{a} = \mathbb{a}^{\dagger}$
- Majorana neutrinos $\implies$ $\mathbb{\mu} = -\mathbb{\mu}^{T} \quad \mathbb{\epsilon} = -\mathbb{\epsilon}^{T} \quad \mathbb{q} = -\mathbb{q}^{T} \quad \mathbb{a} = \mathbb{a}^{T}$

  no diagonal charges and electric and magnetic moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu^{\text{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}} \right) \qquad \varepsilon^{\text{D}}_{kk} = 0$$

$$\left. \begin{array}{r} \mu^{\text{D}}_{kj} \\ i\varepsilon^{\text{D}}_{kj} \end{array} \right\} \simeq -3.9 \times 10^{-23} \mu_{\text{B}} \left(\frac{m_k \pm m_j}{\text{eV}} \right) \sum_{\ell=e,\mu,\tau} U^{*}_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu^{\text{M}}_{kj} \simeq -7.8 \times 10^{-23} \mu_{\text{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \text{Im}\left[U^{*}_{\ell k} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

$$\varepsilon^{\text{M}}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\text{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \text{Re}\left[U^{*}_{\ell k} U_{\ell j} \right] \frac{m_\ell^2}{m_W^2}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments [Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

Method	Experiment	Limit	CL	Reference
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\,\mu_{\rm B}$	90%	Vidyakin *et al.* (1992)
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\,\mu_{\rm B}$	95%	Derbin *et al.* (1993)
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}\,\mu_{\rm B}$	90%	Daraktchieva *et al.* (2005)
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\,\mu_{\rm B}$	90%	Wong *et al.* (2007)
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\,\mu_{\rm B}$	90%	Beda *et al.* (2012)
Accelerator ν_e-e^-	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}\,\mu_{\rm B}$	90%	Allen *et al.* (1993)
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\,\mu_{\rm B}$	90%	Ahrens *et al.* (1990)
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\,\mu_{\rm B}$	90%	Allen *et al.* (1993)
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\,\mu_{\rm B}$	90%	Auerbach *et al.* (2001)
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\,\mu_{\rm B}$	90%	Schwienhorst *et al.* (2001)
Solar ν_e-e^-	Super-Kamiokande	$\mu_{\rm S}(E_\nu \gtrsim 5\,{\rm MeV}) < 1.1 \times 10^{-10}\,\mu_{\rm B}$	90%	Liu *et al.* (2004)
	Borexino	$\mu_{\rm S}(E_\nu \lesssim 1\,{\rm MeV}) < 5.4 \times 10^{-11}\,\mu_{\rm B}$	90%	Arpesella *et al.* (2008)

[CG, Studenikin, RMP 87 (2015) 531]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_{\rm B}$ prediction of the minimal Standard Model extensions.

- $\mu_\nu \gg 10^{-19}\,\mu_{\rm B}$ discovery $\Longleftrightarrow$ non-minimal new physics beyond the Standard Model.

- Neutrino spin-flavor precession in a magnetic field

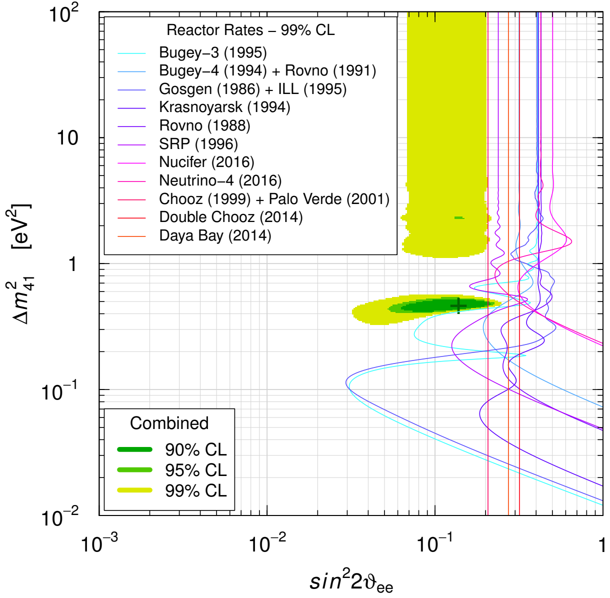
[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

Conclusions

- Exciting indications of light sterile neutrinos at the eV scale:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.
  - Reactor $\bar{\nu}_e$ disappearance.
  - Gallium ν_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.
- Neutrinos provide a Window to the New Physics beyond the Standard Model through:
  - Small (Majorana) Masses.
  - Sterile Neutrinos.
  - Non-Unitarity of Mixing Matrix.
  - Non-Standard Interactions.
  - Electromagnetic Interactions.
  - ...

Backup Slides

Reactor Rates



No Oscillations

$\chi^2/\text{NDF} = 34.9/30$

GoF = 25%

Oscillations

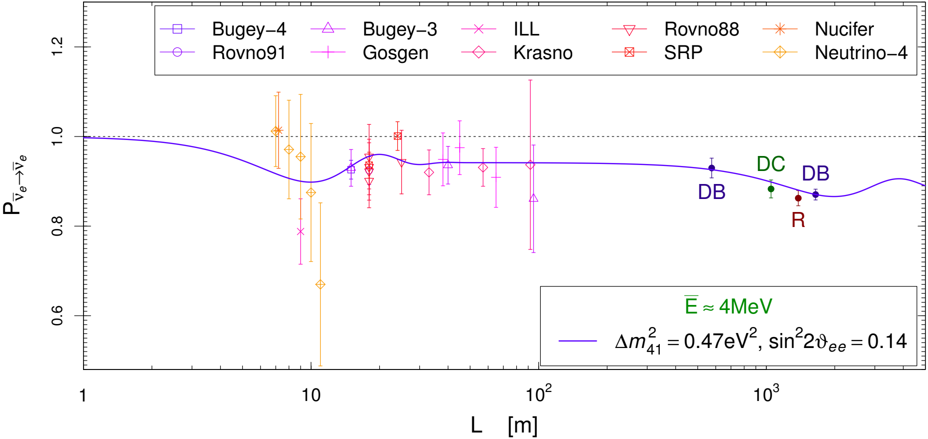
$\chi^2_{\text{min}}/\text{NDF} = 18.1/28$

GoF = 92%

Best Fit

$\Delta m^2_{41} = 0.47\,\text{eV}^2$

$\sin^2 2\vartheta_{ee} = 0.14$

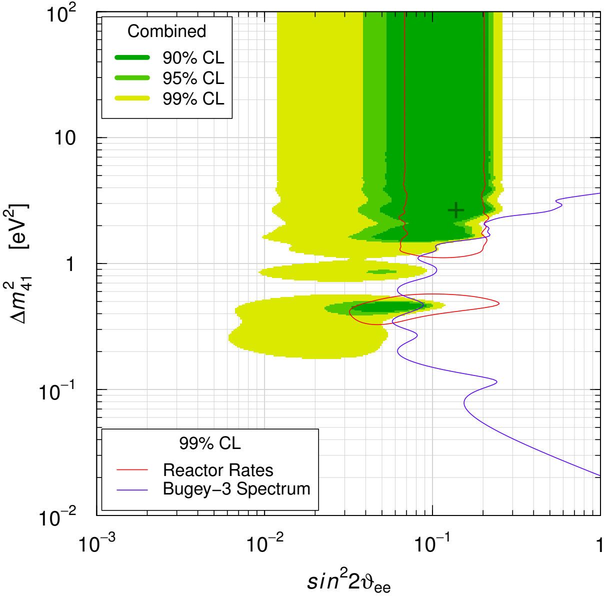


$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) = \sin^2 2\vartheta_{14}$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_e\to\overset{(-)}{\nu}_e} \simeq 1 - \sin^2 2\vartheta_{14}\,\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$P^{\text{LBL}}_{\overset{(-)}{\nu}_e\to\overset{(-)}{\nu}_e} \simeq 1 - \frac{1}{2}\sin^2 2\vartheta_{14} - \cos^4\vartheta_{14}\,\sin^2 2\vartheta_{13}\,\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Reactor Rates + Bugey-3 Spectrum



No Oscillations

$\chi^2/\text{NDF} = 50.3/54$

GoF = 62%

Oscillations

$\chi^2_{\text{min}}/\text{NDF} = 39.4/52$

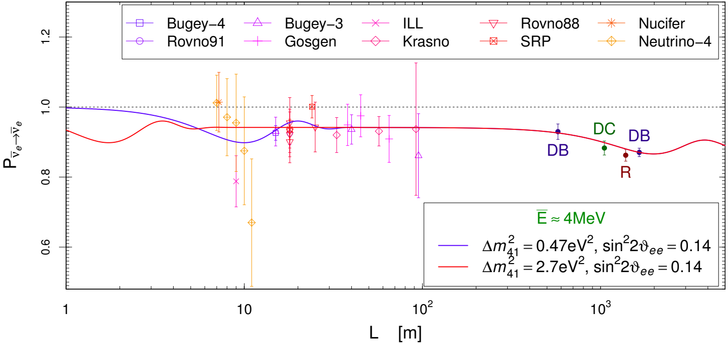
GoF = 90%

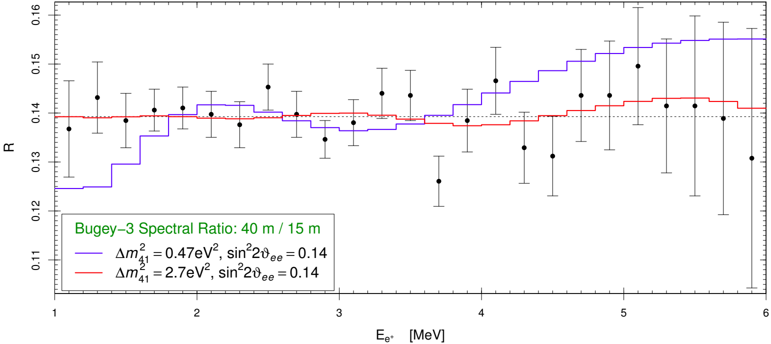
Best Fit

$\Delta m^2_{41} = 2.7\,\text{eV}^2$

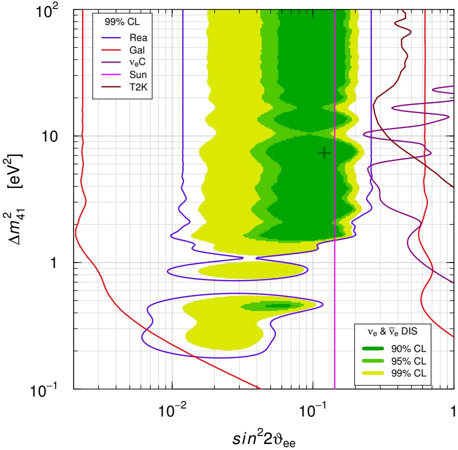
$\sin^2 2\vartheta_{ee} = 0.14$

We use the Bugey-3 40 m / 15 m spectral ratio, which is independent from the 5 MeV bump!


Bugey−4
Rovno91
Bugey−3
Gosgen
ILL
Krasno
Rovno88
SRP
Nucifer
Neutrino−4
$P_{\overline{\nu}_e \to \overline{\nu}_e}$
1.2
1.0
0.8
0.6
DB
DC
DB
R
$\overline{E} \approx 4\text{MeV}$
$\Delta m^2_{41} = 0.47\text{eV}^2$, $\sin^2 2\vartheta_{ee} = 0.14$
$\Delta m^2_{41} = 2.7\text{eV}^2$, $\sin^2 2\vartheta_{ee} = 0.14$
1
10
10^2
10^3
L [m]


R
0.16
0.15
0.14
0.13
0.12
0.11
Bugey−3 Spectral Ratio: 40 m / 15 m
$\Delta m^2_{41} = 0.47\text{eV}^2$, $\sin^2 2\vartheta_{ee} = 0.14$
$\Delta m^2_{41} = 2.7\text{eV}^2$, $\sin^2 2\vartheta_{ee} = 0.14$
1
2
3
4
5
6
E_{e^+} [MeV]

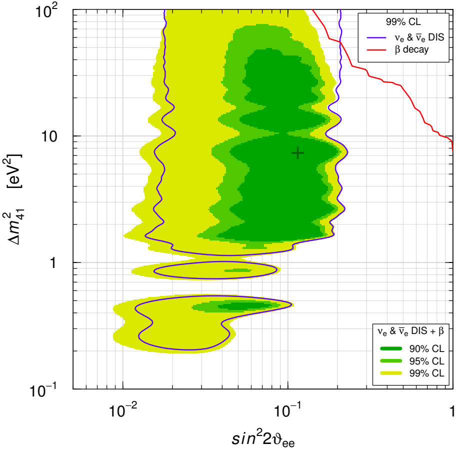
Global ν_e and $\bar{\nu}_e$ Disappearance



KARMEN + LSND $\nu_e + {}^{12}C \to {}^{12}N_{g.s.} + e^-$
[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]

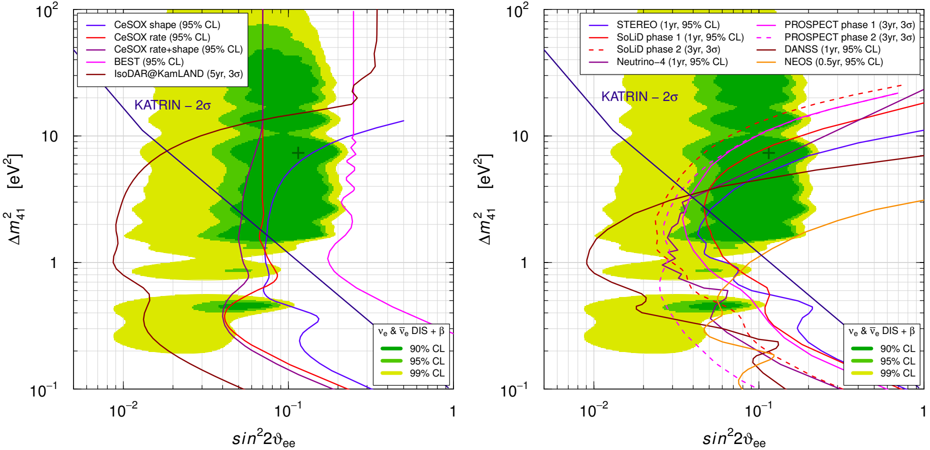


Mainz + Troitsk Tritium β decay
[Mainz, EPJC 73 (2013) 2323]
[Troitsk, JETPL 97 (2013) 67; JPG 41 (2014) 015001]

No Osc. excluded at 2.9σ
$(\Delta\chi^2/\text{NDF} = 11.4/2)$

$$7\,\text{cm} \lesssim \frac{L_{41}^{\text{osc}}}{E\,[\text{MeV}]} \lesssim 6\,\text{m} \qquad (2\sigma)$$

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]

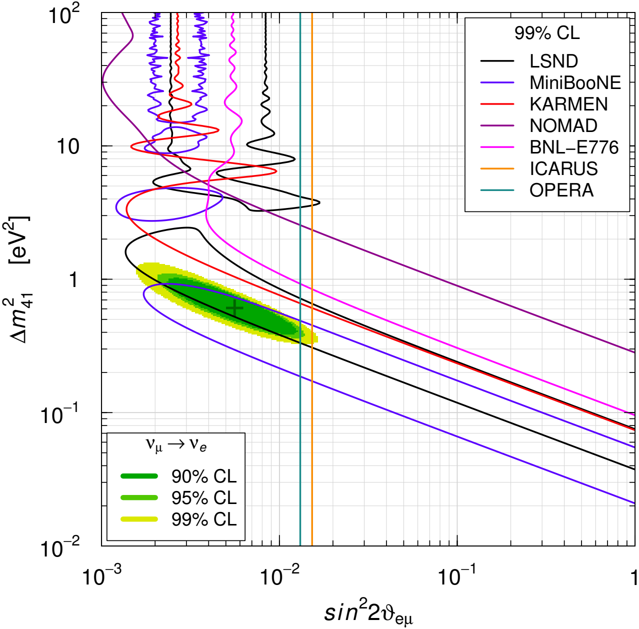
BEST (Baksan, Russia) $^{51}\text{Cr} \to \nu_e$
$L \simeq$ 5-12m [PRD 93 (2016) 073002]

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

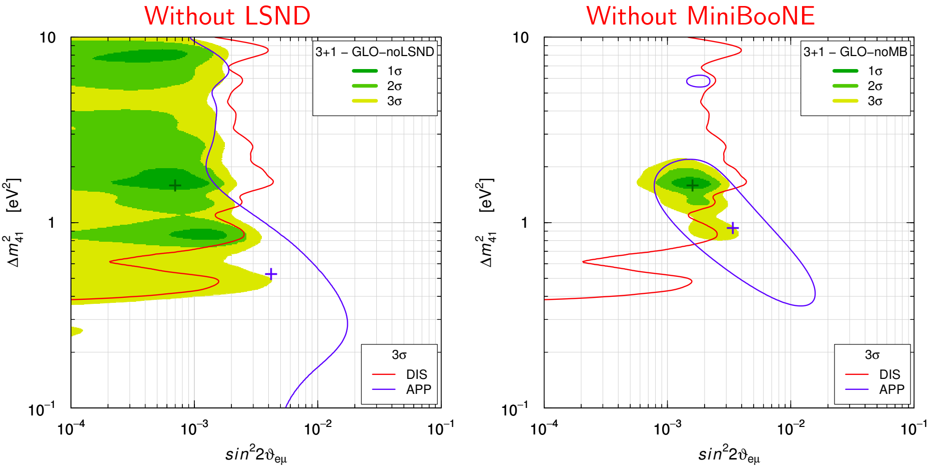
KATRIN (Karlsruhe, Germany) $^{3}\text{H} \to \bar{\nu}_e$
Mass Measurement [Mertens@TAUP2015]

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) $L \simeq$ 25m [Oh@WIN2015]

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



Origin of Appearance Signal



Without LSND	Without MiniBooNE
Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$	Best Fit: $\Delta m^2_{41} = 1.6\,\text{eV}^2$
$\lvert U_{e4}\rvert^2 = 0.022 \quad \lvert U_{\mu 4}\rvert^2 = 0.0080$	$\lvert U_{e4}\rvert^2 = 0.028 \quad \lvert U_{\mu 4}\rvert^2 = 0.014$
GoF $= 13\%$ $(\chi^2_{\text{min}}/\text{NDF} = 289.7/264)$	GoF $= 16\%$ $(\chi^2_{\text{min}}/\text{NDF} = 251.2/230)$
$\text{GoF}_{\text{PG}} = 0.5\%$ $(\chi^2/\text{NDF} = 10.7/2)$	$\text{GoF}_{\text{PG}} = 5\%$ $(\chi^2/\text{NDF} = 6.2/2)$
$\text{GoF}_{\text{null}} = 7\%$ $(\chi^2/\text{NDF} = 302.7/267)$	$\text{GoF}_{\text{null}} = 0.2\%$ $(\chi^2/\text{NDF} = 299.2/233)$
$\Delta\chi^2/\text{NDF} = 13.0/3$ $(\approx 2.8\sigma)$	$\Delta\chi^2/\text{NDF} = 48.1/3$ $(\approx 6.4\sigma)$