Global Status of Sterile Neutrino Scenarios

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NeuTel 2015
XVI International Workshop on Neutrino Telescopes

Venice, Italy

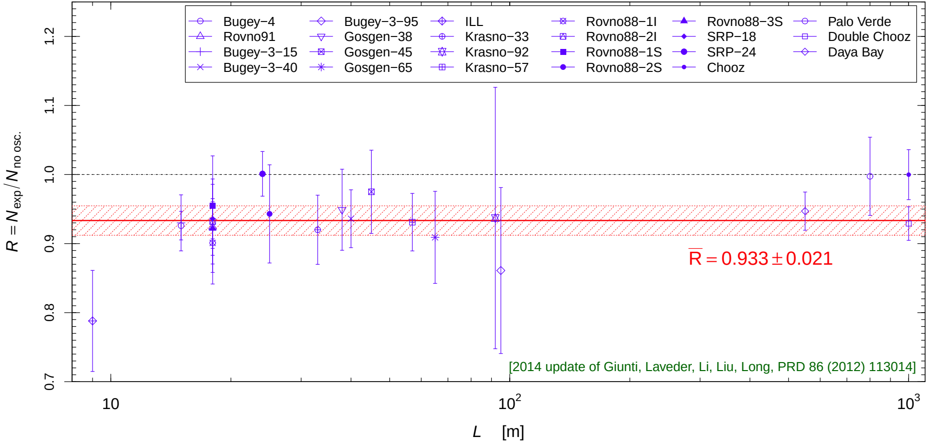
2-6 March 2015

Indications of SBL Oscillations Beyond 3ν

Reactor Electron Antineutrino Anomaly

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

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



$\bar{\nu}_e \to \bar{\nu}_e$ $L \sim 10 - 100\,\text{m}$ $E \sim 4\,\text{MeV}$

Nominal $\approx 3.1\sigma$ deficit $\Delta m^2 \gtrsim 0.5\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

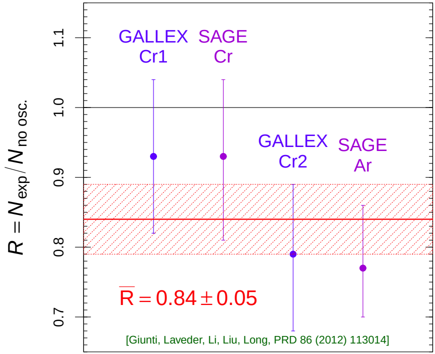
unknown $\bar{\nu}_e$ flux uncertainties: Daniel Dwyer talk

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



$\bar{\nu}_e \to \bar{\nu}_e$ $\quad E \sim 0.7\,\text{MeV}$

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

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

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\text{eV}^2 \quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

[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]

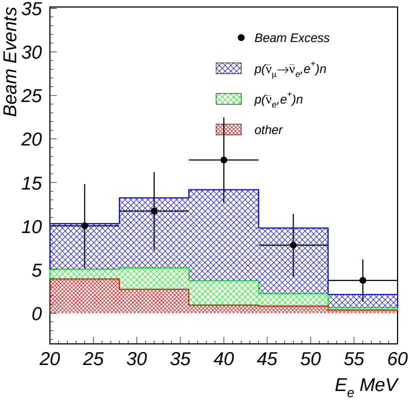
[Mention et al, PRD 83 (2011) 073006]

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

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 30\,\text{m}$ $\quad 20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



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

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

- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\text{m}]{} \bar{\nu}_e$

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

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

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

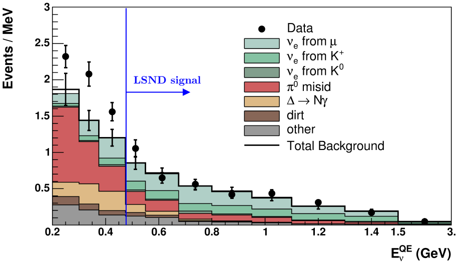
[PRD 65 (2002) 112001]

Nominal $\approx 3.8\sigma$ excess $\quad \Delta m^2 \gtrsim 0.2\,\text{eV}^2 \quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

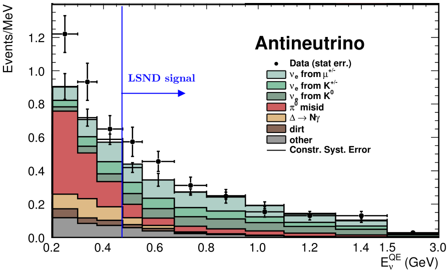
MiniBooNE

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

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

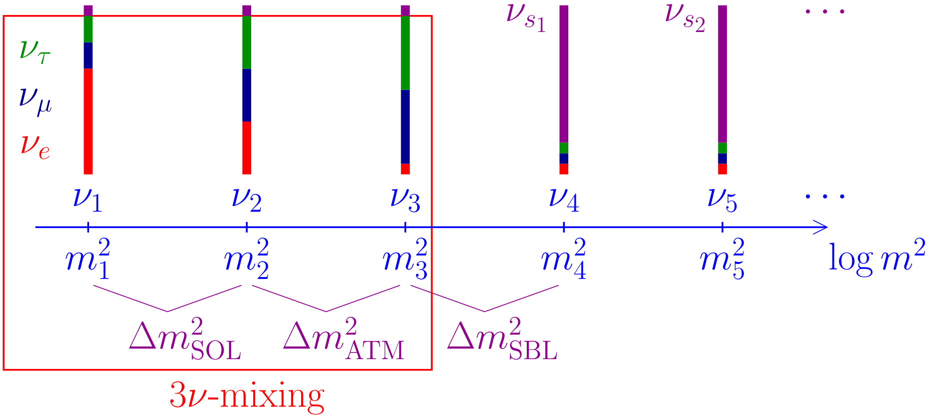


$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- 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!

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

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

Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos [Alexei Smirnov talk]
- Light anti-ν_R are light sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\begin{array}{ccccccccc} \Delta m^2_{21} & \ll & |\Delta m^2_{31}| & \ll & |\Delta m^2_{41}| & \leq & \ldots \\ \nu_1 & \nu_2 & & \nu_3 & & \nu_4 & \ldots \\ \nu_e & \nu_\mu & & \nu_\tau & & \nu_{s_1} & \ldots \end{array}$$

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\mathrm{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.

- Other possibilities (not incompatible):

  - Very light sterile neutrinos with mass scale $\ll 1\,\mathrm{eV}$: important for solar neutrino phenomenology

    [de Holanda, Smirnov, PRD 69 (2004) 113002; PRD 83 (2011) 113011]

    [Das, Pulido, Picariello, PRD 79 (2009) 073010]

    Recent Daya Bay constraints for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1}\,\mathrm{eV}^2$ [PRL 113 (2014) 141802]

  - Heavy sterile neutrinos with mass scale $\gg 1\,\mathrm{eV}$: could be Warm Dark Matter

    [Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151; Asaka, Shaposhnikov, PLB 620 (2005) 17; Asaka, Shaposhnikov, Kusenko, PLB 638 (2006) 401; Asaka, Laine, Shaposhnikov, JHEP 0606 (2006) 053, JHEP 0701 (2007) 091]

    [Reviews: Kusenko, Phys. Rept. 481 (2009) 1; Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191; Boyarsky, Iakubovskyi, Ruchayskiy, Phys. Dark Univ. 1 (2012) 136; Drewes, IJMPE, 22 (2013) 1330019]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

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

SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!
- May be observable in future high-precision solar exp. sensitive to Δm^2_{21} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004] and accelerator exp. sensitive to Δm^2_{31} [de Gouvea, Kelly, Kobach, arXiv:1412.1479]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

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

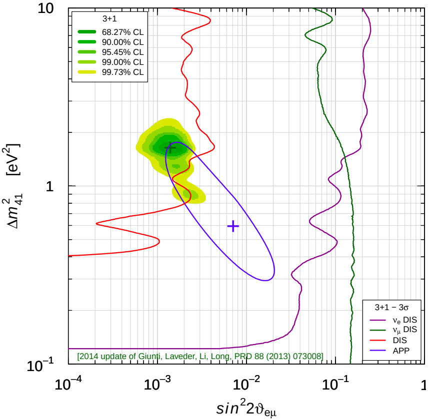
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

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

- Similar constraint in 3+2, 3+3, ..., 3+N_s !

Global 3+1 Fit

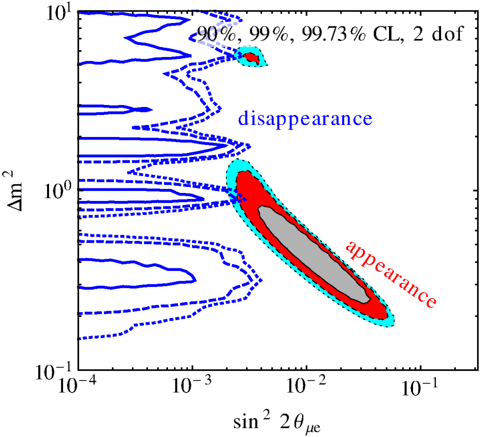
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



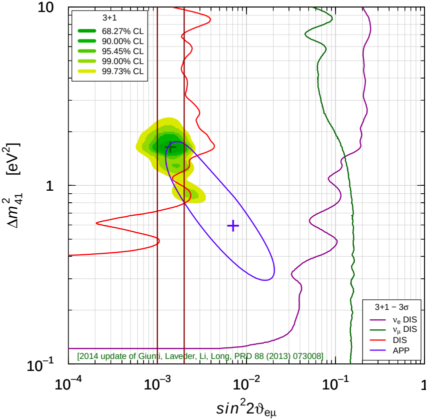
GoF = 19%

PGoF = 0.01%

[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

Global 3+1 Fit

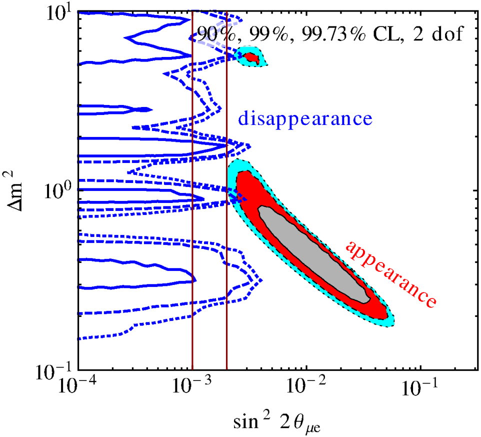
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



GoF = 19%

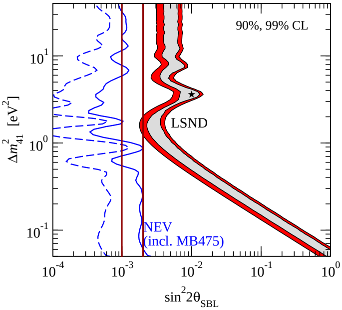
PGoF = 0.01%

[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

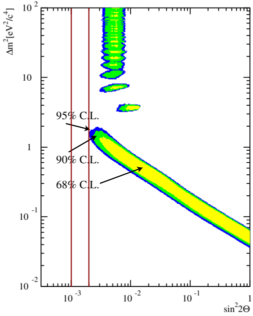
Different LSND Treatments

only LSND data from $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay at rest

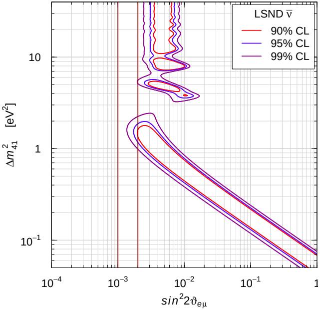
[Kopp, Machado, Maltoni, Schwetz]
[Maltoni, Schwetz,
PRD 76 (2007) 093005]



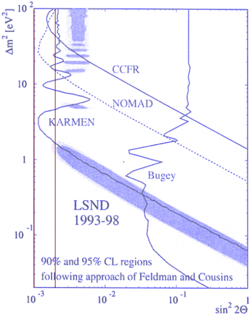
[Church, Eitel, Mills, Steidl,
PRD 66 (2002) 013001]



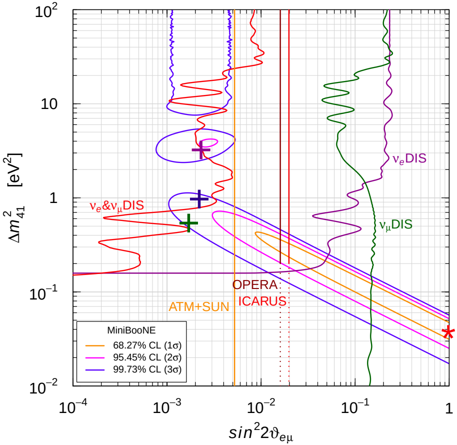
[Our Fit]
[improvement of Giunti, Laveder,
PRD 82 (2010) 093016]

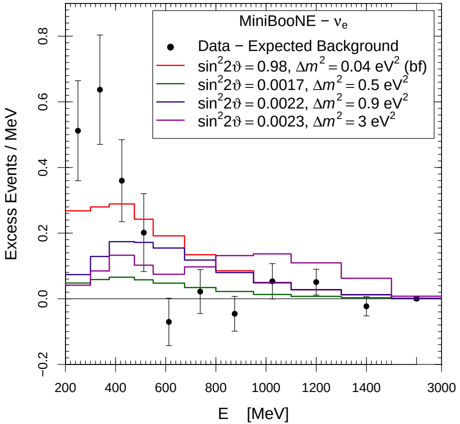


[Church (LSND),
NPA 663 (2000) 799]



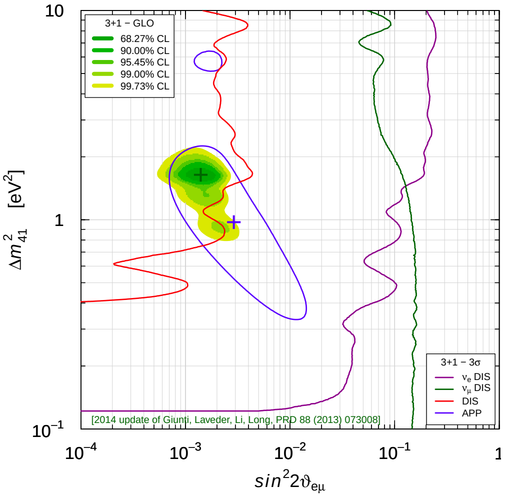
MiniBooNE Low-Energy Excess?





- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- MB low-energy excess is the main cause of bad APP-DIS PGoF = 0.1%
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Pragmatic 3+1 Fit



MiniBooNE $E > 475$ MeV

GoF $= 26\%$ PGoF $= 7\%$

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA (~~ν_s~~), ICARUS (~~ν_s~~), KARMEN (~~ν_s~~), NOMAD (~~ν_s~~), BNL-E776 (~~ν_s~~)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC (~~ν_s~~), Solar (~~ν_s~~)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (~~ν_s~~), MINOS (~~ν_s~~), Atmospheric (~~ν_s~~), MiniBooNE/SciBooNE (~~ν_s~~)

No Osc. nominally disfavored at $\approx 6.3\sigma$

$\Delta\chi^2/\text{NDF} = 47.7/3$

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\phi_{kj} = \Delta m^2_{kj} L / 4E$$

$$\eta = \arg[U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}]$$

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \phi_{41} + |U_{\alpha 5}|^2 \sin^2 \phi_{51}) - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54}$$

[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Jacques, Krauss, Lunardini, PRD 87 (2013) 083515; Conrad et al, AHEP 2013 (2013) 163897; Archidiacono et al, PRD 87 (2013) 125034; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

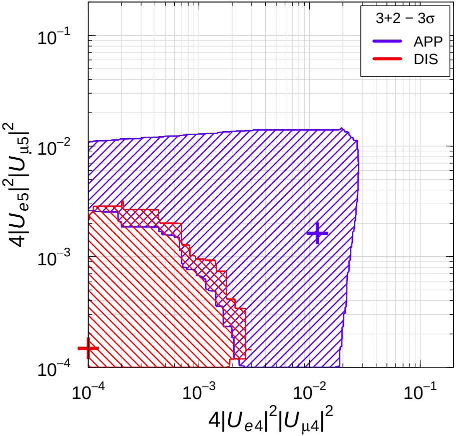
- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu 4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu 5}|^2, \eta$

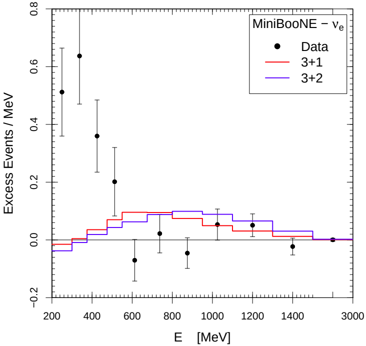
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

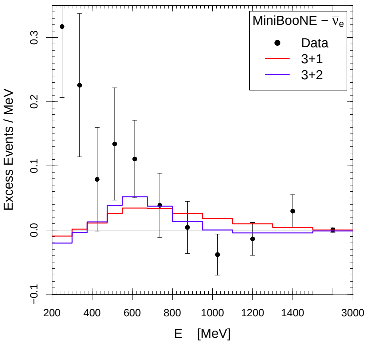
- Our Fit: 2014 update of Giunti, Laveder, Li, Long, PRD 88 (2013) 073008
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050

APP-DIS 3+2 Tension:



3+2 cannot fit MiniBooNE Low-Energy Excess





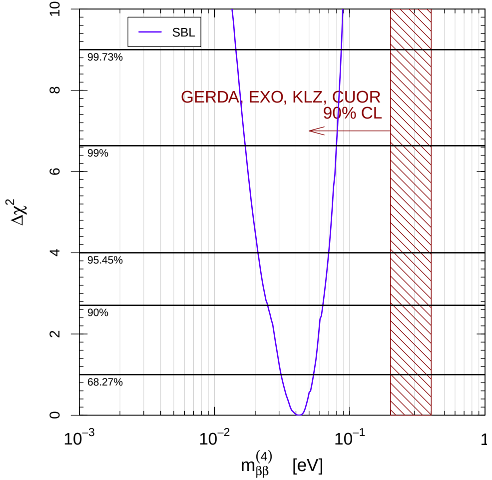
- Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- 3+2 fit of low-energy excess as bad as 3+1
- Claims that 3+2 can fit low-energy excess do not take into account constraints from other data
- Conclusion: forget 3+2! (at least until new data require it)

Future

- Many Exciting New Experiments and Projects with Reactor $\bar{\nu}_e$, Radioactive ν_e and $\bar{\nu}_e$ Sources [Thierry Lasserre talk], Accelerator $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ [talks by Claudio Montanari, Marzio Nessi, Mike Kirby, Ken Long, Mike Shaevitz, Masashi Yokoyama, Marcos Dracos]
- Effects of light sterile neutrinos should also be seen in:
  - 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, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]
  - High-energy atmospheric neutrinos (IceCube, Km3Net)
    [Goswami, PRD 55 (1997) 2931;
    Bilenky, Giunti, Grimus, Schwetz, PRD 60 (1999) 073007;
    Maltoni, Schwetz, Tortola, Valle, NPB 643 (2002) 321, PRD 67 (2003) 013011;
    Choubey, JHEP 12 (2007) 014;
    Razzaque, Smirnov, JHEP 07 (2011) 084, PRD 85 (2012) 093010;
    Gandhi, Ghoshal, PRD 86 (2012) 037301;
    Esmaili, Halzen, Peres, JCAP 1211 (2012) 041;
    Esmaili, Smirnov, JHEP 1312 (2013) 014;
    Rajpoot, Sahu, Wang, EPJC 74 (2014) 2936]
  - Supernova neutrinos
    [Caldwell, Fuller, Qian, PRD 61 (2000) 123005;
    Peres, Smirnov, NPB 599 (2001);
    Sorel, Conrad, PRD 66 (2002) 033009;
    Tamborra, Raffelt, Huedepohl, Janka, JCAP 1201 (2012) 013;
    Wu, Fischer, Martinez-Pinedo, Qian, PRD 89 (2014) 061303;
    Esmaili, Peres, Serpico, PRD 90 (2014) 033013]

Neutrinoless Double-β Decay

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 + |U_{e4}|^2\, e^{i\alpha_{41}}\, m_4$$



Pragmatic 3+1 Fit

[Giunti, Laveder, Li, Long, 2014]

$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

surprise:

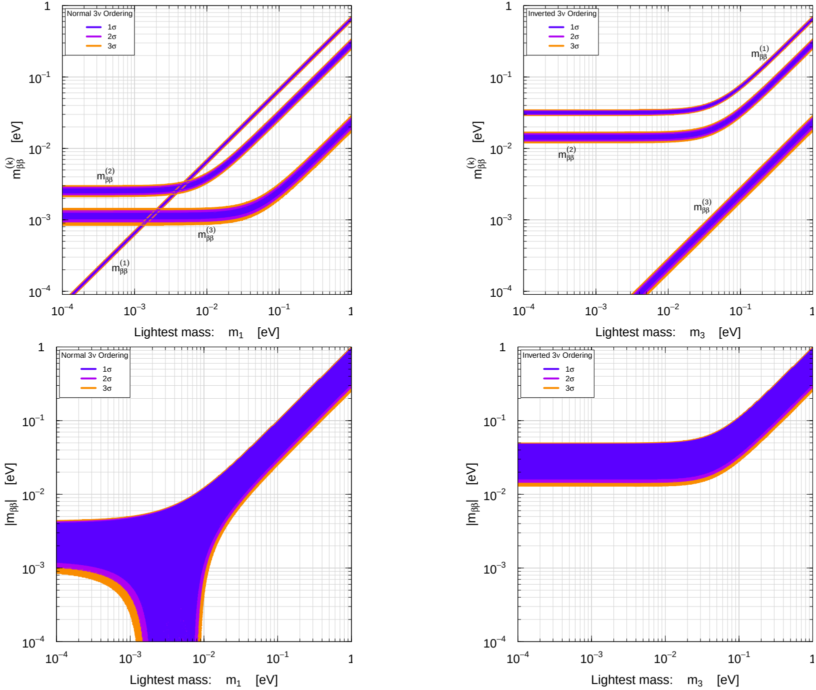
possible cancellation with $m_{\beta\beta}^{(3\nu)}$

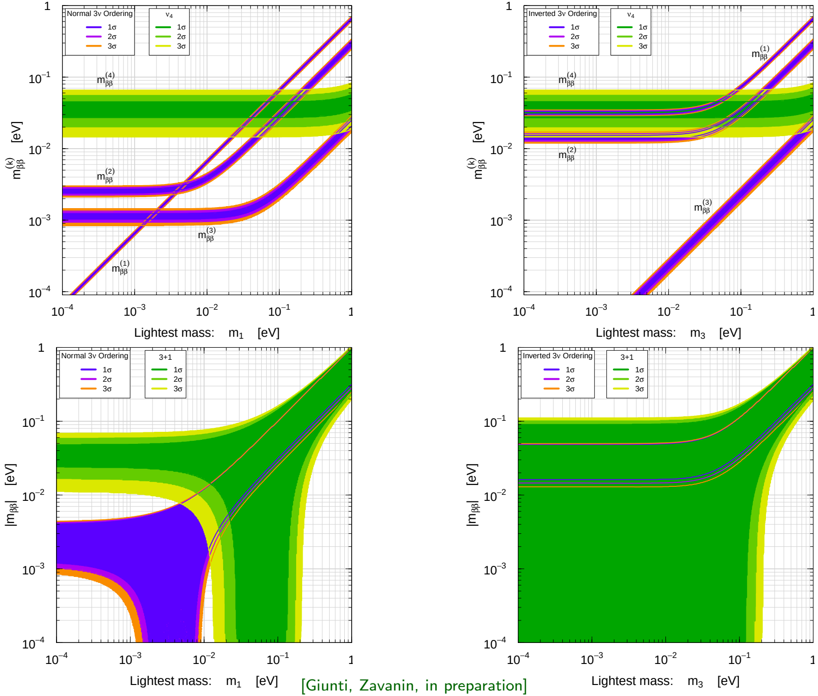
[Barry et al, JHEP 07 (2011) 091]

[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]


Normal 3ν Ordering
1σ
2σ
3σ
$m_{\beta\beta}^{(1)}$
$m_{\beta\beta}^{(2)}$
$m_{\beta\beta}^{(3)}$
$m_{\beta\beta}^{(k)}$ [eV]
Lightest mass: m_1 [eV]
Inverted 3ν Ordering
1σ
2σ
3σ
$m_{\beta\beta}^{(1)}$
$m_{\beta\beta}^{(2)}$
$m_{\beta\beta}^{(3)}$
$m_{\beta\beta}^{(k)}$ [eV]
Lightest mass: m_3 [eV]
Normal 3ν Ordering
1σ
2σ
3σ
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_1 [eV]
Inverted 3ν Ordering
1σ
2σ
3σ
$|m_{\beta\beta}|$ [eV]
Lightest mass: m_3 [eV]



[Giunti, Zavanin, in preparation]

Cosmology

- neutrinos in equilibrium in early Universe through weak interactions:

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N$$

$$\nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

- weak interactions freeze out $\Longrightarrow$ active $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino decoupling

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$

$$T_{\nu\text{-dec}} \sim 1\,\text{MeV} \qquad t_{\nu\text{-dec}} \sim 1\,\text{s}$$

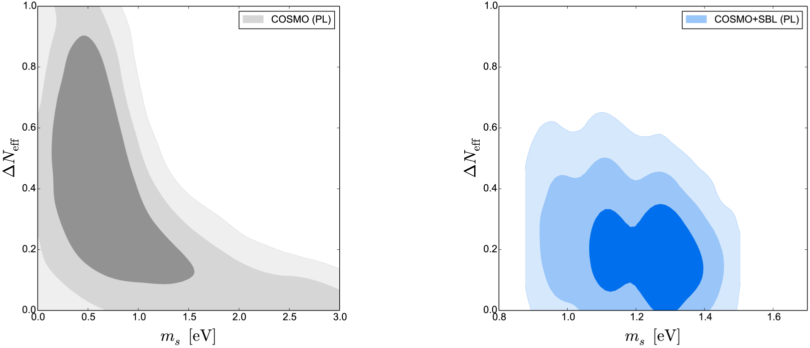
- sterile neutrinos can be produced by $\nu_{e,\mu,\tau} \to \nu_s$ oscillations before active neutrino decoupling $(t_{\nu\text{-dec}} \sim 1\,\text{s})$
- energy density of radiation before matter-radiation equality:

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma \qquad (t < t_{\text{eq}} \sim 6 \times 10^4\,\text{y})$$

$$N_{\text{eff}}^{\text{SM}} = 3.046 \qquad \Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$$

- sterile neutrino contribution: $\rho_s = (T_s/T_\nu)^4 \rho_\nu \quad \Rightarrow \quad \Delta N_{\text{eff}} = (T_s/T_\nu)^4$

- ν_s with $m_s = \simeq \sqrt{\Delta m^2_{41}} \sim 1\,\text{eV}$ become non-relativistic at $T_\nu \sim m_s/3$ ($t_{\nu_s\text{-nr}} \sim 2.0 \times 10^5$ y, before recombination at $t_{\text{rec}} \sim 3.8 \times 10^5$ y)



[Gariazzo, Giunti, Laveder, arXiv:1412.7405]

See also:
- [Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, JCAP 1406 (2014) 031]
- [Bergstrom, Gonzalez-Garcia, Niro, Salvado, JHEP 1410 (2014) 104]

Without oscillation data:
- [Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena, PRD 90 (2014) 043507]
- [Zhang, Li, Zhang, PLB 740 (2015) 359]
- [Dvorkin, Wyman, Rudd, Hu, PRD 90 (2014) 083503]
- [Zhang, Li, Zhang, EPJC 74 (2014) 2954]

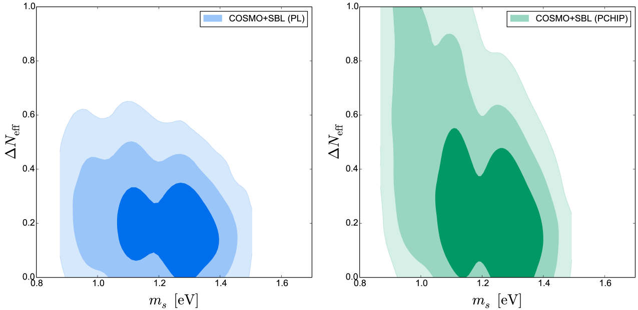
Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$

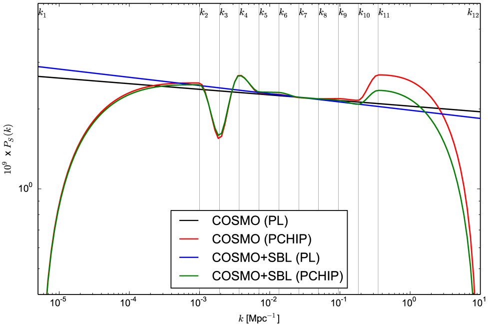
Sterile neutrinos are thermalized $(\Delta N_{\text{eff}} = 1)$ by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

Proposed mechanisms to avoid the tension:

- Large lepton asymmetry [Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano et al., PRD 87 (2013) 073006; Hannestad, Hansen, Tram, JCAP 1304 (2013) 032]
- Enhanced background potential due to interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, JCAP 1407 (2014) 042; Ko, Tang, PLB 739 (2014) 62; Archidiacono, Hannestad, Hansen,Tram, arXiv:1404.5915; Mirizzi, Mangano, Pisanti, Saviano, PRD 90 (2014) 113009, PRD 91 (2015) 025019; Tang, arXiv:1501.00059]
- A larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]
- Free primordial power spectrum of scalar fluctuations (Inflationary Freedom) [Gariazzo, Giunti, Laveder, arXiv:1412.7405]

Inflationary Freedom





Conclusions

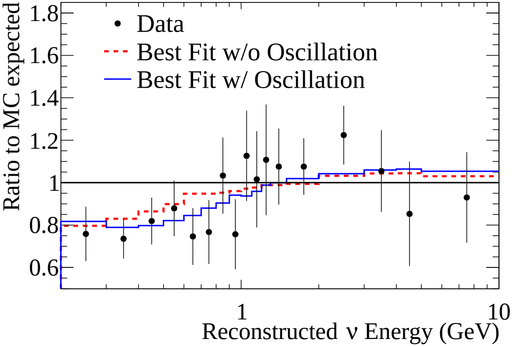
- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: unknown systematic uncertainties (Reactor $\bar{\nu}_e$ flux).
  - Many promising projects to test unambiguously short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources.
  - Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - Not seen by other SBL $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu4}| > 0$? $\Longrightarrow$ $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 > 0$
- Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.
- 3+2 is not needed: same APP-DIS tension as 3+1 and no evidence of CP violation.
- Cosmology:
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.
  - Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.

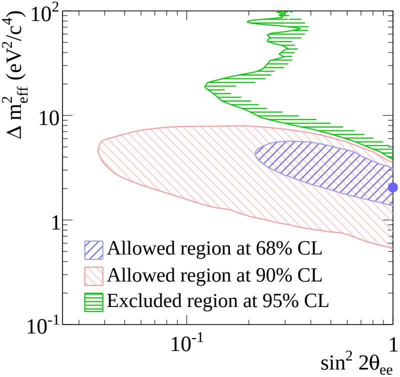
Backup Slides

T2K Near Detector ν_e Disappearance

[arXiv:1410.8811]

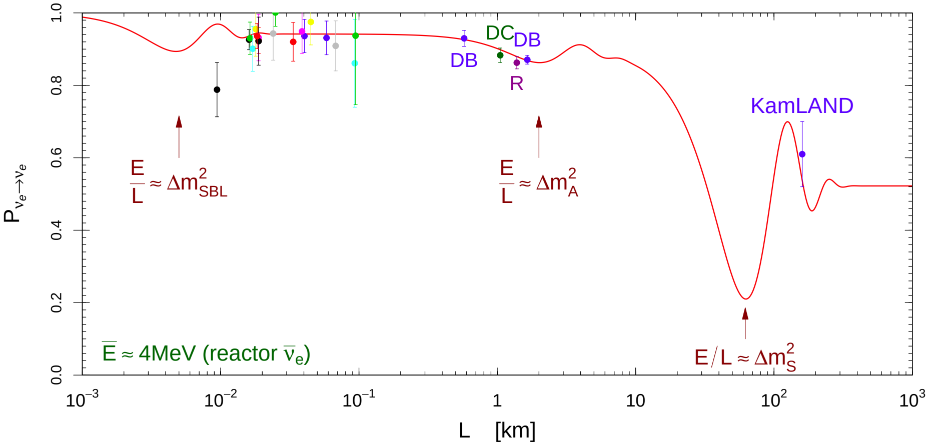
$\nu_e \to \nu_e$ $\quad L \simeq 280\,\mathrm{m}$ $\quad E \sim 500\,\mathrm{MeV}$





No Oscillations: $\chi^2_{\mathrm{min}}/\mathrm{NDF} = 45.86/51$ $\quad \Delta\chi^2/\mathrm{NDF} = 3.7/2$

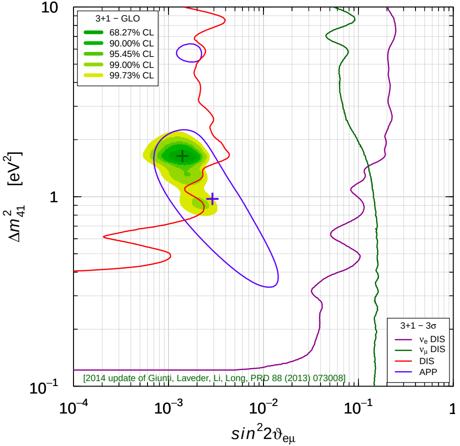
Oscillations: $\chi^2_{\mathrm{min}}/\mathrm{NDF} = 42.16/49$ $\quad \approx 1.4\sigma$ deviation



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

MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE

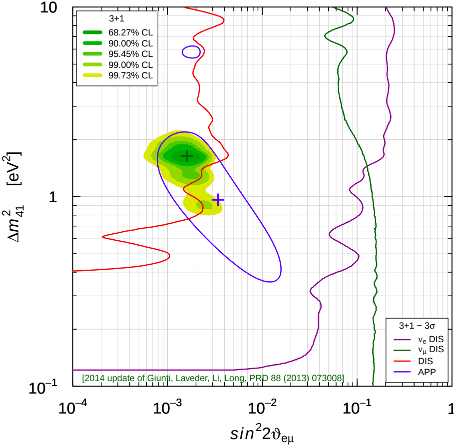


GoF = 26%   PGoF = 7%

No Osc. nominally disfavored

at $\approx 6.3\sigma$ ($\Delta\chi^2$/NDF = 47.7/3)

without MiniBooNE

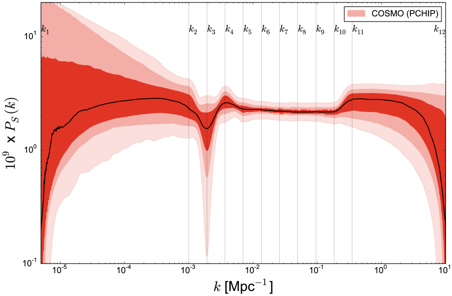


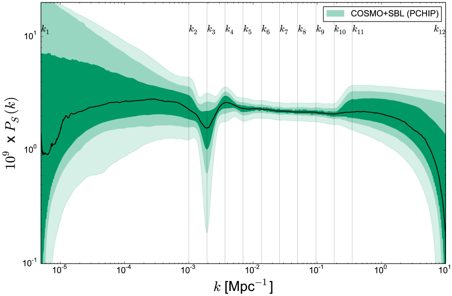
GoF = 16%   PGoF = 5%

No Osc. nominally disfavored

at $\approx 6.4\sigma$ ($\Delta\chi^2$/NDF = 48.1/3)

Without LSND: No Osc. nominally disfavored at $\approx 2.6\sigma$ ($\Delta\chi^2$/NDF = 11.4/3)





[Gariazzo, Giunti, Laveder, arXiv:1412.7405]