

Light Sterile Neutrinos

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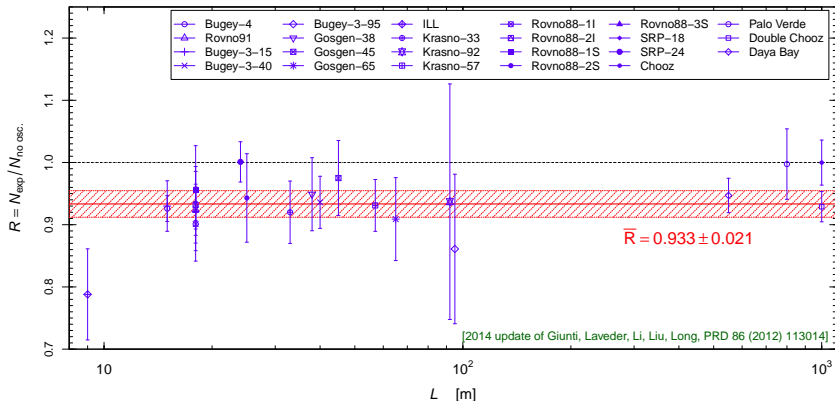
Indications of SBL Oscillations Beyond 3ν

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]



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

$$L \sim 10 - 100 \text{ m}$$

$$E \sim 4 \text{ MeV}$$

Nominal $\approx 3.1\sigma$ deficit

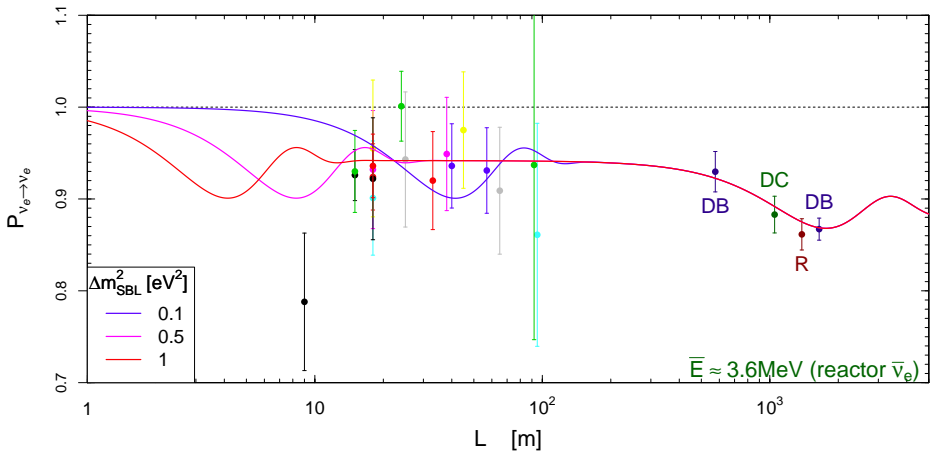
$$\Delta m^2 \gtrsim 0.5 \text{ eV}^2$$

$$(\gg \Delta m_A^2 \gg \Delta m_S^2)$$

[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]

Problem: unknown $\bar{\nu}_e$ flux uncertainties?

[Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501; Dwyer, Langford, PRL 114 (2015) 012502]

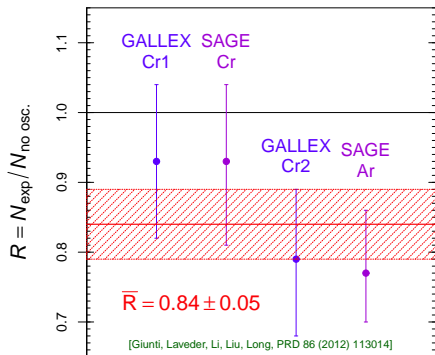


Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



$\bar{\nu}_e \rightarrow \bar{\nu}_e$ $E \sim 0.7 \text{ MeV}$

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

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

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1 \text{ eV}^2$ ($\gg \Delta m_A^2 \gg \Delta m_S^2$)

[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]

▶ ${}^3\text{He} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + {}^3\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

▶ $E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2 \text{ keV}$ [Frekers et al., PLB 722 (2013) 233]

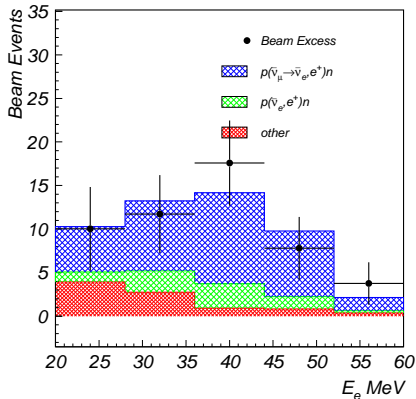
LSND

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

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

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

$$20 \text{ MeV} \leq E \leq 60 \text{ MeV}$$



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

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

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

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

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

- ▶ 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

$$\Delta m^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_{A}^2 \gg \Delta m_{S}^2)$$

MiniBooNE

$L \simeq 541 \text{ m}$

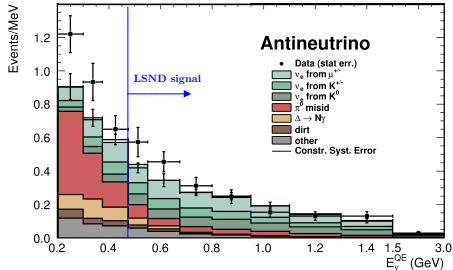
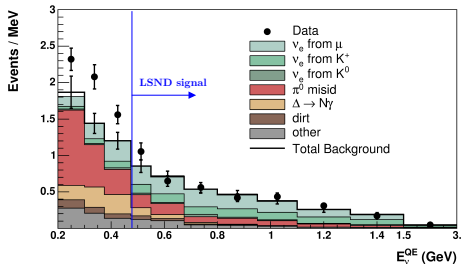
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

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

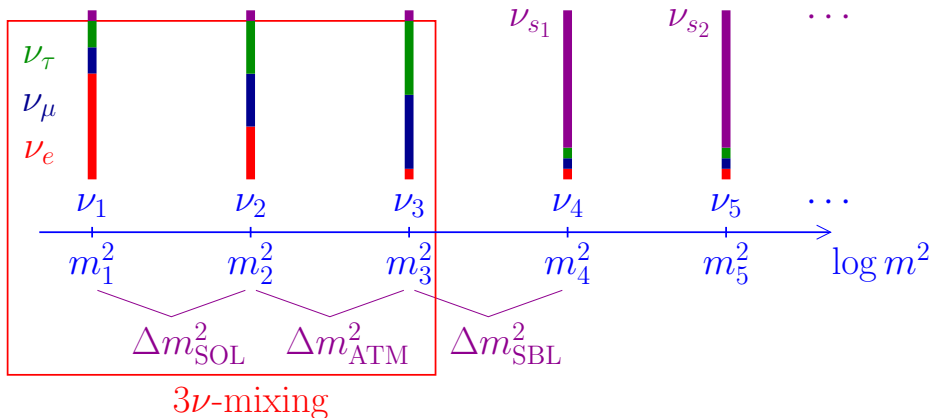
[PRL 110 (2013) 161801]



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

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

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** **Neutrino Portal** [A. Smirnov, arXiv:1502.04530]
- ▶ Light anti- ν_R are **light sterile neutrinos**

$$\nu_R^c \rightarrow \nu_{sL} \quad (\text{left-handed})$$

- ▶ Sterile means **no standard model interactions**
[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) 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:

$$\Delta m_{21}^2 \ll |\Delta m_{31}^2| \ll |\Delta m_{41}^2| \leq \dots$$

ν_1	ν_2	ν_3	ν_4	\dots
ν_e	ν_μ	ν_τ	ν_{s1}	\dots

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

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

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

Perturbation of 3 ν 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!
- ▶ Observable in LBL accelerator exp. sensitive to Δm_{ATM}^2 [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017] and solar exp. sensitive to Δm_{SOL}^2 [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- ▶ Amplitude of ν_e disappearance:

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

- ▶ Amplitude of ν_μ disappearance:

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

- ▶ Amplitude of $\nu_\mu \rightarrow \nu_e$ transitions:

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

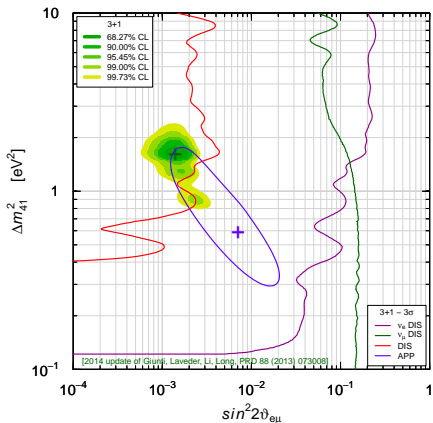
- ▶ Upper bounds on ν_e and ν_μ disappearance \Rightarrow strong limit on $\nu_\mu \rightarrow \nu_e$

[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

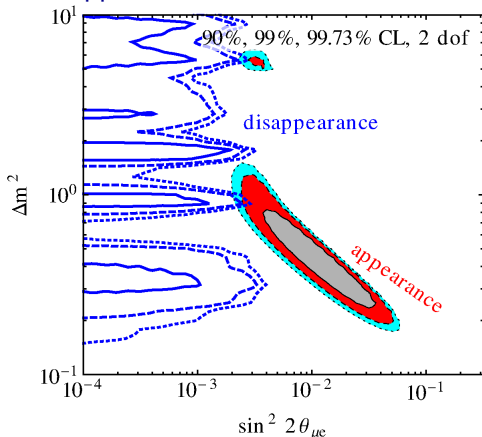
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz

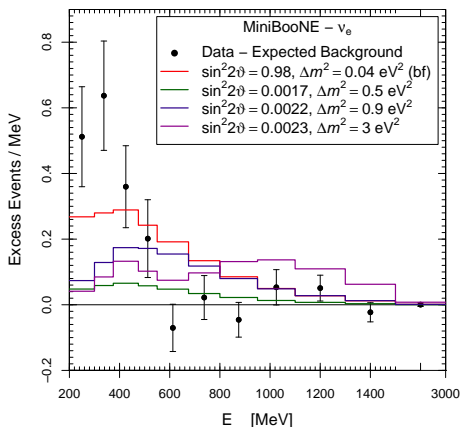
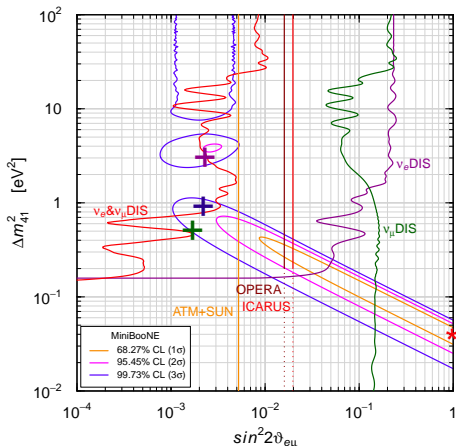


GoF = 19%

PGoF = 0.01%

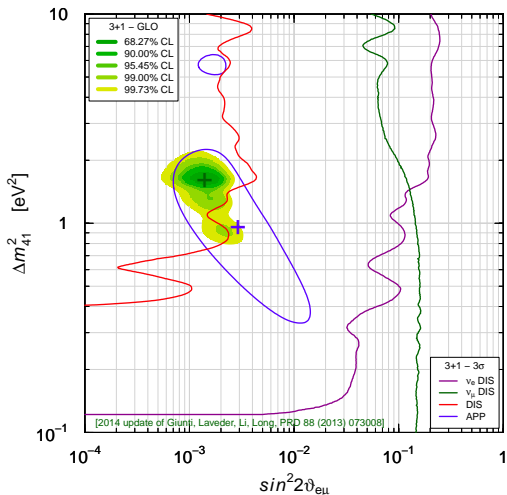
[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

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 $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:
 LSND (ν_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), $\nu_e C$ (~~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

$$\Delta_{kj} = \Delta m_{kj}^2 L / 4E$$

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

$$P_{\nu_{\mu} \rightarrow \nu_e}^{\text{SBL}(-)} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \Delta_{41} + 4|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \Delta_{51} + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin \Delta_{41} \sin \Delta_{51} \cos(\Delta_{54}^{(+)} - \eta)$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{\text{SBL}(-)} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \Delta_{41} + |U_{\alpha 5}|^2 \sin^2 \Delta_{51}) - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \Delta_{54}$$

[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

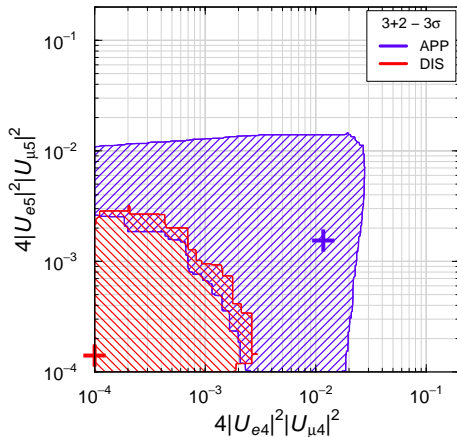
▶ Bad: Two massive sterile neutrinos at the eV scale!

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

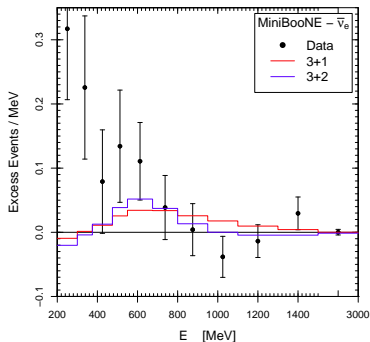
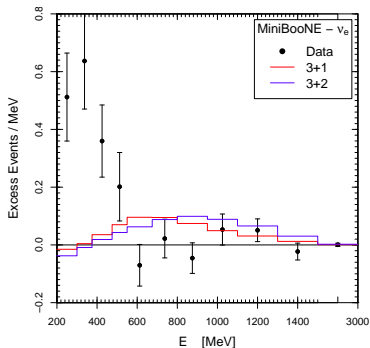
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

- ▶ 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:

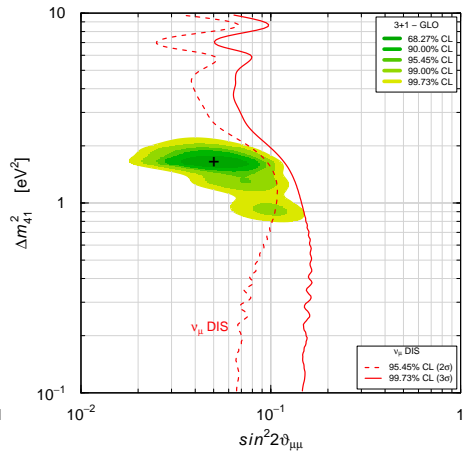
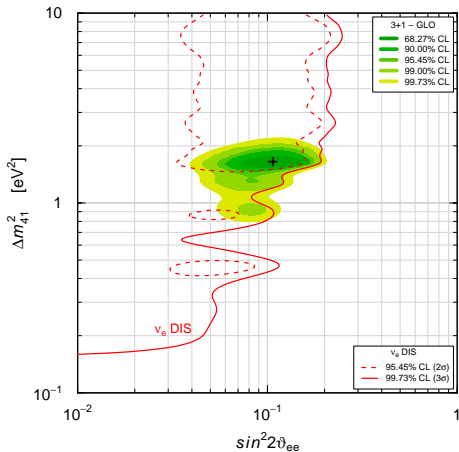


3+2 cannot fit MiniBooNE Low-Energy Excess



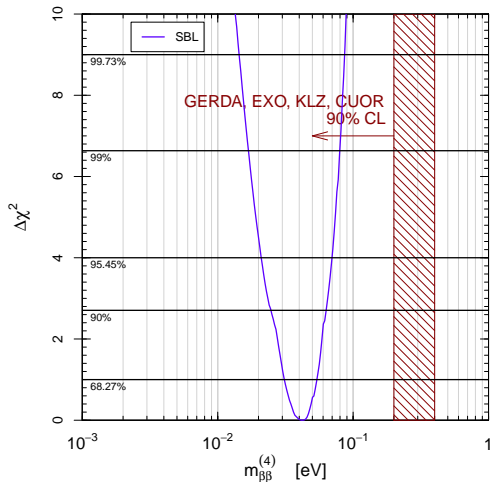
- ▶ Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- ▶ 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- ▶ 3+2 fit of low-energy excess as bad as 3+1
- ▶ Claims that 3+2 can fit low-energy excess do not take into account constraints from other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

ν_e and ν_μ Disappearance



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]

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

$$m_1 \ll m_4$$



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

surprise:

possible cancellation

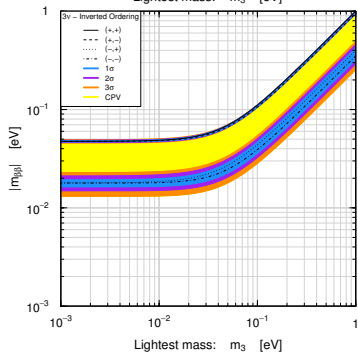
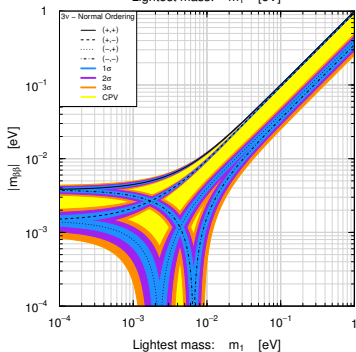
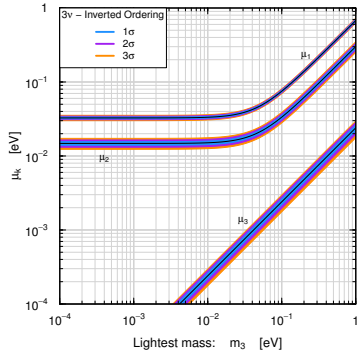
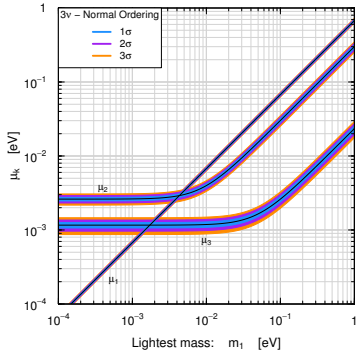
with $m_{\beta\beta}^{(3\nu)}$

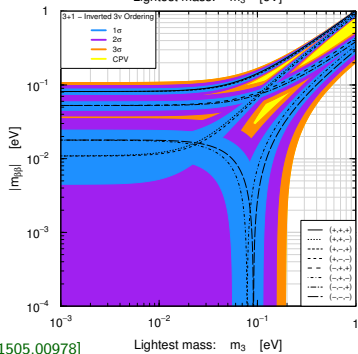
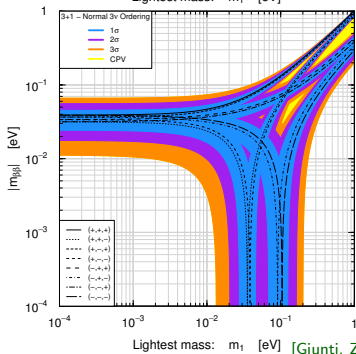
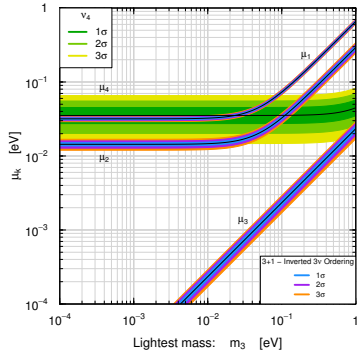
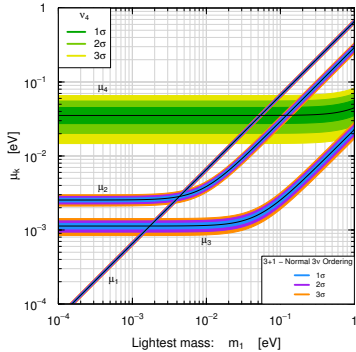
[Barry et al, JHEP 07 (2011) 091]

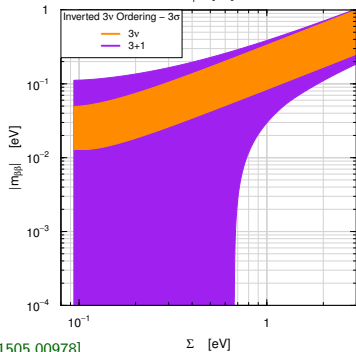
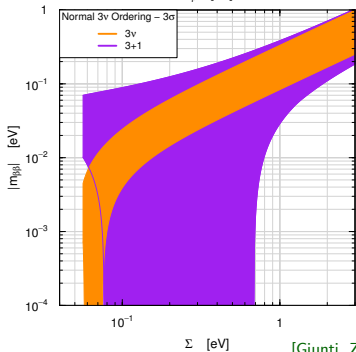
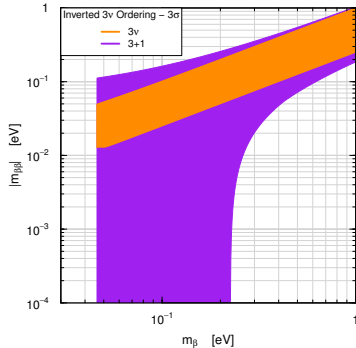
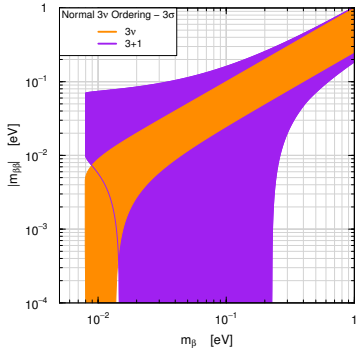
[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

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



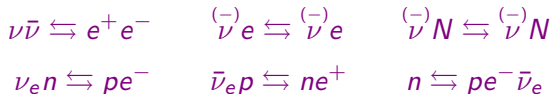




[Giunti, Zavanin, arXiv:1505.00978]

Cosmology

- ▶ neutrinos in equilibrium in early Universe through weak interactions:



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

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

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

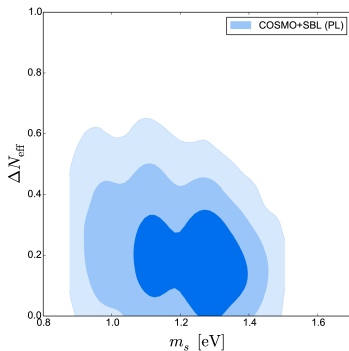
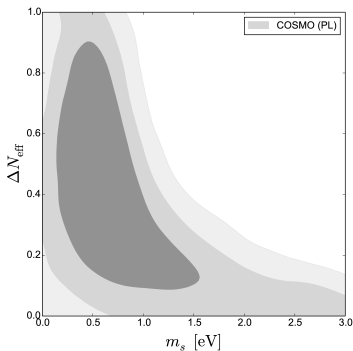
- ▶ sterile neutrinos can be produced by $\nu_{e,\mu,\tau} \rightarrow \nu_s$ oscillations before active neutrino decoupling ($t_{\nu\text{-dec}} \sim 1 \text{ s}$)
- ▶ energy density of radiation before matter-radiation equality:

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

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

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

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



[Gariazzo, Giunti, Laveder, JCAP 1504 (2015) 023]

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 $m_s \approx 1 \text{ eV}$

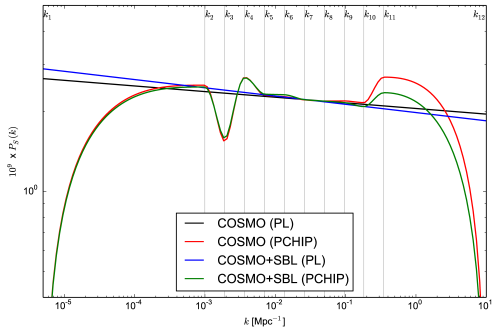
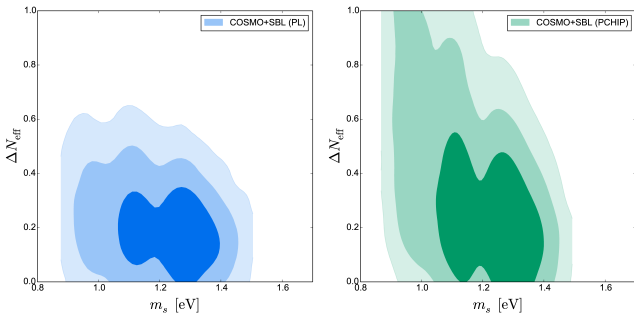
Sterile neutrinos are thermalized ($\Delta N_{\text{eff}} = 1$) by active-sterile oscillations before neutrino decoupling

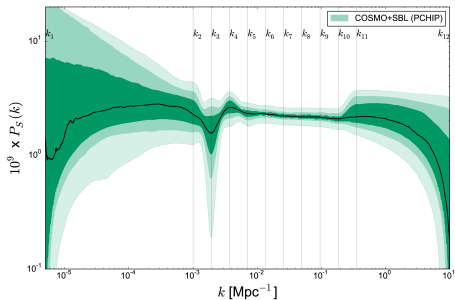
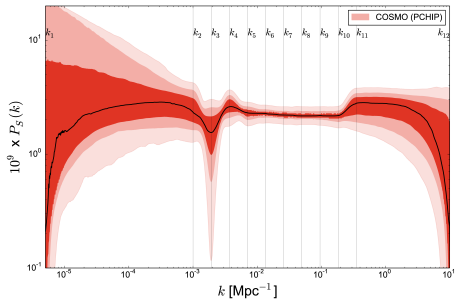
[Dolgov, Villante, NPB 679 (2004) 261]

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, PRD 91 (2015) 065021; 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, JCAP 1504 (2015) 023]

Inflationary Freedom





[Gariazzo, Giunti, Laveder, JCAP 1504 (2015) 023]

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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ LSND Signal:
 - ▶ Not seen by other SBL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ experiments.
 - ▶ MiniBooNE experiment has been inconclusive.
 - ▶ Experiments with near detector are needed to check LSND signal!
 - ▶ If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\implies \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 > 0$
- ▶ 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 $m_s \approx 1$ eV.
 - ▶ Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.