

Phenomenology of Light Sterile Neutrinos

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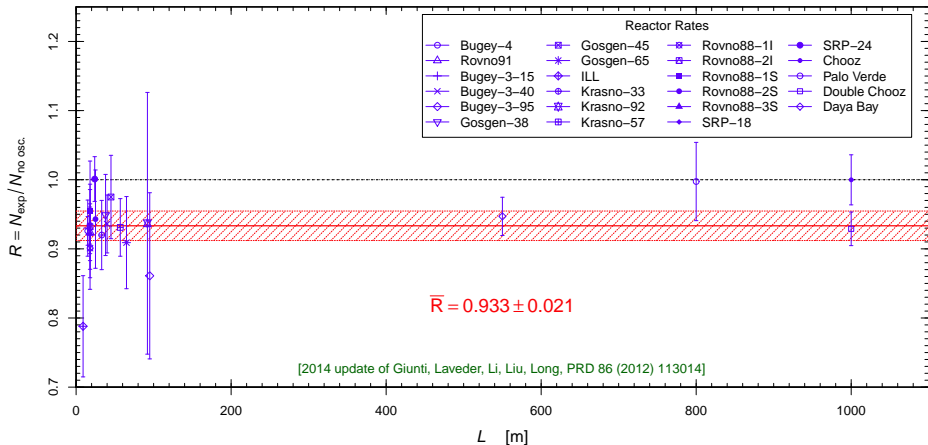
Indications of SBL Oscillations Beyond 3ν

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]



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

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

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

$\sim 3.1\sigma$ deficit

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

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

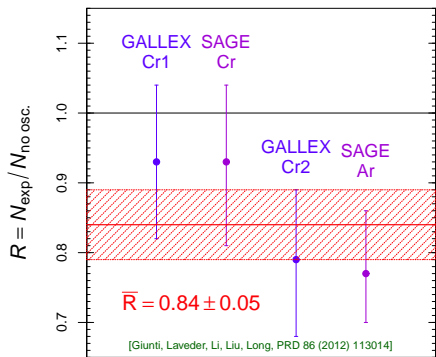
[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



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

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

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

$\sim 2.9\sigma$ 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]

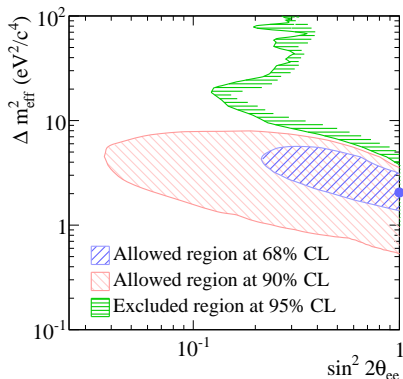
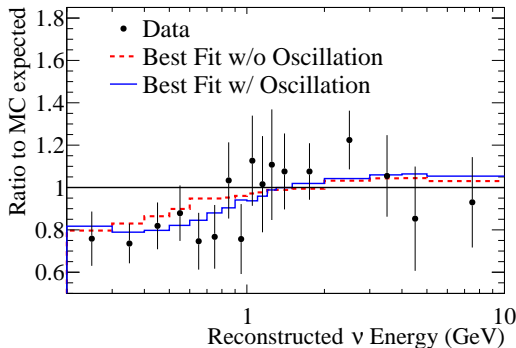
T2K Near Detector ν_e Disappearance

[arXiv:1410.8811]

$\nu_e \rightarrow \nu_e$

$L \simeq 280$ m

$E \sim 500$ MeV



No Oscillations: $\chi^2_{\text{min}}/\text{NDF} = 45.86/51$

Oscillations: $\chi^2_{\text{min}}/\text{NDF} = 42.16/49$

$\Delta\chi^2/\text{NDF} = 3.7/2$

$\sim 1.4\sigma$ deviation

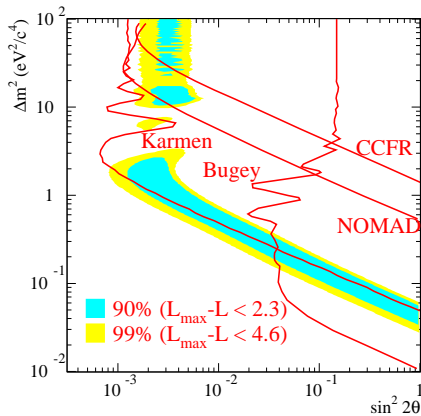
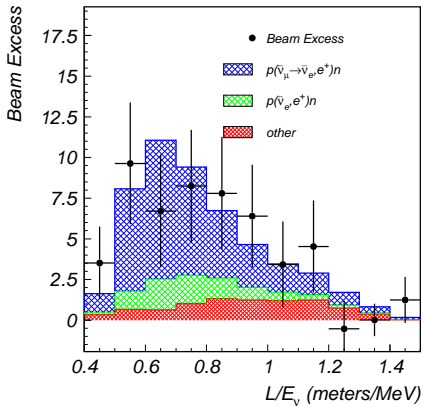
LSND

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

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

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

$$20 \text{ MeV} \leq E \leq 200 \text{ MeV}$$



3.8 σ excess

$$\Delta m^2 \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m_A^2 \gg \Delta m_S^2)$$

MiniBooNE

$L \simeq 541 \text{ m}$

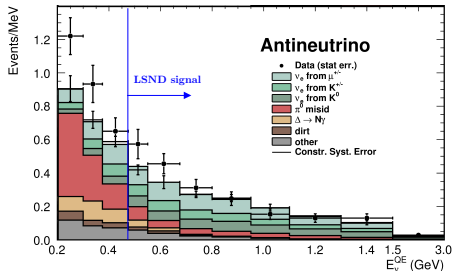
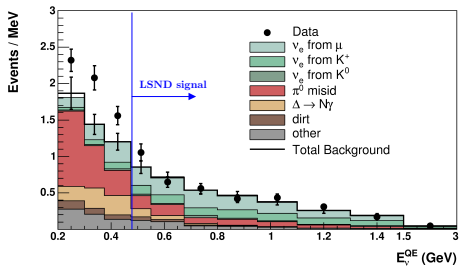
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

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

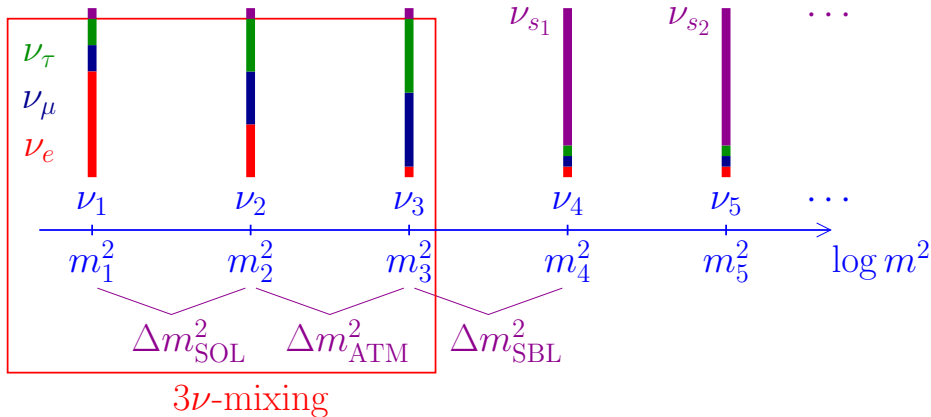
[PRL 110 (2013) 161801]



- ▶ Purpose: check LSND signal.
- ▶ Different L and E .
- ▶ Similar L/E (oscillations).
- ▶ 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**
- ▶ In extensions of SM neutrinos can mix with non-SM fermions
- ▶ SM doublets: $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $\tilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$ $\xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{1}{\sqrt{2}} \begin{pmatrix} \nu \\ 0 \end{pmatrix}$
- ▶ SM singlet: $\overline{L}_L \tilde{\Phi} = (\overline{\nu}_L \quad \overline{\ell}_L) \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} = \overline{\nu}_L \phi^0 + \overline{\ell}_L \phi^-$ $\xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{v}{\sqrt{2}} \overline{\nu}_L$
- ▶ SM singlet $\overline{L}_L \tilde{\Phi}$ can couple to new singlet (**sterile**) fermion field ν_R (**right-handed neutrino**) related to physics beyond the SM
- ▶ $\mathcal{L}^D \sim \overline{L}_L \tilde{\Phi} \nu_R \xrightarrow[\text{Breaking}]{\text{Symmetry}} \frac{v}{\sqrt{2}} \overline{\nu}_L \nu_R$ **Dirac mass term**
- ▶ Surprise: **Majorana mass term** $\mathcal{L}^M \sim \overline{\nu}_R^c \nu_R$ allowed by SM symmetries
- ▶ In general: **Dirac mass term** $\sim \overline{L}_L \tilde{\Phi} \nu_R$ + **Majorana mass term** $\sim \overline{\nu}_R^c \nu_R$
- ▶ Diagonalization of mass matrix $\sim \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \implies 2$ massive Majorana neutrinos
- ▶ If mass splitting is small we have active-sterile $\nu_L \rightarrow \nu_R^c$ oscillations

- ▶ 3 left-handed + N_s right-handed fields $\implies (3 + N_s) \times (3 + N_s)$ mass matrix
- ▶ Diagonalization $\implies 3 + N_s$ massive Majorana neutrinos
- ▶ 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

- ▶ In this talk I consider sterile neutrinos with mass scale $\sim 1 \text{ eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.
- ▶ Other possibilities (not incompatible):
 - ▶ **Very light sterile neutrinos** with mass scale $\ll 1 \text{ eV}$: important for solar neutrino phenomenology
 - [Das, Pulido, Picariello, PRD 79 (2009) 073010]
 - [de Holanda, Smirnov, PRD 83 (2011) 113011]

Recent Daya Bay constraints for $10^{-3} \lesssim \Delta m^2 \lesssim 10^{-1} \text{ eV}^2$

[PRL 113 (2014) 141802, arXiv:1407.7259]

- ▶ **Heavy sterile neutrinos** with mass scale $\gg 1 \text{ eV}$: could be Warm Dark Matter
 - [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

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


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

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

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

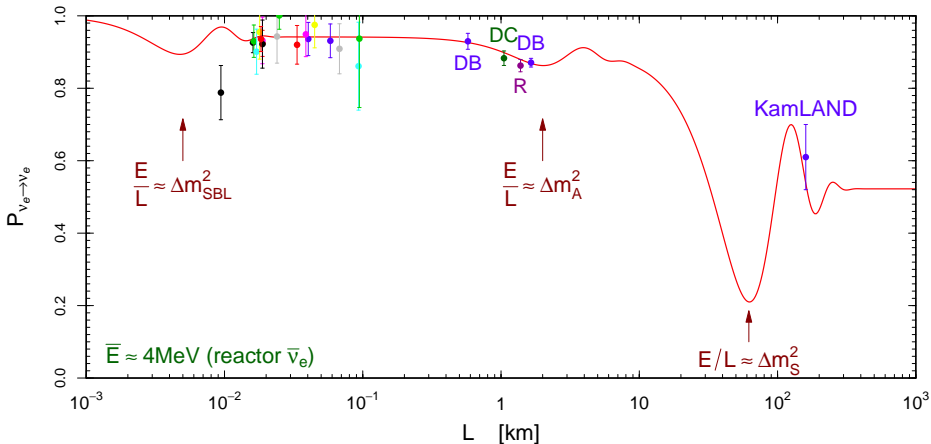
Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1$, $|U_{\mu 4}|^2 \ll 1$, $|U_{\tau 4}|^2 \ll 1$, $|U_{s4}|^2 \simeq 1$

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



 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_{21}^2 [Long, Li, Giunti, PRD 87, 113004 (2013) 113004] and accelerator exp. sensitive to Δm_{31}^2 [de Gouvea, Kelly, Kobach, arXiv:1412.1479]



$$P_{\nu_e \rightarrow \nu_e}^{(-)(-)\text{LBL}} \simeq 1 - \frac{1}{2} \sin^2 2\vartheta_{14} - \cos^4 \vartheta_{14} \sin^2 2\vartheta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

3+1: Appearance vs Disappearance

- ▶ ν_e disappearance experiments:

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

- ▶ ν_μ disappearance experiments:

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

- ▶ $\nu_\mu \rightarrow \nu_e$ experiments:

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

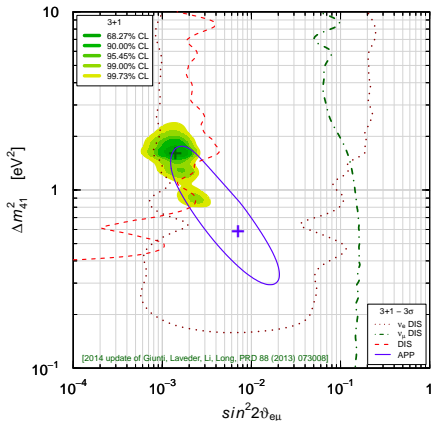
- ▶ Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \implies$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[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

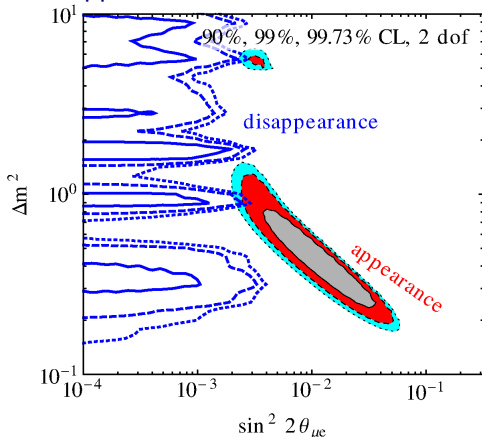
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



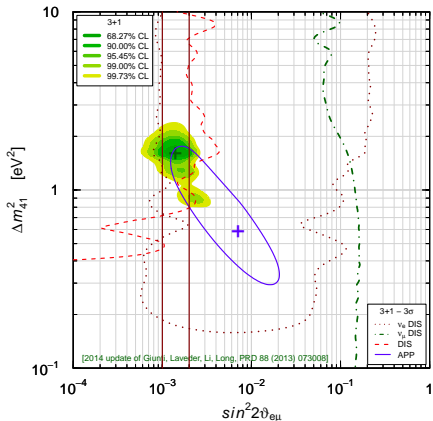
GoF = 19%

PGoF = 0.01%

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

Global 3+1 Fit

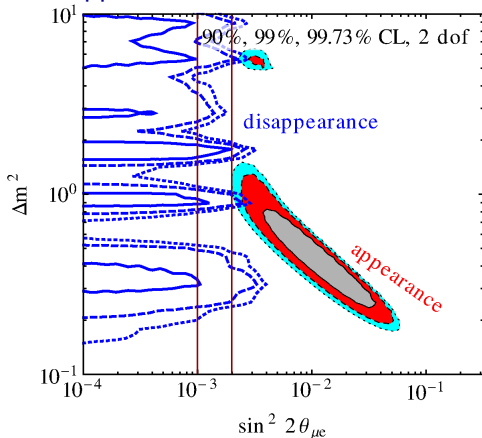
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



GoF = 19%

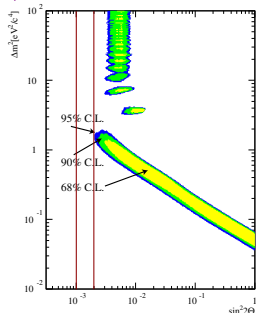
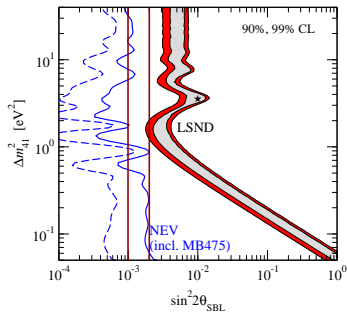
PGoF = 0.01%

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

Different LSND Treatments

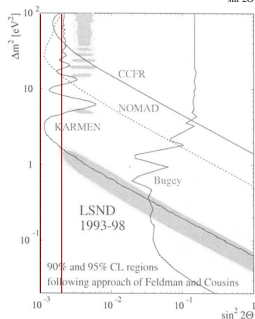
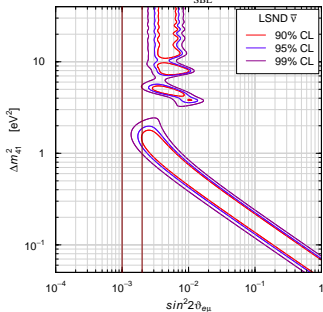
only LSND data from $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ decay at rest

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



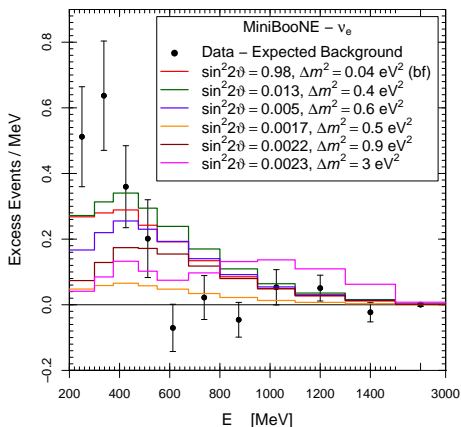
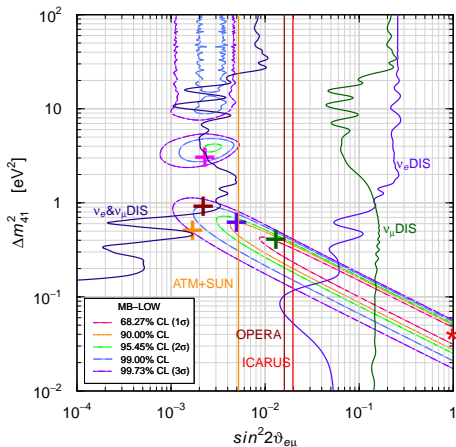
[Church, Eitel, Mills, Steidl,
 PRD 66 (2002) 013001]

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



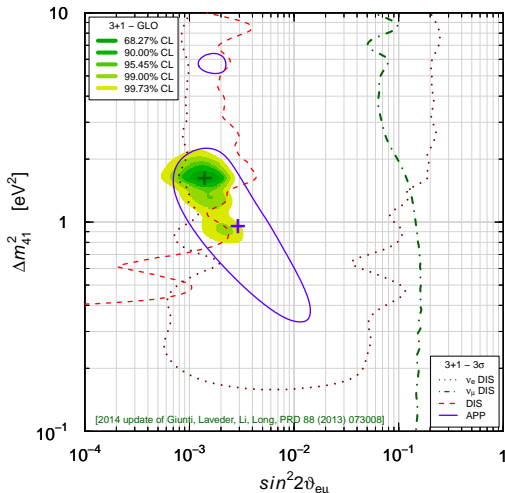
[Church (LSND),
 NPA 663 (2000) 799]

MiniBooNE Low-Energy Excess?



- ▶ No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$
- ▶ APP-DIS PGoF = 0.1%
- ▶ Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- ▶ Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Pragmatic 3+1 Fit



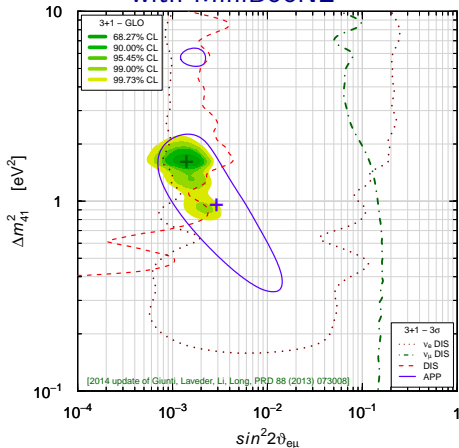
MiniBooNE $E > 475$ MeV
 GoF = 26% PGoF = 7%

- ▶ 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), ν_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. disfavored at 6.3σ
 $\Delta\chi^2/\text{NDF} = 47.7/3$

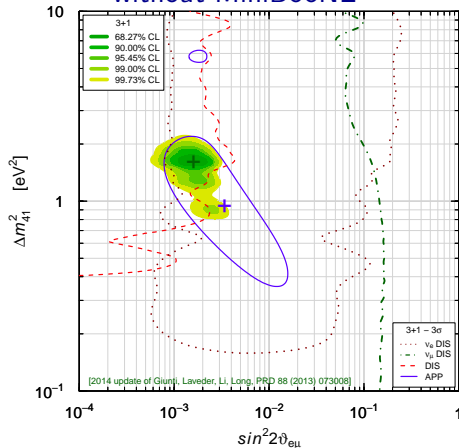
MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE



GoF = 26% PGoF = 7%
No Osc. disfavored at 6.3σ
 $\Delta\chi^2/\text{NDF} = 47.7/3$

without MiniBooNE



GoF = 16% PGoF = 5%
No Osc. disfavored at 6.4σ
 $\Delta\chi^2/\text{NDF} = 48.1/3$

Without LSND: No Osc. disfavored only at 2.6σ ($\Delta\chi^2/\text{NDF} = 11.4/3$)

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

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

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

[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; 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]

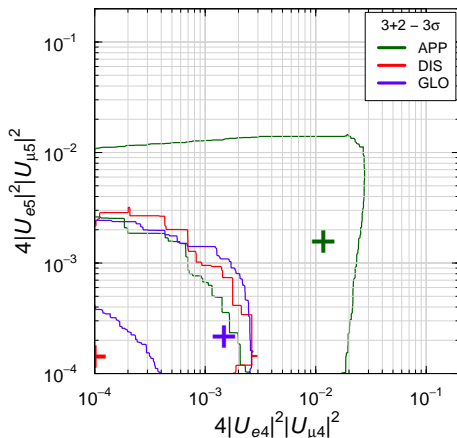
- ▶ Good: CP violation
- ▶ Bad: Two massive sterile neutrinos at the eV scale!

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

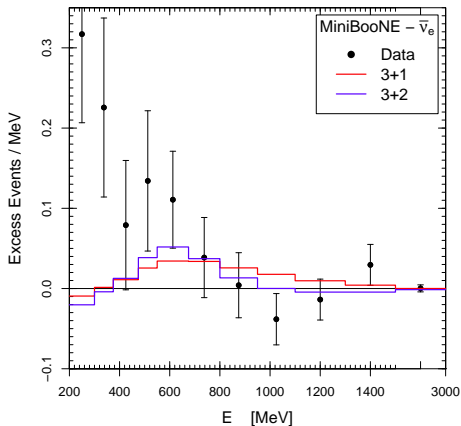
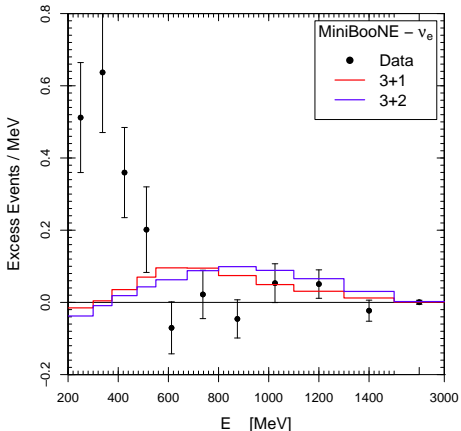
Global Fits	Our Fit		KMMS	
	3+1	3+2	3+1	3+2
GoF	5%	7%	19%	23%
PGoF	0.1%	0.04%	0.01%	0.003%

- ▶ 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

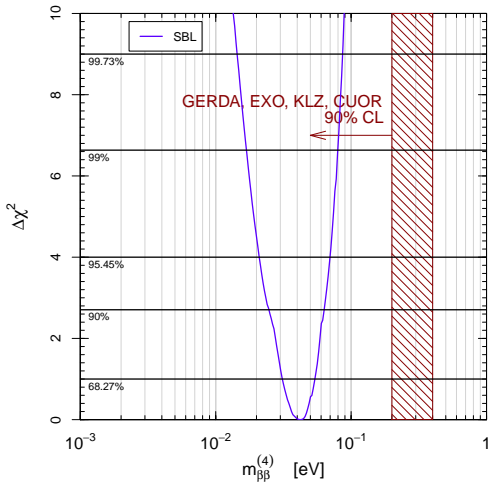


- ▶ Note difference between 3+2 ν_e and $\bar{\nu}_e$ histograms due to CP violation
- ▶ 3+2 can fit slightly better the small $\bar{\nu}_e$ excess at about 600 MeV
- ▶ 3+2 fit of low-energy excess as bad as 3+1
- ▶ Claims that 3+2 can fit low-energy excess do not take into account constraints from other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

No need of 3+2

- ▶ 3+2 should be preferred to 3+1 if
 - ▶ there is consistent evidence of two peaks of the probability corresponding to two Δm^2 's
 - ▶ there is CP-violating difference of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions
- ▶ MiniBooNE low-energy peak not consistent with disappearance constraints
- ▶ final $\nu_e + 2010 \bar{\nu}_e$ MiniBooNE data indicated $\nu_e - \bar{\nu}_e$ difference
 - ⇓
 - reasonable and useful to consider 3+2
- ▶ $\nu_e - \bar{\nu}_e$ difference almost disappeared with 2012 final MiniBooNE $\bar{\nu}_e$ data
- ▶ PGoF of 3+2 is even worse than that of 3+1!
- ▶ 3+2 has more tension with cosmological data than 3+1
- ▶ Conclusion: forget 3+2! (at least until new data require it)

Neutrinoless Double- β Decay



[Giunti, Laveder, Li, Long, 2014]

Pragmatic 3+1 Fit

$$|m_{\beta\beta}| = \left| \sum_{k=1}^4 U_{ek}^2 m_k \right|$$

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

caveat:

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

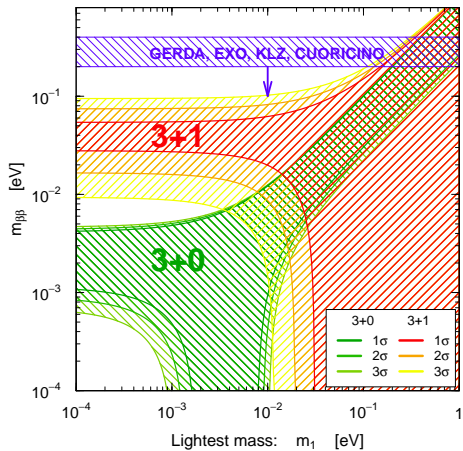
[Barry et al, JHEP 07 (2011) 091]

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

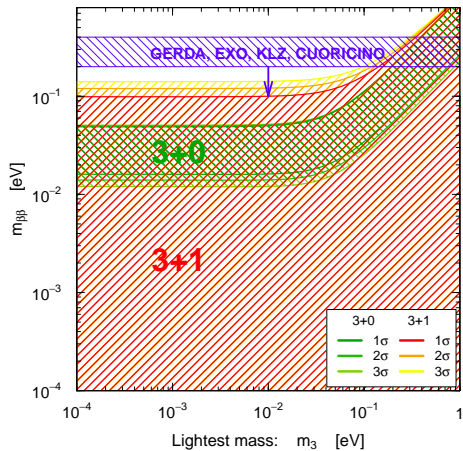
[Rodejohann, JPG 39 (2012) 124008]

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

Normal 3ν Ordering



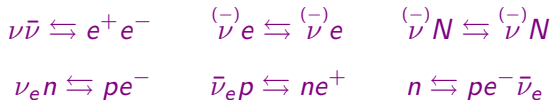
Inverted 3ν Ordering



[Giunti, Laveder, Li, Long, 2014]

Cosmology

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



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

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

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

- ▶ relic neutrinos: $T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945 \text{ K} \implies k T_\nu \simeq 1.676 \times 10^{-4} \text{ eV}$
($T_\gamma = 2.725 \pm 0.001 \text{ K}$)

- ▶ number density: $n_f = \frac{3}{4} \frac{\zeta(3)}{\pi^2} g_f T_f^3 \implies n_{\nu_k, \bar{\nu}_k} \simeq 0.1827 T_\nu^3 \simeq 112 \text{ cm}^{-3}$

- ▶ density contribution: $\Omega_k = \frac{n_{\nu_k, \bar{\nu}_k} m_k}{\rho_c} \simeq \frac{1}{h^2} \frac{m_k}{94 \text{ eV}} \implies \Omega_\nu h^2 = \frac{\sum_k m_k}{94 \text{ eV}}$
($\rho_c = \frac{3H^2}{8\pi G_N}$) [Gershtein, Zeldovich, JETP Lett. 4 (1966) 120; Cowsik, McClelland, PRL 29 (1972) 669]

- ▶ 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:

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

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

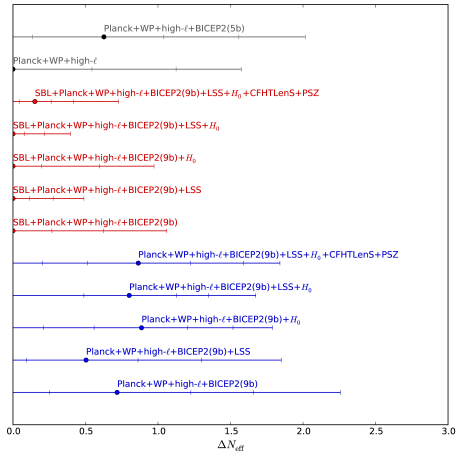
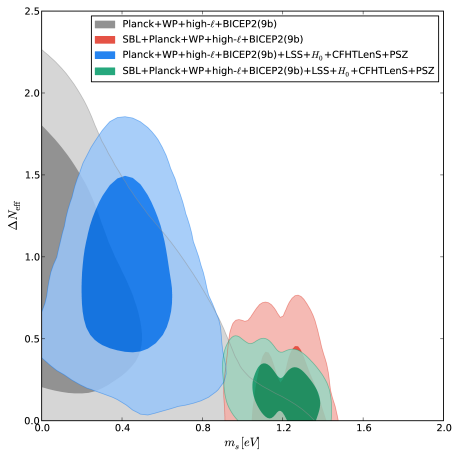
- ▶ sterile neutrino contribution:

$$\rho_s = (T_s/T_\nu)^4 \rho_\nu \implies \Delta N_{\text{eff}} = (T_s/T_\nu)^4$$

- ▶ sterile neutrino with mass $m_s = m_4 \simeq \sqrt{\Delta m_{41}^2} \sim 1\text{ eV}$ becomes non-relativistic at $T_\nu \sim m_s/3$, that is at $t_{\nu_s\text{-nr}} \sim 2.0 \times 10^5 \text{ y}$, before recombination at $t_{\text{rec}} \sim 3.8 \times 10^5 \text{ y}$
- ▶ current energy density of sterile neutrinos:

$$\Omega_s = \frac{n_s m_s}{\rho_c} \simeq \frac{1}{h^2} \frac{(T_s/T_\nu)^3 m_s}{94 \text{ eV}} = \frac{1}{h^2} \frac{\Delta N_{\text{eff}}^{3/4} m_s}{94 \text{ eV}} = \frac{1}{h^2} \frac{m_s^{\text{eff}}}{94 \text{ eV}}$$

$$m_s^{\text{eff}} = \Delta N_{\text{eff}}^{3/4} m_s = (T_s/T_\nu)^3 m_s$$



[Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, arXiv:1404.1794]

See also: [Bergstrom, Gonzalez-Garcia, Niro, Salvado, arXiv:1407.3806]

Without oscillation data:

- [Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena, arXiv:1403.4852]
- [Zhang, Li, Zhang, arXiv:1403.7028]
- [Dvorkin, Wyman, Rudd, Hu, arXiv:1403.8049]
- [Zhang, Li, Zhang, arXiv:1404.3598]

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

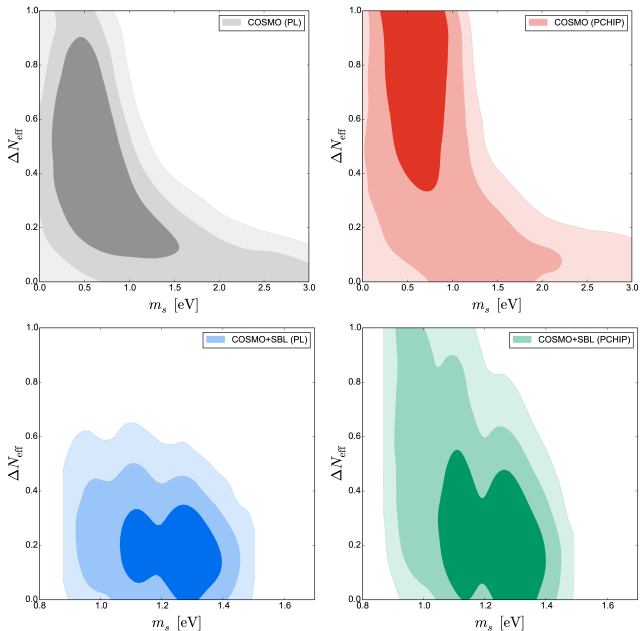
Sterile neutrinos are thermalized ($\Delta N_{\text{eff}} = 1$) by active-sterile oscillations before neutrino decoupling

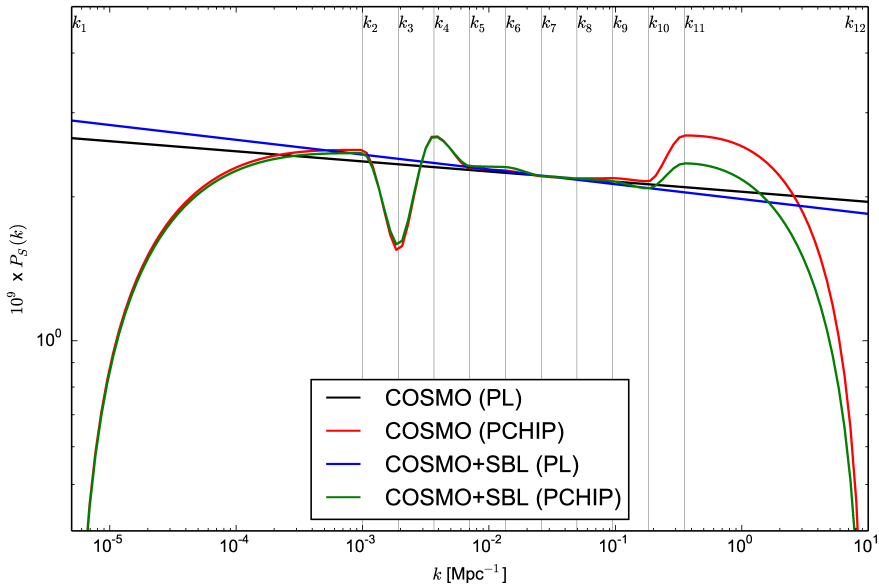
[Dolgov, Villante, NPB 679 (2004) 261]

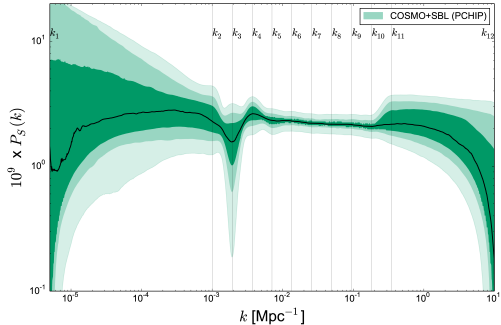
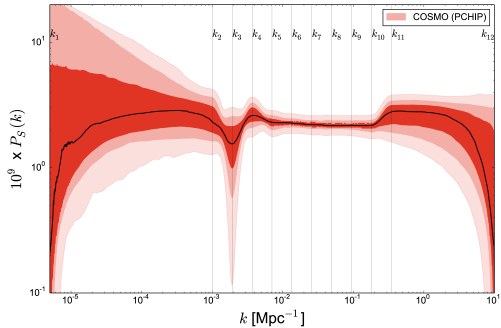
Proposed mechanisms to avoid the tension:

- ▶ 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, arXiv:1312.4947; Ko, Tang, arXiv:1404.0236; Archidiacono, Hannestad, Hansen, Tram, arXiv:1404.5915]
- ▶ 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]
- ▶ 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: systematic uncertainties.
 - ▶ 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:
 - ▶ Cosmological data may allow $\Delta N_{\text{eff}} \approx 1$.
 - ▶ Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1$ eV.
 - ▶ Cosmological and oscillation data may be reconciled by Inflationary Freedom.