

# Light Sterile Neutrinos

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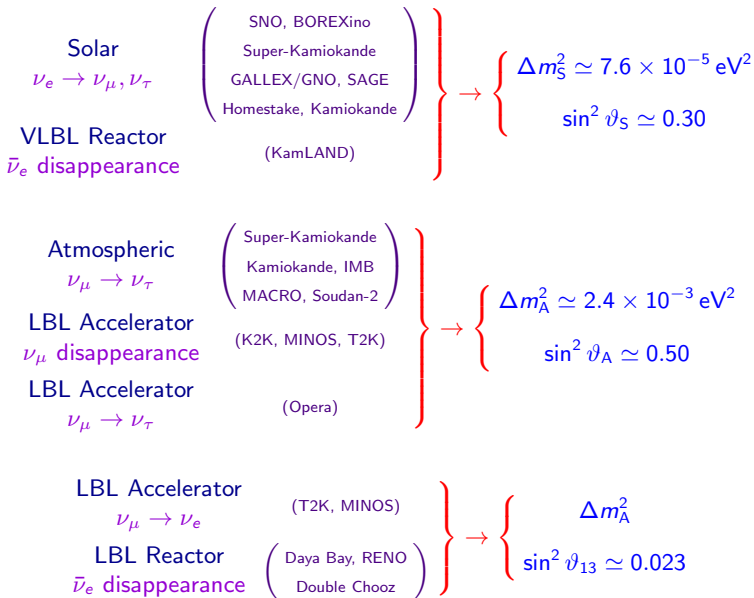
Neutrino Unbound: <http://www.nu.to.infn.it>

Origin of Mass 2015

CP3-Origins, Odense, Denmark

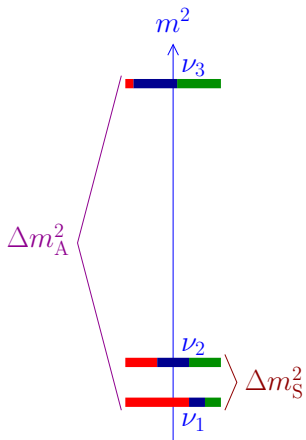
11-22 May 2015

# Experimental Evidences of Neutrino Oscillations



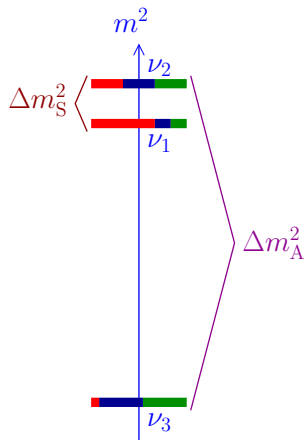
# Three-Neutrino Mixing Paradigm

|         |           |            |
|---------|-----------|------------|
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---------|-----------|------------|



Normal Ordering

$$\Delta m_{31}^2 > \Delta m_{32}^2 > 0$$



Inverted Ordering

$$\Delta m_{32}^2 < \Delta m_{31}^2 < 0$$

absolute scale is not determined by neutrino oscillation data

$$\Delta m_S^2 = \Delta m_{21}^2 \simeq 7.5_{-0.2}^{+0.3} \times 10^{-5} \text{ eV}^2 \quad \text{uncertainty} \simeq 3\%$$

$$\Delta m_A^2 = |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.4_{-0.1}^{+0.1} \times 10^{-3} \text{ eV}^2 \quad \text{uncertainty} \simeq 4\%$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$\vartheta_{23} = \vartheta_A$$

Daya Bay, RENO

$$\vartheta_{12} = \vartheta_S$$

$\beta\beta_{0\nu}$

$$\sin^2 \vartheta_{23} \simeq 0.4 - 0.6$$

Double Chooz

$$\sin^2 \vartheta_{12} \simeq 0.30 \pm 0.01$$

$$P_{\text{osc}} \propto \sin^2 2\vartheta_{23}$$

T2K, MINOS

$$\text{maximal and flat} \quad \sin^2 \vartheta_{13} \simeq 0.023 \pm 0.002$$

$$\text{at } \vartheta_{23} = 45^\circ$$

$$\frac{\delta \sin^2 \vartheta_{23}}{\sin^2 \vartheta_{23}} \simeq 40\%$$

$$\frac{\delta \sin^2 \vartheta_{13}}{\sin^2 \vartheta_{13}} \simeq 10\%$$

$$\frac{\delta \sin^2 \vartheta_{12}}{\sin^2 \vartheta_{12}} \simeq 5\%$$



# Open Problems

- ▶  $\vartheta_{23} \stackrel{\leq}{\gtrsim} 45^\circ$  ?
  - ▶ T2K (Japan), NO $\nu$ A (USA), PINGU (Antarctica), ORCA (EU), INO (India), ...
- ▶ Mass Ordering (Hierarchy) ?
  - ▶ NO $\nu$ A (USA), JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...
- ▶ CP violation ?
  - ▶ T2K (Japan), NO $\nu$ A (USA), DUNE (USA), HyperK (Japan), ...
- ▶ Absolute Mass Scale ?
  - ▶  $\beta$  Decay, Neutrinoless Double- $\beta$  Decay, Cosmology, ...
- ▶ Dirac or Majorana ?
  - ▶ Neutrinoless Double- $\beta$  Decay, ...
- ▶ Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

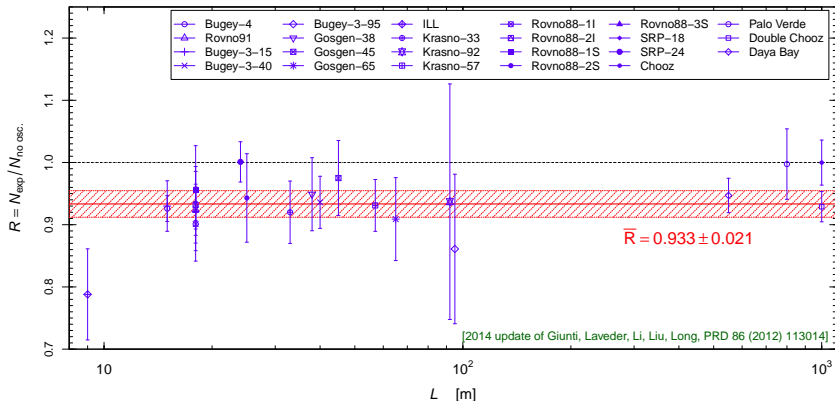
# Indications of SBL Oscillations Beyond $3\nu$

# 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]

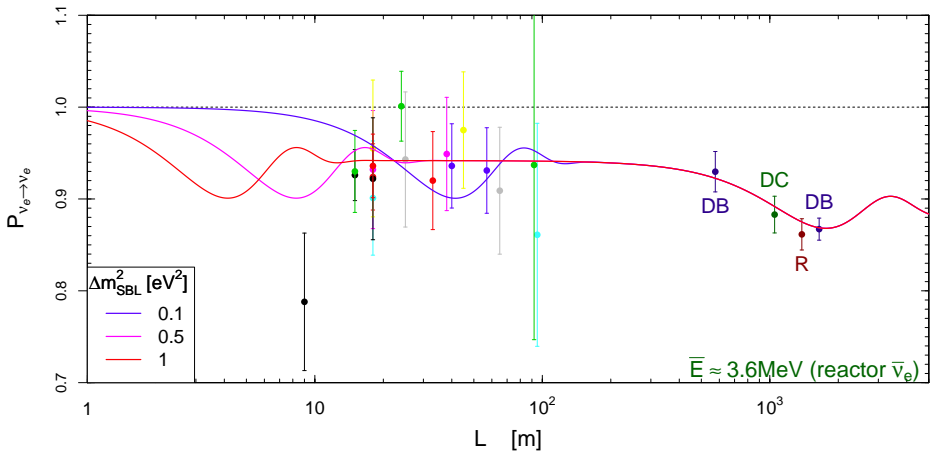


$\bar{\nu}_e \rightarrow \bar{\nu}_e$        $L \sim 10 - 100 \text{ m}$        $E \sim 4 \text{ MeV}$   
Nominal  $\approx 3.1\sigma$  deficit       $\Delta m^2 \gtrsim 0.5 \text{ eV}^2$       ( $\gg \Delta m_A^2 \gg \Delta m_S^2$ )

[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]

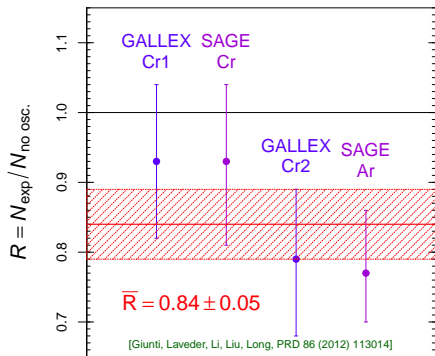


# Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$\nu_e$  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]

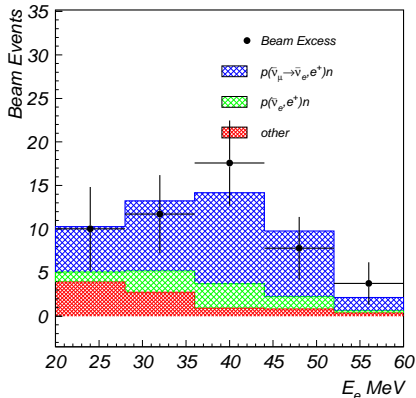
# LSND

[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

$L \simeq 541 \text{ m}$

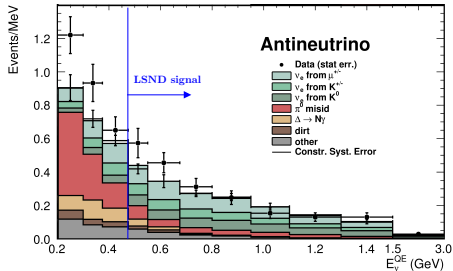
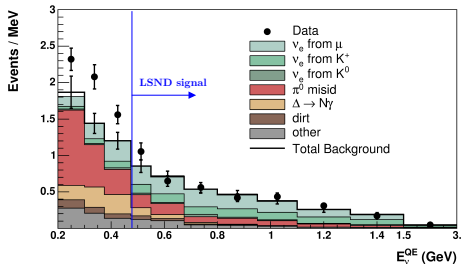
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

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

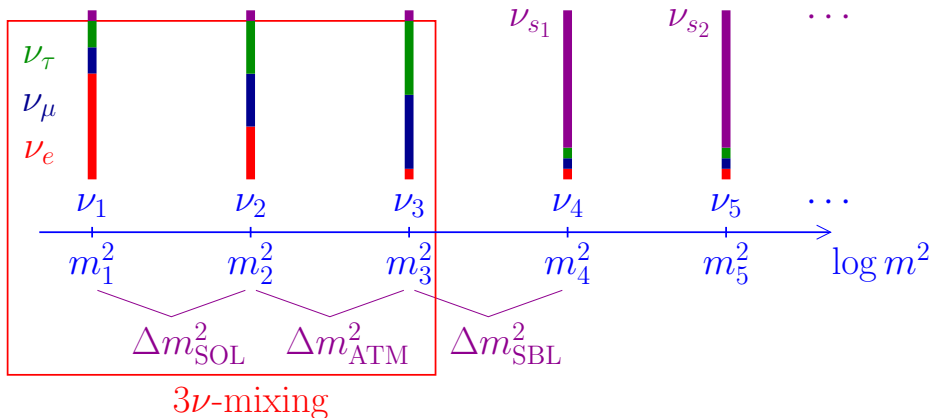
[PRL 110 (2013) 161801]



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

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

|         |           |            |            |     |
|---------|-----------|------------|------------|-----|
| $\nu_1$ | $\nu_2$   | $\nu_3$    | $\nu_4$    | ... |
| $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | $\nu_{s1}$ | ... |

- ▶ 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

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

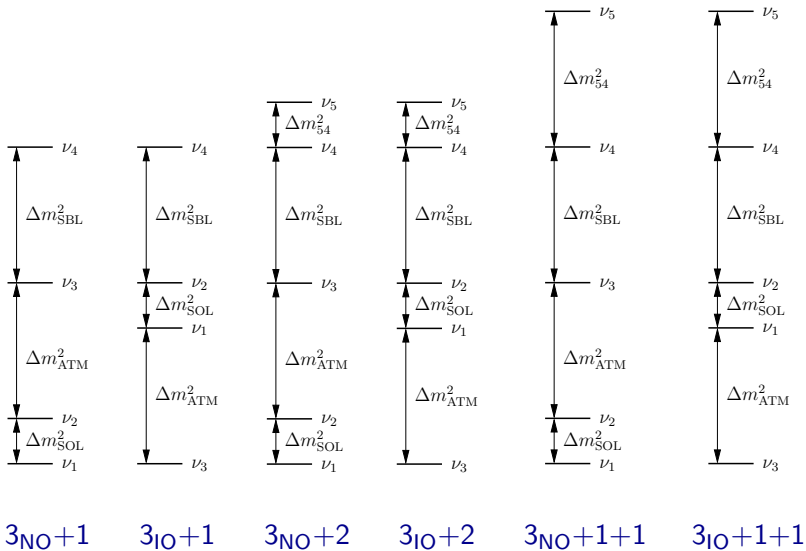
[Das, Pulido, Picariello, PRD 79 (2009) 073010]

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

- ▶ **Heavy sterile neutrinos** with mass scale  $\gg 1 \text{ eV}$ : 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, Iakubovskiy, 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 3 $\nu$  Mixing:  $|U_{e4}|^2 \ll 1$ ,  $|U_{\mu 4}|^2 \ll 1$ ,  $|U_{\tau 4}|^2 \ll 1$ ,  $|U_{s4}|^2 \simeq 1$

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

$U_{e4}$   
 $U_{\mu 4}$   
 $U_{\tau 4}$   
 $U_{s4}$ 
  
↑  
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  $\Delta m_{\text{ATM}}^2$  [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017] and solar exp. sensitive to  $\Delta m_{\text{SOL}}^2$  [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

## 3+1: Appearance vs Disappearance

- ▶ Amplitude of  $\nu_e$  disappearance:

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

- ▶ Amplitude of  $\nu_\mu$  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:

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

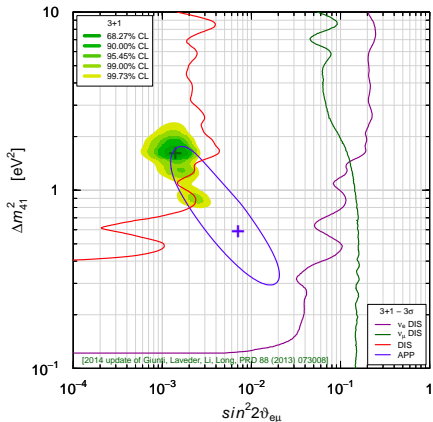
- ▶ Upper bounds on  $\nu_e$  and  $\nu_\mu$  disappearance  $\Rightarrow$  strong limit on  $\nu_\mu \rightarrow \nu_e$

[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

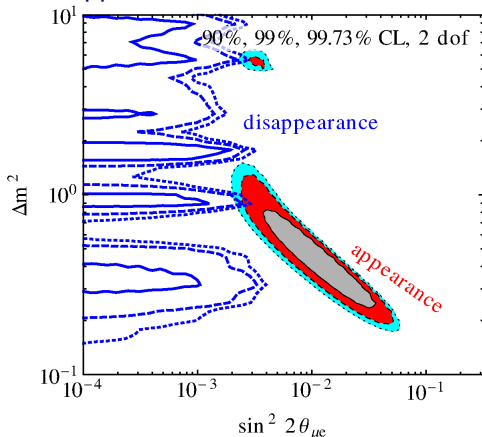
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz



GoF = 19%

PGoF = 0.01%

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

## Goodness of Fit

- ▶ Assumption or approximation: Gaussian uncertainties and linear model
- ▶  $\chi_{\min}^2$  has  $\chi^2$  distribution with Number of Degrees of Freedom

$$\text{NDF} = N_D - N_P$$

$N_D$  = Number of Data       $N_P$  = Number of Fitted Parameters

- ▶  $\langle \chi_{\min}^2 \rangle = \text{NDF}$        $\text{Var}(\chi_{\min}^2) = 2\text{NDF}$

- ▶  $\text{GoF} = \int_{\chi_{\min}^2}^{\infty} p_{\chi^2}(z, \text{NDF}) dz$        $p_{\chi^2}(z, n) = \frac{z^{n/2-1} e^{-z/2}}{2^{n/2} \Gamma(n/2)}$

## Parameter Goodness of Fit

[Maltoni, Schwetz, PRD 68 (2003) 033020]

- ▶ Measure compatibility of two (or more) sets of data points  $A$  and  $B$  under fitting model

- ▶  $\chi_{\text{PGoF}}^2 = (\chi_{\min}^2)_{A+B} - [(\chi_{\min}^2)_A + (\chi_{\min}^2)_B]$

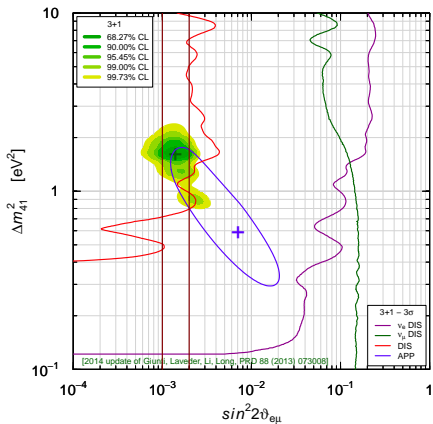
- ▶  $\chi_{\text{PGoF}}^2$  has  $\chi^2$  distribution with Number of Degrees of Freedom

$$\text{NDF}_{\text{PGoF}} = N_P^A + N_P^B - N_P^{A+B}$$

- ▶  $\text{PGoF} = \int_{\chi_{\text{PGoF}}^2}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}}) dz$

# Global 3+1 Fit

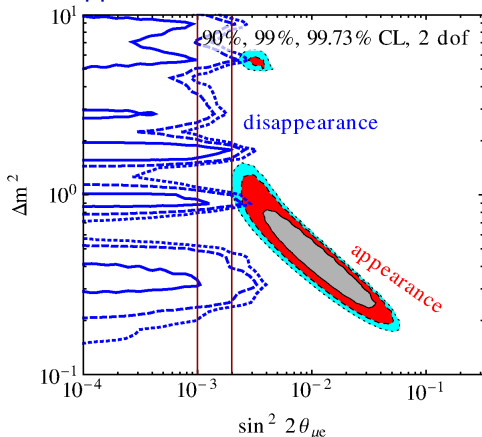
Our Fit



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Kopp, Machado, Maltoni, Schwetz



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PGoF = 0.01%

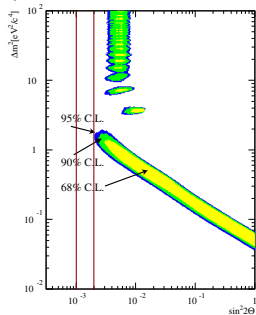
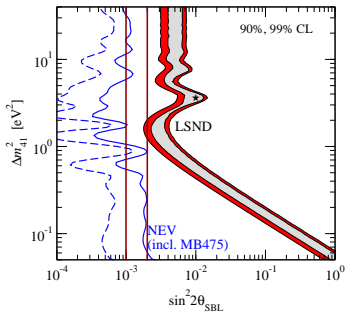
[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]



# Different LSND Treatments

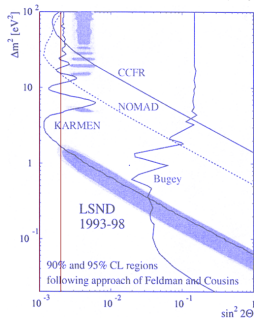
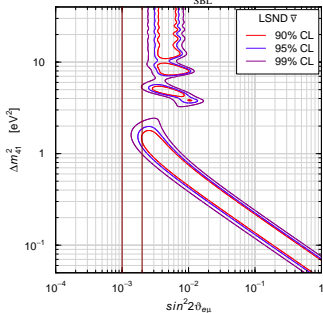
only LSND data from  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$  decay at rest

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



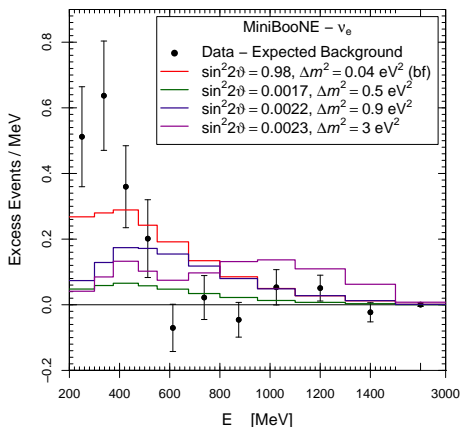
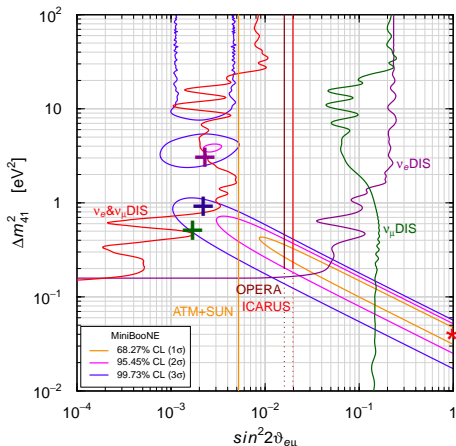
[Church, Eitel, Mills, Steidl,  
 PRD 66 (2002) 013001]

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



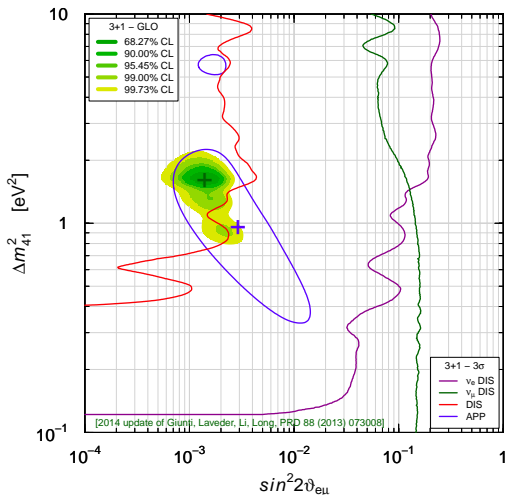
[Church (LSND),  
 NPA 663 (2000) 799]

# MiniBooNE Low-Energy Excess?



- ▶ No fit of low-energy excess for realistic  $\sin^2 2\theta_{e\mu} \lesssim 3 \times 10^{-3}$
- ▶ 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 ( $\nu_s$ ), MiniBooNE (?),  
 OPERA ( ~~$\nu_s$~~ ), ICARUS ( ~~$\nu_s$~~ ),  
 KARMEN ( ~~$\nu_s$~~ ),  
 NOMAD ( ~~$\nu_s$~~ ), BNL-E776 ( ~~$\nu_s$~~ )
- ▶ DIS  $\nu_e$  &  $\bar{\nu}_e$ : Reactors ( $\nu_s$ ),  
 Gallium ( $\nu_s$ ),  $\nu_e C$  ( ~~$\nu_s$~~ ),  
 Solar ( ~~$\nu_s$~~ )
- ▶ DIS  $\nu_\mu$  &  $\bar{\nu}_\mu$ : CDHSW ( ~~$\nu_s$~~ ),  
 MINOS ( ~~$\nu_s$~~ ),  
 Atmospheric ( ~~$\nu_s$~~ ),  
 MiniBooNE/SciBooNE ( ~~$\nu_s$~~ )

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

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

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

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

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

[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

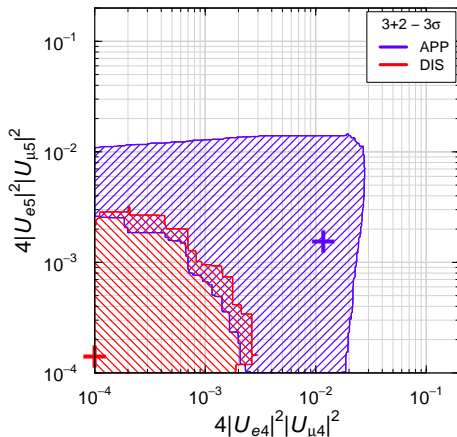
▶ Bad: Two massive sterile neutrinos at the eV scale!

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

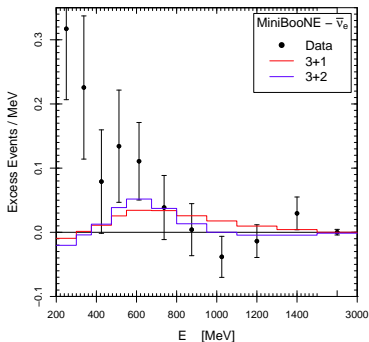
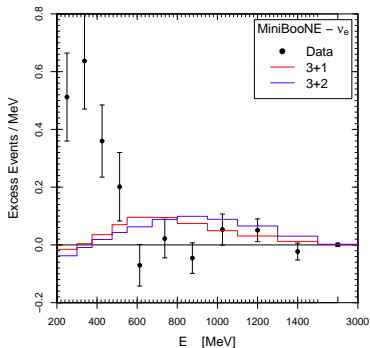
| Global Fits | Our Fit |       | KMMS  |        |
|-------------|---------|-------|-------|--------|
|             | 3+1     | 3+2   | 3+1   | 3+2    |
| GoF         | 5%      | 7%    | 19%   | 23%    |
| PGoF        | 0.1%    | 0.04% | 0.01% | 0.003% |

- ▶ 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:



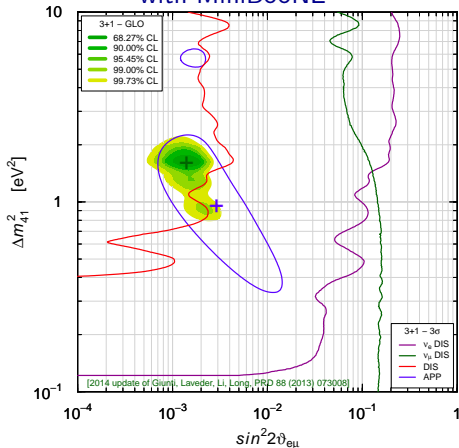
# 3+2 cannot fit MiniBooNE Low-Energy Excess



- ▶ Note difference between 3+2  $\nu_e$  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)

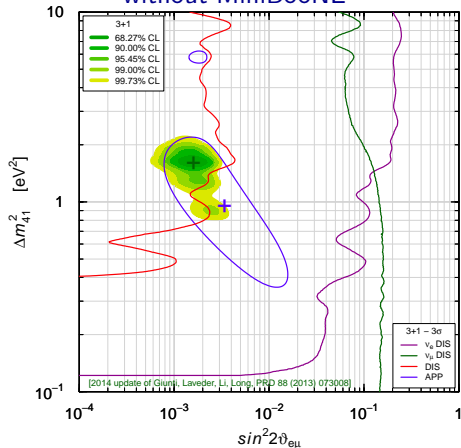
# MiniBooNE Impact in Pragmatic 3+1 Fit?

with MiniBooNE



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

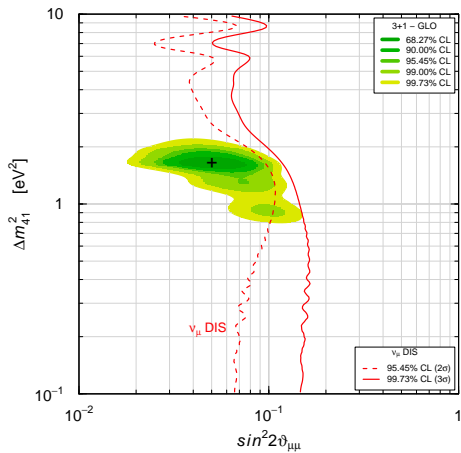
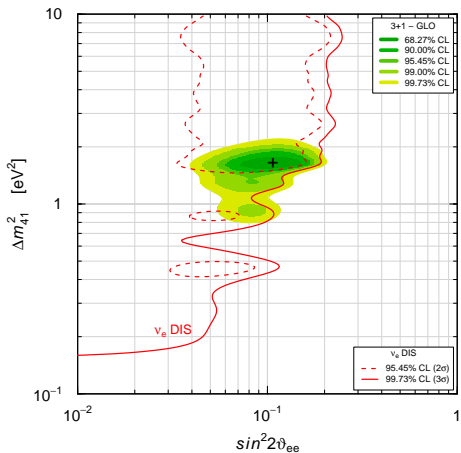
without MiniBooNE



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

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

# $\nu_e$ and $\nu_\mu$ Disappearance



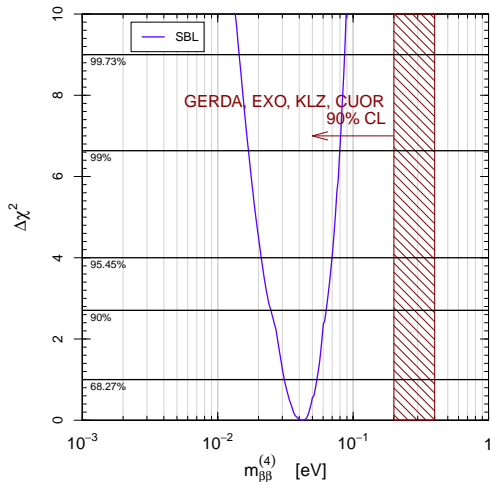


# Future

- ▶ Many Exciting New Experiments and Projects with Reactor  $\bar{\nu}_e$ , Radioactive  $\nu_e$  and  $\bar{\nu}_e$  Sources, Accelerator  $\nu_{\mu}^{(-)} \rightarrow \nu_e^{(-)}$
- ▶ 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- $\beta$ 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

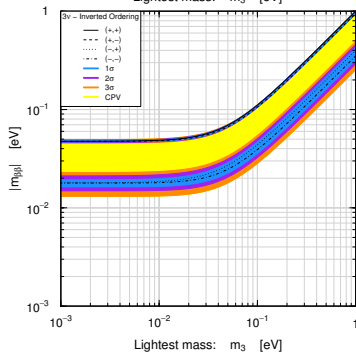
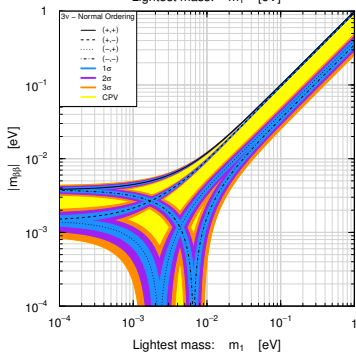
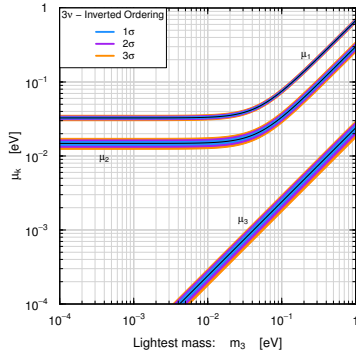
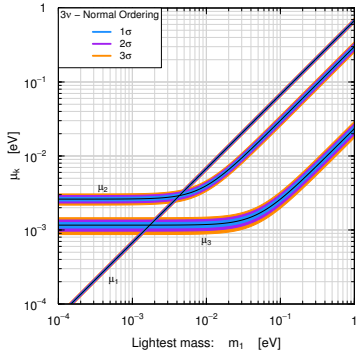
with  $m_{\beta\beta}^{(3\nu)}$

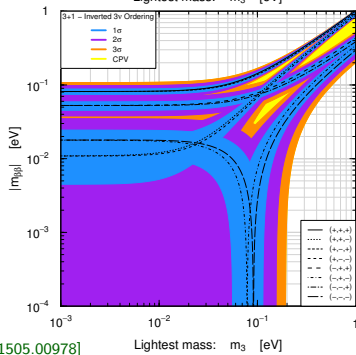
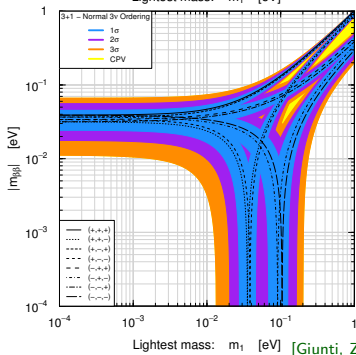
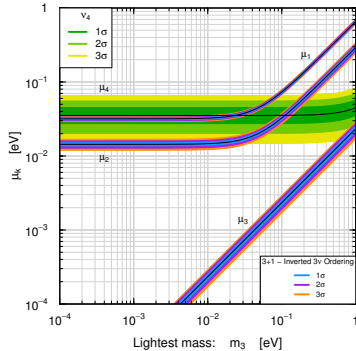
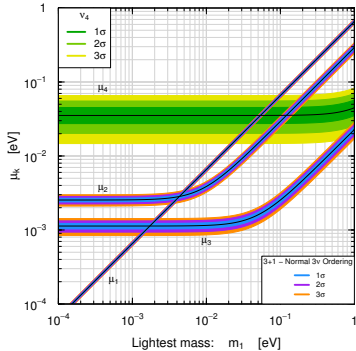
[Barry et al, JHEP 07 (2011) 091]

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

[Rodejohann, JPG 39 (2012) 124008]

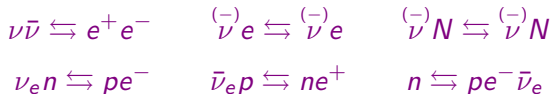
[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]





# Cosmology

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



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

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$
$$T_{\nu\text{-dec}} \sim 1 \text{ MeV} \qquad t_{\nu\text{-dec}} \sim 1 \text{ s}$$

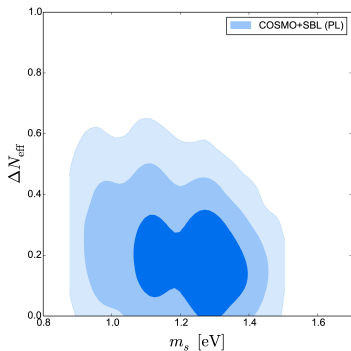
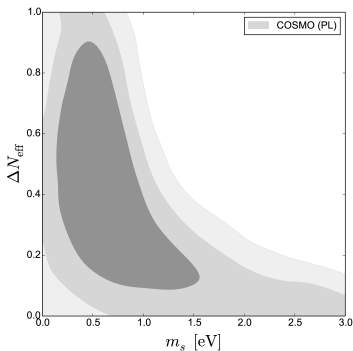
- ▶ sterile neutrinos can be produced by  $\nu_{e,\mu,\tau} \rightarrow \nu_s$  oscillations before active neutrino decoupling ( $t_{\nu\text{-dec}} \sim 1 \text{ s}$ )
- ▶ energy density of radiation before matter-radiation equality:

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

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

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

- $\nu_s$  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 $m_s \approx 1 \text{ eV}$

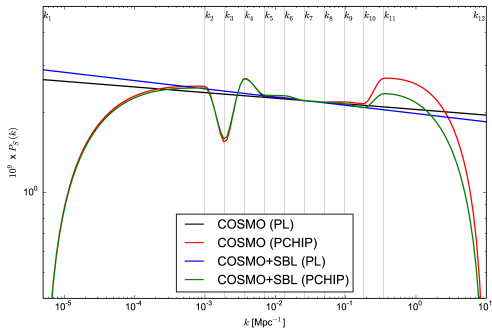
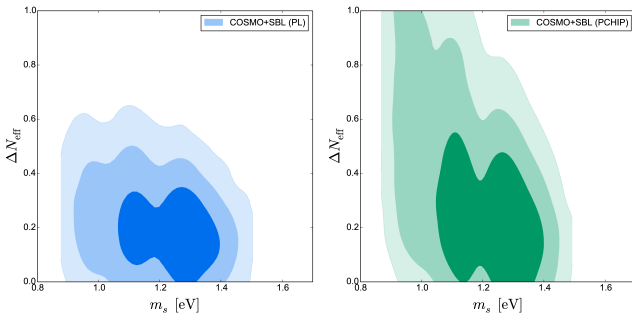
Sterile neutrinos are thermalized ( $\Delta N_{\text{eff}} = 1$ ) by active-sterile oscillations before neutrino decoupling

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

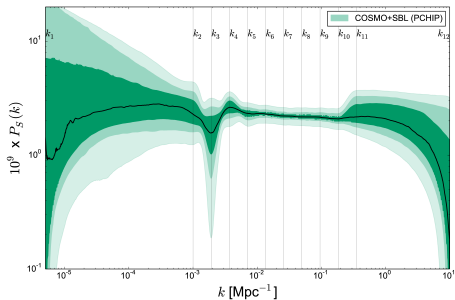
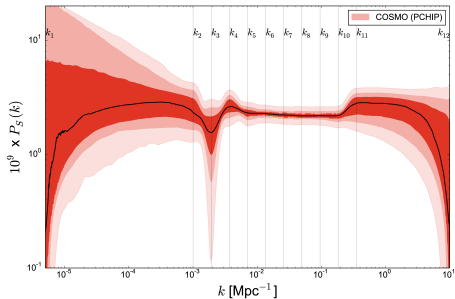
Proposed mechanisms to avoid the tension:

- ▶ 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  $\nu_e$  and  $\bar{\nu}_e$  Disappearance:
  - ▶ Experimental data agree on Reactor  $\bar{\nu}_e$  and Gallium  $\nu_e$  anomalies.
  - ▶ Problem: unknown systematic uncertainties (Reactor  $\bar{\nu}_e$  flux).
  - ▶ Many promising projects to test unambiguously short-baseline  $\nu_e$  and  $\bar{\nu}_e$  disappearance in a few years with reactors and radioactive sources.
  - ▶ Independent tests through effect of  $m_4$  in  $\beta$ -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  $|U_{\mu4}| > 0$ ?  $\implies \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 > 0$
- ▶ 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  $m_s \approx 1$  eV.
  - ▶ Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.