# Status of Short-Baseline Neutrino Oscillation Fits

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LSND

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



Nominal  $\approx 3.8\sigma$  excess

 $\bar{\nu}_{\mu} 
ightarrow \bar{\nu}_{e}$   $L \simeq 30 \,\mathrm{m}$   $20 \,\mathrm{MeV} \leq E \leq 60 \,\mathrm{MeV}$ 

• Well known source of  $\bar{\nu}_{\mu}$ :  $\mu^+$  at rest  $\rightarrow e^+ + \nu_e + \bar{\nu}_{\mu}$  $\blacktriangleright \bar{\nu}_{\mu} \xrightarrow{I \sim 30 \text{ m}} \bar{\nu}_{e}$ • 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  $L \simeq 18$  m [PRD 65 (2002) 112001]

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

### **MiniBooNE**

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



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

- LSND signal: E > 475 MeV.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

### **Reactor Electron Antineutrino Anomaly**



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#### **Gallium Anomaly**

Gallium Radioactive Source Experiments: GALLEX and SAGE  $\nu_{o} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^{-}$ Detection Process:  $e^- + {}^{51}Cr \rightarrow {}^{51}V + \nu_e \qquad e^- + {}^{37}Ar \rightarrow {}^{37}Cl + \nu_e$  $\nu_{e}$  Sources:  $\bar{\nu}_e \rightarrow \bar{\nu}_e \qquad E \sim 0.7 \,\mathrm{MeV}$ GALLEX SAGE 5 Cr1 Cr  $\langle L \rangle_{\text{GALLEX}} = 1.9 \,\text{m}$ 10  $R = N_{exp}/N_{no osc.}$  $\langle L \rangle_{\text{SAGE}} = 0.6 \,\mathrm{m}$ GALLEX SAGE Nominal  $\approx 2.9\sigma$  anomaly Cr2 Ar 0.9  $\Delta m^2 \gtrsim 1 \,\mathrm{eV}^2 \quad (\gg \Delta m_A^2 \gg \Delta m_S^2)$ 0.8 [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;  $\overline{R} = 0.84 \pm 0.05$ PRC 83 (2011) 065504] 0.7 [Mention et al. PRD 83 (2011) 073006] [Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014

►  ${}^{3}\text{He} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + {}^{3}\text{H}$  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]

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#### **Beyond Three-Neutrino Mixing: Sterile Neutrinos**



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

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#### Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

- 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  $\Delta m_{ATM}^2$  [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017; Berryman, de Gouvea, Kelly, Kobach, PRD 92 (2015) 073012, Palazzo, arXiv:1509.03148] and solar exp. sensitive to  $\Delta m_{SOL}^2$  [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

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#### **Global** $\nu_e$ and $\bar{\nu}_e$ **Disappearance**



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### **Near-Future Experiments**



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# $ar{ u}_{\mu} ightarrow ar{ u}_{e}$ and $u_{\mu} ightarrow u_{e}$ Appearance



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### **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:

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

• 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<sub>s</sub>! [Giunti, Zavanin, MPLA 31 (2015) 1650003]

### $u_{\mu}$ and $ar{ u}_{\mu}$ Disappearance



#### Global 3+1 Fit



#### MiniBooNE Low-Energy Excess?



• No fit of low-energy excess for realistic  $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$ 

- 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 [Giunti, Laveder, Li, Long, PRD 88 (2013) 073008]

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## Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

 Effect due to multinucleon interactions whose signal is indistinguishable from that due to quasielastic charged-current scattering

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

► In the MiniBooNE analysis the reconstructed neutrino energy is (E<sub>B</sub> ≃ 25 MeV)

$$E_{\nu}^{\text{QE}} = \frac{2(M_{\text{i}} - E_{\text{B}})E_{e} - (m_{e}^{2} - 2M_{\text{i}}E_{\text{B}} + E_{\text{B}}^{2} + \Delta M_{\text{if}}^{2})}{2(M_{\text{i}} - E_{\text{B}} - E_{e} + p_{e}\cos\theta_{e})}$$

- The MiniBooNE collaboration took into account:
  - Fermi motion of the initial nucleon
  - Charged-current single charged pion production events in which the pion is not observed

(e.g.  $u_e + n 
ightarrow \Delta^+ + e^- 
ightarrow n + \pi^+ + e^-$  with  $\pi^+$  absorbed by a nucleus)



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- Multinucleon interactions can decrease slightly the MiniBooNE low-energy anomaly
- Multinucleon interactions cannot solve the APP-DIS tension
- MicroBooNE is crucial for checking the MiniBooNE low-energy anomaly
- If confirmed it is a real problem

# Pragmatic Global 3+1 Fit



#### Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\begin{split} \Delta_{kj} &= \Delta m_{kj}^2 L/4E \\ \eta &= \arg[U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*] \\ P_{(-)}^{\text{SBL}} &= 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2 \Delta_{41} + 4|U_{e5}|^2 |U_{\mu5}|^2 \sin^2 \Delta_{51} \\ &+ 8|U_{\mu4} U_{e4} U_{\mu5} U_{e5}| \sin \Delta_{41} \sin \Delta_{51} \cos(\Delta_{54} \overset{(+)}{-} \eta) \\ P_{(-)}^{\text{SBL}} &= 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2 \Delta_{41} + |U_{\alpha5}|^2 \sin^2 \Delta_{51}) \\ &- 4|U_{\alpha4}|^2 |U_{\alpha5}|^2 \sin^2 \Delta_{54} \end{split}$$

[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:  $\Delta m_{41}^2, |U_{e4}|^2, |U_{\mu4}|^2, \Delta m_{51}^2, |U_{e5}|^2, |U_{\mu5}|^2, \eta$ 

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: Gariazzo, Giunti, Laveder, Li, Zavanin, JPG 43 (2016) 033001
- KMMS: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050



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## 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: 3+2 is not needed

### **Future Experiments**



 $\begin{array}{l} \mbox{SBN (FNAL, USA)} \\ [arXiv:1503.01520] \\ \mbox{3 Liquid Argon TPCs} \\ \mbox{LAr1-ND } L \simeq 100 \mbox{ m} \\ \mbox{MicroBooNE } L \simeq 470 \mbox{ m} \\ \mbox{ICARUS T600 } L \simeq 600 \mbox{ m} \end{array}$ 

nuPRISM (J-PARC, Japan) [Wilking@NNN2015]  $L \simeq 1 \text{ km}$ 50 m tall water Cherenkov detector  $1^{\circ} - 4^{\circ}$  off-axis can be improved with T2K ND

## $\nu_e$ **Disappearance**



### $\nu_{\mu}$ Disappearance



#### **Neutrinoless Double**- $\beta$ **Decay**

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



$$m^{(k)}_{etaeta} = |U_{ek}|^2 m_k$$

[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]



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# **Conclusions**

- Short-Baseline  $\nu_e$  and  $\bar{\nu}_e$  Disappearance:
  - Experimental data agree on Reactor  $\bar{\nu}_e$  and Gallium  $\nu_e$  disappearance.
  - Problem: total rates may have unknown systematic uncertainties.
  - ► Many promising projects to test unambiguously short-baseline v<sub>e</sub> and v
    <sub>e</sub> and
  - 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  ${}^{(-)}_{\nu_{\mu}} \rightarrow {}^{(-)}_{\nu_{e}}$  experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
  - Promising Fermilab program aimed at a conclusive solution of the mystery: a near detector (LAr1-ND), an intermediate detector (MicroBooNE) and a far detector (ICARUS-T600), all Liquid Argon Time Projection Chambers.
- ▶ Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.
- ► 3+2 is not needed: same APP-DIS tension and no experimental evidence of CP violation.
- Cosmology:
  - Tension between  $\Delta N_{\rm eff} = 1$  and  $m_s \approx 1 \, {\rm eV}$ .
  - Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.

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