

# Neutrino Oscillations and Sterile Neutrino

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## Neutrino Oscillations

- ▶ 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with  $K^0 \leftrightarrow \bar{K}^0$  oscillations (Gell-Mann and Pais, 1955)
- ▶ Flavor Neutrinos:  $\nu_e, \nu_\mu, \nu_\tau$  produced in Weak Interactions
- ▶ Massive Neutrinos:  $\nu_1, \nu_2, \nu_3$  propagate from Source to Detector
- ▶ A Flavor Neutrino is a superposition of Massive Neutrinos

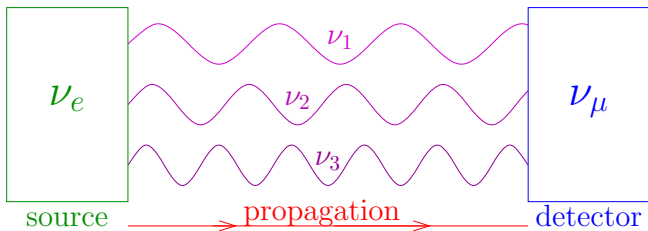
$$|\nu_e\rangle = U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle$$

$$|\nu_\mu\rangle = U_{\mu1} |\nu_1\rangle + U_{\mu2} |\nu_2\rangle + U_{\mu3} |\nu_3\rangle$$

$$|\nu_\tau\rangle = U_{\tau1} |\nu_1\rangle + U_{\tau2} |\nu_2\rangle + U_{\tau3} |\nu_3\rangle$$

- ▶  $U$  is the  $3 \times 3$  Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1} |\nu_1\rangle + U_{e2} |\nu_2\rangle + U_{e3} |\nu_3\rangle$$



$$|\nu(t > 0)\rangle = U_{e1} e^{-iE_1 t} |\nu_1\rangle + U_{e2} e^{-iE_2 t} |\nu_2\rangle + U_{e3} e^{-iE_3 t} |\nu_3\rangle \neq |\nu_e\rangle$$

$$E_k^2 = p^2 + m_k^2$$

at the detector there is a **probability**  $> 0$  to see the neutrino as a  $\nu_\mu$

### Neutrino Oscillations are Flavor Transitions

$$\begin{array}{cccc} \nu_e \rightarrow \nu_\mu & \nu_e \rightarrow \nu_\tau & \nu_\mu \rightarrow \nu_e & \nu_\mu \rightarrow \nu_\tau \\ \bar{\nu}_e \rightarrow \bar{\nu}_\mu & \bar{\nu}_e \rightarrow \bar{\nu}_\tau & \bar{\nu}_\mu \rightarrow \bar{\nu}_e & \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \end{array}$$

transition probabilities depend on  $U$  and  $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

# Two-Neutrino Mixing and Oscillations

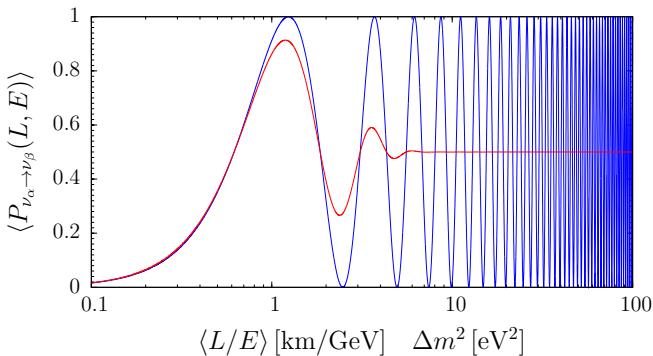
$$|\nu_\alpha\rangle = \cos\vartheta |\nu_1\rangle + \sin\vartheta |\nu_2\rangle$$

$$|\nu_\beta\rangle = -\sin\vartheta |\nu_1\rangle + \cos\vartheta |\nu_2\rangle$$

$$\Delta m^2 \equiv \Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

Transition Probability:  $P_{\nu_\alpha \rightarrow \nu_\beta} = P_{\nu_\beta \rightarrow \nu_\alpha} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

Survival Probabilities:  $P_{\nu_\alpha \rightarrow \nu_\alpha} = P_{\nu_\beta \rightarrow \nu_\beta} = 1 - P_{\nu_\alpha \rightarrow \nu_\beta}$



# Experimental Evidences of Neutrino Oscillations

Solar  
 $\nu_e \rightarrow \nu_\mu, \nu_\tau$

VLBL Reactor  
 $\bar{\nu}_e$  disappearance

(SNO, BOREXino  
 Super-Kamiokande  
 GALLEX/GNO, SAGE  
 Homestake, Kamiokande  
 (KamLAND))

$\rightarrow \left\{ \begin{array}{l} \Delta m_S^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_S \simeq 0.30 \end{array} \right.$

Atmospheric  
 $\nu_\mu \rightarrow \nu_\tau$

LBL Accelerator  
 $\nu_\mu$  disappearance

LBL Accelerator  
 $\nu_\mu \rightarrow \nu_\tau$

(Super-Kamiokande  
 Kamiokande, IMB  
 MACRO, Soudan-2  
 (K2K, MINOS, T2K)  
 (Opera))

$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \vartheta_A \simeq 0.50 \end{array} \right.$

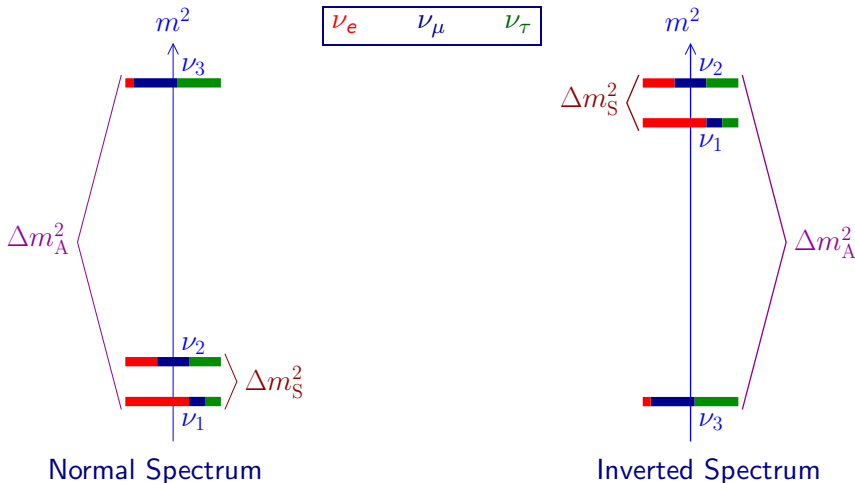
LBL Accelerator  
 $\nu_\mu \rightarrow \nu_e$

LBL Reactor  
 $\bar{\nu}_e$  disappearance

(T2K, MINOS)  
 (Daya Bay, RENO  
 Double Chooz)

$\rightarrow \left\{ \begin{array}{l} \Delta m_A^2 \\ \sin^2 \vartheta_{13} \simeq 0.023 \end{array} \right.$

# Three-Neutrino Mixing Paradigm



## Recent Global Fits

Gonzalez Garcia, Maltoni, Schwetz, Salvado, NuFIT-v1.2 [<http://www.nu-fit.org/>]

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo, arXiv:1312.2878

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

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

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

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

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

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

$$\text{Chooz, Palo Verde}$$

$$\text{T2K, MINOS}$$

$$\text{Daya Bay, RENO}$$

$$\sin^2 \vartheta_{13} \simeq 0.023 \pm 0.002$$

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

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

$$\beta\beta_{0\nu}$$

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

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

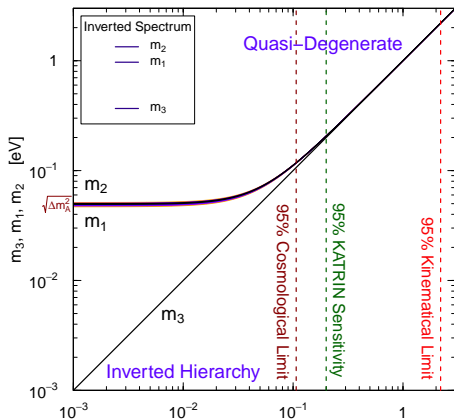
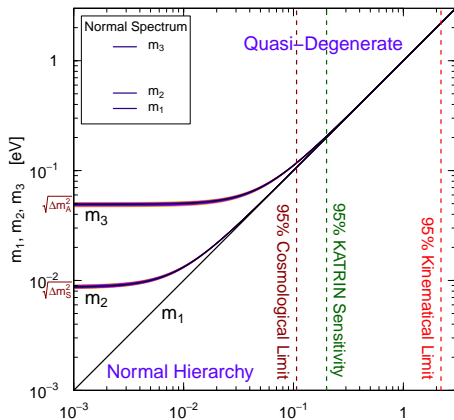
$$\frac{\delta \sin^2 \vartheta_{12}}{\sin^2 \vartheta_{12}} \simeq 5\%$$

# Open Problems

- ▶  $\vartheta_{23} \stackrel{?}{\leq} 45^\circ$  ?
  - ▶ T2K (Japan), NO $\nu$ A (USA), IceCube-PINGU, INO (India), ...
- ▶ Mass Hierarchy ?
  - ▶ NO $\nu$ A (USA), JUNO (China), RENO-50 (Korea), IceCube-PINGU, INO (India), ...
- ▶ CP violation ?
  - ▶ NO $\nu$ A (USA), LBNE (USA), LAGUNA-LBNO (EU), 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 ?



# Absolute Scale of Neutrino Masses



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$

$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$

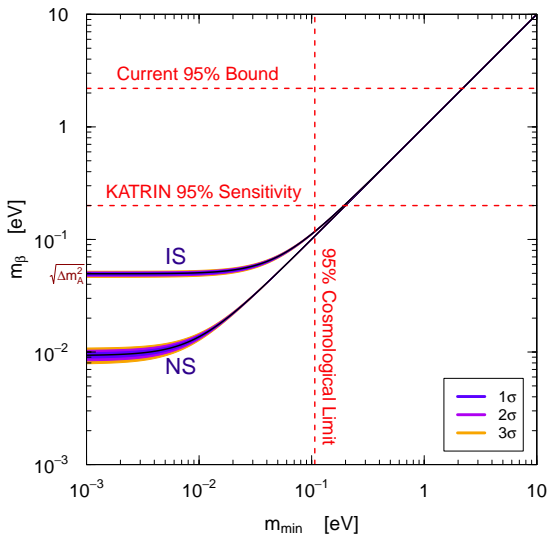
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for  $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2} \text{ eV}$

95% Cosmological Limit: Planck + WMAP9 + highL + BAO [arXiv:1303.5076]

# Effective Neutrino Mass in Beta-Decay

$$m_\beta^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$



- ▶ Quasi-Degenerate:

$$m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$$

- ▶ Inverted Hierarchy:

$$m_\beta^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2$$

- ▶ Normal Hierarchy:

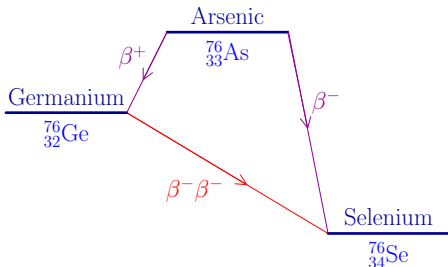
$$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2 \\ \simeq 2 \times 10^{-5} + 6 \times 10^{-5} \text{ eV}^2$$

- ▶  $m_\beta \lesssim 4 \times 10^{-2} \text{ eV}$



Normal Spectrum

# Majorana $\nu$ : Neutrinoless Double-Beta Decay



$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 m_{\beta\beta}^2$$

Effective Majorana Mass

$$m_{\beta\beta} = \left| \sum_{k=1}^3 U_{ek}^2 m_k \right|$$

EXO + KamLAND-Zen



[PRL 109 (2012) 032505; PRL 110 (2013) 062502]

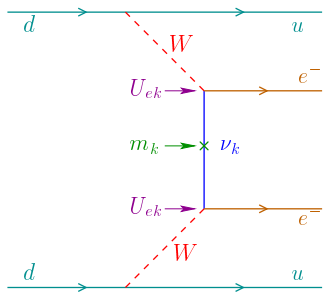
$$|m_{\beta\beta}| \lesssim 0.12 - 0.25 \text{ eV} \quad (90\% \text{C.L.})$$

GERDA



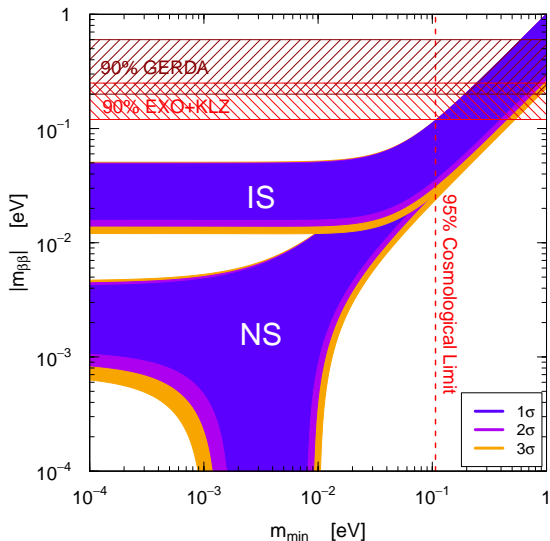
[PRL 111 (2013) 122503]

$$|m_{\beta\beta}| \lesssim 0.2 - 0.6 \text{ eV} \quad (90\% \text{C.L.})$$



# Effective Majorana Neutrino Mass

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$



► Quasi-Degenerate:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2}$$

► Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m_A^2 (1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2)}$$

► Normal Hierarchy:

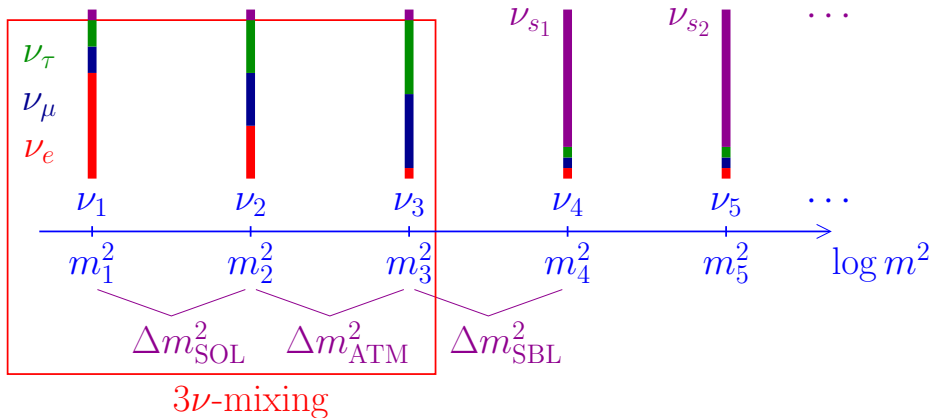
$$|m_{\beta\beta}| \simeq |s_{12}^2 \sqrt{\Delta m_S^2} + e^{i\alpha} s_{13}^2 \sqrt{\Delta m_A^2}|$$

$$\simeq |2.7 + 1.2e^{i\alpha}| \times 10^{-3} \text{ eV}$$

$$m_1 \gtrsim 10^{-3} \text{ eV} \Rightarrow \text{cancellation?}$$

$$|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV} \Rightarrow \text{Normal Spectrum}$$

# Beyond Three-Neutrino Mixing: Sterile Neutrinos



# 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:  $L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \tilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \xrightarrow[\text{Breaking}]{\text{Symmetry}} \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix}$

- ▶ SM singlet  $\overline{L}_L \tilde{\Phi}$  can couple to new singlet chiral fermion field  $\nu_R$  (**right-handed neutrino**) related to physics beyond the SM
- ▶ Known examples: SUSY, new symmetries, extra dimensions, mirror world, ... [see [http://www.nu.to.infn.it/Sterile\\_Neutrinos/](http://www.nu.to.infn.it/Sterile_Neutrinos/)]
- ▶ **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  $\implies$  massive Majorana neutrinos

# Light Sterile Neutrinos

- ▶ Light anti- $\nu_R$  are called **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:

$$\begin{array}{cccccc} \Delta m_{21}^2 & \ll & |\Delta m_{31}^2| & \ll & |\Delta m_{41}^2| & \leq \dots \\ \nu_1 & & \nu_2 & & \nu_3 & \dots \\ \nu_e & & \nu_\mu & & \nu_\tau & \dots \\ & & & & \nu_{s1} & \dots \end{array}$$

- ▶ 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]
  - ▶ 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]
    - [Drewes, IJMPE, 22 (2013) 1330019]



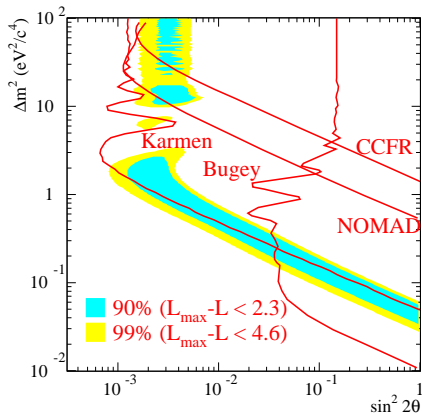
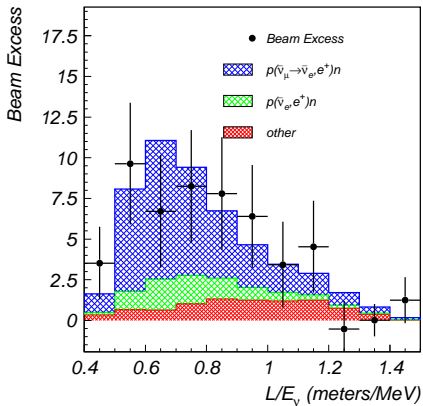
# LSND

[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 $\sigma$  excess

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

# MiniBooNE

$L \simeq 541 \text{ m}$

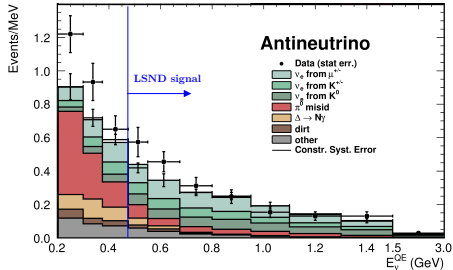
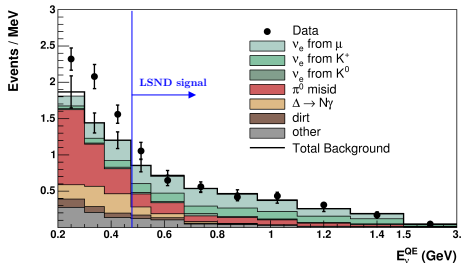
$200 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$

$\nu_\mu \rightarrow \nu_e$

[PRL 102 (2009) 101802]

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

[PRL 110 (2013) 161801]

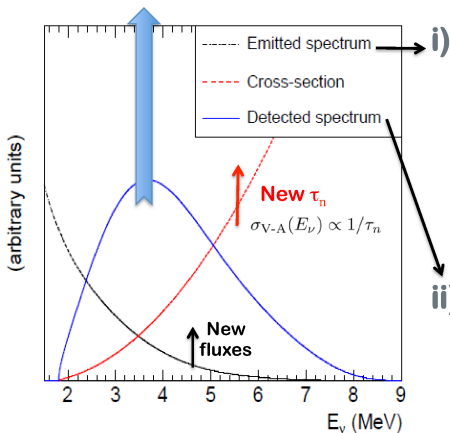


- ▶ Purpose: check LSND signal.
- ▶ Different  $L$  and  $E$ .
- ▶ Similar  $L/E$  (oscillations).
- ▶ LSND signal:  $E > 475 \text{ MeV}$ .

- ▶ Agreement with LSND signal?
- ▶ CP violation?
- ▶ Low-energy anomaly!

# New Reactor $\bar{\nu}_e$ Fluxes

Increased prediction of  
detected flux by 6.5%



## Neutrino Emission:

- Improved reactor neutrino spectra → +3.5%
- Accounting for long-lived isotopes in reactors → +1%

## ii) Neutrino Detection:

- Reevaluation of  $\sigma_{IBD}$  → +1.5%  
(evolution of the neutron life time)
- Reanalysis of all SBL experiments

[T. Lasserre, TAUP 2013]

# 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]

$\sim 2.8\sigma$  anomaly

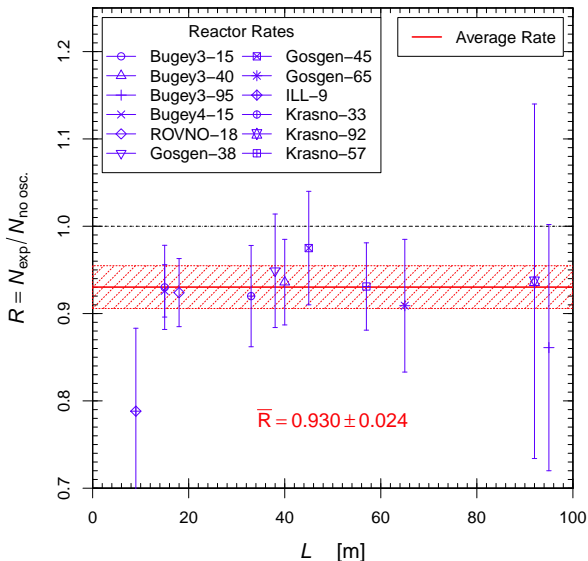
[see also:

Sinev, arXiv:1103.2452;

Ciuffoli, Evslin, Li, JHEP 12 (2012) 110;

Zhang, Qian, Vogel, PRD 87 (2013) 073018;

Ivanov et al, PRC 88 (2013) 055501]



# Gallium Anomaly

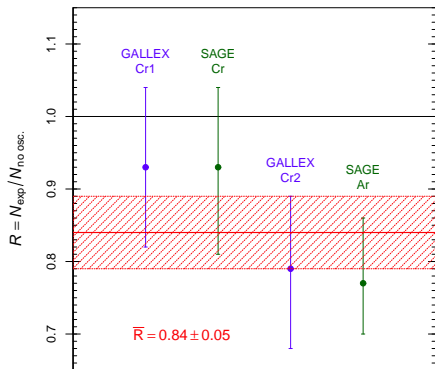
## Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

Anomaly supported by new  ${}^{71}\text{Ga}({}^3\text{He}, {}^3\text{H}){}^{71}\text{Ge}$  cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7 \text{ MeV}$

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

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

$\sim 2.9\sigma$  anomaly

[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; PRD 86 (2012) 113014]

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

## Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

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

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

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

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

- ▶ 6 mixing angles
- ▶ 3 Dirac CP phases
- ▶ 3 Majorana CP phases

↑  
SBL

but CP violation is not observable  
in SBL experiments!

# Effective SBL Oscillation Probabilities in 3+2 Schemes

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

$$\eta = \arg[U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*]$$

$$P_{\nu_{\mu} \rightarrow \nu_e}^{(-) \quad (-)} = 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu5}|^2 \sin^2 \phi_{51} \\ + 8|U_{\mu4} U_{e4} U_{\mu5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta)$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{(-) \quad (-)} = 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2 \phi_{41} + |U_{\alpha5}|^2 \sin^2 \phi_{51}) \\ - 4|U_{\alpha4}|^2 |U_{\alpha5}|^2 \sin^2 \phi_{54}$$

[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]

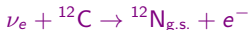
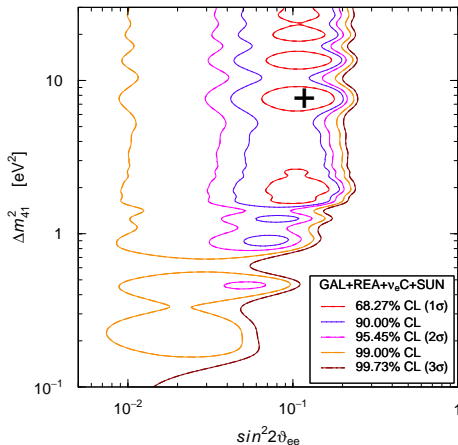
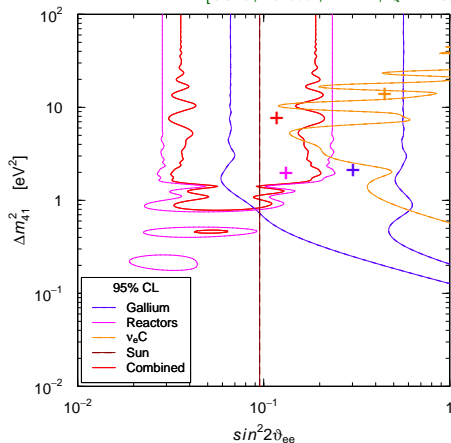
▶ Good: CP violation

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

4 more parameters:  $\underbrace{\Delta m_{41}^2, |U_{e4}|^2, |U_{\mu4}|^2, \Delta m_{51}^2, |U_{e5}|^2, |U_{\mu5}|^2}_{3+1}, \eta$

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

[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]



KARMEN + LSND

[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

solar  $\nu_e$  + KamLAND  $\bar{\nu}_e$  +  $\vartheta_{13}$

[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]

GoF = 62%      PGoF = 4%

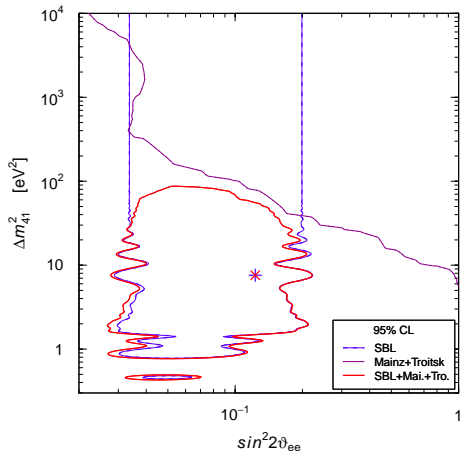
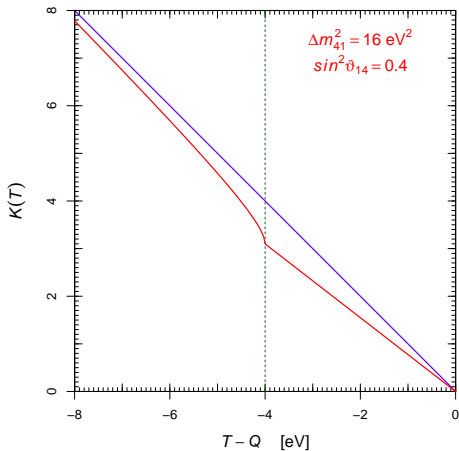
No Osc. excluded at  $2.7\sigma$

$\Delta\chi^2/\text{NDF} = 10.1/2$



# Mainz and Troitsk Limit on $m_4^2$

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323] [Belesev et al, JETP Lett. 97 (2013) 67; JPG 41 (2014) 015001]

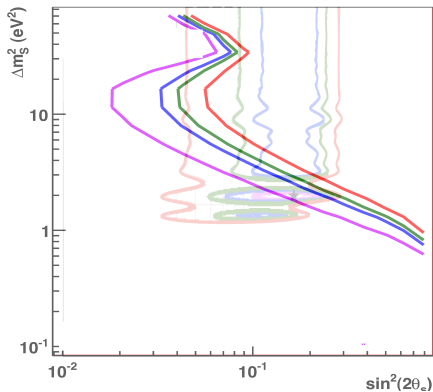


$$m_4 \gg m_1, m_2, m_3 \implies \Delta m_{41}^2 \equiv m_4^2 - m_1^2 \simeq m_4^2$$

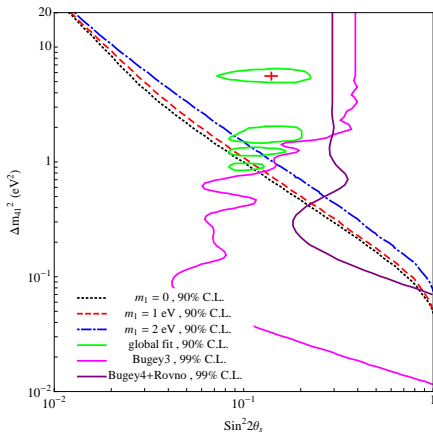
$$2\sigma : 0.85 \lesssim \Delta m_{41}^2 \lesssim 43 \text{ eV}^2 \implies 6 \text{ cm} \lesssim \frac{L_{41}^{\text{osc}}}{E [\text{MeV}]} \lesssim 3 \text{ m}$$

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 87 (2013) 013004]

# KATRIN Sensitivity



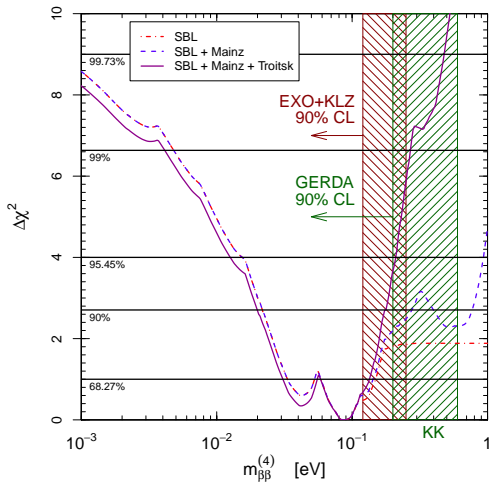
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also: Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

# Neutrinoless Double- $\beta$ Decay



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

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

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]

# 3+1: Appearance vs Disappearance

- ▶  $\nu_e$  disappearance experiments:

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

- ▶  $\nu_\mu$  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:

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

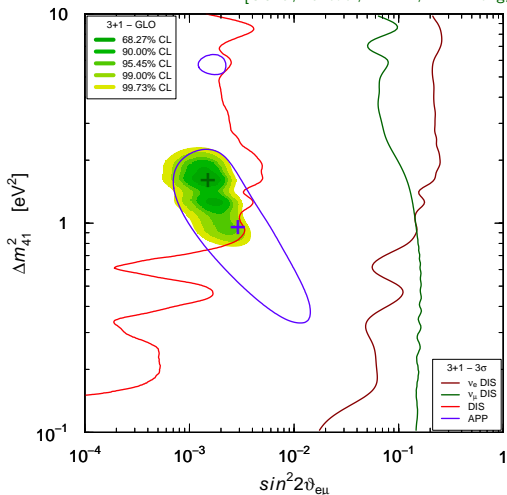
- ▶ Upper bounds on  $\sin^2 2\vartheta_{ee}$  and  $\sin^2 2\vartheta_{\mu\mu} \implies$  strong limit on  $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

# 3+1 Global Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008]



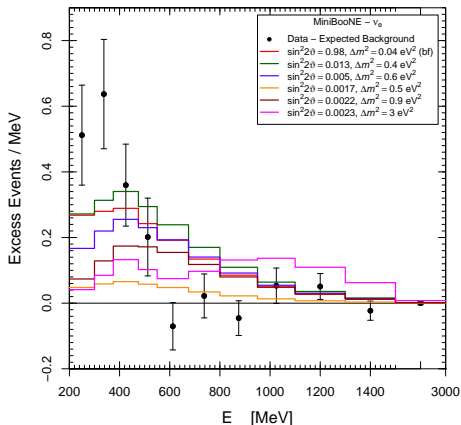
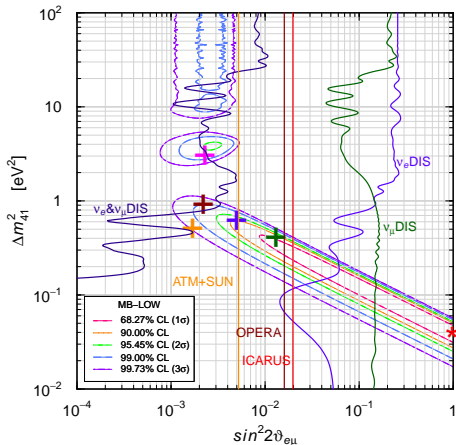
MiniBooNE  $E > 475$  MeV  
GoF = 29%      PGoF = 9%

- ▶ APP  $\nu_\mu \rightarrow \nu_e$  &  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ : LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- ▶ DIS  $\nu_e$  &  $\bar{\nu}_e$ : Reactors (Y), Gallium (Y),  $\nu_e C$  (N), Solar (N)
- ▶ DIS  $\nu_\mu$  &  $\bar{\nu}_\mu$ : CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

No Osc. excluded at  $6.2\sigma$   
 $\Delta\chi^2/\text{NDF} = 46.2/3$

[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

# MiniBooNE Low-Energy Excess?

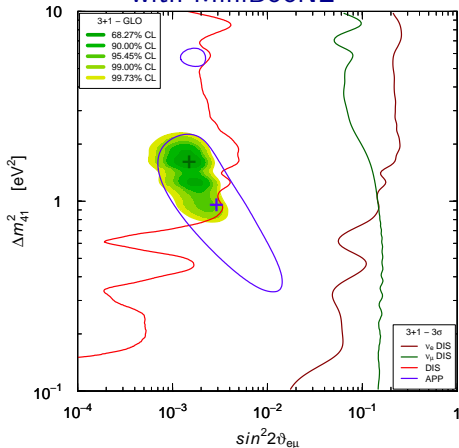


- ▶ No fit of low-energy excess for realistic  $\sin^2 2\vartheta_{e\mu} \lesssim 5 \times 10^{-3}$
- ▶ APP-DIS PGoF = 0.1%
- ▶ Neutrino energy reconstruction problem?

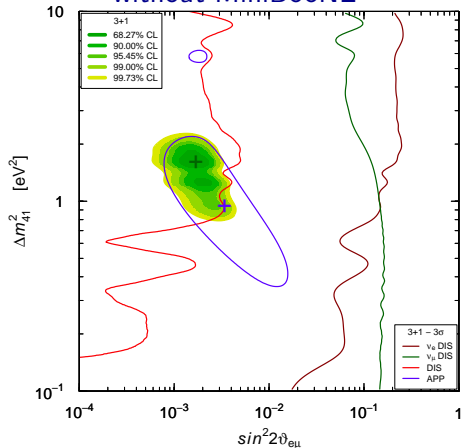
[Martini, Ericson, Chanfray, PRD 85 (2012) 093012; PRD 87 (2013) 013009]

# MiniBooNE Impact on SBL Oscillations?

with MiniBooNE



without MiniBooNE



GoF = 29%      PGoF = 9%

No Osc. excluded at 6.2 $\sigma$

$\Delta\chi^2/\text{NDF} = 46.2/3$

GoF = 19%      PGoF = 8%

No Osc. excluded at 6.3 $\sigma$

$\Delta\chi^2/\text{NDF} = 47.1/3$

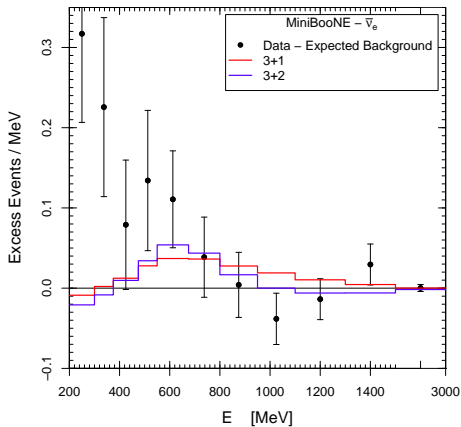
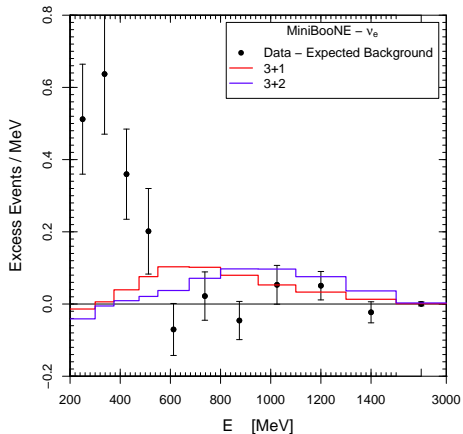
Without LSND: No Osc. excluded only at 2.1 $\sigma$  ( $\Delta\chi^2/\text{NDF} = 8.3/3$ )

# 3+2

- ▶  $3+2$  should be preferred to  $3+1$  only if
  - ▶ there is evidence of two peaks of the probability corresponding to two  $\Delta m^2$ 's
  - or
  - ▶ there is CP-violating difference of  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  transitions
- ▶ 2008  $\nu$  + 2010  $\bar{\nu}$  MiniBooNE data indicated  $\nu-\bar{\nu}$  difference
  - ⇓
  - reasonable and useful to consider  $3+2$
- ▶  $\nu-\bar{\nu}$  difference almost disappeared with 2012  $\bar{\nu}$  data
- ▶ Okkam razor:  $3+1$  is enough!
- ▶ Different approach and conclusions:
  - ▶ Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050:  
Use all MiniBooNE data. No  $3+1$  global fit.  $3+2$  slightly preferred? Small allowed region.
  - ▶ Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897:  
Use all MiniBooNE data.  $3+2$  strongly preferred. Very small allowed regions.

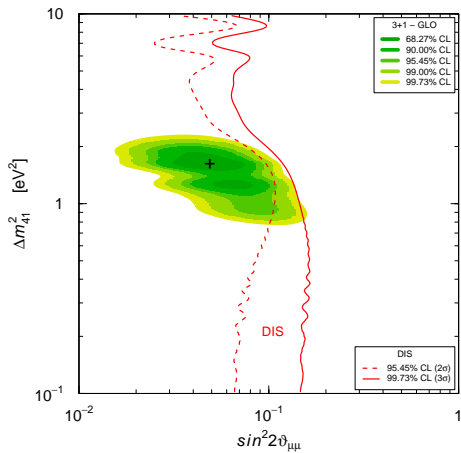
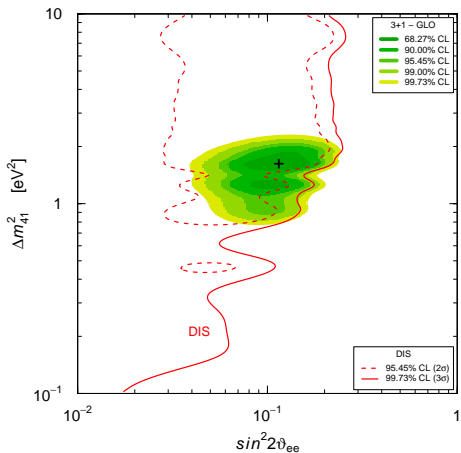


# MiniBooNE Low-Energy Excess?



- ▶ 3+1: GoF = 6%      PGoF = 0.2%
- ▶ 3+2: GoF = 8%      PGoF = 0.1%

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



# Many Exciting New Experiments and Projects

- ▶ Reactor  $\bar{\nu}_e$  Disappearance:
  - ▶ Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - ▶ DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - ▶ SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - ▶ CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - ▶ Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- ▶ Radioactive Source  $\nu_e$  and  $\bar{\nu}_e$  Disappearance:
  - ▶ SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - ▶ CeLAND ( $^{144}\text{Ce}$ @KamLAND, Japan) [arXiv:1107.2335]
  - ▶ SAGE (Baksan, Russia) [arXiv:1006.2103]
  - ▶ IsoDAR (DAE $\delta$ ALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - ▶ SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- ▶ Accelerator  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  Appearance:
  - ▶ ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - ▶ nuSTORM [arXiv:1308.0494]
  - ▶ OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

## Effects of light sterile neutrinos can be also 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]

### ▶ Atmospheric neutrinos

[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, arXiv:1307.6824]

### ▶ 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, arXiv:1305.2382]

# Conclusions

- ▶ Short-Baseline  $\nu_e$  and  $\bar{\nu}_e$  3+1 Disappearance:
  - ▶ Reactor  $\bar{\nu}_e$  anomaly is alive and exciting.
  - ▶ Gallium  $\nu_e$  anomaly strengthened by new cross-section measurements.
  - ▶ Many promising projects to test 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:
  - ▶ MiniBooNE experiment has been inconclusive.
  - ▶ Better experiments are needed to check LSND signal!
  - ▶ If  $|U_{e4}| > 0$  why not  $|U_{\mu4}| > 0$ ?  $\implies$  Maybe LSND luckily observed a fluctuation of a small  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  transition probability with amplitude  $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2$ , which has not been seen by other appearance experiments.
- ▶ Cosmology:
  - ▶ Important effects of sterile neutrinos.
  - ▶ Implications depend on theoretical framework and considered data set.
  - ▶ Cosmological indications must be checked by laboratory experiments.