

Phenomenology of Sterile Neutrinos

Carlo Giunti

INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino

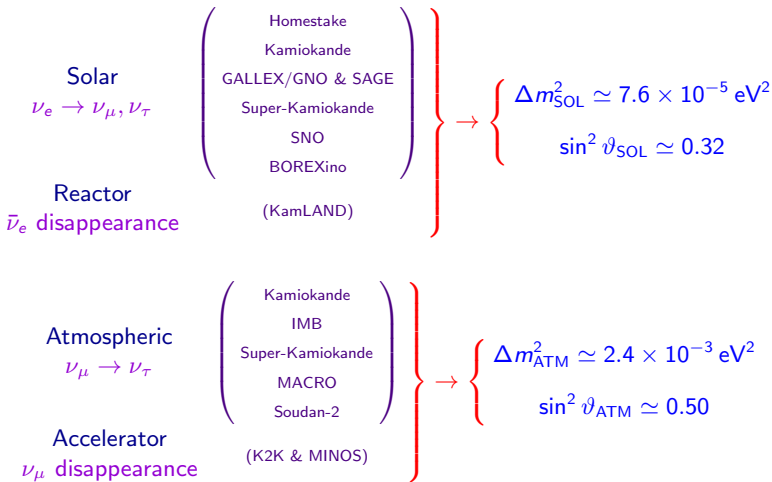
<mailto://giunti@to.infn.it>

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

Moscow State University

15 February 2012

Three-Neutrino Mixing Paradigm



Two scales of $\Delta m^2 \iff$ Three-Neutrino Mixing

$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$$

Three-Neutrino Mixing

$$\nu_{\alpha L} = \sum_{k=1}^3 U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau)$$

three flavor fields: ν_e, ν_μ, ν_τ

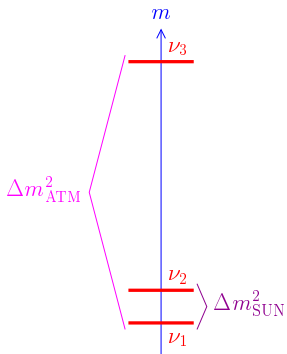
three massive fields: ν_1, ν_2, ν_3

$$\Delta m_{21}^2 + \Delta m_{32}^2 + \Delta m_{13}^2 = m_2^2 - m_1^2 + m_3^2 - m_2^2 + m_1^2 - m_3^2 = 0$$

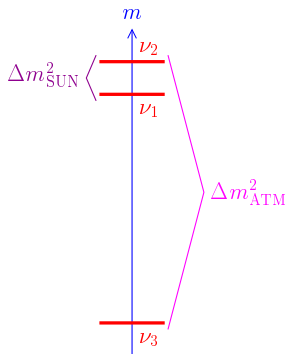
$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.6 \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$$

Allowed Three-Neutrino Schemes



"normal"



"inverted"

different signs of $\Delta m_{31}^2 \simeq \Delta m_{32}^2$

absolute scale is not determined by neutrino oscillation data

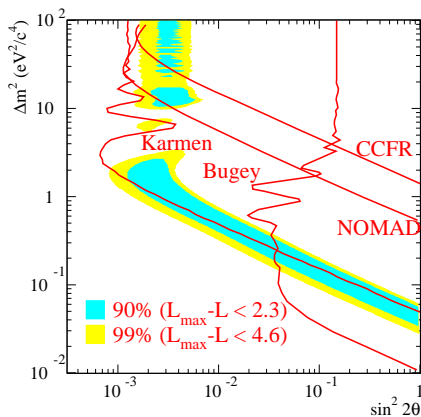
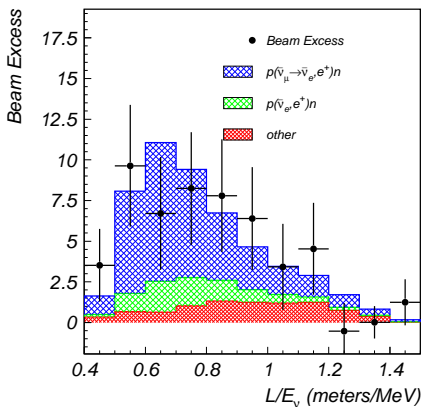
LSND

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

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

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

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



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

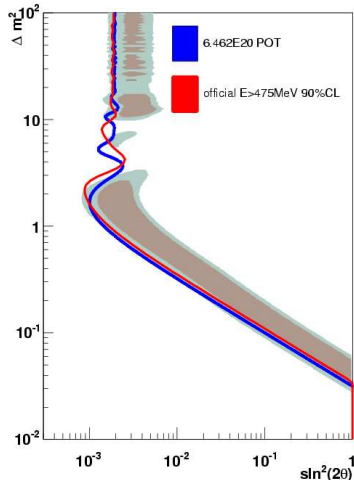
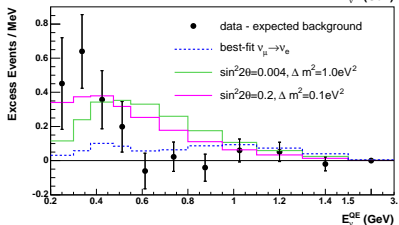
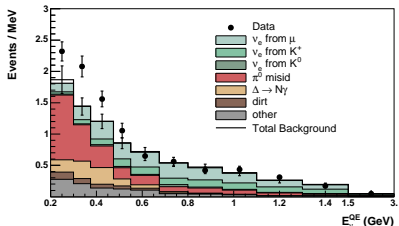
MiniBooNE Neutrinos

[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

$$\nu_\mu \rightarrow \nu_e$$

$$L \simeq 541 \text{ m}$$

$$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]

[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

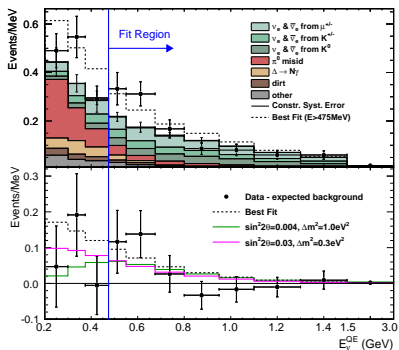
MiniBooNE Antineutrinos

[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

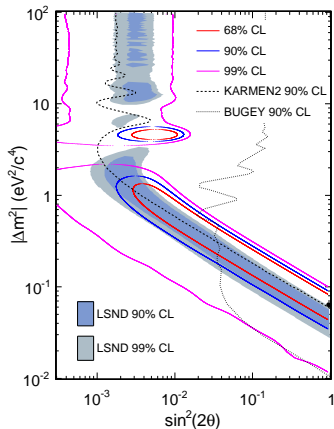
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$L \simeq 541 \text{ m}$$

$$475 \text{ MeV} \leq E \lesssim 3 \text{ GeV}$$



[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



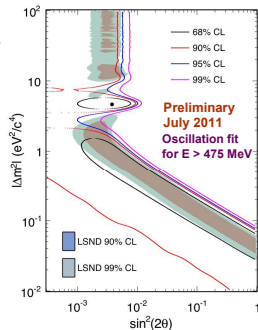
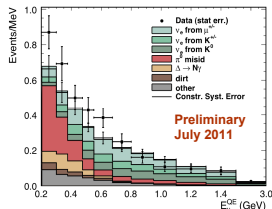
Agreement with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal!

Similar L/E but different L and $E \implies$ Oscillations!

Updated MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result

- Updated result from previous publication
 - 5.66E20 \Rightarrow 8.58E20 protons-on-target (x1.5)
 - Reduced systematic uncertainties especially backgrounds from beam K^+ decays
- For $E > 475$ MeV (>200 MeV), oscillations favored over background only (null) hypothesis at the 91.1% CL (97.6% CL)
 - Consistent with LSND but less strong than previous result (99.4%)
 - Best fit: χ^2 prob. = 35.5% (51%)
Null: χ^2 prob. = 14.9% (10%)
- Low energy excess now more prominent for antineutrino running than previous result
 - For $E < 475$ MeV, excess = 38.6 ± 18.5 (For all energies, excess = 57.7 ± 28.5)
 - Neutrino and antineutrino results are now more similar.
- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (\sim x2 from this update)
 - Full data set will probe LSND signal at the 2-3 sigma level

See E. Zimmerman talk yesterday for details



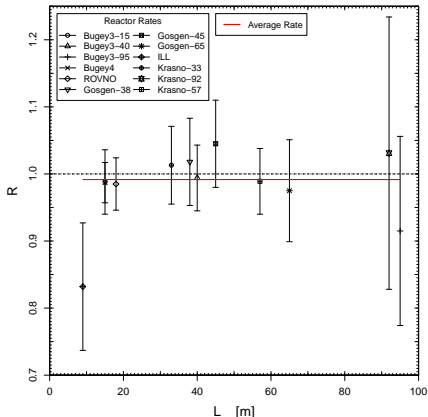
M. Shaevitz, PANIC11, 26 July 2011

[E. D. Zimmerman, arXiv:1111.1375; Z. Djurcic, arXiv:1201.1519]

Reactor Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006, arXiv:1101.2755]

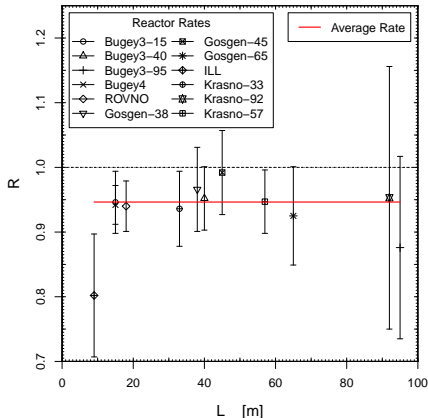
Old Reactor $\bar{\nu}_e$ Fluxes



$$\bar{R} = 0.992 \pm 0.024$$

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

[Mueller et al, PRC 83 (2011) 054615, arXiv:1101.2663]



$$\bar{R} = 0.946 \pm 0.024$$

Gallium Anomaly

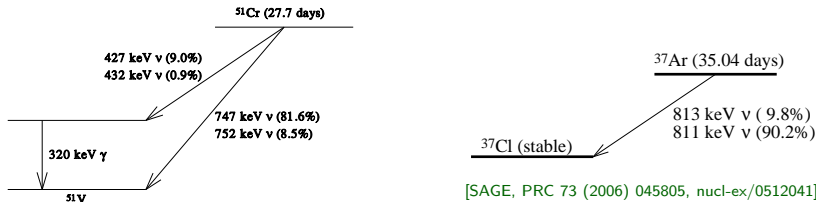
Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors **GALLEX** (Cr1, Cr2) and **SAGE** (Cr, Ar)

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

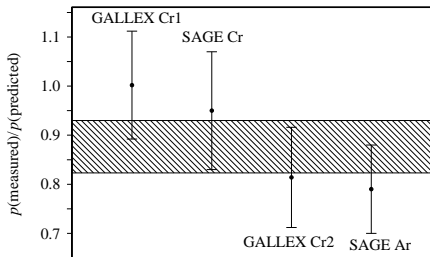
ν_e Sources: $e^- + {}^{51}\text{Cr} \rightarrow {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \rightarrow {}^{37}\text{Cl} + \nu_e$

	${}^{51}\text{Cr}$				${}^{37}\text{Ar}$	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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

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

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$R_B^{\text{Gallex-Cr1}} = 0.953 \pm 0.11$$

$$R_B^{\text{Gallex-Cr2}} = 0.812^{+0.10}_{-0.11}$$

$$R_B^{\text{SAGE-Cr}} = 0.95 \pm 0.12$$

$$R_B^{\text{SAGE-Ar}} = 0.791^{+0.084}_{-0.078}$$

$$R_B^{\text{Ga}} = 0.86 \pm 0.05$$

Bahcall cross section without uncertainty

[Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

$$R^{\text{Gallex-Cr1}} = 0.84^{+0.13}_{-0.12}$$

$$R^{\text{Gallex-Cr2}} = 0.71^{+0.12}_{-0.11}$$

$$R^{\text{SAGE-Cr}} = 0.84^{+0.14}_{-0.13}$$

$$R^{\text{SAGE-Ar}} = 0.70^{+0.10}_{-0.09}$$

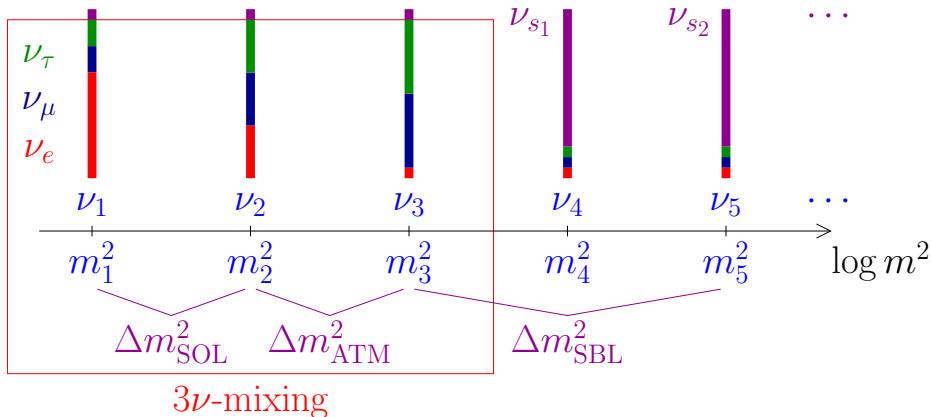
$$R^{\text{Ga}} = 0.76^{+0.09}_{-0.08}$$

[Giunti, Laveder, PRC 83 (2011) 065504, arXiv:1006.3244]

Haxton cross section and uncertainty

[Haxton, PLB 431 (1998) 110, arXiv:nucl-th/9804011]

Beyond Three-Neutrino Mixing



Standard Model

- ▶ Neutrinos are the only massless fermions
- ▶ Neutrinos are the only fermions with only left-handed component ν_L

Extension of the SM: Massive Neutrinos

- ▶ Simplest extension: introduce right-handed component ν_R
- ▶ Dirac mass $m_D \overline{\nu_R} \nu_L$ + Majorana mass $m_M \overline{\nu_R^c} \nu_R$
- ▶ $\nu_{eL}, \nu_{\mu L}, \nu_{\tau L} + \nu_{eR}, \nu_{\mu R}, \nu_{\tau R} \implies$ 6 massive Majorana neutrinos

Sterile Neutrinos

- ▶ Light anti- ν_R are called sterile neutrinos

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

- ▶ Sterile means no standard model interactions
- ▶ Active neutrinos (ν_e, ν_μ, ν_τ) can oscillate into sterile neutrinos (ν_s)
- ▶ Observables:
 - ▶ Disappearance of active neutrinos (neutral current deficit)
 - ▶ Indirect evidence through combined fit of data (current indication)
- ▶ Powerful window on new physics beyond the Standard Model

- ▶ In this talk I consider sterile neutrinos with mass scale ~ 1 eV in light of LSND, MiniBooNE, Reactor Anomaly, Gallium Anomaly.
- ▶ Other possibilities (not exclusive):
 - ▶ Very light sterile neutrinos with mass scale $\ll 1$ eV: important for solar neutrino phenomenology
 - ▶ Heavy sterile neutrinos with mass scale $\gg 1$ eV: could be Warm Dark Matter

[de Holanda, Smirnov, PRD 83 (2011) 113011, arXiv:1012.5627]

[Kusenko, Phys. Rept. 481 (2009) 1, arXiv:0906.2968]

[Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191, arXiv:0901.0011]

Cosmology

- ▶ N_s = number of thermalized sterile neutrinos (not necessarily integer)
- ▶ CMB and LSS in Λ CDM: $N_s = 1.3 \pm 0.9$ $m_s < 0.66$ eV (95% C.L.)

[Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301, arXiv:1006.5276]

$$N_s = 1.61 \pm 0.92 \quad m_s < 0.70 \text{ eV} \quad (95\% \text{ C.L.})$$

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, PRD 83 (2011) 115023, arXiv:1102.4774]

$$N_s = 1.12^{+0.86}_{-0.74} \quad (95\% \text{ C.L.}) \quad [\text{Archidiacono, Calabrese, Melchiorri, PRD 84 (2011) 123008, arXiv:1109.2767}]$$

- ▶ BBN: $\begin{cases} N_s = 0.22 \pm 0.59 & [\text{Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033}] \\ N_s = 0.64^{+0.40}_{-0.35} & [\text{Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440}] \\ N_s \leq 1 \text{ at } 95\% \text{ C.L.} & [\text{Mangano, Serpico, PLB 701 (2011) 296, arXiv:1103.1261}] \end{cases}$

- ▶ CMB+LSS+BBN: $N_s = 0.85^{+0.39}_{-0.56}$ (95% C.L.)

[Hamann, Hannestad, Raffelt, Wong, JCAP 1109 (2011) 034, arXiv:1108.4136]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

No CP Violation!

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

Perturbation of 3 ν Mixing

$$|U_{e4}|^2 \ll 1, \quad |U_{\mu 4}|^2 \ll 1, \quad |U_{\tau 4}|^2 \ll 1, \quad |U_{s4}|^2 \simeq 1$$

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

↑
SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

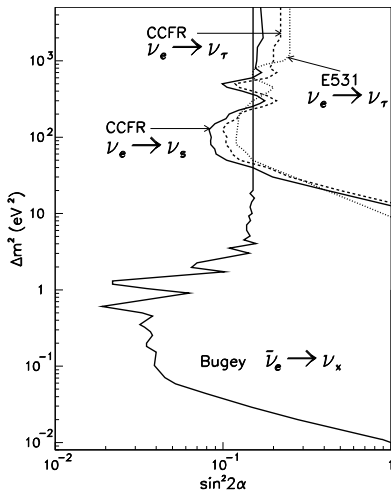


$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$

Direct Searches of Active-Sterile Transitions

CCFR

[PRD 59 (1999) 031101, arXiv:hep-ex/9809023]



NC interactions

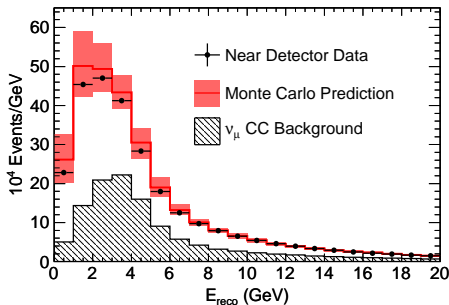
$E \sim 100 \text{ GeV}$

$L \simeq 1.4 \text{ km}$

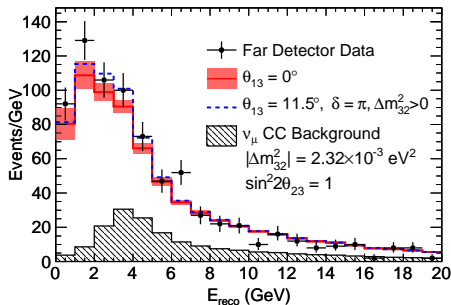
MINOS

[MINOS, PRL 107 (2011) 011802, arXiv:1104.3922]

NC sample: 89% efficiency and 61% purity
97% of ν_e -induced CC events misidentified as NC



$L_{\text{ND}} = 1.04$ km



$L_{\text{FD}} = 735$ km

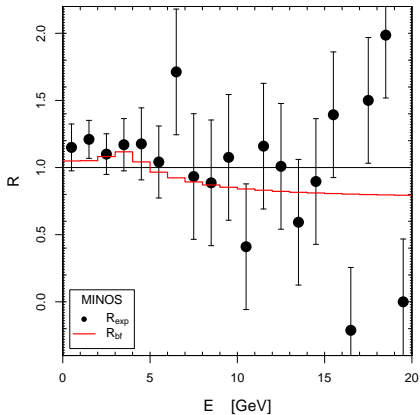
ϑ_{13}	χ^2/NDF	ϑ_{23}	ϑ_{24}	ϑ_{34}
0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$
11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$

$$\vartheta_{24} \lesssim 8^\circ \text{ at } 90\% \text{ C.L.} \implies |U_{\mu 4}|^2 \simeq \sin^2 \vartheta_{24} \lesssim 0.019$$

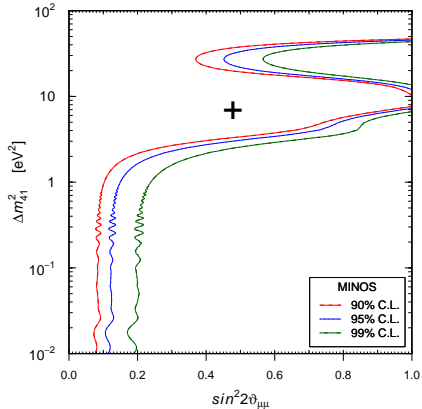
$$|U_{\mu 4}|^2 \lesssim 0.035 \text{ at } 99\% \text{ C.L.}$$

Hernandez, Smirnov, PLB 706 (2012) 360, arXiv:1105.5946

- ▶ Limit valid for $\Delta m_{41}^2 \lesssim 0.5 \text{ eV}^2$.
- ▶ For $\Delta m_{41}^2 \gtrsim 0.5 \text{ eV}^2$ SBL oscillations at Near Detector.
- ▶ MINOS insensitive to oscillations for $\Delta m_{41}^2 \gtrsim 15 \text{ eV}^2$ because oscillations already averaged at Near Detector.

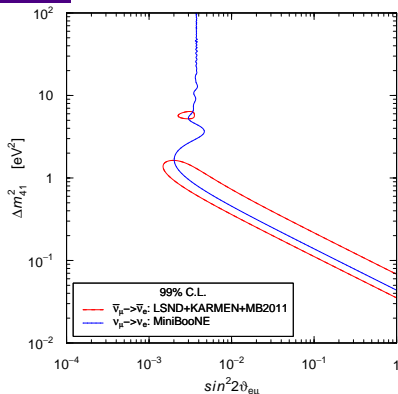
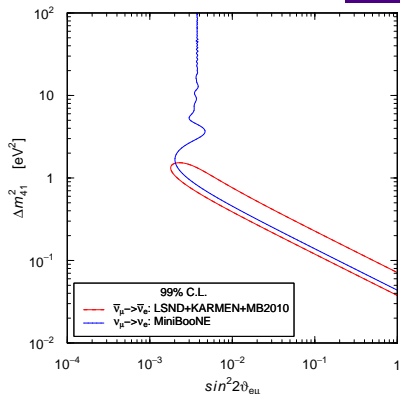


$$R = \frac{\langle 1 - P_{\nu_\mu \rightarrow \nu_s} \rangle_{\text{FD}}}{\langle 1 - P_{\nu_\mu \rightarrow \nu_s} \rangle_{\text{ND}}}$$



[Giunti, Laveder, PRD 84 (2011) 093006, arXiv:1109.4033]

MiniBooNE



GoF = 17%, PGoF = 0.15%

GoF = 36%, PGoF = 3.3%

- ▶ Tension between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data is reduced with MiniBooNE 2011 antineutrino data.
- ▶ **3+2 \implies CP Violation** [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255], [Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107], [Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997], [Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801, arXiv:1103.4570], [Giunti, Laveder, PRD 84 (2011) 073008, arXiv:1107.1452]
- ▶ **3+1+NSI \implies CP Violation** [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]

Goodness of Fit

- ▶ Assumption or approximation: Gaussian uncertainties and linear model
- ▶ χ^2_{\min} has χ^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

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

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

Parameter Goodness of Fit

Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

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

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

- ▶ χ^2_{PGoF} has χ^2 distribution with Number of Degrees of Freedom

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

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

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

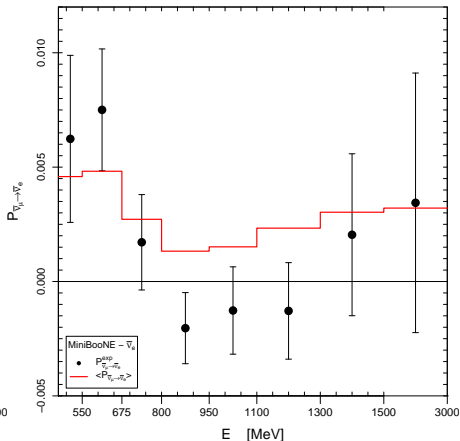
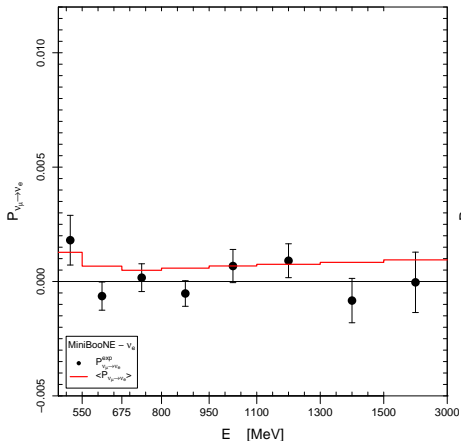
$$\eta = \arg[U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*]$$

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

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

- ▶ **Good:** CP violation can solve the $\nu_{\mu} \rightarrow \nu_e$ vs $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$ tension.
- ▶ **Bad:**
 - ▶ More parameters: 7 (vs 3 in 3+1)
 - ▶ 2 sterile neutrinos are disfavored by BBN.
 - ▶ A large sum of masses is disfavored by CMB+LSS.

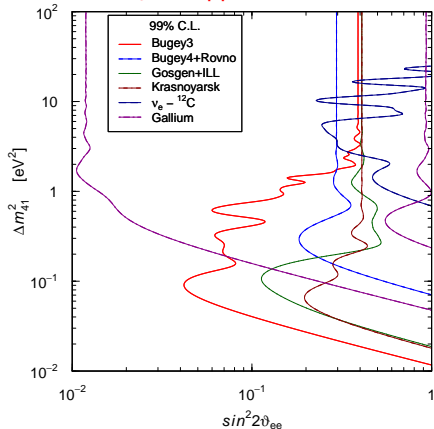
3+2: MiniBooNE $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



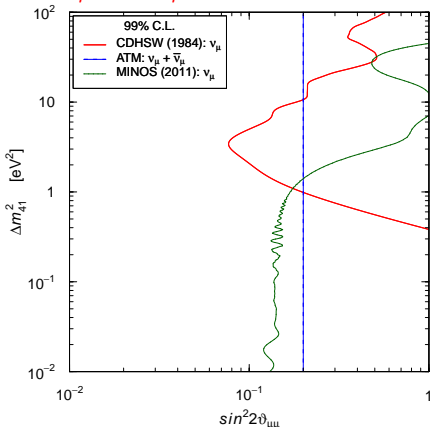
$$\begin{aligned}
 P_{(-)}^{(-)} = & 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2 \phi_{51} \\
 & + 4|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \cos \eta [\sin^2 \phi_{41} + \sin^2 \phi_{51} - \sin^2 \phi_{54}] \\
 & - 2|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \sin \eta [\sin(2\phi_{41}) - \sin(2\phi_{51}) + \sin(2\phi_{54})]
 \end{aligned}$$

Disappearance Constraints

$\bar{\nu}_e$ Disappearance



ν_μ and $\bar{\nu}_\mu$ Disappearance



▶ New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al., arXiv:1101.2663]

[Mention et al., arXiv:1101.2755]

▶ KARMEN+LSND $\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N}_{\text{g.s.}} + e^-$

[Conrad, Shaevitz, arXiv:1106.5552]

[Giunti, Laveder, arXiv:1111.1069]

▶ ATM constraint on $|U_{\mu 4}|^2$

[Maltoni, Schwetz, arXiv:0705.0107]

▶ MINOS constraint on $|U_{\mu 4}|^2$

[Giunti, Laveder, arXiv:1109.4033]

3+1

- ▶ 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:

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

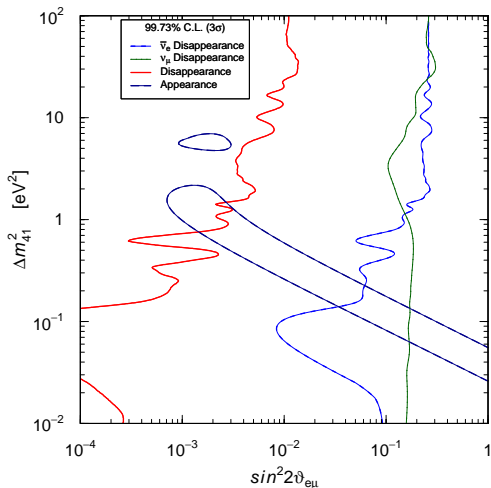
- ▶ $\nu_\mu \rightarrow \nu_e$ experiments:

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

- ▶ 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, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]



3+1

GoF = 50%

PGoF = 0.3%

[Giunti, Laveder, arXiv:1111.1069]

▶ 3+1: Appearance-Disappearance tension

▶ 3+2: same tension

[Kopp, Maltoni, Schwetz, arXiv:1103.4570], [Giunti, Laveder, arXiv:1107.1452]

▶ Tension reduced in 3+1+NSI

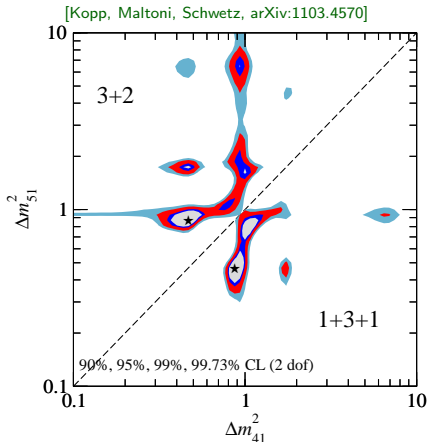
[Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]

▶ No tension in 3+1+CPTV

[Barger, Marfatia, Whisnant, PLB 576 (2003) 303]

[Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

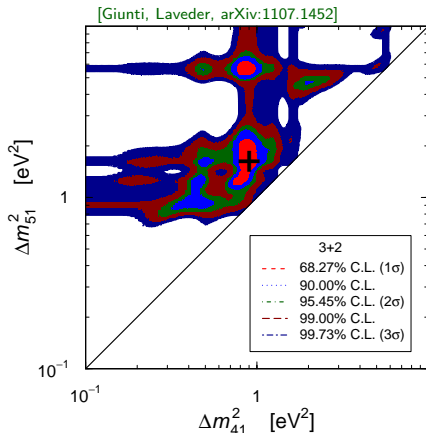
Global 3+2 Fits



Best Fit: $\eta = 1.64\pi$

$\Delta m_{41}^2 = 0.47 \text{ eV}^2$	$\Delta m_{51}^2 = 0.87 \text{ eV}^2$
$ U_{e4} ^2 = 0.016$	$ U_{e5} ^2 = 0.019$
$ U_{\mu 4} ^2 = 0.027$	$ U_{\mu 5} ^2 = 0.022$

$\chi_{\min}^2/\text{NDF} = 110.1/130$



Best Fit: $\eta = 1.52\pi$

$\Delta m_{41}^2 = 0.90 \text{ eV}^2$	$\Delta m_{51}^2 = 1.60 \text{ eV}^2$
$ U_{e4} ^2 = 0.017$	$ U_{e5} ^2 = 0.017$
$ U_{\mu 4} ^2 = 0.018$	$ U_{\mu 5} ^2 = 0.0064$

$\chi_{\min}^2/\text{NDF} = 91.6/100$

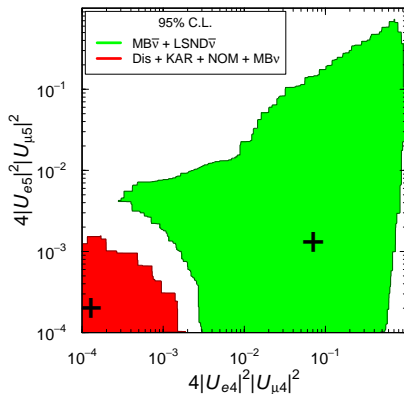
3+2: Persisting Tension

	3+1	3+2
$\Delta\chi_{PG}^2$	21.5	19.9
NDF_{PG}	2	5
PGoF	2×10^{-5}	1.3×10^{-3}

[Kopp, Maltoni, Schwetz, arXiv:1103.4570]

	3+1	3+2
$\Delta\chi_{PG}^2$	24.1	22.2
NDF_{PG}	2	5
PGoF	6×10^{-6}	5×10^{-4}

[Giunti, Laveder, arXiv:1107.1452]

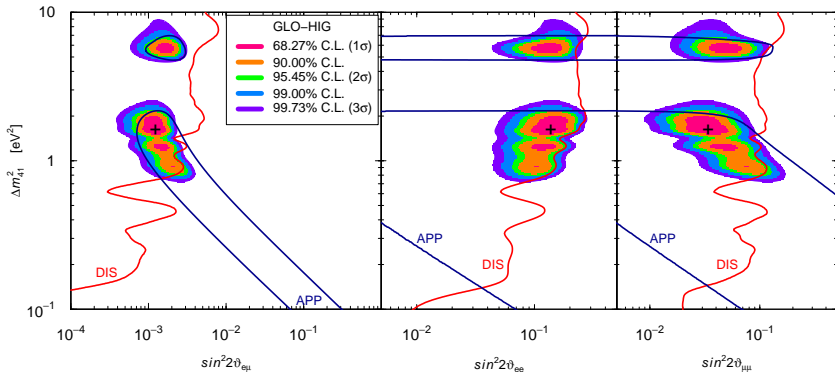


- ▶ 3+2 improvement of PGoF is mainly a statistical effect!
- ▶ 3+2 is preferred to 3+1 only for CP-violating MiniBooNE neutrino antineutrino difference.

Back to 3+1 Neutrino Mixing

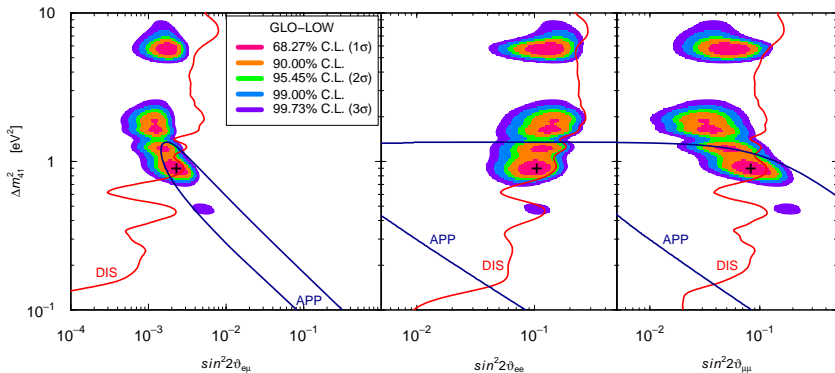
[Giunti, Laveder, arXiv:1109.4033, arXiv:1111.1069]

- ▶ Simplest scheme beyond standard three-neutrino mixing which can partially explain the data.
- ▶ It corresponds to the natural addition of one new entity (a sterile neutrino) to explain a new effect (short-baseline oscillations).
- ▶ Global χ^2 is good: $\chi_{\min}^2/\text{NDF} = 137.5/138$.
- ▶ Marginal compatibility with cosmology for $\Delta m_{41}^2 \lesssim 1 \text{ eV}^2$.



- ▶ Best fit at $\Delta m_{41}^2 \approx 1.62 \text{ eV}^2 \implies m_4 \approx 1.3 \text{ eV}$
- ▶ Large Δm_{41}^2 preferred by MiniBooNE 2011 $\bar{\nu}_e$ data, reactor, Gallium and MINOS disappearance data.
- ▶ Small Δm_{41}^2 preferred by MiniBooNE ν_e data, KARMEN and NOMAD $\bar{\nu}_e$ data, CDHS and $\nu_e - {}^{12}\text{C}$ disappearance data.
- ▶ Marginal tension with standard cosmology.

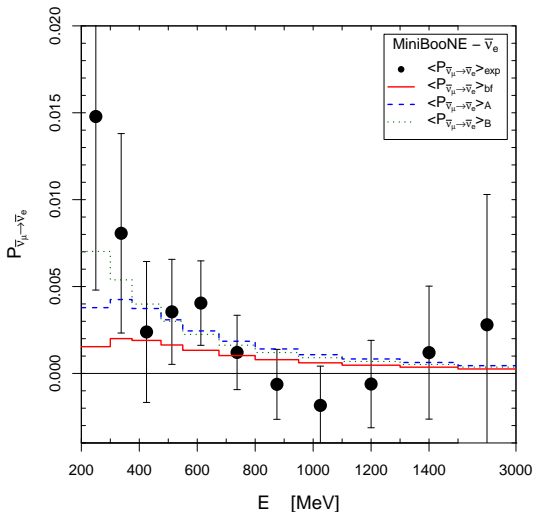
MiniBooNE Low-Energy Anomaly



GoF = 30%

PGoF = 0.008%

- ▶ Best fit at $\Delta m_{41}^2 \approx 0.89 \text{ eV}^2 \implies m_4 \approx 0.94 \text{ eV} \implies$ Better compatibility with cosmological bound on m_4 .
- ▶ APP-DIS tension indicates that MiniBooNE low-energy anomaly may have an explanation different from $\nu_{\mu}^{(-)} \rightarrow \nu_e^{(-)}$ oscillations.



bf: $\sin^2 2\vartheta_{e\mu} = 0.0023$
 $\Delta m_{41}^2 = 0.89 \text{ eV}^2$

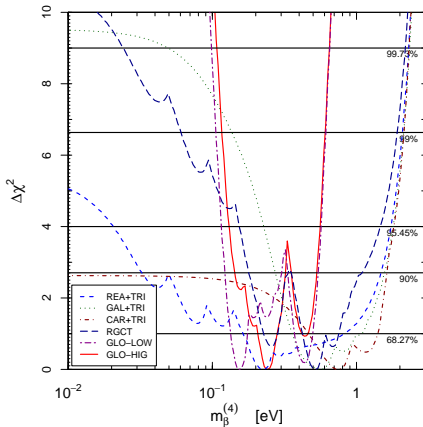
A: $\sin^2 2\vartheta_{e\mu} = 0.005$
 $\Delta m_{41}^2 = 0.8 \text{ eV}^2$

B: $\sin^2 2\vartheta_{e\mu} = 0.01$
 $\Delta m_{41}^2 = 0.5 \text{ eV}^2$

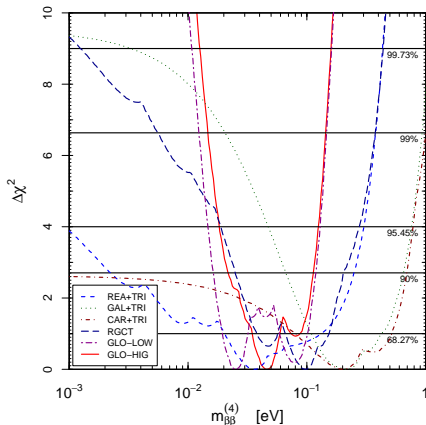
Testable Implications

[Giunti, Laveder, PLB 706 (2011) 200, arXiv:1111.1069]

β Decay



$(\beta\beta)_{0\nu}$ Decay



$$m_\beta = \sqrt{\sum_k |U_{ek}|^2 m_k^2}$$

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

$$m_{\beta\beta} = \left| \sum_k U_{ek}^2 m_k \right|$$

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

Future

- ▶ MiniBooNE is continuing to take antineutrino data.

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

- ▶ ICARUS@CERN-PS: $L \sim 1\text{km}$ $E \sim 1\text{GeV}$ [C. Rubbia et al, CERN-SPSC-2011-012]

$$\bar{\nu}_\mu^{(-)} \rightarrow \bar{\nu}_e^{(-)} + \bar{\nu}_\mu^{(-)} \rightarrow \bar{\nu}_\mu^{(-)} + \bar{\nu}_e^{(-)} \rightarrow \bar{\nu}_e^{(-)}$$

- ▶ MicroBooNE will test the MiniBooNE low-energy anomaly by measuring $\pi^0 \rightarrow 2\gamma$ background.

- ▶ LSND reloaded? Super-Kamiokande doped with Gadolinium

[Agarwalla, Huber, PLB 696 (2011) 359, arXiv:1007.3228.]

- ▶ Reactor Anomaly: Nucifer, small scintillator detector at $L = 7\text{m}$

[Lasserre, talk at EPS-HEP 2011]

- ▶ Possible experiment at a small-size fast neutron reactor

[Yasuda, JHEP 1109 (2011) 036, arXiv:1107.4766]

- ▶ Gallium Anomaly: new SAGE Gallium source experiments with 2 spherical shells [Gavrin et al, arXiv:1006.2103]
- ▶ ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold detectors.
- ▶ Borexino: $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ [Cribier et al, PRL 107 (2011) 201801, arXiv:1107.2335]
[Pallavicini, talk at BEYOND3NU]
[Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]
- ▶ LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]
 - $\nu_e + {}^{115}\text{In} \rightarrow {}^{115}\text{Sn} + e^- + 2\gamma$ $E_{\text{th}} = 0.1 \text{ MeV}$
 - $\bar{\nu}_e + p \rightarrow n + e^+$ $E_{\text{th}} = 1.8 \text{ MeV}$
- ▶ Spherical Gaseous TPC: [Vergados, Giomataris, Novikov, NPB 854 (2012) 54, arXiv:1103.5307]
 - Targets: ${}^{131}\text{Xe}$, ${}^{40}\text{Ar}$, ${}^{20}\text{Ne}$, ${}^4\text{He}$. Sources: ${}^{37}\text{Ar}$, ${}^{51}\text{Cr}$, ${}^{65}\text{Zn}$, ${}^{32}\text{P}$.
- ▶ Coherent neutrino-nucleon scattering in low-temperature bolometers [Formaggio, Figueroa-Feliciano, Anderson, PRD 85 (2012) 013009, arXiv:1107.3512]

- ▶ Near-Detector Beta-Beam experiments: [Agarwalla, Huber, Link, JHEP 01 (2010) 071]

$$N(A, Z) \rightarrow N(A, Z + 1) + e^- + \bar{\nu}_e \quad (\beta^-)$$

$$N(A, Z) \rightarrow N(A, Z - 1) + e^+ + \nu_e \quad (\beta^+)$$

- ▶ ND Neutrino Factory experiments: [Giunti, Laveder, Winter, PRD 80 (2009) 073005]

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

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

- ▶ ND+FD at Low Energy Neutrino Factory (LENF) [Pascoli and Wong, poster at NUFAC 11]

- ▶ CPT tests: $A_{\alpha\beta}^{\text{CPT}} = P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha}$

Conclusions

- ▶ Suggestive LSND, MiniBooNE, Reactor and Gallium indications in favor of short-baseline neutrino oscillations \implies sterile neutrinos
- ▶ 3+1 Neutrino Mixing:
 - ▶ No CP violation \implies Neutrinos vs Antineutrinos tension
 - ▶ Appearance vs Disappearance tension
 - ▶ Marginal compatibility with cosmology.
- ▶ 3+2 Neutrino Mixing:
 - ▶ CP violation \implies no Neutrinos vs Antineutrinos tension
 - ▶ Appearance vs Disappearance tension
 - ▶ Tension with cosmology.
- ▶ Neutrinos vs Antineutrinos tension has diminished with 2011 MiniBooNE data.
- ▶ Simpler 3+1 Neutrino Mixing may be enough (Occam's Razor).
- ▶ New short-baseline neutrino oscillation experiments are needed!