Current Status of ν Anomalies & Their Impact on Astrophysics

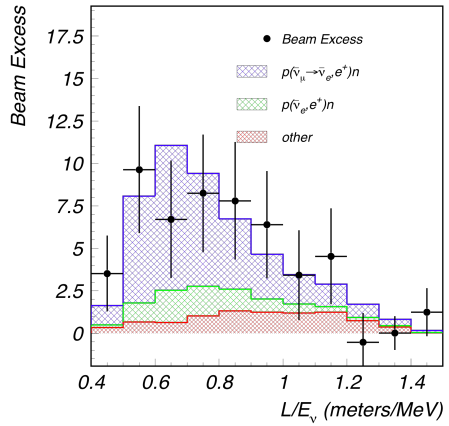
W. C. Louis

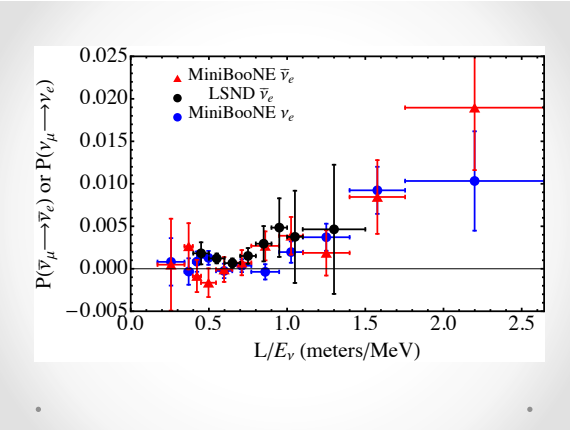
SLAC Intensity Frontier Workshop

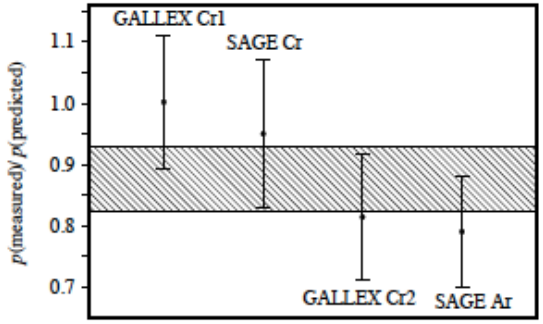
March 6, 2013

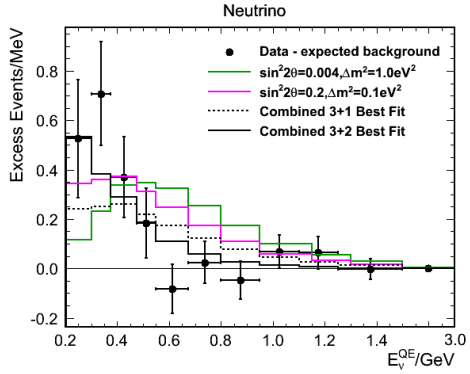
- Summary of Neutrino Anomalies
- Explaining the Anomalies with 3+N Sterile Neutrino Models
  (Although there are other possibilities!)
- Global Fits to the World Data
- Impact of Sterile Neutrinos on Astrophysics
- Future Experiments

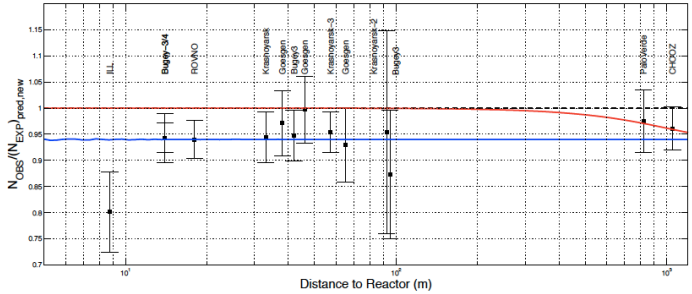
Short-Baseline Neutrino Anomalies

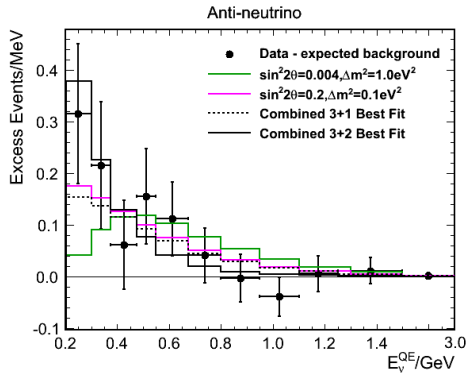


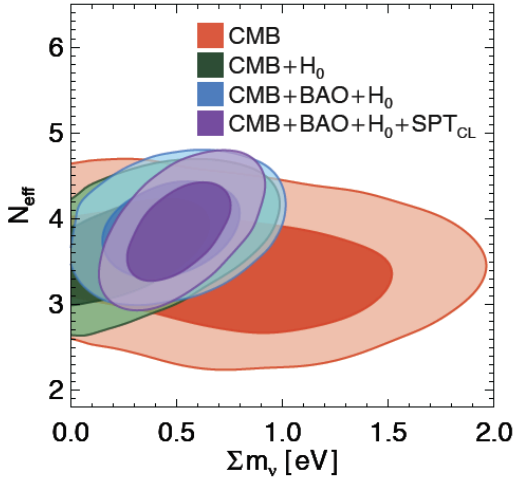






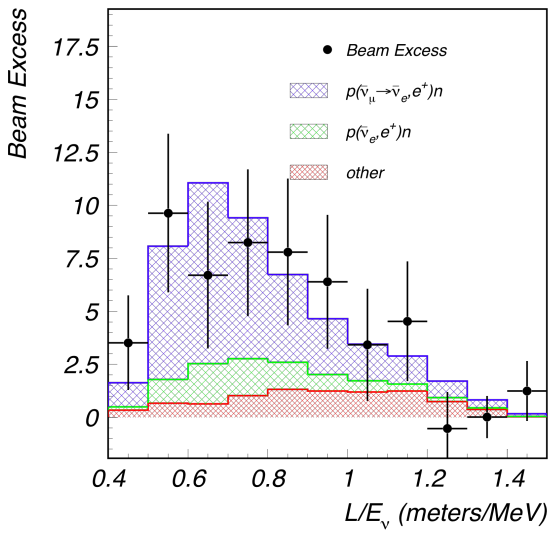


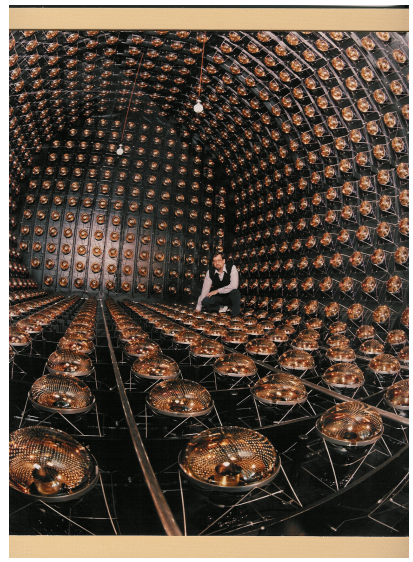


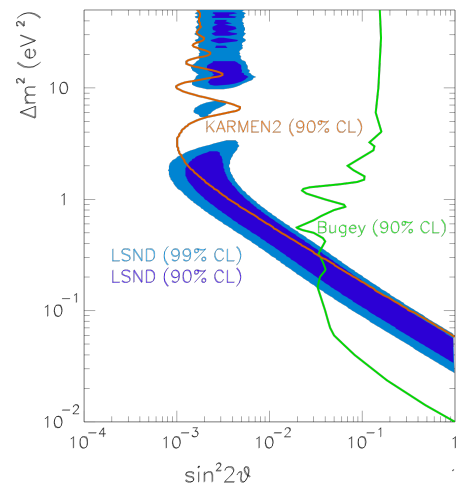


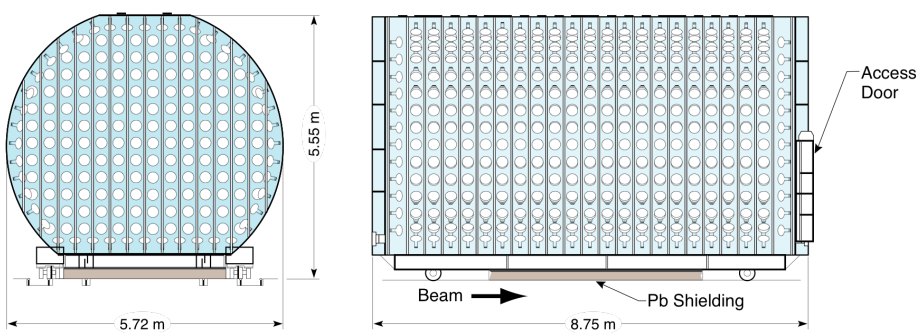
LSND Anomaly

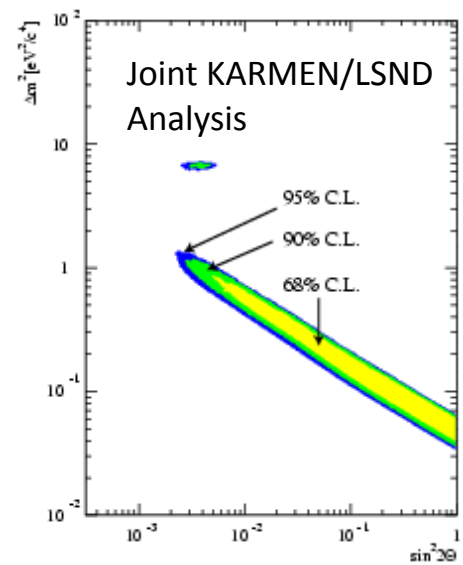
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)







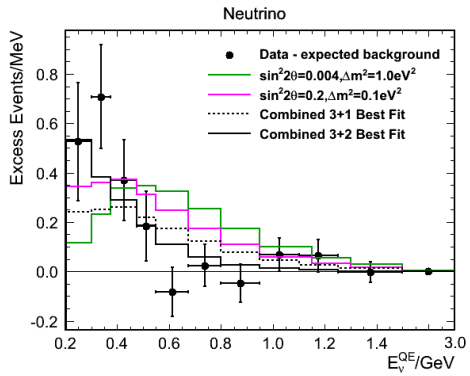


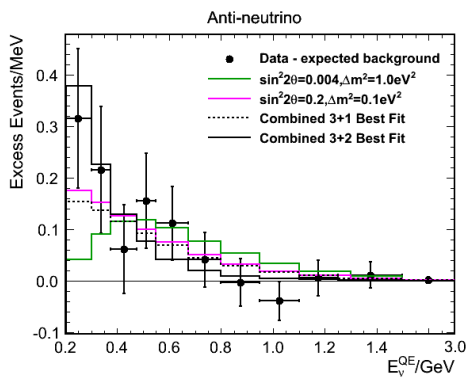


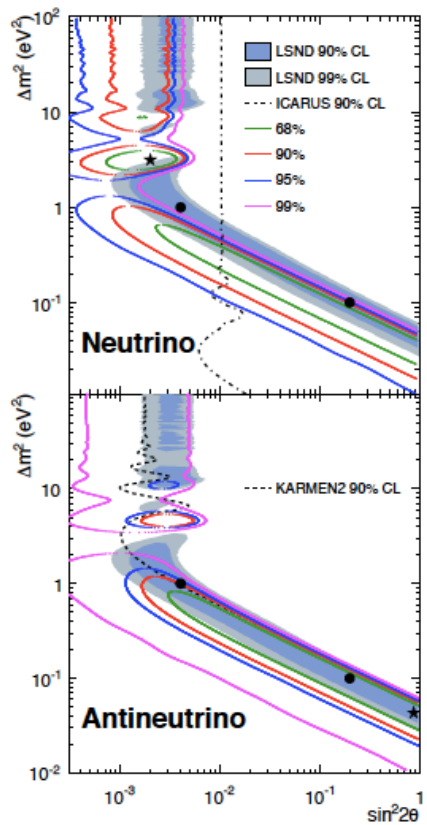
LSND observes a 3.8 σ excess of events consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

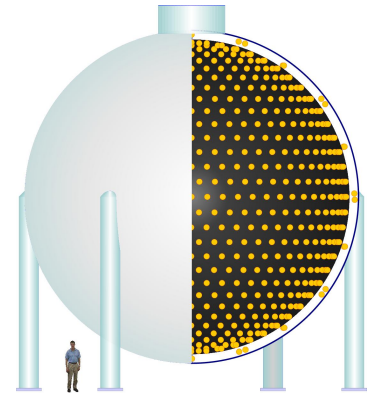
MiniBooNE Anomaly

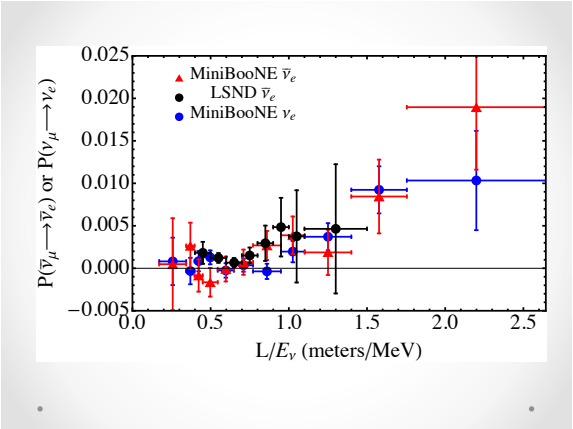
A. A. Aguilar-Arevalo et al., arXiv:1207.4809







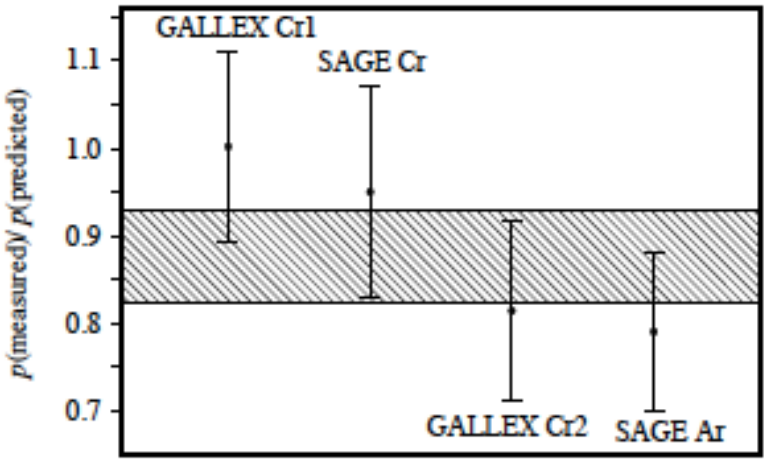




MiniBooNE observes a 3.8 σ excess of events consistent with ν_μ -> ν_e and $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations and with the LSND event excess

Radioactive Neutrino Source Anomaly

SAGE, Phys. Rev. C 73 (2006) 045805



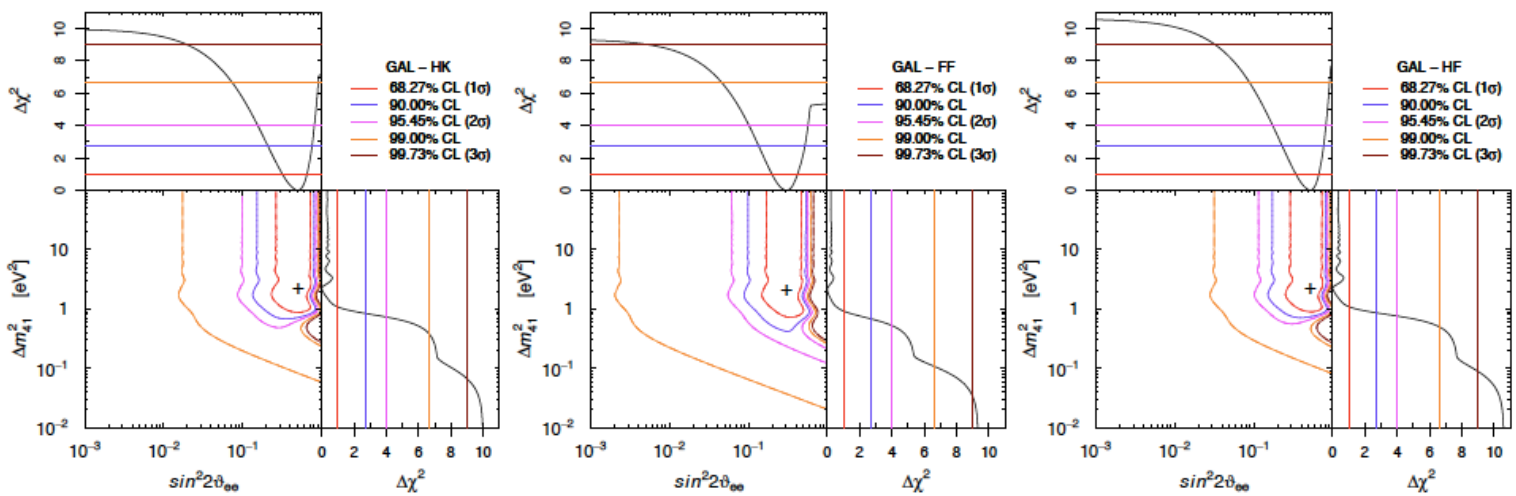
R=0.86+-0.05

Giunti et al.; arXiv:1210.5715

TABLE II. Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments. G1 and G2 denote the two GALLEX experiments with ^{51}Cr sources [30–32], S1 denotes the SAGE experiment with a ^{51}Cr source, and S2 denotes the SAGE experiment with a ^{37}Ar source [33–36]. AVE denotes the weighted average.

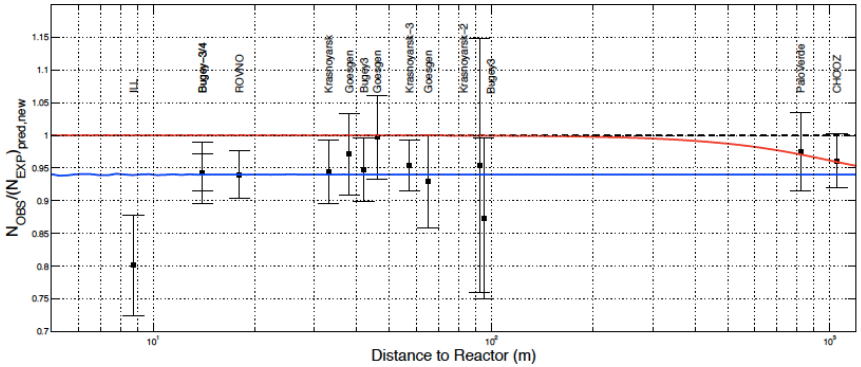
	G1	G2	S1	S2	AVE
R_B	$0.95^{+0.11}_{-0.11}$	$0.81^{+0.10}_{-0.11}$	$0.95^{+0.12}_{-0.12}$	$0.79^{+0.08}_{-0.08}$	$0.86^{+0.05}_{-0.05}$
R_{HK}	$0.85^{+0.12}_{-0.12}$	$0.71^{+0.11}_{-0.11}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.09}_{-0.09}$	$0.77^{+0.08}_{-0.08}$
R_{FF}	$0.93^{+0.11}_{-0.11}$	$0.79^{+0.10}_{-0.11}$	$0.93^{+0.11}_{-0.12}$	$0.77^{+0.09}_{-0.07}$	$0.84^{+0.05}_{-0.05}$
R_{HF}	$0.83^{+0.13}_{-0.11}$	$0.71^{+0.11}_{-0.11}$	$0.83^{+0.13}_{-0.12}$	$0.69^{+0.10}_{-0.09}$	$0.75^{+0.09}_{-0.07}$

GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos



Reactor Neutrino Anomaly

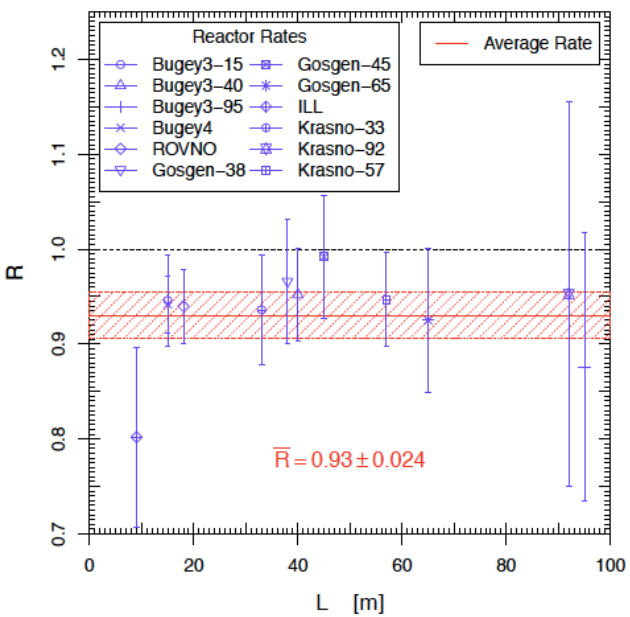
G. Mention et al., Phys.Rev.D83:073006,2011

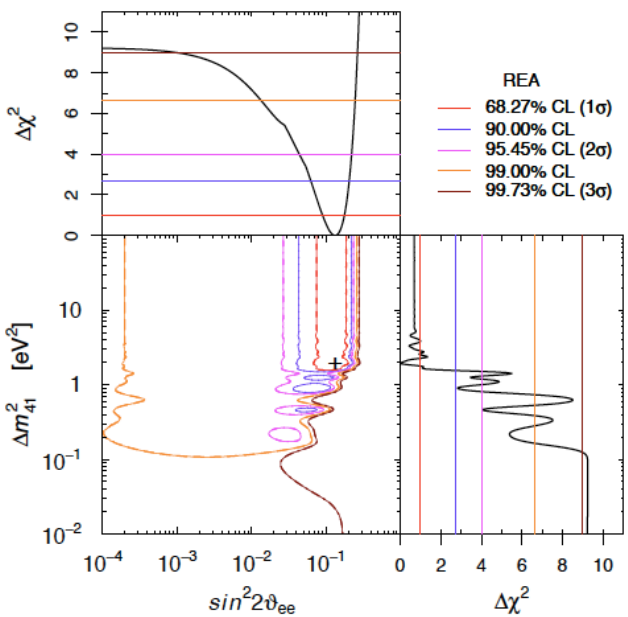


Reactor Neutrino experiments observe fewer events than expected, consistent with $\overline{\nu}_e$ disappearance to sterile neutrinos

R=0.937+-0.027

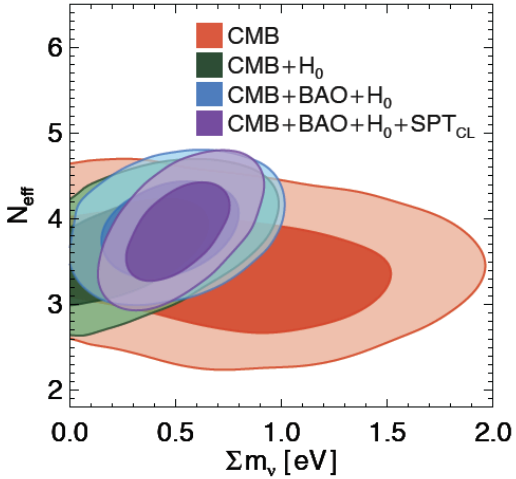
Giunti et al.; arXiv:1210.5715



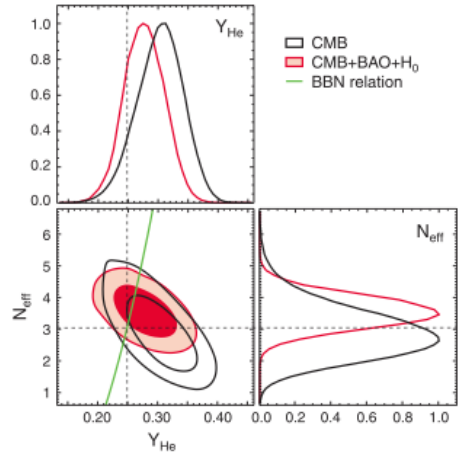


N_{eff} Anomaly?

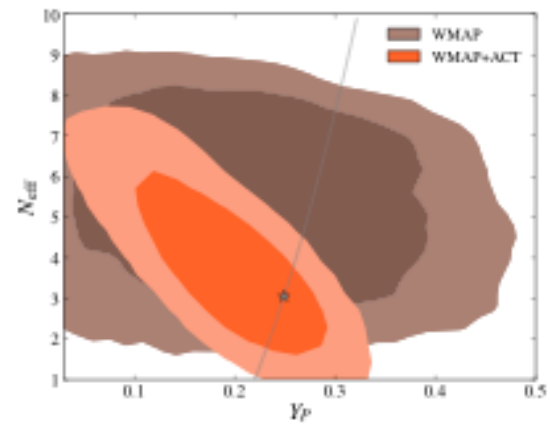
SPT-SZ Survey; arXiv:1212.6267



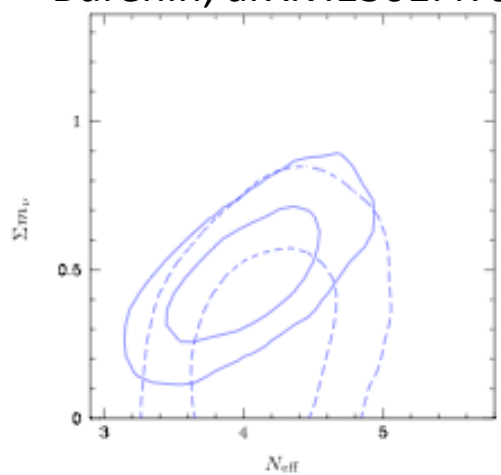
WMAP; arXiv:1212.5226



ACT; arXiv:1301.0824



Burenin; arXiv:1301.4791



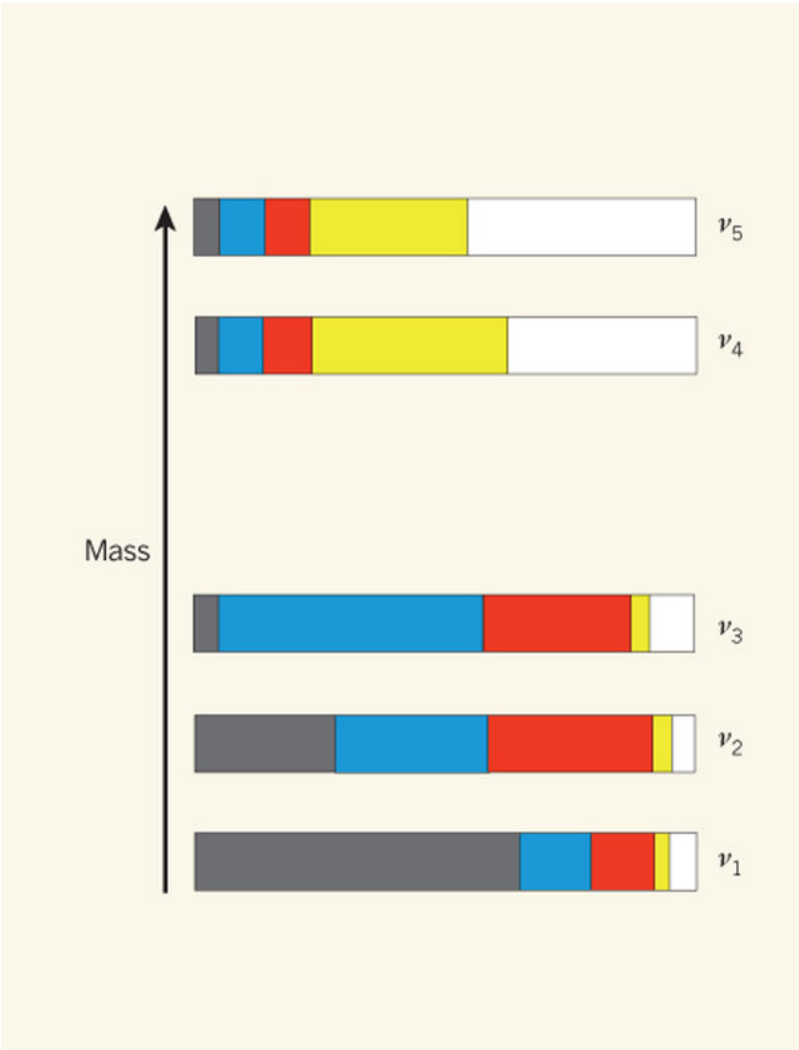
N_{eff} From CMB

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[26]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[26]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[29]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[26]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[18]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[18]
	W-7+ACT	5.3 ± 1.3	[23]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[23]
	W-7+SPT	3.85 ± 0.62	[24]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[24]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[30]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[31]
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[32]
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[31]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[32]
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[31]
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[32]
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[33]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[33]

Is N_{eff} > 3.046?

More precise information will come from the Planck satellite.

Sterile Neutrinos

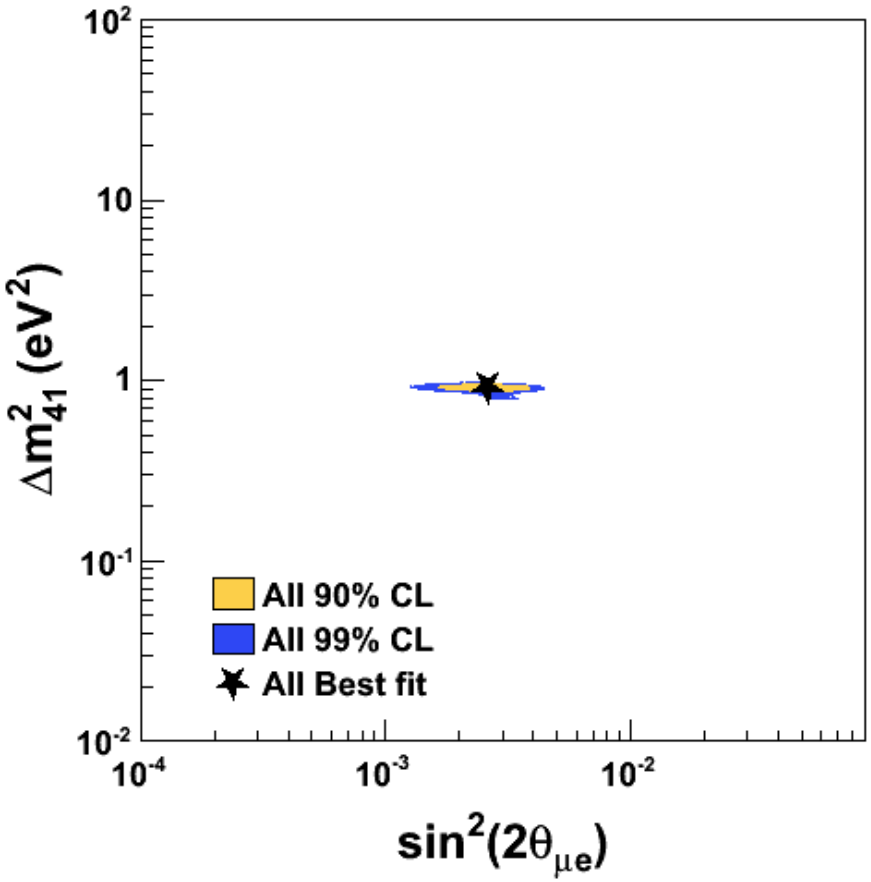


- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

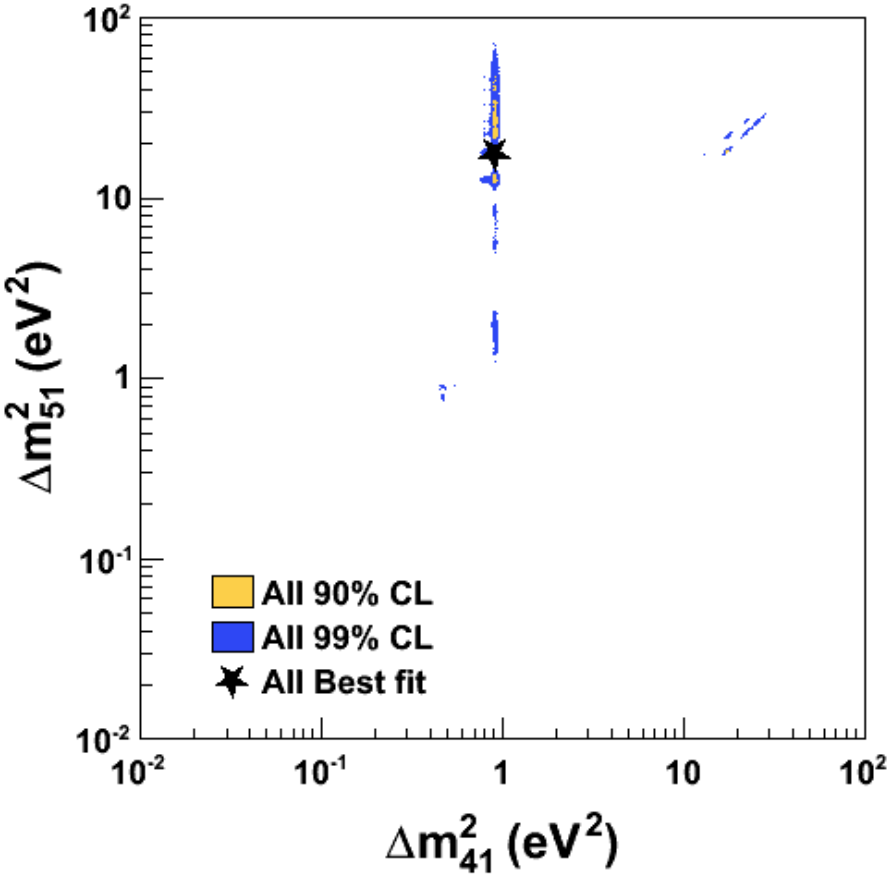
Global 3+N Fits to World Data

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, & J. Spitz, arXiv:1207.4765

3+1



3+2

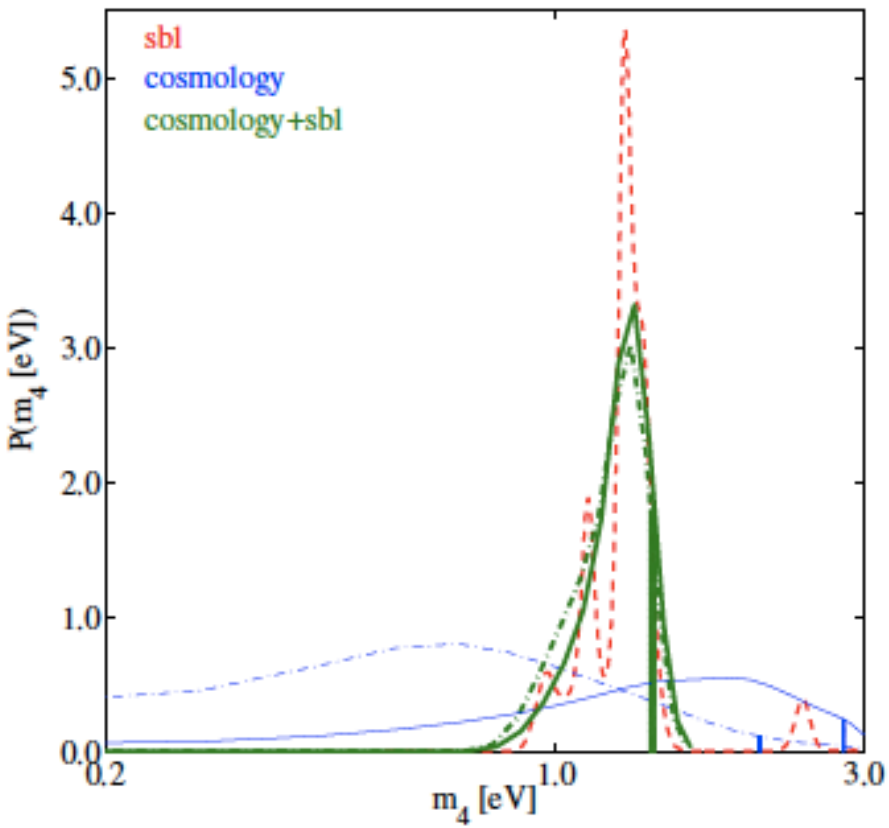


Global 3+N Fits to World Data

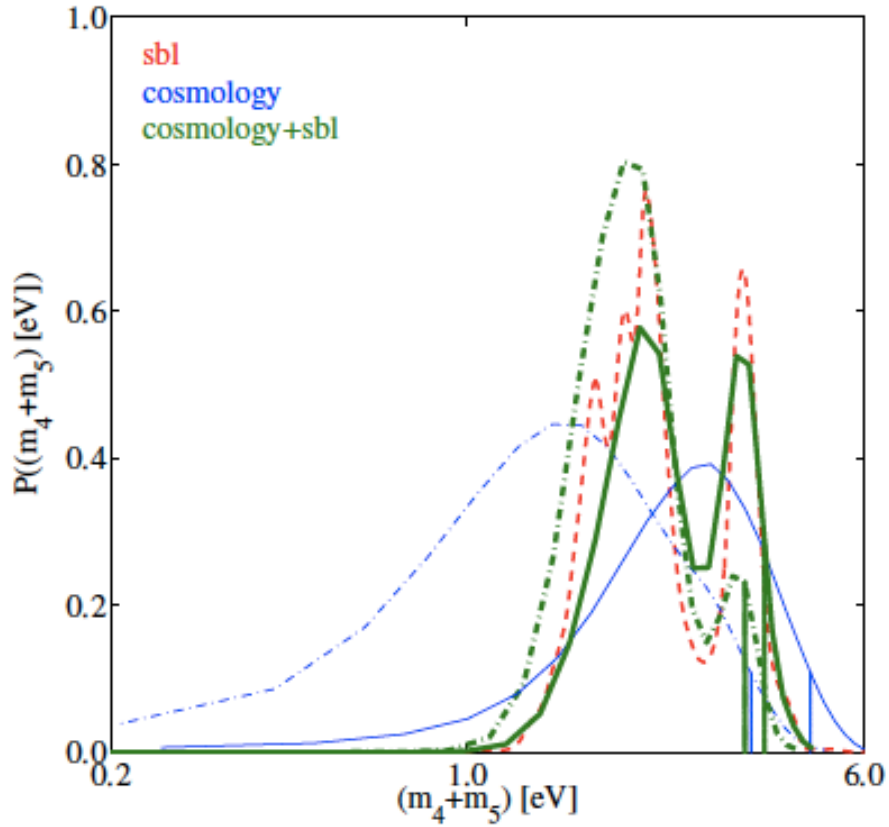
Maria Archidiacono, Nicolao Fornengo, Carlo Giunti, Steen Hannestad, & Alessandro Melchiorri

arXiv:1302.6720

3+1



3+2



Impact of Sterile Neutrinos on Astrophysics

- Sterile neutrinos will contribute to the dark matter of the universe (although their density is not precisely known)
- Light, sterile neutrinos will contribute to the number of relativistic degrees of freedom (N_{eff})
- Sterile neutrinos will contribute to pulsar kicks
- Sterile neutrinos may help explain the R-process in supernovae neutrino bursts (J. Fetter, G. C. McLaughlin, A. B. Balantekin, G. M. Fuller, Astropart.Phys. 18 (2003) 433-448)

Future ν Experiments

- There is a diverse set of experiments, spanning vastly different energy Scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

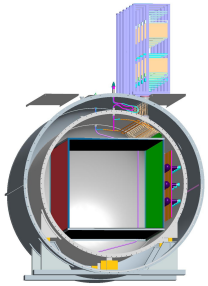
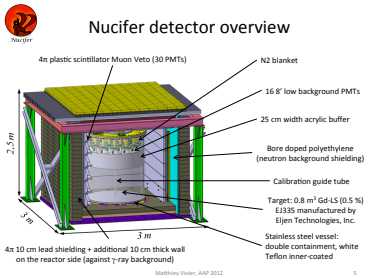


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

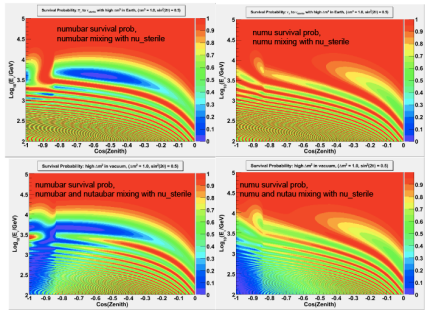
- Accelerator ν Experiments: MicroBooNE, MINOS+, NuStorm at FNAL, ICARUS at CERN, OscSNS at ORNL or J-PARC, IsoDAR

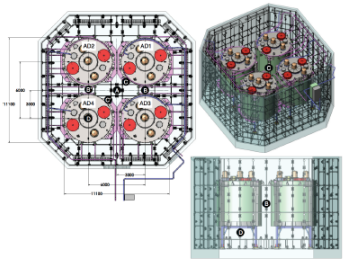
- Reactor ν Experiments: SCRAAM, NUCIFER, Stereo



- Radioactive Source ν Experiments: BOREXINO, KamLAND, Daya Bay, Baksan, LENS

- Atmospheric ν Experiments: IceCube





Conclusion

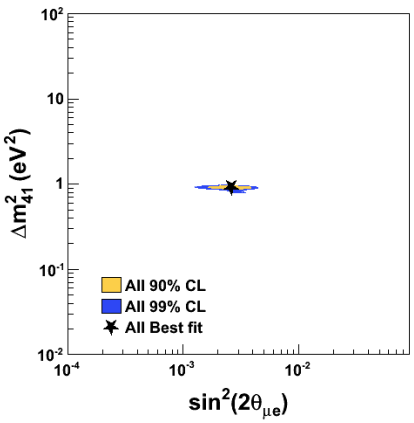
- The anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile ν.
- Sterile ν would contribute to the dark matter of the universe and would have a big impact on astrophysics and cosmology.
- The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model.
- Upcoming experiments (over a wide range of energies) have the potential of proving whether light, sterile neutrinos exist!

Backup

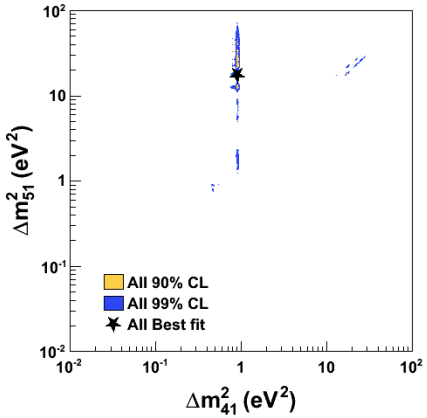
Global 3+N Fits to World Data

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, & J. Spitz, arXiv:1207.4765

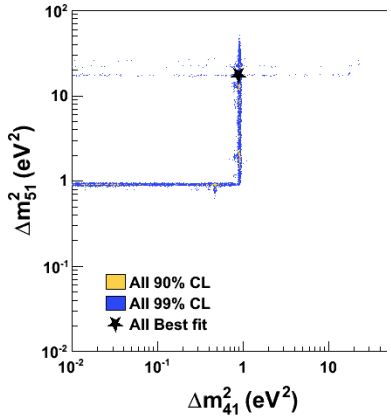
3+1

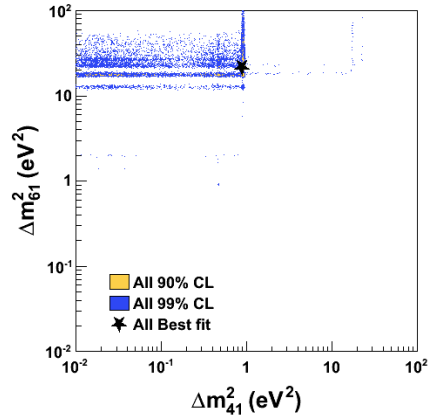


3+2



3+3





	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

Table 2: The χ^2 values, degrees of freedom (dof) and probabilities associated with the best-fit and null hypothesis in each scenario. Also shown are the results from the Parameter Goodness-of-fit tests. P_{best} refers to the χ^2-probability at the best fit point and P_{null} refers to the χ^2-probability at null.

3+1	Δm^2_{41}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$
All	0.92	0.17	0.15
App	0.15	0.39	0.39
Dis	18	0.18	0.18
ν	7.8	0.059	0.26
$\overline{\nu}$	0.92	0.23	0.13

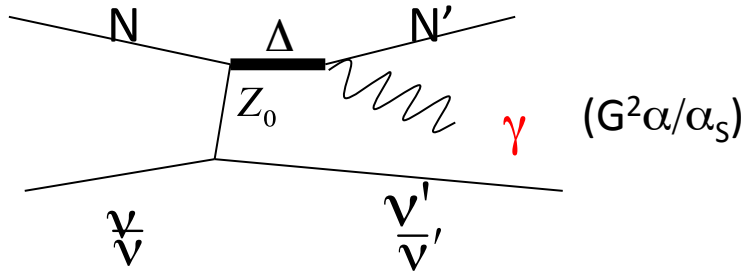
3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π
App	0.31	1.0	0.31	0.31	0.17	0.17	1.1π
Dis	0.92	18	0.015	0.12	0.17	0.12	N/A
ν	7.6	17.6	0.05	0.27	0.18	0.052	1.8π
$\overline{\nu}$	0.92	3.8	0.25	0.13	0.12	0.079	0.35π

3+3	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 6}\rvert$	$\lvert U_{e6}\rvert$	ϕ_{54}	ϕ_{64}	ϕ_{65}
All	0.90	17	22	0.12	0.11	0.17	0.11	0.14	0.11	1.6π	0.28π	1.4π
App	0.15	1.8	2.7	0.37	0.37	0.12	0.12	0.12	0.12	1.4π	0.32π	0.94π
Dis	0.92	7.2	18	0.013	0.12	0.019	0.16	0.15	0.069	N/A	N/A	N/A
ν	13	17	26	0.076	0.24	0.16	0.067	0.10	0.017	1.1π	1.8π	0.037π
$\overline{\nu}$	7.5	9.1	18	0.024	0.28	0.098	0.11	0.18	0.029	1.8π	2.0π	0.61π

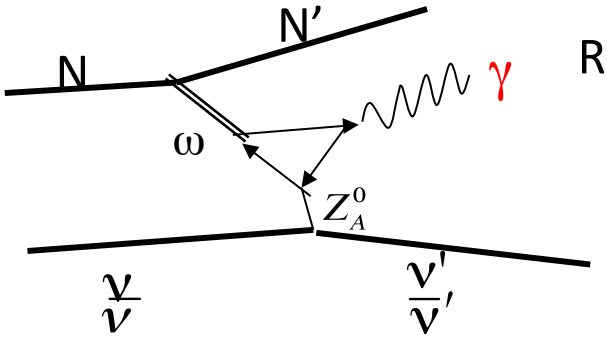
Table 3: The oscillation parameter best-fit points in each scenario considered. The values of Δm^2 shown are in units of eV^2

NCγ Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

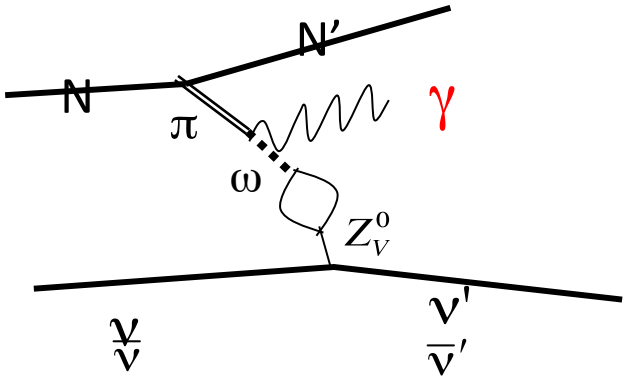
Dominant process accounted for in MC!



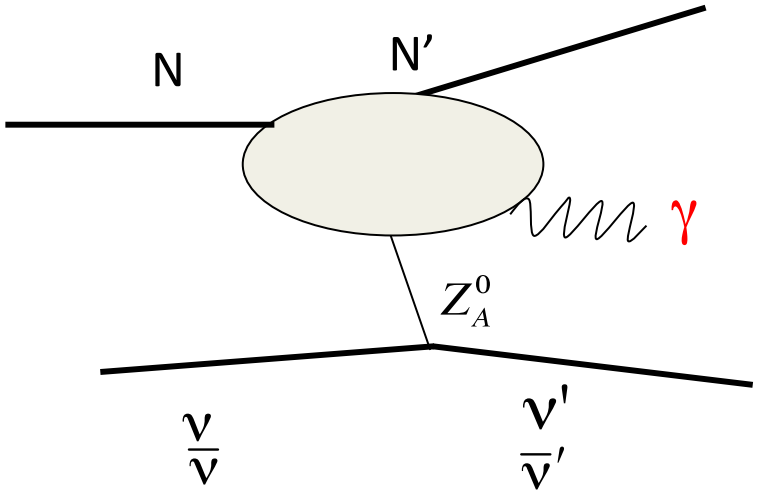
Radiative Delta Decay



Axial Anomaly



Other PCAC



So far no one has found a NC process to account for the ν low-energy excess. Work is in progress:

R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

Zhang & Serot, arXiv:1210.3610

Multi-Nucleon Nuclear Effects & Neutrino Energy

Martini, Ericson, & Chanfray, arXiv:1211.1523

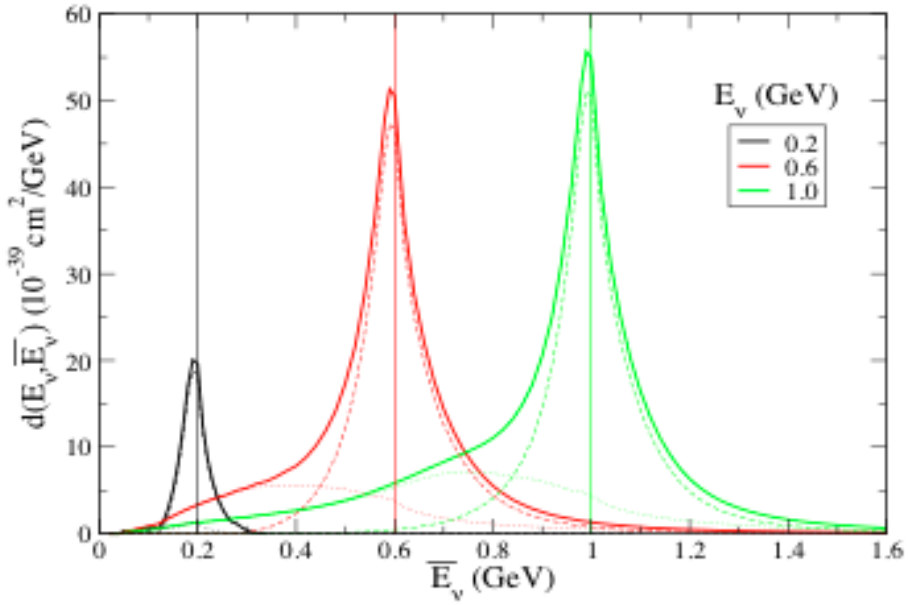


FIG. 1: (Color online) The spreading function $d(E_\nu, \overline{E_\nu})$ of Eq. (4) per neutron of ^{12}C in the case of electrons evaluated for three E_ν values. The genuine quasielastic (dashed lines) and the multinucleon (dotted lines) contributions are also shown separately.

Multi-Nucleon Nuclear Effects cause MiniBooNE to underestimate E_ν!

Nominal best antineutrino fit: Δm^2=0.043 eV^2, $\sin^2 2\theta$=0.88

Martini Inspired Model: Δm^2=0.059 eV^2, $\sin^2 2\theta$=0.64

ν_μ & ν_e Disappearance

- MB fits performed to date assume small ν_e & ν_μ disappearance
- However, ν_e (ν_μ) disappearance in 3+N models will cause the intrinsic ν_e background to be overestimated (underestimated)
- Therefore, MB is now working on fitting Δm^2 & both U_{e4} & $U_{\mu 4}$:

$$\sin^2 2\theta_{\mu e} = 4(U_{e4}U_{\mu 4})^2$$

$$\sin^2 2\theta_{\mu\mu} = 4(U_{\mu 4})^2(1-(U_{\mu 4})^2)$$

$$\sin^2 2\theta_{\mu e} = 4(U_{e4})^2(1-(U_{e4})^2)$$

Nominal best antineutrino fit: Δm^2=0.043 eV^2, $\sin^2 2\theta$=0.88
Model with Disappearance: Δm^2=0.177 eV^2, $\sin^2 2\theta$=0.07