Review of Sterile Neutrino Data

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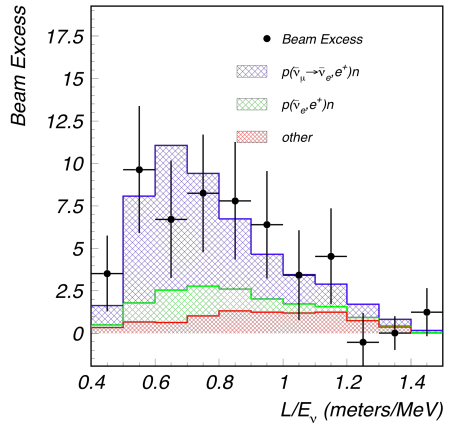
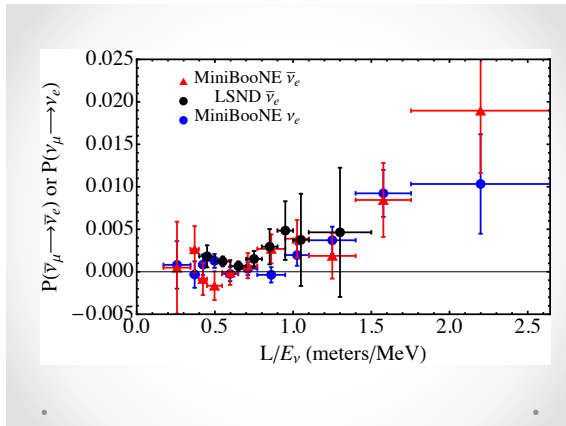
SLAC Intensity Frontier Workshop

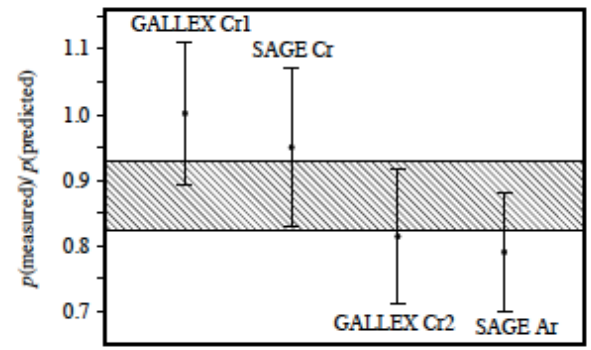
March 6, 2013

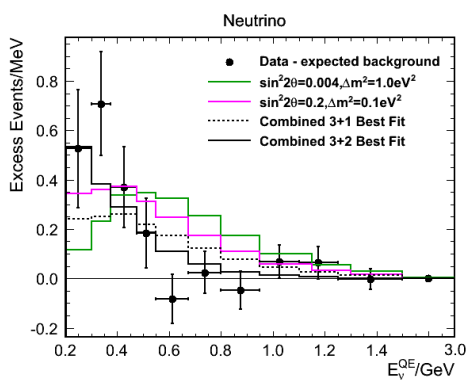
- Short Baseline Neutrino Anomalies
- Explaining the Data with 3+N Sterile Neutrino Models
  (Although there are other possibilities!)
- Global Fits to the World Data

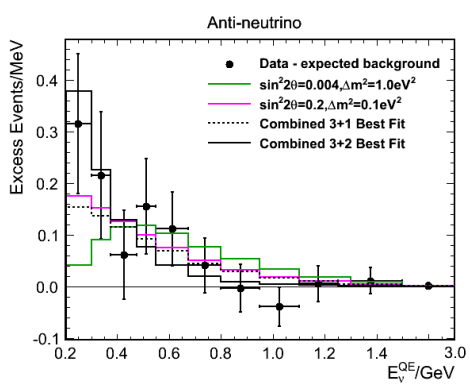
Short-Baseline Neutrino Anomalies

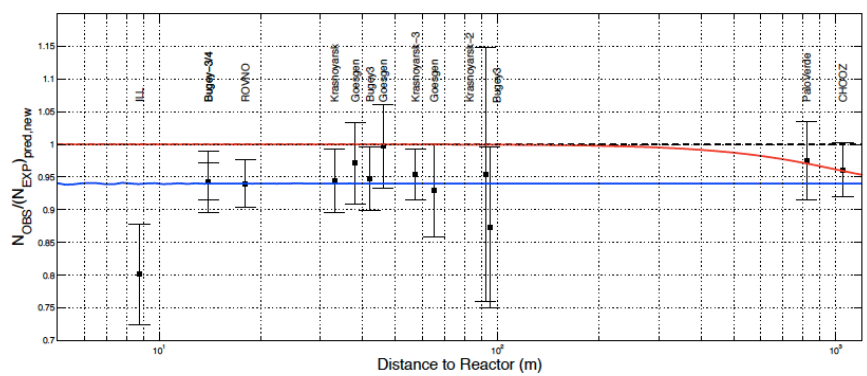








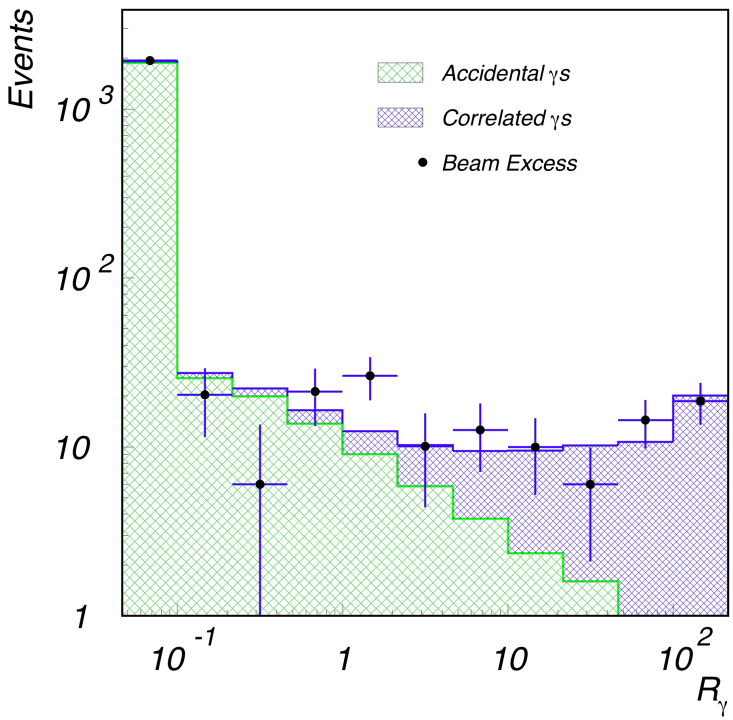


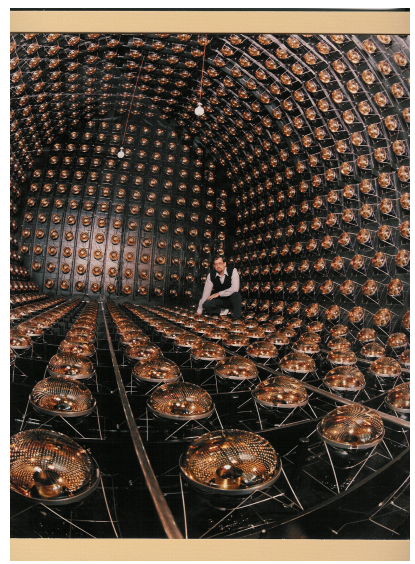


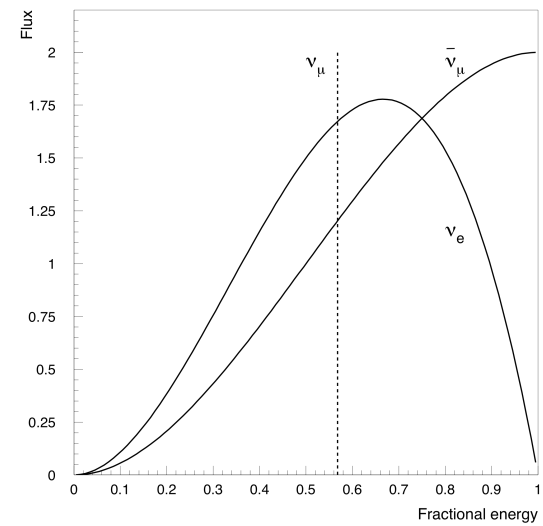
LSND Event Excess

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

Correlated γ = 117.9+-22.4 events
Excess = 87.9+-22.4+-6.0 events





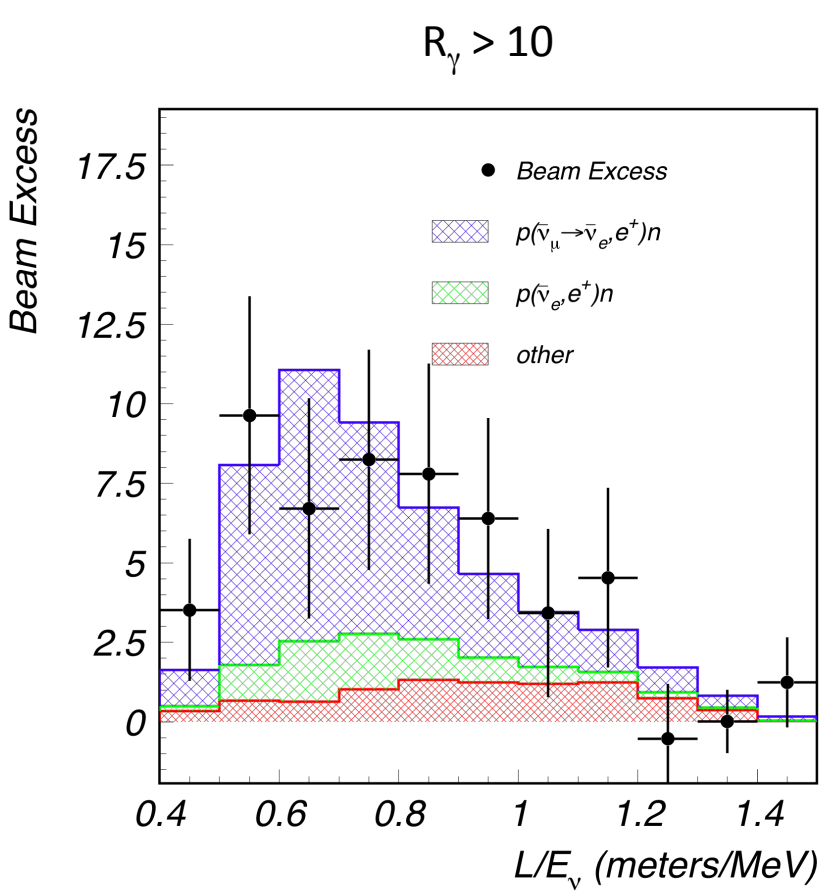


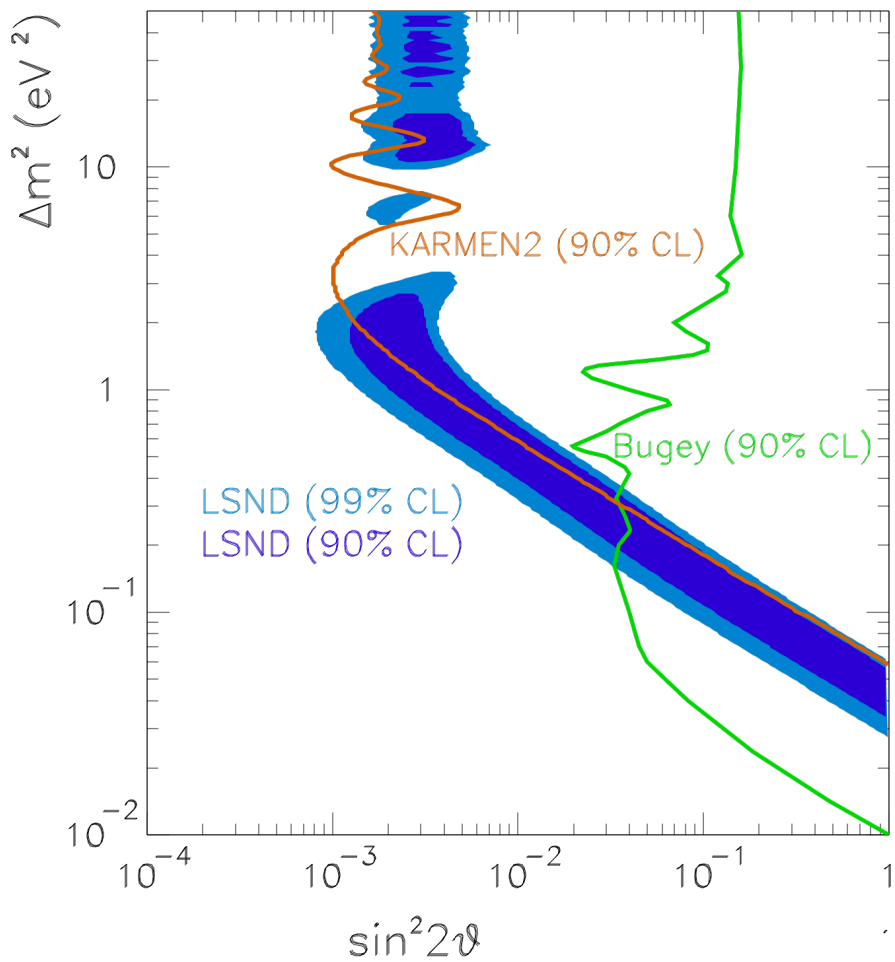
$\bar{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

LSND collected 28,896 C on target and observed a 3.8 σ excess of events consistent with $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations, corresponding to P_{osc} = (0.264+-0.067+-0.045)%

LSND Event Excesses

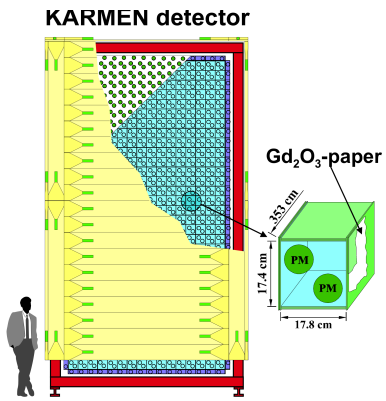
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)





Joint LSND/KARMEN Analysis

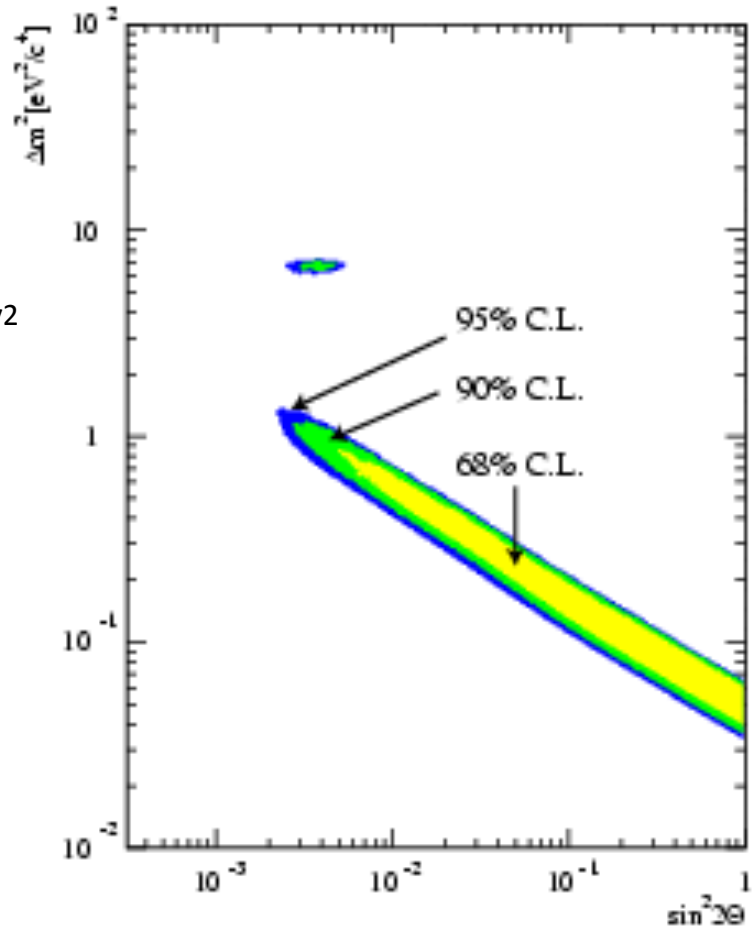
E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002)

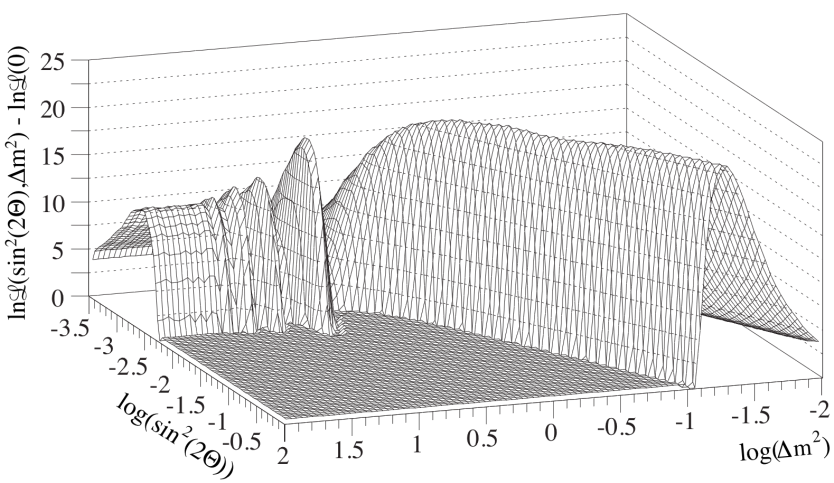


96% active volume of ^{12}C and p

$$\varepsilon \quad \frac{11.5\%}{\sqrt{E[MeV]}} \qquad t_{ISIS} \quad 2ns$$

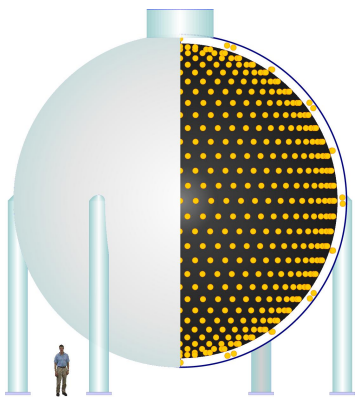
KARMEN observed no event excess; however, a joint analysis of KARMEN (17.7m) & LSND (30m) reveals a favored region of $\Delta m^2 < 1\ eV^2$

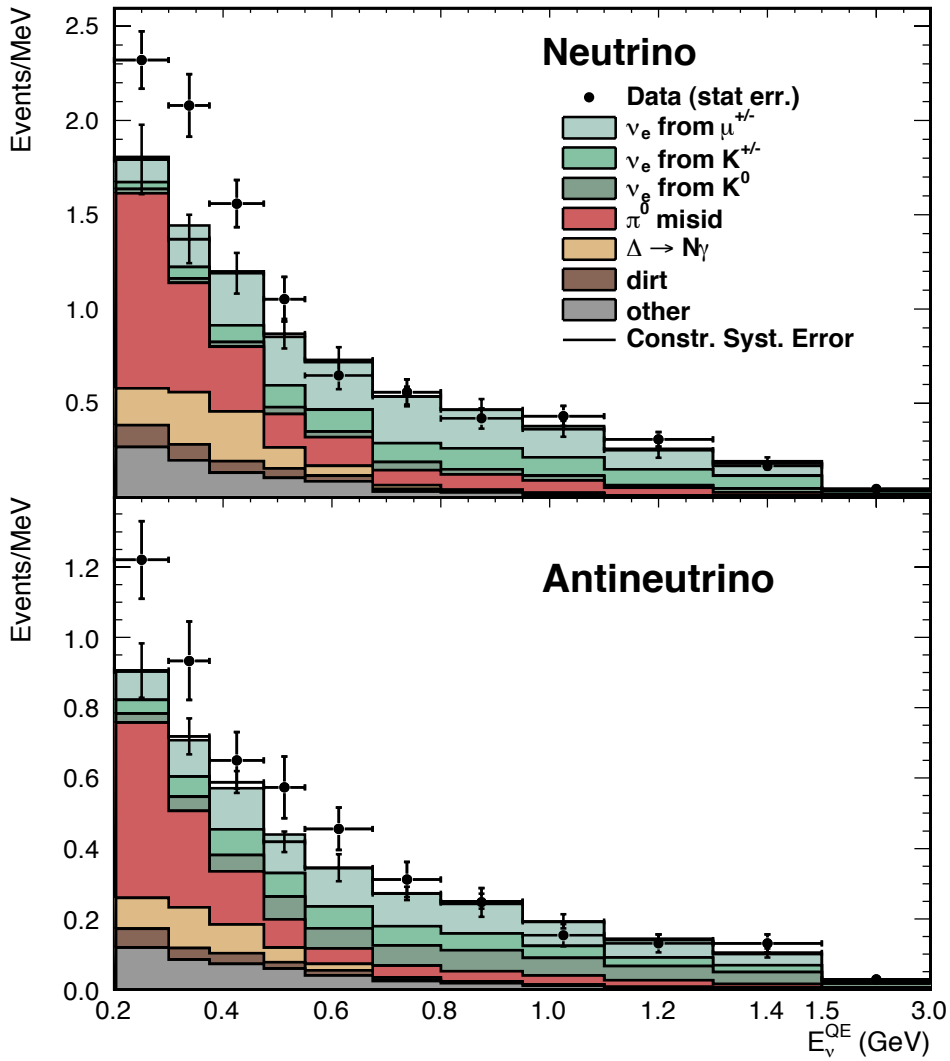




MiniBooNE ν_e Data/MC Comparison (10y)

arXiv:1207.4809





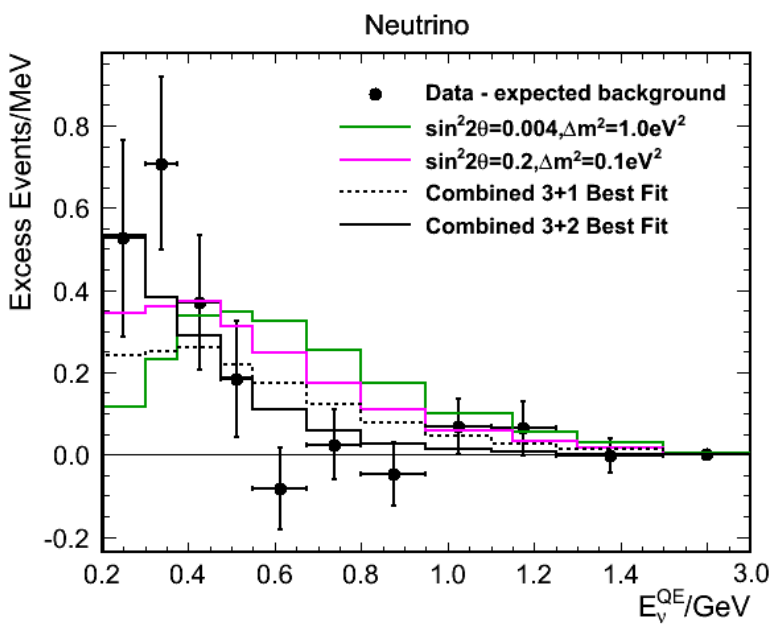
6.46x10^{20} POT

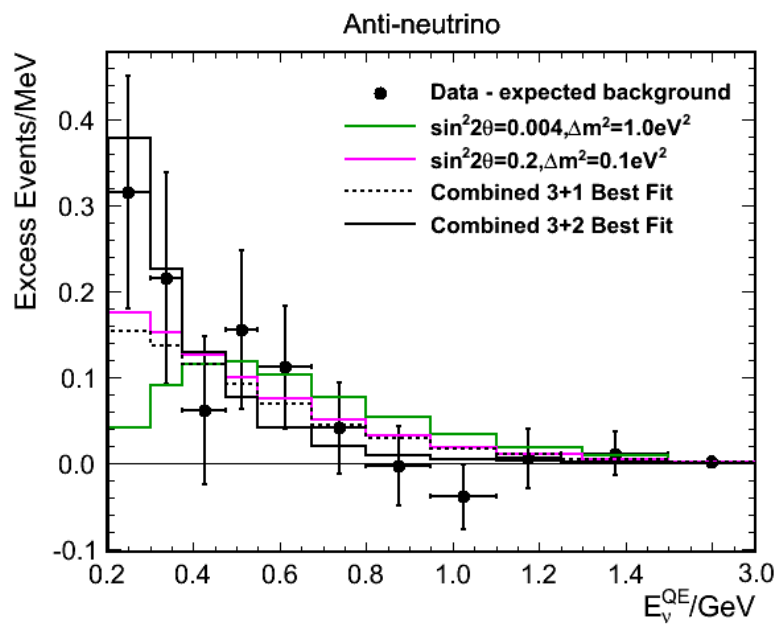
11.27x10^{20} POT

MiniBooNE observes an excess of events consistent with ν_μ -> ν_e & $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillations

MiniBooNE Event Excesses

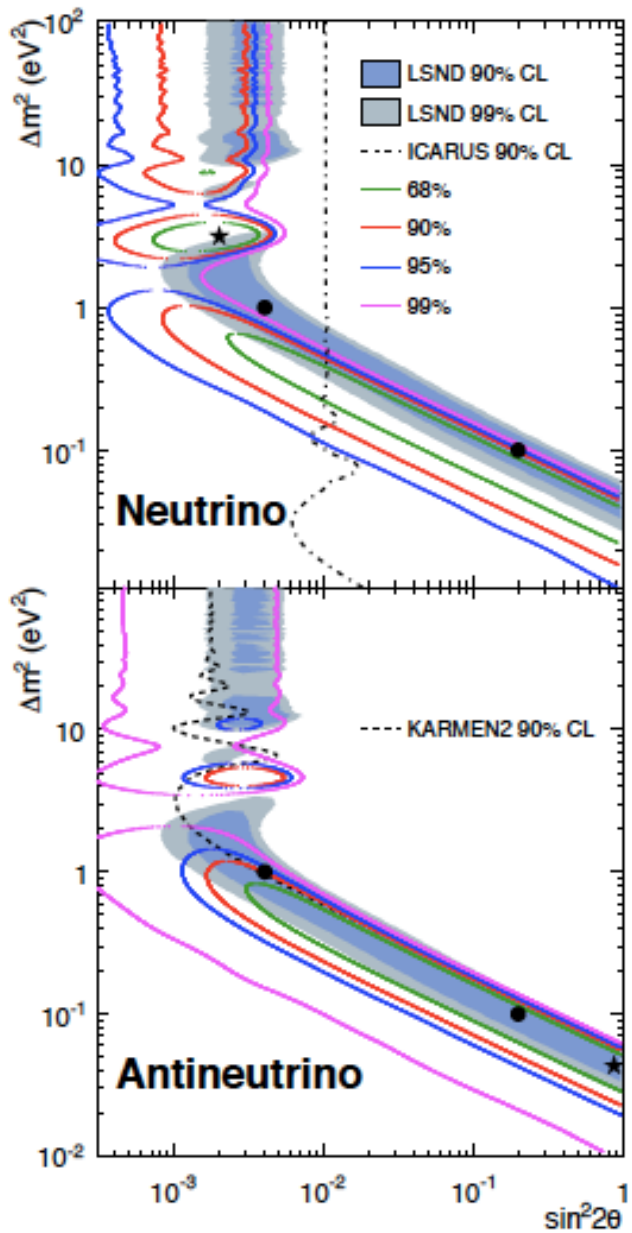
arXiv:1207.4809





Neutrino Event Excess from 200-1250 MeV = 162.0+-28.1+-38.7 (3.4σ)
Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)
Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

MiniBooNE Allowed Regions



Neutrino

P_{bf} = 6.1% , P_{null} = 0.5%

P_{null} relative to P_{bf} = 2.0%

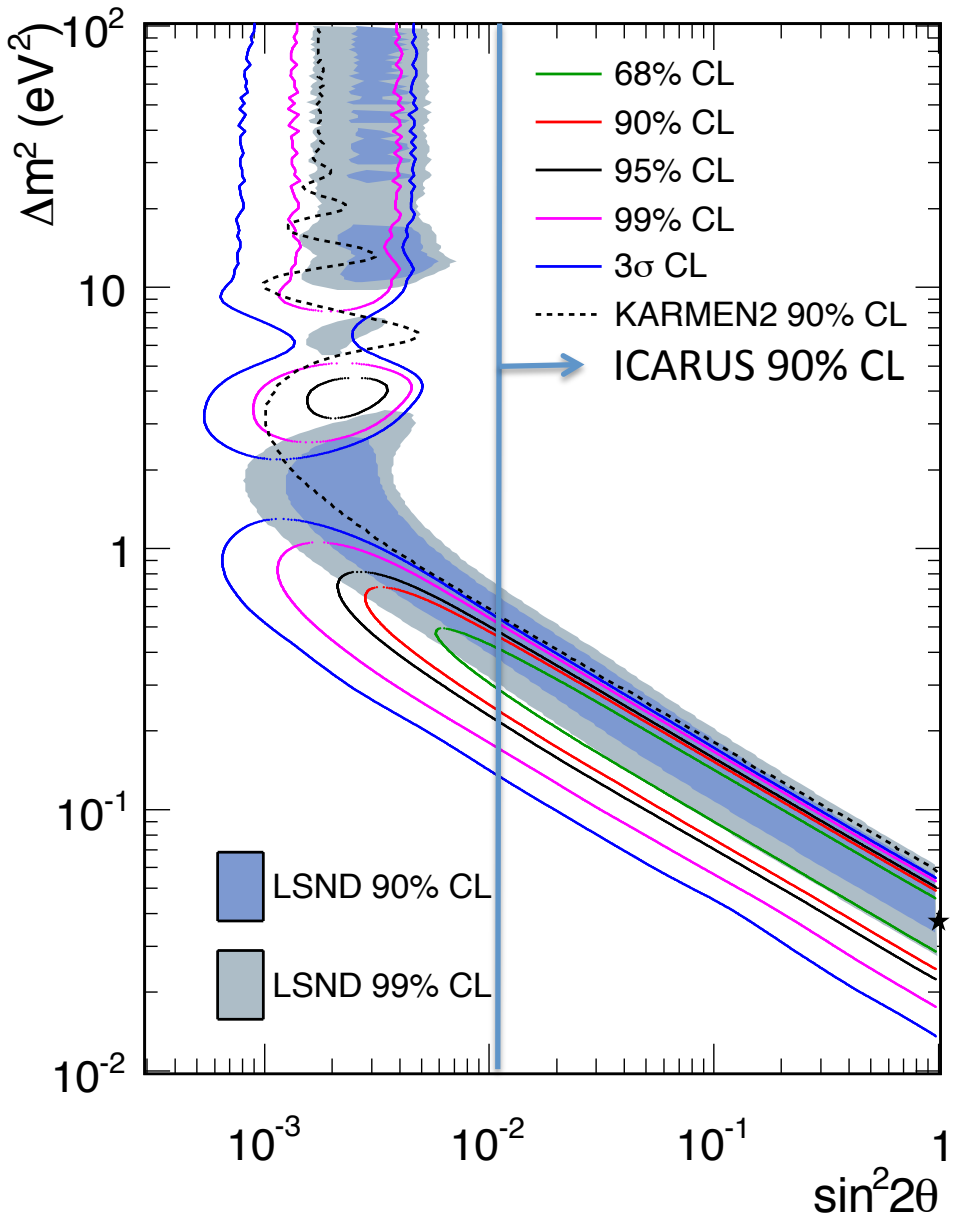
Antineutrino

P_{bf} = 66% , P_{null} = 5.4%

P_{null} relative to P_{bf} = 0.5%

MiniBooNE Combined Neutrino + Antineutrino 2ν Fit

arXiv:1207.4809

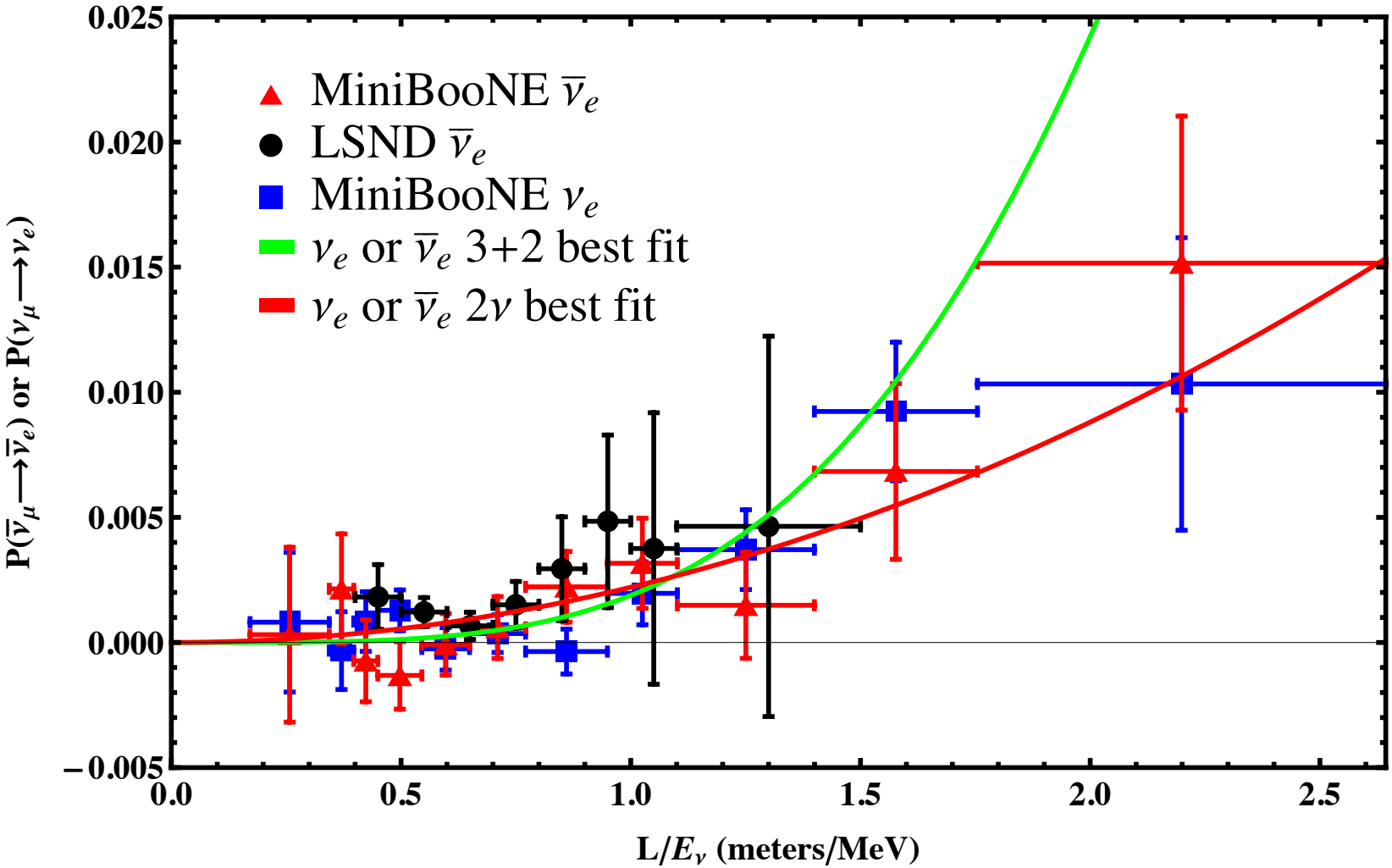


P_{bf} = 6.7%, P_{null} = 0.1%

P_{null} relative to P_{bf} = 0.03%

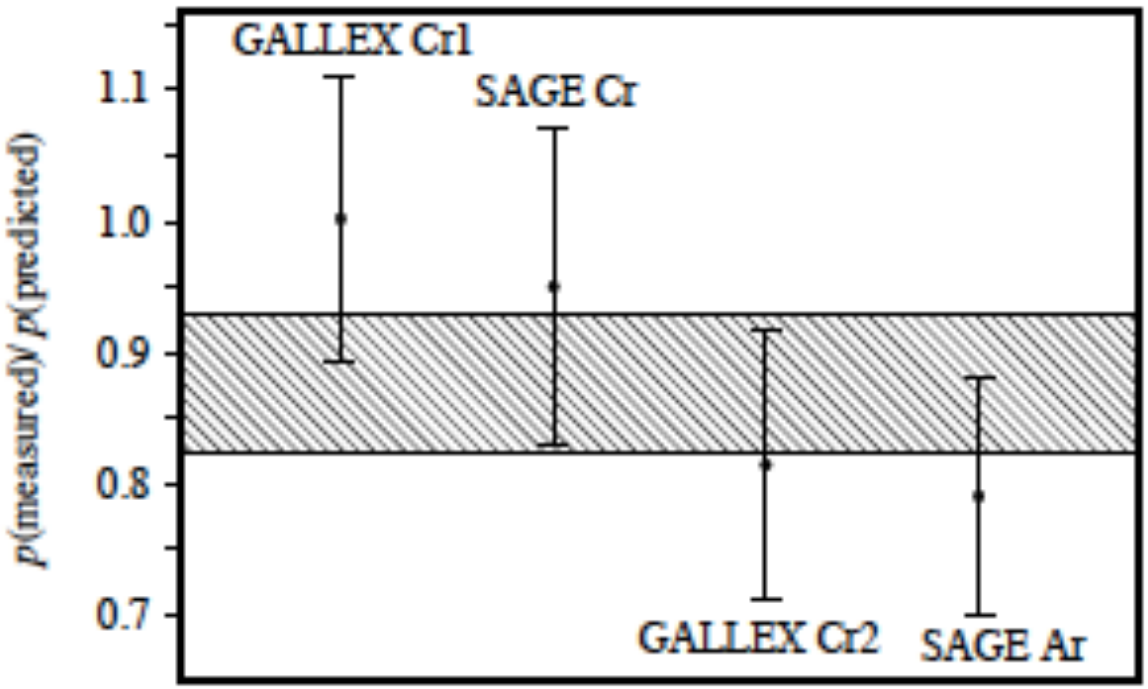
MiniBooNE L/E Distributions

arXiv:1207.4809



Radioactive Neutrino Source Anomaly

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



R=0.86+-0.05

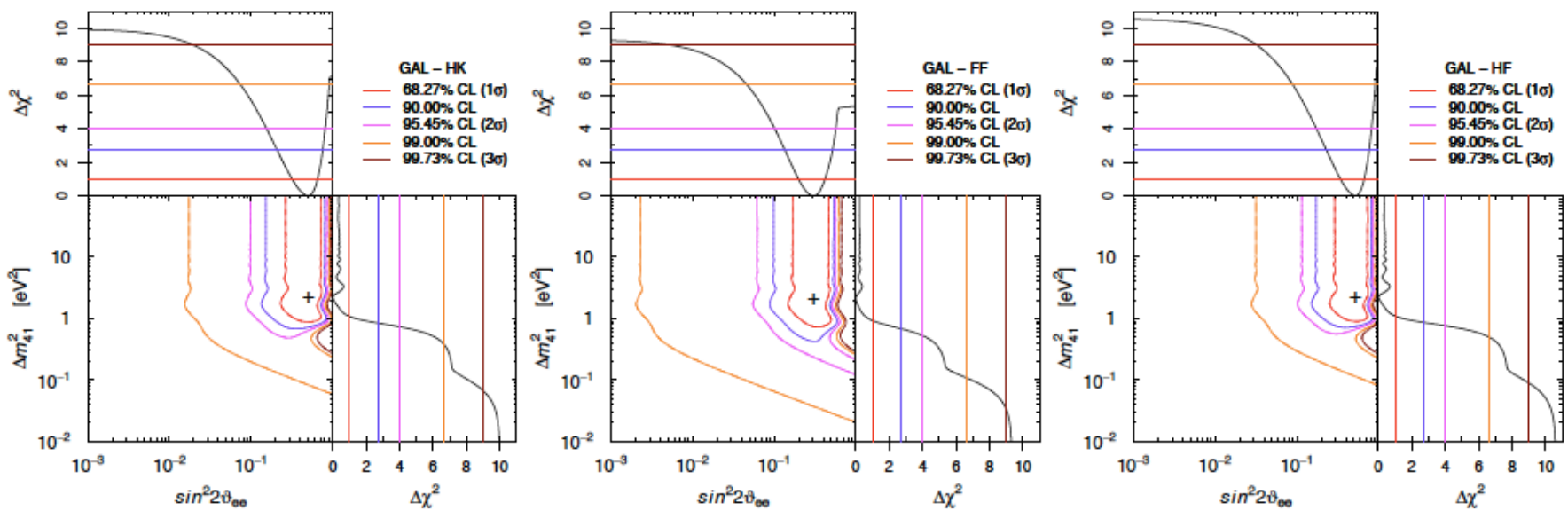
GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos

Radioactive Neutrino Source Anomaly

Giunti et al.; arXiv:1210.5715

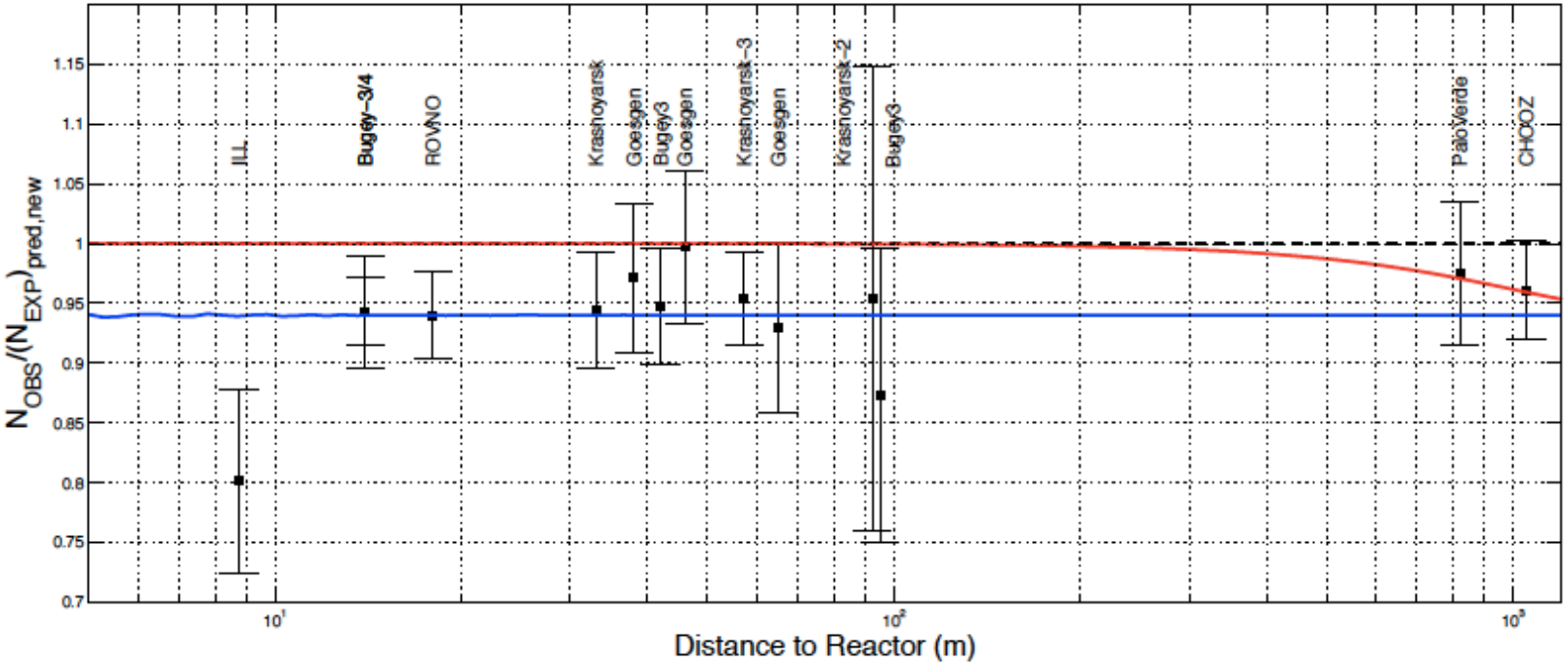
TABLE II. Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments. G1 and G2 denote the two GALLEX experiments with ^{51}Cr sources [30–32], S1 denotes the SAGE experiment with a ^{51}Cr source, and S2 denotes the SAGE experiment with a ^{37}Ar source [33–36]. AVE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

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



Reactor Neutrino Anomaly

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

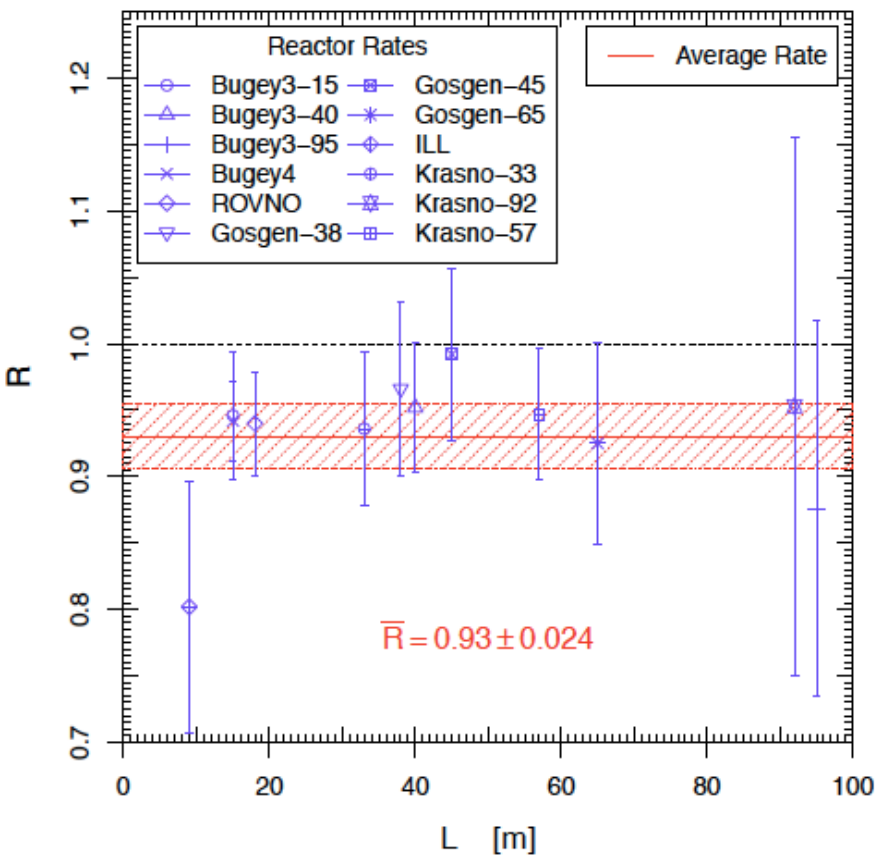


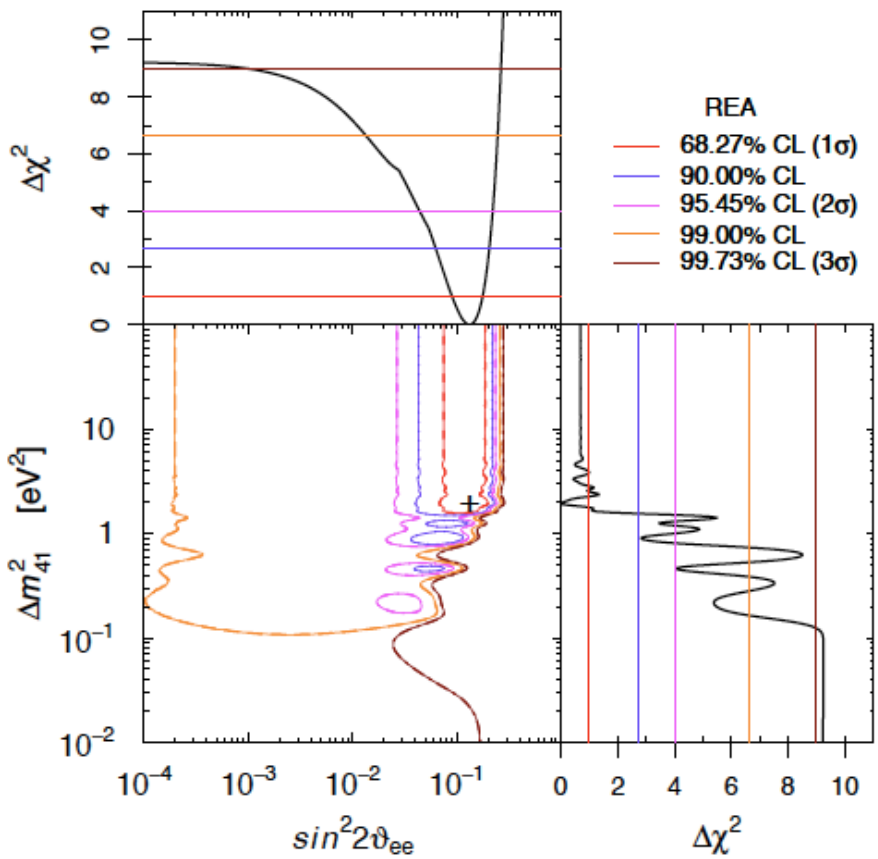
R=0.937+-0.027

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

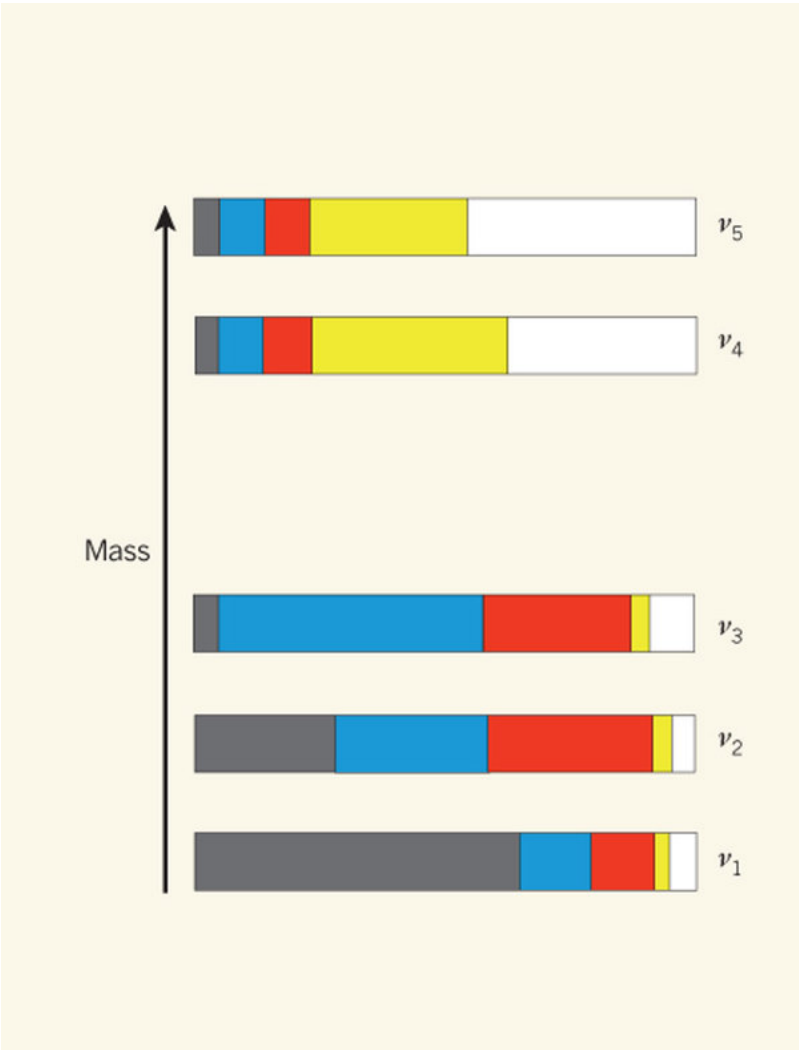
Reactor Neutrino Anomaly

Giunti et al.; arXiv:1210.5715





Sterile Neutrinos



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

3+N Models Requires Large ν Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) < \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

Reactor Experiments: $P(\nu_e \rightarrow \nu_x) \sim 15\%$

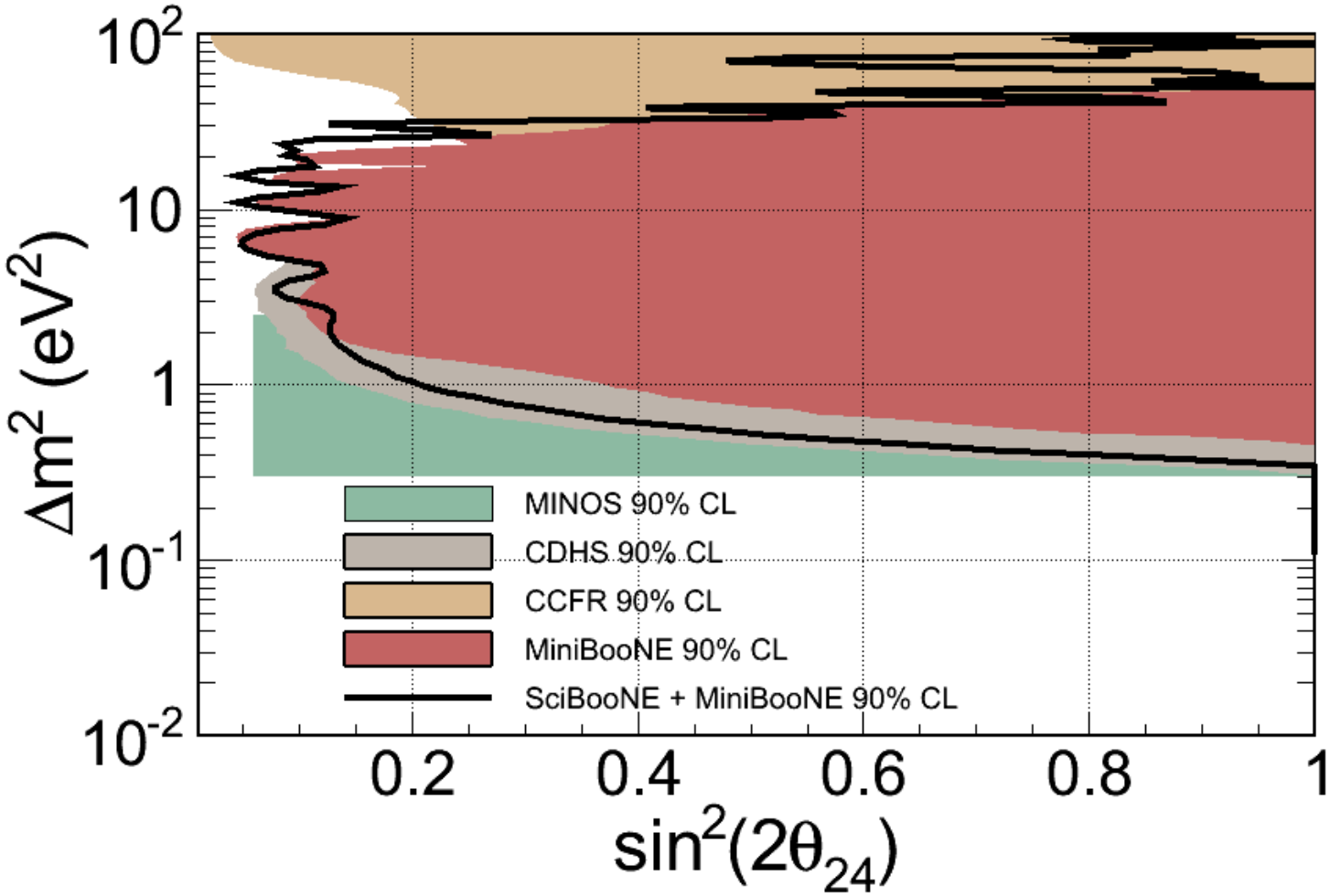
LSND/MiniBooNE: $P(\nu_\mu \rightarrow \nu_e) \sim 0.25\%$

Therefore: **$P(\nu_\mu \rightarrow \nu_x) > 7\%$**

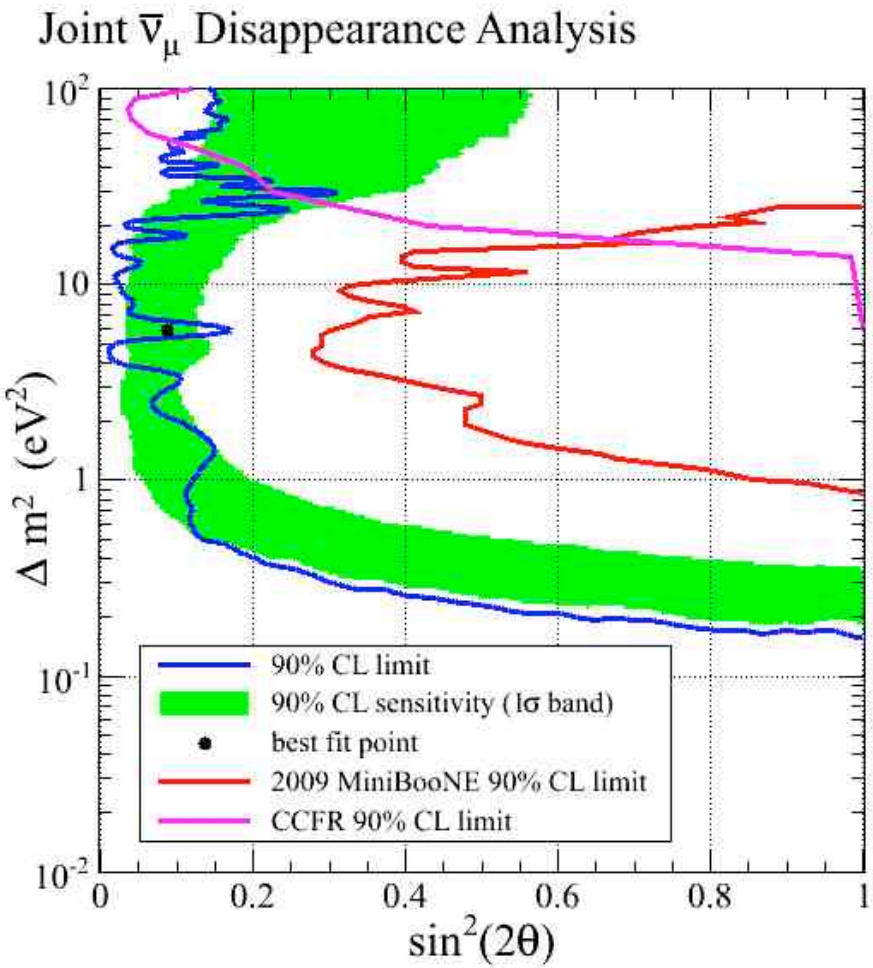
Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

MINOS Limits on ν_μ Disappearance

Alexandre Sousa, arXiv:1110.3455



ν_μ Disappearance Results



MiniBooNE + SciBooNE

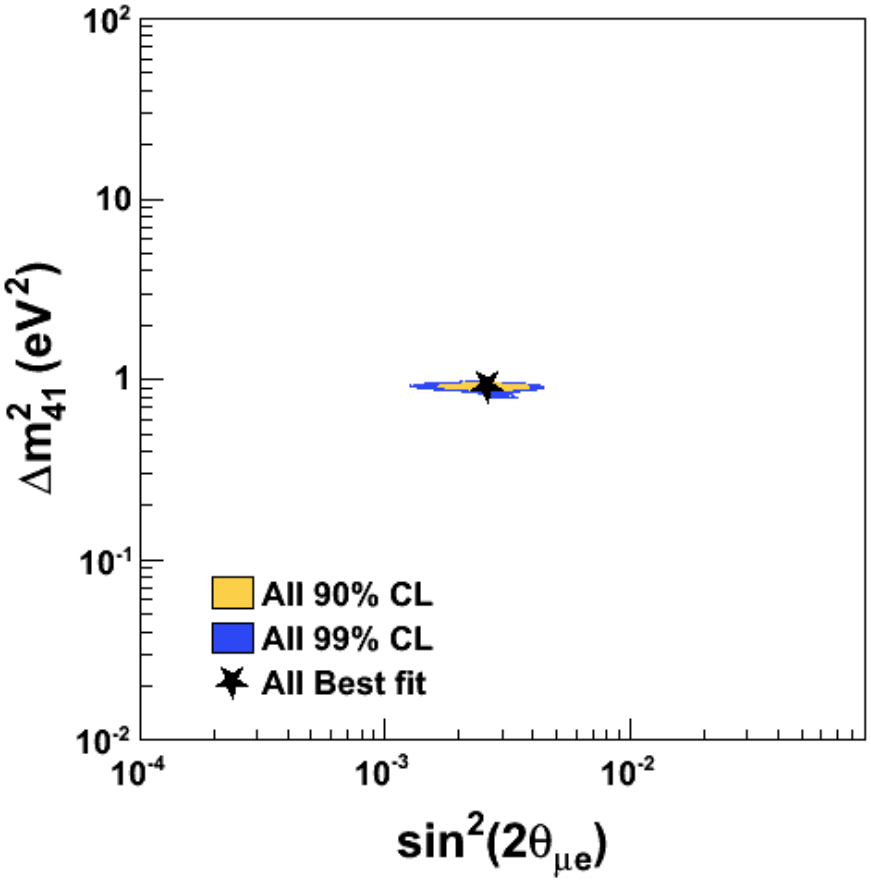
- Consistent with no disappearance
- Best fit point: $\Delta m^2 = 5.9$ eV^2, $\sin^2 2\theta = 0.086$
- $\chi^2 = 40.0$ (probability 47.1%) at the best fit point
- $\chi^2 = 43.5$ (probability 41.2%) for the null hypothesis
- With $\Delta\chi^2 = 3.5$, null is excluded at 81.9% confidence level
- Probabilities are based on fake data studies

G. Cheng et al., Phys. Rev. D86, 052009 (2012)

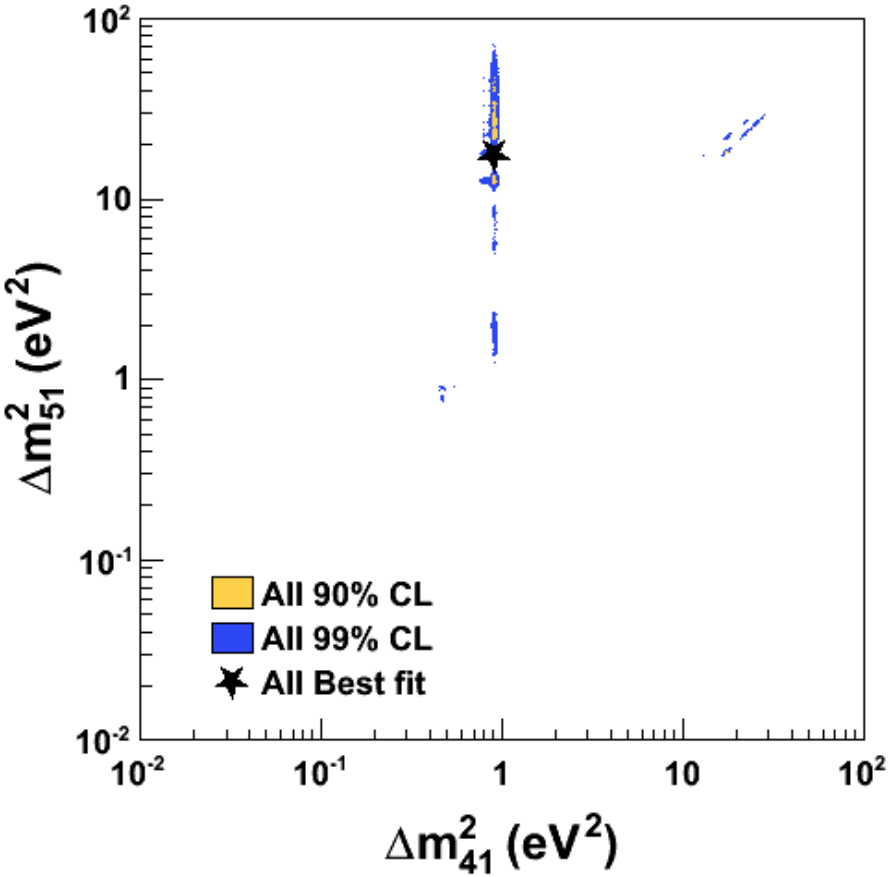
Global 3+N Fits to World Data

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

3+1



3+2



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, although there is some tension between appearance and disappearance experiments.
- Upcoming experiments (over a wide range of energies) have the potential of proving whether light, sterile neutrinos exist!

Backup

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:

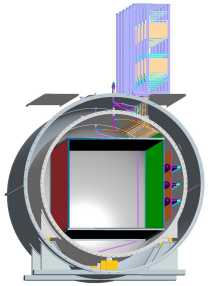
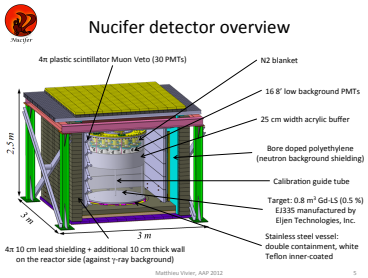


Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

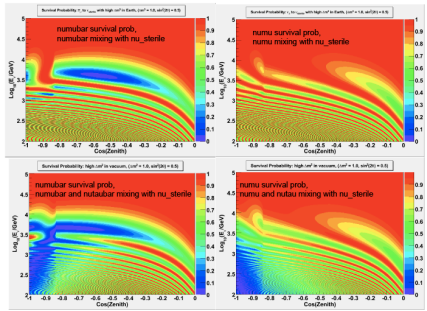
- Accelerator ν Experiments: MicroBooNE, MINOS+, NuStorm at FNAL, ICARUS at CERN, OscSNS at ORNL or J-PARC, IsoDAR

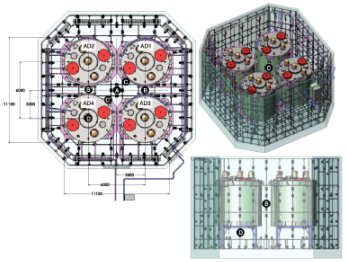
- Reactor ν Experiments: SCRAAM, NUCIFER, Stereo



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

- Atmospheric ν Experiments: IceCube



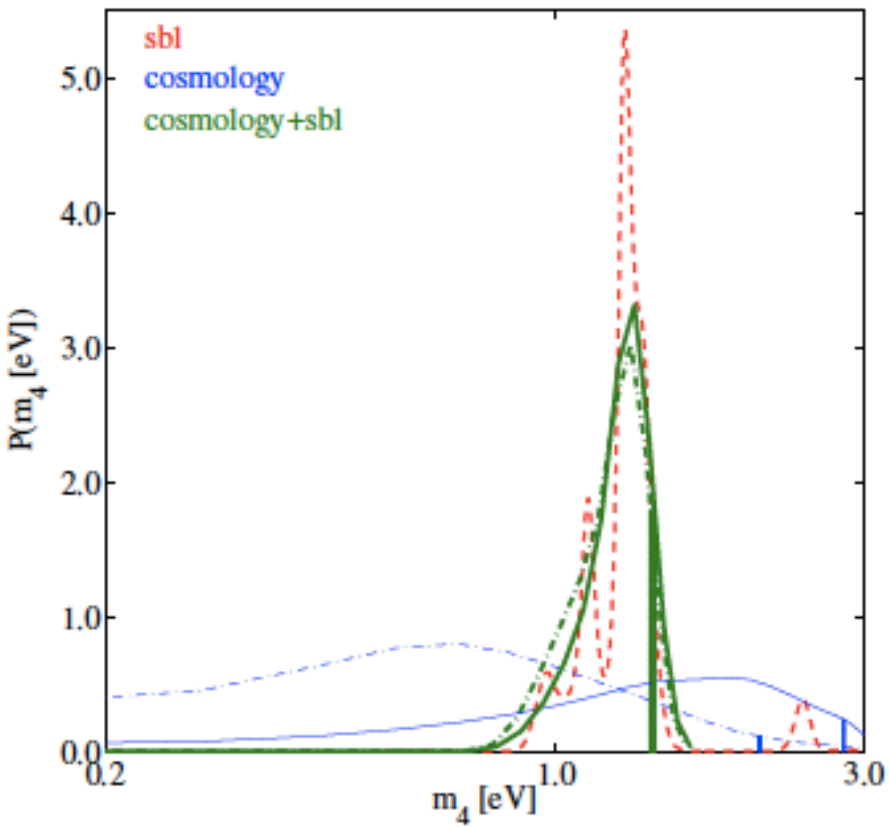


Global 3+N Fits to World Data

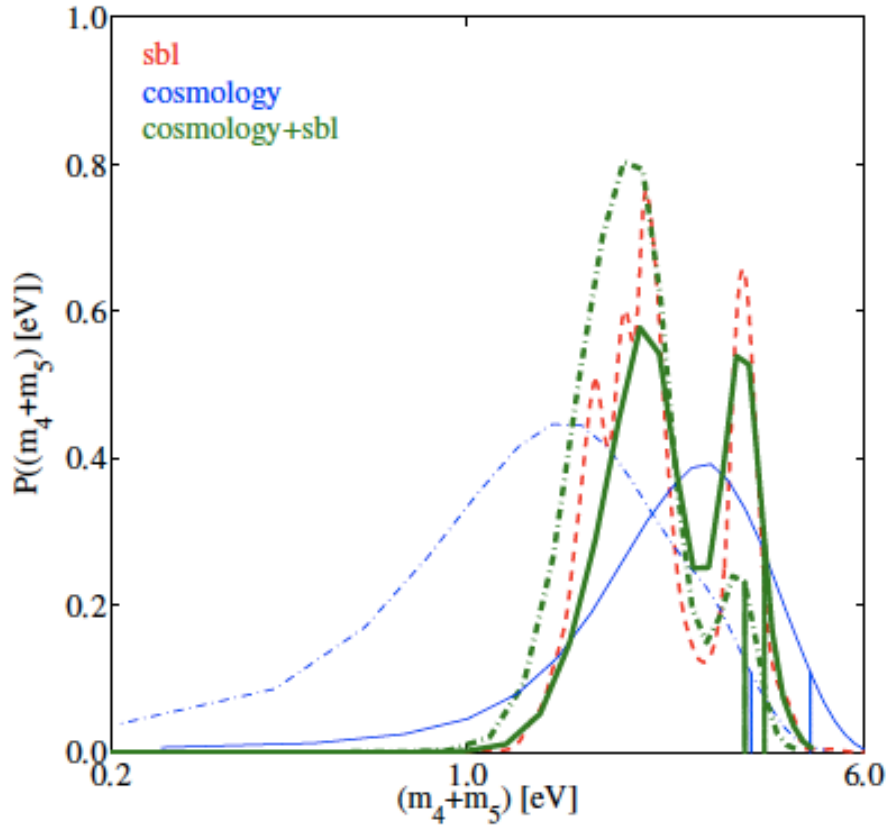
Maria Archidiacono, Nicolao Fornengo, Carlo Giunti, Steen Hannestad, & Alessandro Melchiorri

arXiv:1302.6720

3+1



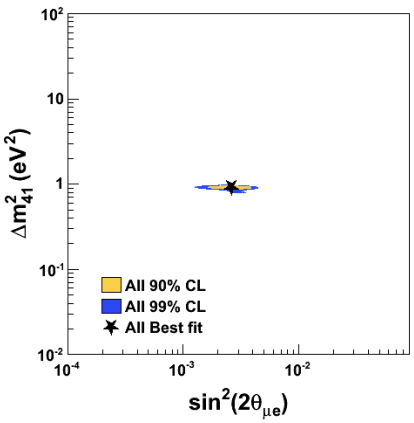
3+2



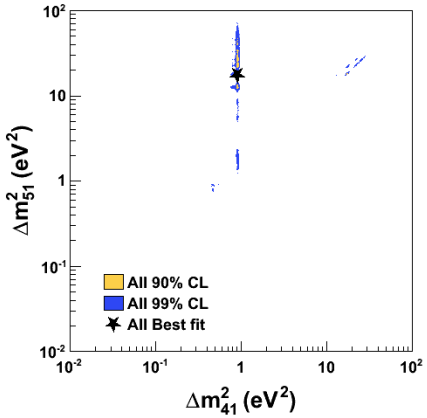
Global 3+N Fits to World Data

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

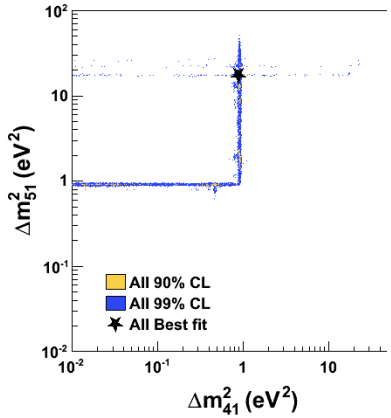
3+1

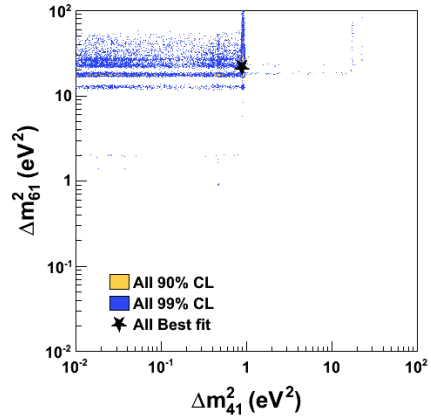


3+2



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

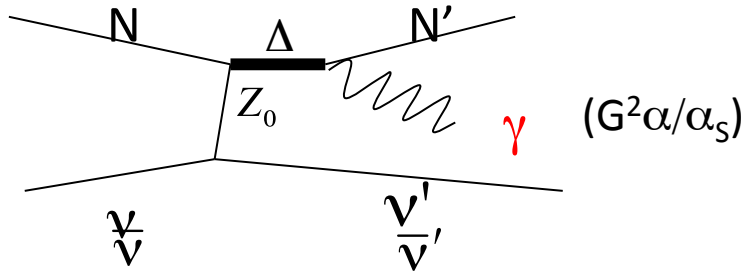
3+2	Δm^2_{41}	Δm^2_{51}	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 5}\rvert$	$\lvert U_{e5}\rvert$	ϕ_{54}
All	0.92	17	0.13	0.15	0.16	0.069	1.8π
App	0.31	1.0	0.31	0.31	0.17	0.17	1.1π
Dis	0.92	18	0.015	0.12	0.17	0.12	N/A
ν	7.6	17.6	0.05	0.27	0.18	0.052	1.8π
$\overline{\nu}$	0.92	3.8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

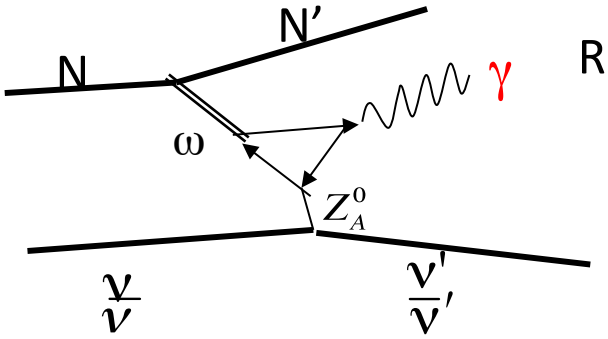
Table 3: The oscillation parameter best-fit points in each scenario considered. The values of Δm^2 shown are in units of eV^2

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

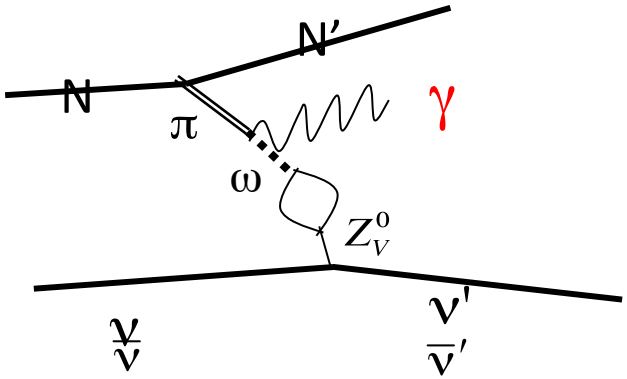
Dominant process accounted for in MC!



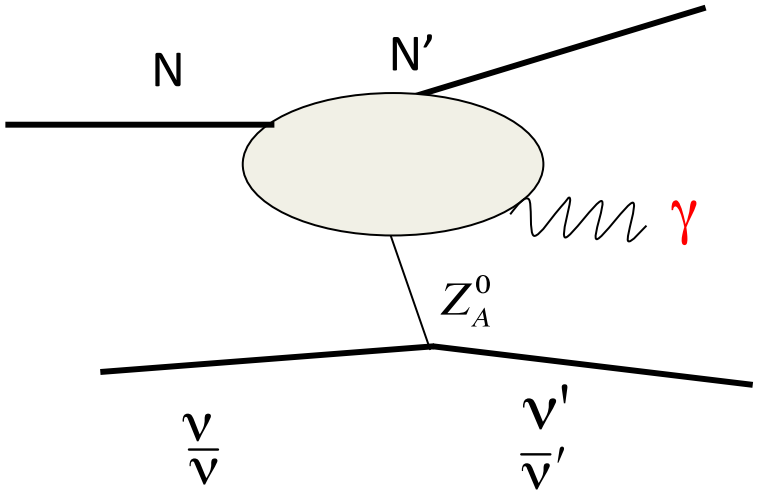
Radiative Delta Decay



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

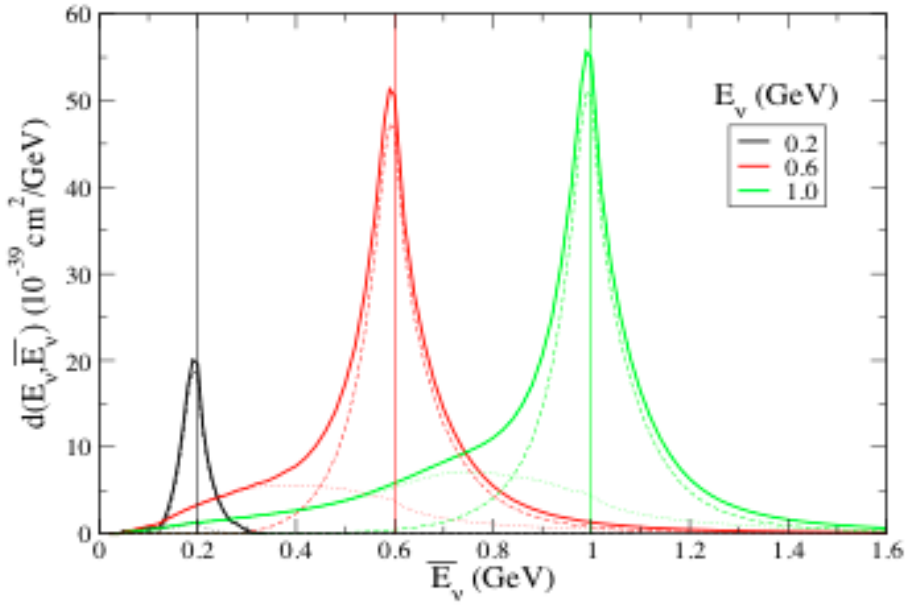


FIG. 1: (Color online) The spreading function $d(E_\nu, \overline{E_\nu})$ of Eq. (4) per neutron of ^{12}C in the case of electrons evaluated for three E_ν values. The genuine quasielastic (dashed lines) and the multinucleon (dotted lines) contributions are also shown separately.

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