Neutrino Anomalies and Sterile Neutrino Phenomenology

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BASED ON 1205. 1791
WITH K. ZUREK AND S. MCDERMOTT

Outline

- Status of 3 neutrino oscillations
  - Solar, atmospheric, θ_{13}
- Theoretical Motivation for Sterile Neutrinos
  - Easy to accommodate and generically occurring
- Experimental Motivation for Sterile Neutrinos
  - Gallium Anomaly – Lower than expected $Ga + \nu_e \rightarrow Ge + e^-$ rate (2.7σ) .
  - Reactor Anomaly – Deficit in $\bar{\nu}_e$ flux expected from nuclear reactors (2.5σ)
  - LSND & MiniBoone – Appearance of $\nu_e(\bar{\nu}_e)$ in a $\nu_\mu(\bar{\nu}_\mu)$ beam ($>3\sigma$)
  - Cosmology – BBN and CMB

Outline

- Oscillation Constraints
  - Disappearance experiments – Reactors, unitarity, Beam dumps
  - Appearance experiments – KARMEN, NOMAD, NuTeV
- LSND and MiniBoone fits in 3+1 model
- LSND and MiniBoone fits in 3+1+1 model
  - Motivation & Formalism
- Reactor and Gallium Anomaly fits
- Direct Constraints
  - Supernova, collider, meson decays, …

Status of 3 Neutrino Oscillations

Standard Lore

- Non-diagonal mass matrix causes mixing among flavor states

$$|\nu_i\rangle = U_{i\beta}|\nu_\beta\rangle$$

i,j: mass index α, β: flavor index

- Produce a flavor eigenstate which evolves over time

$$|\nu_i(t)\rangle = e^{i\,(E\cdot t - p\,\cdot x)}|\nu_i\rangle \qquad P_{\alpha\to\beta} = \left|\langle\nu_\beta|\nu_\alpha(t)\rangle\right|^2$$

Assuming only 1 mass difference is relevant

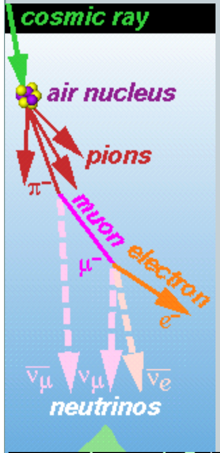
$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\Delta\mathrm{m}^2[eV^2]\frac{L[m]}{E[MeV]}\right)$$

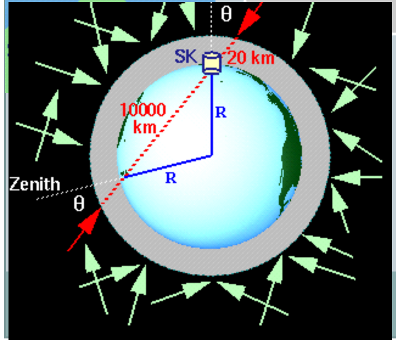
- Sensitive to oscillations when $\Delta\mathrm{m}^2[eV^2]\frac{L[m]}{E[MeV]}\sim 1$

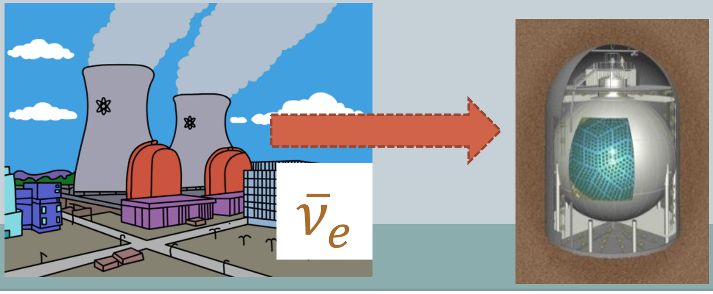
Status of 3 Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

Atmospheric	Solar	θ_{13}
Super Kamiokande. measured the disappearance of muon neutrinos produced in the atmosphere.	KamLAND measured the disappearance of electron neutrinos produced Japanese nuclear rectors.	Disappearance of electron neutrinos produced in reactors to long baselines.
$\sin^2 2\theta_{23} = 1$ $\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$	$\sin^2 2\theta_{12} = 0.86$ $\Delta m^2_{21} = 7.6 \times 10^{-5} eV^2$	$\sin^2 2\theta_{13} = 0.09$







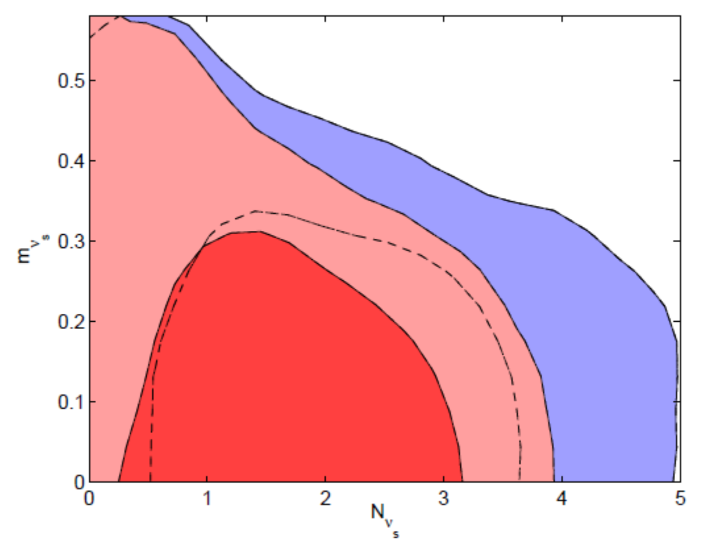
Why sterile neutrinos?

- Singlets generically come out of many BSM models
  - Remnants of GUTs (SO(10), E6,…)
  - Electroweak Leptogenesis, Low-scale sea-saw….

- Weakly coupled so masses can be anywhere…

- CMB, LSS, and BBN prefers additional relativistic degrees of freedom

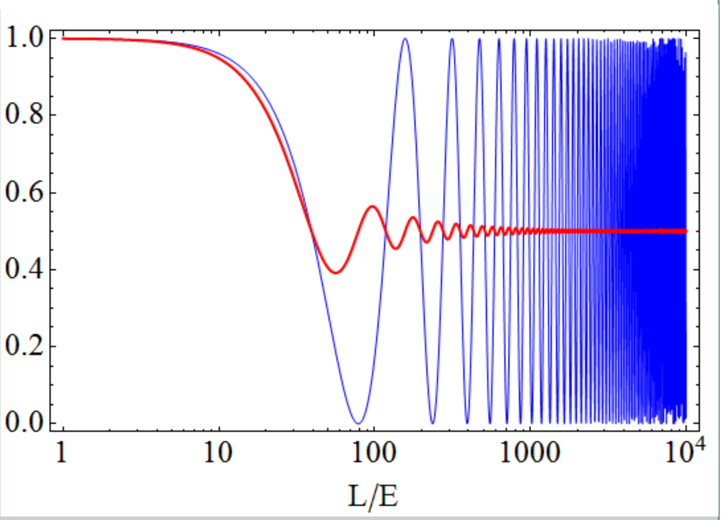
- Oscillation anomalies ….

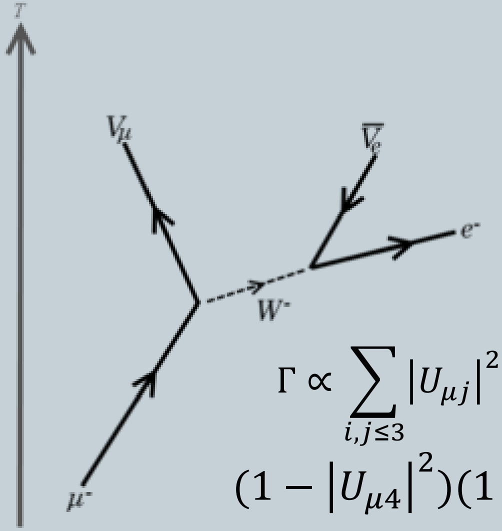


Giusarma et al. 1102.4774

Oscillation Signatures

- Disappearance ($\nu_{e,\mu} \rightarrow \nu_s$) at L/E not affected by 3 neutrino scenario
  - L/E dependence
  - Very fast oscillations-averaged over, no L/E dependence
  - A heavy neutrino, whose mass is above the available energy. Since it is integrated out, making the lighter mixing matrix non-unitary. It's effect will be to decrease the production and detection rates, by eating some of the $\nu_{e,\mu,\tau}$ components.
- Similarly for appearance





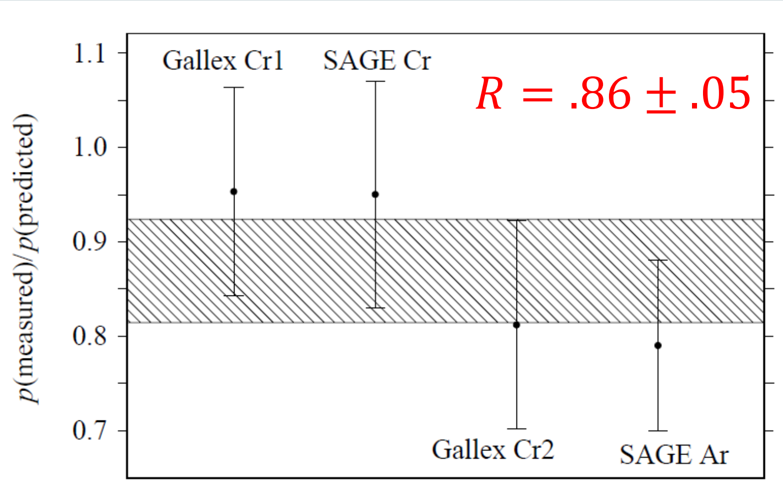
$$\Gamma \propto \sum_{i,j\leq 3} \left|U_{\mu j}\right|^2 |U_{ei}|^2 = (1 - \left|U_{\mu 4}\right|^2)(1 - |U_{e4}|^2)$$

The Gallium Anomaly

- Cr and Ar sources are placed in the GALLEX and SAGE solar neutrino detectors
- .5 MeV ν_e's are detected by $Ga + \nu_e \rightarrow Ge + e^-$
- 3σ lower than expected

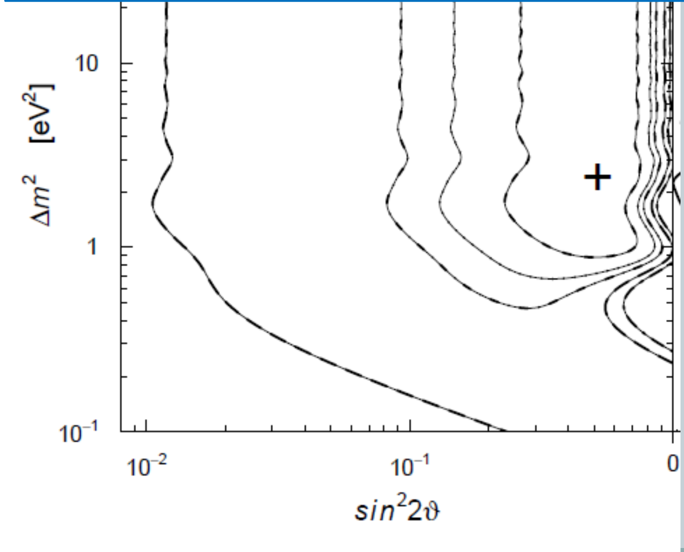
$$P = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta \mathrm{m}^2 \frac{L}{E}\frac{[eV^2 m]}{[MeV]}\right)$$

$$\sin^2 2\theta > 0.07, \qquad \Delta m^2 > 0.25\ eV^2$$



$R = .86 \pm .05$

Abdurashitov et al, SAGE 2009

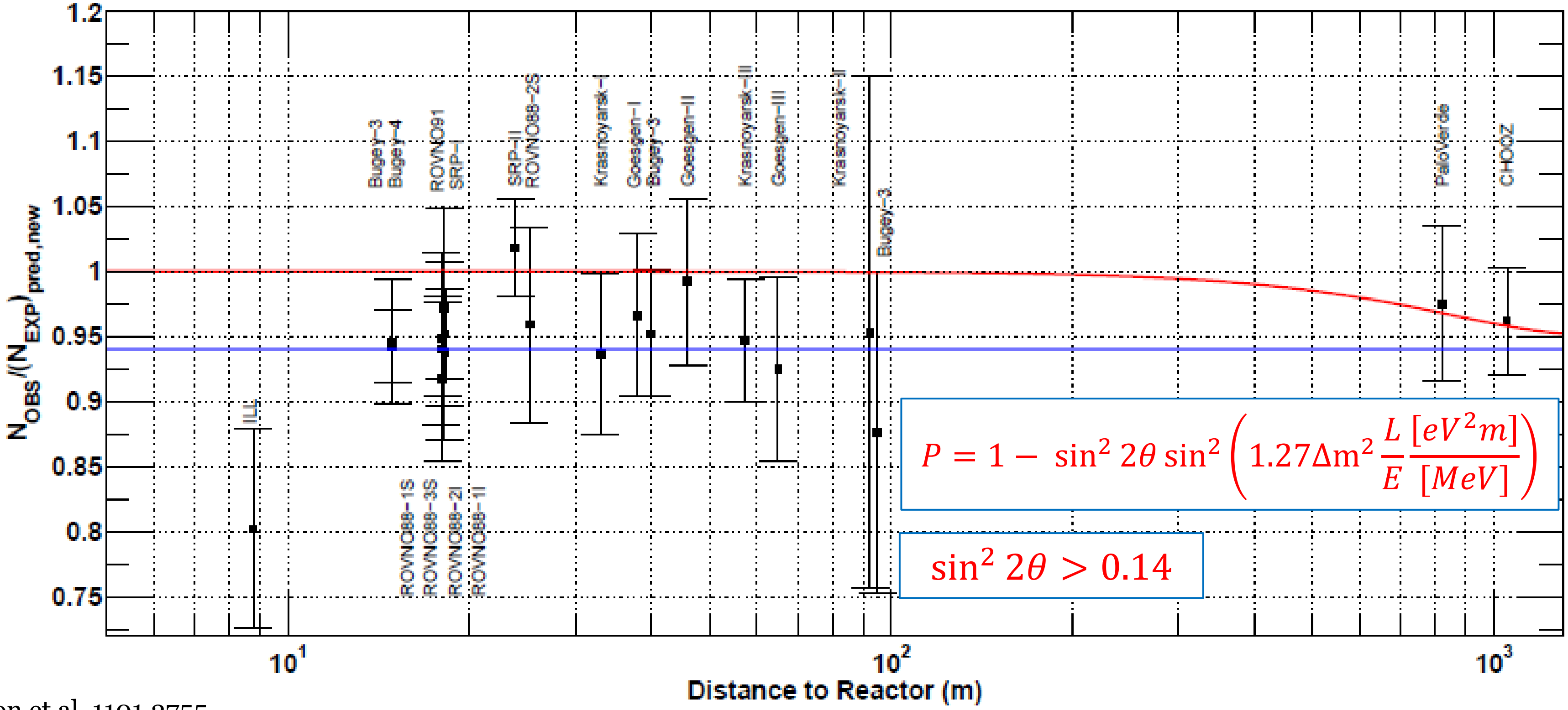


Guinti & Laveder 1006.3244

The Reactor Antineutrino Anomaly (1101.2755)

- Re-evaluation of predicted reactor fluxes shows an increase of flux about 3% higher than previously calculated - *Mueler et al 1101.2663 and confirmed by Huber 1106.0687*
  - Use ILL reactor β measurements to convert β spectra to ν spectra. New calculation takes into account 1000's of fission decays, only 10% fitted with 5 effective β-decays (old: 100% fitted to 30 effective β-decays)

Deficit of $\bar{\nu}_e$ from reactors $R = 0.943 \pm 0.023$ (98.6% C.L.)



$$P = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\frac{[eV^2 m]}{[MeV]}\right)$$

$$\sin^2 2\theta > 0.14$$

Mention et al, 1101.2755

Combined $\nu_e, \bar{\nu}_e$ Disappearance Anomalies

$$R = 0.943 \pm 0.023 \text{ (98.6\% C.L.)}$$

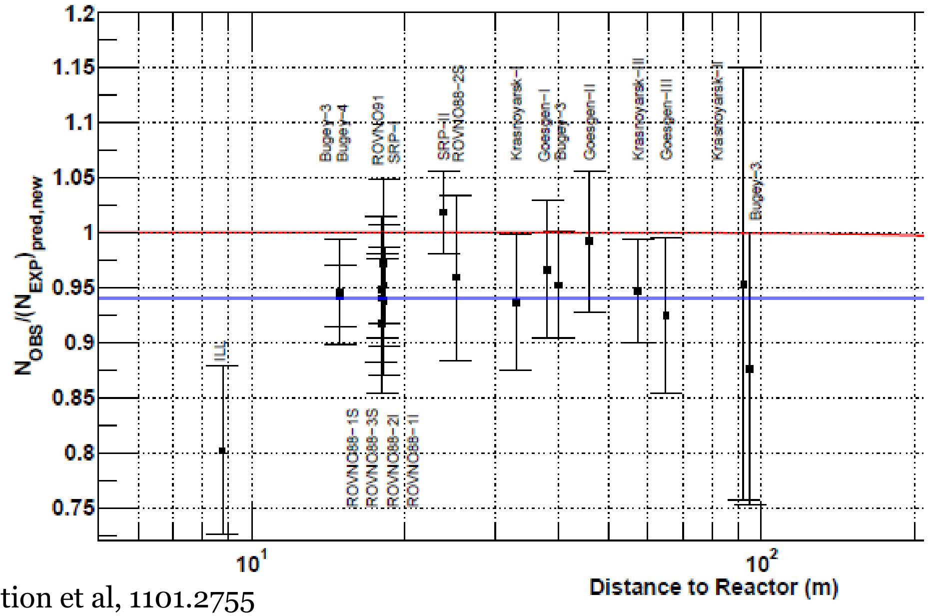
- No L/E dependence – anomaly depends crucially on the overall flux

$$\Delta m^2 > 0.3 \text{ eV}^2$$

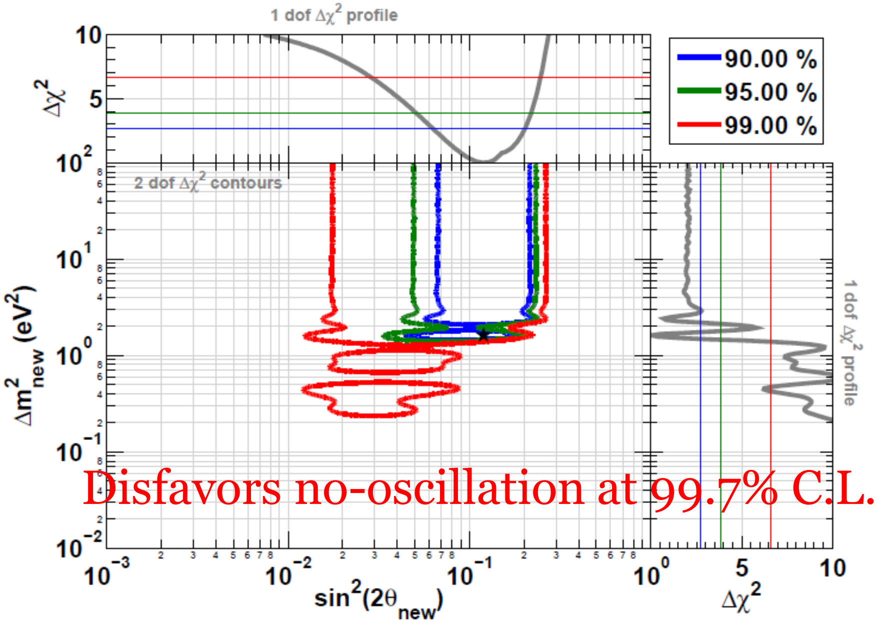
- Very fast oscillations that average quickly $\left(P = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \to 1 - \frac{1}{2}\sin^2 2\theta\right)$

$$\sin^2 2\theta > .14$$

- Or very heavy neutrinos that reduce the $\bar{\nu}_e$ components on reactor energies



Mention et al, 1101.2755



Disfavors no-oscillation at 99.7% C.L.

LSND (2001)

- Produce neutrinos from pions at rest

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

- Measure $\bar{\nu}_e$ from inverse beta decay

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

- Significant excess of events (3σ)

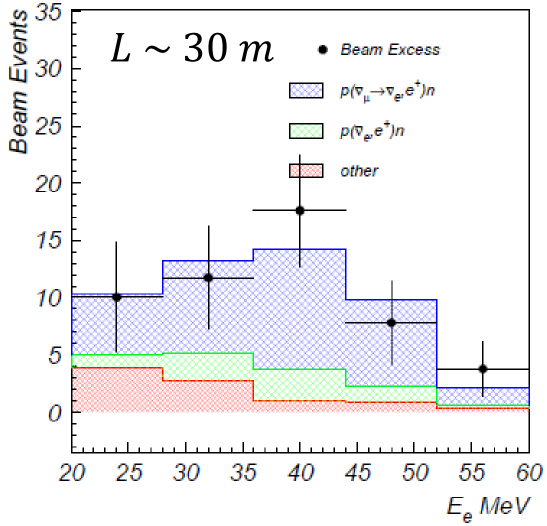
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

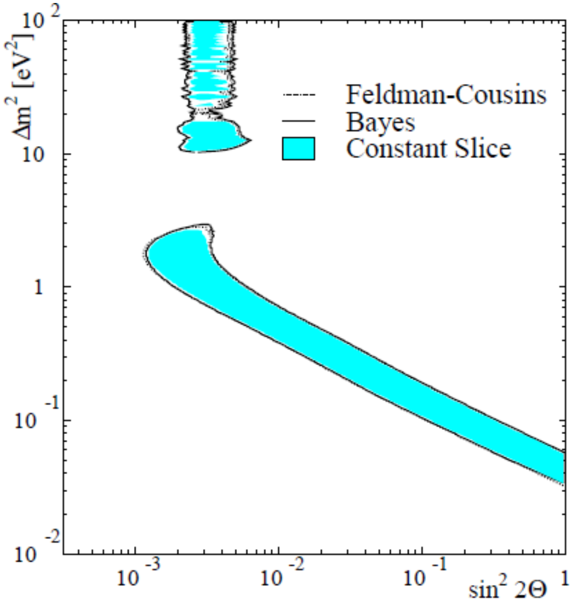
- Oscillation probability

$$P \sim (.264 \pm 0.081)\%$$

- Best fit oscillations

$\sin^2 2\theta = 0.003$ $\Delta\, m^2 = 1.2\; eV^2$

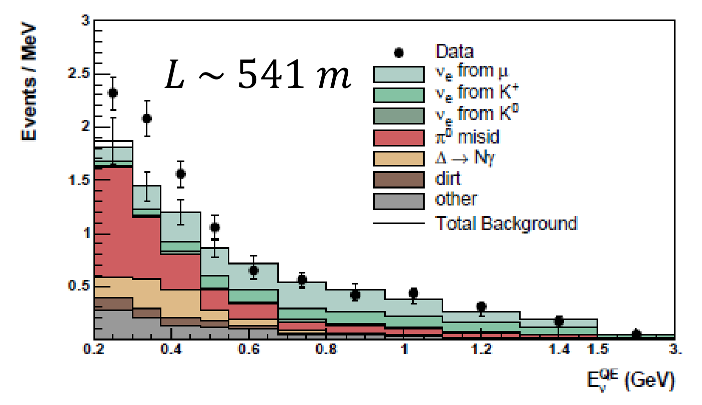


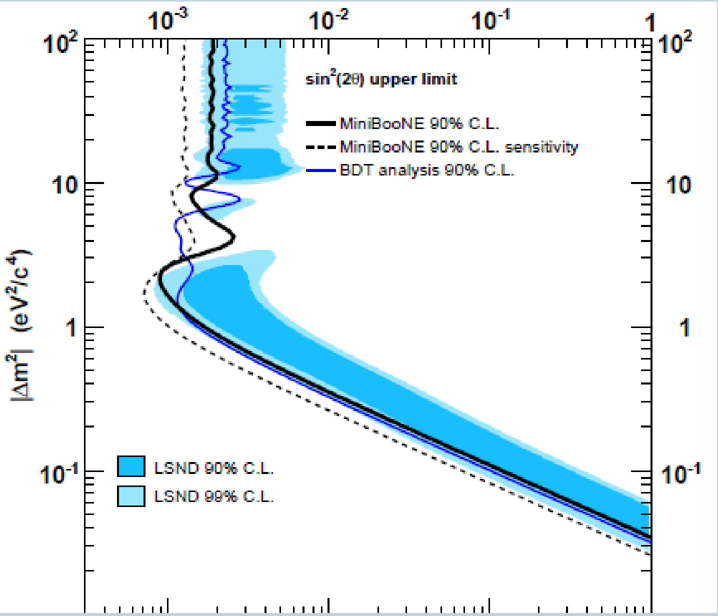


MiniBoone Neutrinos (2009)

$\nu_\mu \rightarrow \nu_e$ appearance

- $E > 475$ MeV in good agreement with background
  - Rules our LSND region at 90% in 2 neutrino model
- $E < 475$ MeV there is a 3.4σ excess, but inconsistent with LSND oscillation shape, but consistent with the magnitude.





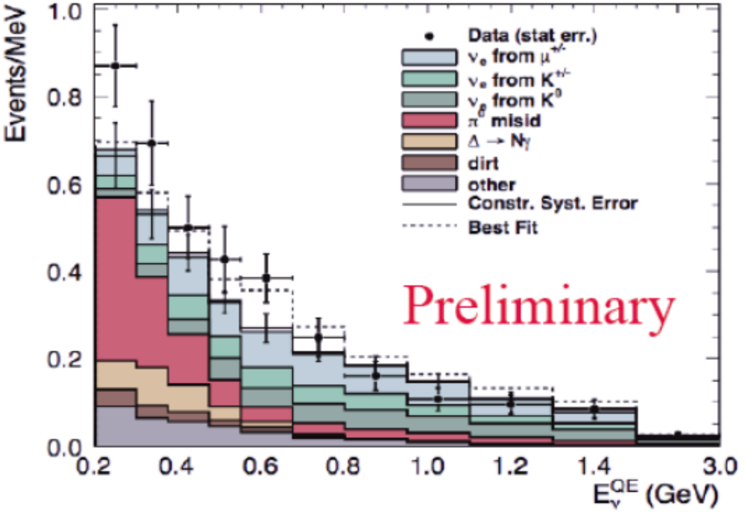
MiniBoone Antineutrinos (2011)

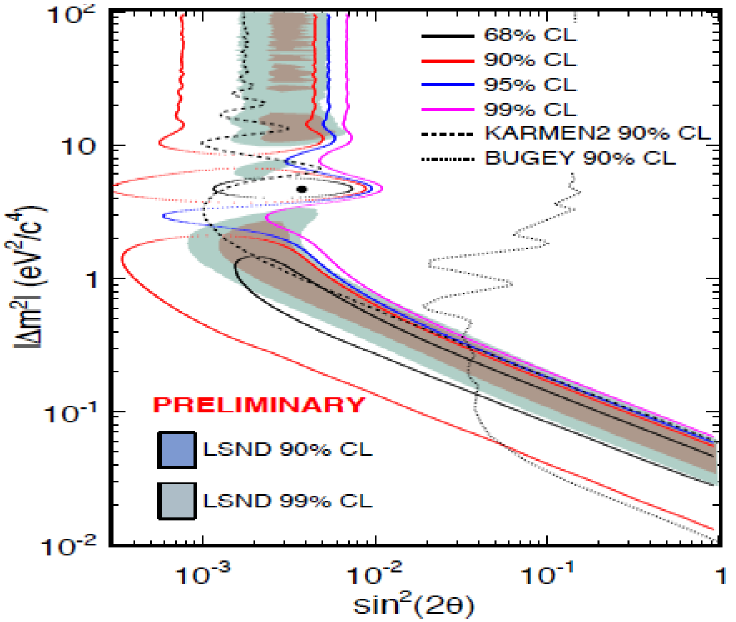
$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance

- $E > 475$ MeV in good agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.
  - Oscillations preferred at 99.4% CL
- $E < 475$ MeV events in agreement with neutrino appearance
  - Oscillations preferred at 97.6% CL

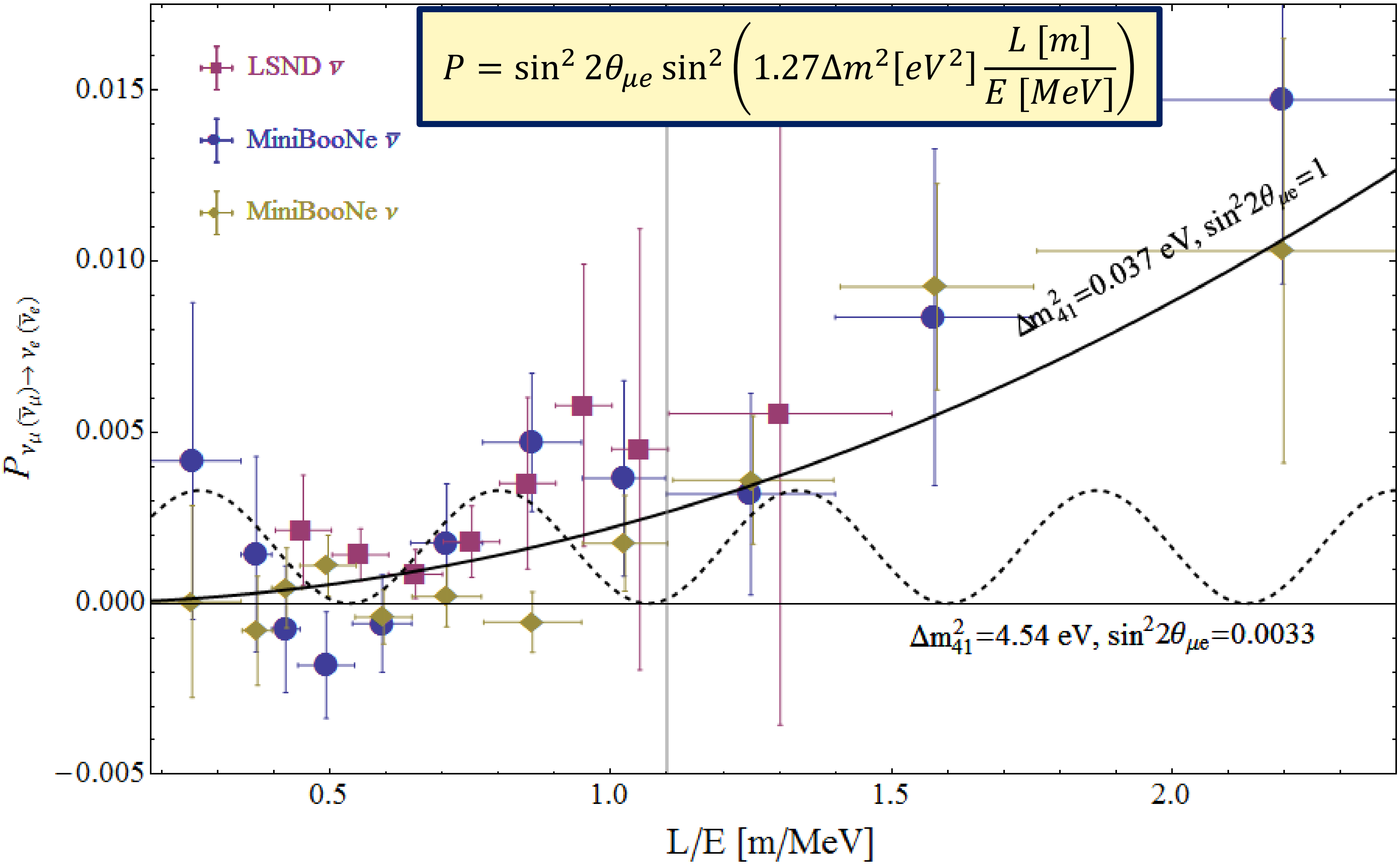
$\bar{\nu}_\mu \to \bar{\nu}_e$ Summary

LSND:	$\sin^2 2\theta = 0.003$	$\Delta\, m^2 = 1.2\, eV^2$
MB$\bar{\nu}$ >475 :	$\sin^2 2\theta = 0.003$	$\Delta\, m^2 = 4.6\, eV^2$





LSND & MiniBoone



$$P = \sin^2 2\theta_{\mu e} \sin^2\left(1.27\Delta m^2[eV^2]\frac{L\ [m]}{E\ [MeV]}\right)$$

Constraints on LSND + MB

- Well-known tension between LSND+MB and null experiments; worse with new MB data
- 3 + 1 Model -new Δm^2 from additional sterile neutrino

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}|^2 \left|U_{\mu 4}\right|^2$$

$$\sin^2 2\theta_e = 4\,|U_{e4}|^2(1 - |U_{e4}|^2)$$

Constrained by null $\bar{\nu}_e$ disappearence (Reactors)

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

Constrained by null $\bar{\nu}_\mu$ disappearance (Super-K, beam dumps)

Take constraints from reactors with new fluxes (with new fluxes they are weaker!)
Statistics dominated by Bugey; include 40/15 Bugey data.

SuperK measures maximal mixing for muon neutrino disappearance

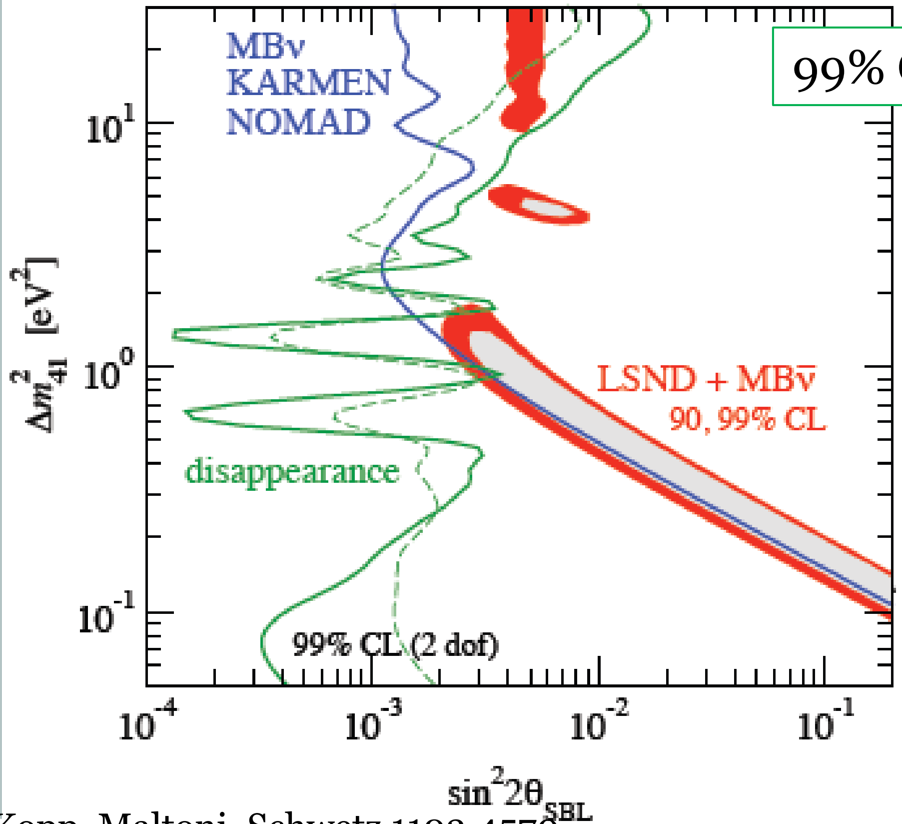
$$1 \sim \sin^2 2\theta_{atm} = 4\left|U_{\mu 3}\right|^2\left(1 - \left|U_{\mu 3}\right|^2 - \left|U_{\mu 4}\right|^2\right)$$

If $\left|U_{\mu 4}\right|^2$ is too large $\sin^2 2\theta_{atm}$ cannot reach its maximal value.

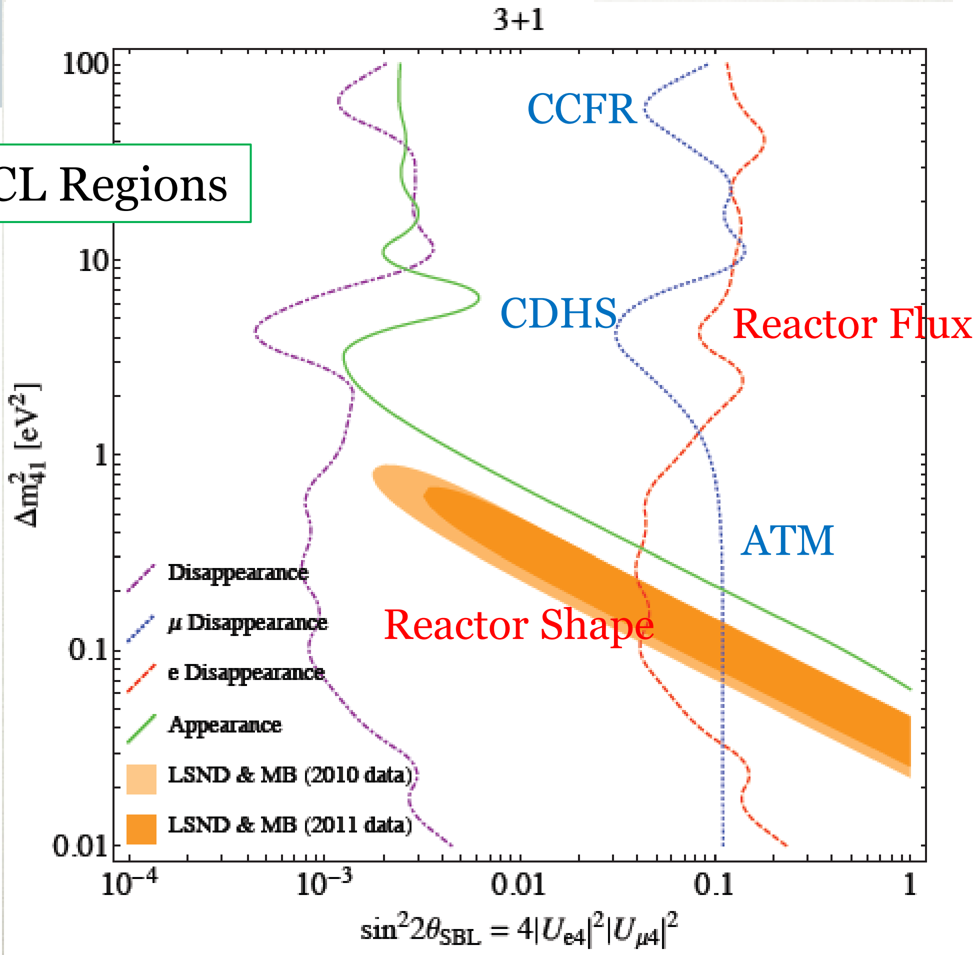
3+1 Fits + Constraints

Fit looks poor when combined with null experiments

Worse with MB2011 data



99% CL Regions



Kopp, Maltoni, Schwetz 1103.4570

3+1+more?

Can additional neutrinos improve the fits?

- 3+2: Two $\Delta m^2 \sim eV^2$ish sterile neutrinos
  - More parameters, including CP violation that help fit to the MB$\nu/\bar{\nu}$ differences
  - Improvement, but still over 99% CL discrepancy with disappearance constraints -Kopp, Maltoni, Schwetz 1103.4570
- 3+1+1: One $\Delta m^2 \sim eV^2$ish and one $\Delta m^2 \gg MeV^2$
  - Proposed by Nelson 1010.3970
  - Heavy neutrino is averaged over or integrated out. Does not contribute to the *shape* of oscillations.
    - For disappearance $\Delta m_{51}^2 \gg E_\nu \sim MeV^2$ - no oscillation, but lowers reaction rates.
  - Includes CP violation.
  - More compatible with BBN

3+1+1: Formalism

- r: enhances $\sin^2 2\theta_{\mu e}$ for fixed $U_{\mu 4}U_{e4}$. $U_{\mu 5}U_{e5}$ is not constrained by the shape of oscillations
- β: CP Violation, distinguishes ν / $\bar{\nu}$ oscillations in LSND and MB
- κ: Constant oscillation term can shift oscillation curves

$$P = \sin^2 2\,\theta_{\mu e}\ \sin^2(\Delta m_{41}^2 L/4E \pm \beta) + \kappa$$

$$\begin{aligned}\sin^2 2\,\theta_{\mu e} &= 4\left|U_{\mu 4}U_{e4}\right|^2 r \\ &= 4\left|U_{\mu 4}U_{e4}\right|^2 \left|U_{\mu 4}^* U_{e4} + U_{\mu 5}^* U_{e5}\right| / \left|U_{\mu 4}^* U_{e4}\right|\end{aligned}$$

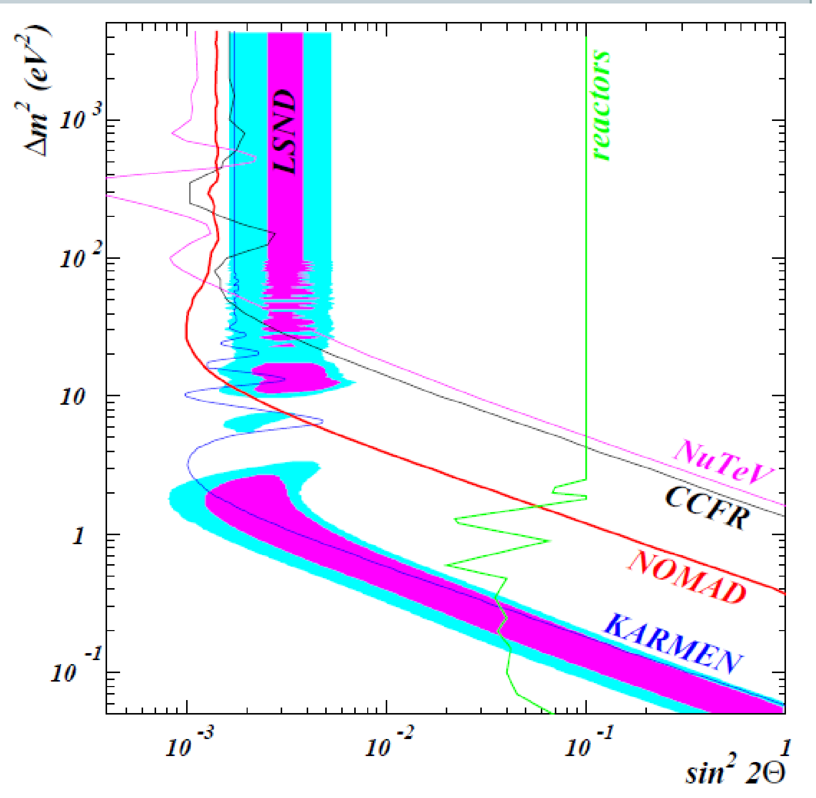
Null Appearance Constraints

- Many collider experiments looked for $\nu_\mu\ (\bar{\nu}_\mu) \to \nu_e\ (\bar{\nu}_e)$. Some with very high energies $E_\nu > GeV$, but low L/E. Thus sensitive only to large $\Delta m^2 \gg eV^2$.

- Unaffected by $\Delta m_{41}^2 \sim eV^2$ oscillations.

$$\sin^2 2\theta_{\mu e} \to 4\,|U_{e5}|^2 \left|U_{\mu 5}\right|^2 \sim < 10^{-3}$$

Constrains r and κ

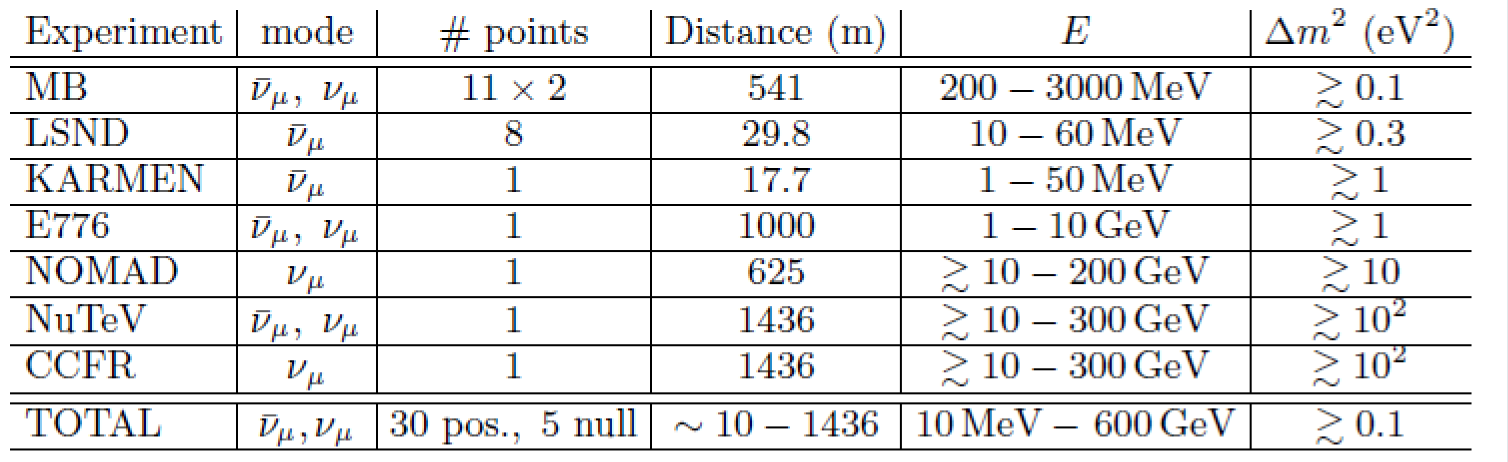


Some Details About the Fit

Our Fitting Philosophy

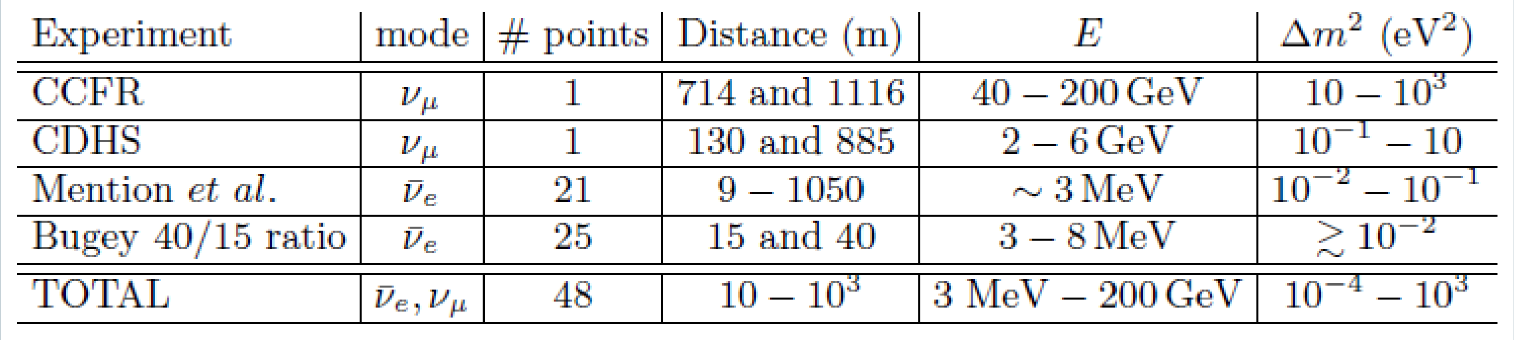
Appearance Fits

Null Appearance Constraints



Experiment	mode	# points	Distance (m)	E	Δm^2 (eV^2)
MB	$\bar{\nu}_\mu,\ \nu_\mu$	11×2	541	$200 - 3000$ MeV	$\gtrsim 0.1$
LSND	$\bar{\nu}_\mu$	8	29.8	$10 - 60$ MeV	$\gtrsim 0.3$
KARMEN	$\bar{\nu}_\mu$	1	17.7	$1 - 50$ MeV	$\gtrsim 1$
E776	$\bar{\nu}_\mu,\ \nu_\mu$	1	1000	$1 - 10$ GeV	$\gtrsim 1$
NOMAD	ν_μ	1	625	$\gtrsim 10 - 200$ GeV	$\gtrsim 10$
NuTeV	$\bar{\nu}_\mu,\ \nu_\mu$	1	1436	$\gtrsim 10 - 300$ GeV	$\gtrsim 10^2$
CCFR	ν_μ	1	1436	$\gtrsim 10 - 300$ GeV	$\gtrsim 10^2$
TOTAL	$\bar{\nu}_\mu, \nu_\mu$	30 pos., 5 null	$\sim 10 - 1436$	10 MeV $-$ 600 GeV	$\gtrsim 0.1$

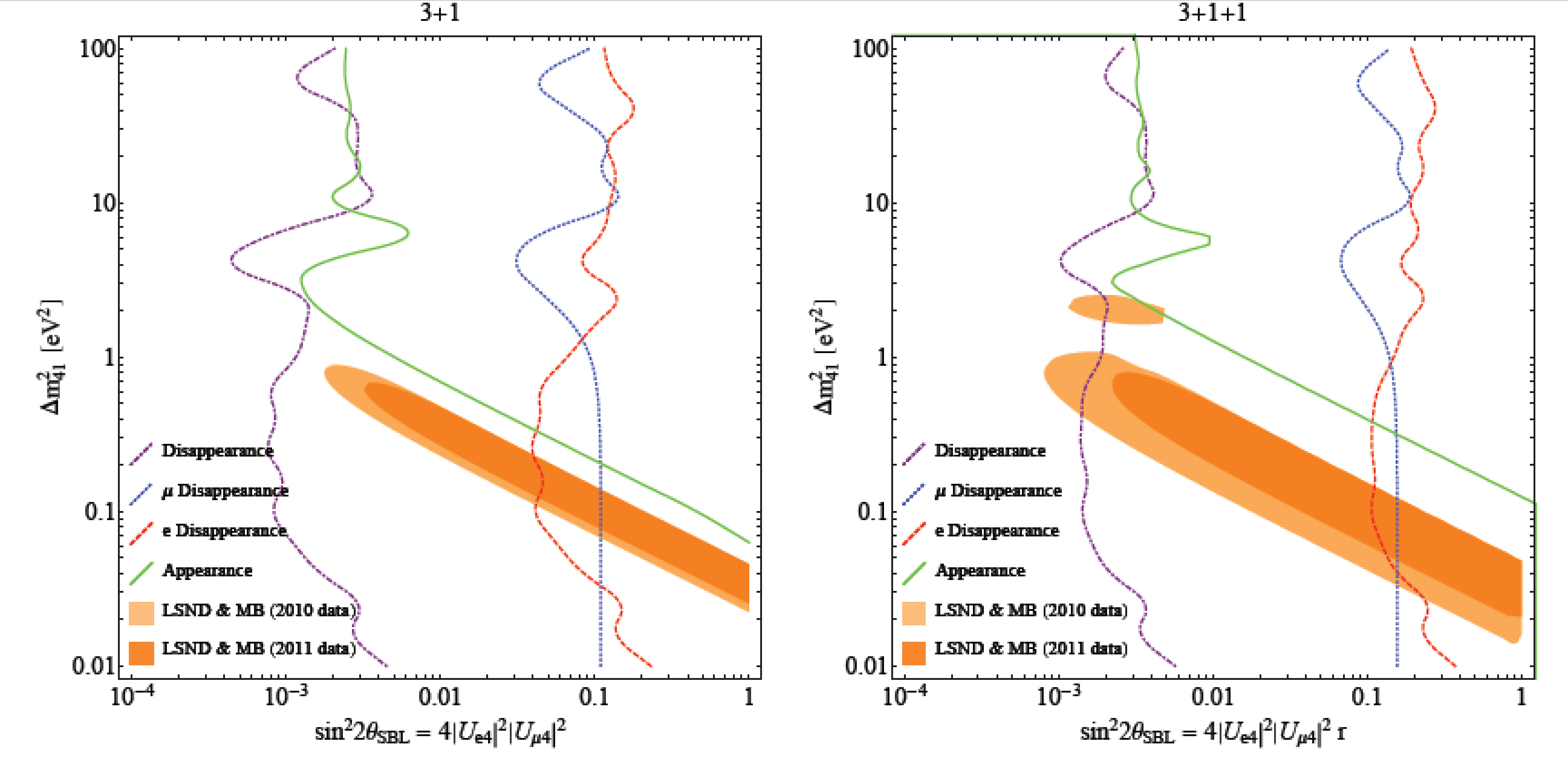
Null Disappearance Constraints



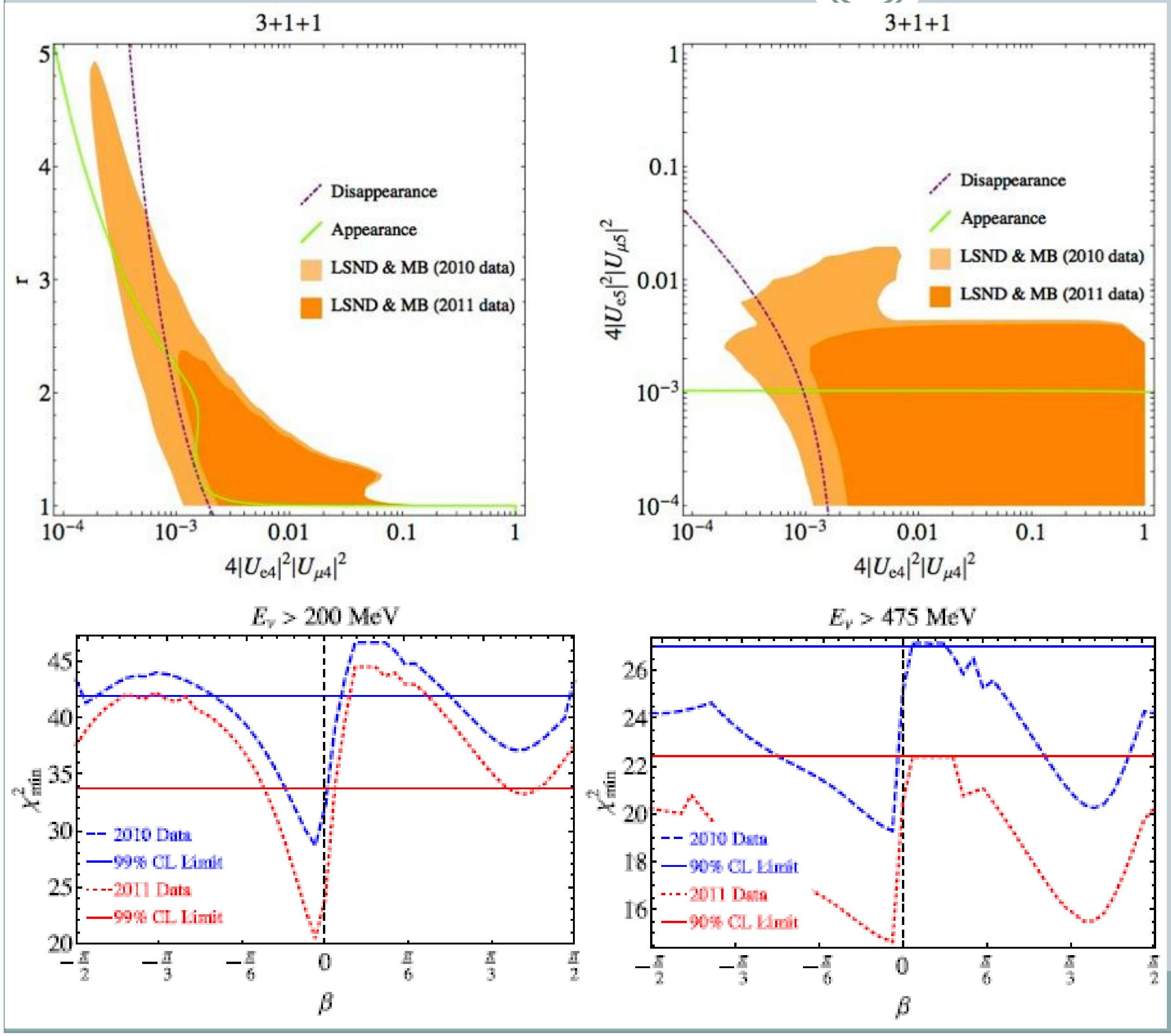
Experiment	mode	# points	Distance (m)	E	Δm^2 (eV^2)
CCFR	ν_μ	1	714 and 1116	$40 - 200$ GeV	$10 - 10^3$
CDHS	ν_μ	1	130 and 885	$2 - 6$ GeV	$10^{-1} - 10$
Mention *et al.*	$\bar{\nu}_e$	21	$9 - 1050$	~ 3 MeV	$10^{-2} - 10^{-1}$
Bugey 40/15 ratio	$\bar{\nu}_e$	25	15 and 40	$3 - 8$ MeV	$\gtrsim 10^{-2}$
TOTAL	$\bar{\nu}_e, \nu_\mu$	48	$10 - 10^3$	3 MeV $-$ 200 GeV	$10^{-4} - 10^3$

Does it work? No.

- Still a huge discrepancy in 3+1+1 model
  - 3+1+n model would be the same – the effects of heavier neutrinos is just to decrease the unitarity of the 4x4 mixing.



Why?



r offers a multiplicative enhancement but is bound to be very close to one.

β offers more parameter freedom, less sensitivity to mass and mixing, but new low-energy data doesn't like CP violation.

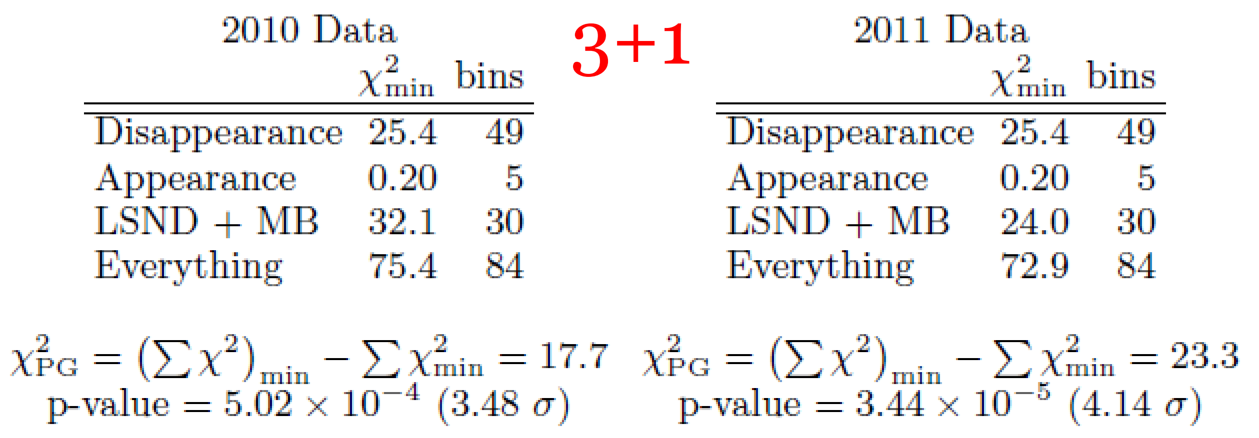
Quantitatively

Parameter Goodness of Fit test (Maltoni, Schwetz hep-ph/0304176]

$\chi^2_{PG} = (\sum\chi^2)_{min} - \sum\chi^2_{min}$

Measures the worsening of the fit from fitting to all of the data sets instead of fitting to each individually.

3+1



2010 Data

	$\chi^2_{\rm min}$	bins
Disappearance	25.4	49
Appearance	0.20	5
LSND + MB	32.1	30
Everything	75.4	84

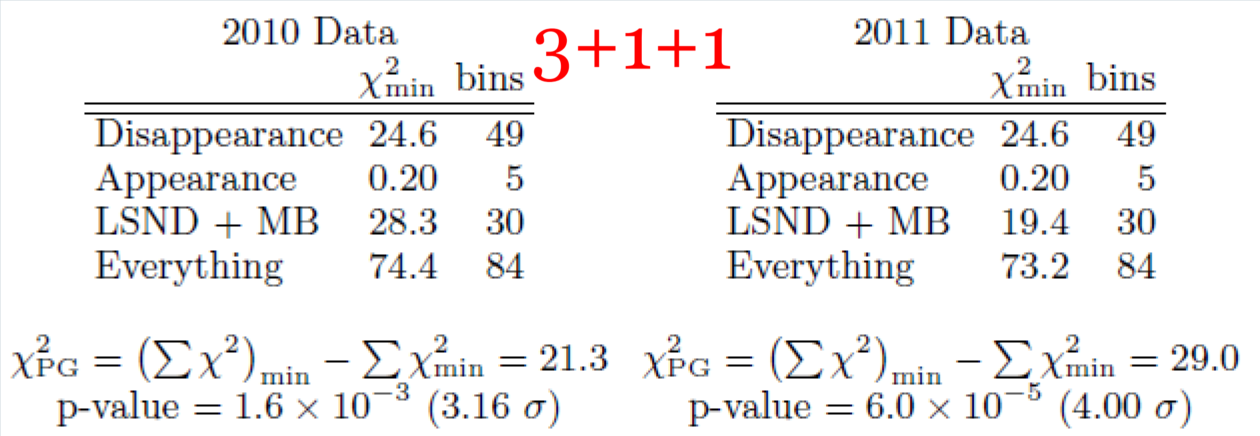
$$\chi^2_{\rm PG} = \left(\sum\chi^2\right)_{\rm min} - \sum\chi^2_{\rm min} = 17.7$$
$$\text{p-value} = 5.02\times10^{-4}\ (3.48\ \sigma)$$

2011 Data

	$\chi^2_{\rm min}$	bins
Disappearance	25.4	49
Appearance	0.20	5
LSND + MB	24.0	30
Everything	72.9	84

$$\chi^2_{\rm PG} = \left(\sum\chi^2\right)_{\rm min} - \sum\chi^2_{\rm min} = 23.3$$
$$\text{p-value} = 3.44\times10^{-5}\ (4.14\ \sigma)$$

3+1+1



2010 Data

	$\chi^2_{\rm min}$	bins
Disappearance	24.6	49
Appearance	0.20	5
LSND + MB	28.3	30
Everything	74.4	84

$$\chi^2_{\rm PG} = \left(\sum\chi^2\right)_{\rm min} - \sum\chi^2_{\rm min} = 21.3$$
$$\text{p-value} = 1.6\times10^{-3}\ (3.16\ \sigma)$$

2011 Data

	$\chi^2_{\rm min}$	bins
Disappearance	24.6	49
Appearance	0.20	5
LSND + MB	19.4	30
Everything	73.2	84

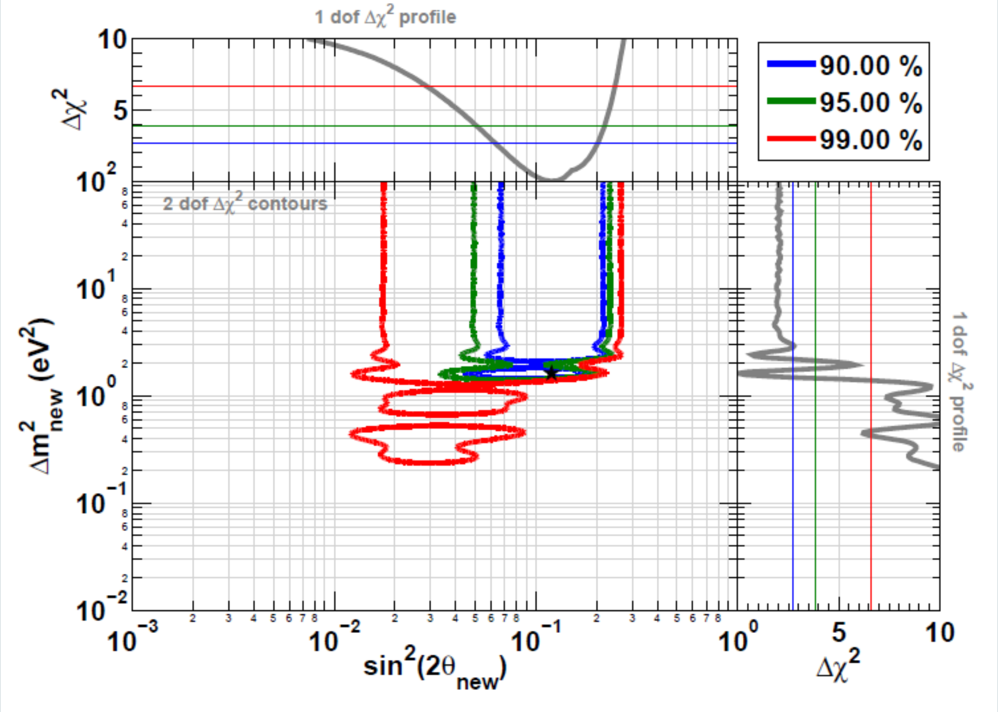
$$\chi^2_{\rm PG} = \left(\sum\chi^2\right)_{\rm min} - \sum\chi^2_{\rm min} = 29.0$$
$$\text{p-value} = 6.0\times10^{-5}\ (4.00\ \sigma)$$

Reactor and Gallium Anomalies?

- Can a heavy neutrino explain the reactor and gallium Anomalies?

$$|U_{e5}|^2 = 0.036 \pm 0.013$$

Anomaly	$sin^2 2\theta_{e5}$
Gallium	0.27±0.12
Reactor	0.11±0.06
Total	0.14±0.05



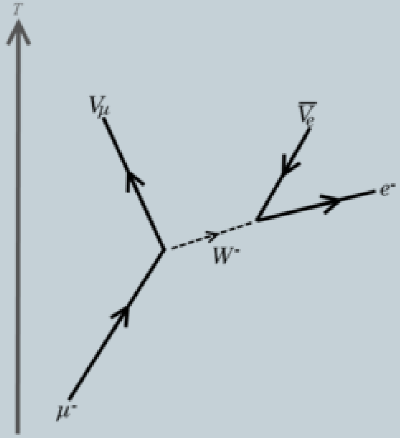
- A heavy (non-relativistic at BBN) neutrino can evade cosmological constraints

$$\boxed{\Delta m^2 \leq eV^2 \qquad N_\nu \geq 3}$$

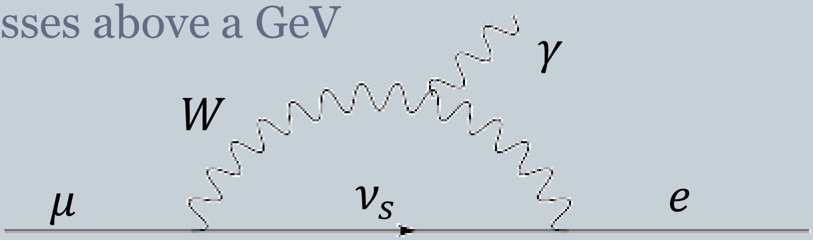
Giusarma et al. 1102.4774

Direct Constraints on Sterile Neutrinos

- Supernova 1987A (Kainulainen, Maalampi, Peltoniemi 1991)
  - Sterile neutrinos are produced from the core, causing the supernova to cool to quickly
  - Strong from 100 eV to 100 MeV
- Line Searches: $\pi, K \rightarrow l\,\nu$
  - If the neutrino is heavy, it can distort the leptonic spectrum relative to the case with only massless neutrinos. Constraints strong from 30 MeV – 500 MeV.
- Muon Lifetime (Biggio, Blennow, Fernandez-Martinez 0907.0097)
  - For $m > m\_\mu$, the muon lifetime will be increased relative to the SM prediction due to the non-unitarity in the neutrino mixing matrix.
  - Constraints strong above m_μ

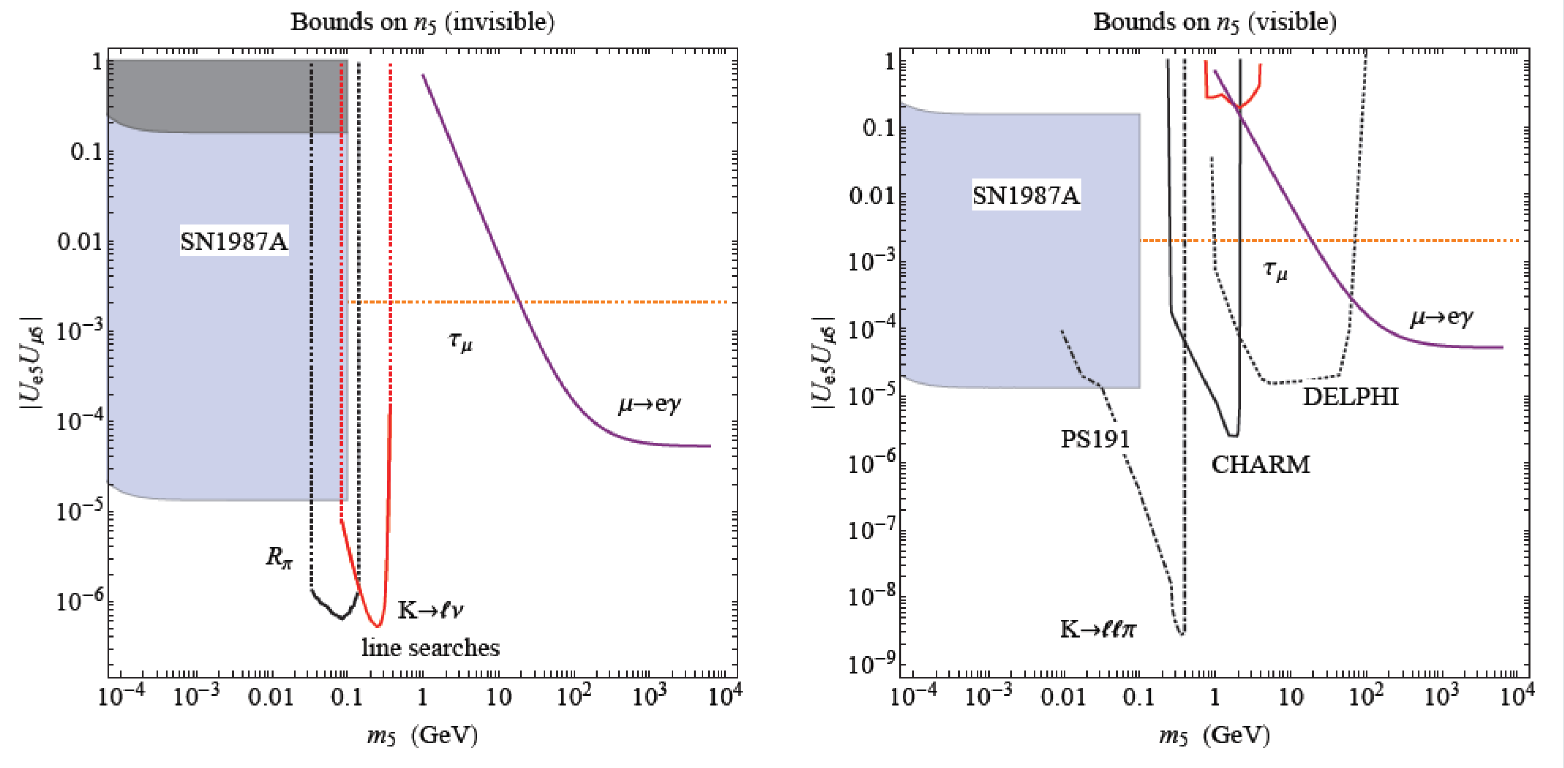


- $\mu \rightarrow e\gamma$
  - Non-observation constrains mixing for masses above a GeV
- Visible Decays
  - ν decays to leptons



Nice review by Atre, Han, Pascoli, Zhang, 0901.3589

Too Strong



1. RAA and Ga do not see L/E dependence, which requires $\Delta m^2 > eV$.
2. LSS + CMB restricts $\Delta m^2 < eV$ if thermalized.
3. Direct bounds rule out large mixings for $\Delta m^2 > 100\ eV$.

No good explanation of the RAA and Ga anomalies!

Also MB & LSND even more constrained (Lots of σ).

Conclusions

All neutrino anomalies in conflict with everything.

- Many different data sources prefer additional neutrinos.
- LSND + MB oscillations in conflict with null disappearance experiments.
- Reactor and Gallium anomalies in conflict with cosmology and direct searches.