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# Sterile Neutrino Physics Motivation & Experiment Status

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Fermilab PAC Meeting

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# Overview

- I aim to describe the evidence and counter evidence for "eV scale" sterile neutrinos and future efforts in this area
- I aim to stick to the facts and not deliver opinions
  - You can judge how successful I am at this
- I'm pitching the content at the non-neutrino PAC members
  - Neutrino experts should see nothing new in this talk

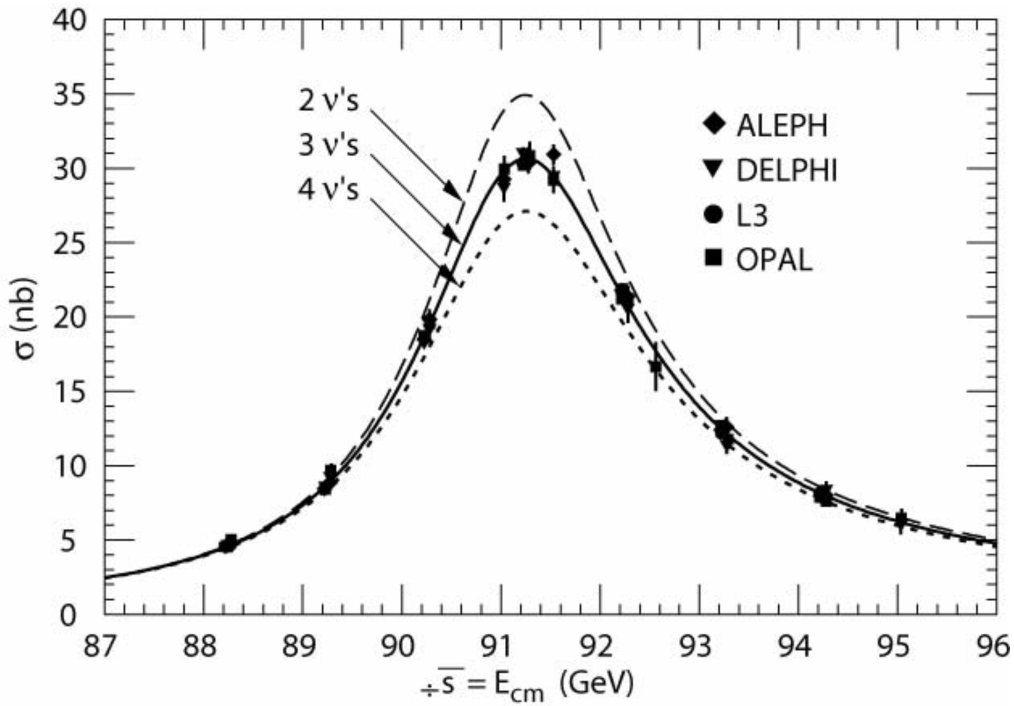
# Summary of Tensions in the 3ν Mixing Scheme

- Gallium: 2.7σ evidence for $\nu_e$ disappearance
- LSND: 3.8σ evidence for anti-$\nu_e$ appearance
- MiniBooNE: 3.8σ evidence for $\nu_e$ and anti-$\nu_e$ appearance
- Reactor: 3.0σ evidence for anti-$\nu_e$ disappearance
- These can be interpreted as evidence for a 4$^{th}$ neutrino state at ~eV mass

- However ….
- There are a number of results that are sensitive, but see no evidence for a 4$^{th}$ neutrino state with ~eV mass:-
  - CDHS and MiniBooNE searches for $\nu_\mu$ disappearance
  - MiniBooNE search for $\bar{\nu}_\mu$ disappearance
  - MINOS search for $\nu_\mu \rightarrow \nu_s$
  - Karmen search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - OPERA and ICARUS searches for $\nu_\mu \rightarrow \nu_e$
- It is hard (impossible?) to fit all data with a single oscillation hypothesis

# Three Active Neutrino Species

- Only 3 light, Weakly interacting neutrinos (LEP Z width)




- Oscillations with $\Delta m^2_{solar}$ and $\Delta m^2_{atm}$ are well established

- Therefore a 4th light state must be sterile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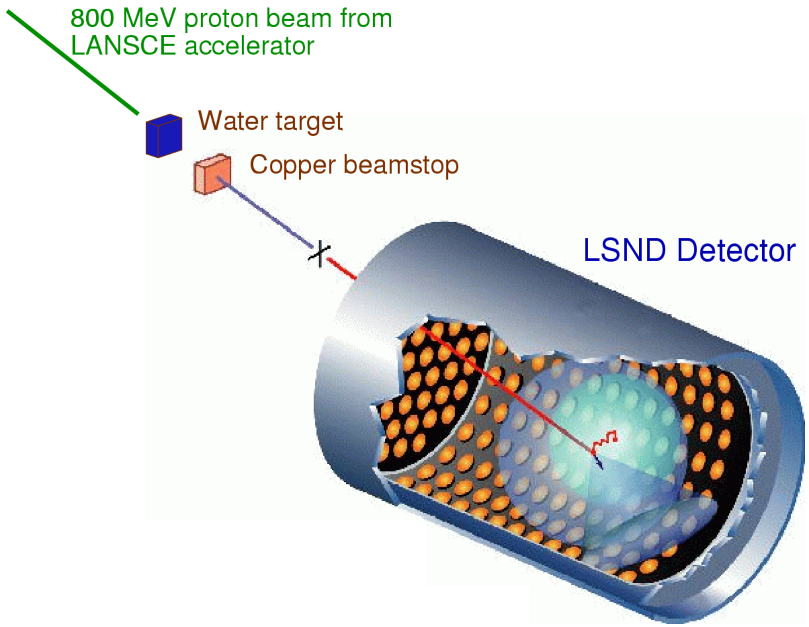
# Anti-$\nu_e$ Appearance at ~40MeV



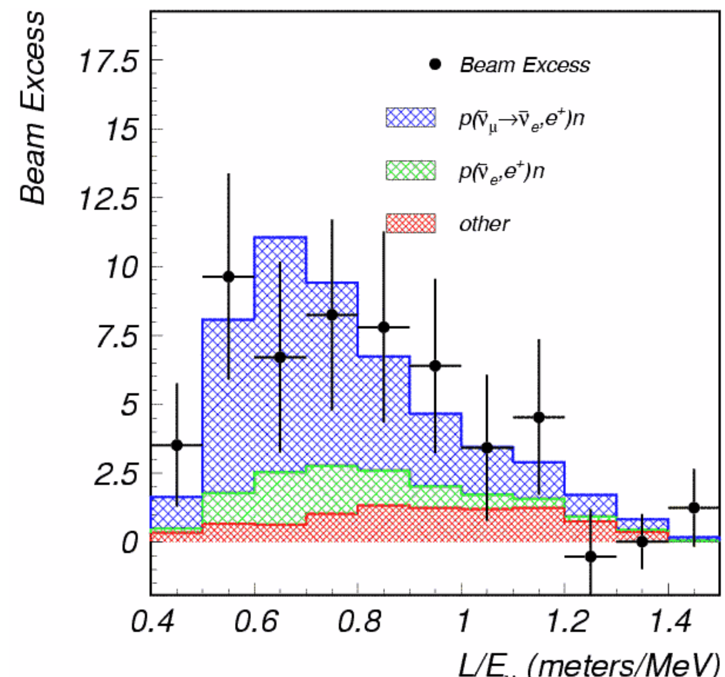

- LSND used 800 MeV protons from LAMPF at Los Alamos in the 1990's

- Searched for anti-$\nu_e$ appearance in neutrino beam from pion decay at rest.

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

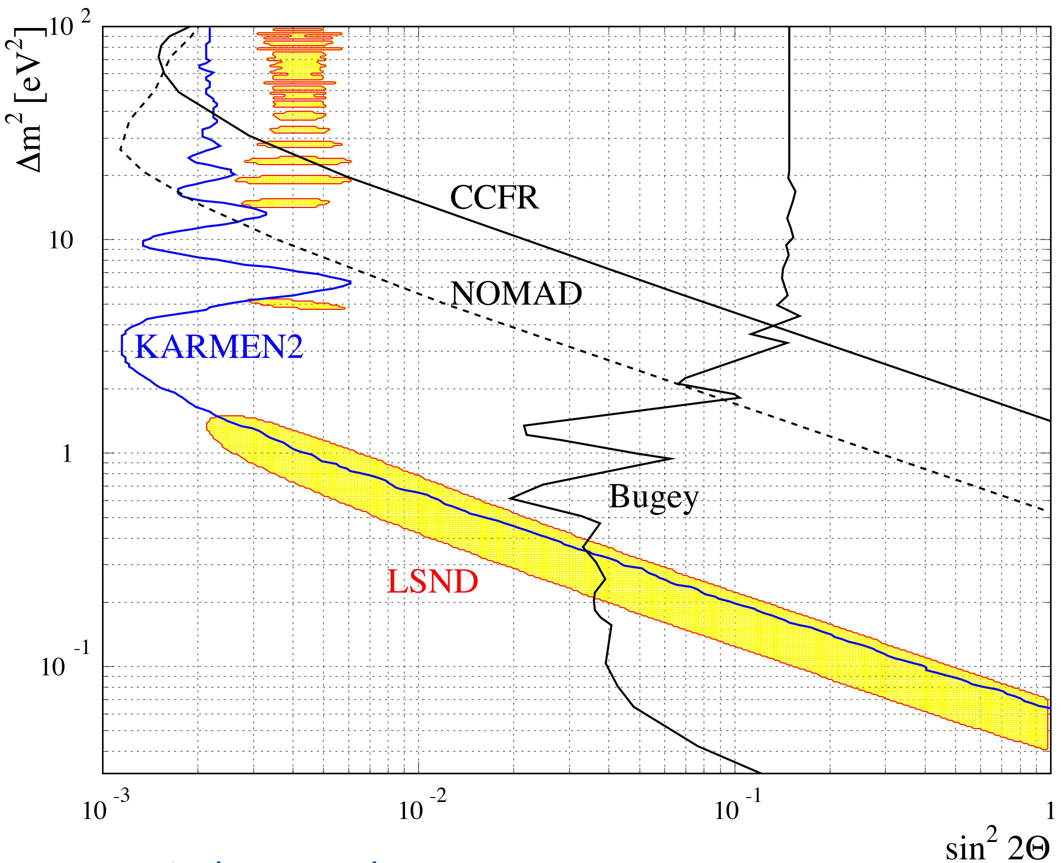
$$\bar{\nu}_\mu \xrightarrow{?} \bar{\nu}_e$$




- Found an excess of anti-$\nu_e$ over background prediction -
  - $87.9 \pm 22.4 \pm 6.0$ $(3.8\sigma)$

# Anti-$\nu_e$ Appearance at ~40MeV

- A similar experiment, KARMEN, ran at RAL at the same time and found no significant excess



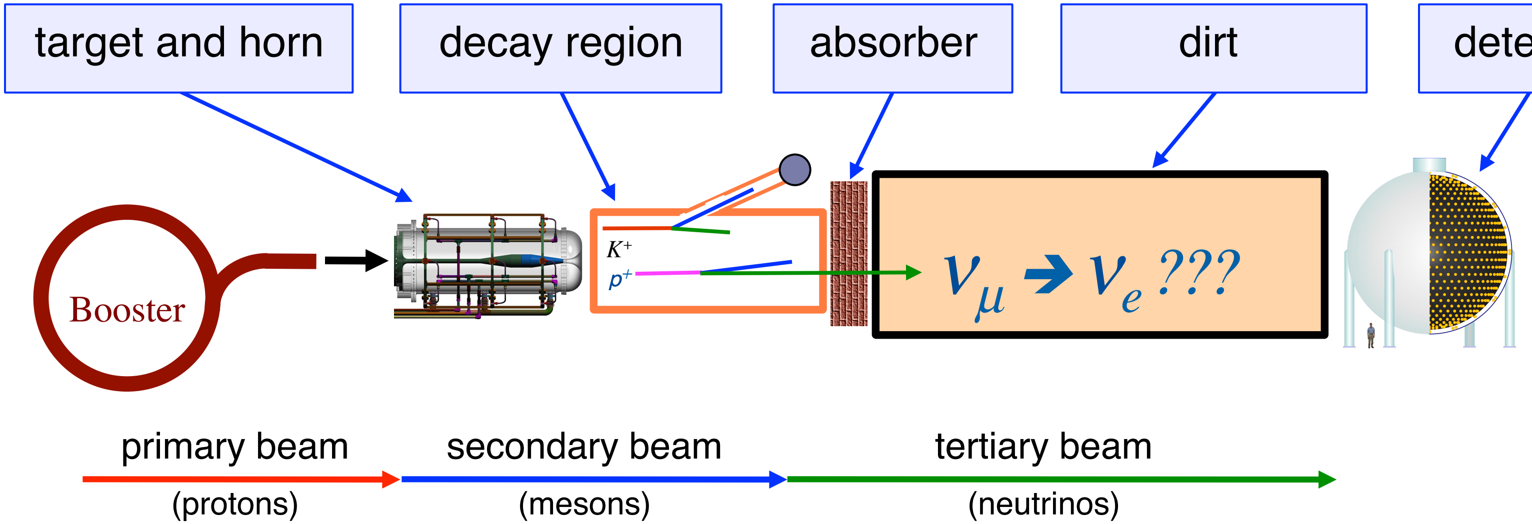

K. Eitel, NewJ.Phys.2:1,2000

- The two results are not incompatible when interpreted with an 2v oscillation hypothesis

# $\nu_e$ and anti-$\nu_e$ Appearance at ~1GeV: MiniBooNE

Keep L/E same as LSND
while changing systematics, energy & event signature

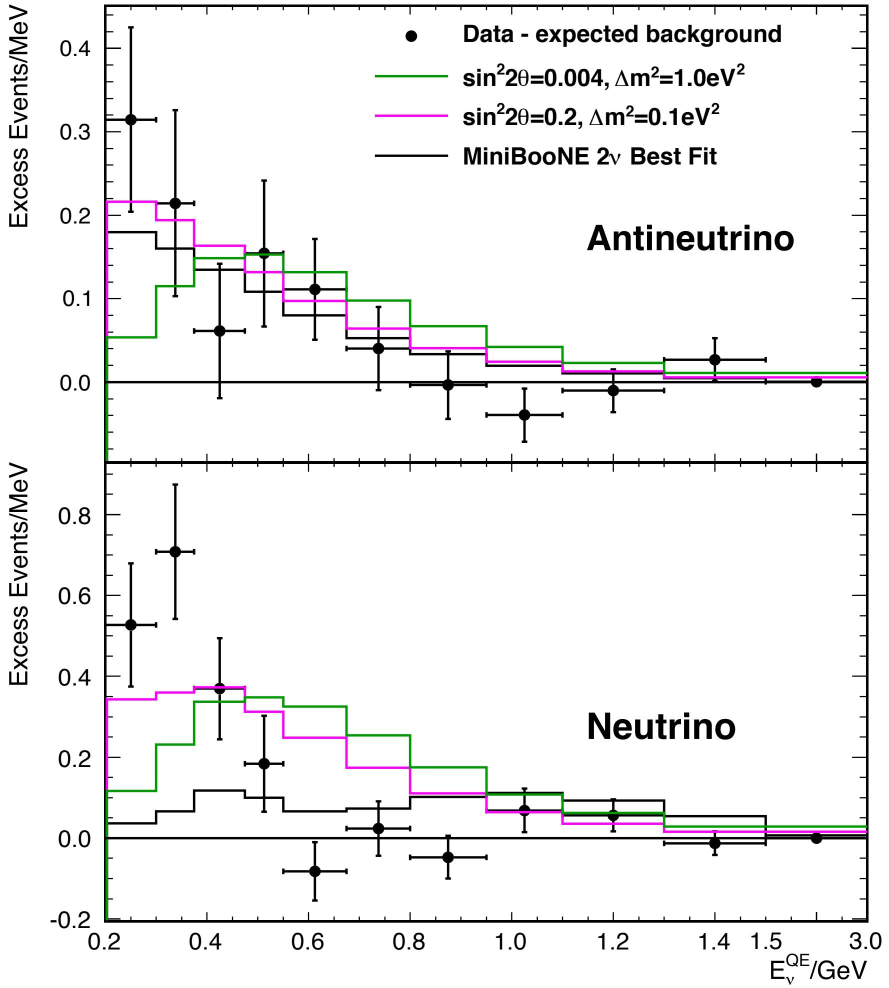
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$




Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

# $\nu_e$ and anti-$\nu_e$ Appearance at ~1GeV: MiniBooNE



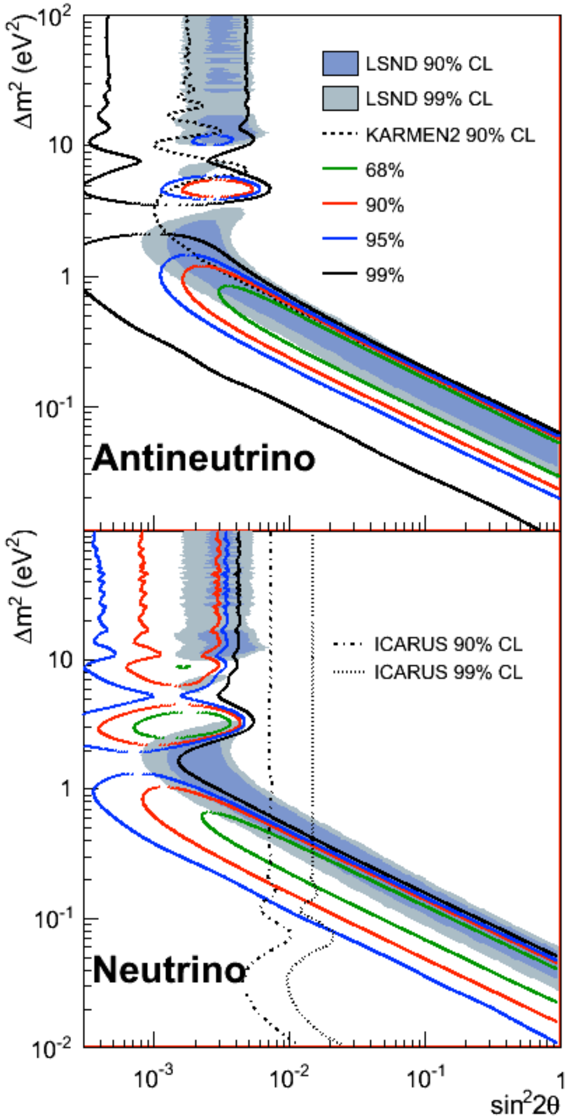

Phys. Rev. Lett. 110, 161801 (2013)

Antineutrino Event Excess
from 200-1250 MeV
= 78.4+-20.0+-20.3 (2.8s)

Neutrino Event Excess
from 200-1250 MeV
= 162.0+-28.1+-38.7 (3.4s)

Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8s)

# $\nu_e$ and anti-$\nu_e$ Appearance at ~1GeV: MiniBooNE




Under a 2ν oscillation hypothesis…

Antineutrino

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

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

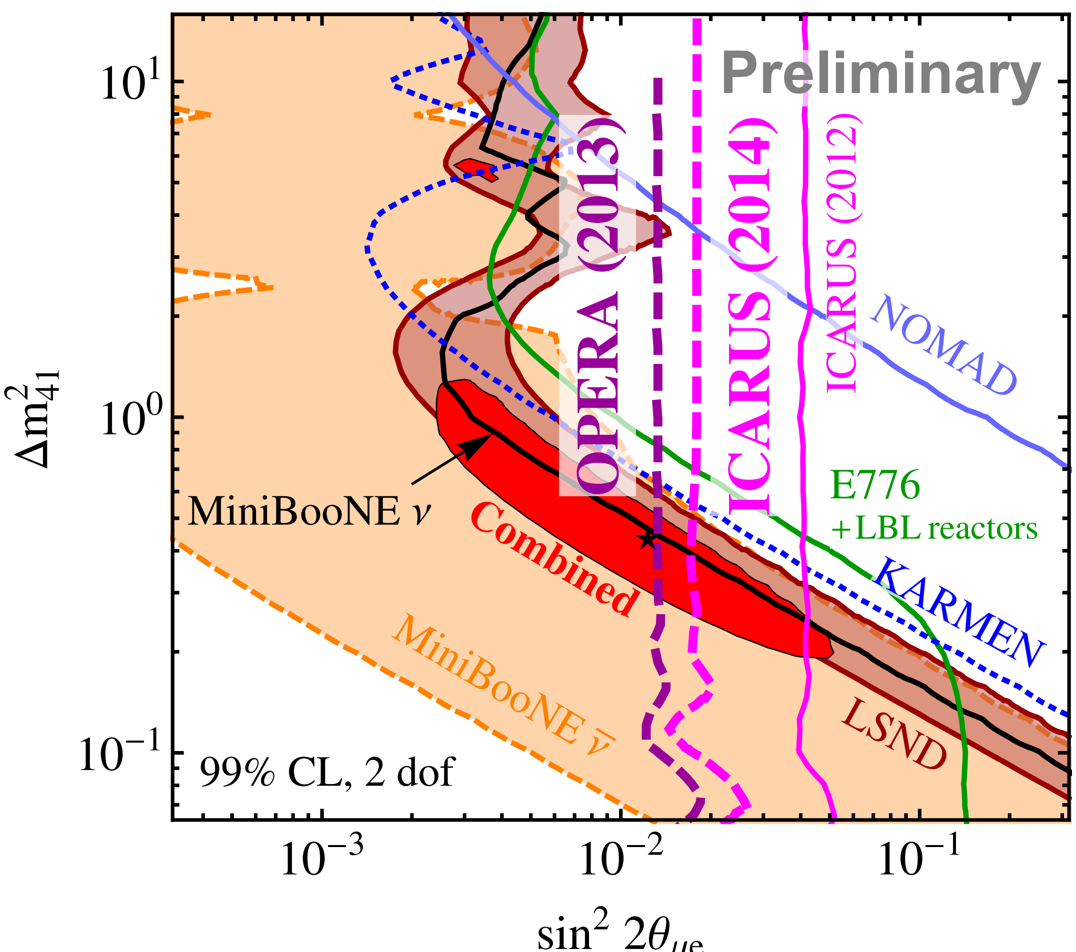
Neutrino

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

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

Phys. Rev. Lett. 110, 161801 (2013)

# $\nu_e$ and anti-$\nu_e$ Appearance at Multi GeV

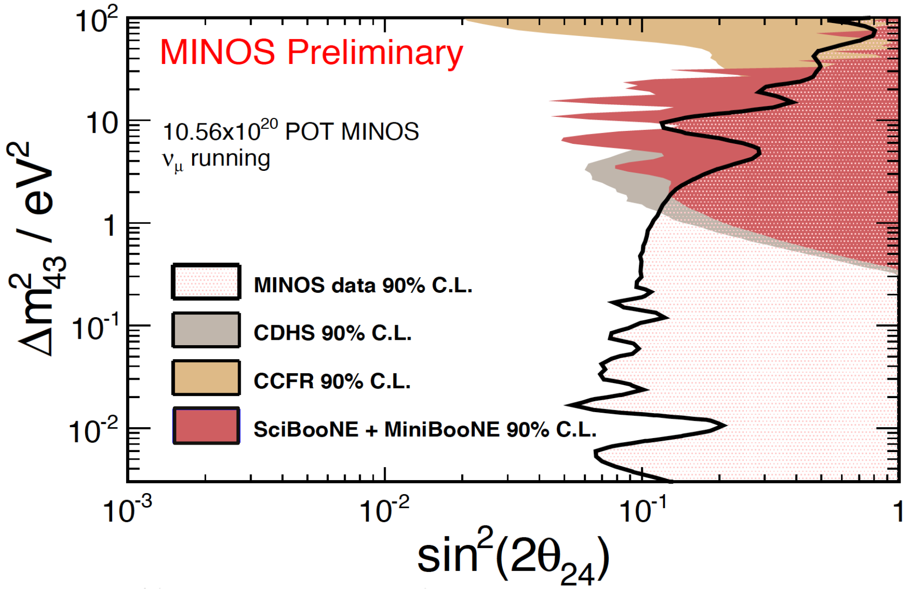



Adapted from Kopp, Machado, Maltoni, Schwetz, 1303.3011

- ICARUS and Opera at Gran Sasso running in the Multi-GeV CNGS beam from CERN see no evidence of $\nu_e$ appearance

# $\nu_\mu$ and Anti-$\nu_\mu$ Disappearance at ~1 and Multi GeV

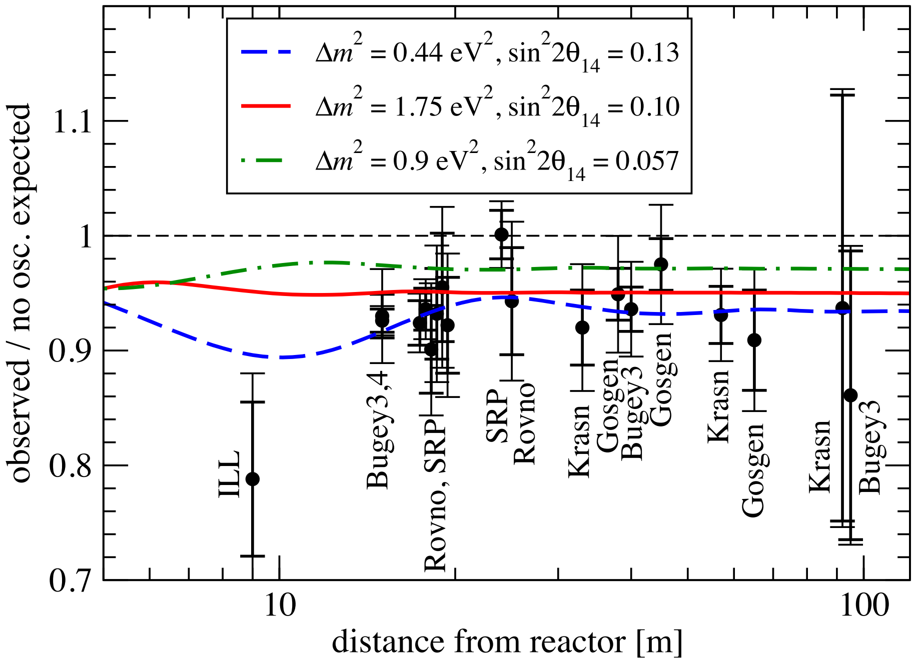
- There is no evidence for $\nu_\mu$ disappearance from multiple experiments looking in the region L/E ~1 m/MeV and E from ~1 GeV to multi-Gev




CDHS, CCFR, MiniBooNE, SciBooNE, MINOS,

# Anti-$\nu_e$ Disappearance at ~few MeV: Reactor Anomaly

- In the last few years there has been a re-evaluation of the predicted reactor neutrino flux causing it to move up by 3.5%
- This results in the measurements now sitting 3.0σ below the prediction (Mueller et al. 1101.2663, Huber 1106.0687, Hayes et al. 1309.4146)




- Can be interpreted as oscillation involving a ~1eV sterile state

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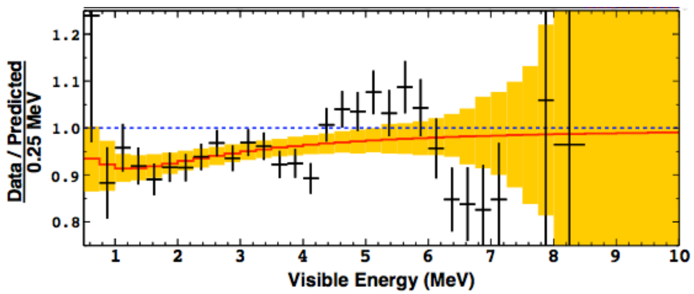
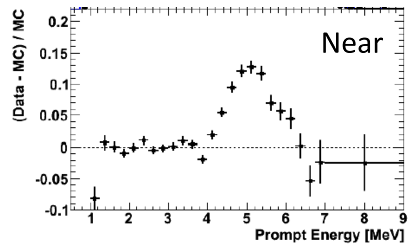
# Anti-$\nu_e$ Disappearance at ~few MeV: Reactor 5MeV Bump

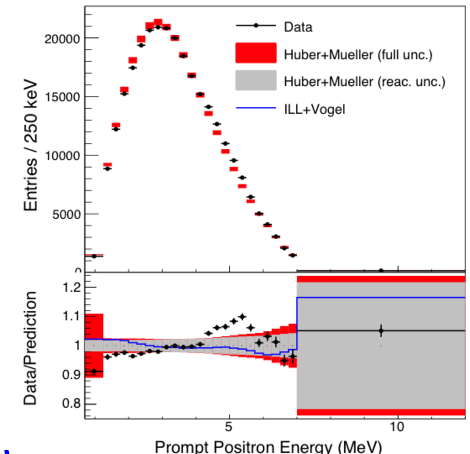
- The reactor spectrum also varies from prediction at the 5% level, but in a way that seems hard to produce via oscillation

***Double Chooz, this conference***

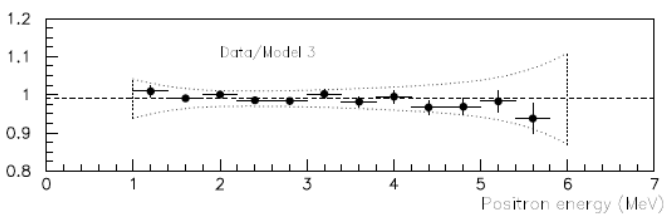



***RENO, this conference***

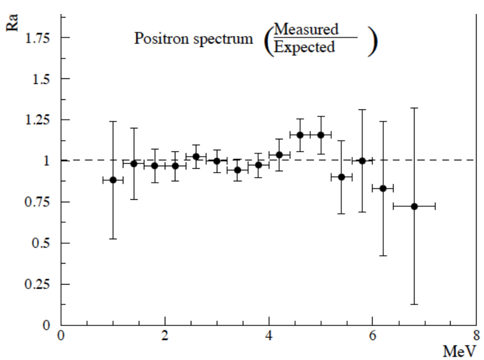


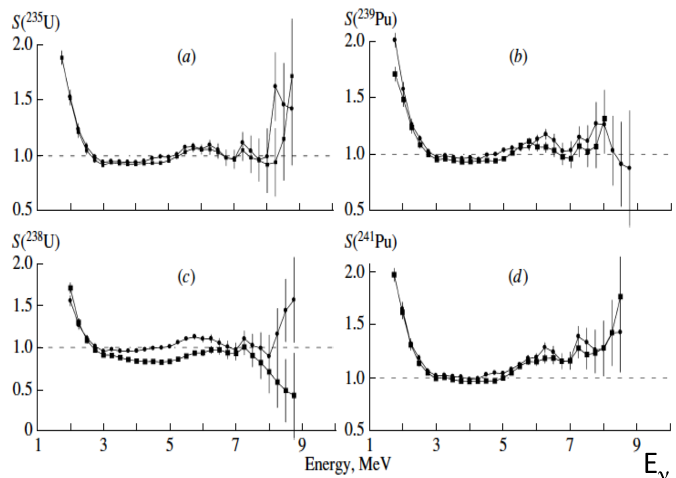

Daya Bay ICHEP 2014




***Bugey, Phys.Lett. B374 (1996) 243-248***




***CHOOZ, Phys.Lett. B466 (1999) 415-430***




$E_\nu$ (MeV)

***Rovno, V. Sinev, arXiv:1207.6956***

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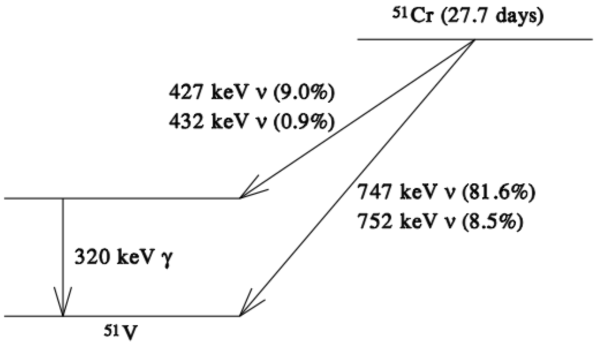
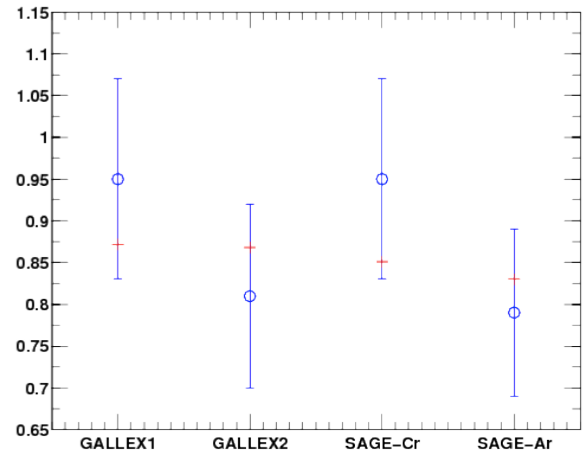
**Slide adapted from David Lhuillier's Neutrino 2014 talk**

# $\nu_e$ Disappearance at ~sub MeV: Gallium Anomaly

- Calibration of the Gallium Solar ν Detectors
- e-capture sources
  - $^{51}Cr$ (750 keV) & $^{37}Ar$ (810keV)




- The goal was to test (*not* calibrate) the production-extraction-detection efficiency of the SAGE and GALLEX experiments



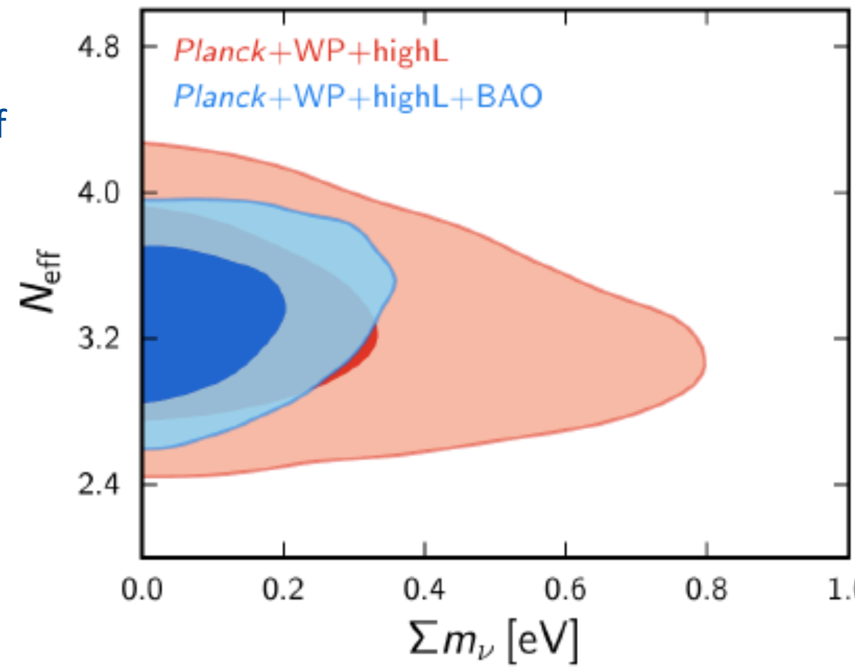

- Deficit observed
- $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
- $R_{obs/pred}$=0.76±0.085 ($\sigma_{Haxton}$)

- *"A probable explanation for this low result is that the cross section for neutrino capture by the two lowest-lying excited states in $^{71}Ge$ has been overestimated"* SAGE Collab. in abstract of Phys. Rev. C80, 015807 (2009)

# CMB and Large Scale Structure

- Number of relativistic species $N_{eff}$
- $N_{eff} = 4$ is mildly disfavored by current data

Ade et al. (Planck), arXiv:1303.5076
Gonzalez-Garcia Maltoni Salvado, arXiv:1006.3795
Hamann Hannestad Raffelt Tamborra Wong, arXiv:1006:5276




*"Cosmological data is rare and precious stuff for determining the properties of the early Universe. We shouldn't waste it measuring ν properties. ν properties should be inputs to cosmology, not outputs. That statement is (to me) independent of the quality of the cosmological data."* Dave Wark, Neutrino 2014

# Summary Tables

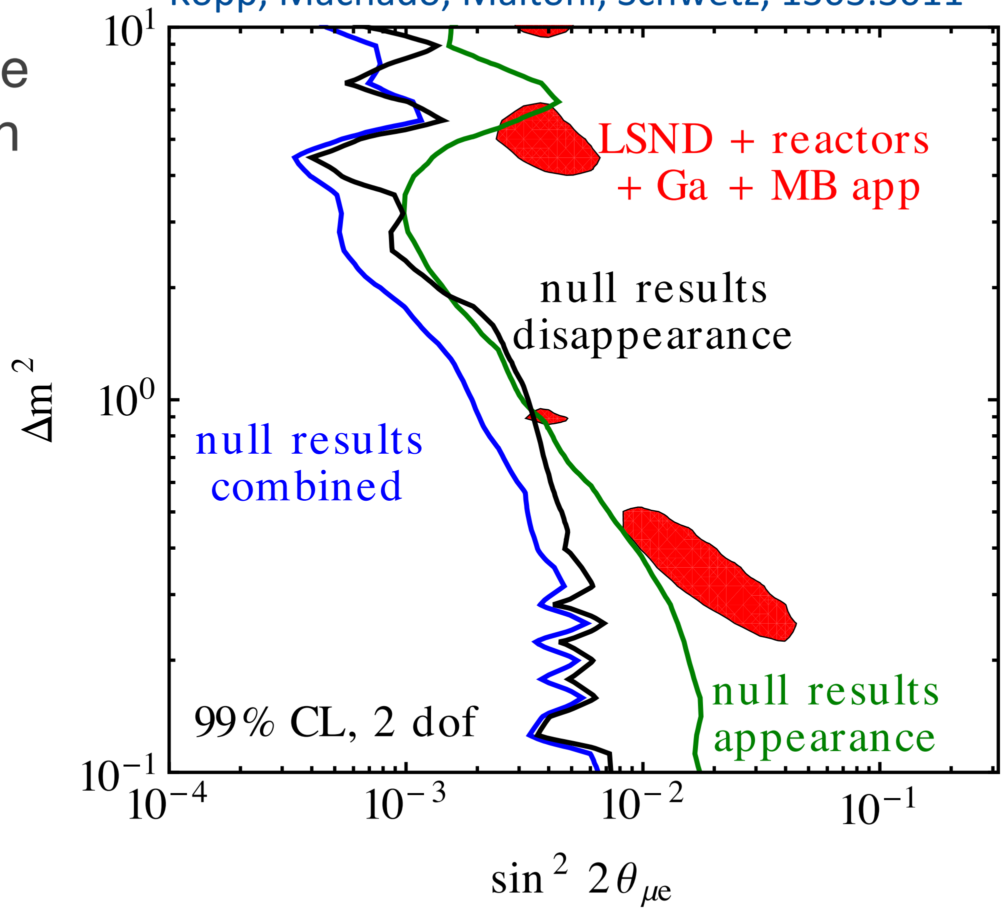
| Anomalies | | | |
|---|---|---|---|
| | Strength of effect (σ) | Channel | Energy Scale |
| LSND | 3.8 | anti-$\nu_e$ app. | ~40 MeV |
| MiniBooNE | 3.8 | $\nu_e$/anti-$\nu_e$ app. | ~1 GeV |
| Reactor | 3.0 | anti-$\nu_e$ disapp. | Few MeV |
| Gallium | 2.7 | $\nu_e$ disapp. | Sub MeV |

| Null Results | | |
|---|---|---|
| | Channel | Energy Scale |
| CDHS | $\nu_\mu$ disapp. | 30-200 GeV |
| MiniBooNE | $\nu_\mu$ and anti-$\nu_\mu$ disapp | ~1 GeV |
| MINOS | $\nu_\mu$ disapp. | several GeV |
| KARMEN | anti-$\nu_e$ app | ~40 MeV |
| OPERA & ICARUS | $\nu_e$ app | Tens of GeV |

# The Global Picture Assuming One Additional Sterile State

- Interpreting all the relevant data with one extra sterile neutrino
- Severe tension

Kopp, Machado, Maltoni, Schwetz, 1303.3011

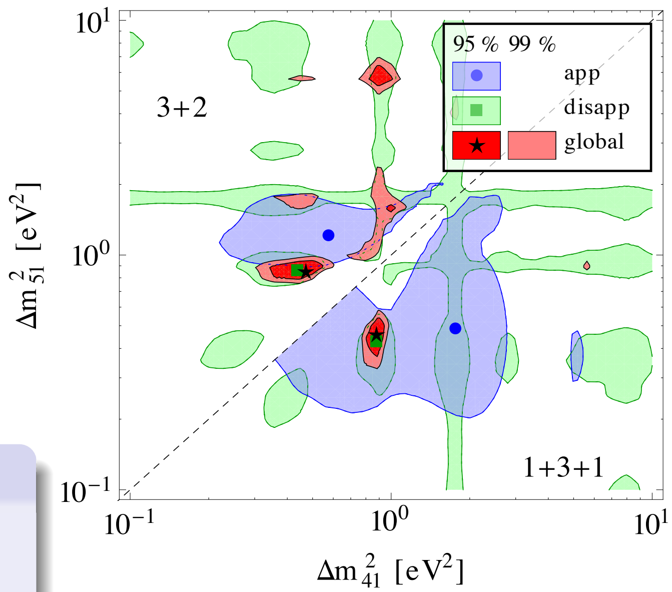


# The Global Picture Assuming Additional Sterile States

## The global oscillation fit

JK Machado Maltoni Schwetz, arXiv:1303.3011

- **3 + 1** Severe tension between appearance and disappearance and between exp's with and without a signal
- **3 + 2** Tension remains for two sterile neutrinos
- **3 + 3** No significant improvement expected




**Parameter goodness of fit (PG) test:**

Compares $\chi^2_{\text{min}}$ from global and separate fits to test compatibility of 2 data sets

| | $\chi^2_{\text{min}}$/dof | GOF | $\chi^2_{\text{PG}}$/dof | PG |
|---|---|---|---|---|
| 3+1 | 712/(689 − 9) | 19% | 18.0/2 | $1.2 \times 10^{-4}$ |
| 3+2 | 701/(689 − 14) | 23% | 25.8/4 | $3.4 \times 10^{-5}$ |
| 1+3+1 | 694/(689 − 14) | 30% | 16.8/4 | $2.1 \times 10^{-3}$ |

**Slide taken from Joachim Kopp's Neutrino 2014 talk**

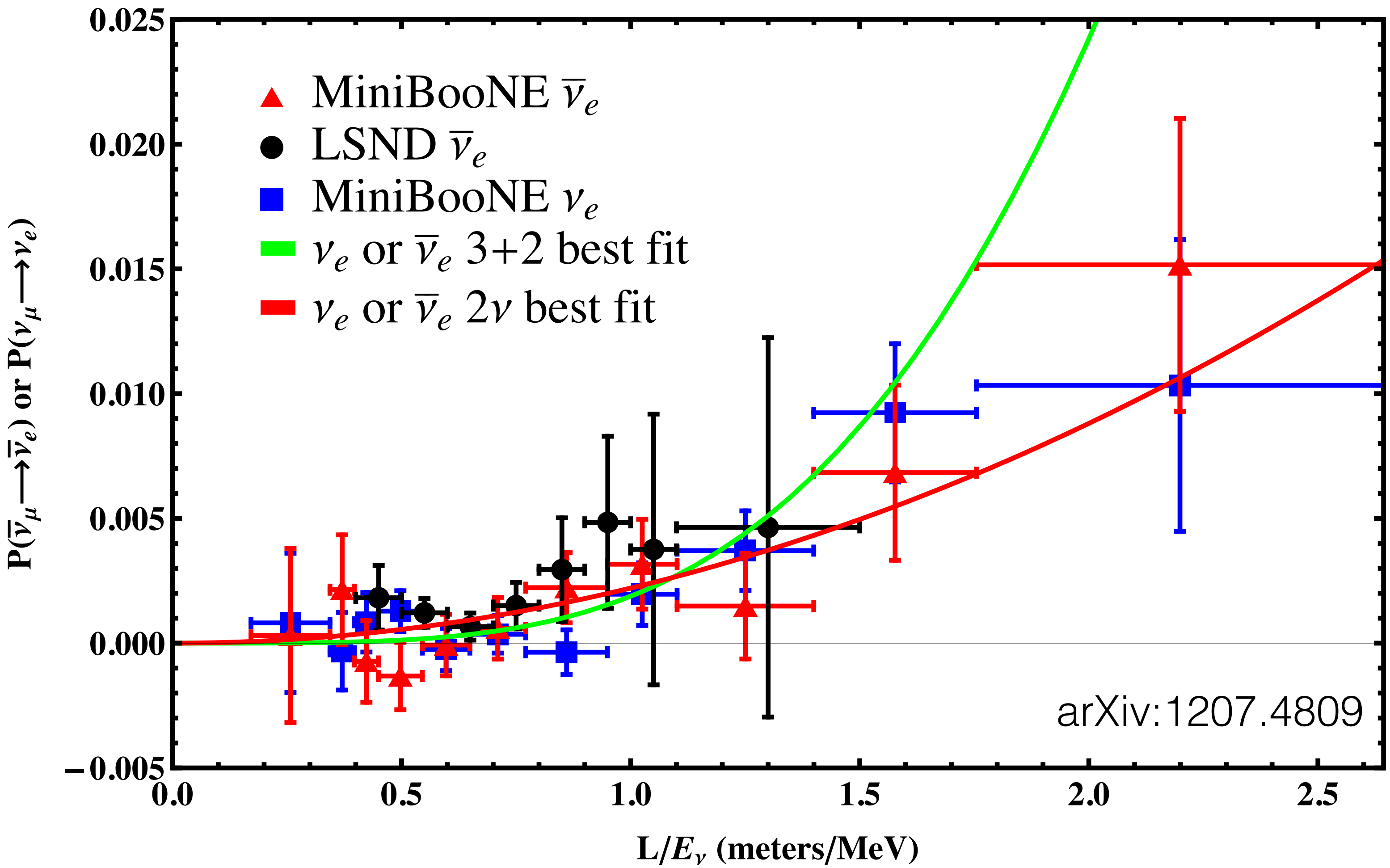
# How to Compare Experimental Results and Models

- Usual plots assume 3+1 – the one scenario we know is in severe tension with the data

- Plots of L/E provide a somewhat more general way of comparing experiments.
  - L/E scales with the relativistic proper time
  - The relevant variable for many phenomena other than oscillations e.g. decay

- Being careful about L/E plots
  - The full error matrix of the data is needed to compare experiments
  - The effects of energy mis-reconstruction are needed to compare experiment with model
  - Neglecting either can lead to sizeable mistakes – see Bill's talk to follow

# L/E Plots



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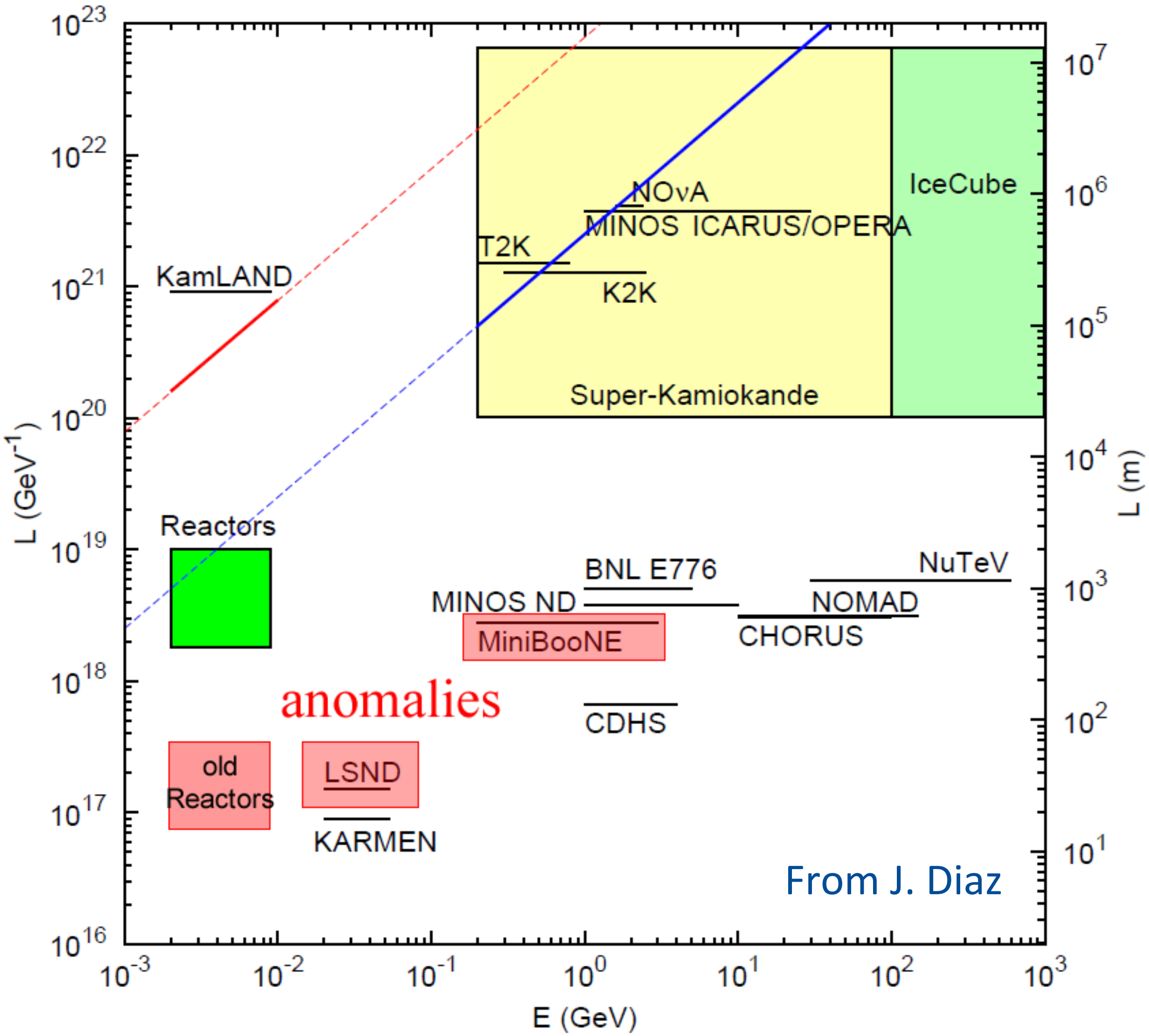
# Direct Tests and Oscillation Tests

- Two approaches to testing the anomalies

- Test the oscillation hypothesis by operating at the right L/E but not necessarily the same E
  - e.g. MiniBooNE was an oscillation test of LSND

- Test the experimental anomaly directly by operating at the same L/E and the same E
  - i.e. Do a better version of the experiment that generated the anomaly
  - e.g. OscSNS would be a direct test of LSND

# Direct Tests and Oscillation Tests



# Future Accelerator Based Tests

| | Primary Channel | Other osc channels | Definitive sterile? | Other physics | Tech R&D? | Cost | Why worry? | Comment |
|---|---|---|---|---|---|---|---|---|
| MicroBooNE (π DIF) | $\nu_\mu \to \nu_e$ | $\nu_\mu \to \nu_\mu$ | | GeV-scale xsec | Yes | $20M | tech, cosmics | Exists! |
| LAr1-ND (π DIF) | $\nu_\mu \to \nu_e$ | $\nu_\mu \to \nu_\mu$ | | GeV-scale xsec | Yes | $13M | tech, cosmics | |
| ICARUS@FNAL (π DIF) | $\nu_\mu \to \nu_e$ | $\nu_\mu \to \nu_\mu$ | | GeV-scale xsec | Yes | Under study | tech, cosmics | |
| TripleLAr@FNAL (π DIF) | $\nu_\mu \to \nu_e$ <br> $\bar{\nu}_\mu \to \bar{\nu}_e$ | $\nu_\mu \to \nu_\mu$ <br> $\bar{\nu}_\mu \to \bar{\nu}_\mu$ | Probably | GeV-scale xsec | Yes | Under study | tech, cosmics | Work in progress. Anti-nu? |
| OscSNS (π,μ DAR) | $\bar{\nu}_\mu \to \bar{\nu}_e$ | $\nu_e \to \nu_e$ | Yes | Supernova xsec | No | $20M | intrinsic $\bar{\nu}_e$ | |
| JPARC MLF (π,μ,K DAR) | $\bar{\nu}_\mu \to \bar{\nu}_e$ | $\nu_e \to \nu_e$ <br> $\nu_\mu \to \nu_e$ | Not in phase 1 | Supernova and 235 MeV $\nu_\mu$ xsec | No | $5M | intrinsic $\bar{\nu}_e$ | Phase 1 |
| IsoDAR-KamLAND (Isotope DAR) | $\bar{\nu}_e \to \bar{\nu}_e$ | - | Yes | $\bar{\nu}_e e^-$ (electroweak) | Yes | $30M | timeline, tech | |
| nuSTORM (μ DIF) | $\nu_e \to \nu_\mu$ | $\bar{\nu}_\mu \to \bar{\nu}_\mu$ <br> $\nu_e \to \nu_e$ | Yes | GeV-scale xsec | Yes | $300M | timeline, tech, cost | P5 says no |

Table taken from Josh Spitz Neutrino 2014 talk

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# $\nu_e$ and Anti-$\nu_e$ Disappearance at ~few MeV: Hot Source Experiments

- Place a very hot (MCi scale) β or EC source near (or inside) one of the very capable low energy neutrino detectors we now have or soon will have
- Look for disappearance of $\nu_e$ or anti-$\nu_e$
  - Look for spatial pattern of oscillations within the detector volume
- Powerful, simple(ish), relatively cheap, relatively fast
- First data available with SOX-Ce by the end of 2015 / beginning 2016
- One or more of these experiments should be completed within the next 5 years

# $\nu_e$ and Anti-$\nu_e$ Disappearance at ~few MeV: Hot Source Experiments

| Technique | Detector | Sources | Reaction | Activity | Reference |
|---|---|---|---|---|---|
| Large Liquid scintillator detectors | SOX (Borexino) | $^{51}Cr$, | $\nu+e \rightarrow \nu+e$ | 10MCi | *JHEP08(2013)038,* |
| | | $^{144}Ce$-$^{144}Pr$ | $\nu+p \rightarrow e^{+}+n$ | 100kCi | *Phys. Rev. Lett. 107, 201801 (2011)* |
| | KamLAND | $^{8}Li$ (ISODAR) | $\bar{\nu}+p \rightarrow e^{+}+n$ | 8.2 x 10 $^{14}$ $\nu$/sec | *arXiV:1205.4419, arXiV:1310.3857* |
| | | $^{144}Ce$(CeLAND) | $\bar{\nu}+p \rightarrow e^{+}+n$ | 100kCi | arXiv:1312.0896 |
| | Daya-Bay | $^{144}Ce$-$^{144}Pr$ | $\bar{\nu}+p \rightarrow e^{+}+n$ | 500kCi | *arXiV:1109.6036* |
| | LENS | $^{51}Cr$ | $\nu+^{115}In \rightarrow ^{115}Sn^{*}+e$ | 10MCi | *Phys.Rev.D75 093006(2007)* |
| | JUNO | $^{8}Li$ (ISODAR) | $\bar{\nu}+p \rightarrow e^{+}+n$ | 8.2 x 10 $^{14}$ $\nu$/sec | *arXiV:1310.3857* |
| Radiochemical | BEST | $^{51}Cr$ | $\nu+^{70}Ga \rightarrow ^{71}Ge+e$ | 3MCi | arXiV:1204.5379 |
| Bolometers | Richochet | $^{37}Ar$ | $\nu+N \rightarrow \nu+N$ | 5MCi | Phys. Rev. D85, 013009, (2012) |

Table taken from Barbara Caccianiga's Neutrino 2014 talk

# Anti-$\nu_e$ Disappearance at ~few MeV: Reactor Proposals

- Get a high resolution MeV neutrino detector in close to a reactor
- Preferably movable or multiple detectors
- Proposals for both research and commercial reactors
- Large range of L (5-20m) and E (1-8MeV)
- Relative fast and relatively cheap
- Likely that more than one experiment completed within 5 years

# Anti-$\nu_e$ Disappearance at ~few MeV: Reactor Proposals

| | Gd | $^6$Li | Highly Segmented | Moving detector | 2 det. |
|---|---|---|---|---|---|
| Nucifer (FRA) | ■ | | | | |
| Poseidon (RU) | ■ | | | | |
| Stéréo (FRA) | ■ | | | ■ | |
| Neutrino 4 (RU) | ■ | | | ■ | |
| Hanaro (KO) | ◣ | ◥ | ■ | ■ | |
| DANSS (RU) | ■ | | ■ | | |
| Prospect (USA) | ◣ | ◥ | ■ | | ■ |
| SoLid (UK) | | ■ | ■ | | |

Table taken from David Lhuillier's Neutrino 2014 talk

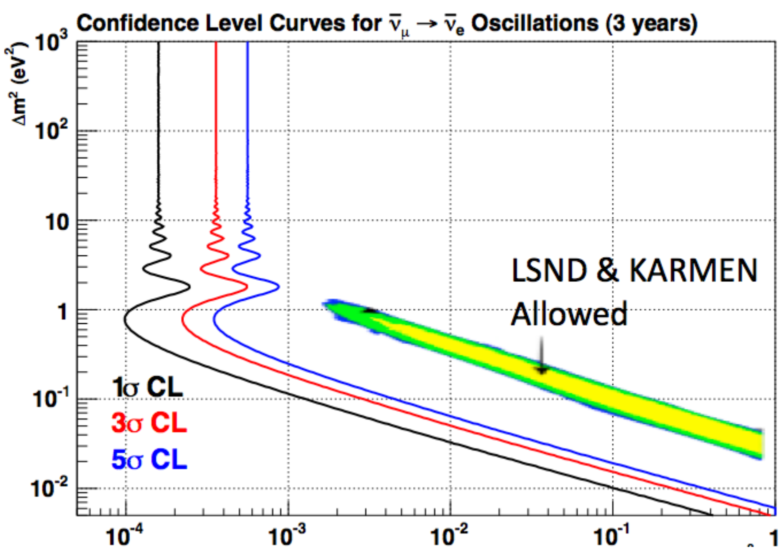
# Summary

- A number of intriguing hints at oscillations involving a $4^{th}$ $\nu$ state
- No single hint is compelling
- Much experimental evidence is in tension with such a $4^{th}$ state
- Nonetheless the situation cannot be ignored
- Definitive experiments are needed in more than one experimental domain
- Direct and oscillation tests needed
- Hot source and reactor tests will be completed before the next generation of accelerator based short-based experiments

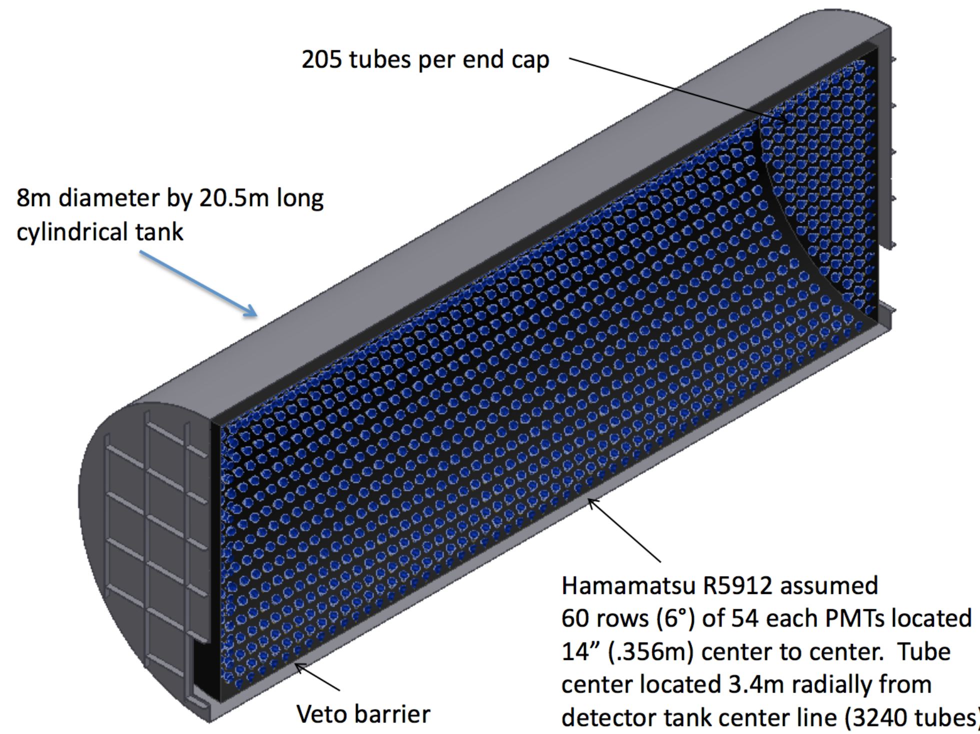
# Extra Slides

# Anti−$\nu_e$ Appearance at ~40MeV: OscSNS

- A proposed LSND-style decay-at-rest experiment at the 1.4 MW SNS (1 GeV protons on an Hg target)
- Can provide definitive coverage of the sterile neutrino region with an 800 ton LS detector, 60 m away.




OscSNS White Paper, arXiv:1307.7097



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