MiniBooNE and the Status of Sterile Neutrinos

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Outline

- Introduction
- Motivation for sterile neutrinos: LSND
- Sterile neutrino phenomenology
- MiniBooNE (arxiv:1303.2588)
- Other recent anomalies
- Constraints from other experiments
- Global Fits (arxiv:1207.4765)
- Future

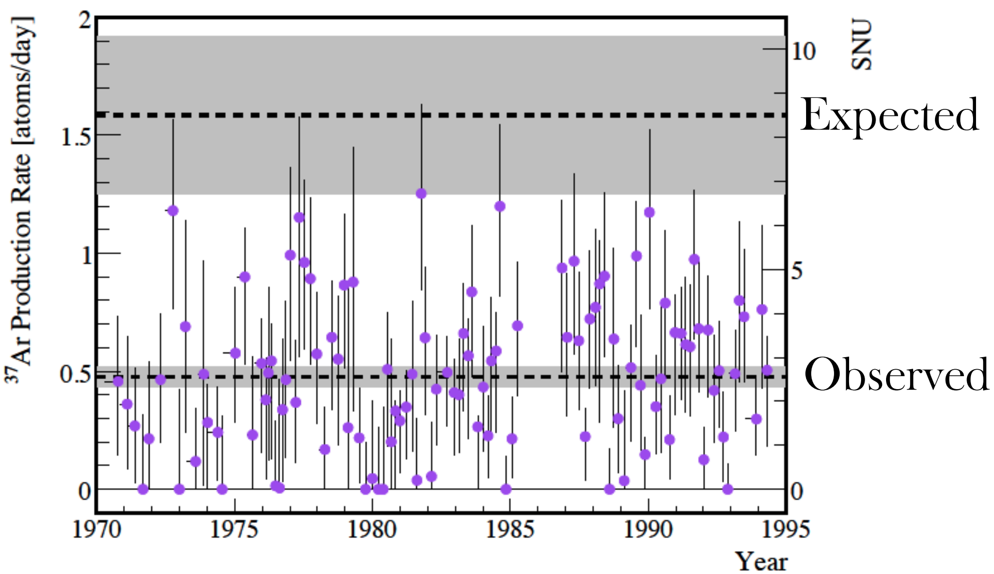
Neutrinos in the standard model

- Only interact via the "weak force" (W and Z bosons)
- Three flavors:
  - Electron $\nu_e \rightarrow e$
  - Muon $\nu_\mu \rightarrow \mu$
  - Tau $\nu_\tau \rightarrow \tau$
- Massless

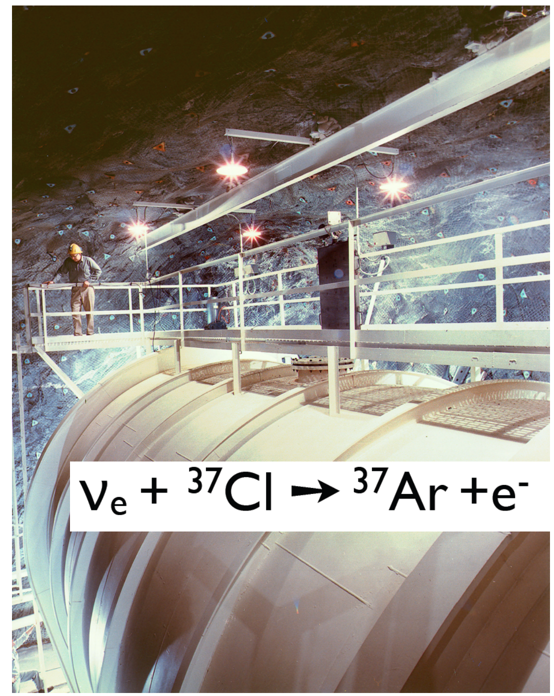
http://www.particlezoo.net/

Anomaly in the neutrino sector

"Solar neutrino problem"



Missing neutrinos!



Neutrino Oscillations

Maybe neutrinos "mix" like in the quark sector

Two neutrino Oscillations:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(t)\rangle = -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle \qquad E \approx p + \frac{m^2}{2E}$$

$$|\langle \nu_e | \nu_\mu(t)\rangle|^2 = \sin^2 2\theta(1 - \cos(E_2 - E_1)t) \qquad v \approx c = \frac{L}{t}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(\underbrace{1.27}\Delta m^2 \frac{L}{E})$$

in m (km)

Not unitless

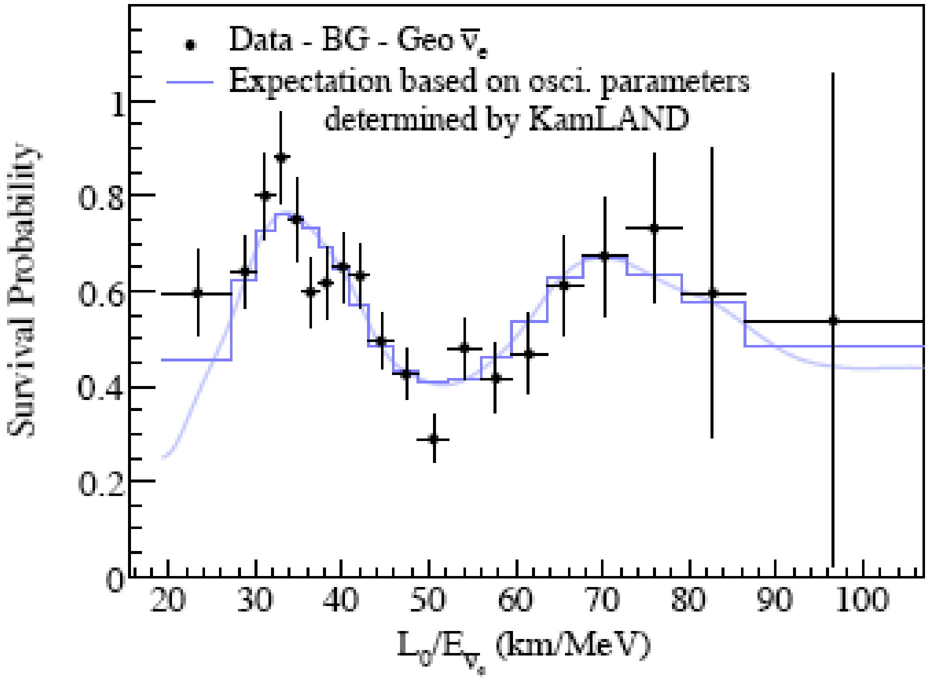
in MeV (GeV)

Neutrino Oscillations

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$

Distance from source (chosen)

Energy (measured by detector)



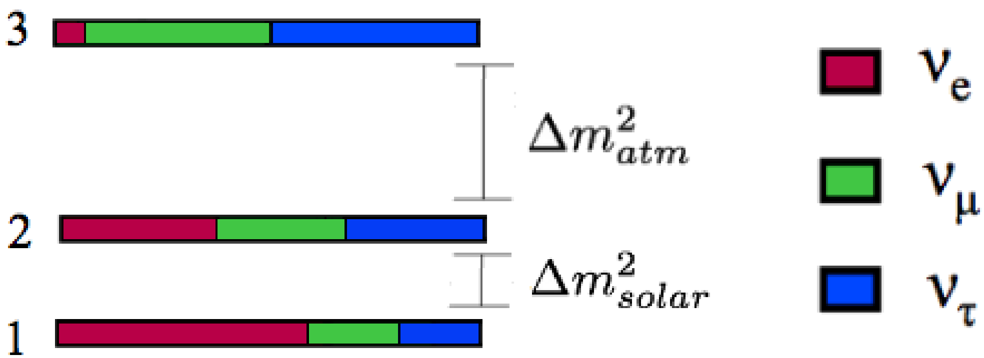
Neutrino Oscillations

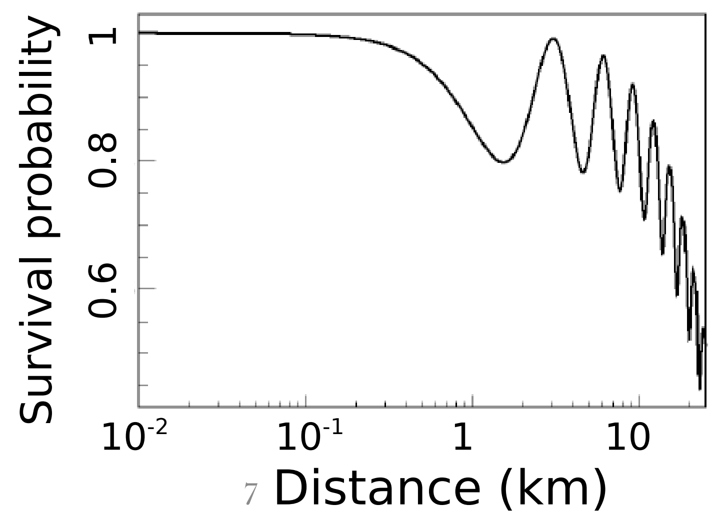
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3x3 rotation matrix

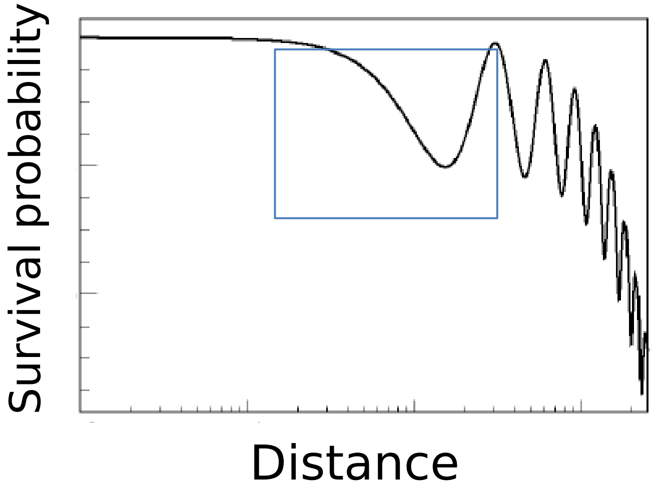
$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

phase which may be non-zero (cp-violation)

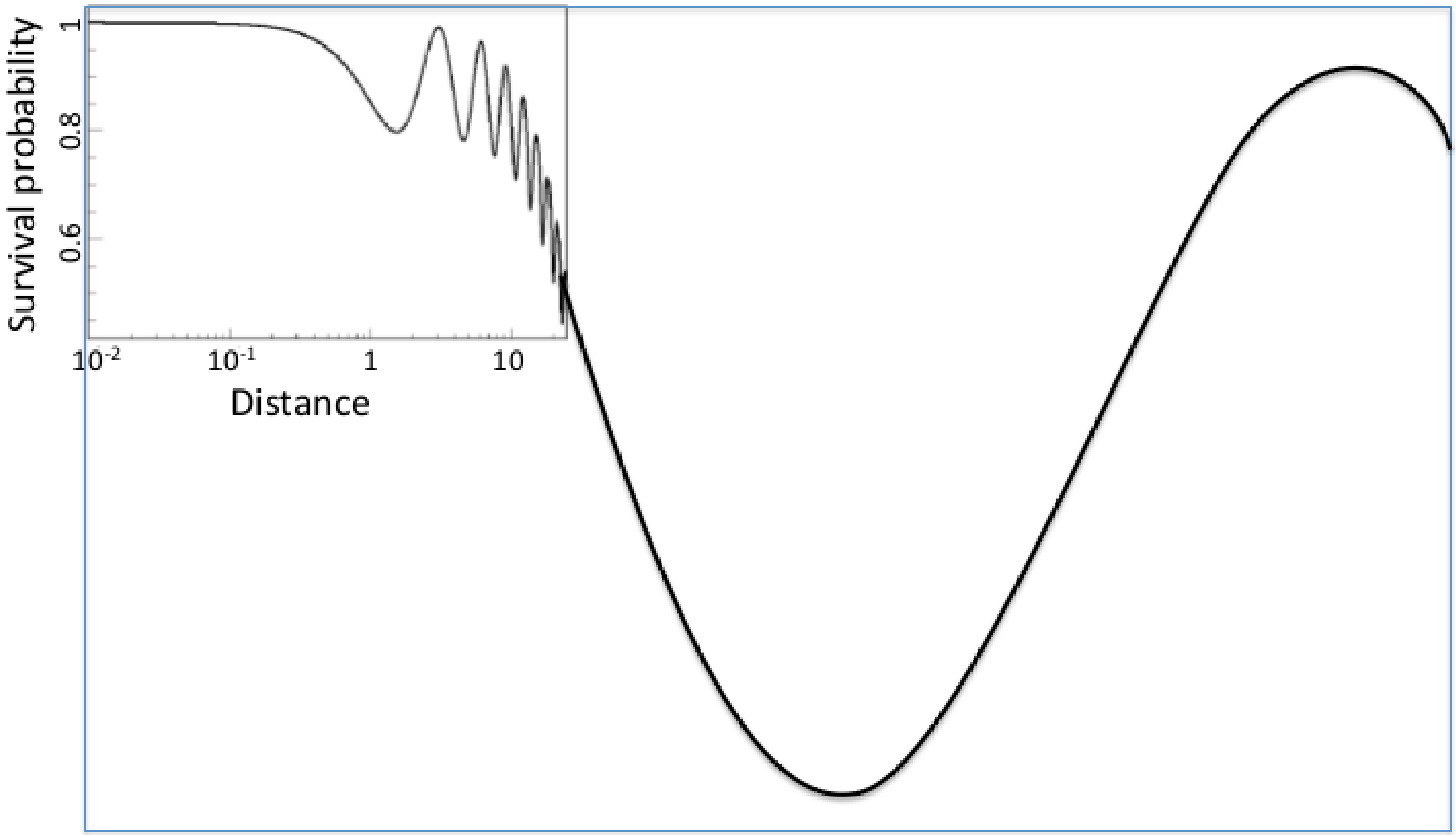




2-Neutrino Approximation



2-Neutrino Approximation



Great, now we have a "nu" standard model!

So what's the problem?

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- Sterile neutrino phenomenology
- MiniBooNE (arxiv:1303.2588)
- Other recent anomalies
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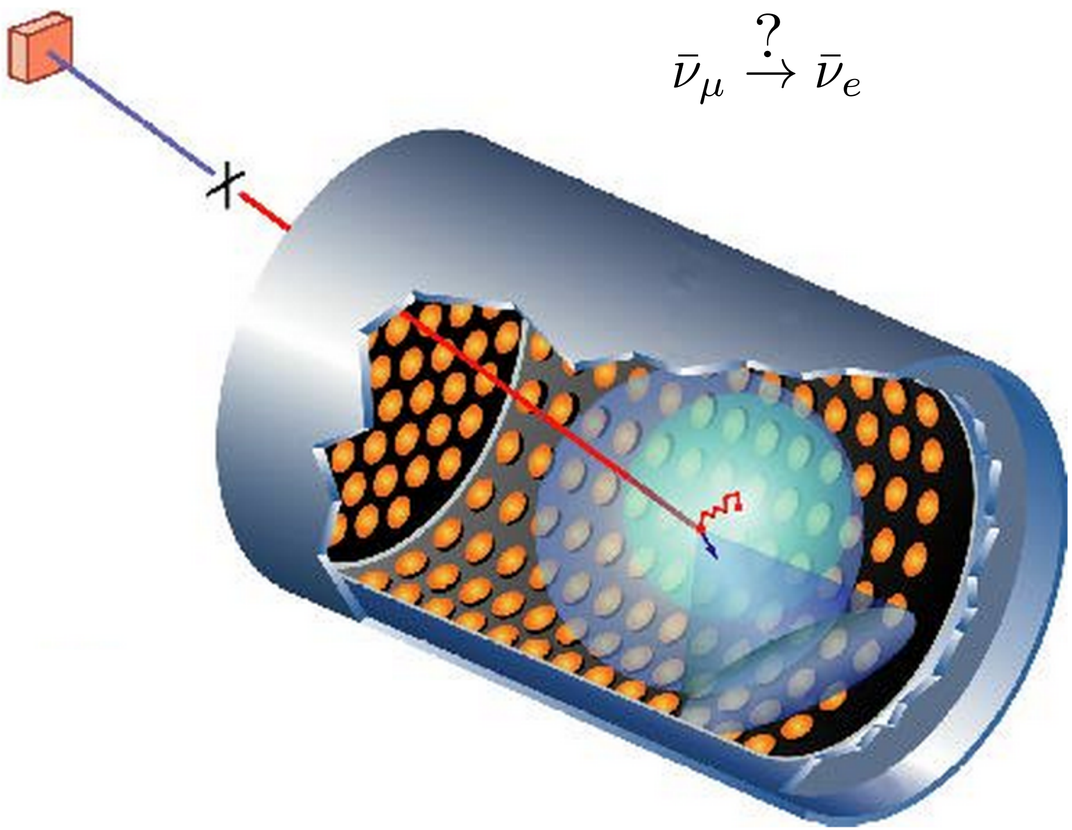
LSND Anomaly

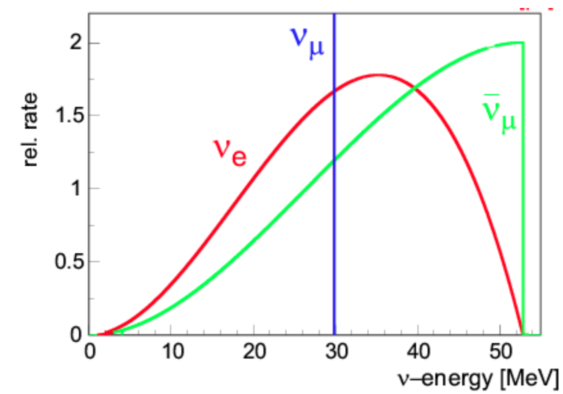
Liquid scintillator detector using stopped pion beam

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

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

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



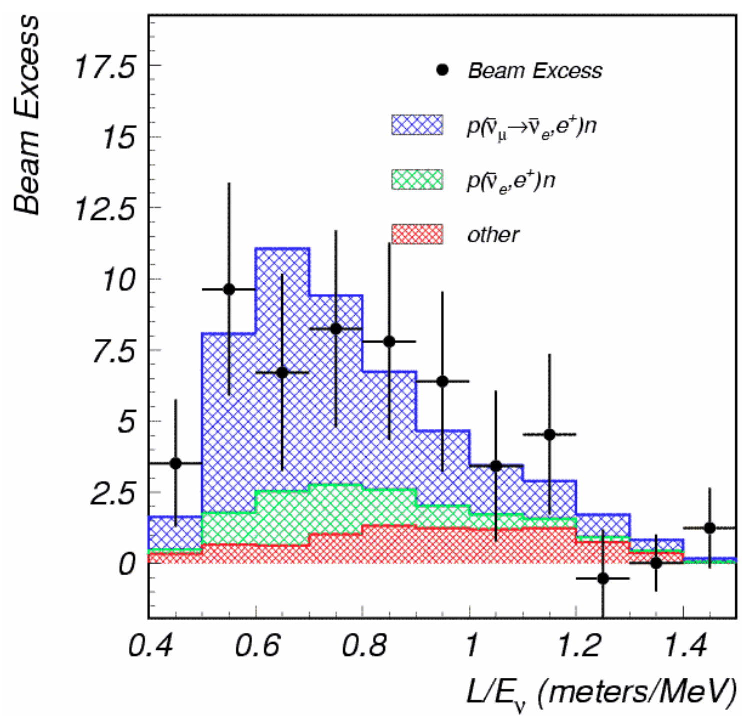


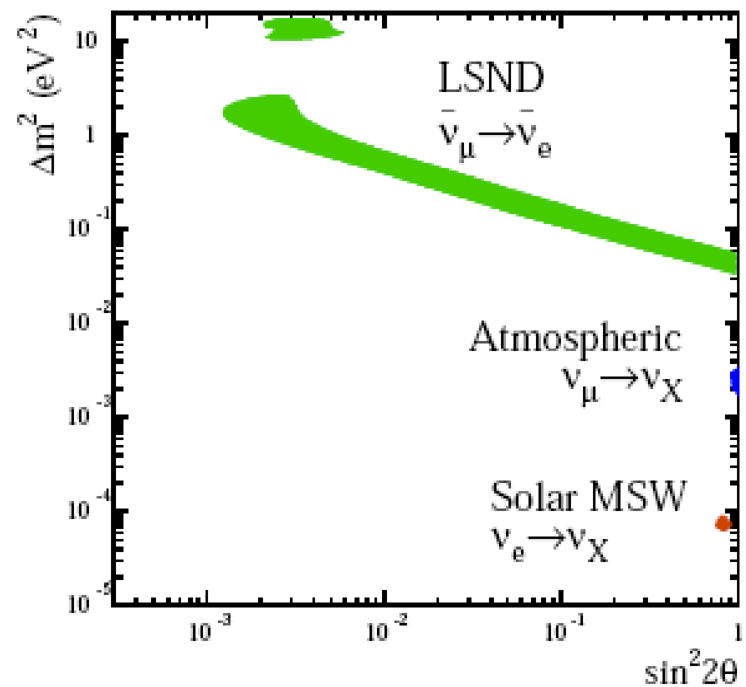
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

LSND Anomaly

Observed excess of $\bar{\nu}_e$'s, which corresponds to oscillations (for 2 neutrino fit) on the order of $\Delta m^2 \sim 1\ eV^2$(3.8 σ)

- Not consistent with known mass splittings!





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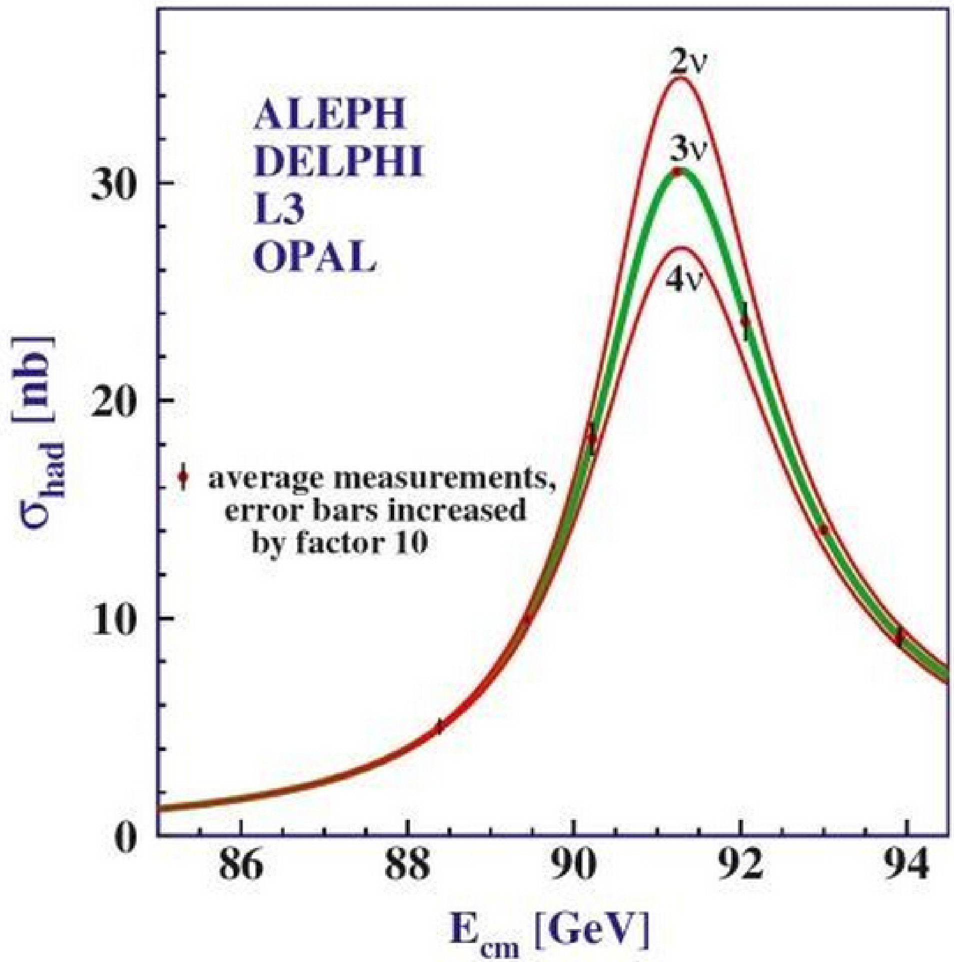
Why "Sterile"?



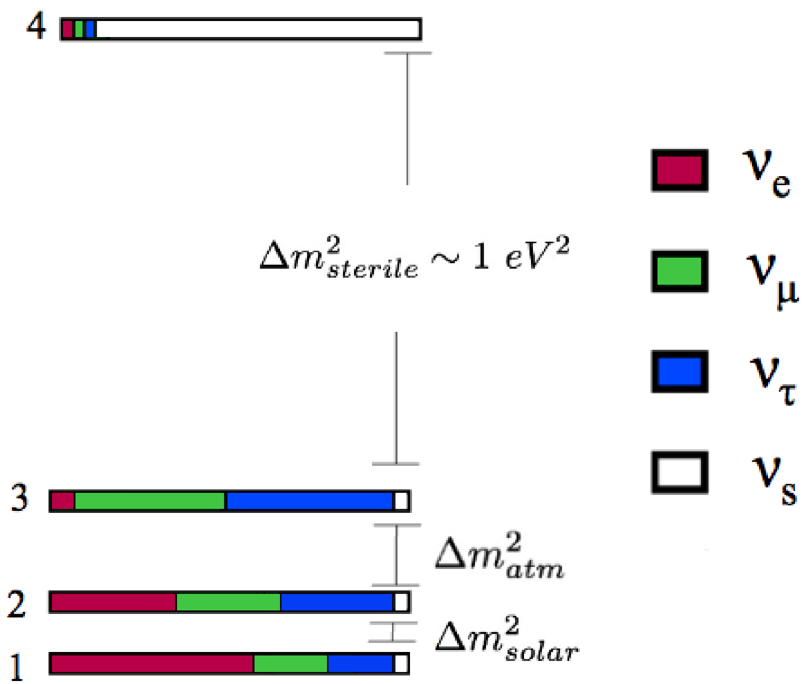
$$e^+ + e^- \to Z \to f + \bar{f}$$

$$N_\nu = 2.9840 \pm 0.0082$$

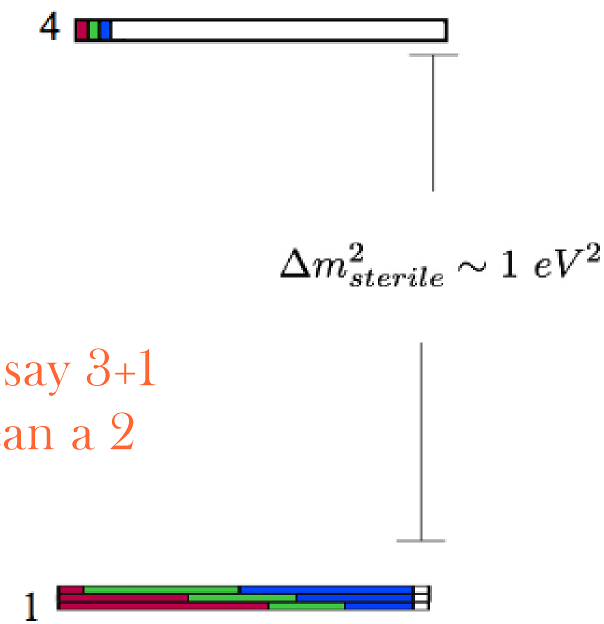
# of weakly interacting neutrino flavors

3+1 Model

- Assume one more neutrino that doesn't interact through the weak force but can still oscillate with other neutrinos
- Assume $\Delta m^2_{sterile} \gg \Delta m^2_{atm}$ and Δm^2_{solar} so only fit to one Δm^2 and one mixing parameter per experiment.



So when we say 3+1 we really mean a 2 neutrino fit



3+1 Model Fit Parameters:

Oscillation Probabilities:

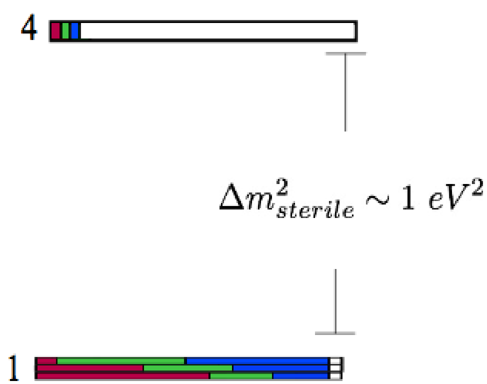
Appearance: $P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2(1.27\Delta m^2 \frac{L}{E})$

Disappearance: $P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2(1.27\Delta m^2 \frac{L}{E})$

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

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

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



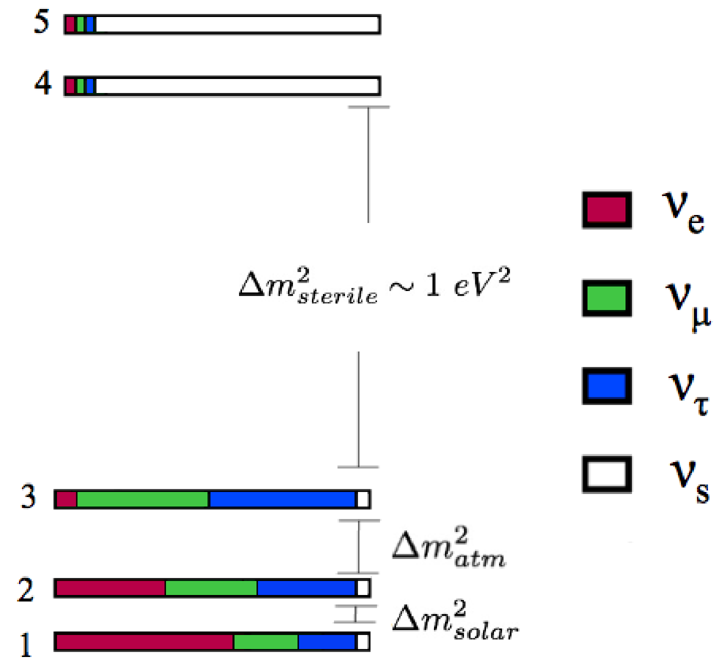
3+1 Fit parameters: $\Delta m^2_{41}, |U_{\mu 4}|$, and $|U_{e4}|$

3+2 model

$$\Delta m^2_{51} \geq \Delta m^2_{41} \gg \Delta m^2_{atm}$$

The 3 original mass eigenstates remain degenerate so now we are doing a 3 neutrino fit

7 parameters: $\Delta m^2_{41}, \Delta m^2_{51}, U_{\mu 4}, U_{e4}, U_{\mu 5}, U_{e5}, \Phi_{45}$



Disappearance: $$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 \frac{1.27\Delta m^2_{41} L}{E} + |U_{\alpha 5}|^2 \sin^2 \frac{1.27\Delta m^2_{51} L}{E}) + |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \frac{1.27\Delta m^2_{54} L}{E}]$$

"- " for $\bar{\nu}$

Appearance: $$P(\nu_\alpha \to \nu_{\beta \neq \alpha}) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \frac{1.27\Delta m^2_{41} L}{E} + 4|U_{\alpha 5}|^2 |U_{\beta 5}|^2 \sin^2 \frac{1.27\Delta m^2_{51} L}{E} + 8|U_{\alpha 4}||U_{\beta 4}||U_{\alpha 5}||U_{\beta 5}| \sin \frac{1.27\Delta m^2_{41} L}{E} \sin \frac{1.27\Delta m^2_{51} L}{E} \cos(\frac{1.27\Delta m^2_{54} L}{E} + \phi_{45})$$

3+3 Model (new for arxiv:1207.4765)

- 3rd mostly sterile state, Introduce $\Delta m^2_{61}, U_{\mu 6}, U_{e6}, \Phi_{46}, \Phi_{56}$
- 12 total parameters

Appearance:

$$\begin{aligned}
P(\nu_\alpha \to \nu_\beta) \simeq & -4|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} \sin^2(1.27\Delta m^2_{54} L/E) \\
& -4|U_{\alpha 6}||U_{\beta 6}||U_{\alpha 4}||U_{\beta 4}| \cos\phi_{64} \sin^2(1.27\Delta m^2_{64} L/E) \\
& -4|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 6}||U_{\beta 6}| \cos\phi_{65} \sin^2(1.27\Delta m^2_{65} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| + |U_{\alpha 5}||U_{\beta 5}| \cos\phi_{54} + |U_{\alpha 6}||U_{\beta 6}| \cos\phi_{64})|U_{\alpha 4}||U_{\beta 4}| \sin^2(1.27\Delta m^2_{41} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} + |U_{\alpha 5}||U_{\beta 5}| + |U_{\alpha 6}||U_{\beta 6}| \cos\phi_{65})|U_{\alpha 5}||U_{\beta 5}| \sin^2(1.27\Delta m^2_{51} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| \cos\phi_{64} + |U_{\alpha 5}||U_{\beta 5}| \cos\phi_{65} + |U_{\alpha 6}||U_{\beta 6}|)|U_{\alpha 6}||U_{\beta 6}| \sin^2(1.27\Delta m^2_{61} L/E) \\
& +2|U_{\beta 5}||U_{\alpha 5}||U_{\beta 4}||U_{\alpha 4}| \sin\phi_{54} \sin(2.53\Delta m^2_{54} L/E) \\
& +2|U_{\beta 6}||U_{\alpha 6}||U_{\beta 4}||U_{\alpha 4}| \sin\phi_{64} \sin(2.53\Delta m^2_{64} L/E) \\
& +2|U_{\beta 6}||U_{\alpha 6}||U_{\beta 5}||U_{\alpha 5}| \sin\phi_{65} \sin(2.53\Delta m^2_{65} L/E) \\
& +2(|U_{\alpha 5}||U_{\beta 5}| \sin\phi_{54} + |U_{\alpha 6}||U_{\beta 6}| \sin\phi_{64})|U_{\alpha 4}||U_{\beta 4}| \sin(2.53\Delta m^2_{41} L/E) \\
& +2(-|U_{\alpha 4}||U_{\beta 4}| \sin\phi_{54} + |U_{\alpha 6}||U_{\beta 6}| \sin\phi_{65})|U_{\alpha 5}||U_{\beta 5}| \sin(2.53\Delta m^2_{51} L/E) \\
& +2(-|U_{\alpha 4}||U_{\beta 4}| \sin\phi_{64} - |U_{\alpha 5}||U_{\beta 5}| \sin\phi_{65})|U_{\alpha 6}||U_{\beta 6}| \sin(2.53\Delta m^2_{61} L/E) \ .
\end{aligned}$$

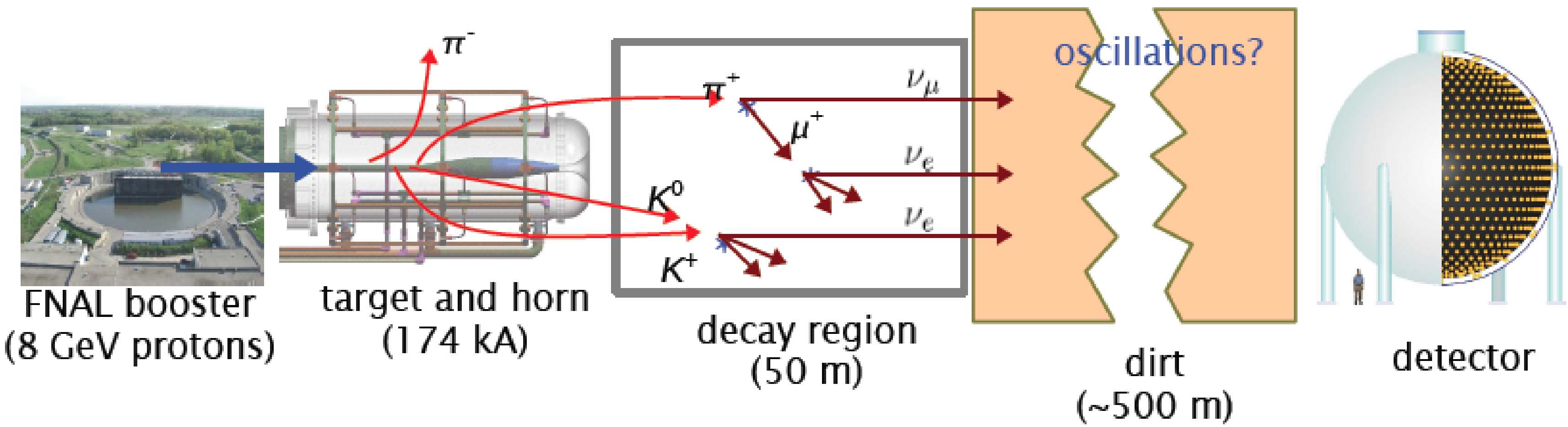
Disappearance:

$$\begin{aligned}
P(\nu_\alpha \to \nu_\alpha) \simeq & \ 1 - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2(1.27\Delta m^2_{54} L/E) \\
& -4|U_{\alpha 4}|^2|U_{\alpha 6}|^2 \sin^2(1.27\Delta m^2_{64} L/E) - 4|U_{\alpha 5}|^2|U_{\alpha 6}|^2 \sin^2(1.27\Delta m^2_{65} L/E) \\
& -4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2 - |U_{\alpha 6}|^2)(|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \\
& +|U_{\alpha 5}|^2 \sin^2(1.27\Delta m^2_{51} L/E) + |U_{\alpha 6}|^2 \sin^2(1.27\Delta m^2_{61} L/E)) \ .
\end{aligned}$$

OK, LSND motivated introducing sterile neutrinos… is there any other data to back this up?

MiniBooNE

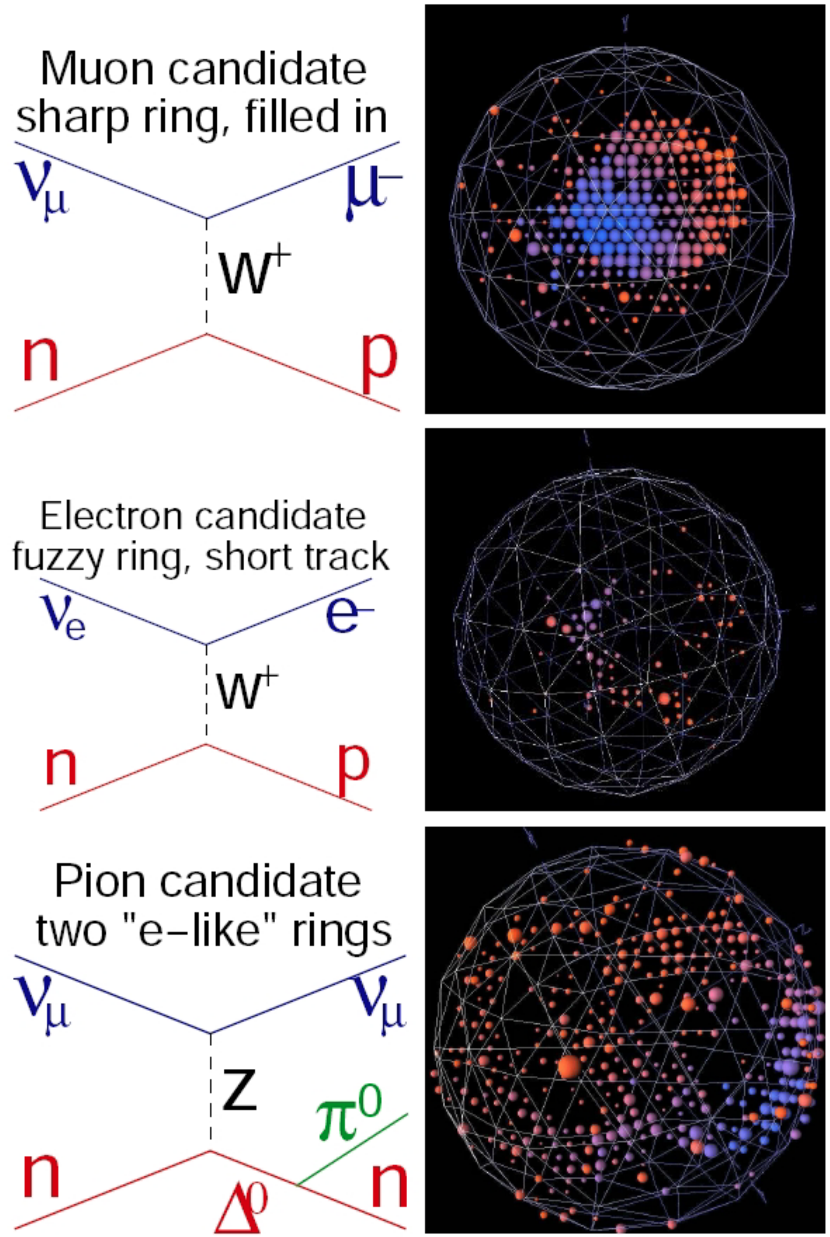
- Designed to explore LSND anomaly (similar L / E)
  - Different detector design and systematics
  - Can run in neutrino or antineutrino mode by choosing positive or negative mesons with a focusing horn



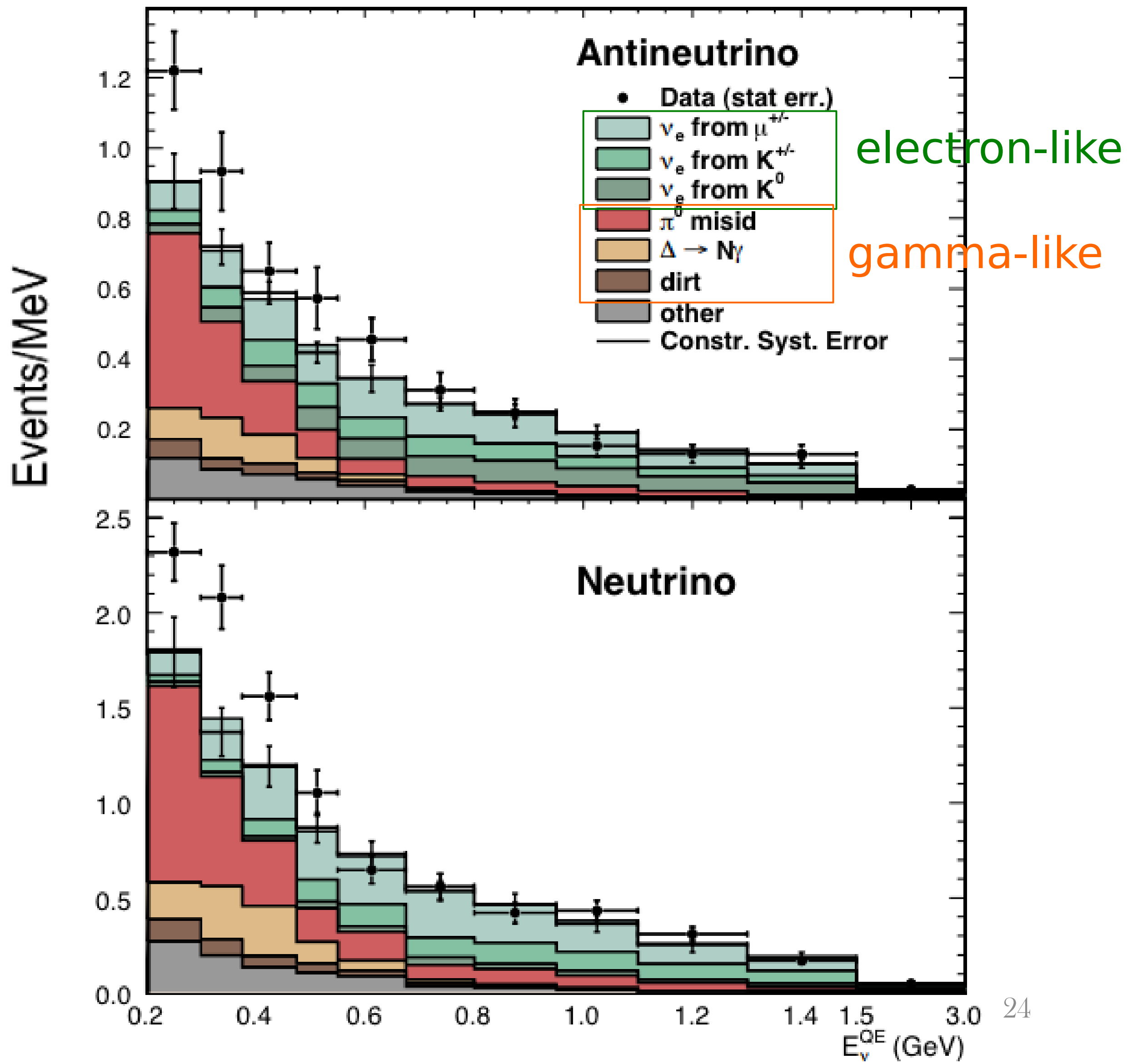
MiniBooNE

- Cherenkov Detector
  - Detects Cherenkov rings created by charged particles

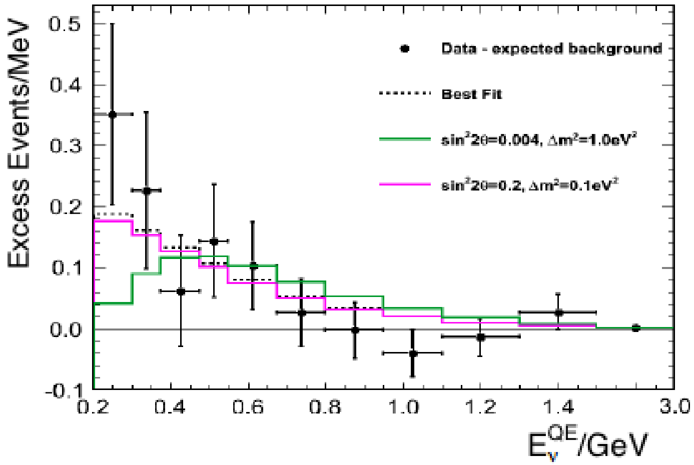
- Main sources of background from intrinsic ν_e in the beam and mis ID ($\gamma \to e^+ e^-$) from $\pi^0 \to \gamma\gamma, \Delta \to N\gamma$

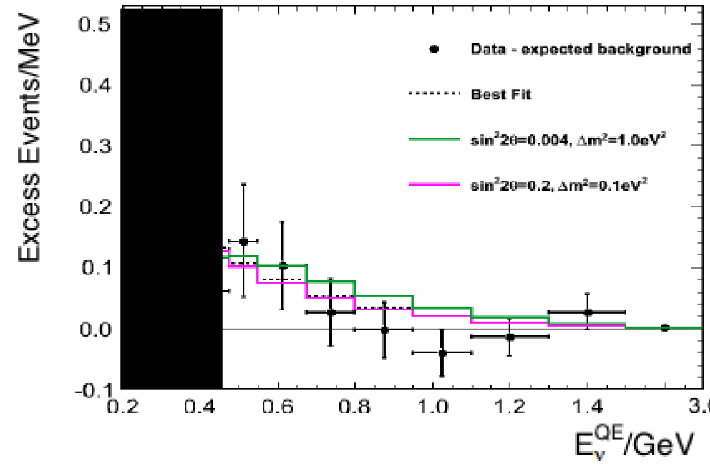


MiniBooNE Data and Backgrounds

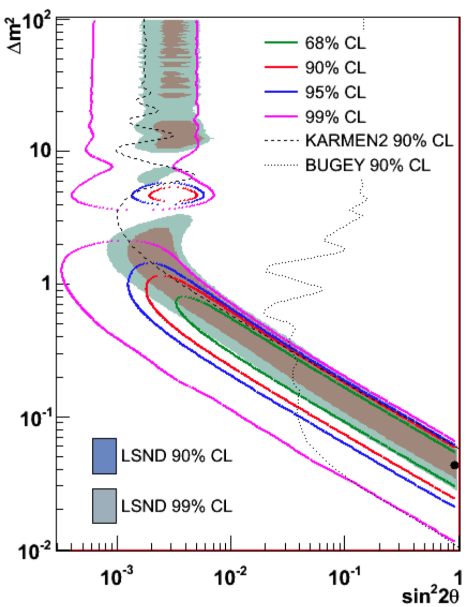


MiniBooNE $\bar{\nu}$ mode



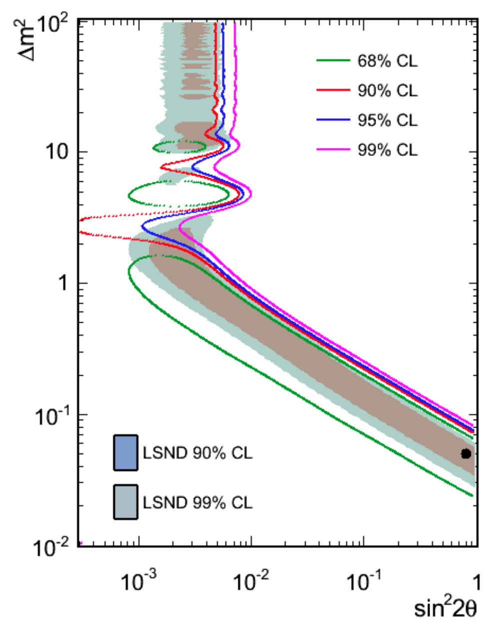


E > 200 MeV

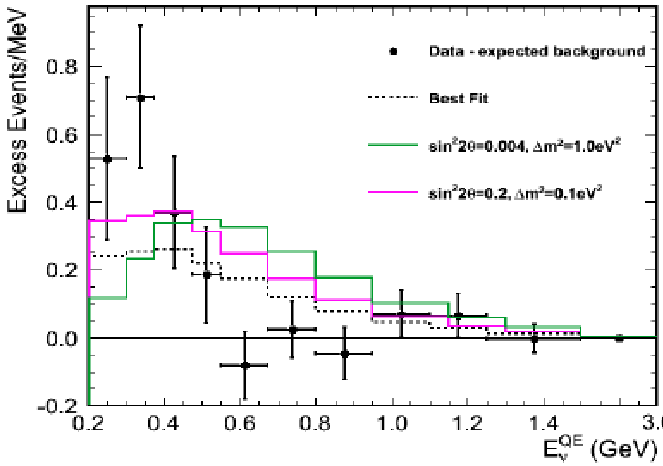


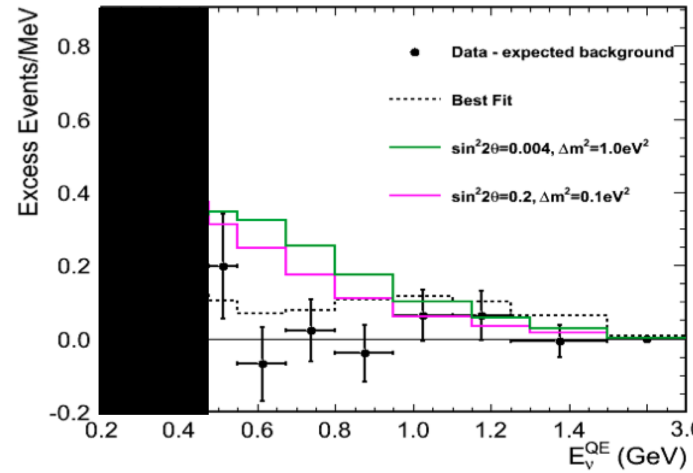
	E > 200	E > 475
χ2 (null)	16.3	7.59
P (null)	5.8%	26.4%
χ2 (bf)	4.76	3.23
P (bf)	67.5%	50.2%

E > 475 MeV



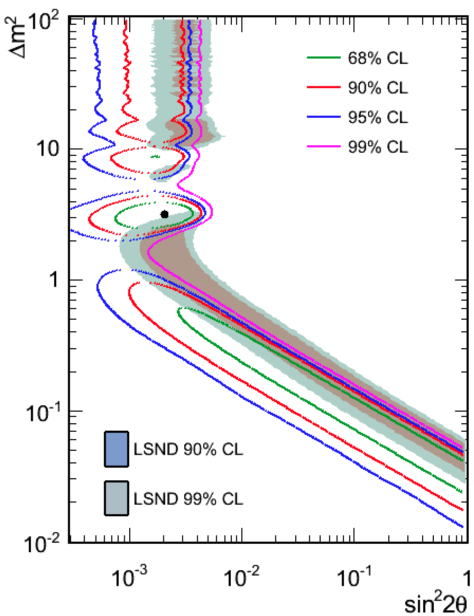
MiniBooNE ν mode



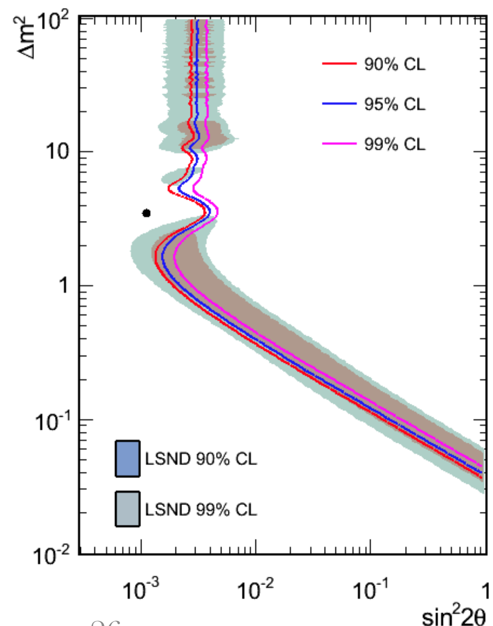


E > 200 MeV

E > 475 MeV

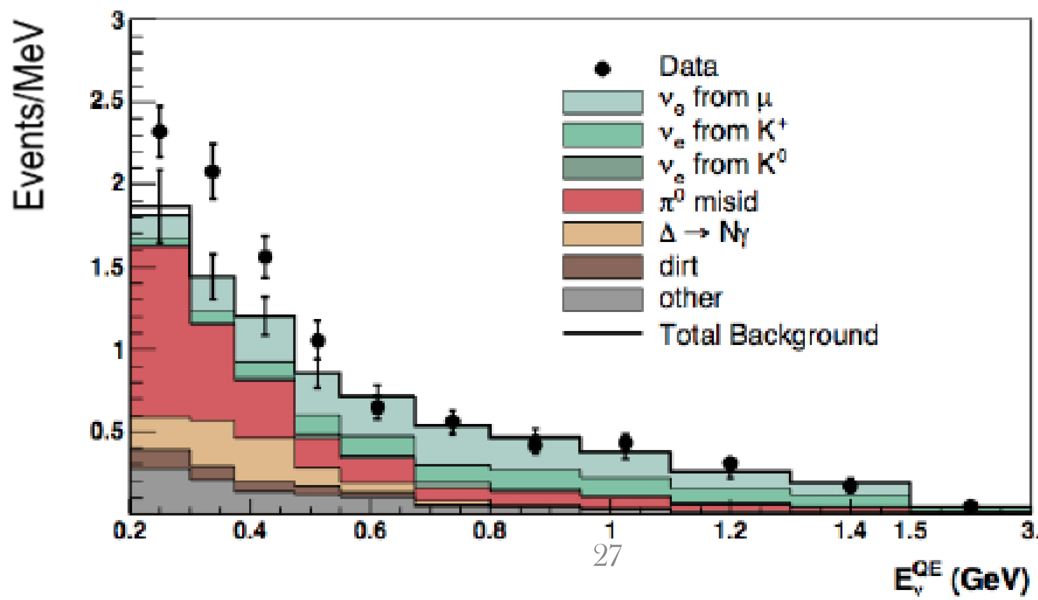


	E > 200	E > 475
χ2 (null)	22.81	6.35
P (null)	0.5%	36.6%
χ2 (bf)	13.24	3.73
P (bf)	6.12%	42.0%

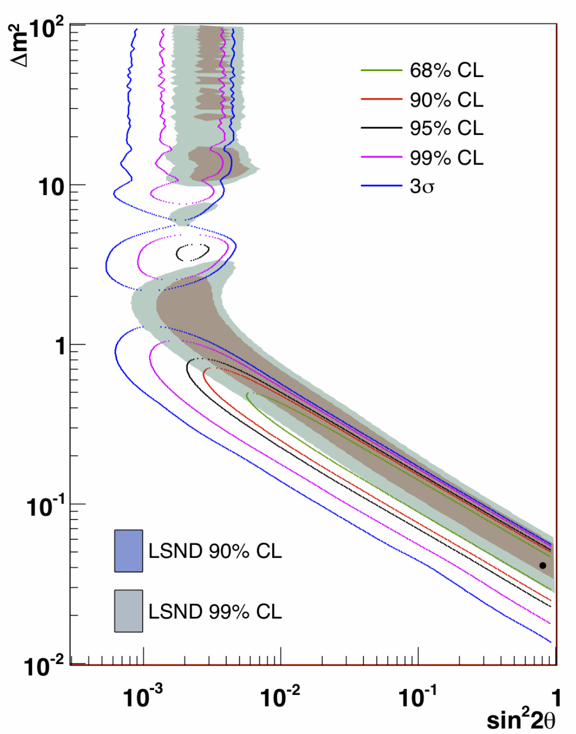


Low energy excess

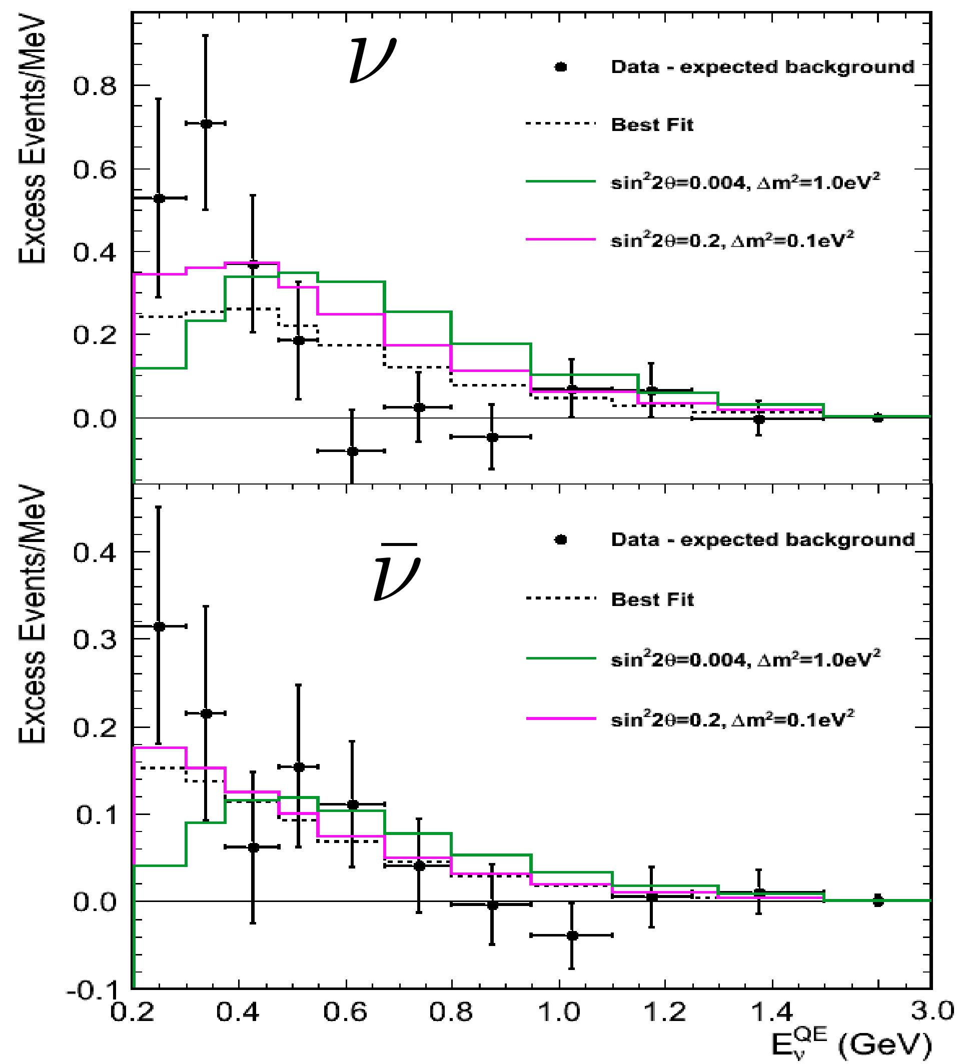
- Still unexplained
- Not a statistical fluctuation of background (6σ)
- Unlikely intrinsic ν_e (low bg here)
- NC π_0 bg dominates
  - Constrained by NC π_0 direct measurements
- Δ-> Nγ rate tied to NC π_0 rate
  - Theoretical calculations agree within 20%



MiniBooNE Combined Fit

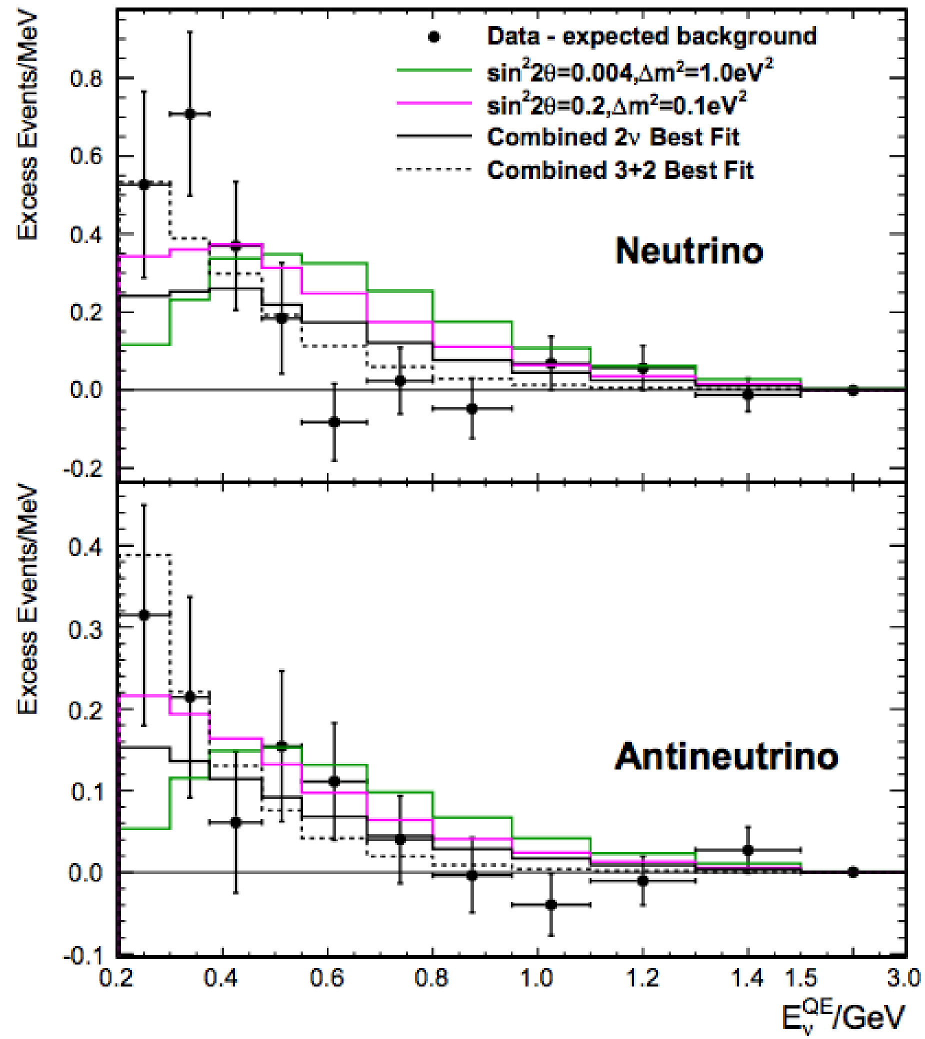


	E > 475	E > 200
χ2 (null)	12.87	42.53
P (null)	35.8%	0.1%
χ2 (bf)	10.67	24.72
P (bf)	35.8%	6.7%



3+2 combined fit

- CP violation allows for difference between neutrinos and antineutrinos
- Much better fit than 3+1
- No ν_e or ν_μ disappearance constraints
  - Limited value outside of a global picture



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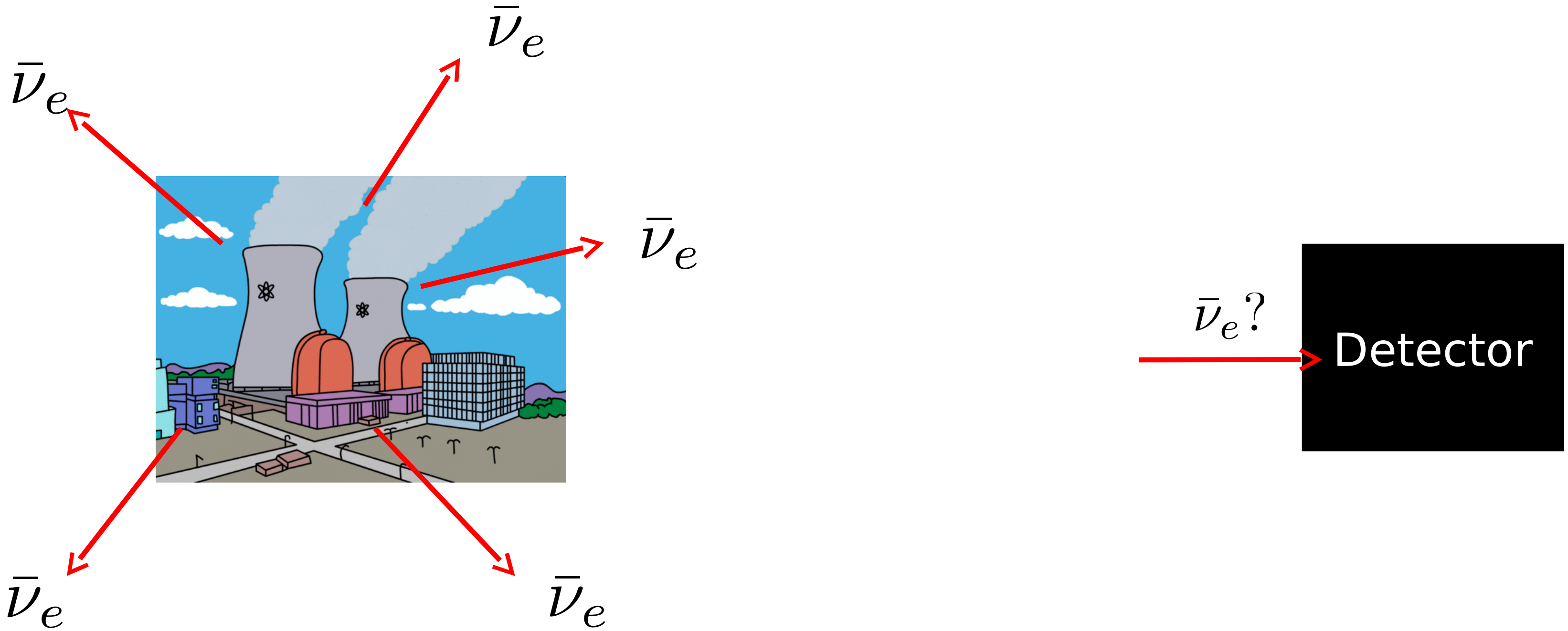
Reactor Anomaly

- Reactor experiments often used to measure neutrino mixing in a 3 neutrino scenario



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{ee} \sin^2(1.27 \Delta m^2 \frac{L}{E})$$

Reactor Anomaly

How do you get the expected flux without a near detector?

Monte Carlo simulations: 2 components

- Fission rates

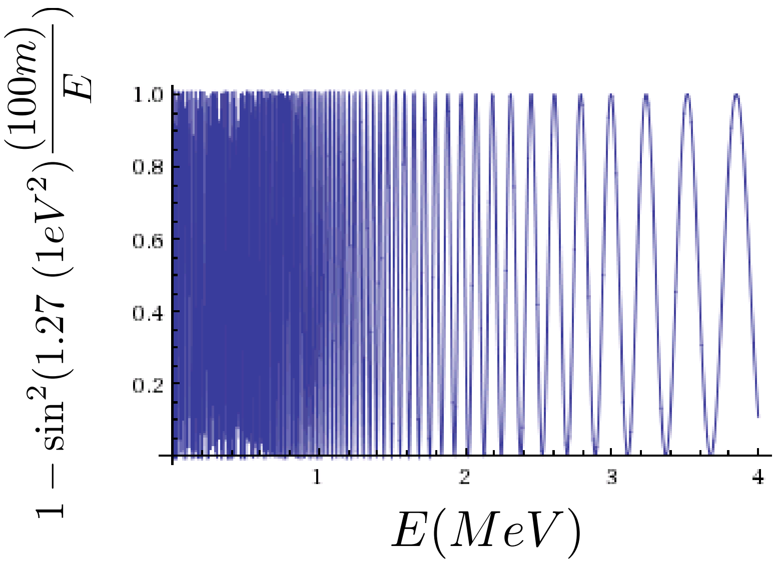
(which we know very well)

- Predicting neutrinos from fissions
  - This has changed recently! (arxiv:1101.2663) We have more information than we did ~30 years ago
- Raised the predicted number of neutrino events
  - So now there is a deficit in observed events compared to prediction!

Reactor Anomaly

- What do oscillations look like in an experiment designed to look for much smaller mass splittings?

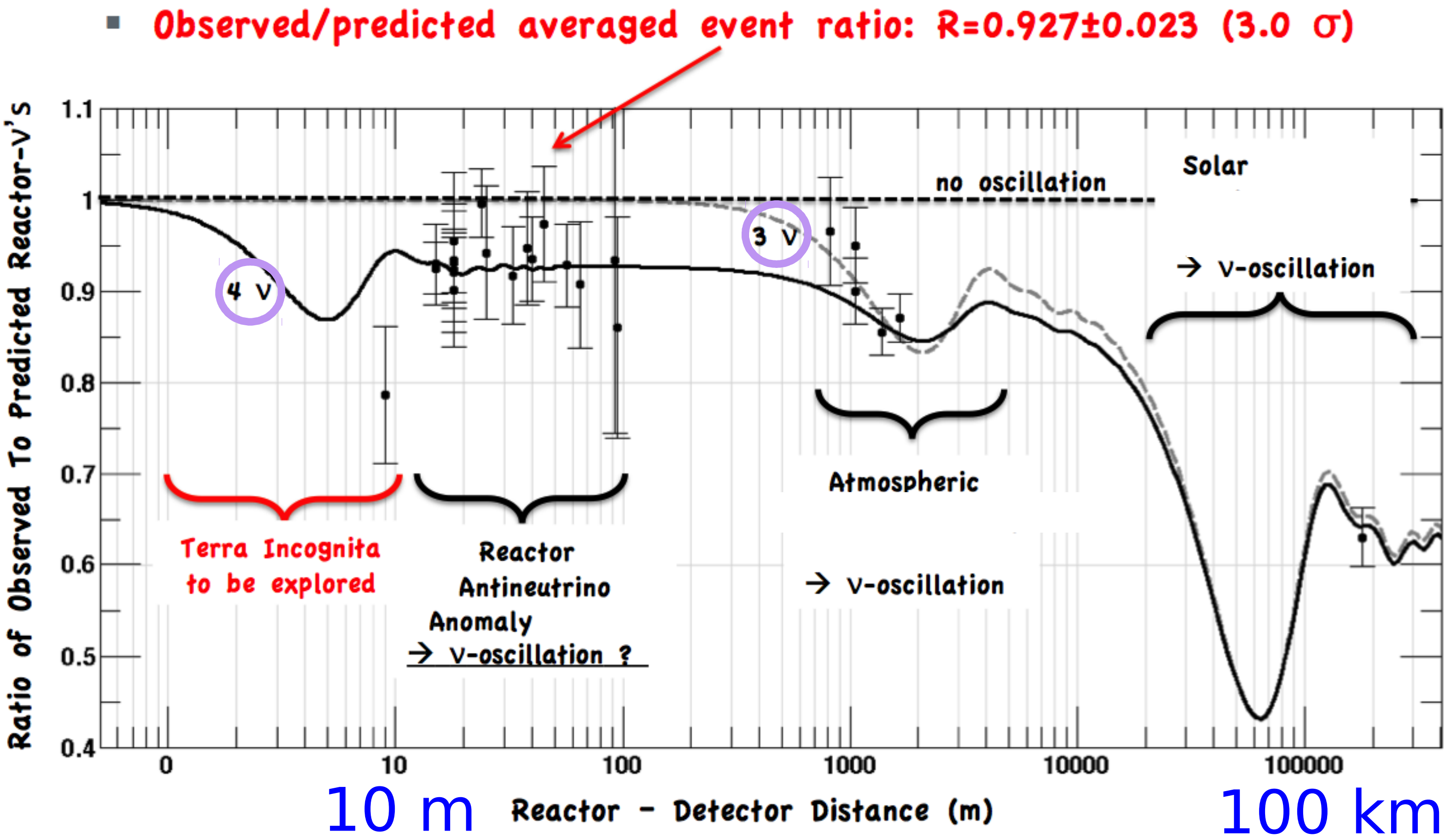
- Get fast oscillations: oscillations occur much more rapidly than energy resolution of detector can resolve



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \underbrace{\sin^2(1.27\Delta m^2 \frac{L}{E})}_{1/2}$$

Get Deficit of events corresponding to ½ oscillation amplitude

Reactor Anomaly

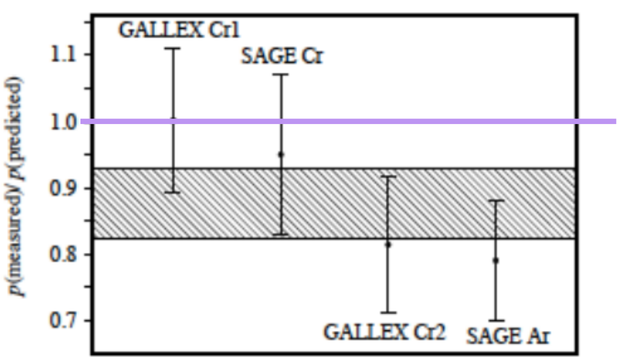


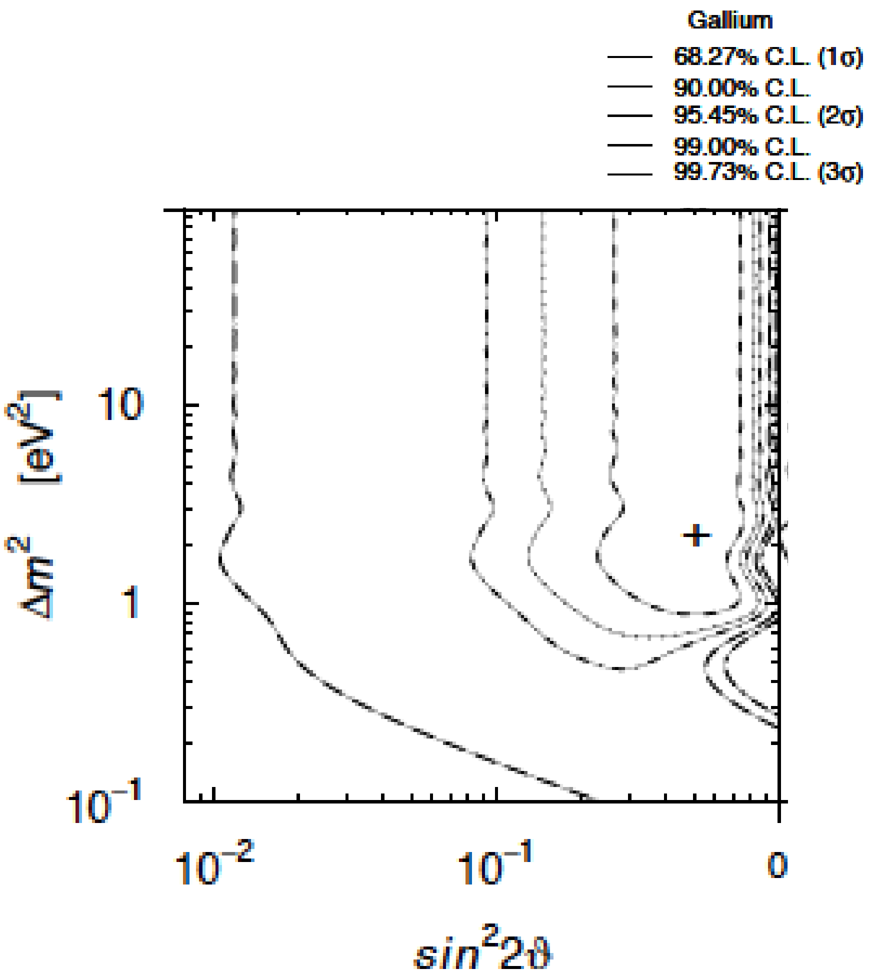
The addition of one or more sterile neutrinos could resolve this issue

Gallium Anomaly

- Cr-51 and Ar-37 sources were used to calibrate the GALLEX and SAGE solar neutrino experiments
- Very short baseline (meter scale) so sensitive to ~1 eV^2 neutrino oscillation

$\nu_e \not\to \nu_e$





arXiv:1006.3244

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- Other recent anomalies
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- Global Fits (arxiv:1207.4765)
- Future

Included data sets

ν_e and $\bar{\nu}_e$ Appearance:

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

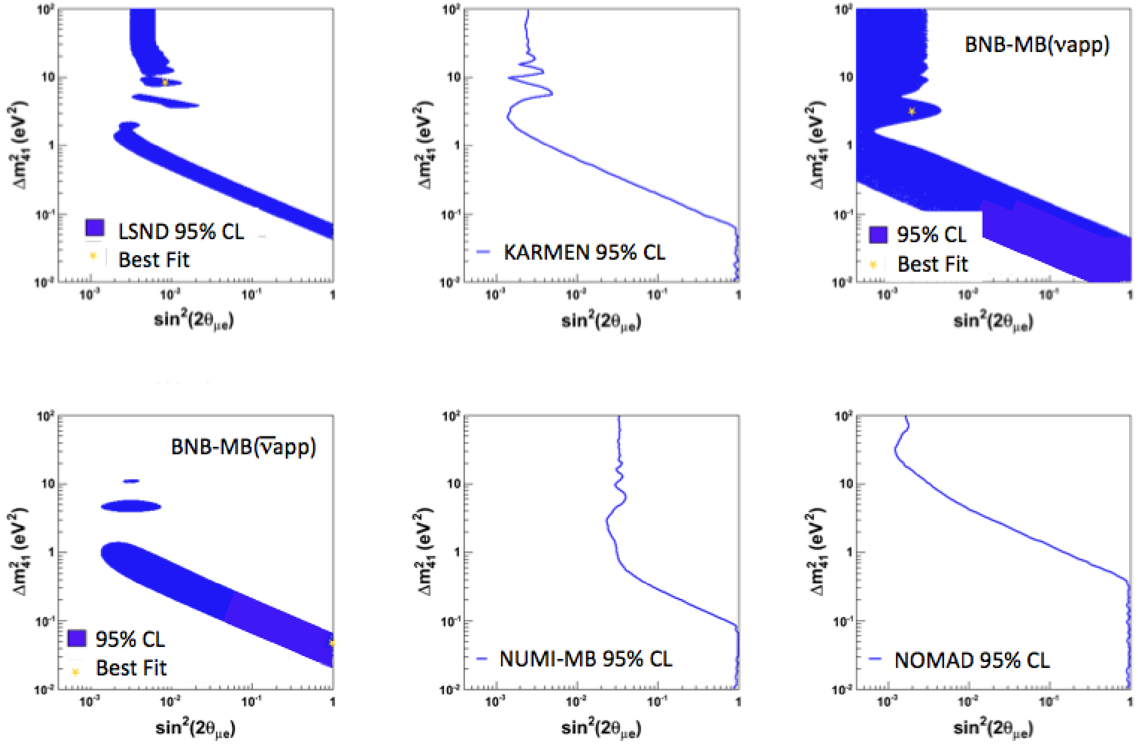
MiniBooNE $\nu_\mu \to \nu_e$

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

NOMAD $\nu_\mu \to \nu_e$

NuMI in MB $\nu_\mu \to \nu_e$

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



Included data sets

ν_μ and $\bar{\nu}_\mu$ Disappearance:

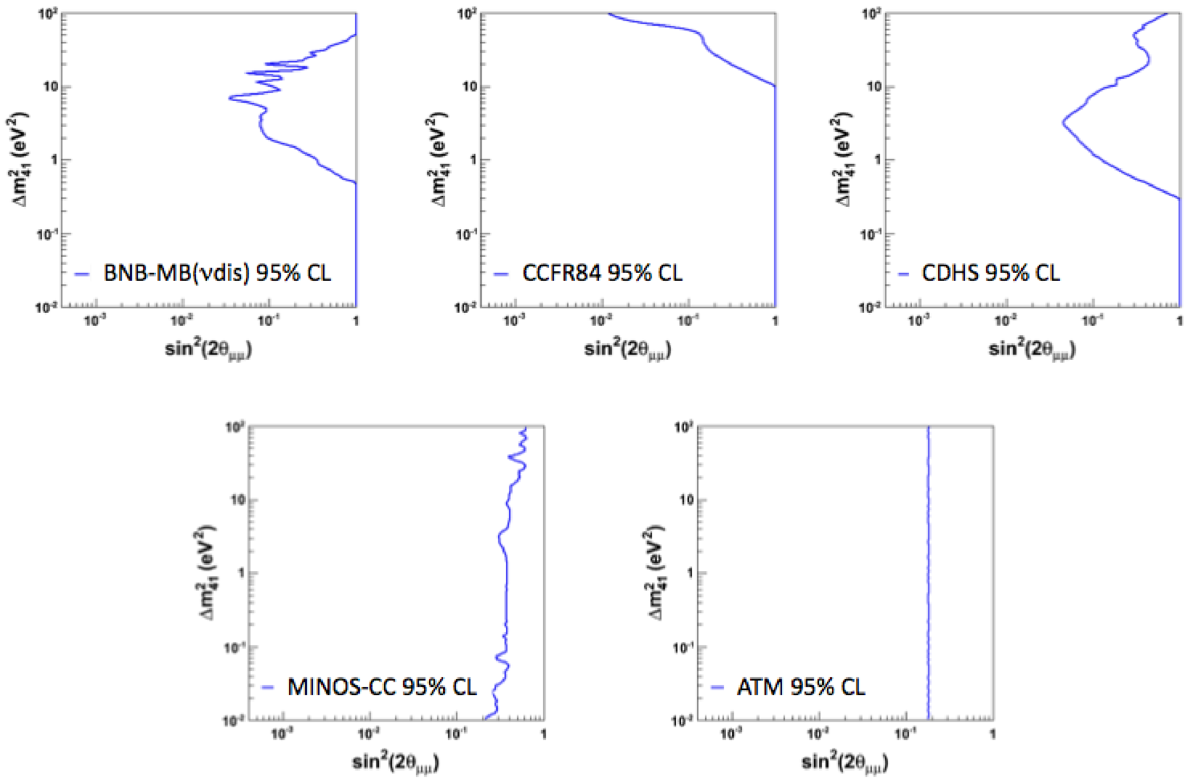
MiniBooNE $\nu_\mu \nrightarrow \nu_\mu$

CCFR84 $\nu_\mu \nrightarrow \nu_\mu$

CDHS $\nu_\mu \nrightarrow \nu_\mu$

Atmospheric $\nu_\mu \nrightarrow \nu_\mu$

MINOS CC $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$



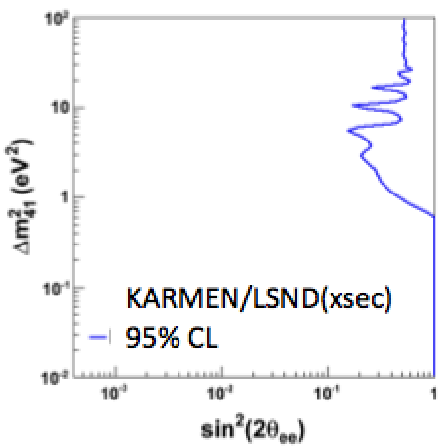
Included data sets

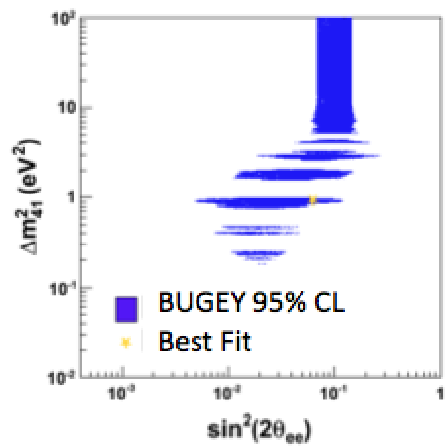
ν_e and $\bar{\nu}_e$ Disappearance:

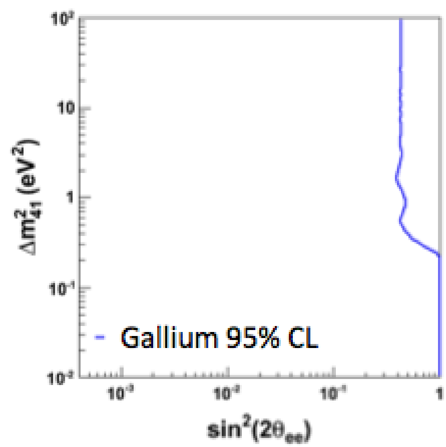
Bugey $\bar{\nu}_e \nrightarrow \bar{\nu}_e$ (with new reactor fluxes)

Gallium $\nu_e \nrightarrow \nu_e$

Karmen/LSND xsec $\nu_e \nrightarrow \nu_e$



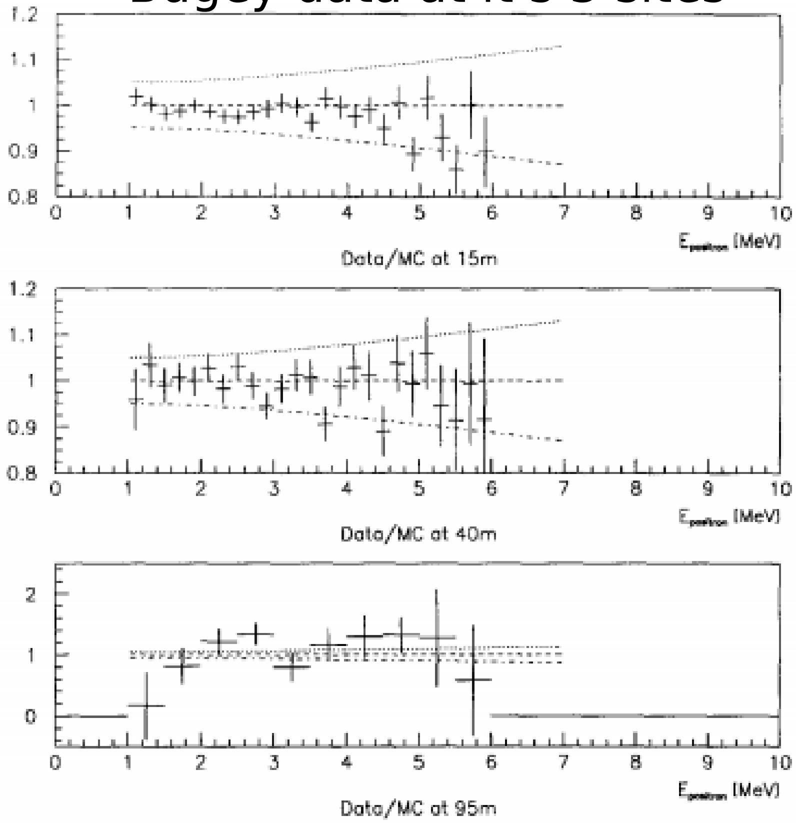




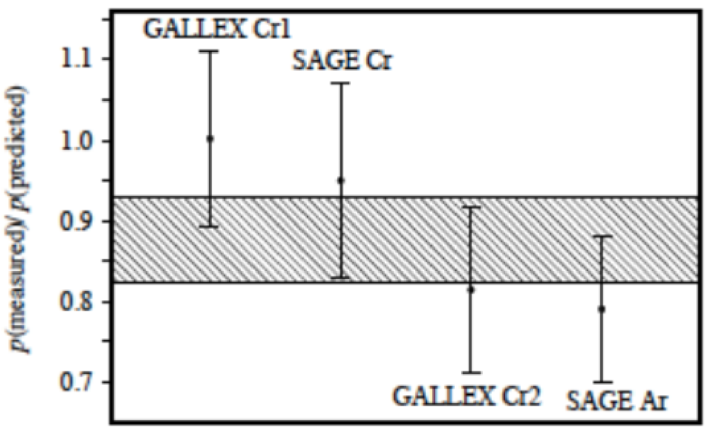
Problem with χ^2 in global fits

- Some experiments have 50 bins while others have 4…
- Treats all bins equally rather than all experiments equally
  - High bin experiments dominate χ^2

Bugey data at it's 3 sites



Gallex/Sage data



Parameter Goodness of Fit

Tests how well different groups of datasets agree with each other

$$PG = Prob(\chi^2_{PG}, ndf_{PG})$$

$$\chi^2_{PG} = \chi^2_{min,combined} - \sum_i \chi^2_{min,d}$$

i runs over datasets

$$ndf_{PG} = \sum_d N_{p_d} - N_{p_{combined}}$$

N_{p_d}: Independent parameters per dataset

$N_{p_{combined}}$: Independent parameters in global fit

Reference: M. Maltoni and T. Schwetz 2003 arXiv:hep-ph/0304176

Parameter Goodness of Fit

Tests how well different sets of data agree with each other

Ex. $\nu \ vs \ \bar{\nu}$ for 3+1 fit

$$\chi^2_{PG}(\nu \ vs \ \bar{\nu}) = \boxed{\chi^2_{min}(all)} - \boxed{\chi^2_{min}(\nu)} - \boxed{\chi^2_{min}(\bar{\nu})}$$

χ^2 from global fit

χ^2 from fit to ν experiments only

χ^2 from fit to $\bar{\nu}$ experiments only

$$ndf_{PG}(\nu \ vs \ \bar{\nu}) = \boxed{3} + \boxed{3} - \boxed{3}$$

Parameters in ν 3+1 fit

Parameters in $\bar{\nu}$ 3+1 fit

parameters in global 3+1 fit

3 parameters in each for this case: $\Delta m^2_{41}, U_{\mu 4}$, and U_{e4}

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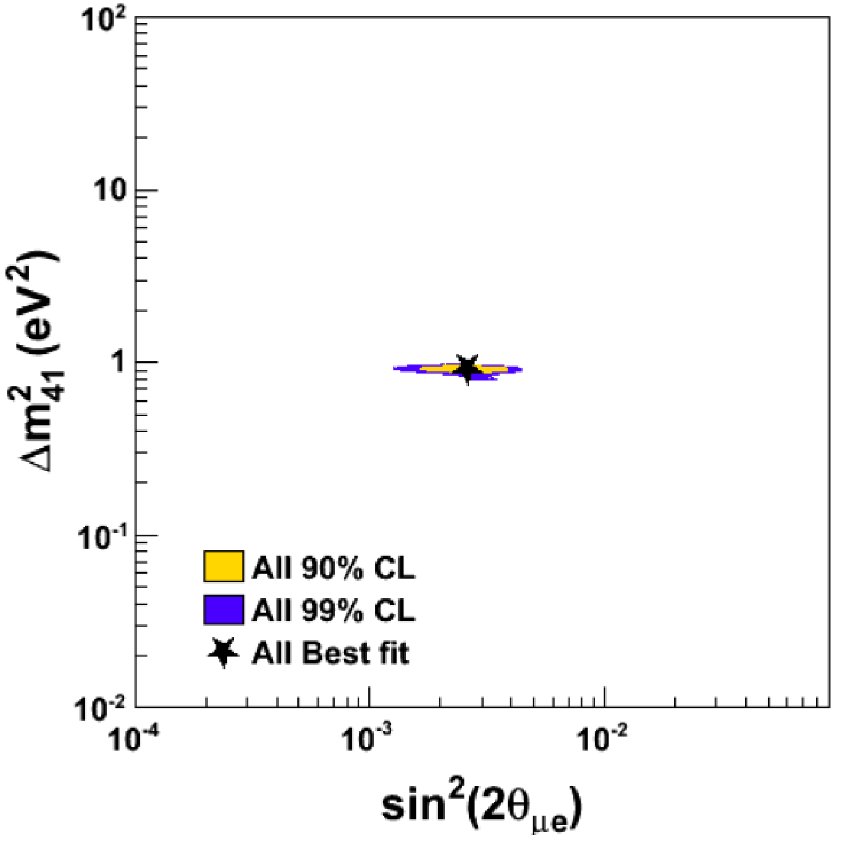
3+1 Global Fit



$\chi 2_{bf}$ (dof)	$\chi 2_{null}$ (dof)	P_{bf}	P_{null}
233.9 (237)	286.5 (240)	55%	2.1%

Subsets of data

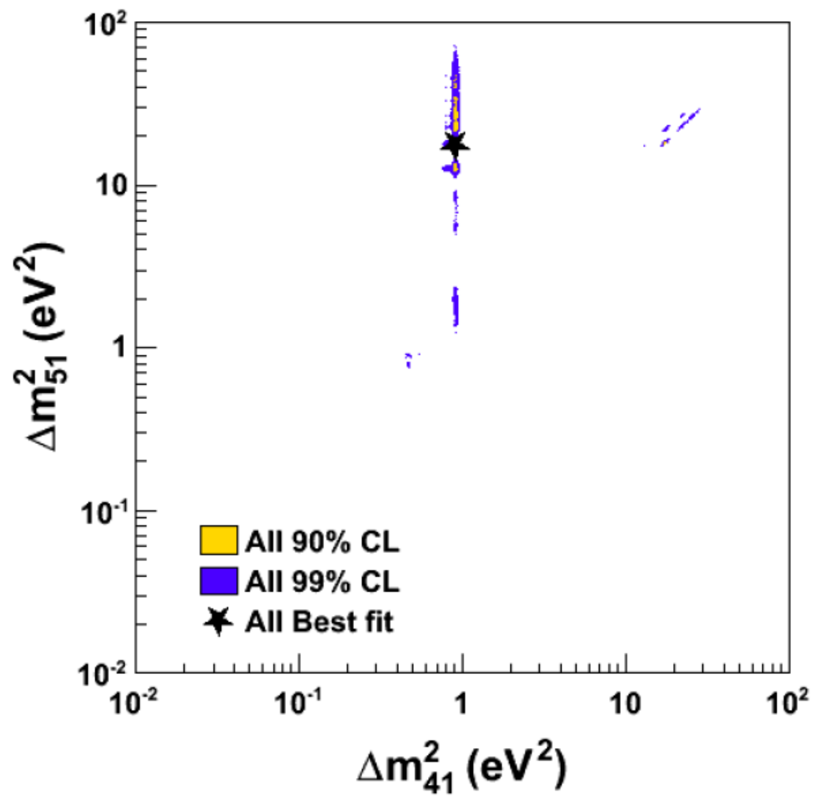
	χ^2_{min} (dof)	P_{best}	χ^2_{null} (dof)	P_{null}
3+1				
All	233.9 (237)	55%	286.5 (240)	2.1%
App	87.8 (87)	46%	147.3 (90)	0.013%
Dis	128.2 (147)	87%	139.3 (150)	72%
ν	123.5 (120)	39%	133.4 (123)	25%
$\overline{\nu}$	94.8 (114)	90%	153.1 (117)	1.4%

	χ^2_{PG} (dof)	PG (%)
App vs. Dis	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	15.6 (3)	0.14%

Best Fit Values

3+1	Δm^2_{41}	$\|U_{\mu 4}\|$	$\|U_{e4}\|$
All	0.92	0.17	0.15

3+2 Global Fit



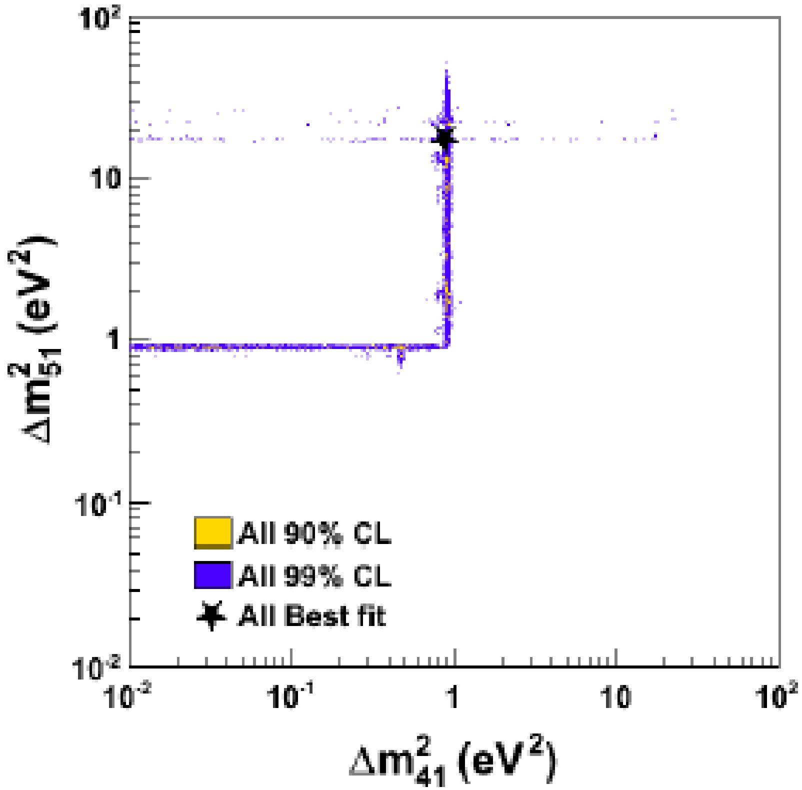
$\chi 2_{bf}$ (dof)	$\chi 2_{null}$ (dof)	P_{bf}	P_{null}
221.5 (233)	286.5 (240)	69%	2.1%

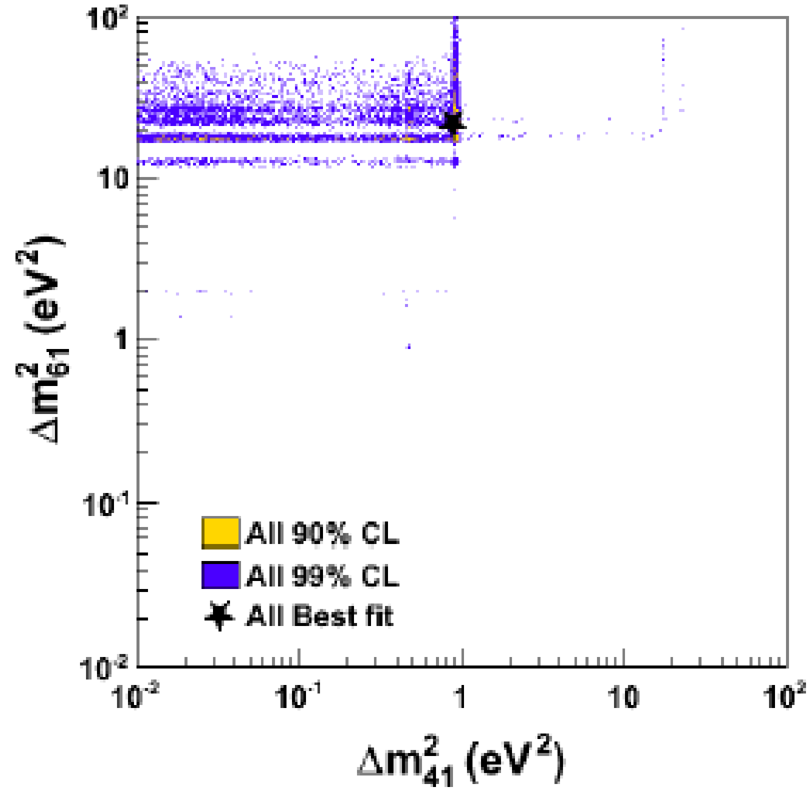
	χ^2_{min} (dof)	P_{best}
3+1		
All	233.9 (237)	55%
App	87.8 (87)	46%
Dis	128.2 (147)	87%
ν	123.5 (120)	39%
$\overline{\nu}$	94.8 (114)	90%
3+2		
All	221.5 (233)	69%
App	75.0 (85)	77%
Dis	122.6 (144)	90%
ν	116.8 (116)	77%
$\overline{\nu}$	90.8 (110)	90%

	χ^2_{PG} (dof)	PG (%)
3+1		
App vs. Dis	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	15.6 (3)	0.14%
3+2		
App vs. Dis	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	13.9 (7)	5.3%

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

3+3 Global Fit





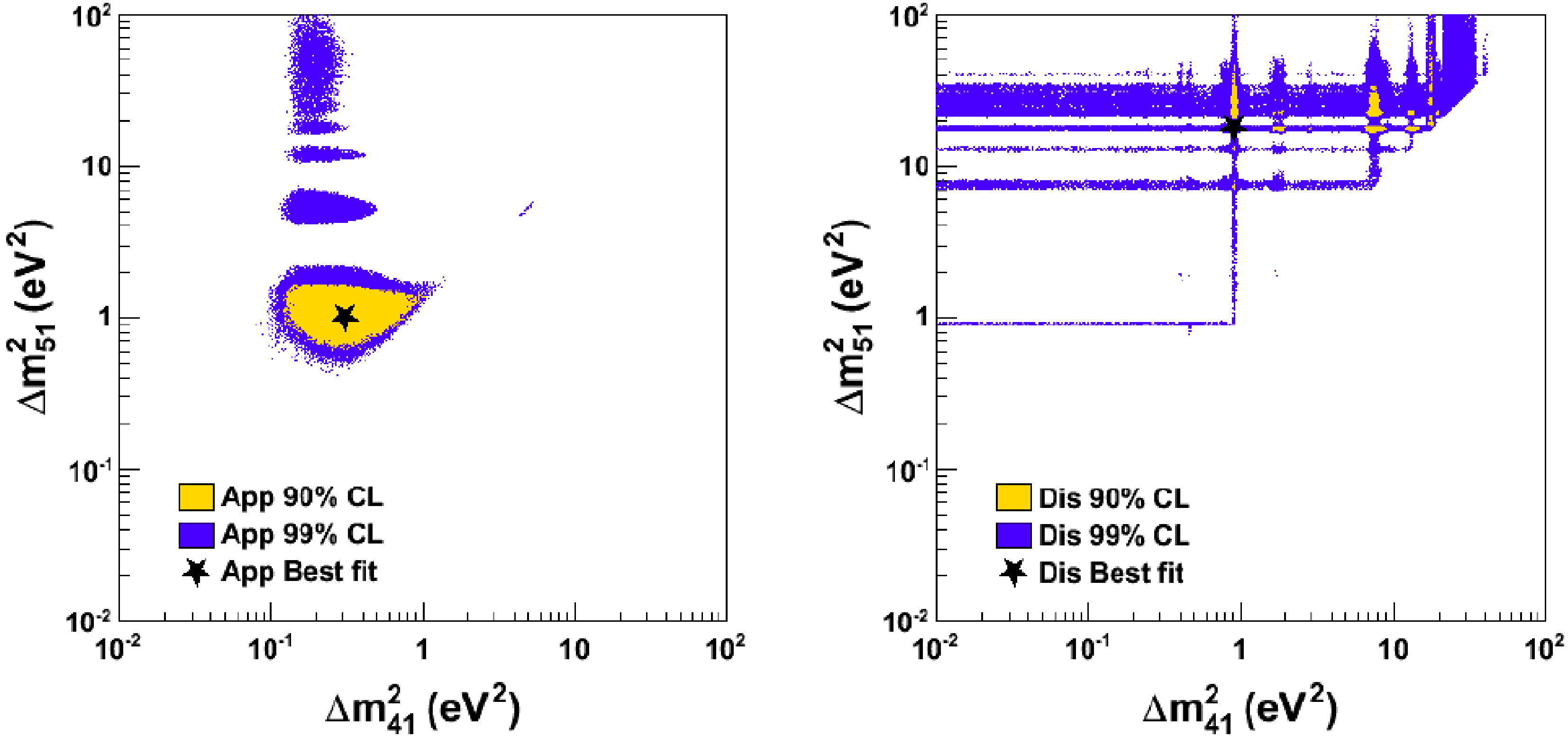
$\chi 2_{bf}$ (dof)	$\chi 2_{null}$ (dof)	P_{bf}	P_{null}
218.2 (228)	286.5 (240)	67%	2.1%

	χ^2_{min} (dof)	P_{best}
3+1		
All	233.9 (237)	55%
App	87.8 (87)	46%
Dis	128.2 (147)	87%
ν	123.5 (120)	39%
$\overline{\nu}$	94.8 (114)	90%
3+2		
All	221.5 (233)	69%
App	75.0 (85)	77%
Dis	122.6 (144)	90%
ν	116.8 (116)	77%
$\overline{\nu}$	90.8 (110)	90%
3+3		
All	218.2 (228)	67%
App	70.8 (81)	78%
Dis	120.3 (141)	90%
ν	116.7 (111)	34%
$\overline{\nu}$	90.6 (105)	84%

	χ^2_{PG} (dof)	PG (%)
App vs. Dis	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	15.6 (3)	0.14%
App vs. Dis	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	13.9 (7)	5.3%
App vs. Dis	27.1 (6)	0.014%
ν vs. $\overline{\nu}$	10.9 (12)	53%

Why Does App vs. Dis not get better?

3+2 fits (3+3 is similar)

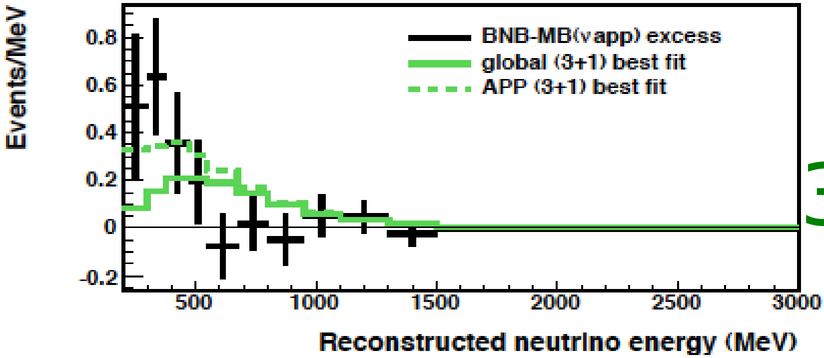


They are finding different best fit points…

It turns out the appearance fit is largely driven by MB

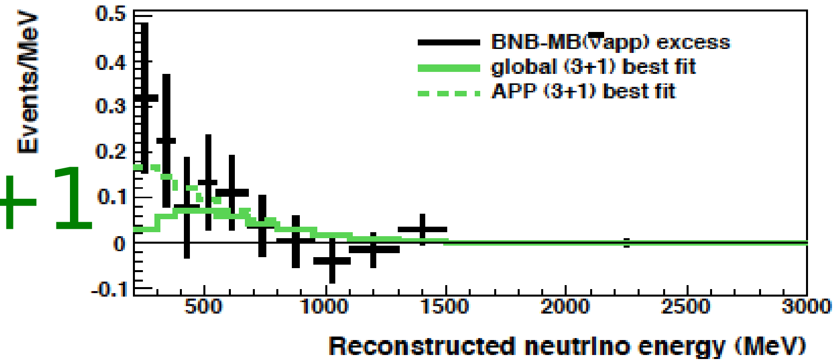
Does Not explain MiniBooNE low energy excess

ν

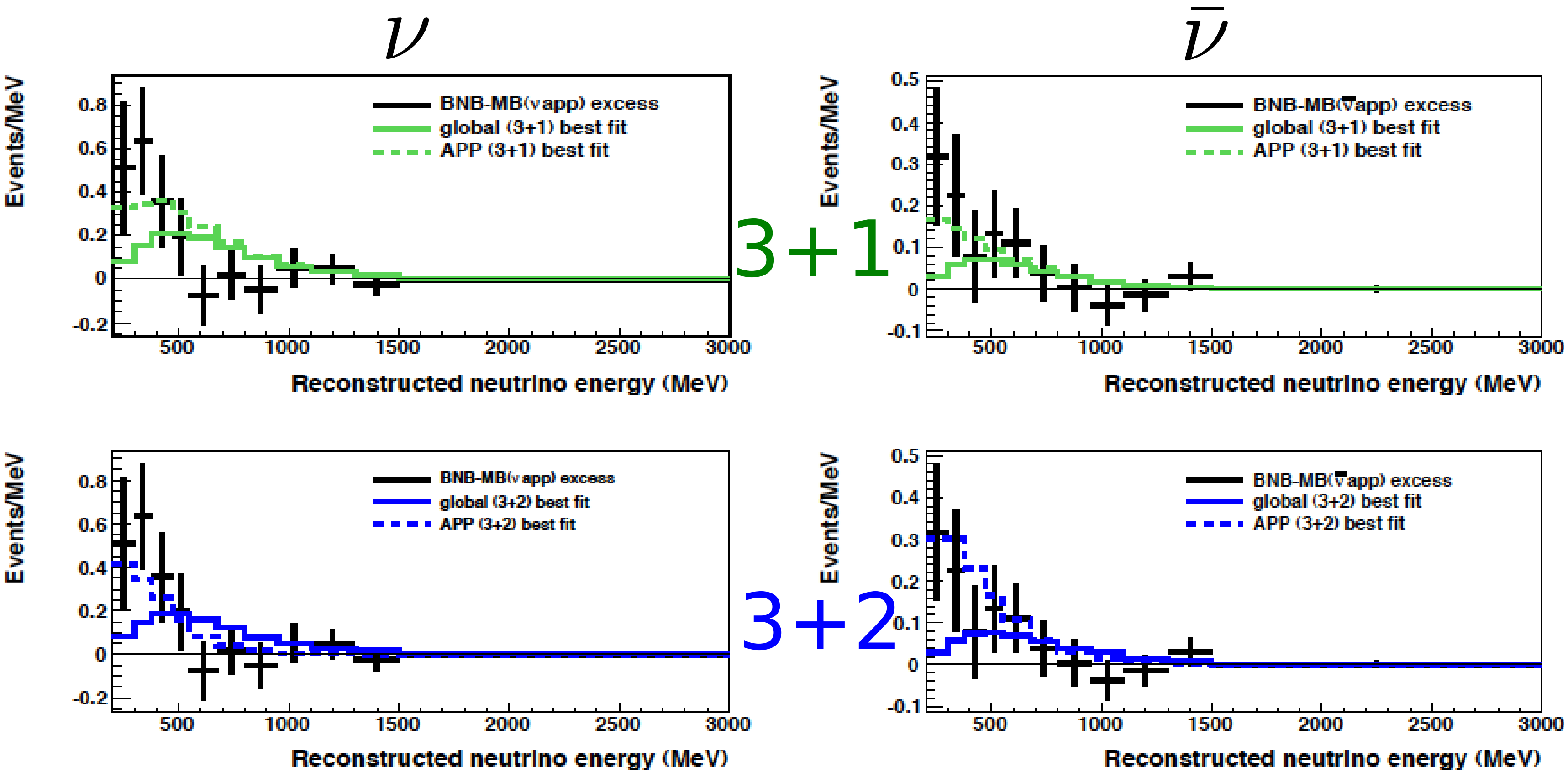


3+1

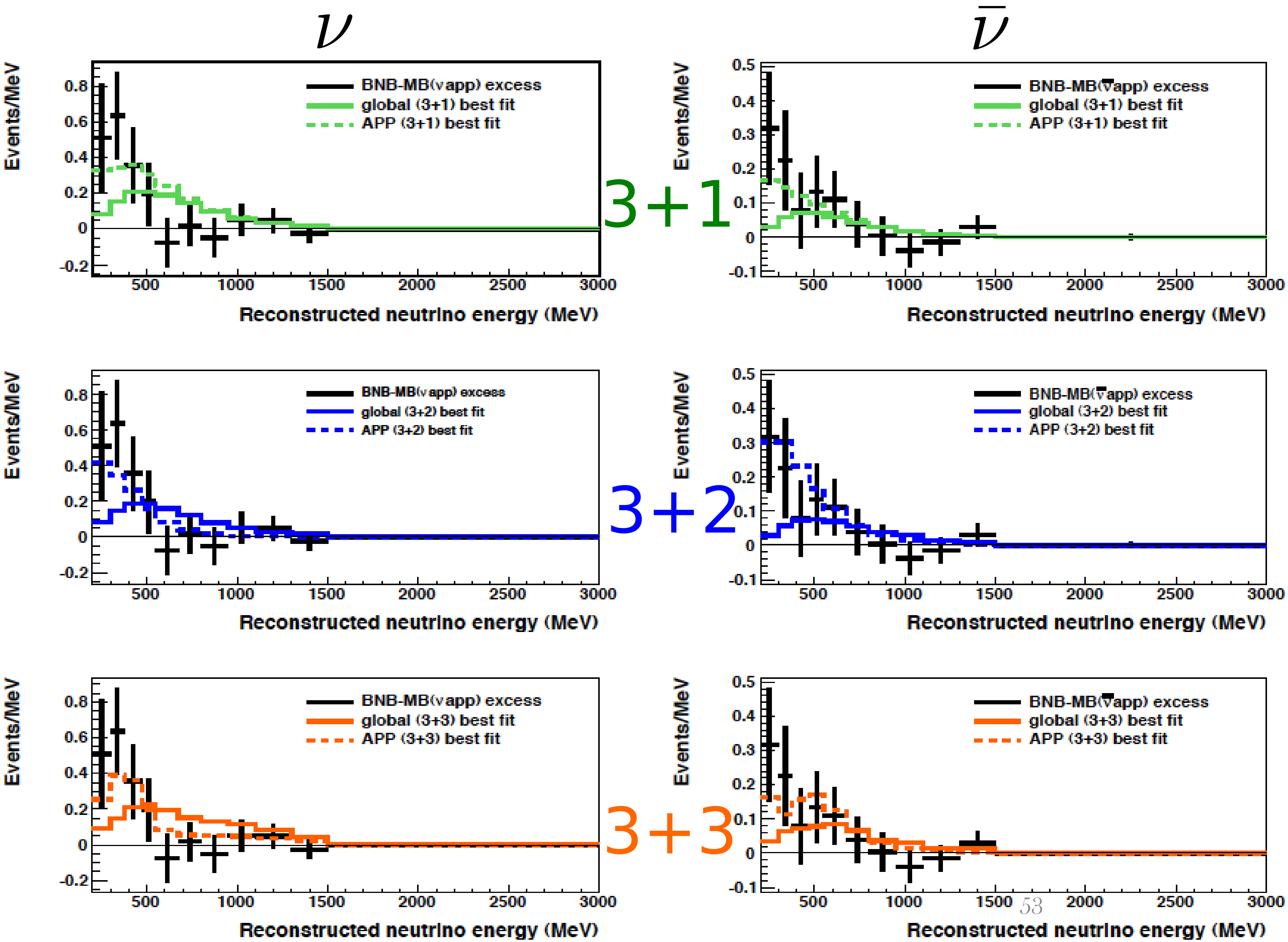
$\bar{\nu}$



Does Not explain MiniBooNE low energy excess



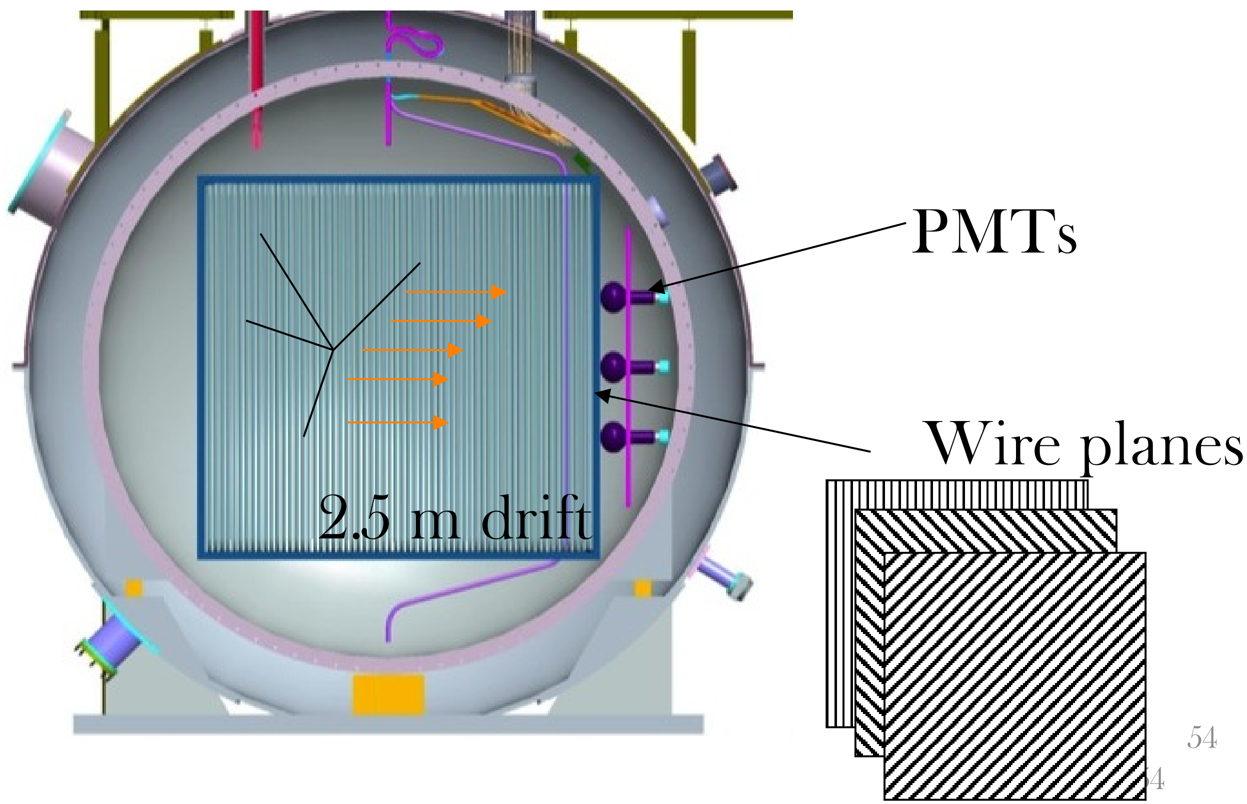
Does Not explain MiniBooNE low energy excess



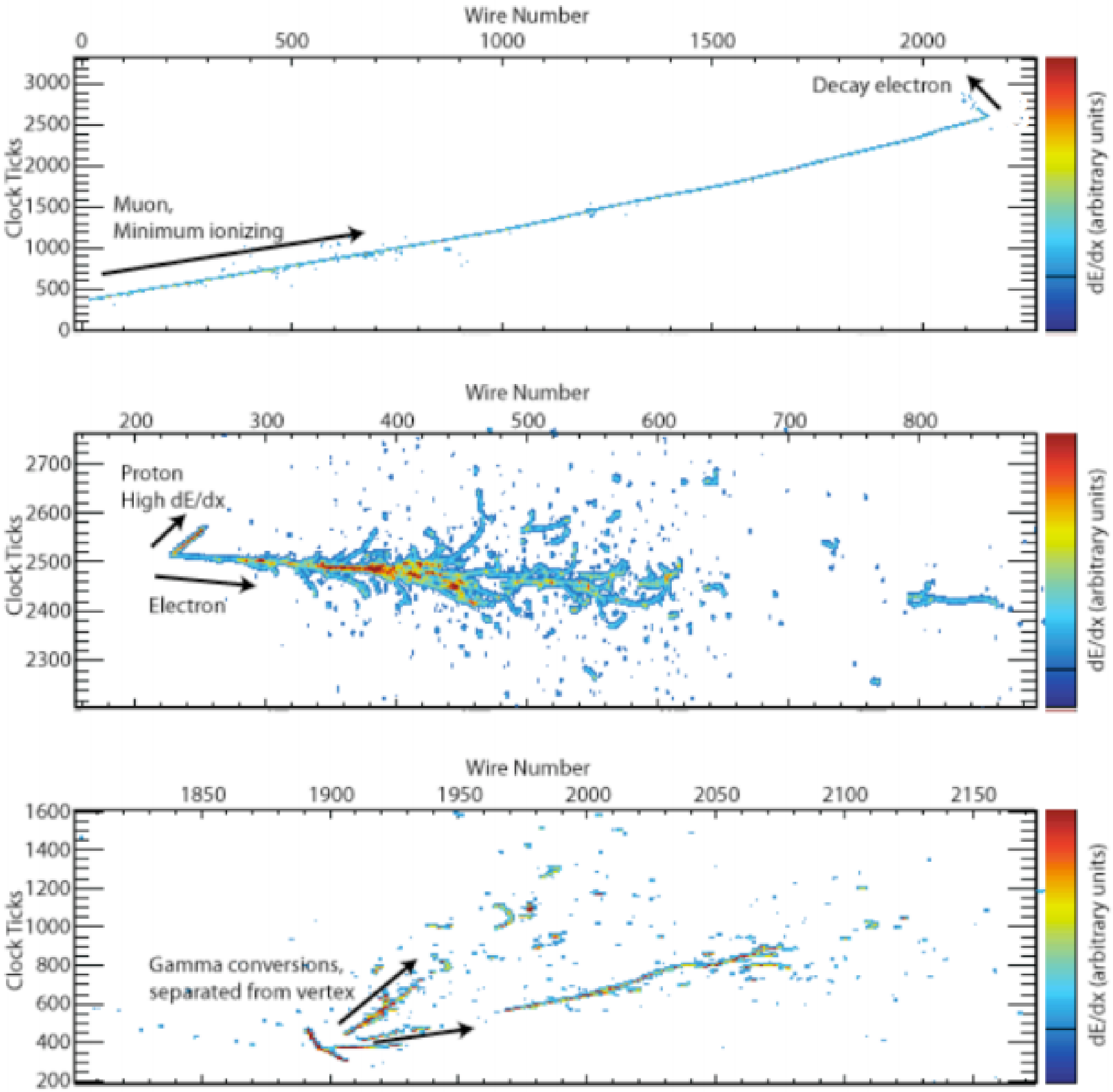
Can MicroBooNE explain the MiniBooNE low energy excess?

- MiniBooNE excess is not consistent with the global picture even within sterile neutrino models
- MicroBooNE will explore this: new detector technology which can tell the difference between νes and γs (data-taking to begin this year!)

- Dimensions: 10 m x 2.3 m x 2.5 m
- High Voltage: 125 kV
- Drift field: 500 V/cm

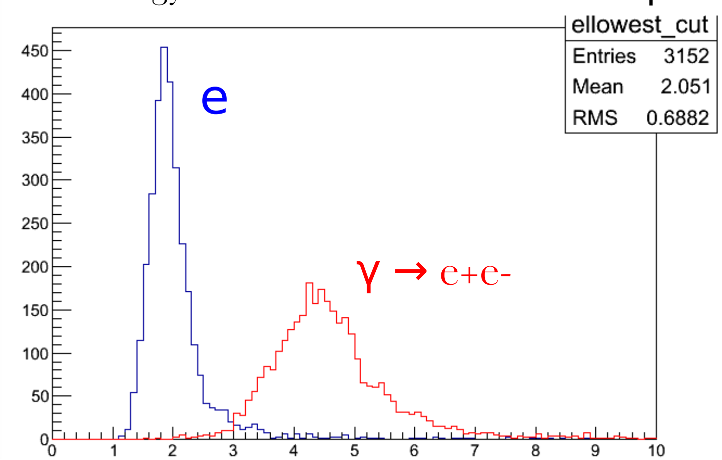


Events in MicroBooNE



Uses dE/dx and event topology to distinguish e's from gammas

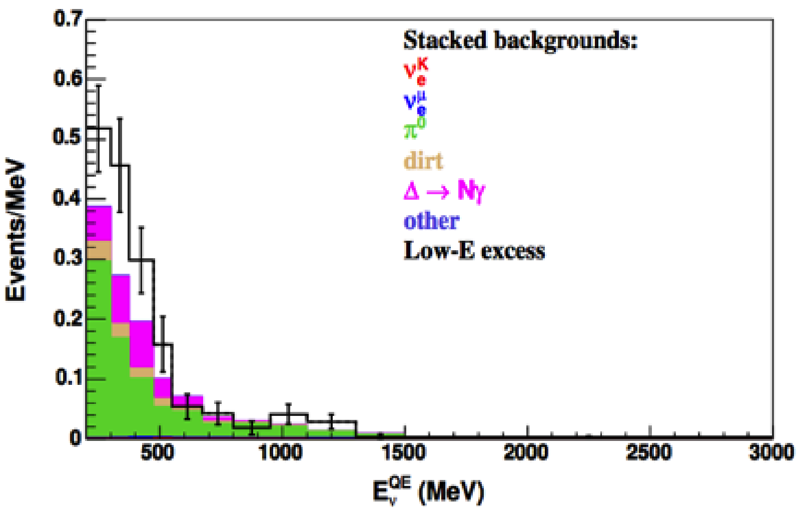
Energy loss for 0.5 –4.5 GeV e's and γ's



dE/dx (MeV/cm2)

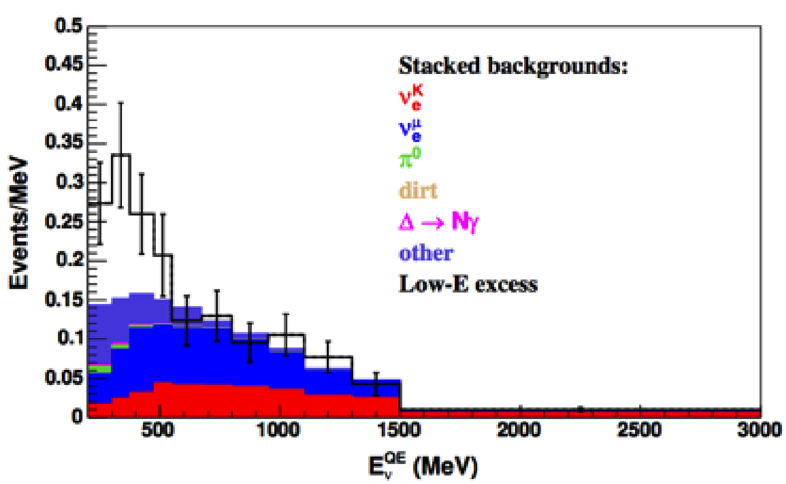
e-γ separation

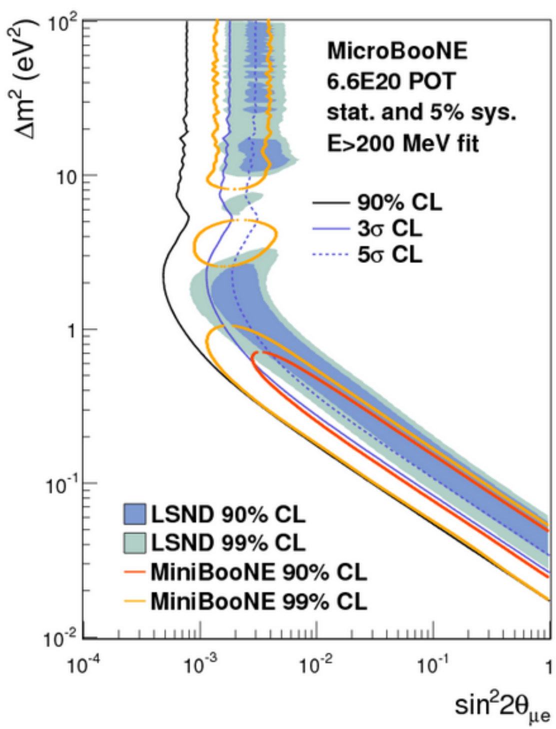
If γ-like signal in μBooNE over γ backgrounds



If some or all of the MiniBooNE low energy excess is due to γ's, MicroBooNE will be able to tell!

If e-like signal in μBooNE over e backgrounds





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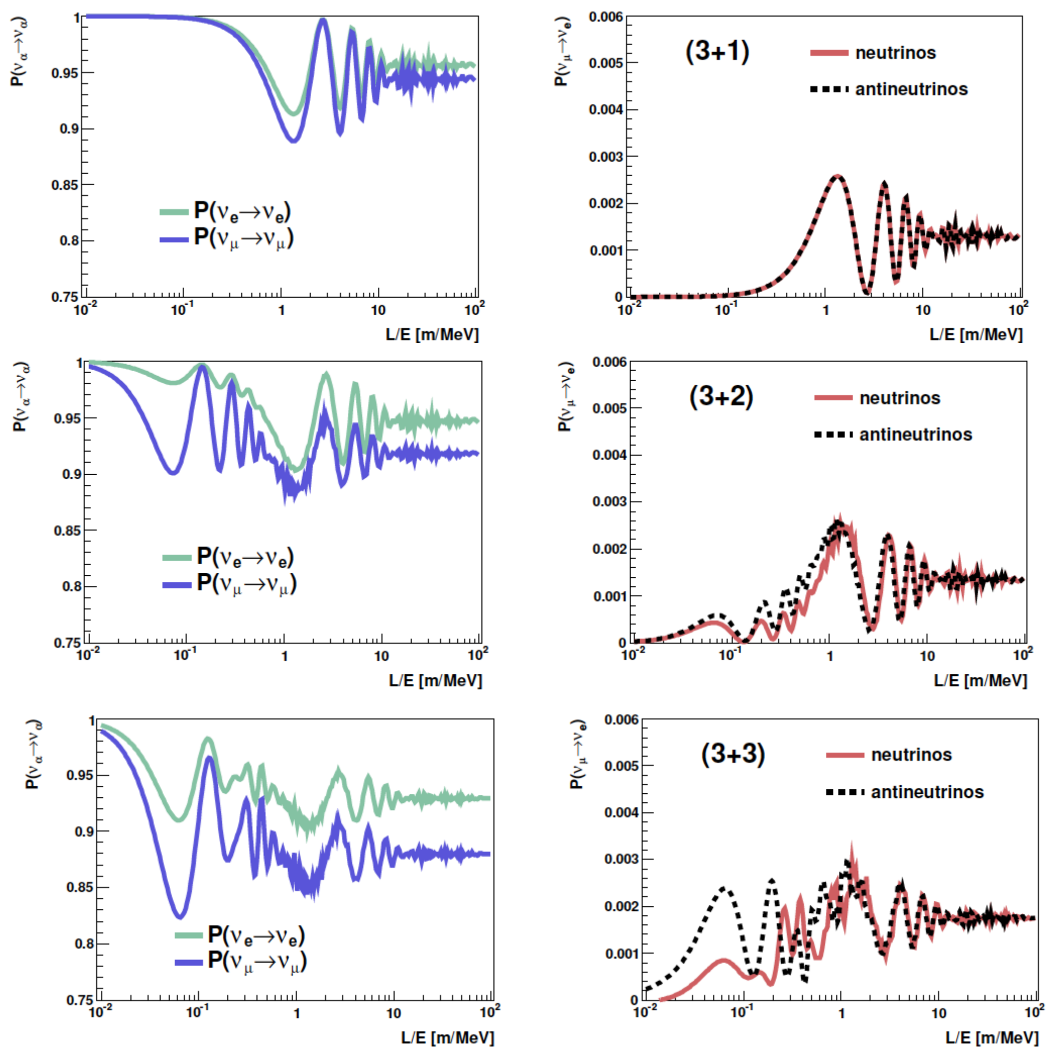
Oscillation Probabilities for Global Best Fit Parameters



Future experiments should aim to have sensitivities in these regions

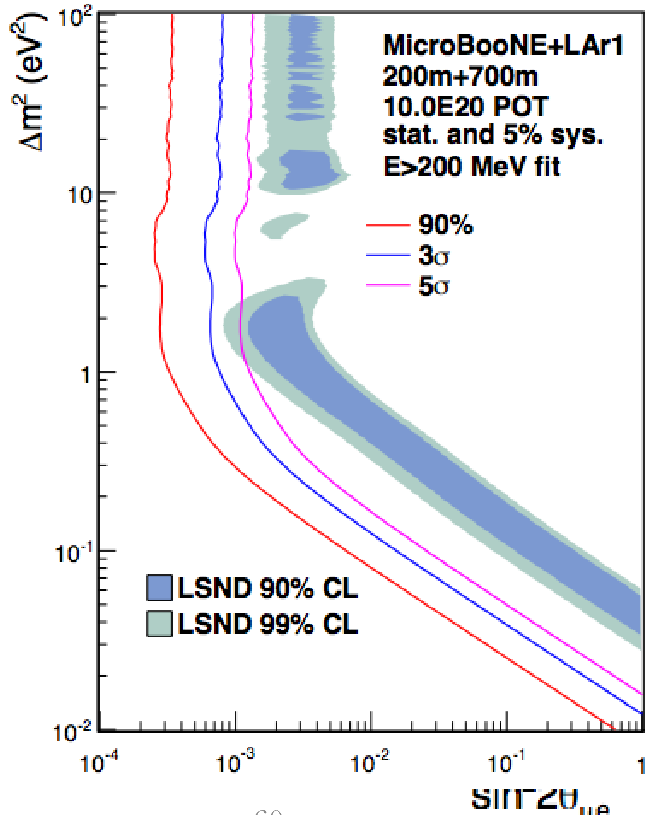
Future Experiments

Future and proposed experiments for sterile neutrino searches

Source	App/Dis	Channel	Experiment
Reactor	Dis	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stereo, SCRAMM, NIST, Neutrino4, DANSS
Radioactive	Dis	$\nu_e \to \nu_e$ $\bar{\nu}_e \to \bar{\nu}_e$	Baksan, LENS, Borexino, SNO+, Ricochet, CeLAND, Daya Bay
Accelerator-based isotope	Dis	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon DAR	App & Dis	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$ $\nu_\mu \to \nu_e$	OscSNS, DAEδALUS, KDAR
Accelerator (Pion DIF)	App & Dis	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-energy ν-Factory	App & Dis	$\nu_e \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$	νSTORM

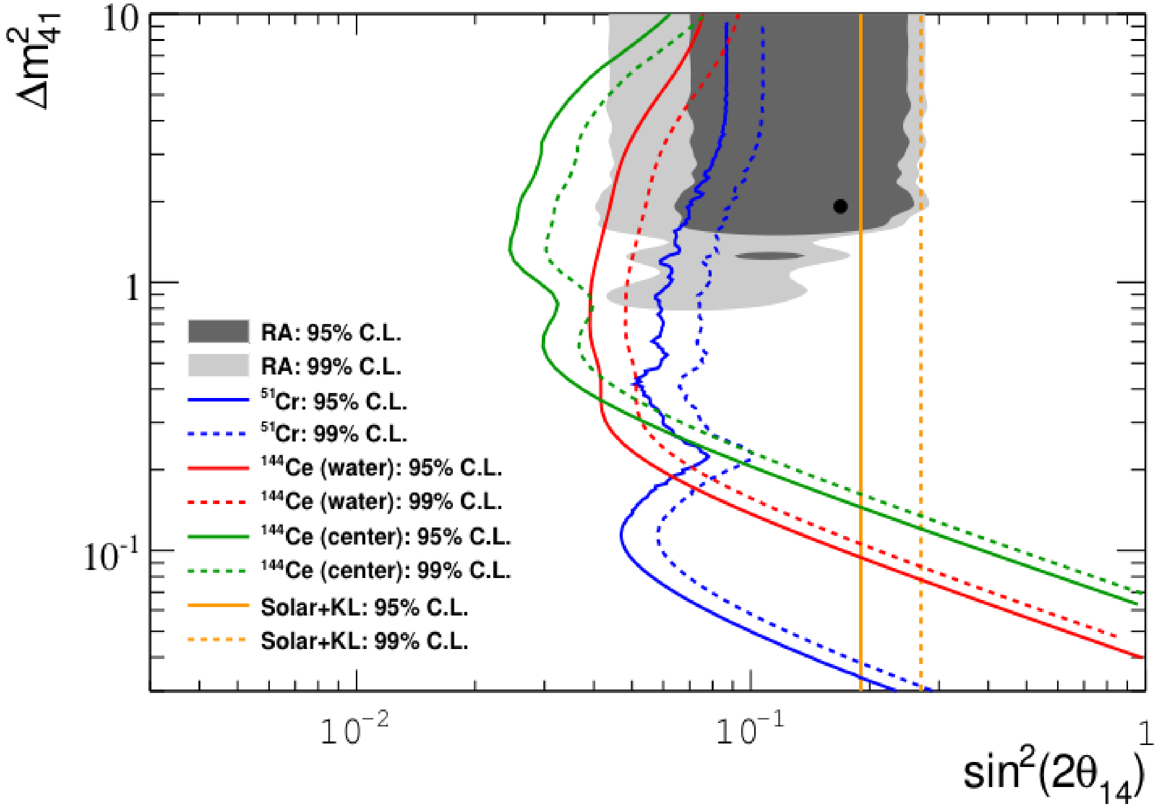
LAr1

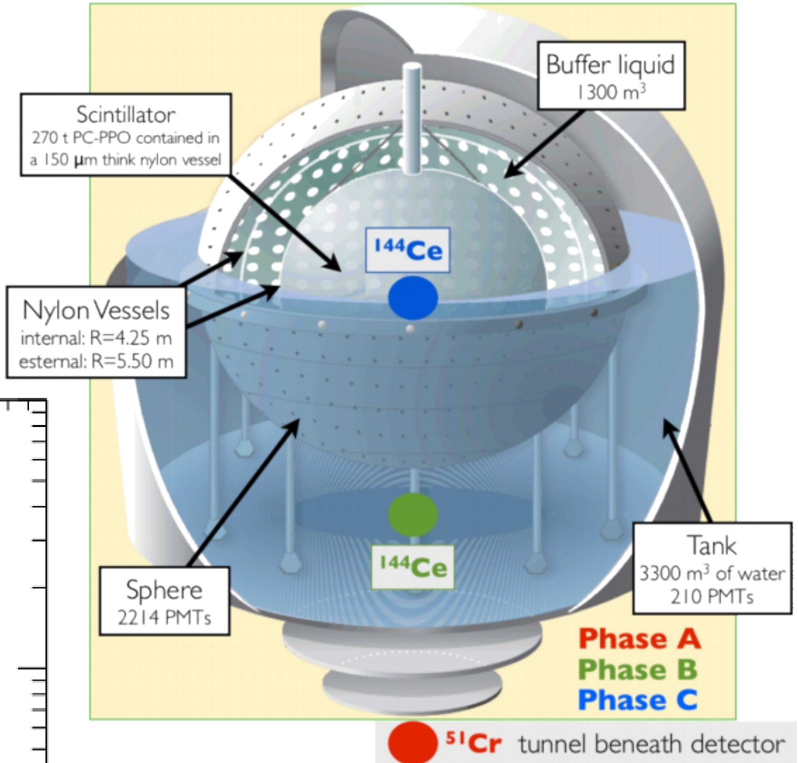
- Far detector to MicroBooNE
- Step in the U.S. Liquid Argon TPC program (leading up to LBNE)



SOX

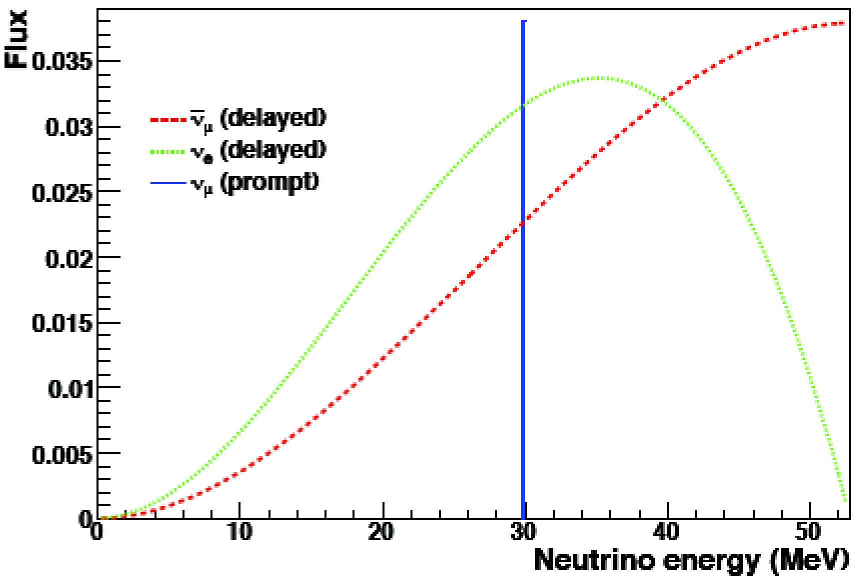
- ^{51}Cr and ^{144}Ce-^{144}Pr sources to be placed in and around the Borexino detector

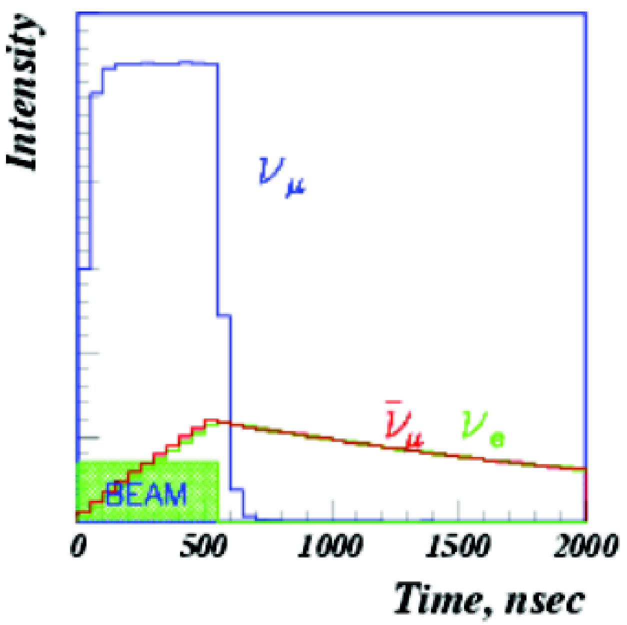




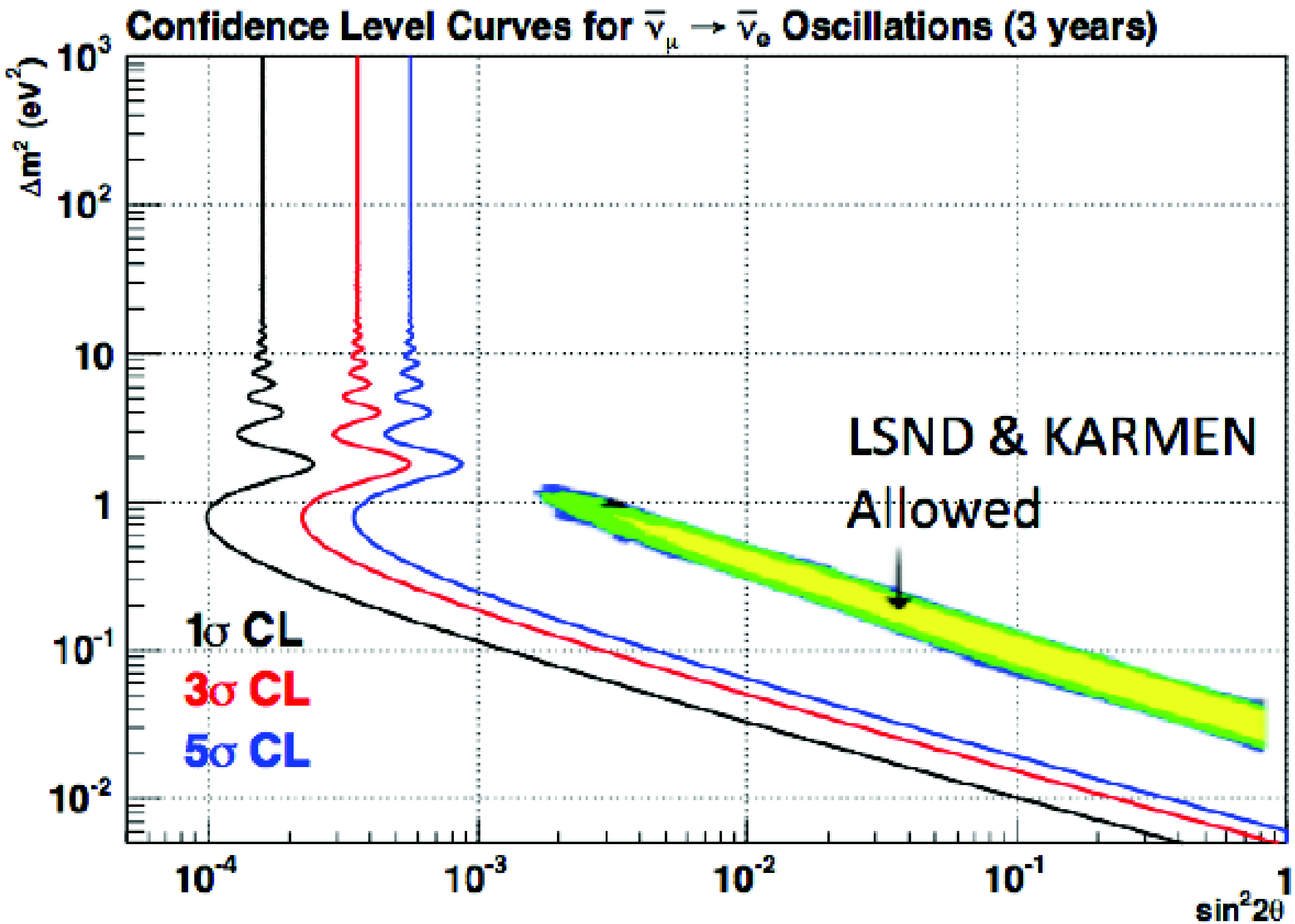
OscSNS

- LSND-style experiment
- Located at the Spallation Neutron Source at Oak Ridge
- Uses the monoenergetic (29.8 MeV) ν_μ s to look for $\nu_\mu \rightarrow \nu_\mu$ in the neutral current channel
  - This is very powerful since the flavored neutrinos have the same NC cross-sections, and are indistinguishable from each other, meaning any observed disappearance is due to sterile neutrinos

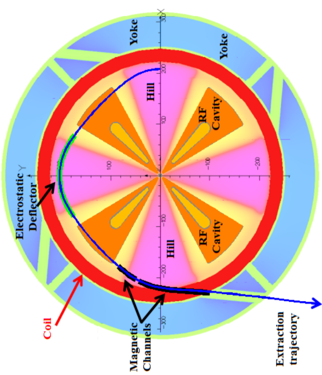




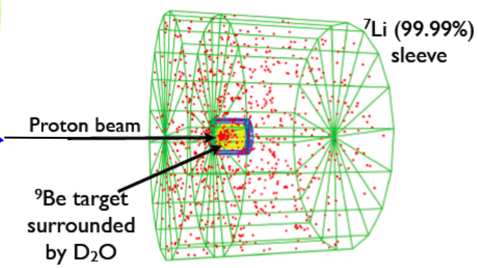
OscSNS


Confidence Level Curves for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations (3 years)
Δm^2 (eV^2)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
LSND & KARMEN
Allowed
1σ CL
3σ CL
5σ CL

IsoDAR

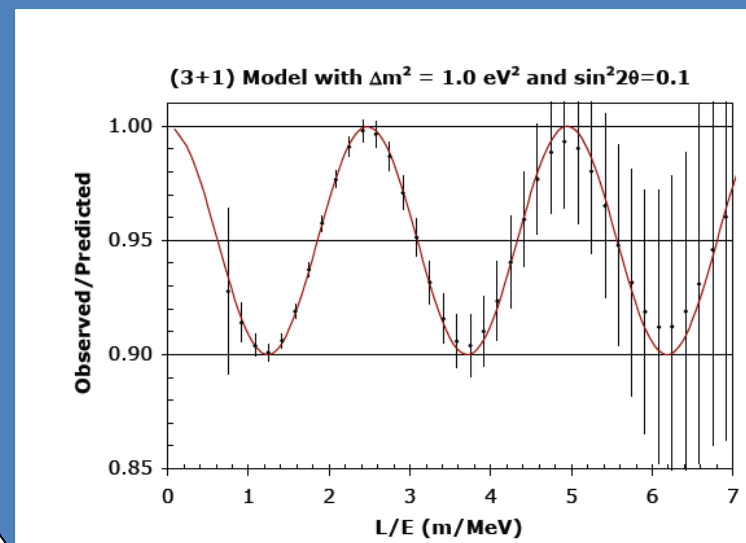


$^{8}Li \rightarrow {}^{8}Be + e^{-} + \overline{\nu}_e$



Low energy, high-powered cyclotron

1 kton LS detector

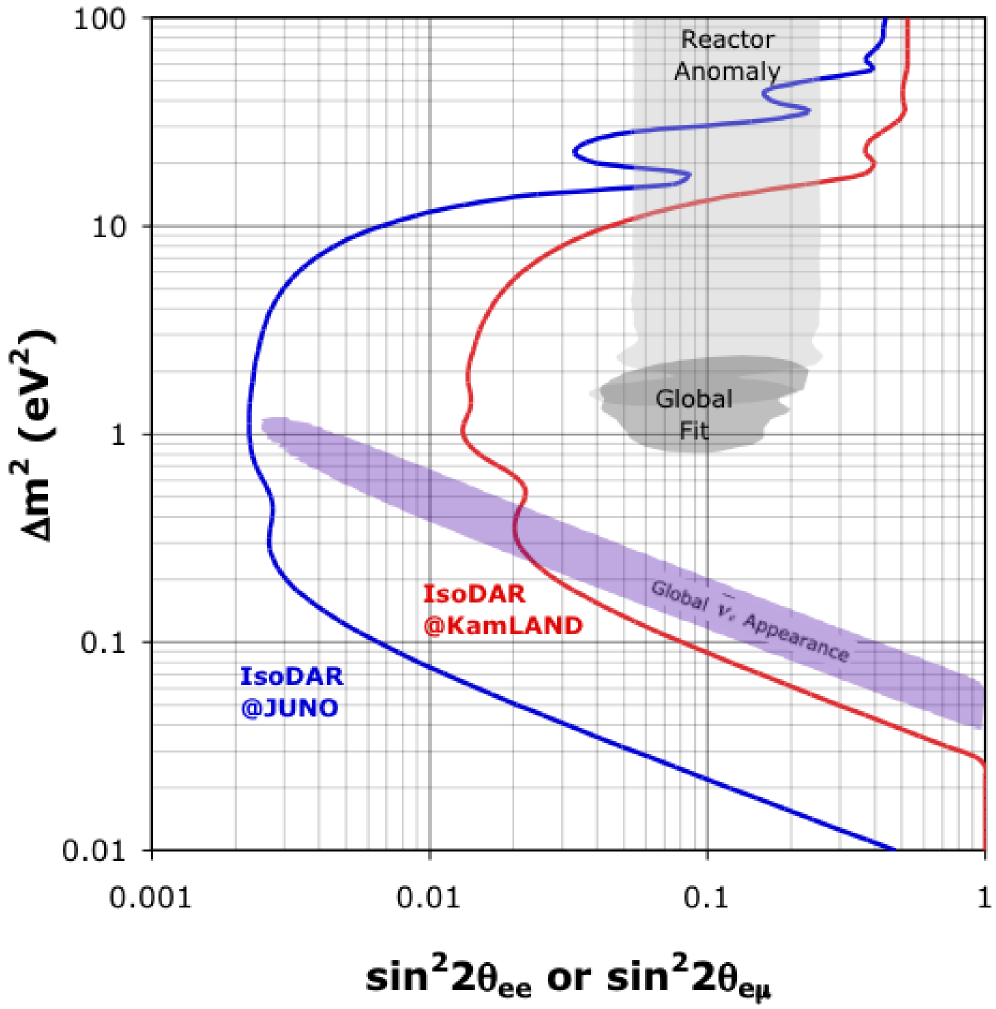


Not to scale

16.5 m

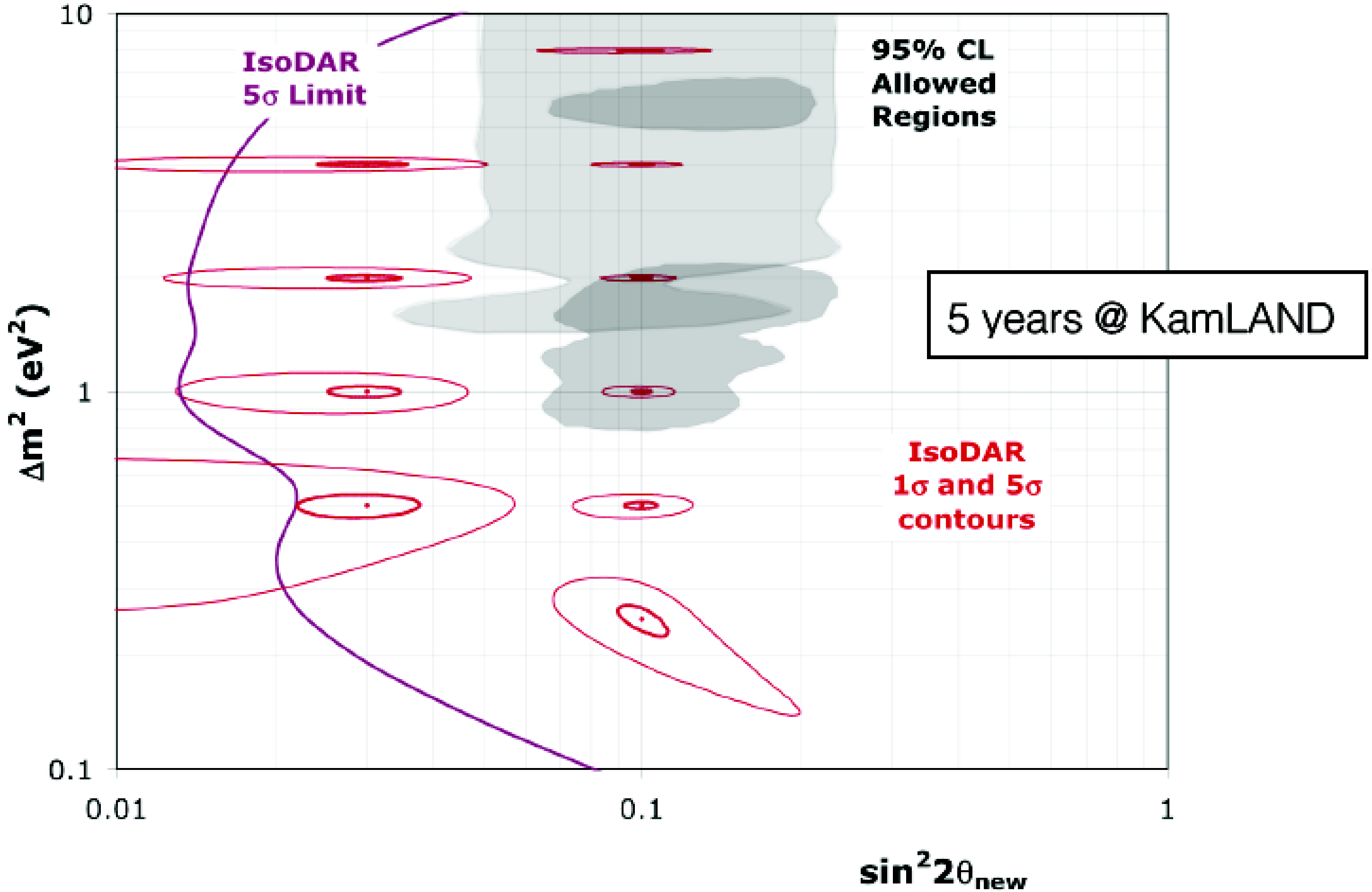
arXiv:1205.4419

IsoDAR



100
10
1
0.1
0.01
0.001
0.01
0.1
1
Δm² (eV²)
sin²2θ_ee or sin²2θ_eμ
Reactor
Anomaly
Global
Fit
Global ν_e Appearance
IsoDAR
@KamLAND
IsoDAR
@JUNO

IsoDAR

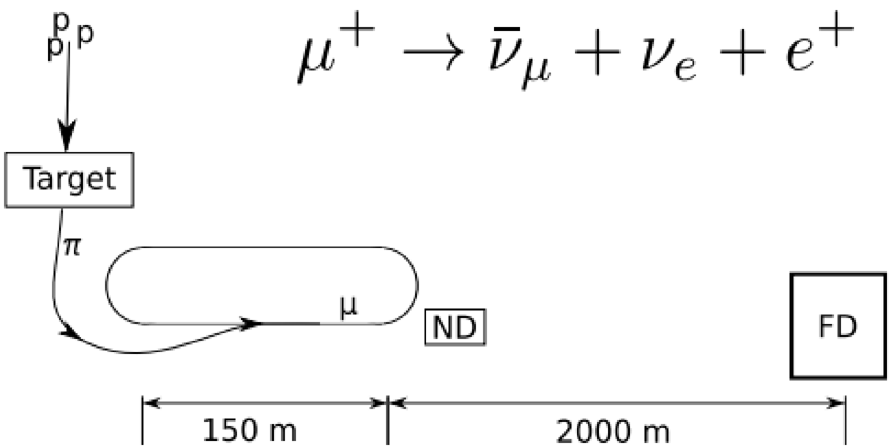


IsoDAR
5σ Limit
95% CL
Allowed
Regions
5 years @ KamLAND
IsoDAR
1σ and 5σ
contours
10
1
0.1
0.01
0.1
1
Δm² (eV²)
sin²2θnew

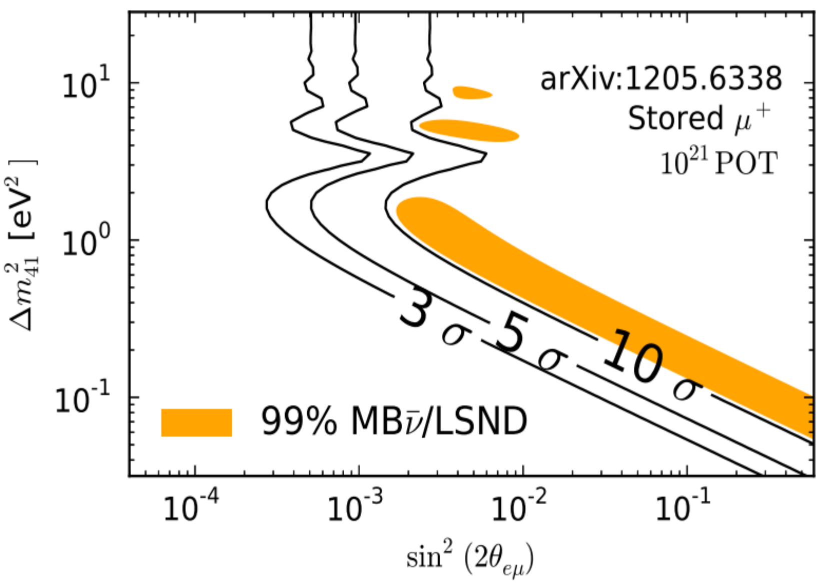
νStorm

Look for $\nu_e \to \nu_\mu$ oscillations at neutrino factory

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



statistics-only χ2 using spectral information



arXiv:1206.0294

Conclusions

- There are anomalies in short baseline experiments that need to be addressed
- 3+1 fits are not a good description of world data, but they are better than fits with no sterile neutrinos
- 3+2 helps -- cp violation helps resolve tension between neutrino and antineutrino data
- 3+3 is not a significant improvement over 3+2
- Still tension between appearance and disappearance experiments
- Does not explain MiniBooNE low energy excess
- Need future experiments to shed light on this!

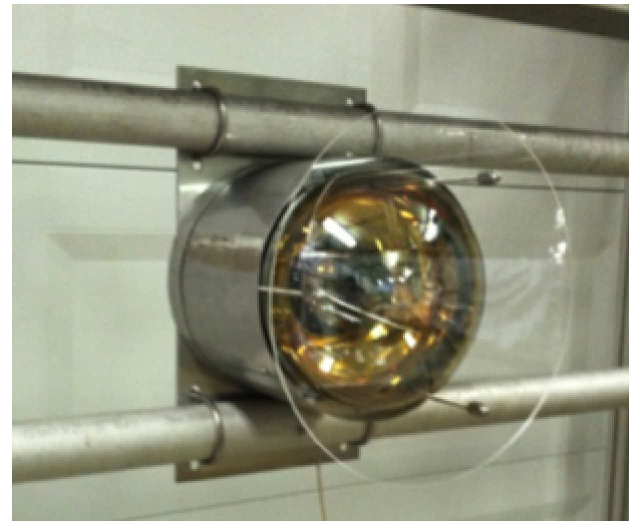
Thank You!

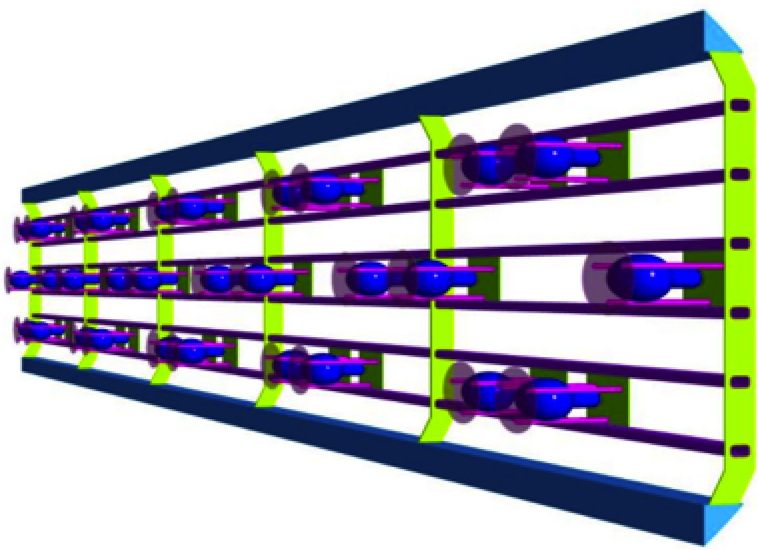
Backup

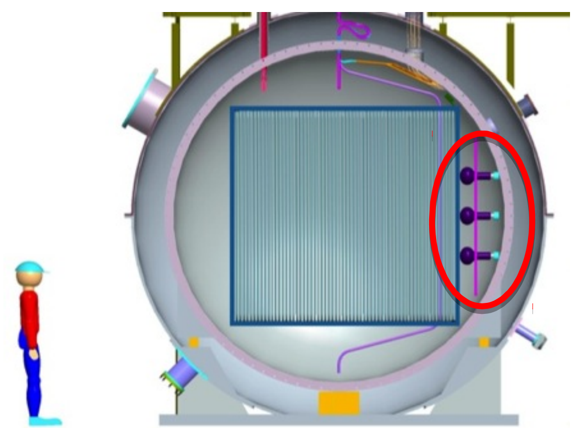
MicroBooNE light collection system

arXiv:1304.0821

- 30 PMTs behind wavelength shifting plates on the side of the cryostat.
- Primarily used for triggering, background rejection, and correcting for charge losses and diffusion as a function of drift distance



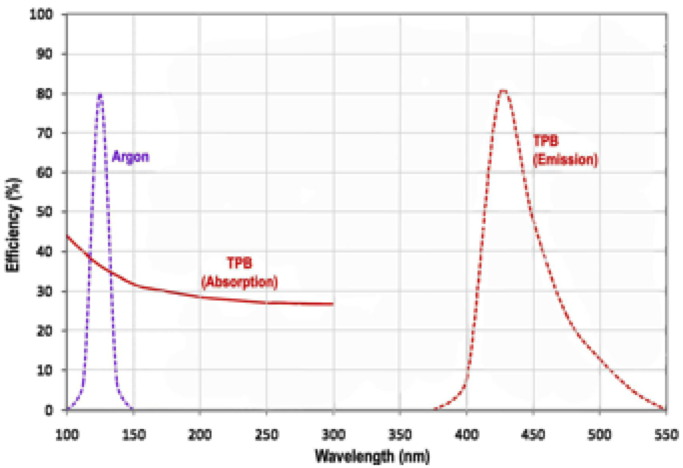




Wavelength shifting for light detection

Light produced at 128 nm (invisible to PMTs)

- We use a wavelength shifting material called Tetraphenyl Butadiene (TPB) to coat plates which will go in front of the PMTs
- We use a mixture of 50% TPB and 50% polystyrene (PS) for our plate coating
- We find that mixing the TPB in PS makes the plates more durable and is much more cost effective than an evaporative coating



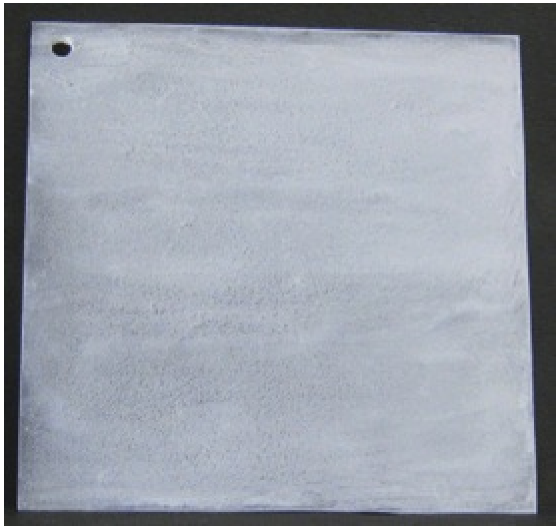
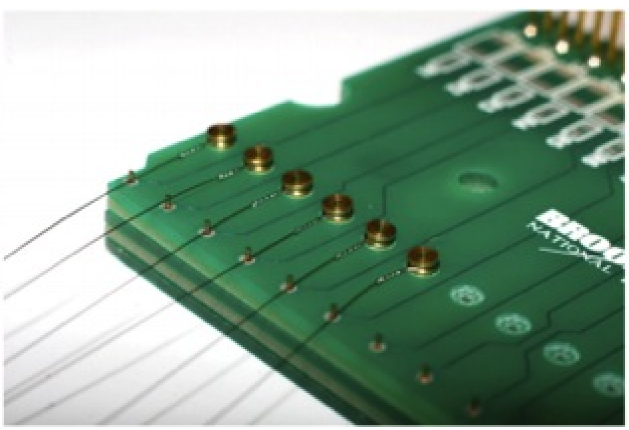


Plate sample with a 50% TPB-PS coating

Wire planes

- 3 mm spacing
- Stainless steel coated with copper and gold
- Y: vertical plane (2.5 meter long wires), U,V planes: +/- 60 degrees from vertical (5 meters long)

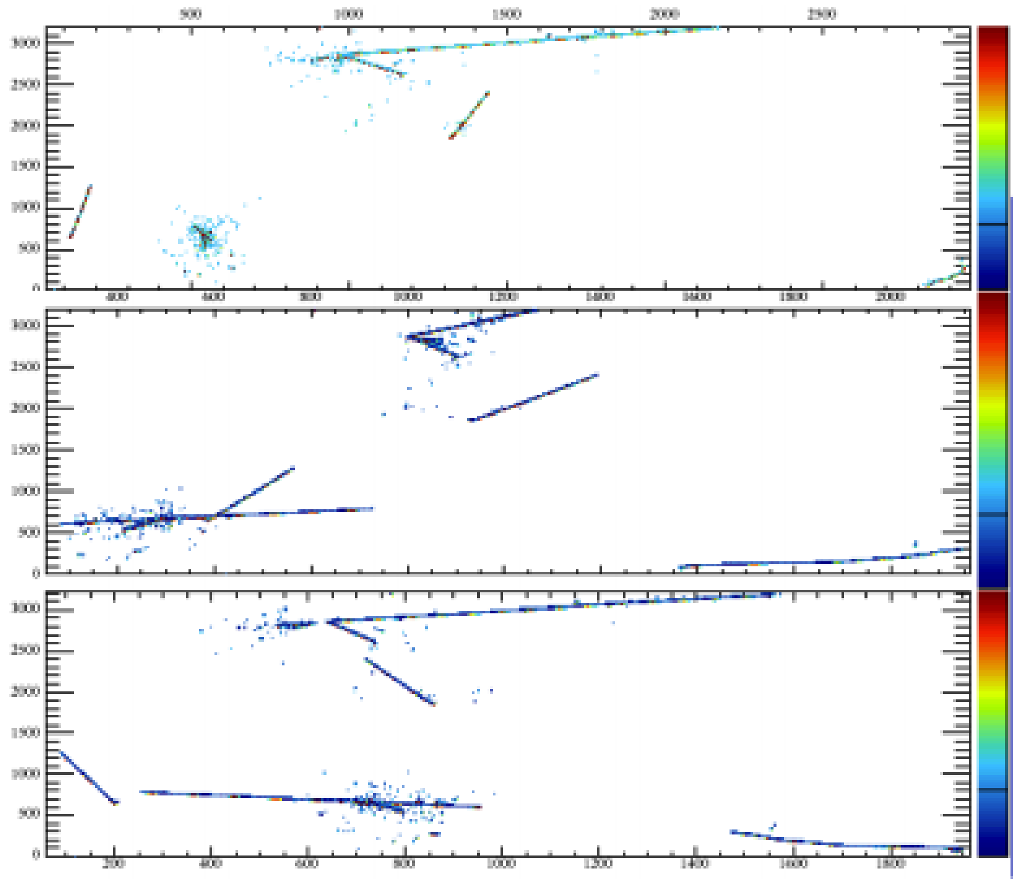


More MicroBooNE Physics Goals

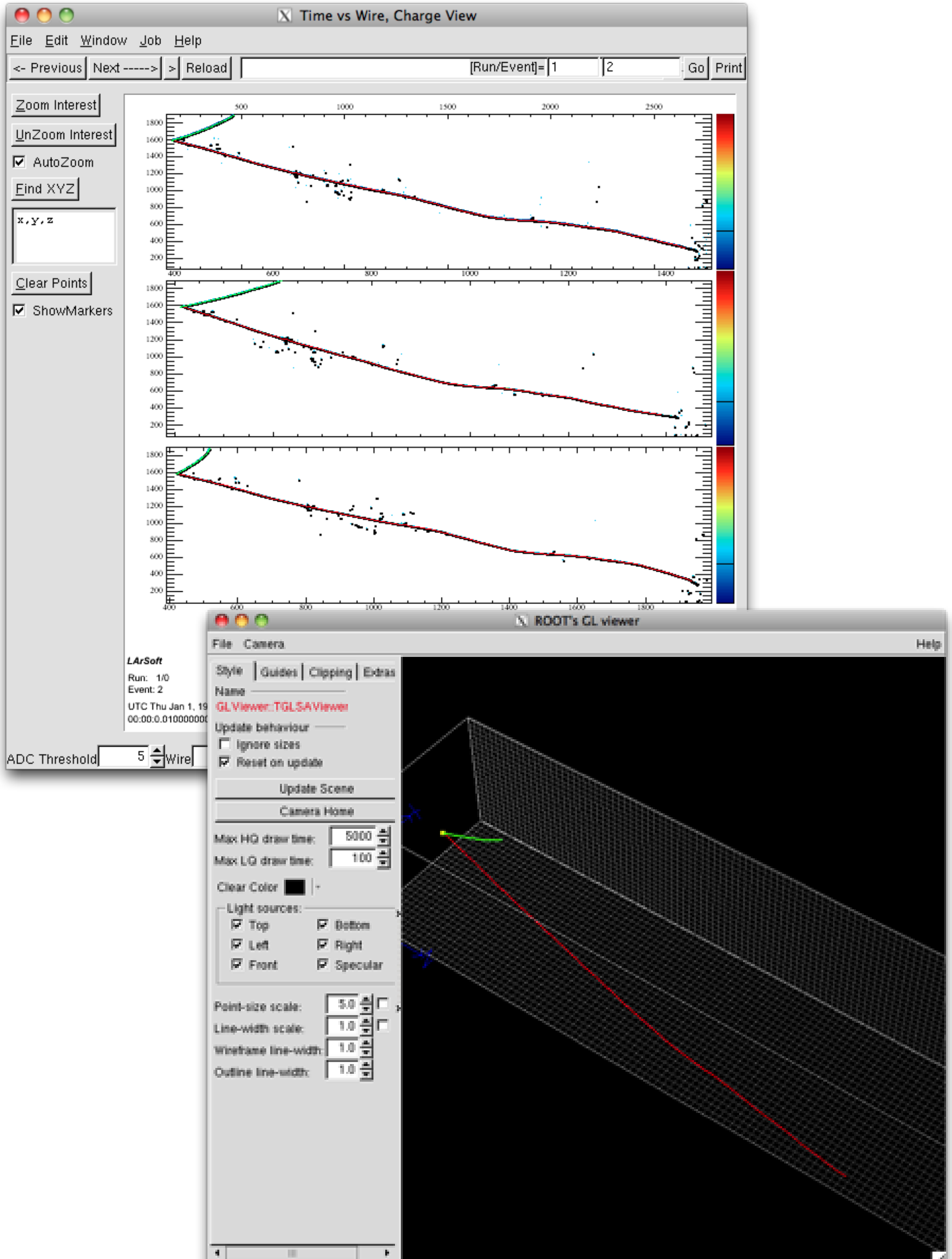
- Low energy cross section measurements
  - Coherent vs. resonant pion production, K production, ν_e cross sections
- Burst supernova detection capability
  - Data buffer, trigger from SNEWS
  - Would have gotten about 29 events for SN1987a
- Prepare for future proton decay searches ($p^+ \rightarrow K^+ \nu$) possible with larger LArTPCs.
  - Prepare PID, triggers, study backgrounds
- Sensitive to ΔS (fraction of proton spin carried by strange quark)
  - Information on final states for modeling events in LAr, input for spin-dependent WIMP searches,

MicroBooNE Software: LArSoft

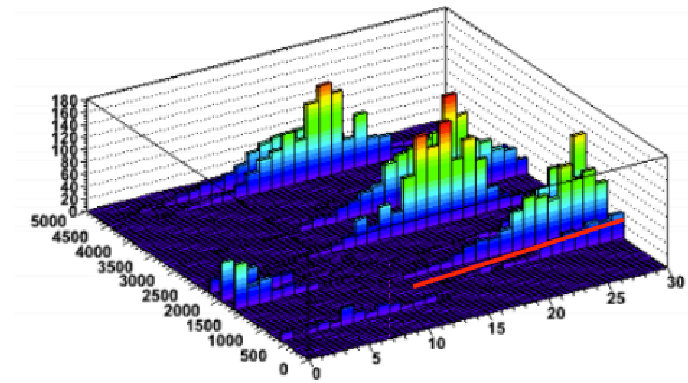
- Simulation, analysis and reconstruction in MicroBooNE are performed in the LArSoft framework
- LArSoft supports all US LArTPC efforts : MicroBooNE will both build on the work of ArgoNeuT and contribute to software for LBNE.
- LArSoft simulations interface with specialized neutrino and cosmic ray event generators and implement a full Geant4 particle simulation
- Electron drift and photon propagation are treated and realistic digitized detector signals are simulated
- Liquid argon TPC reconstruction effort is ongoing, and great progress is being made

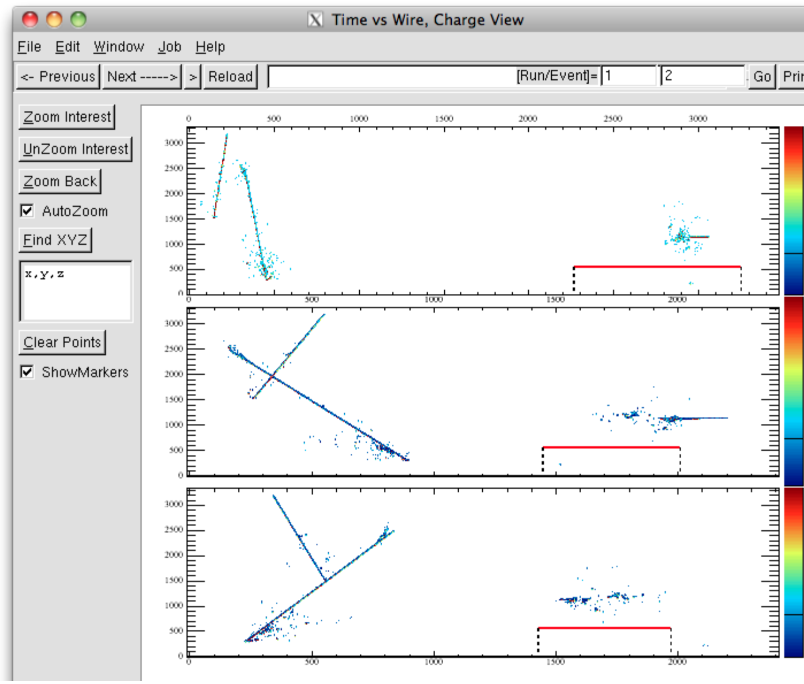


A simulated neutrino event with expected cosmic ray background overlaid



A 3D reconstructed CCQE event in LArSoft



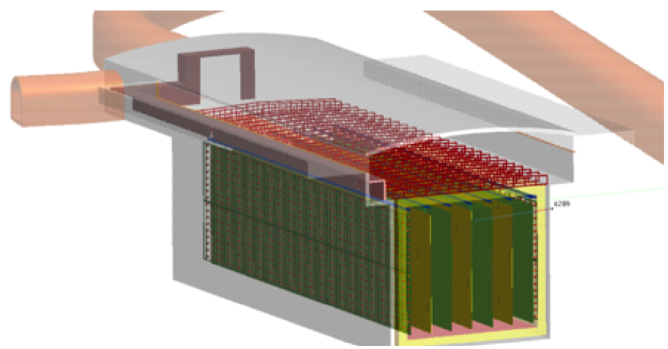


PMT system timing information used to highlight beam event

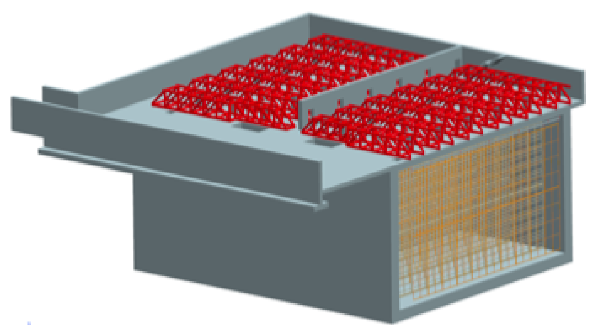
MicroBooNE is also important R&D for the development of future LArTPCs

- Demonstrate scalability of technology
- Cold electronics
- Purity
- Analysis tools

Example future LAr detectors:



- LAr1: 1 kton:
  2 detector sterile neutrino search



- LBNE: 10 kton (or 35 kton)
  CP violation