Hunting for Sterile Neutrinos I

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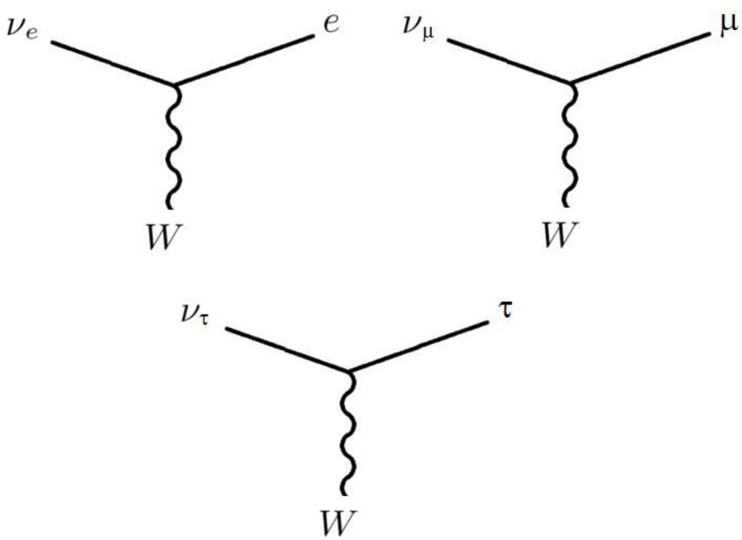
Sterile Neutrinos

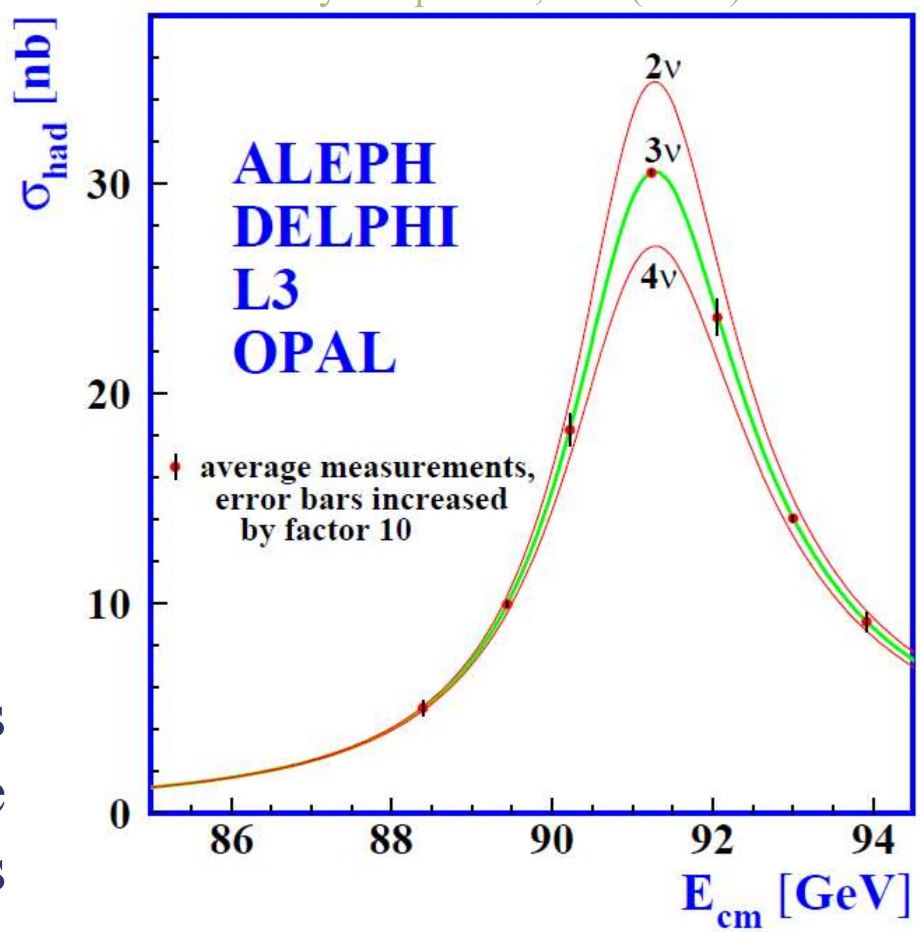
A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

Active neutrinos:



LEP Invisible Z^0 Width is consistent with only three light active neutrinos

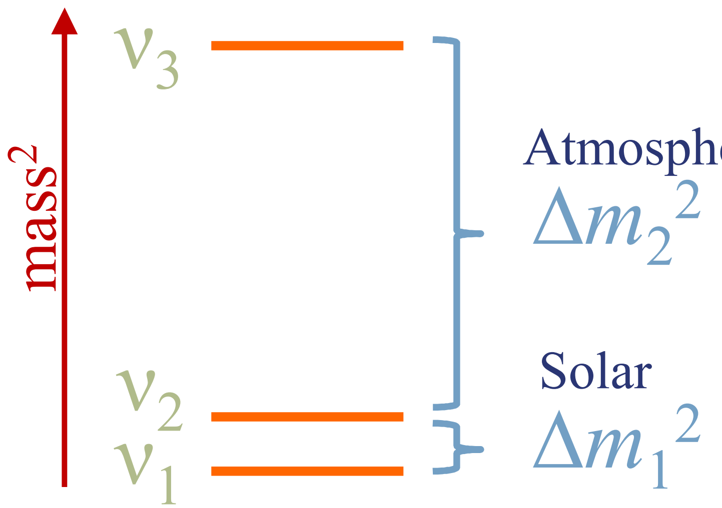
Phys.Rept. 427, 257 (2006)



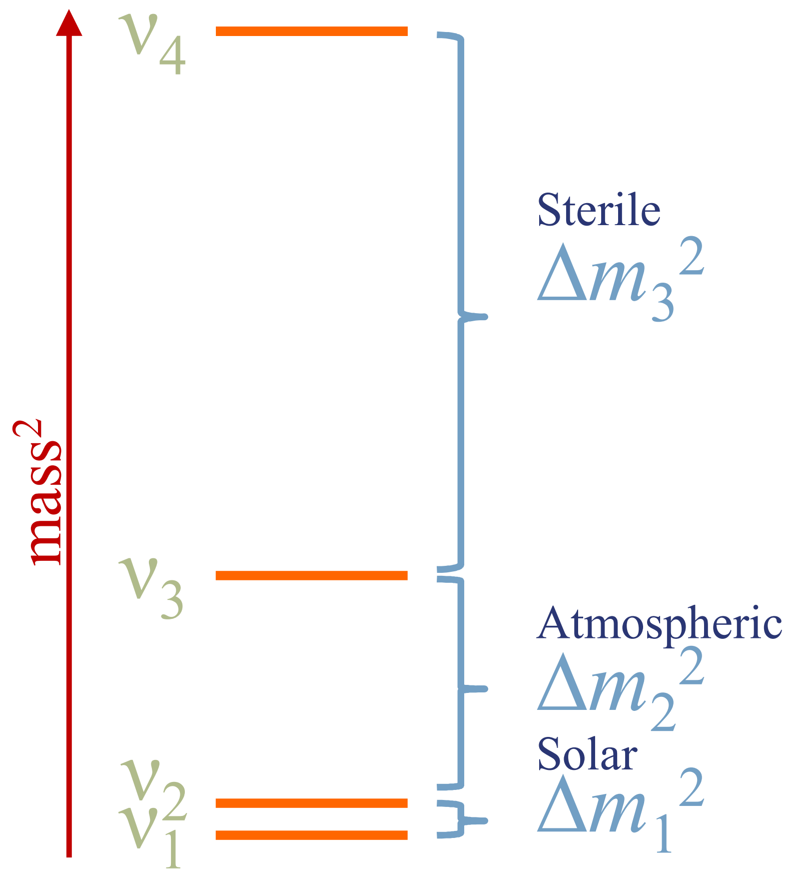
Sterile Neutrinos

A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

Three neutrinos allow only 2 independent Δm^2 scales.



If there is a third Δm^2 scale there must be a fourth neutrino.



What's the Evidence for a 4th Δm^2 Scale?

1. $\bar{\nu}_e$ appearance in a π decay-at-rest beam (LSND)

2. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance in a decay-in-flight beam (MiniBooNE)

3. Gallium Anomaly: ν_e disappearance (Gallex and SAGE)

4. Reactor Anomaly: $\bar{\nu}_e$ disappearance

5. ν_e disappearance (T2K)

What's the Evidence ~~for~~ Against a 4th Δm^2 Scale?

1. $\bar{\nu}_e$ appearance in a π decay-at-rest beam (LSND)

1b. $\bar{\nu}_e$ appearance in a π decay-at-rest beam (KARMEN)

2. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance in a decay-in-flight beam (MiniBooNE)

2b. $\nu_\mu \rightarrow \nu_e$ appearance in a DIF beam (MiniBooNE, ICARUS)

3. Gallium Anomaly: ν_e disappearance (Gallex and SAGE)

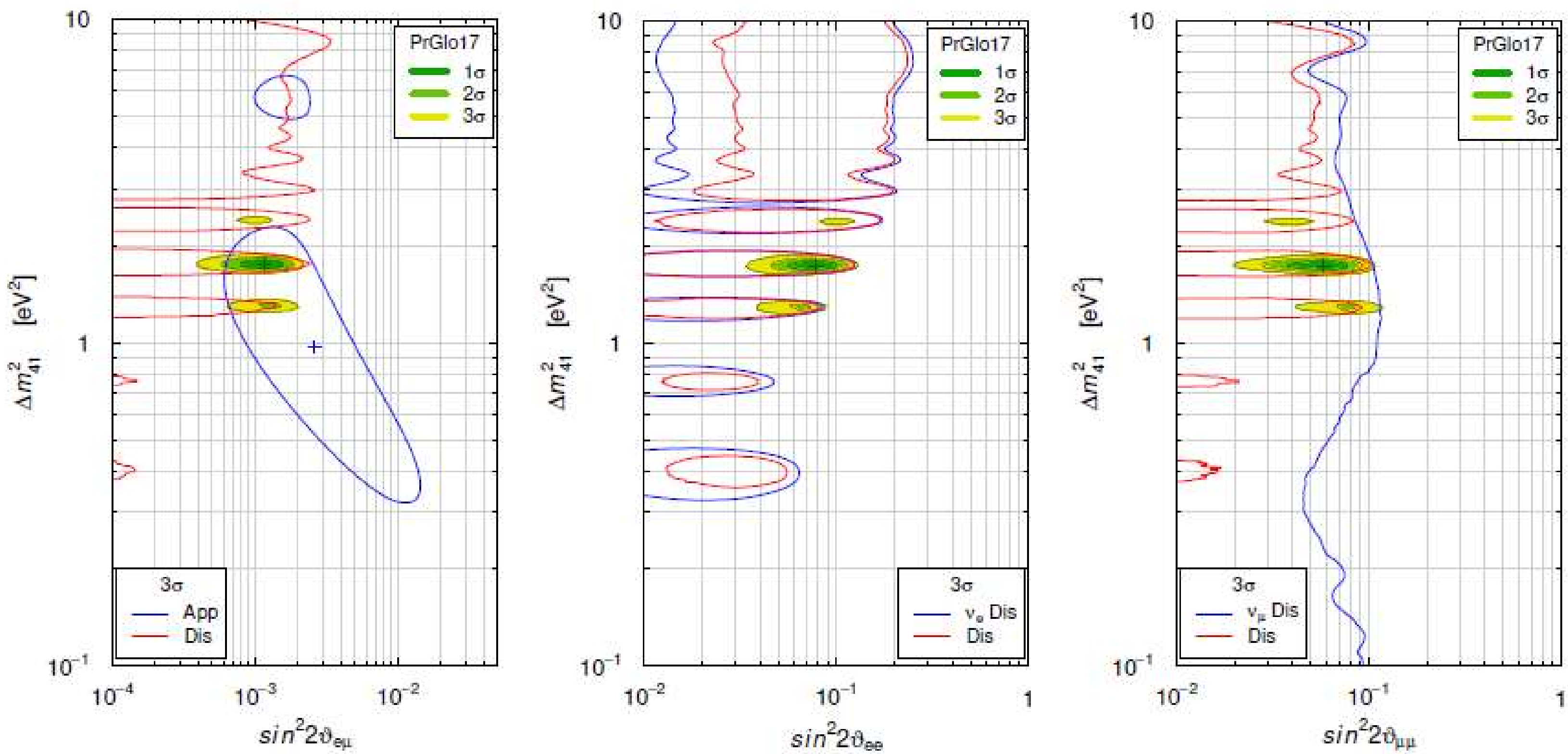
4. Reactor Anomaly: $\bar{\nu}_e$ disappearance

5. ν_e disappearance (T2K)

6. ν_μ disappearance (MiniBooNE/SciBooNE, Minos)

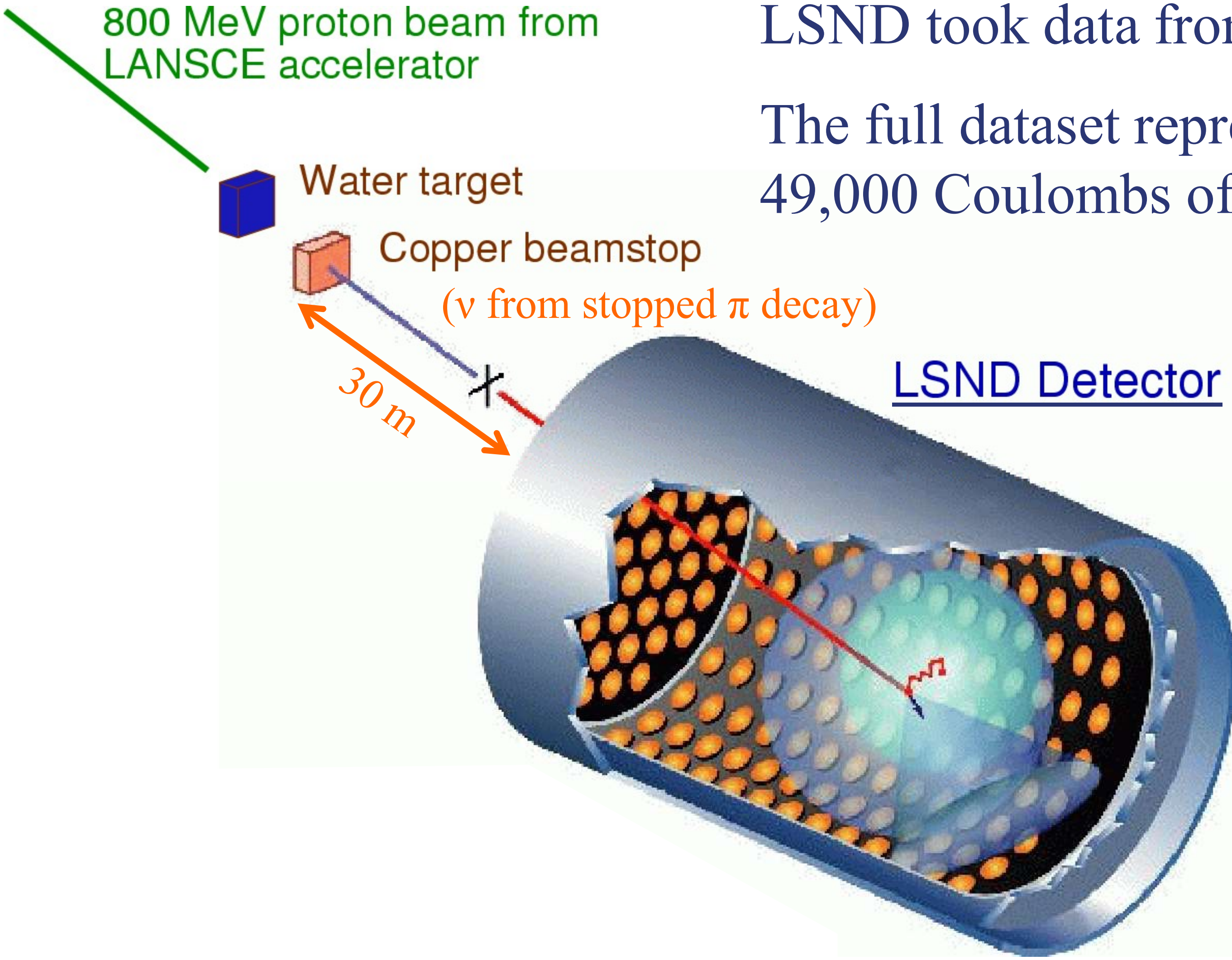
What's the Evidence for a 4th Δm^2 Scale?

There is no single experiment providing definitive evidence for the sterile neutrino, neither is their one providing evidence strong enough to rule it out. Even the best global fits fall short:



Giunti *et al.*, JHEP 06, 135 (2017)

The LSND Experiment



LSND took data from 1993-98

The full dataset represents nearly 49,000 Coulombs of protons on target.

Baseline: 30 m

Energy range:
20 to 55 MeV

Stopped Pion Beam

A stopped pion beam is a great source of neutrinos with a well defined energy spectrum and flavor profile.

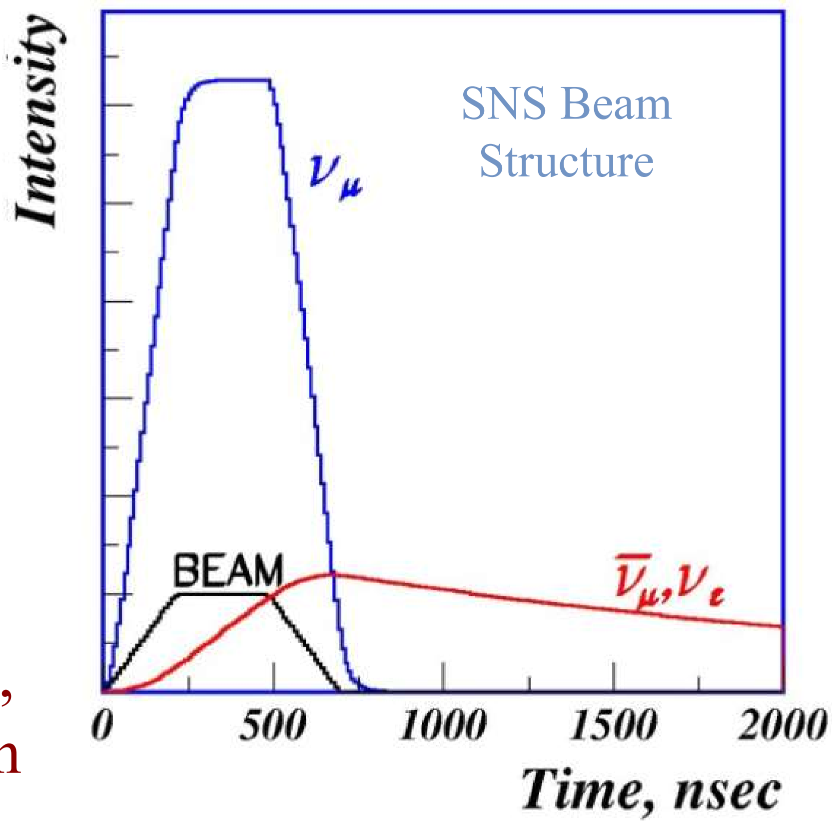
The pions are produced when an intense proton beams hits a target.

The pions come to rest, π^- are absorbed on a nucleus, while π^+ decay:

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

Golden Mode

The ν_μ come promptly with the beam, while the $\bar{\nu}_\mu$ and ν_e have a 2.2μs mean delay from muon decay.



The LSND Experiment

LSND took data from 1993-98

The full dataset represents nearly 49,000 Coulombs of protons on target.

LSND was a scintillating detector with a little bit of Cerenkov light.

LSND's Signature

Baseline: 30 m

Energy range: 20 to 55 MeV

L/E ~ 1 m/MeV

Inverse Beta Decay

Inverse beta decay (IBD) is a golden mode for $\bar{\nu}_e$ detection:

$\bar{\nu}_e$

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

followed by neutron capture which tags the IBD event.

p n e^+

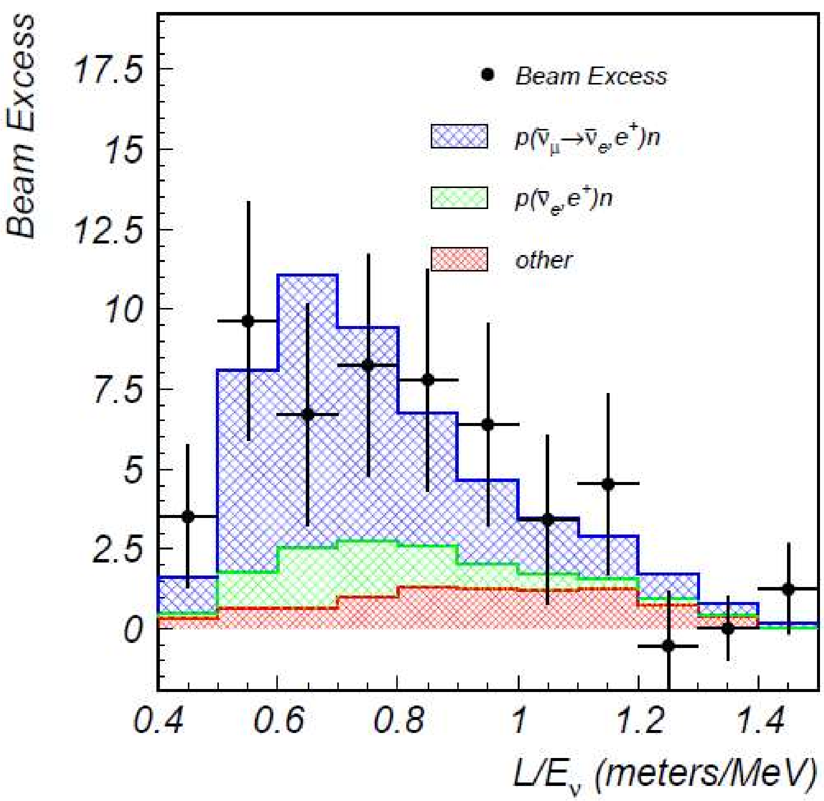
^1H ^2H

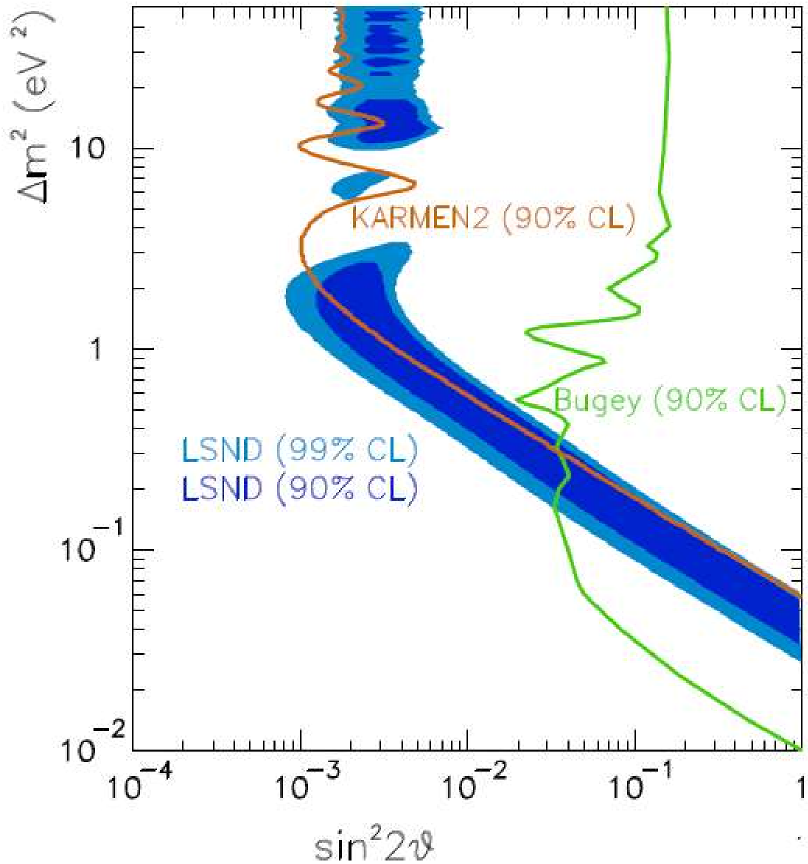
Capture Isotope	Products
^1H (p)	γ (2.2 MeV)
Gd	γs (8 MeV)
^6Li	$^4He + {}^3H$ (4.78 MeV)

LSND used hydrogen capture to tag their IBD events.

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

Aguilar-Arevalo *et al.*, Phys.Rev. D64, 112007 (2001)

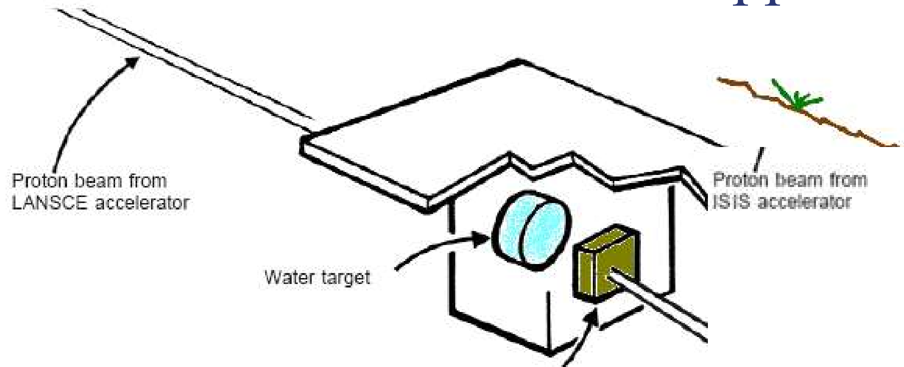




Event Excess: $32.2 \pm 9.4 \pm 2.3$

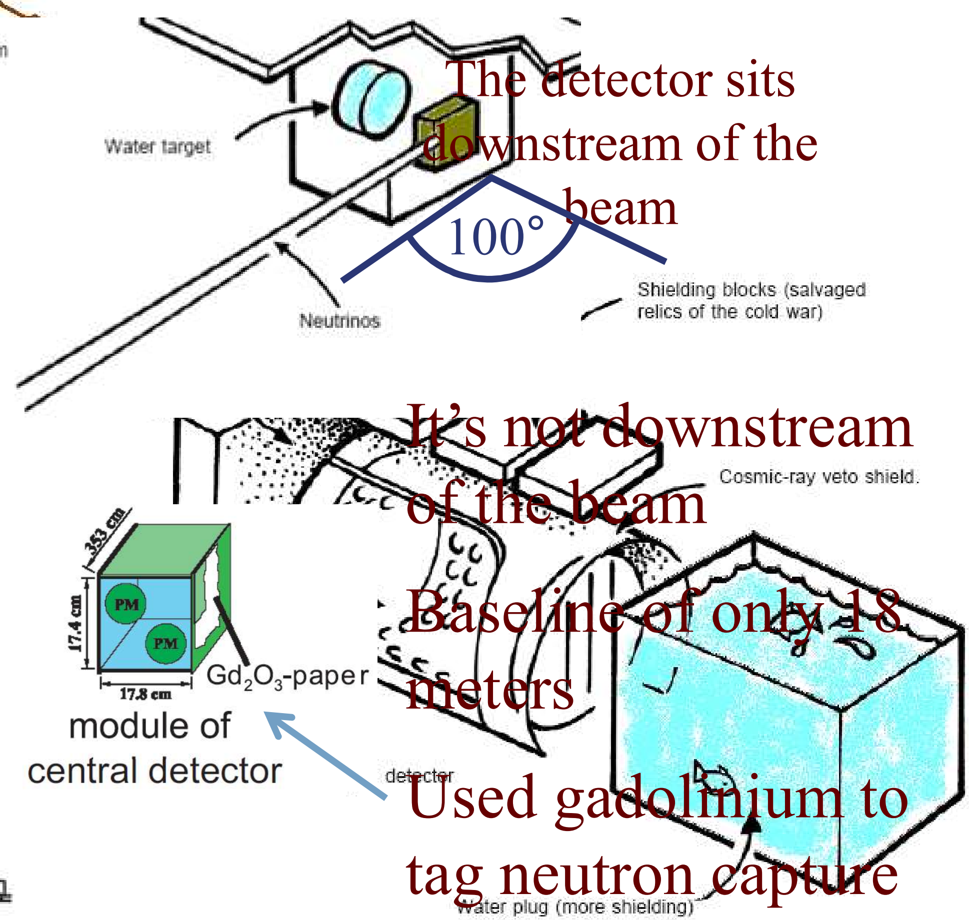
The KARMEN Experiment

KARMEN was a stopped π^+ beam experiment like LSND

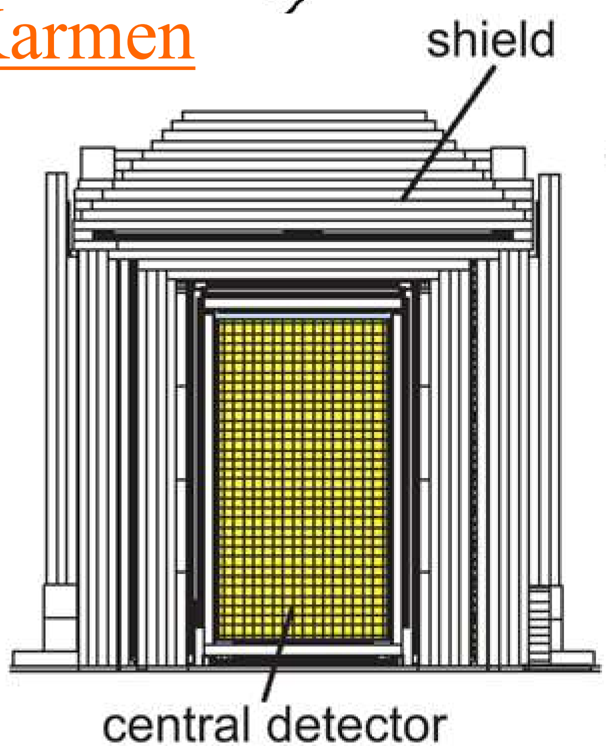


LSND

The detector sits downstream of the beam



Karmen



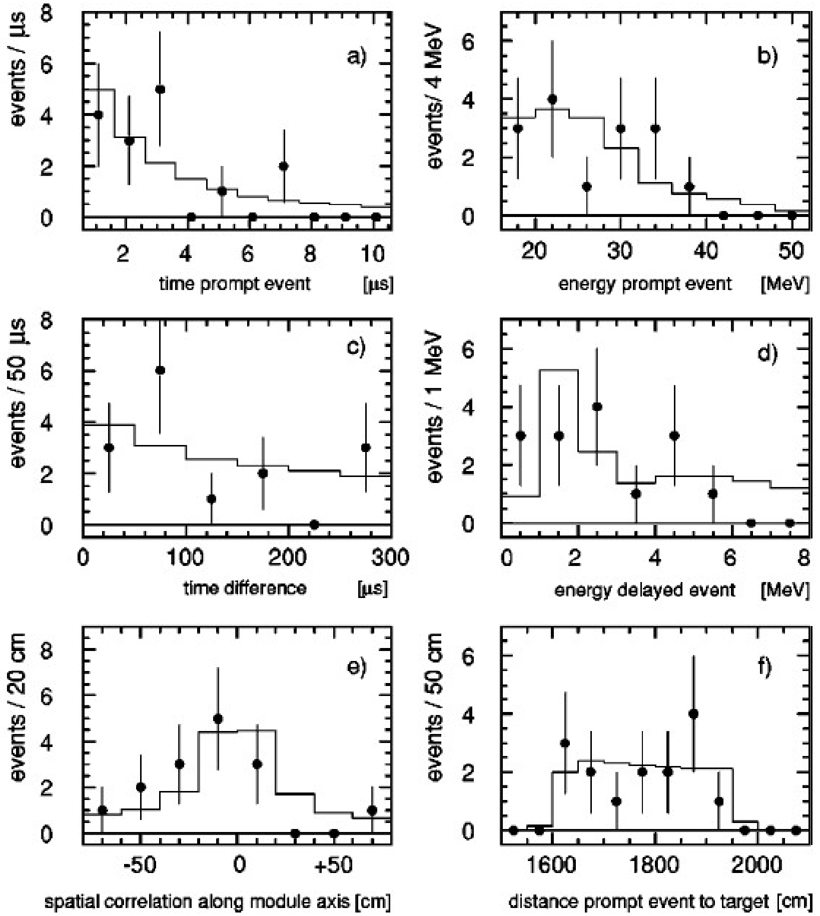
It's not downstream of the beam

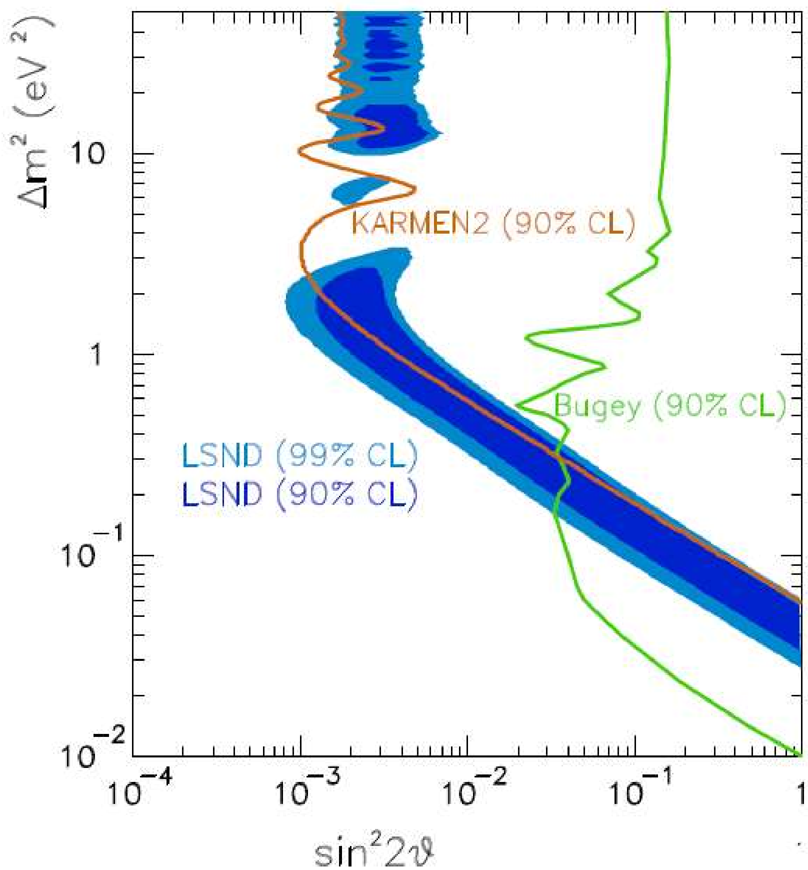
Baseline of only 18 meters

Used gadolinium to tag neutron capture

KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Search

Armbruster *et al.*, Phys.Rev.D65 112001 (2002)





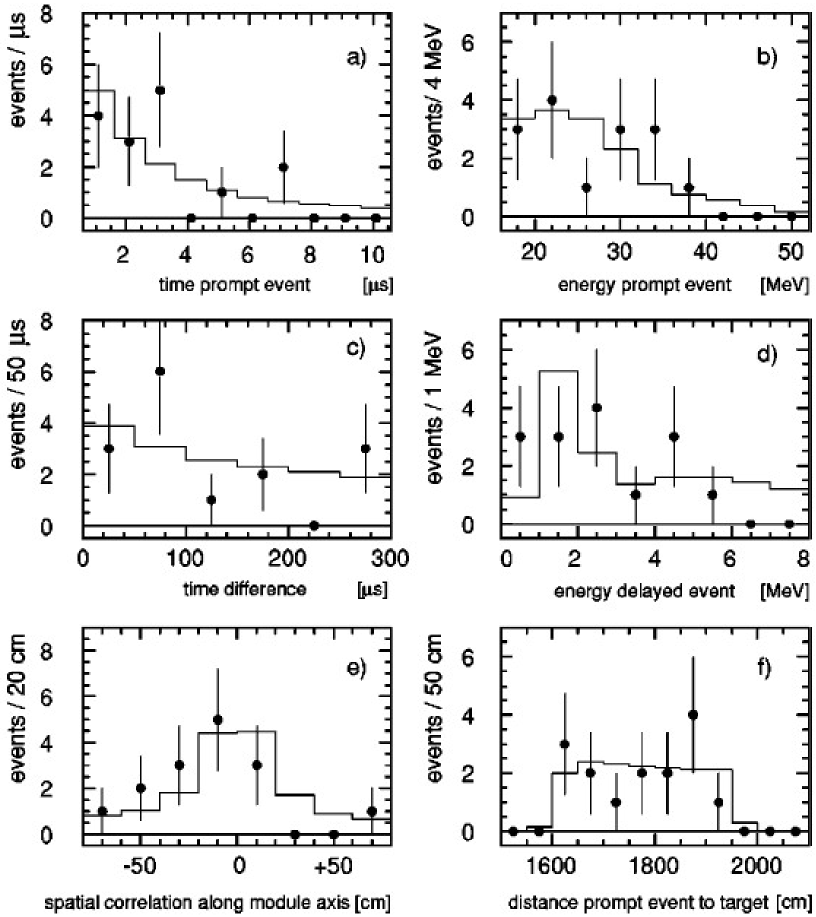
15 $\bar{\nu}_e$ candidate events which are in agreement with the background expectation

Energy range: 20 to 55 MeV

L/E ~ 1/2 m/MeV

KARMEN $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Search

Armbruster *et al.*, Phys.Rev.D65 112001 (2002)



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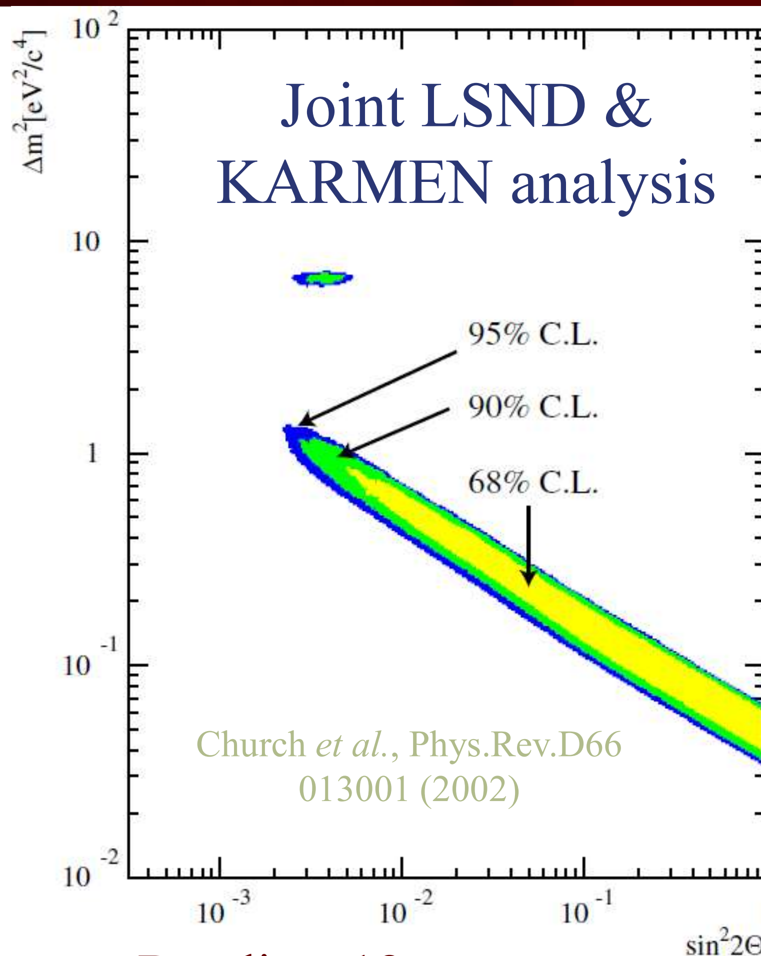


Baseline: 18 m

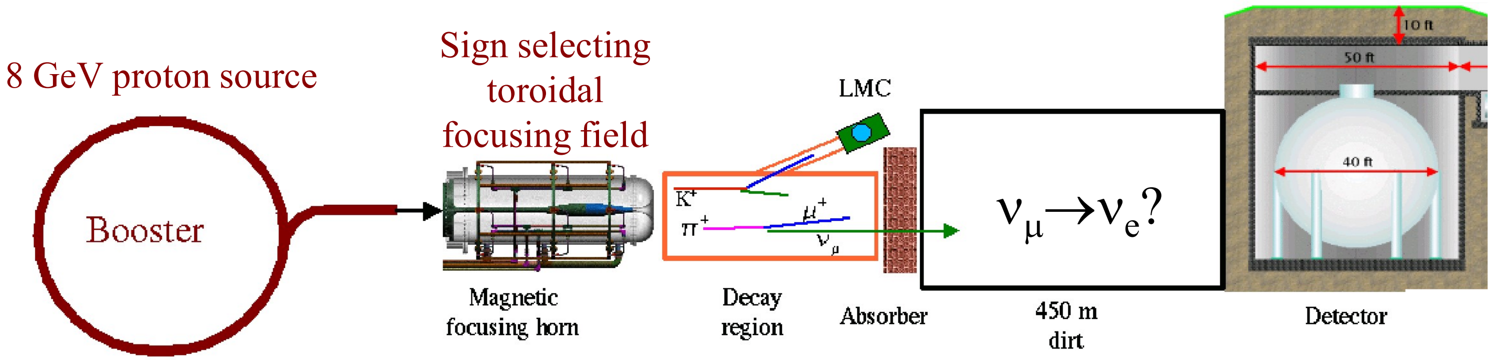
Energy range: 20 to 55 MeV

L/E ~ 1/2 m/MeV

The MiniBooNE Experiment

MiniBooNE's primary objective was to look for ν_e appearance in a ν_μ beam as a test of LSND.

Most pions will decay in the 50 meter decay pipe, but most muons will not, resulting in a ν_μ beam.



π^+ (π^-) decay in flight beam

Baseline (L) = 500 m (about 15× LSND)

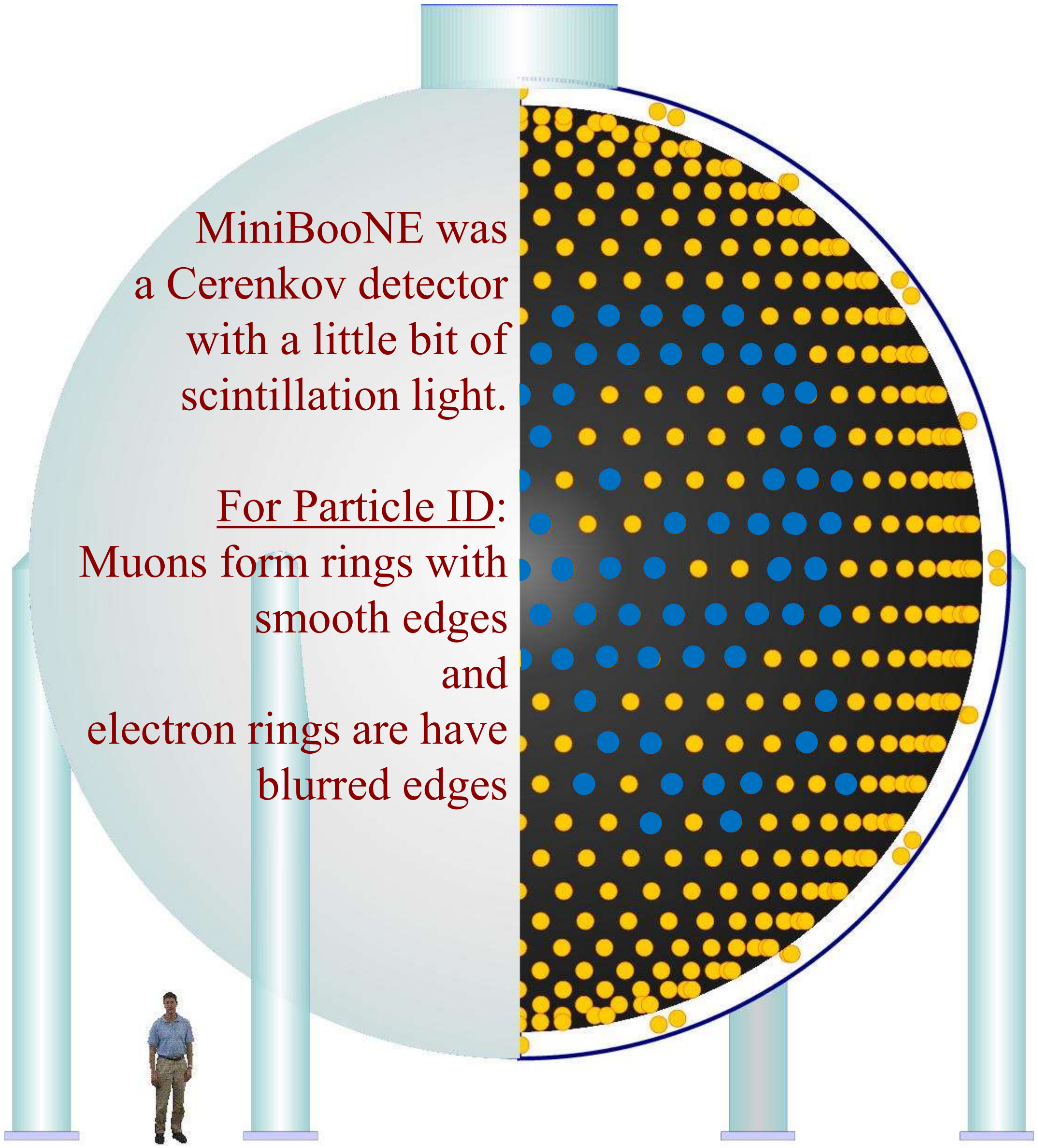
$\langle E_\nu \rangle \sim 500$ MeV (about 15× LSND)

L/E ~ 1 m/MeV (about the same as LSND)

Unavoidable ν_e backgrounds from muon and kaon decay (K_{e3} decays).

NC π^0 events may also look like ν_e in Cerenkov detectos.

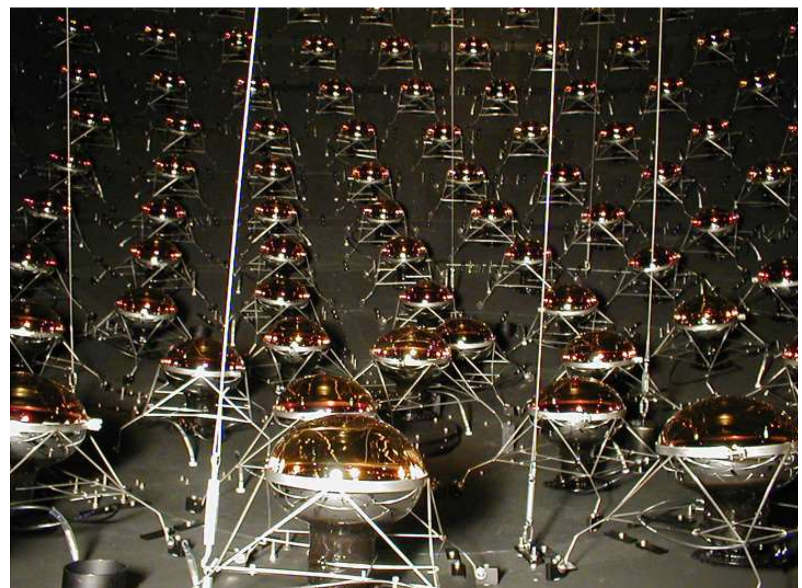
The MiniBooNE Detector



MiniBooNE was a Cerenkov detector with a little bit of scintillation light.

<u>For Particle ID</u>:
Muons form rings with smooth edges
and
electron rings are have blurred edges

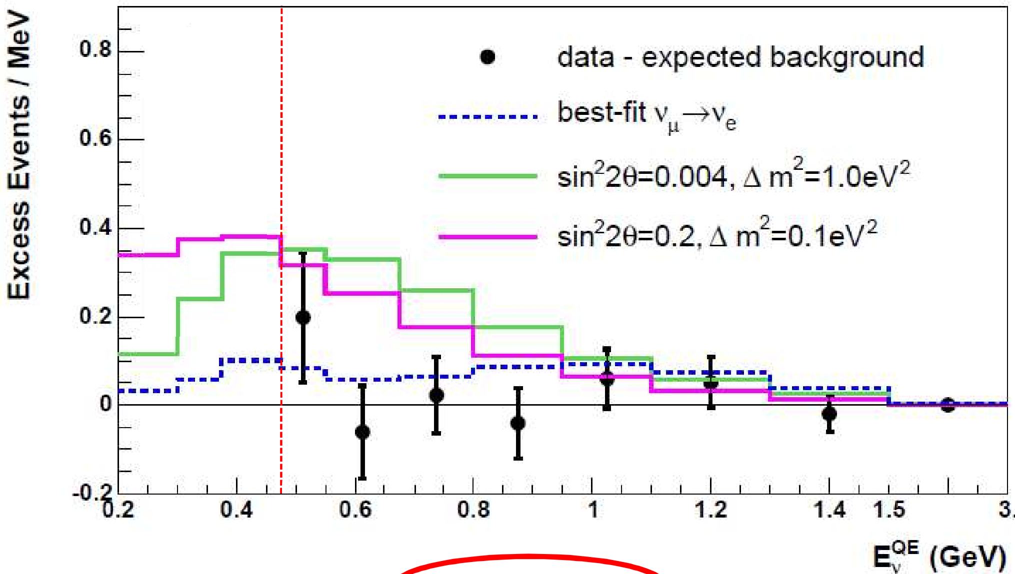
- 12 meter diameter sphere
- Filled with 950,000 liters of pure mineral oil
- Light tight inner region with 1280 photomultiplier tubes
- Outer veto region with 240 PMTs.



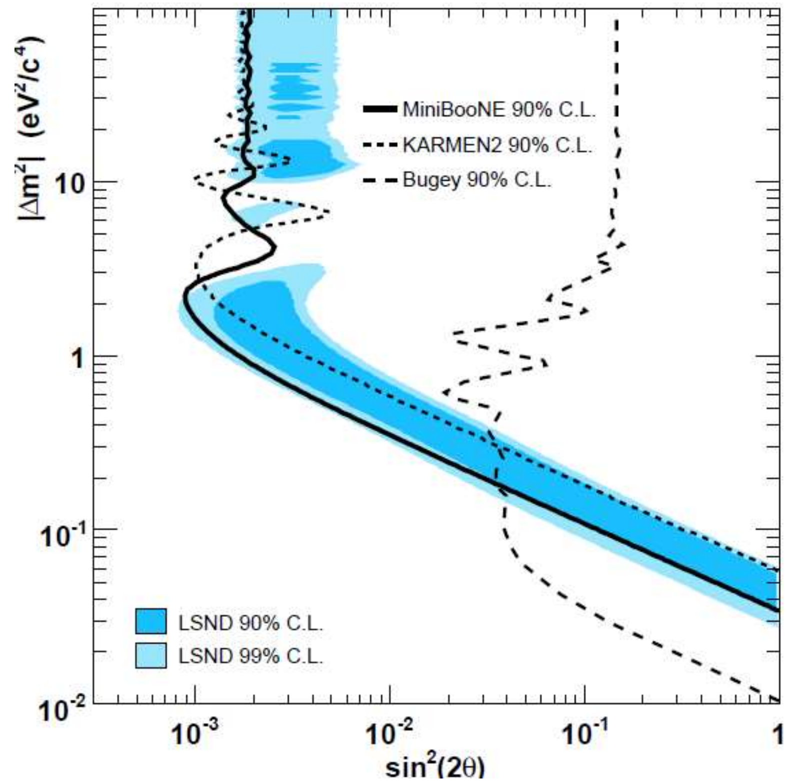
MiniBooNE $\nu_\mu \rightarrow \nu_e$ Appearance Search

Excess of low-energy events

Aguilar-Arevalo *et al.*, Phys.Rev.Lett. 98, 231801 (2007)



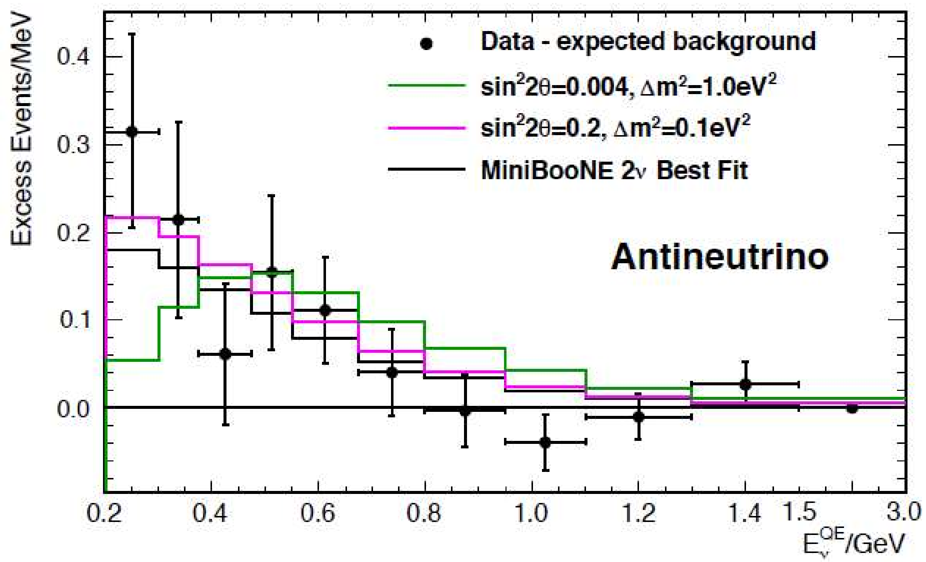
	475 – 1250 MeV	
Data	Analysis window selected before opening the box.	408
Background		385.9 ± 19.6 ± 29.8
Excess		22.1 ± 19.6 ± 29.8
Significance		0.6σ

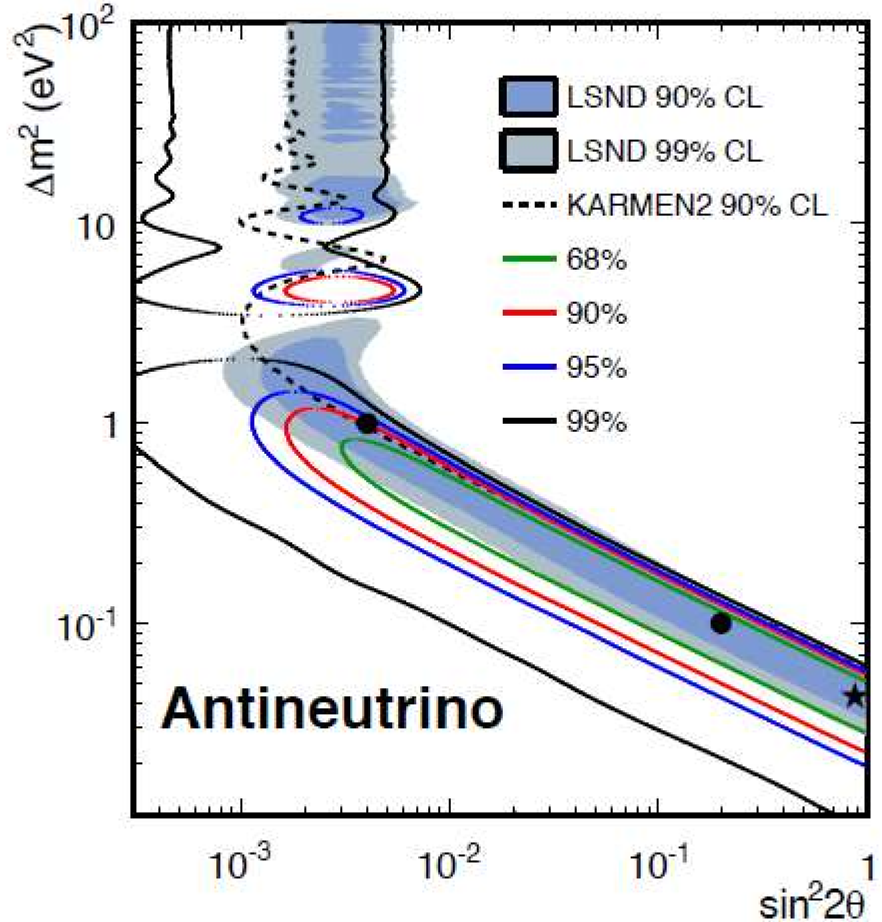


MiniBooNE's neutrino search found no significant excess consistent with LSND

MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Search

Aguilar-Arevalo *et al.*, Phys.Rev.Lett. 110, 161801 (2013)





Event Excess: 78.4 ± 28.5

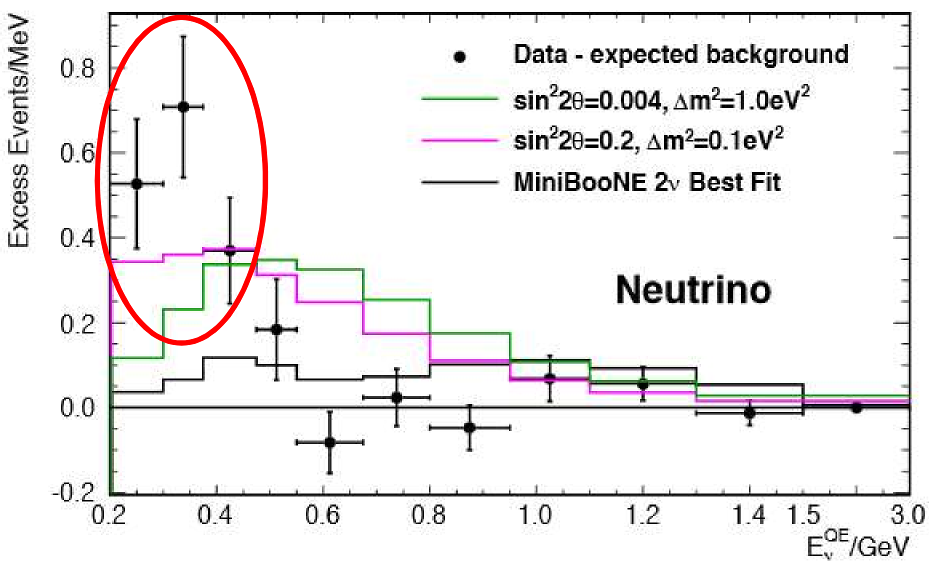
Consistent with LSND

MiniBooNE $\nu_\mu \rightarrow \nu_e$ Appearance Search

MiniBooNE revisited their neutrino data in 2013

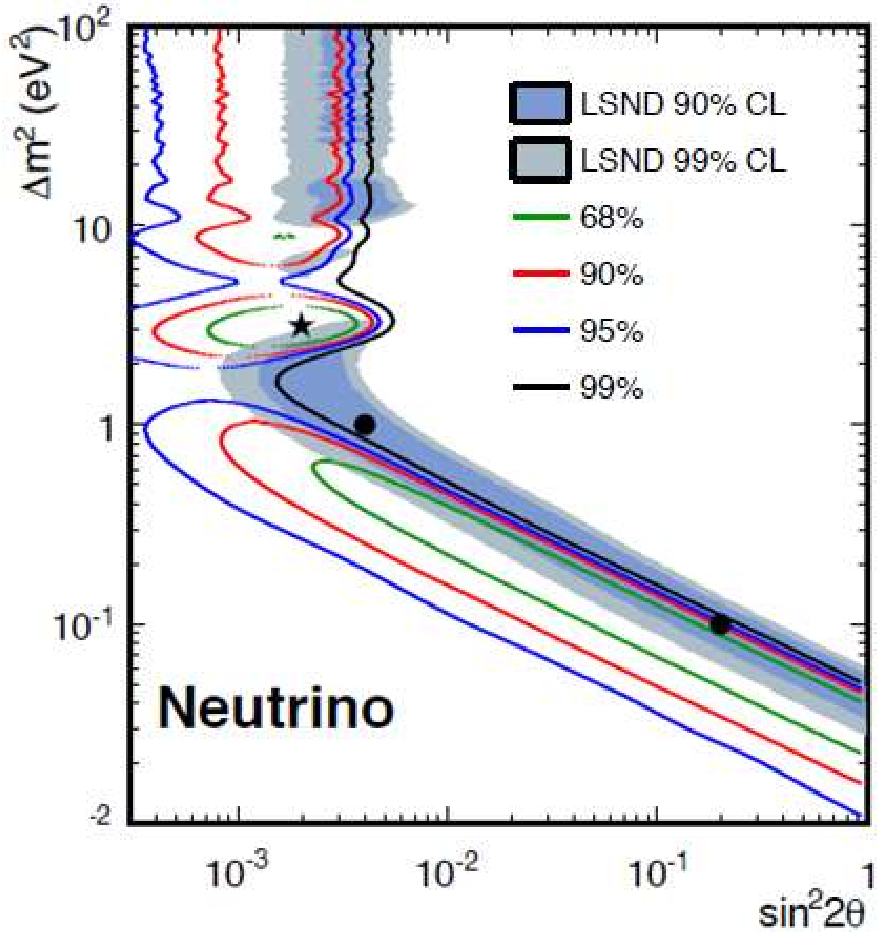
Aguilar-Arevalo *et al.*, Phys.Rev.Lett. 110, 161801 (2013)

This time they included
the lowest energy events



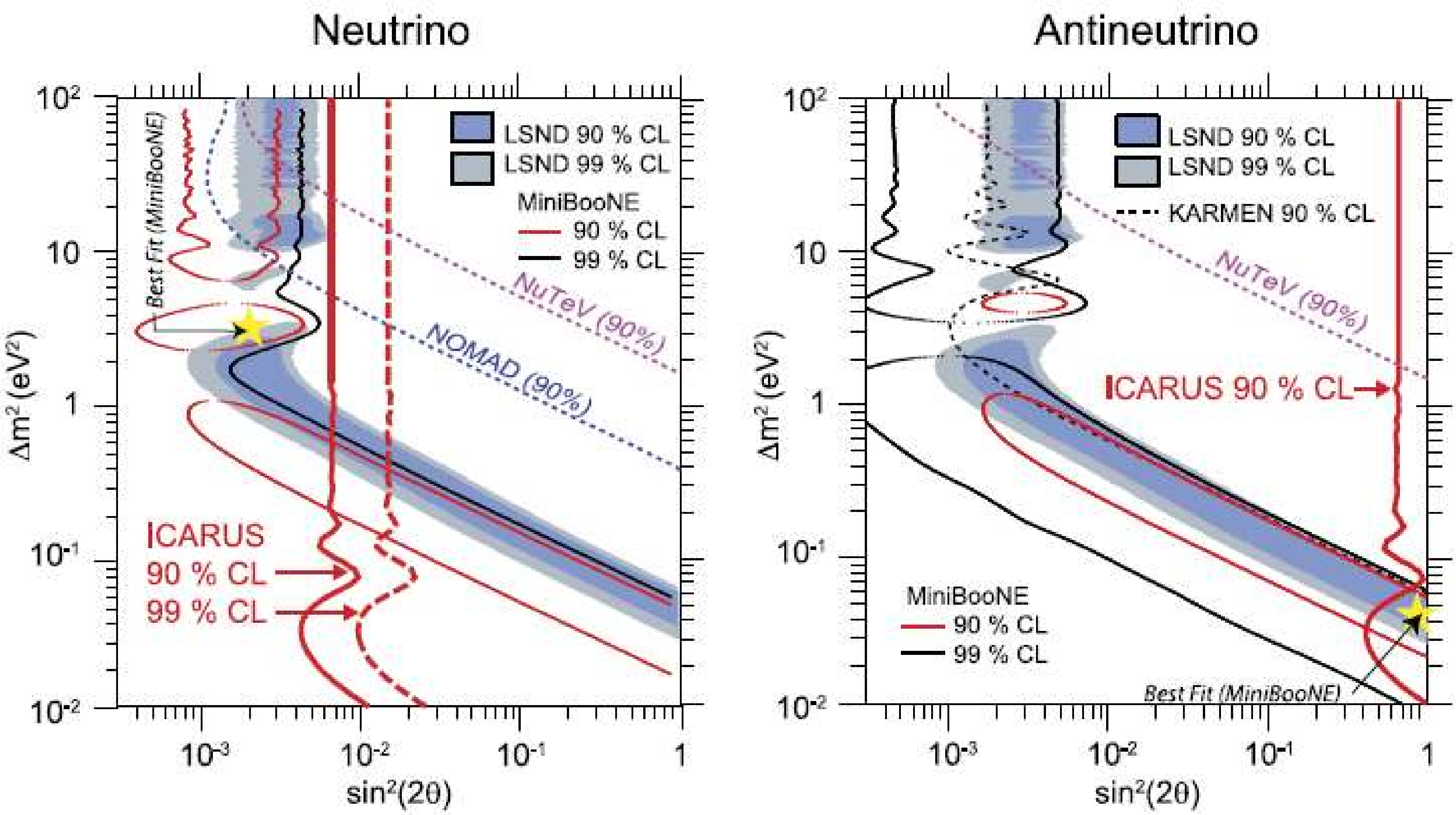
Event Excess: 162.0 ± 47.8

But it's still not very consistent
with LSND



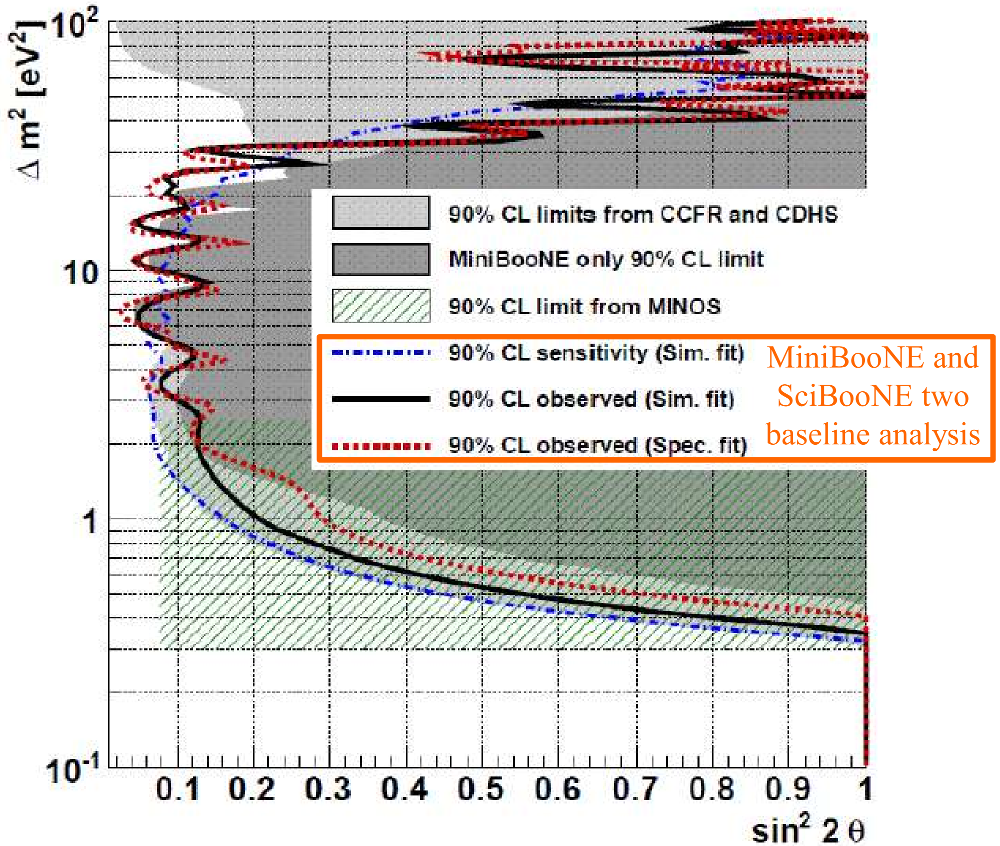
ICARUS $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ Appearance Search

In the LNGS beam from CERN to Gran Sasso (Italy)



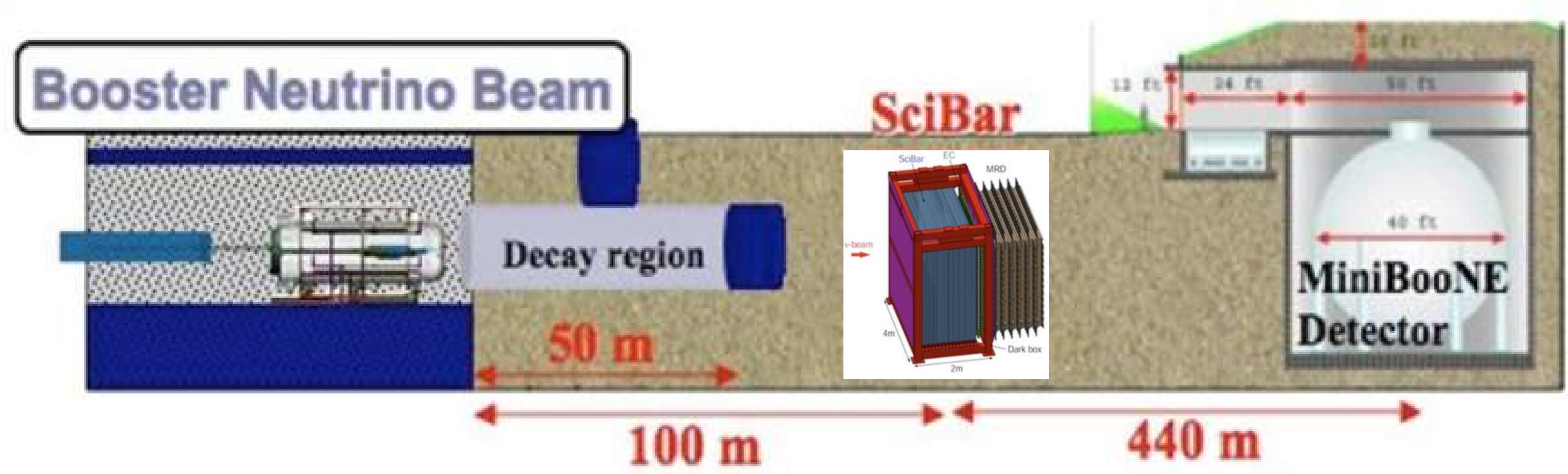
ν_μ and $\bar{\nu}_\mu$ Disappearance

(Neutrino and antineutrino disappearance rates should be equal, assuming CPT is conserved)



Mahn *et al.*, Phys.Rev.D85, 032007 (2012)

The SciBooNE MiniBooNE Co-Deployment



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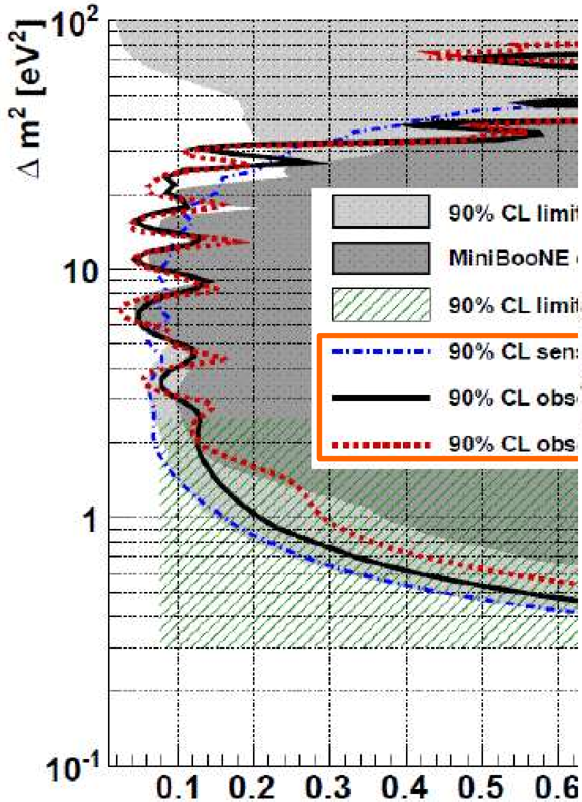
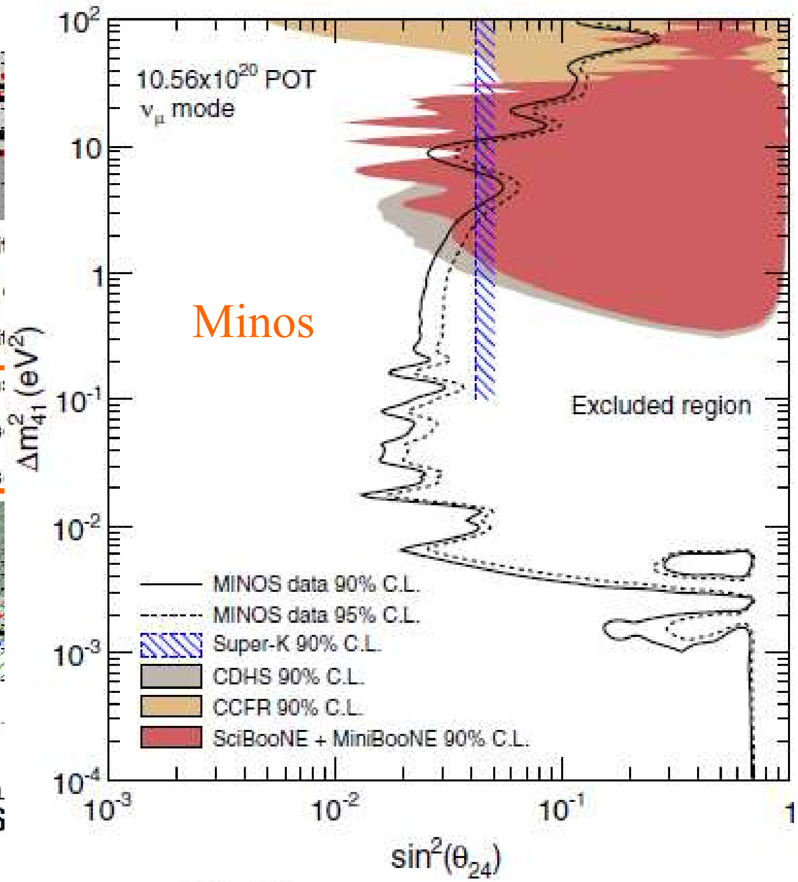




Mahn *et al.*, Phys.Rev.D85, 032007 (2012)

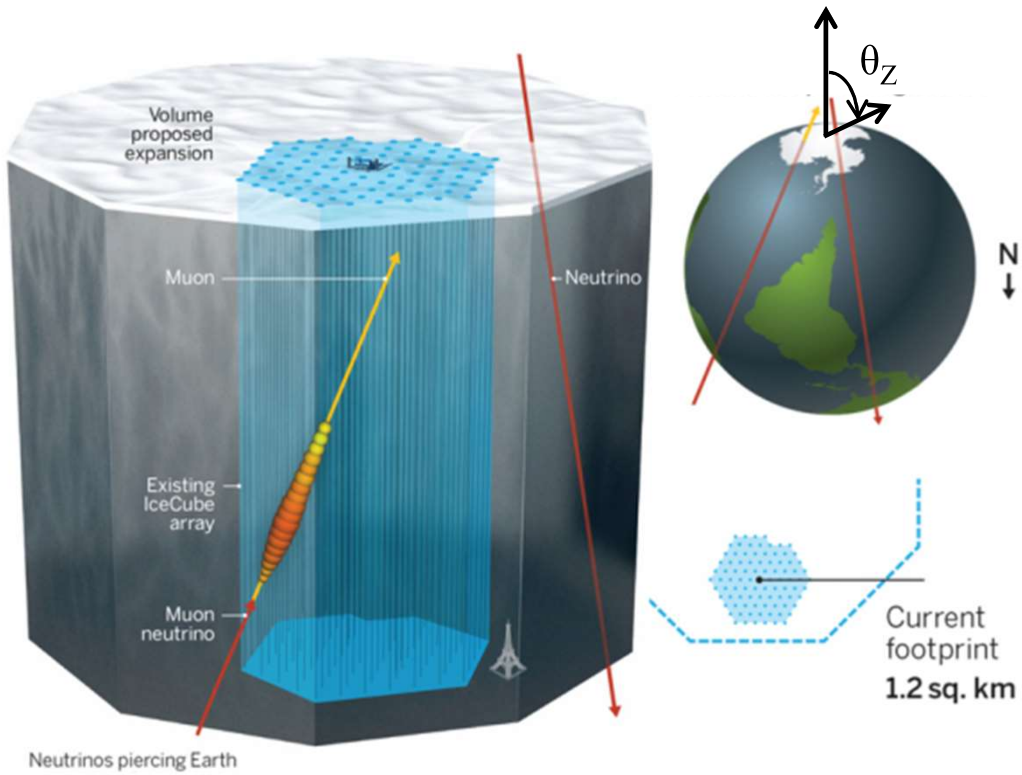
Adamson *et al.*, Phys.Rev.Lett. 117, 151803 (2016)

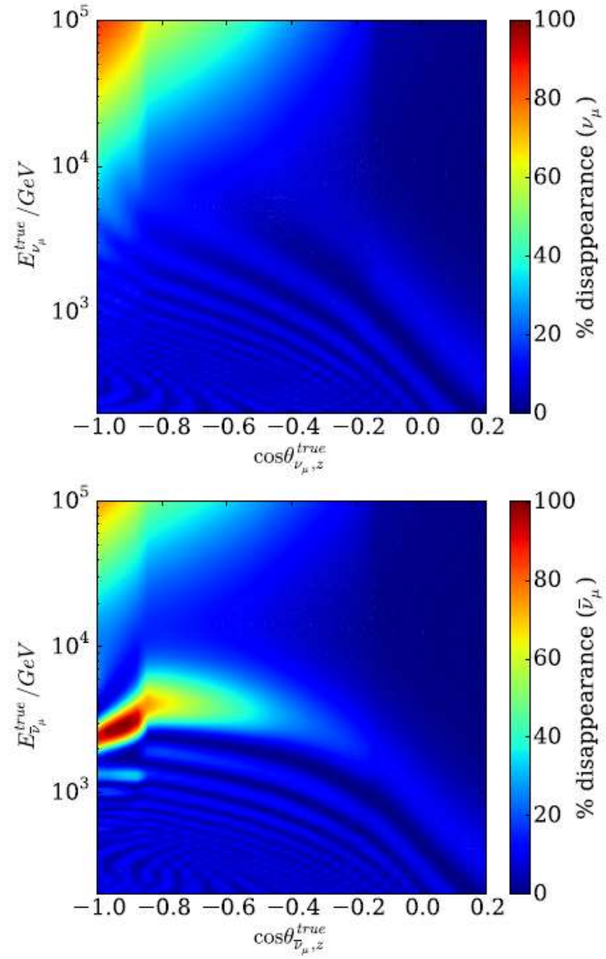
$U_{\mu 4}$ is small throughout the region of interest

IceCube ν_μ Disappearance

With a sterile neutrino matter effects from NC interactions distort the muon neutrino disappearance probability for high energy neutrinos passing through the Earth.

Vacuum sterile oscillations are too rapid and can't be resolved here.

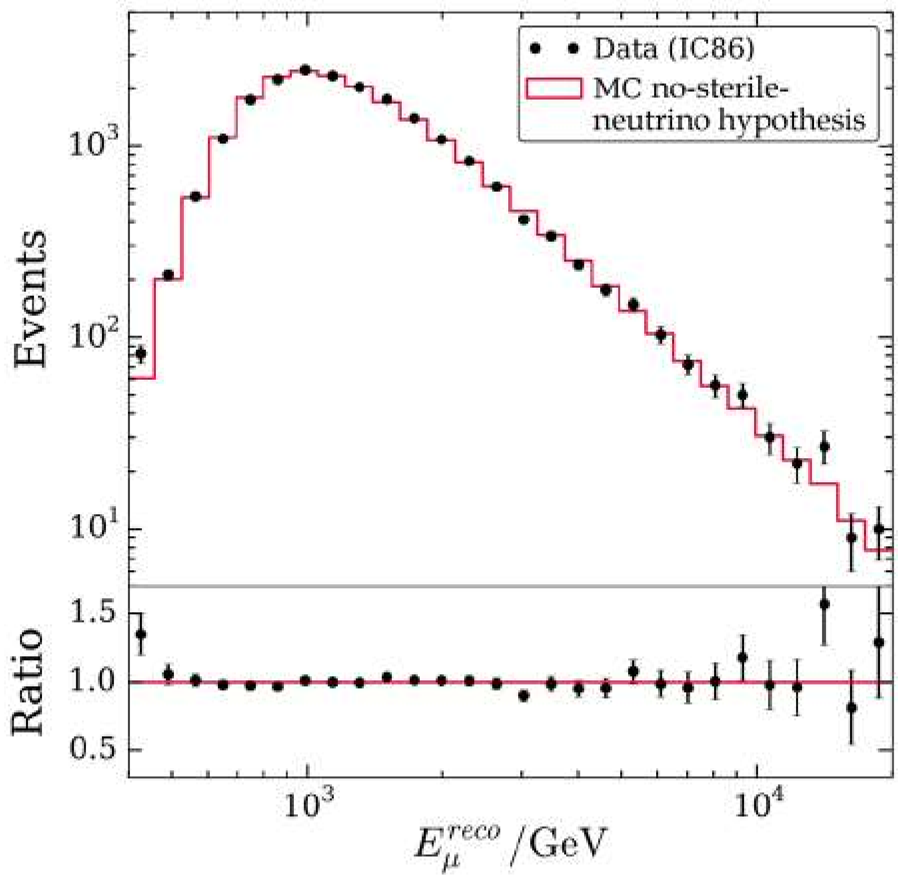


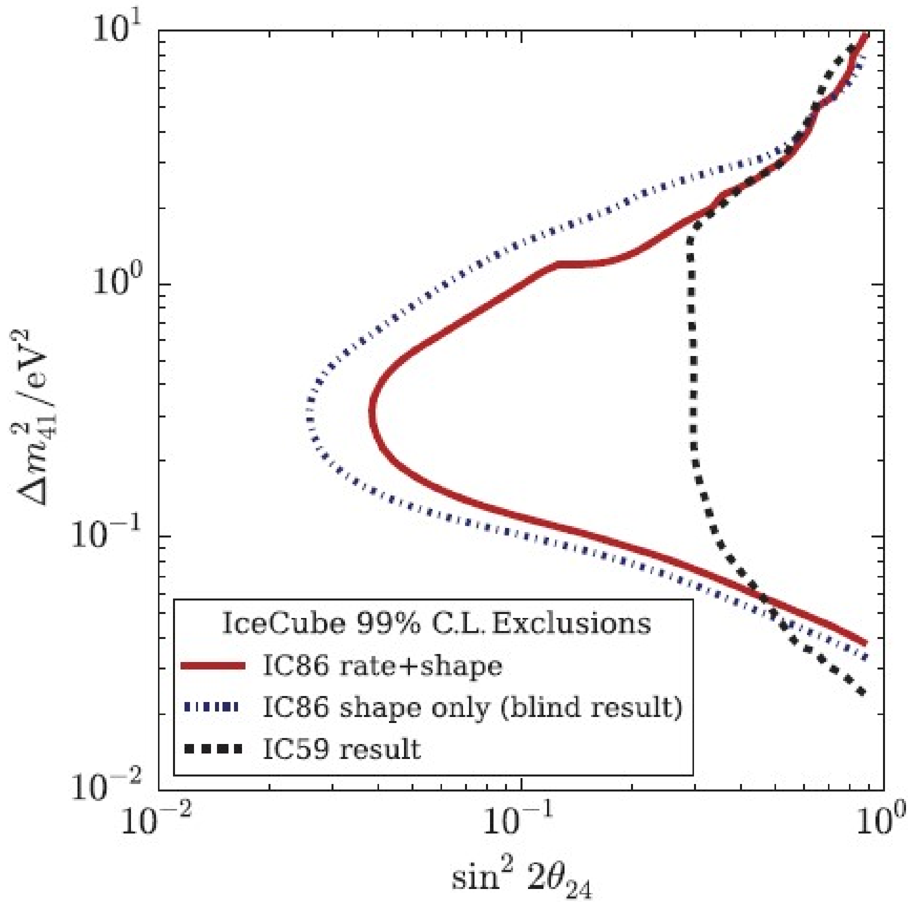


IceCube, Phys.Rev.Lett. 117, 071801 (2016)

IceCube ν_μ Disappearance

The data match the expectation for no sterile neutrino in energy and angle.

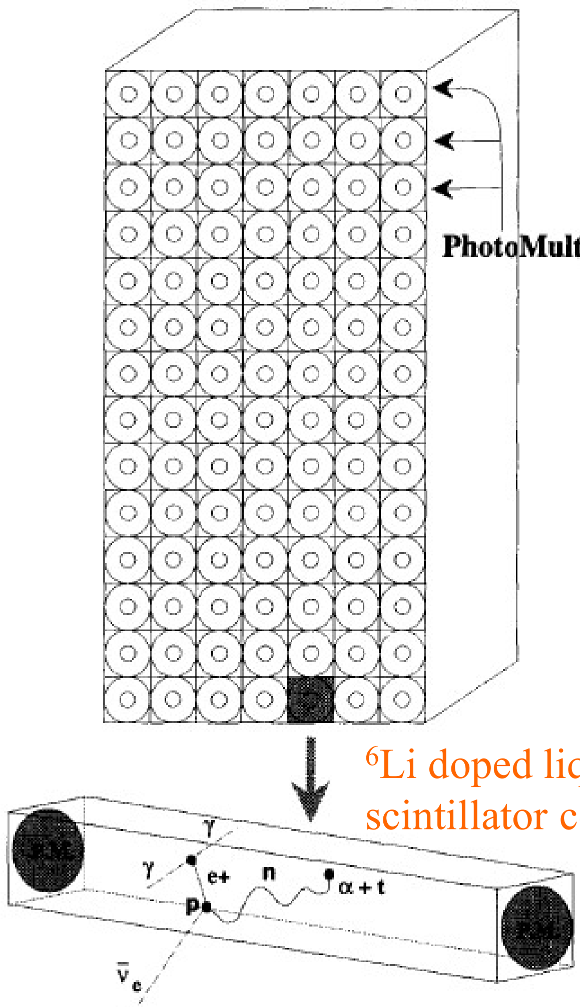




IceCube, Phys.Rev.Lett. 117, 071801 (2016)

The Bugey Experiment and $\bar{\nu}_e$ Disappearance

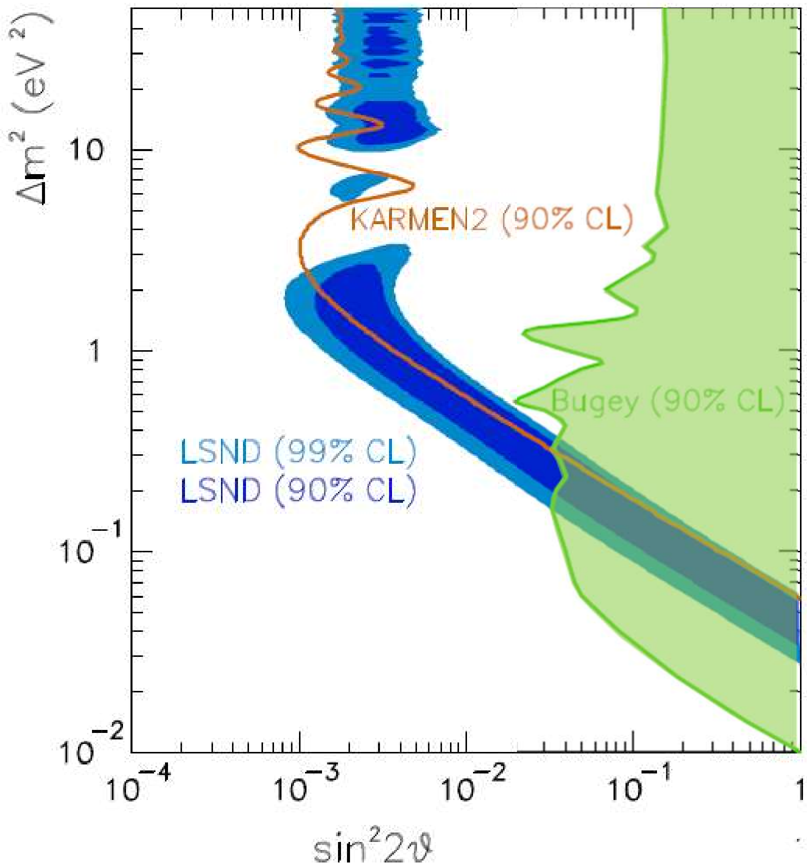
Reactor antineutrinos observed at three baselines: 15, 40 and 95 m



^{6}Li doped liquid scintillator cells

Achkar *et al.*, Nucl.Phys.B434, 503 (1995)

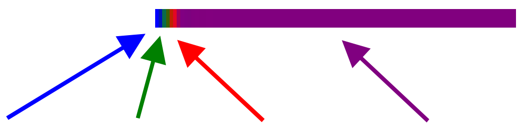
Sensitivity from absolute rate *and* near/far comparisons



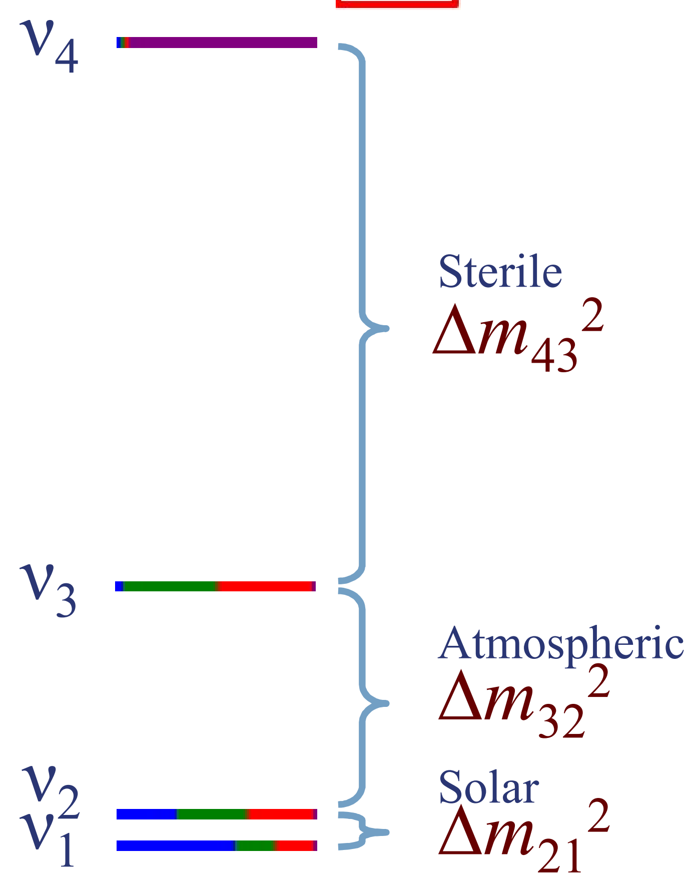
Relating Appearance and Disappearance Probabilities

With a single sterile neutrino we get a 4×4 PMNS mixing matrix and 3 independent Δm^2s.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



$$U_{e4}^2 + U_{\mu4}^2 + U_{\tau4}^2 + U_{s4}^2 = 1 \quad \text{(PMNS Unitarty)}$$



The appearance probability:

$$P_{\mu e} \approx 4U_{e4}^2 U_{\mu4}^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

The ν_e disappearance probability:

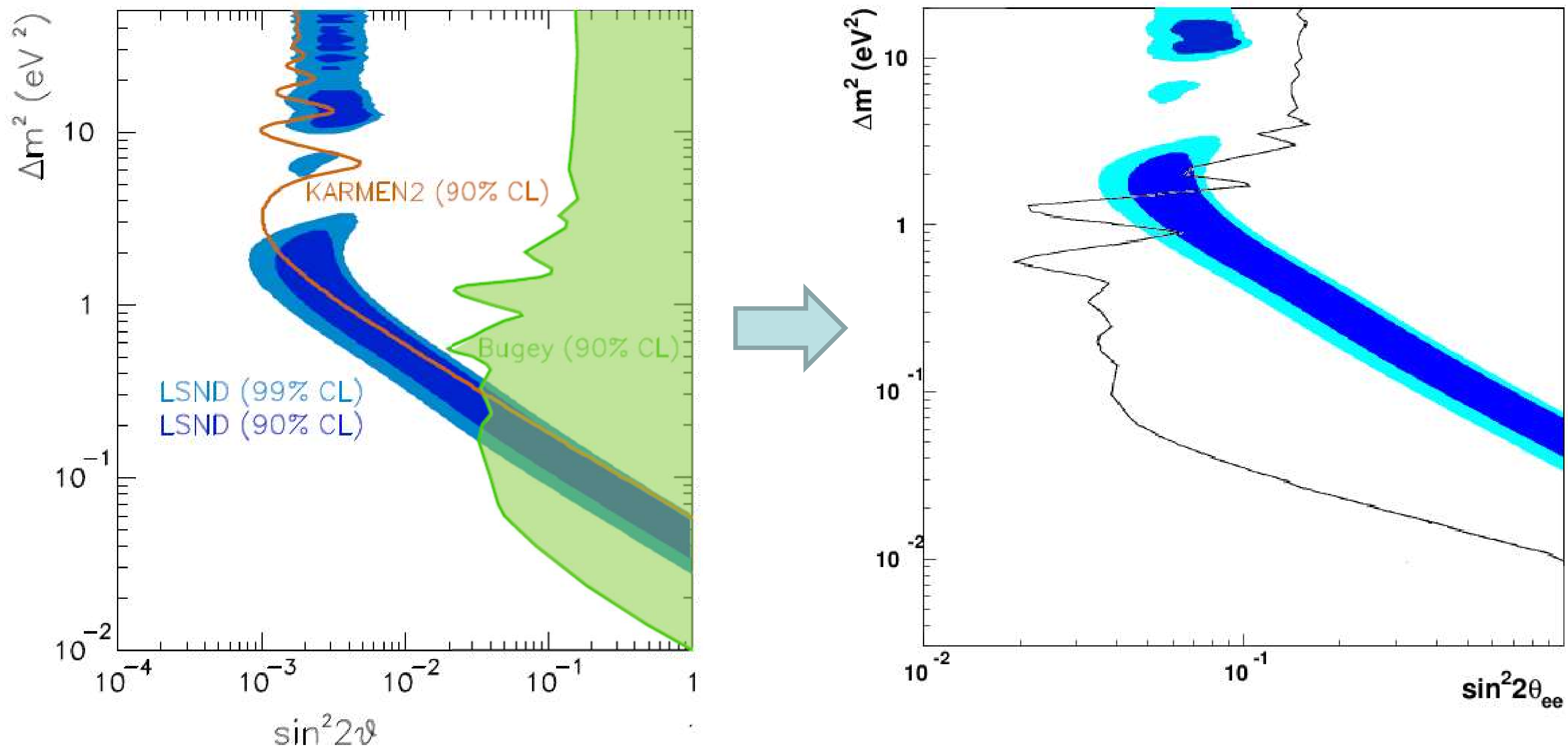
$$P_{ee} \approx P_{es} = 4U_{e4}^2 U_{s4}^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

The ν_μ disappearance probability:

$$P_{\mu\mu} \approx 4U_{\mu4}^2 U_{s4}^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

Bugey $\bar{\nu}_e$ Disappearance

Assuming $U_{e4}=U_{\mu4}$ and $U_{s4}\approx1$, we can convert LSND's $\sin^2 2\theta_{\mu e}$ into $\sin^2 2\theta_{ee}$ to find Bugey provides a sever constraint on LSND

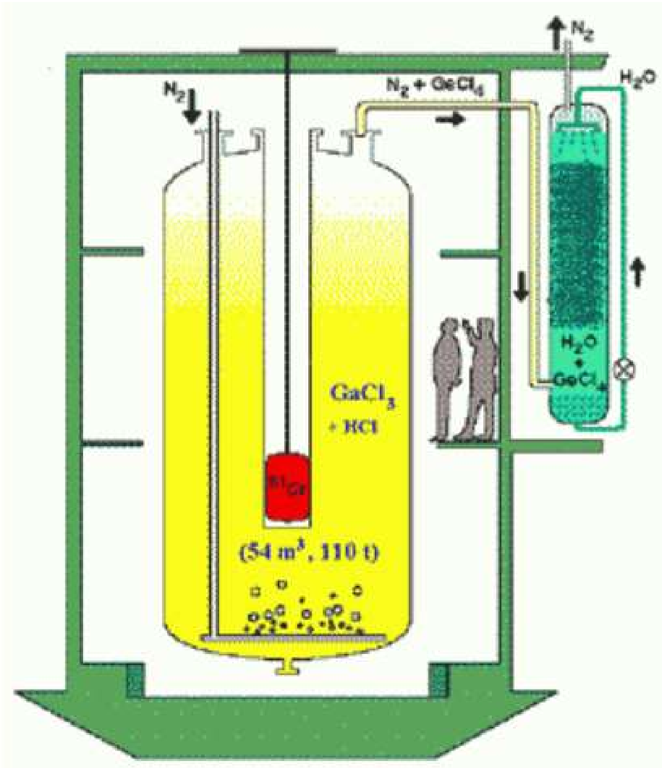


This constraint weakens for larger $U_{\mu4}$.

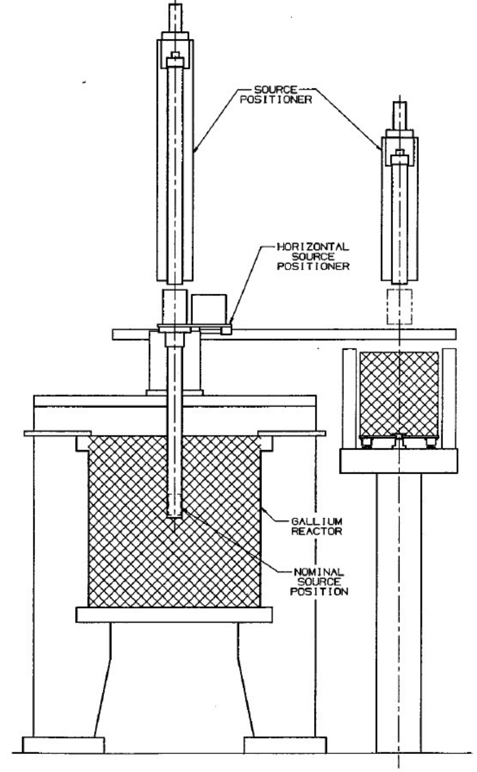
The Gallium Anomaly (ν_e Disappearance)

The solar radiochemical detectors GALLEX and SAGE used intense EC sources (^{51}Cr and ^{37}Ar) to calibrate the ν_e detection efficiency.

GALLEX Sources: 1.7 MCi of ^{51}Cr
1.8 MCi of ^{37}Ar



SAGE Sources: 680 kCi of ^{51}Cr
409 kCi of ^{37}Ar



Neutrinos interact in the CC process, $\nu_e + ^{71}Ga \rightarrow ^{71}Ge$, and are detected by the decay of ^{71}Ge.

Electron Capture Neutrino Source: ^{51}Cr

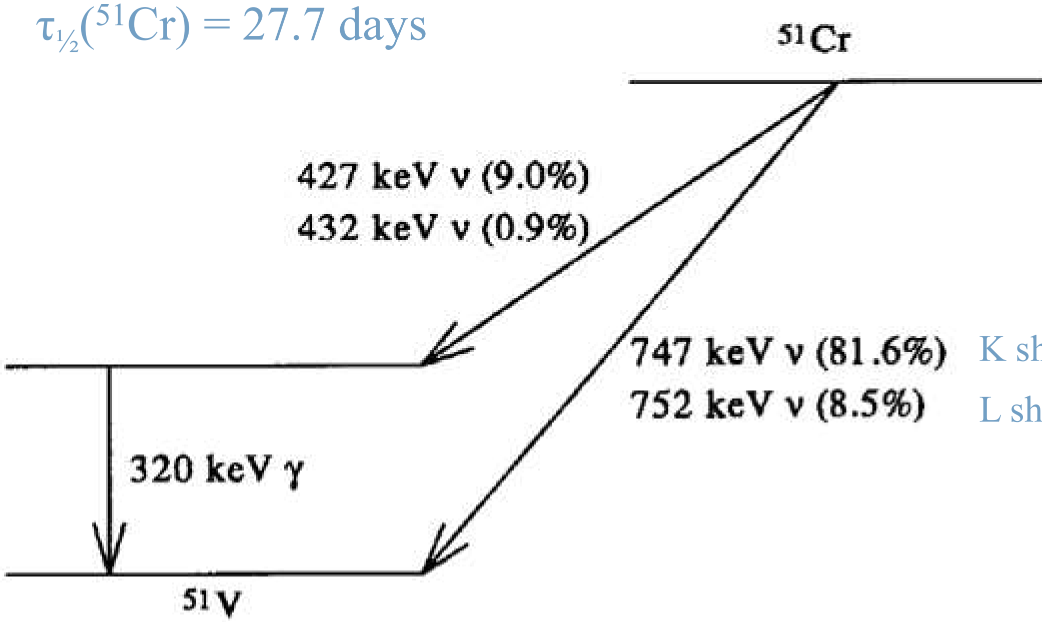
Can be easily produced with thermal neutron capture; ^{50}Cr has a 17 barn capture cross section.

90% of the time the capture goes directly to the ground state of ^{51}V and you get a 750 keV neutrino.

Has only one, relatively easy-to-shield gamma that accompanies 10% of decays.

Natural Cr must be significantly enriched in ^{50}Cr (4.35% abundance)

$\tau_{1/2}(^{51}Cr) = 27.7$ days



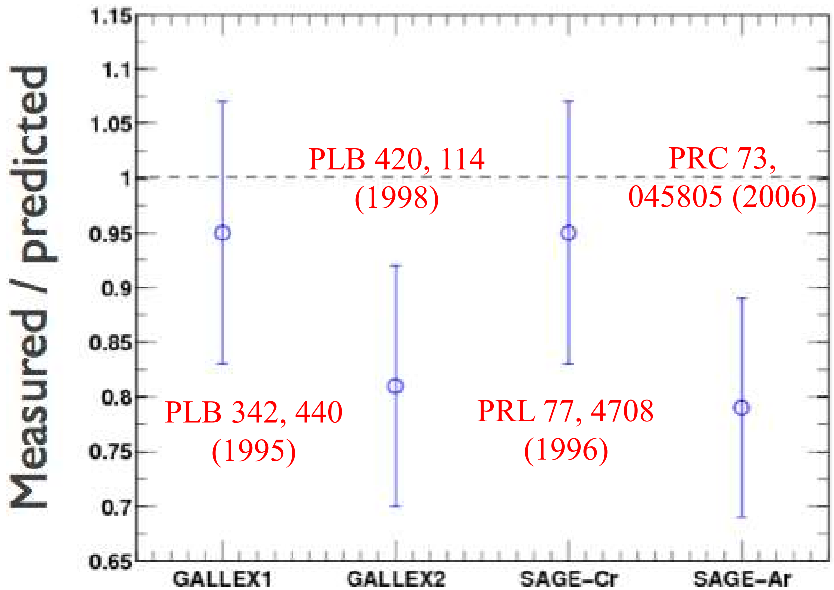
K shell capture

L shell capture

Decay scheme of ^{51}Cr to ^{51}V through electron capture.

The Gallium Anomaly (ν_e Disappearance)

Giunti and Laveder, Mod.Phys.Lett. A22, 2499 (2007)
Acero, Giunti and Laveder, Phys.Rev. D78, 073009 (2008)
Giunti and Laveder, Phys.Rev.C83, 065504 (2011)]



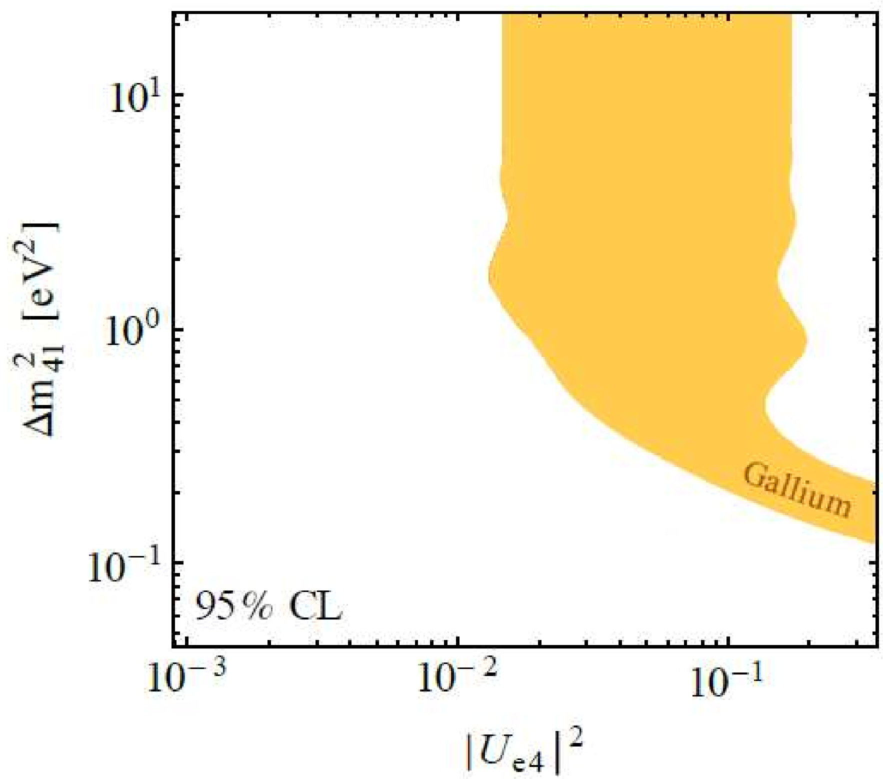
Average ratio of measurement to predicted

R=0.86±0.05 (Bahcall)

Or even worse (better?)

$R=0.76^{+0.09}_{-0.08}$ (Haxton)

Kopp *et* al., JHEP 1305, 051 (2013)



Reactor Anomaly ($\bar{\nu}_e$ Disappearance)

Nuclear reactors are a very intense sources of $\bar{\nu}_e$ coming from the β-decay of the neutron-rich fission fragments.

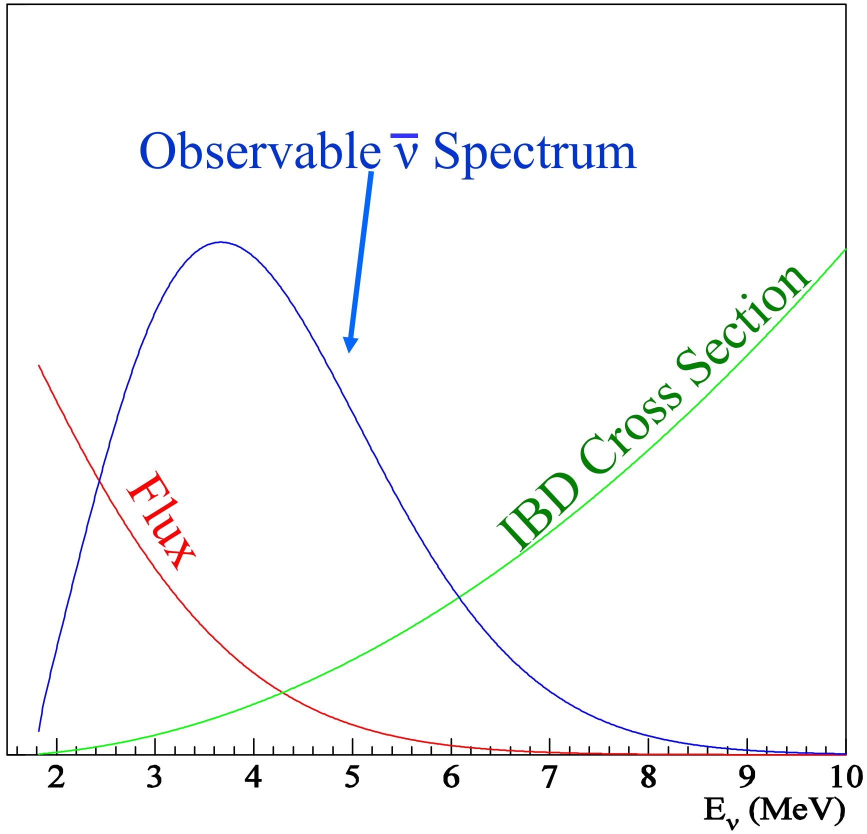
A typical commercial reactor, with 3 GW thermal power, produces 6×10^{20} ν/s

The observable ν_e spectrum is the product of the flux and the cross section.

Reactor neutrinos are detected by inverse beta decay.

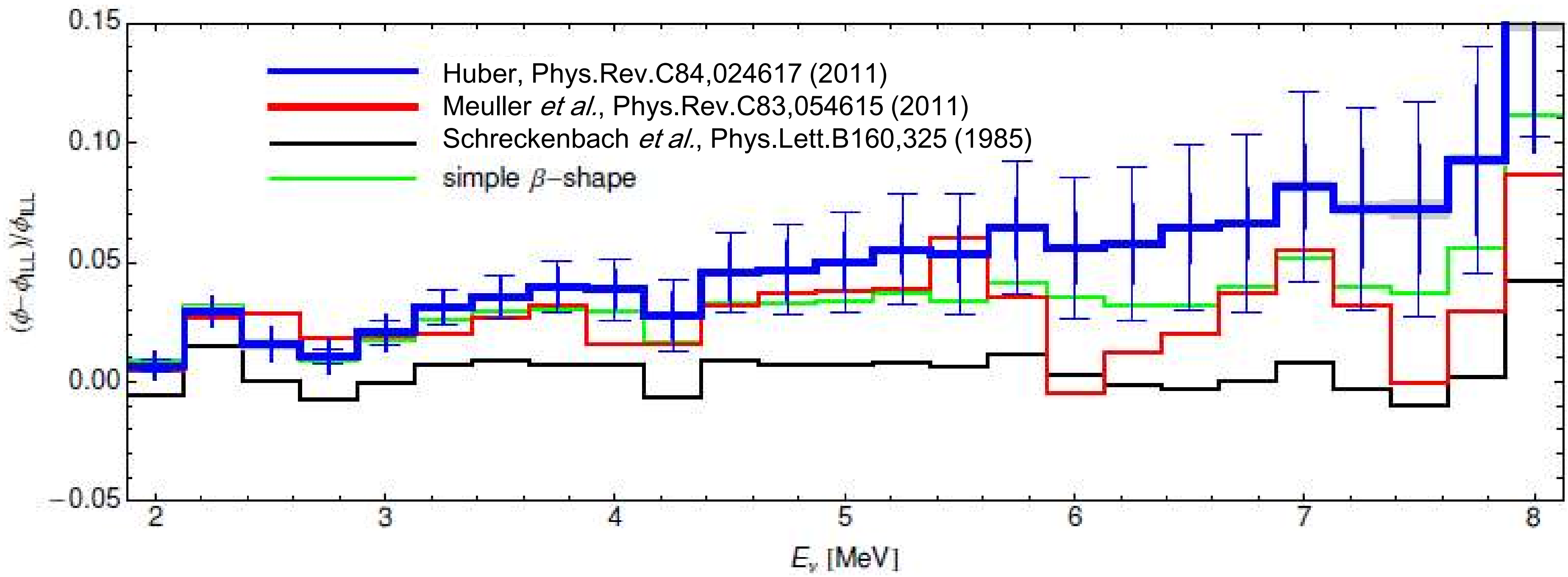
There have been many short baseline experiments to measure the reactor rate and spectrum.

Bemporad, Gratta & Vogel, Rev.Mod.Phys. 74, 297 (2002)

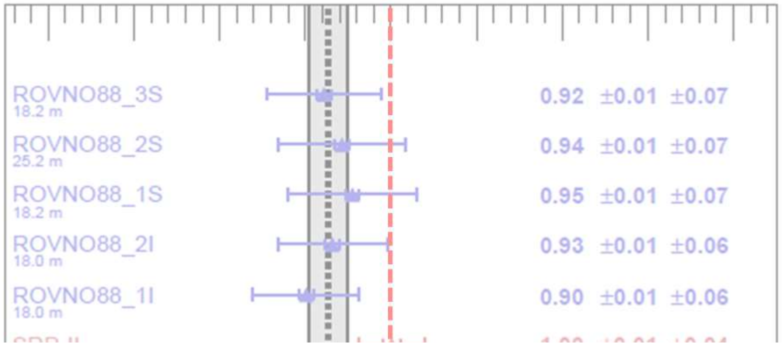


Reactor Anomaly

New analyses (blue and red) of the reactor $\bar{\nu}_e$ spectrum predict a 6% higher flux than the earlier calculation (black).

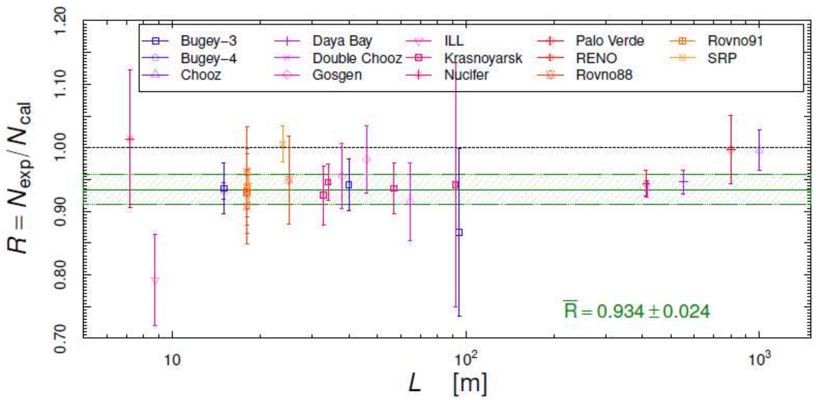


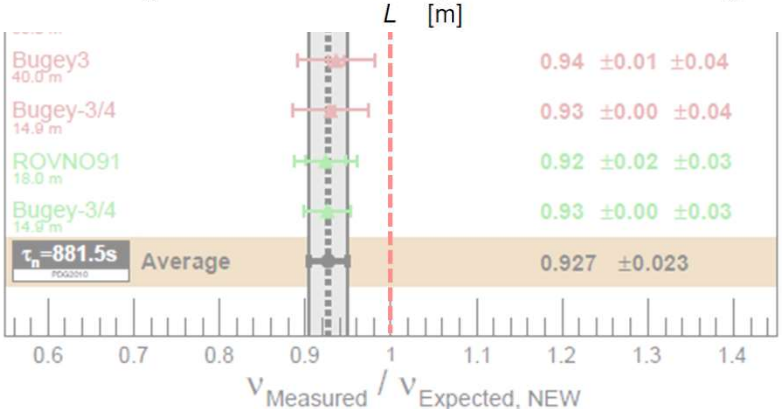
Reactor Anomaly ($\bar{\nu}_e$ Disappearance)



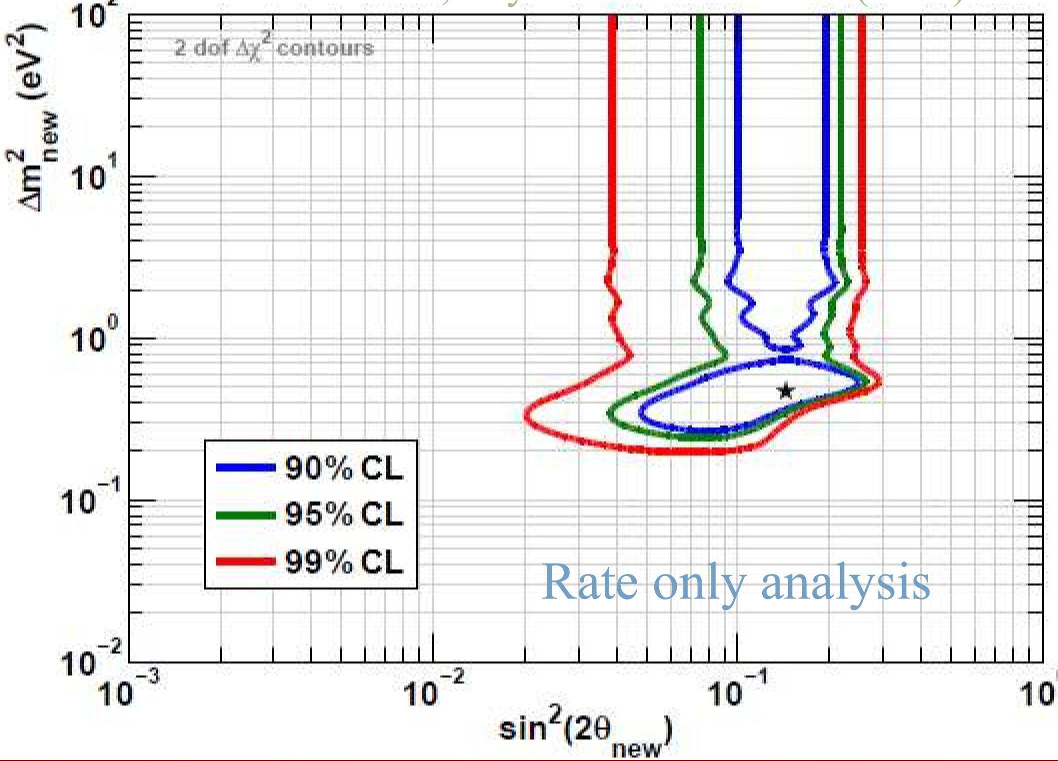
Recent calculations of the reactor $\bar{\nu}_e$ flux and spectrum predict a higher rate than the earlier calculation. This resulted is an apparent deficit of reactor neutrinos across all experiments.

Giunti *et al.*, JHEP 06, 135 (2017)





Mention *et al.*, Phys.Rev.D83 073006 (2011)



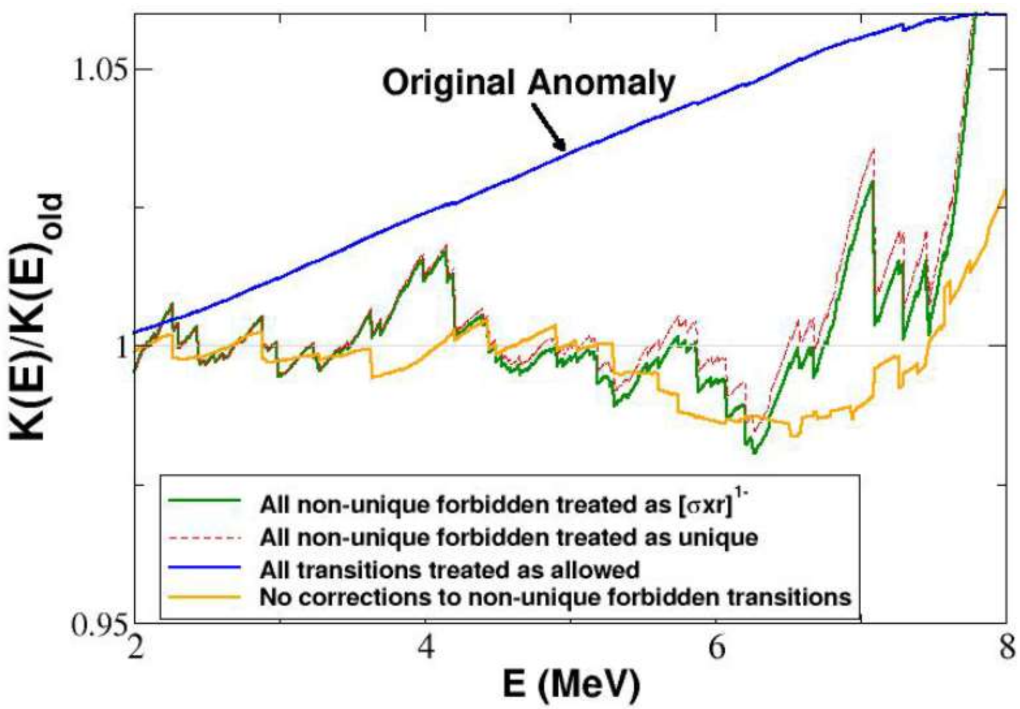
Rate only analysis

Further Theory Work on the Reactor Anomaly

A flux calculation out of Los Alamos has called the Reactor Anomaly into question

It shows that the anomaly depends on how nuclear matric elements for forbidden decays are treated

Hayes *et al.*, Phys.Rev.Lett. 112, 202501 (2014)



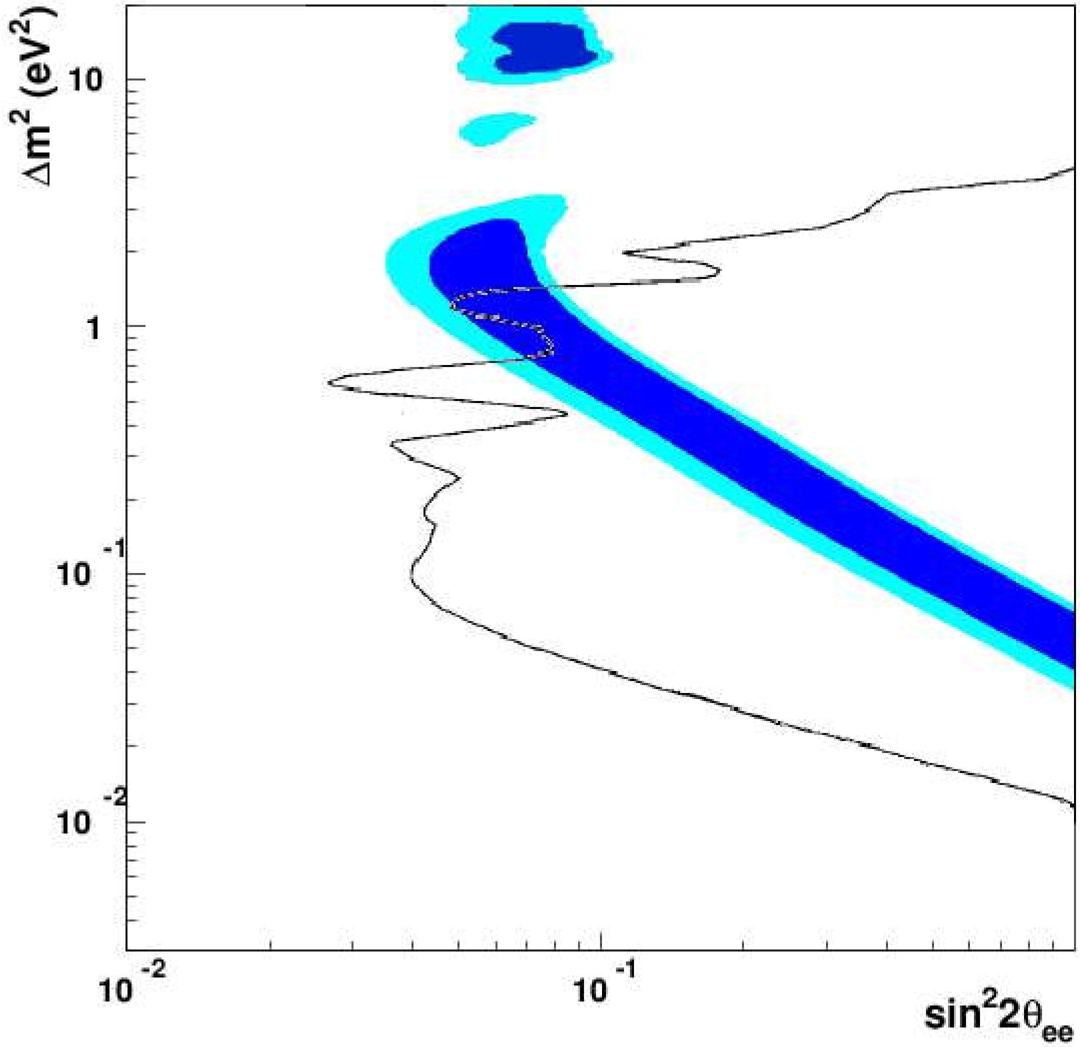
The net result is that the theoretical uncertainty in the reactor flux should be more like 5%, not 2%.

This undercuts the reactor anomaly, but it also undercuts most reactor sterile constraints.

Any future SBL reactor experiment must search for oscillations in L/E

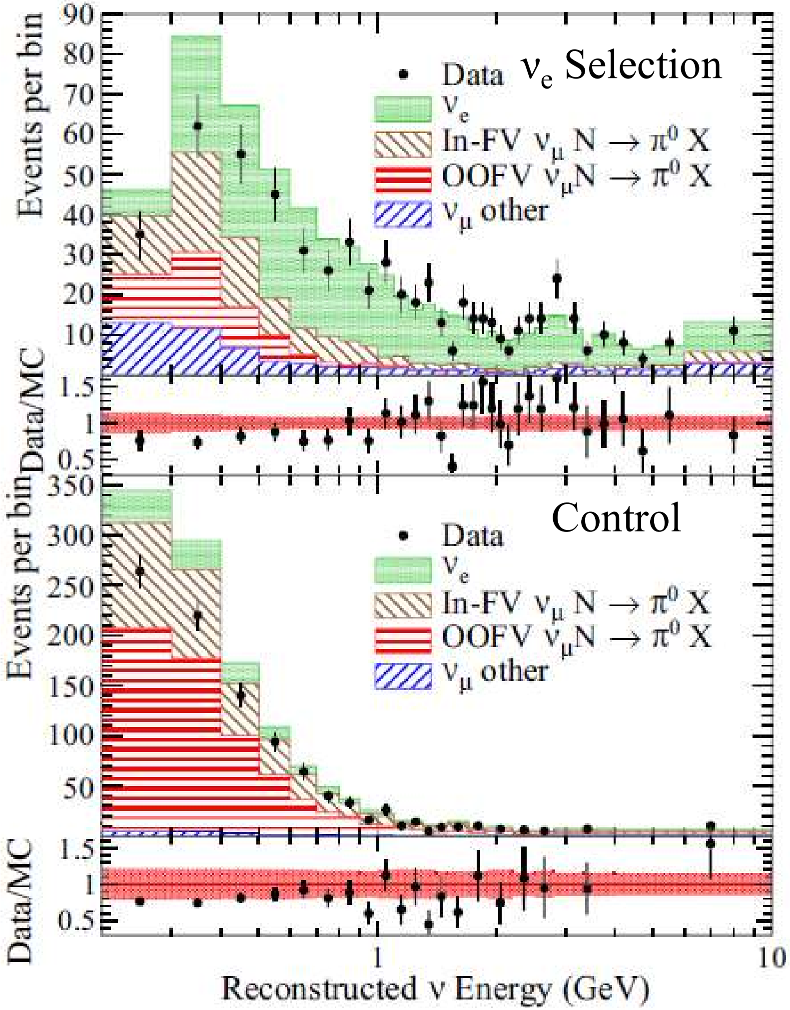
Bugey Revisited in Light of Reactor Anomaly

If we can't trust the absolute reactor flux, the constraint from rate goes away:

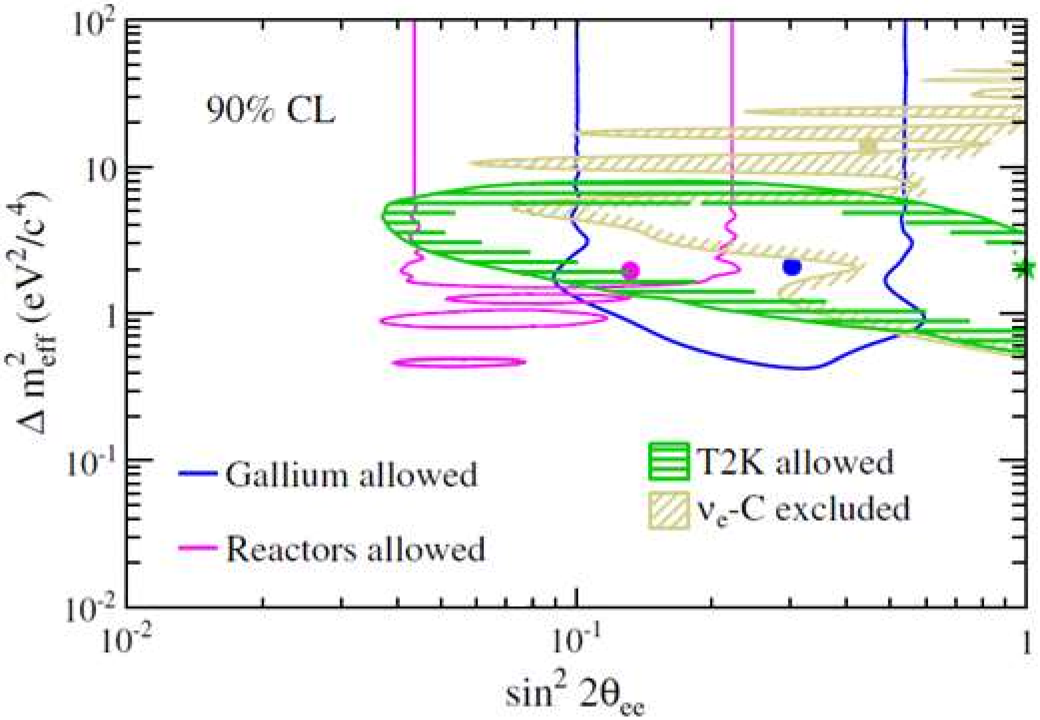


T2K Near Detector (ν_e Disappearance)

Although the T2K beam is predominantly a ν_μ beam, the small ν_e component can be used in the near detector for a ν_e disappearance search.



Phys.Rev. D91, 051102(R) (2015)



Short-baseline ν_e appearance from the much larger ν_μ component of the beam could fill in the exact region depleted by ν_e disappearance, so $\nu_\mu \rightarrow \nu_e$ is assumed to be zero in this analysis.

Comparing/Combining Different Measurements

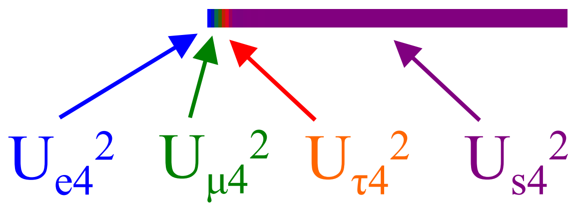
1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

$$P_{\mu e} \approx \tfrac{1}{4} P_{e\not{e}} P_{\mu\not{\mu}} \quad \text{(at oscillation maximum)}$$

Relating Appearance and Disappearance Probabilities

At Oscillation Maximum

With $U_{s4} \approx 1$



The appearance probability:

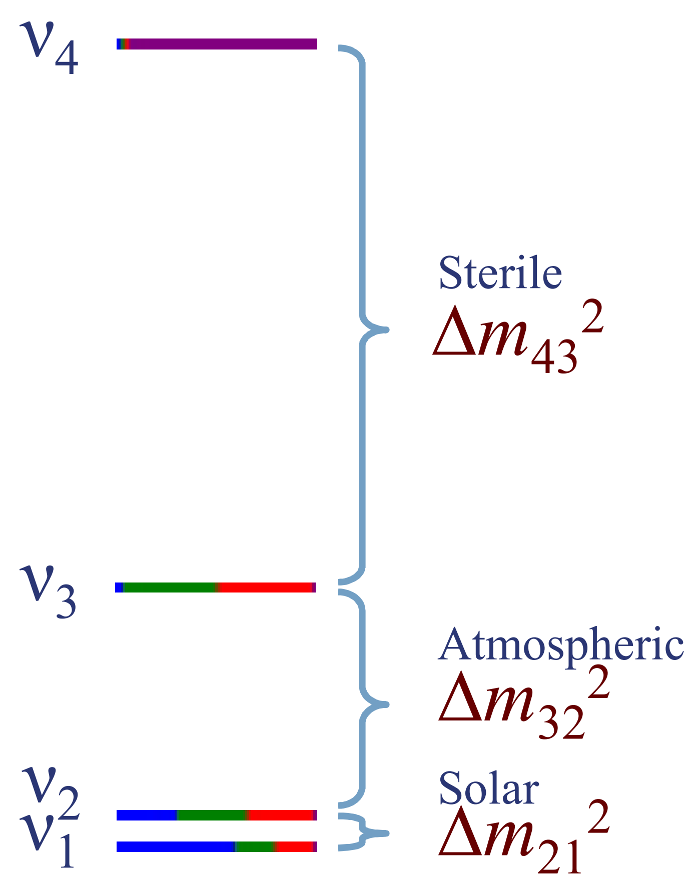
$$P_{\mu e} = 4U_{e4}^2\, U_{\mu 4}^2 \approx \tfrac{1}{4}\, P_{e\not{e}}\, P_{\mu\not{\mu}}$$

The ν_e disappearance probability:

$$P_{e\not{e}} \approx 4U_{e4}^2$$

The ν_μ disappearance probability:

$$P_{\mu\not{\mu}} \approx 4U_{\mu 4}^2$$

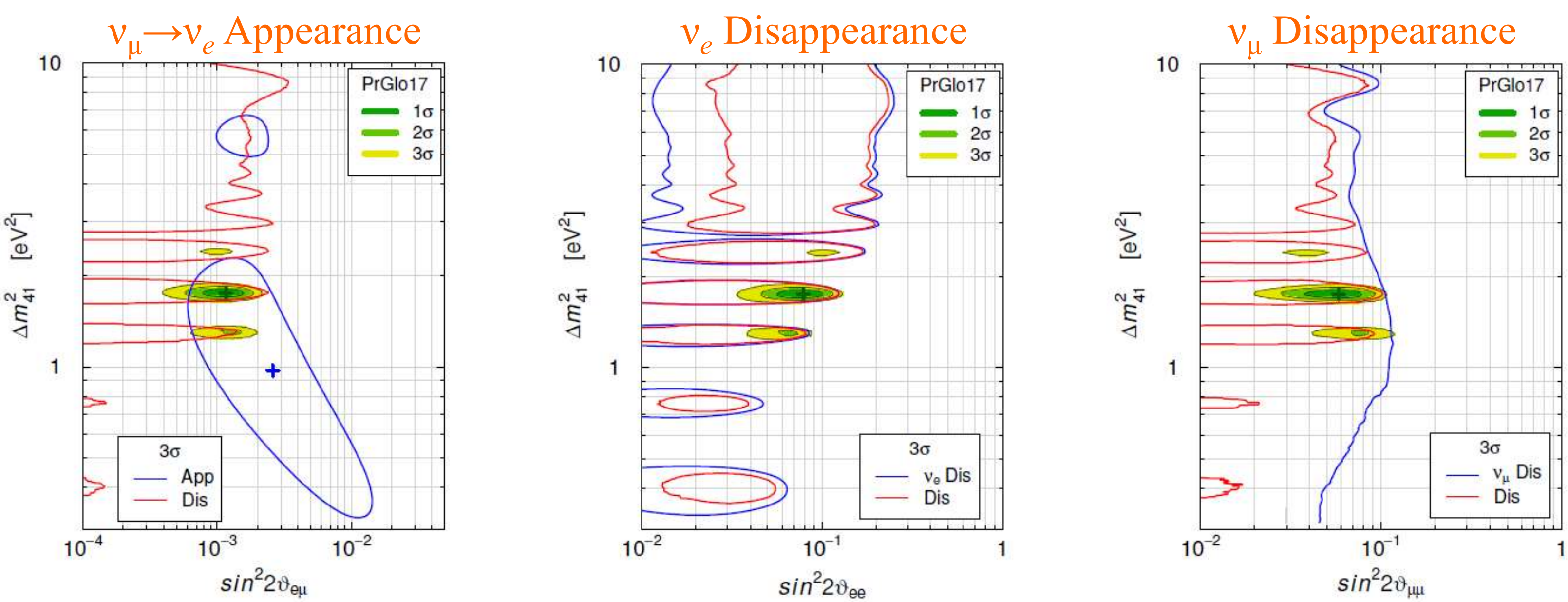


Comparing/Combining Different Measurements

1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

$$P_{\mu e} \approx \tfrac{1}{4} P_{ee} P_{\mu\mu} \quad \text{(at oscillation maxium)}$$

2. So you can have ν_e disappearance without ν_e appearance, but you can't have ν_e appearance without ν_μ disappearance.



Giunti *et al.*, JHEP 06, 135 (2017)

The absence of ν_μ disappearance is a huge problem for the LSND and MiniBooNE appearance signals, while the ν_e disappearance anomalies are consistent with all existing data.

Lessons Learned from the Different Methods

The different experiments have different strengths and weaknesses.

Method	Examples	Sources of Uncertainty				
		Flux	Cross Section	Event ID	Statistics	Background
Decay-at-Rest Appearance	LSND, KARMEN					
Decay-in-Flight Appearance	MiniBooNE					
Decay-in-Flight ν_μ Disappearance	MiniBooNE, Minos, ICARUS					
Decay-in-Flight ν_e Disappearance	T2K					
Reactor	Bugey					
Source	Gallex, SAGE					
Atmospheric Matter Enhanced ν_μ Disappearance	IceCube					

Good Marginal Limiting

Requirement for Disappearance Experiments

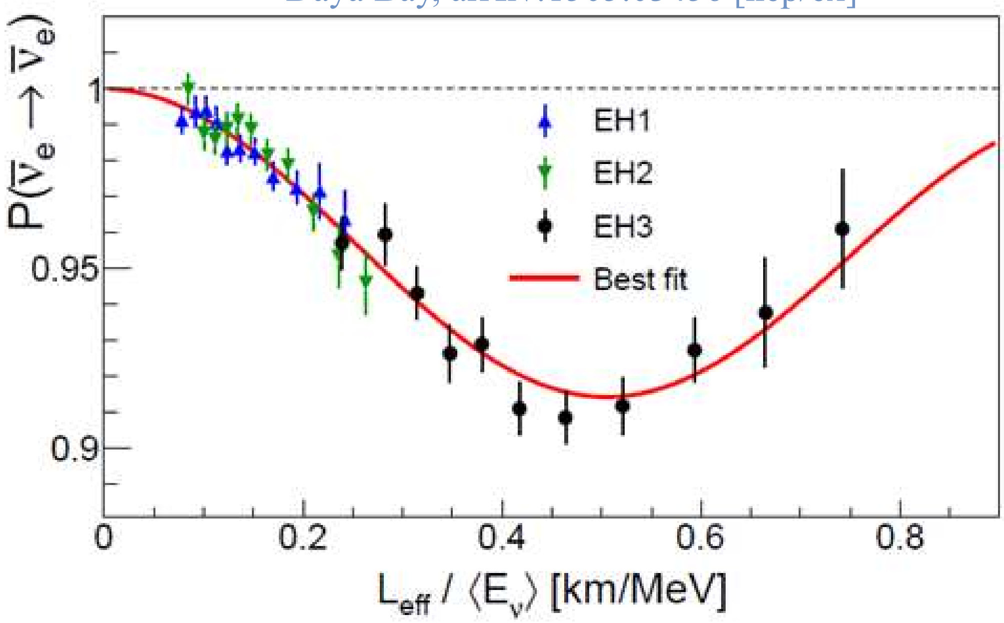
"It don't mean a thing if it ain't got that swing"

–American jazz great Duke Ellington

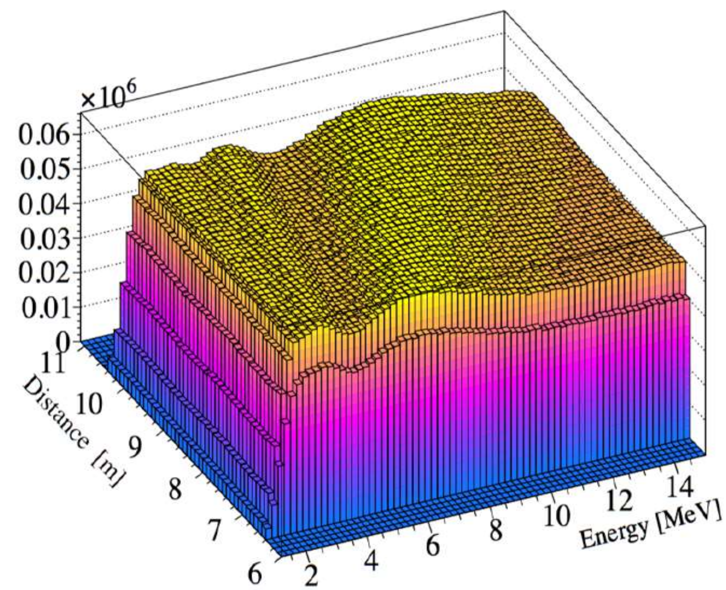
Definition:

oscillometry, *n.*, The observation and measurement of oscillations.

Daya Bay, arXiv:1505.03456 [hep/ex]



Possible oscillations in a short-baseline reactor experiment



In disappearance experiments the existence of sterile neutrinos can ***only*** be convincingly established through oscillometry.

In Tomorrow's Lecture…

Today I've shown you the data up to about a year ago, before the start of a new round of experiments purpose built to address the sterile neutrino issue.

Tomorrow we will look at these new experiments in depth. They include:

- New *many* new reactor experiments
- One approved source experiment and other interesting source proposals
- A three baseline liquid argon detector program in Fermilab's Booster Neutrinos Beam, and
- A few powerful new concepts that have been proposed.