Sterile Neutrinos I

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VIRGINIA TECH

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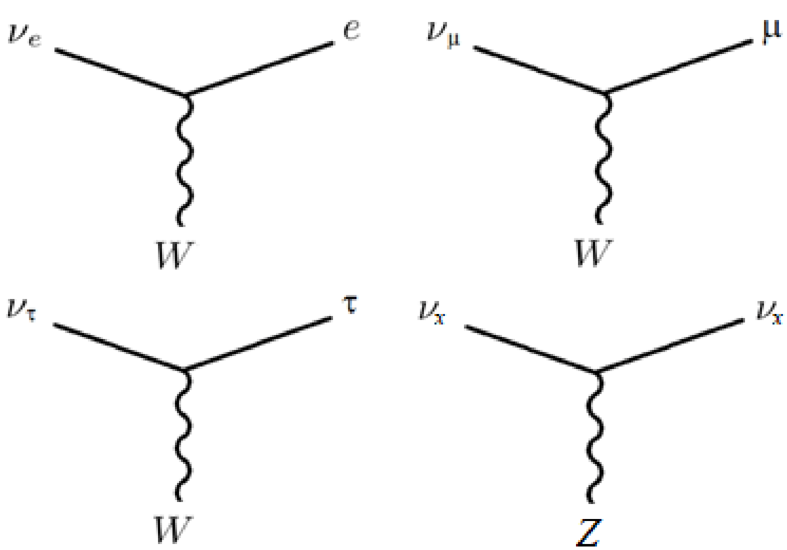
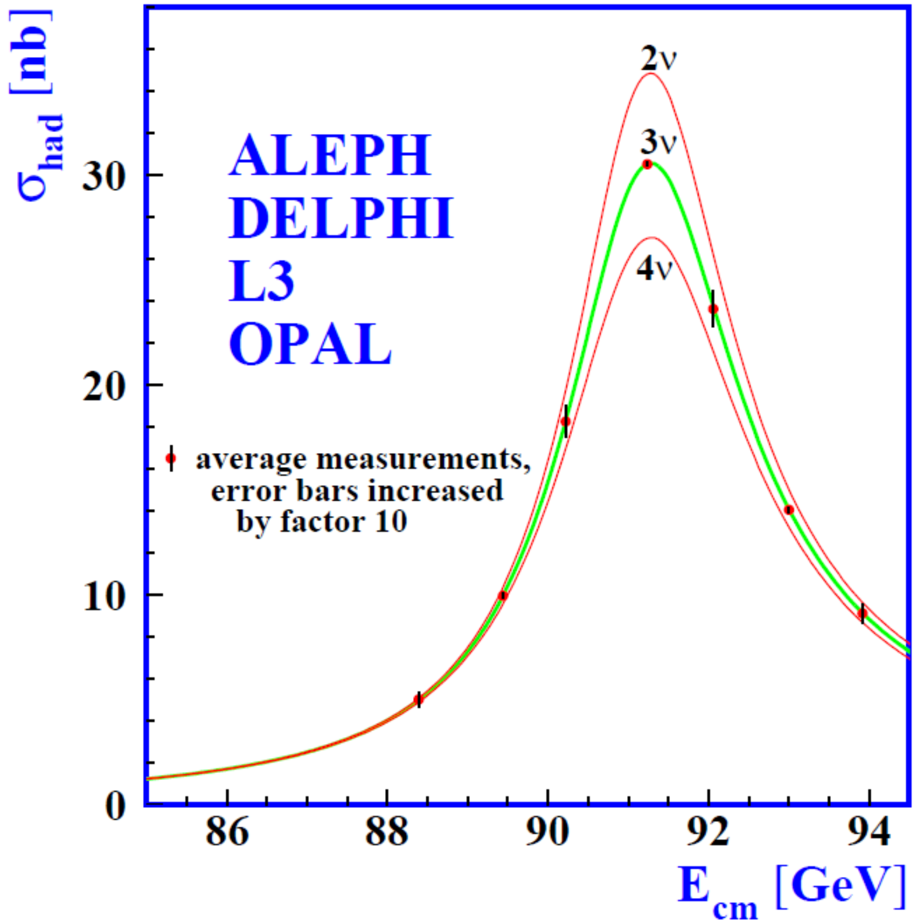
Sterile Neutrinos

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

Active neutrinos:



Phys.Rept. 427, 257 (2006)

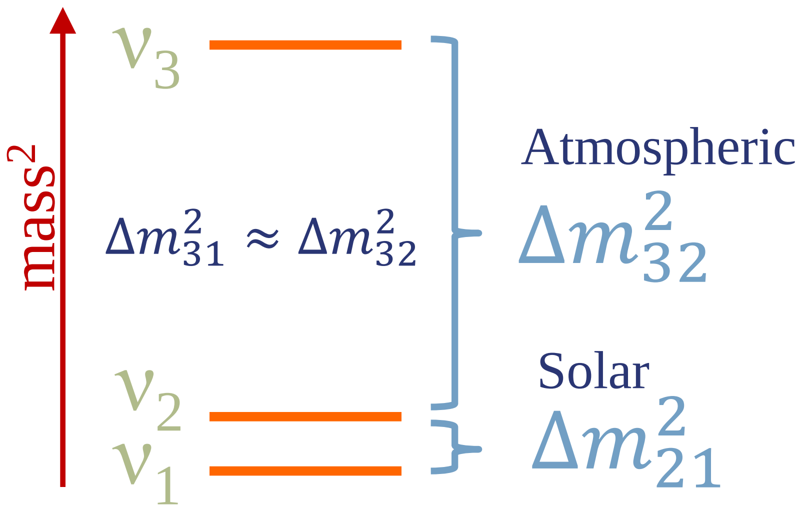


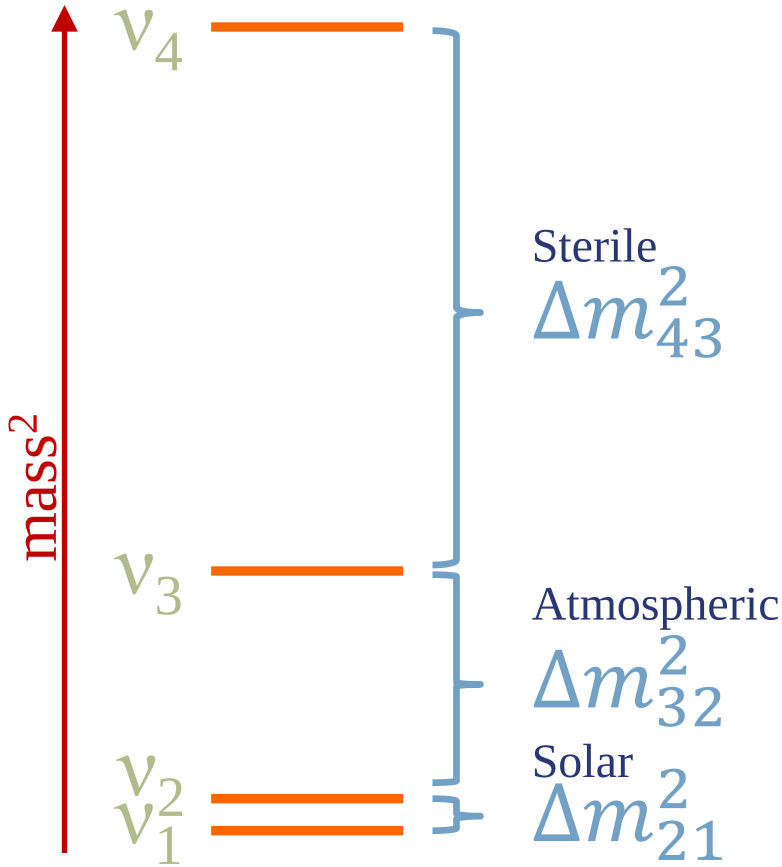
LEP Invisible Z^0 Width is consistent with only three light active neutrinos

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's a third Δm^2 scale there must be a fourth neutrino.

What's the Evidence for a 4th Neutrino?

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 (many experiments)

5. ν_e disappearance (T2K)

What’s the Evidence ~~for~~ *Against* a 4th Neutrino?

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

1b. $\bar{\nu}_e$ appearance in a π DAR 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 DIF beams (MiniBooNE, ICARUS)

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

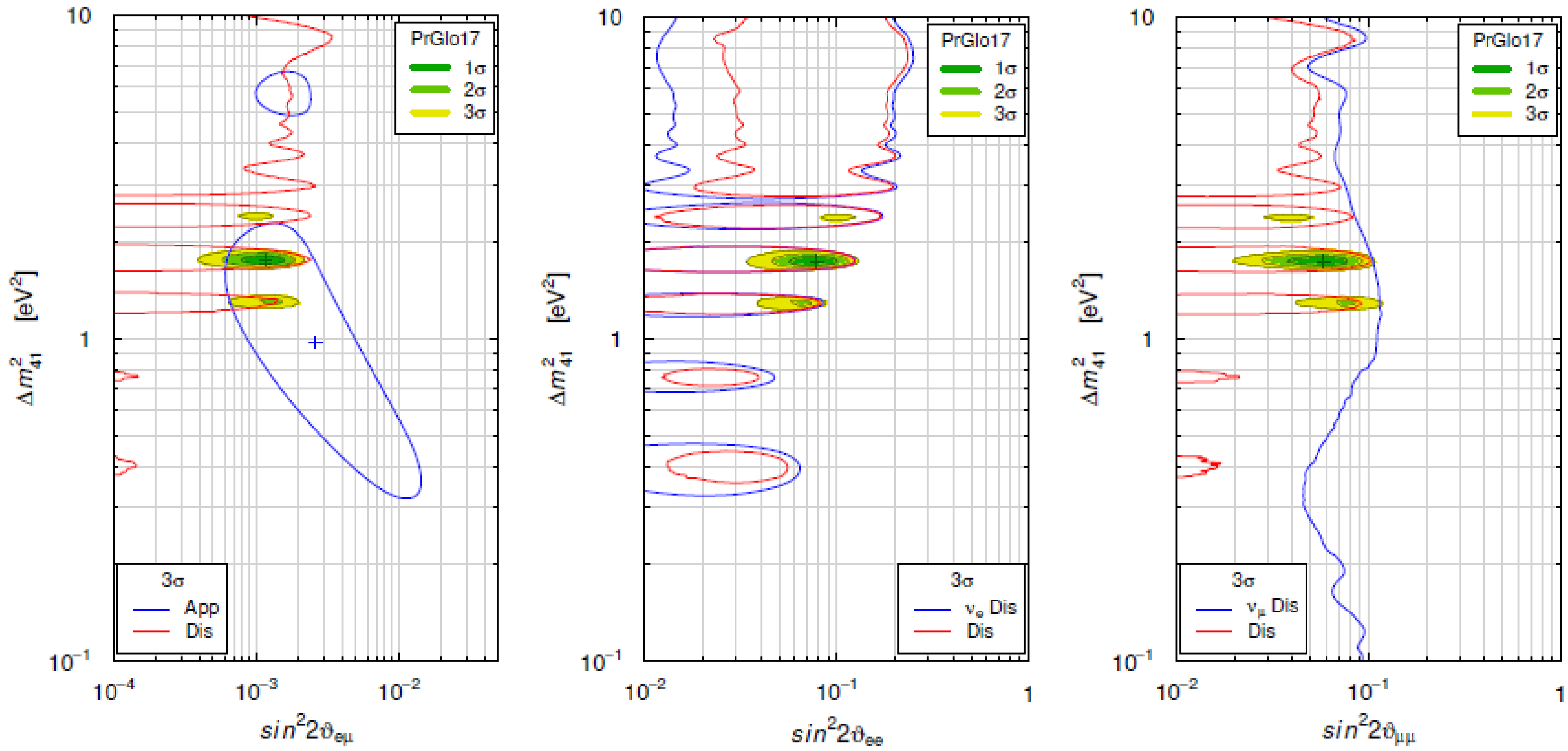
4. Reactor Anomaly: $\bar{\nu}_e$ disappearance (many experiments)

5. ν_e disappearance (T2K)

6. ν_μ disappearance (MiniBooNE/SciBooNE, Minos)

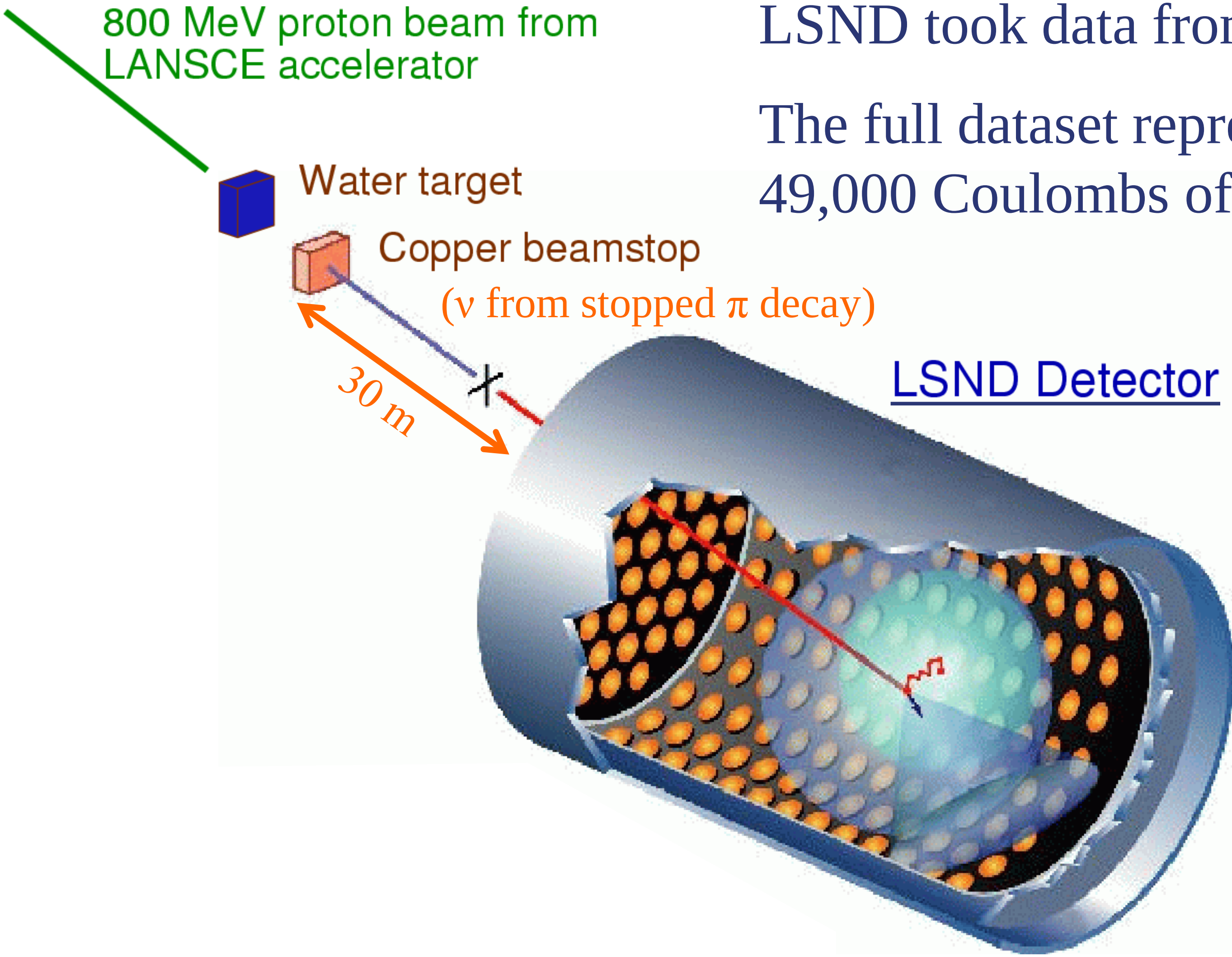
What's the Evidence for a 4th Δm^2 Scale?

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

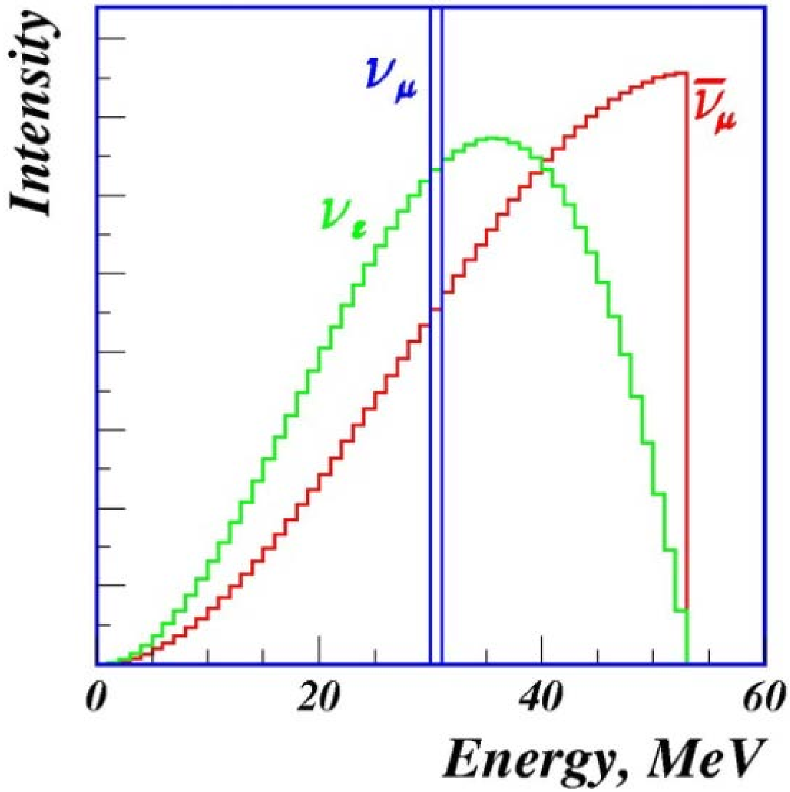
Stopped Pion Beam

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:

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



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.

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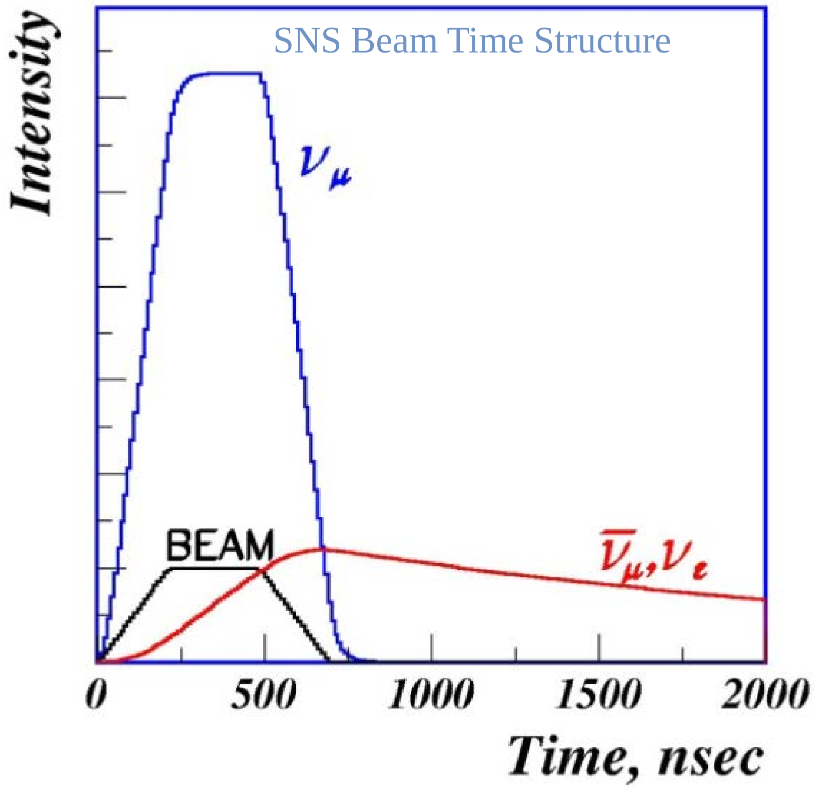

The ν_μ come promptly with the beam, while the $\bar{\nu}_\mu$ and ν_e have a 2.2μs mean delay from muon decay.

Oscillation Signal Golden Mode:

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation followed by $\bar{\nu}_e$ inverse beta decay detection

The LSND Experiment

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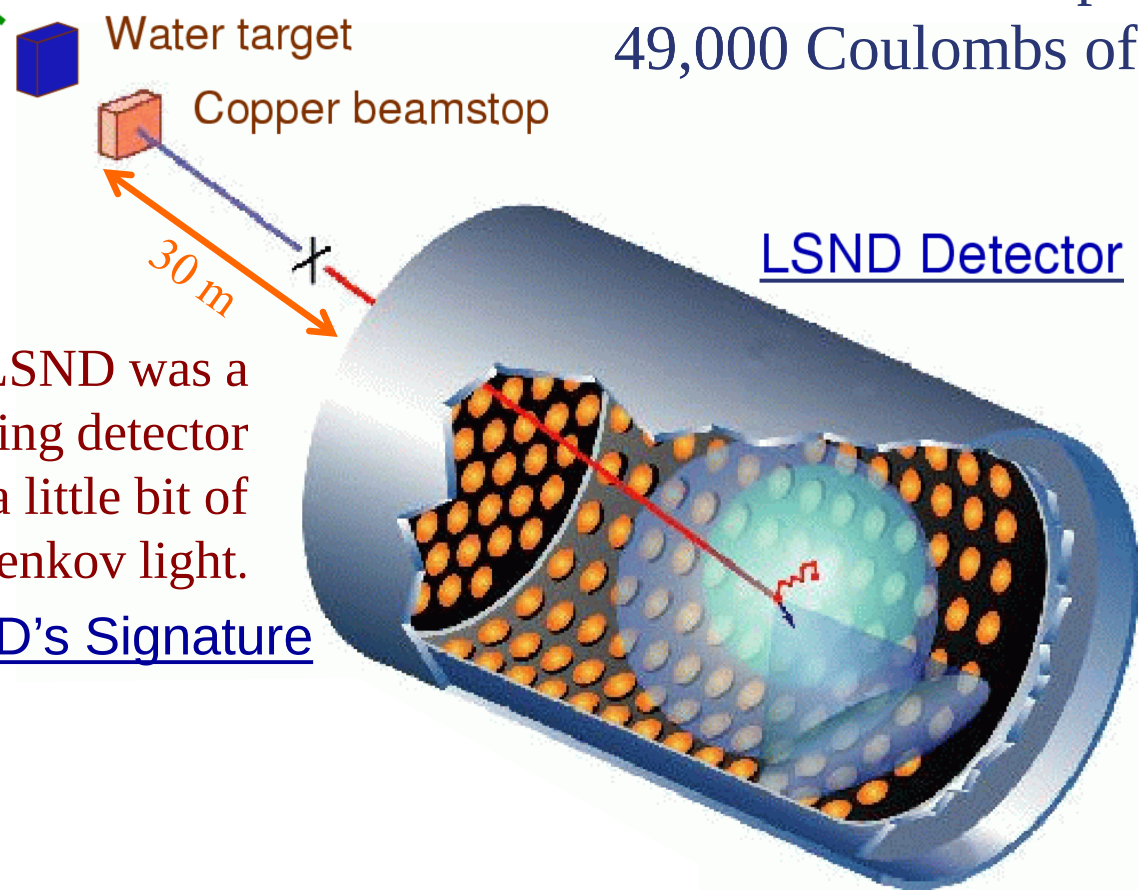
The full dataset represents nearly 49,000 Coulombs of protons on target.



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

LSND's Signature

Baseline: 30 m

Energy range:
20 to 55 MeV

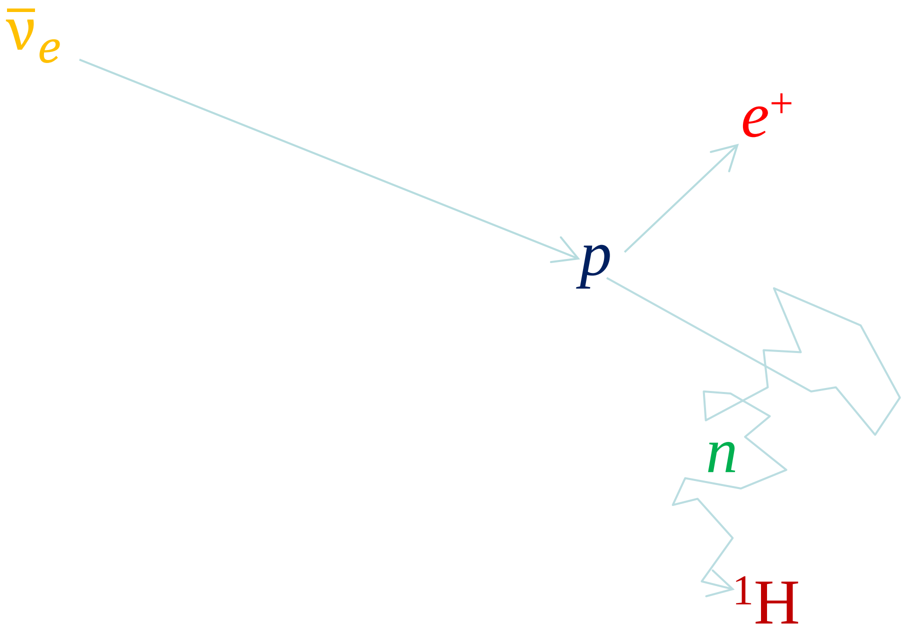
L/E ~ 1 m/MeV

Inverse Beta Decay

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

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

Followed by neutron capture which tags the IBD event.

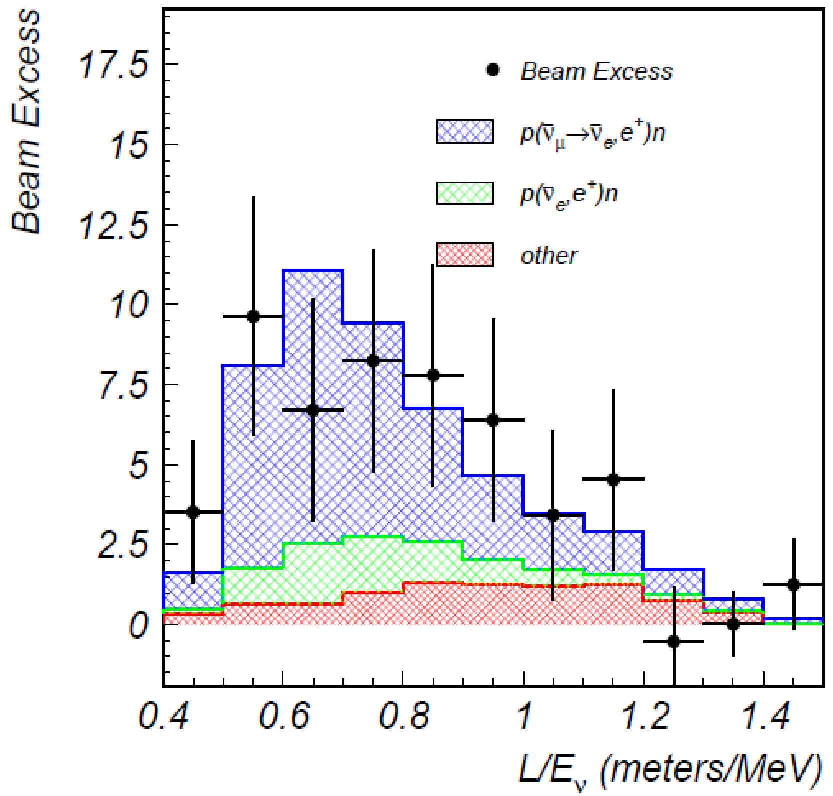


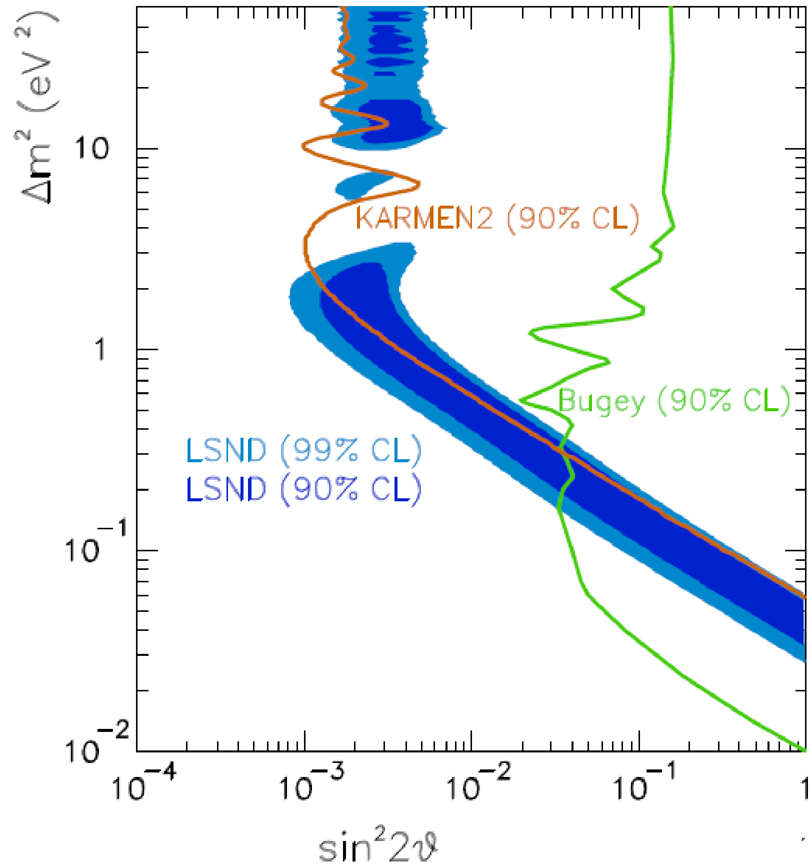
Capture Isotope	Products
^1H (p)	γ (E= 2.2 MeV)
Gd	γs (E_{tot} = 8 MeV)
^6Li	$^4He + {}^3H$ (E_{tot}= 4.78 MeV)

LSND used hydrogen

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

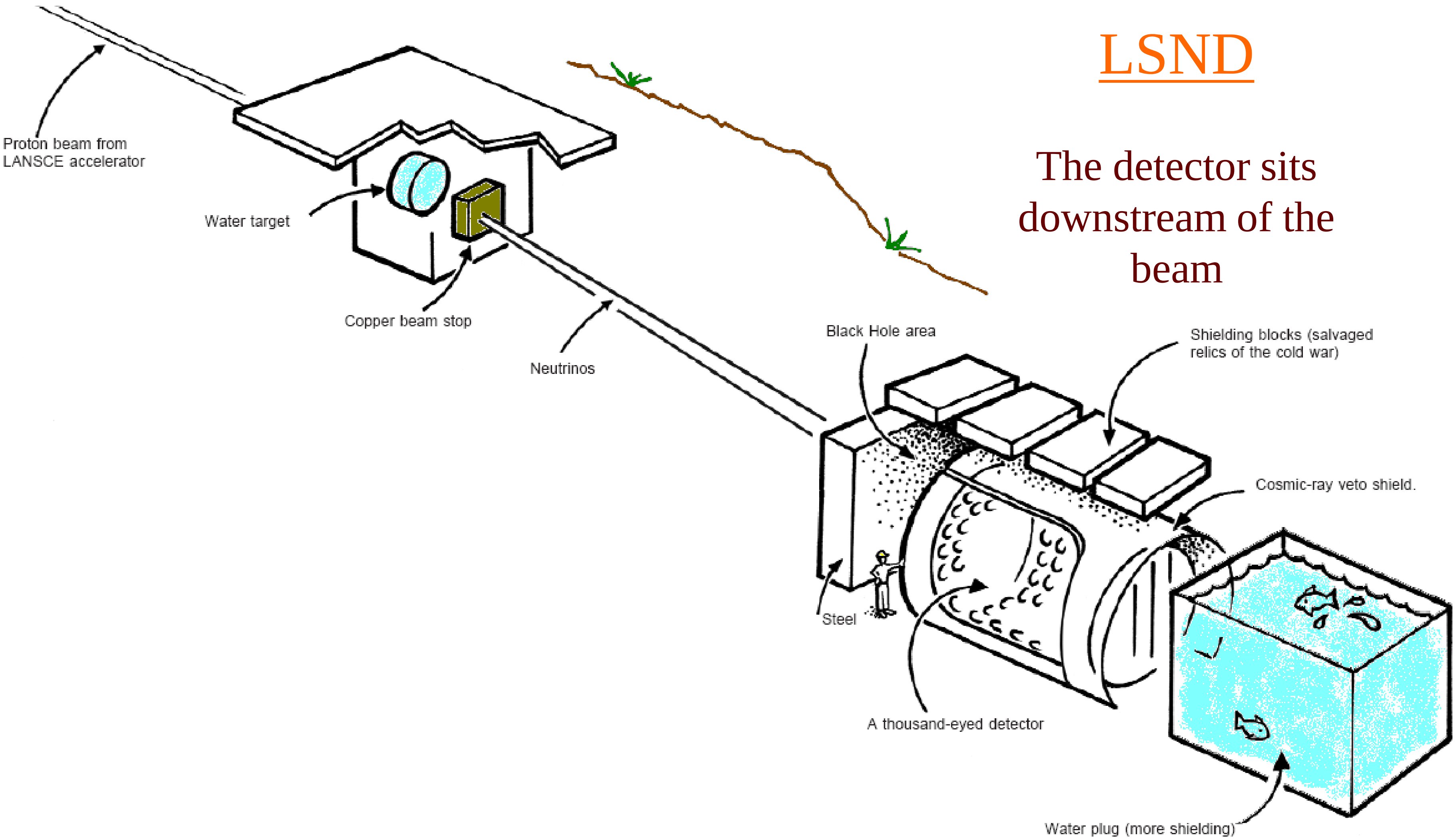
Aguilar-Arevalo *et al.*, Phys.Rev. D64, 112007 (2001)





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

The LSND Experiment

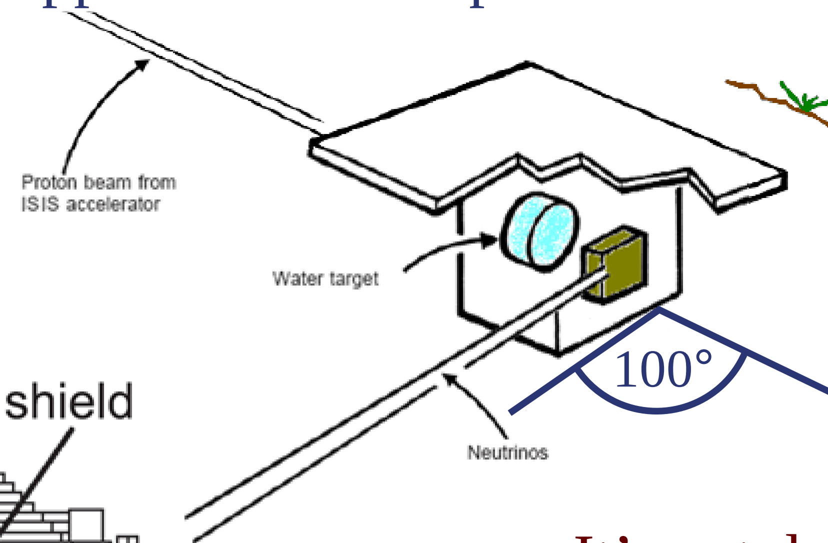


LSND

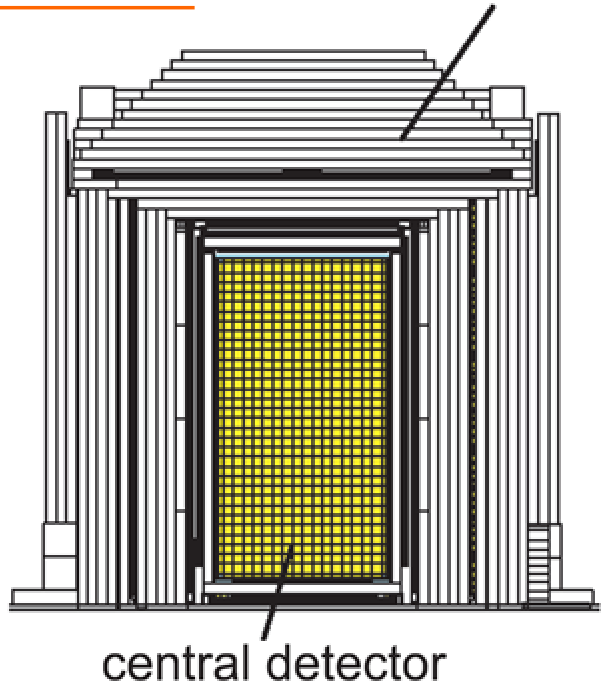
The detector sits downstream of the beam

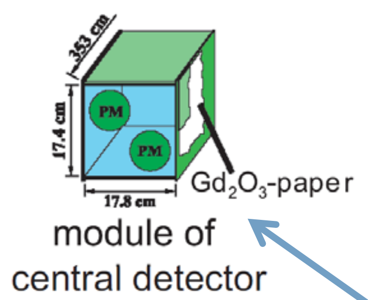
The KARMEN Experiment

KARMEN was a stopped π^+ beam experiment like LSND



[Karmen]





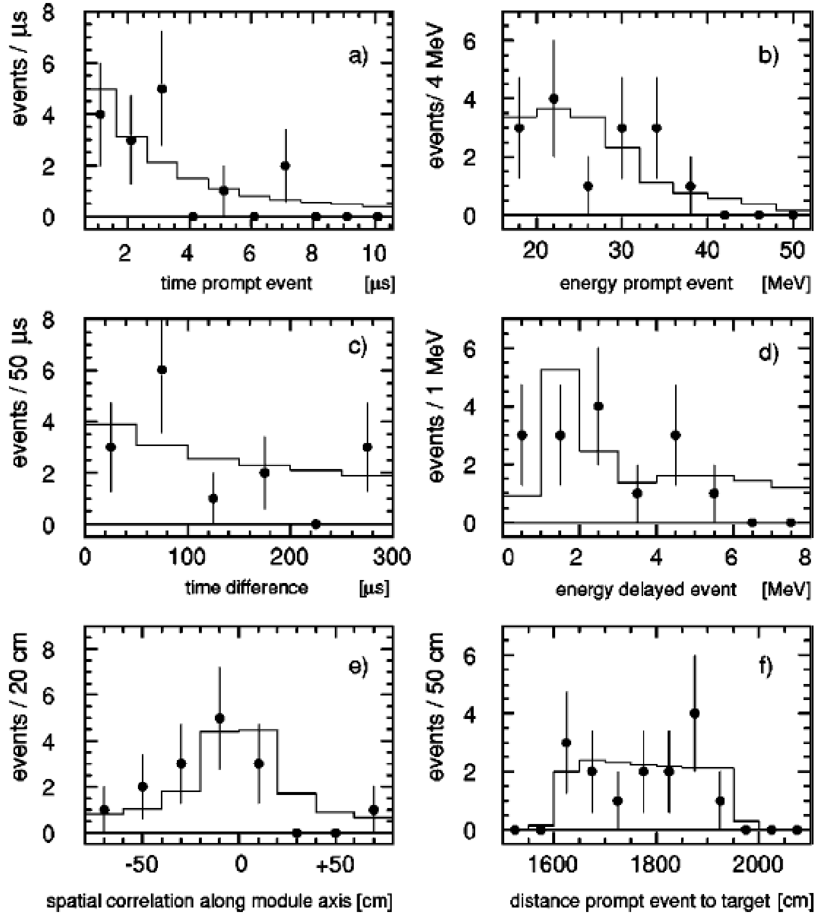
It's not downstream of the beam

The baseline is only 18 meters

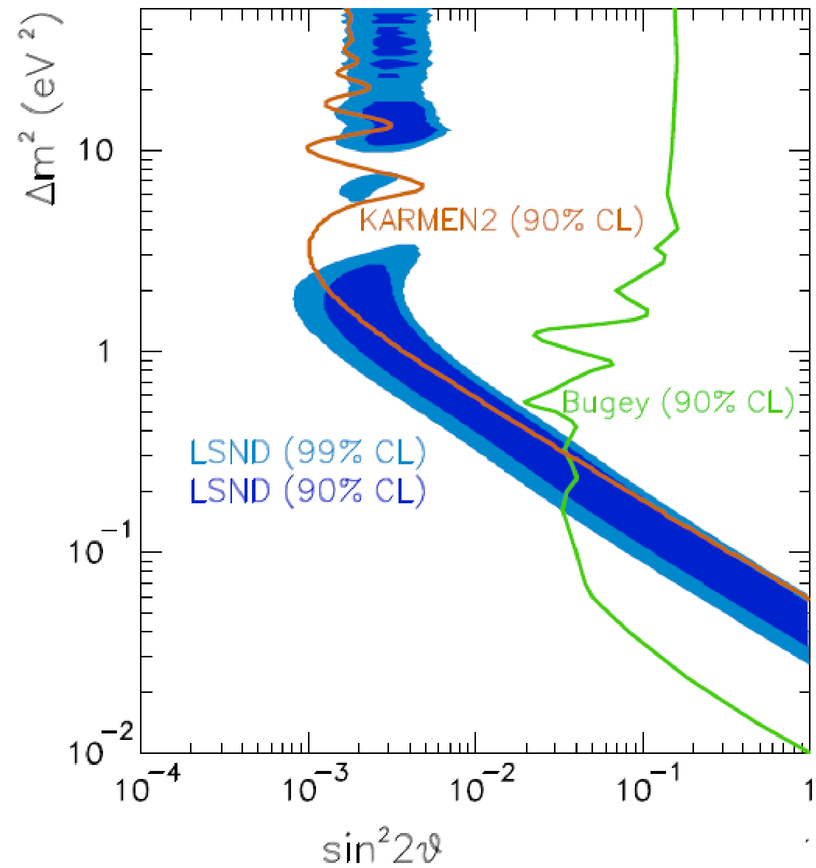
It used gadolinium to tag neutron capture

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



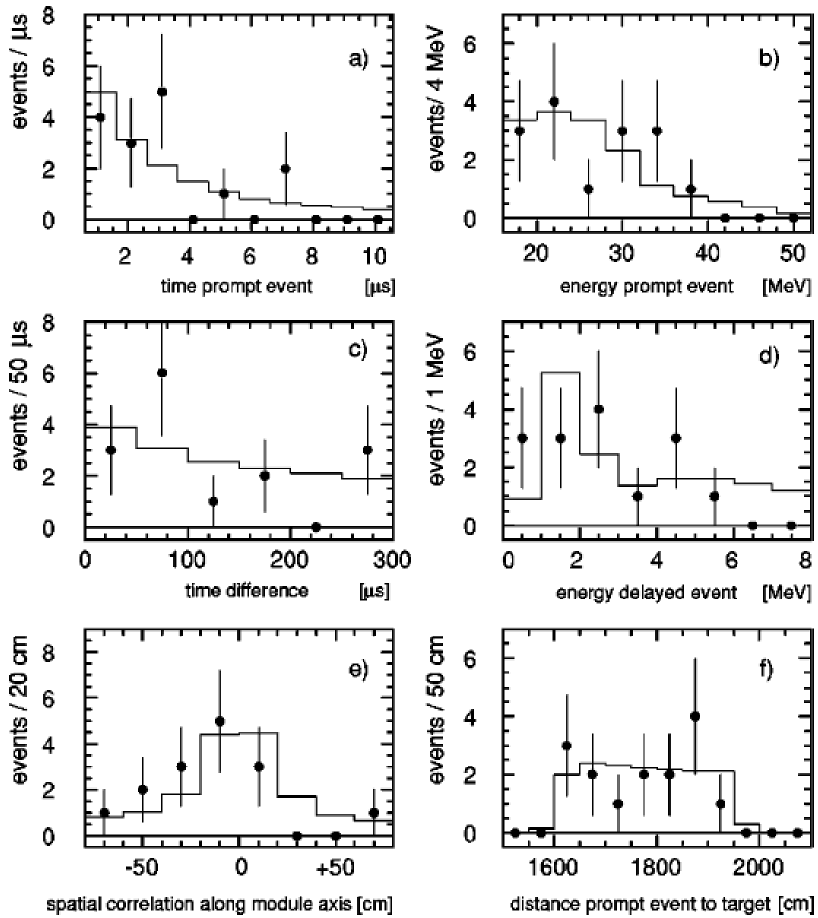
Baseline: 18 m

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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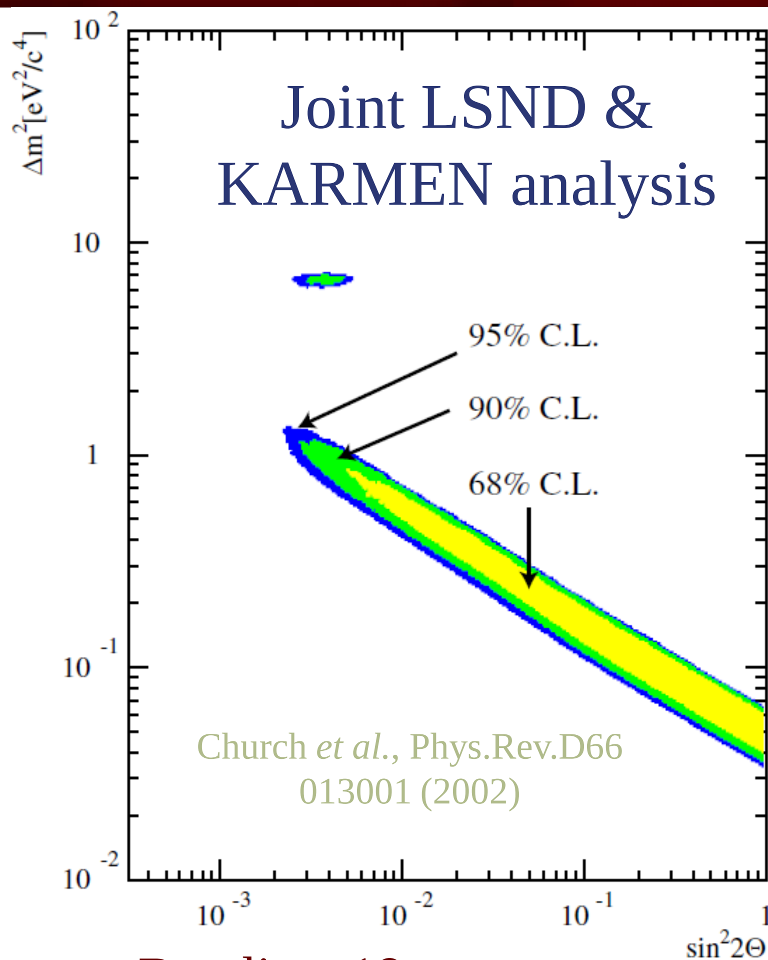


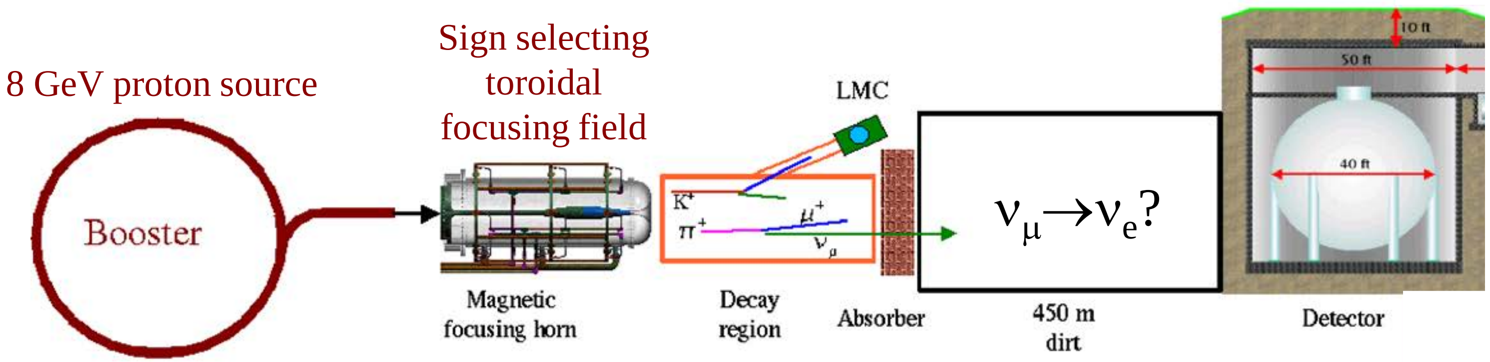
Baseline: 18 m

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 decay within the 50 meter decay pipe, but most muons do not. The result is a ν_μ beam.

<u>π^+ (π^-) decay in flight beam</u>

Baseline (L) = 500 m (about 15× LSND)

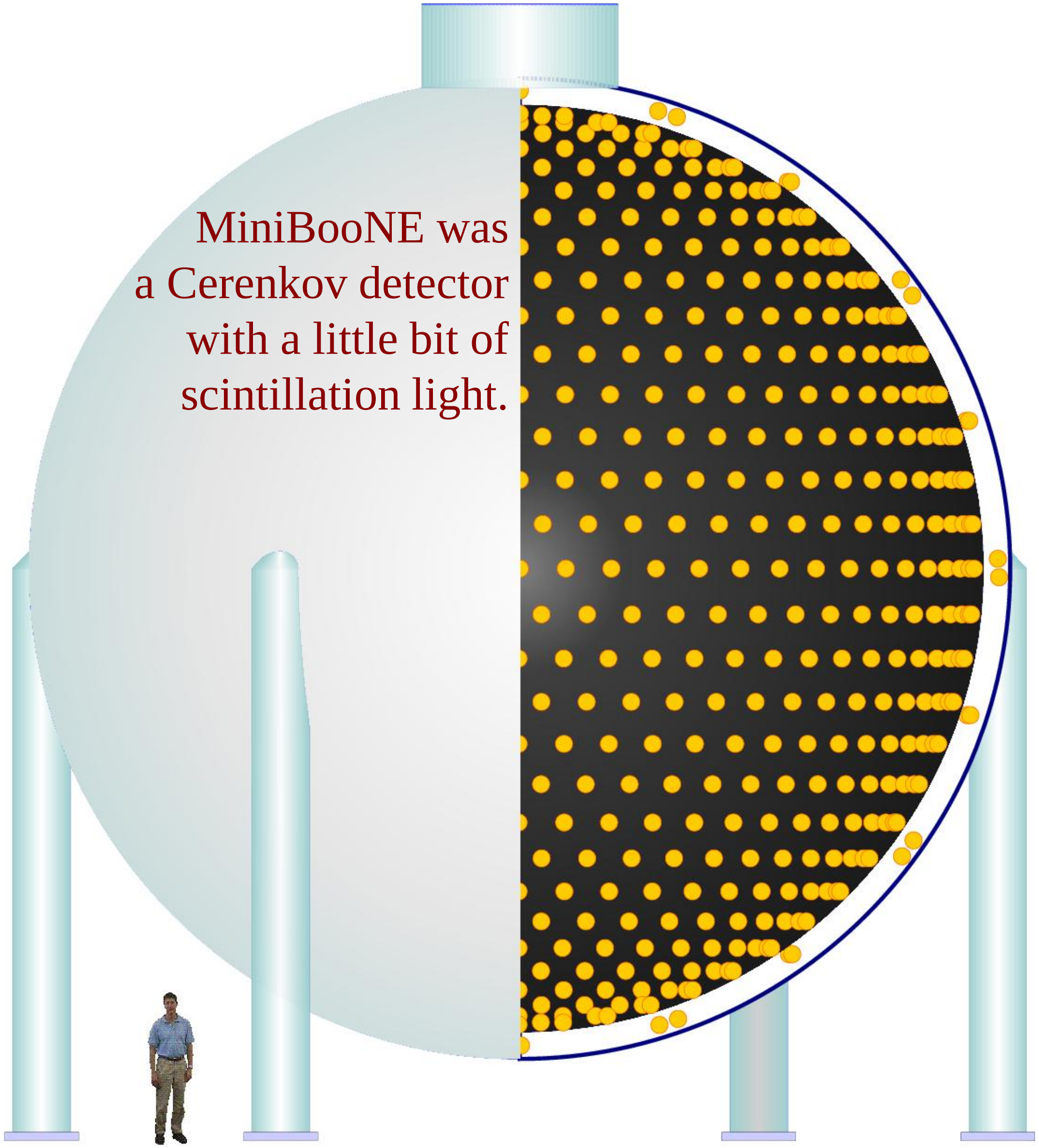
$\langle E_\nu \rangle \sim 500$ MeV (about 15× LSND)

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 detectors.

The MiniBooNE Detector

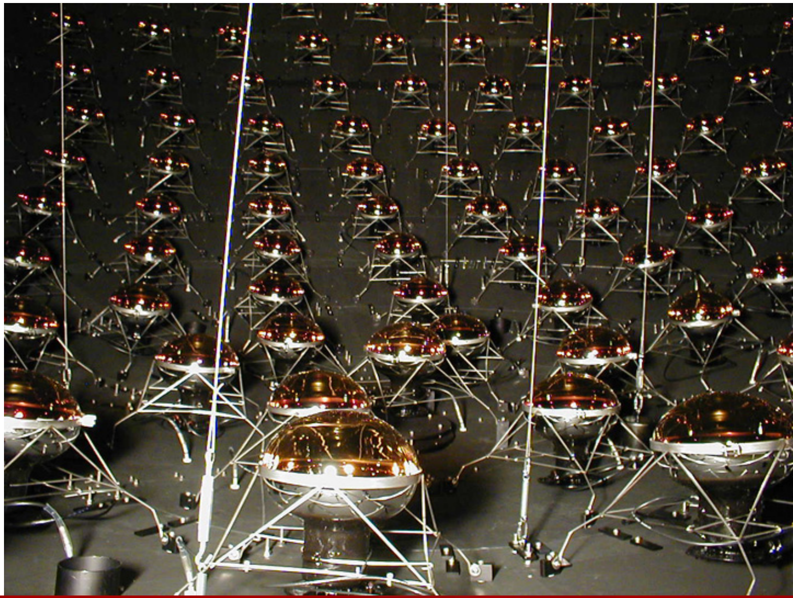


12 meter diameter sphere

Filled with 950,000 liters of pure mineral oil

Light-tight inner region with 1280 photomultiplier tubes

Outer veto region with 240 PMTs.



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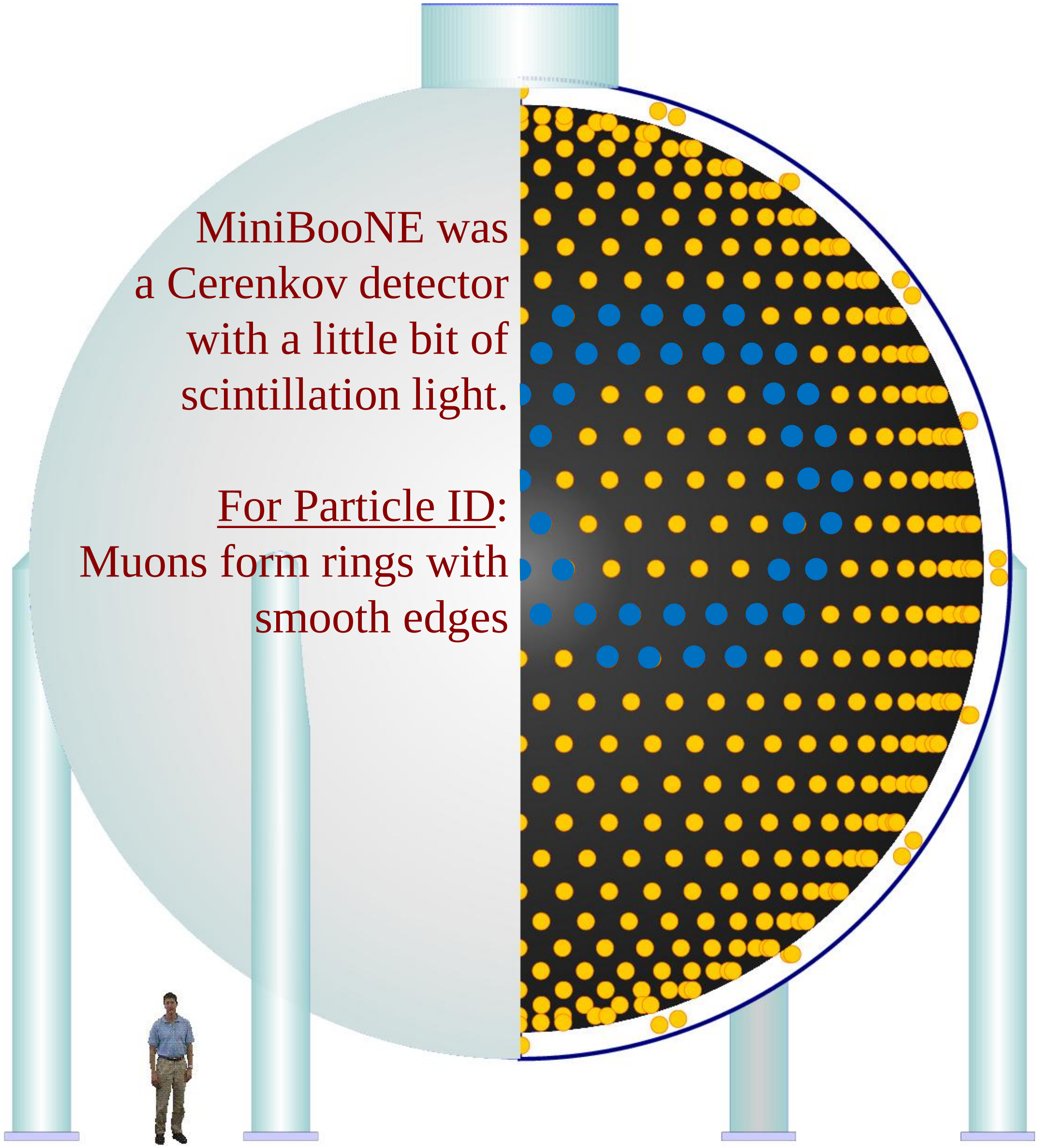

MiniBooNE was
a Cerenkov detector
with a little bit of
scintillation light.

<u>For Particle ID</u>:
Muons form rings with
smooth edges

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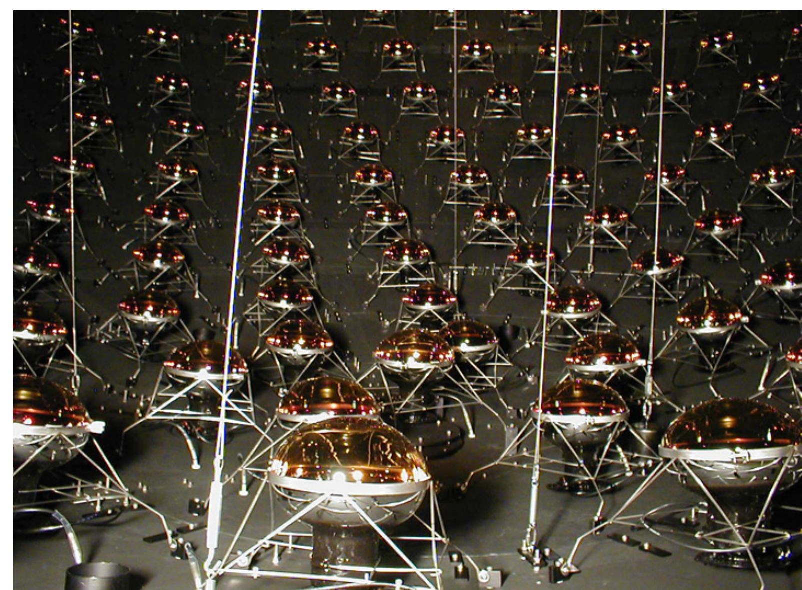

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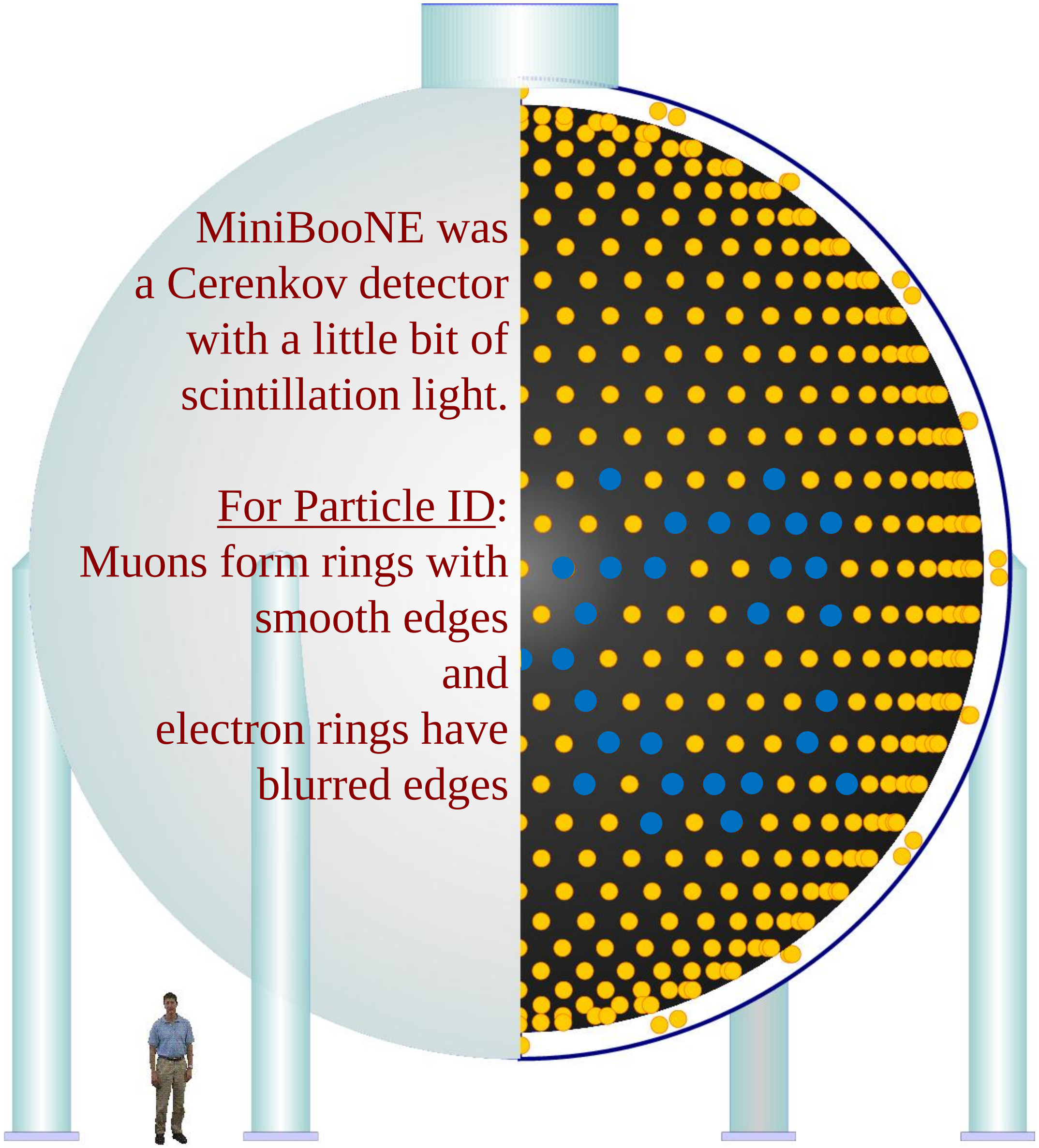

MiniBooNE was
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<u>For Particle ID</u>:
Muons form rings with
smooth edges
and
electron rings have
blurred edges

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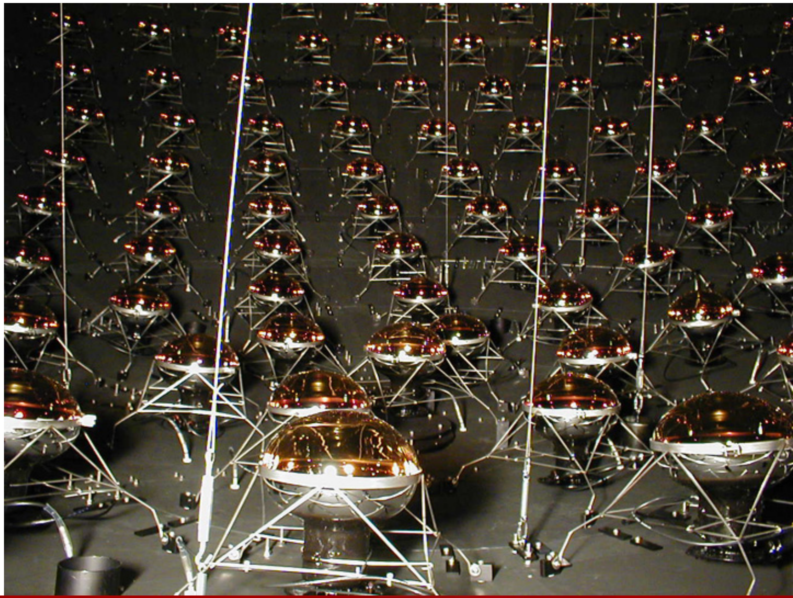
Light-tight inner region with 1280 photomultiplier tubes

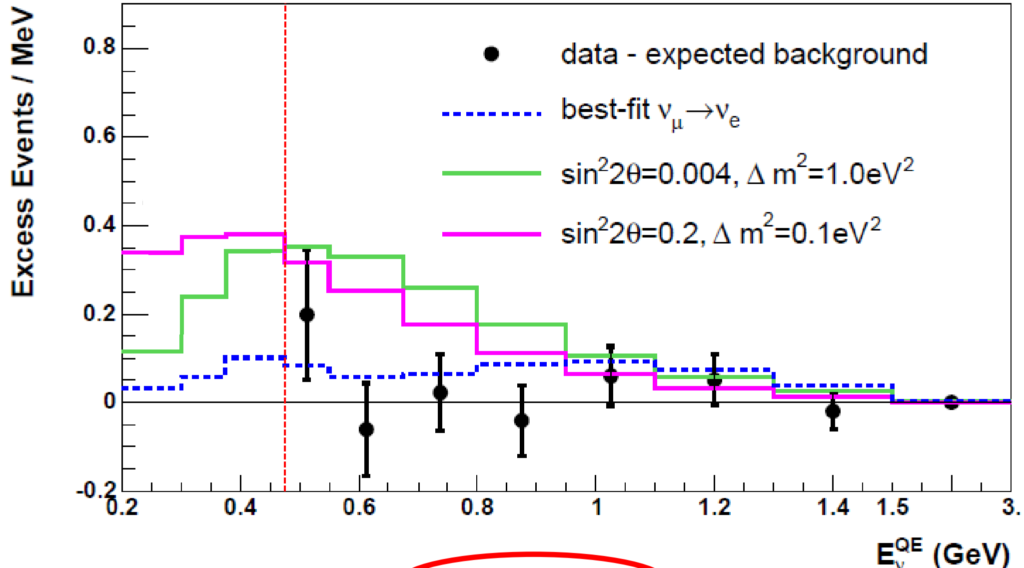
Outer veto region with 240 PMTs.

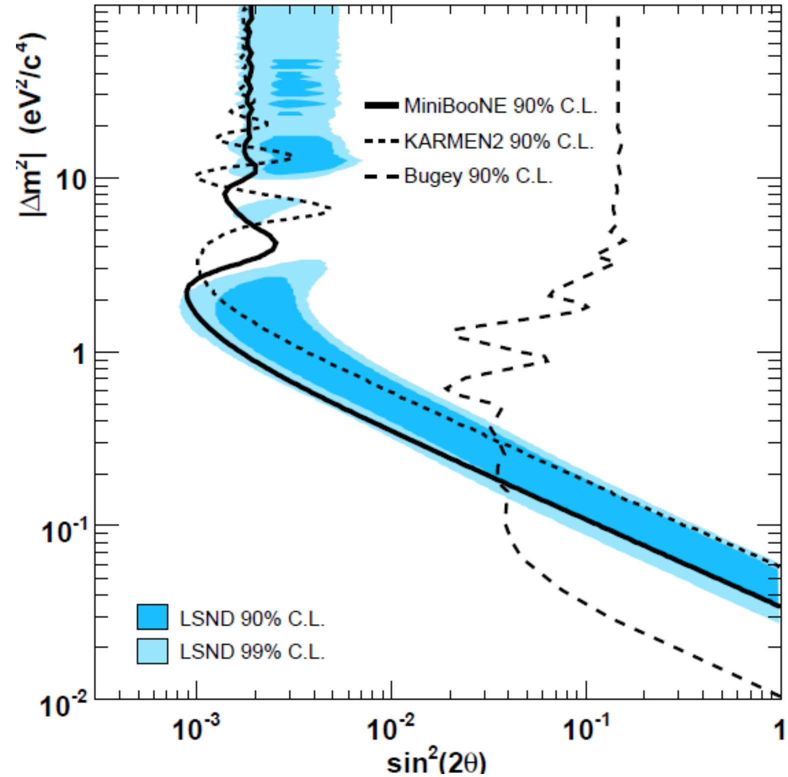


MiniBooNE: $\nu_\mu \rightarrow \nu_e$ Appearance Search

Excess of low-energy events

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





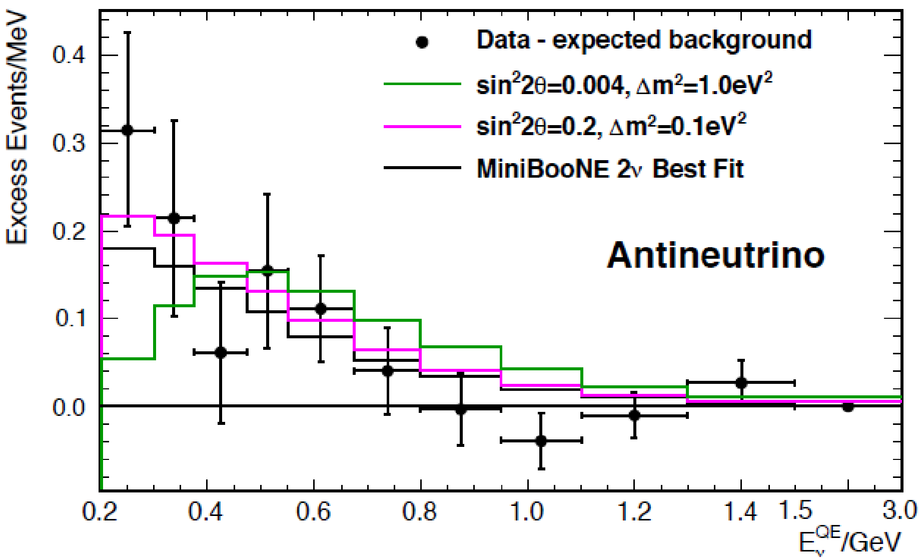
	475 – 1250 MeV
Data	408
Background	385.9 ± 19.6 ± 29.8
Excess	22.1 ± 19.6 ± 29.8
Significance	0.6σ

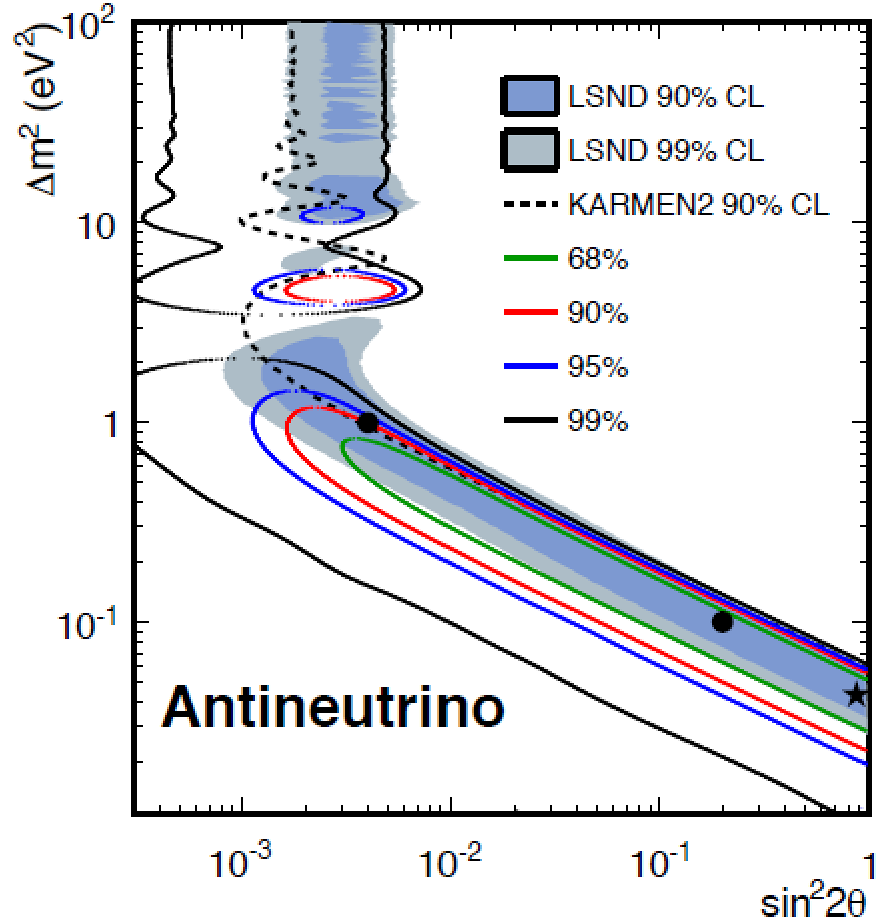
Analysis window selected before opening the box.

MiniBooNE's neutrino search found **no** significant excess that would be consistent with LSND's excess.

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

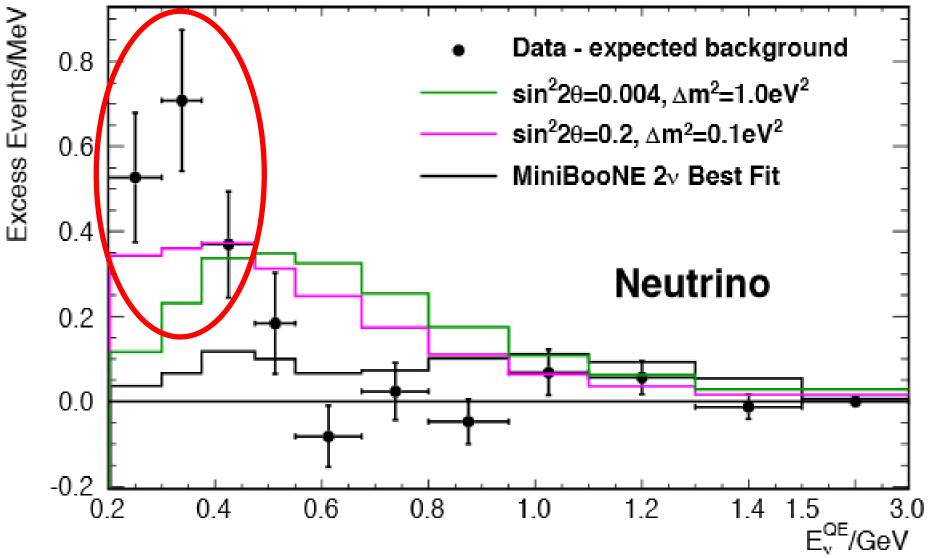
Consistent with LSND

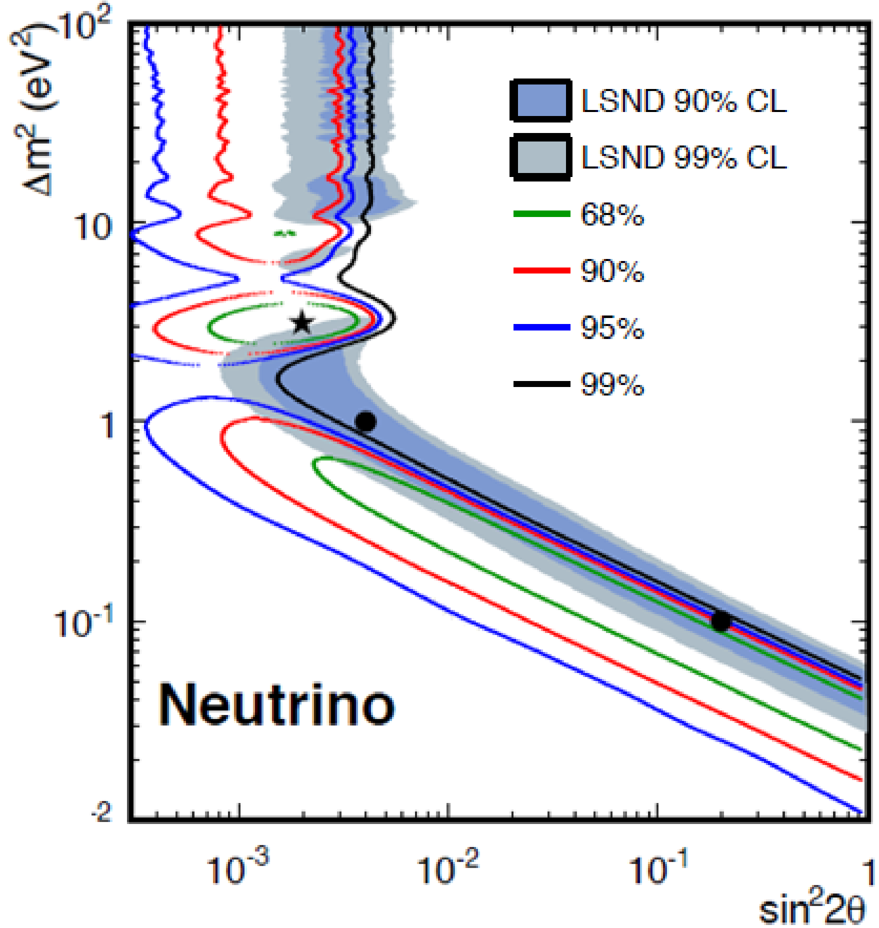
MiniBooNE: $\nu_\mu \rightarrow \nu_e$ Appearance Search

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



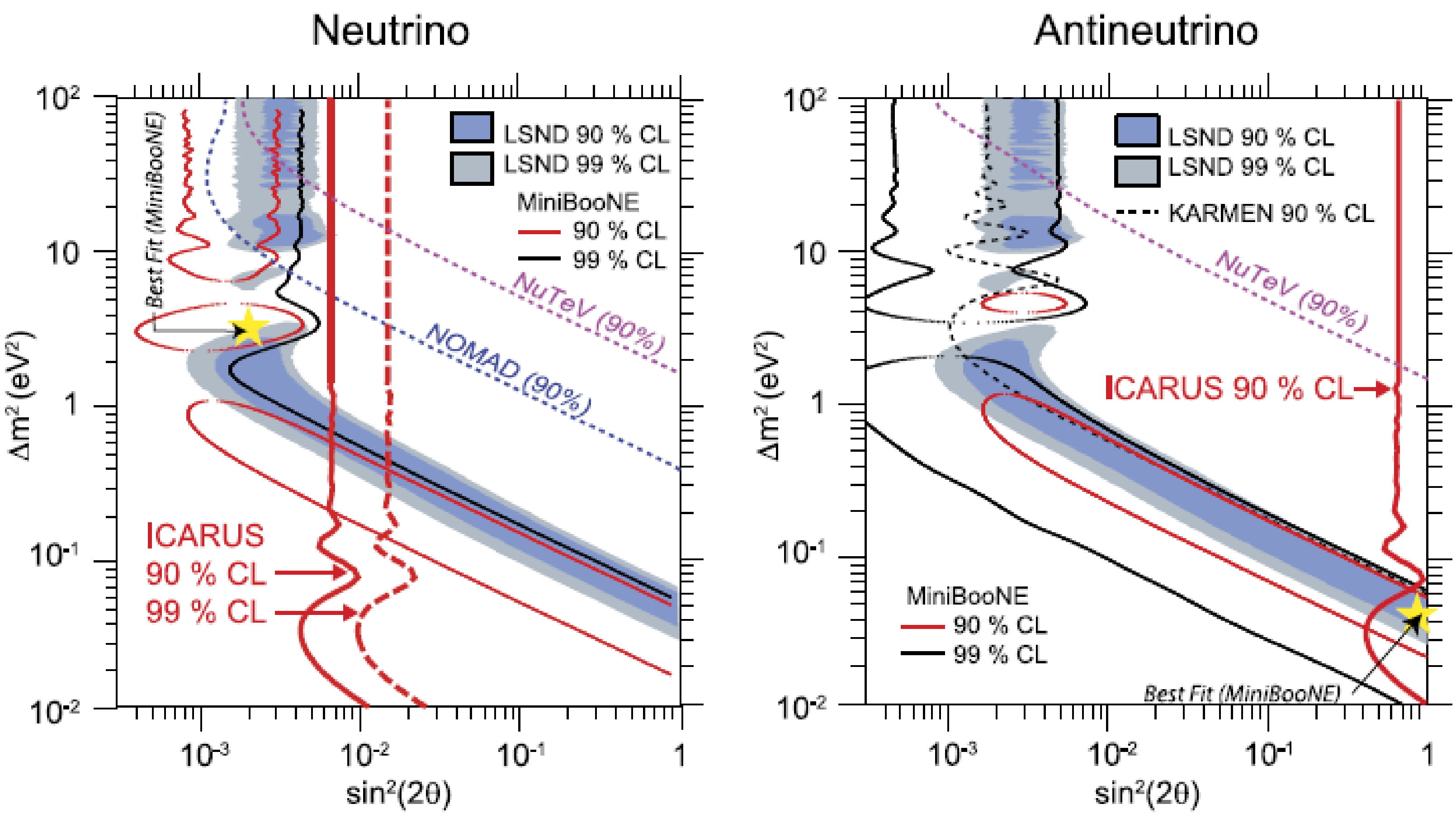


Event Excess: 162.0 ± 47.8

But it's still not very consistent with LSND

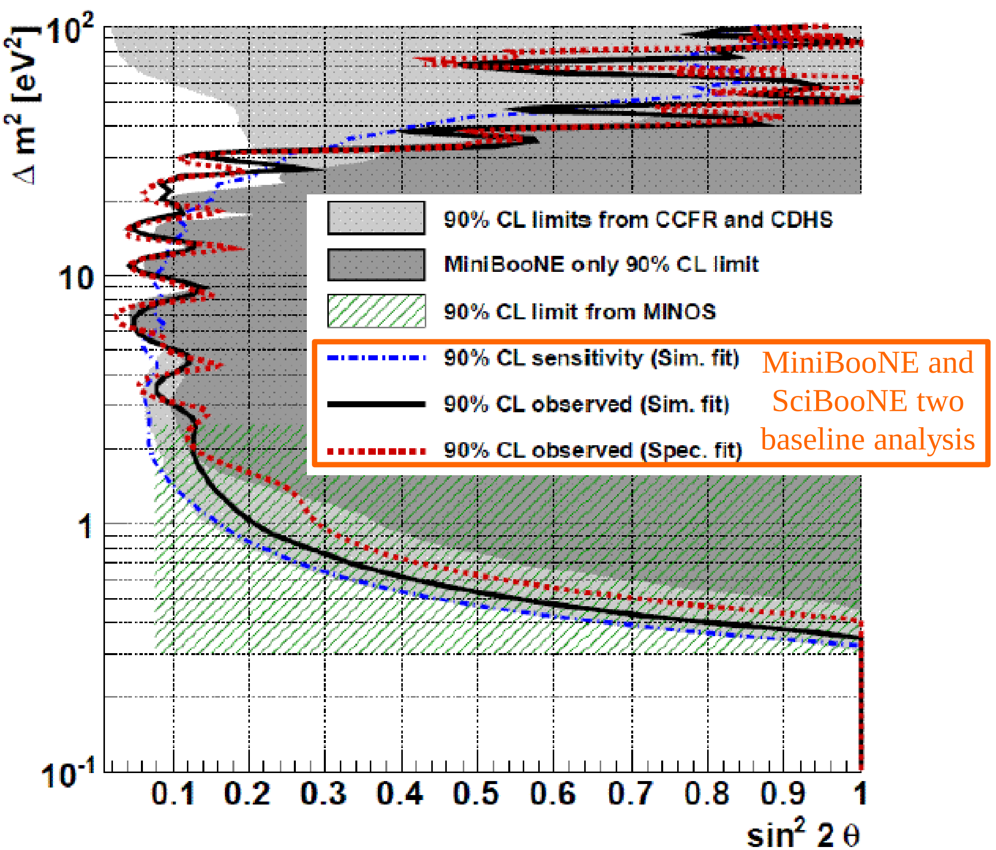
ICARUS: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance Search

In the LNGS beam from CERN to Gran Sasso



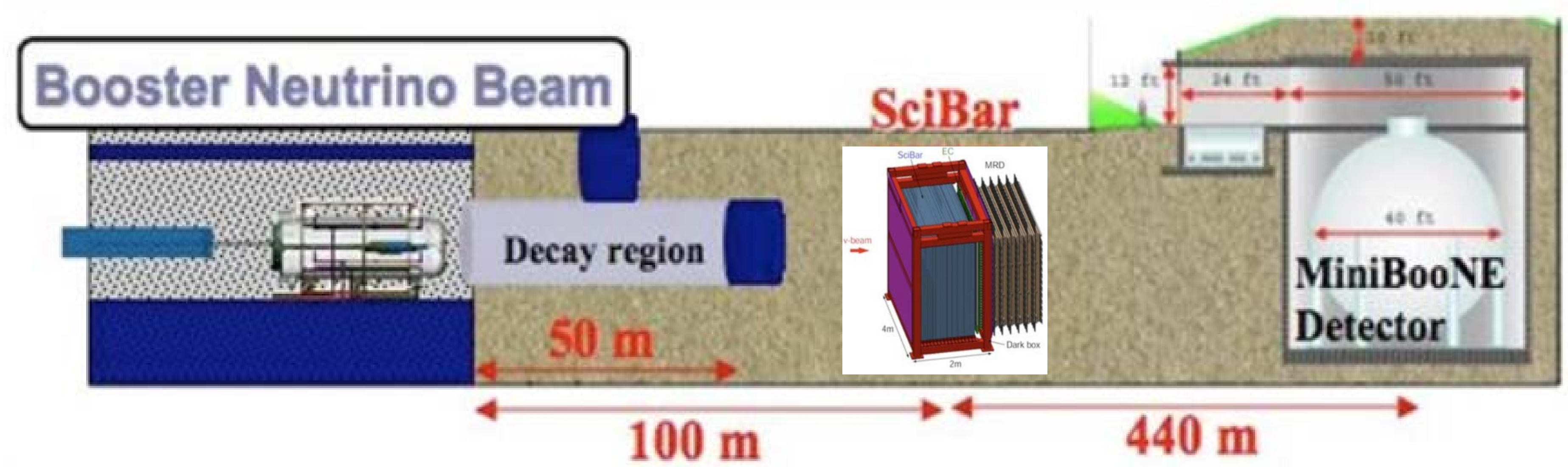
ν_μ and $\bar{\nu}_\mu$ Disappearance

(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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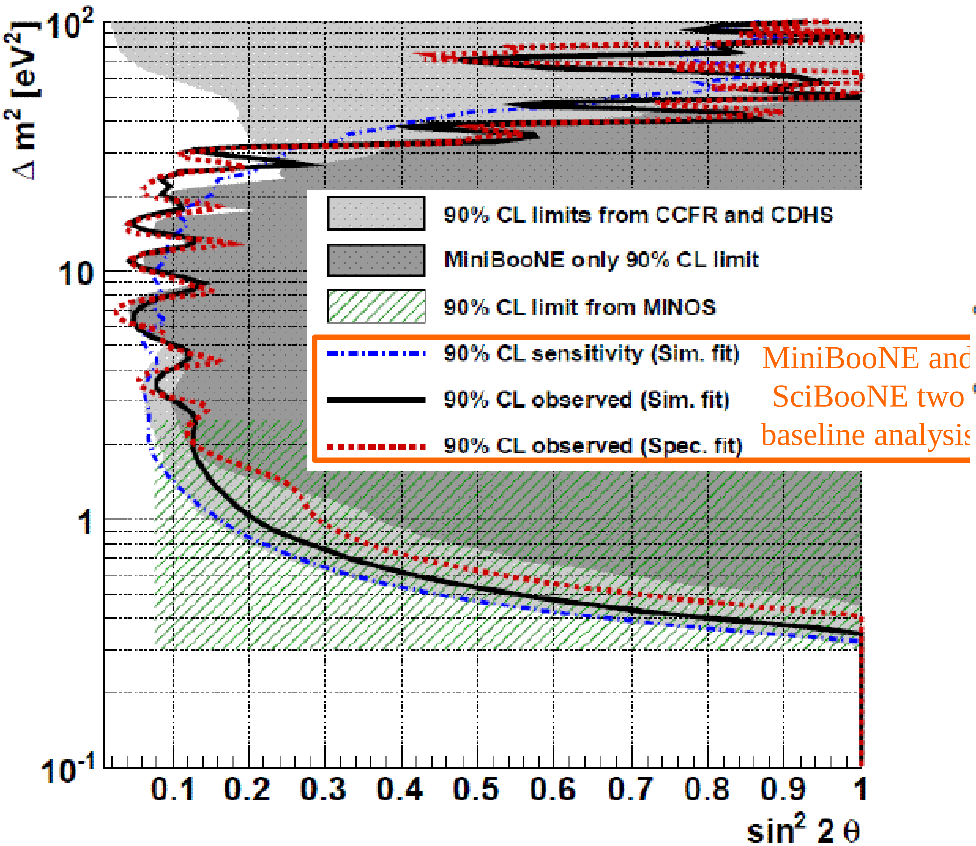

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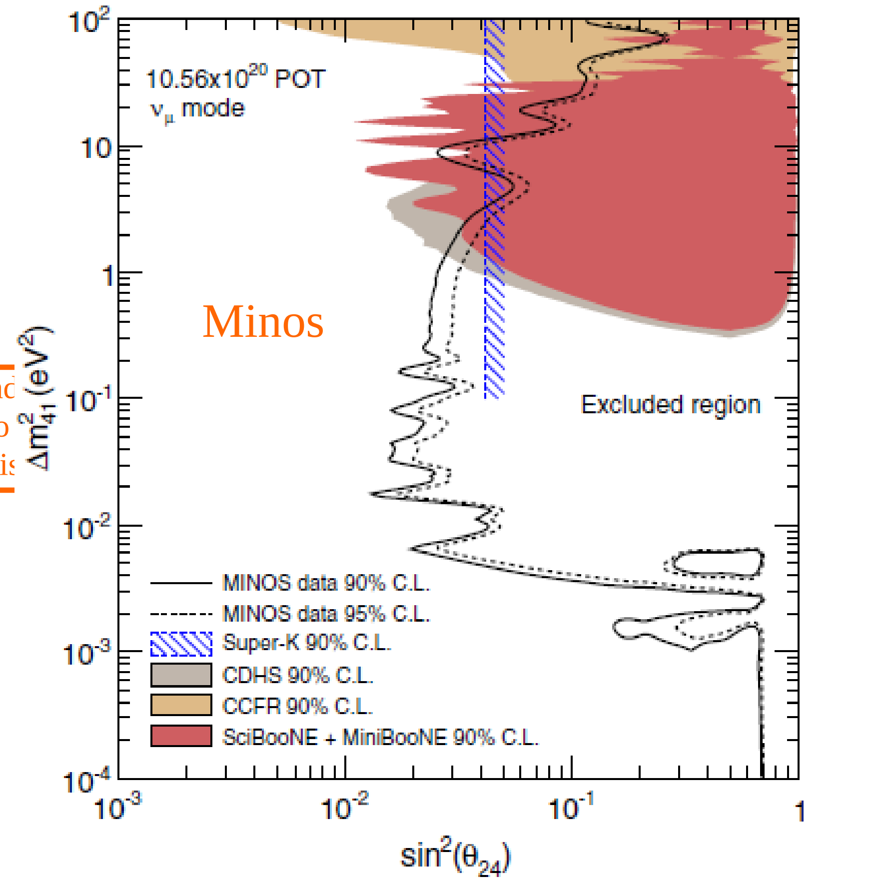


Anderson *et al.*, Phys.Rev.Lett. 117, 151803 (2016)

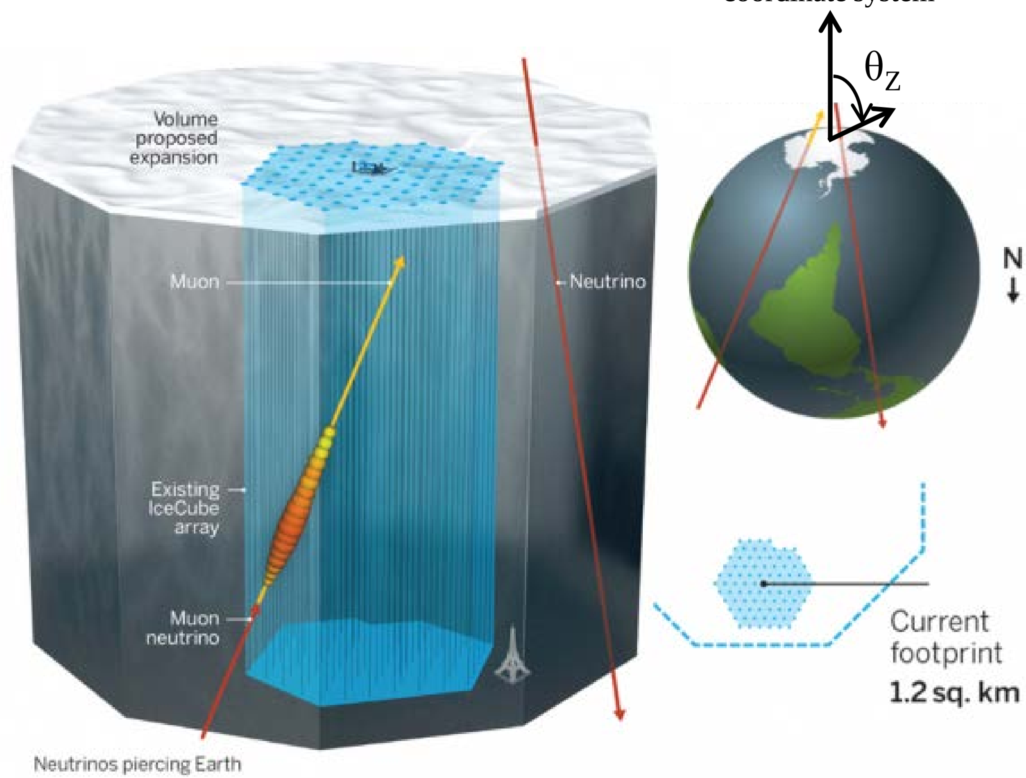
$\sin^2 2\theta_{24}$ is small throughout the region of interest

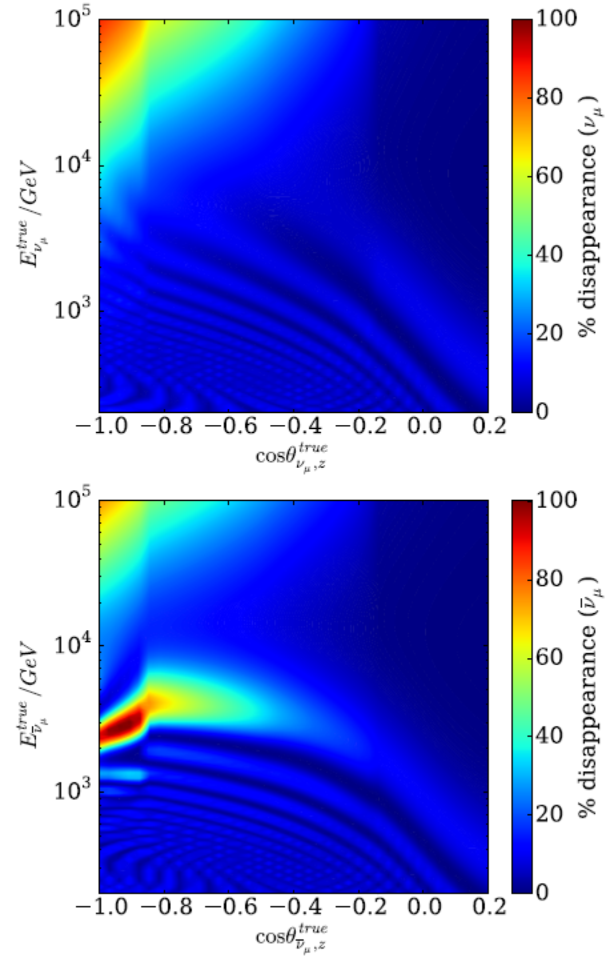
IceCube: ν_μ Disappearance

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.

Definition of their coordinate system

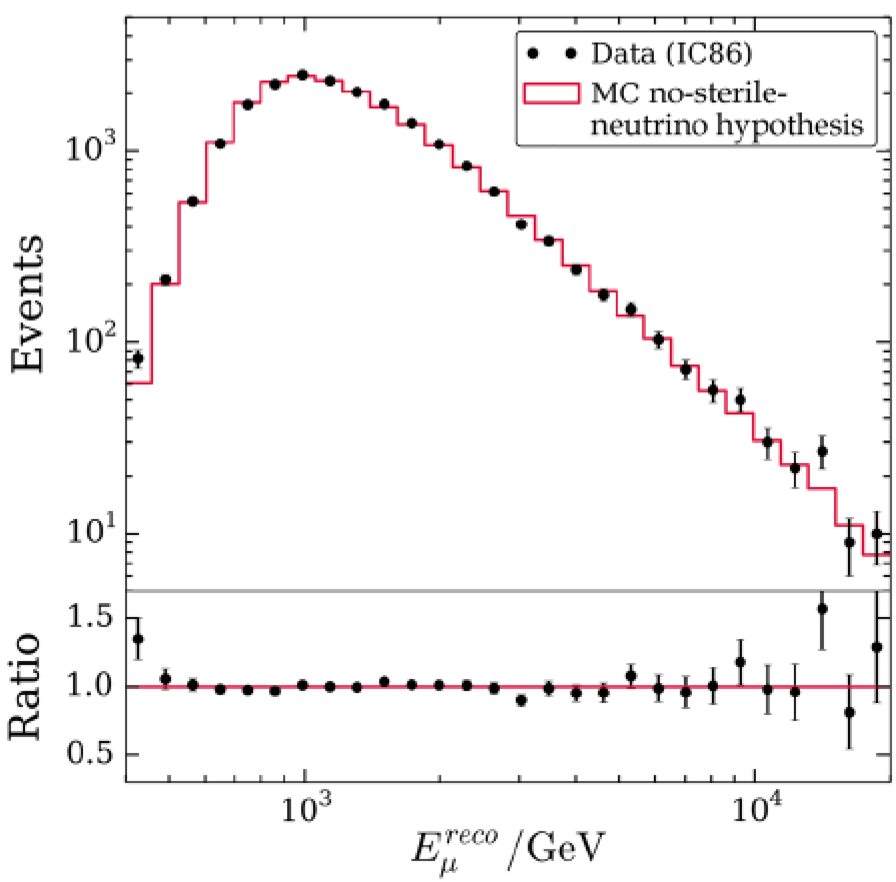


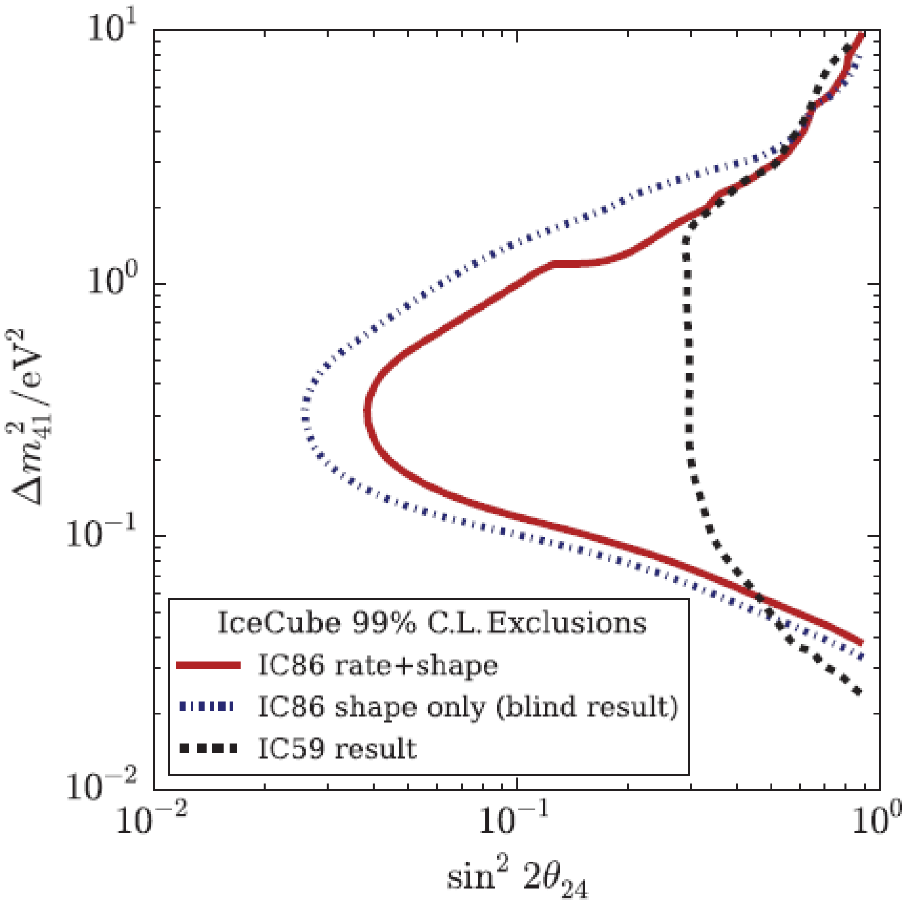


IceCube, Phys.Rev.Lett. 117, 071801 (2016)

IceCube: ν_μ Disappearance

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

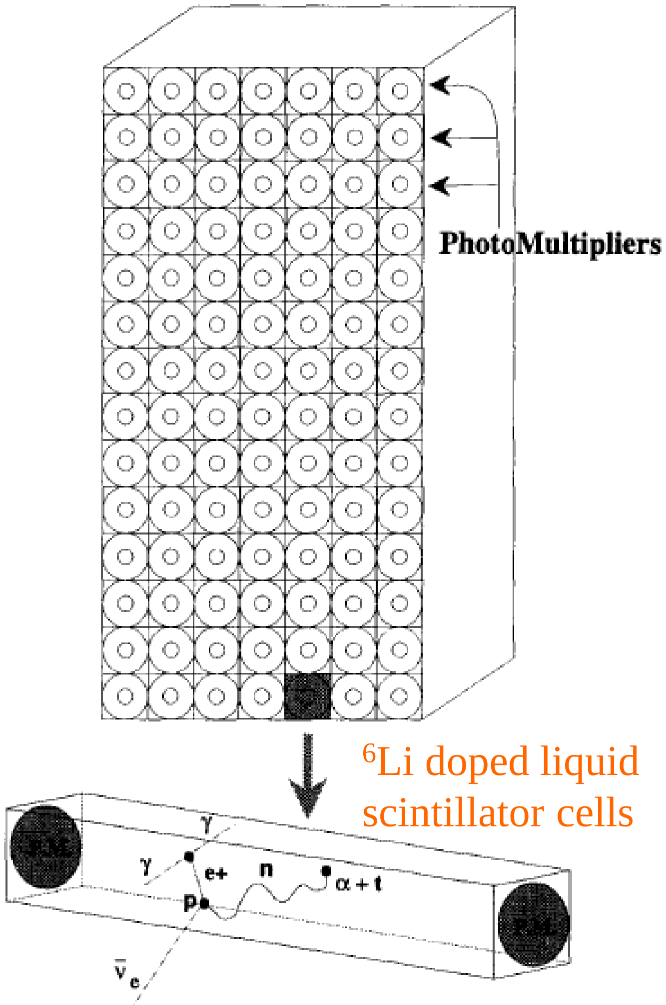




IceCube, Phys.Rev.Lett. 117, 071801 (2016)

Bugey: $\bar{\nu}_e$ Disappearance Search

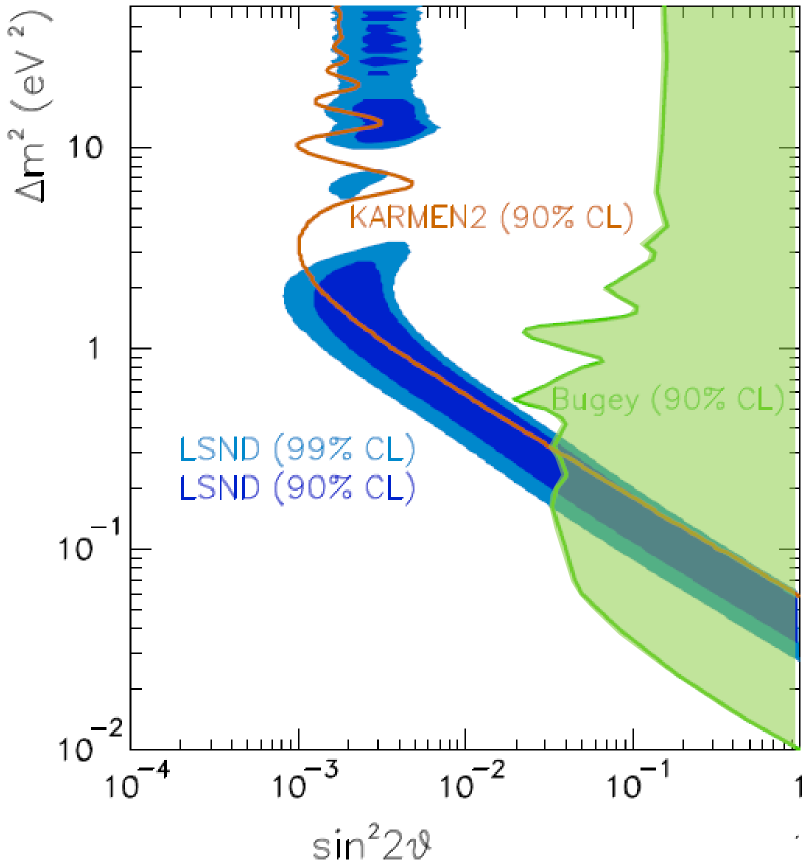
Reactor antineutrinos observed at three baselines:15, 40 and 95 m



^{6}Li doped liquid scintillator cells

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

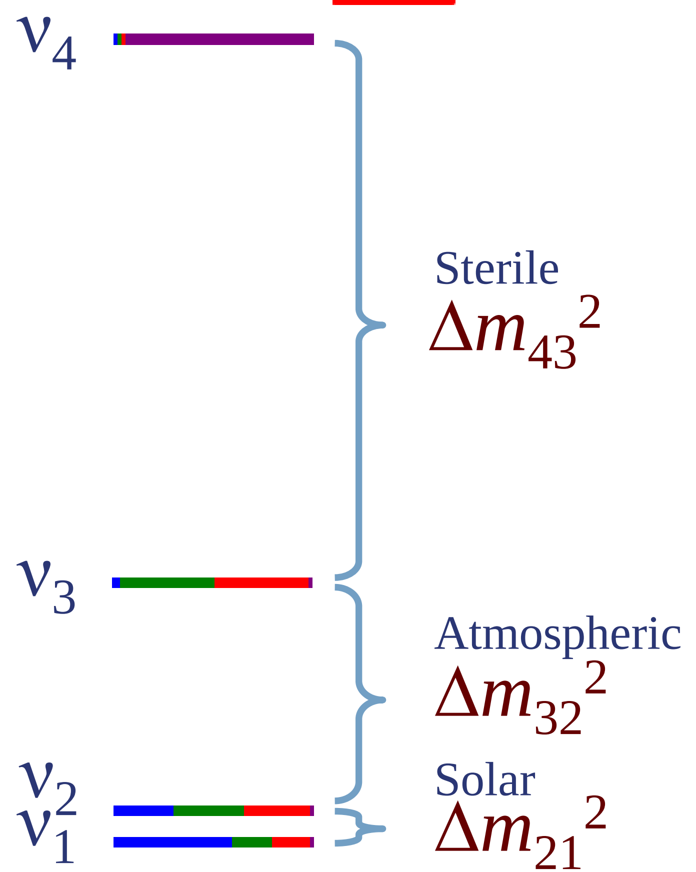
Sensitivity from absolute rate *and* near/far comparisons



Relating Appearance and Disappearance Probabilities

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



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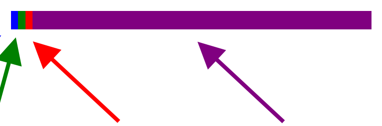
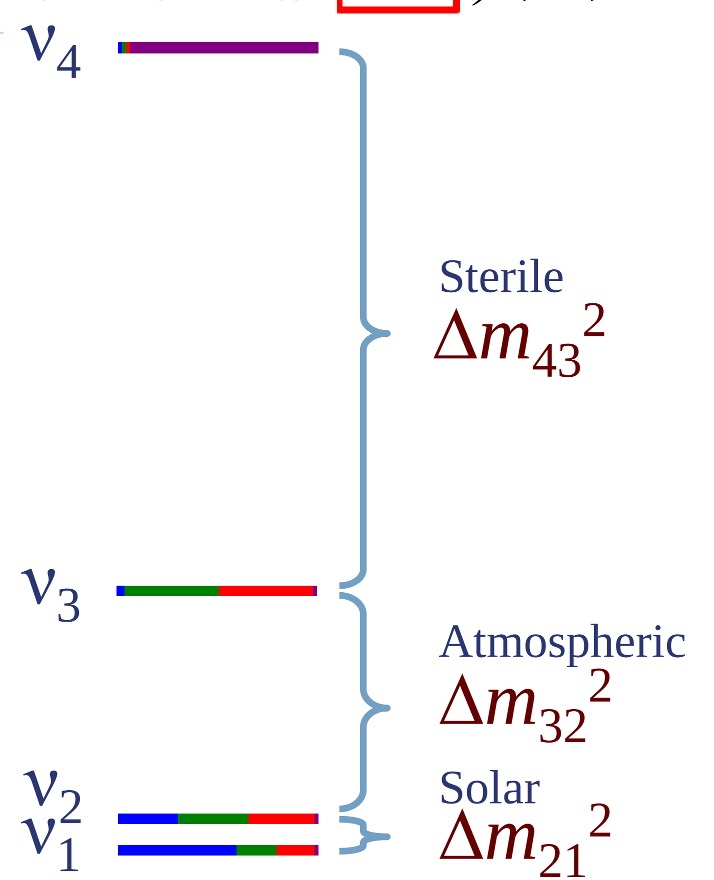


$$U_{e4}^2 + U_{\mu 4}^2 + U_{\tau 4}^2 + U_{s4}^2 = \mathbf{1}$$ (PMNS Unitarty)



The appearance probability:

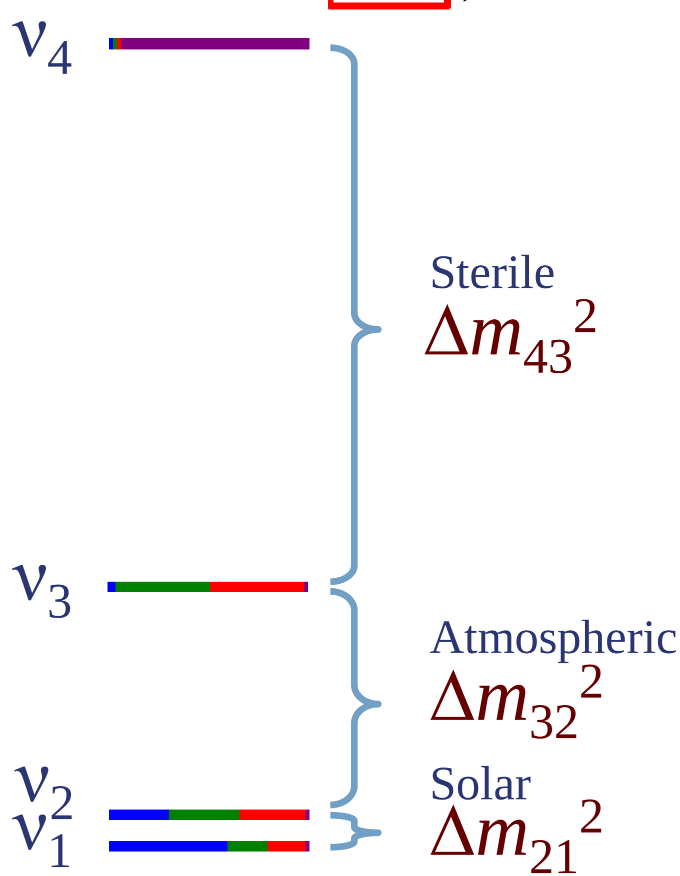
$$P_{\mu e} = \sin^2 2\theta \sin^2(1.27\Delta m_{41}^2 L/E)$$

Relating Appearance and Disappearance Probabilities

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$U_{e4}^2 + U_{\mu 4}^2 + U_{\tau 4}^2 + U_{s4}^2 = \mathbf{1}$ (PMNS Unitarty)



The appearance probability:

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

Relating Appearance and Disappearance Probabilities

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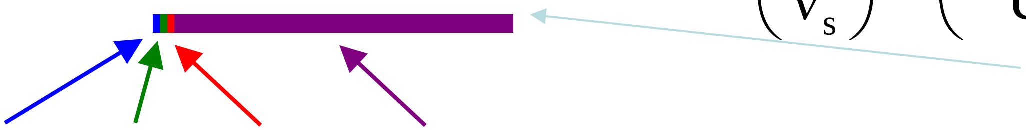

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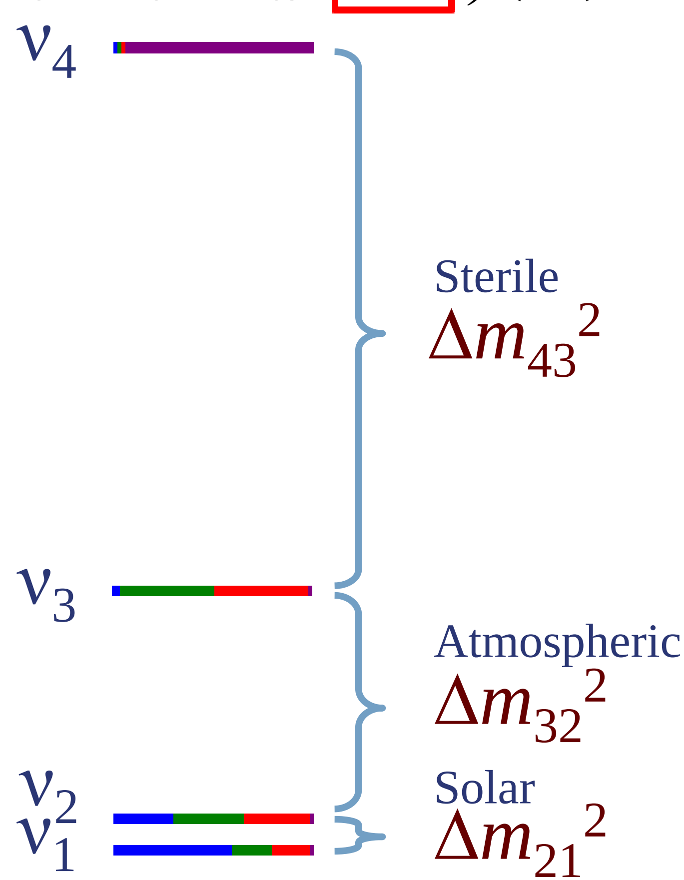

The appearance probability:

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The ν_e disappearance probability:

$$P_{ee} = P_{es} + P_{e\mu} + P_{e\tau}$$

Relating Appearance and Disappearance Probabilities

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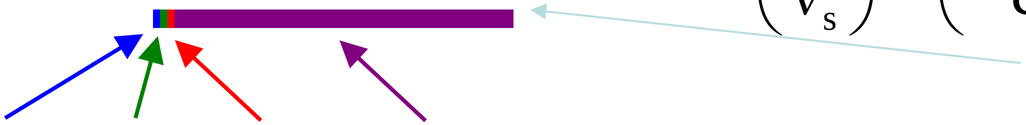

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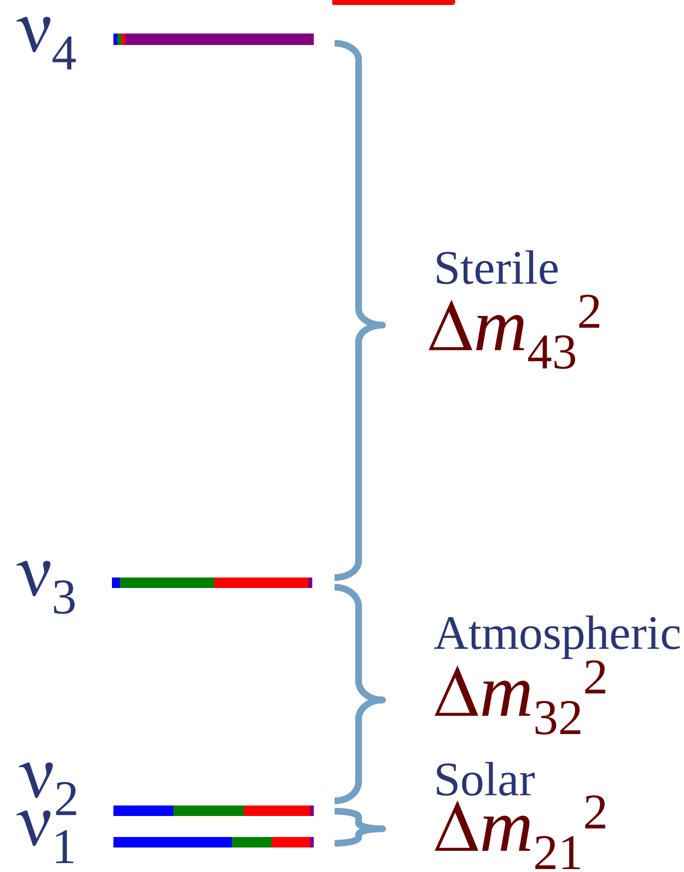

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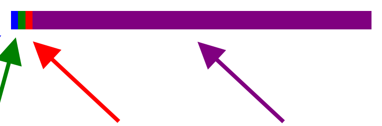

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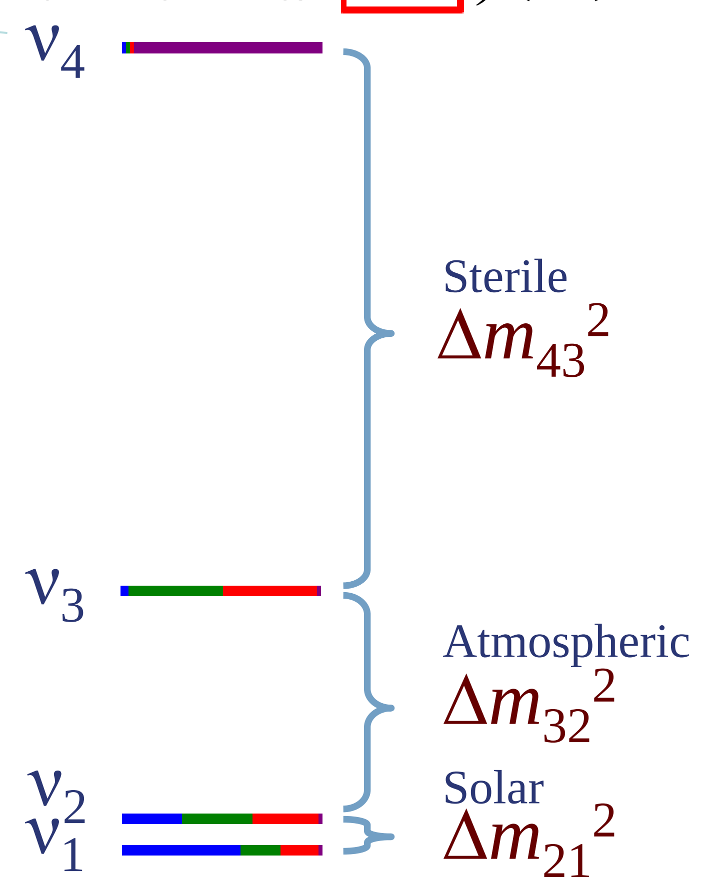

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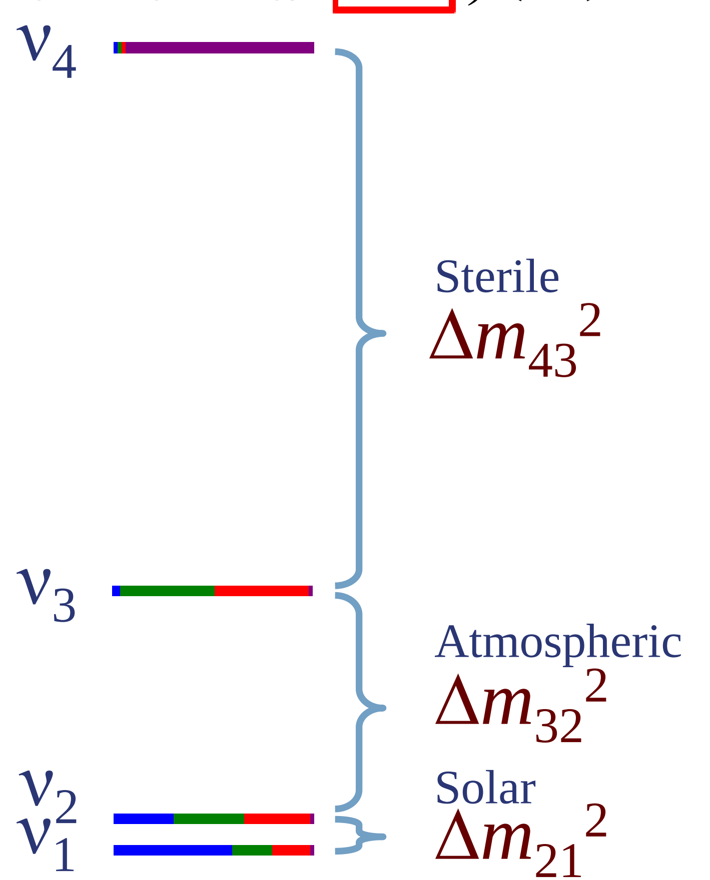

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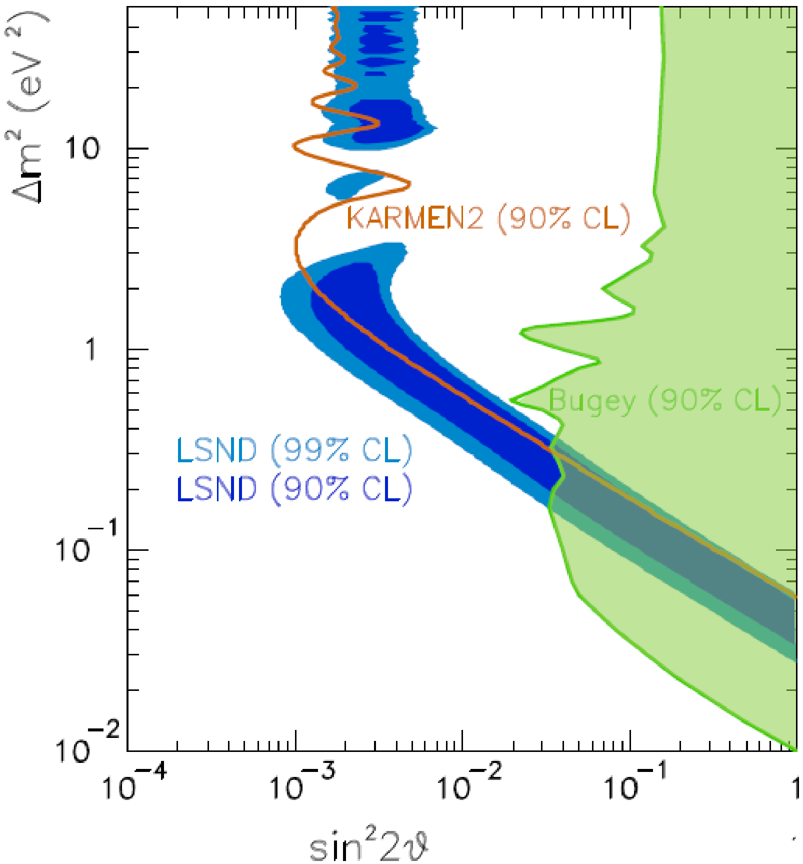
$$P_{ee} \approx P_{es} = 4U_{e4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$

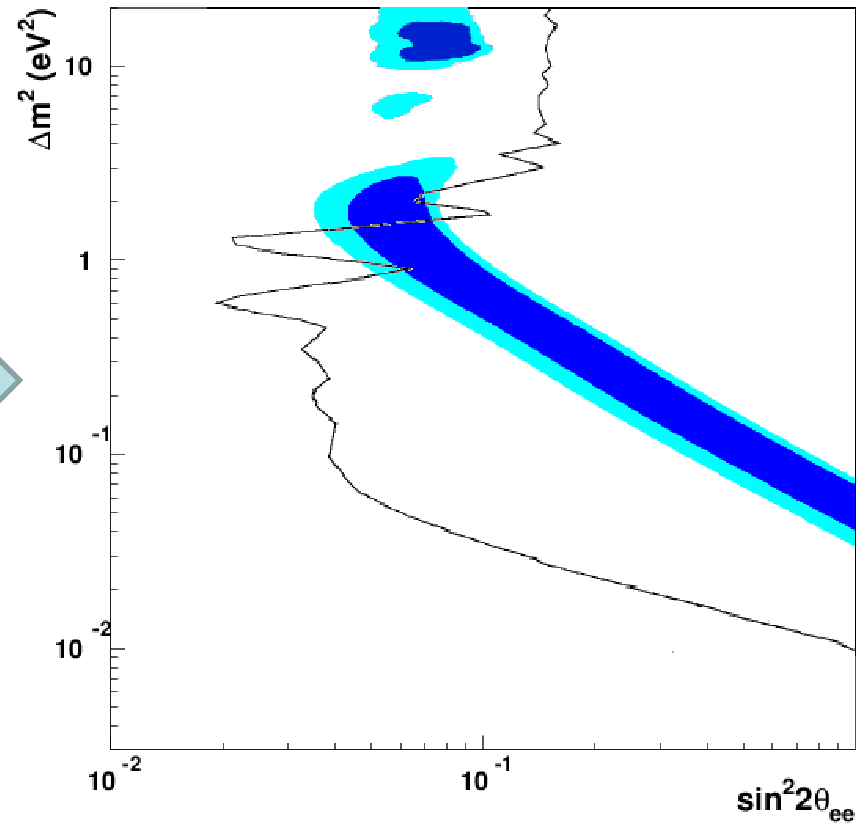
The ν_μ disappearance probability:

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

Bugey: $\bar{\nu}_e$ Disappearance Search

Assuming $U_{e4} = U_{\mu 4}$ and $U_{s4} \approx 1$, 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



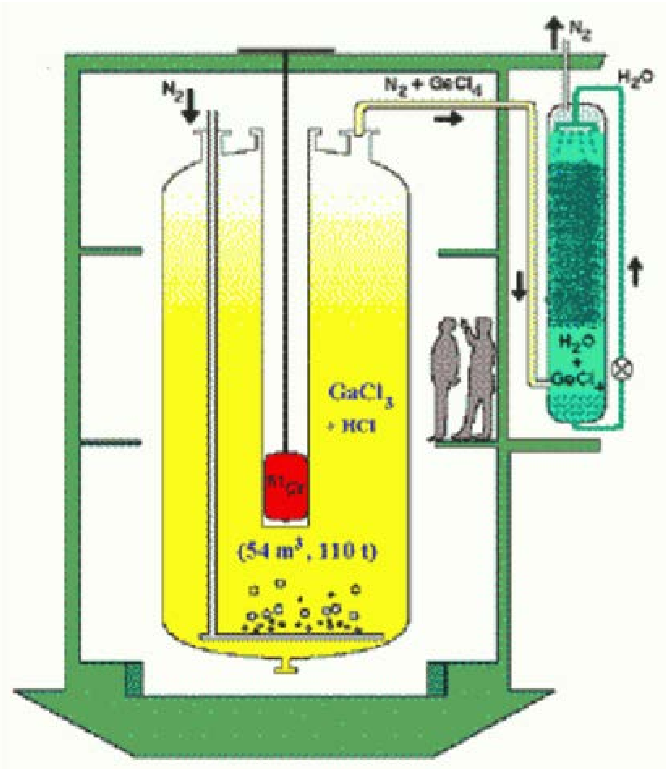


This constraint weakens for larger $U_{\mu 4}$.

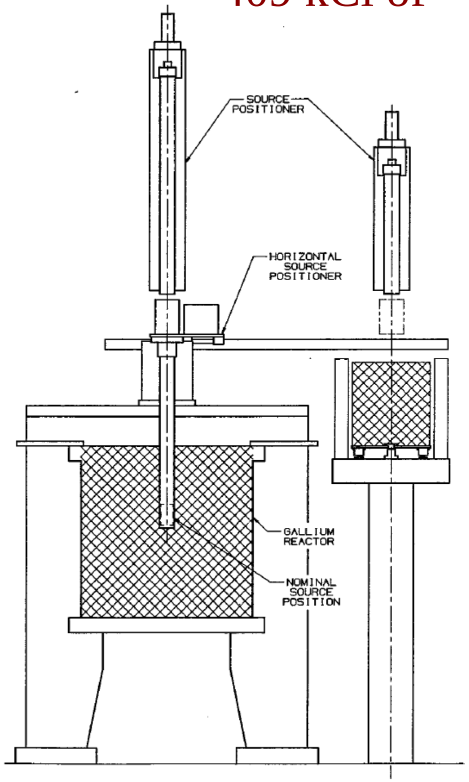
The Gallium Anomaly: ν_e Disappearance

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

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



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

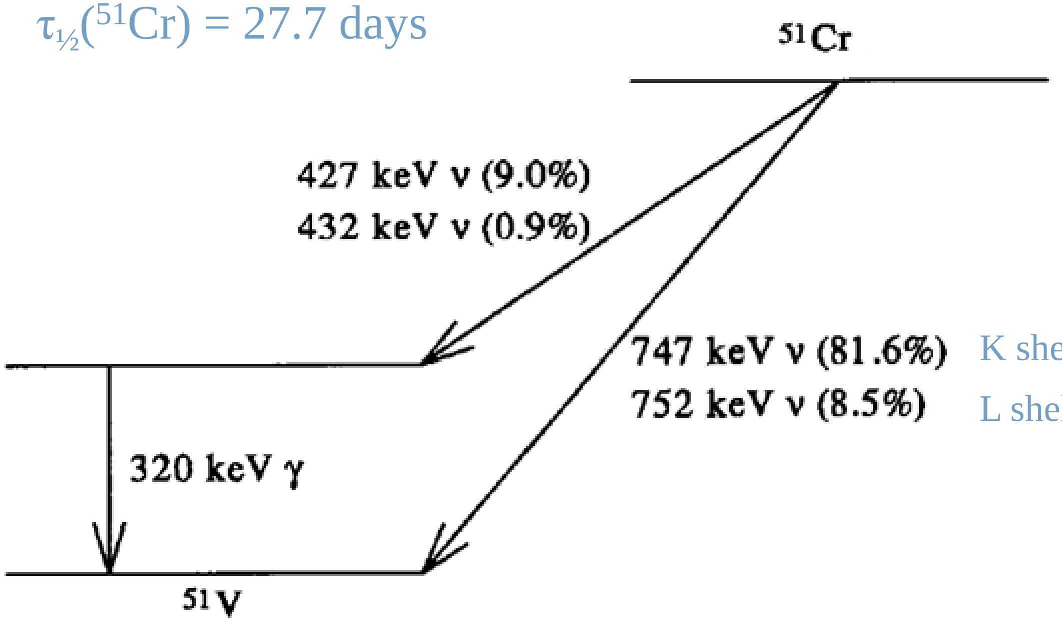
Can be easily produced with thermal neutron capture; ^{50}Cr has a 17 barn capture cross section.

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



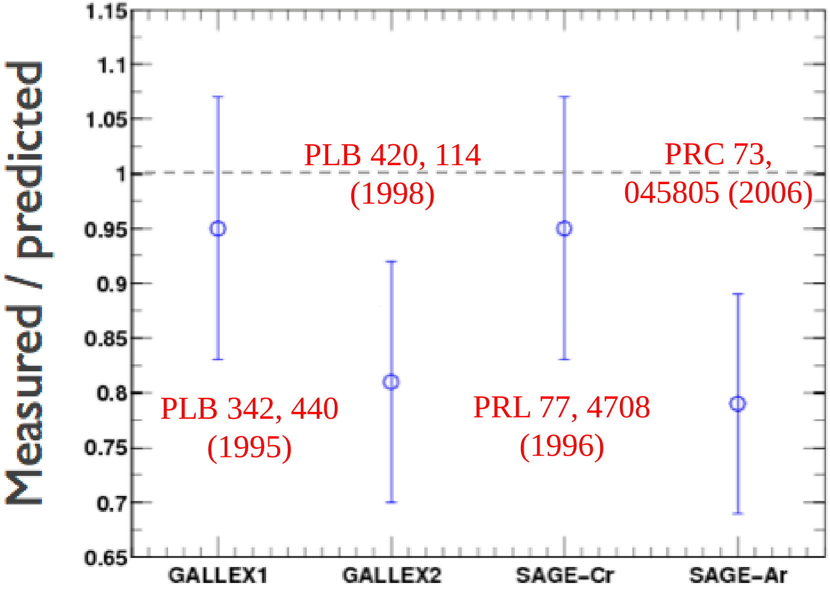
K shell capture

L shell capture

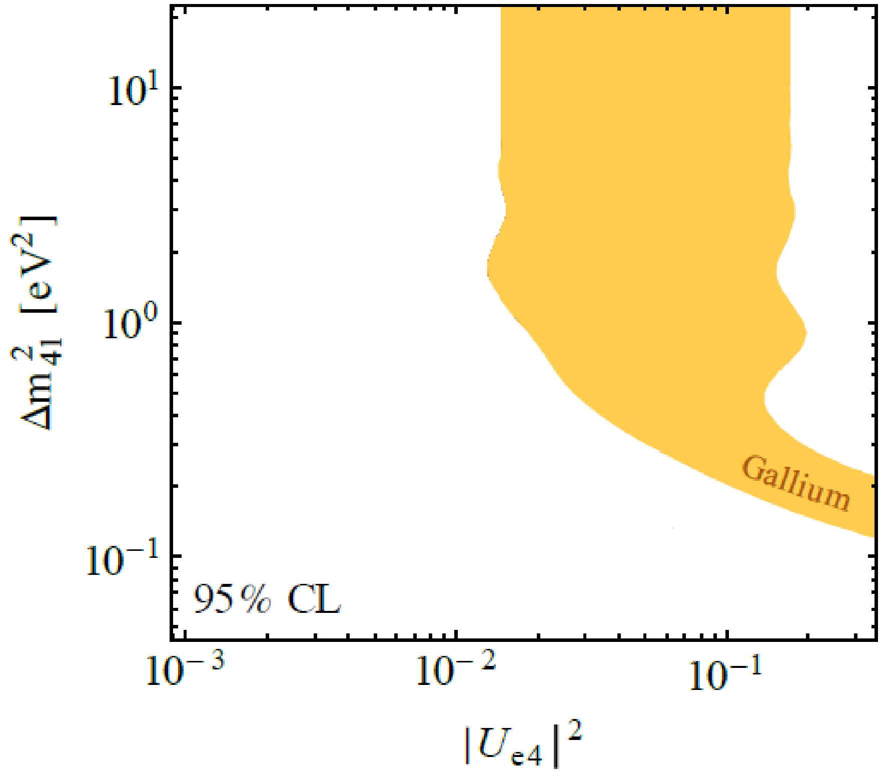
Decay scheme of ^{51}Cr to ^{51}V through electron capture.

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)]



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



Average ratio of measurement to predicted

$R=0.86\pm0.05$ (Bahcall)

Or even worse (better?)

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

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.

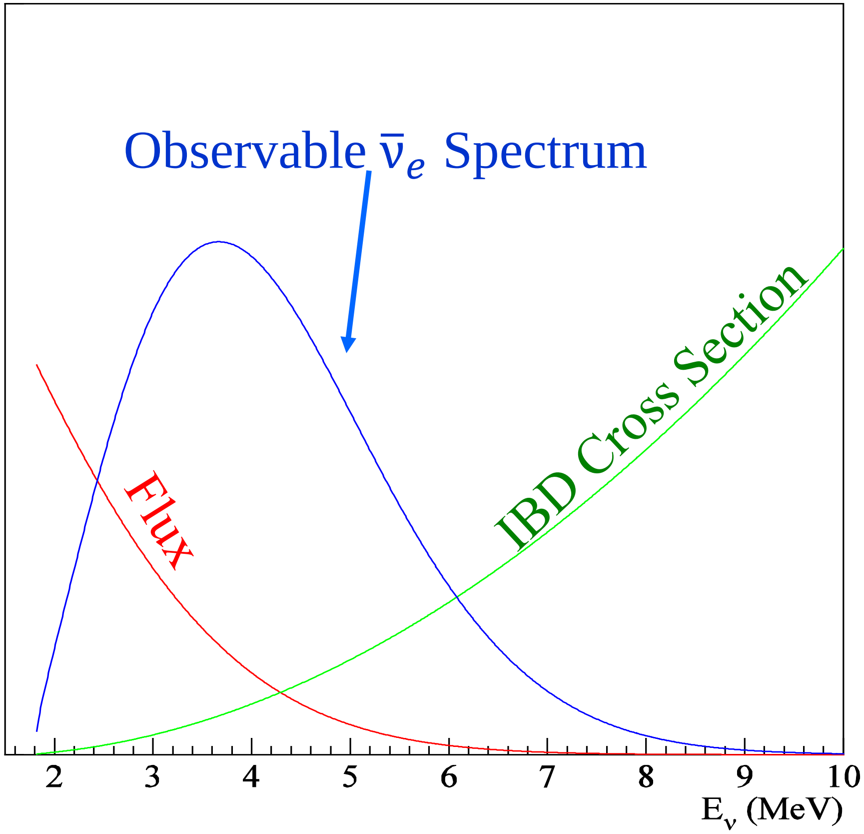
A typical commercial reactor, with 3 GW thermal power, produces 6×10^{20} ν/s

The observable $\bar{\nu}_e$ spectrum is the product of the flux and the cross section.

Reactor neutrinos are detected by inverse beta decay.

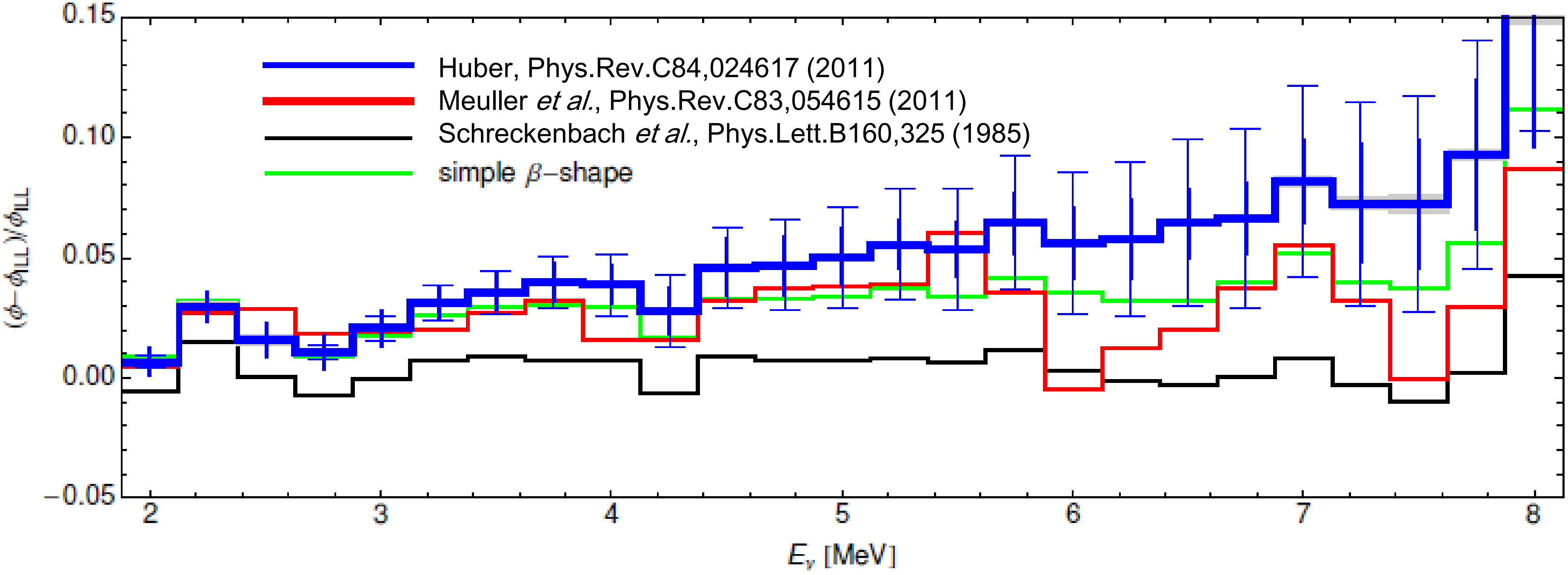
There have been many short baseline experiments to measure the reactor rate and spectrum.

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



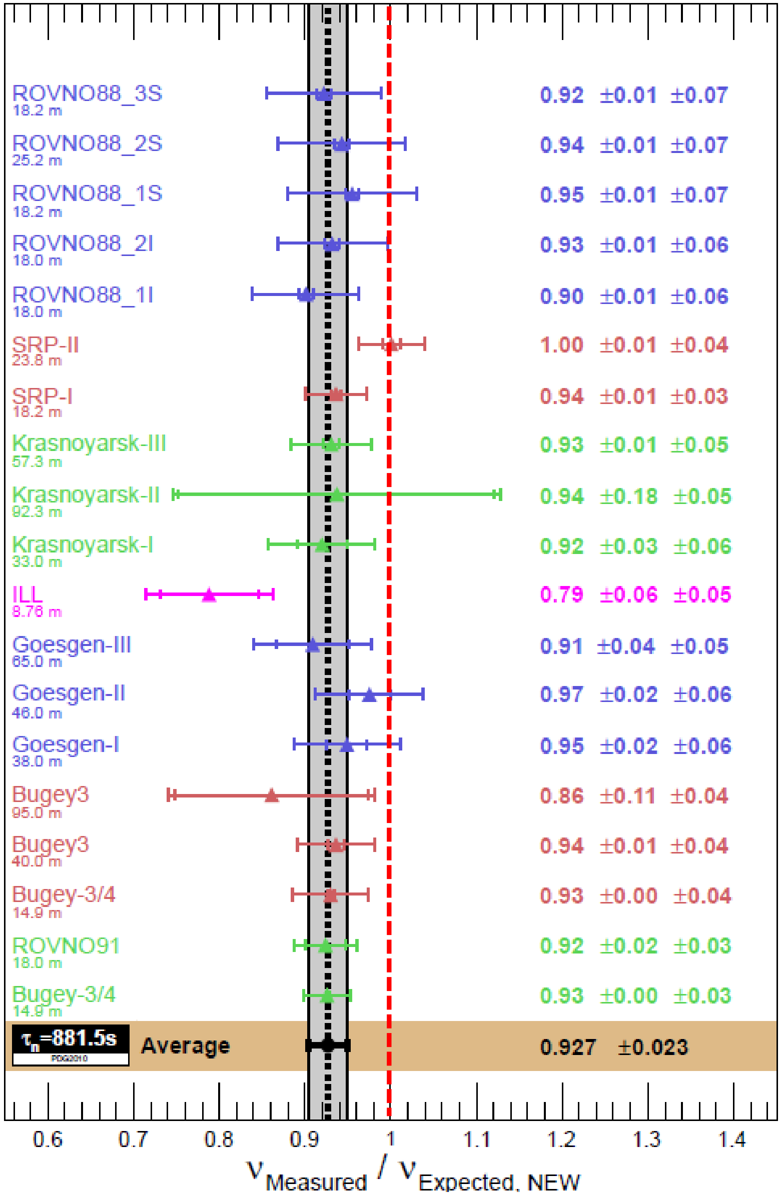
Reactor Anomaly

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



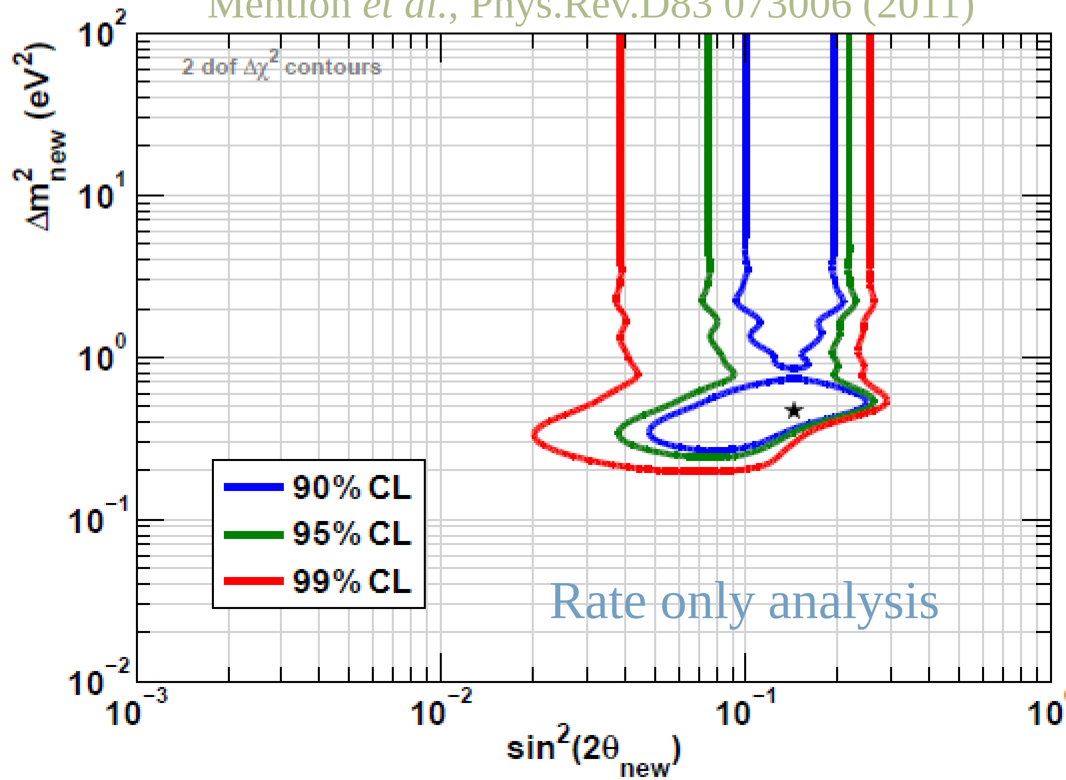
See lectures next week by Patrick Huber, for more details…

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.

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



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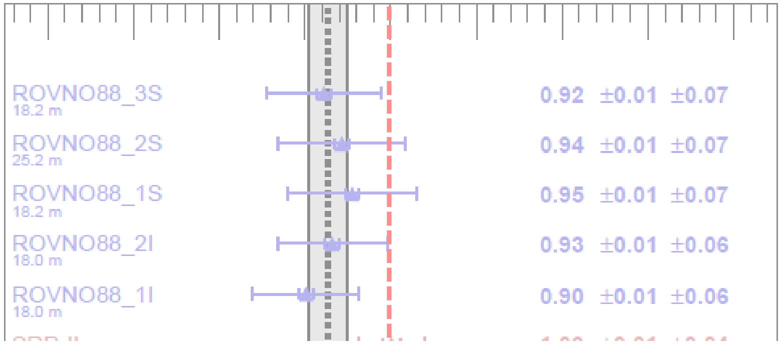
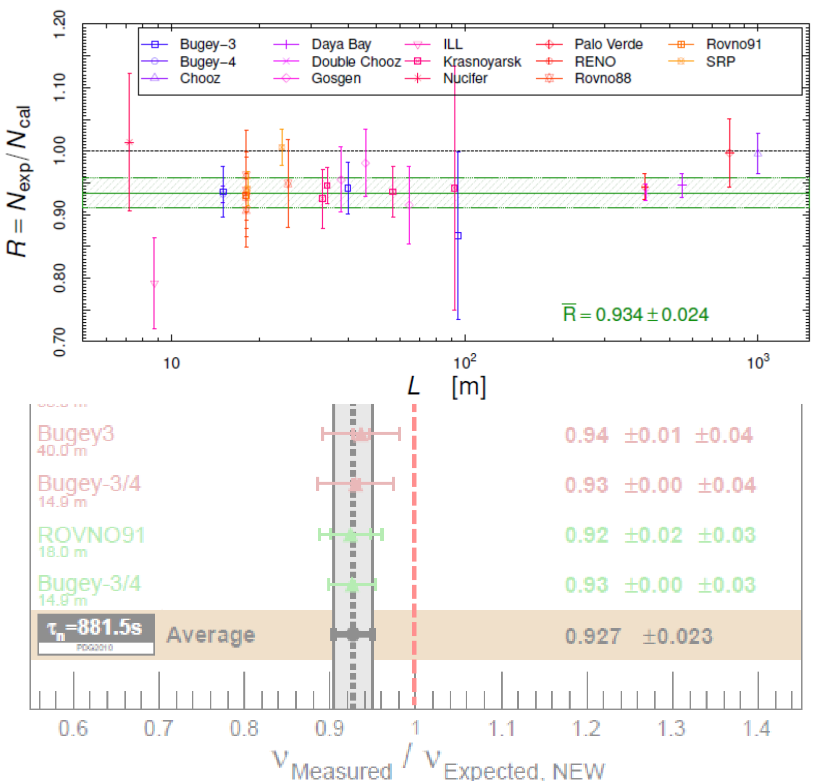


Giunti *et al.*, JHEP 06, 135 (2017)



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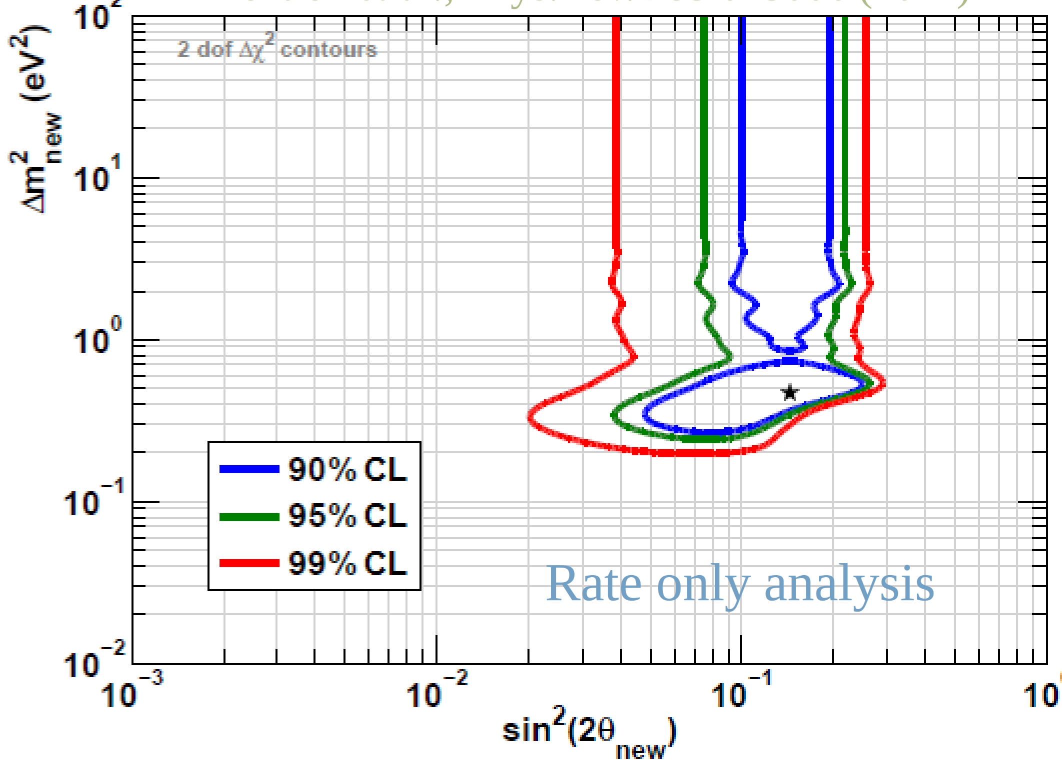
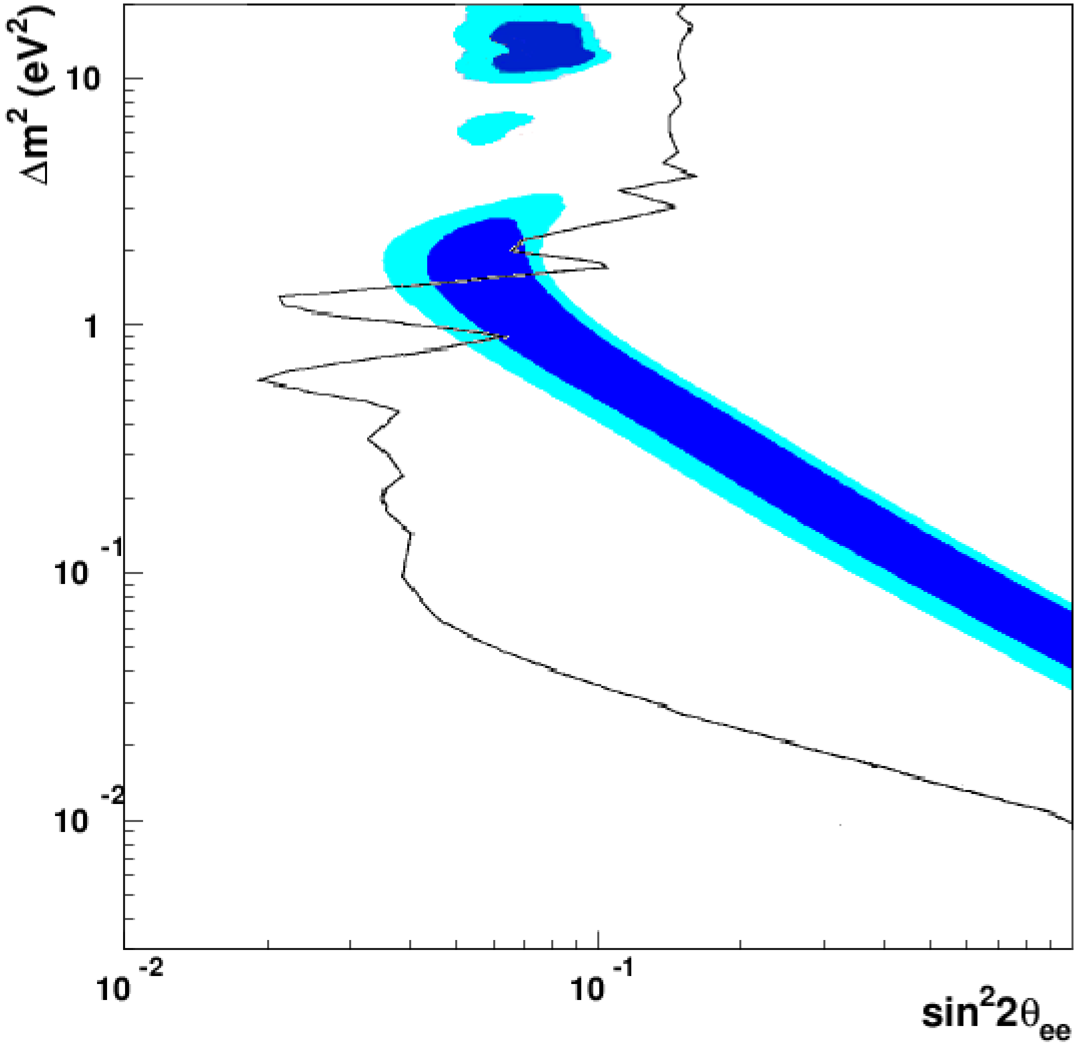


Bugey Revisited in Light of Reactor Anomaly

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



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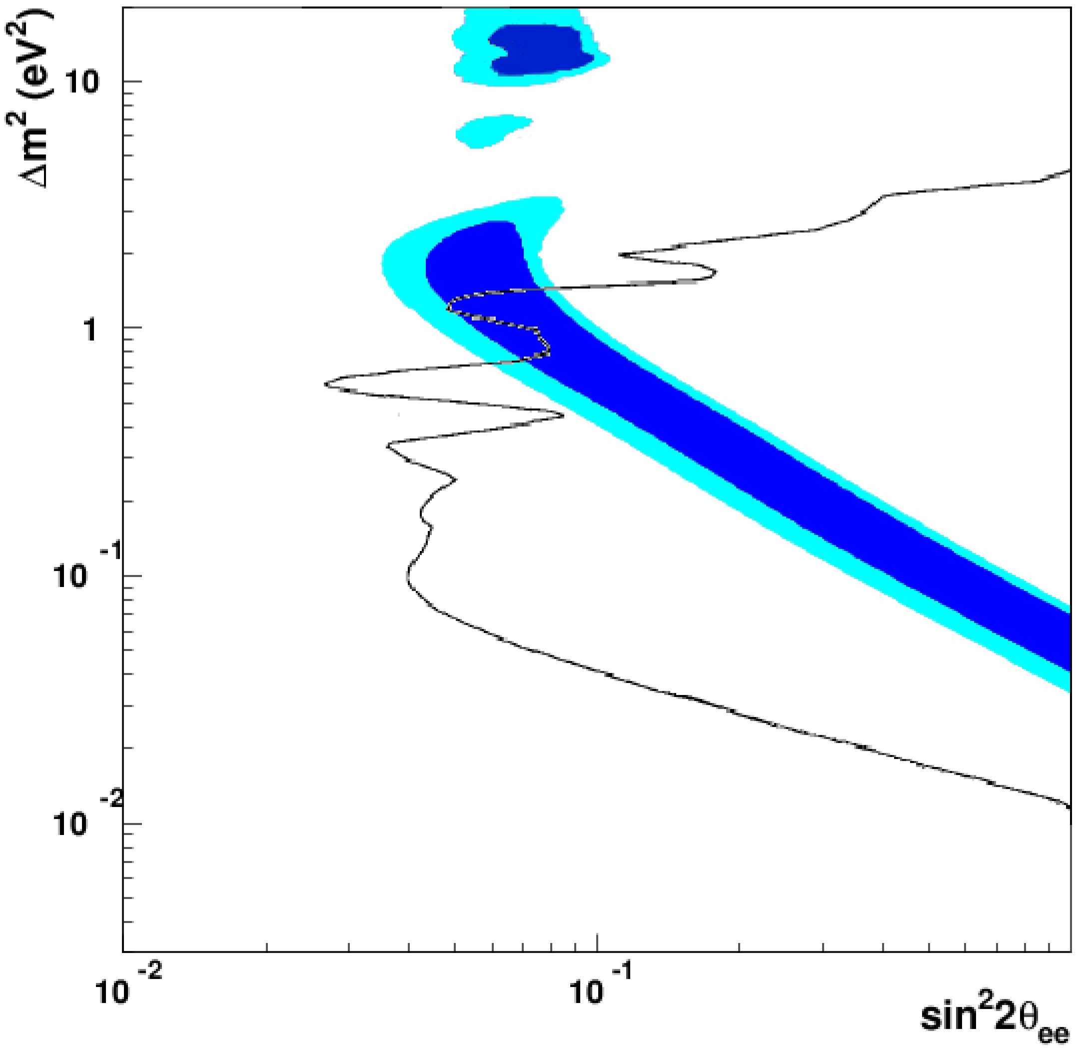
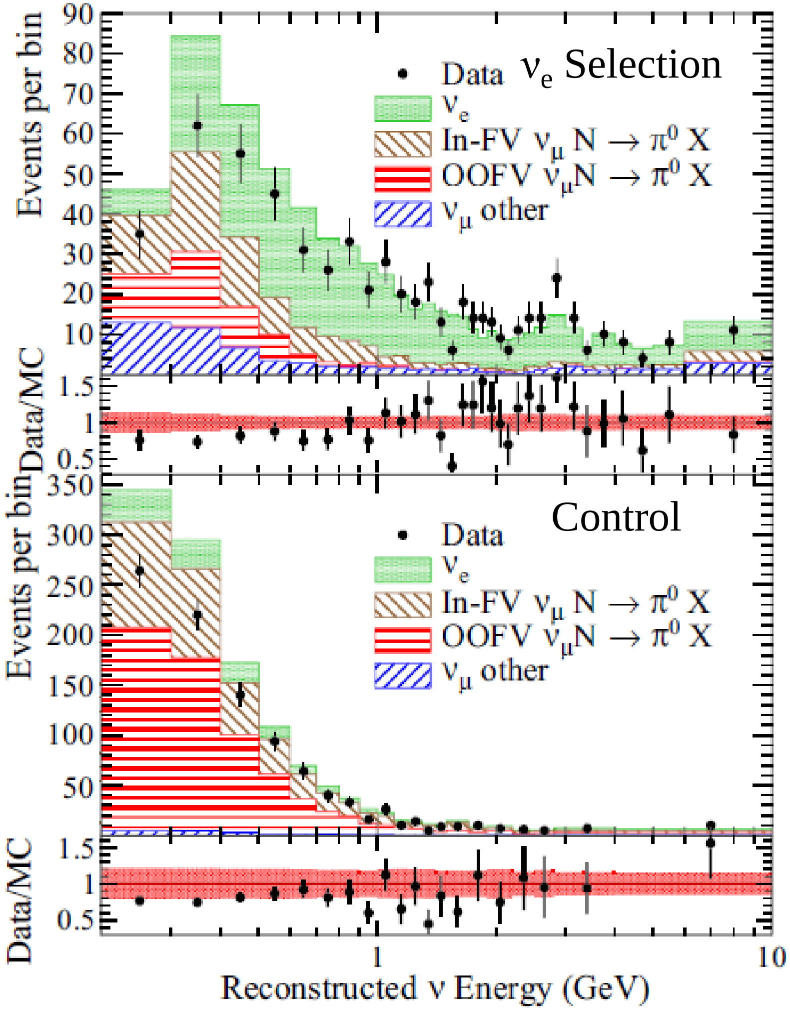
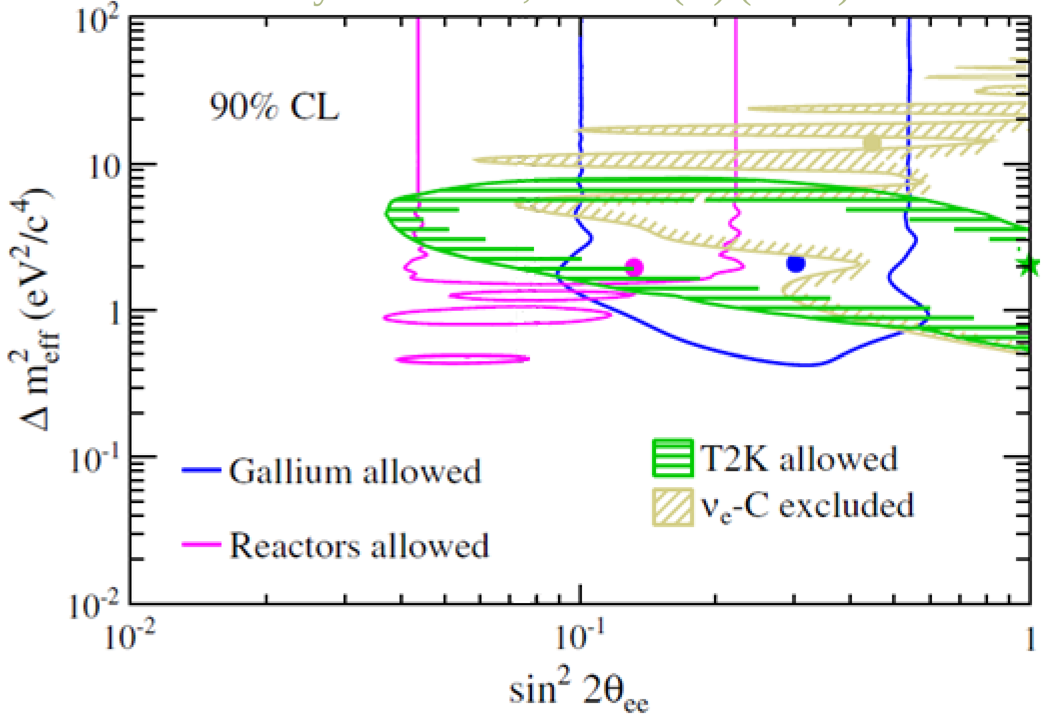


T2K Near Detector: ν_e Disappearance

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)



* Any ν_e appearance from the much larger ν_μ component of the beam would fill-in 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

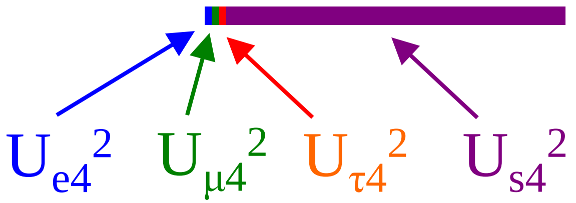
1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

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

Relating Appearance and Disappearance Probabilities

At Oscillation Maximum

And with $U_{s4} \approx 1$



The appearance probability:

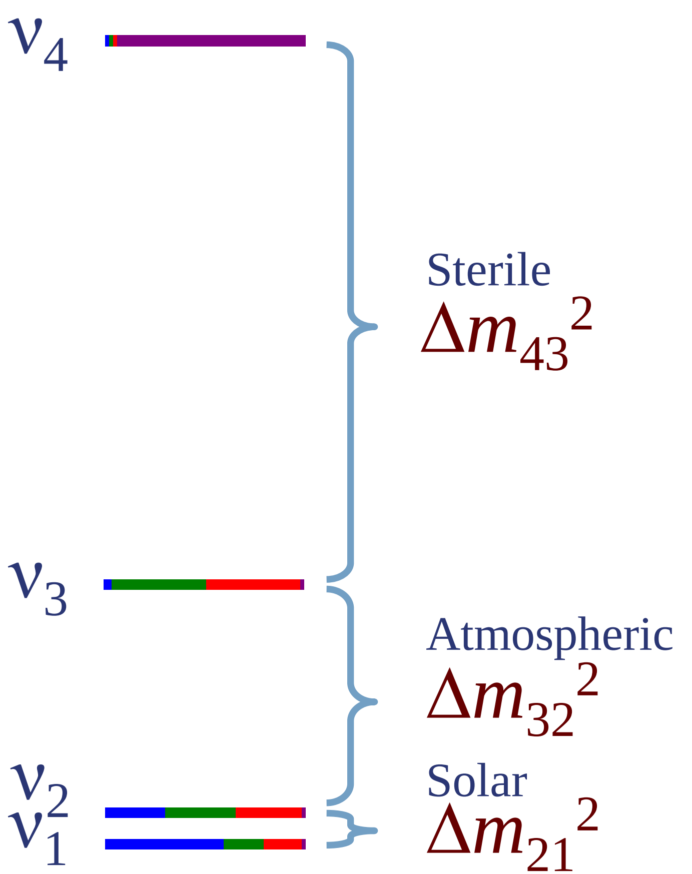
$$P_{\mu e} = 4U_{e4}^2 U_{\mu4}^2 \approx \tfrac{1}{4} P_{e\not{e}} P_{\mu\not{\mu}}$$

The ν_e disappearance probability:

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

The ν_μ disappearance probability:

$$P_{\mu\not{\mu}} \approx 4U_{\mu4}^2$$



Comparing/Combining Different Measurements

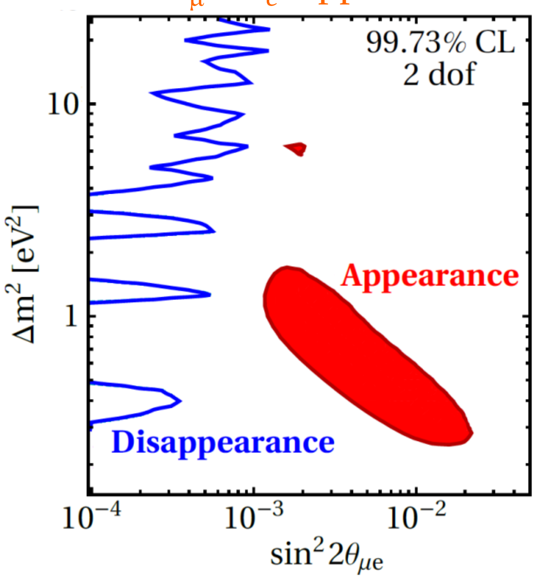
1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

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

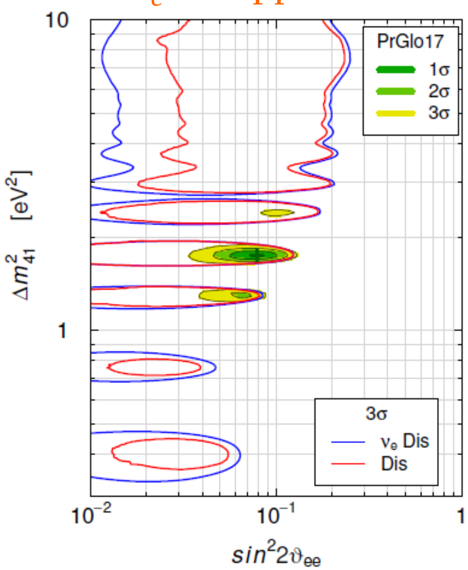
2. So you can have ν_e disappearance without ν_e appearance, but you can't have ν_e appearance without ν_μ disappearance.

Dentler *et al.*, arXiv:1803.10661

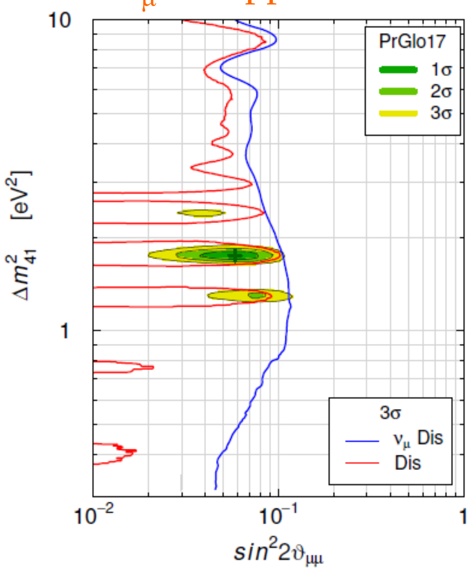
$\nu_\mu \to \nu_e$ Appearance



ν_e Disappearance



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.

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	Good	Good	Marginal / Good	Marginal	Good
Decay-in-Flight Appearance	MiniBooNE	Good	Good	Limiting	Good	Marginal
Decay-in-Flight ν_μ Disappearance	MiniBooNE, Minos, ICARUS	Marginal / Good	Marginal / Good	Good	Good	Good
Decay-in-Flight ν_e Disappearance	T2K	Marginal	Good	Good	Good	Marginal
Reactor	Bugey	Good / Limiting	Good	Good	Good	Good
Source	Gallex, SAGE	Marginal	Limiting	Good	Marginal	Good
Atmospheric Matter Enhanced ν_μ Disappearance	IceCube	Marginal	Good	Good	Good	Good

Good Marginal Limiting

Requirement for Disappearance Experiments

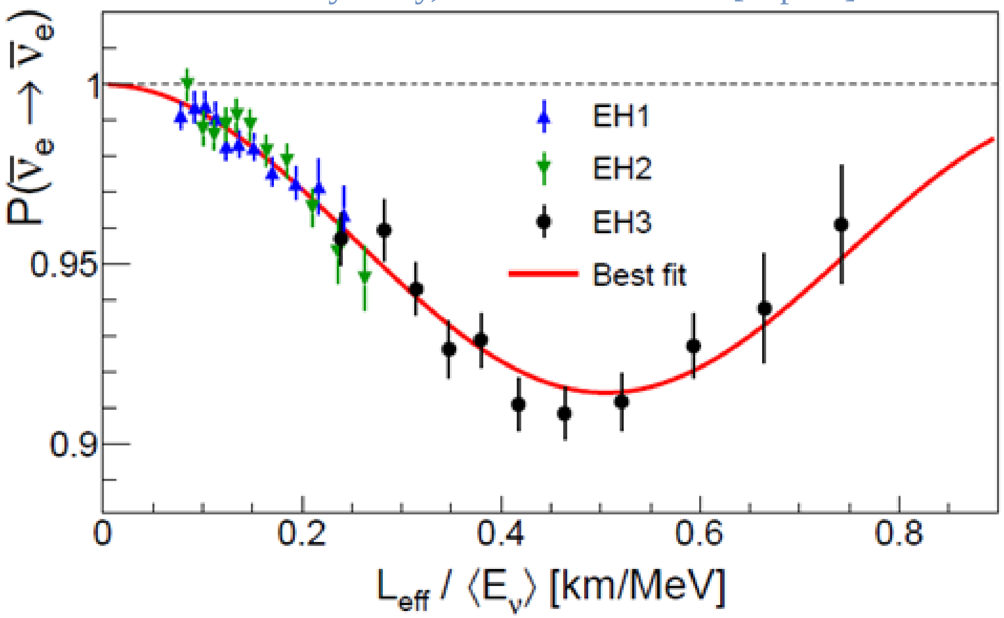
"It don't mean a thing if it ain't got that swing"

–American jazz great Duke Ellington

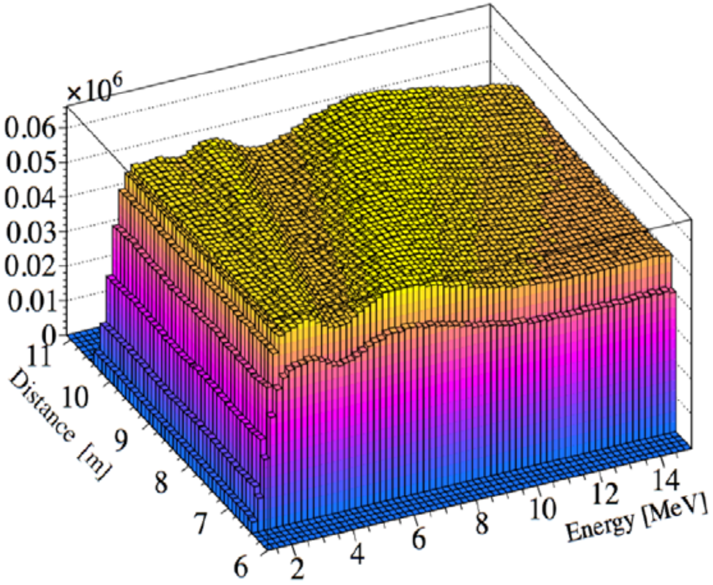
Definition:

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 from up to about two years ago, before the start of a new round of experiments purpose built to address the sterile neutrino issue.

Tomorrow we will look at the new and upcoming round of experiments in depth, which includes:

- Many new reactor experiments and proposals
- Source experiments, proposals and concepts
- A three baseline liquid argon detector program in Fermilab's Booster Neutrinos Beam, and
- A few powerful new concepts that don't fit into these categories.