Short-Baseline Experiments

Jonathan Link

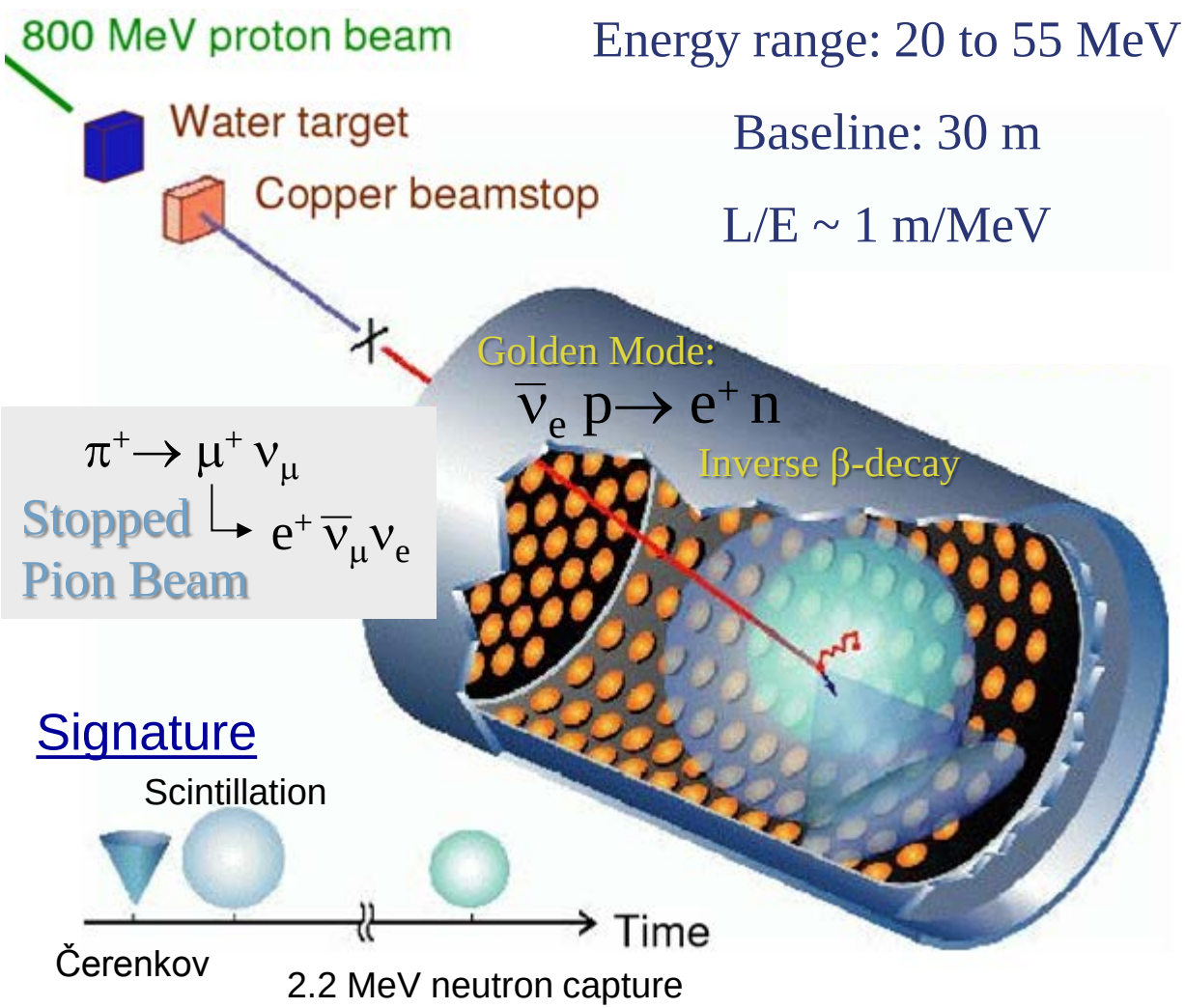
Center for Neutrino Physics, Virginia Tech

Topics in Astroparticle and Underground Physics

September 10, 2015

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

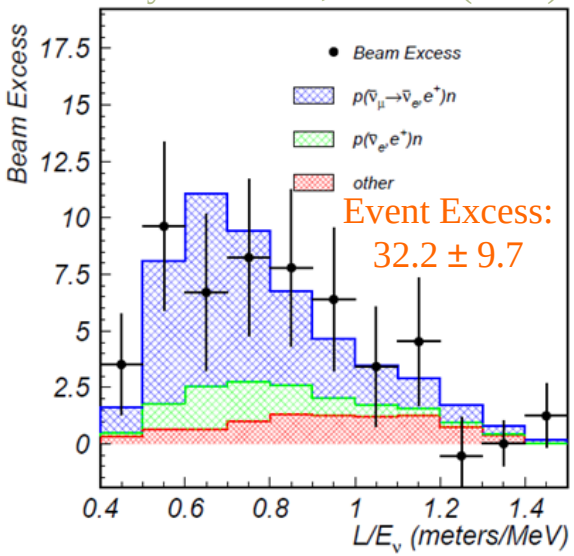
Phys.Rev.D64, 112007 (2001)

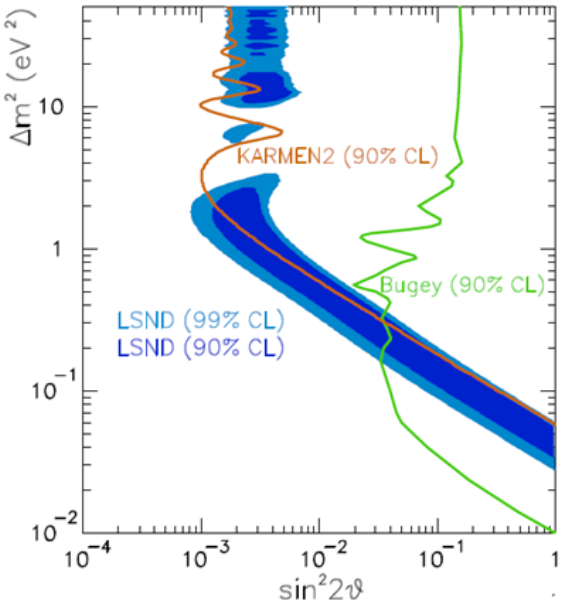


Energy range: 20 to 55 MeV

Baseline: 30 m

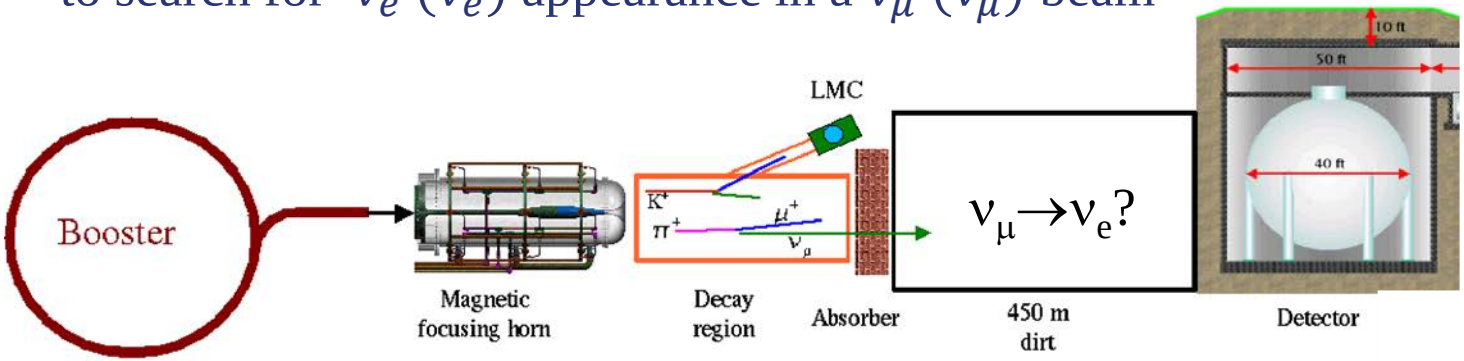
L/E ~ 1 m/MeV





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

MiniBooNE used a π^+ (π^-) decay in flight beam and a liquid Cherenkov detector to search for ν_e ($\bar{\nu}_e$) appearance in a ν_μ ($\bar{\nu}_\mu$) beam



Baseline ~ 500 m

$\langle E_\nu \rangle$ ~ 500 MeV

L/E ~ 1 m/MeV

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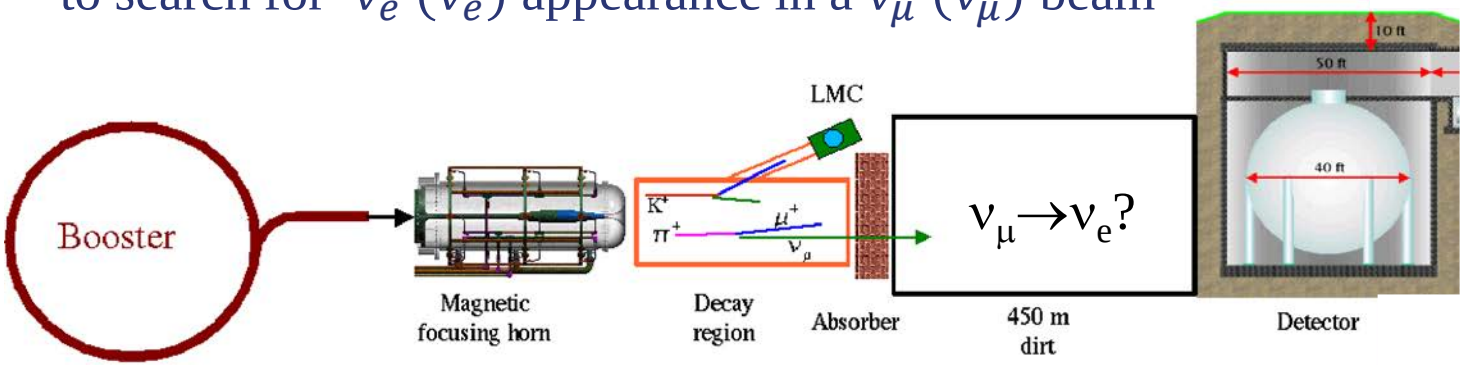

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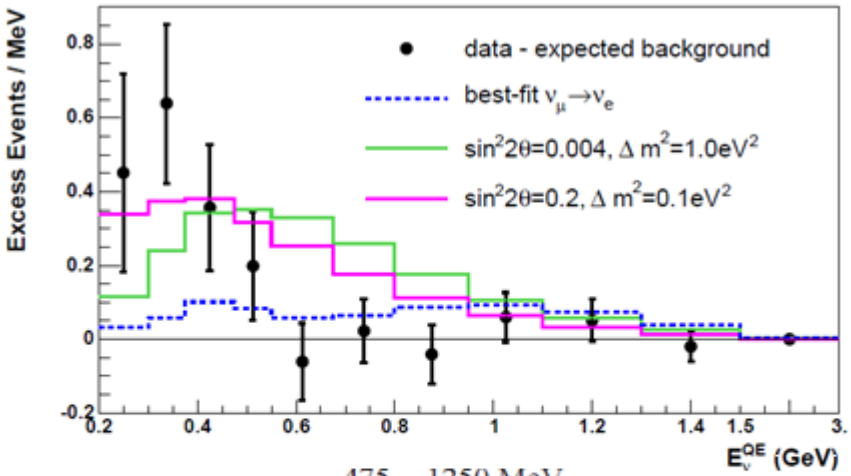
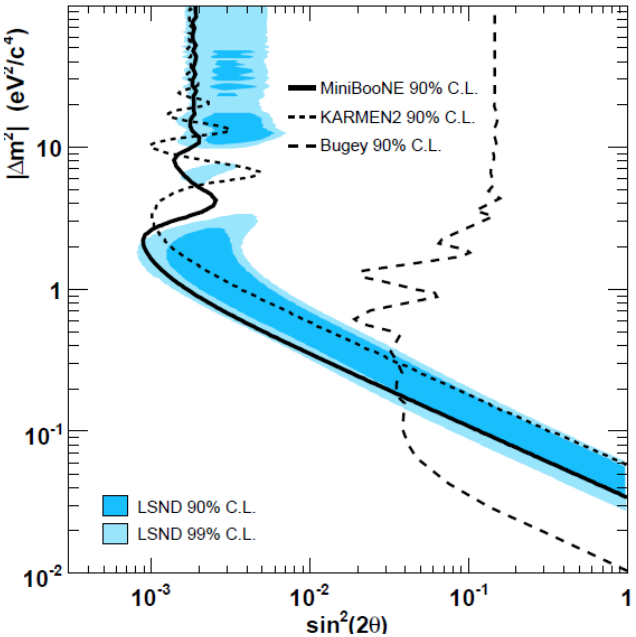


475 – 1250 MeV

Data	408
Background	385.9 ± 19.6 ± 29.8
Excess	22.1 ± 19.6 ± 29.8
Significance	0.6σ



Phys.Rev.Lett. 98, 231801 (2007)

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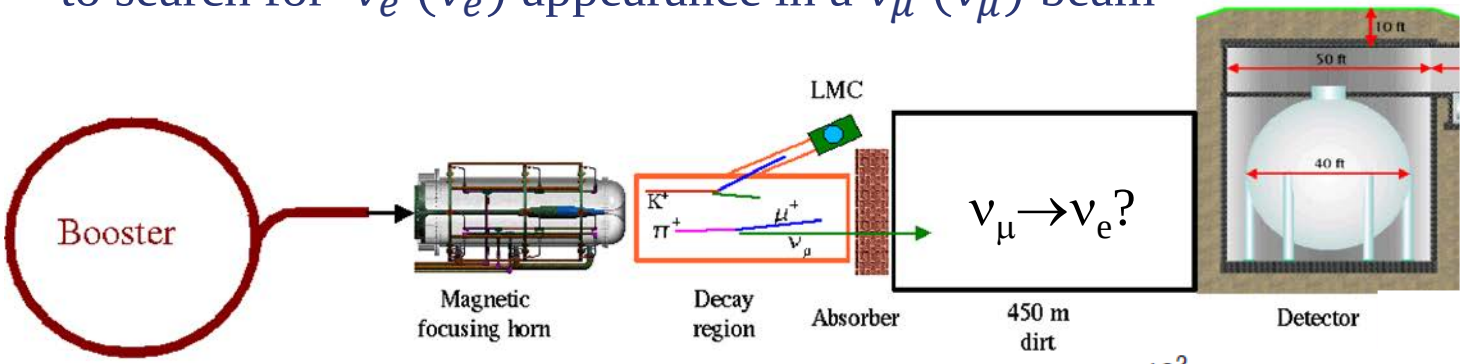

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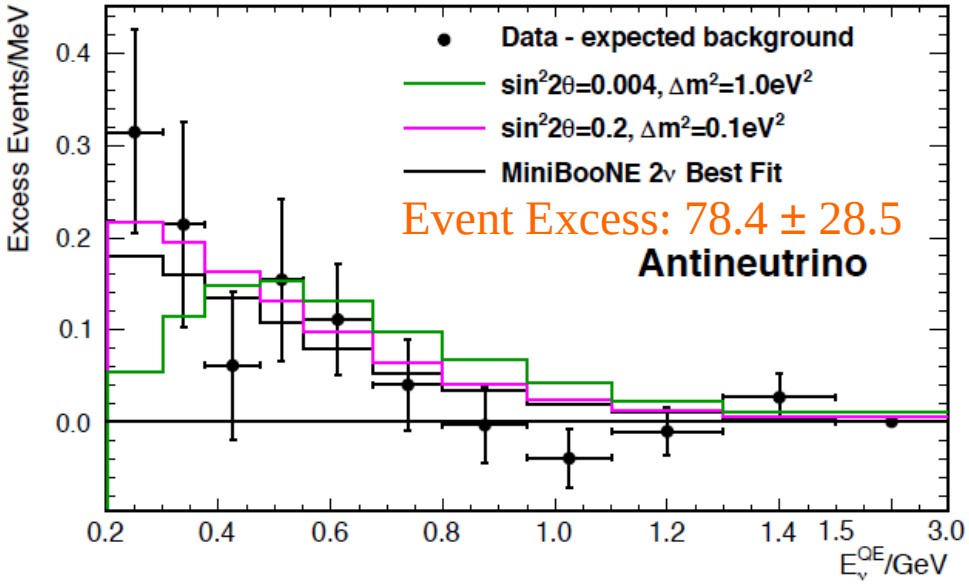
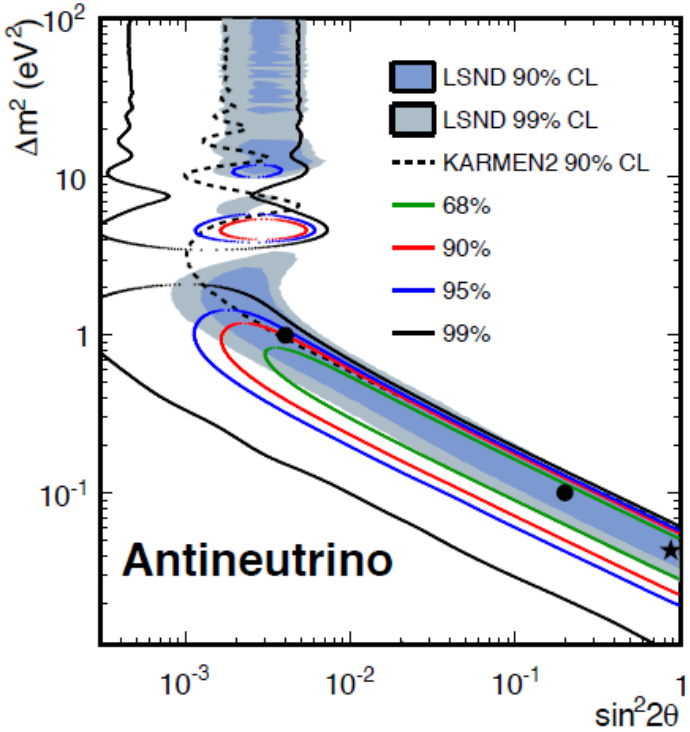
Phys.Rev.Lett. 110, 161801 (2013)





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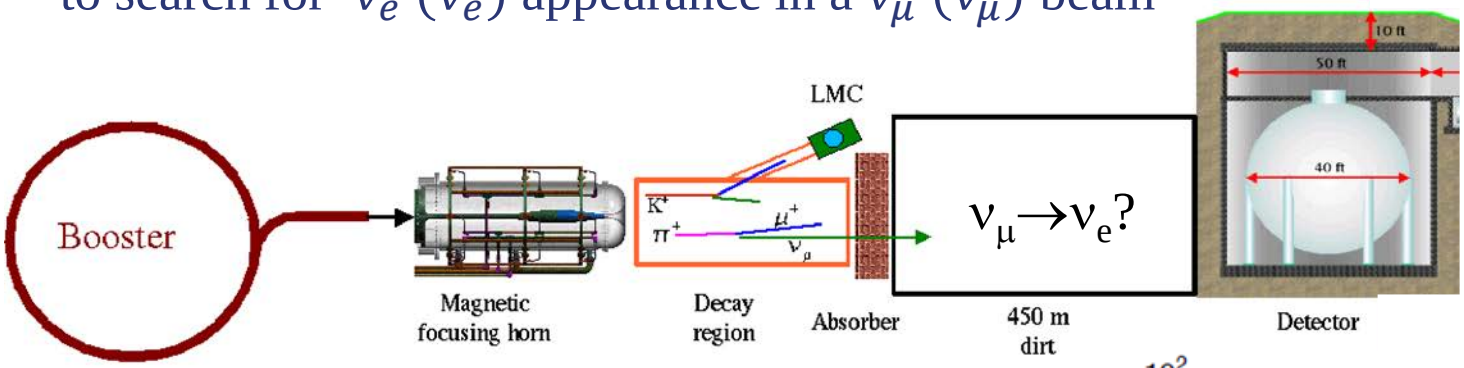

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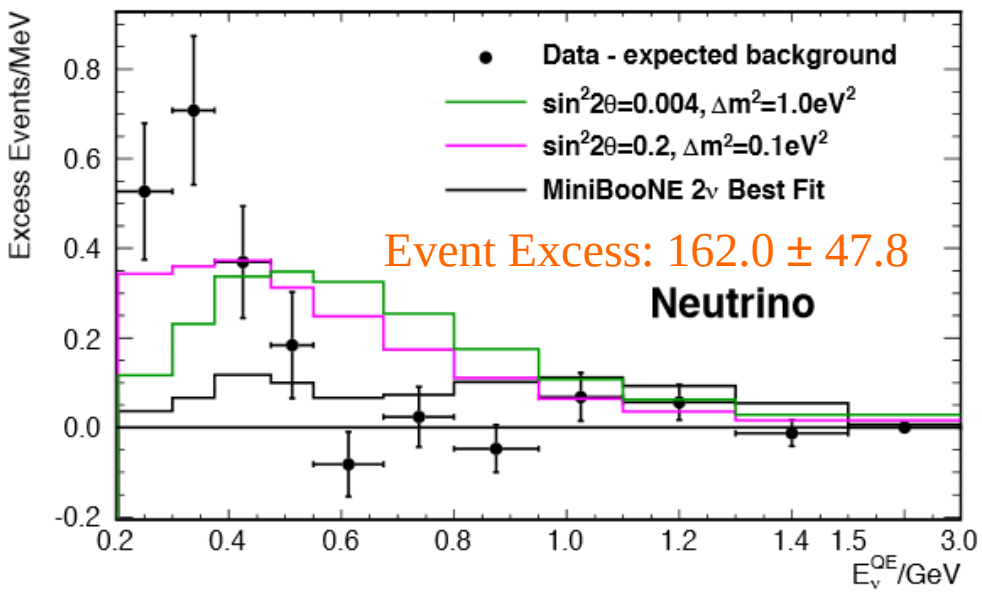

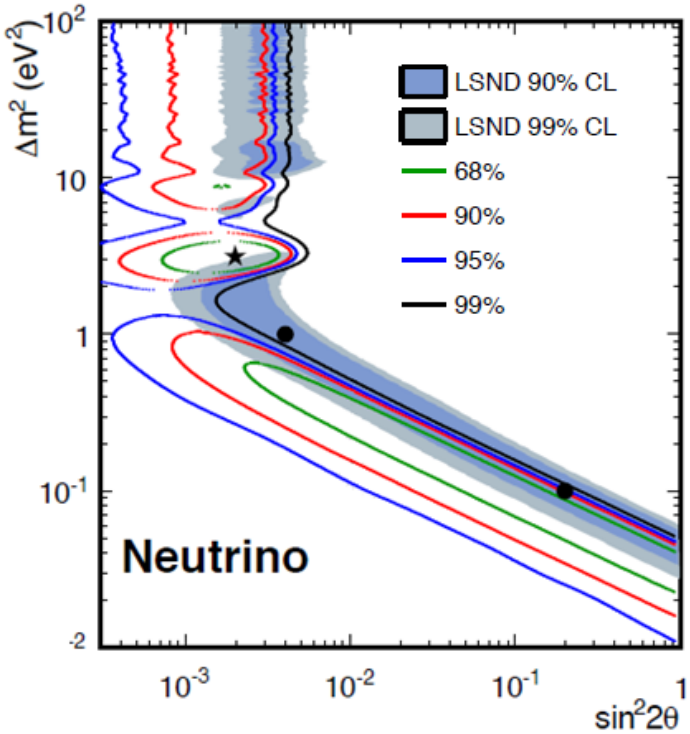

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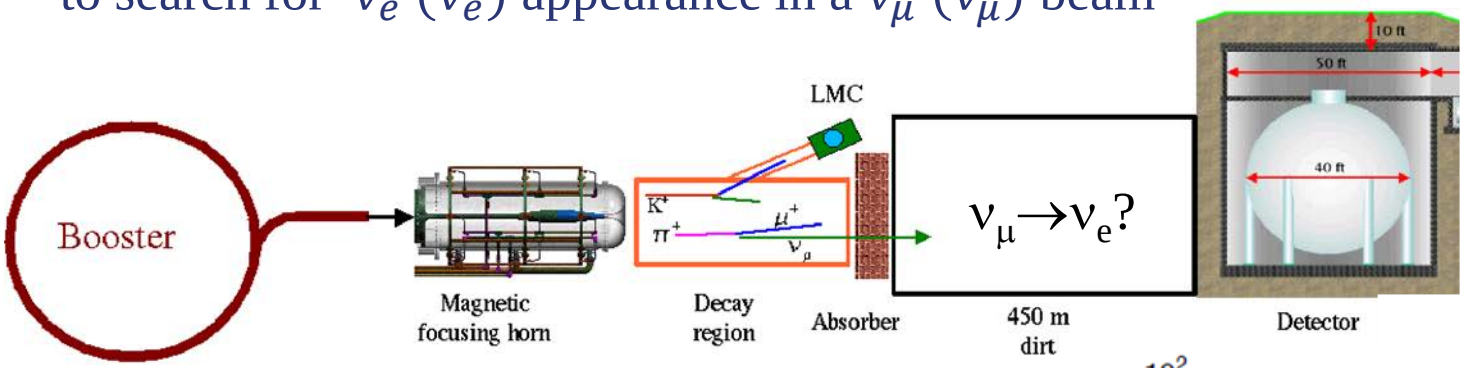

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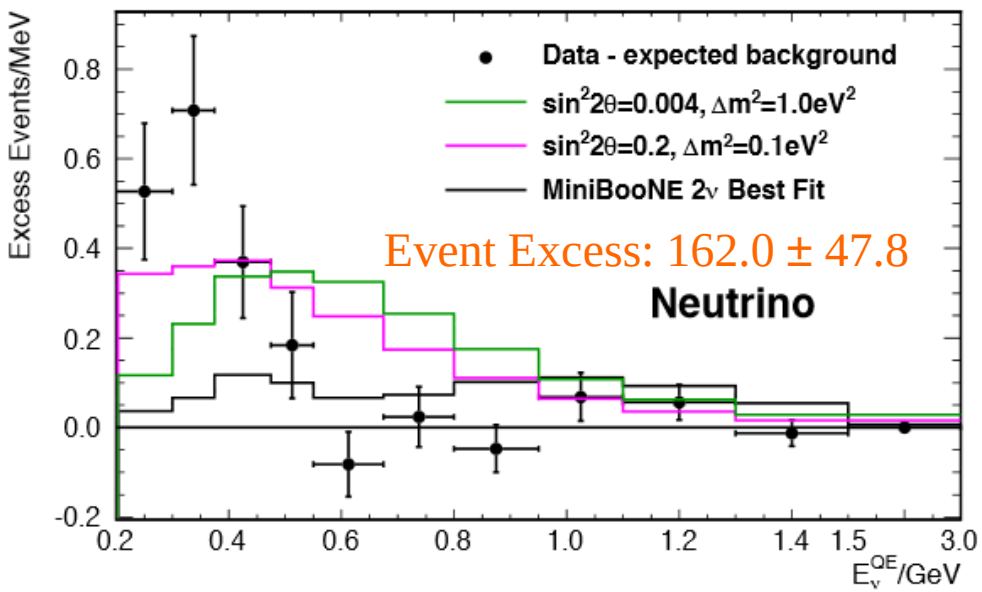
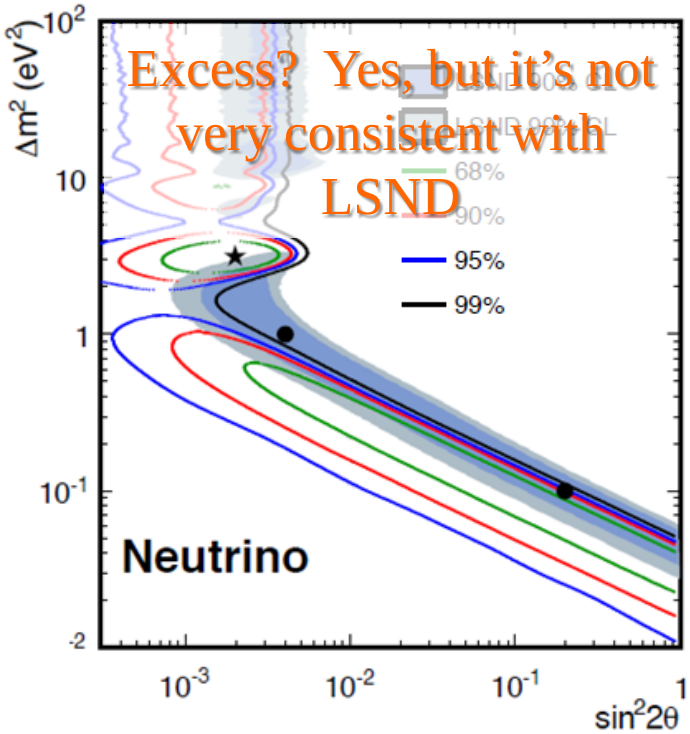
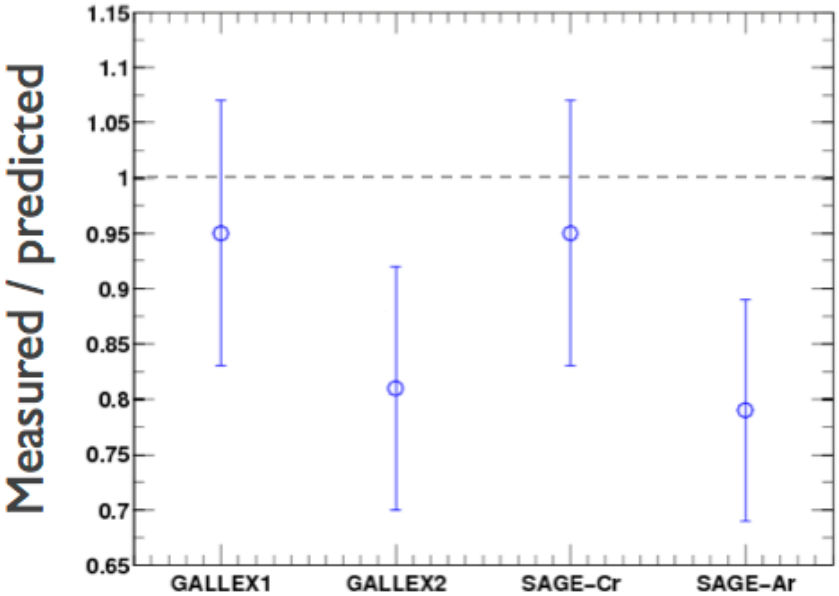




Gallium Anomaly (ν_e Disappearance)

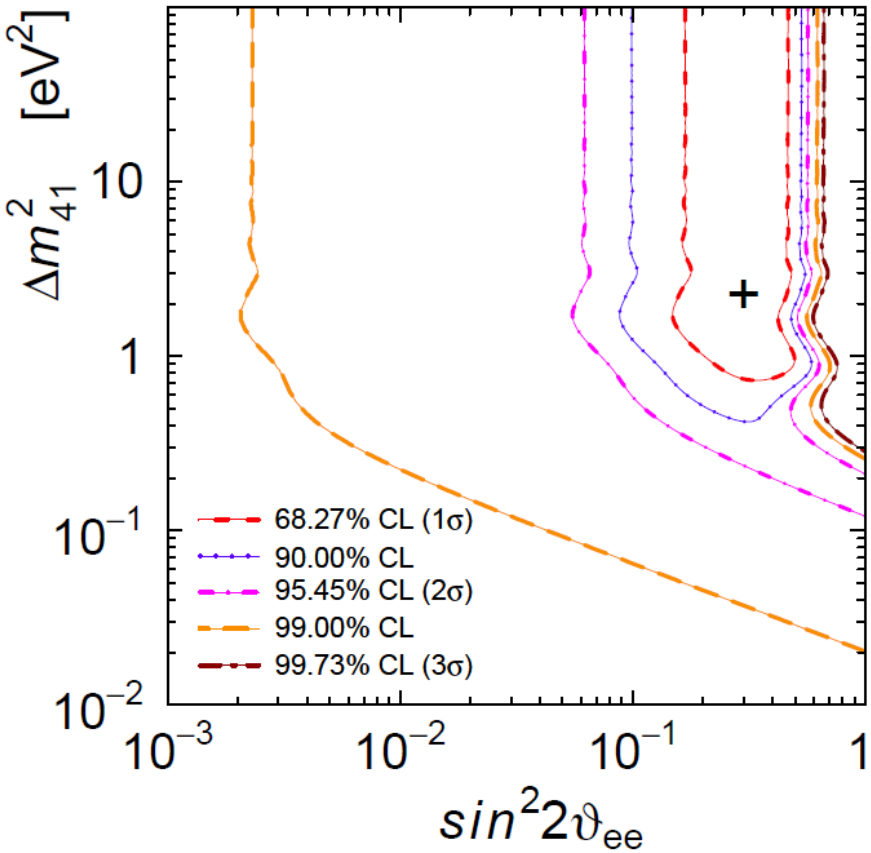
The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to "calibrate" the ν_e ^{71}Ga interaction/detection rate.

A reanalysis, based on new cross section calculations, suggests that were too few events.

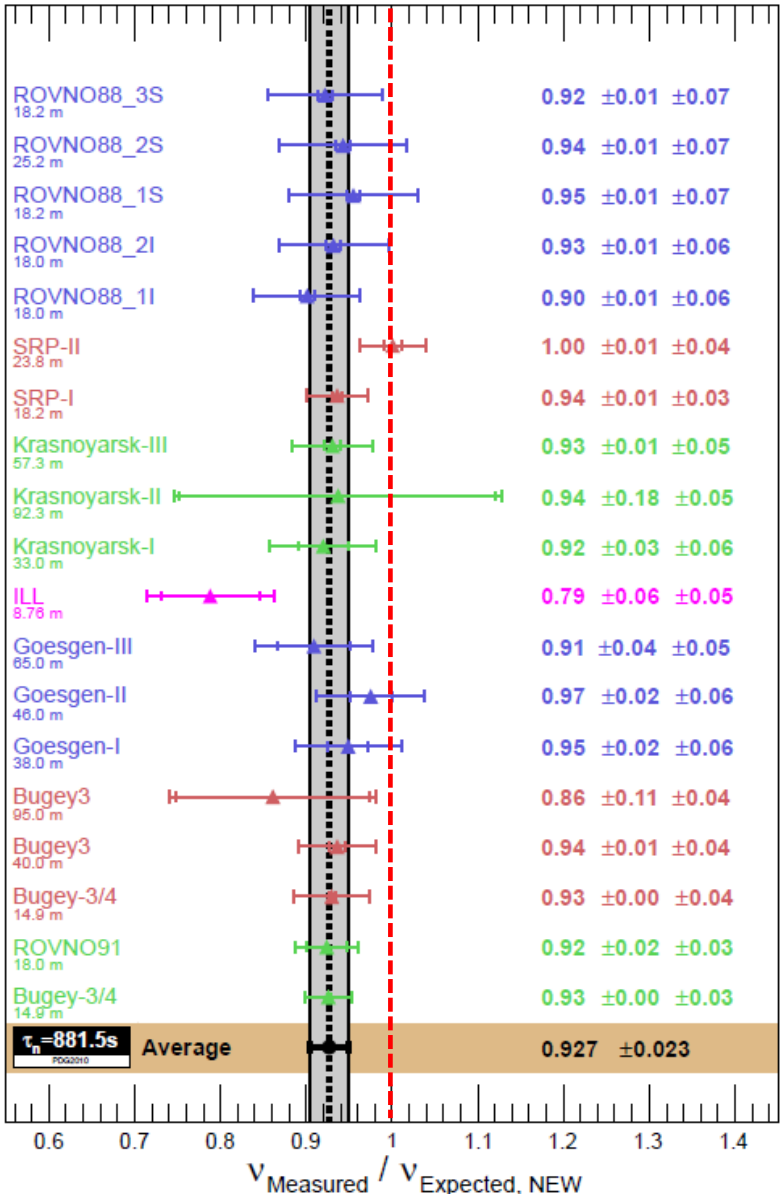


Giunti & Laveder, Phys.Rev.C83, 065504 (2011)

Giunti *et al.*, Phys.Rev.D86, 113014 (2012)

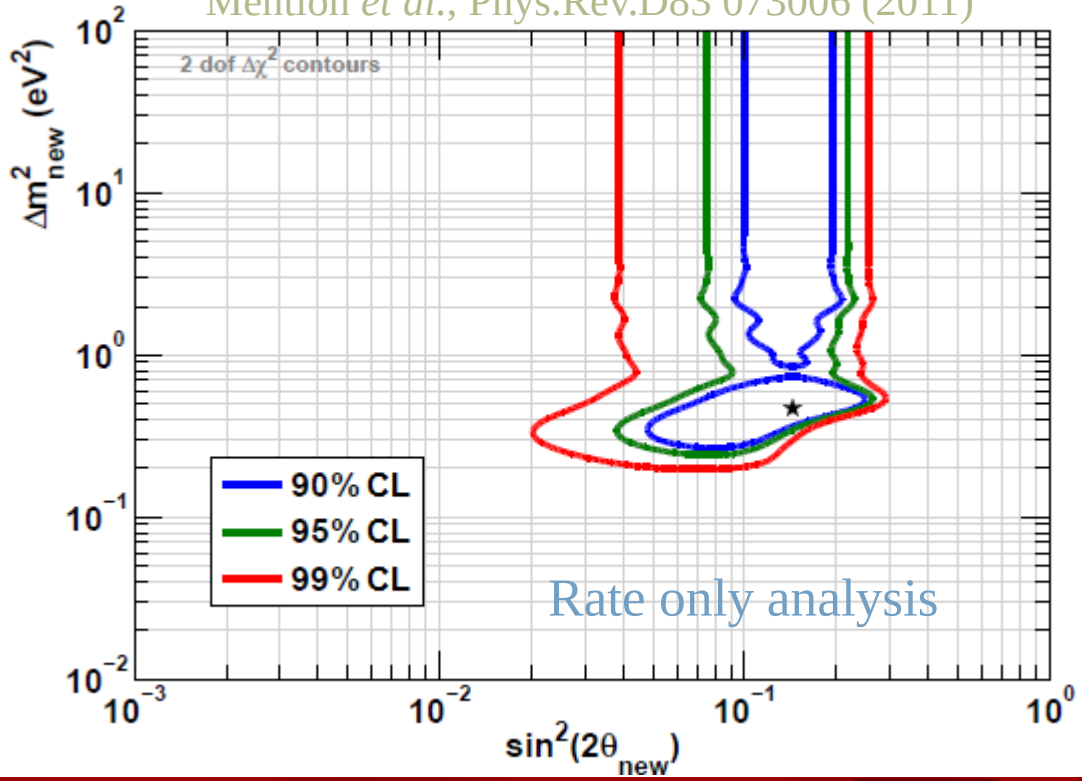


Reactor Anomaly ($\bar{\nu}_e$ Disappearance)



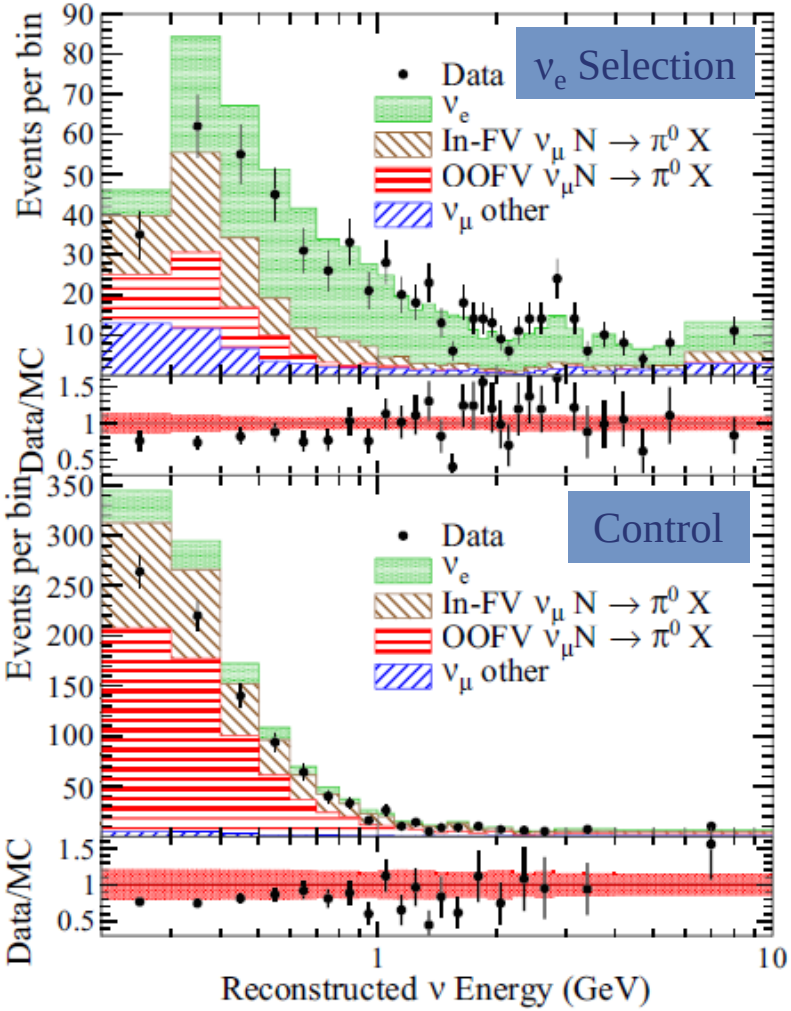
Recent calculations of the reactor $\bar{\nu}_e$ flux and spectrum predict a higher rate than the earlier calculation. This resulted is an apparent deficit of reactor neutrinos across all experiments.

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

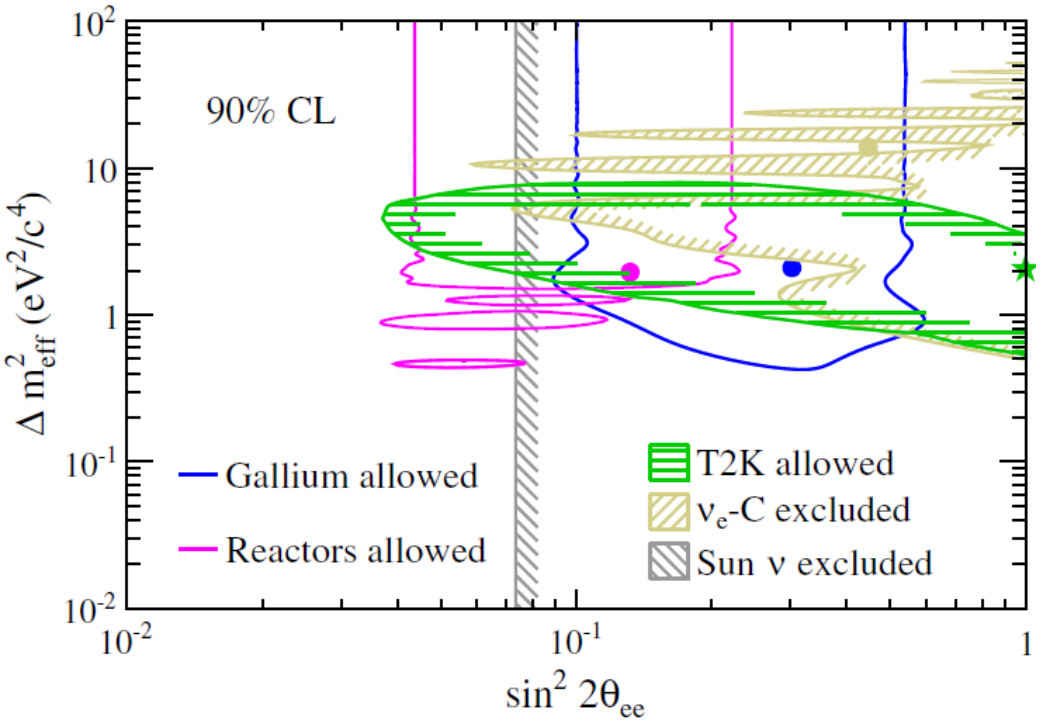


T2K Near Detector (ν_e Disappearance)

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)

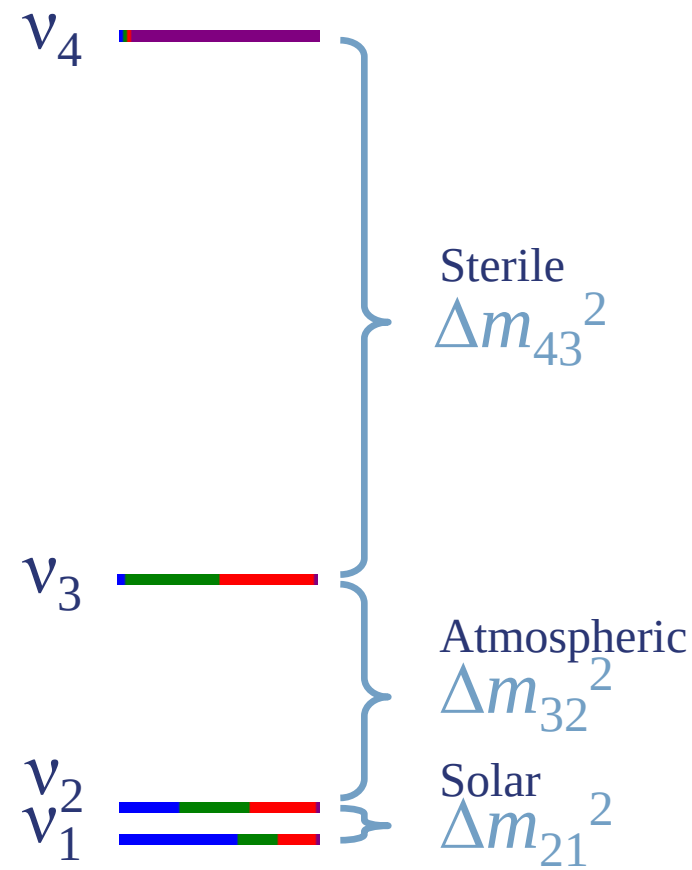


Short-baseline ν_e appearance from the much larger ν_μ component of the beam could fill in the exact region depleted by disappearance, so it is assumed to be zero in this analysis.

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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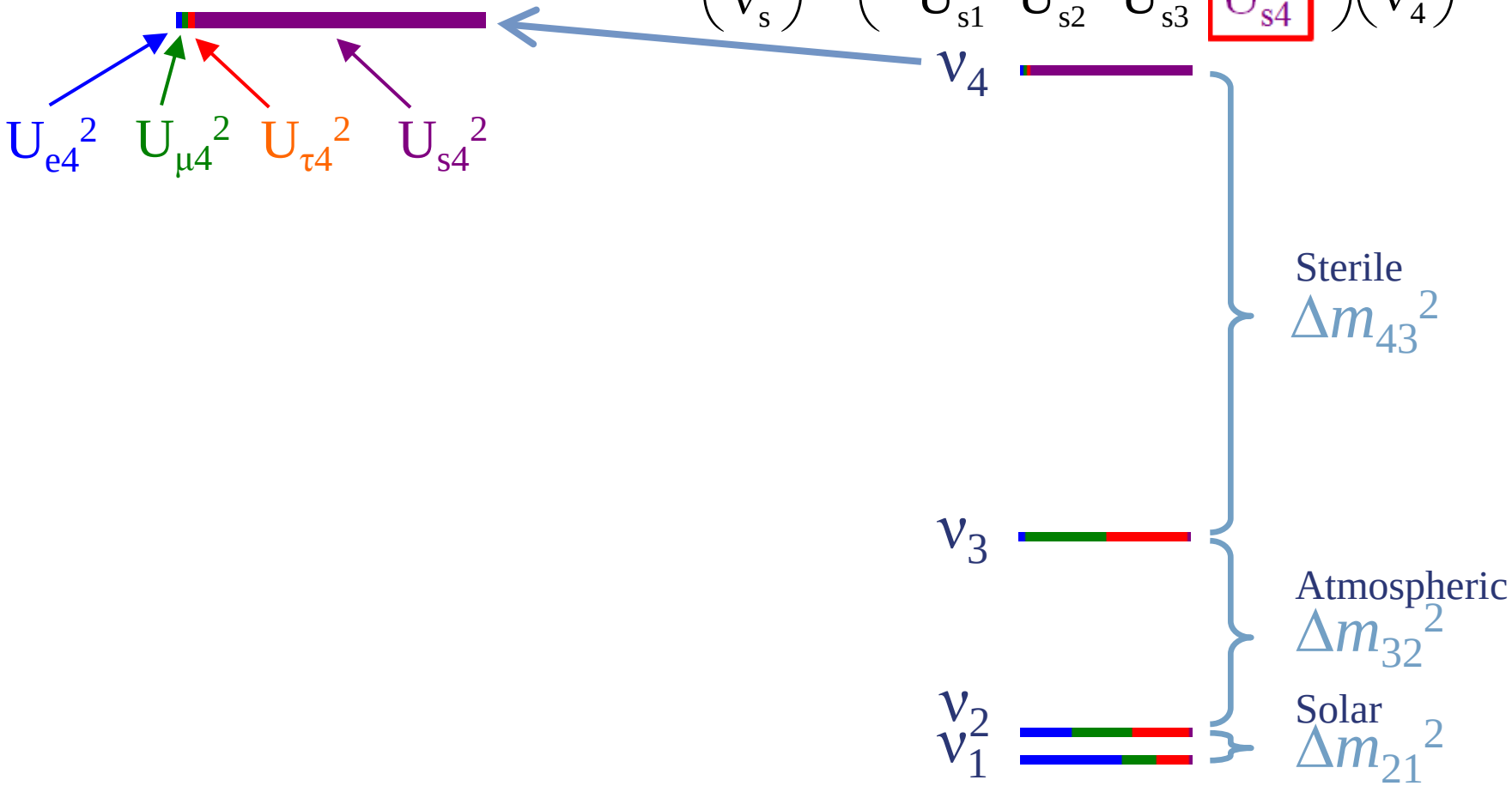

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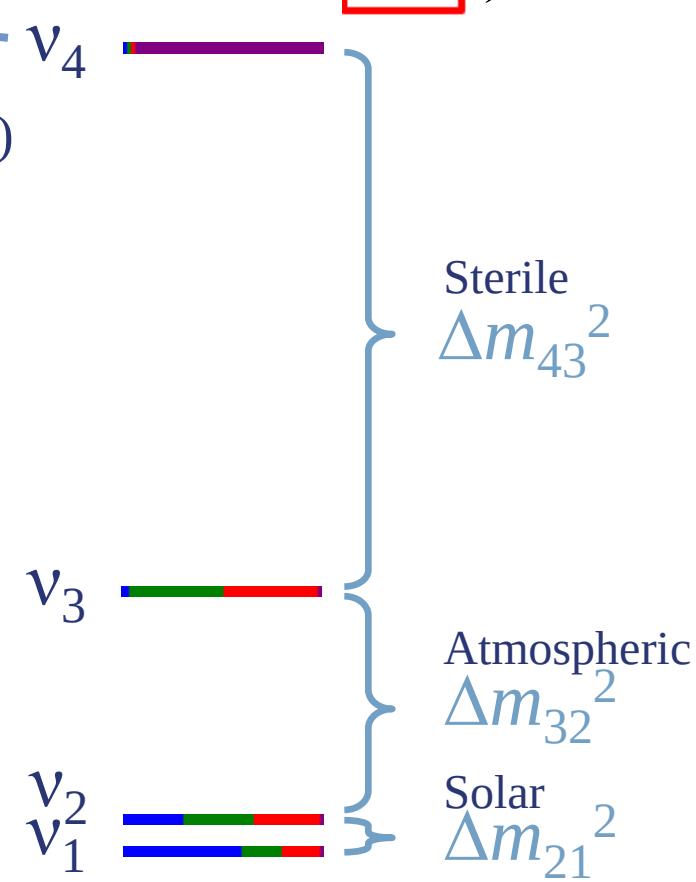
$$U_{e4}^2 + U_{\mu4}^2 + U_{\tau4}^2 + U_{s4}^2 = \mathbf{1} \quad \text{(PMNS Unitarity)}$$



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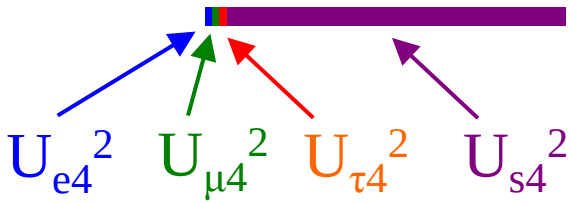

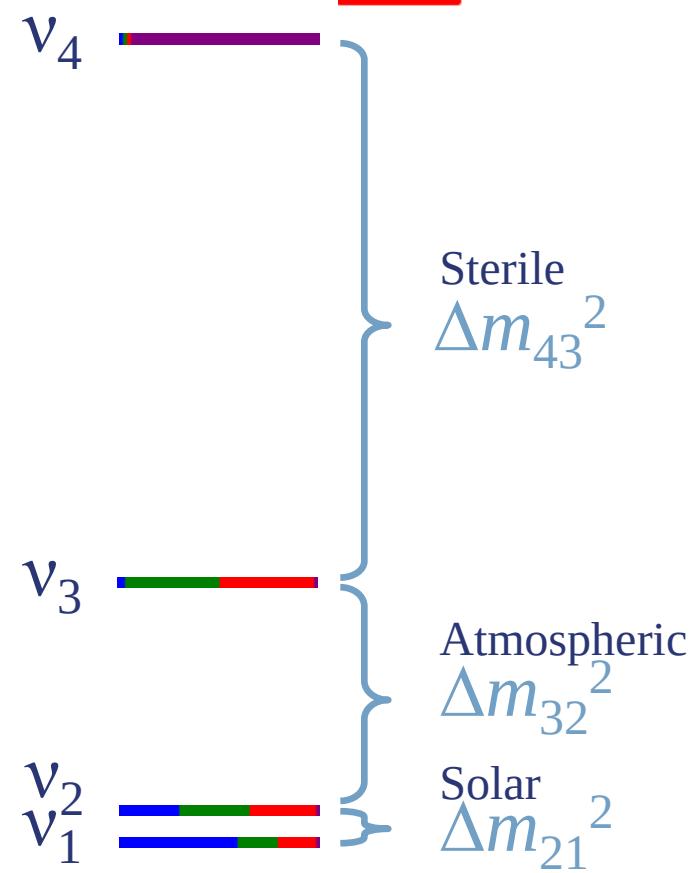

The appearance probability:

$$P_{\mu e} = \sin^2 2\theta \sin^2(1.27\Delta m_3^2 L/E)$$

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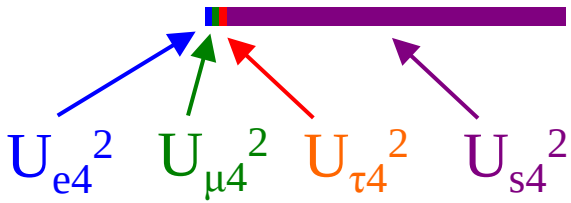

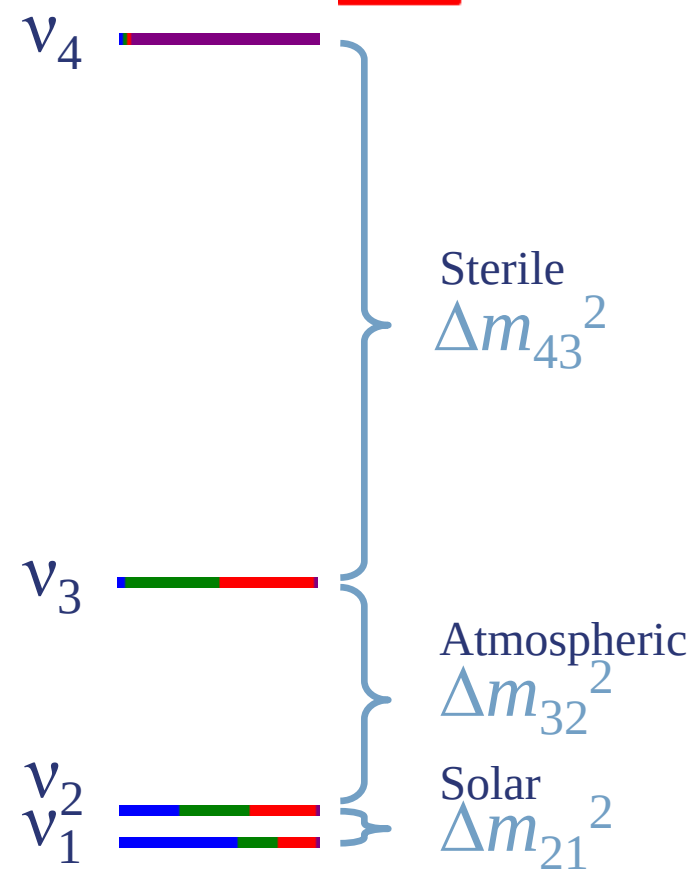

The appearance probability:

$$P_{\mu e} = 4U_{e4}^2 U_{\mu4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

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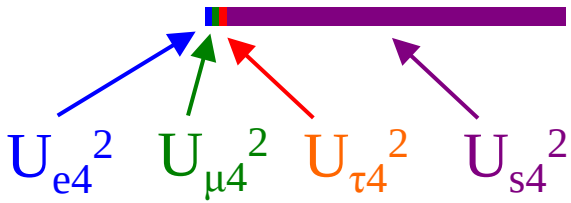

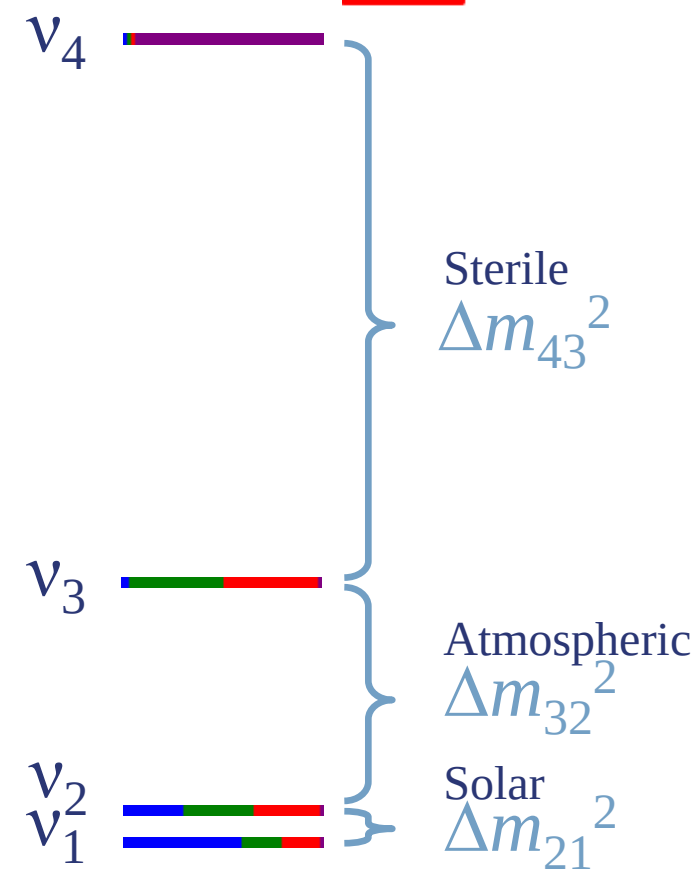

The appearance probability:

$$P_{\mu e} = 4U_{e4}^2 U_{\mu4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

The ν_e disappearance probability:

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

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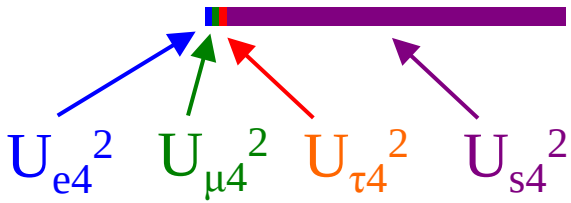

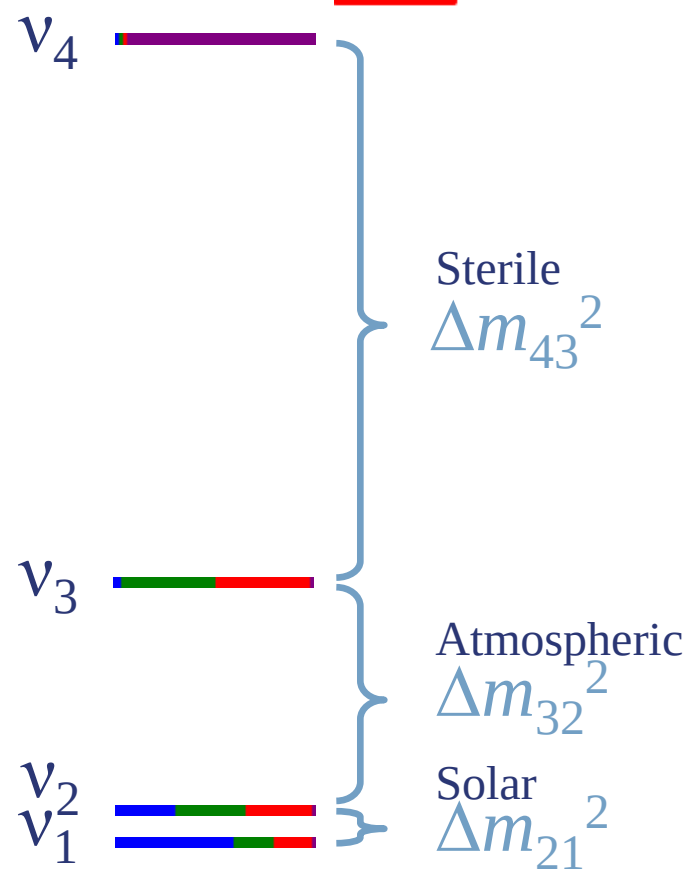

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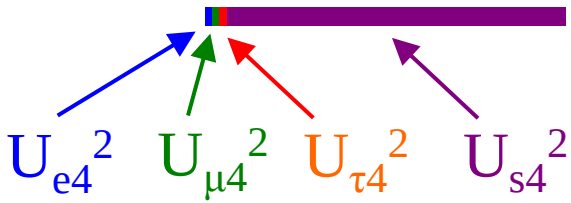

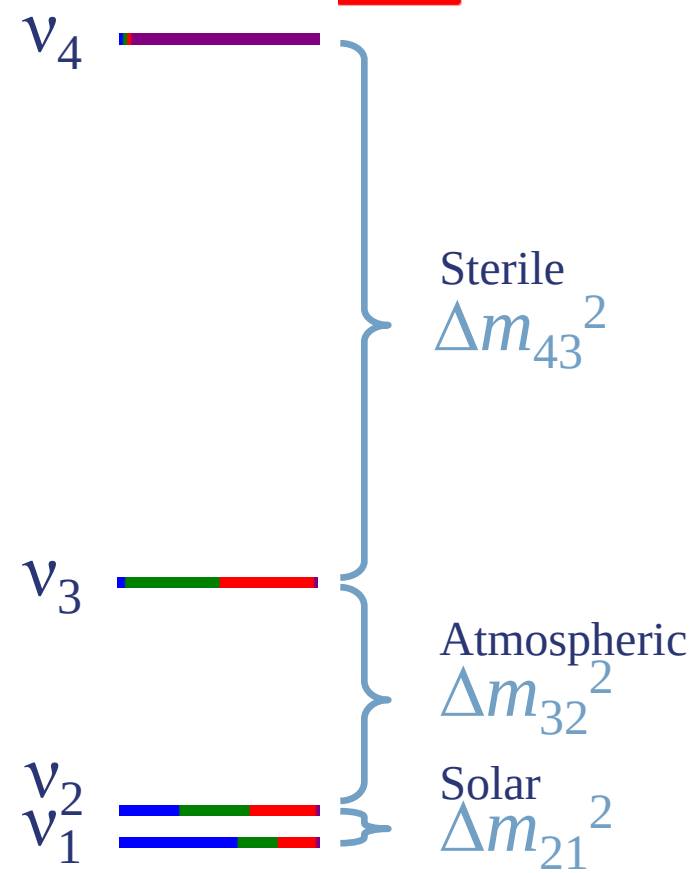

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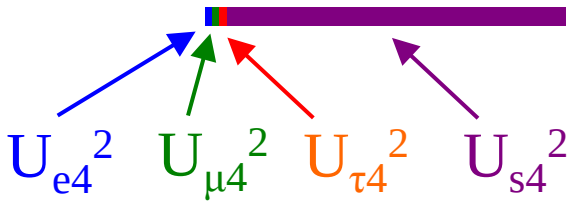

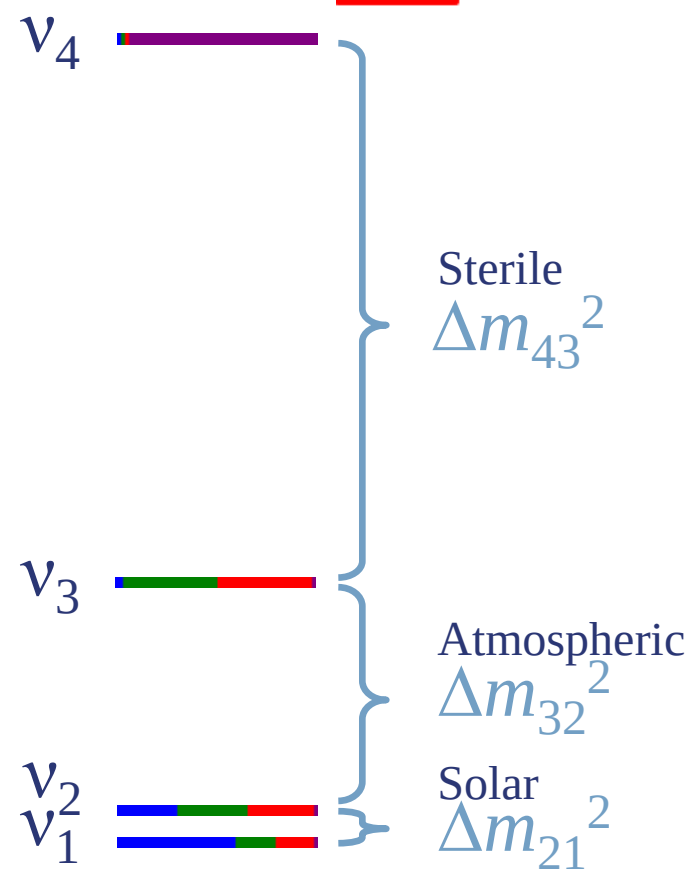

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The ν_μ disappearance probability:

$$P_{\mu\cancel{\mu}} \approx 4U_{\mu 4}^2 U_{s4}^2 \sin^2(1.27\Delta m_3^2 L/E)$$

Appearance vs. Disappearance

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

$$P_{\mu e} \approx \frac{1}{4} P_{ee} \times P_{\mu\mu} \qquad \text{or} \qquad \sin 2\theta_{\mu e} = \frac{1}{4} \sin 2\theta_{ee} \sin 2\theta_{\mu\mu}$$

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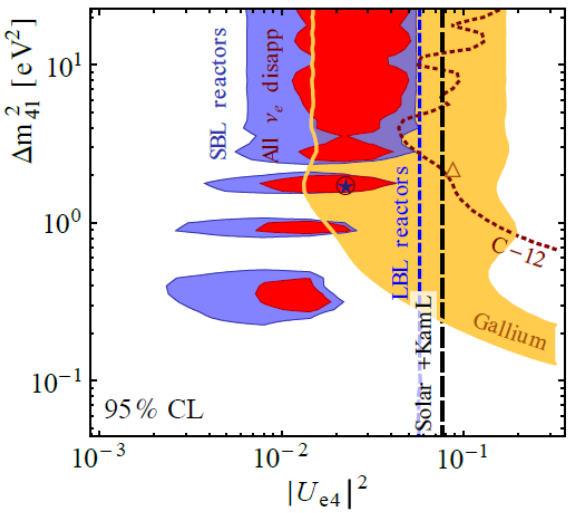
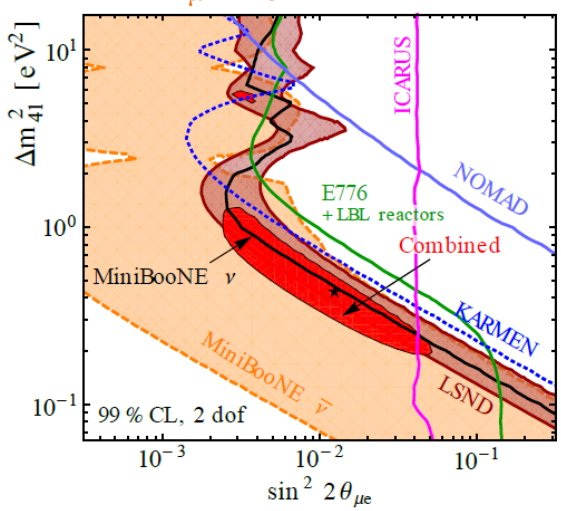
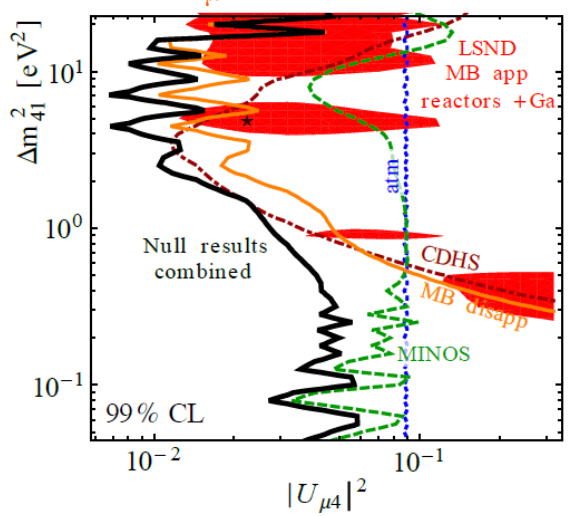
ν_e Disappearance



$\nu_\mu \rightarrow \nu_e$ Appearance



ν_μ Disappearance



Global fit from Kopp *et al.* JHEP 1305, 050 (2013)

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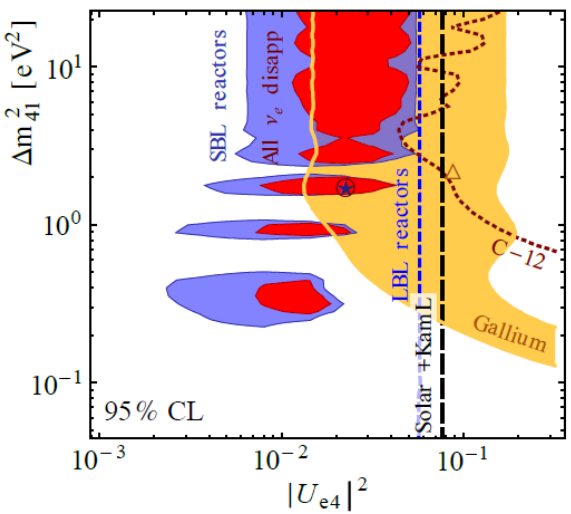

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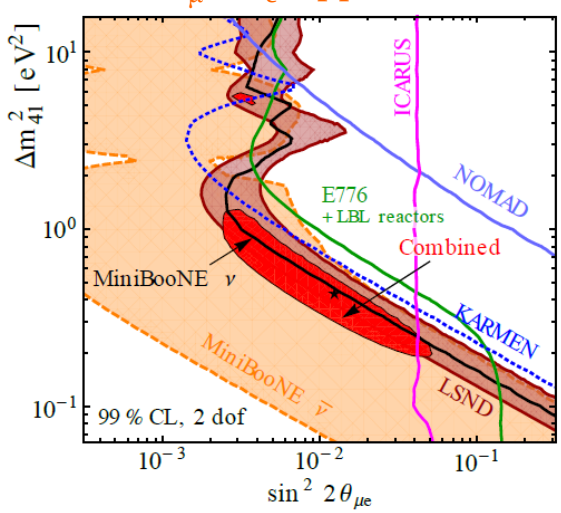

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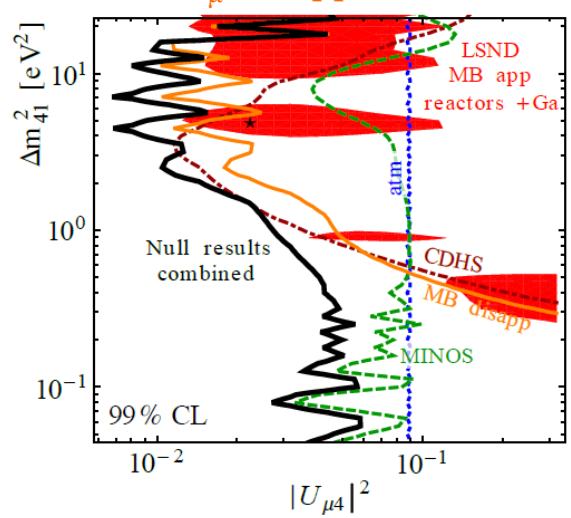

Global fit from Kopp *et al.* JHEP 1305, 050 (2013)

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

Ongoing & Future Short-Baseline Experiments

TAUP Presentations: Talks Posters

Accelerator Decay-in-Flight:

Fermilab Short-Baseline (SBND, MicroBooNE (Toups), ICARUS (Varanini))

T2K Near Detector

nuSTORM

Accelerator Decay-at-Rest:

OscSNS

IsoDAR

KDAR/KPipe

Reactor Experiments:

Nucifer

DANSS

CARR

NuLAT

Stereo (Haser)

POSIDON

Korean SBL

CHANDLER

Solid (Yarmia)

Neutrino-4

Prospect (Heeger)

…

Radioactive Neutrino Sources:

SOX (Vivier)

LZ-Cr (McKinsey)

RICCOCHET

Sterile Searches that are not Short-Basline:

OPERA (Di Crescenzo)

MINOS+ (Holin)

IceCube (Salvado)

Plank (Lattanzi)

SHiP (De Serio)

KATRIN (Mertens)

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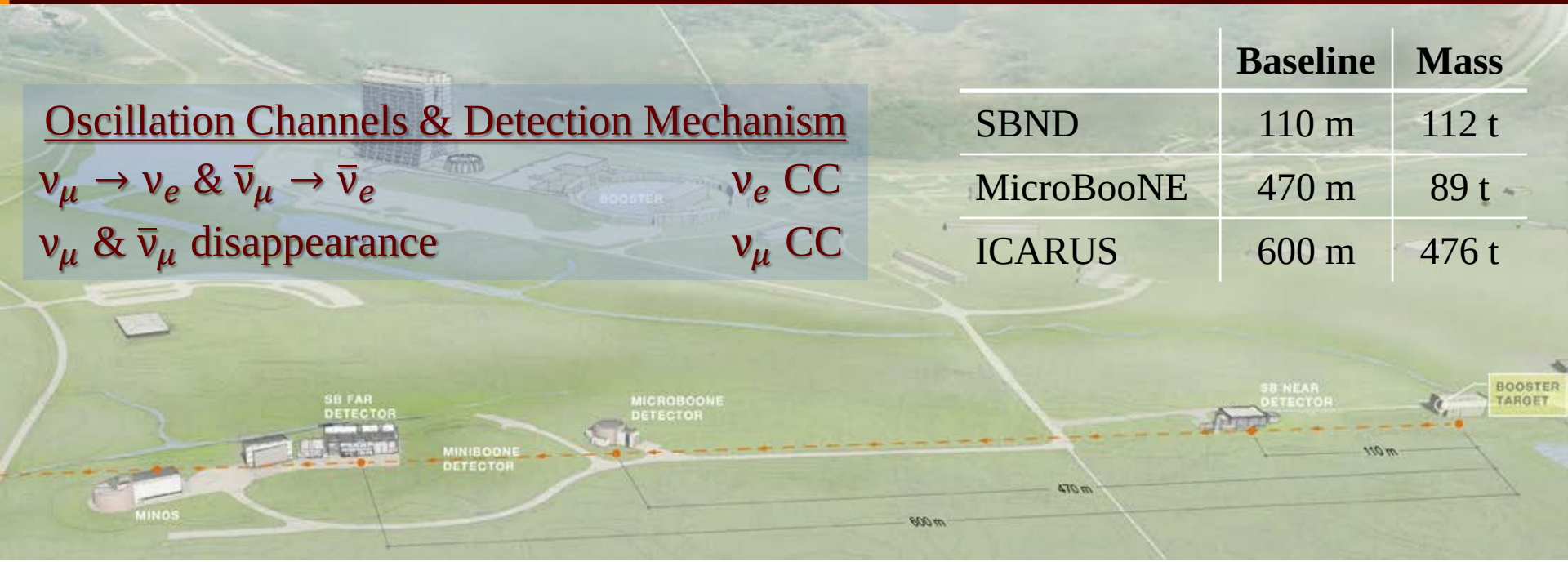
The Fermilab Short-Baseline Program



Oscillation Channels & Detection Mechanism

$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_e CC
ν_μ & $\bar{\nu}_\mu$ disappearance	ν_μ CC

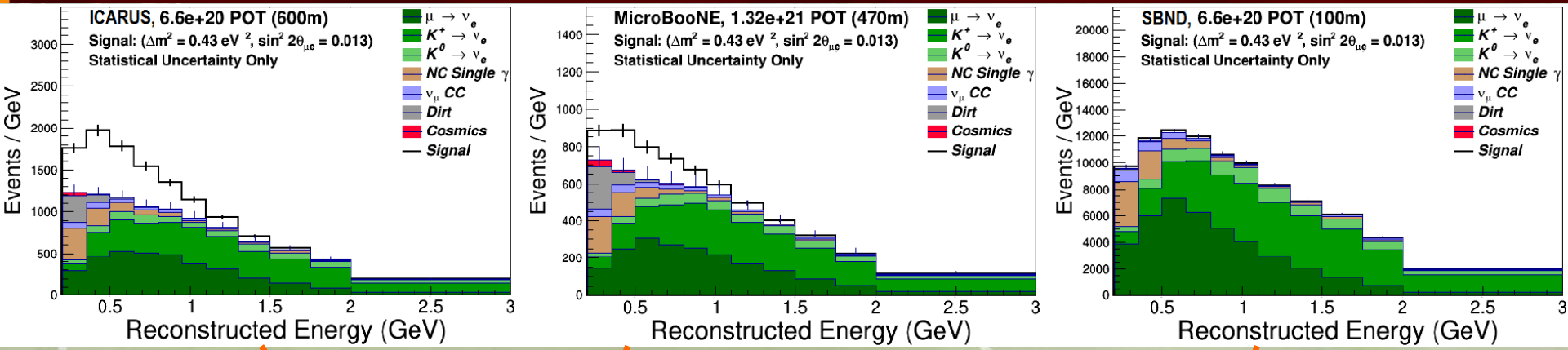
	Baseline	Mass
SBND	110 m	112 t
MicroBooNE	470 m	89 t
ICARUS	600 m	476 t

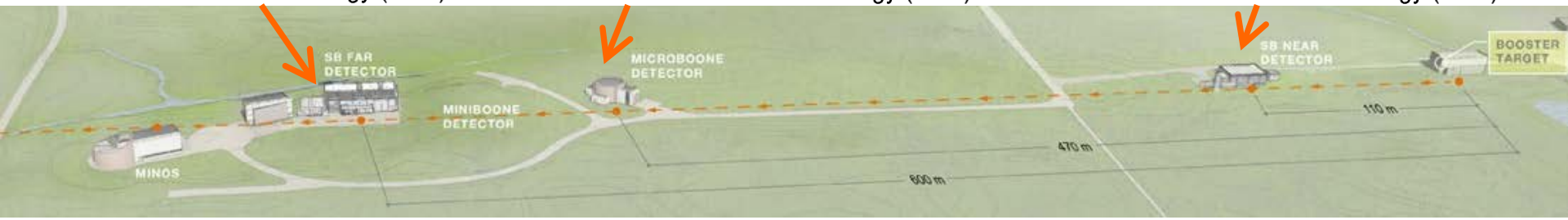
The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

The near detector provides an inclusive measure of beam and misID backgrounds.

The ICARUS T600 at a third baseline significantly boosts the statistics and the dynamic range in L/E.

The Fermilab Short-Baseline Program





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Oscillation Char

$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow$

ν_μ & $\bar{\nu}_\mu$ disappe

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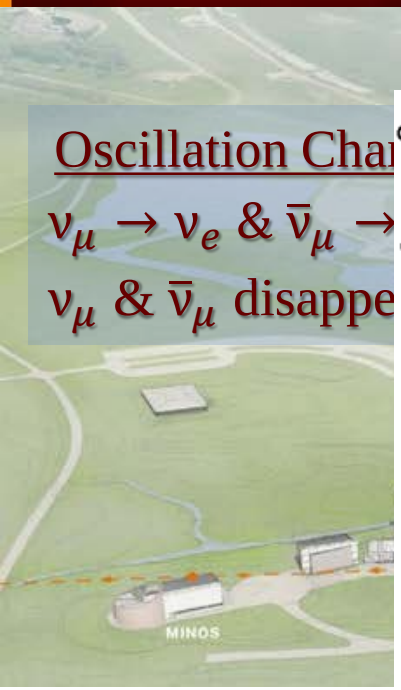
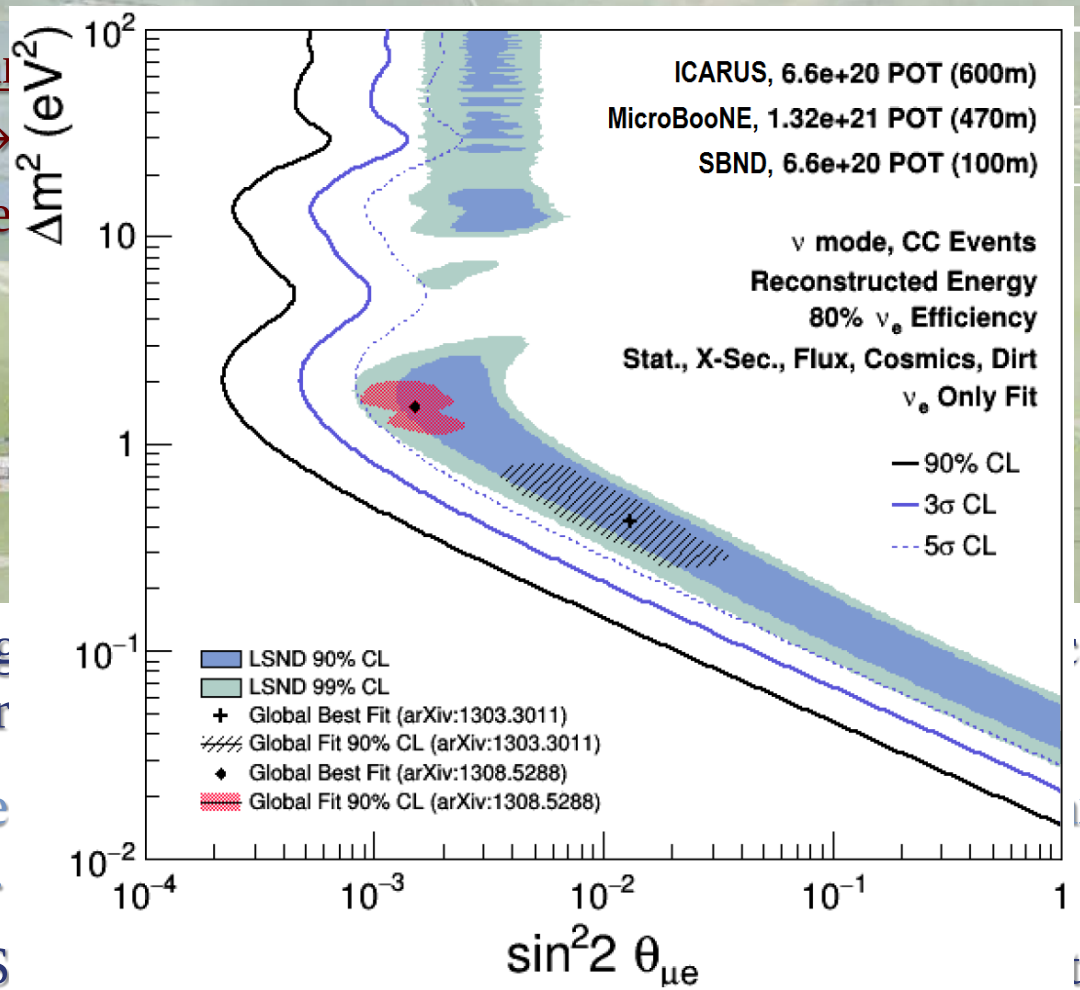
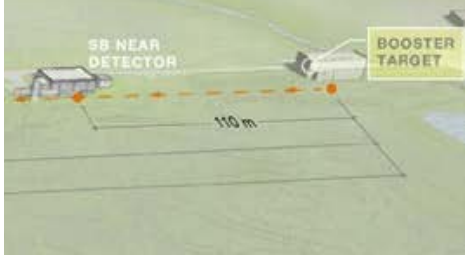






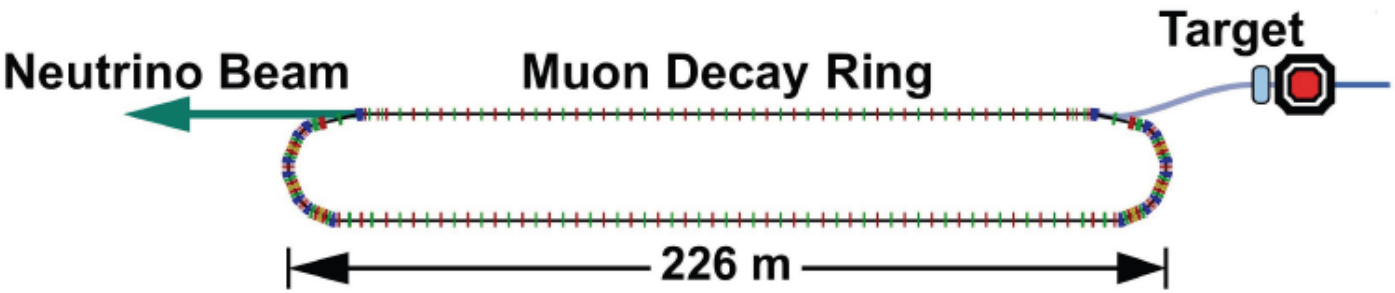
The liquid arg ... antly reduce misID backgr

The near dete ... misID backgrounds.

The ICARUS ... statistics and the dynamic range in L/E.

Muon Storage Ring: nuSTORM

nuSTORM is a low-energy muon storage ring that produces pure and well-characterized beams of ν_μ and $\bar{\nu}_e$, or $\bar{\nu}_\mu$ and ν_e depending on which sign muons are stored.



In the ν_μ appearance channel, the sign of the outgoing muon is all that's needed to establish oscillations.

Oscillation Channels & Detection Mechanism		
$\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	Golden Mode	ν_μ CC
$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$		ν_e CC
ν_μ, $\bar{\nu}_\mu$, ν_e & $\bar{\nu}_e$	disappearance	ν_μ CC

Pion Decay-at-Rest: OscSNS

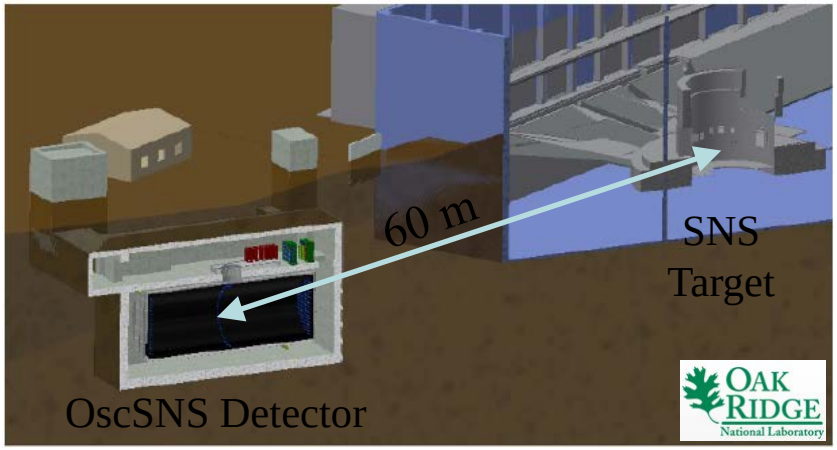
OscSNS is direct test of LSND using the Spallation Neutron Source as a pion decay-at-rest source.

LSND is individually the most significant evidence for sterile neutrinos.

Neither the beam nor the detector is particularly innovative, but they have the opportunity to fix certain weaknesses of LSND:

- Detector located upstream of the target
- Possible use of Gd to tag neutrons
- Covers a wider range in L/E

Oscillation Channels & Detection Mechanism		
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Golden Mode	Inverse β-decay
$\nu_\mu \rightarrow \nu_e$		$\nu_e + {}^{12}C \rightarrow e^- (12.5\ MeV) + {}^{12}N$
ν_e disappearance		$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$



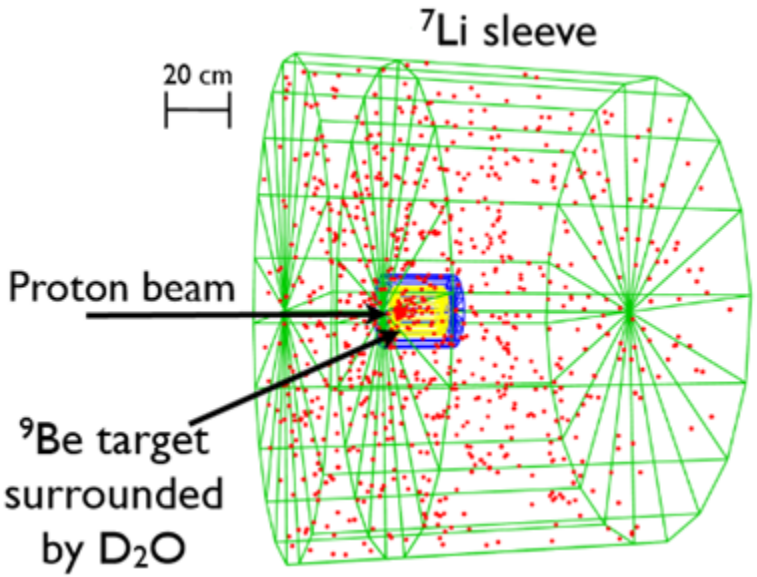
Cyclotron Produced Isotopes: IsoDAR

The IsoDAR proposal uses an intense beam of protons to produce ^{8}Li. The ^{8}Li decays producing $\bar{\nu}_e$ with a β-spectrum.

Neutrinos are detected via inverse β-decay. KamLAND and RENO-50 are possible host detectors.

Oscillations observed through a disappearance channel.

Oscillation Channels & Detection Mechanism	
$\bar{\nu}_e$ disappearance	Inverse β-decay Golden Mode



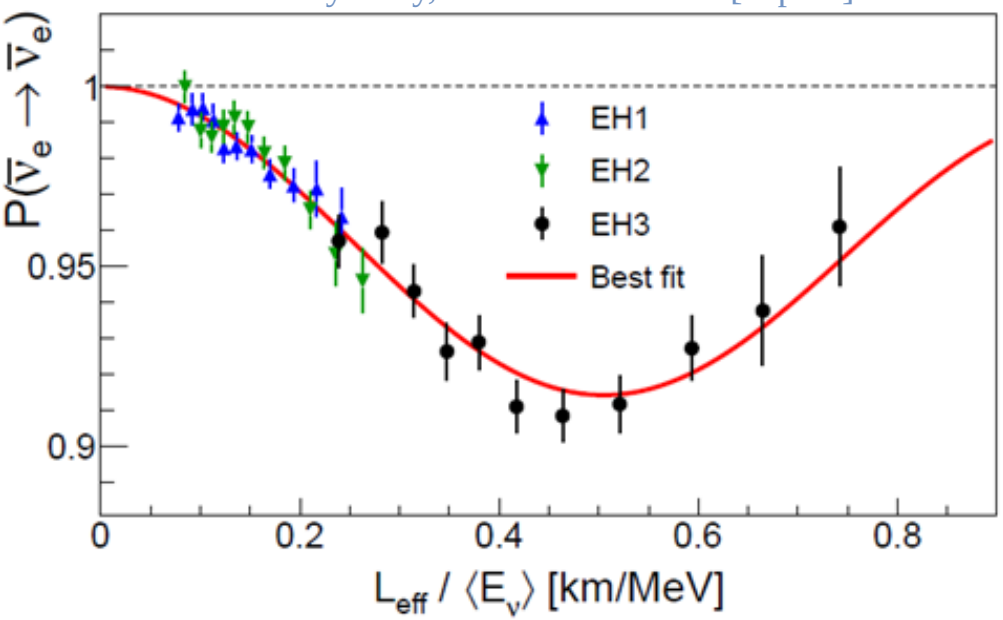
Requirement for Disappearance Experiments

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

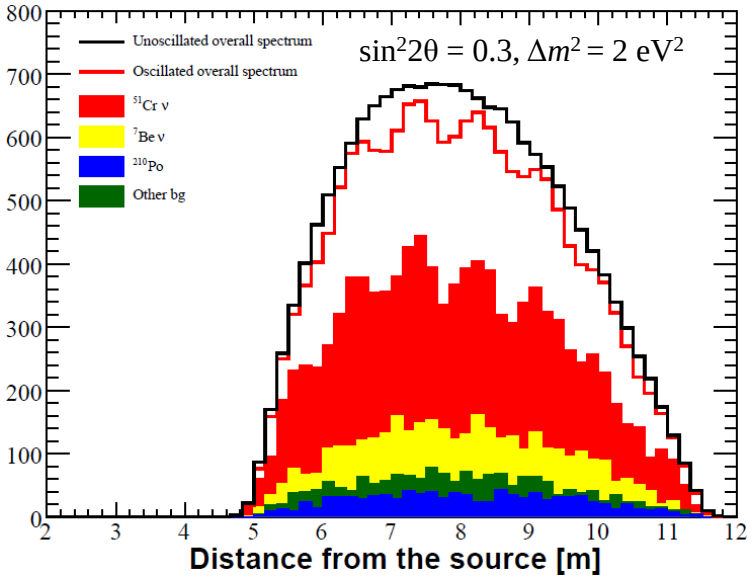
–American jazz great Duke Ellington

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

Daya Bay, arXiv:1505.03456 [hep/ex]



Borexino/SOX, JHEP 1308, 038 (2013)



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

Bring the Source vs. Bring the Detector

Reactor Experiments: the detector is brought to a pre-existing source

1. Nuclear reactors are the most prolific terrestrial neutrino sources, producing 6×10^{17} $\bar{\nu}_e$ per second per MW_{th}.
2. It is unlikely that a reactor would ever be constructed specifically for use as a neutrino source, nevertheless, neutrino experiments can use existing reactors without any impact on their normal operations.
3. Once the detector has been delivered, neutrino statistics accumulate with minimal operational costs.

Radioactive Source Experiments: the source is brought to a pre-exiting detector

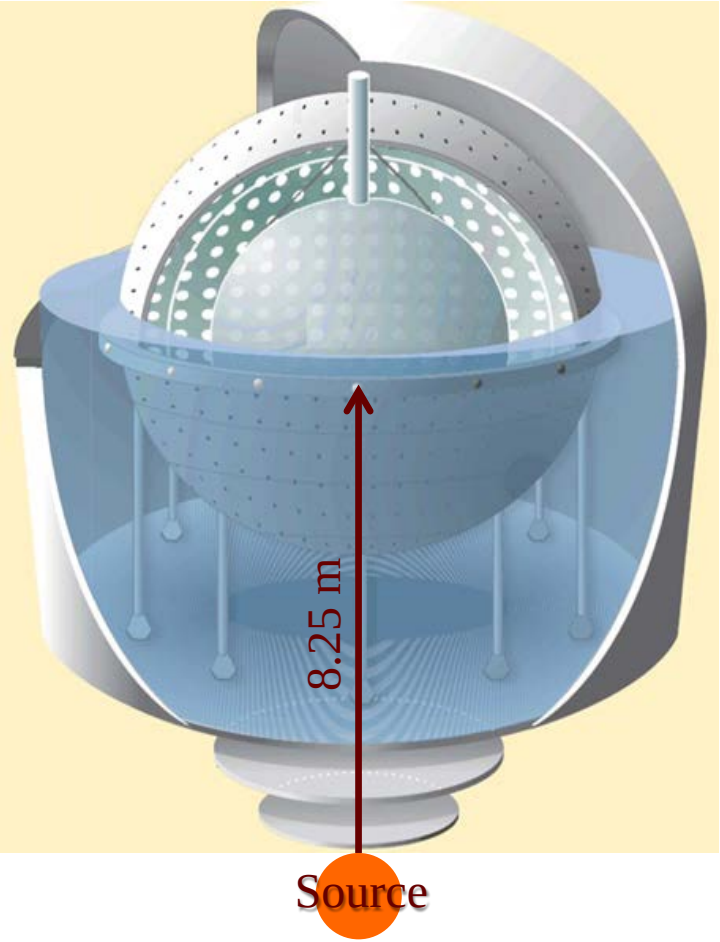
1. Leverages detectors built for other applications (*e.g.* solar neutrinos, dark matter).
2. Often these detectors have exisiting reconstructions, well measured backgrounds and a well understood energy response.
3. The source decays away, so to accumulate additional statistics requires a new investment on the scale of the original deployment.

Source Experiment: SOX

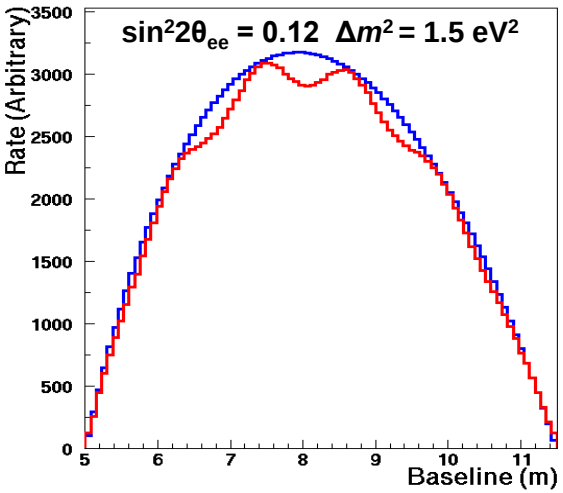
Combines the Borexino detector with a ^{144}Ce $\bar{\nu}_e$ source and/or a ^{51}Cr ν_e source.

See talk by Vivier

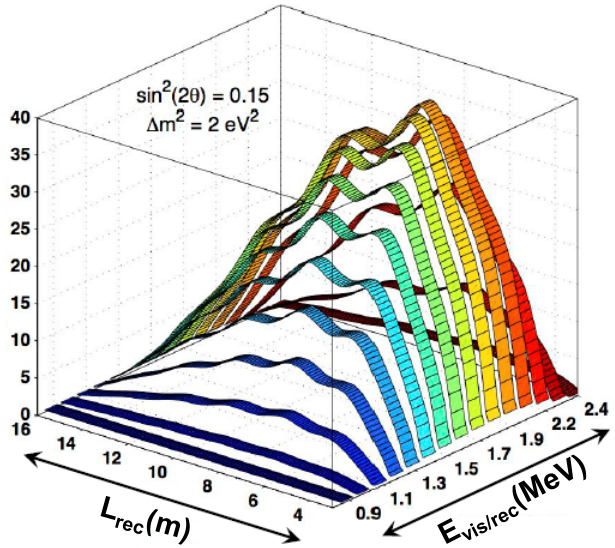
At the typical sterile Δm^2, multiple oscillation wavelengths may be observed inside the detector.



^{51}Cr Source



^{144}Ce Source



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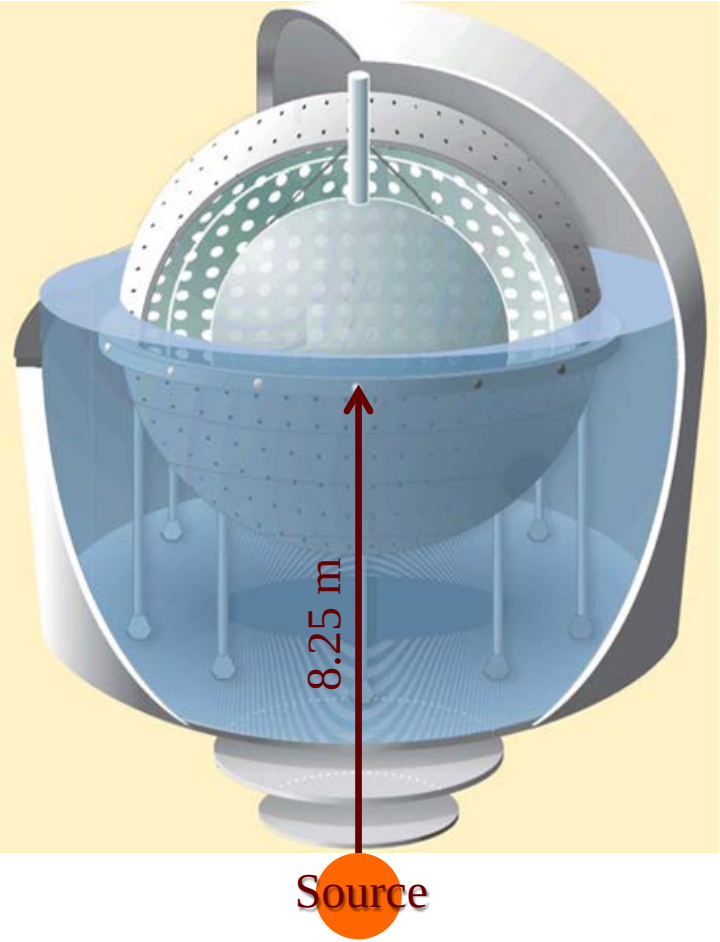

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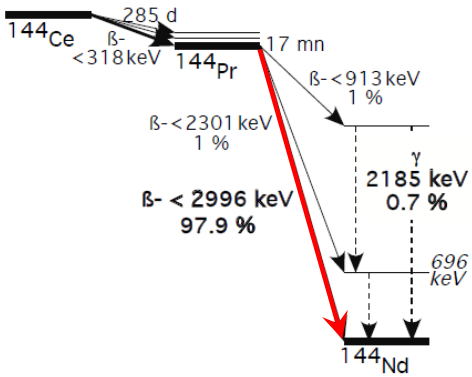
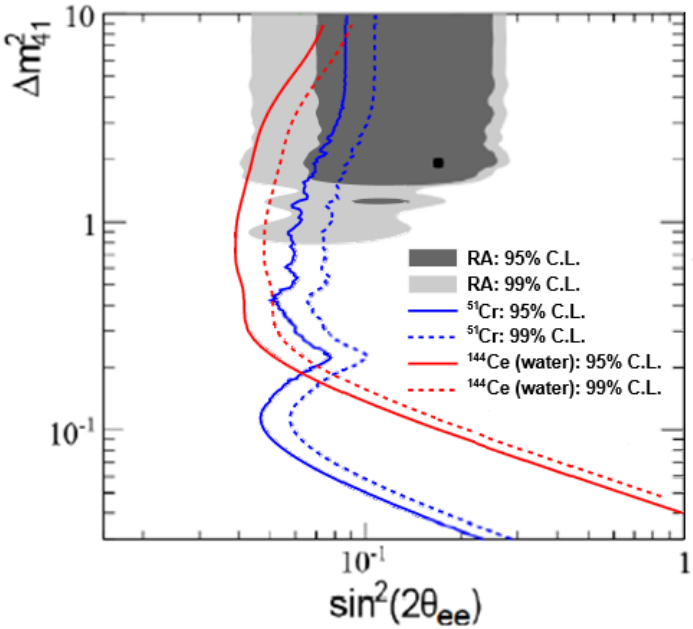
^{144}Ce $\bar{\nu}_e$ neutrinos have a β spectrum with a 3 MeV endpoint and are observed by inverse beta decay.

^{144}Ce-^{144}Pr Decay





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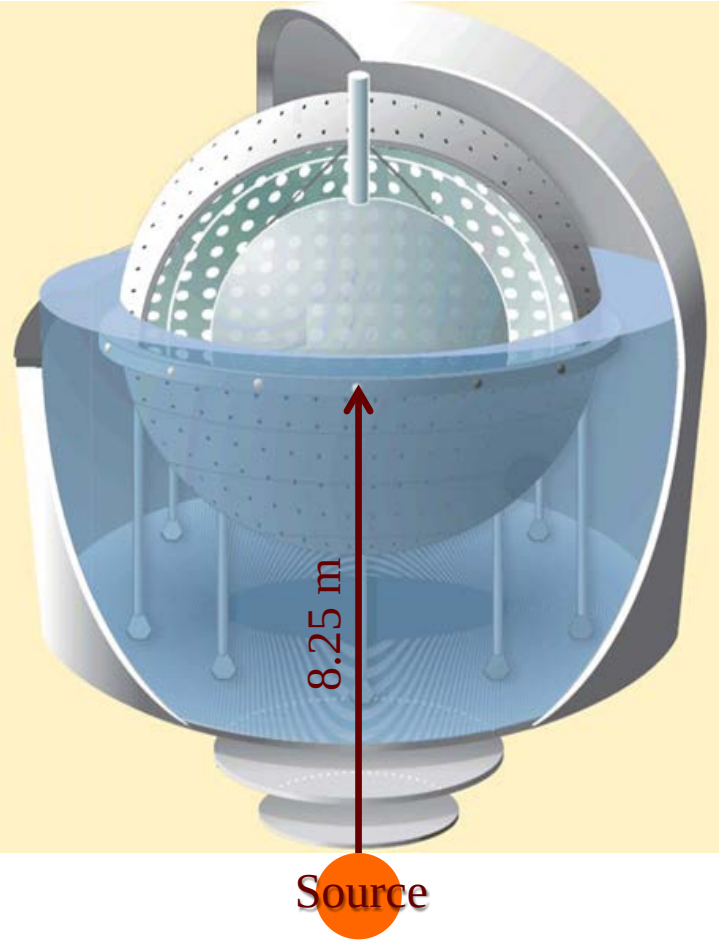

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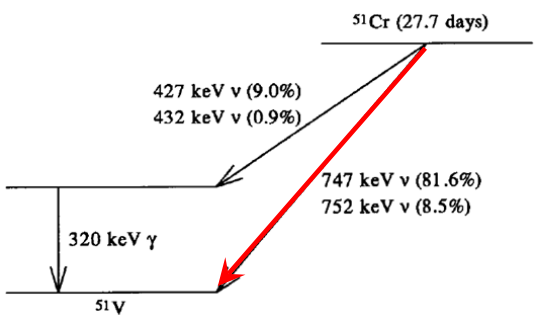
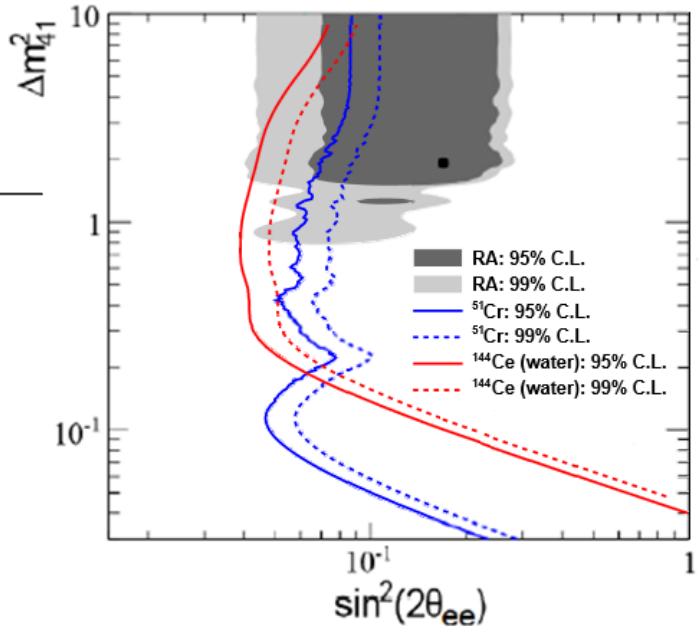
^{144}Ce $\bar{\nu}_e$ neutrinos have a β spectrum with a 3 MeV endpoint and are observed by inverse beta decay.

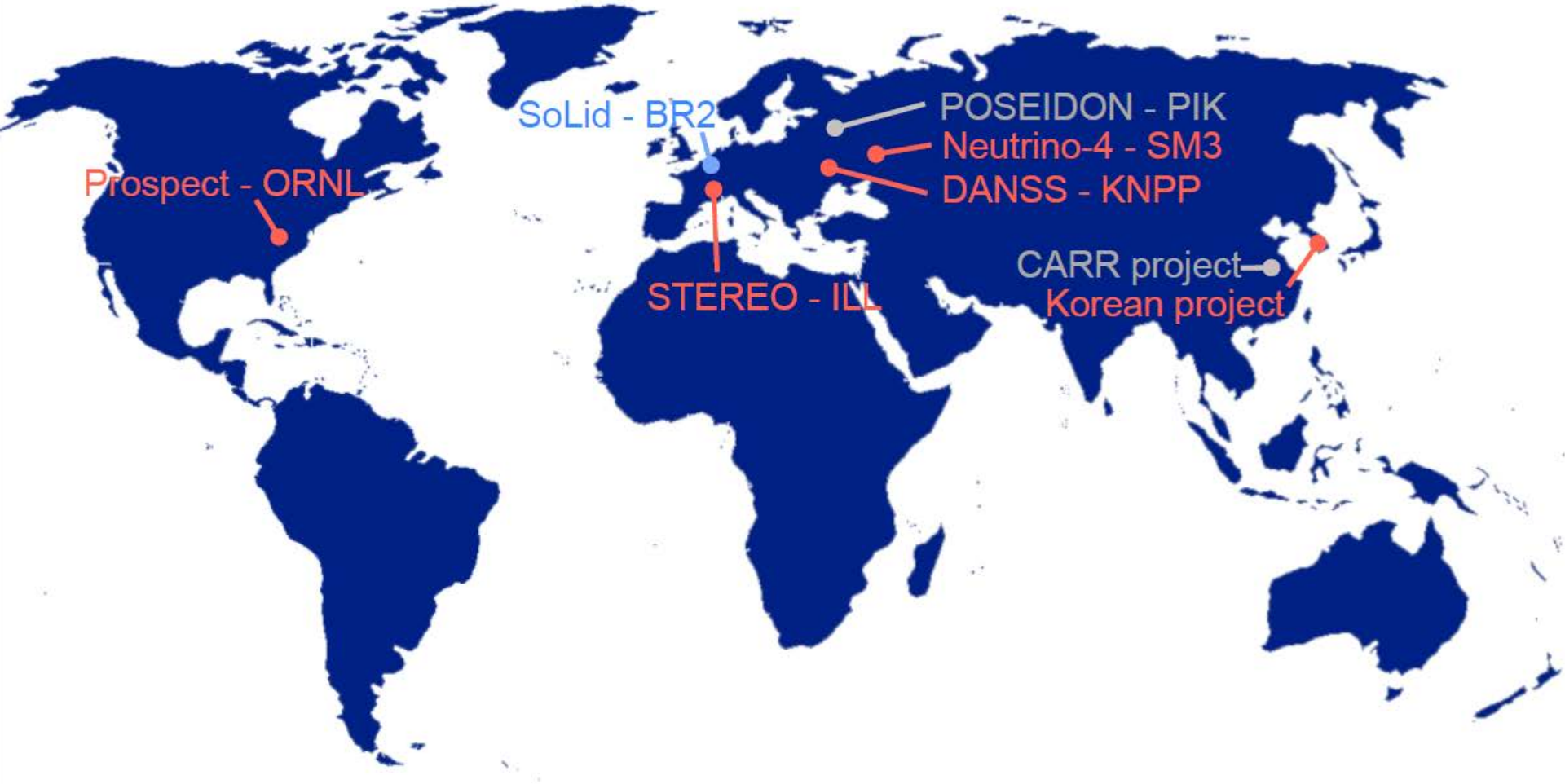
Mono-energetic ^{51}Cr ν_e oscillate as a pure function of L, and are detected by electron elastic scattering.

^{51}Cr Decay





New Reactor experiments

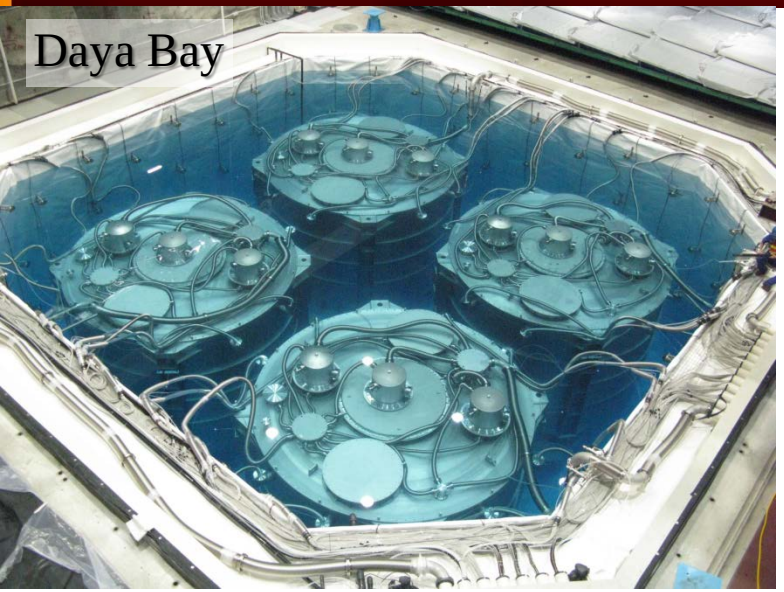


from Antonin Vacheret

Comparison of Reactor Experiments

	Pow	re Size	Mass	n Tag	)	L min	L max
Stereo	58	ct	1.75 tons	Gd			
DANSS		3	1 ton	Gd		9.7 m	12 m
POSEIDON	TW	40 cm	5 tons	Gd	25	6 m	15 m
Neutrino-4	TW	Compact		Gd			
SBL-Korea	TW W	Compact Large	30	Gd or ^{6}Li		6 m 27 m	
Prospect	W	50 cm	2.5 tons	^{6}Li		7 m	11 m
SoLid		50 cm	3 tons			5.5 m	11 m
NuLat		Compact		^{6}			

Reactor Experiments



Unlike the reactor θ_{13} experiments, short-baseline reactor experiments are done

- on the surface
- with small detectors
- without space for massive clean shielding
- and gamma catcher

Random coincidence backgrounds are one of the significant challenges.

<u>How can we deal with Random Coincidence Backgrounds?</u>

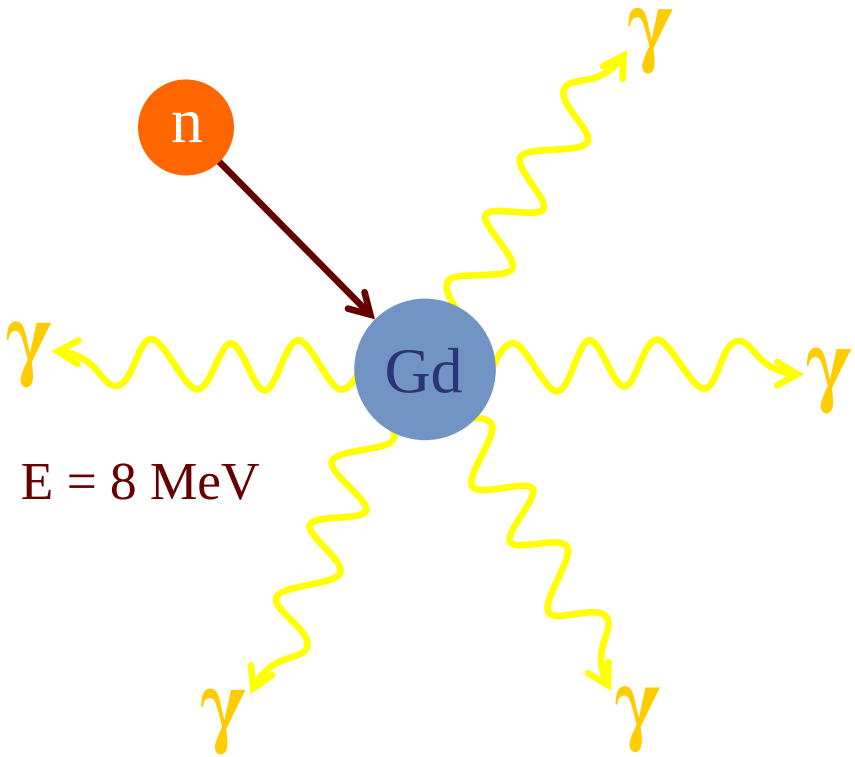
1. Neutron and gamma shielding
2. Unbiased spatial resolution ➡ Segmentation
3. High neutron capture efficiency and purity ➡ Gd and ^{6}Li

Neutron Capture Options

Daya Bay, RENO and Double Chooz tag neutrons with Gd capture, in conjunction with a large gamma catcher to contain the gammas.

This may not work as well in the small short-baseline detectors.

Neutron Capture on Gadolinium



Poorly contained in small detectors

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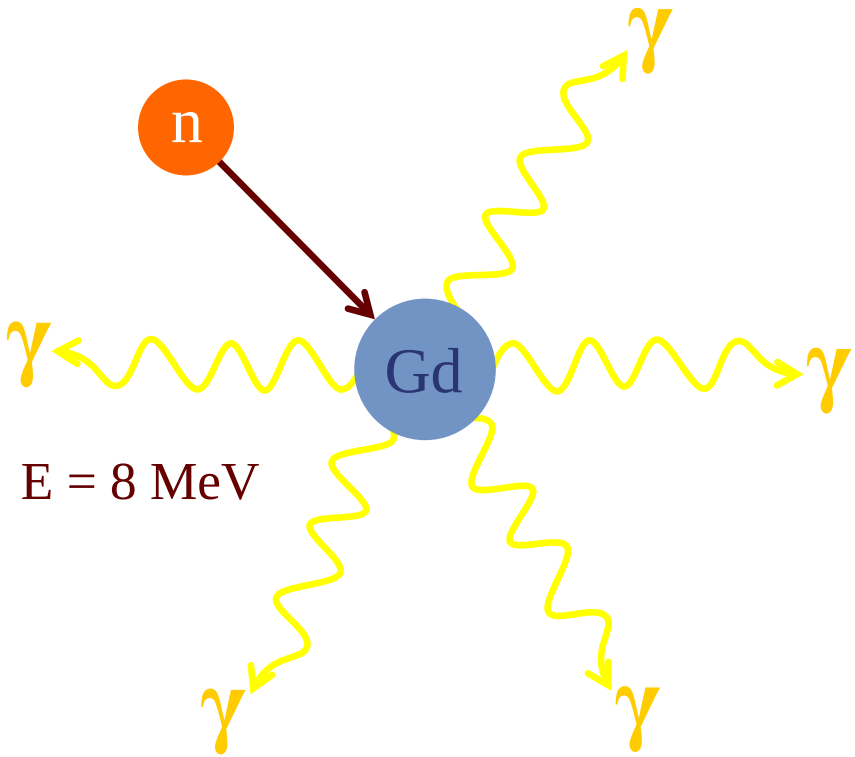
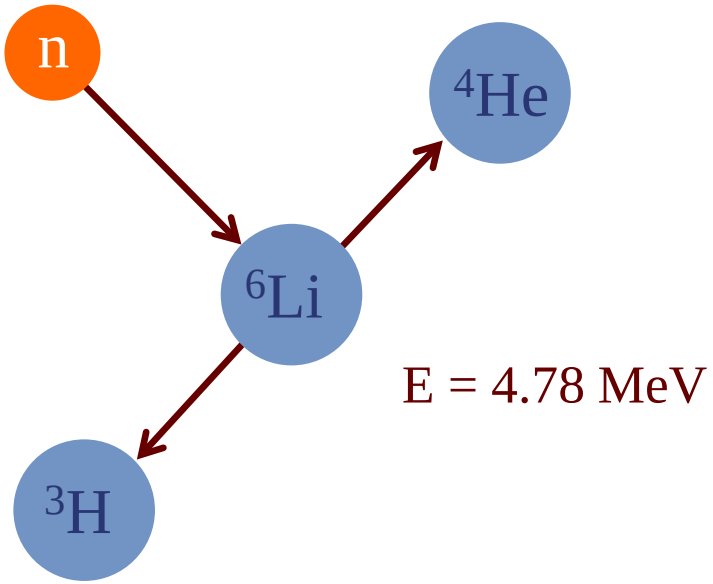


Poorly contained in small detectors

Neutron Capture on Lithium-6



Contained in a few microns

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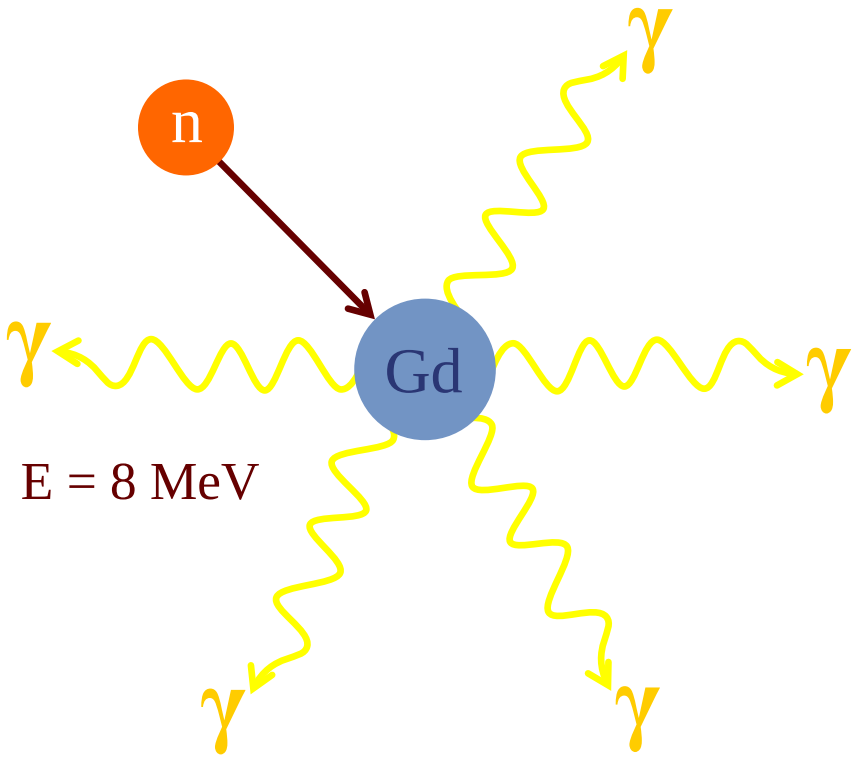

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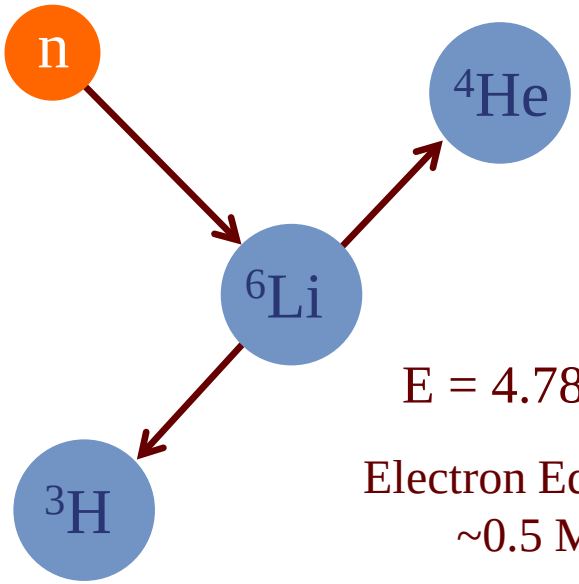


E = 4.78 MeV

Electron Equivalent ~0.5 MeV

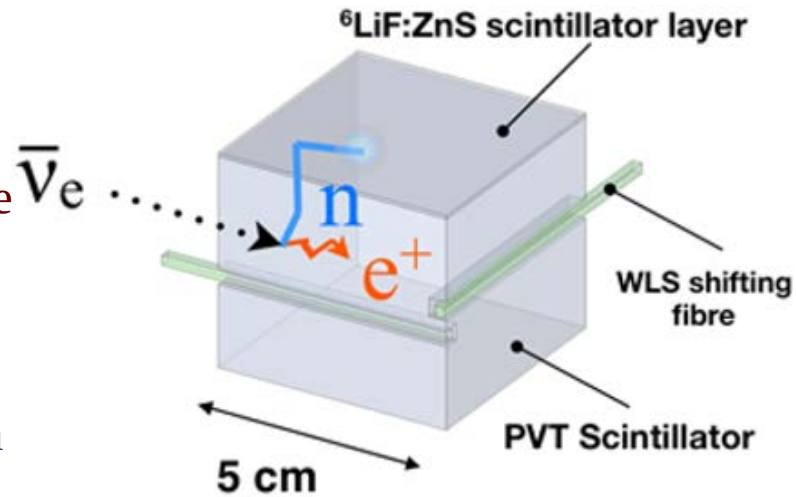
Contained in a few microns

SoLi∂: Tagging with ^{6}Li in ZnS:Ag Sheets

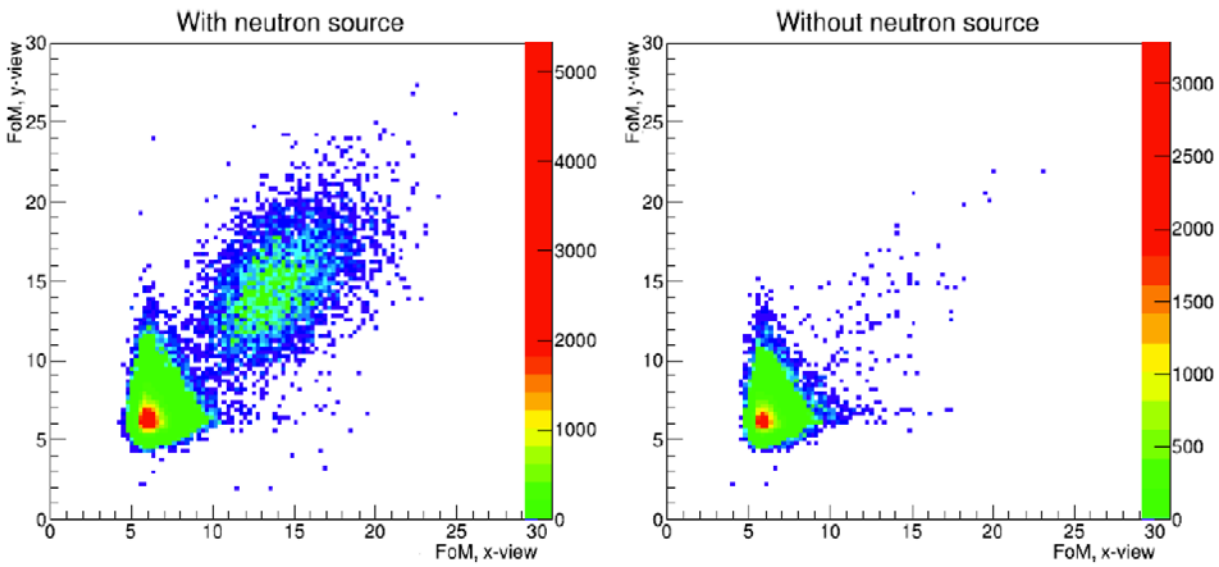
The SoLi∂ detector tags neutrons in thin sheets of ^{6}Li-loaded Zinc Sulfide scintillator (ZnS:Ag)

ZnS:Ag releases light with a 200 ns mean emission time which forms a very pure, high efficiency neutron tag.

SoLi∂ achieves unprecedented spatial resolution by segmenting its scintillator in cubes which are readout in two dimensions by wavelength shifting fibers.



See SoLi∂ talk by Yermia



Neutron tag in the SoLi∂ inspired CHANDLER detector, which is readout by total internal reflection.

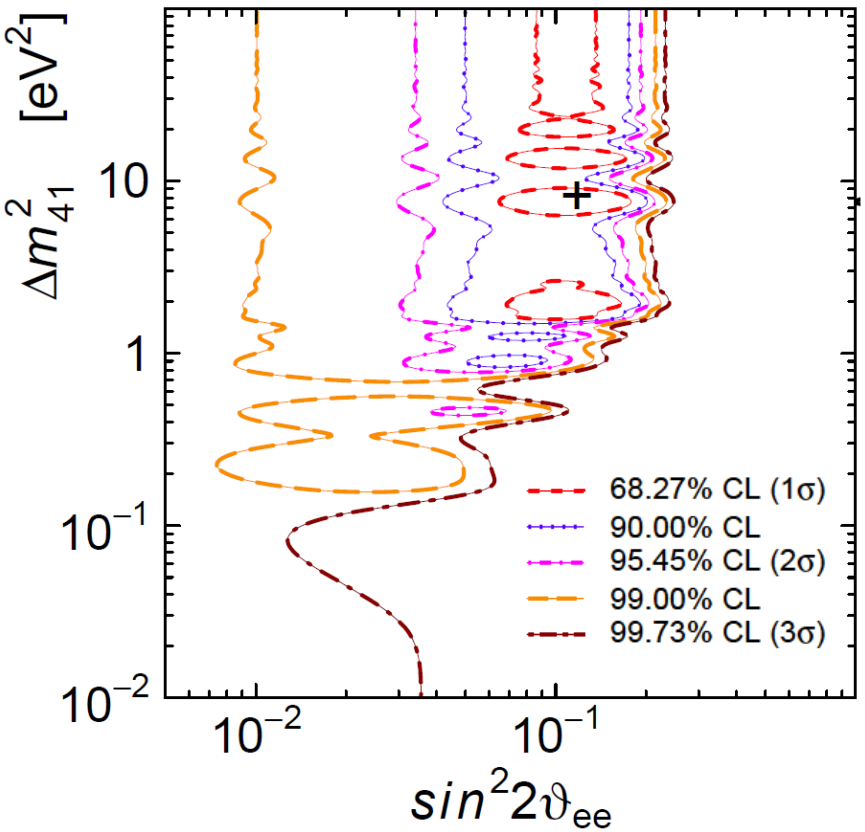
Reactor Experiments

Other things to look for:

1. A compact core (~50 cm)
2. A close detector site (5 to 7 m)
3. Good energy resolution (<7% @ 1 MeV)

These things are need to probe Δm^2 in the range of 2 to 10 eV^2.

Giunti *et al.*, Phys.Rev.D86, 113014 (2012)



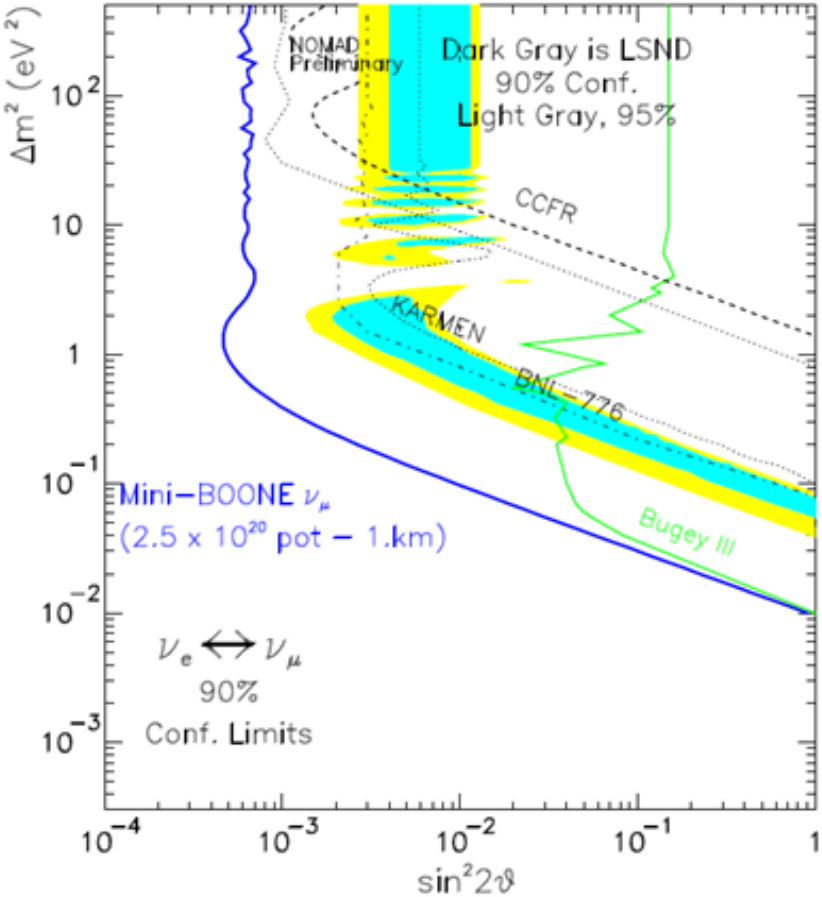
Conclusions

- We have hints for a sterile neutrino coming from at least 5 different types of terrestrial measurements,
- And in two distinct channels: $\nu_\mu \rightarrow \nu_e$ appearance and ν_e disappearance.
- The Fermilab short-baseline program will soon start taking data to search for ν_e appearance and ν_μ disappearance.
- SOX, the Borexino source experiment, will start taking ν_e disappearance data by the end of 2016.
- Multiple reactor experiments are expected to ramp up on a similar time scale and will attempt to compete in the search for ν_e disappearance.

We may have interesting new results for TAUP 2017!

Caution on Proposal Sensitivities

MiniBooNE LOI arXiv:nucl-ex/9706011 (1997)



Phys.Rev.Lett. 98,231801 (2007)