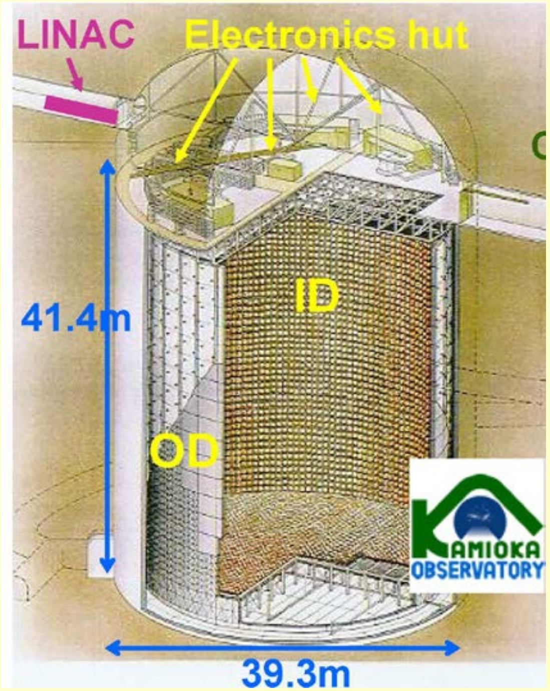
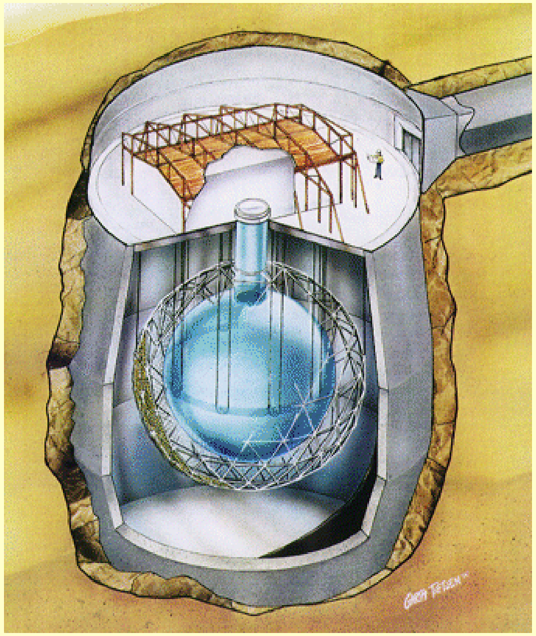
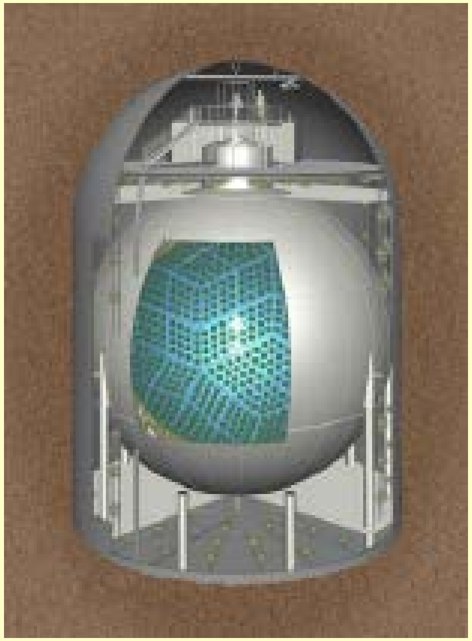
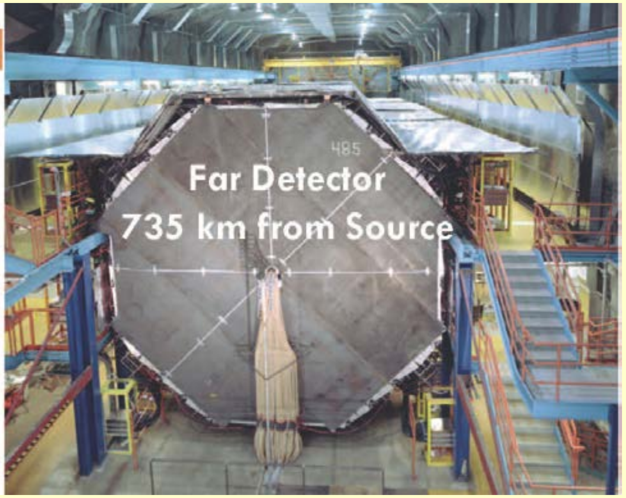
Neutrino Oscillation Measurements, Past and Present

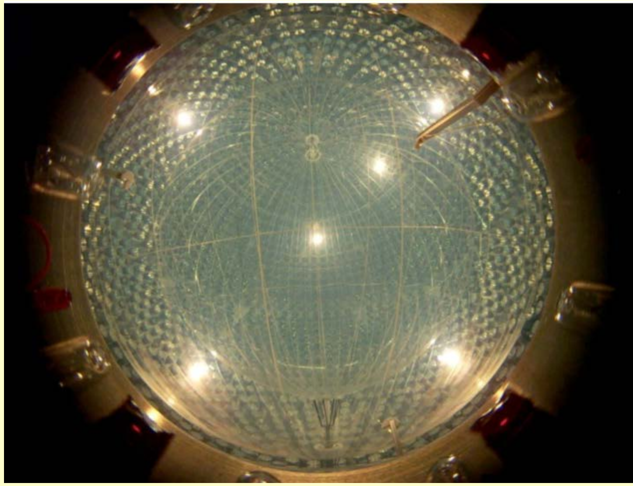








Art McDonald
Queen's University
And
SNOLAB



Early Neutrino Oscillation History

-**1940's to 1960's:**
- Neutrino oscillations were proposed by Pontecorvo in 1957 motivated by initial reports of measurements by Davis with a Chlorine detector at a reactor. At that point, the transitions being considered were electron neutrino to electron anti-neutrino.

- Interestingly, in a originally classified 1946 Chalk River report, Pontecorvo had proposed the detection of neutrinos from reactors and from the sun with a chlorine detector.(At that point, the distinction between neutrino and anti-neutrino was unknown.)

- In 1962, Maki, Nakagawa and Sakata considered the representation of electron and muon neutrinos in terms of ν_1 and ν_2 states.

- In 1968, Gribov and Pontecorvo suggested that one possible reason for low neutrino fluxes from the sun in Davis' experiment could be oscillation of electron neutrinos into muon neutrinos, undetectable by the chlorine detector.

Neutrino Oscillation History

- **1970's:**
  - Accelerator based oscillation measurements **CHORUS, NOMAD, CDHSW**… No oscillation effects seen.
  - Solar neutrinos: Davis continues at **Homestake**

- **1980's**:
  - **Kamiokande** solar neutrinos: Confirms deficit
  - Mikheyev, Smirnov (Wolfenstein) describe the **MSW** effect that modifies the behaviour of oscillations through matter interactions
  - The Atmospheric neutrino anomaly: **IMB, Kamiokande**: The ratio of total muon neutrinos to total electron neutrinos is low by about a factor of two. Not seen in FREJUS, NUSEX.
  - <100m reactor based measurements find no oscillation evidence: **Bugey, Krasnoyarsk, ROVNO, Goesgen, ILL**

- **1990's:**
  - **Palo Verde, CHOOZ:** no oscillation seen at ~ I km from reactor.
  - **SAGE, GALLEX, GNO** confirm solar neutrino deficit for pp neutrinos.
  - **LSND** finds small effect for muon neutrino to electron neutrino conversion, with restrictions by **KARMEN, E776/BNL**.
  - **SuperKamiokande** finds clear disappearance of atm. mu neutrinos as a function of zenith angle that fits well the pattern for oscillations.

Neutrino Oscillation History

- **2000's:**
  - **SNO** observes clear flavor change for solar neutrinos. Appearance of muon or tau neutrinos

  - **KamLAND** observes clear disappearance of electron anti-neutrinos from reactors with same oscillation parameters as electron neutrinos from the sun (with MSW effect applied).

  - The number of experiments and results associated with neutrino oscillations expands greatly:
    - Muon Neutrinos: **KARMEN, K2K, MINOS, MiniBoone**…
    - Muon anti-neutrinos: **MINOS, MiniBoone**
    - Solar Neutrinos: **Borexino**
- **2010's:**
  - A dominant mechanism for neutrino flavor change appears to be oscillations among three active flavors of massive neutrinos. Parameters for these oscillations are becoming increasingly accurate and future experiments seek θ_{13}, Hierarchy, Low Energy solar…..

  - Other questions remain from results at the few sigma level in several experiments: Sterile neutrinos, CPT violation…

Oscillation of 3 massive active neutrinos is a dominant mechanism for flavor change. Neutrinos have a finite mass but only differences are known.

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

Neutrino types e, μ, τ

Mass states 1,2,3

Maki-Nakagawa-Sakata-Pontecorvo matrix

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Atmos., Accel | CP Viol. Phase ? | Reactor, Accel ? | Solar, Reactor | Majorana Phases ?

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

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

Matter Effects – the MSW effect

(Mikheyev, Smirnov, Wolfenstein)

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

The extra term arises because solar ν_e have an extra interaction via W exchange with electrons in the Sun or Earth.

In the oscillation formula:

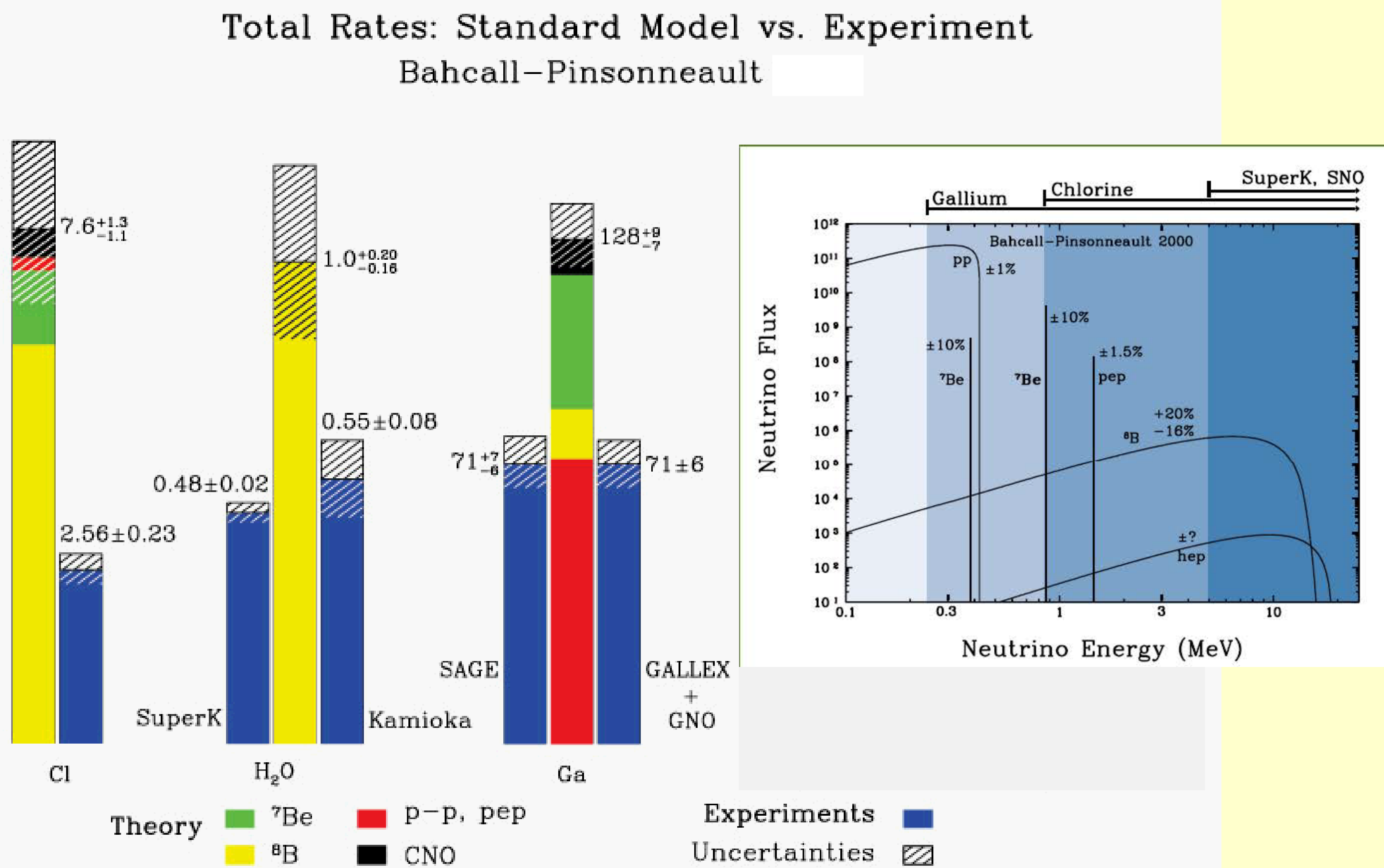
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

MSW effect can produce an energy spectrum distortion and flavor regeneration in Earth giving a Day-night effect.
If observed, matter interactions define the mass hierarchy.

As of 1997: "The Solar Neutrino Problem"

Solar Neutrinos



Is The "Problem" Neutrino Flavor Change or Solar Models?

LSND 1996

Measurement of muon antineutrino to electron antineutrino conversion at LAMPF facility:

Excess of $51.8^{+18.7}_{-16.9} \pm 8$ events.

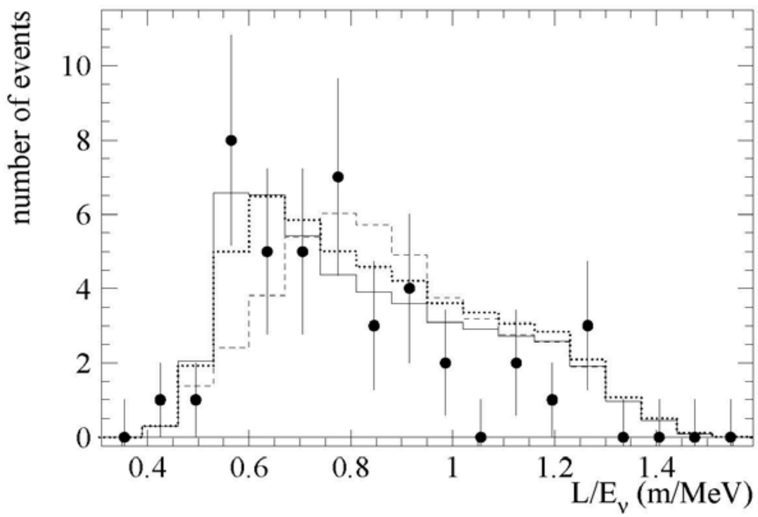


FIG. 31. Distribution of L/E_ν for the beam-on data with high R compared with the expected distributions at ($19eV^2, \sin^2 2\theta = 0.006$: solid line), ($4.3eV^2, \sin^2 2\theta = 0.01$: dashed line), and ($0.06eV^2, \sin^2 2\theta = 1.$: dotted line).

Shaded: LSND accepted region
Dashed: KARMEN exclusion
Dotted: E776/BNL Exclusion
DOT-DASH: Bugey Exclusion

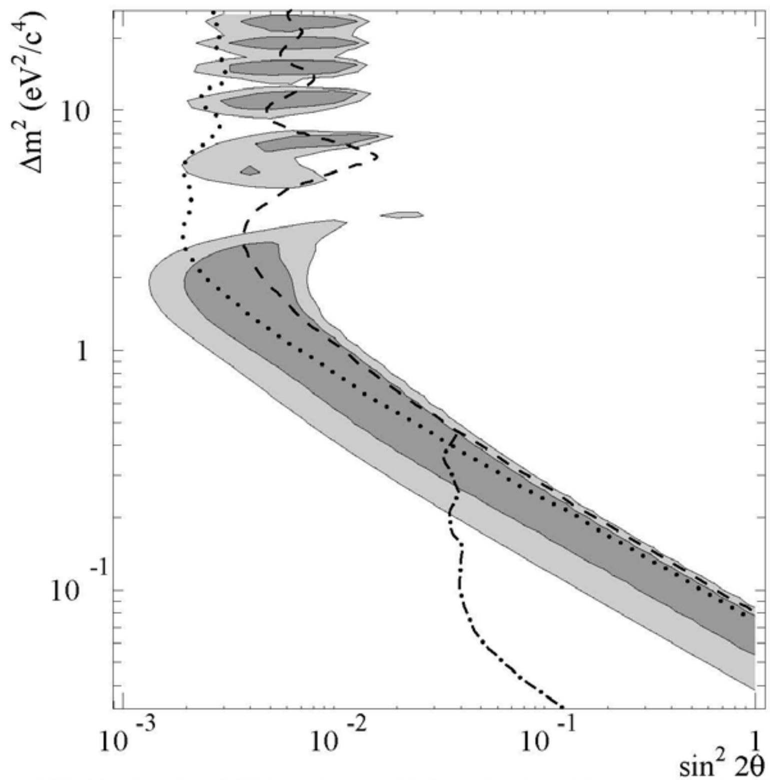


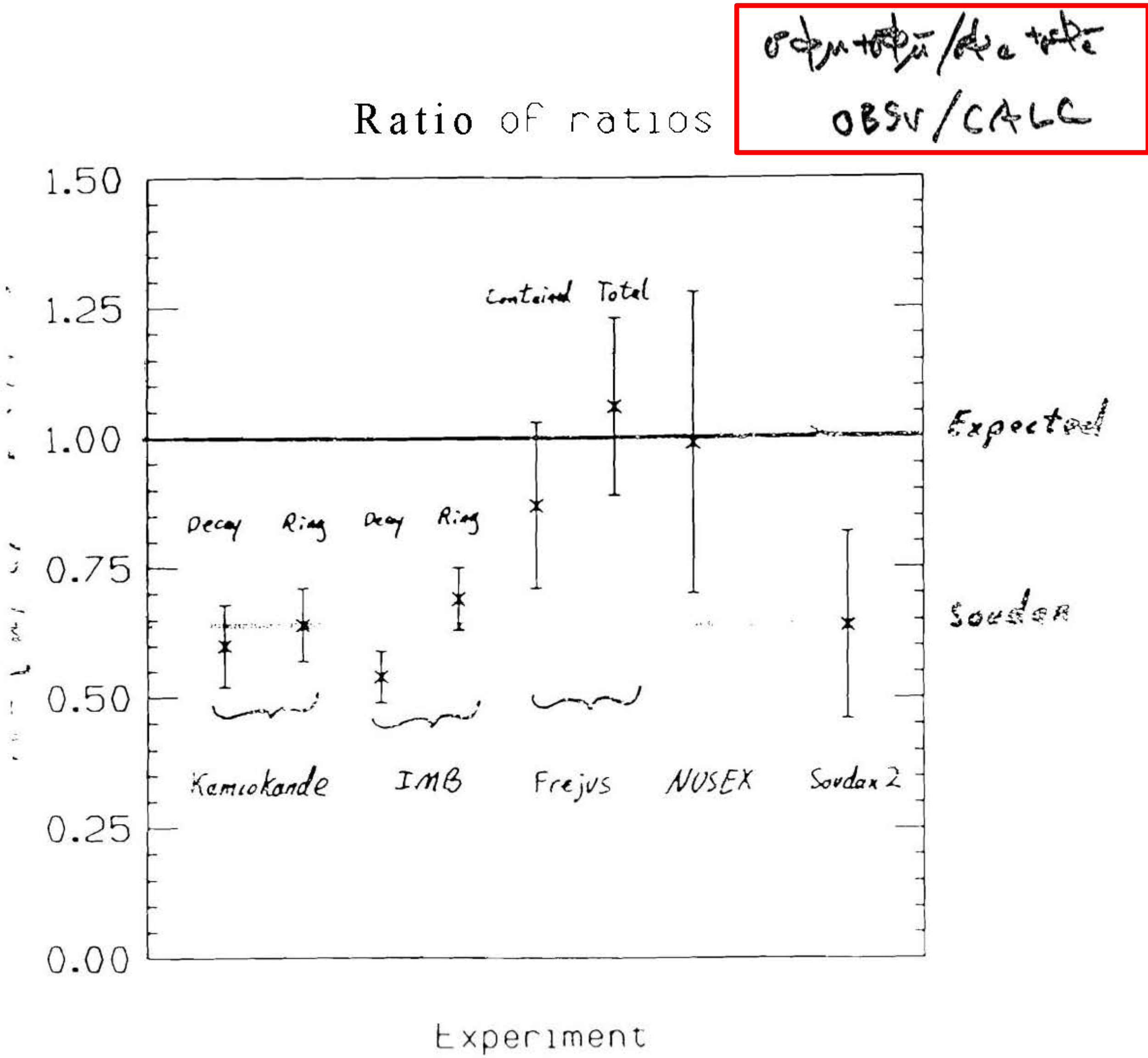
FIG. 30. Plot of the LSND Δm^2 vs $\sin^2 2\theta$ favored regions. The method used to obtain these contours is described in the text. The darkly-shaded and lightly-shaded regions correspond to 90% and 99% likelihood regions after the inclusion of the effects of systematic errors. Also shown are 90% C.L. limits from KARMEN at ISIS (dashed curve), E776 at BNL (dotted curve), and the Bugey reactor experiment (dot-dashed curve).

Atmospheric Neutrinos

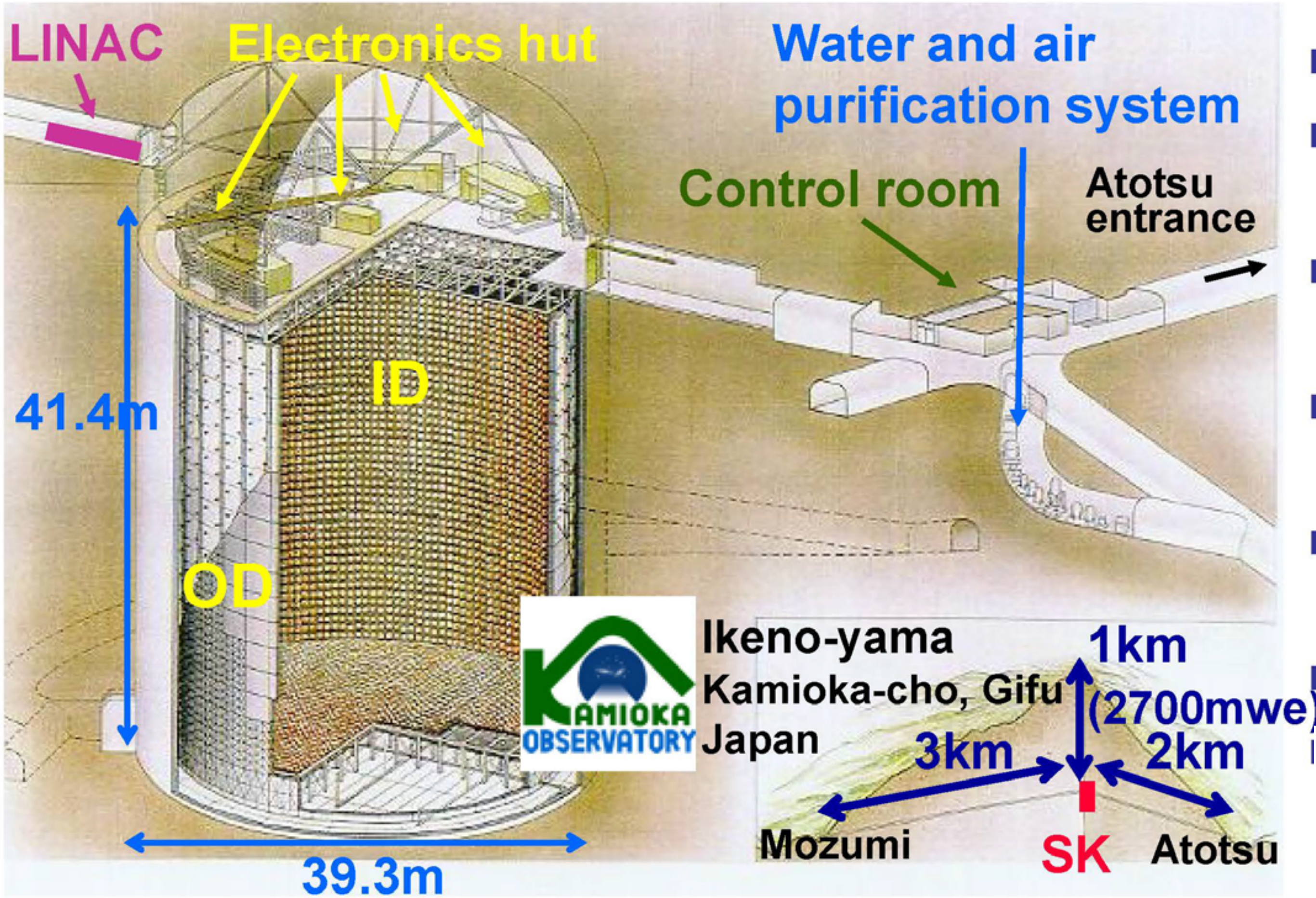
$$\frac{\dfrac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}(Observed)}{\dfrac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}(Calculated)}$$

Neutrino '94 Eilat Israel May 28-June 3
Atmospheric Neutrinos in Soudan 2

FROM GOODMAN



Super-Kamiokande detector

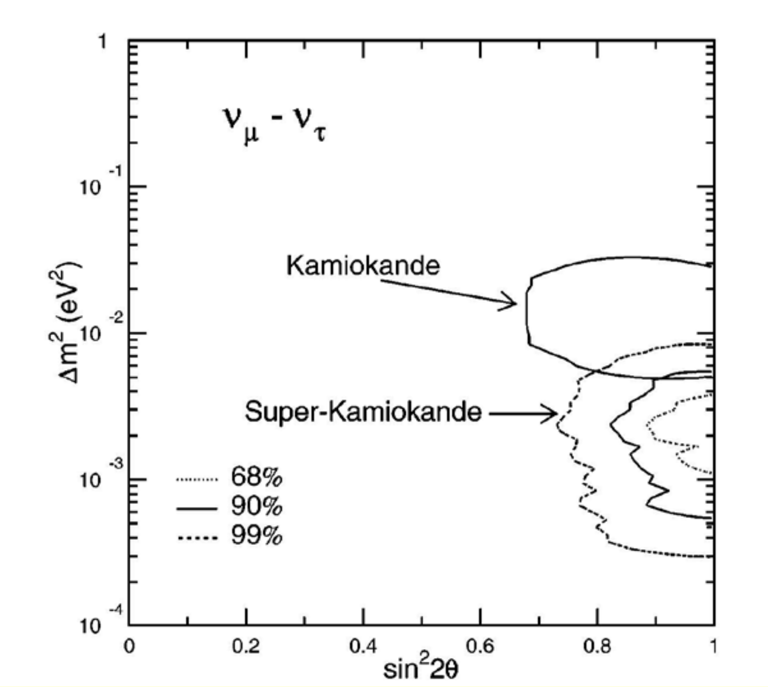


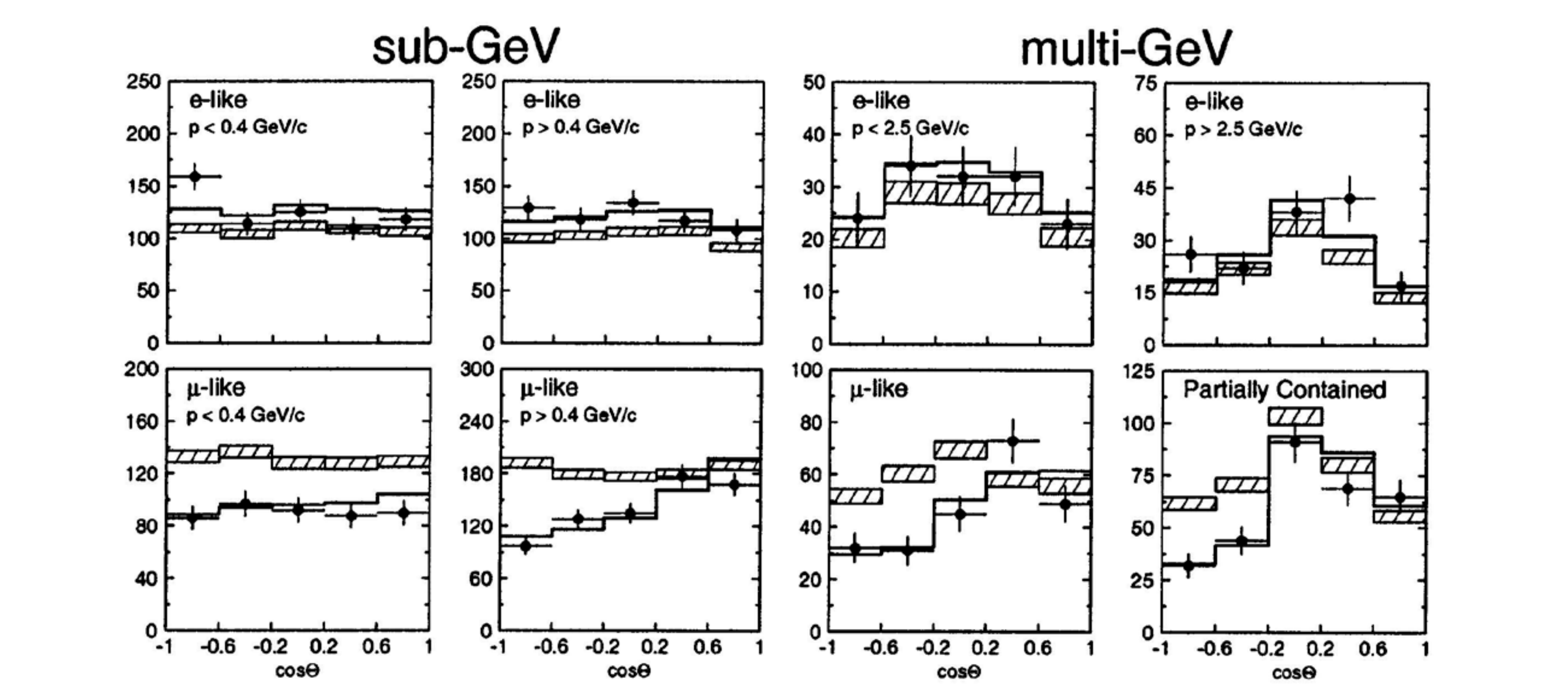
- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- ~4.5MeV energy threshold
- SK-I: April 1996~

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

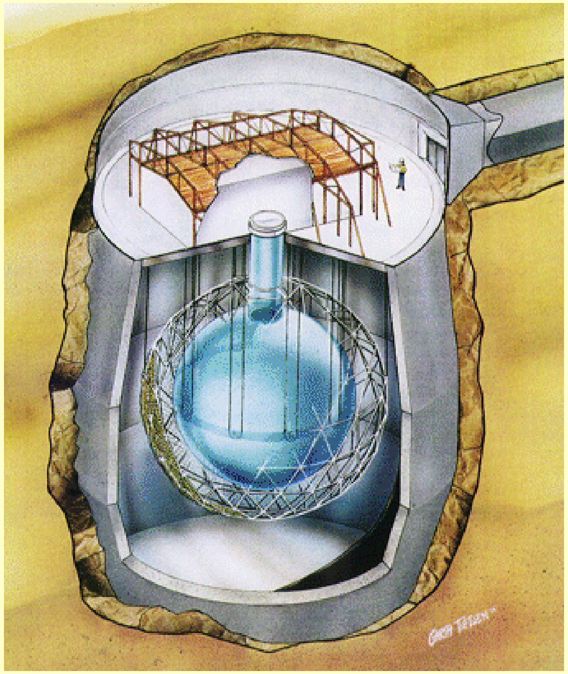
SUPERKAMIOKANDE 1998:
Atmospheric Neutrinos

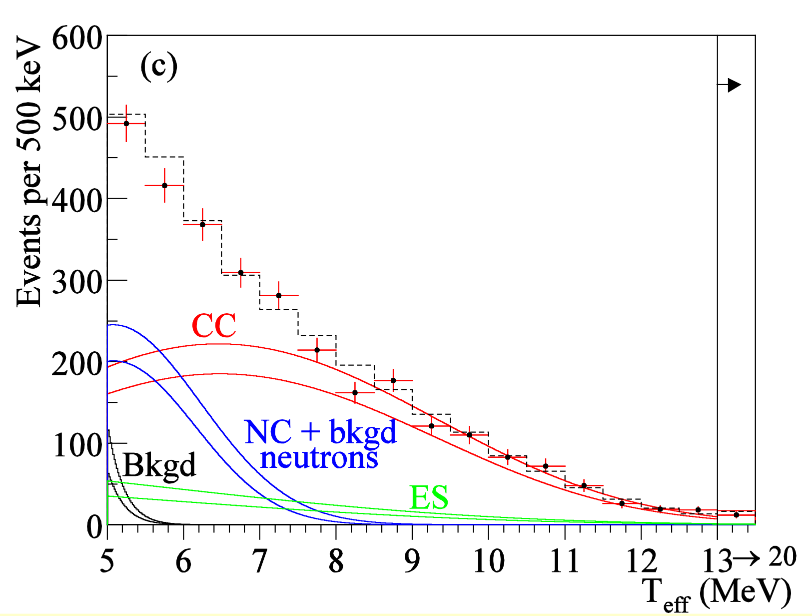
"The data are **consistent with two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillations** with $\sin^2\theta > 0.82$ and $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}$ eV^2 at the 90% confidence level."

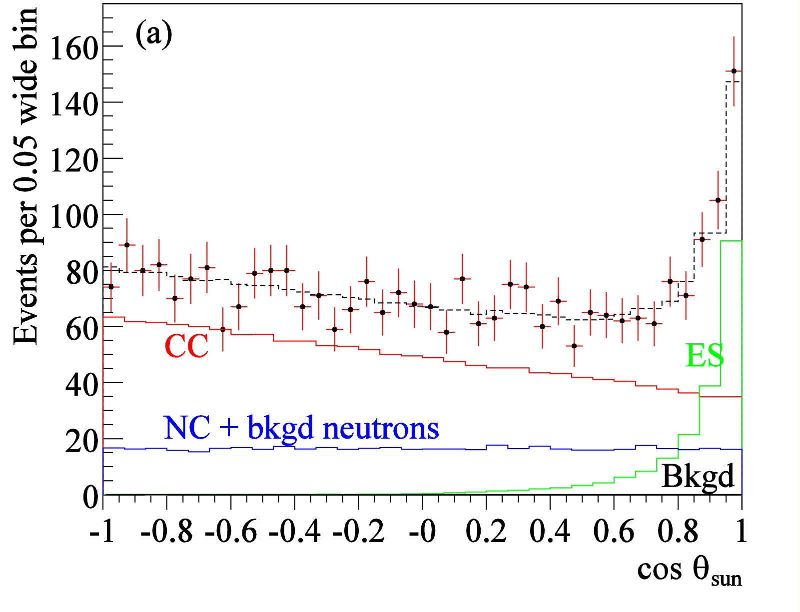




SNO Results: Pure Heavy Water: 2001, 2002







$$\nu_e + d \rightarrow p + p + e^- \text{(CC)}$$

$$\nu_x + d \rightarrow p + n + \nu_x \text{(NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \text{(ES)}$$

where x = e, μ,τ

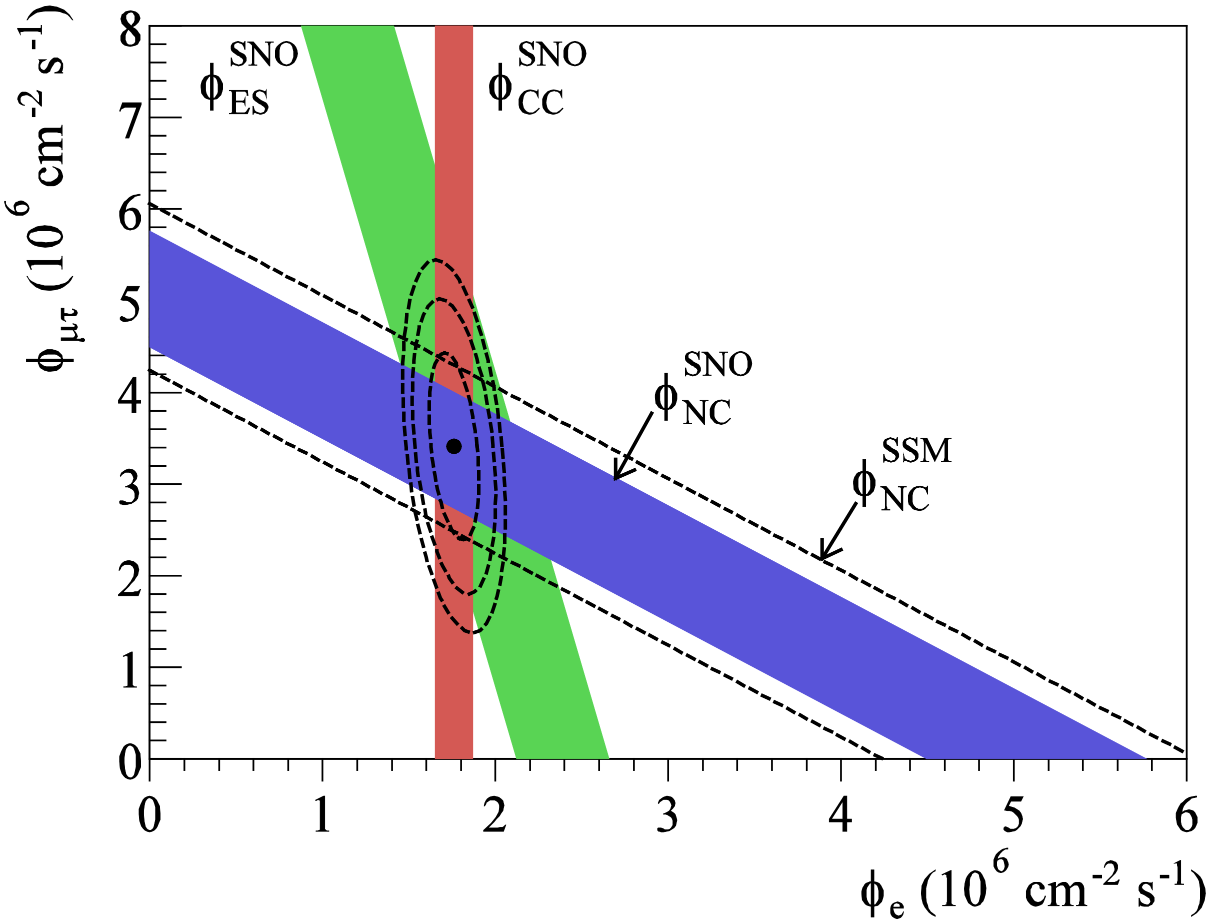
Equal sensitivity for NC,

6 times larger for e in ES

Physics Implication: Flavor Content

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44\,+0.46}_{-0.43\,-0.43}$

$\Phi_{\mu\tau}$ is 5.3 σ from zero



First SNO paper in 2001 obtains 3.3 σ variance from null oscillation hypothesis by comparing SNO CC with ES from SuperK.

Clear indication of oscillation from ν_e to other active neutrinos (ν_μ or ν_τ)

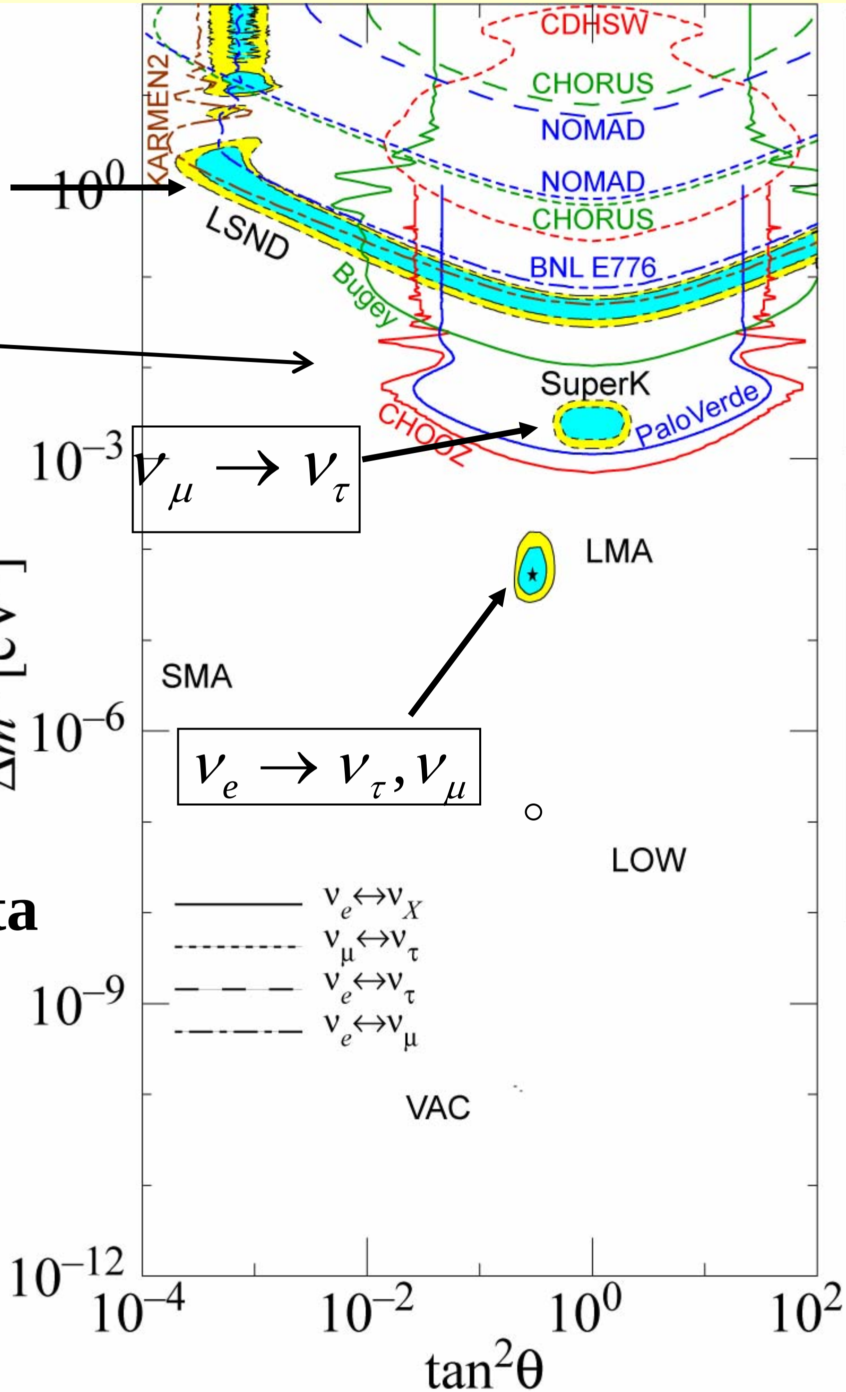
Neutrino Data
2002

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

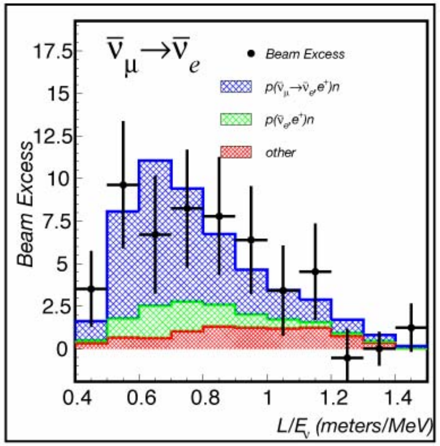
CHOOZ + SK Provides restriction on θ_{13}

$\nu_\mu \rightarrow \nu_\tau$

$\nu_e \rightarrow \nu_\tau, \nu_\mu$

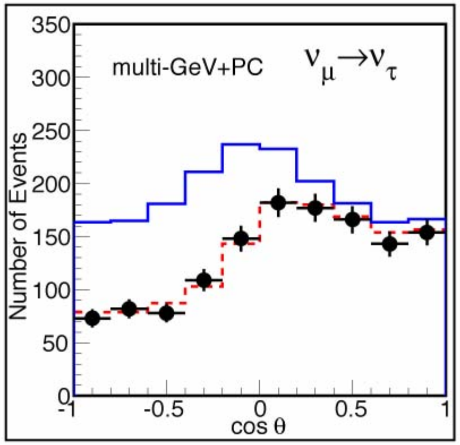


LSND



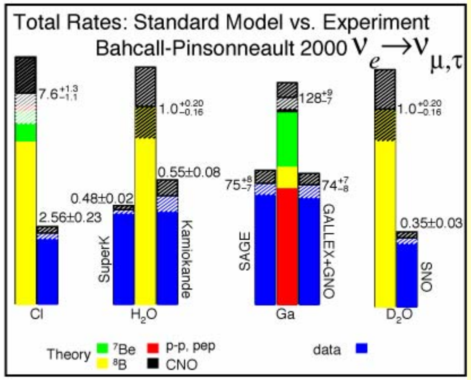
Super-K

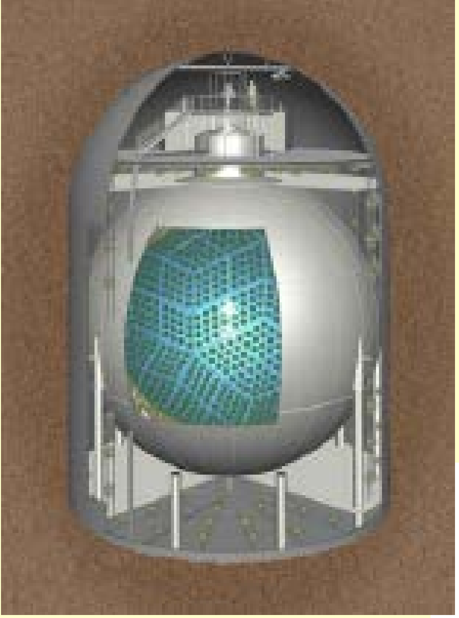
Δm_{23}



Solar

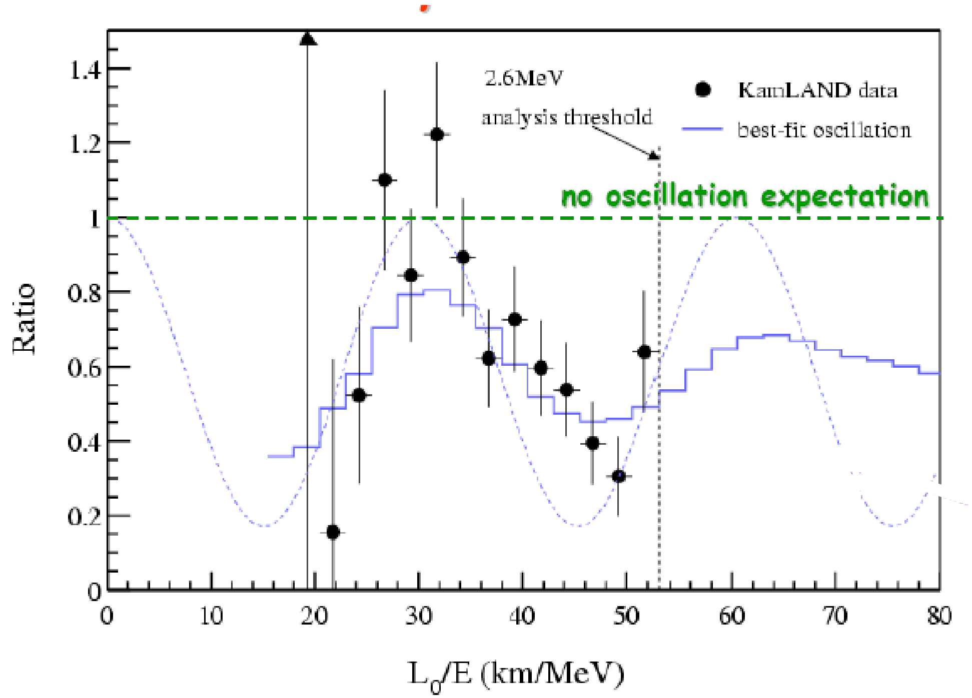
Δm_{12}





KamLAND 2002, updated in 2004:

- **182 GW of reactor power in Japan, Korea**
- **Average distance 180 km**
- **515 days vs 145 days in 2002 paper**
- **258 events vs 365 +- 24 expected for no oscillations**
- $\overline{\nu}_e + p \rightarrow n + e^+$



Best fit to oscillations:

$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2

$\sin^2 2\theta = 0.83$

Straightforward χ^2 on the histo is 19.6/11

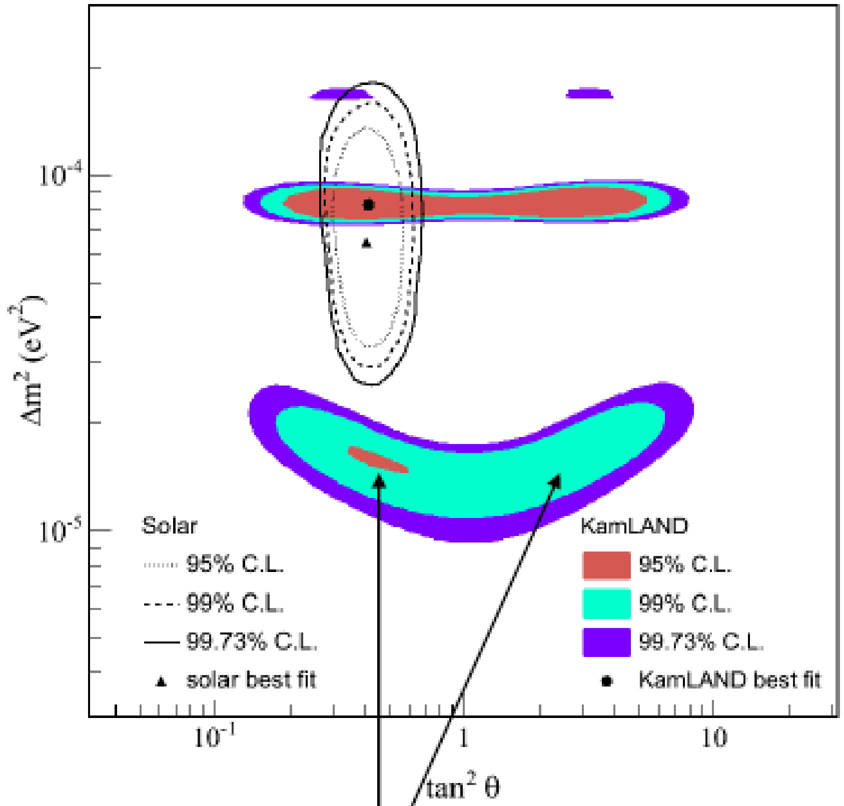
Using equal probability bins χ^2/dof=18.3/18 *(goodness of fit is 42%)*

A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

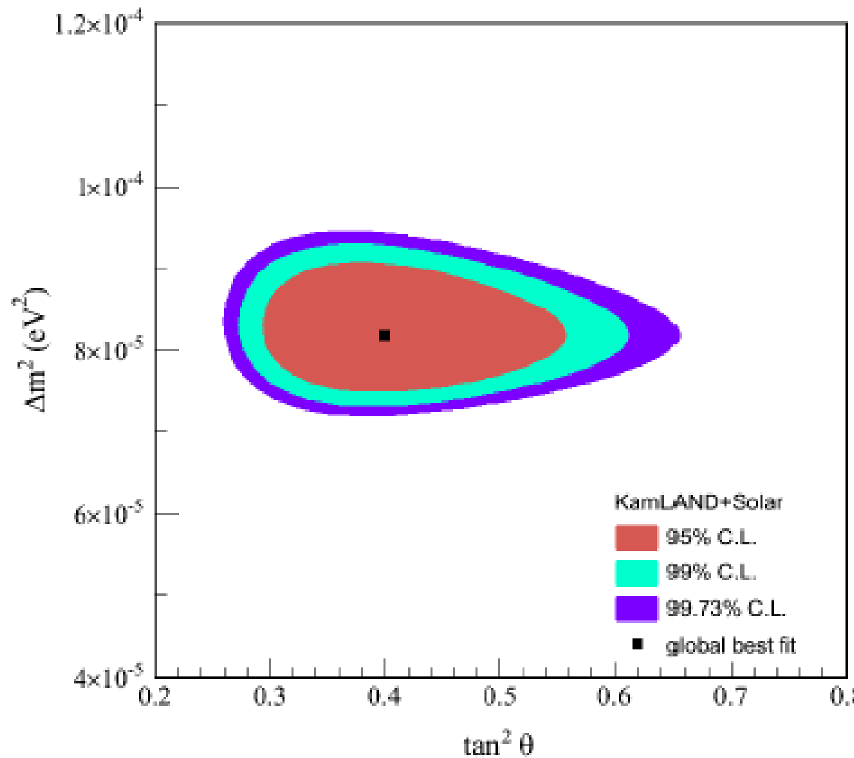
Combined solar ν – KamLAND 2-flavor analysis

$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

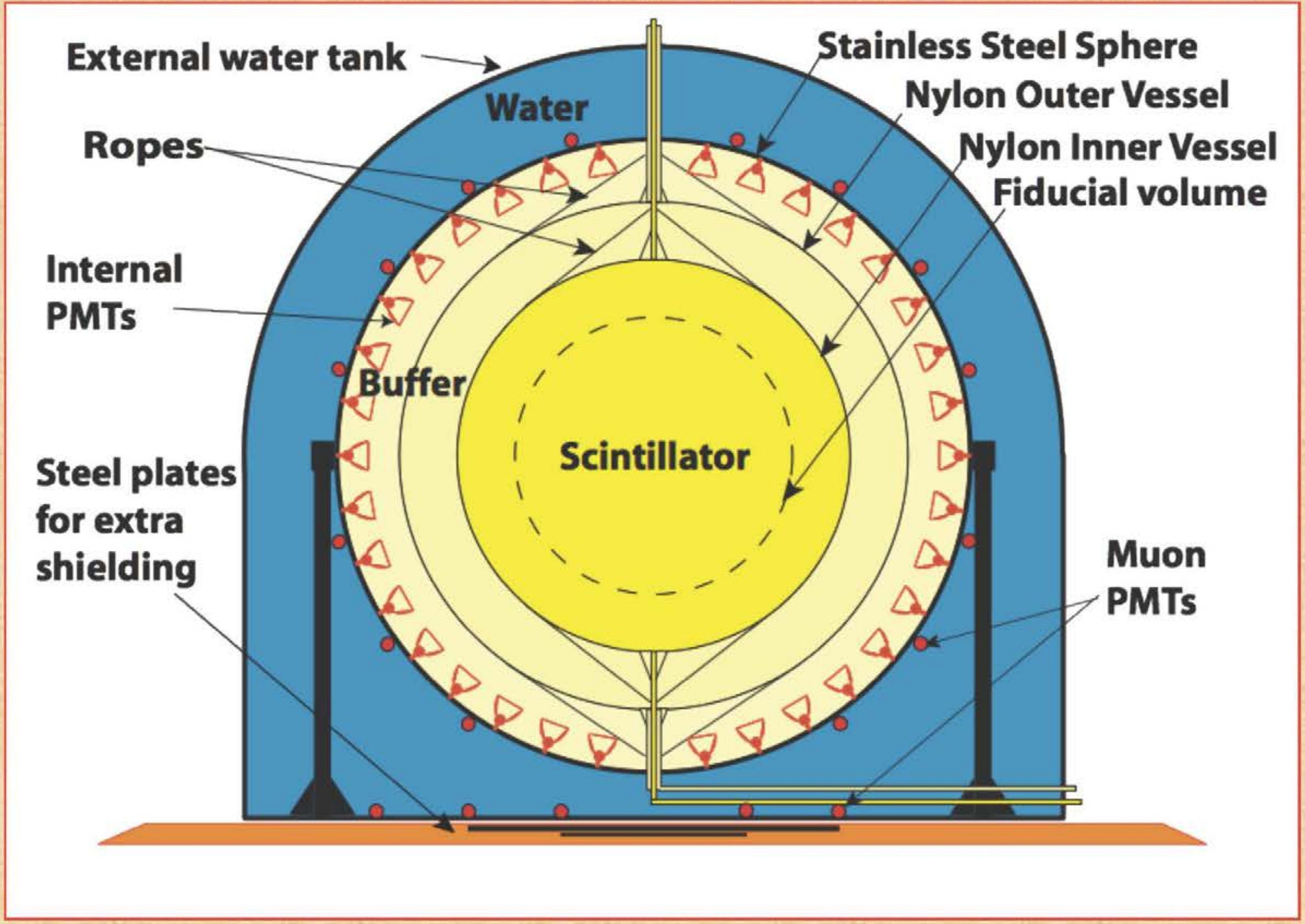
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



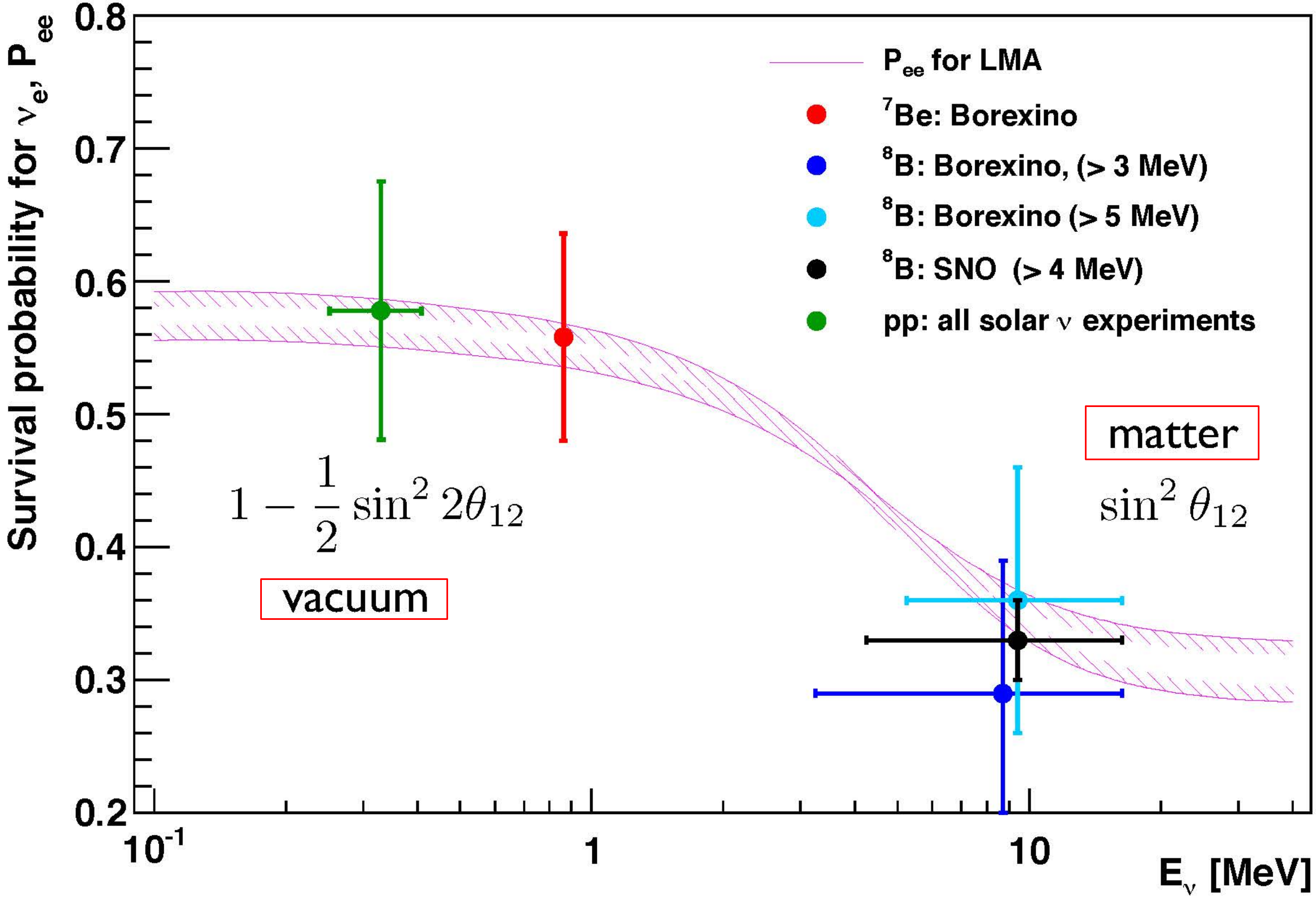
Includes (small) matter effects



The Borexino Detector



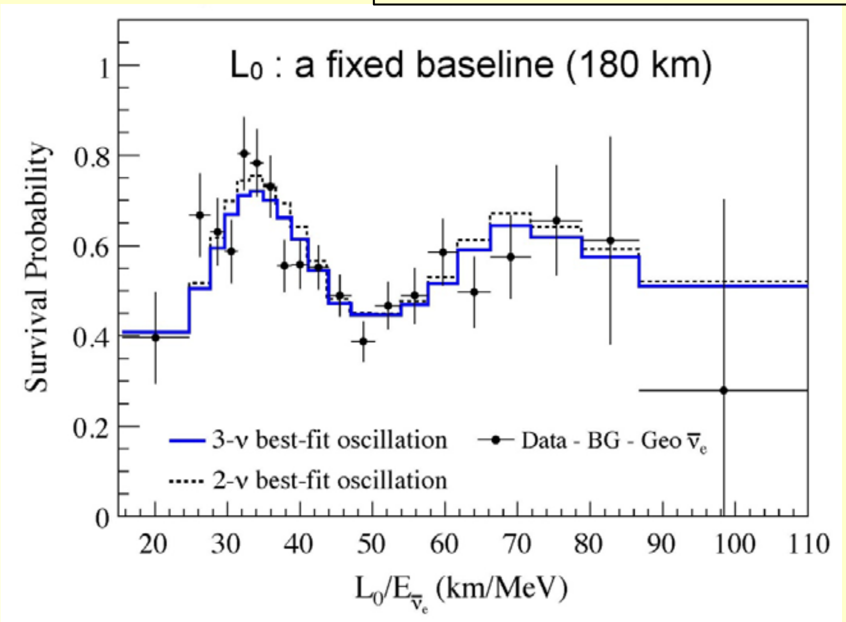
Solar Neutrinos

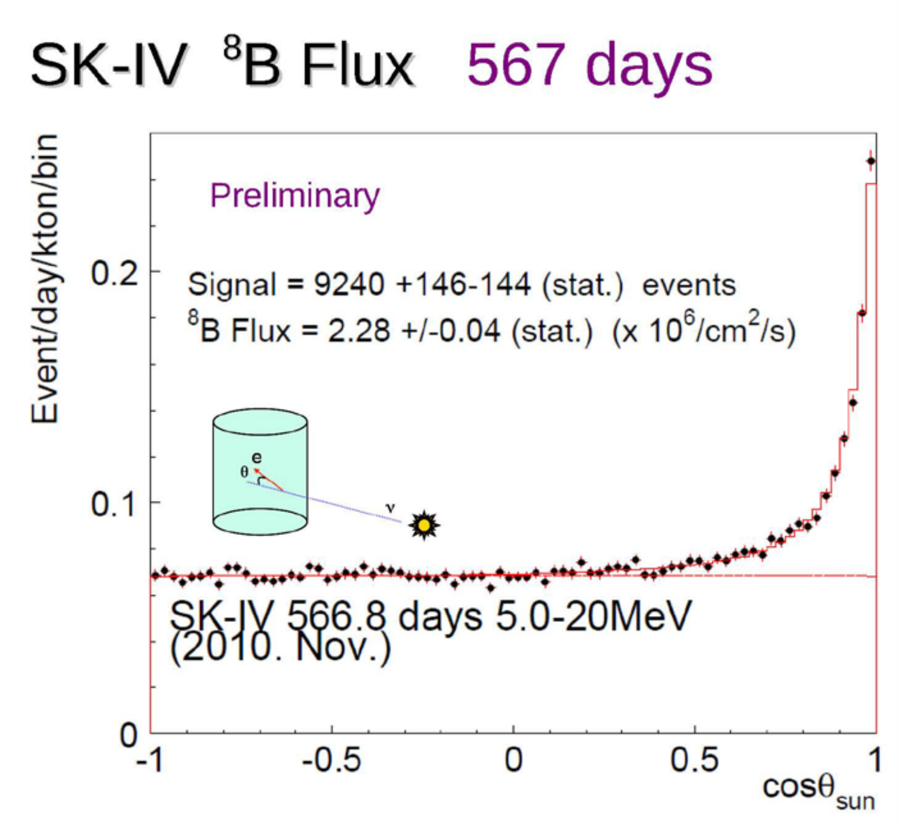


2000's: SNO, Kamland, SuperK, SAGE, Borexino continue to improve their statistics and/or analyses providing further restrictions on the m_{12} parameters:

KamLAND Reactor $\overline{\nu}$

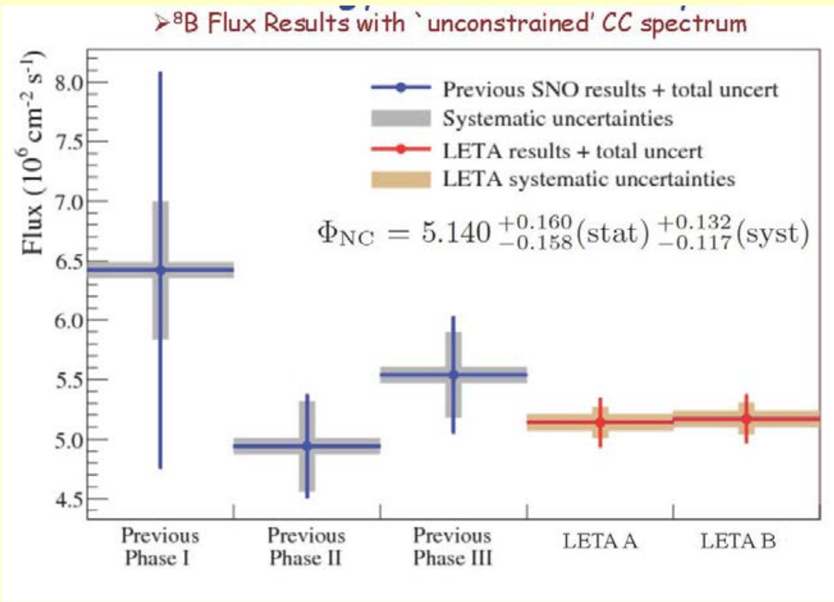
Improves accuracy of Δm^2





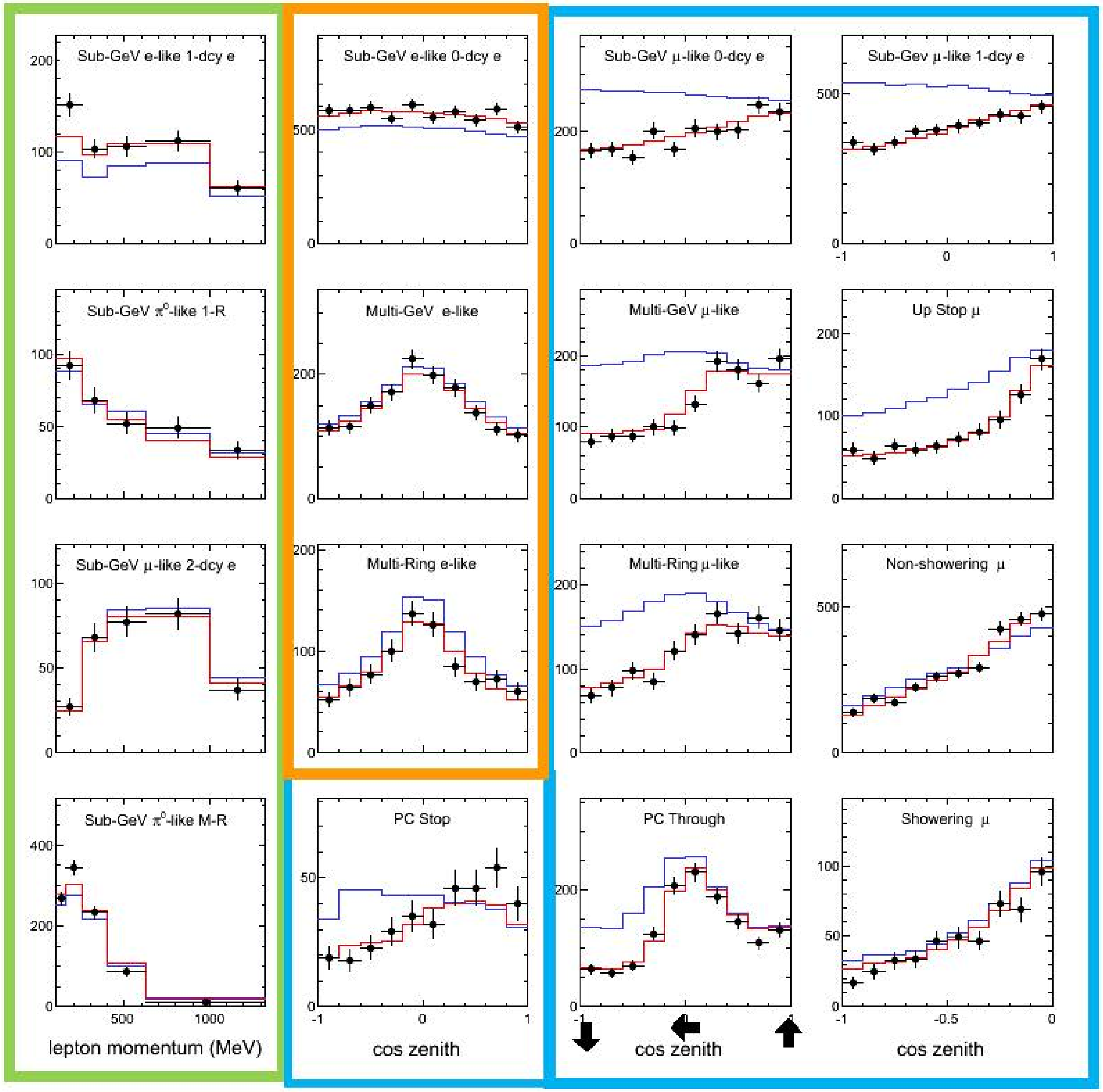
SNO NC: All active ν's

Improves accuracy of $\sin^2 \theta_{12}$



SuperKamiokande Atmospheric Neutrinos

Zenith angle & lepton momentum distributions : SK-I+II+III



$\nu_\mu - \nu_\tau$ oscillation (best fit)

null oscillation

μ-like

e-like

momentum

Live time:

SK-I

1489d (FCPC)

1646d (Upmu)

SK-II

799d (FCPC)

827d (Upmu)

SK-III

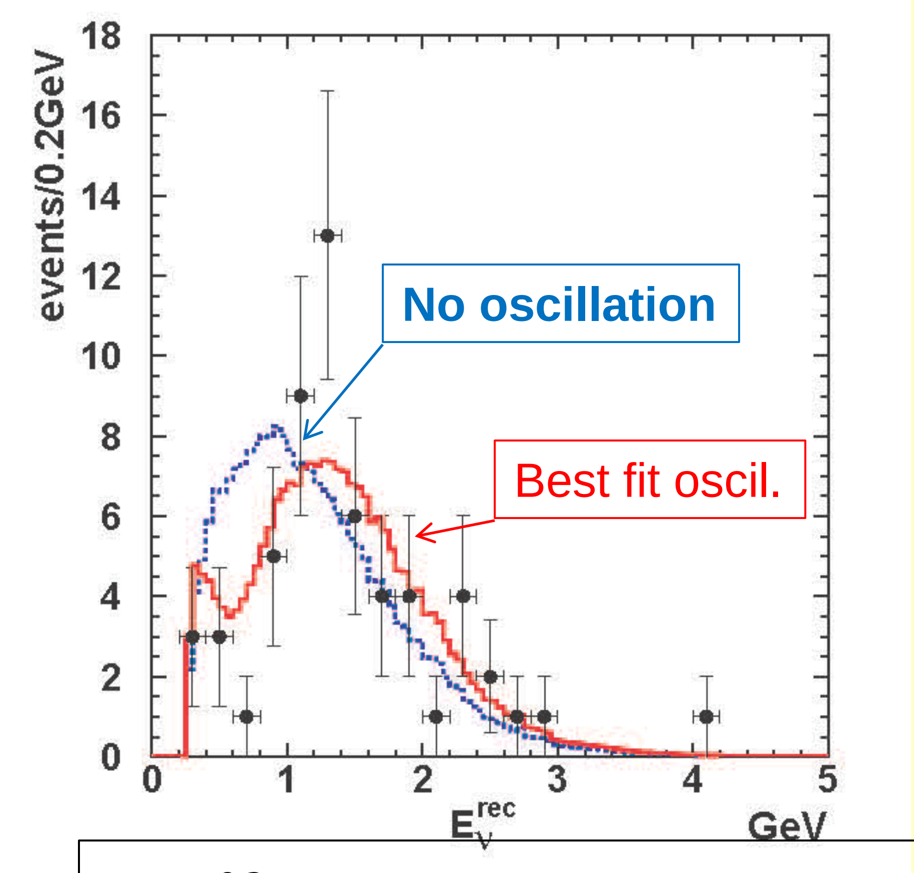
518d (FCPC)

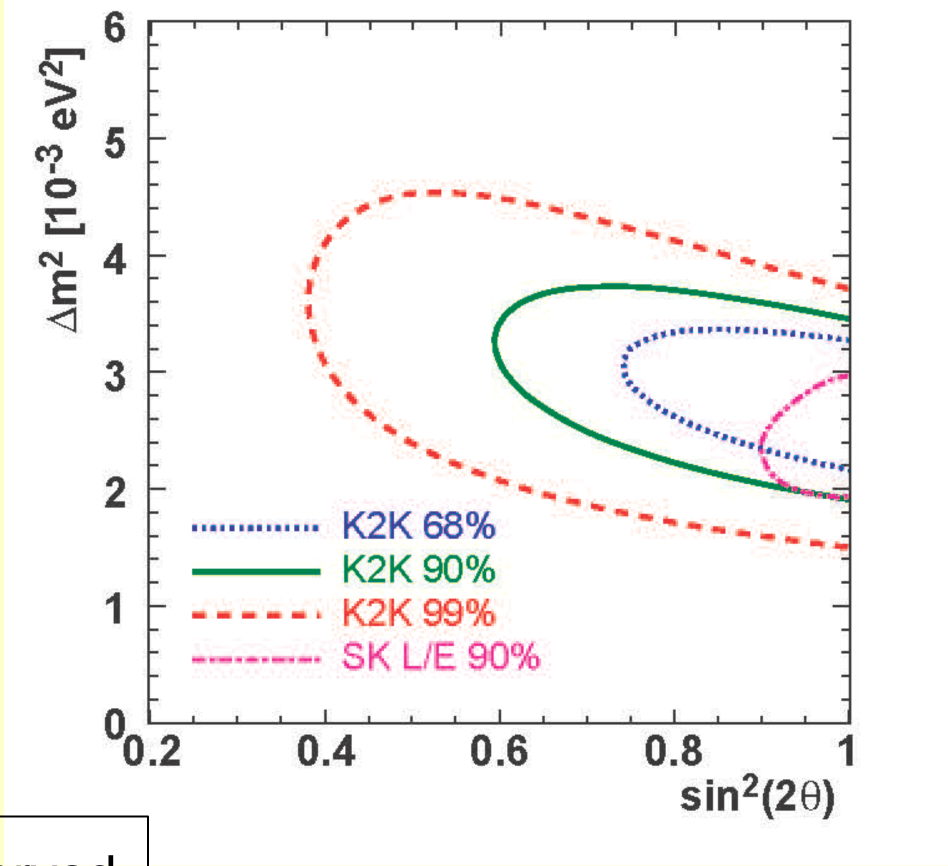
636d (Upmu)

μ–like samples show large deficits in the upward-going bins that are well described by oscillations.

Continuing with the discussion of further experiments observing oscillations of active neutrinos related to m_{23} mixing:

K2K has provided a very nice confirmation of the SuperK Atmospheric results by shooting a neutrino beam 250 km from the KEK accelerator to SuperK and observing ν_μ disappearance.





$158^{+9.2}_{-8.6}$ for no oscillation, 112 observed

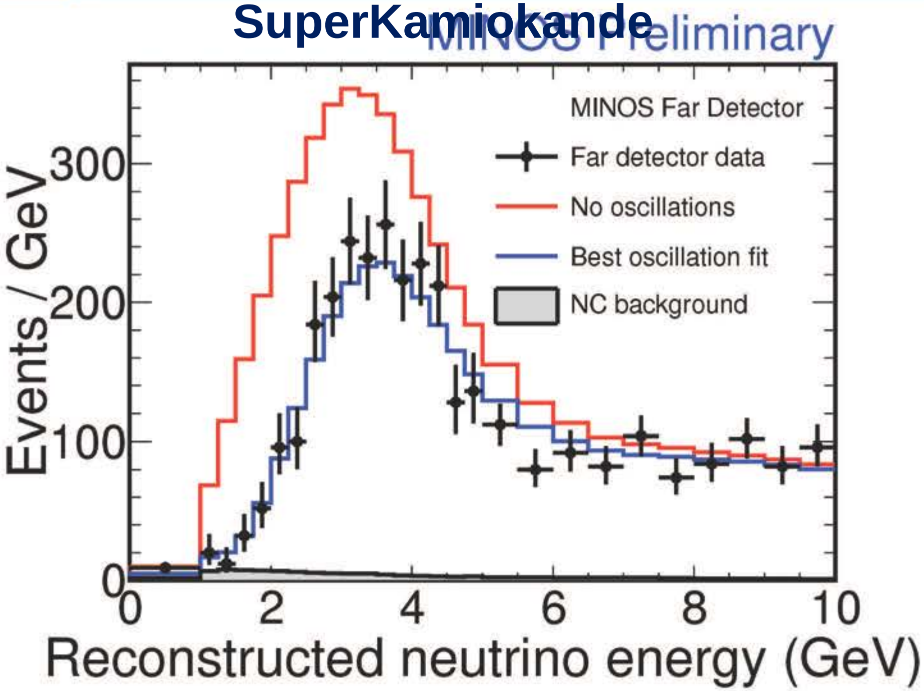
The MINOS Experiment

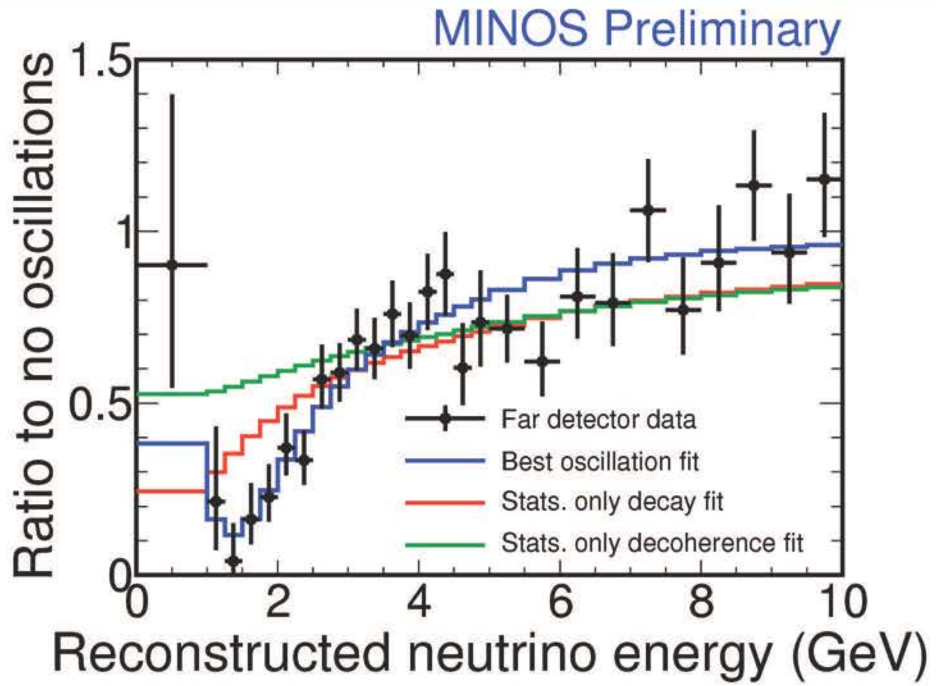
- Long base-line neutrino oscillation experiment
- Neutrinos from NuMI beam line
- L/E ~ 500 km/GeV
  - atmospheric Δm^2
- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties

$$\nu_\mu \to \nu_\mu$$

Far Detector Energy Spectrum

SuperKamiokande





- Oscillations fit the data well, 66% of experiments have worse χ^2
- Pure decoherence† disfavored: $> 8\sigma$
- Pure decay‡ disfavored: $> 6\sigma$

(**7.8σ** if NC events included)

†G.L. Fogli *et al.*, PRD 67:093006 (2003) ‡V. Barger *et al.*, PRL 82:2640 (1999)

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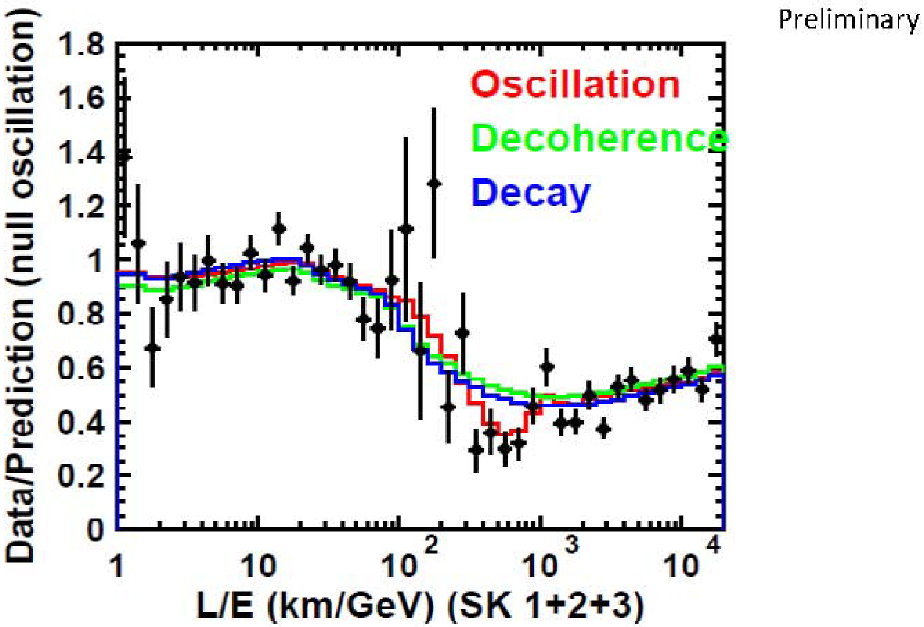


Neutrino decay (4.4σ)
Neutrino decoherence (5.4σ)

$$\nu_\mu \rightarrow \nu_\mu$$

Contours

$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

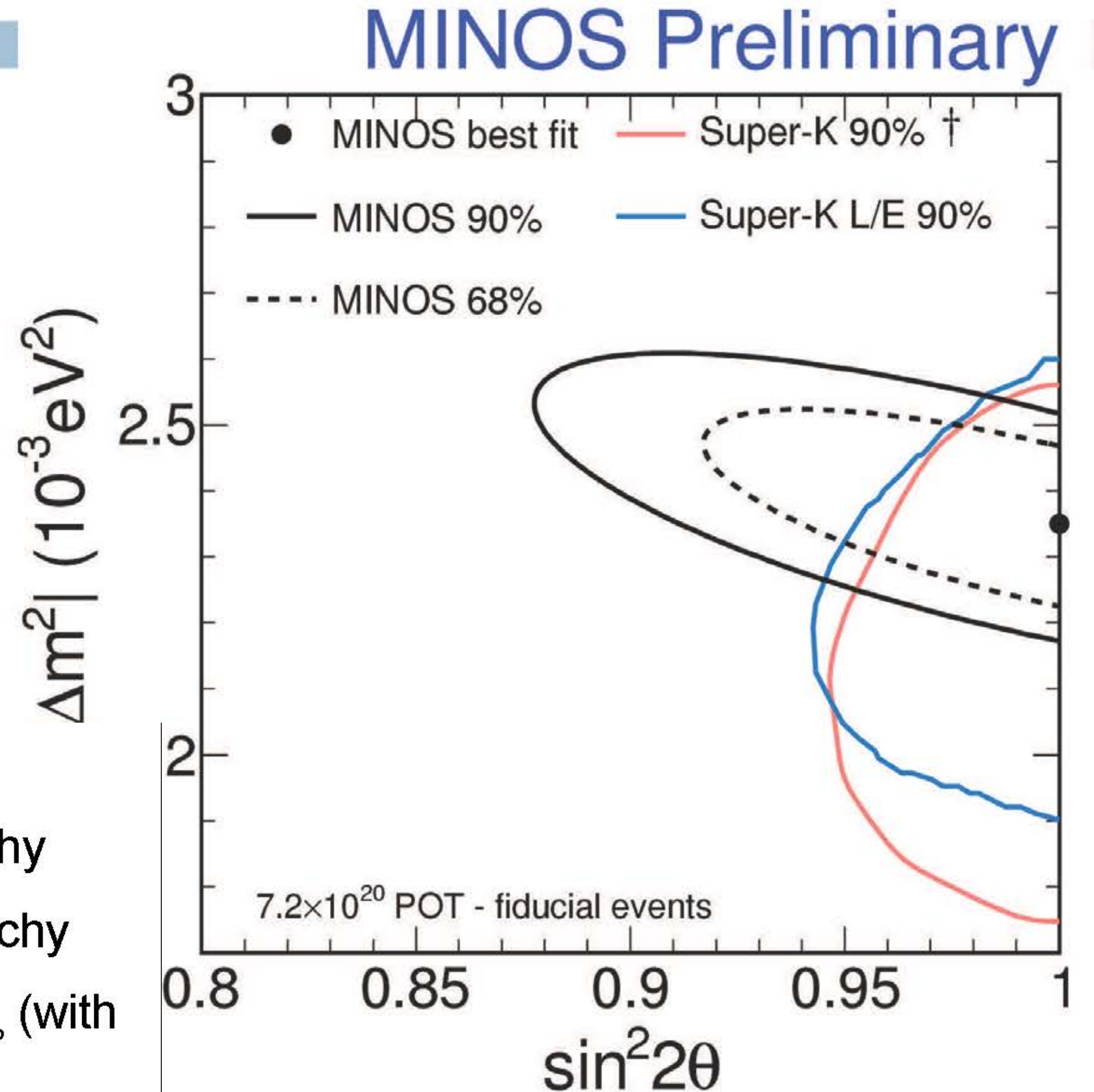
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

$$\nu_\mu \rightarrow \nu_e$$

90% C.L. at $\theta_{23} = 45^\circ$ and $\delta_{CP} = 0$

- $\sin^2(2\theta_{13}) < 0.12$ normal hierarchy
- $\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

Best limit for nearly all values of δ_{CP} (with normal hierarchy and maximal θ_{23})



†Super-Kamiokande Collaboration (preliminary)

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OPERA

The first $\nu_{\mu} \rightarrow \nu_{\tau}$ candidate event was found

Physics Letters B 691 (2010) 138–145

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ELSEVIER

Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

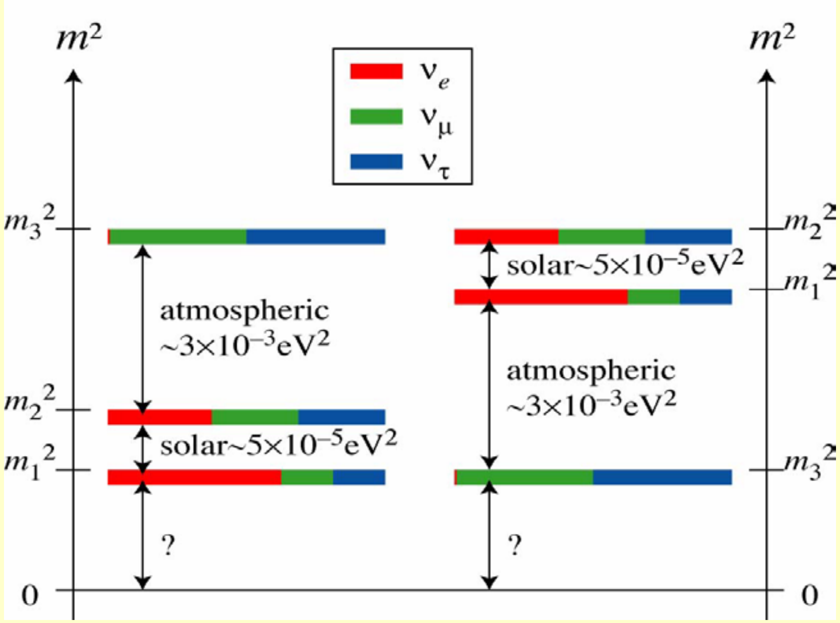
Event number 9234119599,
taken on 22 August 2009, 19:27 (UTC), opened June 10, 2010

- **If one considers all τ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5%. This corresponds to a significance of 2.01 σ.**
- **OPERA expects about 2 events per year with a total running period of about 5 years.**

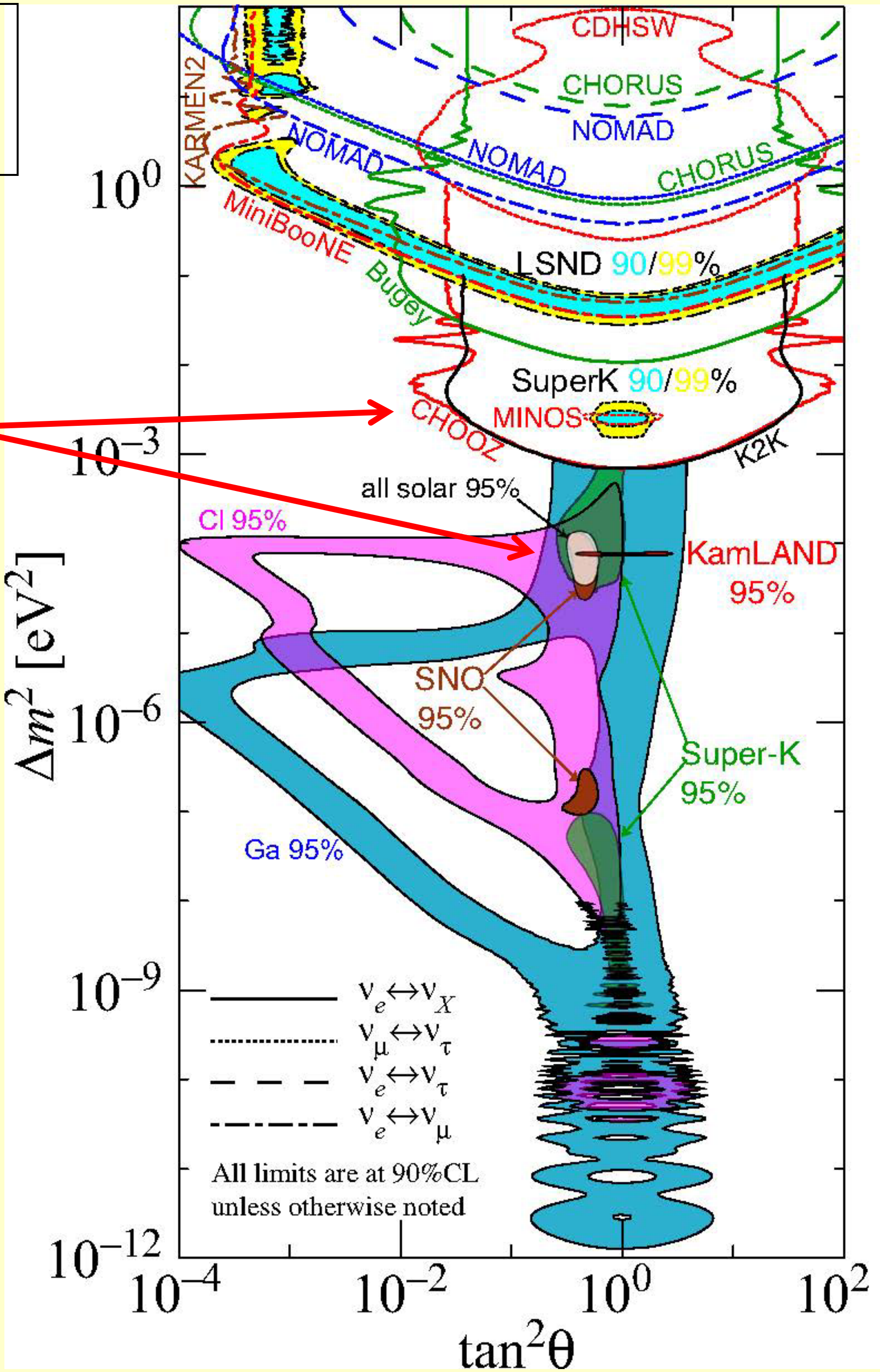
SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

parameter	best fit	2σ
Δm^2_{21} [10^{-5}eV^2]	$7.59^{+0.23}_{-0.18}$	7.22–8.03
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18–2.64
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29–0.36
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039

Mass Hierarchies



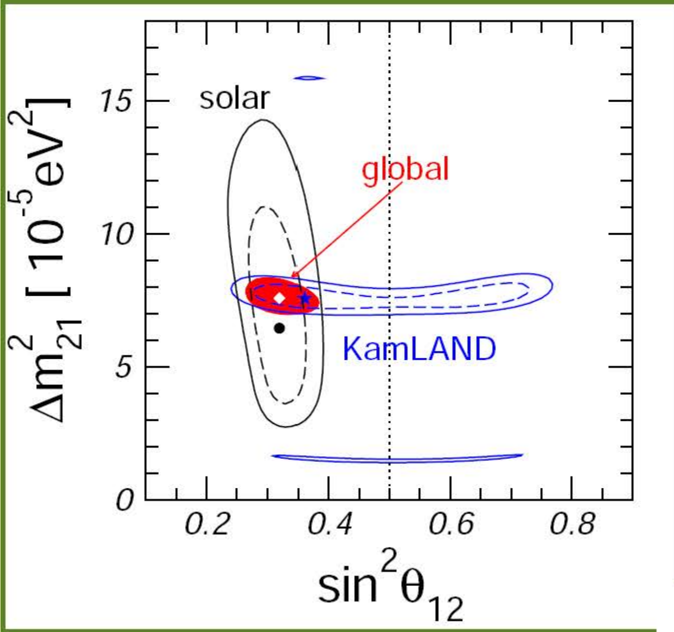
Normal Inverted

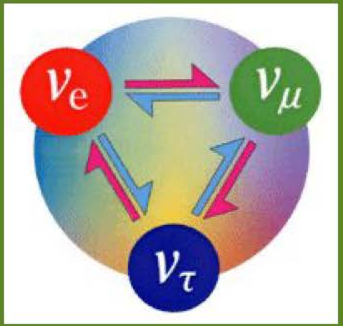


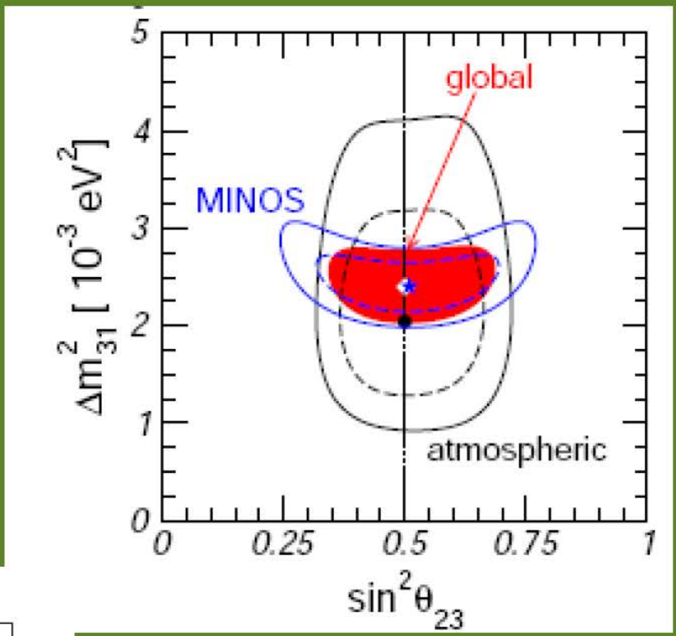
NEUTRINO OSCILLATIONS 2010

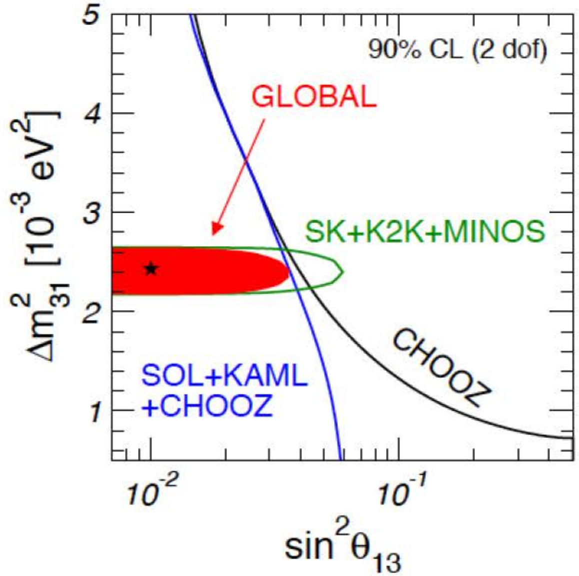
Valle Nu2010

Update of Schwetz et al, NJP 10 (2008) 113011 [rev. Maltoni et al, NJP 6 (2004) 122]









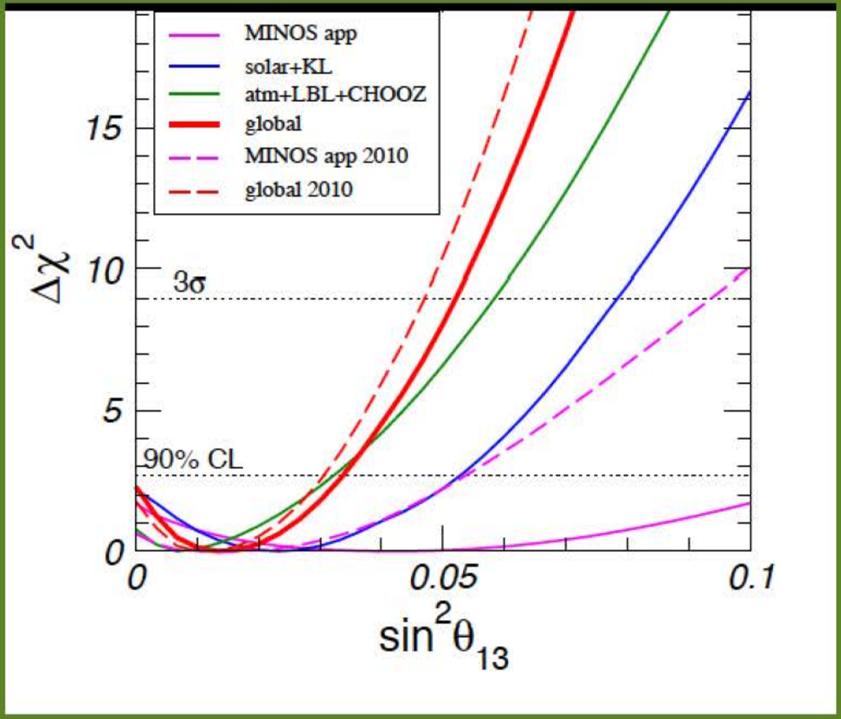
Homestake, SAGE
GALLEX/GNO,
Super-K, SNO-leta, SSM
Borexino
KamLAND (180 Km)

... Super-K

K2K (250 Km)
MINOS latest app
(735 Km)

THETA13 in 2010

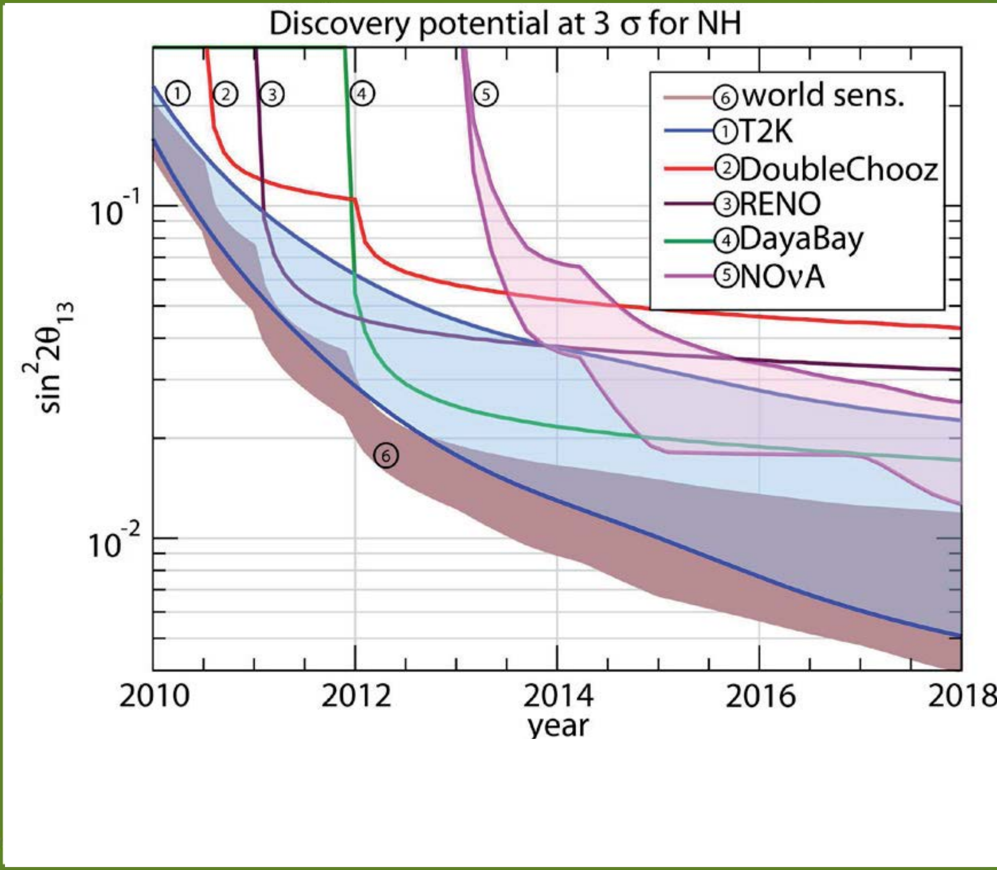
Update of **NJP 10 (2008) 113011**



$$\sin^2\theta_{13} \leq \begin{cases} 0.053\ (0.078) & \text{(solar+KamLAND)} \\ 0.033\ (0.061) & \text{(CHOOZ+atm+K2K+MINOS)} \\ 0.031\ (0.047) & \text{(global data)} \end{cases}$$

FUTURE

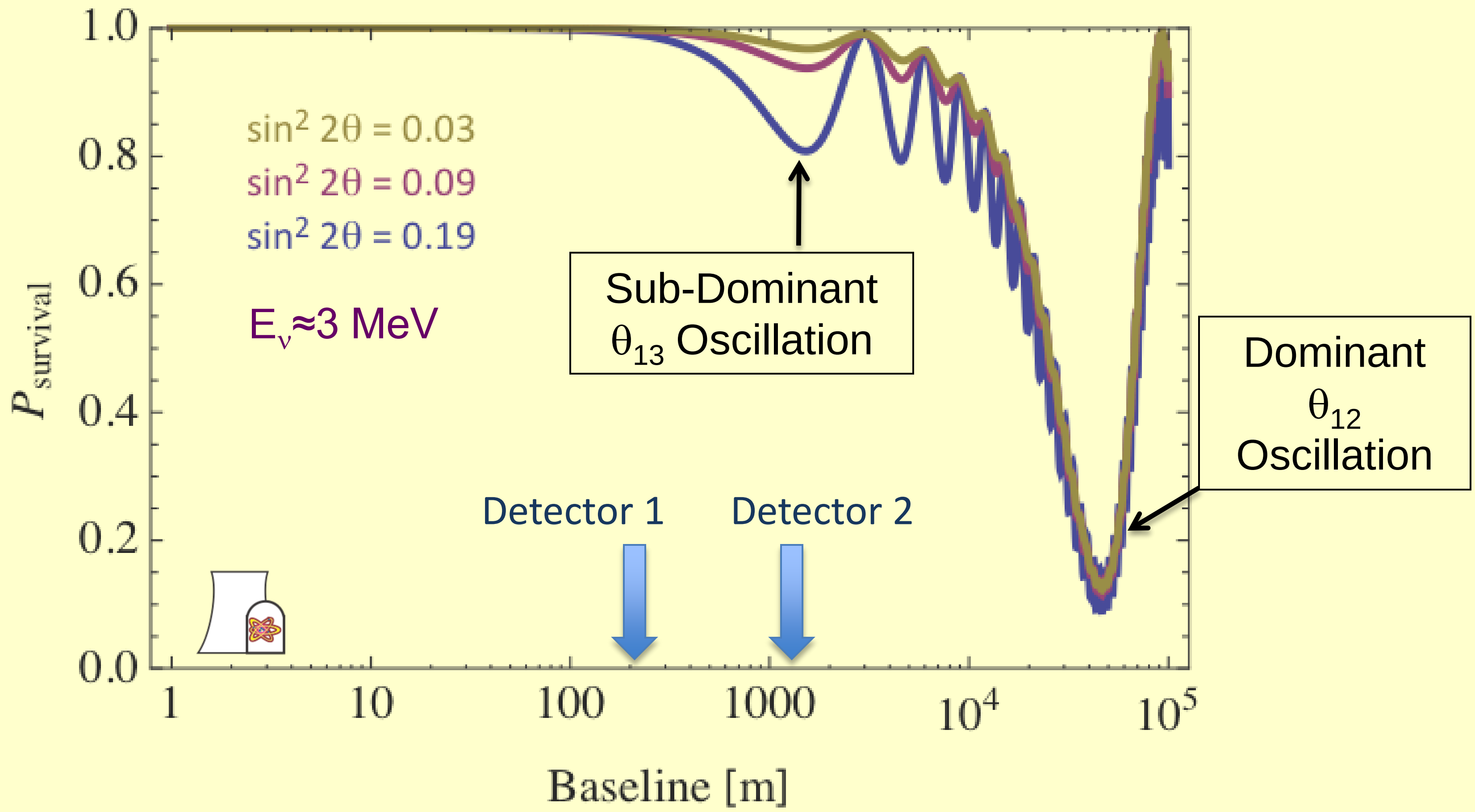
Huber, Lindner, Schwetz, Winter, 2009
Mezzetto,Schwetz, 2010



Precision Reactor Experiments

L. Mikaelyan, arXiv:hep-ex/0008046v2 (Krasnoyarsk)

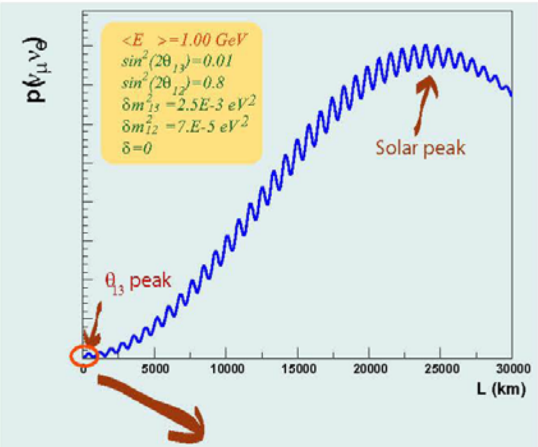
Objective: Determine θ_{13}

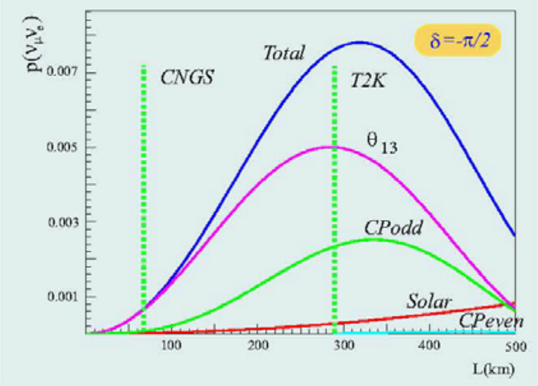


build nearly identical detectors with nearly identical efficiency

Long Baseline Oscillations for: θ_{13}, Hierarchy (Matter), CP Violation, (also θ_{23} from $\nu_\mu \to \nu_\mu$)

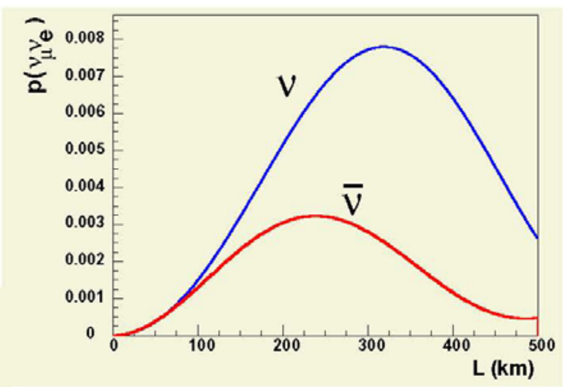
Sub leading $\nu_\mu - \nu_e$ oscillations





$$
\begin{aligned}
p(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} && \theta_{13} \text{ driven} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CPeven} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CPodd} \\
& + 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
& - 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) && \text{matter effect (CP odd)}
\end{aligned}
$$

θ_{13} discovery requires total probability greater than solar driven probability

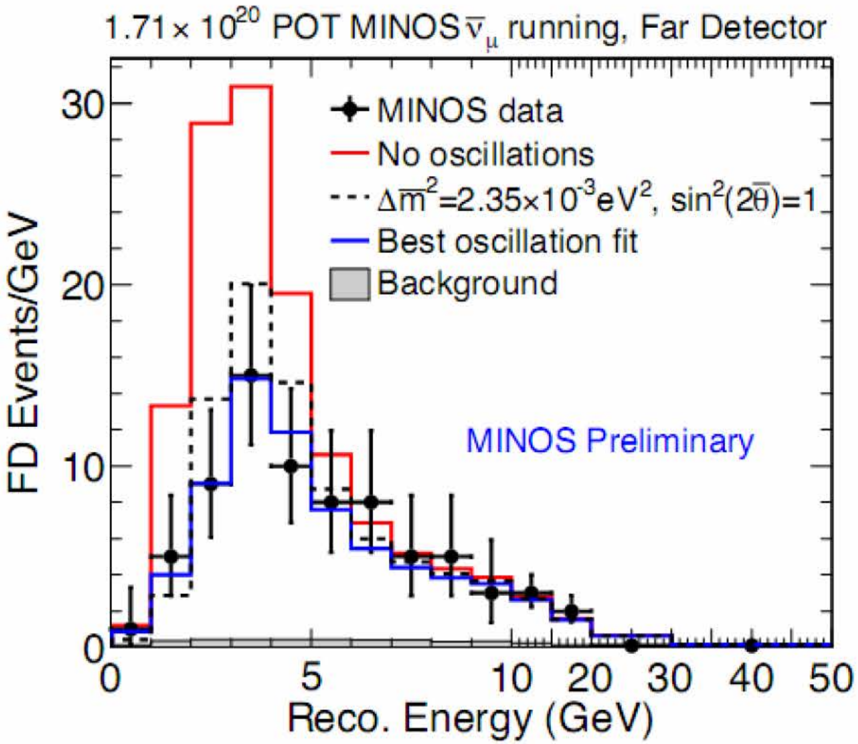


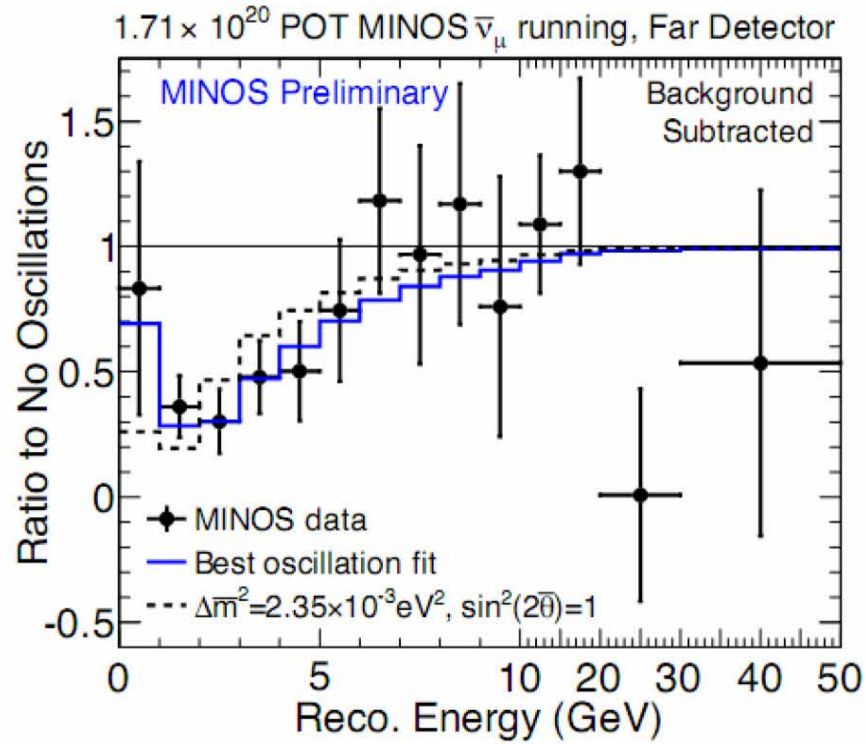
Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

Now for some surprises…

MINOS $\bar{\nu}_\mu$ result





- Expected (no osc.): 155 events
- Observed: 97 events

- No oscillation is disfavored at 6.3σ

Danko NNN2010

$\bar{\nu}_\mu$ versus ν_μ

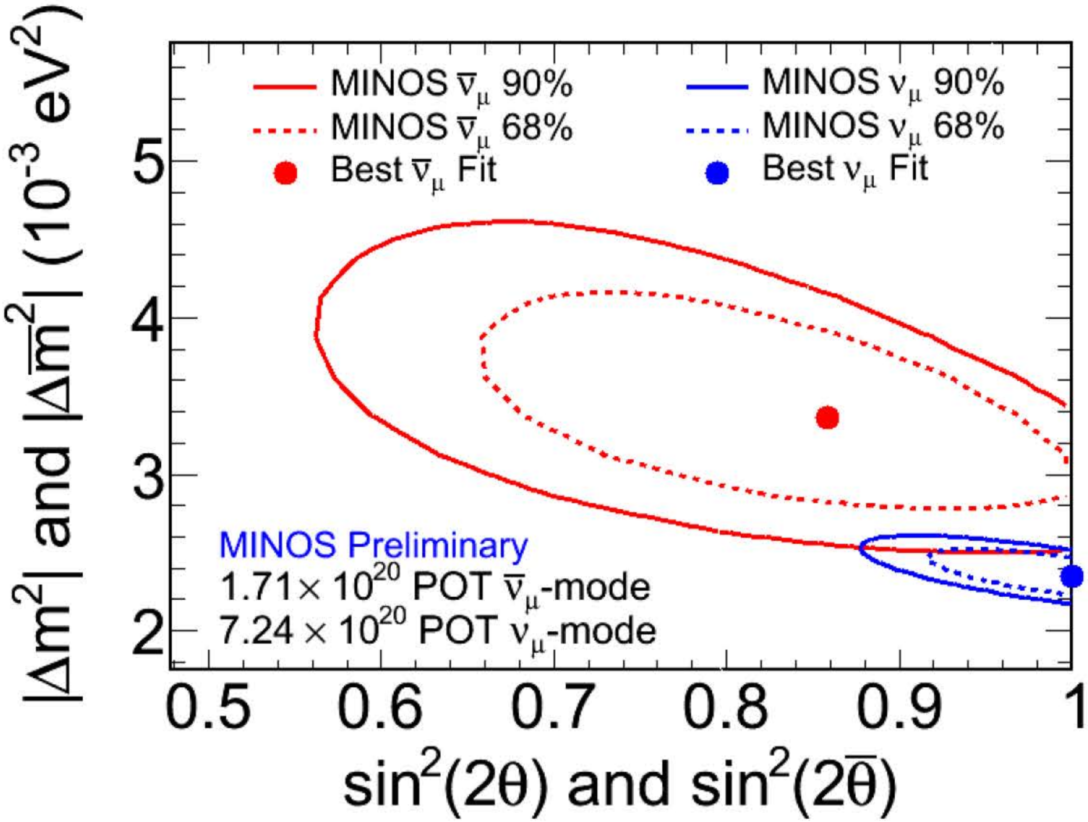
$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

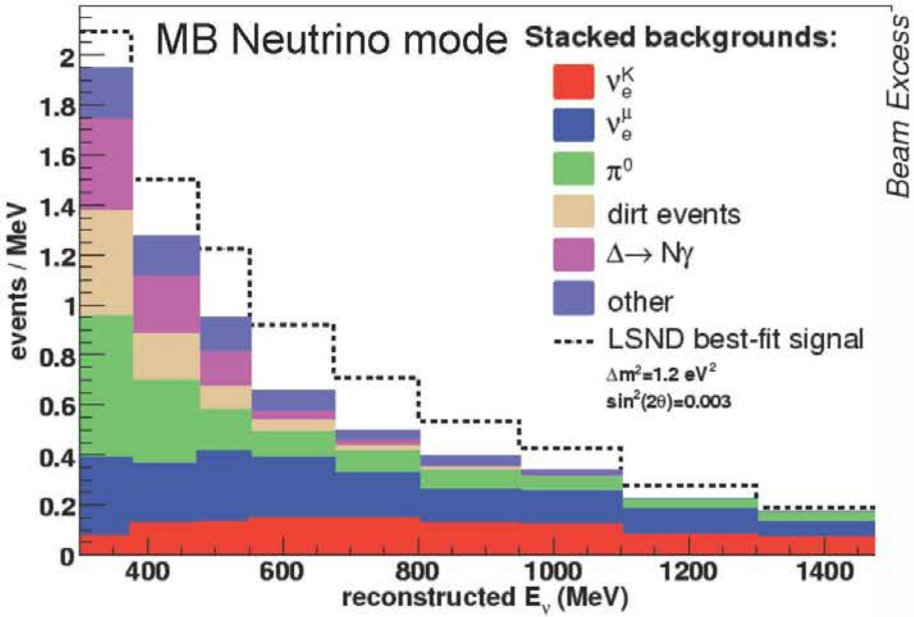
- ~2σ inconsistency
- more antineutrino running is under way to improve nu-bar measurement

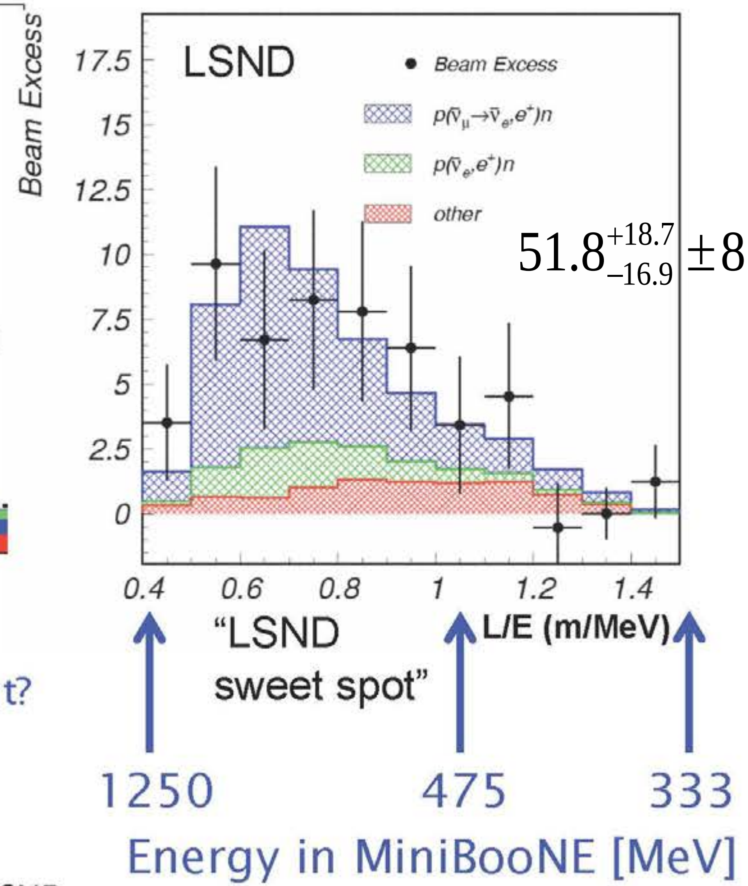


See also SuperK: Jeff Wilkes at 11:15 today

MiniBoone

Reminders of some pre-unblinding choices





- Why is the 200-475 MeV region unimportant?
  - Large backgrounds from mis-ids reduce S/B.
  - Many systematics grow at lower energies, especially on signal.
  - Most importantly, not a region of L/E where LSND observed a significant signal!

R. Van de Water Nu2010

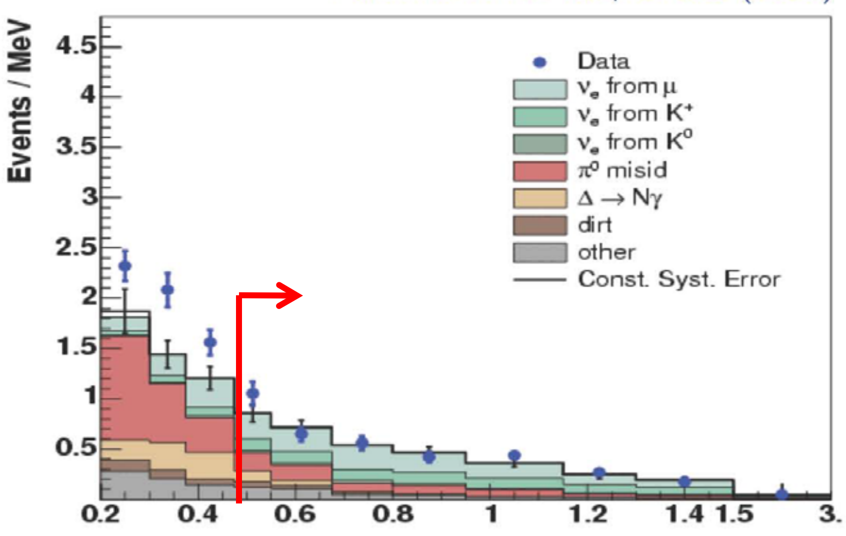
MiniBoone

$\nu_\mu \rightarrow \nu_e$

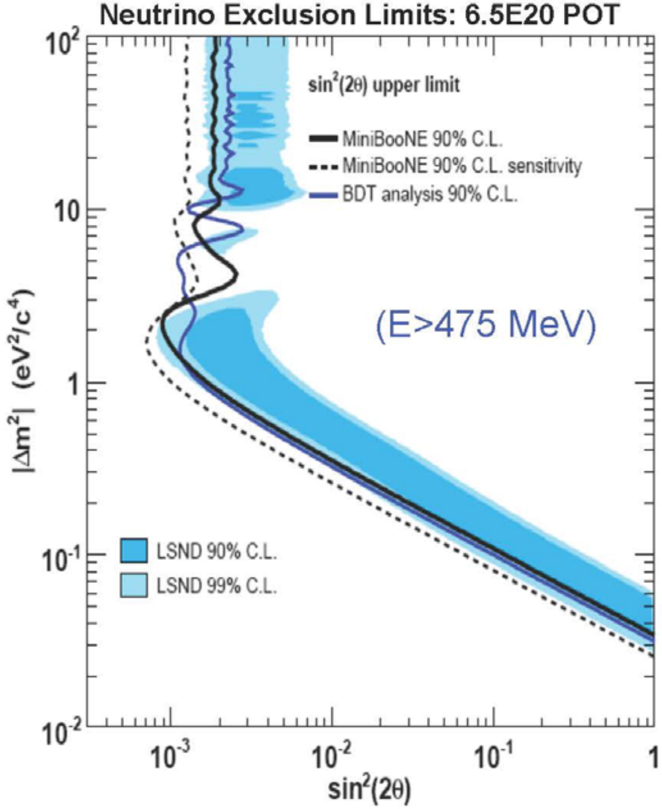
Neutrino mode MB results (2009)

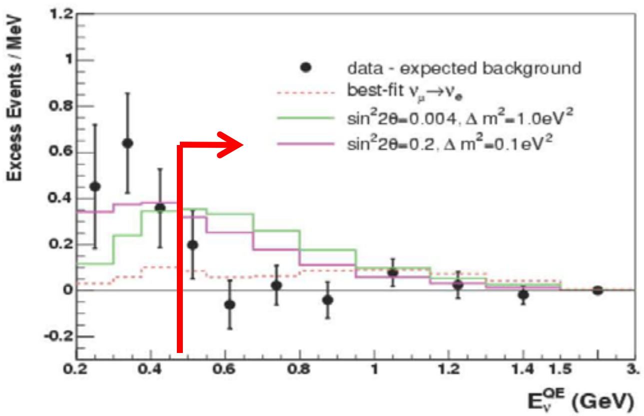
- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess
  - Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

Published PRL 102,101802 (2009)



475 MeV





R. Van de Water Nu2010

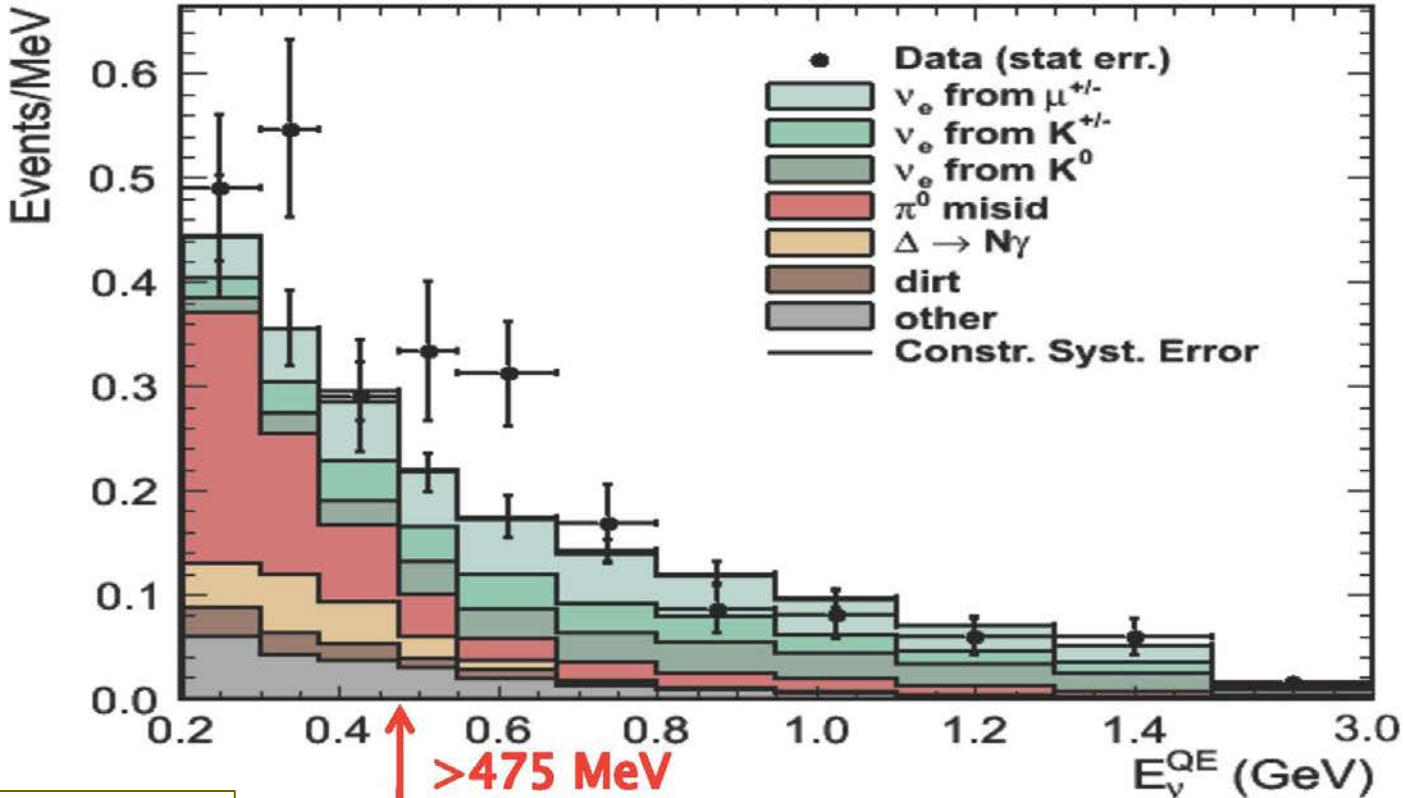
MiniBoone

$$\overline{\nu}_\mu \to \overline{\nu}_e$$

Consistent with LSND

New Antinuetrino Result with 5.66E20 POT

	200-475 MeV	475-1250 MeV	200-3000 MeV
Data	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat)	18.5 ± 10.0 (1.9σ)	20.9 ± 10.0 (2.1σ)	43.2 ±15.3 (2.8σ)
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)

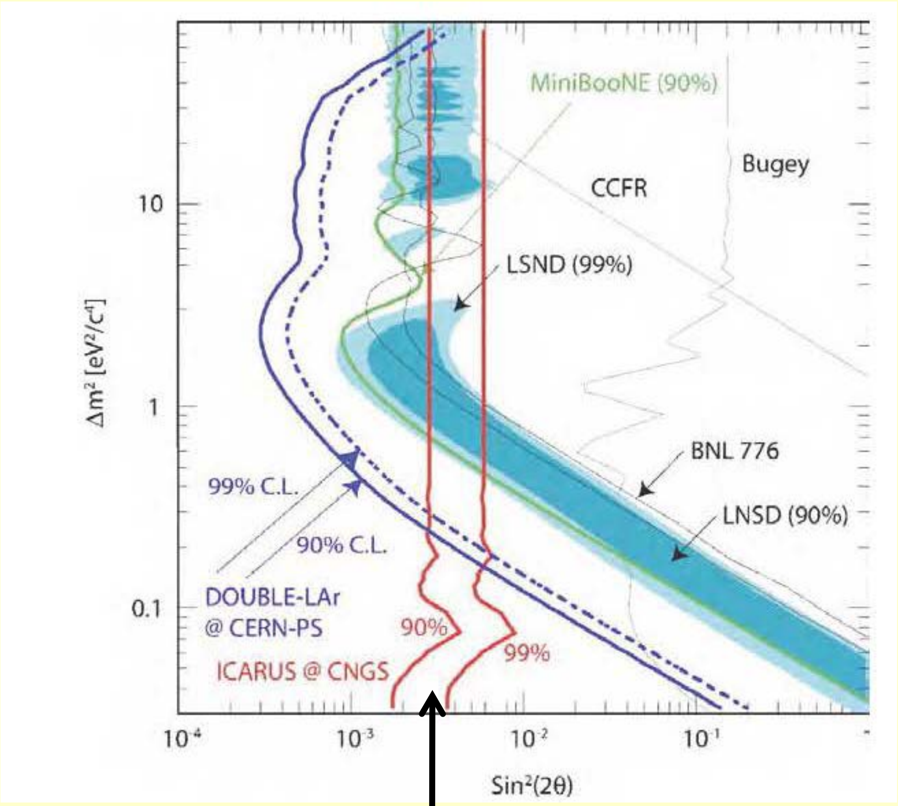


R. Van de Water Nu2010

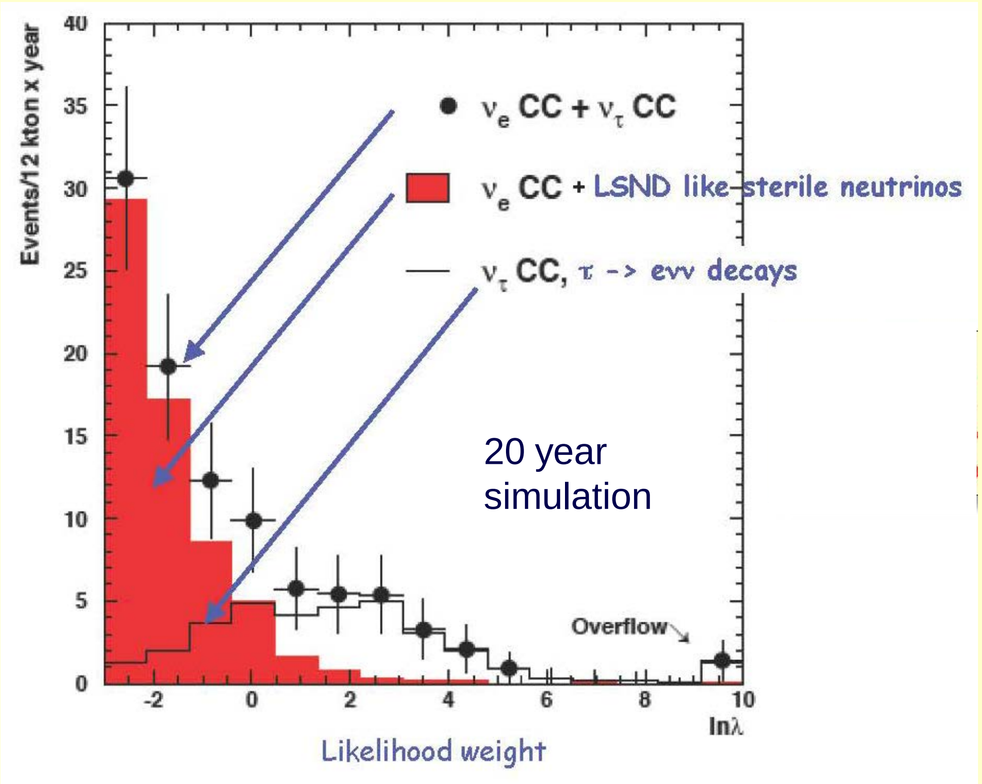
More running has been approved

ICARUS – 600 Tons of Liquid Ar now in operation at Gran Sasso observing the neutrino beam from CERN.

- **Can observe ν_τ similar to OPERA.**
- **Can observe $\nu_\mu \rightarrow \nu_e$ to study LSND and MiniBoone physics.**



Two Years of operation planned for ICARUS at Gran Sasso

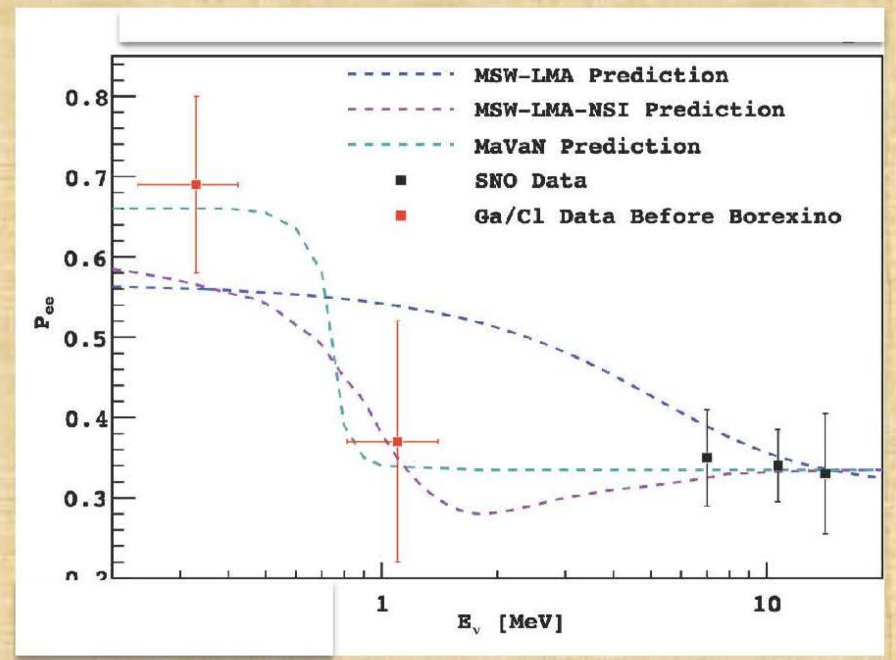


Likelihood distributions may separate an hypothetical LSND excess from the expected presence of τ –> ενν decays

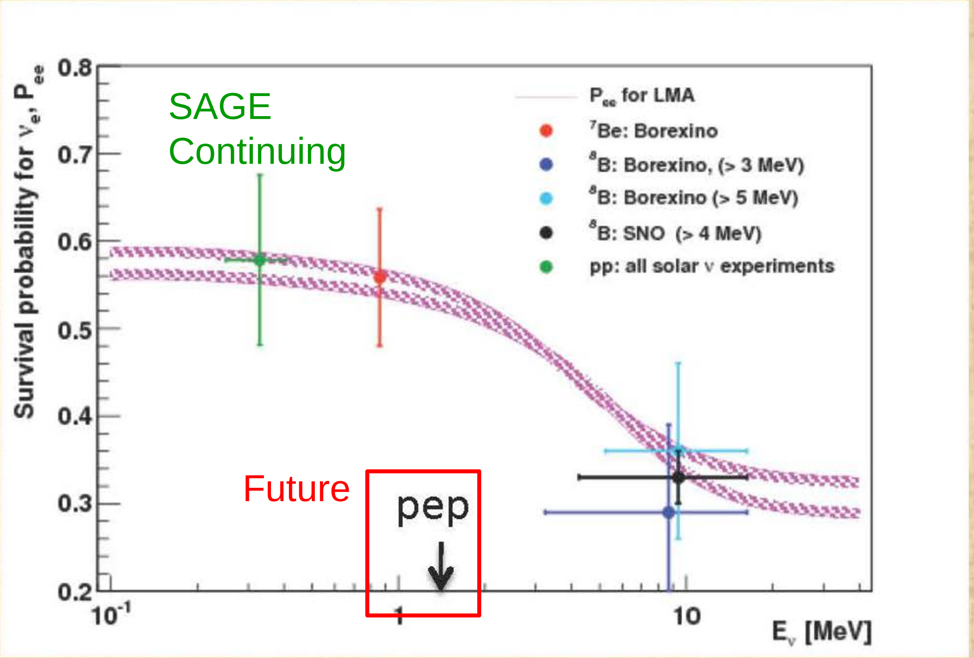
C. Rubbia NNN2010

Improved data for solar neutrinos also restricts possible sub-dominant oscillation effects such as:

- **Mass varying neutrinos**
- **Flavor changing neutral currents**
- **Low mass sterile neutrinos**



Before Borexino Data



After Borexino Data

The Reactor Antineutrino Anomaly: G. Mention et al: arXiv:0179257 (Th. A. Mueller et al: arXiv:1101.2663)

Jan 14,2011

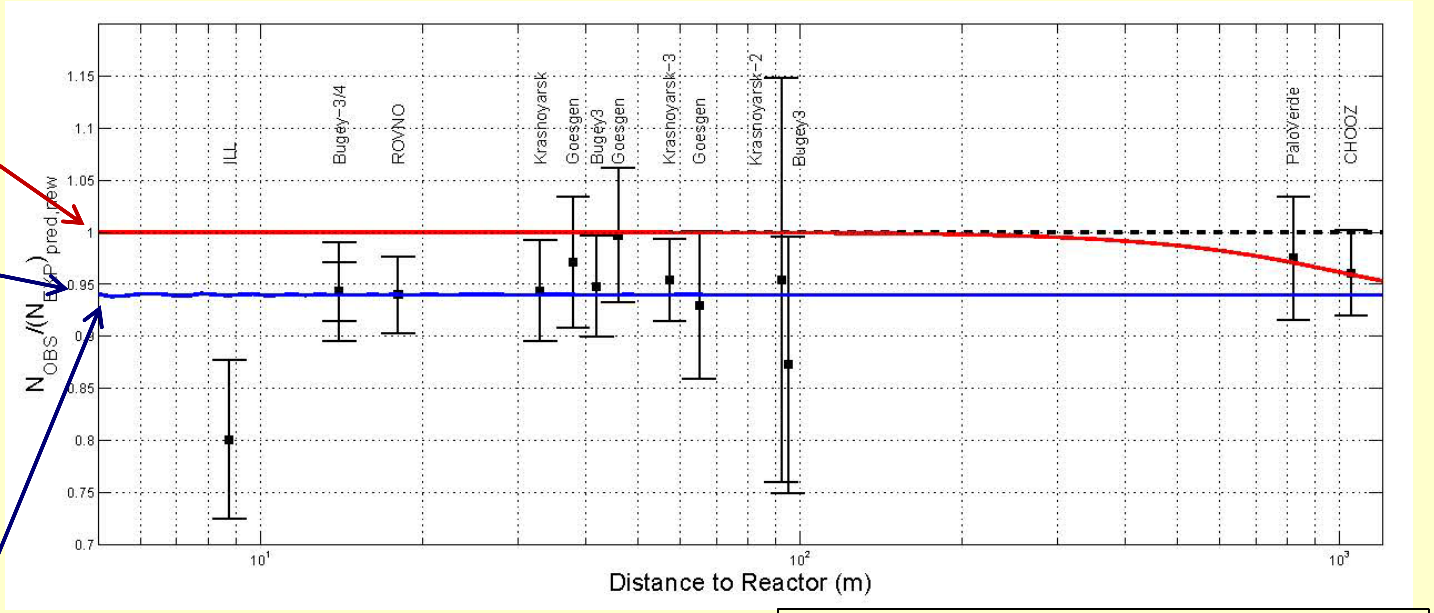
Assuming oscillation with $\sin^2 2\theta_{13} = 0.06$

Assuming $\theta_{13} = 0$ and suppression due to sterile neutrino with $\sin^2 2\theta_{14} \sim 0.17 \pm 0.1$ and $|\Delta m^2| > 1.5\ \mathrm{eV}^2$

Observed/Predicted =

0.937 ± 0.027

For < 100m.



See T. Lasserre Wed: 14:45

- **Very careful, detailed work by the authors who also state: "We would like to stress here that other explanations are also possible, such as a correlated artifact in the experiments, or an erroneous prediction of the antineutrino flux from the nuclear reactor cores."**
- **Reactor Flux normalization is increased by over 3% in the new calculation mainly due to change in calculation of Coulomb and Weak Magnetism corrections for fission product beta decay. Uncertainty still assigned as < 1% for these corrections because of stated improvements in the calculations.**
- **2.7% total reactor flux uncertainty mainly via 1985 measurements of fission product electron spectra.**
- **Average of experimental measurements assigned 1% uncertainty, dominated by Bugey4 with 1.4 % result.**
- **The authors also call for future experiments for verification, such as short baseline reactor neutrino measurements or neutrino source measurements in a detector with energy and spatial resolution.**

Other experiments cited in the Reactor antineutrino anomaly paper with effects possibly arising from a sterile neutrino with $|\Delta m^2| > \sim 1\ eV^2$:

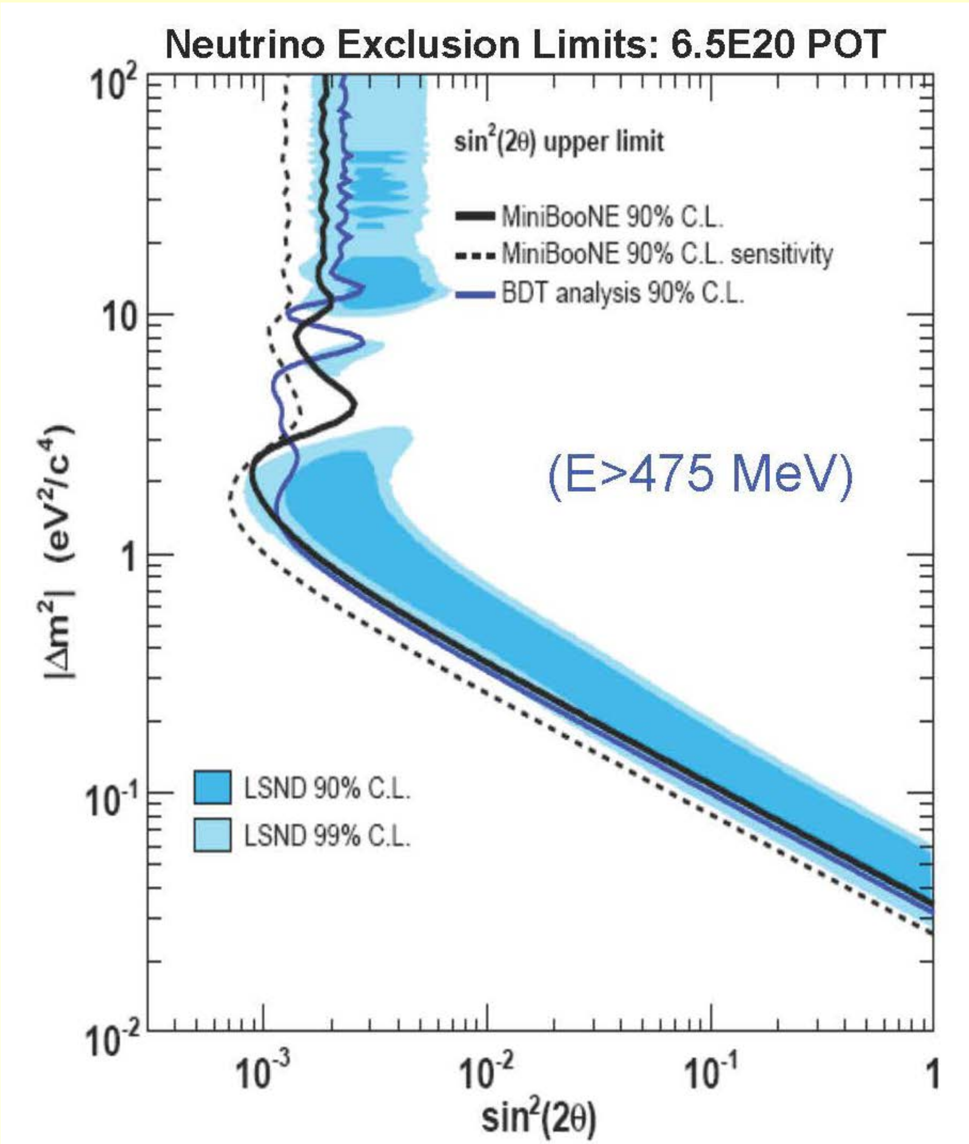
- ^{51}Cr and ^{37}Ar source measurements for SAGE and GNO experiments: Observed/Predicted = 0.86 ± 0.05

- MiniBoone (C. Giunti, M. Laveder, Phys. Rev. D82 (2010) 053005)

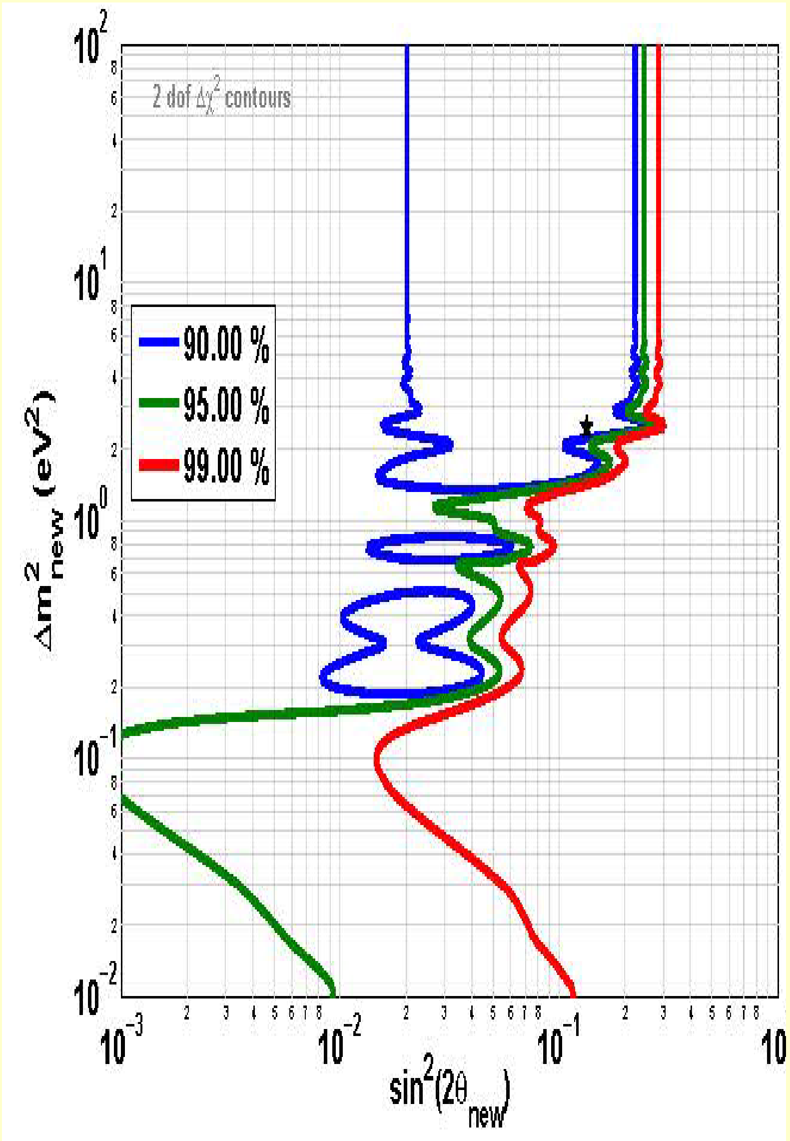
- Numbers of Neutrinos fit for Cosmological data:
    - WMAP + BAO: 4.35 ± 0.87 , WMAP + Atacama: 5.3 ± 1.3
    - Non-standard Big Bang Nucleosynthesis: 3.78 ± 0.75

Assuming a 3+1 sterile neutrino scenario (2+2 is disfavored by solar+KamLAND+ atmospheric), the effects in other experiments from a sterile neutrino with $\sin^2 2\theta_{14} \sim 0.2$ and $|\Delta m^2| \sim 1.5\ eV^2$ would be:

- Small change in CHOOZ limit (They had used BUGEY4 to normalize).
- Very small effect on mass 1-2 and 2-3 mixing parameters except a small reduction in the θ_{13} value derived from KamLAND and solar.
- Contribution to KATRIN ν mass measurement at ~ 0.2 eV level.
- Contribution to neutrino-less double beta decay at ~ 0.02 eV^2 level.
- About 8% reduction in the expected active solar neutrino flux.



Neutrino Exclusion Limits: 6.5E20 POT
sin²(2θ) upper limit
MiniBooNE 90% C.L.
MiniBooNE 90% C.L. sensitivity
BDT analysis 90% C.L.
(E>475 MeV)
LSND 90% C.L.
LSND 99% C.L.
|Δm²| (eV²/c⁴)
sin²(2θ)



2 dof Δχ² contours
90.00 %
95.00 %
99.00 %
Δm²new (eV²)
sin²(2θnew)

Summary of Experiments:

(Weapons of Mass Instruction)

(neutrino) (and mixing)

- **Known Knowns**

- **Known Unknowns**

2-3 Hierarchy, absolute mass,

Majorana/Dirac, θ_{13}, δ

- **Semi-known previously unknowns**

Sterile ν, CPT violation??

- **Unknown Unknowns??**

Who Knows?? That's the fun!!

- **Stay tuned as running proceeds**