Current Neutrino Oscillation Results: Lecture 2

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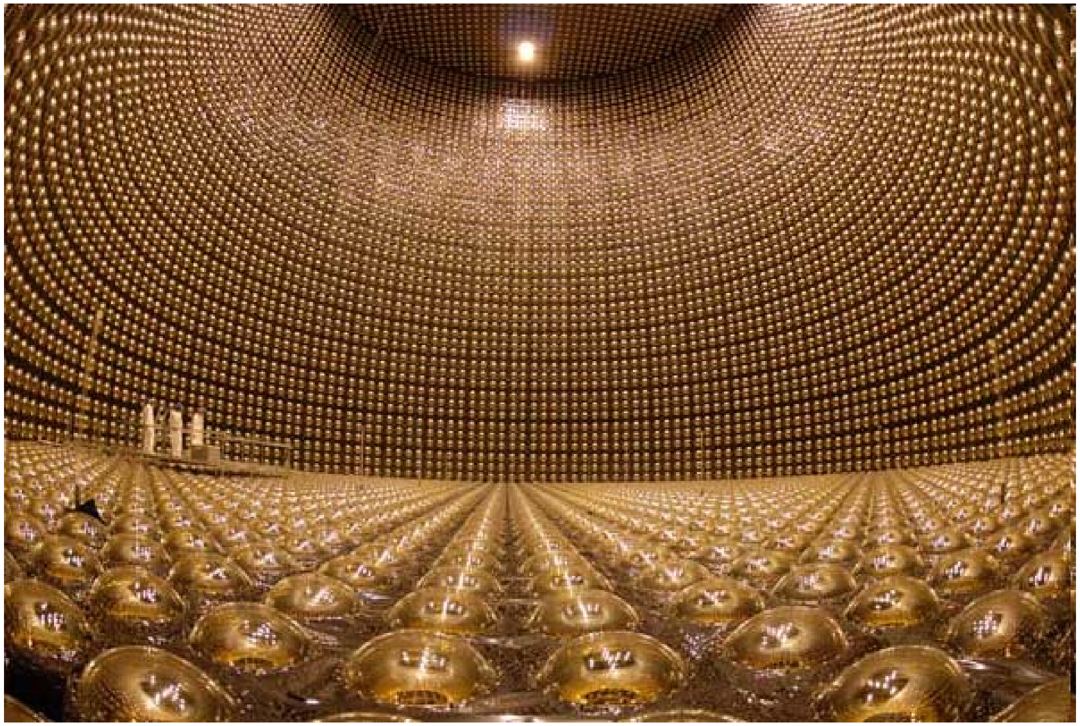

Outline

- Lecture 1: Experimental Neutrino Physics
  - Neutrino Physics and Interactions
  - Neutrino Mass Experiments
  - Neutrino Sources/Beams and Detectors for Osc. Exp's
- Lecture 2: The Current Oscillation Results
  - Solar and Kamland Neutrino Results
  - Atmospheric and Accelerator Neutrino Results
  - Global Oscillation Fits
- Lecture 3: Present and Future Oscillation Experiments
  - The Fly in the Ointment: LSND and MiniBooNE
  - Searches for θ_{13} / Mass Hierarchy / CP Violation
    - Current Hints
    - Reactor Experiments
    - Longbaseline experiments
    - Combining Experiments
  - Future Plans for Oscillation Experiments

Neutrino Oscillations

The observation of neutrino oscillations where one type of neutrino can change (oscillate) into another type implies:

1. Neutrinos have mass

and

2. Lepton number (electron, muon, tau) is not conserved
   ($\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\tau$)

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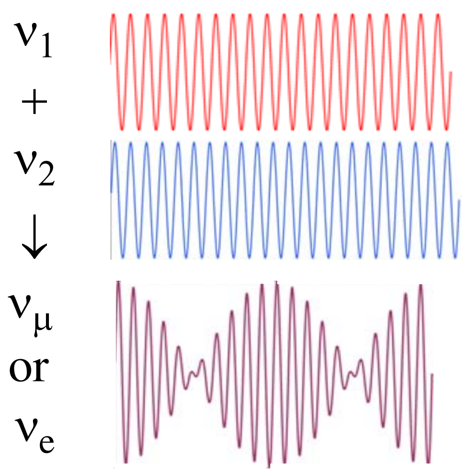
mass eigenstates ≠ flavor eigenstates



$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 L / E\right)$$

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$

Derivation of Oscillation Formula
(A favorite graduate exam problem)

Take the mixing matrix to be:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

At production ($t = 0$:)

$$|\nu_\mu(0)\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

At a later time:

$$\begin{aligned} |\psi(t)\rangle &= -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle \\ &= (\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t})|\nu_e\rangle + \\ &\quad \sin\theta\cos\theta(e^{-iE_2 t} - e^{-iE_1 t})|\nu_\mu\rangle \end{aligned}$$

And the probability is:

$$\begin{aligned} P_{osc} &= |\langle\nu_e|\psi(t)\rangle|^2 \\ &= \frac{1}{2}\sin^2 2\theta[1 - cos(E_2 - E_1)t] \end{aligned}$$

Use $E_1 = \sqrt{p^2 - m_1^2} \approx p + m_1^2/2p$ (and same for E_2)
and $(t/p) = (tc)/(pc) = L/E$; then convert to "real" units

$$\begin{aligned} P_{osc} &\approx \frac{1}{2}\sin^2 2\theta\left(1 - cos\left(\frac{(m_2^2 - m_1^2)L}{E}\right)\right) \\ &= \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \end{aligned}$$

$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

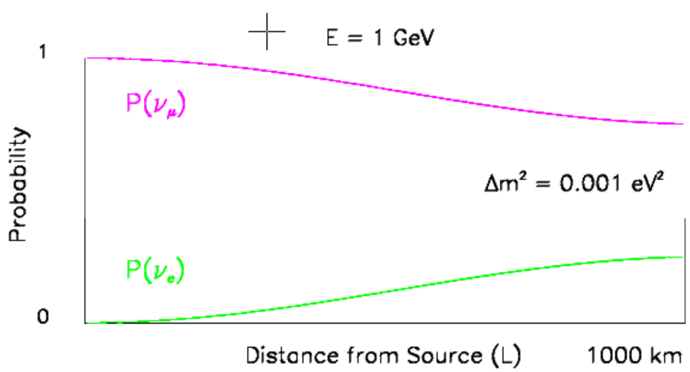
See if you can derive the 1.27 factor in the formula by recovering from the hbar = c =1.

Oscillation Phenomenology

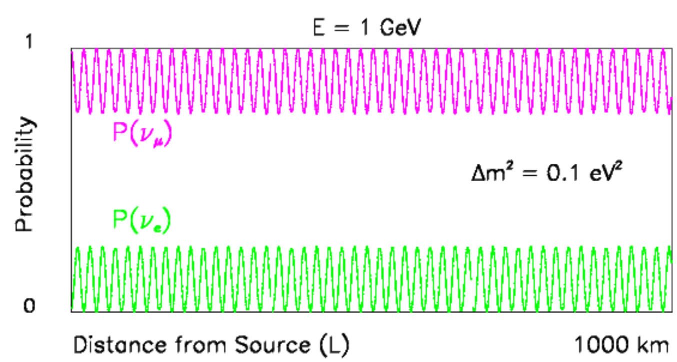
- Two types of oscillation searches:
  - ***Appearance Experiment:***
    Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
    - Need to know the backgrounds
  - ***Disappearance Experiment:***
    Look for a change in ν_μ flux as a function of L and E
    - Need to know the flux and cross sections

- $P_{osc} = \sin^2 2\theta \sin^2(1.27\ \Delta m^2\ L/E)$ sets the details of search
  - Mixing angle $\sin^2 2\theta$ sets the needed statistics

Small Δm^2 (Need large L/E)

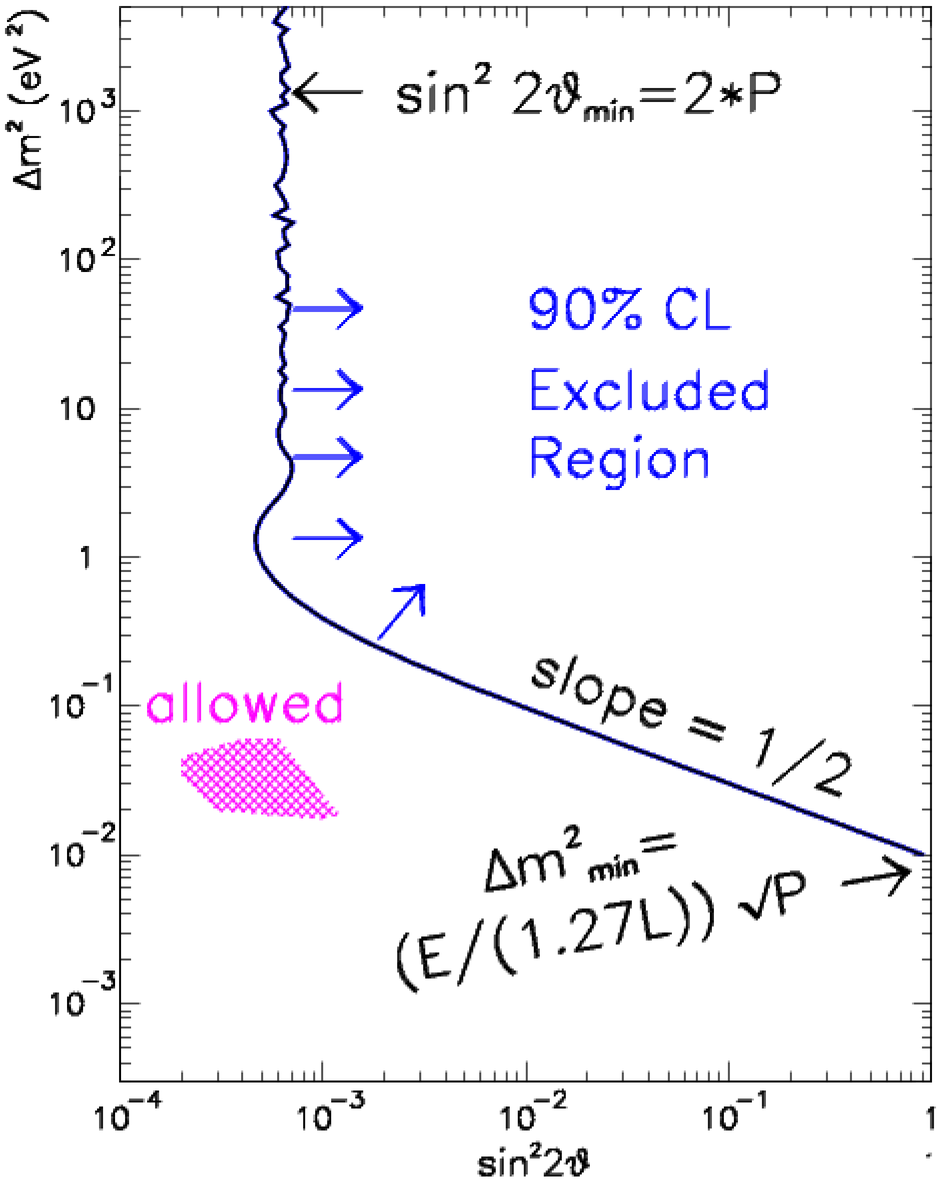


Large Δm^2: $\langle\sin^2(1.27\ \Delta m^2\ L/E)\rangle = 1/2$



Oscillation Plots

$$P_{osc} = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$



- If you see an oscillation signal with

  P_{osc} = P ± δP

  then carve out an **allowed region** in (Δm^2,$\sin^2 2\theta$) plane.

- If you see no signal and limit oscillation with

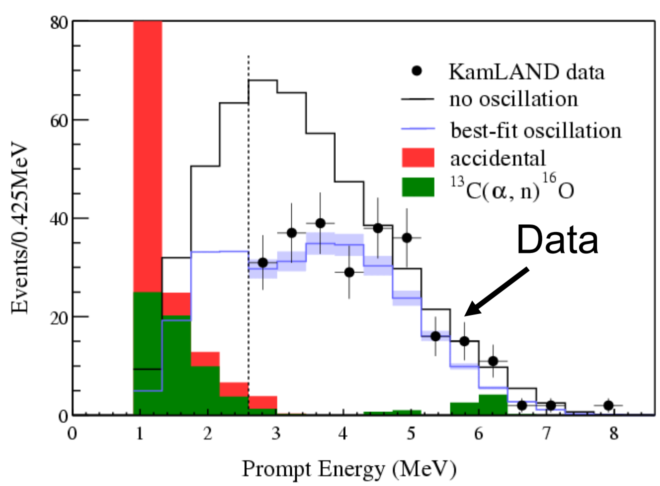
  P_{osc} < P @ 90% CL

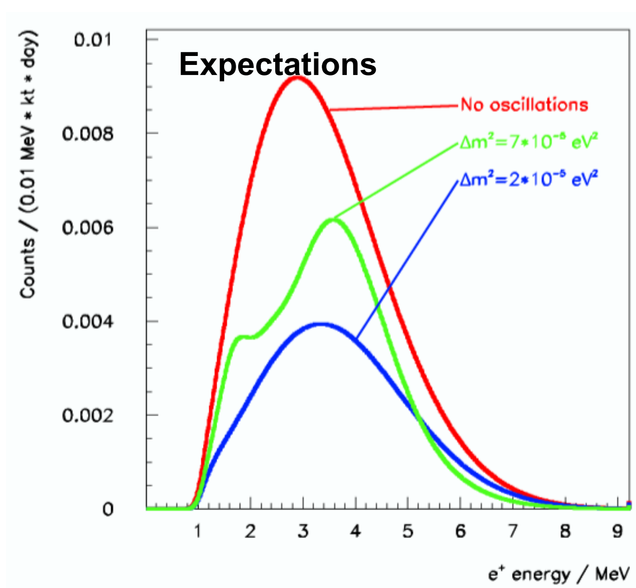
  then carve out an **excluded region** in the (Δm^2,$\sin^2 2\theta$) plane.

Example of an Oscillation Signal
(Kamland Reactor Neutrino Exp)

$$P_{osc} = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

- The Kamland experiment measured the number of antineutrinos hitting its detector as a function of energy
  - Antineutrino source was all reactors in Japan: mean distance = 180km
- Compare measured data to expectation with and without neutrino oscillations
  - Find best set of oscillation parameters $\Delta m^2/\sin^2 2\theta$ and uncertainties that explain the data.
- With $E \approx 3$ MeV and $L = 180$ km, 2nd oscillation maximum occurs when $1.27\ \Delta m^2\ L/E = 3\pi/2 \Rightarrow \Delta m^2 \approx 3.7 \times 3\ \text{MeV}/180{,}000\text{m} = 6.3\times10^{-5}\ \text{eV}^2$

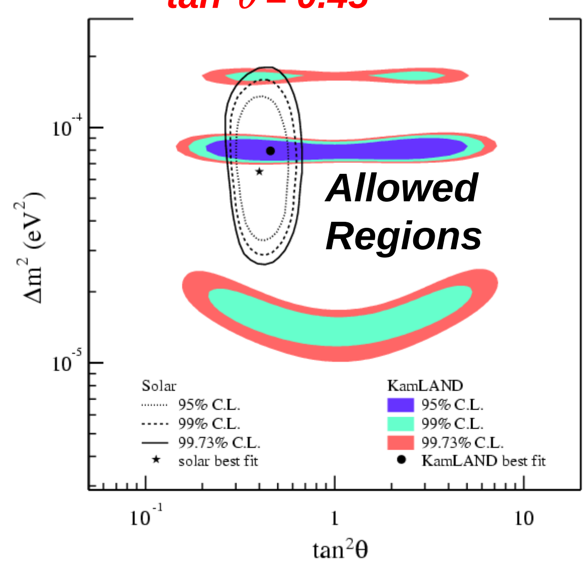




KamLAND best fit :

$\Delta m^2 = 7.9 \times 10^{-5}\ eV^2$

$\tan^2\theta = 0.45$



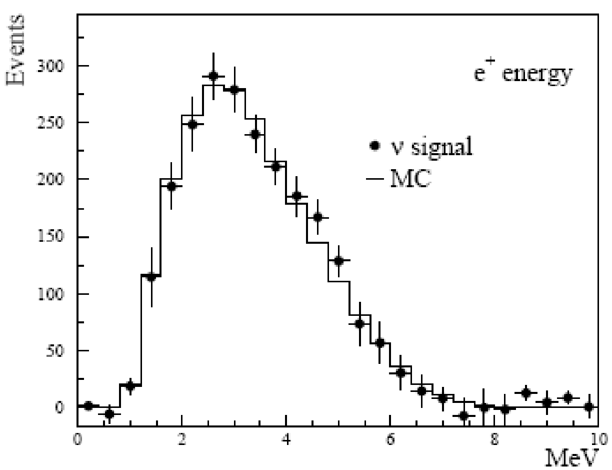
Example of an Oscillation Exclusion

(Double Chooz Reactor Neutrino Exp)

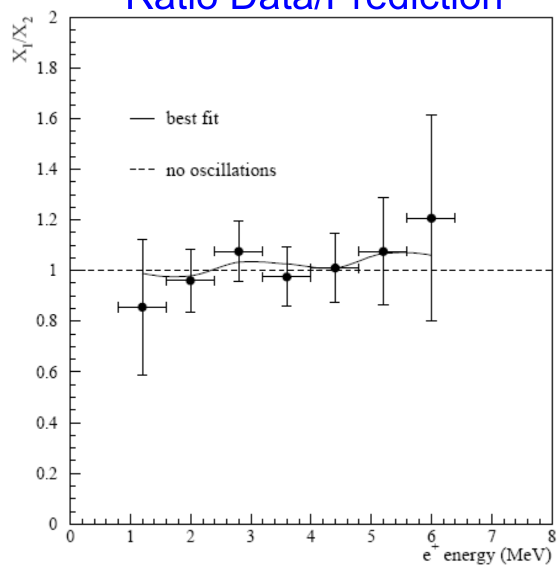
$$P_{osc} = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

- The Double Chooz experiment measured the number of events hitting its detector as a function of energy
  - Antineutrino source was two reactors which were ~1km away.
- Compare measured data to expectation with and without neutrino oscillations
  - Data agreed with the no oscillation hypothesis so exclude ranges of $\Delta m^2/\sin^2 2\theta$ that are inconsistent with this agreement.
- With E $\approx$ 3 MeV and L = 1 km, 1st oscillation maximum occurs when $1.27\ \Delta m^2\ L/E = \pi/2 \Rightarrow \Delta m^2 \approx 1.24 \times 3\ \text{MeV}/1000\text{m} = 3.7\times10^{-3}\ \text{eV}^2$

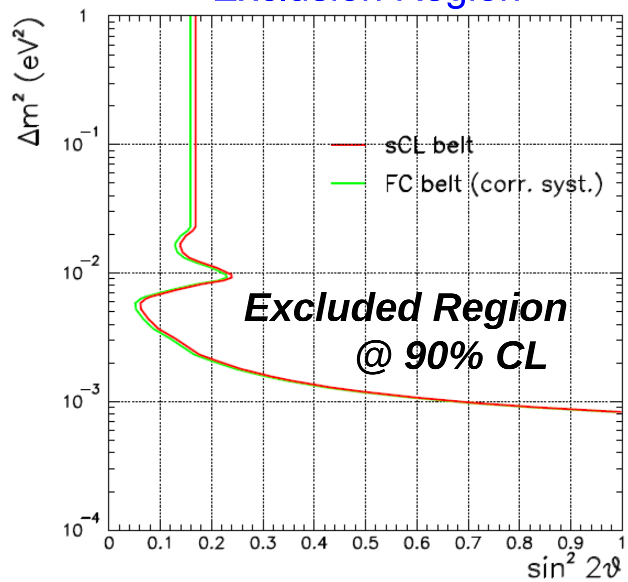
Data vs Expectation



Ratio Data/Prediction



Exclusion Region

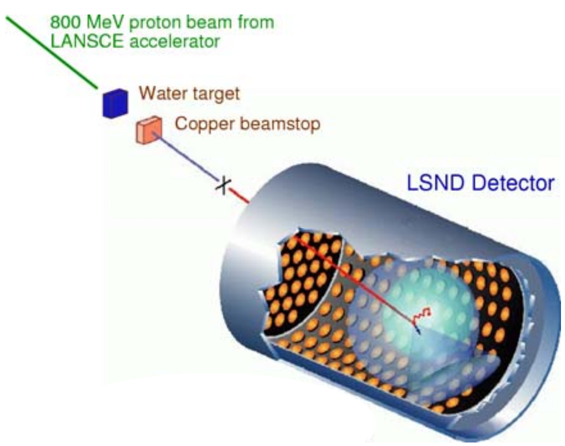


Situation in mid-1990's: Three Experimental Indications for Neutrino Oscillations

LSND Experiment

L = 30m
E = ~40 MeV

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

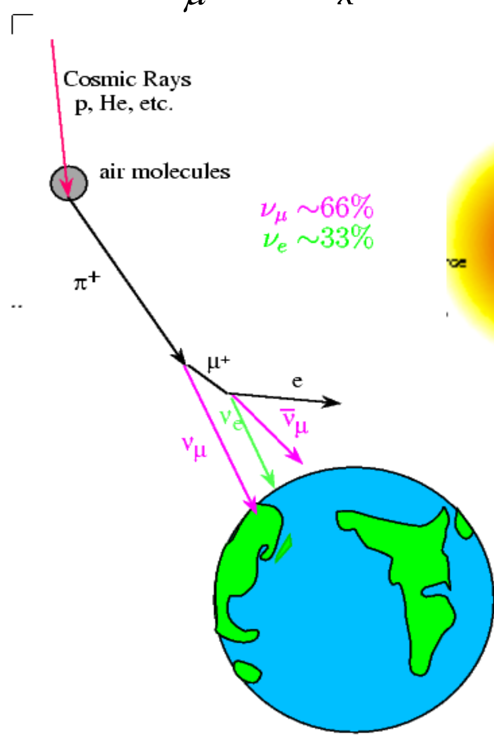


Δm^2 = .3 to 3 eV^2
$Prob_{OSC}$ = 0.3 %

Atmospheric Neutrinos

L = 15 to 15,000 km
E =300 to 2000 MeV

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

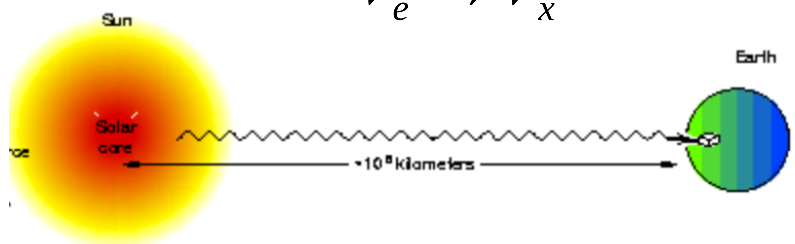


Δm^2 = ~ 1 to 7 × 10^{-3} eV^2
$Prob_{OSC}$ = ~100%

Solar Neutrinos

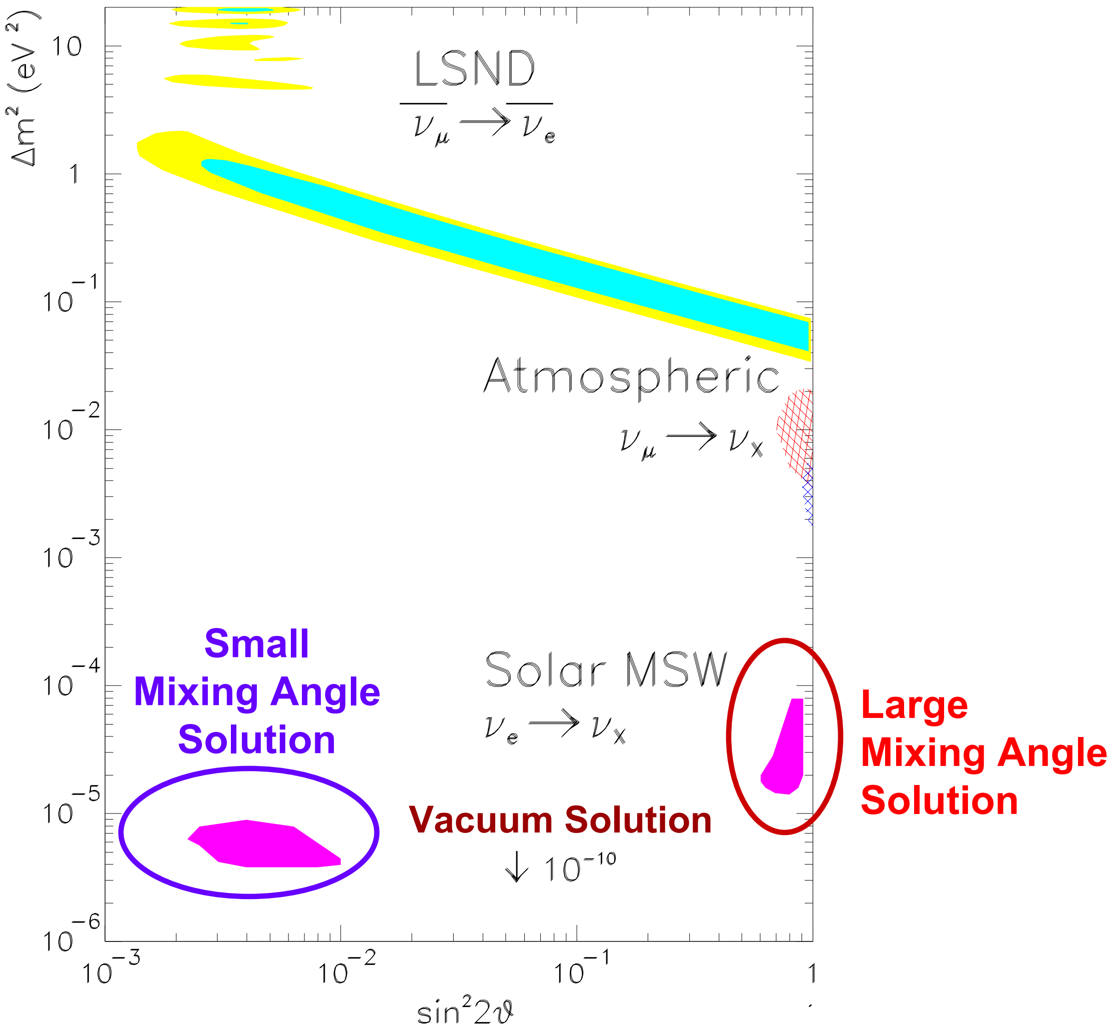
L = 10^8 km
E =0.3 to 3 MeV

$$\nu_e \rightarrow \nu_x$$



Δm^2 = ~ 2 to 8 × 10^{-5} eV^2
$Prob_{OSC}$ = ~100%

Three Signal Regions
(Mid 1990's)



Theoretical Prejudices before 1995

- Natural scale for $\Delta m^2 \sim 10 - 100\ eV^2$ since needed to explain dark matter
- Oscillation mixing angles must be small like the quark mixing angles
- Solar neutrino oscillations must be small mixing angle MSW solution because it is “cool”
- Atmospheric neutrino anomaly must be other physics or experimental problem because it needs such a large mixing angle
- LSND result doesn’t fit in so must not be an oscillation signal

Theoretical Prejudices before 1995

	What we know now
• Natural scale for $\Delta m_{23}^2 \sim 10 – 100\ eV^2$ since needed to explain dark matter	Wrong
• Oscillation mixing angles must be small like the quark mixing angles	Wrong
• Solar neutrino oscillations must be small mixing angle MSW solution because it is "cool"	Wrong
• Atmospheric neutrino anomaly must be other physics or experimental problem because it needs such a large mixing angle	Wrong
• LSND result doesn't fit in so must not be an oscillation signal	????

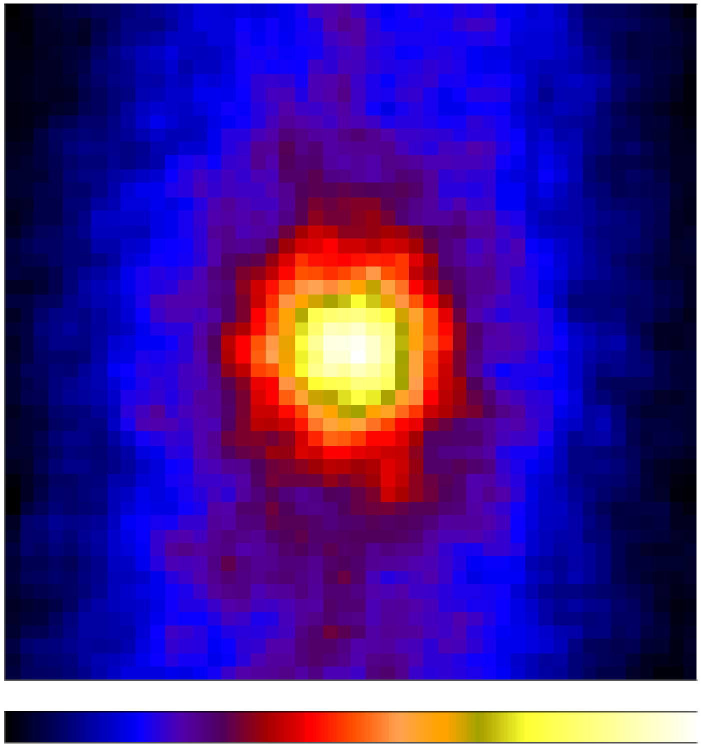
Neutrino Revolution: 1995 - Present

- Solar Neutrino Oscillations Confirmed and Constrained
  - SNO experiments sees that total neutrino flux correct from sun but just changing flavor
  - Kamland experiment using reactor neutrinos confirms solar oscillations
  - Borexino measures ^{7}Be neutrino rate
  - Combination of experiments $\Rightarrow$ Large Mixing Angle Solution
- Atmospheric neutrino oscillations definitively confirmed
  - "Smoking Gun" $\Rightarrow$ Super-K flux change with zenith angle (distance)
  - Accelerator neutrino confirmation with KEK to Super-K exp.
  - MINOS experiment makes improved Δm^2_{Atm} determination
  - Value of Δm^2 goes down to ~2.5×10^{-3} eV^2

Solar Neutrino Deficit

Flux of solar neutrinos detected at the earth is much less than expected

⇒ Is it due to neutrino oscillations?



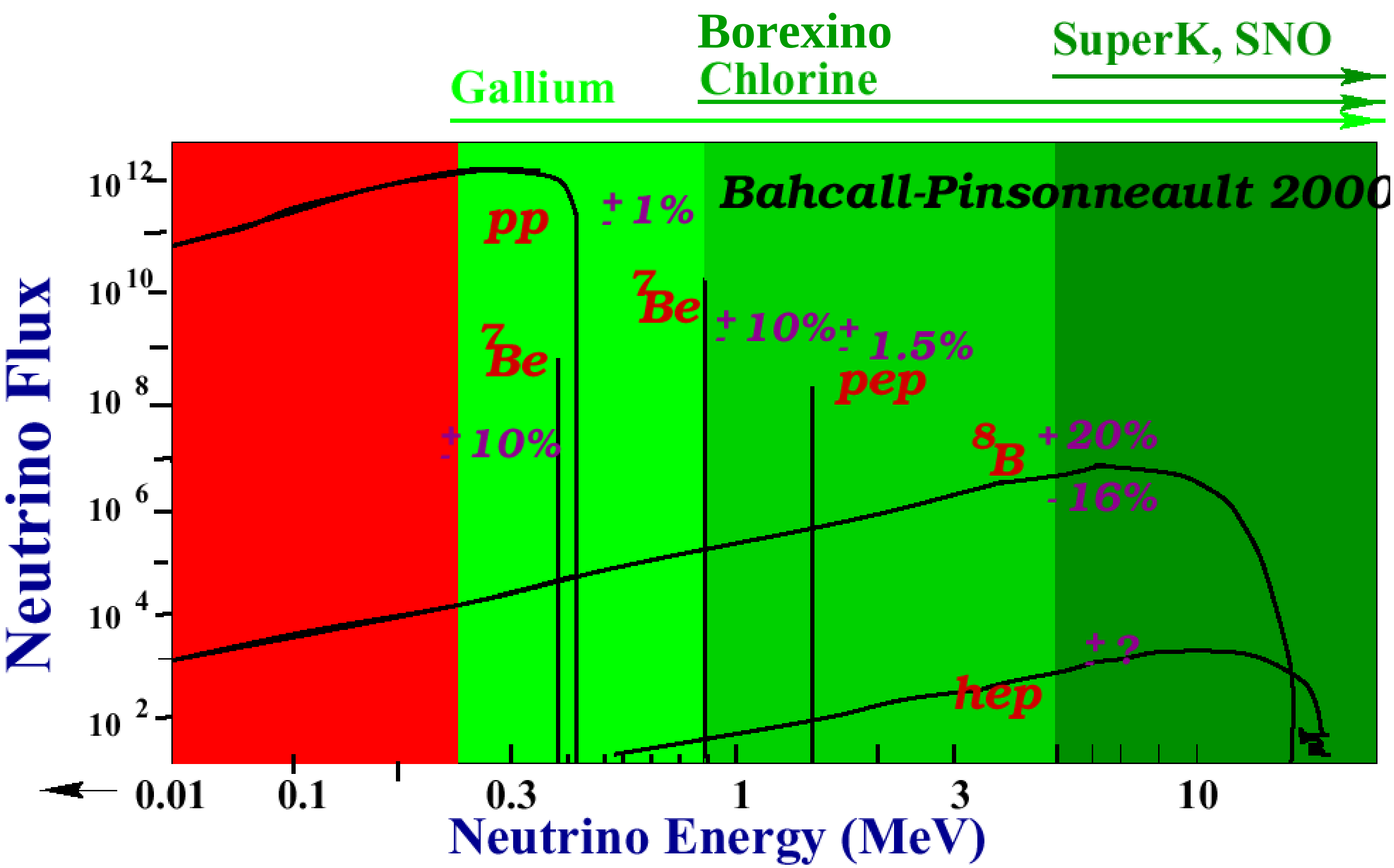
Super- K (Japan) image of the sun using neutrinos

Super-K Exp can see the sun underground from the other side of the earth using:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

(Note: actual size of sun is <1 pixel. This is a blurry image!)

Solar Neutrino Spectrum



Solar Neutrino Experiments

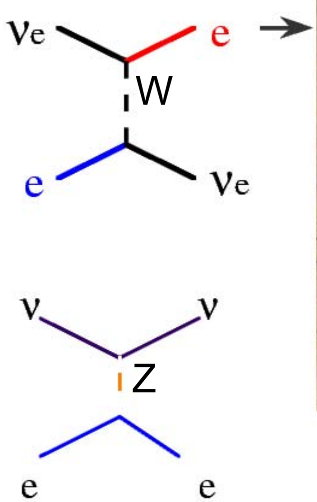
- Two types of experiments:
  - Chemical Extraction experiments
    - Homestake ("Chlorine") $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
    - Sage and Gallex ("Gallium") $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
  - Scattering experiments
    - SuperKamioka (Kamioka) (Light water) $\nu_{x,e} + e^- \rightarrow \nu_{x,e} + e^-$
    - SNO (Heavy water) $\nu_e + d \rightarrow e^- + p + p$; $\nu_x + d \rightarrow \nu_x + n + p$
    - Borexino (Liquid Scintillator) $\nu_{x,e} + e^- \rightarrow \nu_{x,e} + e^-$

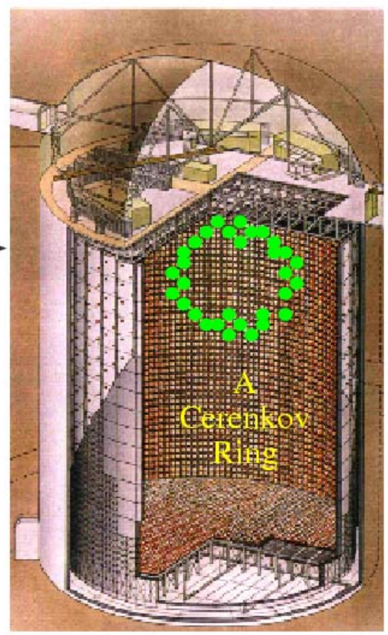
Super-K Experiment
H_2O Cerenkov Detector

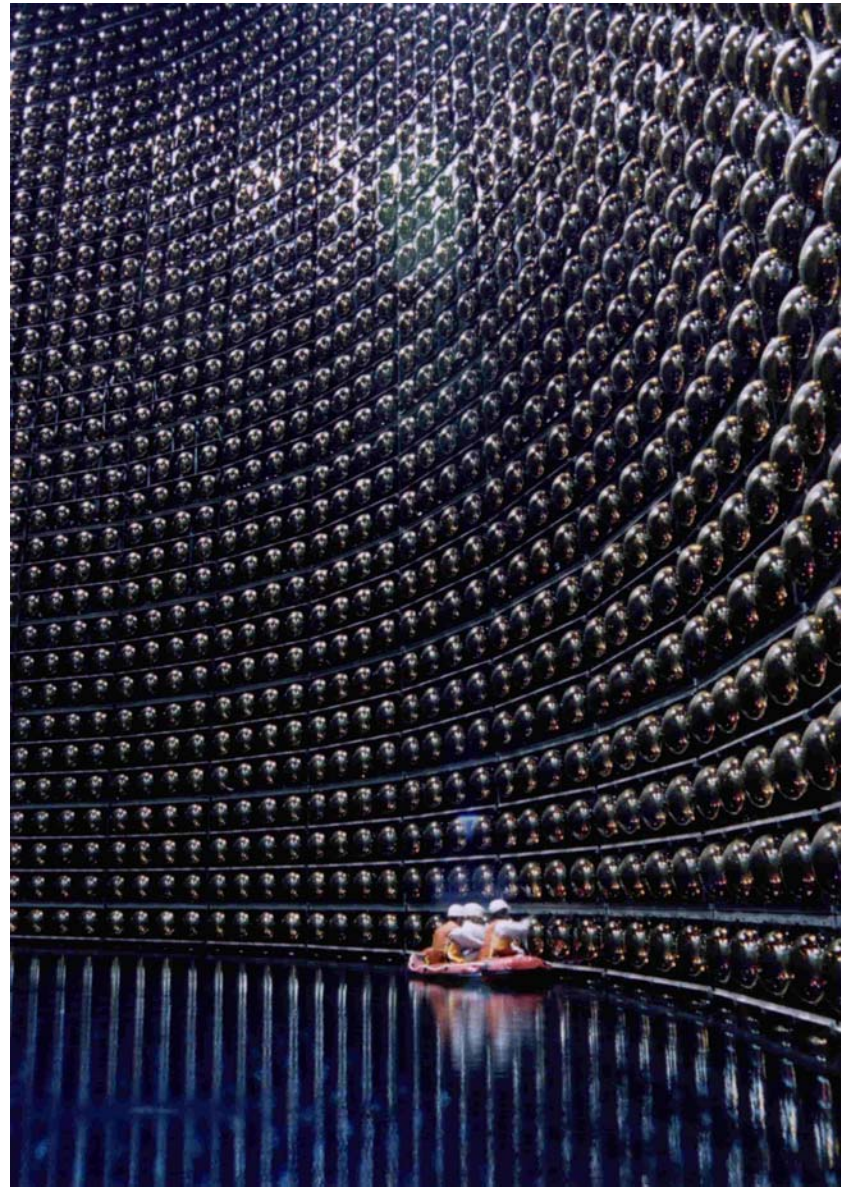
- SuperK
  - 22.5 kton fiducial volume
  - 36 m high, 34 m diam.
  - 11,146 phototubes (50 cm)
  - Energy threshold: 6.5 MeV
  - Linac (5 – 16 MeV) for in-situ calibration

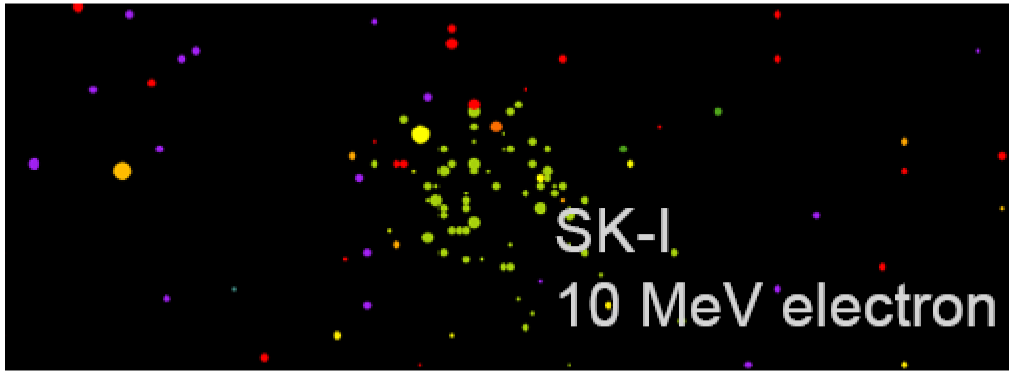
Both NC & CC scatters

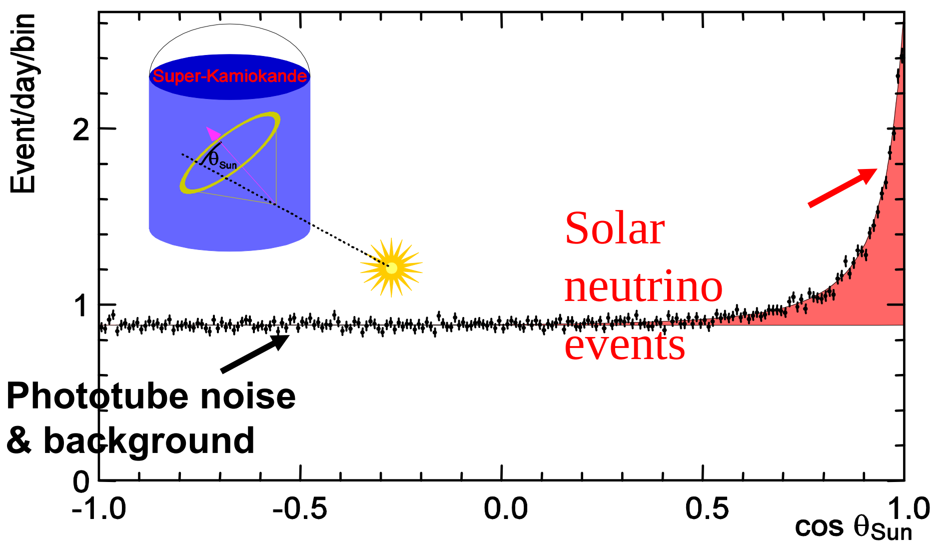
ν_e Rate $\times$5 Higher than ν_μ and ν_τ

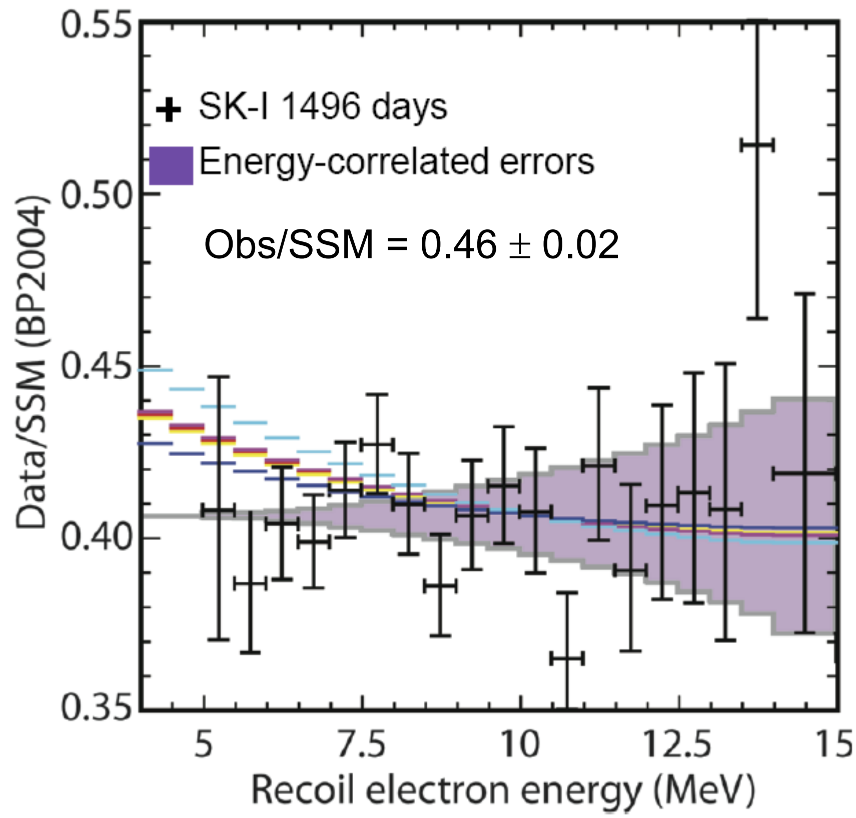






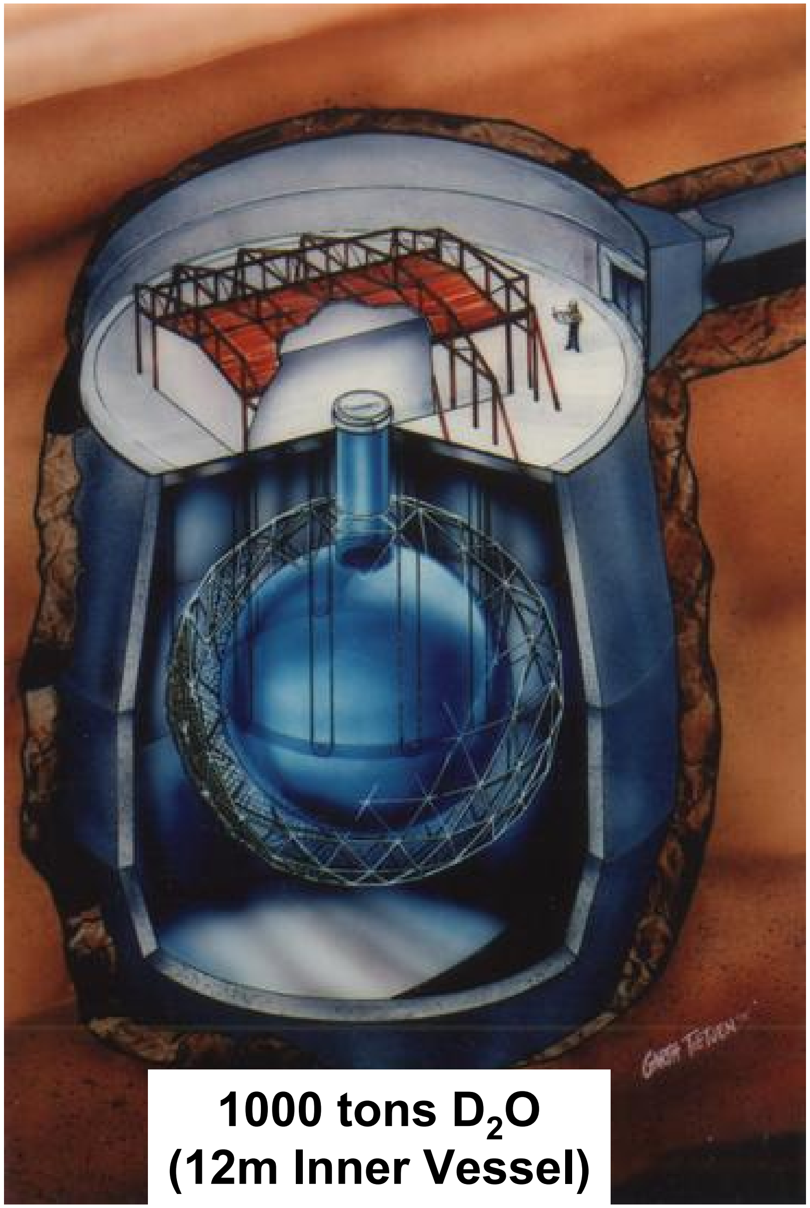


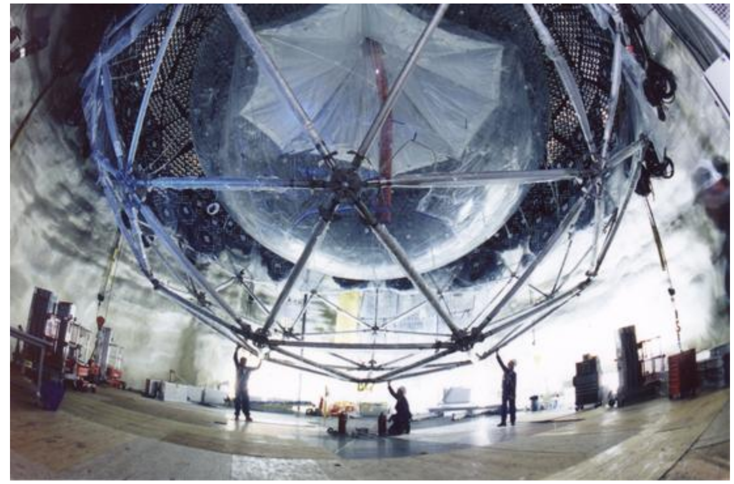




Main Backgrounds:
- Radon
- CR spallation

Sudbury Neutrino Observatory (SNO)





- Advantages of Heavy vs Light Water
  - $\nu_x + d \rightarrow \nu_x + n + p$ (D_2O)
  - $\nu_e + d \rightarrow p + p + e^-$ (D_2O)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (H_2O or D_2O)

  - Cross section $\propto (E_{cm})^2 = s$
    - $s = 2\, m_{target}\, E_\nu$
      $\Rightarrow s_N/s_{e-} = M_p/M_e \approx 2000$
  - But x5 more electrons in H_2O than n's

SNO (1kton) 8.1 CC events/day
SuperK (22ktons) 25 events/day

Neutrino Reactions in SNO

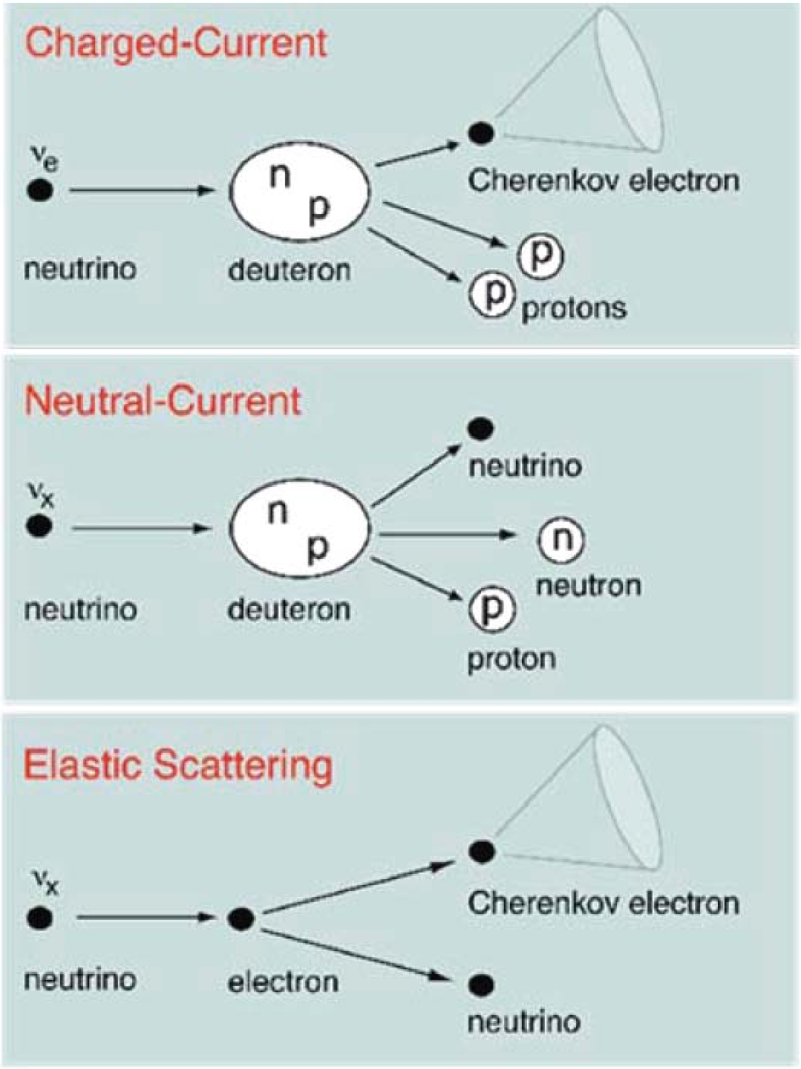
CC $\nu_e + d \rightarrow p + p + e^-$

- pure ν_e measurement

NC $\nu_x + d \rightarrow p + n + \nu_x$

- measures total ^8B ν flux from the Sun
- equal cross section for all active ν flavors

ES $\nu_x + e^- \rightarrow \nu_x + e^-$



Three Phases for neutron capture:

1) On Deuterium
2) On Salt
3) Using ^{3}He Counters

SNO Physics

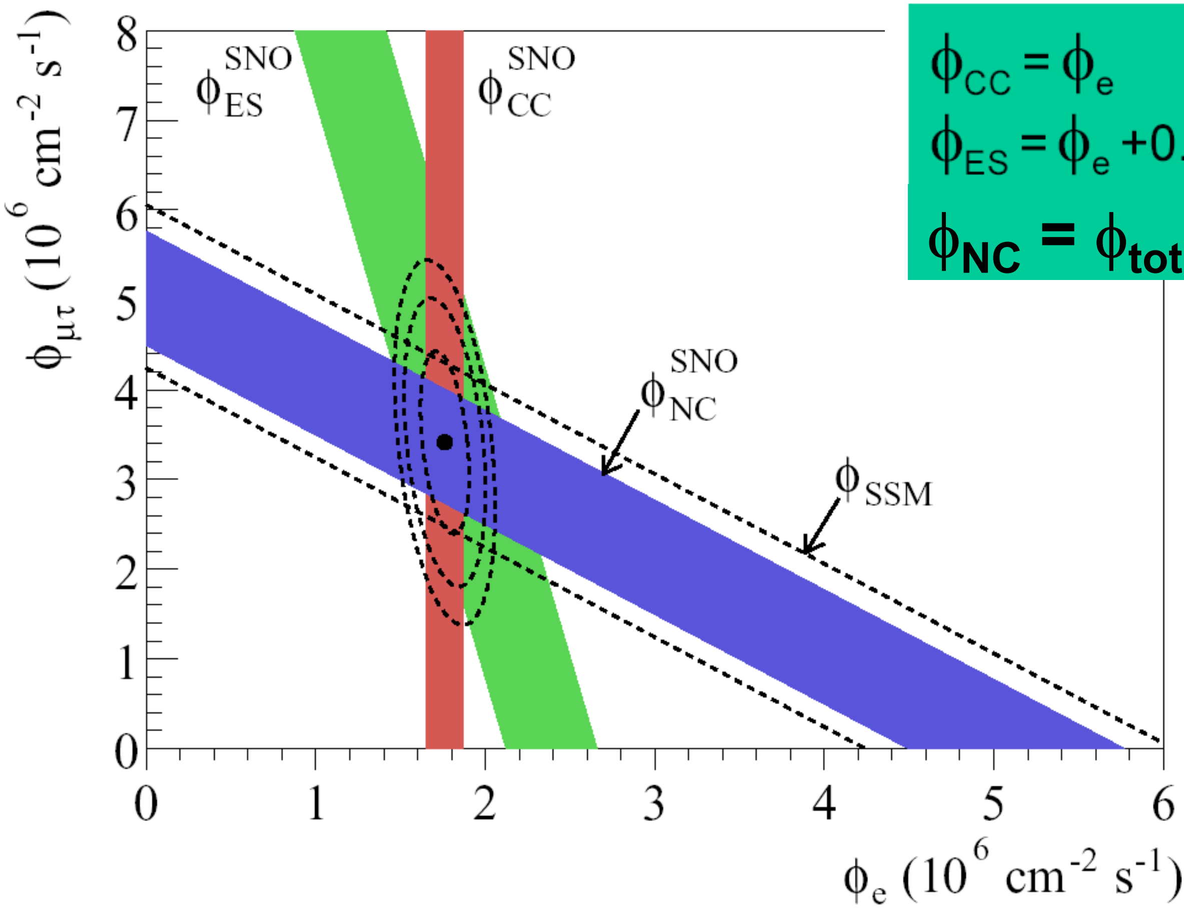
- First measurement of the total flux of ^{8}Be neutrinos:

$\phi_{total}(^{8}Be) = 5.21 \pm 0.47 \times 10^{6}\ cm^{-2}s^{-1}$

- Agrees well with solar models:

$\phi_{total}(^{8}Be) = 5.05 \pm 1.00 \times 10^{6}\ cm^{-2}s^{-1}$

$\Rightarrow$ Solar Oscillations not totally to sterile neutrinos



$\phi_{CC} = \phi_{e}$

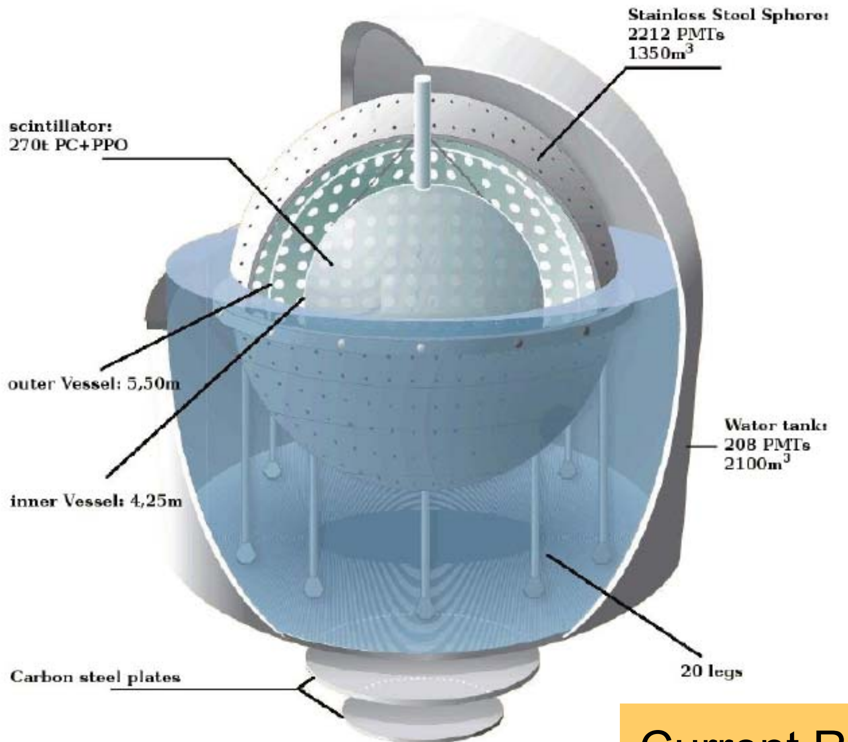
$\phi_{ES} = \phi_{e} + 0.154\ \phi_{\mu,\tau}$

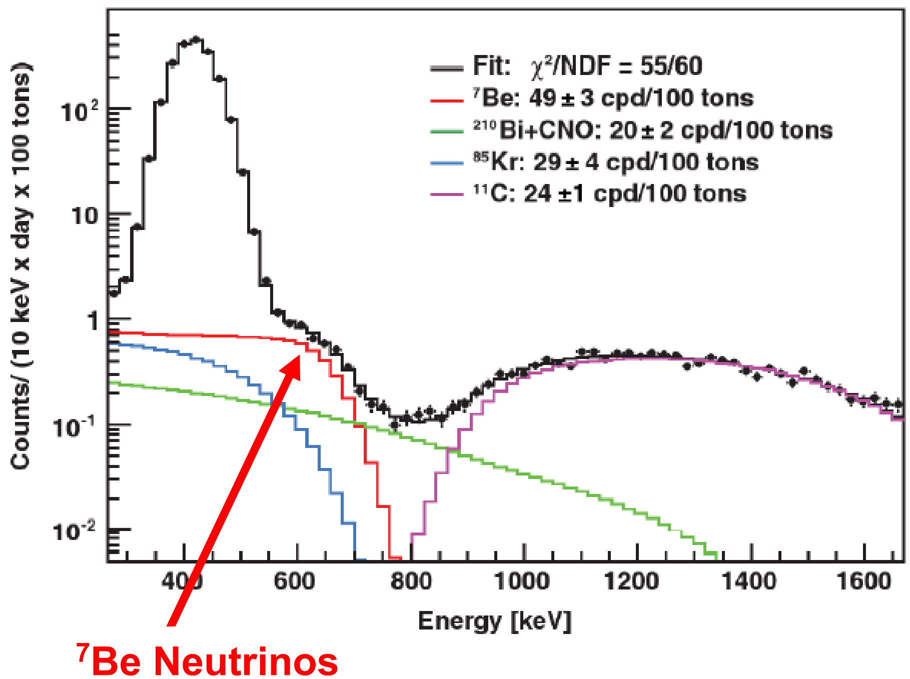
$\boldsymbol{\phi_{NC} = \phi_{total} = \phi_{e} + \phi_{\mu,\tau}}$

Borexino

- Neutrino-Electron scattering at Low energy ⇒ ^{7}Be neutrinos
- Liquid scintillator neutrino target (~100t fiducial mass)
- Main issue is radioactive contamination
  - Need to use very "clean" material
  - Reduce cosmic muons

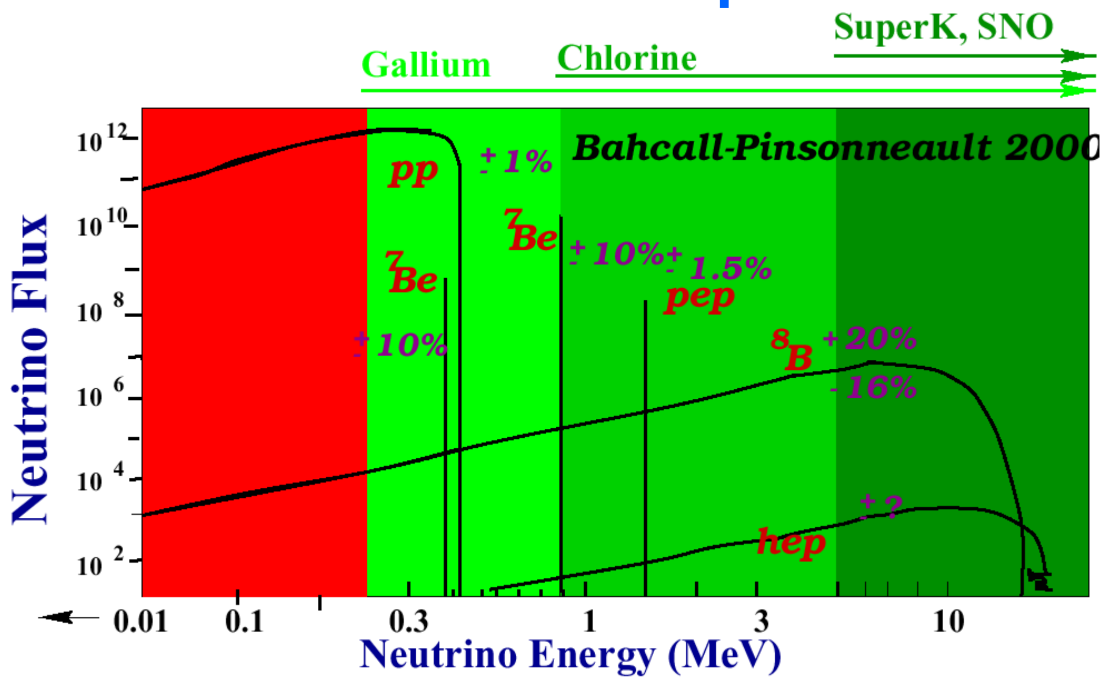
$$\nu_{x,e} + e^- \rightarrow \nu_{x,e} + e^-$$





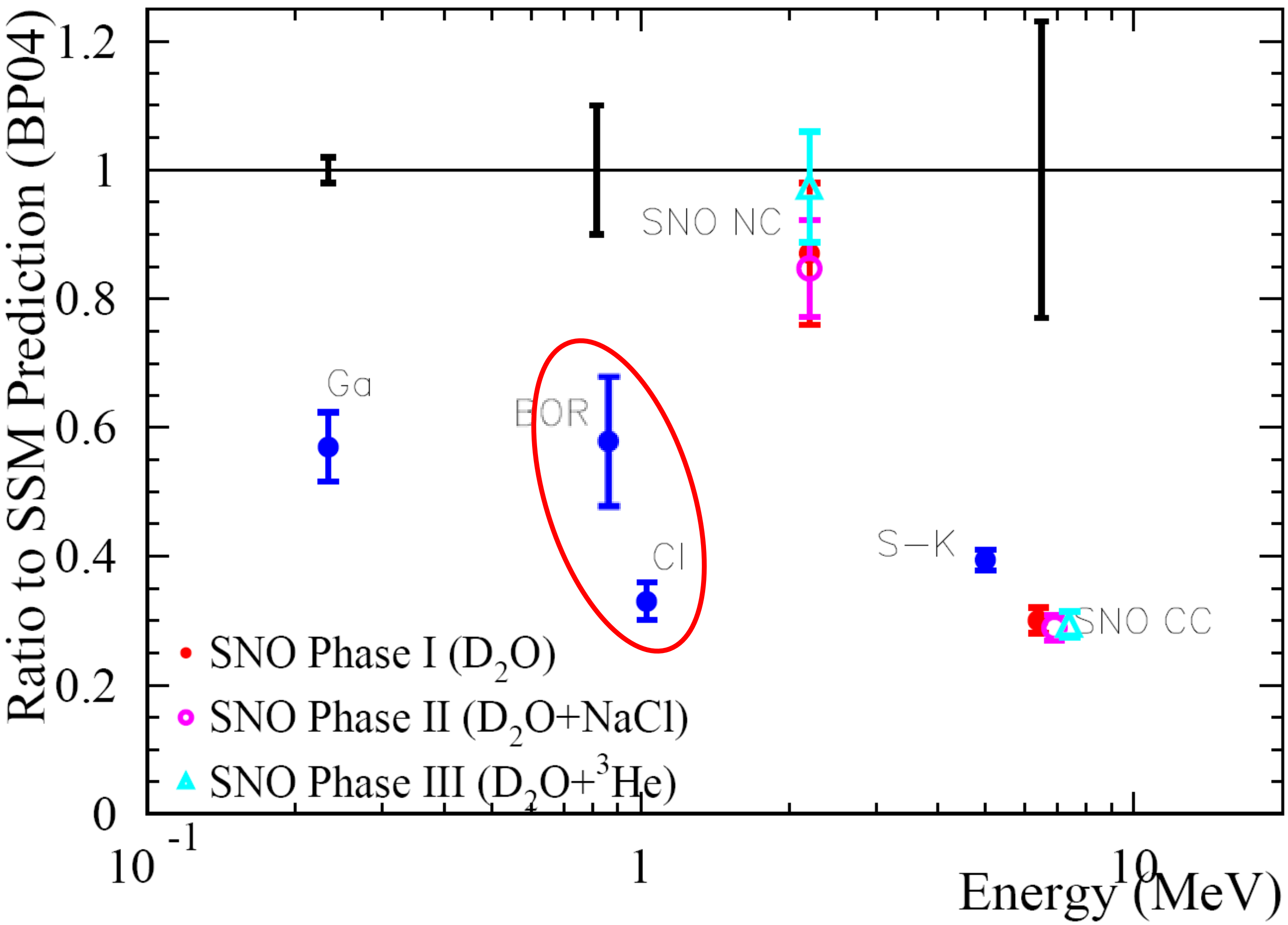
Current Result: 49 ± 3$_{stat}$ ± 4$_{syst}$ Counts/day/100 tons
Obs/SSM = 0.56 ± 0.08

Solar Neutrino Experiments

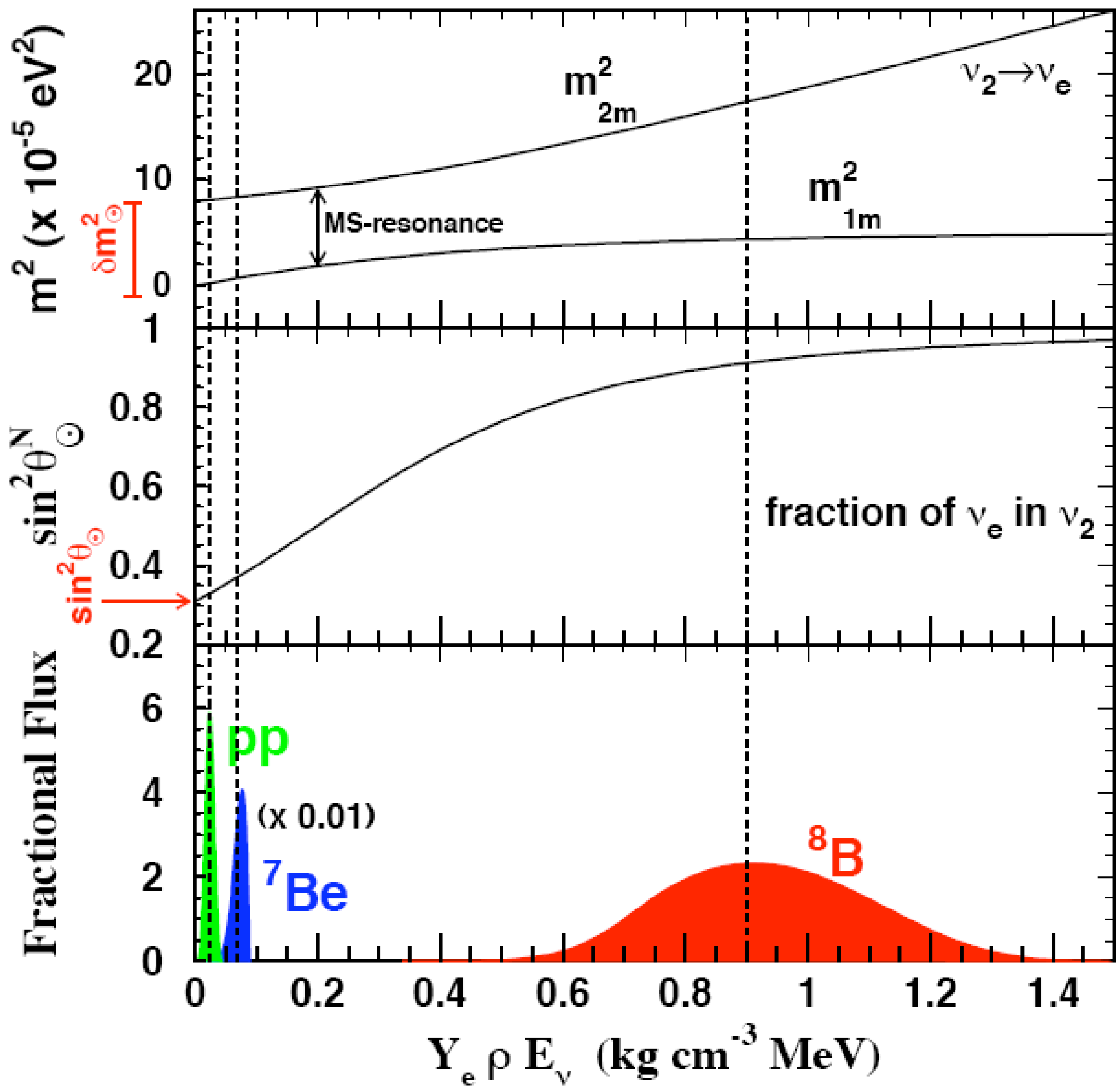


Rate measurement	Reaction	Obs / Theory
• Homestake (US)	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.04
• SAGE (Russia)	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.59 ± 0.06
• Gallex+GNO (Italy)	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.58 ± 0.05
• Super-K (Japan) H_2O	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
• SNO (Canada) D_2O	$\nu_e + d \rightarrow p + p + e^-$	0.35 ± 0.03
• BOREXINO	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.56 ± 0.08

Solar Measurements



Matter Effects in the Sun



hep-ph/0601198

In Vacuum

$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5}\ eV^2$$

$$\sin^2\theta_\odot = 0.31 \pm 0.03$$

Whereas for ^{8}B
at center of Sun

$$\delta m^2_N = 14 \times 10^{-5}\ eV^2$$

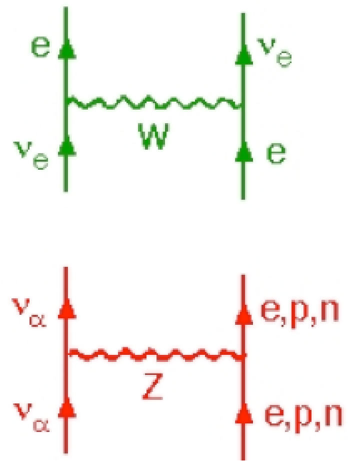
$$\sin^2\theta^N_\odot = 0.91$$

From Stephen Parke
(See PRD 74 (2006) 13006)

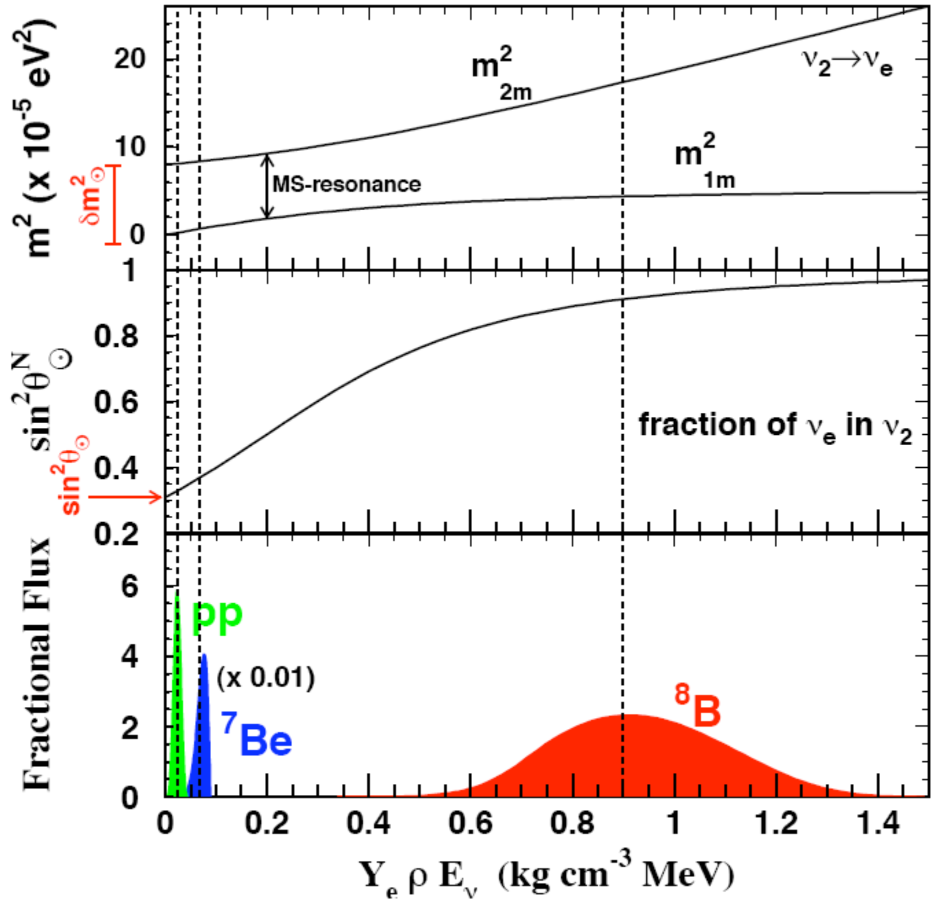
Comes about because there are many free electrons in the sun

⇒ Which makes ν_e interaction rate different from $\nu_{\mu/\tau}$ interactions

Coherent Forward Scattering:

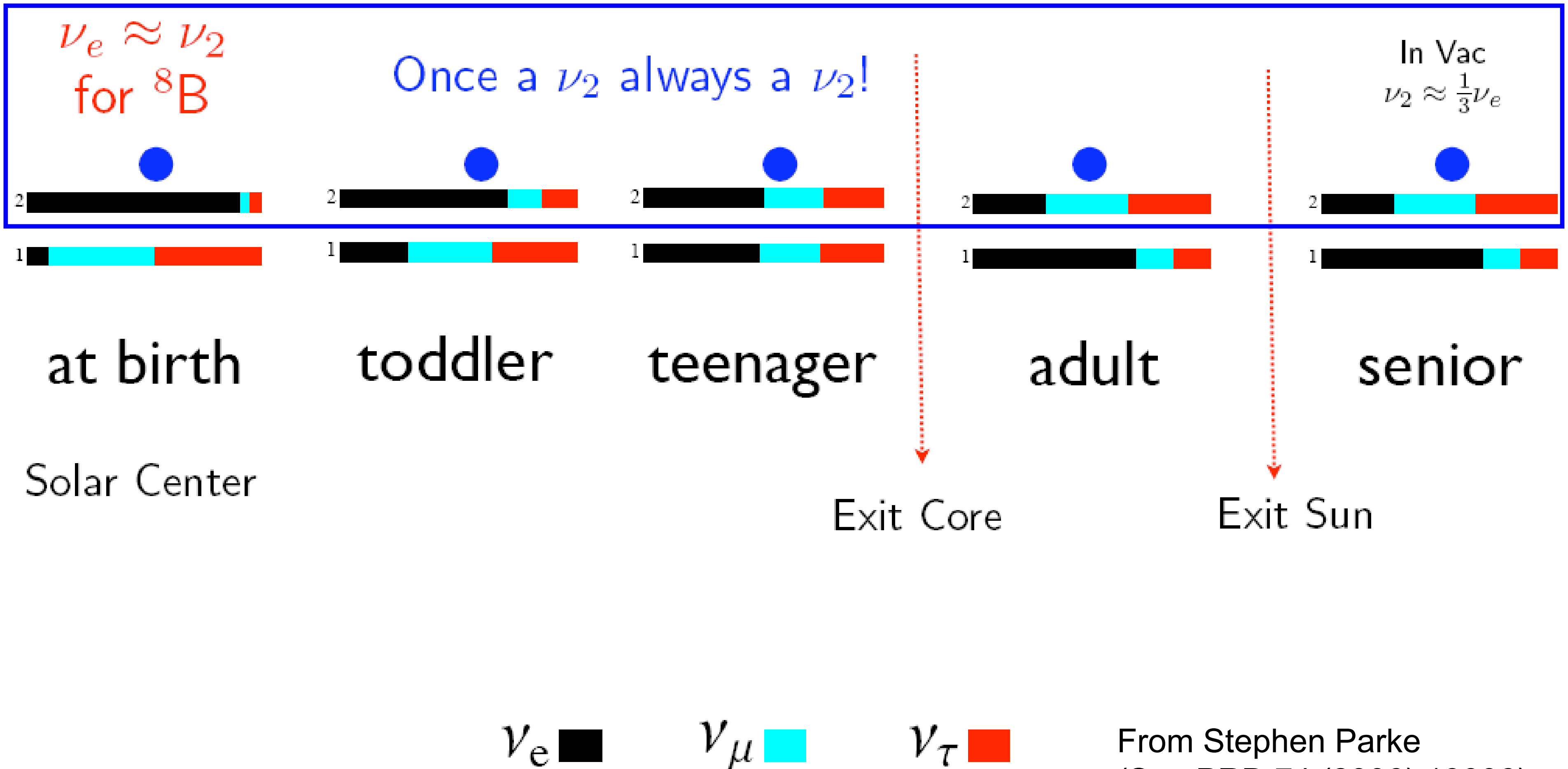


Wolfenstein '78



These matter effects change masses and mixings of the neutrino eigenstates

Life of a Boron-8 Solar Neutrino:



From Stephen Parke
(See PRD 74 (2006) 13006)

Solar Oscillation Summary

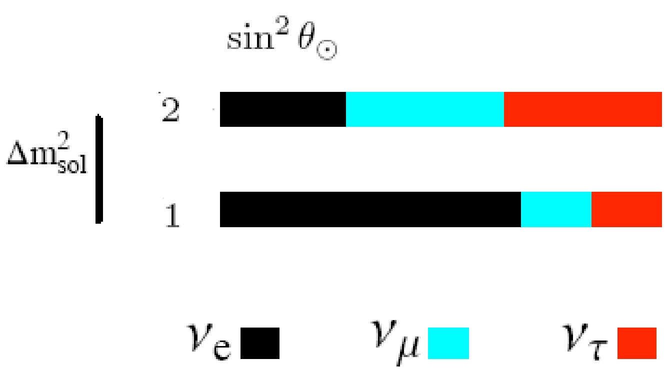
$f_1 = \cos^2 \theta_\odot^N$ and $f_2 = \sin^2 \theta_\odot^N$ $\quad\quad \langle P_{ee} \rangle = f_1 \cos^2 \theta_\odot + f_2 \sin^2 \theta_\odot$

The low energy pp and ^{7}Be Solar Neutrinos exit the sun as two thirds ν_1 and one third ν_2 due to (quasi-) vacuum oscillations.

$f_1 = 65 \pm 2\%$, $f_2 = 35 \mp 2\%$ with $P_{ee} \approx 0.56$

The high energy ^{8}B Solar Neutrinos exit the sun as "PURE" ν_2 mass eigenstates due to matter effects.

$f_2 = 91 \pm 2\%$ and $f_1 = 9 \mp 2\%$ with $P_{ee} \approx 0.35$.



$$\delta m^2_\odot = 8.0 \pm 0.4 \times 10^{-5} eV^2$$

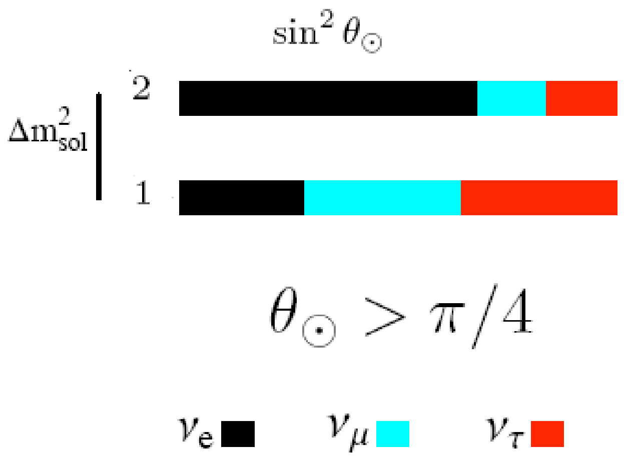
$$\sin^2 \theta_\odot = 0.310 \pm 0.026$$

at 68% CL

SNO, KamLAND, SK/K, GNO/Gallex, SAGE, Cl

Solar Mass Hierarchy Is Determined From Matter Effects

If we chose the wrong mass hierarchy for the ν_1 and ν_2 , then:



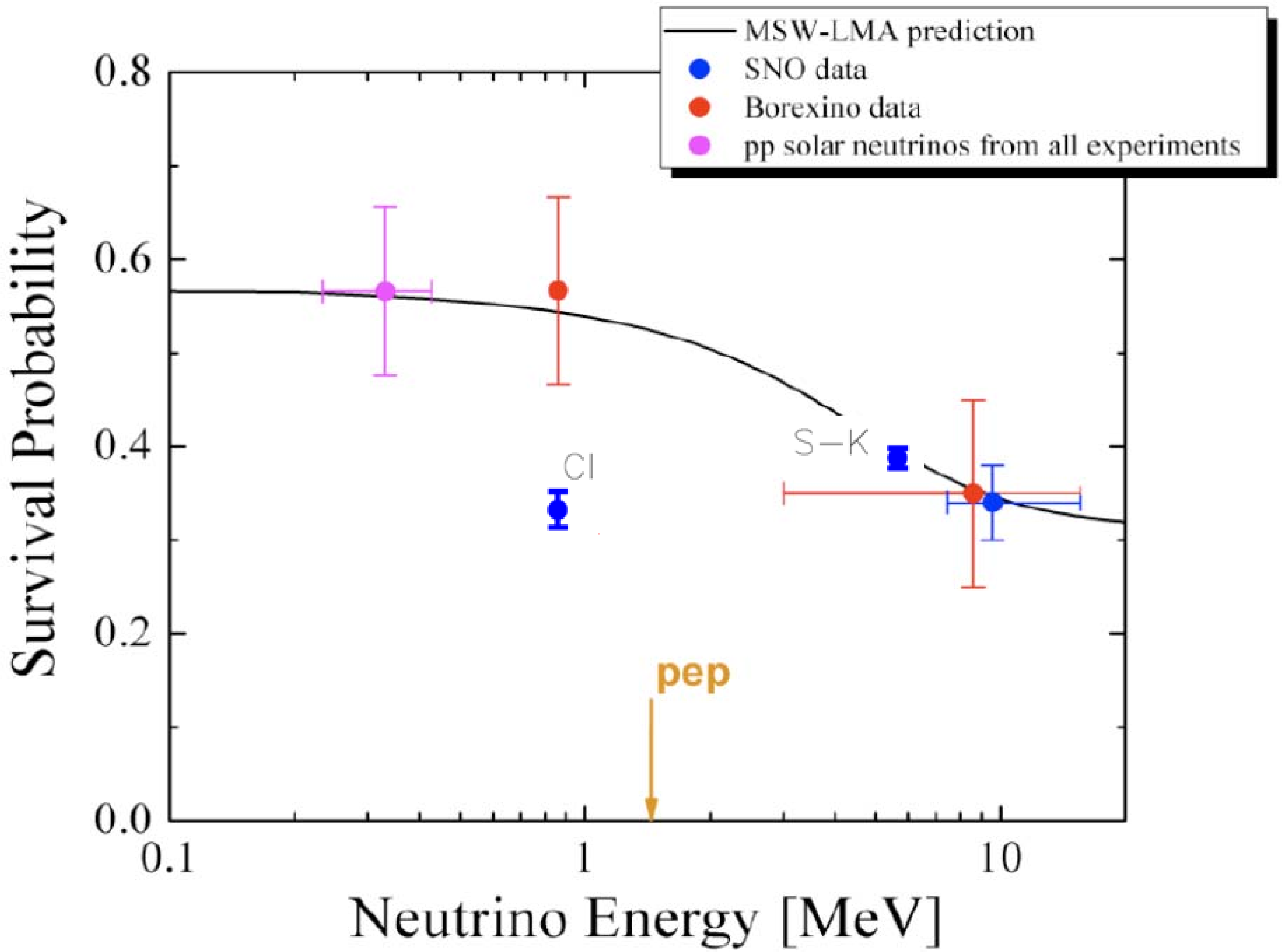
Solar matter effects put more of the neutrino into ν_2. This raises the survival probability above vacuum value since ν_2 has more ν_e. But the minimum of P_{ee} in vacuum is $1/2$.

For this hierarchy $P_{ee}^{matter} \geq P_{ee}^{vac} \geq 1/2$

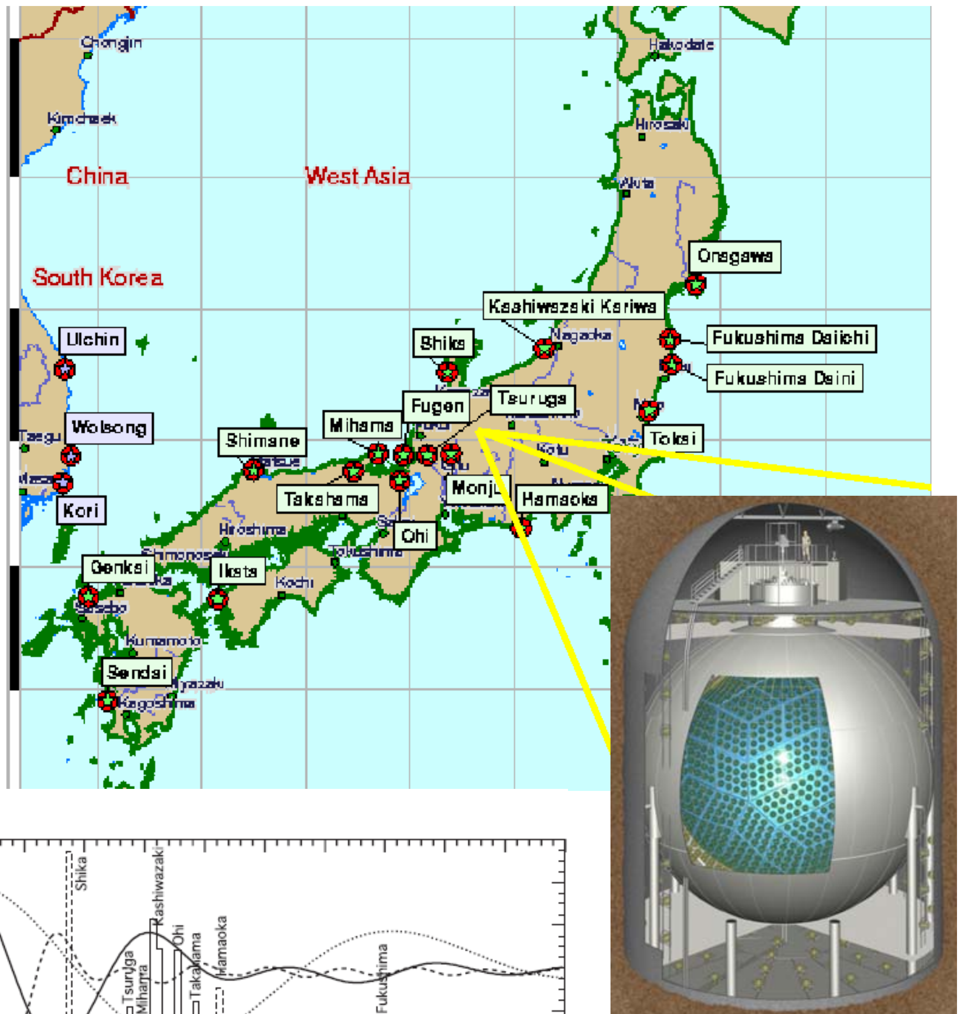
But $P_{ee}^{SNO} = 0.347 \pm 0.038 < 1/2$

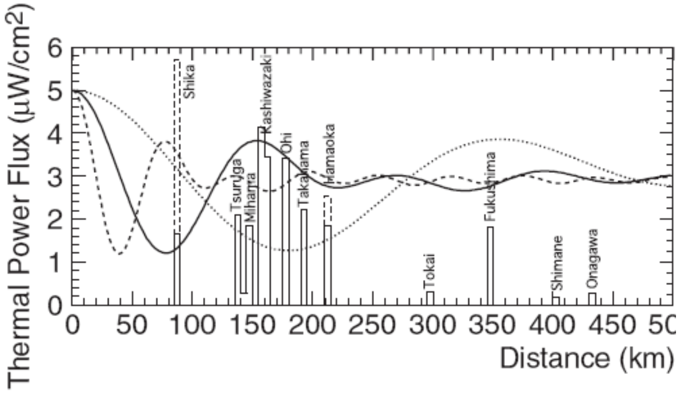
This solar hierarchy EXCLUDED !!!.

Transition from Vacuum to Matter Oscillations

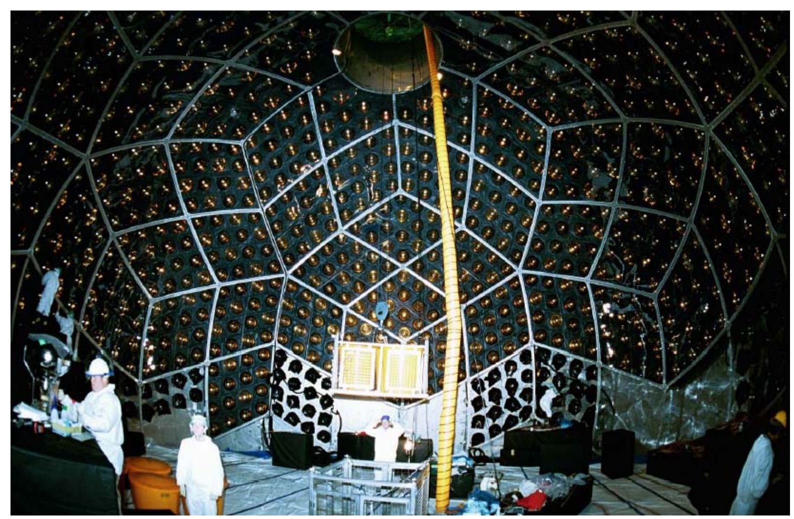


Kamland Reactor Exp.
(Probes for $\bar{\nu}_e$ Osc. In the Solar Region)

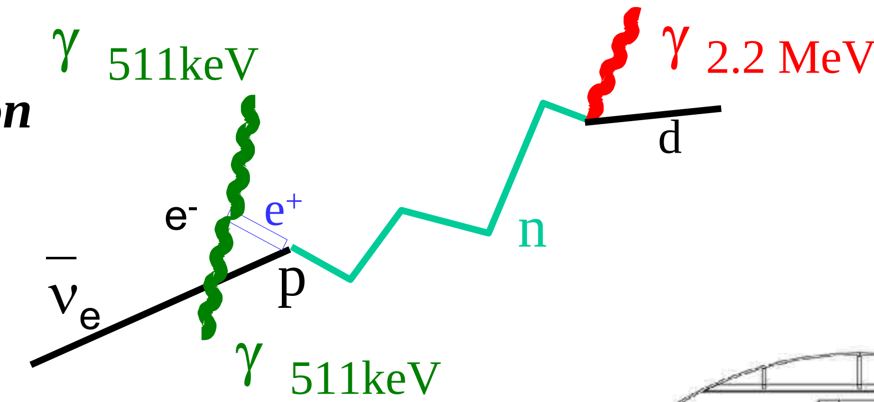




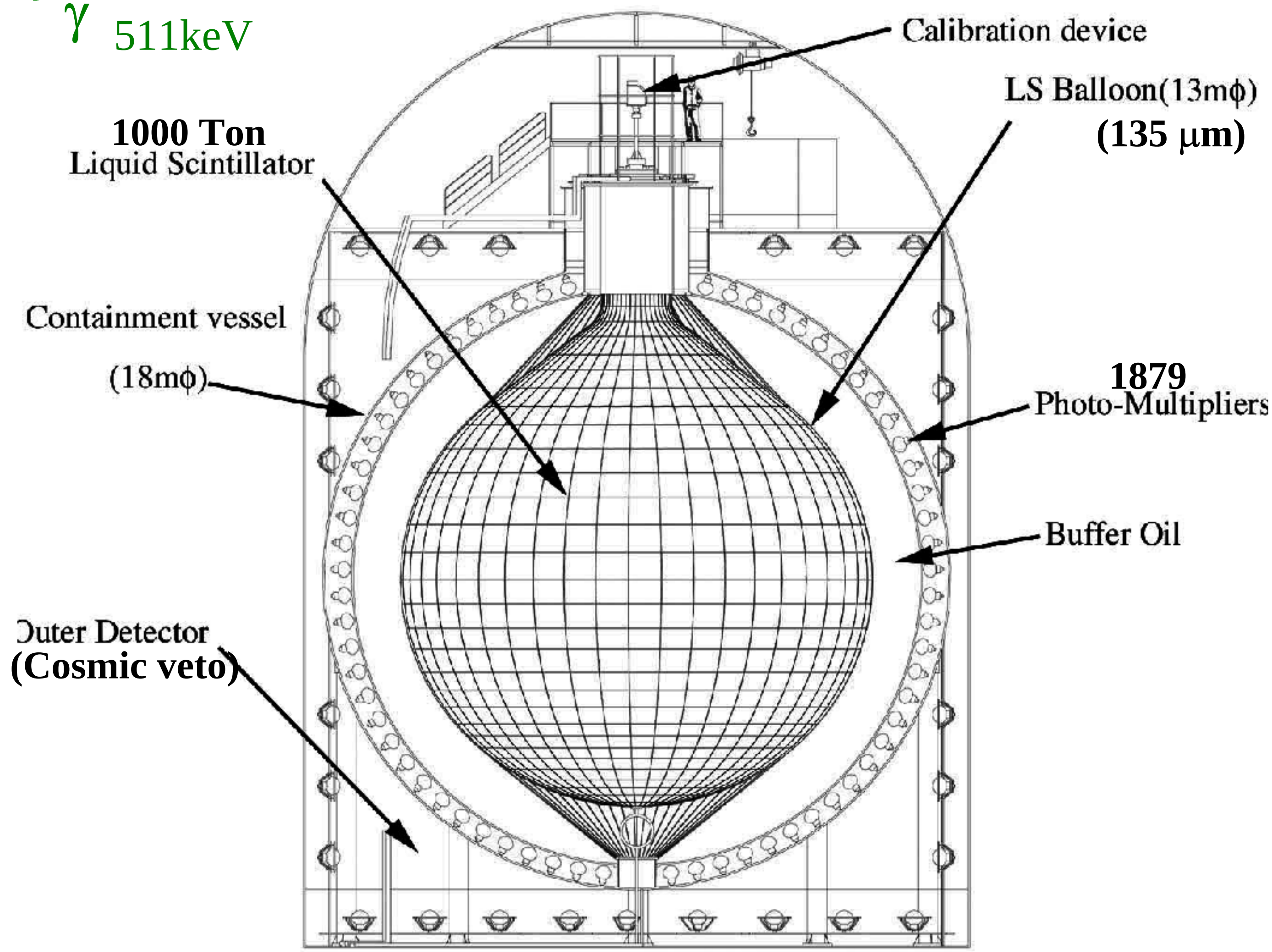
- Uses $\bar{\nu}_e$ from all the reactors in Japan
- 85% of signal events from:
  - Closest 60 GW of power
  - Distance range 140km-344 km with mean 180km
- KamLAND is a 1 kton liquid scintillator detector
  - 2000 photomultiplier tubes
  - 1 km underground
- Began data taking in Sept., 2001.

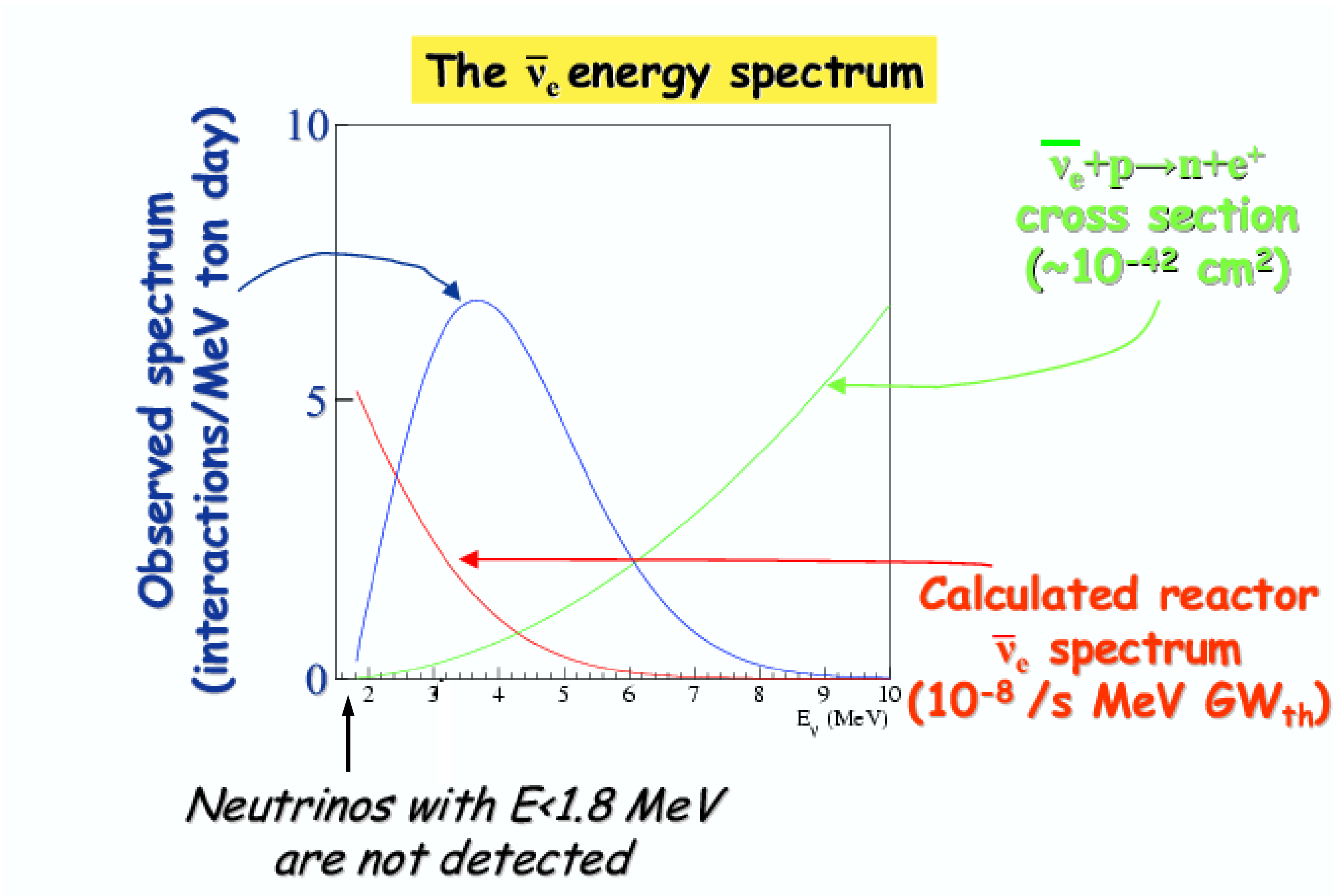


e⁺ plus neutron delayed coincidence



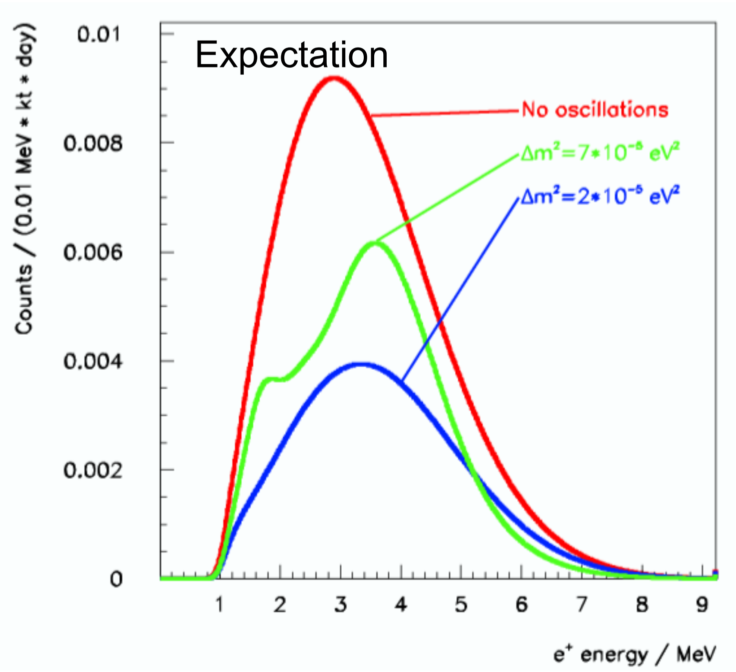
KamLAND Detector

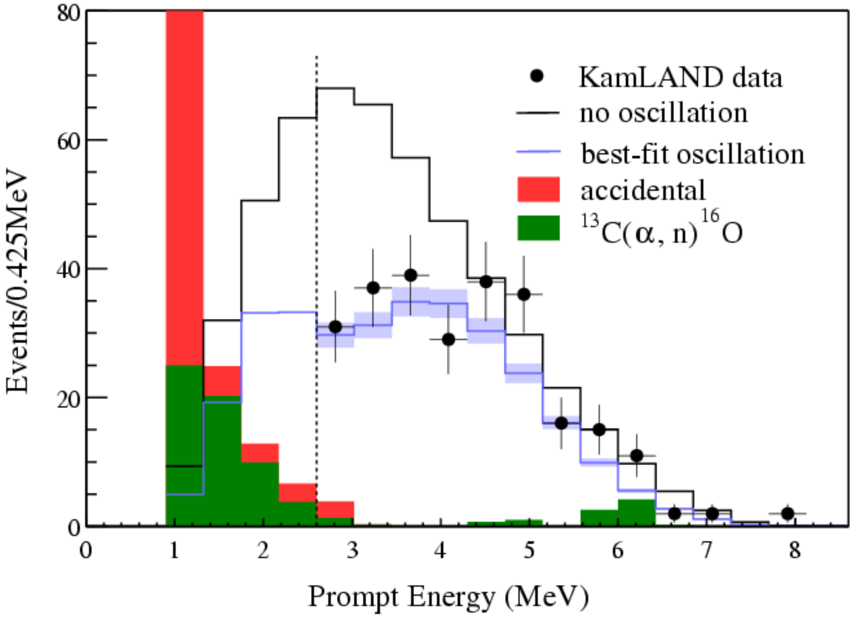




The $\bar{\nu}_e$ energy spectrum
Observed spectrum (interactions/MeV ton day)
10
5
0
2
3
4
5
6
7
8
9
10
E_ν (MeV)
$\bar{\nu}_e + p \rightarrow n + e^+$ cross section ($\sim 10^{-42}$ cm^2)
Calculated reactor $\bar{\nu}_e$ spectrum (10^{-8} /s MeV GW_{th})
Neutrinos with E<1.8 MeV are not detected

KamLAND Results





Observed: 258 events
No-oscillation: 365.2 ± 23.7 events
Background: 17.6 ± 7.2 events

$(N_{obs} - N_{bkgnd})/N_{no\text{-}osc}$ =
0.658 ± 0.044 (stat) ± 0.047 (syst)
(99.998 % CL signal)

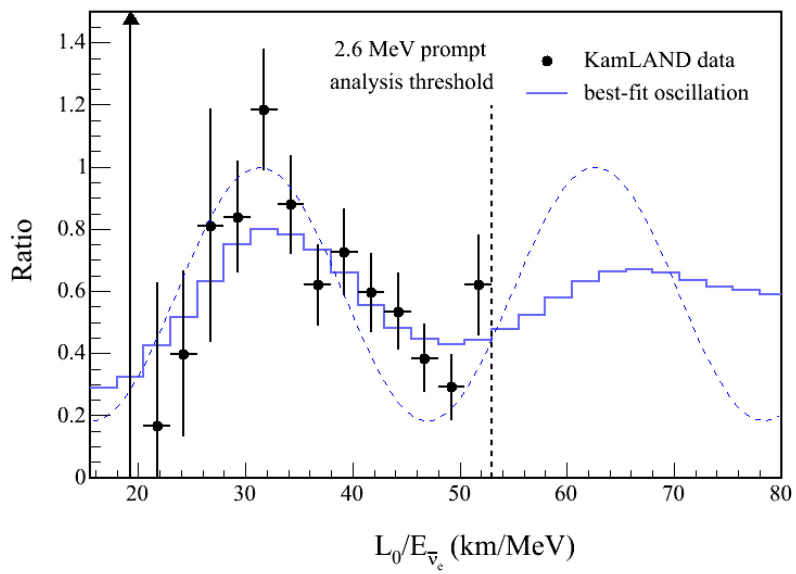
Neutrino Oscillation Interpretation

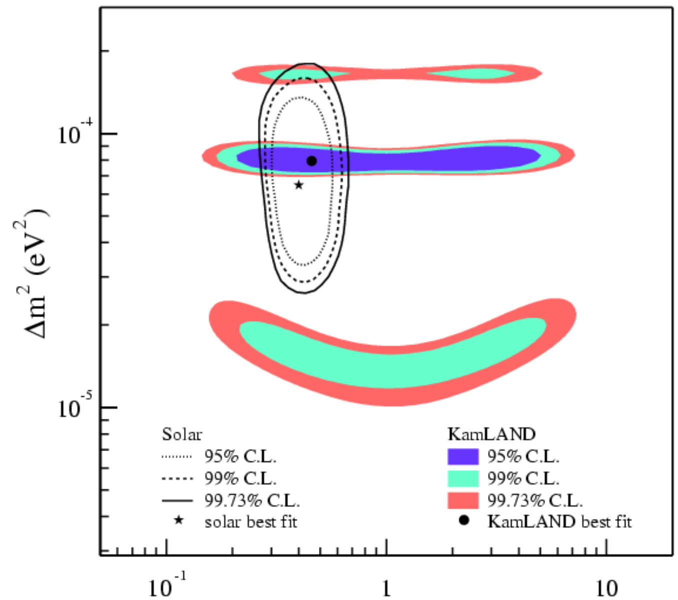
Distribution has L/E behavior expected for neutrino oscillations

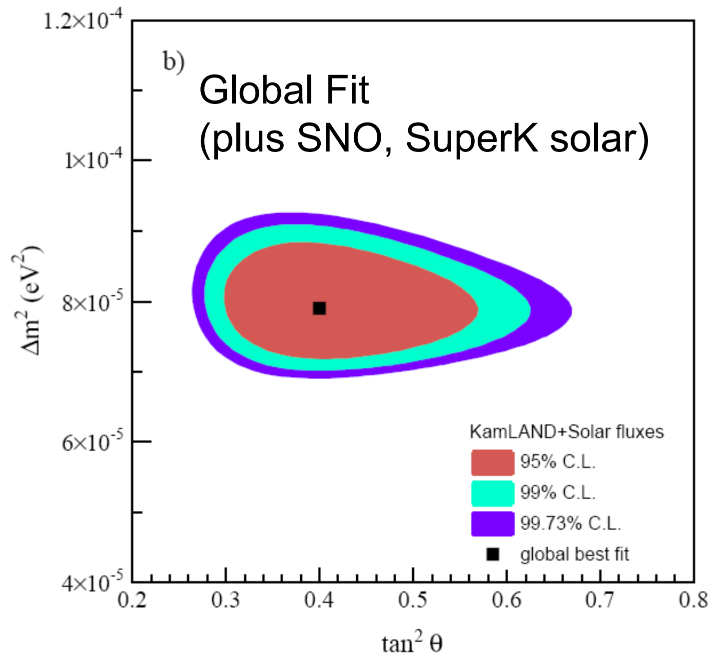
$\Rightarrow$ **KamLAND best fit :**

$\Delta m^2 = 7.9 \times 10^{-5}$ eV²

$\tan^2\theta = 0.45$







$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV²

$\tan^2\theta = 0.40^{+0.10}_{-0.07}$

($\sin^2 2\theta_{12} = 0.82^{+0.07}_{-0.07}$)

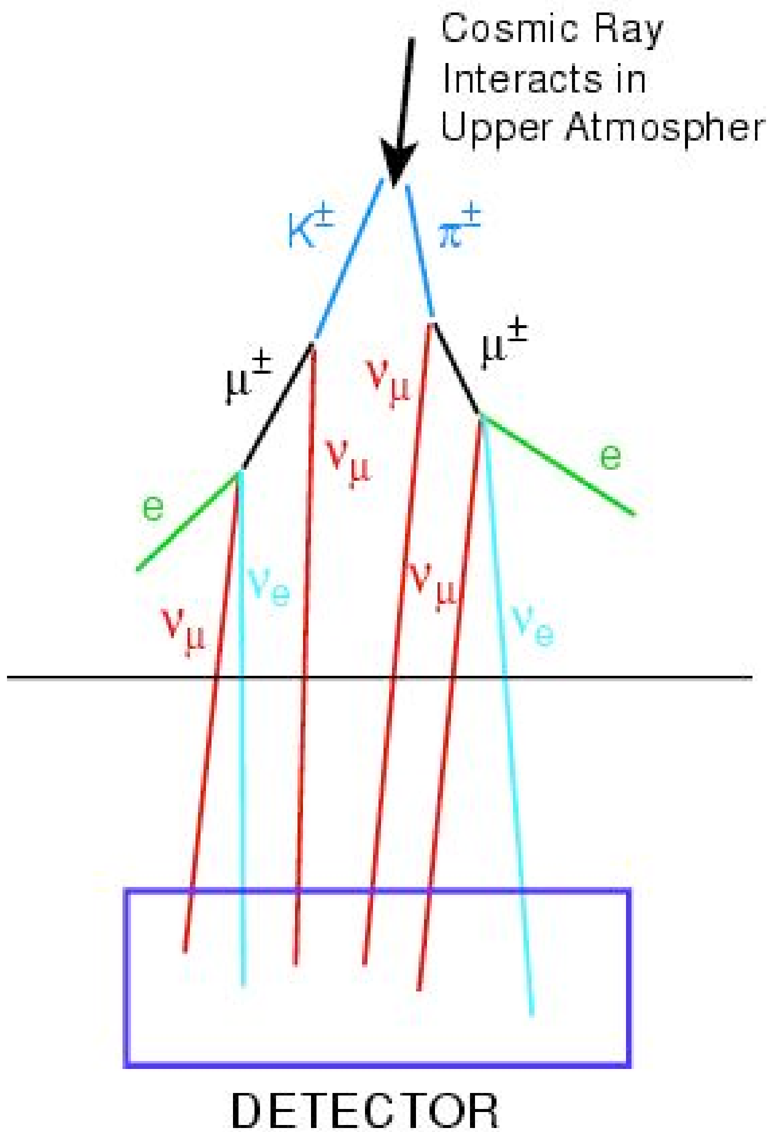
Summary Solar Data and Neutrino Oscillations

- Know that solar model is giving correct flux due to SNO neutral current measurement

- Solar disappearance probability depends on energy
  $\Rightarrow$ Need to include matter effects (electron density)

- Kamland reactor experiment agrees with solar oscillation parameters
  $\Rightarrow$ Constrains Δm^2

Atmospheric Neutrinos: ν_e and ν_μ

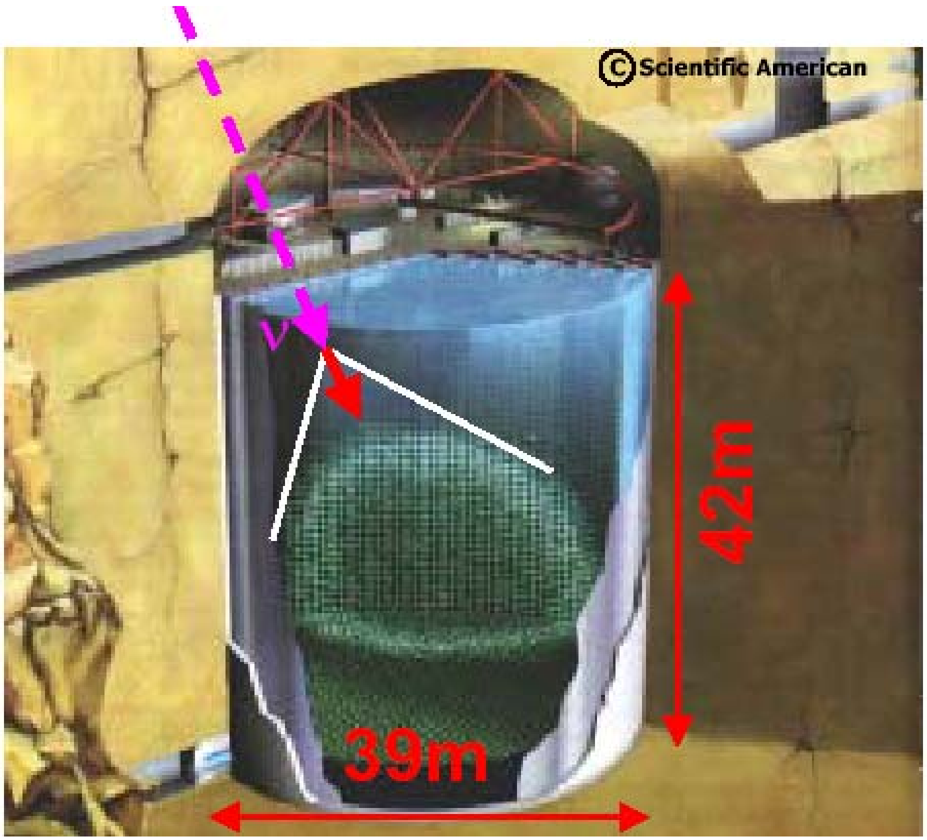


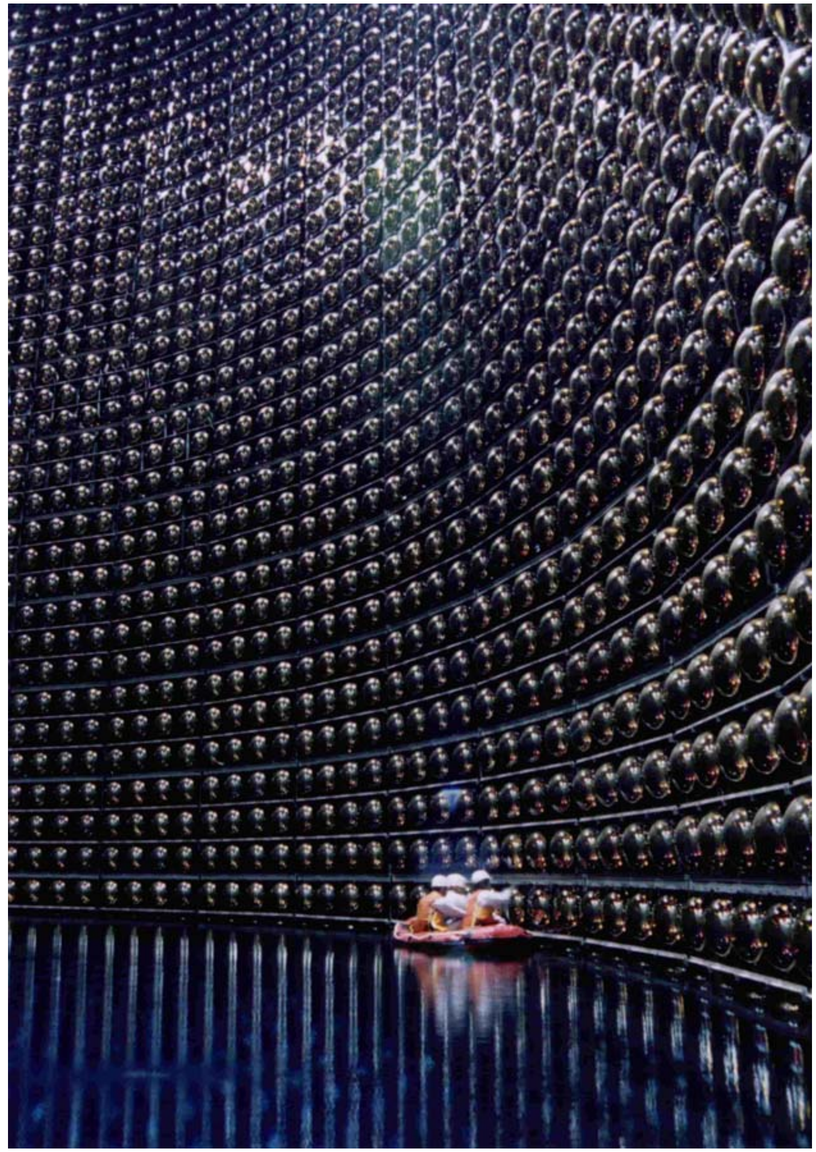
- π or K decay ---> $\mu + \nu_\mu$.
- Then the muon decays to e + ν_e + ν_μ

- $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ ratio should be **= 2.**
- Measured to be **1** by some experiments.
- Some others closer to 2.
- Inconclusive.
- Then SuperKamiokande was built.

Super-Kamiokande (Super-K) Detector

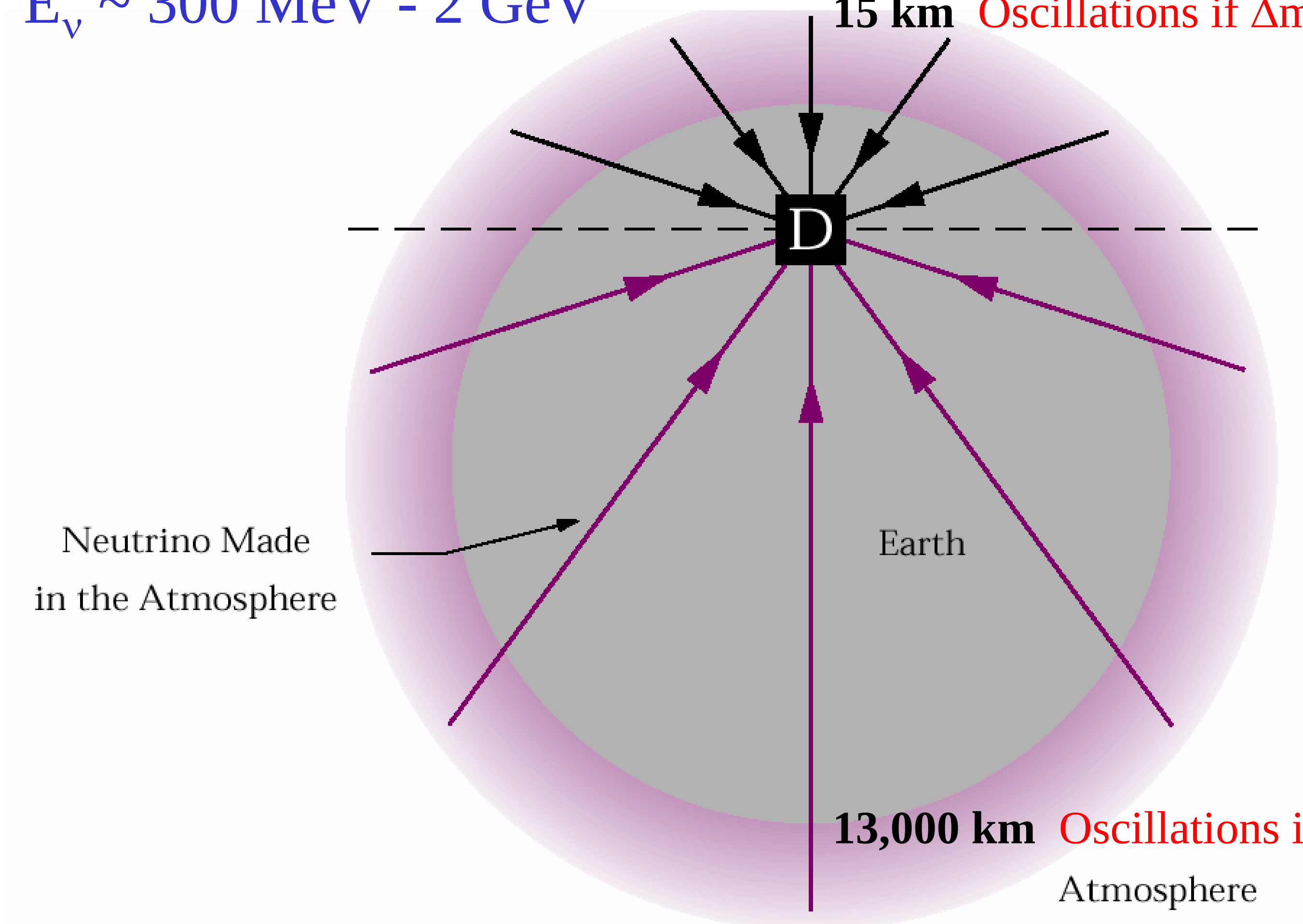
- 22.5 kton of ultra-pure water
- 11,150 20 inch phototubes
- Located in Kamioka mine at a depth of 1000m below the surface





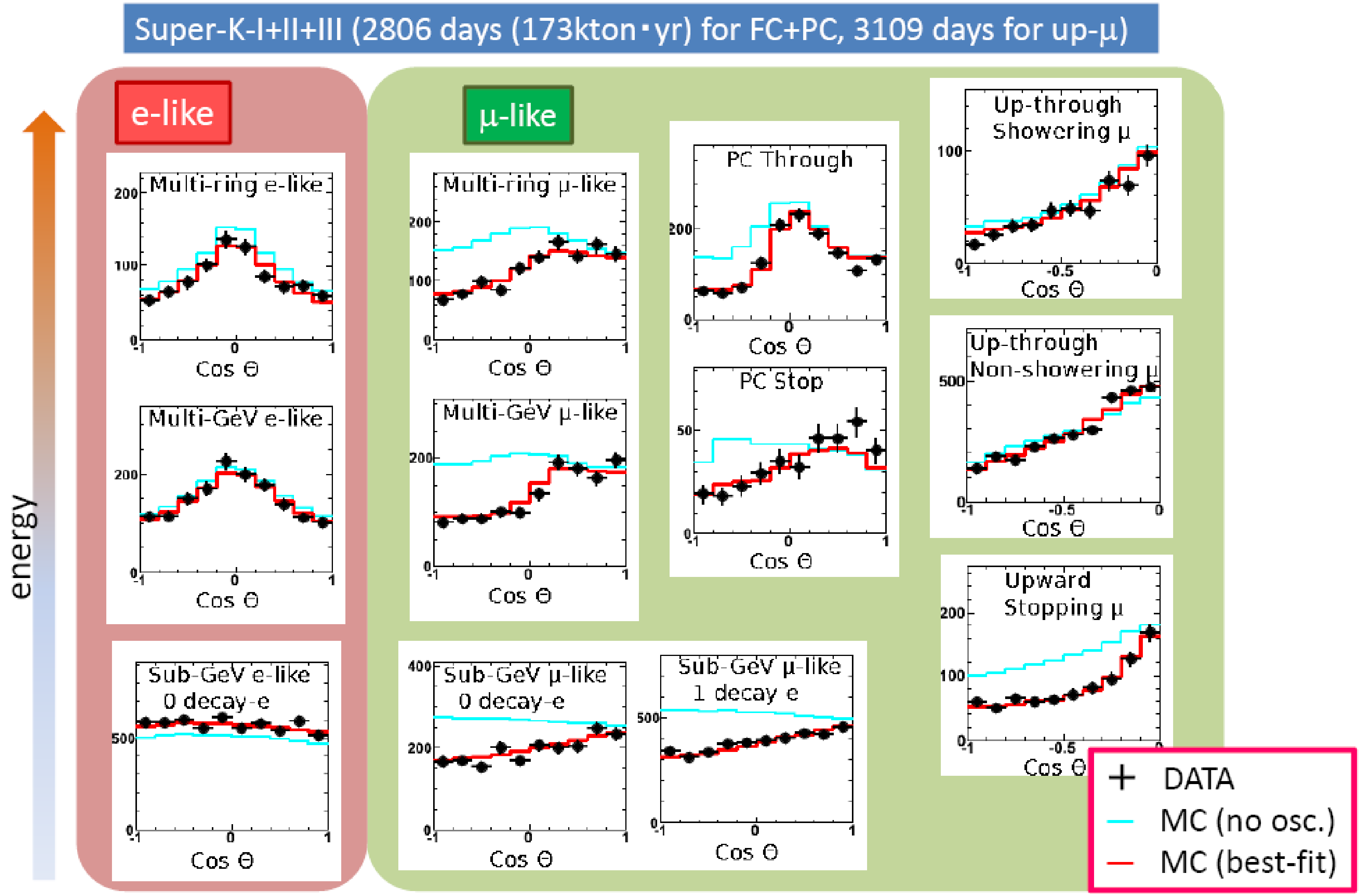
Atmospheric Neutrino Studies

$E_\nu \sim$ 300 MeV - 2 GeV



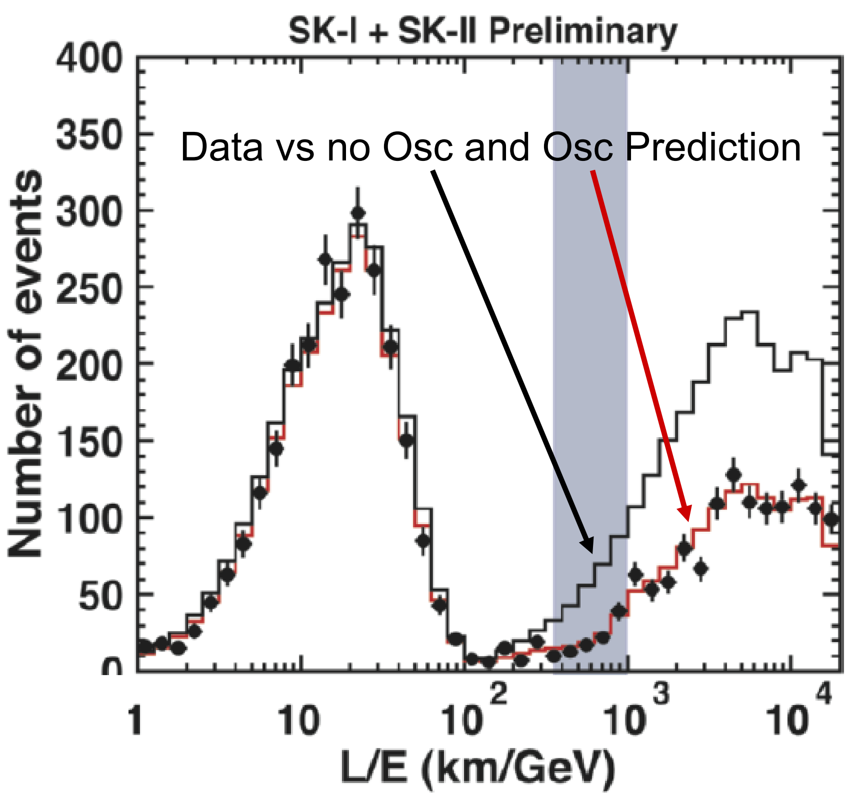
- **Flux dependence on azimuth is directly related to distance traveled**
  - **Perfect laboratory to search for oscillations**

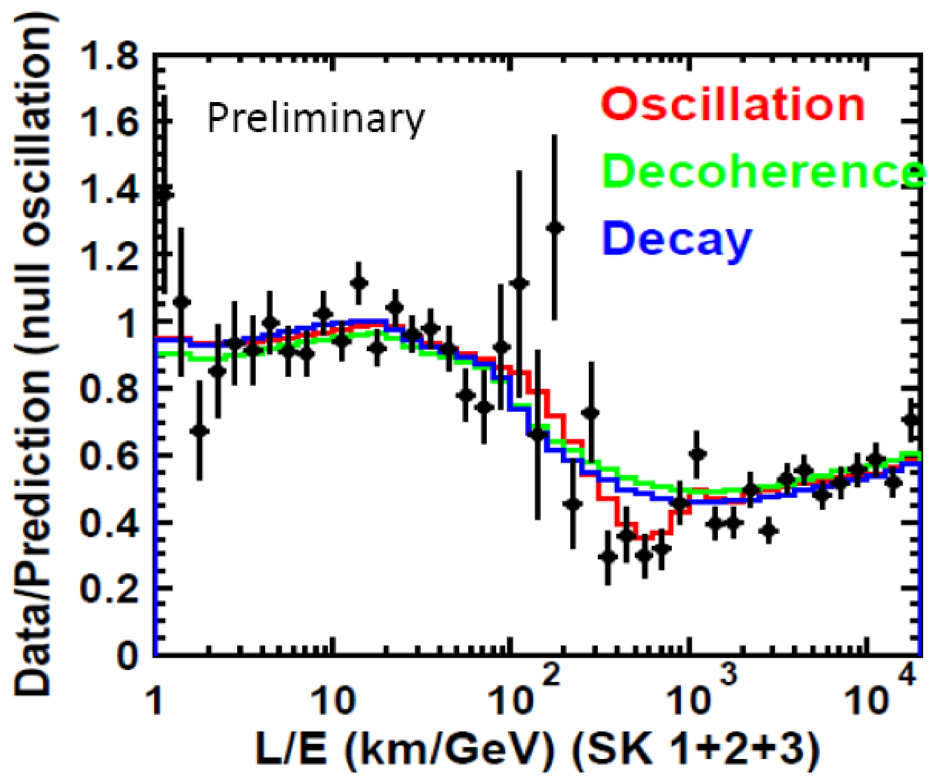
Atmospheric Neutrino Data from Super-K



Atmospheric Oscillation Results vs L/E Osc Behaviior

$$P_{osc} = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$



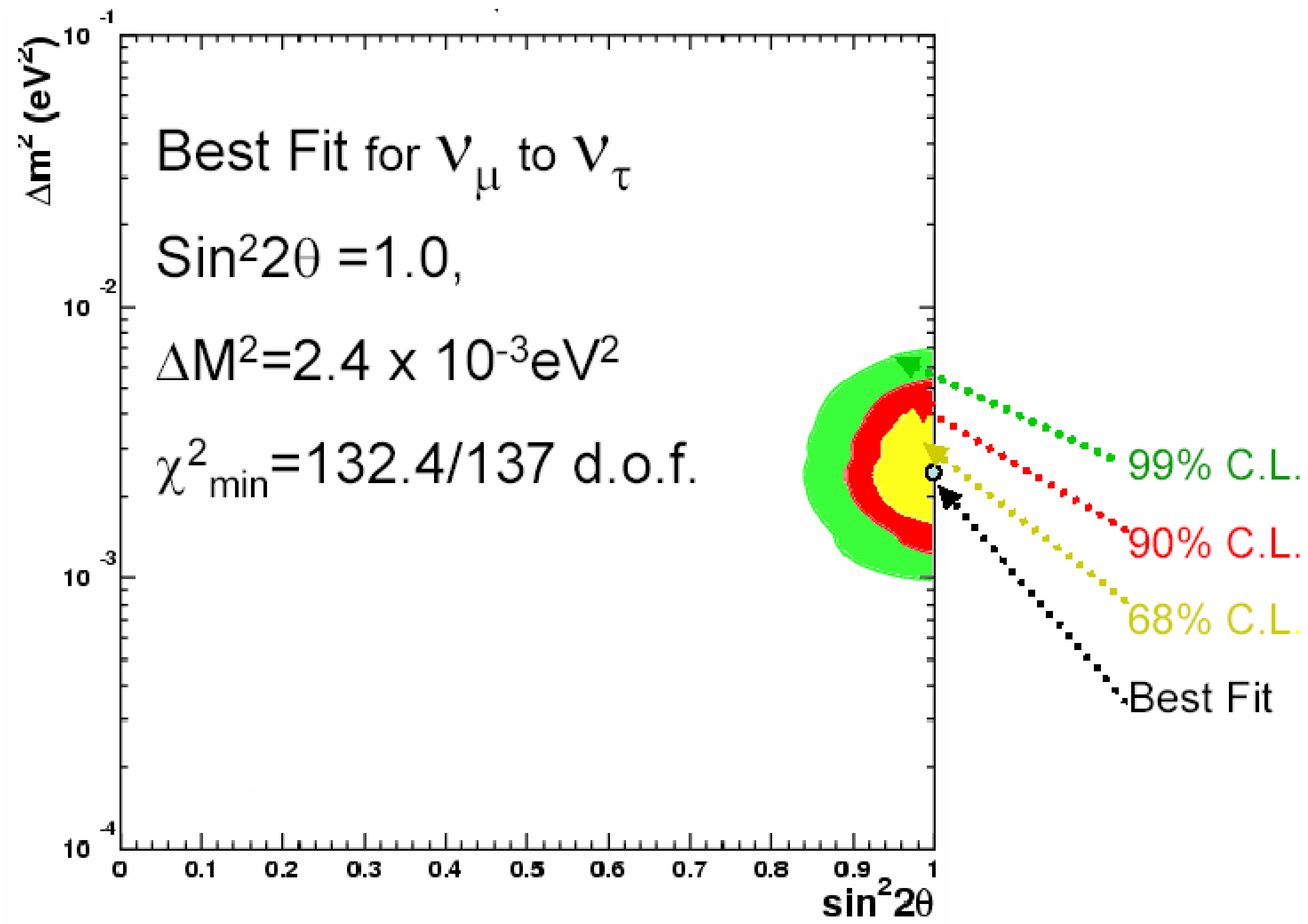


Inconsistent with:

Neutrino decay (4.4σ)

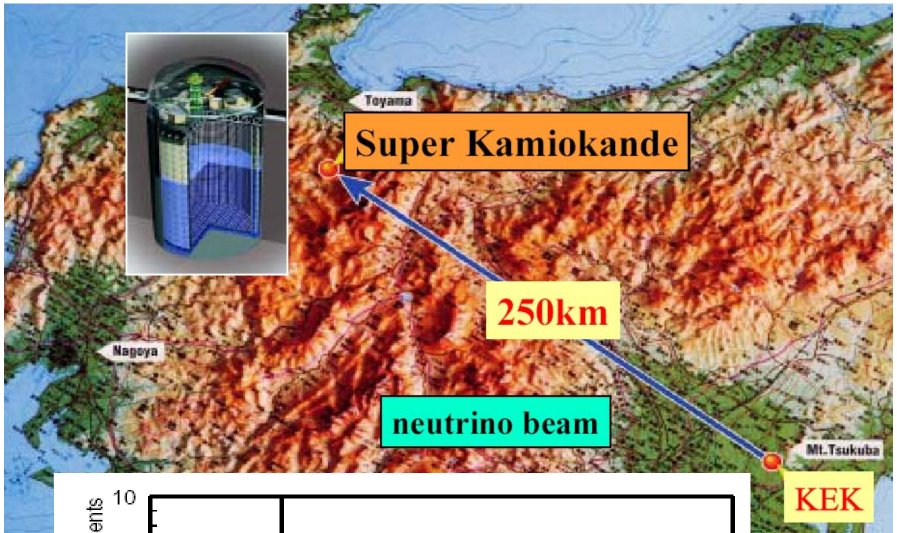
Neutrino decoherence (5.4σ)

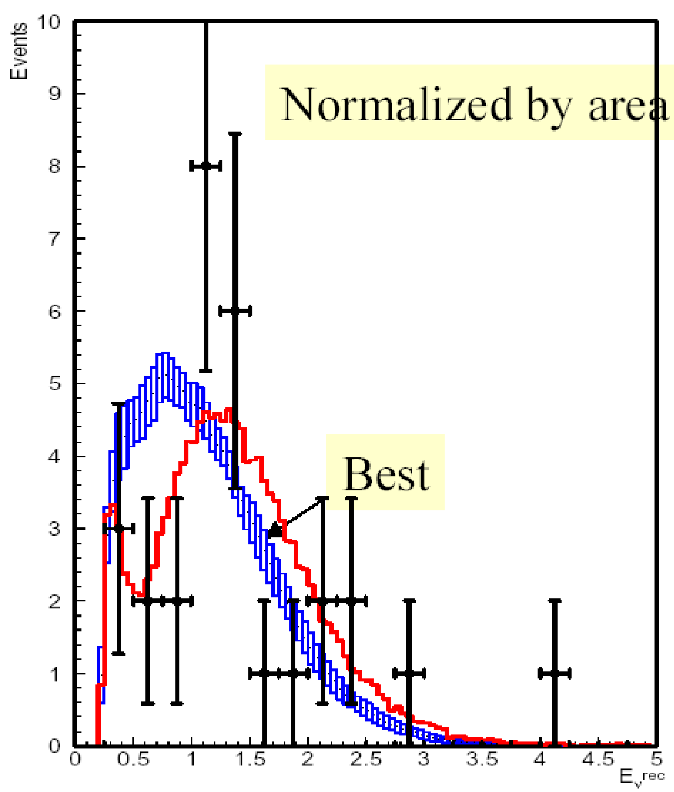
Super-K Fits to $\nu_\mu \to \nu_\tau$

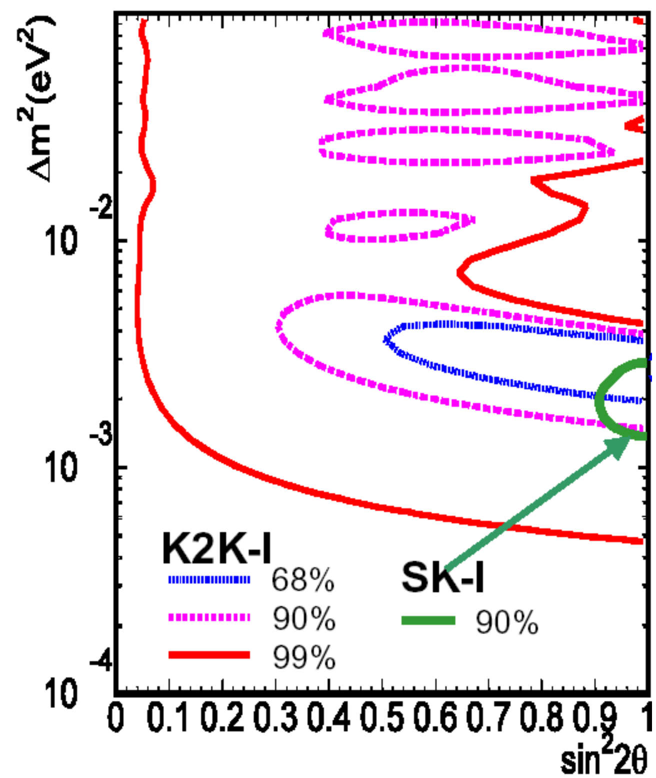


K2K (KEK to Super-K) Oscillation Experiment (Accelerator Check of Atmospheric Osc.)

- Low energy, $\langle E_\nu \rangle = 1.4$ GeV, beam sent from KEK to SuperK (250 km)
- See large deficit of neutrinos (~50%)
- **Confirm Atmospheric oscillations using an accelerator neutrino beam**







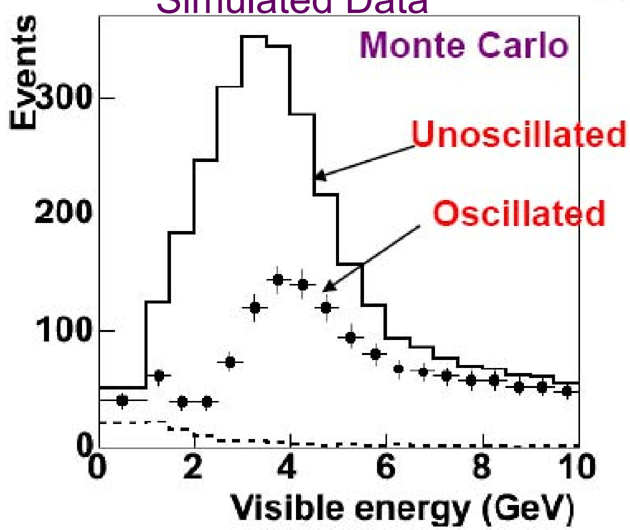
MINOS Accelerator Oscillation Experiment at Fermilab

A,Habig, July 2

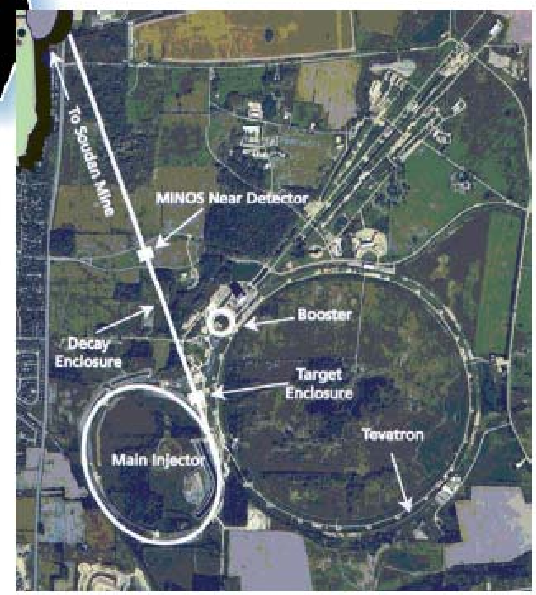
5.4 kton MINOS far detector

1 kton near detector

Simulated Data

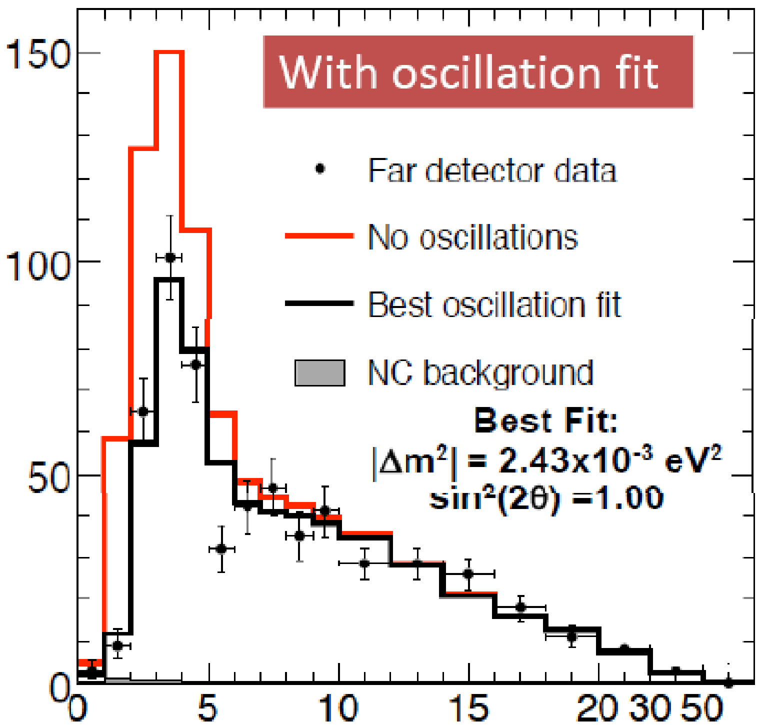


NuMI
beam line

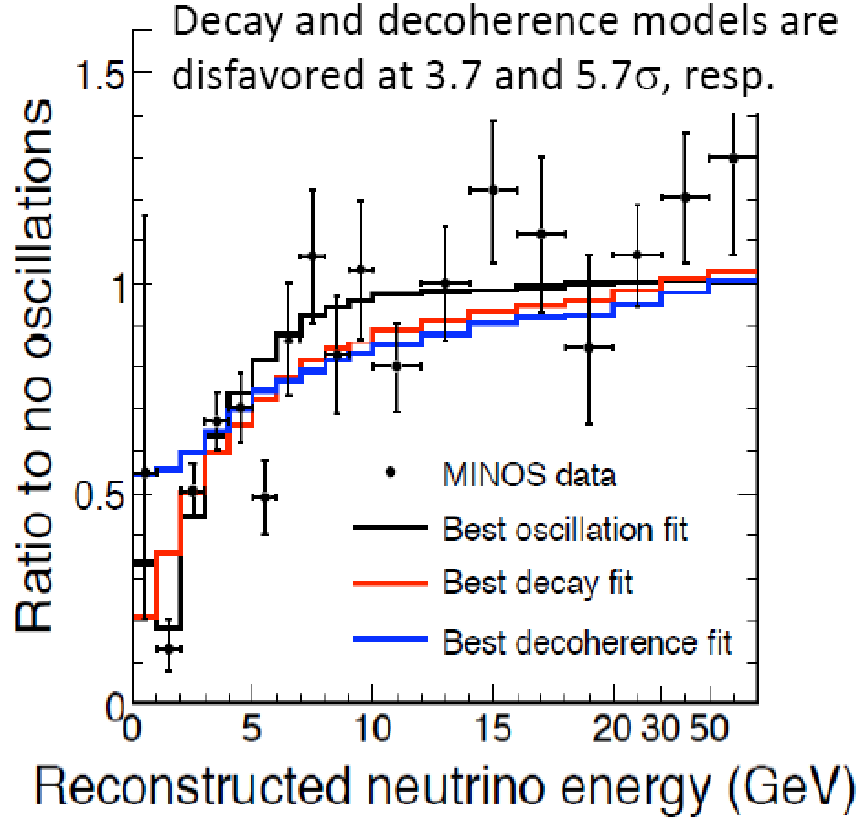


MINOS ν_μ Disappearance Results

848 CC ν_μ candidates ←→ 1065±60(syst) no-osc. prediction



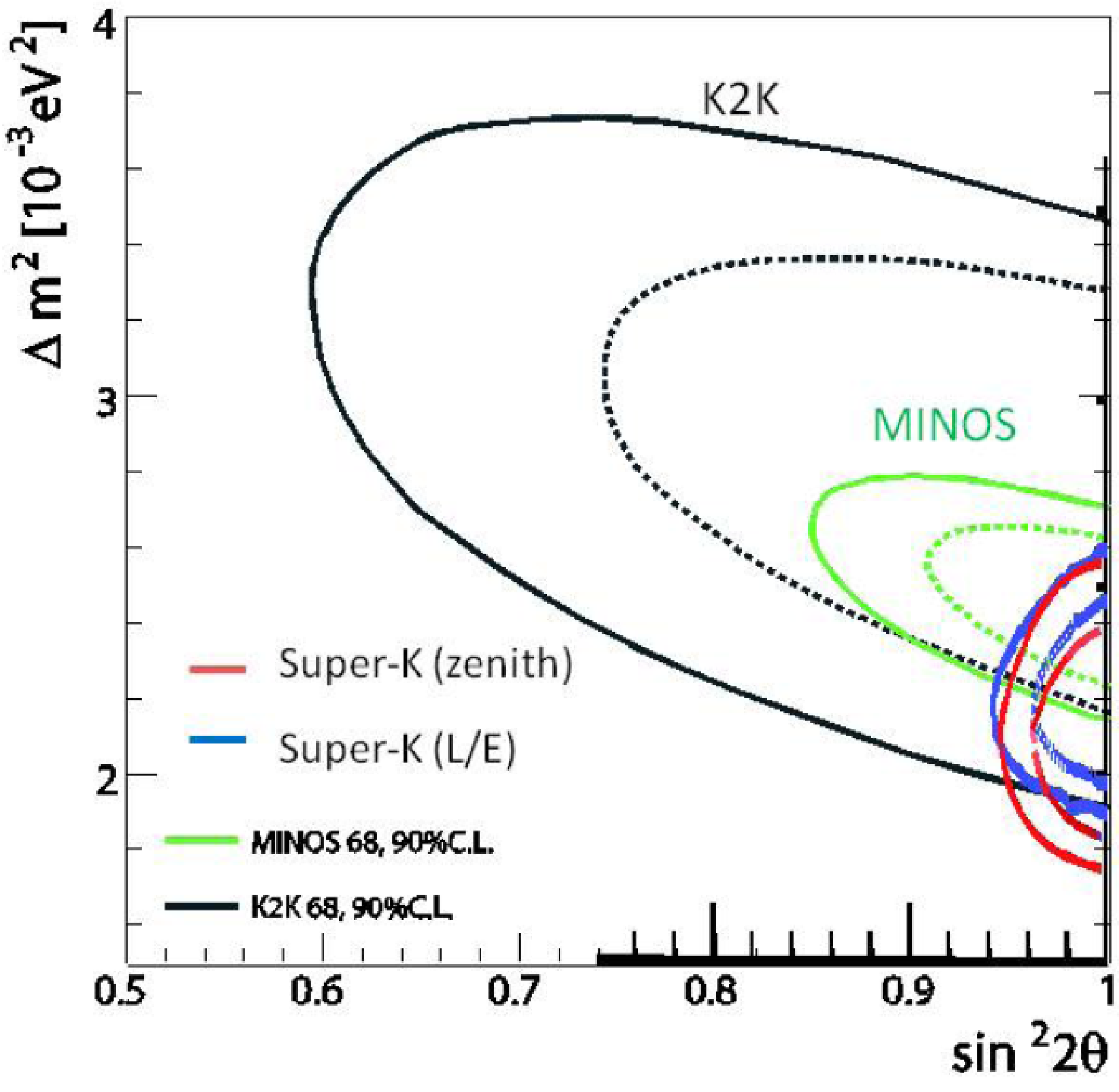
Decay and decoherence models are disfavored at 3.7 and 5.7σ, resp.



PRL 101 (2008) 131802

(hep-ex/0806.2273)

Summary of Current "Atmospheric" Region Results



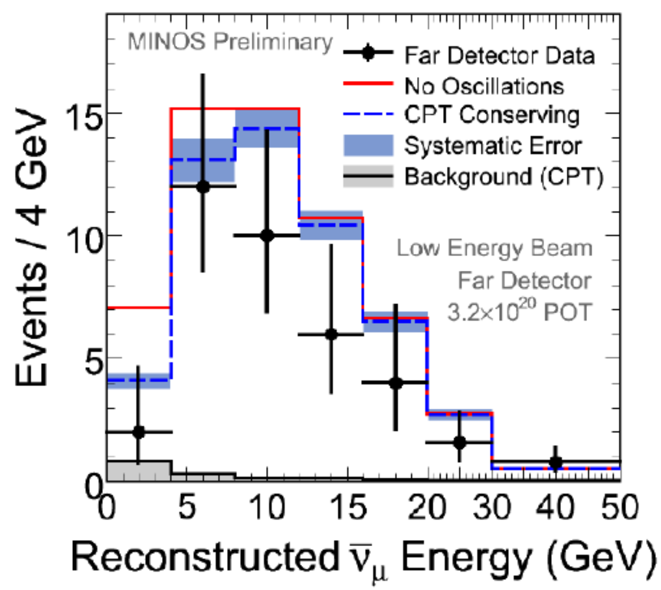
$$\Delta m^2_{23} = 2.43 \pm 0.13 \times 10^{-3}\,eV^2$$

(5% accuracy, MINOS)

1^{st} MINOS "Pure" $\bar{\nu}_\mu$ Disappearance Results

- CPT invariance requires that $\bar{\nu}_\mu$ and ν_μ disappearance should be the same
- MINOS is first longbaseline experiment that can separate $\bar{\nu}_\mu$ and ν_μ interactions using the sign of the outgoing muon.
  - For the standard ν_μ running, 6.4% of CC interactions from $\bar{\nu}_\mu$ with 82% efficiency and 97% purity.

$\Rightarrow$ Can search for $\bar{\nu}_\mu$ disappearance!

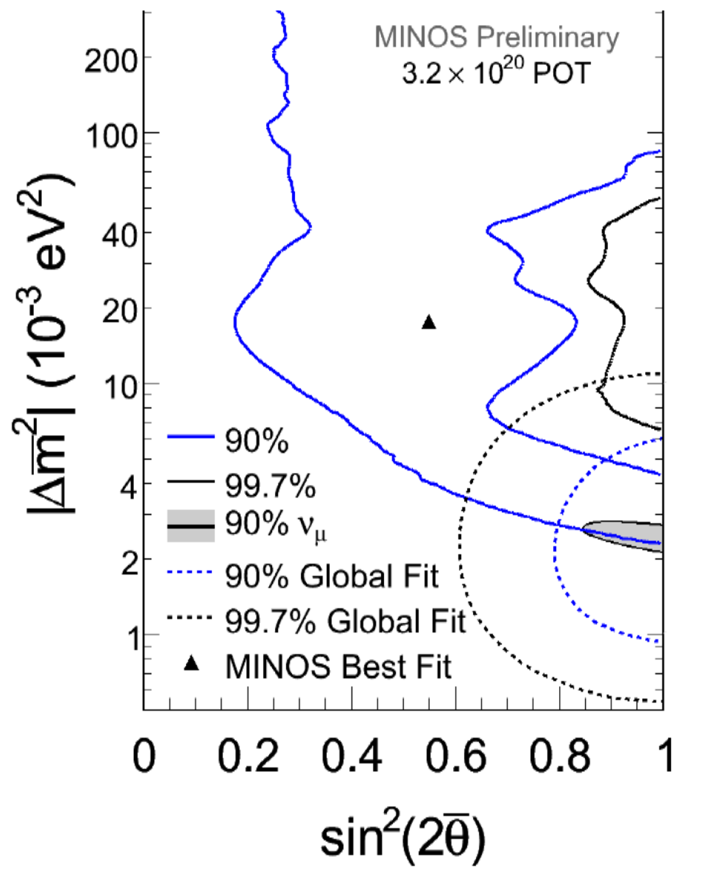


Results: 42 events observed

Expect: No osc: $65 \pm 8_{stat} \pm 4_{syst}$

CPT conserving: $58 \pm 8_{stat} \pm 4_{syst}$

$\bar{\nu}_\mu$ and ν_μ Compatible within statistical uncertainties



Next: Plan to run $\bar{\nu}_\mu$ starting next year

MINOS Search for Oscillations to Sterile Neutrinos

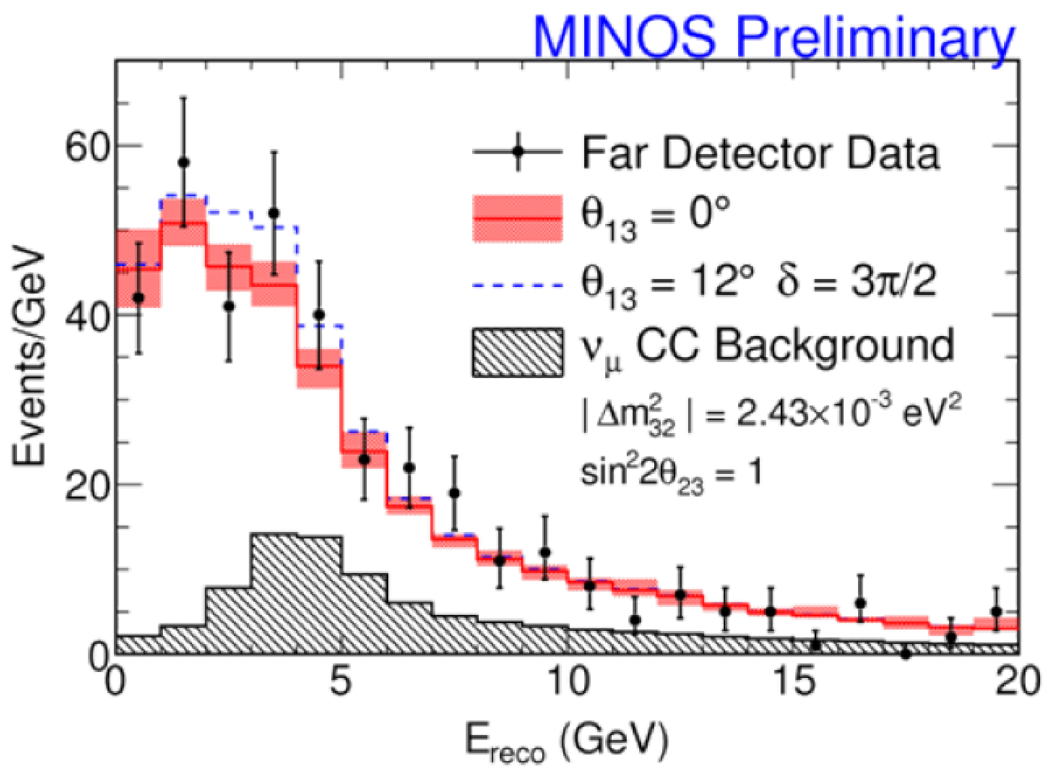
- "Atmospheric region" oscillations from $\nu_\mu \rightarrow \nu_\tau$ but ν_τ energy is below threshold to produce τ leptons $\Rightarrow$ only ν_τ NC interactions

  For Neutral Current Interactions:

  $\nu_\mu + N \rightarrow \nu_\mu + N'$ Same as $\nu_\tau + N \rightarrow \nu_\tau + N'$

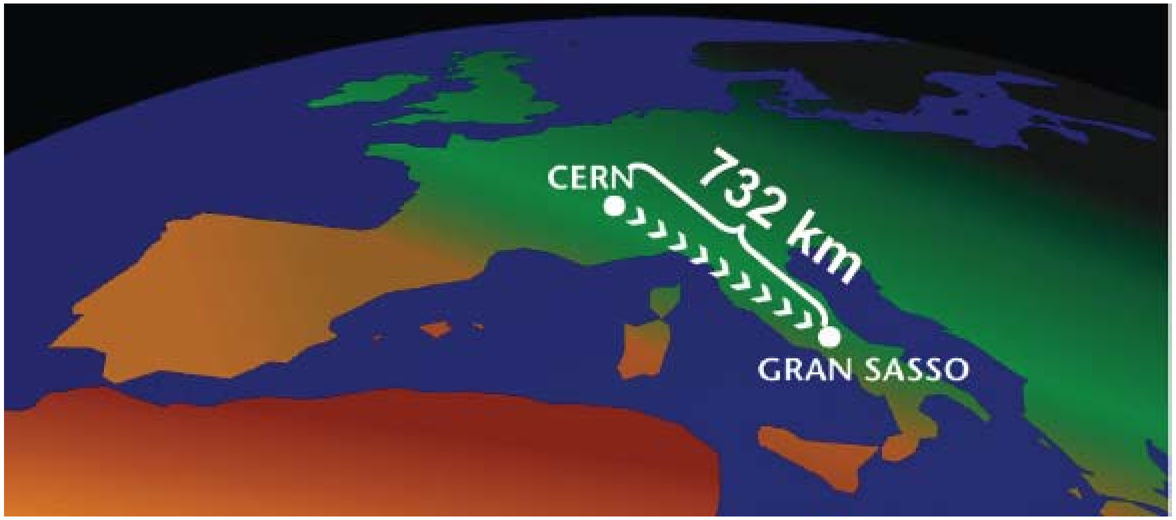
  $\Rightarrow$ NC rate in near and far detector should be the same

- If $\nu_\mu \rightarrow \nu_{sterile}$ then NC rate should be less in far detector

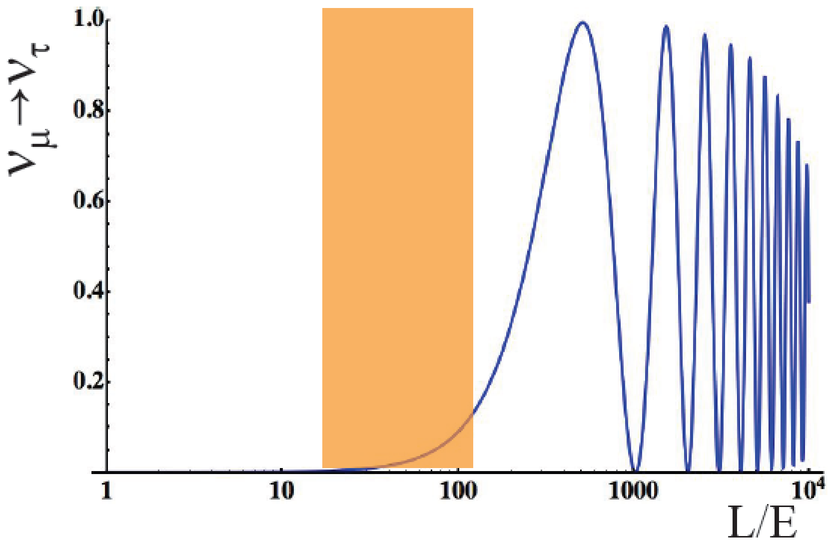


Data are consistent with no NC deficit at FD and thus with no sterile neutrino mixing

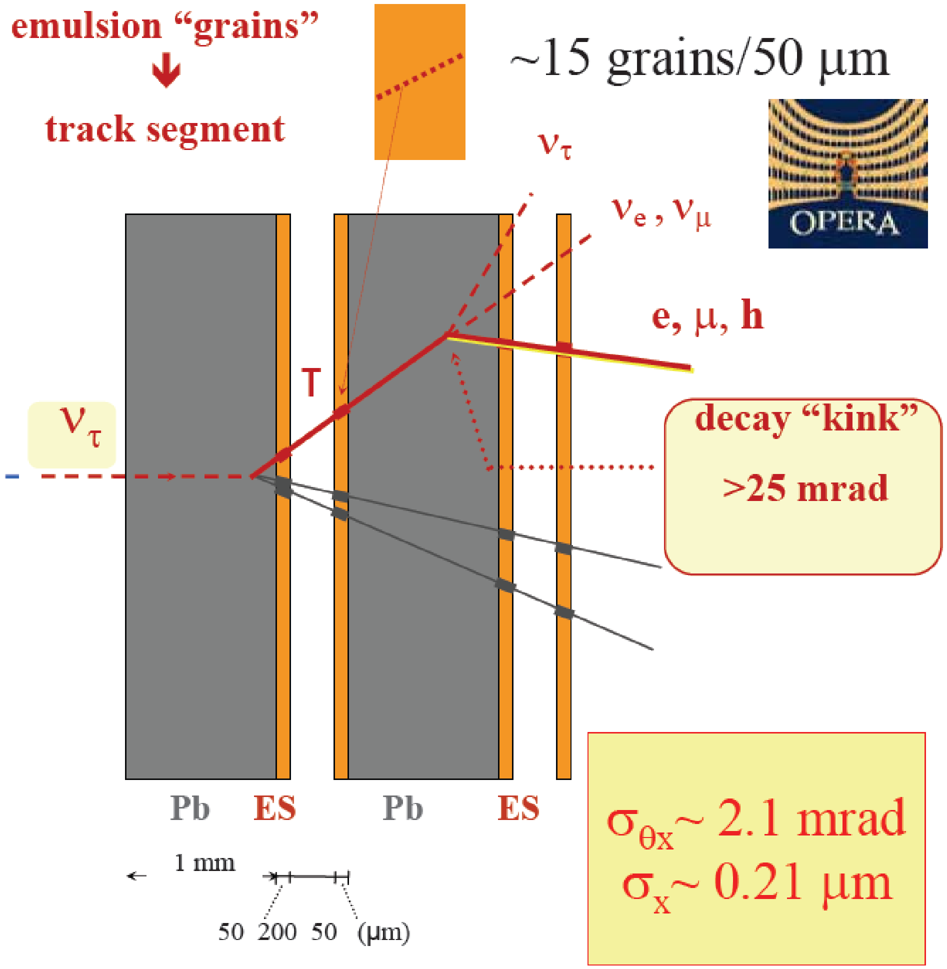
OPERA and ICARUS: ν_τ Appearance Search



- Uses 400 GeV protons to produce neutrino beam $\langle E_\nu \rangle \approx$ 17 GeV
- $\langle E_\nu \rangle$ above threshold to produce τ leptons from ν_τ
- $\langle L/E \rangle \approx 43$ so oscillation probability for Δm^2_{atm} is small



OPERA: Nuclear Emulsion plus Lead



- Scintillator Strips isolate emulsion brick with an event
- Robot then picks out brick to be scanned.
- 1st event 2007 ⇒ 10% run completed (1700 ν-events recorded)

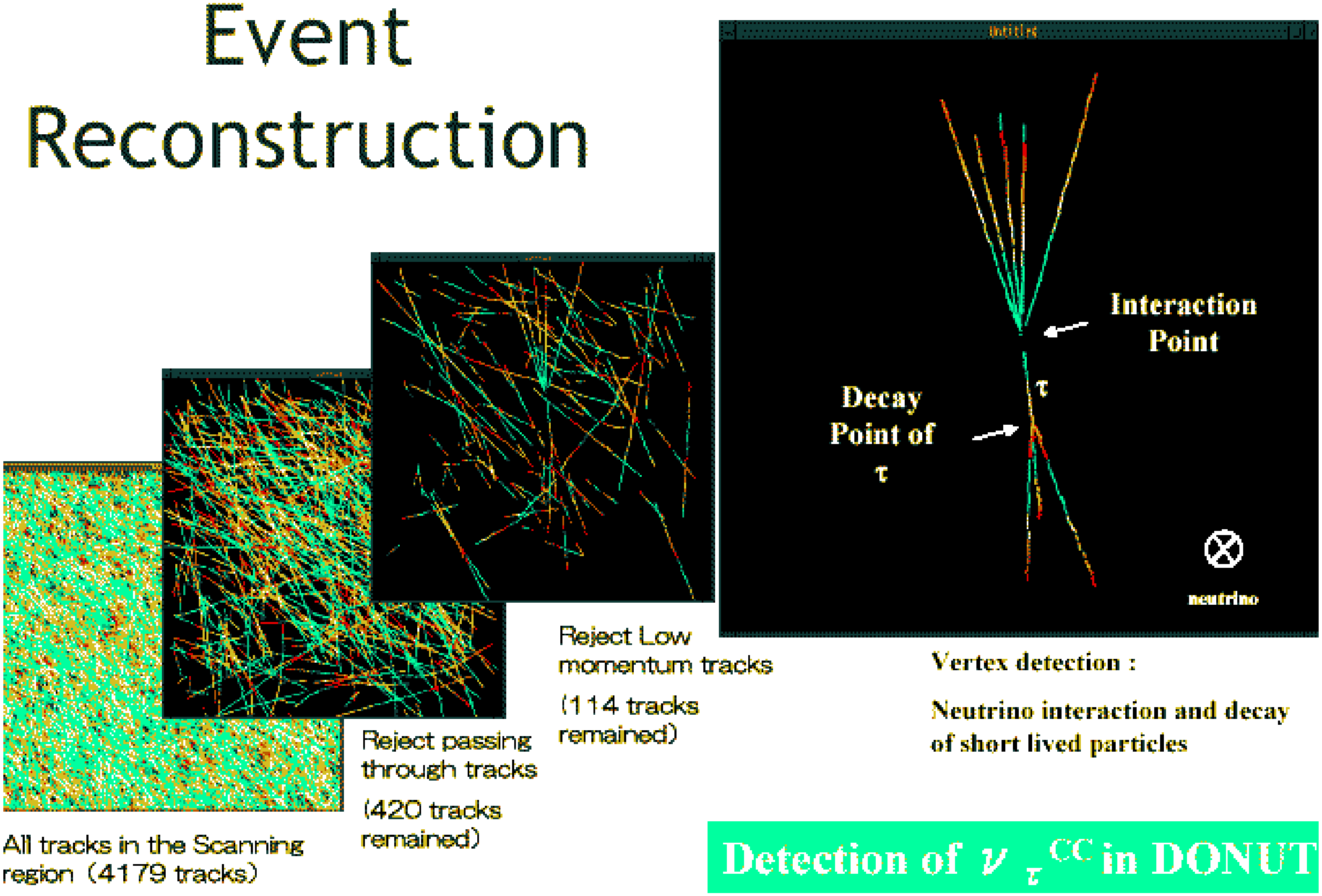
ICARUS: Liquid Argon TPC 600 Tons

- Will use kinematic reconstruction to isolate ν_τ-events.
- 1st event expected by end of 2009

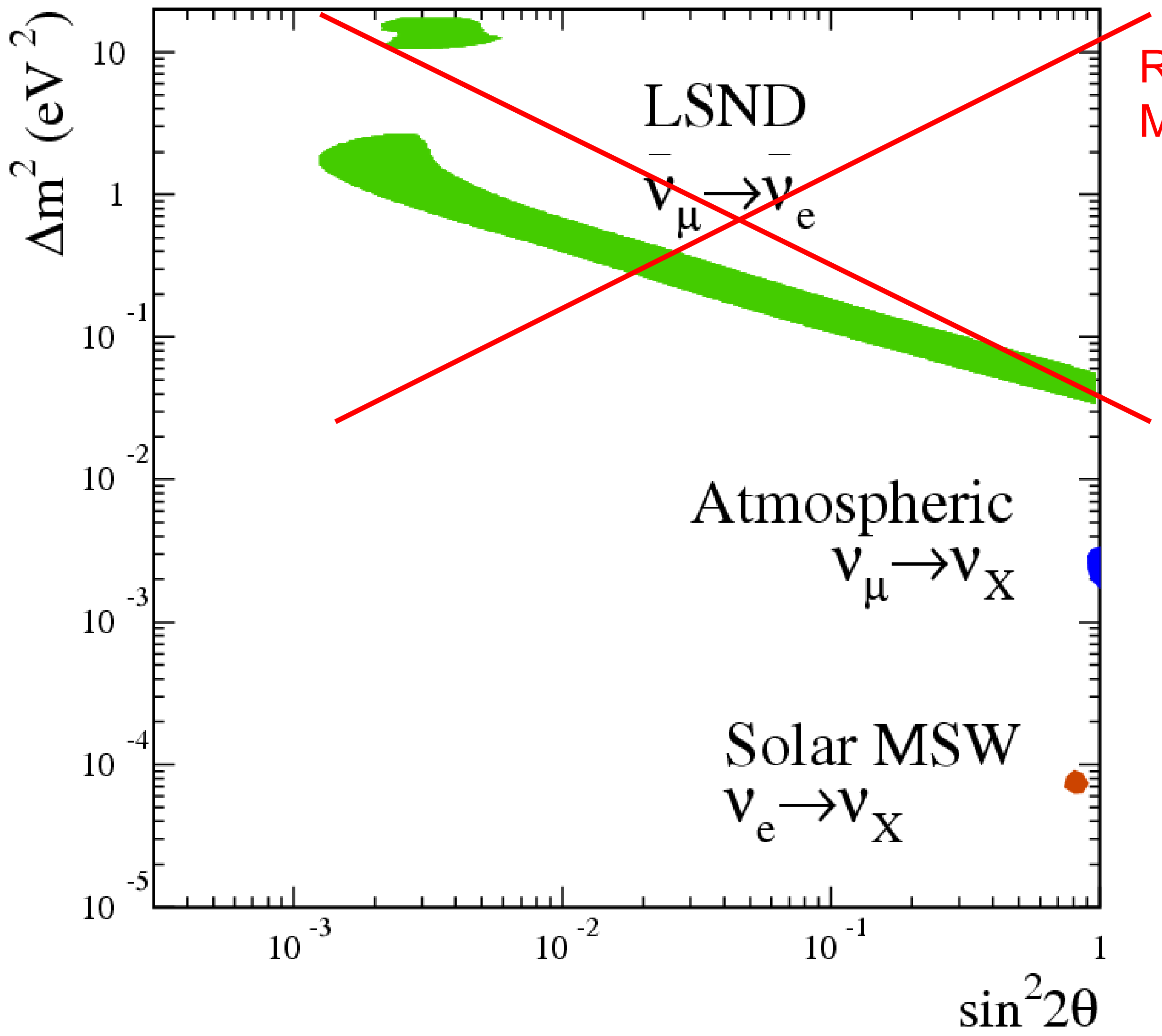
OPERA

Expect about 15 events in 5 years.

Event Reconstruction



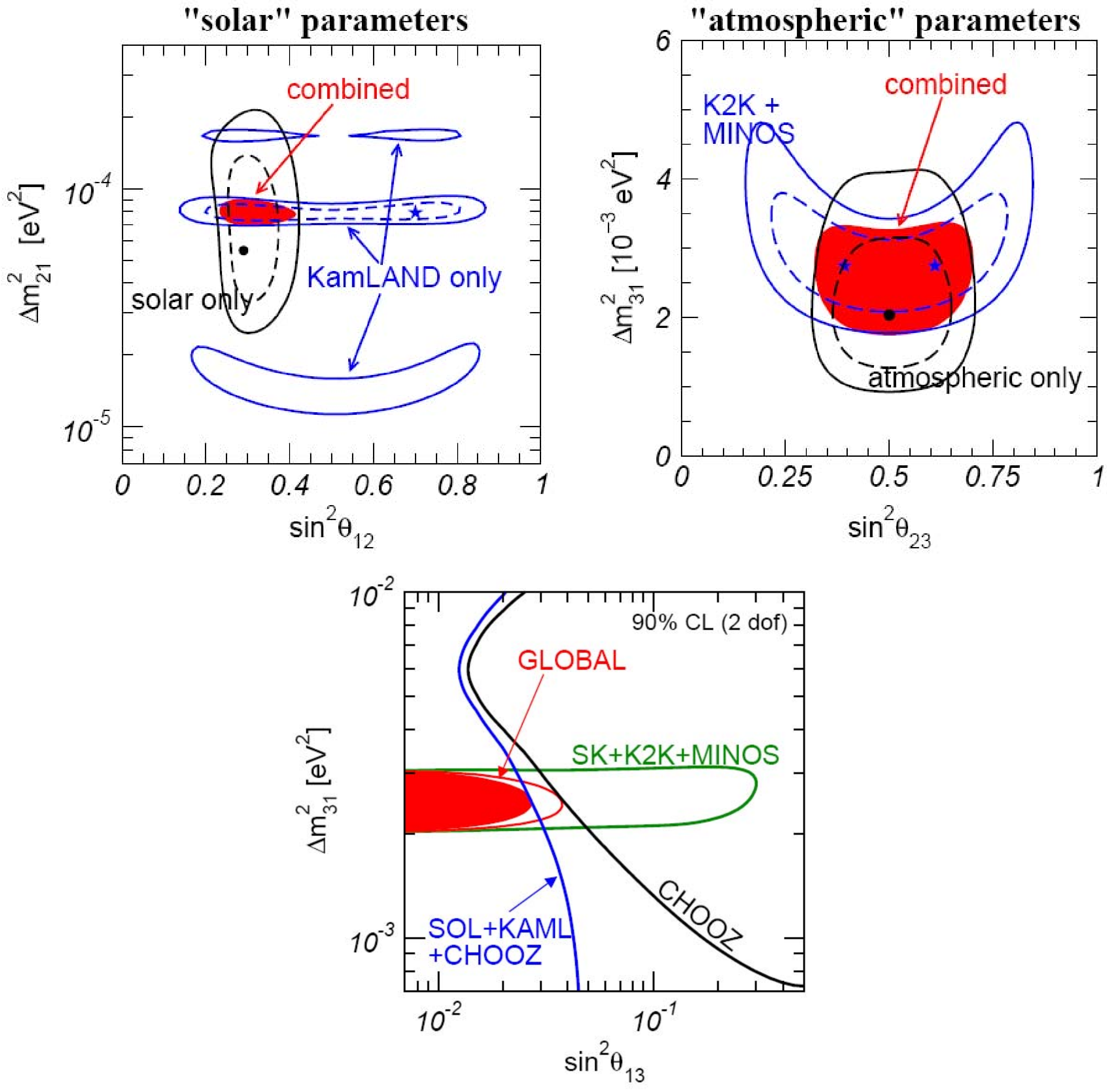
Current Oscillation Summary



Ruled out by MiniBooNE (almost)

($\bar{\nu}$ running; low-E excess)

Current Global Fits to Solar, Atmospheric, Accelerator, and Reactor Data



Big Questions in Neutrino Oscillations

Still missing some information

1. What is ν_e component in the ν_3 mass eigenstate?
   $\Rightarrow$ The size of the "little mixing angle", θ_{13} ?
   – Only know $\theta_{13}<13^0$
2. Is the μ - τ mixing maximal?
   – $35^0 < \theta_{23} < 55^0$
3. What is the mass hierarchy?
   – Is the solar pair the most massive or not?
4. What is the absolute mass scale for neutrinos?
   – We only know Δm^2 values
5. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?