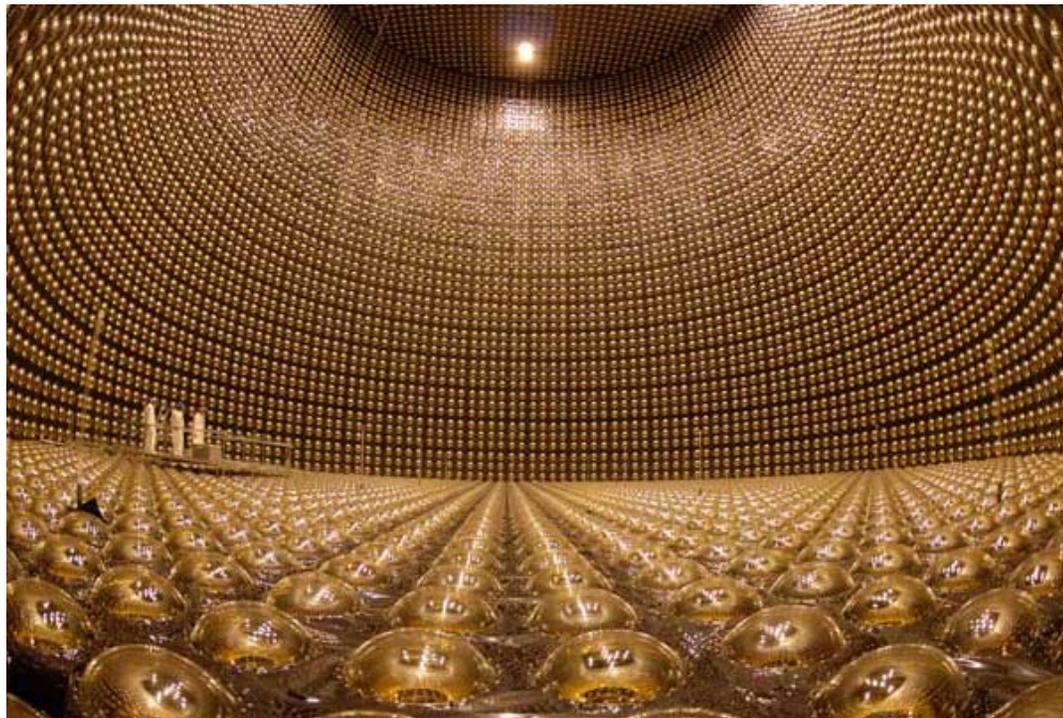


Neutrino Experiments: Lecture 2
M. Shaevitz
Columbia University



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:

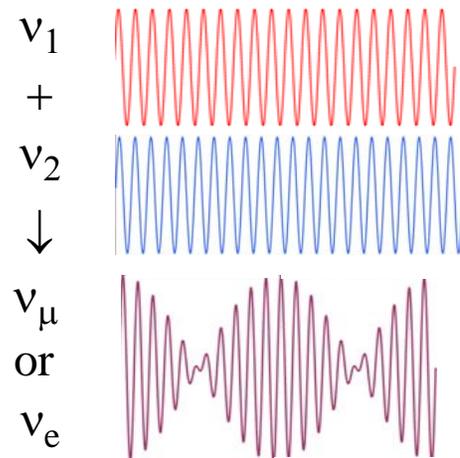
1. Neutrinos have mass

and

2. Lepton number (electron, muon, tau) is not conserved

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

mass eigenstates \neq 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:

- $\Delta m^2 = m_1^2 - m_2^2$ (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

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

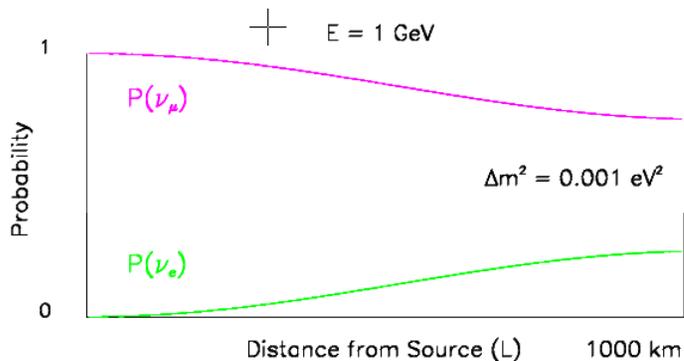
$$P_{Osc} = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L / E)$$

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

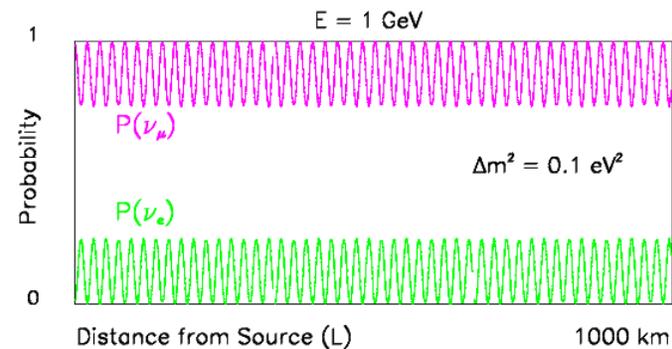
Oscillation Phenomenology

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

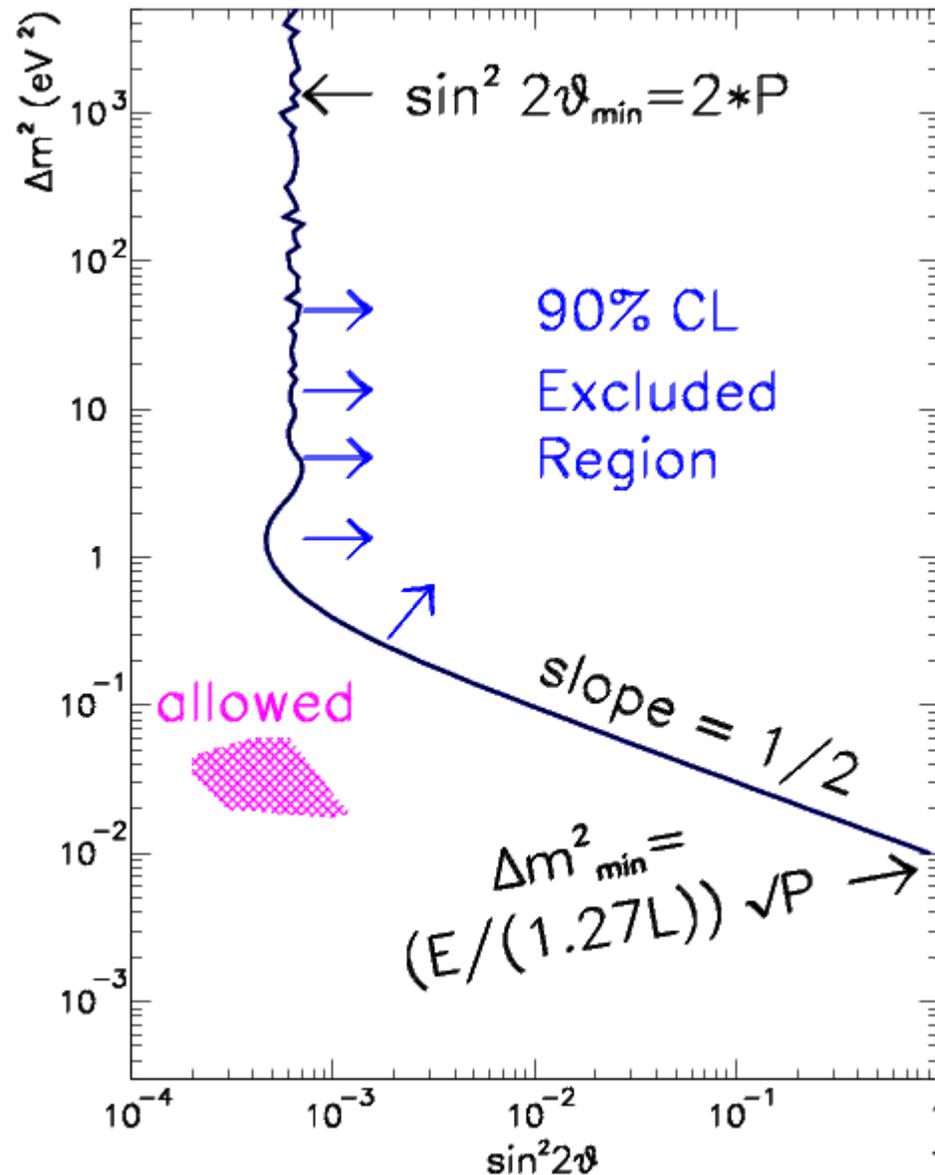
Small Δm^2 (Need large L/E)



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



Oscillation Plots



- If you see an oscillation signal with

$$P_{\text{osc}} = P \pm \delta P$$

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

- If you see no signal and limit oscillation with

$$P_{\text{osc}} < P \text{ @ 90\% CL}$$

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

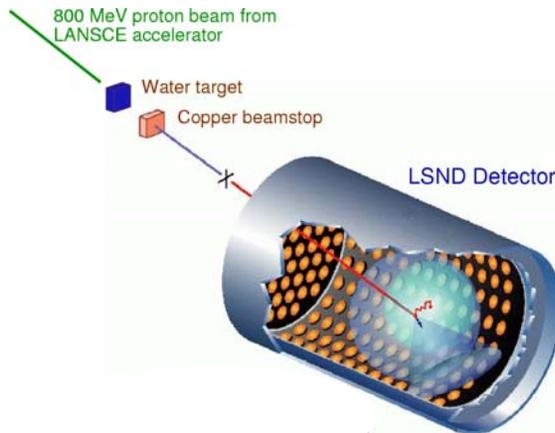
Situation in mid-1990's: Three Experimental Indications for Neutrino Oscillations

LSND Experiment

$L = 30\text{m}$

$E = \sim 40\text{ MeV}$

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



$$\Delta m^2 = .3 \text{ to } 3 \text{ eV}^2$$

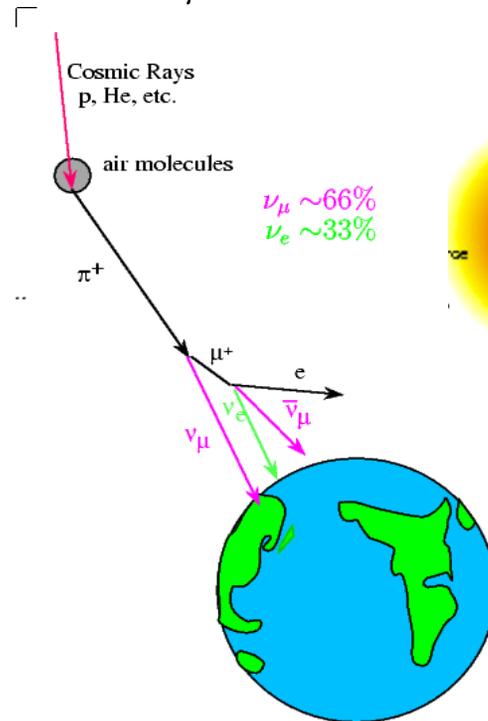
$$\text{Prob}_{\text{OSC}} = 0.3 \%$$

Atmospheric Neutrinos

$L = 15 \text{ to } 15,000 \text{ km}$

$E = 300 \text{ to } 2000 \text{ MeV}$

$$\nu_{\mu} \rightarrow \nu_{x}$$



$$\Delta m^2 = \sim 1 \text{ to } 7 \times 10^{-3} \text{ eV}^2$$

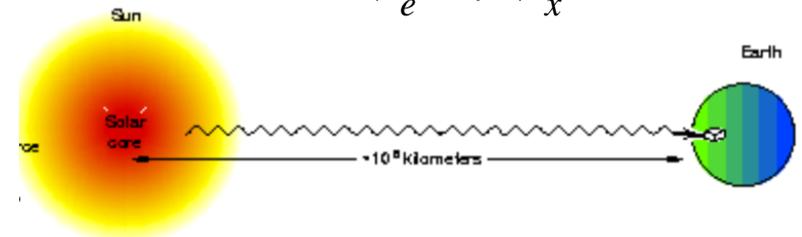
$$\text{Prob}_{\text{OSC}} = \sim 100\%$$

Solar Neutrinos

$L = 10^8 \text{ km}$

$E = 0.3 \text{ to } 3 \text{ MeV}$

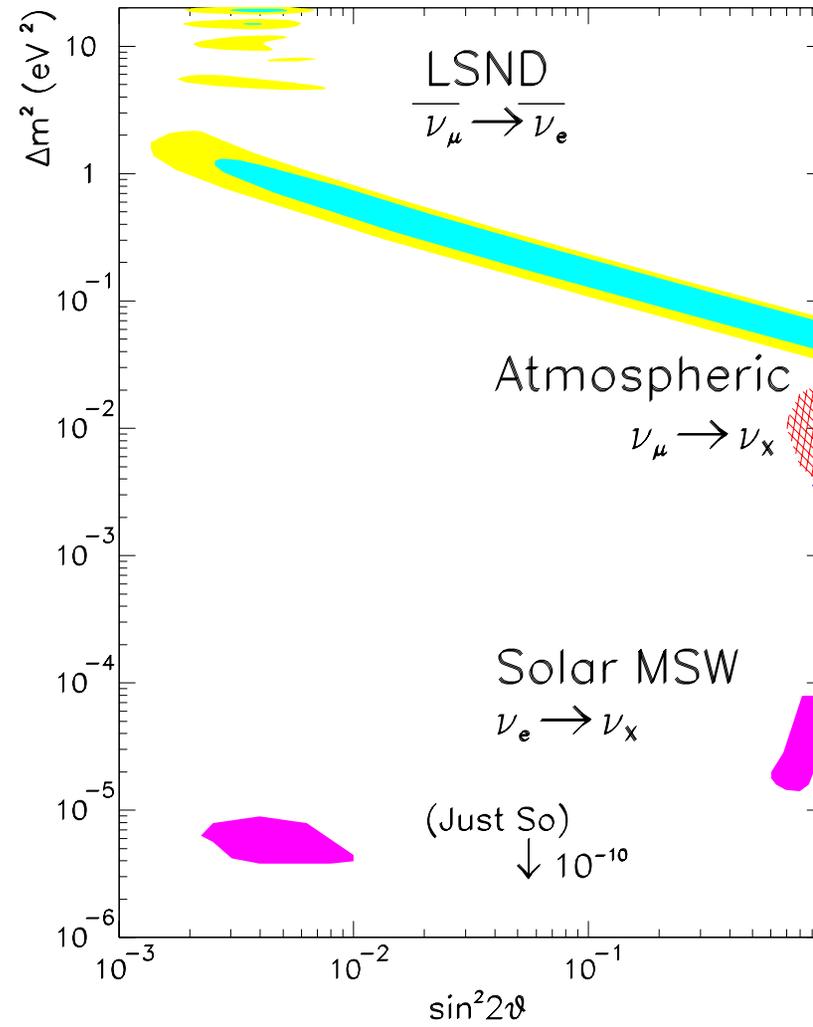
$$\nu_e \rightarrow \nu_x$$



$$\Delta m^2 = \sim 2 \text{ to } 8 \times 10^{-5} \text{ eV}^2$$

$$\text{Prob}_{\text{OSC}} = \sim 100\%$$

Three Signal Regions (Mid 1990's)



Theoretical Prejudices before 1995

- Natural scale for $\Delta m^2 \sim 10 - 100 \text{ eV}^2$
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 $\Delta m_{23}^2 \sim 10 - 100 \text{ eV}^2$
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 ????

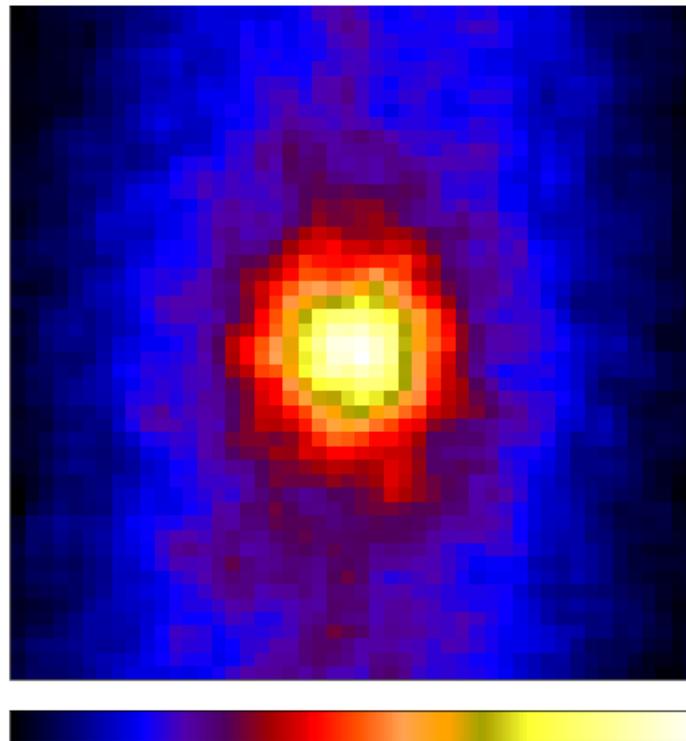
Neutrino Revolution: 1995 - Present

- 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 ${}^7\text{Be}$ 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 $\sim 2.5 \times 10^{-3} \text{ eV}^2$

Solar Neutrino Deficit

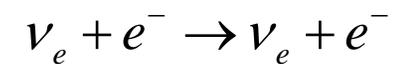
Flux of solar neutrinos detected at the earth is much less than expected

⇒ Is it due to neutrino oscillations?

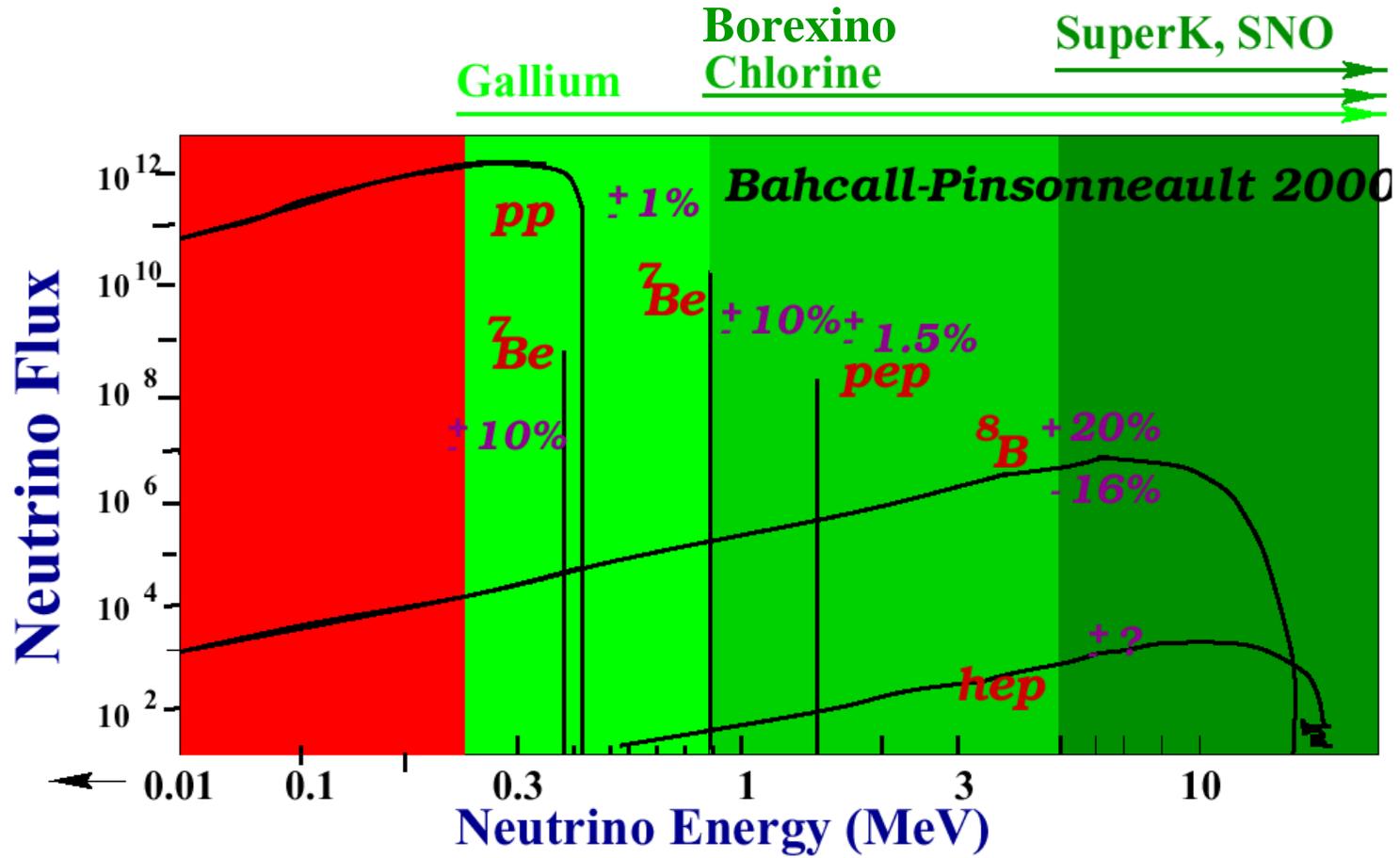


Super- K (Japan) image of the sun using neutrinos

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



Solar Neutrino Spectrum

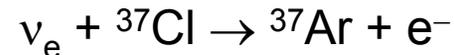


Solar Neutrino Experiments

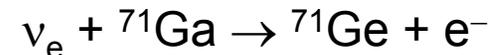
- Two types of experiments:

- Chemical Extraction experiments

- Homestake (“Chlorine”)



- Sage and Gallex (“Gallium”)

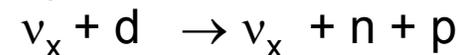
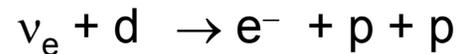


- Scattering experiments

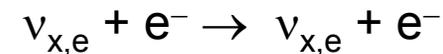
- SuperKamioka (Kamioka)
(Light water)



- SNO
(Heavy water)



- Borexino
(Liquid Scintillator)



Super-K Experiment

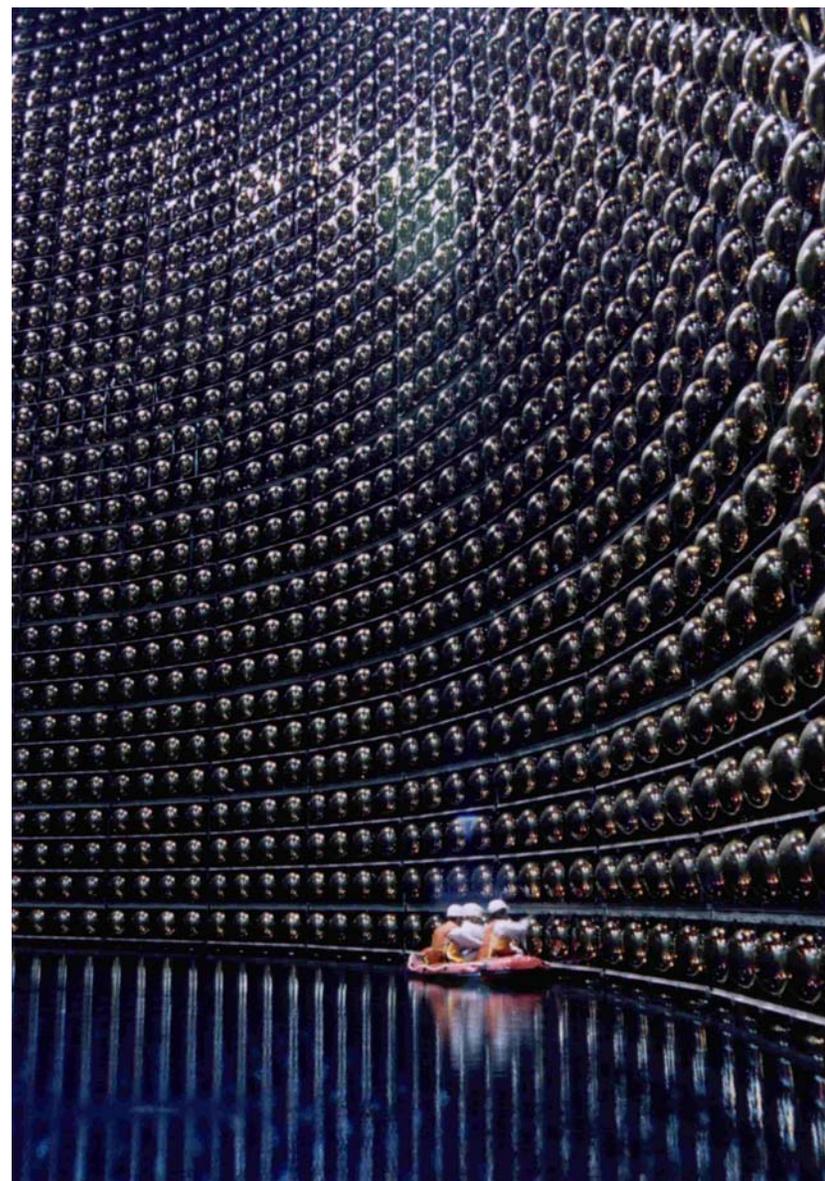
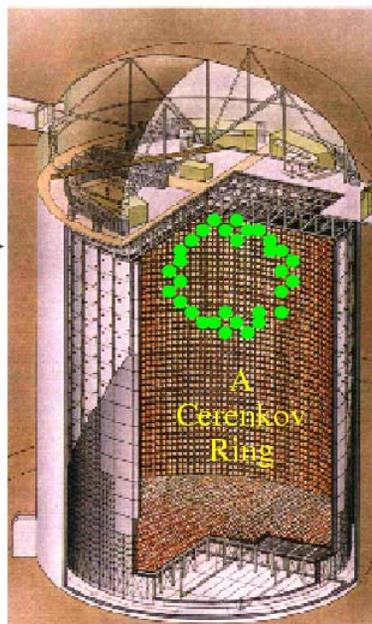
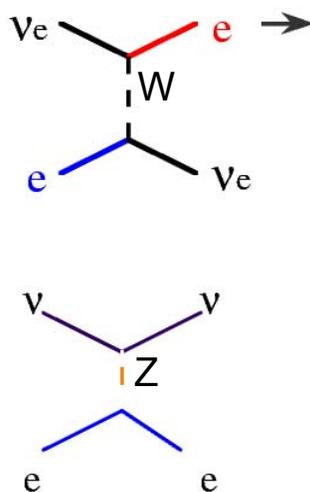
H₂O Cerenkov Detector

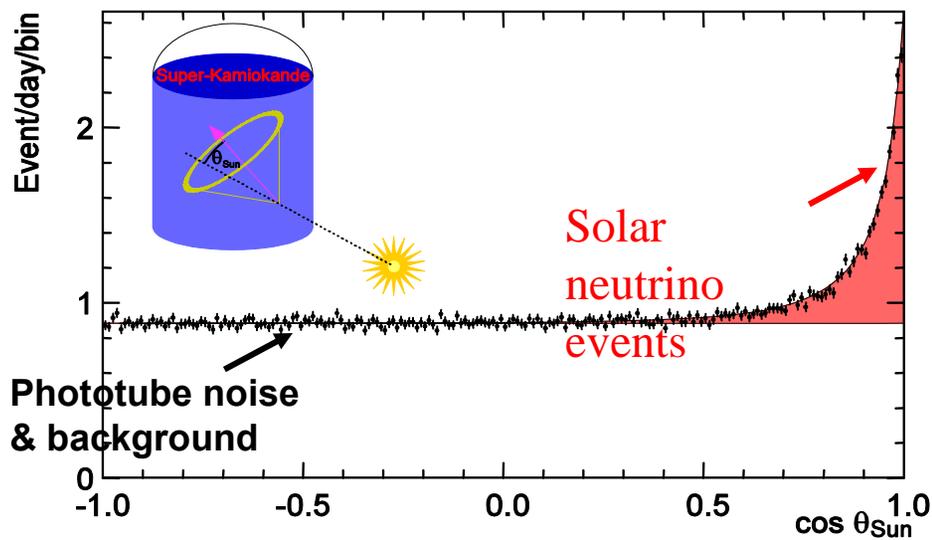
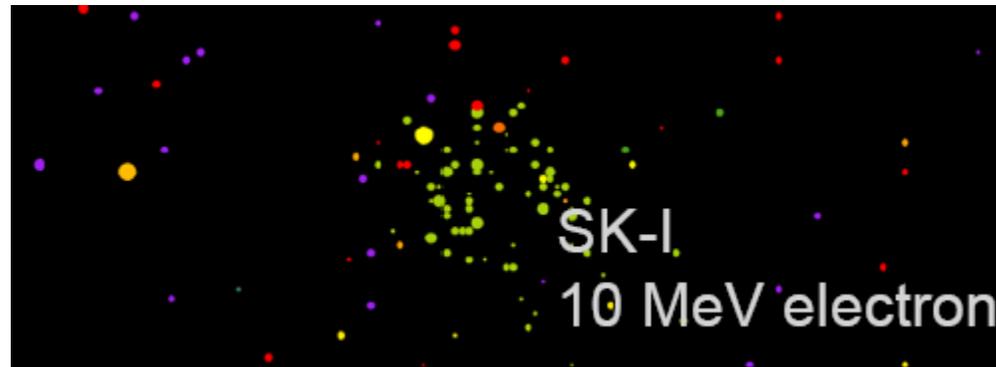
- SuperK

- 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

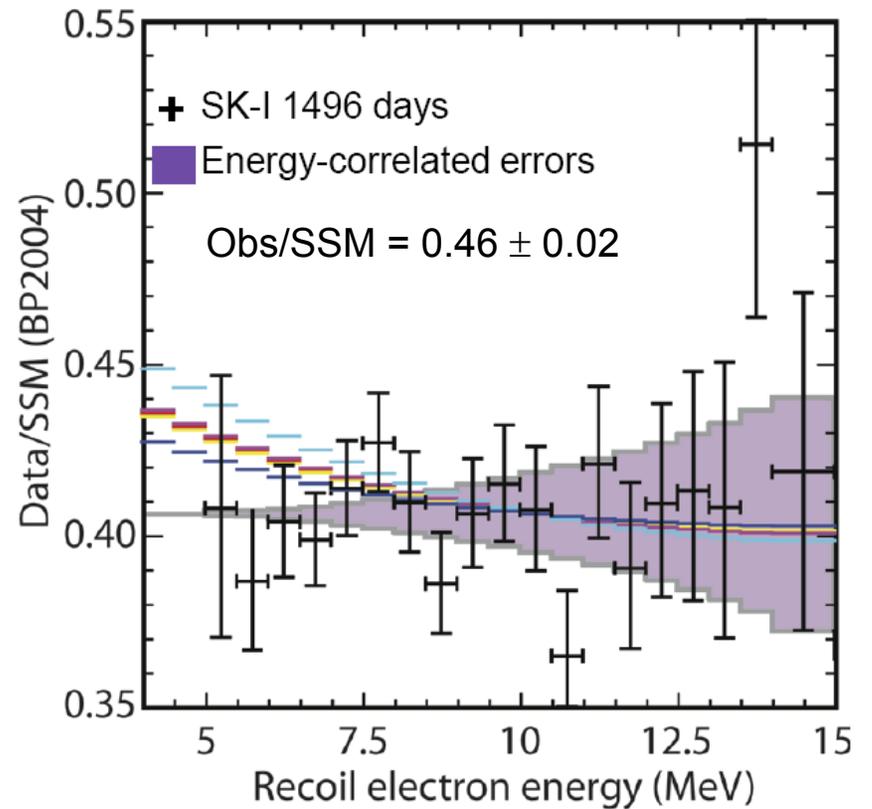
ν_e Rate
×5 Higher
than
 ν_μ and ν_τ



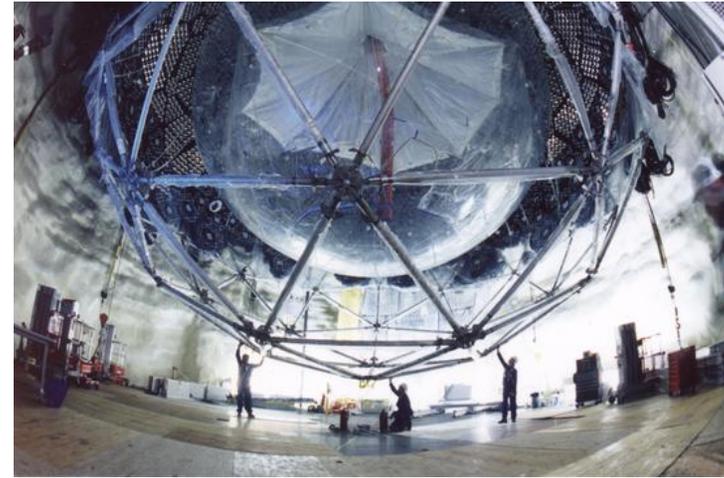
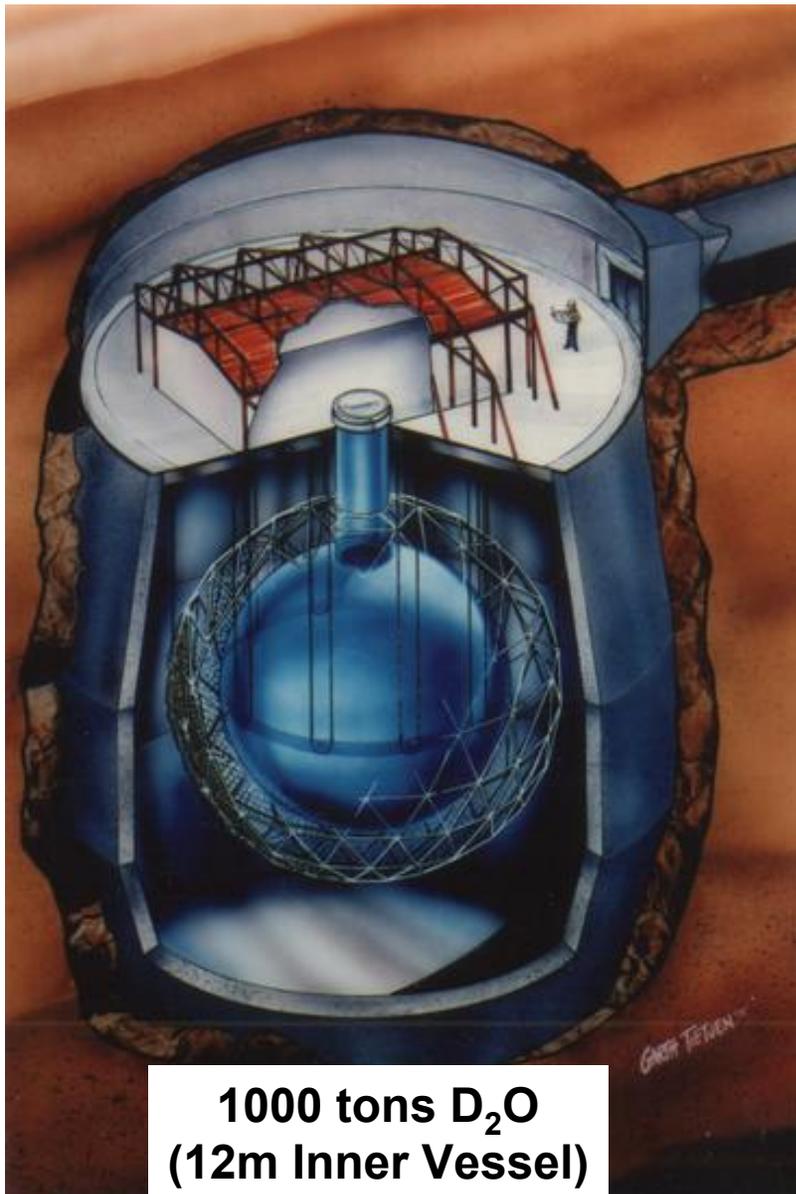


Main Backgrounds:

- Radon
- CR spallation



Sudbury Neutrino Observatory (SNO)



- Advantages of Heavy vs Light Water
 - $\nu_x + d \rightarrow \nu_x + n + p$ (D₂O)
 - $\nu_e + d \rightarrow p + p + e^-$ (D₂O)
 - $\nu_x + e^- \rightarrow \nu_x + e^-$ (H₂O or D₂O)
 - 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 H₂O than n's

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

Neutrino Reactions in SNO



- pure ν_e measurement

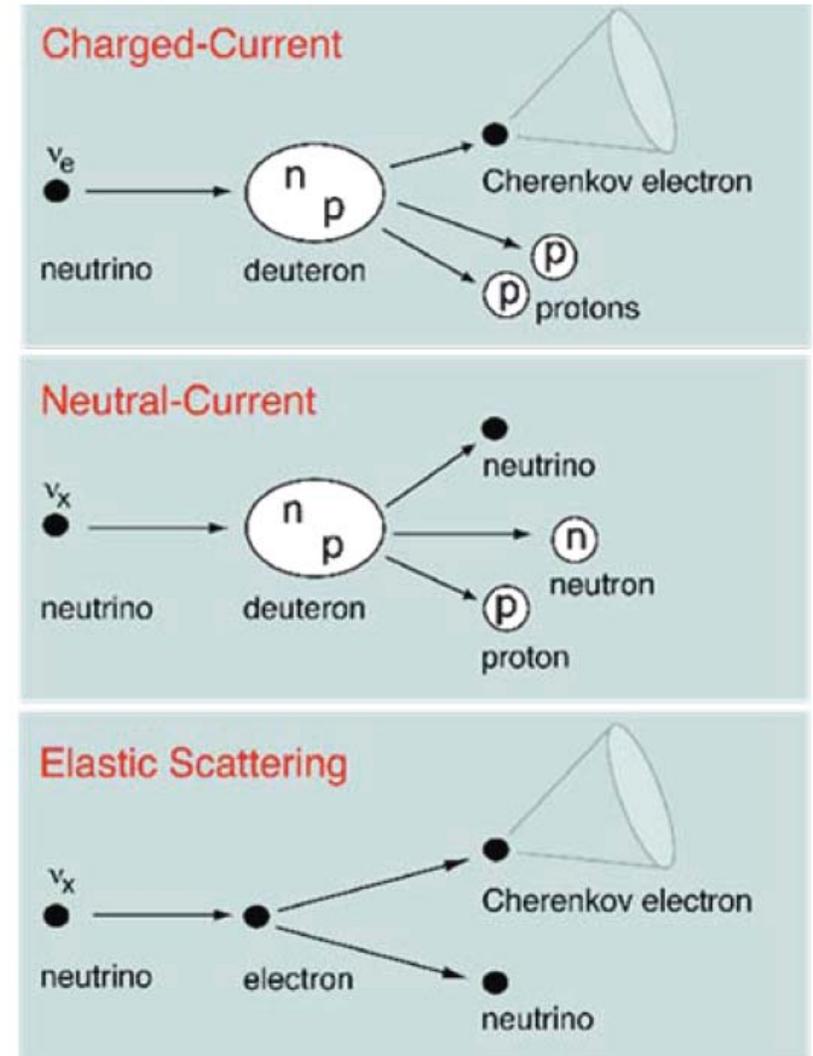


- measures total ^8B ν flux from the Sun
- equal cross section for all active ν flavors



Three Phases for neutron capture:

- 1) On Deuterium
- 2) On Salt
- 3) Using ^3He Counters



SNO Physics

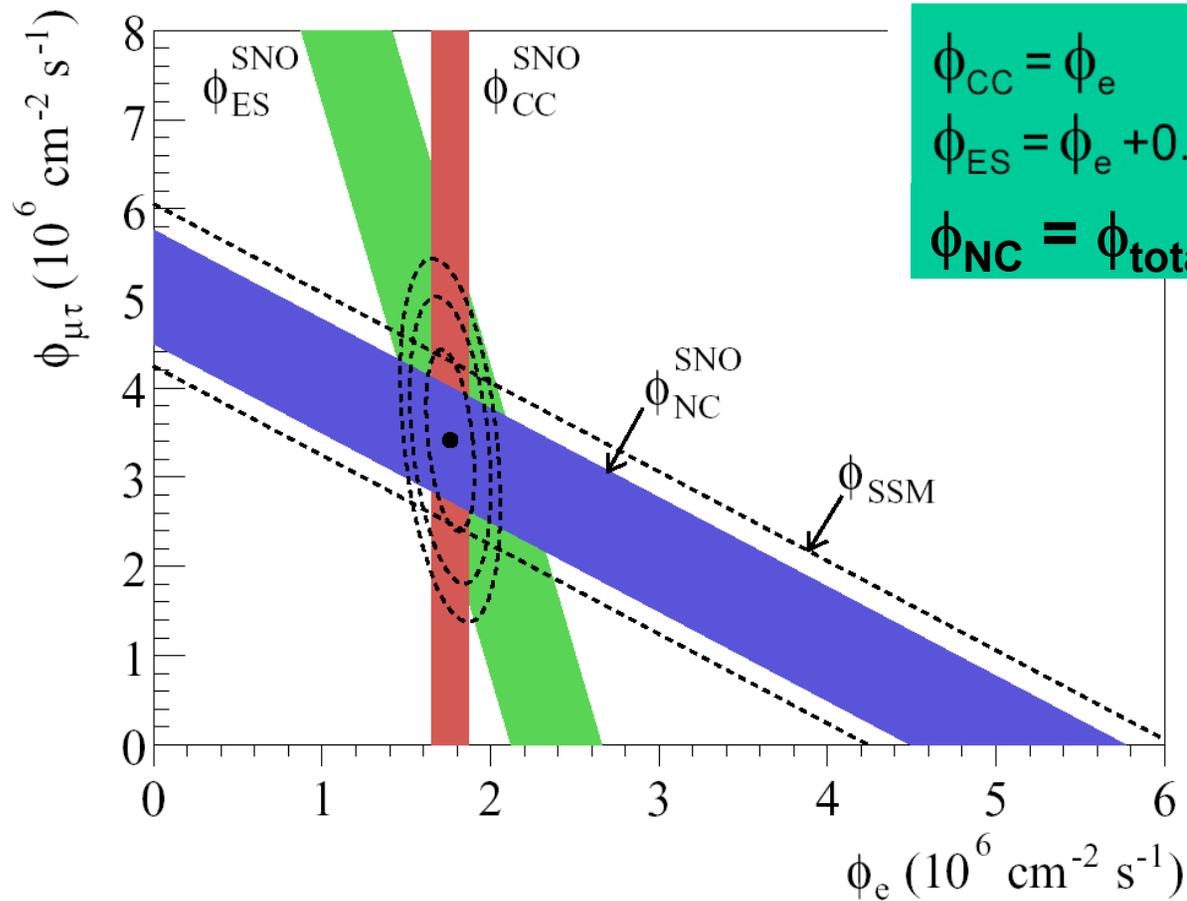
- First measurement of the total flux of ^8Be neutrinos:

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

\Rightarrow **Solar Oscillations
not totally to sterile
neutrinos**

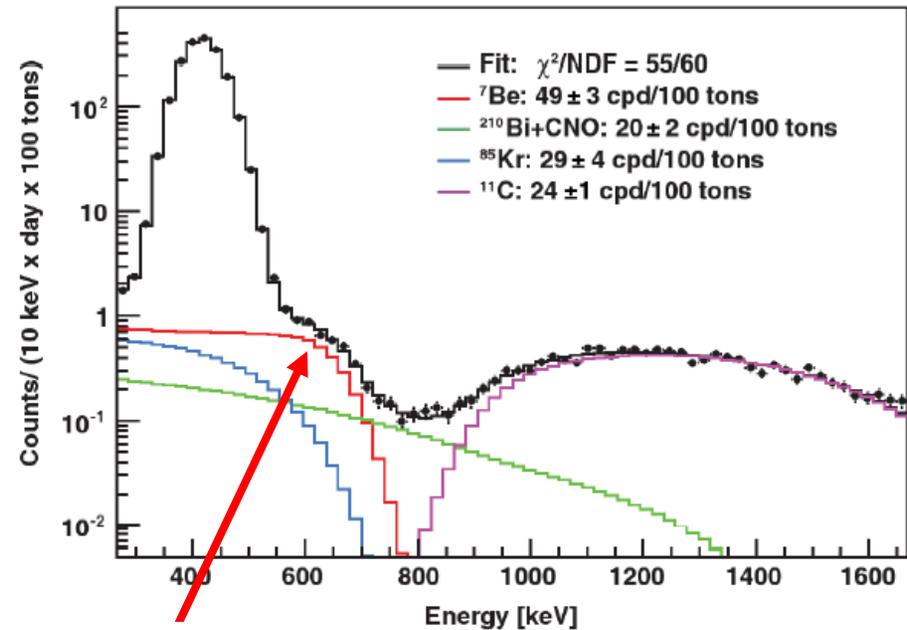
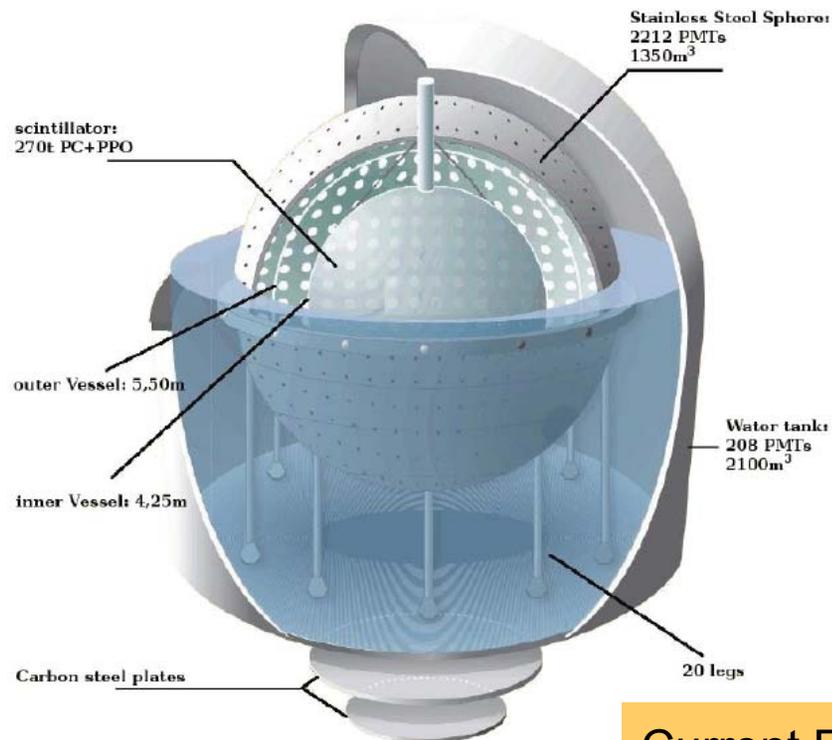
- Agrees well with solar models:

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



Borexino

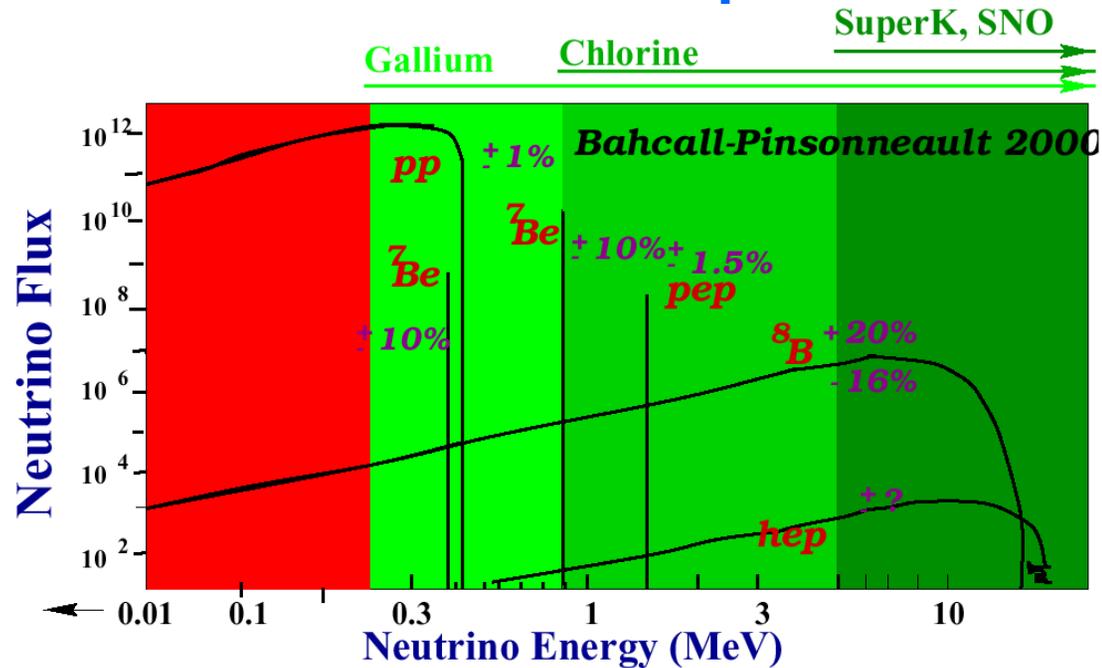
- Neutrino-Electron scattering at Low energy \Rightarrow ${}^7\text{Be}$ neutrinos
- Liquid scintillator neutrino target ($\sim 100\text{t}$ fiducial mass)
- Main issue is radioactive contamination
 - Need to use very “clean” material
 - Reduce cosmic muons



${}^7\text{Be}$ Neutrinos

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

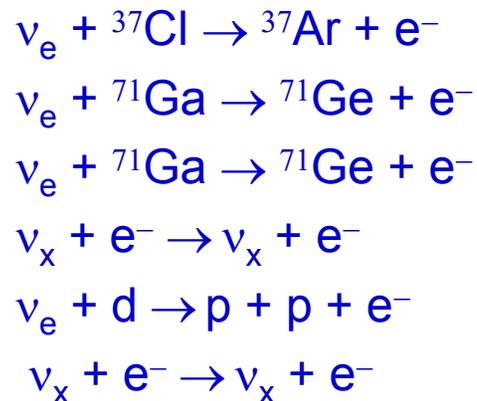
Solar Neutrino Experiments



Rate measurement

- Homestake (US)
- SAGE (Russia)
- Gallex+GNO (Italy)
- Super-K (Japan) H_2O
- SNO (Canada) D_2O
- BOREXINO

Reaction



Obs / Theory

$$0.34 \pm 0.04$$

$$0.59 \pm 0.06$$

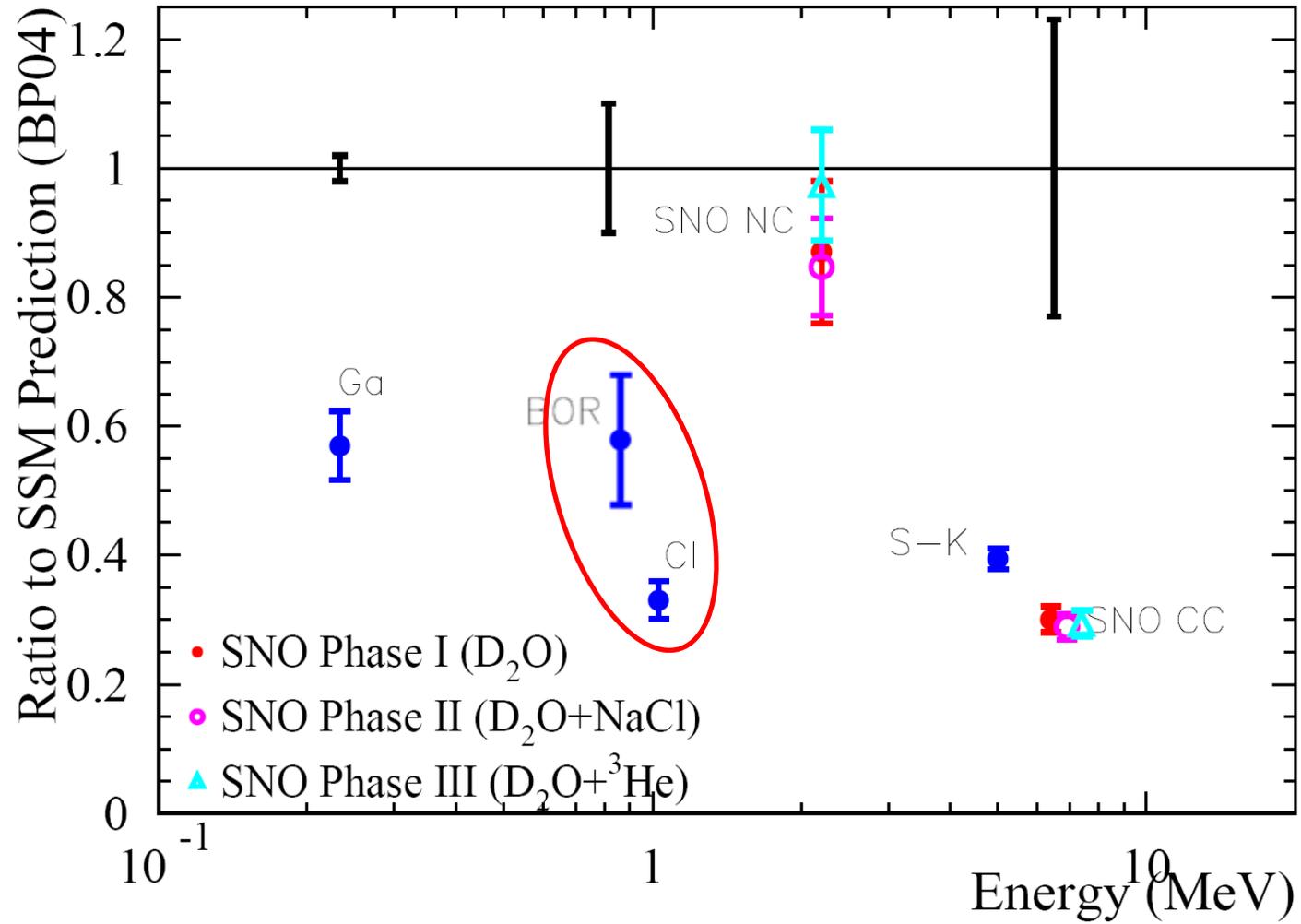
$$0.58 \pm 0.05$$

$$0.46 \pm 0.02$$

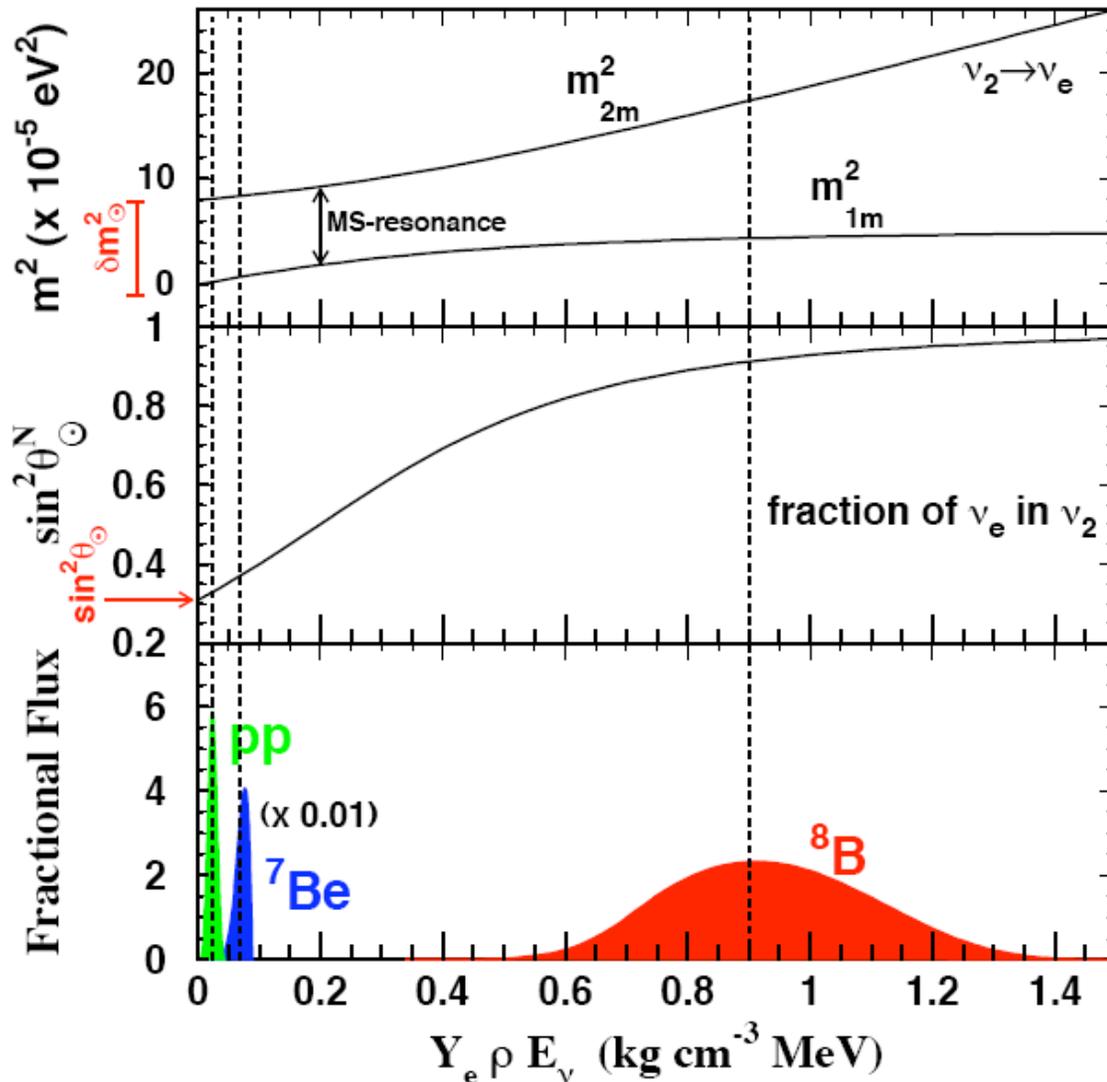
$$0.35 \pm 0.03$$

$$0.56 \pm 0.08$$

Solar Measurements



Matter Effects in the Sun



In Vacuum

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

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

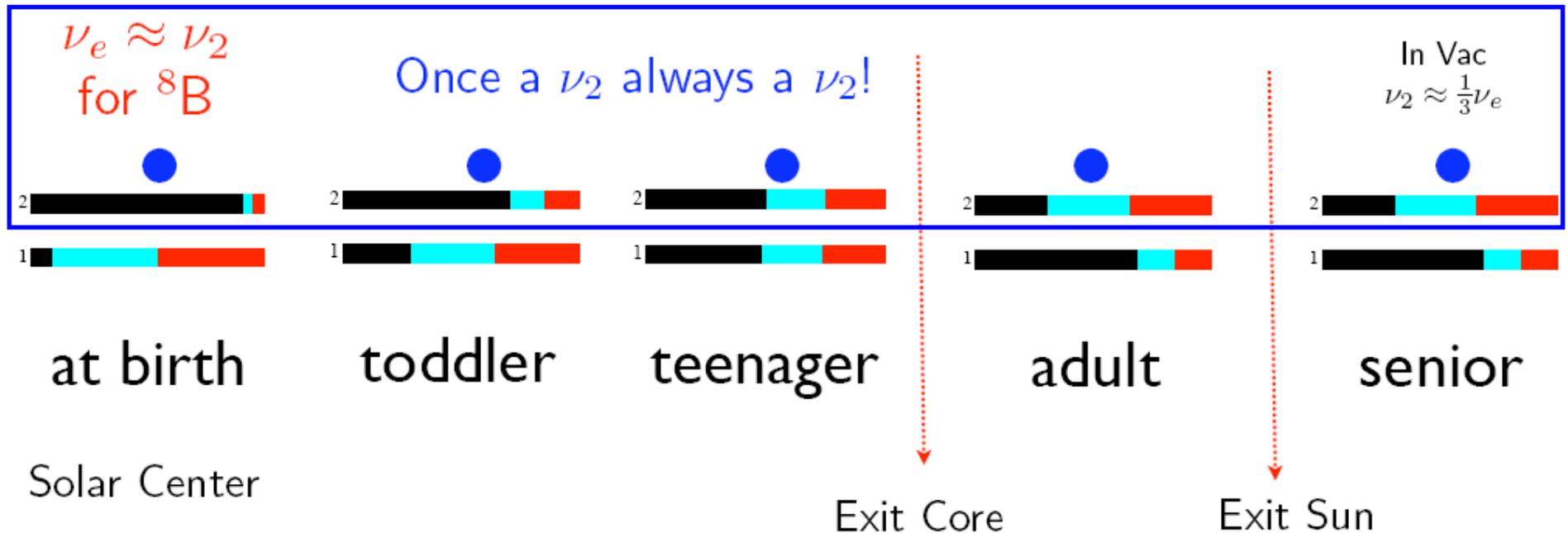
\sin^2

Whereas for ${}^8\text{B}$
at center of Sun

$$\delta m_N^2 = 14 \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_\odot^N = 0.91$$

Life of a Boron-8 Solar Neutrino:



ν_e ■ ν_μ ■ ν_τ ■

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

Solar Oscillation Summary

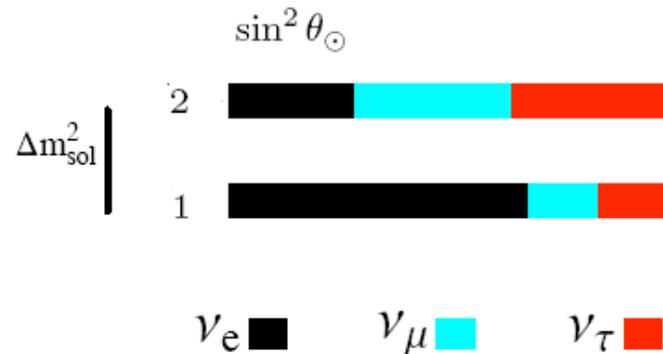
$$f_1 = \cos^2 \theta_{\odot}^N \text{ and } f_2 = \sin^2 \theta_{\odot}^N \qquad \langle P_{ee} \rangle = f_1 \cos^2 \theta_{\odot} + f_2 \sin^2 \theta_{\odot}$$

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

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

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

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



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

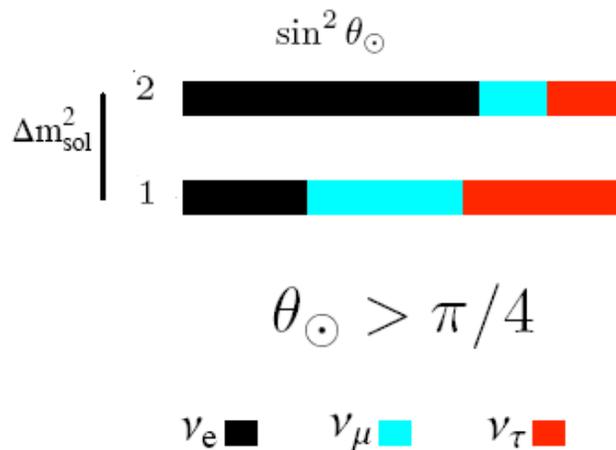
$$\sin^2 \theta_{\odot} = 0.310 \pm 0.026$$

at 68% CL

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

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 .

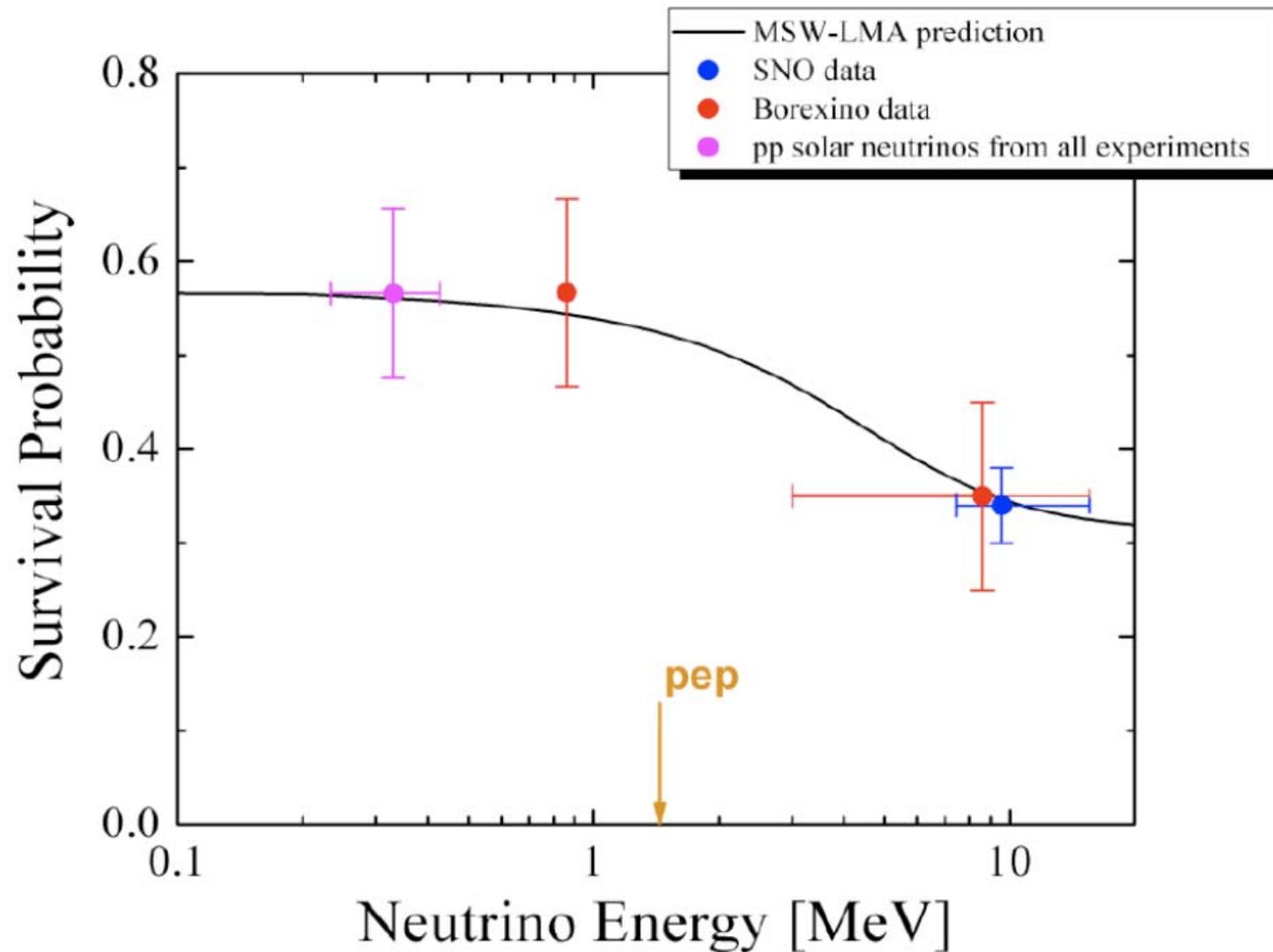
This raises the survival probability above vacuum value since ν_2 has more ν_e . But the minimum of P_{ee} in vacuum is $1/2$.

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

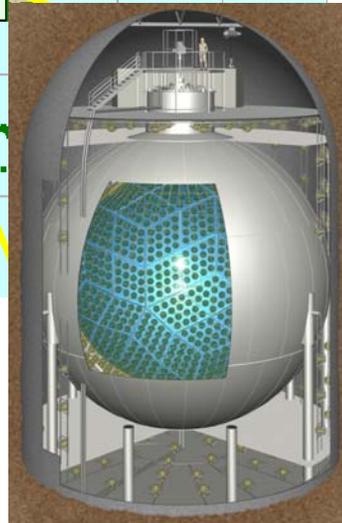
But $P_{ee}^{\text{SNO}} = 0.347 \pm 0.038 < 1/2$

This solar hierarchy EXCLUDED !!!.

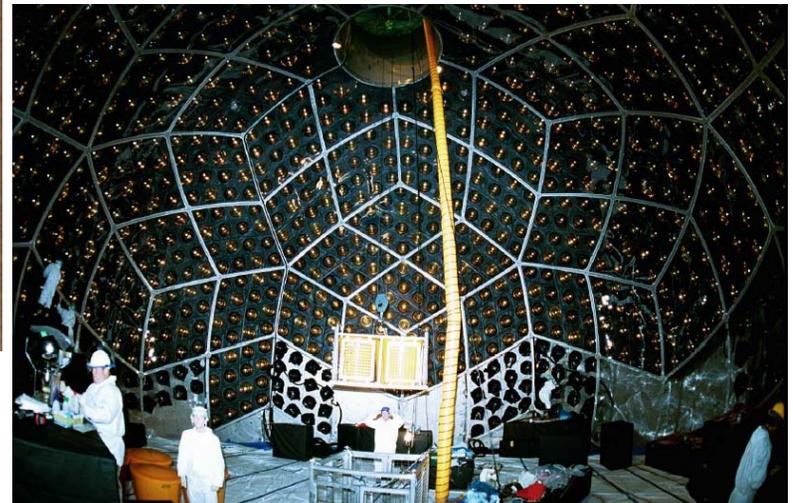
Transition from Vacuum to Matter Oscillations



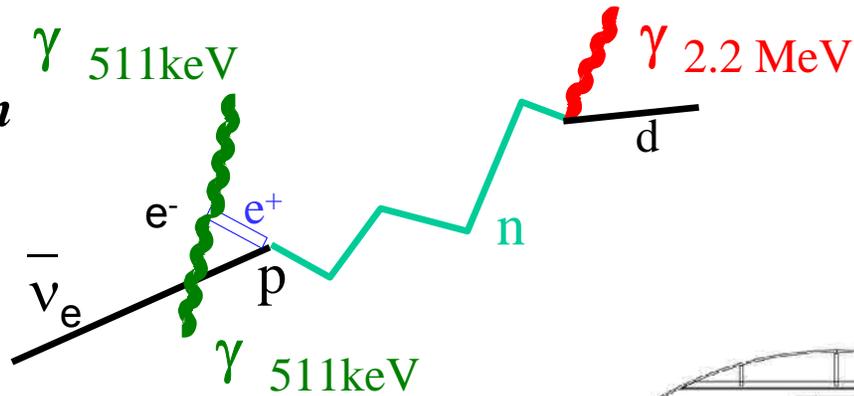
Kamland Reactor Exp. (Probes for $\bar{\nu}_e$ Osc. In the Solar Region)



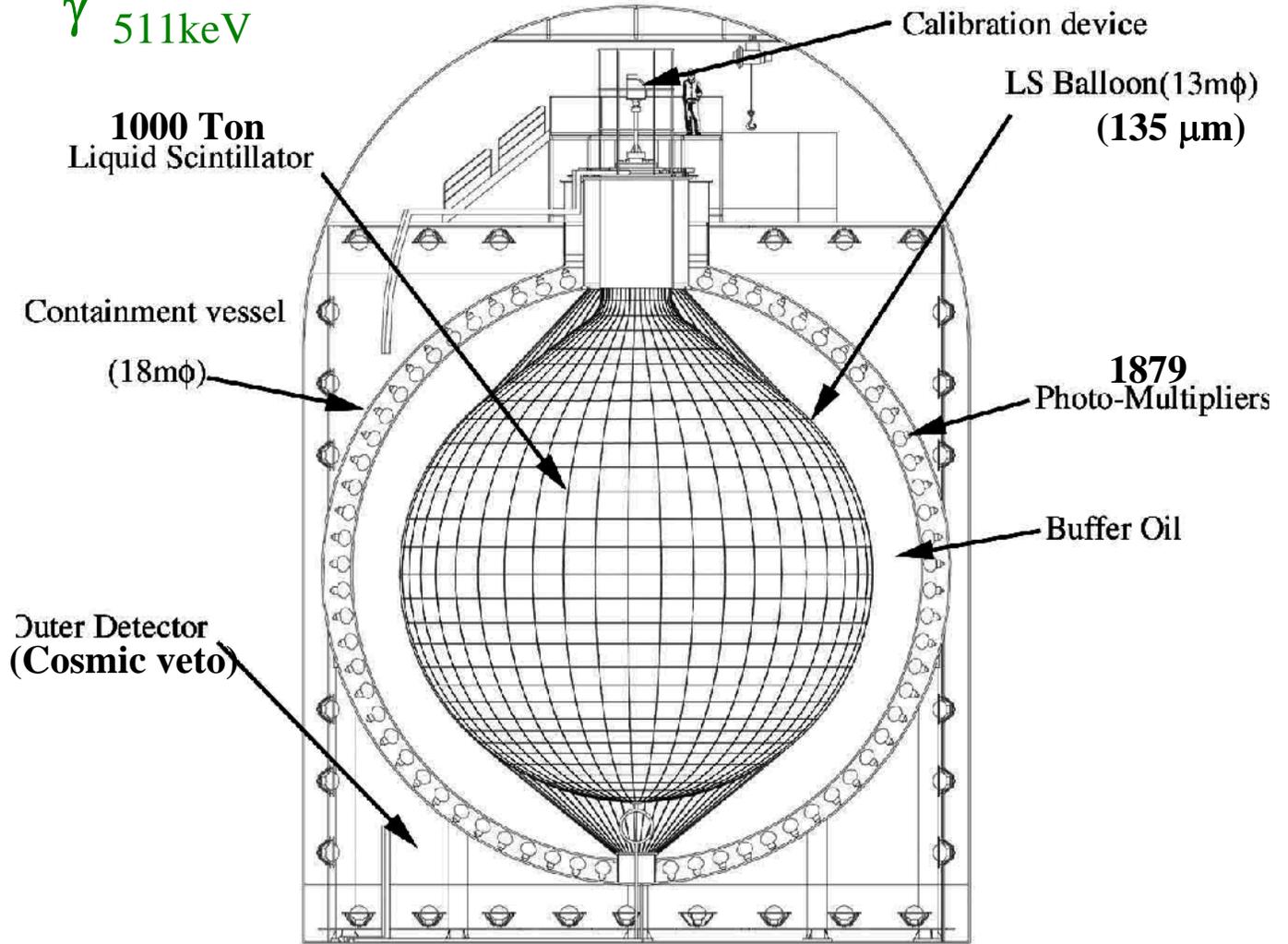
- Uses $\bar{\nu}_e$ from all the reactors in Japan
- 85% of signal events from:
 - Closest 60 GW of power
 - Distance range 140km to 344 km
- KamLAND is a 1 kton liquid scintillator detector
 - 2000 photomultiplier tubes
 - 1 km underground
- Began data taking in Sept., 2001.

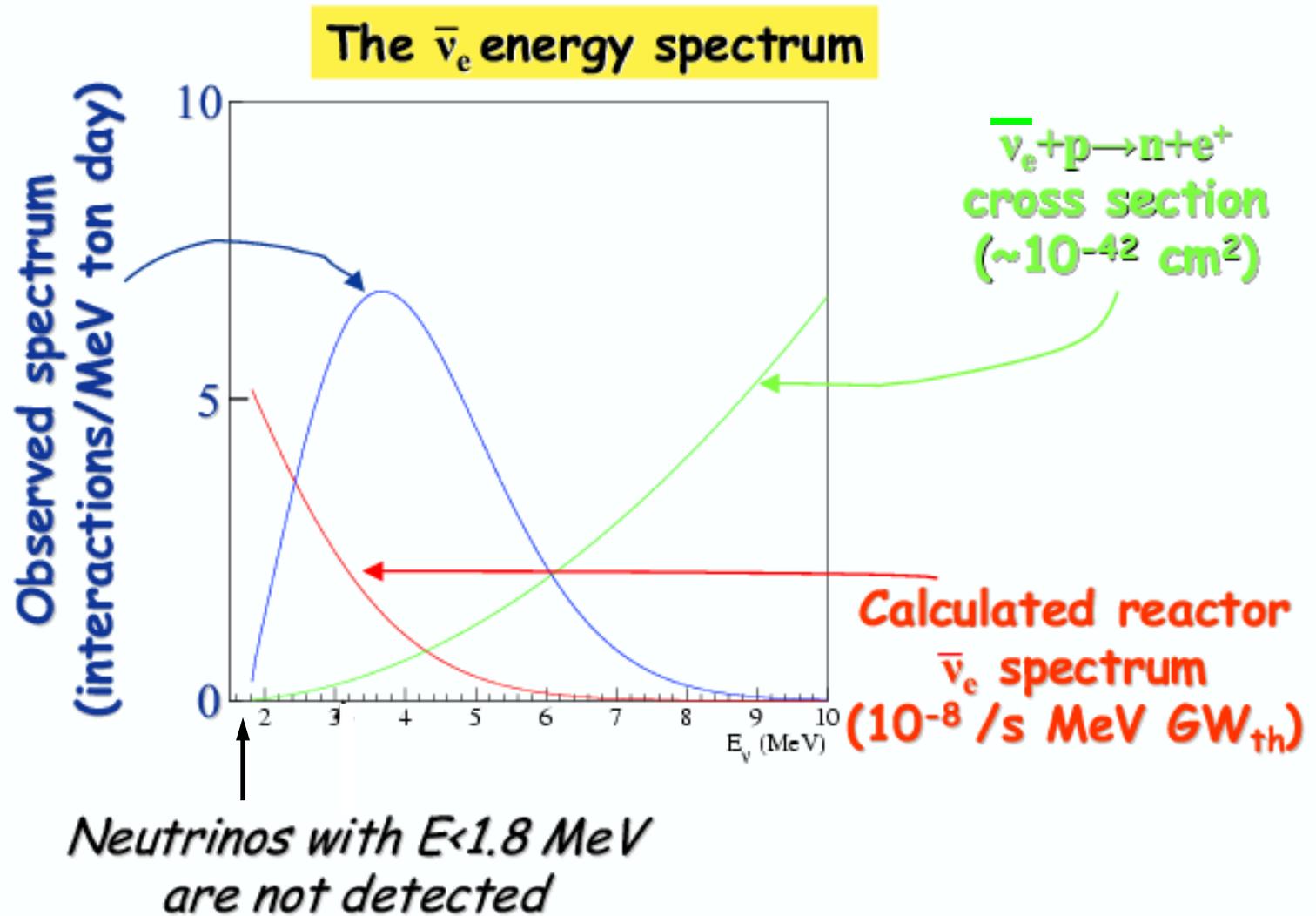


*e⁺ plus neutron
delayed
coincidence*

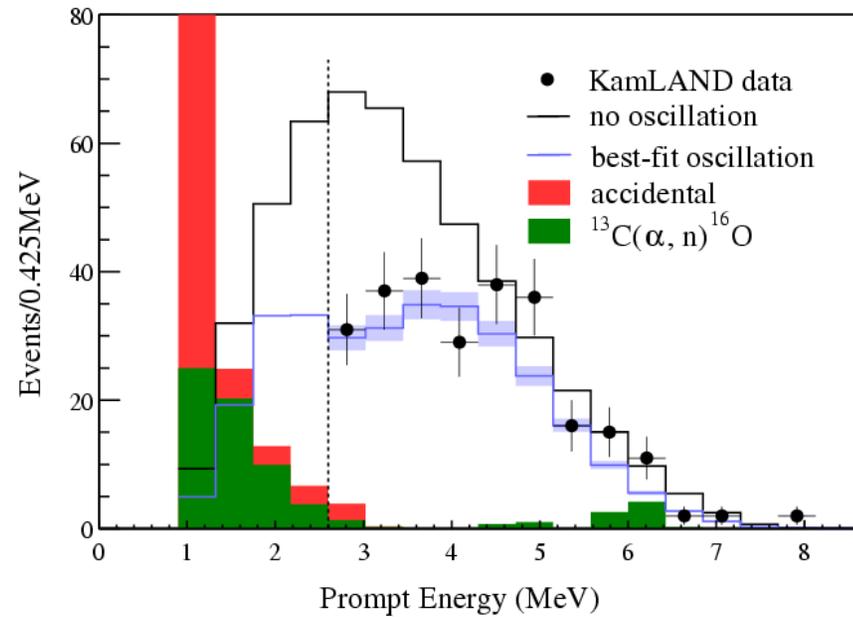
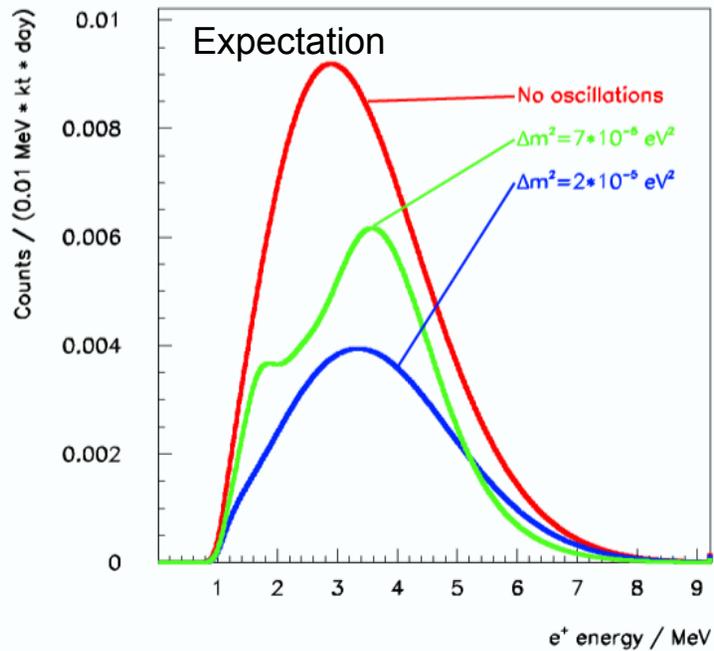


KamLAND Detector





KamLAND Results



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

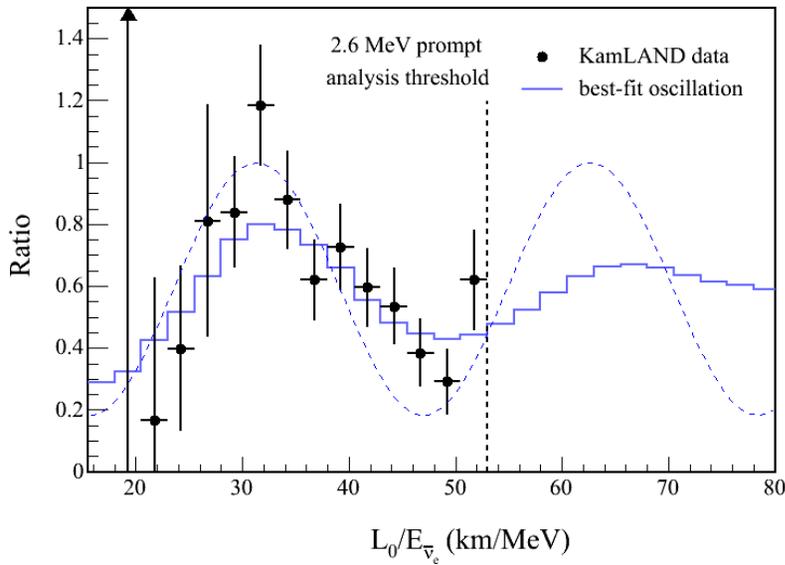
$$\frac{(N_{\text{obs}} - N_{\text{bkgnd}})}{N_{\text{no-osc}}} = 0.658 \pm 0.044 \text{ (stat)} \pm 0.047 \text{ (syst)}$$

(99.998 % CL signal)

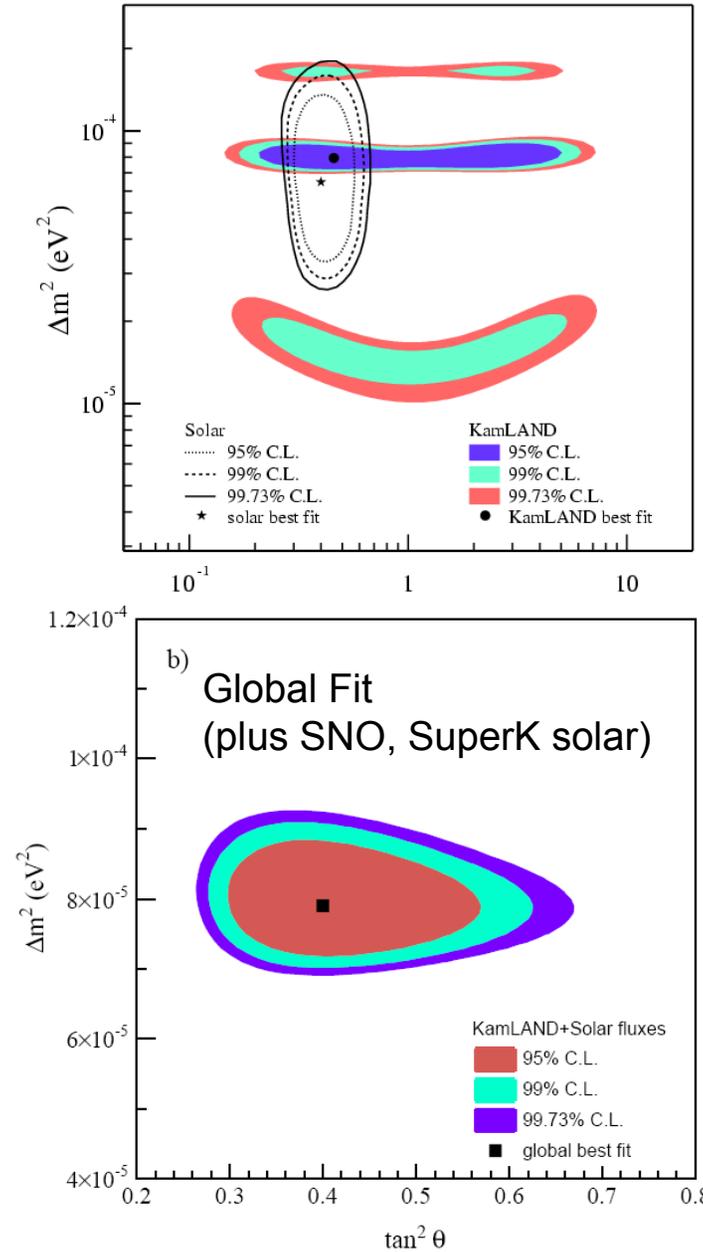
Neutrino Oscillation Interpretation

Distribution has L/E behavior expected for neutrino oscillations

KamLAND best fit :
 $\Delta m^2 = 7.9 \times 10^{-5} \text{ eV}^2$
 $\tan^2 \theta = 0.45$



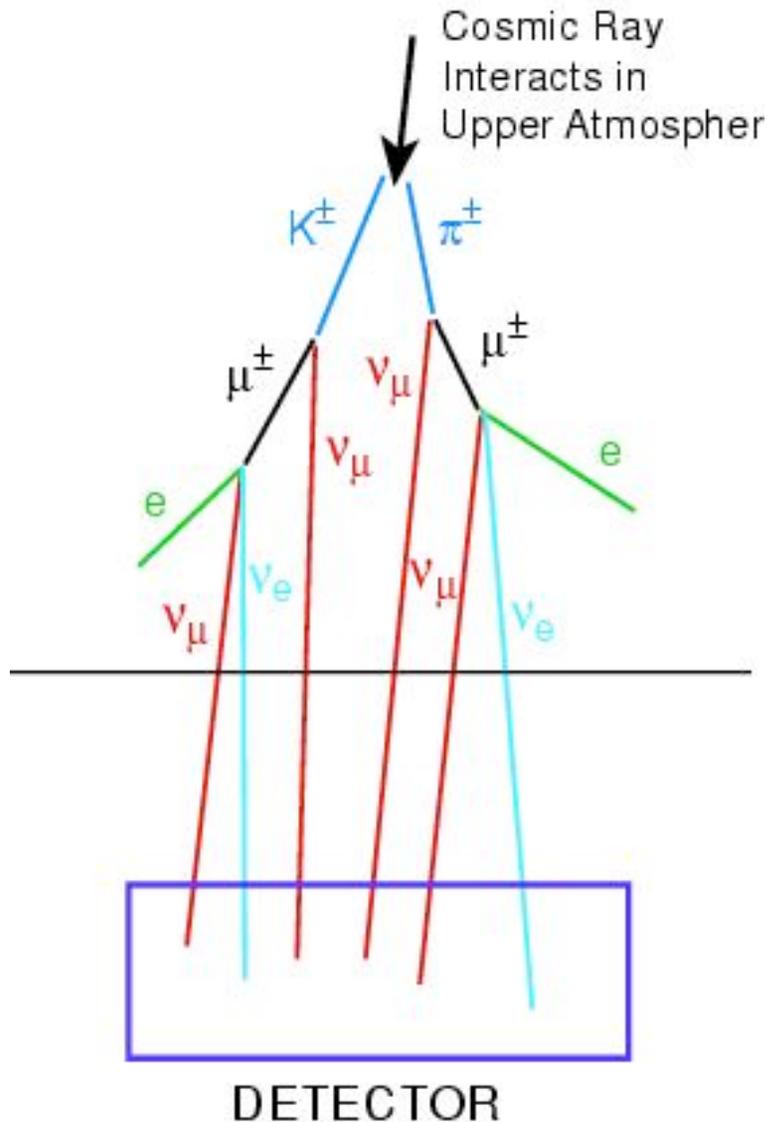
$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$
 $\tan^2 \theta = 0.40^{+0.10}_{-0.07}$
 ($\sin^2 2\theta_{12} = 0.82^{+0.07}_{-0.07}$)



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
⇒ Need to include matter effects (electron density)
- Kamland reactor experiment agrees with solar oscillation parameters
⇒ Constrains Δm^2

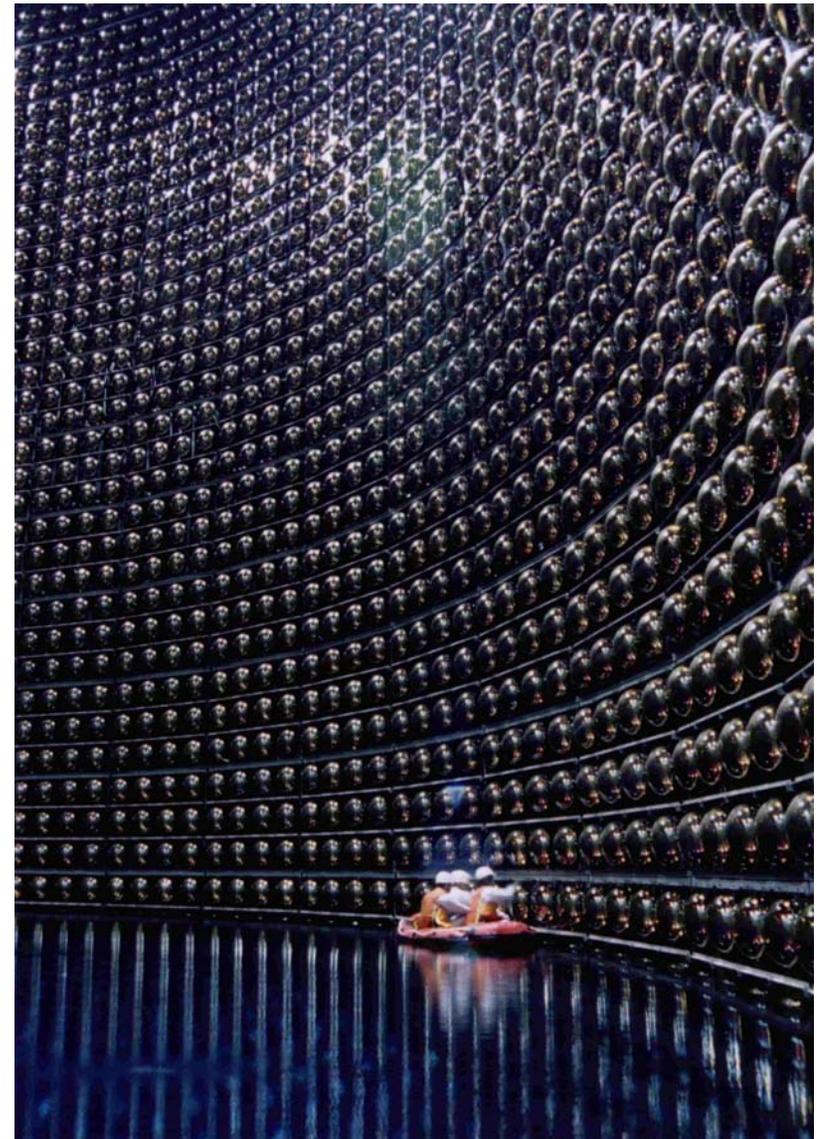
Atmospheric Neutrinos: ν_e and ν_μ



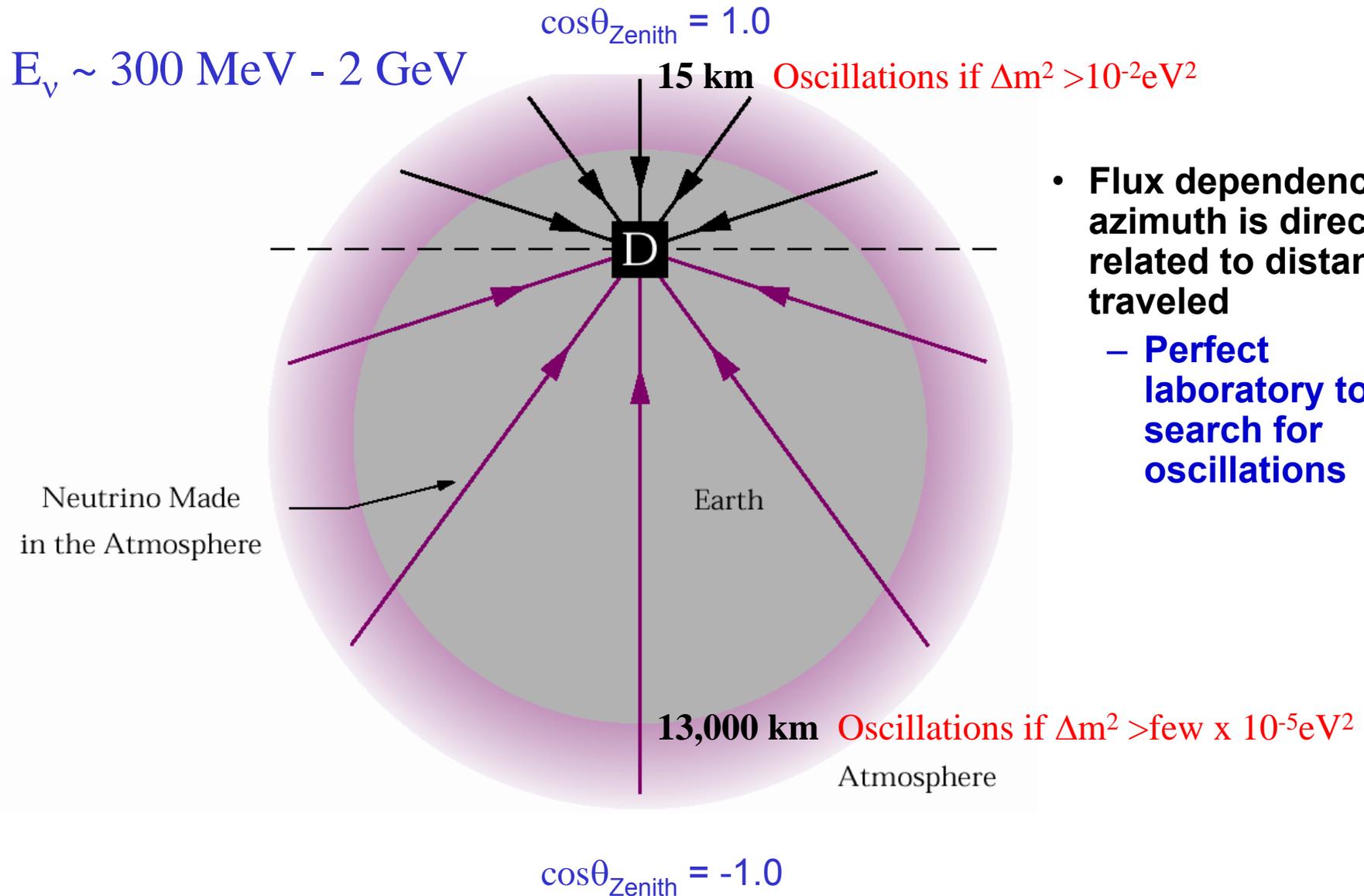
- π or K decay $\rightarrow \mu + \nu_\mu$.
- Then the muon decays to $e + \nu_e + \nu_\mu$
- $(\nu_\mu + \bar{\nu}_\mu) / (\nu_e + \bar{\nu}_e)$ ratio should be **= 2**.
- Measured to be **1** by some experiments.
- Some others closer to 2.
- Inconclusive.
- Then SuperKamiokande was built.

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

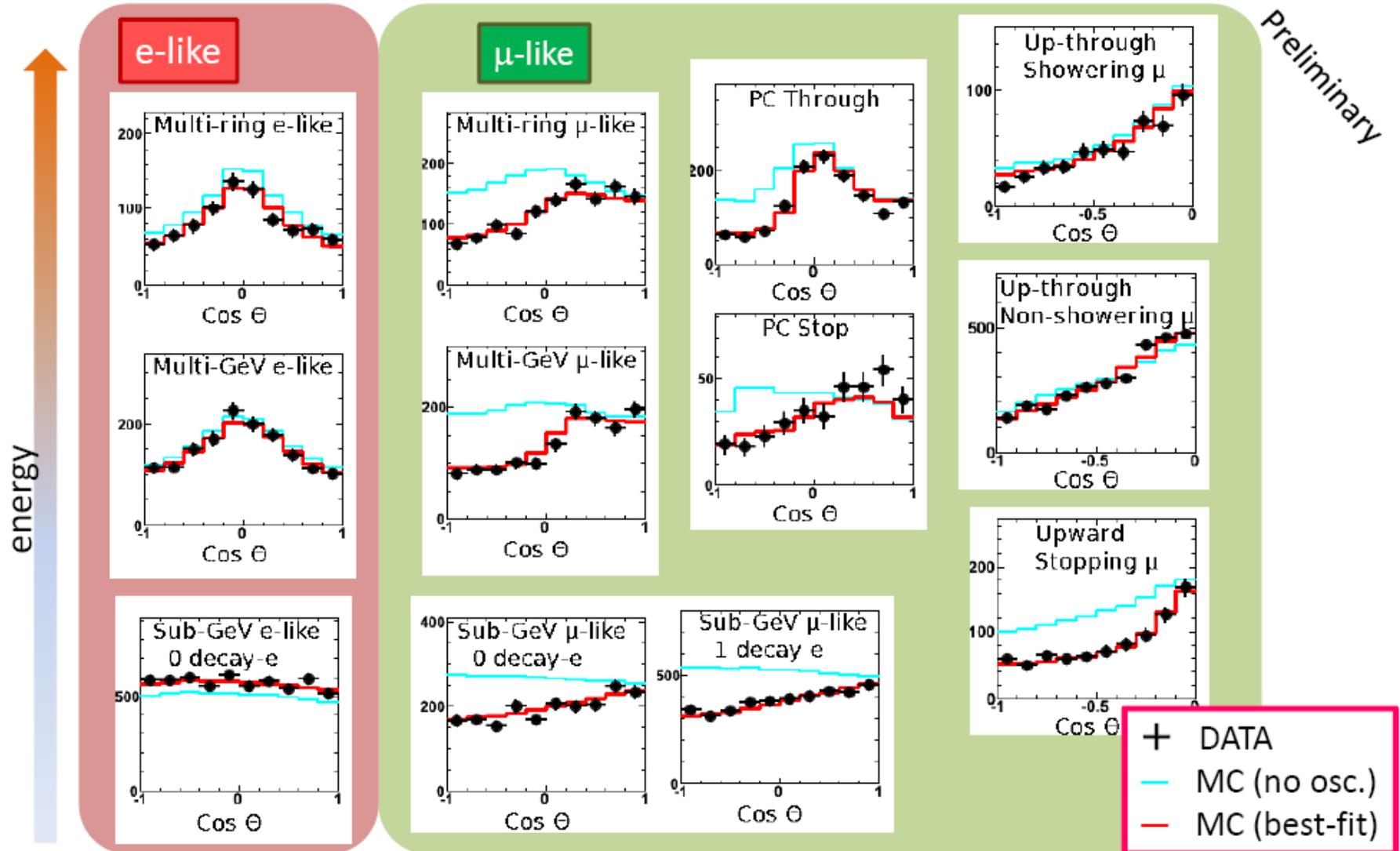


Atmospheric Neutrino Studies

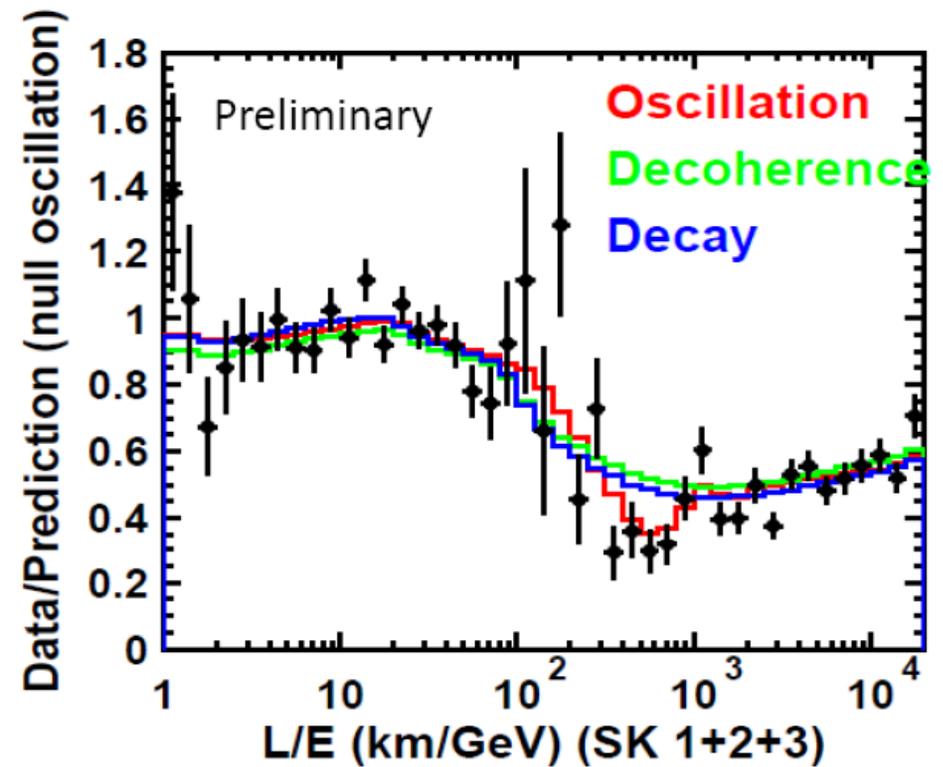
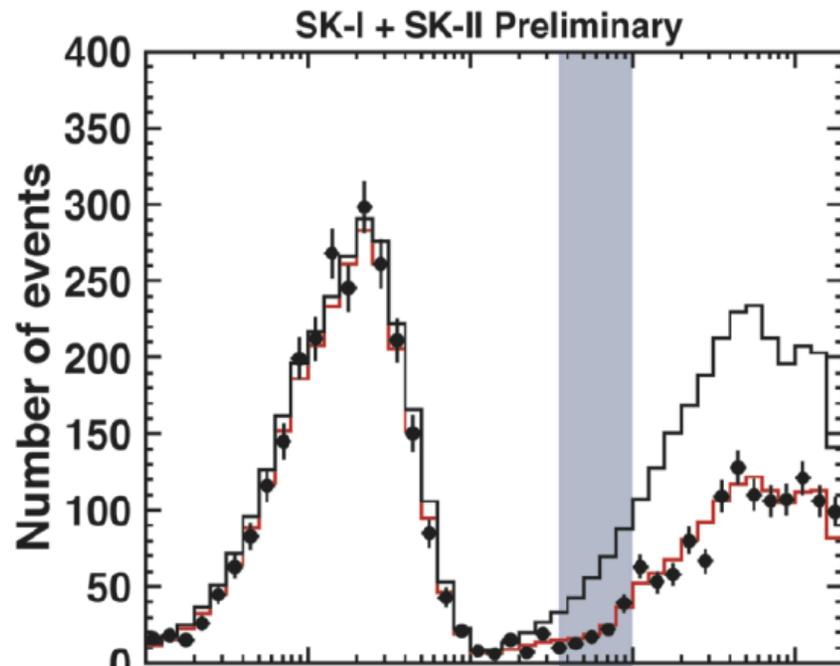


Atmospheric Neutrino Data from Super-K

Super-K-I+II+III (2806 days (173kton·yr) for FC+PC, 3109 days for up- μ)



Atmospheric Oscillation Results

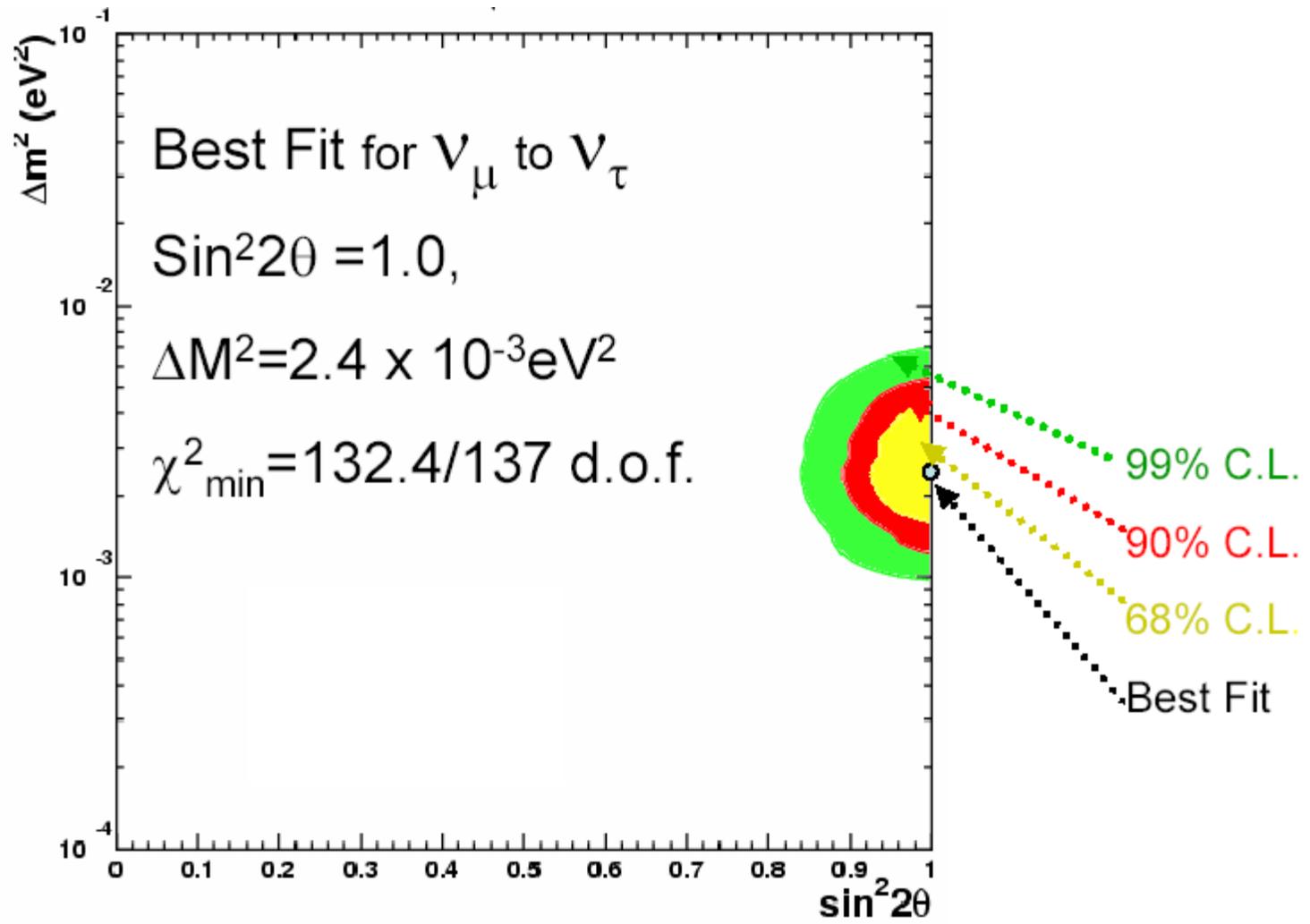


Inconsistent with:

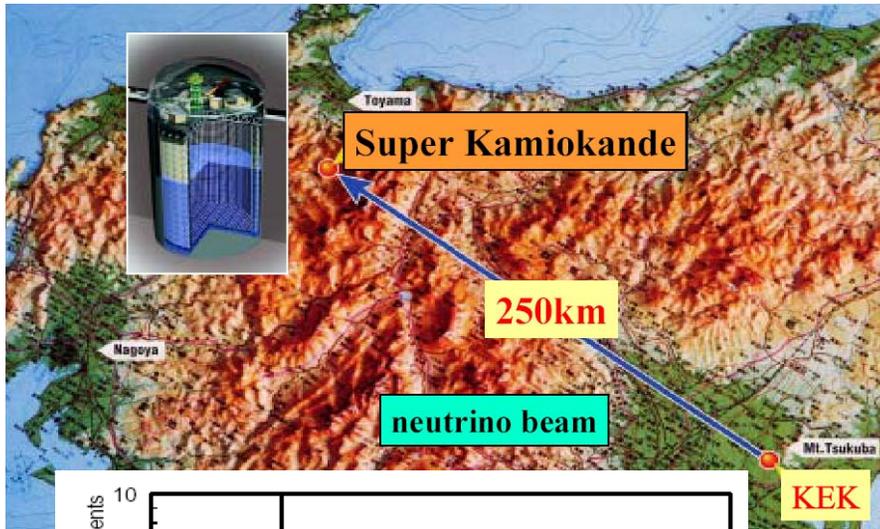
Neutrino decay (4.4σ)

Neutrino decoherence (5.4σ)

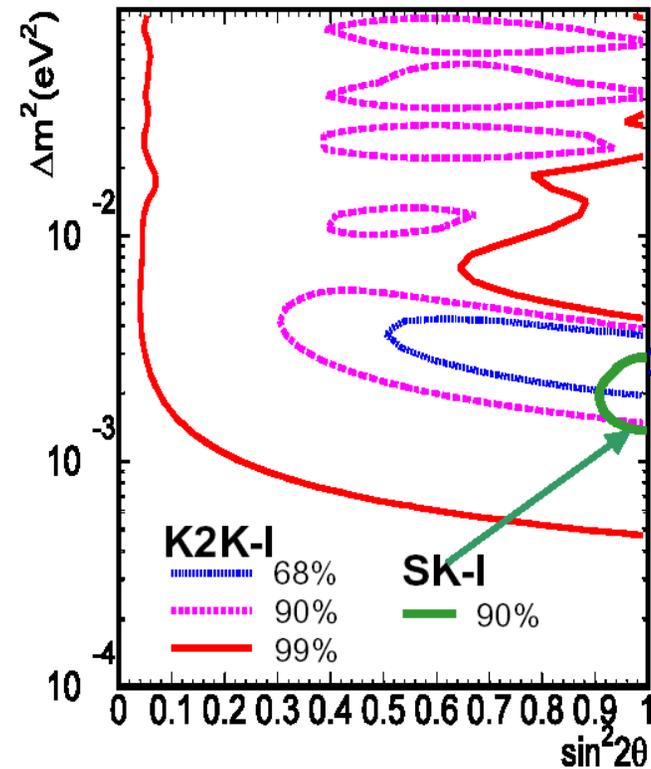
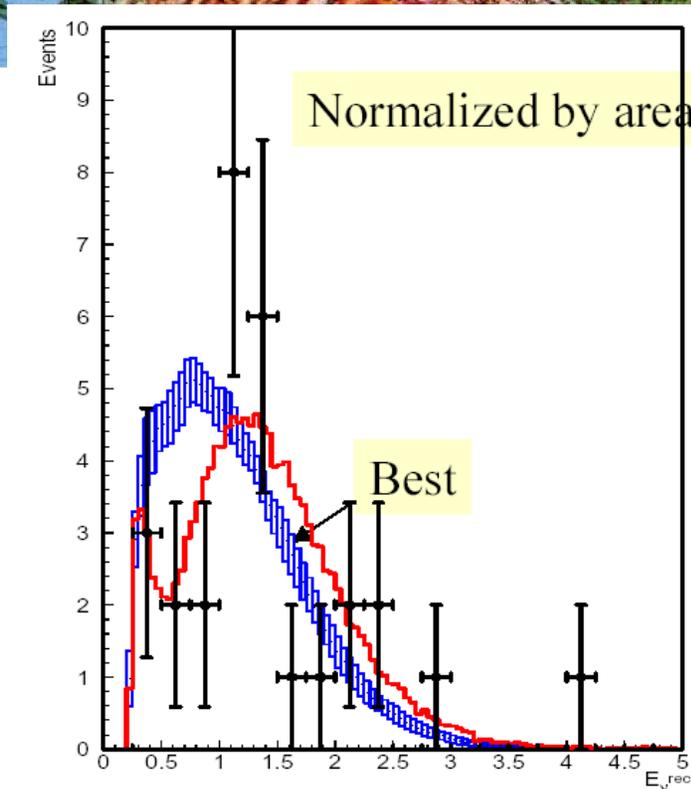
Super-K Fits to $\nu_\mu \rightarrow \nu_\tau$



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



5.4 kton MINOS far detector

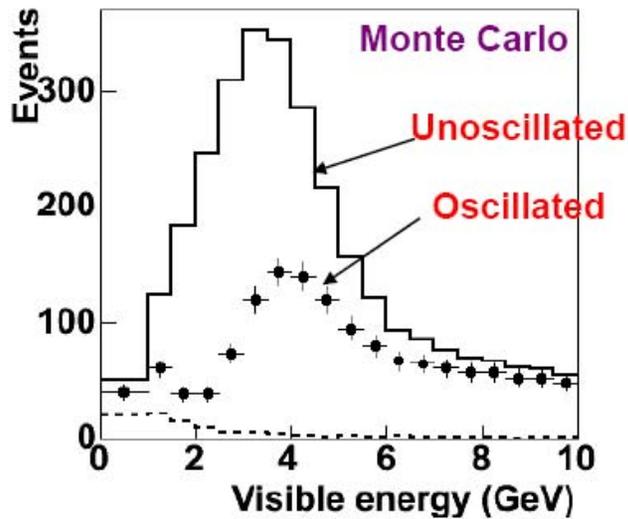


1 kton near detector

A,Habig, July 2

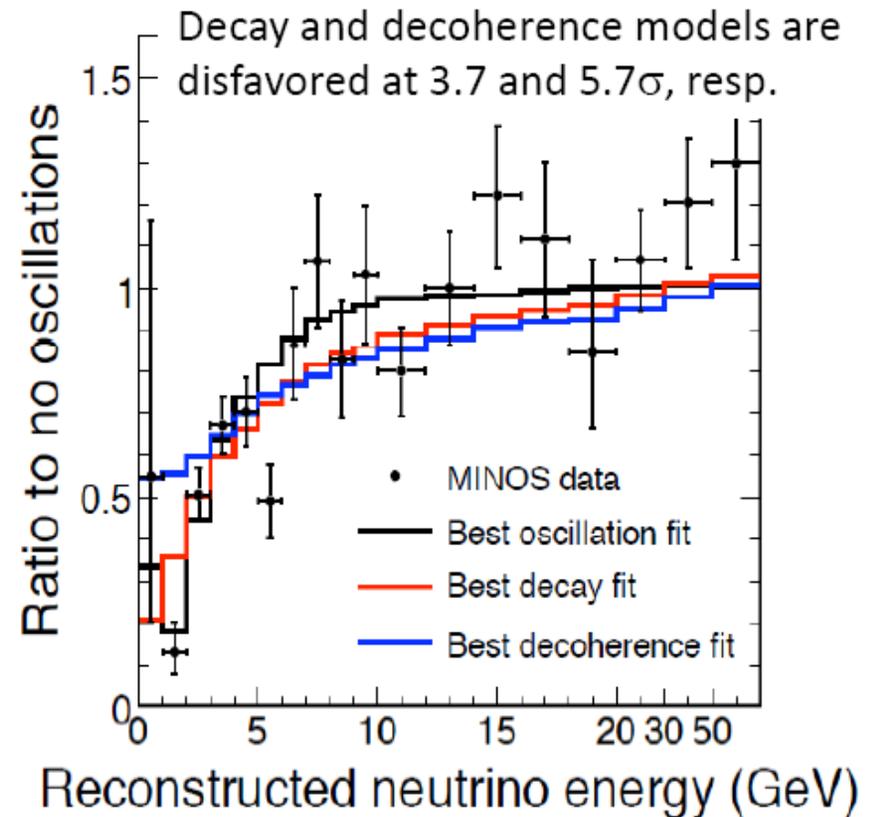
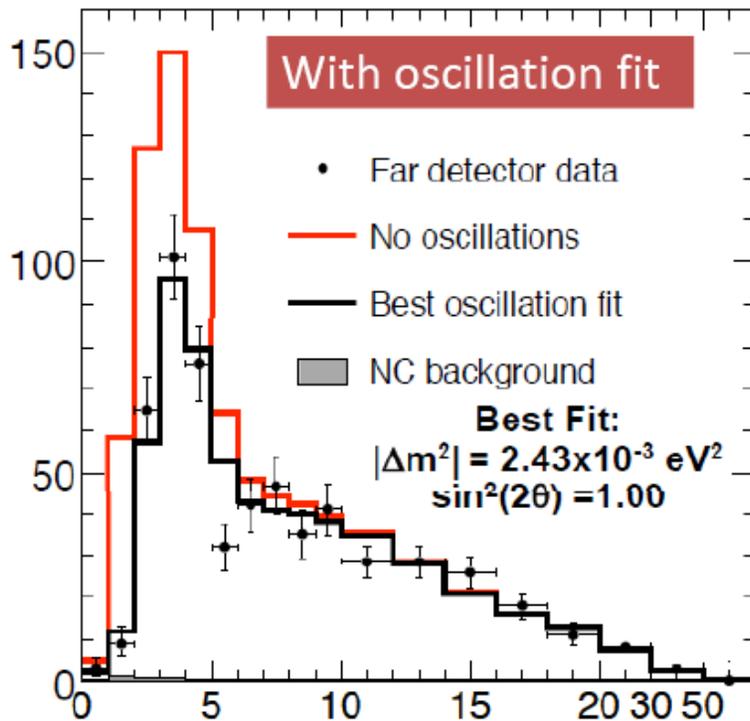


NuMI beam line



MINOS ν_μ Disappearance Results

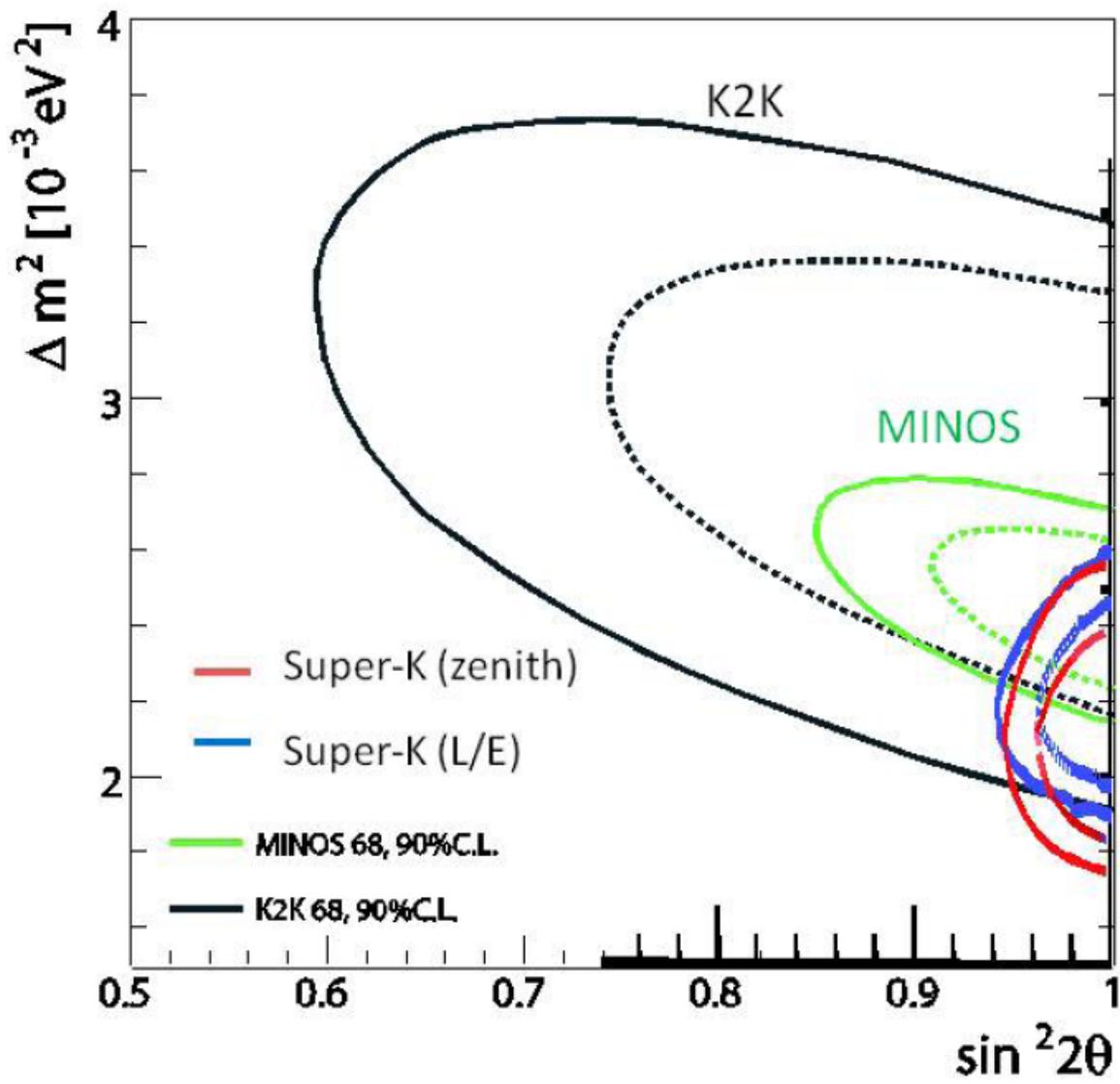
848 CC ν_μ candidates \leftrightarrow $1065 \pm 60(\text{syst})$ no-osc. prediction



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(hep-ex/0806.2273)

Summary of Current “Atmospheric” Region Results

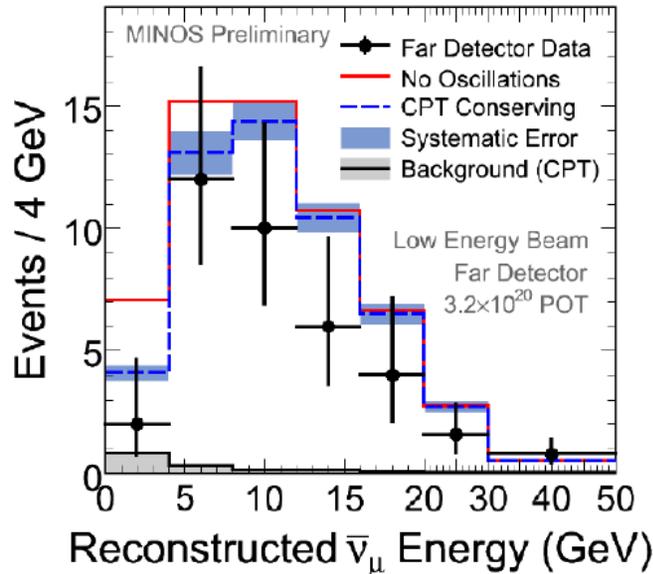


$$\Delta m_{23}^2 = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2$$

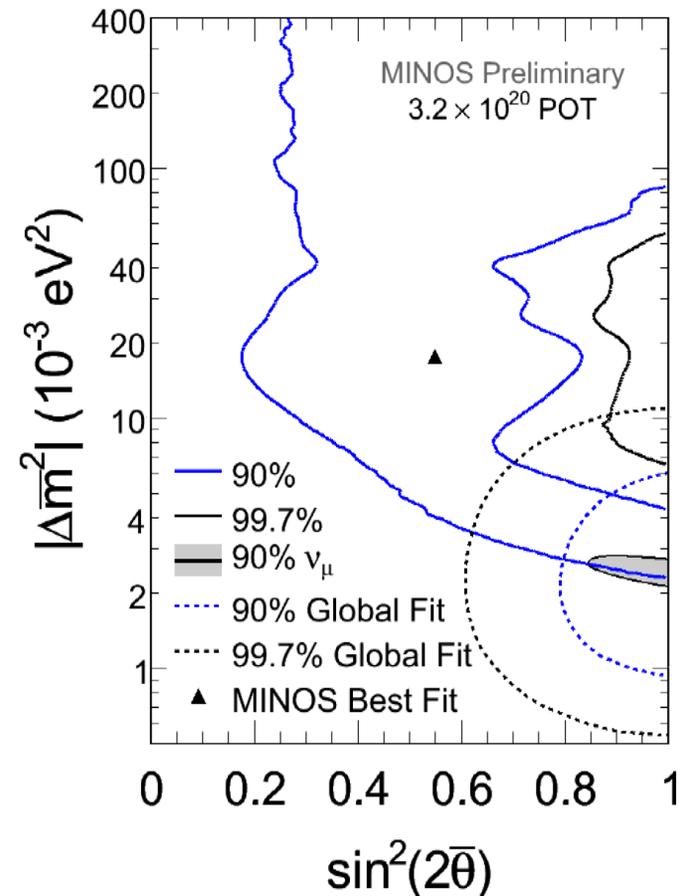
(5% accuracy, MINOS)

1st MINOS “Pure” $\bar{\nu}_\mu$ Disappearance Results

- 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.
- ⇒ Can search for $\bar{\nu}_\mu$ disappearance!



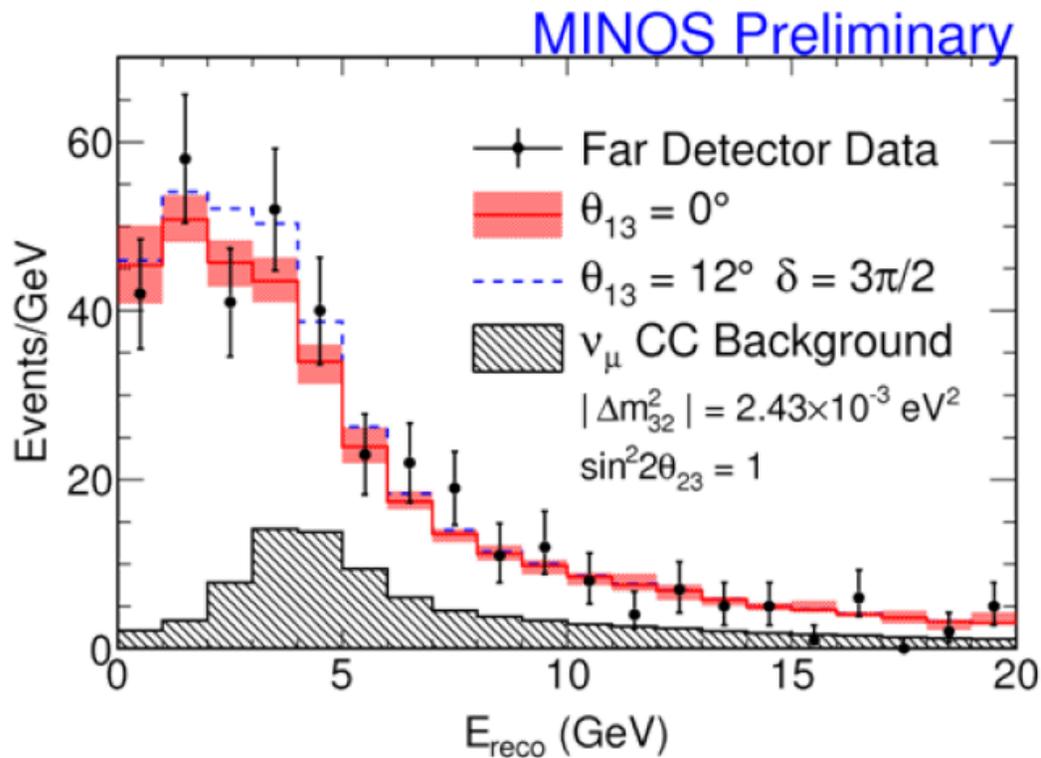
Results: 42 events observed
 Expect: No osc: $65 \pm 8_{\text{stat}} \pm 4_{\text{syst}}$
 CPT conserving: $58 \pm 8_{\text{stat}} \pm 4_{\text{syst}}$



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

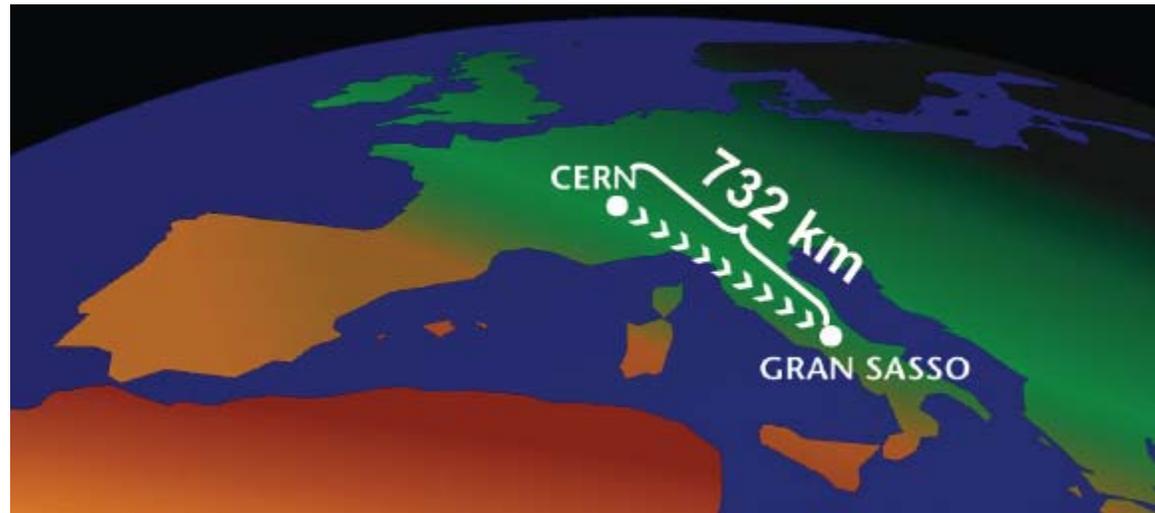
MINOS Search for Oscillations to Sterile Neutrinos

- “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 \Rightarrow NC rate in near and far detector should be the same
- If $\nu_\mu \rightarrow \nu_{\text{sterile}}$ then NC rate should be less in far detector

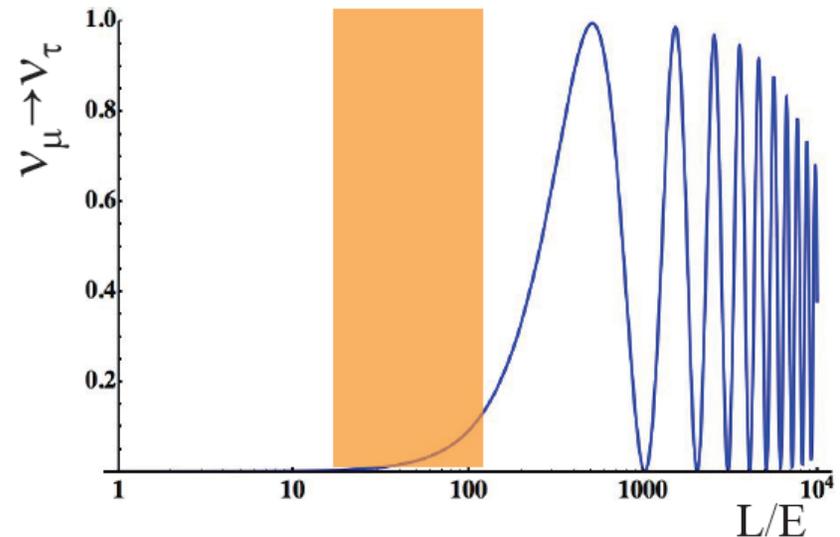


Data are consistent with no NC deficit at FD and thus with no sterile neutrino mixing

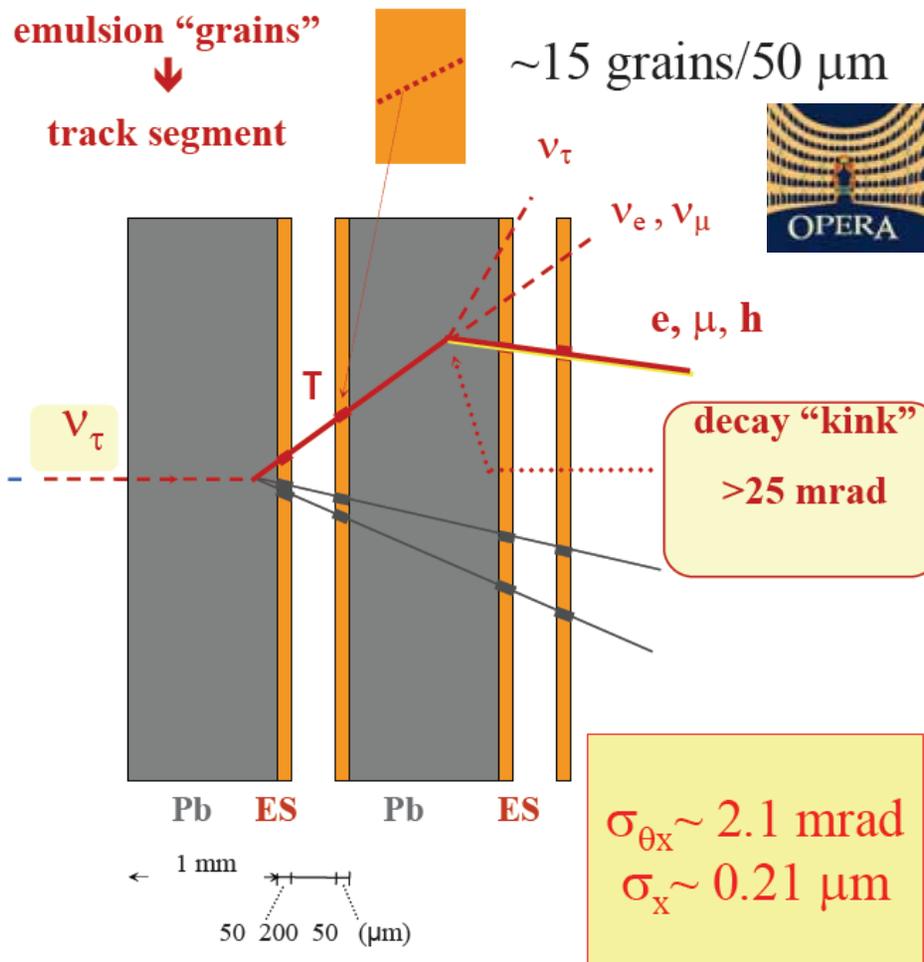
OPERA and ICARUS: ν_τ Appearance Search



- 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 \Rightarrow 10% run completed (1700 ν -events recorded)

ICARUS: Liquid Argon TPC 600 Tons



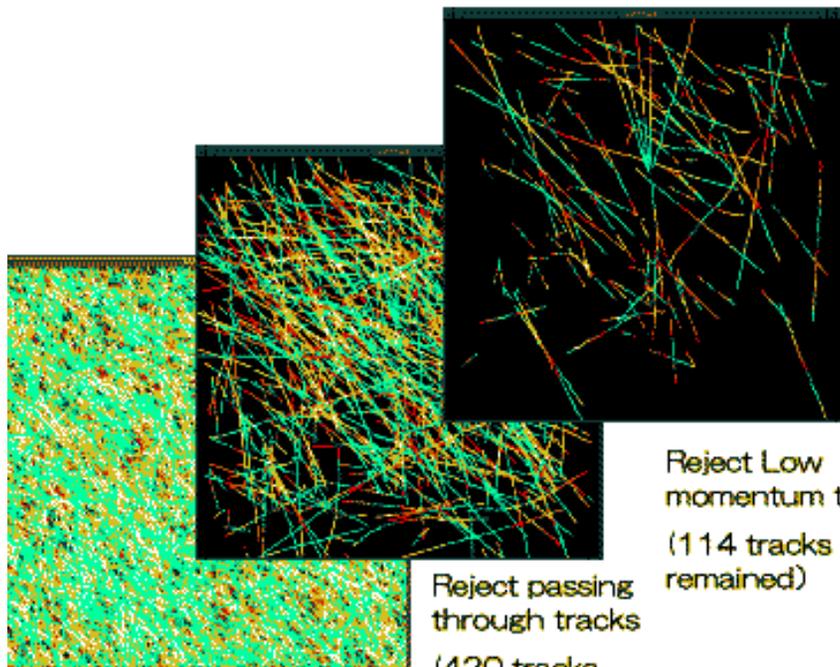
- Will use kinematic reconstruction to isolate ν_τ -events.
- 1st event expected by end of 2009



OPERA

**Expect about 15 events
in 5 years.**

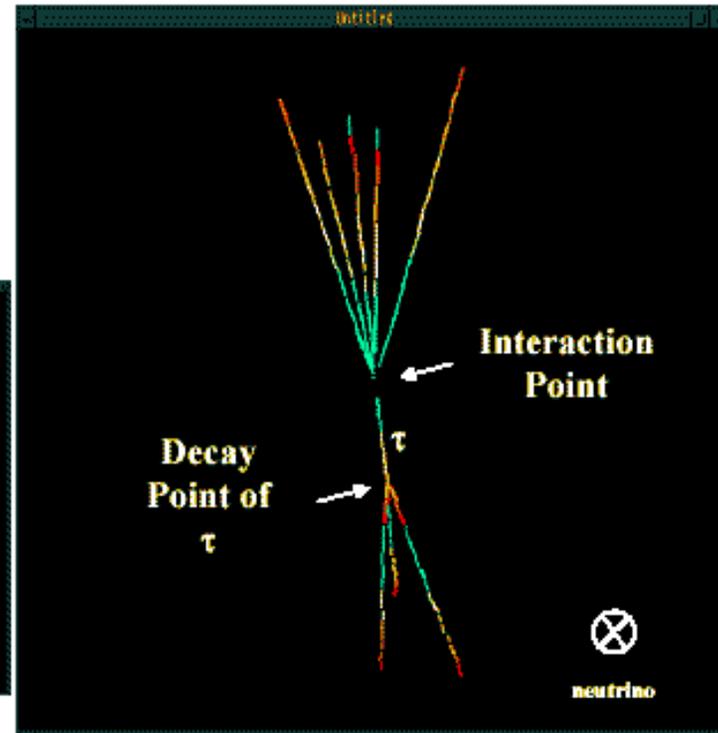
Event Reconstruction



All tracks in the Scanning region (4179 tracks)

Reject passing through tracks (420 tracks remained)

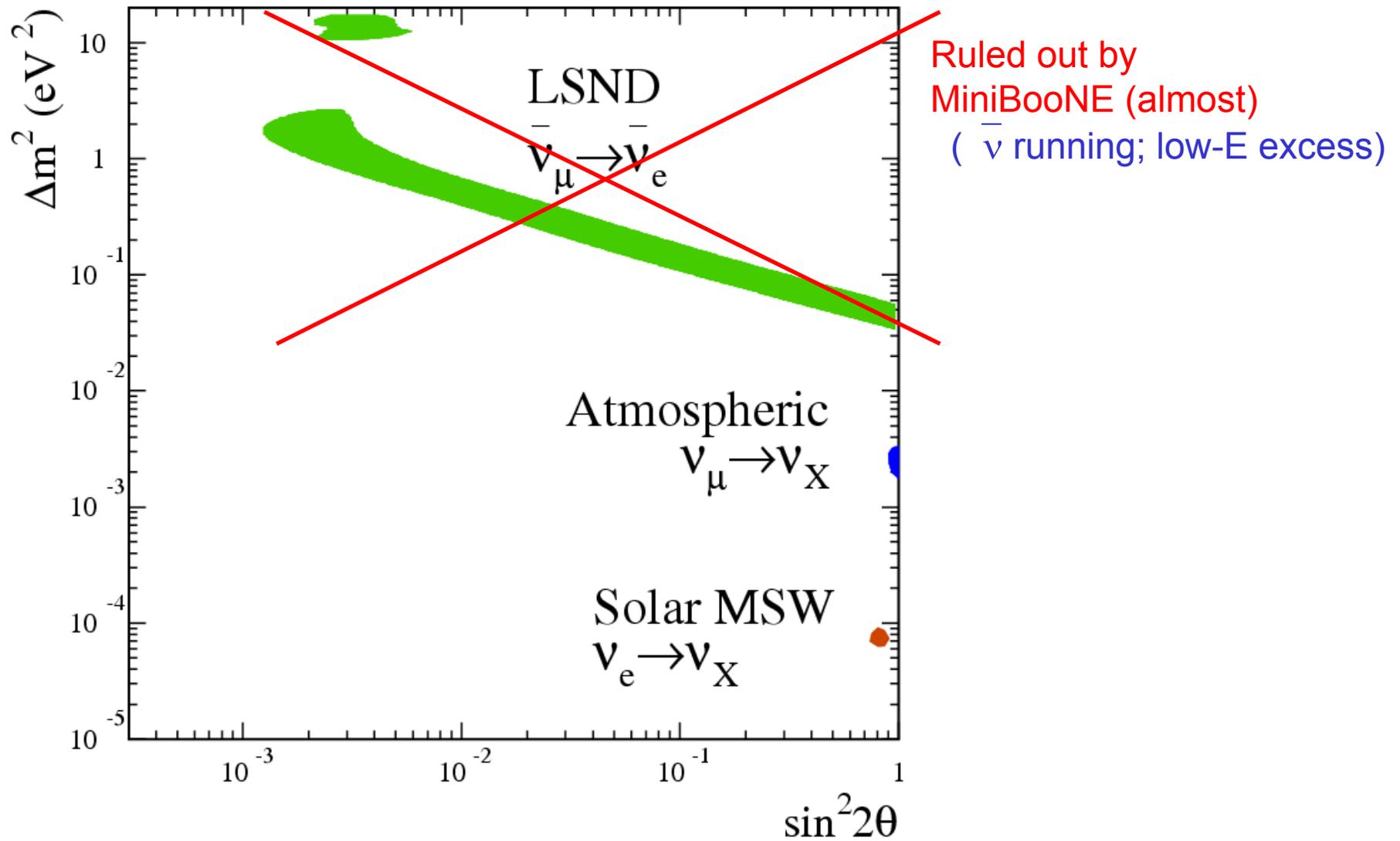
Reject Low momentum tracks (114 tracks remained)



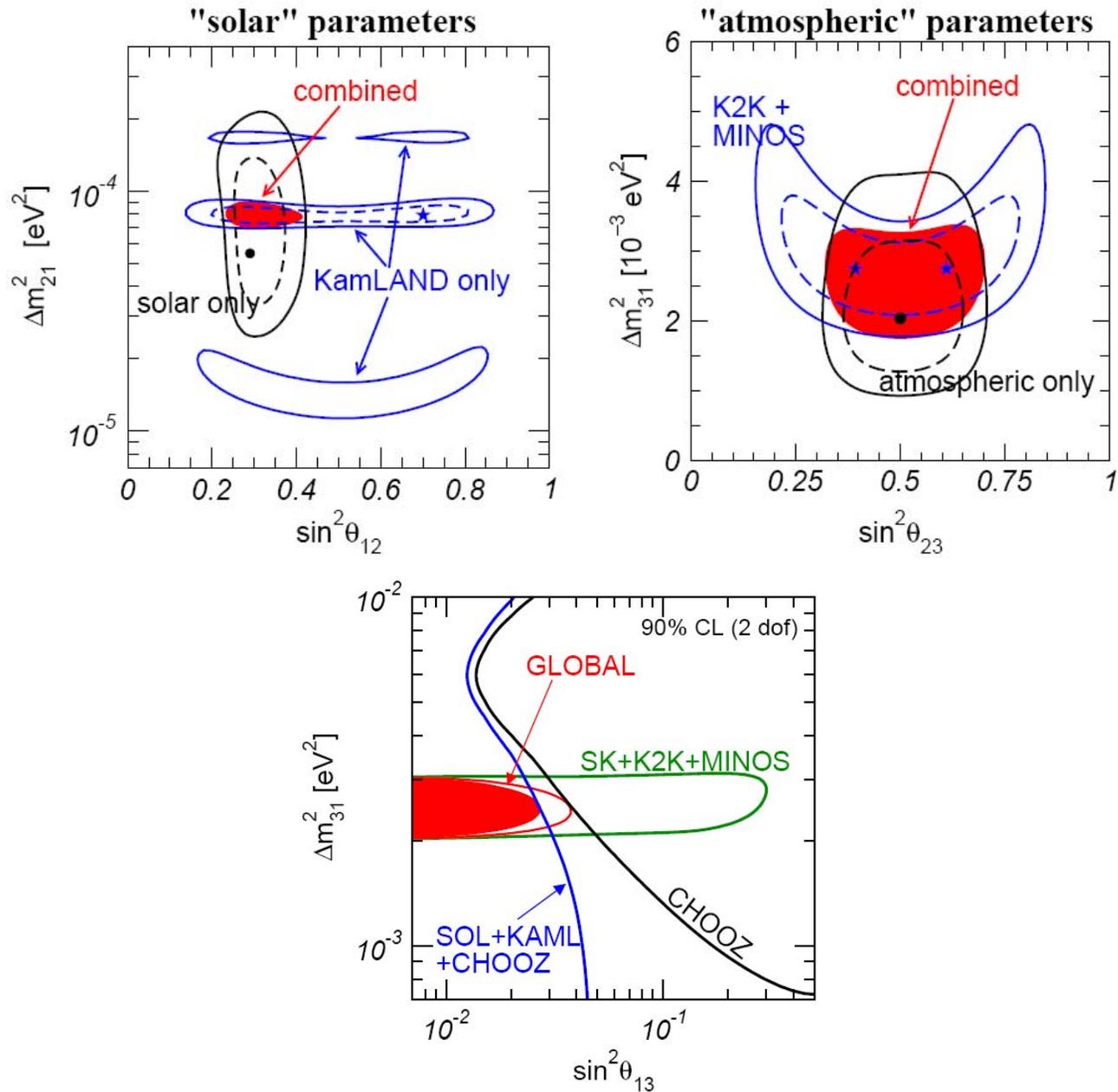
Vertex detection :
Neutrino interaction and decay of short lived particles

Detection of ν_{τ}^{CC} in DONUT

Current Oscillation Summary



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 $\theta_{13} < 13^\circ$
2. Is the $\mu - \tau$ mixing maximal?
 – $35^\circ < \theta_{23} < 55^\circ$
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 $\delta \neq 0$?

