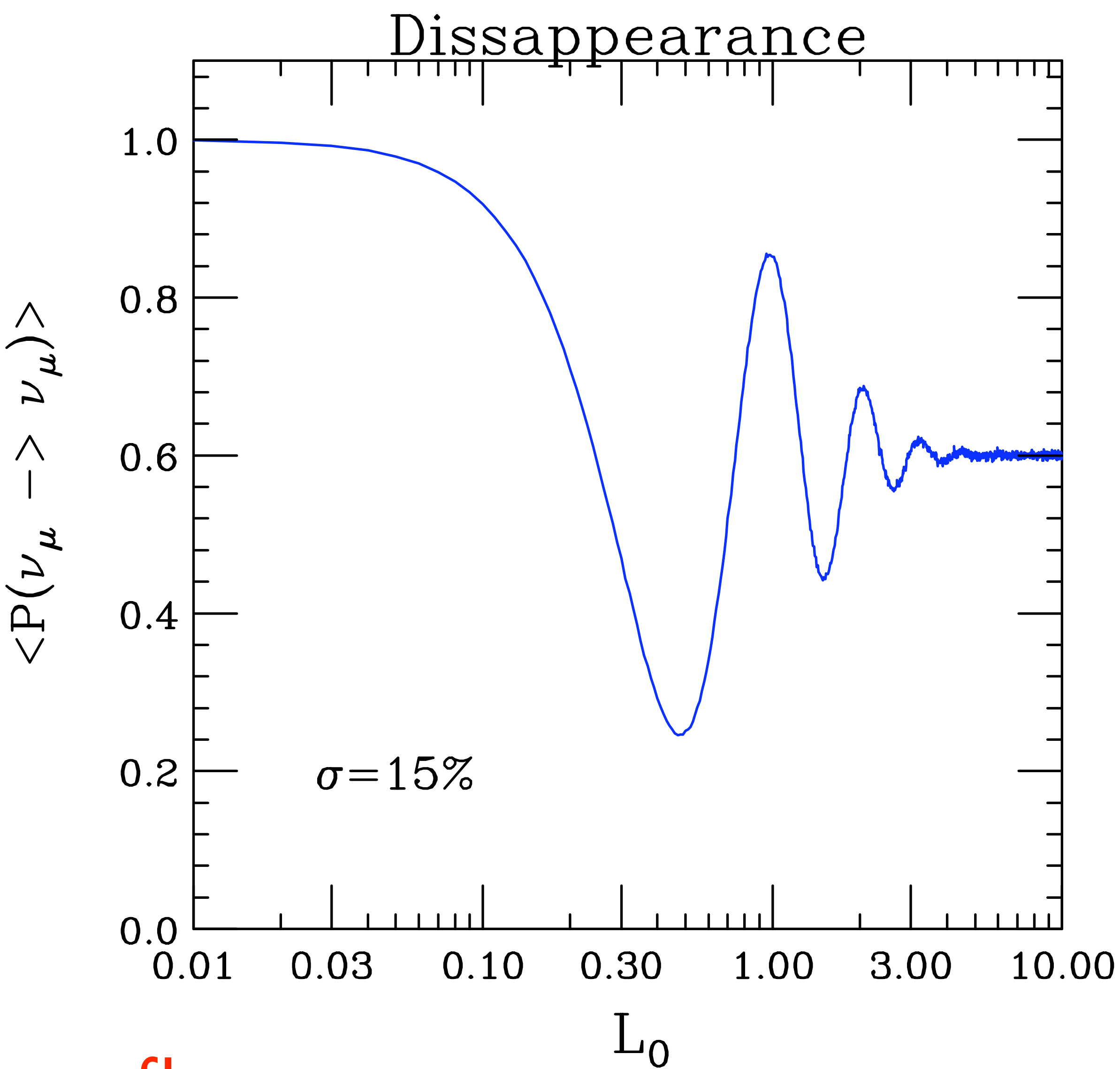
$$\langle P(\nu_\mu \to \nu_\mu)\rangle = 1 - \sin^2 2\theta \left\langle \sin^2 \frac{\delta m^2 L}{4E} \right\rangle$$

Spread E_ν



$$1 - \sin^2 2\theta(\tfrac{1}{2}) = \cos^4\theta + \sin^4\theta$$

Understood in terms of probability

$W^+ \to \mu^+ + \nu_1$ probability $\cos^2\theta$

$W^+ \to \mu^+ + \nu_2$ probability $\sin^2\theta$

probability ν_1 contains ν_μ is $\cos^2\theta$

probability ν_2 contains ν_μ is $\sin^2\theta$

flavor

flavor oscillations

effectively incoherent
mass eigenstates

Neutrinos,

In and Beyond the Standard Model:

Stephen Parke
Fermilab

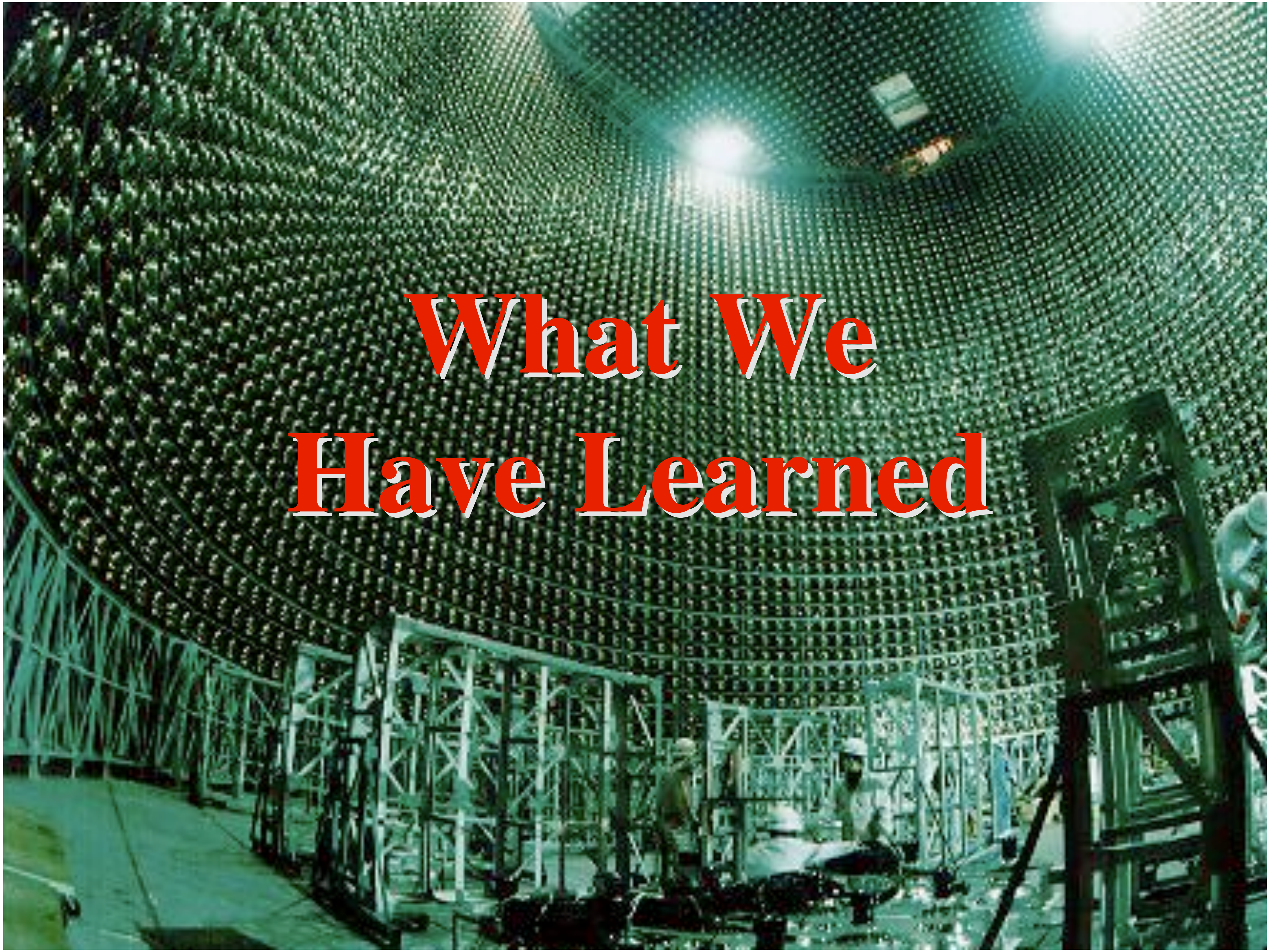
Evidence for Flavor Change:

Evidence for Flavor Change:

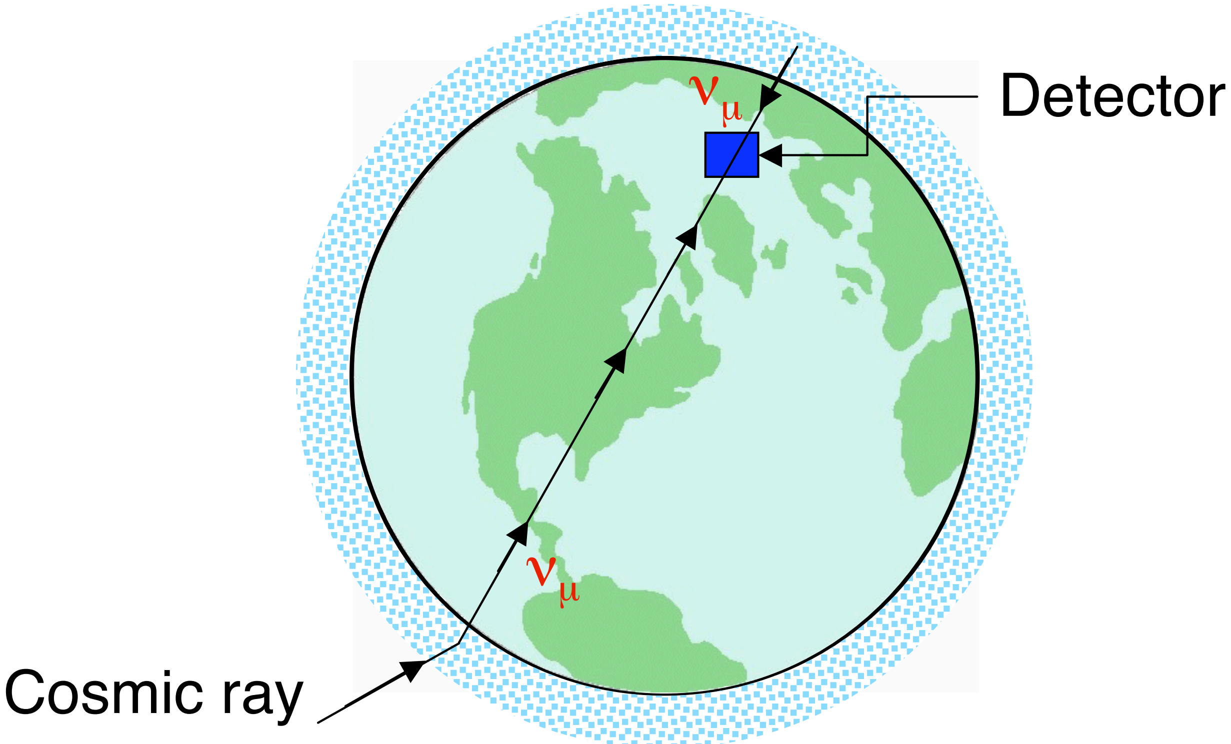
$\star\star\star$ Atmospheric and Accelerator Neutrinos with $L/E = 500$ km/GeV

$\star\star\star$ Solar and Reactor Neutrinos with $L/E = 15$ km/MeV

Neutrinos from Stopped muons $L/E = 2$m/MeV (Unconfirmed)


What We
Have Learned

Atmospheric Neutrinos

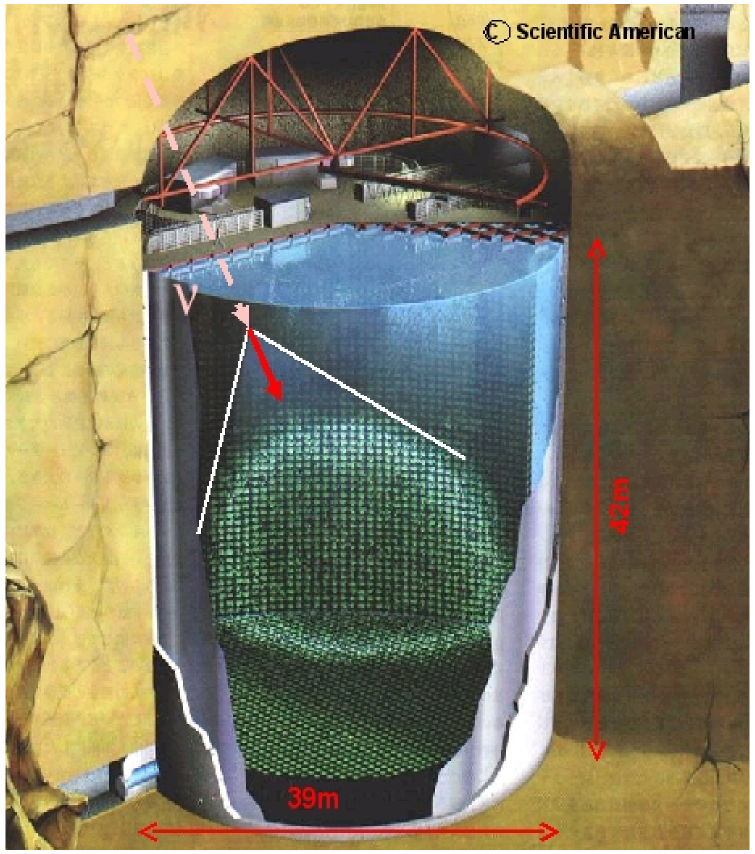


Isotropy of the $\gtrsim$ 2 GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Rightarrow \quad \frac{\phi_{\nu_\mu}(\mathrm{Up})}{\phi_{\nu_\mu}(\mathrm{Down})} = 1 \ .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV

$$\frac{\phi_{\nu_\mu}(\mathrm{Up})}{\phi_{\nu_\mu}(\mathrm{Down})} = 0.54 \pm 0.04 \ .$$



Half of the upward-going, long-distance-traveling ν_μ are disappearing.

Voluminous atmospheric neutrino data are well described by —

$$\nu_\mu \longrightarrow \nu_\tau$$

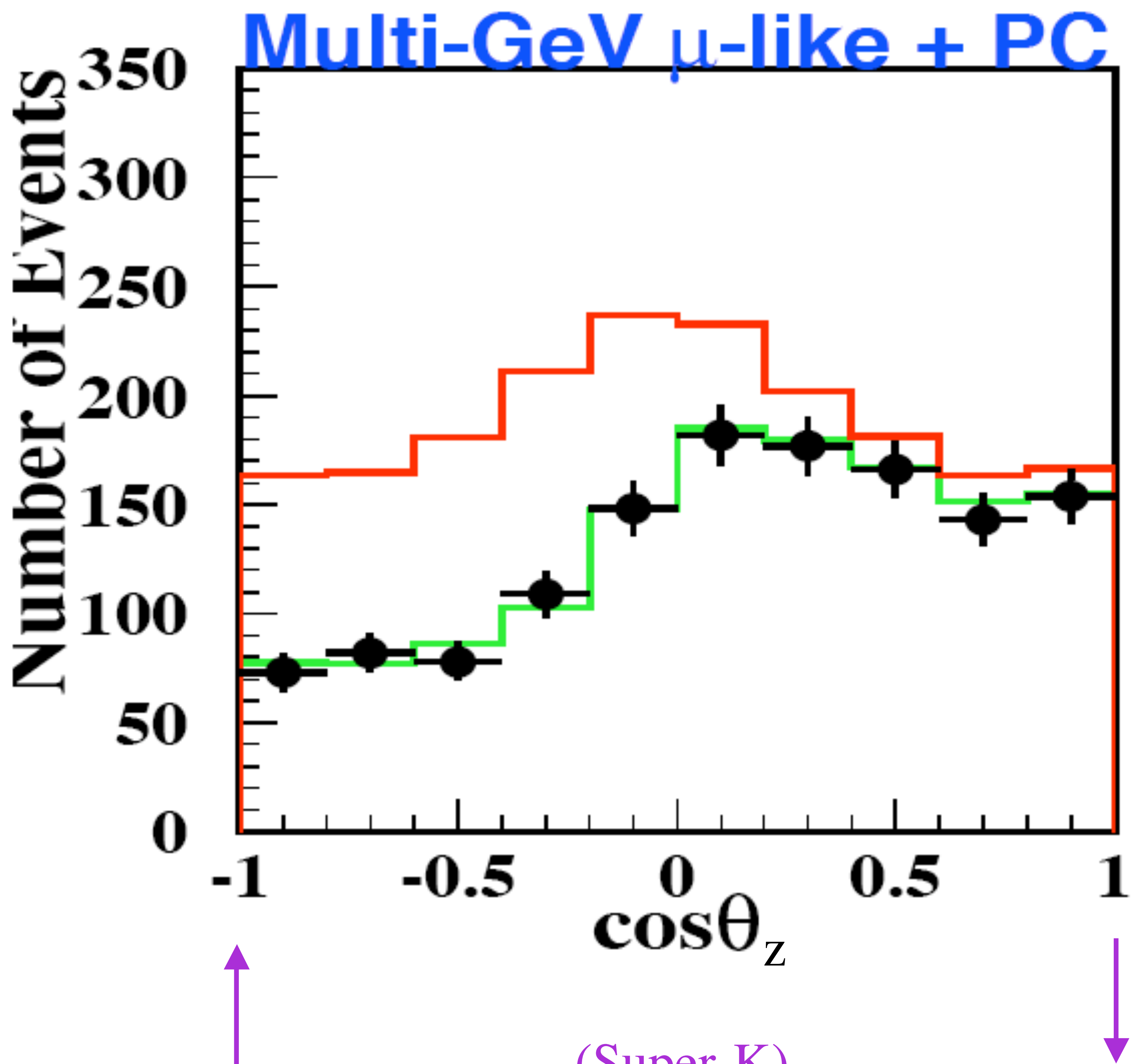
with —

$$1.9 \times 10^{-3} < \Delta m^2_{atm} < 3.0 \times 10^{-3}\ eV^2$$

and —

$$\sin^2 2\theta_{atm} > 0.92$$

$\left(\begin{matrix}\text{Super-K}\\ \text{90\%CL}\end{matrix}\right)$

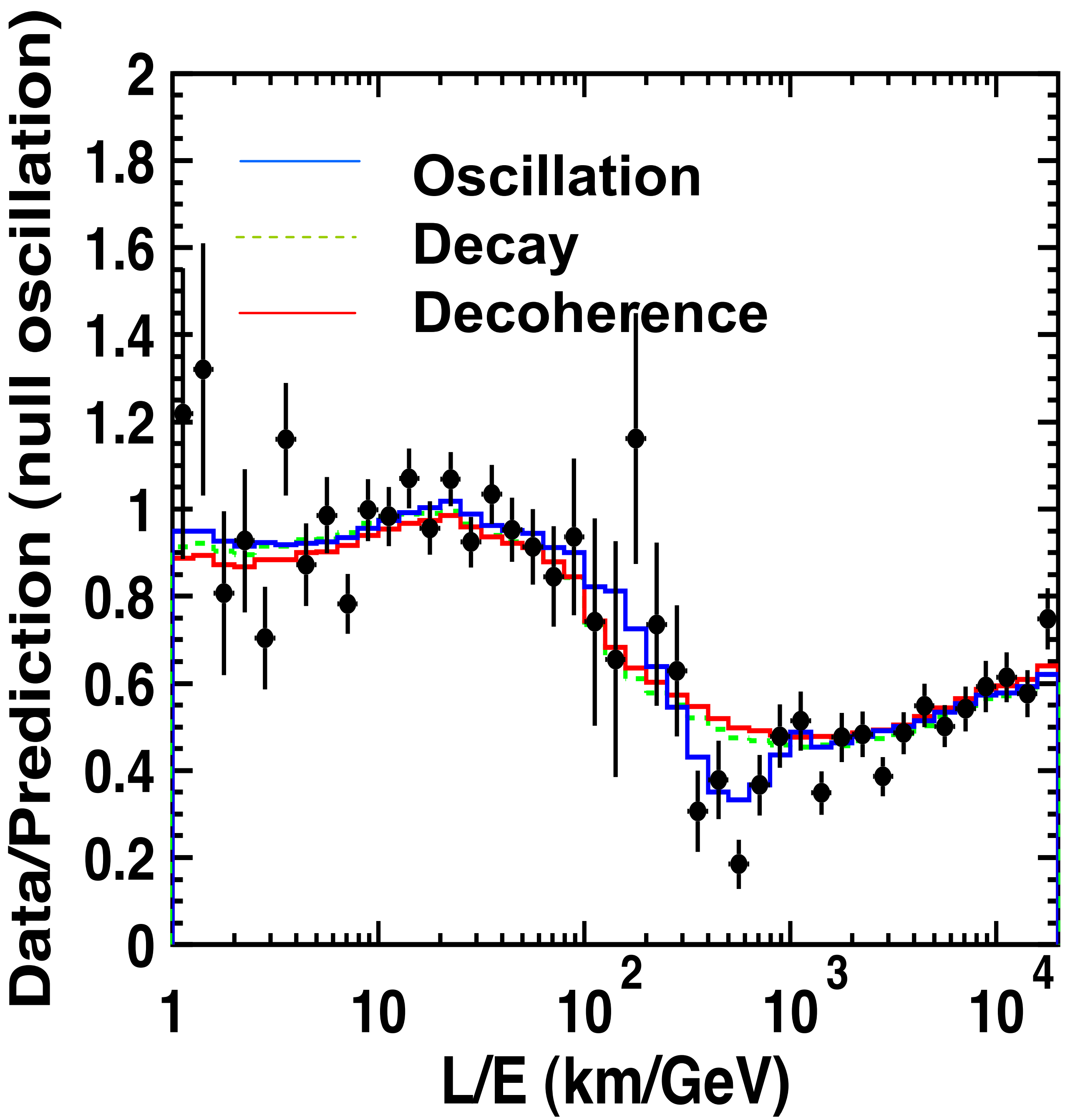

Multi-GeV μ-like + PC
Number of Events
350
300
250
200
150
100
50
0
-1
-0.5
0
0.5
1
cosθz

(Super-K)

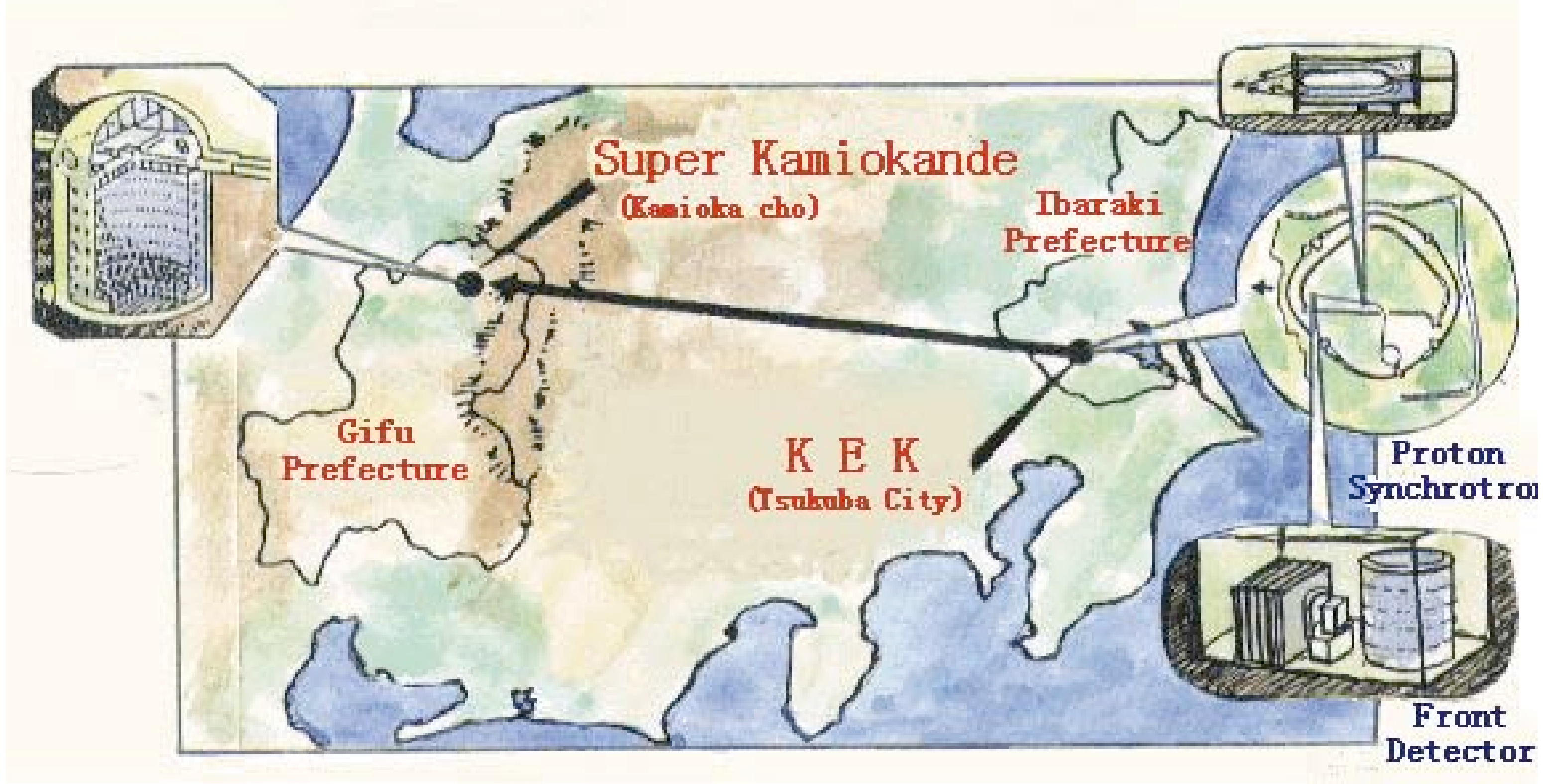
L/E Analysis

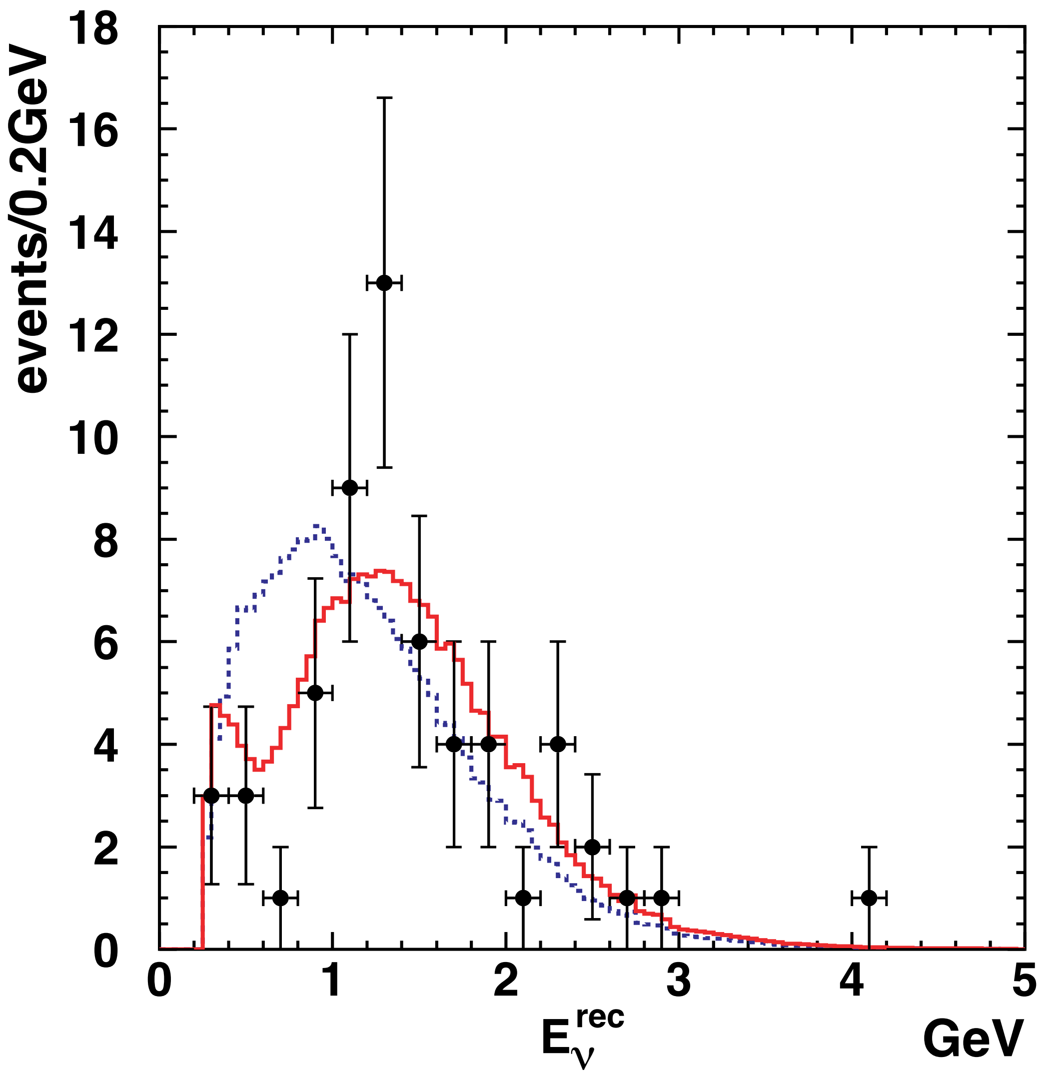
- Oscillation, decay and decoherence models tested

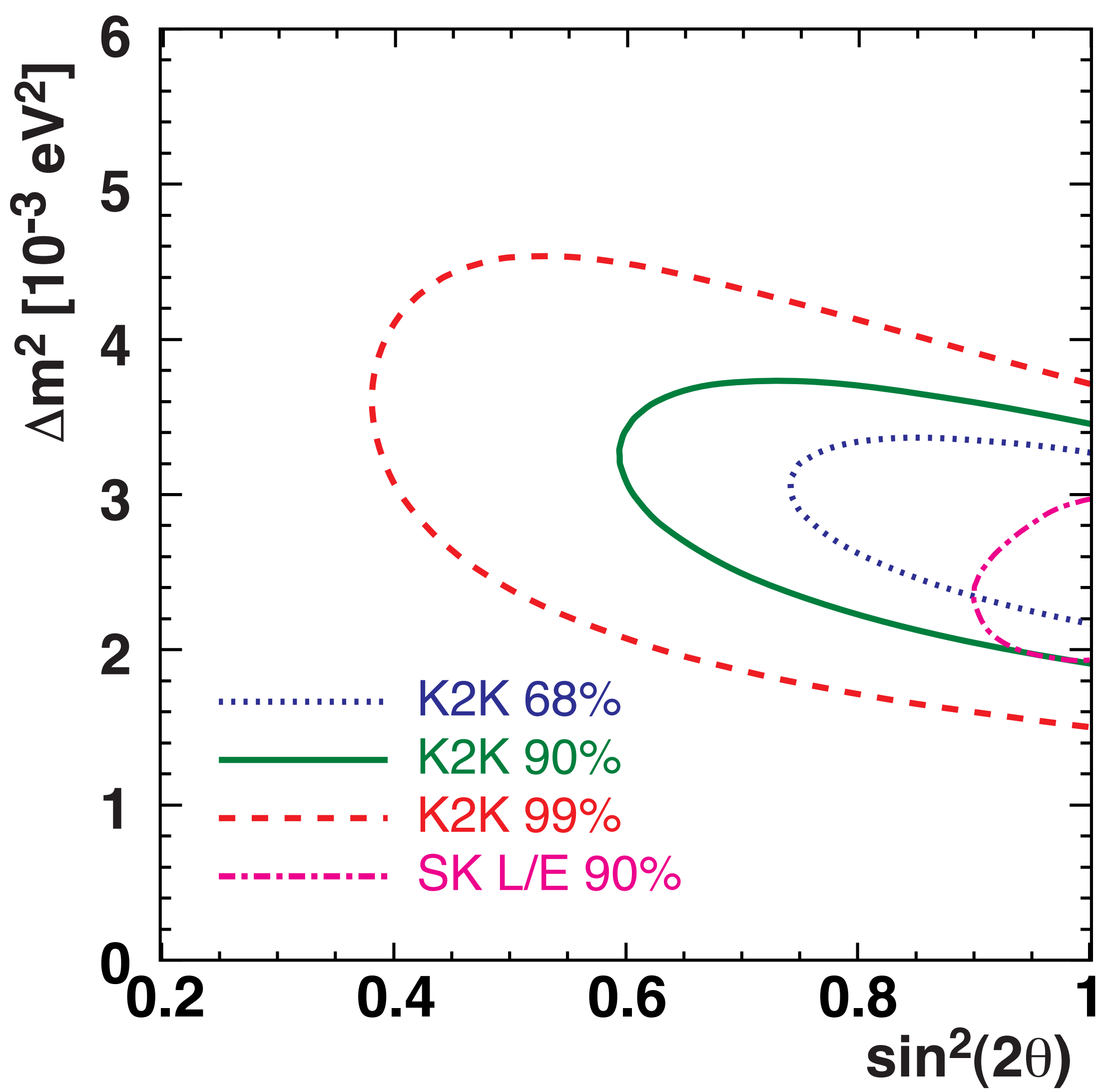
χ^2_{osc} = 83.9/83
χ^2_{dcy} = 107.1/83, $\Delta\chi^2$ = 23.2(**4.8σ**)
χ^2_{dec} = 112.5/83, $\Delta\chi^2$ = 27.6(**5.3σ**)



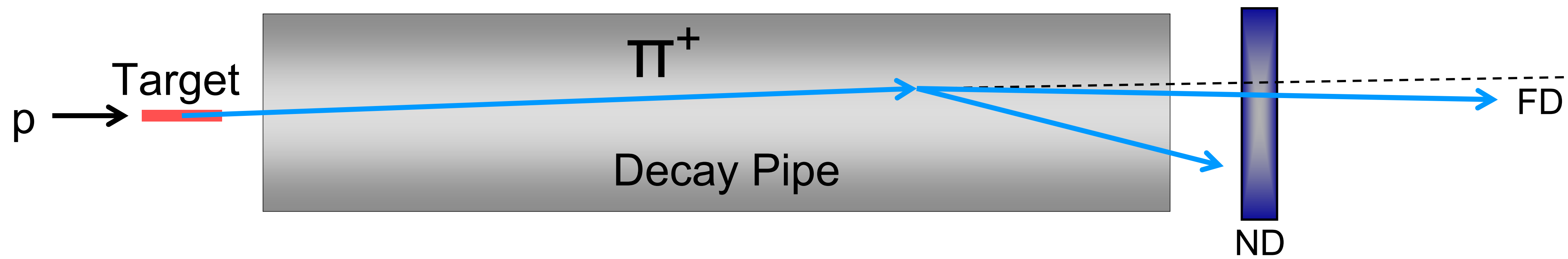
K2K

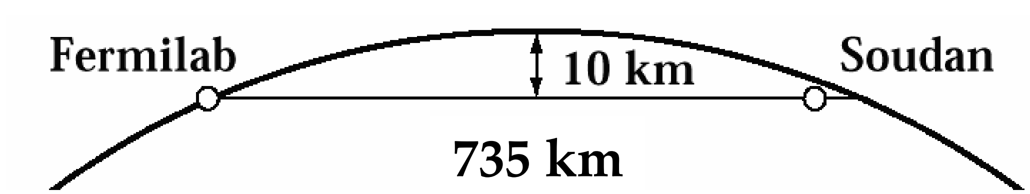

Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotron
Front
Detector


events/0.2GeV
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
E_ν^{rec}
GeV


Δm^2 [10^{-3} eV^2]
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8
1
$\sin^2(2\theta)$
K2K 68%
K2K 90%
K2K 99%
SK L/E 90%

The MINOS Experiment





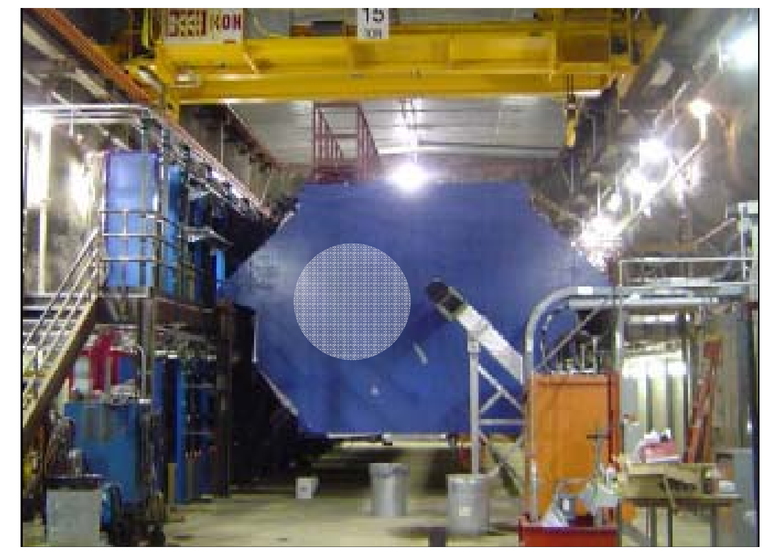
Near Detector

1 kton

$3.8 \times 4.8 \times 15$ m^3

282 steel planes

153 scintillator planes

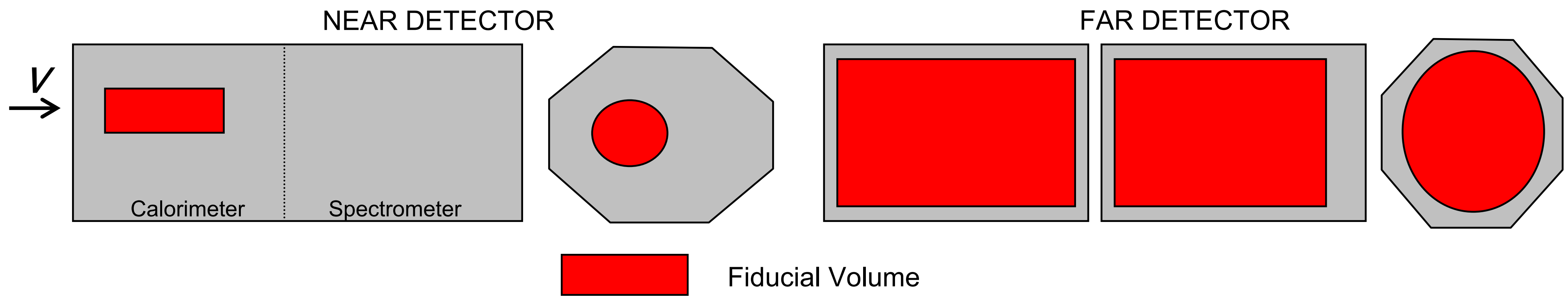


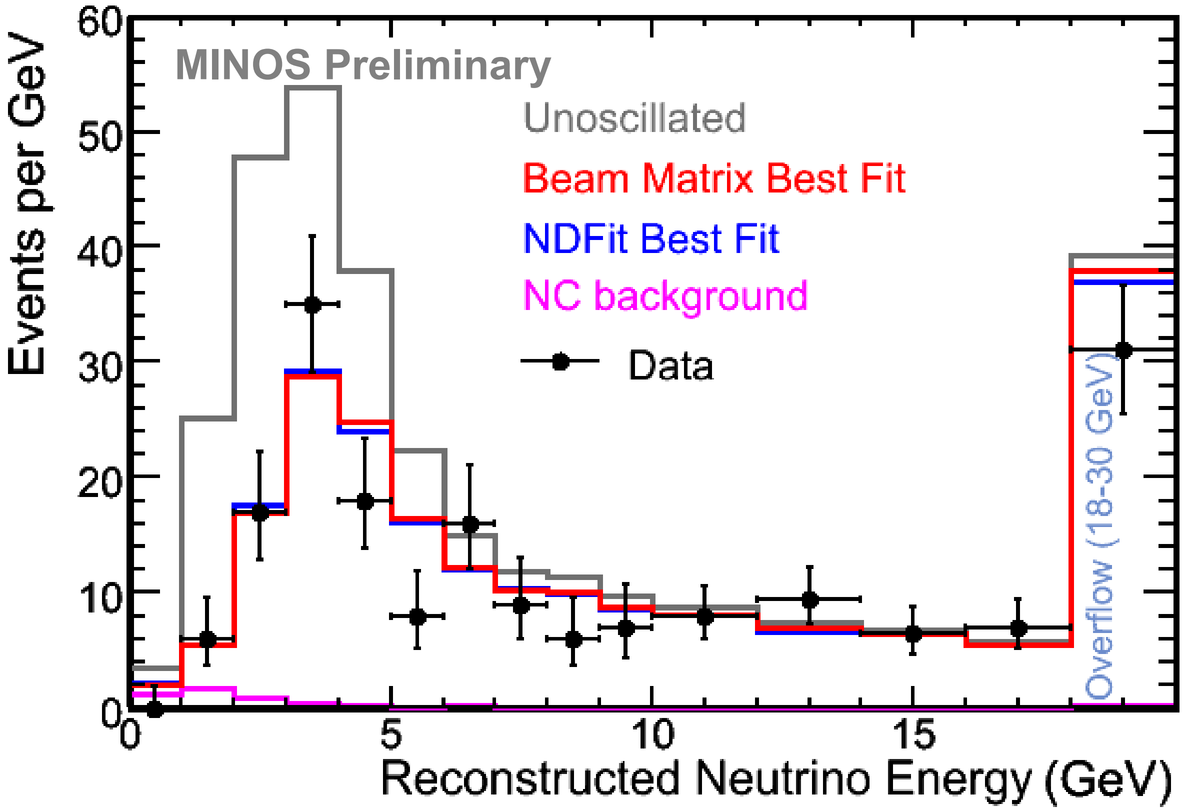
Far Detector

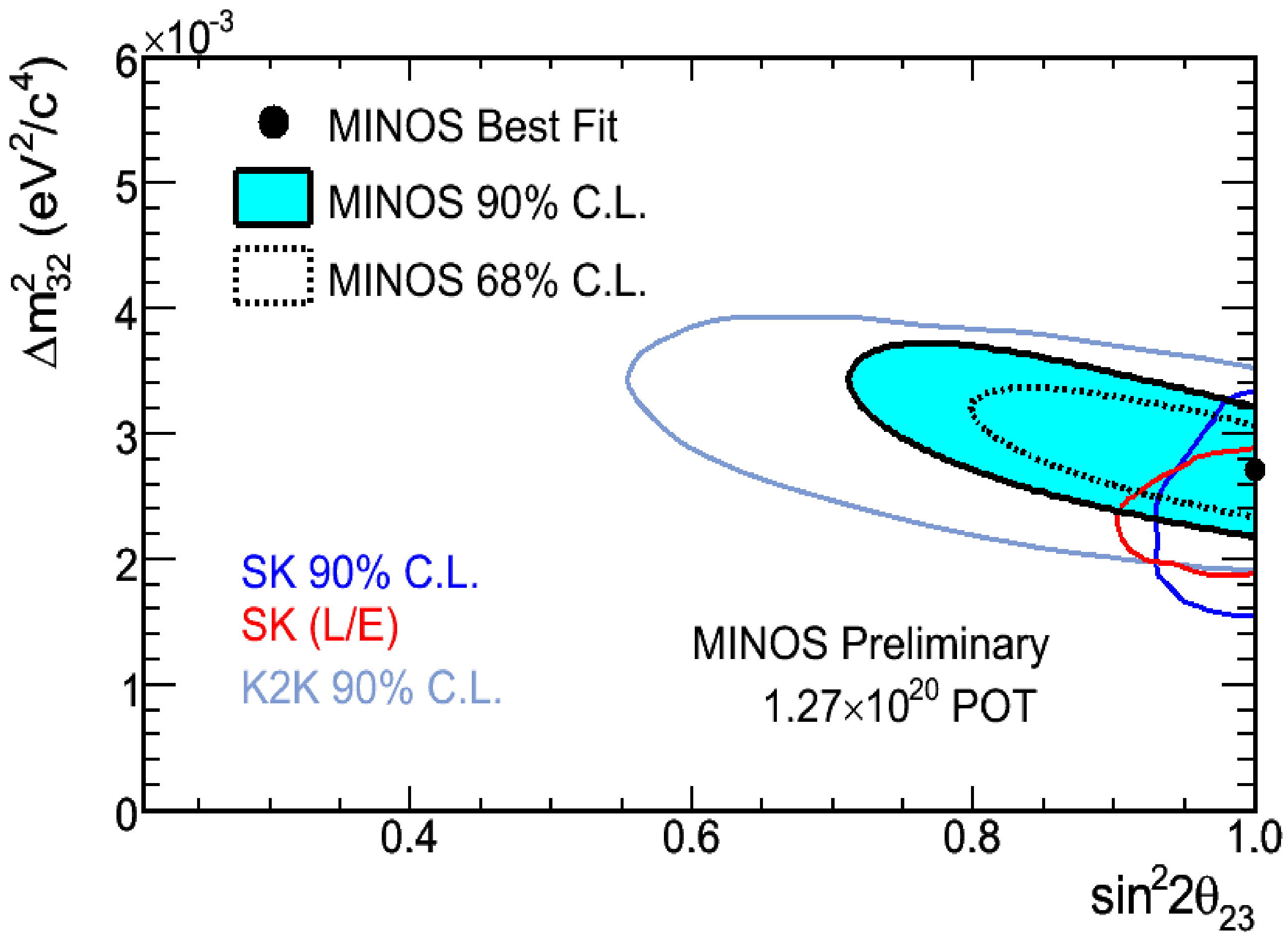
5.4 kton

$8 \times 8 \times 30$ m^3

484 planes







$$\left|\Delta m^2_{32}\right| = 2.72^{+0.38}_{-0.25}(\text{stat}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat})$$

Normalization = 0.98

$$\left|\Delta m^2_{32}\right| = 2.72^{+0.38}_{-0.25}(\text{stat}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat})$$

Constrained to $\sin^2(2\theta_{23}) \leq 1$

Statistical errors

"Atmospheric" Neutrino Summary

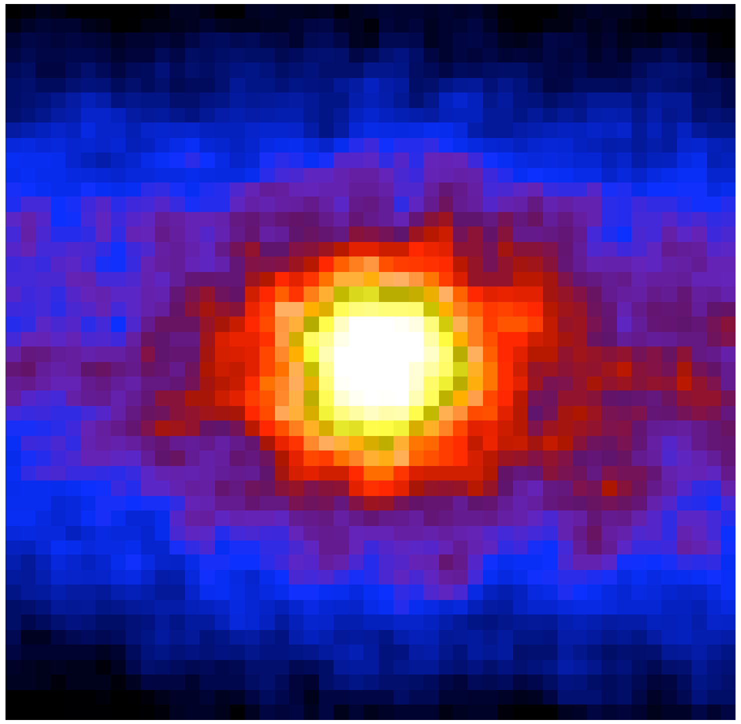
$$\nu_\mu \longrightarrow \nu_\tau$$

no evidence of ν_e involvement:

$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2$ $\qquad$ $L/E = 500\ km/GeV$

$\sin^2 2\theta_{atm} > 0.92$ $\qquad$ $\Rightarrow 0.35 < \sin^2 \theta_{atm} < 0.65$

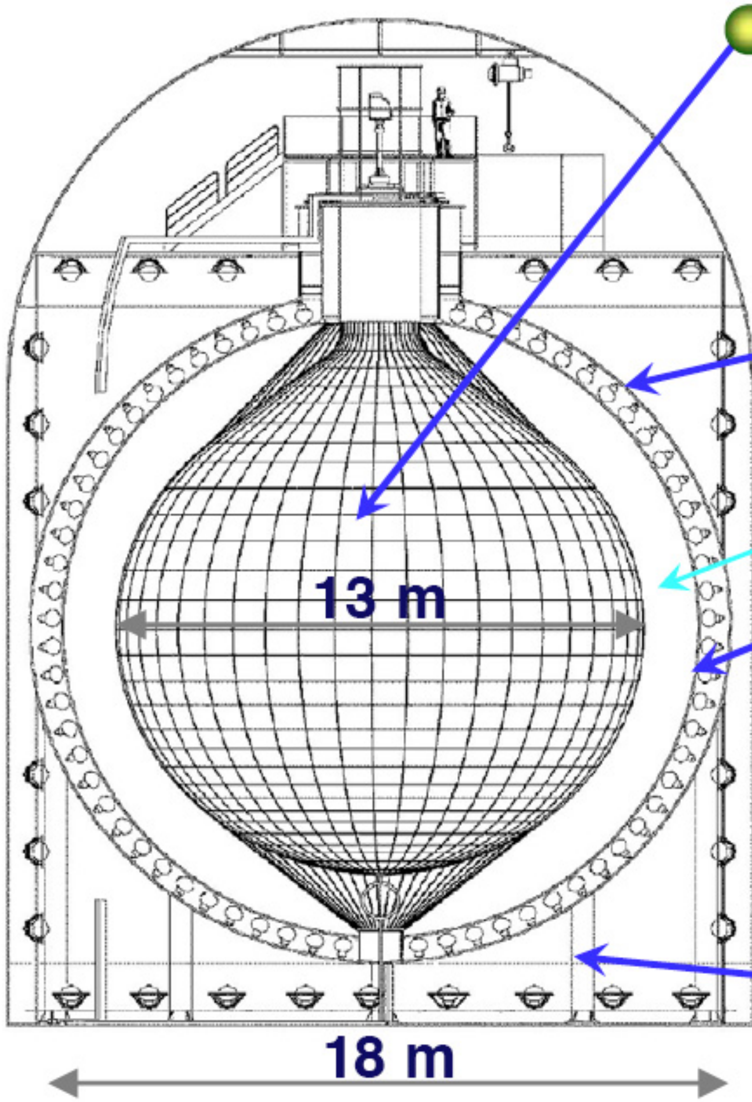
Solar δm^2



Reactor Neutrinos

KamLAND Detector

- detector location: old Kamiokande site
  : 2700 m.w.e.



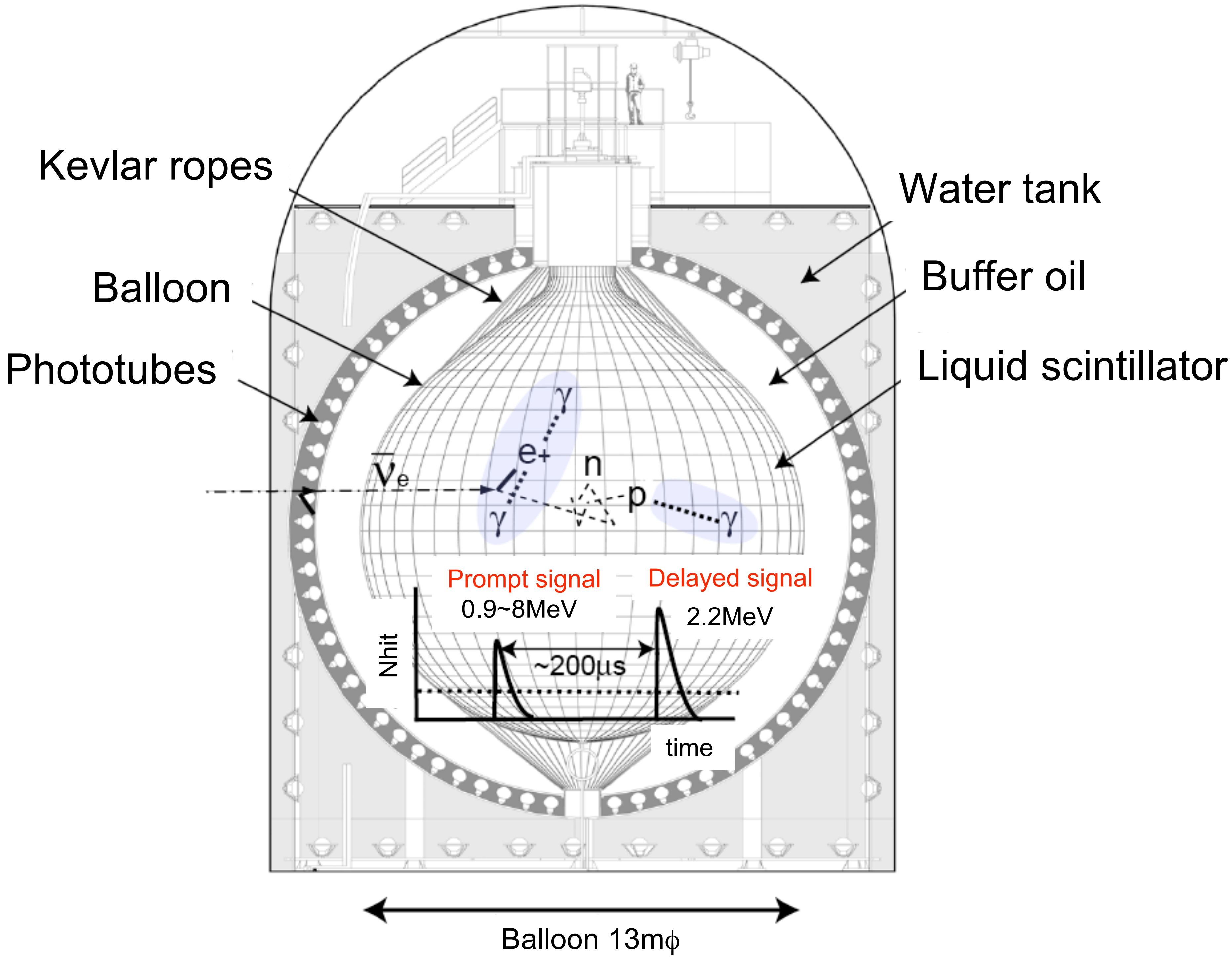
- 1000 ton liquid scintillator
  : 80% (dodecane) + 20% (pseudocumene) + 1.52 *g/l* PPO
  : housed in spherical plastic balloon
- 3000 m³ stainless steel vessel
  : filled with a mixture of paraffin oil and dodecane ($\Delta\rho$ = 0.04%)
- 1325 17-inch + 554 20-inch PMT's

commissioned in February, 2003

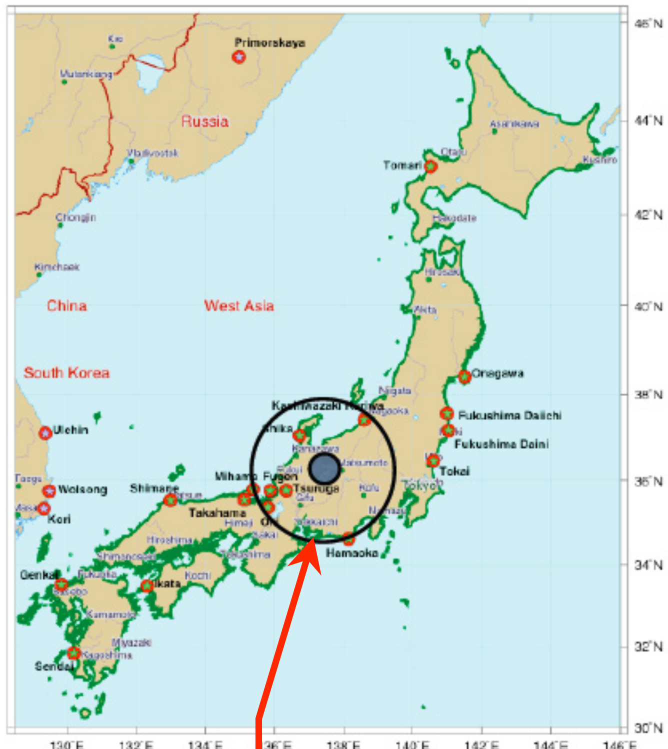
photocathode coverage : 22% → 34%
energy resolution at 1 MeV : 7.3% → 6.3%

- water Cerenkov outer detector

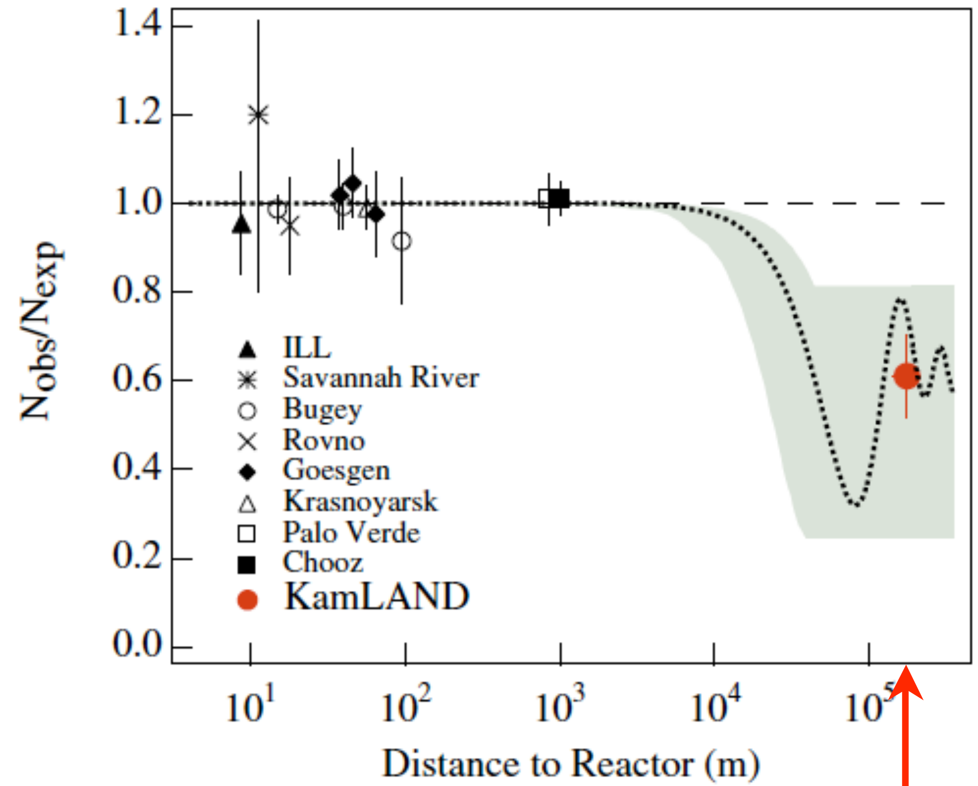
Kamioka Liquid *Antineutrino* Detector



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

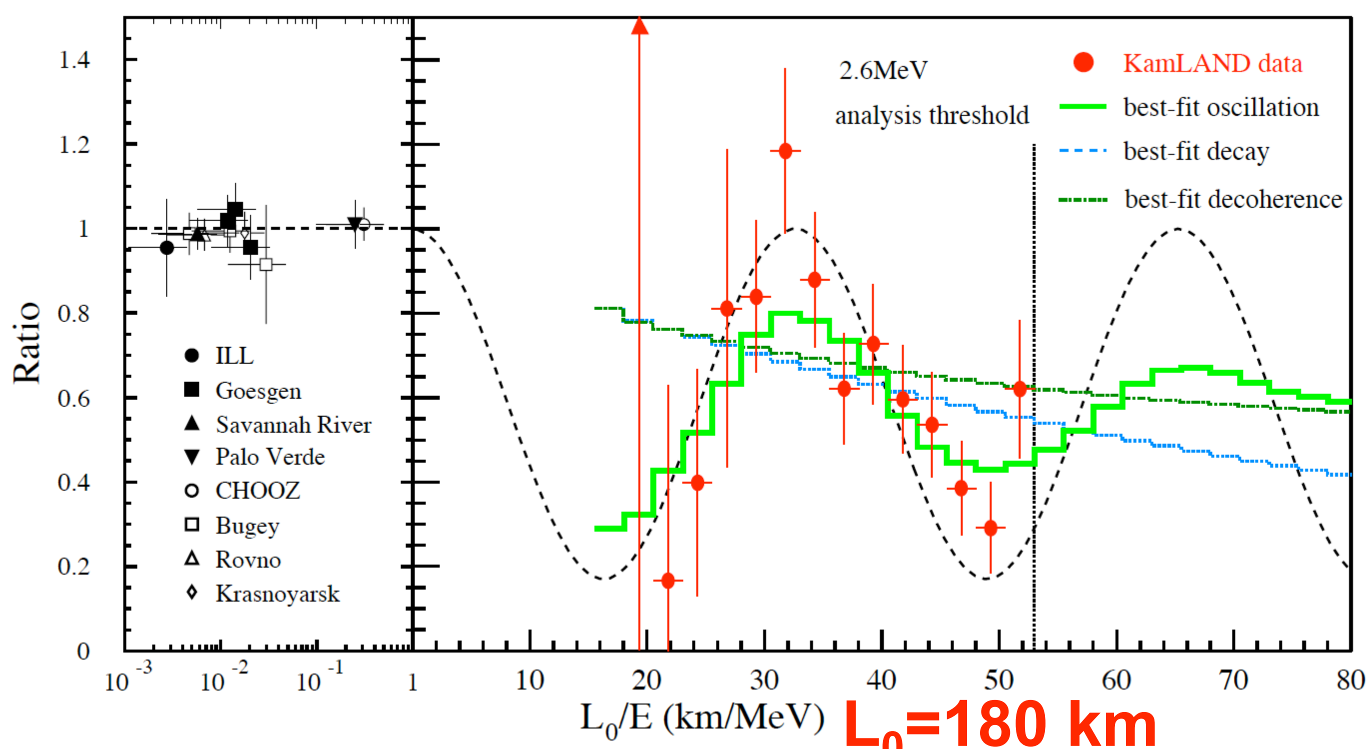


180 km



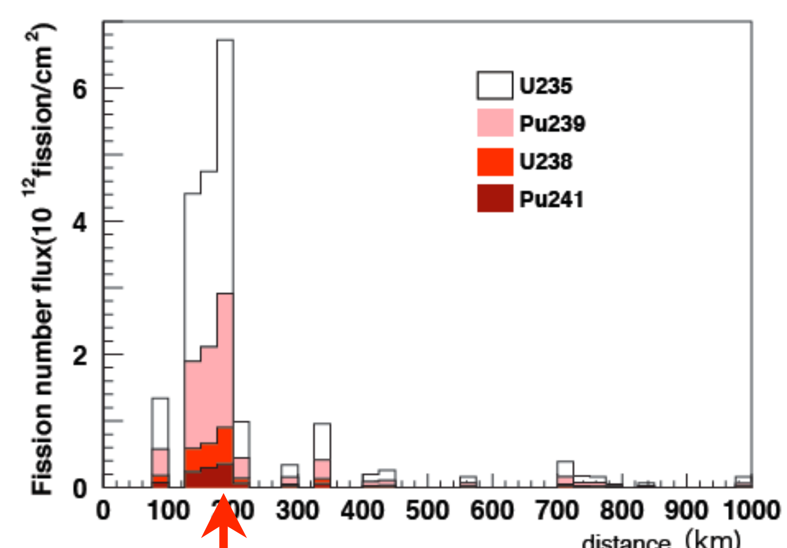
180 km

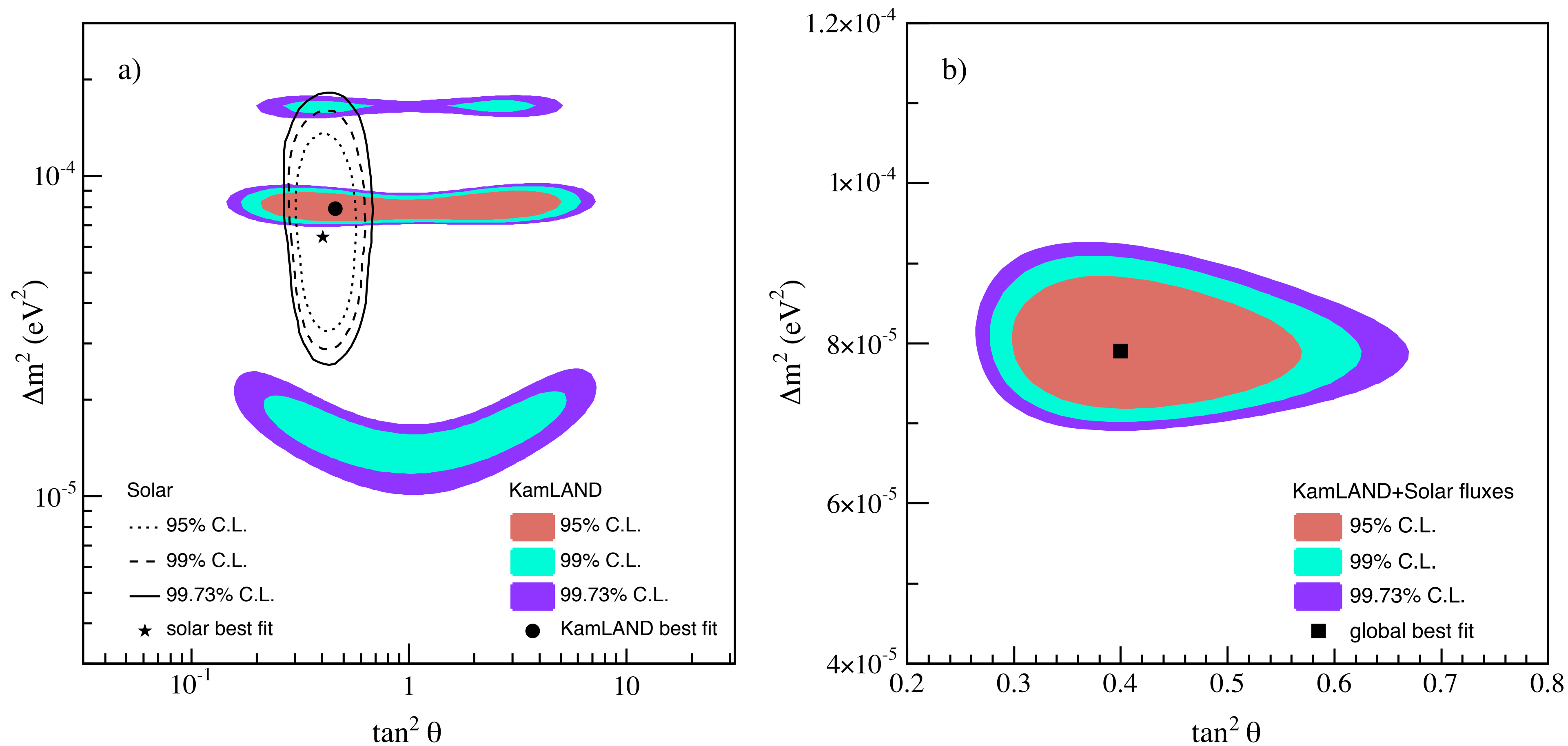
Disappearance: 99.95%C.L.



L_0=180 km

L_0





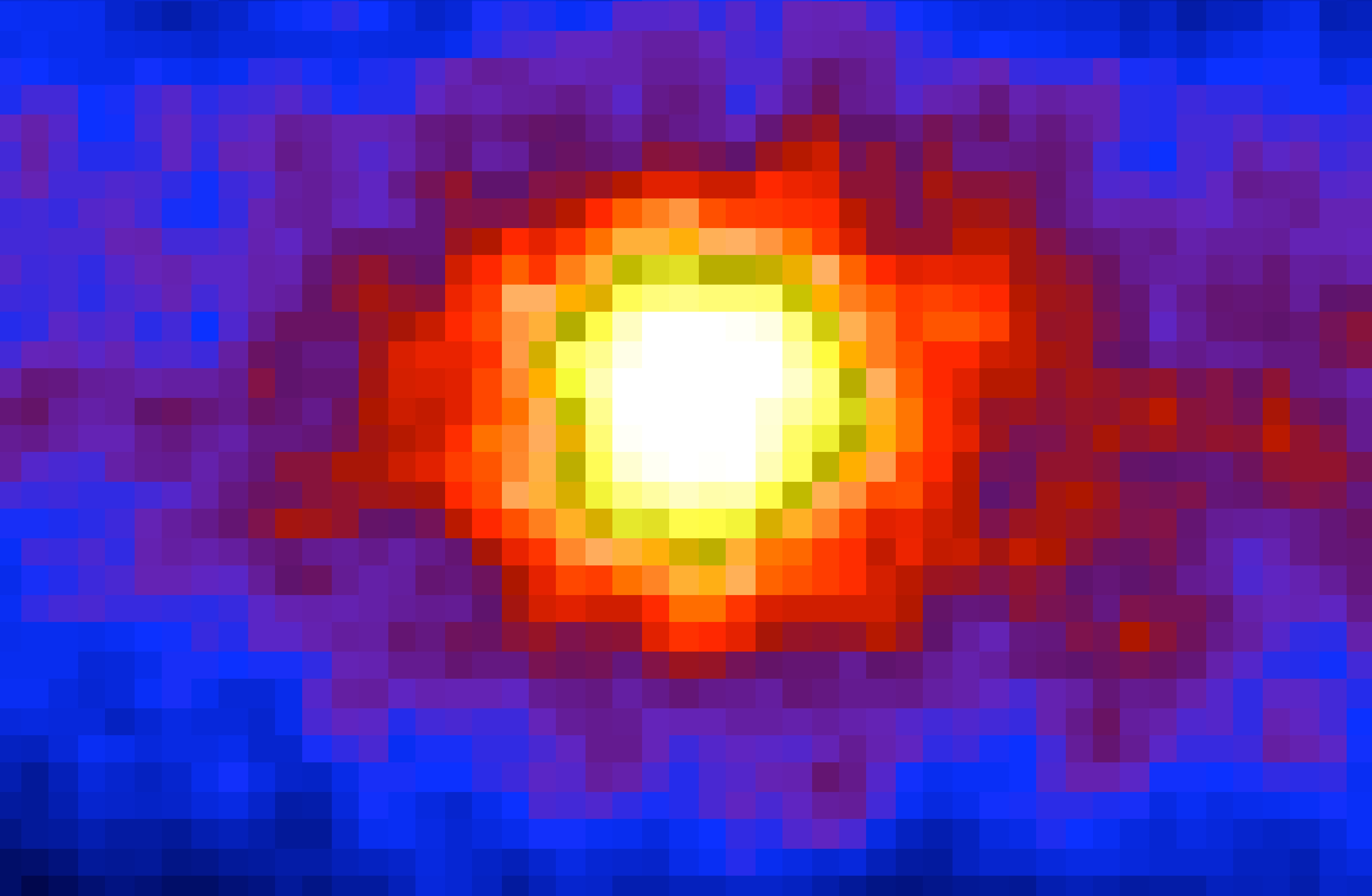
KamLAND Only

Solar + KamLAND

$$\delta m^2_\odot = 8.0^{+0.4}_{-0.3} \times 10^{-5}\mathrm{eV}^2,$$

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

Solar Neutrinos:



Solar Engine:

$$4p + 2e^- \rightarrow ^4He + 2\nu_e + 26.7MeV$$

$$E = mc^2$$

1 ν_e for every 13.4 MeV (=2.1 $\times 10^{-12}$ J)

$\mathcal{L}_\odot$ at earth's surface 0.13 watts/cm^2

$$\phi_\nu = \frac{0.13}{2.1 \times 10^{-12}} = 6 \times 10^{10}/cm^2/sec$$

This corresponds to an average of 2 ν's per cm^3
since they are going at speed c.

Solar Spectrum:

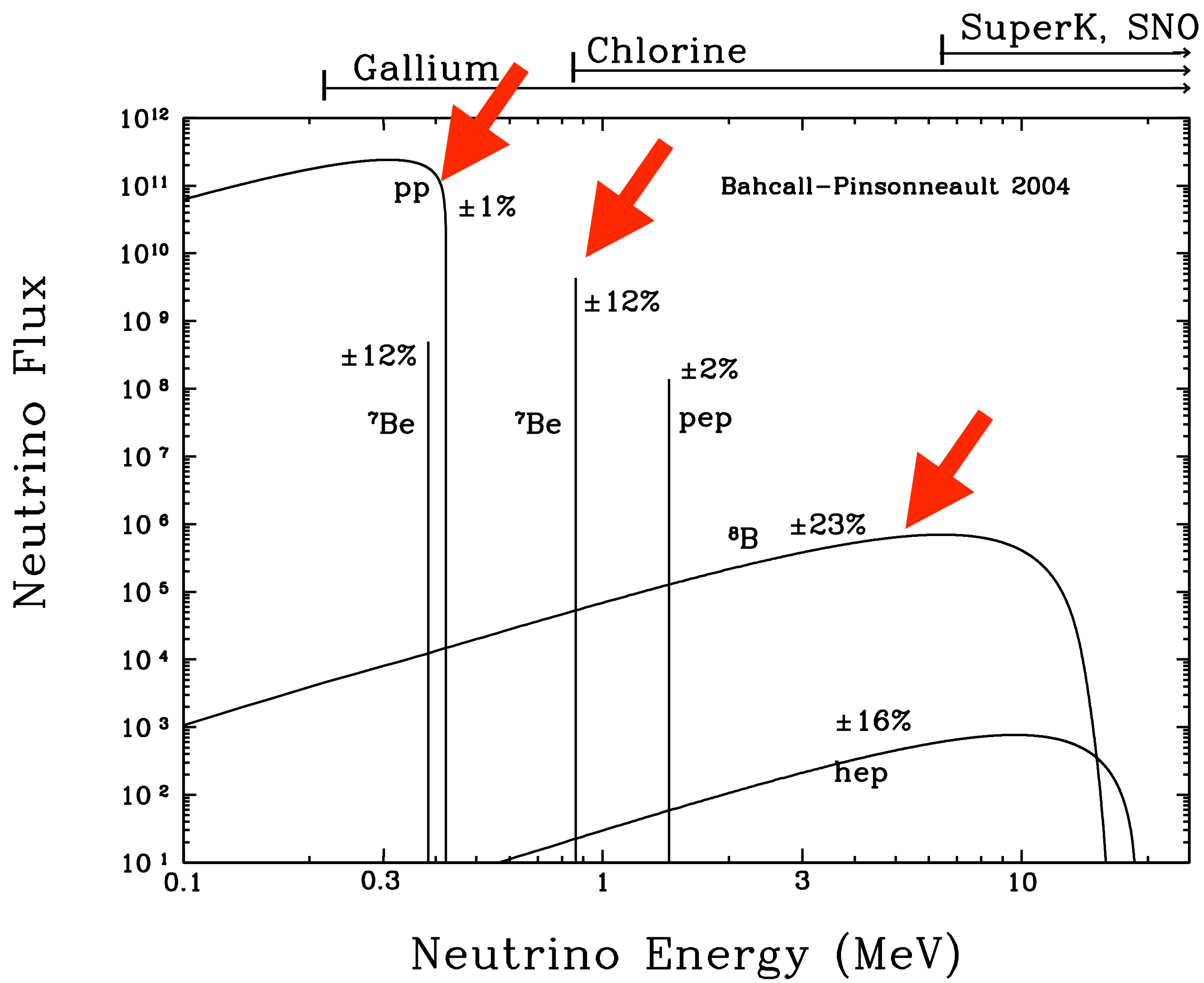


Figure 1. The predicted solar neutrino energy spectrum. The figure shows the energy spectrum of solar neutrinos predicted by the BP04 solar model [22]. For continuum sources, the neutrino fluxes are given in number of neutrinos $cm^{-2}\,s^{-1}\,MeV^{-1}$ at the Earth's surface. For line sources, the units are number of neutrinos $cm^{-2}\,s^{-1}$. Total theoretical uncertainties taken from column 2 of table 1 are shown for each source. To avoid complication in the figure, we have omitted the difficult-to-detect CNO neutrino fluxes (see table 1).

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

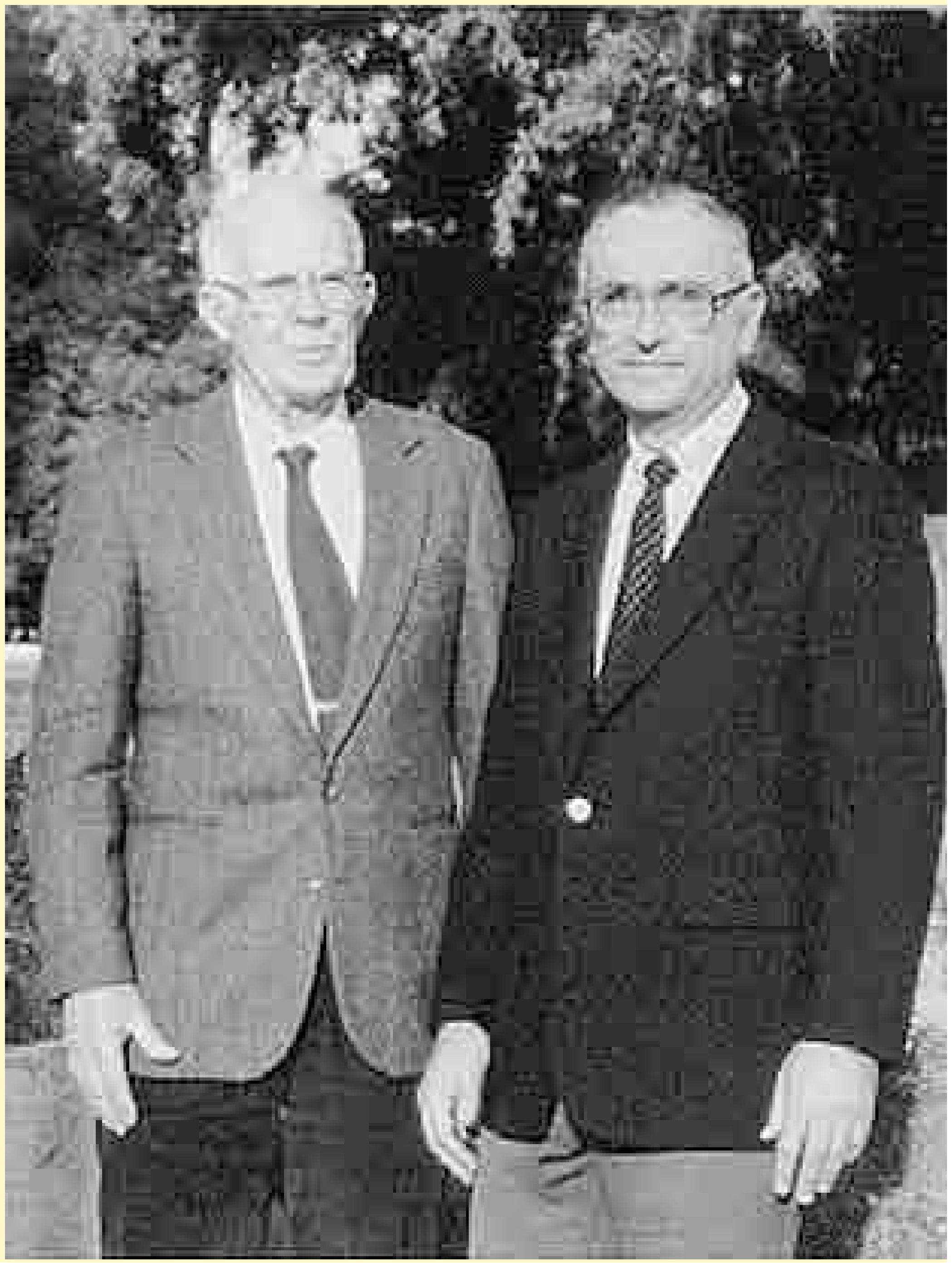
$$\phi_{pp} = 5.94(1 \pm 0.01) \times 10^{10} cm^{-2} sec^{-1}$$

$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

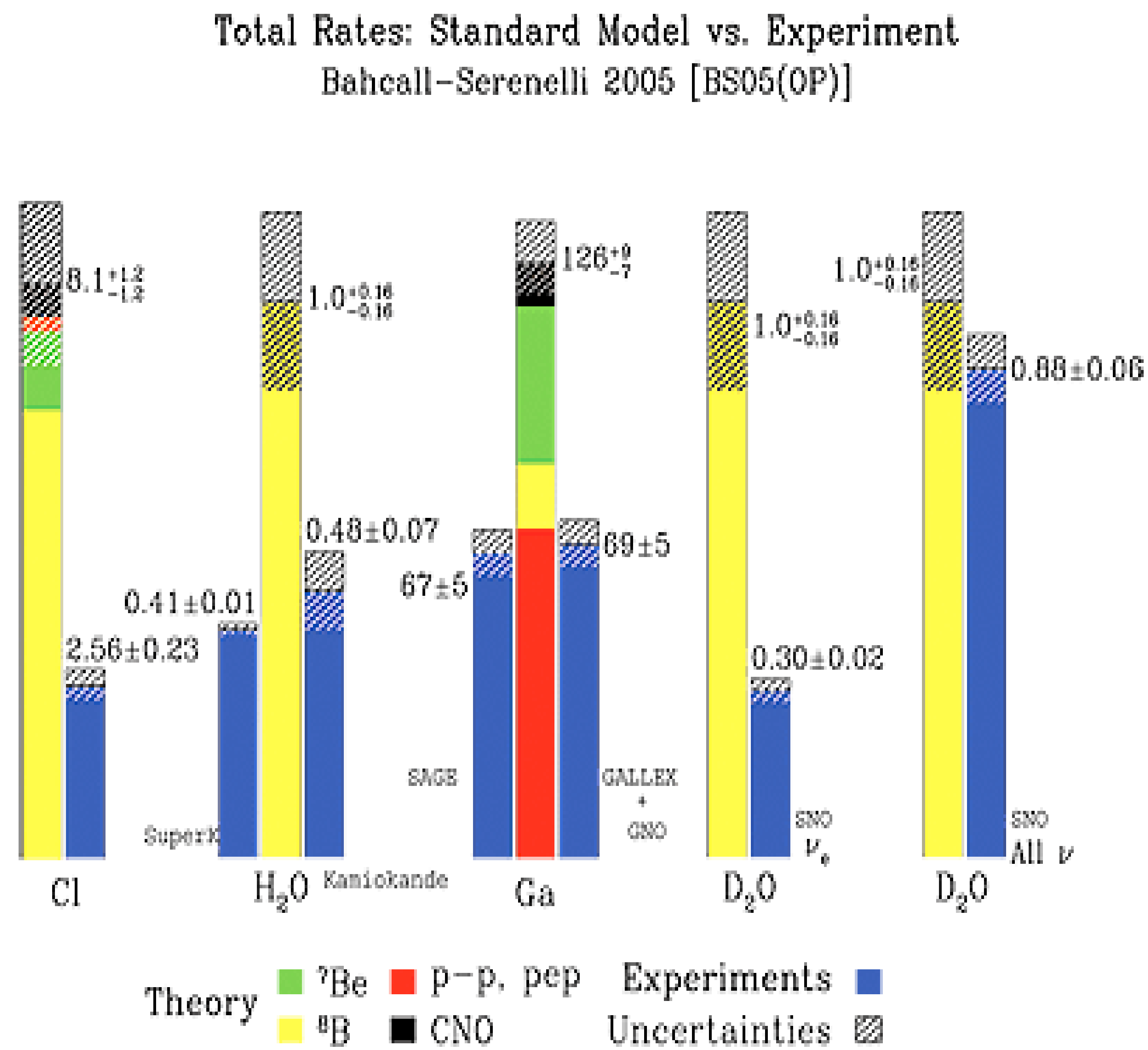
$$\phi_{^7Be} = 4.86(1 \pm 0.12) \times 10^{9} cm^{-2} sec^{-1}$$

$$^7Be + p \rightarrow {}^8B \rightarrow {}^8Be^* + e^- + \nu_e$$

$$\phi_{^8B} = 5.82(1 \pm 0.23) \times 10^{6} cm^{-2} sec^{-1}$$



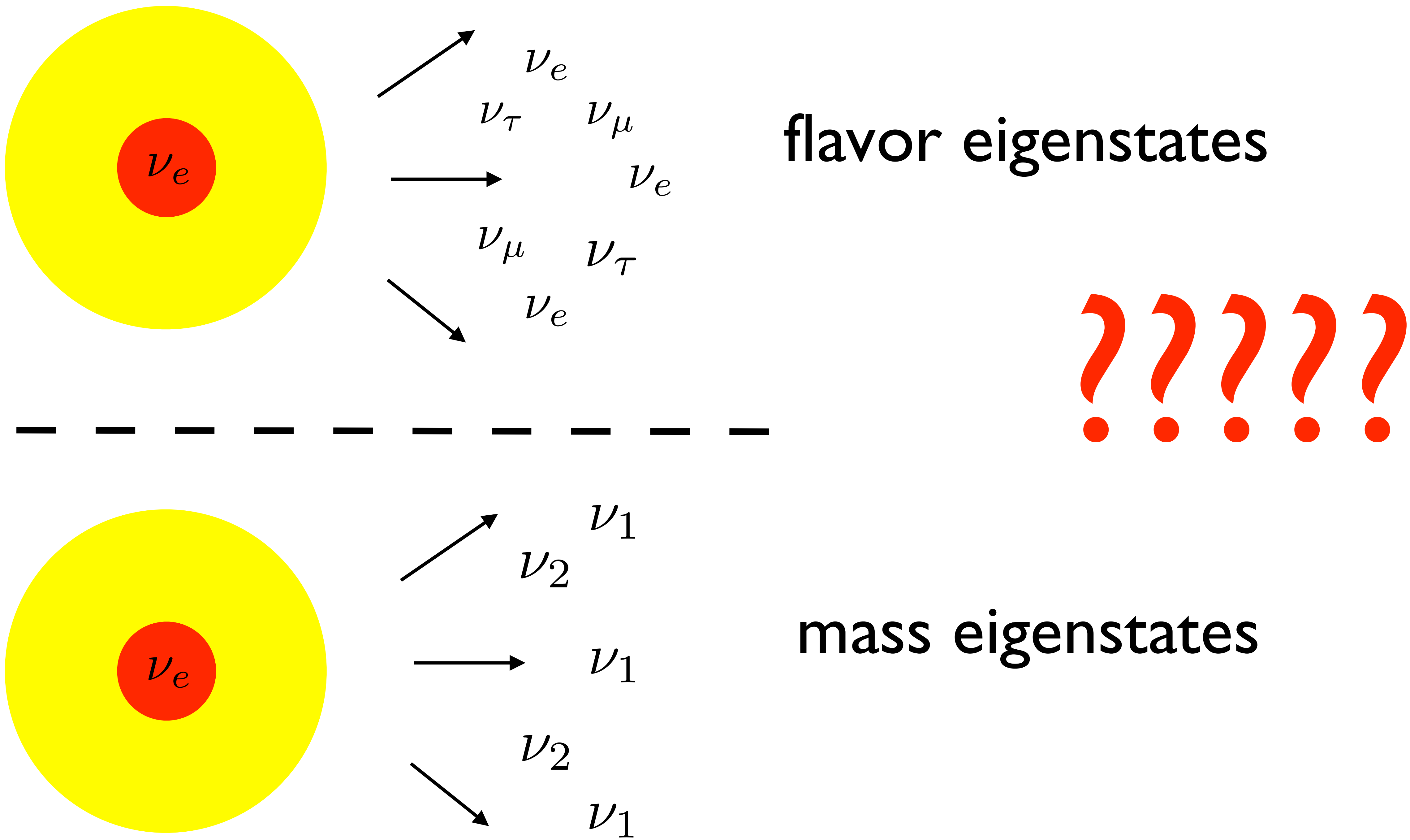
Ray Davis & John Bahcall



Theory v Exp.

Neutrino Flavor Transistions!!!

Identical Solar Twins:



Kinematical Phase:

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

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

$$\Delta_\odot = \frac{\delta m^2_\odot L}{4E} = 1.27 \quad \frac{8\times10^{-5}\ eV^2 \cdot 1.5\times10^{11}\ m}{0.1-10\ MeV}$$

???

$$\Delta_\odot \approx 10^{7\pm1}$$

Effectively Incoherent !!!

Vacuum ν_e Survival Probability:

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

where f_1 and f_2 are the fraction of ν_1 and ν_2 at production.

In vacuum $f_1 = \cos^2\theta_\odot$ and $f_2 = \sin^2\theta_\odot$.

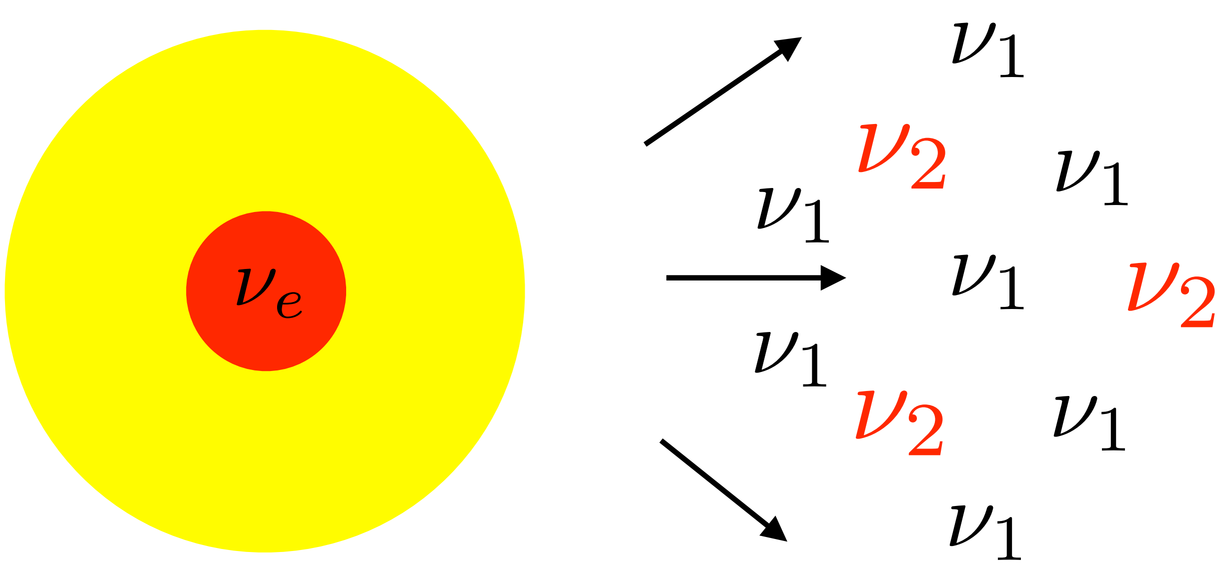
Note energy independence.

$$\langle P_{ee} \rangle = \cos^4\theta_\odot + \sin^4\theta_\odot = 1 - \frac{1}{2}\sin^2 2\theta_\odot$$

for pp and ^{7}Be this is approximately THE ANSWER.

$f_1 \sim 69\%$ and $f_2 \sim 31\%$ and $\langle P_{ee} \rangle \approx 0.6$

pp and ^{7}Be



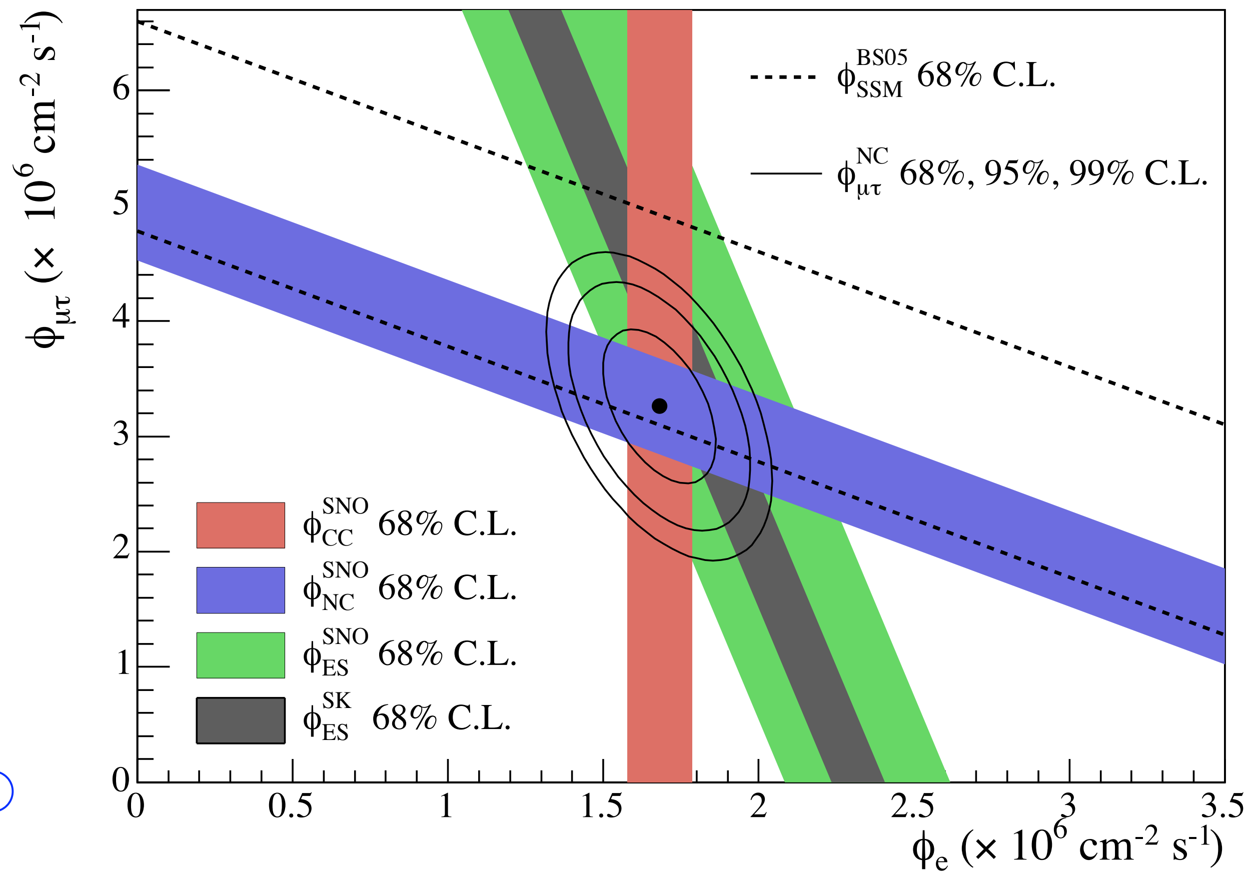
$f_1 \sim 69\%$

$f_2 \sim 31\%$

$$\langle P_{ee} \rangle \approx 0.6$$

$f_3 = \sin^2 \theta_{13} < 4\%$

What about ^8B ?



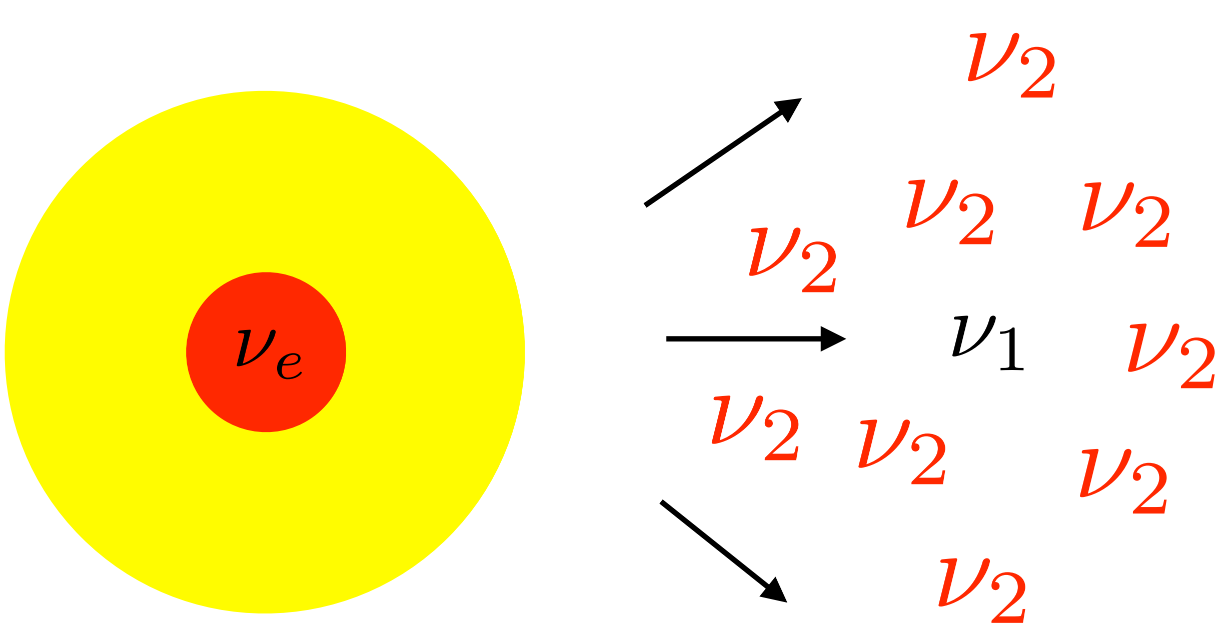
SNO's CC/NC

$$\frac{CC}{NC} = \langle P_{ee} \rangle = f_1 \cos^2\theta_\odot + f_2 \sin^2\theta_\odot$$

$$f_1 = \left(\frac{CC}{NC} - \sin^2\theta_\odot\right) / \cos 2\theta_\odot$$

$$= (0.35 - 0.31)/0.4 \approx 10 \ \pm \ ???\%$$

^{8}B



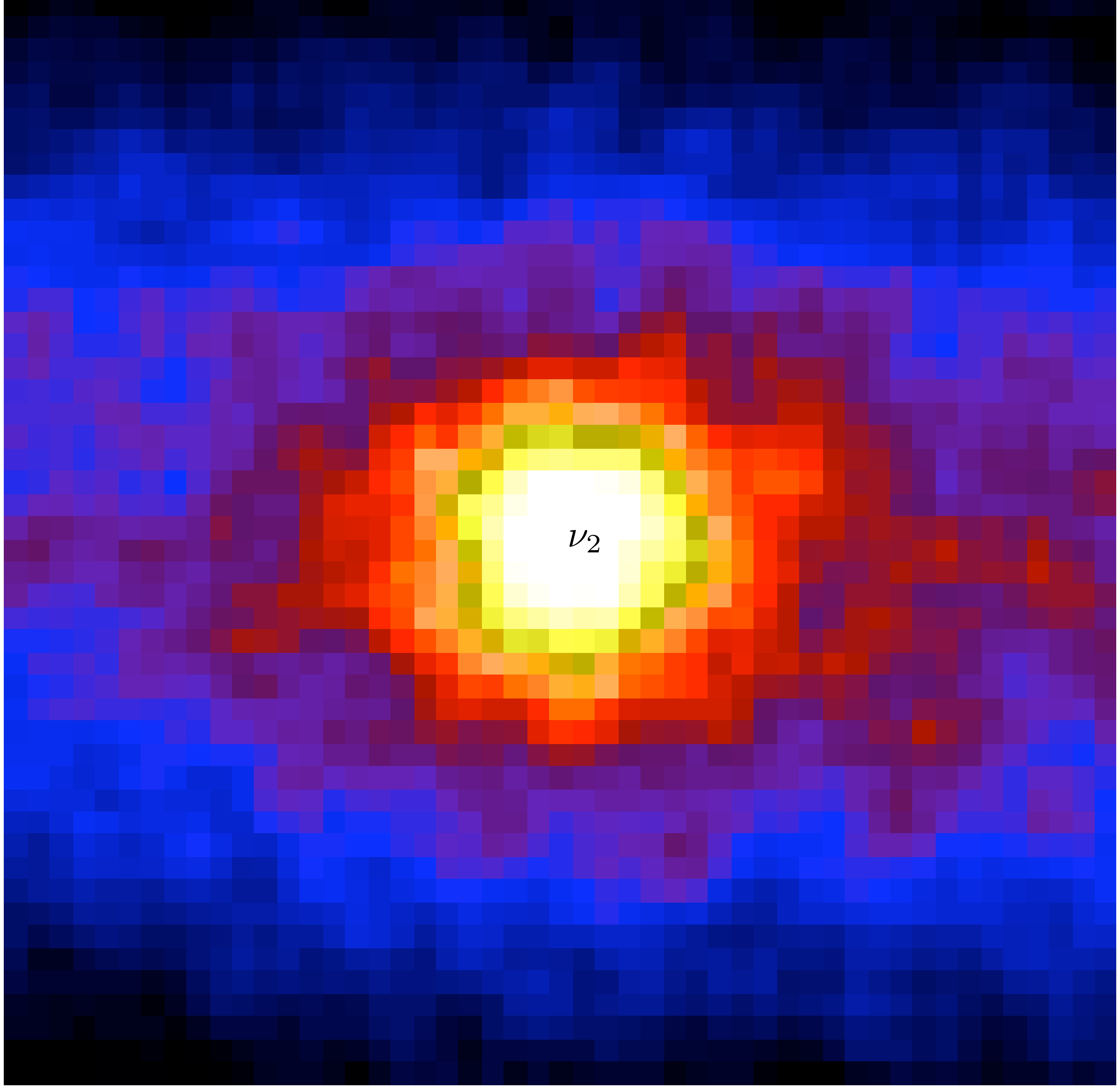
$$f_2 \sim 90\%$$

$$f_1 \sim 10\%$$

$$\langle P_{ee} \rangle = \sin^2\theta + f_1 \cos 2\theta_\odot \approx \sin^2\theta_\odot = 0.31$$

Wow!!! How did that happen???

energy dependence!!!



These are ν_2 Neutrinos !!!