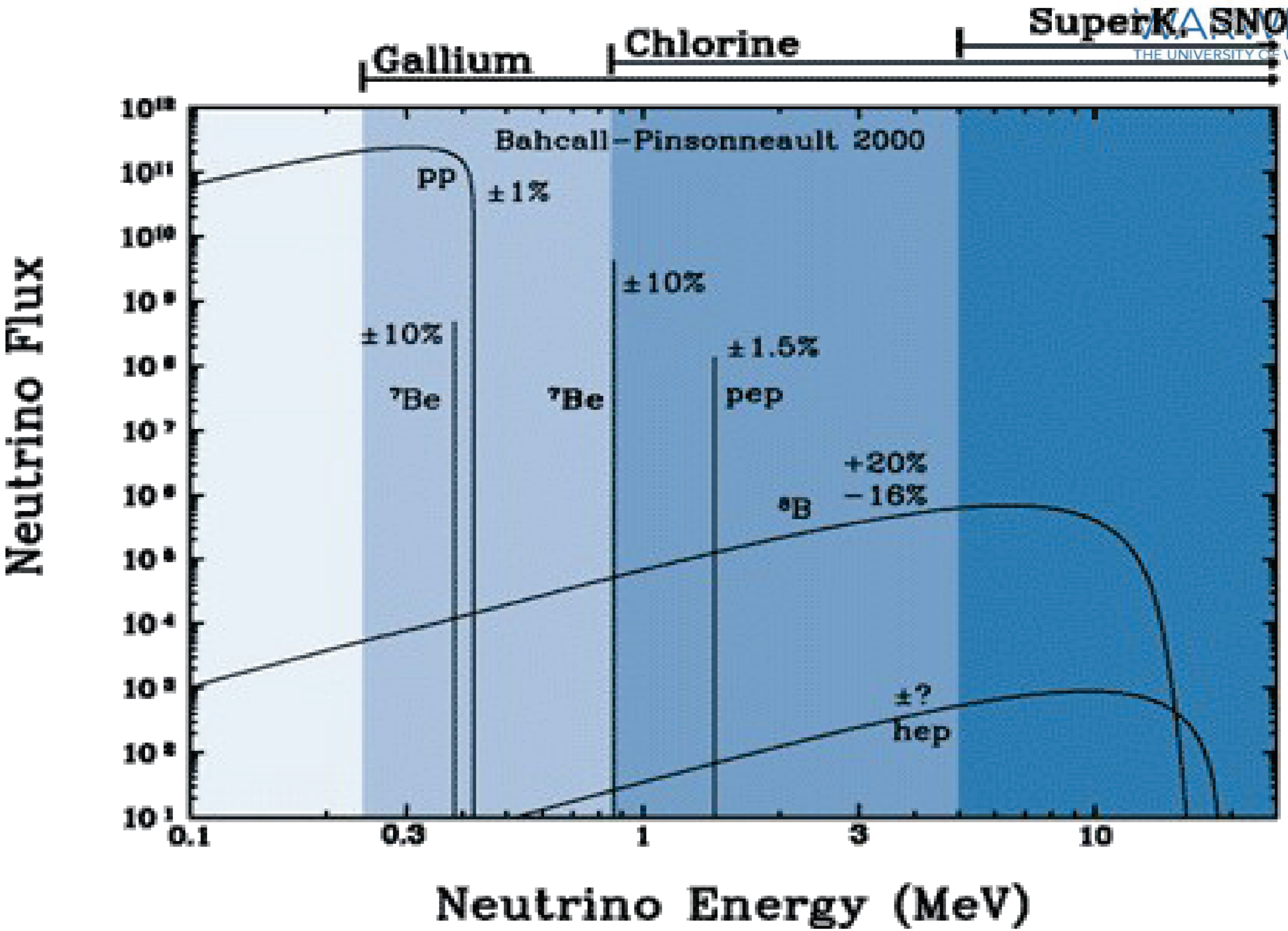
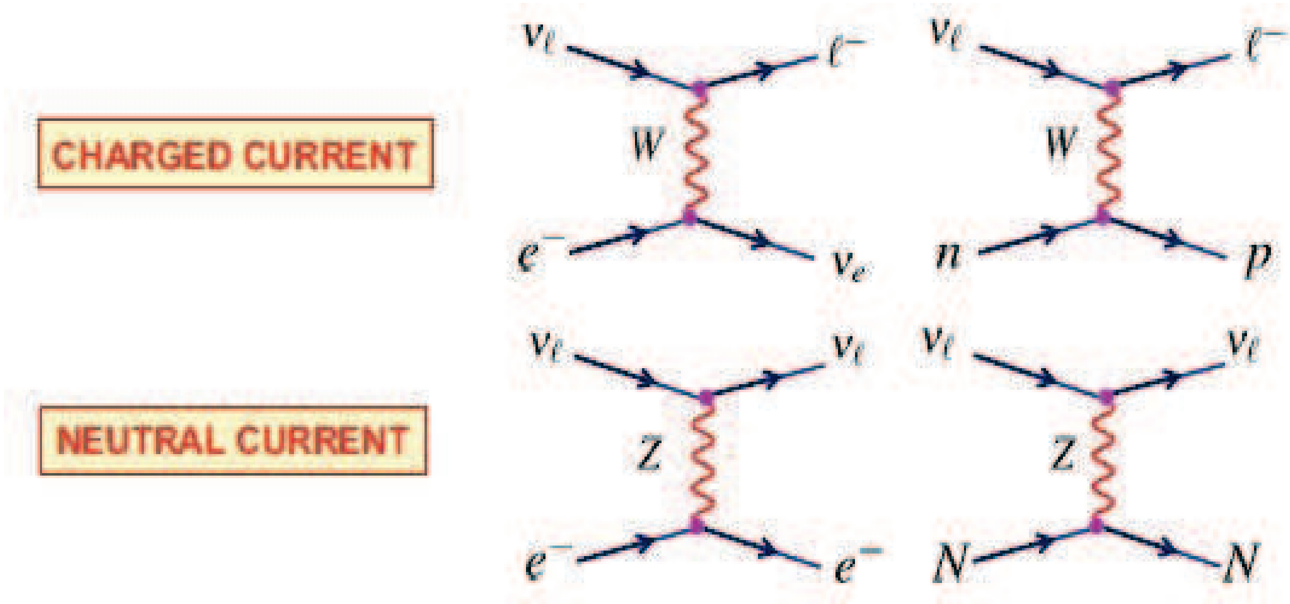
Neutrino Flavour Oscillations



SuperK, SNO
Chlorine
Gallium
Bahcall-Pinsonneault 2000
Neutrino Flux
Neutrino Energy (MeV)
PP
±1%
±10%
±10%
±1.5%
^{7}Be
^{7}Be
pep
+20%
−16%
^{8}B
±?
hep
0.1
0.3
1
3
10

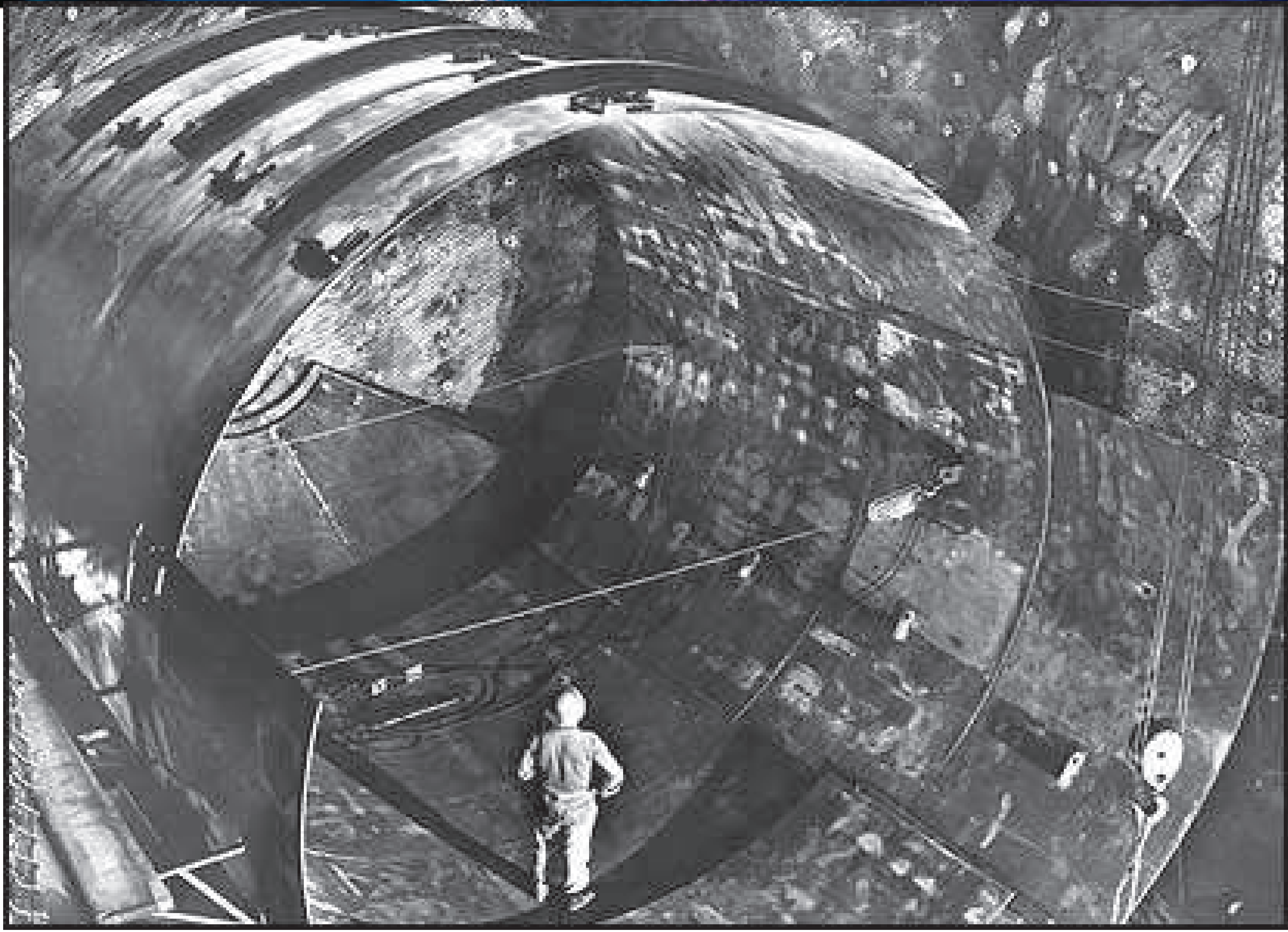
Interaction Thresholds

WARWICK
THE UNIVERSITY OF WARWICK



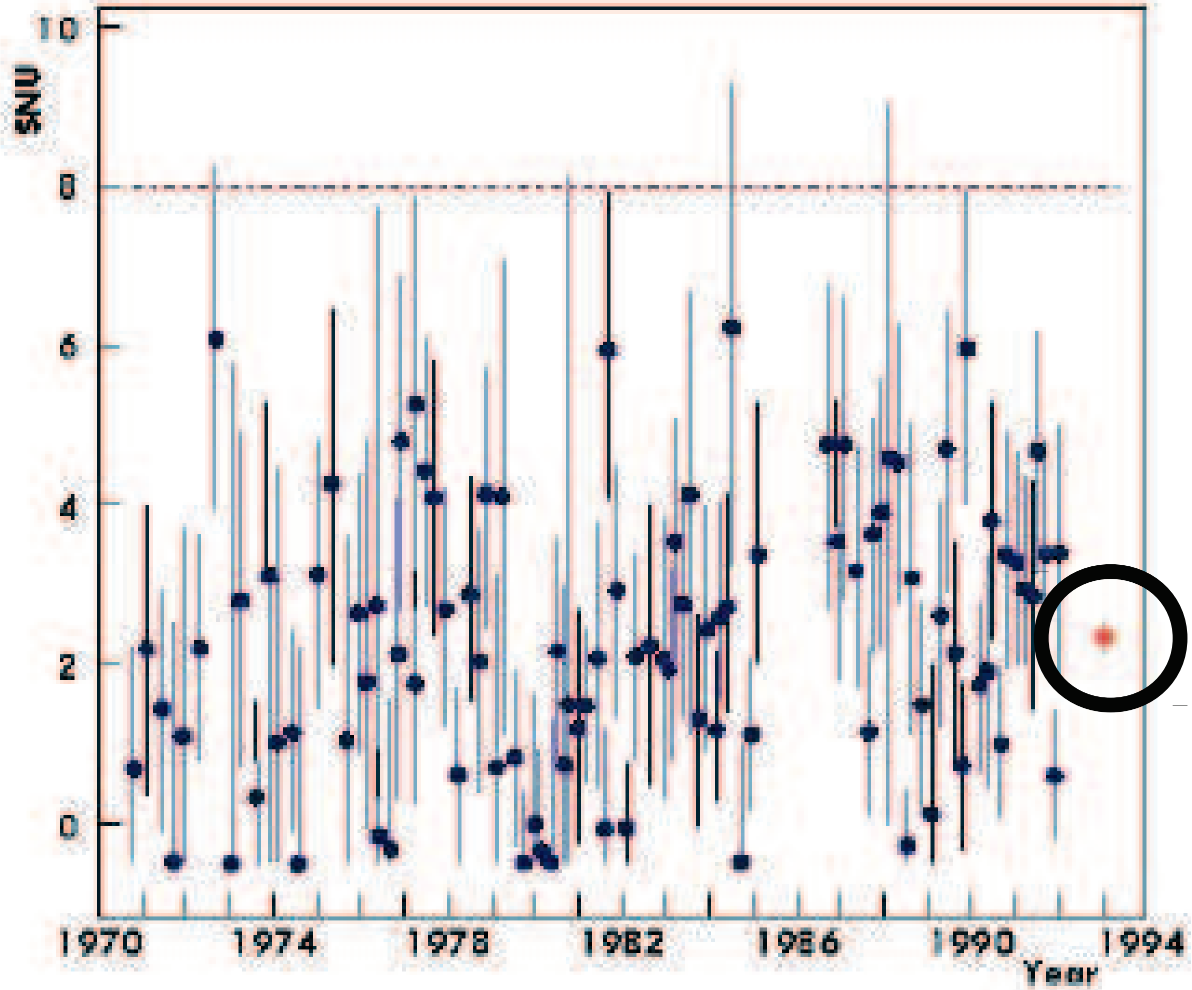
- Neutrinos from sun : E_ν ~ 1 MeV
- Neutrinos from cosmic rays : E_ν ~ 1 GeV

CC interactions :	$E(\nu_e) > 0$ MeV	$E(\nu_\mu) > 110$ MeV	$E(\nu_\tau) > 3.5$ GeV
NC interactions :	$E(\nu_e) > 0$	$E(\nu_\mu) > 0$ MeV	$E(\nu_\tau) > 0$ GeV



Homestake Experiment

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- ; E_{\nu_e} > 800\,keV$$



SSM

2.56 SNU

1 SNU = 10^{-36} captures/atom/s

SAGE and GALLEX

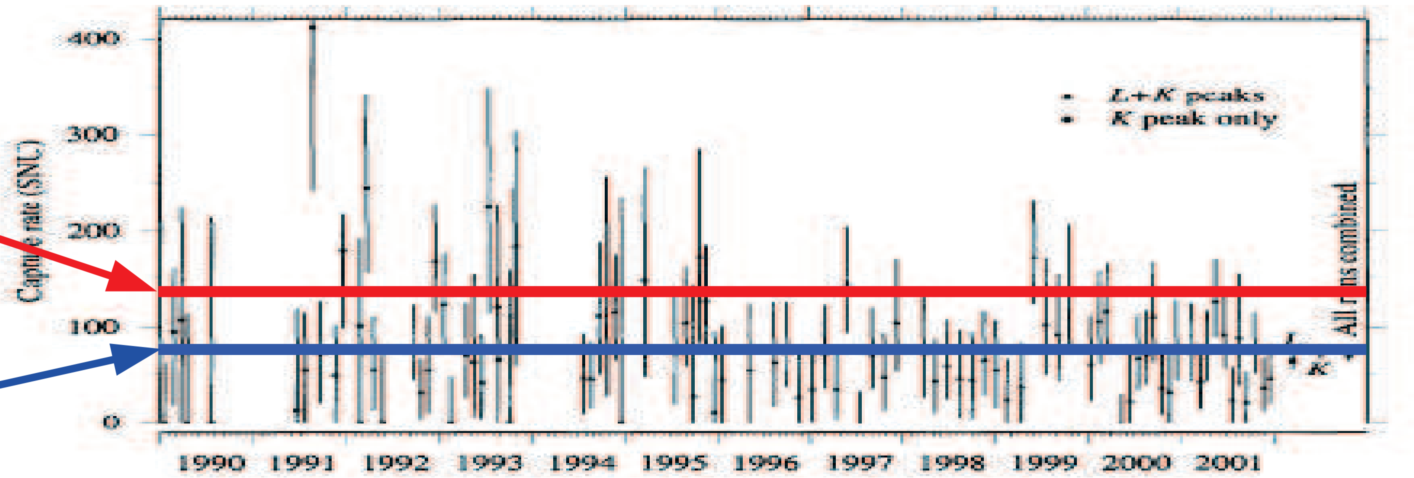
$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}\mathrm{Ge}\,;\, E_{\nu_e} > 233 \quad keV$$

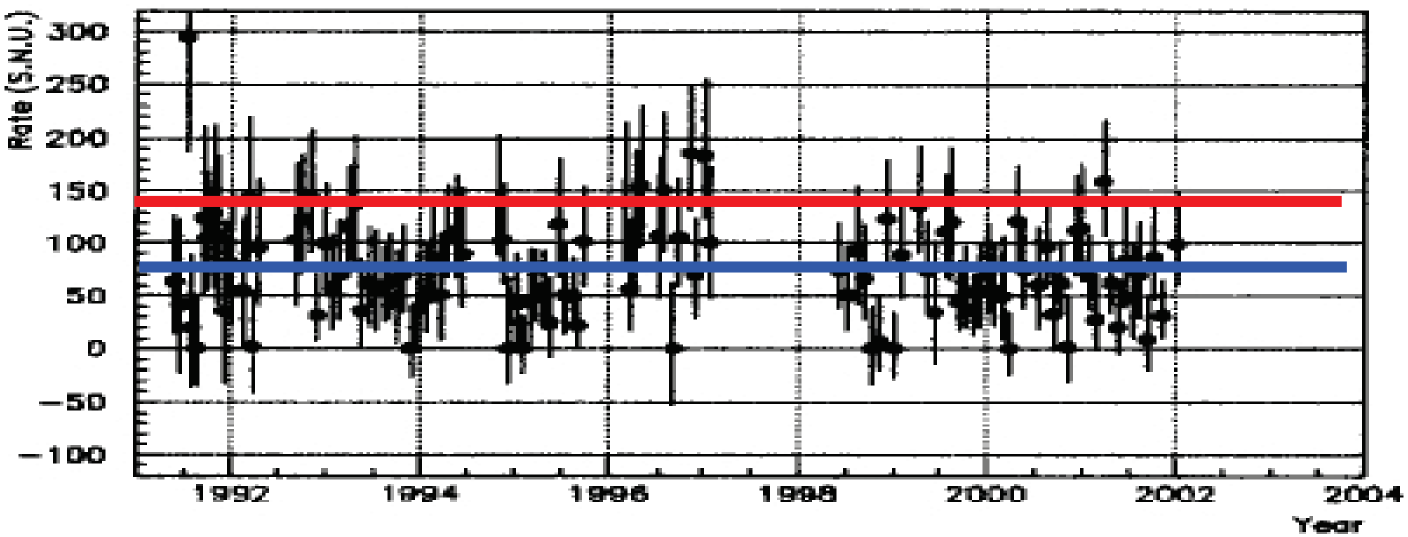
Expected

129 ± 8 SNU

Measured

70 ± 6 SNU





I. Something wrong with the experimental method. Either experiment is faulty or we the neutrinos we are seeing aren't coming from the sun.

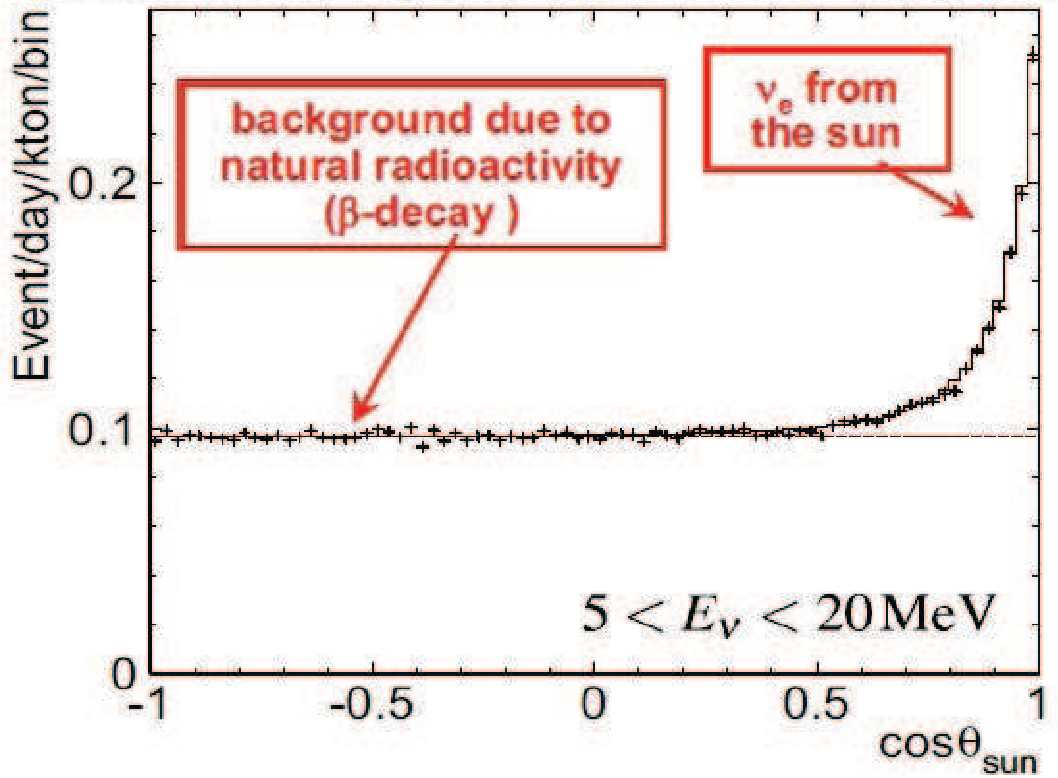
II. Something wrong with the solar model

III. Something wrong with the neutrinos

(Super)Kamiokande

1987 – Kamiokande : 1000 phototubes, 5000 tons of water
1997 – SuperKamiokande : 11000 PMT, 50000 tons of water

S.Fukada et al., Phys. Rev. Lett. 86 5651-5655, 2001



SuperK can only observe the ^{8}B flux (> 5 MeV)

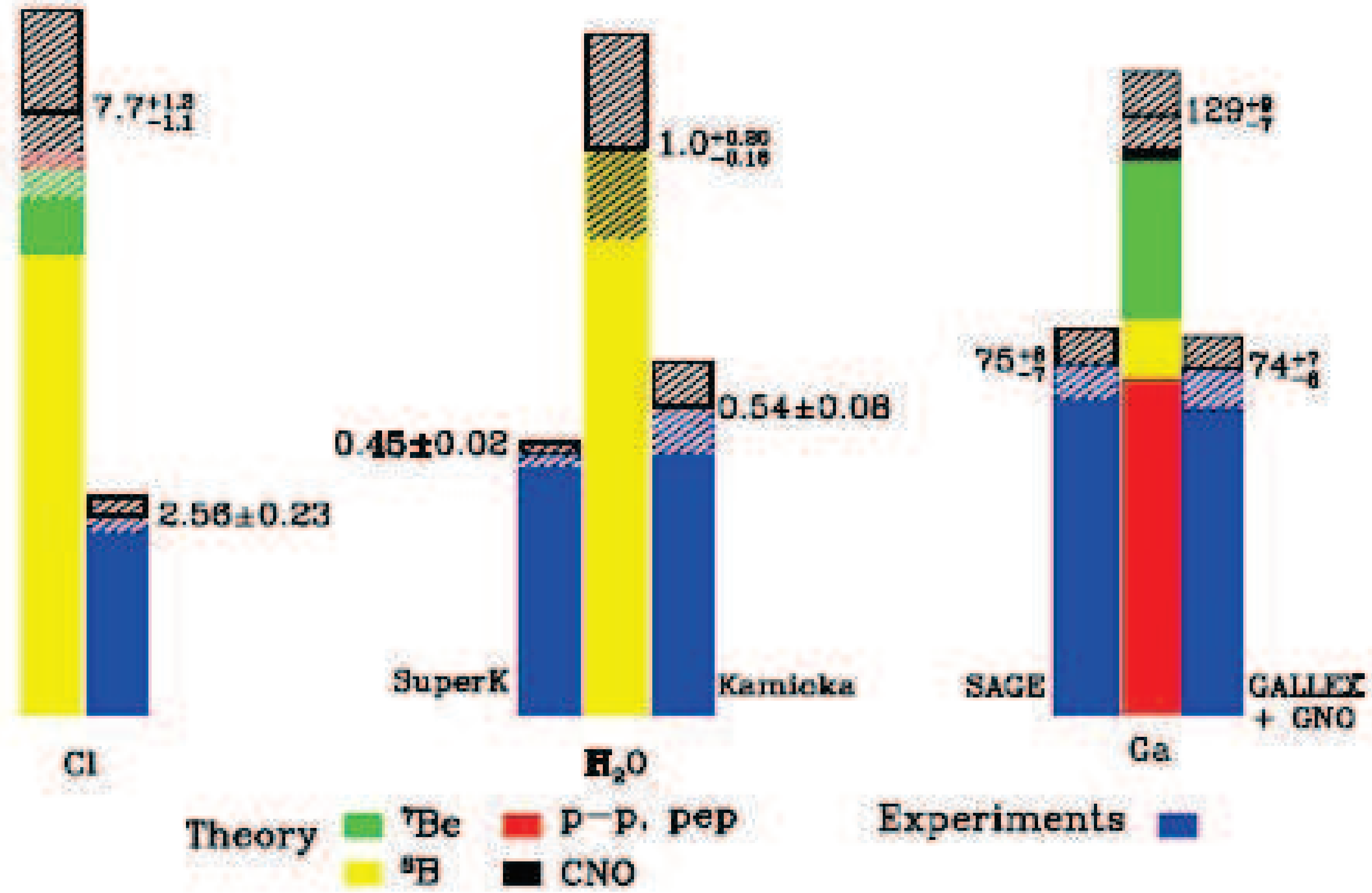
$$\frac{Data}{SSM} = 0.451 \pm 0.017$$

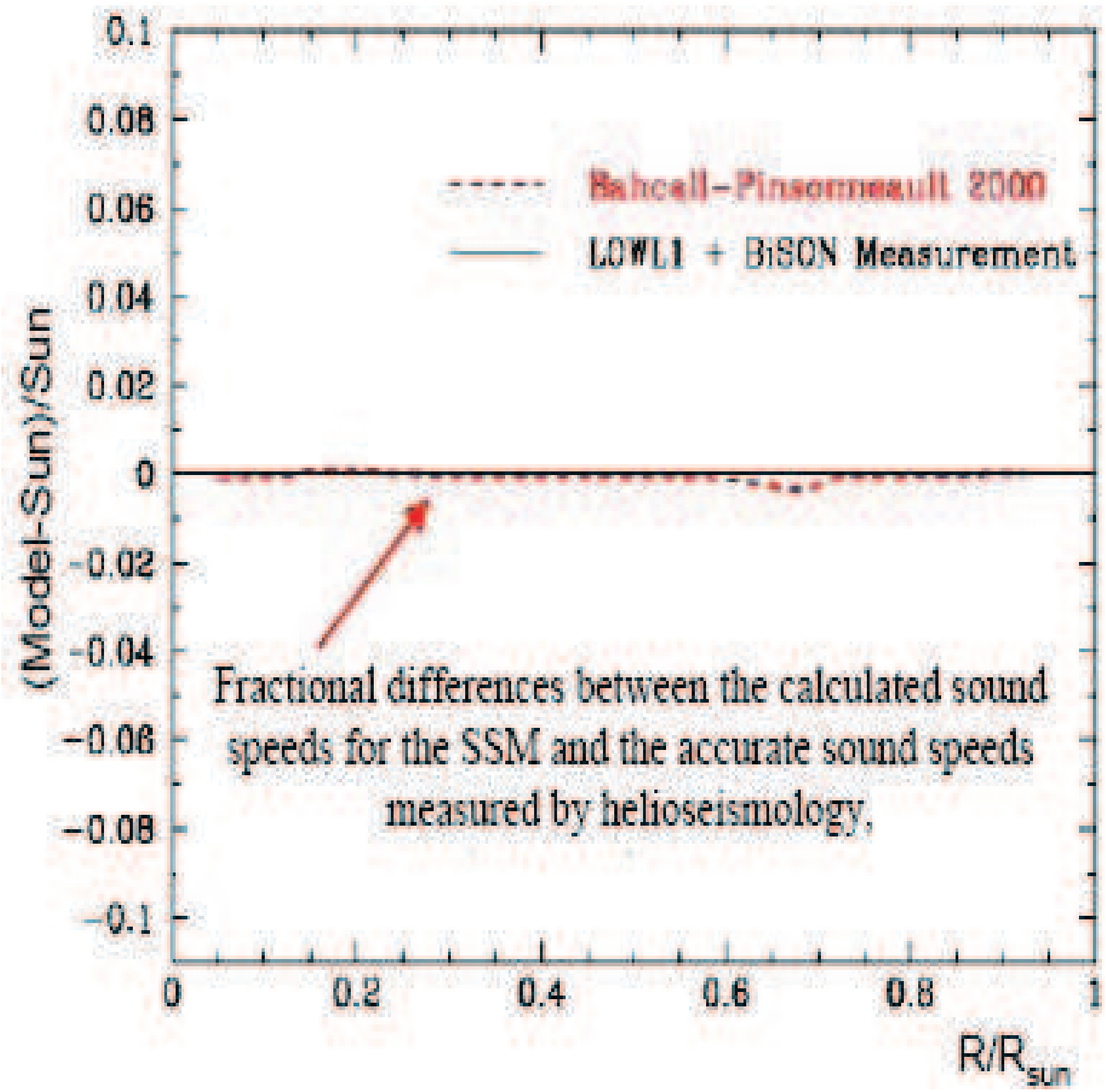
Confirmation that
it wasn't just the radio-
Chemical experiments

SuperK only sensitive to ν_e

Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 2000





$$\Phi_\nu \propto T^{10-25}$$

Sound speed depends
on plasma density
and therefore temperature

I. Something wrong with the experimental method. Either experiment is faulty or we the neutrinos we are seeing aren't coming from the sun.

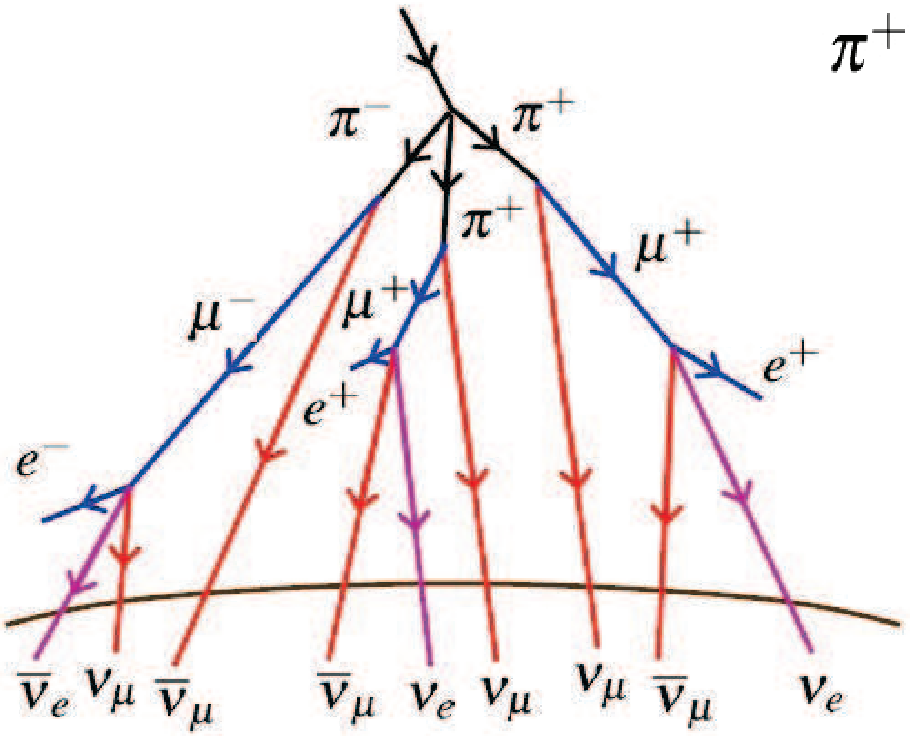
II. Something wrong with the solar model

III. Something wrong with the neutrinos

The Solar Neutrino Problem

Atmospheric neutrinos

High energy cosmic rays interact in the upper atmosphere producing showers of mesons (mostly pions)



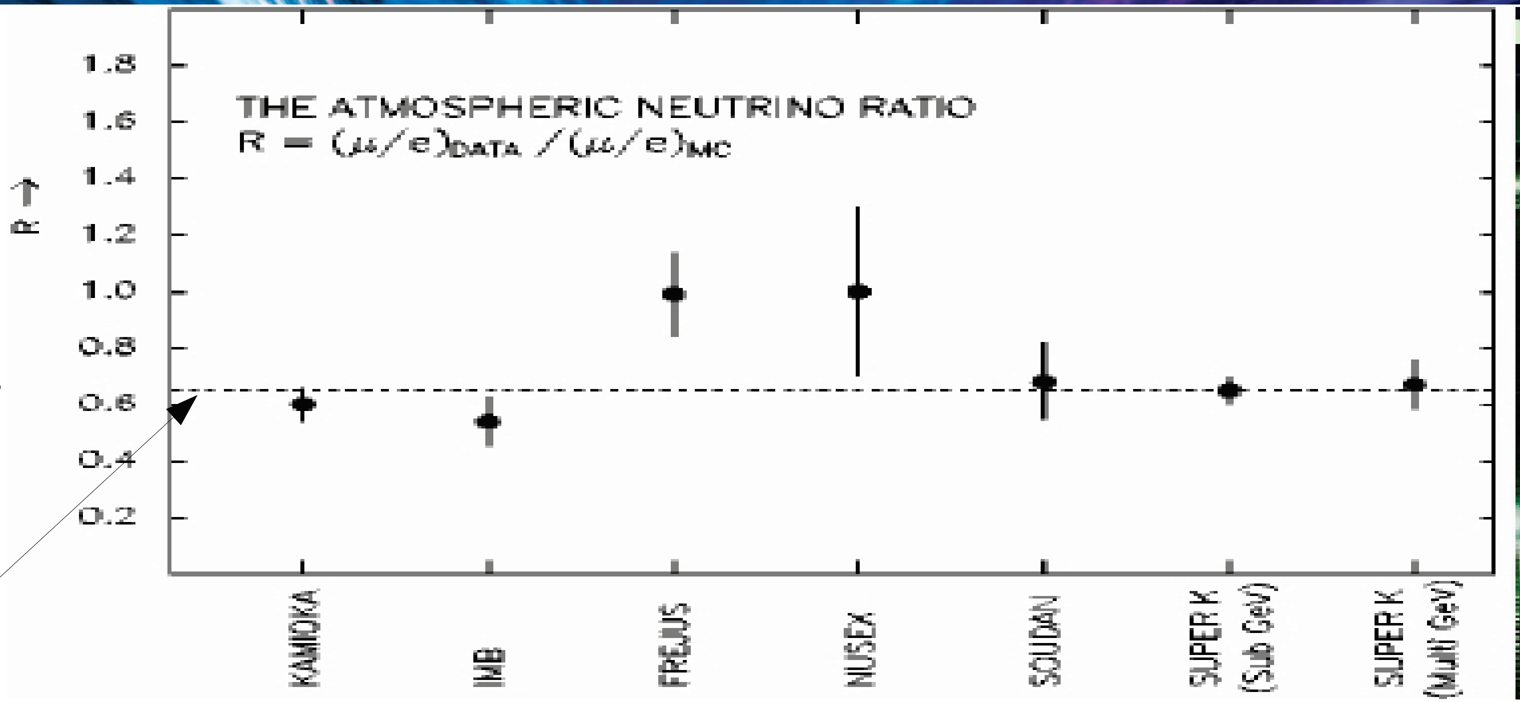
Neutrinos produced by

$$\pi^+ \to \mu^+ \nu_\mu \qquad \pi^- \to \mu^- \overline{\nu}_\mu$$
$$\hookrightarrow e^+ \nu_e \overline{\nu}_\mu \qquad \hookrightarrow e^- \overline{\nu}_e \nu_\mu$$

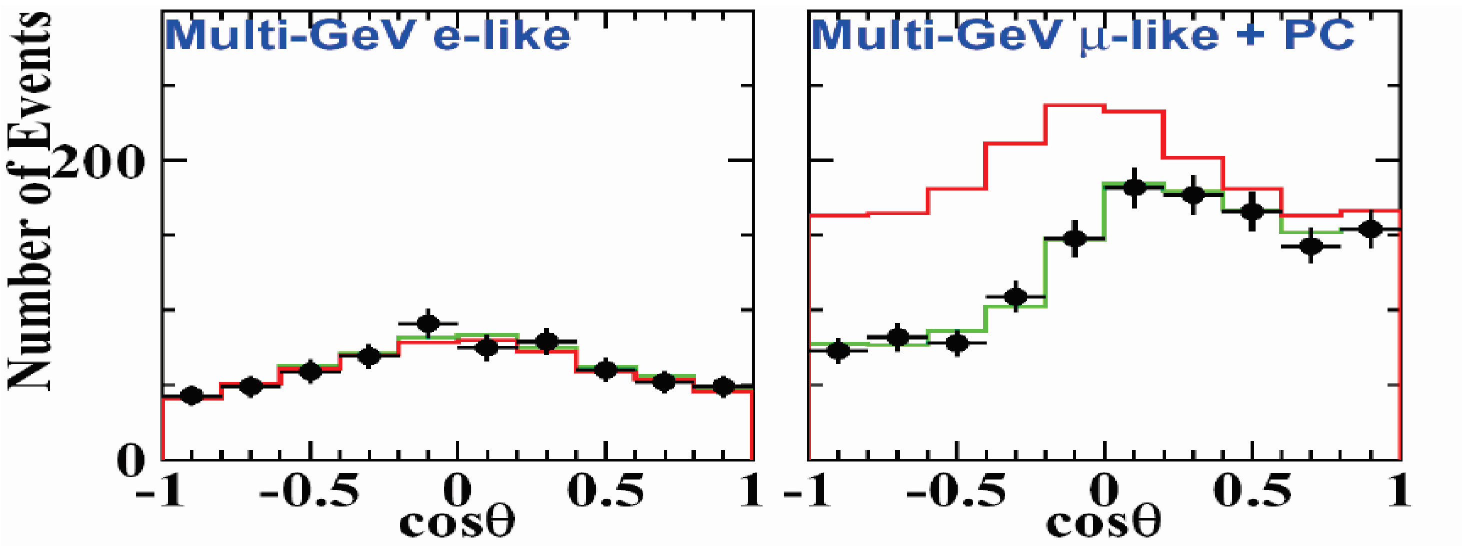
Expect $$\frac{N\left(\nu_\mu + \overline{\nu_\mu}\right)}{N\left(\nu_e + \overline{\nu_e}\right)} \approx 2$$

At higher energies, the muons can reach the ground before decaying so ratio increases

$$R=\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}$$



R ~ 0.6 - 0.7



The Atmospheric Neutrino Anomaly

Solar Neutrino Problem

Experiment	Type	Measurement	Prediction
Homestake	Radiochemical	2.56 SNU	7.6 SNU
Sage	Radiochemical	69.1 SNU	128 SNU
Gallex	Radiochemical	77.5 SNU	128 SNU
Kamiokande	Water Cerenkov	2.80 SNU	5.2 SNU
SNO	Water Cerenkov	1.75 SNU	5.2 SNU

Atmospheric Neutrino Anomaly

Experiment	Type	R
Kamiokande	Water Cerenkov	0.6
IMB	Water Cerenkov	0.58
Super-K	Water Cerenkov	1
Soudan	Iron Calorimeter	0.62
Frejus	Iron Calorimeter	0.62

$$R = \frac{(\mu / e)_{Data}}{(\mu / e)_{MC}}$$

Hypothesis : What if neutrinos could change flavour as they propagated from source to detector?

Solar neutrino problem

ν_e from sun would change to $\nu\mu$ or $\nu\tau$.

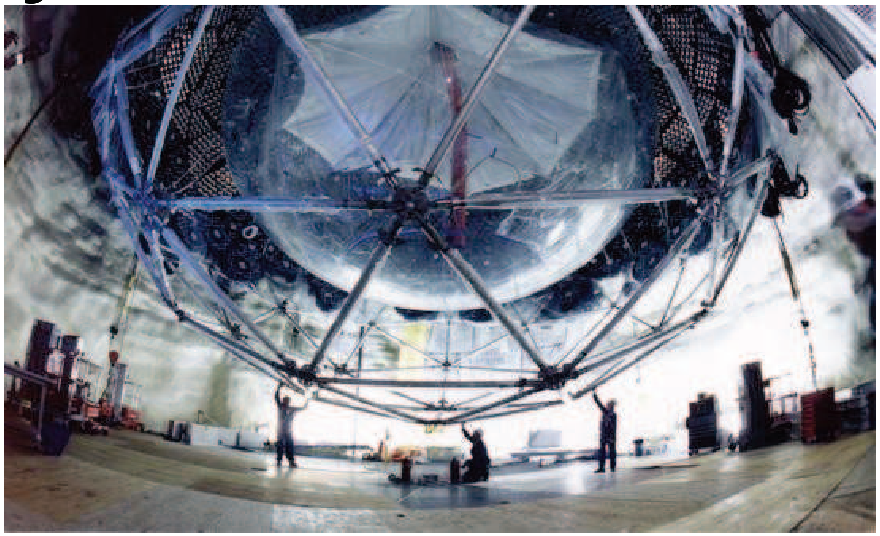
Radiochemical experiments are only sensitive to ν_e CC

Water experiments are sensitive to $\nu\mu$ CC as well, but at low energies ($E_\nu < 115$ MeV) these neutrinos can't interact via the CC

ν_μ / ν_τ component would effectively disappear, reducing the apparent ν_e flux.

Proof : Neutral current event rate shouldn't change.

Sudbury Neutrino Observatory



1000 tonnes of D_20

6500 tons of H_20

Viewed by 10,000 PMTS

In a salt mine 2km underground in Sudbury, Canada

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

Produces Cherenkov Light Cone in D_2O

- $Q = 1.445$ MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

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

n captures on deuteron
$^2H(n, \gamma)^3H$
Observe 6.25 MeV γ

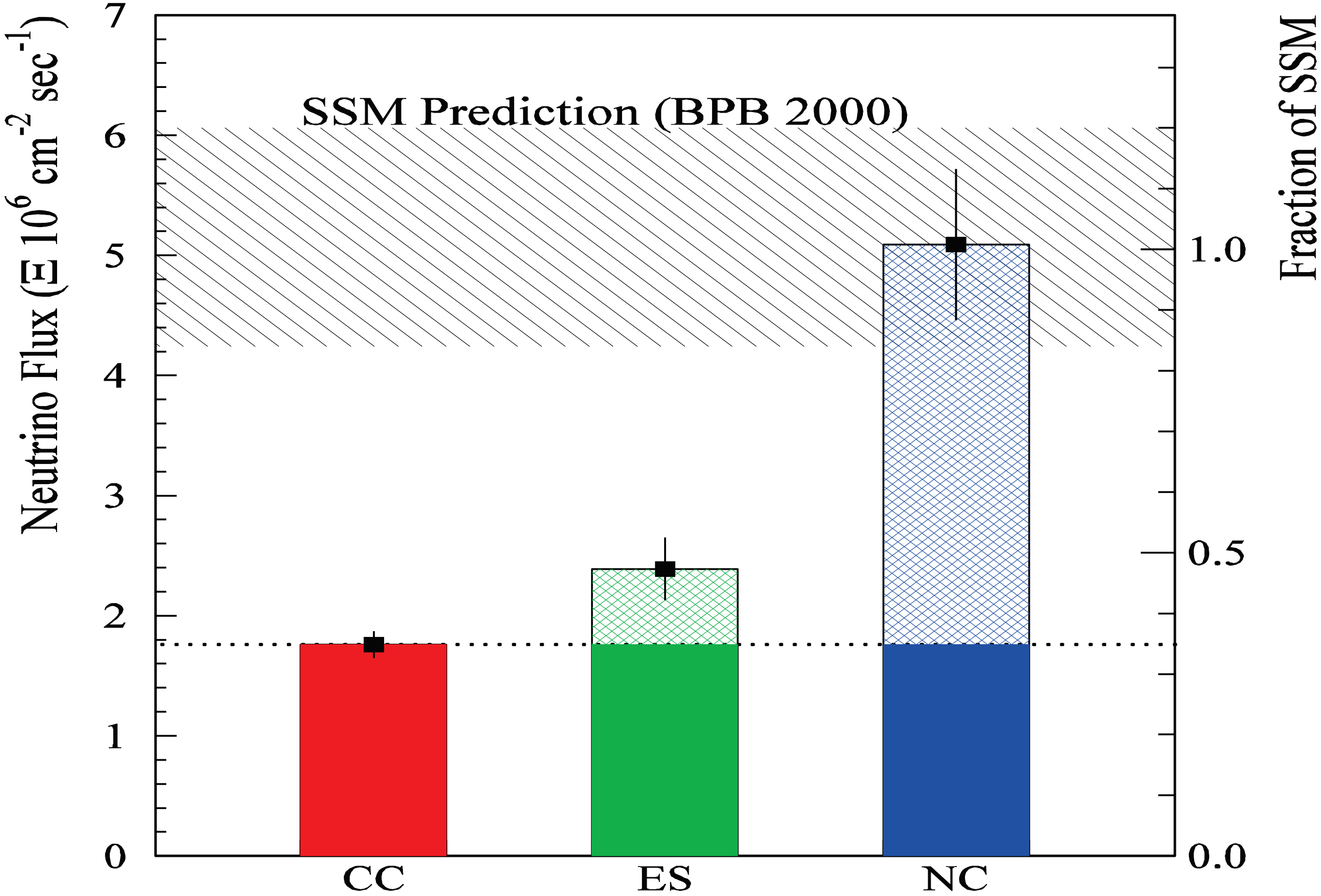
- $Q = 2.22$ MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

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

Produces Cherenkov Light Cone in D_2O

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

SNO Results



5.3 σ appearance of $\nu_{\mu\tau}$ in a ν_e beam

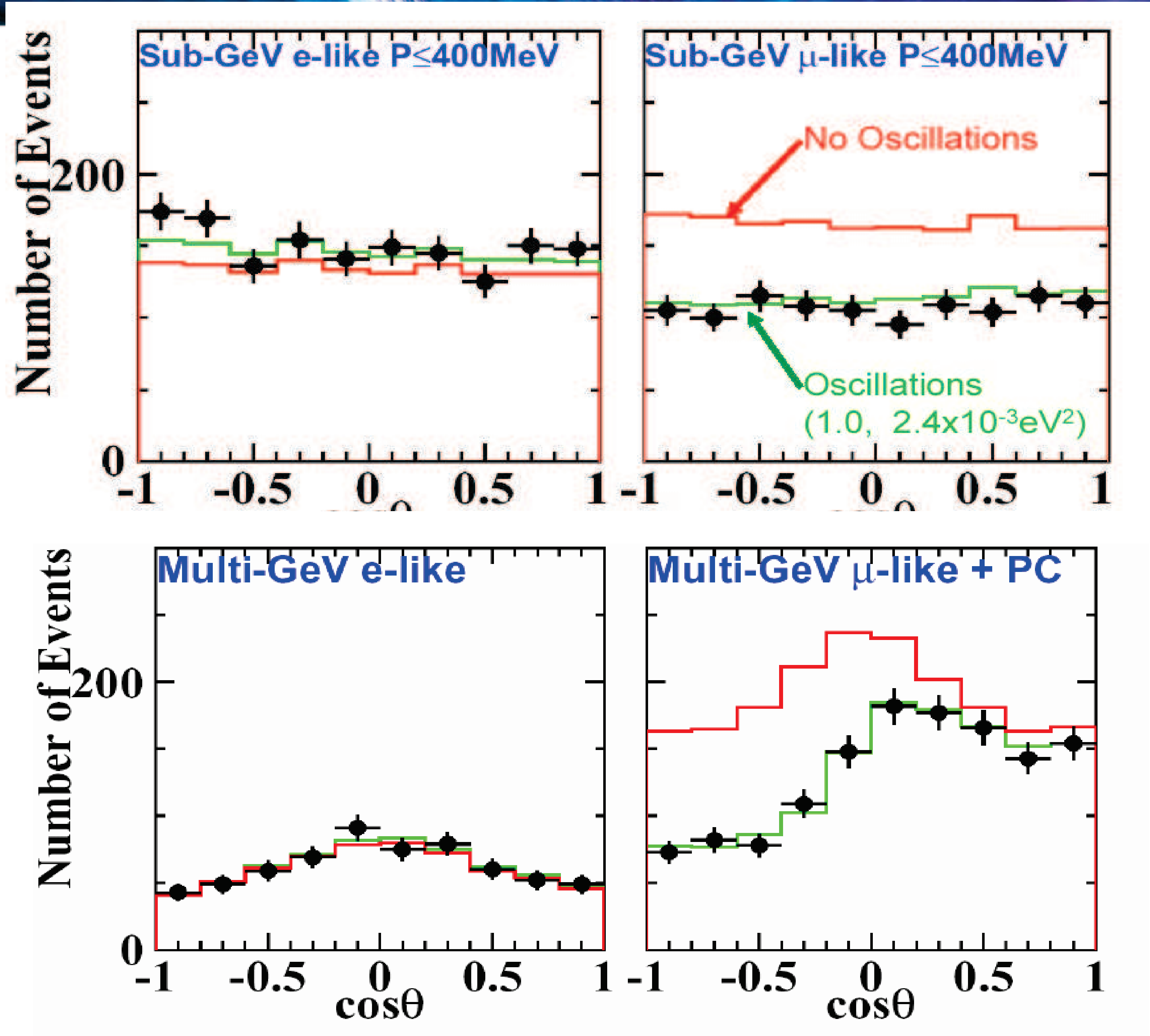
Roughly 70% of ν_e oscillates away

Hypothesis : What if neutrinos could change flavour as they propagated from source to detector?

Atmospheric neutrino anomaly

If ν_μ in the cosmic ray shower were to change flavour to ν_τ on the way to the detector, but not to ν_e, then the ν_e rate would be as expected but the ν_μ rate would decrease. Double ratio would decrease as well.

SuperK is not sensitive to ν_τ so would not see this component.

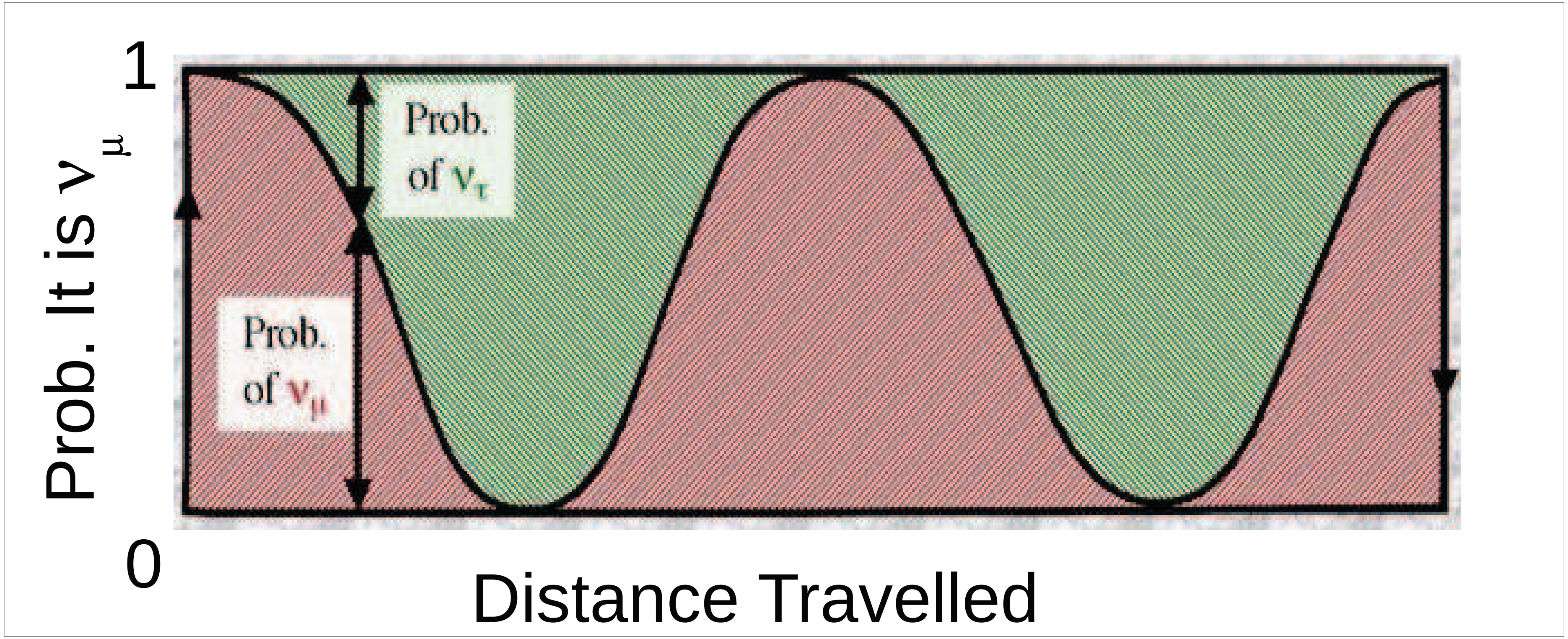


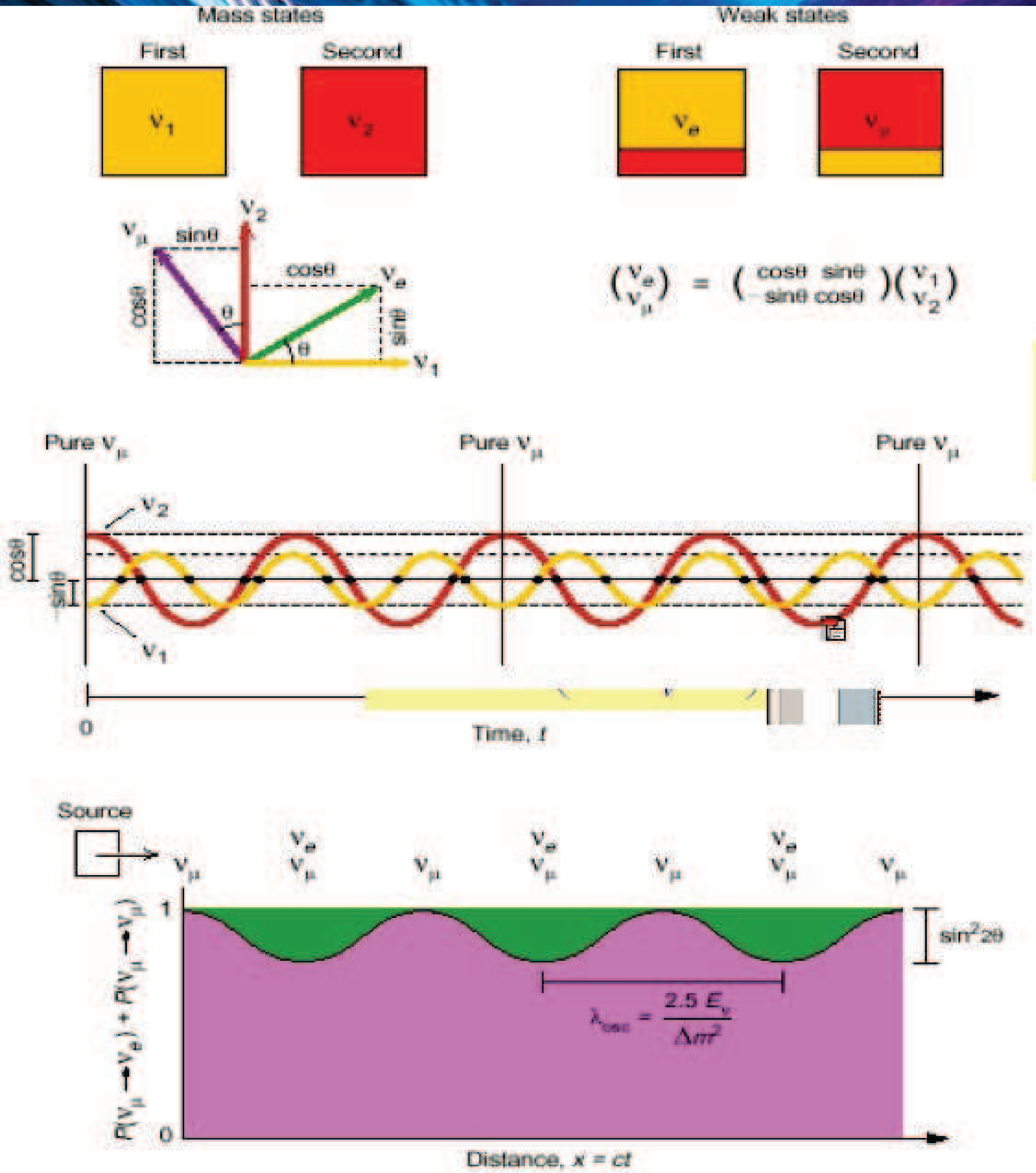
Sub-GeV e-like P≤400MeV
Sub-GeV μ-like P≤400MeV
No Oscillations
Oscillations
(1.0, 2.4x10-3eV2)
Multi-GeV e-like
Multi-GeV μ-like + PC
Number of Events
cosθ

Neutrino Flavour Oscillations

We now know that as a neutrino propagates through space between source and detector its flavour can oscillate in such a way that if you start off with a ν_μ, say, then at some later distance

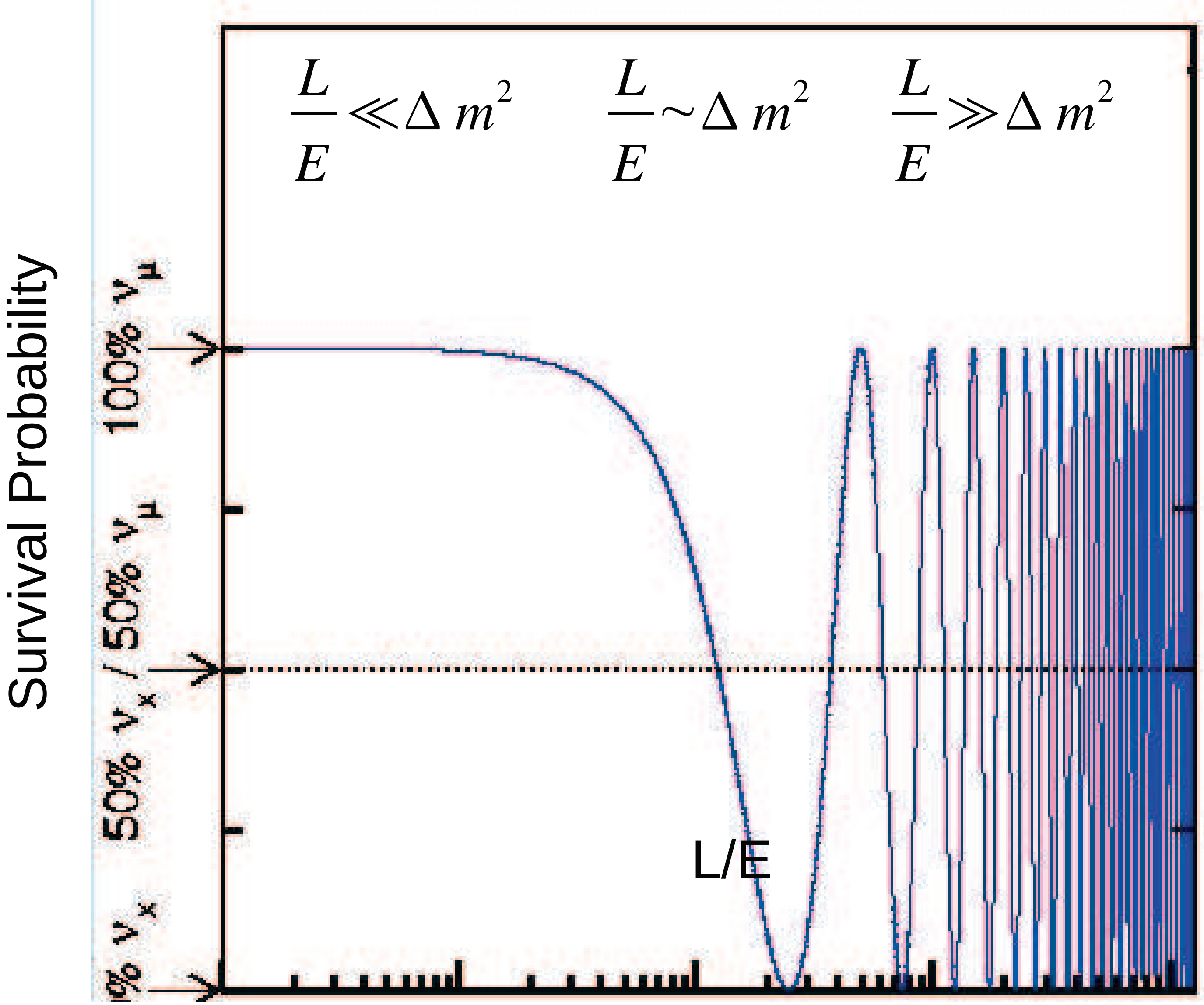
you may be able to detect a ν_τ – the probability depends on the energy of the neutrino and the distance travelled.



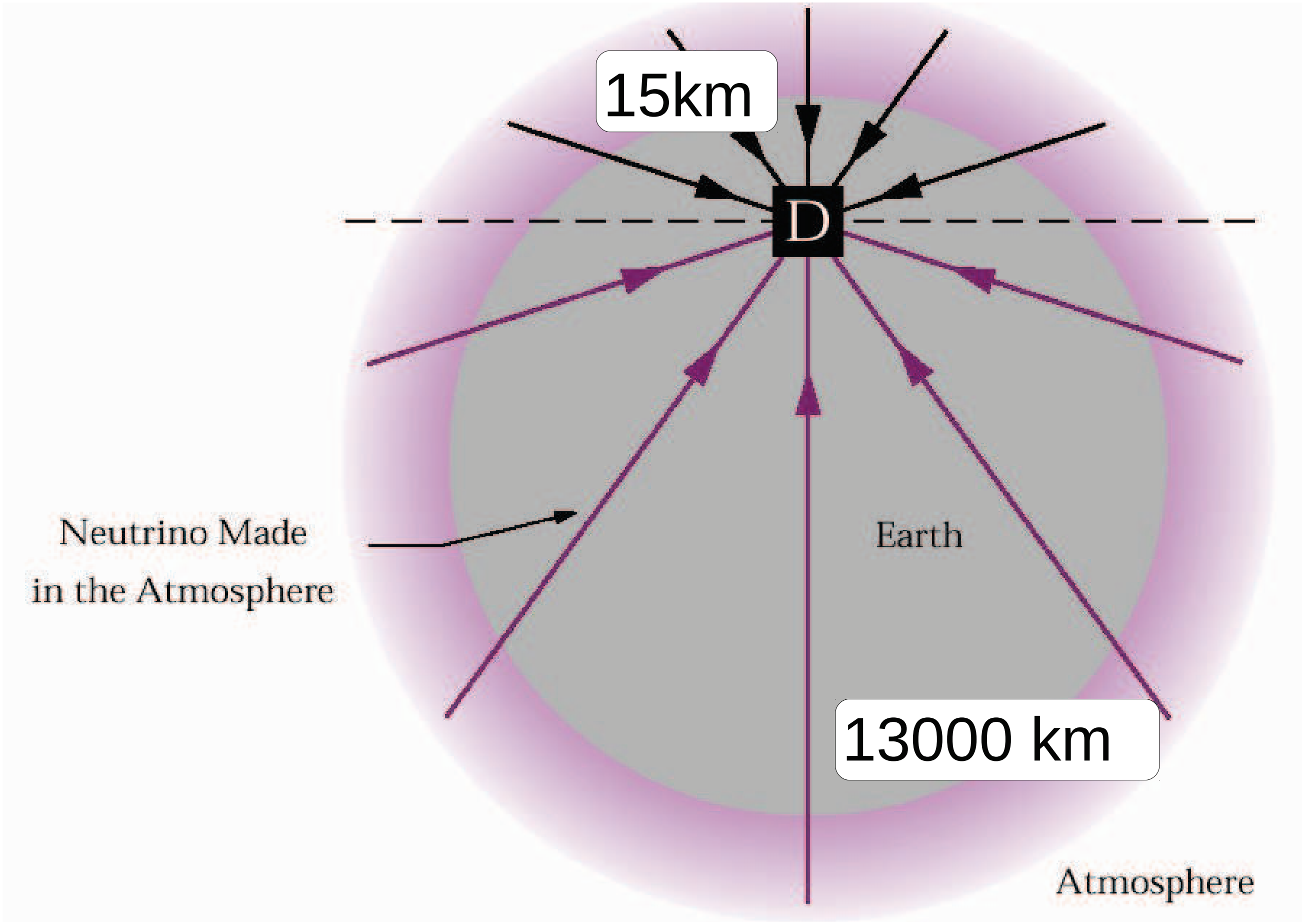


Mass states
First
Second
Weak states
First
Second
sinθ
cosθ
θ
θ
cosθ
sinθ
Pure
Pure
Pure
cosθ
sinθ
Time, t
0
Source
1
0
sin²2θ
2.5 E
Δm²
Distance, x = ct

$$P(\nu_\alpha(0)\rightarrow\nu_\alpha(x)) = 1-\sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{(L/km)}{(E/GeV)}\right)$$



$\cos\theta_{zenith} = 1.0$



$\cos\theta_{zenith} = -1.0$