Neutrinos

Overview

- Pauli postulates Neutrino
- Discovery of neutrino flavours
  - Electron, muon and tau neutrinos
- Neutrino Interactions
  - Cross sections

- Neutrino mass
  - Direct measurement
- Neutrino oscillations
  - Lepton flavour violation
  - Formalism
- Solar neutrinos
  - Homestake, Super-K and SNO
- Atmospheric neutrinos
  - Super-K
- Discovery of Neutrino Mass
  - neutrino oscillations
- Cosmology

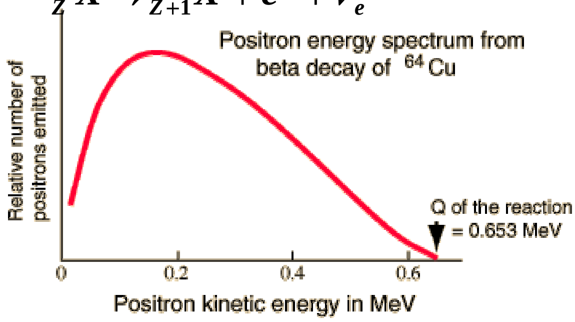
Pauli's Letter

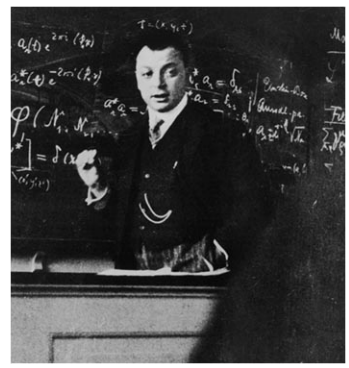
Particle Physics in 1930

Only 3 knowns fundamental particles: e-, p, γ

Continuous energy spectrum of e^- in beta decay

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + e^- + \bar{\nu}_e$$





Pauli

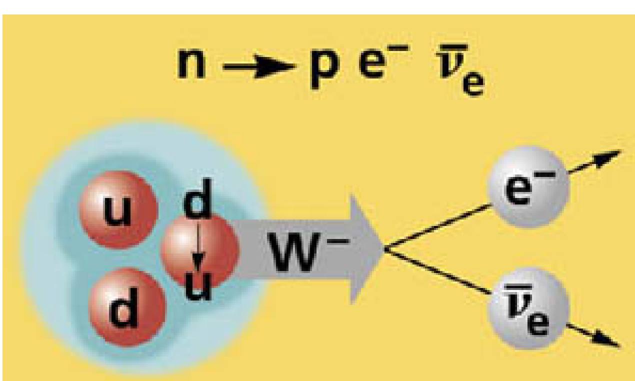
Pauli postulates Neutrino

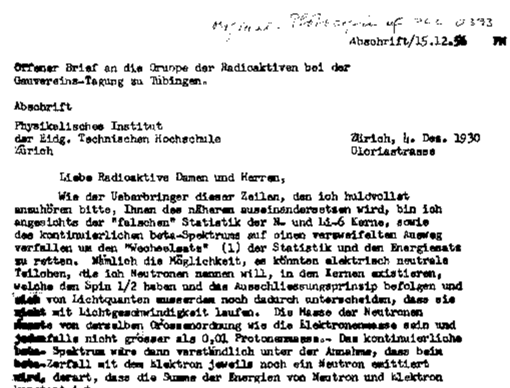
Dear radioactive Ladies and Gentleman

" … desperate remedy to save … the law of conservation of energy"

" … that there could exist … neutrons"

"in beta decay a neutron is emitted in addition to the electron"





Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

1934 name - "neutrino" coined by Fermi

1932 neutron discovered by Chadwick

Neutrino Interactions

Neutrinos

point-like leptons

do not interact strongly, no colour charge

charge Q = 0 → no electromagnetic interactions

Only weak interactions by coupling to $W^{\pm}$ and Z^0

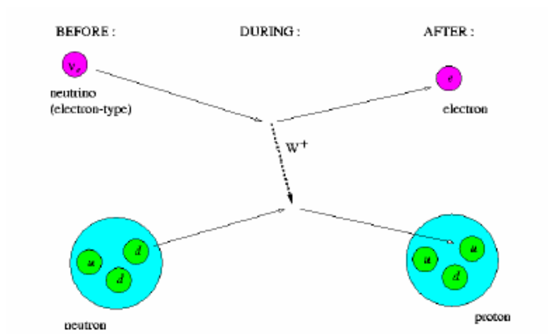
Expect very small detection rates

" I have done a terrible thing. I have postulated a particle that cannot be detected." Pauli

Inverse Beta Decay

$$\nu_e + n \to p + e^-$$

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



Cross section

$$\sigma\left(\bar{\nu}_e + p \to n + e^+\right) \approx 5 \cdot 10^{-44} \left(\frac{E_{\bar{\nu}}}{\text{MeV}}\right)^2 \text{cm}^2$$

Mean Free Path

60 light years of water for 1 MeV anti-neutrino

$$\lambda = \frac{1}{n\sigma} \approx 6 \cdot 10^{19}\ \text{cm} \approx 60\ \text{light years} \qquad \text{n} = Z\frac{N_A}{A} = 3.34 \cdot 10^{23}\ \text{cm}^{-3}$$

1 ν in 10^{11} interacts when crossing the earth

Require huge rates as neutrino sources

Discovery of Neutrinos

Electron Neutrino ν_e — discovered 1956 by Reines and Cowan

Anti-neutrino source

Nuclear reactor --- anti-ν flux $6 \cdot 10^{20}\ s^{-1}$

Target and **Detector** --- 400 l liquid scintillator

Water and Cadmium Chloride

Detection of anti-neutrino $\bar{\nu}_e + p \to n + e^+$

e+ annihilates with atomic e- $e^+e^- \to \gamma\gamma$

n Cd reaction delayed by 20 μs $nCd \to Cd^* \to \gamma\, Cd$

Delayed coincidences only produced by signal

Muon Neutrino ν_μ — 1962 at Brookhaven by Ledermann, Steinberger, Schwartz

Pion beam

Iron absorber --- only muons survive

π-beam $\quad \pi^+ \to \mu^+ \nu_\mu \qquad \pi^- \to \mu^- \bar{\nu}_\mu$

observe $\quad \nu_\mu + n \to \mu^- + p \qquad \bar{\nu}_\mu + p \to \mu^+ + n$

don't see $\quad \nu_\mu + n \to e^- + p \qquad \bar{\nu}_\mu + p \to e^+ + n$

➔ ν_μ and ν_e are different

Tau Neutrino ν_τ — 2000 at Fermilab - Donut

p on tungsten target

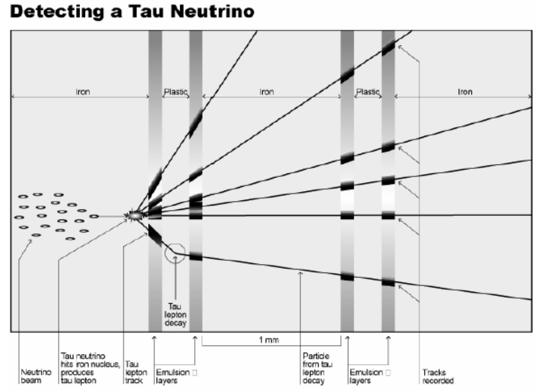
produce D_s mesons

$$D_s^+ \to \tau^+ + \nu_\tau$$

$$\nu_\tau + N \to \tau^- + X$$

$$\tau^- \to \mu^- + \nu_\tau + \bar{\nu}_\mu$$

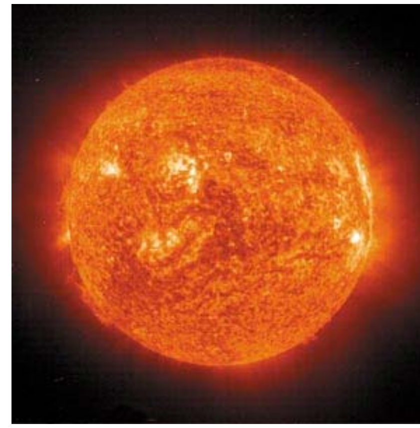
Detecting a Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

Neutrino Physics

Neutrino Sources



Natural radioactivity – e.g. rocks

Cosmic rays hitting the atmosphere

Nuclear reactors

Particle accelerators

Sun - nuclear fusion reactor

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$

Flux on earth ~10^{11} $cm^{-2}s^{-1}$

100 billions/sec through your finger nail

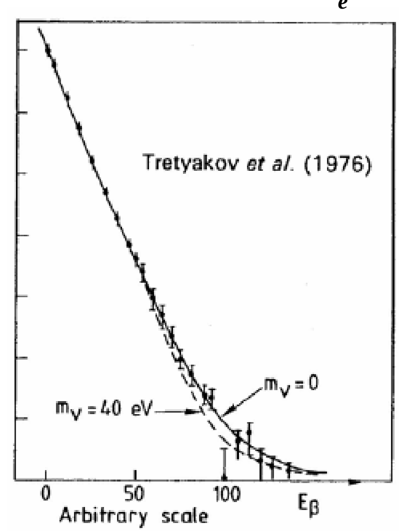
Neutrino Mass

No apparent "reason" for neutrino to be massless

all other fermions have mass

Direct mass measurements

$${}^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$



Beta decay energy spectrum

$$\frac{d\Gamma}{dE} = \frac{G_F^2}{2\pi^3}(E_0 - E_e)^2 E_e^2$$

$$\sqrt{\frac{d\Gamma}{dE}\frac{1}{E_e^2}} \propto E_0 - E_e$$

Kurie plot

linear

Endpoint modified by resolution

and non-zero ν_e mass

Tritium Beta Decay Mass $m(\nu_e) < 3$ eV

Neutrino Oscillations

No apparent "reason" for neutrinos not to oscillate

into each other $\nu_e\ \nu_\mu$ $\nu_\mu\ \nu_\tau$

Neutrino Oscillations

Lepton flavour conservation

L_e, L_μ, L_τ are conserved separately

Neutrinos with mass can mix - weak eigenstates are linear superpositions of mass eigenstates

➔ L_e, L_μ, L_τ not absolutely conserved

L_e, L_μ, L_τ Violation too small to observe BF < 10^{-40}

2 Neutrino flavours

Easy to understand, can be expanded to 3 generations

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

Time evolution
$$\nu_1(t) = \nu_1(0)\exp(-iE_1 t)$$
$$\nu_2(t) = \nu_2(0)\exp(-iE_2 t)$$

Intensity I(t) for initial ν_e beam

$$I_{\nu_e}(t) = I_{\nu_e}(0)\left(\left(\cos^2\theta + \sin^2\theta\right)^2 - 4\sin^2\theta\cos^2\theta\sin^2\left(\frac{(E_2 - E_1)t}{2}\right)\right)$$

Neutrino energy E and mass difference Δm_{12}^2

$$E_i^2 = p_i^2 + m_i^2 \qquad E_i >> m_i \qquad \Delta m_{12}^2 \equiv m_2^2 - m_1^2$$

$$\Rightarrow E_i \approx p_i + \frac{m_i^2}{2p_i} \qquad \Rightarrow \Delta E \equiv E_2 - E_1 \approx \Delta m_{12}^2 / 2E$$

Neutrino Oscillation Probabilities

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m_{12}^2[\text{eV}]L[\text{m}]}{E[\text{MeV}]}\right)$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m_{12}^2[\text{eV}]L[\text{m}]}{E[\text{MeV}]}\right)$$

Distance from source L [m], E[MeV] and Δm_{12}^2 [eV^2]

Solar Neutrinos

Standard Solar Model (SSM)

Bahcall

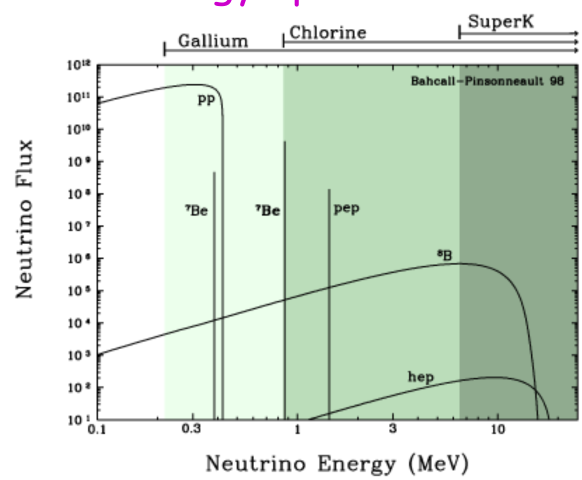
Predicts rates and solar neutrino energy spectra

pp flux below 0.42 MeV

^8B ν_e up to 14 MeV

pp cycle

pp	$\rightarrow$	$^2H + e^+ + \nu_e$	
$^2H + p$	$\rightarrow$	$^3He + \gamma$	
$^3He + {}^3He$	$\rightarrow$	$^4He + 2p$	85%
$^3He + {}^4He$	$\rightarrow$	$^7Be + \gamma$	15%
$e^- + {}^7Be$	$\rightarrow$	$^7Li + \nu_e$	
$^7Li + p$	$\rightarrow$	$2\,{}^4He$	
$p + {}^7Be$	$\rightarrow$	$^8B + \gamma$	0.02%
^8B	$\rightarrow$	$^8Be^* + e^+ + \nu_e$	
$^8Be^*$	$\rightarrow$	$2\,{}^4He$	



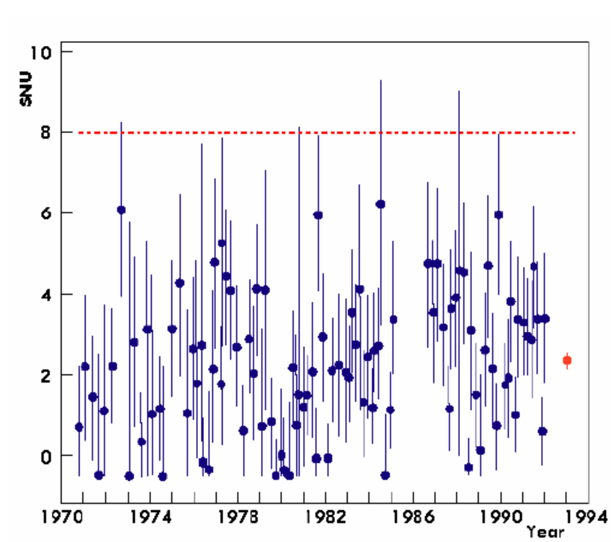
Homestake Experiment

First observed solar neutrinos in 1970s

Davies

100,000 gallons of

cleaning fluid C_2Cl_4



Measurement

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

0.5 Ar atoms/day

2.56±0.23 SNU

SSM prediction

1.5 Ar atoms/day

7.7±1.3 SNU

Puzzle - What is wrong?

Experiment, SSM, Neutrinos

1 SNU = 1 interaction

10^{36} target atoms/sec

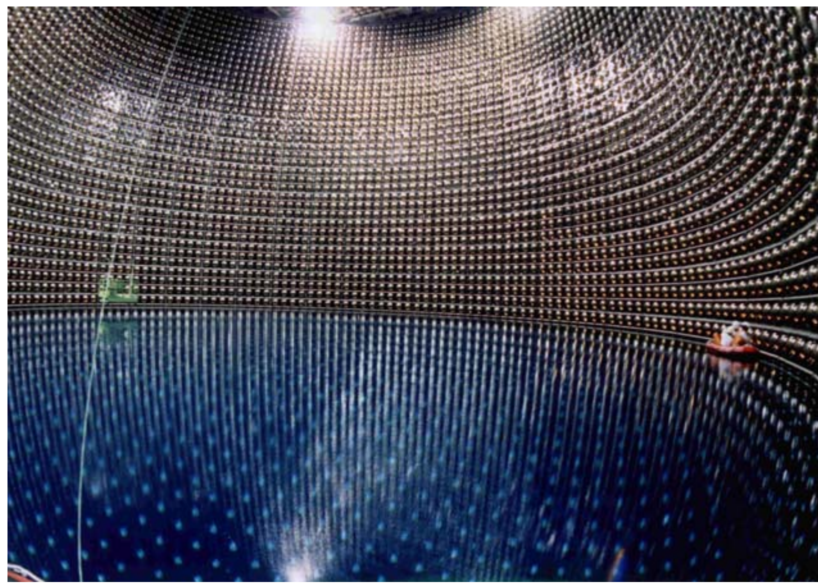
Solar Neutrinos II

Super-Kamiokande

50,000 tons of water, 11,000 phototubes

underground inside a mine in Japan, started 1997

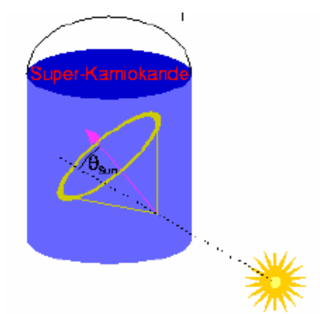
ν_e Detection



Elastic scattering

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

Directional sensitivity

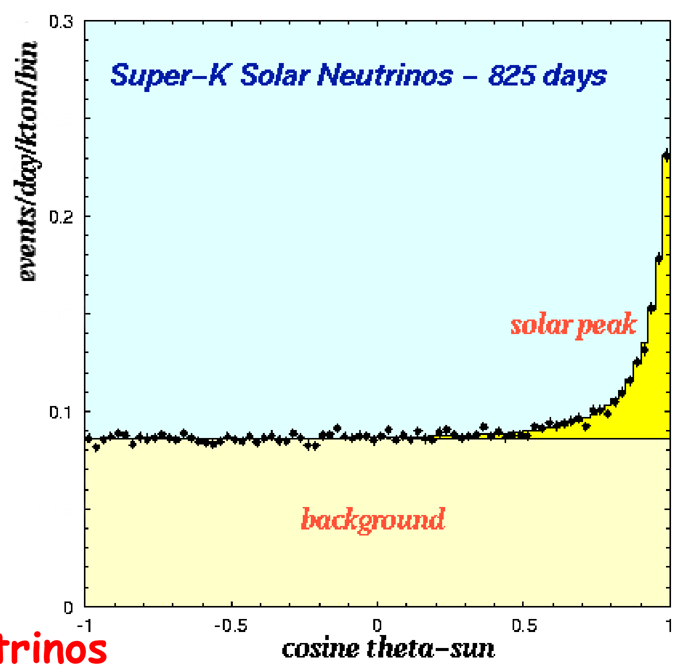


Measurements

$(0.465 \pm 0.005 + 0.016 - 0.015) \times SSM$

ν_e definitely from sun

Signal from centre of sun



Puzzle - What is wrong?

Homestake experiment confirmed

~~Experiment~~, SSM, Neutrinos

Solar Neutrinos III

SNO --- Sudbury Neutrino Observatory

1000 tons of heavy water (D_2O)
10,000 photo multipliers tubes

Sensitivity

SNO is able to measure ν_e - Charged Current
but also ν_μ and ν_τ ($\nu_{i=e,\mu,\tau}$) - Neutral Current

Charged current (CC) $\nu_e + D \to p + p + e^-$

Elastic scattering (ES) $\nu_i + e^- \to \nu_i + e^-$

Neutral current (NC) $\nu_i + D \to n + p + \nu_i$

Measurements

2003 results

$Flux_{CC} = 1.59^{+0.10}_{-0.11} \times 10^{-6}\, cm^{-2} s^{-1}$ 31% of SSM

$Flux_{ES} = 2.21^{+0.33}_{-0.28} \times 10^{-6}\, cm^{-2} s^{-1}$

$Flux_{NC} = 5.21 \pm 0.47 \times 10^{-6}\, cm^{-2} s^{-1}$ 100% of SSM

$CC/NC = 0.306 \pm 0.036$

31 % of solar ν's arrive as ν_e at earth
100% of solar ν's detected if ν_μ and ν_τ are included

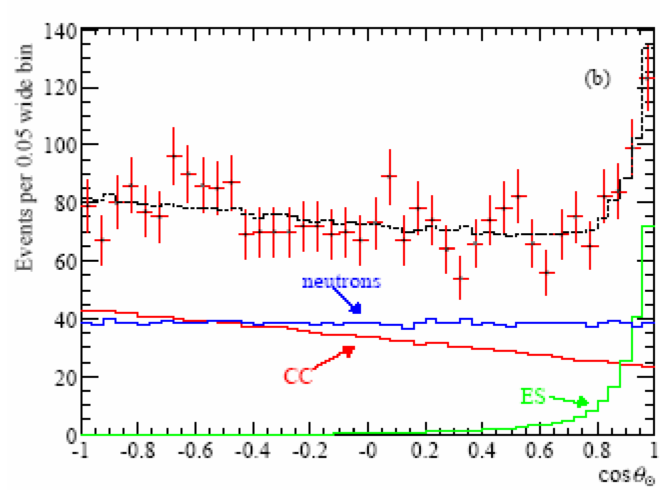
Puzzle - What is wrong?

~~Experiment~~, ~~SSM~~,
Neutrinos

Neutrino Oscillations

ν_e change to ν_μ in flight

ν_e ν_μ ν_μ ν_τ



Atmospheric Neutrinos

Cosmic Rays

Protons hit nuclei in upper part of atmosphere

Producing chain of particles

copious source of neutrinos

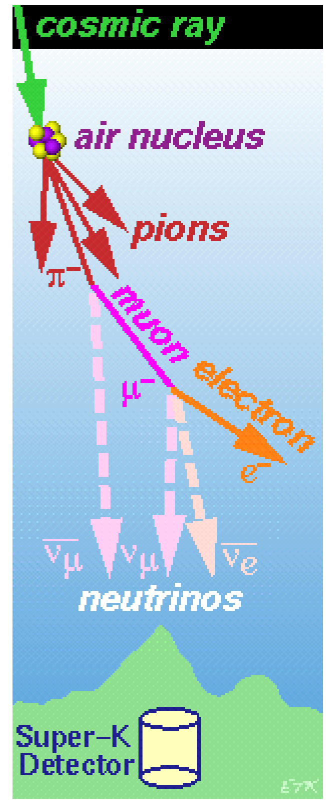
Main decay sequence

$\pi^+ \to \mu^+ \nu_\mu$ and $\pi^- \to \mu^- \bar{\nu}_\mu$

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ $\quad$ $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

Expect 2 ν_μ for each ν_e

~1990 1st indications for "too few ν_μ"



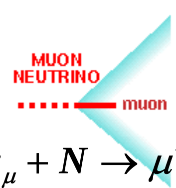
Super-Kamiokande

Can discriminate ν_μ from ν_e

$\nu_\mu + N \to \mu^- + X$ $\quad$ $\nu_e + N \to e^- + X$

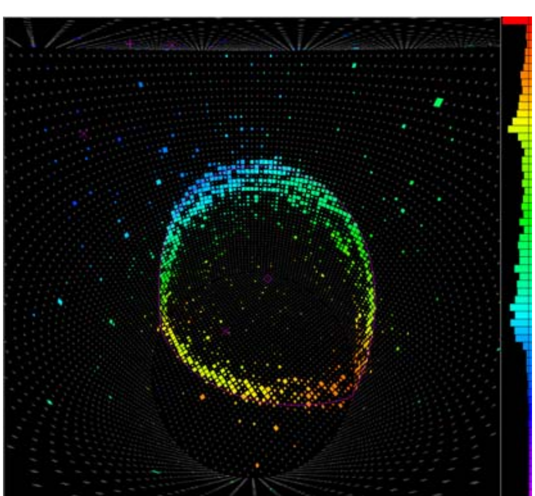
Recoil muon produces clean ring

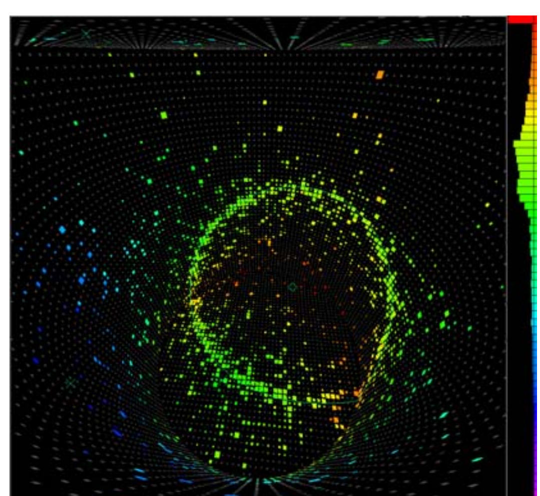
Recoil e- produces fuzzy ring



$\nu_\mu + N \to \mu^- + X$

$\nu_e + N \to e^- + X$





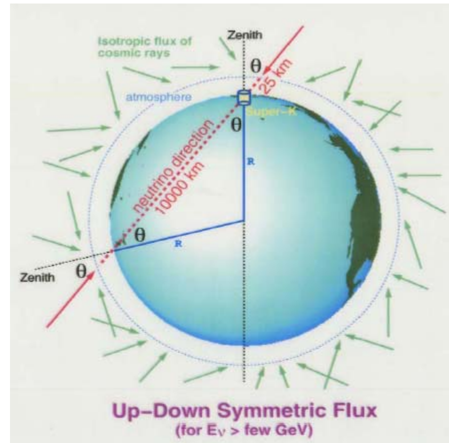
Atmospheric Neutrinos II

Measurements

1998 Super-Kamiokande

Observe significant deficit of ν_μ

and agreement for ν_e

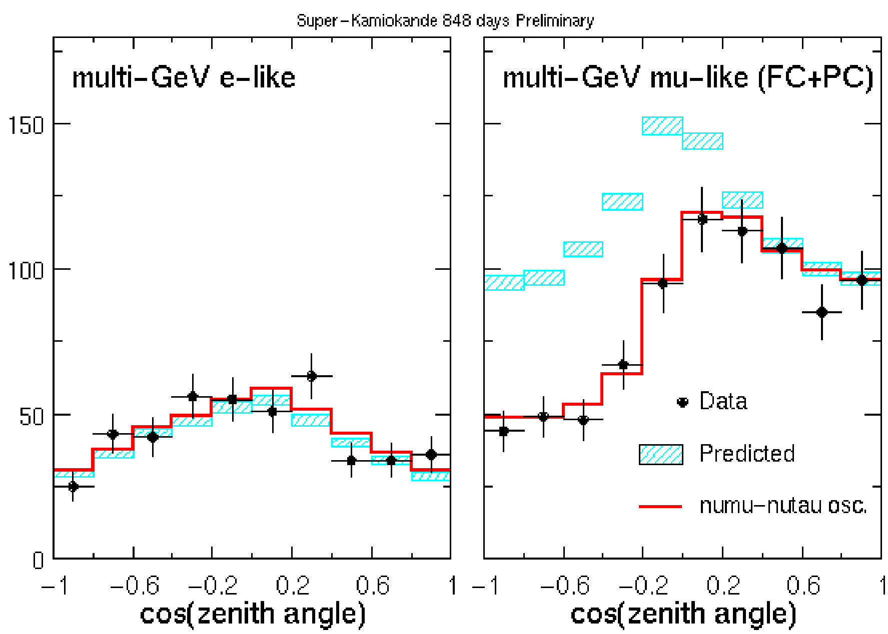


Neutrino Disappearance

ν_μ traversing the earth

i.e arriving at the detector

from below disappear



Neutrino Oscillations

Atmospheric neutrinos

ν_μ change to ν_τ in flight

ν_e ν_μ ν_μ ν_τ

First Evidence for

Neutrino Oscillations

Discovery of Neutrino Mass

Atmospheric Neutrino Oscillations

Atmospheric ν_μ change into ν_τ

Oscillation probability

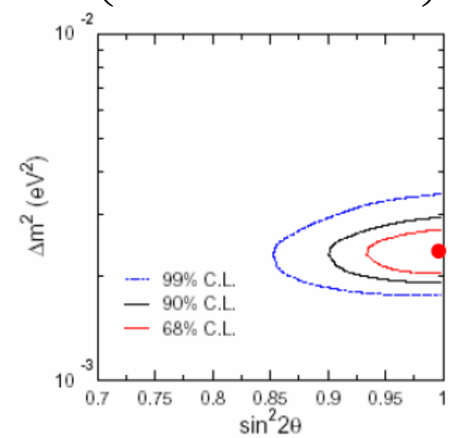
$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{\mu\tau})\sin^2\left(\frac{1.27\Delta m^2_{\mu\tau}[\mathrm{eV}]L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$

Fit data for best values of mass difference Δm_{23}^2 and mixing angle $\theta_{\mu\tau}$

Find $\theta_{\mu\tau} \approx 45^0$ and

$\Delta m_{23}^2 \approx 2.4 \cdot 10^{-3}$ eV^2

➔ Neutrinos have Mass



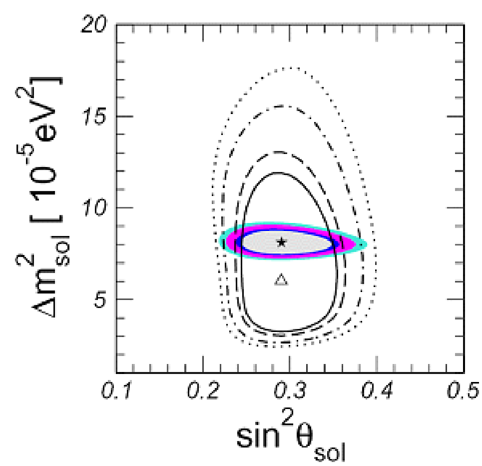
Solar Neutrino Oscillations

Super-Kamiokande, SNO

Kamland – reactor anti-ν_e

Find $\theta_{e\mu} \approx 33^0$ and

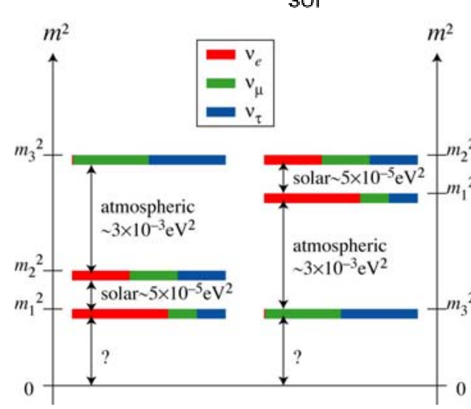
$\Delta m_{12}^2 \approx 8.0 \cdot 10^{-5}$ eV^2



Neutrino mass

Minimum m_ν ~ 0.05 eV

2 scenarios



Cosmology

Big Bang large nr. of neutrinos

Neutrinos are hot dark matter candidates

Supernova 1987A

Kamiokande and IMB

Observed ~ 10 neutrinos