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# An introduction to Neutrino physics and oscillations

# Suggested readings

Notice that an exterminated number of (pedagogical and technical) articles, reviews, books, internet pages… can be found on the subject of Neutrino (Astro)Physics. To avoid an "overload" of readings, here I have listed just a very few number of articles and books which (probably) are not the most representative of the subject.

Pedagogical introductions on neutrino physics and oscillations:

- "*TASI lectures on neutrino physics*", A. de Gouvea, hep-ph/0411274
- "*Celebrating the neutrino*" Los Alamos Science n°25, 1997 (old but still good), http://library.lanl.gov/cgi-bin/getfile?number25.htm
- Dubna lectures by V. Naumov, http://theor.jinr.ru/~vnaumov/

Recent reviews:

- "*Neutrino masses and mixings and…*", A. Strumia & F. Vissani, hep-ph/0606054
- "*Global analysis of three-flavor neutrino masses and mixings*", G.L. Fogli *et al.*, Prog. Part. Nucl. Phys. 57 742 (2006), hep-ph/0506083

Books:

- "*Massive Neutrinos in Physics and Astrophysics*", R. Mohapatra & P. Pal, World Scientific Lecture Notes in Physics - Vol. 72
- "*Physics of Neutrinos*", M. Fukugita & T. Yanagida, Springer

Links:

- "*The neutrino unbound*", by C. Giunti & M. Laveder, http://www.nu.to.infn.it/

# A NEUTRINO TIMELINE

- **1927** Charles Drummond Ellis (along with James Chadwick and colleagues) establishes clearly that the beta decay spectrum is really continous, ending all controversies.

- **1930** Wolfgang Pauli hypothesizes the existence of neutrinos to account for the beta decay energy conservation crisis.

- **1932** Chadwick discovers the neutron.

- **1933** Enrico Fermi writes down the correct theory for beta decay, incorporating the neutrino.

- **1937** Majorana introduced the so-called Majorana neutrino hypothesis in which neutrinos and antineutrinos are considered the same particle.

- **1956** Fred Reines and Clyde Cowan discover (electron anti-)neutrinos using a nuclear reactor.

- **1956** Discovery of parity violations in beta decay by Chien-Shiung Wu.
- **1957** Neutrinos found to be left handed by Goldhaber, Grodzins and Sunyar.
- **1957** Bruno Pontecorvo proposes neutrino-antineutrino oscillations analogously to $K_0$–anti$K_0$, leading to what is later called oscillations into sterile states.
- **1962** Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations.
- **1962** Muon neutrinos are discovered by Leon Lederman, Mel Schwartz, Jack Steinberger and colleagues at Brookhaven National Laboratories and it is confirmed that they are different from $\nu_e$.
- **1964** John Bahcall and Ray Davis propose feasability of measuring neutrinos from the Sun.
- **1967** Stewen Weimberg, Sheldon Lee Glashow, Abdus Salam formulate the Standard Model of Electroweak interactions, in which electromagnetic and weak forces are unified in sigle fashion.

- **1968** Ray Davis and colleagues get first radiochemical solar neutrino results using cleaning fluid in the Homestake Mine in North Dakota, leading to the observed deficit known as the "solar neutrino problem".

- **1973** First observation of neutral current of neutrinos in the Gargamelle experiment at CERN. First indirect confirmation of the Standard Model.

- **1976** The $\tau$ lepton is discovered by Martin Perl and colleagues at SLAC in Stanford, California. After several years, analysis of tau decay modes leads to the conclusion that tau is accompanied by its own neutrino nutau which is neither $\nu_e$ nor $\nu_\mu$.

- **1976** Designs for a new generation neutrino detectors made at Hawaii workshop, subsequently leading to IMB, HPW and Kamioka detectors.

- **1980-90** The IMB, the first massive underground nucleon decay search instrument and neutrino detector is built in a 2000' deep Morton Salt mine near Cleveland, Ohio. The Kamioka experiment is built in a zinc mine in Japan.

- **1983** Discovery of the gauge bosons $W$ and $Z$ by the UA1 and UA2 collaborations. First direct confirmation of the Standard Model.

- **1985** The "atmospheric neutrino anomaly" is observed by IMB and Kamiokande. The anomaly is at first believed to be an artifact of detector inefficiencies.

- **1986** Kamiokande group makes first directional counting observation solar of solar neutrinos and confirms deficit.

- **1987** The Kamiokande and IMB experiments detect burst of neutrinos from Supernova 1987A, heralding the birth of neutrino astronomy, and setting many limits on neutrino properties, such as mass.

- **1988** Lederman, Schwartz and Steinberger awarded the Nobel Prize for the discovery of the muon neutrino.

- **1989** The LEP accelerator experiments in Switzerland and the SLC at SLAC determine that there are only 3 light neutrino species (electron, muon and tau).

- **1991-2** SAGE (in Russia) and GALLEX (in Italy) confirm the solar neutrino deficit in radiochemical experiments.

- **1995** Frederick Reines and Martin Perl get the Nobel Prize for discovery of electron neutrinos (and observation of supernove neutrinos) and the tau lepton, respectively.

- **1996** Super-Kamiokande, the largest ever detector, begins searching for neutrino interactions on 1 April at the site of the Kamioka experiment, with Japan-US team (led by Yoji Totsuka).

- **1998** After analyzing more than 500 days of data, the Super-Kamiokande team reports finding oscillations and, thus, mass in muon neutrinos. After several years these results are widely accepted and the paper becomes the top cited experimental particle physics paper ever.

- **2000** The DONUT Collaboration working at Fermilab announces observation of tau particles produced by tau neutrinos, making the first direct observation of the tau neutrino.

- **2000** SuperK announces that the oscillating partner to the muon neutrino is not a sterile neutrino, but the tau neutrino.

- **2001-2** SNO announces observation of neutral currents from solar neutrinos, along with charged currents and elastic scatters, providing convincing evidence that neutrino oscillations are the cause of the solar neutrino problem.

- **2002** Masatoshi Koshiba and Raymond Davis win Nobel Prize for measuring solar neutrinos(as well as supernova neutrinos).

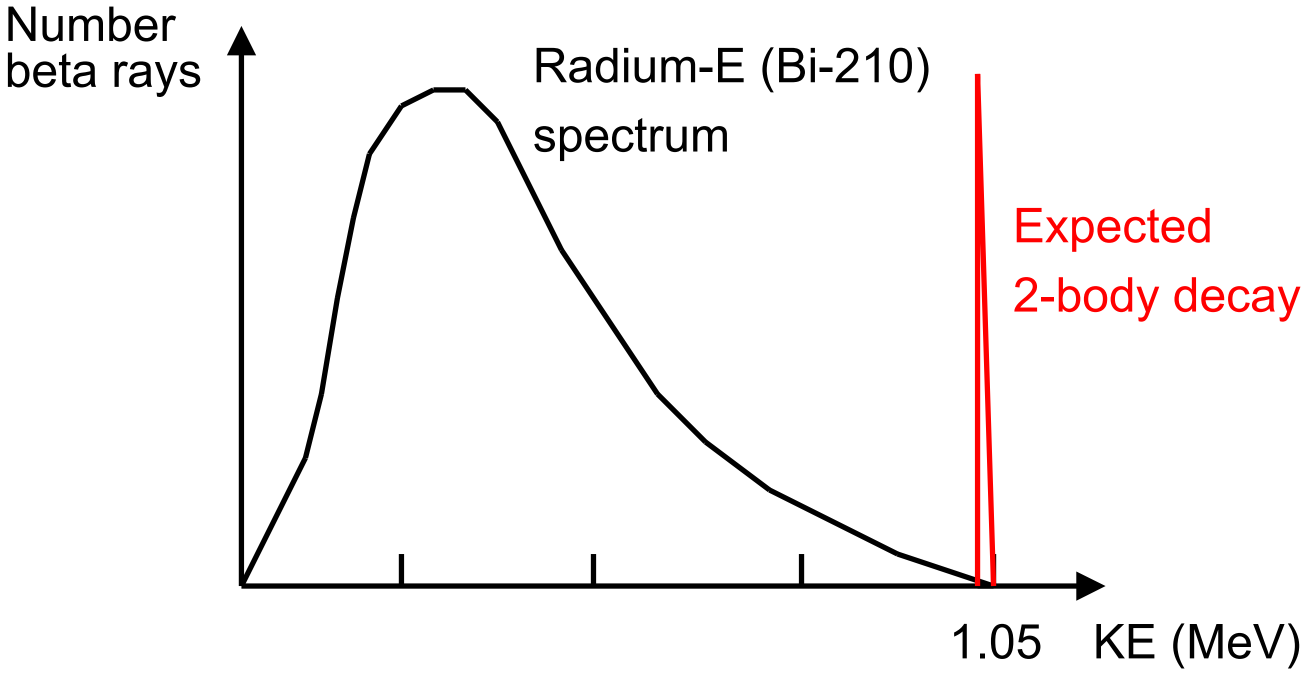
- **2002** KamLAND begins operations in January and in November announces detection of a deficit of electron anti-neutrinos from reactors at a mean distance of 175 km in Japan. The results combined with all the earlier solar neutrino results establish the correct parameters for the solar neutrino deficit.

- **2004** SuperKamiokande and KamLAND present evidence for neutrino disappearance and reappearance, eliminating non-oscillations models.

- **2005** KamLAND announces first detection of neutrino flux from the earth and makes first measurements of radiogenic heat from earth.

# History: beta decay

- 1914: discovery continuous energy spectrum of beta decay (Chadwick)



- Problem: nucleus (A,Z) thought to be A protons + (A-Z) electrons
- Beta decay: (A,Z)→(A,Z+1) + $e^-$ (two body decay, monoenergetic $e^-$)

# History: neutrino hypothesis

- Wrong explanations:
  - L. Meitner: $\beta^-$ undergo secondary interactions in nucleus, losing energy that goes into additional $\gamma$ rays.
    - Proved wrong (Ellis & Wooster) by calorimetric experiment that measured average energy per decay to be ~0.34 MeV (average value of beta spectrum)
  - N. Bohr: energy not conserved in $\beta$ decay.
- Further problems: spin of nuclei ($_3Li^6$ and $_7N^{14}$) measured to be integer
  - $_3Li^6$ : 6 protons+3 electrons= 9 fermions
  - $_7N^{14:}$ 14 protons + 7 electrons = 21 fermions

# History: neutrino hypothesis

- Pauli proposes existence of "neutron" (with spin ½ and mass not more than 0.0 1 mass of proton) inside nucleus in a famous letter (4 December 1930):

  "Dear radioactive ladies and gentlemen,
  I have hit upon a desperate remedy to save the laws of energy conservation. This is the possibility of the existence in the nucleus of neutral particles…which I will call neutrons…"

  Beta decay is a three body decay with a continuous distribution.

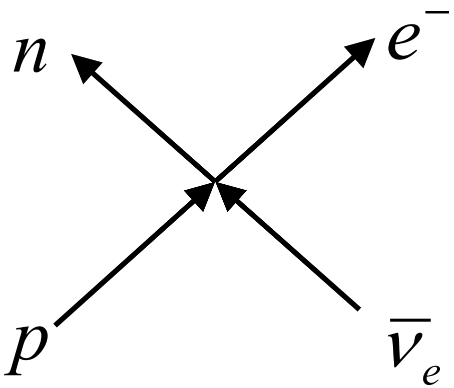
- Chadwick discovers neutron (1932):
  - Solves nuclear spin problem: A = Z(protons) + N(neutrons)
  - Mass of neutron similar to mass of proton: not Pauli's particle!
  - Fermi introduces name "neutrino" ($\nu_e$), which is different to neutron, and beta decay is decay of neutron:

$$n \rightarrow p + e^- + \overline{\nu}_e$$

# Fermi theory of beta decay (1932)

- Existence of a point-like four fermion interaction (Fermi, 1932):

$$n \rightarrow p + e^{-} + \nu_e$$



- Lagrangian of the interaction:

$$L(x) = -\frac{G_F}{\sqrt{2}}\left[\overline{\phi}_p(x)\gamma^{\mu}\phi_n(x)\right]\left[\overline{\phi}_e(x)\gamma_{\mu}\phi_{\nu}(x)\right]$$

$G_F$ = Fermi coupling constant = $(1.16637 \pm 0.00001)\times 10^{-5}\ GeV^{-2}$

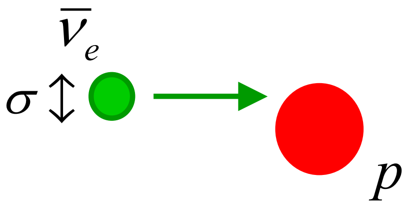
- Gamow-Teller interaction when final spin different to initial nucleus:

$$L(x) = -\frac{G_F}{\sqrt{2}}\sum_i\left[\overline{\phi}_p(x)\Gamma^{i}\phi_n(x)\right]\left[\overline{\phi}_e(x)\Gamma_{i}\phi_{\nu}(x)\right] + h.c.$$

Possible interactions: $\Gamma_i = 1, \gamma_5, \gamma_{\mu}, \gamma_5\gamma_{\mu}, \sigma_{\mu\nu} = S, P, V, A, T$

# Neutrino cross-section

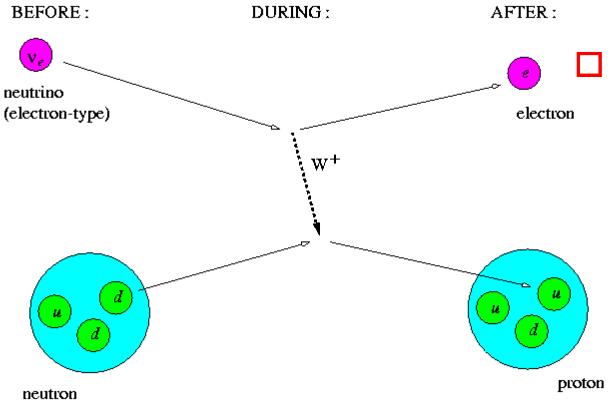
- Bethe-Peierls (1934): calculation of first cross-section for inverse beta reaction $\bar{\nu}_e + p \rightarrow n + e^+$ or $\nu_e + n \rightarrow p + e^-$ using Fermi theory



$$\sigma \approx 10^{-44}\ cm^2 \quad \text{for} \quad E(\bar{\nu}) = 2\ MeV$$

Conversion from natural units: $\hbar c = 197.3\ MeV \cdot fm$

Cross-section: multiply by $(\hbar c)^2 = 0.3894 \times 10^{-27}\, GeV^2 \cdot cm^2$



- Mean free path of antineutrino in water:

$$\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21}\ cm \approx 1600 \quad light - years$$

$$n = \frac{\text{num. free protons}}{\text{volume}} \approx 2 \frac{N_A}{A} \rho$$

In water: $n = \dfrac{2 \times 6 \times 10^{23}}{18} = 6.7 \times 10^{22}\ cm^{-3}$

- Probability of interaction:

$$P = 1 - \exp\left( -\frac{L}{\lambda} \right) \approx \frac{L}{\lambda} = 6.7 \times 10^{-20}\ (m\ water)^{-1}$$

Need very intense source of antineutrinos to detect inverse beta reaction.

# Neutrino discovery (1956)

- Nuclear reactors: fission of ${}_{92}U^{235}$ produces chain of beta reactions

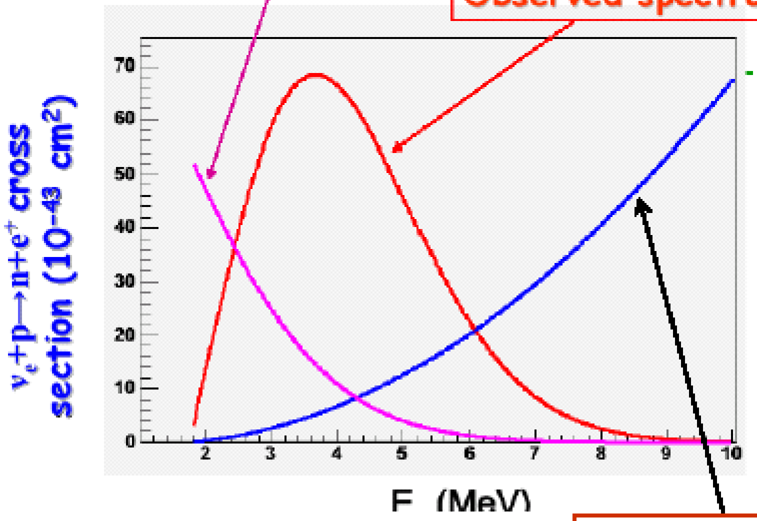
$$(A,Z)\rightarrow(A,Z+1)+e^{-}+\bar{\nu}_e\rightarrow(A,Z+2)+e^{-}+\bar{\nu}_e\rightarrow\ldots$$

- On average 6 antineutrinos/fission, 300 MeV average energy per chain

$$N_{\bar{\nu}}=\frac{6P_{th}}{1.6\times10^{-19}\times10^{6}\times200MeV}\approx1.9\times10^{11}P_{th}\ \bar{\nu}/s$$

$$P_{th}\approx3\times10^{9}\ Watt\Rightarrow N_{\bar{\nu}}\approx5.6\times10^{20}\ s^{-1}\ in\ 4\pi$$

Continuous spectrum:



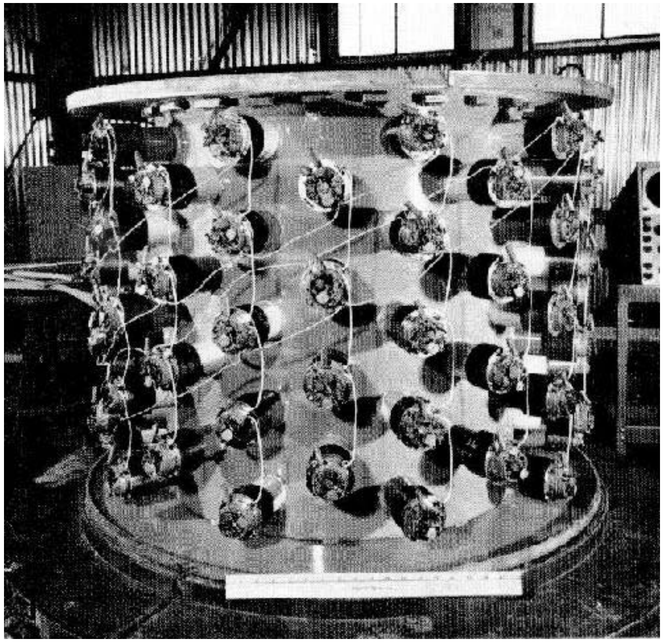
Reactor $\nu_e$ spectrum (a.u.)

Observed spectrum (a.u.)

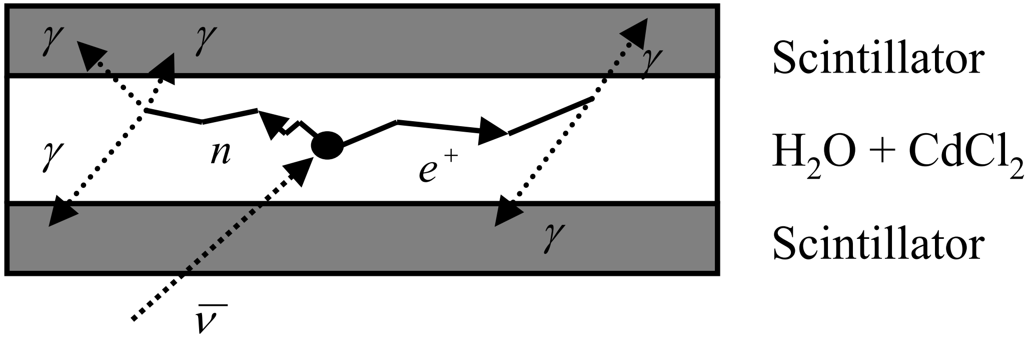
Cross section

# Neutrino discovery (1956)

- Reines and Cowan detect $\overline{\nu}_e + p \rightarrow n + e^+$ in 1953 (Hanford) (discovery confirmed 1956 in Savannah River):
  - Detection of two back-to-back $\gamma$s from prompt signal $e^+e^- \rightarrow \gamma\gamma$ at t=0.
  - Neutron thermalization: neutron capture in Cd, emission of late $\gamma$s <t>~ 20 ms



**4200 l scintillator**



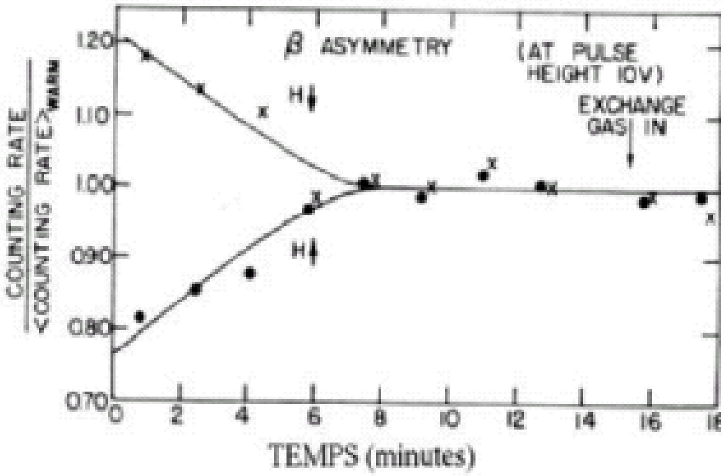
**Reactor on – off: 2.88+-0.22 $hr^{-1}$**

**$\sigma$= (11+-2.6) $x10^{-44}$ $cm^2$ (within 5% expected)**

**Nobel prize Reines 1995**

# Parity violation and V-A

- Parity violation in weak decays postulated by **Lee & Yang** in 1950
- Parity violation confirmed through forward-backward asymmetry of polarized $^{60}Co$ (**Wu**, 1957).



$$^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \overline{\nu}_e$$

More electrons emitted in direction opposite to $^{60}Co$ spins, implying maximal parity violation

- Helicity operator:

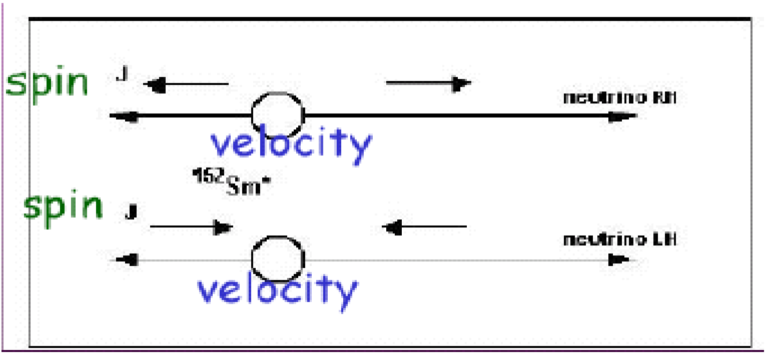
$$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} \xrightarrow{P} \frac{\vec{\sigma}\cdot(-\vec{p})}{|\vec{p}|} = -H$$

# Parity violation and V-A

- Goldhaber, Grodzins, Sunyar (1958) measure helicity of neutrino from K capture of $^{152}$Eu:

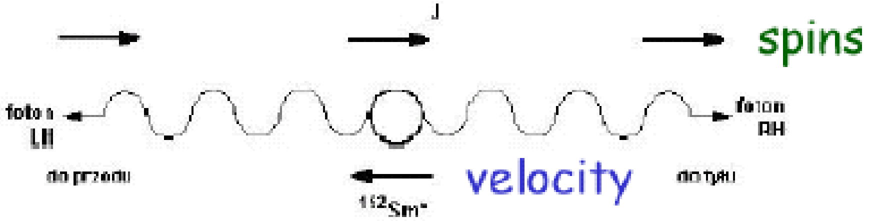
$$^{152}Eu(0^-) + e^- \rightarrow {}^{152}Sm^*(1^-) + \nu_e$$

$$^{152}Sm^*(1^-) \rightarrow {}^{152}Sm^*(0^+) + \gamma$$



$p_\gamma$=-$p_\nu$
$\sigma_\gamma$=-$\sigma_\nu$
$H_\gamma$=$H_\nu$

γ-forward



γ-backward

Asymmetry of photon spectrum in magnetic field determines helicity of $\nu_e$:

$$H(\nu_e) = -1 \Rightarrow H(\overline{\nu}_e) = +1$$

Neutrinos are “left-handed” and antineutrinos “right-handed”.

# Parity violation and V-A

- Left and right handed projections:

$$\nu_L = P_L \nu = \frac{1}{2}(1-\gamma_5)\nu \qquad \nu_R = P_R \nu = \frac{1}{2}(1+\gamma_5)\nu$$

- Chirality operator $\gamma_5$: same as helicity operator for massless neutrinos ($E=p$).

$$\gamma_5 \nu_L = H\nu_L = -\nu_L \qquad \gamma_5 \nu_R = H\nu_R = +\nu_R$$

- If only $\nu_L$ interact and $\nu_R$ do not interact, then $\Gamma_i$ have to transform as: $\bar{\phi}_e \Gamma_i \phi_\nu \rightarrow \left(\overline{P_L \phi_e}\right)\Gamma_i\left(P_L \phi_\nu\right) = \bar{\phi}_e P_R \Gamma_i P_L \phi_\nu$

$$V: P_R \gamma^\mu P_L = \frac{1}{2}\gamma^\mu\left(1-\gamma_5\right) \qquad A: P_R \gamma^\mu \gamma_5 P_L = -\frac{1}{2}\gamma^\mu\left(1-\gamma_5\right)$$

- The only possible coupling is V-A, due to maximal parity violation in weak interactions (Feynman, Gell-Mann, 1958):

$$L_{V-A} = -\frac{G_F}{\sqrt{2}}\left[\bar{\phi}_p \gamma^\mu (1-g_A\gamma_5)\phi_n\right]\left[\bar{\phi}_e \gamma_\mu (1-\gamma_5)\phi_\nu\right] \text{with } g_A = -1.2573 \pm 0.0028$$

**(determined empirically)**

# Muon neutrinos

- It was thought that $\nu_\mu$ and $\nu_e$ must be different since certain reactions not observed: conservation of lepton number (for each family).

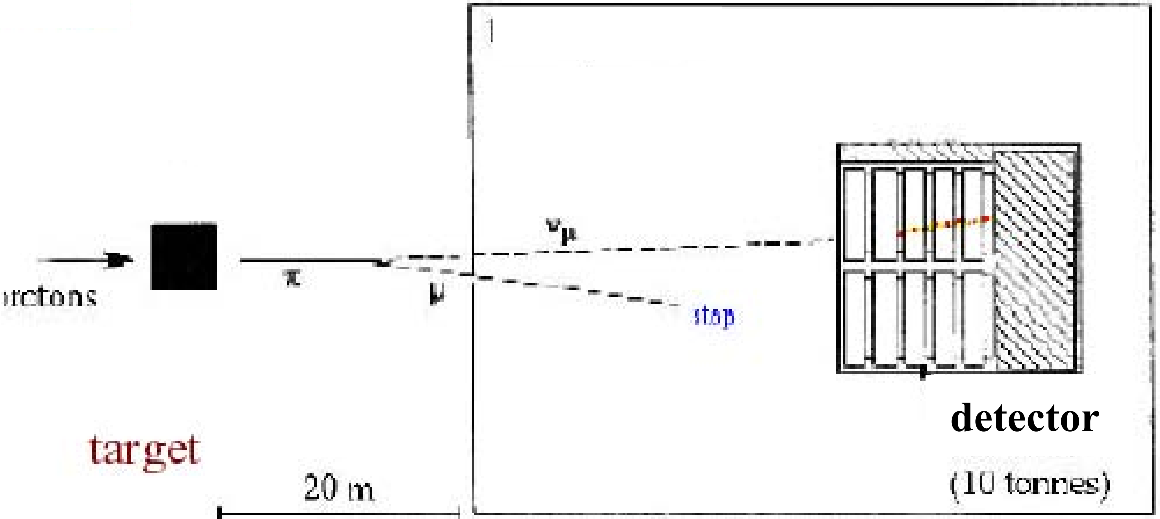
$$\mu^+ \to e^+ + \gamma \qquad \mu^+ \to e^+ + e^+ + e^- \qquad \mu^+ + N \to e^+ + N$$

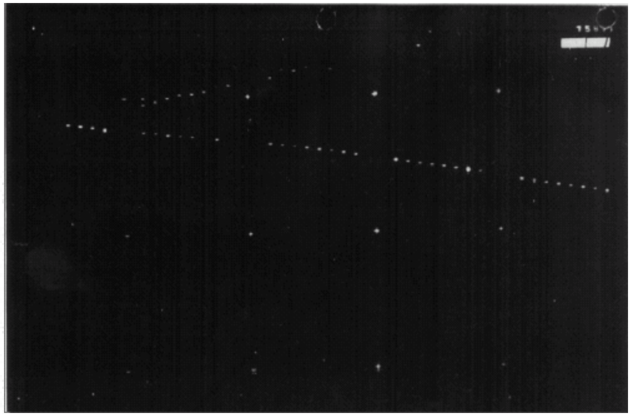
- Existence of “second” (muon) neutrino established in 1962 by Schwartz, Lederman and Steinberger at Brookhaven National Laboratory:

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

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

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

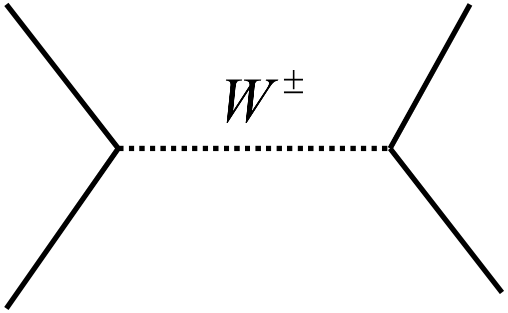


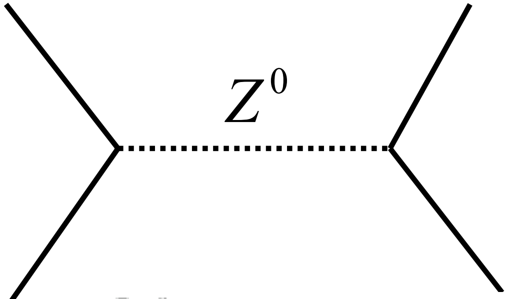


Experimental signature

# Neutral currents

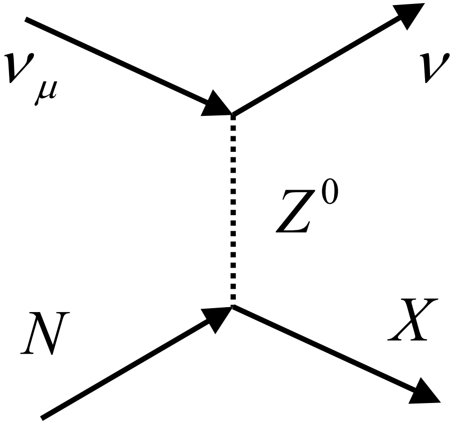
- Two types of weak interaction: charged current (CC) and neutral current (NC) from electroweak theory of Glashow, Weinberg, Salam.

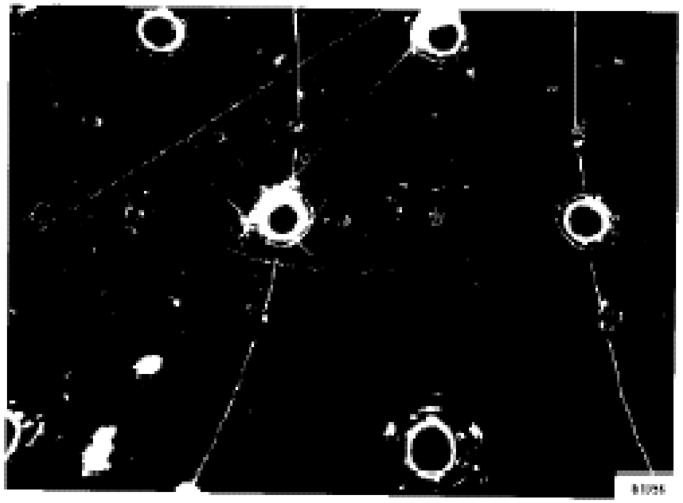


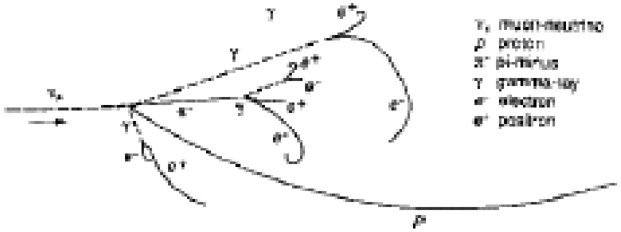


- First example of NC observed in 1973, inside the Gargamelle bubble chamber filled with freon ($CF_3Br$): no muon!

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







# Tau neutrino

- First direct evidence for tau neutrino $\nu_\tau$ in year 2000 by DONUT collaboration at Fermilab:
- Protons hitting tungsten target produce $D_s$ mesons ( $D_s^+ = c\bar{s}$ ).

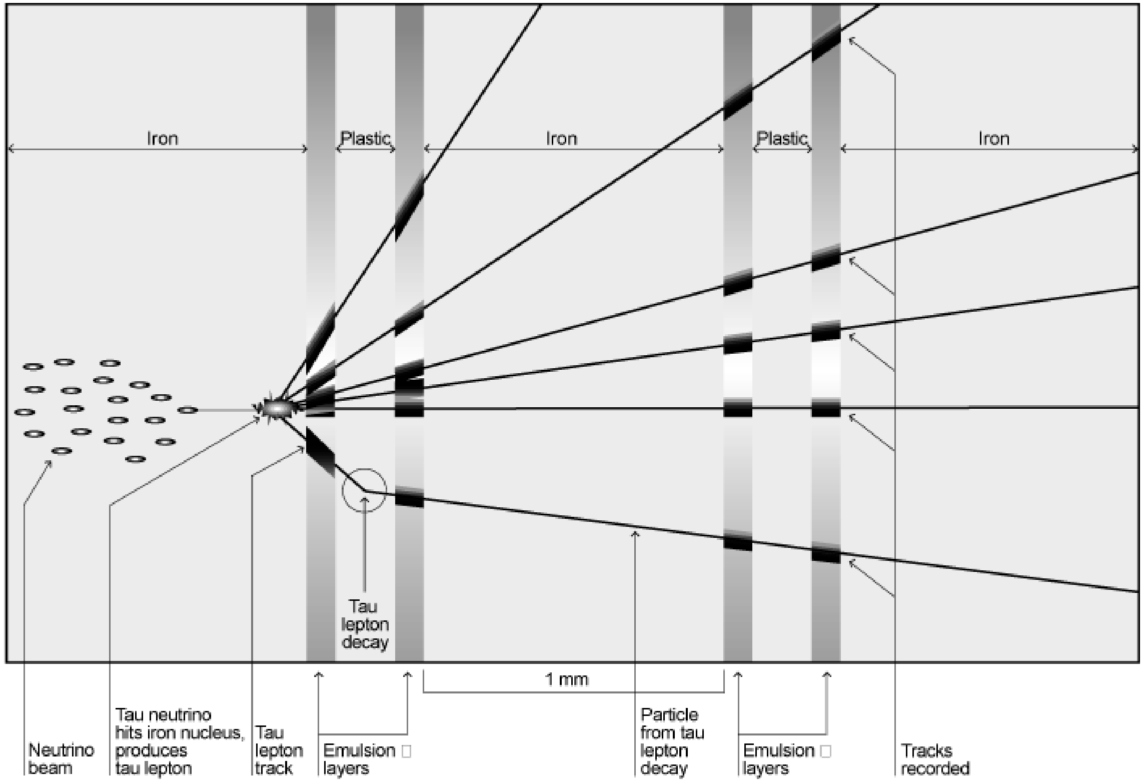
$$D_s^+ \rightarrow \tau^+ + \nu_\tau$$

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

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

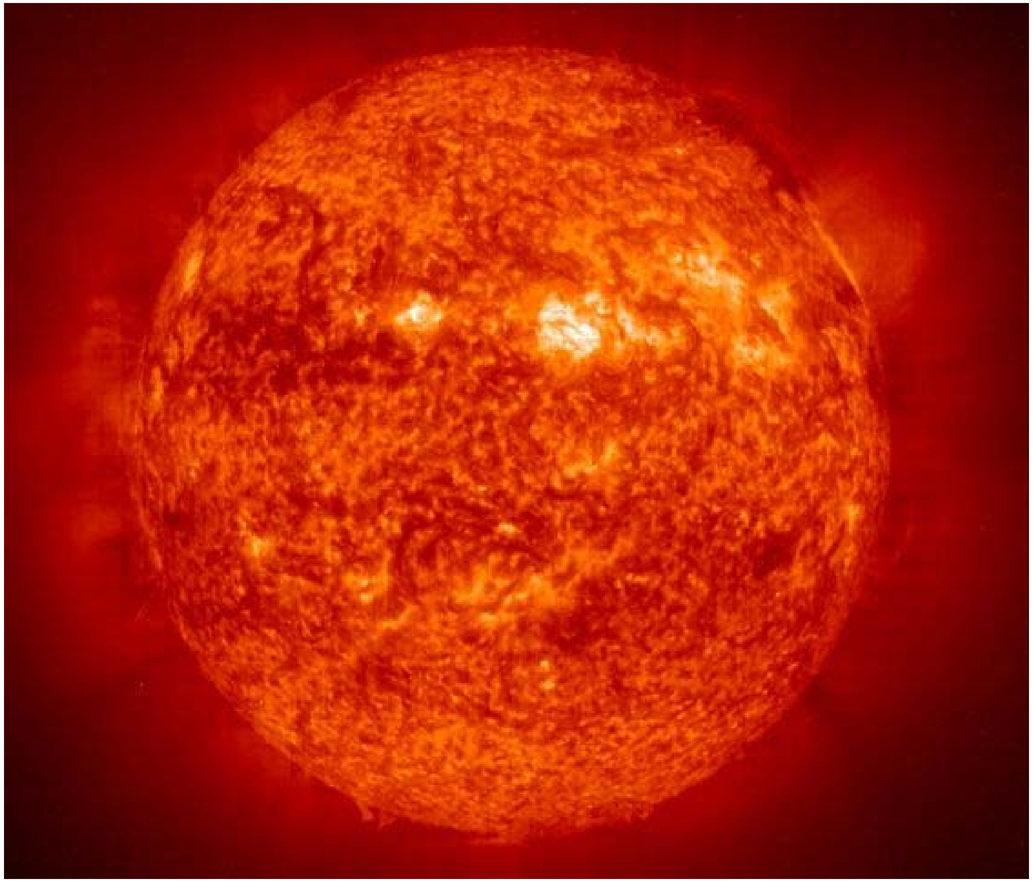
Tau decay observed in emulsion with a 1 mm long track ending in a kink

**Detecting a Tau Neutrino**



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

# Solar neutrinos



- ☐ Standard Solar Model predicts that sun is powered by fusion reactions in the core of the sun.
- ☐ 4 hydrogen atoms burn in thermo-nuclear reactions to produce helium, neutrinos and energy:

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + \gamma(26.7\ MeV)$$

- ☐ Measured photon luminosity is: $3.9 \times 10^{26}$ J $s^{-1}$.

  Energy per neutrino = 26.7 MeV= $4.3 \times 10^{-12}$ J

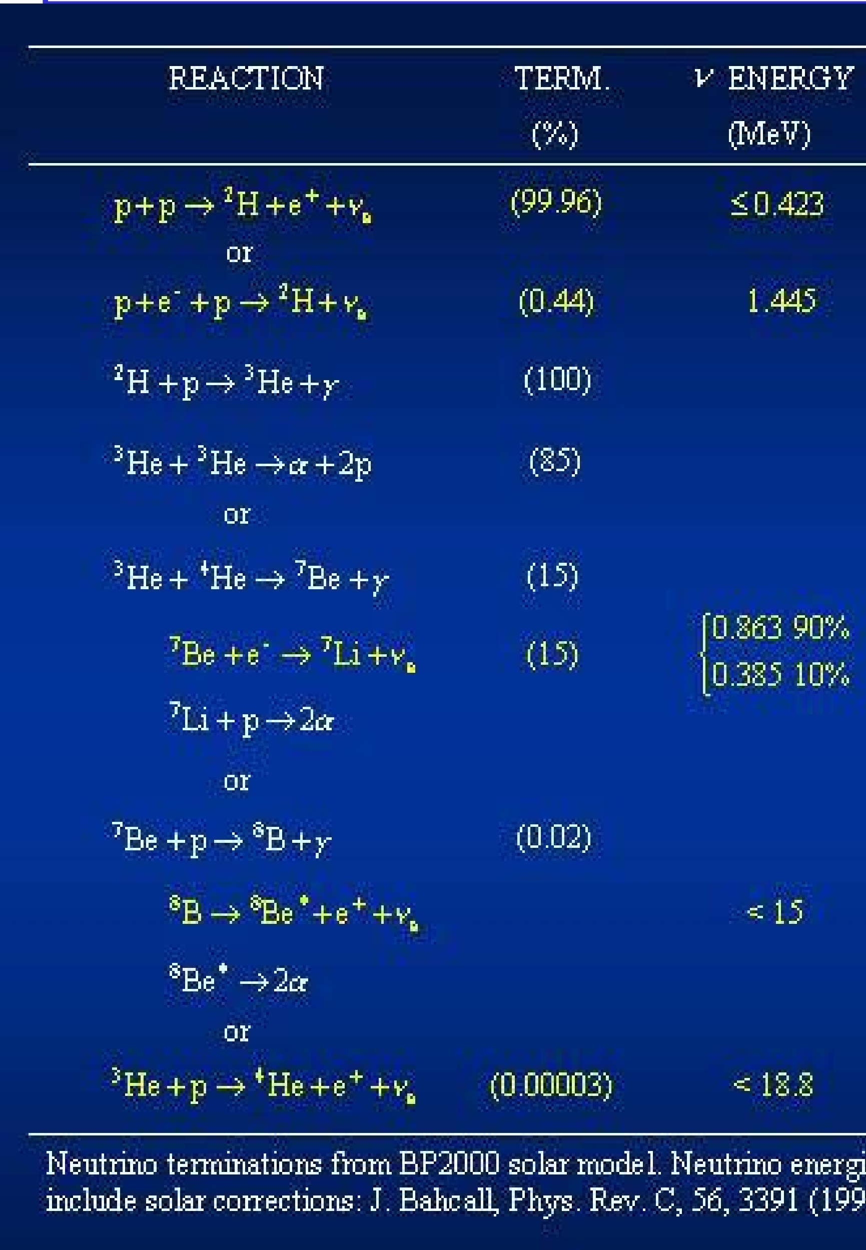
  Number of reactions = $3.9 \times 10^{26} / 4.3 \times 10^{-12} = 9.1 \times 10^{37}$ $s^{-1}$

  Distance sun-earth = $1.5 \times 10^{13}$ cm.

$$Flux\ of\ \ neutrinos = \frac{N_\nu}{4\pi R^2} = \frac{2 \times 9.1 \times 10^{37}}{4\pi \times (1.5 \times 10^{13})^2} = 6.4 \times 10^{10}\ \nu_e\ s^{-1} cm^{-2}$$

(64 billion neutrinos per second through your finger nail of 1 $cm^2$ !!!!)

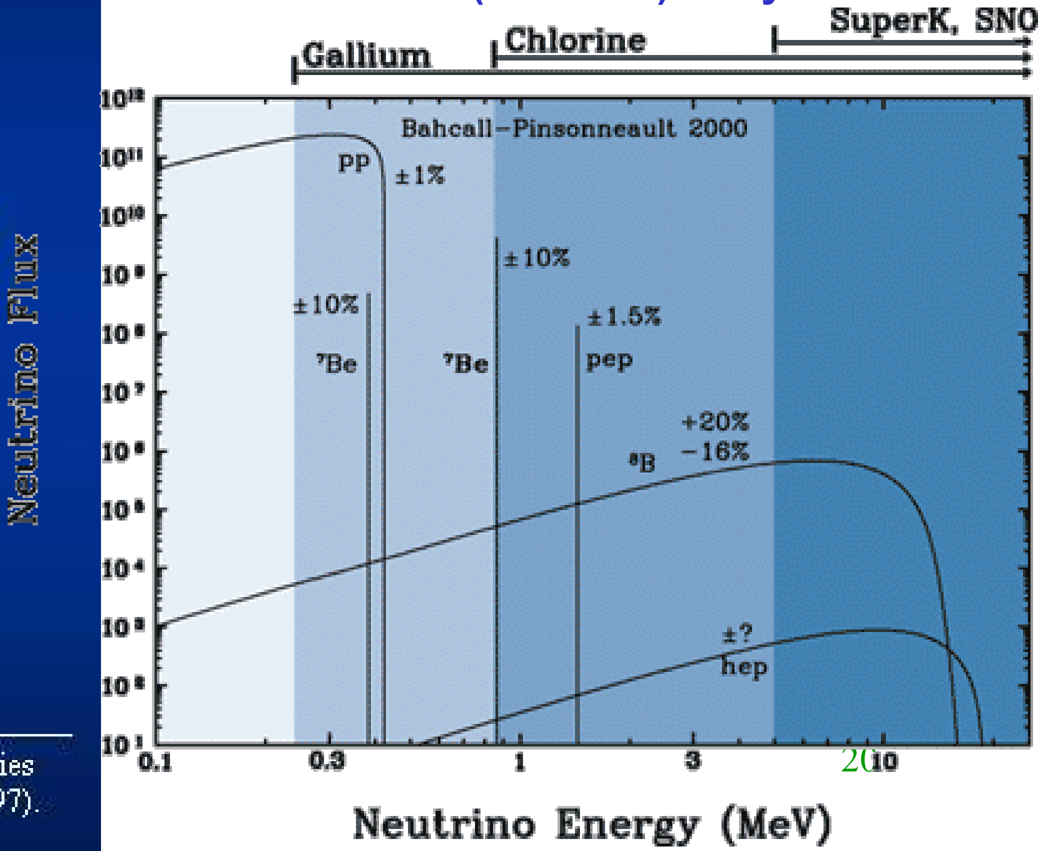
# Solar neutrinos (cont.)



| REACTION | TERM. (%) | ν ENERGY (MeV) |
|---|---|---|
| $p+p\to{}^2H+e^++\nu_e$ | (99.96) | ≤0.423 |
| or | | |
| $p+e^-+p\to{}^2H+\nu_e$ | (0.44) | 1.445 |
| $^2H+p\to{}^3He+\gamma$ | (100) | |
| $^3He+{}^3He\to\alpha+2p$ | (85) | |
| or | | |
| $^3He+{}^4He\to{}^7Be+\gamma$ | (15) | |
| $^7Be+e^-\to{}^7Li+\nu_e$ | (15) | 0.863 90%<br>0.385 10% |
| $^7Li+p\to2\alpha$ | | |
| or | | |
| $^7Be+p\to{}^8B+\gamma$ | (0.02) | |
| $^8B\to{}^8Be^*+e^++\nu_e$ | | < 15 |
| $^8Be^*\to2\alpha$ | | |
| or | | |
| $^3He+p\to{}^4He+e^++\nu_e$ | (0.00003) | < 18.8 |

Neutrino terminations from BP2000 solar model. Neutrino energies include solar corrections: J. Bahcall, Phys. Rev. C, 56, 3391 (1997).

- **pp cycle:** 98.5% of the total sun's power comes from these reactions
- **CNO cycle:** catalysed by C, N and O only produces 1.5% of power output
- Low energy (<0.42 MeV) **pp reaction** (flux $6.0\times10^{10}$ $cm^{-2}$ $s^{-1}$) most abundant
- **$^8B$ neutrinos** (<14 MeV): only $10^{-4}$ total



# Solar neutrinos (cont)

- Experiments that have detected solar neutrinos:
  - Chlorine experiment (Homestake mine, South Dakota): Ray Davis (Nobel prize 2002) and collaborators detected neutrinos in 390 $m^3$ of $C_2Cl_4$ (520 tons Cl, 24% $^{37}Cl$).

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}A + e^-$$ **(Threshold>814 keV)**

**Expected: 7.6+-1.3 SNU** **Observed (>20 years): 2.56+-0.16+-0.15 SNU**

**1 SNU = 1 event per second per $10^{36}$ target atoms**

  - Super-Kamiokande: Imaging water Cherenkov detector with 50,000 tons water (22,000 tons fiducial), 11,000 photomultiplier tubes in Kamioka mine in Japan (M. Koshiba Nobel prize 2002). Neutrino elastic scattering: $\nu_e + e^- \rightarrow \nu_e + e^-$

**Rate = 0.465+-0.005+-0.016 x (Standard Solar Model)**

  - Gallium experiments: GALLEX at Gran Sasso, Italy, 30.3 tons Ga in HCl

    SAGE at Baksan, Russia, 57 tons metallic, liquid at 40°

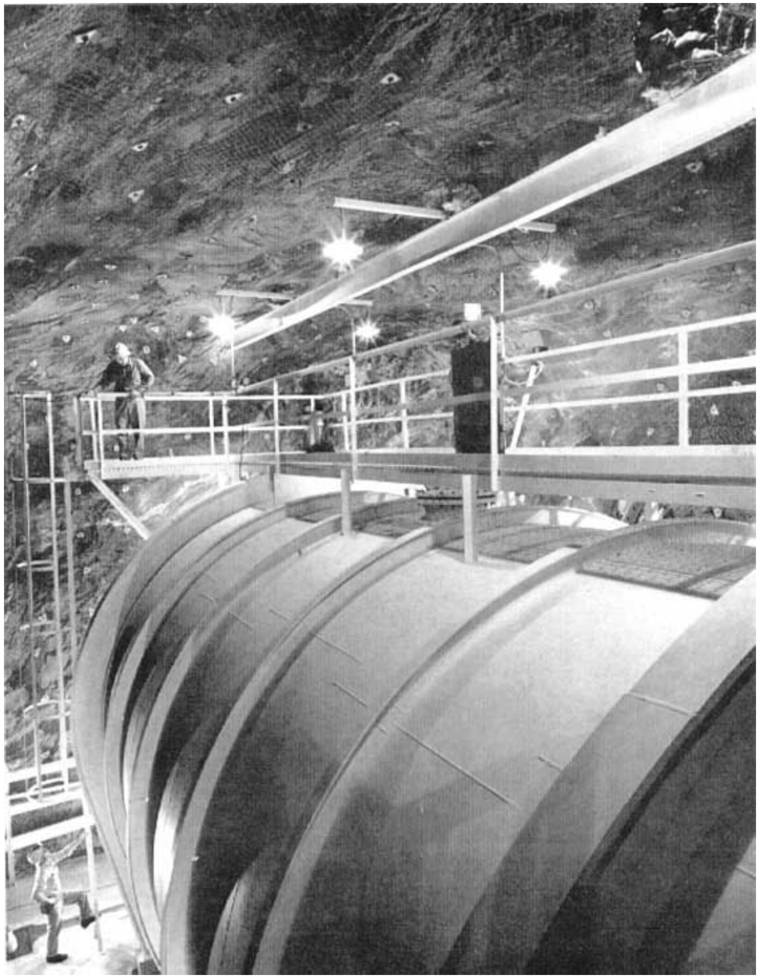
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$ **(Threshold>233 keV)**

**Expected: $129^{+8}_{-6}$ SNU** **Observed (GALLEX+GNO): 70.8+-4.5+-3.8 SNU**

**Observed(SAGE): $69.1^{+4.3}_{-4.2}$ SNU**

# Solar neutrinos (cont.)

- Ray Davis' Chlorine experiment inside Homestake mine in Lead, South Dakota:



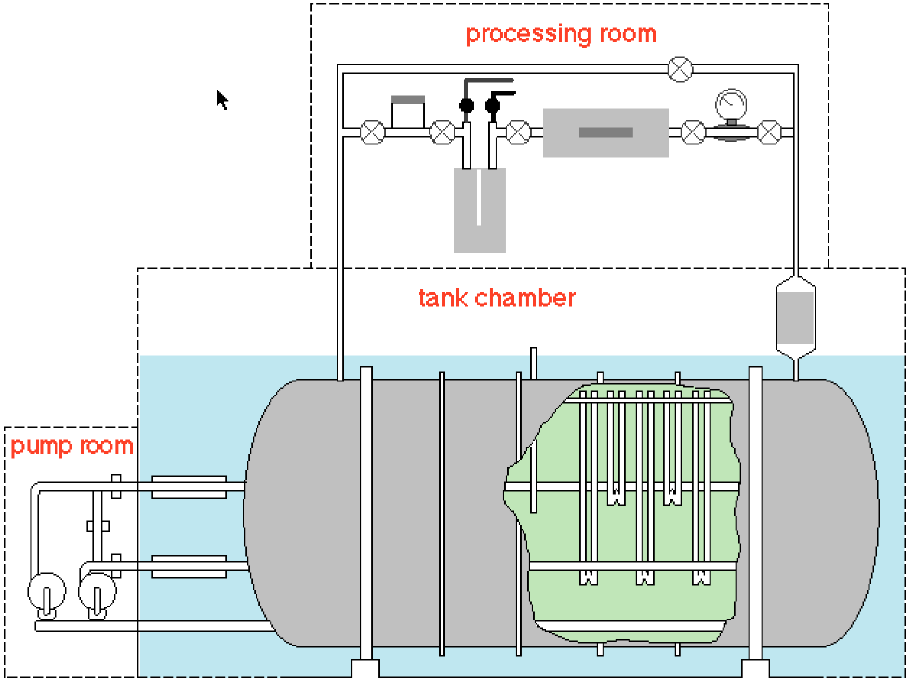
100,000 gallons (615 tons) cleaning fluid ($C_2Cl_4$)

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

Expect about 1.5 Ar atoms/day

Extract Ar and count in proportional counter:

$${}^{37}Ar \rightarrow {}^{37}Cl + e^- + \overline{\nu}_e$$ 2.82 keV K-shell x-rays



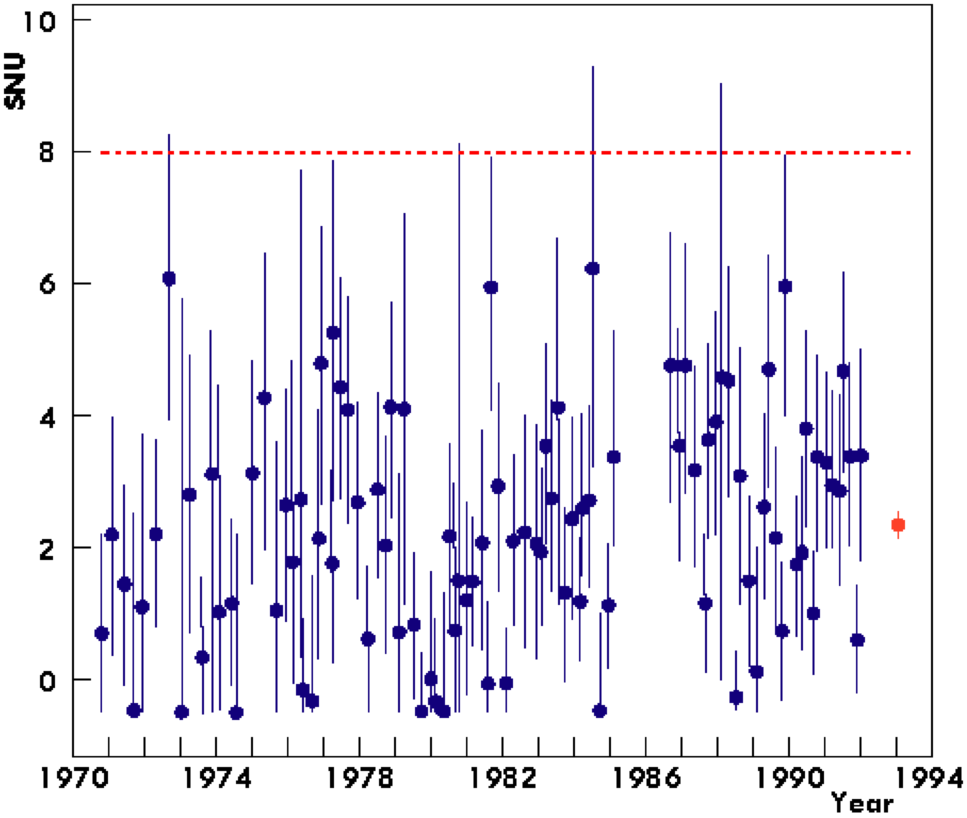
# Solar neutrinos (cont.)

- Results from the Ray Davis chlorine experiment: sensitive to $^{8}$B and $^{7}$Be neutrinos (0.814 MeV threshold).

  Measured 2.56+-0.23 SNU (0.48 atoms/day),

  Solar Model Expectation = 7.6+-1.3 SNU (1.5 atoms/day)

  Observation about 1/3 the expected number of solar neutrinos

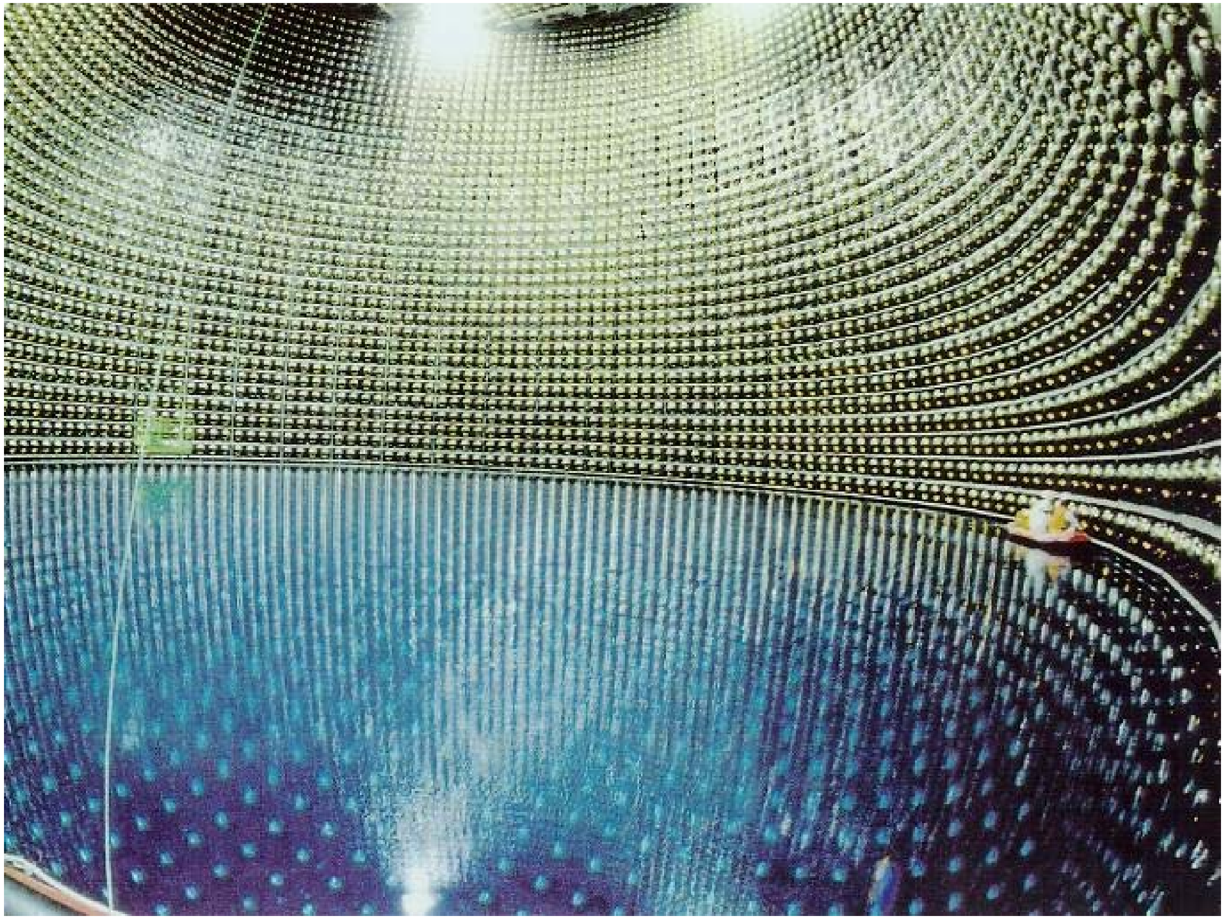


1 SNU = 1 interaction per $10^{36}$ target atoms per second

Is there something wrong with experiment, something wrong with solar model or something wrong with the neutrinos?

# Solar neutrinos (cont.)

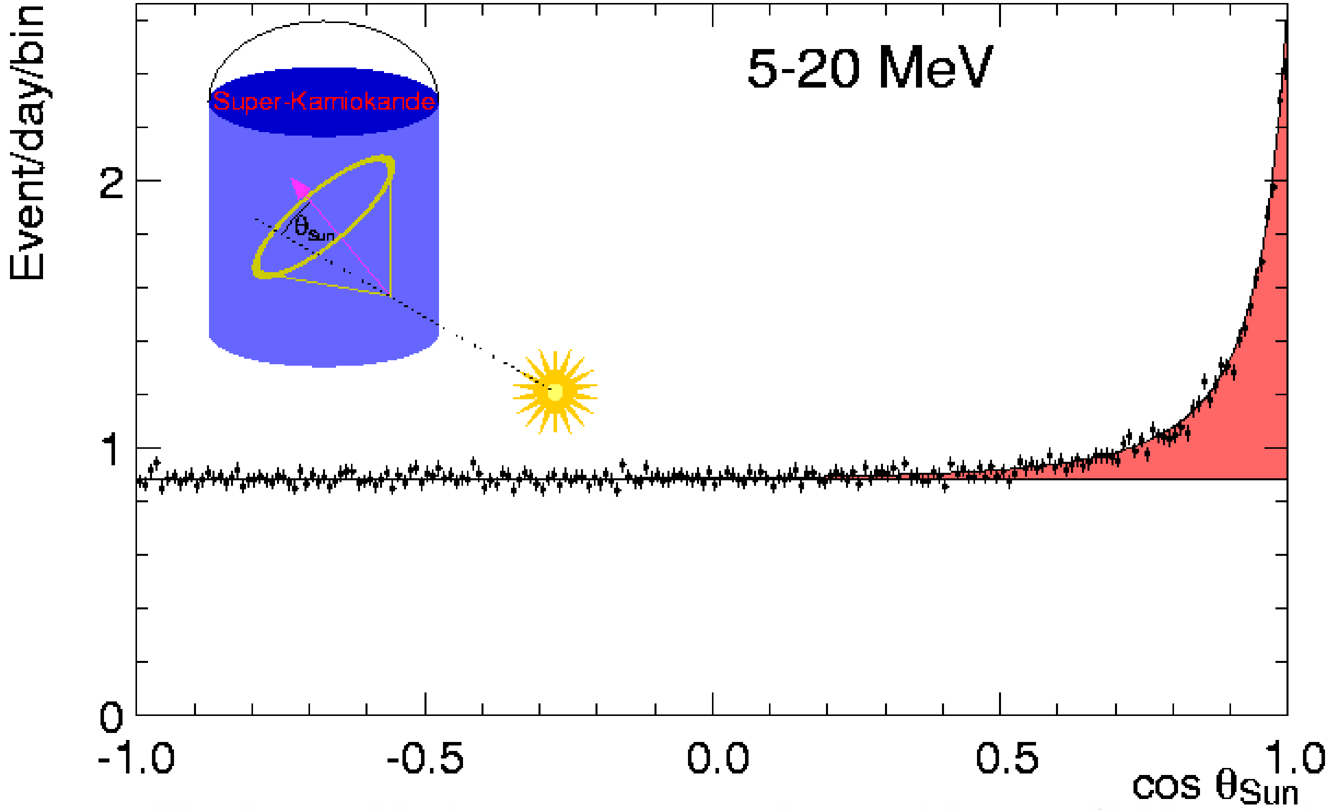
- Kamiokande experiment: started 1987, 5000 tons water, 1000 photomultipliers
- Super-Kamiokande experiment: started 1997 (M. Koshiba leader experiment) 50,000 tons of water, surrounded by 11,000 phototubes to detect flashes of light in the water.



Super-Kamiokande experiment is underground Inside a mine in Japan to shield it from the very large number of cosmic rays.

# Solar neutrinos (cont.)

- Results Super-Kamiokande experiment:
  - Proof that neutrinos come from sun: angular correlation
  - Neutrino flux is 46.5% that expected from the solar model



Confirmation Solar Neutrino Puzzle!

$$0.465 \pm 0.005(\mathrm{stat.})^{+0.016}_{-0.015}(\mathrm{sys.}) \times \mathrm{SSM}$$

# Solar neutrinos (cont.)

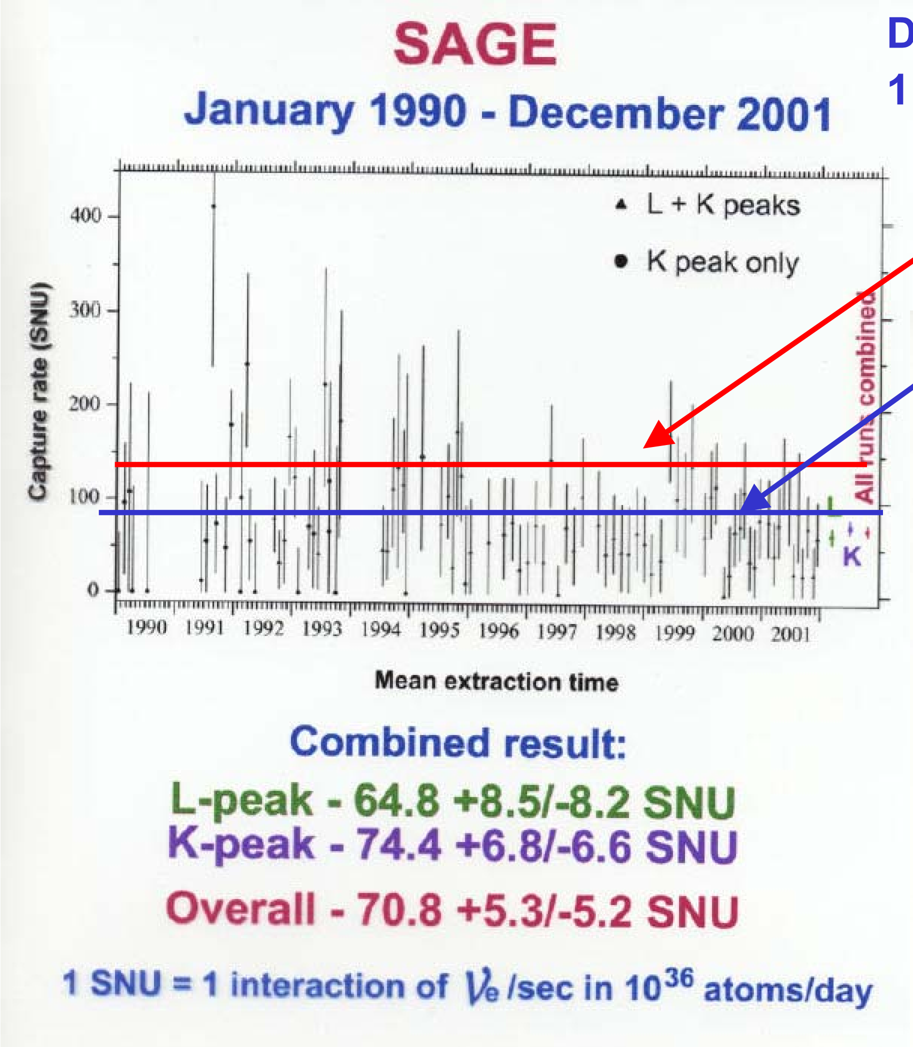
- Gallium experiments: similar to chlorine but with gallium $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
  - Lower threshold (0.233 MeV) so sensitive to the lower end of the pp chain
  - Further evidence of missing solar neutrinos (55% of expectation)

**Detection: electron capture** $^{71}Ge + e^- \rightarrow {}^{71}Ga + \nu_e$

**1.2 keV, 10.37 keV K,L shell X-rays**

Expectation: 129+-8 SNU

Observed: 70.8+-6 SNU



**SAGE**

**January 1990 - December 2001**

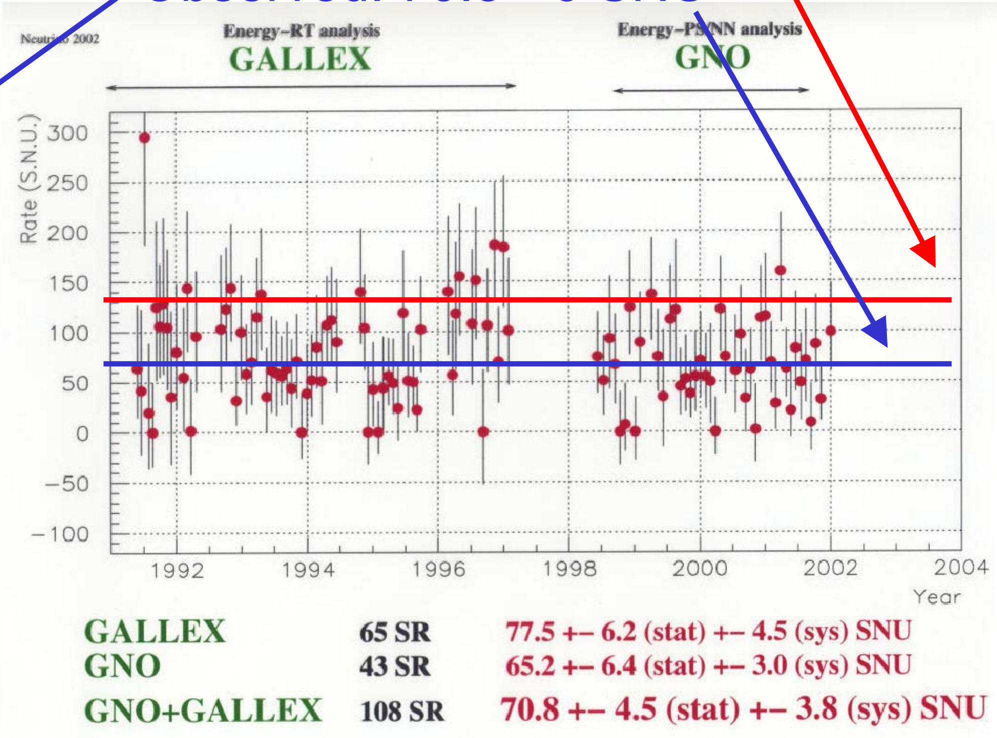
**Combined result:**

**L-peak - 64.8 +8.5/-8.2 SNU**

**K-peak - 74.4 +6.8/-6.6 SNU**

**Overall - 70.8 +5.3/-5.2 SNU**

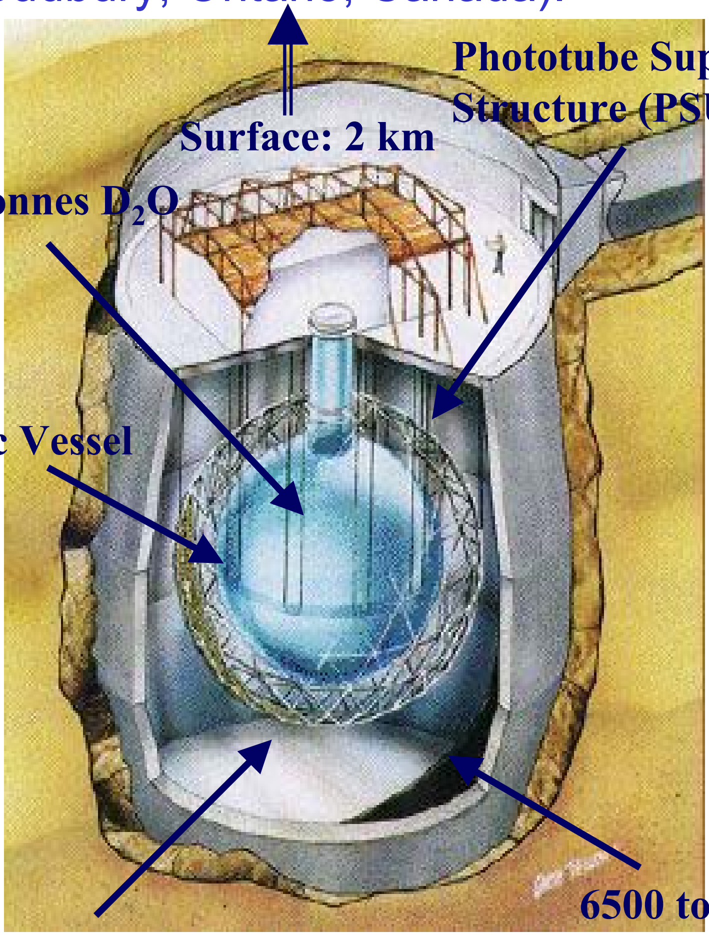
**1 SNU = 1 interaction of $\nu_e$ /sec in $10^{36}$ atoms/day**



| | | |
|---|---|---|
| GALLEX | 65 SR | 77.5 +– 6.2 (stat) +– 4.5 (sys) SNU |
| GNO | 43 SR | 65.2 +– 6.4 (stat) +– 3.0 (sys) SNU |
| GNO+GALLEX | 108 SR | 70.8 +– 4.5 (stat) +– 3.8 (sys) SNU |

# Solar neutrinos (cont)

- Sudbury Neutrino Observatory: 1000 tonnes $D_2O$, 6500 tonnes $H_2O$, 10,000 PMTs (Sudbury, Ontario, Canada).



**Surface: 2 km**

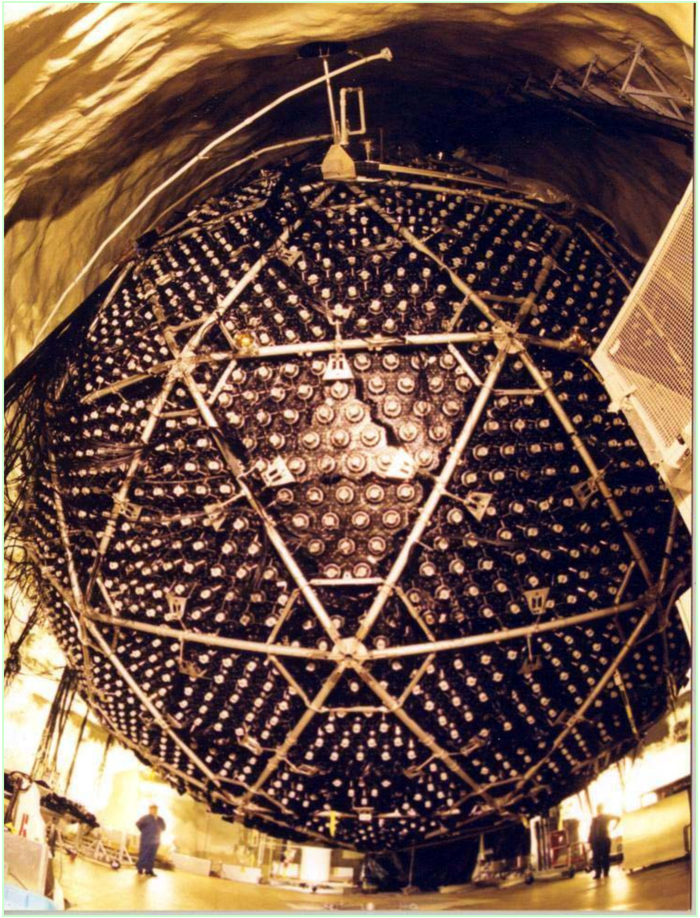
**Phototube Support Structure (PSUP)**

**1000 tonnes $D_2O$**

**Acrylic Vessel**

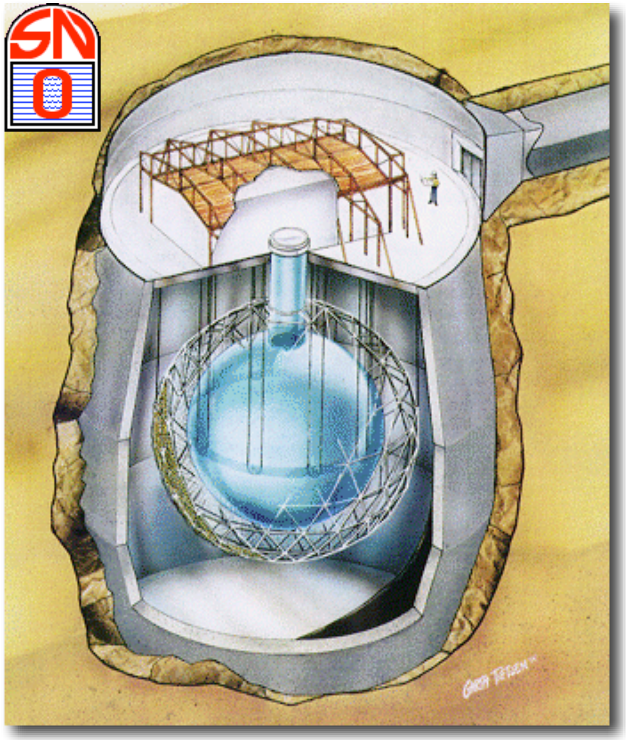
**6500 tonnes $H_2O$**

**$10^4$ 8” PMTs**

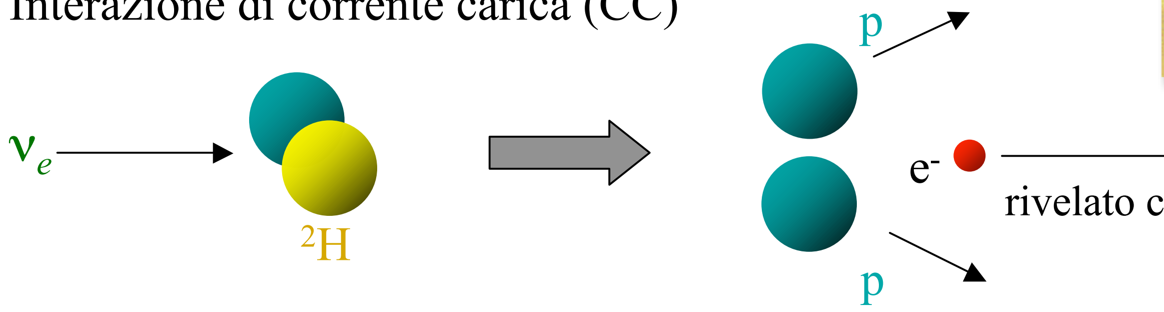


# Il Subdury Neutrino Observatory (*SNO*)

L'esperimento SNO è costituito da una sfera contenente 1000 tonnellate di $D_2O$. Esso è in grado di misurare sia il flusso totale di neutrini dei neutrini $^8B$ che la componente di $\nu_e$ proveniente dal Sole.

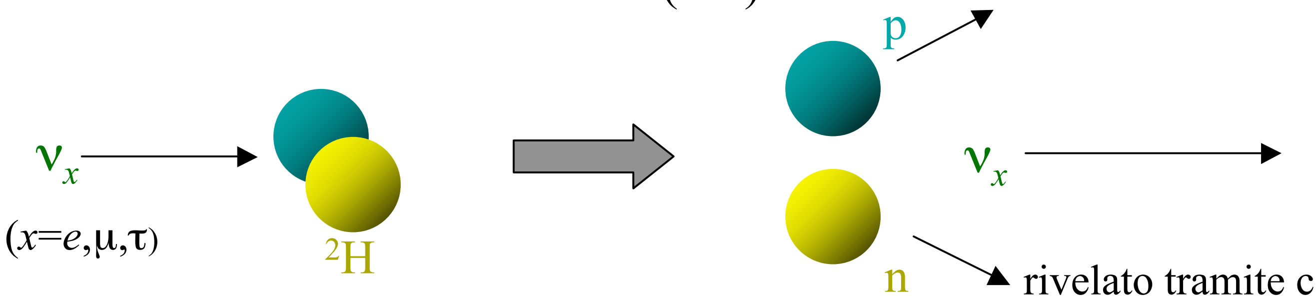


- Interazione di corrente carica (CC)



rivelato con tecniche Cherenkov

- Dissociazione di corrente neutra (NC)



rivelato tramite cattura su $^{35}Cl$

# Solar neutrinos (cont.)

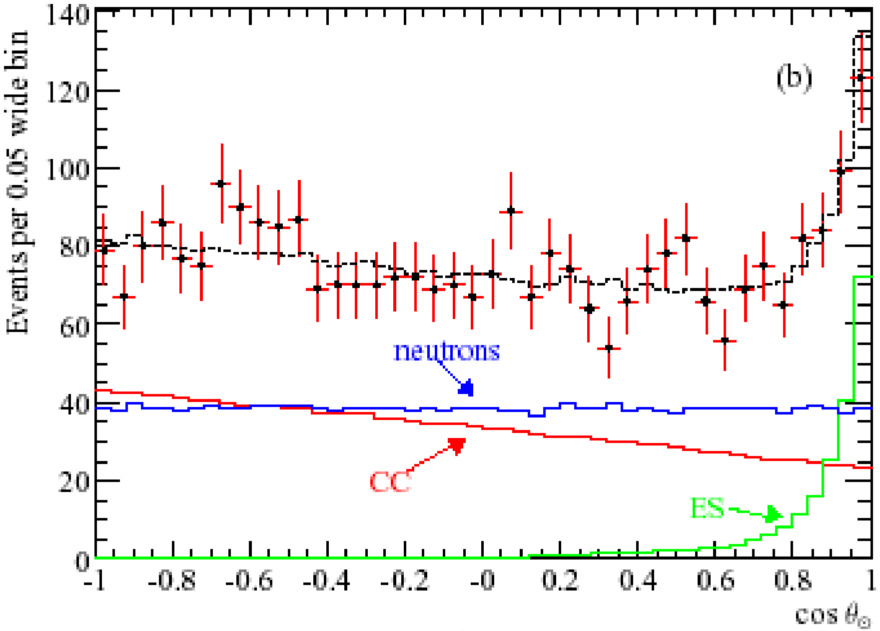
- First results with $D_2O$:
  - Charged current (CC): $\nu_e + d \rightarrow p + p + e^-$ (0.35+-0.02 SSM) **(Threshold>1.442 keV)**
  - Elastic scattering (ES): $\nu_x + e^- \rightarrow \nu_x + e^-$
  - Neutral current (NC): $\nu_x + d \rightarrow n + p + \nu_x$ (1.01+-0.12 SSM) **(Threshold>2.225 keV)**

**#EVENTS**

**CC** $1967.7^{+61.9}_{+60.9}$

**ES** $263.6^{+26.4}_{+25.6}$

**NC** $576.5^{+49.5}_{+48.9}$

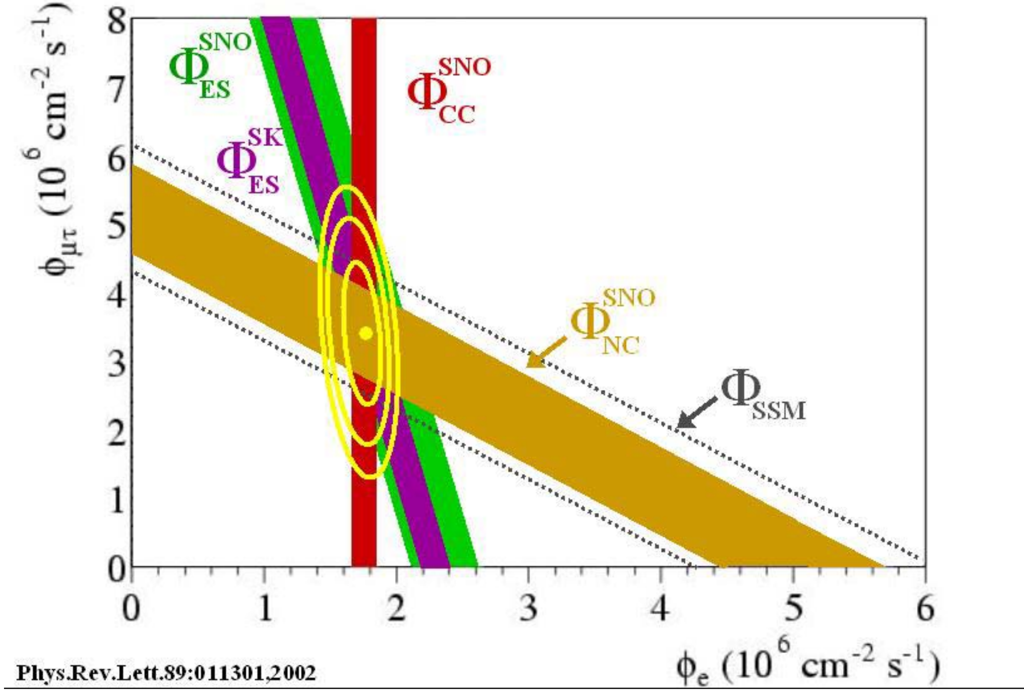


About 35% electron neutrinos make it to earth (from CC) but flux of all neutrino species (from NC and ES) as expected:

**Neutrinos change species in flight: Neutrino Oscillations!**

# Solar neutrinos (cont.)

- Confirmation of results with with salt data:
- All results are consistent with oscillations: NC rate (all ν) is as expected from SSM, $\nu_e$ CC rate is 0.31 SSM and ν ES rate is consistent with Super-Kamioka.
- Initial results confirmed with a second run with salt (NaCl). Neutral currents detected through neutron capture on $^{35}$Cl (increases NC sensitivity)



Phys.Rev.Lett.89:011301,2002

**CC 1339.6 $^{+63.8}_{+61.5}$**

**ES 170.3 $^{+23.9}_{+20.1}$**

**NC 1344.2 $^{+69.8}_{+69.0}$**

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

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

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

$$CC / NC = 0.306 \pm 0.036$$

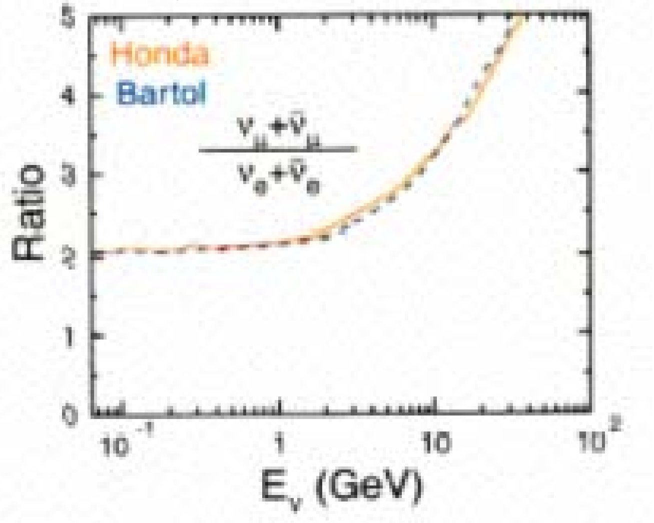
# Atmospheric neutrinos

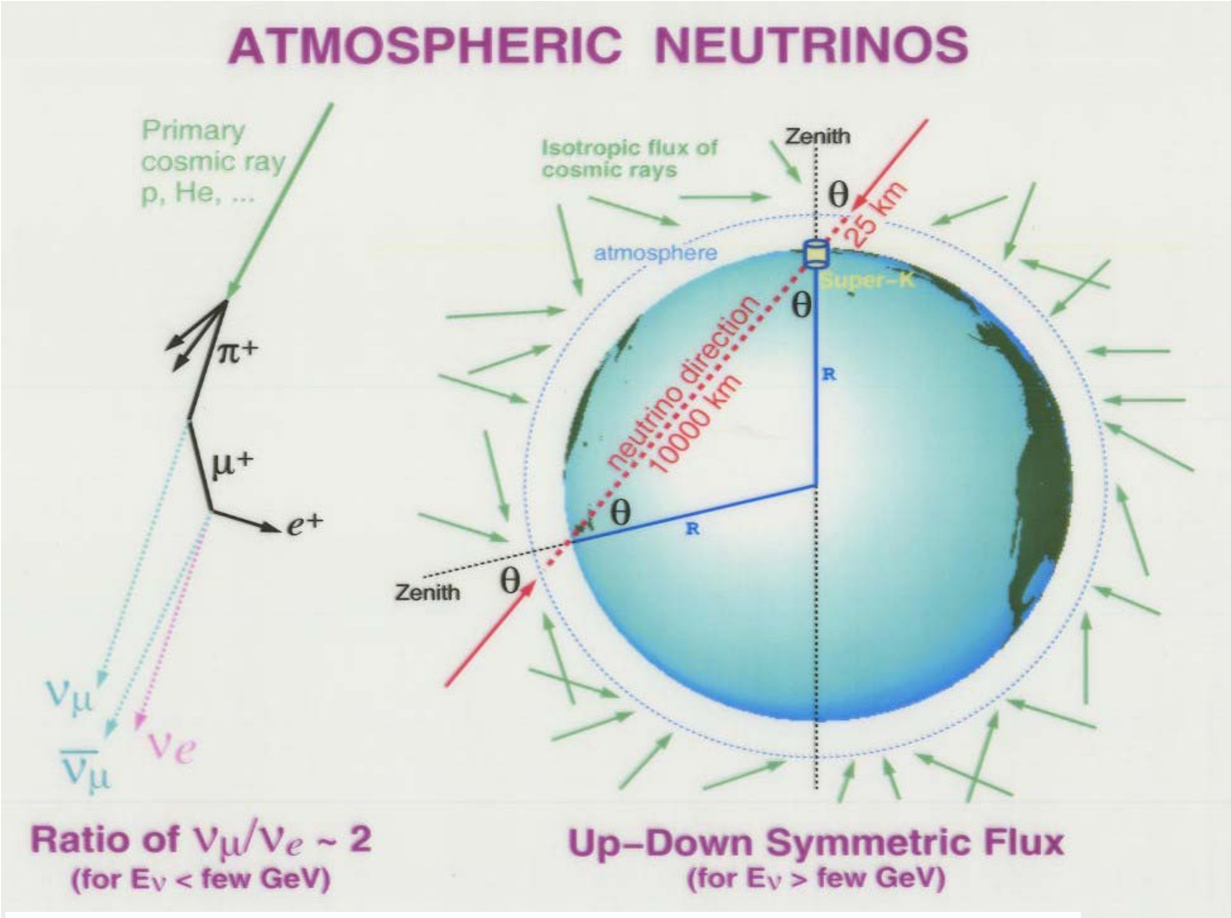
- Atmospheric neutrinos: neutrino production from cosmic rays in atmosphere
- Protons hit upper part of atmosphere producing cascade of particles including pions that decay (on average) into 2 muon neutrinos for each electron neutrino produced in an interaction

$$\begin{cases} \pi^+ \to \mu^+ + \nu_\mu \\ \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \end{cases}$$

$$\begin{cases} \pi^- \to \mu^- + \bar{\nu}_\mu \\ \mu^- \to e^- + \nu_\mu + \bar{\nu}_e \end{cases}$$

$$\frac{\Phi(\nu_\mu)}{\Phi(\nu_e)} \approx 2 \ \ (E_\nu < 3\,GeV)$$





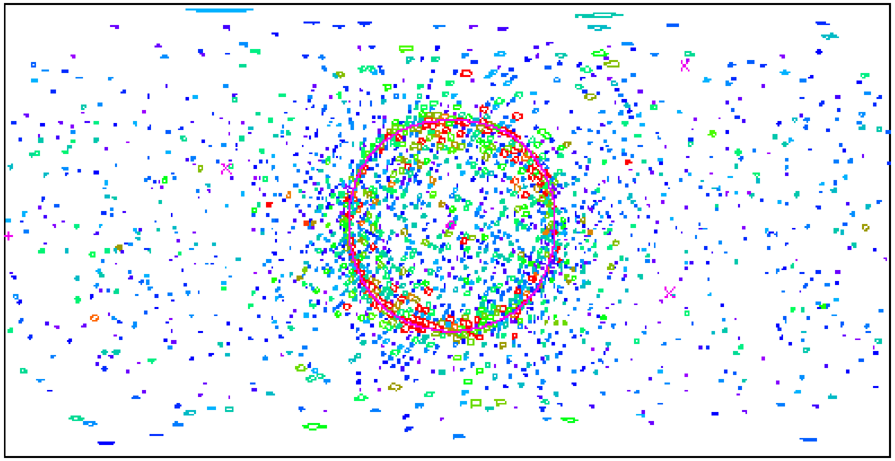
# Atmospheric neutrinos

- Super-Kamiokande detects faint flashes of Cherenkov light inside huge tank of 50,000 tons of water.
- Electron neutrinos make a recoil electron and muon neutrinos make a recoil muon in quasi-elastic interactions:

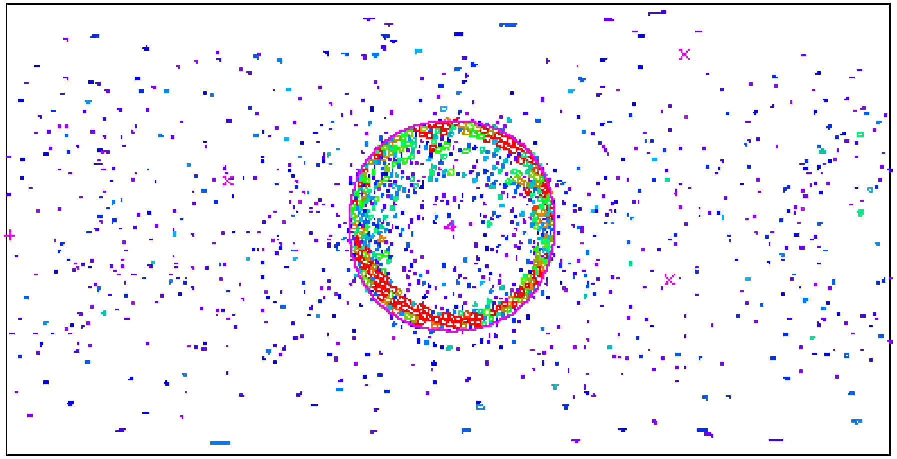
$$\nu_\mu(\nu_e)+n\rightarrow\mu^-(e^-)+p \qquad \bar{\nu}_\mu(\bar{\nu}_e)+p\rightarrow\mu^+(e^+)+n$$

- Rings of Cherenkov light are formed from the electron or the muon. The detector can distinguish between electrons (fuzzy rings) and muons (clean edge on ring).

Electron-like



Muon-like



# Atmospheric neutrinos (cont)

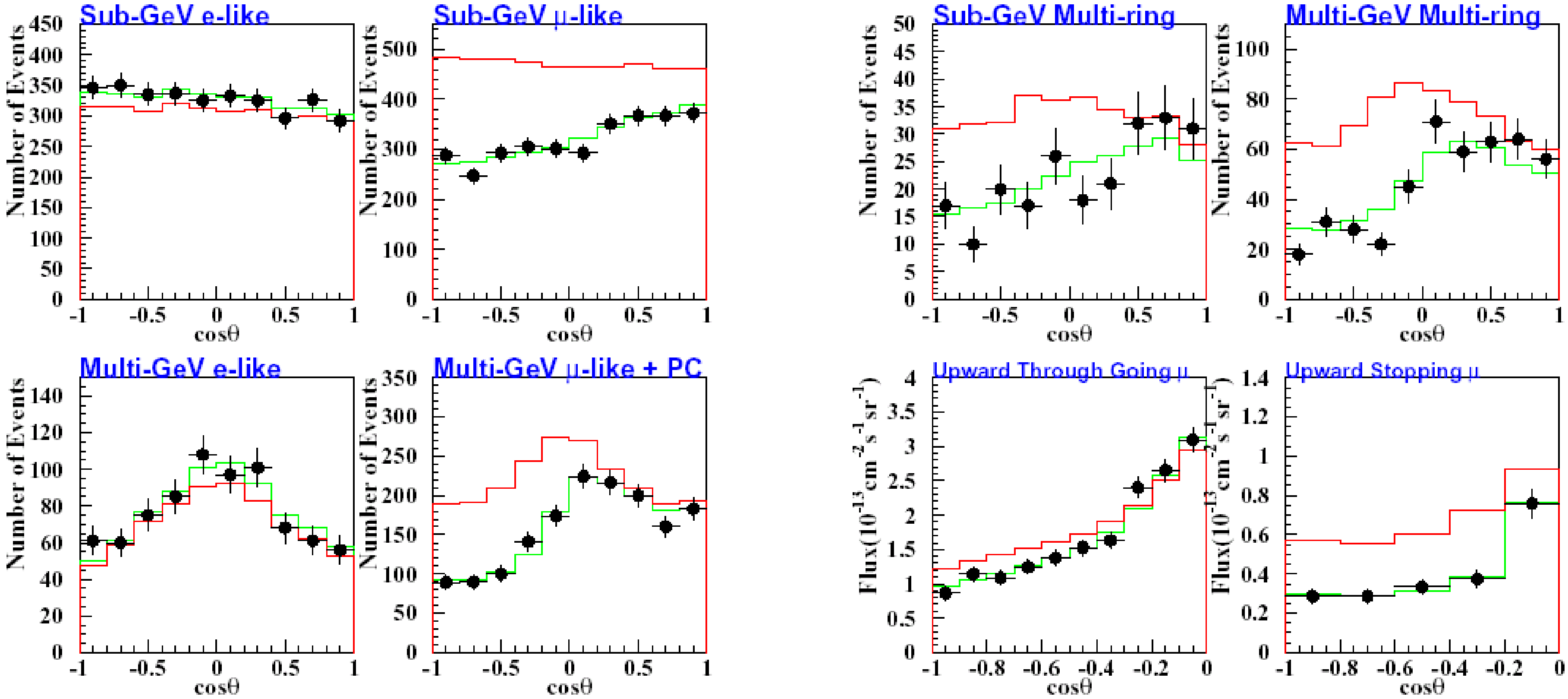
- Ratio of muon-type neutrinos versus electron-type neutrinos is less than expected:

$$R = \frac{(\nu_\mu / \nu_e)\ measured}{(\nu_\mu / \nu_e)\ predicted}$$

- Experiments:
  - Kamiokande: $R=0.60^{+0.06}_{-0.05}$+-0.05
  - IMB: R=0.54+-0.05+-0.12
  - Frejus: R=1.00+-0.15+-0.08
  - NUSEX: $R=0.99^{+0.35}_{-0.25}$
  - SOUDAN2: R=0.58+-0.11+-0.05
  - Super-Kamiokande: $R=0.668^{+0.024}_{-0.023}$ +-0.052
- But, proof of oscillations came from zenith-angle distribution in Super-Kamiokande due to having less muons in the upward direction than in the downward direction.

# Atmospheric neutrinos (cont)

- Super-Kamiokande zenith angle distributions:

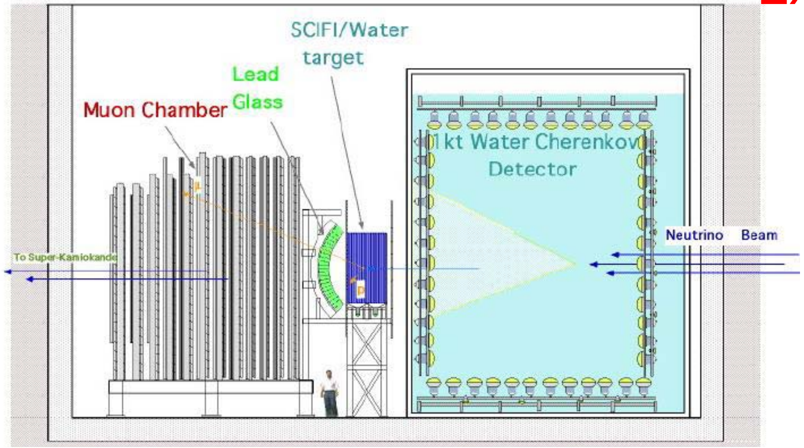


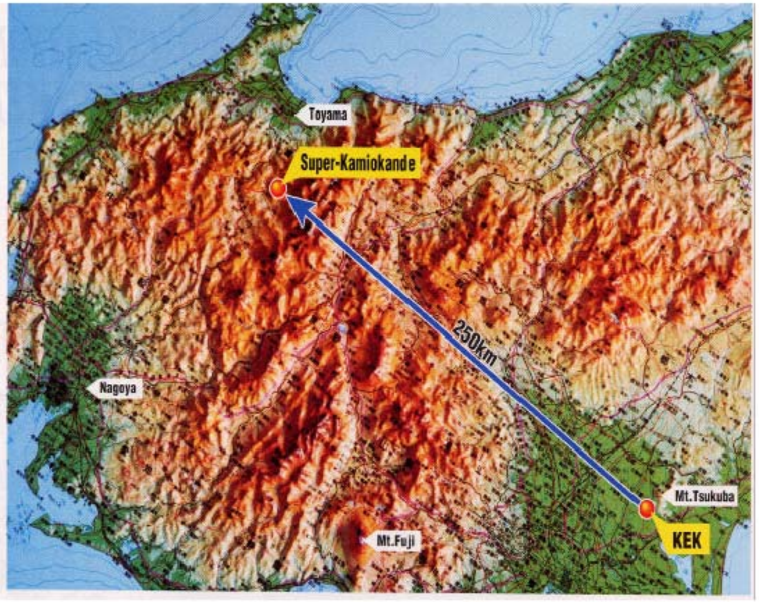
**Upward-going neutrinos depleted, while upward-going electron neutrinos slightly higher than expected: proof of neutrino oscillations!**

# Accelerator based oscillation expts

- K2K: 12 GeV proton synchrotron at KEK to Kamioka mine (Japan). L=250 km, <E>=1.4 GeV. Running.

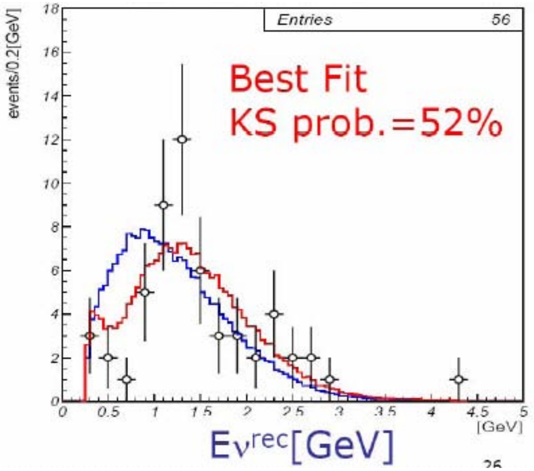
**K2K Front Detector**





Observed: 108 events in Super-K

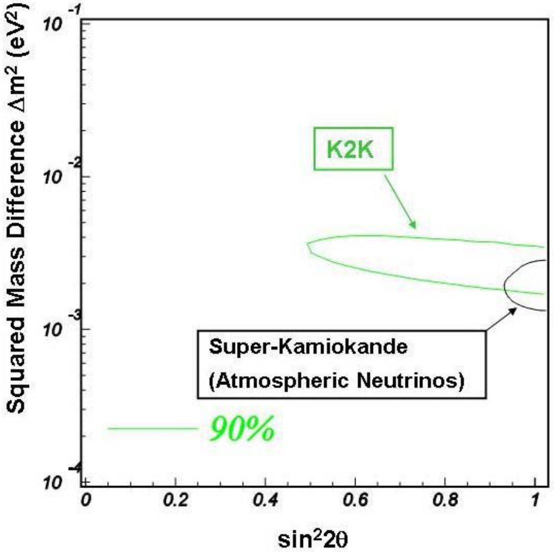
Expected (no oscillation): $150.9^{+11.6}_{-10.0}$



Best fit:

104.8 events

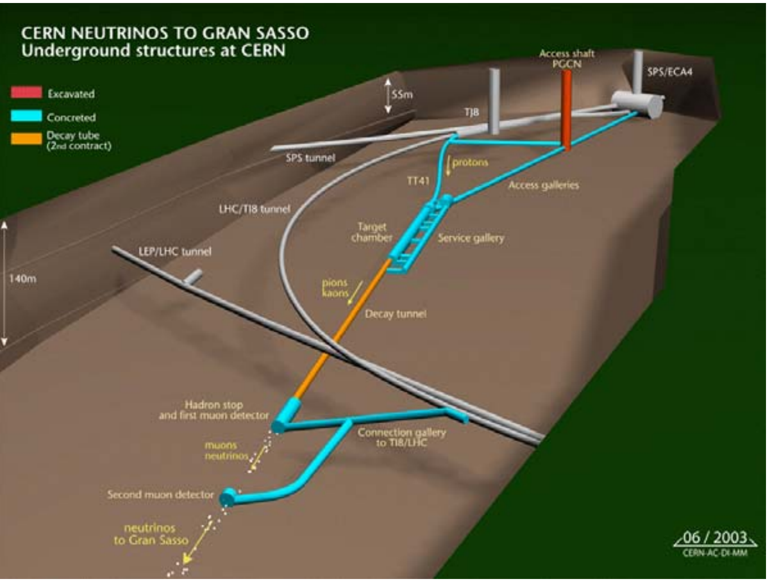
Probability no oscillation < 1%



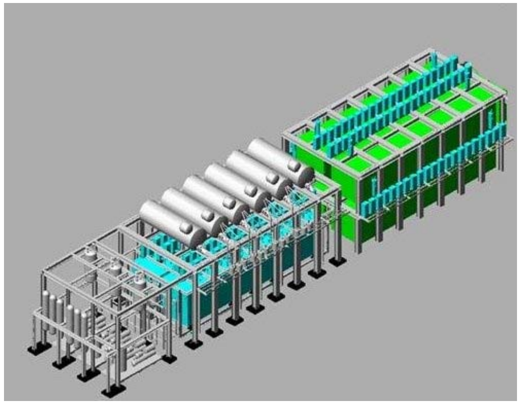
Compatible with Super-K atmospheric Oscillation parameters.

# Accelerator based oscillation expts (cont)

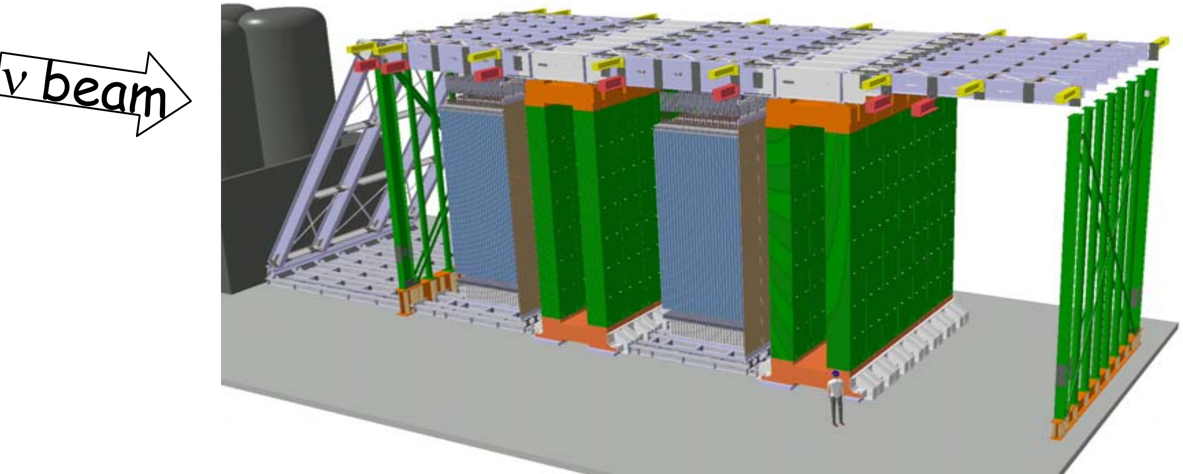
- CNGS: CERN to Gran Sasso (Italy). L= 732 km, <E> = 30 GeV. Start 2006.



- ICARUS (600 ton liquid argon TPC): kinematic selection of $\nu_\tau$

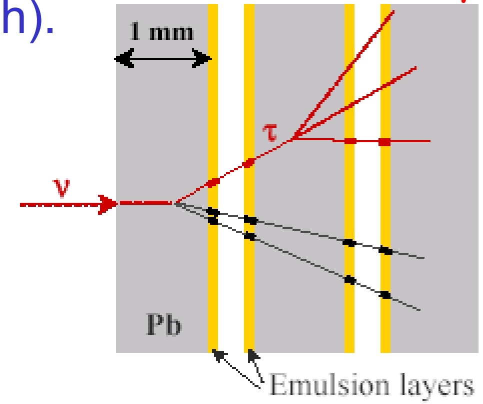


- OPERA (1.8 kton emulsion based $\nu_\tau$ appearance search).



es

206,336 "ECC bricks"
(56 Pb/Emulsion layers)



**6.6 $\nu_\tau$ signal events**
**($\Delta m^2=1.9\text{x}10^{-3}\text{eV}^2$)**

# Reactor based oscillation expts

- CHOOZ experiment (France) set limits on $\overline{\nu}_\mu \leftrightarrow \overline{\nu}_\mu$ oscillations: <E>~6MeV, L~1km

$$P(\nu_\mu \leftrightarrow \nu_\tau) < 0.05\,(90\%\,CL) \quad \sin^2 2\theta_{13} < 0.1\,(90\%\,CL)$$

- KAMLAND reactor experiment in Kamioka mine (Japan) confirms Large Mixing Angle (LMA) solution of solar neutrino problem.
- Observed/Expected= 0.611+-0.085+-0.041
- Average distance (L) to reactors 175+-35 km