Neutrino Physics

(Selected topics)
Lecture 1

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Likely biased towards experiment...

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Outline

1. Neutrinos in the Standard Model
2. Neutrino sources: relic neutrinos, geoneutrinos, supernova neutrinos
3. Atmospheric neutrinos
4. Solar neutrinos
5. Neutrino oscillations

Neutrinos in the Standard Model

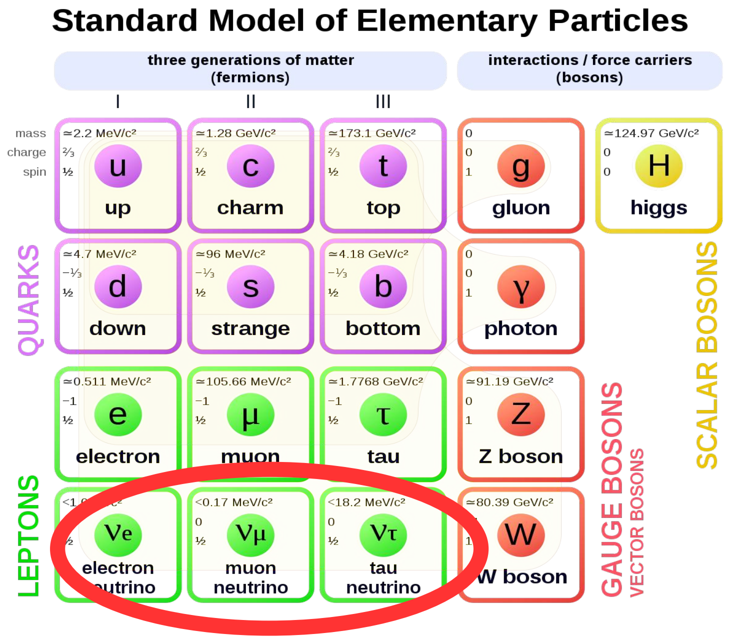
- Neutrinos in the Standard Model are elementary particles with the following properties:
  - Fermions, part of the lepton doublets
  - Have only weak interactions
  - No electric charge
  - Massless
  - Three flavor states: electron neutrino: ν_e, muon neutrino: ν_μ, taon neutrino: ν_τ). LEP experiment results: $N_\nu = 2.984 \pm 0.008$ (Z^0 boson width measurement).
  - Only left-handed neutrinos and right-handed antineutrinos are observed

$$\begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}$$ Lepton doublets $\quad \ell = e, \mu, \tau$

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \sum_\ell \bar{\nu}_{L\ell} \gamma^\mu \ell_L^- W_\mu^+ + \text{h.c.}\,,$$

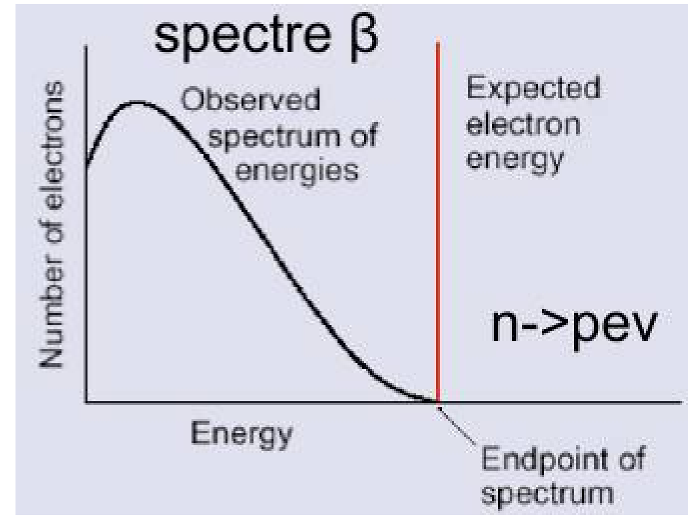
$$-\mathcal{L}_{NC} = \frac{g}{2\cos\theta_W} \sum_\ell \bar{\nu}_{L\ell} \gamma^\mu \nu_{L\ell} Z_\mu^0\,.$$

Neutrino interactions



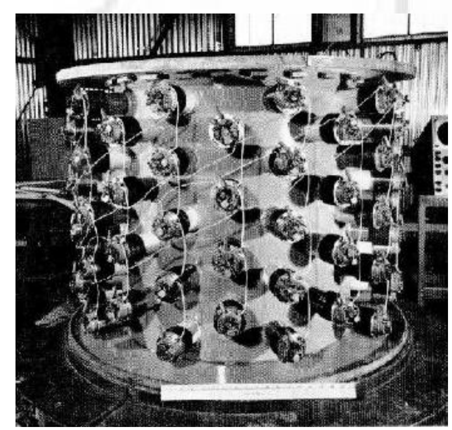
Short history

- 1930 – W. Pauli introduces hypothethical particle to solve the missing energy problem in beta decays
- 1933 – E. Fermi calculates the cross section for interaction of a typical neutrino from reactor (few MeV of energy) to be ~10^{-44} cm^2. Mean free path in steel of 1 MeV neutrino is 10 light years! We need a very strong neutrino source to detect signal.
- 1956 – Reines and Cowan observe for the first time neutrino interaction. Their detector was located close to the nuclear power plant (5 x 10^{20} ν/s) in Savannah River (USA).
- 1962 – Lederman, Schwartz, Steinberger ν_μ discovery. First experiment with artificial (accelerator) neutrinos. Nobel prize in 1988.
- 1975 - SLAC (USA), τ particle discovery and ν_τ hypothesis
- 2000 - DONUT experiment (Fermilab, USA) detects ν_τ

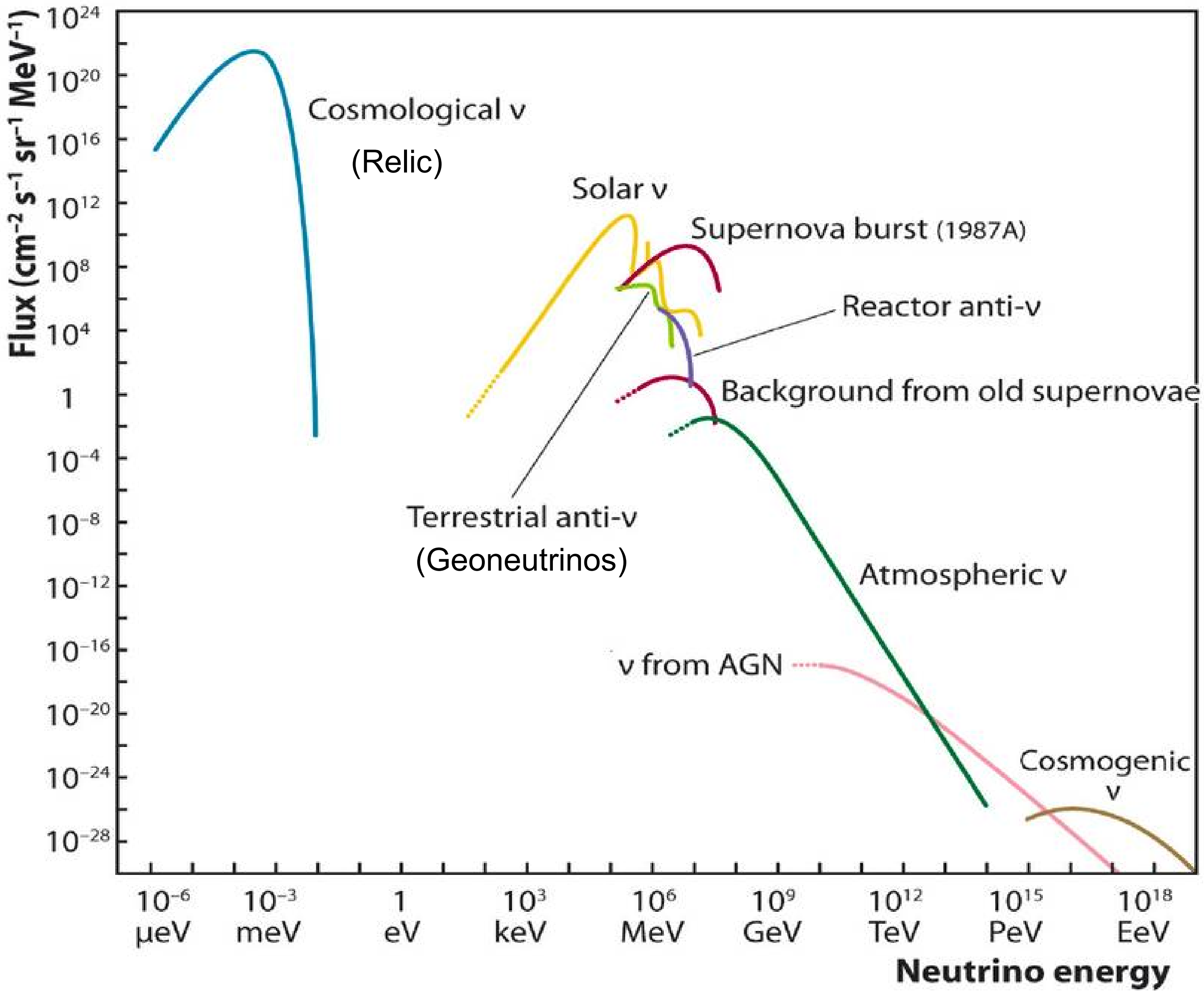


"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

Wolfgang Pauli



Natural neutrino sources

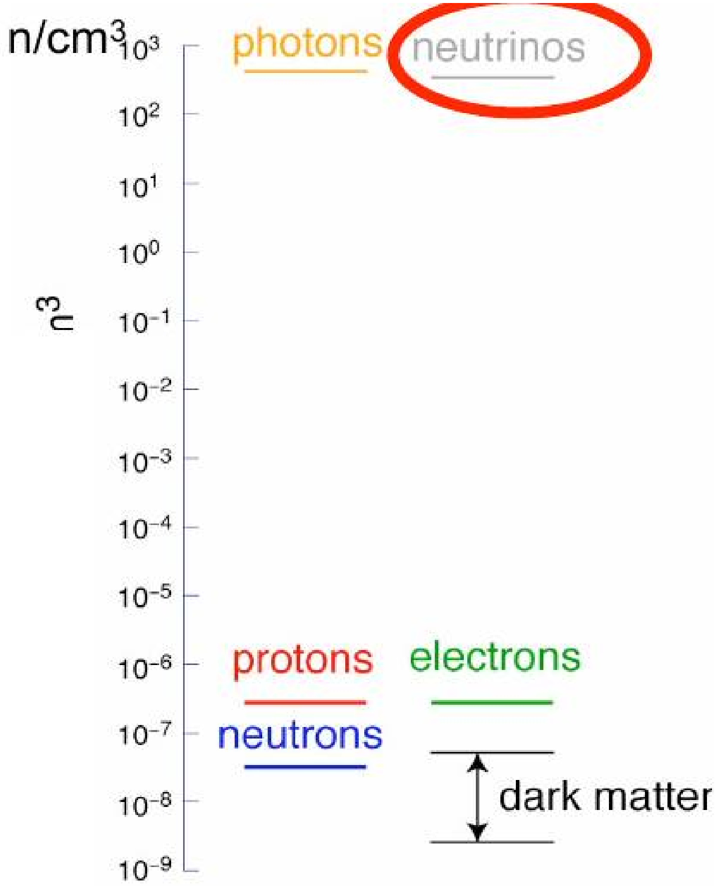


Relic (cosmological) neutrinos

- In the early universe neutrinos were in thermal equilibrium with protons, neutrons and electrons maintained through the weak interactions.
- Production of neutrinos in the early Universe happened in the weak process:

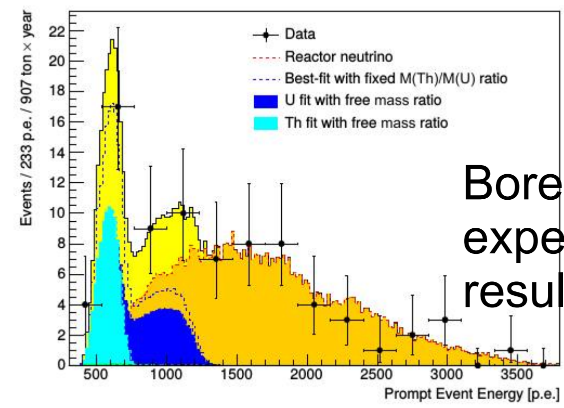
$$e^{+} + e^{-} \rightarrow \nu_e + \bar{\nu}_e$$

- Rate of this reactions smaller than the rate of expansion of the universe → neutrinos exit the thermal equilibrium and decouple from other types of matter with kT < 3 MeV at $t>10^{-2}$ s
- In consequence there are ~330 cm^{-3} of 'relic' neutrinos in the Universe with temperature ~ 1.95 K.
- They have very low energies (~10^{-4} eV) therefore are very difficult to detect. Not detected so far.

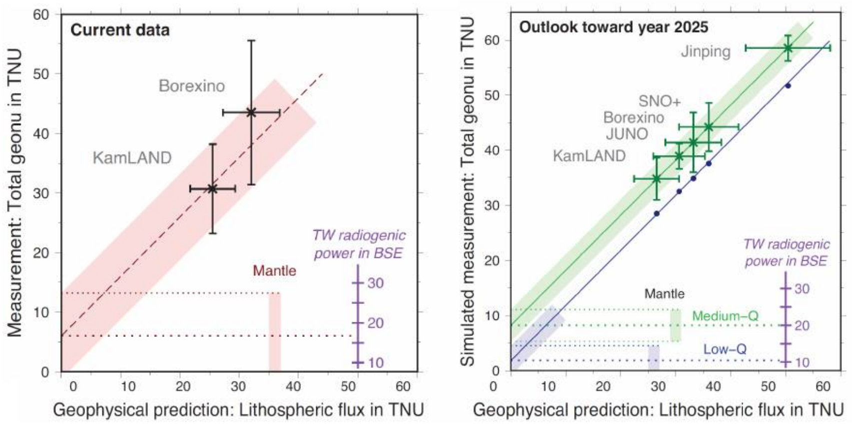


Geoneutrinos

- Neutrinos are produced inside the Earth by the radioactive decays of long-lived natural isotopes: Uranium (U), Thorium (Th), Potassium (K), Radium (Ra),…
- Beta decays are the source of electron antineutrinos. The flux of geoneutrinos ~ $6*10^6$ $cm^{-2}s^{-1}$.
- Applications:
  - Geology, Geophysics. Studies of Earth's interior by measuring the fluxes of neutrinos at the surface. Studying the composition of our planet without drilling below the surface.
  - Geoneutrinos are background in many neutrino experiments (KamLand, Borexino) and future ones: SNO+, Juno.



Borexino experiment results



Lithospheric geoneutrino flux data vs predictions

Supernova neutrinos

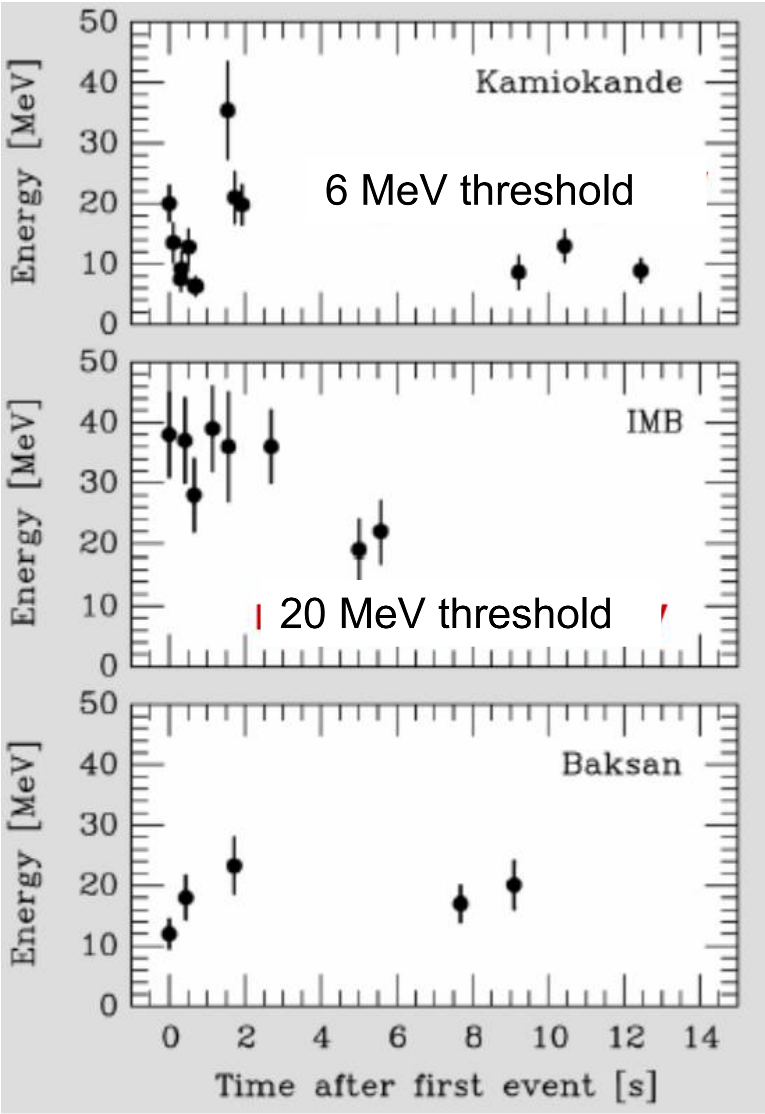
- Neutrinos are produced during the gravitational collapse of the core of the massive star (m>10M_{Sun}).
- Emmision of the neutrinos from the neutronization process (~ms): $e^{-}+p \rightarrow n+\nu_e$. Core density increases to nuclear matter density and neutrinos are trapped. Neutron star is created.
- External layers fall into the core and bounce back causing a shockwave → Supernova explosion. Neutrinos are released in the shockwave.
- Neutrinos are also produced in: $e^{+}e^{-} \rightarrow Z^{0} \rightarrow \nu_e+\bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$

Supernova neutrinos

- During the neutron star cooling:
  - 99% of the gravitational energy is emmited in the form of neutrino pulse lasting several seconds (~10^{58} neutrinos)
  - 1% is a kinetic energy of the explosion
  - 0.01% photons
- Main detection channel:

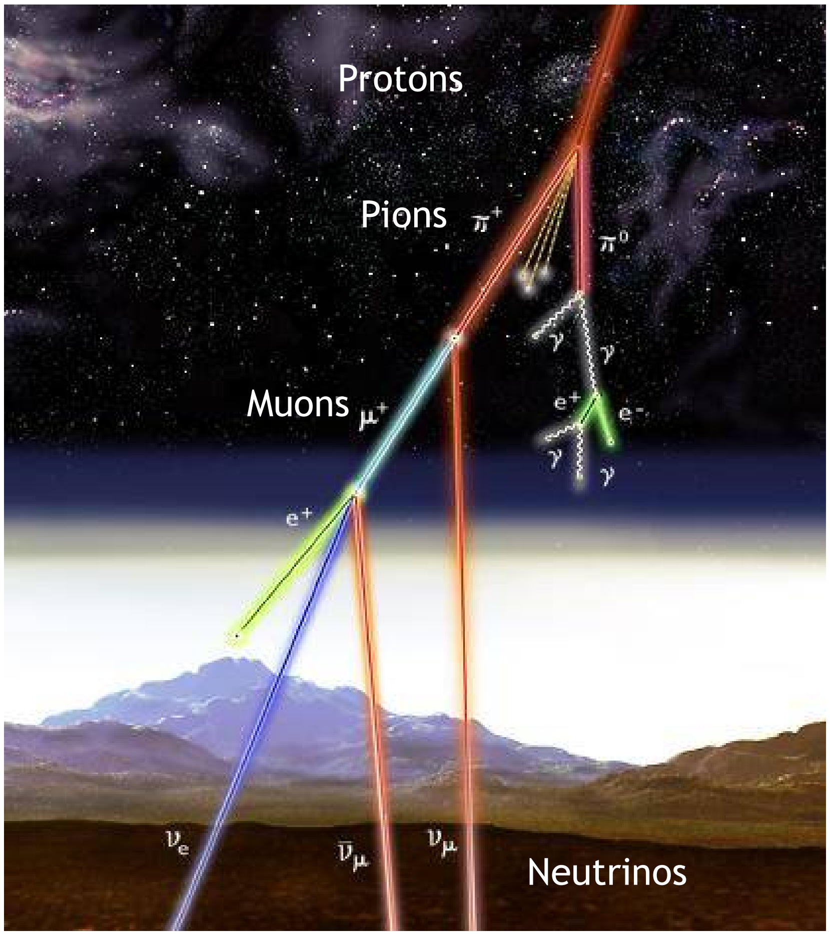
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- Kamiokande (Japan), IMB (USA) water Cherenkov detectors and Baksan (USSR) scintillation detector measured the electrons from Supernova 1987A neutrinos with energy ~10-15 MeV



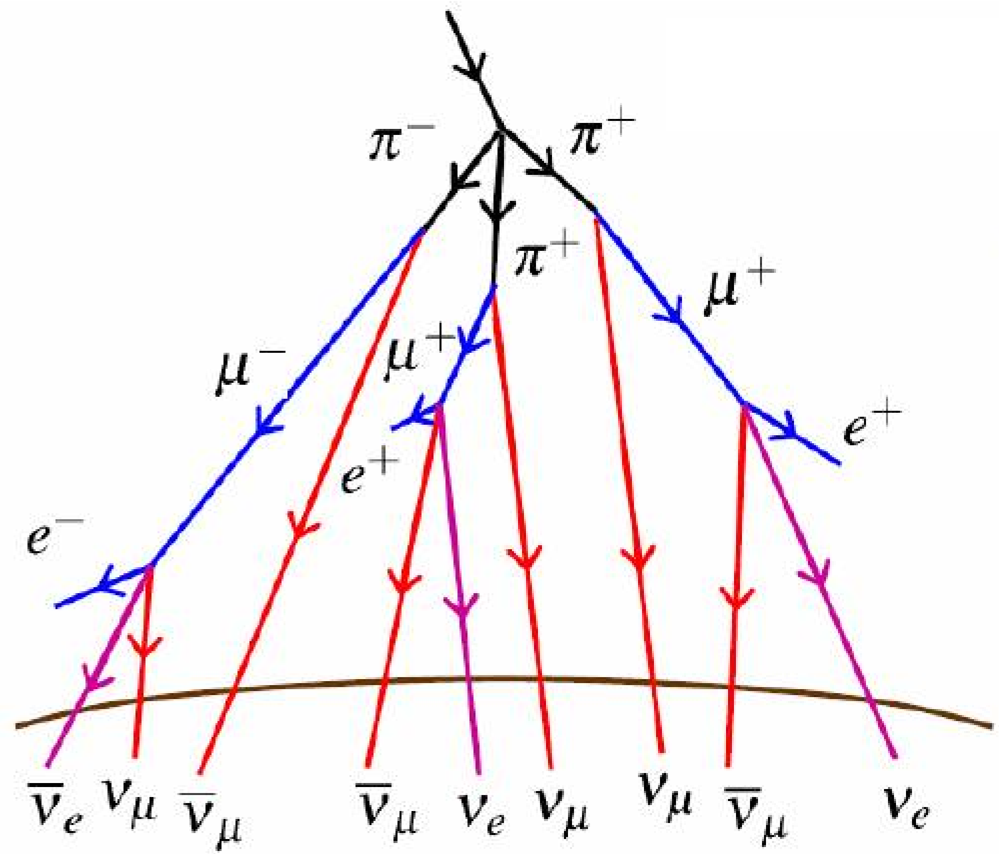
Supernova 1987A observation

Atmospheric neutrinos



- Primary cosmic rays - very high energy (up to 10^{20} eV) particles (86% of protons) interact with the nuclei in the higher parts of the atmosphere producing secondary particles, mainly pions.
- Charged pions decay into muons and muon neutrinos
- Muons decay into positons and electron neutrinos
- Atmospheric neutrino flux ~1 $cm^{-2}\,s^{-1}$
- Mean energy of atmospheric neutrinos ~ 1 GeV (MPV ~100 MeV)

Ratio of muon to electron neutrinos



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

$$\llcorner\ e^+ + \nu_e + \bar{\nu}_\mu \qquad \llcorner\ e^- + \bar{\nu}_e + \nu_\mu$$

- The ratio of number of muon neutrinos and antineutrinos to number of electron neutrinos and antineutrinos below 1 GeV should be equal approximately 2

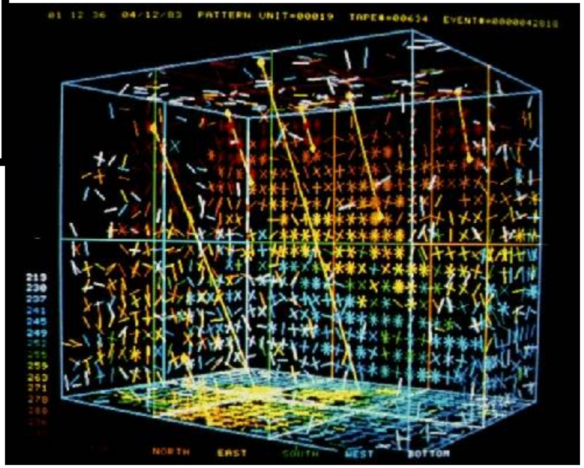
$$\frac{N_\mu}{N_e} = \frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$

- Experimentally it is convenient to estimate double ratio R to reduce the systematic uncertainties. It is defined as observed ratio / theoretical ratio.

$$R = \frac{(N_\mu / N_e)_{Obs}}{(N_\mu / N_e)_{Teor}}$$

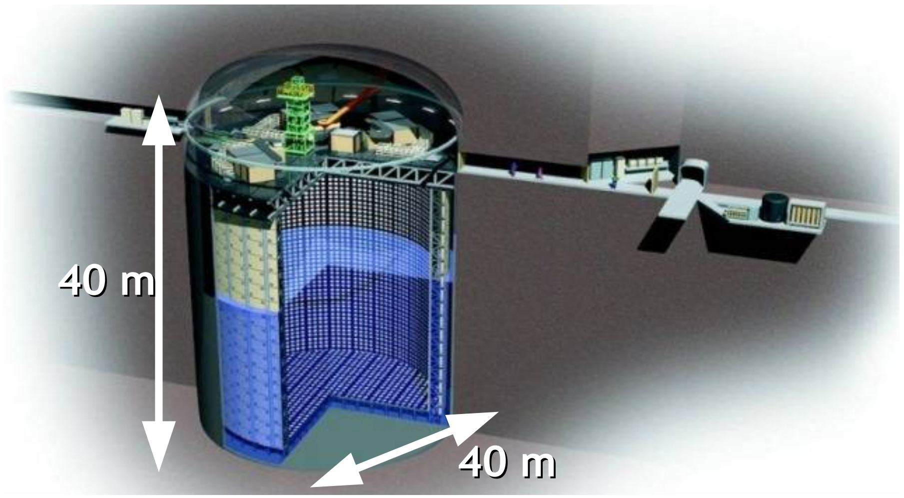
Atmospheric neutrinos anomaly

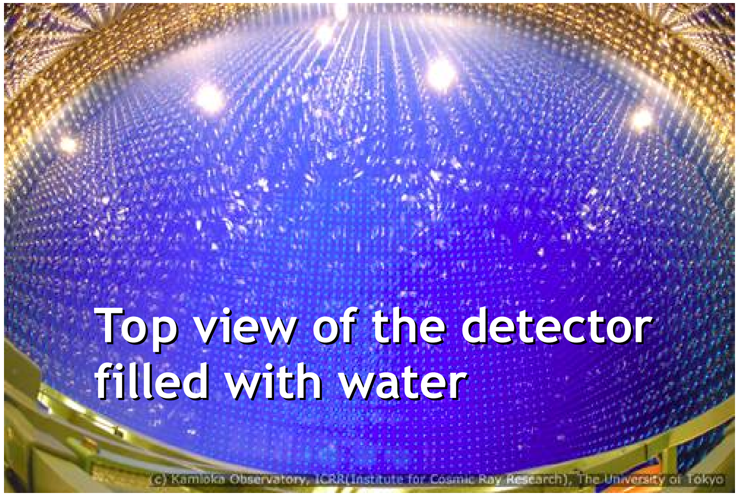
- In the 1980s several experiments reported a deficit in the number of detected atmospheric muon neutrinos
  - IMB (USA, 1986): $R = 0.54 \pm 0.05 \pm 0.12$
  - Kamiokande (Japan, 1988): $R = 0.60^{+0.06}_{-0.05} \pm 0.05$
- ...on the other hand there were experiments that didn't observe any deficit:
  - Frejus (France, 1989): $R = 1.00 \pm 0.15 \pm 0.08$
  - NUSEX (France/Italy, 1982): $R = 0.99^{+0.35}_{-0.25}$
- No final conclusion...

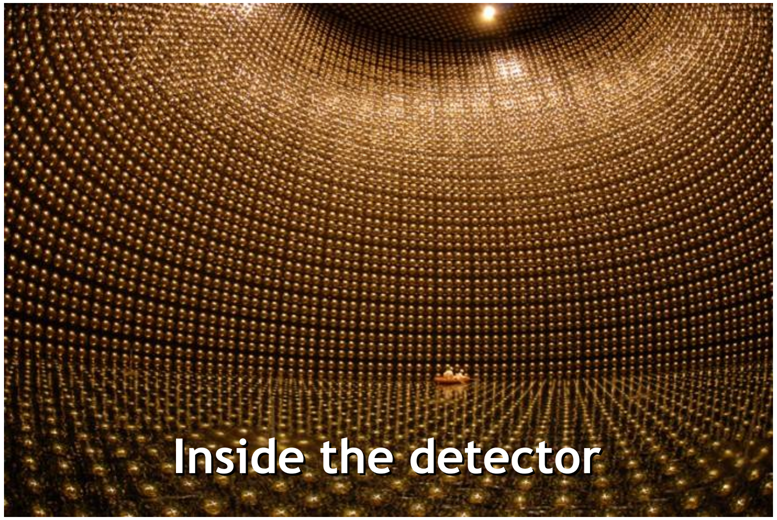


Super-Kamiokande experiment

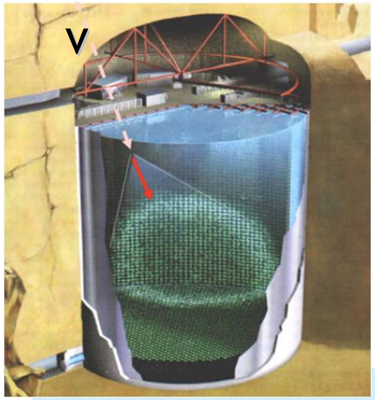
- ...until Super-Kamiokande - World largest neutrino detector (operating since 1996):
  - Cylindrical tank with the diameter and height of 40m,
  - 1km underground, in the Zinc mine Mozumi in Japan
  - Tank filled with kton of ultra pure water
  - 11 000 of photomultipliers on the walls of the tank detecting Cherenkov light produced by charged particles

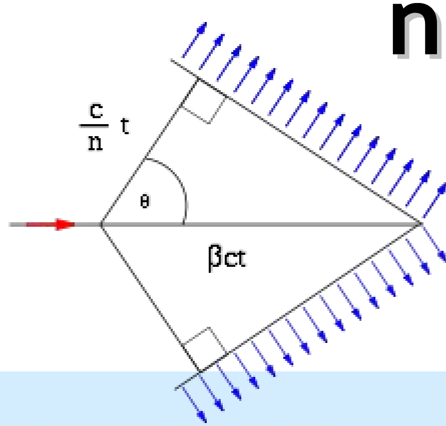




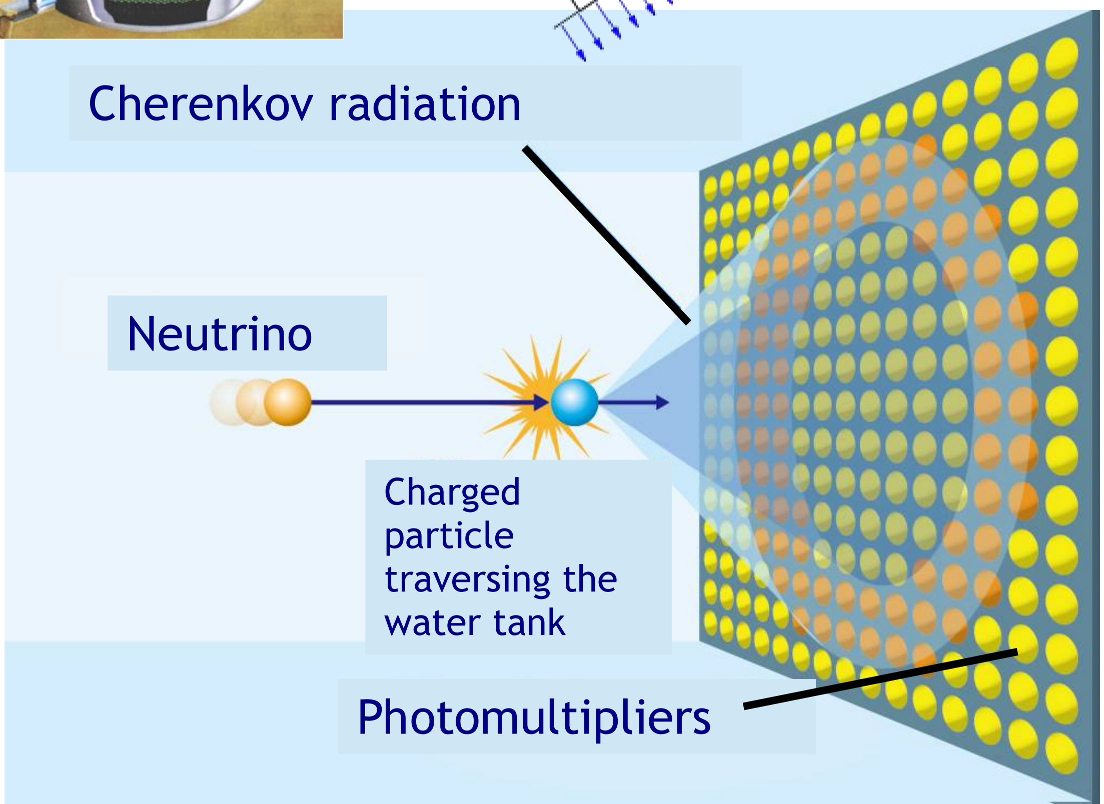


How Super-Kamiokande „sees” neutrinos?





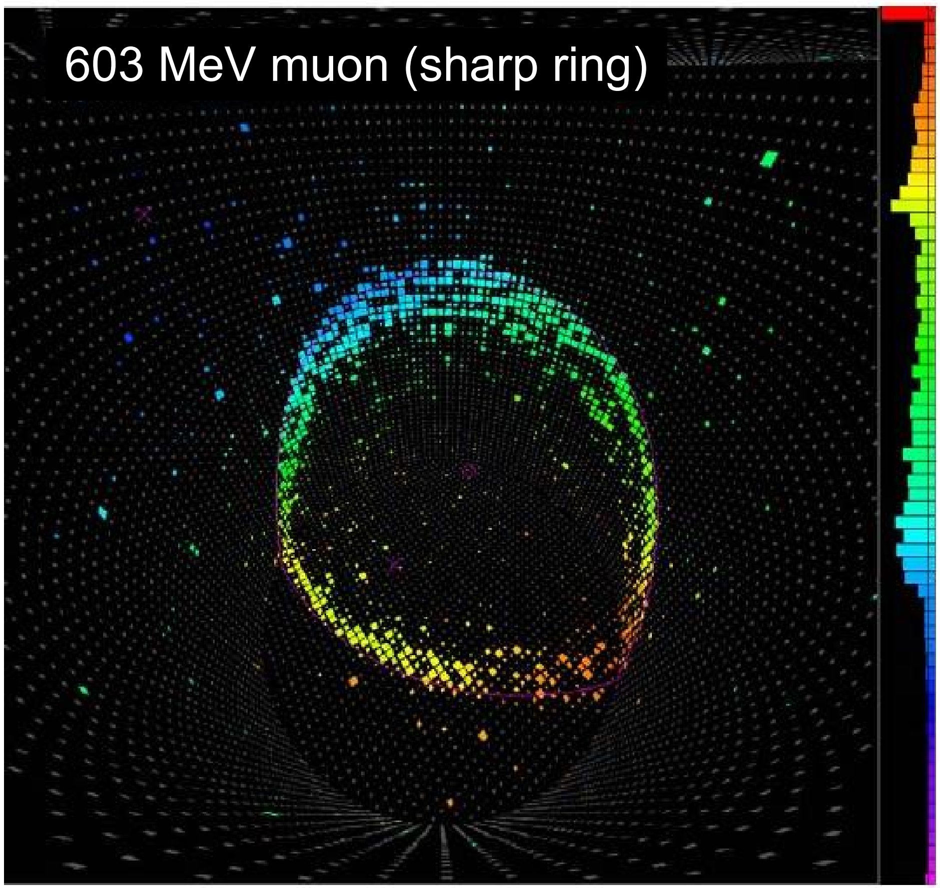
$$\cos\theta = \frac{1}{n\beta}$$



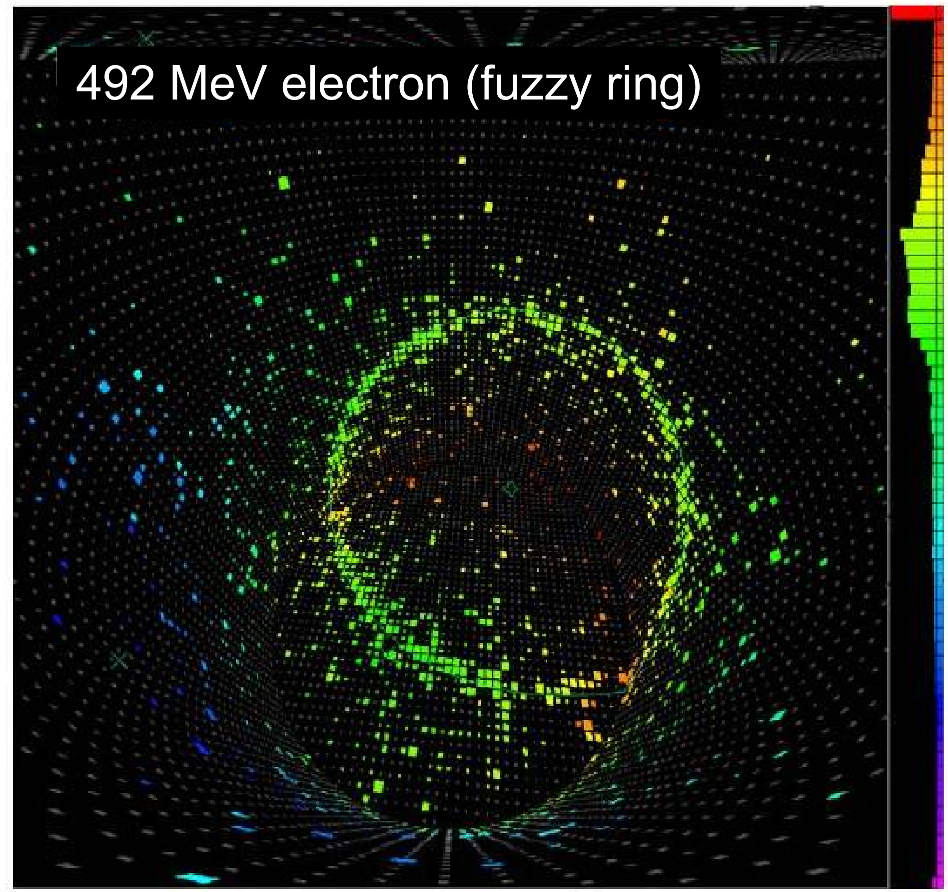
- Neutrinos interact with the oxygen nuclei inside the tank and produce charged particles
- Charged particles travelling in the medium (eg. water) faster than the speed of light emit photons of the Cherenkov light along their trajectory
- Photomultipliers detect the characteristic rings of the Cherenkov radiation
- Spatial and the time distribution of the Cherenkov light allow to reconstruct the direction of charged particle (and neutrino direction)
- Amplitude of the signal, the opening angle of the cone and characteristic pattern of ring allow to discriminate between muons and electrons and measure their energy

How Super-Kamiokande „sees" neutrinos?

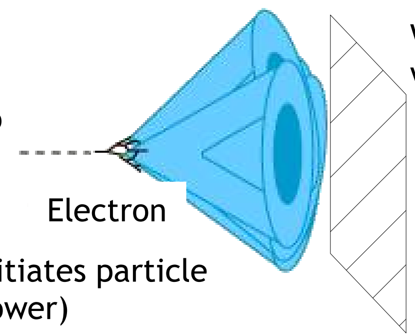
$\nu_\mu + n \rightarrow \mu^- + p$

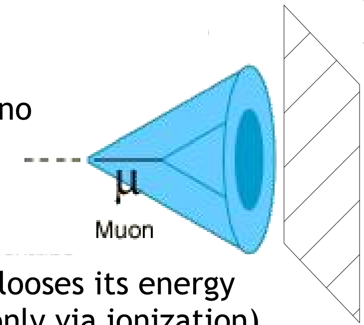


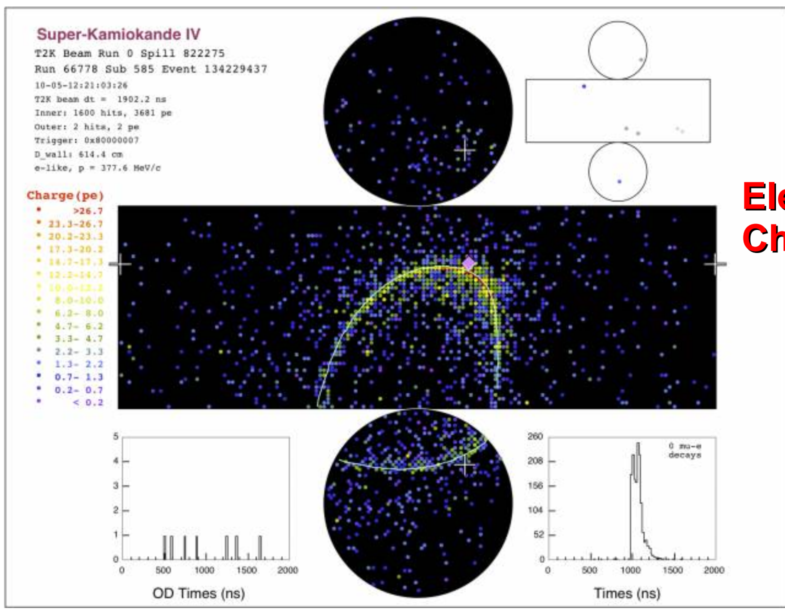
$\nu_e + n \rightarrow e^- + p$



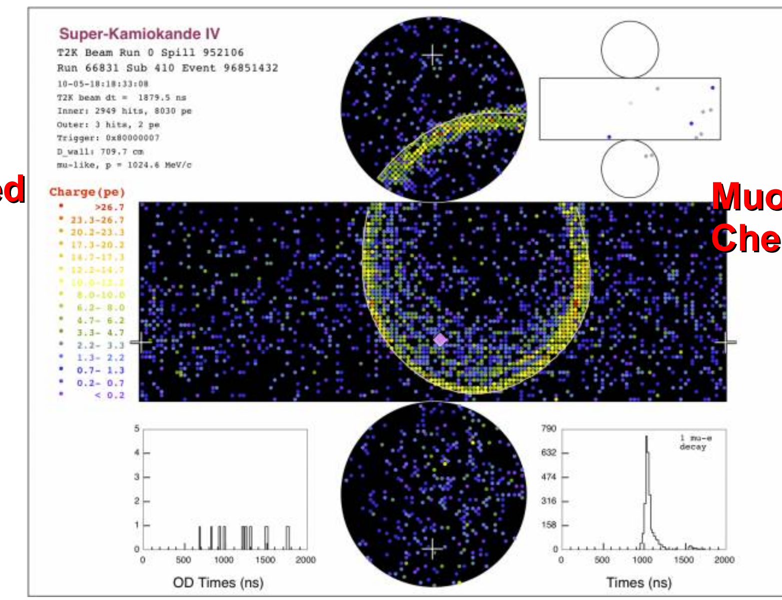
Atmospheric neutrinos in Super-Kamiokande







Electron-induced Cherenkov ring

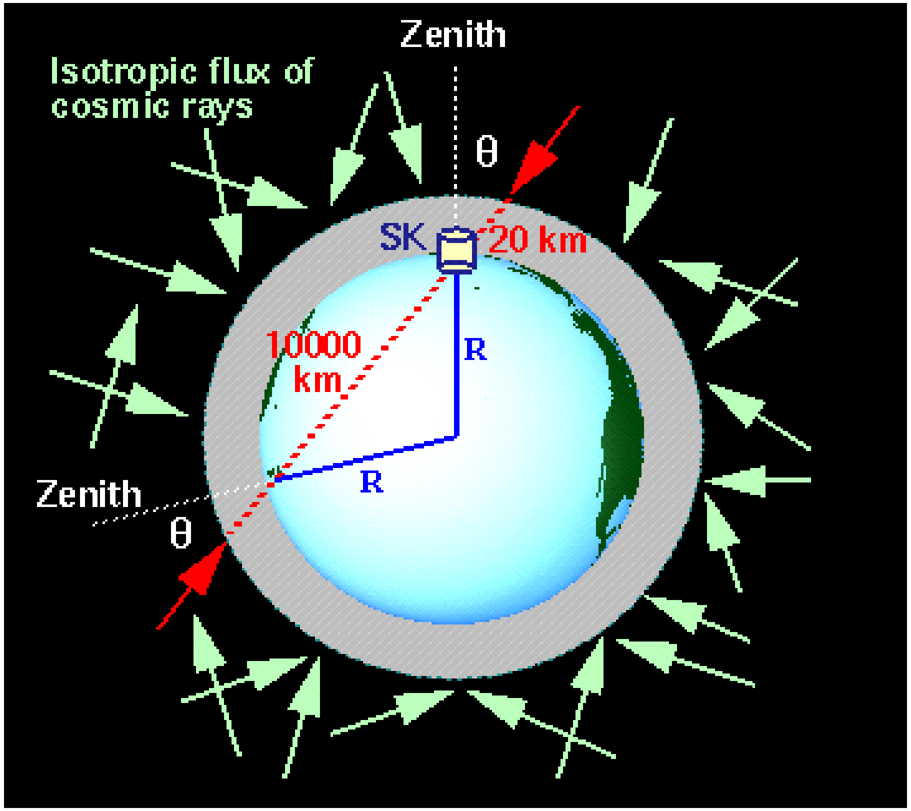


Muon induced Cherenkov ring

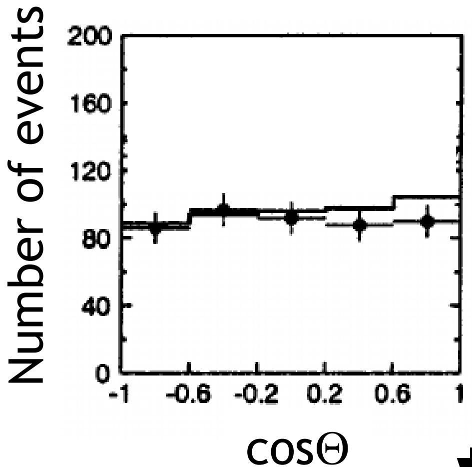
- Super-Kamiokande online event display:

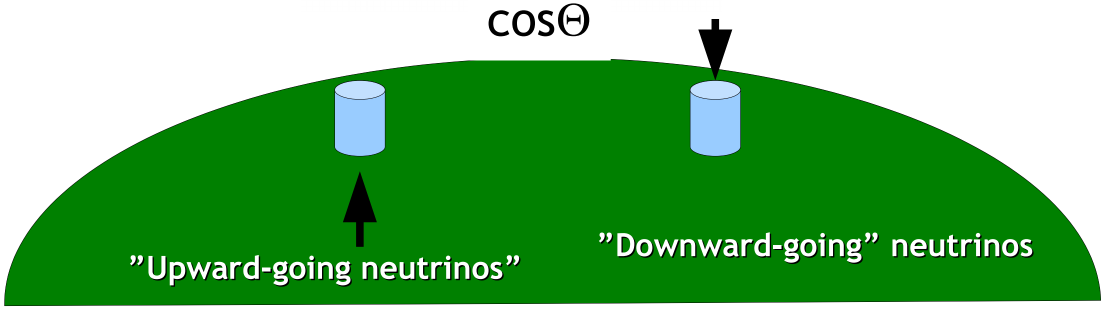
http://www-sk.icrr.u-tokyo.ac.jp/realtimemonitor/

Zenith angle dependence for atmospheric neutrinos



- Isotropic flux of cosmic rays → The flux of atmospheric neutrinos should be isotropic.
- The ratio of the number of ”upward-going” and ”downward-going” muons from atmospheric neutrinos should be equal 1.
- Zenith angle Θ measures the length of the trajectory of neutrino from the production point to the detector





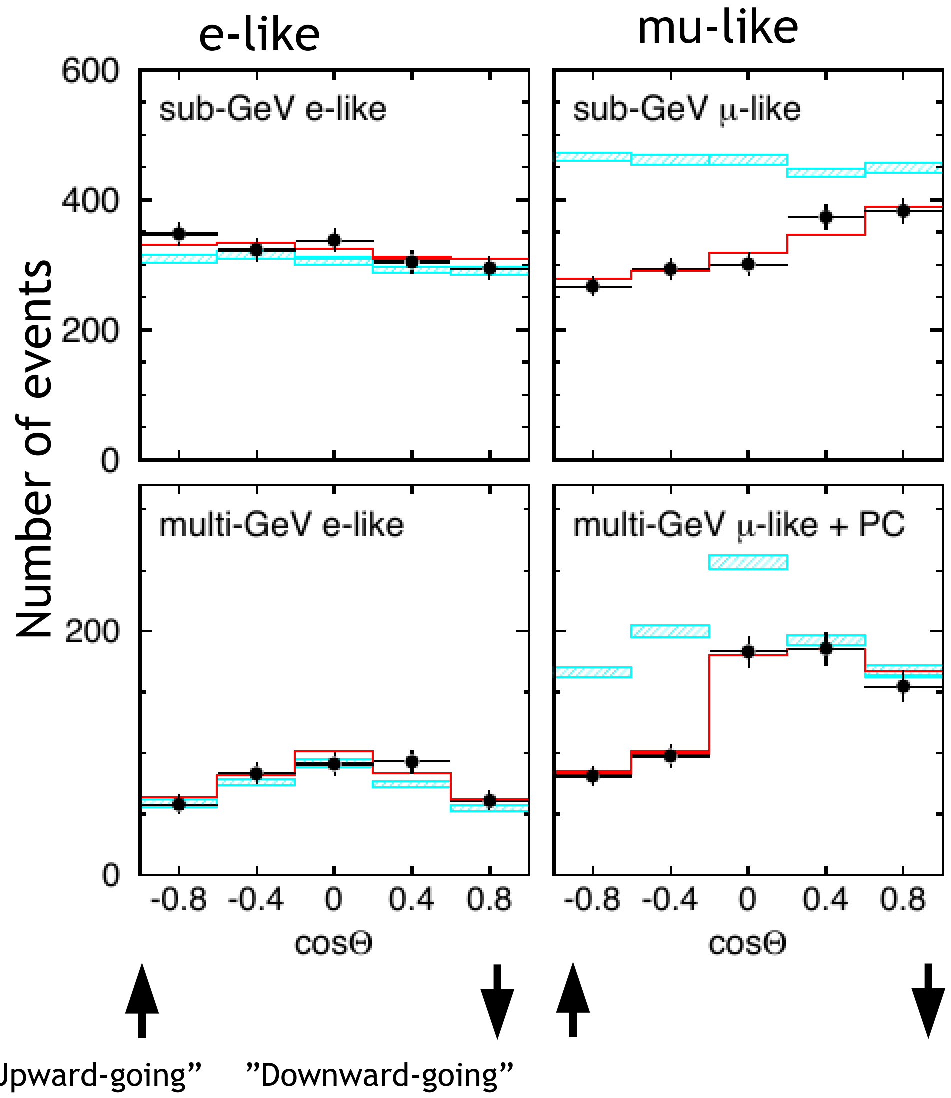
Super-Kamiokande results (1998)

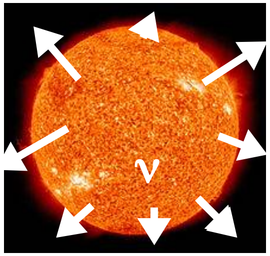
- After two years of data taking (1996-1998) experiment reported:

$$R = \frac{(N_\mu / N_e)_{Obs}}{(N_\mu / N_e)_{MC}} = 0.63 \pm 0.03\,(stat) \pm 0.05\,(syst)$$

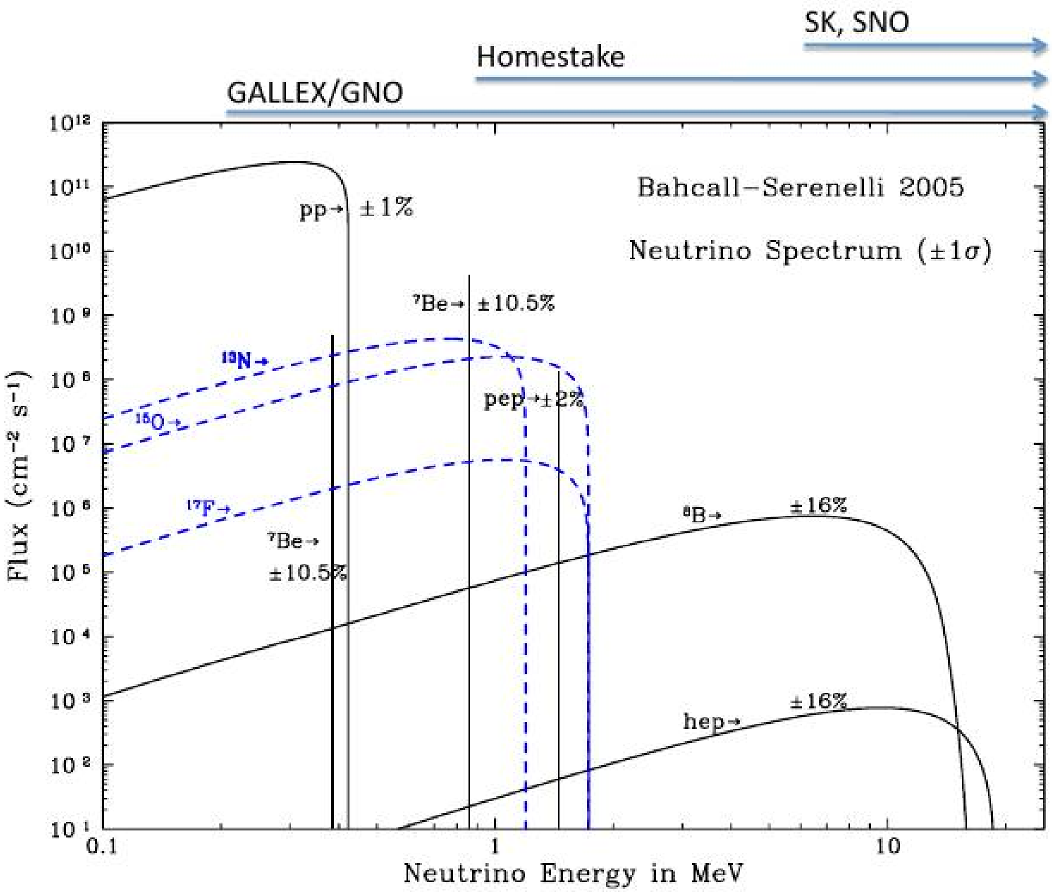
- Observed ratio wrt theoretical ratio is close to 2/3 (muon neutrino deficit).

- There's a dependence of the number of muon neutrinos on the length of the trajectory. There's larger deficit of "upward-going" (cosΘ ~ -1) wrt theoretical predictions.





Solar neutrinos

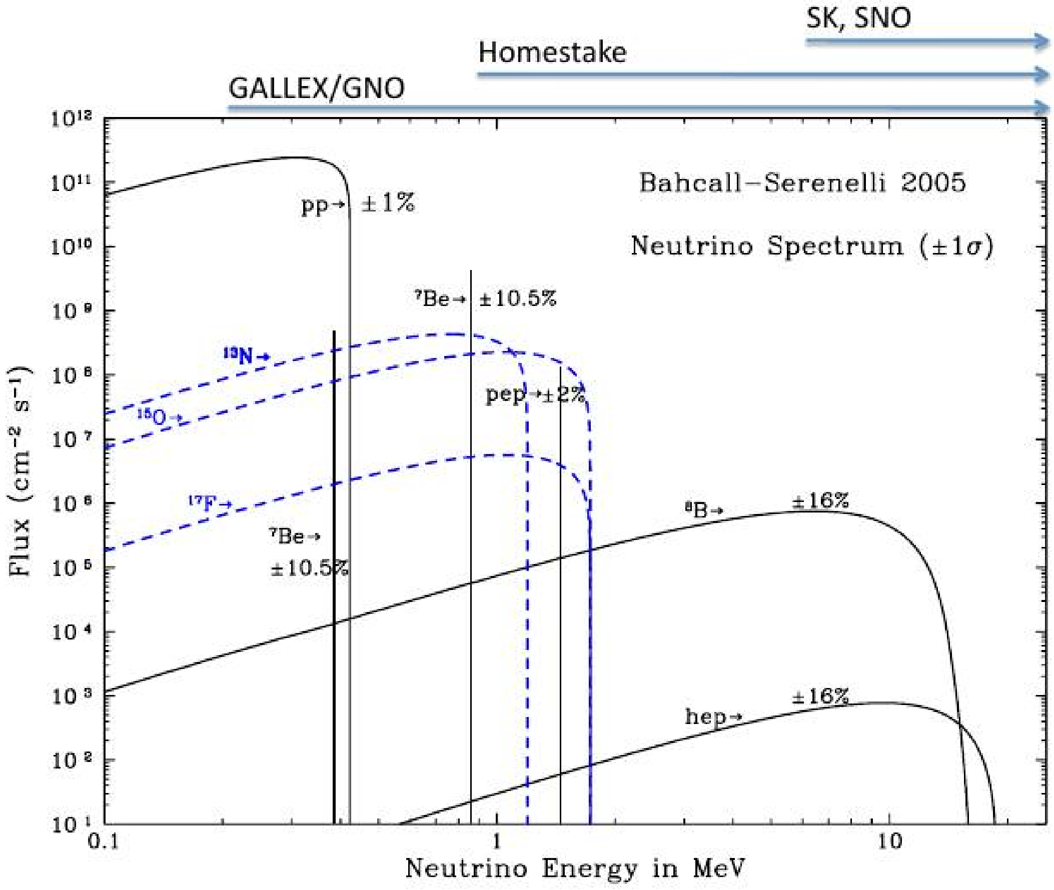


Most of the solar neutrinos come from:

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 2\gamma$$

- Electron neutrinos are produced in the Sun in the thermonuclear reactions:
  - pp and CNO cycle
  - Electron capture on ^{7}Be
  - Beta decay of ^{8}B
- Overall flux of solar neutrinos on earth: 6.5×10^{10} cm^{-2} s^{-1}
- Theoretical predictions come from the well established Standard Solar Model (SSM) developed since 1963 and continously updated by J. Bahcall et al. over a several decades.

Solar neutrinos - detection methods



Radiochemical:

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \qquad \nu_e + {}^{71}Ga \rightarrow {}^{71}\mathrm{Ge} + e^-$$

Water Cherenkov:

$$\nu_X + e^- \rightarrow \nu_X + e^- \qquad \nu_X + n \rightarrow \nu_X + n$$

- Low energy ν_e - radiochemical experiments (Ga, Cl) GALLEX, GNO, Homestake:
  - Low energy threshold
  - Only counting nuclei in the final state of the reaction
  - No information about the time of interaction
  - No information about neutrino direction
- Neutrinos with Eν>5 MeV – Water Cherenkov detectors - Super-Kamiokande, SNO:
  - Higher energy threshold
  - Neutrino time and direction information available

Solar neutrino puzzle

- 1969 – 1999 – R. Davis Jr.'s experiment in the Homestake mine in USA was constantly reporting a deficit of solar neutrinos.
  - Measured flux: 2.56 ± 0.16 (stat) ± 0.16 (sys) SNU
  - Predictions: 8.5 ± 0.9 SNU
- 1992-2010: GALLEX/GNO experiment in Italy and SAGE (USSR): observed ~50% lower solar neutrino flux than predicted by SSM
- 1989: Kamiokande experiment in Japan observed ~50% lower solar neutrino flux

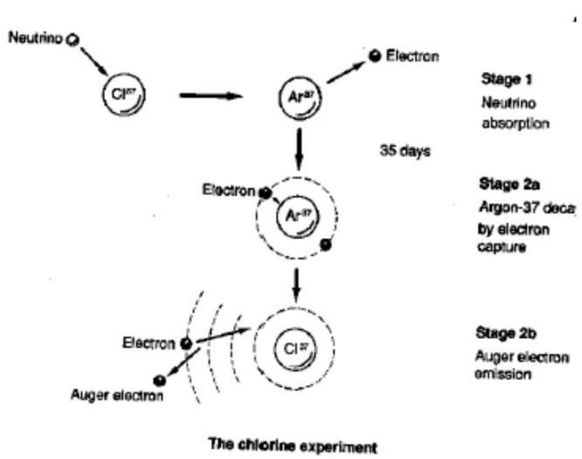
Three options:

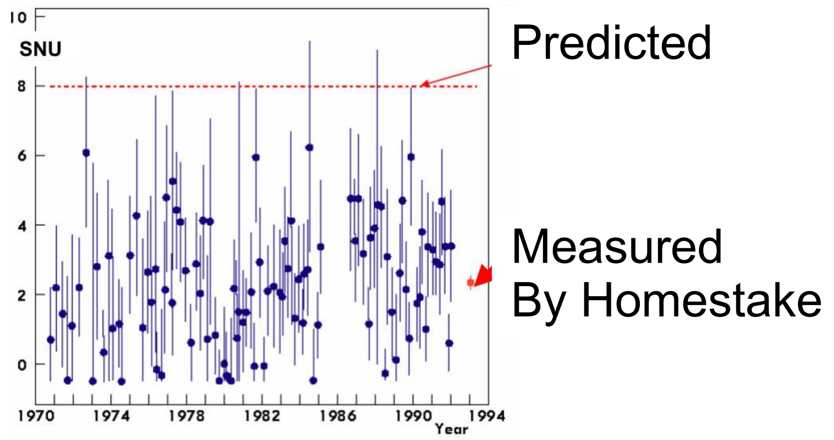
SSM is wrong, experiments don't control well their systematic errors or something is happening with the neutrinos during their travel from Sun to the the Earth

1 SNU (Solar Neutrino Unit) = 1 neutrino interaction / (s x 10^{36} target nuclei).

Homestake experiment

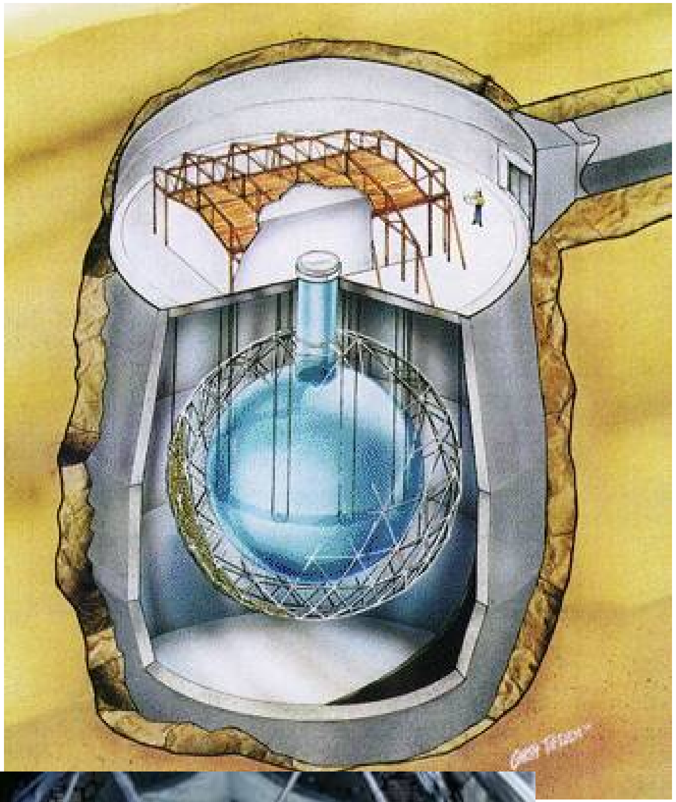
- Pioneering radiochemical experiment operating through 30 years: 1969 – 1999 by Raymond Davis Jr.
- 615 ton of carbon chlorine in the tank in the old gold mine Homestake in South Dakota
- Challenging and time consuming experiment – every 2-3 month ^{37}Ar atoms were extracted from the tank and counted by looking at Auger electrons emmitted during the Argon decay.
- Nobel prize for R. Davis Jr. in 2002

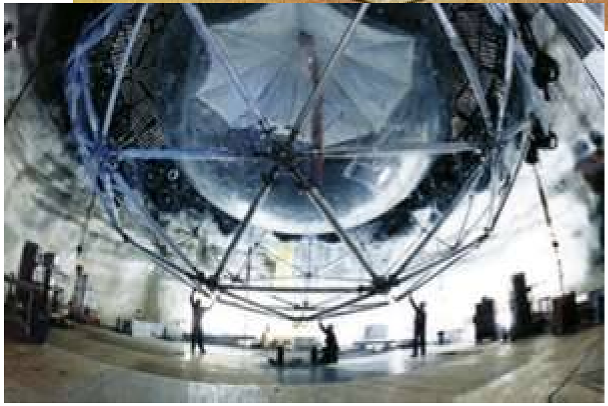




Solar Neutrino Observatory (SNO)

- 2 km underground in the nickel mine near Sudbury (Ontario, Canada)
- 1000 ton of ultra pure heavy water (D_2O) in the spherical tank with 12 meters of diameter
- 9500 photomultipliers detecting Cherenkov light (similar to Super-Kamiokande)
- Additional veto detector filled with water to tag the particles from radioactive decays.

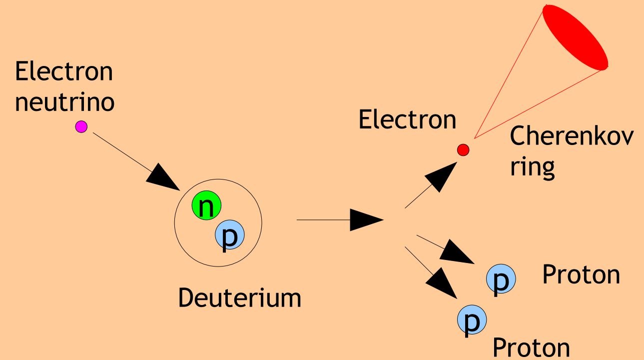




Solar neutrino interactions in SNO

Charged Current (CC) interaction:

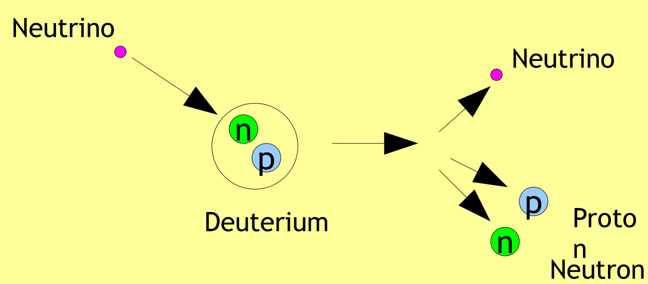
$$\nu_e + d \rightarrow p + p + e^-$$



Only electron neutrinos can be detected

Neutral Current (NC) interaction:

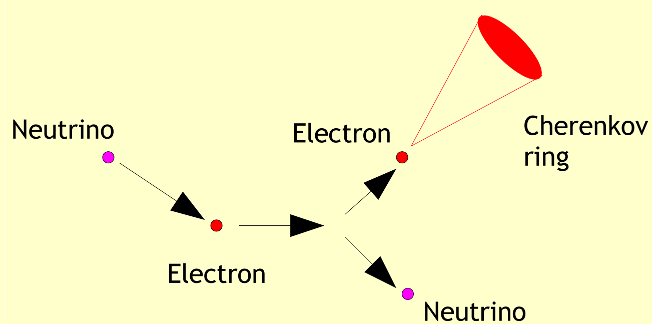
$$\nu_x + d \rightarrow p + n + \nu_x$$



All neutrino flavors can be detected

Electron Scattering (ES):

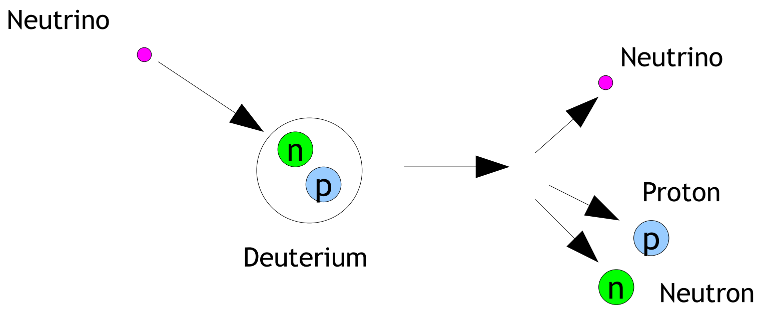
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



All neutrino flavors can be detected (but with different weights - cross section different for ν_e than for ν_μ, ν_τ)

NC interactions in SNO

- First phase: NC interactions in SNO are detected by measuring the photons from the neutron capture on deuterium:



$$n + {}^{2}H \rightarrow {}^{3}H + \gamma$$

Photon energy (γ): 6.26 MeV

- Second phase: 2 tons of NaCl were added to the detector tank and increased the NC detection efficiency from 24% to 84% (neutron capture on chlorine)

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum \gamma$$

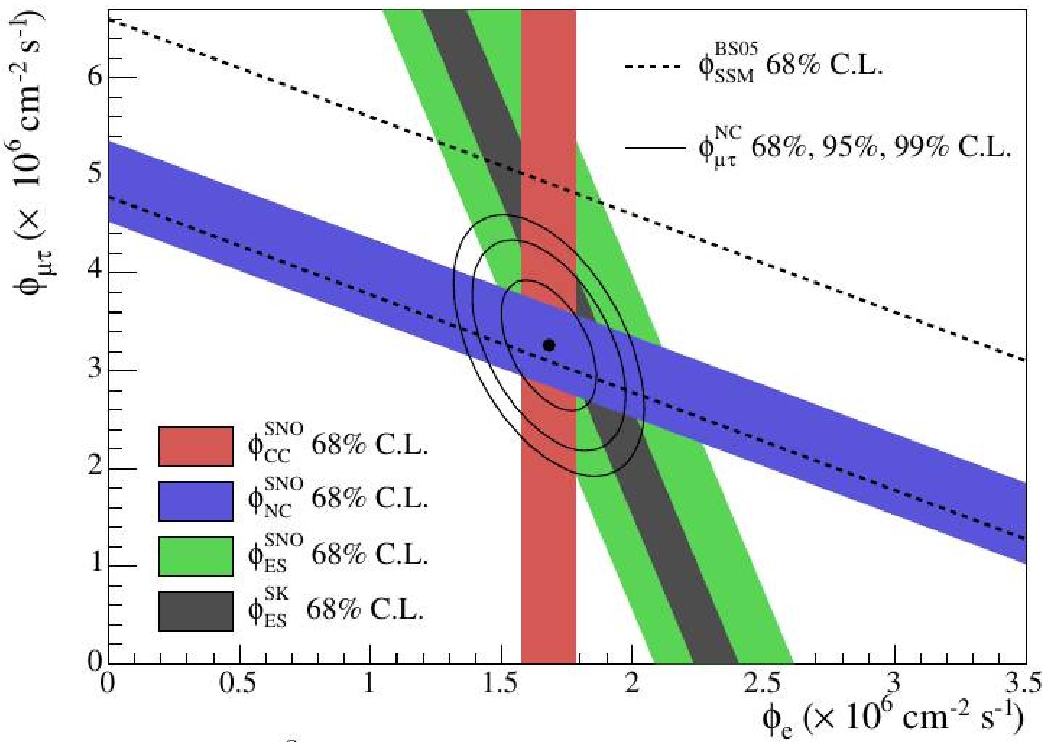
Energy of the photons ($\Sigma\gamma$): 8.58 MeV

- Third phase: helium counters were put into D_2O to estimate the systematic uncertainties for NC interactions independently:

$$n + {}^{3}He \rightarrow p + {}^{3}H$$

SNO – final results (2001 i 2002)

- Measuring CC and NC interactions simultaneously → SNO was able to calculate:
  - Electron neutrino flux only
  - Overal flux of all neutrino flavors.



$$\Phi_{CC}^{II-unc.} = 1.68 \pm 0.06(stat.)^{+0.08}_{-0.09}(syst.)$$
$$\Phi_{ES}^{II-unc.} = 2.35 \pm 0.22(stat.) \pm 0.15(syst.)$$
$$\Phi_{NC}^{II-unc.} = 4.94 \pm 0.21(stat.)^{+0.38}_{-0.34}(syst.)$$

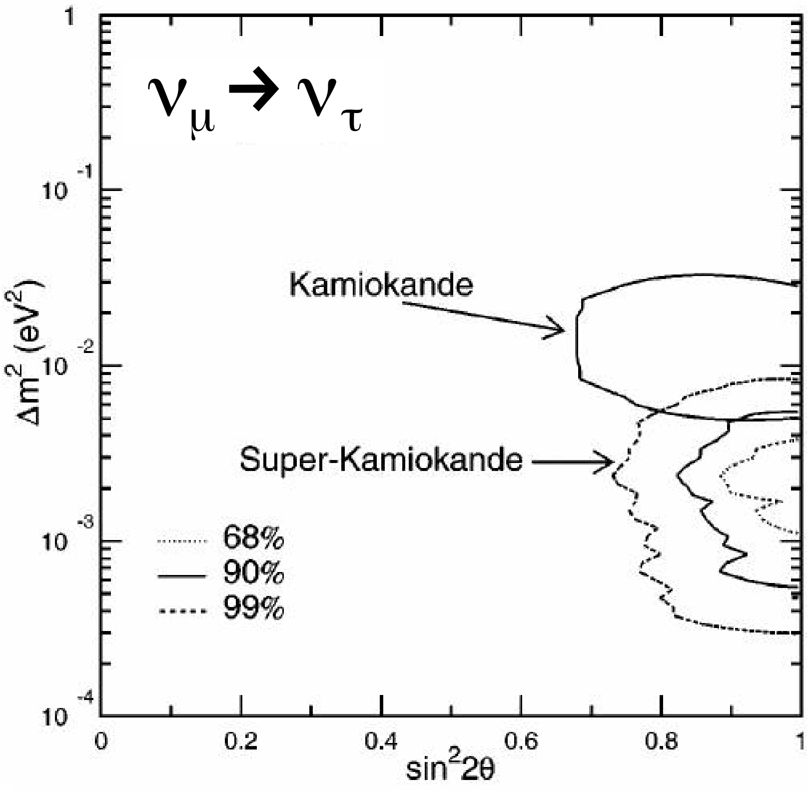
$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

Atmospheric neutrinos oscillations

- Atmospheric muon neutrinos oscillate – change their flavor on their way to the detector to taon neutrinos → the ratio of muon neutrinos to electron neutrinos is different than predictions

- The longer source-detector path the more muon neutrinos disappear → dependence on the zenith angle

- Based on the measurements Super-Kamiokande experiment calculated the corresponding mass splitting and the mixing angle from the so-called PMNS model.



Results confirmed later by a number of experiments:
K2K, MINOS, T2K, OPERA ...

$$\sin^2 2\theta > 0.82 \qquad 90\% \, C.L.$$

$$5\times10^{-4} < \Delta m^2 < 6\times10^{-3}\, eV^2$$

Solar neutrinos puzzle solved

- In the Sun only ν_e are produced. Electron neutrinos change their flavor into muon and taon neutrinos before they reach earth.

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

- SNO experiment showed that:
  - Electron neutrino flux is ~1/3 of the total neutrino flux, because electron neutrinos transform into ν_μ i ν_τ
  - Total neutrino flux from the Sun agrees with SSM

- Homestake, GALLEX/GNO, SAGE were sensitive only on electron neutrinos. ν_μ and ν_τ were not detected → deficit.

$$\nu_e + {}^{37}Cl\left({}^{71}Ga\right) \rightarrow {}^{37}Ar\left({}^{71}\mathrm{Ge}\right) + e^-$$

- Kamiokande and Super-Kamiokande were measuring total neutrino flux but with different weights → deficit.

Summary

- Neutrinos are the second most common particles in the universe
- Their energies range from meV up to EeV
- They can provide us information about the following objects: early universe (relic neutrinos), structure and processes inside the Earth (geoneutrinos), structure and processes inside the Sun (solar), cosmic rays (atmospheric), Supernovae explosions and others...
- They oscillate → have non-zero mass → physics beyond Standard Model
- There are still some open questions in neutrino oscillations: CP violation, mass ordering etc.