Neutrino Physics

(Selected topics)
Lecture 1

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Zakład Promieni Kosmicznych i Neutrin
(NZ15)

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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

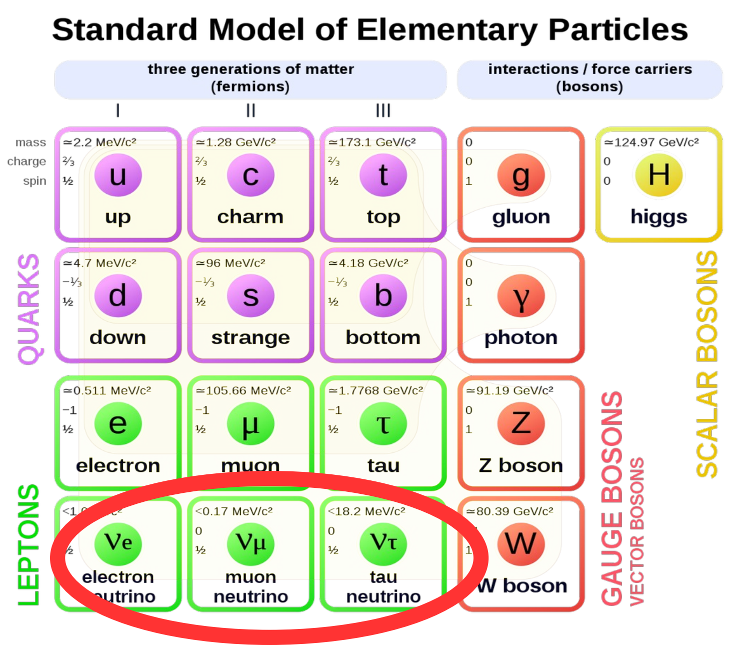
- Neutrinos in the Standard Model are elementary particles with the following properties:
  - They are fermions, part of the lepton doublets
  - They interact only via weak interactions (charge current – CC, neutral current NC)
  - Have no electric charge
  - They are massless (within Standard Model)
  - We have three flavor states of neutrinos: electron neutrino: ν_e, muon neutrino: ν_μ, taon neutrino: ν_τ. LEP experiment result: $N_\nu = 2.984 \pm 0.008$ (From Z^0 boson width measurement).
  - Only left-handed neutrinos and right-handed antineutrinos are observed

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

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

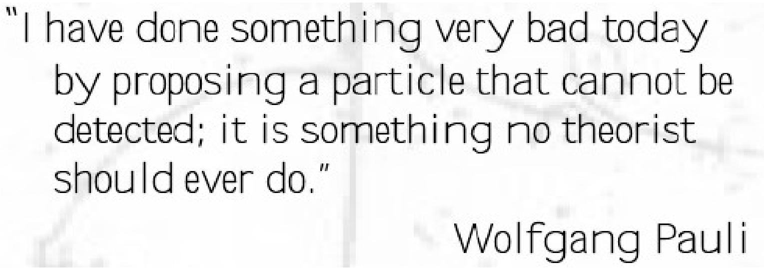
$$-\mathcal{L}_{\mathrm{NC}} = \frac{g}{2\cos\theta_W} \sum_\ell \bar{\nu}_{L\ell} \gamma^\mu \nu_{L\ell} Z_\mu^0\,.$$

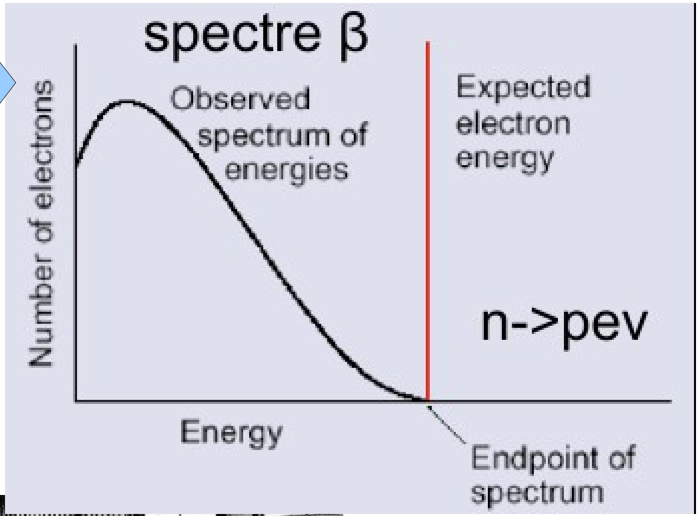
Neutrino interactions

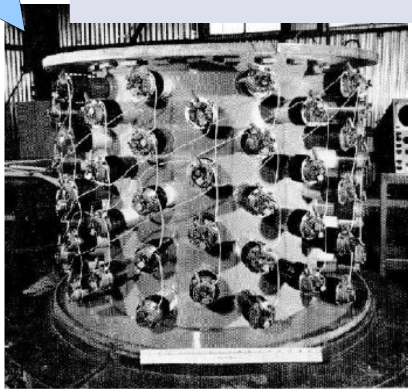


Short history of neutrinos

- 1930 – Wolfgang Pauli introduces hypothethical particle to solve the missing energy problem in beta decays
- 1933 – Enrico 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 – First neutrino detected! 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 discover muon neutrinos ν_μ with first experiment using 'accelerator neutrinos'. Nobel prize in 1988.
- 1975 - τ particle discovery at SLAC (USA) and ν_τ hypothesis
- 2000 - DONUT experiment (Fermilab, USA) detects tau neutrinos ν_τ

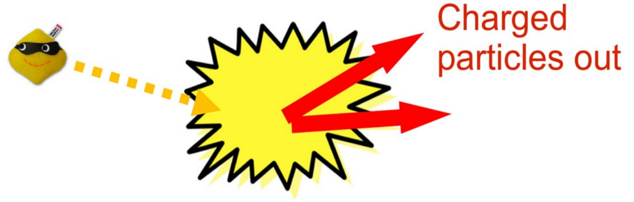






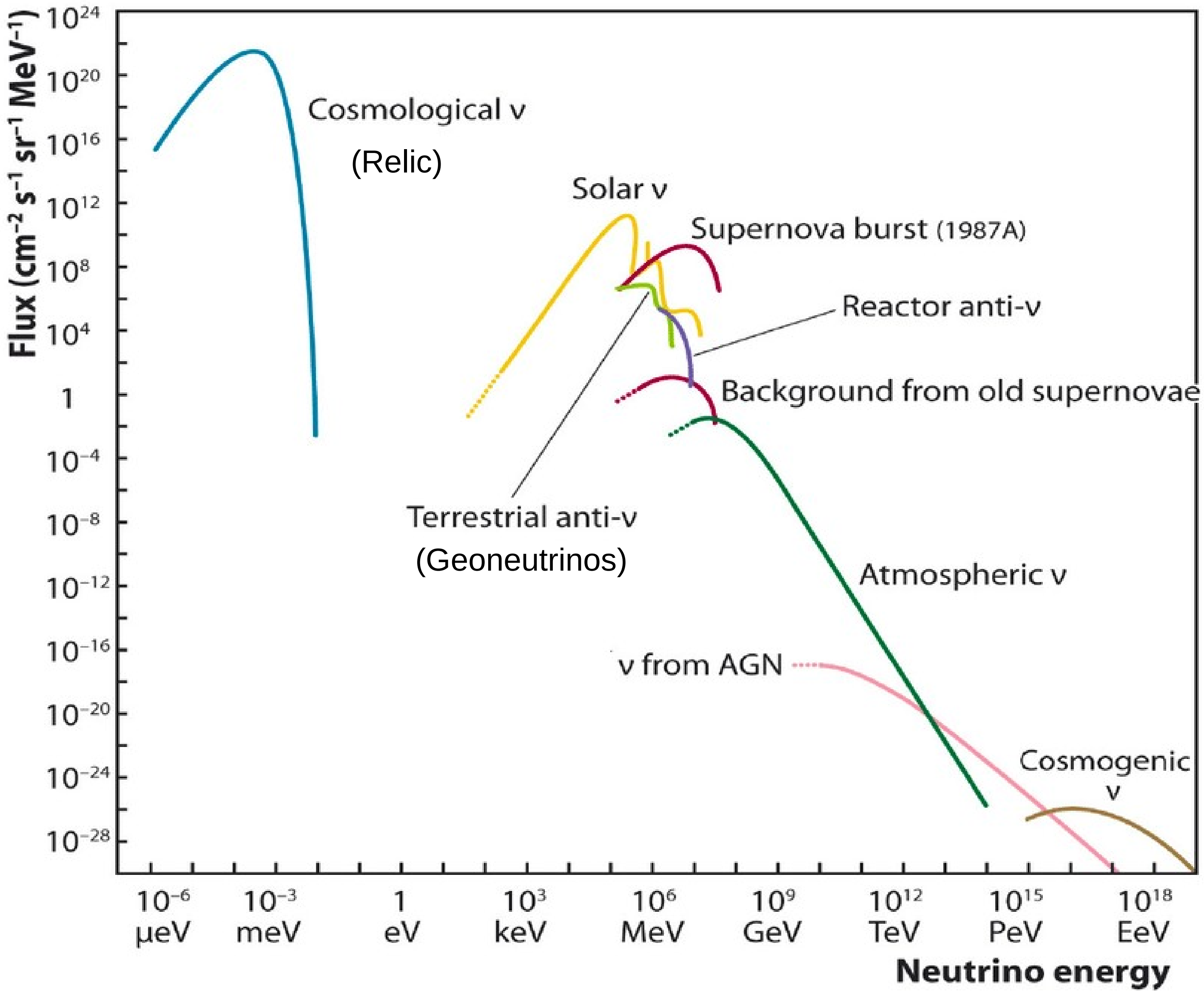
How to ’see’ neutrino?

- Neutrinos are neutral and don’t interact with photons → are literally invisible
- When neutrino interacts in matter it may produce charged particles
- They are visible and seem to appear out of nowhere...
- The interaction length for 1 MeV photon in lead is **~2 cm**
- For the neutrino of the same energy it’s **~5 light years!**

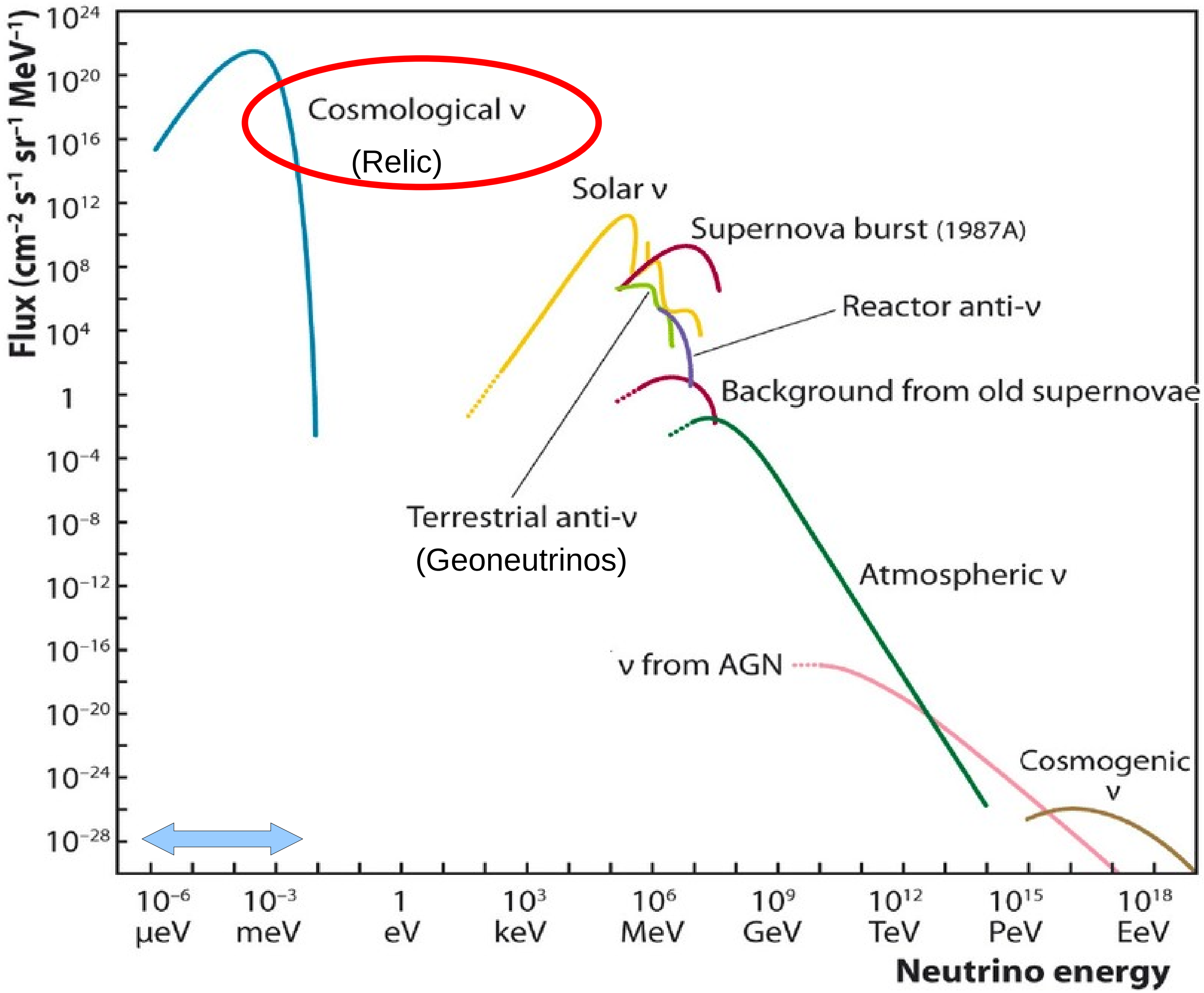


From A. Himmel

Neutrinos in nature



Relic (cosmological) neutrinos

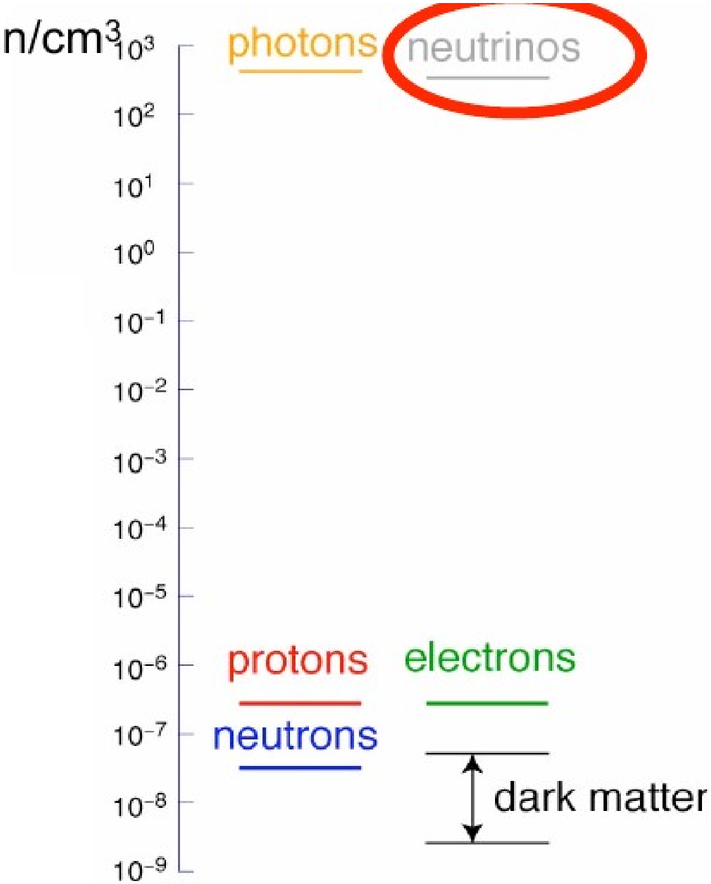


Relic (cosmological) neutrinos

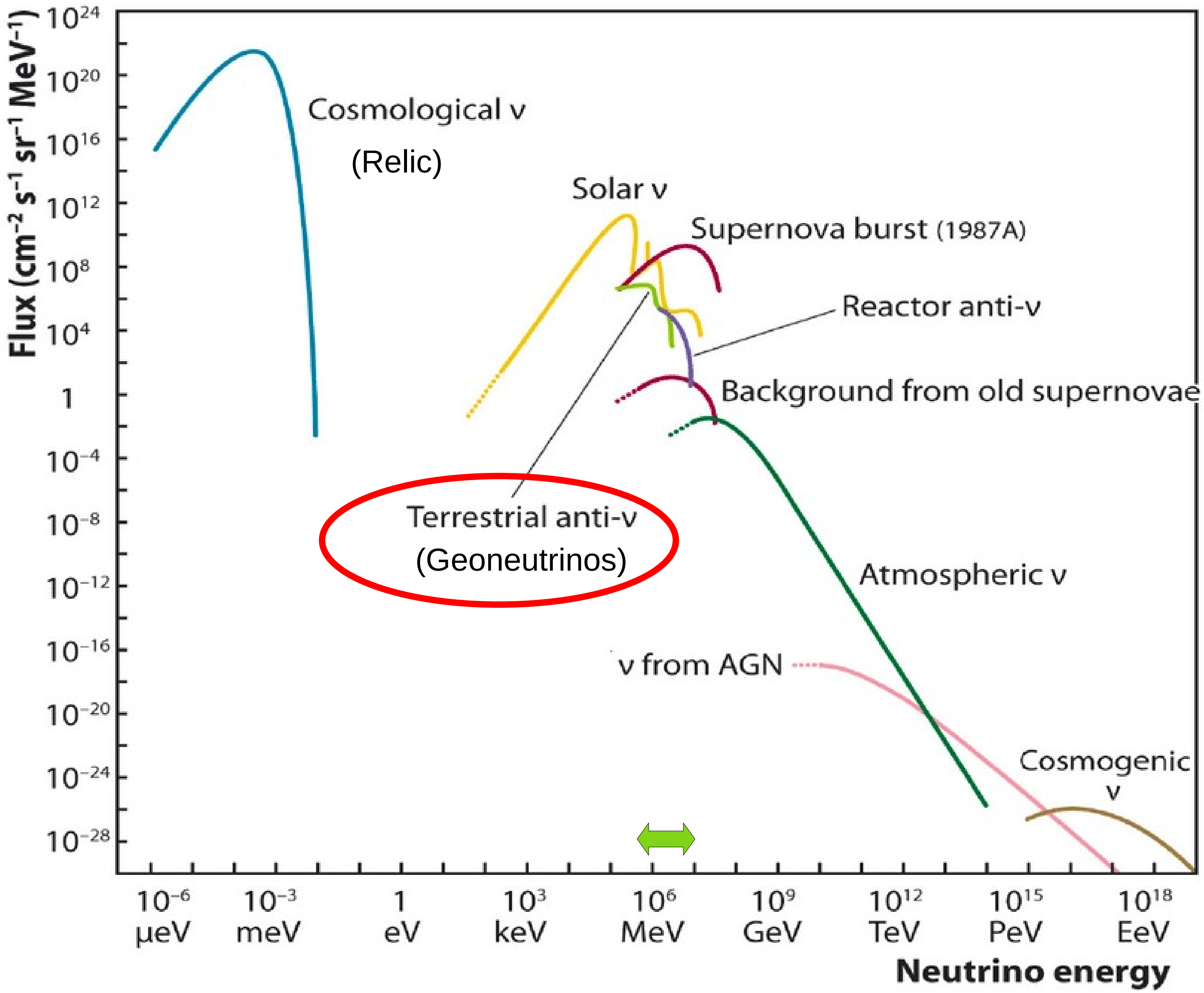
- In the early universe neutrinos were in thermal equilibrium with protons, neutrons and electrons maintained through the weak interactions.
- Production of neutrinos in the early Universe happened in the weak process:

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

- Neutrinos exit the thermal equilibrium and decouple from other types of matter with temperature kT < 3 MeV at time $t>10^{-2}$ s
- In consequence there should be ~330 cm^{-3} of 'relic' neutrinos in the Universe with temperature ~ 1.95 K ...
- ...but they have very low energies (~10^{-4} eV) therefore are very difficult to detect. Experimental challenge for future experiments!

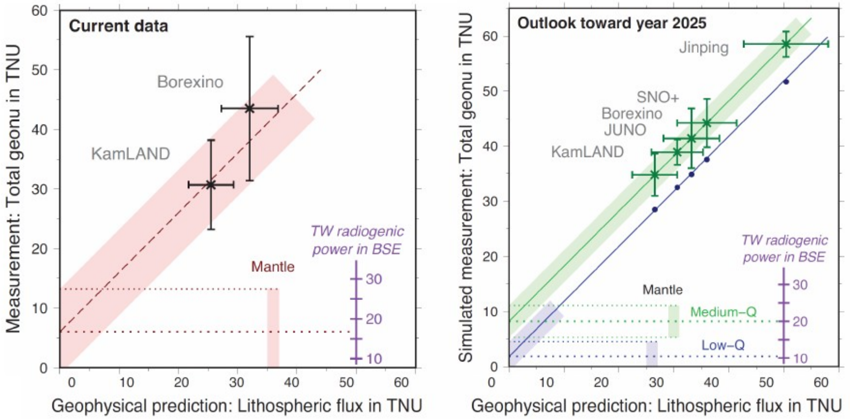


Geoneutrinos

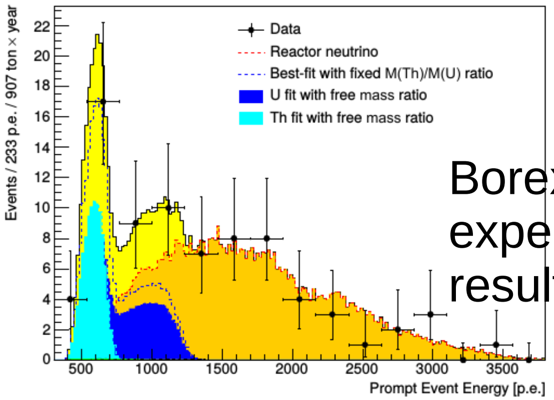


Geoneutrinos

- 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 ~ $6*10^6$ $cm^{-2}s^{-1}$.
- The most 'applied' field of neutrino physics. Possible applications of geoneutrinos:
  - 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.
- Additionally geoneutrinos consitute a significant background in experiments measuring solar neutrinos: KamLAND, SNO+, JUNO, Borexino

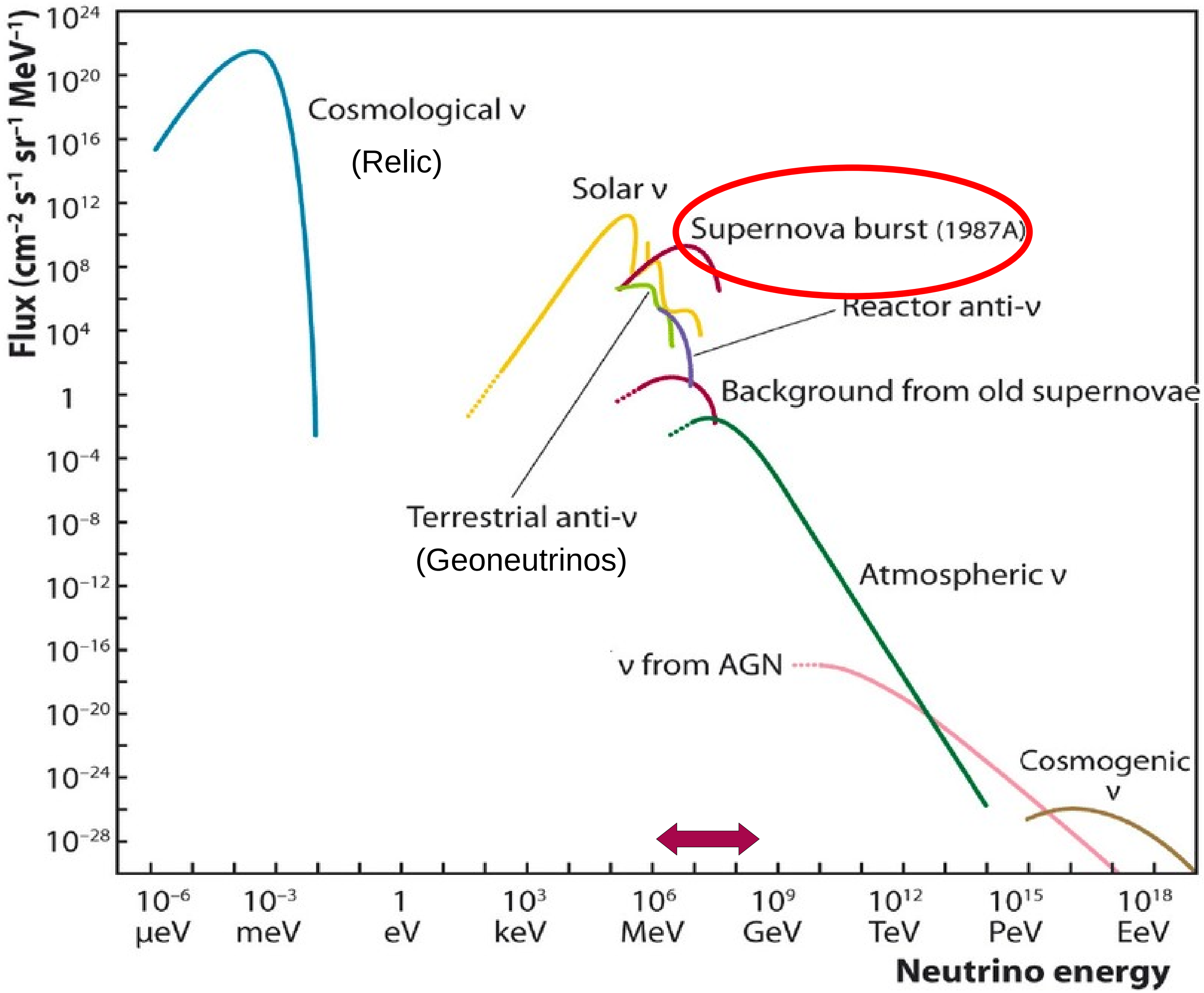


Lithospheric geoneutrino flux data vs predictions



Borexino experiment results

Neutrinos from Supernovae



Supernova neutrinos

- Neutrinos are produced during the gravitational collapse of the core of the massive star (m > ca. 8-9 M_{Sun}).
- Emission 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:

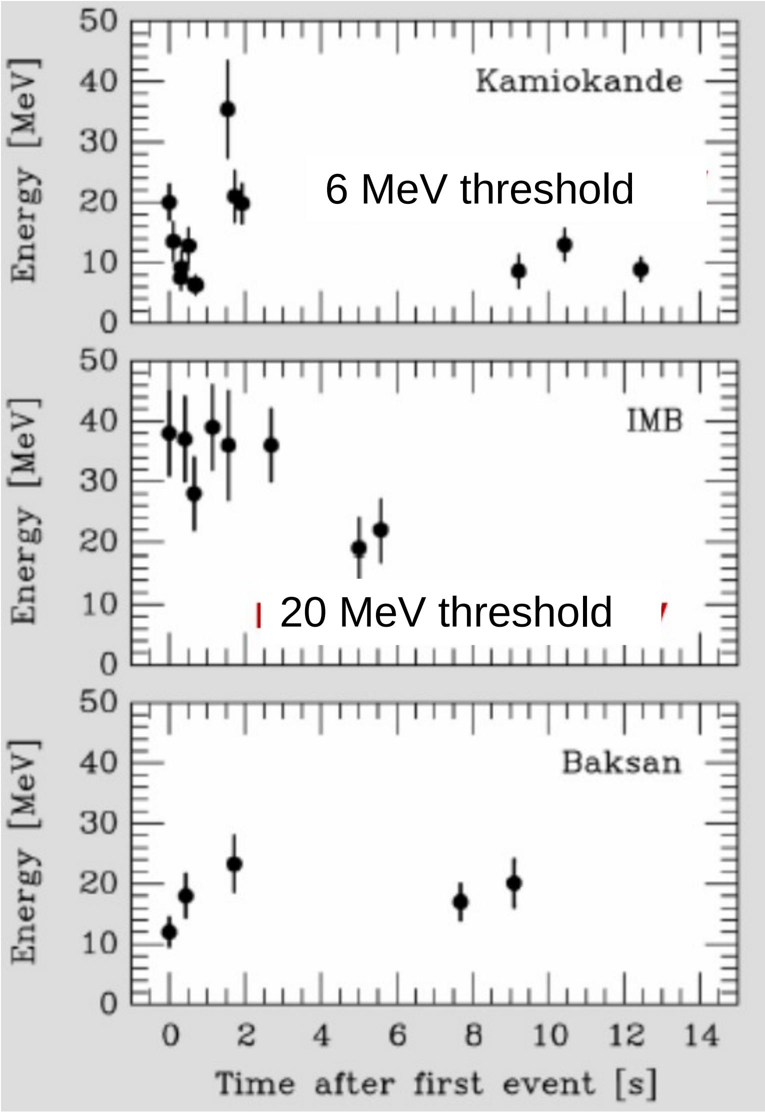
$$e^+ e^- \rightarrow Z^0 \rightarrow \nu_e + \bar{\nu}_e , \nu_\mu \bar{\nu}_\mu , \nu_\tau \bar{\nu}_\tau$$

Supernova neutrinos

- During the neutron star cooling 99% of the gravitational energy is emitted in the form of neutrino pulse (!) lasting several seconds (~10^{58} neutrinos)
- We can detect neutrinos from Supernovae via inverse beta decay:

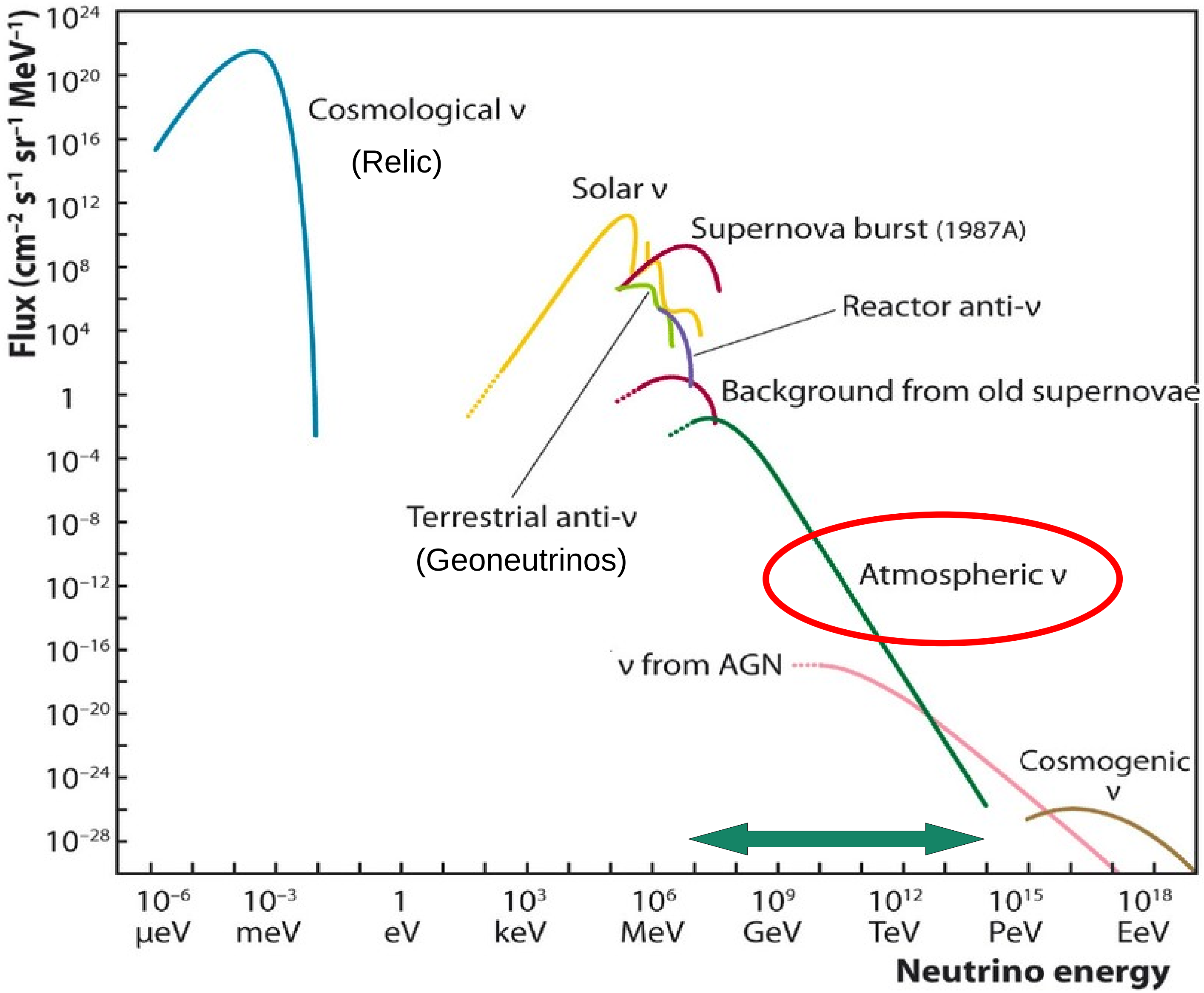
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- Famous detection of neutrinos (10-15 MeV) from Supernova 1987A explosion by Kamiokande (Japan), IMB (USA), Baksan (USSR) experiments

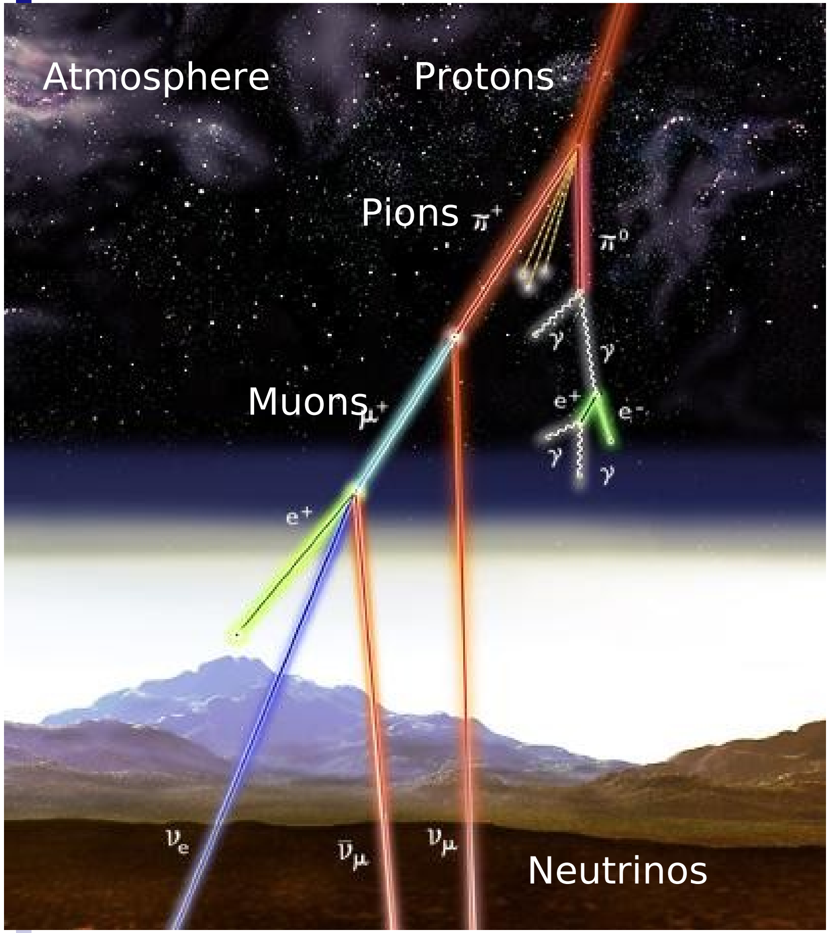


Supernova 1987A observation

Atmospheric neutrinos

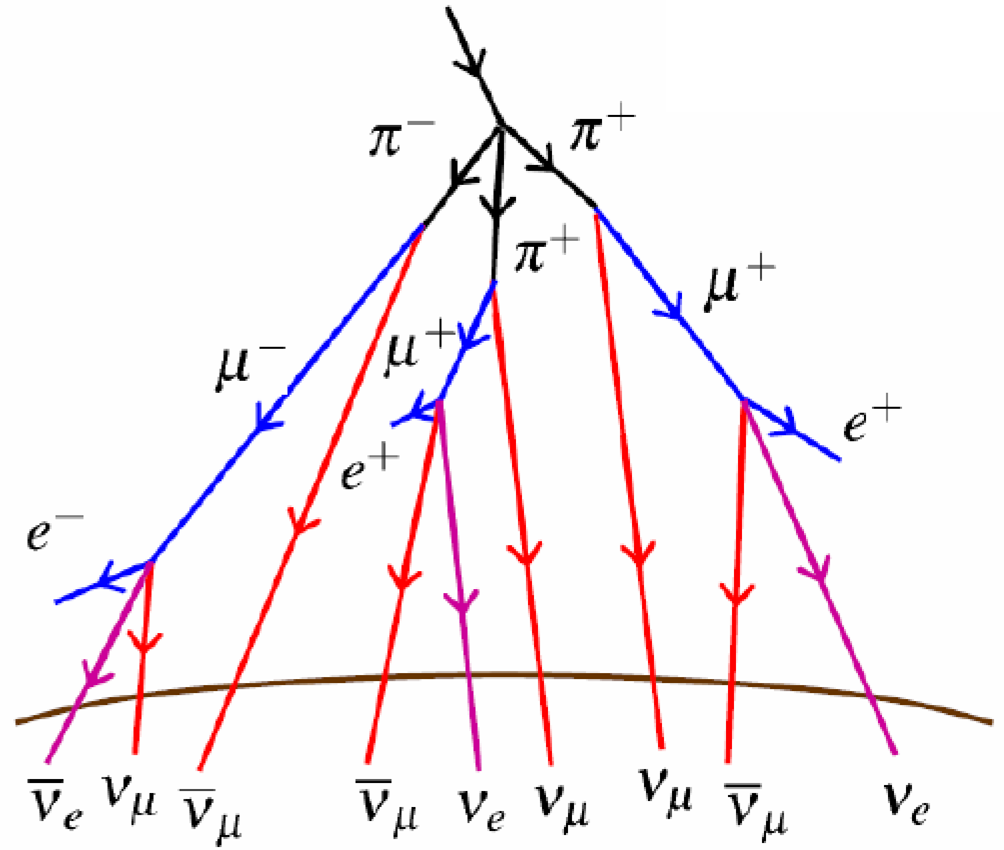


Atmospheric neutrinos



- Primary cosmic rays - very high energy (up to 10^{20} eV) particles (86% 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 positrons, electron neutrinos and muon neutrinos
- Atmospheric neutrino flux ~1 cm^{-2} s^{-1}
- Mean energy of atmospheric neutrinos ~ 1 GeV (energy distribution peak ~100 MeV)

Atmospheric muon and electron neutrinos



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\quad \llcorner\ e^+ + \nu_e + \bar{\nu}_\mu$

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

$\quad \llcorner\ e^- + \bar{\nu}_e + \nu_\mu$

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

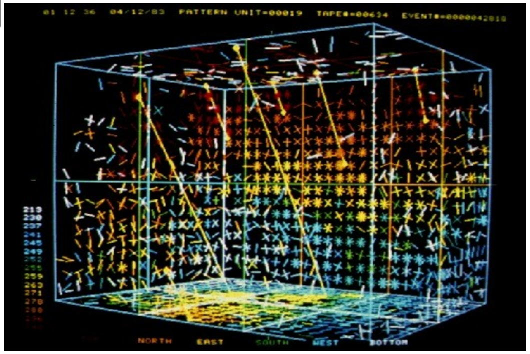
$$\frac{N_\mu}{N_e} = \frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$

- Experimentally it is convenient to measure double ratio R to reduce the systematic uncertainties. It is defined as observed ratio / theoretical ratio. R should be equal to 1

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

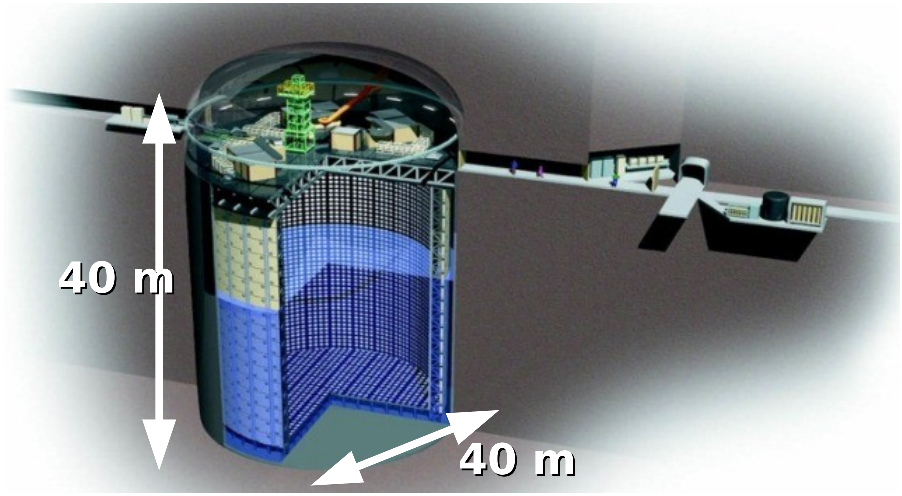
Atmospheric neutrinos anomaly

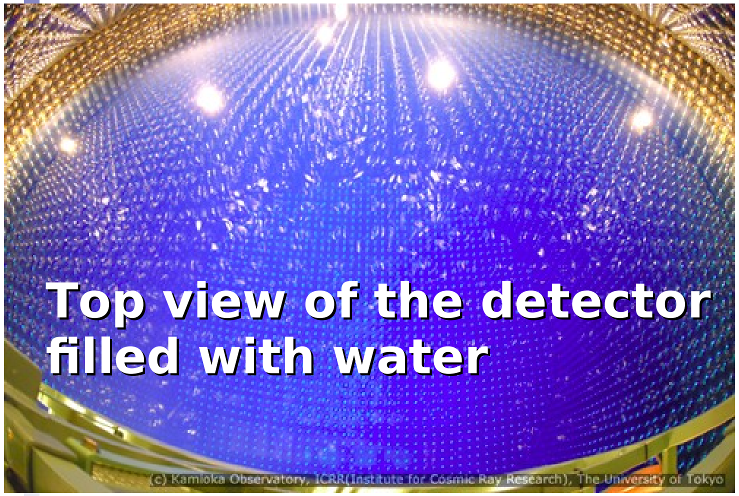
- In the 1980s several experiments reported a deficit in the number of detected atmospheric muon neutrinos
  - IMB (USA, 1986): $R = 0.54 \pm 0.05 \pm 0.12$
  - Kamiokande (Japan, 1988): $R = 0.60^{+0.06}_{-0.05} \pm 0.05$
- ...on the other hand there were experiments that didn't observe any deficit:
  - 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...

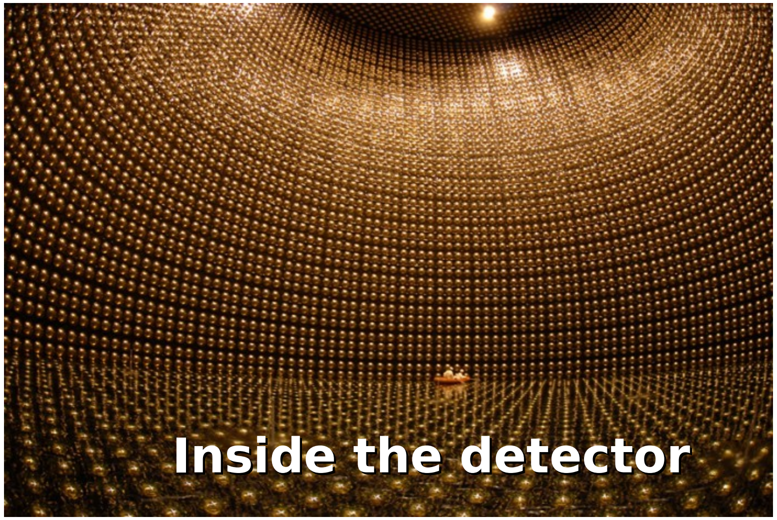


Super-Kamiokande experiment

- ...until Super-Kamiokande - world largest neutrino detector was built (operating since 1996):
  - Cylindrical tank with the diameter and height of 40m,
  - Located 1km underground, in the zinc/copper mine near Mozumi in Japan
  - Tank filled with 50 000 tons of ultra pure water
  - 11 000 of photomultipliers (PMTs) on the walls of the tank detecting Cherenkov light

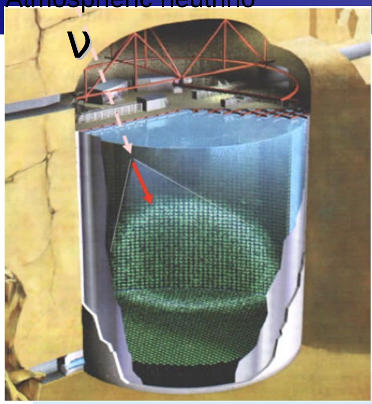


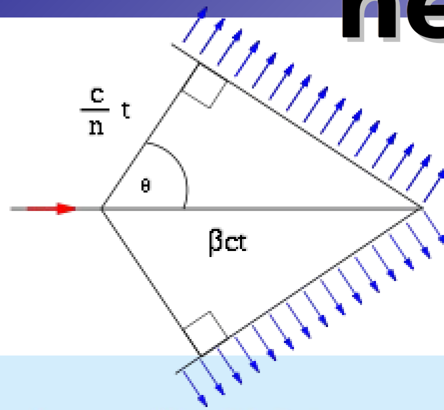




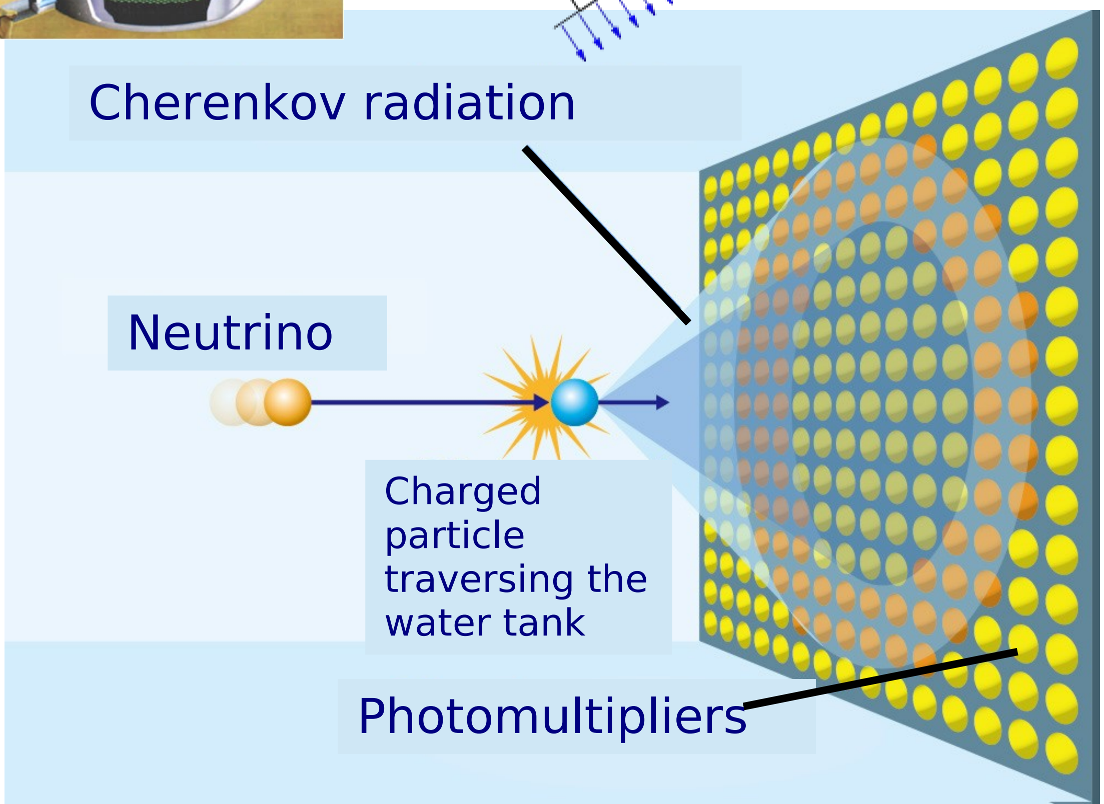
How Super-Kamiokande „sees” neutrinos?

Atmospheric neutrino





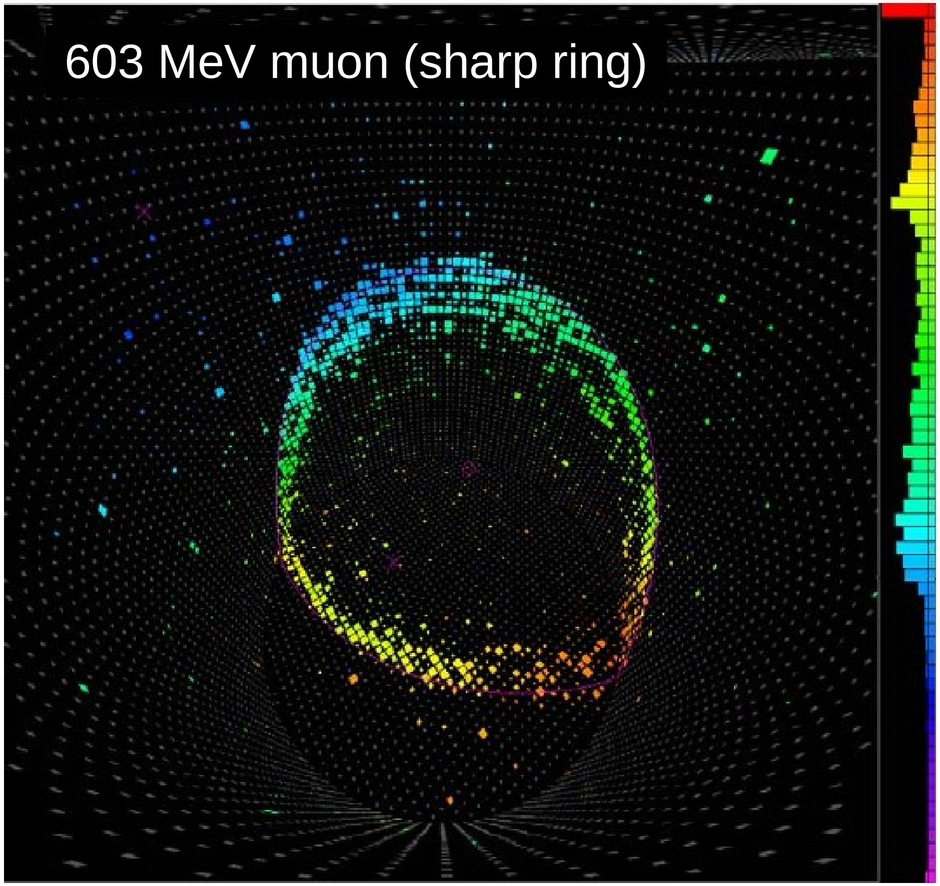
$$\cos\theta = \frac{1}{n\beta}$$



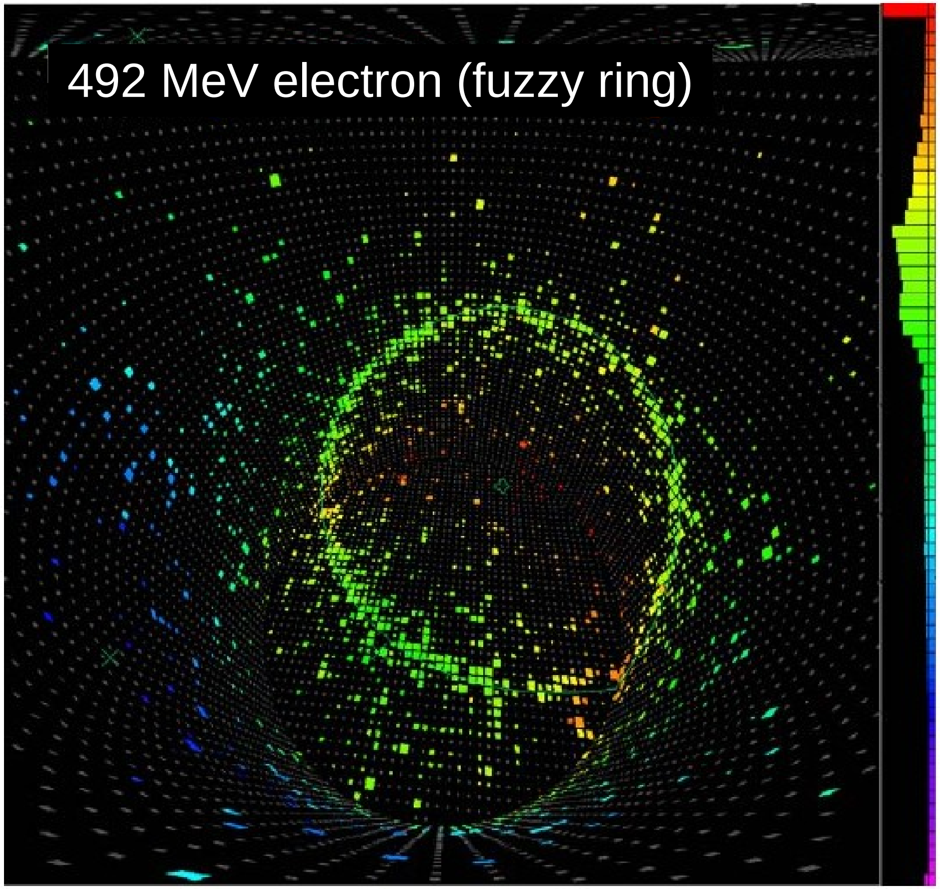
- Neutrinos interact with the nuclei inside the tank and produce charged particles
- Charged particles traveling in the medium (eg. water) faster than the speed of light emit cause the Cherenkov radiation along their trajectory
- Photomultipliers detect the characteristic rings of the Cherenkov light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

How Super-Kamiokande „sees” neutrinos?

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



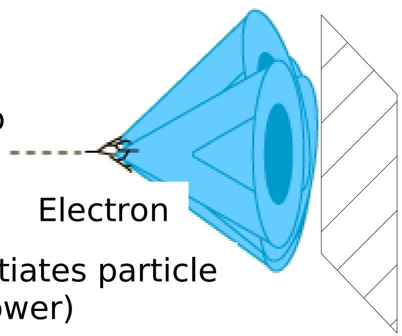
$\nu_e + n \rightarrow e^- + p$



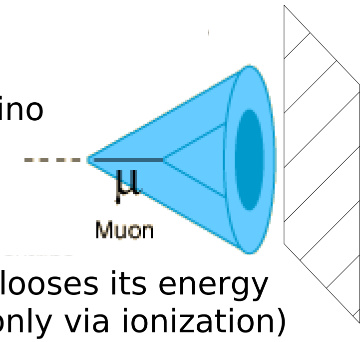
Event displays from Super-Kamiokande

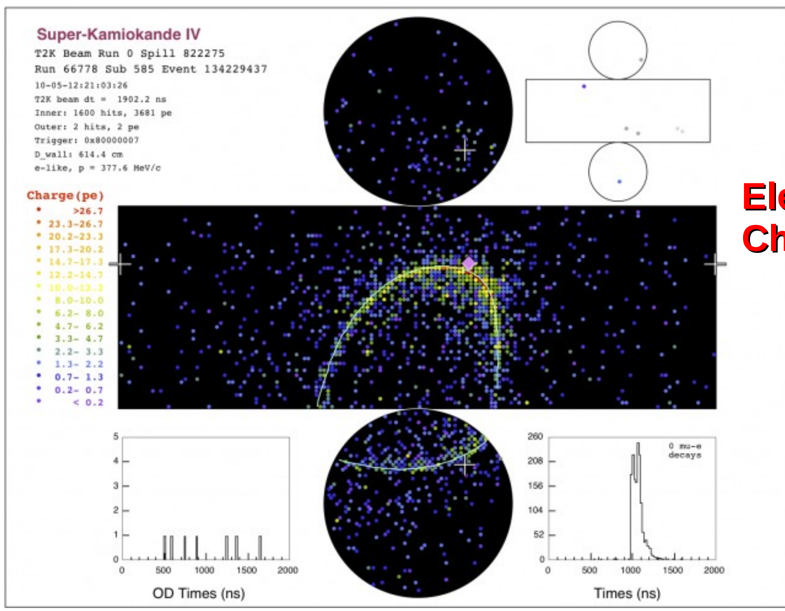
Atmospheric neutrinos in Super-Kamiokande

Electron neutrino

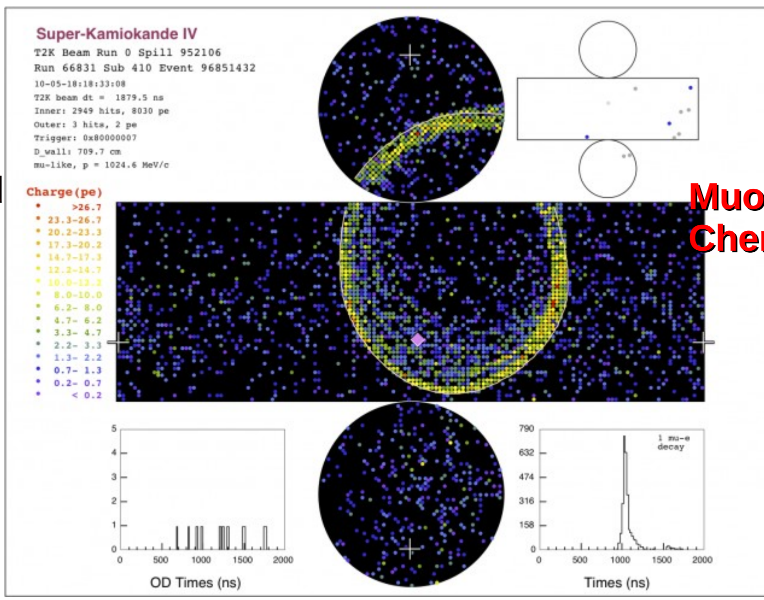


Muon neutrino





Electron-induced Cherenkov ring

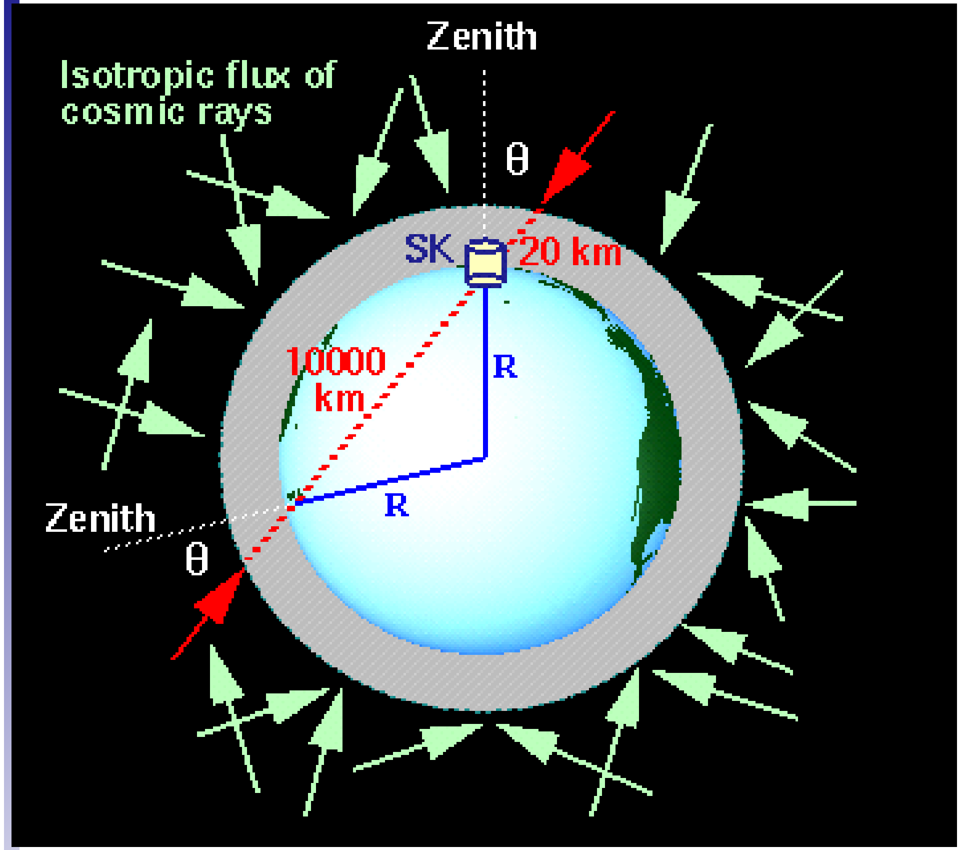


Muon induced Cherenkov ring

- Super-Kamiokande online event display:

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

Zenith angle dependence in Super-Kamiokande



- 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 experiment results (1998)

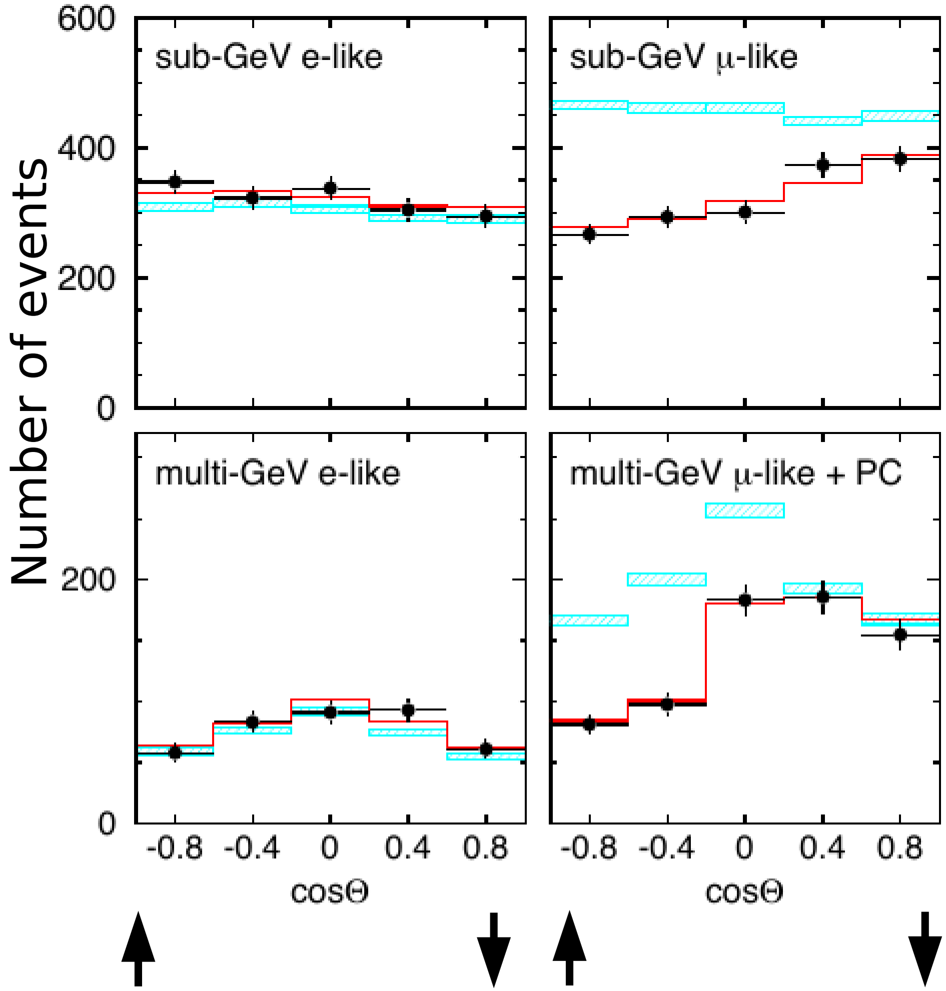
- After two years of data taking (1996-1998) experiment reported:

$$R=\frac{(N_\mu/N_e)_{Obs}}{(N_\mu/N_e)_{MC}}=0.63\pm0.03\,(stat)\pm0.05\,(syst)$$

- Observed ratio with respect to 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.

e-like mu-like



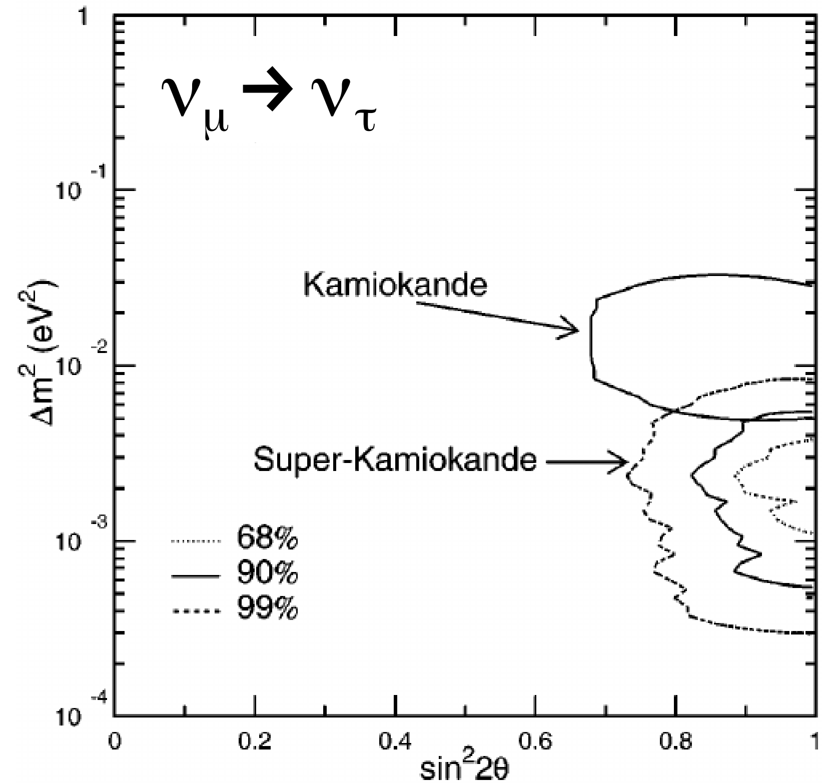
"Upward-going" "Downward-going"

Atmospheric neutrinos oscillations

- Explanation of Super-Kamiokande result: atmospheric muon neutrinos change their flavor on their way from the source to the detector to taon neutrinos → the ratio of muon neutrinos to electron neutrinos is different than predictions

- The longer is the source - detector distance the more muon neutrinos disappear → explanation of the dependence of number of detected muon neutrinos on the zenith angle

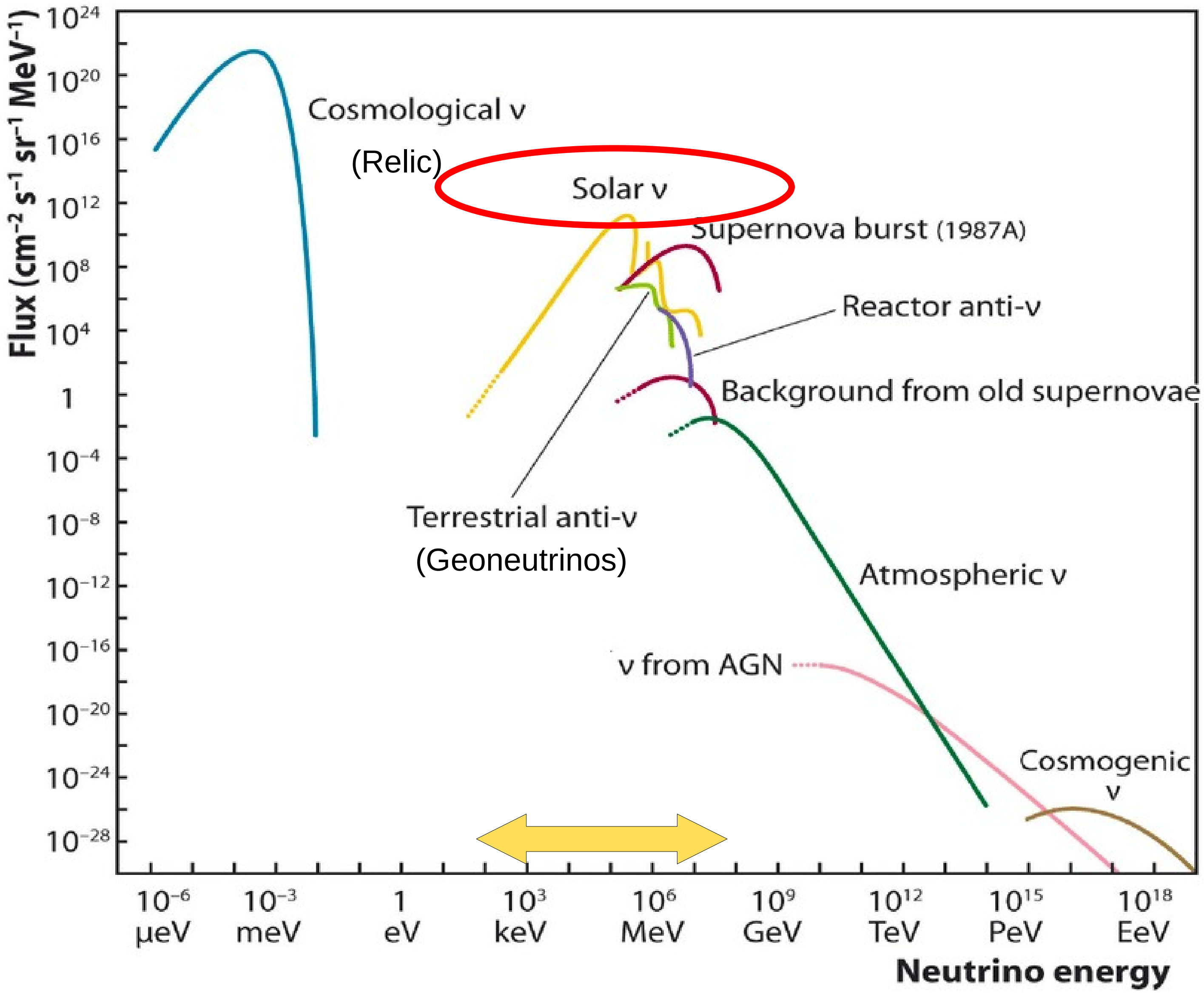
- Based on the measurements Super-Kamiokande experiment calculated the corresponding mass splitting and the mixing angle from theoretical model of neutrino mixing called Pontercorvo-Maki-Nakagawa-Sakata (PMNS) model.



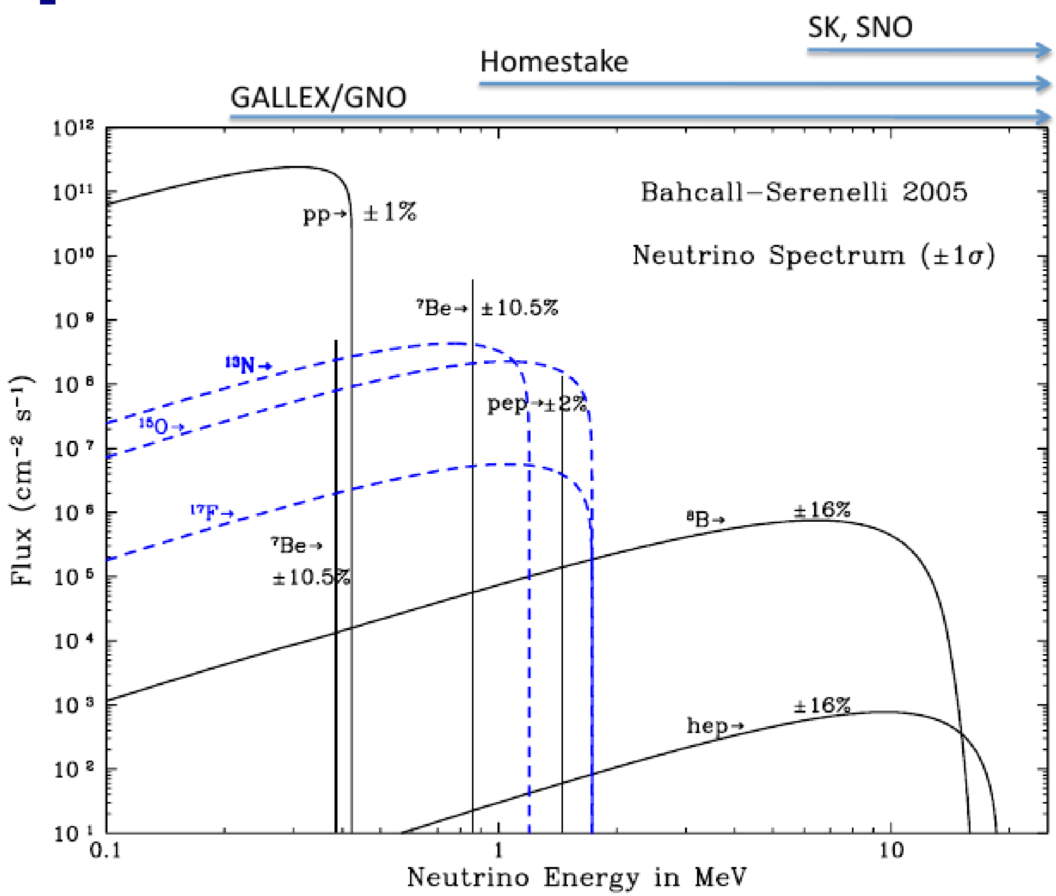
Results were confirmed later by a number of experiments:
K2K, MINOS, T2K, OPERA ...

$$\sin^2 2\theta > 0.82 \qquad 90\%\, C.L.$$
$$5\times10^{-4} < \Delta m^2 < 6\times10^{-3}\, eV^2$$

Neutrinos from the Sun



Solar neutrinos



Most of the solar neutrinos come from:

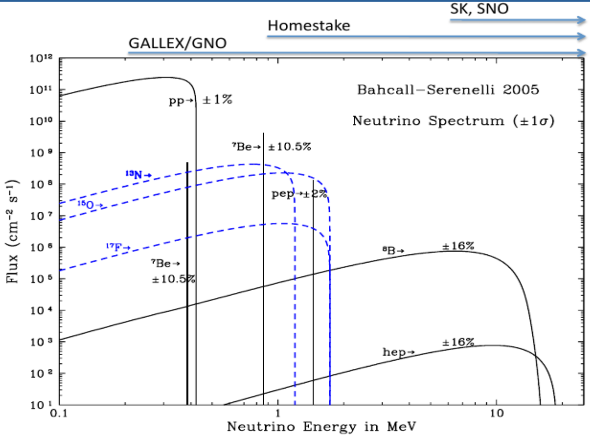
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 2\gamma$$

- Electron neutrinos are produced in the Sun in the thermonuclear reactions:
  - pp and CNO cycle
  - Electron capture on ^7Be
  - Beta decay of ^8B
- 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 continuously updated by J. Bahcall et al. over 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:

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

- Radiochemical experiments: detecting low energy ν_e : GALLEX, GNO, Homestake:
  - Had low energy threshold
  - Only counted nuclei in the final state of the reaction
  - Had no information about the time of interaction
  - Had no information about neutrino direction
- Water Cherenkov experiments: detecting neutrinos with energy E>5 MeV: Super-Kamiokande, SNO:
  - Higher energy threshold
  - Had neutrino time and direction information (for electron recoil events).

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 than SSM predictions

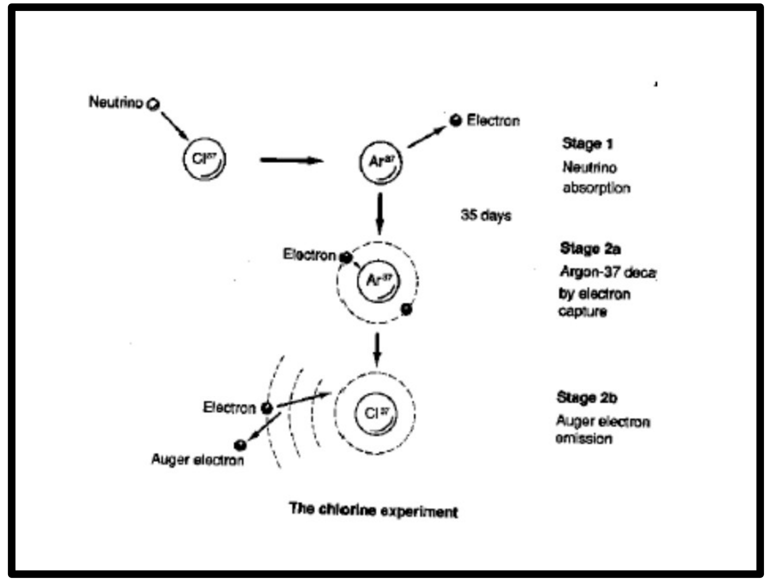
Three options:

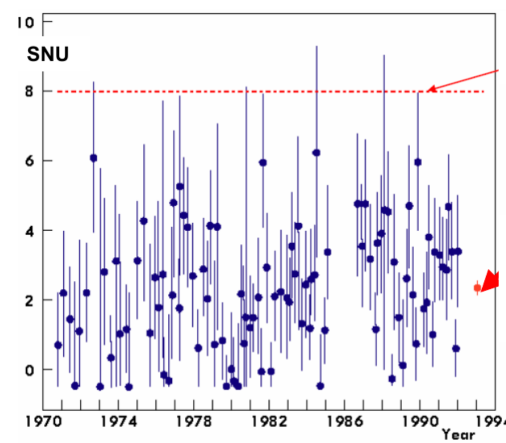
SSM model is wrong, experiments don't control well their systematic errors or something is happening with the neutrinos during their travel from Sun to the the Earth

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
- Very 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



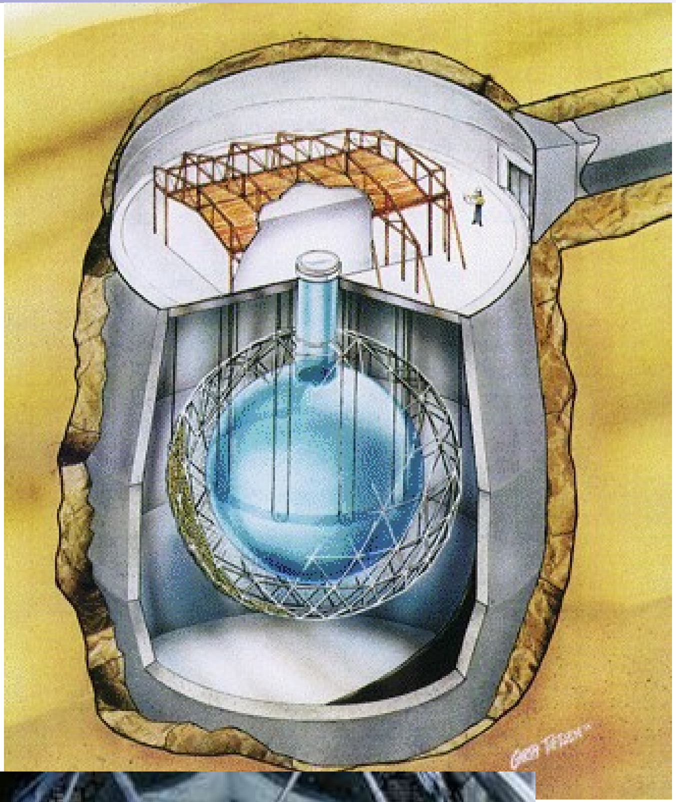


Predicted

Measured
By Homestake

Solar Neutrino Observatory (SNO)

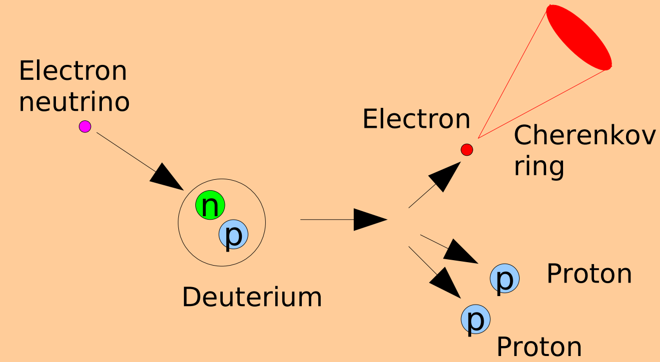
- 2 km underground in the nickel mine near Sudbury in Ontario, Canada
- 1000 ton of ultra pure heavy water (D_2O) in the spherical tank with 12 meters of diameter
- 9500 photomultipliers detecting Cherenkov light on the walls of the tank (similar detection principle to Super-Kamiokande)
- Additional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



Solar neutrino interactions in SNO

Charged Current (CC) interaction:

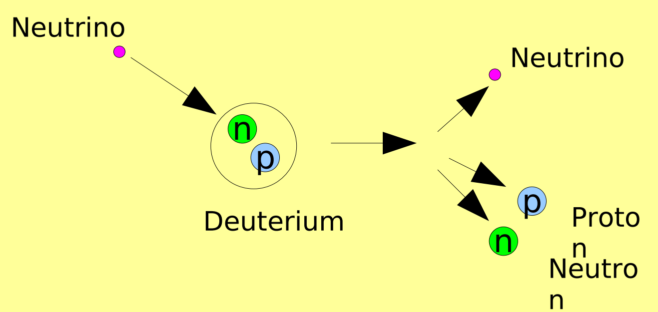
$$\nu_e + d \rightarrow p + p + e^-$$



Only electron neutrinos can be detected

Neutral Current (NC) interaction:

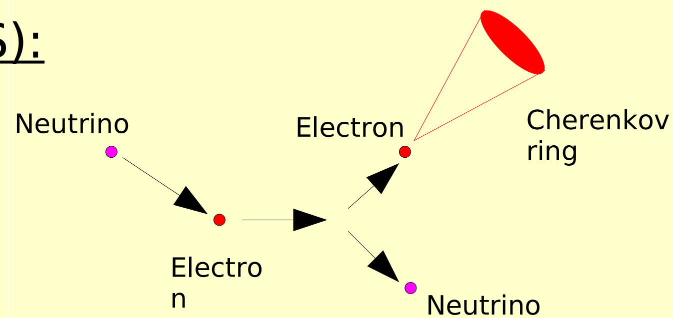
$$\nu_x + d \rightarrow p + n + \nu_x$$



All neutrino flavors can be detected

Electron Scattering (ES):

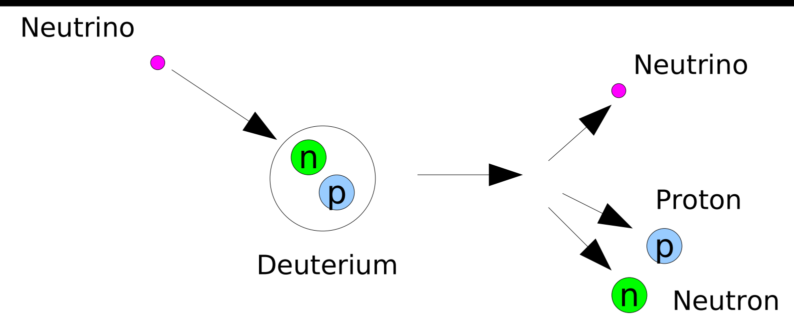
$$\nu_x + e^- \rightarrow \nu_x + e^-$$



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)

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

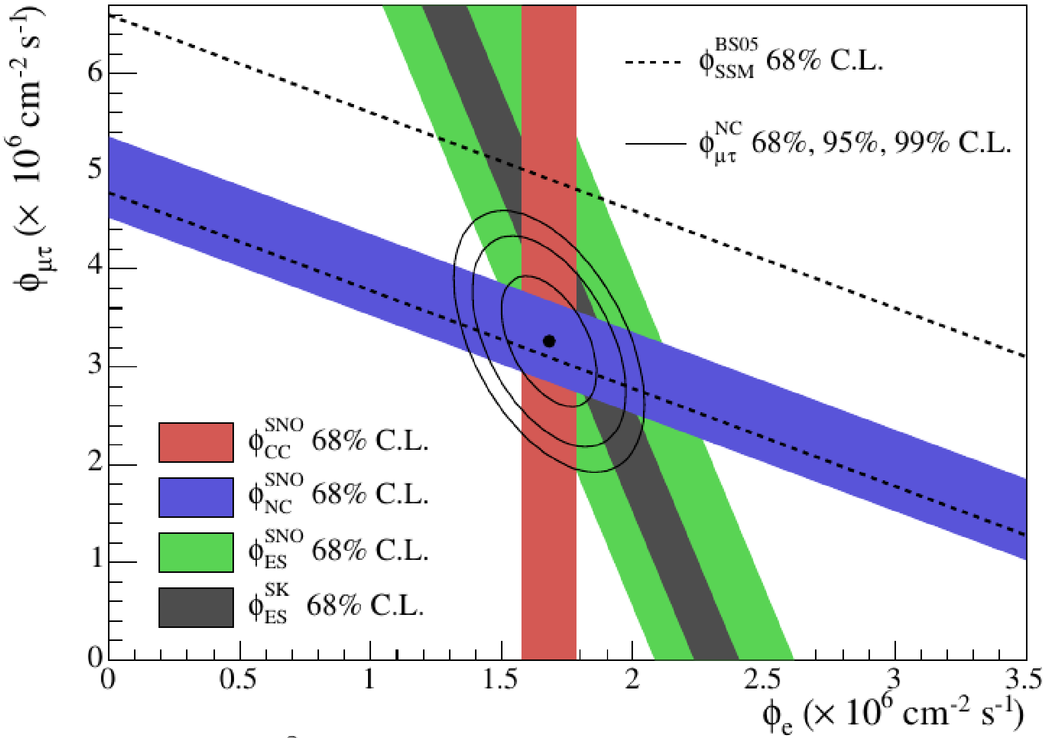
Energy of the photons ($\Sigma\gamma$): 8.58 MeV

- 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)

- Measured number of charge current CC (only electron neutrinos) and neutral current NC (all neutrinos) interactions simultaneously → SNO was able to calculate:
  - Electron neutrino flux only (Φ_{CC})
  - Overal flux of all neutrino flavors (Φ_{NC})



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

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

Solar neutrinos puzzle solved

- In the Sun only electron neutrinos ν_e are produced
- SNO experiment showed that:

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

  - 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 able to detect only electron neutrinos → they measured deficit.

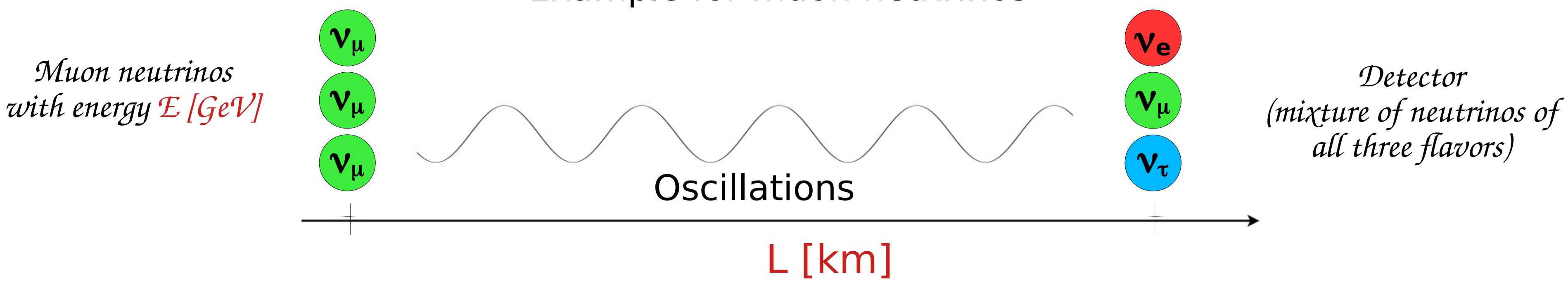
$$\nu_e + {}^{37}Cl\left({}^{71}Ga\right) \rightarrow {}^{37}Ar\left({}^{71}\text{Ge}\right) + e^-$$

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

Neutrino mixing – basic concept

- Reminder: neutrinos change their flavor with time. Experimentally confirmed by a number of experiments: Super Kamiokande, SNO...

Example for muon neutrinos

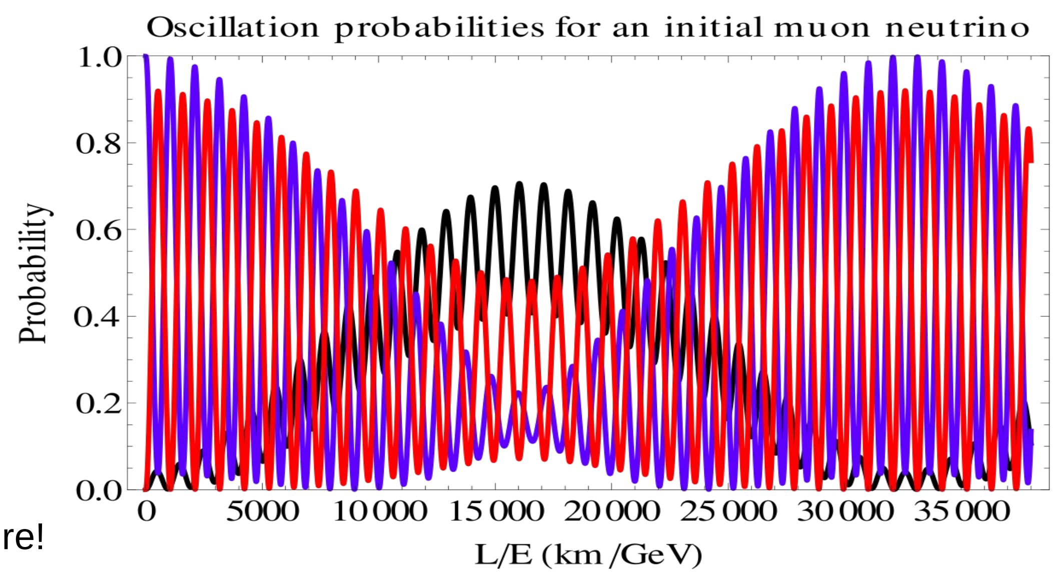


Probability of transition

$P(\nu_\alpha \rightarrow \nu_\beta)$

'oscillates' with L/E

Details in the next lecture!



$P(\nu_\mu \rightarrow \nu_\mu)$

$P(\nu_\mu \rightarrow \nu_e)$

$P(\nu_\mu \rightarrow \nu_\tau)$

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...

- Neutrinos change flavor on their way from the source to detector → neutrino oscillations phenomenon
- Presence of neutrino oscillations implies that at least two of them have non-zero mass → Physics beyond Standard Model → Stay tuned for more details IN LECTURE 2!

References

- Fermilab’s neutrino university (slides and videos): https://npc.fnal.gov/neutrino-university/