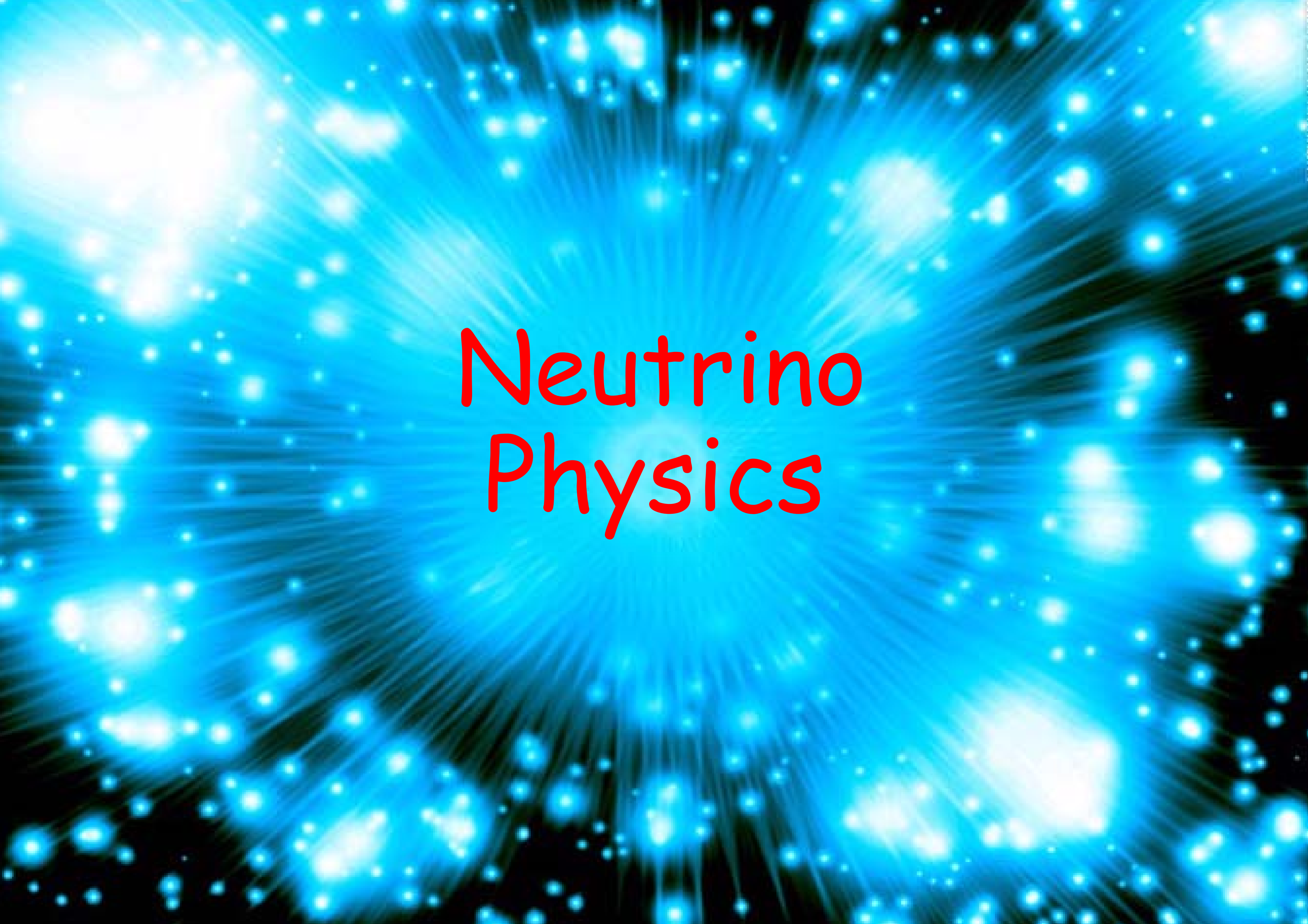

Neutrino
Physics

The neutrino

- The neutrino is the only particle that is only interacting weakly and this makes it difficult to study. The very low cross section for neutrino-nucleon interactions mean that a neutrino can easily traverse the earth without being stopped.

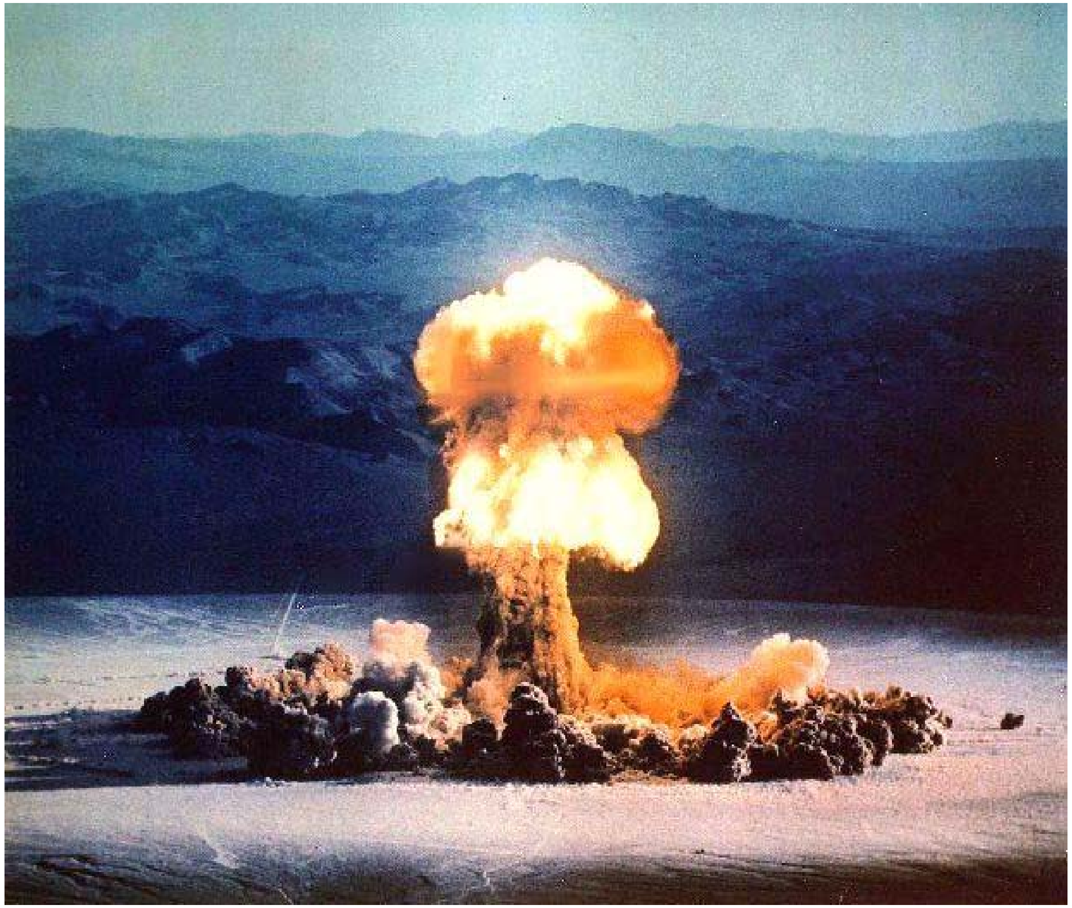
- The neutrino is a fermion (spin 1/2 particle) but it only exists in one helicity state. One say that neutrinos are left-handed and anti-neutrinos are right-handed.

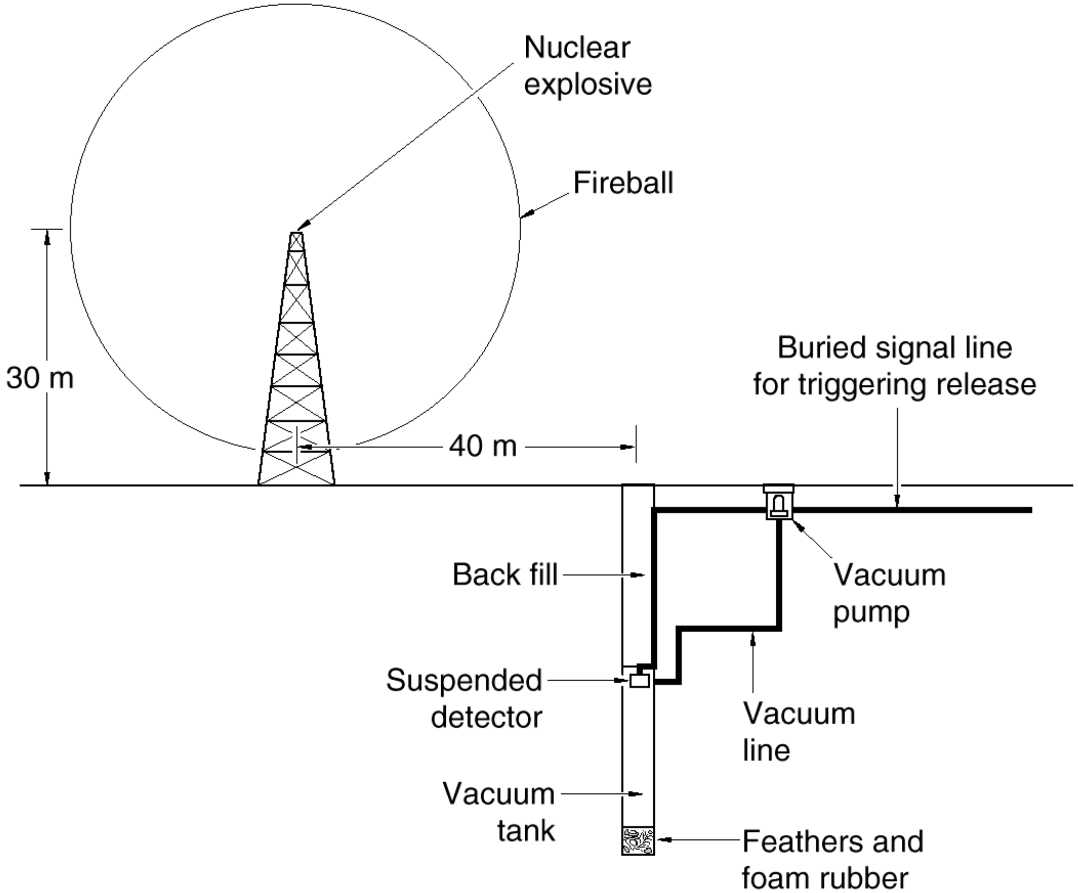
- Its existance was postulated by Pauli in 1930 to explain why electrons from β-decay has a continuos energy spectrum.

- Fermi used Pauli's idea of a neutrino to develop a theory for weak interactions.

The neutrino

- One idea of how to create enough neutrinos to be able to detect them was by detonating a nuclear explosion.





- The project was approved at Los Alamos but ....

The discovery of the neutrino

➡ The discovery of the electron neutrino

- It took 26 years before the existance of the neutrino could be verified experimentally in the Cowan-Reines experiment at the Savanna River nuclear reactor in 1956.

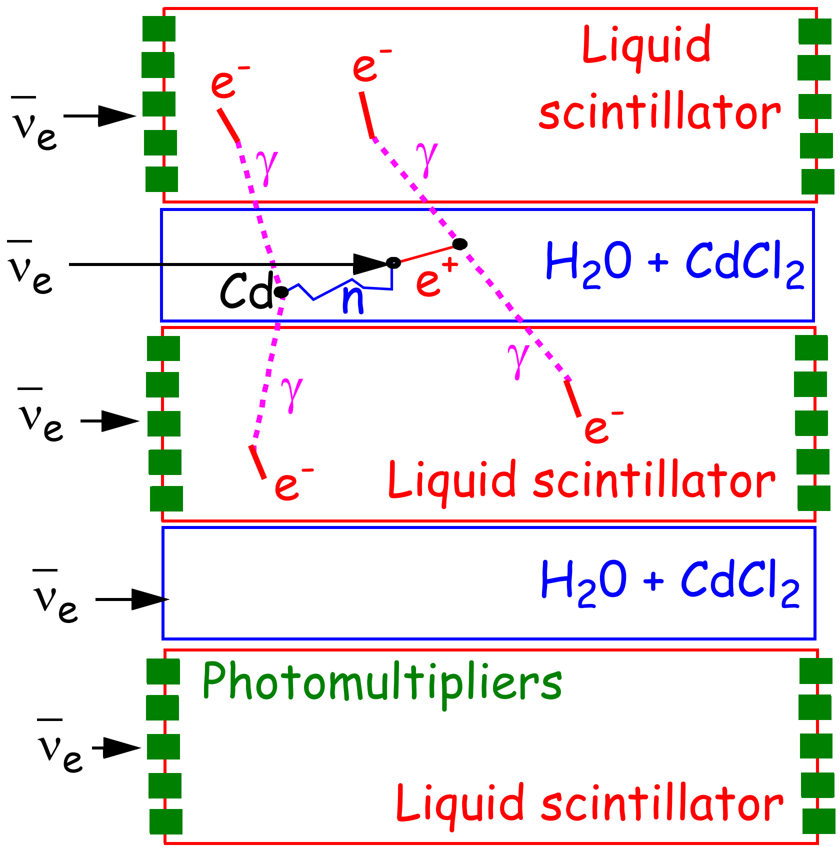
- A huge amount of neutrons are produced in a reactor and these decay to anti-neutrinos in the reaction $n \rightarrow p + e^- + \bar{\nu}_e$ which resulted in a neutrino flux of 10^{13} cm^{-2}s^{-1} around the reactor.

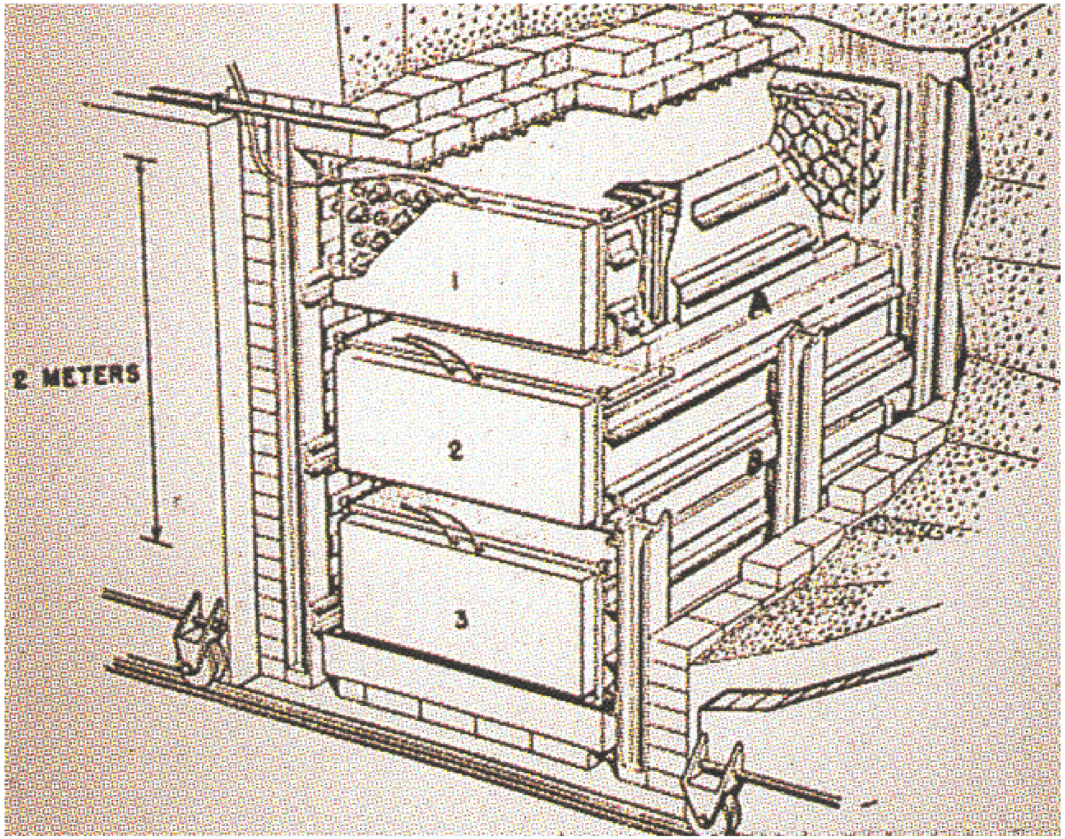
- The very rare process used to detect the anti-neutrinos was $\bar{\nu}_e + p \rightarrow n + e^+$.

- The positrons would annihilate with electrons to two photons that were detected and the neutrons would be captured by Cadmium atoms that would produce more photons that were also detected.

The discovery of the neutrino

- The experiment consisted of **two tanks of water** with Cadmium chloride diluted into it. Sandwiched between the water tanks were **three tanks** with liquid **scintillator**.

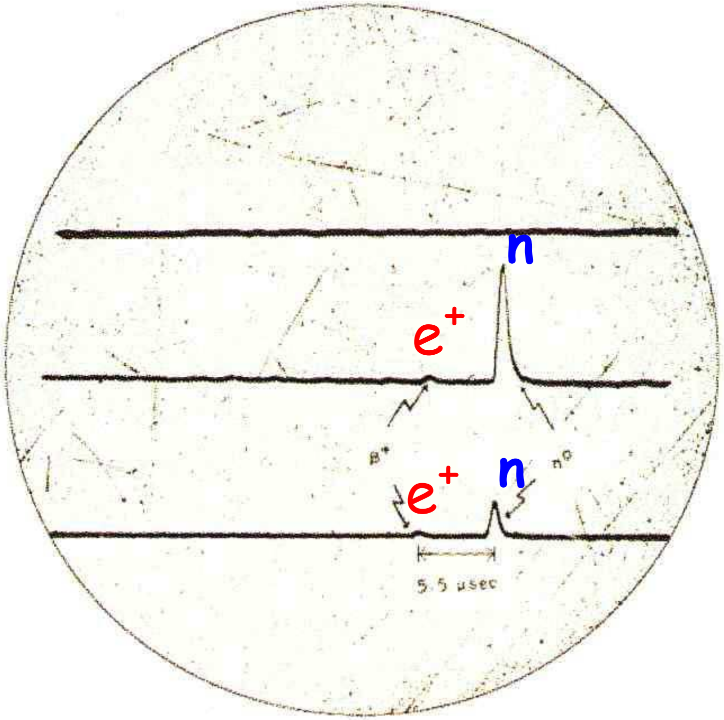


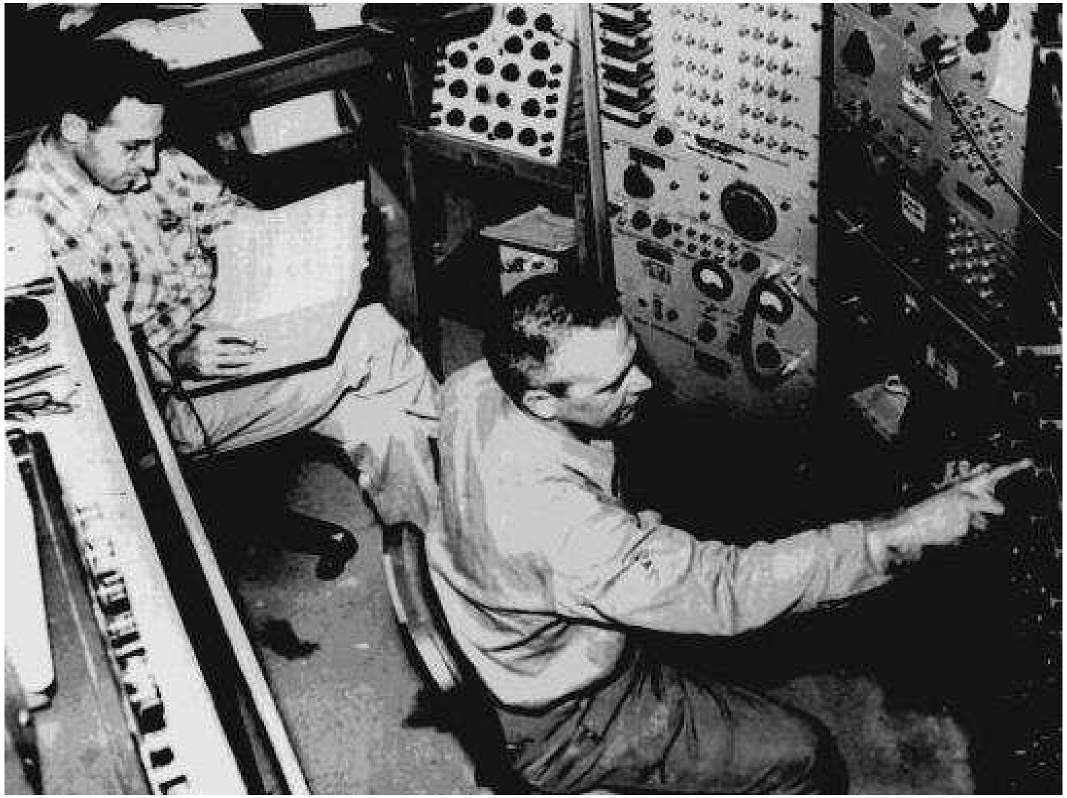


- **Photons** are not directly detected by a scintillator but they produce **electrons** by the **Compton effect** that are detectable.

The discovery of the neutrino

- It would take a few μs before the neutrons had slowed down in the water and been captured by the Cadmium and so the signature one was looking for was two small signals at the same time followed by a large signal a bit later from the neutron.





- One got about 2 neutrino events and 1 background event per hour.

The discovery of the neutrino

➡ The discovery of the muon neutrino

- After the discovery of the neutrino, the big question was if it existed in several flavours.

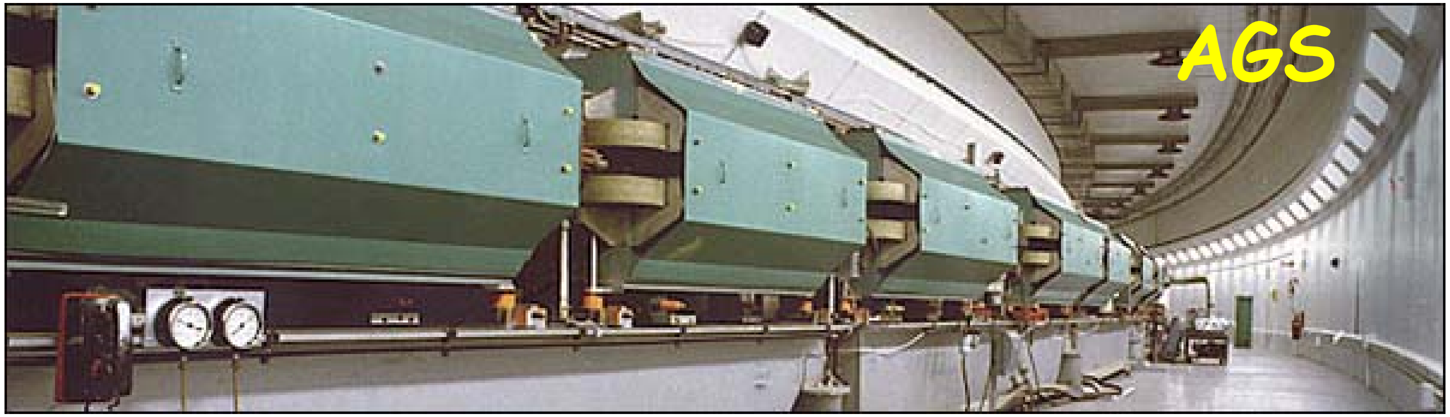
- The newly started *AGS* accelerator was in 1962 used to produce the world's first neutrino beam by shooting 15 GeV protons on a Beryllium target.

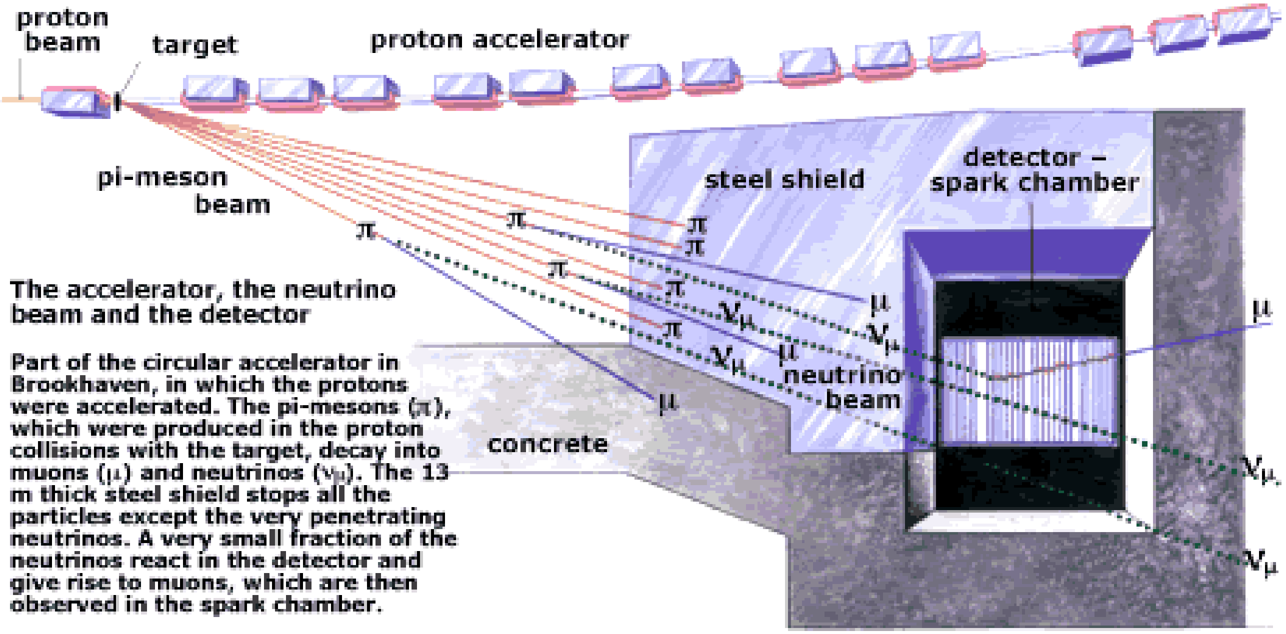
- Pions were selected and after a 20 m decay distance most of them had decayed to muon and muon neutrinos. The muons were then stopped in a 13 m thick steel shielding before they could decay:

$$\pi^- \xrightarrow{10^{-8}s} \mu^- + \bar{\nu}_\mu, \quad \mu^- \xrightarrow{10^{-6}s} e^- + \bar{\nu}_e + \nu_\mu$$

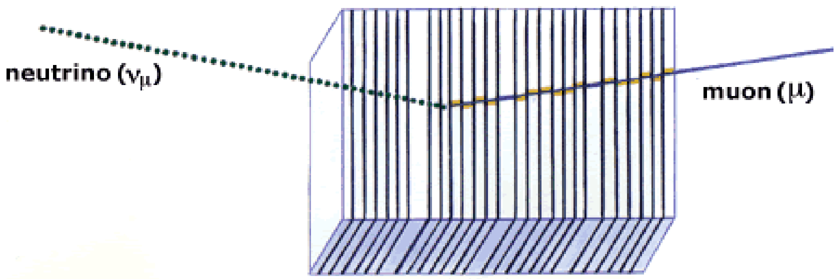
$$\pi^+ \xrightarrow{10^{-8}s} \mu^+ + \nu_\mu, \quad \mu^+ \xrightarrow{10^{-6}s} e^+ + \nu_e + \bar{\nu}_\mu$$

The discovery of the neutrino





Sandwich of Aluminium plates and spark chambers



A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

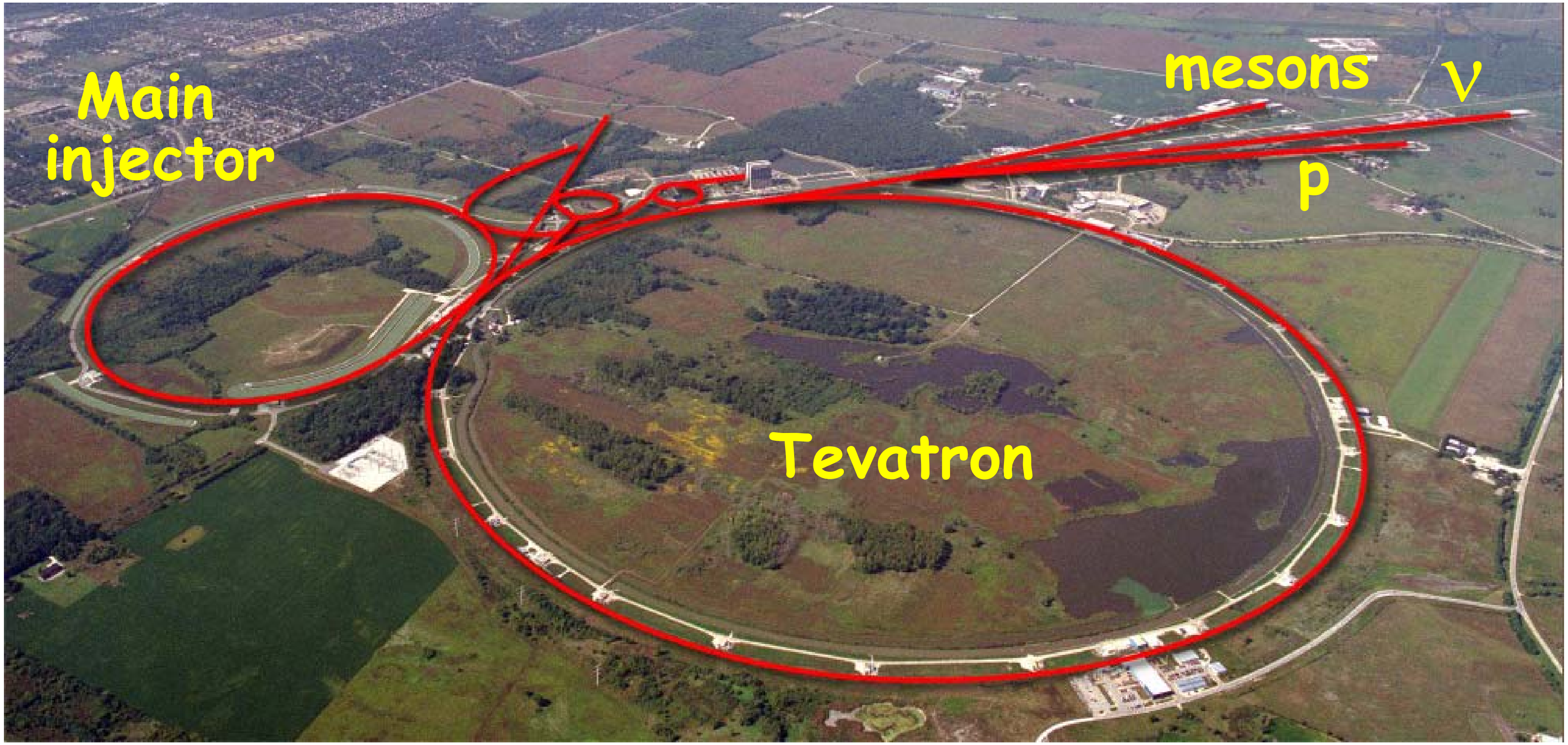
$\bar{\nu}_\mu + p \rightarrow n + \mu^+$ $\quad$ $\nu_\mu + n \rightarrow p + \mu^-$

- The **muon neutrinos** interacted with the nucleons in the **Aluminium** and **photos** of the reaction products were recorded. 29 events were recorded with muons and none with electrons.

The discovery of the neutrino

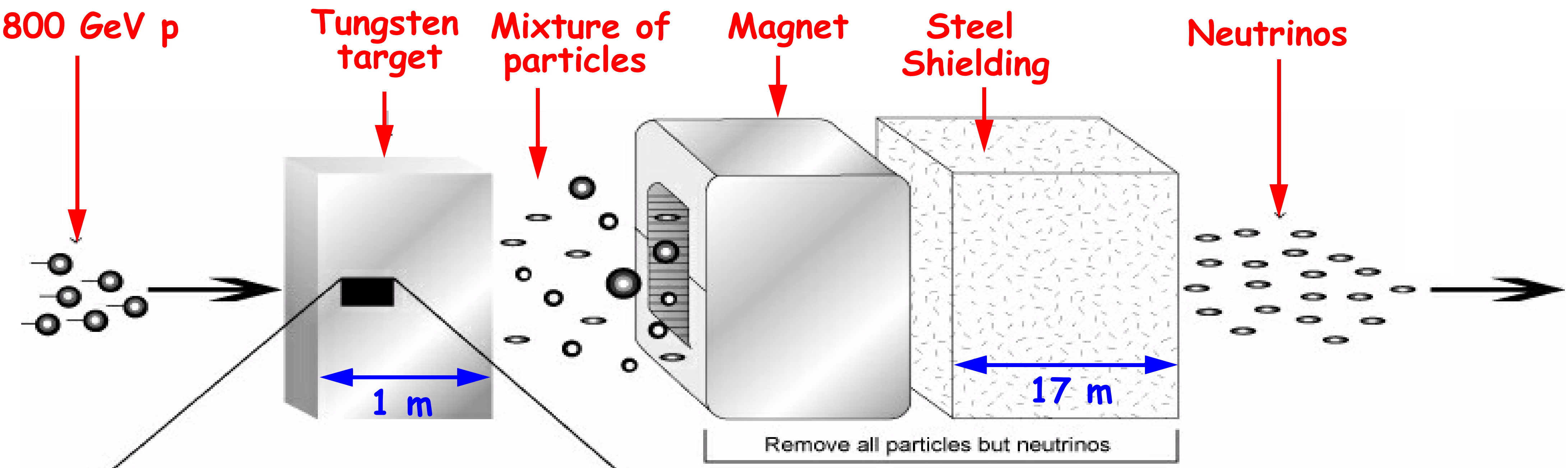
➡ The discovery of the tau neutrino

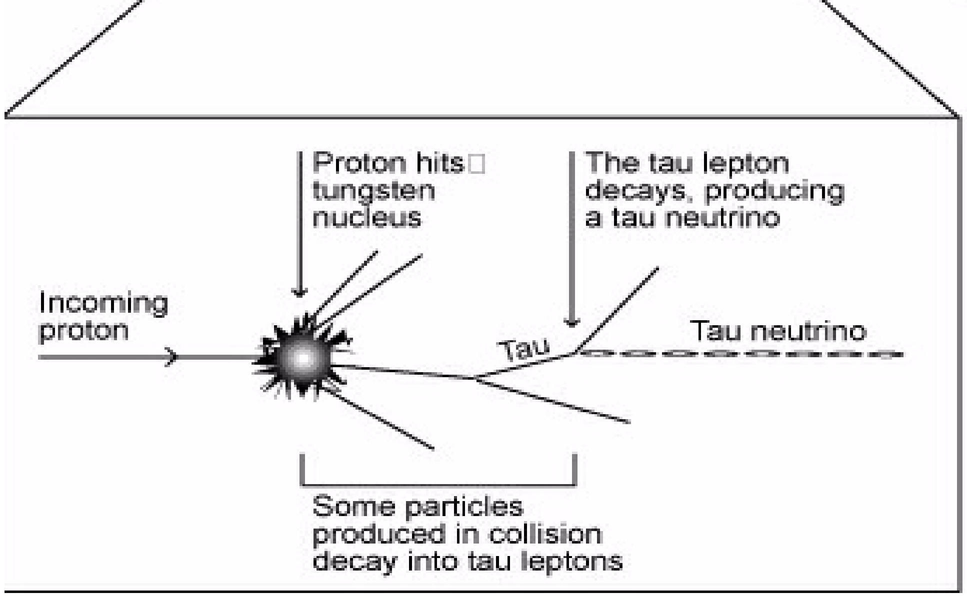
- It took until year 2000, almost 40 years after the muon neutrino discovery, until the tau neutrino was seen directly for the first time at Fermilab.



The discovery of the neutrino

- The tau neutrinos were created by having protons hit a target:





$p + n \rightarrow D_s + X$

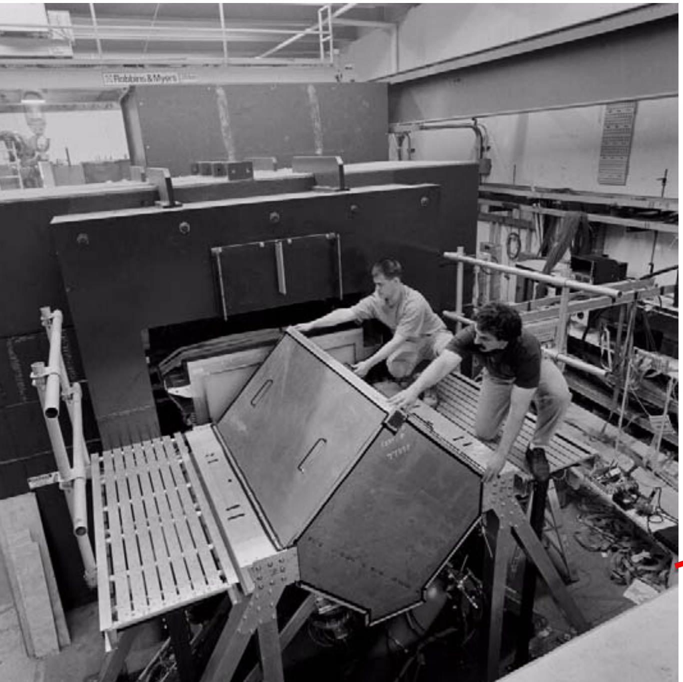
$p + p \rightarrow D_s + X$

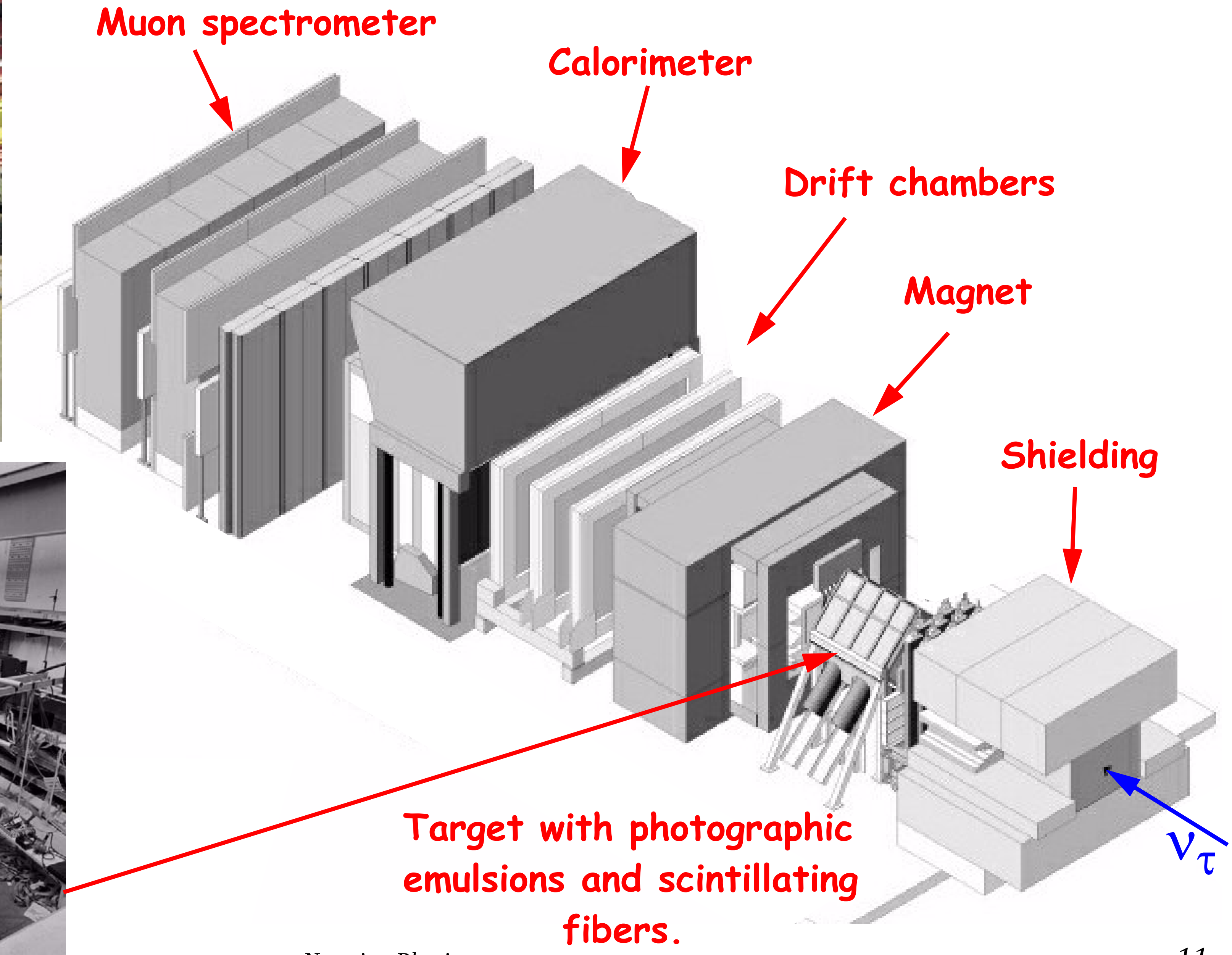
$\quad \hookrightarrow \tau + \bar{\nu}_\tau$

$\qquad \hookrightarrow \nu_\tau + X$

The discovery of the neutrino

- DONUT: Detector for direct observation of tau neutrinos.





The discovery of the neutrino

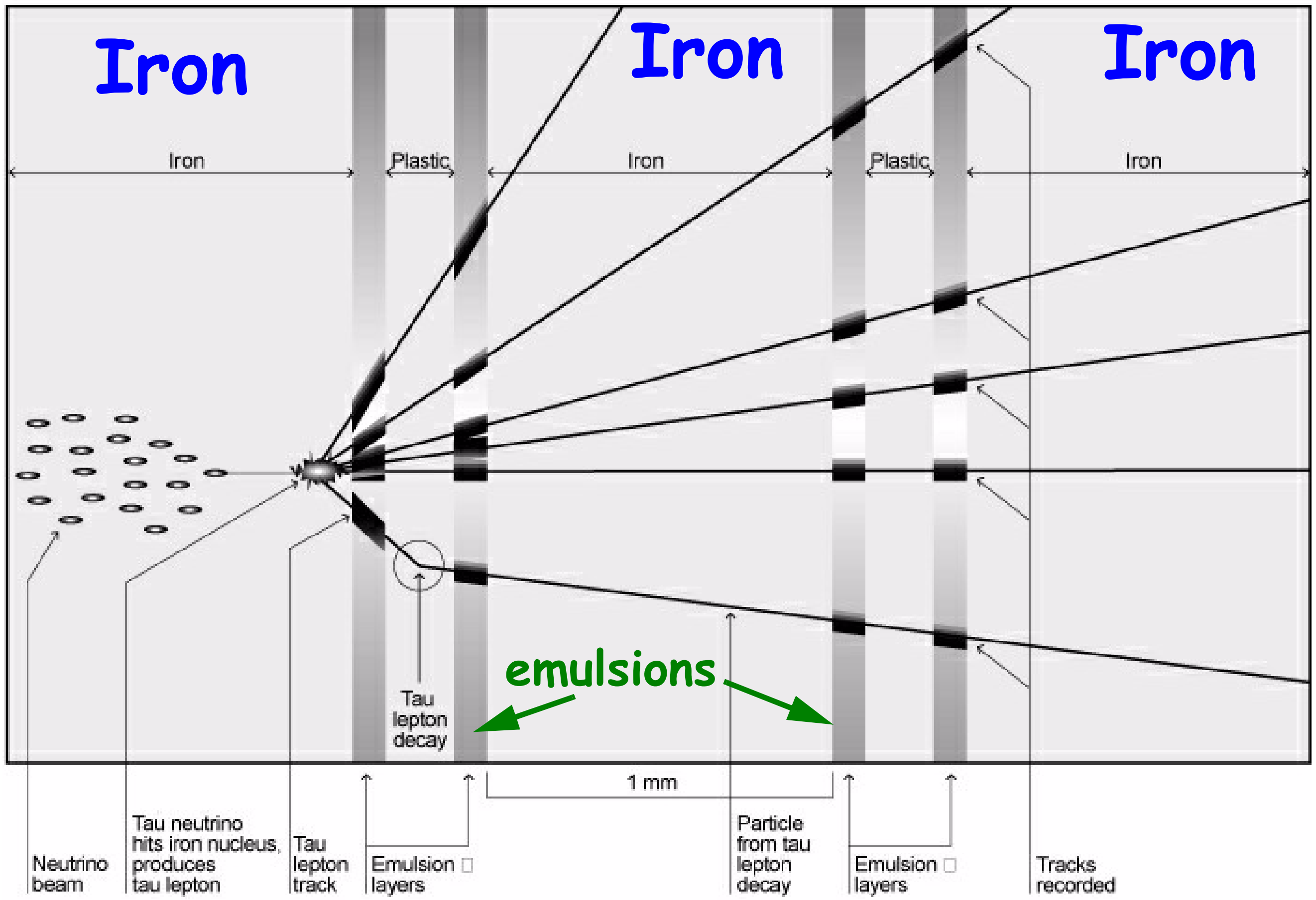
- The experiment looked for the reactions:

$\nu_\tau + n \rightarrow \tau + X$

$\nu_\tau + p \rightarrow \tau + X$

$\quad \rightarrow \nu_\tau + e$

$\quad \rightarrow \nu_\tau + \mu$



- Only one ν_τ of a million would interact in the target.

- After years of running and after analyzing 6 million events, the experiment had found 4 that had all the signatures of a tau to tau-neutrino decay. These had a characteristic kink that was recorded by the photographic emulsions.

Neutrino mass

- One of the major question in particle physics is if neutrinos have a mass. Attempts at direct measurement of the neutrino mass has only produced upper limits.

- Direct measurement of the ν_e mass using β-spectrum:

$$m_\nu < 2.1 \text{ eV}$$

- Direct measurement of the ν_μ mass using pion decays at rest ($\pi^+ \rightarrow \mu^+ + \nu_\mu$):

$$m_\nu < 170 \text{ keV}$$

- Direct measurement of the ν_τ mass using $Z^0 \rightarrow \tau^+\tau^-$ at LEP:

$$m_\nu < 18.2 \text{ MeV}$$

Neutrino oscillations

- If neutrinos have non-zero masses they should, according to theory, be subject to something called neutrino mixing.

- I case of only two neutrino flavours, one would get the electron and muon states by a linear combination of two states ν_1 and ν_2 which have the masses m_1 and m_2:

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

- The mixing angle θ has to be determined by experiments that study neutrino oscillations.

- Neutrino oscillations is the phenomena in which a pure beam of ν_e develops a ν_μ component as it travels through space (and vice versa).

Neutrino oscillations

- Neutrinos created at t=0 can be written as:

$$\begin{cases} \nu_e(0) = \nu_1(0)\cos\theta + \nu_2(0)\sin\theta \\ \nu_\mu(0) = -\nu_1(0)\sin\theta + \nu_2(0)\cos\theta \end{cases}$$

the initial electron neutrino state

the initial muon neutrino state

this can be re-written as:

$$\begin{cases} \nu_1(0) = \nu_e(0)\cos\theta - \nu_\mu(0)\sin\theta \\ \nu_2(0) = \nu_e(0)\sin\theta + \nu_\mu(0)\cos\theta \end{cases}$$

- After a period of time t the states can be described by

$$\begin{cases} \nu_e(t) = \nu_1(0)\cos\theta\, e^{-iE_1 t} + \nu_2(0)\sin\theta\, e^{-iE_2 t} \\ \nu_\mu(t) = -\nu_1(0)\sin\theta\, e^{-iE_1 t} + \nu_2(0)\cos\theta\, e^{-iE_2 t} \end{cases}$$

the electron neutrino state at t

the muon neutrino state at t

where $e^{-iE_i t}$ are oscillating time factors and E_1 and E_2 are the energies of neutrino ν_1 and ν_2.

- Combining this gives:

$$\begin{cases} \nu_e(t) = (\nu_e(0)\cos\theta - \nu_\mu(0)\sin\theta)\cos\theta\, e^{-iE_1 t} + (\nu_e(0)\sin\theta + \nu_\mu(0)\cos\theta)\sin\theta\, e^{-iE_2 t} \\ \nu_\mu(t) = -(\nu_e(0)\cos\theta - \nu_\mu(0)\sin\theta)\sin\theta\, e^{-iE_1 t} + (\nu_e(0)\sin\theta + \nu_\mu(0)\cos\theta)\cos\theta\, e^{-iE_2 t} \end{cases}$$

Neutrino oscillations

- The expressions can be simplified

$$\nu_e(t) = (\nu_e(0)\cos\theta - \nu_\mu(0)\sin\theta)\cos\theta\, e^{-iE_1 t} + (\nu_e(0)\sin\theta + \nu_\mu(0)\cos\theta)\sin\theta\, e^{-iE_2 t}$$

$$\nu_e(t) = \nu_e(0)\underbrace{(\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t})}_{A(t)} + \nu_\mu(0)\underbrace{\sin\theta\cos\theta\,(e^{-iE_2 t} - e^{-iE_1 t})}_{B(t)}$$

- The squares of A(t) and B(t) are the probabilities to find ν_e and ν_μ in a beam of electron neutrinos:

$$P(\nu_e \to \nu_\mu) = |B(t)|^2 = \sin^2(2\theta)\sin^2\frac{(E_2 - E_1)t}{2} = \sin^2(2\theta)\sin^2\frac{(\sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2})t}{2}$$

$$P(\nu_e \to \nu_e) = |A(t)|^2 = 1 - P(\nu_e \to \nu_\mu)$$

- If neutrinos have equal (zero) masses then $E_1 = E_2$ and there are no oscillations !

Neutrino oscillations

- The time t, in an experiment looking for neutrino oscillations, is determined by the distance between the detector and the source of neutrinos.

- The probability that a neutrino with flavour 1 oscillate to flavour 2 can therefore be written as

$$P(\nu_1 - \nu_2) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2 L}{E_\nu})$$

where

θ is the mixing angle between flavour 1 and 2
L is the neutrino flight path in km
E_ν is the neutrino energy in GeV
$\Delta m^2 = |m_1^2 - m_2^2|$ is the squared mass difference in eV^2

Neutrino oscillations

- Several neutrino sources can be considered in an experiment looking for neutrino oscillations:

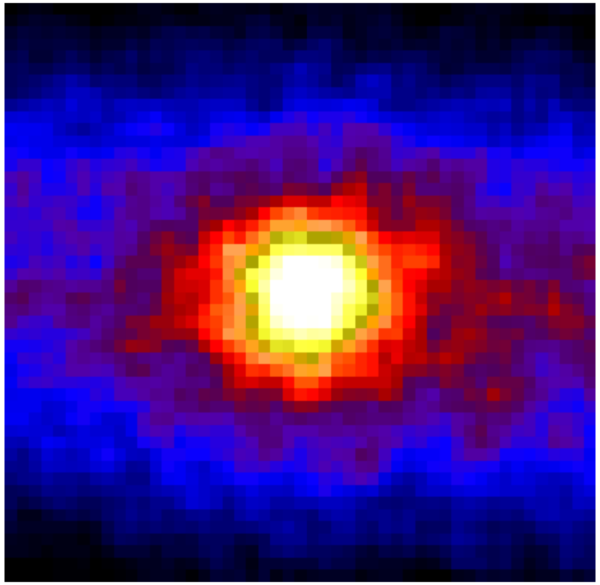
The sun
Cosmic rays ("atmospheric neutrinos")
Secondary accelerator beams
Nuclear reactors
Natural radioactivity
Supernovas
The Big Bang

- ν_e and ν_μ can be distinguished by their interaction with neutrons since the former produce electrons and the latter muons:

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

The solar neutrino problem

- Experiments have for many years studied the neutrinos from the sun. The number of detected neutrinos have, however, never been in agreement with theory. This is called the solar neutrino problem.



"Portrait" of the Sun made with neutrinos.

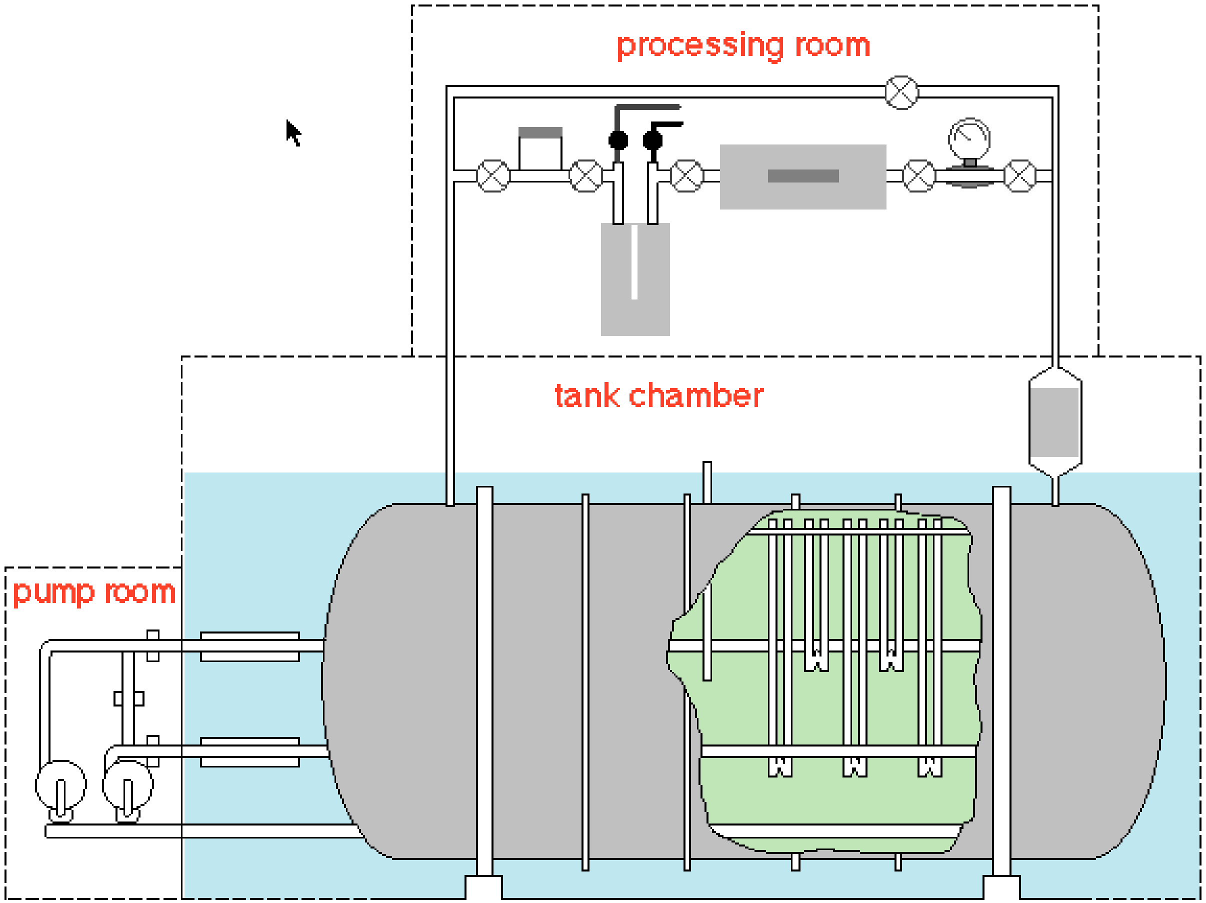
- Several methods have been used by these experiments to detect neutrinos:

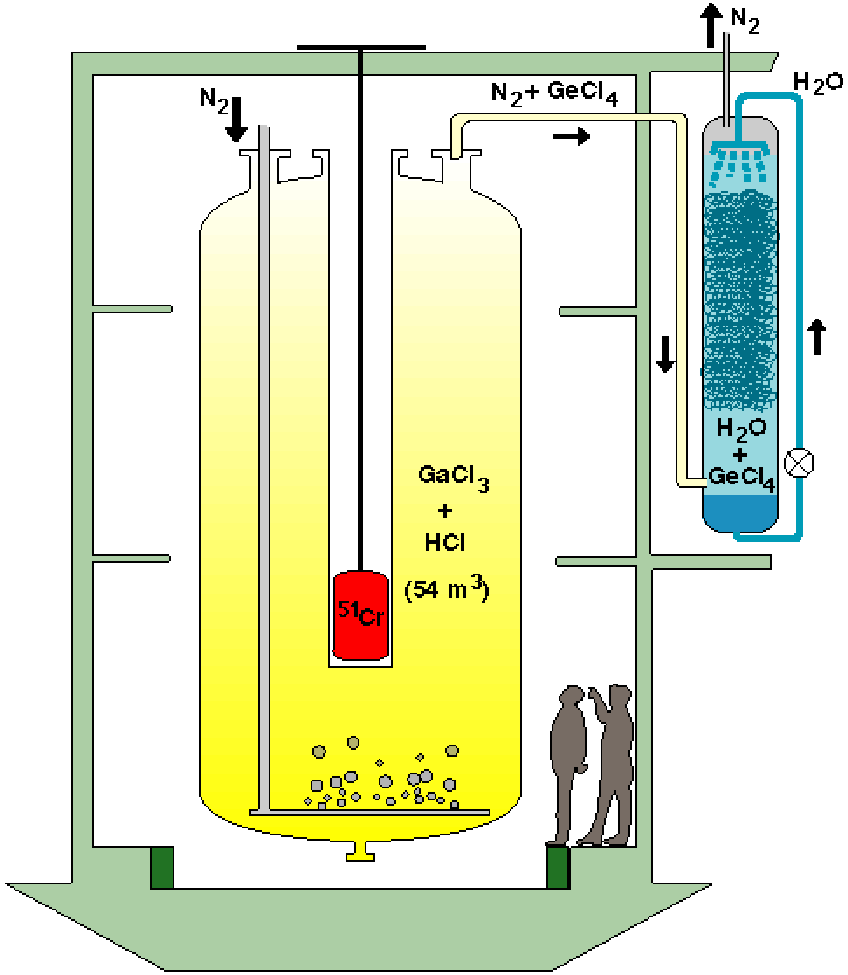
$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$
$$\nu_e + {}^{98}Mo \rightarrow e^- + {}^{98}Tc$$
$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

- The experimental installations are typically tanks filled with corresponding medium and placed deep underground.

The solar neutrino problem

- The Homestake gold mine detector (USA).
- The Gallex detector under the Gran Sasso mountain.





The reaction $\nu_e + {}^{37}Cl \rightarrow e + {}^{37}Ar$ is used.

The reaction $\nu_e + {}^{71}Ga \rightarrow e + {}^{71}Ge$ is used.

The solar neutrino problem

- The most important reactions producing solar neutrinos are:

$$p + p \rightarrow {}^2H + e^+ + \nu_e \qquad E_{\nu,max}=0.42 \text{ MeV } (85\%)$$

$$e^- + {}^7Be \rightarrow {}^7Li + \nu_e \qquad E_{\nu,max}=0.86 \text{ MeV } (15\%)$$

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e \qquad E_{\nu,max}=15 \text{ MeV } (0.02\%)$$

GALLEX measures all of them, Homestake only the last one.

- For the Homestake detector the predicted neutrino flux is 7.9±0.9 SNU but the measured flux is 2.56±0.16 SNU where a SNU is a "solar neutrino unit": 1 capture / 1 second / 10^{36} target atoms

- The GALLEX experiment has a predicted flux of 129±8 SNU and a measured flux of 71±4 SNU.

- The lack of electron neutrinos coming from the sun could be explained by neutrino oscillations that turn them into ν_μ and ν_τ.

The solar neutrino problem

The Sudbury Neutrino Observatory

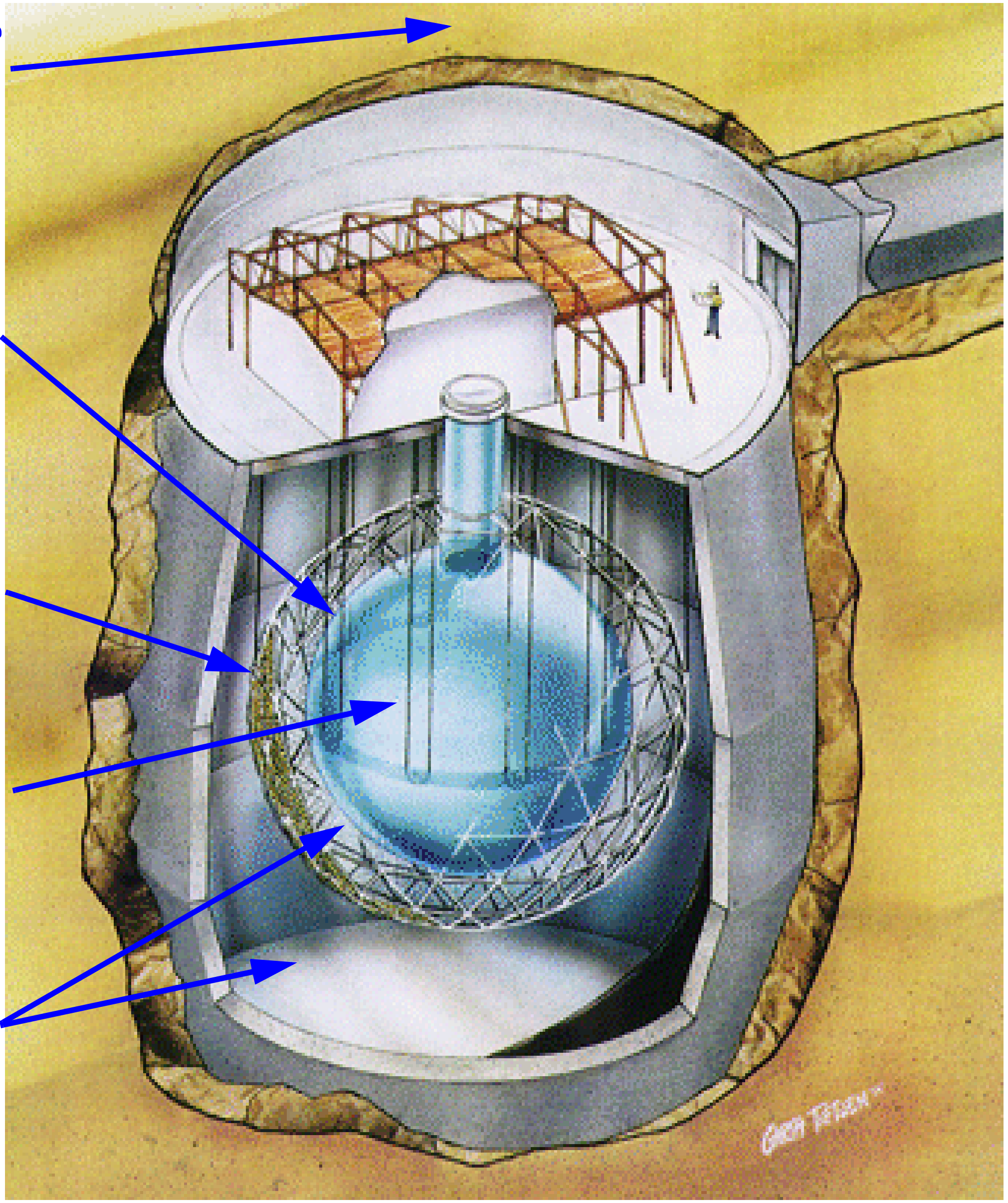
2 km under ground

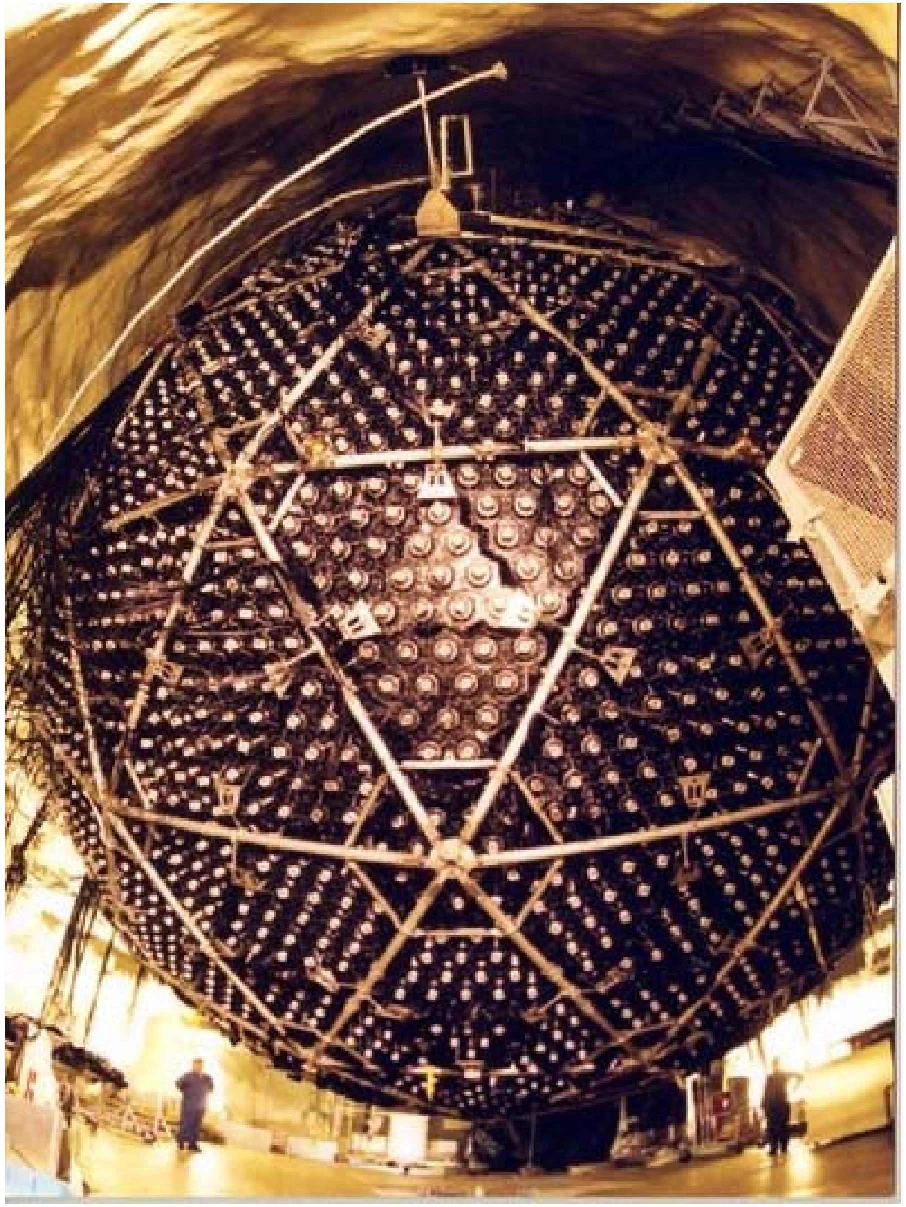
12m acrylic vessel

10,000 photo-multipliers

1000 tonnes D_2O

7000 tonnes H_2O



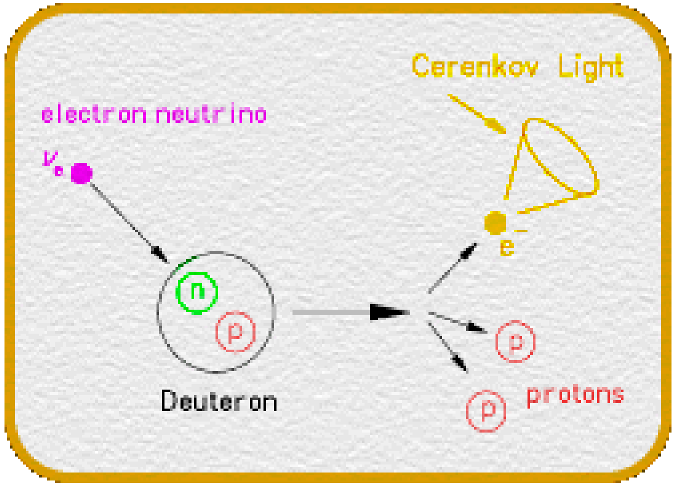


The solar neutrino problem

- The SNO experiment could measure neutrinos in three ways:

Charged current reactions

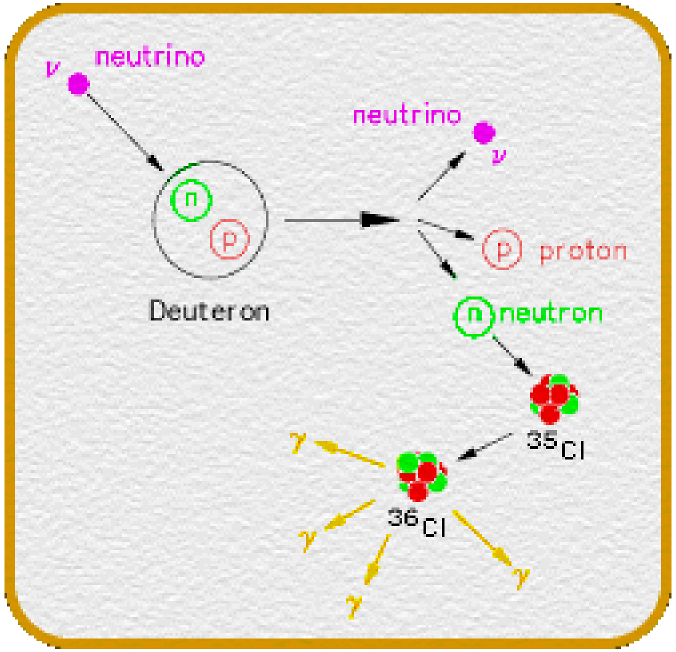
$\nu_e + d \rightarrow p + p + e^-$



The amount of Cerenkov light and the pattern of photo multipliers with a signal could be used to determine the neutrino energy and direction.

Neutral current reactions

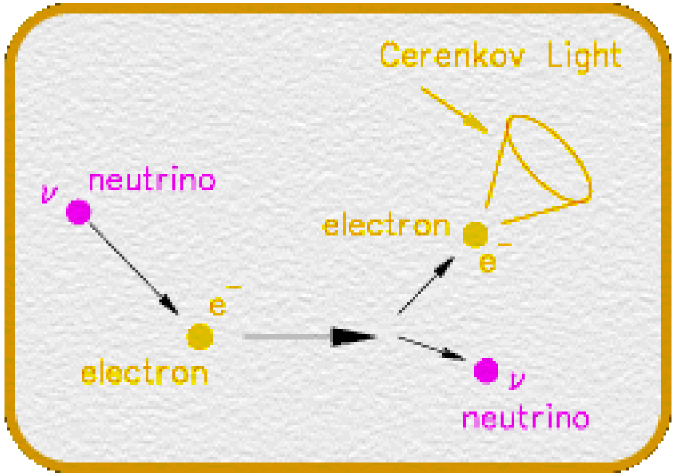
$\nu_x + d \rightarrow p + n + e^-$



The photons would Compton scatter electrons that would produce Cerenkov lights. Proportional counters in the water was also used to measure this process directly.

Electron scattering

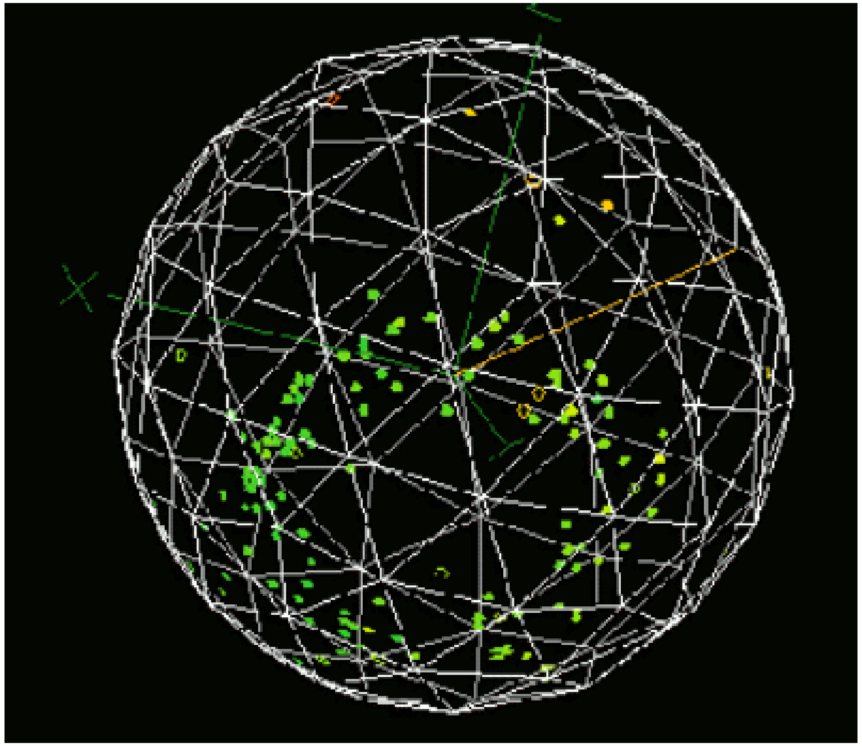
$\nu_x + e- \rightarrow \nu_x + e^-$



This process was mostly sensitive to electron neutrinos.

The solar neutrino problem

- The difference bewteen the SNO experiment and other previous experiments was that it could measure both the electron neutrino flux and the total neutrino flux.



- Neutral current measurement:

$$\frac{\text{Measured total neutrino flux}}{\text{Predicted total neutrino flux}} = 1.01 \pm 0.12$$

- Charged current measurement:

$$\frac{\text{Measured electron neutrino flux}}{\text{Predicted electron neutrino flux}} = 0.35 \pm 0.02$$

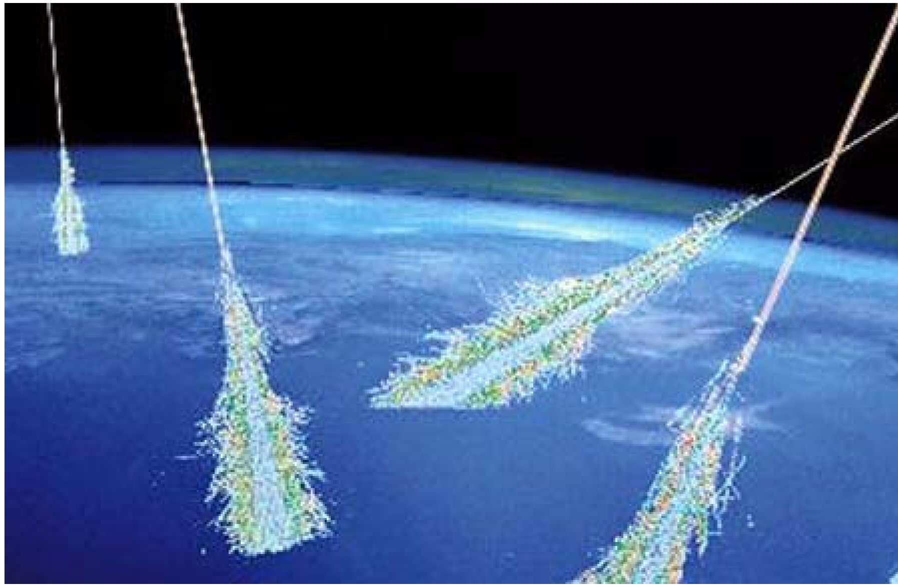
- The conclusion was that the solar model was correct and that the missing electron neutrinos were due to neutrino oscillations.

- The results combined with other experiments gave:

$$\Delta m^2 = 7.6 \times 10^{-5}\ eV^2$$
$$\tan^2(\theta) = 0.468$$

The atmospheric neutrino problem

- The earth is bombarded with high-energy particles, mostly **protons**, that shower when they hit the atoms in the **atmosphere**. The charged pions in the showers decay to neutrinos:
  $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

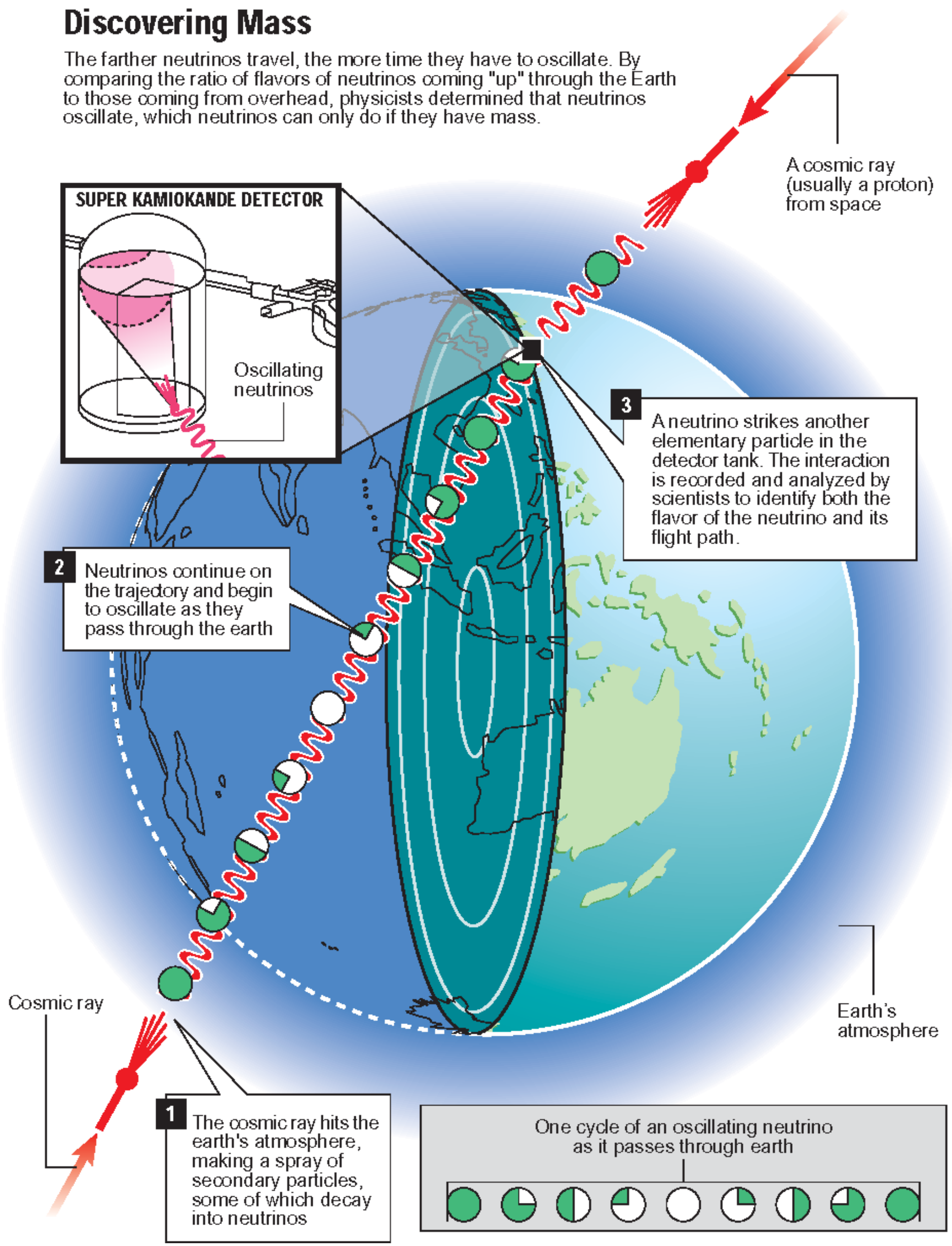


- The experiments looking for these neutrinos have to be shielded against other particles created in the cosmic showers (particularly muons) and are therefore put **deep under ground**.
- The neutrinos are **detected** by their **interaction with neutrons** and since the probability of such an interaction is low, the experiments have to have a very large volume.
- From the pion decay one would **expect twice** as many ν_μ as ν_e but one see the same number: **The atmospheric neutrino problem**.

The atmospheric neutrino problem

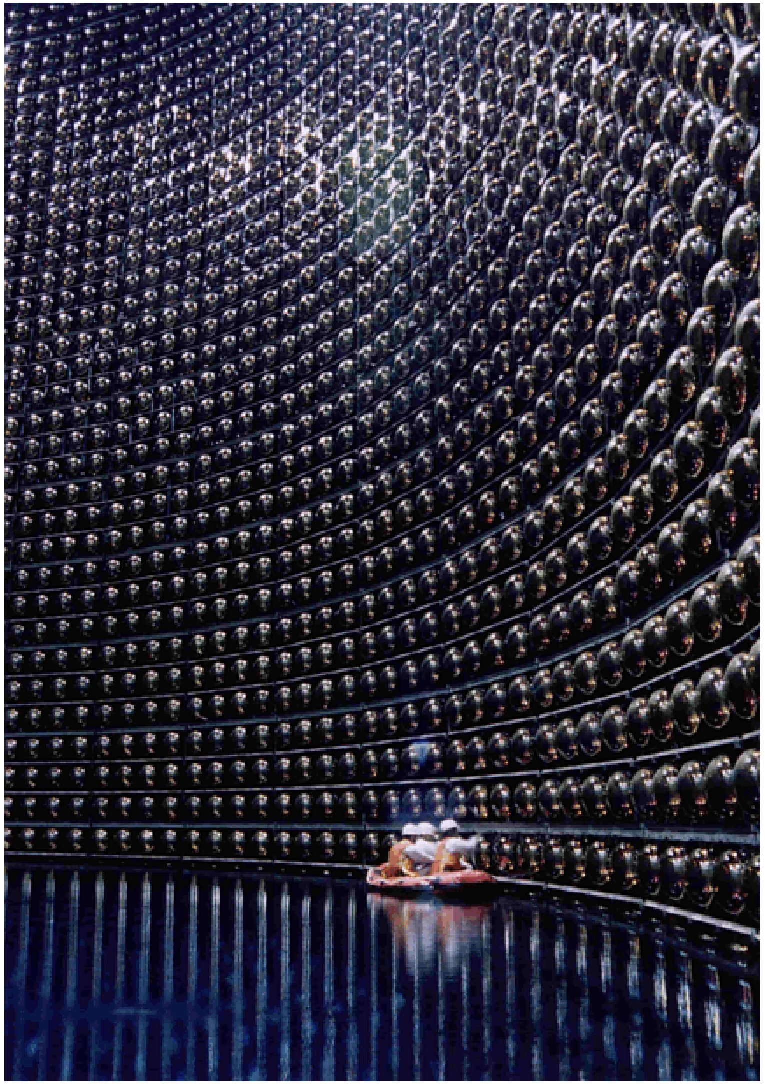
- Since neutrinos can pass through the earth without interacting, it is possible for a neutrino detector to see neutrinos created in the atmosphere above and in the atmosphere on the other side of the planet.

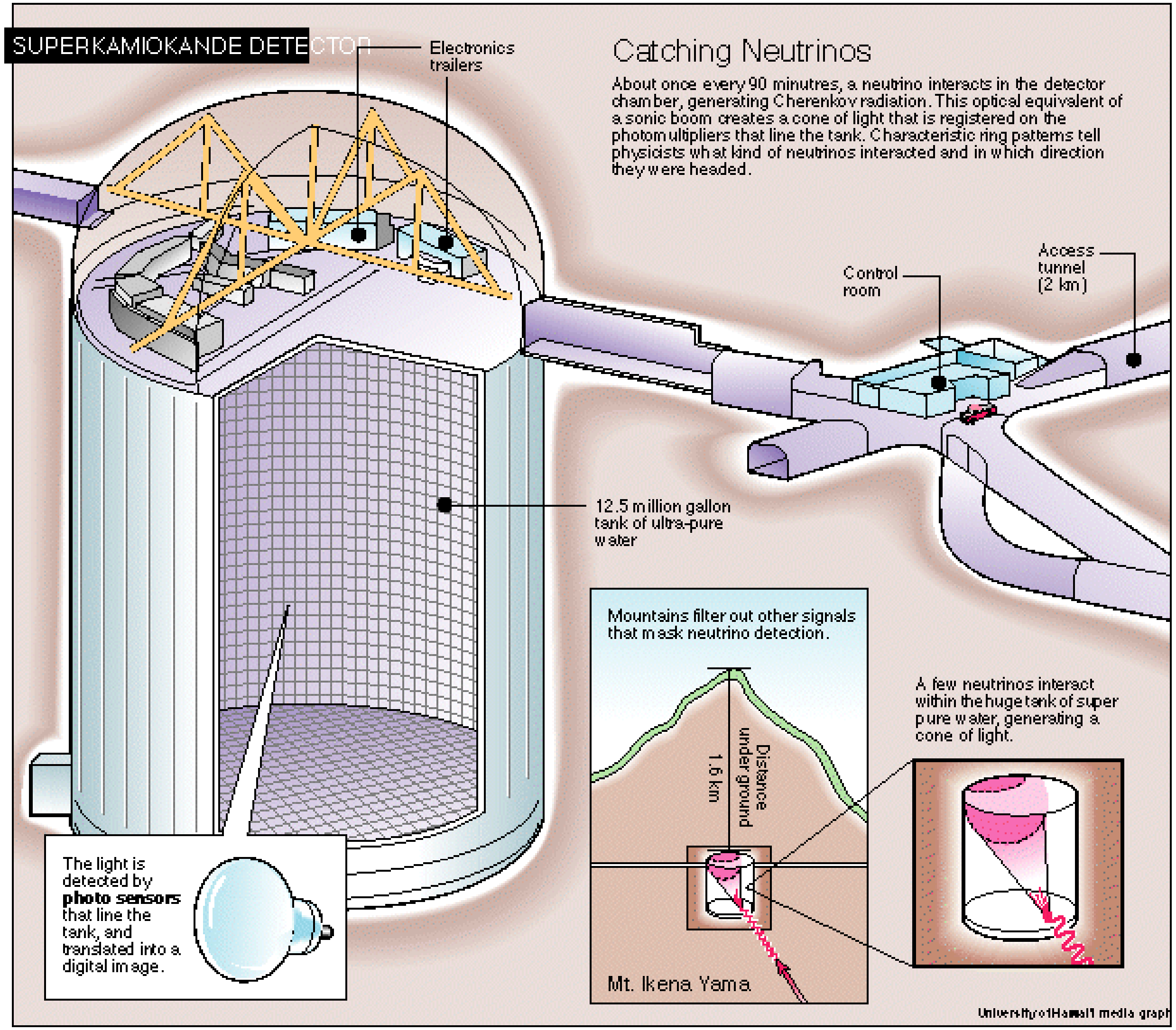
- So the detector will see neutrinos that have travelled between 15 km and 13,000 km depending on where in the atmosphere around the planet that they were created.



The atmospheric neutrino problem

➡ The Super-Kamiokande detector

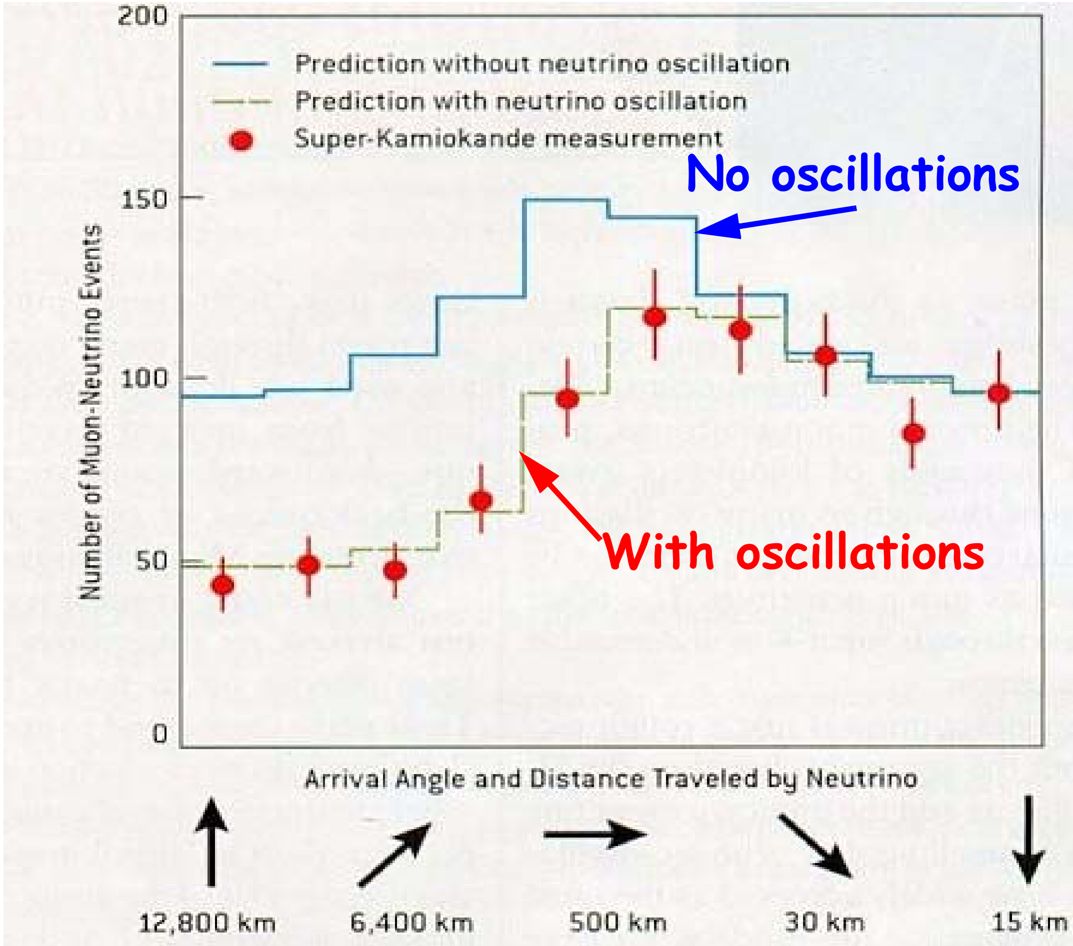




The detector consists of a 50,000 m^3 water tank surrounded by 13,000 photomultipliers.

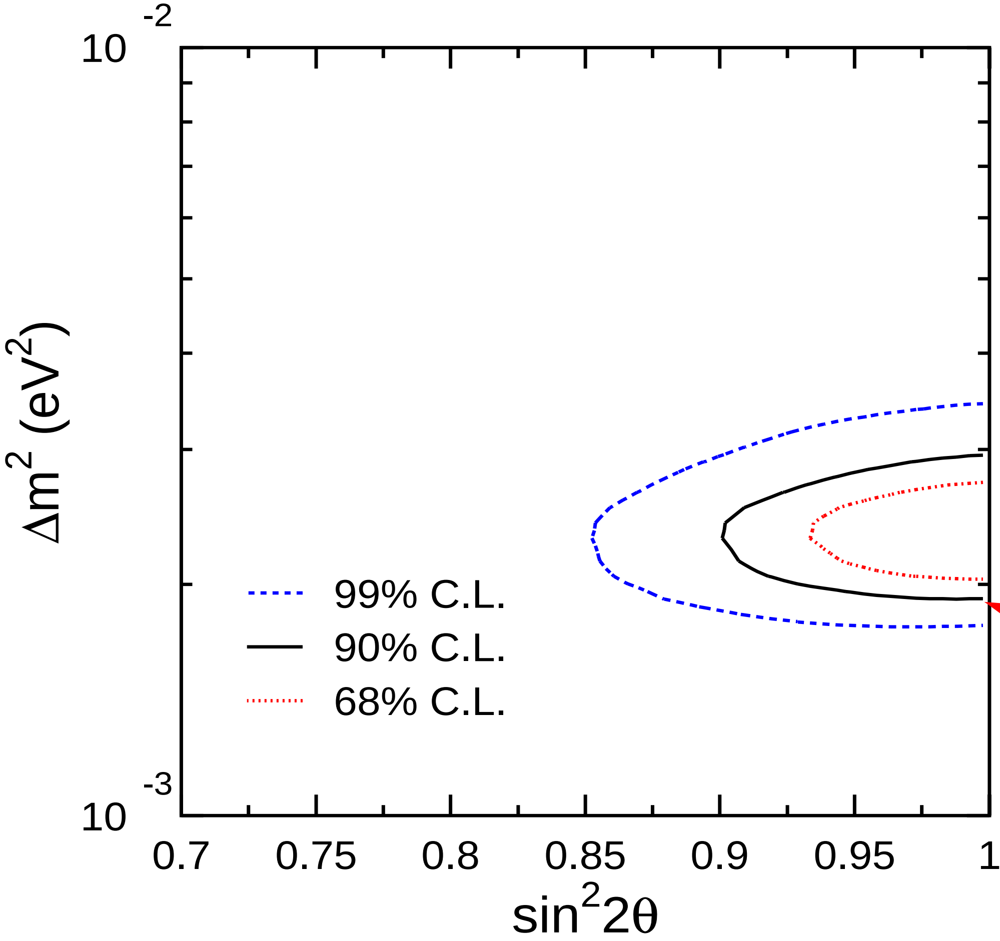
The atmospheric neutrino problem

- The neutrinos interact with neutrons in the water: $\begin{cases} \nu_e + n \to e^- + p \\ \nu_\mu + n \to \mu^- + p \end{cases}$
- The electrons and muons produce Cerenkov light in the water with characteristic rings that can be used to identify muons and electrons.
- The light detected by the photomultipliers can also be used to determine the neutrino trajectory and energy.
- A sample of 2700 ν_μ events were used to compare the expected distributions with the measured distribution.



The atmospheric neutrino problem

- The lack of neutrinos with a long travel distance was interpreted as evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations i.e. some of the muon neutrinos had turned into tau neutrinos that were not detected.



- The measurement could be used to set limits on the mixing angle and the neutrino mass difference:

$$2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-3}\ eV^2$$

$$\sin^2(2\theta) > 0.90$$

Short baseline neutrino experiments

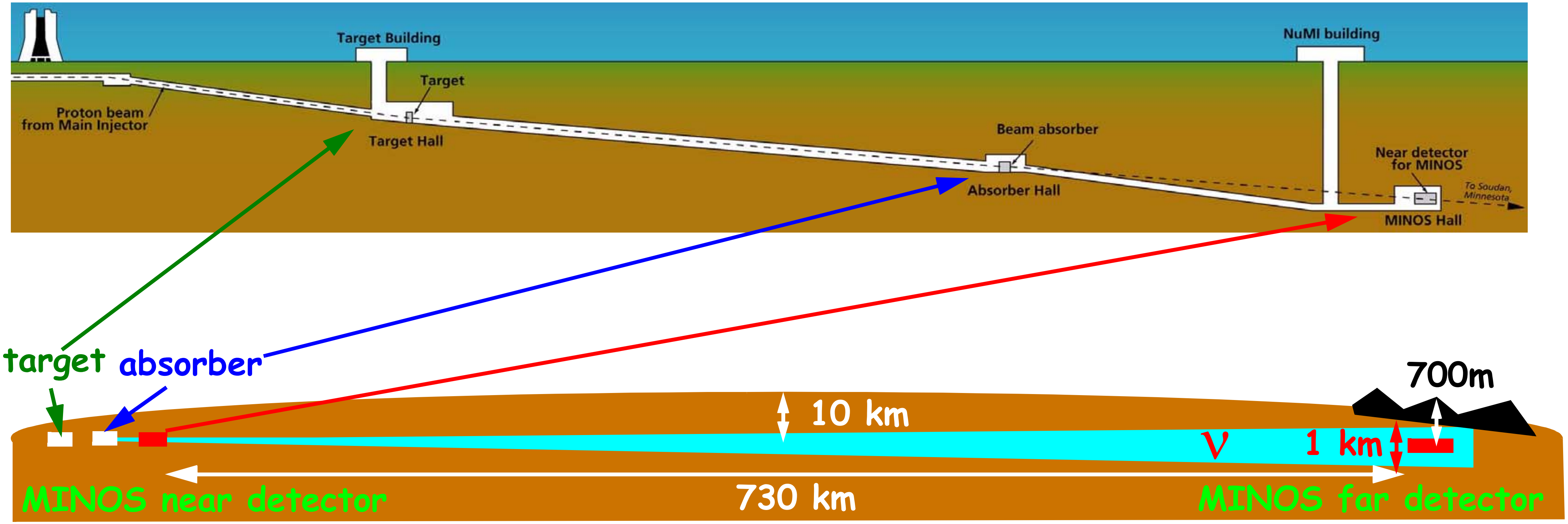
- High intensity proton beams from accelerators can be used to create neutrino beams that are pointing towards experiments.
- The neutrino beams are created by letting the intense proton beam hit a target. Charged pions and kaons are created in the collision. These decay to neutrinos e.g. $\pi^+ \rightarrow \mu^+ + \nu_\mu$.
- If the experiment are less than a km away from the target one calls it a short baseline experiment.
- Two large short baseline experiments (NOMAD and CHORUS) were built at CERN in the nineties. They were situated some 800m away from a target hit by protons from the SPS accelerator.
- Both experiments were searching for $\nu_\mu - \nu_\tau$ but they did not find a ν_τ signal.

Long baseline neutrino experiments

- If an experiment is located hundreds of kilometers away from from the target one is talking about a long baseline experiment.

➡ The NuMI beam from Fermilab

- One such a facility is the NuMI beam created at Fermilab and pointing at experiments situated in mines some 730 km away.



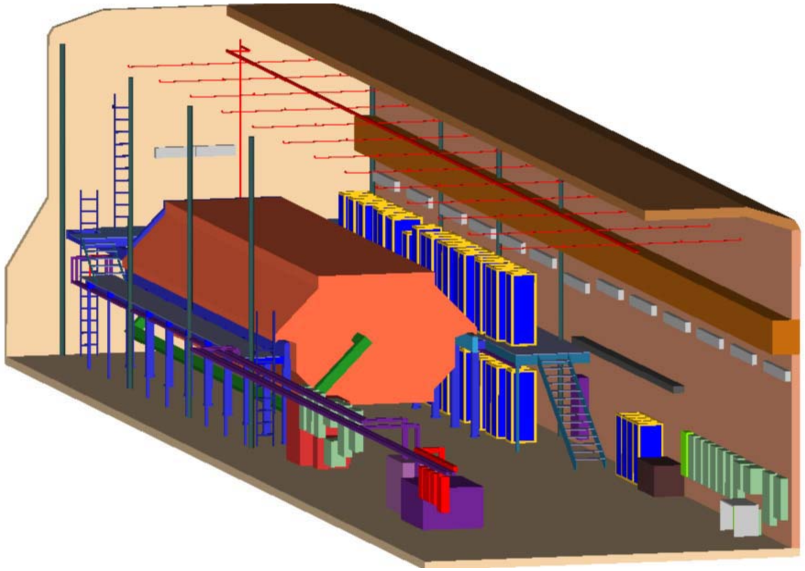
Long baseline neutrino experiments

The MINOS experiment

The Near Detector

Used to measure the neutrinos before they can oscillate.

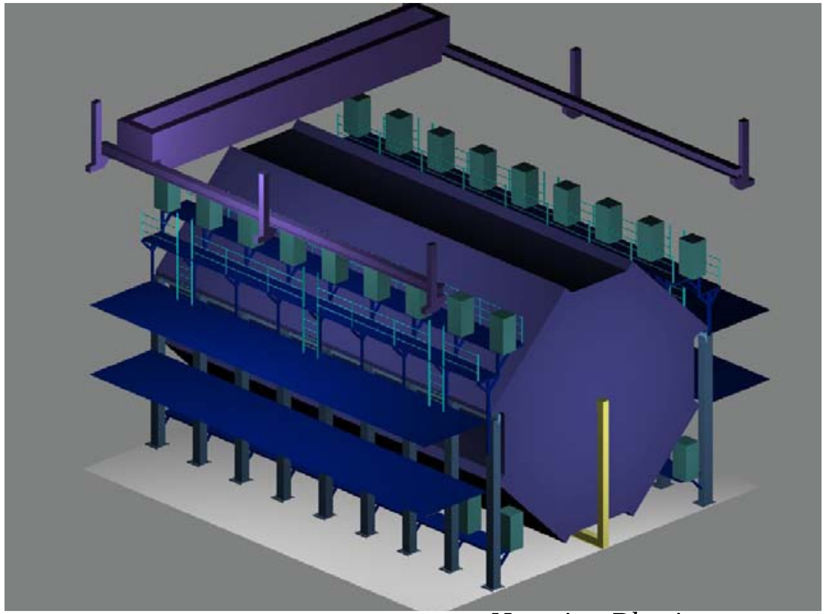
980 tonnes of magnetized iron + scintillators.



The Far Detector

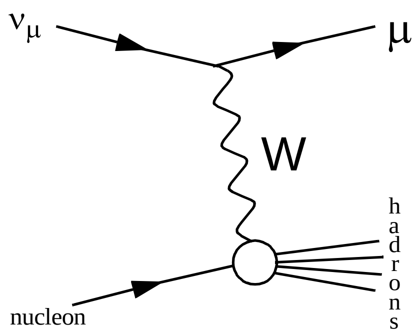
Used to measure the neutrinos after they have oscillated.

5400 tonnes of magnetized iron + scintillators.



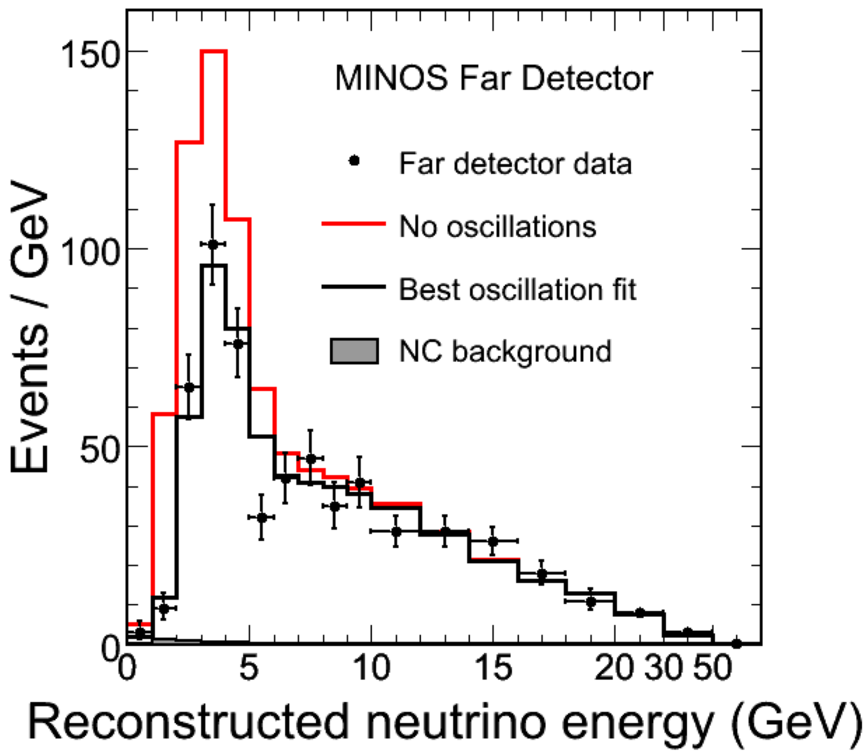
Long baseline neutrino experiments

- **Charged current reactions** can be used to measure the **energy of the neutrinos** from the energy of muons and the hadrons.



$E_\nu = E_\mu + E_{hadrons}$

- Measurement of the neutrino energy spectrum in the far detector showed **fewer neutrinos** than what was expected if there were no neutrino oscillations.



- The measurement gave the result:

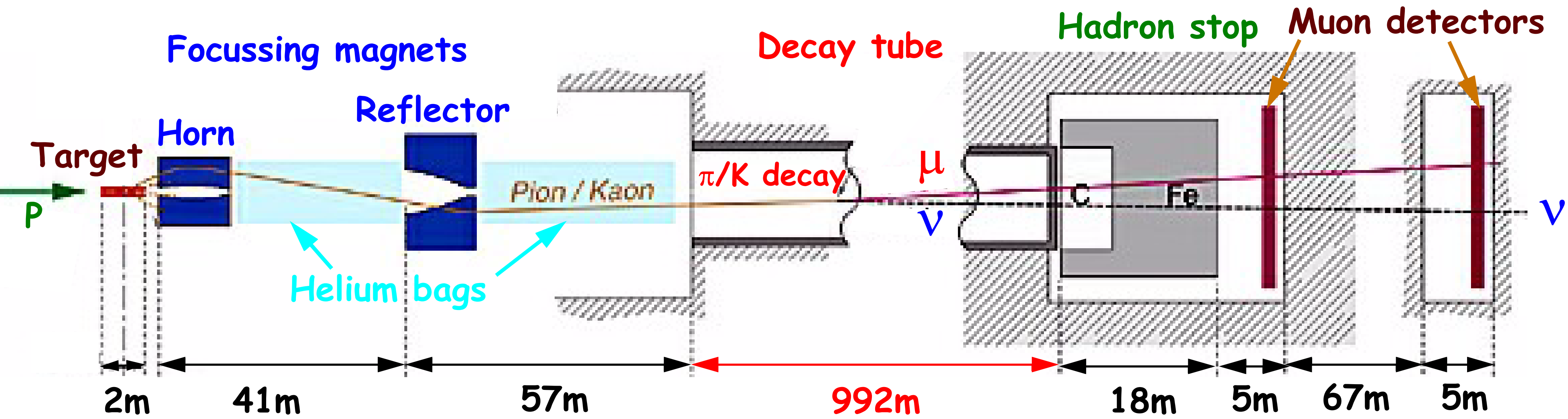
$$\Delta m^2 = 2.4 \pm 0.1 \times 10^{-3}\ eV^2$$

$$\sin^2(2\theta) = 1.00 \pm 0.05$$

Long baseline neutrino experiments

➡ CNGS - CERN Neutrinos to Gran Sasso

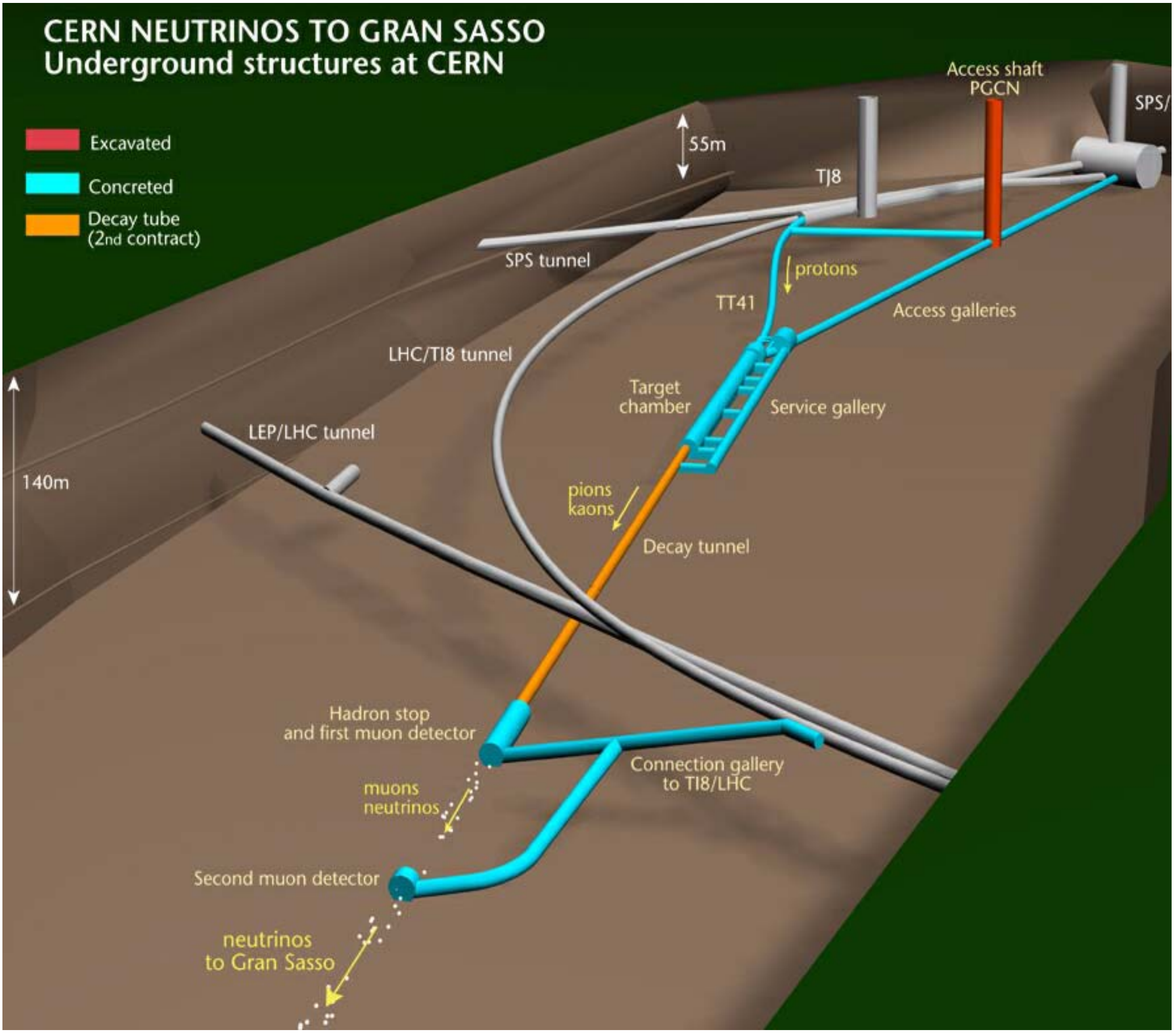
- The Kamiokande and Minos measurements are example of disapperance studies, i.e., one looks for the disapperance of ν_μ.
- Much more difficult are apperance measurements in which one looks for ν_τ to appear in a ν_μ beam.
- The layout of the CNGS neutrino facility at CERN is shown below:



Long baseline neutrino experiments

➡ CNGS - CERN Neutrinos to Gran Sasso

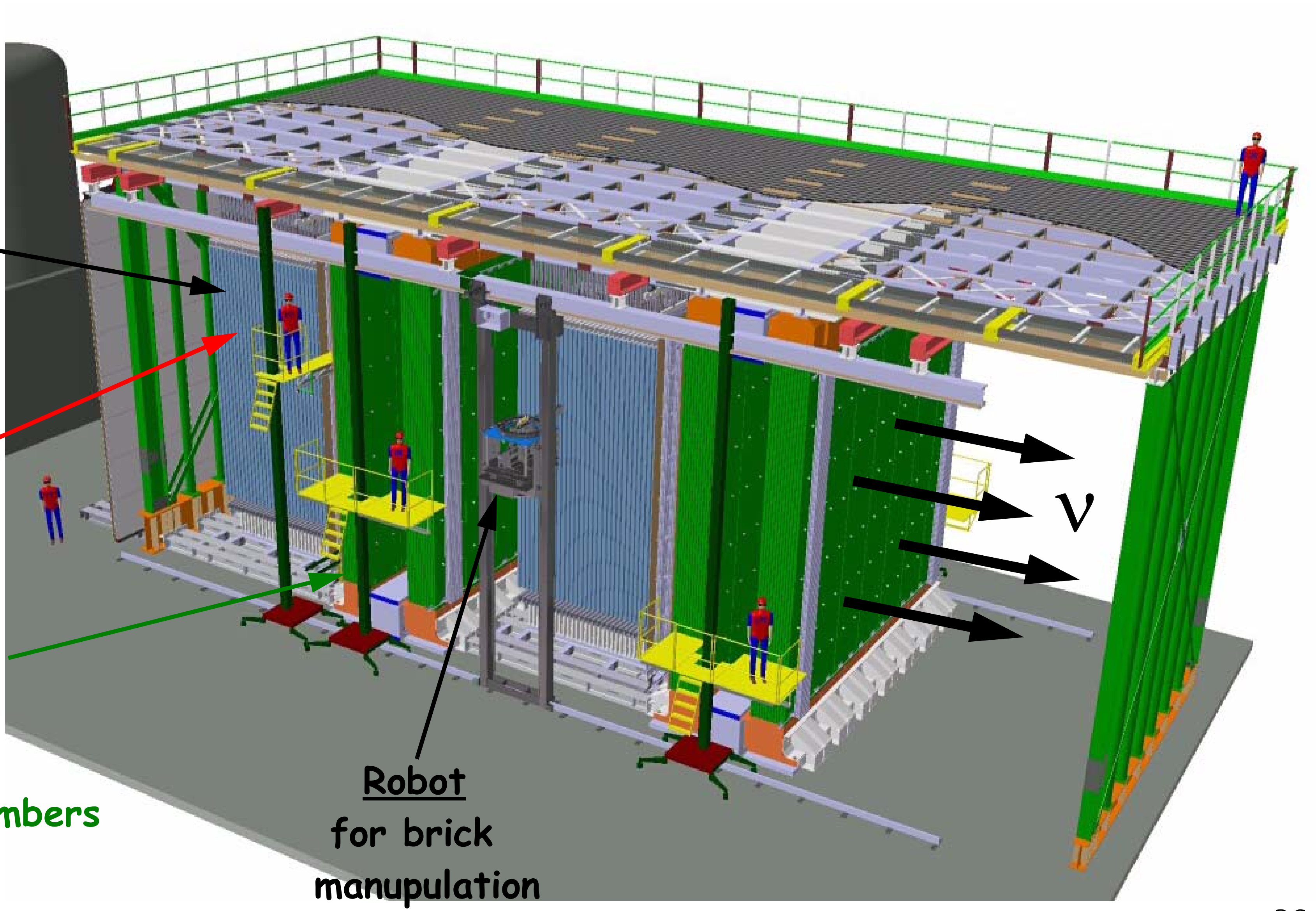
- **CNGS at CERN shoots neutrinos on experiments located 732 km away in Italy.**



Long baseline neutrino experiments

➡ The OPERA experiment

- The Opera experiment is using **photographic emulsions** to look for ν_τ.



Neutrino Target
Bricks made of
lead plates
& emulsions

Scintillator walls

Muon spectrometer
Magnets
Drift tubes
Resistive Plate Chambers

Robot
for brick
manupulation

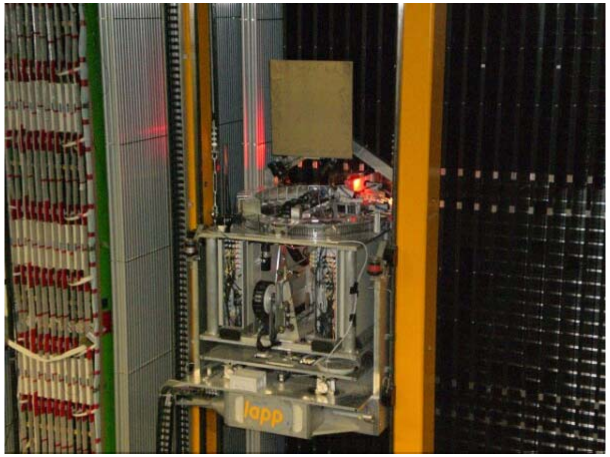
Long baseline neutrino experiments

The OPERA experiment

The Opera experiment down in its underground hall.

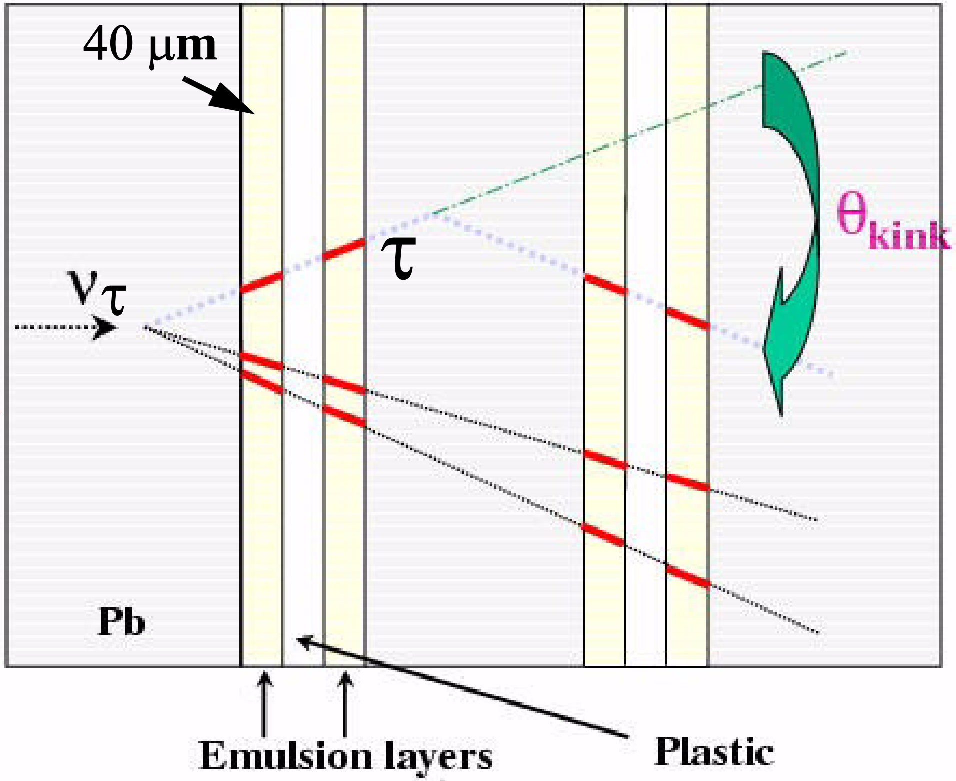
150,000 Lead/emulsion bricks are used in the target.

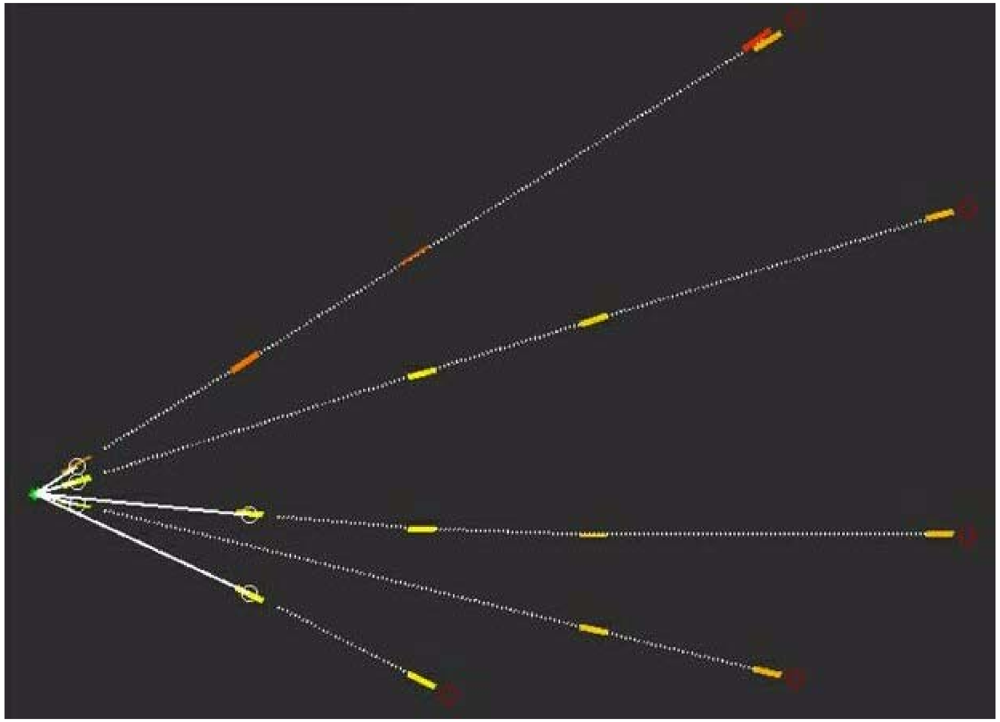
The brick robot



Long baseline neutrino experiments

- The experiments is looking for events with kinks which show that tau neutrinos have interacted with the lead plates. 2-3 ν_τ events per year are expected if oscillation occur.





- Sofar (2008) only events with interactions of muon neutrinos in the lead have been observed.

Neutrino oscillations

Present status

SNO Solar: $\nu_1 - \nu_2$

$\Delta m^2 = 7.6 \times 10^{-5}\ eV^2$

$\theta = 34^o$

Kamiokande Atm: $\nu_2 - \nu_3$

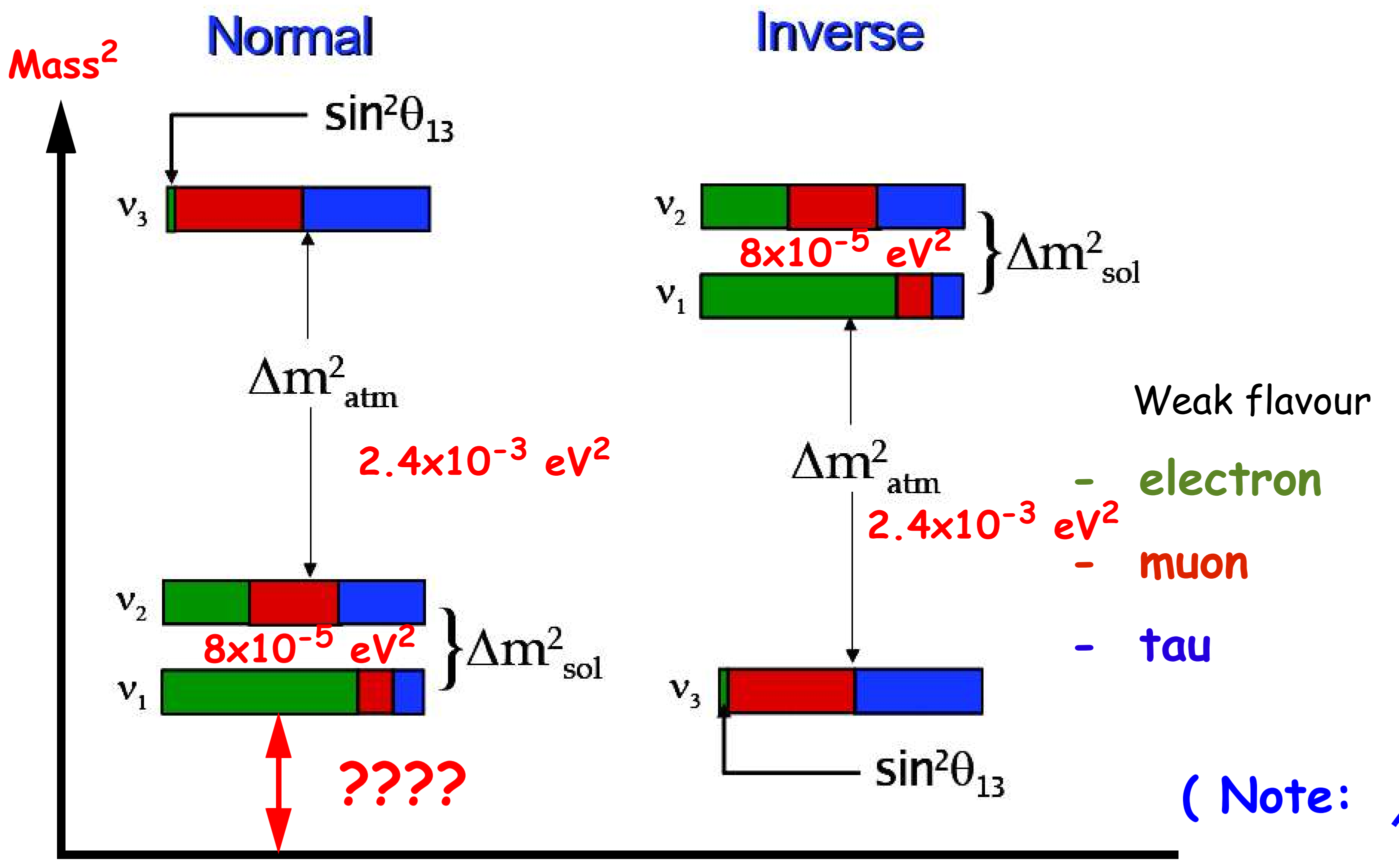
$2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-3}\ eV^2$

$\theta > 36^o$

MINOS Atm: $\nu_2 - \nu_3$

$\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$

$\theta = 45^o$



(Note: $\sqrt{\Delta m^2} \neq m_1 - m_2$)

Extra-galactic neutrinos

➡ Supernova explosion

- The Kamiokande and IMB detectors recorded a burst of neutrino interactions during 15s on February 23, 1987.

- They came from an explosion of the SN1987a supernova which is 160,000 light years away. It was the first time extra-terrestrial neutrinos, not coming from the sun, was observed.

Supernova SN1987a as seen by the Hubble telescope: →

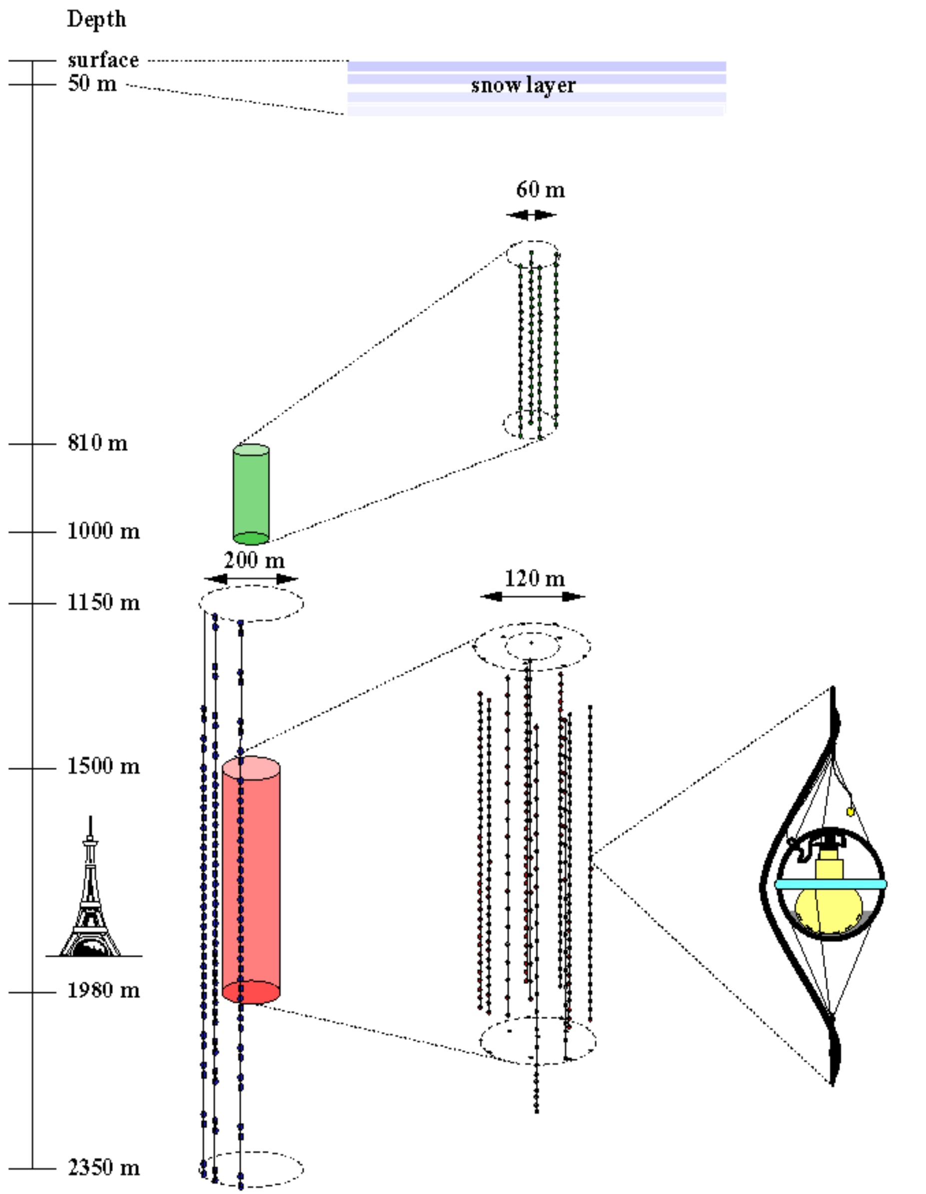
Extra-galactic neutrinos

➡ The AMANDA experiment

- Experiments have been built specially to look for TeV neutrino sources from outside of our galaxy.

- One of these experiments is called AMANDA and has Swedish participation.

- The experiment is situated on the South Pole and consists of strings of photomultipliers in holes drilled deep down into the ice.



AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Extra-galactic neutrinos

- A neutrino interaction in the ice would produce charged particles which would give rise to Cerenkov light which can be detected by the photomultipliers.
- The pattern of the light makes it possible to determine the direction and energy of the neutrinos.
- No extra-galactic neutrinos have been detected so far.

Extra-galactic neutrinos

The ICECUBE experiment

- A new much larger experiment called ICECUBE is now being built using the same technique and it is expected to be ready by 2011.
- It will have 80 strings with 4200 photomultipliers buried between 1450m and 2450 m down into the ice.
- On the surface will be a detector (IceTop) with 4 pms in two surface tanks at each string location. It will cover one square kilometer.