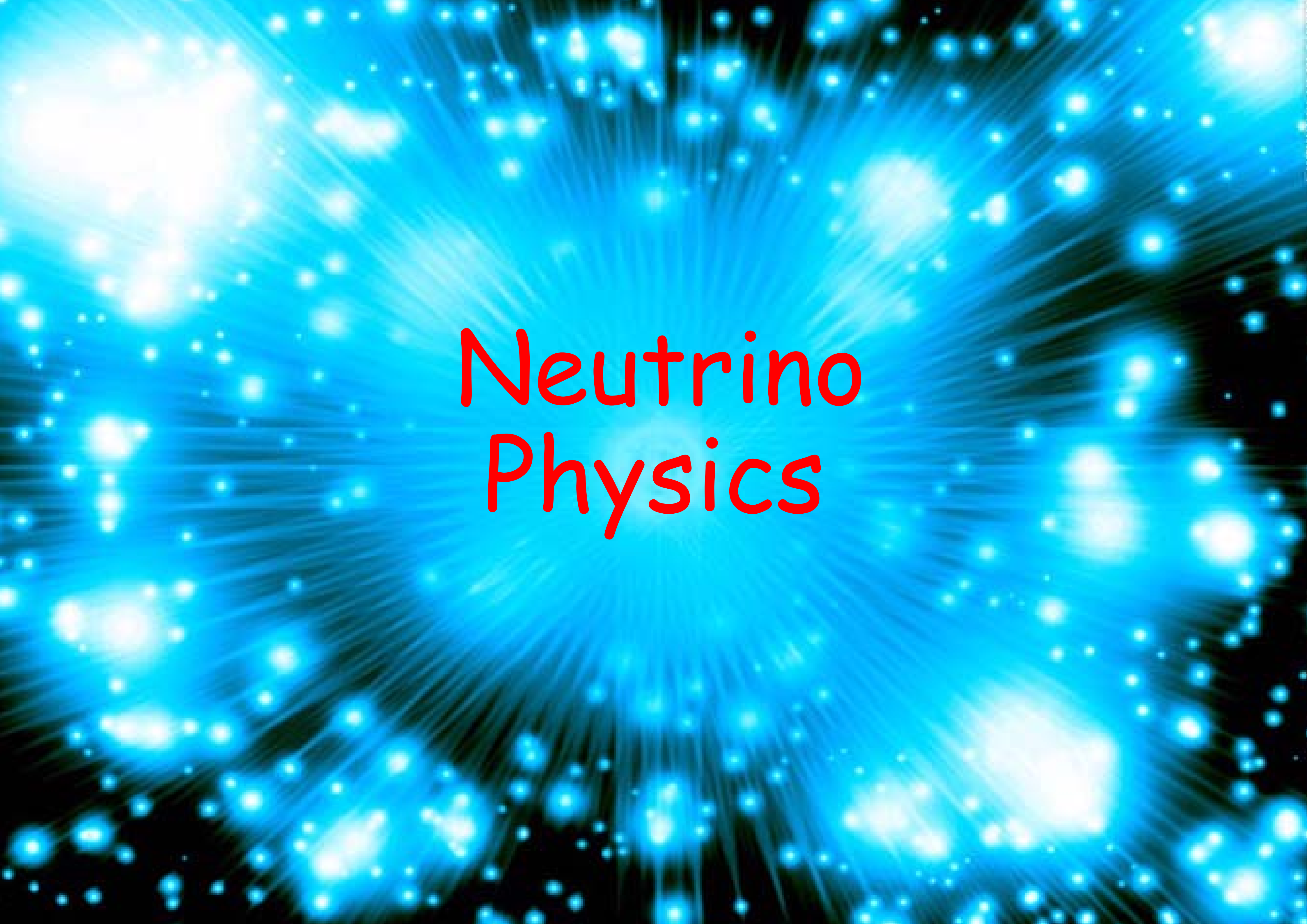


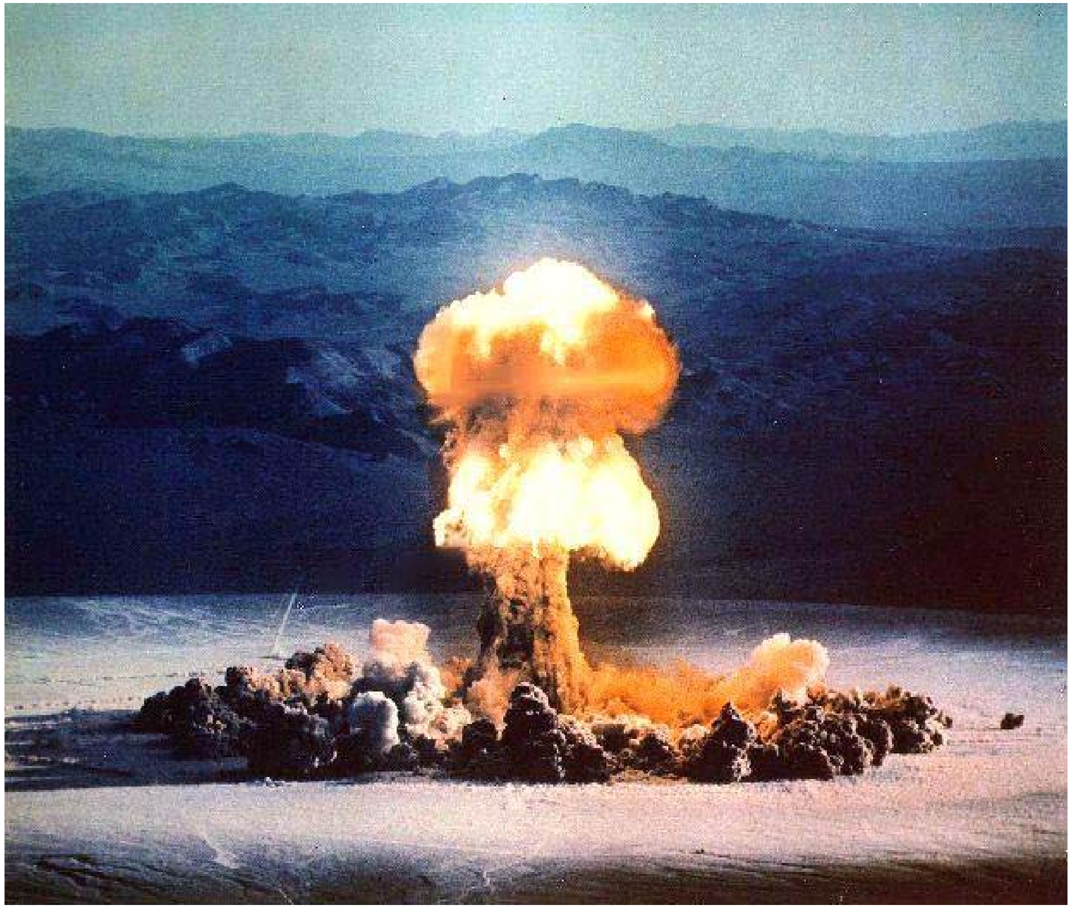
Neutrino Physics

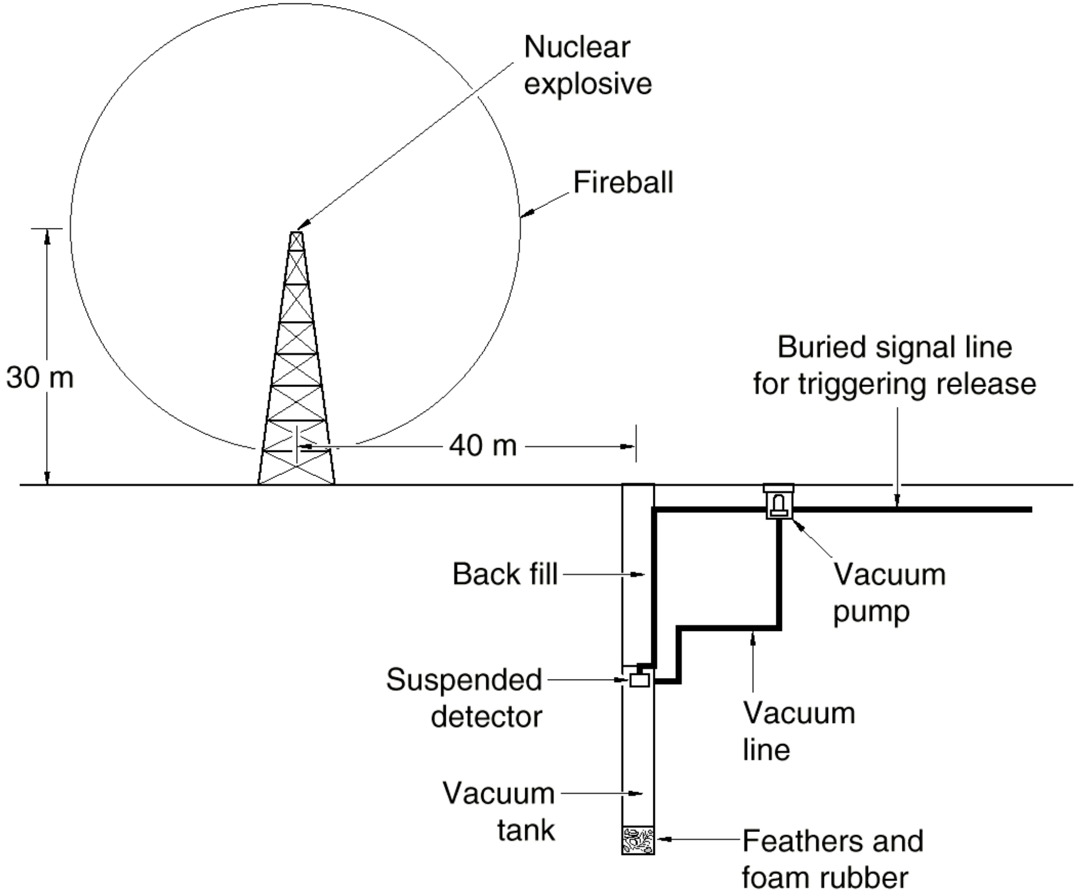
The neutrino

- Postulated by Pauli ⇨ β-decay has continuos energy spectrum.
- Fermi + neutrino ⇨ theory for weak interactions.
- The neutrino is only interacting weakly ⇨ very low cross section
- Neutrinos can traverse the earth ⇨ difficult to detect and study
- The neutrino is a fermion (spin 1/2 particle)
- It exists in only one helicity state.
- Massless neutrinos are left-handed
- Anti-neutrinos are right-handed.

The neutrino

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



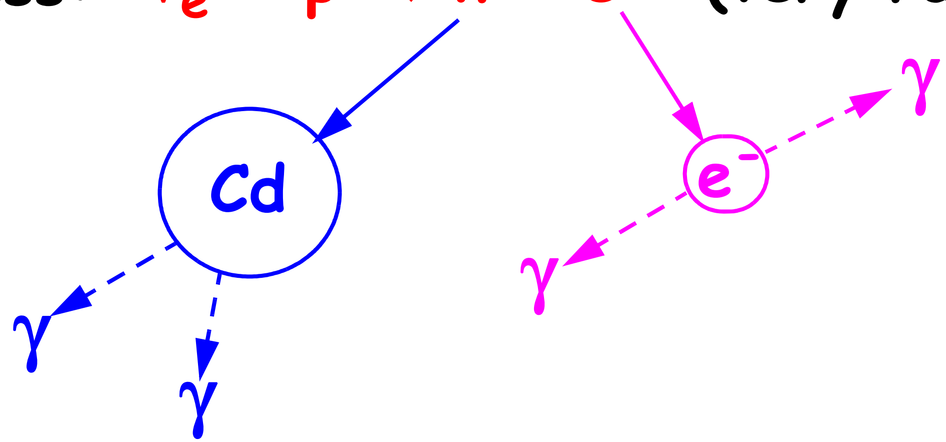


- The project was approved at Los Alamos but ....

The discovery of the neutrino

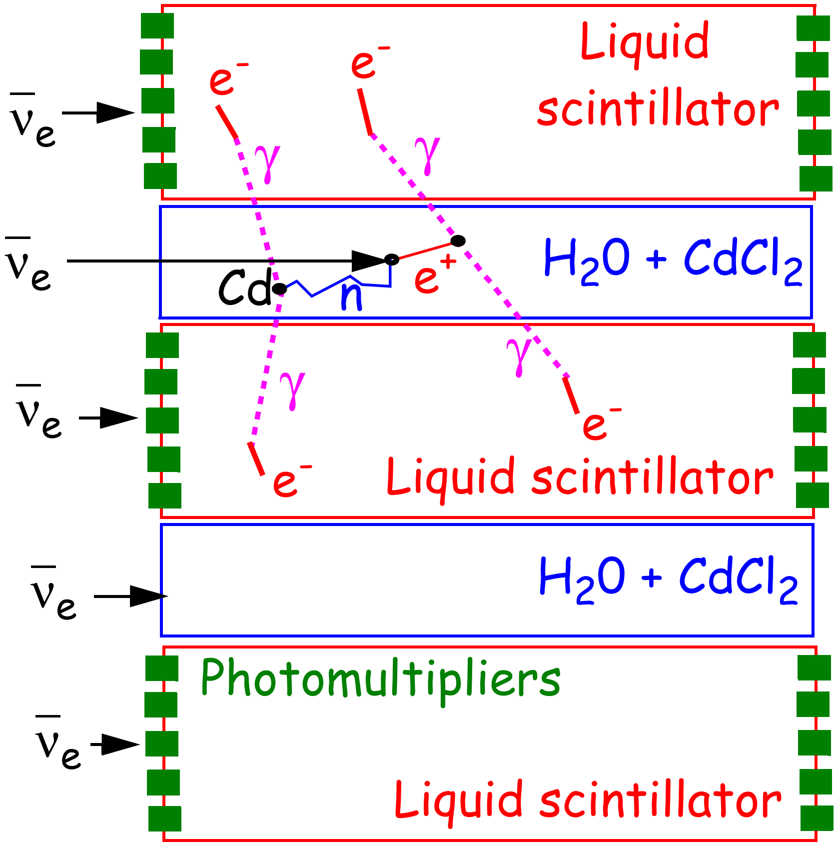
➡ The discovery of the electron neutrino (1956)

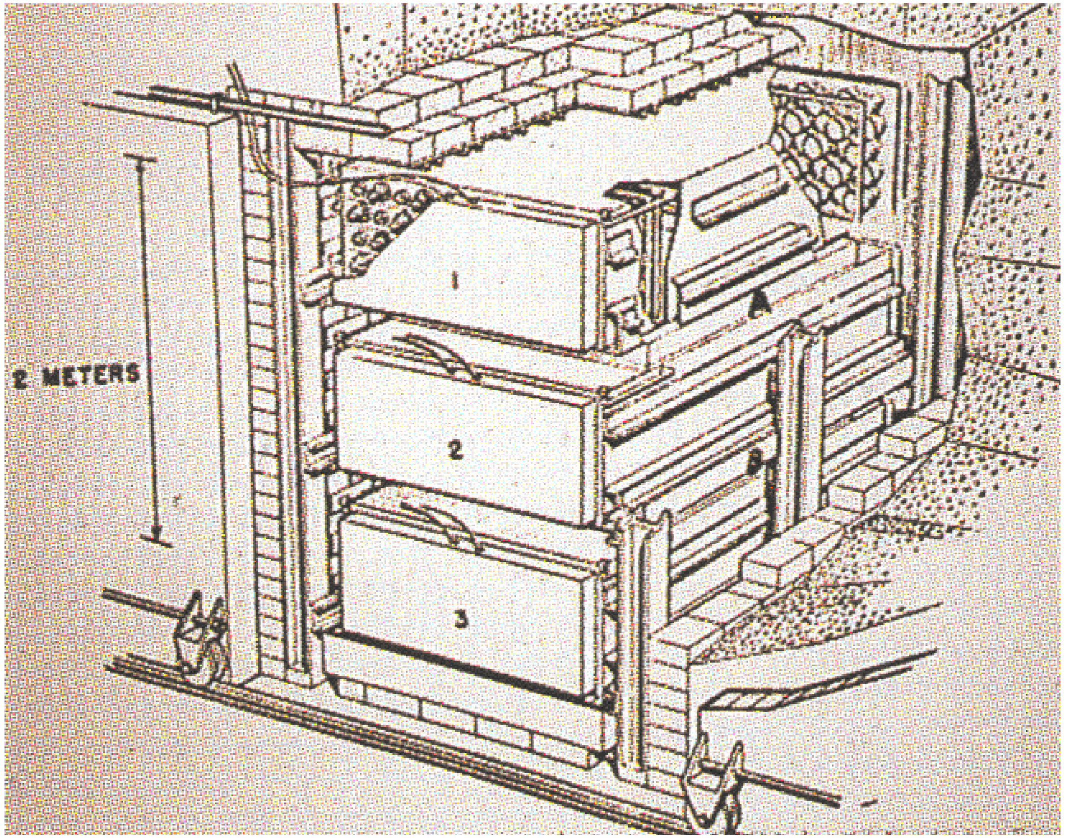
- 26 years between Pauli's idea and experimental discovery.
- Discovery in the Cowan-Reines experiment at the Savanna River nuclear reactor.
- A reactor produces neutrons ⇨ $n \rightarrow p + e^- + \bar{\nu}_e$ ⇨ anti-neutrino flux of 10^{13} $cm^{-2}s^{-1}$
- Detection process: $\bar{\nu}_e + p \rightarrow n + e^+$ (very rare process)



The discovery of the neutrino

- **Two tanks of water** with Cadmium chloride
- **Three tanks** with liquid **scintillator** between the water tanks

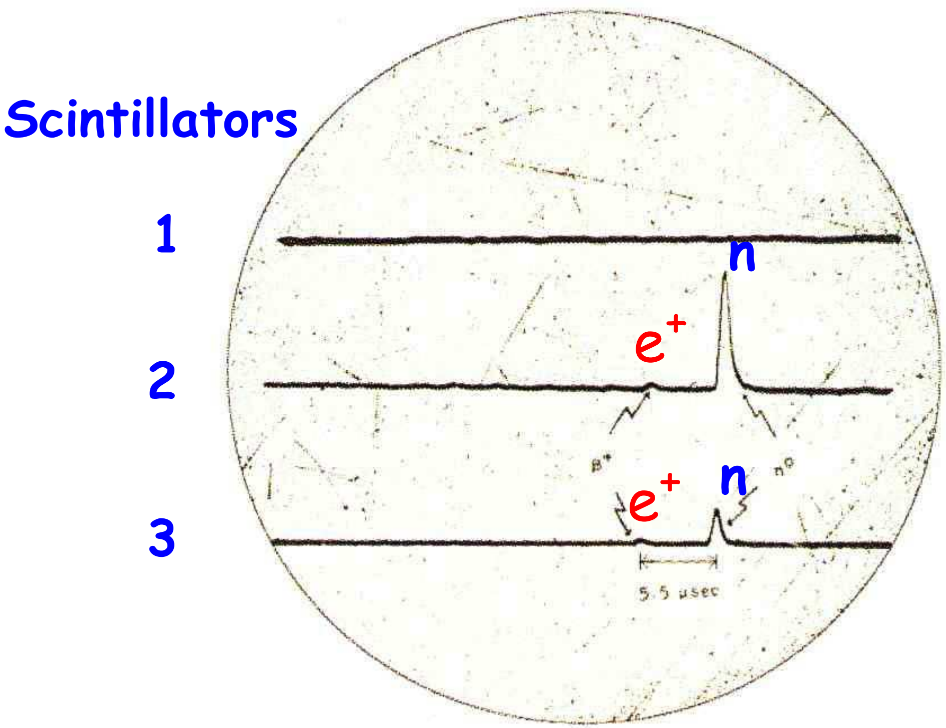


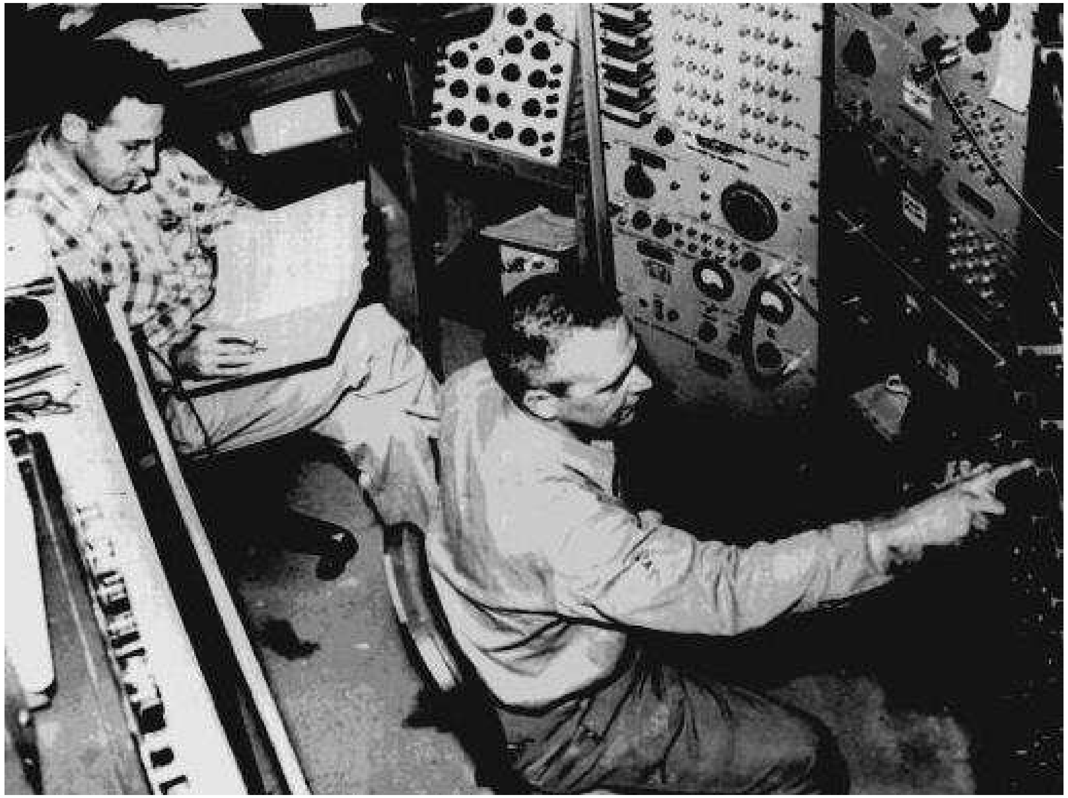


- **Photons** produce electrons by the Compton effect.
- **Electrons** produce light in the scintillators

The discovery of the neutrino

- Signal signature ⇨ two small signals at the same time from e^+ & large signal after few μs from the neutron.
- 2 neutrino events and 1 background event per hour.





The discovery of the neutrino

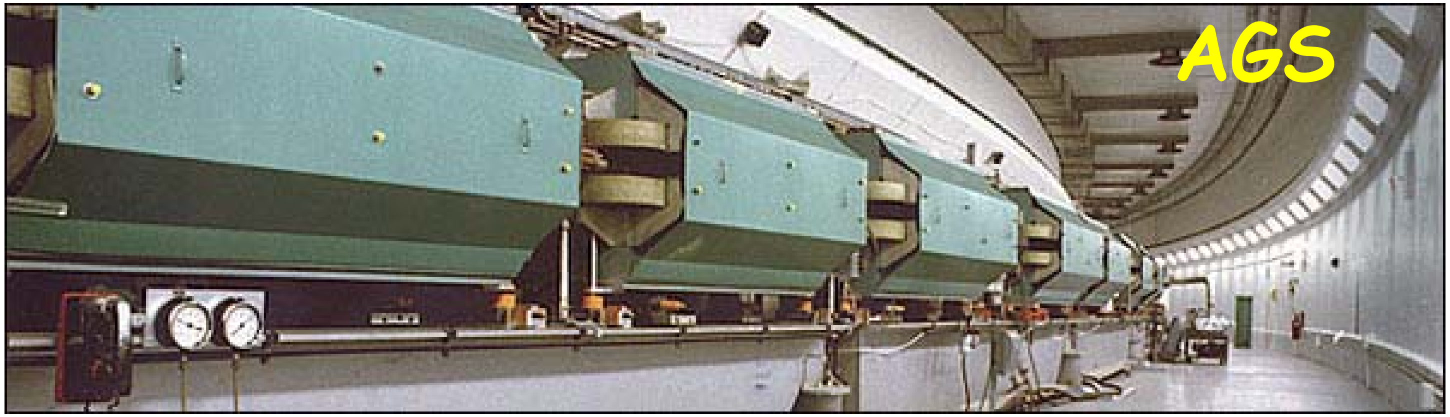
➡ The discovery of the muon neutrino (1962)

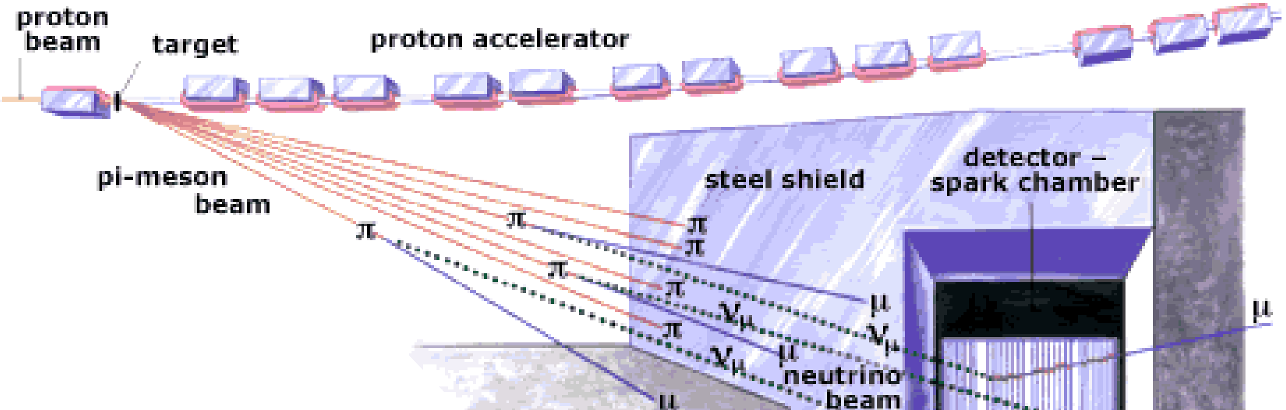
- Several neutrino flavours ???
- AGS accelerator ⇨ produced the world's first neutrino beam.
- Step 1. 15 GeV protons on a Beryllium target.
- Step 2. Select pions.
- Step 3. Let the pions decay to muons and muon neutrinos.
- Step 4. Stop the muons with a 13 m thick steel shielding.

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

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

The discovery of the neutrino

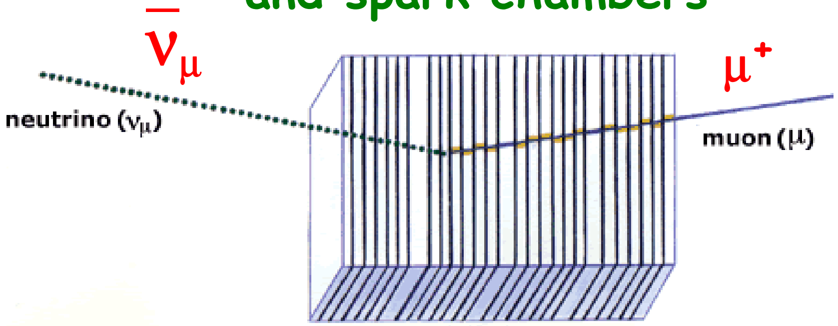




$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (10^{-8}\,s)$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (10^{-6}\,s)$$

Sandwich of Aluminium plates and spark chambers



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

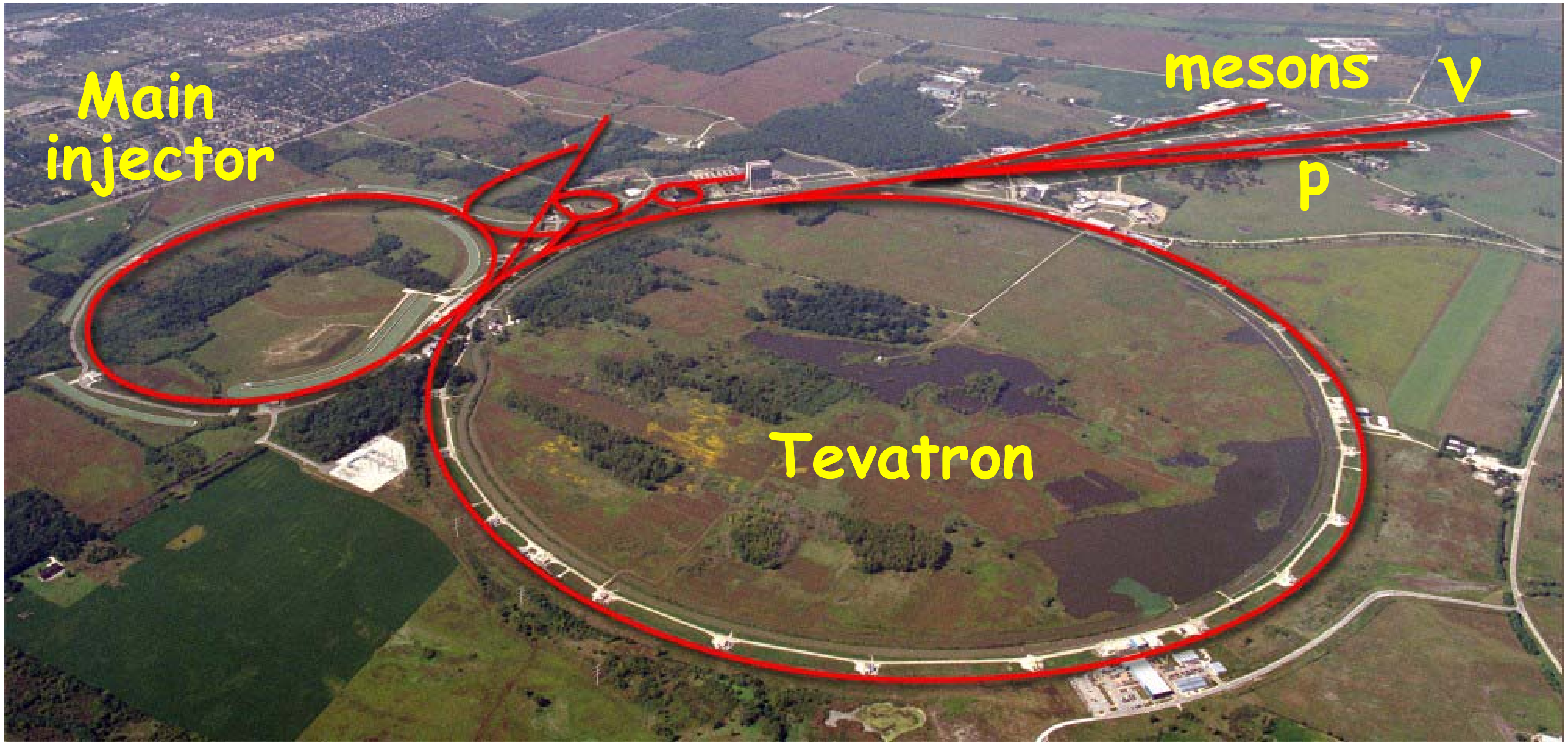
$$\nu_\mu + n \rightarrow p + \mu^-$$

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

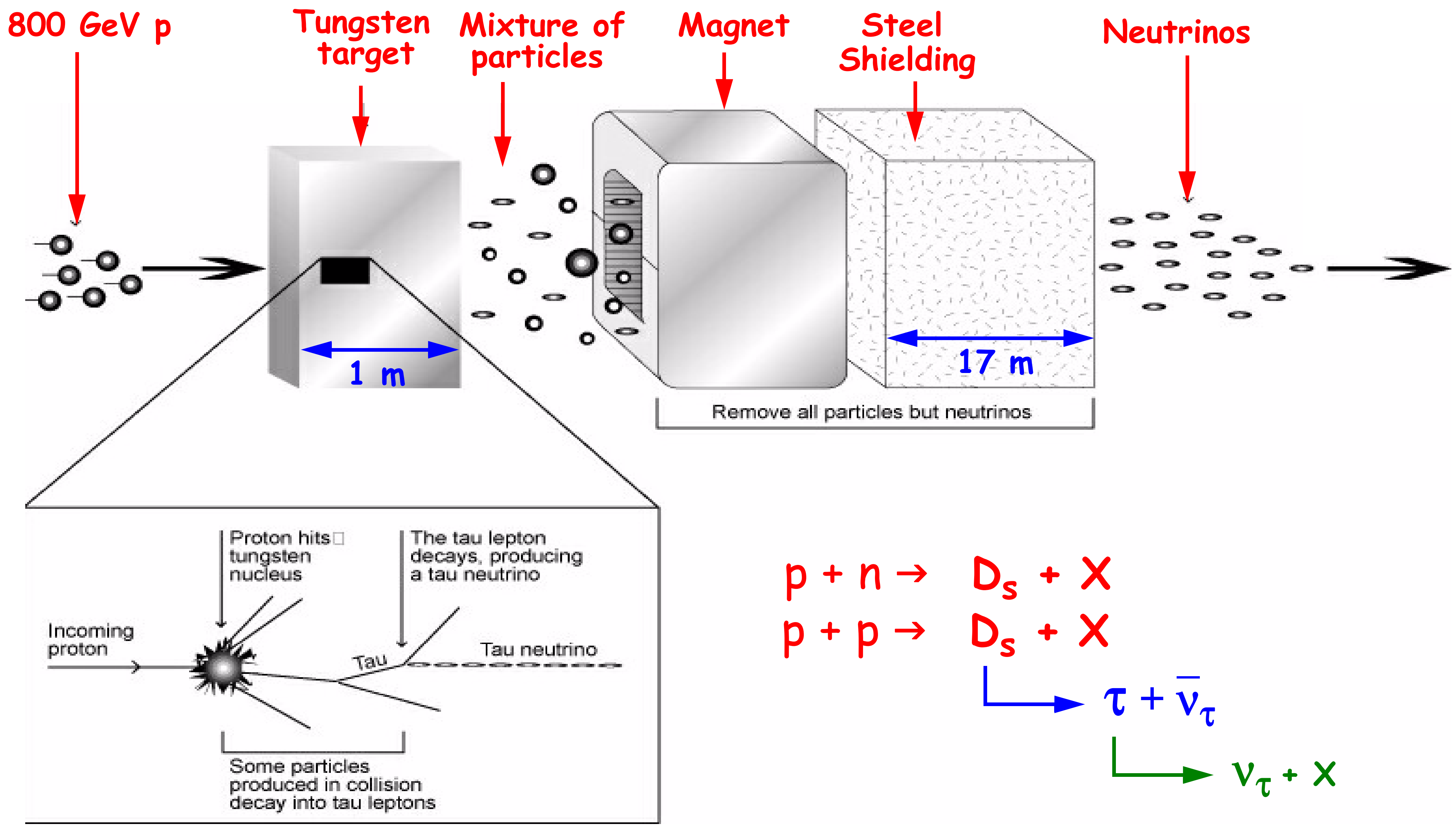
The discovery of the neutrino

➡ The discovery of the tau neutrino (2000)

- **The tau neutrino was discovered at Fermilab.**
- **Almost 40 years after the muon neutrino.**



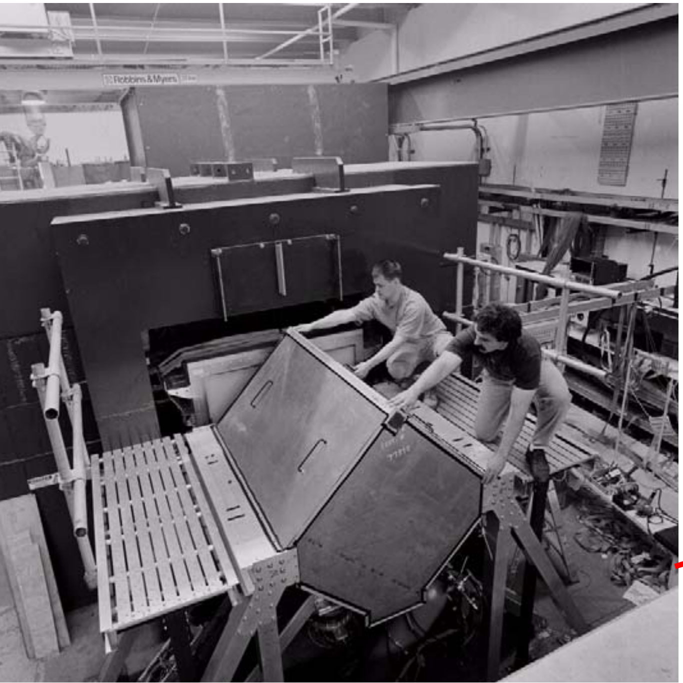
The discovery of the neutrino

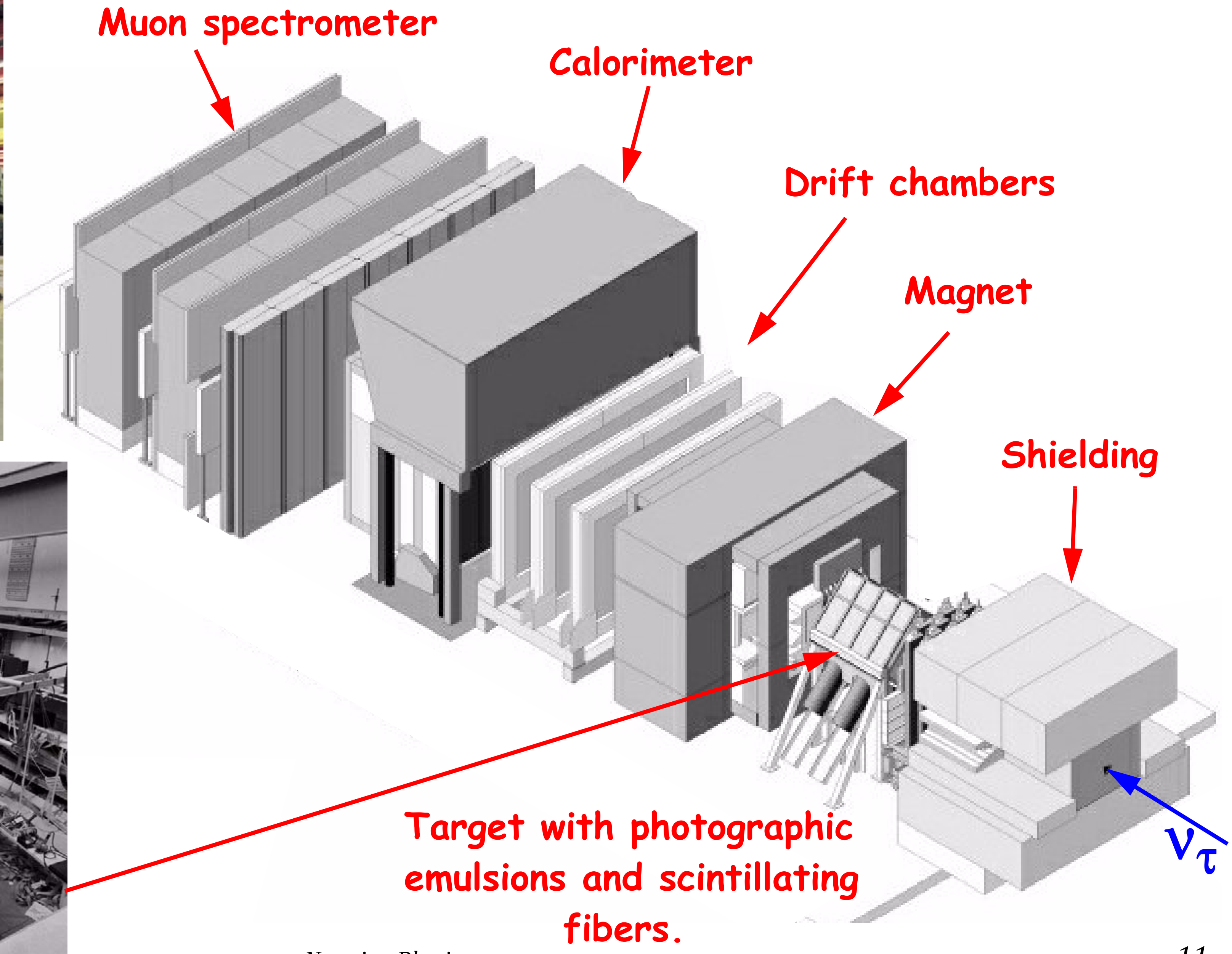


$$p + n \rightarrow D_s + X$$
$$p + p \rightarrow D_s + X$$
$$\quad \hookrightarrow \tau + \bar{\nu}_\tau$$
$$\quad\quad \hookrightarrow \nu_\tau + X$$

The discovery of the neutrino

DONUT: Detector for direct observation of tau neutrinos.





The discovery of the neutrino

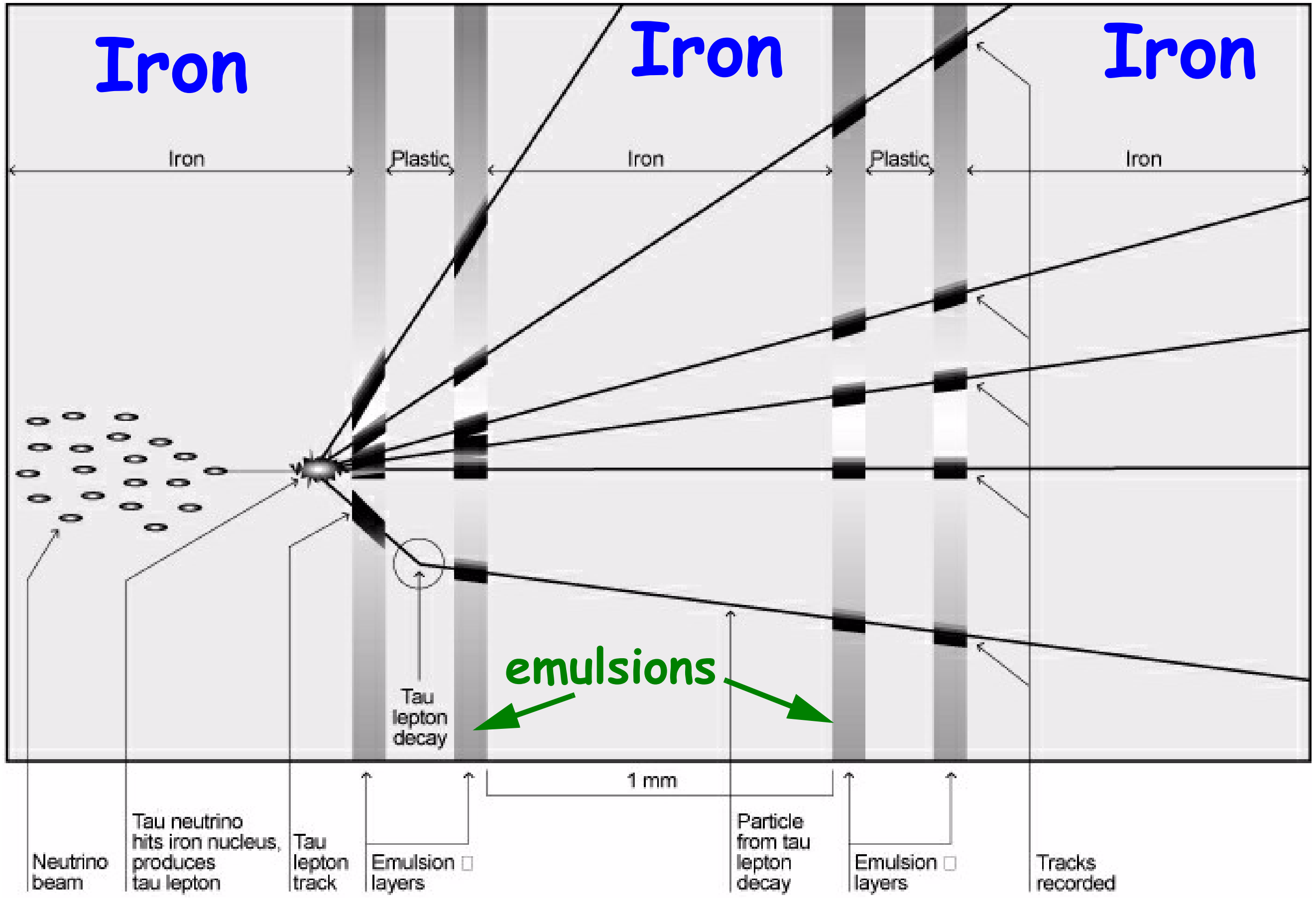
- The reactions:

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

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

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

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



- One ν_τ out of a million would interact.

- Years of running + analysis of 6 million events ⇨ 4 events with all the signatures of a tau to tau-neutrino decay.

- Characteristic kink recorded by the photographic emulsions.

Neutrino mass

- Direct measurement of the neutrino mass $\Rightarrow$ only upper limits.

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

  $m_\nu < 2.1$ eV

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

  $m_\nu < 170$ keV

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

  $m_\nu < 18.2$ MeV

Neutrino oscillations

- Neutrino **masses** $\neq 0$ ⇨ **neutrino mixing**.
- Assume only **two neutrino flavours** ⇨

  the electron and muon states are linear combinations of two mass states ν_1 and ν_2 with 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**.
- **Neutrino oscillations**: pure beam of ν_e develops a ν_μ component
  pure beam of ν_μ develops a ν_e component

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

$$\begin{cases} \nu_e(t) = \nu_1(0)\cos\theta\, e^{-iE_1t} + \nu_2(0)\sin\theta\, e^{-iE_2t} \\ \nu_\mu(t) = -\nu_1(0)\sin\theta\, e^{-iE_1t} + \nu_2(0)\cos\theta\, e^{-iE_2t} \end{cases}$$

the electron neutrino state at t

the muon neutrino state at t

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

- Combining this gives:

$$\begin{cases} \nu_e(t) = (\nu_e(0)\cos\theta - \nu_\mu(0)\sin\theta)\cos\theta\, e^{-iE_1t} + (\nu_e(0)\sin\theta + \nu_\mu(0)\cos\theta)\sin\theta\, e^{-iE_2t} \\ \nu_\mu(t) = -(\nu_e(0)\cos\theta - \nu_\mu(0)\sin\theta)\sin\theta\, e^{-iE_1t} + (\nu_e(0)\sin\theta + \nu_\mu(0)\cos\theta)\cos\theta\, e^{-iE_2t} \end{cases}$$

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) ⇨ the distance (L) between the detector and the source of neutrinos.

- The probability that a neutrino with flavour 1 oscillate to flavour 2:

$\Delta m^2 = |m_1^2 - m_2^2|$
the squared mass difference (in eV^2)

neutrino flight path (in km)

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

mixing angle between flavour 1 and 2

neutrino energy (in GeV)

Neutrino oscillations

Neutrino sources

The sun

Cosmic rays ("atmospheric neutrinos")

Secondary accelerator beams

Nuclear reactors

Natural radioactivity

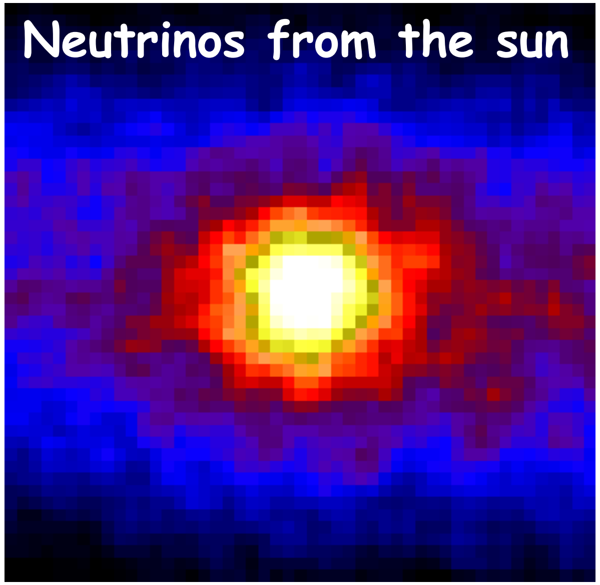
Supernovas

The Big Bang

- **Neutrino detection ⇨ neutron interaction ⇨ e,μ detection**

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

The solar neutrino problem



- **The solar neutrino problem:**

  Fewer ν_e are detected than what is predicted by theory.

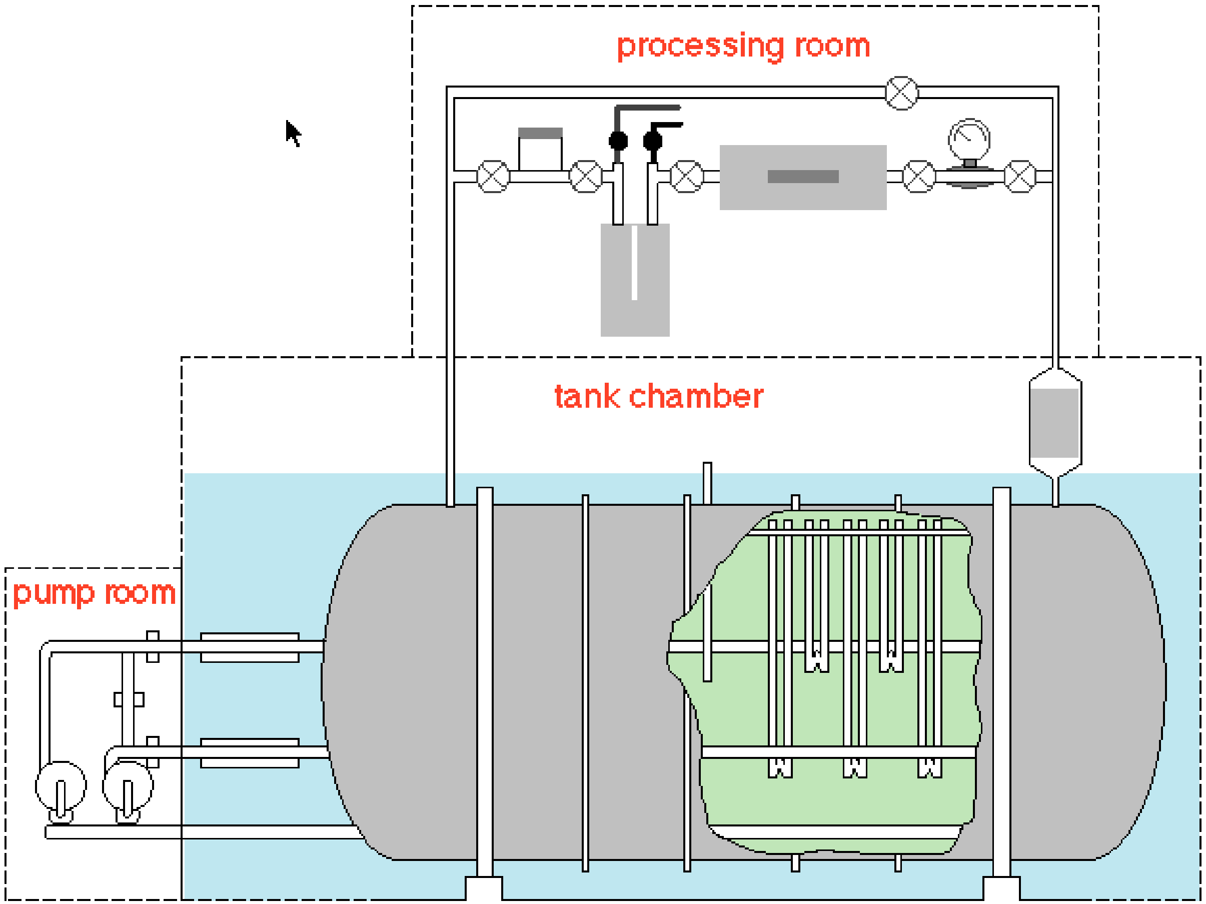
- **Detection methods:** →

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

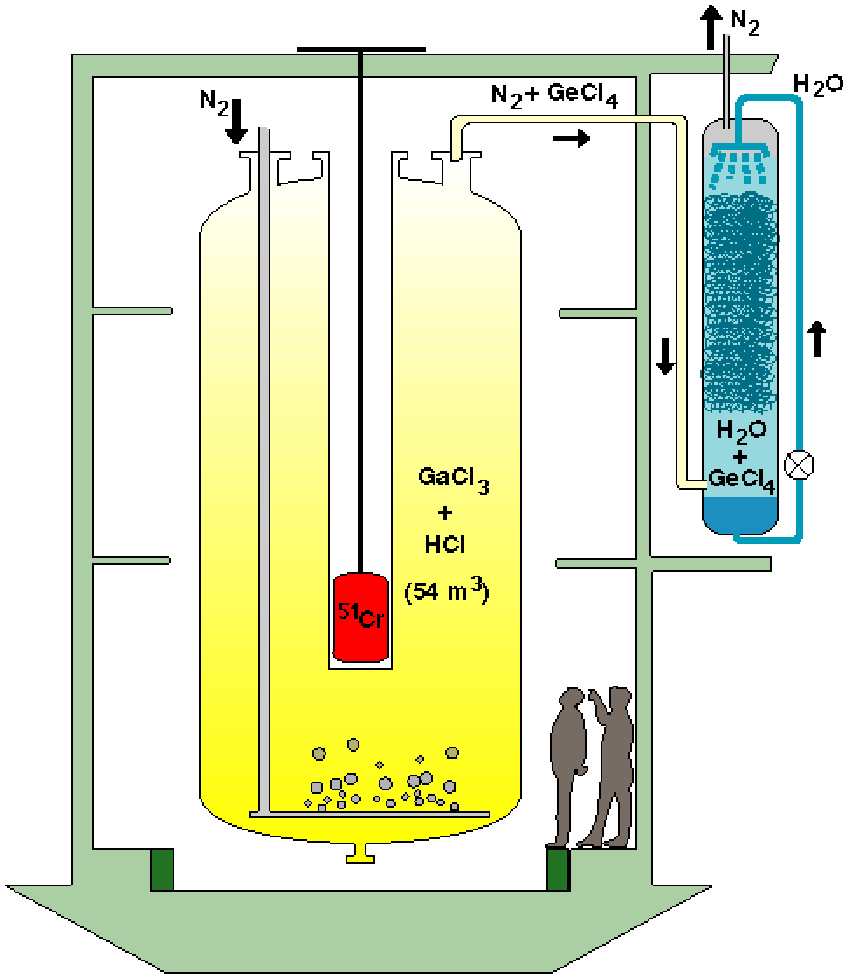
- **The experiments ⇒ underground tanks filled with liquid medium.**

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

- Production **reactions**:

$p + p \rightarrow {}^2H + e^+ + \nu_e$	$E_{\nu,max} = 0.42$ MeV (85%)
$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$	$E_{\nu,max} = 0.86$ MeV (15%)
${}^8B \rightarrow {}^8Be + e^+ + \nu_e$	$E_{\nu,max} = 15$ MeV (0.02%)

- GALLEX measures all. Homestake measure only the last one.
- SNU is a "solar neutrino unit": 1 capture / 1 second / 10^{36} target atoms

	theory	measurement
Homestake:	7.9±0.9 SNU	2.56±0.16 SNU
GALLEX:	129±8 SNU	71±4 SNU

- Lack of electron neutrinos coming from the sun ⇨ explained by **neutrino oscillations** that turn them into ν_μ and ν_τ.

The solar neutrino problem

➡ The Sudbury Neutrino Observatory

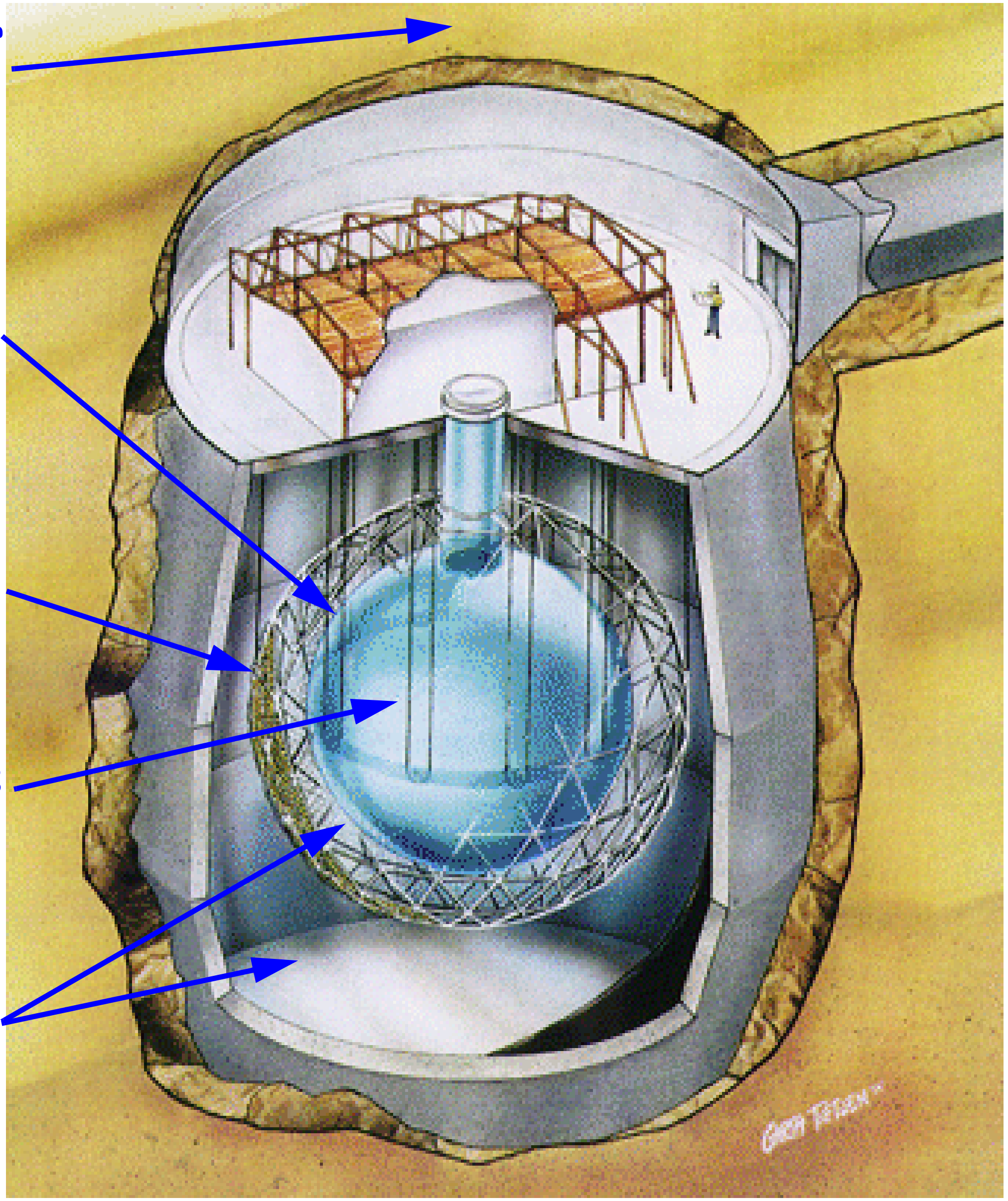
2 km under ground

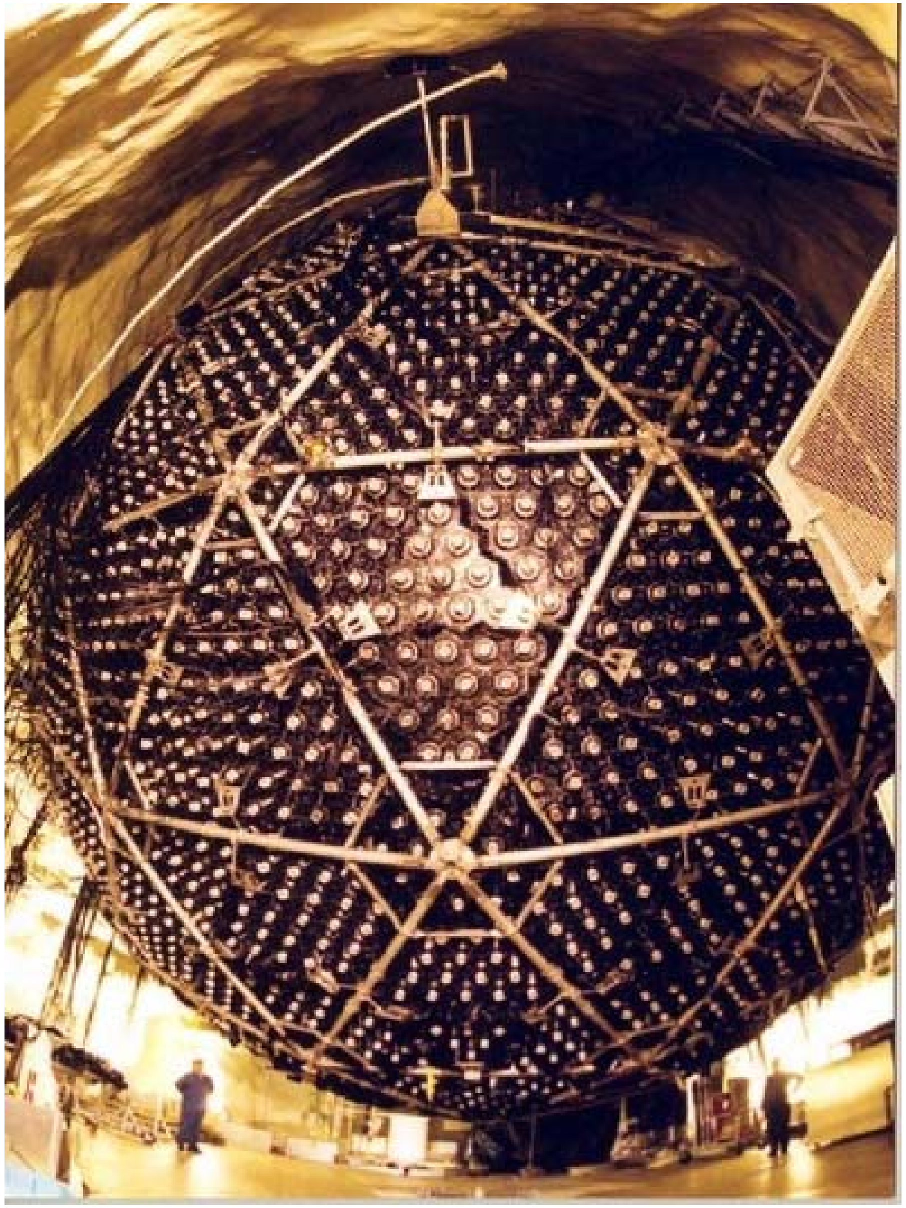
12m acrylic vessel

10,000 photo-multipliers

1000 tonnes D_2O

7000 tonnes H_2O



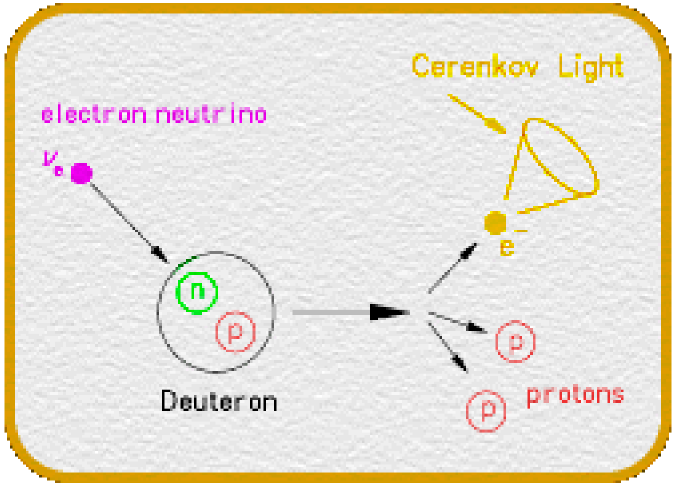


The solar neutrino problem

- The SNO experiment could measure neutrinos in three ways:

Charged current reactions

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

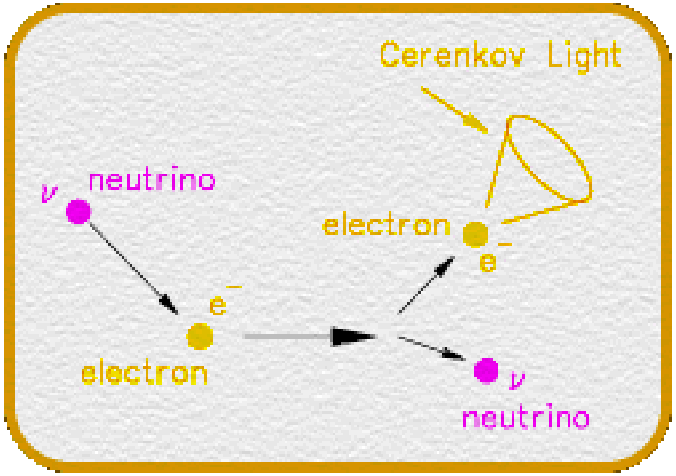


Only sensitive to electron neutrinos.

Electrons ⇨ Cherenkov light ⇨ Pattern of photo multiplier signals ⇨ Neutrino direction

Electron scattering

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

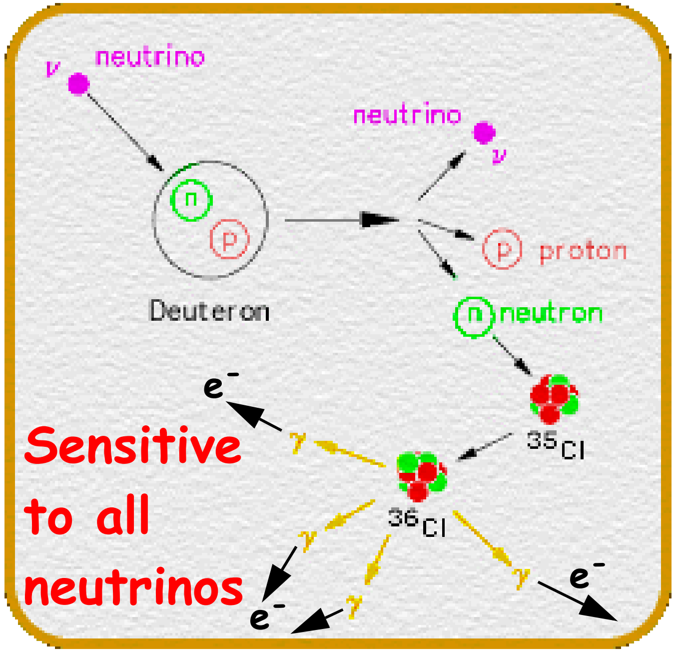


Mostly sensitive to electron neutrinos.

Electrons ⇨ Cherenkov light ⇨ The amount of Cerenkov light ⇨ Neutrino energy

Neutral current reactions

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

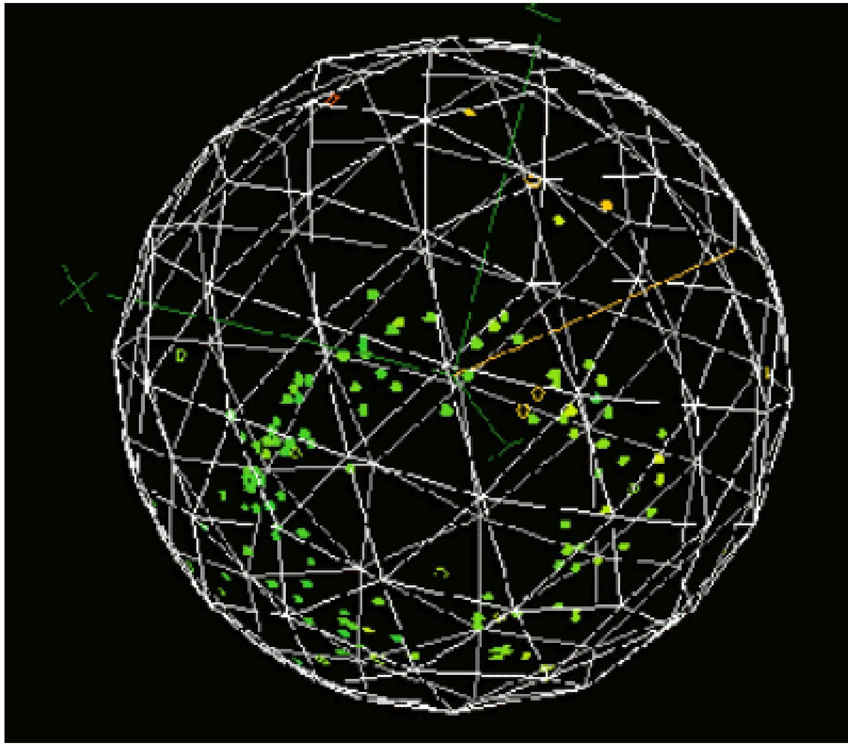


Sensitive to all neutrinos

Photons ⇨ Compton electrons ⇨ Cherenkov light ⇨ Photomultiplier signals

Neutrons also detected by tritium filled proportional counters.

The solar neutrino problem



- SNO could for the first time measure the electron neutrino flux and the total neutrino flux.
- Neutral current measurement:

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

Solar model is correct

- Charged current measurement:

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

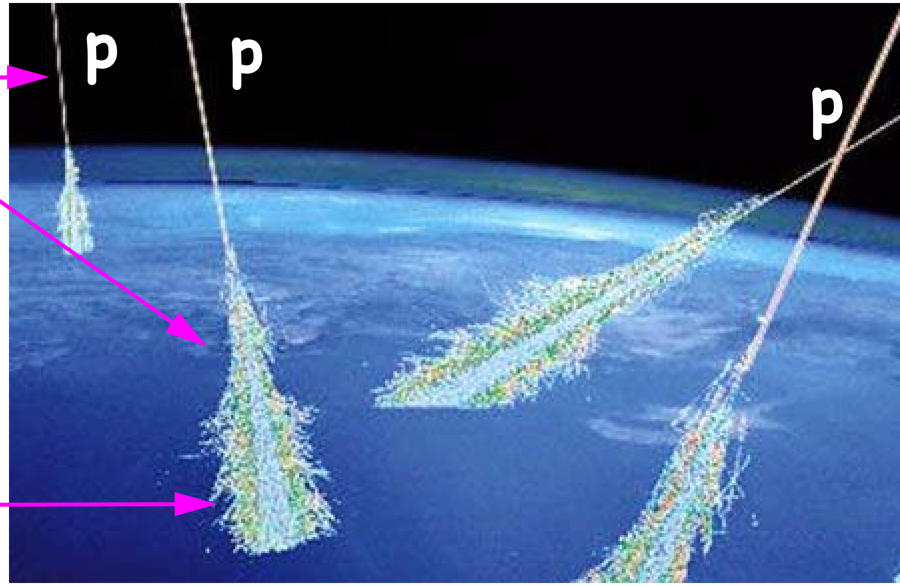
Neutrino oscillations

- The results (combined with other experiments)

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

The atmospheric neutrino problem

- Cosmic high-energy radiation
- Hadronic showers



$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

- The experiments have to be shielded against muons ⇨ deep under ground.
- Detection: neutrino-neutron interactions.
- The probability is very low ⇨ a very large detector volume.
- Prediction (from π decay) ⇨ twice as many ν_μ as ν_e
- The atmospheric neutrino problem: One measure the same amount !

The atmospheric neutrino problem

- Neutrinos can pass through the earth without interacting

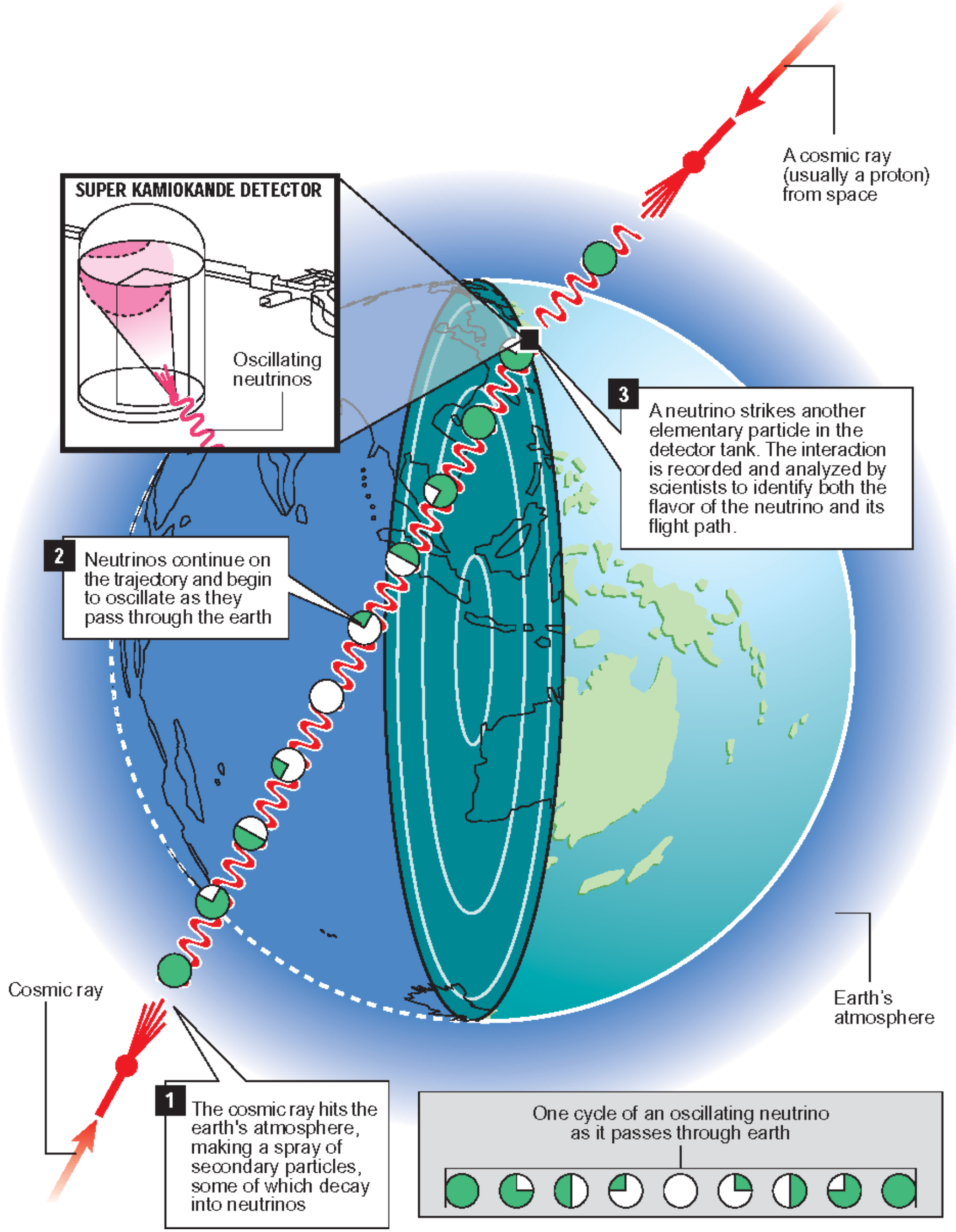
  ⇨

  A neutrino detector can detect neutrinos created in the atmosphere above

  &

  on the other side of the planet.

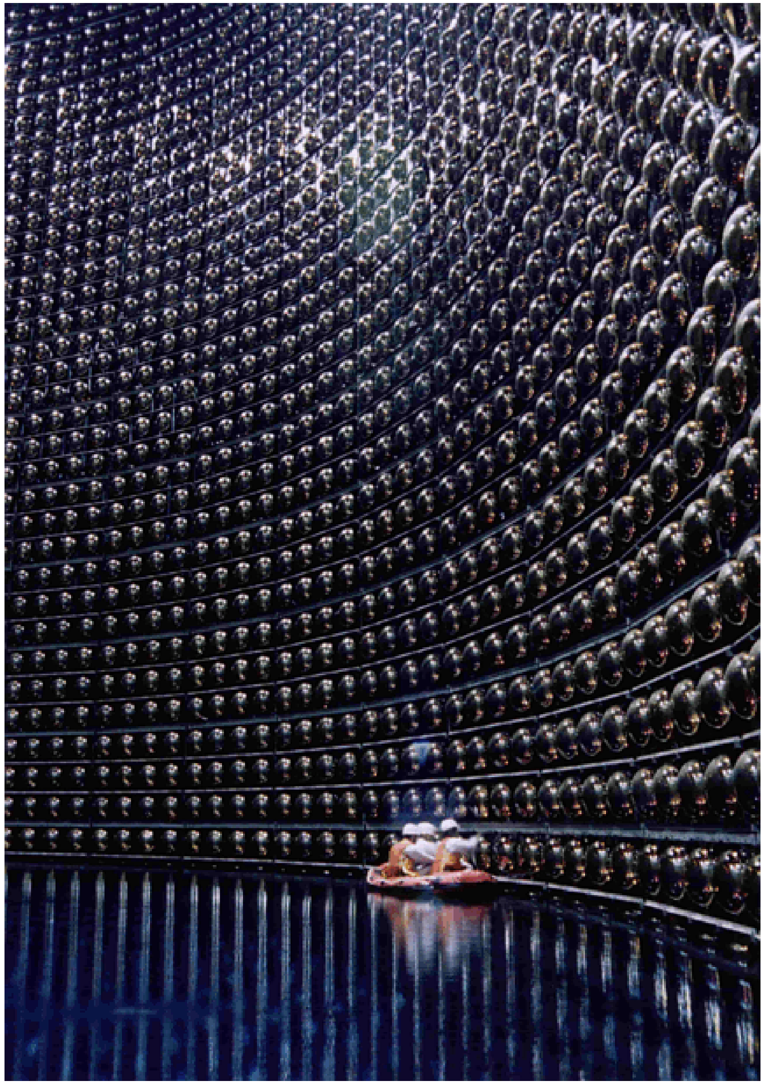
- The neutrinos will have travelled between 15 km and 13,000 km (depending on where in the atmosphere around the planet that they were created).

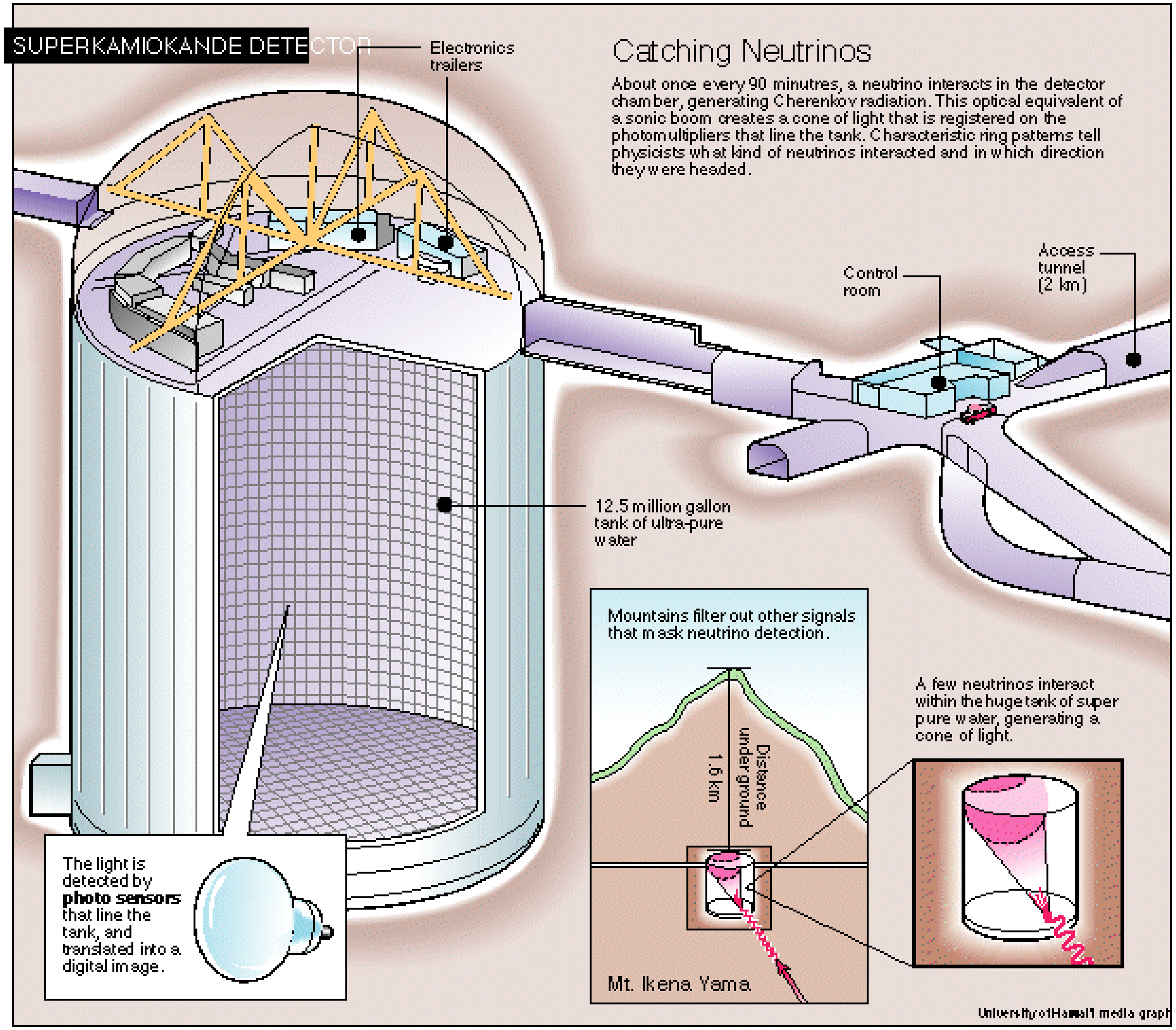


The atmospheric neutrino problem

➡ The Super-Kamiokande detector

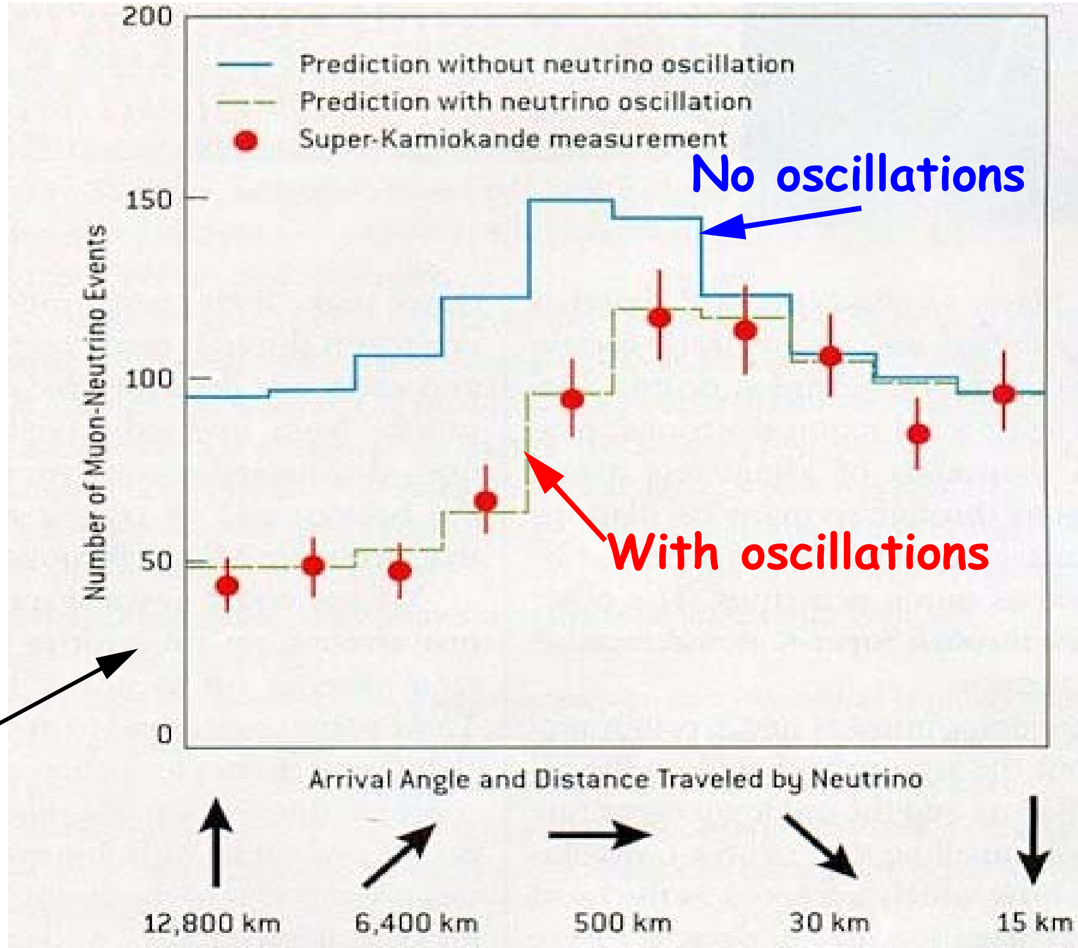
The detector consists of a 50,000 m^3 water tank surrounded by 13,000 photomultipliers.





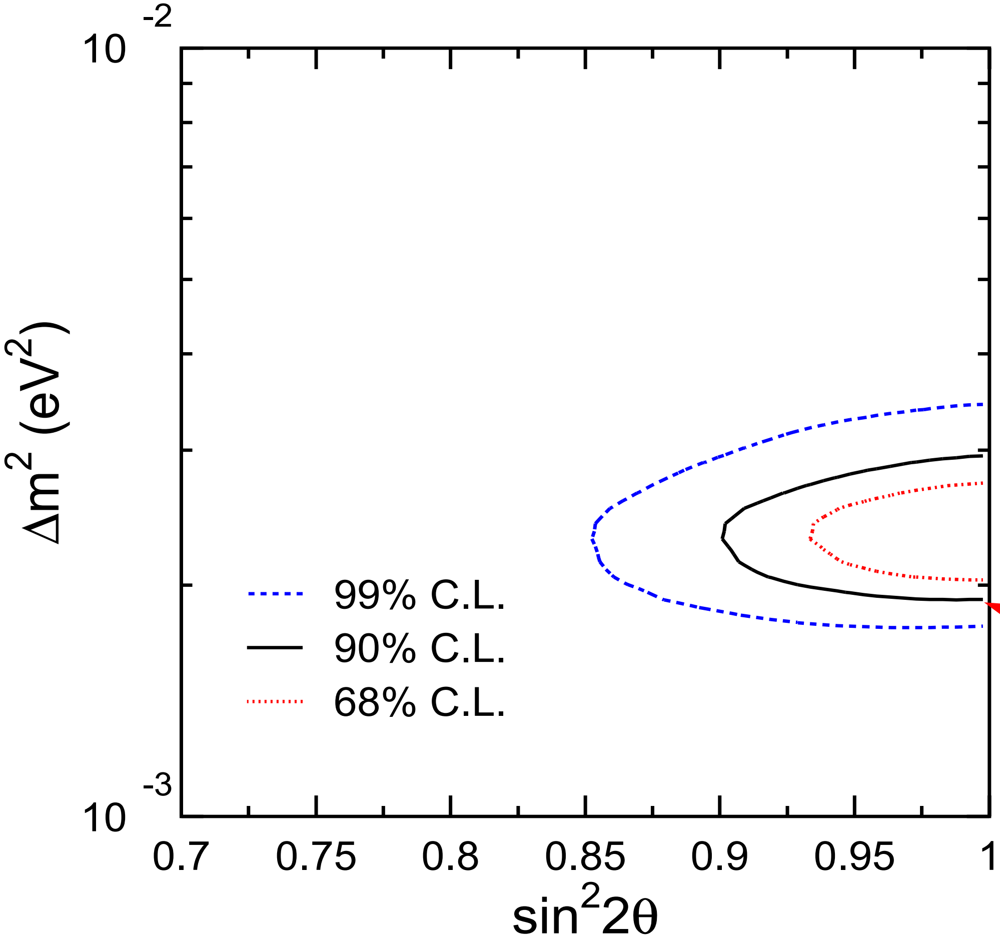
The atmospheric neutrino problem

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



The atmospheric neutrino problem

- Lack of neutrinos with a long travel distance ⇨ evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations ⇨ muon neutrinos had turned into tau neutrinos that were not detected.



- The measurement ⇨ set limits on the mixing angle and the neutrino mass difference:

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

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

Short baseline neutrino experiments

- High intensity proton beams ⇨ target ⇨ kaons and pions ⇨ decays $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ⇨ neutrino beams

- Short baseline experiment: The experiment is less than one km away from the target.

- Long baseline experiment: The experiment is located hundreds of kilometers away from the target.

- NOMAD and CHORUS: Two short baseline experiments at CERN. They were 800 m away from a target hit by protons from the SPS accelerator.

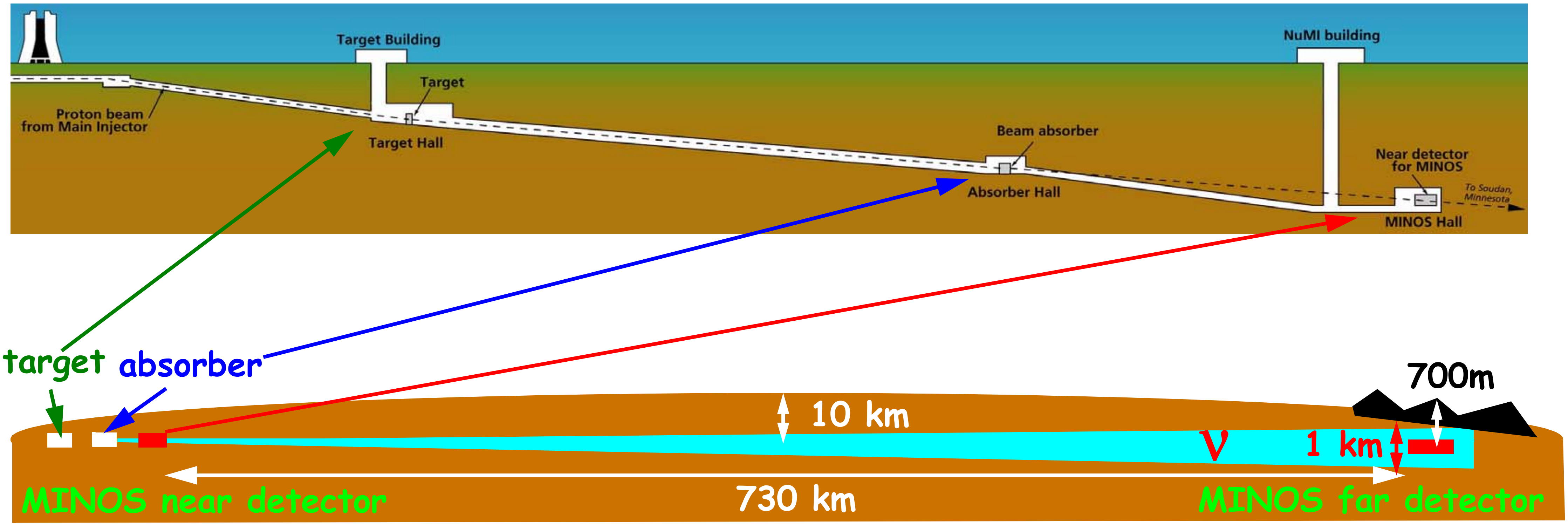
- Goal: Both experiments were searching for $\nu_\mu - \nu_\tau$ oscillations.

- Result: No ν_τ signal was observed.

Long baseline neutrino experiments

➡ The NuMI beam from Fermilab

- **The NuMI beam:** A neutrino beam created at Fermilab.
- The Numi beam points at experiments situated in mines some 730 km away (long baseline experiments).



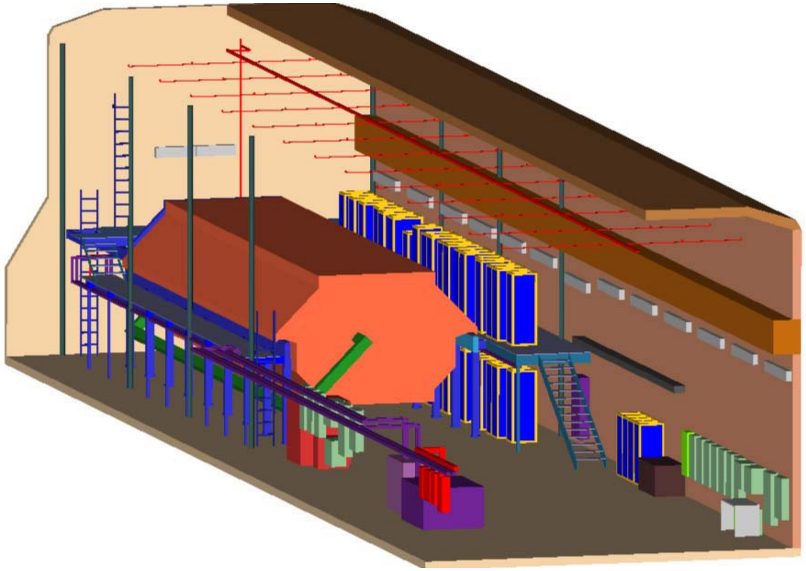
Long baseline neutrino experiments

➡ The MINOS experiment

The Near Detector

Used to measure the neutrinos before they can oscillate.

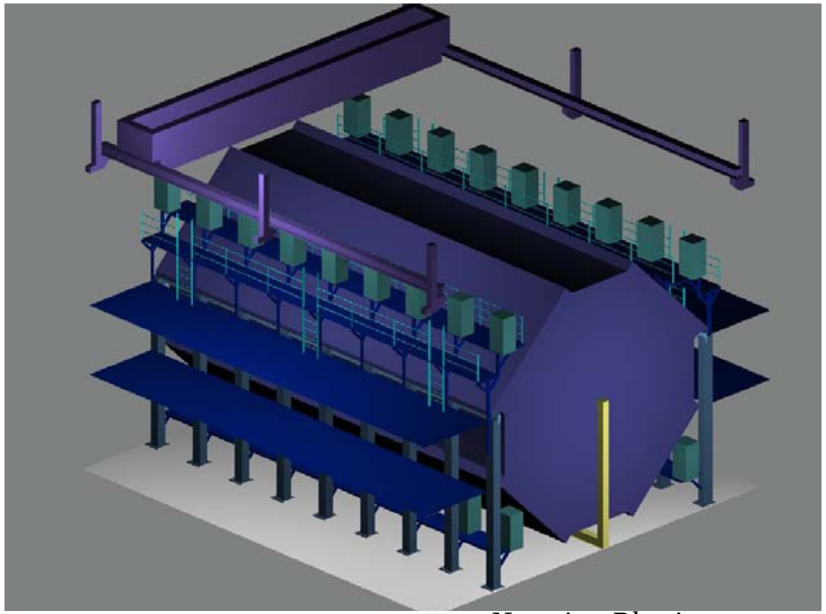
980 tonnes of magnetized iron + scintillators.



The Far Detector

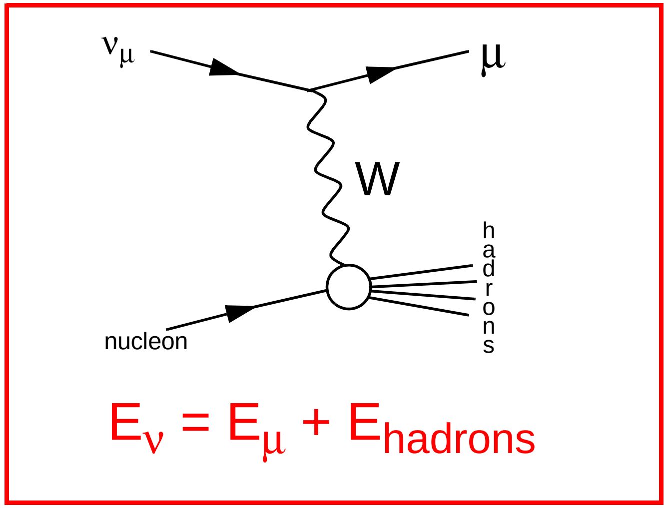
Used to measure the neutrinos after they have oscillated.

5400 tonnes of magnetized iron + scintillators.

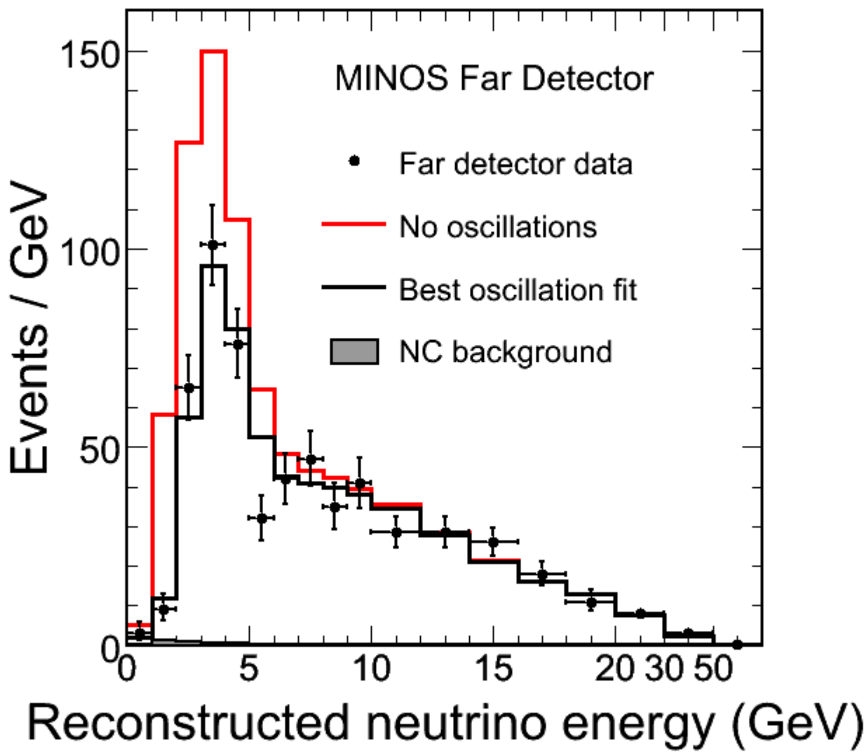


Long baseline neutrino experiments

- **Charged current reactions** ⇨ measure the **energy of the neutrinos** from the energy of muons and the hadrons. ⟶



- Neutrino energy spectrum in far detector ⇨ **fewer neutrinos** than expected if no neutrino oscillations. ⟶



- The measurement gave the result:

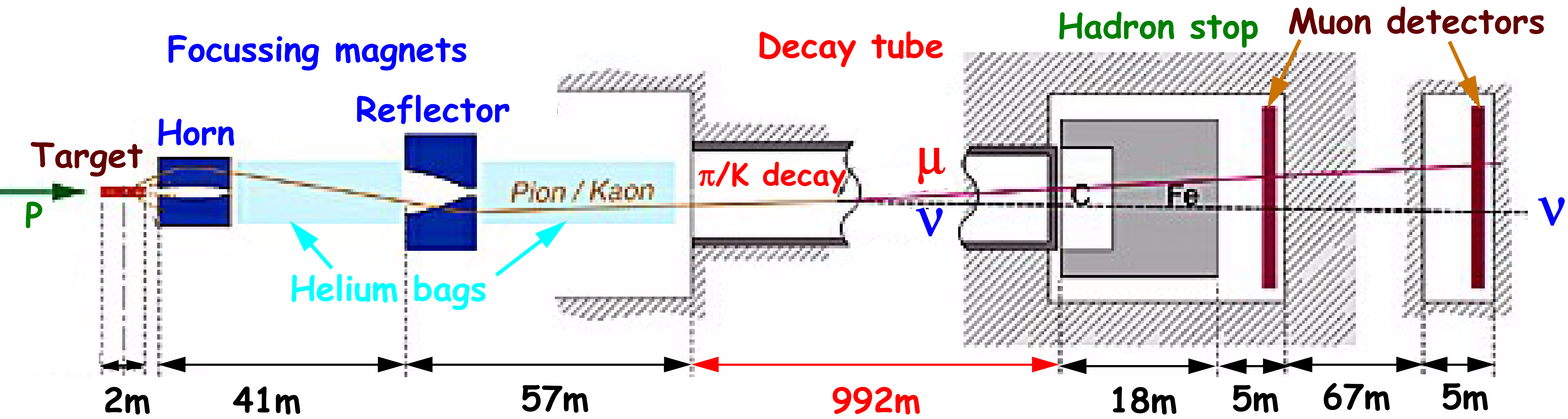
$$\Delta m^2 = 2.4 \pm 0.1 \times 10^{-3}\ \mathrm{eV}^2$$

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

Long baseline neutrino experiments

➡ CNGS - CERN Neutrinos to Gran Sasso

- The Kamiokande and Minos measurements ⇨ examples of disapperance studies ⇨ the disapperance of ν_μ.
- More difficult are apperance measurements ⇨ ν_τ appear in a ν_μ beam.
- The CNGS neutrino beam facility at CERN:



Long baseline neutrino experiments

➡ CNGS - CERN Neutrinos to Gran Sasso

- **CNGS shoots neutrinos on experiments located 732 km away.**

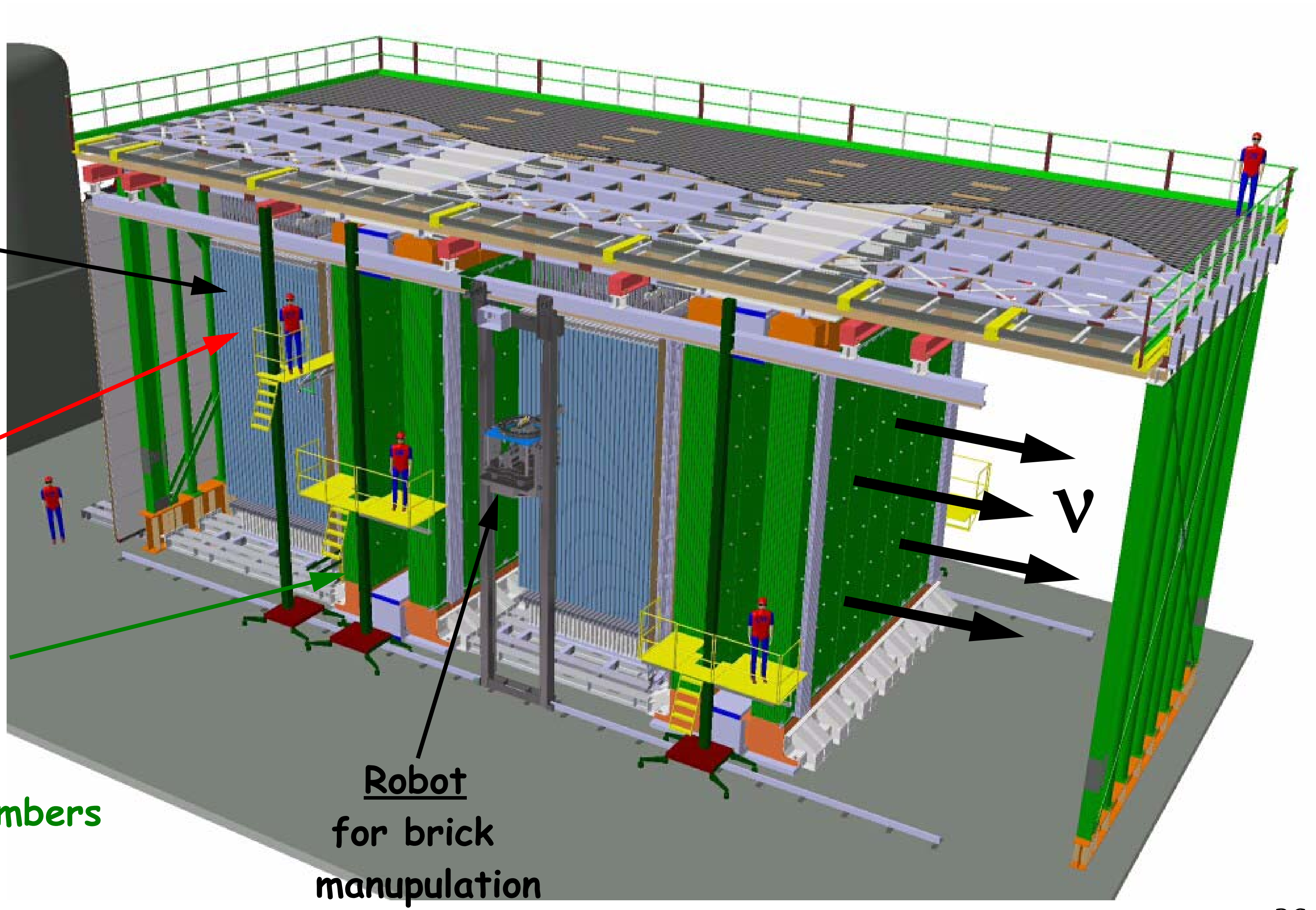
Long baseline neutrino experiments

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

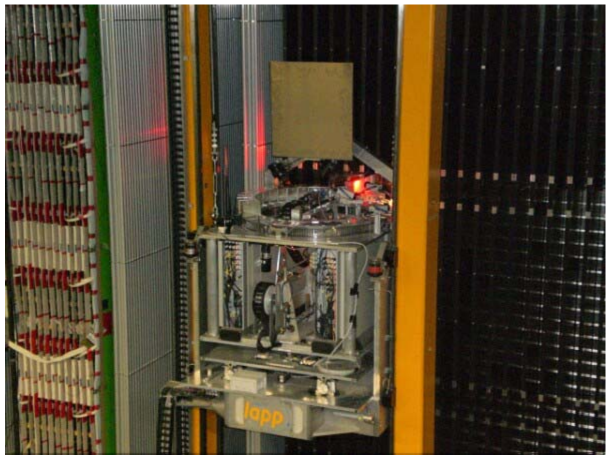
Long baseline neutrino experiments

➡ The OPERA experiment

The Opera experiment down in its underground hall.

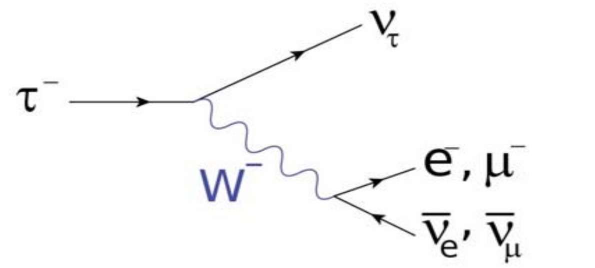
150,000 Lead/emulsion bricks are used in the target.

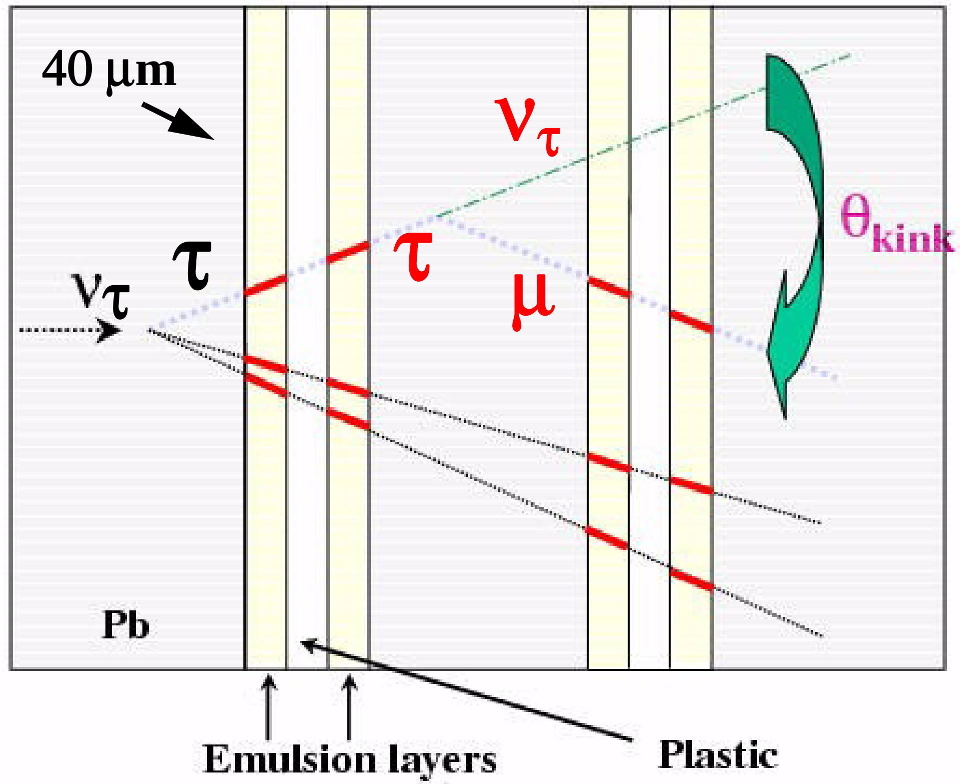
The brick robot



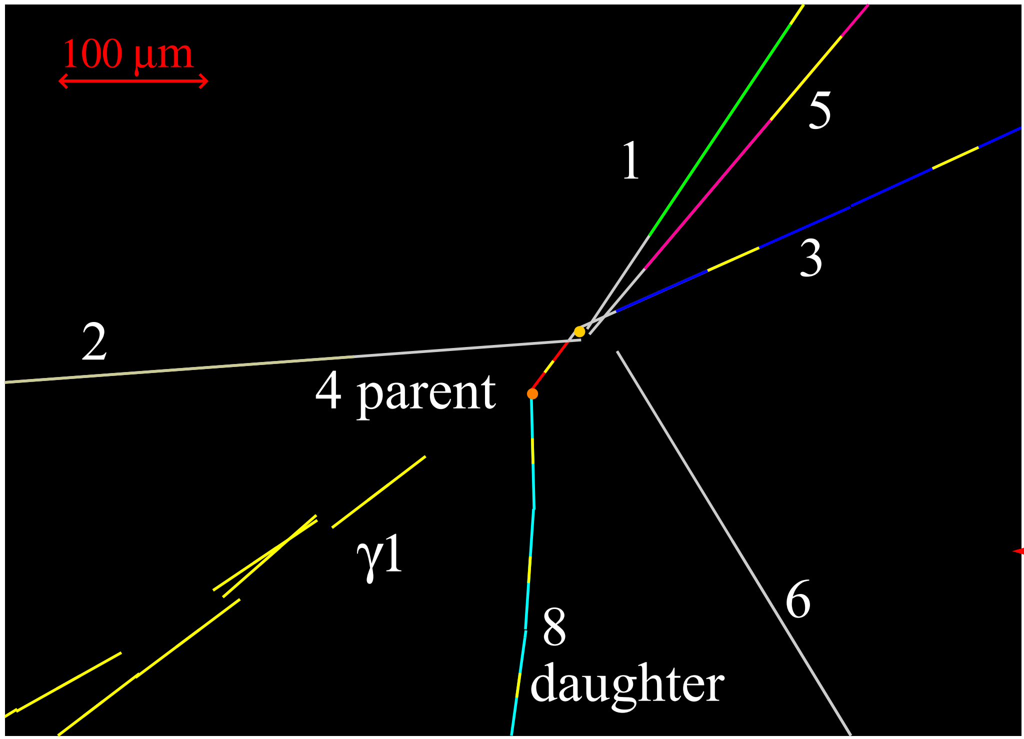
Long baseline neutrino experiments

- Goal: find events with kinks ⇨ tau neutrinos have interacted with the lead plates.





- 2-3 ν_τ events per year are expected if oscillation occur.



- Two candidates for ν_τ events observed.

Neutrino oscillations

➡ Present status

SNO Solar: ν_1 - ν_2

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

$\theta = 34°$

Kamiokande Atm: ν_2 - ν_3

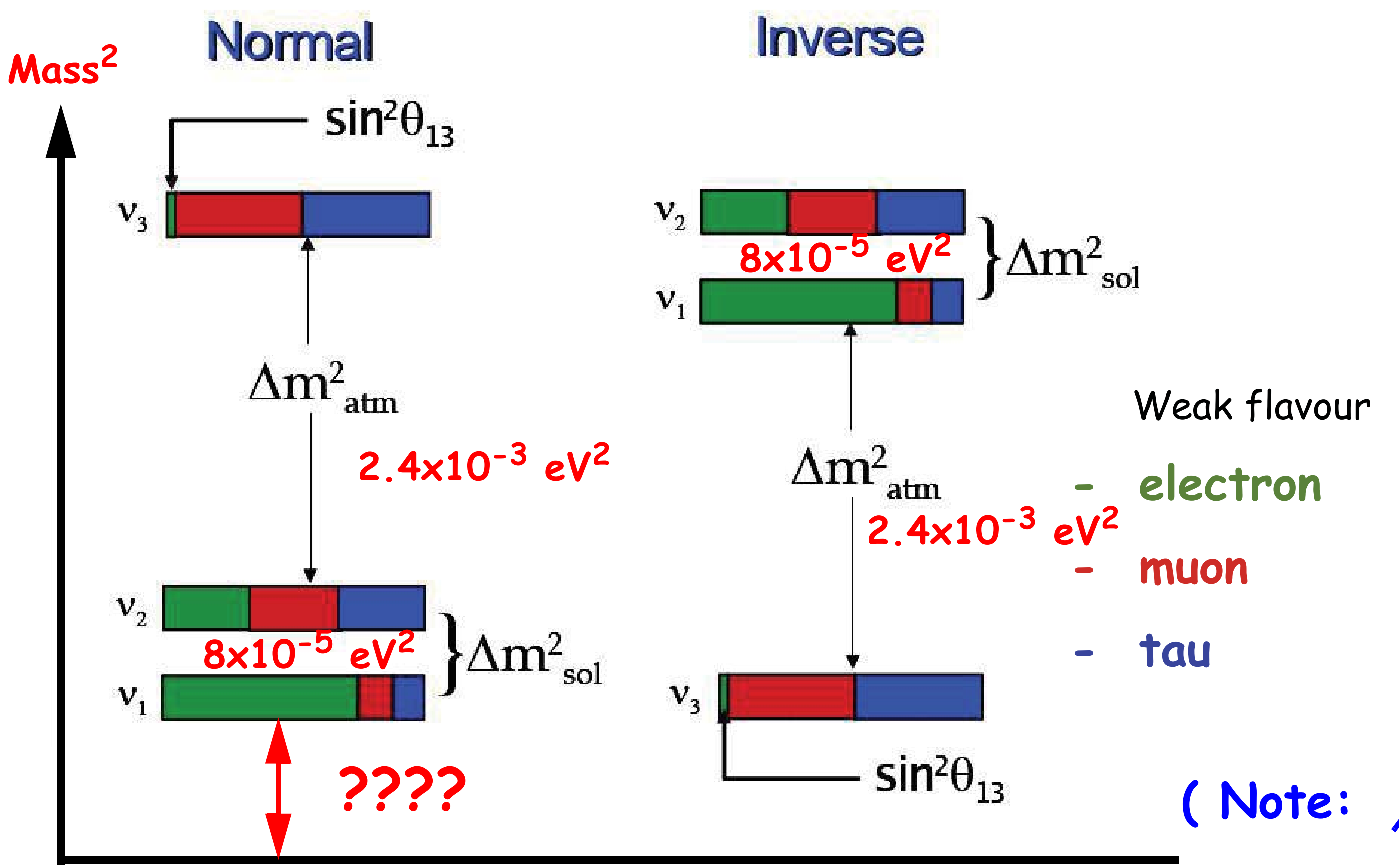
$2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-3}$ eV^2

$\theta > 36°$

MINOS Atm: ν_2 - ν_3

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

$\theta = 45°$



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

Extra-galactic neutrinos

➡ Supernova explosion

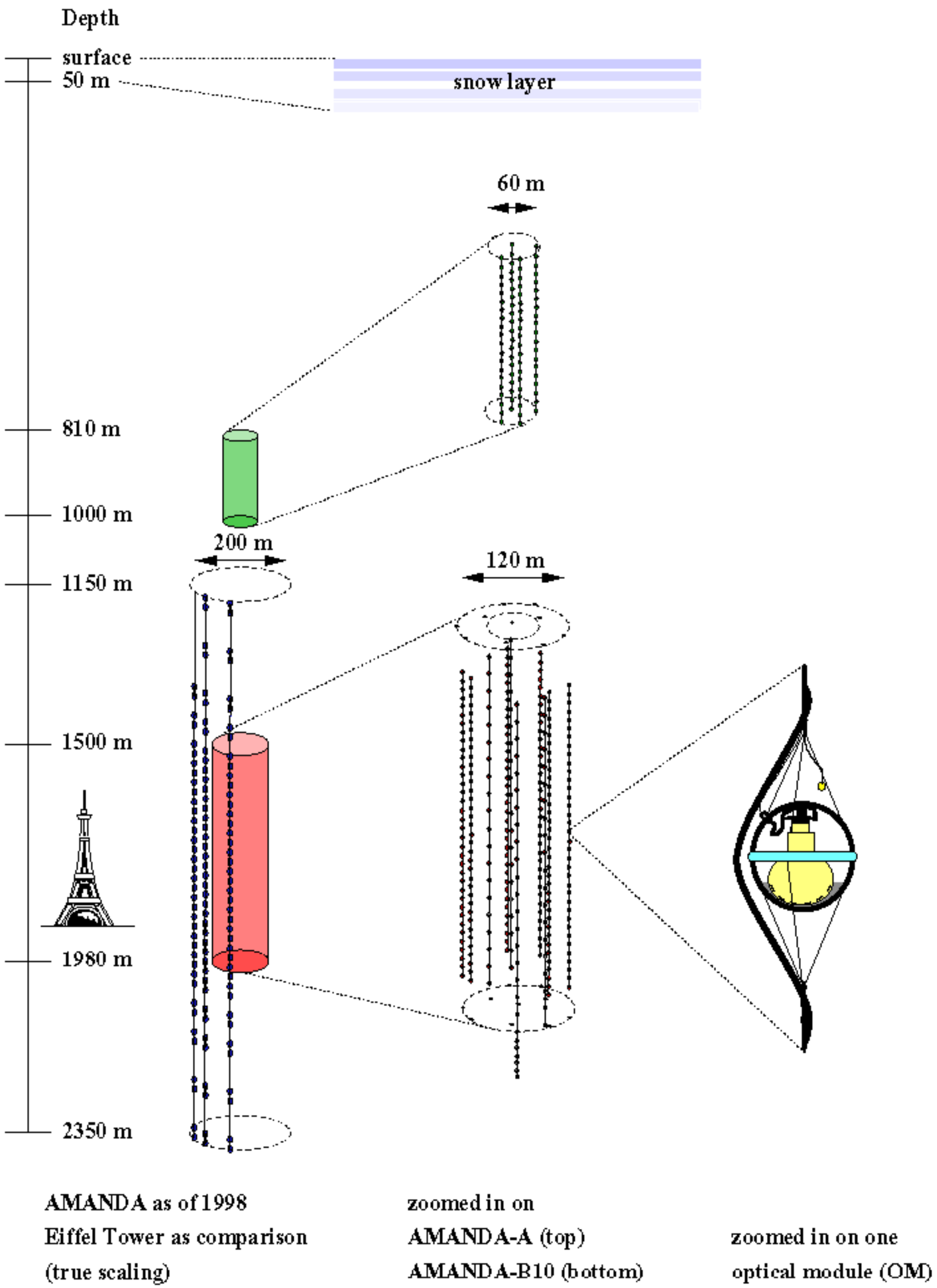
- The Kamiokande and IMB detectors recorded a burst of neutrino interactions during 15s on February 23, 1987.
- They came from an explosion of the SN1987a supernova which is 160,000 light years away.
- The first time extra-terrestrial neutrinos, not coming from the sun, were observed.

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.
- AMANDA consists of strings of photomultipliers in holes drilled deep down into the ice.



Extra-galactic neutrinos

- Neutrino interaction in the ice ⇨ charged particles (e or μ) ⇨ Cerenkov light ⇨ detected by the photomultipliers.

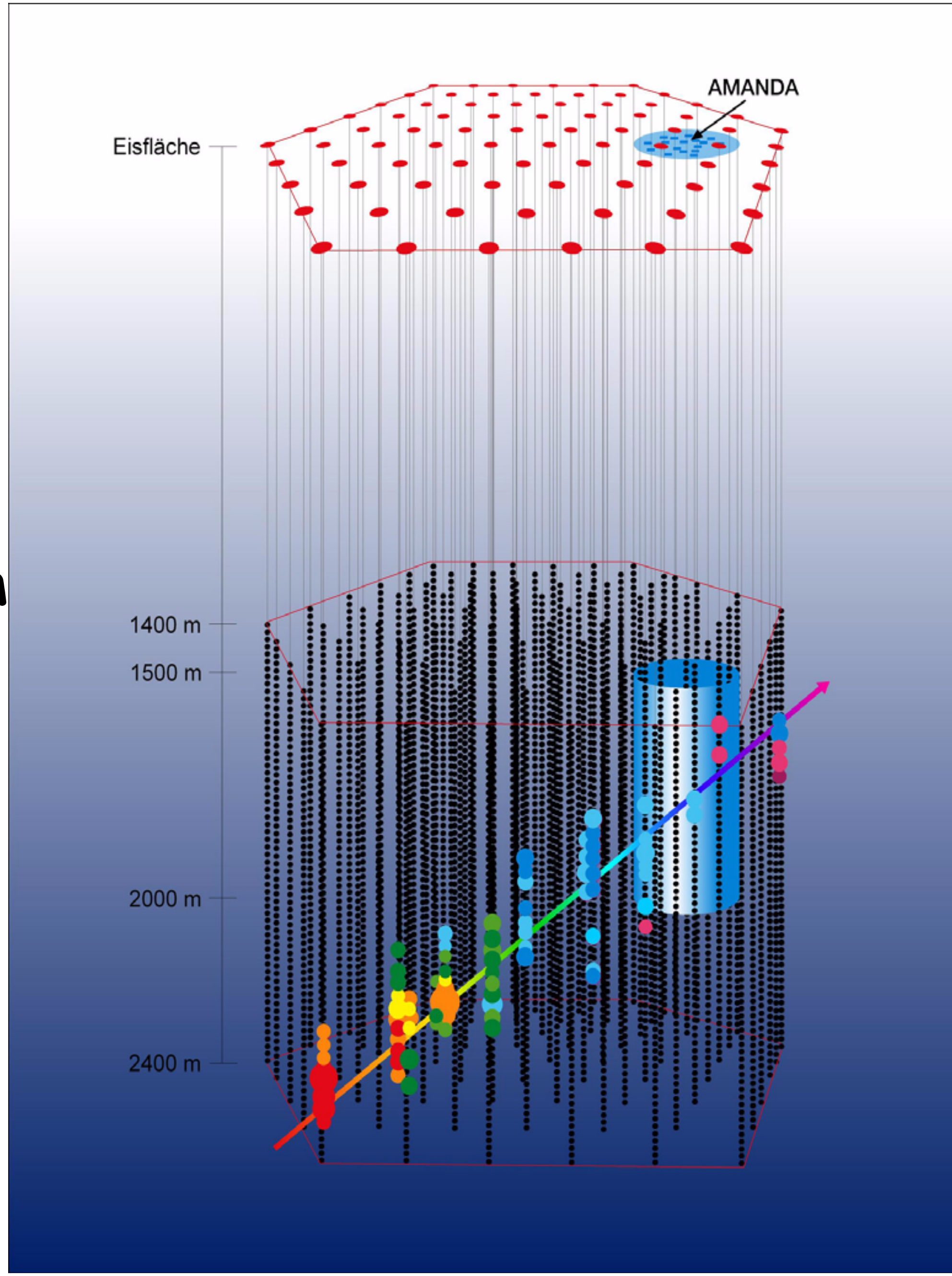
- The pattern of the light makes ⇨ the direction and energy of the neutrinos.

- No extra-galactic neutrinos have been detected so far.

Extra-galactic neutrinos

➡ The ICECUBE experiment

- A new much larger experiment called ICECUBE has been built using the the same technique. →
- It has 86 strings with 5000 photomultipliers buried between 1450m and 2450 m down into the ice.
- Icetop: A detector on the surface with 4 pms in two surface tanks at each string location.
- Tens of thousands of atmospheric neutrinos have been detected but no extra-galactic neutrinos.



The neutrinos anti-particle

➡ Is the neutrino a Dirac or Majorana particle ?

- **Anti-particle:** A particle with opposite electric charge or opposite magnetic moment.

- If the neutrino has zero mass ⇨

  Neutrinos exists only in one helicity state: Left-handed ⇨ ν_L

  Anti-neutrinos exist only in one helicity state: Right-handed ⇨ $\bar{\nu}_R$

- If the neutrino has a mass ⇨

  a neutrino can be either a Dirac or a Majorana fermion.

- Dirac fermion: has a distinct anti-particle like the electron ⇨

  Particles: ν_L, ν_R Anti-particles: $\bar{\nu}_L, \bar{\nu}_R$

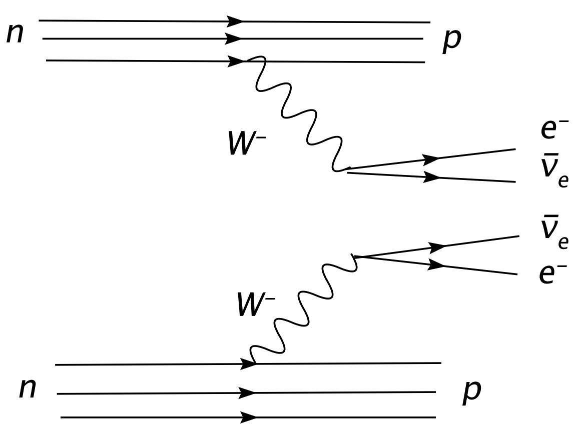
- Majorana fermion: do not have a distinct anti-particle ⇨

  Two neutrino states: ν_L, ν_R

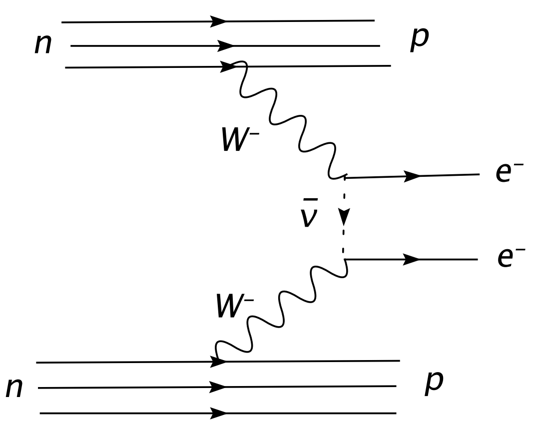
The neutrinos anti-particle

➡ Searching for Majorana neutrinos in double β-decay

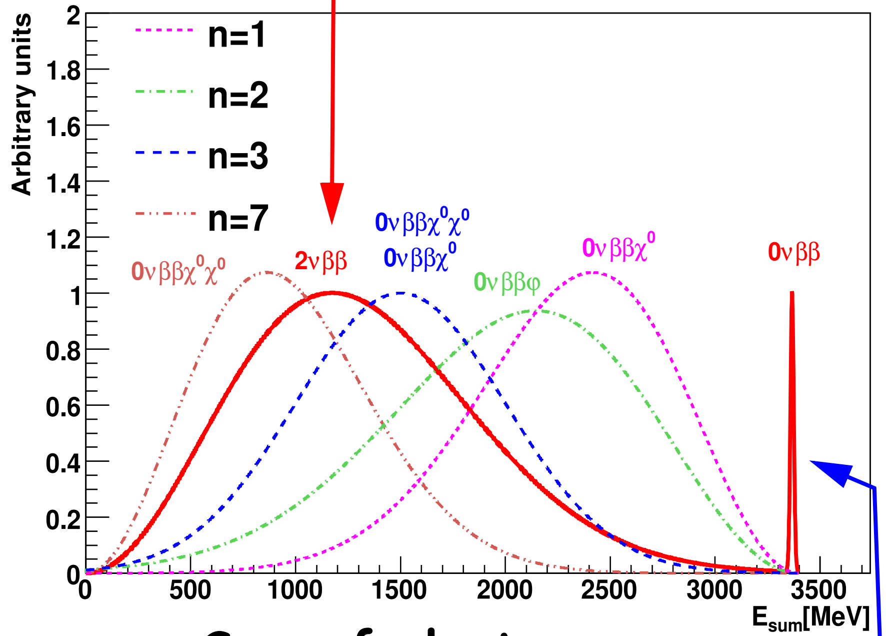
- **For some radioactive isotopes the single β-decay process is forbidden. In this case it can be possible to see double β-decays.**



2νββ: Allowed for both Dirac and Majorana neutrinos



0νββ: Allowed only for Majorana neutrinos.



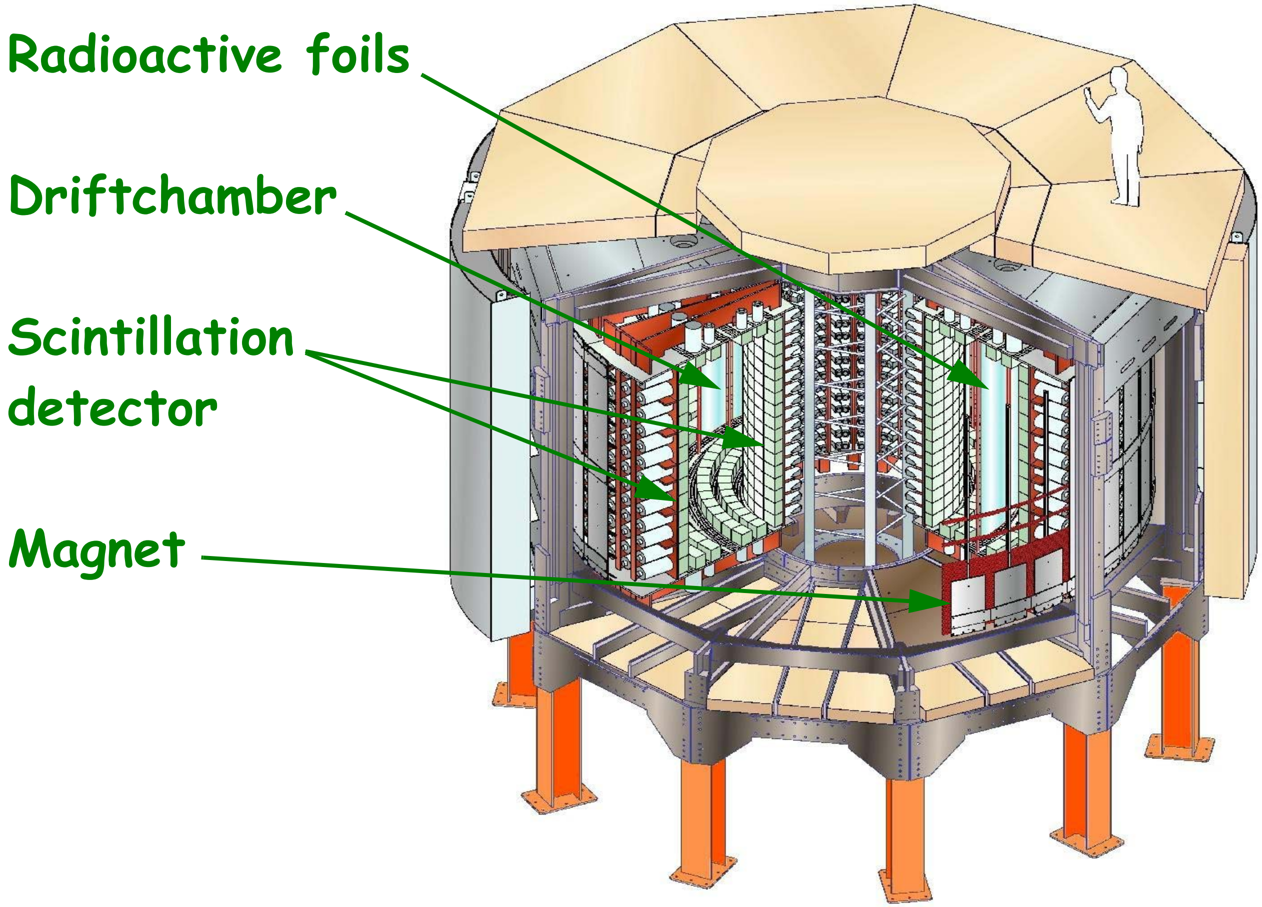
Sum of electron energy

Experiments search for these decays !

The neutrinos anti-particle

➡ The NEMO3 experiment under Mont Blanc

- **Double β-decays from thin sheets of different radioactive materials in an underground experiment.**



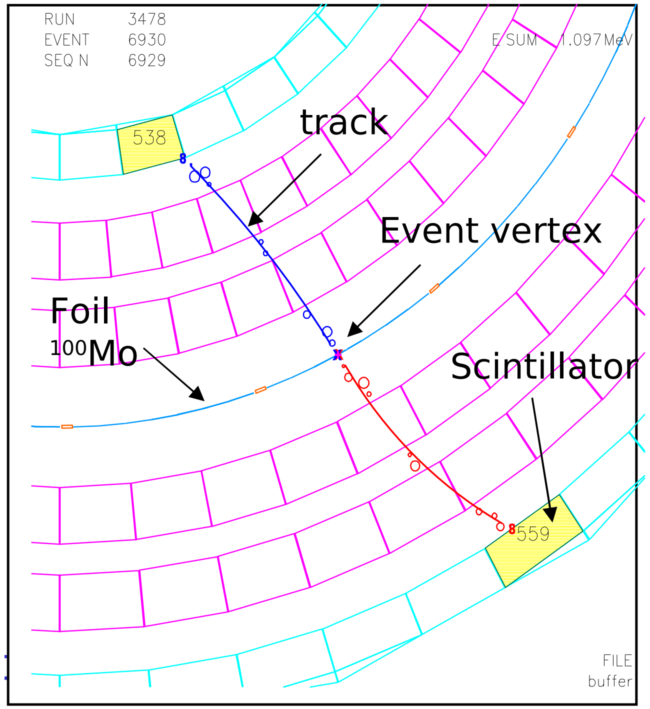
The neutrinos anti-particle

➡ Results from the NEMO3 experiment

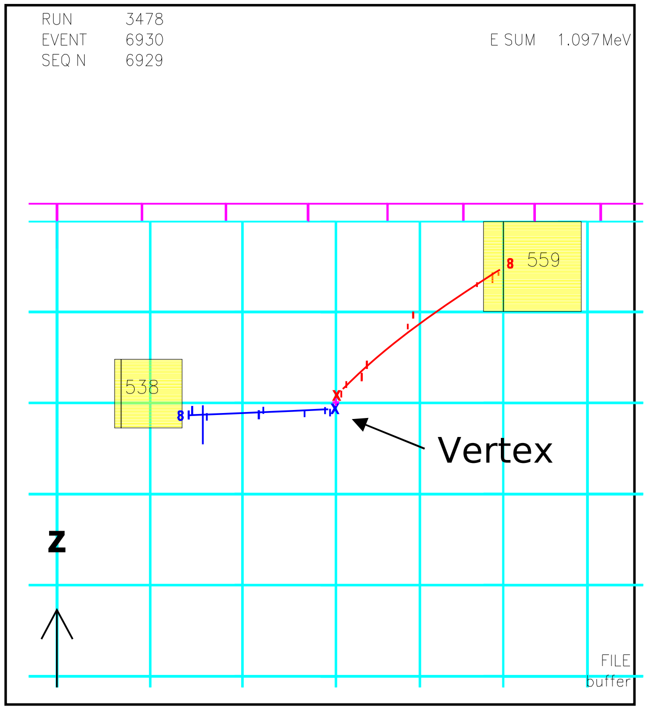
- **Events with double β-decays but no significant signal of events without neutrinos.**

Example of an event

Transverce view



Longitudinal view



Energy distribution of electrons