# 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**.

- 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.**
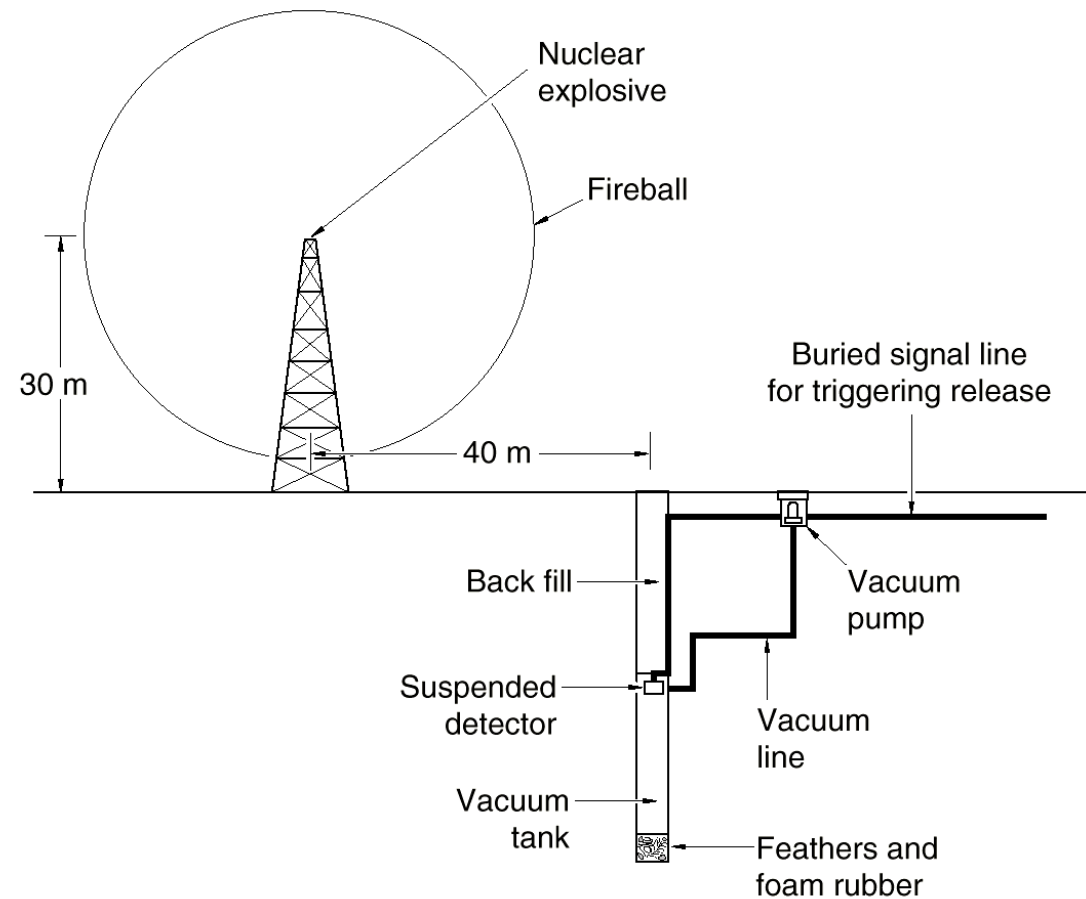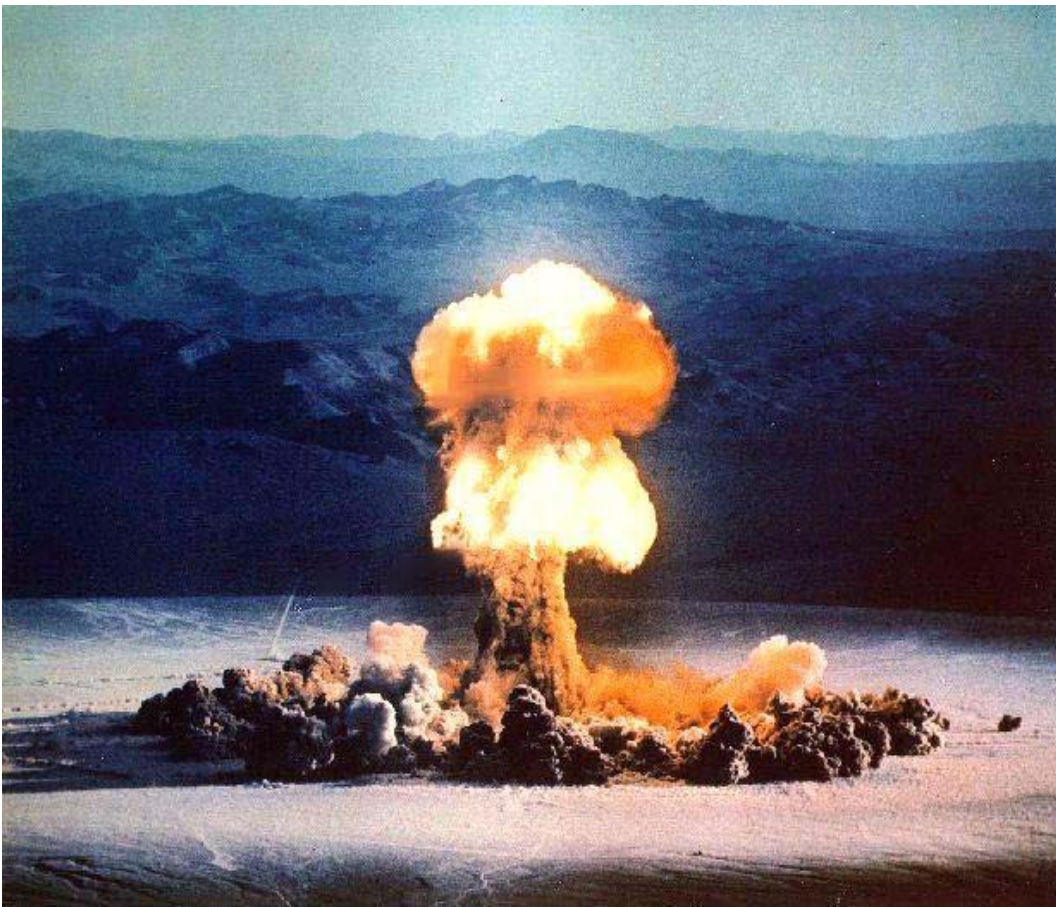

● **The project was approved at Los Alamos but ....**
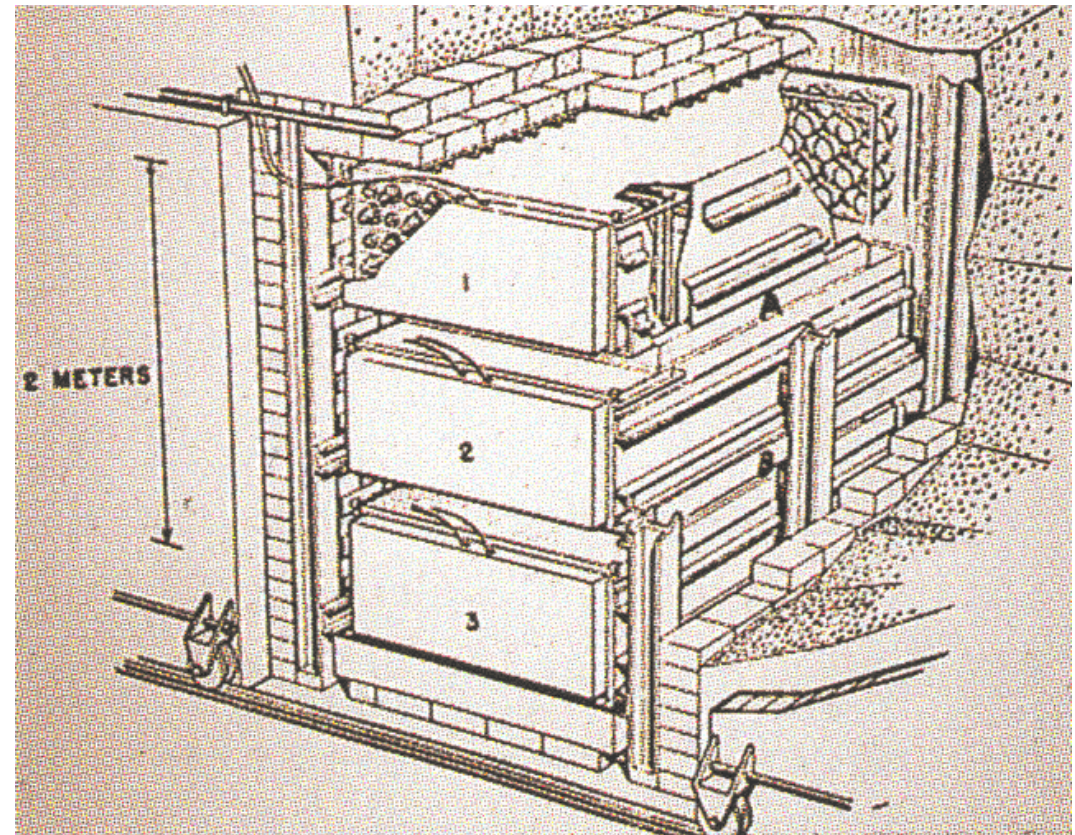
The discovery of the neutrino

➡️ **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)**

Cd

e⁻

γ

γ

γ

γ
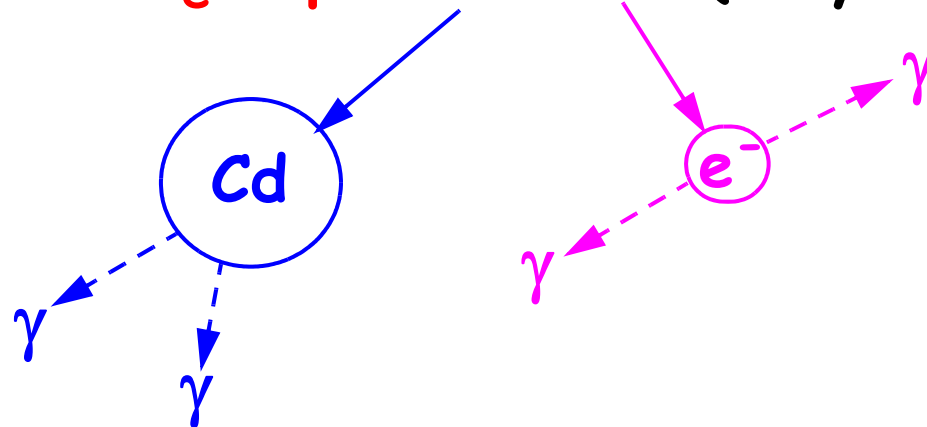
The discovery of the neutrino

● **Two tanks of water** with Cadmium chloride

● **Three tanks** with liquid **scintillator** between the water tanks

$\bar{\nu}_e$ → Liquid scintillator

e^- e^-

γ γ

$\bar{\nu}_e$ → $H_2O + CdCl_2$

Cd n e^+

γ

$\bar{\nu}_e$ → γ e^-

e^- Liquid scintillator

$\bar{\nu}_e$ → $H_2O + CdCl_2$

Photomultipliers

$\bar{\nu}_e$ → Liquid scintillator

2 METERS
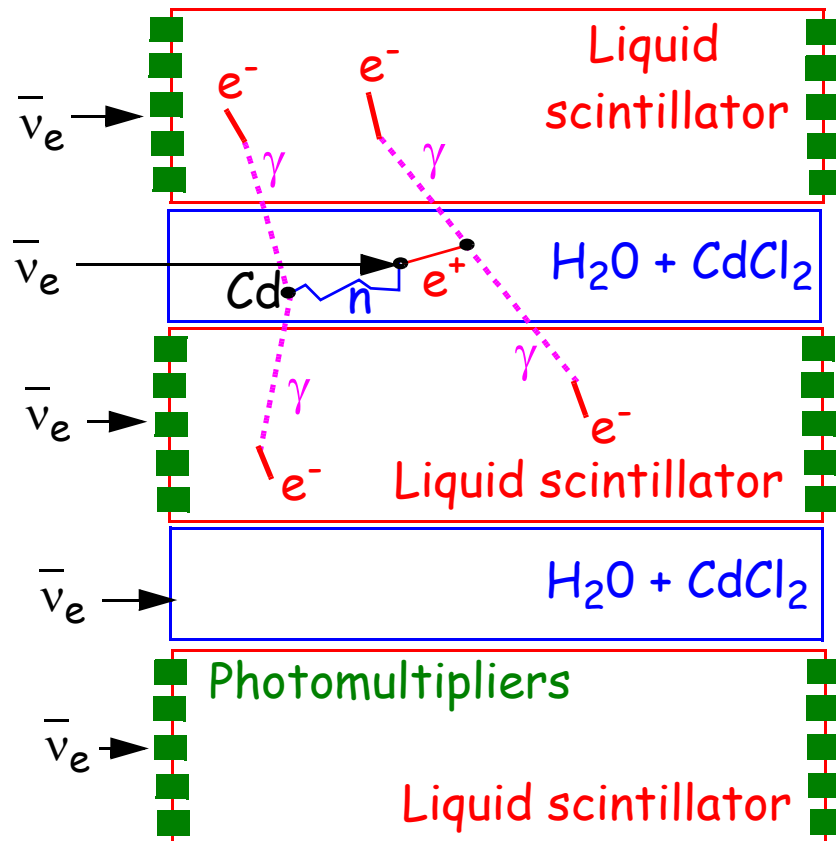
● **Photons** produce electrons by the Compton effect.

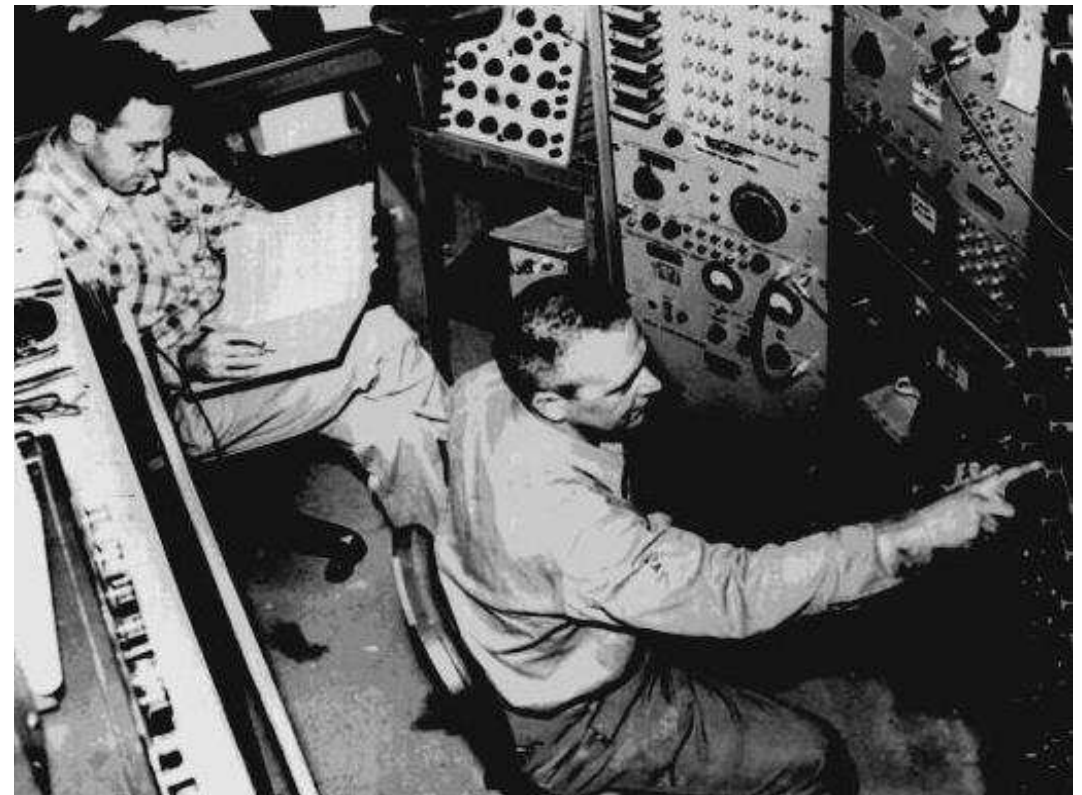● **Electrons** produce light in the scintillators

The discovery of the neutrino

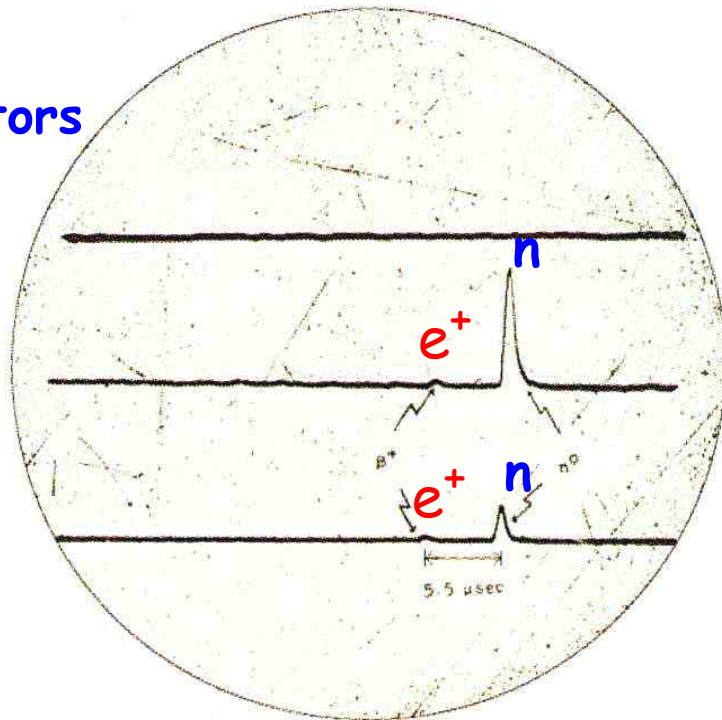● **Signal signature** ⇨ **two small signals** at the same time from e^+ & **large signal** after few μs from the **neutron**.

● **2 neutrino events and 1 background event per hour.**

Scintillators

1

2
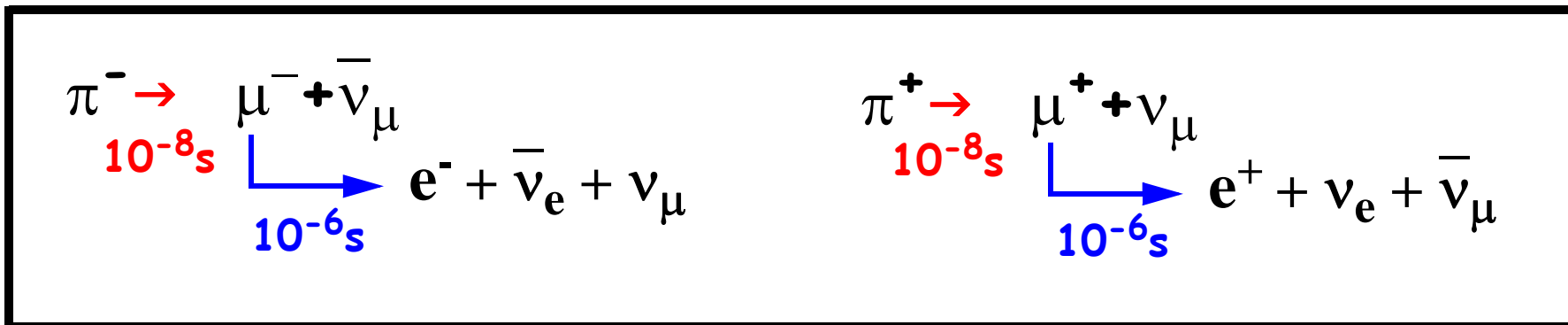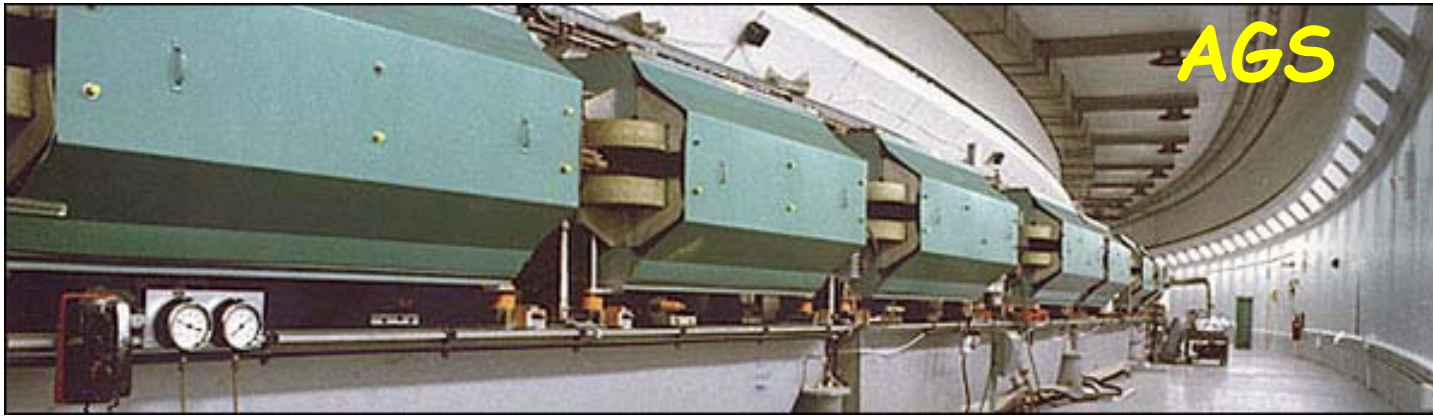
3

n

e^+

e^+ n

5.5 μsec

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.

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

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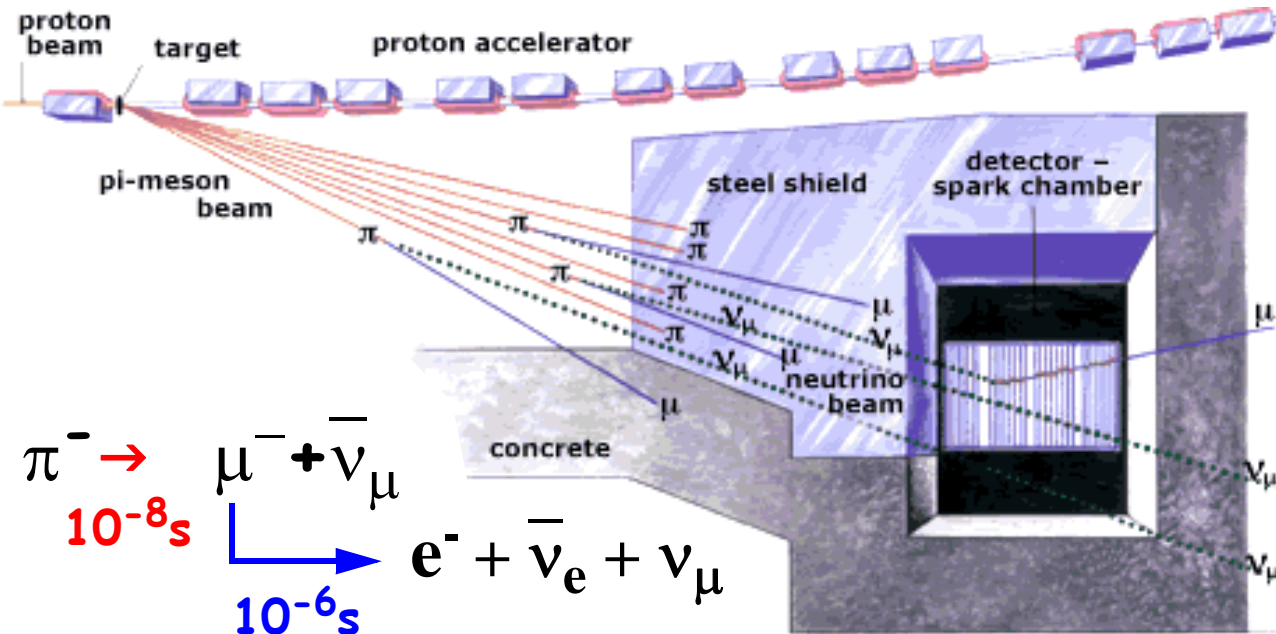$$10^{-6}s$$

The discovery of the neutrino

AGS

Spark chambers

Sandwich of Aluminium plates and spark chambers

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

$10^{-8}s$

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

$10^{-6}s$

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

$\nu_\mu + n \rightarrow p + \mu^-$
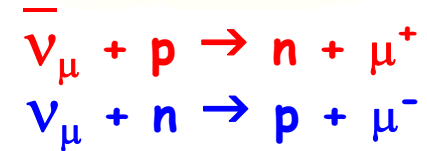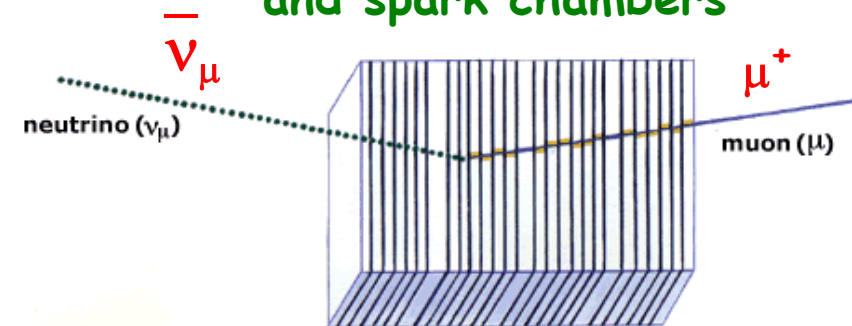
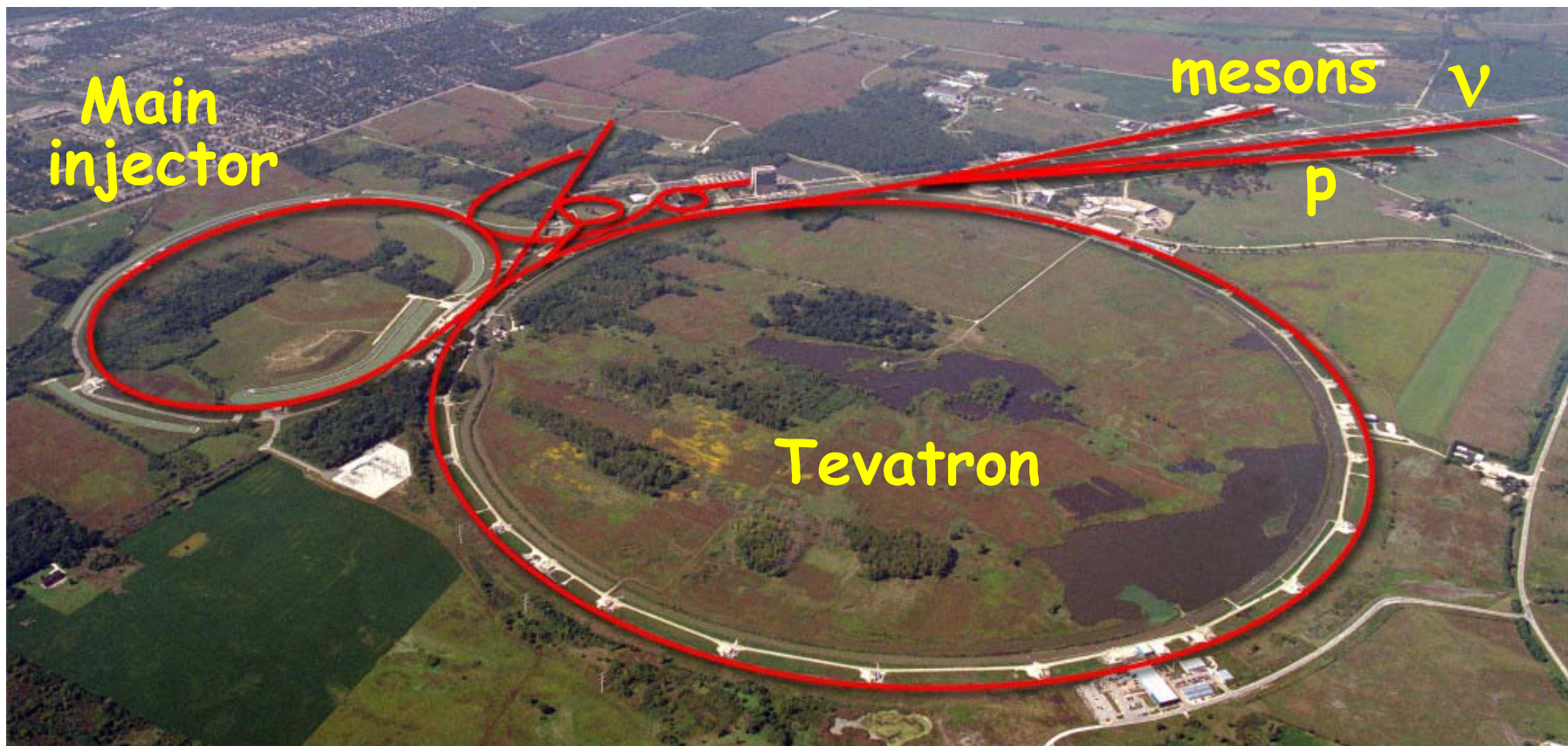● The **muon neutrinos** interacted with the nucleons in the **Aluminium** and **photos** of the reaction products were recorded.

● 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

Tungsten target

Mixture of particles

Magnet

Steel Shielding

Neutrinos

1 m

17 m

Remove all particles but neutrinos

Proton hits tungsten nucleus

The tau lepton decays, producing a tau neutrino

Incoming proton

Tau

Tau neutrino

Some particles produced in collision decay into tau leptons

$$p + n \rightarrow D_s + X$$
$$p + p \rightarrow D_s + X$$

$$\rightarrow \tau + \bar{\nu}_\tau$$

$$\rightarrow \nu_\tau + X$$
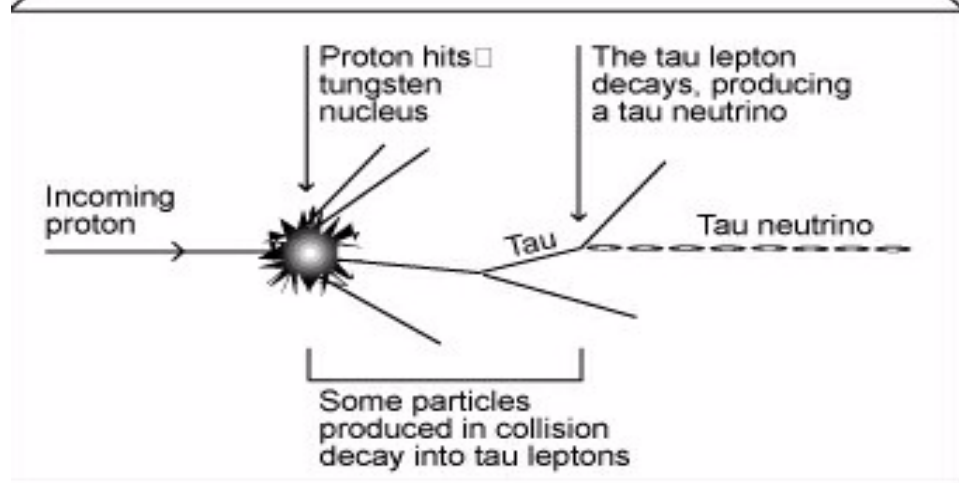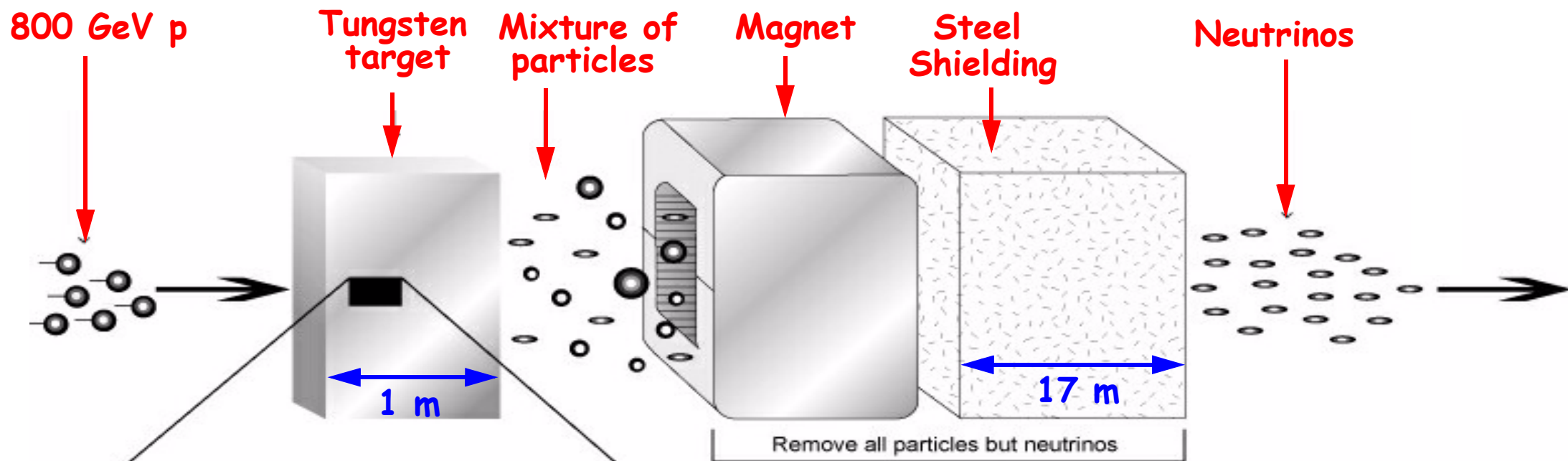
The discovery of the neutrino

DONUT: Detector for direct observation of tau neutrinos.

Muon spectrometer

Calorimeter

Drift chambers

Magnet

Shielding

Target with photographic emulsions and scintillating fibers.

ν_τ
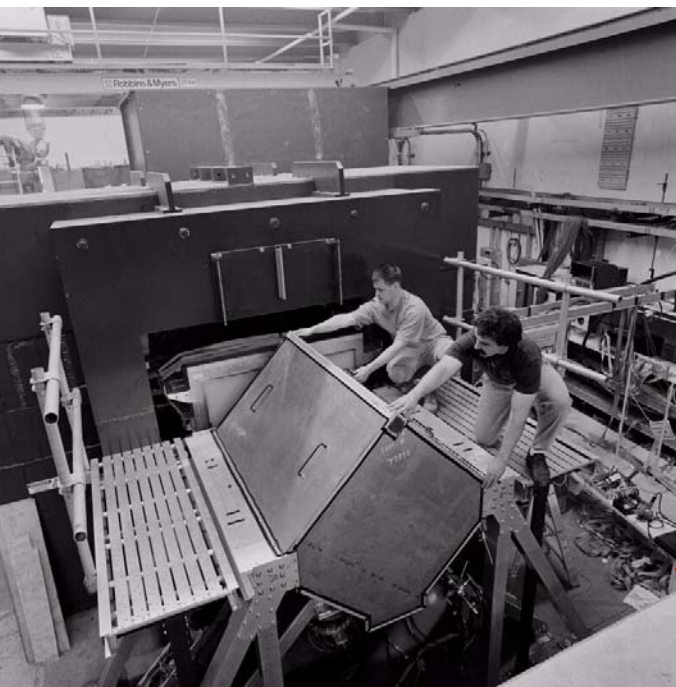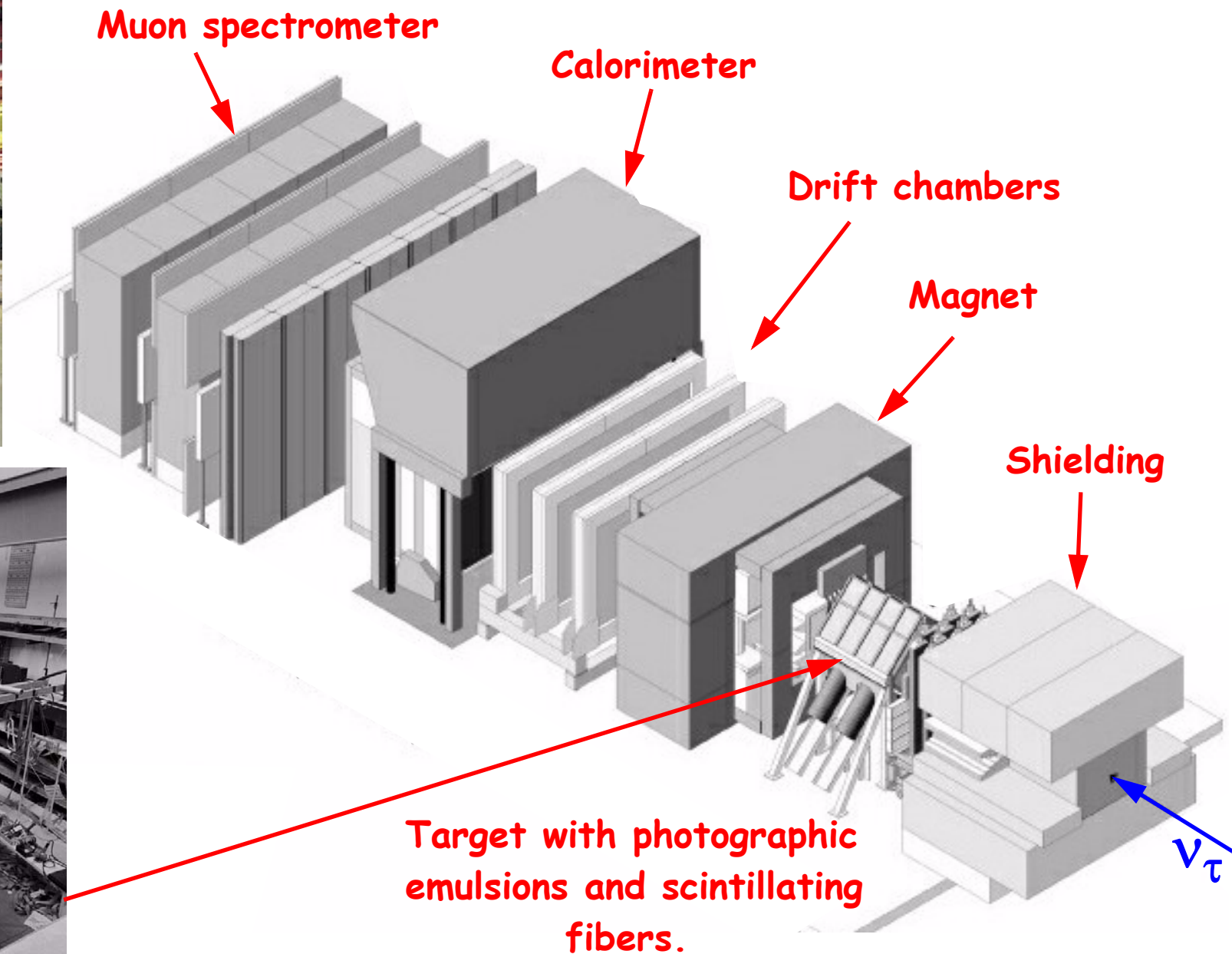
The discovery of the neutrino

- **The reactions:**

$$\nu_\tau + n \rightarrow \tau + X$$
$$\nu_\tau + p \rightarrow \tau + X$$
$$\longrightarrow \nu_\tau + e$$
$$\longrightarrow \nu_\tau + \mu$$

Iron   Iron   Iron

emulsions

Tau
lepton
decay

1 mm

Neutrino
beam

Tau neutrino
hits iron nucleus,
produces
tau lepton

Tau
lepton
track

Emulsion
layers

Particle
from tau
lepton
decay

Emulsion
layers

Tracks
recorded
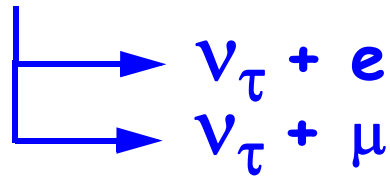
- **One ν_τ out of a million** would interact.
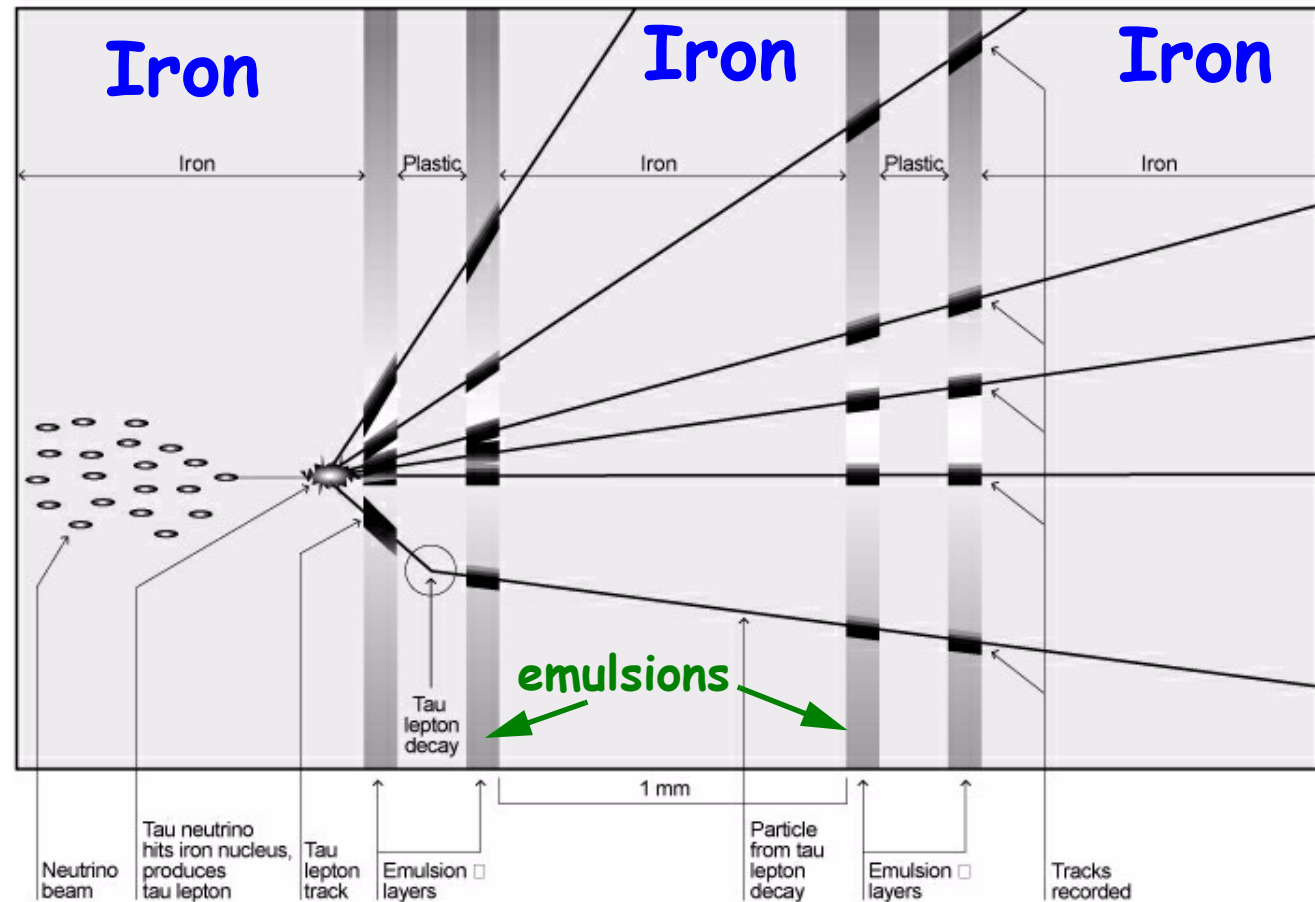
- Years of running + **analysis of 6 million events** $\Rightarrow$ **4 events** with all the signatures of a tau to tau-neutrino decay.

- 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**:

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

- 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

● **Neutrino masses ≠ 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**

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

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:**

$$P(\nu_e \rightarrow \nu_\mu) = |B(t)|^2 = \sin^2(2\theta)\sin^2\frac{(E_2 - E_1)t}{2} = \sin^2(2\theta)\sin^2\frac{(\sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2})t}{2}$$
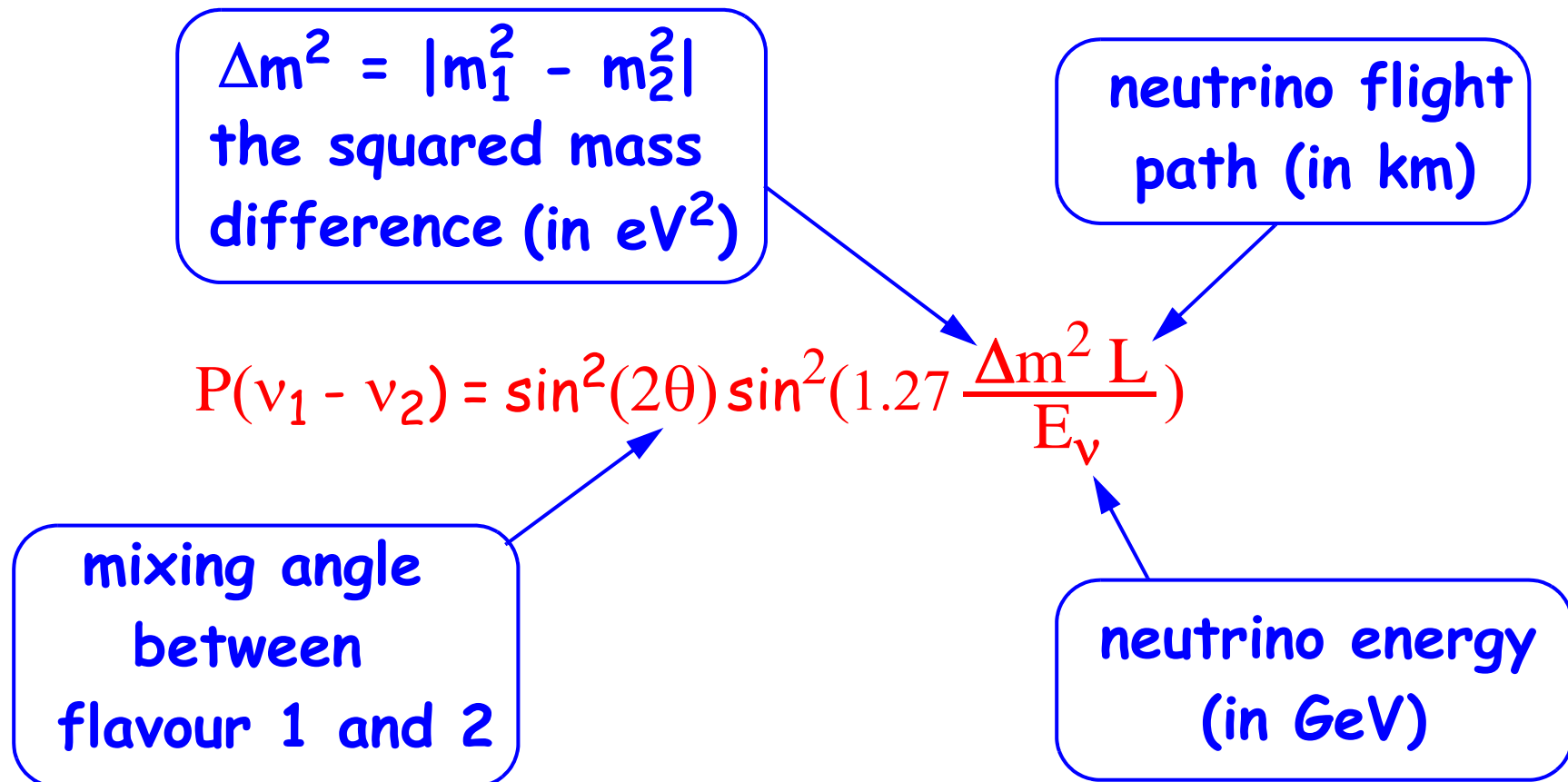
$$P(\nu_e \rightarrow \nu_e) = |A(t)|^2 = 1 - P(\nu_e \rightarrow \nu_\mu)$$

● **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

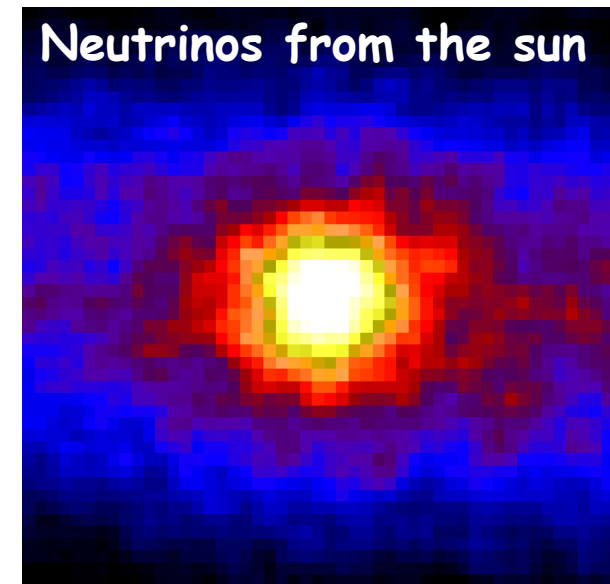**Nuclear reactors**

Natural radioactivity

Supernovas

The Big Bang

● **Neutrino detection ⟹ neutron interaction ⟹ e,μ detection**

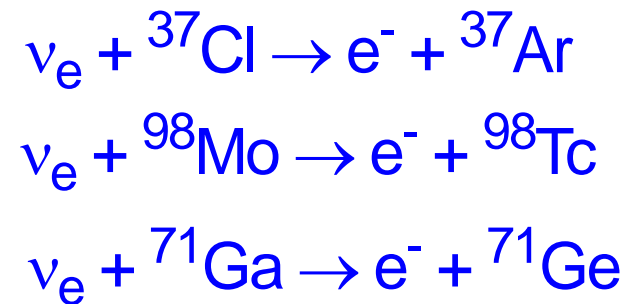$$\nu_e + n \rightarrow e^- + p$$
$$\nu_\mu + n \rightarrow \mu^- + p$$
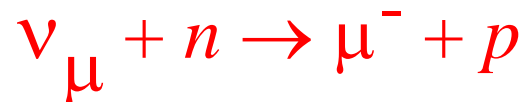
The solar neutrino problem

- **The solar neutrino problem:**

  Fewer ν_e are detected than what is predicted by theory.

Neutrinos from the sun

- Detection methods:

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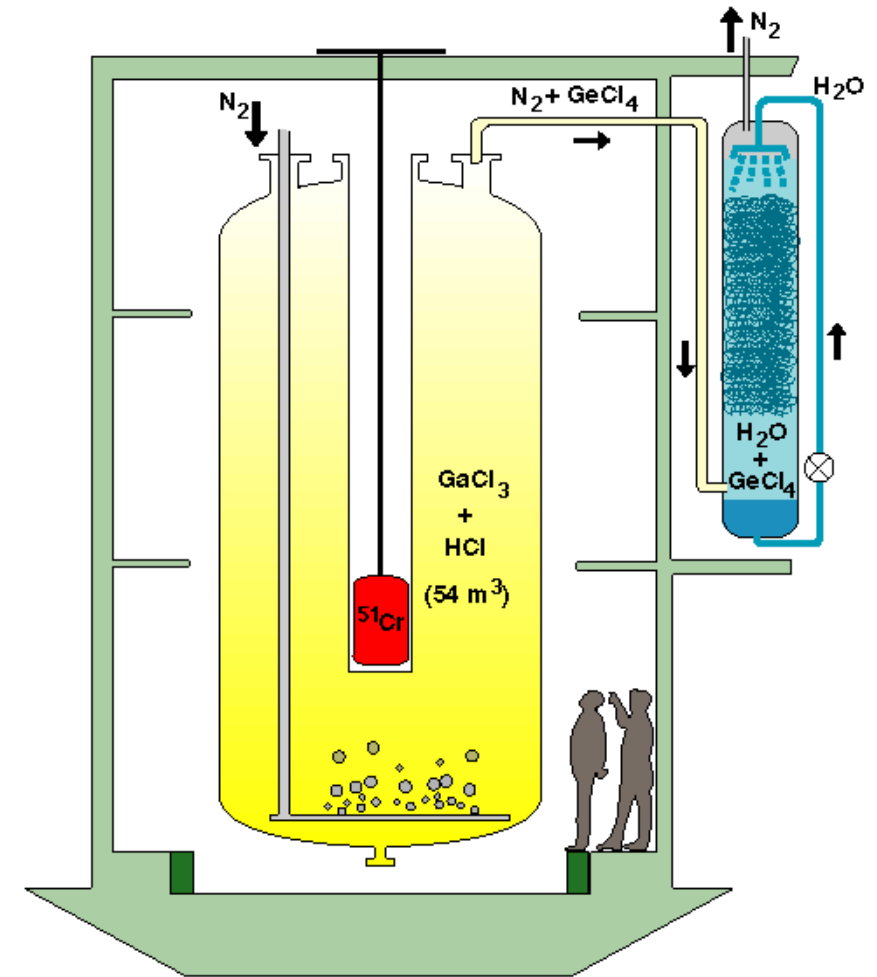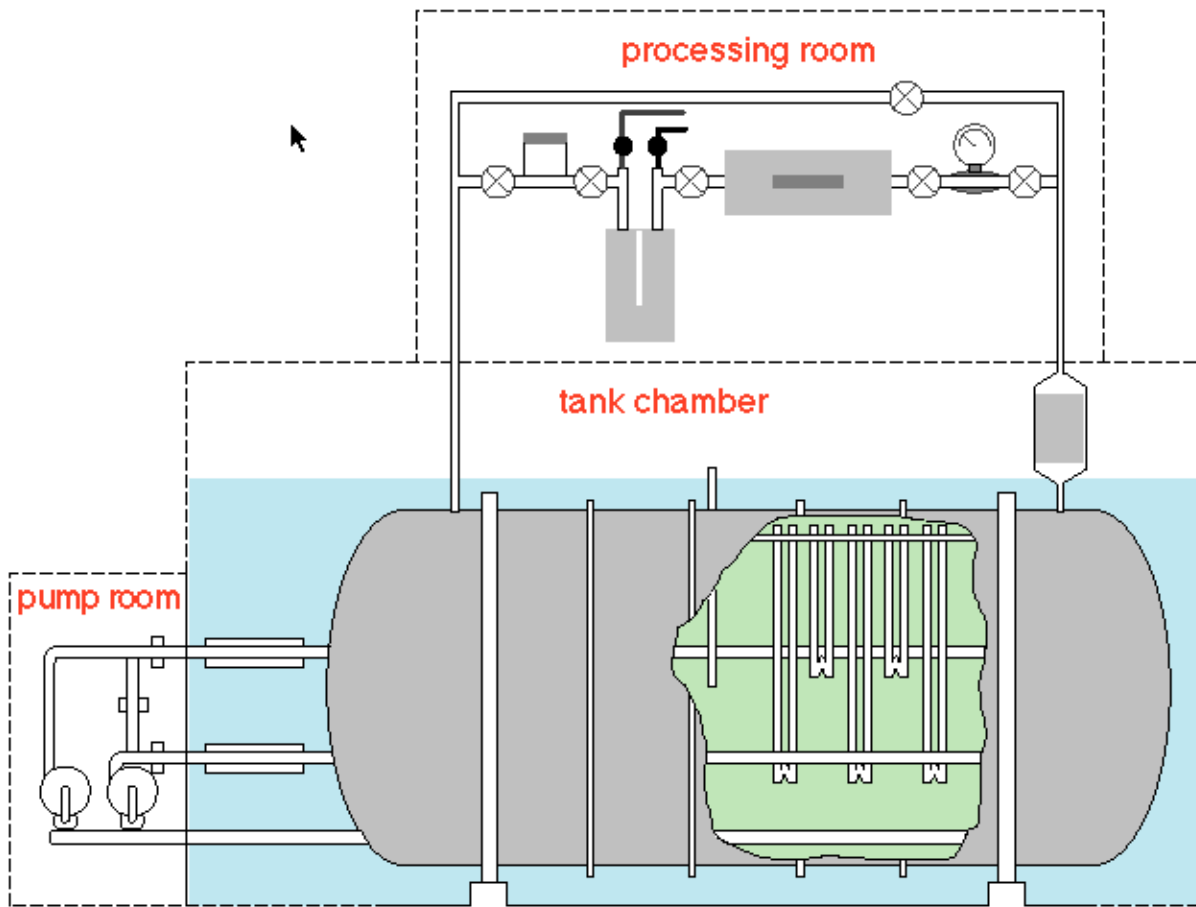$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

- The experiments $\Rightarrow$ 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**:

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

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

$$ {}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e \qquad E_{\nu,max} = 15 \text{ MeV } (0.02\%)$$
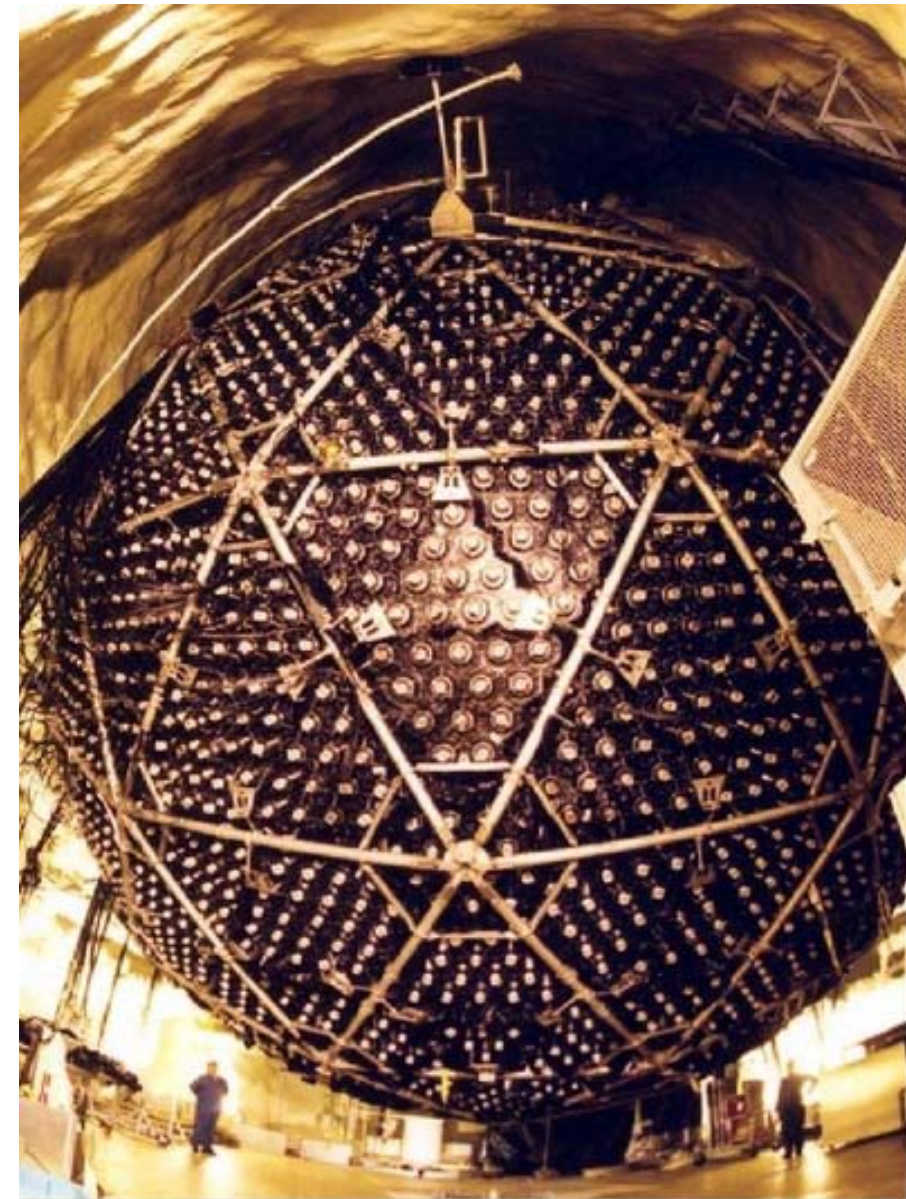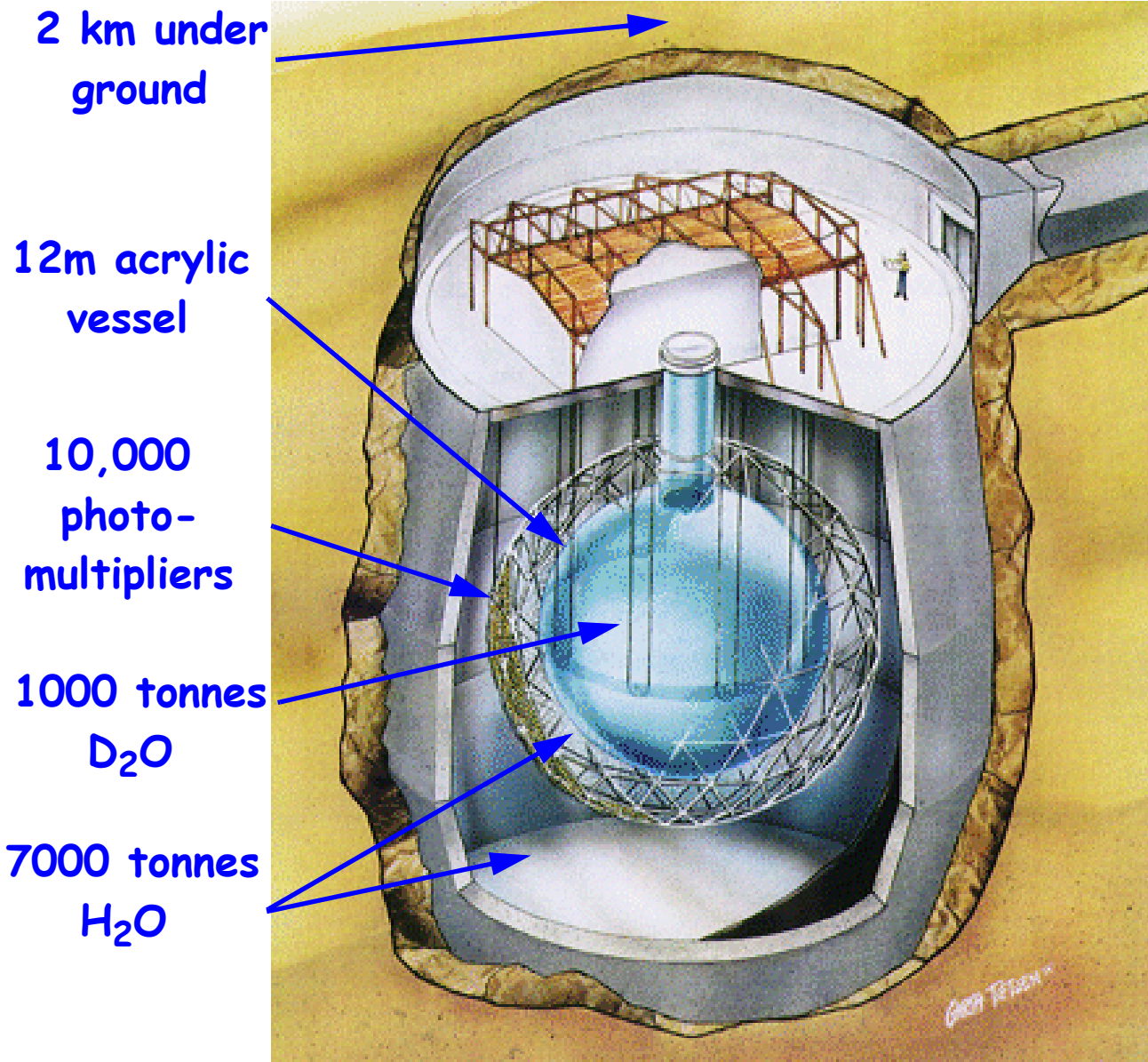
● GALLEX measures all.   Homestake measure only the last one.

● 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 $\Rightarrow$
explained by **neutrino oscillations** that turn them into ν_μ and ν_τ.
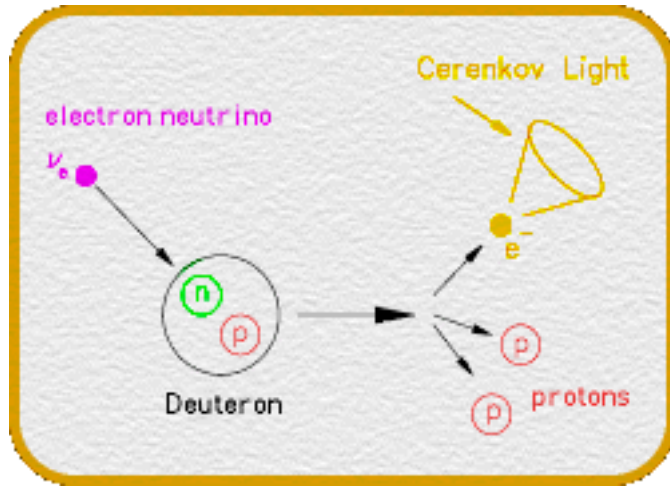
The solar neutrino problem

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

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

Neutral current reactions
$$\nu_x + d \rightarrow p + n + \nu_x$$

Only sensitive to electron neutrinos.

Mostly sensitive to electron neutrinos.
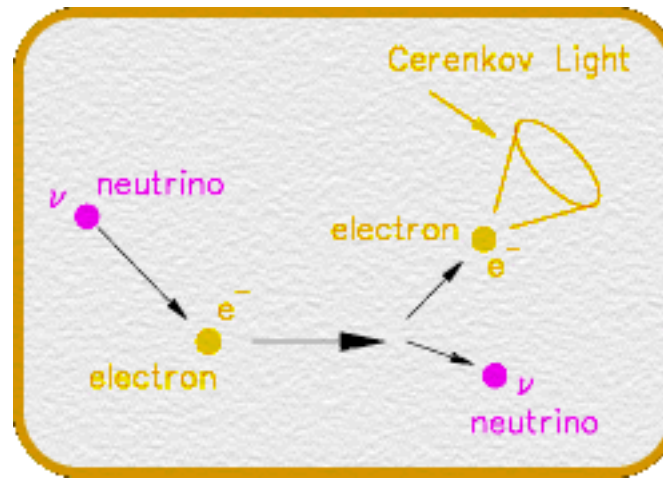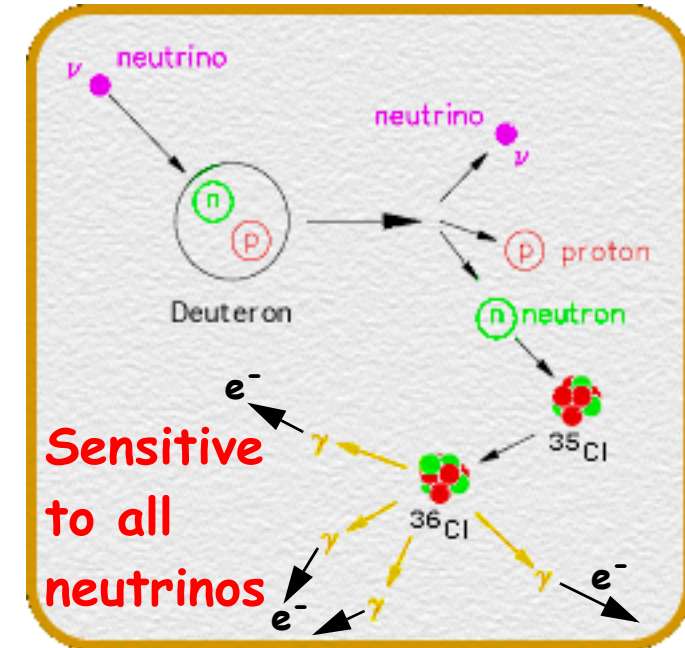
Sensitive to all neutrinos

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

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

Neutrons detected by tritium-filled proportional counters.

Photons ⇒
Compton electrons ⇒
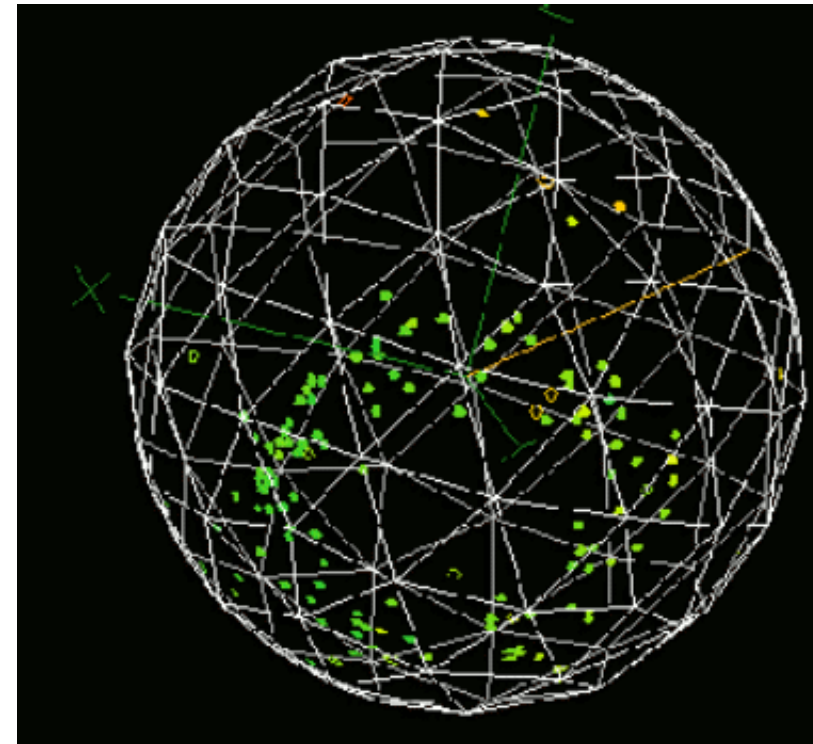Cherenkov light ⇒
Photomultiplier signals

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:

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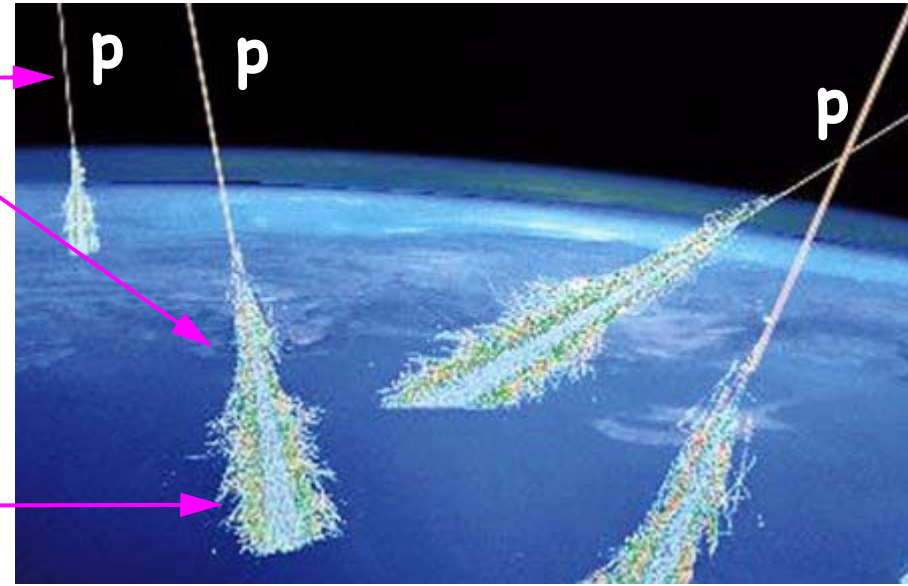
Neutrino oscillations

- The results (combined with other experiments)

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

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

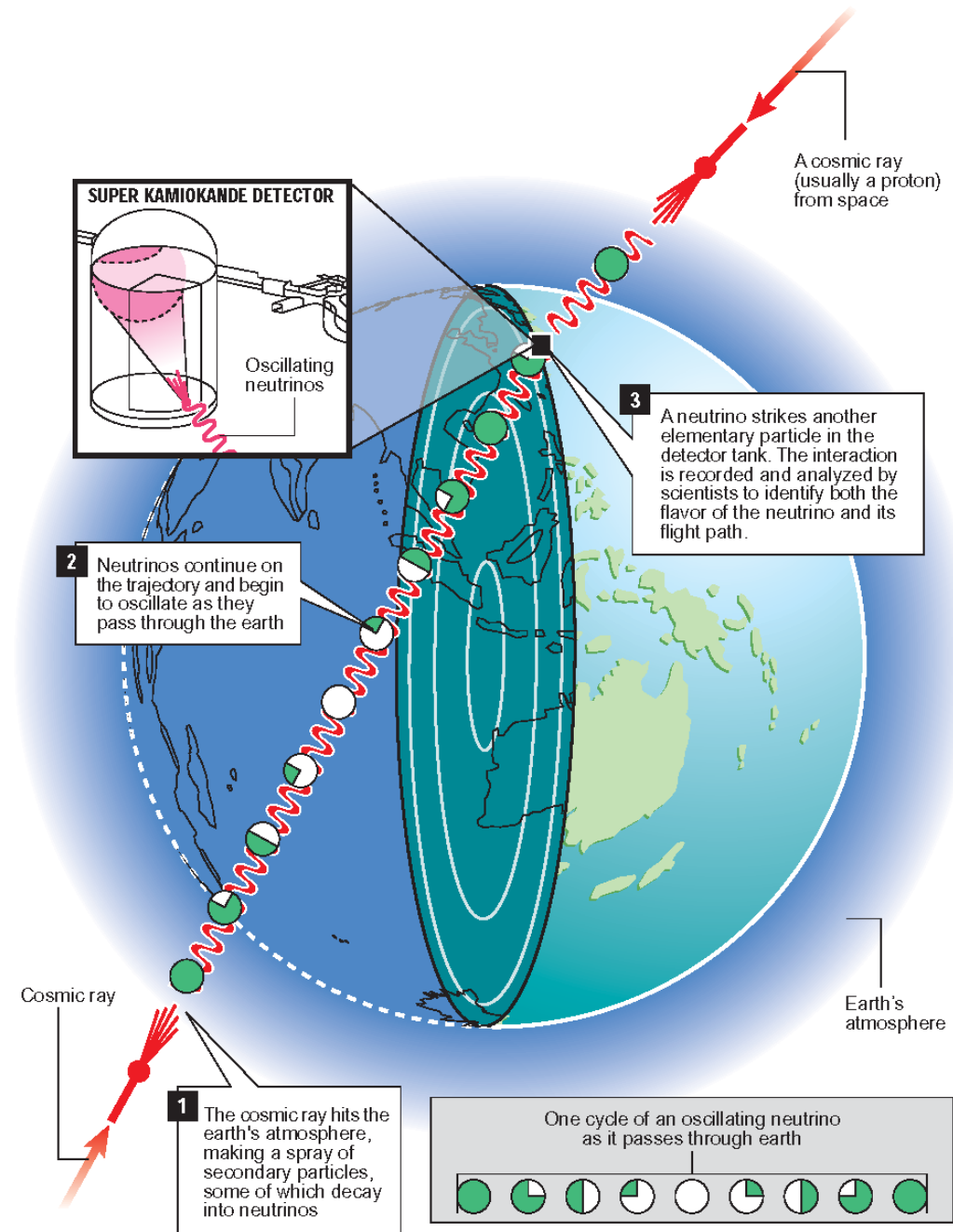● **Neutrinos can pass through the earth without interacting**

⇒
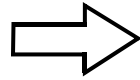
A neutrino detector can detect neutrinos created in the atmosphere above

&

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).**

SUPER KAMIOKANDE DETECTOR

Oscillating neutrinos

A cosmic ray (usually a proton) from space

3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

Cosmic ray

Earth's atmosphere

1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

One cycle of an oscillating neutrino as it passes through earth

The atmospheric neutrino problem

➡ **The Super-Kamiokande detector**

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

SUPERKAMIOKANDE DETECTOR

Electronics trailers

Catching Neutrinos

About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

Control room

Access tunnel (2 km)

12.5 million gallon tank of ultra-pure water

Mountains filter out other signals that mask neutrino detection.

Distance underground 1.6 km

A few neutrinos interact within the huge tank of super pure water, generating a cone of light.

The light is detected by **photo sensors** that line the tank, and translated into a digital image.

Mt. Ikena Yama
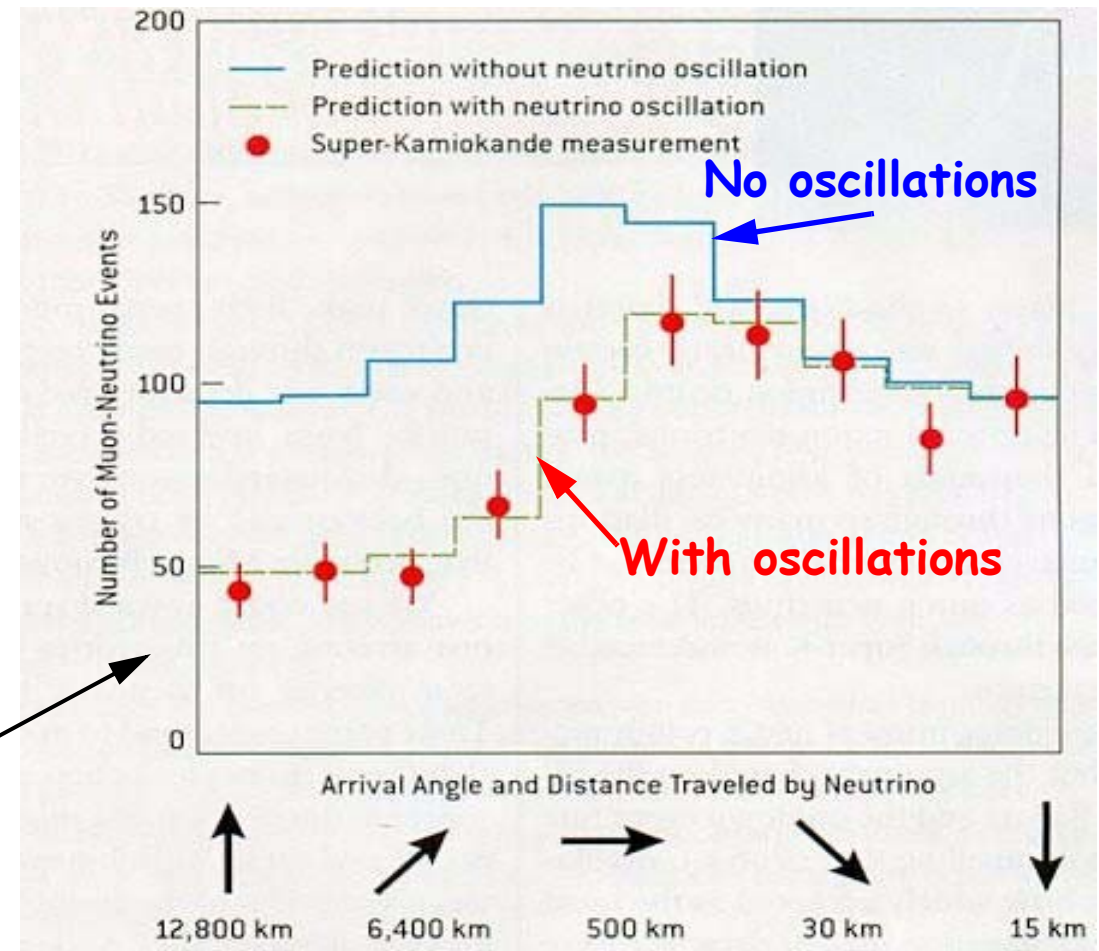
University of Hawaii media graph

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 $\Longrightarrow$ identify muons and electrons.**

● **The light detected by the photomultipliers $\Longrightarrow$ determine the neutrino trajectory and energy.**

● **A sample of 2700 ν_μ events $\Longrightarrow$ compare the expected distributions with the measured distribution.**

Prediction without neutrino oscillation
Prediction with neutrino oscillation
Super-Kamiokande measurement

No oscillations

With oscillations

Number of Muon-Neutrino Events

Arrival Angle and Distance Traveled by Neutrino

12,800 km   6,400 km   500 km   30 km   15 km

The atmospheric neutrino problem

● **Lack of neutrinos** with a long travel distance $\Rightarrow$ evidence for $\nu_\mu \leftrightarrow \nu_\tau$ **oscillations** $\Rightarrow$ muon neutrinos had turned into tau neutrinos that were not detected.
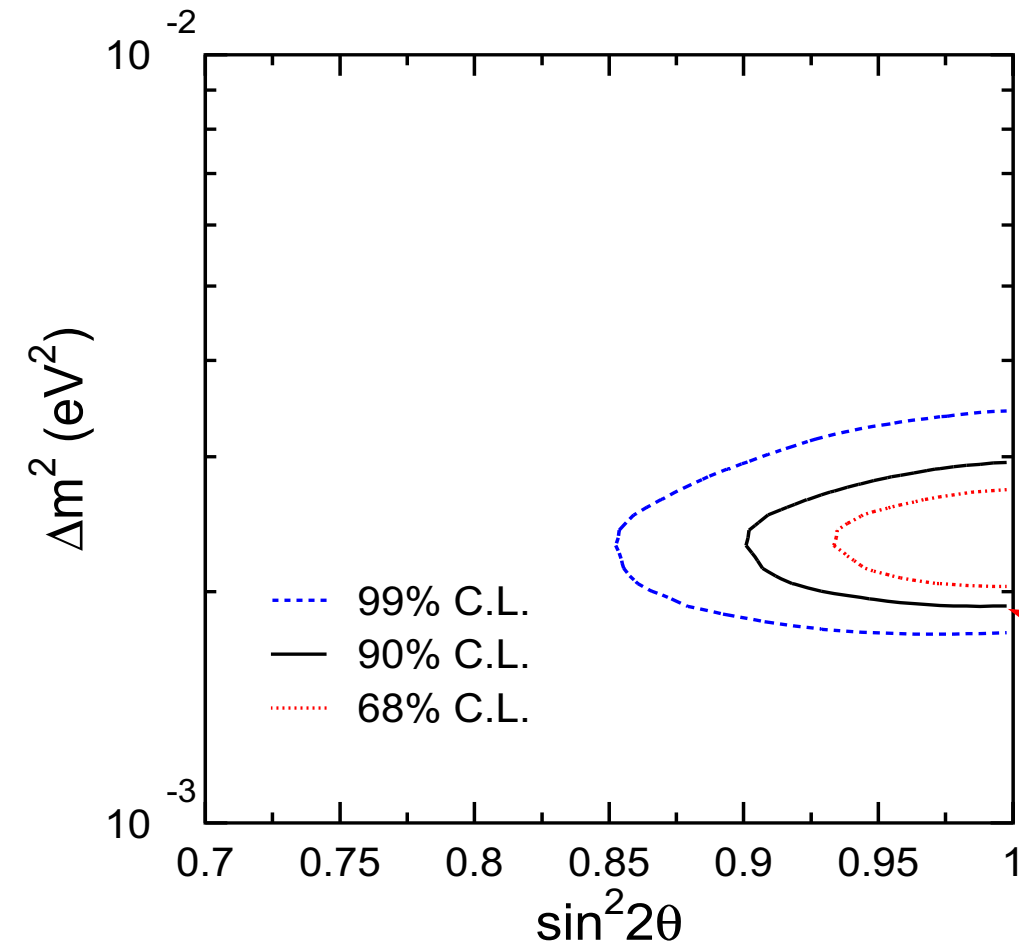
● The measurement $\Rightarrow$ **set limits** on the mixing angle and the neutrino mass difference:

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

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

Plot axes: Δm^2 (eV^2) from 10^{-3} to 10^{-2} vs $\sin^2 2\theta$ from 0.7 to 1.

Legend:
- 99% C.L.
- 90% C.L.
- 68% C.L.

Short baseline neutrino experiments

● **High intensity proton beams** $\Rightarrow$ **target** $\Rightarrow$ **kaons and pions**

   $\Rightarrow$ **decays** $\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\Rightarrow$ **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).
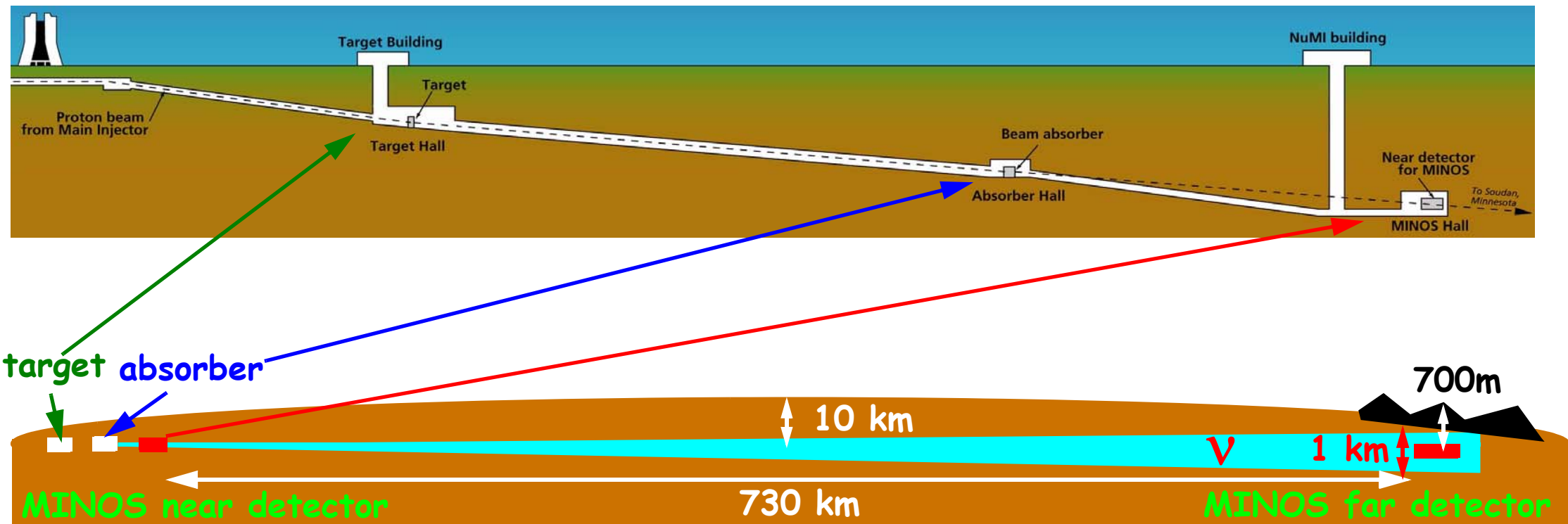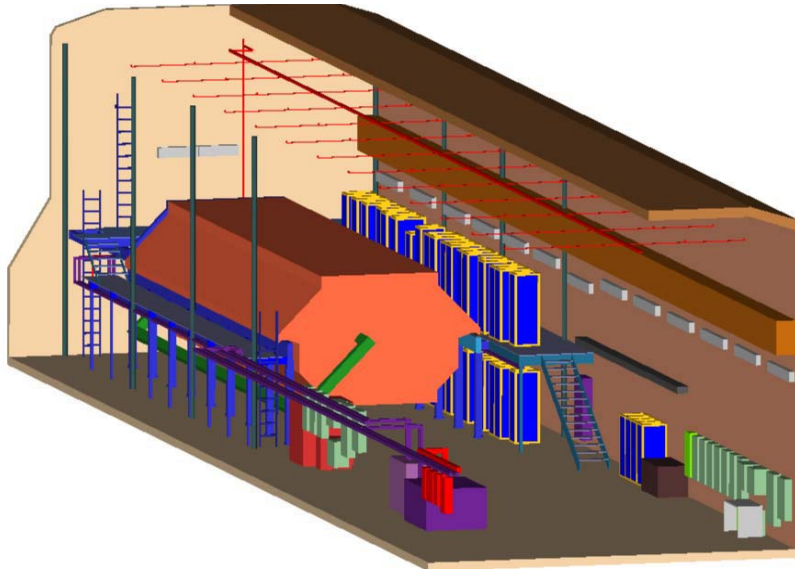
Long baseline neutrino experiments

➡️ The MINOS experiment

The Near Detector

Used to measure the neutrinos before they can oscillate.
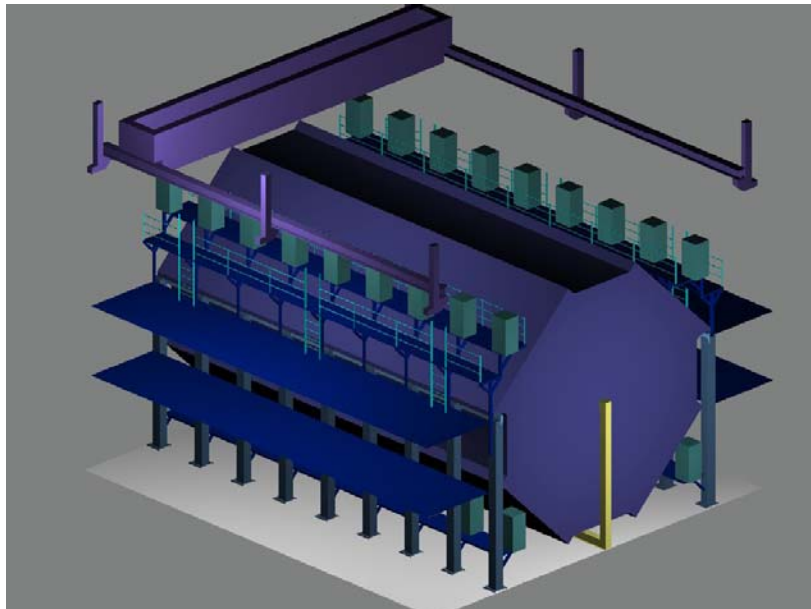
980 tonnes of magnetized iron + scintillators.
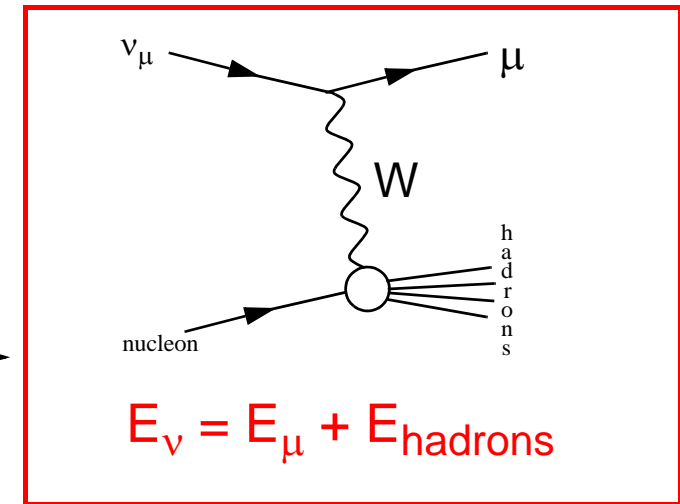
The Far Detector

Used to measure the neutrinos after they have oscillated.
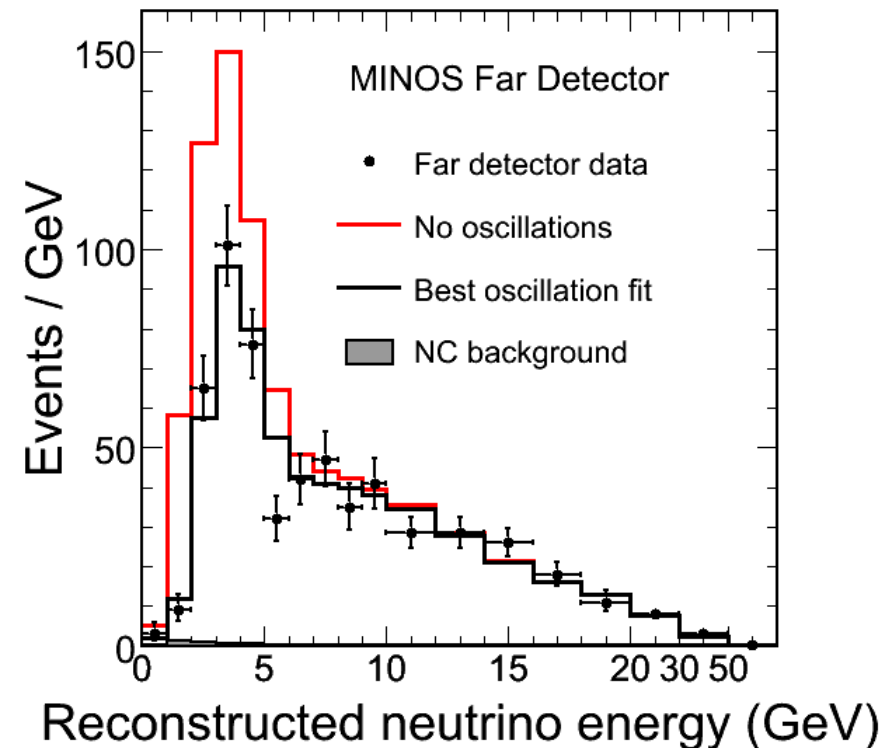
5400 tonnes of magnetized iron + scintillators.

Long baseline neutrino experiments

● **Charged current reactions** $\Rightarrow$ measure the **energy of the neutrinos** from the energy of muons and the hadrons.

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

● **Neutrino energy spectrum in far detector** $\Rightarrow$ **fewer neutrinos** than expected if no neutrino oscillations.
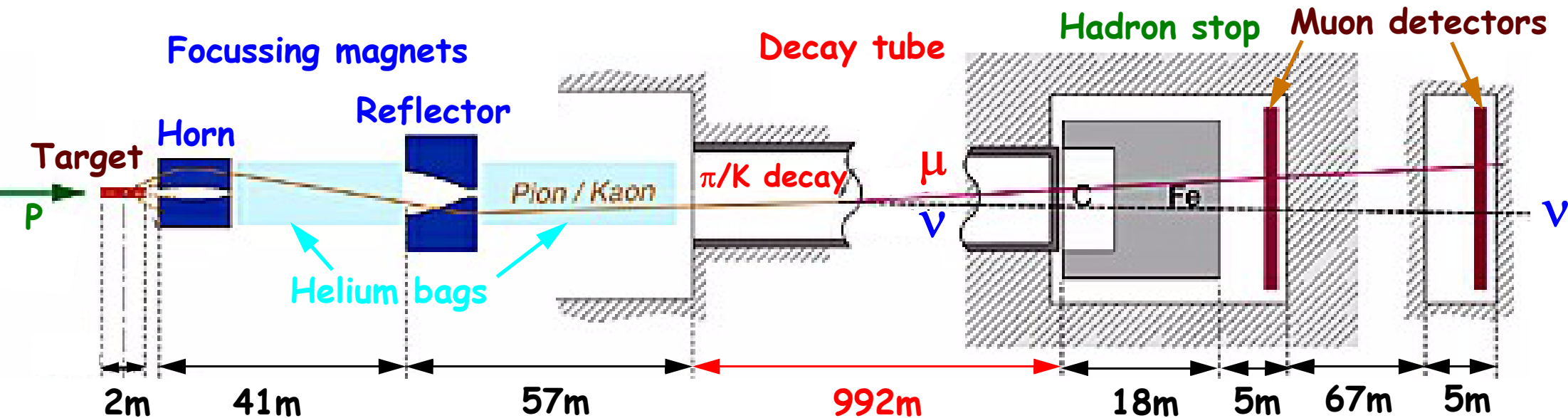

● **The measurement gave the result:**

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

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

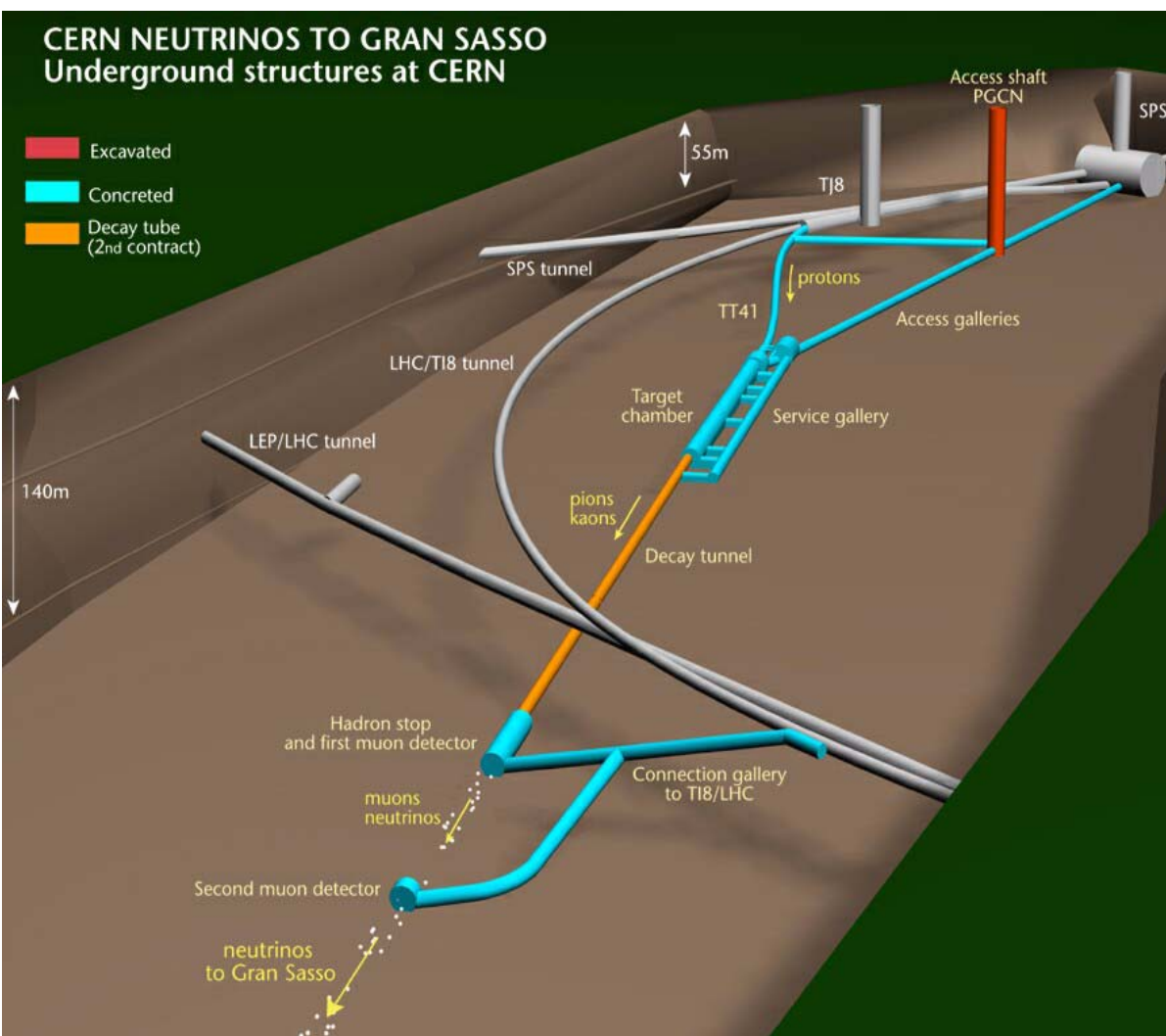# Long baseline neutrino experiments

➡ CNGS - CERN Neutrinos to Gran Sasso

- The Kamiokande and Minos measurements ⟹ 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:

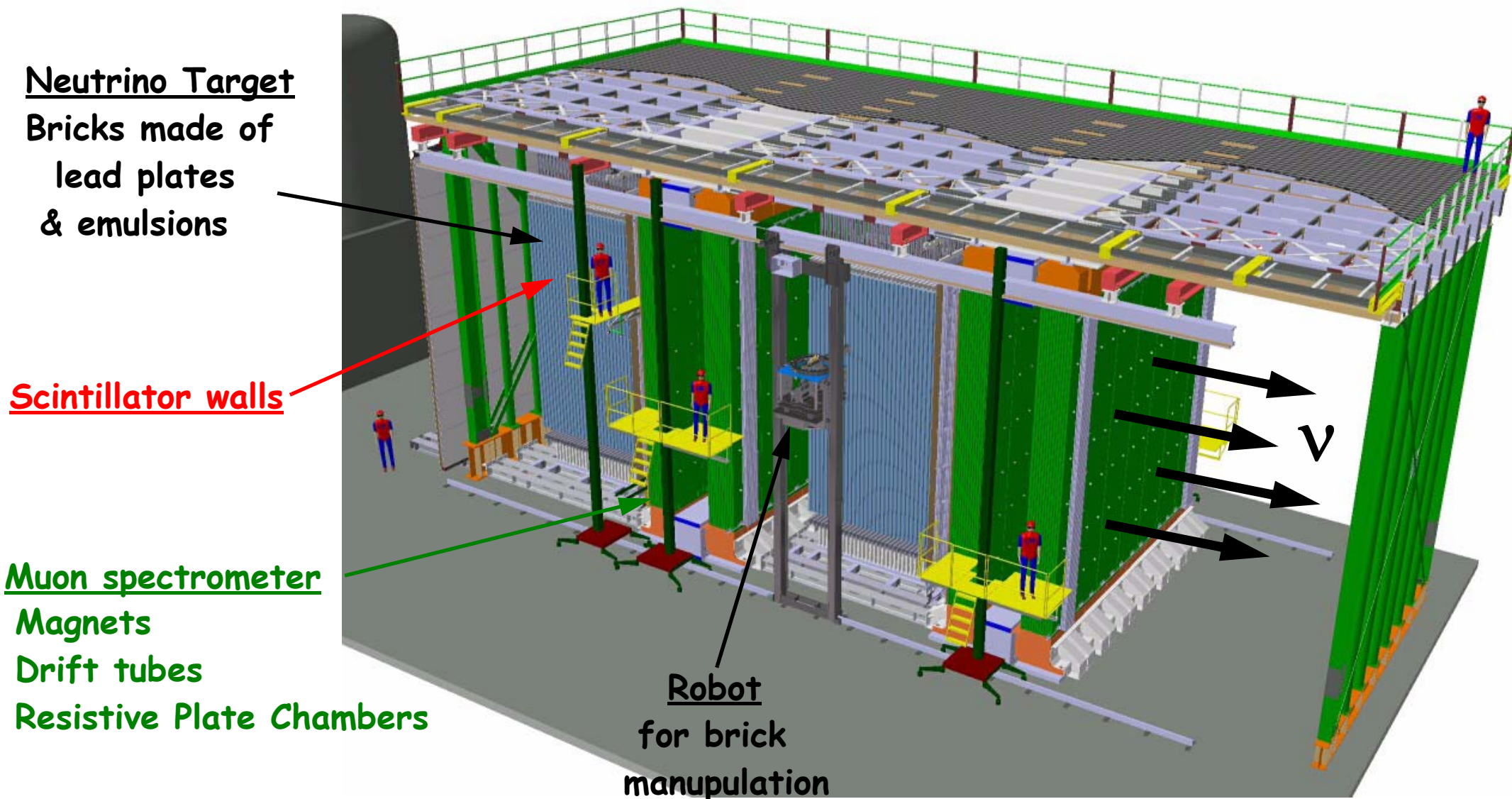# Long baseline neutrino experiments

➡ 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
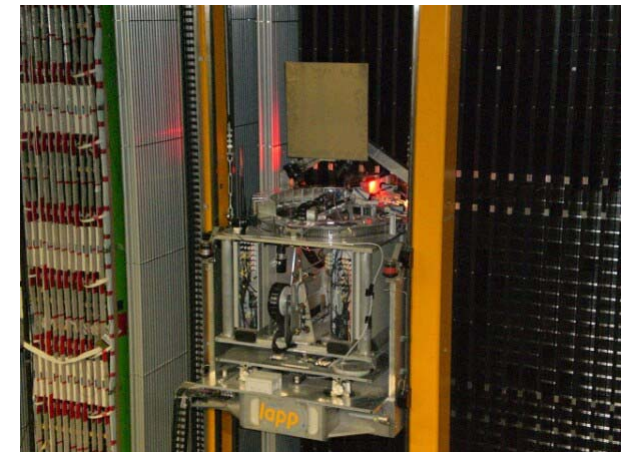
ν

Robot
for brick
manupulation

Long baseline neutrino experiments

➡ The OPERA experiment
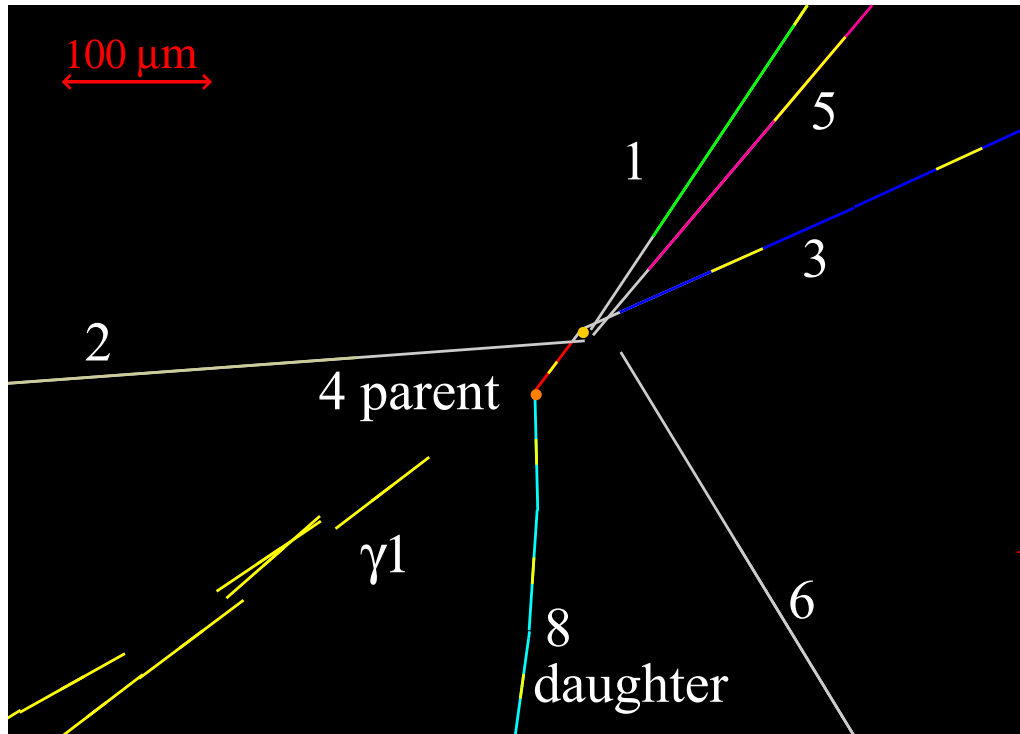
150,000 Lead/emulsion bricks are used in the target.

Target

Muon Spectrometer
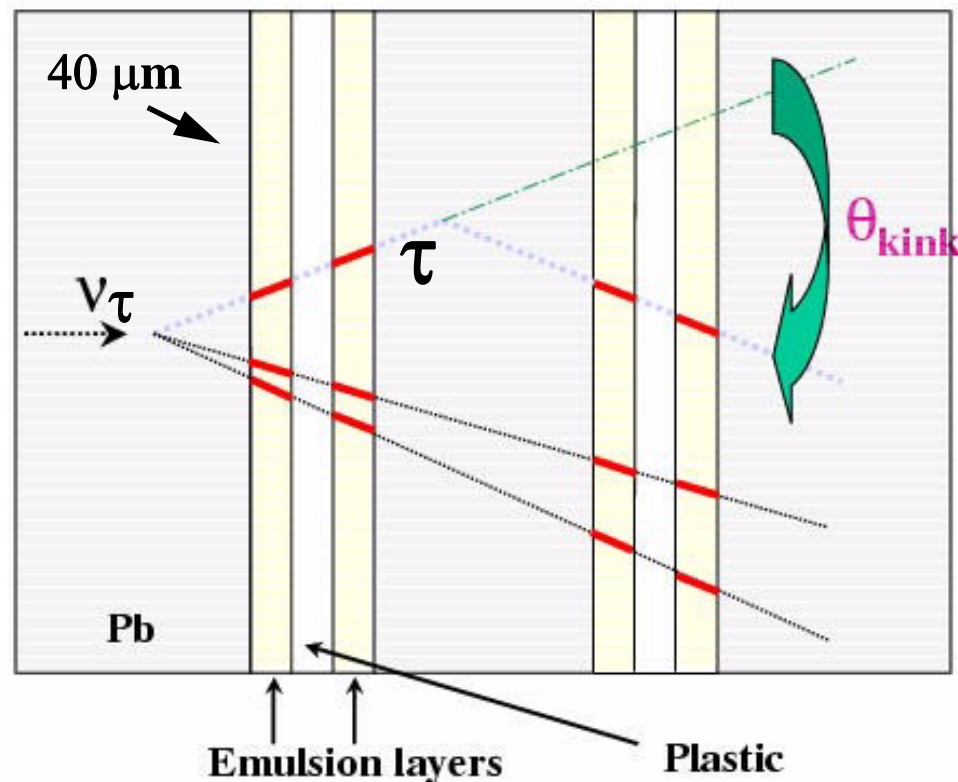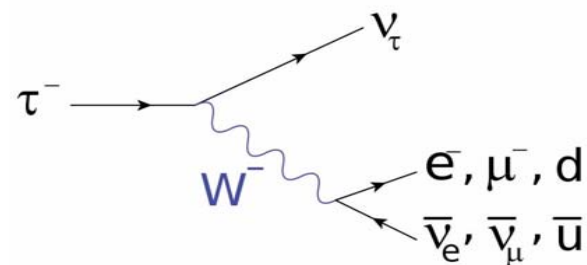

The Opera experiment down in its underground hall.

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.

● **One and only one candidate for a ν_τ event has sofar been observed.**

Neutrino oscillations

➡️ **Present status**

SNO Solar: $\nu_1 - \nu_2$

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

$\theta = 34°$

Kamiokande Atm: $\nu_2 - \nu_3$
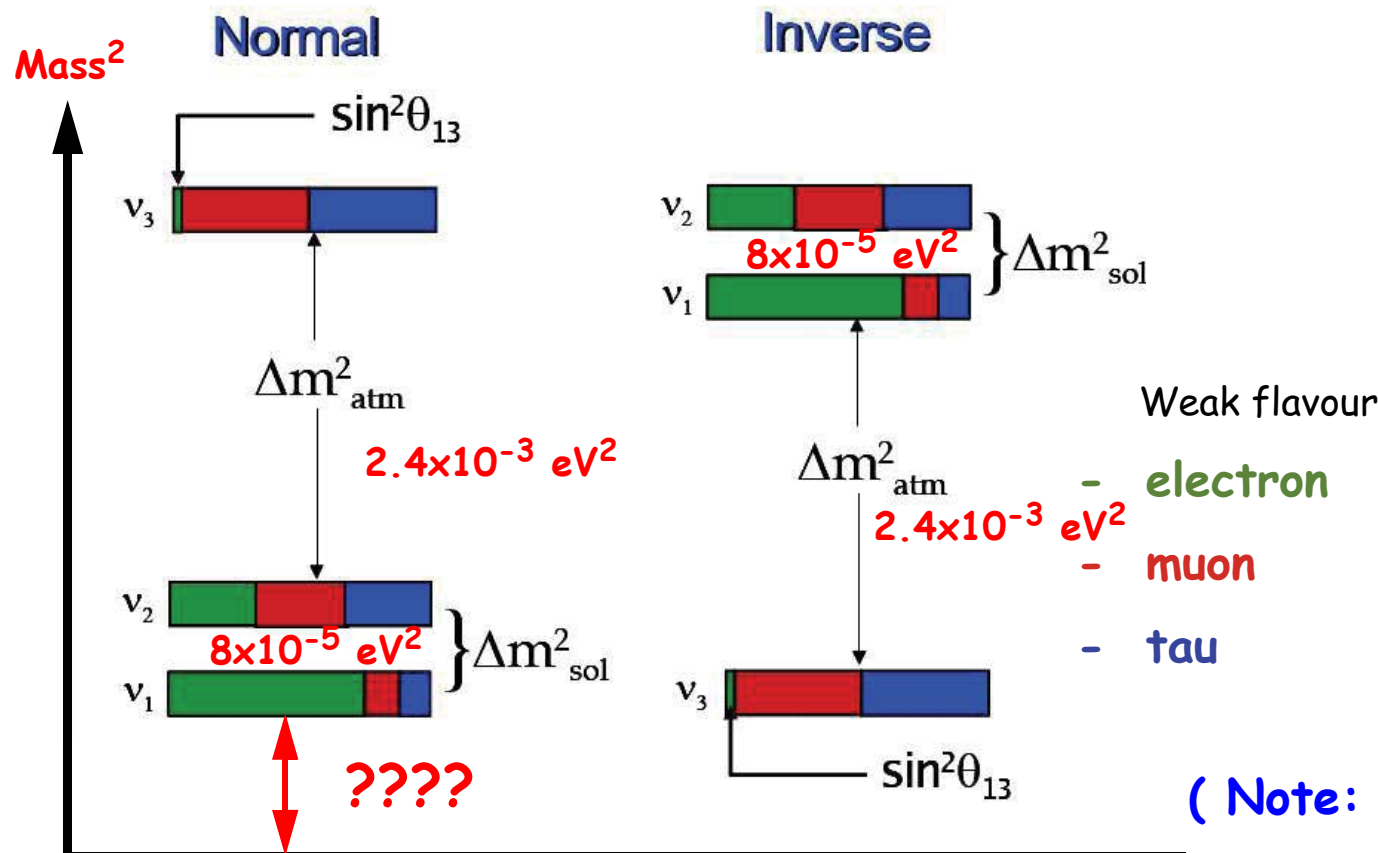
$2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-3}$ eV^2

$\theta > 36°$

MINOS Atm: $\nu_2 - \nu_3$

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

$\theta = 45°$

Mass^2

Normal

$\sin^2\theta_{13}$

ν_3

Δm^2_{atm}

2.4×10^{-3} eV^2

ν_2

ν_1

8×10^{-5} eV^2 $\}\Delta m^2_{sol}$

????

Inverse

ν_2

ν_1

8×10^{-5} eV^2 $\}\Delta m^2_{sol}$

Δm^2_{atm}

2.4×10^{-3} eV^2

ν_3

$\sin^2\theta_{13}$

Weak flavour

- **electron**
- **muon**
- **tau**

(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.**
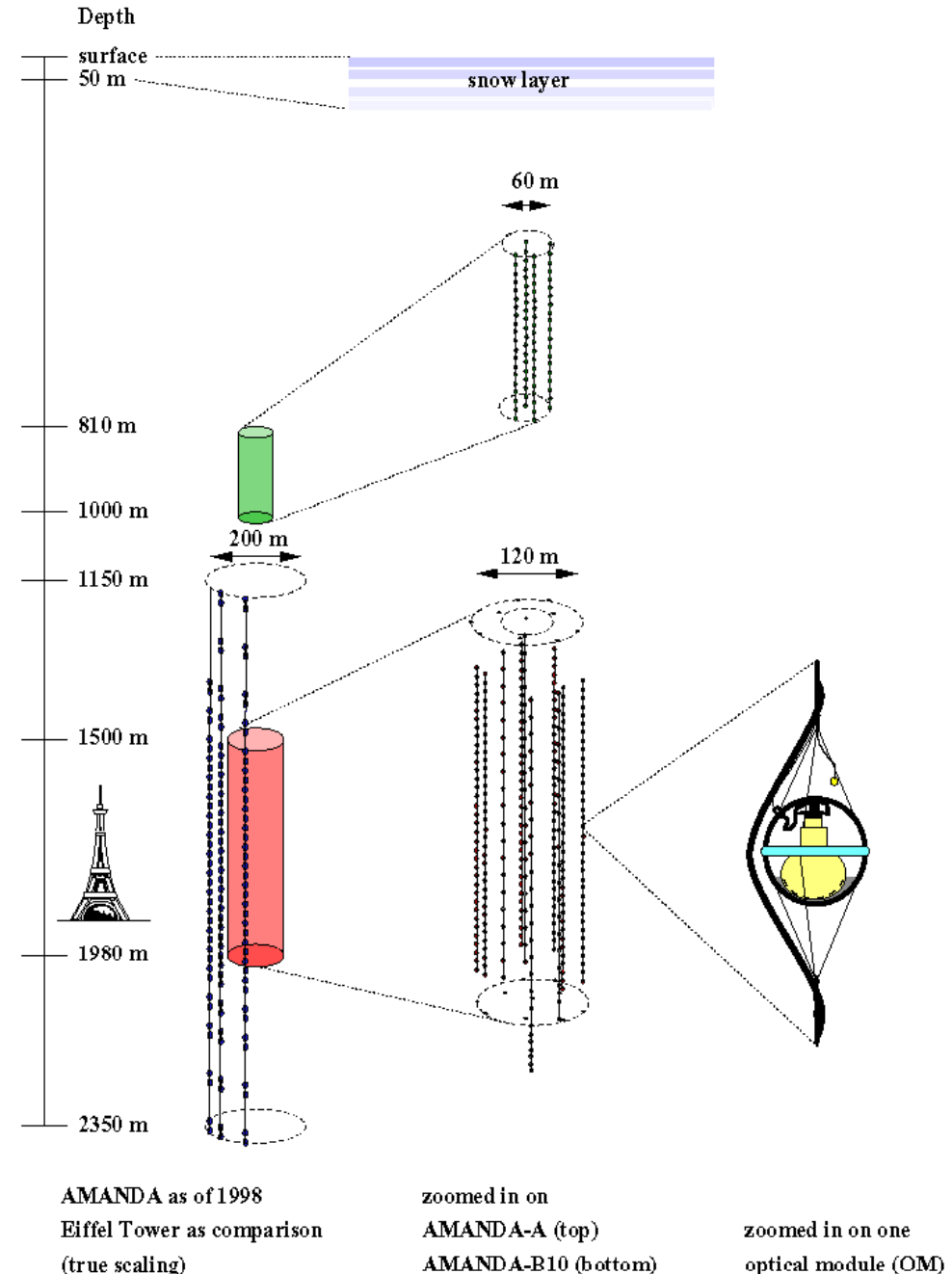
Supernova SN1987a as seen by the Hubble telescope: ⟶

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**.

Depth
surface
50 m — snow layer

60 m

810 m

1000 m
200 m
1150 m
120 m

1500 m

1980 m

2350 m

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

● **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**.
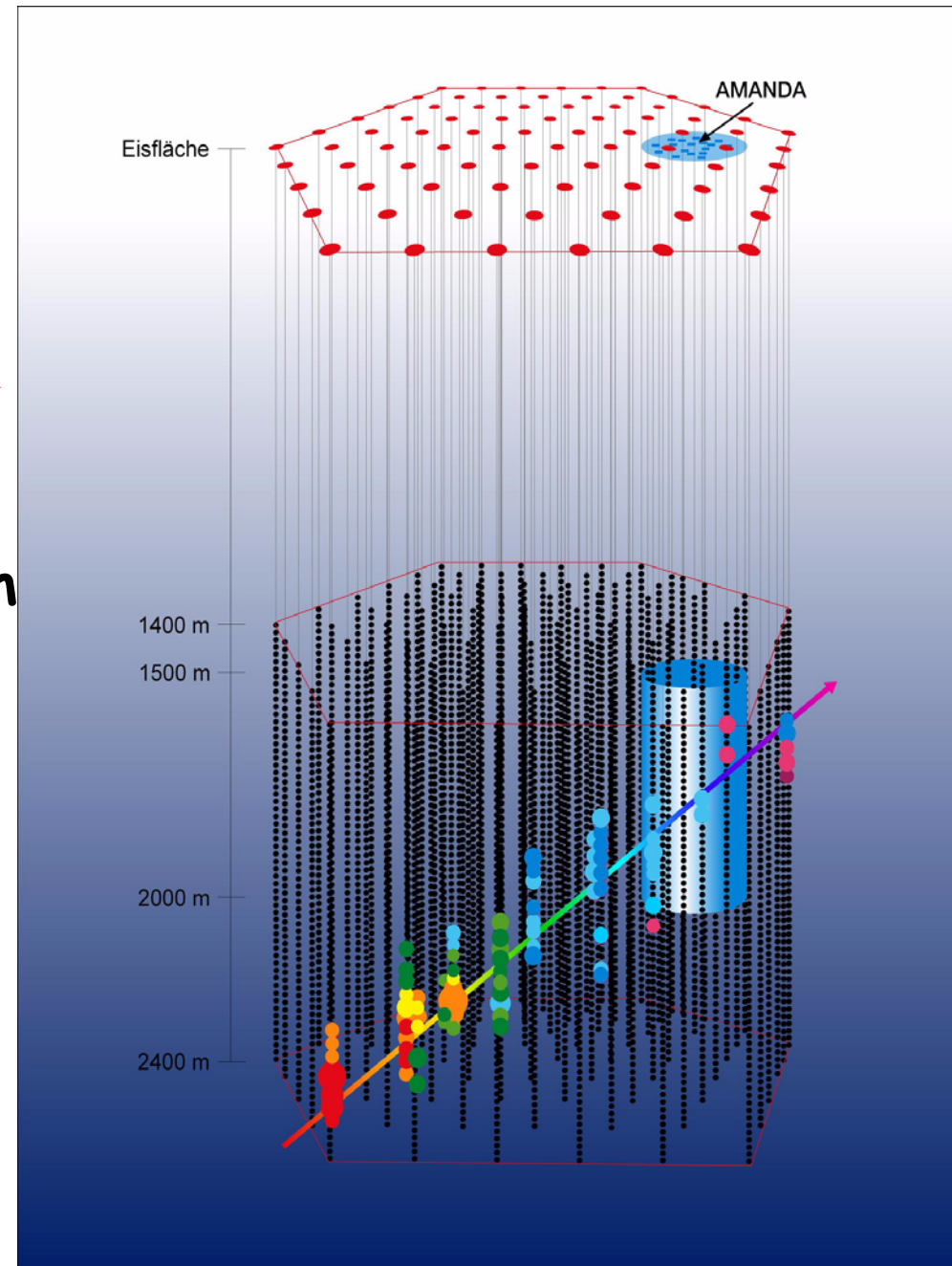
The neutrinos anti-particle

➡️ 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 ⇨ $\overline{\nu}_R$

● 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 ⇨

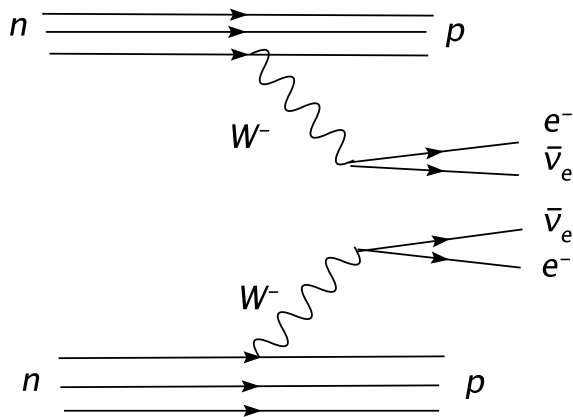Particles: ν_L, ν_R Anti-particles: $\overline{\nu}_L, \overline{\nu}_R$

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

Two neutrino states: ν_L, ν_R
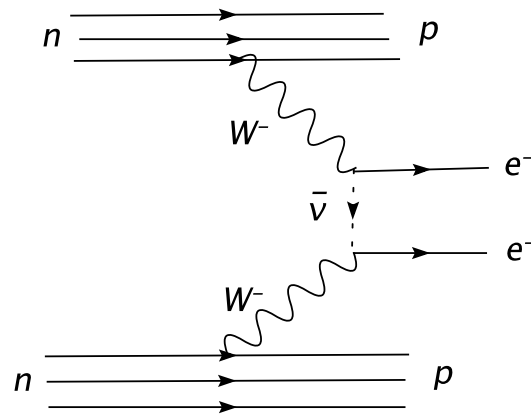
The neutrinos anti-particle
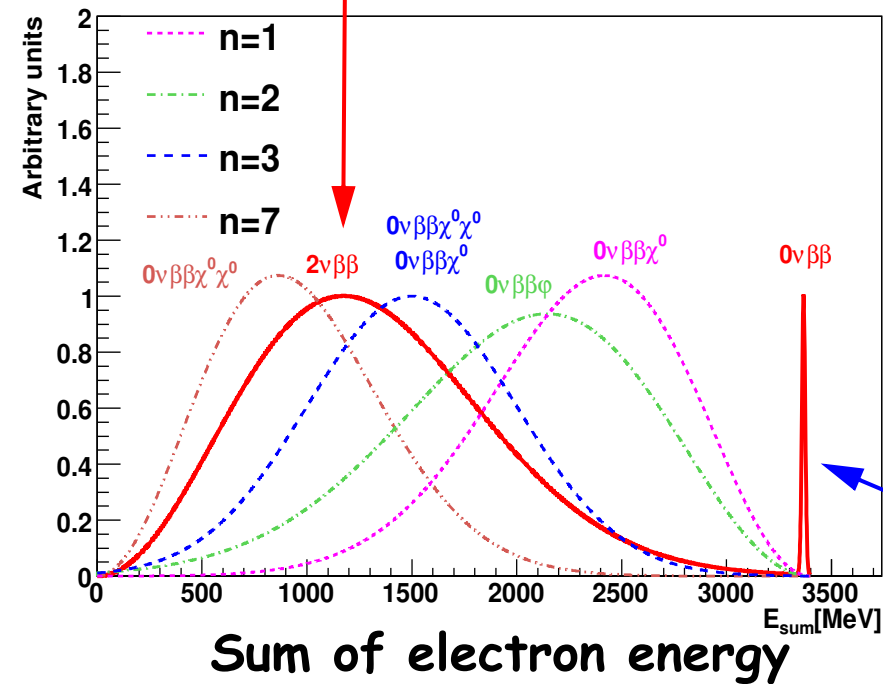
➡️ **Searching for Majorana neutrinos in double β-decay**

● **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.

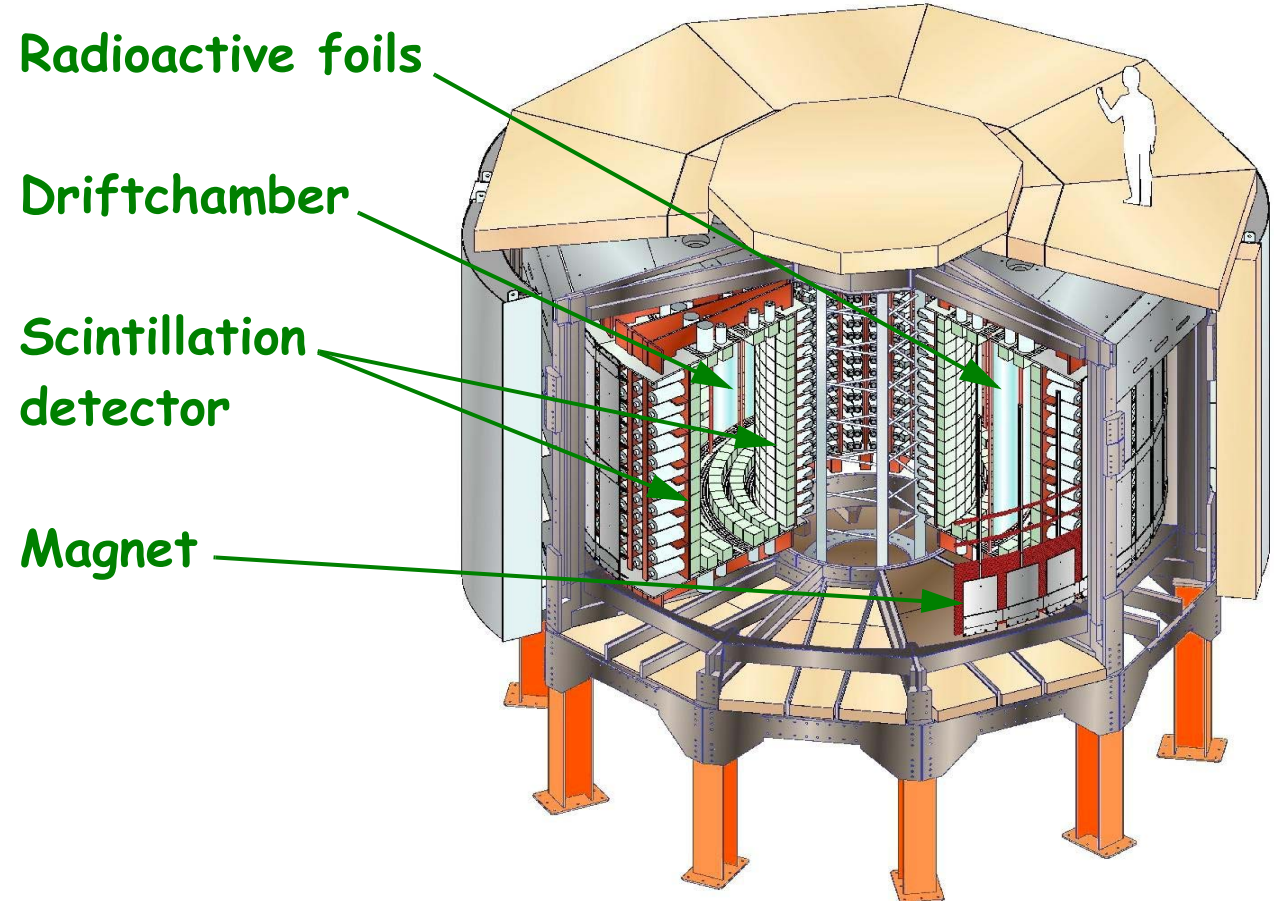**Experiments search for these decays !**

The neutrinos anti-particle

➡️ The NEMO3 experiment under Mont Blanc

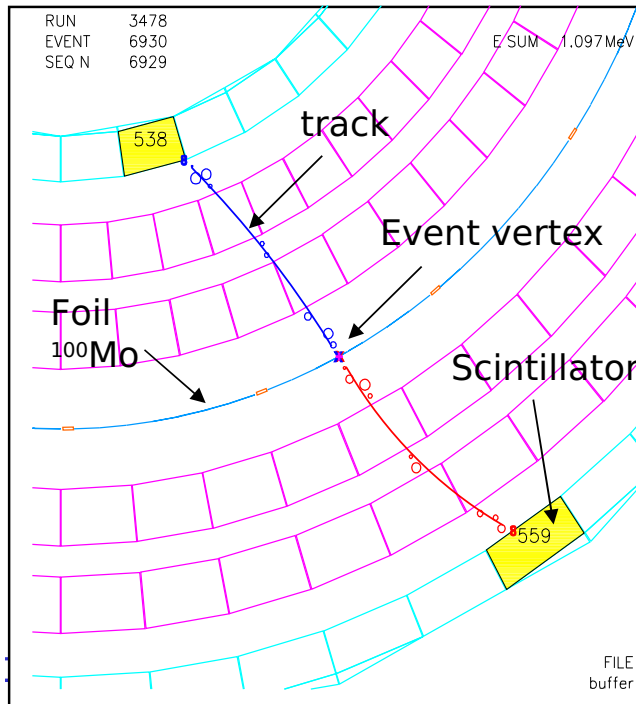● Double β-decays from thin sheets of different radioactive materials in an underground experiment.

Radioactive foils

Driftchamber

Scintillation detector

Magnet

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
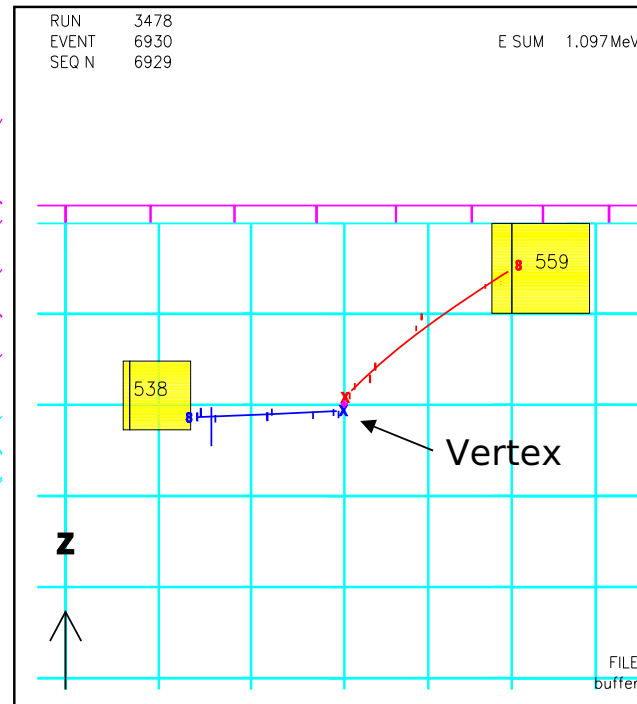
Energy distribution of electrons

Transverce view

```
RUN      3478
EVENT    6930          E SUM   1.097 MeV
SEQ N    6929
```

538

track

Event vertex

Foil
^{100}Mo

Scintillator

559

Longitudinal view

```
RUN      3478
EVENT    6930          E SUM   1.097 MeV
SEQ N    6929
```

559

538

Z

Vertex

FILE
buffer

FILE
buffer

^{100}Mo, Phase 2, 2.83 years

N events / 0.1 MeV

- ● Data
- 2νββ ^{100}Mo
- ^{222}Rn
- internal BKG
- 0νββ ^{100}Mo

Expected signal

E_{TOT} (MeV)