XI. Beyond the Standard Model

→ While the Standard Model appears to be confirmed in all ways, there are some unclear points and possible extensions:

- Why do the observed quarks and leptons have the masses they do?
- Do neutrinos have any mass ?
- If yes, are they the *Dark Matter*?

Neutrino masses

→ If neutrinos have non-zero masses, they must be subject to *neutrino-mixing*

Reminder: quark mixing in weak interactions

$$\begin{aligned} d' &= d\cos\theta_C + s\sin\theta_C \\ s' &= -d\sin\theta_C + s\cos\theta_C \end{aligned}$$

By analogy, neutrinos can be represented as linear combinations

$$\begin{aligned} \nu_e &= \nu_1\cos\alpha + \nu_2\sin\alpha \\ \nu_\mu &= -\nu_1\sin\alpha + \nu_2\cos\alpha \end{aligned} \qquad (158)$$

if neutrinos ν_1 and ν_2 have masses m_1 and m_2.

→ The mixing angle α must be determined from experiment by studying *neutrino oscillations*.

→ Neutrino oscillation: a beam of ν_e develops a ν_μ component as it travels through space, and vice versa.

Neutrinos created at t=0 can be written as:

$$\begin{aligned} \nu_e(0) &= \nu_1(0)\cos\alpha + \nu_2(0)\sin\alpha \\ \nu_\mu(0) &= -\nu_1(0)\sin\alpha + \nu_2(0)\cos\alpha \end{aligned} \qquad (159)$$

and after a period of time t it evolves to:

$$\begin{aligned} \nu_e(t) &= \nu_1(0)e^{-iE_1t}\cos\alpha + \nu_2(0)e^{-iE_2t}\sin\alpha \\ \nu_\mu(t) &= -\nu_1(0)e^{-iE_1t}\sin\alpha + \nu_2(0)e^{-iE_2t}\cos\alpha \end{aligned} \qquad (160)$$

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

$$\begin{aligned} E_1 &= \sqrt{m_1^2 + p^2} \\ E_2 &= \sqrt{m_2^2 + p^2} \end{aligned}$$

If one starts with a pure ν_e state then after a time *t* one has a mixture of electron and muon neutrinos given by

$$\nu_e(t) = A(t)\nu_e(0) + B(t)\nu_\mu(0) \tag{161}$$

where

$$\begin{aligned} A(t) &= e^{-iE_1t}\cos^2\alpha + e^{-iE_2t}\sin^2\alpha \\ B(t) &= \sin\alpha\cos\alpha[e^{-iE_2t} - e^{-iE_1t}] \end{aligned} \tag{162}$$

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

$$P(\nu_e \to \nu_e) = |A(t)|^2 = 1 - P(\nu_e \to \nu_\mu) \tag{163}$$

$$P(\nu_e \to \nu_\mu) = |B(t)|^2 = \sin^2(2\alpha)\sin^2\frac{(E_2 - E_1)t}{2} \tag{164}$$

$$= \sin^2(2\alpha)\sin^2\frac{(\sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2})t}{2}$$

→ If neutrinos have equal (zero) masses ⇒ E_1=E_2 ⇒ no oscillations !

Ways to detect neutrino oscillations:

- 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 time *t* is determined by the distance between the detector and the source of neutrinos

→ Several neutrino sources can be considered:

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

The atmospheric neutrino anomaly

→ This was first observed in the 1980's. Instead of having the predicted $N(\nu_\mu) \approx 2N(\nu_e)$ the rates of both neutrino types were approximately equal.

❖ The Super-Kamiokande detector measures rates and flavours of neutrinos coming both from zenith and nadir

- A neutrino created in cosmic rays travels at most 20 km in the atmosphere ⇒ it has no time to oscillate (proven by other experiments)
- A similar neutrino created on the other side of the Earth travels ≈13000 km ⇒ it has a good chances to oscillate
- If the ratio of ν_e and ν_μ is different in the two cases above ⇒ there are oscillations ⇒ at least one neutrino is massive.

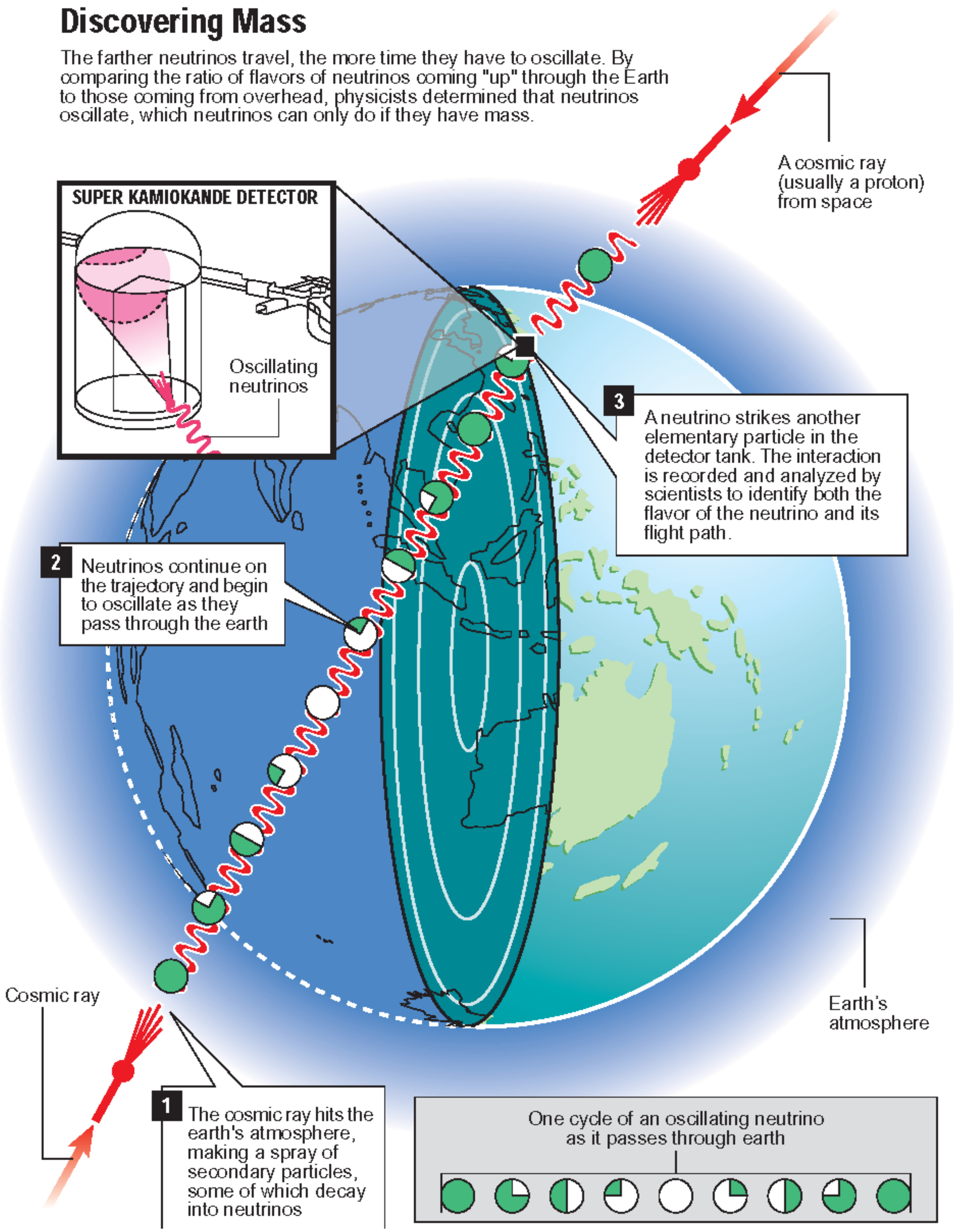
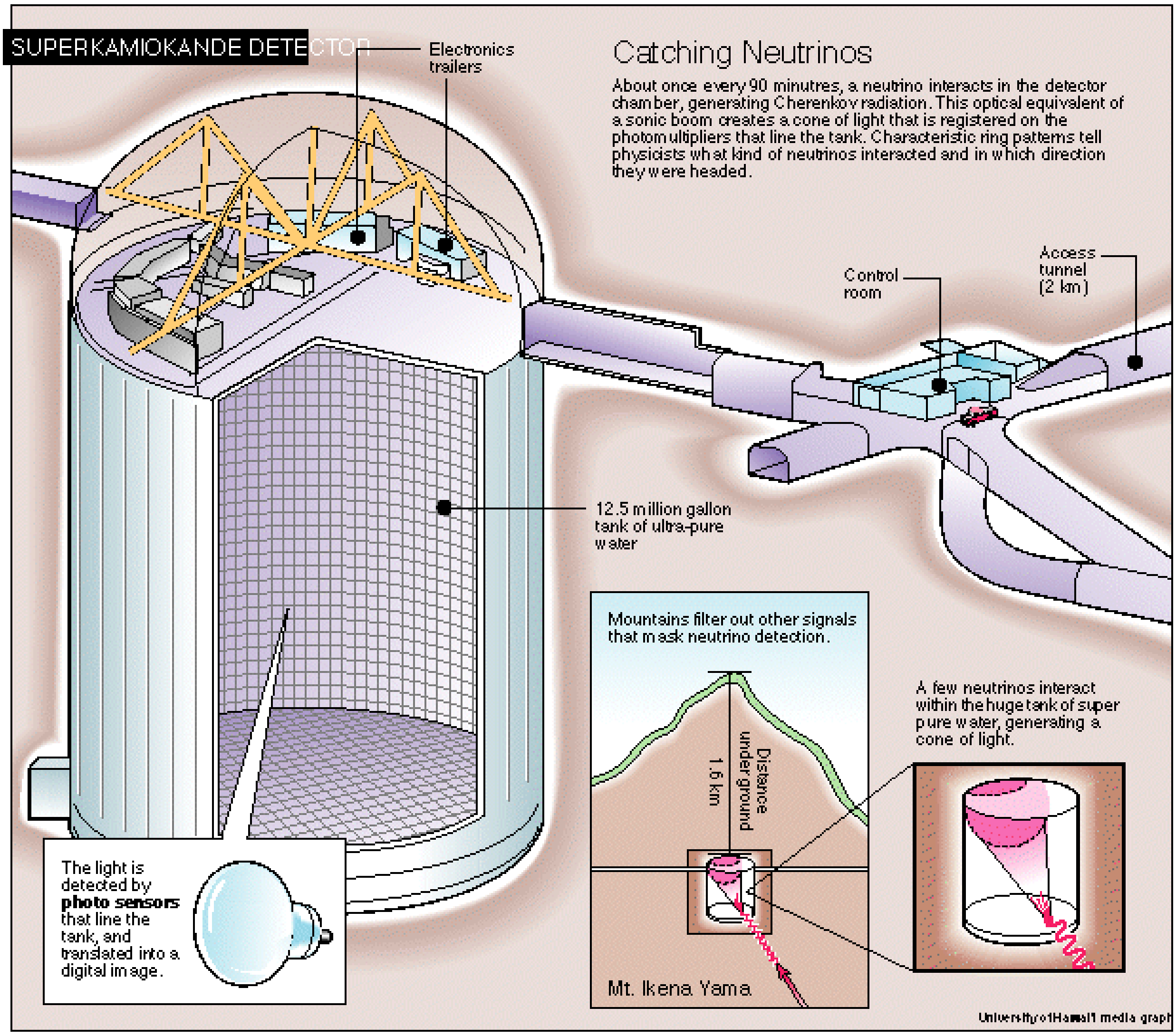


Figure 134: Neutrino oscillations through Earth



Catching Neutrinos

About once every 90 minutres, 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.

Mountains filter out other signals that mask neutrino detection.

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.

University of Hawaii media graph

Figure 135: Schematics of the Super-Kamiokande detector

– The detector is placed in a deep mine to reduce the background.

– 50 000 m^3 of water and 13 000 photomultipliers work as a Cherenkov detector.

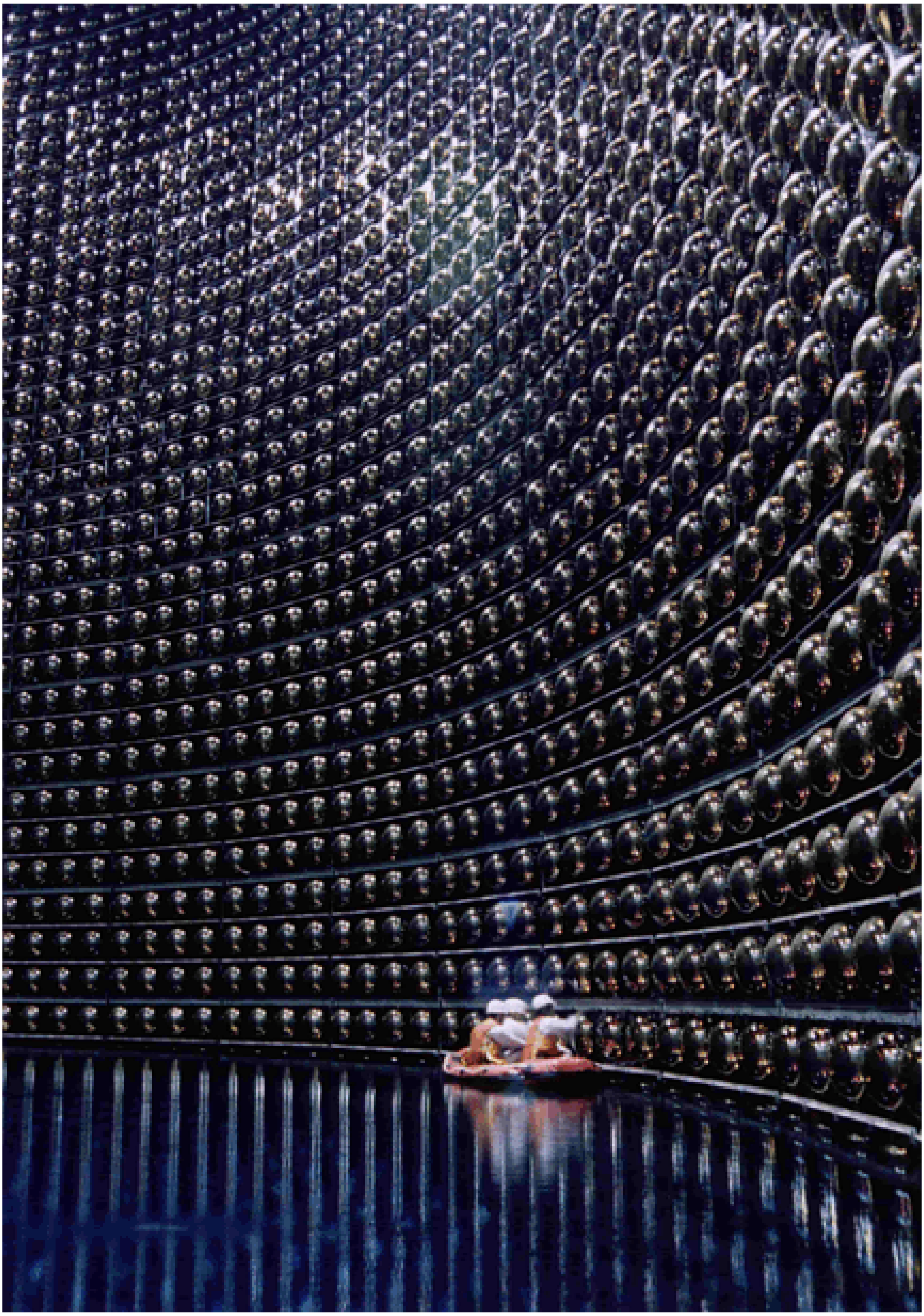


Figure 136: Interior of the Super-Kamiokande detector (during construction)

→ In 1998, the Super-Kamiokande Collaboration announced:

a) 4654 observed events – by far the largest sample in the world

b) the ν_μ data exhibited a deficit with a zenith angle dependence

c) hence the “atmospheric neutrino anomaly” can only be explained by oscillations $\nu_\mu \leftrightarrow \nu_\tau$, which leads to a muonic neutrino deficiency in cosmic rays.

d) the mixing angle and neutrino mass difference Δm was estimated to be

$$\begin{gathered} \sin^2(2\alpha) > 0{,}82 \\ 5\times10^{-4} < \Delta m^2 < 6\times10^{-3}\ eV^2 \end{gathered} \qquad (165)$$

The solar neutrino problem

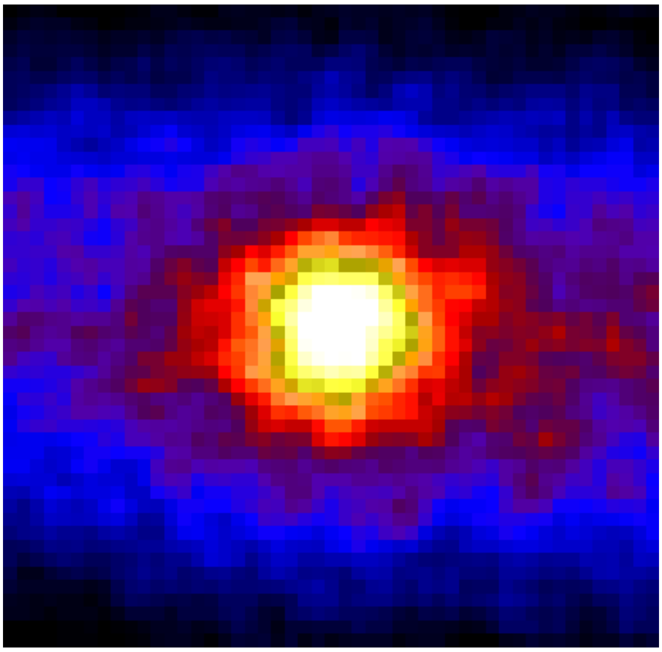


Figure 137: "Portrait" of the Sun made with neutrinos

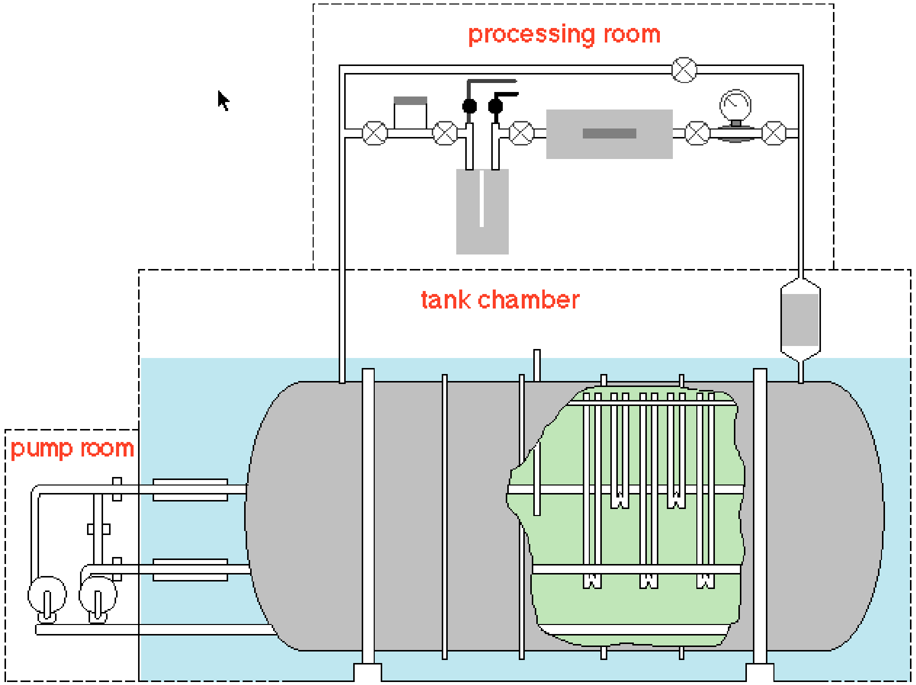
Several (similar) methods are used to detect solar neutrinos:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

$$\nu_e + {}^{98}\mathrm{Mo} \rightarrow e^- + {}^{98}\mathrm{Tc}$$

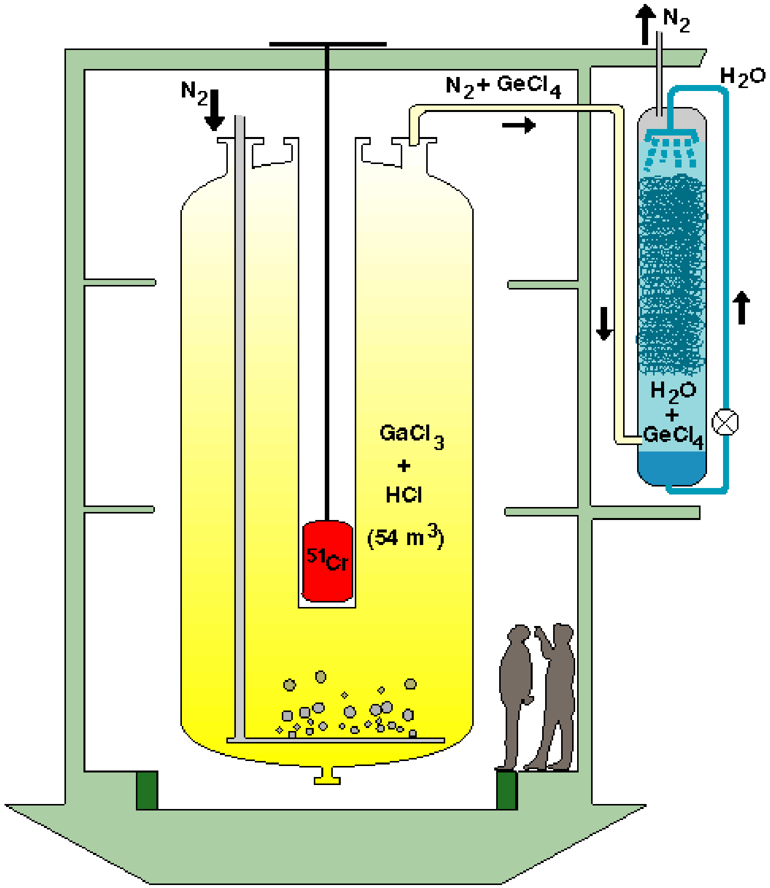
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$$

Experimental installations typically are tanks filled with corresponding medium and placed underground.



The Homestake gold mine detector (USA).

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



GALLEX detector under the Gran Sasso mountain (Italy).

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

Figure 138: Typical layouts of solar neutrino detectors.

The solar neutrino flux is measured in SNU ("solar neutrino unit"):

1 SNU = 1 capture / 1 second / 10^{36} target atoms

"The solar neutrino problem":

→ For the Homestake detector the predicted neutrino flux is 7.3 ± 2.3 SNU but the measured is 2.5 ± 0.2 SNU

→ GALLEX: The predicted flux is 132 ± 9 SNU and the measured flux is 79 ± 11 SNU

Reactions producing solar neutrinos are:

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

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

3) ${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$ $E_{\nu,max}$=15 MeV (0.02%)

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

→ Neutrino oscillations is one of the possible explanation for the lack of ν_e coming from the sun.

→ During 15s on February 23 1987 the IMB and Kamiokande detectors recorded 20 neutrino interactions coming from a supernova explosion (SN1987a) only 160 000 light years away.

This was the first time extra-terrestrial neutrinos, not coming from the sun, was observed.

→ From the energy (E_ν), the length of the burst (Δt) and the time of flight (t_ν) it is possible to estimate the neutrino mass (m_ν):

$$m_\nu = E_\nu \sqrt{\frac{2\Delta t}{t_\nu}}$$

→ *Example:* E_ν=10 MeV, Δt=10 s and t_ν=5x10^{12}s gives m_ν=20 eV.

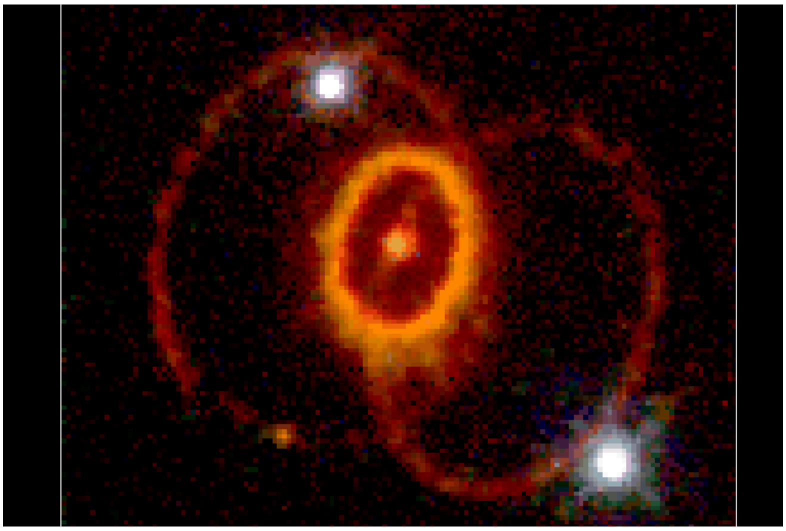


Figure 139: SN1987a as seen by the Hubble telescope.

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

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

→ The experiments is situated on the south pole and consist of strings of photomultipliers drilled deep down into the ice.

→ A neutrino interaction will give rise to Cherenkov light in the ice which is detected by the photomultipliers.

→ So far no extra-galactic neutrinos have been observed.

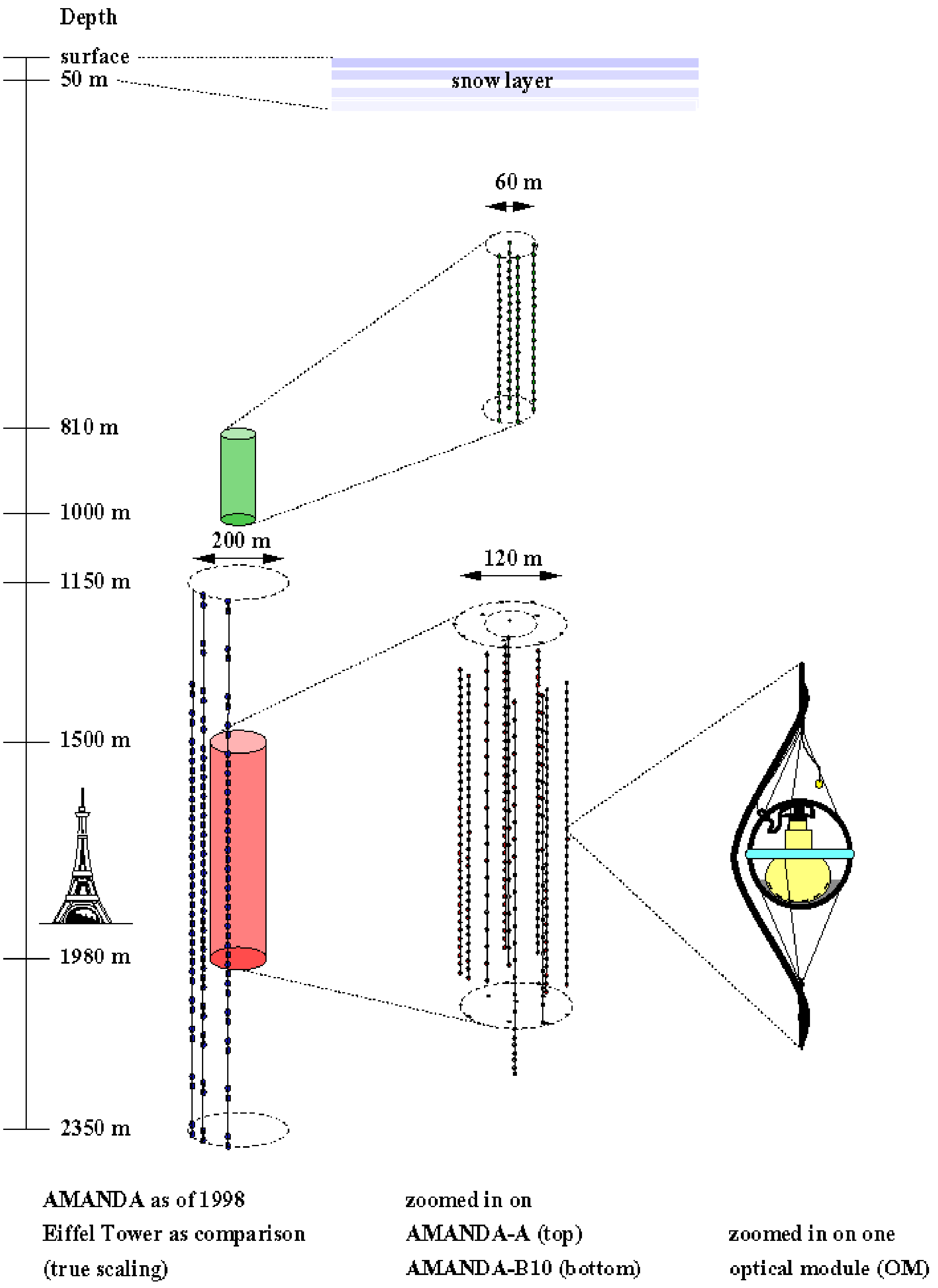


Figure 140: Schematics of the AMANDA neutrino telescope at the South Pole