Special Topics in Particle Physics

Primary Cosmic Rays - Neutrinos

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Neutrino Astronomy

The disadvantage of classical astronomy (observing EM waves) is that electromagnetic radiation is generally absorbed in matter (depending on the wavelength). Therefore, **one can only observe the surfaces of astronomical objects**. In addition, energetic γ rays from distant sources are attenuated via interactions with photons of the blackbody radiation $\gamma + \gamma \to e^+ + e^-$.

Charged primaries can in principle also be used in astroparticle physics. However, the directional information is only conserved for very energetic protons ($>10^{19}$ eV) because otherwise the Galactic magnetic fields will randomize their original direction. In addition the GZK cutoff also comes into play.

We loose information while the particles propagate from the source to us

Neutrino Astronomy

As a consequence of these, the requirement for an **optimal astronomy** can be defined in the following way:

1. The optimal astroparticles or radiation **should not be influenced by magnetic fields.**
2. The particles **should not decay from source to Earth.** This practically excludes neutrons as carriers unless neutrons have extremely high energy (τ = 885.7 s; at $E = 10^{19}$ eV one has $\gamma c\tau \approx$ 300 000 light-years).
3. **Particles and anti particles should be different.** This would in principle allow to find out whether particles originate from a matter or antimatter source. This requirement excludes photons because a photon is its own antiparticle, $\gamma = \bar{\gamma}$.
4. The **particles must be penetrating** so that one can look into the central part of the sources.
5. **Particles should not be absorbed** by interstellar or intergalactic dust or loose energy to infrared or blackbody photons.

Is all of this possible?

Neutrino Astronomy

These requirements are fulfilled by **neutrinos**!

Why *neutrino astronomy* has not been a major branch of astronomy all along?

The fact that neutrinos can escape from the center of the sources is related to their **low interaction cross section.** This, unfortunately, goes along with an **enormous difficulty to detect** these neutrinos on Earth.

For solar neutrinos in the range of several 100 keV the cross section for neutrino– nucleon scattering is

$$\sigma(\nu_e N) \approx 10^{-45}\ \mathrm{cm}^2/\mathrm{nucleon}\,.$$

The **interaction probability** of these neutrinos with our planet Earth at central incidence is

$$\phi = \sigma\ N_{\mathrm{A}}\ d\ \varrho \approx 4 \times 10^{-12}$$

(NA is the Avogadro number, d the diameter of the Earth, ϱ the average density of the Earth).

Out of the **7×10^{10} neutrinos per cm^2 and s** radiated by the Sun and arriving at Earth **only one or two at most are 'seen' by our planet.**

Neutrino Astronomy

As a consequence of this, neutrino **telescopes must have an enormous target mass,** and one has to envisage **long exposure times.**

For high energies the interaction cross section rises with neutrino energy. Neutrinos in the energy range of several **100 keV** can be detected by **radiochemical methods**.

For energies exceeding **5 MeV** large-volume **water Cherenkov counters** are used.

Neutrino astronomy is a very young branch of astroparticle physics. Up to now five different sources of neutrinos have been investigated.

Atmospheric neutrinos

For real neutrino astronomy **neutrinos from atmospheric sources are an annoying background.**

For the particle physics aspect of astroparticle physics atmospheric neutrinos have turned out to be a very interesting subject. **Primary cosmic rays interact in the atmosphere with the atomic nuclei of nitrogen and oxygen.**

In these proton-air interactions **nuclear fragments and predominantly charged and neutral pions are produced.** The **decay of charged pions** (lifetime 26 ns) produces **muon neutrinos**:

$$\boxed{\pi^+ \to \mu^+ + \nu_\mu\,, \quad \pi^- \to \mu^- + \bar{\nu}_\mu\,.}$$

Muons themselves are also unstable and decay with an average lifetime of 2.2 μs according to

$$\boxed{\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu\,, \quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu\,.}$$

Atmospheric neutrinos

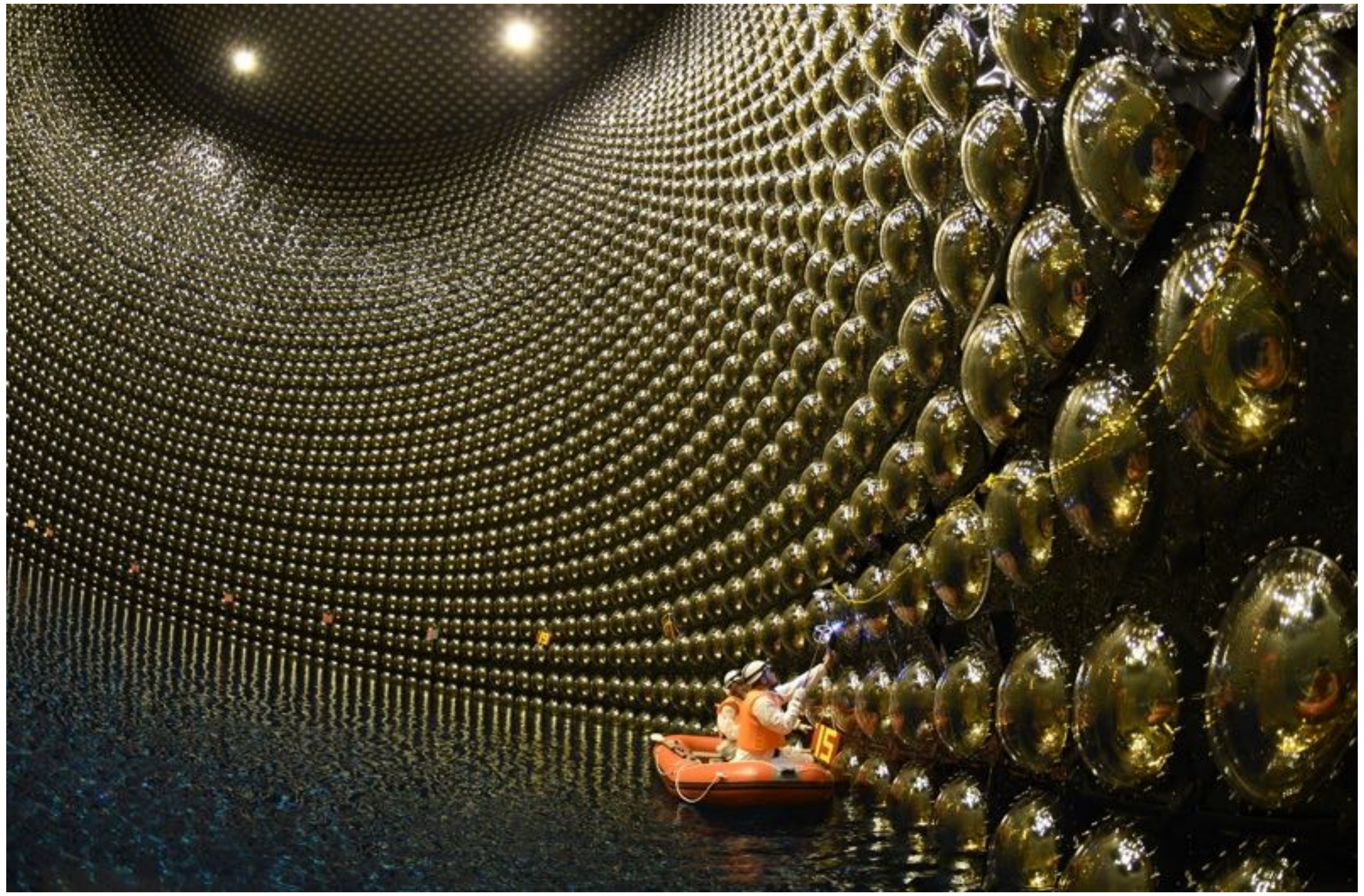
Therefore, the atmospheric neutrino beam contains **electron and muon neutrinos** and one would expect a **ratio**

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

as can be easily seen by counting the decay neutrinos from the reactions.

The presently largest experiments measuring atmospheric neutrinos are Super-Kamiokande and ICECUBE.

How do these detectors work?



The Super-Kamiokande detector.

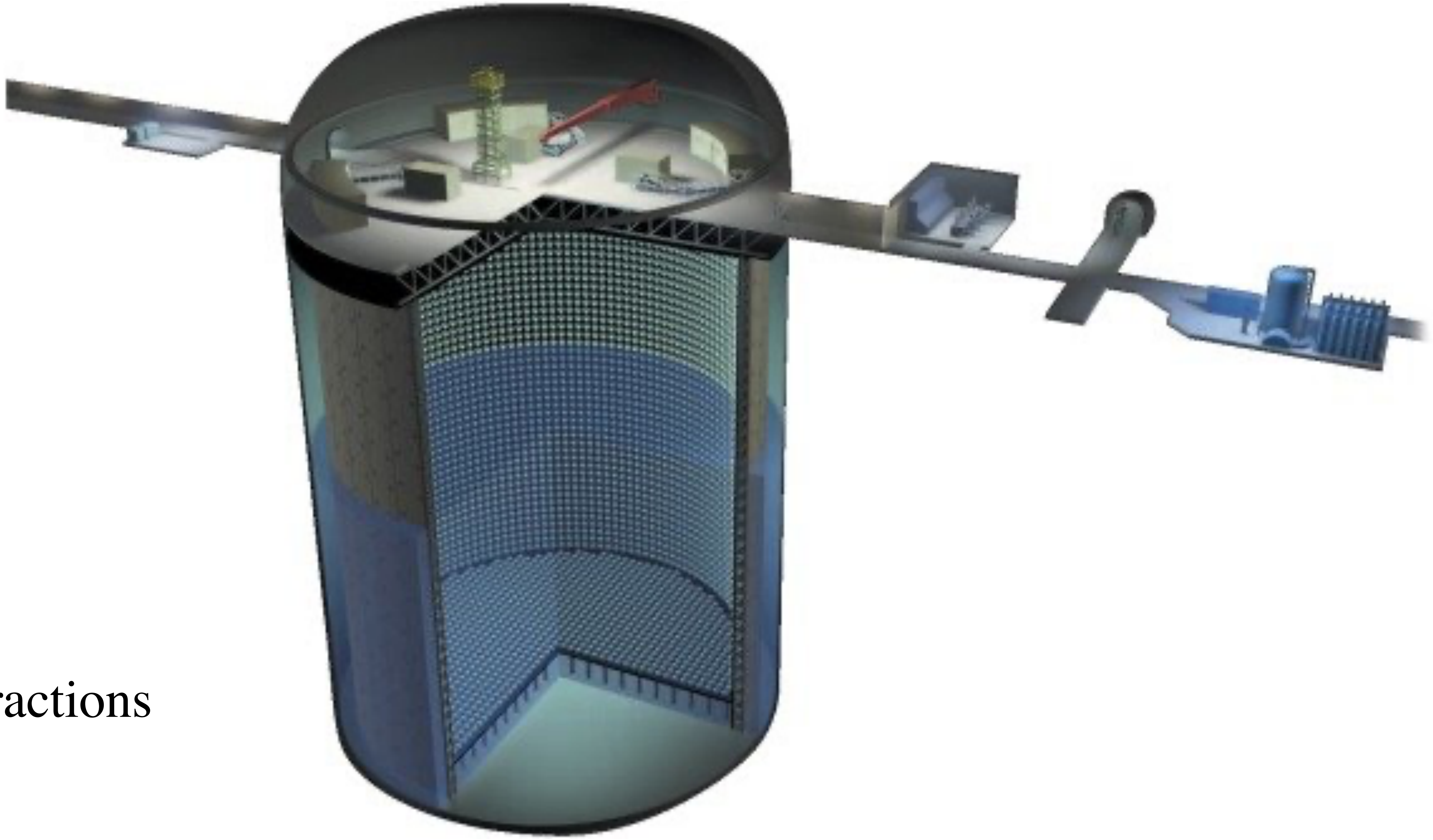
Atmospheric neutrinos

Neutrino interactions in the Super-Kamiokande detector are recorded in a **tank of approximately 50 000 tons of ultrapure water** in the Kamioka mine in Japan. The cylindrical steel tank is about 40 m in height. **Electron neutrinos transfer part of their energy to electrons,**

$$\nu_e + e^- \rightarrow \nu_e + e^- ,$$

or produce electrons in neutrino–nucleon interactions

$$\nu_e + N \rightarrow e^- + N' .$$



The Super-Kamiokande detector, in cutaway, showing the inner and outer detector, partially filled with water. The detector dome contains front-end electronics and calibration devices such as the electron LINAC (tower is shown). Also shown are access drifts, the control room, and water purification system.

https://www.researchgate.net/figure/The-Super-Kamiokande-detector-in-cutaway-showing-the-inner-and-outer-detector_fig1_301344727

Atmospheric neutrinos

Muon neutrinos are detected in neutrino–nucleon interactions according to

$$\nu_\mu + N \to \mu^- + N' \, .$$

Electron antineutrinos and muon antineutrinos produce correspondingly positrons and positive muons.

The charged leptons (e^+, e^-, μ^+, μ^-) can be detected via the **Cherenkov effect in water.**

The produced Cherenkov light is measured in Super-Kamiokande with 13 000 **photomultipliers** of 50 cm cathode diameter.

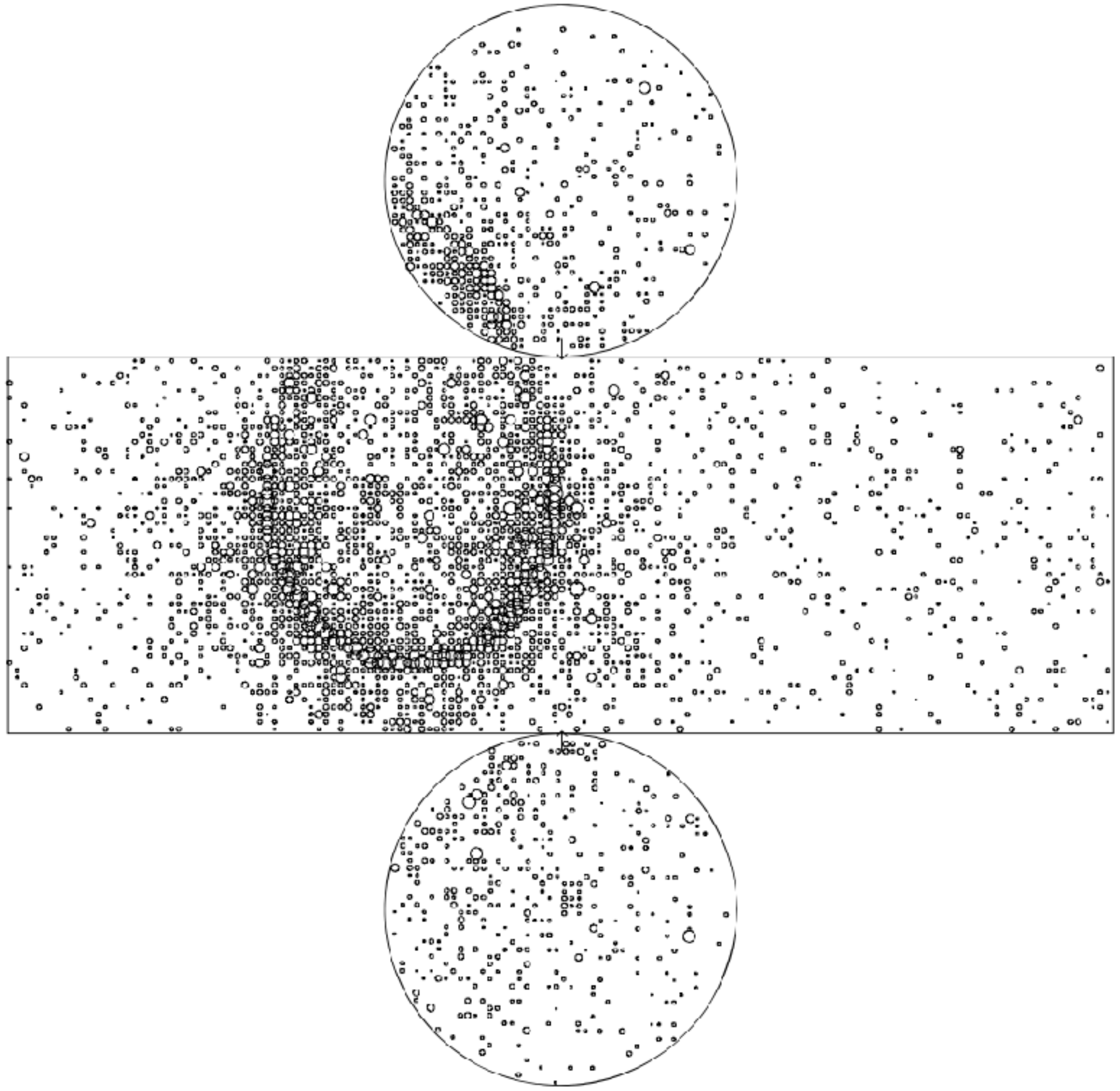
In the GeV range electrons initiate characteristic electromagnetic cascades of short range while muons produce long straight tracks. This presents a basis for **distinguishing electron from muon neutrinos**.

On top of that, **muons can be identified by their decay in the detector** thereby giving additional evidence concerning the identity of the initiating neutrino species.

Atmospheric neutrinos

Figures 6.15 and 6.16 show an electron and muon event in Super-Kamiokande.

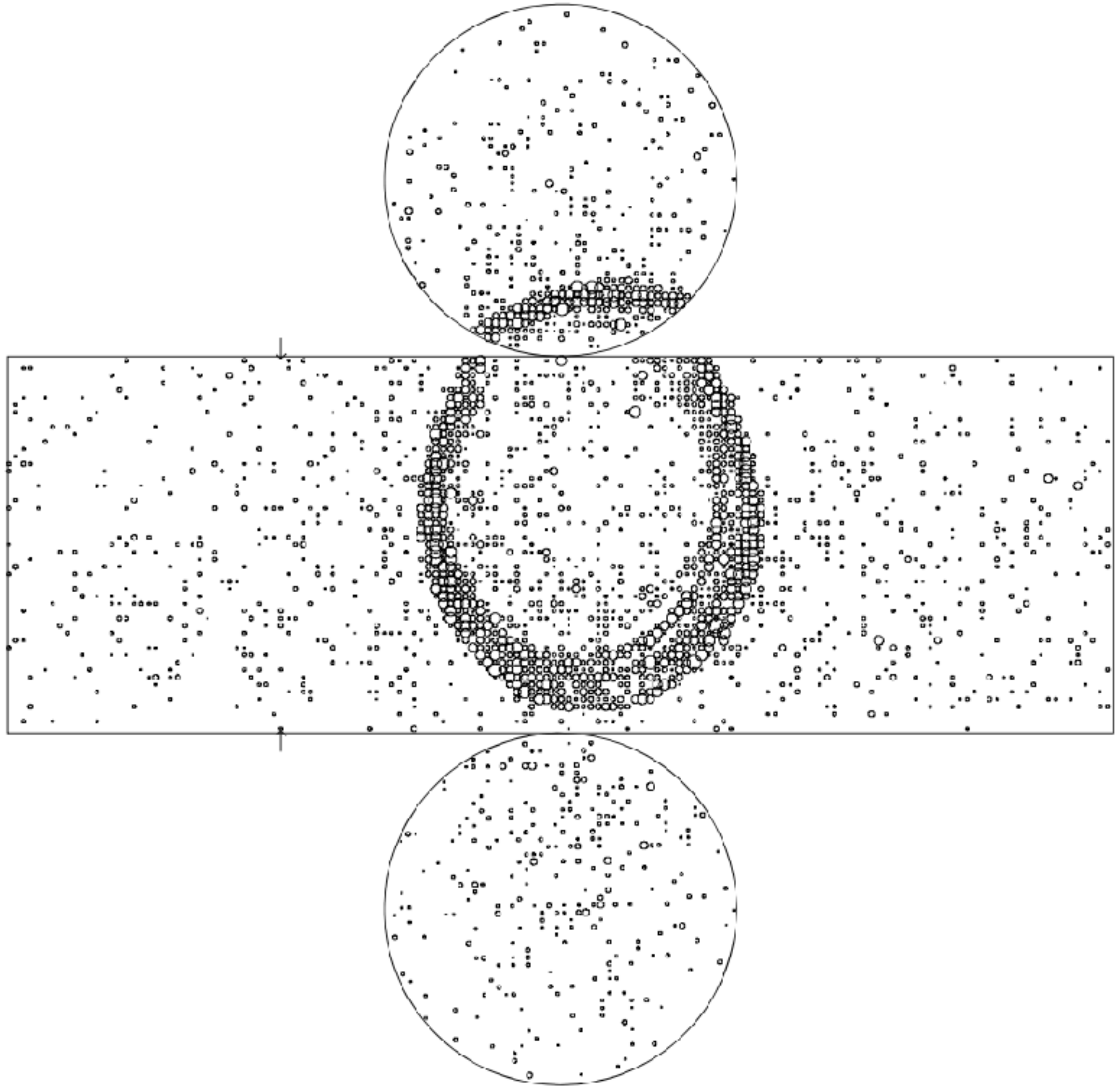
Fig. 6.15 Cherenkov pattern of an electron in the Super-Kamiokande detector. The contour of an electron is somewhat fuzzy because of the shower development [63]



Muons have a well-defined range and produce a **clear Cherenkov pattern with sharp edges** while **electrons** initiate electromagnetic cascades thereby creating a **fuzzy ring pattern.**

Atmospheric neutrinos

Fig. 6.16 Cherenkov pattern of a muon in the Super-Kamiokande detector. The contour of the muon is sharply bounded compared to the electron pattern [63]



Muons have a well-defined range and produce a **clear Cherenkov pattern with sharp edges** while **electrons** initiate electromagnetic cascades thereby creating a **fuzzy ring pattern.**

Atmospheric neutrinos

The result of the Super-Kamiokande experiment is that **the number of electron-neutrino events corresponds to the theoretical expectation while there is a clear deficit of events initiated by muon neutrinos.**

Because of the different acceptance for electrons and muons in the water Cherenkov detector, the ratio of neutrino-induced muons to electrons is compared to a Monte Carlo simulation. For the double ratio

$$R = \frac{(N_\mu/N_e)_{\text{data}}}{(N_\mu/N_e)_{\text{Monte Carlo}}}$$

one would expect the value $R = 1$ in agreement with the standard interaction and propagation models. However, the Super-Kamiokande experiment obtains

$$R = 0.69 \pm 0.06\,,$$

which represents a clear deviation from expectation (see Fig. 6.17).

What is the reason for this?

Atmospheric neutrinos

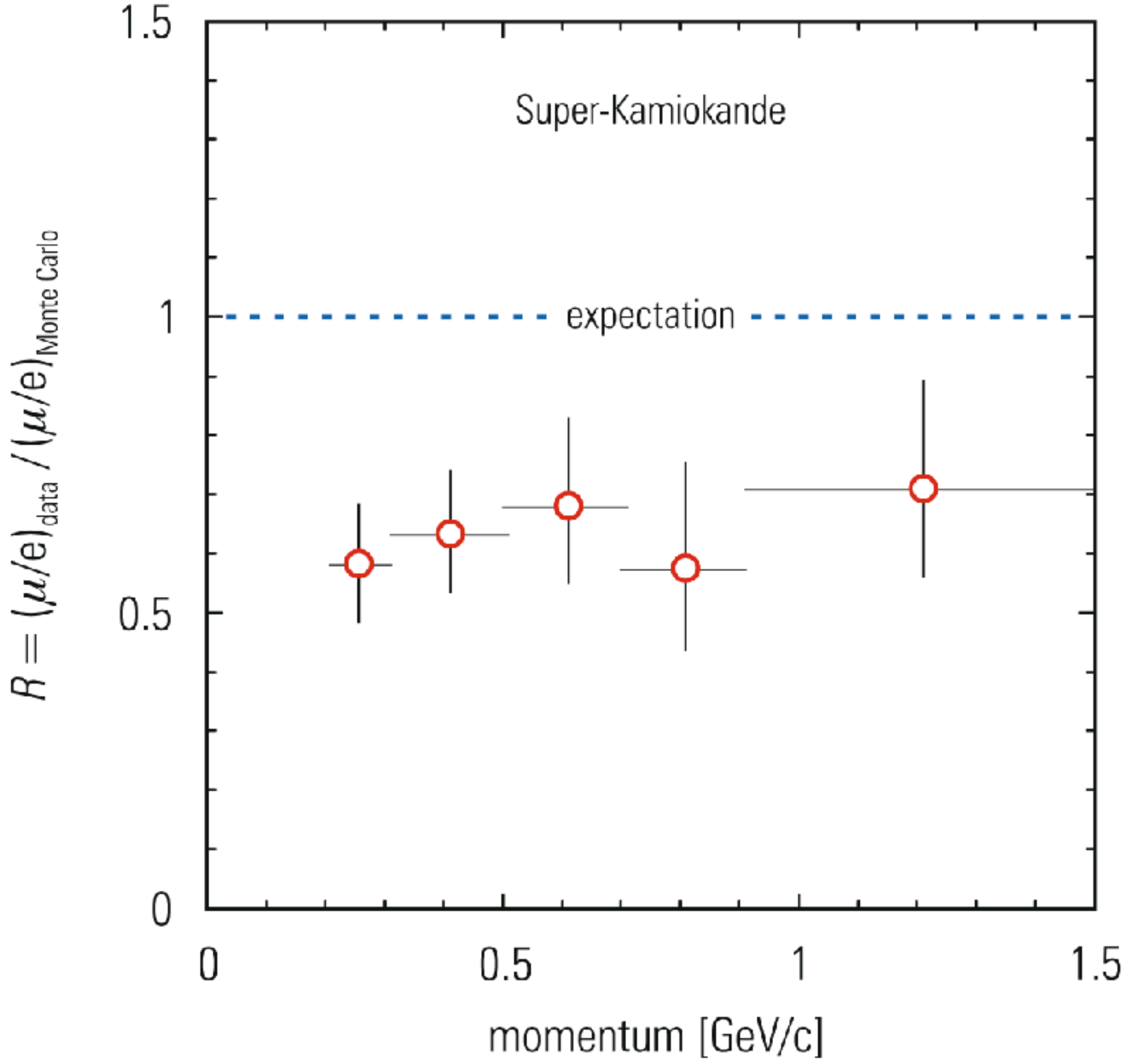


Fig. 6.17 Double ratio of the electron–muon rate comparing data and Monte Carlo [63]

Atmospheric neutrinos

After careful checks of the experimental results and investigations of possible systematic effects the general opinion prevails that the deficit of muon neutrinos can only be explained by ***neutrino oscillations*.**

Mixed particle states are known from the **quark** sector.

Similarly, it is conceivable that **in the lepton sector the eigenstates of weak interactions ν_e, ν_μ, and ν_τ are superpositions of mass eigenstates ν_1 , ν_2 , and ν_3** .

A muon neutrino ν_μ born in a pion decay could be **transformed during the propagation from the source to the observation** in the detector into a different neutrino flavour. If the muon neutrino in reality was a mixture of two different mass eigenstates ν_1 and ν_2, these **two states would propagate at different velocities if their masses were not identical** and so the **mass components get out of phase with each other**. This could possibly **result in a different neutrino flavour at the detector**.

If all neutrinos were massless, they would all propagate precisely at the velocity of light, and the mass eigenstates can never get out of phase with each other.

Atmospheric neutrinos

For an assumed two-neutrino mixing of ν_e and ν_μ the weak eigenstates could be related to the mass eigenstates by the following two equations:

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

The ***mixing angle*** **θ** determines the degree of mixing.

This assumption requires that the **neutrinos have non-zero** mass and, in addition, $m_1 \neq m_2$ must hold. In the framework of this oscillation model the probability that an electron neutrino stays an electron neutrino, can be calculated to be:

$$P_{\nu_e \to \nu_e}(x) = 1 - \sin^2 2\theta \sin^2\left(\pi \frac{x}{L_\nu}\right) \,,$$

where x is the distance from the source to the detector and L_ν is the oscillation length

$$L_\nu = \frac{2.48 \; E_\nu[\mathrm{MeV}]}{(m_1^2 - m_2^2)\;[\mathrm{eV}^2/c^4]} \, \mathrm{m} \,.$$

Atmospheric neutrinos

The expression $m_1^2 - m_2^2$ is usually abbreviated as δm^2. The equations and can be combined to give

$$P_{\nu_e \to \nu_e}(x) = 1 - \sin^2 2\theta \sin^2 \left(1.27\, \delta m^2 \frac{x}{E_\nu}\right)$$

where δm^2 is measured in eV^2, x in km, and E_ν in GeV.

The idea of a two-neutrino mixing is graphically presented in Fig. 6.18.

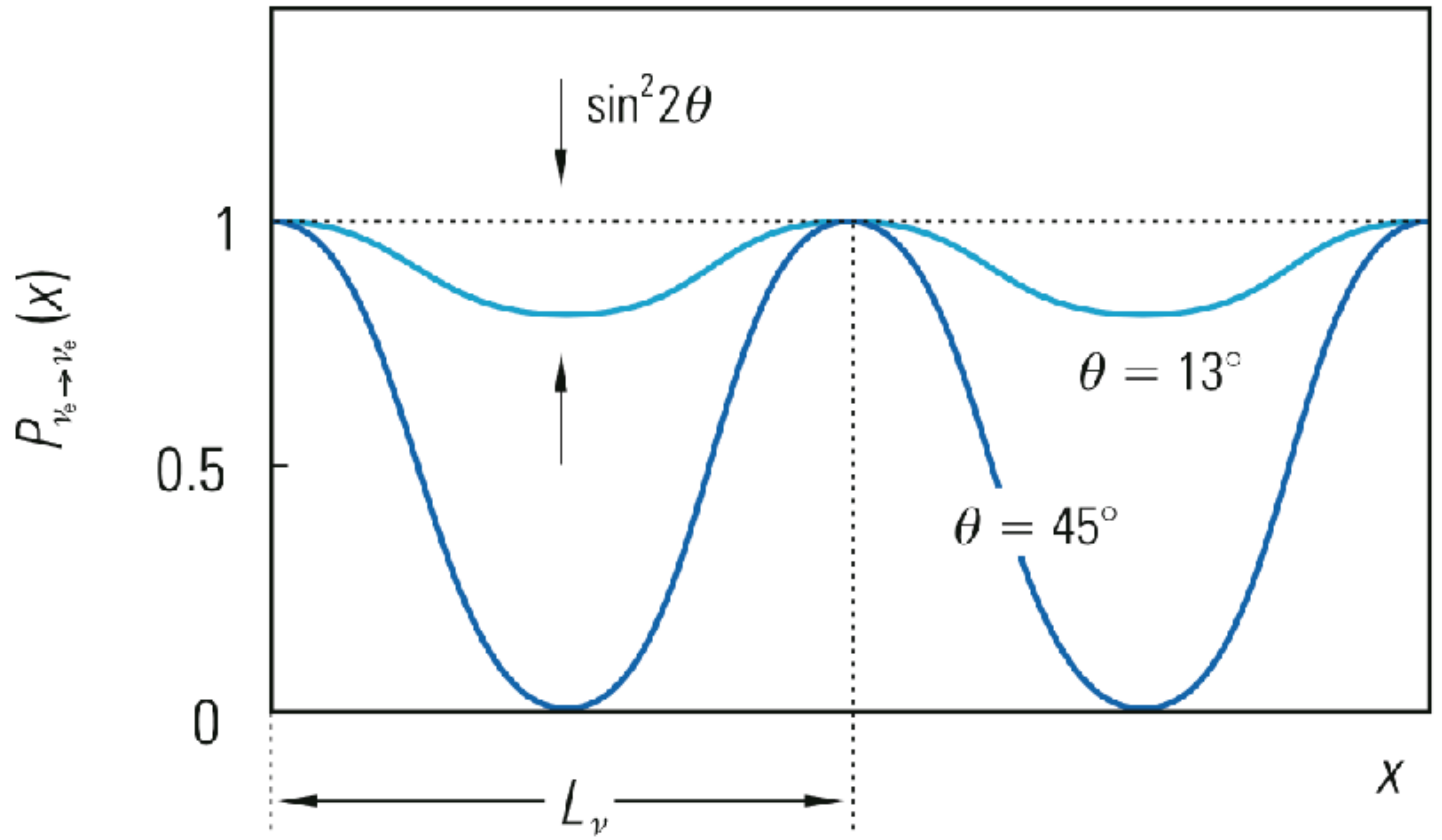


Fig. 6.18 Oscillation model for $(\nu_e \leftrightarrow \nu_\mu)$ mixing for two different mixing angles; shown is the probability $P_{\nu_e \to \nu_e}(x)$

Atmospheric neutrinos

For the general case of mixing of all three neutrino flavours one obtains as generalisation of

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

$$\downarrow$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_N \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where U_N is the (3×3) **neutrino mixing matrix. (Pontecorvo–Maki–Nakagawa–Sakata matrix)**

This matrix is constructed analogously to the Cabibbo–Kobayashi–Maskawa mixing matrix, just as in the quark sector. The idea of neutrino mixing originated from the works of Pontecorvo, Maki, Nakagawa, and Sakata, consequently this matrix is named **PMNS matrix.**

Atmospheric neutrinos

The deficit of muon neutrinos can now be explained by the assumption that some of the muon neutrinos transform themselves during propagation from the point of production to the detector into a different neutrino flavour, e.g., into tau neutrinos.

The sketch shown in Fig. 6.18 demonstrated that for an assumed **mixing angle of 45° all neutrinos of a certain type have transformed themselves into a different neutrino flavour after propagating half the oscillation length.** If, however, **muon neutrinos have oscillated into tau neutrinos, a deficit of muon neutrinos** will be observed in the detector because tau neutrinos would only produce taus in the water Cherenkov counter, but not muons. Since, however, the mass of **the tau is rather high** ($1.77\,\mathrm{GeV}/c^2$), tau neutrinos normally would **not meet the requiremen**t to provide the necessary center-of-mass energy **for tau production**. Consequently, they **would escape from the detector without interaction**. If the deficit of muon neutrinos would be interpreted by ($\nu_\mu \to \nu_\tau$) oscillations, the **mixing angle and the difference of mass squares δm^2 can be determined from the experimental data.**

Atmospheric neutrinos

The measured value of the double ratio $R = 0.69$ leads to

$$\delta m^2 \approx 2 \times 10^{-3}\,\mathrm{eV}^2$$

at maximal mixing ($\sin^2 2\theta = 1$, corresponding to $\theta = 45^\circ$).

If one assumes that in the neutrino sector a similar mass hierarchy as in the sector of charged leptons exists ($m_e \ll m_\mu \ll m_\tau$), then the mass of the heaviest neutrino can be estimated,

$$m_{\nu_\tau} \approx \sqrt{\delta m^2} \approx 0.045\,\mathrm{eV}\,.$$

The validity of this conclusion **relies on the correctly measured absolute fluxes of electron and muon neutrinos.** Because of the different Cherenkov pattern of electrons and muons in the water Cherenkov detector the efficiencies for electron neutrino and muon neutrino detections might be different.

Atmospheric neutrinos

To support the oscillation hypothesis one would therefore prefer to have an **additional independent experimental result**. This is provided in an impressive manner by **the ratio of upward- to downward- going muons.**

Upward-coming atmospheric neutrinos have traversed the whole Earth (≈12 800 km). They would have a much **larger probability to oscillate into tau neutrinos** compared to downward-going neutrinos, which have traveled typically only 20km. Actually, according to the experimental result of the Super-Kamiokande collaboration, **the upward-going muon neutrinos,** which have traveled through the whole Earth, **are suppressed by a factor of two compared to the downward-going muons.** This is taken as a strong indication for the existence of oscillations. For the ratio of upward- to downward-going muon neutrinos one obtains

$$S = \frac{N(\nu_\mu, \mathrm{up})}{N(\nu_\mu, \mathrm{down})} = 0.54 \pm 0.06\,,$$

which presents a clear effect in favour of oscillation.

Atmospheric neutrinos

Details of the observed zenith-angle dependence of atmospheric ν_e and ν_μ fluxes also represent a particularly strong support for the oscillation model.
Since the production altitude L and energy E_ν of atmospheric neutrinos are known (≈20 km for vertically downward-going neutrinos), **the observed zenith-angle dependence of electron and muon neutrinos can also be converted into a dependence of the rate versus the reconstructed ratio of L/E_ν.**

Figure 6.20 shows the ratio **data/Monte Carlo** for fully contained events as measured in the **Super-Kamiokande** experiment.

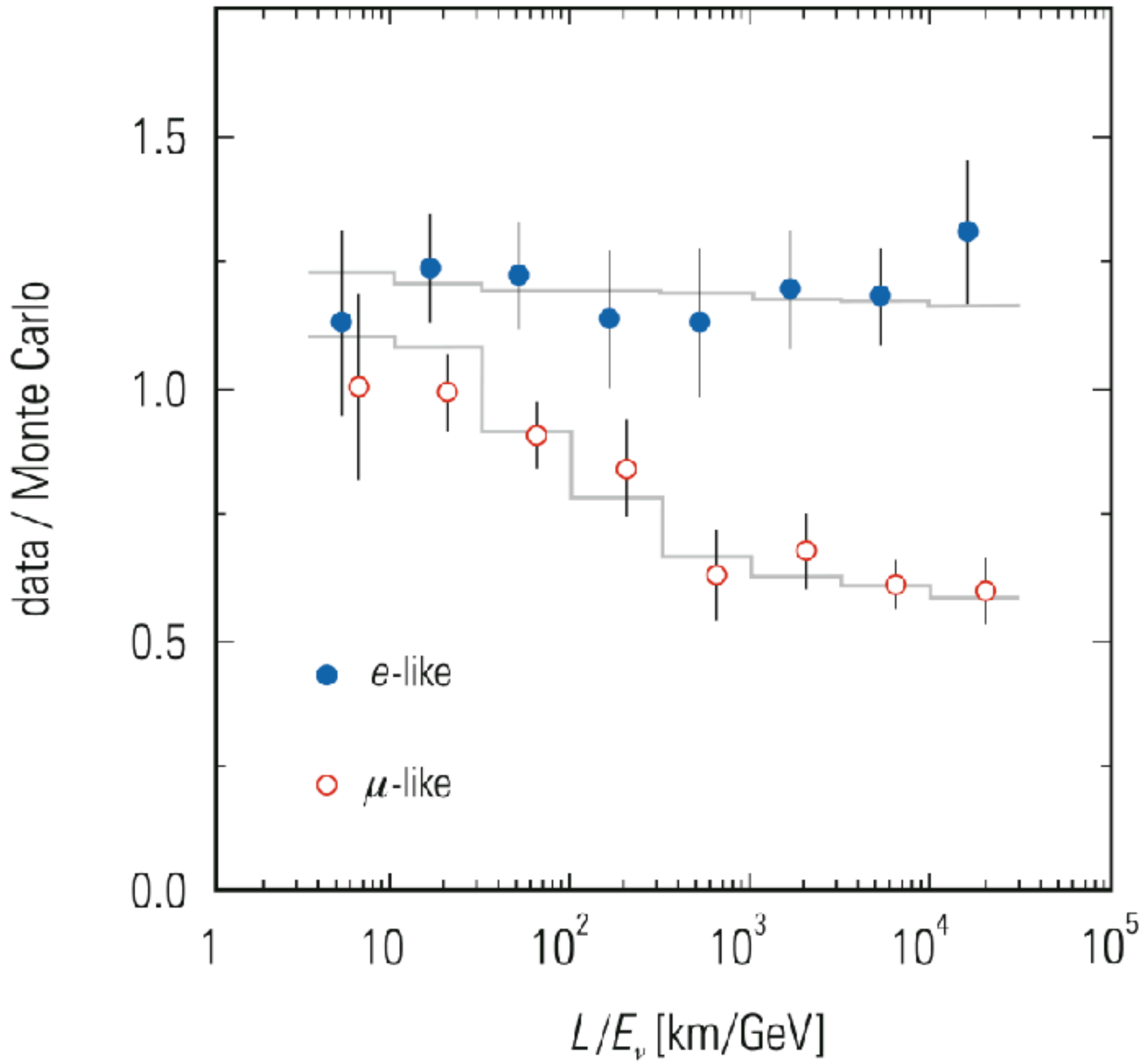


Fig. 6.20 Ratio of the fully contained events in Super-Kamiokande as a function of $\frac{L}{E_\nu}$, where L is the reconstructed production altitude of the neutrinos for electron and muon events. The *lower histogram* for muon-like events corresponds to the expectation for ν_μ oscillations into ν_τ with the parameters $\delta m^2 = 2.2 \times 10^{-3}\ \mathrm{eV}^2$ and $\sin 2\theta = 1$ [63]

Atmospheric neutrinos

The data exhibit a **zenith-angle-** (i.e., distance-) **dependent deficit of muon neutrinos,** while the electron neutrinos follow the expectation for no oscillations.

The observed behaviour is consistent with ($\nu_\mu \leftrightarrow \nu_\tau$) **oscillations,** where a best fit is obtained for $\delta m^2 = 2.2 \times 10^{-3}$ eV^2 for maximal mixing ($\sin 2\theta = 1$).

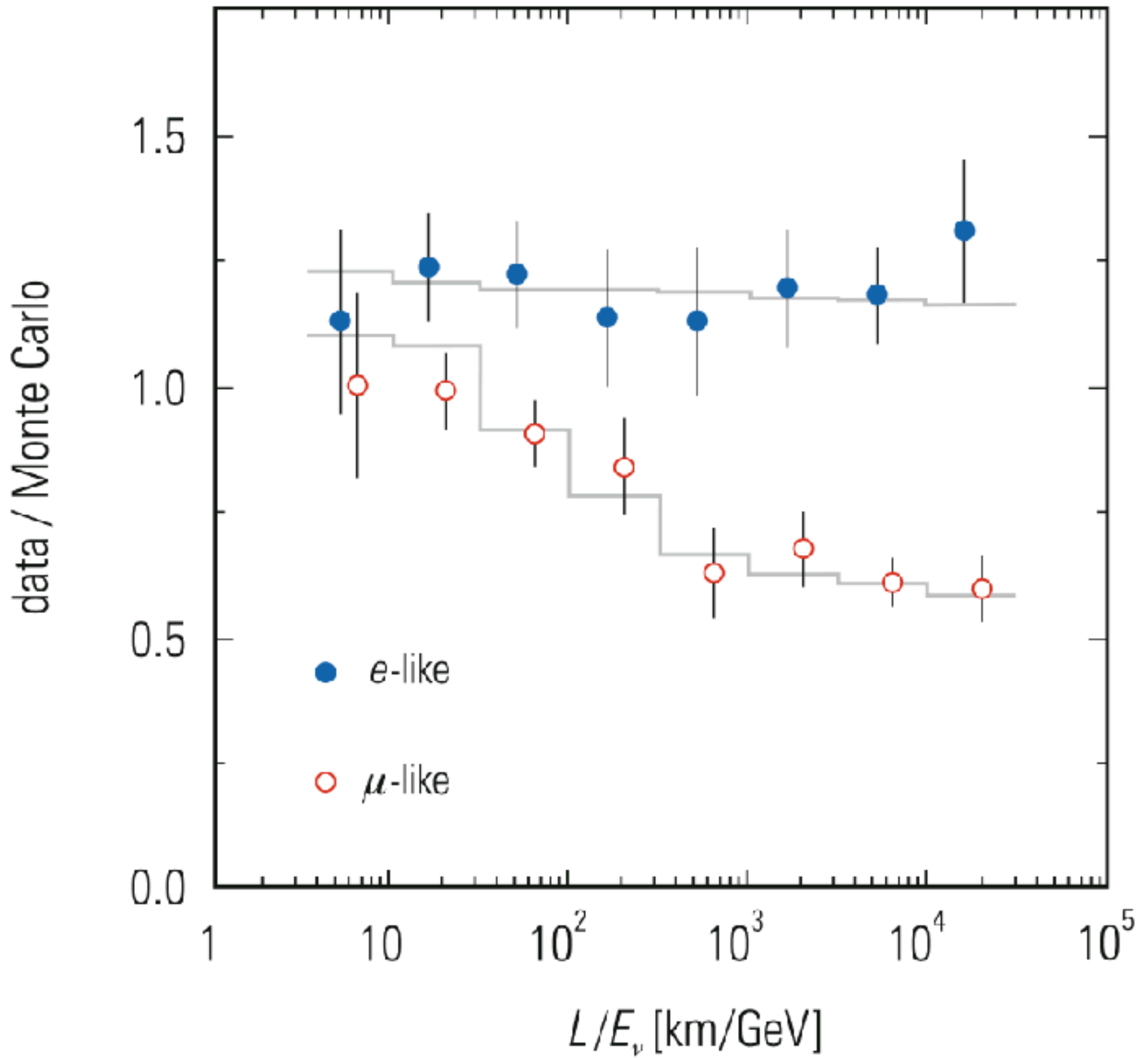


Fig. 6.20 Ratio of the fully contained events in Super-Kamiokande as a function of $\frac{L}{E_\nu}$, where L is the reconstructed production altitude of the neutrinos for electron and muon events. The *lower histogram* for muon-like events corresponds to the expectation for ν_μ oscillations into ν_τ with the parameters $\delta m^2 = 2.2 \times 10^{-3}$ eV^2 and $\sin 2\theta = 1$ [63]

Atmospheric neutrinos

If all results of the Super-Kamiokande experiment are put together, one gets under the assumption of ($\nu_\mu \leftrightarrow \nu_\tau$) oscillations of atmospheric neutrinos the parameters $\delta m^2 = 2.4 \times 10^{-3}$ eV^2 and $\sin^2(2\theta) > 0.95$.

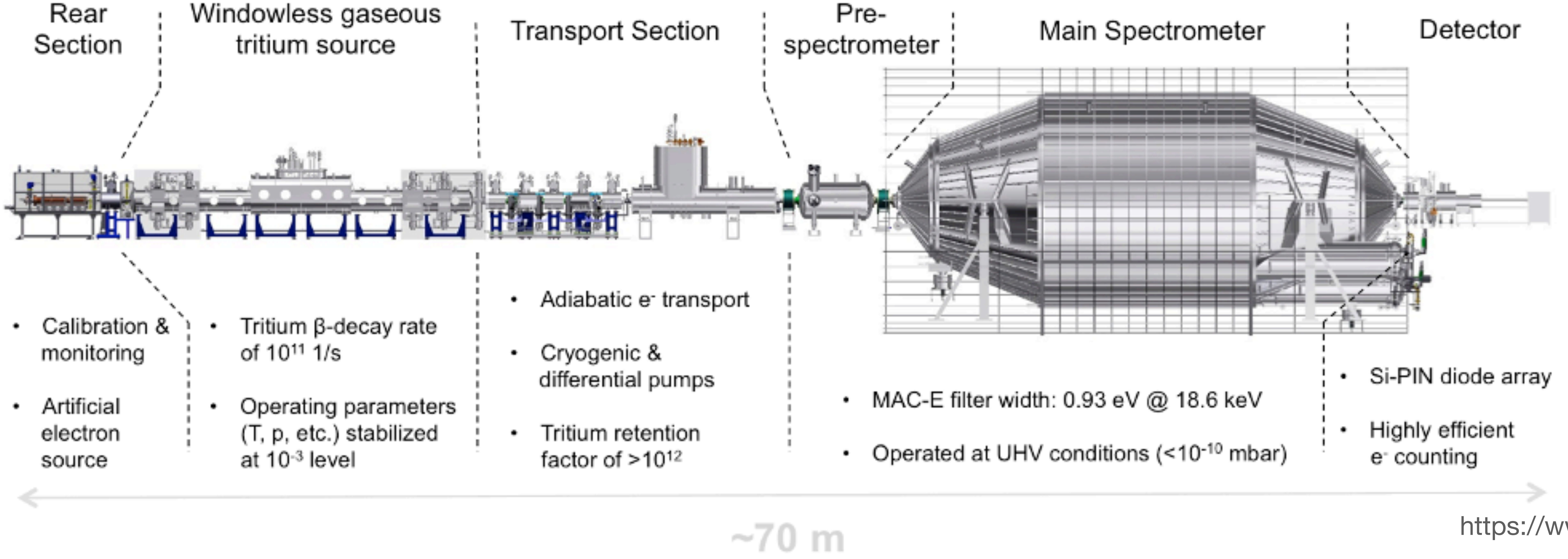
It is, of course, also **conceivable that the muon neutrinos oscillate into electron neutrinos**. For this possibility one would get $\delta m^2 = 7.5 \times 10^{-5}$ eV^2 resp. $\sin^2(2\theta) = 0.85$.

Assuming a **mass hierarchy as in the sector of charged leptons** and assuming ($\nu_\mu \leftrightarrow \nu_\tau$) oscillations one would get for he mass of the heaviest neutrino $\nu_\tau m_{\nu_\tau} \approx \sqrt{\delta m^2} \approx 50$ MeV.

In the Standard Model of elementary particles neutrinos have zero mass. Therefore, neutrino oscillations represent an important **extension of the physics of elementary particles.** In this example of neutrino oscillations the synthesis between astrophysics and particle physics becomes particularly evident.

KATRIN (Karlsruhe Tritium neutrino experiment)

KATRIN **measures the neutrino mass in a model-independant way** via ultrahigh precision measurements of the **kinematics of electrons from beta-decay.** To detect the subtle effects of a massive neutrino on the kinematics of the beta electrons requires on one hand the provision of a strong gaseous windowless Tritium source with well-known properties and precision control. On the other hand it requires a high resolution spectrometer (MAC-E filter) with large diameter (10 m) to analyze precisely the electron energies from the source. All components are in operation and KATRIN started beta-decay data taking officially in spring 2019.



https://www.katrin.kit.edu/

KATRIN (Karlsruhe Tritium neutrino experiment)

Neutrino masses as tiny as 10^{-36} kg would be measured with KATRIN. This is achieved via the spectroscopic energy measurement of the beta-electrons from **tritium beta-decay** with the KATRIN spectrometer. The **fixed energy amount released in a beta decay** (e.g. tritum ^{3}H) is shared by the electron, the neutrino and the nuclear recoil (e.g. ^{3}He).

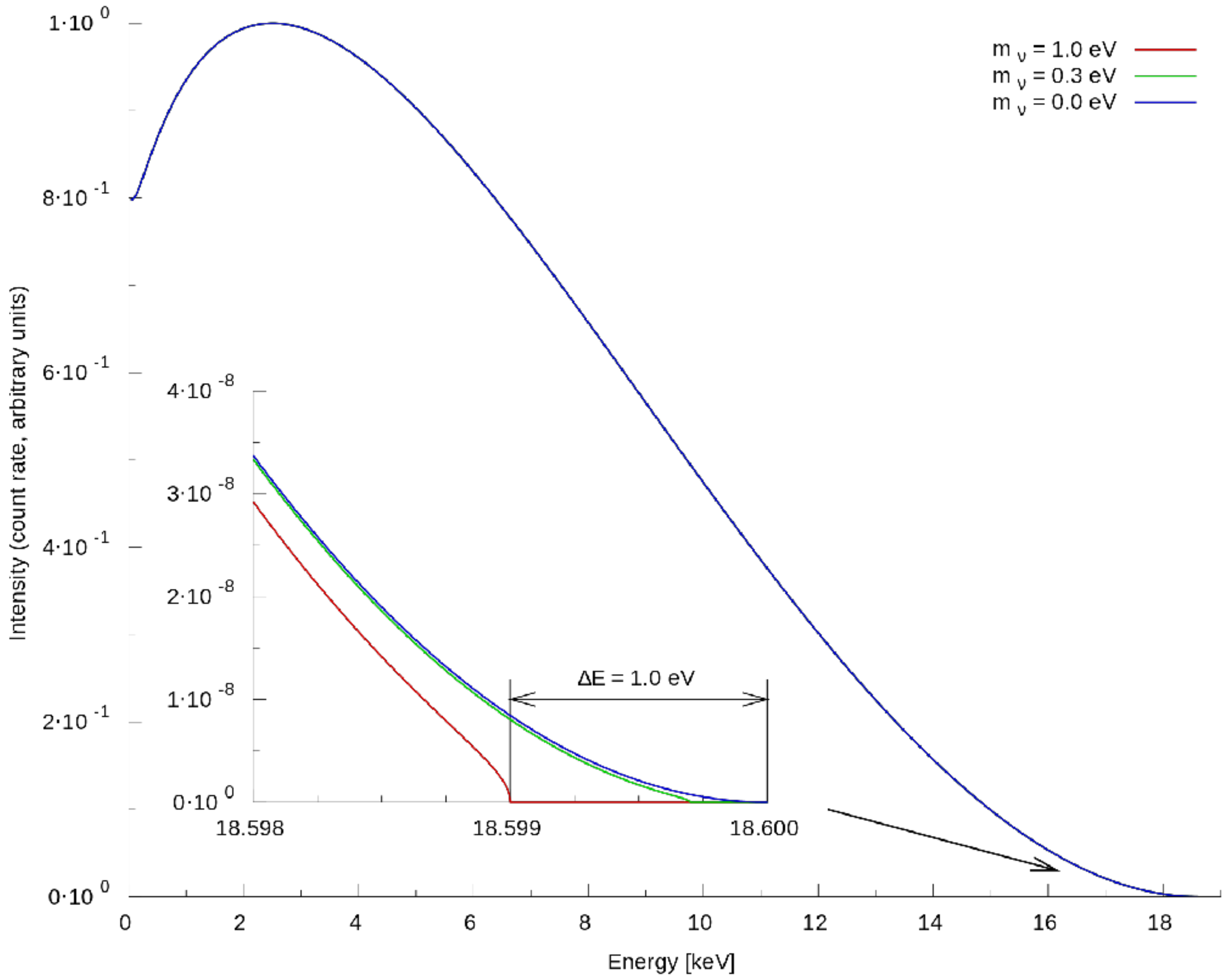
When we now look for the **maximum energies of the electrons and compare the measured values to the transition energy, we can check if it sums up together with the known nuclear recoil to the transition energy.** If there is **no difference the neutrino must be massless,** if there is a **difference** this energy gap can be calculated into a **neutrino mass**.

In practice of course, it turns out to be a little bit more complicated, as we have **molecular tritium which in addition can rotate and vibrate.** Another complication is that the **transition energy is not known from theory** and must also be inferred from the measurement. Nevertheless, the tritium spectrum at its endpoint together with some theoretical and experimental corrections are known at such a good level, that this kind of measurement is regarded as a model-independent method to measure the neutrino mass.

The experimental challenges of course are a tritium source with sufficient beta decays near the endpoint, where this principle only works and a spectrometer, which measures the kinetic energy of the electrons with 10^{-5} precision. First results in 2019.

https://www.katrin.kit.edu/

KATRIN (Karlsruhe Tritium neutrino experiment)



Energy spectrum of the electrons emitted in tritium beta decay. **Three graphs for different neutrino masses are shown.**
These graphs differ only in the range near the high-energetic end-point; the **intersection with the abscissa depends on the neutrino mass.** In the KATRIN experiment the spectrum around this end-point is measured with high precision to obtain the neutrino mass.

https://en.wikipedia.org/wiki/KATRIN

Solar neutrinos

The Sun is a nuclear fusion reactor. In its interior hydrogen is burned to helium. The longevity of the Sun is related to the fact that the initial reaction

$$p + p \to d + e^+ + \nu_e$$

proceeds via the weak interaction. **86% of solar neutrinos are produced in this proton– proton reaction.** Deuterium fuses with a further proton to produce helium 3,

$$d + p \to {}^3\mathrm{He} + \gamma \, .$$

In ^{3}He–^{3}He interactions

$${}^3\mathrm{He} + {}^3\mathrm{He} \to {}^4\mathrm{He} + 2p$$

the isotope helium 4 can be formed. On the other hand, the isotopes ^{3}He and ^{4}He could also produce beryllium,

$${}^3\mathrm{He} + {}^4\mathrm{He} \to {}^7\mathrm{Be} + \gamma \, .$$

Solar neutrinos

^{7}Be is made of four protons and three neutrons. Light elements prefer symmetry between the number of protons and neutrons. ^{7}Be can capture an electron yielding ^{7}Li,

$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$

where a proton has been transformed into a neutron. On the other hand, ^{7}Be can react with one of the abundant protons to produce ^{8}B,

$$^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$$

^{7}Li produced will usually interact with protons forming helium,

$$^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$

while the boron isotope ^{8}B will reduce its proton excess by β^+ decay,

$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$$

Solar neutrinos

$^8B \to {}^8Be + e^+ + \nu_e \qquad {}^7Be + e^- \to {}^7Li + \nu_e$

and the resulting ^{8}Be will disintegrate into two helium nuclei.

Apart from the **dominant *pp* neutrinos,** further **14% are generated in the electron-capture reaction**, while the **^{8}B decay contributes only at the level of 0.02%** albeit yielding high-energy neutrinos.

In total, the solar neutrino flux at Earth amounts to about **7×10^{10} particles per cm^2 and second.**

The energy spectra of different reactions, which proceed in the solar interior at a temperature of **15 million K,** are shown in Fig. 6.21. The Sun is a **pure electron-neutrino source**. It does not produce electron antineutrinos and, in particular, no other neutrino flavours (ν_μ, ν_τ).

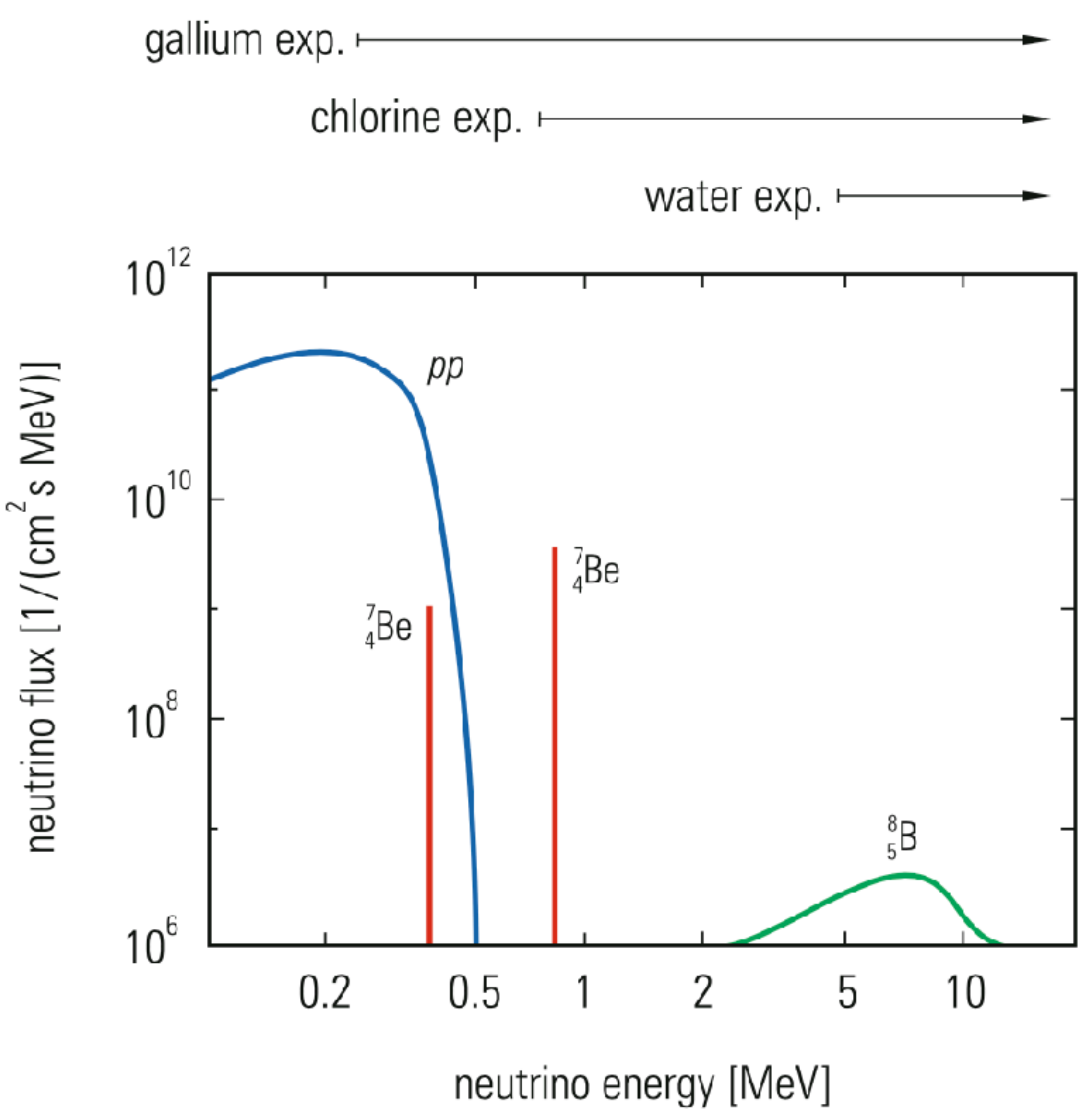


Fig. 6.21 Neutrino spectra from solar fusion processes. The reaction thresholds for the gallium, chlorine, and water Cherenkov experiments are indicated. The threshold for the SNO experiment is around 5 MeV. The line fluxes of the beryllium isotopes are given in cm^{-2} s^{-1}

Solar neutrinos

$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu_e \qquad {}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$$

Three **radiochemical experiments and two water Cherenkov experiments** have been or are trying to measure the flux of solar neutrinos.

The historically first experiment for the search of solar neutrinos is based on the reaction

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

where the produced ^{37}Ar has to be extracted from a huge tank filled with 380 000 liters of perchloroethylene (C_2Cl_4). Because of the low capture rate of less than one neutrino per day **the experiment must be shielded against atmospheric cosmic rays**. Therefore, it is operated in a gold mine at about 1500m depth under the Earth's surface (see Fig. 6.22).

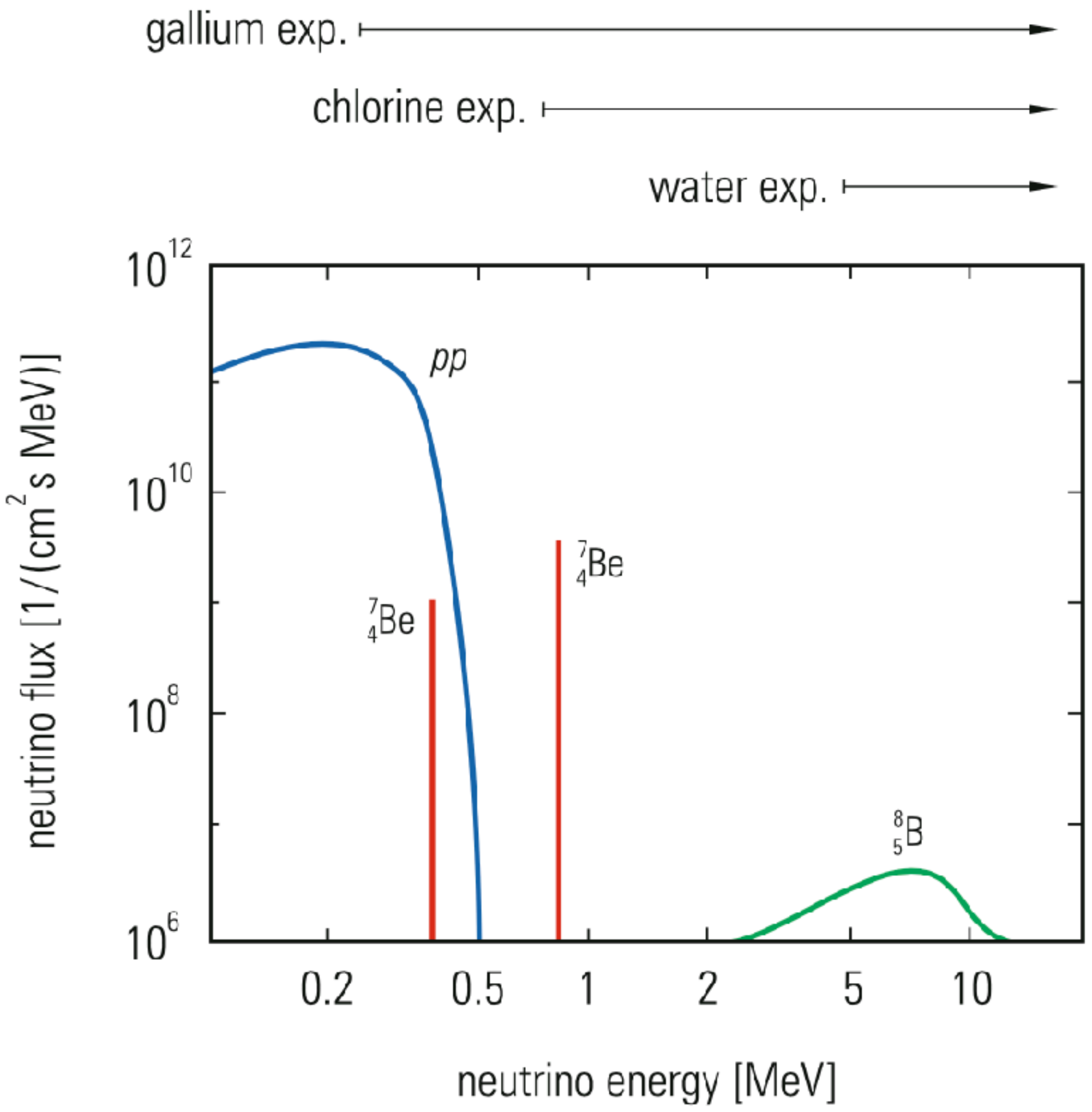


Fig. 6.21 Neutrino spectra from solar fusion processes. The reaction thresholds for the gallium, chlorine, and water Cherenkov experiments are indicated. The threshold for the SNO experiment is around 5 MeV. The line fluxes of the beryllium isotopes are given in cm^{-2} s^{-1}

Solar neutrinos

After a run of typically one month the tank is flushed with a noble gas and **the few produced ^{37}Ar atoms are extracted** from the detector and subsequently **counted**. Counting is done by means of the electron-capture reaction of ^{37}Ar, where again ^{37}Cl is produced. Since the electron capture occurs predominantly from the *K* shell, the produced **^{37}Cl atom is now missing one electron in the innermost shell** (in the *K* shell). The atomic **electrons of the ^{37}Cl atom are rearranged under emission of either characteristic X rays or by the emission of Auger electrons**. These Auger electrons and, in particular, the characteristic X rays are the basis for counting ^{37}Ar atoms produced by solar neutrinos.

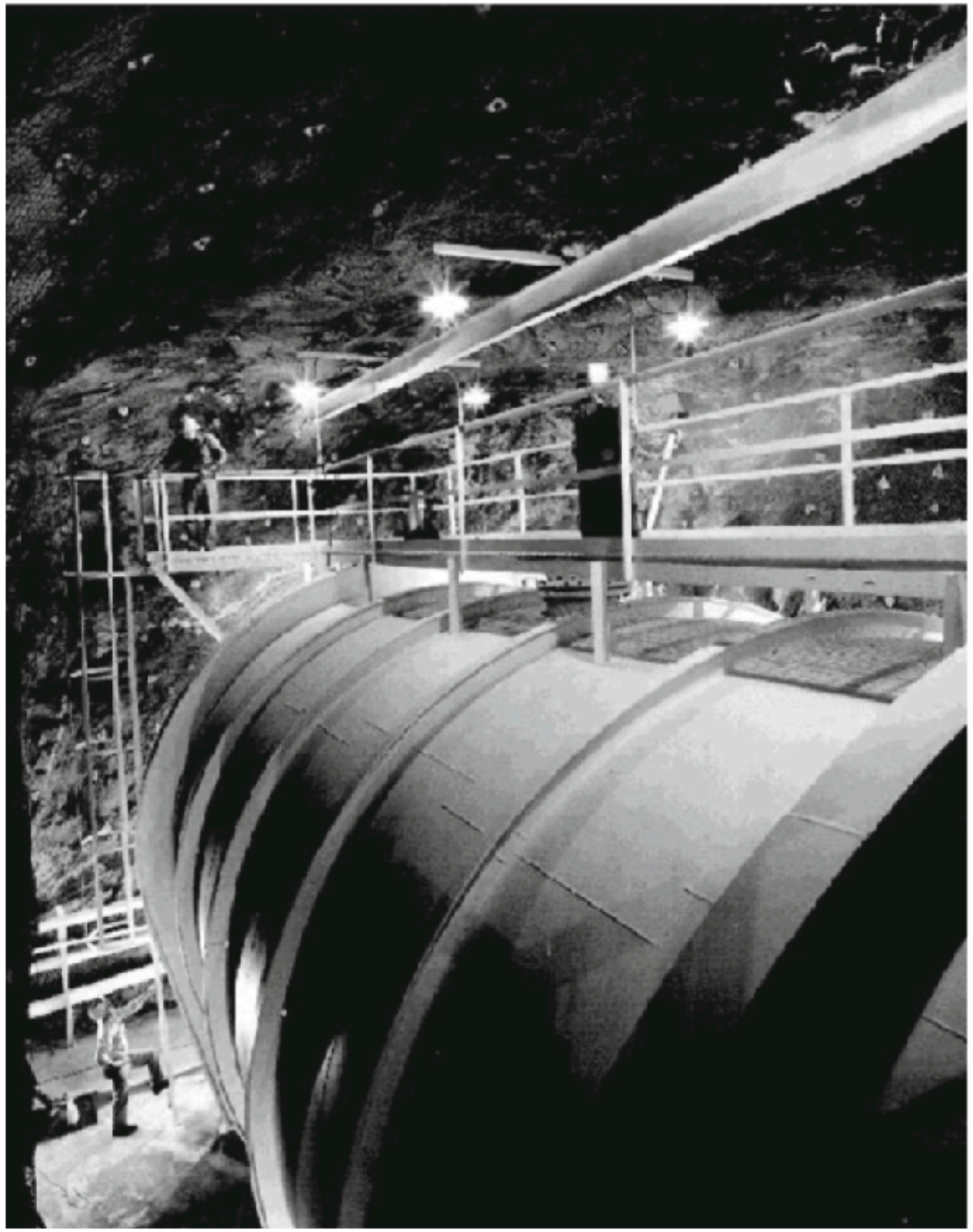
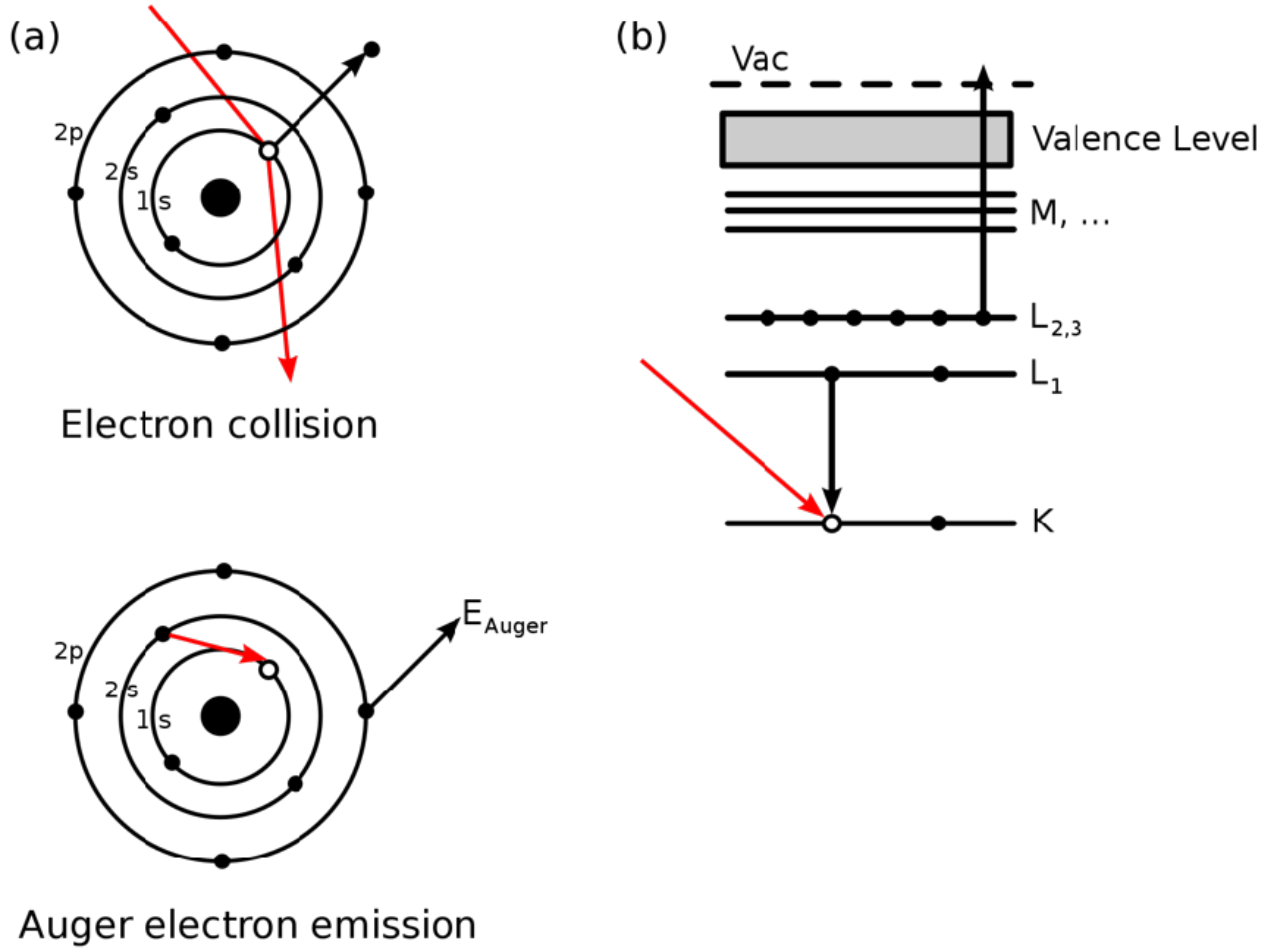


Fig. 6.22 The detector of the chlorine experiment of R. Davis for the measurement of solar neutrinos. The detector is installed at a depth of 1480 m in the Homestake Mine in South Dakota. It is filled with 380 000 liters of perchloroethylene [67]. With kind permission of the Brookhaven National Laboratory

Solar neutrinos

The **Auger effect or Auger–Meitner effect** is a physical phenomenon in which **the filling of an inner-shell vacancy of an atom is accompanied by the emission of an electron from the same atom**.

When a core electron is removed, leaving a vacancy, an electron from a higher energy level may fall into the vacancy, resulting in a release of energy. **For light atoms (Z<12), this energy is most often transferred to a valence electron which is subsequently ejected from the atom.** This second ejected electron is called an Auger electron. For heavier atomic nuclei, the release of the energy in the form of an emitted photon becomes gradually more probable.



Solar neutrinos

In the course of 30 years of operation a **deficit of solar neutrinos** has become more and more evident. The experiment led by Davis only finds 27% of the expected solar neutrino flux. To solve this neutrino puzzle, two further neutrino experiments were started.

The **gallium experiment** GALLEX in a tunnel through the Gran Sasso mountains in Italy and the Soviet–American gallium experiment (SAGE) in the Caucasus measure the flux of solar neutrinos also in radiochemical experiments. Solar neutrinos react with gallium according to

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

In this reaction ^{71}Ge is produced and extracted like in the Davis experiment and counted. The gallium experiments have the big advantage that the **reaction threshold is as low as 233 keV** so that these experiments are **sensitive to neutrinos from the proton–proton fusion** while the **Davis experiment** with a threshold of 810keV essentially **only measures neutrinos from the ^{8}B decay.**

GALLEX and SAGE have also measured a **deficit of solar neutrinos.** They only find 52% of the expected rate, which presents a clear discrepancy to the prediction on the basis of the standard solar model.

Solar neutrinos

However, the discrepancy is not so pronounced as in the Davis experiment. A strong point for the gallium experiments is that the neutrino capture rate and the extraction technique have been checked with neutrinos of an artificial ^{51}Cr source. It could be convincingly shown that the produced ^{71}Ge atoms could be successfully extracted in the expected quantities.

The Kamiokande and Super-Kamiokande experiment, respectively, measure solar neutrinos via the reaction

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

at a threshold of 5 MeV in a water Cherenkov counter. **Since the emission of the knock-on electron follows essentially the direction of the incident neutrinos,** the detector can really 'see' the Sun. This **directionality gives the water Cherenkov counter a superiority** over the radiochemical experiments.

Solar neutrinos

Figure 6.23 shows the neutrino counting rate of the Super-Kamiokande experiment as a function of the angle with respect to the Sun.

The Super-Kamiokande experiment also measures a low flux of solar neutrinos representing only 40% of the expectation.

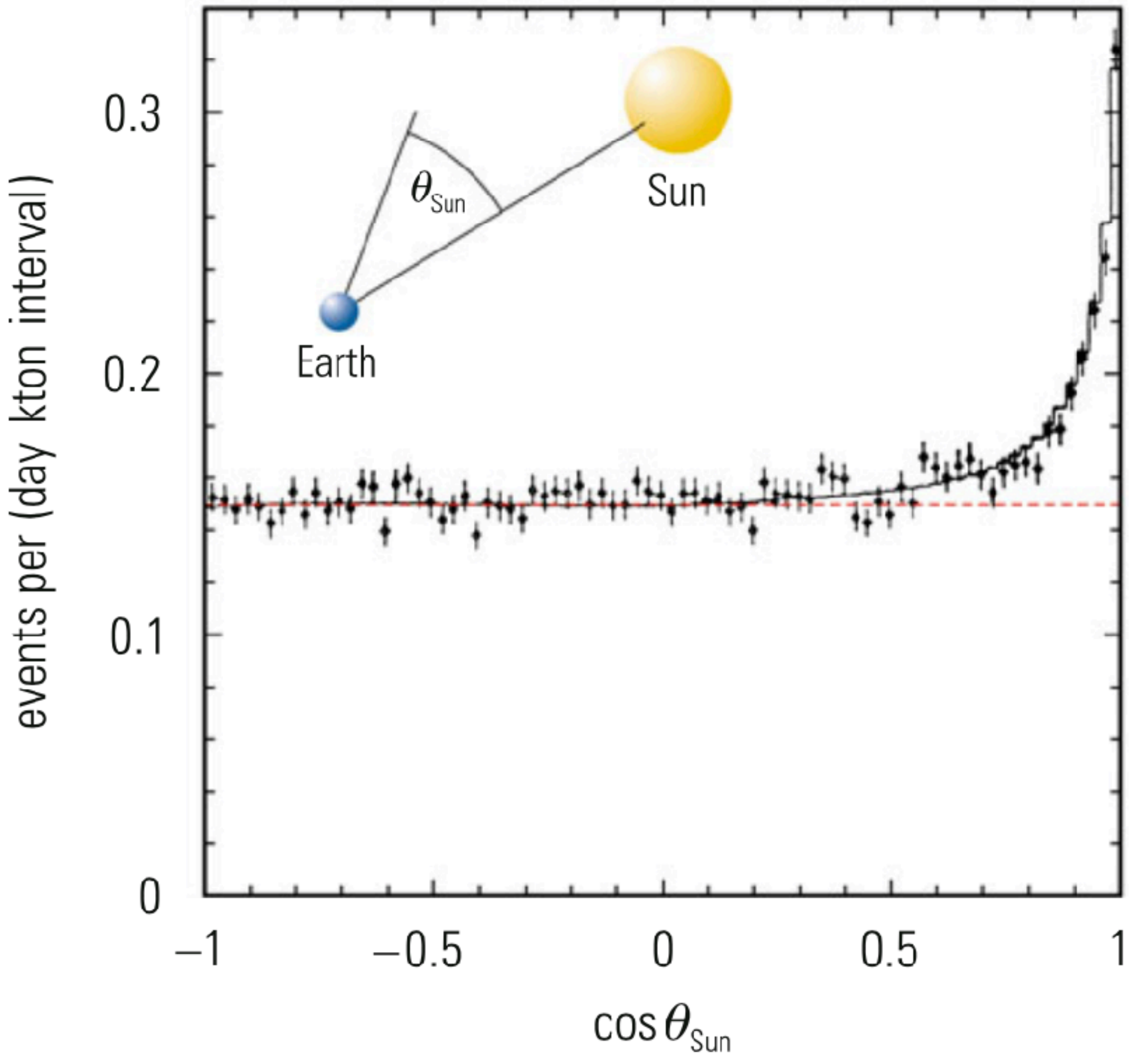


Fig. 6.23 Arrival directions of neutrinos measured in the Super-Kamiokande experiment [63]

Solar neutrinos

A reconstructed image of the Sun in the light of neutrinos is shown in Fig. 6.24.

Many proposals have been made to solve the solar neutrino problem. The obvious idea for elementary particle physicists was to doubt the correctness of the standard solar model.

The flux of ^{8}B neutrinos varies with the central temperature of the Sun like $\sim T^{18}$. A reduction by only 5% of the central solar temperature would bring the Kamiokande experiment already in agreement with the now reduced expectation. **However, solar astrophysicists consider even a somewhat lower central temperature of the Sun rather unlikely.**

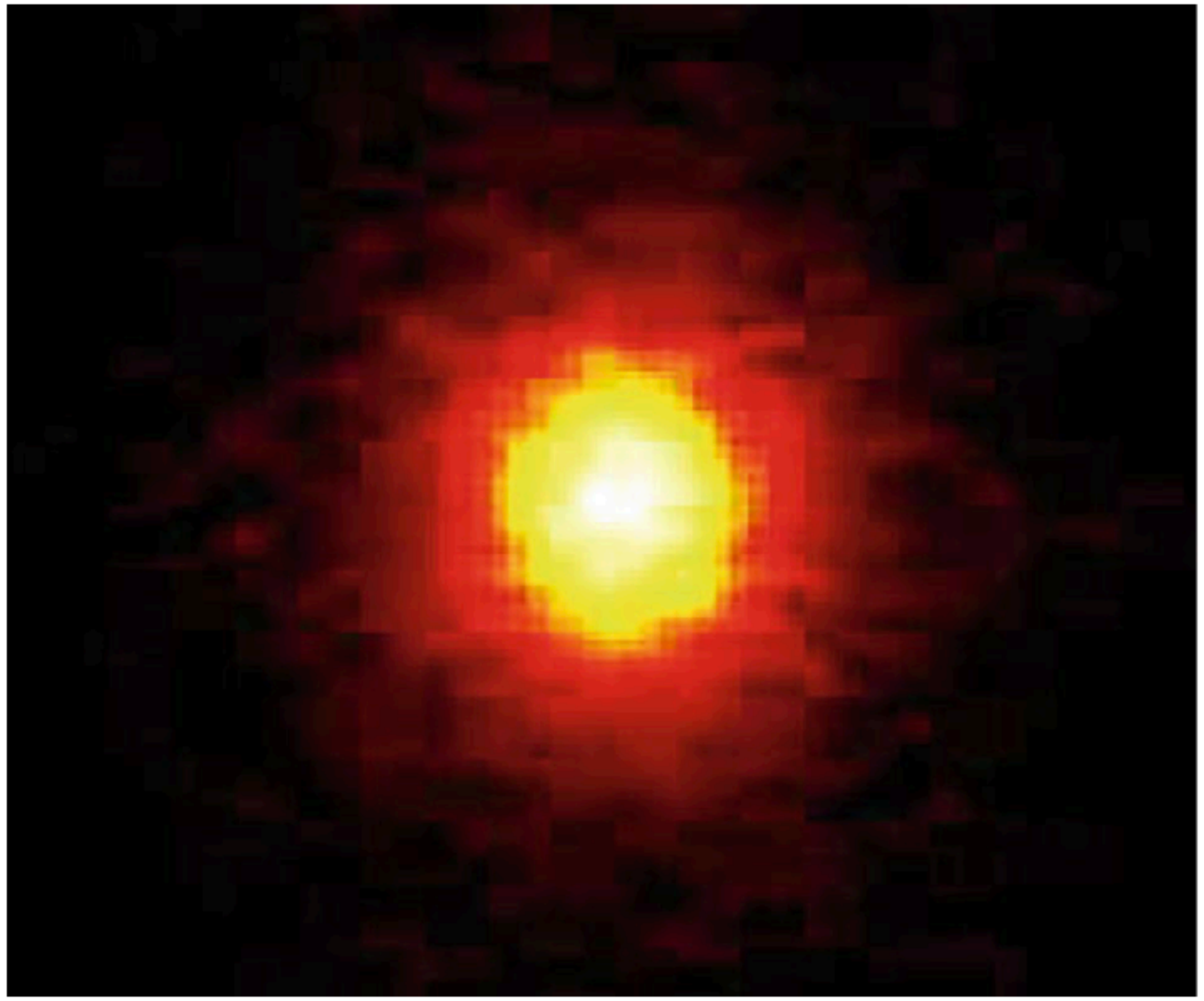


Fig. 6.24 Reconstructed image of the Sun in the light of solar neutrinos. Due to the limited spatial and angular resolution of the Super-Kamiokande experiment and the small scattering angle of the electron with respect to the incoming neutrino the image of the Sun appears larger as it actually is. About 50 days of exposure were needed to detect these solar neutrinos in the 50 000-ton water detector. Photo credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo [63]

Solar neutrinos

An **overestimate of the reaction cross sections** would also lead to a too high expectation for the neutrino flux. A variation of these cross sections in a range, which is considered realistic by nuclear physicists, was **insufficient to explain the discrepancy between the experimental data and expectation.**

There have been **further ideas proposed** to solve the solar neutrino problem. If neutrinos had a mass, they could also possess a magnetic moment. If their spin is rotated while propagating from the solar interior to the detector at Earth, one would not be able to measure these neutrinos because the detectors are insensitive to neutrinos of wrong helicity.

Finally, solar neutrinos could decay on their way from Sun to Earth into particles, which might be invisible to the neutrino detectors.

A drastic assumption would be that the solar fire has gone out. In the light of neutrinos this would become practically immediately evident (more precisely: in 8 min). The energy transport from the solar interior to the surface, however, requires a time of several 100 000 years so that the Sun would continue to shine for this period even though the nuclear fusion at its center has come to an end.

Solar neutrinos

The Sudbury Neutrino Observatory (SNO) has finally demonstrated that the solar model for neutrino generation is correct. The SNO detector is installed in a nickel mine in Ontario in Canada at a depth of 2000 m. It consists of a **1000-ton heavy-water target** (D_2O), which is mounted in an acrylic vessel of 12 m diameter (see Fig. 6.25).

The interaction target is viewed by 9600 photomultipliers. The detector cavity outside the vessel contains **7000 tons of normal, light water.** The purpose of this shield is to reduce the radiation background from cosmic rays and the environmental radiation from the rock and the dust in the mine.

The **detection threshold is with 5 MeV** in this experiment rather high. To break up the deuterons in the heavy water at least the binding energy of 2.2 MeV must be provided.

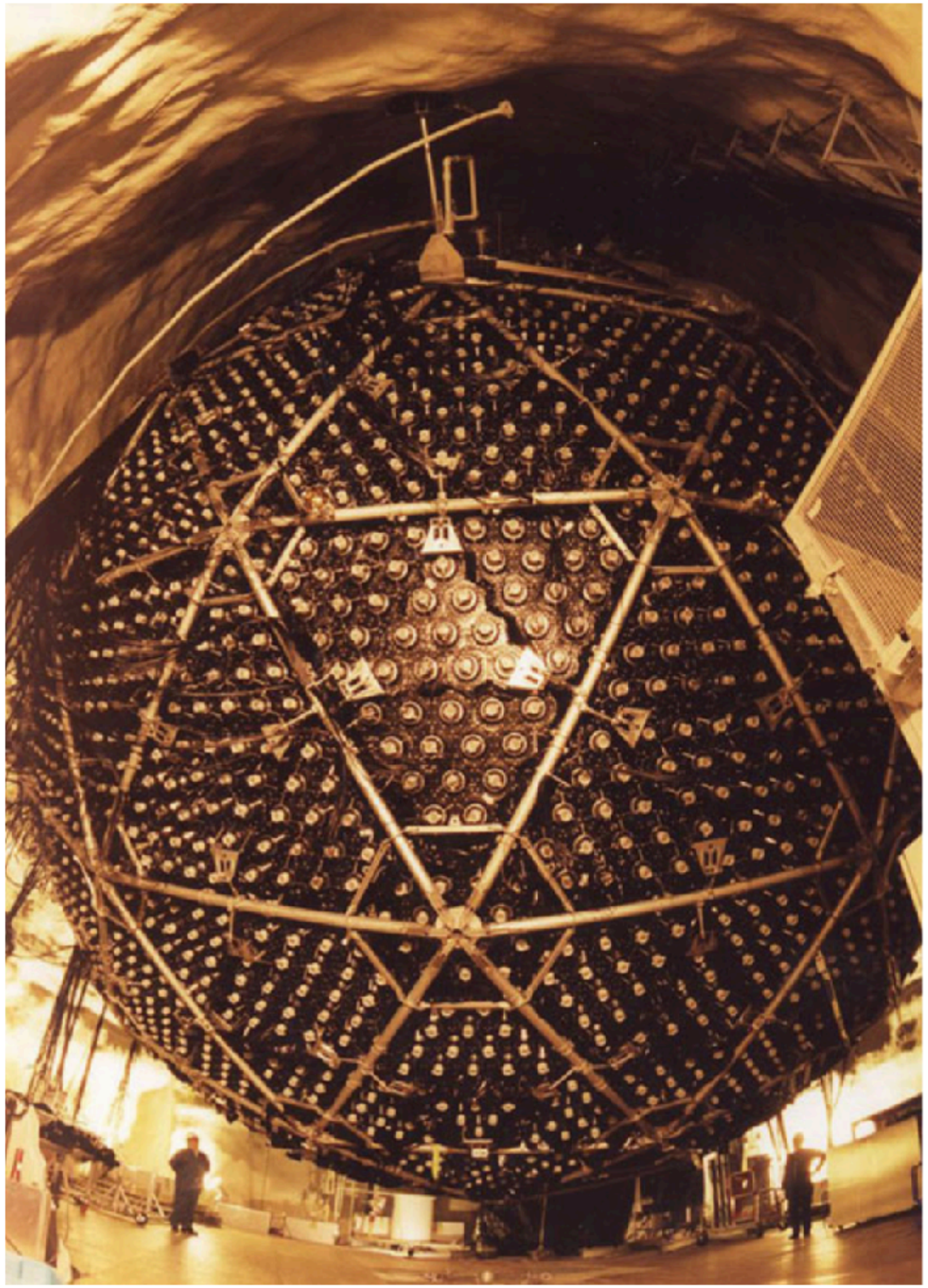


Fig. 6.25 The large SNO detector in a nickel mine in Ontario, Canada [68]

Solar neutrinos

The big advantage of the **SNO experiment is that it can tell the difference between charged and neutral currents.** The reaction

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

can only proceed via charged currents with electron neutrinos, while **neutral currents,** such as

$$\nu_x + d \rightarrow p + n + \nu_x' \quad (x = e, \mu, \tau),$$

are possible for all neutrino flavours. The **neutrons produced in this reaction are captured by deuterons giving rise to the emission of 6.25-MeV photons**, which signal the NC interaction.

While the ν_e flux as obtained by the CC reaction is only 1/3 of the predicted solar neutrino flux, **the total neutrino flux measured by the NC reaction is in agreement with the expectation of solar models**.

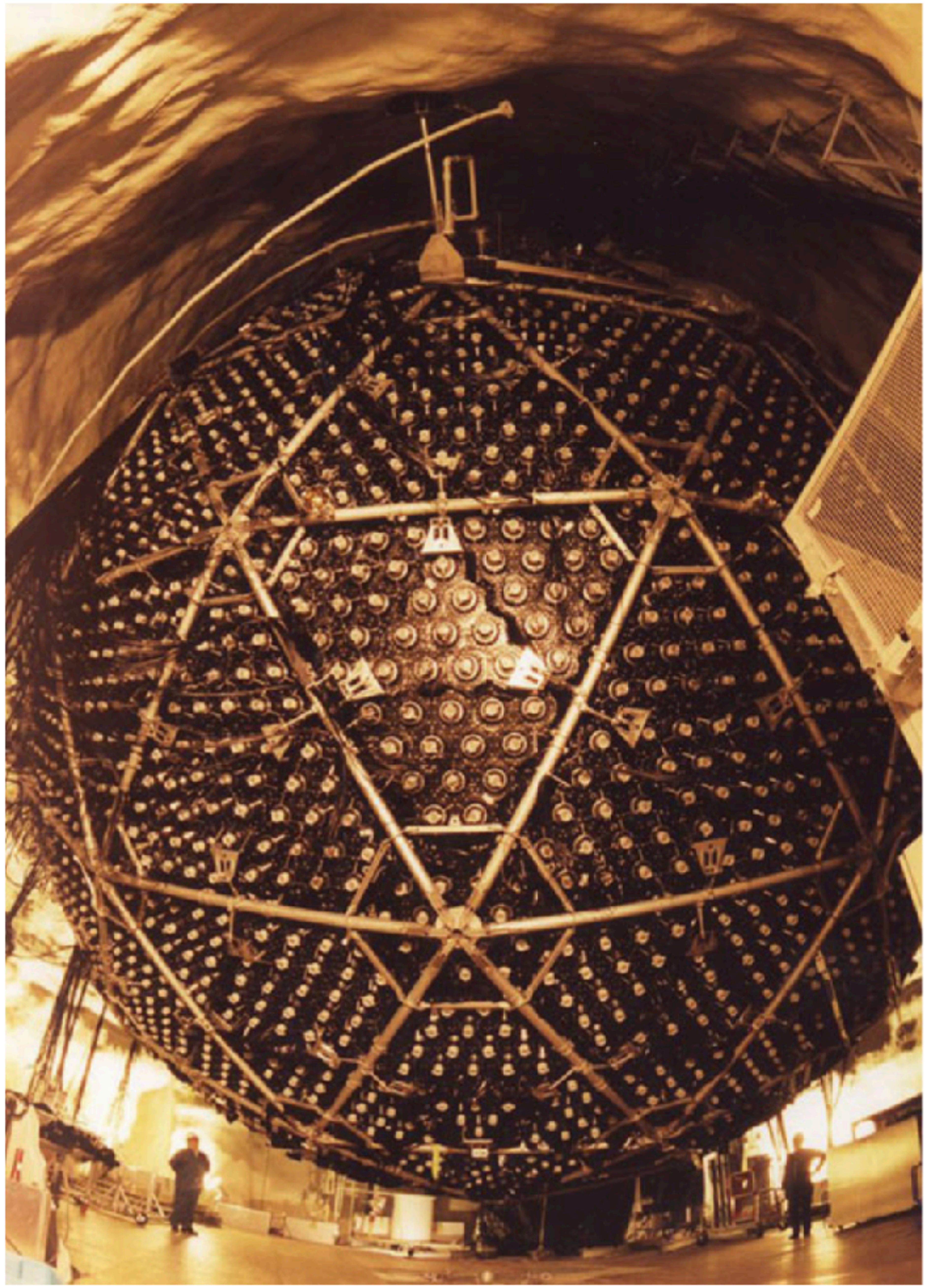


Fig. 6.25 The large SNO detector in a nickel mine in Ontario, Canada [68]

Solar neutrinos

This result solves the long-standing neutrino problem.

It does not, however, resolve the underlying mechanism of the oscillation process. It is not at all clear, whether the ν_e oscillate into ν_μ or ν_τ . It is considered very likely that matter oscillations via the **MSW effect in the Sun play a role for the transmutation of the solar electron neutrinos** into other neutrino flavours, which unfortunately cannot directly be measured in a light-water Cherenkov counter.

The oscillation mechanism suggested by the different solar experiments **(**$\nu_e \to \nu_\mu$**) was confirmed** at the end of 2002 by the KamLAND (Kamioka Liquid-scintillator Anti-Neutrino Detector) reactor-neutrino detector, which removed all doubts about possible uncertainties of the standard solar model predictions.

Solar neutrinos

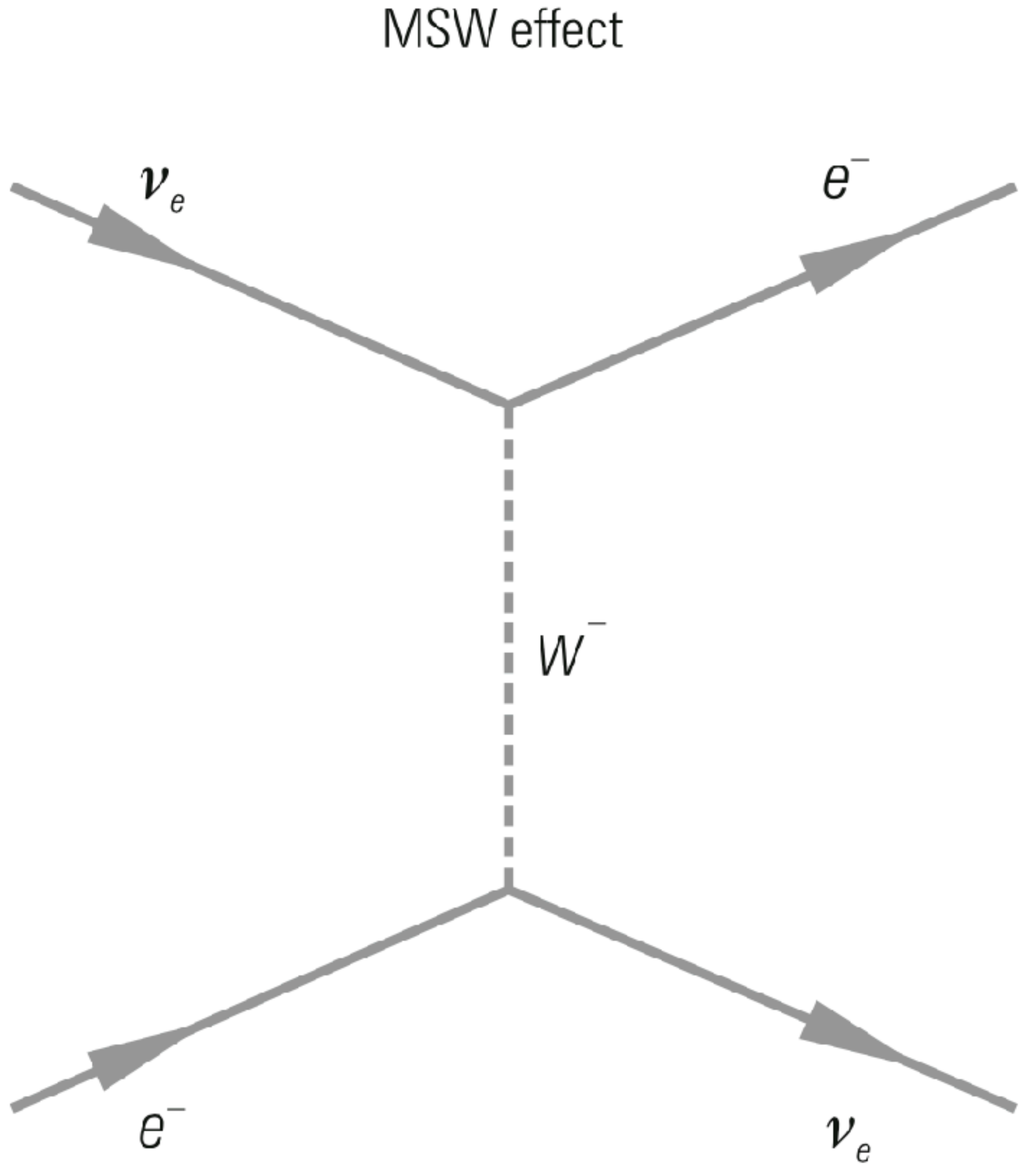
In addition to the vacuum oscillations, **solar neutrinos can also be transformed by so-called matter oscillations.** The flux of electron neutrinos and its oscillation property can be modified by **neutrino–electron scattering when the solar neutrino flux from the interior of the Sun encounters collisions with the abundant number of solar electrons**.

This matter effect is particularly relevant for high-energy solar electron neutrinos. **Flavour oscillations can even be magnified in a resonance-like fashion by matter effects** so that certain energy ranges of the solar ν_e spectrum are depleted. The possibility of matter oscillations has first been proposed by Mikheyev, Smirnov, and Wolfenstein. The oscillation property of the **MSW effect** is different from that of vacuum oscillations.

It relates to the fact that $\nu_e \, e^-$ **scattering contributes a term to the mixing matrix that is not present in vacuum.** Due to this charged-current interaction (Fig. 6.26), which is not possible for ν_μ and ν_τ in the Sun, the interaction Hamiltonian for ν_e is modified compared to the other neutrino flavours. This leads to alterations for the energy difference of the neutrino eigenvalues in matter compared to vacuum. Therefore, electron neutrinos are singled out by this additional interaction process in matter.

Solar neutrinos

Fig. 6.26 Feynman diagram for matter oscillations via the MSW effect. Given the energy of solar neutrinos and the fact that there are only target electrons in the Sun, this process can only occur for ν_e, but not for ν_μ and ν_τ



Solar neutrinos

Depending on the electron density in the Sun the **originally dominant mass eigenstate of ν_e can propagate into a different mass eigenstate,** for which the neutrino detectors are not sensitive.

One might wonder, how such matter oscillations work in the Sun. **The probability for a neutrino to interact in matter is extremely small.** The way the solar electron density affects the propagation of solar neutrinos, however, depends on amplitudes, which are square roots of probabilities. Therefore, **even though the probabilities of interactions are small, the neutrino flavours can be significantly altered** because of the amplitude dependence of the oscillation mechanism.

If the three neutrino flavours ν_e, ν_μ, ν_τ would completely mix, only 1/3 of the original electron neutrinos would arrive at Earth. Since the neutrino detectors, however, are blind for MeV neutrinos of ν_μ and ν_τ type, the **experimental results could be understood in a framework of oscillations**.

The results of the four so far described experiments that measure solar neutrinos **do not permit a unique solution in the parameter space $\sin^2 2\theta$ and** δm^2.

Solar neutrinos

If ($\nu_e \rightarrow \nu_\mu$) or ($\nu_e \rightarrow \nu_\tau$) oscillations are assumed and if it is considered that the MSW effect is responsible for the oscillations, a δm^2 on the order of 4×10^{-4}–2×10^{-5} eV^2 and a large-mixing-angle solution, although disfavouring maximal mixing, is presently favoured.

Assuming a mass hierarchy also in the neutrino sector, this would lead to a ν_μ or ν_τ mass of 0.02– 0.004 eV. This is not necessarily in contradiction to the results from atmospheric neutrinos since solar neutrinos could oscillate into muon neutrinos and atmospheric muon neutrinos into tau neutrinos (or into so far undiscovered sterile neutrinos, which are not even subject to weak interactions).

For the numerous low-energy solar neutrinos, as they are measured in the Homestake and the gallium experiments, one can neglect the MSW effect, and one can apply the **formalism of vacuum oscillations**. This is related to the fact that the solar core, where the hydrogen fusion proceeds, is much larger than the oscillation length. Therefore, one has to average over the oscillation factor, which leads to the standard behaviour of vacuum oscillations.

With these oscillation scenarios one can **explain consistently the different experiments** (Homestake, Gallium, Borexino, and SNO experiment), which have provided slightly different results on the solar neutrino fluxes.

Solar neutrinos

Under the **assumption that solar electron neutrinos oscillate into** ν_μ one would get for the oscillation parameters $\sin^2 2\theta \approx 0.09$ and $\delta m^2 = 2.4 \times 10^{-3}$ eV^2.

Of course, one has to **aim at determining all parameters of the neutrino mixing matrix**. **Presently one favours that electron neutrinos oscillate into muon neutrinos and muon neutrinos convert into tau neutrinos.** This is also supported by the size of the mixing angles ($\nu_e \rightarrow \nu_\mu$: $\sin^2 2\theta \approx 0.85$; resp. $\nu_\mu \rightarrow \nu_\tau$: $\sin^2 2\theta > 0.95$).

The oscillations scenario, which is favoured for the solar neutrinos ($\nu_e \rightarrow \nu_\mu$), was also **supported by the KamLAND experiment** (Kamioka Liquid-scintillator Anti-Neutrino Detector) in 2002 **using reactor neutrinos**. This finally eliminated all doubts about the oscillation hypothesis.

Still, details of neutrino oscillations and **the determination of the various mixing parameters in the Pontecorvo–Maki–Nakagawa–Sakata matrix is a matter of current research.**

The possible effect of **Majorana-type neutrinos** and **hypothetical sterile neutrinos** complicates the phenomenon of neutrino oscillations considerably.

Sterile neutrinos

Sterile neutrinos (or inert neutrinos) are hypothetical particles that **interact only via gravity and not via any of the other fundamental interactions** of the Standard Model.
The term sterile neutrino is used to **distinguish them from the known, ordinary active neutrinos** in the Standard Model, which carry an **weak isospin** charge of $\pm\frac{1}{2}$ and engage in the weak interaction.
The term typically refers to neutrinos with right-handed chirality (see right-handed neutrino), which may be inserted into the Standard Model. Particles that possess the quantum numbers of sterile neutrinos and masses great enough such that they do not interfere with the current theory of Big Bang nucleosynthesis are **often called neutral heavy leptons (NHLs) or heavy neutral leptons (HNLs)**.
The existence of right-handed neutrinos is theoretically well-motivated, because the known active neutrinos are left-handed and all other known fermions have been observed with both left and right chirality. They could also explain in a natural way the small active neutrino masses inferred from neutrino oscillation. The mass of the right-handed neutrinos themselves is unknown and could have any value between 10^{15} GeV and less than 1 eV. To comply with theories of leptogenesis and dark matter, there must be at least 3 flavors of sterile neutrinos (if they exist).
The search for sterile neutrinos is an active area of particle physics.

https://en.wikipedia.org/wiki/Sterile_neutrino

Weak isospin

In particle physics, **weak isospin is a quantum number** relating to the electrically charged part of the weak interaction: **Particles with half-integer weak isospin can interact with the $W^{\pm}$ bosons; particles with zero weak isospin do not.**

Weak isospin is a construct **parallel to the idea of isospin under the strong interaction.** Weak isospin is usually given the symbol T or I, with the third component written as T_3 or I_3.

https://en.wikipedia.org/wiki/Sterile_neutrino

Solar neutrinos

A follow-up project on Super-Kamiokande will be the **very large water Cherenkov detector Hyper-Kamiokande** to be installed in Kamioka at 650m underground. Hyper-Kamiokande will use 260000 tons of pure water viewed at by 40000 photomultipliers to **investigate neutrino oscillations and search for *CP* violation in the neutrino sector.** Understanding the neutrino is not only important for particle physics but it is also connected to deep questions on the origin of matter and the understanding of cosmology.

The recent **Borexino experiment** aims at a very special goal by **measuring low-energy solar neutrinos.** The experiment is installed in the Gran Sasso laboratory in Italy. Borexino is a **liquid scintillator detector** with a sensitive volume of 315 m^3. The main goal is to measure the low-energy neutrinos from the ^7Be capture. The energy threshold for this process is rather low (250 keV), which requires to carefully shield the experiment against all kinds of cosmic and local environmental background. Apart from that this detector is also sensitive to **geoneutrinos**, e.g., from the uranium–thorium decay chain.

Borexino

- In 2010, "geoneutrinos" from Earth's interior were observed for the first time.
- The lowest-threshold (3 MeV) measurement of the ^{8}B solar neutrino flux.
- The first direct detection of *pp* neutrinos.
- In 2020 Borexino detected the first deep solar core CNO Neutrinos. (The CNO cycle contributes ~1% of the fusion in the Sun)

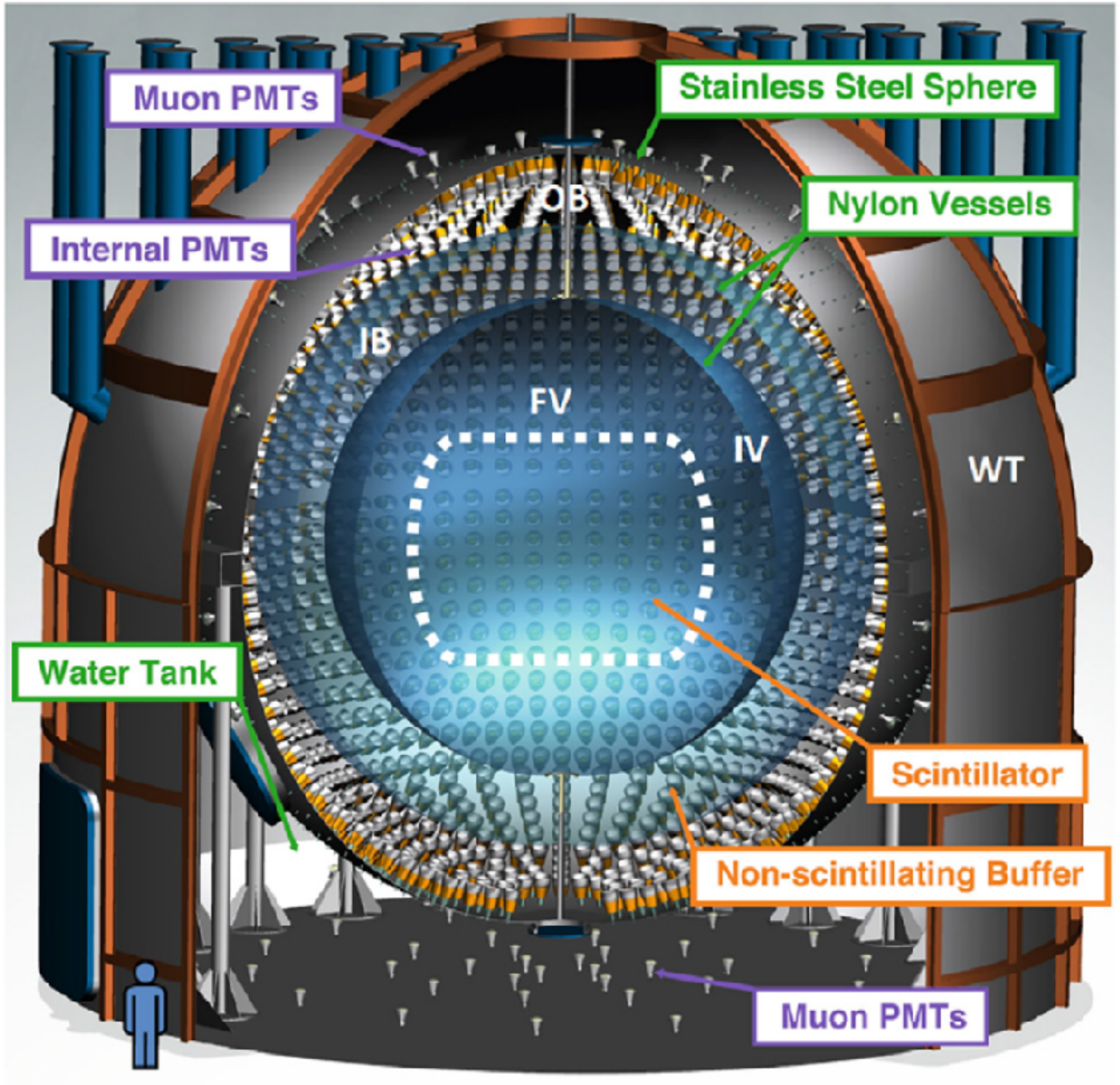
The Borexino detector @ LNGS

Active volume: 280 tons of liquid scintillator.

Detection principle

$$\nu_x + e \rightarrow \nu_x + e$$

Elastic scattering off the electrons of the scintillator. Threshold at ~ 60 keV (electron energy)



https://en.wikipedia.org/wiki/Borexino

https://borex.lngs.infn.it/about-borexino/