Special Topics in Particle Physics

Primary Cosmic Rays - Neutrinos

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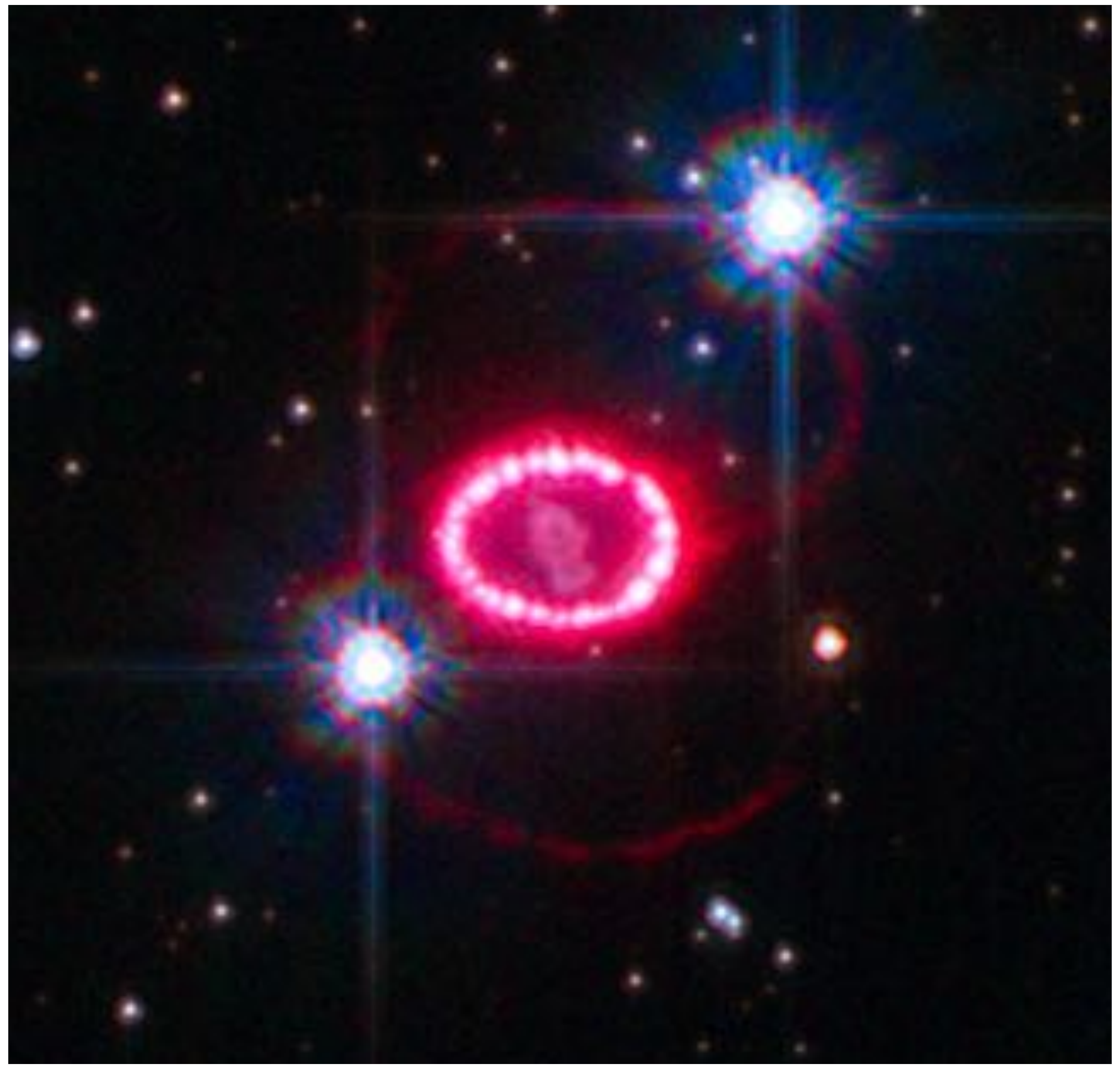
Supernova neutrinos

The brightest supernova since the observation of Kepler in the year 1604 was discovered by Ian Shelton at the Las Campanas observatory in Chile on February 23, 1987 **(SN 1987A)**. The region of the sky in the Tarantula Nebula in the **Large Magellanic Cloud.**

For the first time a progenitor star of the supernova explosion could be located. Using earlier exposures of the Tarantula Nebula, a bright blue supergiant, was found to have exploded. The star was **10 $M_\odot$ with a surface temperature of 15 000 K.**

During the hydrogen burning period the star increased its brightness reaching a luminosity 70 000 higher than the solar luminosity. After the hydrogen supply was exhausted, the star expanded to become a red supergiant. In this process its central temperature and pressure rose to such values that **He burning became possible.** In a relatively short time (600 000 years) the helium supply was also exhausted.

Hubble Space Telescope image



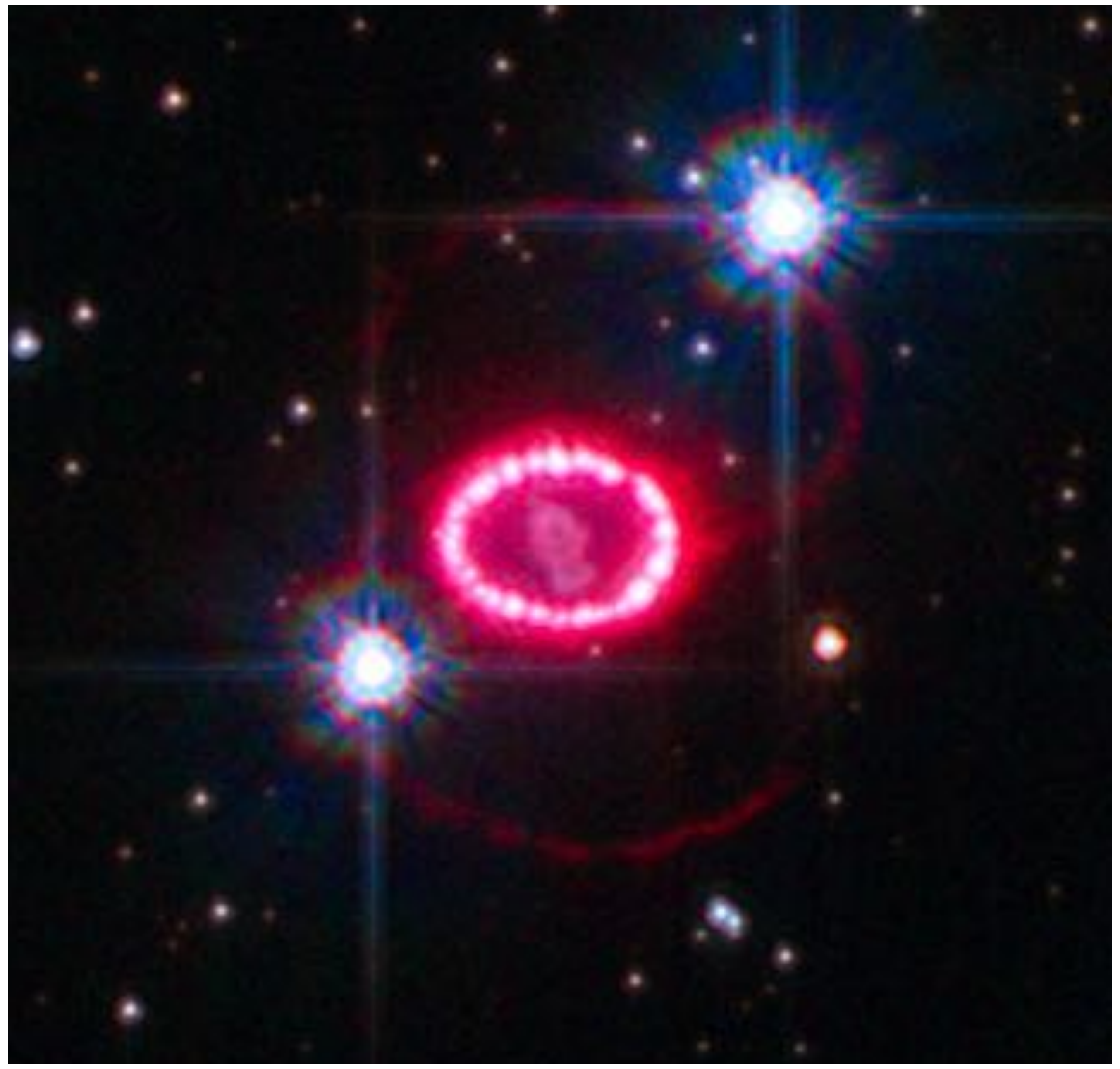
James Webb Space Telescope image

Supernova neutrinos

Helium burning was followed by a gravitational contraction, in which the nucleus of the star reached a temperature of 740 million kelvin and a central density of 240 kg/cm^3. These conditions enabled **carbon to ignite**. In a similar fashion contraction and fusion phases occurred leading **via oxygen, neon, silicon, and sulphur finally to iron**, the element with the highest binding energy per nucleon.

The pace of these successive contraction and fusion phases got faster and faster until finally iron was reached. Once the star has reached such a state, there is no way to gain further energy by fusion processes. Therefore, the stability of the star could no longer be maintained. Finally, in the last period of its life (≈100 000 years) the star shrank to **become a blue supergiant and the star collapsed under its own gravity.**

As a consequence of the **various burning and collapse phases a number of shock waves were generated,** which **emitted spherical matter jets that formed different rings.** The detailed course of events of the supernova explosion and the formation of ring-like structures was tried to reconstruct with Monte Carlo simulations, without so far leading to conclusive results.



Supernova neutrinos

During this process the electrons of the star were forced into the protons and a **neutron star of approximately 20km diameter was produced**. In the course of this deleptonization a *neutrino burst* of immense intensity was created,

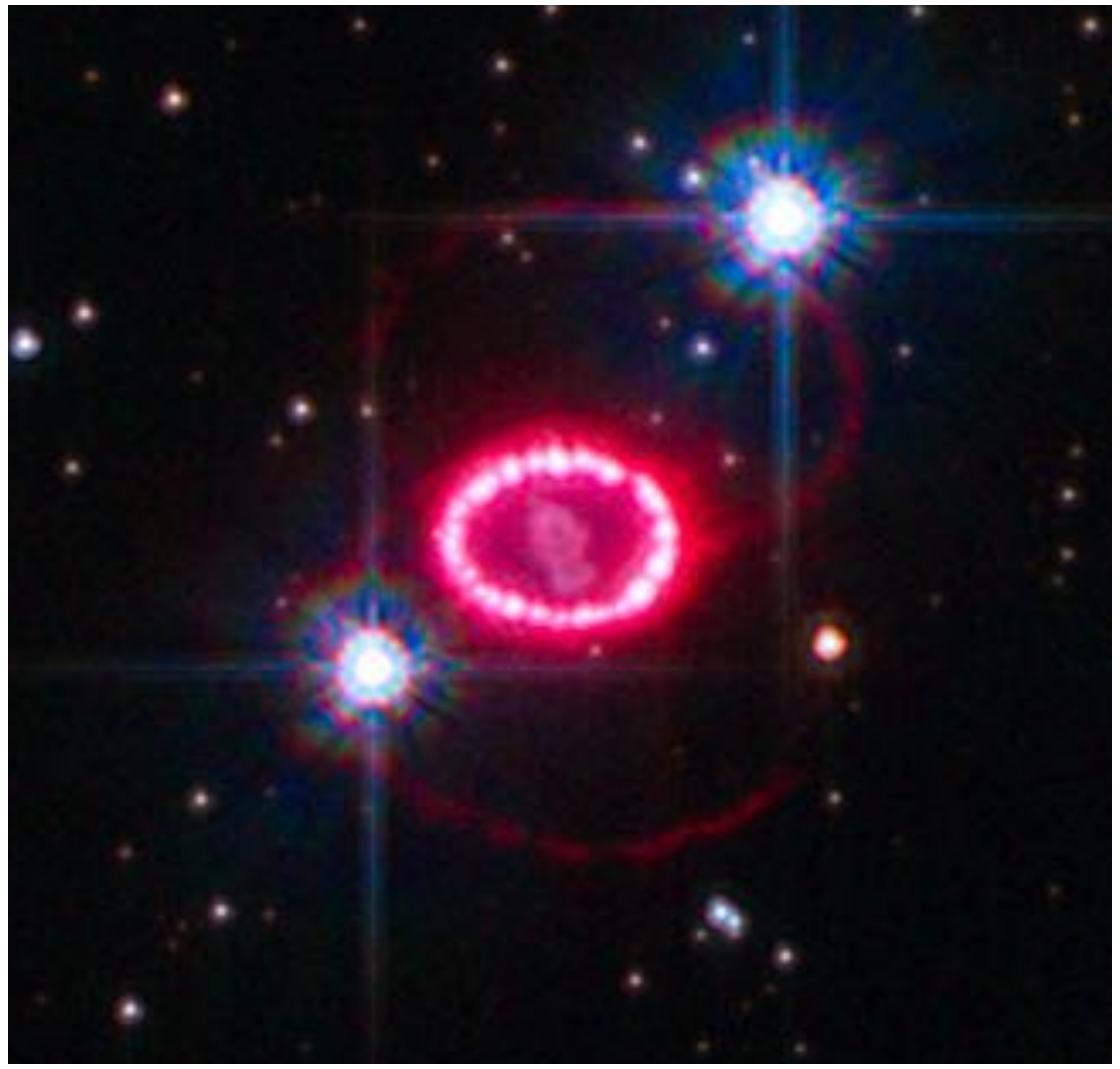
$$e^- + p \rightarrow n + \nu_e$$

In the hot phase of the collapse corresponding to a temperature of 10 MeV ($\approx 10^{11}$ K), the **thermal photons produced electron–positron pairs** that, however, **were immediately absorbed** because of the high density of the surrounding matter. Only the weak-interaction process via a virtual *Z*,

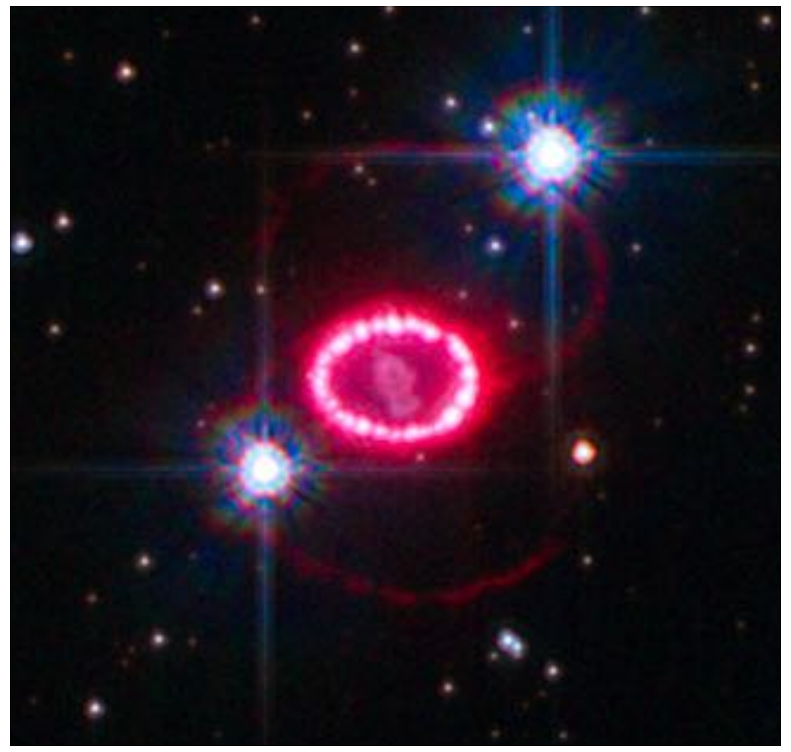
Draw the Feynman diagram

$$e^+ + e^- \rightarrow Z \rightarrow \nu_\alpha + \bar{\nu}_\alpha$$

allowed energy to escape from the hot stellar nucleus in the form of neutrinos. In this reaction **all three neutrino flavours ν_e, ν_μ, and ν_τ were produced in equal numbers.** The total neutrino burst comprised 10^{58} neutrinos and even **at Earth the neutrino flux from the supernova was comparable to that of solar neutrinos for a short period.**



Supernova neutrinos



Actually, **the neutrino burst** of the supernova **was the first signal to be registered** on Earth. The large **water Cherenkov counters** of Kamiokande and IMB (Irvine– Michigan–Brookhaven) and the Baksan experiment **recorded a total of 25** out of the emitted 10^{58} **neutrinos** (see Fig. 6.29).

The energy threshold of the Kamiokande experiment was as low as 5 MeV. In contrast, the IMB collaboration could only measure neutrinos with energies exceeding 19 MeV. The Baksan liquid scintillator was lucky to record five coincident events with energies between 10 and 25 MeV.

Since the neutrino energies in the range of 10MeV are insufficient to produce muons or taus, only electron-type neutrinos were recorded via the reactions

$$\begin{aligned} \bar{\nu}_e + p &\rightarrow e^+ + n \\ \bar{\nu}_e + e^- &\rightarrow \bar{\nu}_e + e^- \\ \nu_e + e^- &\rightarrow \nu_e + e^- \end{aligned}$$

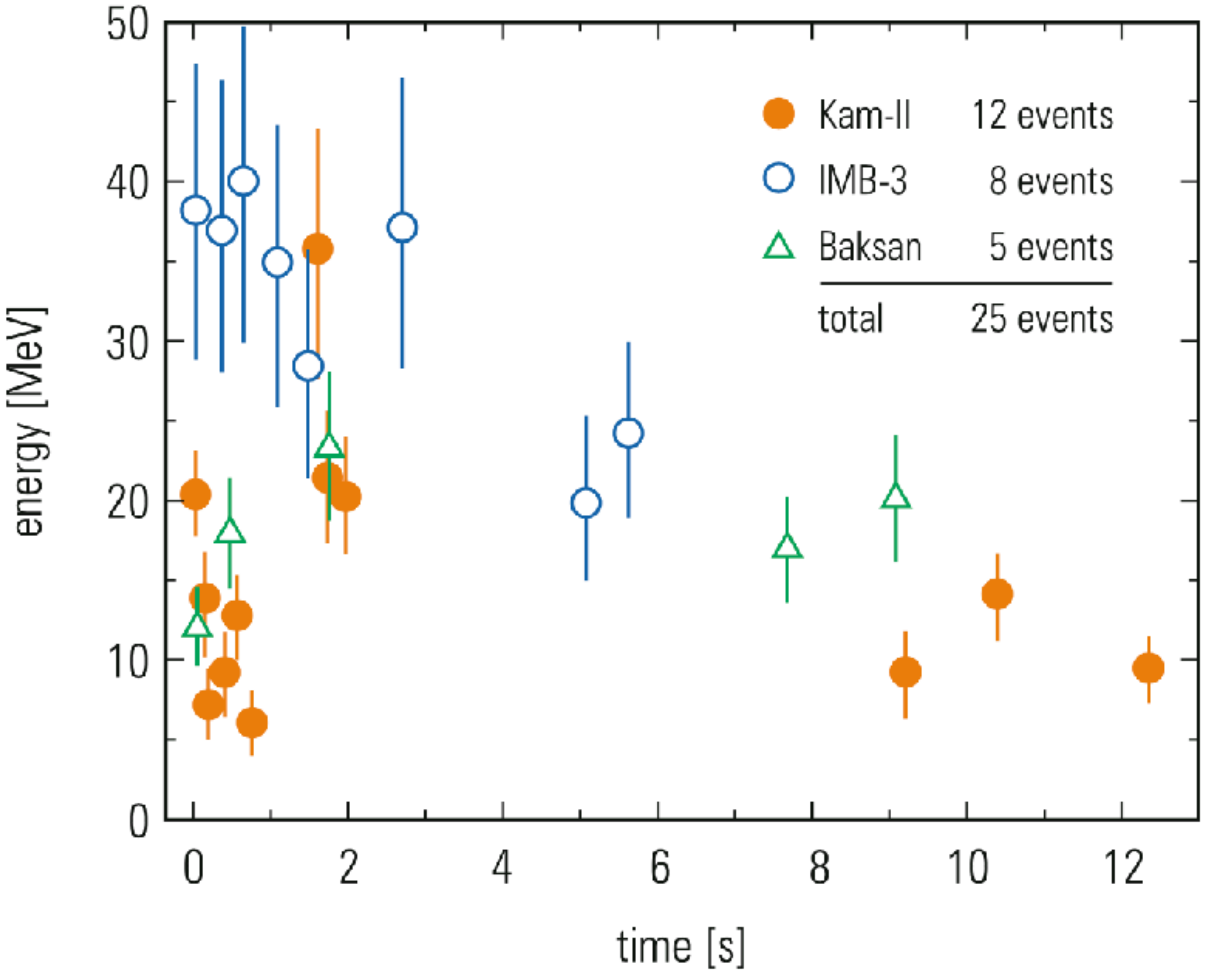
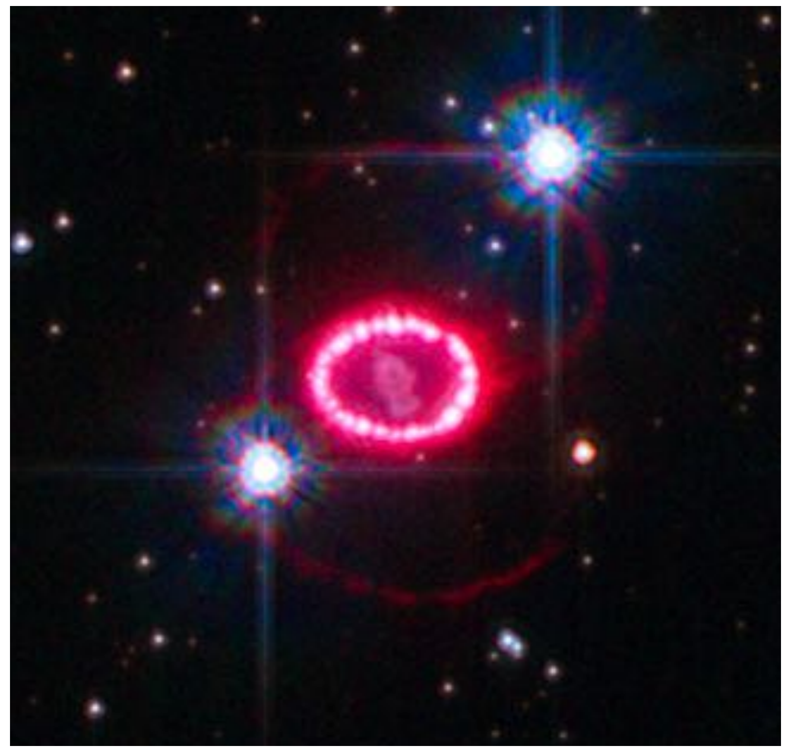


Fig. 6.29 Measured neutrino events from the supernova SN 1987A [73]

Supernova neutrinos



In spite of the low number of measured neutrinos on Earth some interesting **astrophysical conclusions** can be drawn from this supernova explosion.

If E_ν^i is the energy of individual neutrinos measured in the detector ϵ_1 the probability for the interaction of a neutrino in the detector, and ϵ_2 the probability to also see this reaction, then **the total energy emitted in form of neutrinos can be estimated to be**

$$E_{\text{total}} = \sum_{i=1}^{20} \frac{E_\nu^i}{\varepsilon_1(E_\nu^i)\,\varepsilon_2(E_\nu^i)} 4\pi r^2\, f(\nu_\alpha, \bar{\nu}_\alpha)$$

where the correction factor f takes into account that the water Cherenkov counters are not sensitive to all neutrino flavours.

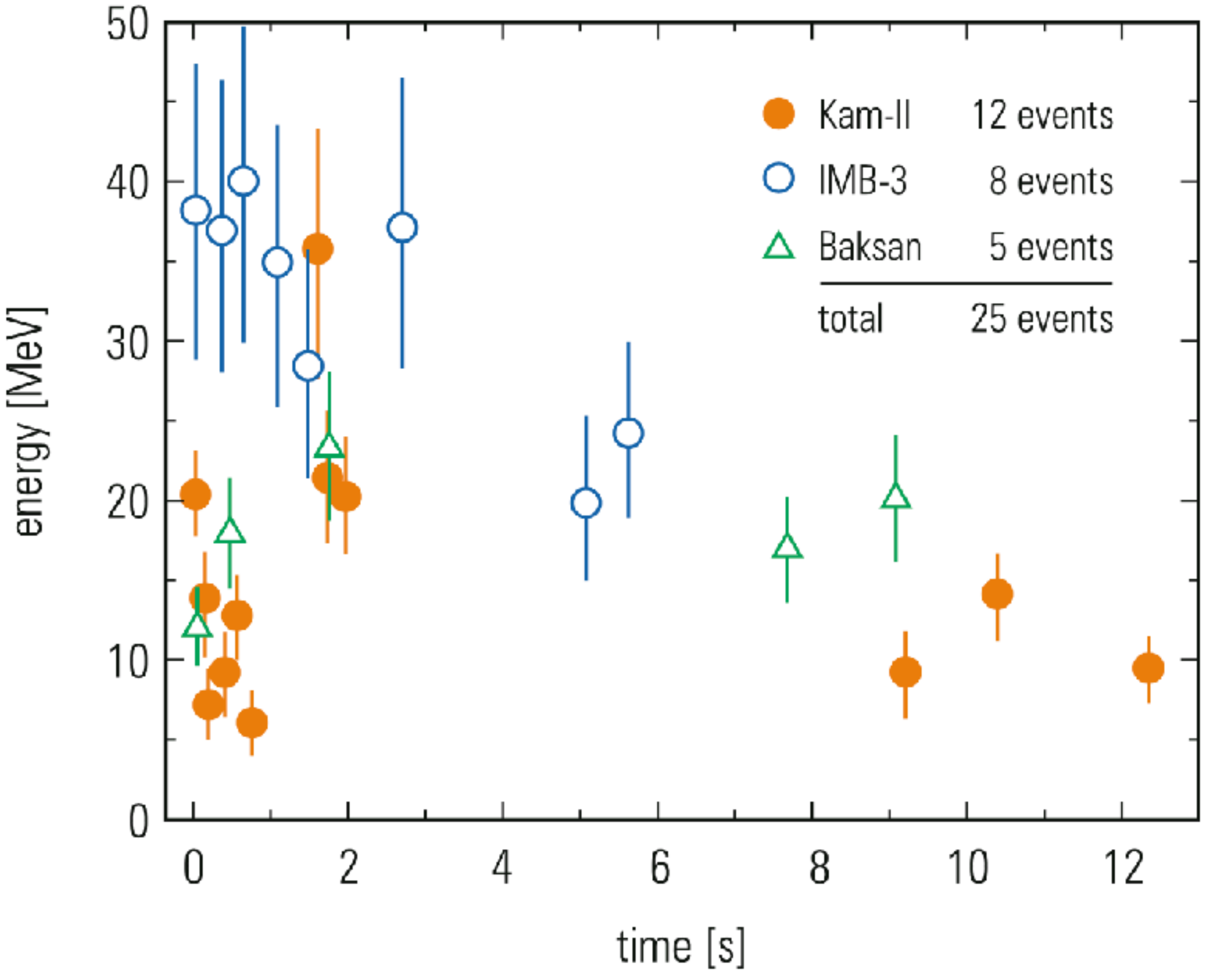
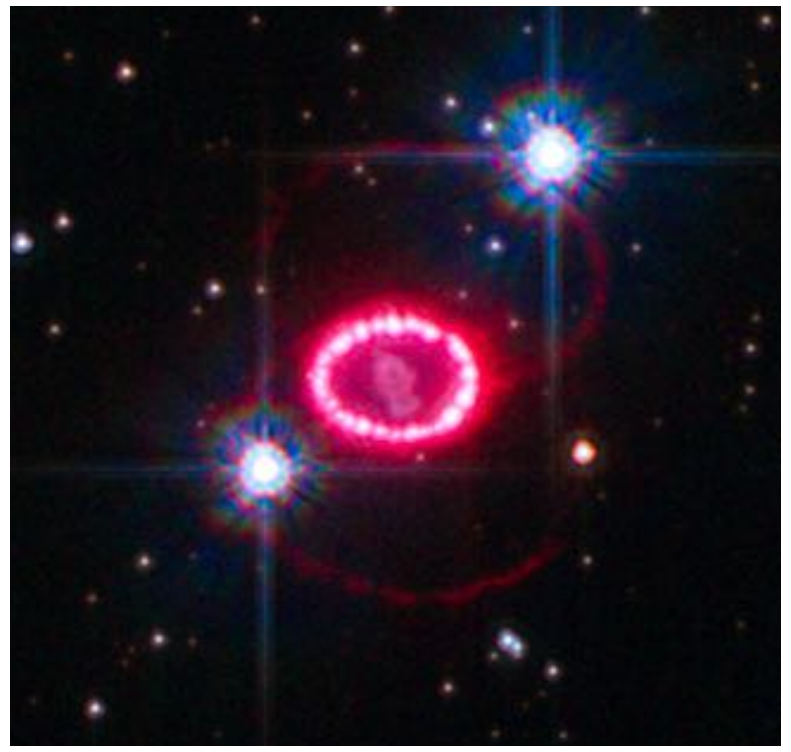


Fig. 6.29 Measured neutrino events from the supernova SN 1987A [73]

Supernova neutrinos



Based on the 25 recorded neutrino events in Super-Kamiokande, the IMB experiment, and at Baksan a total energy of

$$E_{\text{total}} = (6 \pm 2) \times 10^{46}\ \text{J}$$

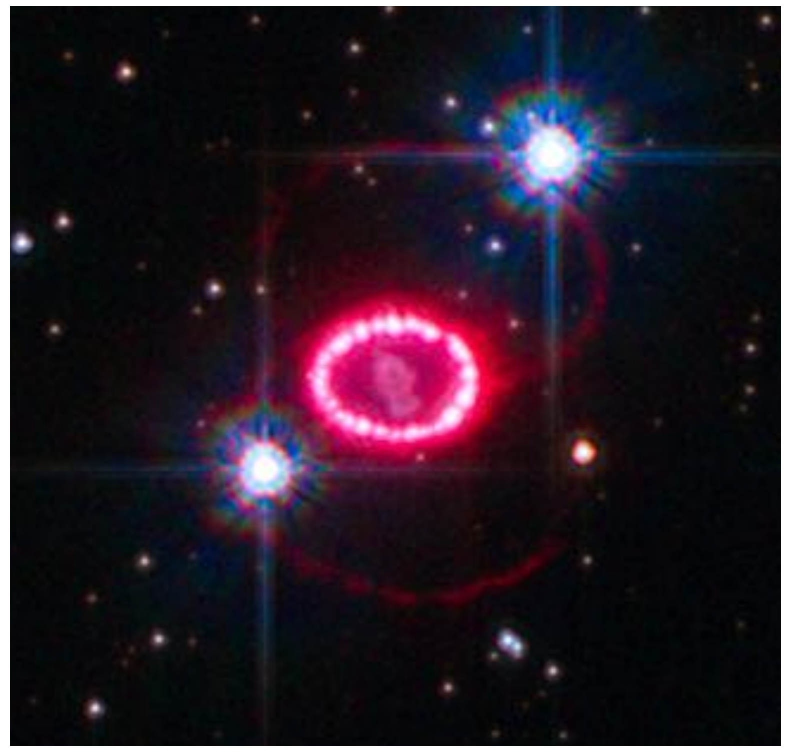
is obtained. It is hard to comprehend this enormous energy.

During the **10 s lasting neutrino burst** the star radiated more energy than the rest of the universe and hundred times more than the Sun in its total lifetime of about 10 billion years.

Measurements over the last 40 years have ever tightened the limits for neutrino masses. At the time of the supernova explosion the **mass limit for the electron neutrino** from measurements of the **tritium beta decay** ($^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$) **was about 10 eV**.

Under the **assumption that all supernova neutrinos are emitted practically at the same time**, one would expect that **their arrival times at Earth would be subject to a certain spread if the neutrinos had mass**.

Supernova neutrinos



Neutrinos of **non-zero mass have different velocities depending on their energy**. The expected difference of arrival times Δt of two neutrinos with velocities v_1 and v_2 emitted at the same time from the supernova is

$$\Delta t = \frac{r}{v_1} - \frac{r}{v_2} = \frac{r}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{r}{c}\,\frac{\beta_2 - \beta_1}{\beta_1\,\beta_2}$$

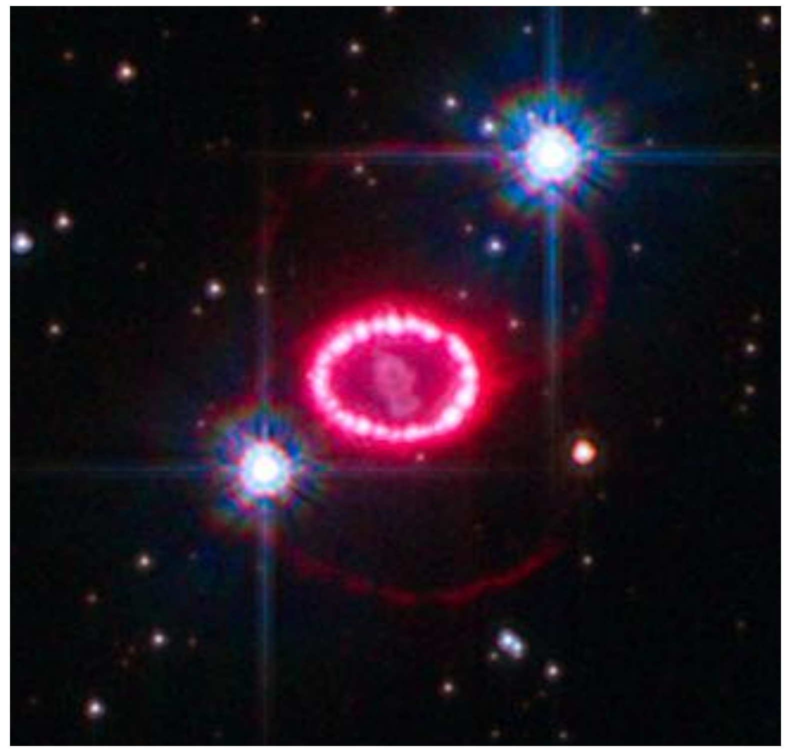
If the recorded electron neutrinos had a rest mass m_0, their energy would be

$$E = mc^2 = \gamma m_0 c^2 = \frac{m_0 c^2}{\sqrt{1-\beta^2}}$$

and their velocity

$$\beta = \left(1 - \frac{m_0^2 c^4}{E^2}\right)^{1/2} \approx 1 - \frac{1}{2}\,\frac{m_0^2 c^4}{E^2}$$

Supernova neutrinos



since one can safely assume that $m_0c^2 \ll E$. This means that the **neutrino velocities are very close to the velocity of light.** Obviously, the arrival-time difference Δt depends on the velocity difference of the neutrinos.

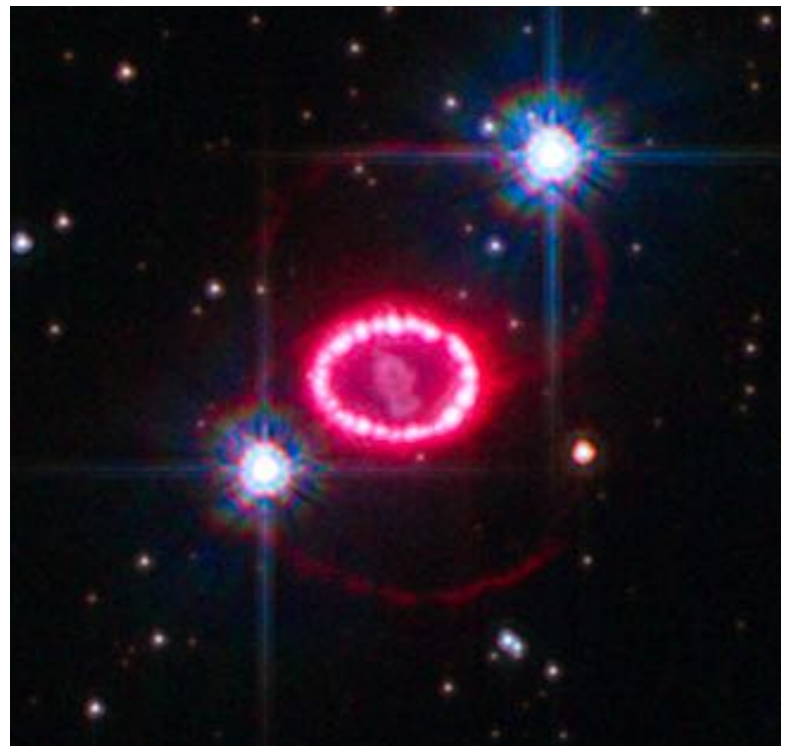
$$\Delta t \approx \frac{r}{c}\,\frac{\frac{1}{2}\,\frac{m_0^2c^4}{E_1^2} - \frac{1}{2}\,\frac{m_0^2c^4}{E_2^2}}{\beta_1\beta_2} \approx \frac{1}{2}\,m_0^2c^4\,\frac{r}{c}\,\frac{E_2^2 - E_1^2}{E_1^2\,E_2^2}$$

The experimentally measured arrival-time differences and individual neutrino energies allow in principle to work out the **electron neutrino rest mass**

$$m_0 = \left\{\frac{2\Delta t}{r\,c^3}\,\frac{E_1^2\,E_2^2}{E_2^2 - E_1^2}\right\}^{1/2}$$

Since, however, **not all neutrinos are really emitted simultaneously**, this only allows to derive **an upper limit** for the neutrino mass using pairs of particles of known energy and known arrival-time difference.

Supernova neutrinos



Using the results of the Kamiokande and IMB experiments a mass limit of the electron neutrino of

$$m_{\nu_e} \leq 10\,\mathrm{eV}$$

could be established. This result was obtained in a **measurement time of approximately 10 s**.

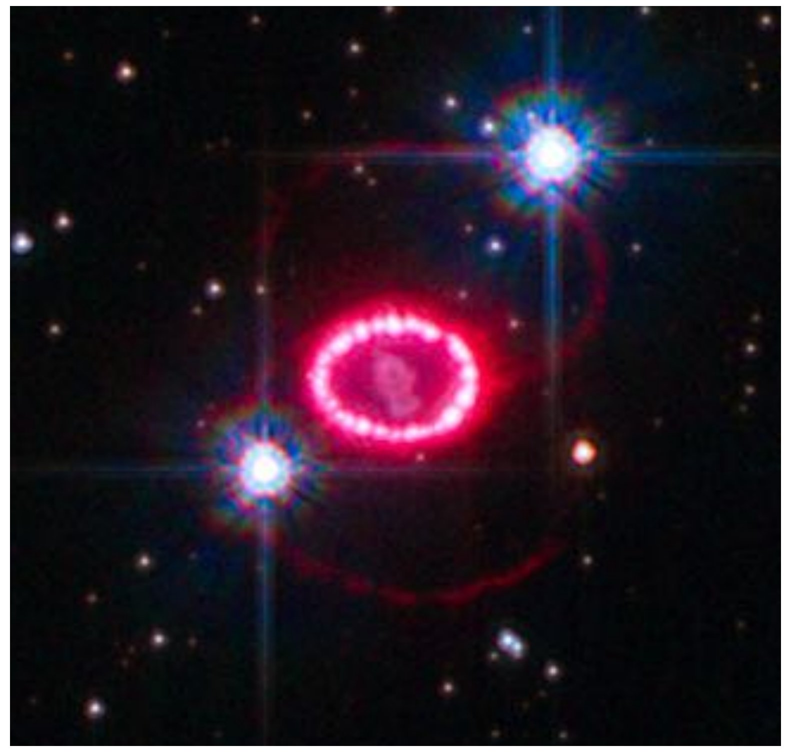
Similarly, a possible explanation for the deficit of solar neutrinos by assuming neutrino decay was falsified by the mere observation of electron neutrinos from a distance of 170 000 light-years. For an assumed neutrino mass of m_0 = 10 meV the Lorentz factor of 10-MeV neutrinos would be

$$\gamma = \frac{E}{m_0 c^2} \approx 10^9$$

This would allow to derive a lower limit for the neutrino lifetime from $\tau_\nu^0 = \dfrac{\tau_\nu}{\gamma}$ to

$$\tau_\nu^0 = 170\,000\,\mathrm{a}\,\frac{1}{\gamma} \approx 5000\,\mathrm{s}$$

Supernova neutrinos



The supernova 1987A has turned out to be a rich astrophysical laboratory. It has shown that the available supernova models can describe the death of massive stars on the whole correctly.

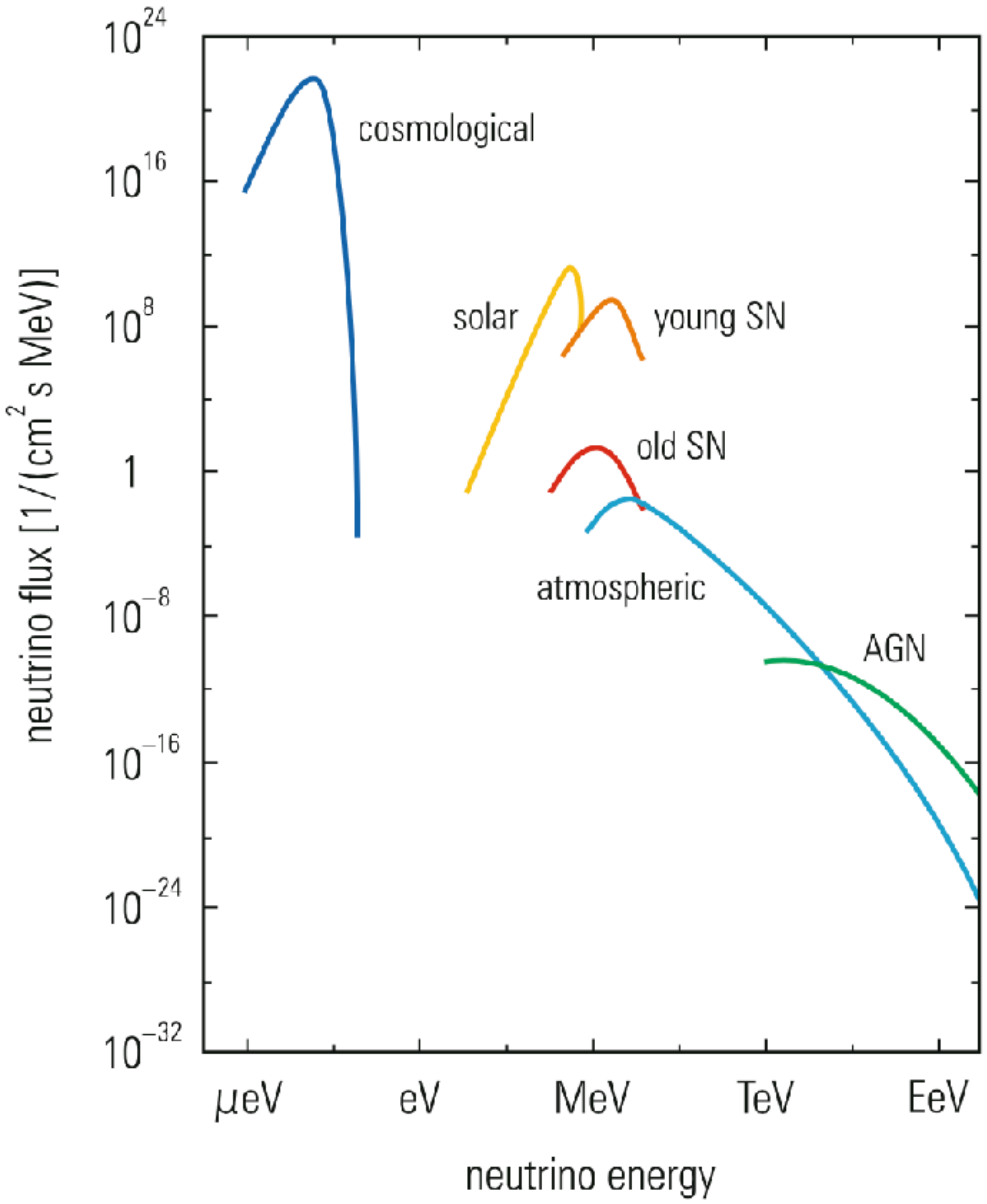
Given the agreement of the measured neutrinos fluxes with expectation, the supernova neutrinos do not seem to require oscillations. On the other hand, the **precision of simulations** and the **statistical errors of measurements** are insufficient to draw a firm conclusion about such a subtle effect for supernova neutrinos.

If a supernova would happen in our Milky Way, one might expect to record tens of thousands neutrinos with the present and future much larger detectors. **This might then give a further input to the effect of long-distance neutrino oscillations.**

It is not a surprise that the decision on the oscillation scenario has come from observations of solar and atmospheric neutrinos and accelerator experiments with well-defined, flavour-selected neutrino beams. With the experimental evidence of cosmic-ray-neutrino experiments (Davis, GALLEX, SAGE, Super-Kamiokande, SNO) and accelerator and reactor experiments (K2K, KamLAND) there is now unanimous agreement that **oscillations in the neutrino sector are an established fact.**

Galactic and extragalactic neutrinos

Fig. 6.30 Comparison of different neutrino fluxes in different energy domains [74]



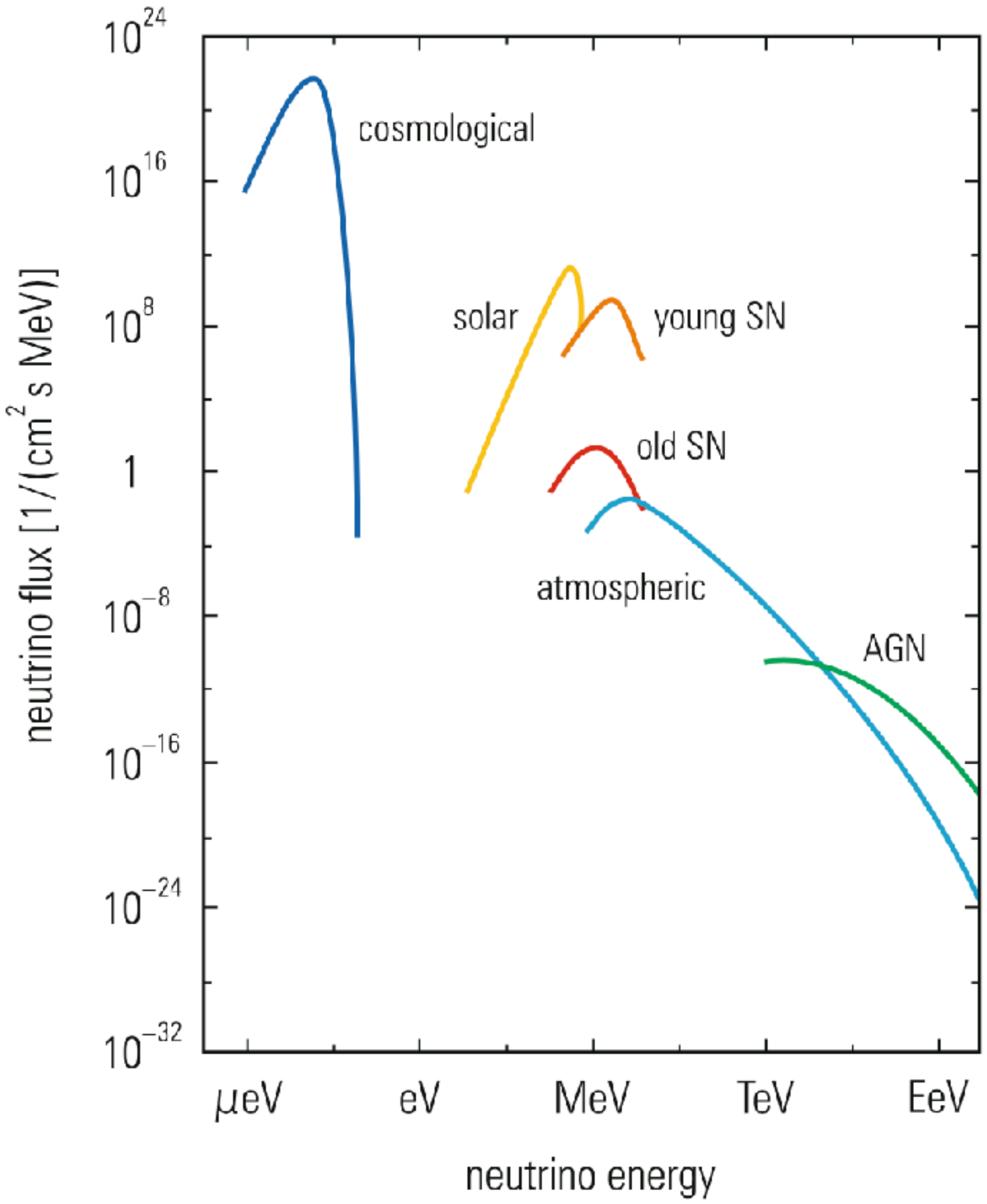
The measurement of **high-energy neutrinos (≥TeV range)** represents a big **experimental challenge**. The arrival direction of such neutrinos, however, would **directly point back to the sources of cosmic rays.**

Therefore, a substantial amount of work is devoted to studies for neutrino detectors in the TeV range and the development of experimental setups for the measurement of galactic and extragalactic high-energy neutrinos.

The reason to restrict oneself to high-energy neutrinos is obvious from the inspection of Fig. 6.30.

Galactic and extragalactic neutrinos

Fig. 6.30 Comparison of different neutrino fluxes in different energy domains [74]



The neutrino echo of the **Big Bang has produced energies below the meV range**.

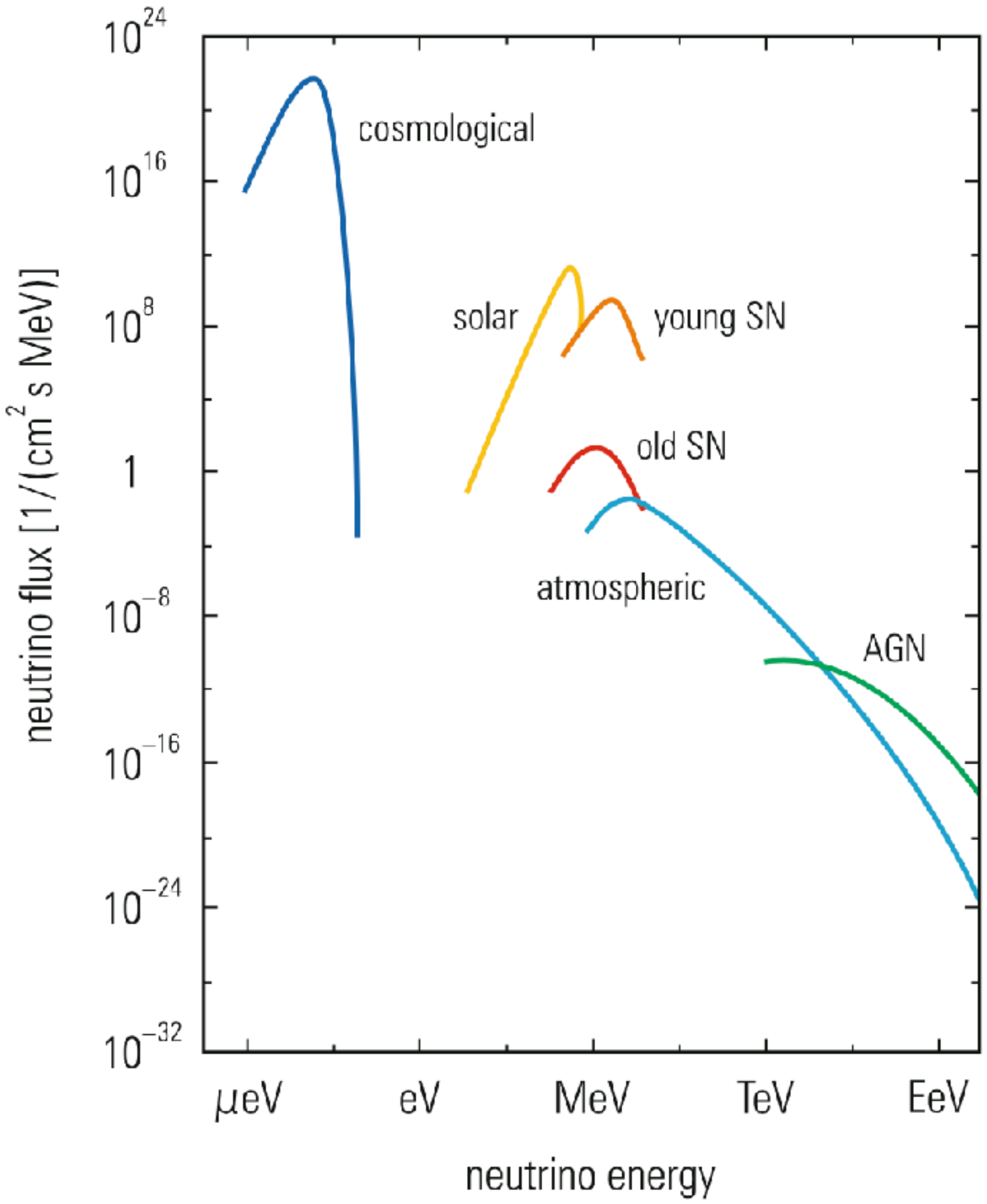
About a second after the Big Bang **weak interactions have transformed protons into neutrons and neutrons into protons** thereby producing neutrinos ($p + e^- \to n + \nu_e, n \to p + e^- + \bar{\nu}_e$).

The temperature of these primordial neutrinos should be at **1.9 K at present time**. The detection of these **blackbody neutrinos is a real challenge**, and nobody presently has an idea how to measure them. However, the **measurement of neutrinos of higher energy is by now standard.**

The observation of solar (≈MeV range) and supernova neutrinos (≈10 MeV) is experimentally established. Atmospheric neutrinos represent a background for neutrinos from astrophysical sources.

Galactic and extragalactic neutrinos

Fig. 6.30 Comparison of different neutrino fluxes in different energy domains [74]



Atmospheric neutrinos originate essentially from pion and muon decays.

Their production spectra can be inferred from the **measured atmospheric muon spectra**. However, they have also been **measured directly**, but their intensity is only known to an accuracy of about 30%.

The different sources of cosmic neutrinos are sketched in Fig. 6.30, where the flux of very-high-energy neutrinos is only a rough estimate.

Galactic and extragalactic neutrinos

Pioneer work was started with **large-volume water and ice Cherenkov detectors**.

The **Baikal Deep Underwater Neutrino Telescope** below the surface of Lake Baikal started early (2003).

First attempts to measure high-energy neutrinos in the ocean with **DUMAND (Deep Underwater Muon And Neutrino Detector)** failed because of difficulties to deploy **long strings of photomultipliers in the Pacific Ocean near Hawaii**. As a consequence of this, the Hawaii team **moved to the Antarctic and installed AMANDA (Antarctic Muon And Neutrino Detector Array)** in the antarctic ice. AMANDA was quite successful, but is was too small to collect the rare interactions of very-high-energy cosmic neutrinos.

Consequently it was **enlarged to a detection volume of 1 km^3 (ICECUBE).** There are even plans to upgrade ICECUBE by a factor of 10 in volume.

In the **Mediterranean** smaller detectors are installed (**NESTOR** (Neutrino Extended Submarine Telescope with Oceanographic Research Project), **ANTARES** (Astronomy with a Neutrino Telescope and Abyss environmental RESearch), **NEMO** (Neutrino Ettore Majorana Observatory)) and a common large neutrino detector (**KM3NeT**) with a volume of 1 km^3 is being prepared.

Galactic and extragalactic neutrinos

The **Baikal Deep-Underwater Neutrino Telescope** is located at a distance of 3.5 km from the shore at a depth of 1100-1300 m in the south part of lake Baikal. The design of the neutrino telescope is an array of photomultiplier tubes detecting Cherenkov radiation generated by secondary muons and particle cascades which are produced in neutrino interactions in the water.

It was constructed to study high-energy muon and neutrino fluxes and search for new types of elernentary particles: magnetic monopoles, WIMPs - massive particles which can be considered as candidates to "dark" matter, and others.

The telescope is one of the world's largest neutrino detectors. It is planned to increase the effective volume of the detector up to l km^3.

he Baikal infrastructure is a multipurpose laboratory conducting research in the fields of hydrology, limnology and geophysics employing state of the art detectors.

Between 2018–2021, **eleven cascade events were selected with an energy of above 15 TeV** from under the horizon caused by astrophysical neutrinos, which confirms the results of the Antarctic IceCube detector.

https://www.inr.ru/eng/ebgnt.html

https://www.jinr.ru/posts/launching-regular-expedition-to-construct-baikal-neutrino-telescope/

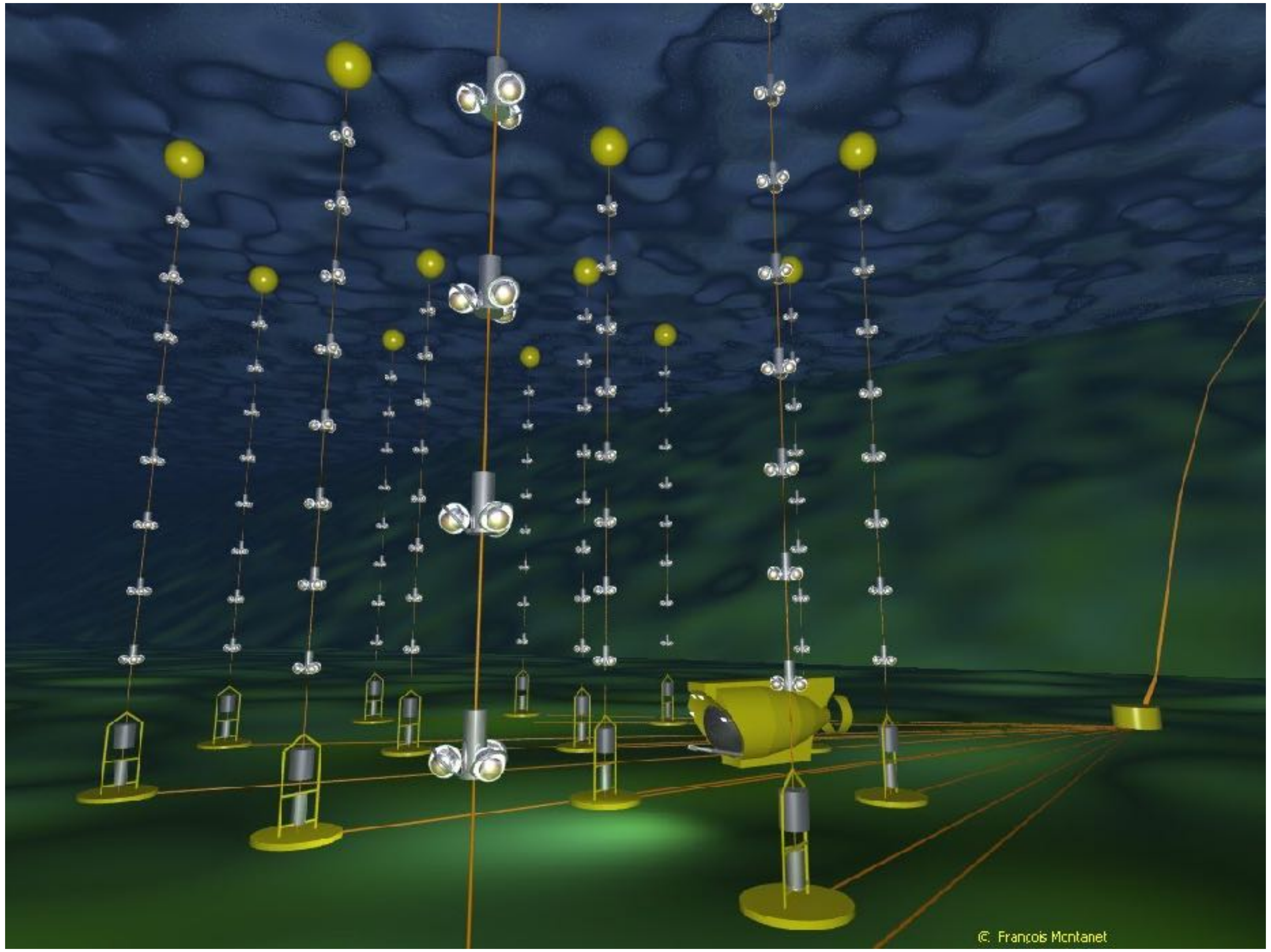
Galactic and extragalactic neutrinos

Because neutrinos are very weakly interacting, neutrino detectors must be very large to detect a significant number of neutrinos. After completion, NESTOR will consist of a large number of glass balls (the "eyes") containing photomultiplier tubes. The "eyes" are connected with star-shaped titanium frames. Many frames compose a NESTOR tower. The whole construction is placed at the bottom of the sea to reduce noise from cosmic radiation (depth 4000m). The detectors are connected with the terminal station through a 31-km-long deep-sea, optic fiber cable for data collection.

https://www.europarl.europa.eu/topics/en/article/20140327STO40046/nestor-unravelling-the-universe-s-mysteries-from-the-bottom-of-the-sea

Galactic and extragalactic neutrinos

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch project) is a neutrino detector residing **2.5 km under the Mediterranean Sea off the coast of Toulon, France**. It is designed to be used as a directional neutrino telescope to locate and observe neutrino flux from cosmic origins in the **direction of the Southern Hemisphere** of the Earth, a complement to IceCube.
The data taking of ANTARES was finished in February 2022, after **16 years of continuous operation**.



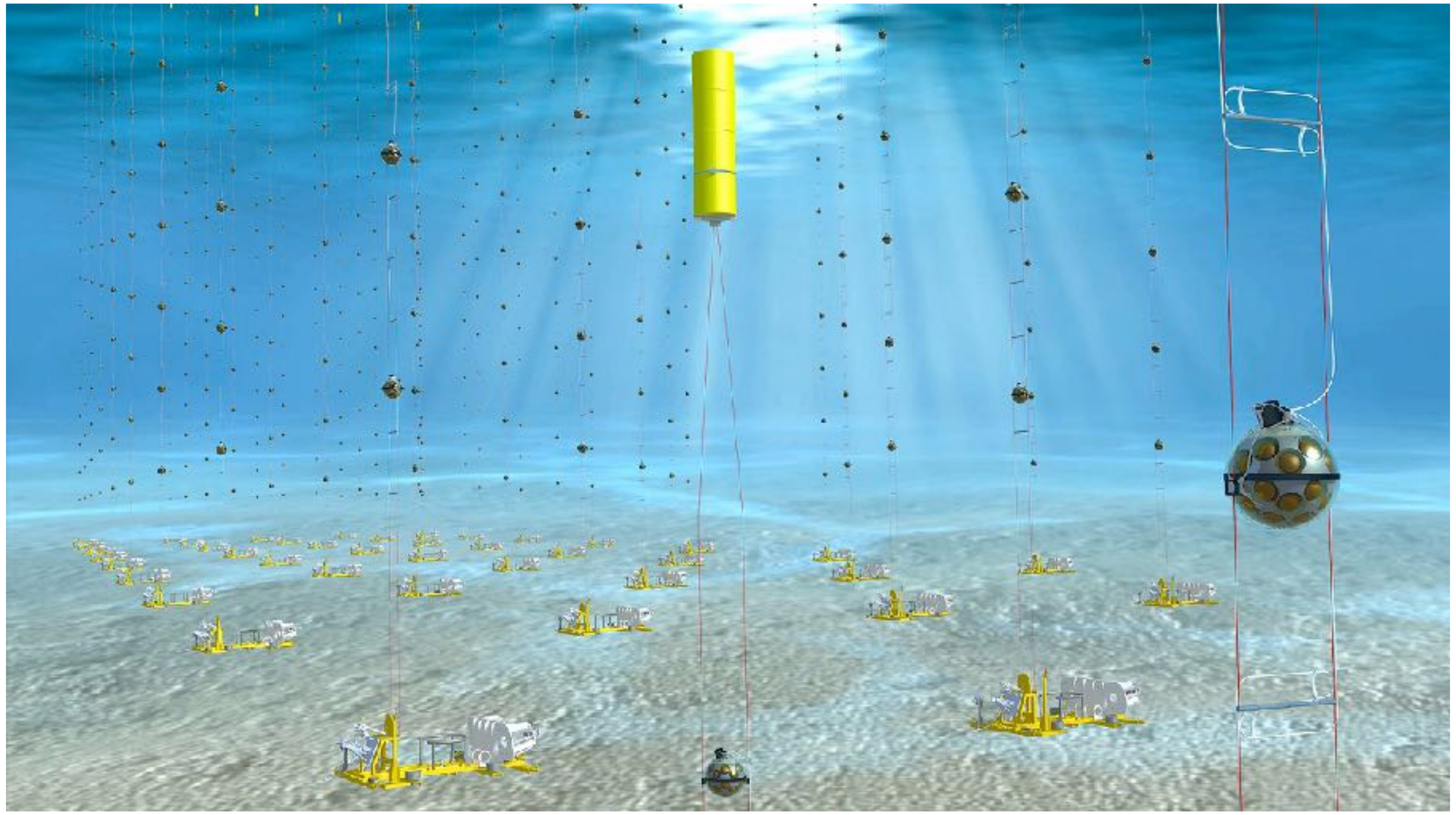
https://en.wikipedia.org/wiki/ANTARES_(telescope)

KM3NeT

The **Cubic Kilometre Neutrino Telescope**, or **KM3NeT**, is a European research infrastructure located at the bottom of the Mediterranean Sea. It hosts the next-generation neutrino telescope with water Cherenkov detectors.

When completed, KM3NeT will have a total instrumented volume of several cubic kilometres distributed over three locations in the Mediterranean: KM3NeT-Fr (offshore Toulon, France), KM3NeT-It (offshore Portopalo di Capo Passero, Sicily, Italy) and KM3NeT-Gr (offshore Pylos, Peloponnese, Greece).

The KM3NeT project continues the work done for the neutrino telescope ANTARES operated offshore the coast of France between 2008 and 2022.



https://en.wikipedia.org/wiki/KM3NeT

Galactic and extragalactic neutrinos

It is generally assumed that **binaries** are good candidates for the production of energetic neutrinos. A binary consisting of a pulsar and a normal star could represent a strong neutrino source (Fig. 6.31).

The pulsar and the star rotate around their common center of mass. If the stellar mass is large compared to the pulsar mass, one can assume that the pulsar orbits the companion star on a circle.

There are models, which suggest that the **pulsar can manage to accelerate protons to very high energies.** These accelerated protons **collide with the gas of the atmosphere of the companion star** and produce predominantly **secondary pions** in the interactions. The neutral pions **decay relatively fast** ($\tau_{\pi^0} = 8.4 \times 10^{-17}$ s) into two energetic γ rays, which would allow to locate the astronomical object in the light of γ **rays.**

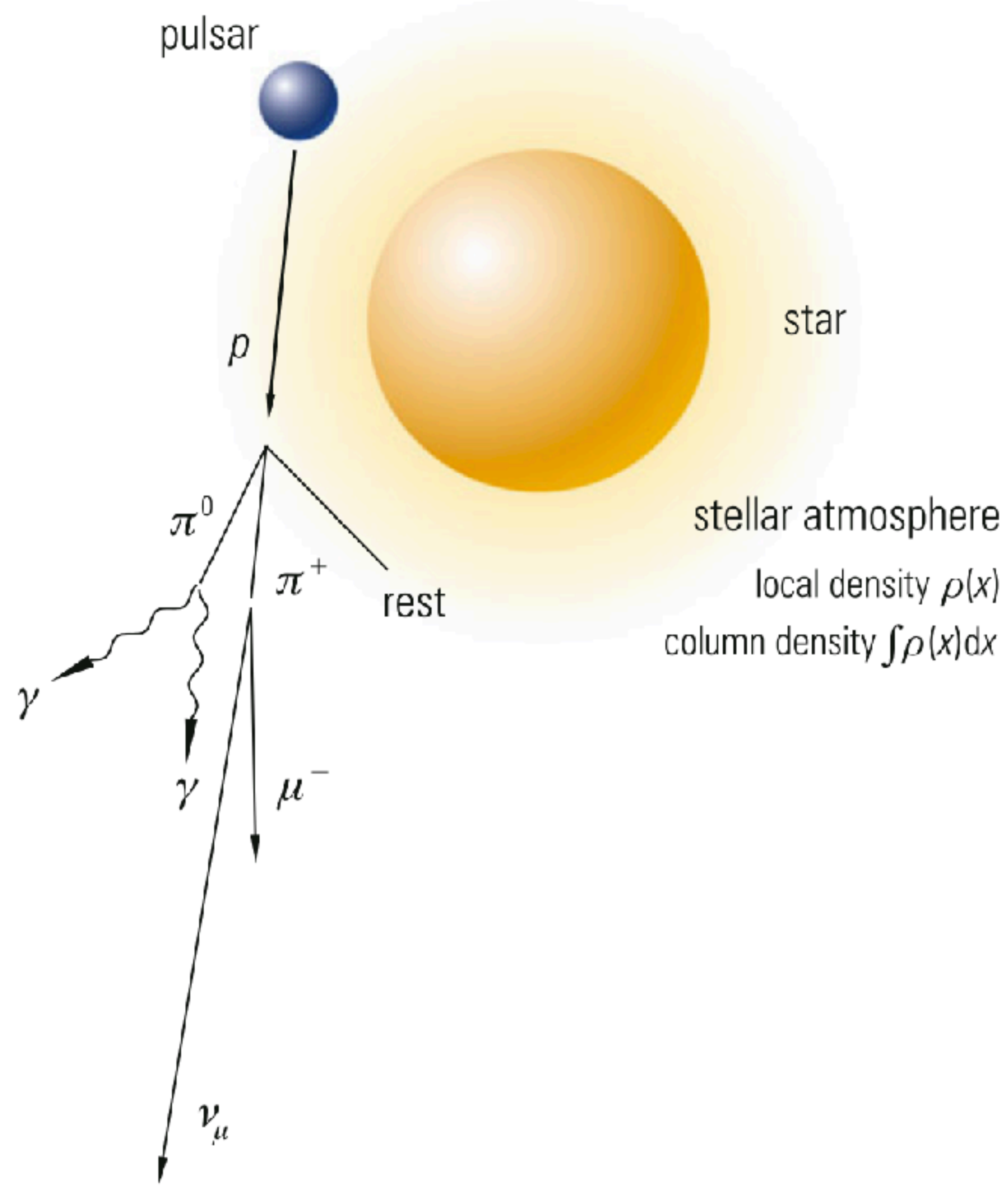
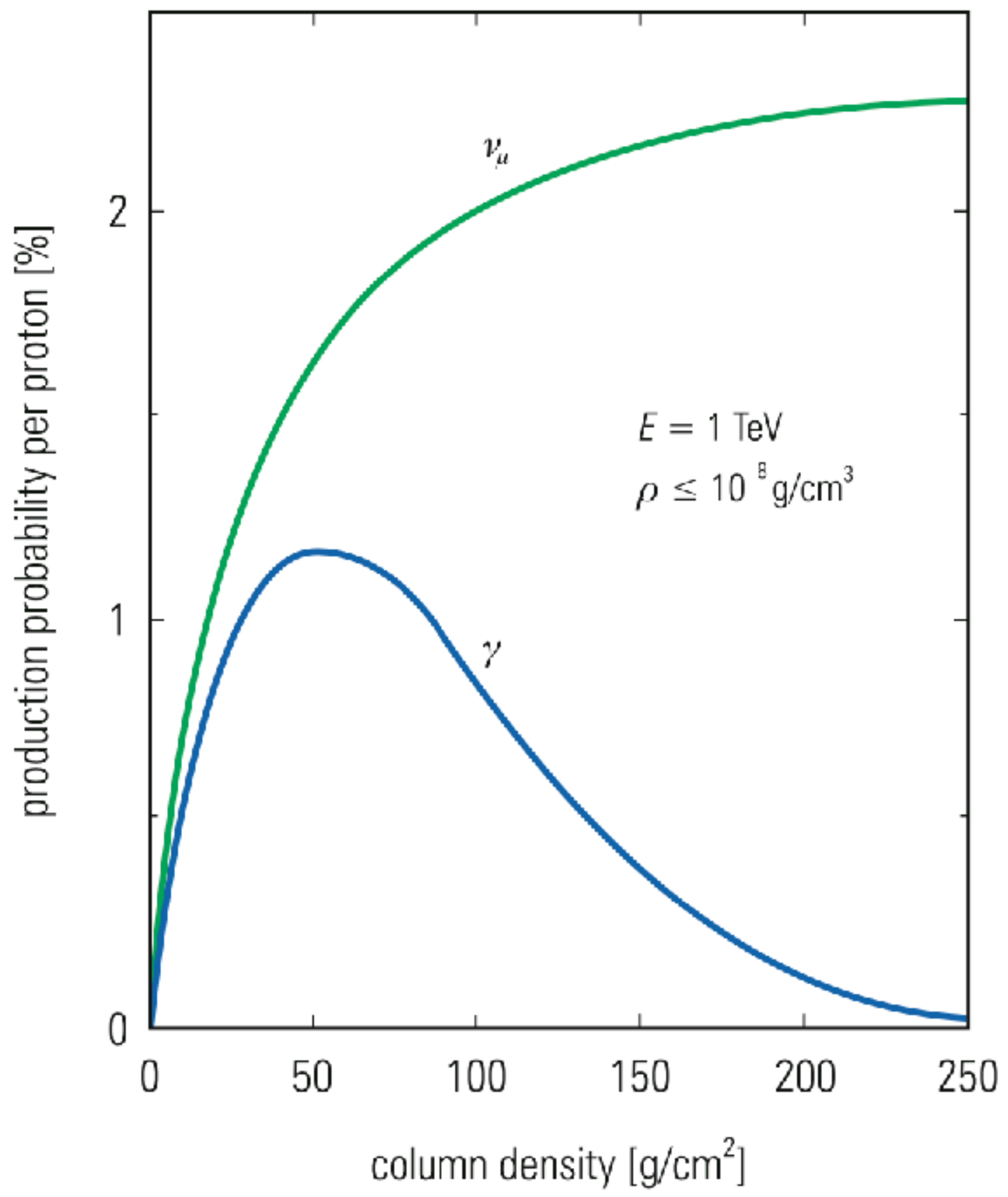


Fig. 6.31 Production mechanism of high-energy neutrinos in a binary

Galactic and extragalactic neutrinos

Fig. 6.32 Competition between production and absorption of photons and neutrinos in a binary system [75]



The charged pions **produce energetic neutrinos** by their ($\pi \to \mu\nu$) decay. Whether such a source radiates high-energy γ quanta or neutrinos **depends crucially on** subtle **parameters of the stellar atmosphere**.

If pions are produced in a proton interaction such as **equal amounts of neutrinos and photons** would be produced by the decays of charged and neutral pions

$(\pi^+ \to \mu^+ + \nu_\mu, \pi^- \to \mu^- + \bar{\nu}_\mu, \pi^0 \to \gamma + \gamma)$.

With increasing column density of the stellar atmosphere, however, **photons would be re-absorbed,** and for densities of stellar atmospheres of $\rho \leq 10^{-8}$ g/cm^3 and column densities of more than 250 g/cm^2 this source would **only be visible in the light of neutrinos** (Fig. 6.32).

Galactic and extragalactic neutrinos

The source would **shine predominantly in muon neutrinos** (ν_μ or $\bar{\nu}_\mu$). These neutrinos can be recorded in a detector via the weak charged current, in which they produce muons (Fig. 6.33).

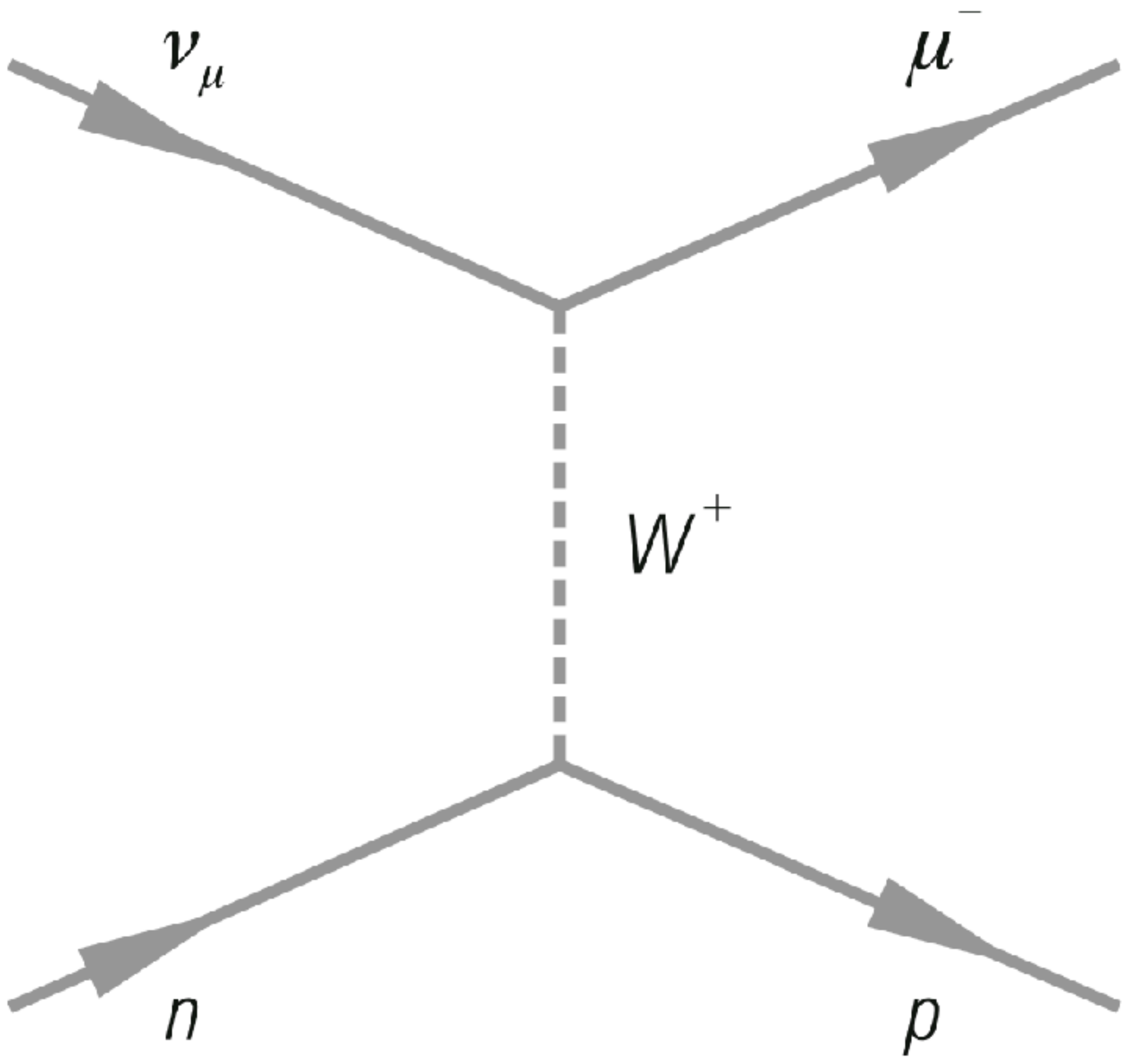


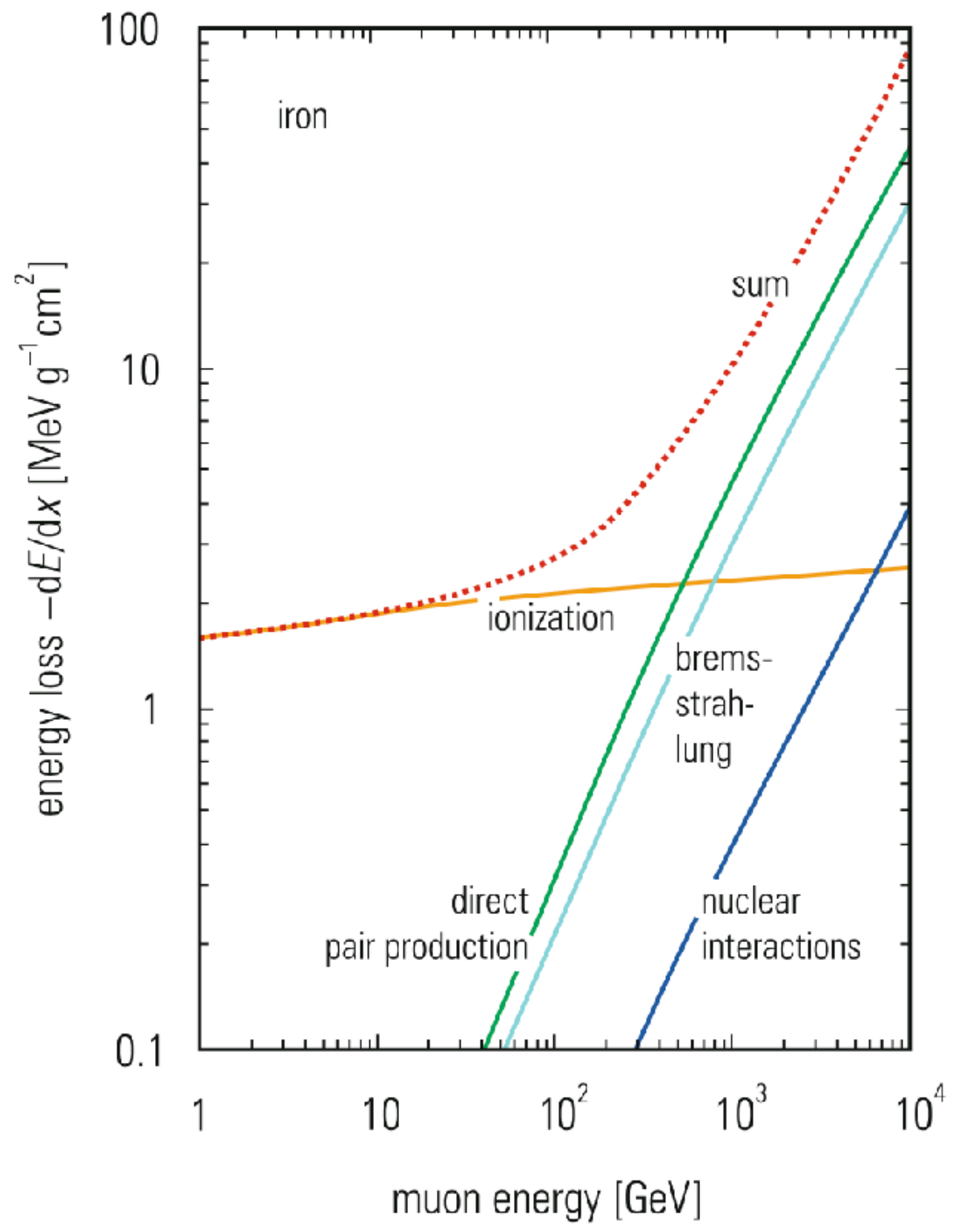
Fig. 6.33 Reaction for muon-neutrino detection

Galactic and extragalactic neutrinos

Muons created in these interactions follow essentially the **direction of the incident neutrinos.** The energy of the muon is measured by its energy loss in the detector.

For energies exceeding the TeV range, muon bremsstrahlung and direct electron pair production by muons dominate. The energy loss by these two processes is proportional to the muon energy and therefore allows a **calorimetric determination of the muon energy** (compare Sect. 7.3, Fig. 7.17).

Fig. 7.17 Contributions to the energy loss of muons in iron



Galactic and extragalactic neutrinos

Because of the low interaction probability of neutrinos and the small neutrino fluxes, **neutrino detectors must be very large and massive**. Since the whole detector volume has to be instrumented to be able to record the interactions of neutrinos and the energy loss of muons, it is necessary to construct a **simple, cost-effective detector.**

The only practicable candidates, which meet this condition, are **huge water or ice Cherenkov counters**.

Because of the **extremely high transparency of ice at large depths in Antarctica** and the relatively simple instrumentation of the ice, ice Cherenkov counters are presently the most favourable choice for a realistic neutrino telescope.

To protect the detector against the relatively high flux of atmospheric particles, it has become common practice to use the Earth as an absorber and concentrate on neutrinos, which enter the detector 'from below'.

The principle of such a setup is sketched in Fig. 6.34.

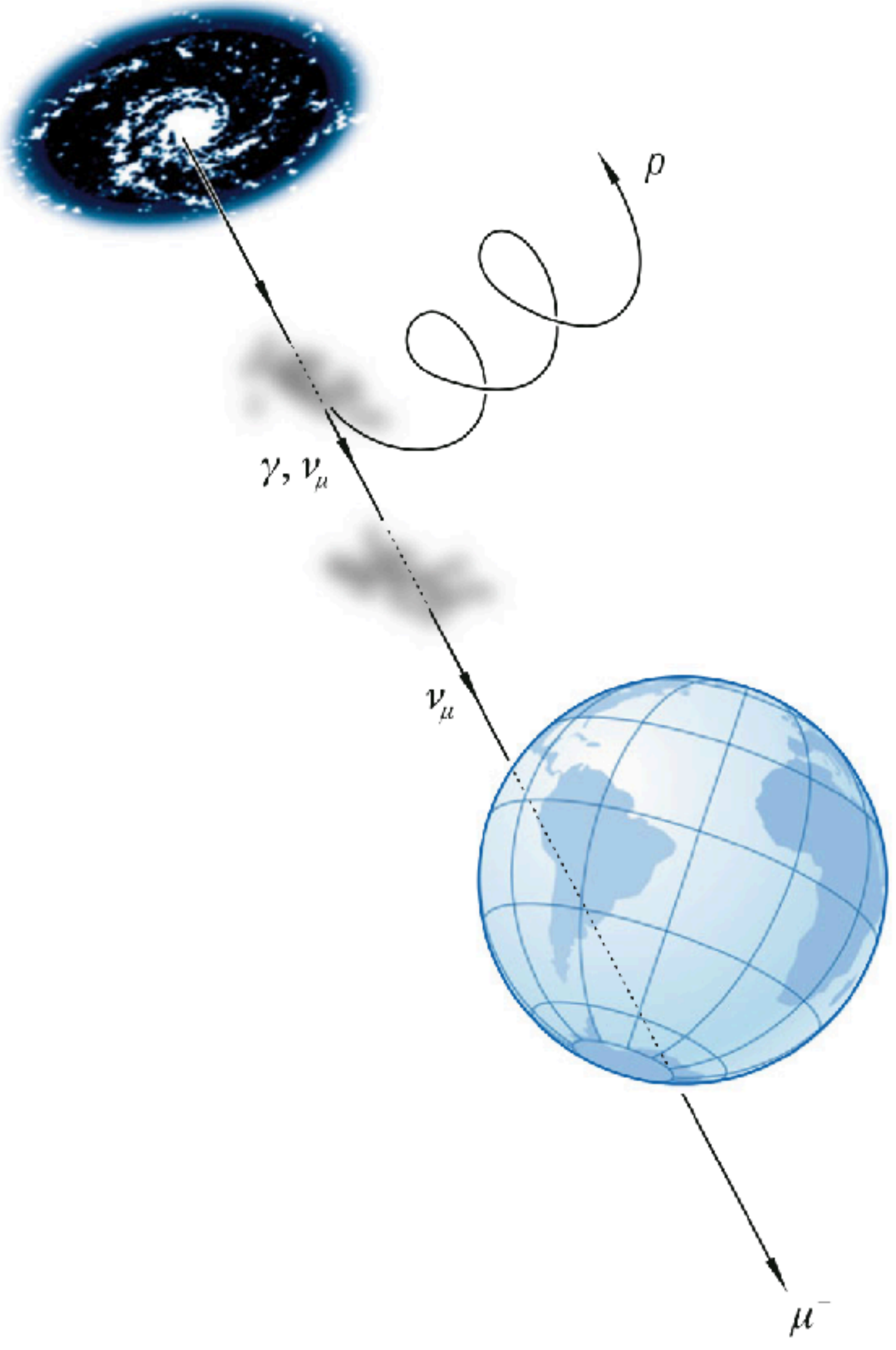


Fig. 6.34 Neutrino production, propagation in intergalactic space, and detection at Earth

Galactic and extragalactic neutrinos

In general: **Protons** from cosmic-ray sources **produce pions on a target** (e.g., stellar atmosphere, galactic medium), which **provide neutrinos and γ** in their decay.

Photons are frequently absorbed in the galactic medium or disappear in $\gamma\gamma$ interactions with blackbody photons, infrared radiation, or starlight photons. The **remaining neutrinos traverse the Earth** and are detected in an underground detector.

The neutrino **detector** itself **consists of a large array of photomultipliers that record the Cherenkov light of muons produced in ice** (or in water). In such neutrino detectors the **photomultipliers have to be mounted in a suitable distance on strings and many of such strings will be deployed in ice (or water)**.

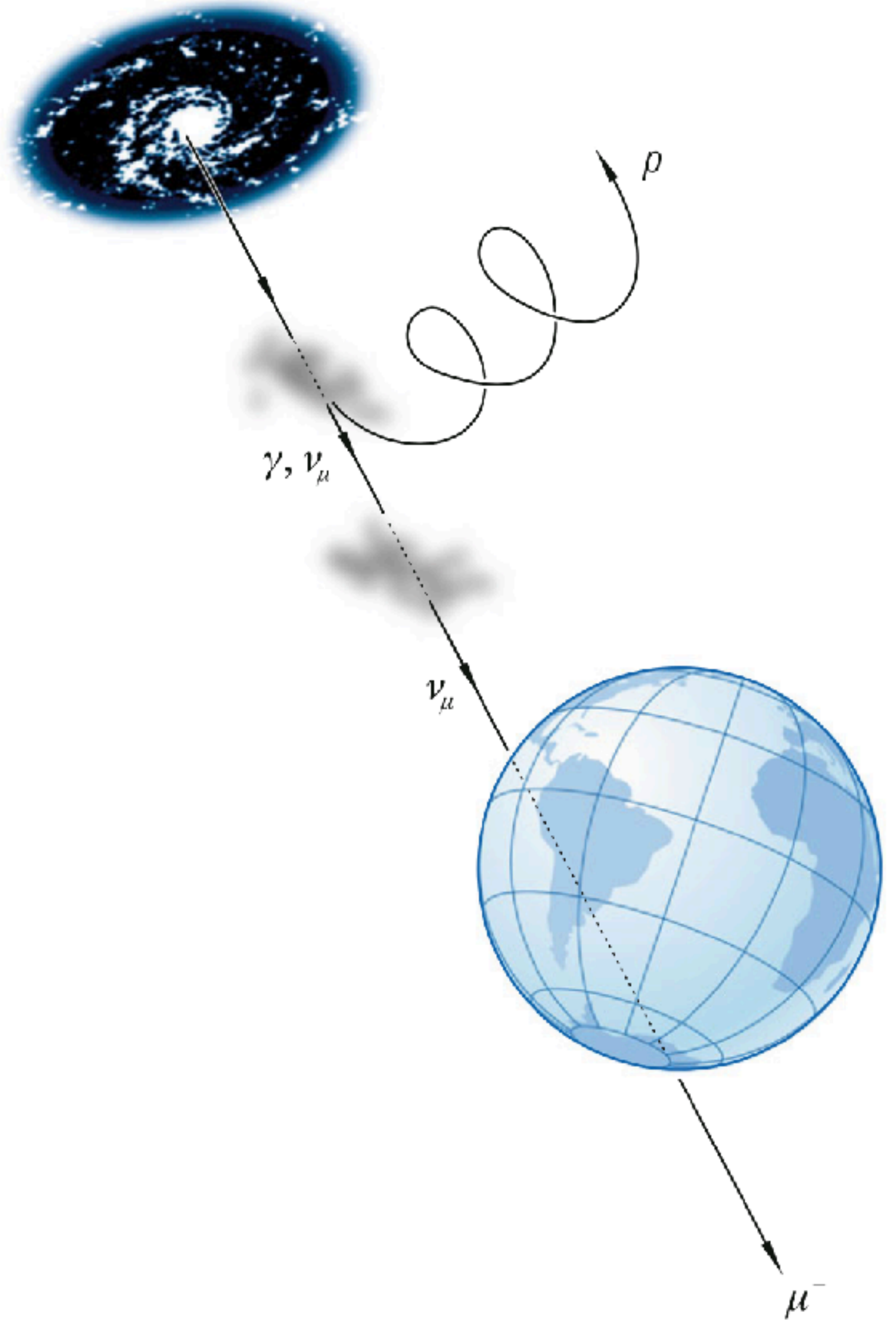


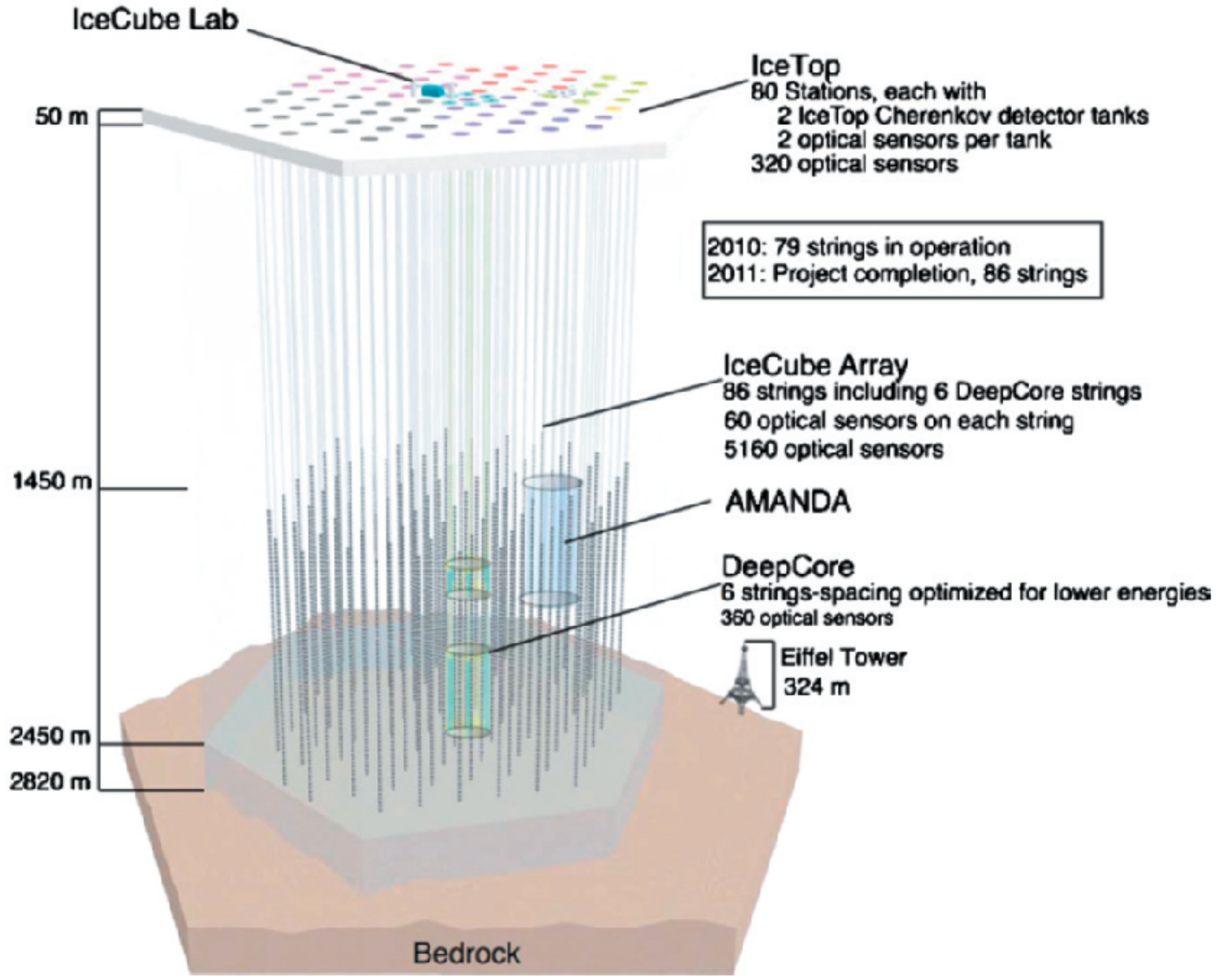
Fig. 6.34 Neutrino production, propagation in intergalactic space, and detection at Earth

Galactic and extragalactic neutrinos

The mutual distance of the photomultipliers on the strings and the string spacing depends on the absorption and scattering length of Cherenkov light in the detector medium.

The installation of photomultiplier strings at a depth of 1000 m in AMANDA had shown that the **ice was not free from bubbles.**

Only at **depth of more than 1500 m** the pressure (≥150 bar) is sufficient to make the **bubbles disappear,** thereby providing **excellent transparency** with absorption lengths of 300 m.



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

Galactic and extragalactic neutrinos

The **direction of incidence of neutrinos can be inferred from the arrival times of the Cherenkov light at the photomultipliers**.

In a **water Cherenkov counter in the ocean bioluminescence and potassium-40 activity presents an additional background,** which is not present in ice. In practical applications it became obvious that the installation of photomultiplier strings in the antarctic ice is much less problematic compared to the deployment in the ocean.

Figure 6.35 shows the ICECUBE detector at the South Pole.

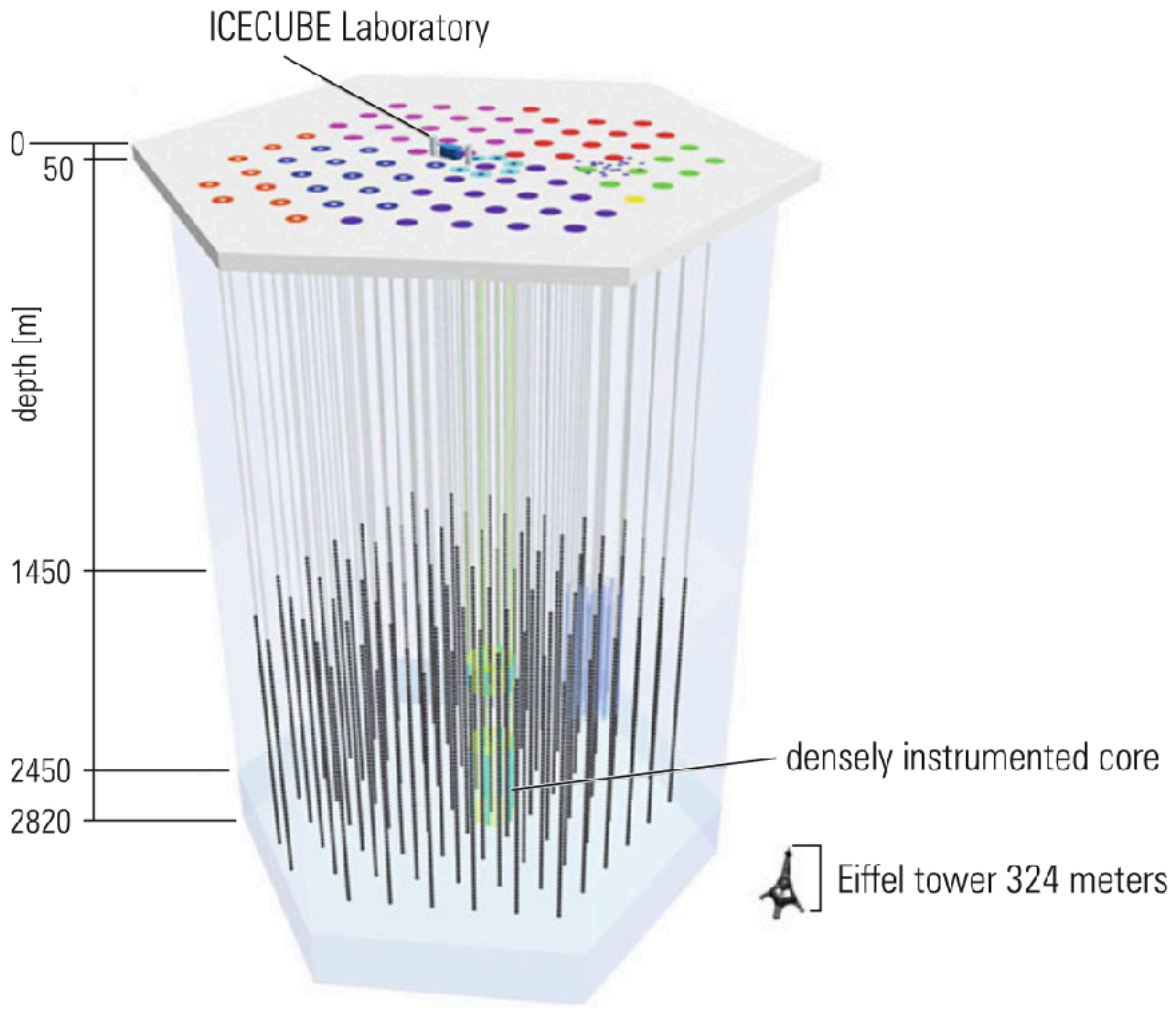


Fig. 6.35 Setup of the ICECUBE experiments at the South Pole [76]

Galactic and extragalactic neutrinos

Presently, **the ICECUBE detector is the largest neutrino telescope**.

It has an instrumented volume of one cubic kilometer. It extends to a depth of 2820m **under the antarctic ice shield.**

The experiment is complemented by a **surface detector IceTop, a radio array, and a denser instrumented DeepCore**.

ICECUBE has 86 strings with approximately 5500 digital optical modules. Figure 6.36 shows an energetic muon in ICECUBE.

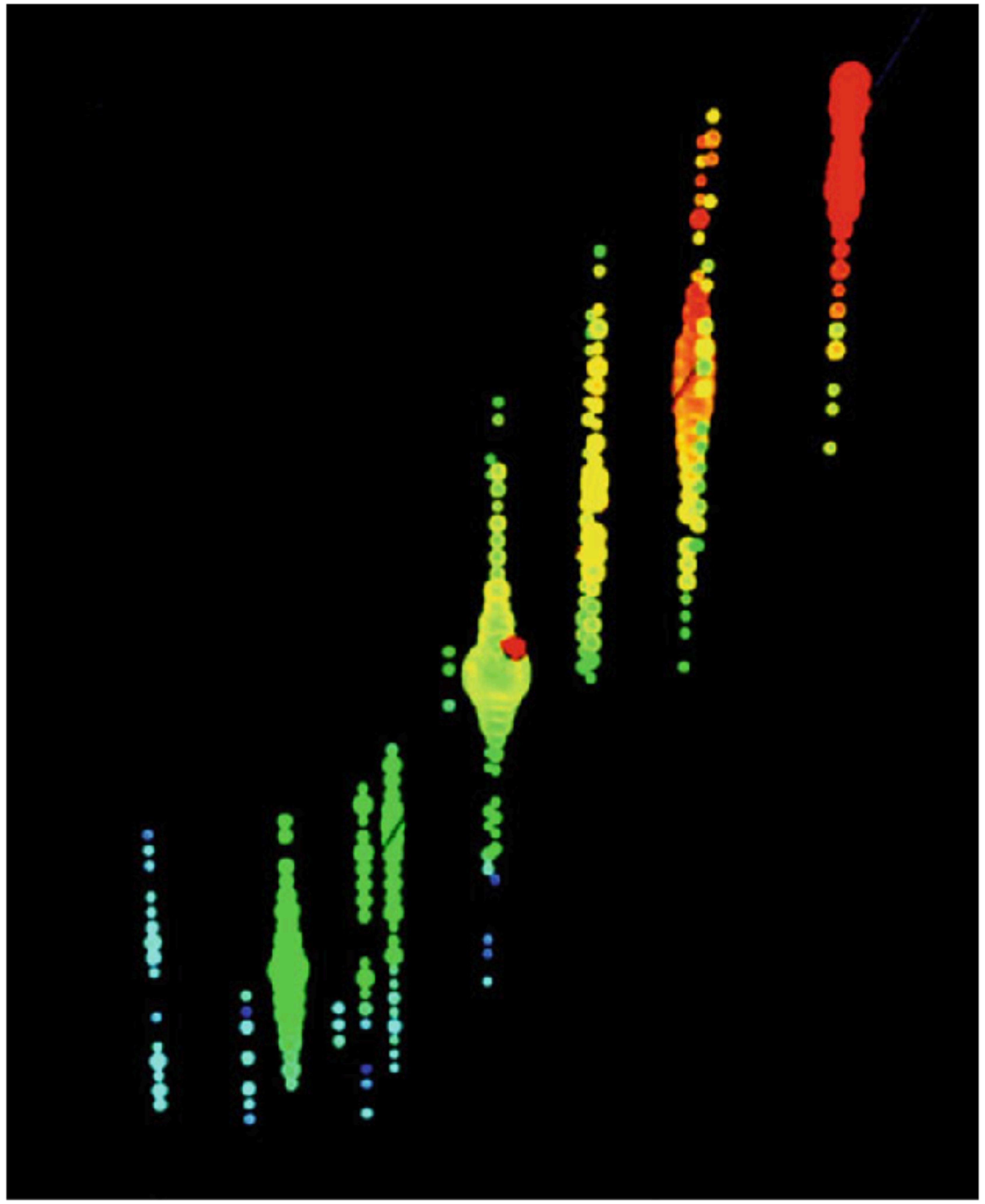
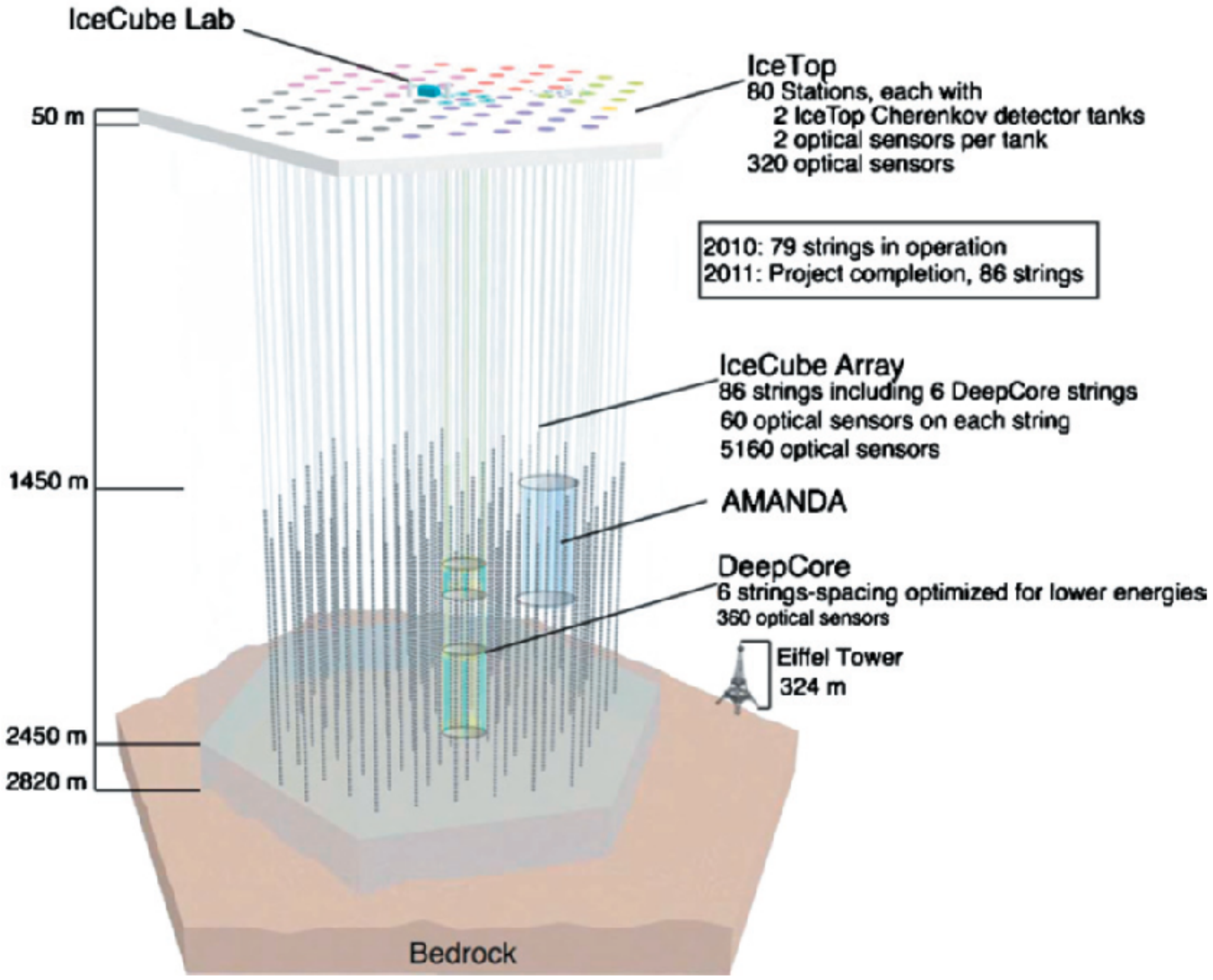


Fig. 6.36 Track of a muon, which has been produced in ICECUBE by a high-energy cosmic muon neutrino [76]

ICE CUBE

- **The IceCube detector is one cubic kilometer of ice.**
- IceCube is comprised of **86 cables, each holding 60 digital optical modules (DOMs).**
- Each of the 86 cables has a theme, and each DOM has a name that reflects that theme.
- The 5,160 in-ice DOMs hold extremely sensitive light detectors, or **photomultiplier tubes**, along with minicomputers that relay data to the surface. An additional **324 DOMs make up a surface detector called IceTop.**
- DOMs are attached to the cables beginning at a **depth of 1,450 meter and ending at a depth of 2,450 meters.**
- IceCube is frozen in optically clear ice that is very stable. **The ice at the South Pole moves about 10 meters per year as single piece.**

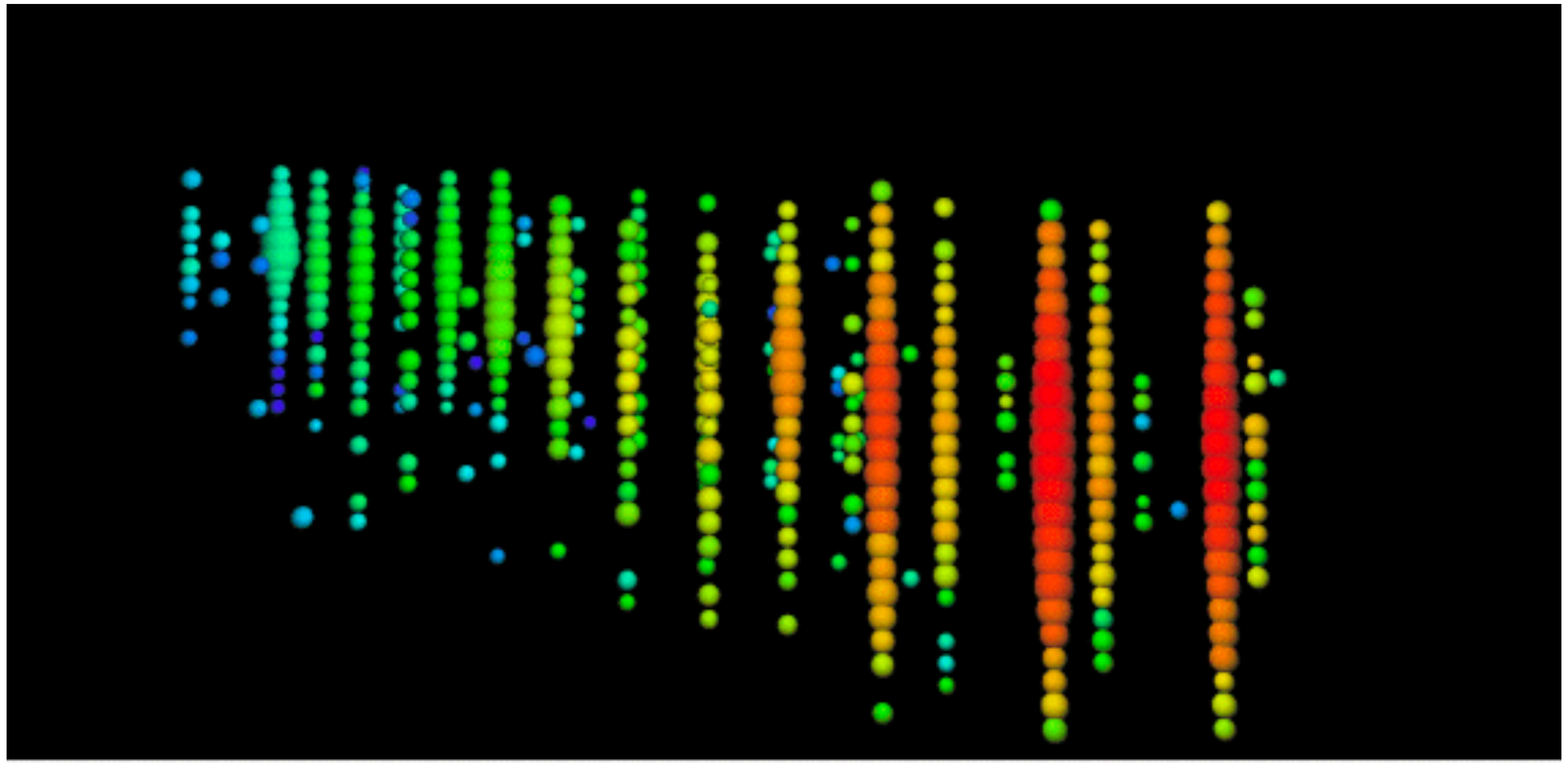


https://en.wikipedia.org/wiki/Neutrino_astronomy

https://icecube.wisc.edu/science/research/

ICE CUBE

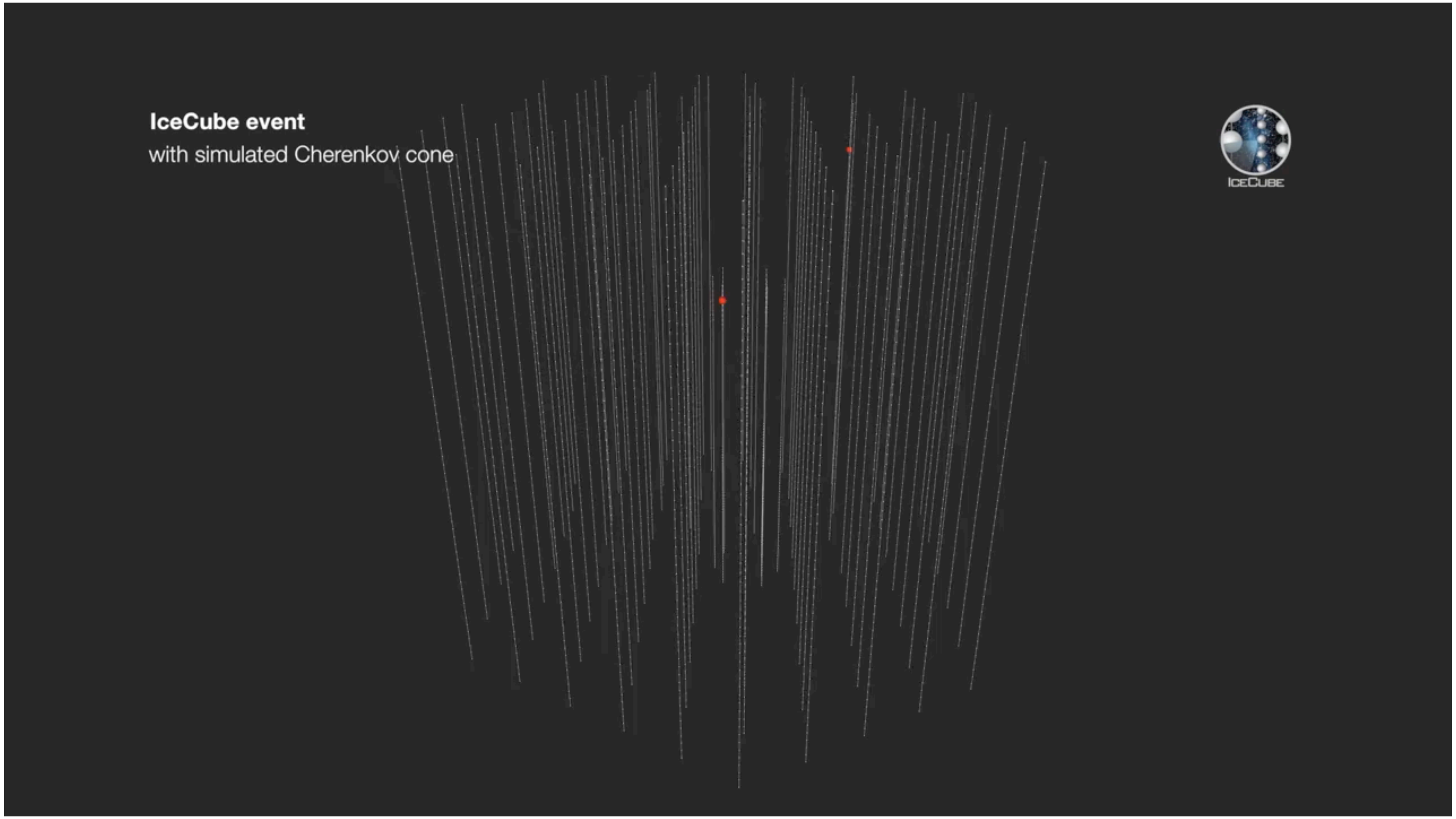
- About 100 trillion neutrinos pass through your body each second.
- You would have to wait **about 100 years for a neutrino to interact in a detector the size of a person**. For the energy range that IceCube looks at, it would take 100,000 years to see a neutrino interact.
- IceCube is designed to detect particles from cataclysmic events that have energies a million times greater than nuclear reactions.
- **IceCube detects 275 atmospheric neutrinos daily** and about 100,000 per year.
- About 350 scientists at 59 institutions in 14 countries conduct IceCube science (as of November 2023).
- **One terabyte of unfiltered data is collected daily** and about 100 gigabytes are sent over satellite for analysis.



IceCube real-time alert IC170922A was a **muon neutrino with an estimated energy of 290 TeV**. It pointed within 0.06 degrees at the **active galaxy TXS0506+06** located four billion light-years from Earth.

https://icecube.wisc.edu/science/research/

ICE CUBE

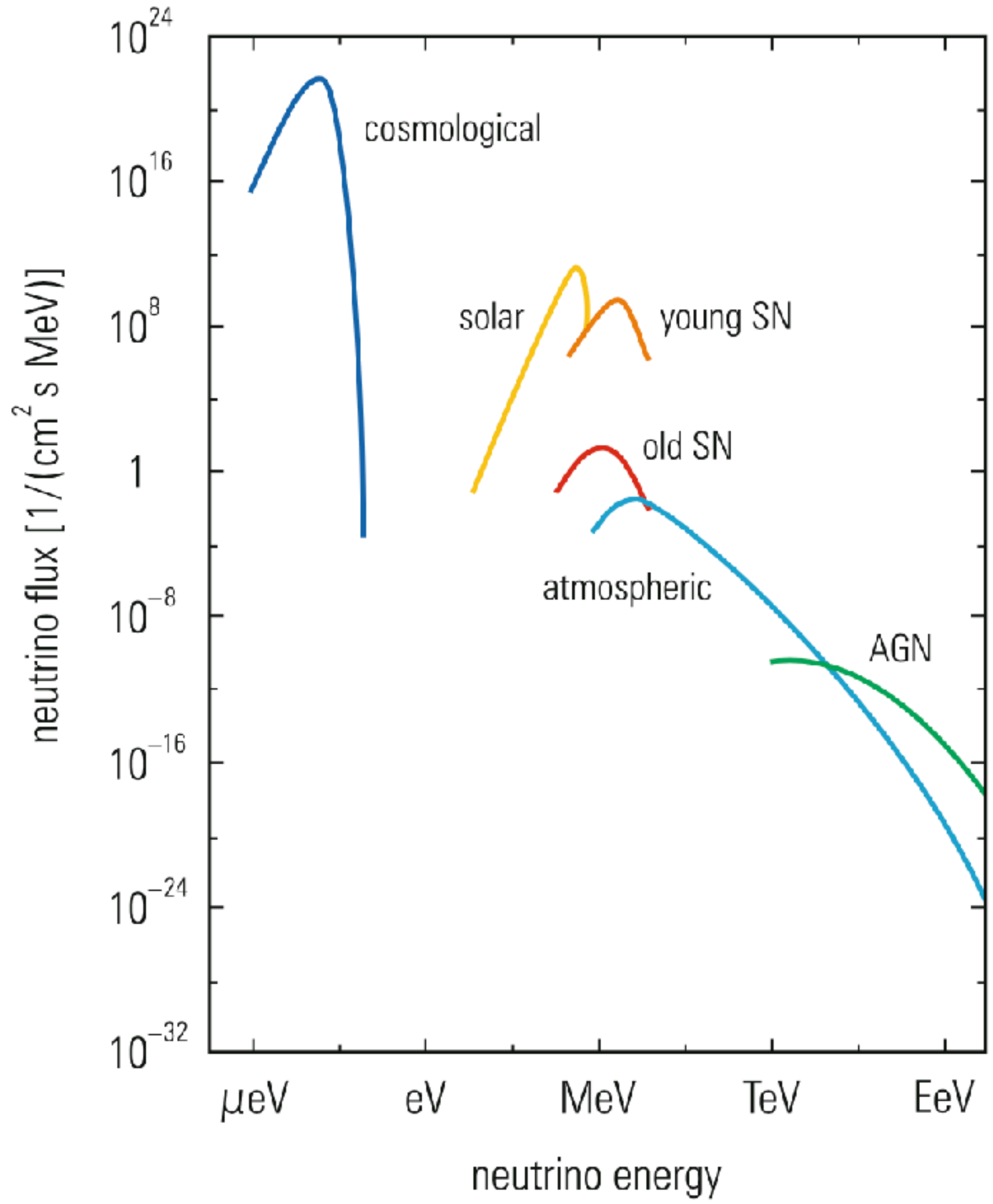


IceCube detects high-energy neutrinos using the Cherenkov light produced by relativistic charged particles that result from the interaction of these neutrinos with a nucleus of Antarctic ice. The highest energy neutrinos detected to date are included in this video, which also shows a simulated event and the blue Cherenkov cone.

https://icecube.wisc.edu/science/research/

Galactic and extragalactic neutrinos

Fig. 6.30 Comparison of different neutrino fluxes in different energy domains [74]



To measure the low **fluxes of extragalactic neutrinos** an instrumented volume of at least 1 km^3 is needed. A s**hort estimation** is in order to show this.

It is considered realistic that a point source in our galaxy produces a neutrino spectrum according to

$$\frac{dN}{dE_\nu} = 2 \times 10^{-11} \frac{100}{E_\nu^2\,[\mathrm{TeV}^2]} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

This leads to an **integral flux of neutrinos** of

$$\Phi_\nu(E_\nu > 100\,\mathrm{TeV}) = 2 \times 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Galactic and extragalactic neutrinos

The interaction **cross section of high-energy neutrinos** was measured at accelerators to be

$$\sigma(\nu_\mu N) = 6.7 \times 10^{-39}\ E_\nu\ [\mathrm{GeV}]\ \mathrm{cm}^2/\mathrm{nucleon}$$

If this linear dependence is valid up to high energies, one would arrive at a cross section of 6.7×10^{-34} cm^2/nucleon for 100-TeV neutrinos. For a target thickness of one kilometer an **interaction probability *W* per neutrino of**

$$W = N_\mathrm{A}\, \sigma\, d\, \varrho = 4 \times 10^{-5}$$

is obtained ($d = 1$ km $= 10^5$ cm, ϱ(ice) ≈ 1 g/cm^3).

The total interaction rate R is obtained from the integral neutrino flux Φ_ν , the interaction probability W, the effective collection area $A_\mathrm{eff} = 1\mathrm{km}^2$, and a measurement time t. This leads to an **event rate** of

$$R = \Phi_\nu\, W\, A_\mathrm{eff}$$

corresponding to 250 events per year.

Galactic and extragalactic neutrinos

For large absorption lengths of the produced Cherenkov light the effective collection area of the detector is even larger than the cross section of the instrumented volume. Assuming that there are about half a dozen sources in our galaxy, the preceding estimate would lead to a **counting rate of about four events per day.**

In addition to this rate from point sources one would also **expect to observe events from the diffuse neutrino background** that, however, carries little astrophysical information.

Excellent candidates within our galaxy are the **supernova remnants** of the Crab Nebula and Vela, the galactic center, and Cygnus X3. **Extragalactic candidates** could be represented by the Markarian galaxies Mrk 421 and Mrk 501, by M87, or by **quasars** (e.g., 3C273).

Galactic and extragalactic neutrinos

ICECUBE has already measured a large number of neutrino events of astrophysical interest.

Figure 6.37 shows a **high-energy event**, which was presumably initiated by an **electron neutrino**.

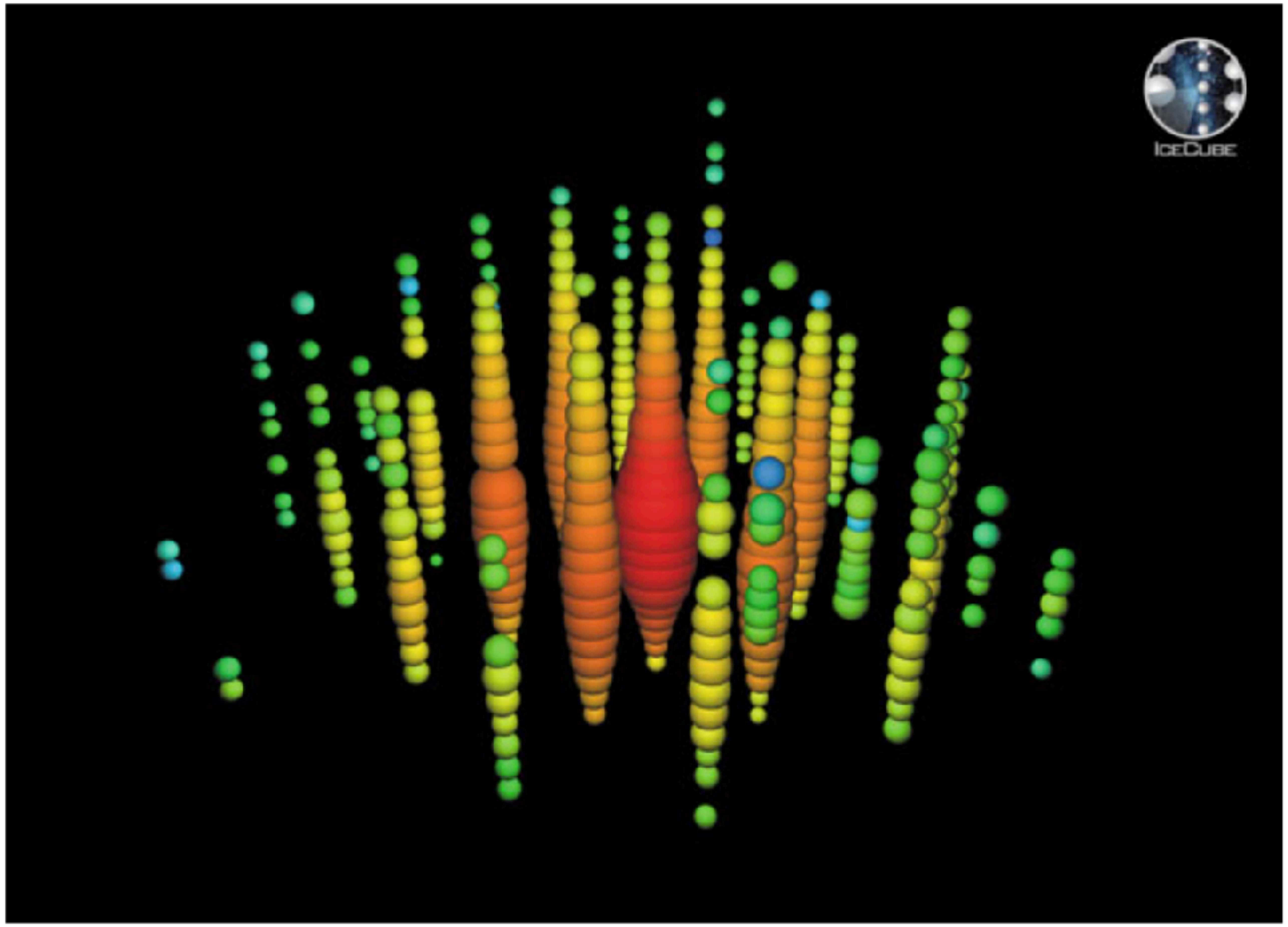


Fig. 6.37 High-energy event in the ICECUBE detector, presumably induced by an electron neutrino. The energy of this event is 1.14 PeV. The event pattern also shows the difficulty to determine the direction of incidence of the original neutrino [76]

Galactic and extragalactic neutrinos

Figure 6.38 is a sky map showing the **arrival directions of cosmic neutrinos.**

There is no clear clustering of events, even though there are some events pointing back to the **galactic center.**

However, one has to consider that the angular resolution, i.e., the **pointing accuracy** for events generated by electron neutrinos, which produce electromagnetic showers in the detector, is only **moderate**.

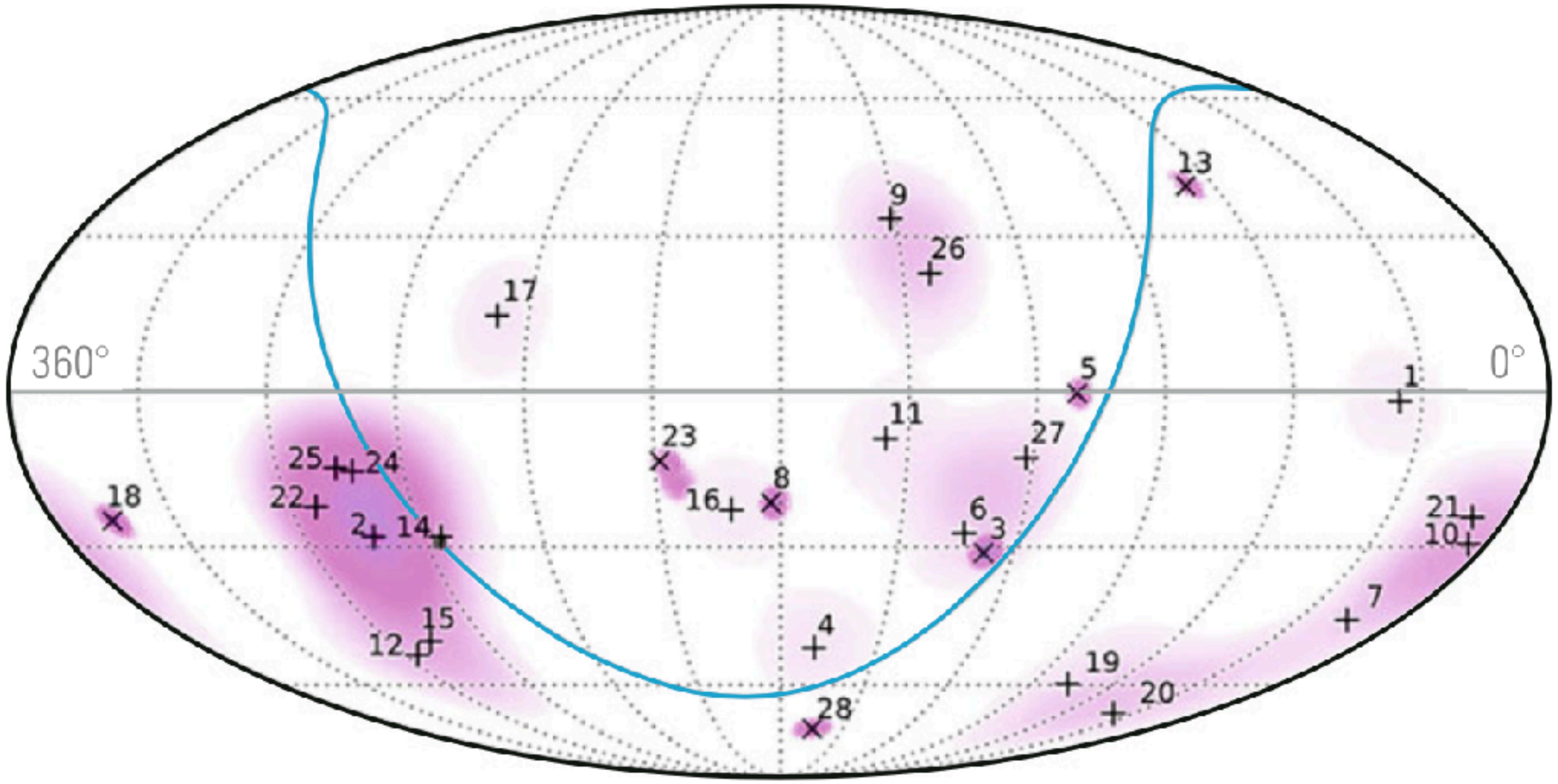


Fig. 6.38 Sky map of neutrino events in ICECUBE in equatorial coordinates. The *blue line* is the galactic plane. The galactic center is close to the event with the number 14. ν_μ-like events (with a detected muon) are flagged with '×' and ν_e-like events (with an electron shower) with '+' [76]

Galactic and extragalactic neutrinos

In September 2017 ICECUBE recorded an **energetic neutrino of 290TeV** (2.9×10^{14} eV), which was coincident in **time and direction with an energetic gamma-ray flare** observed by the Fermi satellite, where the signal pointed to a known **blazar (TXS 0506+056)** in the northern sky (see Fig. 6.39).

The distance of the source was estimated to be about four billion light-years. Gamma rays with energies up to 400 GeV from this source were **also observed by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes**.

This neutrino event from ICECUBE was the first observation of a hadronic cosmic accelerator.

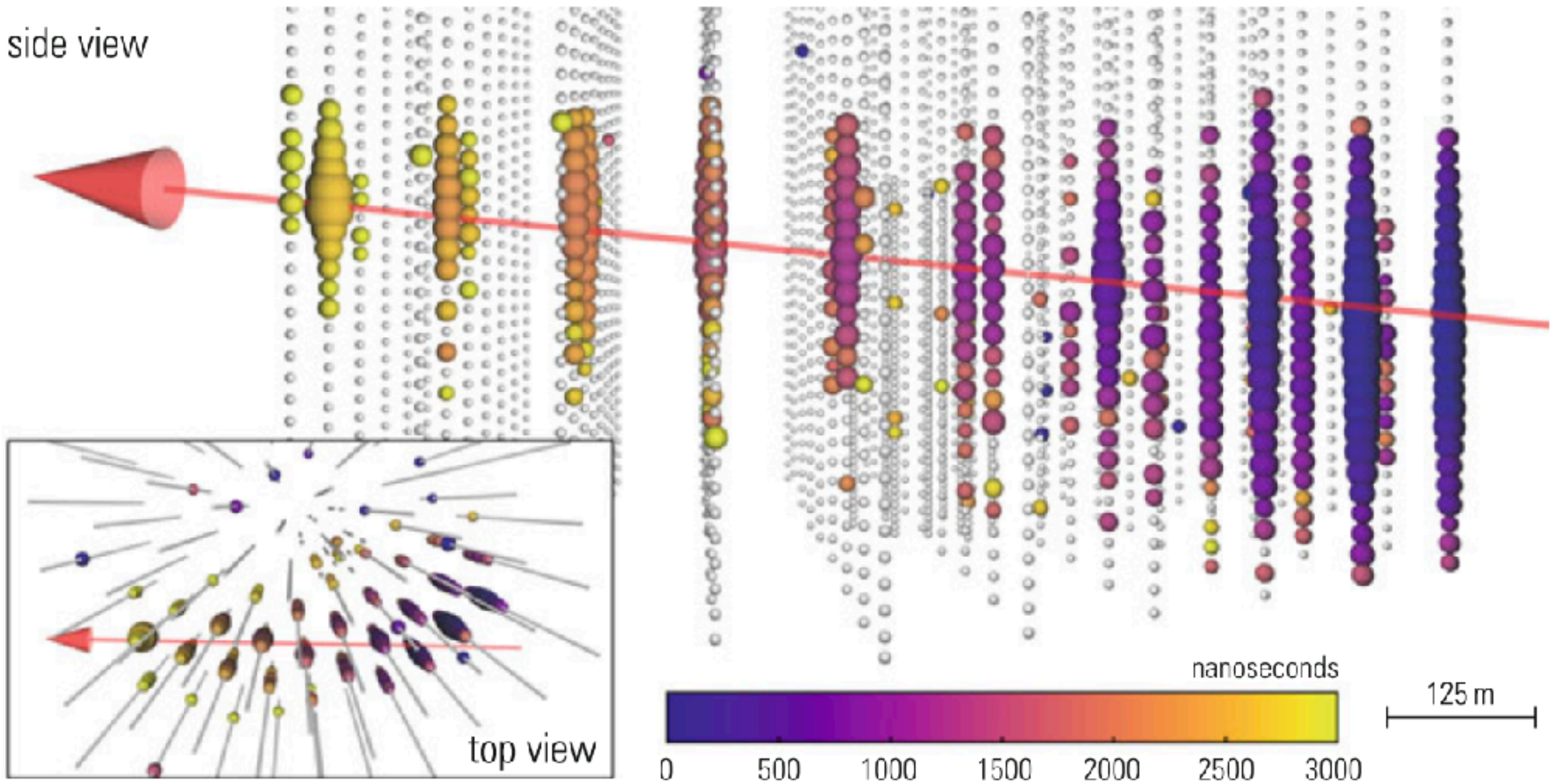


Fig. 6.39 Event display for neutrino event IceCube-170922A coincident in time and direction with an energetic gamma-ray flare observed by the Fermi satellite and the MAGIC telescope from the blazar TXS 0506+056 [77]. The high-energy neutrino (≈300 TeV) enters from below from the right-hand side and produces a muon that initiates a large shower

Galactic and extragalactic neutrinos

These successes demonstrate that ICECUBE can provide excellent results to neutrino astrophysics. To obtain better statistics an extension of ICECUBE to an instrumented volume of 10 km^3 is planned (ICECUBE-Gen2).

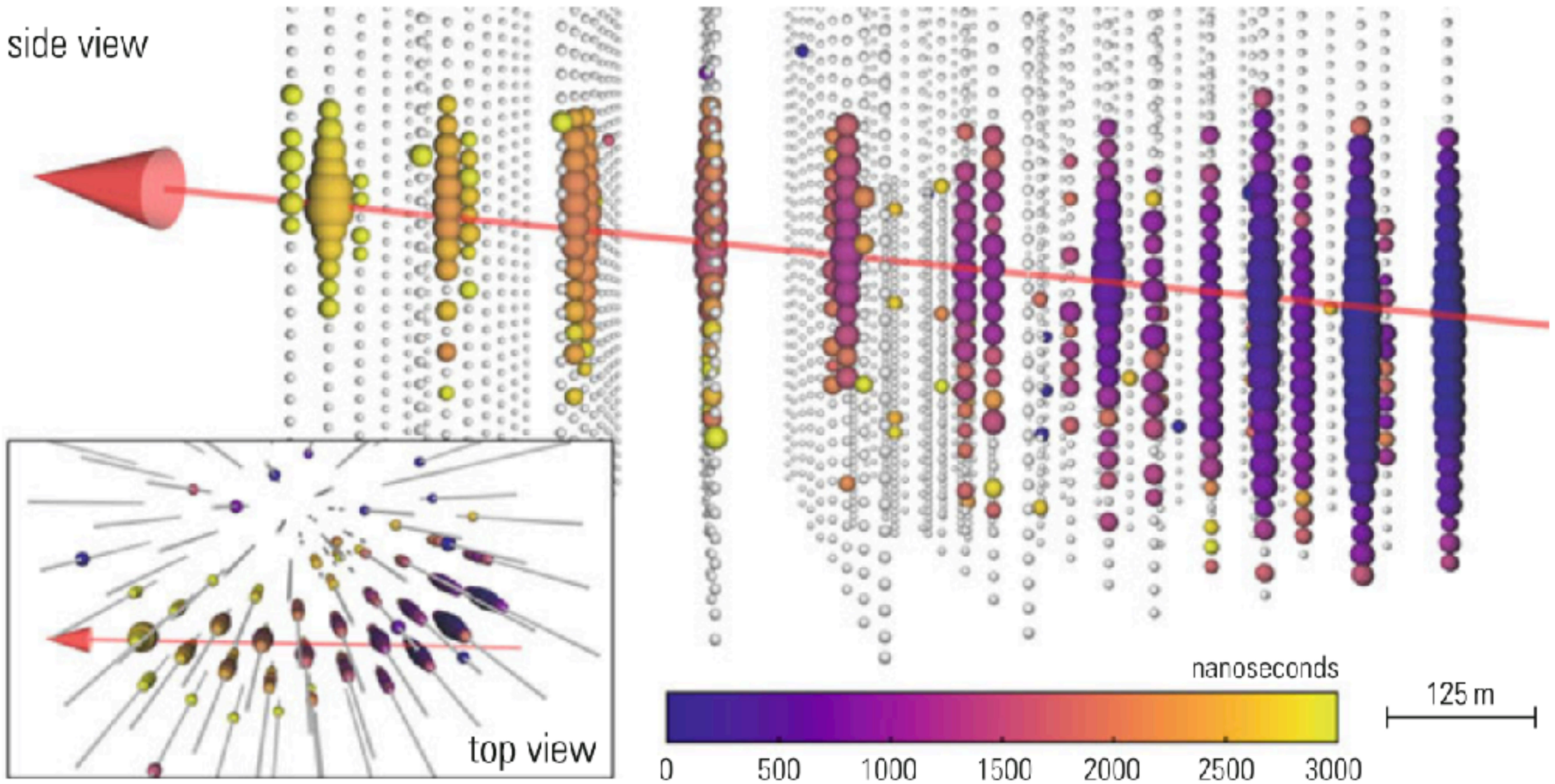


Fig. 6.39 Event display for neutrino event IceCube-170922A coincident in time and direction with an energetic gamma-ray flare observed by the Fermi satellite and the MAGIC telescope from the blazar TXS 0506+056 [77]. The high-energy neutrino (≈300 TeV) enters from below from the right-hand side and produces a muon that initiates a large shower

ICE CUBE

Also surprising is the fact that, unlike the case for observations of electromagnetic radiation of any wavelength, the neutrino sky map is not dominated by nearby sources in our own galaxy. **Powerful extragalactic sources outshine the neutrino sources in the Milky Way.** This galactic flux has recently been observed by IceCube at the level of 10% of the extragalactic flux.

After having collected a decade of data with the completed IceCube detector, we searched a high-purity sample of **670,000 muon neutrinos for sources of astrophysical origin**. Their arrival directions reveal the most significant excess, **80 neutrino events of TeV energy, to be within 0.18 degrees of the active galaxy NGC 1068 (M77).** NGC 1068 is also the most significant astrophysical neutrino source identified from a search at the positions of 110 preselected high-energy gamma-ray sources.

Messier 77 is an active galaxy with an active galactic nucleus (AGN)

ICE CUBE

A search for subdominant sources in the sky map reveals evidence for **two more active galaxies, PKS 1424+240 and TXS 0506+056**. TXS 0506+056 had already been identified as a neutrino source from a multimessenger campaign triggered by an IceCube-detected neutrino of 290 TeV energy as well as from the observation in archival IceCube data of an earlier neutrino burst from TXS 0506+056 in 2014-15. The multimessenger campaign involved follow-up observations by gamma-ray, X-ray, and optical telescopes that were triggered by a real-time neutrino alert from IceCube on September 22, 2017.

The data point at the **obscured dense cores near the supermassive black holes of some active galaxies,** typically within **10~100 Schwarzschild radii**, as the site where cosmic rays are accelerated and neutrinos produced. As a result, the gamma rays that inevitably accompany cosmic neutrinos rays lose energy in the obscured core and emerge with MeV energies or below.

For more science highlights from ICE CUBE see: https://icecube.wisc.edu/science/research/

Geoneutrinos

Geoneutrinos are not directly a topic on astroparticle physics. However, the availability of experiments looking for cosmic neutrinos has opened up this new type of research as a byproduct.

Nearly half of the Earth's heat comes from the decay of radioactive isotopes inside. To better understand the sources of the Earth's heat, the **measurement of antineutrinos from the decay of radioactive elements** is a relatively new tool.

Geoneutrinos provide a technique to probe directly the Earth's interior beyond the depth of 12 km, which so far has been achieved by drilling.

The key elements responsible for a major fraction of the heat production are: **^{238}U, ^{232}Th, and ^{40}K,** which lead to a calculated neutrino luminosity of the Earth of 10^6 cm^{-2} s^{-1} corresponding to a **total neutrino flux of 32×10^{24} s^{-1}.**

According to various estimates the decay of these elements generates a **radiogenic heating of about 20TW**, which constitutes about **50% of the total heat power of the Earth**.

Geoneutrinos

The uranium ($^{238}U \rightarrow {}^{206}Pb + 8\ {}^{4}He + 6e^{-} + 6\bar{\nu}_e$) and thorium ($^{232}Th \rightarrow {}^{208}Pb + 6\ {}^{4}He + 4e^{-} + 4\bar{\nu}_e$) decay chains provide electron antineutrinos of about **3MeV** maximum energy.

The potassium decay ($^{40}K \rightarrow {}^{40}Ca + e^{-} + \bar{\nu}_e$) with a branching ratio of 89% only leads to $\bar{\nu}_e$ of maximum energy of **1.3 MeV**.

The flux of antineutrinos from the ^{235}U decay chain is relatively low.

To measure the antineutrinos one uses the inverse-beta-decay reaction $\bar{\nu}_e + p \rightarrow e^{+} + n$.

For this reaction there is a **threshold energy of 1.8 MeV** corresponding to the difference between the rest-mass energies of the neutron plus positron and the proton.

Due to this threshold **antineutrinos from the potassium decay cannot be recorded** in this reaction. However, these neutrinos can be **measured by scattering on electrons.**

Antineutrinos from ^{238}U and ^{232}Th decay are detected by **light signals from positron annihilation and photons from deuteron formation** after $n + p \rightarrow d + \gamma$. These two signals are **coincident in time and space** and provide a powerful tool to reject, e.g., cosmic rays, which would only cause single signals.

It does not, however, veto **reactor antineutrinos,** because they would exhibit the same signature as geoneutrinos.

Geoneutrinos

The first measurement of **geoneutrinos was accomplished by Kamiokande** (2003) and KamLAND (2005) (Kamioka Liquid Scintillator Antineutrino Detector) and later by Borexino (see Figs. 6.40 and 6.41).

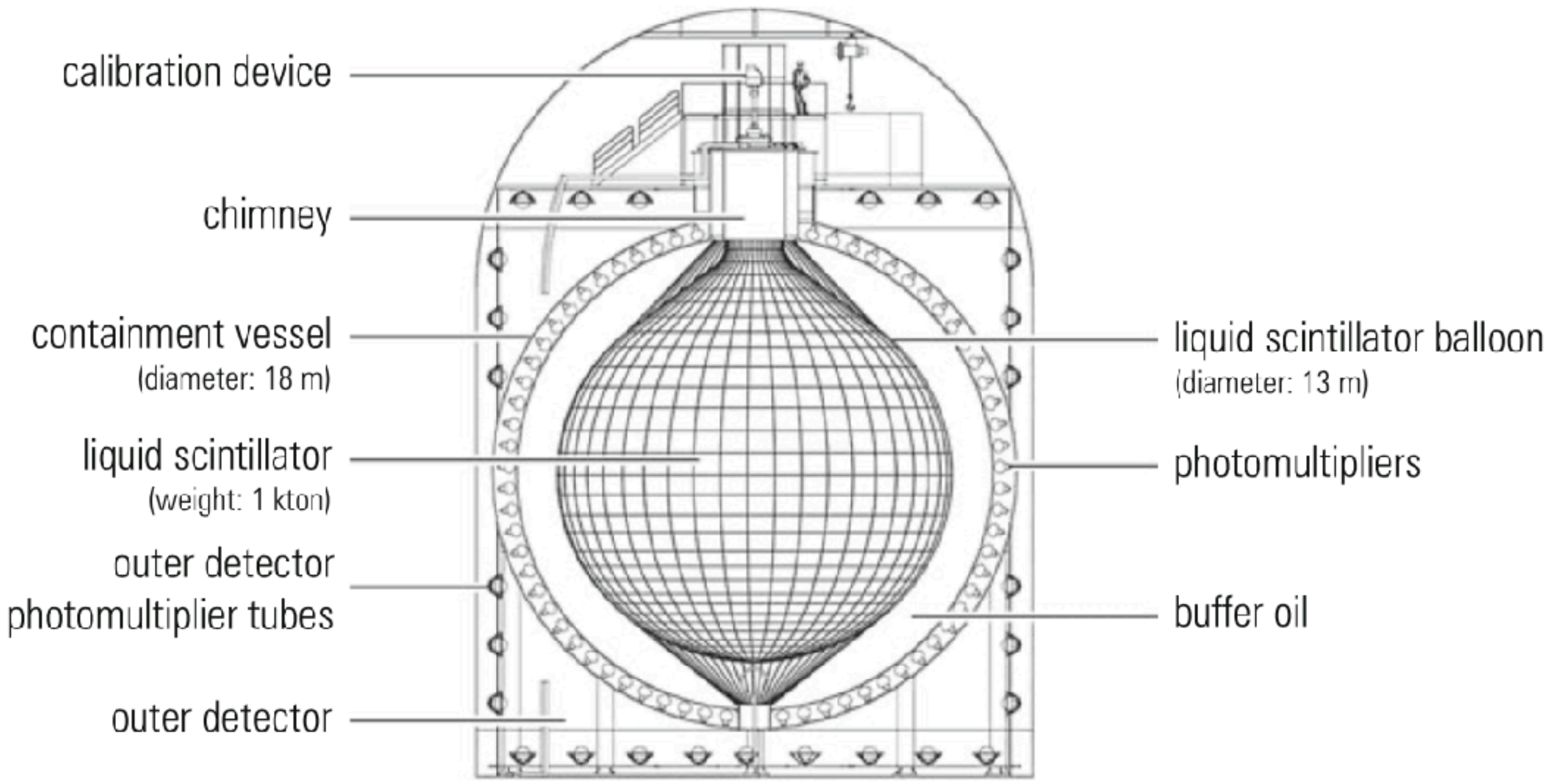


Fig. 6.40 The KamLAND antineutrino detector at the Kamioka observatory at 1000 m underground

Geoneutrinos

The first measurement of geoneutrinos
(Kamioka Liquid Scintillator Antineutr
KamLAND consists of a 1000-ton liqu

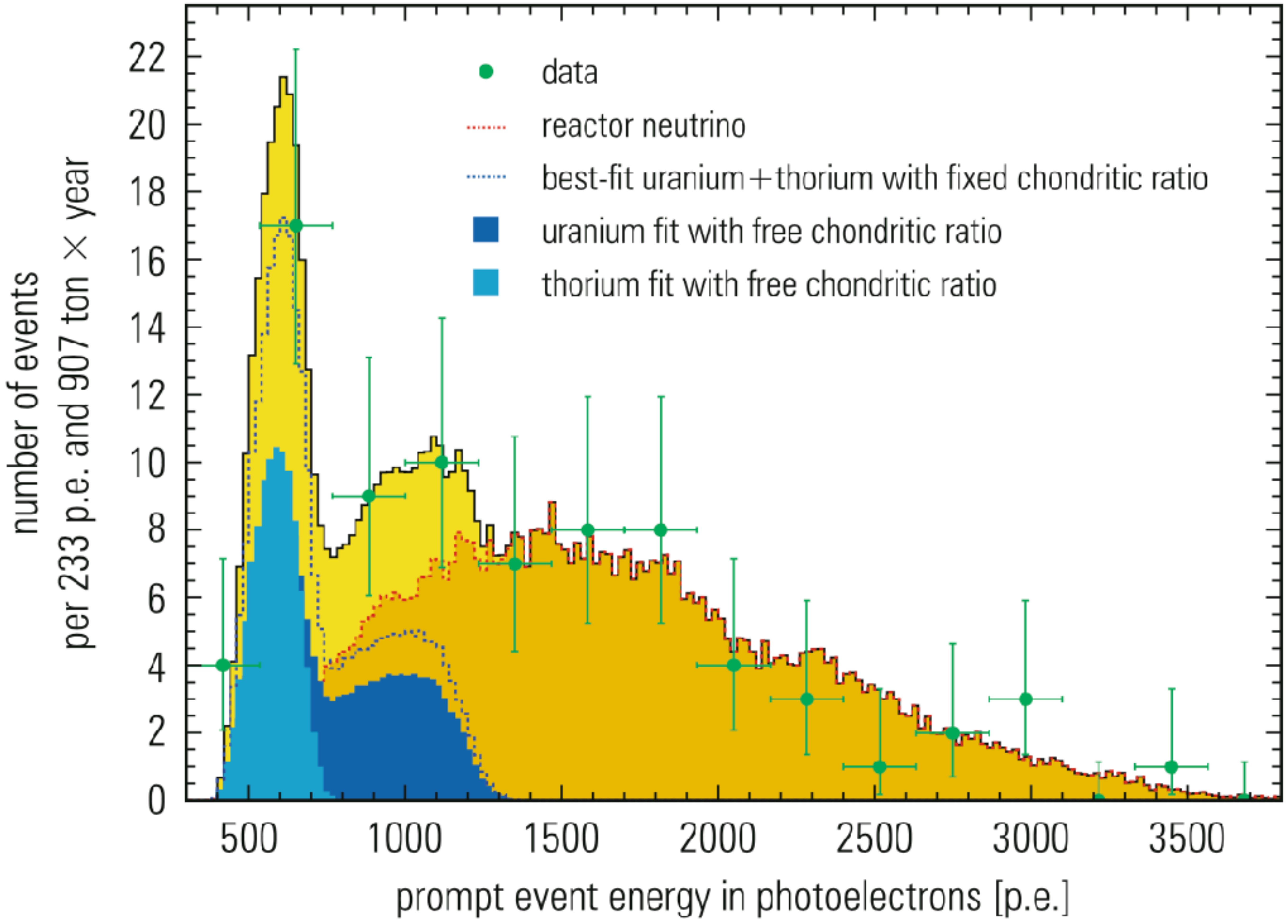


Fig. 6.41 Energy spectrum of 46 prompt $\bar{\nu}_e$ candidates from the Borexino experiment. The maximum energy of $\bar{\nu}_e$ from the ^{238}U decay is 3.26 MeV corresponding to about 1400 photoelectrons measured, and the maximum energy from ^{232}Th is 2.25 MeV (signal of ^{238}U and ^{232}Th *in yellow*). For the contribution of the uranium (*in blue*) and thorium (*in turquoise*) antineutrinos a free parameter was used. For the best fit for the sum of uranium and thorium antineutrinos a fixed chondritic ratio (typical for terrestrial upper-mantle rocks) was assumed. The *full line* is a fit to the data. The background from reactor antineutrinos is substantial (*ocher area*). However, the expected geogenic antineutrino signal (*dashed blue line*) stands clearly out at low energies [80]

Geoneutrinos

KamLAND consists of a 1000-ton **liquid scintillator detector** surrounded by 1845 photomultipliers. It is set up in the Kamioka observatory 1000 m underground to shield against cosmic rays.

Borexino is a high-purity **liquid scintillator calorimeter** with extremely low intrinsic radioactivity. The scintillation counter is placed in a stainless-steel container. It is shielded by a water tank to protect it against external radiation and cosmic-ray muons. The experiment is installed in the Italian Gran Sasso.

Geoneutrinos have to be detected against the strong **background of antineutrinos from some ~450 man-made reactors.** In the past there have been also antineutrinos from natural reactors, such as the Oklo reactor in Gabon.

Many larger experiments are being prepared or proposed to improve the knowledge about the Earth's interior, which cannot by studied at the moment by other means.

Problems

1. What is the reason that primary cosmic-ray nuclei like carbon, oxygen, and neon are more abundant than their neighbours in the periodic table of elements (nitrogen, fluorine, sodium)?

Problems

1. Neutrons as candidates for the highest-energy cosmic rays have not been discussed so far. What are the problems with neutrons?

Problems

2. The Oh-My-God event observed by John Linsley at Dugway Proving Ground had an energy of 3×10^{20} eV. Assuming that the particle was initiated by a proton, work out the velocity of this extremely-high-energy event.

Problems

4. There are many estimates for cross sections for the detection of dark-matter particles. Many predictions for a nuclear cross section of a 1-TeV SUSY dark-matter particle range in the region of around 10^{-9} pb. If this were correct, would ICE-CUBE have a chance to see such particles?

Problems

1. The Sun converts protons into helium according to the reaction

$$4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e \,.$$

The solar constant describing the power of the Sun at Earth is $P \approx 1400\,\mathrm{W/m^2}$. The energy gain per reaction corresponds to the binding energy of helium ($E_\mathrm{B}({}^{4}\mathrm{He}) = 28.3\,\mathrm{MeV}$). How many solar neutrinos arrive at Earth?

Problems

2. If solar electron neutrinos oscillate into muon or tau neutrinos they could in principle be detected via the reactions

$$\nu_\mu + e^- \;\rightarrow\; \mu^- + \nu_e\,,\;\; \nu_\tau + e^- \;\rightarrow\; \tau^- + \nu_e\,.$$

Work out the threshold energy for these reactions to occur.

Problems

3. Radiation exposure due to solar neutrinos.

   (a) Use (6.3.1) to work out the number of interactions of solar neutrinos in the human body (tissue density $\varrho \approx 1\,\mathrm{g\,cm^{-3}}$).

   (b) Neutrinos interact in the human body by

   $$\nu_e + N \to e^- + N' ,$$

   where the radiation damage is caused by the electrons. Estimate the annual dose for a human under the assumption that on average 50% of the neutrino energy is transferred to the electron.

   (c) The equivalent dose is defined as

   $$H = (\Delta E/m)\, w_\mathrm{R} \tag{6.7.1}$$

   (m is the mass of the human body, w_R the radiation weighting factor ($= 1$ for electrons), $[H] = 1\,\mathrm{Sv} = 1 w_\mathrm{R}\,\mathrm{J\,kg^{-1}}$, and ΔE the energy deposit in the human body). Work out the annual equivalent dose due to solar neutrinos and compare it with the normal natural dose of $H_0 \approx 2\,\mathrm{mSv/a}$.