Special Topics in Particle Physics

Particle and Radiation Detection

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Cryogenic detection techniques

The detectors described so far can be used for the spectroscopy of particles from the keV range up to the highest energies. For many investigations the detection of **particles of extremely low energy in the range between 1 and 1000 eV** is of great interest.

Calorimeters for such low-energy particles could be or are used for the detection of and search for low-energy cosmic neutrinos, weakly interacting massive particles (WIMPs) or other candidates of dark, non-luminous matter, for X-ray spectroscopy in astrophysics and material science, single-optical-photon spectroscopy, and in other experiments. Since more than 20 years this field of experimental particle physics is developing intensively and by now it comprises dozens of projects.

Figure 4.11 demonstrates the better performance of a cryogenic detector even when comparing it to an already excellent solid-state counter.

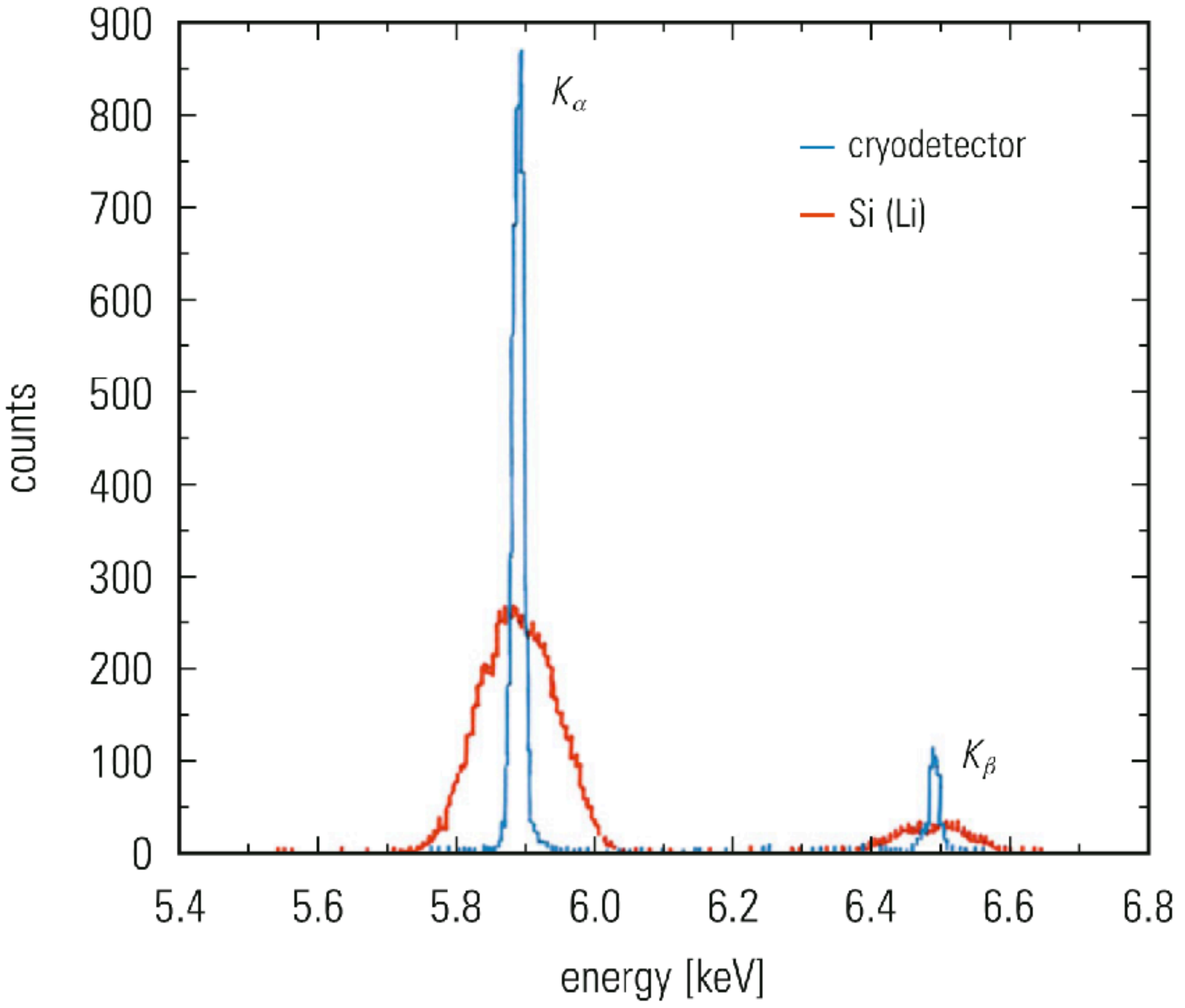


Fig. 4.11 X-ray spectrum of a ^{55}Fe (^{55}Mn) source showing the K_α and K_β lines. The narrow peaks were recorded with a superconducting tunnel diode with a resolution of 14.5 eV FWHM (0.24%). The curves labeled Si(Li) were measured at a twofold higher rate with a lithium-drifted silicon detector showing a resolution of 131 eV (2.2%) [35, 36]

Remember the phonons from nuclear physics?

Particle and radiation detection

To reduce the detection threshold and improve at the same time the energy resolution, it is only natural to replace the ionization or electron–hole pair production by ***quantum transitions*** **requiring lower energies.**

Phonons in solid-state materials have energies around **10^{-5} eV for temperatures around 100 mK.**

The other types of quasiparticles at low temperature are ***Cooper pairs*** in a superconductor, which are **bound states of two electrons with opposite spin that behave like bosons** and will form at sufficiently low temperatures a Bose condensate. Cooper pairs in superconductors have binding energies in the range between 4×10^{-5} eV (Ir) and 3×10^{-3} eV (Nb). Thus, **even extremely low energy depositions would produce a large number of phonons or break up Cooper pairs**. To avoid thermal excitations of these quantum processes, such **detectors, however, would have to be operated at extremely low temperatures**, typically in the milli-kelvin range. For this reason, such devices are called cryogenic detectors.

Cryogenic calorimeters **or** ***cryogenic detectors*** can be subdivided in two main categories: firstly, detectors for **quasiparticles in superconducting materials** or suitable crystals, and secondly, **phonon detectors in insulators.**

Phonon

In physics, a **phonon is a collective excitation** in a periodic, elastic arrangement of atoms or molecules in condensed matter, specifically in solids and some liquids. A type of quasiparticle, a phonon is an **excited state in the quantum mechanical quantization of the modes of vibrations** for elastic structures of interacting particles. Phonons can be thought of as quantized sound waves, similar to photons as quantized light waves.

Quasiparticle

In condensed matter physics, **a quasiparticle is a concept used to describe a collective behavior of a group of particles that can be treated as if they were a single particle.** Formally, quasiparticles and collective excitations are closely related phenomena that arise when a microscopically complicated system such as a solid behaves as if it contained different weakly interacting particles in vacuum.

For example, as an electron travels through a semiconductor, its motion is disturbed in a complex way by its interactions with other electrons and with atomic nuclei. The electron behaves as though it has a different effective mass travelling unperturbed in vacuum. Such an electron is called an electron quasiparticle. In another example, the aggregate motion of electrons in the valence band of a semiconductor or a hole band in a metal behave as though the material instead contained positively charged quasiparticles called ***electron holes***. Other quasiparticles or collective excitations include the **phonon, a quasiparticle derived from the vibrations of atoms in a solid**, and the ***plasmons***, a particle derived from plasma oscillation.

These phenomena are typically called quasiparticles if they are related to fermions, and called collective excitations if they are related to bosons. Thus, electrons and electron holes (fermions) are typically called quasiparticles, while phonons and plasmons (bosons) are typically called collective excitations.

Cooper pair

To In condensed matter physics, a **Cooper pair** or **BCS pair (Bardeen–Cooper–Schrieffer pair)** is a pair of electrons (or other fermions) bound together at low temperatures in a certain manner.

An arbitrarily small attraction between electrons in a metal can cause a paired state of electrons to have a lower energy than the Fermi energy, which implies that the pair is bound. In conventional superconductors, this attraction is due to the **electron–phonon interaction**. The Cooper pair state is responsible for superconductivity.

Although Cooper pairing is a quantum effect, the reason for the pairing can be seen from a simplified classical explanation. An electron in a metal normally behaves as a free particle. The electron is repelled from other electrons due to their negative charge, but it also attracts the positive ions that make up the rigid lattice of the metal. This attraction distorts the ion lattice, moving the ions slightly toward the electron, increasing the positive charge density of the lattice in the vicinity. This positive charge can attract other electrons. At long distances, this attraction between electrons due to the displaced ions can overcome the electrons' repulsion due to their negative charge, and cause them to pair up. The rigorous quantum mechanical explanation shows that the effect is due to electron–phonon interactions, with the phonon being the collective motion of the positively-charged lattice.

The energy of the pairing interaction is quite weak, of the order of 10^{-3} eV, and thermal energy can easily break the pairs.

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

Cryogenic detection techniques

One detection method is based on the fact that the **superconductivity of a substance is destroyed by energy deposition** if the detector element is sufficiently small. This is the working principle of superheated superconducting granules; see Fig. 4.12.

In this case the cryogenic calorimeter is made of a large number of superconducting spheres with diameters in the 100 μm range. If these granules are embedded in a magnetic field, and the energy deposition of a low-energy particle transfers one particular granule from the superconducting to the normal-conducting state, this transition can be detected by the suppression of the ***Meissner effect*.**

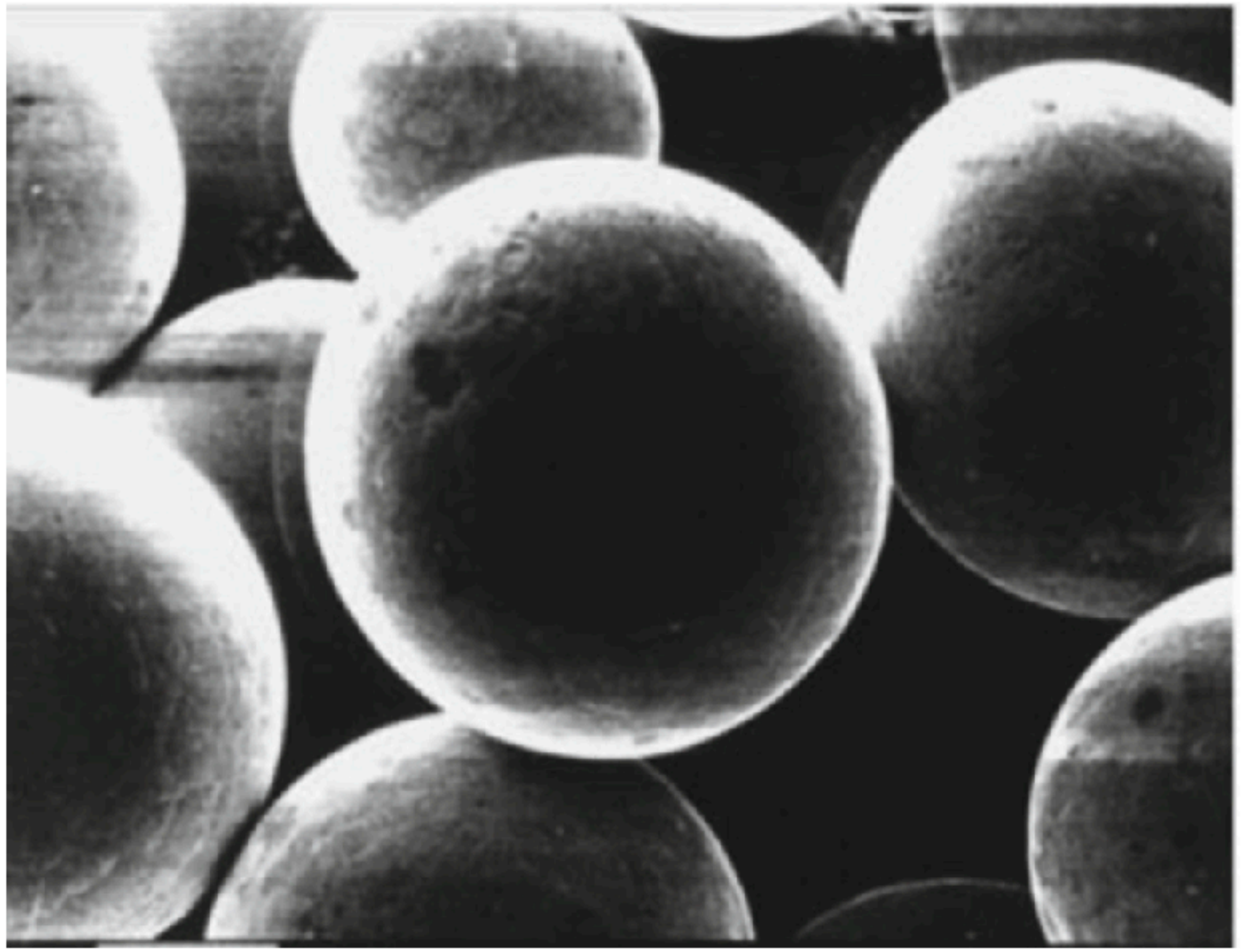


Fig. 4.12 Tin granules (130 μm diameter) as cryogenic calorimeter. A relatively small energy transfer can be sufficient to transfer a granule from the superconducting state into the normal-conducting state, thereby creating a detectable signal [39, 40]

Meissner effect

The Meissner effect (or Meißner–Ochsenfeld effect) is the **expulsion of a magnetic field from a superconductor during its transition to the superconducting state** when it is cooled below the critical temperature. This expulsion will repel a nearby magnet.

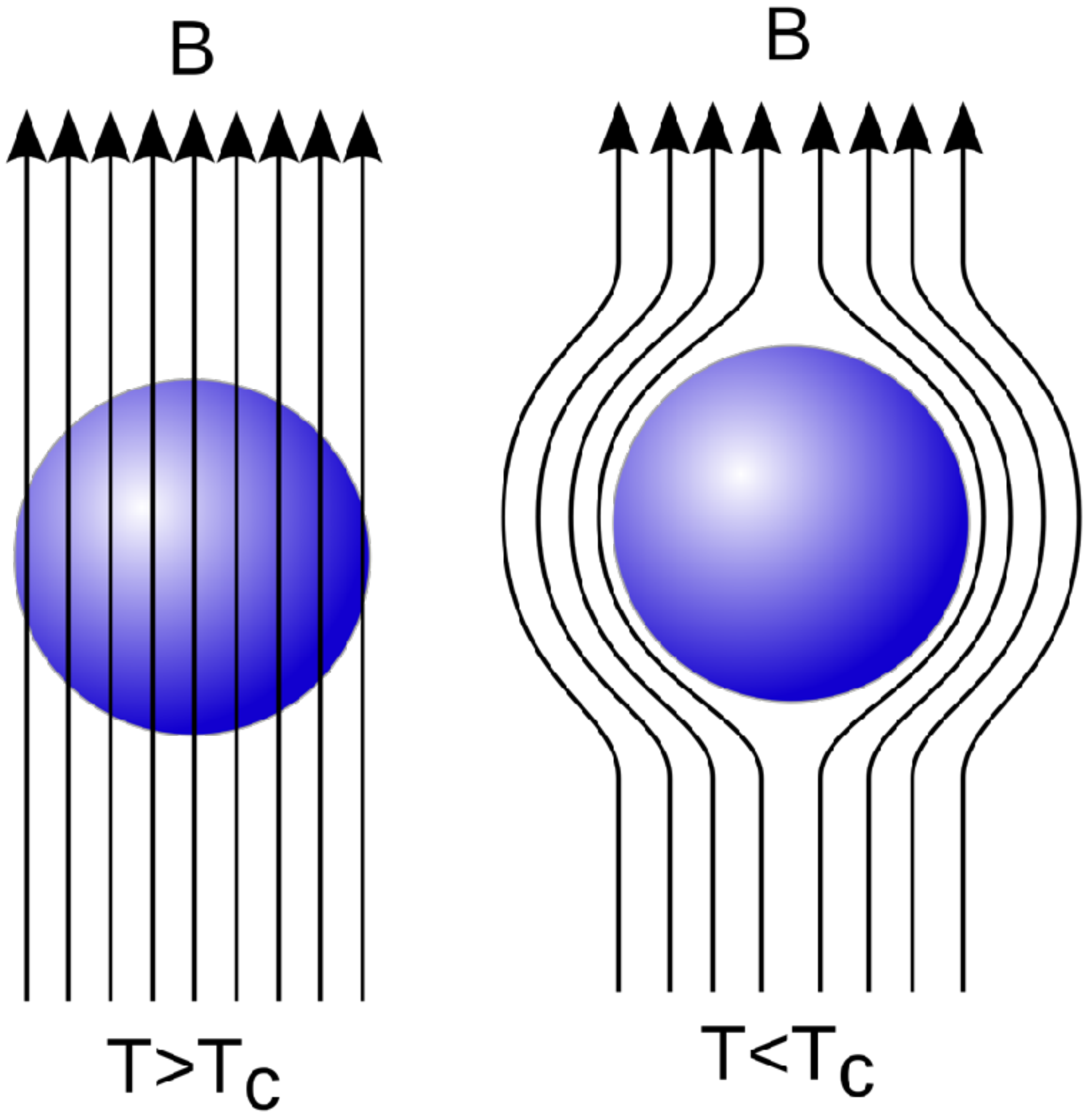


Diagram of the Meissner effect. Magnetic field lines, represented as arrows, are excluded from a superconductor when it is below its critical temperature.

Cryogenic detection techniques

This is, where the magnetic field, which does not enter the granule in the superconducting state, now again passes through the normal-conducting granule. The **transition from the super-conducting to the normal-conducting state can be detected** by pickup coils coupled to very sensitive preamplifiers or by SQUIDs (*Superconducting Quantum Interference Devices*). These ***quantum interferometers*** are extremely sensitive detection devices for magnetic effects. The operation principle of a SQUID is based on the ***Josephson effect*,** which represents a tunnel effect operating between two superconductors separated by thin insulating layers. In contrast to the normal one-particle tunnel effect, known, e.g., from alpha decay, the **Josephson effect involves the tunnelling of Cooper pairs.** In Josephson junctions, interference effects of the tunnel current occur that can be influenced by magnetic fields. The structure of these interference effects is related to the size of the magnetic flux quanta.

The detection of transitions from the superconducting into the normal-conducting state is possible with appropriate materials and can yield signal amplitudes of about 100 μV and recovery times of 10–50 ns. This already indicates that *superconducting strip counters* are possible candidates for **microvertex detectors** for future generations of particle physics experiments or even astroparticle experiments on board the International Space Station in the future, **if sufficient cooling can be provided.**

SQUID

A SQUID (superconducting quantum interference device) is a very sensitive magnetometer used to measure extremely weak magnetic fields, based on superconducting loops containing Josephson junctions.

SQUIDs are **sensitive enough to measure fields as low as 5×10^{-14} T** with a few days of averaged measurements. Their noise levels are as low as 3 $fT\cdot Hz^{-1/2}$.

For comparison, a typical **refrigerator magnet produces 0.01 tesla (10^{-2} T)**, and some processes in animals produce very small magnetic fields between 10^{-9} T and 10^{-6} T.

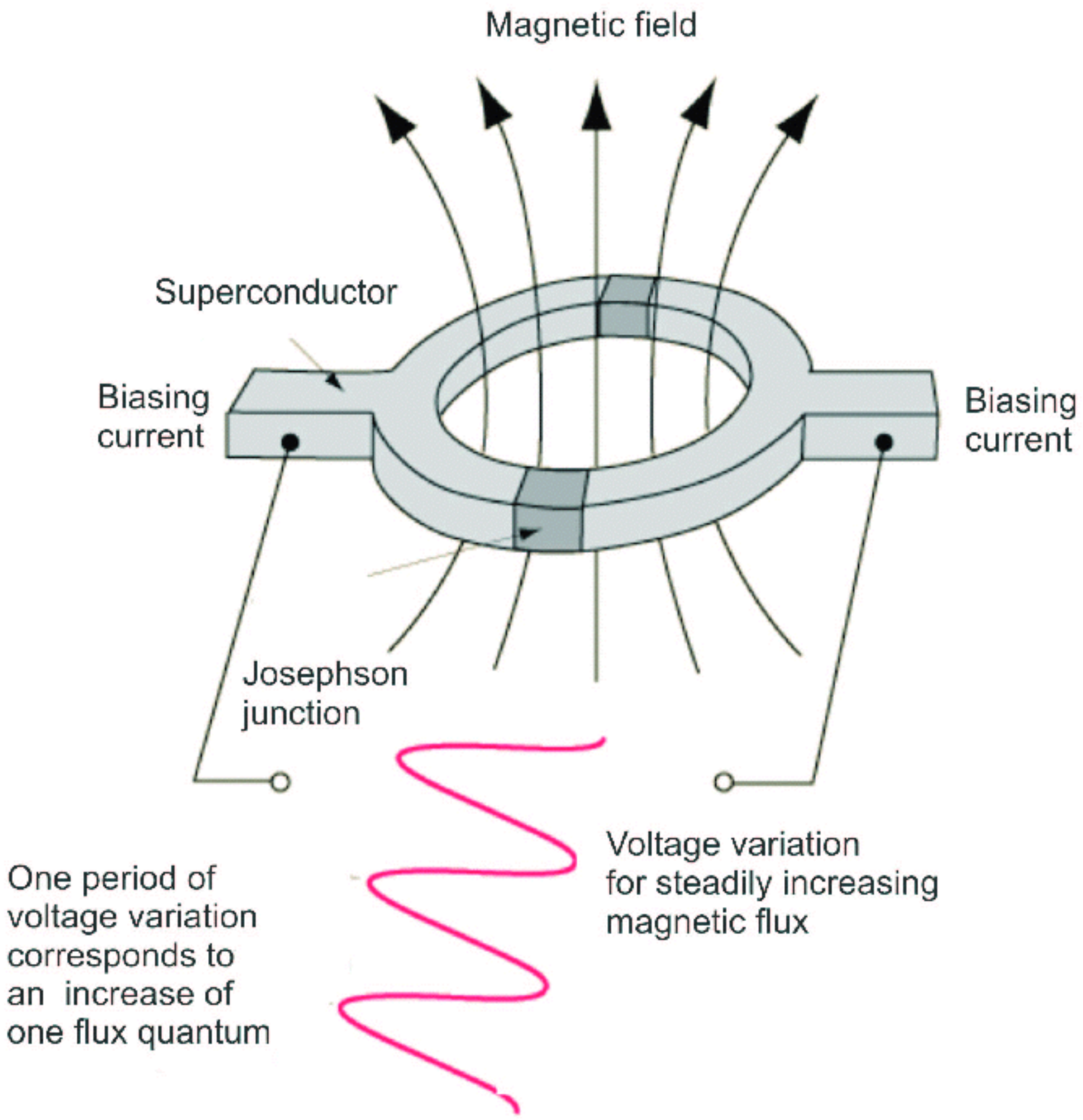
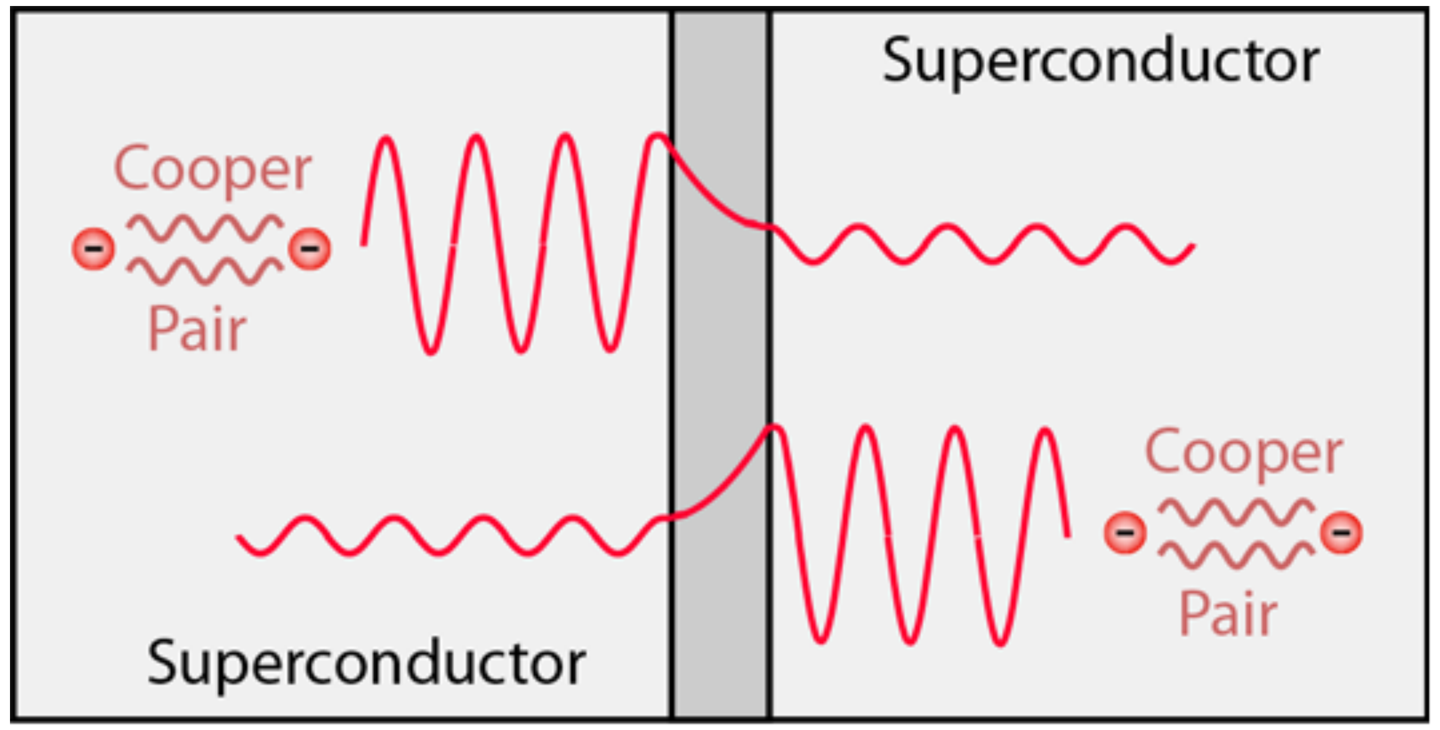


Diagram of a DC SQUID. The current enters and splits into the two paths, each with currents and . The thin barriers on each path are Josephson junctions, which together separate the two superconducting regions. represents the magnetic flux threading the DC SQUID loop.

Marcon et al. 2012

Josephson effect



In physics, the **Josephson effect** is a phenomenon that occurs when two superconductors are placed in proximity, with some barrier or restriction between them. It is an example of a macroscopic quantum phenomenon, where the effects of quantum mechanics are observable at ordinary, rather than atomic, scale. The Josephson effect has many practical applications because it exhibits a precise relationship between different physical measures, such as voltage and frequency, facilitating highly accurate measurements.

The Josephson effect produces a current, known as a supercurrent, that flows continuously without any voltage applied, across a device known as a Josephson junction (JJ). These consist of two or more superconductors coupled by a weak link. The weak link can be a thin insulating barrier (known as a **superconductor–insulator–superconductor junction, or S-I-S**), a short section of non-superconducting metal (S-N-S), or a physical constriction that weakens the superconductivity at the point of contact (S-c-S).

Josephson junctions have important applications in quantum-mechanical circuits, such as SQUIDs, superconducting qubits, and RSFQ digital electronics. The NIST **standard for one volt** is achieved by an array of 20,208 Josephson junctions in series.

http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/Squid.html

Cryogenic detection techniques

An alternative method to detect *quasiparticles* is to let them **directly tunnel through an insulating foil between two superconductors** (SIS—Superconducting– Insulating–Superconducting transition). In this case the problem arises of keeping undesired leakage currents at an extremely low level. In contrast to Cooper pairs, phonons, which can be excited by energy depositions in insulators, **can be detected with methods of classical calorimetry**. If ΔE is the absorbed energy, this results in a temperature rise of

$$\Delta T = \Delta E / mc$$

where ***c* is the specific heat capacity** and ***m* the mass of the calorimeter.** If these calorimetric measurements are performed at very low temperatures, where c can be very small (the lattice contribution to the specific heat is proportional to T^3 at low temperatures), this method is also used to **detect individual particles.** In a real experiment, the temperature change is recorded with a **thermistor, which is basically an NTC resistor** (Negative Temperature Coefficient → the resistance decreases with increasing temperature), embedded into or fixed to an **ultrapure crystal**. The crystal represents the absorber, i.e., the detector for the radiation that is to be measured. Because of the discrete energy of phonons, one would expect discontinuous thermal energy fluctuations, which can be detected with electronic filter techniques.

Cryogenic detection techniques

In Fig. 4.13 the principle of such a calorimeter is sketched.

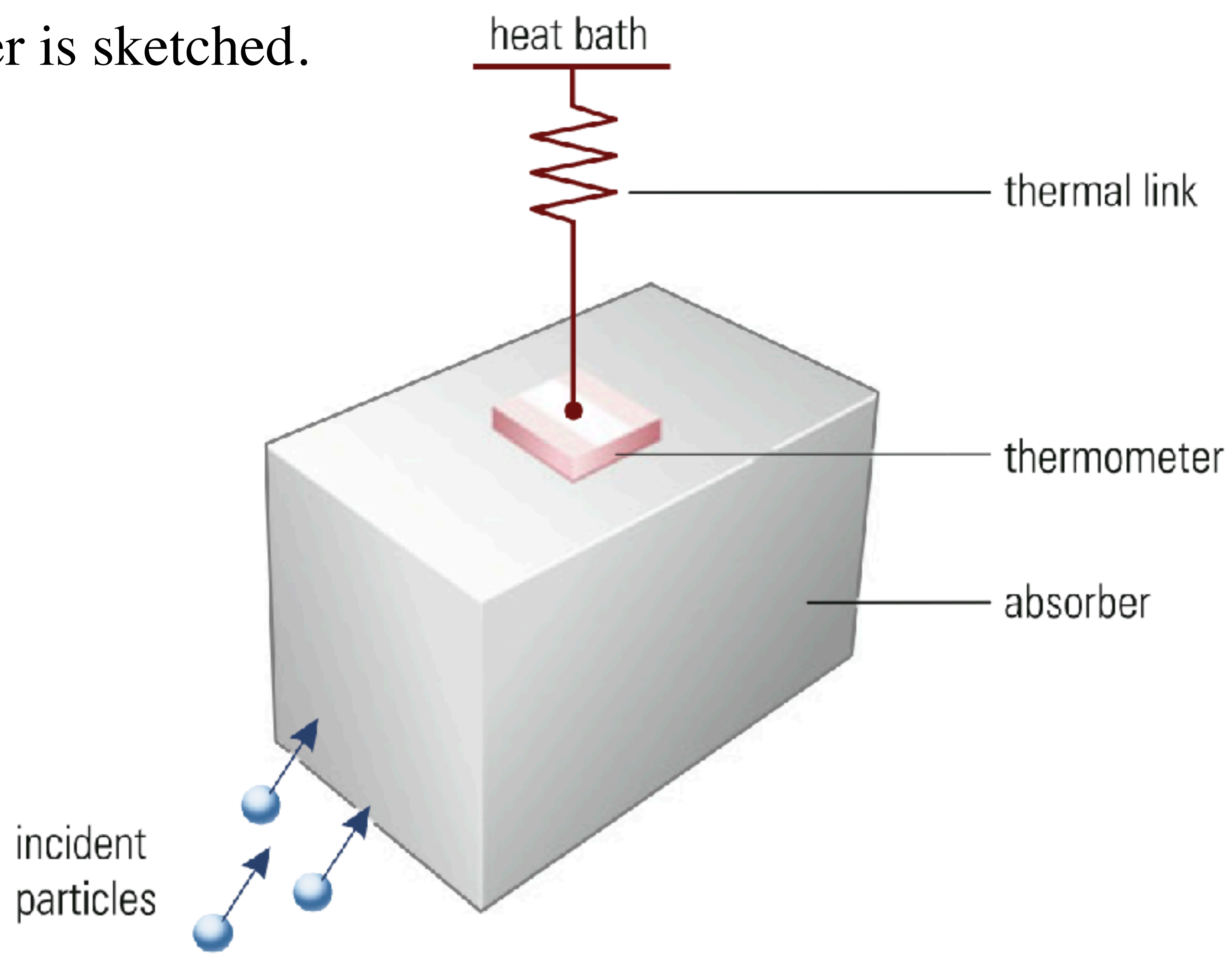


Fig. 4.13 Schematic view of a cryogenic calorimeter. The main components are the absorber for the incident particles, the thermometer for the measurement of the heat signal and the thermal coupling to the cryo bath [38, 41, 42]

Cryogenic detection techniques

In this way **α particles and γ rays have been detected** in a large TeO_2 crystal at 15 mK in a purely thermal detector with thermistor readout with an energy resolution of 4.2 keV FWHM for 5.4-MeV α particles. Special **bolometers** have also been developed, in which **heat and ionization signals are measured simultaneously**.

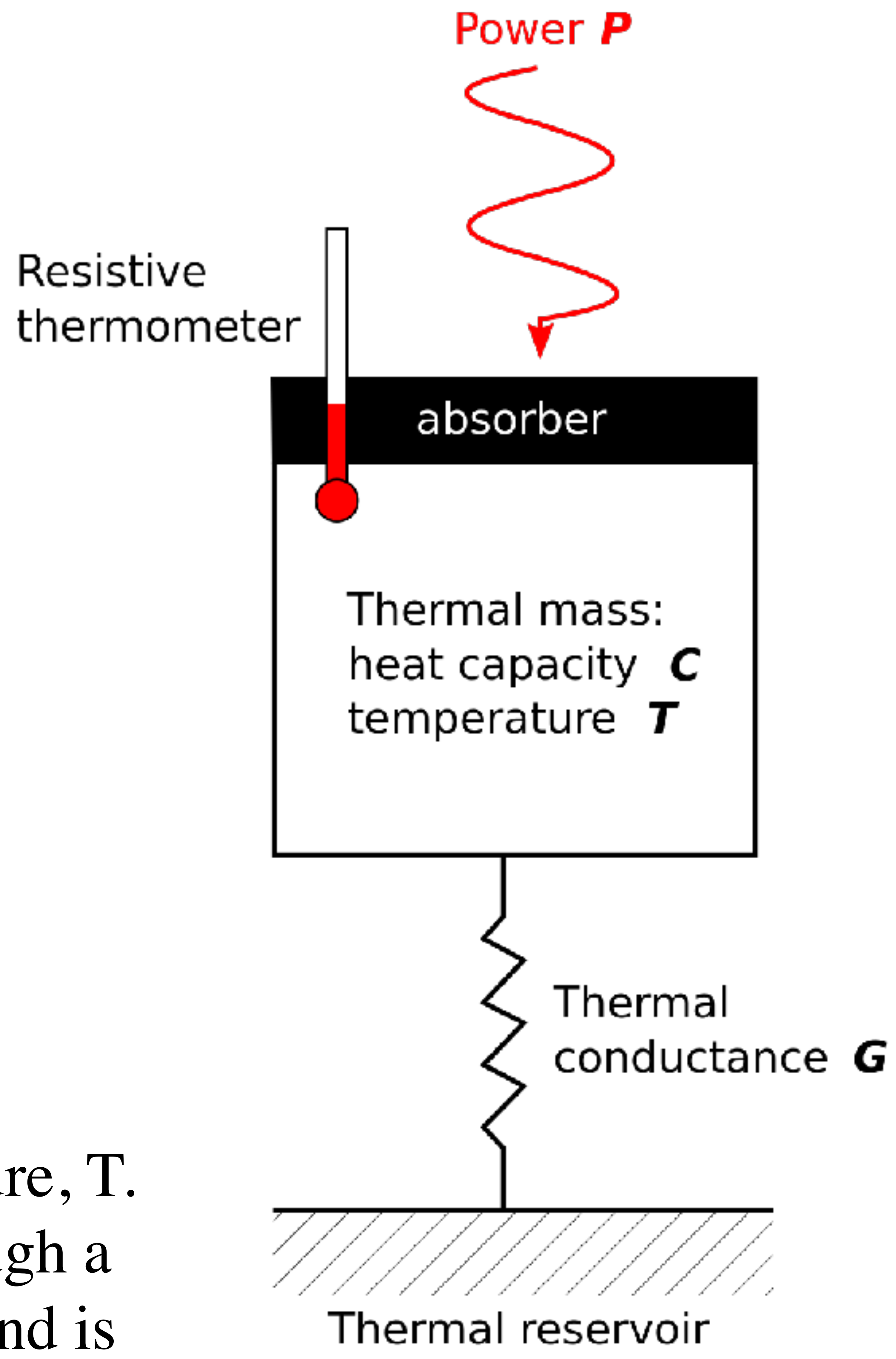
Thermal detectors **provide promise for improvements of energy resolutions.** For example, a 1-mm cubic crystal of silicon kept at 20 mK would have a heat capacity of 5×10^{-15} J/K and a FWHM energy resolution of 0.1 eV (corresponding to $\sigma = 42$ meV).

There are, **however, still various important problems to be solved**, before these values can be reached.

Bolometer

A bolometer is a device for **measuring radiant heat** by means of a material having a temperature-dependent electrical resistance.

Metal bolometers usually work without cooling. They are produced from thin foils or metal films. **Today, most bolometers use semiconductor or superconductor absorptive elements** rather than metals. These devices can be operated at cryogenic temperatures, enabling significantly greater sensitivity.



Conceptual schematic of a bolometer. Power, P, from an incident signal is absorbed and heats up a thermal mass with heat capacity, C, and temperature, T. The thermal mass is connected to a reservoir of constant temperature through a link with thermal conductance, G. The temperature increase is $\Delta T = P/G$ and is measured with a resistive thermometer, allowing the determination of P. The intrinsic thermal time constant is $\tau = C/G$.

Cryogenic detection techniques

Joint efforts in the fields of cryogenics, particle physics, and astrophysics are required, which may lead to exciting and unexpected results. One **interesting goal would be to detect relic neutrinos of the Big Bang with energies around 200 μeV,** or find evidence for dark-matter particles.

Cryogenic detectors allow to detect single photons over a wide spectral range. Therefore, these detectors **have been used in astronomy already**. Energy-dispersive **X-ray detectors** benefit from the high energy resolution of cryodetectors, which allow to investigate the low-energy part of atomic spectra (below several keV).

The required low temperatures for cryogenic detectors can be reached, e.g., by adiabatic demagnetisation, liquid nitrogen cooling.

Cryogenic detection techniques

As an example for an application of cryodetectors the search for *weakly interacting massive particles* (WIMPs) will be described in some more detail.

The interaction cross section for WIMP interactions is extremely small, so that possible backgrounds have to be reduced to a very low level. Unfortunately also the energy transfer of a WIMP to a target nucleus in a cryogenic detector is only **in the range of ≈20keV**. An excellent method to discriminate a WIMP signal against the **background caused, e.g., by local radioactivity,** is to use scintillating crystals like $CaWO_4$, $CdWO_4$, or $ZnWO_4$.

These scintillators allow **to measure the light yield at low temperatures and the phonon production by WIMP interactions at the same time**.

Nuclear recoils **due to WIMP–nucleon scattering produce mainly phonons and very little scintillation light**, while in ***electron recoils*** **also a substantial amount of scintillation light is created**. A schematic view of such a cryogenic detector system is shown in Fig. 4.14.

Cryogenic detection techniques

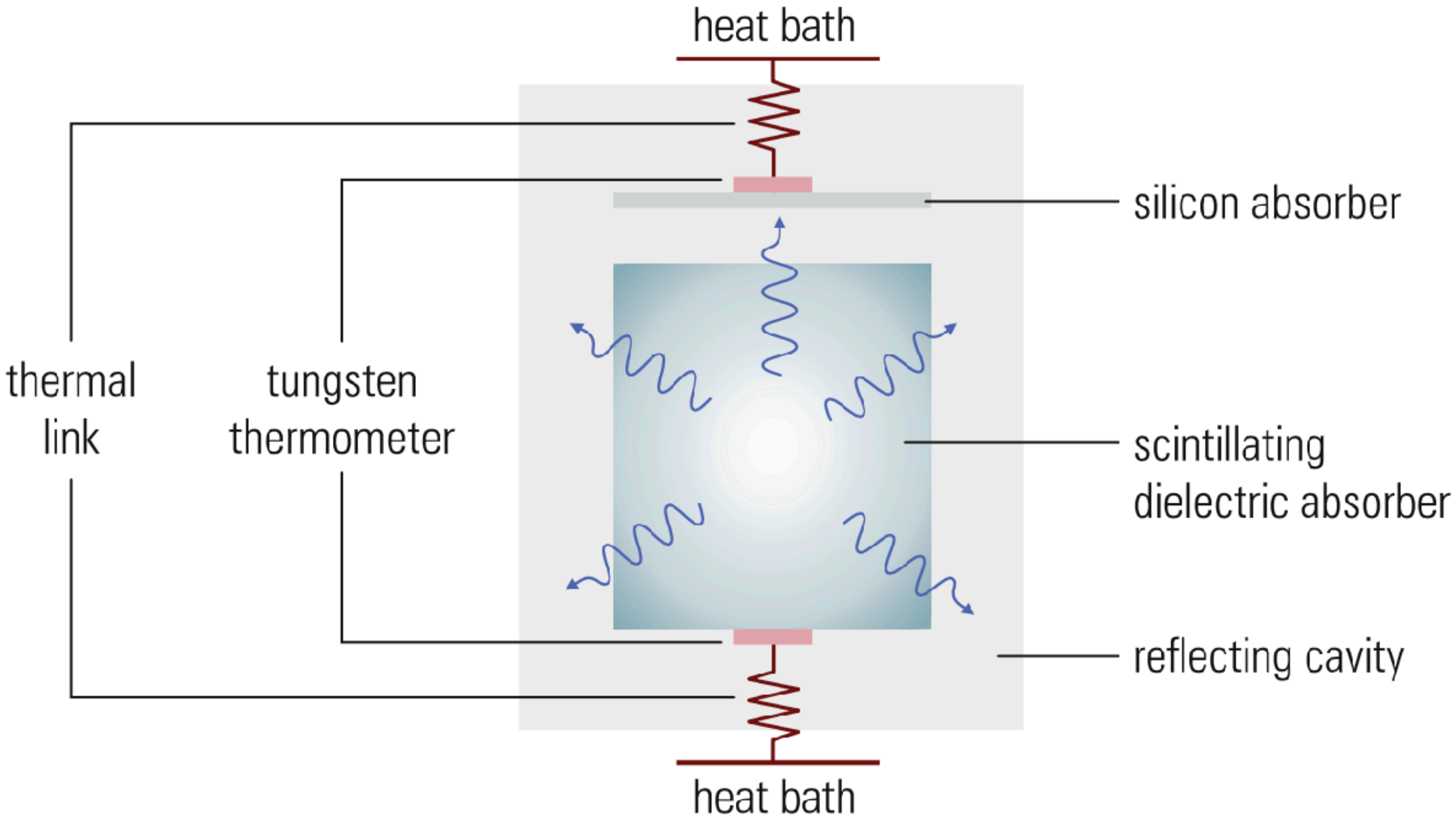


Fig. 4.14 Schematic of a cryogenic calorimeter with simultaneous measurement of the thermal due to phonons and the optical signal from photons [38, 41]

Cryogenic detection techniques

Particles are absorbed in a scintillating dielectric crystal.

The **scintillation light** is detected in a silicon wafer while the phonons are measured in two tungsten **thermometers**, one of which can be coupled to the silicon detector to increase the sensitivity of the detector.

The whole detector setup is enclosed in a reflecting cavity and **operated at milli-kelvin temperatures**. The response of a $CaWO_4$ cryogenic calorimeter to electron recoils and nuclear recoils is shown in Fig. 4.15.

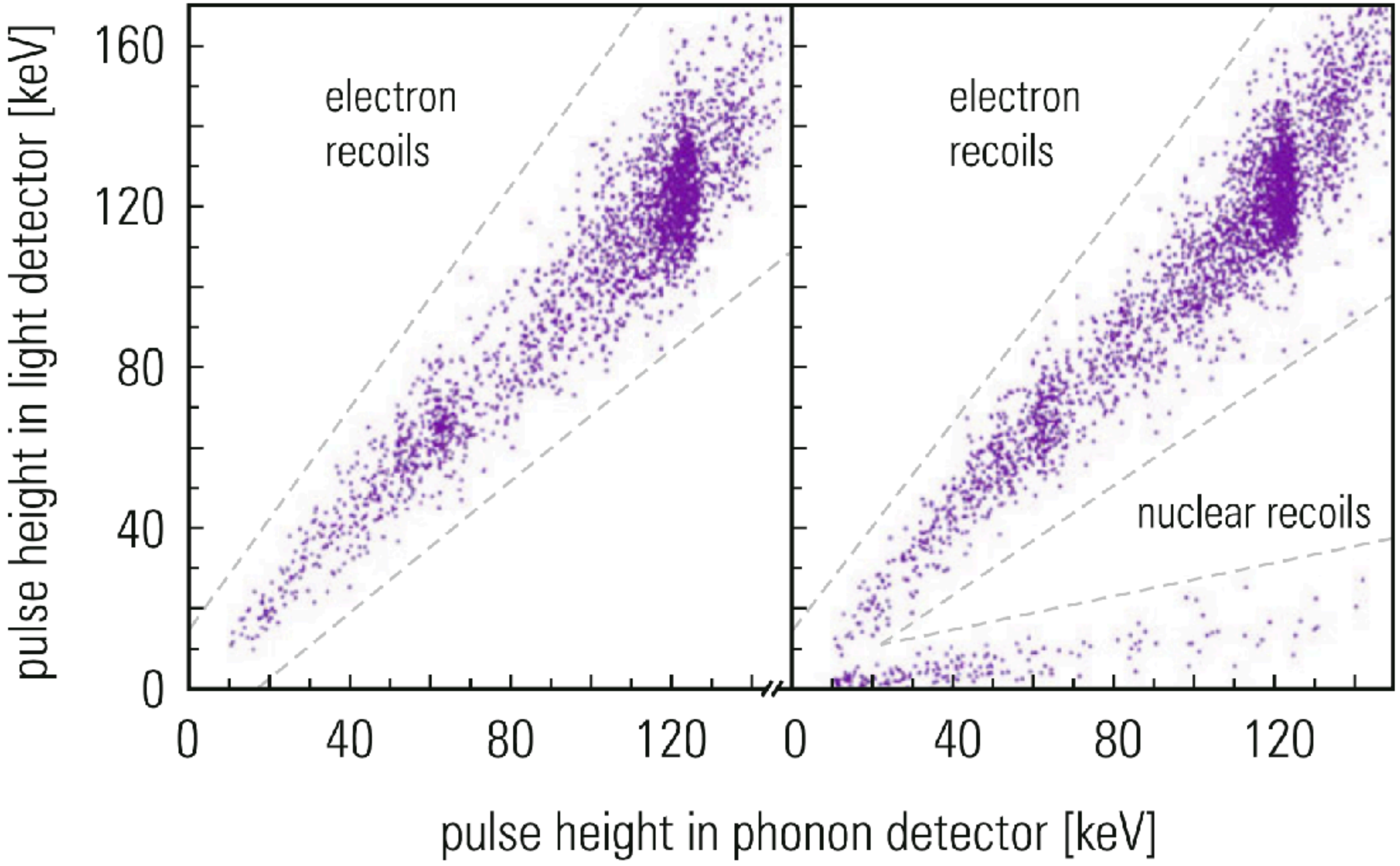
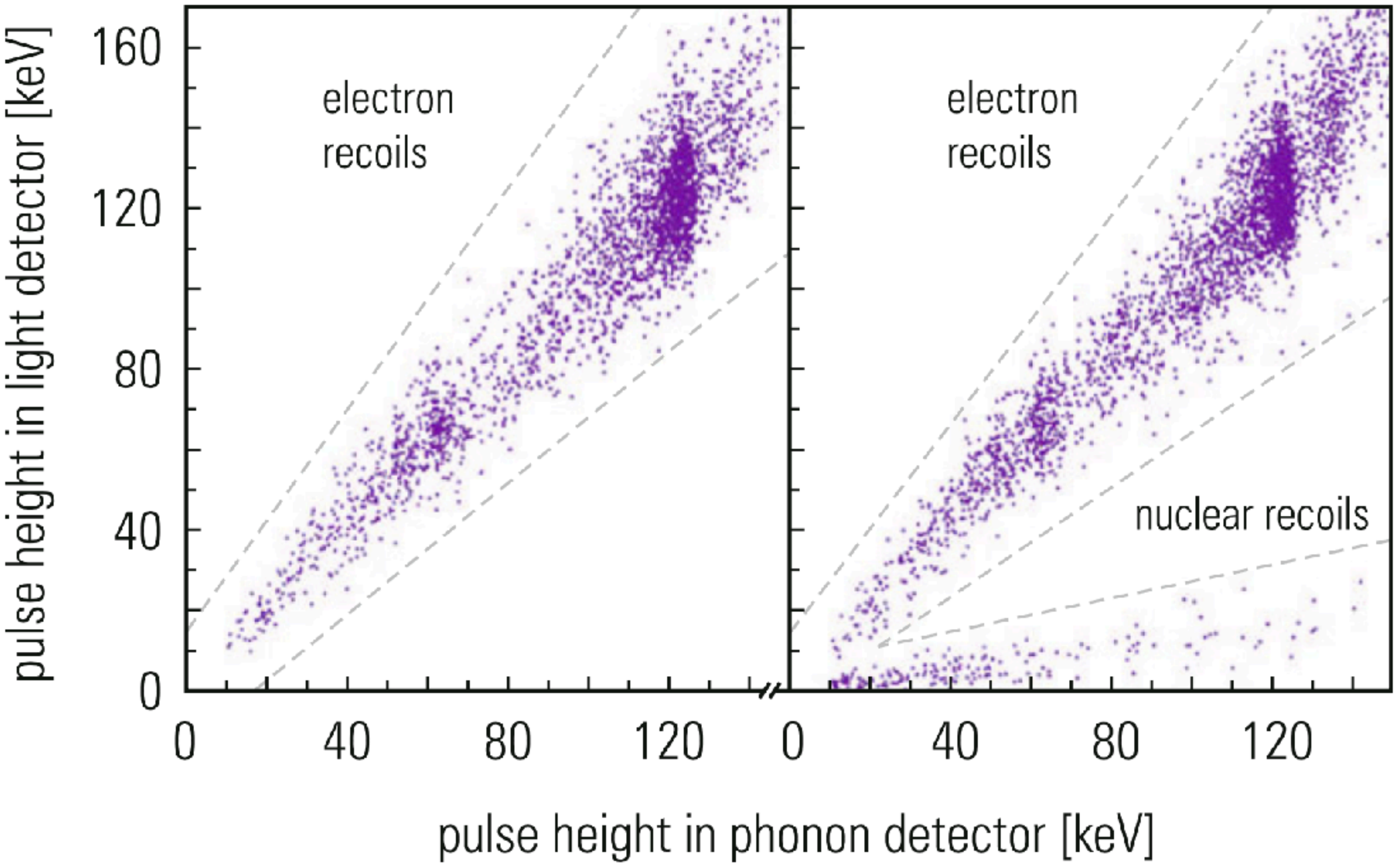


Fig. 4.15 Scatter diagram of the pulse height of the light signal versus the phonon signal in a $CaWO_4$ crystal. The *left-hand part* of the figure shows the response of the detector to photons and electrons only, while in the *right-hand part* also neutron interactions are included, which are supposed to simulate a WIMP signal [38, 41, 46]

Cryogenic detection techniques

Electron recoils were created by irradiating the crystal with 122-keV and 136-keV photons from a ^{57}Co source and electrons from a ^{90}Sr β source (left panel).

To simulate also WIMP interactions the detector was bombarded additionally with neutrons from an americium–beryllium source leading to phonon and scintillation-light yields as shown in the right-hand plot of Fig. 4.15.



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Cryogenic detection techniques

The light output due to electron recoils caused by photons or electrons (which constitute the main background for WIMP searches) is quite high, **whereas nuclear recoils created by neutrons provide a strong phonon signal with only low light yield.**

It is **estimated that WIMP interactions will look similar to neutron scattering**, thus allowing a substantial background rejection if appropriate cuts in the scatter diagram of light versus phonon yield are applied.

However, the figure also shows that the suppression of electron recoils at energies **below 20 keV becomes rather difficult.**

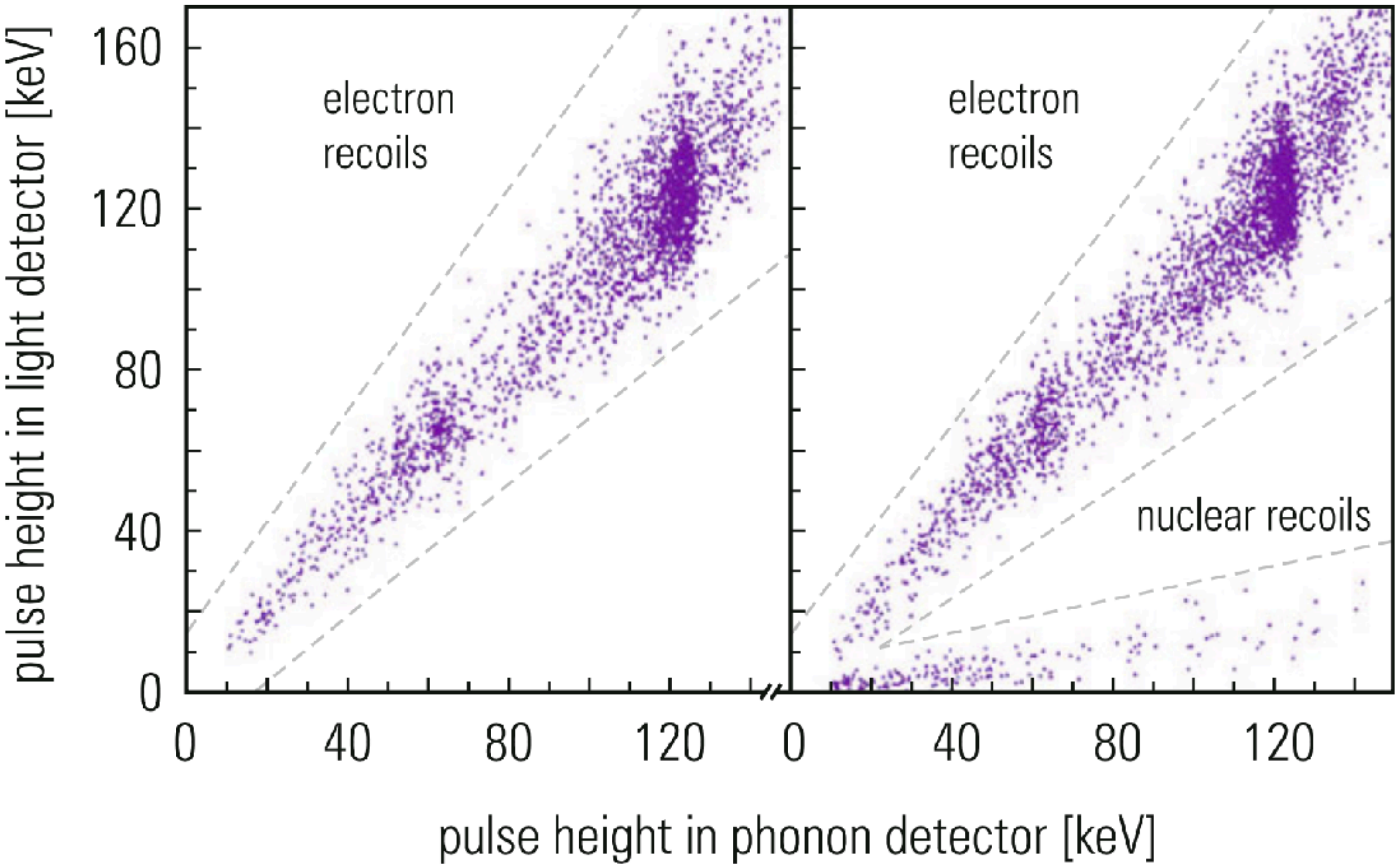


Fig. 4.15 Scatter diagram of the pulse height of the light signal versus the phonon signal in a $CaWO_4$ crystal. The *left-hand part* of the figure shows the response of the detector to photons and electrons only, while in the *right-hand part* also neutron interactions are included, which are supposed to simulate a WIMP signal [38, 41, 46]

Propagation of astroparticles

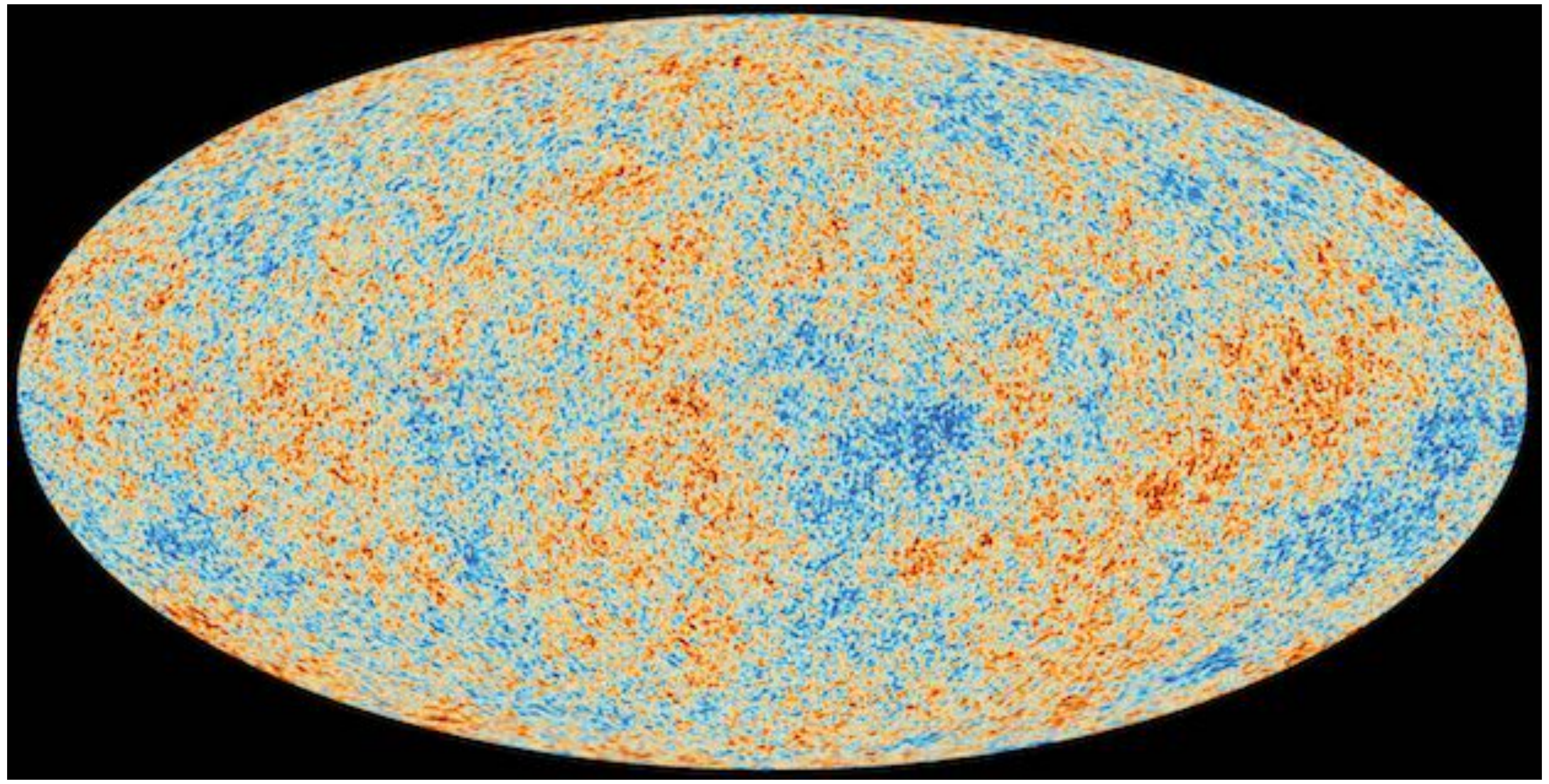
Now that the principles for the detection of primary and secondary particles have been described, the **interactions of astroparticles traveling from their sources to Earth through galactic and extragalactic space** shall be briefly discussed.

Neutrinos are only subject to weak interactions with matter, so their range is extremely large. The galactic or intergalactic space does not attenuate the neutrino flux, and magnetic fields do not affect their direction; therefore, **neutrinos point directly back to their sources.** Large hopes of neutrino astronomy rest on the ICECUBE detector at the South Pole and its planned extensions. These seem to be justified after their observation of **high-energy neutrinos in the PeV range from extragalactic distances.**

The **matter density in our galaxy, and particularly in intergalactic space, is very low.** This signifies that the **ionization energy loss** of primary protons traveling from their sources to Earth is **extremely small.**

Propagation of astroparticles

Protons can, **however, interact with cosmic photons**. **Blackbody photons**, in particular, represent a very-**high-density target** (≈400 photons/cm^3). The energy of these photons is very low, typically 250μeV, and they follow a Planck distribution (Fig. 4.16).



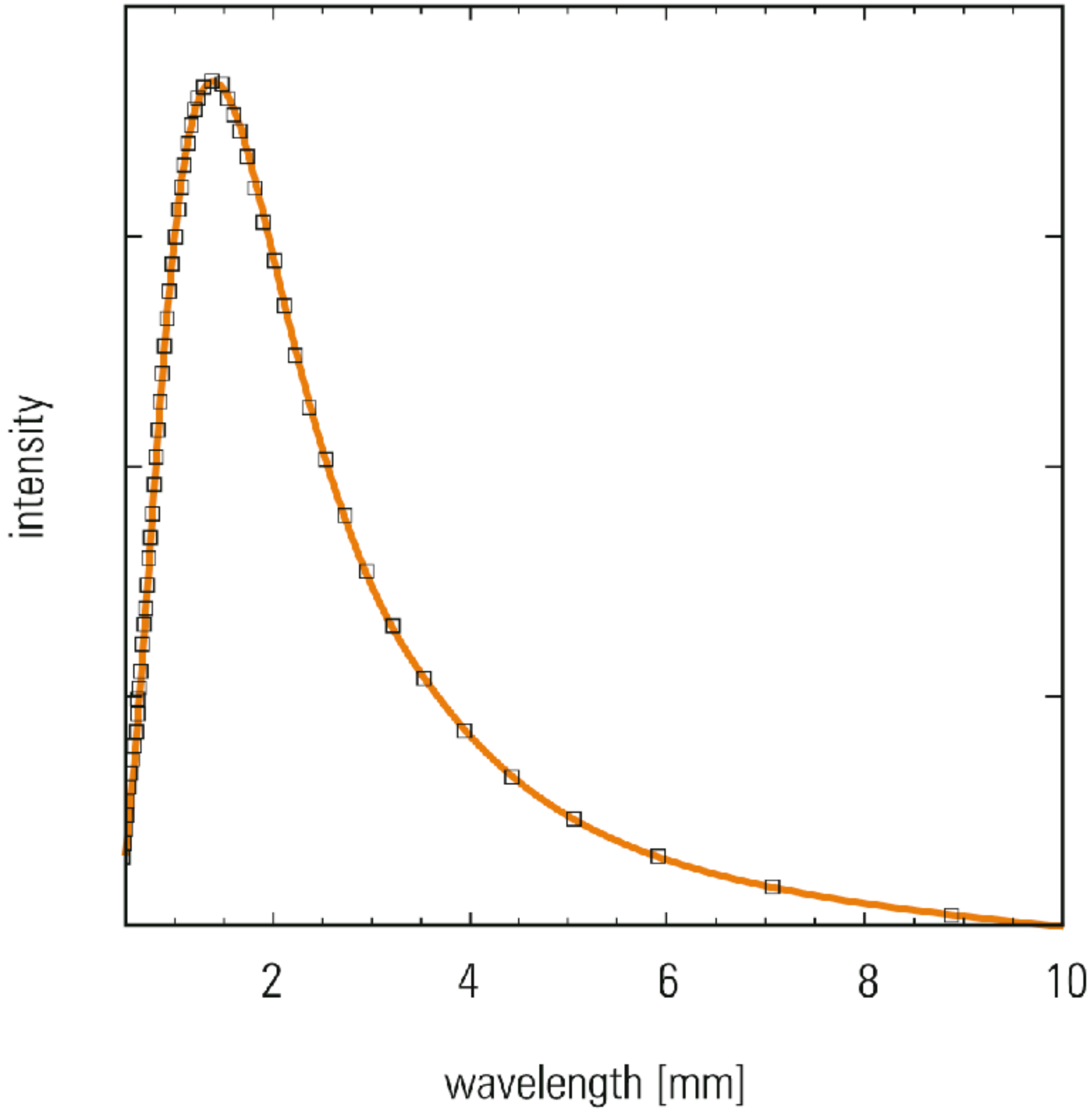


Fig. 4.16 Blackbody spectrum of cosmic microwave background photons

Propagation of astroparticles

The process of **pion production** by blackbody photons interacting with high-energy protons requires the **proton energy to exceed a certain threshold (Greisen-Zatsepin-Kuzmin cutoff)**. This threshold is reached if photo–pion production via the Δ resonance is kinematically possible in the photon–proton center-of-mass system ($p + \gamma \rightarrow p + \pi^0$).

If protons exceed this threshold energy, they **quickly lose their energy** and fall below the threshold. **The GZK cutoff limits the mean free path of the highest-energy cosmic rays** (energy $> 6 \times 10^{19}$ eV) to less than about 50 Mpc, quite a small distance in comparison to typical extragalactic scales.

Of course, energetic protons **lose also energy by inverse Compton scattering on blackbody photons**. **This process has no threshold.** Moreover, the cross section varies like $1/E_\gamma$, i.e., deceases rapidly with increasing photon energy. Compared to the resonant π^0 production **the cross section for inverse Compton scattering** of protons on blackbody photons **is small** and therefore has **no significant influence** on the shape of the primary proton spectrum.

Greisen-Zatsepin-Kuzmin cutoff

They predicted that cosmic rays with energies over the threshold energy of 5×10^{19} eV would interact with cosmic microwave background photons relatively blueshifted by the speed of the cosmic rays, to produce pions through the resonance,

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \text{ or } p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

Pions and neutrons produced in this manner proceed to decay in the standard pion channels, so that ultimately the energy of any cosmic ray proton is drained off by production of high-energy photons plus (in some cases) high-energy electron–positron pairs and neutrino pairs.

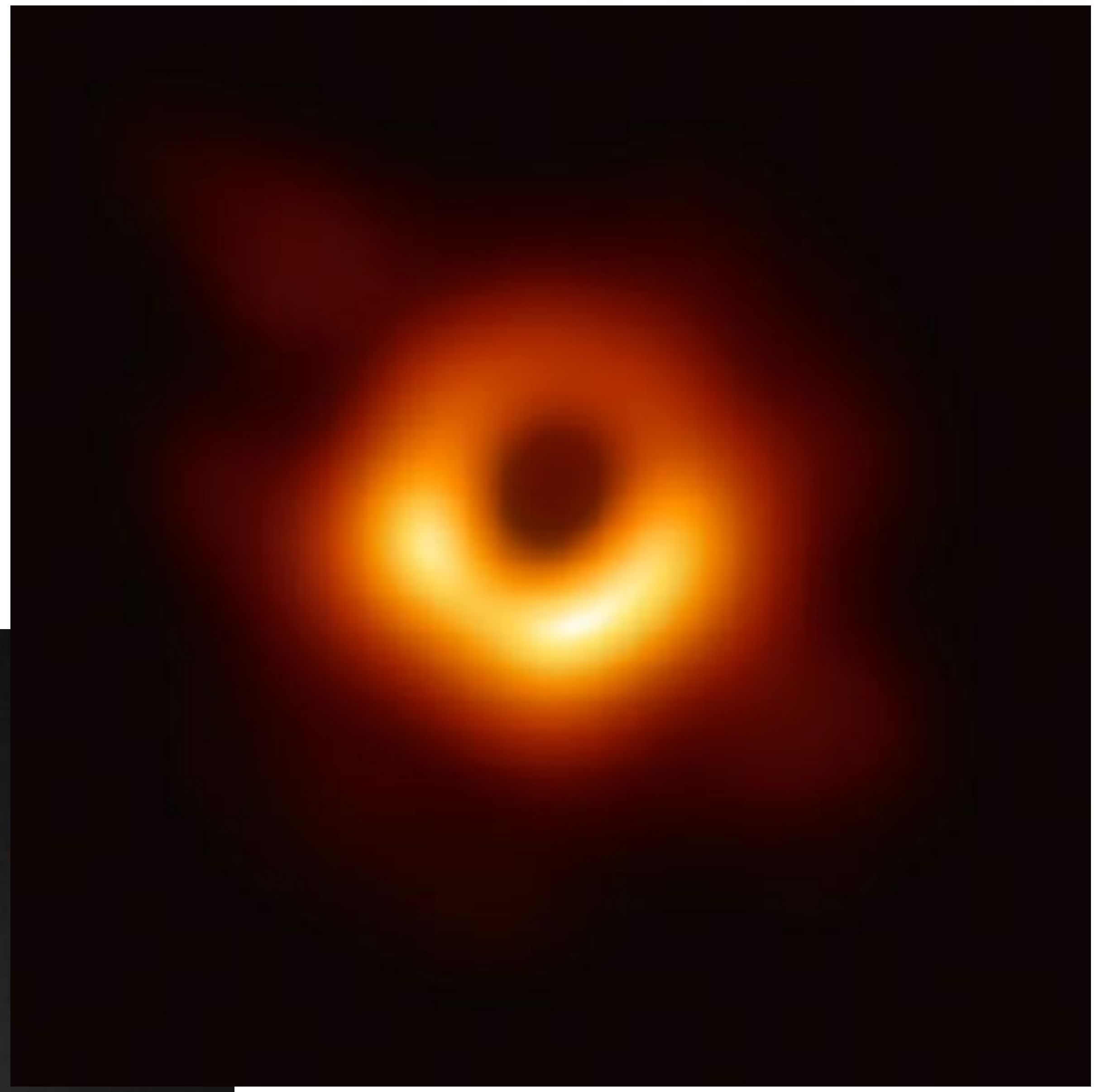
The pion production process starts at cosmic-ray proton energies of only about 10^{17} eV and drain 20% of the energy of a cosmic-ray proton, as compared with only 0.1% of its energy for electron–positron pair production. **The much larger total energy losses from pion production result in pion production becoming the process limiting high-energy cosmic-ray travel**, rather than the lower-energy process of light-lepton production.

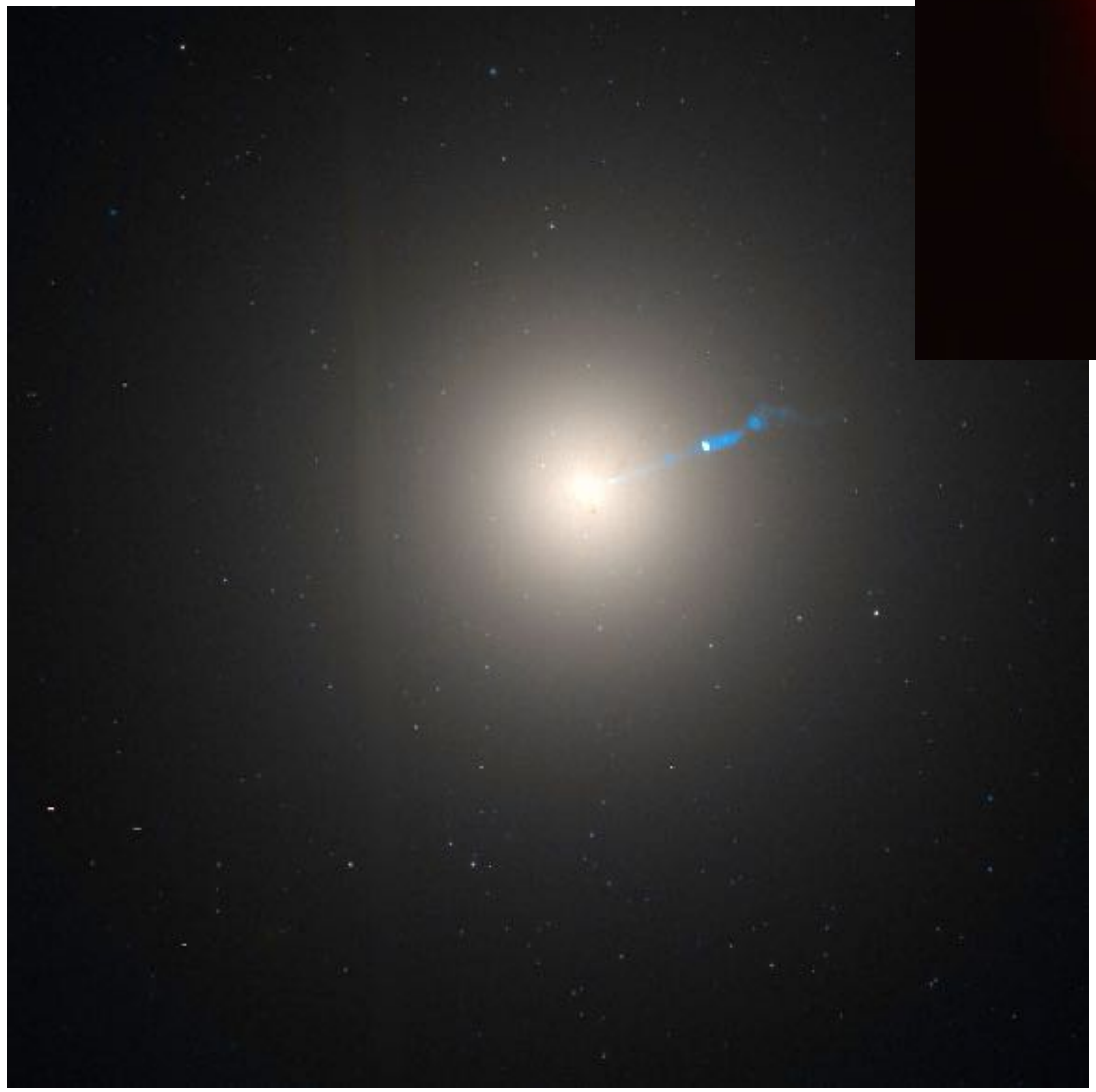
The pion production process **continues until the cosmic ray energy falls below the threshold for pion production**. Due to the **mean path associated with this interaction,** extragalactic cosmic ray protons traveling over distances larger than **50 Mpc** and with energies greater than the threshold should never be observed on Earth. This distance is also known as GZK horizon.

There are about ~15000 galaxies within 50 Mpc. (Centaurus A is 3-5 Mpc away from us.)

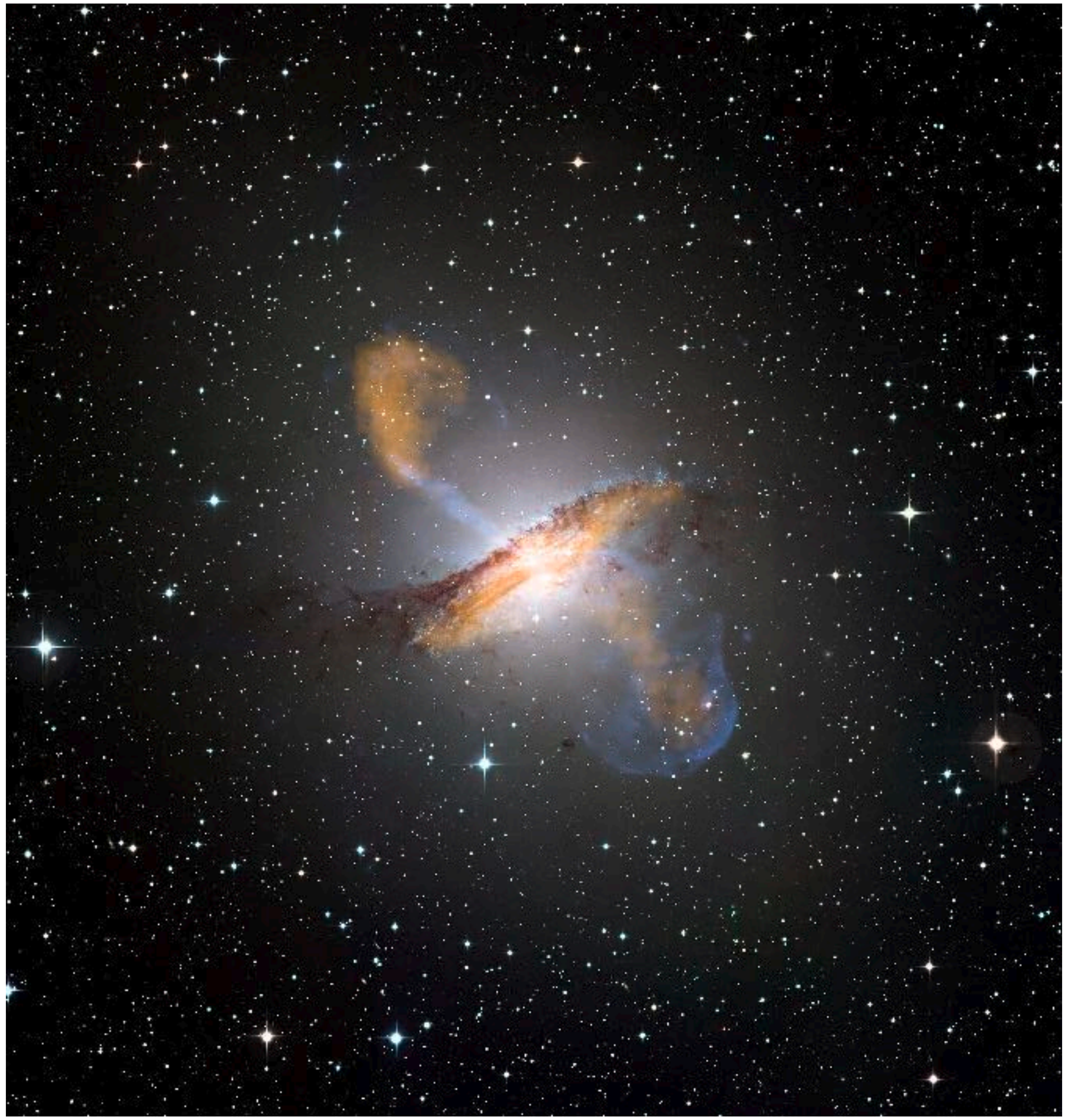
Nearby AGN

M87
16 MPc





Centaurus A
One of the closest AGNs to Earth
3-5 MPc

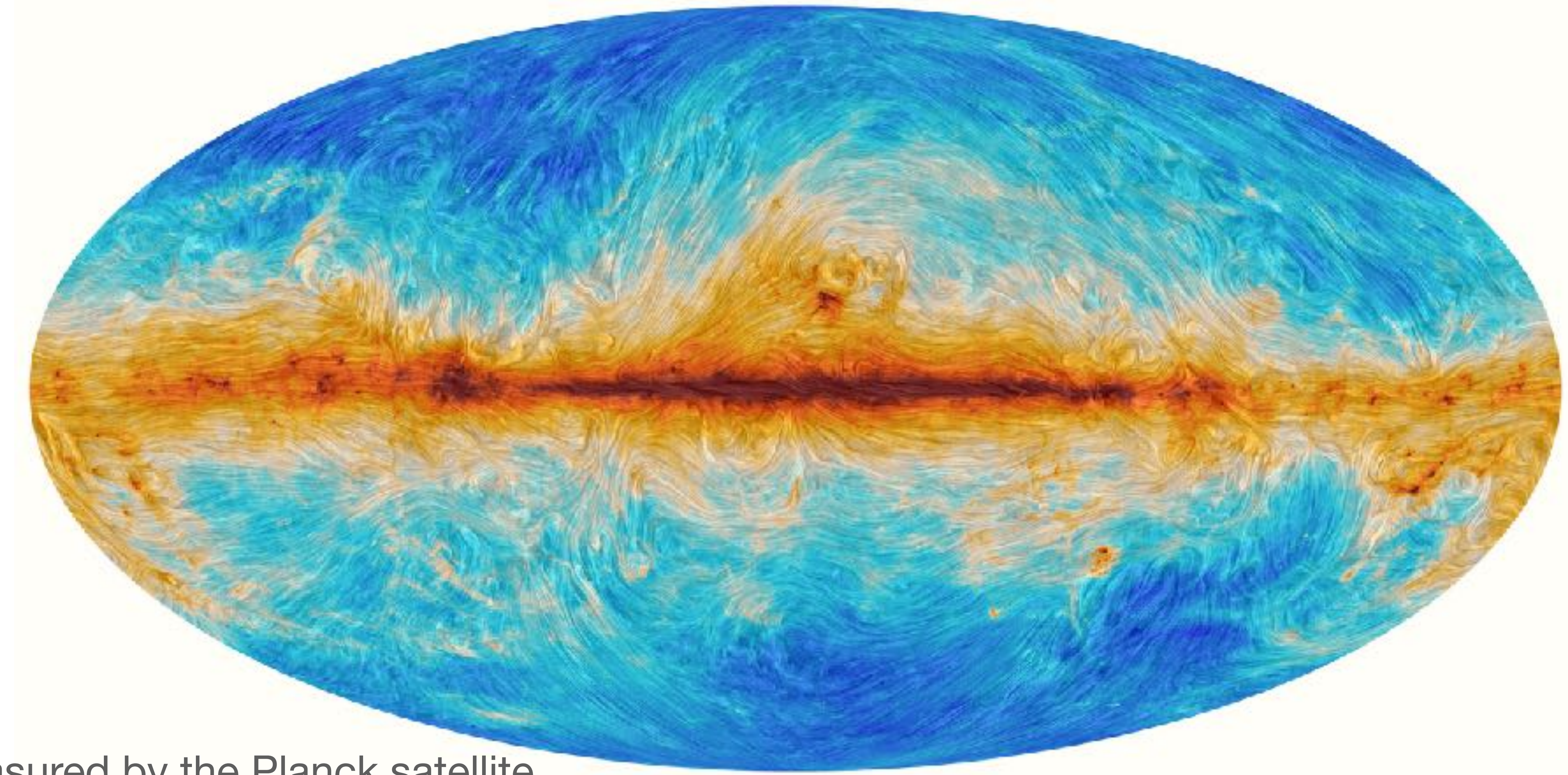


Propagation of astroparticles

A further possible process, $p + \gamma \rightarrow p + e^{+} + e^{-}$, even though it **has a lower threshold** than $p + \gamma \rightarrow p + \pi^{0}$, **does not proceed through a resonance**, and therefore its influence on the propagation of energetic protons in the dense photon field is of **little importance.** It does, however, modify the shape of the primary spectrum at the highest energies.

In addition, **primary protons** (as charged particles) naturally **interact with the galactic and extragalactic magnetic fields as well as the Earth's magnetic field.** Only the most energetic protons (energy $\gg 10^{18}$ eV), which experience a sufficiently small magnetic deflection, can be used for particle astronomy.

Magnetic Field in the Whirlpool galaxy, M51
Based on infrared polarisation measurements



The Galactic magnetic field measured by the Planck satellite

Propagation of astroparticles

Photons are not influenced by magnetic fields. (Says the book) → not entirely true, the photon energy is not influenced. **Which property is influenced?**

They can interact with blackbody photons to create electron–positron pairs via the $\gamma + \gamma \rightarrow e^+ + e^-$ process. Owing to the low electron and positron masses, the **threshold energy for this process is only about ≈10^{15} eV**.

The attenuation of primary photons (by interactions with blackbody photons), as a function of the primary photon energy, is shown in Fig. 4.17 for several distances to possible γ -ray sources.

The process $\gamma + \gamma \rightarrow e^+ + e^-$ **limits the range of energetic photons (>10^{15} eV) effectively to about 50 kpc (inside the Galaxy)**. For higher energies, $\gamma\gamma$ processes with different final states ($\mu^+\mu^-$, ...) also occur.

Do we detect photons with higher energies?

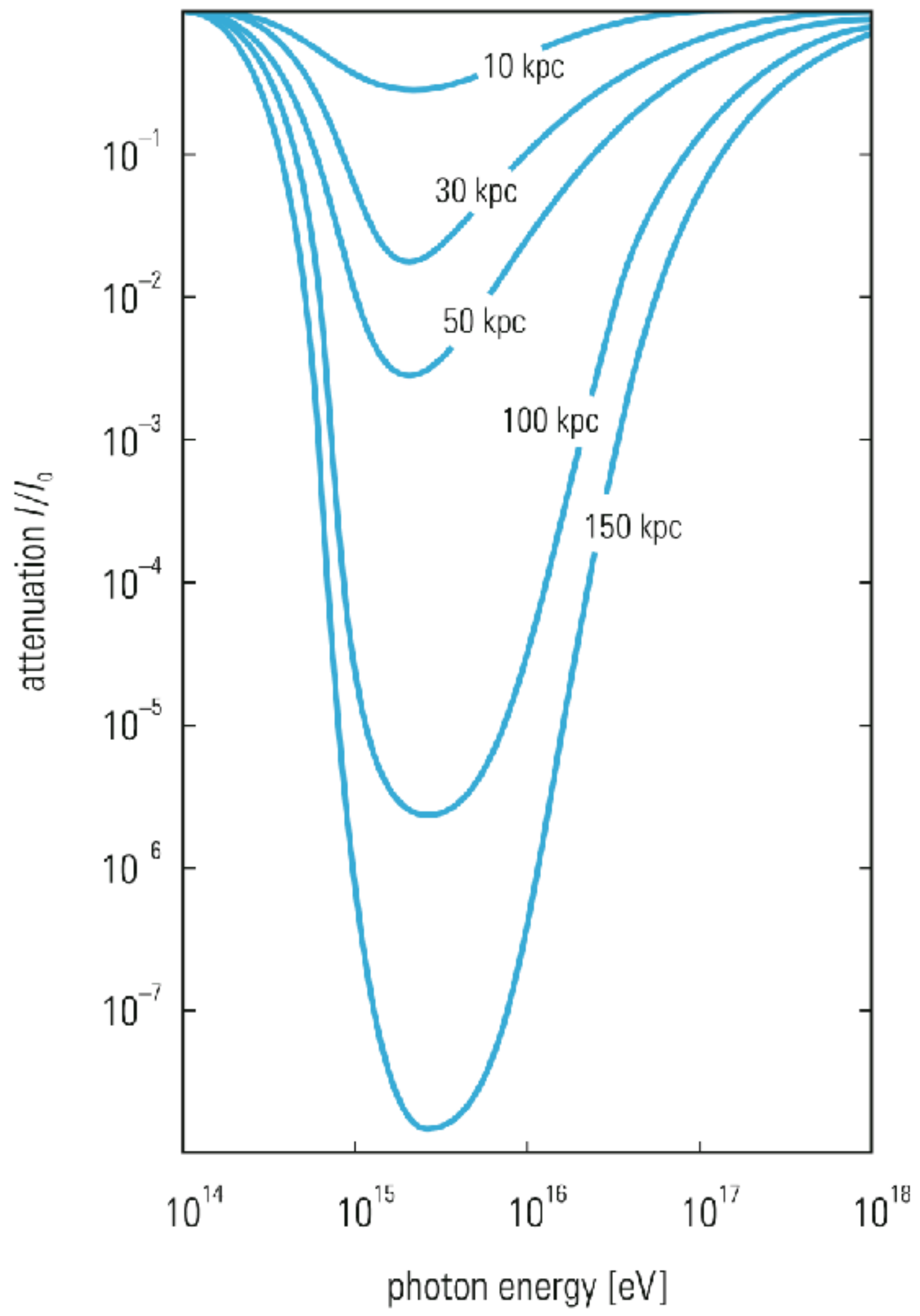
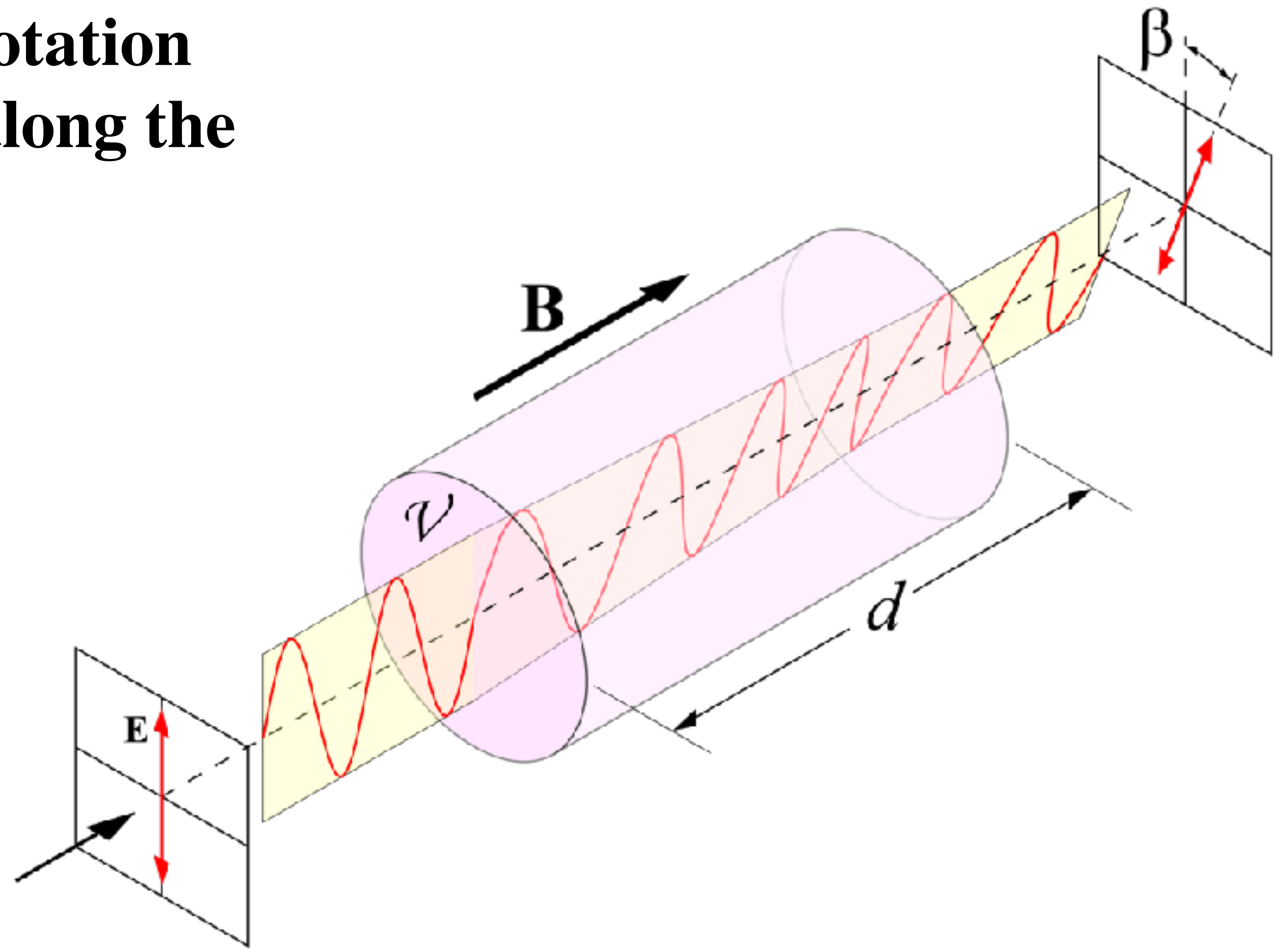


Fig. 4.17 Attenuation of the intensity of energetic primary photons by interactions with blackbody radiation

Faraday rotation

The Faraday effect or **Faraday rotation,** sometimes referred to as the magneto-optic Faraday effect (MOFE), is a physical magneto-optical phenomenon. The Faraday effect causes **a polarization rotation which is proportional to the projection of the magnetic field along the direction of the light propagation.**



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

Propagation of astroparticles

A potentially competing process, $\gamma + \gamma \rightarrow \gamma + \gamma$, is connected with a very small cross section (it is proportional to the fourth power of the fine-structure constant). In addition, the angular deflection of the photons due to this process is extremely small.

Apart from the attenuation of photons due to interactions with the cosmological background radiation, **also processes at lower energies with starlight photons and infrared radiation become relevant. Even radiation from the radio domain attenuates photons at higher energies** (Fig. 4.18).

In addition, photons can also produce electron–positron pairs on cosmic protons, albeit with lower cross sections.

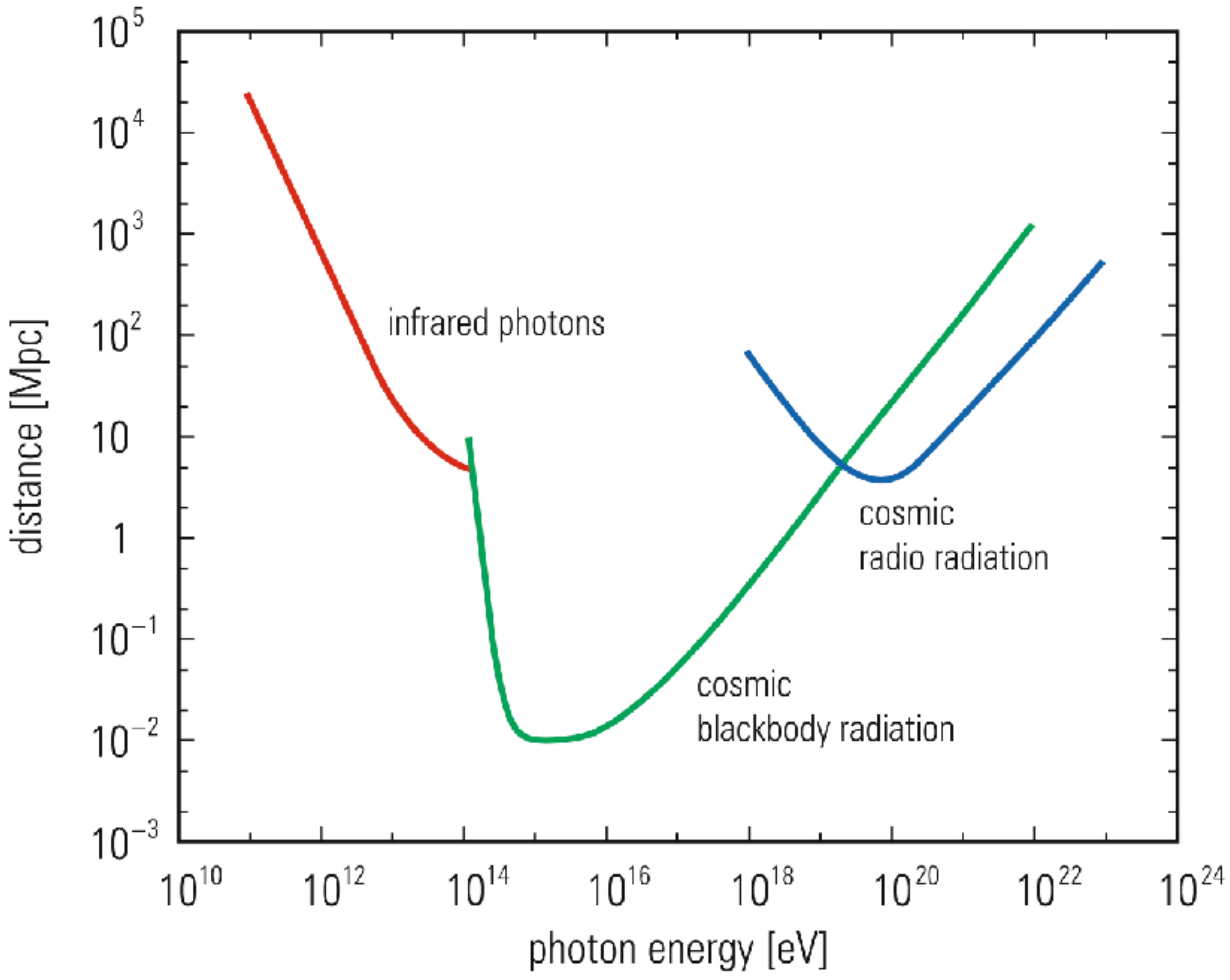


Fig. 4.18 Attenuation of high-energy photons by interactions with infrared photons, the cosmic blackbody radiation, and cosmic radio emission in its respective dependence on the photon energy. On the ordinate the distance is given that the photons of a given energy can pass without significant attenuation [47]

Characteristic features of detectors

The secondary interaction products of astroparticles are detected in an appropriate device, which can be a detector on board of a satellite, in a balloon, or at ground level, or even in an underground laboratory. The quality of the measurement depends on the energy and position resolution of the detector. In most cases the ionization energy loss is the relevant detection mechanism.

- In gaseous detectors an average of typically 30eV is required to produce an electron–ion pair. The liberated charges are collected in an external electric field and produce an electric signal that can be further processed.
- In contrast, in solidstate detectors, the average energy for the creation of an electron–hole pair is only ≈3eV, resulting in an improved energy resolution.
- If, instead, excitation photons produced by the process of scintillation in a crystal detector are recorded, e.g., by photomultipliers, energy deposits of about 25 eV are necessary to yield a scintillation photon in inorganic materials (like NaI(Tl)),
- while in organic crystals ≈100 eV are required to create a scintillation photon.
- In cryogenic detectors much less energy is needed to produce charge carriers. This substantial advantage, which gives rise to excellent energy resolutions, is only obtained at the expense of operating the detectors at cryogenic temperatures, mostly in the milli-kelvin range.

Characteristic features of detectors

Apart from these classical techniques also new methods of particle detection become popular.

- Different techniques are, for example, used for extensive air showers by measuring scintillation photons with fluorescence telescopes
- or photons created via geosynchrotron radiation.
- Also Cherenkov-generated radio emission or even acoustic detection of energetic events is used or is under investigation.

Problems

4. Show that the mass of a charged particle can be inferred from the Cherenkov angle θ_C and momentum p by

$$m_0 = \frac{p}{c}\sqrt{n^2 \cos^2 \theta_C - 1}\,,$$

where n is the index of refraction.

Problems

5. In a cryogenic argon calorimeter ($T = 1.1$ kelvin, mass 1 g) a WIMP (weakly interacting massive particle) deposits 10 keV. By how much does the temperature rise?
   (The specific heat of argon at 1.1 K is $c_{\text{sp}} = 8 \times 10^{-5}\,\text{J}/(\text{g K})$.)

Problems

7. Work out the maximum energy that can be transferred to an electron in a Compton process! As an example use the photon transition energy of 662 keV emitted by an excited ^{137}Ba nucleus after a beta decay from ^{137}Cs,

$$
\begin{aligned}
{}^{137}\mathrm{Cs} \rightarrow\ & {}^{137}\mathrm{Ba}^{*} + e^{-} + \bar{\nu}_e \\
& \hookrightarrow {}^{137}\mathrm{Ba} + \gamma\ (662\,\mathrm{keV}) .
\end{aligned}
$$

What kind of energy does the electron get for infinitely large photon energies? Is there, on the other hand, a minimum energy for the backscattered photon in this limit?

Problems

9. Equation (4.4.3) shows that the number of emitted Cherenkov photons N is proportional to $1/\lambda^2$. The wavelength for X-ray photons is shorter than that for the visible light region. Why then is Cherenkov light not emitted in the X-ray region?

$$\begin{aligned}\frac{\mathrm{d}N}{\mathrm{d}x} &= 2\pi\alpha z^2 \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \sin^2\theta_{\mathrm{C}} \\ &\approx 490\, z^2 \sin^2\theta_{\mathrm{C}}\ \mathrm{cm}^{-1}\,.\end{aligned} \tag{4.4.3}$$