Special Topics in Particle Physics

Big Bang Nucleosynthesis

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The thermal history of the first 10μs

The Planck mass, length, time, etc. are the unique quantities with the appropriate dimension that can be **constructed from the fundamental constants linking quantum mechanics and relativity**: $\hbar$, c, and G. Since henceforth $\hbar$ and c will be set equal to one, and one has

$$m_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}} \approx 2.2 \times 10^{-5}\,\mathrm{g}\,, \qquad l_{\mathrm{Pl}} = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \times 10^{-35}\,\mathrm{m}\,. \qquad t_{\mathrm{Pl}} = \frac{l_{\mathrm{Pl}}}{c} = \sqrt{\frac{\hbar G}{c^5}} \approx 5.4 \times 10^{-44}\,\mathrm{s}$$

We will skip most of the cosmology and general relativity and just focus on the particle physics aspect. Of course, I recommend to read the cosmology chapters for a better understanding of the topic.

The thermal history of the first 10μs

The time-dependent energy density of the Universe (assuming thermal equilibrium):

$$\varrho = \frac{3m_{\mathrm{Pl}}^2}{32\pi}\frac{1}{t^2}\,. \tag{9.4.18}$$

We can work out the **energy density and temperature of the universe as a function of time**.

As a start, one can use (9.4.18) to give the **energy density at the Planck time,** although one needs to keep in mind that the assumption of thermal equilibrium may not be valid. In any case the formula gives

$$\varrho(t_{\mathrm{Pl}}) = \frac{3m_{\mathrm{Pl}}^2}{32\pi}\frac{1}{t_{\mathrm{Pl}}^2} = \frac{3}{32\pi}m_{\mathrm{Pl}}^4 \approx 6\times 10^{74}\,\mathrm{GeV}^4\,, \tag{9.5.1}$$

where $m_{\mathrm{Pl}} = 1/t_{\mathrm{Pl}} \approx 1.2\times 10^{19}$ GeV has been used. One can convert this to normal units by dividing by $(\hbar c)^3$,

$$\begin{aligned}\varrho(t_{\mathrm{Pl}}) &\approx 6\times 10^{74}\,\mathrm{GeV}^4 \times \frac{1}{(0.2\,\mathrm{GeV\,fm})^3}\\ &\approx 8\times 10^{76}\,\mathrm{GeV/fm}^3\,. \end{aligned} \tag{9.5.2}$$

This density corresponds to about **10^{77} proton masses in the volume of a single proton!**

The thermal history of the first 10μs

Proceeding now more systematically, one can find the **times and energy densities, at which different temperatures were reached.** By combining this with the knowledge of particle physics, one will see **what types of particle interactions were taking place at what time.** To do this numerically, we need all particles, which have contributed to the energy density, including all their spin and colour states. In good **approximation we can treat all particles of the Standard Model as being relativistic** (T larger than a few hundred GeV). Possibly existing heavier particles from supersymmetric theories will change the results only insignificantly.

Table 9.2 shows values for the temperature and energy density at several points within the first 10 ms after the Big Bang, where most of the values have been rounded to the nearest order of magnitude.

Table 9.2 Thermal history of the first 10 ms

Scale	T (GeV)	ϱ (GeV^4)	t (s)
Planck	10^{19}	10^{77}	10^{-43}
GUT	10^{16}	10^{66}	10^{-39}
Electroweak	10^{2}	10^{10}	10^{-11}
QCD	0.2	0.01	10^{-5}

Particle masses

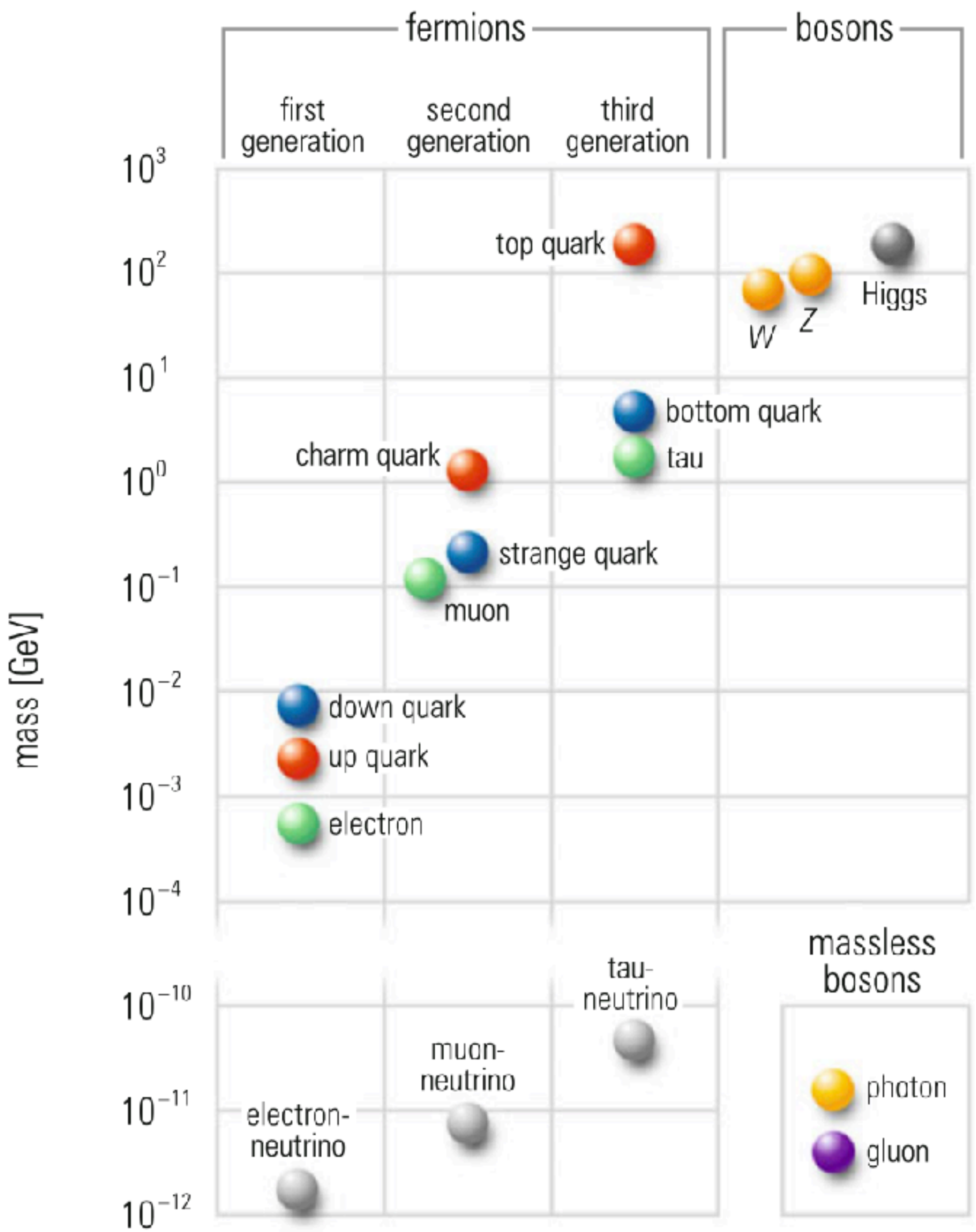

Fig. 9.1 Hierarchy of particle masses. The masses of neutrinos are not yet known. From direct measurements together with cosmology one gets a limit for each neutrino flavour of below 10^{-9} GeV. Neutrino oscillations are only sensitive to the difference of the squares of the masses. Assuming a mass hierarchy similar to the sector of charged leptons one can have a guess at the neutrino masses [169]

The thermal history of the first 10μs

At the Planck scale, i.e., with energies on the order of **10^{19} GeV**, and earlier times than 10^{-39} s, the **limit of our ability to speculate** about cosmology and cosmoparticle physics has been reached.

At temperatures or corresponding energies of **10^{16} GeV the different interactions separate into strong and electroweak interactions** with their own couplings strengths. This is the scale of Grand Unified Theories (GUT scale). One expects that this **phase transition is related to the Higgs field.** The vacuum expectation value of the Higgs field above the GUT scale should be zero. **Up to this moment the masses of elementary particles were zero. During the transition the vacuum expectation value of the Higgs field will adopt non-zero values. This phenomenon is called spontaneous symmetry breaking (SSB).** As a result, the hypothetical X and Y bosons from earlier times go from being massless to having very high masses on the order of the GUT scale. So, at lower temperatures, **baryon-number-violating processes mediated by exchange of X and Y bosons** are highly suppressed.

X and Y bosons

In particle physics, the **X and Y bosons** (sometimes collectively called "X bosons") are **hypothetical elementary particles analogous to the W and Z bosons**, but corresponding to a unified force predicted by the Georgi–Glashow model, a grand unified theory (GUT).
Since the X and Y boson mediate the grand unified force, they would have **unusual high mass**, which requires more energy to create than the reach of any current particle collider experiment. Significantly, **the X and Y bosons couple quarks to leptons, allowing violation of the conservation of baryon number thus permitting proton decay.**
However, the Hyper-Kamiokande has put a lower bound on the proton's half-life as around 10^{34} years. Since some grand unified theories such as the Georgi–Glashow model predict a half-life less than this, then the existence of X and Y bosons, as formulated by this particular model, remain hypothetical.

Grand Unified Theory (GUT) is any model in particle physics that merges the electromagnetic, weak, and strong forces into a single force at high energies. Although this unified force has not been directly observed, many GUT models theorize its existence. If the unification of these three interactions is possible, **it raises the possibility that there was a grand unification epoch in the very early universe in which these three fundamental interactions were not yet distinct.**

https://en.wikipedia.org/wiki/Grand_Unified_Theory https://en.wikipedia.org/wiki/X_and_Y_bosons

The thermal history of the first 10μs

After around **10^{-11} s**, the temperature is on the order of **100 GeV**; this is called the **'electroweak scale'**. Here another **SSB phase transition is expected to occur, whereby the electroweak Higgs field acquires a non-zero vacuum expectation value.** As a result, ***W* and *Z* bosons as well as the quarks and leptons acquire their masses.** At temperatures significantly lower than the electroweak scale, the masses $M_W \approx 80$ GeV and $M_Z \approx 91$GeV are large compared to the kinetic energies of other colliding particles, and the *W* and *Z* propagators effectively suppress the strength and the range of the weak interaction.

At temperatures around **0.2 GeV (the 'QCD scale'),** the effective coupling strength of the strong interaction, α_s, becomes very large. At this point **quarks and gluons become confined into colour-neutral hadrons**: protons, neutrons, and their antiparticles. This process, called ***hadronization***, occurs around $t \approx$ **10^{-5} s**. Here one has to keep in mind that the assumption of highly relativistic particles becomes a little questionable.

The Density at this time is **about seven times the density of ordinary nuclear matter**.

Experiments at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory near New York are currently underway to recreate these conditions by colliding together heavy ions at very high energies. This will allow more detailed studies of the 'quark–gluon plasma' and its transition to colour-neutral hadrons.

The thermal history of the first 10μs

This short sketch of the early universe has ignored **at least two major issues**. First, it has not yet been explained **why the universe appears to be composed of matter, rather than a mixture of matter and antimatter.** There is no definitive answer to this question but there are plausible scenarios, whereby the so-called baryon asymmetry of the universe could have arisen at very early times, perhaps at the GUT scale or later at the electroweak scale.

One will also see that the model that has been developed thus far fails to **explain several observational facts, the most important of which are related to the cosmic microwave background radiation**. A possible remedy to these problems will be to suppose that **the energy density at some very early time was dominated by vacuum energy**. In this case one will **not find $R \sim t^{1/2}$ but rather an exponential increase, known as *inflation*.**

The Baryon Asymmetry

For several decades after the discovery of the positron, it appeared that the laws of nature were completely symmetric between matter and antimatter.

The universe known to us, however, seems to consist of matter only. One has to examine **how this asymmetry could evolve from a state that initially contained equal amounts of matter and antimatter**, a **process called *baryogenesis***. For every proton there is an electron, so **the universe also seems to have a non-zero lepton number.** This is a bit more difficult to pin down, however, since the lepton number could in principle be compensated by unseen antineutrinos. In any case, models of baryogenesis generally incorporate in some way lepton production (***leptogenesis***) as well.

Baryogenesis provides a nice example of the interplay between particle physics and cosmology. In the final analysis it will be seen that **the Standard Model as it stands cannot explain the observed baryon asymmetry of the universe**. This is a compelling indication that the Standard Model is incomplete.

Experimental evidence for the Baryon Asymmetry

If antiparticles were to exist in significant numbers locally, one would see **evidence of this from proton–antiproton or electron–positron annihilation**.

$p\bar{p}$ **annihilation produces typically several mesons** including neutral pions, **which decay into two photons. So, one would see γ rays in an energy range up to around 100 MeV**. No such gamma rays resulting from asteroid impacts on other planets are seen, man-made space probes landing on Mars survived, so one can conclude that **the entire solar system is made of matter.**

One actually finds some **antiprotons bombarding the Earth as cosmic rays at a level of around 10^{-4}** compared to cosmic-ray protons, so one may want to leave open the possibility that more distant regions are made of antimatter.

But the observed antiproton rate is **compatible with production in collisions of ordinary high-energy protons with interstellar gas or dust** through reactions of the type

$$p + p \to 3p + \bar{p}\,.$$

Experimental evidence for the Baryon Asymmetry

There is currently no evidence of antinuclei in cosmic rays. The PAMELA satellite and the Alpha Magnetic Spectrometer (AMS) on board the International Space Station **failed to find antinuclei, like antihelium or even heavier antinuclei,** even though heavy antinuclei, like antihelium, have been created at CERN and RHIC (Relativistic Heavy Ion Collider in Brookhaven) in heavy-ion collisions.

The STAR experiment was able to produce **18 antihelium-4 events at the relativistic heavy ion collider** RHIC. This indicates that also heavier antinuclei might be produced in cosmic rays.

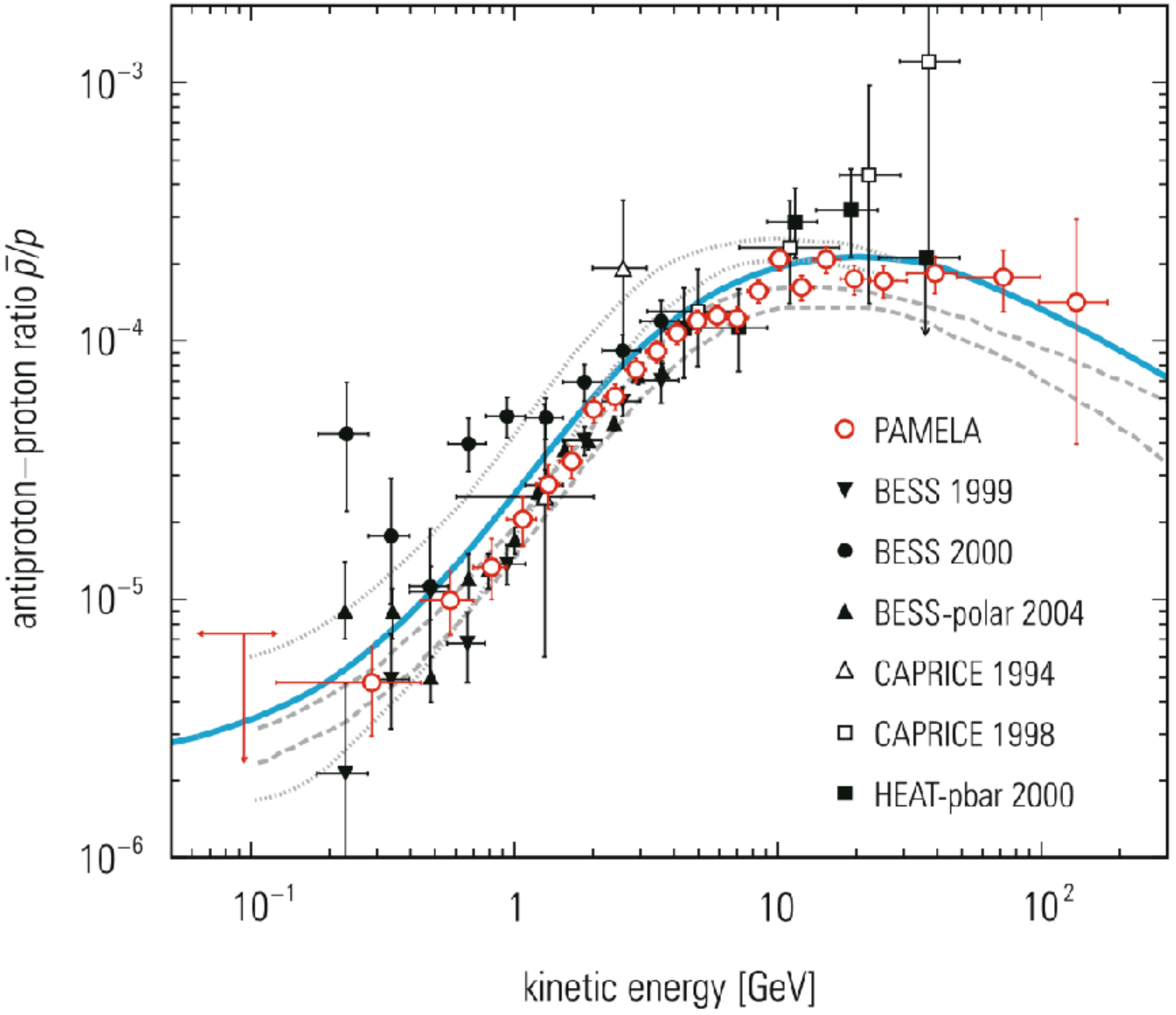

Fig. 9.2 Antiproton–proton ratio in primary cosmic rays according to the PAMELA experiment. The different calculations (*curves*) clearly show that antiproton production can be understood in terms of secondary production [171]

Experimental evidence for the Baryon Asymmetry

If there would exist appreciable numbers of positrons in the universe and in the Milky Way, one would also expect to find evidence for the 511-keV annihilation line according to the reaction $e^+ + e^- \rightarrow \gamma + \gamma$. Actually one finds **such a line in the gamma-ray spectrum from our galaxy** (s. Fig. 9.3).

However, the intensity of this line can also be understood by **the annihilation of locally produced positrons.**

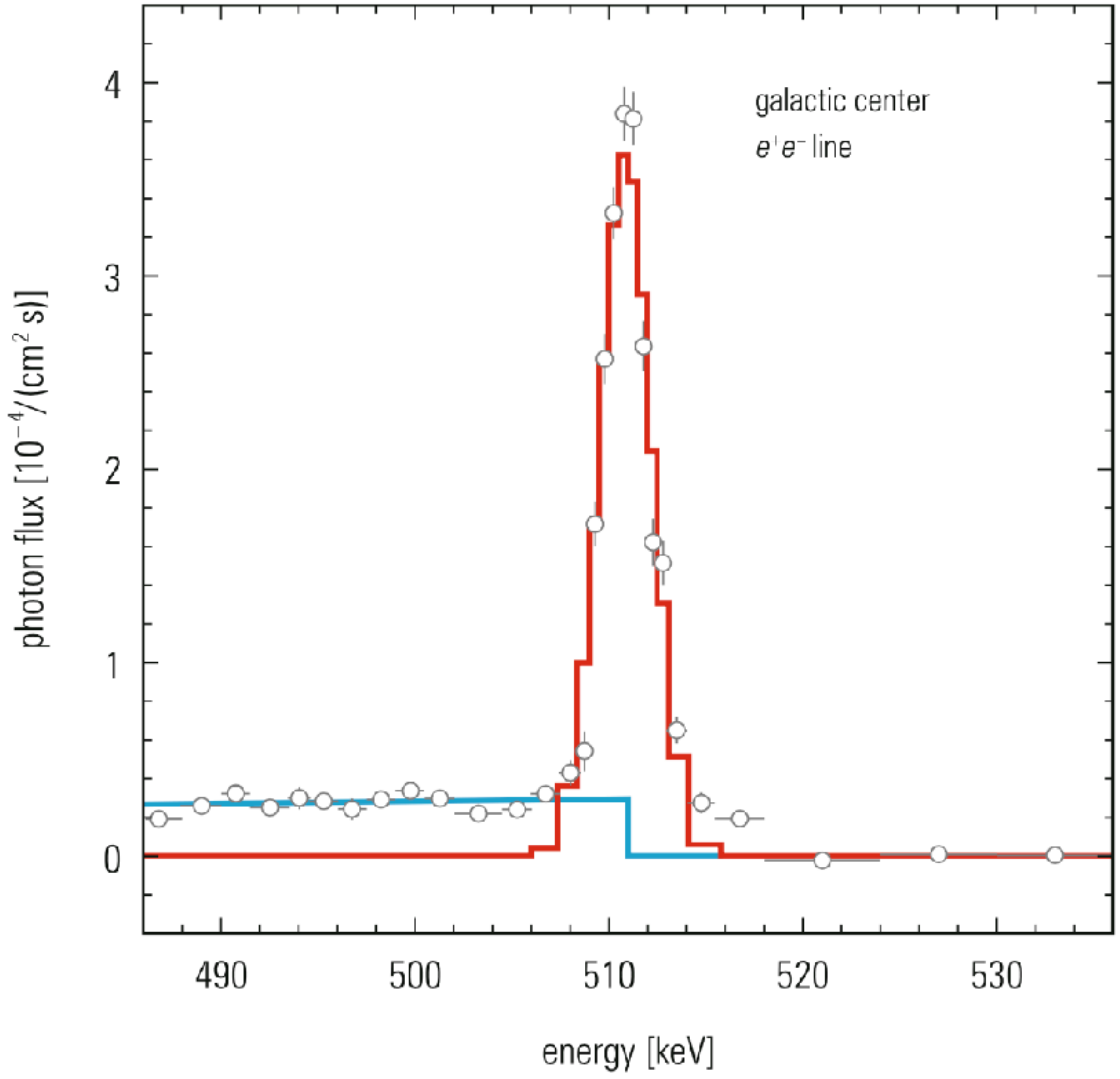

Fig. 9.3 The 511-keV positron annihilation line (*red curve*), observed from the galactic center. The *blue continuum line* originates from the positron annihilation into three photons [173, 174]

Experimental evidence for the Baryon Asymmetry

On the other hand, one finds **in the high-energy regime a positron flux, which cannot easily be understood** by local positron production (s. Figs. 9.4, 9.5). But then **it is conceivable that a relatively close supernova has injected cosmic particles, and thereby also positrons, into the Milky Way a long time ago.**

On the other hand, the positron excess has also been **attributed to the decay of candidates of heavy dark-matter particles.**

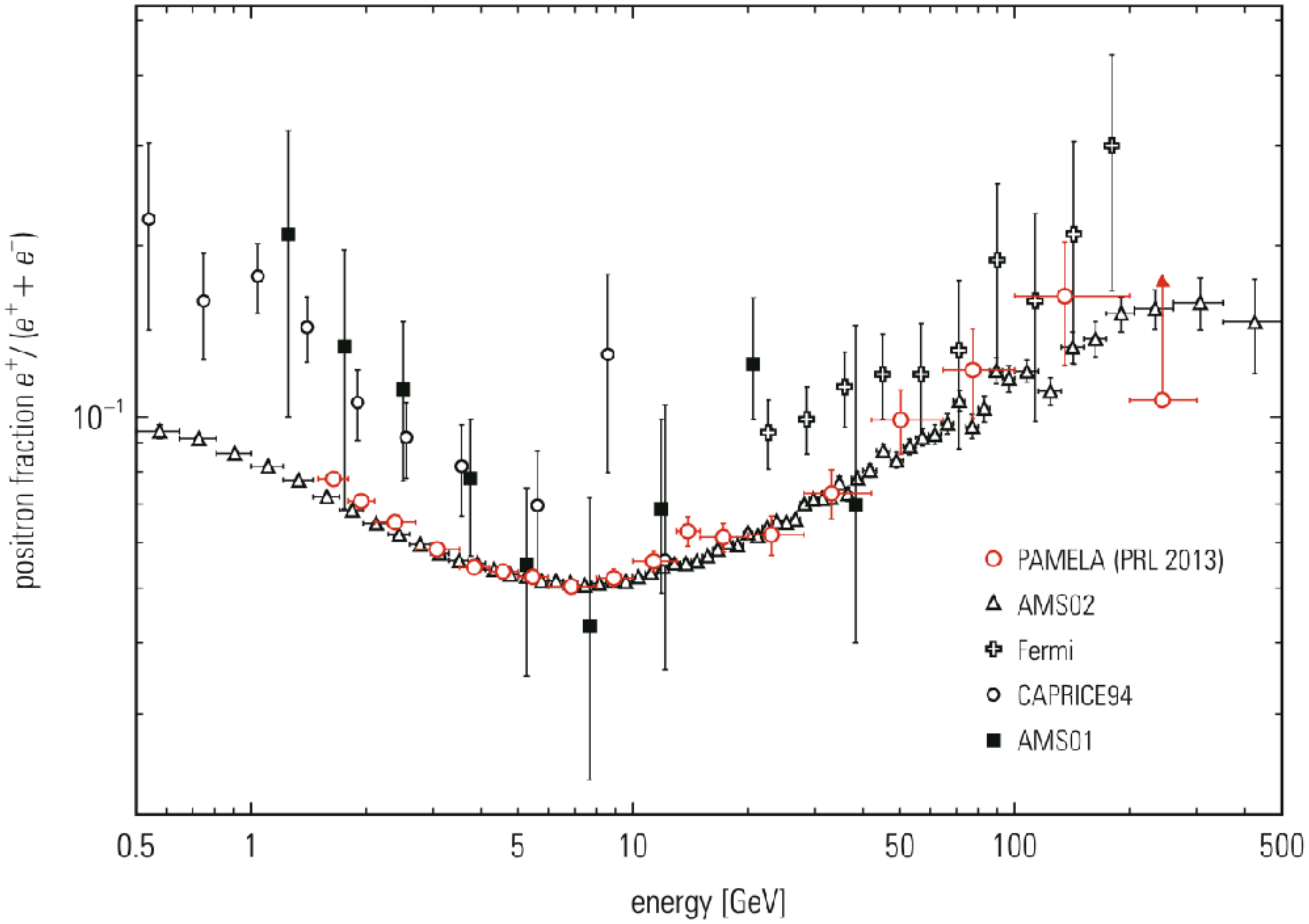

Fig. 9.4 The positron fraction in primary cosmic rays according to the PAMELA experiment [175]. At low energies the positron fraction follows the expectation on secondary local production. In contrast, at energies beyond 10 GeV there are significant deviations, which are not yet understood. The AMS experiment has confirmed the PAMELA result and extended the measurements to higher energies [176]

Experimental evidence for the Baryon Asymmetry

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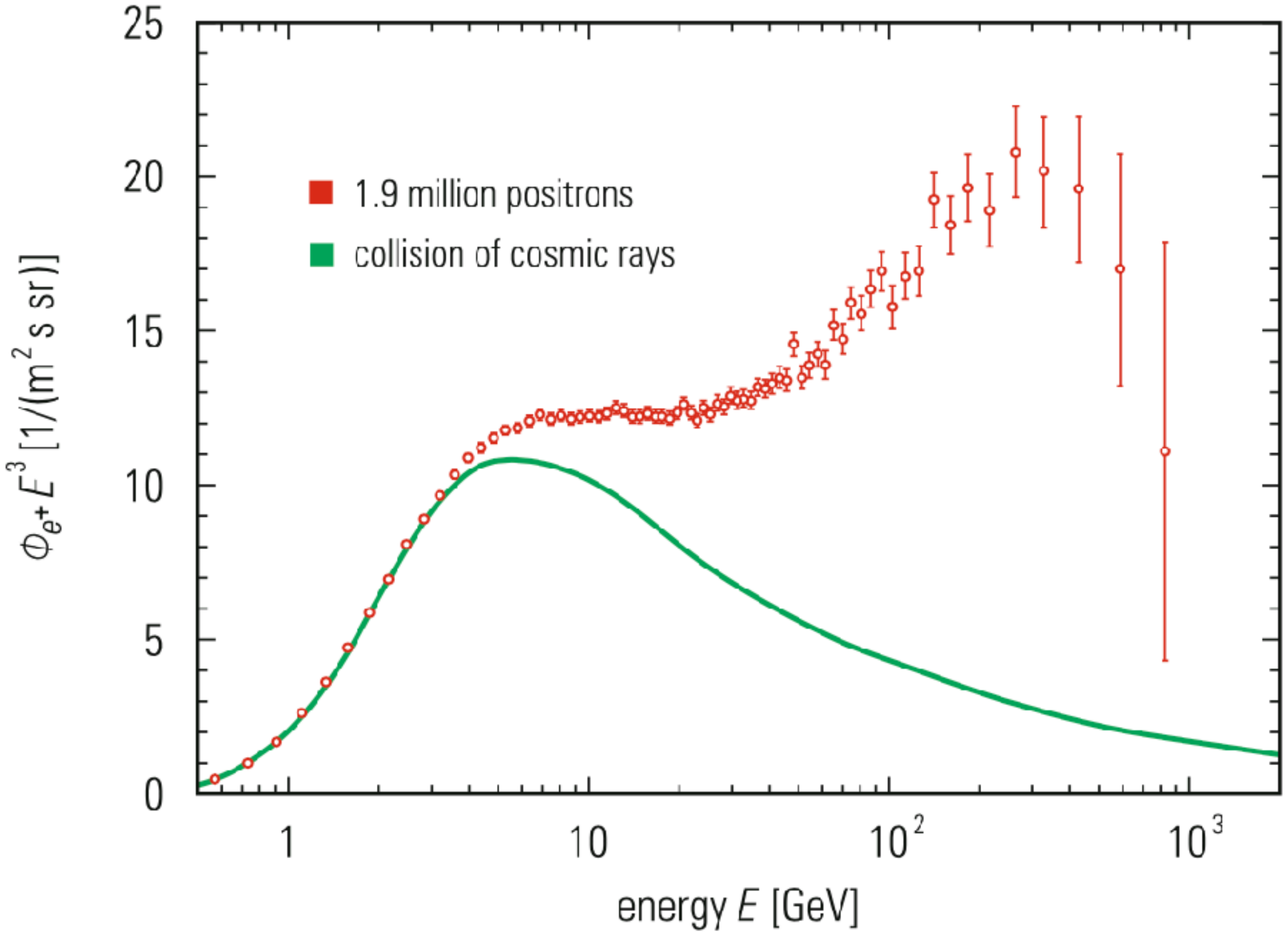


Fig. 9.5 The most recent data from the AMS Collaboration on the positron flux up to energies of 1 TeV. The flux exhibits a sharp drop at energies around 1 TeV [60]

Experimental evidence for the Baryon Asymmetry

It is also conceivable that the **sources of positrons are in very distant region**s even beyond the local group of galaxies. In that case one would **expect deviations in the observed gamma-ray spectrum from expectation**. Model calculations for a matter–antimatter symmetric universe are, **however, incompatible with data from the Compton Gamma Ray Observatory.** The calculations refer to very distant domains of 20Mpc or 1Gpc in size, respectively (s. Fig. 9.6). If there would exist in the universe, or at least in part of it, regions dominated by antimatter they should be at very large distances (> some Gpc).

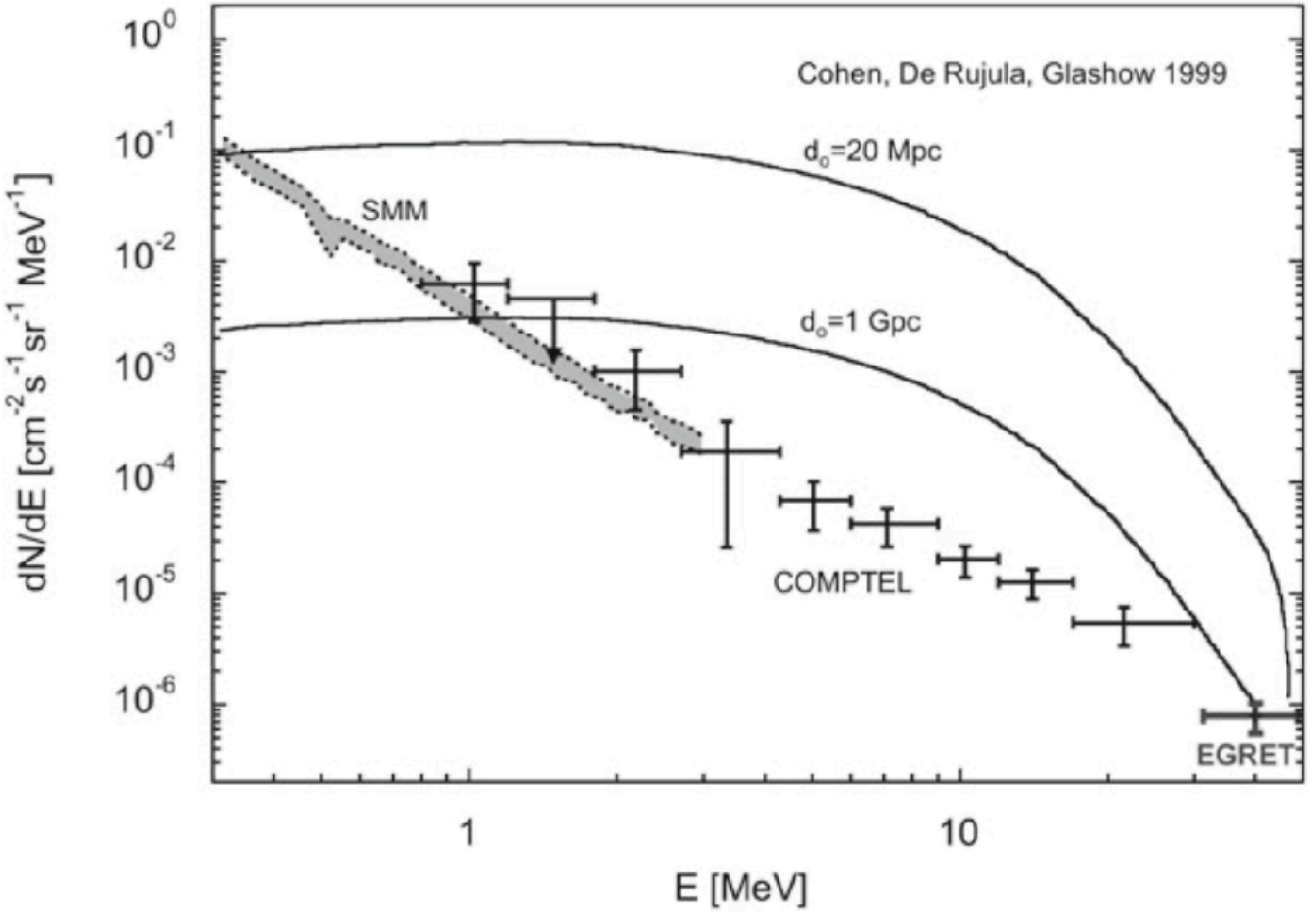


Fig. 9.6 The gamma-ray spectrum of the Compton telescope (COMPTEL) and EGRET calorimeters on board the Compton Gamma Ray Observatory, and the gamma-ray spectrometer for the Solar Maximum Mission (SMM) in comparison with model calculations for a matter–antimatter-symmetric universe at domains of size 20 Mpc resp. 1 Gpc separated from us [177]

Experimental evidence for the Baryon Asymmetry

So one can conclude that, if antimatter regions of the universe exist, they must be separated by distances on the order of a gigaparsec or larger, which is already a significant fraction of the observable universe. Given that there is no plausible mechanism for separating matter from antimatter over such large distances, **it is far more natural to assume that the universe is made of matter, i.e., that it has a net non-zero baryon number.** Also **the absence of a significant flux of 511-keV γ rays from electron–positron annihilation adds to this conclusion.**

If one then takes as working hypothesis that **the universe contains much more matter than antimatter, one needs to ask how this could have come about**.

One possibility is that the non-zero baryon number existed **as an initial condition,** and that this was preserved up to the present day. This is **not an attractive idea for several reasons**. First, although the asymmetry between baryons and antibaryons today appears to be large, **at times closer to the Big Bang, there were large amounts of both and the relative imbalance was very small.** Going back towards the Big Bang one would like to think that nature's laws become in some sense more fundamental, and one would prefer to avoid the need to impose any sort of small asymmetry by hand.

Furthermore, it now appears that **the laws of nature allow, or even require, that a baryon asymmetry would arise from a state that began with a net baryon number of zero.**

Baryon Asymmetry

Although the universe today seems completely dominated by baryons and not antibaryons, the **relative asymmetry was very much smaller at earlier times**.

This can be seen roughly by considering a time **when quarks and antiquarks were all highly relativistic, at a temperature of, say, $T \approx 1$ TeV**, and suppose that since that time there have been no baryon-number-violating processes. The net baryon number in a comoving volume R^3 is then constant, so one has

$$(n_{\mathrm{b}} - n_{\bar{\mathrm{b}}})R^3 = (n_{\mathrm{b},0} - n_{\bar{\mathrm{b}},0})R_0^3 \,, \tag{9.6.2}$$

where the subscript 0 on the right-hand side denotes present values. Today, however, there are essentially no antibaryons, so one can approximate $n_{\bar{b},0} \approx 0$. **The *baryon– antibaryon asymmetry A*** is therefore

$$A \equiv \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{n_{\mathrm{b}}} = \frac{n_{\mathrm{b},0}}{n_{\mathrm{b}}} \frac{R_0^3}{R^3} \,. \tag{9.6.3}$$

Baryon Asymmetry

$$n \sim T^3 \tag{9.2.2}$$

One can now relate the ratio of scale factors to the ratio of temperatures, using the relation $R \sim 1/T$. Therefore, one gets

$$A \approx \frac{n_{\mathrm{b},0}}{n_{\mathrm{b}}} \frac{T^3}{T_0^3} \,. \tag{9.6.4}$$

Now one can use the fact that the number densities are related to the temperature. Equation (9.2.2) had shown

$$n_{\mathrm{b}} \approx T^3 \,, \tag{9.6.5}$$

$$n_{\gamma,0} \approx T_0^3 \,, \tag{9.6.6}$$

where these are rough approximations with the missing factors of order unity. Using these ingredients one can express the **asymmetry as**

$$\boxed{A \approx \frac{n_{\mathrm{b},0}}{n_{\gamma,0}} \,. \qquad (9.6.7)}$$

Baryon Asymmetry

Further, the **baryon-number-to-photon ratio** can be defined:

$$\boxed{\eta = \frac{n_{\mathrm{b}} - n_{\bar{\mathrm{b}}}}{n_\gamma} . \qquad (9.6.8)}$$

One expects this ratio to remain **constant as long as there are no further baryon-number-violating processes** and there are no extra influences on the photon temperature beyond the Hubble expansion. So one can also assume that **η refers to the current value,** $(n_{b,0} - n_{\bar{b},0})/n_{\gamma,0} \approx n_{b,0}/n_{\gamma,0}$, although—strictly speaking—one should call this η_0.

So one finally obtains that **the baryon–antibaryon asymmetry *A* is roughly equal to the current baryon-to-photon ratio η.** A more careful analysis, which keeps track of all the missing factors, gives $\boldsymbol{A \approx 6\eta}$.

The **current photon density** $n_{\gamma,0}$ is well determined **from the CMB temperature** to be 410.4 cm^{-3}.

In principle, one could **determine** $n_{b,0}$ **by adding up all of the baryons** that one finds in the universe. This in fact is expected to be an underestimate, since some matter such as gas and dust will not be visible and these will also obscure stars further away.

Baryon Asymmetry

A more accurate determination of η comes from the **model of Big Bang Nucleosynthesis combined with measurements of the ratio of abundances of deuterium to hydrogen**. From this one finds $\eta \approx 5 \times 10^{-10}$. So, finally, the **baryon asymmetry** can be expressed as

$$A \approx 6\eta \approx 4 \times 10^{-9} \,. \tag{9.6.9}$$

This means that at early times, for every billion antiquarks there were a billion and four quarks. The matter in the universe one sees today is just the tiny amount left over after essentially **all of the antibaryons annihilated and this led to the large photon density** (s. also Fig. 9.7).

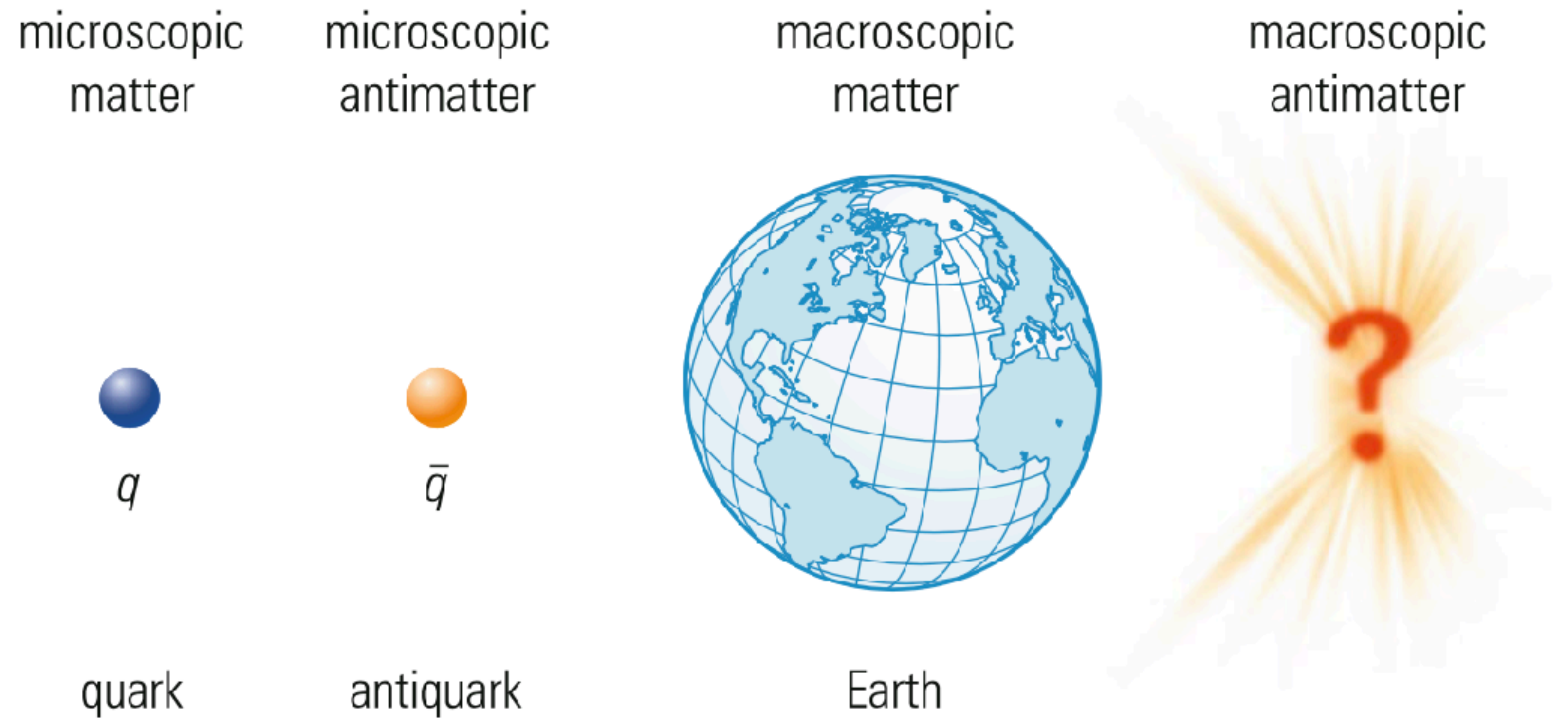


Fig. 9.7 The matter–antimatter symmetry on microscopic scales is obviously broken at macroscopic level

The Sakharov conditions

In 1967 Andrei Sakharov pointed out that **three conditions must exist in order for a universe with non-zero baryon number to evolve from an initially baryon-symmetric state.** Nature must provide:

1. **baryon-number-violating processes**;
2. **violation of *C* and *CP* symmetry**;
3. **departure from thermal equilibrium**.

The first condition must clearly hold, or else a universe with $B = 0$ will forever have $B = 0$.

In the second condition, C and CP symmetry roughly means that **a system of particles behaves the same as the corresponding system made of antiparticles**. If all matter and antimatter reactions proceed at the same rate, then no net baryon number develops; thus, violation of C and CP symmetry is needed.

The third condition on departure from equilibrium is necessary in order to obtain **unequal occupation of particle and antiparticle states,** which necessarily have the same energy levels. A given theory of the early universe that satisfies at some level the Sakharov conditions will in principle predict a baryon density or, equivalently, a baryon-to-photon ratio η.

The Sakharov conditions

One wants the net baryon number to be consistent with the measured baryon-to-photon ratio $\eta = n_b/n_\gamma \approx 5\times10^{-10}$. It is not entirely clear how this can be satisfied, and a detailed discussion goes beyond the scope of this book. Here only some of the currently favoured ideas will be mentioned.

Baryon-number violation is predicted by Grand Unified Theories (GUT), but it is difficult there to understand how the resulting baryon density could be preserved when this is combined with other ingredients such as inflation.

Surprisingly, a non-zero baryon number is also **predicted by *quantum anomalies* in the usual Standard Model, and this is currently a leading candidate for baryogenesis.** (Quantum anomalies can arise if a classical symmetry is broken in the process of quantization and renormalization. The perturbative treatment of quantum field theories requires a renormalization, and this adds non-invariant counter terms to the invariant Lagrange density that one gets at the classical level.)

The Sakharov conditions

***CP* violation is observed in decays of *K* and *B* mesons** and it is predicted by the Standard Model of particle physics but at a level far too small to be responsible for baryogenesis. If nature includes further *CP*-violating mechanisms from additional Higgs fields, as would be present in supersymmetric models, then the effect could be large enough to account for the observed baryon density.

This is one of the clearest indications from cosmology that the Standard Model is incomplete and that other particles and interactions must exist. It has been an important motivating factor in the experimental investigation of *CP*-violating decays of *K* and *B* mesons. These experiments have not, however, revealed any effect incompatible with Standard Model predictions.

The **departure from thermal equilibrium** could be achieved simply through **the expansion of the universe,** i.e., when the reaction rate needed to maintain equilibrium falls below the expansion rate: $\Gamma \ll H$. Alternatively, it **could result from a phase transition** such as those associated with spontaneous symmetry breaking.

The Sakharov conditions

The present situation with the baryon asymmetry of the universe is a collection of incomplete and inconclusive experimental observations and partial theories, which **point towards the creation of a non-zero baryon density at some point in the early universe**. The details of baryogenesis are an active topic of research.

Until the details are worked out one needs to take the baryon density of the universe or, equivalently, the baryon-to-photon ratio, as a free parameter that must be obtained from observation, see also Fig. 9.7.

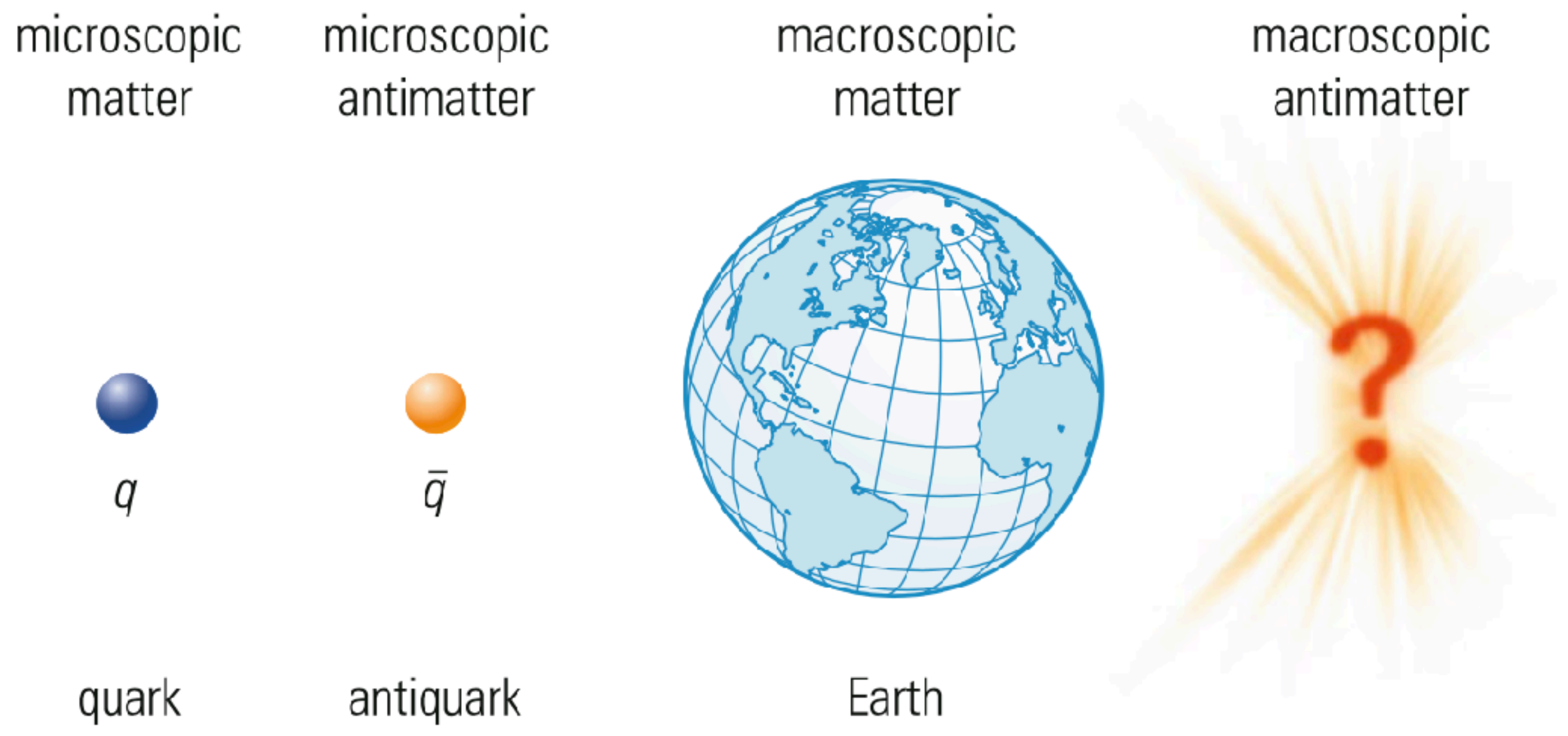
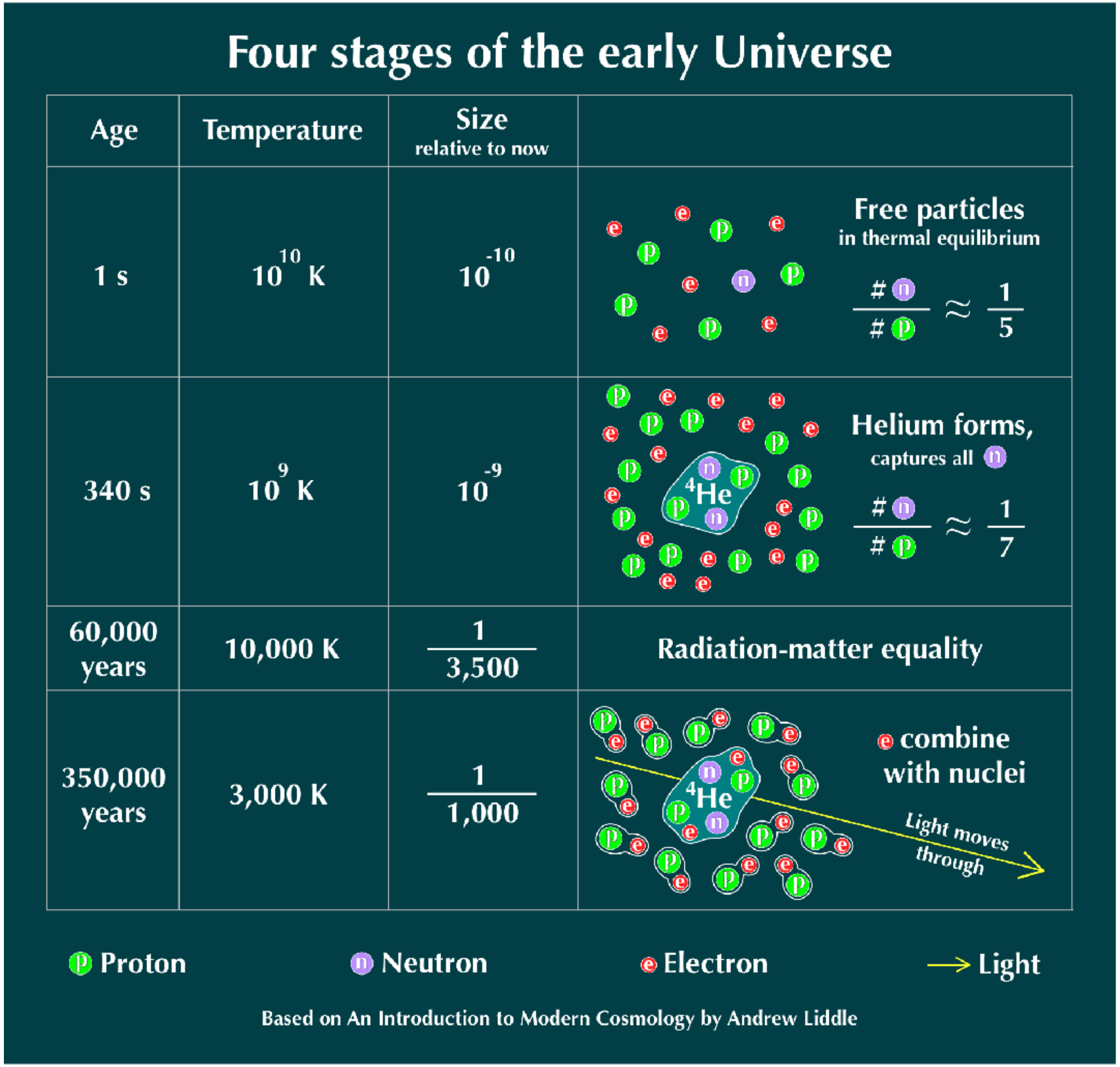


Fig. 9.7 The matter–antimatter symmetry on microscopic scales is obviously broken at macroscopic level

Before the CMB



https://evgenii.com/blog/stages-of-the-early-universe/