Part III: Misconceptions about the Multiverse

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Introduction

The multiverse refers to a picture discussed in current theoretical physics, which says that what we once thought as the entire universe is only one of the many universes in which physical laws take different forms. There are lots of misconceptions in public about this picture, which we will discuss in this part. Common misconceptions include "The multiverse is not a scientific, or scientifically motivated, theory"; "Adopting the anthropic principle, implied by the multiverse picture, is equivalent to giving up scientific explanations for any phenomena we observe"; and "The multiverse theory is not testable even in principle." We will see that all these statements are false; in particular, we will see that the approach of multiverse cosmology is exactly that of conventional science.

Chapter 13

The Basic Picture

In this section, we overview the multiverse theory. We will see that it is a concrete proposal based on fundamental theories of physics. In particular, we will see that it is scientifically well motivated, both observationally and theoretically.

13.1 Definition

What does the end of the universe look like—what exists outside of it? How was the universe born—what was there before it was born?

To answer these questions, we first need to define what we mean by the "universe." For example, suppose there is some "end" of the universe, and there is "something" outside of it. But if we decide to call everything including that something as the universe, then *by definition* there would be no such thing as the outside of the universe. Since we will be talking about a *concrete* picture, we need to define things precisely.

We know from the era of Copernicus and Galilei that the land we live on is only the surface of one of the planets in the solar system. We also now know that our solar system is only one of many such objects in our Milky Way galaxy, which in turn is only one of many galaxies. If we keep

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Our universe is almost homogeneous when viewed at large scales.

looking at larger scales in this way, we find that our universe is roughly homogeneous (after "coarse-graining" structures at smaller scales). Furthermore, this homogeneous region is well described by the so-called standard model of particle physics, more precisely the standard model extended to include what are called dark matter and dark energy. We call this homogeneous region, described by a single particle physics model, our universe.

One of the major discoveries in the twentieth century is that this region, which we call the universe, is expanding. (What was actually found is that the more distant a galaxy is, the faster it recedes from us, which implies that the universe is expanding as a whole.) When you hear that the universe is expanding, you might imagine that the size of the universe is finite and increasing in time. This is, however, not necessarily the case.

▷▷▷ **Misconception !!** The expanding universe means a finite universe expanding in ambient space.

The precise meaning of the universe being expanding is, as shown in Fig. 13.1, that the distance between arbitrary chosen two points keeps increasing as time passes. In particular, the "size" of the universe can be infinite *from the beginning*, except possibly at the exact time zero when the distance between any points can be said zero or undefined. (We usually consider what happens at the exact time zero to be a result of mathematical idealization anyway.)

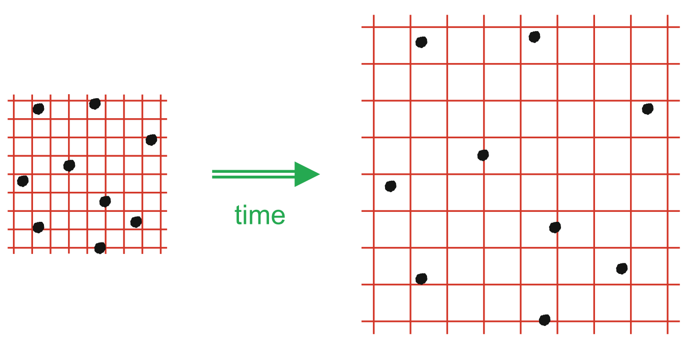

Fig. 13.1 In the expanding universe, the distance between arbitrary two points increases as time passes.

⊳⊳⊳ **More Accurate !!** The size of the expanding universe can be infinite all the way through its history.

The fact that the universe is expanding—in the sense described above—means that at early times it was much more dense and hence at higher temperature. Namely, the universe must have started from a hot "big bang" phase. In fact, the universe in the early hot phase was observed directly. Since the speed of light is finite, seeing a distant object (e.g., at a thousand light years away) means that we are seeing the light emitted from the object in the past (a thousand years ago). So, if we keep looking farther and farther, at some point we must see a hot, high temperature and high density, universe. This implies that the background night sky must be shining! On the other hand, the night sky is obviously dark. What is going on?

The answer is that because the universe is expanding, the light from the hot phase is subject to the Doppler effect, so that its frequency is in the microwave region when received on the Earth. In other words, when viewed by microwave, the night sky is shining. This radiation, coming uniformly from all the angles in the sky, is called the cosmic microwave background (CMB)—it is light emitted when the universe was $400,000$ years old (which is only $1/35,000$ of the current age of the universe, 13.8 billion years); see Fig. 13.2.

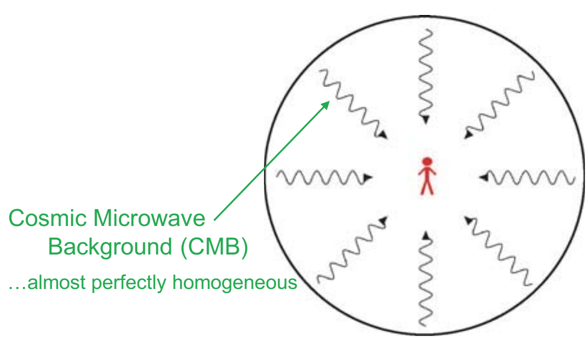

Fig. 13.2 We receive the cosmic microwave background (CMB) from all the directions in the sky, which is almost perfectly homogeneous.

Following the initial discovery in 1964, the CMB has been measured in many ground-based and satellite experiments. A striking fact is that these measurements tell us that the universe, when it was young (400, 000 years old), was incredibly homogeneous. In fact, the fluctuations of energy density at that time were only at the level of one part in 100, 000. All the structures we see today—stars, galaxies, galaxy clusters, and so on—have been formed because these tiny fluctuations were amplified by "gravitational instability." Namely, a region slightly more dense than the surroundings becomes more dense as gravity attracts more matter to that region; accordingly, regions that were less dense have become even less dense. We can indeed use the measured map of the CMB to simulate what happens to the universe afterward, and the result well agrees with the observed structure of galaxies and galaxy clusters in the current universe.

According to the measurement of the CMB, our universe was almost perfectly homogeneous when it was younger.

The universe before 400, 000 years old cannot be seen directly by light, since the high density of the universe prevents any light from propagating. We can, however, extrapolate the history of the universe further back, using the equations of general relativity and the standard model of particle physics. (The current age of the universe—13.8 billion years old—is obtained in this manner.) Through this, we know what happened in the earlier universe, for example, how light chemical elements were synthesized when the age of the universe was only about 1–10 minutes—the predicted relative abundances of the elements agree well with the observation. The history before this "big-bang nucleosynthesis" era was not fully settled observationally, but we have a rough idea: at some early time, the universe was subject to exponential expansion called inflation (which provided the origin of small fluctuations needed to form structures), after which an asymmetry between the amounts of matter and antimatter was created through the process called baryogenesis (whose details are still debated). In any event, it seems clear that the early universe was very homogeneous, i.e., it looked very much the same everywhere.

Let us consider drawing this history of the universe in a figure which looks "scientific." In doing so, physicists often draw a "spacetime" figure in which a spatial (time) direction is taken to be in the horizontal (vertical) direction and in which the trajectory of a light ray is taken to be in a

45° direction. (This type of figures is called Penrose diagrams, and it makes causal relations between events manifest. For example, since no signal can propagate faster than the speed of light, the spacetime region a point in the figure can affect is that between the upper left and upper right directed 45° lines drawn from that point.) According to this rule, (the history of) the universe we have been discussing so far, naively, seems to be summarized as in Fig. 13.3.

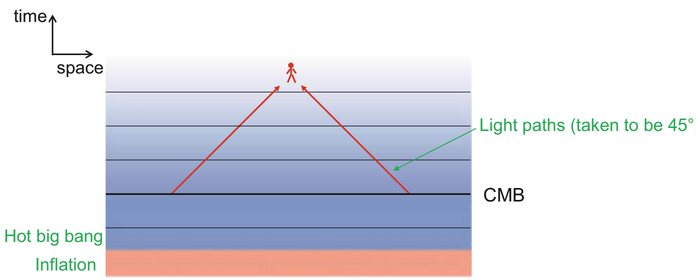

Fig. 13.3 The naive picture of the universe in the form of a Penrose diagram.

What the multiverse theory says is that this innocently-looking figure is wrong, at least in one important way. In particular, if we look at Fig. 13.3, we might conclude that there is no room to consider other universes spatially separated from our own. This is, however, not correct. As we will see, according to the multiverse theory, the structure of spacetime is more intricate than that in Fig. 13.3, so there can be other universes even in a region spatially separated from us (in some specific sense; see below).

▷▷▷ **Misconception !!** The multiverse is a vague idea just suggesting that there are many universes.

▷▷▷ **More Accurate !!** The multiverse, as discussed currently in the theoretical physics community, is a specific proposal for the structure of space and time, replacing the naive picture of the universe in Fig. 13.3.

13.2 Motivation: Observational

To go beyond the naive picture of Fig. 13.3, we need some hints. Below we will discuss some of them, which played important roles in the development of the multiverse picture. In doing so, we will address the following misconception:

▷▷▷ **Misconception !!** The multiverse is a random guess which is not scientifically well motivated.

In particular, we will see that the multiverse is well motivated both observationally and theoretically.

One of the greatest mysteries of our universe is that it appears that it is designed too well for us humans. For example, let us imagine changing the value of the mass-squared parameter μ^2 of the Higgs field in the standard model, which can theoretically take any value in the range $-10^{32}\mu_0^2 \lesssim \mu^2 \lesssim 10^{32}\mu_0^2$, where μ_0^2 is the value in our universe. We then find that unless μ^2 is in an extremely narrow range, $0 \lesssim \mu^2 \lesssim$ a few $\times\, \mu_0^2$, there is no stable nucleus (except for hydrogen, which is the proton). Namely, our universe acquires enough complexity to have nuclear physics, and hence chemistry and life as we know, only if this parameter is carefully chosen to be in this tiny window. We also find that the masses of various elementary particles (which are determined by certain coupling constants in the standard model) must also be chosen carefully in order for the theory to possess complexity. These complexities are presumably a necessary condition for life to emerge. Who made such careful adjustments of the theory?

Our universe seems to be carefully designed so that complex structures, including intelligent life, can emerge.

This issue became even more mysterious when experimental collaborations led by Perlmutter, Riess, and Schmidt discovered in 1998 that the expansion of the universe is accelerating, rather than decelerating. Under normal circumstances, the expansion of the universe is only decelerating because the gravitational force between any matter is attractive. However, the expansion can accelerate if space is filled by the "energy of the vacuum." The 1998 discovery, therefore, implies that our universe is filled with the vacuum energy (or at least something that effectively behaves as the vacuum energy).

What surprised people was that the size of the observed vacuum energy density was extremely small—120 orders of magnitude smaller than theoretically expected! And yet it was nonzero. Theoretically, the vacuum energy density ρ_Λ is expected to take any value in the range $-\rho_{\Lambda,*} \lesssim \rho_\Lambda \lesssim \rho_{\Lambda,*}$, where $\rho_{\Lambda,*} \sim 10^{90}\,\mathrm{g/cm^3}$ represents a theoretically expected size, and yet the actual value found by the observations is surprisingly close to zero, $\rho_\Lambda \sim 10^{-120}\rho_{\Lambda,*}$. Moreover, the observed value of ρ_Λ is very special—it is only about a factor of 2 different from the energy density of matter:

$$\rho_\Lambda \sim 2.2\,\rho_{\mathrm{matter}} \tag{13.1}$$

Note that the two could have taken values many orders of magnitude different, and yet they are this close. This becomes even more mysterious if we realize the fact that the time dependencies of the two quantities are completely different: as the universe expands, the energy density of matter is diluted inversely proportional to the volume, while the vacuum energy density stays constant. What we find is the fact that these two components are comparable in size *when humans make cosmological observations* (see Fig. 13.4). In other words, if we try to explain the smallness of the vacuum energy by some mechanism that operated in the early universe, then the mechanism must know when intelligent life—humans—will emerge and make cosmological observations, to adjust the vacuum energy density in such a way that it becomes comparable to the matter energy density at the time the observations are made. Can we imagine any such mechanism?

Our universe has comparable vacuum and matter energy densities now.

In 1987, 11 years before the discovery of accelerating expansion, Steven Weinberg published a paper about the vacuum energy in *Physical Review Letters*. The problem of smallness of the vacuum energy density was already known by then. Most physicists, however, were thinking that this was not a pressing problem. Their thinking was: given that the vacuum energy density was already smaller than its natural size by more than 100 orders of magnitude, its true value would be zero due to some unknown mechanism, and in any case the solution to this problem would not much affect the rest of physics.

Most physicists once thought that the vacuum energy in our universe is zero.

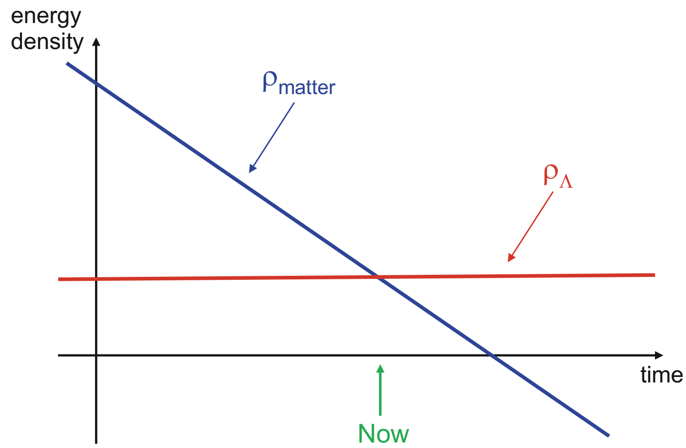

Fig. 13.4 We live in a very special era in which the energy densities of vacuum and matter are comparable. Here, the *horizontal* and *vertical* axes should be understood to represent the logarithms of time and energy densities.

Weinberg did not think that way. There were some suggestions for how the vacuum energy could be zero, but none of them was working well. (He wrote a review article, summarizing why these ideas do not work.) Instead of pursuing another such mechanism, he considered what would happen if the vacuum energy were much (e.g., by a few orders of magnitude) larger than the current matter energy density. He then found that in such a universe, there would be no structure such as galaxies (and hence any intelligent life). This implies the following. Suppose there are a large number of universes in which the vacuum energy takes different values. (In the discussion here, it is not important how these universes are realized.) Then, some of these universes would accidentally have a value of the vacuum energy small enough to lead to nontrivial structures. Since intelligent life would emerge only in such universes, when they make cosmological observations, they always find a surprisingly small value of the vacuum energy density; see Fig. 13.5.

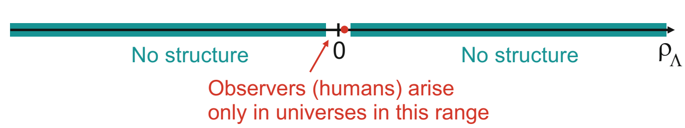

Fig. 13.5 Observers arise only in universes in which the vacuum energy density is sufficiently small.

An important point is that in this picture, which postulates many universes or the multiverse, the vacuum energy is expected to be *not much smaller than needed*. In other words, the size of the vacuum energy density is expected to be roughly comparable to the current matter energy density. This is in sharp contrast with what most physicists were imagining back then. And indeed, the observations by Perlmutter, Riess, and Schmidt found that the vacuum energy density is within only about a factor of 2 from the current matter energy density!

▷▷▷ **More Accurate !!** The multiverse scenario was considered in order to address a specific scientific problem that could not be solved by other theories. It not only explained the smallness of the vacuum energy but also predicted that it is comparable to the current matter energy density. This prediction was confirmed observationally a decade later.

Similarly, other "miraculous" features of the standard model that seem to be carefully designed for the existence of life can also be understood if we take the view that we live only in one of the many universes which satisfies the conditions for life to exist.

13.3 Motivation: Theoretical

It is certainly a major assumption that there are many possible universes in the world. Is there any independent argument supporting this hypothesis beyond the fact that it can explain the seemingly well-designed nature of our universe? In fact, there is.

Finding a complete quantum mechanical theory of gravity has been a challenging avenue. A problem is that when one straightforwardly quantizes Einstein's theory of general relativity, the resulting theory suffers from uncontrollable divergences at the fundamental level, suggesting that we need to do something more dramatic to have a consistent theory of quantum gravity. String theory is the leading contender for such a theory. In string theory, the extended nature of fundamental constituents tames these divergences. This is virtually the only quantum gravitational theory we currently have in our hands (although they are people who are exploring alternatives, such as loop quantum gravity).

String theory predicts the existence of extra spatial dimensions.

String theory predicts that the dimension of spacetime is higher than $four$, the number we see around (three spatial dimensions and one time dimension). In a certain way of counting, the number of extra dimensions is 6, and they are all spatial. What does it mean that there are extra spatial dimensions? Imagine that our world exists on the surface of a thin tube. This space is clearly two-dimensional at the fundamental level. However, if we are interested only in physics at large distance scales, e.g., because we are large, then this space appears as one-dimensional as illustrated in Fig. 13.6. So, for such "large" observers, the space appears

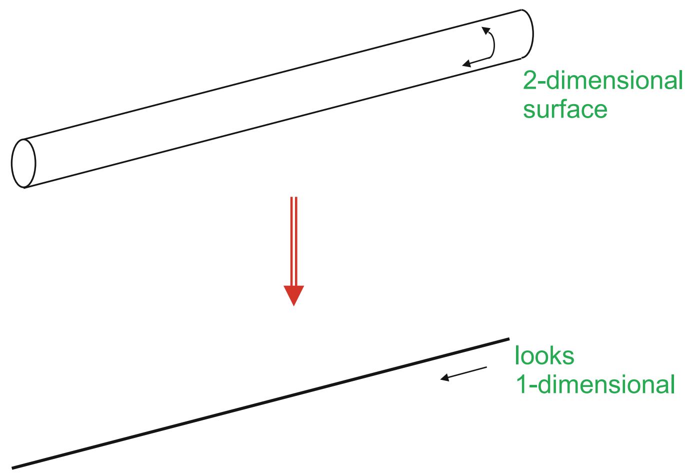

Fig. 13.6 The surface of a thin tube, which is two-dimensional, appears as one-dimensional at long distances.

as one-dimensional, with one extra dimension—in this case a circle—attached at each point in space. Similarly, in string theory, we must consider that six-dimensional space is attached at each point of our four-dimensional spacetime.

An important point is that the properties of the theory describing physics in four-dimensional spacetime at long distances depend on the shape and size of the extra dimensions because it results, in a sense, from averaging out the physics associated with these tiny compact dimensions. In particular, the content and properties of elementary particles and the value of the vacuum energy change if the shape and size of the extra dimensions are varied. (In fact, the number of "compactified" dimensions may also be other than six, so the number of spacetime dimensions at long distances may also differ from four.)

How many different configurations for the extra dimensions does the theory allow? It is quite common in nature that even if the fundamental equation is simple, a system governed by the equation shows remarkable complexity and varieties. A good example is organic macromolecules that all arise as quasi-stable solutions to a simple Schrödinger equation. Likewise, even though the equation governing the dynamics of the extra dimensions is simple, these dimensions can have an enormous number of quasi-stable configurations—an estimate says that there are 10^{500} or more such configurations. We can illustrate this situation schematically as in Fig. 13.7, where the horizontal directions represent possible configurations of the extra dimensions and the vertical axis corresponds to the potential energy associated with each configuration. Each quasi-stable configuration corresponds to a minimum of the potential valleys. This picture is often called the string landscape.

There are an enormous number of quasi-stable configurations for the extra dimensions.

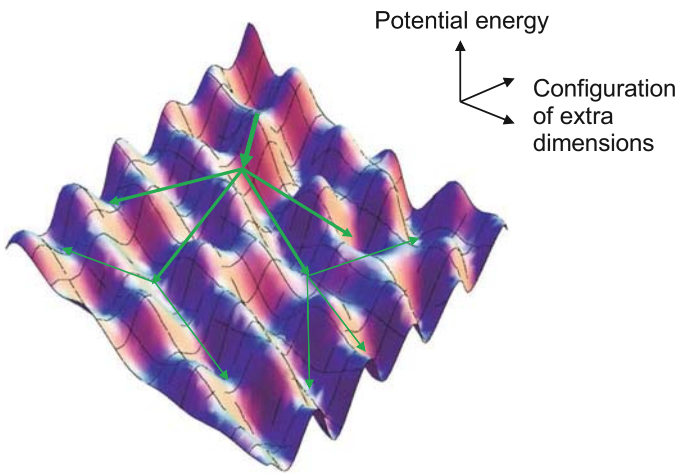

Fig. 13.7 A sketch of the potential energy as a function of the configuration (shape and size) of the extra dimensions. Each minimum corresponds to a different low-energy universe.

We conclude that each minimum of the above potential corresponds to a possible four-dimensional universe, having distinct elementary particles and the vacuum energy. However, this by itself is not sufficient to solve the problem of the vacuum energy, since it merely says that string theory has many universe as possible *solutions*. In order to lead to the multiverse and hence for Weinberg's solution to the problem to operate, these universes must be *physically realized*. What does the theory say about this?

Suppose the system was originally at some minimum of the landscape potential which has a positive potential energy. In this case, Einstein's equation tells us that space-time expands exponentially. The system, however, does not simply stay there forever. Quantum mechanics allows a transition from that minimum to a lower minimum through a quantum tunneling process. Under a normal circumstance, such a quantum tunneling process occurs in the following manner. Initially, the system is everywhere in the state of a higher minimum. At some point, however, small bubbles form in which the system is in the state of a lower minimum (like bubbles in boiling water). These bubbles then expand almost at the speed of light, and they collide with each other, eventually turning the entire system into the new state in the lower minimum of the potential.

However, in the case of cosmic tunneling under consideration, ambient space in which bubbles form is expanding exponentially, in fact at a rate faster than the speed of bubble expansion. The bubbles, therefore, cannot fill the entire space—there is always ambient space exponentially expanding, in which new bubbles keep forming. Bubbles formed in this way can be of various different kinds: interiors of these bubbles correspond to different minima in the potential landscape, as indicated by the arrows in Fig. 13.7. In fact, it is generally expected that all the different universes in string theory are physically realized as bubble universes in this manner. This process of eternally creating bubble universes in exponentially expanding ambient space is called the eternal inflating multiverse.

Different universes predicted in string theory are physically realized as bubble universes through eternal inflation.

This setup, therefore, is exactly the one needed by Weinberg to solve the problem of small vacuum energy. According to this picture, our universe is only one of (infinitely) the many bubble universes formed through eternal inflation; see Fig. 13.8 for illustration.

Interestingly, the fact that string theory can lead to a huge number of low energy theories and that inflationary expansion at a high potential energy minimum lasts eternally was known from the 1980s, but people viewed them as nuisances. In particular, many people thought that the existence of extra dimensions in string theory is an unfortunate feature of the theory (as they thought it would have been better if it predicted four dimensions), and the eternal nature of inflation is a problem, since in our universe such

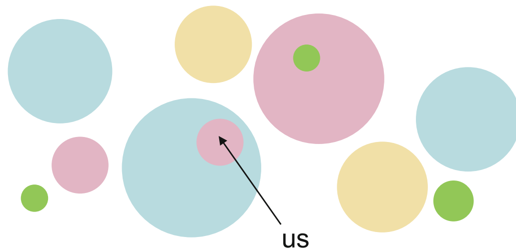

Fig. 13.8 Eternally inflating space produces an infinite number of bubble universes, one of which is our own universe.

expansion certainly ended before the hot big bang era. It is quite suggestive that properties of the fundamental theories which once people thought as bad features are exactly those needed to understand aspects of our universe as we observe it today.

▷▷▷ **More Accurate !!** The multiverse picture is suggested by the fundamental theories—string theory and eternal inflation—that were developed independently of the multiverse. It is, therefore, theoretically well motivated.

13.4 New Spacetime Picture

According to the multiverse theory, we live in one of the bubble universes which is nucleated in inflating space and expanding afterward. This may sound like our universe is not homogeneous even approximately—in particular, there is a special point corresponding to the center of the bubble, and if we go far in the bubble, then we would hit its wall, i.e., the edge. Doesn't this contradict the fact that our universe appears observationally very homogeneous as we saw in Sect. 13.1?

In fact, two statements that (i) we live in a bubble universe which was born small in ambient space and expanding afterward and (ii) our universe is (almost perfectly) homogeneous do not contradict with each other. How is this possible?

It is often the case that when a revolutionary change of the picture occurs, it is accompanied by the corresponding change of a concept. For example, when ancient people realized the possibility that our land might be spherical, one of the strongest "scientific" objections was that if it is indeed spherical, then people in the other side would "fall to the sky." Of course, we now know what is wrong with this argument—the concept of "down" is not universal to everyone; it is defined (only) with respect to the Earth through gravitational attraction. Similarly, in the multiverse picture, we need to embrace some revision of a concept, which makes the two statements above consistent.

What concept do we need to revise among those we take for granted in our daily life? The point here is to realize that there is no *absolute* definition of equal time at spatially separated points. For example, there is no invariant meaning to the question "what is going on at some specific point in the Andromeda galaxy when you are reading this sentence," since we cannot uniquely determine what time in the Andromeda galaxy corresponds to "now" here. You might think that we can define equal time in two different places if we prepare two clocks synchronized at some location and then move them to the two places, e.g., one here and one in the Andromeda galaxy. But because of relativistic effects, such a definition depends on how we carry the clocks, e.g., the path and speed of the transportation.

There is no absolute concept of equal time at spatially separated points.

This fact plays a crucial role in understanding the structure of a bubble universe. Let us imagine that we are seeing a bubble universe from outside. Then, the universe is born small and then becomes larger in ambient space. If we write this in a Penrose diagram, in which a trajectory of light is drawn as a 45° line, it becomes as in Fig. 13.9. Here, the

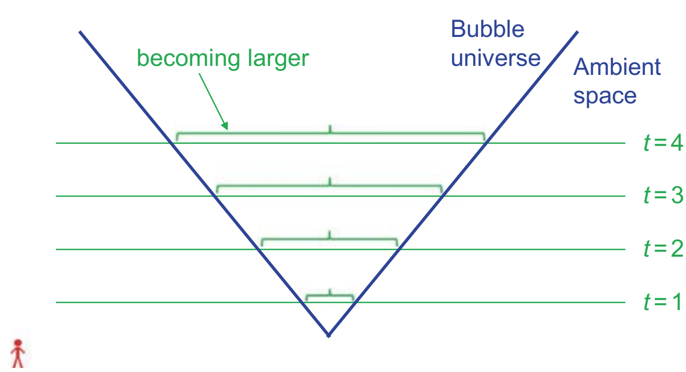

Fig. 13.9 Nucleation of a bubble universe as viewed from an exterior observer.

region inside (outside) the inverse triangle represents the interior (exterior) of the bubble universe. (The reason why the boarder of the two regions is given by 45° lines is that the bubble wall expands almost at the speed of light.) The equal time slices as viewed from the exterior observer are drawn as horizontal lines, denoted as $t = 1, 2, 3$, and 4. One can see that the size of the universe (the portions of the horizontal lines inside the inverse triangle) becomes larger as time passes.

On the other hand, if we see the same bubble nucleation process from the viewpoint of an observer inside the bubble, then it appears quite differently. In this case, equal time slices are given as in Fig. 13.10, denoted by $t' = 0, 1, 2, \cdots$. (Technically, equal time slices as viewed from an interior

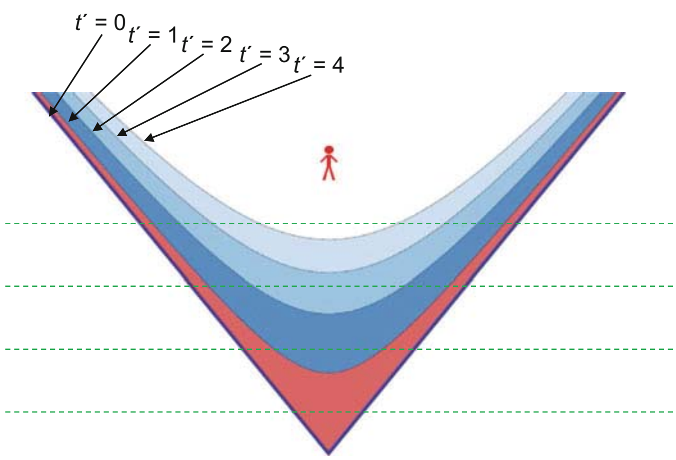

Fig. 13.10 A bubble universe as viewed from an interior observer.

observer are given by contours of quantum fields responsible for the nucleation.) We find that in this view, the universe is infinitely large already when it was born, i.e., the length of any constant t' line is infinite. Moreover, the universe, as viewed from the interior, is completely homogeneous, i.e., any point on a given constant t' line looks the same as any other point on the same line. (For $t' = 0$, there appears to be a special point—the vertex of the inverse triangle. This is an artifact of the drawing. Indeed, for any

$t' > 0$—how small it is—there is no special point on the equal time surface.)

When viewed from outside, a bubble universe is born small, and its size becomes larger as time passes. When the same universe is viewed from the interior, however, it is homogeneous and infinitely large already at the time it is born.

This is how the two statements about a bubble universe—that it is born small and becomes larger and that it is homogeneous—can be compatible. The former is a statement when the universe is viewed from outside, and the latter is that when viewed from the interior.

This picture replaces the naive picture given by Fig. 13.3. When our universe is drawn in the form of a Penrose diagram, it must be drawn as in Fig. 13.9 or Fig. 13.10, instead of Fig. 13.3. The new figure makes it clear that the spacetime region an exterior observer describes as "outside the universe" is the region "before the universe began" for an interior observer. And this is the region where other universes, born in the ambient eternally inflating space, as well as the ambient space itself reside. The full picture of the multiverse drawn in a Penrose diagram, therefore, is given by Fig. 13.11. One finds that it exhibits a "fractal" structure. Note, however, that many universes drawn near the top are in fact large universes because the entire spacetime is expanding. The fact that these universes appear small is an artifact of the rule of Penrose diagrams in which the trajectories of light are drawn as 45° lines.

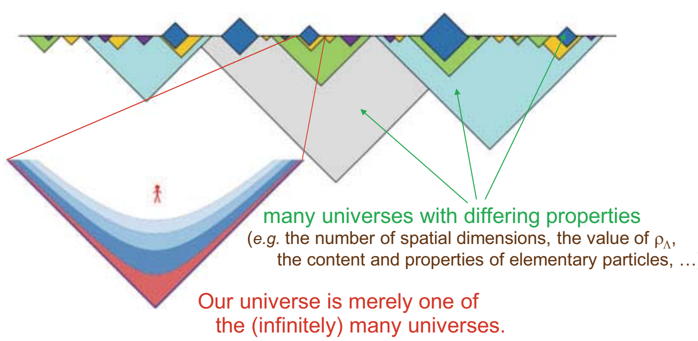

Fig. 13.11 A Penrose diagrammatic depiction of the multiverse.

Chapter 14

Demystifying the Multiverse

In this section we discuss some misconceptions about the multiverse, often existing even in the scientific community.

14.1 Scientific and Conservative

People sometimes say that the multiverse theory sounds "mystical." This is probably because it talks about a very big picture such as outside of our own universe.

▷▷▷ **Misconception !!** The multiverse picture, talking about things like outside of our universe, is mystical.

The true situation, however, is the opposite.

Suppose there was only one universe. Then it would be very difficult to explain miraculous features of our universe, such as the structure of elementary particles and the value of the vacuum energy, without resorting to some sort of creator. In the multiverse picture, however, there are an enormous number (10^{500} or more) of different universes, so some of them possess these miraculous features that lead to intelligent life, without a help of any creator. This, of course, does not prove that there is no such creator, but

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given that a goal of science is to try to understand our physical nature as much as possible without relying on such an almighty person, the approach of the multiverse is exactly that of science.

▷▷▷ **More Accurate !!** The approach of the multiverse theory is exactly that of science.

In fact, the logic that has led to the multiverse picture is a very traditional one in science. A progress in science, especially in physics, often occurs in the following steps. First, to explain known facts, a new equation—or theory—is written down. Then, by studying that equation, we find new phenomena that were not known before. Finally, by accumulating evidence for these new phenomena, we build up our confidence about the equation, and through this process the new theory is becoming a part of our established scientific knowledge.

Two well-known historical examples are the following (see Fig. 14.1). The first is a story about relativity and gravity. When Einstein presented special relativity in 1905, this theory was not compatible with the known theory of gravity. (In relativity no signal can propagate faster than the speed of light, but gravity in Newton's theory propagates instantaneously.) This problem was solved when Einstein replaced Newton's theory with his theory of general relativity in 1916. This new theory—mathematically represented by the so-called Einstein equation—predicted new

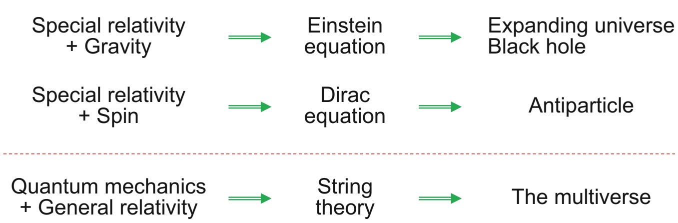

Fig. 14.1 The development of the multiverse theory in analogy with other scientific theories.

phenomena such as the expanding universe and black holes, which were not known at the time but confirmed later observationally.

The second example is when Paul Dirac tried to find an equation that allowed for describing a particle with spin in a way consistent with special relativity. The equation he found—the Dirac equation—predicted the existence of an antiparticle: for any particle there is a partner that has the same mass but the opposite charge. In Dirac's case, he was interested in writing the equation for the electron, so this antiparticle was what is now known as the positron, which was discovered 4 years after Dirac wrote down his equation.

An interesting thing is that in both these cases, those who originally wrote down the equations could not accept these predictions initially. It is well known that Einstein could not accept the prediction that the universe must be expanding (or contracting); the prejudice that the universe must be static was so strong back then. Dirac also tried to identify the positively charged particle predicted by his equation as the proton—the only known positively charged particle at the time—despite the fact that the equation was telling that the mass of the particle was the same as the electron. Even with the geniuses of Einstein and Dirac, it was not easy to overcome prejudices deeply insinuated in people's mind. And in both these cases, the equations once written down were describing the nature correctly beyond their originators' imagination.

The situation in the multiverse is not so different from these two examples (see Fig. 14.1). String theory has been considered as the virtually unique candidate for reconciling quantum mechanics and general relativity. Studying the structure of this theory has led to extra dimensions and hence many different universes at long distances. As in the case of the above two examples, this prediction had not been taken too seriously in the 1980s among people who originally developed string theory. But the discovery of the universe's accelerating expansion in 1998 made people pay attention to this implication of the equation.

▷▷▷ **More Accurate !!** The progress of the multiverse theory is very much analogous to those of other scientific theories.

In fact, one can even say that the multiverse is a "conservative" picture in the sense that it is more along the lines of the past progresses in science. When string theory turned out to be a consistent theory of quantum gravity in the 1980s, many physicists thought that all the aspects of our universe—including the masses of all the elementary particles and the value of the vacuum energy—could be derived merely by solving its equation, and this picture dominated the particle physics community for two decades afterward. Such a picture, however, is much more "radical"—we have never reached such an ideal situation in our history of science.

Throughout the history of science, we learned many times over that we were much tinier substances than we had previously thought and that we do not in any sense occupy a central position in the physical world. In ancient times, we thought we lived on the unique, disklike world, but we now know that we live on one of the eight planets around the Sun, which is only one of a few hundred billion stars in our galaxy, which is in turn one of many galaxies in our observable universe. Given this, it does not seem unreasonable—or even seem natural—that what we considered the whole universe is actually only a small portion of some larger structure.

Given the history of science, the multiverse is a conservative picture.

14.2 Anthropic "Principle"

The reasoning used by Weinberg to address the smallness of the vacuum energy is often called (the weak form of) the anthropic principle. This term, however, is misleading. When you hear the phrase anthropic principle, you might imagine that we are introducing some new principle that has somehow to do with humans. However, once we admit that there are many different universes, it is nothing more than a statement of consistent logic. What we want to explain is the fact that "when we made observation, we found a small value of the vacuum energy." To see if this is consistent with a theory, there is no point in discussing the value of the vacuum energy without taking observers into account. In other words, there is absolutely no problem if the value of the vacuum energy is large in universes in which there is no observer to measure it.

With sufficiently many universes, the anthropic reasoning is nothing more than a statement of consistent logic.

A statement that is typically made to the anthropic reasoning is the following:

▷▷▷ **Misconception !!** Once we admit the anthropic principle, we can explain everything with it, so it is equivalent to giving up a scientific explanation for any phenomenon; in particular, the anthropic principle means that there is no point in searching for any mechanism for explaining natural phenomena.

This statement is wrong in many respects. First, it is wrong that the anthropic reasoning can explain *everything* by itself. For example, the standard model of particle physics contains a quantity called the θ parameter, which controls the size of the electric dipole moments of elementary particles. This parameter is known to be smaller than its theoretically expected size by more than ten orders of magnitude. The origin of this smallness, however, cannot be explained by the anthropic reasoning alone, since we can show that even if this parameter was larger than the current experimental upper bound by many orders of magnitude, there would virtually be no effect for the structure of our universe. This implies that there must be some mechanism (other than the simple anthropic reasoning) that is making this parameter small.

Another reason for why the statement quoted above is incorrect is that the anthropic principle by itself does *not* mean that there is no conventional mechanism to explain the structure of a theory. As seen in Sect. 13.2, the standard model has another parameter that is much smaller than the theoretically expected value: the Higgs mass-squared parameter μ^2. The origin of this smallness appears to be anthropic because there is no complex chemistry if this parameter takes a value slightly different from the observed one. On the other hand, there are many mechanisms/theories considered in particle physics which explain the smallness of μ^2, most notably weak scale supersymmetry. Suppose that the anthropic reasoning for the smallness of μ^2 is correct. Does it mean that a mechanism explaining the smallness of μ^2 is absent in our universe?

It doesn't. In the multiverse, intelligent life emerges only in universes in which μ^2 is sufficiently small to accommodate complex structures. Some of these universes have small μ^2 "accidentally" (as in the case of the vacuum energy), while some have it through a mechanism such as weak scale supersymmetry. In this case, which type of universe we find ourselves in depends on how many each type of universes exists in the multiverse, or more precisely the relative probability of finding two types of universes given the condition that intelligent life exists. If the latter type dominates, we would find ourselves living in a universe in which the smallness of μ^2 is *realized* through a mechanism, even if its ultimate *reason* is anthropic. Until we become capable of calculating the relevant probability, we cannot conclude the existence or absence of a mechanism without using observations. (In the case of the vacuum energy, we could not find *any* mechanism making it small, so we believe that the vacuum energy is small "accidentally.")

▷▷▷ **More Accurate !!** The fact that some feature has an anthropic origin does not mean that there is no mechanism leading to that feature. The existence or absence of a mechanism is determined by the statistics in the multiverse (which we still cannot calculate from the first principle).

Chapter 15

Relation to Observation

As discussed in Sect. 14.1, the final stage of developing a scientific theory is to compare it with observations. What is the situation of the multiverse about this?

First, it should be emphasized that a small but nonzero vacuum energy density was a prediction of the multiverse, which was confirmed observationally in 1998. As discussed before, most physicists thought that the vacuum energy density was smaller than its natural size by more than 120 orders of magnitude because it was zero. One can say that one of the predictions of the multiverse theory was already tested observationally.

A prediction of the multiverse, i.e., a small but nonzero vacuum energy density, was already tested observationally.

Are there any other tests of the multiverse? A common misconception is:

▷▷▷ **Misconception !!** Since we cannot physically go to other universes, the multiverse theory can never be tested, and hence is not scientific.

This is incorrect in several respects. First, as the diagram in Fig. 13.9 or Fig. 13.10 shows, the fact that we cannot go to the region outside our universe (outside the inverse triangle) does not mean that we cannot obtain a signal from that region. Note that we cannot even go to a distant galaxy or an era in which dinosaurs lived, but studying these subjects certainly belongs to the realm of science.

Y. Nomura et al., *Quantum Physics, Mini Black Holes, and the Multiverse*, Multiversal Journeys, DOI 10.1007/978-3-319-41709-7_15

Another point is that to test a scientific theory, we need not confirm *all* of its predictions. Indeed, even for "well-established" theories like quantum mechanics and the standard model of particle physics, not all the predictions have been experimentally tested—in fact, it would be impossible to do such a thing. In the case of the multiverse, the relevant question is what this theory predicts for things we can observe within our own universe. (A small but nonzero vacuum energy density is one of such predictions.)

The multiverse predicts that our universe has negative curvature.

In this respect, the multiverse theory based on string theory and eternal inflation as discussed here makes an important prediction: our universe must have negative spatial curvature. What is the curvature of the universe? Imagine that we take three points in the universe and construct a triangle by connecting these points by the "shortest paths." Here, the shortest paths can be considered to be the paths light rays would follow. In this case, it is not guaranteed in general that the three inner angles add up to 180° as we learned in middle schools. Even on a two-dimensional surface, the sum of the angles is larger (smaller) than 180° if the surface is, e.g., a sphere (has a saddle shape). We call space in which the sum of the inner angles of a triangle is larger (smaller) than 180° positively (negatively) curved space.

As seen in Fig. 13.10, the multiverse theory tells us that our universe is only one of many bubble universes, and for observers living inside it, the equal time slices are given as in constant t' lines in the figure. One can then show mathematically that such equal time slicing makes the space look negatively curved. Namely, the sum of the inner angles of a large triangle drawn in our universe must be always smaller than 180°!

▷▷▷ **More Accurate !!** The multiverse makes predictions for observables that can be measured in our universe, and hence the theory is testable.

The multiverse theory, however, cannot predict how much the space in our universe is curved. This leads to the following possible future scenarios (see Fig. 15.1). The measurement of the curvature of the universe is expected to improve by about two orders of magnitude in the next cou-

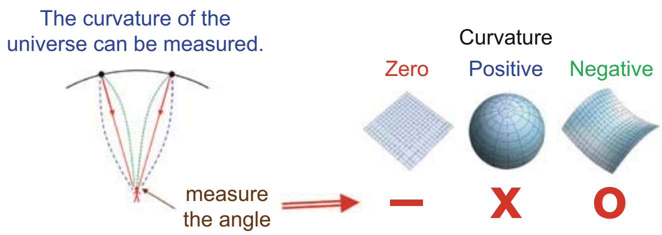

Fig. 15.1 The multiverse theory predicts that the spatial curvature of the universe is negative. If the future measurement finds the curvature to be (**a**) consistent with zero, (**b**) positive, and (**c**) negative, then the multiverse theory will be (**a**) unaffected, (**b**) excluded, and (**c**) supported, respectively.

ple of decades. The curvature of space can be found by measuring the angle between the two light rays emitted from an object whose size and distance from us are known (or calculated); see the left part of Fig. 15.1. Currently, a deviation of the sum of the inner angles of the largest triangle one can possibly draw in the universe is less than about a degree. The sensitivity to this deviation is expected to improve to the level of 0.01°.

Let us imagine that future measurements keep finding that the spatial curvature of the universe is consistent with zero. In this case, the result would be inconclusive for the multiverse. As mentioned above, the multiverse does not tell us how much the universe is curved—it depends on the length of slow-roll inflation that occurred in our bubble universe, which cannot (so far) be predicted from the first principle. This implies that the sum of the inner angles of a triangle may be, e.g., 179.999999999, in which case it is impossible to discriminate it from 180° observationally.

On the other hand, if a future measurement finds negative curvature, it would provide strong evidence for the multiverse. This is not only because the multiverse predicts negative curvature but also because it would be difficult to obtain a sufficiently small and yet measurable amount of curvature naturally, i.e., without fine-tuning, in a theory other than the multiverse. (In the multiverse, one can obtain a small but measurable amount of curvature quite naturally; for more details, see the paper quoted alongside.) If this happens, the multiverse theory would have another

For detailed discussions about the implications of the curvature measurement for the multiverse, see A.H. Guth and Y. Nomura, "What can the observation of nonzero curvature tell us?" Phys. Rev. D86 (2012) 023534 [arXiv:1203.6876 [hep-th]].

observational support in a way similar to the case of the small vacuum energy.

An interesting thing is that if a future measurement finds a positive nonzero curvature, then the multiverse as discussed here (based on string theory and eternal inflation) would be excluded. People often take falsifiability as a criterion for a good scientific theory. I myself think that we must be careful in applying this criterion idolatrously, since the judgment of falsifiability is often difficult, especially for a modern physical theory. But even if we adopt this criterion, the multiverse theory *is* falsifiable.

▷▷▷ **More Accurate !!** The multiverse theory is falsifiable.

If we are very lucky, we might even see more direct signals such as the remnant of a collision of our universe with another one. A Penrose diagram of this process is given in Fig. 15.2. As is clear from the figure, for an interior observer like ourselves, the effect appears as a signal from the spacetime region before the beginning of our universe; specifically, it appears as a slight deviation from homogeneity which existed already at the time the universe was born. The strength of the signal, however, is diluted by slow-roll inflation that has occurred within our bubble universe, so in order for the signal to be detectable, the length of slow-roll inflation must not be too long.

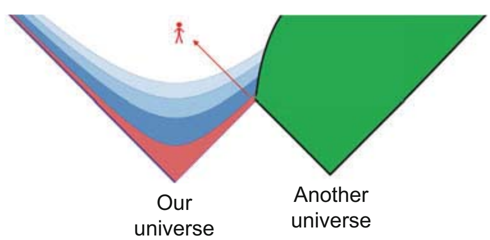

Fig. 15.2 A Penrose diagram representing a collision of our universe with another one.

As we have seen so far, the basic strategy to increase confidence about the multiverse is to accumulate observations that can naturally be explained by the multiverse picture but are difficult to obtain in any other way. Since we cannot physically go to other universes, this is clearly indirect, but this situation is not much different in some other cases, such as the big bang and inflationary theories. One might also be unsatisfied because the correspondence between the theory and observation is not "one to one": for example, even if we find a nonzero negative curvature in future observation, this measurement by itself would not uniquely select the multiverse as it is possible to come up with other theories that lead to such curvature even though the resulting theory would be contrived/fine-tuned. This situation, however, is also not so different from many other theories in the modern era. For example, in particle physics there is a theory called grand unified theory in which the three forces of the standard model are unified into a single force. It is often said that a smoking gun signature of this theory is that the proton decays (though with an incredibly long lifetime). Even in this case, however, it would not be impossible to come up with a model which leads to proton decay, although it may not be as elegant as grand unified theory.

The process in which we are observationally convinced with the multiverse theory could be frustratingly slow and likely would not be as dramatic as, e.g., a discovery of a new particle. However, here we are asking a particularly big question, and this is the cost we pay for it. At least, the framework is well motivated both observationally and theoretically to the extent we could probe so far. So it seems worth pursuing it further and see where it leads us to.

Epilogue

We have discussed misconceptions about the multiverse. A danger of these misconceptions is that they are sometimes used to argue against pursuing research on the subject. It is true that studying a big question involves risks, so it is legitimate if anyone decides personally not to participate in it. However, we never know how far a scientific theory can be developed until we seriously try to develop it. It seems fair to say that not everyone needs to study the multiverse, but someone should.

References and Further Reading

Here I list some selected textbooks and papers relevant to the subject discussed here. The list is in no sense exhaustive, but it gives an introduction to the vast number of articles written on the subject.

For the general subjects of early universe cosmology, string theory, and the anthropic principle, see, e.g.,

- J.D. Barrow, F.J. Tipler, *The Anthropic Cosmological Principle* (Oxford University Press, Oxford, 1988)
- K. Becker, M. Becker, J.H. Schwarz, *String Theory and M-Theory: A Modern Introduction* (Cambridge University Press, Cambridge, 2007)
- E.W. Kolb, M. S. Turner, *The Early Universe* (Westview Press, 1990)

and reference therein. For some key papers on the topics discussed here and on the multiverse in general, see, e.g.,

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