# Universe or multiverse?

Bernard Carr and George Ellis present their differing views on whether speculations about other universes are part of legitimate science.

**Abstract**

Recent developments in cosmology and particle physics suggest there could be many other universes, with different physical constants and possibly even different laws. This proposal could explain the origin of our universe and why it is fine-tuned for the development of life. But are speculations about other universes that can never been seen, based on theories that may never be testable, philosophy or science?

Although the word "universe" literally means all that exists, the longer we have studied the world, the larger it appears to have become. It is not surprising therefore that the usage of this term has changed as we have progressed from the geocentric to heliocentric to galactocentric to cosmocentric view.

Nowadays most cosmologists accept the Big Bang theory, in which the universe started in a state of great compression some 14 billion years ago. In this case, one can never see further than the distance light has travelled since the Big Bang (roughly 40 billion light-years – three times the naïve value because of expansion of space) and this might be taken to define the horizon of the *observable* universe. However, it would be perverse to claim that nothing *exists* beyond this distance. One would expect there to be other unobservable expanding domains that are still part of our Big Bang.

Recent developments in cosmology and particle physics have led to the much more radical proposal that there could also be other Big Bangs that might be completely disconnected from ours. The ensemble of universes is then sometimes referred to as the "multiverse". As we will see, there are many motivations for invoking a multiverse. For some, it is claimed as the inevitable outcome of the physical process that generated our own universe. For others, it is proposed as an explanation for why our universe appears to be fine-tuned for life and consciousness. For others, it is seen as the result of an underlying philosophical stance that "everything that can happen in physics does happen". The multiverse therefore arises in many different contexts and one needs to distinguish between these in assessing the idea.

It should be stressed at the outset that physicists are polarized about the notion of a multiverse. The title of this article is taken from a recent book (Carr 2007), which is based on three recent conferences on the topic, with contributions from many eminent researchers in the field. The question mark in the title indicates their broad range of attitudes to the multiverse proposal – from strong support through open-minded agnosticism to strong opposition. Nevertheless, there is no doubt that the idea has become increasingly popular in recent years. In his contribution to the book, Frank Wilczek (2007) describes the change in attitude between the first meeting in 2001 and the last one in 2005:

> *"The previous gathering had a defensive air. It prominently featured a number of physicists who subsisted on the fringes, voices in the wilderness who had for many years promoted strange arguments about conspiracies among fundamental constants and alternative universes. Their concerns and approaches seemed totally alien to the vanguard of theoretical physics, which was busy successfully constructing a unique and mathematically perfect universe. Now the vanguard has marched off to join the prophets in the wilderness."*

Indeed perhaps the most remarkable aspect of the book is that it testifies to the large number of eminent physicists who now find the subject interesting enough to be worth writing about.

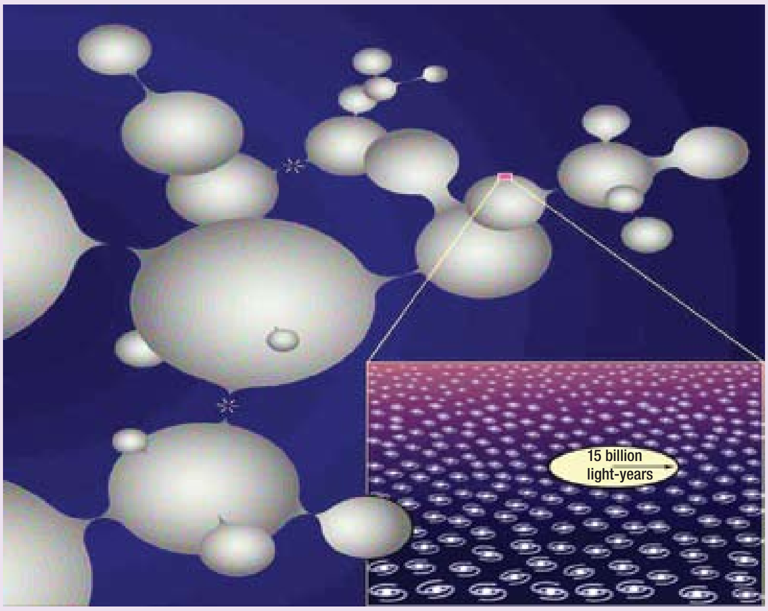
Despite this, there is no doubt that the concept of the multiverse raises deep conceptual issues. The problem is that scientific progress has not only changed our view of the universe, it has also changed our view of the nature of science itself, and physicists are divided in their reactions to this. Indeed the authors of this article are also divided. We both accept that the multiverse has explanatory value but we differ on whether it should be regarded as legitimate science. We have written this first part of the article together, because this merely describes the various multiverse scenarios and there is no essential disagreement here. However, we have written separate sections where our views diverge, focusing on seven specific bones of contention. Readers will need to draw their own conclusions but we hope to convey the nature of the controversy.

## Different multiverse proposals

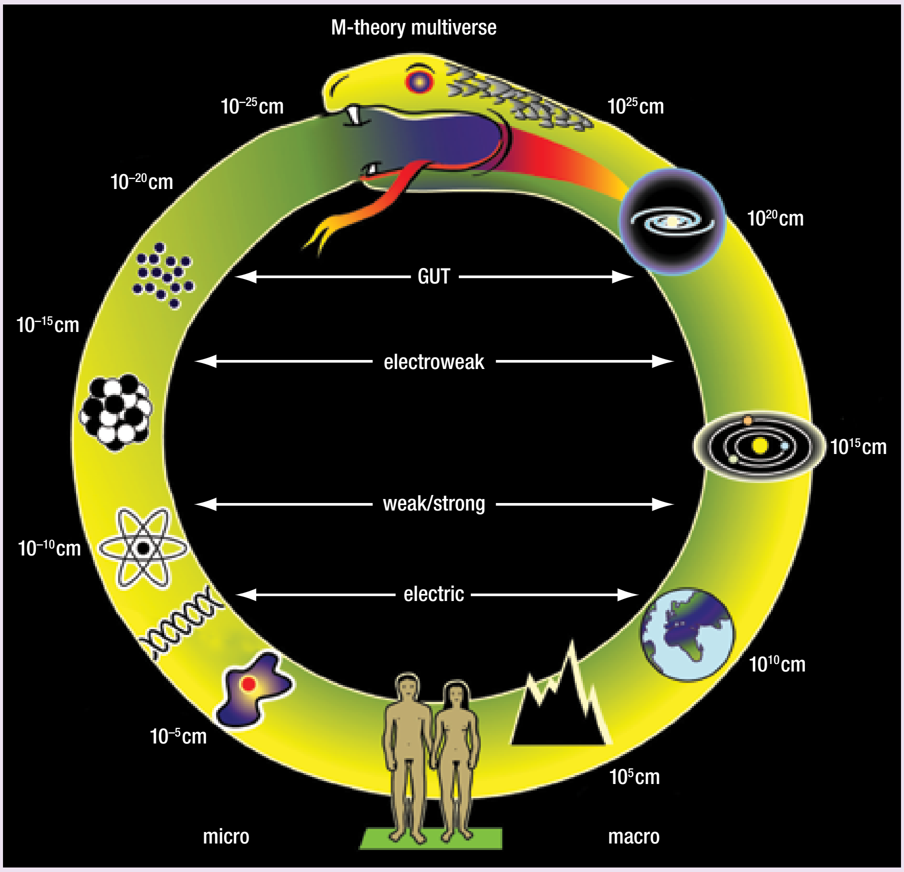
Max Tegmark (2003) classifies multiverse scenarios into four different types and we start by describing these. We have mentioned that in the Big Bang theory there should be many expanding domains beyond the horizon distance. Tegmark describes this as the "Level I" multiverse, and it is relatively uncontroversial. If pursued to its logical conclusion, it leads to some bizarre possibilities (like our having identical clones at great distance if space is infinite) and these entail some philosophical problems; but it would be hard to deny its existence if not taken to extremes.

The suggestion that there could be other Big Bangs that are completely disconnected from ours is much more challenging and leads to deeper philosophical difficulties. This sort of multiverse proposal – which Tegmark labels "Level II" – usually arises from attempts to understand how our universe originated. Advocates of the Big Bang theory used to assume that known physics would break down at the BBig Bang itself because it would correspond to a "singularity" of infinite density, so one could never hope to understand what happened there (let alone before it). However, in the last few decades cosmologists have begun to address this question and with remarkable success. So if one has a model for generating our own Big Bang, it is not surprising that it can also produce other Big Bangs. The problem is that physicists have widely different views on how the different universes might arise, so there are competing models for the multiverse. Some of these come from cosmologists and others from particle physicists. Let us first examine the cosmological proposals.

- Some invoke "oscillatory" models in which a single universe undergoes cycles of expansion and recollapse (Tolman 1934), though without necessarily understanding what causes the bounce. In this case, the different universes are strung out in time.
- Others invoke the "inflationary" scenario, in which our observable domain is a tiny part of a single bubble that underwent an extra-fast accelerated expansion phase at some early time as a result of the effect of a scalar field (Guth 1981). This explains why the universe is so smooth and why it has almost exactly the critical density that separates ever-expanding from recollapsing models. Inflation not only implies that the observable domain is a tiny patch of a much larger universe – some versions also predict that there could be many other bubbles,




1: In inflation our universe may be a minuscule part of one of many bubbles. (E Mallove)




2: The Cosmic Uroborus, a summary of the different types of structure in the universe. Near the bottom is *Homo sapiens*. As we move to the right, we encounter successively larger objects: a mountain, a planet, the solar system, a galaxy and finally the entire observable universe. As we move to the left, we encounter successively smaller objects: a cell, a DNA molecule, an atom, a nucleus, various types of fundamental particles and finally the scale at which quantum gravity effects become important. As one moves anticlockwise from the tail to the head, the scale of structure increases through 60 decades, so the Uroborus provides a "clock" in which each "minute" corresponds to a factor of 10 in scale. The horizontal lines correspond to the forces that link the microphysical and macrophysical domains. The "electric" line connects an atom to a planet because the structure of a solid object is determined by intermolecular forces which are electrical in origin. The "weak/strong" line connects a nucleus to a star because these forces are involved in the nuclear reactions which power a star. The "GUT" line connects the grand unification scale with galaxies because the density fluctuations which lead to galaxies arise when the universe has the GUT temperature.

corresponding to other universes with different properties spread out in space (figure 1). A variant of this idea is "eternal" inflation, in which the universe is continually self-reproducing, so that there are an infinite number of bubbles extending in both space and time (Vilenkin 1983, Linde 1986).

- A more radical proposal is to invoke quantum cosmology effects at the Planck time. These occur at around $10^{-43}$ s after the Big Bang, when the classical space-time description of general relativity breaks down. In this approach one has a superposition of different histories for the universe and uses what is termed the "path integral" approach to calculate the probability of each of these. This replaces the Big Bang singularity with a bounce – time becoming imaginary there according to Hartle and Hawking (1983) – and leads to a form of the cyclic model. Quantum cosmology is most naturally interpreted in the context of the "many worlds" interpretation of quantum mechanics (Everett 1957), in which the universe branches every time an observation is made (rather than the alternative view in which the wave-function collapses). Tegmark describes this quantum multiverse as "Level III" and it is the oldest scientific form of the idea.

We now turn to multiverse proposals inspired by particle physics. The holy grail of particle physics is to find a "Theory of Everything" that unifies all the known forces. Models that unify the weak, strong and electromagnetic interactions are commonly described as "grand unified theories" and – although still unverified experimentally – have been around for nearly 30 years. Incorporating gravity into this unification has proved more difficult but there have been exciting strides in recent years, with superstring theory being the currently favoured model. There are various versions of superstring theory but they are amalgamated in what is termed "M-theory". This supposes that the universe has more than the three dimensions of space which we actually observe, with four-dimensional physics emerging from the way in which the extra dimensions are compactified; this is described by what is called a Calabi–Yau manifold.

- In one version of M-theory our universe could correspond to a four-dimensional "brane" imbedded in a higher dimensional "bulk" (Randall and Sundrum 1999). In this case, there might be many other branes and collisions between the branes might even generate Big Bangs of the kind that initiated the expansion of our own universe. This might take place repeatedly to give a form of the cyclic model (Steinhardt and Turok 2006).
- It was originally hoped that M-theory would predict all the constants of Nature uniquely. However, recent developments suggest that this is not the case and that the number of compactifications could be enormous (e.g. $10^{500}$), each one corresponding to a different vacuum state

and a different set of constants (Bousso and Polchinksi 2000). This is sometimes described as the "string landscape" scenario. Each solution is associated with a different minimum of the vacuum energy and corresponds to a different universe, so the values of the physical constants would be *contingent* on which one we happen to occupy (Susskind 2005). A crucial feature of the string landscape proposal is that the vacuum energy would be manifested as what is termed a cosmological constant. This is an extra term in the field equations of general relativity, originally introduced by Einstein to make the universe static. One of the most exciting recent developments in cosmology has been the discovery from observations of distant supernovae that the expansion of the universe is accelerating. This suggests that the density of the universe is dominated by some form of "dark energy" and this is most naturally interpreted as a cosmological constant. It is this discovery that has attracted so many string theorists to the subject.

- Finally, what Tegmark describes as the "Level IV" multiverse contains completely disconnected universes, governed by different laws or mathematical structures. The assumption here is that any mathematically possible universe must exist somewhere.

We thus see how a confluence of developments in cosmology and particle physics has led to the popularity of the multiverse proposal. Indeed, the idea might be regarded as the culmination of scientific attempts to understand the largest and smallest scales. This is encapsulated in the image of the Cosmic Uroborus (figure 2), which shows the link between the macrophysical and microphysical domains of structure provided by the various forces. The significance of the head meeting the tail is that distances close to the horizon correspond to very early times, when today's observable universe was compressed to a tiny size. This is why early universe studies have led to an exciting collaboration between particle physicists and cosmologists. As one approaches the intersect point, one encounters the multiverse on the macroscopic side and M-theory on the microscopic side.

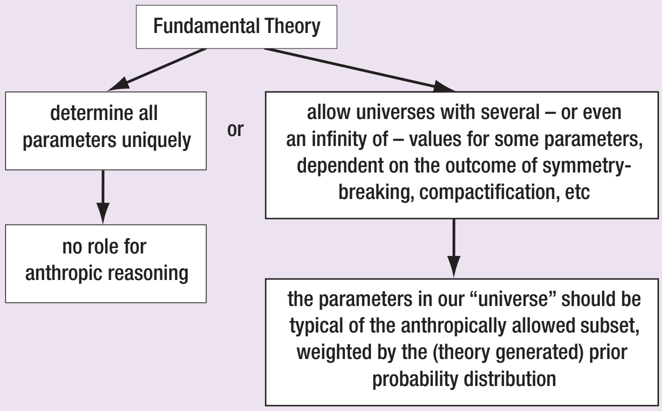
## The anthropic principle

One of the remarkable features of our universe is that some of the constants of physics seem to be fine-tuned for the emergence of observers (Carter 1974, Carr and Rees 1979, Barrow and Tipler 1986, Hogan 2000, Rees 2001). These fine-tunings – dubbed "anthropic" by Brandon Carter – have been studied for some 30 years and involve both the physical constants and various cosmological parameters. Some of them are summarized in table 1. As far as we know, these anthropic relationships are not predicted by any unified theory and, even if they were, it would be remarkable that the theory should yield exactly the coincidences required. Although *anthropos* is the Greek for "man", this is a misnomer because the fine-tunings have nothing to do with *Homo sapiens* in particular. They just seem necessary if an increasing degree of complexity is to develop as the universe expands and cools. This suggests that the anthropic principle should really be interpreted as a complexity principle.

### Table 1: Possible anthropic fine-tunings

$N$ = ratio of electric and gravitational force between protons ~ $10^{36}$
$E$ = nuclear binding energy as a fraction of rest mass energy ~ 0.007
$\Omega$ = matter density in universe in units of critical density ~ 0.3
$\Lambda$ = cosmological constant in units of critical density ~ 0.7
$Q$ = amplitude of density fluctuations at horizon epoch ~ $10^{-5}$

**3: The "decision tree" which determines whether anthropic explanations are irrelevant or the best we can ever hope for. (M Rees)**




Anthropic arguments used to be regarded with disdain by many physicists – and in some quarters still are – because they seem to exclude the more usual type of physical explanation for the values of the constants. The fact that people of a theological disposition interpreted the fine-tunings as evidence for a creator perhaps enhanced that reaction. Three very different views of the anthropic principle are illustrated by the quotations on page 2.32 from Freeman Dyson (1979), Heinz Pagels (1985) and Brandon Carter (1974). However, the multiverse proposal has led to a shift in the status of anthropic arguments because the constants may be different in the other universes. We have seen that this arises explicitly in the string landscape scenario and the constants may also vary in the different bubbles of the inflationary scenario. So although multiverse models have not generally been motivated by an attempt to explain the anthropic fine-tuning, it now seems clear that the two concepts are interlinked. For if there are many universes, the question arises as to why we inhabit this particular one and (at the very least) one would have to concede that our own existence is a relevant selection effect. Many physicists therefore regard the multiverse as providing the most natural explanation of the anthropic fine-tunings. If one wins the lottery, it is natural to infer that one is not the only person to have bought a ticket.

A multiverse with varied physical properties is certainly one possible explanation for fine-tunings: an infinite set of universes allows all possibilities and combinations to occur, so somewhere – just by chance – things will work out right for life. In assessing this view, a key issue is whether some of the physical constants are contingent on accidental features of symmetry breaking and the initial conditions of our universe or whether some fundamental theory will determine all of them uniquely. The two cases essentially correspond to the multiverse and single universe options (figure 3). This relates to a famous question posed by Einstein: "Did God have any choice when he created the universe?" If the answer is no, there would be no room for the anthropic principle. Most physicists would prefer the physical constants to be determined uniquely, but we have seen that this now appears unlikely. What we call "laws of Nature" may be local by-laws, in which case trying to predict the values of the constants may be as forlorn as Kepler's attempts to predict the spacing of the planets in our solar system based on the properties of Platonic solids.

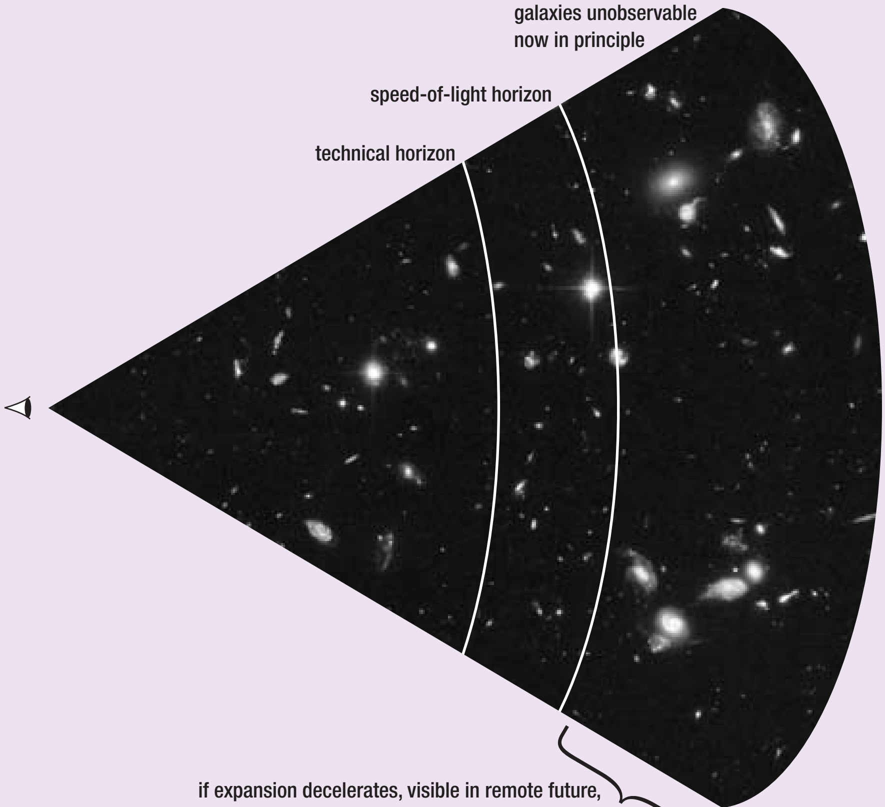
A particularly interesting anthropic argument is associated with the cosmological constant (denoted by $\Lambda$). In the string landscape picture one might expect the value of $\Lambda$ across the different universes to have a uniform distribution ranging from minus to plus the Planck value (which is 120 orders of magnitude larger than observed). The actual value therefore seems implausibly small. There is also the puzzling feature that the observed vacuum density is currently very similar to the mean matter density, a

### Three views on the anthropic principle

**"I do not feel like an alien in this universe. The more I examine the universe and examine the details of its architecture, the more evidence I find that the universe in some sense must have known we were coming."**
Freeman Dyson

**"The influence of the anthropic principle on contemporary cosmological models has been sterile. It has explained nothing and it has even had a negative influence. I would opt for rejecting the anthropic principle as needless clutter in the conceptual repertoire of science."**
Heinz Pagels

**"The anthropic principle is a middle ground between the primitive anthropocentrism of the pre-Copernican age and the equally unjustifiable antithesis that no place or time in the universe can be privileged in any way."**
Brandon Carter




**4: This shows the transition between the observable and unobservable as a succession of horizons. There is the limit to how far our present-day telescopes can probe; the limit set by the distance light could have travelled since the Big Bang; there are galaxies which emerged from the same Big Bang as ours but which we will never see in an accelerating universe; finally there are galaxies emerging from separate Big Bangs. (M Rees)**

coincidence that would only apply at a particular cosmological epoch. However, as pointed out by Steven Weinberg (1987), the value of $\Lambda$ is constrained anthropically because galaxies could not form (and hence life could not arise) if it were much larger than observed. So anthropic considerations in a multiverse with a wide spread of values of $\Lambda$ in different domains mean that the value we observe will be much smaller than in almost any other domain. This is not the only explanation for the smallness of $\Lambda$ but there is a reluctant acceptance that it may be the most plausible one.

One important question is whether our universe is typical or atypical within the ensemble. Advocates of the anthropic principle usually assume that life forms similar to our own will be possible in only a tiny subset of universes. More general life forms may be possible in a somewhat larger subset but life will not be possible everywhere. On the other hand, by invoking a Copernican perspective, Lee Smolin (1997) has argued that *most* of the universes should have properties like our own, so that we are typical. His own model proposes that the physical constants have *evolved* to their present values through a process akin to mutation and natural selection. The assumption is that whenever matter gets sufficiently compressed to undergo gravitational collapse into a black hole, it gives birth to another expanding universe in which the fundamental constants are slightly mutated. Our own universe may itself have been generated in this way (i.e. via gravitational collapse in some parent universe). Cosmological models with constants permitting the formation of black holes will therefore produce progeny (which may each produce further black holes since the constants are nearly the same), whereas those with the wrong constants will be infertile. A Darwinian process can take place, leading preferentially to universes that produce many black holes; in this case, life may be incidental.

## But is the multiverse science?

Despite the growing popularity of the multiverse proposal, many physicists remain deeply uncomfortable with it. One should note that the proposal being made is that there is a *really existing* multiverse. Nobody has any problem imagining a hypothetical or potential ensemble of universes – cosmologists do that all the time. The question is whether such an ensemble exists in physical reality. The idea is highly speculative and, from both a cosmological and particle physics perspective, the reality of a multiverse is currently untestable – and it may always remain so. That is to say, astronomers may never be able to observe the other universes with their telescopes and particle physicists may never be able to detect the extra dimensions with their accelerators. So although physicists such as Leonard Susskind favour the multiverse because it does away with the need for a creator, other physicists regard the idea as just as metaphysical.

Martin Rees (2001) defends the notion that the multiverse is part of science by invoking what he calls the "slippery slope" argument (figure 4). Not everyone is convinced – indeed it is one of the bones of contention we discuss later – but it highlights the difficulty of delineating a clear boundary between scientific and non-scientific speculations. For defences of the multiverse idea, see Deutsch (1997), Lewis (2000), Rees (2001), Tegmark (2003), Susskind (2006) and Vilenkin (2006). For criticisms, see Gardner (2003), Ellis *et al.* (2004) and Smolin (2007). ●

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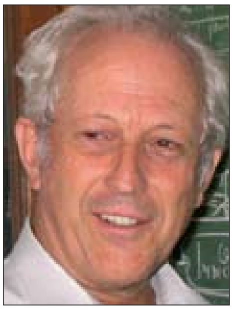
# Opposing the multiverse



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The very nature of the scientific enterprise is at stake in the multiverse debate. Its advocates propose weakening the nature of scientific proof in order to claim that the multiverse hypothesis provides a scientific explanation. This is a dangerous tactic. Two central scientific virtues are testability and explanatory power. In the cosmological context, these are often in conflict with each other and there has been an increasing tendency in theoretical physics and cosmology to say it does not matter whether a proposal is testable: if it fits into our other theories in a convincing way, with great explanatory power, then testing is superfluous. The extreme case is the multiverse proposal, where no direct observational test of the hypothesis is possible. Despite this, many articles and books dogmatically proclaim that the multiverse is an established scientific fact.

In this context one must re-evaluate what the core of science is: can one maintain one has a genuine scientific theory when direct and indeed indirect tests of the theory are impossible? If one claims this, one is altering the meaning of science. One should be very careful before so doing. There are many other theories waiting in the wings, hoping for a weakening of what is meant by "science". Those proposing this weakening in the case of cosmology should be aware of the flood of alternative scientific theories whose advocates will then state that they too can claim the mantle of scientific respectability.

## Observational problems and infinity

The key observational point is that the domains considered are beyond the visual horizon and are therefore unobservable. You cannot receive signals of any kind from beyond the horizon, as there has not been time for messages to reach us from there since the universe began. Hence no object out there is detectable by any kind of astronomical observation. To see this clearly one should look at the space-time diagrams of our past light cone (figure 5). The assumption made in justifying the multiverse is that we can extrapolate to $10^{100}$ times the horizon distance or even more (the word "infinity" is casually used in these writings). The extraordinary pretentiousness of this attempt should be clear.

The often claimed existence of physical infinities in the multiverse context – of either universes or spatial sections of universes (Vilenkin 2006) – is dubious. What has been forgotten here is that infinity is an unattainable state rather than a large number – its character is totally different from any finite number and it is a mathematical rather than physical entity. According to David Hilbert (1964): "The infinite is nowhere to be found in reality, no matter what experiences, observations, and knowledge are appealed to." Even if there *were* an infinite number of galaxies, and we could see them all (which we could not), we could not count them in a finite time. So there is no way the existence of an infinity can ever be proven correct by observation or any other test. The concept of physical infinities is not a scientific one if science involves testability by either observation or experiment. The claim of infinites in the multiverse context emphasizes how tenuously scientific that idea is. It is a huge act of hubris to extrapolate from one small domain to infinity when infinity is never attainable.

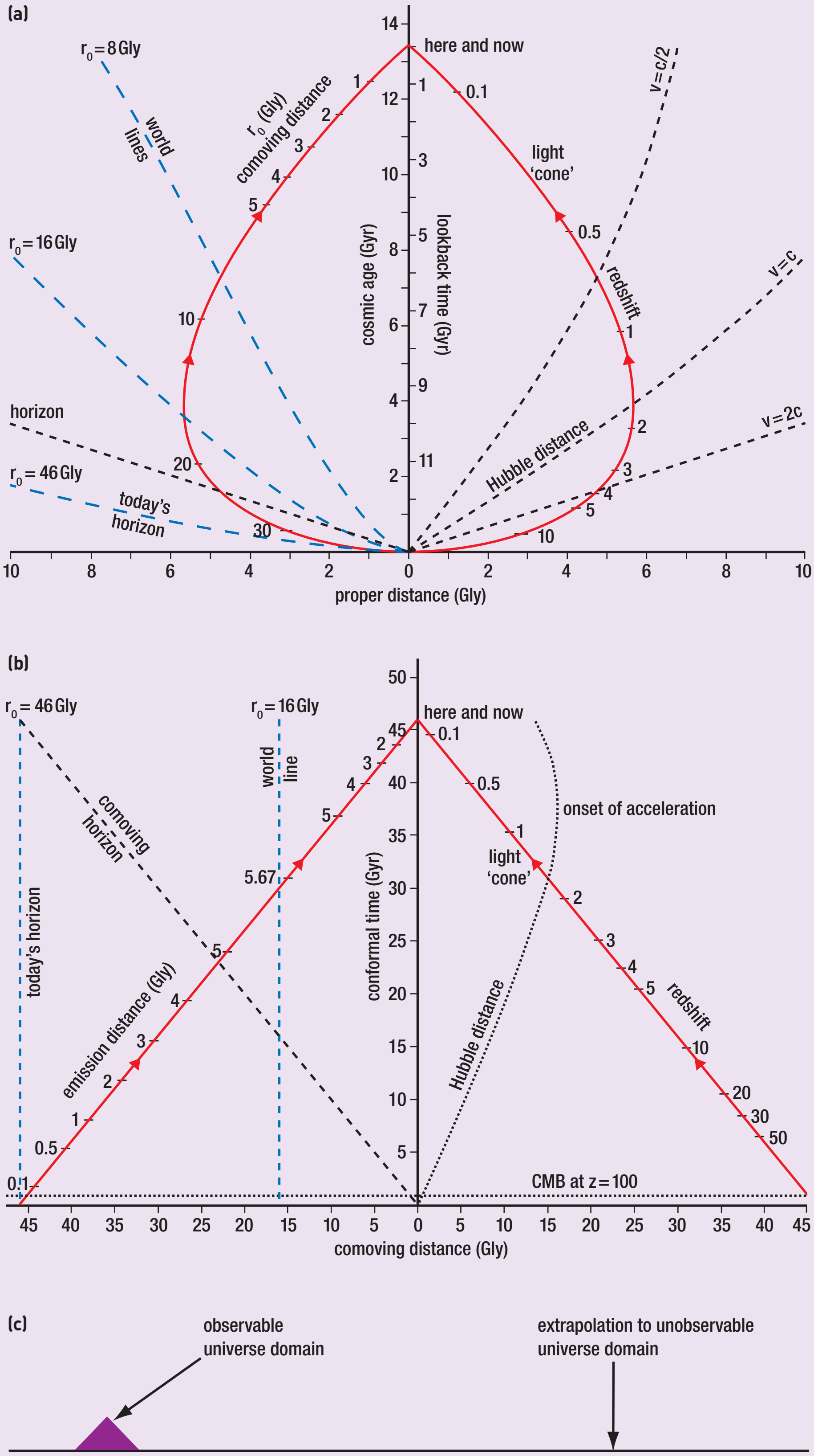
## Bones of dispute

Seven different kinds of justification have been proposed for the existence of a multiverse and I will now consider these in turn.

❶ **There are plausibly galaxies just beyond the visual horizon, where we cannot see them, so we can extend this argument, step by step, to way beyond the horizon and infer there are many different universes that we cannot see.**

This is the "slippery slope" argument and Rees (2001) uses it to defend both Level I and Level II multiverses. The argument is fine as regards extrapolation in the vicinity of the visual horizon, but the assumption that it can be continued to very distant domains or other universes is an untestable major extrapolation, which assumes a continuity that may or may not be true. If each link in a chain of evidence is well understood and tenable, then indirect evidence such as this carries nearly as much weight as direct evidence. But not all the links in the chain are tenable. If employed to its logical conclusion it seems *a priori* to lead to the old idea of spatial homogeneity extending forever ("The Cosmological Principle") rather than the multiverse of chaotic cosmology with domain walls separating different phases. For if the universe within the horizon is almost exactly Friedmann–Robertson–Walker

> **"Can one maintain one has a genuine scientific theory when direct and indeed indirect tests of the theory are impossible?"**




**5: This shows the space–time diagrams of our past light cone in both the usual form (a) and conformal form (b), in which one expands the spatial distances in order to see the causal structure. The light cones are then at ±45°, making clear the observational and causal limits; any observation beyond the visual horizon is impossible. The Hubble distance is where galaxies recede at the speed of light ($v=c$). The redshift measures the expansion factor and goes to infinity at the horizon itself. (c) shows more clearly the vast extrapolation envisaged in justifications of the multiverse. Note that there is a distinction between the visual horizon and the event horizon. The latter relates to causality in the far distant future and is irrelevant to present-day observations, but becomes relevant if the universe accelerates. (Mark Whittle, University of Virginia)**

(FRW) – a statistically spatially homogenous and isotropic space-time – it is plausible that it is also FRW just outside the horizon, and a simple extrapolation suggests that it is spatially homogeneous without limit. But supporters of chaotic inflation claim that there are completely different domains out there with different values of the constants, so which is the case? You can say what you like and nobody can *prove* it right or wrong.

**❷ The existence of a multiverse is implied by inflation, which is verified by the Cosmic Microwave Background anisotropy observations. In particular, known physics leads to chaotic inflation and this implies a multiverse.**

A multiverse is implied by some forms of inflation but not others. Inflation is not yet a well defined theory and chaotic inflation is just one variant of it. For example, inflation in a small closed universe fits all the observations, without requiring a multiverse. In any case, the key physics involved in chaotic inflation (Coleman–de Luccia tunnelling) is extrapolated from known and tested physics to quite different regimes; that extrapolation is unverified and indeed unverifiable. The physics is hypothetical rather than tested. We are being told that what we have is "known physics → multiverse". But the real situation is "known physics → hypothetical physics → multiverse" and the first step involves a major extrapolation which may or may not be correct.

**❸ The multiverse idea is testable, because it can be disproved if we determine there are closed spatial sections in the universe (for example, if the curvature is positive).**

The claim is that only negatively curved FRW models can exist in a multiverse based on chaotic inflation, either because Coleman–de Luccia tunnelling only gives negative curvature or because a closed spatial section necessarily implies a single universe. But the first argument is disputed (there are already papers suggesting that tunnelling to positively curved universes is possible) and the second argument would not apply if we lived in a high-density lump imbedded in a low-density universe (i.e. the extrapolation of positive curvature to very large scales may not be valid). Neither argument is conclusive. Certainly observational confirmation of negatively curved space sections would not constitute proof of a multiverse, for that can occur in a single universe. However, chaotic inflation versions of the multiverse can be disproved if we observationally prove that we live in a universe with closed spatial sections that are so small that we have already seen round the universe. We can test this possibility by searching for identical circles in the CMB, together with low anisotropy power at large angular scales (which is indeed observed). This is an important test as it would disprove the chaotic inflation variety of multiverse. But not seeing the circles would not prove a multiverse exists: their non-detection is a necessary but not sufficient condition for multiverses.

**❹ The existence of a multiverse is the only physical explanation for the fine-tuning of parameters that leads to our existence.**

The multiverse is a reasonable theoretical explanation of the fine-tunings, but this does not help in observationally confirming the hypothesis. The issue here is, which is more important in cosmology: theory (explanation) or observations (tests against reality)? The essential proposal is that one should downgrade observational testing in favour of theory – a dangerous road to take. In any case, the major problem with this proposal is that it can explain anything at all, because in a multiverse with an infinite or extremely large variety of universe properties – for example, the $10^{500}$ possibilities allowed by the landscape of string theory – virtually anything can happen. In that case, the hypothesis does not predict any specific testable fact. The existence of universes with giraffes is certainly predicted by many multiverse proposals, but universes where giraffes do not exist are also predicted. Observing a giraffe neither confirms nor disproves the multiverse.

**❺ The existence of a multiverse is implied by a probability argument: the universe is no more special than it need be to create life. In particular, the small value of the cosmological constant shows that other universes exist.**

But the statistical argument invoked here only applies if a multiverse exists; it is simply inapplicable (because the probability distribution has no meaning) if there is no multiverse, so it cannot prove a multiverse exists. It is a calculation that assumes the answer (that a multiverse exists) before it begins. If we only have one object to observe, we can make many observations of that object, but it is still only one object (one universe), and you cannot do statistical tests on its nature. This is a consistency test if there is indeed a multiverse, but it says nothing if there is not. It is not a sufficient condition for its existence. The argument that the actual value of $\Lambda$ is extremely different from the "natural" one predicted by theoretical physics (120 orders of magnitude smaller!) makes very clear the nature of the multiverse project: it is an attempt to make the extremely improbable appear probable.

**❻ Even if one does not accept inflation, multiverses are predicted by many theories of particle physics.**

One example of this is the string landscape of M-theory, but that is a hypothetical proposal with no solid evidence in its favour. Indeed, even many string theorists are sceptical about the landscape, despite the enthusiasm with which some propose it. A major problem arises when one has a theory where no verification is possible. It is not necessary to check all the predictions of a theory for it to be considered scientific – one can check some predictions to help the theory gain credence, but that does not prove the theory because it has to be the *only* one that makes the prediction for it to carry weight; it cannot be conclusive unless no other explanation is possible

> **"The multiverse theory cannot make any testable predictions because it can explain anything at all."**

Let me illustrate with an example. I can propose that there are leopards hidden in the mountains of Scotland. They are very shy, so they hide away and no-one ever sees them. But you can tell they are there because sheep vanish without trace every year. I can put together an exciting research project that will look at statistics of lost sheep in Scotland for the past 50 years, and hence prove the existence of these rare mountain leopards. This seems to me to be analogous to the argument for proof of the existence of a multiverse through any specific property (e.g. the smallness of $\Lambda$) that might possibly exist somewhere in the landscape. This may be something that is predicted by some multiverse theory, but it hardly proves it true.

I am all for the exercise of applying known physics in more extreme conditions: do it and see what happens. But admit that it is an untested extrapolation and that different extrapolations are possible. You can extrapolate different aspects of known physics to the unknown and different predictions will result. For example, if one extrapolates classical physics to the quantum domain, the answers will be wrong. But in that case you can show this is so by experimental tests. That is what is missing in the multiverse case: you can make the extrapolation but cannot then determine if it is right or not.

**❼ The nature of science changes, so what is illegitimate science today may be legitimate tomorrow.**

This is true, but the foundations must be respected if one is to preserve the core features of science that have led to its phenomenal success: that is the feedback from reality to theory provided by experiment and observational testing. One abandons that at one's peril. For example, today's philosophical definition of science excludes astrology, despite all the claimed theory and data supporting it. But now astrologers can take hope from the arguments of string theorists and multiverse enthusiasts: with the weakened kinds of criteria proposed, astrology too will soon be a strong candidate for recognition as a genuine science. The Popperazi (a derogatory term used by Susskind for those who believe testing scientific theories is an indispensible aspect of science) will no longer be able to deny astrology its place as a proper scientific theory. Is that what we really want? At the very least, we must be given a clear statement as to what broader definition of the nature of science is being proposed, and in particular what criteria of testing will be taken to be adequate (Ellis 2006); this then needs to be assessed in relation to cases such as astrology and "intelligent design", as well as multiverses and string theory, in order to see what its implications are.

## Summing up

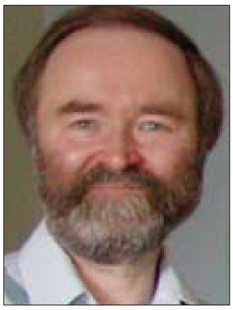
The multiverse idea is provable neither by observation, nor as an implication of well established physics. It may be true, but it cannot be shown to be true. It does have great explanatory power – it provides an empirically based rationalization for fine tuning, developed from known physical principles – but one must distinguish between explanation and prediction. Successful scientific theories make predictions that can be tested. The multiverse theory cannot make any testable predictions because it can explain anything at all.

Even though multiverse proposals are good empirically based philosophical proposals for the nature of what exists, they are not strictly within the domain of science. There is nothing wrong with empirically based philosophical explanation – indeed it is of great value provided it is labelled for what it is – but I suggest that cosmologists should be very careful not to make methodological proposals that erode the essential nature of science in their enthusiasm to support specific theories. For if they do so, there will very likely be unintended consequences in other areas where the boundaries of science are in dispute.

Let me state it more strongly: it is dangerous to weaken the grounds of scientific proof in order to include multiverses under the mantle of "tested science". It is a retrograde step towards the claim that we can establish the nature of the universe by pure thought without having to confirm our theories by observational or experimental tests. This abandons the key principle that has led to the extraordinary success of science. The claim that multiverses exist is a belief rather than an established scientific fact. It is a reasonable belief with strong explanatory nature, but a belief nonetheless. The appropriate statement we can make is not "multiverses exist" or "multiverses have been proved to exist" or even "multiverses can be proved to exist", but rather "multiverses are a useful explanatory hypothesis". We should not state more. Martin Gardner (2003) puts it this way:

> *"There is not the slightest shred of reliable evidence that there is any universe other than the one we are in. No multiverse theory has so far provided a prediction that can be tested. As far as we can tell, universes are not as plentiful as even two blackberries."* ●

# Defending the multiverse



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From a historical perspective, the multiverse is just one more step in our progress from geocentric to heliocentric to galactocentric to cosmocentric worldview. Indeed, several lessons of relevance to the multiverse debate can be gleaned from considering the history of this progression.

## Lessons of history

To the ancient Greeks, the heavenly spheres were the unchanging domain of the divine and therefore outside science by definition. It required Tycho de Brahe's observation of a supernova in 1572 and the realization that its apparent position did not change as the Earth moved around the Sun to dash that view. Because this contradicted the Aristotelian view that the heavens cannot change, the claim was at first received sceptically. Frustrated by those who had eyes but would not see, Brahe wrote: "O crassa ingenia. O coecos coeli spectators." (Oh thick wits. Oh blind watchers of the sky.) *Lesson 1: Theoretical prejudice should not blind one to the evidence.* Of course, we will never see the other universes themselves – in that sense we are necessarily blind, so this point might seem irrelevant to the multiverse. However, I would claim that the analogue of Tycho's supernova is the fine-tunings.

Long after Galileo had speculated that the Milky Way consists of stars like the Sun and Newton had shown the laws of Nature could be extended beyond the solar system, there was still a prejudice that the investigation of this region was beyond the domain of science. In 1842 August Comte said of the study of stars:

> *"Never, by any means, will we be able to study their chemical compositions. The field of positive philosophy lies entirely within the Solar System, the study of the universe being inaccessible in any possible science."*

Comte had not foreseen the advent of spectroscopy, which identified absorption features in stellar spectra with chemical elements. *Lesson 2: New observational developments are hard to anticipate.* Perhaps we will find extra dimensions at the Large Hadron Collider or even create baby universes in the laboratory one day.

Cosmology attained the status of a proper science in 1915, when the advent of general relativity gave it a secure mathematical basis. Nevertheless, for a further decade there was resistance to the idea that science could be extended beyond our galaxy. Indeed many astronomers refused to believe that there *was* anything beyond. Although Kant had speculated as early as 1755 that some nebulae are "island universes" similar to the Milky Way, most astronomers continued to adopt a galactocentric view until the 1920s. Indeed, the most popular model of the galaxy at the start of the 20th century – Kapteyn's Universe – even had the Sun at its centre! The controversy came to a head in 1920 when Heber Curtis defended the island universe theory in a famous debate with Harlow Shapley. The issue was finally resolved in 1924, when Edwin Hubble measured the distance to M31 using Cepheid variable stars. In many ways this parallels the current debate about whether anything exists beyond our horizon. *Lesson 3: More conservative cosmologists might prefer to maintain the cosmocentric view but perhaps the tide of history is against them.* The evidence for other universes can never be as decisive as that for extragalactic nebulae but the transformation of worldview required may be just as necessary.

A few years later Hubble obtained radial velocities and distance estimates for several dozen nearby galaxies, thereby discovering that all galaxies are moving away from us with a speed proportional to their distance. The most natural interpretation of this is that space itself is expanding, as indeed had been predicted by Alexander Friedmann in 1920 on the basis of general relativity. Einstein rejected this model at the time because he believed the universe (i.e. the Milky Way) was static and he even introduced an extra repulsive term into his equations – the cosmological constant – to allow this possibility. After Hubble's discovery, he described this as his "biggest blunder". *Lesson 4: One should not necessarily reject theoretical predictions because they have no observational support.* In fact, Einstein continued to uphold the static model even after the evidence was against it – he only accepted the Friedmann model in 1931, several years after Hubble published his data – so knowing how much weight to attach to theory and observation can be tricky.

## Bones of contention

Let me now address George's specific issues.

❶ **There are plausibly galaxies just beyond the visual horizon, where we cannot see them, so we can extend this argument, step by step, to way beyond the horizon and infer there are many different universes that we cannot see.**

Even though we can never prove what happens outside our visual horizon, the standard FRW model has been well tested within it, so there is surely some probabilistic sense in which one can extrapolate models at least some way beyond it. Also the smooth dependence of the CMB fluctuations on angular separation (whatever the source of those fluctuations) gives no reason to suppose that anything strange happens just beyond the horizon. George himself seems to accept this, which illustrates the problem of regarding speculations as non-scientific just because they involve the unobservable. Admittedly one's confidence in any proposed model must decrease as one extrapolates ever further beyond the horizon, but one should beware of using Rees's slippery slope argument in reverse: we cannot extrapolate to scales *much* larger than the horizon, so we should not extrapolate to scales only *slightly* outside it. The problem comes when one makes the jump from the Level I to Level II multiverse (which is where George's argument that the FRW solution extends everywhere must fail). In fact, the inflationary scenario does provide an answer to this. For if the amplitude of the density fluctuations increases slightly with scale (as appears to be the case), one can predict the scale at which the FRW approximation breaks down. Current data suggest that this happens at around $10^{100}$ horizon scales.

❷ **The existence of a multiverse is implied by inflation, which is verified by the CMB anisotropy observations. In particular, known physics leads to chaotic inflation and this implies a multiverse.**

There are two distinct issues here: does one believe in inflation and does inflation lead to a multiverse? Inflation is attractive because it resolves several cosmological conundra. Quantum fluctuations of the scalar field can also generate the small density perturbations that eventually give rise to galaxies and large-scale structure and it is impressive that the predicted dependence of the CMB fluctuations on angular separation is almost exactly as observed by the WMAP satellite (Spergel *et al.* 2003). Of course, the evidence for inflation is not conclusive – there is still no evidence for any scalar field in Nature! – but the Level I multiverse is still a good bet. As regards the second issue, I agree with George that the evidence for the sort of chaotic inflation that leads to a Level II multiverse is more equivocal, and certainly one cannot infer this from the form of the CMB anisotropies. There are now around 100 models of inflation and, while Linde (1990) claims that the existence of other domains with different coupling constants is generic, this is debatable.

❸ **The multiverse idea is testable, because it can be disproved if we determine there are closed spatial sections in the universe (for example, if**

**the curvature is positive).**

This is really a straw man argument because we have seen that inflation is only one of several multiverse proposals – for example, quantum cosmology models give closed spatial sections – and not all inflationary models require that the spatial sections be open anyway. However, George is surely right to stress the importance of looking for circles in the CMB. The idea of small universes is not mainstream but it has the advantage that it can be tested.

**❹ The existence of a multiverse is the only physical explanation for the fine-tuning of parameters that leads to our existence.**

In the absence of direct evidence for other universes, I regard the anthropic fine-tunings as the best indirect evidence. (A multiverse in which the constants were the same everywhere would have no explanatory value.) I agree with George that the fine-tunings do not constitute proof, but they still carry weight. One can argue about how impressive the fine-tunings are (could we really exclude life if the constants changed a lot?), but I still think the number and precision of the tunings is remarkable. Nearly 30 years ago I wrote a review with Martin Rees about these fine-tunings (Carr and Rees 1979). In the intervening period a few of them have gone away (e.g. inflation may explain the value of the cosmological density parameter) but most of them have got stronger. Without a multiverse one may be forced to adopt a non-physical explanation like a fine-tuner, which is why Neil Manson (2003) claims that "the multiverse is the last resort of the desperate atheist". This is not necessarily true – Paul Davies (2006) advocates a "third way" in which the laws of Nature evolve in a single universe in such a way that life can arise – but if you reject the multiverse, you certainly lower the scientific status of the anthropic arguments. I agree with George's argument against physical infinities. However, we do not need an infinity to validate the anthropic principle – just a large number.

> **"One needs some degree of falsifiability, but the question is, how much and how soon?"**

**❺ The existence of a multiverse is implied by a probability argument: the universe is no more special than it need be to create life. In particular, the small value of the cosmological constant shows that other universes exist.**

George argues that multiverse theories are not useful because they cannot be disproved: if all possibilities exist somewhere, then they can explain all conceivable observations. However, the fact that we only observe one sample of the multiverse still allows the proposal to be refuted at a given confidence level. Statistical predictions still qualify as science and that is why Rees has stressed the importance of calculating the probability distribution for various parameters across the universes. Indeed, a core difference between the Bayesian and frequentist views is the former's willingness to make inferences from single, and possibly unrepeatable, pieces of data. George rejects the $\Lambda$ argument but there is no doubt that this has been very influential in attracting many physicists to the multiverse cause. It used to be thought that $\Lambda$ was exactly zero and it was then plausible that there might be some physical (non-anthropic) explanation for this. However, the fact that $\Lambda$ is non-zero but very tiny is a profound mystery that completely changes the situation. Critics say that we cannot know what distribution for $\Lambda$ is predicted across the multiverse and that is correct. It may be simplistic to assume that the distribution is uniform, but postulating that there is a spike in precisely the observed region is just as improbable as what we are trying to explain.

**❻ Even if one does not accept inflation, multiverses are predicted by many theories of particle physics.**

It is still legitimate to invoke the existence of other universes for which there can be no direct evidence if one has a theory (like M-theory) that predicts this. It is not necessary to check *all* predictions of the theory for it to be considered scientific (e.g. we cannot probe inside black holes and we cannot see quarks but we still regard these as subjects for scientific discourse); it is only necessary to test *some* of them. Does M-theory qualify in this respect? George claims no; it does not come under the purview of science because our confidence in it is based on faith and aesthetic considerations (mathematical beauty etc) rather than experimental data. Certainly he is not alone in this attitude. For example, Woit (2006) and Smolin (2007) dismiss M-theory as mathematics rather than physics because it has not made contact with observations after 20 years. However, I feel this rejection is premature. It may take 200 years to solve the equations of M-theory and test them, but the definition of what constitutes a scientific question should not depend on how difficult it is.

**❼ The nature of science changes, so what is illegitimate science today may be legitimate tomorrow.**

The fundamental issue in the dispute between myself and George concerns which features of science are to be regarded as sacrosanct. Experimentation used to be regarded as sacrosanct but by that criterion all of astronomy would be excluded since one cannot experiment with stars and galaxies. Fortunately, one can still make observations and – since there are billions of these objects – Nature effectively performs experiments for us. Cosmologists are in worse shape because there is only one universe to observe and speculations about processes at very early and very late times have to be viewed as ultra-speculative. For this reason, more conservative physicists regard even relatively standard cosmological speculations as trespassing into metaphysics. George places a lot of emphasis on falsifiability, but not everybody in the philosophy of science agrees with Popper on this and it is surely dangerous to impose a philosophical prescription that prevents scientists changing the border of their field. As Susskind cautions, it would be a pity to miss out on some fundamental truth because of an over-restrictive definition of science. Of course, one needs some degree of falsifiability, but the question is, how much? It is certainly not fair to put M-theory in the same class as astrology. On the other hand, I share George's scepticism of the Level IV multiverse, which corresponds to universes governed by different mathematical structures. The view that any mathematically possible universe must exist somewhere seems untestable in a deeper sense than Levels I to III.

## Summing up

The notion of a multiverse entails a new perspective of the nature of science and it is not surprising that this causes intellectual discomfort. But this situation has often occurred before and one should not be surprised if it happens again. The Cosmic Uroborus in figure 2 shows that the history of physics might be regarded as the extension of knowledge into ever smaller and ever larger scales. The ideas encountered at the two frontiers have often been viewed as part of philosophy rather than science, so in a sense the debate is nothing new.

However, there is another sense in which the current situation is very special. This is because – for the first time – the boundaries at the largest and smallest scales have connected, as indicated by the top of the Cosmic Uroborus, so the two science/philosophy frontiers have merged. Does this merging represent the *completion* of science or merely the sort of *transformation* in the perceived nature of science that accompanies every paradigm shift? This is a contentious issue and clearly we do not yet know the answer. I accept that there may eventually be a limit to the sort of questions that science can address; George and I merely disagree on whether we have reached that limit with the multiverse. In any case, we are surely behoven to try to take science as far as possible. I will end with a comment by Steven Weinberg (2007) in his contribution to *Universe or Multiverse?*:

> *"We usually mark advances in the history of science by what we learn about Nature, but at certain critical moments the most important thing is what we discover about science itself. These discoveries lead to changes in how we score our work, in what we consider to be an acceptable theory."* ●