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Fine-Tuning, Complexity, and Life in the Multiverse

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Abstract

The physical processes that determine the properties of our everyday world, and of the wider cosmos, are determined by some key numbers: the constants of microphysics and the parameters that describe the expanding Universe in which we have emerged. We identify various steps in the emergence of stars, planets, and life that are dependent on these fundamental numbers and explore how these steps might have been changed – or completely prevented – if the numbers were different. We then outline some cosmological models where physical reality is vastly more extensive than the Universe that astronomers observe (perhaps even involving many big bangs) – which could perhaps encompass domains governed by different physics. Although the concept of a multiverse is still speculative, we argue that attempts to determine whether it exists constitute a genuinely scientific endeavour. If we indeed inhabit a multiverse, then we may have to accept that that there can be no explanation other than anthropic reasoning for some features of our world.

1.1 Introduction

At their fundamental level, phenomena in our Universe can be described by certain laws – the so-called laws of nature – and by the values of some three dozen parameters (e.g., [38]). Those parameters specify such physical quantities as the coupling constants of the weak and strong interactions in the Standard Model of particle physics and the dark-energy density, the baryon mass per photon, and the spatial curvature in cosmology.

What actually determines the values of those parameters, however, is an open question. Many physicists believe that some comprehensive ‘theory of everything’ yields mathematical formulae that determine all these parameters uniquely. But growing numbers of researchers are beginning to suspect that at least some parameters are, in fact, random variables, possibly taking different values in different members of a huge ensemble of universes – a multiverse (see, e.g., [23] for a review). Those in the latter camp take the view that the question ‘Do other universes exist?’ is a genuine scientific one. Moreover, it is one that may be answered within a few decades. We address such arguments later in this chapter, but first we address the evidence for *fine-tuning* of key parameters.

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A careful inspection of the values of the different parameters has led to the suggestion that at least a few of those constants of nature must be fine-tuned if life is to emerge. That is, relatively small changes in their values would have resulted in a universe in which there would be a blockage in one of the stages in emergent complexity that lead from a ‘big bang’ to atoms, stars, planets, biospheres, and eventually intelligent life (e.g., [2, 3, 6, 25]).

We can easily imagine laws that were not all that different from the ones that actually prevail but would have led to a rather boring universe – laws which would have led to a universe containing dark matter and no atoms; laws where there were hydrogen atoms but nothing more complicated and, therefore, no chemistry (and no nuclear energy to keep the stars shining); laws where there was no gravity; laws where there was a universe where gravity was so strong that it crushed everything; laws where the cosmic lifetime was so short that there was no time for evolution; or laws where the expansion was too fast to allow gravity to pull stars and galaxies together.

Some physicists regard such apparent fine-tunings as nothing more than statistical flukes. They would claim that we should not be surprised that nature seems ‘tuned’ to allow intelligent life to evolve – we would not exist otherwise. This attitude has been countered by John Leslie, who gives a nice metaphor. Suppose you were up before a firing squad. A dozen bullets are fired at you, but they all miss. Had that not happened, you would not be alive to ponder the matter. But your survival is still a surprise – one that it’s natural to feel perplexed about.

Other physicists are motivated by this perplexity to explore whether ‘fine-tuning’ can be better understood in the context of parallel universe models. In this connection, it’s important to stress that such models are consequences of several much-studied physical theories – for instance, cosmological inflation and string theory. The models were not developed simply to remove perplexity about fine-tuning.

Before we explore some prerequisites for complexity, it is instructive to examine a pedagogical diagram that demonstrates in a simple way the properties of a vast range of objects in our Universe. This diagram (Figure 1.1), adapted from Carr and Rees [5], shows the mass vs size (on a logarithmic scale) of structures from the subatomic scale to the cosmic scale. Black holes, for example, lie on a line of slope 1 in this $\log M - \log R$ plot. A black hole the size of a proton has a mass of some 10^{38} protons, which simply reflects how weak the force of gravity is. Solid objects such as rocks or asteroids, which have roughly the atomic density, lie along a line of slope 3, as do animals and people. Self-gravity is so weak that its effects are unnoticeable up to objects even the size of most asteroids. From there on, however, gravity becomes crucial – causing, for instance, planets to be spherical – and by the time objects reach a mass of about $0.08 M_{\odot}$, they are sufficiently squeezed by gravity to ignite nuclear reactions at their centres and become stars. The bottom-left corner of Figure 1.1 is occupied by the subatomic quantum regime. On the extreme left is the ‘Planck length’ – the size of a black hole whose Compton wavelength is equal to its Schwarzschild radius. Classical general relativity cannot be applied on scales smaller than this (and indeed may break down under less extreme conditions). We then need a quantum theory of gravity. In the absence of such a theory, we cannot understand

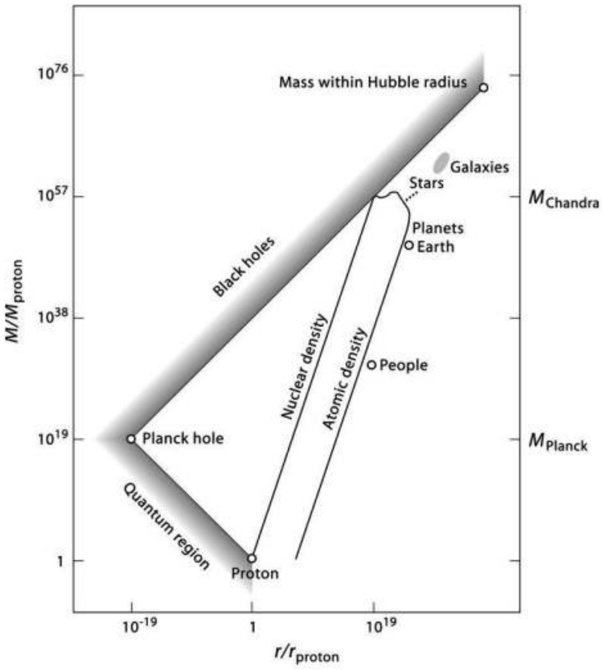

Figure 1.1 This diagram summarises the scales of stars, planets, black holes, and other bodies in a log-log plot of mass against radius. Ordinary lumps lie on the line of slope 3. The mass, in units of the proton mass, scales roughly as the cube of the radius. That line would eventually cross the black hole line (of slope one) at a mass of about 100 million suns. However, it is curtailed before it can do so. The reason is that any mass above about that of Jupiter (containing more than 10^{54} atoms) would be crushed by gravity to a higher density than an ordinary solid. If G were different, the shape of the diagram would not change much, but the number of powers of 10 between the scale of stars and of atoms would scale as the inverse 3/2 power.

the Universe's very beginnings (i.e., what happened at eras comparable to the Planck time of 10^{-43} seconds).

Despite this unmet challenge, it is impressive how much progress has been made in cosmology. In the early 1960s, there was no consensus that our Universe had expanded from a dense beginning. But we have now mapped out, at least in outline, the evolution of our Universe, and the emergence of complexity within it, from about a nanosecond after the Big Bang. At that time, our observable Universe was roughly the size of the solar system, and characterised by energies of the order of those currently realised at the Large Hadron Collider (LHC) near Geneva. Nucleosynthesis of the light elements gives us compelling corroboration of the hot and dense conditions in the first few seconds of the Universe's existence (see Chapter 7; see also, e.g., [8] for a recent review).

The cosmic microwave background (CMB) provides us with not only an astonishingly accurate proof for a black-body radiation state that existed when the Universe was

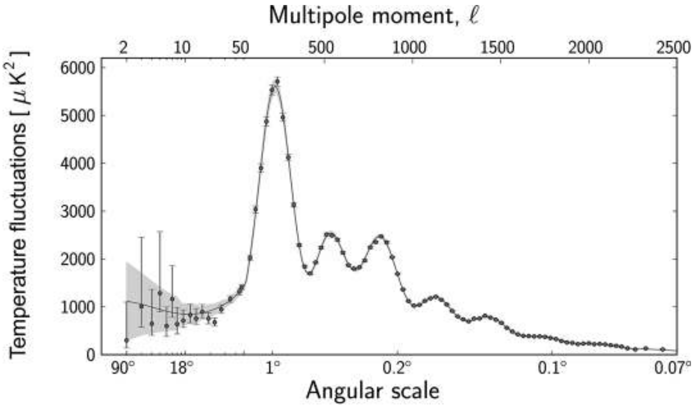

Figure 1.2 The fluctuations in the microwave background on different angular scales. The data come from the Planck spacecraft. The angular scale of the strongest peak is consistent with a flat universe, and the relative heights of the other peaks determine the baryon and dark matter densities.

400,000 years old but also a detailed map of the fluctuations in temperature (and density), $\Delta T/T \sim 10^{-5}$, from which eventually structure emerged. Peaks in the power spectrum of the CMB fluctuations, mapped with great accuracy by the WMAP and Planck satellites, can, even without any other information, offer precise determinations of a few cosmological parameters (e.g. [13, 30]), such as the fractions of baryonic matter, dark matter, and so-called dark energy in the cosmic energy budget (Figure 1.2).

The latter is a mysterious form of energy latent in empty space which has a negative pressure and causes the cosmic expansion to accelerate. It was discovered through observations of Type Ia supernovae [29, 31]. Since then, however, its existence has been confirmed through other lines of evidence, including the CMB, baryon acoustic oscillations, and the integrated Sachs-Wolfe effect (see [28] for a brief review). The simplest hypothesis is that the dark energy has the same properties as the cosmological constant ‘lambda’ which Einstein introduced in his original equations, but it is possible that it has more complicated properties. In particular, it could change with time and could correspond to just one of many possible vacua. In addition, many lines of evidence have led to the realisation that some form of gravitating dark matter outweighs ordinary baryonic matter by about a factor of five in galaxies and clusters of galaxies. Here are four: (1) flat rotation curves in galaxies extending out beyond the stellar disk; (2) the motions of galaxies in clusters of galaxies; (3) the temperature of the hot gas in clusters of galaxies; (4) gravitational lensing. All of these measure the depth of the gravitational potential well in galaxies or clusters and reveal the presence of mass that does not emit or absorb light. While all the attempts to detect the constituent particles of dark matter have so far been unsuccessful (see Chapter 9; see also, e.g., [11] for a review), this may not be so surprising when we realise that there are some 10 orders of magnitude between the currently observed mass-energies and the GUT unification energy where these particles could hide. Moreover, there are other options such as axions and ultra-low-mass bosons.

Dark matter provided the scaffolding on which the large-scale structure formed. In fact, while some uncertainties about the details remain (see, e.g., [6]), computer simulations can generally reproduce the types of structures we observe on the galactic and cluster scale while starting from the fluctuations observed by Planck and WMAP (see, e.g., [1]).

Similarly, a combination of hydrodynamics, thermodynamics, and nuclear physics has led to a fairly satisfactory understanding of the main processes involved in stellar structure, star formation, evolution, and stellar deaths (e.g., [17, 18]), as well as the formation of planetary systems. Thanks to observations in the past two decades (especially by the Kepler Space Observatory), we now know that the Milky Way contains about one Earth-size habitable-zone planet for every six M-dwarfs [9], which makes the prospects of finding extrasolar life (at least in simple form) with planned or proposed telescopes more promising [26, 35, 36].

Given our current understanding of the evolution of our Universe and of galaxies, stars and planets within it, we may attempt to identify the prerequisites for life. However, since our knowledge of the processes involved in the emergence of life lags far behind our comprehension of fundamental physical processes, we shall only list those very basic requirements that we think should apply to any generic form of complexity.

1.2 Prerequisites for Complexity

There are (at least) five prerequisites for the emergence of complexity in a universe; these prerequisites would not be fulfilled in a counterfactual universe where the fundamental constants are too different from their actual values.

‘Counterfactual’ exercises of this type are useful for developing an intuition about the role of physical constants in the evolution of the Universe and in the emergence of complexity. Similar studies are used by historians to explore various ‘what if?’ scenarios, such as speculating what might have happened had Archduke Franz Ferdinand of Austria not been shot by a Serb nationalist in Sarajevo in 1914. Biologists similarly wonder about how the history of life on Earth might have changed had the dinosaurs not been wiped out by an asteroid impact.

If the acceptable range of values for some parameter is small, we would define it as ‘fine-tuned’. We shall briefly discuss the extent to which this is the case for some key parameters.

1.2.1 Constraints on Gravity

As numerical simulations of structure formation in the Universe have demonstrated, gravity enhances density fluctuations (see Chapter 6). In our Universe, gravity caused the denser regions to lag behind the cosmic expansion and form the sponge-like structure that characterises the Universe on its largest scales. Eventually, gravity led to the formation of galaxies

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at the density peaks, of stars, and of planets. Stellar evolution also represents one continuous battle with gravity, the latter pushing the stellar central densities and temperatures to higher and higher values. On the surface of planets, gravity played crucial roles in keeping an atmosphere bound and bringing different elements into contact to initiate the chemical reactions that eventually led to life. But gravity in our Universe is a very weak force – the ratio of the repulsive electric force between two protons to their gravitational mutual attraction is $e^2/Gm_p^2 \sim 10^{36}$. The reason gravity becomes important on the scale of large asteroids and higher is that large objects have a net electric charge that is close to zero, so gravity wins once sufficiently many atoms are packed together.

Figure 1.1 allows us to make a first attempt to examine what would happen in a universe in which the values of some 'constants of nature' are different. How would Figure 1.1 be different if gravity were not so weak? The general structure of the diagram would remain the same, but there would be fewer powers of 10 between the subatomic and cosmic scales. Stars, which effectively are gravitationally bound nuclear fusion reactors, would be smaller in such a universe and would have shorter lives. If gravity were much stronger, then even small solid bodies (such as rocks) might be gravitationally crushed. If gravity's strength were such that it would still have allowed tiny planets to exist, life forms the size of humans would be crushed on the planetary surface. Overall, the universe would be much smaller, and there would be less time for complexity to emerge. In other words, to have what we may call an 'interesting' universe (in the sense of complexity), we must have many powers of 10 between the microscale and the cosmic scale, and this requires gravity to be very weak. It is important to note, however, that gravity does not need to be fine-tuned for complexity to emerge. In fact, a universe in which gravity is ten times weaker than in our Universe, may be even more 'interesting' in that it would allow bigger stars and planets and more time for life to emerge and evolve.

1.2.2 CP Violation – More Matter Than Antimatter

The Big Bang in our Universe created a slight excess (by about one part in three billion) of matter over antimatter (see Chapter 5). It has been shown that for such an imbalance to be created, baryon number and CP symmetry (charge conjugation and parity) had to be violated in the Big Bang and interactions had to be out of thermal equilibrium (the so-called Sakharov conditions [32]). Had the matter-antimatter imbalance not existed, particles and antiparticles would have all been annihilated to form only radiation (what we observe today as the CMB) – leaving no atoms and therefore no galaxies, no stars, no planets, and no life. Within the Standard Model of particle physics the most promising source of CP violation appears to be in the lepton sector, where it generates matter-antimatter asymmetry via a process known as leptogenesis. If, however, CP violation in the lepton sector will be experimentally determined to be too small to explain the matter–anti-matter imbalance (as was the case with the Cabibbo-Kobayashi-Maskawa matrix in the quark sector [22]), physics beyond the Standard Model would be required.

1.2.3 Fluctuations

'Curvature fluctuations' were imprinted into the Universe at a very early era. Their amplitude is almost independent of scale. Many theorists suspect that they originated as quantum fluctuations during an inflationary phase, when the presently observable universe was of microscopic size. The physics of this ultra-early era is, of course, still speculative and uncertain. However, we know from observations that the fluctuations gave rise to temperature fluctuations that grew to $\Delta T/T \sim 10^{-5}$ at the time of recombination.

These fluctuations were crucial for the emergence of complexity. If the early Universe had been entirely smooth, then, even with the same microphysics, the Universe today would have been filled only with cold hydrogen and helium. Stars, galaxies, and, indeed, people would never have formed. The parameter that measures the 'roughness' of the Universe is called Q. At recombination, the temperature fluctuations across the sky $\Delta T/T$ are of order Q. There is no firm theoretical argument that explains why it has the observed value of about 10^{-5} (see, e.g., [37, 38] for a discussion). Computer simulations have offered a huge boost to the credibility of our current ΛCDM model by showing that under the action of gravity and gas dynamics, the fluctuations observed in the CMB would evolve into galaxies with the morphological properties and luminosity functions observed, grouped into clusters whose statistical properties also match the observations.

But what would happen in a counterfactual universe where Q were different from its actual value but all other cosmic parameters stayed the same? If the amplitude of the fluctuations were larger, say $Q \sim 10^{-4}$, masses of about $10^{14} M_\odot$ would condense at a cosmic age of about 300 million years. At that time, Compton cooling on the (then warmer) microwave background would allow the gas to collapse into huge disc galaxies. The virial velocity in large-scale systems scales as $Q^{1/2}c$, and these giant galaxies would find themselves (after some 10^{10} years) in clusters with masses of $\gtrsim 10^{16} M_\odot$. A universe with $Q \sim 10^{-4}$ would have an even larger range of non-linear scales than ours. It would offer more spectacular cosmic vistas; and the only reason why it might be somewhat less propitious for life is that stars in the galaxies would be more close-packed, rendering it less likely that a planetary system could remain undisrupted by a passing star for long enough to permit biological evolution. However, if Q were even larger ($Q \gtrsim 10^{-3}$), conditions would be very unfavourable for life. Enormous masses of gas (far larger than a cluster of galaxies in our present Universe) would condense out early on, probably collapsing to massive black holes – an environment too violent for life.

(Incidentally, any observers who could exist in a high-Q universe would find it far more challenging to interpret and quantify their surroundings. Because Q is small in our actual universes, even the largest non-linear structures are very small compared to the cosmic horizon [they are smaller by a factor of order $Q^{1/2}$]. We can therefore observe a large number of independent patches and define average smoothed-out properties of the Universe – the mean density, etc – and use the standard homogeneous cosmological models as a good approximation. By analogy, a sailor watching ocean waves can meaningfully describe their statistical properties because even the longest wavelength is small compared

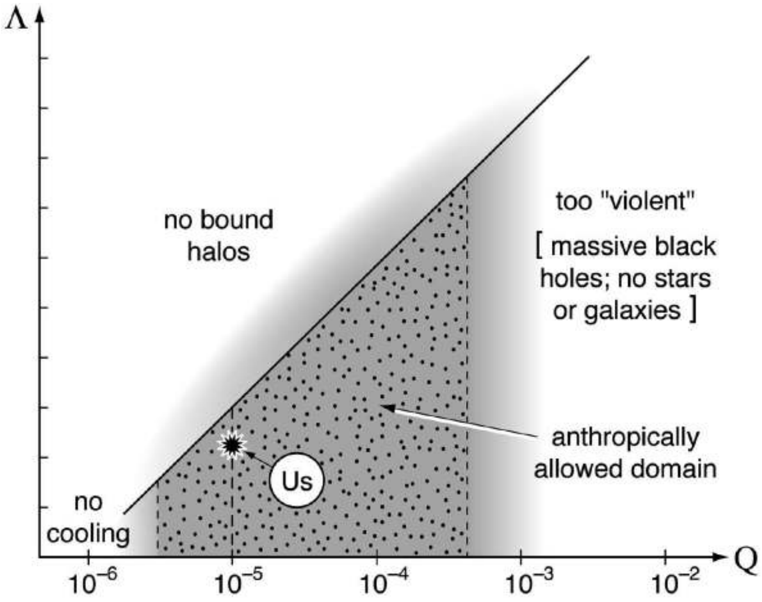

Figure 1.3 Plot of the cosmological constant Λ versus amplitude of fluctuations in cosmic microwave background Q. The shaded-dotted region shows conditions that allow for the existence of complexity.

to the distance of the horizon. In contrast, an astronomer in a high-Q universe would resemble a climber in a mountain landscape, where one peak could dominate the view, and averages are not well defined.)

What about the other extreme, a ‘smoother’ universe with $Q \lesssim 10^{-6}$? In this case, the disruptive dark energy would push protogalaxies apart before they had a chance to collapse. Even if the dark energy were not there, any galaxies that formed in a lower-Q universe would be small and rather loosely bound (and forming later than in our actual Universe). At $Q \lesssim 10^{-6}$, stars would still form, but material enriched in heavy elements and ejected via stellar winds or supernovae may escape from the shallow gravitational potential wells, not allowing for second-generation stars and planetary systems to form. For values of Q that are significantly smaller than 10^{-6}, there would be inefficient radiative cooling, and therefore, stars would not form within a Hubble time. The conclusion from this discussion (summarised also in [25]; see Figure 1.3) is that for a universe to be conducive for complexity and life, the amplitude of the fluctuations should best be between 10^{-6} and 10^{-4} and, therefore, not particularly finely tuned.

1.2.4 Non-Trivial Chemistry

For life to emerge, the Universe requires nuclear fusion. Fusion not only powers the stars; nucleosynthesis at the hot stellar centres also forges elements such as carbon, oxygen, iron, and phosphorus, all of which are essential for life as we know it. In general, many of the elements in the periodic table participate in the complex chemistry required for the formation of planets and the evolution of their biospheres.

To obtain the nuclear fusion reactions that lead to the creation of the periodic table requires a certain balance between the strength of the electromagnetic force (that repels two protons from each other) and the strong nuclear force (that attracts them). This balance, in our Universe, where the strong nuclear force is about a hundred times stronger than the electromagnetic force, is responsible for the fact that we do not have atomic numbers higher than 118. Had the ratio of the two interactions been much smaller, carbon and heavier elements could not have formed, but the necessary tuning is not excessive.

Similarly, much has been written about Fred Hoyle's prediction of the existence of a 7.65 MeV resonant level of ^{12}C [14, 16]. However, while the prediction itself was indeed remarkable, the degree of fine-tuning required for the energy of that level is not fantastic (e.g., [27, 33]; see [10] for a recent study of this energy level).

The topic of chemistry actually allows us to examine a much more extreme counterfactual universe – a 'nuclear-free universe' – in which hydrogen is the only element that exists. Surprisingly, on the large scale, such a universe would not look much different from ours. Gravity would ensure that galaxies would still form, and even stars would shine (albeit generally for shorter times) by releasing their gravitational energy as they contract to form white dwarfs and black holes. Even Jupiter-like planets composed of solid hydrogen could exist. Of course, no complexity or life of the types we are familiar with will emerge in such a universe (only perhaps something similar to Fred Hoyle's science fiction concept of *The Black Cloud* [15]).

1.2.5 'Tuned' Cosmic Expansion Rate

The results from the Planck satellite depicted in Figure 1.2 (in combination with observations of baryon acoustic oscillations, lensing reconstruction and a prior on the Hubble constant) give for the cosmic energy budget $\Omega_{\rm m} \sim 0.3$, $\Omega_\Lambda \sim 0.7$, with baryons making less than 5% of this budget [30]. If the cosmic acceleration is indeed driven by a cosmological constant (energy of the physical vacuum, with an equation of state parameter $w = P/\rho = -1$), then the acceleration will continue forever (see Chapter 3). It is clear, however, that if the dark-energy density would have dominated over the matter density (dark matter + baryons) much earlier in the life of our Universe, galaxies would never have formed (this is also dependent on the value of Q; see discussion in the next section). This means that for complexity to arise, some constraints are needed on the ratios of $\Omega_{\rm m}/\Omega_\Lambda$ and $\Omega_{\rm b}/\Omega_{\rm DM}$ (where $\Omega_{\rm b}$ denotes the baryon fraction and $\Omega_{\rm DM}$ the dark matter fraction). The second ratio is crucial because even though dark matter dominates over baryonic matter in our Universe, without the latter, there would be no stars, no planets, and no life.

As an aside we should note that the nature of the dark energy that propels the cosmic acceleration is one of the most fascinating puzzles in modern cosmology (and one that may not be solved until we have a better understanding of the granular structure of space-time on the Planck scale). Despite its importance for fundamental physics, the dark energy hardly affected any astrophysical phenomena in our Universe; in contrast, the evolution of our Universe so far – the emergence of and morphology of galaxies, clusters, and so forth – has been dominated by the effects of dark matter.

1.3 The Multiverse

As far as we can tell, the laws of physics and the values of the cosmological parameters are the same throughout our entire observable Universe. But the observable Universe is limited by the horizon, which is determined by the finite age of our Universe. What lies beyond this Hubble volume? The homogeneity and isotropy of our observable Universe, with the absence of any perceptible gradient across it (to the 10^{-5} level) suggest (though, of course, do not prove) that the same laws continue to apply thousands of times further. Indeed, many arguments suggest that galaxies beyond the horizon outnumber those we see by a vast factor – perhaps so vast that all combinatorial options would occur repeatedly, and we'd all, far beyond the horizon, have avatars.

Furthermore, some models for the inflationary phase lead to what has been dubbed 'eternal inflation' [24, 39]. According to these models, our Big Bang could be just one 'pocket universe' in a huge ensemble – one island of space-time in a vast archipelago. This scenario also fits well with the 'landscape' concept of string theory, in which there are some 10^{500} metastable vacua solutions, of which our Universe is but one [4, 19]. So the question arises: how large is physical reality?[1]

The first thing to realise is that because we live in an accelerating universe, galaxies are disappearing over an 'event horizon', so we will not observe their far future (rather, as we cannot observe the fate of an object that falls into a black hole after it has crossed the horizon). If the acceleration continued, then after about a trillion years, observers in the remnant of the Milky Way (or its merged product with the Local Group) would not be able to see (again, even in principle) any galaxy other than their own. This does not mean that those galaxies whose light would have been stretched beyond the cosmic scale would not exist.

Moreover, galaxies that are already beyond our current horizon will never become observable, even in principle. Yet most researchers would be relaxed about claims that these galaxies exist in the same way that, in the middle of the ocean, you expect that an ocean extends beyond the terrestrial horizon. These never-observable galaxies would have emerged from the same Big Bang as we did. But suppose that we imagine separate Big Bangs. Are space-times completely disjoint from ours any less real than regions forever

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[1] It's perhaps necessary, especially in addressing philosophical readers, to inject a clarification at the start. Many would define 'the Universe' as 'everything there is' – and if that's the definition, then there plainly cannot be more than one. If there are other domains (perhaps originating in other Big Bangs, and perhaps differing from our observable domain in size, content, or dimensionality), then we should really define the whole enlarged ensemble as 'the Universe'. We then need a new word – 'metagalaxy', for instance – to denote the domain to which cosmologists and astronomers have observational access. However, so long as this whole idea remains speculative, it is probably best to leave the term 'universe' undisturbed, with its traditional connotations, even though this then demands a new term, 'multiverse', for the whole (still hypothetical) ensemble.