Fine Tuning

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Miriam Frankel

FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

JOHN TEMPLETON FOUNDATION

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1. INTRODUCTION

I. WHAT IS FINE TUNING?

Imagine standing before a firing squad, with 50 trained marksmen aiming rifles at your heart. You're certain that this is your last moment, but somehow the bullets all miss and you survive. This could simply be a very lucky coincidence; rerun the event enough times and the squad would be statistically likely to miss a few times. But chances are you would feel perplexed about your survival and want to seek answers about how this happened.

This metaphor was put forward by John Leslie to demonstrate how the existence of life in the universe similarly relies on hugely improbable cosmic conditions, with physical variables seemingly aligning perfectly to enable the evolution of intelligent beings (Leslie, 1989). While our hospitable universe could just be a fluke, it is only natural for us to try to dig deeper. Over the last few decades, the subject of fine tuning has attracted some of the sharpest minds in physics. By probing the universe's physical laws and precisely pinning down the values of physical constants, such as the masses of elementary particles, physicists have discovered that surprisingly small variations in these values could have prevented the formation of bio-friendly elements, planets, stars, and galaxies—rendering the cosmos lifeless.

1. Fine-Tuned Parameters

The scientific study of the fine-tuning problem has a long history, stretching back a century. Research on fine tuning involves investigating what ingredients are actually necessary for life to evolve. Chapter 2 will explore how this ingredient list was compiled, in historical context. By tweaking the laws of physics in calculations, physicists can examine whether, in theory, life could have arisen in a different kind of universe. Table 1 summarizes the most prominent examples of fine tuning, thus far.[1] The analyses that led to their discoveries will be described in depth in the next chapter.

Table 1: Examples of fine tuning in the universe.

Category	Example	Constraint
Masses	Difference between neutron and proton mass	Must be larger than the electron mass
	Electron to proton mass ratio (1/1836)	Must be less than 1/81
	Mass difference between the down quark and the up quark (1.29 MeV)	Must be between 1 and 4 Mev
Forces	Strong force coupling constant (0.1187)	Must be between 0.11 and 0.12
	Fine structure constant (0.007)	Must be between 0.006 and 0.01

[1] This list is by no means exhaustive. More comprehensive lists have been compiled and can be found in the extensive review by Fred Adams (Adams, 2019) and the deeply informative book, *Fine-Tuning in the Physical Universe*, edited by David Sloan, Rafael Alves Batista, Michael Towsen Hicks, and Roger Davies (Sloan et al., 2020).

Category	Example	Constraint
	Gravitational force to electromagnetic force ratio (10^{-36})	Must be smaller than 10^{-32}
Structure	Cosmological Constant, Λ (Dark Energy)	Can't be more than 10 times larger
	Q (smoothness parameter)	Must be between 10^{-6} and 10^{-4}
	Omega, Ω (flatness parameter)	Must have been almost exactly 1 in the early universe
Dimensions	Space (macroscopic dimensions)	Must be 3
	Time	Must be 1

For example, the chapter will look at the claim that the masses of subatomic particles are precisely tuned to allow atoms to remain stable—an essential condition for the chemistry of life. Physicists have also discovered evidence of fine tuning to some extent in all the four fundamental forces of nature—the electromagnetic force, gravity, and the strong and weak nuclear forces that affect subatomic particles. If these had slightly different strengths, they have argued, stars could not have formed. Stars are the factories that produced heavy elements in the universe, including carbon. And since life—at least as we know it—is based on carbon, without stars, any universe would be bereft of organic life.

The values of cosmological parameters also have profound implications for the evolution of structure and intelligent life. For example, astronomers now know that the universe is expanding at an accelerating rate. The mysterious force driving this outward growth, dubbed 'dark energy,' is measured to be tiny. Had it been just a tad greater in the early universe, the cosmos would have expanded so quickly after the Big Bang that any burgeoning matter would have been diluted, unable to clump together into galaxies, and so planets and thus life would never have formed. It seems at first glance that we are inordinately lucky that dark energy lies within the perfect range needed to enable intelligent life to exist. As we shall see in Chapter 2, its value has arguably caused the biggest fine-tuning headache in physics because it is not only small enough to give rise to life, it is also considerably smaller than theory suggests it should be—making it a conundrum on several levels.

The second chapter will also look at the claim that the number of spatial and temporal dimensions are precisely tuned for the universe to be able to host life.

2. Explaining Fine Tuning

Many natural explanations have been proposed for fine tuning; however, each has shortcomings. Fine tuning is tied to the development of the 'anthropic principle'—discussed in detail in Chapter 3— which crudely states that humans should not be surprised to discover themselves in a universe that has the exact conditions needed for intelligent life to evolve, since we could hardly expect to find ourselves in one that is uninhabitable to people. The anthropic principle was developed in the 1970s and remained unpopular for many decades because it appeared to be the scientific equivalent of throwing one's hands in the air and giving up on the search for a fundamental reason for why the properties of the universe take the form and values we see.

However, the anthropic principle has seen a resurgence in the past 20 years—coupled with 'multiverse theory,' which suggests that our cosmos is not unique, but one of nigh on infinite neighboring parallel universes, each with their own physical laws and parameters. In this context, it makes sense that we find ourselves in a universe that can support life. Other universes exist, in this framework, which are bereft of life. But statistically, a minority will arise with bio-friendly potential, and humans can evolve in one of those hospitable cosmoses. Chapter 3 will delve into the development of the multiverse and its implications for fine-tuning arguments, in depth.

The multiverse is a natural consequence of the theory of 'inflation,' part of the current cosmological paradigm that states that the early universe underwent a period of rapid expansion. It also invokes aspects of 'string theory'—one of the best current candidates for a 'theory-of-everything' that proposes that elementary particles are comprised of tiny vibrating threads of energy. However, as will be noted in Chapter 3, both inflation and string theory, and consequently the multiverse, have been criticized. Inflation is the more established of these concepts. However, it is still not clear how inflation would have been triggered in the infant cosmos; it possibly needs some extremely precise conditions in the early universe—ironically, requiring some degree of fine tuning itself.

String theory is more speculative than inflation, and remains controversial because there is currently no direct experimental proof for its validity—and such evidence may lie beyond the reach of our best current experiments. Some have also argued that in all likelihood cosmologists will never be able to directly test whether the multiverse exists; by definition, we can never enter into another universe (let alone measure its properties and compare them to those in our cosmos, to see if they differ from our own). Chapter 3 will thus also briefly survey alternative—but even more speculative—cosmological models and how they attempt to explain fine tuning, without invoking string theory or the multiverse. These include cyclic models, in which the universe grew and contracted multiple times, cycling through a series of Big Bangs and Big Crunches, and top-down cosmologies, in which today's universe, in some sense, rewrites history, selecting the perfect initial cosmic conditions in the past that would bring it forth.

It is worth noting that some theologians and physicists have argued that fine tuning lends support to the notion that a God, or gods, created the universe with just the right properties for life. Theism—or more specifically any argument that invokes supernatural causes—lies beyond the purview of science, by definition. So this idea will not be developed in depth in this review—aside from briefly mentioning the relevance of such arguments within a historical and sociological context. However, Chapter 3 will close with a discussion of the somewhat related scientific musings about whether our universe was created—or even computationally simulated—by an advanced alien intelligence.

3. Testing Explanations for Fine Tuning

The fourth chapter discusses experimental probes of fine tuning. The first avenue of study investigates whether there really is a fine-tuning issue that needs to be explained. Fine-tuning arguments often cite the serendipitous values of certain physical constants. But there have been conflicting studies regarding whether or not all these fundamental 'constants' of nature are quite as constant as they seem. Some physicists claim to have found evidence that the values of some of the constants actually vary slowly over the aeons. This could allow for the possibility that the parameters explored a far wider range of values—some bio-friendly, but many others inhospitable to life—during the evolution of our universe, than has been assumed. If corroborated, this would imply that the constants are not, in fact, finely-tuned to any one specific human-friendly value.

Chapter 4 reviews past tests and future proposed experiments to investigate the possibility that physical constants drift over time. The ESPRESSO instrument (Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations) has been installed at the Very Large Telecope, in Chile, for instance. Its scientific mission includes measuring any possible variation in the "fine-structure constant"—a measure of the strength of the electromagnetic interaction—and estimating the ratio between the masses of two subatomic particles, the proton and electron. There are similar experiments underway that will investigate the properties of dark energy—including whether it has always been constant—employing, for example, the Dark Energy Spectroscopic Instrument installed on the Mayall Telescope, in Arizona.

A second line of attack looks for evidence for the best-established scientific explanation for fine tuning: the multiverse. As noted, critics have argued the multiverse is unscientific because there is currently no direct evidence for it (and such evidence may be difficult, if not impossible to ever find). However, some cosmologists have countered that it is actually possible in principle, and maybe even in practice, to find direct evidence of neighboring universes. They argue that if our cosmos briefly collided with another, the encounter would leave a subtle but detectable scar on the sky that may be picked up by astronomers. Such searches have been carried out, and are discussed in Chapter 4. The chapter also discusses attempts to establish indirect evidence for the multiverse.

There are also efforts to test string theory and to search for signs of other models that go beyond standard physics. The fourth chapter discusses how experiments at the Super-Kamiokande Neutrino Detection Experiment in Japan, and at future particle colliders at CERN, near Geneva, in Switzerland, or elsewhere, may be able to look for such evidence. It also discusses hints of new physics, new particles and potentially a new force of nature—and thus the need for a new fundamental theory—being found by the Muon g-2 experiment at Fermilab, in Illinois, and the LHCb experiment at CERN.

It should be noted that, thus far, it has proven to be incredibly difficult to test string theory because enormous energies are required to probe the universe on the minute scales where signs of its effects may manifest. Many proposed future tests of string theory lie beyond the reach of our current technological capabilities and may require billions of dollars of investment. As discussed in the fourth chapter, critics of string theory and the multiverse concept have argued that this money might be better spent on other projects. Such arguments, though largely dealing with funding questions and the sociology of science, are pertinent to the topic of this review, because it has been argued that fine-tuning arguments are somewhat overblown. It has been noted that if fine tuning is not actually a problem, then physicists do not need to invoke speculative theories to explain it, and thus expensive experiments designed to test such theories should not be a funding priority.

The fifth chapter of this review thus delves more deeply into the question of whether fine tuning is really a problem that needs addressing, at all.

4. Is Fine Tuning a Figment of Our Imagination?

Fine-tuning arguments hinge on the idea that intelligent life could not have arisen in a universe with slightly different physical properties. However, in recent years, some astronomers have calculated that intelligent life may well have arisen in a universe with wildly different properties, rendering such fine-tuning arguments meaningless. Some have proposed that carbon-production in stars may still be possible in a universe with different properties to our own; others argue that silicon-based life could arise even in a universe completely free of carbon; and some have calculated that life could have evolved much earlier in our own universe, regardless of the strength of dark energy.

Another line of criticism is that fine-tuning calculations tend to only consider what would happen if one physical parameter is varied, while holding all other parameters fixed. In such cases, it is indeed found that if one parameter is tweaked, the conditions needed for life to evolve are violated. However, as discussed in Chapter 5, it has been suggested that if multiple parameters are varied simultaneously, the conditions for life can be met once more.

The remainder of this introductory chapter sets out the development of the fine-tuning problem in greater detail, and introduces the anthropic principle.

II. THE ANTHROPIC PRINCIPLE

The scientific question of whether the universe is fine tuned for life goes back a century; but it is only in the past 60 years or so that experimental physics has advanced enough to be able to shed useful light on the debate. This is largely thanks to advances in cosmology—the study of the universe at the largest scales—and particle physics—the study of nature at the level of atoms and their constituents. In both fields, researchers have discovered parameters and values that appear unnaturally (and conveniently from the human perspective) small or large.

1. The Birth of Fine Tuning

One of the earliest examples of a fine-tuning debate in physics concerns an odd feature surrounding some large numbers governing the scale of physical effects. In the 1920s and 1930s, Arthur Eddington and Paul Dirac, respectively, noticed that ratios between very large and very small aspects of the universe always seem to be on the order of 10^{40} (10 followed by 40 zeroes) (Eddington, 1931; Dirac, 1938). This number is what you get when you divide the size of the universe (the distance light has traveled since the Big Bang) with the size of an elementary particle such as an electron, called the elementary length. The same number appears when you divide the age of the universe by the time it takes light to travel across the elementary length—dubbed an elementary time. Even more oddly, on the smallest of scales, the ratio between the electrostatic force between two elementary particles and their gravitational force is also roughly 10^{40}.

Dirac pointed out that since the age of the universe changes, these ratios would not always have been equal. This raised an important question: why do we—intelligent creatures—happen to live at a time when those completely unrelated numbers are mysteriously synced? Dirac, who found this coincidence uncomfortable, came up with a simple mathematical relation that connected the numbers. In an effort to remove the apparent fine tuning, he argued (as it turned out erroneously) that the strength of gravity must also vary with time—getting weaker and weaker as the universe aged. This would keep the 10^{40} ratio constant and remove worries over the current alignment. But observations of planetary orbits and the motion of spacecraft later showed that this hypothesis was wrong: the strength of gravity does not vary with time (Schlamminger et al., 2015).

In 1961, Robert Dicke came up with a new and radical explanation. He suggested that Dirac's relation could be an example of something that scientists call a "selection effect" (Dicke, 1961). Paul Davies has explained this effect using the following metaphor: Consider the seemingly astonishing fact that for you to be alive, not one of your ancestors could have died childless. Going back through human history, with its centuries of high infant mortality, and then tracking back through evolutionary processes for billions of years to the very first life forms, the odds of this happening seem shockingly low—making you nothing less than a miracle. But you are not that special, according to science. This is just an example of a selection effect. When individual observers look at the world they must see exactly what was necessary for them to arise—they are, after all, there to look (Davies, 2006).

Dicke realized that a similar bias could explain Dirac's supposed number enigma. We do not live at a random moment in time, he argued. Instead, we live at a time when the universe is able to produce physicists like Dirac who question its laws. All human life is made of carbon, so a prerequisite for life to evolve is that the universe has been around long enough to produce carbon. We know that carbon is produced in stars and that this life-essential element is only released into the universe when stars die, exploding in a supernova (see Chapter 2.II).

This means that carbon-based life could not originate until at least one generation of stars had lived and died. (Our sun is a third generation star.) Dicke then showed that a star's lifetime depends exactly on the ratio of electric to gravitational forces. The fact that this ratio is about 10^{40} means that life could evolve only at a time when the ratio between the age of the universe and the elementary time is also 10^{40}. So the number isn't a coincidence; we observe this number because it is compatible with conscious life. It is not in any way mysterious, just as it is not scientifically remarkable that none of your ancestors died childless.

2. The Weak vs the Strong Anthropic Principle

Fine tuning as a field of research was really kick-started in the 1970s by Brandon Carter. In a series of talks and papers during the 1960s and 1970s, Carter investigated what would have happened in the universe if various physical laws were tweaked. He discovered that very small variations would have been fatal for the formation of complex structures, such as stars and planets—and thereby also life (Carter, 1974). Carter articulated the 'anthropic' view—*anthropos* is the Greek for "man"—that it is not surprising for humans to find ourselves in a universe capable of supporting life, since we could not find ourselves in one that was not. This later became known as the 'weak anthropic principle.'

The 'strong anthropic principle' was developed in the 1970s by John Barrow and Frank Tipler, and states that the universe is somehow compelled to deliver life, perhaps having an inbuilt life-maximizing principle (Barrow and Tipler, 1986). Anthropic reasoning was thus initially seen as quasi-religious (why would the universe have purpose?). It has also been invoked in support of the argument that a God or gods must have created the universe for humans (Craig, 2014). Ironically, however, today the anthropic principle plays a pivotal role in support of the most prominent scientific explanation for fine tuning, multiverse theory, as will be discussed in Chapter 3. Many current proponents of anthropic arguments now subscribe to the idea that our universe is just one in an infinite multiverse that contains neighboring cosmoses, each harboring different physical parameters. Thus it is unremarkable that we should find ourselves in one of the cosmoses that happens to contain conditions conducive to intelligent life.

Bernard Carr has noted that the "anthropic principle" is a misnomer, however, since the finely-tuned conditions discussed in such calculations are not particular to the production of human life. Rather, these conditions are necessary for any complexity to form as the universe expands and cools. Thus, Carr argues, it may be better—and less controversial—to refer to a "complexity principle" (Carr, 2020).

So what are the specific quantities that appear to be fine tuned for life? The next chapter focuses on some key examples.

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2. THE INGREDIENTS FOR LIFE

Myriad examples of fine tuning have been cited over the decades. These can be grouped into four key types: particle masses; the forces of nature; cosmic parameters; and spatial and temporal dimensions. In this chapter, we shall discuss examples of each, for illustrative purposes.

I. MASSES

The idea that matter is built up of indivisible particles, or 'atoms' (from the Greek *atomos* meaning "uncuttable"), dates back to ancient Greece and India (Pullman, 1998). Experimental evidence that atoms themselves contain a nucleus, carrying the bulk of their mass—which in turn is made up of a number of positively-charged protons and (a roughly equal number of) neutral neutrons—accumulated in the early 20th century. The nucleus is orbited by much lighter, negatively-charged electrons (Figure 1).

Each chemical element in the Periodic Table is made of identical atoms, which are characterized by the number of protons they hold.

We now know that the atomic nucleus can be split, in a process called fission, and also that nuclei can fuse together to create atoms of new elements, in a process called fusion—accompanied by the release of energy. As we will see in section II, nuclear processes also play a key role in fueling stars. These processes lie at the heart of nuclear reactors and the development of atomic weapons.

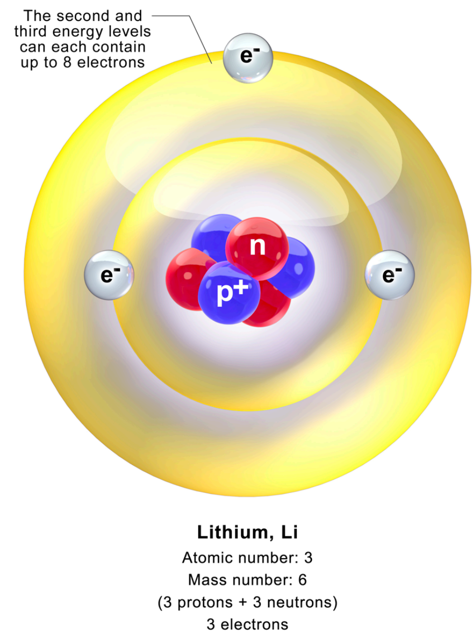

Figure 1: Lithium atom. (Image credit: BruceBlaus, shared under a creative commons license CC BY-SA 4.0.)

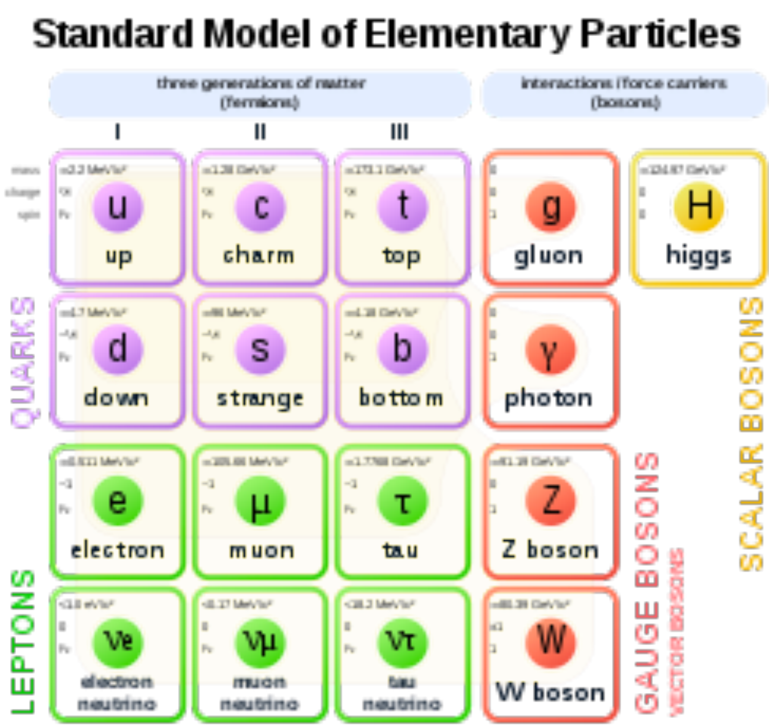

Figure 2: The Standard Model of Particle Physics. (Image credit: MissMJ, shared under creative commons attribution 3.0 unported license.)

Interest in manipulating the atomic nucleus grew in the 1950s and 1960s, alongside particle-physics experiments that smash together beams of particles at high energies. From the debris of such collisions, physicists have inferred the existence of 61 elementary particles —a whole "particle zoo"—which form the bedrock of the Standard Model of Particle Physics—our best theory for describing the microcosmos of atoms and particles, to date (Figure 2). A total of 36 of these particles are quarks, which make up the protons and neutrons in the atomic nucleus. The top quark was the last to be discovered as late as 1995 (Carithers and Grannis, 1995).

The Standard Model has proved hugely successful since its development in the 1970s—allowing physicists to, for instance, predict the existence of the Higgs boson, which was famously discovered at the Large Hadron

Collider near Geneva, Switzerland, in 2012. The Higgs boson was predicted to exist as a product of the process through which elementary particles gain their mass, in the early universe. (See JTF's Cosmological Origins review for a more detailed discussion of the model.) But no theory can yet explain why the particles take on the specific masses that they do. Thus, particle masses are ripe for citation as examples of fine tuning, as described below.

1. Protons and Neutrons

Protons and neutrons have almost the same mass, of around 1.67×10^{-27} kilograms, with neutrons a fraction more massive. For complex matter to form successfully, protons and neutrons must be able to remain stable in the atomic nucleus. Protons are also stable outside the nucleus; in fact, much ordinary matter in galaxies is in the form of a hot plasma, or gas, of free protons and electrons. Isolated neutrons, however, are unstable, quickly decaying within minutes into the slightly lighter proton, an electron, and another subatomic particle called an antineutrino (Zyla, 2020).

Physicists have noted that if neutrons were just one percent lighter, and consequently less massive than protons, then actually, isolated protons would become unstable—they would decay into neutrons rather than the other way around. In fact, the difference between the neutron and the proton mass must be larger than the electron mass, which is about 9.11×10^{-31} kg (Wilczek, 2015). And if isolated protons decayed rapidly after the Big Bang, atoms would not form and there would be no chemistry at all (Davies, 2006). (It's worth noting, however, that this argument has been criticized. Many studies asserting that the ratio of the neutron mass and the proton mass is finely tuned make certain assumptions that can be challenged. One is that in these hypothetical tweaked circumstances, isolated protons do not couple up and become stable as pairs—a claim that has since been questioned (Adams, 2019).)

A tiny adjustment to the proton:neutron mass ratio would also have implications for the stability of the atomic nucleus. Both protons and neutrons are comprised of quarks. A proton is made up of two so-called "up" quarks and one "down" quark, while a neutron contains one up quark and two down quarks. If there were a large difference between the masses of these two kinds of quarks, the heavier quark could decay into the lighter one inside the nucleus—with protons turning into neutrons or vice versa—preventing stable nuclei. Thus, for the nucleus to remain intact, the difference between the up and down quark masses must be very small, varying by minute amounts only (Hogan, 2000). This is especially true for the down quark, which cannot be too heavy (Barr and Khan, 2007). In fact the mass of this quark is the most constrained out of the particle masses—if it varies by more than a factor of seven, our bio-friendly universe would be jeopardized (Adams, 2019).

2. Electrons

While the mass of the proton and neutron must be astonishingly similar, the ratio of the mass of the electron to the mass of the proton is tiny—about 1/1,836 (Barnes, 2012). As it turns out, this ratio is highly important, alongside the electromagnetic force, for chemistry to act in a similar way to that seen in our universe. If the electron mass weren't much, much smaller than the proton mass, we couldn't have stable, ordered structures such as living cells. Neither could we have stable stars that lived for long enough to allow life to evolve.

Research has shown that the ratio of the electron mass to the proton mass must be much smaller than one—in fact it must be smaller than 1/81 (Barnes, 2012).

II. FORCES

Many of the early examples of fine tuning concerned analyses of the four fundamental forces of nature—the electromagnetic force, the gravitational force, the strong force that binds subatomic particles together in the atomic nucleus, and the weak force that governs radioactive decay. Studies have suggested that all of these forces are fine tuned to some extent. The story is intimately tied to how elements are formed in stars.

1. The Carbon Resonance

All life that we know of is based on carbon, which contains six positively-charged protons and six neutrons. As mentioned above, carbon is formed in stars—the only arenas hot enough to produce heavy elements by fusing together the nuclei of smaller atoms produced during the Big Bang. (See JTF's Cosmological Origins review for a longer discussion of how light elements were formed in the early universe.)

A reasonable supposition was thus that three helium atoms (each containing two protons and two neutrons) fuse together to form one carbon atom, in a process that involves a delicate interplay between electrostatic forces trying to push positive charges apart, and the strong force, trying to pull subatomic particles together. However, in the early 1950s, Fred Hoyle calculated that the odds of three helium atoms coming together at roughly the same time and place in order to create carbon are extremely low—too low to account for the abundance of carbon we see.

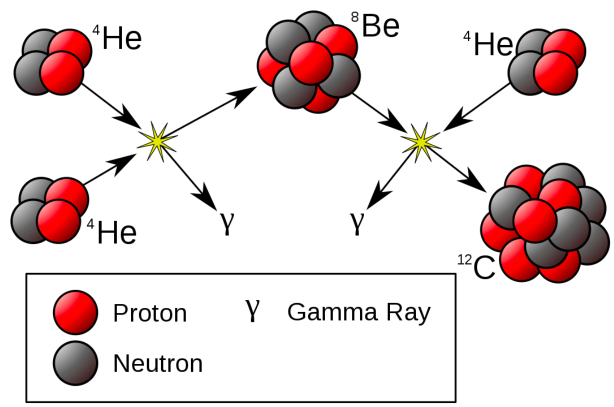

Figure 3: The Triple-Alpha Process. (Image credit: Borb, shared under creative commons license CC-BY-SA-3.0.)

An alternative possibility, called the "Triple-Alpha Process," was suggested by Edwin Saltpeter in 1952 (Figure 3) (Saltpeter, 1952). (Helium nuclei are also known as "alpha particles.") This process involved an intermediate step, in which two helium atoms first fuse together to create the element beryllium (with four protons and four neutrons). One problem with this idea was that beryllium is extremely unstable, and would likely decay, within a fraction of a second, back into smaller particles. However, if the beryllium atom managed to collide with a helium atom, before decaying, it could fuse to create carbon. But again, there was a hitch. This reaction was still relatively unlikely to occur at a fast enough rate to account for the levels of carbon seen in the universe. To get around this obstacle, Hoyle suggested there must be a specific "resonance" between beryllium and helium when they come together—an effect that enhances their likelihood for forming stable carbon.

To understand how this resonance works, consider that physical systems always tend to try to lower their energy. Take, for instance, a ball placed on a shelf. It has what is called gravitational "potential energy" due to its height. That is because, if the shelf were removed, the ball would drop thanks to gravity, converting this potential energy to kinetic energy (energy of motion). Once on the ground, it would lie motionless, which represents its lowest energy state. Similarly, atoms have internal energy states, with their lowest ground state and higher excited states that are analogous to being put on a series of shelves. Atoms will tend to drop from an excited energy state to a lower state, emitting energy in the process.

Hoyle thus reasoned that a newly-formed carbon nucleus must have an excited state with an energy level that lies close to the energy state of a beryllium nucleus and a helium nucleus separately. The chances of the two separate atoms fusing in these conditions was greatly increased. Although most of the carbon atoms produced would then decay back into smaller atoms again, for roughly every 2,500 that decayed, one excited carbon would drop down to carbon's lowest energy state—like the ball falling off a shelf on to the floor—and become stable. This was enough to explain the carbon production levels seen in the universe and needed to produce life. If there weren't such a resonance energy, we wouldn't be here.

Hoyle even calculated what the resonance energy would be (Hoyle, 1953)—something that was later confirmed by experiments (Livio, 1989). This is often cited as the first example of anthropic reasoning—we wouldn't be here if stars couldn't produce carbon—leading to a scientific prediction—there must be a resonance—that was later confirmed. Although historians have recently questioned whether Hoyle really had anthropic reasoning in mind (Kragh, 2020), the example gives the anthropic principle more scientific weight.

The finding was deeply disturbing to many physicists. Why should the balance of the forces that govern the atomic nucleus give rise to the specific resonance energy needed to enable the evolution of carbon-based life? To this day, carbon production remains a key argument when it comes to fine tuning.

2. The Fine-Structure Constant—"One of the Greatest Damn Mysteries in Physics"

The carbon resonance described above is determined by the balance between the electromagnetic force and the strong force. These strengths are described by two fundamental physical constants, α (alpha) and α_s (alpha_s), respectively. The reason they are so important is because they ultimately decide how long stars can live and what elements they can produce.

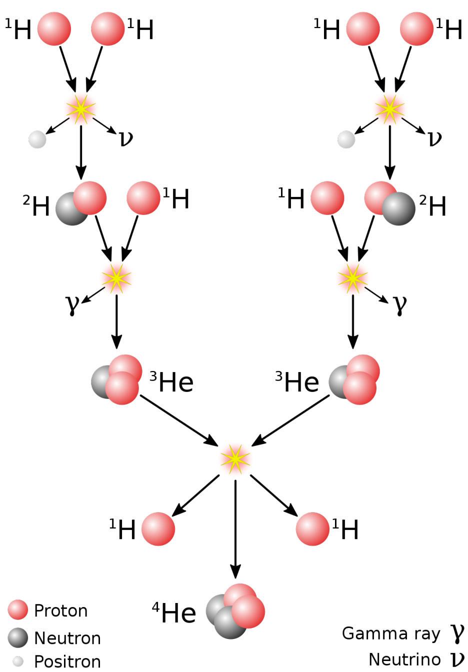

Figure 4: Helium (^4He) production in stars involves both hydrogen (^1H) and deuterium (^2H). (Image credit: Sarang, Public Domain.)

The fine-structure constant, α, which represents the strength of the electromagnetic force between two elementary particles, was discovered in 1916 by Arnold Sommerfeld. He uncovered that the constant needed to be baked into the equations describing the energy of an atom in order to match experimental observations. The fine-structure constant is equivalent to 1/137, its exact value recently determined with an accuracy of 81 parts per trillion— more than twice as good as the previous best attempt (Morel, 2020). The fine-structure constant determines how tightly atomic nuclei can bind together. But why it takes this precise value is not known—there is no theory explaining it. This conundrum has long fascinated physicists. In the 1930s, for instance, Max Born suggested that the universe would simply fall apart without this number being exactly what it is, and suggested that its value must simply be a law of nature (Miller, 2009). Decades later, Steven Weinberg described it as "one of the greatest damn mysteries of physics" (Weinberg, 1985).

But does our universe really depend on α being 1/137 (roughly 0.007)? John Barrow and Frank Tipler argued that if α were slightly bigger, just about 0.008, say, protons would be able to bind together too easily. If that were true in the early universe, it would have prevented hydrogen—which has a nucleus made up of only one lone proton—from surviving. Hydrogen is the fuel for stars, so without it, stars would have blown up before they could create heavy elements like carbon. Meanwhile, if α were only slightly weaker, about 0.006, say, a proton could no longer bind to a neutron. That would mean that deuterium, or 'heavy hydrogen'—which is a hydrogen atom with an extra neutron in the nucleus—couldn't form. Deuterium plays a key role in helium formation, however (Figure 4); so this would have made helium production difficult. And as described in section II.1 above, this in turn would have reduced the production of carbon (Barrow and Tipler, 1986).

3. The Strong Force vs the Electromagnetic Force

Similar problems would arise if the strong force were weaker or stronger relative to the electromagnetic force. It has been shown that, if α_s were only four percent larger than it is, protons would be able to bind together much more easily, rather than being repeled from each other because of their mutual positive charges (Tegmark, 1998). What's more, if the strong force had been slightly stronger or weaker, the binding energies of atomic nuclei would change so much that Hoyle's carbon resonance, described in section II.1 above, which is responsible for the required abundance of carbon, wouldn't be able to arise (Oberhamer et al., 2000).

Sean Phillip Uzan has also recently made detailed calculations to see whether certain stars ('Population III' stars[2]), which contain virtually no heavy elements, could somehow still have produced carbon in the early universe, had there been different values of α and α_s. Uzan discovered that these constants, and thus the balance of forces, could not change by more than a couple of percent at most, otherwise it would jeopardize carbon production (Uzan, 2020). This result again favors the view that these constants are fine tuned to just the right values for life to evolve. However, as we shall see in the fifth chapter, such arguments have been challenged.

4. The Electromagnetic Force vs Gravity

Even more serious constraints arise when considering the ratio between the electromagnetic and the gravitational force. As we have seen, this ratio is a whopping 10^{40}. It is easy to see why the electromagnetic force must be so much stronger than the gravitational force. Gravity only really matters on large scales, the scale of stars and planets, and it is cumulative. If gravity had been a lot stronger, stars could have formed from smaller amounts of material. They would thus have been smaller and had shorter lifetimes, making it difficult for the evolution of intelligent life to run its course (Adams, 2008; Barnes, 2012). If gravity had been twice as strong, for instance, a star's lifetime would drop from 10 billion years to less than 100 million years, which is hugely problematic given that human life took billions of years to evolve on Earth (Livio and Rees, 2018).

On the other hand, gravity could not be significantly weaker, because then matter in the early universe would not have been drawn together, so galaxies, stars, and planets could not have developed. That said, if gravity was only slightly weaker, that could have allowed larger and more complex structures to form in the universe (Davies, 2006). However, stars such as our sun would have been much colder and would not have exploded in supernovae, so heavier elements would not have been released into the universe (Carr and Rees, 1979).

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[2] Stars are categorized into populations based on their content. Population I stars are young and metal-rich—containing lots of heavy elements. Population II stars are metal-poor, containing relatively few elements that are heavier than helium. In the 1970s, Population III stars that have virtually no metals or heavy elements were hypothesized to exist in the very early universe.

5. Types of Stars

Astronomers classify stars according to their size, luminosity (that is, their intrinsic brightness), and their lifespan (Figure 5).

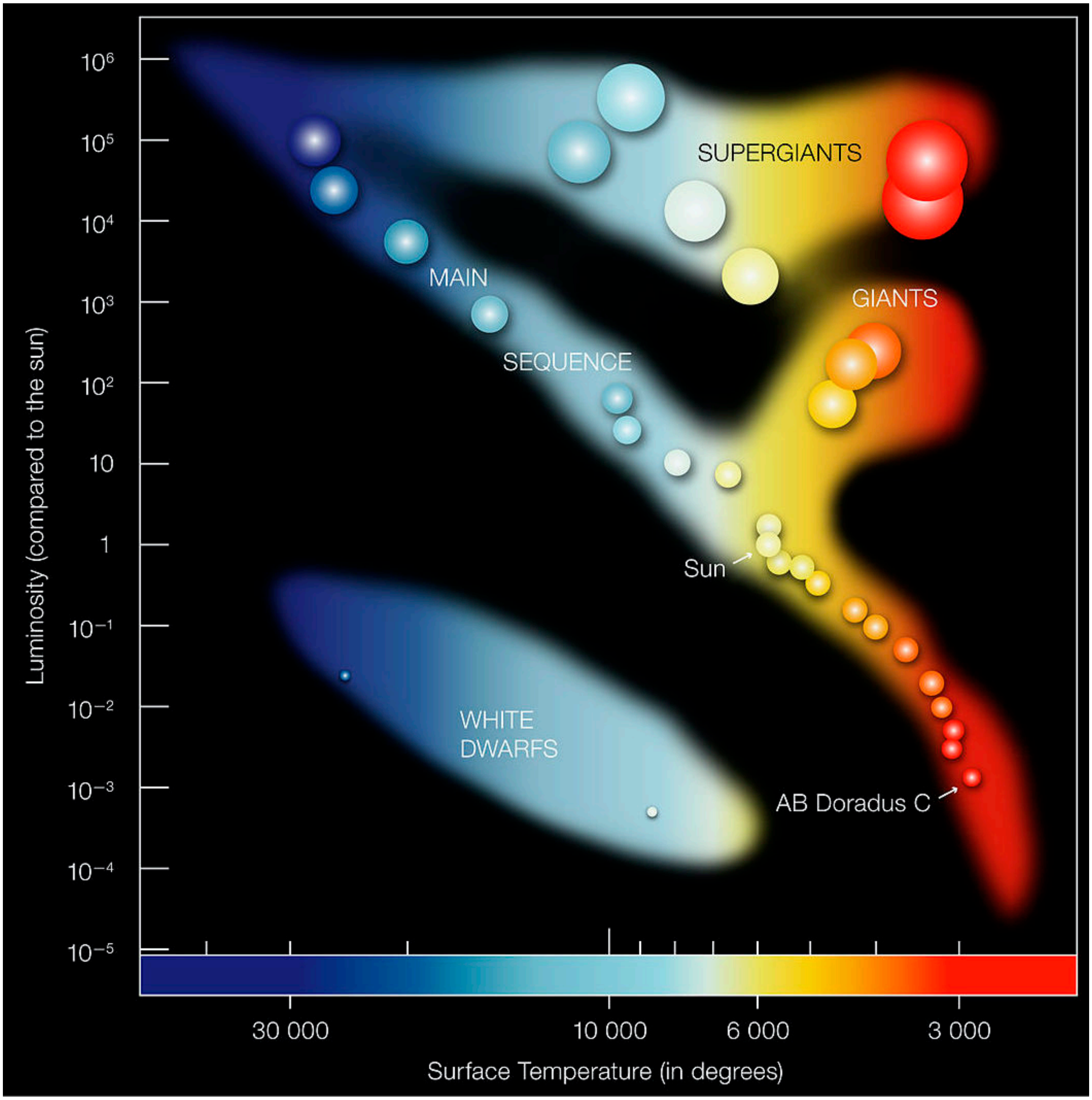

Figure 5: Astronomers plot the temperatures of stars against their luminosities in Hertzsprung Russell diagrams. The position of a star in the diagram provides information about its present stage in its life cycle and its mass. Stars that burn hydrogen into helium, such as our sun, lie on the diagonal branch, the so-called main sequence. Red dwarfs like AB Doradus C lie in the cool and faint corner. AB Doradus C has itself a temperature of about 3,000 degrees and a luminosity which is 0.2% that of the sun. When a star exhausts all the hydrogen, it leaves the main sequence and becomes a red giant or a supergiant, depending on its mass. Stars with the mass of the sun which have burnt all their fuel evolve finally into a white dwarf (left low corner). (Image credit: European Southern Observatory (ESO), shared under a Creative Commons Attribution 4.0 International License.)

The tuning between the gravitational and the electromagnetic forces plays a vital role in determining what kinds of stars exist, which in turn, has repercussions for the evolution of life. The strength of gravity is roughly equal to α^{20} and this value enables the existence of both small ("red dwarf") stars and large ("blue giant") stars. If the gravitational constant were only slightly larger, astronomers have calculated that all stars would be blue giants. If it were slightly smaller, all stars would be red dwarfs. But life seems to require both kinds of stars. Giant stars are needed as the factories that make a lot of heavy elements. They end their short lives in powerful explosions known as supernovae (Figure 6), which disseminate the heavy metals—needed to both create smaller stars and the chemicals necessary for life—into the universe. Such smaller stars live longer and do not bombard planets with harsh radiation, making their planets more suitable for harboring life. Other factors come into play too. For instance, dwarf stars may generate winds that blow away thick hydrogen atmospheres on planets in their vicinity—raising the chances of Earth-like planets with oxygen atmospheres developing (Carr, 2020).

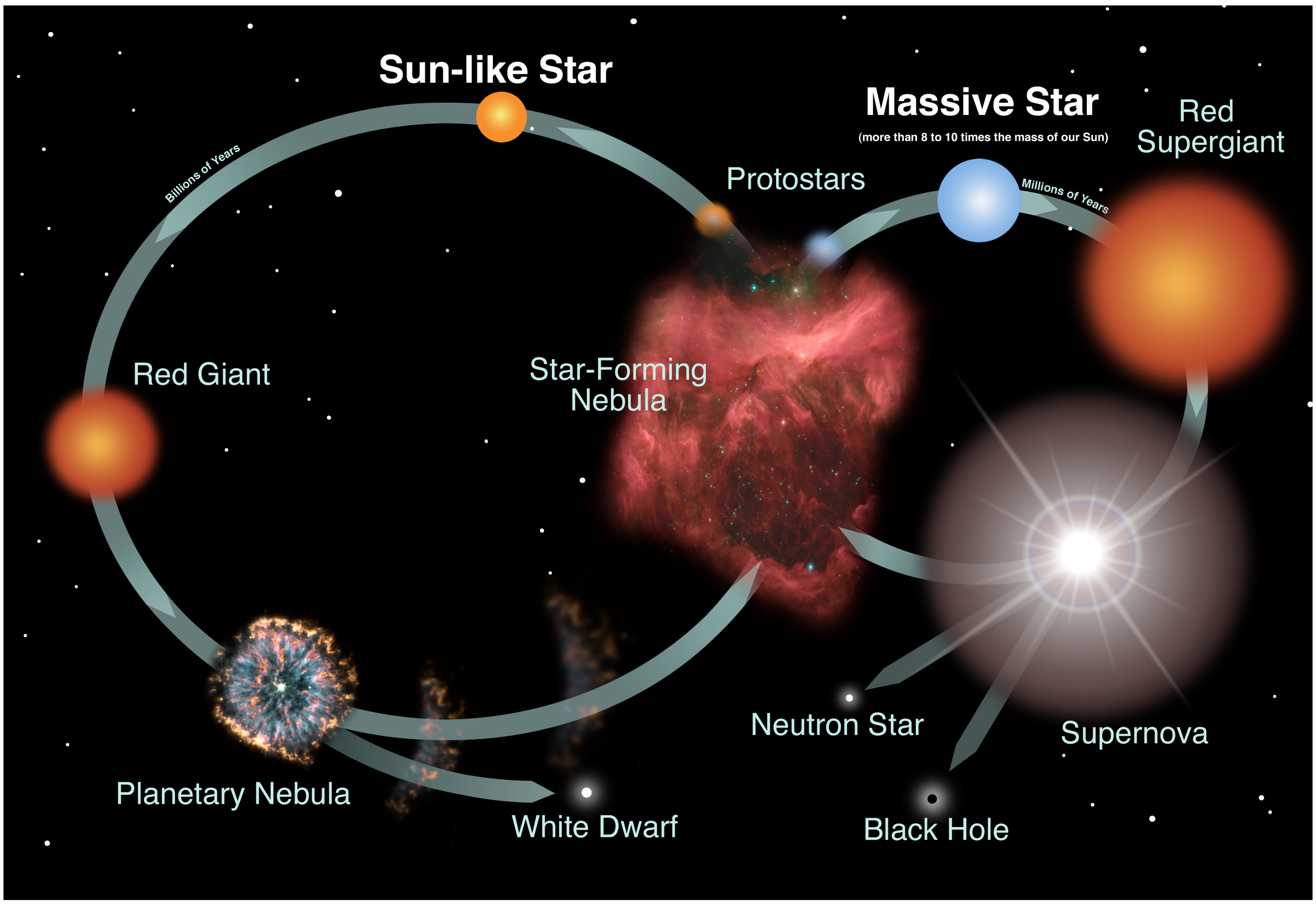

Figure 6: The life cycles of sun-like and massive stars. (Image credit: NASA and the Night Sky Network.)

6. The Weak Force and Radioactive Decay

The weak force, which governs the radioactive decay of atoms, also plays an important role in the implosion of stars, at the end of their lives. During these supernovae explosions, neutrons and protons get squashed together tightly.

During such processes, neutrons can turn into protons, while also releasing electrons and neutrinos (Figure 7). Although neutrinos are small, with barely any mass, all these neutrinos together create an outward pressure, which helps to eject material in the star outwards to space. But if the weak force were stronger or weaker, this wouldn't happen successfully (Davies, 2006).

It is also thanks to the weak force that the universe got its deuterium, which, as mentioned in section II.2, has traditionally been deemed crucial for helium-formation and, in turn, carbon-formation. Studies have shown that if the weak force had been stronger, free neutrons in the early universe would have decayed into protons so rapidly that hydrogen atoms would not have had time to mop up the extra neutron needed to form deuterium (Rees, 2000). And if the weak force had been about ten times weaker, there would have been fewer protons around to form hydrogen, at all, which is crucial for stable and long-lived stars like our sun (Hall, 2014; Davies, 2006).

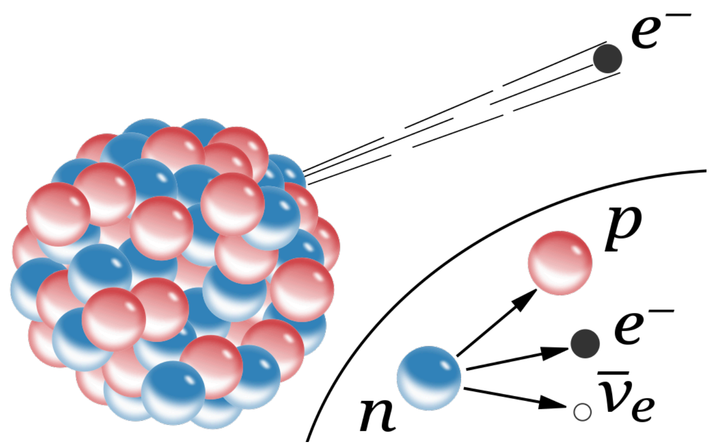

Figure 7: Radioactive beta decay is due to the weak interaction, which transforms a neutron into a proton, an electron, and an electron antineutrino. (Image credit: Inductiveload.)

So, at least upon initial investigation, all the four fundamental forces of nature seem to display some degree of fine tuning. However, we will discuss challenges to these claims in Chapter 5.

III. STRUCTURE

1. Dark Energy

Possibly the biggest fine-tuning conundrum in physics arises when you examine the universe on very large scales. In the late 1990s, astronomers were shocked to discover that the entire universe is growing at an accelerating rate. While they had evidence since the 1930s that the universe was expanding, astronomers expected that this growth would be slowing down rather than speeding up, given the gravitational attraction between galaxies and other structures would pull everything back inwards. The force driving this acceleration was dubbed "dark energy." (See JTF's Cosmological Origins review for a detailed discussion of the discovery of dark energy.)

Cosmologists do not yet know exactly what dark energy is or how it works. But one of the most powerful possible explanations is that it is a result of the energy of the vacuum of empty space itself. This outward push would be a "cosmological constant," denoted by the Greek letter lambda, Λ, having an equal and unchanging influence throughout the entire universe, and throughout its entire cosmic evolution. If dark energy was too strong, structures like galaxies or planets could never have formed in the early cosmos—matter would have been ripped apart too quickly. But serendipitously, Λ has been measured to be immensely small—so weak that gravity wins out on local scales, allowing matter to clump together.

But why should empty space have some intrinsic energy? The answer is that even in a vacuum, "virtual" particles are constantly popping up, lasting for a fleeting moment, before disappearing again—known as "quantum fluctuations." (See JTF's Emergence review for more about this and other quantum effects.) Paul Davies and others have investigated whether vacuum fluctuations can explain the level of accelerated expansion seen. It is possible to calculate how much quantum energy should theoretically reside in a single cubic centimeter of empty space using particle-physics models; the answer is a mind-bogglingly large amount, 10^{93} grams.[3] Strangely, however, this value is way more than the dark-energy mass density that astronomers actually measure, which only adds up to a meagre 10^{-28} grams—120 powers of ten less than theory had suggested.

It is thus highly confusing that the measured value is so small. Physicists have calculated that if the dark-energy mass density had been only about ten times greater than its measured value today, galaxies, planets, and life wouldn't have been able to form—which seems a shockingly small margin. Dark energy could, however, have been a lot smaller without preventing the formation of structure (Davies, 2006).

2. The Shape of the Universe and the Flatness Problem

Another feature of the universe that intrigues cosmologists is its curvature, which is also tied to its ultimate fate. Cosmologists realized in the 20th century that there are three theoretically possible shapes the cosmos could take: It could be "open"—in which case it would grow at an ever-increasing pace forever; it could be "closed"—in which case, gravity would eventually draw its contents back inwards, and it would shrink down in a Big Crunch; or it could be "flat"—poised on a knife-edge between these two possibilities. The universe's fate depends on the density of energy and matter it contains. A flat universe corresponds to a "critical density"; an open universe will arise if the density is lower than this value; and a closed universe will have a density above this critical value.

The density is determined by the matter in the universe and the amount of dark energy. As described in detail in Chapters 4 and 5 of JTF's Cosmological Origins review, multiple measurements confirm that the density of the universe is extremely close to the "critical density" required for a geometrically flat universe—one that also has the correct balance between gravity and dark energy for galaxies, planets, and life to evolve. Theory suggests that to be close to the critical value today, the universe must have started out even closer to this critical number. But it is difficult to explain why that should have happened. This is referred to as the "flatness problem"—another example that has been cited as evidence of fine tuning (Rees, 2000; Martin, 2020).

The consensus resolution to the flatness problem is "inflation theory," which asserts that the infant universe went through a short period of rapid expansion. Inflation lasted for only a fraction of a second, flattening cosmic curvature in that moment. We shall discuss inflation in detail in Chapter 3. In the following section, however, we will briefly note that inflation is related to another fine-tuning puzzle involving the formation of cosmic structure, such as galaxies.

3. Structure Formation

Cosmologists now think that the evolution of large-scale structure, such as galaxies, can be traced back to slight density fluctuations imprinted in the early universe, which caused matter to clump together, attracted by gravity. These density fluctuations in turn originated from tiny quantum fluctuations—produced when inflation was triggered, and amplified by the rapid expansion of the cosmos during inflation.

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[3] The energy has been converted into units of mass using Einstein's famous relationship, $E=mc^2$, which relates mass, energy, and c, the speed of light.

The universe is actually surprisingly smooth, with a similar temperature and structure in all directions. The density fluctuations from which structure arose were minuscule—wrinkles of roughly 10^{-5} or just one part in 100,000. This number is denoted by the parameter *Q*. Here we encounter another example of fine-tuning: Had *Q* been larger, galaxies would have become so dense and violent, with abundant black holes, that planetary systems that are conducive to life could not have formed. If the size of the fluctuations were smaller, however, there would be almost no structure—the universe would be perfectly smooth, but largely barren (Rees, 2000; Martin, 2020). In Chapter 3, we shall see how inflation addresses this fine-tuning issue.

IV. DIMENSIONS

1. Space

The universe has three spatial dimensions—depth, height, and width. Sometimes objects can appear to have fewer dimensions, when viewed from a distance. If you look at a hose lying 50 meters ahead of you on a road, for example, it looks like a single line—a one-dimensional object. As you get closer, you will realize that it has width as well as length—it appears two-dimensional. But it is only when you are close enough to the hose so that you can lift it and look inside it that you realize that it also has a curved interior, which gives it depth, representing its full three dimensions. Beyond this, you cannot distinguish any more dimensions.[4]

In the 1920s, Paul Ehrenfest investigated whether there was something special about three spatial dimensions. Would it matter if there were four or five large spatial dimensions, instead? Ehrenfest discovered that when you try to tinker with the number of dimensions, you lose the cosmic structure that makes life possible (Ehrenfest, 1918; Carr, 2020).

To understand why changing dimensions would have a catastrophic effect, it is important to note that gravity governs how planets orbit stars, while electromagnetism controls how electrons orbit the atomic nucleus. The evolution of life is tied to the stability of these orbits. In our universe, at least, gravity and electromagnetism follow what's known as an inverse square law. This means that the strength of the force between two objects—the Earth and the sun, say, in the case of gravity—drops the further they are separated. If the distance between them is given by r, then the strength decreases by a factor of r^2.

In such conditions, orbits (both planetary and atomic) remain stable. If a planet were to slow down ever so slightly, say, it would simply shift into a smaller orbit around its star.

In a universe with four spatial dimensions, however, these forces would decrease with a factor of r^3, and so on, for universes with higher spatial dimensions. In the four-dimensional case, in which gravity follows an inverse cube law, just a slight reduction in a planet's speed would make it crash into its star. Similarly, if it were to slightly speed up, it would be ejected far, far away into empty space (Rees, 2000). So a universe with more than three spatial dimensions could not produce life.

But what about a universe with just two spatial dimensions? Fred Adams has shown that planetary orbits could remain stable in such hypothetical universes (Adams, 2019). However, it is unlikely that

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[4] As we will see in the next chapter, certain theories of physics require the existence of extra hidden dimensions. Our best current candidate "theory of everything," string theory, posits that elementary particles are actually comprised of tiny threads of energy vibrating in as many as ten or 11 dimensions. Most of these extra dimensions are somehow "compactified"—rolled up on such a small scale that we can't see them directly. Even if this theory proves to be true, in the future, it is still the case that as far as macroscopic matter is concerned, only the three large spatial dimensions are really relevant.

intelligent creatures could evolve in such a simple world, in one or two dimensions, without, for instance, the intricate three-dimensional structure of a DNA spiral that forms the basis of life.

So it appears that three spatial dimensions *are* special. But physicists do not really understand why the universe has three spatial dimensions.

2. Time

Our universe has one time dimension.[5] As discussed in some depth in the fourth chapter of JTF's Time review, physicists and philosophers have puzzled over why we can only move along this temporal dimension in one direction, from the past to the future, and never in reverse.

One consequence of an additional traversable time dimension is that it could make time travel possible. For instance, just as you can travel around a circle on a two-dimensional spatial plane, you may be able to loop backwards in time, if there is a two-dimensional temporal plane. While this possibility sounds exciting, it would lead to many strange occurrences that would interfere with the habitability of the universe. Cause-and-effect relationships are the cornerstone of fundamental physics, and this would be under threat. A famous example from science fiction is the grandfather paradox: you may be able to travel to the past and kill your ancestor, preventing your future birth. So it appears that time must be constrained to one large traversable time dimension, for life to develop.

In the next chapter, we will review current models that attempt to explain why we live in a universe with these seemingly fortuitous parameters. Chapter 4 will describe how physicists are trying to probe the validity of such proposed explanatory models. The fifth chapter will return to some of the parameters we have introduced here and discuss recent analyses suggesting that they may not be quite as finely tuned as they appear.

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3. EXPLAINING FINE TUNING

It was one of the weirdest requests of Alan Guth's career. The cosmologist is one of the founders of inflation theory—the idea that the infant universe went through a period of rapid expansion. In 2014, Guth was asked to swear an affidavit stating that his research does not prove that the universe had a beginning. His colleague Sean Carroll then brandished the document in a debate, titled "God and Cosmology," against theologian William Lane Craig, to argue that there is no need to invoke a God when trying to explain the origin of the cosmos—the universe may have always existed according to the latest scientific understanding (Merali, 2017).

A central theme in the debate between Carroll and Craig was whether the universe is fine tuned for life to exist. If so, then this perhaps implies that a supernatural being must necessarily have created it (Craig, 2014). Supernatural forces as an explanation for fine tuning are clearly untestable, however, by virtue of being unconstrained by the regularities of nature, by definition. As such, we will not address this particular issue directly in this review, other than to note that theism has been offered as an explanation—and pitted against the multiverse view—and this is one of the reasons why the fine-tuning problem has ignited mainstream interest in a wider cultural context.

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[5] Physicists have investigated the strange possibility that we live in a universe with two time dimensions, but as in the case of extra spatial dimensions in string theory, this extra time dimension would be hidden, and could not be traversed by humans (Bars, 2001).

Paul Davies has stated that, at least until fairly recently, most scientists who thought about these issues at all actually favored the view that any apparent fine tuning is simply an inexplicable coincidence. Our universe happens to have the physical laws that we observe, and that it's pointless trying to work out why (Davies, 2006).

However, that situation may be shifting. Inflation theory has spawned a maverick offshoot that itself may provide an explanation for fine tuning, removing the need to look for supernatural explanations. The work of Guth and others independently shows that our universe may be one of many in an ever-growing multiverse, each populated with different laws. The historical development of inflation and multiverse theory is covered in some detail in JTF's Cosmological Origins review. In the first section of this chapter, we shall briefly outline the multiverse framework and the development of string theory—our best current candidate model for unifying physics, which posits that elementary particles are composed of tiny vibrating energetic strings. Taken together, these provide a physical explanation for why our cosmos should be so handily habitable for humans; in an infinite multiverse, obviously cosmoses conducive to life will pop up every so often.

Both the multiverse and string theory are speculative—though well-respected—models. However, their physical predictions have proven difficult to test and may (or may not) forever lie beyond the bounds of human technology. Perhaps ironically this has led to a similar criticism being leveled at them, as at theism: if untestable, they are unscientific. George Ellis, for instance, has argued that while multiverse hypotheses are "plausible," they are not observationally or experimentally testable "and never will be" (Ellis, 2011). As we shall see in Chapter 4, this claim has now been contested, as direct observational tests of the multiverse have been proposed. However, it is certainly true that such observational evidence may not be forthcoming, and there appears to be no way to falsify the multiverse hypothesis in the meantime. Sabine Hossenfelder has also argued that physicists seduced by the mathematical beauty of string theory are blind to the fact that there is no concrete scientific evidence for it (Hossenfelder, 2019).

Section II of this chapter thus touches on a number of niche models that invoke neither string theory nor the multiverse, but offer alternative cosmologies that might explain fine tuning in a different way. It may also be the case, of course, that a future as-yet-undiscovered unifying theory of physics could help explain why certain physical parameters take the specific (and serendipitous) values that they do. Perhaps we'll find that they are not fine tuned, after all. (JTF's Emergence review outlines the current avenues towards unification being pursued, in its third chapter.)

Finally, section III discusses some of the most speculative explanations for fine tuning proposed—that our universe *was* created or simulated, not by a supernatural power, but by a technologically advanced civilization.

But first, we shall turn to a theory that was proposed, in part, to directly tackle fine-tuning puzzles, and which now underpins string theory: 'supersymmetry.'

I. SUPERSYMMETRY

First proposed in the 1960s and largely developed in the 1970s, supersymmetry, or 'SUSY,' is an extension of the Standard Model of Particle Physics that predicts that each of our familiar known particles is paired with a heavier (and as yet undetected) 'super-partner.' For instance, the electron would have a super-partner electron, called a "selectron." The motivation for this seeming extravagance was an attempt to address some fine-tuning issues. For instance, as mentioned in Chapter

2.II, there is no fundamental reason why the relative strengths of the forces take the values they do—yet it is supremely lucky for us that they do.

There are other mysteries surrounding the charge, mass, and size of elementary particles. When physicists examined the observed charge and mass properties of the electron, they calculated that its diameter would be larger than the proton—which is not the case—unless you take into account a number of quantum effects. Physicists realized that similar quantum effects could help explain the small sizes of other particles too, provided that an additional spacetime symmetry exists, which in turn led to the existence of a host of new super-particles. (Chapter 3 of JTF's Emergence review has a more thorough discussion of spacetime and its known and proposed symmetries.) This elegant so-called supersymmetry posited specific relationships between the properties of the particles and their super-partners that could help explain the low masses of the particles we have detected, and also helped to mathematically explain why forces have these peculiar relative strengths. SUSY is also attractive because it is an example of a Grand Unified Theory, as described in more depth in section II.2 below. And as discussed in Chapter 5 of JTF's Cosmological Origins review, physicists were also excited because heavy super-partners might be good candidates for dark matter—the unknown invisible substance that makes up the bulk of matter in the universe.

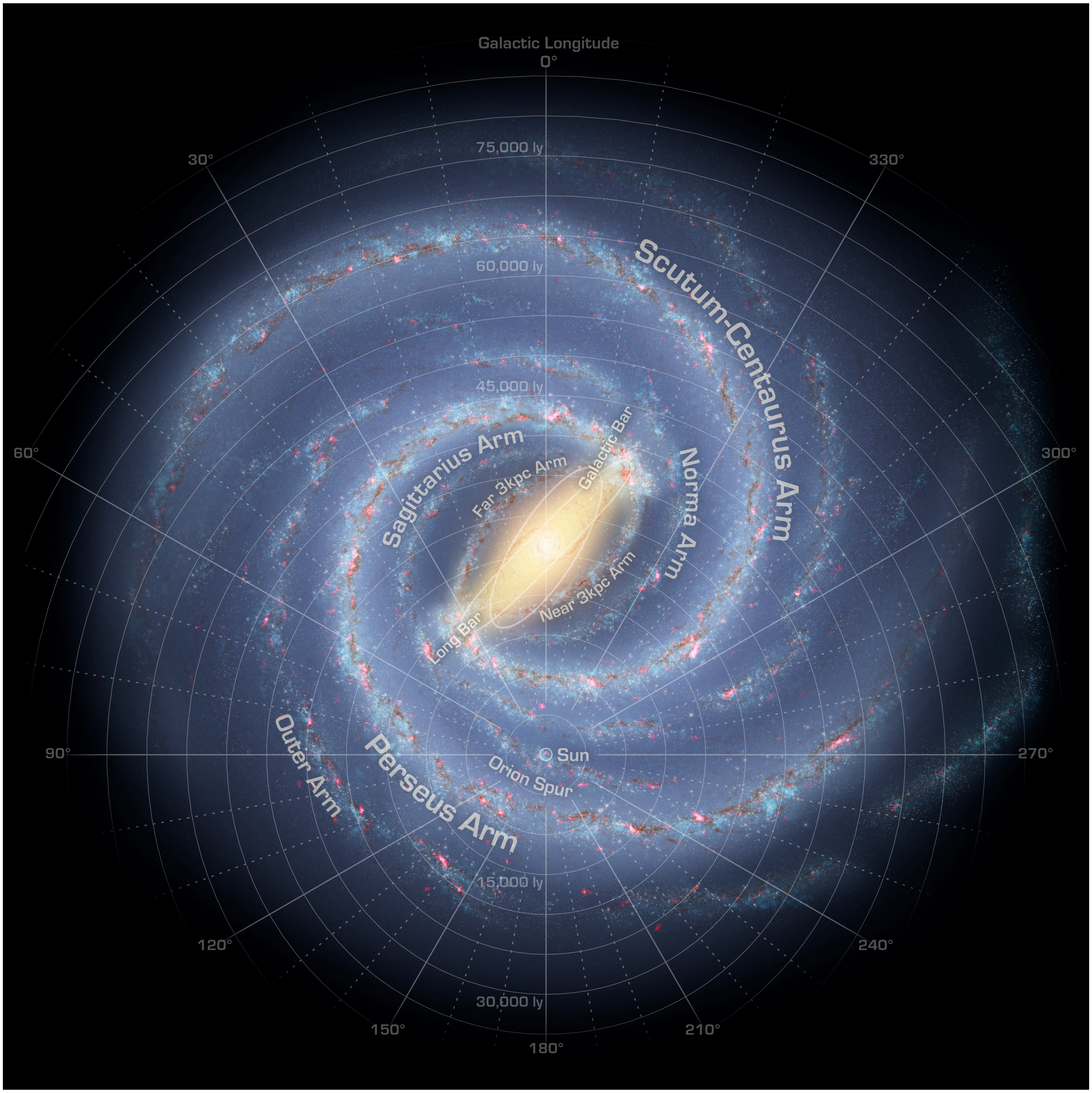
Such superpartners would be too heavy for us to have observed in everyday life—or even to have been produced in early particle colliders. But physicists eagerly awaitied the startup of the Large Hadron Collider (LHC), at CERN, near Geneva, Switzerland, in 2008, in the hope that super-partners, or other evidence of supersymmetry, would appear in the debris of their high-energy particle collisions. Indeed, some were so enamored by the beauty of supersymmetry's solutions to so many problems that they laid bets that such evidence would be found (Jepsen, 2016). That this did not transpire has been a major theoretical blow to SUSY, especially the simplest versions of the model that physicists initially favored. In fact, the LHC has yet to reveal any confirmed evidence of physics beyond the Standard Model. Chapter 4 discusses plans to find evidence of more complicated SUSY models in future experiments, along with hints from recent experiments that new particles and forces beyond those described in the Standard Model may exist.

Still it remains an open question whether evidence of SUSY will be found, and—if it is—whether SUSY alone will suffice to quell concerns about fine tuning by providing the long-sought fundamental explanation for the fortuitous values taken by certain physical parameters, as some hope. But SUSY plays another important role within a fine-tuning context. It forms the foundation of string theory, one of the best candidate models for a theory-of-everything, which when taken together with the inflationary multiverse framework provides the most popular current scientific explanation for fine-tuning, as described in the next section.

II. THE INFLATIONARY MULTIVERSE

In a way, the multiverse is just a continuation of a story begun by Copernicus almost five centuries ago, when the astronomer published a heliocentric model of the universe. Earth no longer sat at its privileged position at the center of the universe. Since then, our place in the universe has became increasingly less remarkable as the centuries have passed. Our solar system, it turns out, isn't at the center of the universe, either; nor is our galaxy (Figure 8). Now, it seems, even our universe might be only one of myriad cosmoses.

Figure 8: Using infrared images from NASA's Spitzer Space Telescope, scientists have discovered that the Milky Way's elegant spiral structure is dominated by just two arms wrapping off the ends of a central bar of stars. (Previously, our galaxy was thought to possess four major arms.) This annotated artist's concept illustrates the galaxy's two major arms (Scutum-Centaur-us and Perseus), and two now-demoted minor arms (Norma and Sagittarius). Our sun lies near a small, partial arm called the Orion Arm, or Orion Spur, located between the Sagittarius and Perseus arms. (Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech).)



1. Inflation

In Chapter 2.III, we learned that the universe is extraordinarily smooth, with only slight wrinkles in temperature and structure across the cosmos. And it appears to be geometrically "flat"—teetering between extreme expansion forever and a fate in which it ultimately contracts and crunches back down. To cosmologists in the 1970s, there was a problem: Both the smoothness and flatness seem to have been fine tuned to the perfect values required for life to evolve. After all, it makes no sense that distant parts of the universe look the same and have the same temperature, when conventional wisdom said that they were too far apart to ever have been in contact, even when you traced time back to the Big Bang.

The standard explanation, arrived at in the 1980s and attributed to Guth and independently to Andrei Linde and others, is that the early universe went through a period of extremely rapid expansion. The scale of this inflation is mind-boggling: the universe blew up by a factor of 10^{26} in just 10^{-32} seconds. This dramatic but brief phase in the universe's early history solved the problem of why the universe looks so similar in every direction. In this model, far-flung regions of the universe today would once have been connected—able to mix and homogenize in the moments after the Big Bang—before inflation hurled them apart.

Inflation is thought to be triggered by the behavior of some kind of quantum field, called an "inflaton" field, pervading the universe (Figure 9). When the energy of this field dominates, it inflates. During inflation, the vacuum that pervades the empty universe has an unusually large amount of energy—it's called a "false vacuum." In Guth's original conception, the universe could be thought of like a ball that could either sit at the top of a hill, nestled in a dimple so it was relatively stable (representing that it was in the higher-energy false vacuum), where it would inflate, or it could drop down to the bottom (into the true low-energy vacuum), not inflating (Figure 9a) (Guth, 1981). It turned out that this model was not viable because Guth could not explain how the universe would shift from the false to the true vacuum—and thus could not explain how inflation would ever end in the cosmos (see JTF's Cosmological Origins review for more details). Linde (Linde, 1982)—and independently Paul Steinhardt and Andreas Albrecht (Albrecht and Steinhardt, 1982)—envisaged a slightly different variation, called "new inflation" that solved this problem (Figure 9b).

Since then, many kinds of inflaton field have been proposed and examined theoretically by cosmologists, however there is no consensus as to which is correct. This ambiguity has left the theory open to criticism (Ijjas et al., 2013). It has also been noted that while inflation solves one set of fine-tuning problems, it raises its own. It appears that certain specific initial conditions have to be met in the early universe for inflation to occur—and there is no clear explanation for why the universe would have started with those handy characteristics (Finn and Karamitsos, 2019). Others have countered that these conditions can be explained and are not so unlikely to have occurred naturally, however (Ashtekar et al., 2016; Martin, 2020).

Despite these niggles, most cosmologists currently favor inflation above alternative views (some of which are discussed in section III) because it has made several predictions that have been observationally verified (Ade et al., 2016; Martin, 2020). For example, as mentioned in Chapter 2, it predicts that our universe's density should add up to the "critical value" we observe. Thus the perfectly flat cosmos discovered and repeatedly confirmed by experiments is not just consistent with inflation, it is a prediction of the theory.

The most stunning vindication of inflation has come from measurements of the temperature of the cosmic microwave background radiation (CMB)—the relic radiation of the Big Bang. (See Chapter 3 of JTF's Cosmological Origins review for a discussion of the prediction of the existence of this radiation and its discovery.) Physicists are able to calculate the size and pattern of the subtle temperature variations they would expect to see today imprinted in this radiation, which would have been created by quantum fluctuations during inflation. Experiments by NASA (Spergel et al., 2017) and by the European Space Agency continue to verify these predictions with greater precision (Morel et al., 2020).

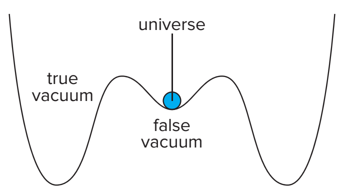
The idea that there are many universes, perhaps an infinite number of them, has been around for centuries. But it is only in the last few decades that this became a serious possibility within cosmology. As described above, inflation was proposed in the 1980s. Soon after, cosmologists working on the theory, including Linde and Alexander Vilenkin, realized that, if inflation could happen once, it could occur countless times (Linde, 1986; Vilenkin, 1995). In fact, different patches of the cosmos could

The Inflationary Multiverse

Inflation may start and end at different times and places, creating a multiverse of parallel neighboring cosmoses. String theory suggests these universes may have different properties, laws and even dimensions.

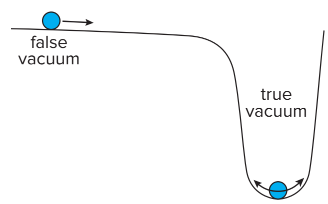
Old Inflation

(a) While the universe is nestled in the higher-energy 'false vacuum' state, it inflates, expanding at an exponential rate. Inflation only ends when the universe is in the true vacuum. But how can it reach there?



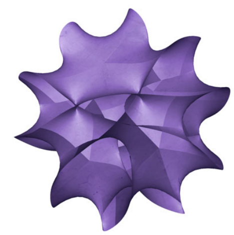
New 'Slow-Roll' Inflation

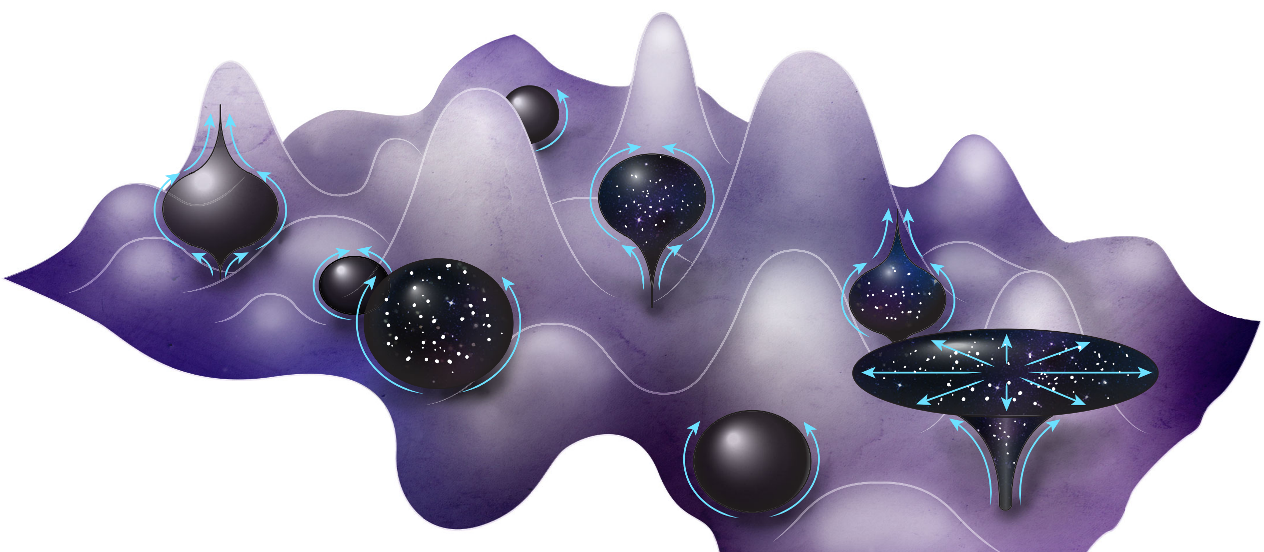
(b) The false vacuum is represented by a shallow incline. As the universe slowly rolls down, it continues to inflate. Inflation ends when it hits the true vacuum, rolling back and forth in the valley, releasing energy to create new particles.



Extra Dimensions

(c) String theory predicts there are a number of extra dimensions, hidden from us because they are small and curled up in complex ways. The image shows a 2-dimensional slice of one such proposed 6-dimensional folding pattern.





String Landscape

(d) There are around 10^{500} possible configurations for wrapping up the extra dimensions–each one corresponding to a universe with different physical laws. Combining string theory with inflation suggests that there may be near infinite other universes, generated by inflation, and populated with different parameters, forces and dimensions by string theory. Only very rarely will one be produced that has the right parameters for stars, galaxies, planets and people to evolve.

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Created by Maayan Harel for FQXi, the Foundational Questions Institute
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Figure 9: The Inflationary Multiverse. (Image created by Maayan Harel.)

suddenly start inflating and blow up to huge volumes—each effectively a universe in its own right.

Physicists began to realize that the existence of a multiverse could have profound implications for the fine-tuning problem. If multiple universes exist, with different parameters, it is no longer surprising that one should have the parameters we see in our own universe, just by chance (Linde, 2017).

This would make the apparent fine-tuning mysteries evaporate.

It was not, however, immediately obvious why different inflating patches, born from the same parent multiverse, would have different physical parameters. That changed when physicists brought together ideas from cosmology with those being developed in the context of physicists' best current model for unifying physics: string theory.

2. The String Landscape

By the 1980s, physicists had used quantum physics, the theory that governs the behavior of small particles, to explain three of the four fundamental forces of nature: electromagnetism; the weak nuclear force, which is a subtle interaction responsible for certain forms of radioactivity; and the strong nuclear force, which binds subatomic particles known as "quarks" together inside protons, neutrons, and certain other particles. (See Chapter 3 of JTF's Time review for a primer on quantum theory.) The first success was the development of the "electroweak theory," which combined electromagnetism and the weak force (Yang and Mills, 1954; Glashow, 1961; Weinberg, 1967; Salam and Ward, 1959). Then the strong nuclear force was brought into the fold, in a theory that came to be known as Quantum Chromodynamics (Fritzsch, Gell-Mann, and Leutwyler, 1973). Physicists have come up with several ways to embed all known particles and forces into a Grand Unified Theory, or GUT, that encompasses them all in a natural way. GUTs, which will be described in more detail in Chapter 4, suggest that in the very early universe these three forces were combined into one. As the cosmic temperature cooled, one by one, the individual forces we recognize condensed out, while some initially massless particles acquired mass. (Attempts to find experimental evidence in support of candidate GUTs will be described in more detail in Chapter 4.)

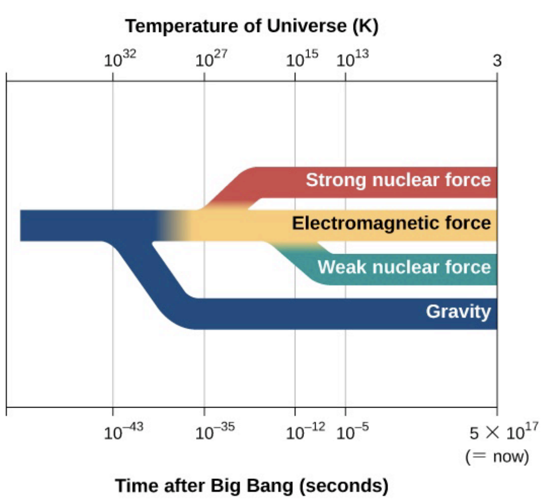

Figure 10: As the temperature of the universe cooled, it is thought that the four forces separated. (Image credit: openstax.org/details/books/astronomy, Rice University, shared under a creative commons 4.0 international license.)

The next natural step would be to bring in gravity, the final fundamental force—creating a "theory of everything" that can explain all physical phenomena based on a simple, underlying mathematical framework (Figure 10). It could ultimately explain why the parameters that we currently think of as finely tuned have the values they do.

The best candidate that physicists currently have for a theory of everything is string theory. It has a long history of discovery, abandonment, and rediscovery over many decades, going through many iterations, most notably rising once more to the fore in the 1980s. A major obstacle for physicists attempting to unify quantum theory and gravity had been that when they put the equations of these two theories together and tried to solve them, they got nonsensical answers, predicting that spacetime contains infinite energy and could not be stable. This problem seemed to be linked to the conception of elementary particles as infinitely small points. But if this view is relaxed, and elementary particles are instead conceived of as tiny vibrating loops of energy, the equations become manageable.

A key feature of string theory is that it requires the existence of up to 11 spacetime dimensions for the strings to oscillate in, depending on the framework you use (Witten, 1995). Yet, we only detect three space dimensions and one time dimension and—as explained in Chapter 2.IV—it's lucky for us that this seems to be what the universe prefers, or human life could not exist. So, in string theory, the extra dimensions must somehow be rolled up, or "compactified," on such a small scale that we wouldn't notice them (see Figure 9c). It was not until the 2000s, however, that string theorists realized that a huge number of different compactifications are possible, each of which would correspond to different values of physical parameters and a range of physical laws. It has been estimated that 11 dimensions can be rolled up in 10^{500} different ways—each representing a differently configured universe (Susskind, 2005).

This is often described as a "string landscape" of universes, with hills and valleys (see Figure 9d). Each valley is a stable universe like our own; some may be similar to our own while others would be unimaginably different. This landscape doesn't provide a physical mechanism for making these universes, however; it's abstract—a multiverse of possibilities.

Physically, it has been posited that inflation is the driver that births new universes—and string theory populates them with different parameters (Linde and Vanchurin, 2020). This is how the inflationary multiverse, coupled with string theory, strengthens the anthropic principle. Suddenly, it makes sense that we should be in a universe with parameters that can support life; there is nothing special about our universe.

That the entire universe may be just one of many is further humbling and perhaps raises the question of why we should spend so much time asking why we—humans—are so special and what a universe must do to produce us.

3. Criticisms of the Multiverse as a Solution to the Fine-Tuning Problem

As tantalizing as all this sounds, it's important to be clear that there is no evidence that multiple universes actually exist—nor indeed that string theory is correct. In Chapter 4, we will turn to ongoing experimental tests and observations that are searching for evidence to strengthen support for these ideas. Nonetheless the inflationary multiverse has gained significant support among many physicists due to the observational support for inflation, and the strength of the mathematical arguments stating that a multiverse is likely to result from inflation.

It is also important to note that there has been vocal criticism of the multiverse, with some physicists dismissing it as little better than mumbo-jumbo. Some of the multiverse's most vocal critics have labeled the theory as "unscientific" because they claim it is untestable (Ellis, 2011). In the next chapter we shall discuss proposals for directly testing the multiverse that contradict this assertion. But setting those aside for the moment, it is worth stating that dismissing a theory as unscientific because it is not directly testable with current technologies seems a little cheap. There are, after all, many scientific predictions that we cannot directly test, but which we take seriously. For instance, we cannot prove that in around 5-10 billion years' time, the sun will turn into a red giant and engulf the Earth before dying out as a faint white dwarf star. (Chances are high that there will be no humans around to do that experiment.) Yet, we accept this as the likely fate of the sun and of our planet because astrophysicists have confidence in their equations of stellar structure and evolution, and astronomers have seen red giants and white dwarfs elsewhere in the universe. In a similar vein, astronomers assume there are many more galaxies in the universe than they can currently observe. These lie beyond the maximum distance that light could have traveled over the age of the universe, and so by definition, astronomers cannot observe them (Livio and Rees, 2020). It's also worth noting that it took a century for physicists to build the apparatus needed to detect gravitational waves—ripples in the fabric of spacetime—first predicted by Einstein, in 1916. In the interim, the idea of gravitational waves was not deemed unscientific.

But other criticisms are more subtle, and point to the specific nature of inflation's predictions. Here the issue is not so much that the multiverse makes no testable predictions, but that it is a slippery framework that comes in multiple flavors, that make too many conflicting predictions, making it tough to falsify. Steinhardt, one of the developers of inflation and an early investigator of the multiverse, has now turned his back on the program. He has criticized the failure for inflation's proponents to pin down the mechanism for triggering inflation, or to reach a consensus on the form of the inflaton field. This ambiguity in the inflationary paradigm makes it difficult to falsify; if the predictions of the model using one version of the inflaton field fail to match observations, inflationary cosmologists can simply switch to another model, with another version of the field, which does match. "My concern was that the multiverse is a 'theory of anything,' a proposal that allows all possible cosmological outcomes (smooth or not smooth, curved or flat, etc.) and, consequently, is not subject to empirical tests," Steinhardt has stated (Horgan, 2014).

Similar arguments have been leveled at the string landscape. Where it was once hoped that string theory's equations would lead to a unique fundamental underpinning for the forces and parameters in the universe—finally explaining why they take the serendipitous values they do—instead its equations now seem to be able to conjure up any possible universe you can imagine (Woit, 2006).

Indeed, in a multiverse with nigh on infinite cosmoses, it does seem impossible to make any meaningful predictions for what values physical constants should take. After all, any possible value could occur somewhere. Still some cosmologists are attempting to work out mathematically whether some parameter values—say the seemingly unusually small value of the cosmological constant driving the expansion of the universe to accelerate—are more likely to occur in an infinite multiverse than others. If our measured cosmological constant turned out to be typical, rather than rare, it would provide a huge boost for multiverse theory, for example. The strategy they use to calculate probabilities among infinite possibilities has raised its own bizarre puzzles, however, suggesting that a universe populated by floating disembodied brains is more likely to occur than one such as our own (see "Boltzmann Brains and Multiverse Mathematics").

Controversies over whether multiverse theory and string theory are truly testable and really scientific—rather than metaphysical—models have made entertaining newspaper fodder for over a decade. But these debates may also have profound implications for the allocation of future funding resources, with critics arguing that potential future tests of such theories are too expensive and unlikely to yield definitive results, and that a multiverse is unnecessary for solving fine-tuning problems, either because fine tuning can be explained by other means, or fine tuning is not truly a problem at all (Hossenfelder, 2018). After all, in the absence of a probability distribution for the possible values that a fine-tuned parameter might take to compare against its actual measured value, we simply cannot know if it really is in an unlikely, and bizarrely lucky, range. Perhaps rather than funding billion-dollar international physics experiments, the money could be better divided up on multiple smaller projects—or directed at tackling climate change or future pandemics. The implications for the sociology of science are large.

It has also been argued that even if we could somehow definitively prove that there is an infinite multiverse out there, this would not necessarily provide a satisfying solution to fine-tuning concerns. The multiverse might successfully explain the origin of the improbably fortuitous conditions that make our universe habitable, but then one can simply ask where the 'meta-laws' that govern the multiverse came from, allowing it to spawn hospitable cosmoses, even if only rarely (Davies, 2007). In fact, it just moves the problem up a level: What created the multiverse and is the multiverse fine turned? What was there before it?

Thus the remainder of this chapter will discuss a selection of alternative—and also highly speculative—explanations for fine tuning that avoid invoking a multiverse; Chapter 4 will assess the feasibility of current and future tests of the multiverse and string theory; and the final chapter will examine whether the fine-tuning problem is a real problem, at all.

Boltzmann Brains and Multiverse Mathematics

How do you compare infinities? That's the conundrum for cosmologists trying to work out the odds of an observer in the multiverse finding the particular fundamental parameters that we do. If they could do so successfully, they might be able to use multiverse mathematics to make testable predictions about the masses of as yet undiscovered particles, say.

The puzzle goes by the somewhat mundane name of the "measure problem": If you have an infinite number of universes propagating forever, anything that can happen will happen over and over again. Consider, for example, that it is possible to count to infinity in either odd (1, 3, 5…) or even numbers (2, 4, 6…). Both lists will go on forever, without end. But what if you take three odd numbers (1, 3, 5; 7, 9, 11; 13, 15, 17…) for every even number (2; 4; 6…) and create another two lists? Once again, you get two infinite sets—even though the odd pile should be larger. The same difficulty arises when cosmologists try to work out which infinitely large subset of cosmoses is more likely to occur than another infinitely large set, in the multiverse. How do you get numbers that make sense?

Figure 11: Are we Boltzmann brains? (Image credit: Johan Swanepoel @Shutterstock.)

Over the years cosmologists have come up with a way to tackle this, by counting universes only up to a certain cutoff. Some might choose to only tally up universes created within a certain time—say 200 billion years—and ignore anything that comes after that. But early attempts to use a cutoff hit a bizarre new obstacle. Cosmologists calculated that the chances of human life having evolved in a cosmos such as own were far lower than the odds that a disembodied brain would pop out of the vacuum, complete with false memories of being a human that had evolved in the familiar way (Figure 11). Such entities are called "Boltzmann brains," after 19th-century physicist Ludwig Boltzmann (who first posited them in a different context), and they leave cosmologists with major problems (not least wondering if they themselves are real or Boltzmann brains). Sean Carroll, for instance, has argued that theories that predict that Boltzmann brains should dominate observations "are cognitively unstable: they cannot simultaneously be true and justifiably believed" (Carroll, 2017).

Cosmologists have since developed alternative ways to cut off their universe count and have shown that some do not raise such issues (Vilenkin and Yamada, 2020). There is still no fundamental reason why one cutoff should be preferred over another; although it has been argued that choosing to count within a restricted volume is a 'natural' choice, and successfully avoids Boltzmann brains (Sloan and Silk, 2016).

III. ALTERNATIVE EXPLANATIONS FOR FINE TUNING

1. Cyclic Universes

The idea that the universe is cyclic is ancient. Hindu texts describe time as infinite, while our current universe was preceded by others and will be followed by endless more. Within physics, in the 1920s, Albert Einstein briefly considered the possibility of an everlasting cyclic universe. His own equations of gravity, derived from his general theory of relativity, were hinting that the universe may be expanding and may have had a finite beginning in the past—a notion he found abhorrent. Cyclic universes provided a more philosophically palatable alternative. However, astronomical observations later confirmed that the universe is expanding, forcing Einstein to accept it, despite his discomfort. (JTF's Cosmological Origins review has more on the history of the development of the Big-Bang model.)

Cyclic models had a resurgence in the early 2000s, however, when Steinhardt and Neil Turok proposed that the universe cycles through an expansive phase, then a contracting phase, crunching back down again, before bouncing out and birthing a new universe. This model uses aspects of string theory. Each cycle, lasting about a trillion years, is said to be akin to a different universe with different physical constants—exploring a new part of the string theory landscape (Steinhardt and Turok, 2006).

The major advantage of this model was its explanatory power when it comes to fine tuning. Take the surprisingly small value of dark energy: According to the cyclic model, the universe could indeed have had a large value for the cosmological constant—10^{120} times the value observed today, just as predicted by particle-physics calculations (see Chapter 2). But with each successive cycle, the value would shrink. Each iteration of the universe would also last longer than the previous. That would mean that the universe would spend most of its time with a low value of the cosmological constant, exactly as seen today. This approach is controversial, however, and there is some debate over whether it has been ruled out (Planck Collaboration et al., 2014b) by observations of the relic radiation of the Big Bang, the CMB, made by the European Space Agency's Planck satellite, or remains viable (Ijjas and Steinhardt, 2016).

Other cyclic universe models have also been put forward: According to "conformal cyclic cosmology," proposed by Roger Penrose, for instance, each universe expands to the point that all the matter in it decays by being converted into light, at which point there is no sense of scale or time in the universe, echoing the conditions of the Big Bang and allowing a new "Big Bang" to occur (Penrose, 2006). Penrose has argued that unexpected hot spots in the CMB temperature map provide observational support for his model (Penrose et al., 2018); however, others have countered that they are more likely to be a statistical fluke (Cartlidge, 2018).

2. Top-down Cosmologies

Another alternative to the multiverse theory was put forward in 2006 by Stephen Hawking and Thomas Hertog. It is radical because it turns the way physicists usually think about the universe on its head. Most cosmological models start with the initial conditions that they deduce existed at the time of the Big Bang and then consider how today's universe evolved from them. Hawking and Hertog instead started from the conditions we see now and worked backwards rather than forwards (Hawking and Hertog, 2006).

Extrapolating backwards in time sounds straightforward enough, but Hawking and Hertog added a quantum twist. Quantum mechanics, the theory that governs the behavior of very small systems, has a number of peculiar features. One such feature is 'superposition': until a quantum object is measured, it is said to be in a weird state in which it can take on multiple contradictory values at the same time. A particle can be in two places at once, say, or have different energy values. Only when its properties are measured, does it snap into one set identity, at random. (See Chapter 3 of JTF's Time review for a longer discussion of superposition and quantum theory.)

This also implies that each particle has a vast number of different co-existing histories. One way of thinking about measurement is that we see a blend of the histories that lead to the result, though not all will contribute equally. Take, for example, a photon, or particle of light, reaching your eye from your laptop screen. We would expect it to take the shortest route, but according to quantum mechanics it may also take a detour to Saturn and back before reaching you. This more bizarre trajectory does not contribute very much to physicists' calculations of the photon's route, but it remains a possibility.

However, Hawking and Hertog took that idea a step further, arguing that this notion of multiple histories is just as true for the universe as it is for a photon. In their model, at the time of the Big Bang, the universe was in a superposition of all the 10^{500} possible worlds that string theory predicts could exist. But because we are viewing the universe at a certain time—at a point where there are necessarily stars and galaxies and people—when we make observations of the past, we select out the possible history that would have led to our evolution, along with its favorable initial conditions and parameters that are conducive to human life. Hawking and Hertog were optimistic that observations of the CMB might contain signatures that supported their theory, but these have not been forthcoming.

3. Was Our Universe Created?

Multiverse theory can help explain away fine tuning. But a possible alternative is that the universe was designed by an external creator. As mentioned at the start of this chapter, some apparent mysteries of modern physics have ignited popular debates that pit God against the multiverse. For example, John Polkinghorne—who was both a physicist and an Anglican priest—argued that the fine-tuning argument puts the question of God on the agenda, saying: "I myself find the creation view of the universe a more economic and persuasive and attractive explanation of fine tuning than the multiverse idea would be" (Polkinghorne, 2010).

As noted, since the concept of a supernatural creator is not testable, it lies beyond the scope of this review. But what about designers who aren't supernatural? Might our universe have been created by an advanced civilization in another universe?

(i) Creating Baby Universes in the Lab

Soon after inflation was proposed, Guth and his colleagues realized that it may be physically possible—albeit unfeasible with current technologies—to trigger inflation in a particle accelerator, creating a brand new baby universe, within our own. Since then others have proposed blueprints for how to make a universe in the lab (Ansoldi, Merali, and Guendelman, 2018). To the outside world the baby universe would look like a mini black hole, lying in the debris of a typical particle collision. But within, inflation would create an astronomical-scale cosmos—divorced from our spacetime—potentially with its own stars, galaxies, planets, and people.

Linde has investigated whether it might be possible to fine tune the conditions of such a universe from the outside, but has concluded it would be too difficult given our current understanding of physics (Merali, 2017). Anthony Zee and Stephen Hsu have also pondered whether it might be possible to find evidence in the CMB that our own universe was created in such a manner, by an advanced alien civilization (Hsu and Zee, 2006)—but such searches have thus far proven fruitless (Hippke, 2020).

(ii) Do We Live in a Simulation?

Another possibility is that our universe may just be a computer simulation created by an advanced alien species. It has in fact been argued that we are more likely to be simulated beings than real biological ones. This is because if one biologically evolved species anywhere in the universe reaches a level of technical advancement such that they could simulate a bio-friendly universe with sentient beings, then such simulations would proliferate, vastly outnumbering traditional biological universes (Bostrom, 2003).

The idea that we are all just living in The Matrix—perhaps created as entertainment for some bored aliens—is rather depressing. But physicists have suggested ways to test this hypothesis, noting that the resources needed to create an absolutely perfect simulation would be too great to be feasible. So, any real simulation would likely be flawed. John Barrow argued that the simulation would build up minor computational errors, which would gradually accumulate and threaten the simulation, unless the alien programmer intervened to fix the bug (Barrow, 2007). We might experience this intervention as a sudden, mysterious and contradictory experimental result. For example, we may find the constants of nature changing with time. In Chapter 4, we will discuss contentious research, based on quasar spectra, that suggests that the fine-structure constant may be slowly varying over time and space.

It certainly is a possibility that our universe was created in some way. But one scientific argument against this idea is that our universe isn't actually optimally viable for life. As we shall see in Chapter 5, some physicists have proposed alternative "universe designs" that would be much more bio-friendly than ours.

And as intriguing as all the alternative cosmologies noted in this section are, none are anywhere close to being as widely accepted as explanations for the fine-tuning problem as the multiverse—built as it is on the fairly solid foundation of inflation theory, which has moved into cosmology textbooks. Still, by far the biggest problem for proponents is that by definition, we can never see into or enter another universe. So in the next chapter, we will describe proposals to find direct and indirect evidence for the inflationary multiverse and the theories that support it. But we shall begin the chapter by describing experimental tests to probe whether the fundamental constants of nature—that appear to be fine-tuned to a particular value that is conducive to life—are really constant, at all.

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4. TESTING EXPLANATIONS FOR FINE TUNING

The first three chapters have mainly focused on theory. In Chapters 1 and 2, theoretical advances allowed us to calculate just how precisely fixed certain physical parameters had to be to enable life to evolve. Chapter 3, meanwhile, introduced some speculative frameworks that have been invoked as part of a scientific explanation for fine tuning, including string theory and ideas about the multiverse. It is thus natural to ask whether there are experiments, observations, or measurements that we could do to establish whether the universe actually is fine tuned for life. And are there tests currently underway, or proposed for the near future, that could confirm, or at least support, string theory or the multiverse view? Such experiments are the focus of this chapter.

I. INCONSTANT 'CONSTANTS'?

1. Does the Fine-Structure Constant Vary Over Time and/or Space?

One obvious way to deflate the fine-tuning argument would be to prove that the physical constants we talked about in Chapter 1, such as the fine-structure constant and the gravitational constant, are not actually constant, at all. If they were found to vary significantly, perhaps over the aeons, there would not be quite such a pressing need to explain why, at some point, they hit a value that is conducive to the development of intelligent life. As described in the first chapter, Paul Dirac suggested that the gravitational constant may indeed vary over time, in 1938. Since then scientists have been on the hunt for evidence to settle whether or not it does, but these efforts have been hampered by the fact that it is extremely difficult to accurately measure the constant because gravity is so weak (Li et al., 2018). A more promising avenue is the ongoing program testing if the fine-structure constant, introduced in Chapter 2.II.2, changes gradually over time. In both cases, however, there have been conflicting results, in part because these entities are extremely difficult to measure accurately.

Physicists have attempted to measure a potential change in the fine-structure constant, α, over the age of the universe, by looking at how light waves from distant luminous galaxy cores, or 'quasars,' are absorbed as they travel to Earth. This strategy is based on the 19th-century discovery that specific atoms and molecules will emit or absorb light only at certain characteristic wavelengths, called "lines" (Figure 12), and these lines can in turn be used to identify the molecules and atoms in the light source. JTF's Cosmological Origins review has a detailed discussion of this technique, which is called 'spectroscopy,' and is usually used to identify elements in distant stars and help astronomers calculate how far away those cosmic objects are (see Chapter 2 of the Cosmological Origins review).

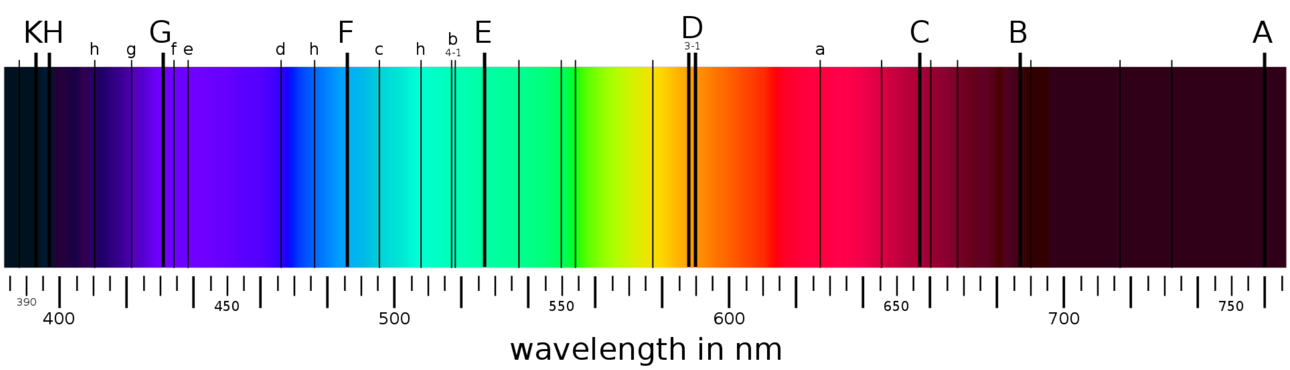

Figure 12: Fraunhofer lines from the sun.

Recall that α represents the strength of the electromagnetic force between two elementary particles. This means that if α changes over time, then it will change how tightly an atom is bound together, which in turn, will affect the look of absorption spectra associated with each element. So, to find out if α has changed over a long period of time, astronomers have compared spectra taken using the Very Large Telescope, in Chile, from distant quasars lying roughly 12 billion light years away—which means that the light we now see from them was emitted 12 billion years ago—with "modern" spectra from light in the lab. A team led by John Webb claimed to have found evidence in the late 1990s that the value of α has indeed drifted (Webb et al., 1999; Webb et al., 2011)—so slightly that it would not have significantly affected the laws of physics over the past 12 billion years. Such results have large margins of error though, and have been called into question by more recent studies (Whitmore and Murphy, 2014).

But one of the latest follow-up studies by Webb and others, published in 2020 and using cutting-edge instrumentation, does support another tantalizing possibility (Wilczynska et al., 2020). The collaboration performed the first analysis of α using four new direct measurements of a distant quasar made with a near-infra-red spectrograph and employing a new artificial-intelligence algorithm. They compared new data with those taken over the years by other groups, creating a sample of 323 measurements, spanning a few billion years in the past to 12 billion years in the past (Webb et al., 2011; Martins and Pinho, 2017; Dumont and Webb, 2017). While they concluded that there appears to be no temporal drift in α, their finding fits with a previous assertion that the constant may change slightly across space; in particular it may be slightly different along a certain axis of the universe.

The hints that α may vary are far from definitive, however; so astronomers are keen for more precise data to arrive. ESPRESSO—the Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations—has been installed at the Very Large Telescope, and is now online and could provide fresh answers. Its scientific mission includes measuring the variation in α and the proton-to-electron mass ratio. The new instrumentation is expected to provide an increase in the accuracy of the measurement of these two constants by at least an order of magnitude compared to the Very Large Telescope.

2. Is Dark Energy Constant?

As described in Chapter 2.III.1, astronomers do not yet know the nature of dark energy—the entity that appears to be causing the expansion of the universe to accelerate. One of the most popular possibilities is that dark energy is a kind of energy inherent in the vacuum of empty space—a cosmological constant—that takes the same value throughout the universe and over all time. However, particle-physics calculations suggest that such a vacuum energy should be astronomically larger than its measured value—so large that matter would be quickly diluted as the universe expanded at an alarming rate, before matter could clump together to form galaxies. By contrast, the measured value is small enough to have allowed large-scale structure, and ultimately intelligent life, to have formed in the universe.

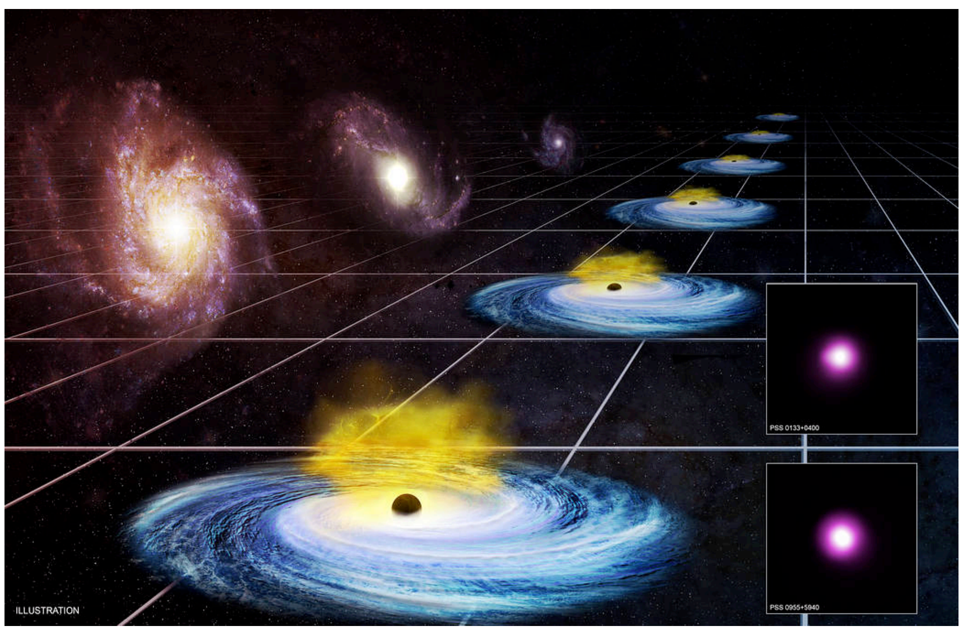

Figure 13: Artist's conception of dark energy changing over the aeons. (Image credit: NASA/CXC/Univ. of Florence/G. Risaliti & E. Lusso.)

There are other theoretical proposals for the origin of dark energy, however. (See JTF's Cosmological Origins review for a brief summary of alternative ideas.) Most interestingly for the purposes of this review, there have also been intriguing hints from observations that dark energy varied across cosmic time. In 2019, a study using data from NASA's Chandra X-Ray Observatory and ESA's XMM-Newton used a new method to determine distances to about 1,600 distant quasars, from ultraviolet and X-ray data, allowing astronomers to track dark energy's effects from the early universe through to the present day. They concluded that the amount of dark energy is growing with time (Figure 13) (Risalti and Lusso, 2019). Should this result be independently confirmed by future experiments, it would not only have implications for the question of whether dark energy's value is finely tuned for life, but it would force cosmologists to reassess the standard model of cosmology.

There are many experiments under way to map the universe and the dark energy that is driving its expansion. These include Euclid, ESA's near-infrared space telescope currently due to launch in the latter half of 2022; the Square Kilometre Array, an intergovernmental radio telescope project planned to be built this decade in Australia and South Africa, and the Vera C. Rubin Observatory (previously known as the Large Synoptic Survey Telescope), under construction in Chile, which is due to be operational in 2022. Perhaps the most exciting, however, is the Dark Energy Spectroscopic Instrument (DESI), installed on the Mayall Telescope in Arizona, US, which achieved first light in 2019. DESI represents a huge leap forward in our capability to measure galaxy distances and map the structure of the universe, and physicists are confident that it will reveal whether dark energy really is just a cosmological constant. It will aim to do so by measuring the ratio of pressure that dark energy exerts to the energy per unit volume. If this ratio is unchanging across both cosmic time and location, it is likely that dark energy really is a cosmological constant—and the question of why it has such a conveniently tiny value remains. But if it is found to vary significantly over time and space, this would weaken fine-tuning arguments based on its current small value.

Thus it may turn out that within the next decade, physicists will have experimental evidence proving that one or more of the fundamental 'constants' of nature are not constant, at all, undermining some of the best examples invoked

Does Dark Energy Need to Be Small?

The serendipitously tiny value of dark energy has been touted as one of the best pieces of indirect evidence for a multiverse and the anthropic principle. If dark energy's mass density had been just 10 times larger than its measured value, the argument goes, galaxies would not have been able to form (Davies, 2006). However, if a multiverse exists with numerous universes taking on a range of values for the dark energy (up to the humungous value predicted by particle physics), then it is natural that some should contain values small enough to lead to life.

But how certain are we that galaxies could not have formed if dark energy had been significantly larger? Astronomers working on the Evolution and Assembly of GaLaxies and their Environments (EAGLE) project are running computer simulations to model some 10,000 galaxies—under different initial parameters and conditions—and then comparing the results with real astronomical observations (Figure 14). Their results may pose trouble for fine-tuning arguments. By monitoring how galaxies develop and evolve for different theoretical values of dark energy, they discovered surprisingly that dark energy could be a hundred times larger, or much, much smaller, and still allow stars and planets to form (Salcido et al., 2018; Barnes et al., 2018). Better insights into galaxy formation may, however, challenge these findings.

Chapter 5 further investigates whether significantly varying other fundamental parameters might not be as devastating for the evolution of life as assumed.

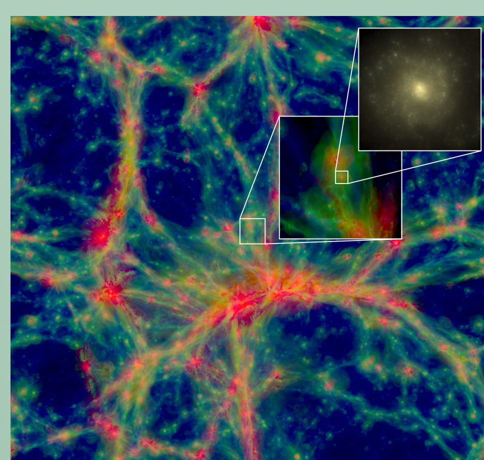

Figure 14: The EAGLE simulation models physics with almost 7 billion particles. (Image credit: Eagle/Virgo Consortium.)

in support of fine-tuning arguments. Or, such constants may prove to be steadfast. Regardless, physicists still hope to find unambiguous experimental evidence of new physics—the existence of new particles and possibly even a "fifth force" of nature—that moves us beyond the Standard Model of Particle Physics. This could lead to the discovery of a new framework that itself provides a fundamental physical explanation for the peculiarly serendipitous values of certain parameters such as the particle masses, as described in the next section. Such new physics might thus alleviate the need to invoke anthropic arguments, and the multiverse, to explain why these parameters take the values that they do.

II. BEYOND THE STANDARD MODEL

Numerous experiments are searching for signs of physics—new particles and/or forces—that are not contained within the Standard Model of Particle Physics. Some may provide a boost to string theory, as described in section 4 below, and with it—indirectly—the string landscape, the multiverse, and anthropic explanations of fine tuning. But others may point the way to a different fundamental theory of reality—one that might fully explain the origin of the convenient values taken by many physical parameters. As described below, a handful of experiments are already showing hints of new physics.

1. The Muon *g*-2 Experiment

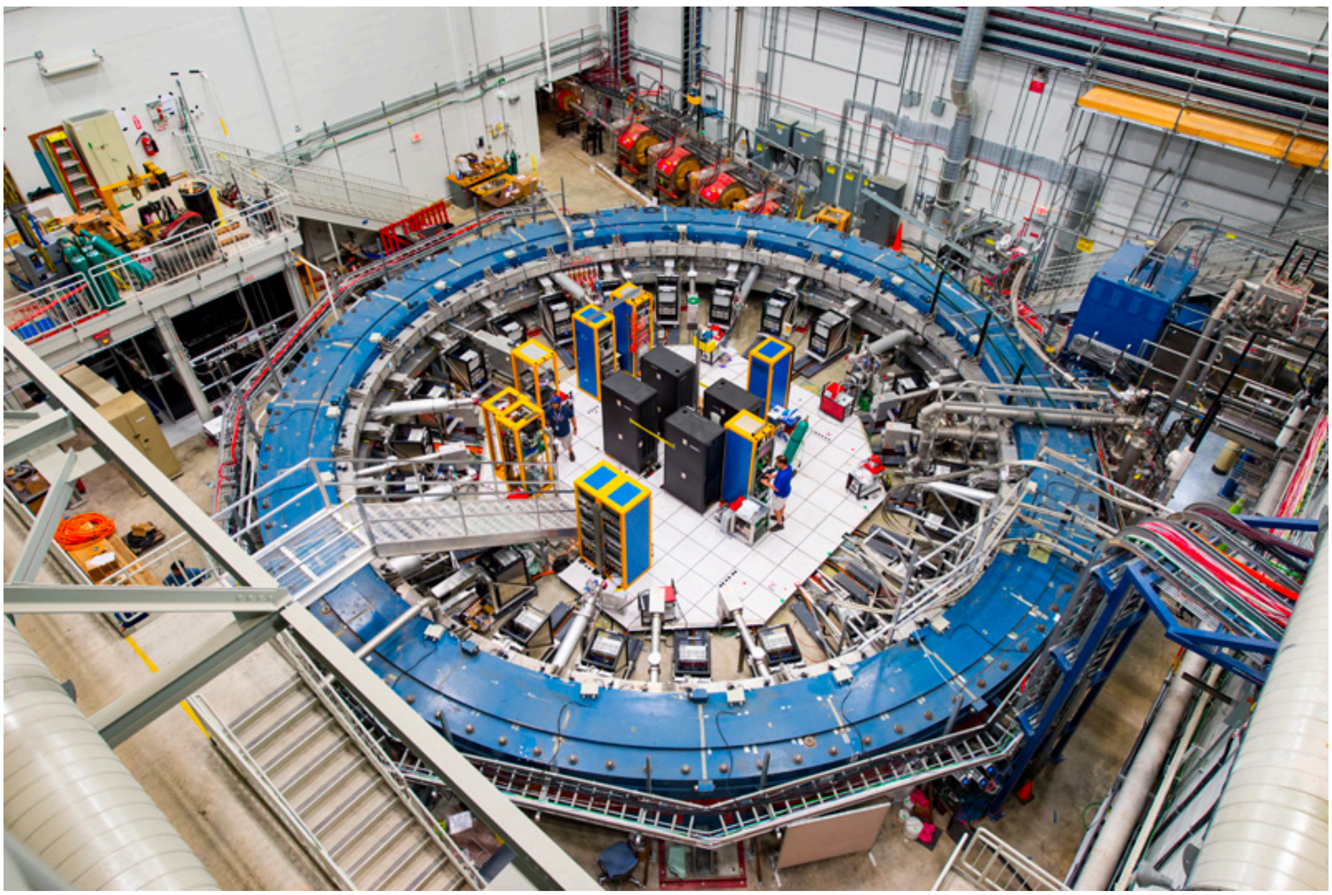

Figure 15: The *g*-2 storage ring magnet at Fermilab. (Image credit Reider Hahn, shared under a creative commons license CC BY-SA 4.0.)

In 2001, physicists at the Brookhaven National Laboratory in Upton, New York, measuring the magnetic properties of the muon—a cousin of the electron—noted a peculiarity. They were investigating the muon's magnetic moment, a property that makes the elementary particle act like a tiny bar magnet, and found that it was slightly bigger than the value expected using calculations based on the Standard Model of Particle Physics (Bennett et al., 2006). The calculation is based on the notion that, according to quantum mechanics, 'virtual' pairs of known particles can briefly pop out of the vacuum before annihilating each other and vanishing. This virtual swarm can influence the magnetic moment of elementary particles such as the muon. Thus, the discrepancy in the measured value of the muon's magnetic moment, and its predicted value, served as a tantalizing hint that there may be other types of virtual particles manifesting from the vacuum.

To corroborate this finding, physicists at Fermilab, in Batavia, Illinois, rebuilt the original experiment, which involved sending muons whizzing around a 15-m diameter superconducting ring and measuring with precise accuracy how the muons wobble in the magnetic field (Figure 15). In 2021, the team reported even stronger evidence that the muon's magnetic moment defies the predictions of the Standard Model (Abi, B. et al., 2021); however, the strength of the evidence lies just shy of the level needed to rule out that the result is a statistical fluke and claim an unambiguous discovery. The team is now collecting and analyzing more data in an effort to improve the precision of the result.

If the result stands up, it will indicate that new particles—potentially associated with a new fifth force of nature—exist. Such a rewrite of standard physics may have a bearing on our fundamental understanding of the apparently fine-tuned parameters associated with our known particles and forces. This possibility has also been hinted at by other experiments looking at particle decays from the Large Hadron Collider, near Geneva, Switzerland, as described in the next section.

2. B Meson Decay

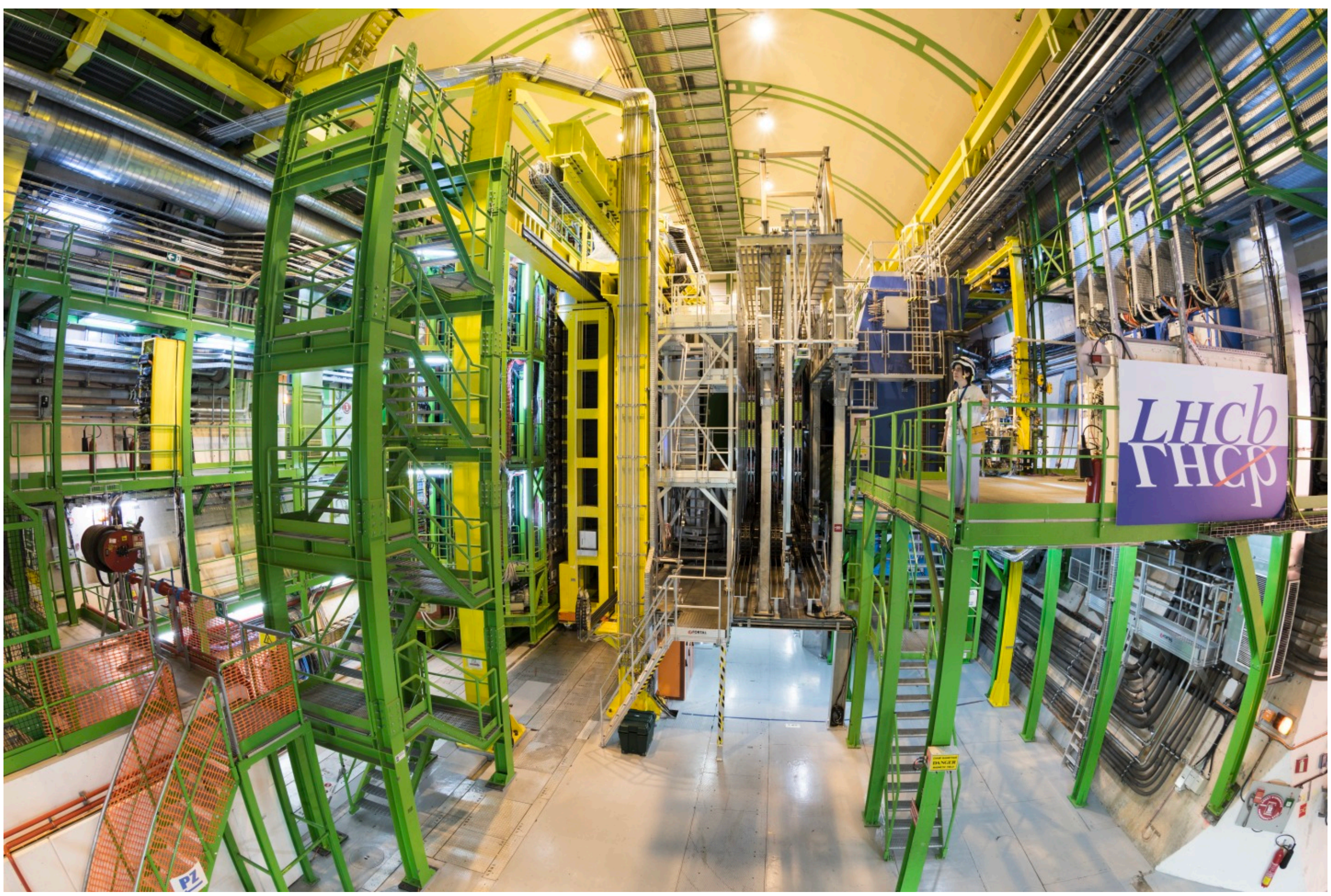

Figure 16: The LHCb experiment at CERN. (Image credit: CERN.)

B mesons are unstable particles made of b quarks (sometimes called 'bottom' or 'beauty' quarks) that are briefly created at the LHCb experiment at CERN, before decaying into products containing either electrons or alternatively muons (Figure 16). The Standard Model predicts that these two decay pathways should occur at the same rate. However, in 2021, LHCb physicists announced that electrons were more likely to be produced in these decays than muons, violating Standard Model predictions (Petridis & Santimaria, 2021). Again, the strength of the evidence does not quite meet the threshold required to claim a definitive discovery, yet. However, physicists have postulated that the discrepancy may be due to the existence of new particles called 'Z primes' or 'leptoquarks' which may be associated with new forces.

3. GUTS and Proton Decay

Even if there is no new fifth force to reckon with, ultimately physicists agree that we need to nail down the high-energy physics at times approaching the Big Bang to better assess if parameters are truly fine tuned for life. As mentioned in Chapter 3, many physicists believe that at this early stage of the universe, the fundamental forces of electromagnetism, the weak force, and the strong force, were merged together into a single force—according to some grand unification theory, or GUT (see Figure 10). GUTs indicate that the universe started out with simpler laws of physics, when the ultra-hot cosmos was only about a trillionth of a second old. As it cooled, it went through a period of "symmetry breaking" in which this underlying force was broken down into the different components we see today. This suggests the possibility that the characteristics of the forces might have been different, had the symmetry broken in a different way, at random. Proponents of the multiverse and anthropic arguments might argue that forces with different relative strengths could thus have been realized in different pockets of the multiverse, where this process played out differently.

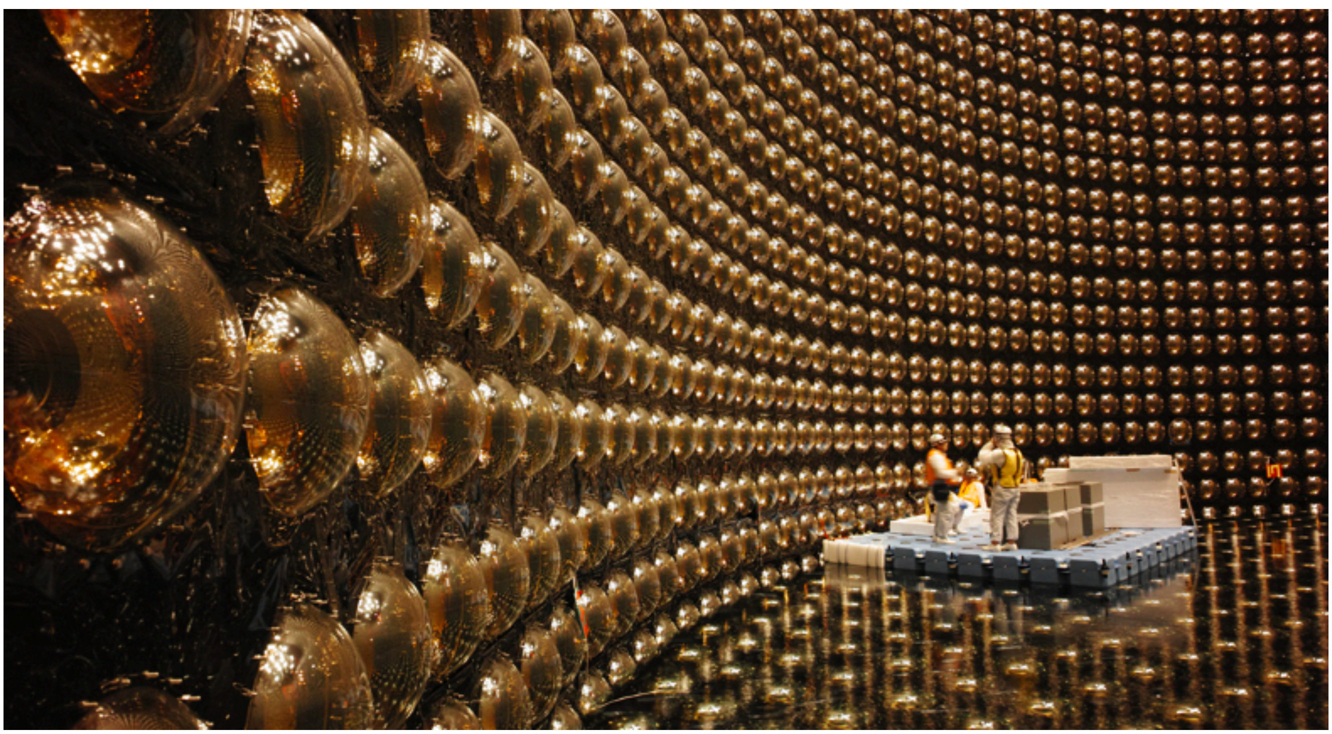

Figure 17: Engineers upgrading the world's largest neutrino detector, Super-Kamiokande. (Image credit: Super-Kamiokande.)

While particle-collider experiments have confirmed that the electromagnetic interaction and weak interaction are unified at high energies (Hasert et al., 1973; UA1 Collaboration, 1983; UA2 Collaboration, 1983), directly testing whether the strong force joins them at even higher energies lies beyond the scope of current particle accelerators, and likely future ones too (Davies, 2006). GUTs do make one striking prediction that lies within experimental grasp, however. In contrast to the predictions of the Standard Model of Particle Physics, some GUTs state that a rare form of decay exists in which protons break down into lighter particles (such as a positron and pion). The underground Super-Kamiokande Neutrino Detection Experiment in Japan is best placed to be able to observe such a decay (Figure 17). It houses a tank of 50,000 tons of pure water, containing 7×10^{33} protons, which is monitored for signs of decay. It began measurements in 1996, but as yet has seen no sign of decay, implying that the lifetime of the proton is longer than 1.67×10^{34} years via positron decay (Bajc et al., 2016), and longer than 1.08×10^{34} years via antimuon decay (Nishino et al., 2009). It will be superseded by the Hyper-Kamiokande experiment, due to be operational in 2027, which should be five to 10 times more sensitive to proton decay than its predecessor. It is no understatement to say that evidence of proton decay would revolutionize physics.

4. String Theory and a Theory of Everything

A unifying framework that comprises all four fundamental forces, including gravity, is referred to as a "Theory of Everything." As described in the previous chapter, our best bet for such a theory remains string theory, which likely brings with it a plethora of tiny hidden extra dimensions and a whole string landscape—allowing for the universe to have been populated by nigh on infinite variations in its physical parameters and forces. These different possible characteristics are realized because the extra dimensions may curl up in a near infinite number of different ways (see Figure 9).

It is undeniable that directly testing string theory is a tough prospect—an issue that has led to many much publicized criticisms of the theory. Even proposed future generations of particle accelerators have little hope of reaching the immense energy scale at which all four forces unite. And strings themselves are believed to be so minuscule that we would never be able to see them—or probe their behavior—with our best instruments. That said, particle physicists have long sought evidence of exotic particles and entities at high-energy colliders that are predicted to exist by some string-theory models.

For instance, as discussed in Chapter 3, string theory is itself built on an elegant theorized extension to the Standard Model of Particle Physics called supersymmetry (SUSY), which does make testable predictions, positing the existence of a host of new superpartner particles for the known particles. These particles have so far not been seen, however. It may also be possible to infer the existence of extra dimensions predicted by string theory from the noticeable absence of certain hypothesized particles. For instance, it has been posited that gravity may be mediated by a particle called a "graviton," just as electromagnetism is mediated by photons, the weak force by W and Z particles, and the strong force by gluons. One possibility is that if gravitons are produced in collisions at the LHC, they might rapidly sneak into an extra dimension before they can be spotted. However, physicists would be able to calculate that the particle had been produced, and was now hidden, by looking at the imbalance in the momentum and energy of the remaining detectable products of the collision.

Experimental evidence for string theory would also lend indirect weight to the multiverse solution to the fine-tuning puzzle, as the inflationary multiverse is partnered with the string landscape in anthropic arguments.

Next-Generation Particle Accelerators

CERN physicists have developed a plan for a Future Circular Collider that would dwarf the LHC and could potentially reach collision energies of 100 Tera electron volts (TeV)—compared with 14 TeV for the LHC (Figure 18). (eV stands for electron volts and is a measure of energy, in atoms.) If this project receives the green light, it would be able to probe the conditions that existed a trillionth of a second after the Big Bang —a moment when an all-pervading energy field known as the Higgs field collapsed into its current state, generating the masses of the fundamental particles. Understanding this process in detail could help explain whether the parameters of these particles really are fine tuned, or are the natural result of the mass-generating mechanism (Cliff, 2019).

China is also considering building a Circular Electron Positron Collider, with a circumference of 80 kilometers (large enough to encircle Manhattan), while an International Linear Collider may be built in Japan, to further probe extensions to the Standard Model.

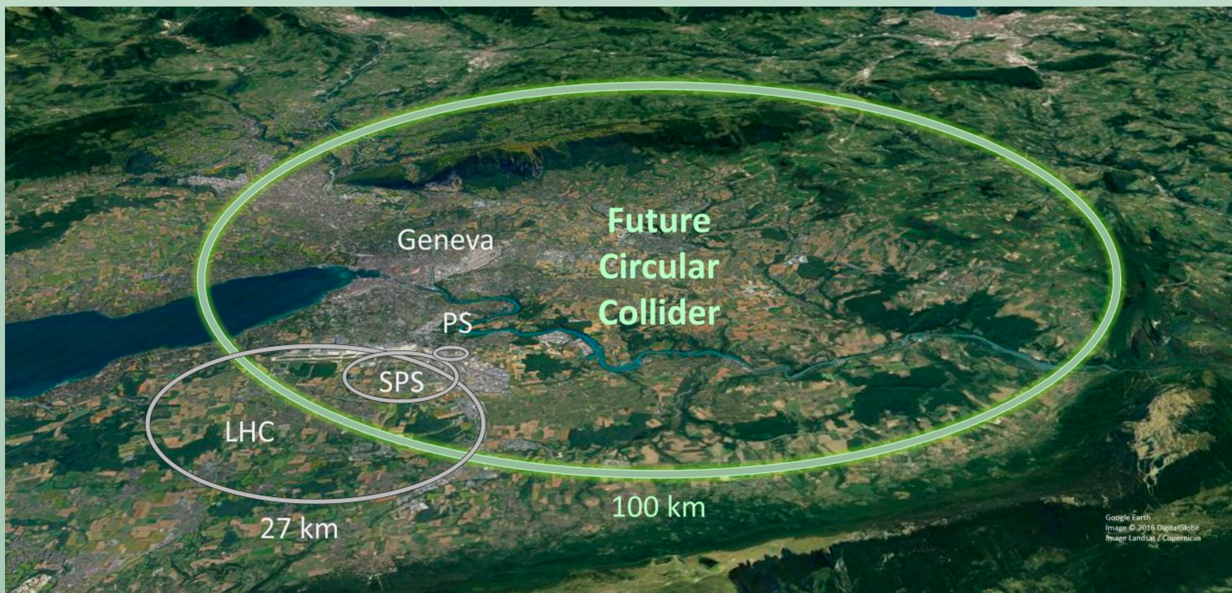

Figure 18: A schematic map showing a possible location for the Future Circular Collider. (Image credit: CERN.)

III. THE HUNT FOR OTHER UNIVERSES

1. Colliding Cosmoses

As described above, experimental evidence of string theory would lend credence to the proposition that the multiverse fixes the fine-tuning problem. Similarly, the multiverse curries favor among many cosmologists because it is derived from inflation theory, a framework that does have substantial observational support. But some cosmologists are exploring more direct ways to test the multiverse. They have speculated that if neighboring universes exist they could, on rare occasion, leave detectable signatures on the cosmic microwave background (CMB)—the radiation left over from the birth of the universe—if they collided with our cosmos soon after its birth (Aguirre et al., 2007).

In Chapter 3, we saw that the CMB's temperature map is extremely smooth, with an almost identical temperature everywhere, deviating for the most part at a level of less than one part in 10,000. Any unusually large anomalous areas may therefore, in theory, represent a bruise from a past collision with a parallel universe, and cosmologists have developed various algorithms to comb the CMB data for such anomalies. An initial examination of the CMB for collision scars in 2011 proved fruitless (Feeney et al., 2011). In 2004, a large cold spot was found in CMB data recorded by NASA's WMAP satellite, which was later confirmed by more detailed measurements by ESA's Planck Satellite (Cruz et al., 2005). The spot is an area of the sky that is about five degrees across and colder than the rest by one part in 18,000. While the variation in temperature isn't unusual, the fact that it spans over five degrees is odd. In 2015, a study suggested it could simply be a "supervoid" in which the density of galaxies is much lower than it is in the rest of the universe (Szapudi et al., 2015), but this has been disputed (Mackenzie et al., 2017), re-opening the possibility that it could be a collision scar. Detailed studies looking for more involved signatures, and ways to definitively identify them, continue (Johnson et al., 2016).

2. Parallel Universes Hidden Inside Black Holes

It has also been suggested that inflation could have birthed baby universes that are today hidden within black holes detectable from Earth (Garriga, Vilenkin, and Zhang, 2016). This notion provides a new mechanism for black-hole creation in our universe—and potentially a way to directly confirm the existence of a multiverse. There are two types of black holes that astronomers are aware of: stellar-mass black holes that form from the collapse of stars and supermassive black holes often found at the center of galaxies. The latter type of hole can have a mass billions of times that of the sun, and astrophysicists are not clear on how they form.

The proposal is that such supermassive black holes could have been formed by inflation, and now house parallel universes, separated from us by wormholes. The idea is that our young universe may have contained little bubbles of vacuum. When our cosmos started inflating, these bubbles also grew. When inflation ended, these bubbles would have collapsed into black holes. Those below some critical mass would hold a singularity at their core, but those formed from bubbles above a critical mass could continue inflating internally. From our perspective, the black hole would appear largely unchanged, but within, it could grow an entire universe—one that could itself give rise to other new universes, hidden inside black holes. The internal universe would be connected to ours via a wormhole.

This is not the first time that physicists have suggested that cosmic black holes may harbor new universes (Smolin, 1997; Gambini and Pullin, 2013), although it is the first study to propose this within an inflationary framework. And intriguingly, the authors outlined possible signatures that might enable astronomers to detect the presence of these hidden cosmoses, by analyzing gamma rays emanating from the black holes, looking for distortions induced on the CMB spectrum, or by examining the mass distribution of black holes in our sky.

As speculative as both the colliding-universe and black-hole-cosmos scenarios are, it is worth noting that the mere fact that astronomers can search for such evidence of their existence runs counter to the common criticism leveled at multiverse theory that it cannot be tested, even in principle.

Regardless of its testability, the multiverse currently stands as the most popular scientific explanation of fine tuning. In the next chapter, however, we will turn to studies that question whether any scientific explanation is needed at all, or whether the fine-tuning problem is a fantasy.

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5. IS FINE TUNING AN ILLUSION?

In the 18th century, astronomer Johann Bode came up with a formula to explain the specific orbits of the (then known) six planets, including an unknown body that later was discovered to be in the asteroid belt (Matthews, 1994). Bode's mathematics explained why these bodies would be found at the particular distances they are from the sun. But since then, astronomers have learned that the planets have not always had those orbits—cosmic collisions and mergers along the way have changed the course of planetary motions. So, there is no fundamental formula or law that is needed to determine the specific details of their orbits—while the law of gravity controls the shape of the orbits, the particulars are partly down to chance. Paul Davies has used this historical example to illustrate how scientists can sometimes search too hard for explanations for the precise values of the parameters we measure in the universe when, in reality, these may just be accidental (Davies, 2006).

In a similar vein, many physicists are skeptical that our universe is fine tuned for life, with some arguing that any apparent fine tuning is an illusion. As discussed in Chapter 4, Sabine Hossenfelder has for instance argued that in the absence of a probability distribution for the possible values of parameters that could occur, it's impossible to argue with conviction that our measured values are actually odd or "lucky." Another major issue is that a lot of the evidence supporting the idea that our universe is fine tuned for life is largely based on investigating how changes to the parameters of the universe would, in theory, affect the evolution of a bio-friendly cosmos like our own. But we cannot rule out the possibility that some kind of life could arise even in a universe with completely different properties, as we will discuss in section I below. We will then turn to another criticism that has been leveled at fine-tuning arguments: Such analyses usually only consider what would happen if one parameter is changed at a time, holding all other parameters fixed. In section II, we shall see that in some cases, if you allow many parameters to vary simultaneously, you can alleviate the apparent fine-tuning problems.

This suggests that the universe may not be so finely tuned after all—it may be able to produce life under a wider range of circumstances than first thought. In fact, as discussed in section III, our universe may not even be maximally optimal for life; there could feasibly be universes with different physical characteristics that would be more bio-friendly than ours.

I. ALTERNATIVE VIABLE UNIVERSES

In Chapter 2, we described how precise conditions have to be to enable carbon-formation in stars. Such arguments have been used to support the notion that the universe is finely tuned for life. But Fred Adams has argued that even if cosmic parameters were modified in such a way that stars could not make carbon, they would still synthesize heavier elements—with a likely abundance of silicon, which is chemically similar to carbon and thus could form an alternative backbone for life (Adams, 2019). Silicon-based life may sound like fodder for science fiction, but one recent study has shown that bacteria can be manipulated to make silicon-carbon bonds (Kan et al., 2016).

In an extensive review, Adams has examined specific 'finely-tuned' parameters and argued that they could be shifted within a perhaps wider range than has been assumed and still give rise to viable universes (Table 2). The numbers listed in the "range" column of Table 2 may not give an immediately intuitive indication of just how much each of these constants can be varied, without impeding the evolution of life. Adams has however found a clever way to illustrate this. He compares the tuning required for these constants to the tuning needed to capture a radio station. Adams has noted that the FM radio band, for example, ranges from 88 to 108 MHz, with stations 200 kHz apart. Thus finding a station requires tuning the frequency to 1 part in 500. By contrast the parameters listed in Table 2 require far less tuning to enable life to evolve.

Table 2: Ranges of Parameters for Viable Universes. The results are expressed in decades, and calculated by taking Log_{10} (*Xmax*/*Xmin*), where *Xmax* is the maximum value a parameter could take while still being compatible with a habitable universe. *Xmin* is the minimum such value. For ranges marked with an asterisk* (the weak coupling constant and the vacuum energy scale) the quoted range only applies to values above that measured in our universe; any values below that measured in our universe are allowed, without limitation (Adams, 2019).

Quantity	Observed Value	Range (decades)
Up quark mass	2.3 MeV	> 3
Down quark mass	4.8 MeV	0.85
Electron-proton mass ratio	1/1836	5
Up-down quark mass difference	2.5 MeV	1
Gravitational constant	6×10^{-39}	> 10
Weak coupling constant	10^{-5}	6*
Fine structure constant	1/137	4
Strong coupling constant	15	3
Fluctuation amplitude	10^{-5}	4
Baryon to photon ratio	6×10^{-10}	6
Dark matter abundance	3×10^{-9}	6
Vacuum energy scale	0.0003 eV	10*

In the following sections we shall discuss two examples in depth to illustrate how a viable universe could exist with very different parameters, despite the fact that modifying their values can have a profound effect on processes deemed essential for life to emerge: carbon production and proton binding.

1. The Carbon Resonance Revisited

Carbon is essential for life as we know it. As described in Chapter 2, section II, carbon's existence depends on an apparently "magic" resonance near 7.65 MeV that allows stars to produce carbon from an unstable and short-lived beryllium atom and a helium atom, in the "triple-alpha process" (see Figure 3). If there was no such resonance, the argument goes, we wouldn't be here to produce reviews on fine tuning. The resonance energy depends on a delicate balance between the strong and electromagnetic forces. Previous research has suggested that, if the strong force had been slightly stronger or weaker, perhaps just by one percent, the binding energies of atomic nuclei would change so much that the resonance could not arise (Oberhamer et al., 2000).

Recent studies contradict this, however, arguing that a resonance could still occur if the strong and electromagnetic forces changed, albeit it would occur at a different energy. But what effect would a lower or higher resonance energy have on the production of carbon? Calculations based on models of stellar evolution show that many stars could actually continue to make carbon even if the resonance energy were a few hundred keV higher, although the amount of carbon would decrease. If the energy were lower, many stars would make even more carbon than they do now. There is a trade-off: oxygen production may be suppressed, but oxygen isn't necessarily crucial for life (Uzan, 2020). Multiple independent studies now estimate that the resonance could vary over a total range of 800 keV and still produce a habitable universe (Schlattl et al., 2004; Huang, Adams, and Grohs, 2019; Adams 2019).

It has also been argued that since a shift in the resonance of about 100 keV would correspond to a 0.5% change in the strong force or a two to four percent change in the electromagnetic force, a universe could produce carbon even if its strong and electromagnetic forces were significantly different to what we see today (Epelbaum et al., 2013; Adams, 2019). Others, however, caution that one should be careful about interpreting results that are based on modifying the energy of the resonance alone. That's because a change in the strong force would affect other nuclear parameters too, such as reaction rates and binding energies, making it hard to predict how the stars would respond (Uzan, 2020). But these subtle shifts could themselves help carbon production. For instance, the small variations in the forces that would be required to shift the carbon resonance could simultaneously make the beryllium nucleus stable. If that were the case, the universe could easily produce carbon without the need for any resonance at all.

Even if stars couldn't produce any carbon at all through the triple-alpha process, Adams has calculated there are other feasible pathways for producing carbon. Stars could simply skip carbon and continue to make other heavy elements, for instance, and then some of these, such as oxygen-16, could decay into carbon (Adams, 2019).

2. Bound Protons and Unbound Deuterium

It is often assumed that the universe would not be habitable if protons could bind together or if deuterium (a hydrogen atom with an extra neutron in the nucleus) could not form (see Chapter 2.II.2). This assumption has helped physicists put constraints on particle masses and stellar nuclear chemistry. If the strong force were just two to four percent stronger, protons would bind together (Tegmark, 1998; Carr, 2020). It has been estimated that this would speed up nuclear reactions in stars. This in turn would lead to stars running out of fuel too quickly, dying before life had a chance to develop on surrounding planets. If the strong force were instead five percent weaker, deuterium could not form (Carr, 2020). This would make it hard for stars to produce helium, which is built up from two deuterium atoms. And, in turn, this would obstruct the main route to producing carbon in stars, which involves fusing helium.

Recent research based on calculations of stellar structure and evolution has called this claim into question, however (Adams, 2019). In our universe, the production of elements in a star depends on both the strong and the weak force. When stars make deuterium in the process of making helium, two protons come together and turn into a proton and a neutron—a conversion governed by the weak force, which acts fairly slowly. These can then fuse into helium through an intermediate step. Once there is helium, they can continue to make beryllium, carbon etc, via the triple-alpha process (see Figure 3). In a universe with bound protons, however, the particles would fuse together directly into diprotons through the strong force, which acts much faster. Recent research argues that diprotons do not necessarily scupper deuterium production. Rather deuterium could be created via an alternative route in which a diproton nucleus captures an electron. (This is simply the opposite of the widely understood radioactive process of beta decay, in which a neutron turns into a proton by emitting an electron.) Although protons would couple up very quickly in such a universe, detailed calculations of stellar evolution have shown that they could still produce a significant amount of deuterium, helium etc. These processes could take place for a fairly large range of different values of the strong force and the electromagnetic force.

Importantly, the creation of deuterium from diprotons through the strong force can happen at much lower temperatures than the deuterium-production process in our universe, where the weak force operates. This has led to the concern that such an accelerated production process might lead to stars running out of fuel faster than in our universe—again, potentially inhibiting the evolution of life. But this possibility has been countered by Adams and others. Adams has noted that although deuterium will be produced faster in this alternative cosmos than in our universe, these particles cannot go on to fuse into helium until the stars are much hotter, meaning that more complex elements will not be created any quicker than they are in our universe. Ultimately, this tells us that the star is unlikely to run out of fuel too quickly. In fact, Adams has noted that a universe with bound protons would actually largely create complex elements around low-mass stars with a low temperature—and we know that these stars actually live longer than more massive, hotter stars. Thus the criticism that there would not be time for life to evolve in a universe with bound diprotons does not hold up.

Adams has also identified alternative mechanisms for carbon production, should deuterium not bind successfully. Even in the absence of nuclear reactions within stars, he has argued, stars can generate energy through gravitational contraction—becoming smaller and hotter. In the final stages of their lives, such stars are so extremely hot and dense that they will trigger nuclear fusion and the production of heavy elements. These types of stars could shine for up to a billion years, which would allow life to develop on planets around it (Adams, 2019).

There is also another route to producing carbon in stars that does not involve deuterium at all called the CNO (carbon, nitrogen, oxygen) cycle. In this cycle, four protons fuse together to create a helium nucleus. Helium is in fact already created this way in stars that are larger than our sun (Adams, 2019).

3. A Universe Without the Weak Force

As discussed in Chapter 2.II.6, the weak force, which governs radioactive decay, cannot be too weak. Stars in fact rely on this force to produce energy by fusing protons together to make helium, with deuterium as an intermediate step. But scientists have suggested that a reduction in the weak force by about ten times would have resulted in fewer protons in the universe (Hall et al., 2014; Davies, 2006). This is because neutrons normally decay into protons though the weak force. Without the weak force, however, stars could still make deuterium through neutrons coupling with protons under the influence of the strong force. Adams has argued that this would create a larger amount of deuterium than in our universe, which could power the stars by fusing into helium (Adams, 2019).

While stars may be able to operate without the weak force, they would struggle if the weak force was too strong. Alterations in the weak force could also compromise the ability of supernovae to spread material into space. The outward pressure in this process comes from neutrinos, released alongside electrons when neutrons turn into protons under the influence of the weak force.

II. VARYING MULTIPLE PARAMETERS AT ONCE

Fine-tuning analysts often look at what would happen if the value of a parameter is changed in isolation. But when you allow many parameters to vary at the same time, a different picture emerges (Rees, 2000; Adams, 2019).

As a case in point, as we saw in Chapter 2.III.1, dark energy poses perhaps the biggest fine-tuning conundrum: Why is the observed value of dark energy so much smaller than the value predicted by particle-physics models? It has been suggested that if the dark-energy mass-density were only about 10 times more than it is today, galaxies, planets, and life would not be able to form (Davies, 2006). But, as we saw in Chapter 4, astronomers working on the Evolution and Assembly of GaLaxies and their Environments (EAGLE) project, which models some 10,000 galaxies and compares the results with astronomical observations, have discovered this may not be the case. By running their simulations on how galaxies evolve for different values of dark energy, they discovered that dark energy could in fact be a hundred times larger, or much, much smaller, and still allow stars and planets to form (Salcido et al., 2018; Barnes et al., 2018). Avi Loeb has also calculated that life could have evolved much earlier in our own universe, regardless of the strength of dark energy (Loeb, 2013).

Cosmological simulations and calculations provide a neat example of how predictions of how the universe's evolution might be altered in hypothetical circumstances can be much more complex than initially predicted, when multiple factors are taken into account. For instance, it has been shown that if the 'fluctuation amplitude' constant *Q*—the ratio of the gravitational energy required to pull a large galaxy apart to the energy equivalent of its mass—could vary alongside dark energy, then dark energy could take a lot more values than currently allowed for (Aguirre and Tegmark, 2005).

Q has been measured to be around 10^{-5}. It cannot be too large because that would lead to such dense galaxies that planets would be scattered around by stars passing closely to them. But calculations show that *Q* can be as large as 10^{-2} and still produce a habitable universe. And as long as *Q* is larger than 10^{-6} and smaller than 10^{-2}, the dark energy constant can vary by an order of 10^{10} and still host galaxies and planets. In other words, it requires no fine tuning, at all. In fact, if yet another parameter—the ratio of particles known as 'baryons' (normal visible particles) to photons—increases, dark energy can vary by even greater amounts (Adams, 2019).

Meanwhile, Anthony Aguirre has created cosmological models assuming that the Big Bang was cold rather than hot (as is it is currently believed to have been), in which some or even all the seemingly fine-tuned constants can vary by several orders of magnitude from the values they take in standard hot-Big-Bang cosmology. Curiously, this does not stop the alternative cosmoses from giving rise to intelligent life, thus providing a counterexample to anthropic arguments (Aguirre, 2001).

III. ALTERNATIVE UNIVERSES THAT ARE MORE BIO-FRIENDLY

From the outset of this review we have taken one crucial point for granted: our universe, with its peculiar parameters, is maximally suitable for life. This assumption seems to be a given, since it is claimed that even slight shifts in certain parameters would render the universe lifeless. But is that really the case? Adams has argued that surprisingly it is not, by considering how the values of the fundamental parameters could theoretically be tweaked to make the universe even more hospitable to life (Adams, 2019).

For example, as stated many times, the value of dark energy is suspiciously small in our universe, which is handy for us because a large value would have caused the early universe to have expanded at an even faster rate, ripping galaxies apart before life could have formed. But if the value of dark energy was actually even smaller than the value measured in our universe, or indeed non-existent, our cosmos would have been even more conducive to life. Without dark energy, it would have been even easier for matter to clump together to form galaxies and galaxy clusters during the evolution of the cosmos, perhaps enabling life to have formed and spread faster. Similarly, if gravity were weaker, then stars and planets could also grow larger in size, as would living creatures.

Other small shifts in the parameters could be similarly helpful. If the strong force were slightly stronger than it is in our universe, there could be a stable beryllium isotope which could fuse with helium to produce carbon more easily. In this case, we would not need to rely on the carbon resonance invoked in Chapter 2 and discussed extensively in section I.1 above. And if the fine-structure constant α (see Chapter 2.II.2) were smaller, we could have more and longer-burning stars (Adams, 2019).

It would also be natural and life-enhancing for the constant *Q* to be larger—but not too large (Garriga and Vilenkin, 2006). While *Q* in our universe is 10^{-5}, the cosmos could be even more habitable if it approached 10^{-2}. This would produce denser galaxies and thus hotter solar systems, so that planets in almost any orbit—even far away from their star—would be habitable (Adams, Coppess, and Bloch, 2015; Adams, 2019). (For a *Q* value above 10^{-2}, the universe would be too violent for life to occur, with too many black holes.)

While many of the alternative universes described in this chapter are highly speculative, the mere fact that they could in theory have physically existed and enabled life to evolve—and potentially more richly than in our universe—lends credibility to the claim that the fine-tuning problem is not necessarily a problem that needs explaining. That is, if the parameters of our universe could plausibly have been wildly different, without defying any laws of physics, and still have given rise to intelligent life, then perhaps our universe is not quite so special, after all.

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6. CONCLUSION

So is the universe ultimately finely tuned for life? As described in the opening two chapters, it does seem to be the case that several laws and constants of nature cannot vary wildly from the values found in our cosmos without rendering the universe lifeless. Altered values for some of these parameters compromise the formation of stable atomic nuclei and the elements necessary for life, such as carbon. Changes in others threaten the formation of planets, stars, and galaxies. On the other hand, as discussed in Chapter 5, it may be possible to create universes that are even more bio-friendly than our own by tweaking some of the very same parameters that have been cited as prime examples of fine tuning. There is also the issue of what life looks like. The only kind of lifeforms we know about are the ones we see on Earth. So while we can try to calculate what it would take for that kind of life to evolve, we cannot rule out that an alternative universe could have harbored life—but not as we know it.

There is certainly evidence that some parameters seem to be fine tuned, as described in Chapter 2, but the degree to which they are tuned is subject to debate—as is whether this level of tuning should be interpreted as being problematic. The parameter that can vary the least is the mass of the down quark. If this were too heavy or too light, it would prevent atomic nuclei from being stable. It is estimated to be able to vary only by a factor of 7, which some consider extremely constraining. However, as noted in Chapter 5, this down quark value is less finely tuned than an AM or FM station on your radio.

If we decide to consider fine tuning to be a real conundrum, then, as discussed in Chapter 3, the most popular explanations are either to accept it as a lucky coincidence or to subscribe to an infinite multiverse. The multiverse allows us to make sense of how the universe may have come to hold the values of the physical constants and laws that it has—among many other possibilities that are realized in neighboring cosmoses. But importantly, it cannot tell us *why* it has those values, in the way that a new fundamental theory of physics might be able to explain. And there is no fundamental reason for why the multiverse is the way it is, governed by string theory, enabling so many different universes within. In a sense, the multiverse explanation just shifts the problem of fine tuning up a level, from the universe to the multiverse. As seen in Chapter 4, there are many ongoing and upcoming experiments that could provide some evidence in support of the multiverse, or perhaps lead us to a new fundamental theory of nature in which the values of physical constants are explained more deeply, rather than having occurred as a whim. Or, forthcoming measurements of the fundamental constants, such as the cosmological constant and the fine-structure constant, could show that these apparent constants actually vary over time and space, rather than being fixed. If this turns out the be the case, and that variation was large, it would be a major blow to fine-tuning arguments.

For now, we could perhaps regard the multiverse and even fine tuning as "meta cosmology," as Bernard Carr does (Carr, 2020). Until experiments address the issues laid out in this review, perhaps the most important question is not whether fine tuning is real or an illusion, but whether it is useful as a scientific concept. Scrutinizing the conditions needed for life to emerge in the universe will ultimately help us understand the foundations of physics and biology—and potentially explore the possibility of life existing beyond our planet. To that end, investigating fine tuning seems to be vital to unveiling the essence of who we are, and our place in the cosmos.

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