Chapter 1

Introduction

Studying the Smallest and the Largest

The Large Hadron Collider, looking south across Lake Geneva and the Swiss Alps

> "In the beginning, the universe was created.
> This has made a lot of people very angry and been widely regarded as a bad move." *Douglas Adams*

We're about to follow a Big Story —the "just so" story of the beginning of the universe. Yes, that one: Everything. The plot of this story seems to have all sorts of twists and turns that we're still unraveling. Surprises await.

Of course, the details are where the devil resides and they are fiercely complex. So much so that two entirely different scientific communities are currently deployed to battle with nature: those of us who work on the "outside" and those who explore the "inside." The outside crew are astronomers and astrophysicists. They measure and characterize the constituents and nature of the cosmos. They look *out.* The inside teams mimic the earliest picoseconds of the universe by recreating its incredibly hot, adolescent conditions in laboratories here on the Earth. These are the particle physicists and they look *in.* This is the story of both.

What's the smallest real thing that you can know about? For people of my *grandparents' generation*, the sophisticated answer would be "what you can see." I was born in the year 1950, and so my grandparents would have been children at the dawn of the 20th century which is when physics got interesting. They would have been taught that to claim existence for an object that the naked eye could not see was absurd. Chemists spoke of atoms, but were disdainful of anyone who thought they were real. They were just a shorthand picture for how to visualize elements. Physicists were even less flexible.

"Quarks"? "Leptons"? Lots of jargon and I'll keep it all straight for you as we go along. For now, quarks are itsy-bitsy pieces of the proton and leptons include the electron and others.

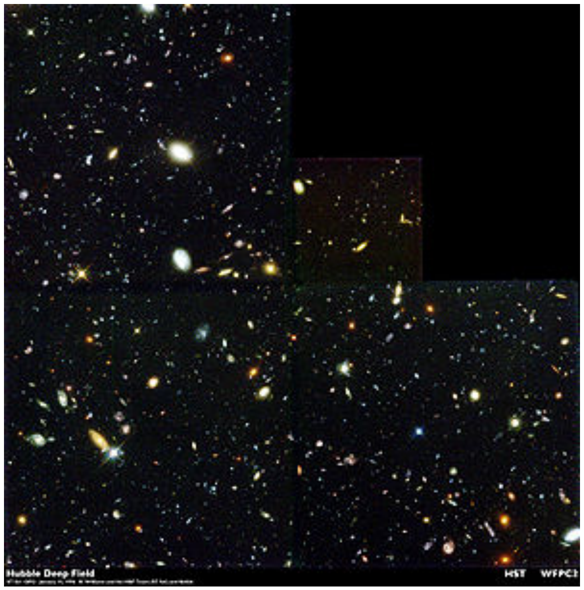

Figure 1.1: The so-called "Hubble Deep Field" view of a tiny spot in the sky, filled with 3,000 galaxies.

For people of my *parents' generation*, the answer would have been "protons, neutrons, and electrons." The atom had been thrust into believability around the turn of the century, and then refined during the next two decades. But the neat planet-like picture of the atom was where it all stopped for many.

In *our generation*, the answer to the "smallest" question has been "quarks and leptons" ...but we fully expect that they are not the end of the "smallest" story. We're hard at work, even as we speak with brand new tools to explore further than ever before.

In *your generation*? The sky's the limit! We've hints at solving some old puzzles and we'll undoubtedly find new ones. We're developing and deploying amazing new instruments and theoretical ideas now rub shoulders with not just nature, but philosophy and the deepest questions asked by humans. Your generation is going to see amazing things.

Through decades of intense experimentation and imaginative theorizing, the tiniest bits of reality are turning out to be a fascinating collection of objects. In the 1950s and 1960s, we just stood back and tried to catch the hundreds of particles that our experiments spit out at us. New particles every year! Names that nobody could remember. Hundreds of them, which was ludicrous! Didn't nature have some plan?

The good news is that we've uncovered a model that's a very good picture of how much of the fundamental particles of the universe work together and we've been exploring it since the 1970s. We've knitted that earlier mess together into a coherent picture of the entities themselves as well as the rules that govern how that stuff behaves.

But we're unhappy. Our grand synthesis of the Tiniest Bits Story—called the Standard Model — now looks a little shakey. While it's been the gold-standard of the successful scientific theory, we expect that *new* tiny bits are lurking in our experiments and we will be astonished if nothing shows up as we dig deeper.[1] This new anticipation would have been met with blank stares only a couple of decades ago.

So much for inside effort.[2]

Okay. So what's the biggest real thing you can know about? For people of my *grandparents' generation* the learned answer to this question would be "the size of the Milky Way," which they would have been taught constituted the whole universe. Everything visible in the night sky was thought to

[1] These new states of matter might be: "additional quarks, the Higgs Boson, Supersymmetric Particles, Weakly Interacting Massive Particles (WIMPs), Dark Matter particles...," all famous candidates for future discovery. Of course whenever we get too cocky, nature plots to surprise us with something completely unexpected—more often than we'd like to admit! So, we're instinctively wary of being too sure of what's coming.

[2] See the frontispiece of this chapter!

be a part of one big, but still cozy cluster of stars which we see to be densest around the southern sky (from North America). Not only was my grandparents' universe compact, it was supposed to be permanent—static and unchanging— built of three kinds of objects: planets, stars, and clusters of stars. Stars twinkled, planets were steadfastly bright, and clusters of stars were fuzzy, indicative of their presumed distances from us. Sure, they all moved with regularity during each night and shifted slightly in a year, but the large scale structure of my grandparents' universe was simple: a nice, intimate, dependable universe.

For people of my *parents' generation*, the universe suddenly became huge. Those fuzzy clusters were found to be other galaxies outside of the Milky Way which are surprisingly far from us—we're not alone in our comfy galaxy. They were taught about thousands—we now know, billions—of others, of which the Milky Way is a relatively modest and ordinary example. But, the real shocker was the overthrow of the static universe of my grandparents era. My parents' universe was found to be flying apart—expanding—at a breakneck speed. No longer a tight-knit, stable thing...the universe is now huge and reckless.

The really unsettling piece of news for *my generation* is that the Big Questions of antiquity are now legitimate scientific research programs: Was there a beginning to the universe?[3] Are we alone? Will the universe end? Are there other universes? Was there anything *before* The Beginning? What drives the expansion of our universe to accelerate? The outside crowd thinks big thoughts now and this is a development of only the last couple of decades.

[3] There was a battle royal between two competing models of the universe in the 1950s. The first was dubbed by a proponent of the second, the "big bang"—not as a compliment. The second model was called the "Steady State" model. We'll talk more about these later. This battle raged until I was in high school.

When I was in graduate school, a professor told me that Cosmology was "physics knitting." Not any more! Cosmology in my and especially *your generation* is going to be flat-out amazing!

1.1 An Auspicious Beginning

Yes. The observable universe had a beginning, and quite a beginning it must have been: it was a roiling mess of radiation and elementary particles at temperatures never to be seen again. Everything that *is* would have been confined into a size smaller than the smallest particle we know of.[4] Unthinkably dense and with growth that was stunningly rapid, our early universe defies imagination. It's so outrageous that comprehending it seems a job for fiction and not science, yet my generation has also found ways to explore it: we probe it through direct telescope observations and we remake it in particle collisions. This is the blending of the outside with the inside pictures that motivates me.

[4] Maybe. Maybe not.

Wait. *I don't believe in the big bang. You appear to, but Isn't what you think just another "belief"? Aren't we each entitled to our own beliefs?*

Glad you asked. *"Believe" is a tricky word that we all use, although in our context, we should be clear. When I say "I believe in X," treat that as shorthand for the sentence: "X is highly confirmed by experiments and X is likely to survive foreseeable experimental tests." If I'm an expert in the field of X, then I have the obligation to describe those experimental tests. If I'm not an expert in X, I should expect that an expert could also enumerate its experimental successes in detail. There are dos and don'ts about this in science. About scientific belief, I can't do three things: 1) I can't say that I believe in X because I want to, 2) I can't say that I believe in X because my gut or a "feeling" tells me to, and 3) I can't say that I believe in X because a non-expert or an ancient text tells me to. Likewise, I can't say that I don't believe in X for any of those same three reasons. Stay with me. What I'll show you are amazing things and a record of success that's hard to ignore. Science is a process as well as a collection of theories and models!*

Quarks, Spacetime, and the Big Bang (which I'll affectionately refer to as "QS&BB") tells the interleaved stories of the two sciences of particle physics and Cosmology and how they have come to be blended together into a believable picture of how we all came to be. We're deep into the narrative—the plot is well understood, the characters are developed, and a "can't put it down" fever has set in. We're eager to see how it comes out and we're doing experiments all around the globe—and in orbit *above* the globe and in deep underground laboratories *inside* the globe— to push ourselves to the story's climax.

Definition: particle physics.
The study of the smallest bits of energy, matter, and the rules that govern their interactions.

1.2 The Inside Game: Particles and Forces

Sure, we've learned a lot in the last four decades about the Particle side of this story—my whole professional life. But, what's particularly interesting about this coming decade in "Elementary particle physics," (aka "EPP") is that we've reached an impasse. We have bushel baskets full of theories about what should come next, but we're starved for new data which will direct us on how to sort out the various theories. You and I are going to explore that situation because new data are coming in right now at extraordinary international laboratories. The coming decade is going to be interesting.

Definition: Cosmology.
The study of history and the future of the whole universe.

The inside story is that of EPP or as it's often called, just "particle physics," while the outside story is that of "Cosmology." We'll travel these narratives sequentially from their common beginnings.

The particle physics side is a well-established field practiced by about 10,000 of us in nearly every country and with major labs on four continents: North America, Europe, Asia, and Antarctica.[5] We build ac-

[5] Antarctica's a continent, right? Lots of experiments at the South Pole.

celerators to provide beams of electrons or protons and crash them together. We then collect the debris from those collisions in gigantic "detectors" that allow us to unravel the resulting debris.[6] Or we build detectors that are exposed to cosmic particles. EPP is one of many sub-disciplines in physics, but it's a little different. Urgent questions in most scientific areas have evolved and sometimes new specialties emerge.[7] In contrast, while particle physics has become specialized and sophisticated, its goals have always been intensely focused on two questions:

What are the most elementary particles in nature? *Key Question 2*

What fundamental forces act among those elementary particles? *Key Question 3*

We think that getting closer and closer to answering them which will lead us to a deep understanding of the early universe. Paradoxically: understanding the tiniest things in nature will help to understand our "origins" which have been debated and argued for 2,500 years.

Box 1.1 A little philosophy

By the way, do you see how these two key questions are different? The first one asks about the existence of "things." An inventory. The second question asks about physical laws *among* the things. We're realists, which is to say, we think that things are real and that our theories are about real processes. These two ideas are still debated in philosophy and scientific realists would refer to them as "entity realism" and "theory realism." The former is more easily defended than the latter. But, we're not philosophers. We're scientists and we believe that the discovered laws of nature are factual statements about how things work. Enough of this.

These first two questions were stated carefully, so let's take them apart: "elementary particles," and "fundamental forces" are both specific concepts in my world that have different meanings from normal peoples' worlds! How about parts?

1.2.1 What's An "Elementary Particle"?

The most basic qualification for some entity of nature to be "elementary" is...that it has no parts. Most things have parts: stars, trees, molecules. Even an atom has parts—the nucleus, which is made up of protons and neutrons, and the atomic electrons.[8] The electron? No parts. It's elementary.[9] So, an atom is not elementary and not a subject of our investigations in particle physics.

[6] Chapters **??**, **??**, and **??**.

[7] For example, Nuclear Physics and particle physics were practiced by the same people until the 1950s when they naturally split into two different subfields of physics. One group pursued the intricacies of more and more complex nuclei and the other pursued the complexities of the simplest objects. Each approach requires specialized devices and each separate theoretical tools.

[8] Chapter **??**

[9] So far.

An elementary particle is a bit of matter and energy that has no constituent parts. *Key Concept 2*

Elementary ≡ no parts is a simple idea.[10] But, as you'll see, a persistent theme of this book is to emphasize how simple ideas about nature can become wonderfully complex.

[10] The symbol ≡ means "defined as" or "equivalent to."

"Here's your moment of zen": "Simple means complex"!

But what a particle is...well, that's actually complicated. We learned in the last century that particles aren't the nitty-gritty of reality because when we combine the theory of quantum mechanics with the theory of relativity, we find that stuff in atoms, nuclei, people, electrons and stars—everything— is actually the consequence of a set of continuous, wiggling *quantum fields*.[11]

[11] Chapters **??**, **??**, **??**, and **??**, and **??**

Wait. *Fields bring to mind something that's spread out, but atoms are individual things. How are they related?*

Glad you asked. *That's right. Fields are indeed spread out. Imagine a wheat field waving in a summer breeze, as far as you can see. Fields imply waves and collective motions of quantum fields are not unlike this image. But if a field is the fundamental substance of everything, then that's indeed unsettling since a field is everywhere, but a particle that comes from it is "there." We'll talk a lot about fields and try to reconcile these two pictures. Be patient.*

In spite of this field-reality, I have to admit to the mental crutch of *particles*. For EPP it's easiest to mostly use the mathematical language of particles and that language came to us from Richard Feynman.[12] So, one side of my brain is full of the sophisticated symbols and manipulations of the relativistic quantum field theory that precisely describes this stuff. But the other side of my head is full of images of billiard balls bouncing off of one another: colliding particles.[13] In any case, QS&BB will cover this growing awareness of the importance of fields and how particles make themselves known.

[12] Chapters **??**, **??**, **??**, **??**, and **??**

[13] By the way, It's not an entirely satisfying picture since in order for this analogy to be precise, my mental quantum billiard balls should also randomly decay into other billiard balls—or into baseballs or bananas,— should pass right through other billiard balls, and even spontaneously leave my pool table and appear on someone else's! But, we have to cling to some picture in our heads and that's mine.

1.2.2 What Is a Fundamental Force?

"Force" is one of those words that has many colloquial meanings.[14] But in physics a force is a precise concept—a noun and not just a verb. Here's the simplest notion of a force, which came from Newton and with embellishments, still works today: if you alter the motion of something, you exerted a force on it.

[14] "You can't force me to eat that!" (You thought I would refer to Star Wars, but I'm better than that.)

Everyday Forces

You and I deal with three kinds of forces every day. Let's talk a little about all three...and then how the forces in particle physics are different from these.

First, take regular pushing—whether it's a push that's through muscles against something, or the push of a tire (or your shoe) against the road—this mechanical thing-to-thing contact seems instinctively to be direct. Solid against solid. You might be satisfied with the phrase "mechanical force" as all you need to say and you'd be consistent with its modern usage in engineering. Write-in this kind of force in pencil for now.

Then of course dropping things can be a bad habit, but whatever you mishandle, it always go to the floor. On the street we'd say that gravity pulls things down to the Earth. But here again, the actual situation is quite a bit more complicated than "gravity made me do it." QS&BB will take us through many of the stories about gravity and you'll be amazed at how that idea has changed. We think Mr. Einstein's picture is closest...right now.

Finally, what about a magnet? Surely at one point in your young life, you've played with a pair of magnets and marveled at the fact that they seem to "communicate" with one another. Without touching, and without any obvious connection between them, a force is transmitted through thin air. Hand, here's another one that doesn't need direct contact to alter motion: your hair's state is affected on a cold, dry day by a comb—your 'do rearranges itself as if by magic without actually touching the apparent cause of the hair motion—a statically charged comb.

One of the neat stories we'll uncover is that the relationship between your hair's unruliness in January and your dog's photograph sticking to your refrigerator is an intimate one: they are both examples of a single force, the "electromagnetic force" and understanding that will take us into Albert Einstein's young life.[15]

[15] Chapters ??, ??, and ??

Here's a well-kept secret: the mechanical thing-on-thing pushes and pulls of everyday life are actually electromagnetic: the reason your hand doesn't go right through the box you're pushing is because the electrons in your hand are repelled by the electrons in the surface atoms of the box and so you... push it.[16]

[16] The reason you don't pass right through the floor is due to the same electrostatic force.

So that first kind of everyday force that I warned you write in pencil? You can erase that now. We only deal in two forces in our human-sized, everyday lives: gravity and electromagnetism.

1.2.3 Particles, Forces, and An Amazing Theory

Enumerating particles is like physics-stamp-collecting: find them and sort them for similarities and differences. But that leaves out much of the story, since we need to know how these particles interact with one another. We need to know about the *forces among them.*[17] These sorts of forces are special and abstract.

[17] Chapter ??

Nature is pretty economical. If there are 12 kinds of particles in the universe, you might guess that maybe there's one force, or 6 or 12. But, it turns out that there appear to be only 4. In our everyday lives we encounter half of them. The others act behind the scenes.

The forces are different from one another in two ways. First, not all forces "see" all particles. An electric force only notices electric charge, so anything that's neutral (like a neutron...or your body) will not be yanked around by the presence of an electric field. The second way they're different is their strengths. Your dog's photo stays on the refrigerator and doesn't fall to the floor because the force of gravity is very much weaker than the force of electromagnetism.

Besides electromagnetism and gravity, the other two forces are called, get ready, the Weak Force and the Strong Force. They are, as you might guess, weaker and stronger than some others.[18] We'll talk a lot more about these later, but from weakest to strongest, the forces order themselves:

[18] We have a lot of fun naming things in particle physics.

1. the Gravitational Force,
2. the Weak Force,
3. the Electromagnetic Force, and
4. the Strong Force.

The role of QS&BB? Describing how we learned there were four forces and how they function in the universe.

1.2.4 The Standard Model of Particle Physics

One of the amazing accomplishments of the last three decades in particle physics is that we now rely on a theory, called colloquially "the standard model" that predicted the existence of new particles (which we found) but also explains how 3 of the 4 the forces of nature originated.[19]The standard model is like no other in the history of physics as it pretty much accounts for everything.[20]

[19] Gravity shuns the Standard Model because of its quantum mechanical roots. Gravity stands alone and that bothers everyone.

[20] In fact, it's so special to us that I'm going to capitalize it. From now on: **Standard Model.** Rolls right off your tongue.

It describes all known elementary particle interactions—on Earth, in cosmic rays, supernova explosions, and the earliest moments of the universe. It also is the mathematical blueprint for how atoms are held together, how nuclei bind, how molecules are constructed: it's the scientific platform on which all of physical science stands.[21]

[21] Of course the complexity of nuclei, chemicals, organic and inorganic molecules is very specialized and so the sciences of Nuclear Physics, Chemistry, and Biology are themselves quite complicated and beautiful. But the basic laws that are at work deep down, are those of the Standard Model.

But there's more: the Standard Model tells a story of the big bang that shows that forces aren't forever. The forces we know now, were born out of entirely different forces as the universe cooled. Even *mass* didn't exist as a concept until these forces changed. It's quite a remarkable intellectual achievement, this Standard Model. I'll construct it for you to admire along with my colleagues and me!

1.2.5 Particle Confusions

Our Standard Model now has no missing pieces. The last bit was revealed in 2012 with the announcement that we had found a strange particle called the "Higgs Boson" in our experiments at the Large Hadron Collider at CERN. But we're still not happy for two reasons. First, there are experimental reasons: something's going on in the universe that causes galaxies to move oddly (see below) and something's going on with nothing— the vacuum, which we tend to think of as related to that theory of fields that I described above. The second reason we're not happy is the Standard Model has some formal features about it that don't quite sit right with us. The mathematical instructions that come with the Standard Model require us to do an odd thing to get it to work, and we're pretty sure that this odd thing should have a deeper purpose and not be as *ad-hoc* as it seems.[22] Let's go large.

[22] Want to know what that odd thing is? We take an equation, and we change the sign of one piece from negative to positive. No particular reason. . . except that it works. Stay tuned, you'll see.

1.3 The Outside Game: The Big Bang

As I've indicated, the big news of the 20th century is that our cosmos had a birthday. Astrophysicists have made huge strides in the last three decades with amazing instruments operated on Earth and launched into orbit around the Earth. Results keep pouring in: our universe had a Beginning.

Definition: **Astrophysics.**
The study of the dynamics and the origins of astronomical objects.

Stand back and think about the implications: this is the most remarkable scientific discovery in history. Of all of the ways people have thought about their place in the world, over thousands of years there was only speculation and myth about a possible Beginning. After decades of patient research, we now know: there was a time—before which there was nothing. Suddenly, in the blink of an instant, space, time, and the energy of matter and radiation were born and then the whole mess cooled eventually. Evolving Into suns, planets, and us.

From the creation stories to the "just-so fables," humankind used mythology and belief to orient itself with the universe they could see. Even then, there was the strong sense that the whole of the universe was bigger than what humans could imagine. Cosmology is an old, old subject, but it only became a *science* in the last century.

Some would call this later version, Physical Cosmology in order to distinguish it from the precursor story-telling. (I'm looking at you, Wikipedia.) But we'll just call it plain, old Cosmology.

Well, we don't just "imagine" any more. We measure. Cosmology is a new science; it became one in the hands of Albert Einstein in the early twentieth century. Things didn't go quite as he'd planned, as we'll see. But he laid the groundwork for a human-based study of the universe using mathematical rules rather than mythology or belief. Today it's among the most exciting branches of all of physics.

The two basic questions that modern cosmology tries to understand the answers to are these:

What are the past and future histories of the universe? *Key Question 4*

What are the ingredients of the universe? *Key Question 5*

These questions area alsoo carefully stated. So let's unpack "history of the universe" and "ingredients."

1.3.1 Histories of the Universe?

You know the meaning of "Universe," right? It's...well...it's everything. At least that's what it used to mean. We'll consider a growing suspicion is that a *universe* might be a relatively local object and that there might be room for an interpretation of the whole cosmos that could incorporate other *universes*.[23]

Perhaps you've read about a "multiverse," a speculative idea in which ours is just one of an infinite number of universes which are born and die spontaneously and for eternity. All of them would have different physical laws and so different particles and varying potential for life. So that's one side of a contentious argument in physics. To opponents, the multiverse is speculation that's beyond wild.[24] In QS&BB we'll talk about why the multiverse is a topic for science seminars and not just comic books. On this, we'll be agnostic. Just the facts, ma'am.

Let's try to define what our universe would entail. Our universe is

1. the one in which we (or our original elements) reside,
2. the one where the same physical laws work throughout, and
3. the one that had the big bang that our evidence points to..[25]

Certainly, the past history of the universe is the hot[26] topic in all of cosmology.

Past History

Our inference to the need for a beginning—a big bang—comes from a) the fact that the universe is expanding, b) that we therefore infer that it was smaller in the past, and importantly, c) that we have a plausible, predictive model that describes this situation. Both the fact of the big bang and the stories that led us to this conclusion are fascinating and QS&BB spends quite a bit of time unraveling them.[27] But just how this happened is a matter of urgent research.

We can play the universe-movie-camera backwards in our models to what we call the big bang. In the conventional model of cosmology we can reliably predict[28] the times at which atoms were formed, then

[23] Now, did you ever think that there could be a plural of that word?

[24] For some, even reckless and unscientific.

[25] It ain't much, but it's home.

[26] No pun intended.

[27] Chapters **??**, **??**, and **??**

[28] post-dict?

back to when nuclei would have formed, and then further back to when protons and neutrons would have been formed. At that point the universe would have been unbelievably hot and dense and only consisted of the most elementary of particles. This birthday of matter is about a picosecond after the big bang: when the universe was about

$$0.000000000001 \text{ seconds old.}$$

Let's call this the "Electroweak time," which we'll study later.[29] We believe we have a good explanation for the universe's evolution from that tiny fraction of a second to the present 13.8B years,

$$430,000,000,000,000,000 \text{ seconds.}$$

.

As tiny as the Electroweak time is, it's still not

$$0 \text{ seconds!}$$

In fact, we don't know how to describe zero since there's a limit, before which, if we keep pushing our models, mathematics fails us with infinities. That's called the "Planck time," 10^{-43} seconds, or…dare I write it?…

$$0.0000000000000000000000000000000000000000001 \text{ seconds.}$$

This is a defining point. Before the Planck time, the very concept of "time" would not exist. But between the Planck and Electroweak times—between the point where we can make mathematical models to the time where we think we start to understand? A lot had to happen in that tiny, tiny time window.

We've hypotheses of what might have happened in that instant and tests we can perform to lend credence to them. [30] So the past history of the universe is an active area of research, world-wide. Theory and experiment in astrophysics and particle physics all work together on this. The good news is that from the Electroweak time forward until now, we can explain how just about everything evolved. The bad news is that before that point, we come up against the 800 pound gorilla-question: **what banged** in the big bang?

Now put on your seatbelt. Could there have been a "before the big bang"? The general consensus is "yes" and the front-runner model—what some have called "an amendment to the big bang"—is called *Inflation*. This 30 year old idea predicts that at about 10^{-35} seconds (not yet as early as the Planck time) the universe went through a phase transition, not unlike when water boils. Before that point, there was only the vacuum…a bubble of nothing. After the inflationary event, radiation and particles were created and our universe evolved until today.

[29] Chapter **??**

[30] To complicate matters, space and time are intimately involved in this event in ways that we can't yet rigorously pin down.

This going from *nothing* to *something*—dubbed the "ultimate free lunch" by inflation's inventor—is heady stuff. But it's testable stuff. And it's bizarre stuff since inflation is part of the inspiration for the far-out notion that ours is only one of a "multiverse." This hypothesized infinite collection of other vacuum bubbles would be eternal (time wouldn't exist) and would be spawning other universes for all eternity. Some might become full-fledged universes with particle and laws amenable to making stars, galaxies, and carbon-based life. Some might not.

Future History

So having teased you with our past, what is our future history? Well, I'm playing a word-game with you since we'll see that in physics the direction of time becomes a different sort of thing than our regular use of that word. But the eventual fate of the universe has been a matter of mathematical modeling since the 1960s. The universe could logically

- expand forever;
- stop, shrink, and collapse; or
- slow down and become static.

Nobody was prepared for the surprise of 1999.

The results of determining the distances to a particular type of supernovae led to the conclusion that not only is the universe expanding, but that expansion appears to be *accelerating*. Something seems to be pushing space to stretch faster and faster and we're not sure what it is. Taken at face-value, the future seems grim for this universe. At some point the expansion will be so fast that light would not be quick enough to be able to travel from one galaxy or star to another. Every celestial object will become isolated. Anyone left alive on any planet in this universe would see only... **black**. It will be a lonely place.

Another future history comes from competitors for whom after the universe's birth and then Big Bang-ish evolution would lead to a contraction of space, all the way to an eventual collapse (the "Big Crunch"). And then the whole process would start over: the universe would be cyclic. An endless repetition of groundhog day cosmic repeats. In this scenario there is no unique beginning, but rather an endless series of beginnings.[31]

So you can see that while the knowing the past and future of the universe are age-old quests their unraveling might be puzzles that humans can actually solve. Our two most compelling models are physically different and even *philosophically different*! Inflation assumes that time had a beginning, while in the cyclic picture time is perpetual—it never starts and never ends. Appreciating the details of these and other advances are a part of the QS&BB mission.

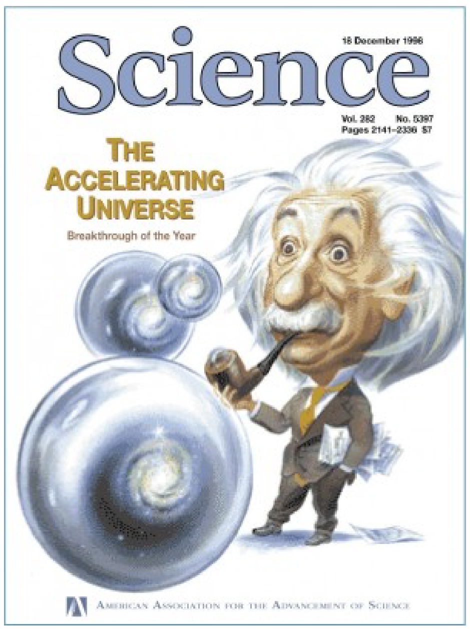

Figure 1.2: sciencemag

[31] This model is also consistent with the accelerating universe, but ascribes the cause differently from inflation.

1.3.2 Ingredients in Our Universe?

In order to inventory the ingredients of your world, you just look around you. Houses, clouds, Earth, the Moon, the Sun, stars, and so on. But the ingredients that I'm speaking of are cosmic. The universe is incredibly big—and we'll get a sense of that—but the smoothed out average amount of actual stuff is actually quite small, not much more than about 3 protons per cubic meter. So the overall density of the universe is minuscule, pretty smooth, and pretty much dominated by hydrogen atoms. So cosmic ingredient number one? The simplest element of all. All of interstellar and intergalactic hydrogen was born out of the big bang. All of the other elements[32] are made in stars.

[32] except for tiny traces of helium and lithium

An inventory of the other cosmic ingredients beyond hydrogen depends on the epoch in which we make the list. During our current era, our accounting would include stars like the Sun, planets and exo-planets,[33] galaxies, a few spectacularly destructive stars (supernovae), and some stellar and galactic black holes. In an era thirteen billion years ago, galaxies wouldn't have been on the scene (but there would still be lots of hydrogen) and thirteen and a half billion years ago, there would have only been particles and radiation (hydrogen wouldn't exist yet). At about 300,000 years after the big bang (about 13.5 B years ago) the universe shined and then cooled and we're now surrounded by a measurable remnant afterglow (called the Cosmic Microwave Background, or CMB) just above the frequency of your microwave oven and studying it has been the mission of a number of famous satellite experiments.

[33] These are planets that are in orbit around other stars.

Figure 1.3: vacuum

So understanding the evolution of the ingredients of the universe is an important undertaking, backed up with very sophisticated computer modeling and very precise satellite observatories. That 13.5 B year CMB mark is about the limit of our astronomical looking-back. Understanding the ingredients of earlier times requires a new partnership.

Because...the cosmic ingredients around the time of the Electroweak time would have been just the most elementary of elementary particles. Some we know about, others would have been different and evolved into our familiar set, and still others are only now hypothetical but discoverable in our experiments. I hope it's obvious by now that QS&BB will be focused on how our well-known particle-ingredients influenced this early time, but also what additional kinds might be found in our coming particle physics experiments.

Beyond particles, galaxies, stars, and other normal things, we're confused by some very exotic cosmic ingredients. For example whatever it is that has grabbed a-hold of galaxies to make them rotate way differently from how we expect them to. Their motions suggest that they're (we're!) surrounded by unseen (not shining) stuff that gravitates but doesn't radiate: Dark Matter is our intriguing name for this stuff.

Finally, the most fascinating ingredient of the universe seems to be nothing. That is, the unseen force that seems to be pushing everything into that newly discovered accelerated expansion, might be a feature of the vacuum.[34] When we don't know what something is, we name it! "Dark Energy" is the placeholder name for the mysterious something that also is a target of frantic experiments and theoretical work.

[34] We'll talk a lot about the vacuum, which until this discovery was the province of particle physics. Now both cosmology and particle physics intellectually own nothing!

1.3.3 Cosmological Confusions

In Cosmology we face some flat-out observational or *experimental* embarrassments. For example, when we add up all of the mass-energy of all of the objects that we can see using all of our observational tools (optical telescopes, infrared telescopes, microwave satellite telescopes, radio telescopes, etc.), 95% of the mass of the universe is missing. No kidding.

A part of the missing stuff appears to be that Dark Matter ingredient (about 30%) and the rest seems to be made up of the mysterious Dark Energy ingredient. When you take the paltry 5% of shining stuff and add in these two Dark ingredients, it actually works out to 100%! This is a major victory for the "standard model of cosmology" or the "hot big bang model" (two names) and getting there is a part of the QS&BB story.

But we're confused about what Dark Matter and Dark Energy actually are. Embarrassed even. So there are major programs all over the Earth to study them.

Want something even stranger? Where are the antimatter galaxies? We don't see any evidence of relic antimatter in the universe. Only matter—the stuff we're made of. So either the universe began with an artificially enhanced matter dominance—an "initial condition" that is not scientifically acceptable—or at some point the originally *symmetric* matter-antimatter soup became our *antisymmetric*, matter-dominant outcome. And the list of puzzles goes on. Let's now play together.

1.4 Particle Physics and Cosmology, Together

After 50 years of successes and surprises in both fields, one thing is clear: the reality of a big bang means that there was a period when the universe consisted of only particles and forces. No protons, atoms, stars, galaxies, or Starbucks. Just elementary particles and the forces among them.

As I noted, that epoch was less than 0.000001 seconds long, but it was critical since the particles and forces were created just before it and what happened after was determined *by* the ingredients and rules of that period. What's more, we suspect that the set of forces *then* was different from those we know of *now* and that the set of primordial elementary particles might have included whole species that we've not yet found in terrestrial experiments.[35]

[35] As a tantalizing tease each of the cosmological problems above has candidate particle physics solutions!

These eras are not connected by a single story thread—yet. But they must be! No physicist thinks that the universe is governed by two contradicting sets of rules. So we have a lofty goal: we're working toward a model of *everything* about the universe from the big bang through to today. Theories abound, but experiment will decide. We can explore the earliest moments of the universe with the most powerful telescopes, but in order to investigate the times earlier than about 3 minutes after that Beginning, we need to do experiments in laboratories on our Earth. It's a bold extrapolation: by colliding protons head-on at very high energies, we're reproducing that early hot cosmic cauldron.

> **Wait.** *How do you know that this is the right connection to make? Maybe the conditions in the big bang were totally different than those in proton collisions?*
>
> **Glad you asked.** *It's a plausible story, and, frankly a nice one. But as pleasing as it is, we have to test it and what's neat about the state of affairs right now is that particle physicists are joining astrophysics collaborations and astrophysical measurements are directly testable in our labs on Earth. This approach could be wrong! But we have to pursue it with a vengeance since the stakes are so high.*

We're currently mounting experiments in both EPP and Cosmology that are going to hit these issues squarely in the next couple of decades. Their results will completely change the way we think. Text-books will be rewritten. If the first 40 years of the twentieth century were wacky, the first couple of decades of the twenty first are likely to be amazing.

In my professional lifetime, these two fields have become kin. Theoretical and experimental advances (or surprises) in one field directly affect the other and visa versa.

That said, the stakes are so high that we can add a third focus for EPP:

How did elementary particles and their forces affect the evolution of the universe? *Key Question 6*

Like the ancient Ouroboros, the snake eating its own tail. Cosmology—the science of the biggest— is dependent on the science of the smallest, particle physics, and *vice versa.* That's our story: Elementary particle physics and Cosmology are now united in a single path of discovery and this book will show you how.

Figure 1.4: Ouroboros

QS&BB is not old "dead white guy physics"! It's all new and the details are still being worked out so we're going to be talking about matters of very current interest. If you make it through with me, you'll be in a good position to appreciate the surprises when they start to occur at the Large Hadron Collider, Fermilab's LBNF and DUNE, Mu2e, g-2, numerous underground laboratories, as well as the Planck Explorer, James Webb Telescope, the Fermi Gamma-ray Space Telescope, and other space-based laboratories. They'll be in the newspaper (if we still have newspapers). You wait.