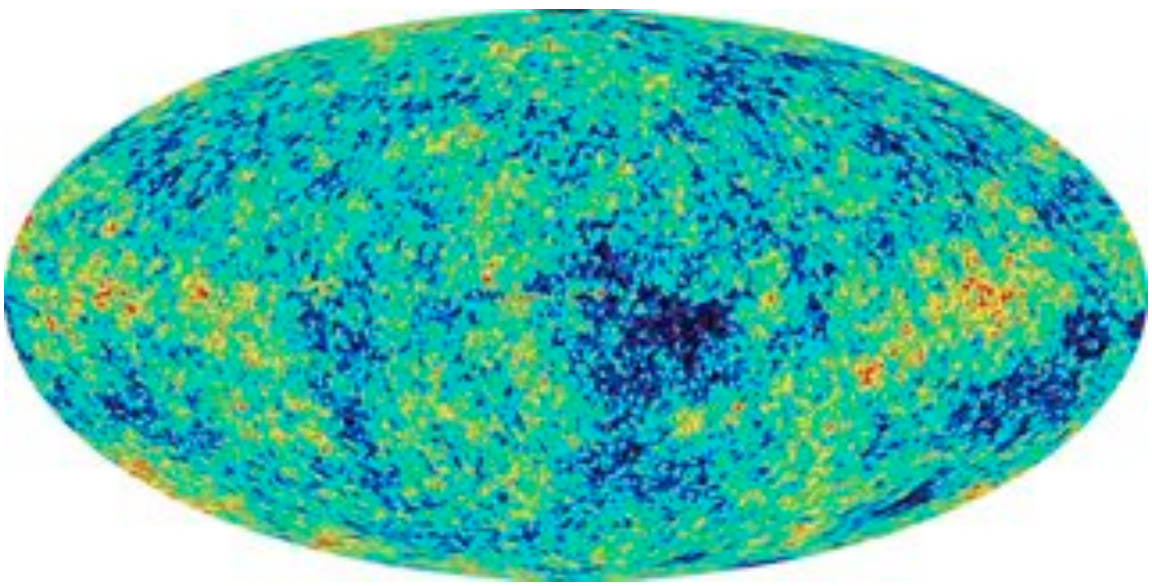
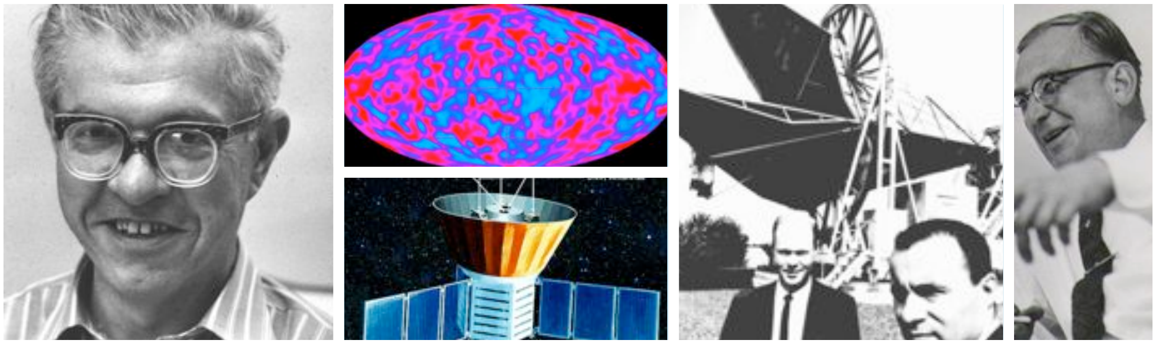
Chapter 4

The Big Bang Theory vs. The Steady State Theory



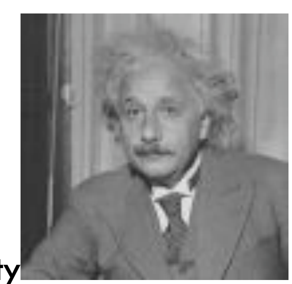
Introduction



Left to right: Fred Hoyle, the Cosmic Microwave Background as measured by COBE and the COBE spacecraft, Penzias and Wilson, George Gamow

Science thrives on controversy. Scientific progress emerges from the ruins of mistaken ideas and discarded theories. The battleground of scientific debate is where our theories are tested, abandoned, and rebuilt. What grander question can scientists debate than this: How did the Universe begin?

In the middle of the 20th century, astronomers debated and argued about two great theories for the origin of the Universe: the Big Bang Theory and the Steady State Theory. Both theories were good theories. Both theories had beauty. Both theories inspired astronomers and motivated research. But they couldn't both be correct. What do you do when you have two competing theories? Use the scientific method! Make predictions from both theories and see which predictions are confirmed in nature! This is how science progresses. Only this time, the very fate of the Universe hung on the outcome.



Einstein and gravity

The story starts with Einstein. Just about everybody has heard of Einstein and knows that he invented the Theory of Relativity, even if they are unsure about exactly the Theory of Relativity is.

By the way, the Theory of Relativity is an example of a theory that, although it's still called a "theory," it's been so thoroughly tested that there's no doubt that it's correct.

Actually, Einstein invented two theories of relativity. The first one, published in 1905, is known as the Special Theory of Relativity. It might better be called the Theory of Fast Motion, because it is about what happens to space and time at high speeds. It has been exhaustively tested in high-energy particle accelerators, where subatomic particles routinely travel at speeds close to the speed of light, so that we now the Special Theory is correct. The second theory, which Einstein completed in 1915, is called the General Theory of Relativity. It is actually Einstein's theory of gravity. It describes what happens to space and time near a massive object like a planet, star, or black hole. The General Theory hasn't been tested quite as well as the Special Theory. Although it has passed every test made of it so far, some of its predictions haven't been tested yet. Nevertheless, it is clear that the General Theory is highly accurate.

It is the General Theory of Relativity that predicts the expansion of space as the Universe expands. Our understanding of the history of the Universe from its earliest moments to the present day is based on the General Theory. In fact, one prediction of the General Theory is that the Universe must be either expanding or contracting. Hubble's discovery that the galaxies are flying away from each other could have been predicted ahead of time. Hubble's Law itself is predicted by the General Theory and its discovery was a dramatic verification of Einstein's Theory. Later on, we'll look at both of Einstein's theories in more detail, but for right now the important thing is that Einstein showed that space can stretch and expand.

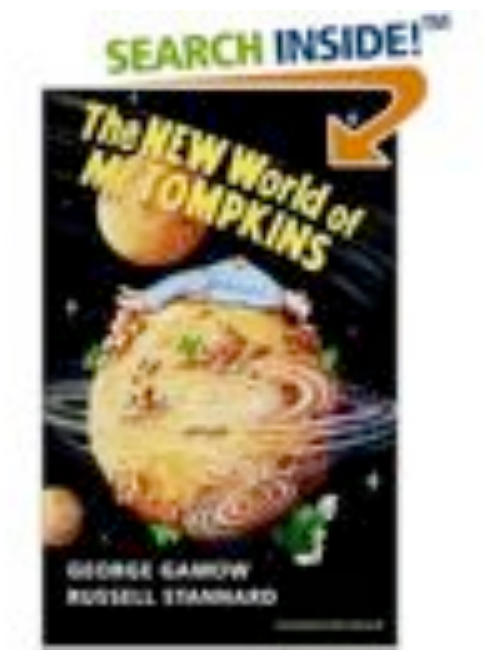
If space is expanding and the galaxies are getting farther apart, then it must be that some time in the past, the galaxies were close together. Even before that, all the matter in the Universe must have been packed tightly together. It must also have been very, very hot, because gas cools as its expands–think of air leaking out of a tire–and if the Universe is cold now it must have been hot in the beginning. So Einstein's theory implies that the Universe started out in a hot, dense state and has expanded to a cold, spread-out state. You could call this a prediction of the theory, although it's a funny kind of "prediction," because it's a statement about what the Universe was like billions of years ago.

One of the first scientists to write about this early period in the history of the Universe was a Belgian Catholic priest, Monsigneur Georges Lemaitre. Writing in the late twenties, he described the hot, dense first few minutes of the Universe as a "primeval atom." His idea was the beginning of what today we call the Big Bang Theory; however, in Lemaitre's day it wasn't yet possible to say much about what was going on in the Universe at that time, because we didn't know much about matter. His use of the word "atom" suggested, perhaps, that the Universe was very small and made of the simplest kind of matter. However, the Universe wasn't necessarily small. If the Universe is infinitely large today, as is likely, then it was already infinitely large in the beginning. In that case, instead of a tiny atom, we should picture in our minds a Universe made of hot, dense gas that extends infinitely far in all directions.

George Gamow and the Big Bang Theory

During the 1930s and 40s, big steps forward were made in understand the nature of the atom and its parts, the nucleus (made of protons and neutrons) and the electron. Physicists discovered the force that holds together the nucleus, the **strong force.** That research led, on the one hand, to the explosion of the first nuclear bomb in 1945, and, on the other hand, to the Big Bang Theory. It is interesting that the same science led to both mankind's most terrible weapon of destruction and to an understanding of the Universe's creation.

The godfather of the Big Bang Theory was the Russian-American physicist George Gamow (pronounced "Gamoff." Gamow, by the way, was not only a brilliant scientist but also an excellent popular writer who wrote a series of entertaining books about science for the lay person. (His book *Gravity,* by the way, is a highly readable account of Einstein's theory of gravity.) During the late 1940s, Gamow decided it was time to re-examine Lemaitre's "primeval atom." Gamow's hope was that he could find the origin of the elements in the fireball of the early Universe.



By the origin of the elements, we mean the formation of atomic nuclei. Recall that an atom consists of a nucleus surrounded by one or more electrons. The nucleus,being made of positively-charged protons and uncharged neutrons, has a positive electric charge; the electrons have negative electric charges. Negative electric charges are attracted to positive electric charges by the **electric force,** another of the forces of nature. Once you have a nucleus, it will attract any electrons in the vicinity to form an atom. Forming the nucleus itself is much harder, because like charges repel each other, so the positively-charged protons in the nucleus are being pushed apart by the electric force. What holds the protons together is a much stronger force—the strong force.

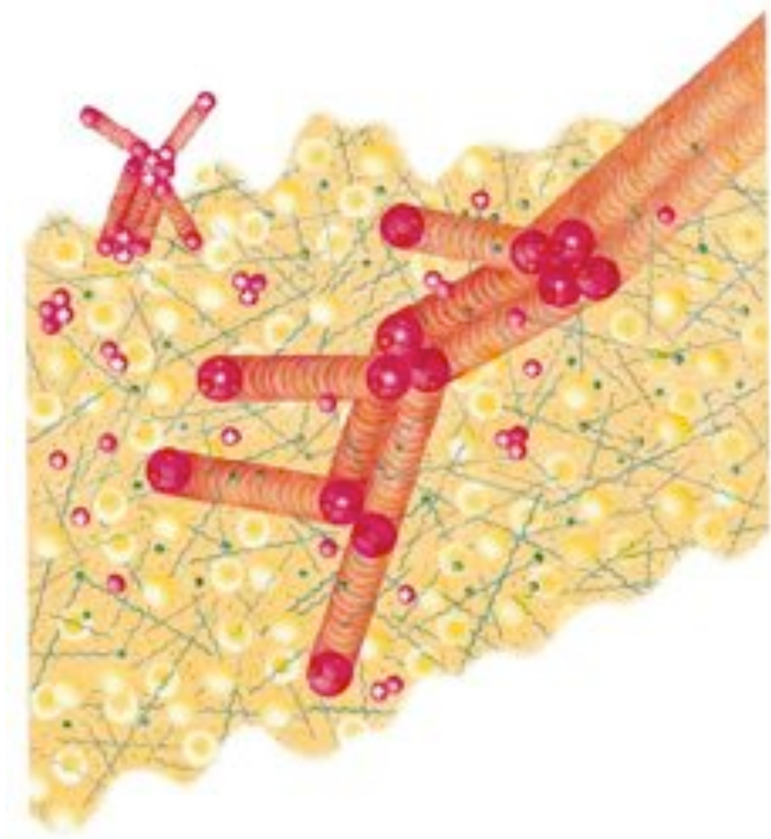
Gamow's idea was that in the first minute of the Universe, it was so hot that nuclei couldn't exist. Hot temperature means that the protons and neutrons were moving at very high speeds, so they would collide at high speed and bounce off each other instead of sticking together. After the first minute, however, the temperature should have cooled enough that protons and neutrons started sticking together to form atomic nuclei. The number of protons in a nucleus determine what element it belongs to: a nucleus containing one proton in hydrogen, two protons is helium, six protons is carbon, and so forth up to uranium with 92 protons in the nucleus. In this way, Gamow imagined that the elements came into existence in the first few minutes of the Universe.

Gamow's student Ralph Alpher worked out the details of the idea. When it came time to publish their results, Gamow, who was known for his offbeat sense of humor, had an idea: he asked his friend Hans Bethe (pronounced like "beta") to allow his name to be put on the paper. So it was that this paper, the first scientific description of the first few minutes of the Universe, became known as the Alpher-Bethe-Gamow paper—a pun on the first three letters of the Greek alphabet (alpha, beta, and gamma). This paper marked the beginning of the modern Big Bang Theory.

The creation of helium

The first big success of the Big Bang Theory (although it wasn't yet called that) was the prediction of the amount of helium in the Universe. Alpher and Gamow predicted that about 1/10 of the protons and neutrons in the Universe combined together to form helium nuclei in the Big Bang. What we observe today is just that: roughly 9/10 of the atoms in the Universe are hydrogen and 1/10 are helium. Success!

Helium nuclei formed after the Universe was three minutes old. Before that, it was too hot. By the time the Universe was three minutes old, the temperature had dropped to about 100 million degrees Celsius and some of the protons and neutrons had started sticking together. The most abundant nucleus they formed contained two protons and two neutrons—the **helium-4** nucleus.



This process, where protons and neutrons stick together to form nuclei, is called **fusion.** Fusion took place for only a few minutes, for two reasons. The main reason is that the Universe was rapidly expanding. As it expanded, the temperature was rapidly dropping. Fusion requires temperatures of millions of degrees. Once the Universe cooled to a lower temperature than that, fusion stopped. The other reason is that free neutrons turn into protons after a few minutes, so after a short while there were no more neutrons left to form nuclei. Only neutrons that managed to become incorporated into nuclei survive to the present time.

The prediction of the amount of helium in the Universe was a big plus for the Big Bang Theory. Unfortunately, the theory couldn't account for the creation of the other elements. Small amounts of element 3 (lithium) were also created in the first few minutes of the Universe, but insignificant amounts of any heavier elements. There just wasn't enough time. To this extent, the Big Bang Theory failed in its original purpose.

What the Big Bang Theory is Not

Here is something that may surprise you: the Big Bang Theory is *not* actually a theory of the creation of the Universe. It says nothing at all about how the Universe came to be. It starts a fraction of a second *after* the creation of the Universe and then seeks to describe how the Universe changed as time went on. Many people are confused about this, so let me reiterate: *the Big Bang Theory doesn't say how the Universe got started.*

Because it brings us almost to the moment of creation, the Big Bang Theory makes many people uncomfortable because it seems to verge on the domain of philosophy and religion. Two different groups of people find the Big Bang Theory hard to accept:

> 1) The first group doesn't like the theory because they believe that it requires a God to get the Universe started. This group prefers to explain nature without resorting to God
>
> 2) The second group believes that the theory seeks to eliminate the need for God. This group seeks to find confirmation of the existence of God in nature.

What with the one group and the other criticizing it, the Big Bang Theory has had a tough time of it over the years. The fact is, however, that the Big Bang Theory doesn't say God exists and it doesn't say God *doesn't* exist. The theory leaves people free to think what they like about how the Universe came to be; it only seeks to explain what happened after it got going. But nevertheless, the theory's critics have been passionate in their dislike. Perhaps its most vocal opponent was the late English physicist, Fred Hoyle. It was Hoyle who coined the name "Big Bang Theory." He meant it as a term of derision, actually, but the name stuck. Hoyle must have been greatly annoyed.

The Steady State Theory

Hoyle (who belonged to group 1 above) came up with an alternative to the Big Bang Theory that he called the Steady State Theory. The idea was that *the Universe has always been here and has always looked the same as it does now.* If the Universe has always existed, then there is no need to invoke a Creator to get it started. At least, that's the way Hoyle looked at it. There's another way to look at it, however: even if the Universe has always existed, the fact that it *does* exists is quite remarkable, when you think about, and demands some kind of explanation. Perhaps the mere existence of the Universe implies the existence of God.

Whether or not the Steady State Theory eliminated the need for God, it did run up against a problem right away: the expansion of the Universe. The expansion of space implies that the Universe was denser in the past and will be less dense in the future. In the Steady State Theory, the Universe always looks the same, so it always has the same overall density of matter. In other words, as the galaxies move apart, new galaxies must somehow appear in the gaps. Hoyle's solution to this problem was the idea of *continuous creation,* the idea that hydrogen atoms *spontaneously* pop into existence all over the Universe. In time, these new atoms pull themselves together to form new galaxies, so the distances between neighboring galaxies is always about the same. You might ask, *why* do hydrogen atoms just suddenly appear in space? Hoyle's response was that the sudden appearance of *atoms* was not nearly as bizarre as the sudden appearance of the *whole Universe,* as is supposed in the Big Bang Theory. In any event, Hoyle showed that the number of hydrogen atoms being created doesn't have to be very big in order to keep the Universe looking the same—in fact, the rate of creation of hydrogen would be far too small to detect in a laboratory on Earth.

Hoyle might have supposed that some helium atoms spontaneously pop into existence as well, but he didn't, so he had to explain where helium is produced. His answer was that helium, as well as all the other elements other than hydrogen, are produced in *stars.* It was already known that stars do turn hydrogen into helium; this process, nuclear fusion, is how stars like the Sun produce their energy. What Hoyle did was to show that all the elements heavier than helium, from carbon to uranium, are also produced in stars. This turned out to be correct and Hoyle is regarded as a pioneer in the study of the origin of the elements. There is a certain irony here. Gamow set out to explain the origin of the elements in the Big Bang and failed; Hoyle sought to explain the origin of the elements in the stars and succeeded; yet today the Big Bang Theory is considered a success, while the Steady State Theory has been relegated to the dustbin of scientific history.

The Big Bang Theory triumphed because it fit the evidence better. Scientific controversies are decided by the inexorable wheels of the Scientific Method, rather than by polls, elections, or coups. Theories are tested by using them to make *predictions* about new observations which can be made when the technology to do so becomes available. The Big Bang Theory and the Steady State Theory made two major differing predictions about the Universe:

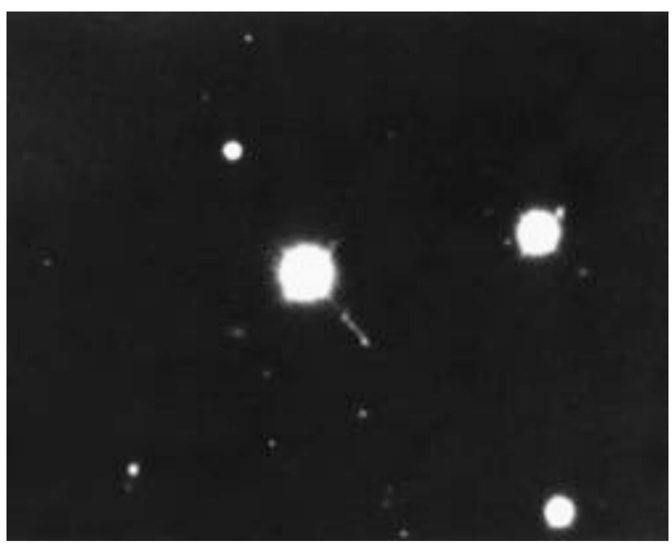
1. The Universe looks the same at all times in the Steady State Theory, but changes in the Big Bang Theory.

2. The Big Bang Theory predicts the existence of the Cosmic Microwave Background (CMB), the leftover of the fireball of the Big Bang. The Steady State Theory makes no such prediction.

In the 1960s the technology became available to test these predictions.

Quasars

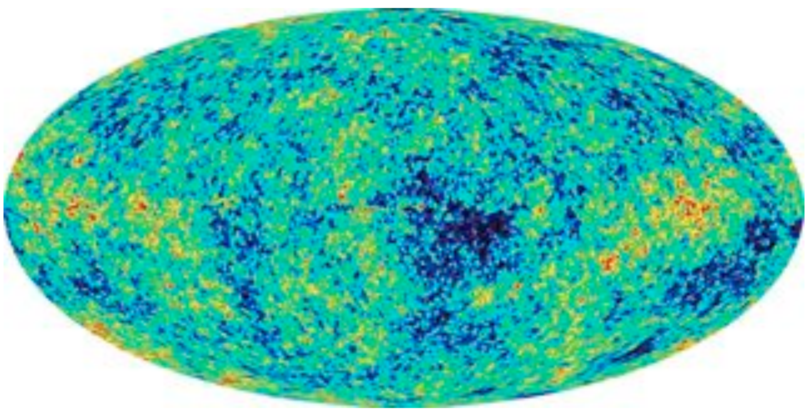
The first bad news for the Steady State Theory was the discovery of **quasars** in 1962. Quasars confounded astronomers because they looked like stars in the telescope but turned out to be galaxies at great distances. The way astronomers knew they were far away was that their spectral lines were shifted far toward the red. Even the closest quasar, 3C373, is a *billion* light-years away. Yet it is a fairly bright object, easily visible in an amateur telescope. Most quasars are even farther away. To be so bright and so distant means that quasars must give off thousands of times as much light as ordinary galaxies. Furthermore, there were indications that this incredible energy came from a small region about the size of the solar system. What energy source could possibly provide that kind of power is such a small space? Although many ideas were considered, only one has survived the test of time: quasars are powered by *supermassive black holes.*



Now, the mere existence of quasars didn't contradict the Steady State Theory. However, the Steady State Theory did predict that quasars, like anything else, should be equally common at all times—otherwise the Universe is changing, which contradicts the theory. Now the thing about quasars is that they are so bright, they can be seen at great distances, and objects at great distances are far back in time. In this way, astronomers discovered that quasars were much more common in the first few billion years than they are today. That discovery flatly contradicted the Steady State Theory.

The Cosmic Microwave Background

The event that was the nail in the coffin for the Steady State Theory was the discovery of something called the Cosmic Microwave Background, the Cosmic Background Radiation, or simply the 3-degree Background. Whatever you call it, it is the leftover from the fireball of the Big Bang, while the Steady State Theory fails to predict its existence.



For the first few thousand years, the Universe was one enormous star: hot, glowing gas filled all of space. As space expanded, the gas became cooler and less dense. During this period there were no *atoms* in the Universe. There were protons, electrons, and helium nuclei, but they had not yet combined to form atoms, because it was too hot. When the Universe was about half a million years old, the temperature cooled to the point where the protons and nuclei started capturing electrons to form atoms for the first time. This event is called **recombination,** which is a bit illogical, since the atoms had never been combined before!

Light

At the time of recombination, the Universe was filled with light. To understand what happened next, we need to understand something about light. Light is wave of electric and magnetic energy traveling through space. You can picture it like a wave in the ocean. The distance between the wavecrests is called the **wavelength.** It is the wavelength that determines the color of light. If you look at a rainbow, you see the pure colors: red, orange, yellow, green, blue, indigo, and violet. (Nobody really knows what color indigo is; it was inserted between blue and violet so that we could use the mnemonic ROY G BIV to remember the order of the colors.) Red has the longest wavelength and blue has the shortest wavelength. For visible light, the wavelengths are very short, measured in *billionths* of a meter. A billionth of a meter is called a **nanometer (nm).** The wavelength of visible light ranges from about 700 nm on the red end to about 400 nm on the violet end. That doesn't mean there isn't light with wavelengths longer than 700 nm or shorter than 400 nm; it just means that our eyes can't detect such light. Light that is longer than 700 nm is called **infrared** light; lighter shorter than 400 nm is **ultraviolet** light.

Radio waves, microwaves, X-rays, and gammas rays are also forms of light. Radio waves and microwaves have wavelengths longer than infrared light; X-ray- and gamma rays have wavelengths shorter than ultraviolet light. Together, all the forms of light are called the **electromagnetic spectrum.** All of the different kinds of light travel at the speed of light.

Effect of the expanding Universe on the light

Now back to the Big Bang. When the Universe was a half million years old, it was red hot and filled with visible light. As the Universe continued to expand, the light was stretched as it traveled through space—its wavelength got longer. The visible light became infrared light and the infrared light became microwaves. Today that light exists as a sea of microwaves that fill the Universe. The wavelength of the microwaves is about 1 mm. This is the wavelength of microwaves given off by a star at a temperature of three degrees above absolute zero, or 3 degrees Kelvin (3 K), so it's often simply called the "3 degree background."

The existence of the Cosmic Microwave Background had been predicted by Alpher in the 1940s, but at that time the technology didn't exist to detect microwaves of that wavelength. The prediction was forgotten until the Background was accidentally discovered by two engineers working for the phone company, Arno Penzias and Thomas Wilson, working at Bell Labs in New Jersey in 1964. The discovery earned them the Nobel Prize for Physics in 1978.

The discovery of the Cosmic Microwave Background was a tremendous triumph for the Big Bang Theory. It was the end of the line for the Steady State Theory. Hoyle and others continued to defend it to the end, but the Steady State Theory gathered no more adherants and gradually faded into history.

It's not up to human beings to tell Nature what to do. All we can do is observe, perform experiments, and try to figure out what Nature is telling us. And Nature is telling us that the Universe started with a Big Bang.