

Krister Sundelin

E-learning Producer (2020–present)

How do scientists know the Big Bang is real?

Q: How do scientists know the Big Bang is real?

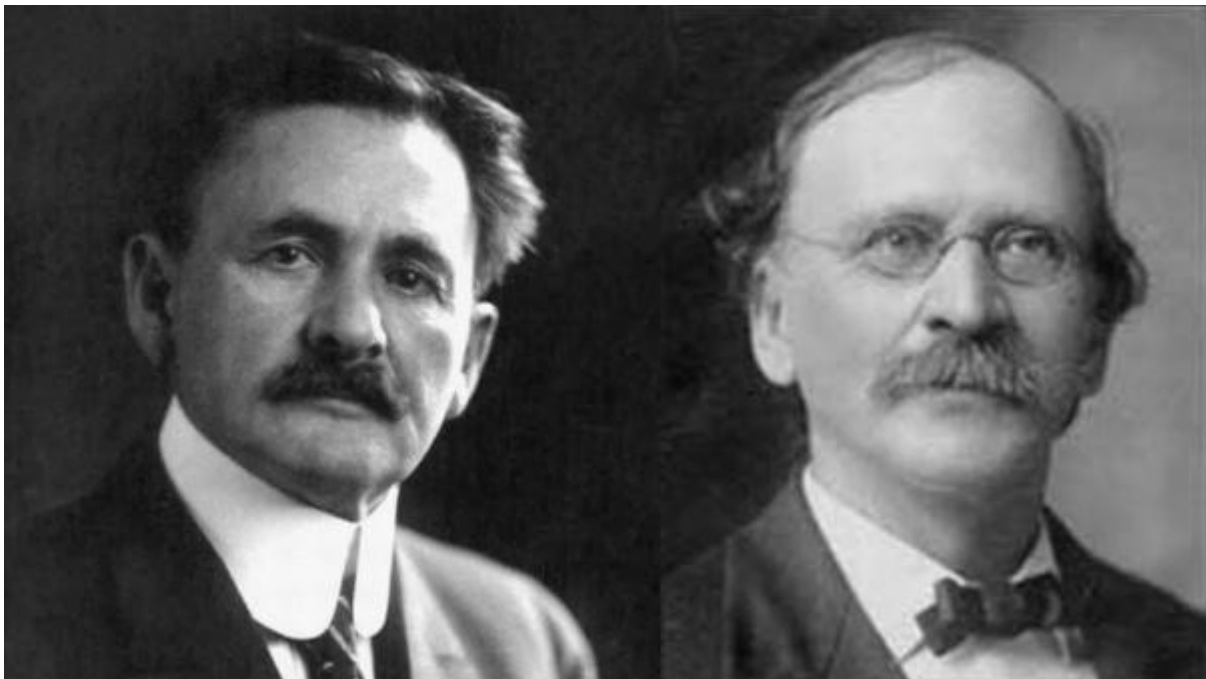
A: It's a long story, so I apologise for the wall of text. But basically, it's about the evidence.

In essence, the Big Bang Theory – which actually is a bad name (we will come back to that later) – explains how the universe got from a hot dense state in the distant past, to the cold empty state we see now.

To explain the evidence, we have to go way back in time, to when science thought that the Milky Way Galaxy was all there is and that it had been around forever without a beginning, banging or otherwise.

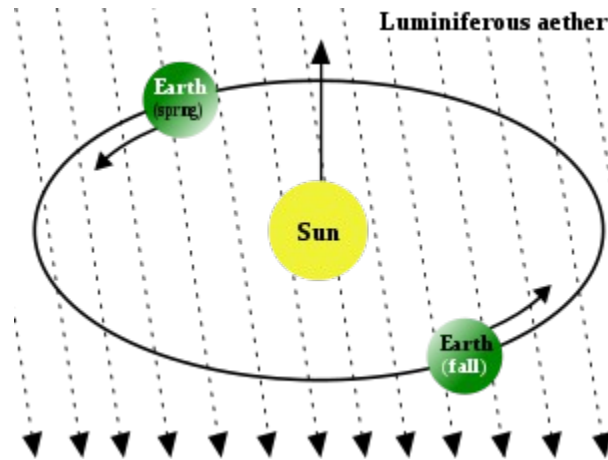
Chapter one: The speed of light

I could probably go back all the way to Newton and the apple, or Michael Faraday and James Clerk Maxwell, but that may be too far back. So say hello to these guys:

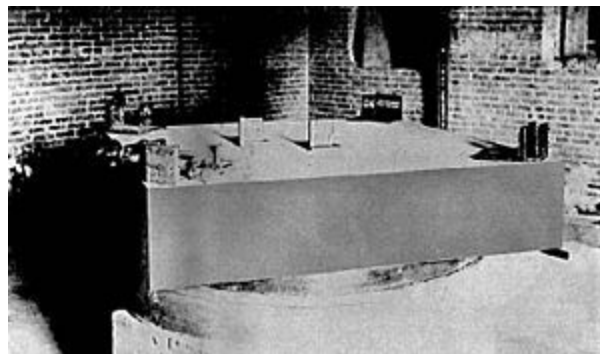


That's **Albert Michelson** and **Edward Morley**, and in a famous experiment they proved that light moved at the same speed regardless of frame of reference.

Thanks to Ernst Mach, and the above mentioned Faraday and Maxwell, scientists thought that light moved as a wave. But through what? That something that waves travel through was called "luminiferous aether", and Michelson and Morley tried to prove that there was such a thing. Since the Earth also moved through this luminiferous aether, it would mean that the light should be faster in some directions than in others.

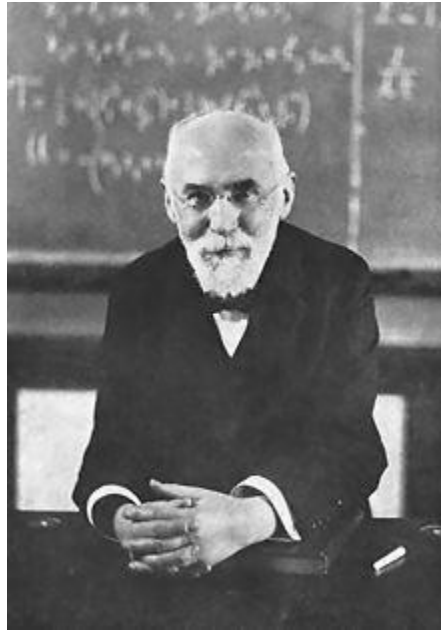


They built a really sensitive device to measure the difference in speed in two different directions, and found ... nothing.



So they redid the experiment, twisted the apparatus and still found ... nothing. No speed difference at all. Light seemed to move at the same speed regardless of direction.

That lack of evidence for the luminiferous aether is actually a pretty important piece of evidence, because it brings us to this guy:

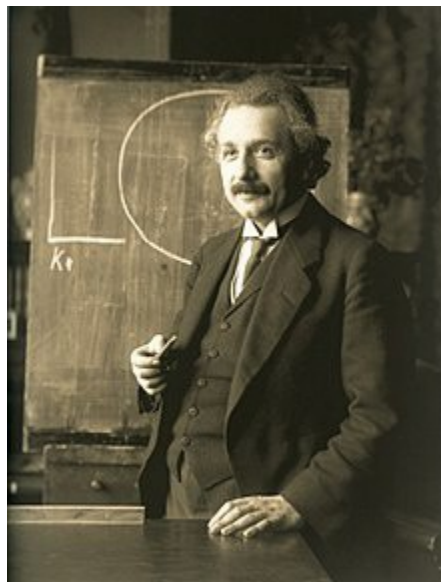


That is **Hendrik Lorentz**, and he produced the Lorentz transformation to explain mathematically the lack of results of the Michelson-Morley experiment and how light could appear to travel at the same speed regardless of direction, thus allowing the idea of luminiferous aether to live on for a while. All that was needed was an invariant of some kind, relative to which length could apparently contract. This way the speed of light could appear to be the same.

He just had one thing wrong: that the invariant was something else.

Chapter two: The bendiness of space

This is where this guy enters the story:



Yes, **Albert Einstein**. We just had to get to him at some point in our story.

The reason that he enters the story is that he finally got rid of the luminiferous aether. He postulated that light did not just appear to move at the same speed, but actually was the invariant Lorentz was looking for, and always moved at the same speed *regardless of the frame of reference*. Using the Lorentz transformations, he formulated *special relativity* of how speed and acceleration affected your frame of reference (and also that nothing can go through space faster than light), and then later *general relativity* of how gravity also affected your frame of reference.

In general relativity, he treated space and time as one unified spacetime, which could be stretched and bent by mass. He thought of gravity as not an attracting force as Newton had, but as a curvature in spacetime, and set up a number of equations to describe how it happened.

This idea was so weird that he didn't get a Nobel Prize for it. The Nobel committee realised that the theory of relativity was something important, so Einstein got a Nobel Prize for his discovery of the photoelectric effect, the thing that makes the camera in your smartphone possible, as a kind of consolation prize.

Scientists in general were much more impressed, especially after the discovery of this guy:



That is **Sir Arthur Eddington**, and in 1919, he showed the curvature effect of gravity during a solar eclipse by photographing how the apparent position of stars shifted near the Sun.

Speaking of Eddington and going back to the Nobel Committee's inability to understand general relativity, there is a joke about him, when a journalist told him that there were just three people in the world who properly understood Einstein's theory of relativity, and asked him what he thought of it. Eddington sucked on his pipe, pondering the question, and finally replied "I'm trying to figure out who the third person would be."

That "third person" could very well be this guy:



That's **Alexander Friedmann**, and like every other scientist in the day, he fiddled with the theory of relativity. He found a solution to general relativity that the universe was not static. In fact, it could not be static!

Still with me? Great, because this is where we *finally* enter Big Bang territory.

Specifically, we get to this guy who wondered what would happen if the universe actually wasn't static.



No, not the guy with the wild hair. That's just Albert Einstein again. The guy to the right is **Georges Lemaître**, Belgian astronomer, mathematician, physicist and Catholic priest.

So Lemaître did the math, and concluded in 1927 that not only was the universe not static, but it also had a beginning where the universe was very small. He called it the “ur-atom” or the “cosmic egg”. Unfortunately, people scoffed at him. Even Einstein dismissed Lemaître’s prediction from his own equations at first.

Chapter three: The expanding universe

Let us stop here and look at what science thought about the universe in about 1927:

1. The universe was static, despite Lemaître and Friedmann. The universe had not changed since literally forever. A universe with a beginning was something out of religion.
2. The universe consisted only of the Milky Way galaxy, beyond which there was nothing.

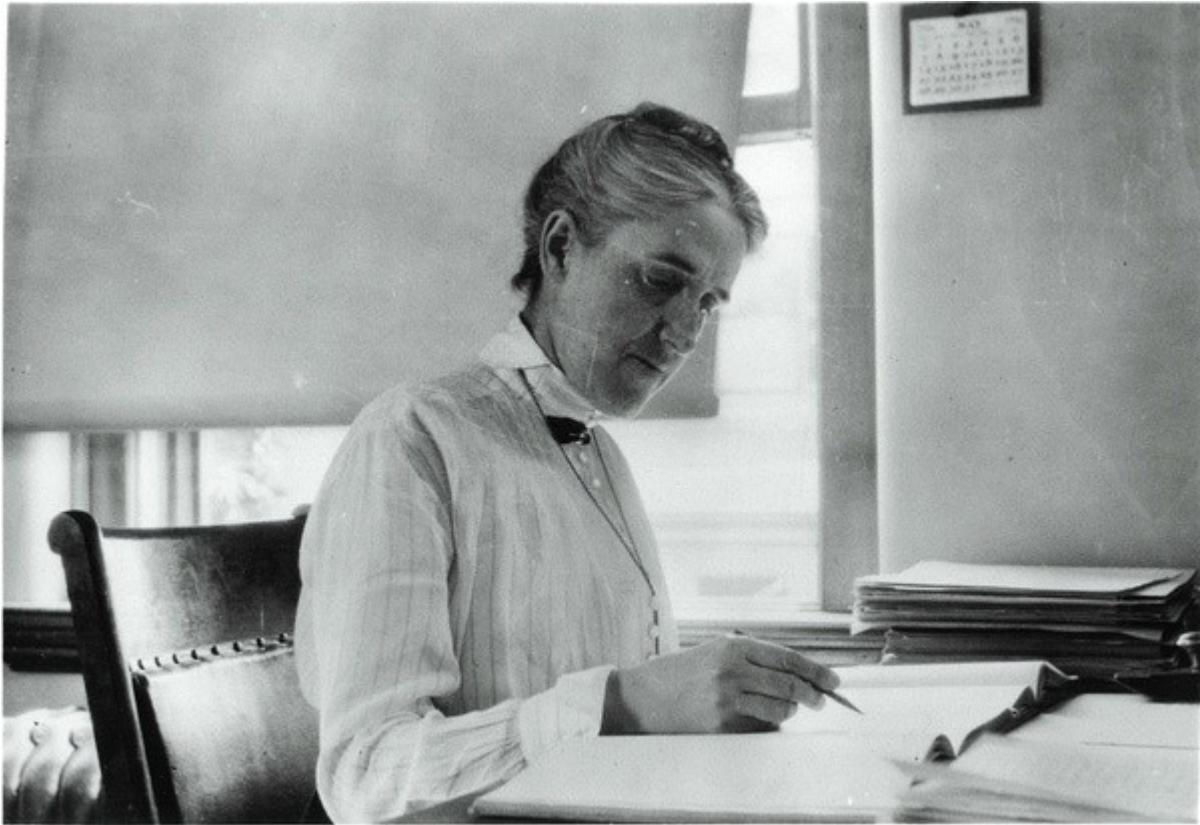
Now, we come to a point where it shows that there is hope for all of us, in the form of this guy.



That’s **Edwin Hubble**, after whom the Hubble Space Telescope is named. Edwin Hubble was a lawyer, but he turned into an astronomer instead, and started to observe the skies. One of the things he did was to show that the fuzzy thing that we had called the Andromeda Nebula (“nebula” means “cloudy or

fuzzy thing”) wasn’t a nebula at all. It looked like a galaxy. And it had cepheids in it.

And that brings us to this woman:

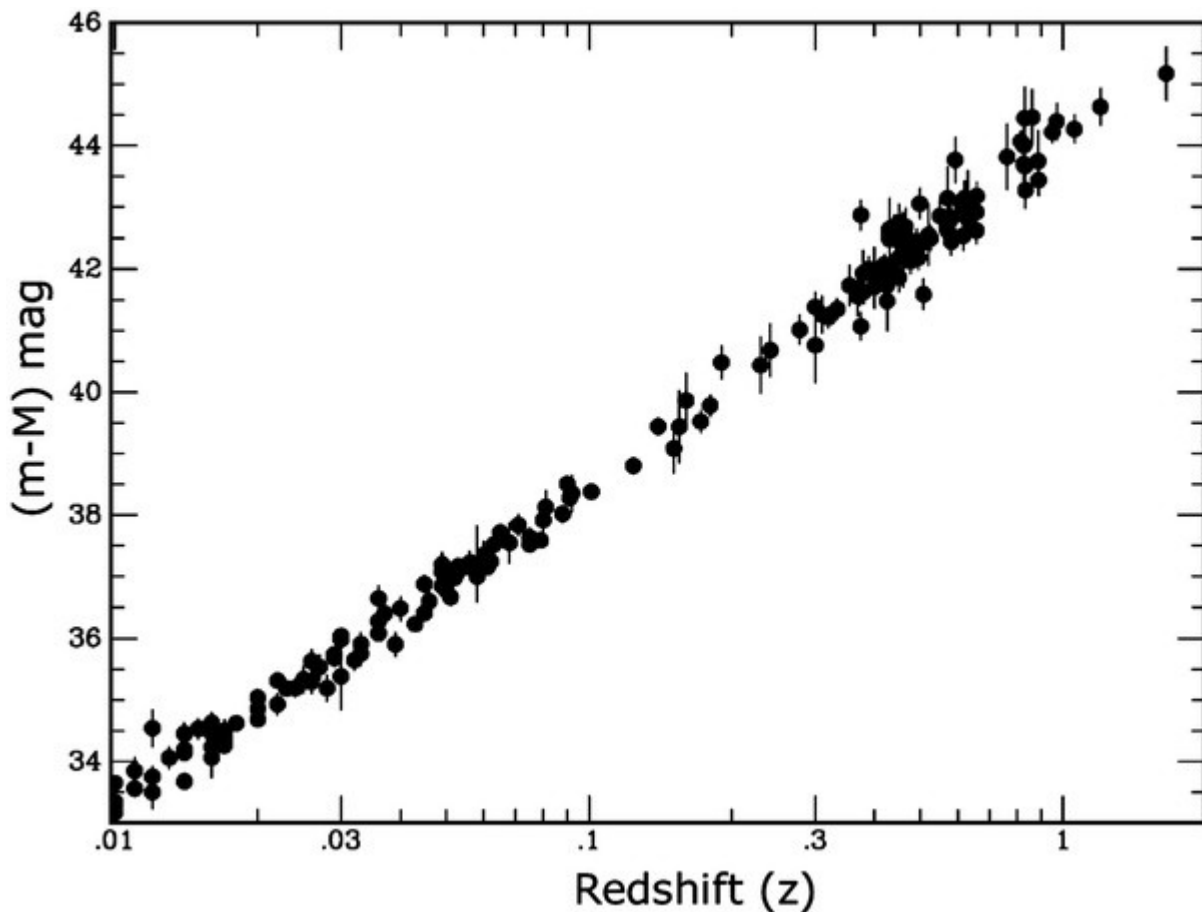


That’s **Henrietta Swan Leavitt**, and she made an important discovery about cepheids. Cepheids are variable stars that appears to blink. Leavitt’s discovery – now known as Leavitt’s law – is that the variance period and luminosity are linked. If you know the period, you know how bright it is or how much light it sends out. The longer the period, the brighter the star.

If you know how much light it sends out, you can use it as a “standard candle”: measure how bright it appears in your telescope, and then you can use the inverse square law to figure out how far away it is.

Hubble used Leavitt’s law, and conclusively proved that the Andromeda Galaxy was way outside the Milky Way, and as such it had to be its own galaxy.

Not only that, he also discovered a lot more galaxies. And he discovered that almost all of them were redshifted more or less, indicating that they were moving away from us; and that the further away they were, the faster they went away from us.

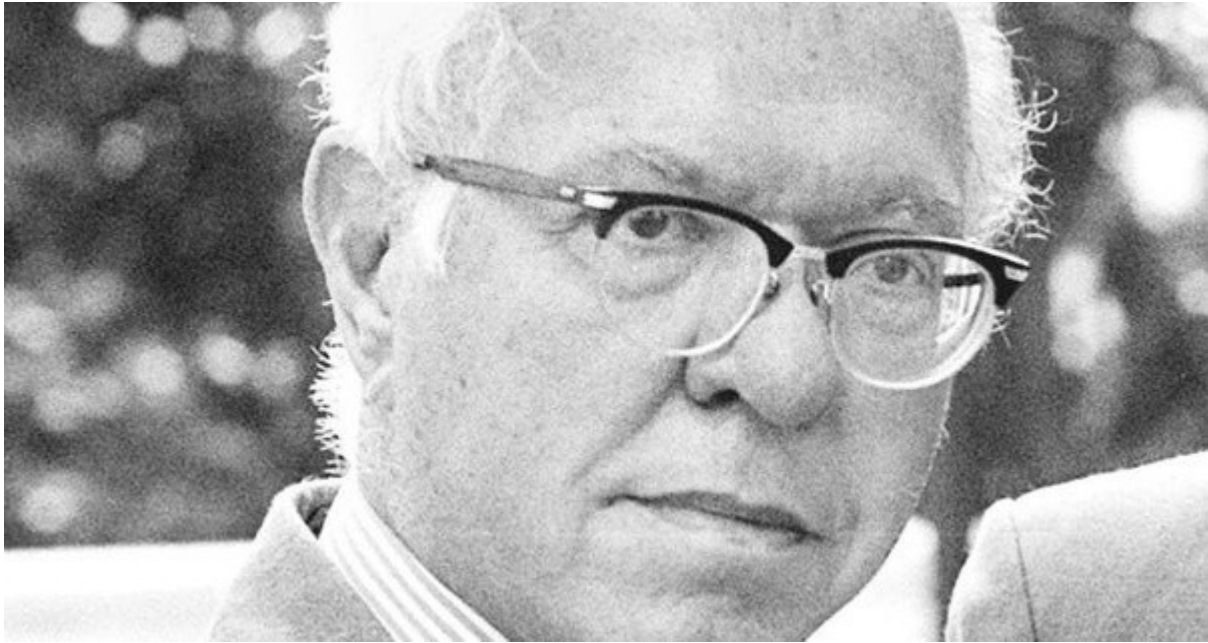


One side note here: the further away something is, the older the light we're observing. If we look at something three million light years away, the light we see now left that something three million years ago. So if we can determine the distance to a thing, we can also determine the age of that light.

But back to the redshift and that distant objects seemed to be more redshifted and thus moving away faster. Hubble made his most brilliant deduction: everything is rushing away from everywhere else. The universe is expanding, just like Lemaître said.

This led to three things. First, Einstein apologised for dismissing Lemaître. Second, Einstein stopped looking for a cosmic constant, and called it his biggest mistake ever. And third, the astronomical society split right down the middle: one part in support of a static universe, and the other in support of an expanding universe.

One of the scientists still in support of a static universe was this guy.

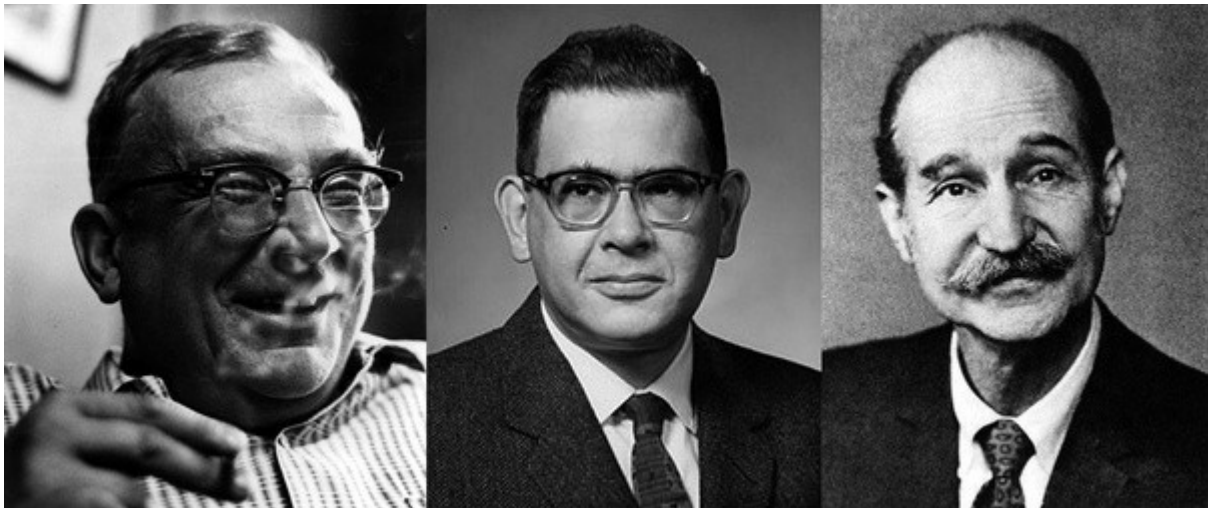


His name is **Fred Hoyle**, he was an atheist, and he was the one that invented the term “Big Bang” on radio in 1949. Hoyle died in 2001, and never accepted the Big Bang theory.

Sadly, the name stuck. This is unfortunate, since the consequence is that everyone now imagines that the big bang was a giant explosion in space, which it is not. It is an expansion of space.

Chapter four: The afterglow of the bang

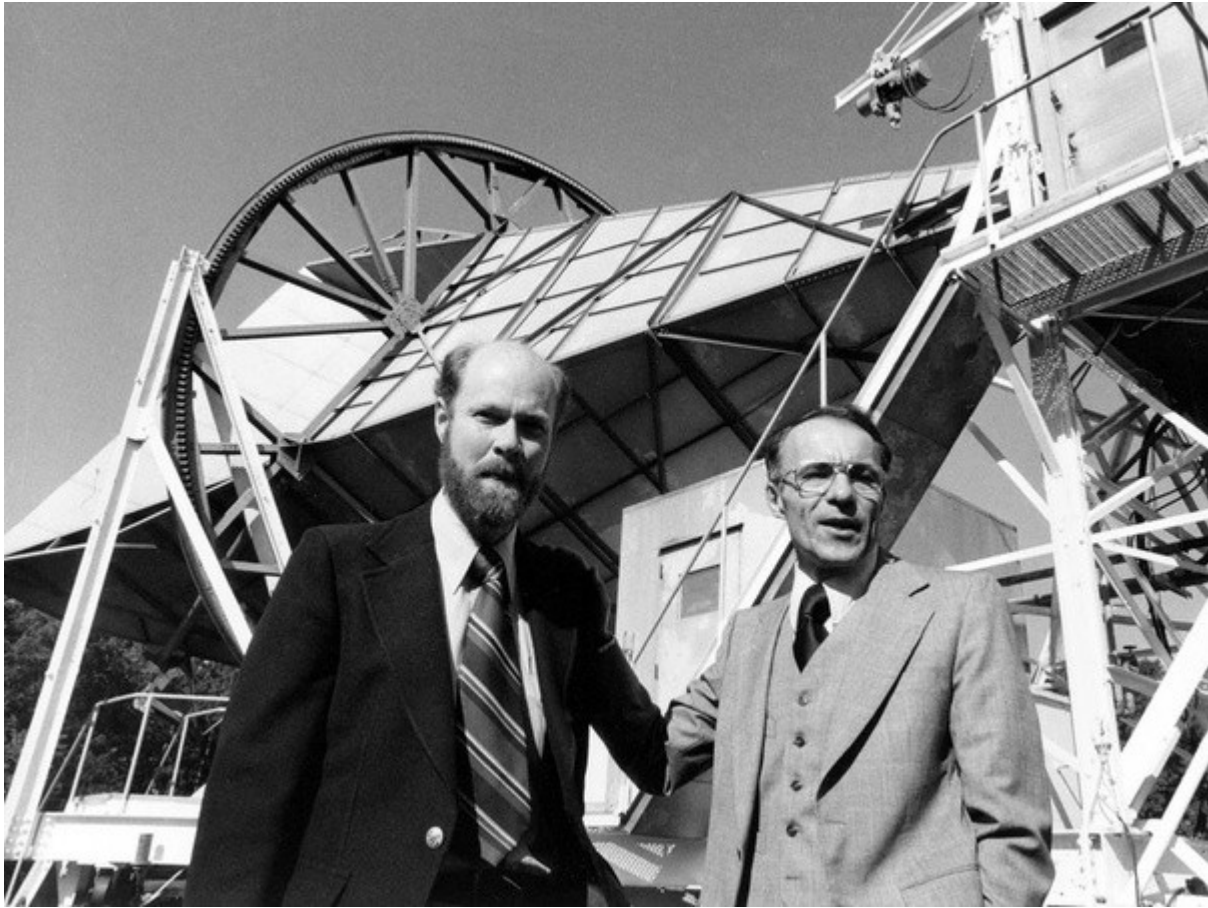
Many other scientists accepted the Big Bang eventually, though. Say hello to these three guys:



This merry trio is **George Gamow**, **Ralph Alpher** and **Robert Herman**. In 1948, they predicted that if there had been an ur-atom in which all matter in the universe exists, then for a period of time after it expanded, the universe must have been so hot and dense that everything in it must have been a plasma. Plasma is very opaque, so you can't see anything through it. Only when the universe cools down so much that plasma can become atoms would the universe be transparent. This is sometimes called “the

surface of last scattering”. This surface should have a blackbody radiation of heat at this stage. That radiation should still be here, but spread out and redshifted to microwave wavelength with a temperature of about 5 Kelvin.

And these two guys found it:



That’s **Arno Penzias** and **Robert Woodrow Wilson**. In 1964, they were using that strange contraption behind them to find out where the hiss in your old AM/FM radio and the “snow” in your old analogue television set came from when you set them to a dead channel. After ruling out things like the sun, the Milky Way, and pigeon poop, they discovered that it came from, well, everywhere, and that it had a temperature of about 4.2 K in the microwave spectrum. It was still a bit off – the actual temperature is about 2.7 K.

They got a Nobel prize for it: they had just showed beyond reasonable doubt that the universe had been expanding.

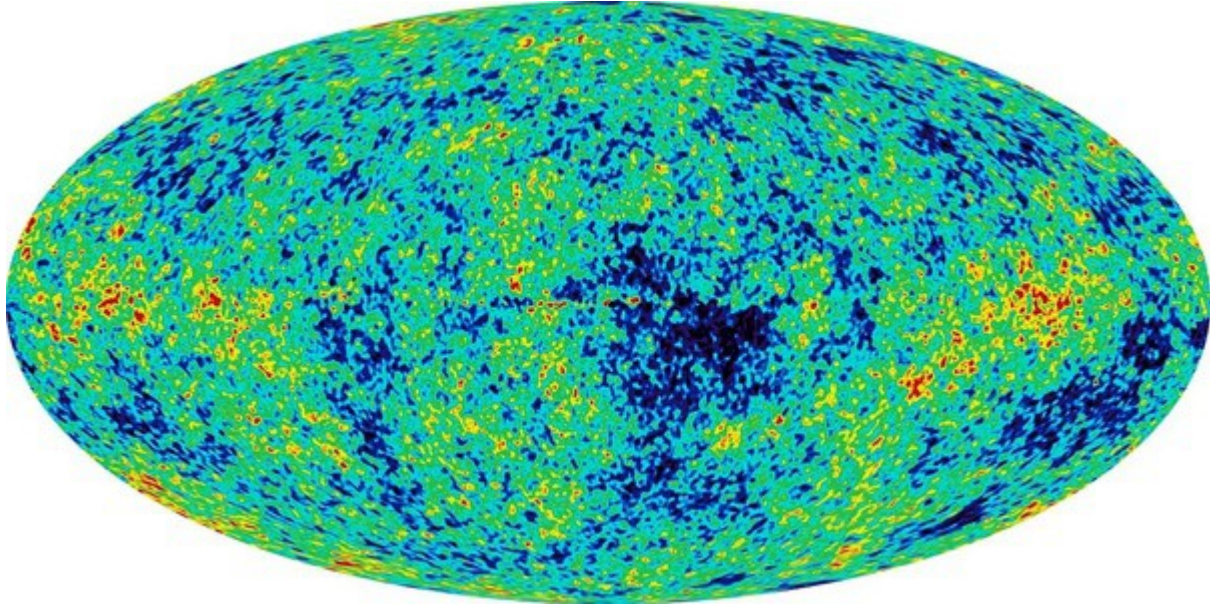
But things in the universe has a mass, and mass attracts mass through gravity. So much like a rock thrown straight up will slow down (eventually it will either leave Earth’s gravity influence, or it will fall down again), the universe ought to slow down. It may go on expanding forever, slower or slower, or it may start collapsing to a Big Crunch.

Let’s again stop to review what science thought about the universe in the 1960s-1970s:

1. The universe had a beginning, around 10–15 billion years ago.
2. The big question was whether it would expand forever but slower and slower; whether it would eventually stop; or whether it would collapse on itself in the distant future.

Chapter five: Late-comers to the party

After that, bigger and better telescopes – one of them in space and bearing Hubble's name – have been used to measure speed and distance to more and more distant galaxies. We have made better measurements of and even mapped the microwave background radiation.



This has introduced a new mystery: the microwave background is incredibly even: the cold blue spots are about 0.015 K colder than the average, and the hot red spots are about 0.015 K hotter than the average. How could the universe be so even, and what did these minute differences mean?

And why is this a problem? Well, even when the microwave background cleared up, the universe was really big. So big, in fact, that there had not been time for the temperature to even out.

This guy proposed an answer:



That's **Alan Guth**, and he had an idea that is still radical among cosmologists and kind of accepted because there is no other idea at the moment: in the earliest moments of the universe, between 10^{-36} and 10^{-32}

seconds or thereabouts, the universe inflated very rapidly – many times faster than the speed of light – from the size of an atom to the size of a grapefruit.

“*Wait a minute,*” I hear you say, “*I thought that nothing could go faster than light?*” Well, almost – nothing can move through space faster than light, but space itself doesn't have a speed limit. Space can go as fast as it wants.

Anyway, Guth's proposal would not only explain how the microwave background is so even – it had the time to even out before it inflated – but could also explain the minute differences that existed, from quantum fluctuations before the inflation that got frozen when the universe inflated.

The weakness of cosmic inflation is that we don't know what caused it to happen or the force behind it. But it kind of explains what we see, so cosmologists grudgingly accept it until someone has a better idea.

But no matter how the minute differences came to be, they allow us to determine the age of the universe with great precision. The current measurement is at about 13.8 billion years.

We have also tried to weigh the universe, through gravitational lensing and measuring galaxy formation, and concluded that the universe weighs too much. There seems to be some mass there that we can only detect through its gravitational influence, and there's a lot of it: five times more than regular observable matter. We have dubbed it “dark matter” as a placeholder name: “dark” because we can't observe it directly, and “matter” because whatever it is, it has gravity.

Not only that, we have also looked at the conditions before the surface of last scattering, by simulating the conditions of that age using particle colliders. We have also measured the curvature of space, which is important to predicting if there will be a big crunch or forever expansion.

One peculiar observation was that galaxies seemed to be speeding up, meaning that the expansion of the universe is accelerating! So the old prediction of a slowing expansion was wrong.

That's where we are today: we get better and better measurements of the age of the universe, and we have an entirely new mystery to explore: why the expansion is speeding up. We don't know why, but whatever it is that causes the accelerating expansion has been named “dark energy” as a placeholder name: “dark” because we can't observe it directly and that it is unknown, and “energy” because it ought to take energy to speed things up.

One final review of what science today thinks about the universe:

1. The universe had a beginning, around 13.8 billion years ago.
2. There was a period of inflation at the earliest moments.
3. The expansion of the universe is speeding up.
4. *And what the heck is this dark matter and dark energy?!!*