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The cosmic microwave background – the afterglow of the Big Bang – is loaded with clues about how the Universe formed

The remains of CREATION

UNDERSTANDING THE CMB

Left over from the Big Bang, the cosmic microwave background gives astronomers an insight into the entire history of our Universe. **Ezzy Pearson** explains

ILLUSTRATION
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Light is the window through which astronomers view the cosmos. It fills the Universe. Once light has been emitted, it travels on and on, moving constantly at the speed of light. It only stops when it hits something, be it a gas particle, a planet or even a black hole.

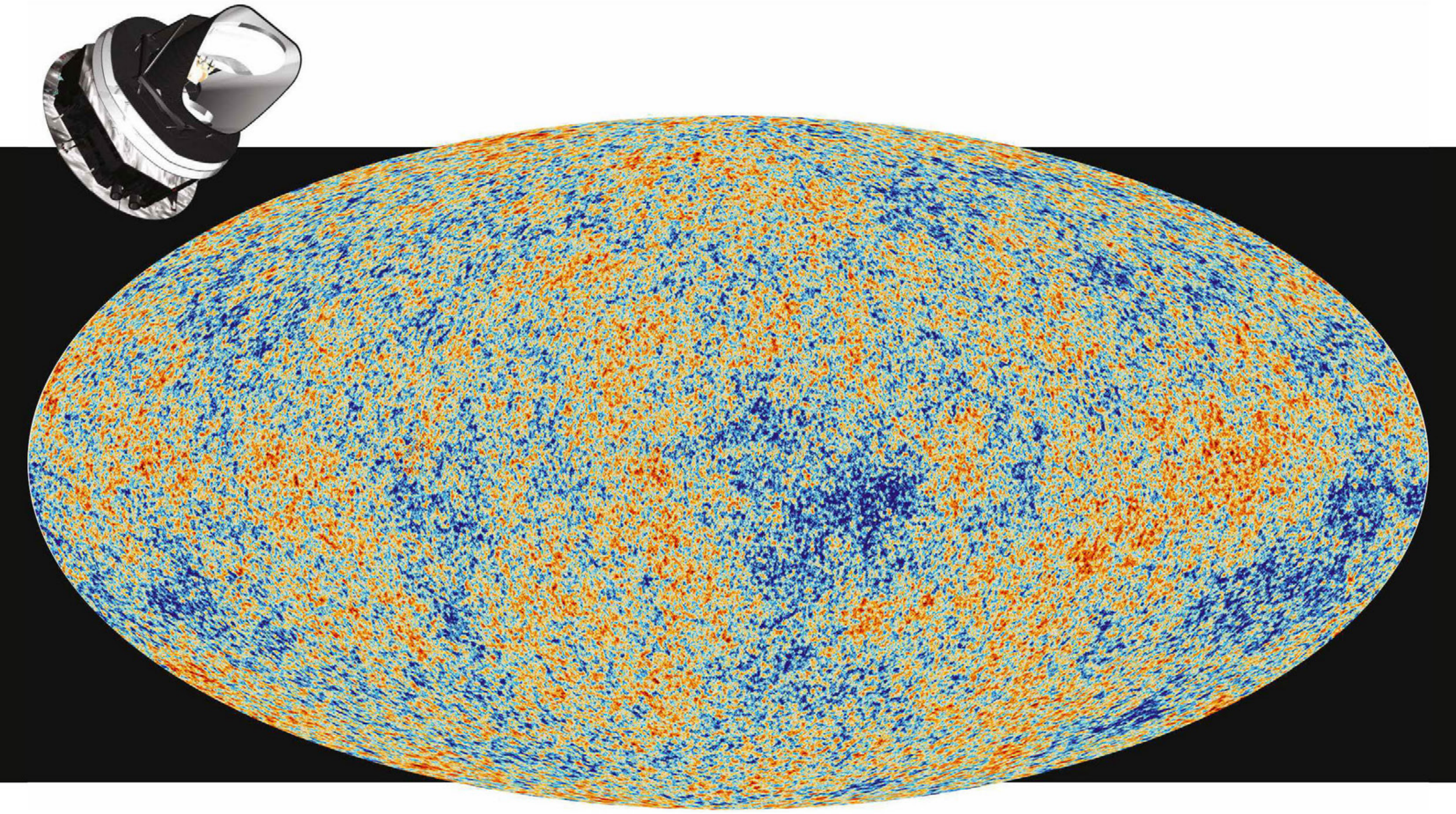
Because of light's eternal nature, we see distant galaxies not as they are now, but as they were when their light was emitted. If it has taken the light from an object a billion years to reach us from a galaxy, then we see that object as it was a billion years ago. Look far enough away, and you could view all the way back to when the first stars began to shine.

Look back even further and it's possible to see light from the very earliest days of our Universe's existence, which we see now as the cosmic microwave background (CMB).

"The simple way to explain the CMB is as the very first light ever emitted in our Universe," says Erminia Calabrese from Cardiff University. "It's been travelling from that moment all the way to today."

In the beginning...

The Big Bang theory states that in the very first moment of the Universe, all the energy and matter of the cosmos was at an infinitely dense point. In the initial fractions of a second of existence, this rapidly expanded, cooling as it went. When the Universe was a second old, it was cool enough for that energy to take on the form of matter particles – such as protons, neutrons and electrons. It also formed light particles known as photons, setting the entire Universe aglow long before the first stars began to shine. ▶



▲ **In 2013, the Planck mission captured the CMB, imprinted on the sky when the Universe was just 380,000 years old, in greater detail than ever before**

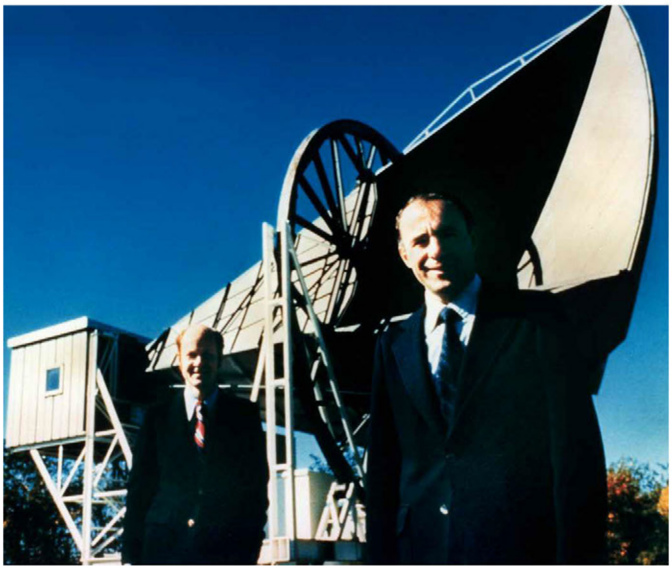
▶ Within the first few minutes, protons and neutrons joined together to form positively charged nuclei, but the negatively charged electrons were so hot they could evade being caught. They floated free and so were able to easily absorb and re-emit the light photons that filled the cosmos. For over 380,000 years, the Universe was filled with an impenetrable fog that prevented light from travelling more than a few fractions of a nanometre.

Then came a time known as Recombination. The Universe had cooled enough that electrons could no longer escape the electromagnetic pull of nuclei and were captured, forming the first hydrogen and helium atoms. Locked away, the electrons no longer absorbed photons, so light could traverse the now transparent cosmos. This was the moment when the CMB was formed.

For the next 13 billion years, this light has journeyed through the stars, but it has not remained unchanged. The very fabric of space-time has expanded during this time, stretching the light travelling through it. This increases its wavelength, meaning visible light has become redder. The radiation from the Big Bang has been travelling for so long it's been stretched beyond visible wavelengths, through the infrared, to become microwave radiation.

This radiation exists everywhere in the Universe, travelling in every direction, but what we see as the CMB is the light that originated over 13 billion years ago, and is only now reaching us. The presence of this radiation was predicted in the 1950s, but it wasn't actually discovered until 1964.

Even then, radio astronomers Arno Penzias and Robert Woodrow Wilson at the Bell Telephone Laboratories in the USA initially thought the signal was an error in their equipment. But when they reported it as a "radio transmission of unknown origin", theorists immediately recognised the signal they'd been looking for. Cosmologists have been mapping the CMB in increasing detail ever since.



▼ **Arno Penzias and Robert Woodrow Wilson were the first to detect the CMB in 1964**

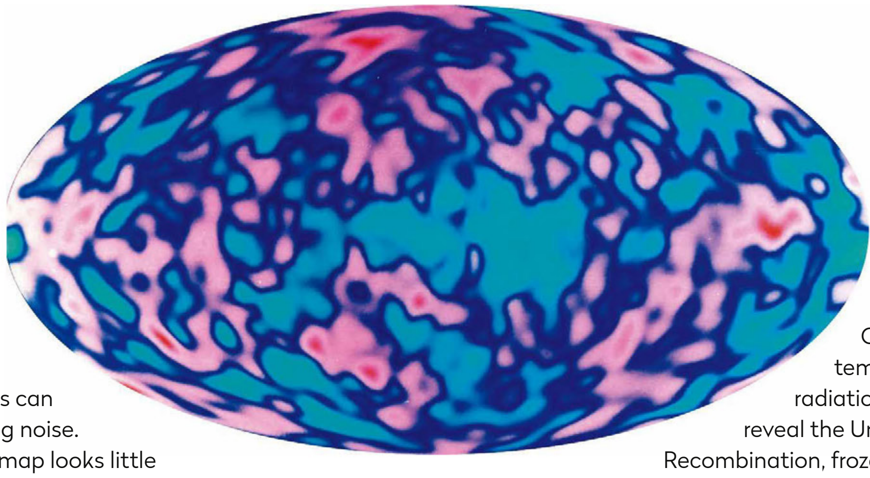
Noise reduction

"We have entire teams and institutions that simply focus on designing the technology and instrumentation that is required to go after these tiny signals," says Calabrese. "There is a huge effort in developing very precise cameras and sensors that you then put on very advanced telescopes, either on the ground or that you launch into space with a satellite."

Early maps could only make out the vague shape of these regions, but the most recent map by ESA's Planck satellite contains a striking amount of detail. Revealing this detail is somewhat of a challenge however, as it is buried under all that the CMB has passed through during its 13-billion-year journey through space. The movement of our Galaxy and the dust within it are just two sources of noise that change and twist the view of the CMB we see. In fact, the CMB is just a tiny fraction of the initial measurement the telescope picks up. Through meticulous corrections, astronomers can clear away this obscuring noise.

Though the resulting map looks little more than a sea of blobs to the untrained eye, to those that know how to look, these colourful patches reveal the history of our Universe from the first moment of the Big Bang until today.

"Because it's been there forever, from the very beginning all the way to today, the cosmic microwave background has picked up signals and information," says Calabrese. "It's been watching out for us. Sometimes I use the example of your great-great-grandfather who has lots of stories to tell you of all the things they've gone through, and they are now here to tell you all about it."



▲ In the 1990s, NASA's COBE revealed the large-scale shape of the entire CMB, but it lacked fine detail

There are three main areas to examine when looking at the CMB. First is the temperature of the radiation. These fluctuations reveal the Universe as it was at Recombination, frozen in time 380,000 years after the Big Bang.

A journey through time

Then there is the polarisation of the light, which shows how the CMB photons scattered off other particles. This showcases two key epochs in cosmic history. The first is Recombination, when the CMB was set down. The other is known as Reionisation, a time just after the first stars began to shine. Their light ionised the surrounding gas, knocking an electron off each atom so they could interact with light photons again. ▶

Taking a look at the CMB

Examining the CMB is difficult, but astronomers have found many ways to go about it

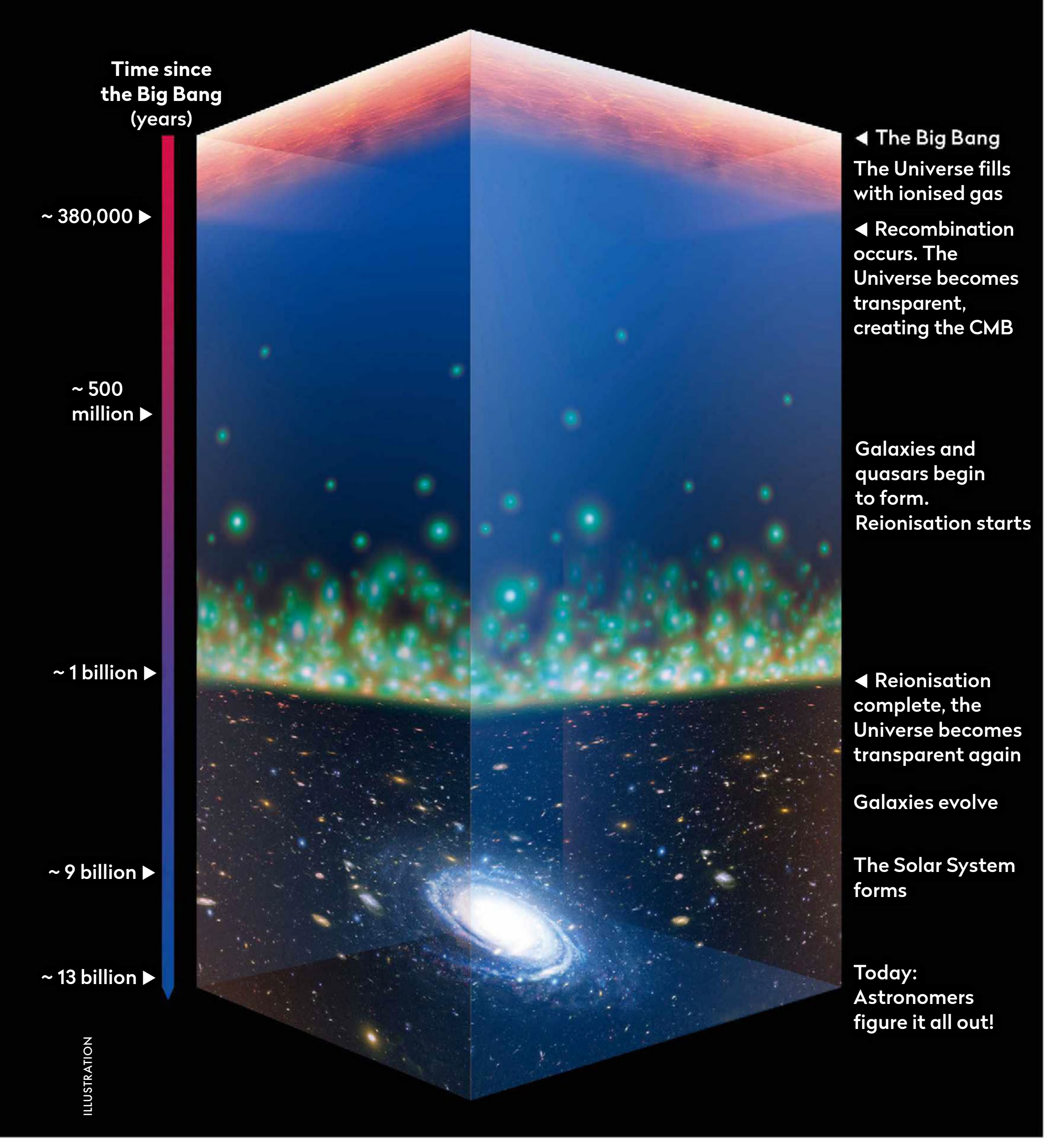
The first observations of the CMB were made from the ground, and there is one big advantage to doing so: the picture can be put together with very large dishes. The larger a telescope is, the greater its resolution, meaning a ground-based telescope can obtain a great amount of detail. However, they are also locked to a single location and so are unable to map the entire sky. Plus, water and oxygen in the atmosphere absorb microwaves, blurring the view. While telescopes built on top of mountains can get past the worst of the atmosphere, the only way to avoid it entirely is to get above it.

One way to do this is to go into space. There have been three such missions to date: NASA's Cosmic Background Explorer (COBE) from the 1990s, the Wilkinson Microwave Anisotropy Probe (WMAP) in the early 2000s and ESA's Planck satellite in the 2010s. A fourth, LiteBIRD, is being developed by the Japanese space agency, with a planned launch by 2030 (see page 14 for details). Such missions can map the entire sky with incredible precision, but they're expensive and their size is limited by what will fit on a rocket.

The final group of observatories split the difference by dangling a telescope from beneath a weather balloon. These can reach altitudes of 50km, where the atmosphere is practically non-existent, and while they can't rival the size of ground-based observatories, they can be made larger than space-based telescopes. The trade-off is controllability: there is no way to steer a balloon, so you are limited to observing from wherever the weather takes them.

What's more, weather balloons can only survive so long before bursting, meaning your telescope has to be able to survive a 50km drop. Most balloon observatories use parachutes to cushion the landing, but even this is fraught. In 2006, one mission's parachute failed to detach once it landed, dragging the telescope across the Antarctic landscape and destroying it.

Balloon-mounted observatories are a cheap, but risky, way to study the CMB



▲ **A brief history of Recombination and Reionisation**

together in those blobs that we see. To understand it, we need to come up with some quantities that then we can more easily interpret."

They do this by conducting a statistical analysis of the maps, examining factors such as the size of the blobs, their temperature or how they are grouped together. But this isn't what cosmologists really want to know. They want to find out what age the Universe is, what kind of matter it's made up of and what rules control how it has grown over time. To be able to extract that information, cosmologists must first create their own universes.

"We write down some very complicated equations and predict what a CMB signal would look like if the Universe had a specific composition, or age, or property," explains Calabrese.

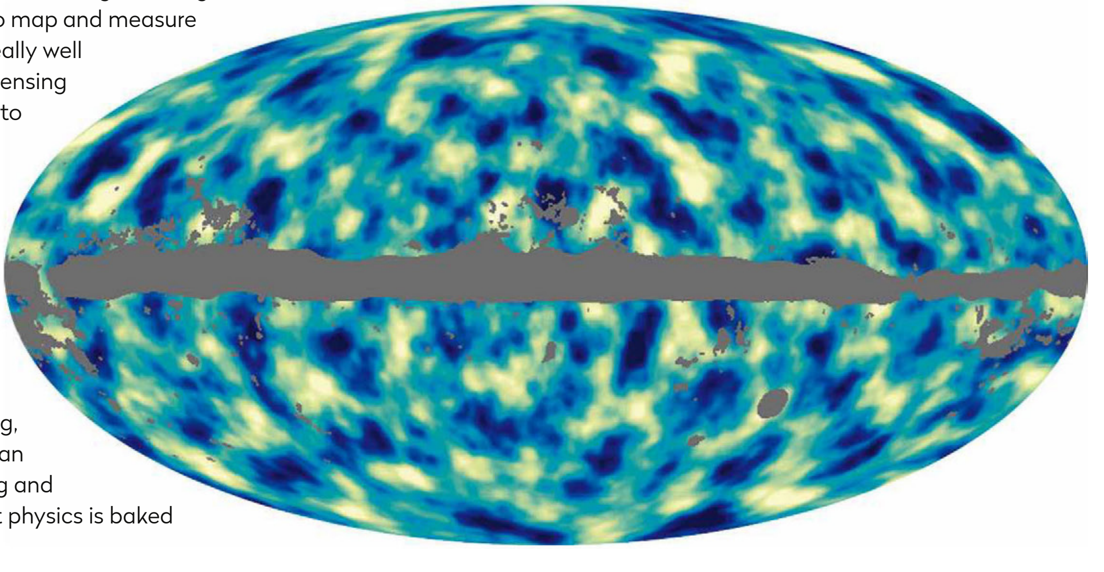
These equations are based on our current understanding of how the Universe operates. Using these, 'model' universes are created that can then be analysed. "You take the model and look at the blob distribution and compare it with your observations. You reverse the process," says Calabrese.

In this way, cosmologists are able to reverse-engineer the properties of our Universe. With increasing access to supercomputers and advancing

▶ Finally, there is the weak lensing signal. The gravity of large objects can bend the path of light travelling past. During its travels, the CMB photons traverse along chains of galaxies and through clusters, all of which deflect the path of photons, leaving their mark on the CMB map.

"This is something that we get by combining temperature and polarisation," says Calabrese. "What this is capturing is all the deviations and fluctuations that these photons felt as they were travelling from Recombination through the large-scale structure. We want to map and measure [the weak lensing signal] really well because the gravitational lensing effect directly translates into the geometry, matter content and distribution of the Universe."

But getting all this information out of the maps is far from a trivial matter, as Calabrese explains. "It's not like discovering a new galaxy," she says. "It's not like saying, I want to find out if there's an object over there and going and spotting it. All the different physics is baked



▼ **An all-sky map showing the lensing effect massive cosmic structures have on the CMB**

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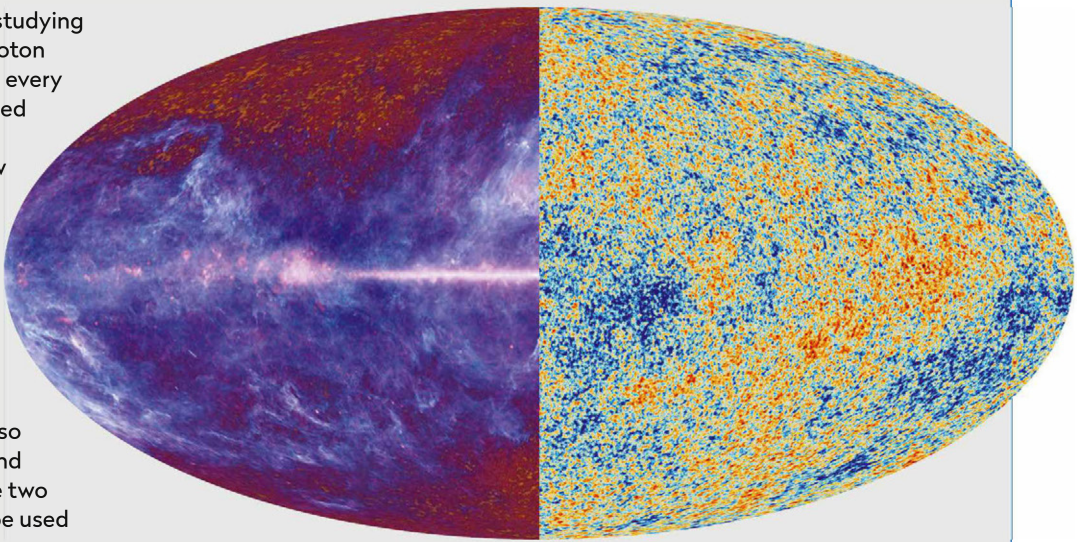
Drowning out the noise

Astronomers have to wade through a sea of information to get to the CMB signal



One of the biggest issues with studying the CMB is noise. Each CMB photon has picked up information from every stage of the Universe it's travelled through, meaning the initial fluctuations make up only a few per cent of the signal picked up by an observatory.

Throughout its journey, a light photon has been bent and distorted by the large-scale structure of the Universe, resulting in the weak lensing signal. This not only changes its path slightly, but also distorts both its temperature and polarisation, and so using these two measurements in concert can be used to extract that signal.

Next, the photon enters our Galaxy, where it encounters a variety of obstacles. The Milky Way's magnetic field again affects the polarisation, which needs to be compensated for. Dust and gas add in more radio waves that pollute the signal, meaning these areas need to be carefully mapped or masked.

▲ **Planck's one-year all-sky survey data from 2010 was initially polluted by bent photons and galactic dust (left), but was carefully cleaned to produce the CMB map**

analytical techniques, they're able to develop ever more detailed simulations to pick apart the increasingly precise maps being produced by every new generation of telescope.

"Over the last two decades we've had a huge jump in quality and quantity of our data," says Calabrese. "That means the answers we get out from them are extremely precise."

Ever-sharper focus

When looking at such huge distances with so many sources of interference, the error margins have the potential to be huge. But while cosmology has historically been a very imprecise science, that is no longer the case.

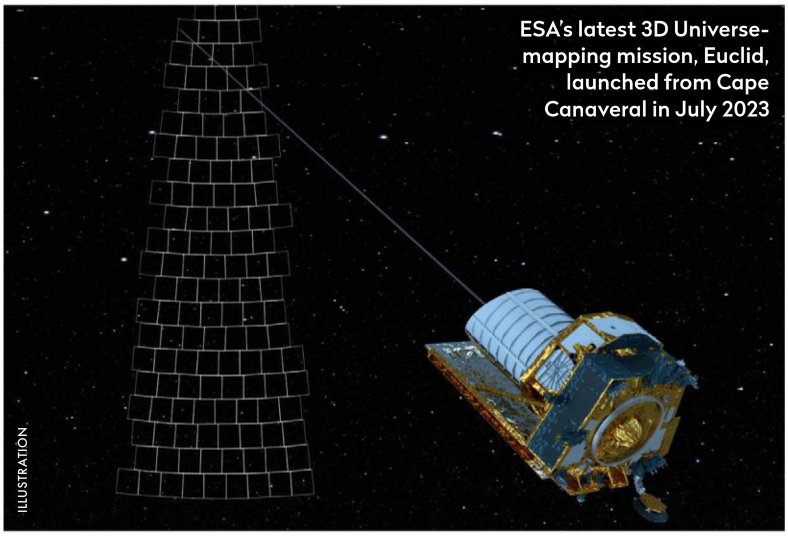
To give one example, when astronomers looked at the data from COBE back in the early 1990s and attempted to determine how much normal matter made up our Universe, they could only say it made up somewhere between 2 and 7 per cent of our Universe's mass. However, when they repeated the measurements with the most recent maps from Planck, they calculated that it made up 2.2 per cent of the overall mass of the Universe, with an error margin of just 0.015 per cent.

"What we see is really an astonishingly perfect agreement between the observations and the models," says Calabrese. "The data is so good that all the key parameters of the model are constrained to sub-per cent precision."

This precision has made the CMB a powerful tool in many other areas of astronomy as well. Upcoming observatories such as Vera Rubin, Euclid and the Dark Energy Survey are all set to map out huge areas of the sky over the next few years. Their aim is to build 3D maps of the Universe to understand the distribution of matter throughout the cosmos – just as the weak lensing data from the CMB will do.

"This will give a lot of opportunities for science across different surveys that will enable things that a single experiment wouldn't be able to do on its own," says Calabrese.

The CMB is a magnificent tool, and through studying it astronomers are able to get closer to understanding the true origins of our Universe with every passing year.



ESA's latest 3D Universe-mapping mission, Euclid, launched from Cape Canaveral in July 2023

Ezzy Pearson is *BBC Sky at Night Magazine*'s features editor. Her book *Robots in Space* is available through History Press