Planck ‘toolkit’ introduction

Welcome to the Planck ‘toolkit’ – a series of short questions and answers designed to equip you with background information on key cosmological topics addressed by the Planck science releases. The questions are arranged in thematic blocks; click the header to visit that section.

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What is the power spectrum?

What is the power spectrum of the distribution of matter in the Universe?

Why are cosmologists interested in the power spectrum of cosmic structure?

What was the distribution of the primordial fluctuations?

How does this relate to the fluctuations in the CMB?

History of structure in the Universe

How did seed fluctuations grow into today's cosmic structures such as galaxies and galaxy clusters?

How did the formation of structure affect the CMB?

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The effect of cosmic structure on the CMB

Did the photons travel freely ever since the CMB was released?

What happens when the Cosmic Microwave Background photons encounter structure in the cosmic web?

Do the CMB photons encounter other particles along their way?

Planck and the Cosmic Microwave Background

What is Planck and what is it studying?

What is the Cosmic Microwave Background?

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How many space missions have studied the CMB?

What does the CMB look like?

What is 'the standard model of cosmology' and how does it relate to the CMB?

Q. What is Planck and what is it studying?

A. Planck is a European Space Agency space-based observatory observing the Universe at wavelengths between 0.3 mm and 11.1 mm (corresponding to frequencies between 27 GHz and 1 THz), broadly covering the far-infrared, microwave, and high frequency radio domains. The mission's main goal is to study the Cosmic Microwave Background – the relic radiation left over from the Big Bang – across the whole sky at greater sensitivity and resolution than ever before. Planck is therefore like a time machine, giving astronomers insight into the evolution since the birth of our Universe, nearly 14 billion years ago.

Q. What is the Cosmic Microwave Background?

A. The Cosmic Microwave Background (or CMB) fills the entire Universe and is leftover radiation from the Big Bang. When the Universe was born, nearly 14 billion years ago, it was filled with hot plasma of particles (mostly protons, neutrons, and electrons) and photons (light). In particular, for roughly the first 380,000 years, the photons were constantly interacting with free electrons, meaning that they could not travel long distances. That means that the early Universe was opaque, like being in fog.

However, the Universe was expanding and as it expanded, it cooled, as the fixed amount of energy within it was able to spread out over larger volumes. After about 380,000 years, it had cooled to around 3000 Kelvin (approximately 2700ºC) and at this point, electrons were able to combine with protons to form hydrogen atoms, and the temperature was too low to separate them again. In the absence of free electrons, the photons were able to move unhindered through the Universe: it became transparent.

Over the intervening billions of years, the Universe has expanded and cooled greatly. Due to the expansion of space, the wavelengths of the photons have grown (they have been ‘redshifted’) to roughly 1 millimetre and thus their effective temperature has decreased to just 2.7 Kelvin, or around -270ºC, just above absolute zero. These photons fill the Universe today (there are roughly 400 in every cubic centimetre of space) and create a background glow that can be detected by far-infrared and radio telescopes.

Q. Why is it so important to study the Cosmic Microwave Background?

A. The Cosmic Microwave Background (CMB) is the furthest back in time we can explore using light. It formed about 380,000 years after the Big Bang and imprinted on it are traces of the seeds from which the stars and galaxies we can see today eventually formed. Hidden in the pattern of the radiation is a complex story that helps scientists to understand the history of the Universe both before and after the CMB was released.

Q. When was the Cosmic Microwave Background first detected?

A. The existence of the Cosmic Microwave Background (CMB) was postulated on theoretical grounds in the late 1940s by George Gamow, Ralph Alpher, and Robert Herman, who were studying the consequences of the nucleosynthesis of light elements, such as hydrogen, helium and lithium, at very early times in the Universe. They realised that, in order to synthesise the nuclei of these elements, the early Universe needed to be extremely hot and that the leftover radiation from this ‘hot Big Bang’ would permeate the Universe and be detectable even today as the CMB. Due to the expansion of the Universe, the temperature of this radiation has become lower and lower – they estimated at most 5 degrees above absolute zero (5 K), which corresponds to microwave wavelengths. It wasn’t until 1964 that it was first detected – accidentally – by Arno Penzias and Robert Wilson, using a large radio antenna in New Jersey, a discovery for which they were awarded the Nobel Prize in Physics in 1978.

Q. How many space missions have studied the Cosmic Microwave Background?

A. The first space mission specifically designed to study the Cosmic Microwave Background (CMB) was the Cosmic Background Explorer (COBE), launched by NASA in 1989. Among its key discoveries were that averaged across the whole sky, the CMB shows a spectrum that conforms extremely precisely to a so-called 'black body' (i.e. pure thermal radiation) at a temperature of 2.73 Kelvin, but that it also shows very small temperature fluctuations on the order of 1 part in 100,000 across the sky. These findings were rewarded with the award of the 2006 Nobel Prize in Physics to John Mather and George Smoot.

NASA's second generation space mission, the Wilkinson Microwave Anisotropy Probe (WMAP) was launched in 2001 to study these very small fluctuations in much more detail. The fluctuations were imprinted on the CMB at the moment where the photons and matter decoupled 380,000 years after the Big Bang, and reflect slightly higher and lower densities in the primordial Universe. These fluctuations were originated at an earlier epoch – immediately after the Big Bang – and would later grow, under the effect of gravity, giving rise to the large-scale structure (i.e. clusters and superclusters of galaxies) that we see around us today. WMAP's results have helped determine the proportions of the fundamental constituents of the Universe and to establish the standard model of cosmology prevalent today, and its scientists, headed by Charles Bennett, have garnered many prizes in physics in the intervening years.

Finally, ESA's Planck was launched in 2009 to study the CMB in even greater detail than ever before. It covers a wider frequency range in more bands and at higher sensitivity than WMAP, making it possible to make a much more accurate separation of all of the components of the submillimetre and microwave wavelength sky, including many foreground sources such as the emission from our own Milky Way Galaxy. This thorough picture thus reveals the CMB and its tiny fluctuations in much greater detail and precision than previously achieved. The aim of Planck is to use this greater sensitivity to prove the standard model of cosmology beyond doubt or, more enticingly, to search for deviations from the model which might reflect new physics beyond it.

Q. What does the Cosmic Microwave Background look like?

A. The Cosmic Microwave Background (CMB) is detected in all directions of the sky and appears to microwave telescopes as an almost uniform background. Planck's predecessors (NASA's COBE and WMAP missions) measured the temperature of the CMB to be 2.726 Kelvin (approximately -270 degrees Celsius) almost everywhere on the sky. The 'almost' is the most important factor here, because tiny fluctuations in the temperature, by just a fraction of a degree, represent differences in densities of structure, on both small and large scales, that were present right after the Universe formed. They can be imagined as seeds for where galaxies would eventually grow. Planck's instrument detectors are so sensitive that temperature variations of a few millionths of a degree are distinguishable, providing greater insight to the nature of the density fluctuations present soon after the birth of the Universe.

Q. What is 'the standard model of cosmology' and how does it relate to the CMB?

A. The standard model of cosmology rests on the assumption that, on very large scales, the Universe is homogeneous and isotropic, meaning that its properties are very similar at every point and that there are no preferential directions in space. In this model, the Universe was born nearly 14 billion years ago: at this time, its density and temperature were extremely high – a state referred to as 'hot Big Bang'. The Universe has been expanding ever since, as demonstrated by observations performed since the late 1920s. The rich variety of structure that we can observe on relatively small scales is the result of minuscule, random fluctuations that were embedded during cosmic inflation – an early period of accelerated expansion that took place immediately after the hot Big Bang – and that would later grow under the effect of gravity into galaxies and galaxy clusters.

The standard model of cosmology was derived from a number of different astronomical observations based on entirely different physical processes. To reconcile the data with theory, however, cosmologists have added two additional components that lack experimental confirmation: dark matter, an invisible matter component whose web-like distribution on large scales constitutes the scaffold where galaxies and other cosmic structure formed; and dark energy, a mysterious component that permeates the Universe and is driving its currently accelerated expansion. The standard model of cosmology can be described by a relatively small number of parameters, including: the density of ordinary matter, dark matter and dark energy, the speed of cosmic expansion at the present epoch (also known as the Hubble constant), the geometry of the Universe, and the relative amount of the primordial fluctuations embedded during inflation on different scales and their amplitude.

Different values of these parameters produce a different distribution of structures in the Universe, and a different corresponding pattern of fluctuations in the Cosmic Microwave Background (CMB). By looking at the CMB, Planck can help astronomers extract the parameters that describe the state of the Universe soon after it formed and how it evolved over billions of years.

Behind the Cosmic Microwave Background – inflation and the meaning of temperature fluctuations

How did the temperature fluctuations get there?

How exactly do the temperature fluctuations relate to density fluctuations?

Q. How did the temperature fluctuations get there?

A. The period of time before the formation of the Cosmic Microwave Background (CMB) plays a key role in determining how and why we see tiny fluctuations in the CMB. At the very beginning, the Universe underwent a rapid inflation that lasted only until 0.00000000000000000000000000000001 seconds (10^{-32} seconds). After inflation the size of the Universe had increased by a factor of about 10^{30} (1 followed by 30 zeroes – an enormous number!). Minute, random quantum fluctuations in the structure of the Universe that were present at the moment when inflation started, were amplified up to cosmologically large scales during inflation. Now the Universe comprised significantly large regions with slightly different properties from one to the other: in particular, the density of matter was slightly larger in some regions of the Universe than it was in others.

The slightly denser regions eventually grew increasingly denser, as gravity caused them to draw more and more matter from the surroundings. These primordial fluctuations in the density of matter in the early Universe are the seeds of the rich network of cosmic structure – stars, galaxies, galaxy clusters – that we observe today. It is thought that the fluctuations seen in the CMB are a result of the brief period of inflation. The exact details are hidden in the CMB, which Planck will be able to extract.

Q: How exactly do the temperature fluctuations relate to density fluctuations?

A: Before the Cosmic Microwave Background (CMB) was released, photons and ordinary particles were tightly coupled together, forming a single 'fluid' of matter and radiation. As soon as the two species decoupled from one another (at the time of recombination, 380,000 years after the Big Bang), photons started to propagate freely across the Universe, eventually reaching the detectors in the instruments on board Planck. The photons carry a memory of how matter and radiation were distributed at the time of the decoupling. If, at the time of decoupling, a photon was in a slightly denser portion of space, it had to spend some of its energy against the gravitational attraction of the denser region to move away from it, thus becoming slightly colder than the average temperature of photons. Vice versa, photons that were located in a slightly less dense portion of space, lost less energy upon leaving it than other photons, thus appearing slightly hotter than average. This is why temperature fluctuations in the CMB reflect the pattern of structure in the matter that was present in the early Universe, right when the CMB was released. The CMB can therefore be considered as the ultimate snapshot of our Universe at the time of recombination.

The distribution of matter in the Universe

How is matter distributed in the Universe?

Has the Universe always had such a rich variety of structure?

How did the Universe evolve from very smooth to highly structured?

How can we study the evolution of cosmic structure?

Q: How is matter distributed in the Universe?

A: A glance through our cosmic neck of the woods reveals that matter in the Universe is distributed in a highly structured fashion. Large concentrations of matter, such as stars and planets, are interspersed with large areas of empty space. The trend continues on larger scales: stars build up galaxies, which are separated from one another by vast and deserted intergalactic spaces. On even larger scales, galaxies assemble in galaxy clusters, the most massive structures in the Universe to be held together by gravity. Galaxy clusters are located in the densest knots of the cosmic web, the wispy network of large-scale structure consisting of dense filaments of matter and gigantic cosmic voids that pervade the Universe.

Q: Has the Universe always had such a rich variety of structure?

A: No, the highly diverse distribution of cosmic matter that we see in the Universe at present – stars, galaxies, galaxy clusters – has not always been in place. The density of matter in the early Universe (at the time of recombination) was pretty much the same everywhere, with only very small changes from place to place, typically of order one part in 100,000.

Q: How did the Universe evolve from very smooth to highly structured?

A: After inflation, the density of matter was almost uniform, punctuated only by tiny fluctuations. As time went by, these fluctuations grew denser and more massive under the pull of gravity, and eventually gave rise to stars, galaxies and the rich variety of cosmic structure that we observe today. The evolution of the matter distribution from almost homogeneous to highly sub-structured entails an enormous amount of information about the Universe's history and the nature of its fundamental constituents.

Q: How can we study the evolution of cosmic structure?

A: In order to understand how cosmic structure formed and evolved, cosmologists try to gather as many 'snapshots' as possible depicting how the distribution of matter has changed throughout the history of the Universe. At the present cosmic epoch, this is achieved by surveying the galaxies that populate the local Universe, whereas observations of increasingly distant galaxies fill in the gaps corresponding to earlier and earlier cosmic times. The CMB is the earliest snapshot we can gather in this series.

Tools to study the distribution of structure in the history of the Universe

How is the distribution of matter in the Universe described mathematically?

What is the power spectrum?

What is the power spectrum of the distribution of matter in the Universe?

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Q: How is the distribution of matter in the Universe described mathematically?

A: On very large scales, matter in the Universe is arranged in a wispy network consisting of huge clusters of galaxies, linked to one another by dense filaments of gas and invisible dark matter and interspersed with gigantic cosmic voids: this network of structure is called the 'cosmic web'. Cosmologists investigate how this complex network of structure formed and evolved, but structure in this cosmic web covers enormous distances – up to billions of light-years and even more – making this task extremely complicated. The closest proxy to a 'bird's eye view' of the large-scale distribution of matter in the Universe is a statistical tool called the power spectrum, which tells cosmologists the ratio between more and less massive cosmic structures overall in the Universe.

Q: What is the power spectrum?

A: A power spectrum is a mathematical function that can be used to describe the distribution of a quantity (any quantity) in space. This concept can be illustrated by considering a city with a variety of buildings in it and assessing the different types of people that live in each type of building. A survey like this might start with counting how many buildings there are of each size: how many one-family houses, how many two-family houses, how many skyscraper blocks, and so on. It doesn't matter if, on an individual street, there is a tiny one family house nearby a huge apartment block – what matters is how many of each size of buildings there are in the overall architecture of the city, to study how this influences the behaviour of the population. Plotting the number of buildings as a function of their size is an example of what it means to 'measure the power spectrum' of the city's urban development.

Q: What is the power spectrum of the distribution of matter in the Universe?

A: When cosmologists study the formation and evolution of cosmic structure in the Universe, they do something very similar to the analysis of the city's urban structure: they plot the relative number of cosmic structures on different sizes in a power spectrum. The shape of this graph reveals the 'power' of structures that populate the Universe on each scale. For example, there may be very few structures at very large scales. But counting all of these very large structures' contributions together gives a measure of their cumulative power. If the power is to be matched with only smaller structures, a much larger number of them are needed.

Q: Why are cosmologists interested in the power spectrum of cosmic structure?

A: Cosmic structures – stars, galaxies, galaxy clusters – grow under the influence of gravity, which causes them to become denser and denser. However, other forces may act against the attractive pull of gravity; for example, the expansion of the Universe or radiation pressure – the pressure force exerted by photons. Every structure that we observe in the Universe is the result of the balance between all these effects. To understand how exactly all of these structures emerged from the almost smooth distribution of matter in the early Universe, it is important to know how many structures of each size there are in the Universe at the present epoch, and how many there were at past times in cosmic history – a piece of information that is summarised in the power spectrum.

Q: What was the distribution of these primordial fluctuations?

A: The simplest model of inflation predicts that, at the end of this phase of accelerated expansion, the fluctuations present in the density of matter are such that their contribution is almost independent of their scale. This means that the cumulative power of all fluctuations of a given scale is the same. Taking the example of the size of buildings in a city, this would mean that, if there is a given number of large apartment blocks, there should be a higher number of smaller, double-family houses and an even higher number of even smaller, single-family houses, to keep the buildings on all scales having the same 'power', that is, equal numbers of people living in each kind of structure.

If fluctuations in the distribution of matter in the primordial Universe have equal power on all spatial scales, cosmologists say that their power spectrum is 'scale-invariant'. This is characterised with a parameter known as the spectral index, n_s. For a perfectly scale-invariant spectrum, n_s = 1. If n_s is smaller than 1, it means that fluctuations on larger scales are dominant, since they are more abundant (in terms of their cumulative power) than those on larger scales; vice versa, if n_s is larger than 1, fluctuations on small scales are the dominant ones.

Q: How does this relate to the fluctuations in the Cosmic Microwave Background?

The fluctuations in the temperature of the Cosmic Microwave Background (CMB) are a snapshot of the distribution of matter at a much later cosmic epoch than inflation, as they date back to 380,000 years after inflation ended. In the meantime, the distribution of matter (the power spectrum) at small scales has been modified, but at very large scales an imprint of the original power spectrum that derives from inflation is still present. In particular, CMB fluctuations on very large scales carry information about the primordial spectral index n_s and allow cosmologists to constrain the distribution of fluctuations as it was at the time of inflation. Furthermore, by measuring the spectral index and how much it is different from n_s =1, cosmologists can learn how long the phase of inflationary expansion lasted and how it ended, before the slower expansion rate began. The end of inflation is a particularly interesting epoch in cosmic history, because it is at this time that particles of matter were created for the first time.

History of structure in the Universe

How did seed fluctuations grow into today's cosmic structures such as galaxies and galaxy clusters?

How did the formation of structure affect the CMB?

How is the history of cosmic structure formation encoded in the CMB and power spectrum?

Q: How did seed fluctuations grow into today's cosmic structures such as galaxies and galaxy clusters?

A: The growth of seed fluctuations into cosmic structure can be summarised into three main phases:

i. Between inflation and the release of the Cosmic Microwave Background

ii. Between the release of the Cosmic Microwave Background and the formation of the first stars and galaxies

iii. After the formation of the first stars and galaxies

i. Between inflation and the release of the Cosmic Microwave Background (t <1 sec to t =380,000 years)

After the end of inflation, the Universe consisted of a more or less uniform bath of fundamental particles, like quarks, electrons and their anti-particles. There were also neutrinos, photons (the particles of light) and dark matter particles, an unknown type of massive particle that does not interact with photons and is therefore dark (as it does not emit light). At this time there was slightly more matter than anti-matter, but as the particles collided with their anti-particles they annihilated, leaving the Universe dominated by particles, and anti-matter disappeared. Quarks then teamed up in trios, forming protons or neutrons – the constituents of atomic nuclei as we know them today. This all happened within the first second after the Big Bang. About three minutes after the Big Bang, protons and neutrons had combined to form the nuclei of hydrogen and helium.

The density and temperature of particles in the early Universe were extremely high, and collisions between the particles were very frequent. Cosmologists refer to this by saying that ordinary matter (such as electrons, protons, neutrons and the few atomic nuclei that had formed by then) was tightly coupled to the photons. Because of these frequent interactions, photons could not travel freely: the Universe was opaque.

Besides, ordinary matter is subject to gravity, and ideally any denser region – such as the seed fluctuations that were present at the end of inflation – would draw more matter from their surroundings, growing denser and more massive. However, ordinary matter at this epoch was coupled to the photons, and the radiation pressure of photons pushes away any concentration of matter that may be created under the effect of gravity. This phenomenon prevents any fluctuations in the distribution of ordinary matter to grow denser as long as matter is coupled to the photons.

At the same time, dark matter particles were not bound to the photons, since the two species do not interact with one another. This type of dark matter particle is also referred to as cold dark matter because the velocity of these particles is much lower than the speed of light. Hence, fluctuations in the distribution of cold dark matter can grow denser and more massive even before the release of the Cosmic Microwave Background.

Astronomers also refer to hot dark matter, or neutrinos – particles with a very small mass and no electric charge that travel nearly at the speed of light. In the first second of the Universe, neutrinos were coupled to the photons, but these two types of particles decoupled immediately after. Since they do not interact with light during most of the Universe's history, neutrinos can be considered as a type of dark matter, and since their velocity is close to the speed of light, they are regarded as hot dark matter. Fluctuations in the distribution of hot dark matter can grow denser and more massive, but due to their high velocity, these particles tend to dissipate and their fluctuations are damped on small scales so, effectively, only fluctuations on intermediate and large scales can grow.

The growth of primordial fluctuations in hot and cold dark matter give rise to two completely different distributions of cosmic structure. In hot dark matter models, the first structures to form are the most massive, that subsequently fragment into smaller and smaller structures. This has been discarded on the basis of observations of galaxies in the early Universe: since the first objects that are seen to emerge in cosmic history have low mass, and they gradually evolve into more massive structures, cosmologists have established that the bulk of dark matter in the Universe is cold. However, a small fraction of hot dark matter is present in the Universe as neutrinos. Depending on the mass of neutrinos (which has not been determined yet) the effect of hot dark matter can be more or less evident in the distribution of cosmic structure on different scales, since neutrinos tend to smooth out the formation of small-scale structures.

ii. Between the release of the Cosmic Microwave Background and the formation of the first stars and galaxies

(t = 380,000 years to t = a few hundred million years)

About 380,000 years after the Big Bang, the Universe had expanded enough so that its density was much lower than at earlier epochs. Likewise, the temperature of the Universe had cooled down from the billions of Kelvin of the first few minutes and had reached about 3000 Kelvin. Protons and electrons could finally combine to form atoms of neutral hydrogen. Electrons disappeared from the view of photons and these two species decoupled from one another. This marked the beginning of the period known as the Dark Ages – a name arising from the fact that there were no individual sources of light, like stars, only clouds of neutral hydrogen.

The decoupling had two effects: photons were free to propagate across the Universe, which was now largely transparent, and which we observe as the Cosmic Microwave Background (CMB); on the other hand, ordinary matter particles were free to assemble under the effect of gravity. From this moment on, ordinary and dark matter could both react to gravity: denser concentrations of matter (both ordinary and dark) grew denser and more massive. Since dark matter particles had already created a network of dense and empty structure, ordinary matter particles could feel the gravitational attraction from the densest concentrations of dark matter and fall toward them. But ordinary matter could also get rid of energy quite effectively by heating up and emitting radiation, which caused it to sink even further into the already existing regions of high matter density. These processes gave rise to a highly sub-structured network of sheets and filaments of ordinary and dark matter known as the cosmic web, which constitutes the skeleton supporting the later emergence of stars and galaxies. Eventually the densest concentrations gave rise to the first stars, leading to the end of the Dark Ages.

iii. After the formation of the first stars and galaxies

(t = a few hundred million years ... t = now = 13.7 billion years)

A few hundred million years after the Big Bang, the distribution of matter in the Universe had produced very dense knots at the intersections of the sheets and filaments that make up the cosmic web. In these knots, the density of ordinary matter was so high that the formation of stars and galaxies became possible. Eventually the first stars and galaxies sparked into existence and light could escape from them, revealing the distant Universe to telescopes today.

The first stars were formed almost exclusively out of hydrogen and helium and are believed to have been extremely massive (about 100 times the mass of the Sun or more) and to have lived very short lives, exploding soon after their formation as supernovae and releasing their material in the surroundings, triggering the birth of new stellar generations. Later generations included other elements formed in the nuclear furnace of previous stars, and their masses were typically smaller. The first generation of stars formed in relatively low-mass galaxies. Massive galaxies, and even more massive structures such as galaxy clusters, formed later.

Q: How did the formation of structure effect the Cosmic Microwave Background?

The birth of the first stars and galaxies had an interesting effect on the Cosmic Microwave Background (CMB) photons. Ultraviolet radiation released by these objects ionised hydrogen atoms, turning them back into protons and electrons. This created a series of expanding bubbles of ionised gas – a bit like the holes in Swiss cheese – and within a few hundred million years these bubbles had merged and the entire Universe was ionised again, a period of time termed reionisation.

The CMB photons were affected by the reionisation; they were scattered off the free electrons in the reionised Universe, washing out some of the primordial fluctuations in the CMB as we observe it today. Since this happened when the Universe was already mature and had reached a substantial size, the effect of reionisation can be detected in the fluctuations of the CMB on large scales. This effect is expressed in terms of the ‘opacity’, which describes the average density of free electrons that are present along the line of sight between an observer (in this case, the telescope on board Planck) and the CMB. This parameter also provides a tool to estimate when the first stars formed.

Q: How is the history of cosmic structure encoded in the Cosmic Microwave Background and power spectrum?

A: The variations in the density of matter at the time when the Cosmic Microwave Background (CMB) formed derive from the seed fluctuations that were produced at the end of inflation and can be deciphered by looking at the power spectrum for cosmic structure in the Universe at a range of scales.

At scales smaller than about one degree – or twice the size of the full Moon on the sky – the graph shows the imprint and oscillation pattern of sound waves that were present in the fluid of ordinary matter and radiation in the very early Universe, before the CMB was released. At this epoch, ordinary matter was tightly coupled to the photons, and the radiation pressure of photons pushed away any concentration of matter that might have been created under the effect of gravity.

The interplay between gravity, which pulled together the fluid of matter and radiation, and the radiation pressure, which pushed it away, caused a series of rhythmical compressions and rarefactions everywhere in the fluid. This results in the pattern of sound waves that is visible in the central part of the power spectrum graph. Since gravity is caused by both dark and ordinary matter particles, but the radiation pressure of photons is only experienced by ordinary matter (because dark matter particles are not coupled to photons), the shape of these oscillations contains information about the amount of ordinary matter relative to the amount of dark matter. As dark matter was not bound to the photons, any concentration of dark matter could grow denser and denser even before the release of the CMB. The relative contribution of ordinary matter particles (also referred to as baryons) to the overall cosmic budget is expressed in terms of the 'Omega_b' parameter, where b stands for baryons, and the relative contribution of cold dark matter particles is expressed in terms of the 'Omega_c' parameter, where c stands for cold. The ‘cold’ in cold dark matter refers to the low speed of these particles (‘warm’ dark matter particles move at higher speed and ‘hot’ dark matter particles move at the speed of light).

While gravity pulls matter together to form structures, the expansion of the Universe may counteract this effect and hamper the formation of cosmic structure. For this reason, the amount of fluctuations in the Universe depends also on the speed of cosmic expansion, and this quantity can be extracted from the shape of the oscillations in the power spectrum of the CMB. The speed of the Universe is expressed in terms of the Hubble constant, H_0, which quantifies the expansion of the Universe at present time.

Q: What does the Cosmic Microwave Background tell us about the overall 'shape' of the Universe?

A: The CMB holds clues to the nature and distribution of structure in the Universe, and the average density of this matter plays a key role in determining the geometry of the Universe. The geometry of the Universe can take on one of three shapes: it can be curved like the surface of a ball and finite in extent (positively curved); curved like a saddle and infinite in extent (negatively curved), or it can be flat and infinite. The geometry and density of the Universe are related in such a way that, if the average density of matter in the Universe is found to be less than the so-called critical density (roughly equal to 6 hydrogen atoms per cubic metre) the Universe is open and infinite. If the density is greater than the critical density the Universe is closed and finite. If the density just equals the critical density, the Universe is flat.

Cosmologists study the relative sizes of the oscillations of the fluid of matter and radiation at the time the CMB was released to learn more about the shape of the Universe. The oscillations translate into regions of higher and lower temperature on the CMB map, and contain information about the amount of particles present. More specifically, the shape of the Universe can be determined by looking at where the first of these oscillations appears in the power spectrum.

The location of the first oscillation corresponds to a specific size in the early Universe called the sound horizon – the maximum distance that a sound wave could have crossed from the Big Bang until the time of the CMB release. To cosmologists, the sound horizon works like a standard measure of known length. By measuring its length in the temperature fluctuations of the CMB, it is possible to determine if the Universe is flat or curved. This is expressed in terms of the parameter 'Omega_K' and is equal to zero for exactly flat space.

The effect of cosmic structure on the CMB

Did the photons travel freely ever since the CMB was released?

What happens when the Cosmic Microwave Background photons encounter structure in the cosmic web?

Do the CMB photons encounter other particles along their way?

Q: Did the photons travel freely ever since the Cosmic Microwave Background was released?

A: Yes, but they ran into a few obstacles along the way. The obstacles are due to the interaction of Cosmic Microwave Background (CMB) photons with cosmic structure that formed since – mainly galaxies, galaxy clusters and the cosmic web in which they are embedded. These can happen in two ways: via the gravitational effect exerted by concentrations of matter, and via the interaction of photons with free electrons. These effects create additional fluctuations in the temperature of the CMB photons, by changing a bit of the information that they carry. But, at the same time, since these effects are produced by the structure that has formed in the Universe ever since the CMB was released, these additional fluctuations carry a wealth of information about the cosmic distribution of matter.

Q: What happens when the Cosmic Microwave Background photons encounter structures in the cosmic web?

A: Cosmic Microwave Background (CMB) photons are subject to 'gravitational lensing' as they cross the Universe and encounter the massive structures that start taking shape after the release of the CMB. Just in the same way as a magnifying glass works, massive structures like galaxy clusters can bend light from the CMB, either magnifying or demagnifying the 'image' of the CMB. This effect does not change the temperature of the photons, but it changes their trajectory and, eventually, washes out some of the information encoded in the CMB.

The distortion due to gravitational lensing affects the pattern of CMB temperature fluctuations on the sky. After careful analysis, Planck scientists can isolate the fluctuations that were created by gravitational lensing. Since they were imprinted on the CMB photons by the network of cosmic structure that pervades the Universe, these fluctuations carry all-important information about the distribution of matter on large scales in the Universe, especially during the last 10-12 billion years of its history.

Q: Do the Cosmic Microwave Background photons encounter other particles along their way?

A: Yes, but not at first. When the Cosmic Microwave Background (CMB) was released, electrons became locked in atomic nuclei. Matter in the Universe remained neutral for several hundred millions of years. Then, after the first stars and galaxies formed, they provided a source of ultraviolet radiation that ionised hydrogen atoms and turned them back into protons and electrons. After this epoch of reionisation, the CMB photons encountered free electrons again, and were scattered off them. This effect also modifies some of the fluctuation patterns in the background CMB and must be taken into account to study both the primary patterns of fluctuations in the CMB as well as the history of the reionisation period.

Free electrons are also present in the hot gas inside galaxy clusters, which form in the densest knots of the cosmic web of matter that pervades the Universe. When CMB photons encounter free electrons in a galaxy cluster, the electrons have more energies than the photons, so when the photons scatter off them they gain energy (this is known as Inverse Compton scattering). This changes the energies of the CMB photons in a characteristic way. When looking at the CMB in the direction of a galaxy cluster, one observes a deficit, with respect to the average CMB signal, of low-energy photons, and a subsequent surplus of more energetic ones. Planck scientists exploit this phenomenon, called the Sunyaev-Zel'dovich effect, to search for galaxy clusters across the sky. Since galaxy clusters trace the cosmic web, the distortion that they imprint on the CMB can be used to refine our knowledge of the distribution of matter in the relatively recent history of the Universe.