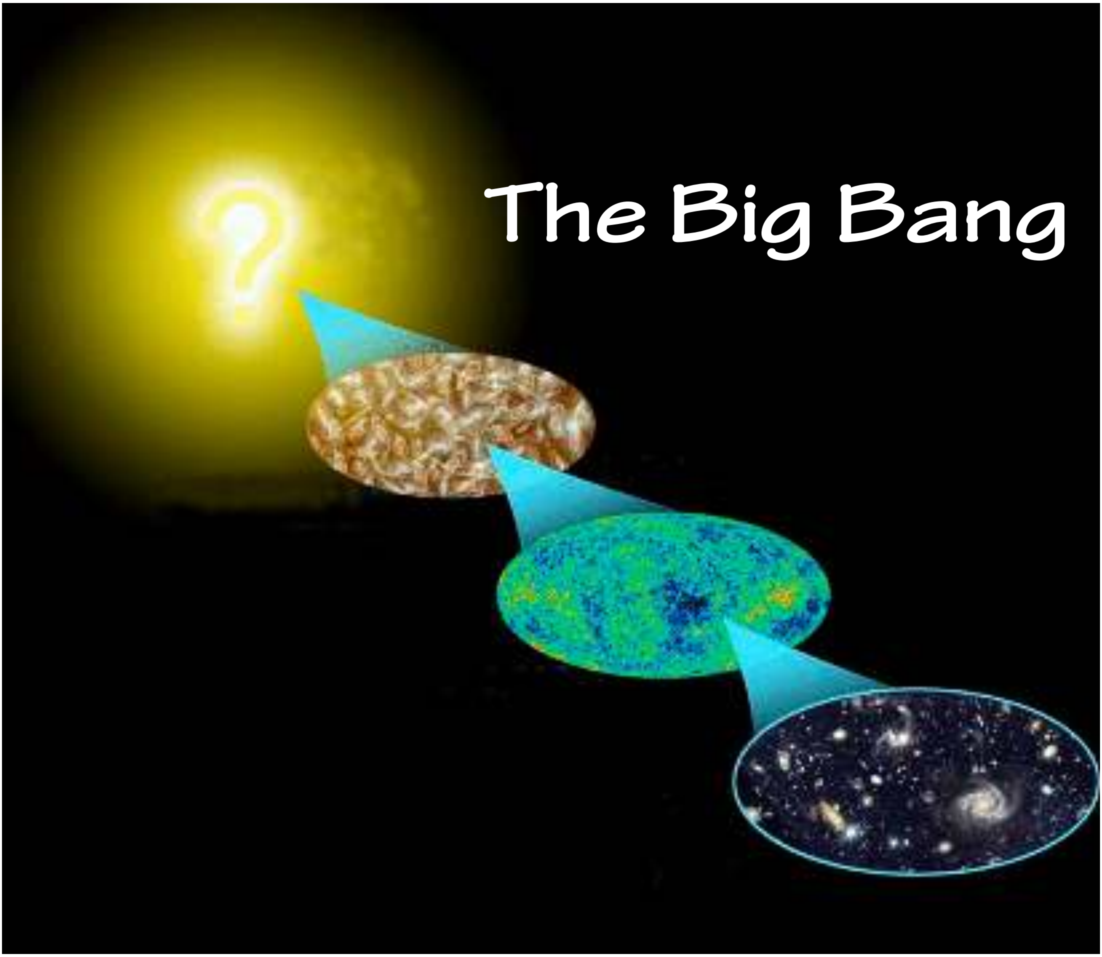
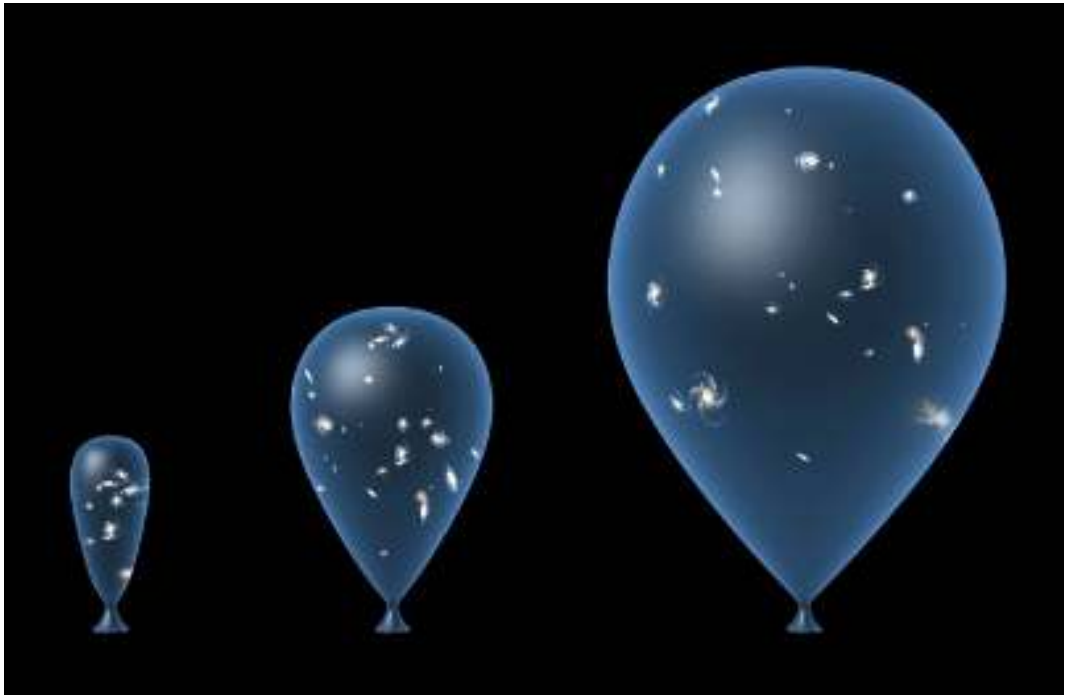
The Universe in my pocket



TUIMP
THE UNIVERSE IN MY POCKET
No. 12

Françoise Combes
Paris Observatory



The Universe is a bit like the surface of an expanding balloon on which galaxies are drawn. Each observer in any given galaxy has the impression that all the other galaxies are moving away, with a speed proportional to their distance. In 1915, Vesto Slipher studied the spectra of spiral nebulae, and discovered that most of them show red-shifted spectral lines, indicating that they are moving away from Earth *. This was the first evidence - not yet recognized at the time - of the expansion of the Universe (see opposite page).

* See TUIMP 10.

The expansion of the Universe

How were galaxies formed? Little was known a century ago, not even if there were galaxies besides our own, the Milky Way. In 1908, Henrietta Leavitt showed that for the Cepheids - a type of variable-brightness star - the time interval between two successive maxima is related to the luminosity. In 1925 when Edwin Hubble identified Cepheids in spiral nebulae, he was therefore able to estimate their distances and prove that they are outside the Milky Way. Spiral nebulae have since come to be called galaxies.

In 1927 Georges Lemaître understood that the "run away" of galaxies is an effect due to the expansion of space. In 1929, Hubble established the relationship between distance and speed-of-flight of galaxies. This crucial relationship, first called Hubble's law, was renamed the Hubble-Lemaître law in 2018.

The Big Bang

Fred Hoyle

If the Universe is expanding, then in the beginning it was necessarily very dense and very hot.

Astronomer Fred Hoyle did not like thiscosmological model. To make fun of it, on a BBC show in 1949 he called it the Big Bang. And that is the name that stuck!

G. Gamow

One of the first arguments in favor of the Big Bang was proposed in 1948 by George Gamow and his student Ralf Alpher. They showed that only under the extreme density and temperature conditions of the Big Bang could helium, deuterium and lithium form, in the quantities that are now observed in the Universe.

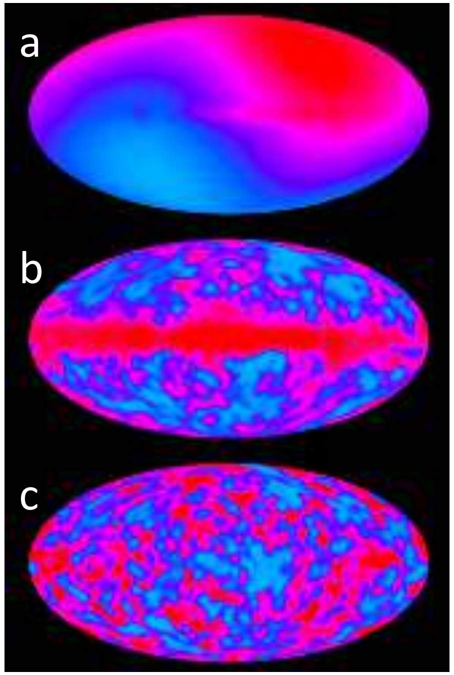
The fossil radiation

Because of its expansion, the Universe cools. Today its temperature is only 3 degrees above absolute zero (3 K or -270° C). The Universe is bathed in radiation at this temperature, which is a relic of the Big Bang.

This radiation was detected by chance in 1965 by radio-astronomers Arno Penzias and Bob Wilson who were working on micro-wave receivers.

Penzias & Wilson

Intrigued by a weak signal coming from all directions, they consulted with astrophysicist Robert Dicke and his colleagues, who suggested that it was the fossil radiation of the Big Bang. For this discovery Penzias and Wilson received the Nobel Prize in 1978.



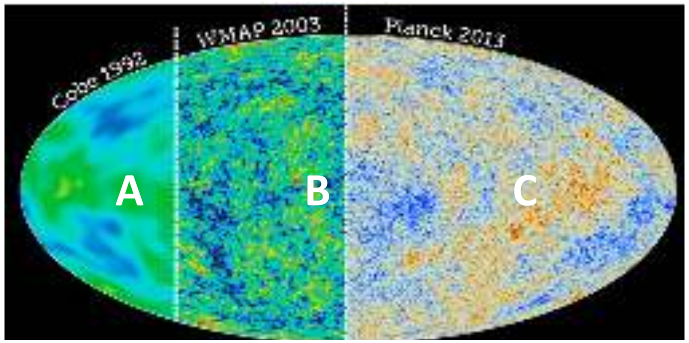
Microwave radiation maps obtained by the COBE satellite

a: after subtracting the uniform part of the cosmic microwave background CMB)

b: after correction of the overall effect due to the motion of our Galaxy relative to the CMB,

c: after removing the radiation from the Milky Way and nearby galaxies, we finally discover the tiny fluctuations of the CMB (1 / 100,000 of amplitude), that is to say the state of the Universe during recombination.

The diffuse background observed by COBE in 1992 (A), by WMAP in 2003 (B) and by the Planck satellite launched by NASA and ESA in 2013 (C).

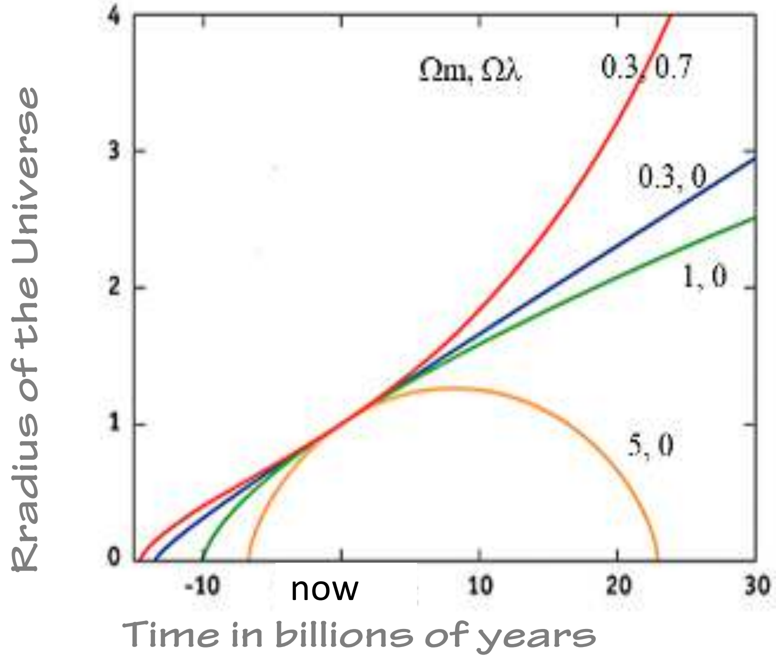


Each mission reveals more detail.

Primordial fluctuations

The fossil radiation from the Big Bang, which fell to 3 degrees Kelvin because of the expansion, was emitted when the Universe was still dense and hot, 380,000 years after the Big Bang. The Universe was then crossed by waves which left their imprint on the cosmic microwave background. These are the primordial fluctuations – the seeds of galaxies (see page 6).

When the temperature of the Universe fell below 3000 K, the protons recombined with the electrons to form hydrogen atoms. Statistical studies of fluctuations show that the Universe contains 5% baryons (matter as we know it), 25% dark matter, and 70% dark energy. They also indicate that the Universe is geometrically flat, and that 13.8 billion years have passed since the Big Bang.



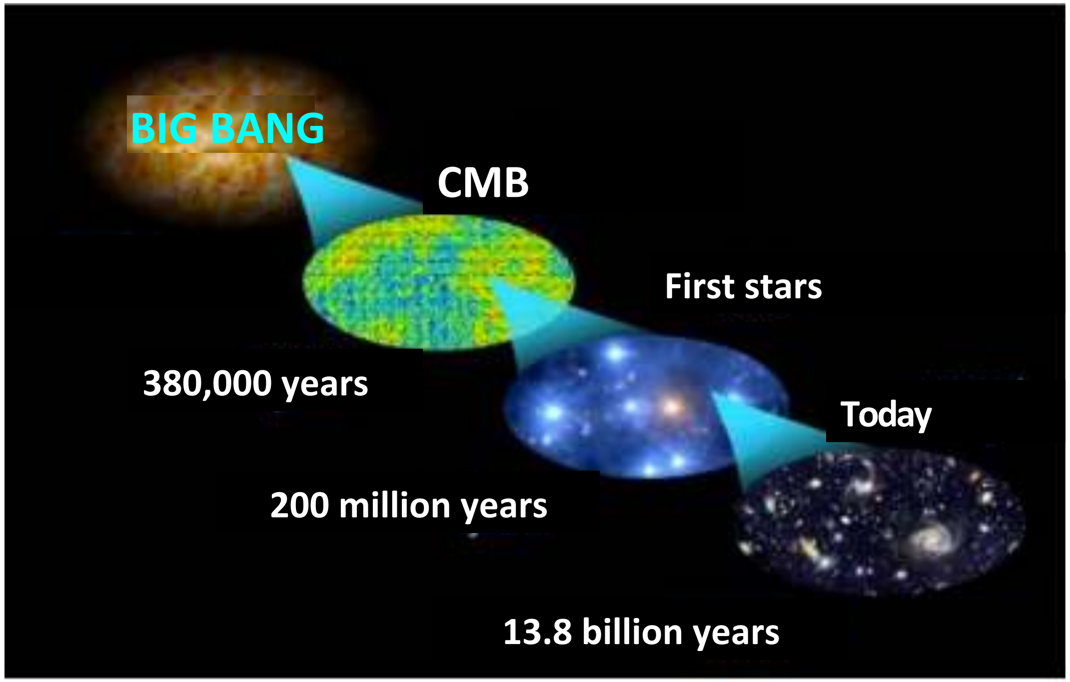
The evolution of the radius of the Universe, according to several cosmological models for different values of the parameters Ω_M, the density of matter and Ω_Λ, the density of energy of the Universe. The evolution of the Universe is linked to the value of $\Omega = \Omega_M + \Omega_\Lambda$. If $\Omega = 5$, the Universe will recondense into a Big-Crunch (yellow curve). If the Universe has zero ($\Omega = 1$), or negative ($\Omega = 0.3$) curvature, the expansion will extend infinitely (green and blue curves).

Current observations lead to the red curve. The curvature is zero, and the expansion accelerates.

The cosmological constant

In 1915, Albert Einstein published the equations of general relativity, that link the geometry of the Universe to the amount of matter and energy it contains. To account for a static universe (which was believed at that time), he had added a term called the cosmological constant, Λ. When it became clear in 1929 that the Universe is expanding, Einstein declared that the introduction of Λ was the biggest mistake of his life.

For most of the 20th century, Λ was ignored. But in 1998, using type Ia supernovae, which are more powerful distance indicators than Cepheids, two groups of observers discovered that the expansion of the Universe is accelerating. They received the Nobel Prize in 2011.



A simplified history of the Universe:

• During the first minutes: the Big Bang, and the formation of elementary particles and radiation.

• After 380,000 years, recombination of protons and electrons into hydrogen atoms.

• After 200 million years, formation of the first stars in the first galaxies, and progressive re-ionization of the Universe.

• Finally, until today, the transformation of galaxies by mergers of smaller galaxies.

Dark energy

Expansion was supposed to be decelerated by the gravitational pull of all the matter in the Universe.

If the expansion accelerates, as we now think, it means that there is another component which exerts a repulsive force. This is the role that the cosmological constant plays. This component is called dark energy. It would make all observations compatible with one other, such as the curvature and the age of the Universe (which cannot be less than the age of the oldest stars). It remains to discover the nature of this dark energy.

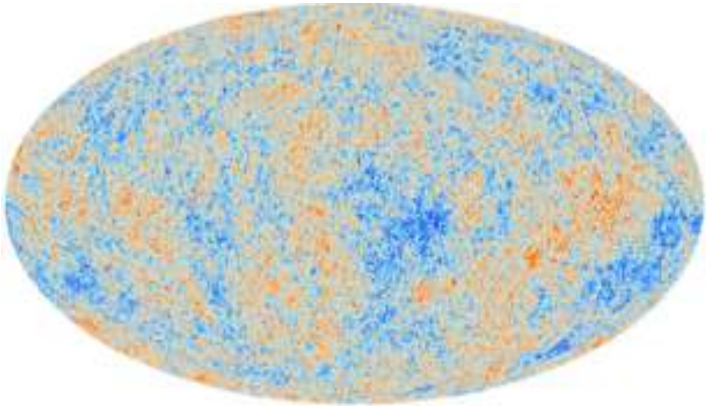
The history of the Universe as we understand it today is described on p.10 and its fate is schematized on p. 8.

You are here, at the centre of the visible Universe

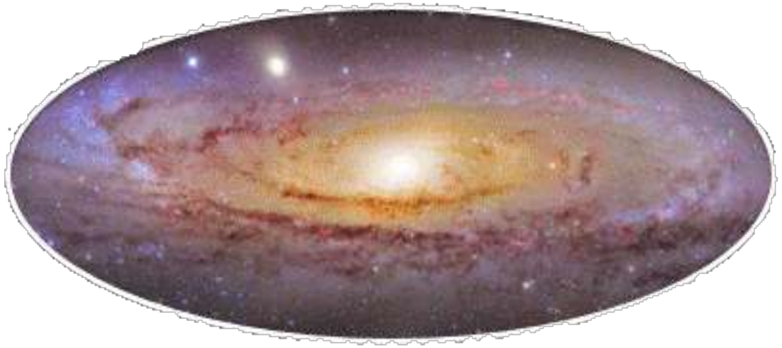
<u>The horizon of the observable Universe.</u> All observers are at the centre of a sphere that represents their observable Universe. They cannot observe beyond this horizon. Galaxies that may exist beyond this horizon have not had time to communicate with the observers because their photons, traveling at the speed of light, have nott had enough time to reach the observers.

The horizon of the Universe

Today we can retrace the entire history of the Universe, beginning with the Big Bang (see p.10). Numerous observations confirm this cosmological model, and astronomers have explored much of the observable Universe. They cannot observe beyond a certain distance, of course, because the signals that arrive on Earth cannot travel faster than light, whose speed is 299,792 km/s. Thus, observing distant objects is like going back in time. The photons we receive today from primordial galaxies were emitted 12 to 13 billion years ago. Thus, we see these galaxies as they were in their youth. When we observe the photons from the cosmic background, we are looking back 13.8 billion years in time (see opposite page).

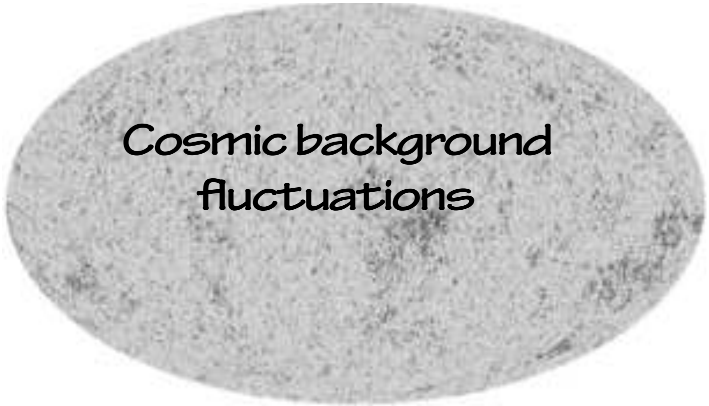


Quiz



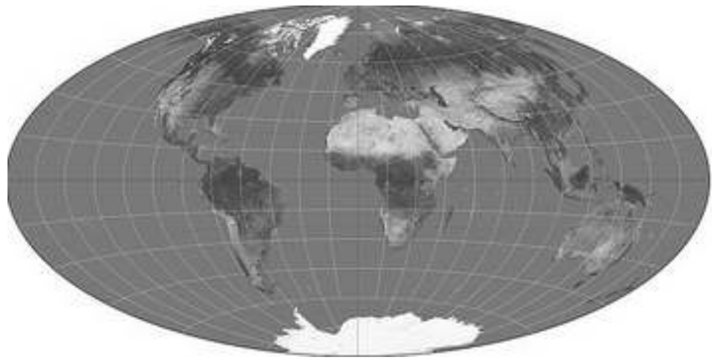
Which of these images shows the cosmic background fluctuations ?

Answer on overleaf



Answers

Map of the continents and oceans of Earth.



The Universe in my pocket No. 12

This booklet was written in 2020 by
Françoise Combes from Paris Observatory
(France).

Nr 1

Cover image: A brief history of the Universe
(see also page 10).
Credit NASA/WMAP

To learn more about this series and about the topics presented in this booklet, please visit
http://www.tuimp.org

Translation: Stan Kurtz