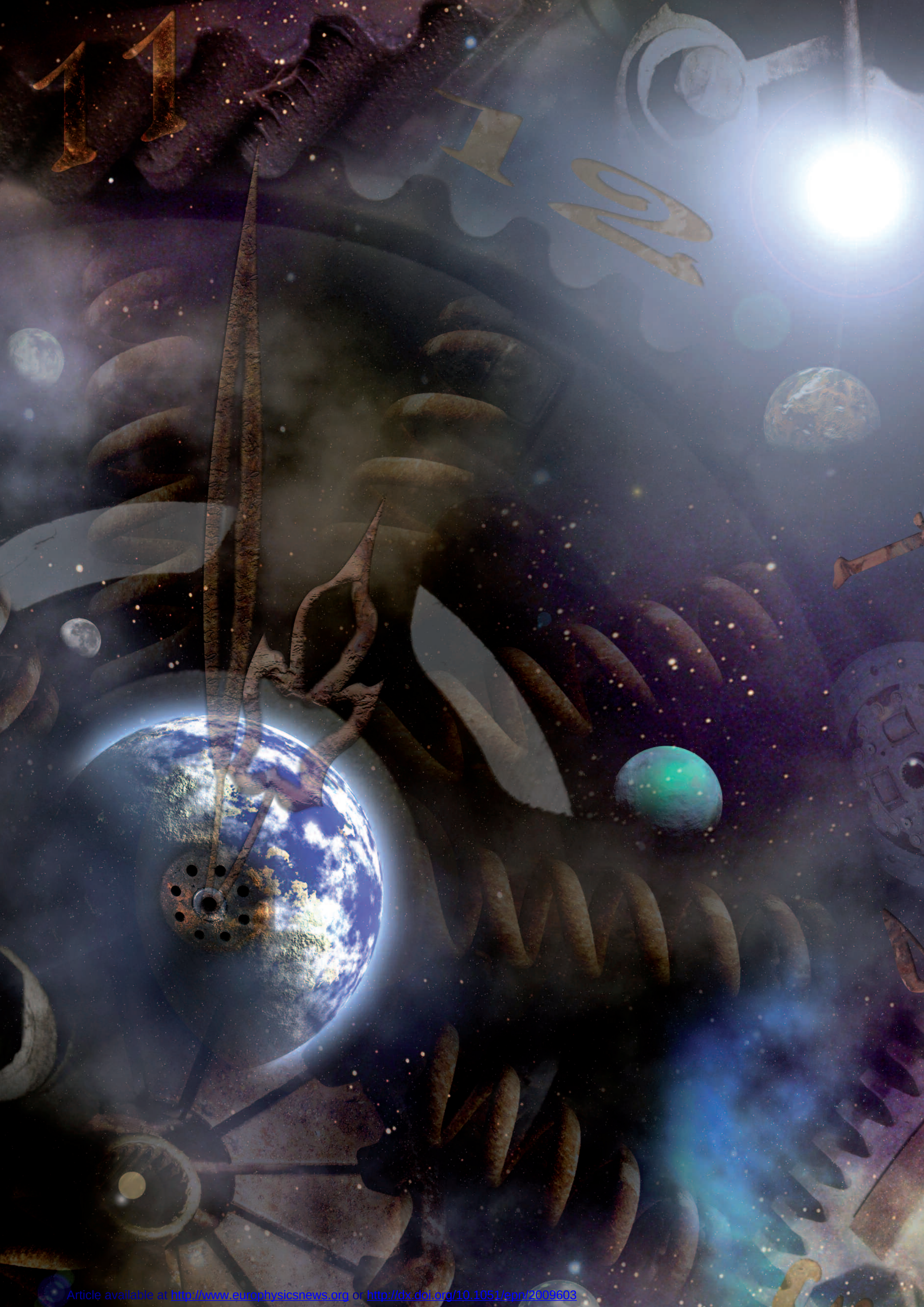

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PROBING THE END OF THE UNIVERSE'S DARK AGES WITH LOFAR

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About four hundred million years after the Big Bang, the first radiation-emitting objects in the Universe formed, and the all-pervasive gas transformed from neutral to ionized. This pivotal era, the Epoch of Reionization, holds the key to structure formation and evolution in the early Universe.

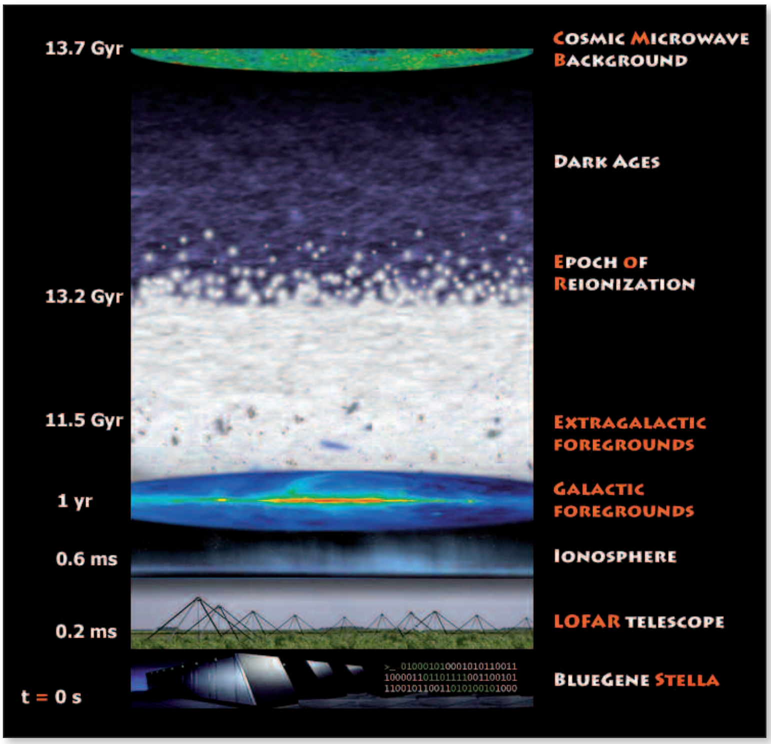
In the last decades an overarching paradigm for the formation and evolution of structure in the Universe has emerged: the cold dark matter (CDM) model. CDM is a refinement of the Big Bang theory, proposing that matter in the Universe consists mostly of slow, non-baryonic particles that interact through gravity. A recent modification of CDM is the addition of a dark energy component that currently dominates the Universe's energy density and accelerates its expansion. According to the CDM paradigm, very early, tiny density fluctuations in an otherwise homogeneous and isotropic Universe took 13.7 billion years to grow into the highly complex cosmos that we observe today.

About 400,000 years after the Big Bang, the Universe's temperature and density decreased to below 3000 K, allowing ions and electrons to (re)combine into neutral hydrogen and helium – heavier elements were negligible. Immediately afterwards, photons decoupled from baryons and the Universe became transparent, leaving a relic radiation known as the cosmic microwave background (CMB) radiation. This event ushered the Universe into a period of darkness, known as the Universe's Dark Ages. These Dark Ages ended about 400 million years later, when the first stars, black holes, etc. formed and started emitting ionizing radiation. When a sufficient number of UV-emitting objects had formed, the temperature and the ionized fraction of the gas in the Universe increased rapidly and most of the neutral hydrogen eventually ionized. This period, in which the cosmic gas went from being almost completely neutral to almost completely ionized, is known as the Epoch of Reionization (hereafter EoR). A cartoon of the various phases featuring in this transition phase is shown in Figure 1.

The EoR was a watershed epoch in the history of the Universe. Prior to it, dark matter dominated the formation and evolution of structure while baryonic matter played a marginal role. After the EoR, the role of cosmic gas in the formation and evolution of structure became prominent and, on small scales, even dominant. Studies of this crucial epoch touch upon fundamental questions in cosmology, galaxy assembly, and formation of quasars and very metal poor stars. Much theoretical effort is currently dedicated to understand the physical processes that triggered and governed the evolution of this epoch, and their ramifications for subsequent structure formation [1-3].

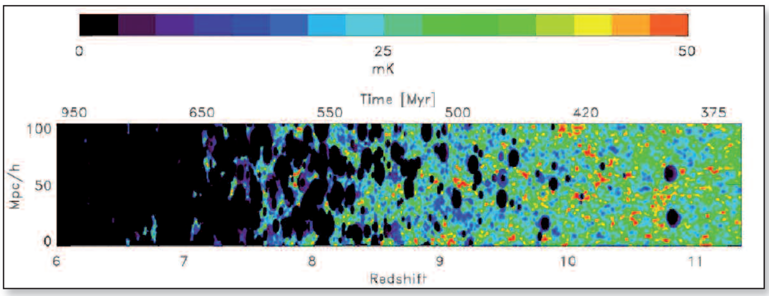
What do we know about the Epoch of Reionization?

Currently, there are only two strong observational constraints on the EoR. The CMB temperature and polarization data obtained by the WMAP satellite allow measurement of the total Thomson scattering of the primordial CMB photons off intervening free electrons produced by the EoR along the line of sight. They show that the CMB intensity has only been damped by ~9%, indicating that the Universe was mostly neutral for 400 million years and then ionized. However, the Thomson scattering measurement is an integral constraint telling us little about the sources of reionization, its duration or how it propagated to fill the whole Universe.



▲ FIG. 1: This sketch illustrates the likely development of the Epoch of Reionization (EoR). About 0.4 million years after the Big Bang (z~1100) hydrogen recombined and remained neutral for about 400 million years until the first radiation emitting sources emerged, an era known as the "Universe's dark ages". At z~10, the first stars, galaxies and quasars began to heat and ionize the intergalactic medium. The neutral IGM can be observed with LOFAR through its redshifted 21cm spin-flip transition to redshift 11.5 (when the Universe was 400 million years old). However, instrumental, ionospheric, Galactic and extra-galactic contaminants corrupt the 21 cm signal. (Courtesy of V. Jelić)

▼ FIG.2: A slice through time of the evolution of the reionization process in the intergalactic medium. The x-axis gives the redshift or time and the y-axis gives the spatial coordinate. At high redshifts the early Universe is neutral except for small volumes around the first ionizing sources. As time progresses the number of ionizing sources increases and the bubbles (black areas) become larger until they fill the whole Universe. The color scheme represents brightness temperatures given in the bar above the figure (Courtesy of Rajat M. Thomas) .



Another constraint comes from specific features in the spectra of distant quasars, known as the Lyman-alpha forest. These features, which are due to neutral hydrogen, indicate two important facts about reionization. First, hydrogen in the recent Universe is highly ionized, only 1 part in 10000 being neutral. Second, the neutral fraction of hydrogen in the distant Universe suddenly increases at redshift 6.5, *i.e.*, about 900 million years after the Big Bang, demarcating the end of the reionization process. Despite these data providing strong constraints on the ionization state of the Universe at redshifts below 6.5, they say very little about the reionization process itself.

A whole slew of possible constraints currently discussed in the literature are either very controversial, very weak or, as is often the case, both. Most are very interesting and exciting; but can be investigated reliably only with a new generation of instruments such as the James Webb Space Telescope, replacing the Hubble Space Telescope in the next decade.

The Reionization process

To ionize hydrogen one needs photons with energies of 13.6 eV or higher: the reionization of the Universe requires ultraviolet photons. A crucial question is which sources in nature provided the UV photons needed to ionize the Universe and maintain it in that state. Obvious candidates are the first stars (so called Population III stars) and (mini)quasars – these are objects powered by massive black holes. Various papers have considered other sources of reionization, like decaying or self-annihilating dark matter particles or decaying cosmic strings. However, the constraints on such objects make it unlikely that they could reionize the Universe by themselves.

Massive black holes powering quasars convert mass to radiation extremely efficiently. They produce a large amount of UV and X-ray radiation above the ionization threshold. In fact, one of the main discoveries of the last decade is that huge quasars, powered by black holes with masses above 10^9 solar masses, already existed at redshift ~6.5 (about 900 million years after the Big Bang). How these black holes managed to accumulate so much mass in such a short time is a puzzle in its own right. However, the mass distribution of the massive black holes in the early Universe is unknown, rendering the role played by quasars during reionization very uncertain.

Population III stars formed from the primordial mix of elements and thus only contain hydrogen and helium. This composition makes them very different from present-day stars. In order for a star to form, the initial proto-star has to radiate some of the energy gained by gravitational contraction, or the collapse will rapidly halt as the cloud reaches hydrostatic equilibrium. Population III stars are poor radiators until the cloud from which they form reaches high temperatures. This causes them to be very massive and hence are very efficient and abundant sources of UV photons yet are very short lived. Theoretically, these objects could have reionized the Universe but our knowledge of them, including the question whether they have existed at all in sufficient numbers, is very uncertain.

The basic scenario for the EoR is simple. The first radiation-emitting objects ionize their immediate surroundings, forming ionized bubbles which expand until the ionization consumes all ionizing photons. As the number of objects increases, so do the number and size of the bubbles which eventually fill the total volume. However, many details must be clarified. What controls the formation of the first objects and how much ionizing radiation do they produce? How do the bubbles expand into the intergalactic medium and what do they ionize first, high-density or low-density regions? In order to answer such questions, cosmologists try to simulate the EoR by combining models that track the formation of dark matter halos with radiation transport mechanisms that track the evolution of the ionization bubbles.

Figure 2 shows a slice through such a simulation where the scale of the vertical axis is 100 comoving Mpc/h (Megaparsecs per h, where h~0.7 is the Hubble constant measured in units of 100 km/s/Mpc) and the horizontal axis is the redshift (bottom) or the corresponding time after the Big Bang (top) [4]. We began with a cosmological structure formation simulation in which we identify possible ionization sources and then used a spherically symmetric radiative transport code to calculate the amount of ionization around each source as a function of redshift (time). Here we assumed that the ionization is driven by black holes with masses ranging from 100 to 107 solar masses in mini-quasars. Obviously, results of the simulation depend on the assumptions. For example, with the same number of ionizing photons stars will produce smaller bubbles but at many more locations.

Studies of this **crucial epoch** touch upon **fundamental questions** in **cosmology**

The 21 cm emission as a probe of the EoR

The study of the 21cm emission line from neutral hydrogen may be our best hope to study the formation of structure in the Dark Ages and the EoR [5-7]. The strength of the 21 cm emission or absorption depends on the relative occupation number of the ground state and the excited state. The 21 cm line can be excited through either collisions or Lyman-alpha excitation – called the Wouthuysen-Field effect [8-10].

◀ **FIG. 3:** **An artist's impression of the layout of the LOFAR telescope over Western Europe. For the EoR, only the central part of the telescope is relevant. (courtesy of Peter Prijs)**

The 21 cm line emission from the EoR is redshifted by the cosmic expansion to meter wavelengths. For example, at a redshift of 9 (550 million years after the Big Bang) the 21 cm line is at 2.1 m (or a frequency of ~140 MHz). This feature allows us to study and map the reionization process time-slice by time-slice. Measuring the 21 cm radiation from the diffuse intergalactic medium prior to and during the EoR holds great promise for studying the matter distribution at these very early stages. It will also tell us the nature of the first ionization sources, their abundance and distribution, as well as how the EoR progressed.

Observational Status and Prospects

Observation of 21 cm radiation from the EoR and earlier requires radio telescopes, which currently lack enough sensitivity. Fortunately, in the coming years, this will change with the introduction of novel radio telescopes with the specific goal to observe redshifted 21-cm line emission from the EoR. These include LOFAR (the LOw Frequency Array)[1] now under construction in a number of European countries led by the Netherlands (see Figure 3); the Murchison Widefield Array (MWA)[2] currently built in western Australia by Australian and US institutes; and the international Square Kilometer Array (SKA)[3], by far the most ambitious project to be built within a decade.

LOFAR and MWA will start to collect data within a year and are set to map the spatial distribution of neutral hydrogen in the Universe over several hundred square degrees of the sky. Each point in these maps will be observed at many frequency- or time-slices between the redshifts of 11.5 and 6.5 in which significant evolution in the neutral hydrogen fraction is expected. These telescopes are interferometric arrays with large collecting areas and will have the sensitivity to detect the very weak signals emitted by the early Universe.

These observations will not be easy due to a number of complicating factors. For example, the redshifted 21 cm emission passes through overwhelming galactic and extra-galactic foregrounds that severely contaminate the data. The radio signal is further badly affected by the Earth's ionosphere, and by the instrument's response. All these effects must be carefully neutralized by an exquisite calibration of the telescope (see Figures 1 & 4 for more detail).

Despite these difficulties, the near future will be very exciting for this field as observational success will open a completely new area in cosmology, shedding light on the Universe's Dark Ages and the Epoch of Reionization, and bridging the huge observational gap in our knowledge of the Universe between 400,000 years after the Big Bang – when recombination occurred – and one billion years later when the Universe was fully ionized. ■

notes

[1] www.lofar.nl
[2] www.haystack.mit.edu/ast/arrays/mwa/
[3] www.skatelescope.org

About the Author

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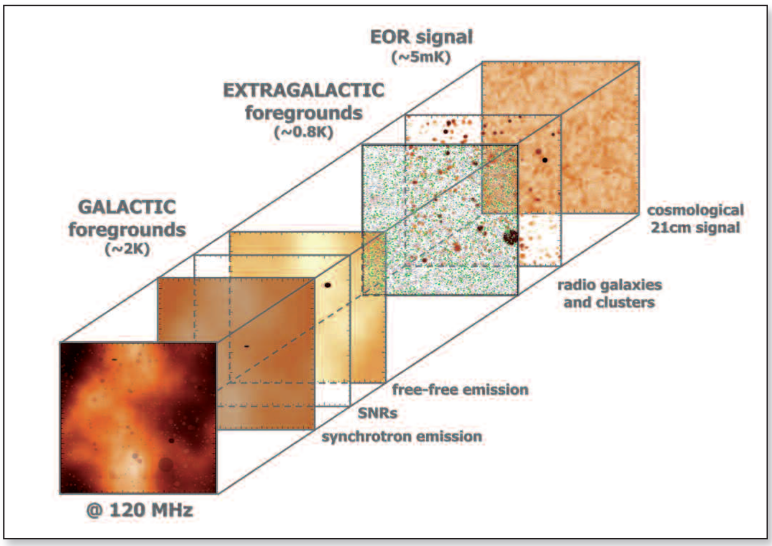

▲ **FIG. 4: The figure illustrates the various galactic and extra-galactic contaminants of the redshifted 21 cm radiation from the EoR. These foregrounds have amplitudes of about 3 orders of magnitude larger than the expected cosmological signal. (Courtesy of V. Jelić)**

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