# What a Wonderful World!

By Avi Loeb on March 4, 2024

Marion Dierickx, former student of Avi Loeb and research fellow in the Cosmic Microwave Background Group led by John Kovac at Harvard University, conducts research regularly at the South Pole. (Credit: Marion Dierickx)

The only reason we can figure out the history of our Universe from the clues we detect today is that the Universe had nearly the same initial conditions everywhere.

We detect particles of light, photons, that started their journey towards us as soon as the Universe became transparent, 400,000 years after the Big Bang. By that time, cosmic expansion cooled the primordial gas below 4,000 degrees, allowing hydrogen atoms to capture free electrons which until then scattered light in the earlier opaque fog. This relic light at a current freezing temperature of 2.73 degrees Kelvin above absolute zero, is the cosmic microwave background, constituting a percent of the white noise on the screens of old television sets.

By now, 13.8 billion years after the Big Bang, this background of photons travelled at the speed of light and reached us from its last scattering surface. This surface receded to a current distance of 42 billion light years as a result of the cosmic expansion. We cannot observe light from farther away.

The last scattering surface of gravitational waves goes farther, all the way back to the Big Bang because the Universe is transparent to them. My Harvard colleague, John Kovac, constructed the most sensitive observatory for detecting these waves in the South Pole, where my former student Marion Dierickx works. This primordial signal was not detected as of yet.

For relic particles traveling at the speed of light, the Big Bang represents a spherical boundary around us, interior to which they could have reached us during the age of the Universe. According to Albert Einstein's Relativity, nothing propagates faster than light, so we cannot receive particles beyond this cosmic horizon. However, we know that there is no cliff where cosmic conditions changed dramatically out to a distance that is 4,000 times farther away, because such a cliff would exert a detectable tidal influence on the volume we see.

Cosmic neutrinos decoupled when the Universe was merely a second old and the temperature was ten million degrees. Their last scattering was earlier than that of photons, but neutrinos are thought to have masses. As the cosmic temperature dropped below the energy corresponding to their rest-mass, the neutrinos started to move at a speed significantly below the speed of light. By now, they traversed only a distance that is a few times larger than the distance they travelled while they were moving near the speed of light. For the expected neutrino masses, this means that the last scattering surface of neutrinos is spatially closer than that of the cosmic microwave background.

Relic particles which are more massive than neutrinos, like most of the dark matter candidates, arrived at our vicinity from an even closer last scattering surface.

Altogether, different cosmic relics reach our cosmic neighborhood from different distances, where they were last scattered after the Big Bang. We can easily interpret the information they give us because the Universe had similar initial conditions everywhere and followed a similar history on large scales. Because of that, what happened close to us – as probed by dark matter or cosmic neutrinos with a nearby large scattering surface, is consistent with the storyline provided by photons from much farther away. If the Universe were to evolve differently in different regions, we would not be able to obtain a consistent picture of our local cosmic history because the photons emitted near us traveled by now to great distances and cannot be detected by us anymore.

How do we know that the initial conditions were similar everywhere? By observing light other than the cosmic microwave background. For example, light emitted by the most distant galaxies observed by the Webb telescope, started its journey hundreds of millions of years after the Big Bang. And light from closer galaxies reflects the way the Universe looked like billions of years later. Galaxies in the local Universe emitted the light we see from them recently. We probe cosmic history by observing how the Universe looked like at larger look-back times. Gathering light from farther away resembles digging deeper into an archaeological site and unravelling layers that are more ancient.

The compilation of information from photons paints a consistent picture in which the Universe started nearly homogeneous and isotropic. This validates the cosmological principle conjectured by the Soviet mathematician Alexander Friedmann a century ago in 1922, and independently in 1927 by the Belgian priest and astronomer Georges Lemaître and in 1935–1937 by the American physicist Howard P. Robertson and the British mathematician Arthur Geoffrey Walker. Their solution to Einstein's equations is currently recognized as the *Friedmann–Lemaître–Robertson–Walker (FLRW) cosmological model.*

The Universe started simple everywhere. However, on small scales particles moving much slower than light, clustered by their self-gravity and assembled into complex structures, like galaxies - inside of which stars like the Sun formed, leaving residues of dense matter from which planets like the Earth where made, on which the chemistry of life emerged, leading to the human brain, which by now constructed artificial intelligence systems with trillions of connections. This extraordinary complexity emerged from relic particles moving much slower than light. Remarkably, the assembly of a small fraction of these particles to intelligent beings allows these beings to figure out cosmic history from the clues provided by particles moving at the speed of light.

In other words, complex assemblies of nearby slow-moving particles can understand cosmic history by studying fast particles from far away. As Luis Armstrong sang:

"I see skies of blue
And clouds of white
The bright blessed day
The dark sacred night
And I think to myself
What a wonderful world."

## ABOUT THE AUTHOR

Credit: Chris Michel (October 4, 2023)

**Avi Loeb** is the head of the Galileo Project, founding director of Harvard University's - Black Hole Initiative, director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics, and the former chair of the astronomy department at Harvard University (2011-2020). He is a former member of the President's Council of Advisors on Science and Technology and a former chair of the Board on Physics and Astronomy of the National Academies. He is the bestselling author of "*Extraterrestrial: The First Sign of Intelligent Life Beyond Earth*" and a co-author of the textbook "*Life in the Cosmos*", both published in 2021. His new book, titled "*Interstellar*", was published in August 2023.