**Phantom transparency of the Universe**

How transparent is the Universe? There is no single answer to this question. Powerful optical telescopes can now see objects located at the edge of the visible part of the Universe but the situation changes when it comes to high-energy radiation. Cosmic particles rush almost at the speed of light through galaxies and their clusters, but on their way they encounter obstacles - matter, radiation, magnetic fields. High-energy gamma rays are absorbed as they propagate in the Universe due to interactions with low-energy radiation - for example, light from stars and galaxies, as well as relic radiation. Therefore, astronomers have to study distant cosmic objects - for example, the so-called blazars, the supermassive nuclei of active galaxies shooting streams of matter at near-light speeds in our direction - with a correction for this "opacity".

High-energy gamma rays themselves are ordinary light, only with photon energies a hundred billion times higher than those visible to the eye. Fortunately, such hard radiation does not reach the Earth's surface - it is absorbed by the atmosphere. It is recorded using special Cherenkov telescopes on Earth. They react to cascade reactions in the atmosphere - showers of charged elementary particles caused by primary gamma photons.

Long ago scientists noticed that some space objects for some reason "ignore" the opacity of the Universe, and the study of such anomalous sources is the subject of an article by the Chief Researcher of the Institute for Nuclear Research of the Russian Academy of Sciences, Corresponding Member of the Russian Academy of Sciences. RAS Sergei Troitsky, published in the authoritative European Physics Journal C (S.V. Troitsky. “The local-filament pattern in the anomalous transparency of the Universe for energetic gamma rays”, European Physical Journal C, 2021, <https://doi.org/10.1140/epjc/s10052-021-09051-6>. The article is also available in the archive of preprints <https://arxiv.org/abs/2004.08321>). This work was supported by Russian Science Foundation grant 18-12-00258.

For some very distant blazars, "anomalous transparency of the Universe" is observed - photons of such energies reach us from them, which, according to all calculations, should have been absorbed on their way through the Universe, interacting with the light of stars and galaxies. About one-third of the studied sources are visible with anomalous transparency and two-thirds with normal transparency. Some bright and well-studied sources turned out to be anomalous. In this work, Sergei Troitsky studied how such "anomalous" sources are distributed across the sky. If you plot them on a sky map, you can immediately see that they are distributed unevenly. One of the "most anomalous" sources - the very famous quasar 3C279, one of the brightest gamma-ray sources in the sky and one of the first quasars discovered in the 1960s - is located in the constellation Virgo. The galaxy in which we live is located in the jumper connecting the galaxy clusters in the constellations Virgo and Fornax. Astronomers call this jumper the Local Filament. It is only called a filament, but in fact it is a rather thick "cord" several megaparsecs wide, that is, millions of light years.

So, quasar 3C279 is much farther away than the cluster in the constellation Virgo, so it is visible through the cluster. This clue made it possible to understand the system: it turned out that other anomalous sources are visible through different elements of our supercluster of galaxies - nearby clusters and the Local Filament. It looks paradoxical - if you look in the directions where these structures of galaxies are located, the Universe turns out to be more transparent than if you look past them, through an empty space. Galaxies with a large number of stars are located inside the structures, so there are more things in them that radiation can "stumble upon" while passing through the Universe, and therefore more chances for photons to be absorbed. And we see, on the contrary, anomalous transparency in these directions. How can this be explained? Scientists even thought that one of the Cherenkov telescopes is out of calibration, and it incorrectly determines the brightness of objects. But the idea was wrong - anomalous objects were seen by all telescopes.

One of the possible explanations for such an unusual phenomenon is that anomalous transparency arises due to a new phenomenon in particle physics, the transformation of photons into axions and vice versa. Axions are amazing, not yet experimentally discovered particles that practically do not interact with matter and radiation - even weaker than the well-known neutrinos freely flying through the Sun, Earth, people ... Therefore, for axions the Universe is transparent. But in an external magnetic field, axions can intensively transform into photons - and vice versa, photons into axions. This is the kind of magnetic field that probably exists in galaxy clusters and filaments. Blazars are also located in filaments (their own, distant ones), so it turns out that photons are first emitted by blazars, fly several million light years and then turn into hypothetical axion-like particles. They, in turn, have already been flying billions of light years through intergalactic space, and then, having got into the magnetic field of our Local filament, they turn back into photons, which reach the Earth.

This is the picture of axion-photon mixing in filaments that was proposed in a 2010 article (Fairbairn, Rashba, Troitsky, <https://doi.org/10.1103/PhysRevD.84.125019> ) to solve another mystery of particle astrophysics - the observation of ultrahigh-energy neutral particles from lacertids. Lacertids are a subclass of the same blazars, distant powerful sources of radiation. In 2004, in the data of the HiRes experiment, which recorded ultrahigh-energy cosmic rays, researchers of INR RAS (Gorbunov, Tinyakov, Tkachev, Troitsky, <https://doi.org/10.1134/1.1808838> ) discovered a mysterious correlation of the directions of arrival of particles with energies above 1019 eV (that is, another hundred million times higher!) with the positions of lacertids in the sky. The correlation was confirmed in the work of the HiRes collaboration in 2005, but other experiments have not yet been able to test it due to the worse accuracy of determining the direction than that of HiRes. The directions coincided with an accuracy up to the resolution of the installation, which meant that the arriving particles did not have, in contrast to the bulk of cosmic particles, an electric charge (charged particles would be deflected in cosmic magnetic fields). In the framework of standard astrophysics, neutral particles of such high energies cannot fly from such distances, and the axion explanation was one of the few that worked.

Therefore, in this work, along with the positions of anomalous gamma-blazars, the directions of arrival of anomalous cosmic particles recorded by HiRes on the celestial sphere were analyzed in the same way - it turned out that the lacertids, from which they came, are also located behind the structures of the Local filament. The total statistical significance of two independent observations is 4 sigma, that is, the probability that this effect happened by chance is only about 1 case in 16000. So far, no other working explanations of the discovered effect, except for axion, have been proposed, but this does not mean that they do not exist - it is too early to talk about the discovery of a new elementary particle, the axion, by such an indirect method.

Now there is a lot of work to be done to study the discovered effect, in particular, using the data of the large international experiment Telescope Array, which studies ultrahigh-energy cosmic rays (the group of the Institute for Nuclear Research of the Russian Academy of Sciences participates). Scientists will try to independently verify the effect found in the HiRes data and investigate it, as well as the "axion" explanation of the anomalous transparency of the Universe for gamma rays of very high energies proposed in this paper.



*On this map of the sky, drawn in supergalactic - associated with the Local Supercluster - coordinates, the positions of blazars, the gamma radiation of which is absorbed abnormally weakly, are plotted in red; the directions of arrival of cosmic particles, which coincide with the positions of the lacertids, recorded by the HiRes experiment – in blue . Unlike similar sources evenly distributed across the sky, which do not exhibit any anomalies, all of them are visible through the elements of the local supercluster of galaxies (shown in purple), that is, through the areas with an increased magnetic field compared to the rest of space.*