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Probing UHECR and cosmic ray ensemble scenarios with a global CREDO network

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Among theoretical approaches in unveiling the physics of ultra-high-energy cosmic rays (UHECR) one can distinguish the models assuming interactions of exotic super-heavy matter (including extra dimensions, Lorentz invariance violation, cosmic strings, dark matter particles or particles beyond the standard model etc.) and acceleration scenarios describing processes, in which the particles are accelerated by a particular astrophysical object (shocks in relativistic plasma jets, unipolar induction mechanisms, second-order Fermi acceleration, energy transfer from black holes or compact stars etc.). Primary UHECR particles can produce cascades already above the Earth atmosphere, which may be detected as the so-called cosmic ray ensembles (CRE) – the phenomena composed of at least two cosmic ray particles, including photons, with a common primary interaction vertex or the same parent particle with correlated arrival directions and arrival times. In this contribution, we give a brief description of a novel approach to the probing of cosmic ray scenarios with the global Cosmic Ray Extremely Distributed Observatory (CREDO) network.

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The standard model of particle physics predicts that if cosmic rays are primarily composed by protons, there should exist a limit on the maximum energy of the particle coming from far distances. This bound is called the GZK cutoff limit [1]. The current experimental data suggests an extragalactic origin for UHECR with energies above the GZK cutoff [2]. Therefore, transient astronomical events are also of the great interest for the emission of tracers of primary UHECR. These include e.g. gamma-ray bursts, supernovae, fast radio bursts, various classes of active galactic nuclei (AGN) with SMBH at their centres, such as Seyfert galaxies, radio galaxies and blazars. Primary UHECR are expected to interact with radiation and matter on their way through the cosmos and give birth to the Cosmic Ray Ensembles (CRE) – the phenomena composed of at least two cosmic ray particles or photons, with a common primary interaction vertex or the same parent particle with correlated arrival directions and arrival times. Such cascades could be formed both within classical models (e.g. products of photon-photon interactions) and exotic scenarios (e.g. result of decay of super-heavy dark matter particles and subsequent interactions). Some of CRE might have a significant spatial extent, which could serve as a unique signature detectable with the existing cosmic ray infrastructure taken as a network of detectors. This signature would be composed of a number of air showers with parallel axes. So far, the cosmic ray research has been oriented on detecting single air showers only, while the search for ensembles of cosmic ray events is a scientific terra incognita.

Experimental searches for cosmic-ray correlations have been realized on different scales with the highest energy events observed by the leading collaborations: Pierre Auger Observatory [3] and Telescope Array [4], as well as the projects with distributed arrays of detectors, such as e.g. CHICOS [5] in the U.S., ALTA [6] in Canada, CZELTA [7] in the Czech Republic, GELATICA [8] in Georgia, EEE [9] in Italy, and LAAS [10] in Japan. Time correlation of registered showers was studied at the distances from 100 m to 7000 km, and in some cases evidence for unexpected coincidences have been found, however without any convincing follow-up studies and data taking campaigns, which is hard without a global coordination. Only very recently the idea of looking for large scale correlations in a general and global way took shape of the Cosmic Ray Extremely Distributed Observatory (CREDO) Collaboration (see, recent review [11]), formalized in September 2019. CREDO is meant to be a multi-technique (different detector types) and doubly open (for both data upload and offering access) infrastructure enabling a global research programs concerning radiation (both cosmic and terrestrial), with a number of multi-messenger, multi-mission and transdisciplinary opportunities. The CREDO initiative with its objectives dedicated to going beyond studying individual cosmic rays and taking under investigation also UHECR products, may provide a precious complementary approach to UHECR studies. The status of the dispute in the UHECR area encourages a closer look at the field and being ready for a major revision or breakthrough in the understanding of physics at the highest energies known.

To date, most of the data collected by CREDO comes from smartphones with the CREDO Detector app, operating on the Android system with already more than 10.5 million detections, and with the Cosmic Ray App dedicated to iOS devices with more than 7 million detections. Therefore, the work in the direction of science communication, popularization, outreach, education and other activities related to public engagement and citizen science is necessary. Another important example of the infrastructure working within the CREDO Collaboration, although not yet connected to the central system, is HEAMS (High Energy Astrophysics Muon System): an array of muon detectors

operated by the University of Adelaide, Australia, consisting of several one square meter scintillator muon detectors in two locations distant by 40 km.

In parallel to testing astrophysical scenarios the CREDO Collaboration develops the algorithms that will make us prepared to notice the unexpected physics effects if they come. These algorithms are based on identification of anomalies in the signals received by known and stable detectors. Once cosmic ray anomalies are efficiently identified, they should feed the global multi-messenger and multi-mission programs searching for correlations between different data channels, not only in astrophysics.

Detailed explanation of the CREDO aims, its objectives, methods and tools is given in a recent review [11] and summarized in the proceedings of the ICRC2021 under the article ID 1448 "Invitation to the Cosmic Ray Extremely Distributed Observatory".

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