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Search for Extensive Photon Cascades with the Cosmic-Ray Extremely Distributed Observatory

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Abstract
Although the photon structure is most efficiently studied at accelerators, there is also a scientifically complementary potential in investigations on photons produced in the outer space. This potential is already being explored with γ-ray telescopes, ultra-high energy cosmic ray observatories and, since very recently, by the Cosmic-Ray Extremely Distributed Observatory (CREDO). Unlike the former instruments focused on detection of single γ, CREDO aims at the detection of cascades (ensembles) of photons originating even at astrophysical distances. If at least a part of such a cascade reaches Earth, it might produce a unique pattern composed of a number of air showers observable by an appropriately dense array of standard detectors. If the energies of air showers constituting the pattern are relatively low and if the typical distances between neighbors are large, the ensemble character of the whole phenomenon might remain uncovered, unless the CREDO strategy is implemented.

Keywords
cosmic rays; ultra-high energy photons; photon ensembles

1 Introduction

While the photon structure and it properties in the high energy regime are investigated mainly using the data from man-made accelerators, one should remain aware of the scientific potential of astrophysical studies: gamma-ray astronomy and ultra-high energy cosmic ray (UHECR) research. Within the former field we deal with photons at energies unavailable in terrestrial instruments which adds complementarity to the accelerator photon investigations, despite incomparably low flux of gamma rays reaching the Earth. Considering the photon energies even larger than in gamma-ray astronomy, one enters the realm of UHECR which concerns particles of energies exceeding 10^{18} eV, with the few extreme events clearly above 10^{20} eV. The existence of such extremely energetic particles have remained a puzzle since decades. Interestingly, the two main classes of scenarios describing production of UHECR: "bottom-up" models based on acceleration of nuclei and "top-down" class postulating stable existence and decay or annihilation of super-massive particles of energies reaching even 10^{23} eV, predict that photons should contribute to the UHECR flux [1]. A clear distinction between the two classes is based on the scale of this contribution: in "bottom-up" models one would expect very small fraction of photons in the UHECR flux while in "top-down" scenarios the photon contribution to the observed flux is expected to exceed even 50% at 10^{20} eV. The research performed over the last decade by the largest cosmic-ray instruments does not indicate the existence of UHE photons, thus stringent upper limits are placed which under some basic assumptions might allow a severe constraining of the "top-down" class as a whole (see e.g. [2]). The point that we undertake in this paper is based on a trivial note concerning the mentioned "basic assumptions": we do not know the physics at UHE, relaying on extrapolations over many orders of magnitude from the accelerator energy region. Being aware of the fundamental theoretical uncertainties involved in

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the interpretation of the UHECR data allows considering the variety of logical and observational consequences of taking significantly different theoretical assumptions. In this paper we highlight one of such consequences: since UHE photons are expected to exist and the available evidence does not confirm their existence, we propose considering scenarios in which UHE photons exist but have negligibly little chance to reach Earth due to the interactions during their propagation on the way to us. Such scenarios prompt a purely technical challenge: can one see the products of these interactions - ensembles of cosmic rays? Actually this question needs an answer also within the state-of-the-art set of assumptions: if UHE photons exist, they should interact with the matter and fields during their propagation through the Universe which would lead to the initiation of extremely large cascades composed mainly of photons. And, continuing the logics within the paradigm, we also ask whether under some circumstances the possible sizes of such cascades might compensate a very small flux, as pointed out by the stringent upper limits to UHE photons. In other words we ask whether the scenarios involving UHECR photons can be tested more efficiently with the focus put on possible detection of photon cascades rather than single particles, complementarily to the current state-of-the-art research. The photon cascade approach has been initiated only recently by the CREDO Collaboration [3] and the scope of the addressed issues defines a wide physics program with long-term perspectives rather than a short term project. The basic research channel proposed by CREDO is the experimental verification of the astrophysical models where particle cascades are initiated, with the emphasis on photon ensembles. Such a verification would be possible only if there is a chance to observe at least partly the products of primary particle (e.g. UHE photons) interactions and this chance should be determined for the scenarios to be verified before proceeding with the experimental effort. Complementarily, we also propose another type of investigation which we call “fishing for unexpected physics”. This approach is oriented on hunting for clearly non-statistical excesses above the diffuse and random cosmic-ray background, or arrival time correlations of air showers and single muons (or other secondary cosmic rays) in distant detectors, independently of the expectations from theoretical models. In this paper we highlight the CREDO science case and instrumentation and analysis strategies related to these two research channels: testing scenarios and fishing for unexpected.

2 N_{ATM}>1: mysterious air shower observations and generalized cosmic-ray research

It seems to be not very well known within the cosmic-ray community, especially among the younger colleagues, that there exist published reports on multi-cosmic-ray events looking like footprints of ensembles of primary cosmic rays correlated in time [4, 5]. The reports discuss a) a burst of air showers at estimated mean energy of 3×10^{15} eV lasting 5 minutes [4], and b) unusual simultaneous increase in the cosmic-ray shower rate at two recording stations separated by 250 km [5]. Both observations were taken in two independent experiments in 1981 and 1975, respectively, and were the only events of their kinds seen during the lifetimes of both detecting systems. Other few hints of such possibly correlated cosmic-ray phenomena were seen by some small cosmic-ray experiments dotted around the world, such as a Swiss experiment that deployed four detector systems in Basel, Bern, Geneva and Le Locle, with a total enclosed area of around 5000 km^2 [6]. As proposed in Ref. [6], a globally coordinated cosmic-ray detection and analysis effort seems to be in place to verify whether the peculiar air shower observations carry any physical essence or maybe are just artifacts. The proposal concerned building small and cheap detectors which were planned to be installed in high schools at different locations around the globe, then operated and maintained by the high school pupils and staff. The science case addressed the cascading processes initiated by nuclei, mainly the photodisintegration of high-energy cosmic-ray nuclei passing through the vicinity of the Sun, first proposed by N. M. Gerasimova and G. Zatsepin back in the 1950s. The challenge had been undertaken in several research centers across the world where scientists in cooperation with their educational partners established small size experiments and approached a global coordination. Insufficient funding together with deficit of enthusiasm among the participants which grew with the continuing lack of exciting observations gave no scientifically meaningful outcome and led to reducing or closing up the activity in most of the involved high schools.

Now the idea of a global cosmic-ray research is being revoked in an enriched incarnation of CREDO with the following novelties:

1. The enriched CREDO science case includes photon cascades which addresses foundations of physics at the highest energies, allowing constraints on e.g. Lorentz invariance violation (LIV) [7], QED nonlinearities and space-time structure [8], or the "top-down" UHECR scenarios [1], similarly as in the UHE photon search. Furthermore, the generalization of the global approach allowing consideration of photon cascades changes the detection strategy. Photon cascades might contain even millions of particles, comparing to few or at best several in case of nuclear cascading like the Gerasimova-Zatsepin effect. This implies the necessity of implementing novel algorithms and triggers, and at the same time gives promising perspectives for unique, global observable signatures enabling event-by-event identification of cosmic-ray ensembles.
2. CREDO points to the necessity of involving as many detectors as possible, regardless the technical diversity or complexity of the whole network, focusing in the first stage only at the timing of single events and particles, looking for excesses in time windows of different scales. This approach addresses a very wide variety of instruments: satellites, stratospheric balloons, cosmic-ray arrays, fluorescence telescopes, radio air shower detectors, gamma-ray telescopes (see Ref. [9] for the first multi-primary gamma ray study in the CREDO context), neutrino observatories, accelerators, educational arrays, university laboratories, high school detectors, popular pocket-size detectors and finally smartphones equipped with a detection app and educational toys with simplest detectors. Such a global network can serve as a universal scenario tester: a subnetwork of detectors meeting the optimum requirements of a specific scenario can be used and more detectors can be built "on demand" if scientifically justified by the expectations of the tested scenario. At the same time the network can be used as a whole to fish for unexpected physics, i.e. unusual rate excesses or arrival time orders, as highlighted in the Introduction.
3. As the acquisition of the data from "everywhere" recorded with "everything" would generate an enormous stream of information, a sensible analysis and interpretation would automatically require an enormous manpower, including an effort of non-professional but enthusiastic scientific partners. Therefore CREDO takes the public engagement as the key scientific tool, putting the emphasis on the clarity of the key objectives, and easy, intuitive usage of the relevant tools. In parallel we will offer the paths for both education and science careers for all the participants.
4. CREDO puts a particular emphasis on the exploration of an alerting potential of the global cosmic-ray network, addressing not only the astrophysical strategies but also multidisciplinary research involving climate changes or seismic studies [3].

With the novel approach to a global cosmic-ray effort proposed by CREDO it becomes evident that a) widening of the scientific perspectives, b) including as much of the available data as possible, and c) involving as many of the potentially interested and enthusiastic colleagues as possible, increases the chances for scientific discoveries of a fundamental importance. Therefore CREDO postulates a fully open project, with free access to data and open source tools, where both financial and in-kind contributions are welcome. It all offers an unprecedented chance for multidisciplinary research and education based on cosmic ray data which are available everywhere and at negligibly small cost.

Following the Introduction and the above considerations one defines the CREDO mission in the simplest way by admitting more than one cosmic ray particle (including photons) entering the atmosphere simultaneously, where the term "simultaneously" denotes a temporal correlation and the specification "more than one" is equivalent to "ensemble" or to the mathematical expression $N_{ATM}>1$ (see Fig. 1).

3 Ensembles of photons: scenarios plus fishing

The "$N_{ATM}>1$" definition brings us to the already mentioned detection channels: A) testing theoretical scenarios and B) hunting for unexpected physics manifestations. Let us illustrate the channel A) with the

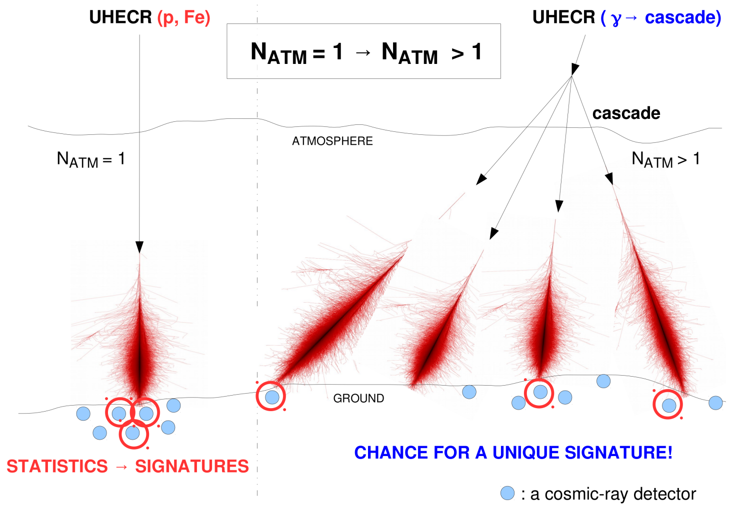

Fig. 1: Generalization of cosmic-ray research by admitting ensembles of particles as observation target.

two examples: exotic and standard. The exotic example is based on noting that there are variants of LIV with critically different predictions concerning the UHE photon fluxes, depending significantly on the assumed alteration of the dispersion relation at the highest energies. E.g. taking the dispersion relation in the shape defined in Ref. [10]:

$$E_\gamma(\vec{k}) = \sqrt{\frac{(1-\kappa)}{(1+\kappa)}}|\vec{k}| \tag{1}$$

one understands that the sign of parameter κ changes the UHE photon flux expectations dramatically. If κ is positive, the pair production by a primary UHE photon is suppressed, which should lead to increased UHE photon fluxes observed at Earth, in comparison to the implications concluded with using non-altered dispersion relation. In this scenario the non-observation result allows constraining κ and therefore also LIV. On the other hand, if κ is negative, the lifetime of a UHE photon would be extremely short, even of the order of 1 second, which on astrophysical scale is equivalent to an immediate decay [11–13]. We note that if the latter scenario is real, non-observation of UHE photons at Earth and the subsequent upper limits would be a trivial, inconclusive result. However, even then one still has at hand one yet not checked research option – approaching an observation of products of a UHE photon decay: cosmogenic electromagnetic cascades. Although it is widely assumed that such cascades get completely dissipated before reaching Earth, thus contributing to the diffuse photon flux, there are no precise calculations of the horizon (the distance within which a cascade can reach Earth at least in part, i.e. as an ensemble of a minimum two particles) with different theoretical assumptions. Such calculations within the Standard Model of particles are possible with the currently available tools [14] and the first steps in this direction have already been made, as described in Ref. [15]. In addition, when one takes into consideration physics beyond the Standard Model, either of particles or cosmological – more scenarios allowing observation of cascade-like signatures at the Earth appear verifiable (see e.g. Ref. [13] for a review on concepts relating to potential observation of quantum gravity manifestations). In this context it becomes apparent that a complete study and search for UHE photons should include both an effort towards identification of single UHE particles and a search for products of their decay: ensembles of photons correlated in time, most likely dispersed significantly in space, maybe also in time, with energies spanning even a very wide spectrum. The existence of a logically obvious and experimentally available, although yet not probed UHE photon search direction can be illustrated with considering two extreme cases: obvious detection of a photon ensemble and its obvious extinction. If photons in a cosmic-ray ensemble which reaches Earth travel very closely to each other, both in space and time, they would induce a set of extensive air showers (EAS) which would effectively behave as one big EAS, being a superposition of the smaller ones, detectable with the state-of-the art techniques, e.g. with a giant array of particle counters or with fluorescence telescopes. On the other hand, if the ensemble components are distant one from another on average more that the size of the Earth, then obviously no conclusion about the cascade-like nature of the phenomenon is possible: we see at best one particle which contributes to the diffuse and random cosmic-ray particle background. What is in between of these two "extremes", ensembles of particles (photons) distant one from another on average by less than the size of the Earth, remains to be studied, and, possibly, observed.

An example of a non-exotic scenario within the channel A is a cascade of photons initiated by a UHE photon primary passing through the vicinity of the Sun and interacting with its magnetic field (see Fig. 2). This phenomenon, known in the literature as the preshower effect [16], is expected within

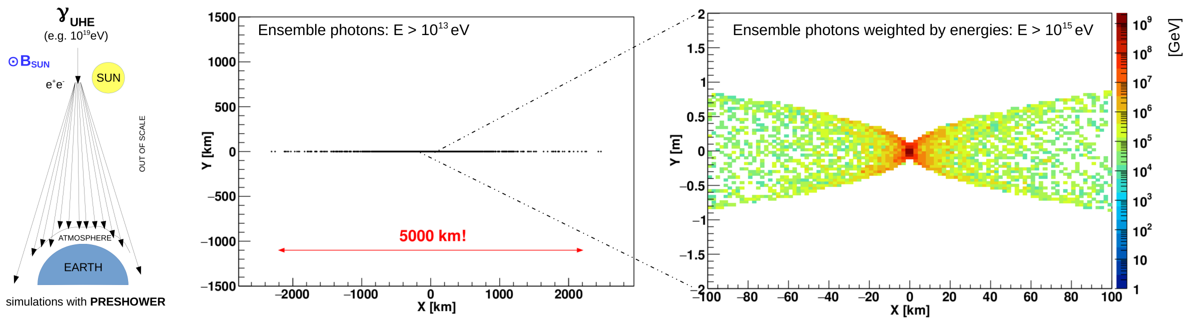

Fig. 2: The particle distribution on Earth of an ensemble of photons originated from an interaction of UHE photon of energy 10^{19} eV with the Sun magnetic field.

the standard quantum electrodynamics and can be simulated with the available open source tools [17] which are also being used as a standard in the studies involving UHE photon-induced EAS [18]. The expected particle distribution at the top of atmosphere is very much elongated (even 10000 km!) in the West-East direction and super-thin (meters) along the North-South line, promising a unique observable signature built of temporal sequence of arrival times of the secondary cosmic rays on ground, and a very characteristic pattern of the triggering detectors [3]. In the preshower effect, once the primary UHE photon converts into an electron-positron pair, the electrons begin to radiate magnetic bremsstrahlung photons. The further the electrons travel the lower their energies and the larger deflection with respect to the primary direction. This is reflected in the photon distribution on ground: the photons near the core corresponding to the primary direction posses high energies as they were emitted right after the electron-positron pair creation, when the electrons still had energies comparable to the primary and they did not get deflected significantly in the magnetic field of the Sun. The further from the core, the lower photon energies. In the example shown in Fig. 2 the primary photon energy is 10^{19} eV and the spectrum of photons at the top of the Earth atmosphere extends from below GeV to above EeV (not the whole spectrum shown!). A feature such as shown in Fig. 2 could be observed with a global cosmic-ray network, or with a single large cosmic-ray observatory, or with a dedicated experiment tuned to the particle densities expected on ground. Testing this scenario, which we call Sun-SPS (SPS for Super Pre-Shower), is one of the first scientific tasks of the CREDO Collaboration. It is worthwhile to mention that the largest observatories are tuned to record EAS with energies typical for the very vicinity of the Sun-SPS core, landing at distances not further than few tens km, while the whole Sun-SPS footprint might be even 3 orders of magnitude longer. It points to the advantage of the global and diversified approach to the available cosmic ray data implemented in CREDO, at least as far as testing the Sun-SPS scenario is considered.

A special attention in CREDO is put to the channel B: fishing for unexpected physics. The idea of the "unexpected physics" trigger based on arrival time correlations and order in distant detecting stations is sketched in Fig. 3. Complementarily to the standard search of neighbor detectors triggered

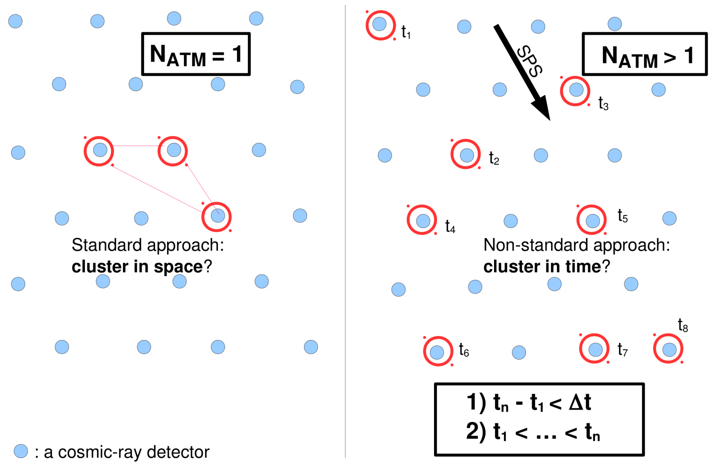

Fig. 3: A standard (cluster in space) vs ensemble (cluster in time) trigger in a ground array of a cosmic-ray observatory.

simultaneously by an EAS (clusters in space) one might also look for distant detectors triggered within some predefined time window by an ensemble of cosmic rays (clusters in time). In addition one might expect some order in the arrival times of the particles or events contributing to the cluster. The presence of such a feature would increase statistical significance of the observation.

4 Observation: public engagement as a scientific tool

As already explained, the scientific success of the CREDO mission is strictly determined by the scale of the project possible to be achieved: total collecting area, geographical distribution of the detecting sites, and availability of manpower. The optimum can be reached by combining the available professional resources and wide public engagement. Apart from social reasons for which the public should be kept informed and even involved in the professional scientific research, it is obvious that public engagement in an exciting scientific project must induce a growth of professional scientific resources bringing profits to the whole science community and to the society as a whole. The key condition for this scientific growth is to show opportunities and paths of individual development and education within the project. In CREDO public engagement is going to be driven by three simple tools that would help to reach both social and scientific objectives of the project. Firstly, a massive participation will be achieved with an open source mobile application which turns a smartphone into a particle detectors. Such applications already exist [19, 20] although they are not yet open, thus not enabling sufficient flexibility required for a society driven software engine. For this reason CREDO opens its own app, to be freely distributed among science enthusiasts across the world with the encouragement to contributing to the development [21]. This of course does not exclude contributions from the users of the other applications to the common worldwide database. Another potentially available channel to involve even the youngest generations of science enthusiasts is related to the educational toys capable of detecting secondary cosmic rays and networked worldwide to help the CREDO mission. The detection of a particle and the link to the community dedicated to reach common and ambitious scientific goals should stimulate the passion, enthusiasm and a desire to get involved deeper in the project, i.e. to get educated.

Both using the smartphone particle detection app or an educational toy will enable passive participation in the CREDO project by collecting the data. The next level of involvement will be the activity within the CREDO community environment. The pilot component of this environment is the CREDO citizen science platform Dark Universe Welcome (DUW) [22] installed on the Zooniverse engine. With the easily understandable analysis format of DUW (see Fig. 4) one will be able to analyze “private” particles in the global context, search for “strange” detection patterns and help to train the “scientific fishing" algorithms. Other social facilities of the CREDO community environment, like e.g. individual and group rankings, will increase the pleasure of doing science and further stimulate the motivation to get involved deeper. The educational and scientific career paths supplementing the popular devices and software will in turn strengthen the stream of creativity and "fresh blood" to power the community of science professionals, that ultimately should be reflected in the increase of the ability of the society as a whole to develop by making scientific discoveries.

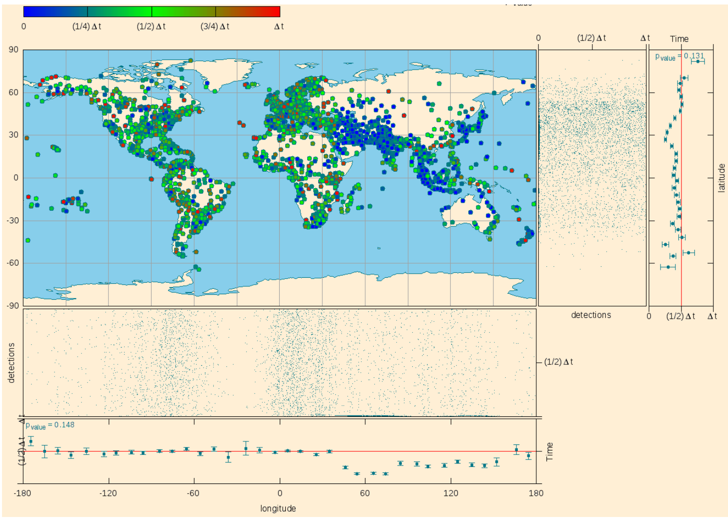

Fig. 4: A simple visualization of the "fishing for unexpected" strategy. The average arrival time within a certain temporal an spatial interval should be statistically consistent with the mean of the time interval if the received signal is composed of uncorrelated particles. A significant departure from the mean might be a footprint of an ensemble of correlated cosmic rays.

The third and scientifically the most exciting tool of the public engagement will be the automated procedure to monitor the cosmic-ray data globally which will provide the easily classifiable monitoring images with the largest discovery potential. The prototype of such a monitoring machine, called CREDO Monitor, fed by some of the publicly available cosmic-ray data, has been launched recently and is internally available for the CREDO members [23]. The available data is migrated periodically from the active acquisition sites to the data storage and computing center maintained at ACC Cyfronet AGH-UST [24], then after basic processing (scanning for time-clustering) classifiable global detector patterns (maps as in Fig. 4) are generated and stored on a web server ready for the inspection with a human eye. The receivers of CREDO Monitor will be able to tune the view of the most interesting discovery proposals selected by classifying machines and initiate a collective human-based classification according to the predefined crowdsourcing requirements, and finally open a professional analysis with a variety of algorithms which would actually lead to specifying of statistical significance of the proposed discovery patterns.

The above three pillars of the public engagement in CREDO should attract large number of participants and increase the chances for a scientific success of the project. Importantly, all the contributions to data acquisition and analysis, no matter from scientists or from "just" science enthusiasts, would give the right to claim co-authorship of scientific publications and the share in the possibly accompanying awards. Moreover, it is planned that the contributions will be easily registered and evaluated, leading to the estimate of the share in the project. Such an evaluation system, including e.g. the already mentioned user rankings, would offer a potential to activate additional motivations of the participants: positive competition.

5 Summary

We consider cosmic-ray cascades composed of photons correlated in time as a yet not checked channel of information about the Universe and the physics at the highest energies known. If such cascades exist they might have a wide spatial distribution which might make them observable only with a worldwide network of detectors, and keep out of the reach of even the largest cosmic-ray observatories with their state-of-the-art configuration. We introduce the Cosmic-Ray Extremely Distributed Observatory, the infrastructure and physics program tuned to cosmic-ray cascades, with potential impact on ultra-high energy astrophysics, the physics of fundamental particle interactions and cosmology, offering also a multidimensional interdisciplinary opportunities. We implement the CREDO strategy by applying a trivially novel approach to the cosmic-ray data taking - a global and massive approach. Within the CREDO strategy based on the collective and global approach to the available and future cosmic-ray data the chances for detecting and studying the astrophysical cascades by definition exceed the capabilities of even the largest observatories and detectors working independently of each other. Everybody, from theorists to non-experts, both institutions and private persons, are invited and welcome to contribute.

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