PROCEEDINGS OF SCIENCE

The Strawman Design of the Global Cosmic Ray Observatory GCOS

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The Global Cosmic Ray Observatory (GCOS) is a concept for a ground-based detector to measure the properties of the highest-energy particles in the Universe with unprecedented precision after the year 2035. We present the strawman/baseline design of GCOS, as developed during the 3rd GCOS workshop in 2023.

For more information the reader is referred to [1].

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1. Introduction

In the Standard Model of particle physics we describe Nature with four fundamental forces: gravity, electromagnetism, the weak force, and the strong force. In multi-messenger astro-(particle) physics we use all four forces to explore the high-energy Universe, as illustrated in Fig. 1. We use the full electromagnetic spectrum from the radio regime to gamma rays in the PeV region (electromagnetic force), we observe neutrinos up to PeV energies (weak force), and (charged) cosmic rays with macroscopic energies of 16 Joule, concentrated in a single atomic nucleus (strong force). Recently, also a new window to the Universe has been opened — the observation of gravitational waves. Since a few years we have all four messengers at our hand and observe the Universe routinely. The challange for the upcoming decade(s) will be to fully understand all measurements and find a connecting underlying theory to describe the processes in the Universe under extreme conditions and, eventually to find the sources of the highest energy particles in the Universe.

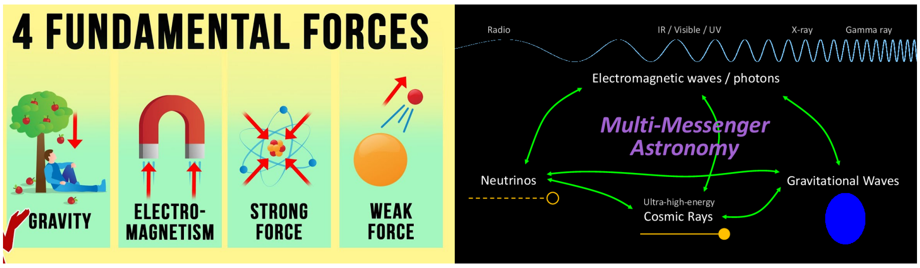

Figure 1: Left: in the Standard Model of particles physics we describe Nature with four forces. Right: In multi-messenger astro(particle)physics we use all four forces to explore the high-energy Universe [2].

First steps to understand the common origin of the various messengers are ongoing. For example Fig. 2 summarizes the current measurements of gamma rays, neutrinos and cosmic rays [3]. The spectral flux of neutrinos inferred from two sets of IceCube data are compared to the flux of unresolved extragalactic gamma-ray sources and ultra-high-energy cosmic rays. Different multi-messenger connections are pointed out: (A) The joined production of charged pions ($\pi^{\pm}$) and neutral pions (π^0) in cosmic-ray interactions leads to the emission of neutrinos (dashed blue line) and gamma rays (solid blue line), respectively. (B) Cosmic-ray emission models (solid green) of the most energetic cosmic rays imply a maximal flux

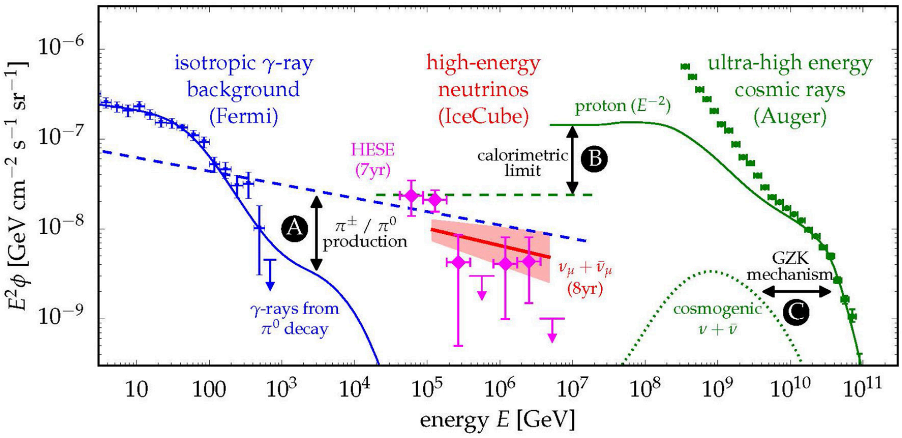

Figure 2: The spectral flux of neutrinos compared to the flux of unresolved extragalactic gamma-ray sources and ultra-high-energy cosmic rays. For details, see [3].

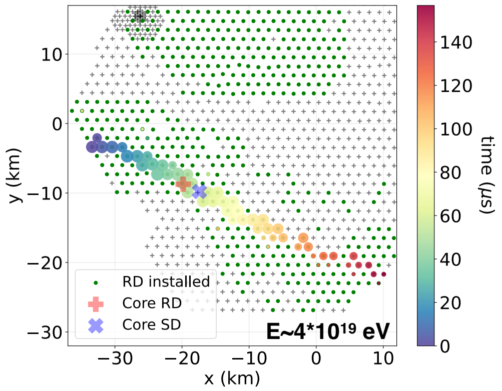

Figure 3: A cosmic ray with an energy of about 40 EeV measured with the Radio Detector of the upgraded Pierre Auger Observatory.

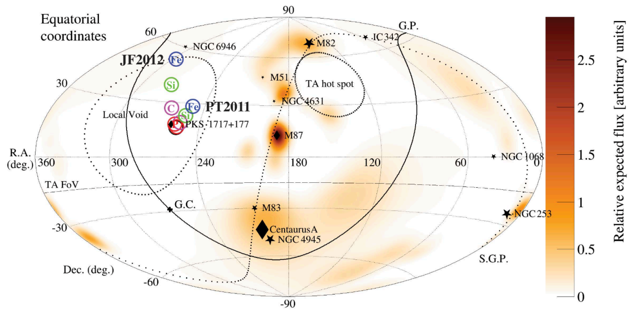

Figure 4: The arrival direction of the 27 May 2021 high-energy cosmic-ray particle, recorded by the Telescope Array (black circle) on a sky map in equatorial coordinates [4].

(calorimetric limit) of neutrinos from the same sources (green dashed). (C) The same cosmic-ray model predicts the emission of cosmogenic neutrinos from the collision with cosmic background photons (GZK mechanism).

In November 2024 the *International Agreement* of the Pierre Auger Observatory has been extended to ensure operations with the upgraded Observatory until the year 2035. First data, collected with the upgraded Observatory look very promising. As illustration, an event coming in almost parallel to the horizon with only about 5° elevation and an enormous energy of about 40 EeV is shown in Fig. 3. If one imagines that such an event would be a neutrino or a gamma ray — this would be quite a break through, opening a new window to the Universe. So far, both species only have been observed at energies up to the PeV range, observing them with thousand times higher energies would be a real novelity. In particular, since those neutral particles are not deflected by magnetic fields, they would point directly to their point of origin.

The Telescope Array collaboration has recently reported the observation of a cosmic ray with an extreme energy of around 244 EeV, as depicted in Fig. 4 [4]. If such a apricle would be a light nucleus, i.e. it would only carry a small charge and, thus, would have a quite high rigidity, it would be expected to be only marginally deflected by (Galactic) magnetic fields. Thus, such extreme particles are expected to point back to their sources.

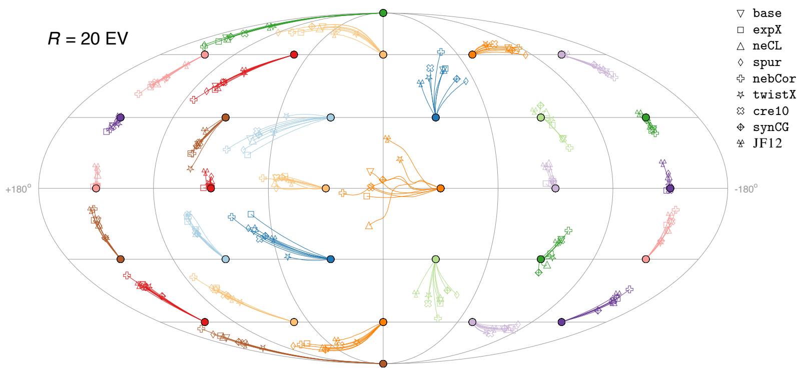

Figure 5: Angular deflection of ultra-high-energy cosmic rays with a rigidity of 20 EV in different models for the Galactic magnetic field, see [5].

If one imagines that there would be more such particles with high rigidity, one could envisage of tracing those particles back to their sources [5]. An example is given in Fig. 5. It shows the deflection of particles with a rigidity of 20 EV, assuming different models of the Galactic magnetic field. The crucial observational parameter is the rigidity of the particle $R = E/Z \approx E/(A/2)$. Thus, an observatory has to provide an accurate measurement of the energy and the particle type/mass of the incoming particle.

With an observatory of the exposure of several times the ones of existing observatories one would expect to see point sources of (charged) cosmic rays on the sky. This is illustrated in Fig. 6. The number of expected source images is plotted as a function of the exposure, the latter is in units of the total exposure, acquired in Auger Phase I.

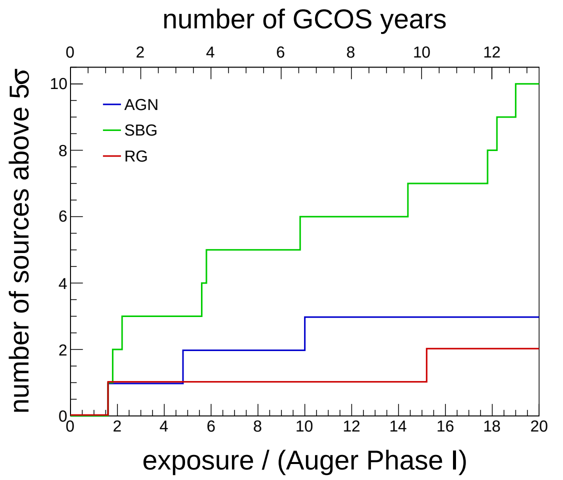

Figure 6: Expected number of source images as a function of exposure for different source classes (M. Unger in [1].

To conduct EeV astronomy with neutral (gamma rays and neutrinos) as well as charged (cosmic rays) particles will require a future observatory with an exposure much bigger than the one from existing observatories. This has been discussed in a series of workshops [6–8] and lead to the concept of a strawman design for the Global Cosmic Ray Observatory — GCOS. The GCOS science objectives are summarized in the box.

Science Targets of GCOS

- discovery of UHE accelerators
- charged-particle astronomy
- UHE neutrinos and photons
- BSM physics
- cosmic magnetism
- multi-messenger studies

2. The Global Cosmic Ray Observatory

GCOS is a planned large-scale facility designed to study ultra-high-energy cosmic particles, including cosmic rays, photons, and neutrinos [1]. Its main objective is to precisely characterize the properties of the most energetic particles in the universe and to pinpoint their mysterious origins. Featuring an aperture that is twenty times larger than current observatories, GCOS aims to begin operations after 2030, coinciding with the gradual phase-out of existing detectors [9].

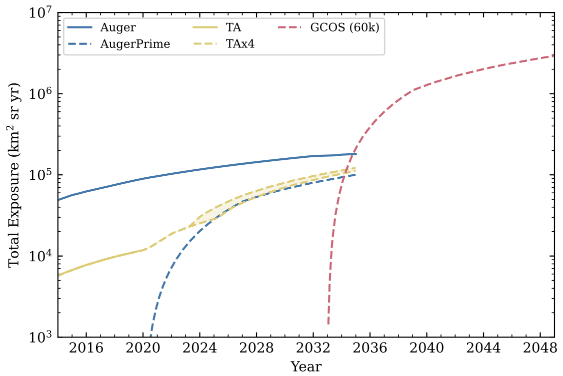

Figure 7: Expected exposures of GCOS and existing air shower arrays as function of time. Adapted from [9].

With the aim to collect in one year the complete exposure accumulated by the Pierre Auger Observatory until 2030 one obtains an exposure as depicted in Fig. 7 together with the values for existing arrays. A band is shown to indicate the exposure for various deployment schedules for TA$\times$4. The solid blue line denotes the total Auger exposure and the exposure collected with the upgraded AugerPrime detectors is indicated by the blue dashed line.

To achieve full-sky coverage one needs at least two sites, one in the northern and one in the southern hemispohere. Locations around $\pm 40^\circ$ latitude provide optimal coverage, as depicted in Fig. 8. The total area needs to be about twenty times the surface of the Pierre Auger Observatory. Main objective is to study the highest-energy particles in the Universe ($E > 10$ EeV) with good resolution for the observational parameters. The general requirements for GCOS are summarized in the box.

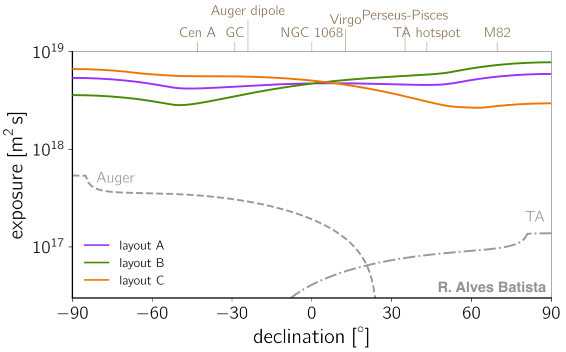

Figure 8: Exposure as a function of declination for existing arrays and different concepts for GCOS [10].

Existing large-scale facilities for observing ultra-high-energy cosmic rays, such as the Pierre Auger Observatory in Argentina (at 35° S) and the Telescope Array in Utah (at 39° N), are positioned in optimal locations. These sites could function as infill arrays, benefiting from increased station density and, consequently, lower energy detection thresholds. Given the established infrastructure at both locations, they present excellent foundations for the expansion of larger GCOS arrays.

GCOS Requirements

- total area: 60 000 km^2
- number of sites ≥ 2
- trigger threshold: 10^{19} eV
- high-quality threshold: 3×10^{19} eV
- σ_E: 10%, $\sigma_{\ln A}$: 1, σ_θ: 1°
- high duty cycle, low maintenance

The Pierre Auger Observatory in Argentina could serve as potential core for a larger GCOS array. If one requires a "flat" area at an altitude around 1 500 m.a.s.l. one could extend the existing array maybe by a factor of two or three. Thus, an area of the order of almost 10 000 km^2 could be reached, i.e. 1/6 of the above mentioned total GCOS area. Also sites in the northern hemisphere are discussed, e.g. the CRAFFT collaboration is looking for a large detection area in the US [11].

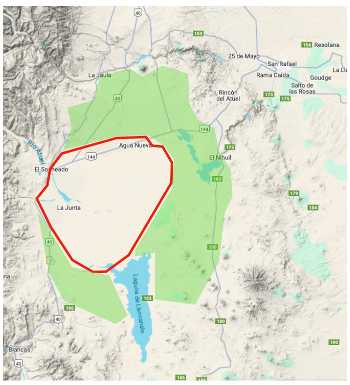

Figure 9: Illustration of a potential extension of the Pierre Auger Observatory.

Particle Detector. To cover the required area of GCOS with a minimal number of particle detector stations, a trade-off between the spacing between detectors and the covered area has to be taken into account. With the footprints of the vertical air showers on the ground not exceeding 20 km^2 a spacing of 2.2 km provides an upper limit to achieve an optimal trigger efficiency. To cover the planned surface of 60 000 km^2 about 18 000 detectors are required.

To have good detection efficiency and enough effective area for inclined air-showers, the detectors should be built to cover a large solid-angle phase space. While different configurations of scintillators can be imagined, the water-Cherenkov detectors are a rather simple solution for this.

A simple water-Cherenkov detector, such as the one used at the Pierre Auger Observatory cannot distinguish directly between the electromagnetic and muonic components, but it has been proven that machine learning techniques might provide very good resolution in extracting the muonic component from the total signal [12] for certain distances to the air-shower axis and energies of the primary particles.

The reconstruction of the number of muons in air showers can be further improved by separating horizontally the optical volume of the detectors in two: the upper layer would be more sensitive to the electromagnetic component, while the bottom layer would contain more light produced by muons. By having these different signals, one can extract via a set of linear equations the individual air-shower components [13]. A combination of scintillators (with photon conversion) and water-Cherenkov detectors can be also investigated.

Particle Detector Design

- layered water Cherenkov detectors
- emag. and muonic EAS component
- detector spacing: 2.2 km
- number of stations: 18 000
- σ_S: 10%, σ_{N_μ}: 10%, $\sigma_{X_{\max}}$: 30 g/cm^2

Fluorescence Detector. The longitudinal development of air showers can be observed directly using fluorescence telescopes. The integral of the profile provides a model-independent measurement of the calorimetric energy of a shower and the depth $X_{\max}$ at which the measured profile reaches its maximum is proportional to the logarithm of the mass of the primary particle. The main purpose of the FD in GCOS will be the calibration of the absolute energy scale of the PD with less than 10% uncertainty and to provide a calibration of its $X_{\max}$ scale. The required coverage is $\geq$50% above the quality energy threshold of the PD, i.e. at $>$ 30 EeV. The resolution should be similar to the one achieved with current FDs: $<$ 10% energy resolution, 15 g/cm^2 $X_{\max}$ resolution and 0.5° angular resolution. Current FDs operate with a duty cycle of $\lesssim$ 15% during clear and moonless nights, but using SiPM cameras, the GCOS FD will be able to safely operate with higher duty cycles of up to 35%.

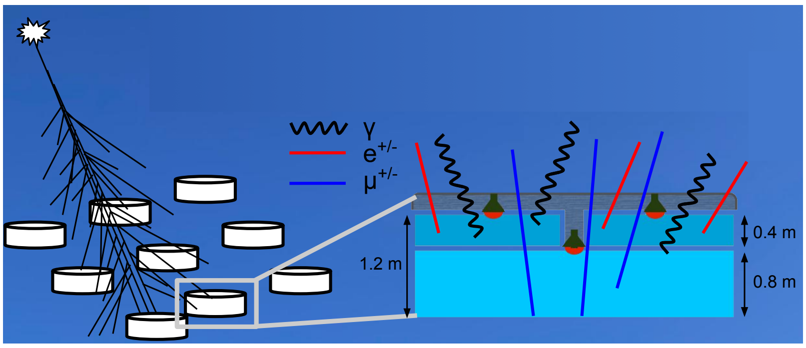

Figure 10: Illustration of a layered water-Cherenkov detector as an option for the Particle Detector array of GCOS [14].

Fluorescence Detector Tasks

- calibration of PD energy scale
- calibration of PD mass scale
- $\sigma_E < 10\%$, $\sigma_{\ln A} \sim 0.4$
- duty cycle 20%

Two layouts of the FD are considered. Layout A of one 30 000 km^2 site of GCOS is illustrated in Fig. 11. The telescopes are located at two sites ("Mastercard" layout). The light- and dark-blue areas denote the FD coverage of the array at 10^{20} eV with low-elevation telescopes and single-pixel telescopes, respectively. Laser facilities, that are needed for a continous monitoring of the aerosol content of the atmosphere, are indicated as red points.

As an alternative setup we consider layout B in which only single-pixel telescopes are deployed. In this case $\geq$ 15 sites need to be operated and again there is minimal overlap between the sites. The air shower geometry is taken from the PD, raising the enery threshold of the FD to the PD trigger threshold of 10^{19} eV.

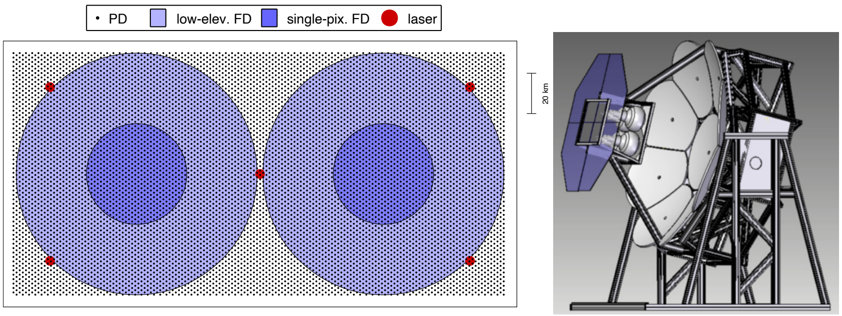

Figure 11: Left: Layout A of the FD at one 30 000 km^2 GCOS site. Right: concept of a single-pixel telescope [15].

Radio Detector. The particle detector array can be complemented by a radio detector array. Radio detection provides a very clean and accurate measurement of the e/m shower component. E.g. for the Auger Radio Detector an accuracy of 6% has been obtained from full end-to-end simulations [16]. It is important to point out that this uncertainty is independent of the cosmic-ray particle type. The fact that $E_{\rm em}$ is reconstructed from radio data with no significant dependence on the incoming cosmic ray particle type makes it a very suitable energy estimator for use in the discrimination of air showers induced by different primary particles [16–18].

Radio Detector Potential

- $\sigma_{\rm e/m} < 10\%$
- independent energy scale, $\sigma_{\rm E} < 10\%$
- hybrid μ & e/m $\rightarrow$ mass
- interferometry $\rightarrow$ mass

The total cosmic-ray energy can be reconstructed with an accuracy of better than 10%. Highly inclined air showers [19] with zenith angles $\Theta > 60^\circ$ traverse a big amount of atmosphere until they are detected. The thickness of the atmosphere in horizontal direction ($\Theta = 90^\circ$) amounts to about 35 times the column density of the vertical atmosphere. Thus, the e/m shower component is mostly absorbed and only muons are detected with the particle detectors. The atmosphere is transparent for radio emission in our band (tens to hundreds MHz) and radio measurements are an ideal tool for a calorimetric measurement of the electromagnetic component in horizontal air showers. The combination of electromagnetic and muonic information is used to derive the mass/particle type of the incoming cosmic ray. Another method with enormous potential to determine the mass/particle type of the incoming cosmic ray is interferometry [20]. This requires sub-ns time resolution, which can be achieved, e.g. by using time synchronization signals from the Galileo satellite GPS system.

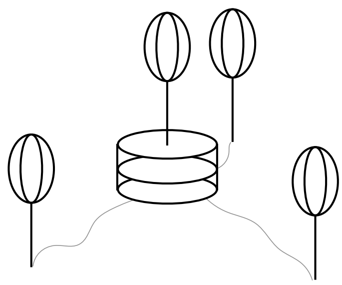

Figure 12: Concept of satellite radio antennas and a central station.

The relatively steep lateral distribution of the radio emission requires a detector spacing around 1 500 m or smaller. This makes radio detection in particular interesting for inclined air showers with zenith angles $\Theta > 60^\circ$. Due to cost constraints, the spacing of the particle detector array (see above) will probably be of the order of 2 km or above. A smaller grid size for the radio detector array could be achieved by introducing satellite radio stations to each particle detector station. They could be rather simple, only being comprised of a radio antenna and a low-noise pre-amplifier, connected to the particle detector station by cables in the ground. Thus, the satellite radio stations could be rather cheap and easy to deploy. The particle detector station could contain the main electronics (filter amplifier and digitization) and communication systems.

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