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Snowmass UHECR Whitepaper: Requirements on Future Instrumentation

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Complementing the overview contribution about the whitepaper on ultra-high-energy cosmic rays (UHECR) prepared for the Snowmass community survey in the U.S. [Astroparticle Physics 149 (2023) 102819 - arXiv:2205.05845], this contribution focuses on Chapter 6, the 'Instrumentation Roadmap' for UHECR physics in the next decades. In addition to an increase in statistics, a higher measurement accuracy of cosmic-ray air showers is needed to answer open questions regarding the astrophysics and particle physics related to UHECR. The needed boost in exposure can be provided by space-borne fluorescence detectors with POEMMA or by huge ground arrays using a single cost-effective technique, such as the giant radio arrays envisioned with GRAND. These observatories maximizing the exposure need to be complemented by ground arrays featuring an event-by-event resolution of the rigidity of the primary particle, which is the essence of GCOS. The required high mass resolution demands the simultaneous measurement of the electromagnetic (energy and X_{max}) and muonic shower components, possibly by combining layered water-Cherenkov with radio detectors and next-generation fluorescence telescopes, together with novel analysis techniques, such as neural networks. The higher accuracy for air-shower measurements is also important for UHECR particle physics because it will enable stricter tests of hadronic interaction models and will help to identify ultra-high-energy photons or neutrinos. This contribution will give an overview of the instrumentation needed for the future of UHECR physics in the context of the next generation experiments discussed in the whitepaper.

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1. Introduction

As part of the Snowmass process in the United States, we have prepared a whitepaper with input from the international ultra-high-energy cosmic ray (UHECR) community summarizing the status and needs of our field [1]. A key chapter of that whitepaper is the 'Instrumentation Roadmap' which describes recent and expected progress in detection and computational methods as well as plans and goals for the major future UHECR experiments. This proceeding provides a brief, thus incomplete, summary of this chapter, which focuses on the science and detector technology of future instrumentation. While other short summaries of the whitepaper are available in Refs. [2, 3], we recommend reading especially the executive summary and also the chapter about the instrumentation roadmap in the original whitepaper [1]. Other important aspects of future experiments, such as fair and open data management, diversity of collaborations, and the carbon footprint, are also covered in the whitepaper.

2. Detection Methods

Cosmic rays with PeV-EeV energies are too rare for direct detection methods, and can only be detected indirectly by observing air showers. In addition to measuring the secondary particles of the electromagnetic and muonic shower components at ground with surface arrays and muons also with underground detectors, the electromagnetic shower component can be detected indirectly through electromagnetic waves: air-Cherenkov light, fluorescence light, and radio emission (see Fig. 1). As air-Cherenkov detectors require a relatively dense spacing, instrumenting large areas can be expensive, and at ultra-high energies, mostly particle detectors, radio arrays and fluorescence telescopes are relevant.

Large apertures can be provided by sparse radio arrays as the radio footprint extends over many km in diameter for very inclined showers of zenith angles $\gtrsim 65^\circ$ [4]. Also fluorescence detectors can provide large apertures with either ground arrays or from space [5], but the fluorescence technique is restricted in duty cycle to clear and dark sky conditions.

The fluorescence technique is mature and proven to provide excellent energy and $X_{\max}$ resolution [6]. Therefore, current developments focused on technical improvements for the usability in space and on more cost-effective designs for ground-based fluorescence telescopes [7, 8]. Although the radio technique has recently been demonstrated to deliver an approximately equal (and in the future possibly better) energy and $X_{\max}$ resolution, these demonstrations have been done with denser arrays suitable for energies up to a few EeV [9, 10]. Therefore, future R&D regarding the radio technique is required especially for huge and sparse arrays. Areas of investigation are a radio self-trigger required for stand-alone operation, and methods for $X_{\max}$ reconstruction for very inclined showers, e.g., using digital interferometry [11, 12] or new computational methods.

Substantial progress has been made for particle detectors applying deep learning techniques [13]. $X_{\max}$ resolutions similar to those of the fluorescence and radio technique seem feasible, at least if the latter are available for crosschecks and calibration because all hadronic interaction models available to produce training data for neural networks have some deficits and do not agree well enough with each other. A unique advantage of particle detector arrays is that they are sensitive to both, the electromagnetic and muonic components. With appropriate detector designs, both

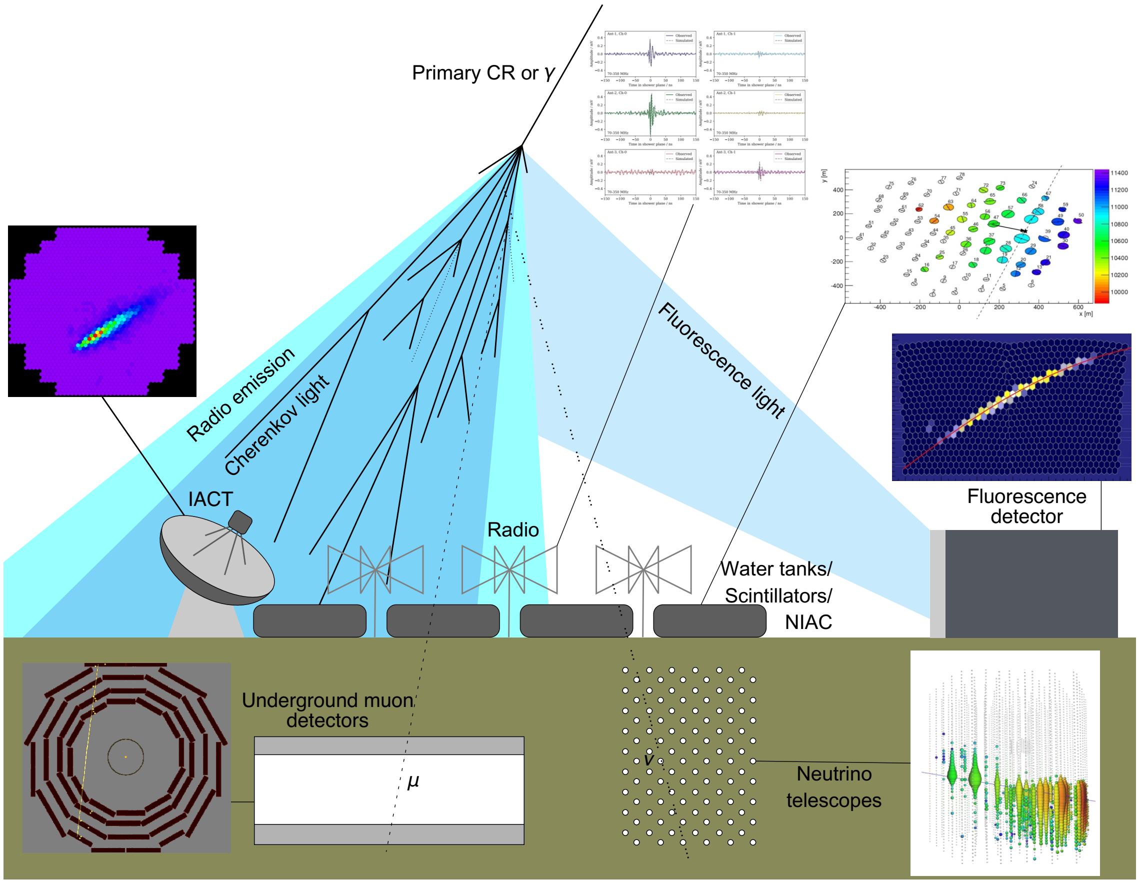

Figure 1: Cosmic-ray air showers can be detected with various methods: particle detectors on ground measure secondary particles, in particular, of the electromagnetic and muonic shower components, and a pure muon measurement is possible with underground detectors. The electromagnetic component can also be measured through it radio emission, air-Cherenkov and fluorescence light. Figure from Ref. [1] (see there for reference for individual figure elements).

components can be measured separately and simultaneously. Hence, for all science goals requiring muon measurements in addition to the electromagnetic shower component, particle detector arrays are the technique of choice. Current R&D focuses on reliable and cost-effective detector concepts providing a precise energy, $X_{\max}$, and muon measurement with sparse surface arrays. Options to be investigated could be segmented water-Cherenkov tanks [14], constructions of scintillators and absorbers for the electromagnetic component, or combinations of scintillators and water-Cherenkov tanks - all of them in combination with sophisticated computational methods for the air-shower reconstruction.

3. Current and Next Generation Experiments

The whitepaper focuses on cosmic rays above 100 PeV, i.e., starting with energies beyond the second knee and covering the energy range of the Galactic-to-extragalactic transition as well as extragalactic cosmic rays at the highest energies.

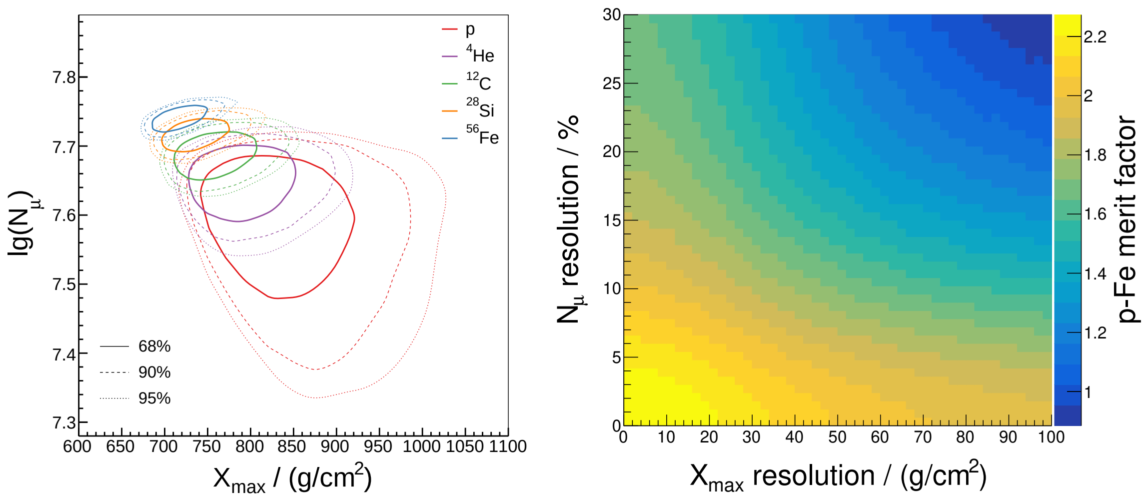

Figure 2: Mass separation with $X_{\max}$ and muons as shower observables at an energy of 10 EeV for CORSIKA simulations with Sybill 2.3d. Left: contour plots for several primary particles. Right: merit factor for the mass separation of proton and iron primaries. Even with perfect resolution on either the muon number or $X_{\max}$, the event-by-event mass separation will be worse than for experiments measuring both observables simultaneously with decent resolutions. Figure from Ref. [1].

We recognize though that important experimental efforts are ongoing at lower energies, too. In particular, the Large High Altitude Air Shower Observatory (LHAASO) [15] and the proposed Southern Wide-Field Gamma-Ray Observatory (SWGO) [16, 17], both optimized for photon detection, can make key contributions also to cosmic-ray physics in the PeV energy range. Also the planned Square Kilometer Array (SKA) [18, 19], with its ultra dense antenna core, will feature unprecedented precision for air showers in the energy range up to about 1 EeV. This can give new insights into the particle physics of these air showers and into their radio emission, and also provide new ways to determine the proton-helium ratio by measuring shape parameters of the shower profile with high resolution and high statistics.

The energy range of the Galactic-to-extragalactic transition is currently covered by IceCube with its IceTop surface array [20], by the low-energy extension of the Telescope Array (TALE) [21], and by the AMIGA enhancement of the Pierre Auger Observatory [22]. In the coming decade, the planned IceCube-Gen2 extension of IceCube [23], will feature an eight times larger and enhanced surface array consisting of elevated scintillation panels and radio antennas, the latter providing and accurate energy and $X_{\max}$ measurement at energies around and above the second knee. Combined with the IceCube and IceCube-Gen2 deep optical arrays measuring TeV muons of air showers, IceCube-Gen2 will not only be a neutrino observatory, but also a unique laboratory for cosmic-ray air showers in the energy range up to several EeV [24].

For the highest energies, the currently deployed AugerPrime upgrade of the Pierre Auger Observatory in the southern hemisphere [25], and the TAx4 upgrade of the Telescope Array in the northern hemisphere [26] will remain the workhorses of UHECR physics for another decade. While the TAx4 upgrade will increase the size of the Telescope Array such that it will have an aperture at the highest energies similar to the Pierre Auger Observatory, the AugerPrime upgrade aims primarily at increasing the measurement accuracy. While an increased duty cycle of the fluorescence telescopes will enhance the statistics of hybrid events at Auger, the major improvement of AugerPrime consists of a set of upgrades of the surface detectors: new local electronics with faster sampling and an additional small photo-multiplier will increase the dynamic range of the water-Cherenkov detectors and provide extra information for computational methods used to reconstruct the air-shower properties; a scintillation detector and a radio antenna added on top of each existing water-Cherenkov detector will improve the separation of the electromagnetic and muonic components for less inclined and very inclined showers, respectively. Therefore, the AugerPrime upgrade will not only enhance the measurement accuracy for the mass composition and provide better tests of hadronic interaction models, it will also enhance the event-by-event separation of light and heavy primary particles. AugerPrime, thus, will pioneer a new class of experiments that may be able to estimate the rigidity of individual primary cosmic rays through a simultaneous measurement of $X_{\max}$ and the electron-muon ratio.

Generally, two types of air-shower observatories are required for the coming decades: those which maximize the accuracy for the primary mass on an event-by-event basis, and those which maximize the exposure at highest energies, but can measure the mass composition only statistically.

The first category of *event-by-event mass sensitive observatories* requires a hybrid detector approach capable of measuring simultaneously the muon content and $X_{\max}$ for each shower (Fig. 2). As even with a perfect resolution, each individual shower observable has intrinsic limitations for the event-by-event mass separation [27], combining these two complementary observables promises a more accurate estimate of the mass and, thus, the rigidity of the individual particle. Depending on the knowledge of Galactic and extragalactic magnetic fields, this will allow for back-tracing particles and may finally enable particle astronomy. Future experiments in this category are IceCube-Gen2 with its surface array for the most energetic Galactic cosmic rays, and the Global Cosmic Ray Observatory (GCOS) for extragalactic cosmic rays [28, 29]. GCOS is planned to consists of ground arrays at multiple sites, possibly complemented by radio and fluorescence detectors. GCOS will offer full sky coverage at an order of magnitude larger exposure than Auger.

The second category is *observatories maximizing the statistics* of UHECR at the highest energies beyond the GZK suppression. By using a single detection technique, they are cost-effective, but offer at most moderate mass separation on an event-by-event level. Nonetheless, depending on what the mass composition is at the highest energies, high statistics may be what counts to identify sources of UHECR. Two complementary experiments are proposed for the next decade in this category. The Giant Radio Array for Neutrino Detection (GRAND) will consist of several sites, covering huge areas with sparse arrays of radio antennas [30, 31]. Although GRAND will primarily search for ultra-high-energy neutrinos, it will also detect a high statistics of very inclined UHECR. However, further R&D is required: while in principle a high energy and $X_{\max}$ seems to be feasible also for very inclined air showers, this still needs to be demonstrated in practice, e.g., by the radio upgrade of Auger. The Probe of Extreme Multi-Messenger Astrophysics (POEMMA) will be a stereo air-fluorescence observatory in space detecting UHECR air showers and also searching for neutrino induced showers [32, 33]. Due to the stereo mode, POEMMA will feature a high $X_{\max}$ resolution, sufficient to determine the mass composition at the highest energies statistically.

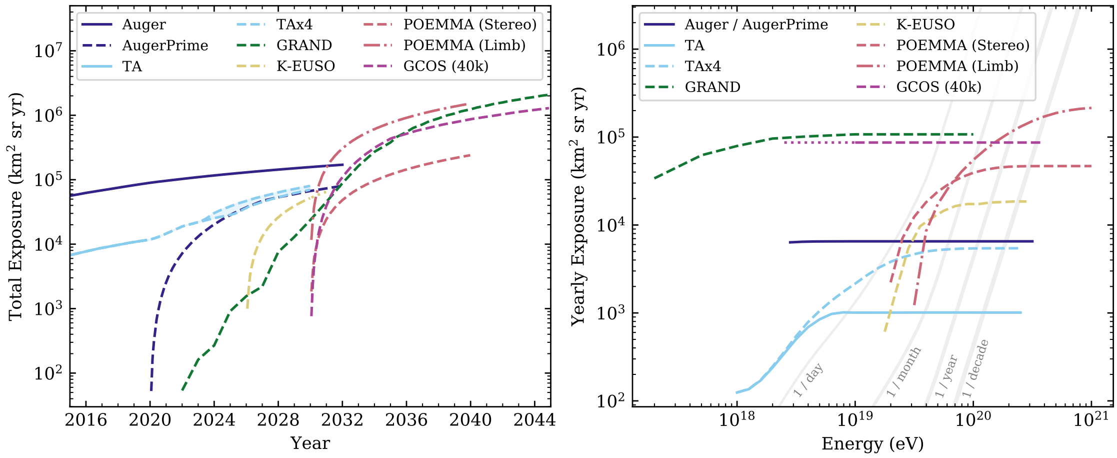

Figure 3: Exposure of current and proposed UHECR experiments. However, exposure is only one dimension to compare experiments with each other. The other dimension not shown in the plot is the measurement accuracy, and especially for the mass composition and the ability to estimate the rigidity of the primary particle on an event-by-event basis (see text). Figure from Ref. [1].

4. Conclusion

A next generation of experiments is necessary to solve the open scientific questions of both the particle physics and the astrophysics side of UHECR: probing interactions beyond the phase space and energy range of accelerator experiments, searching for new physics at ultra-high energies, and understanding the sources of the extragalactic cosmic rays as well as the most energetic cosmic rays of our Galaxy [34, 35]. That next generation will not be ready before the coming decade, and it is mandatory that the upgraded Auger and TA observatories keep running until then - not only to realize their full scientific potential, but also to be available as testbeds and cross-calibration sites for the detectors of the next generation. Expected findings of AugerPrime, TAx4, and IceCube with their enhanced surface arrays will further refine the science case of future observatories and to solve the remaining issues with hadronic interaction models required for an accurate interpretation of air-shower measurements. In the next ten years, the current generation of experiments will thus not only advance cosmic-ray science, but is also critical to prepare detector technology and analysis techniques for the time afterwards.

For the next generation, IceCube-Gen2 will have a unique role beyond its main purpose as neutrino observatory [36]. For cosmic rays in the energy range up to a few EeV, it will be the only experiment that combines a deep optical detector for TeV muons with a multi-detector surface array, providing hybrid detection of air-showers with elevated scintillators and radio antennas.

Three complementary experiments are proposed for the next decade to drive the field of cosmic-ray physics at the highest energies: GCOS, GRAND, and POEMMA. All of them will provide a significantly higher exposure than today's UHECR observatories (Fig. 3). The largest exposure may be delivered by POEMMA's stereo fluorescence observations from space, while the total exposure of GRAND is a bit uncertain and will depend on the final size of this multi-site experiment and on the exact zenith range of cosmic rays that is covered with sufficient accuracy by this radio array.

With the anisotropy measured by Auger and TA at the highest energies, it is clear that the increase in exposure will enable us to measure and understand this anisotropy to a finer level, which may reveal the sources of cosmic rays at the highest energies. However, as the mass composition is mixed at least up to energies of several 10 EeV, back-tracing of individual events to their sources may require an estimate of the rigidity of each primary particle in addition to knowledge of the magnetic fields. GCOS will be designed to deliver the necessary event-by-event mass sensitivity. Offering a somewhat smaller exposure than the other approaches, it will aim for high measurement accuracy by combining muon and X_{max} for all events.

We point out, that these three experiments are not competing, but complementary: observatories offering event-by-event mass estimation (IceCube-Gen2 at lower energies; GCOS at highest energies) need to operate in parallel with observatories maximizing the statistics at the end of the cosmic-ray energy spectrum (GRAND; POEMMA). The latter two are very complementary approaches themselves, with POEMMA using fluorescence detection from space, and GRAND using radio detection on ground. In all cases, further developments of detection and computational reconstruction techniques are required, which need to start now in order to deploy these next-generation observatories in the coming decade.

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