PROCEEDINGS OF SCIENCE

Ultra-High-Energy Cosmic-Rays (UHECR): at the Intersection of the Cosmic and Energy Frontiers – Overview of the Snowmass UHECR white paper and roadmap

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As part of the US "Snowmass" community planning exercise, the UHECR community has come together to write a comprehensive white paper discussing the recent progress and open questions in the field, as they relate to the overarching goals of particle and astroparticle physics. The document outlines strategies and recommendations for answering these questions over the next two decades. It also proposes an integrated timeline, which considers the progress expected to be achieved by the upgraded Pierre Auger Observatory and Telescope Array experiment in this decade, and the need for a set of complementary next-generation experiments combining high-accuracy measurements (GCOS, IceCube-Gen2 with its surface array) and very high exposure at the highest energies (GRAND, POEMMA) in the next decade. The resulting document, entitled "Ultra-High Energy Cosmic-Rays: at the Intersection of the Cosmic and Energy Frontiers", appears as a special issue of Astroparticle Physics (Astropart. Phys. 149 (2023) 102819 – arXiv:2205.05845). This contribution provides a summary of the document with a focus on (selected) recommendations and proposed roadmap.

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1. The need for a UHECR long-range community roadmap

In the United States, there are two long-range exercises that are particularly relevant to astroparticle physics in general, and ultra-high energy cosmic-rays (UHECRs) in particular. The first one is the decadal survey from the National Academies of Sciences, Engineering, and Medicine that identifies the scientific priorities, opportunities, and funding recommendations for the next 10 years of astronomy and astrophysics (a.k.a. “Astro2020” this cycle). Two science contributions related to UHECRs [1, 2] were submitted as part of the process. In the final report [3], the contributions of the current UHECR giant arrays are acknowledged, however, as shown in Fig. 1, the report does not endorse planned projects but instead identifies the need for technical developments to mature and converge toward community-supported next-generation UHECR experiments past 2030.

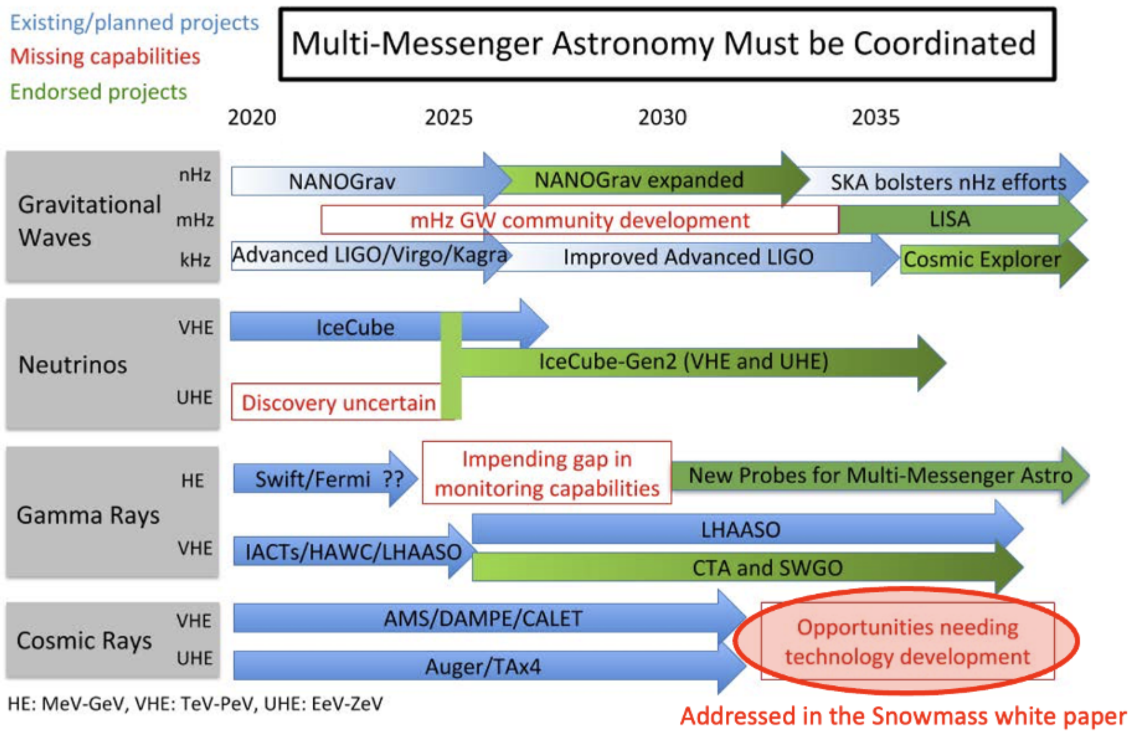

Figure 1: The existing and planned experiments that are or will contribute to multi-messenger astronomy in the next decade and beyond, as identified in the “Pathways to Discovery in Astronomy and Astrophysics for the 2020s” (Astro2020) report. For UHECRs, there are no planned projects endorsed beyond the lifetime of the Auger and Telescope Array leading to a potential continuity gap in the study of UHECRs. This is addressed specifically in the Snowmass white paper (Figure adapted from [3])

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The second long-range exercise, the Particle Physics Community Planning Exercise (a.k.a. “Snowmass”), is organized by the Division of Particles and Fields of the American Physical Society and is the opportunity for the particle physics community (including astroparticle physics) to come together and develop a scientific vision for the future of particle physics in the United States and its international partners. Coming shortly after Astro2020, it was the opportunity for the UHECR community to come together and write a comprehensive roadmap for the next two decades or so, which explicitly identifies its flagship experiments beyond the operation of the current generation of observatories.

2. The Snowmass UHECR white paper

The Snowmass 2021 long-range exercise [4] is structured around ten working groups (or "Frontiers") meant to encompass all the activities of the particle physics community. Cosmic-ray physics belongs to the Cosmic Frontier (CF) [5] and more specifically to the topical group 7 (CF7) entitled "Cosmic Probes of Fundamental Physics" [6]. The CF7 group solicited a white paper regarding the status and future of UHECRs. In light of the Astro2020 report published earlier, seven conveners gathered to lead the writing of a comprehensive document that could also be used as a community roadmap for the next two decades. Note that for the purpose of this white paper, the traditional threshold of 1 EeV for the definition of UHECRs was lowered to 100 PeV to include the energy region around the second knee, which is believed to be the onset of the transition between galactic and extragalactic cosmic-rays. Community inputs were solicited through the conveners and 29 additional topical conveners that helped organize sections and sub-sections of the document, and additionally through a series of online workshops. A draft version of the document was circulated broadly to solicit further comments. In the end, over 200 scientists endorsed the white paper beyond its 97 co-authors. The white paper is now published as a special issue of Astroparticle Physics [7]. This contribution mostly focuses on the executive summary. The reader is encouraged to read a complementary contribution on the instrumentation requirements for next-generation experiments to appear in the same proceedings [8]. The white paper has multiple sections that are not covered in either contributions, e.g. the last two chapters of the document describe the broader scientific impacts of UHECR research in particular in the field of atmospheric sciences and the needed efforts to have a more open and diverse research community respectively. Hence the reader is of course also encouraged to read the actual white paper, or selected sections therein.

3. At the intersection of the Cosmic and Energy Frontiers

The study of UHECRs is not only the opportunity to discover the sources of the most energetic particles in the universe (the Cosmic Frontier), but also a window to particle physics at energies well beyond what is achievable by human-made accelerators (the Energy Frontier). Both are actually intimately intertwined.

The era of giant observatories, which started nearly 20 years ago, has led to a paradigm shift in our understanding of UHECRs and their sources. The shape of energy spectrum is now well established [9–11], but remains to be fully understood. The reason lies partly in the fact that primary mass composition measurements [12–14] appear to favor a mixed composition likely arising from the rise and fall of single mass group (p, He, N and Fe) components, starting from mostly protons just below the ankle and growing heavier as the energy increases [15, 16]. While a proton fraction at the highest energy cannot be completely excluded, UHE photons [17, 18] and neutrinos [19], which may be by-products of proton GZK propagation effects [20, 21], have yet to be detected. The lack of clearly identifiable astrophysical sources [22–24] also supports the absence of a strong proton component at the highest energies, although there is clear evidence that UHECRs above

8 EeV originates from extra-galactic sources [25, 26]. The more complex picture that has emerged presents a challenge to discovering UHECR sources and unraveling how UHECRs are accelerated – one of the key goals of multi-messenger astrophysics for decades. In this context, accurate primary mass composition measurements are going to be paramount in the future.

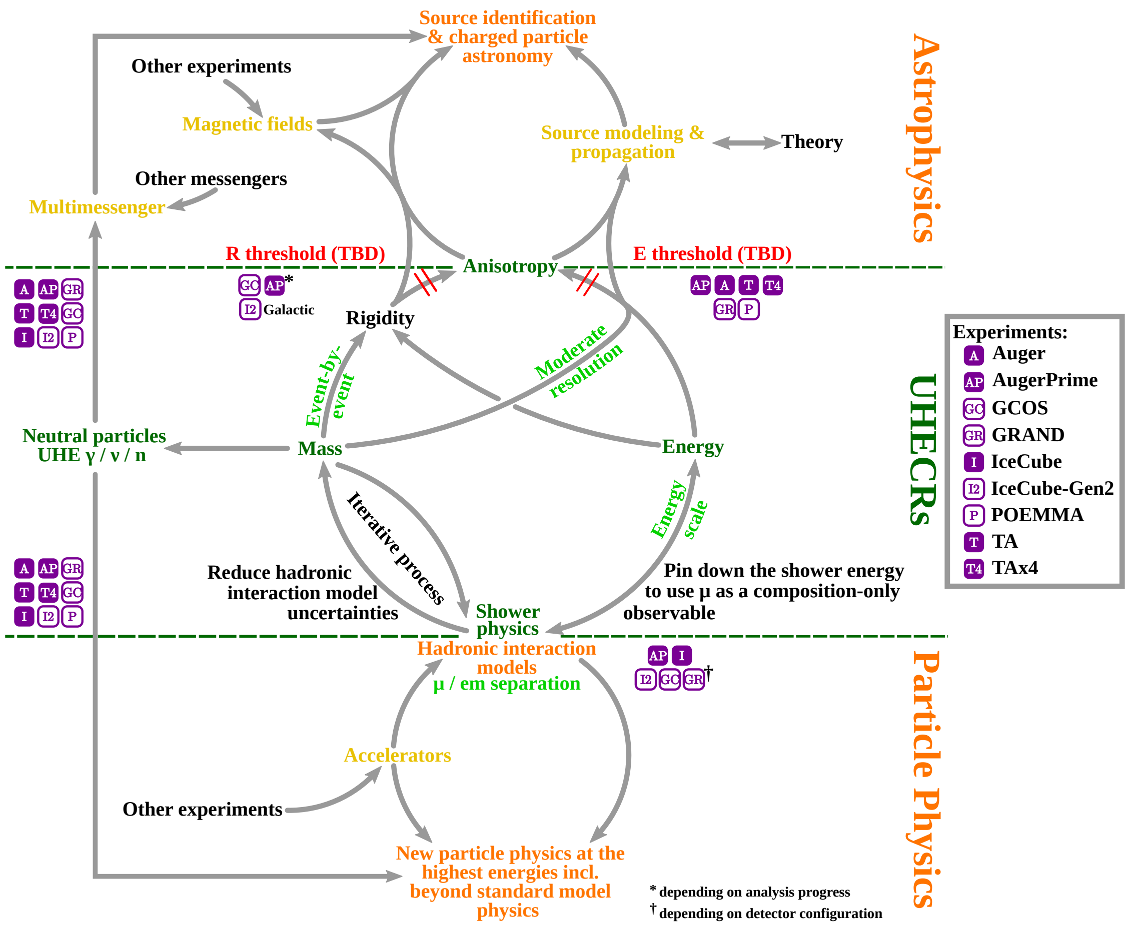

Figure 2: Diagram outlining how the study of UHECRs strongly contributes to particle physics and astrophysics. It summarizes the strategies to be used by existing and next-generation experiments in the next two decades to achieve the overarching goals shown at the very top and the very bottom of the figure (see text for details). Figure taken from Ref. [7]

A significant fraction of the white paper and its recommendations is articulated around Fig. 2, which summarizes how existing and next-generation experiments will contribute to answering the overarching goals in particle and astroparticle physics shown at the bottom and top of the figure respectively. Starting from the canonical UHECR air shower observables (energy, primary mass composition and arrival direction), the figure outlines the relationship between them and highlights, in particular, the importance of shower physics and hadronic interaction modeling, when it comes to determine primary mass composition on an event-by-event basis. In this context, the knowledge of the muon content of the shower, together with the depth of shower maximum X_{max}, is a critical handle on composition. As the total number of muons in the shower depends on both primary mass and energy, a strategy to better ascertain the composition on a (near) event-by-event basis using muons requires measuring the shower energy somewhat independently. For example, AugerPrime [27], the upgrade of the Pierre Auger Observatory [28], is doing this by using a combination of radio antennas, and scintillator and water Cherenkov detectors as its upgraded surface detector. Multiple UHECR experiments have now shown conclusively however that air showers produce more muons than predicted by the current generation of Monte Carlo simulations, and the discrepancy appears to increase with energy [29]. This highlights the critical importance of understanding the particle physics driving air showers, and while there are some leading theories on the origin of the muon puzzle, it largely remains to be explained and new particle physics at the highest energies, including beyond-standard-model (BSM) physics, cannot be excluded yet [30]. In addition to additional UHECR measurements, data from the LHC [31], and particularly from new experiments at a future Forward Physics Facility [32], will be critical to solve the "muon puzzle".

Eventually, modifications of the hadronic models will help pin down primary mass composition to a point where rigidity may be deduced from high-precision energy and composition measurements on an event-by-event basis. Rigidity is more naturally related to magnetic deflections, both galactic and inter-galactic, and optimized event selections may not only allow for source identification, but also perhaps inform the nature of their emission thanks also to the different horizon of each particle group. The rigidity window to observe sources may however only open above 10 EV or so which is on the very edge of the maximum average rigidity estimated by Auger using their current dataset [7, 33]. Hence, a next-generation high-precision experiment focused on estimating rigidity on an event-by-event basis will still need to be many times larger than Auger. A complementary approach to relying on rigidity, also highlighted in Fig. 2, is to achieve only moderate mass resolution but compensate by having an instrument with huge exposure. By selecting the air showers more likely to arise from lighter primaries, composition-enhanced anisotropy studies will be possible. Moreover, the huge exposure will allow probing further past the flux suppression in search of BSM physics, including Lorentz Invariance Violation (LIV) [34] and Super-Heavy Dark Matter (SHDM) candidates [35, 36].

4. Selected recommendations and timeline

In the short space remaining, selected recommendations from the white paper are discussed briefly. For more information, the reader is invited to read the full executive summary of the white paper, as well as the complementary contribution in these proceedings [37] on the existing and planned next-generation experiments.

Selected recommendation #1: *"Even in the most optimistic scenario, the first next-generation experiment will not be operational until around 2030. AugerPrime and TA×4 should continue operation until at least 2032."*

Fig. 3 provides the compiled timeline of all the current leading UHECR (Pierre Auger Observatory [27, 28], Telescope Array [38, 39], IceCube/IceCube-Gen2 [40, 41]) and future next-generation (GRAND [42], POEMMA [43], GCOS [44]) experiments. Given the timeline, it is critical that AugerPrime and TA×4 continue to operate into the next decade. Their results in this decade will continue to inform the science case for the next-generation experiments, and both experiments will also be used as test-beds for new technological developments. Fig. 2 also shows where each experiment contributes or is expected to contribute to the overall science case.

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program → POEMMA
GCOS	Hybrid array with X_{max} + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites
			2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

Figure 3: The six current and next-generation leading UHECR experiments, their features, contributions to UHECR science and timeline of operation (including prototyping and construction whenever appropriate). Figure from Ref. [7])

Selected recommendation #2: *"The next-generation experiments (GCOS, GRAND, and POEMMA) will provide complementary information needed to meet the goals of the UHECR community in the next two decades. They should proceed through their respective next stages of planning and prototyping."*

GRAND is mainly a neutrino experiment, which will contribute to UHECR science thanks to its relative sensitivity to UHECRs and huge exposure. POEMMA is a space-based observatory comprising of two satellites flying in formation allowing for the measurements of Earth-skimming neutrino-induced showers via Cherenkov and/or UHECR air showers via fluorescence. Not only does POEMMA have a huge exposure hence an enhanced ability to detect ZeV particles, but it is, as a space-based detector, also able to achieve naturally full-sky coverage. Finally, GCOS is a dedicated ground array aimed to make precise measurements with a broad science case in particle and astroparticle physics. Both GRAND and GCOS are planning to have multiple sites for full sky-coverage.

Selected recommendation #3: *"At least one next-generation experiment needs to be able to make high-precision measurements to explore new particle physics and measure particle rigidity on an event-by-event basis. Of the planned next-generation experiments, GCOS is the best positioned to meet this recommendation."*

GCOS is the next-generation experiment that will be able to take advantage of future advances in hadronic interaction modeling and improvement in mass composition determination. Even as it is conceived as a precision array, and as mentioned before, its overall size will still need to be many times the size of the current Pierre Auger Observatory to further our understanding of the nature and origin of UHECRs.

Selected recommendation #4: *"As a complementary effort, experiments with sufficient exposure ($\gtrsim 5 \times 10^5$ km^2 sr yr) are needed to search for LIV, SHDM, and other BSM physics at the Cosmic and Energy Frontiers, and to identify UHECR sources at the highest energies."*

Searches for BSM physics do not necessarily require high-precision measurements. Moreover, it is not realistic to build a ground array of arbitrarily huge size with sophisticated, hence expensive, detectors. In order to investigate UHECRs (well) beyond the flux suppression, experiments with huge exposure such as GRAND (with relatively inexpensive radio antennas) and POEMMA (as a space-based observatory) are best suited, even if they are not able to achieve the same level of precision as GCOS. In this respect, both approaches, high precision vs huge exposure, are truly complementary.

Selected recommendation #5: *"Full-sky coverage with low cross-hemisphere systematic uncertainties is critical for astrophysical studies. To this end, next generation experiments should be space-based or multi-site. Common sites between experiments are encouraged."*
After about 15 years of data taking, there appears to be a discrepancy of about 9% between the energy scales of the Auger and TA [45], which is within the range of the systematic uncertainties for both experiments[1]. However, after re-scaling, a large difference remains at and beyond the flux suppression. While this could be due to fundamental differences between the northern and southern UHECR skies (linked to their respective warm / hot spots), it could also be due to unresolved discrepancies in the way the two experiments process air shower data. For next-generation detectors, it is critical that the same instrumentation is used to make measurements of the entire UHECR sky. This is naturally achieved by a space-based observatory like POEMMA, but for ground arrays, it requires multiple sites, which is adding logistical difficulties. Additionally, GCOS and GRAND would naturally benefit from having at least one co-located site for cross-calibration purposes.

5. Conclusion & perspectives

The Snowmass UHECR white paper was an opportunity to write a comprehensive review not only outlining the scientific goals of the community, but also providing a roadmap for the next two decades using the current upgraded observatories (Auger, TA and IceCube) and planning for the development and construction of next-generation experiments (GCOS, GRAND and POEMMA). In the context of this contribution and with regards to national and international decadal planning exercises, it is now critical that the community uses this document, and especially its executive summary, to seek support for the construction of the next-generation experiments from the scientific community, including adjacent fields to UHECR, and from funding agencies.

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