

# What is the Nature and Origin of the Highest-Energy Particles in the Universe?

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**COSMOLOGY AND FUNDAMENTAL PHYSICS - MULTI-MESSENGER ASTRONOMY AND ASTROPHYSICS**



# 1 The big questions and goals for the next decade

Ultra-High-Energy Cosmic-Ray (UHECR) astronomy in the next decade aims to answer the questions: *What is the nature and origin of UHECRs? How are UHECRs accelerated to such extreme energies? Are there multiple types of sources and acceleration mechanisms? Do UHECRs consist of both protons and heavier nuclei, and how does the composition evolve as a function of energy?*

In order to address these questions, the goals for the next decade will be to: identify one or more nearby UHECR sources, refine the spectrum and composition of the highest-energy Galactic and extragalactic cosmic-rays, exploit extensive air showers (EAS) to probe particle physics inaccessible at accelerators, and develop the techniques to make charged-particle astronomy a reality.

This agenda is largely achievable in the next decade, thanks to major experimental upgrades underway and new ground observatories and space missions in development. In combination with improved astrophysical neutrino statistics and resolution, the future UHECR observatories will enable a powerful multi-messenger approach to uncover and disentangle the common sources of UHECRs and neutrinos.

## 2 The UHECR paradigm shift

**Synopsis:** *Results from the current large hybrid detectors have dispelled the pre-existing simple UHECR picture. A new paradigm is emerging and needs to be clarified and understood.*

The discoveries made over the past decade have transformed our understanding of UHECRs and their sources. Prior to the development of very large, hybrid detectors, it was commonly believed that UHECRs were protons, that a spectral cutoff (if indeed there was one!) should be due to “GZK” energy losses on the cosmic microwave background [1, 2], that the Galactic-extragalactic transition would be marked by a shift from Galactic iron to extragalactic protons, and that the *ankle* feature at a few EeV marked the Galactic-extragalactic transition. We know now that this simple picture is mostly, if not entirely, wrong.

This revolution in our understanding was achieved thanks to: (i) hybrid detectors with air-fluorescence telescopes and surface detectors, plus improved measurement of fluorescence yields, giving much better energy calibration and providing greater sensitivity to composition; (ii) large aperture and high statistics, essential to reducing the systematics and particle-physics uncertainties in composition studies and providing sensitivity to tiny anisotropies in the UHECR arrival directions; and (iii) all-sky sensitivity thanks to detectors in both hemispheres, with overlapping regions of the sky. Together, these advances enabled the spectrum, composition and anisotropies to be measured with higher resolution and smaller systematics from  $10^{17}$  to above  $10^{20}$  eV.

### UHECR spectrum – ankle and flux suppression: well established but not well explained

As shown in Fig. 1, the UHECR energy spectrum can be roughly described by a twice-broken power law [4–8]. The first break is a hardening of the spectrum, known as “the ankle.” The sec-

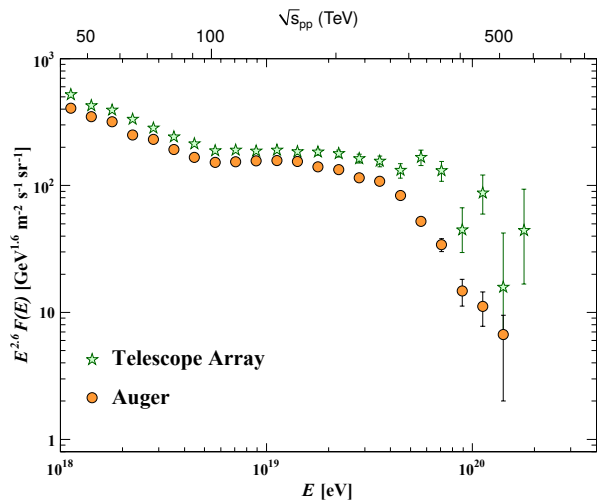


Figure 1: UHECR spectra measured by TA and Auger, located in the northern and southern hemispheres, respectively (adapted from [3]).

ond, an abrupt softening of the spectrum, may be interpreted as the long-sought GZK cutoff [1, 2], or else may correspond to the cosmic accelerators running out of steam [9]. The differential energy spectra measured by the Telescope Array (TA) experiment and the Pierre Auger Observatory (Auger) agree within systematic errors below  $10^{19}$  eV. However, even after energy re-scaling, a large difference remains at and beyond the flux suppression [10] and could be hinting at fundamental differences between the northern and southern UHECR skies, since the spectra seem to agree at all energies in the common region of the sky [11, 12]; see however [13].

### UHECR primary composition – a more complex picture emerges

The atmospheric column depth at which the longitudinal development of a cosmic-ray shower reaches maximum,  $X_{\max}$ , is a powerful observable to determine the UHECR nuclear composition. Breaks in the elongation rate – the rate of change of  $\langle X_{\max} \rangle$  per decade of energy – are associated to changes in the nuclear composition [14], even when uncertainties in the UHE particle physics limit the accuracy of mapping between  $X_{\max}$  and mass  $A$ . The  $X_{\max}$  measurements of both TA [15, 16] and Auger [17–20] indicate a predominantly light composition at around the ankle. At the highest energies (above 10 EeV), the Auger Collaboration reports a significant decrease in the elongation rate, as well as a decrease of the shower-to-shower fluctuations of  $X_{\max}$  with energy. Both effects suggest a gradual increase of the average mass of cosmic rays with energy. Interpreting the data with LHC-tuned hadronic interaction models gives a mean baryon number  $A \approx 14 - 20$  at  $E \approx 10^{19.5}$  eV. The Auger-TA joint working group on composition concluded that the measurements of the average shower maximum by TA and Auger are compatible within experimental uncertainties at all energies [21, 22]. The observed decrease of the standard deviation of the  $X_{\max}$  distributions reported by Auger can currently neither be confirmed nor ruled out by TA because of statistical limitations. Thus the most recent data of UHE observatories reveals a complex evolution of the cosmic-ray composition with energy that challenges the old simplistic models of CR sources.

### UHECR Anisotropy – where are the sources?

Composition measurements have led to a paradigm shift, with cosmic rays now understood to be light (proton dominated) near  $10^{18}$  eV and evolving towards heavier composition with increasing energy, spanning a narrow range of atomic masses at each energy. Below the ankle, the arrival directions are highly isotropic [24], arguing that these protons must be of extragalactic origin. They are consistent with being secondary products of the photo-disintegration

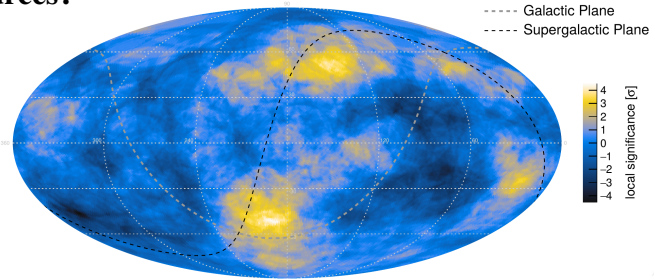


Figure 2: Sky map, in equatorial coordinates, of local over- and under-densities in units of standard deviations of UHECRs above  $47 \pm 7$  EeV. Taken from [31].

of UHECR nuclei in the environment of their sources [25] and/or can share the origin of PeV neutrinos [26, 27]. At higher energies, Galactic and extragalactic deflections of UHECR nuclei are expected to smear point sources into warm/hot spots, for which evidence is accumulating. TA has recorded an excess above the isotropic background-only expectation in cosmic rays with energies above  $10^{19.75}$  eV [28, 29], while Auger has reported a possible correlation with nearby starburst galaxies, with a (post-trial)  $4\sigma$  significance, for events above  $10^{19.6}$  eV [30]. A slightly weaker association ( $2.7\sigma$ ) with active galactic nuclei emitting  $\gamma$ -rays is also found in Auger events above  $10^{19.78}$  eV [30]. A blind search for anisotropies combining Auger and TA data has been recently carried out, with the energy scales equalized by the flux in the common declination band [31]. The

most-significant excess is obtained for a  $20^\circ$  search radius, with a global (post-trial) significance of  $2.2\sigma$ . The local (Li-Ma [32]) significance map of this study is shown in Fig. 2. The tantalizing visual correlation of high-significance regions with the supergalactic plane is currently under study within the Auger/TA anisotropy working group.

### **UHECR $\Leftrightarrow$ neutrino – the missing GZK neutrinos and targets of opportunity**

The non-observation of neutrino candidate events beyond background expectations above  $10^{16}$  eV by IceCube [33], Auger [34], and ANITA [35] severely constrains the magnitude of the very high-energy neutrino flux. This flux has a nearly guaranteed component from the decays of pions produced by UHECR protons interacting en route to Earth [36]. The accumulation of these neutrinos over cosmological time, known as the cosmogenic neutrino flux, constitutes a powerful tool of the multi-messenger program. IceCube, Auger, and ANITA limits already challenge models in which the highest-energy UHECRs are proton-dominated [37–44]. Additionally, UHECR experiments add the capability of searching for neutrinos from target-of-opportunity events [45–47].

### **Closing the loop – Particle physics with UHECRs**

Essential to accurate composition determination is the correct understanding of the physics of EASs, which requires accurate modeling of particle physics at center-of-mass energies up to hundreds of TeV – far beyond the 14 TeV reach of the LHC. Internal-consistency studies of EASs show that state-of-the-art LHC-tuned hadronic event generators do not correctly reproduce in detail the multitude of observables that can be probed by UHECR detectors [48, 49]. Upgraded and next-generation experiments are designed to extend our understanding of hadronic interactions well into the hundreds of TeV regime [50–53]. This will increase the accuracy in determining the UHECR composition, and be a boon to particle physics. The column energy-density in UHECR-air collisions is an order of magnitude greater than in Pb-Pb collisions at the LHC [54], suggesting the potential for new hadronic physics from gluon saturation and the possibility of exploring quark-gluon plasma (QGP) at far higher energies than available in accelerators [55–57]. To find out more about the latest results on UHECRs, see e.g. [58–60].

## **3 Identifying candidate sources for extreme accelerators**

**Synopsis:** *The high-energy (HE) astrophysics community remains abreast with the evolving observational picture and has developed a wide variety of new exciting models that will be further tested by the data collected over the next decade.*

An even greater diversity of sources and acceleration mechanisms is now under consideration as a result of theory advances and the evolving observational picture. If the highest-energy UHECRs are exclusively intermediate mass nuclei, as is consistent with present data, the demands on accelerators are considerably eased compared to a pure-proton scenario, because the maximum required rigidity  $R = E/Z$  and the bolometric luminosity required of the candidate sources are reduced; here  $Z$  is the charge of the UHECR in units of the proton charge. Further refinements in measuring the composition evolution and possible composition anisotropy are crucial to source inference.

Rapid progress in computational HE astrophysics is dramatically advancing the study of acceleration mechanisms. Some of the current contenders for acceleration mechanisms and source types are: shock acceleration [61–68], in systems ranging from the large scale shocks surrounding galaxy clusters [69–71] to internal or external shocks of starburst-superwinds [72, 73], AGN [74–82] or GRB [83–90] jets, and the jets of tidal disruption events (the transient cousins of AGN

jets) [92–94]. Other contenders are: shear acceleration [96, 97] and one-shot mechanisms such as “espresso” [98] in which an AGN or other jet boosts a galactic CR of the host galaxy; EMF acceleration as in fast-spinning pulsars [99–101] and magnetars [102], black holes [103–105], and potentially reconnection, explosive reconnection, gap and/or wakefield acceleration [106–108].

The multitude of possibilities suggests there may well be multiple sources of UHECRs, some of which may be transient, making the identification of sources even more challenging and essential. Anticipating the advent of UHECR-astronomy thanks to composition-tagging and better understanding of the Galactic magnetic field, we can foresee having access to the UHECR spectrum of individual sources. That will be key to determining the acceleration mechanism(s) and identifying the potential sources, whether those are steady or transient [109], much as spectra at X-ray and  $\gamma$ -ray wavelengths have clarified the workings of blazars and their kin.

## 4 Stepping up to the new challenges

**Synopsis:** *Future discoveries will be made through a combination of enhanced statistics, refined analyses afforded by upgraded observatories and next-generation experiments, and the additional constraints provided by multi-messenger astrophysics.*

The more complex picture that has emerged over the past decade presents a challenge to discovering UHECR sources and unraveling how UHECRs are accelerated – the holy grail of multi-messenger astrophysics for decades. Yet, after about a decade of operation, both Auger and TA have provided tantalizing evidence that new discoveries are within reach. In this context, the discovery of a large-scale asymmetry in the arrival direction distribution of events recorded by the Auger [110, 111] (statistical significance  $> 5\sigma$ ) represents a compelling example of the power of accumulating more statistics. By 2025, Auger will roughly double the size of the sample for which the  $4\sigma$  correlation with starburst galaxies was observed [30], allowing for an independent test of the starburst hypothesis. Combining the data samples Auger may actually reach a statistical significance  $> 5\sigma$  by 2025. For TA, a significant increase of exposure will allow the northern hemisphere hot spot to be adequately explored.

### **The path to new discoveries – increased exposure and higher sensitivity**

Both Auger and TA are undergoing upgrades to respond to the evolving observational picture. TA $\times$ 4 is designed to cover the equivalent of Auger’s aperture [112], to allow for a  $5\sigma$  observation of the northern hot spot by 2026 or so. Auger’s upgrade (“AugerPrime” [113]) focuses on more detailed measurements of each shower observed. This will enable event-by-event probabilistic composition assignment (hence selection of low- $Z$  events), enhanced capacity to study UHE hadronic interactions, and increased sensitivity to high-energy neutrinos [114, 115]. Both upgrades contribute to an overall strategy comprising three broad approaches:

- *Detailed information on the composition of UHECRs as a function of energy* can eliminate some source candidates from contention as a dominant contributor, while combining the UHECR spectrum and composition with neutrino and  $\gamma$ -ray spectra, produces powerful constraints on the environment surrounding the sources.
- *Composition-assisted anisotropy studies bring new potential to identify individual UHECR sources.* With a mixed composition, UHECRs can experience large deflections by Galactic and extragalactic magnetic fields, even at the highest energies. Composition-tagging allows the subset of events with highest rigidity and hence smallest deflections to be selected, to strongly enhance source identification both with UHECRs alone and in combination with neutral messengers.



- *Neutral-messenger arrival direction correlations* can identify individual sources, while their temporal associations are sensitive to flaring sources. However, correlations between  $\nu$ 's and  $\gamma$ 's alone cannot give a complete picture. Even if some blazars produce UHECRs, the majority of the AGN jets are beamed away from Earth, thus not all sources may be observable with neutral particles.

By studying the time evolution of the test statistics of the anisotropy searches [28–30], we have projected the required exposures to obtain a  $5\sigma$  confirmation of the various hypotheses. These target exposures, shown in Fig. 3, demonstrate that the continued operation into the next decade of the upgraded observatories will bring us within reach of new discoveries. Based on the existing data, new target exposures and new resolutions on key observables can be inferred and should become the basis for the design of next-generation ground observatories and space instruments.

### Requirements to achieve the science goals and next generation UHECR experiments

Complementing the upgraded Auger and TA detectors, the next generation of UHECR instruments focusing on the flux suppression region ( $E \gtrsim 10^{19.6}$  eV) will need to achieve: (i) Significant gain in exposure, from Fig. 3 we estimate  $\sim 5 \times 10^5$  km<sup>2</sup> sr yr to allow for a  $5\sigma$  observation of all potential signals. (ii) A resolution  $\Delta X_{\max} \sim 20$  g/cm<sup>2</sup> [120]. (Note that  $\langle X_{\max} \rangle$  of  $p$  and Fe are separated by  $\sim 100$  g/cm<sup>2</sup> [121], thus the recommended  $\Delta X_{\max}$  would allow studies with a four-component nuclear composition model [122–125].) (iii) An energy resolution ideally  $\Delta E/E \lesssim 20\%$  to limit the effects of lower-energy event spillover near the flux suppression [126]. (iv) An angular resolution comparable to that of previous experiments to both test the hints for intermediate-scale anisotropies in Auger and TA data and continue the search for small-scale clustering. (v) Full sky coverage to test the hints of declination dependence of the TA spectrum [11, 12].

At present, the most advanced concept in pursuit of these objectives is the Probe of Extreme Multi-Messenger Astrophysics (POEMMA) satellites [127]. POEMMA will reach  $\sim 2.5 \times 10^5$  km<sup>2</sup> sr yr exposure in 5 years with (calorimetric) stereo EAS reconstruction that significantly improves the angular, energy, and  $X_{\max}$  resolutions over that from monocular space-based EAS measurement. A factor  $\times 10$  increase over current UHECR apertures may be achievable on the ground; e.g., the GRAND project has been designed to use low-cost radio antennas deployed over 200,000 km<sup>2</sup> to measure highly-inclined EASs from UHE cosmic-rays and neutrinos [128].

In the new era of multi-messenger astronomy, improved measurements of the highest-energy particles will provide a compelling and complementary view of the extreme universe. The UHECR community is aggressively responding to the new questions posed by the UHECR paradigm shift. The next decade will test the hints of source candidates and build the next-generation experiments that will usher in a new era of charged-particle astronomy.

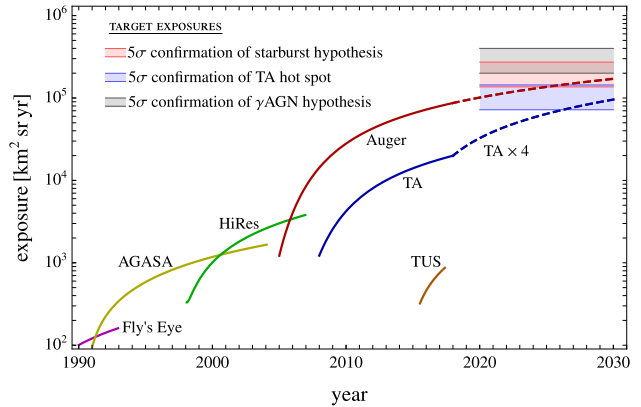


Figure 3: The historical growth of UHECR integrated exposures [7, 8, 116–119]. The projected integrated exposures of Auger and TA $\times 4$  are shown together with the target exposure bands that could achieve a  $5\sigma$  observation of the northern hot spot (TA/blue) and  $5\sigma$  confirmation of the starburst and  $\gamma$ AGN hypotheses (Auger/red and Auger/black). The lower edge of the bands indicates the required exposure of an experiment which permanently observes the same region of the sky as Auger/TA, whereas the upper edge indicates the required exposure for a full-sky instrument which observes the Auger/TA sky only half of the time. Figure by J.F. Soriano (CUNY).

## References

- [1] K. Greisen, [End to the cosmic ray spectrum?](#), Phys. Rev. Lett. **16**, 748 (1966) doi:10.1103/PhysRevLett.16.748.
- [2] G. T. Zatsepin and V. A. Kuzmin, [Upper limit of the spectrum of cosmic rays](#), JETP Lett. **4**, 78 (1966) [Pisma Zh. Eksp. Teor. Fiz. **4**, 114 (1966)].
- [3] M. Tanabashi *et al.* [Particle Data Group], [Review of Particle Physics](#), Phys. Rev. D **98**, no. 3, 030001 (2018). doi:10.1103/PhysRevD.98.030001
- [4] R. U. Abbasi *et al.* [HiRes Collaboration], [First observation of the Greisen-Zatsepin-Kuzmin suppression](#), Phys. Rev. Lett. **100**, 101101 (2008) doi:10.1103/PhysRevLett.100.101101 [astro-ph/0703099].
- [5] J. Abraham *et al.* [Pierre Auger Collaboration], [Observation of the suppression of the flux of cosmic rays above  \$4 \times 10^{19}\$  eV](#), Phys. Rev. Lett. **101**, 061101 (2008) doi:10.1103/PhysRevLett.101.061101 [arXiv:0806.4302 [astro-ph]].
- [6] J. Abraham *et al.* [Pierre Auger Collaboration], [Measurement of the energy spectrum of cosmic rays above  \$10^{18}\$  eV using the Pierre Auger Observatory](#), Phys. Lett. B **685**, 239 (2010) doi:10.1016/j.physletb.2010.02.013 [arXiv:1002.1975 [astro-ph.HE]].
- [7] T. Abu-Zayyad *et al.* [Telescope Array Collaboration], [The cosmic ray energy spectrum observed with the surface detector of the Telescope Array experiment](#), Astrophys. J. **768**, L1 (2013) doi:10.1088/2041-8205/768/1/L1 [arXiv:1205.5067 [astro-ph.HE]].
- [8] A. Aab *et al.* [Pierre Auger Collaboration], [The Pierre Auger Observatory: Contributions to the 35th International Cosmic Ray Conference \(ICRC 2017\)](#), arXiv:1708.06592 [astro-ph.HE].
- [9] D. Allard, N. G. Busca, G. Decerprit, A. V. Olinto and E. Parizot, [Implications of the cosmic ray spectrum for the mass composition at the highest energies](#), JCAP **0810**, 033 (2008) doi:10.1088/1475-7516/2008/10/033 [arXiv:0805.4779 [astro-ph]].
- [10] R. U. Abbasi *et al.* [Telescope Array and Pierre Auger Collaborations], [Pierre Auger Observatory and Telescope Array: Joint contributions to the 35th International Cosmic Ray Conference \(ICRC 2017\)](#), arXiv:1801.01018 [astro-ph.HE].
- [11] R. U. Abbasi *et al.*, [Evidence for declination dependence of ultra-high-energy cosmic ray spectrum in the Northern hemisphere](#), arXiv:1801.07820 [astro-ph.HE].
- [12] R. U. Abbasi *et al.* [Telescope Array Collaboration], [Search for anisotropy in the ultra-high-energy cosmic ray spectrum using the Telescope Array surface detector](#), [arXiv:1707.04967 [astro-ph.HE]].
- [13] A. A. Watson, [The highest energy cosmic rays: the past, the present and the future](#), arXiv:1901.06676 [astro-ph.IM].

- [14] J. Linsley and A. A. Watson, *Validity of scaling to  $10^{20}$  eV and high energy cosmic ray composition*, *Phys. Rev. Lett.* **46**, 459 (1981). doi : 10.1103/PhysRevLett.46.459
- [15] R. U. Abbasi *et al.*, *Study of ultrahigh energy cosmic ray composition using Telescope Array’s Middle Drum detector and surface array in hybrid mode*, *Astropart. Phys.* **64**, 49 (2014) doi:10.1016/j.astropartphys.2014.11.004 [arXiv:1408.1726 [astro-ph.HE]].
- [16] R. U. Abbasi *et al.* [TA Collaboration], *Depth of ultra-high energy cosmic ray induced air shower maxima measured by the Telescope Array Black Rock and Long Ridge FADC fluorescence detectors and surface array in hybrid mode*, arXiv:1801.09784 [astro-ph.HE].
- [17] J. Abraham *et al.* [Pierre Auger Collaboration], *Measurement of the depth of maximum of extensive air showers above  $10^{18}$  eV*, *Phys. Rev. Lett.* **104**, 091101 (2010) doi:10.1103/PhysRevLett.104.091101 [arXiv:1002.0699 [astro-ph.HE]].
- [18] A. Aab *et al.* [Pierre Auger Collaboration], *Depth of maximum of air-shower profiles at the Pierre Auger Observatory I: Measurements at energies above  $10^{17.8}$  eV*, *Phys. Rev. D* **90**, 122005 (2014) doi:10.1103/PhysRevD.90.122005 [arXiv:1409.4809 [astro-ph.HE]].
- [19] A. Aab *et al.* [Pierre Auger Collaboration], *Depth of maximum of air-shower profiles at the Pierre Auger Observatory II: Composition implications,*” *Phys. Rev. D* **90**, 122006 (2014) doi:10.1103/PhysRevD.90.122006 [arXiv:1409.5083 [astro-ph.HE]].
- [20] A. Aab *et al.* [Pierre Auger Collaboration], *Inferences on mass composition and tests of hadronic interactions from 0.3 to 100 EeV using the water-Cherenkov detectors of the Pierre Auger Observatory*, *Phys. Rev. D* **96**, 122003 (2017) doi:10.1103/PhysRevD.96.122003 [arXiv:1710.07249 [astro-ph.HE]].
- [21] R. Abbasi *et al.* [Pierre Auger and TA Collaborations], *Report of the working group on the composition of ultrahigh energy cosmic rays*, *JPS Conf. Proc.* **9**, 010016 (2016) doi:10.7566/JPSCP.9.010016 [arXiv:1503.07540].
- [22] W. Hanlon *et al.*, *Report of the working group on the mass composition of ultrahigh energy cosmic rays*, *JPS Conf. Proc.* **19**, 011013 (2018). doi:10.7566/JPSCP.19.011013
- [23] A. Aab *et al.* [Pierre Auger Collaboration], *Evidence for a mixed mass composition at the “ankle” in the cosmic-ray spectrum*, *Phys. Lett. B* **762**, 288 (2016) doi:10.1016/j.physletb.2016.09.039 [arXiv:1609.08567 [astro-ph.HE]].
- [24] A. Aab *et al.* [Pierre Auger Collaboration], *Large scale distribution of ultra high energy cosmic rays detected at the Pierre Auger Observatory with zenith angles up to  $80^\circ$* , *Astrophys. J.* **802**, 111 (2015) doi:10.1088/0004-637X/802/2/111 [arXiv:1411.6953 [astro-ph.HE]].
- [25] M. Unger, G. R. Farrar and L. A. Anchordoqui, *Origin of the ankle in the ultrahigh energy cosmic ray spectrum, and of the extragalactic protons below it*, *Phys. Rev. D* **92**, 123001 (2015) doi:10.1103/PhysRevD.92.123001 [arXiv:1505.02153 [astro-ph.HE]].



- [26] K. Fang and K. Murase, [Linking high-energy cosmic particles by black hole jets embedded in large-scale structures](#), Phys. Lett. **14**, 396 (2018) [Nature Phys. **14**, no. 4, 396 (2018)] doi:10.1038/s41567-017-0025-4 [arXiv:1704.00015 [astro-ph.HE]].
- [27] M. Kachelrieß, O. Kalashev, S. Ostapchenko and D. V. Semikoz, [Minimal model for extragalactic cosmic rays and neutrinos](#), Phys. Rev. D **96**, no. 8, 083006 (2017) doi:10.1103/PhysRevD.96.083006 [arXiv:1704.06893 [astro-ph.HE]].
- [28] R. U. Abbasi *et al.* [TA Collaboration], [Indications of intermediate-scale anisotropy of cosmic rays with energy greater than 57 EeV in the Northern sky measured with the surface detector of the Telescope Array experiment](#), Astrophys. J. **790**, L21 (2014) doi:10.1088/2041-8205/790/2/L21 [arXiv:1404.5890 [astro-ph.HE]].
- [29] K. Kawata *et al.* [TA Collaboration], [Ultra-high-energy cosmic-ray hotspot observed with the Telescope Array surface detectors](#), PoS ICRC **2015**, 276 (2016).
- [30] A. Aab *et al.* [Pierre Auger Collaboration], [An Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources](#), Astrophys. J. **853**, L29 (2018) doi:10.3847/2041-8213/aaa66d [arXiv:1801.06160 [astro-ph.HE]].
- [31] J. Biteau *et al.* [Pierre Auger and Telescope Array Collaborations], [Covering the celestial sphere at ultra-high energies: full-sky cosmic-ray maps beyond the ankle and the flux suppression](#), To be published in Proceedings of Ultra High Energy Cosmic Rays 2018, 8 - 12 October 2018, Paris.
- [32] T.-P. Li and Y.-Q. Ma, [Analysis methods for results in gamma-ray astronomy](#), Astrophys. J. **272**, 317 (1983). doi:10.1086/161295
- [33] M. G. Aartsen *et al.* [IceCube Collaboration], [Differential limit on the extremely-high-energy cosmic neutrino flux in the presence of astrophysical background from nine years of IceCube data](#), Phys. Rev. D **98**, no. 6, 062003 (2018) doi:10.1103/PhysRevD.98.062003 [arXiv:1807.01820 [astro-ph.HE]].
- [34] A. Aab *et al.* [Pierre Auger Collaboration], [Improved limit to the diffuse flux of ultra-high energy neutrinos from the Pierre Auger Observatory](#), Phys. Rev. D **91**, 092008 (2015) doi:10.1103/PhysRevD.91.092008 [arXiv:1504.05397 [astro-ph.HE]].
- [35] P. W. Gorham *et al.* [ANITA Collaboration], [Constraints on the ultra-high energy cosmic neutrino flux from the fourth flight of ANITA](#), arXiv:1902.04005 [astro-ph.HE].
- [36] V. S. Berezinsky and G. T. Zatsepin, [Cosmic rays at ultrahigh-energies \(neutrino?\)](#), Phys. Lett. **28B**, 423 (1969). doi:10.1016/0370-2693(69)90341-4
- [37] M. Ahlers, L. A. Anchordoqui and S. Sarkar, [Neutrino diagnostics of ultra-high energy cosmic ray protons](#), Phys. Rev. D **79**, 083009 (2009) doi:10.1103/PhysRevD.79.083009 [arXiv:0902.3993 [astro-ph.HE]].

- [38] J. Heinze, D. Boncioli, M. Bustamante and W. Winter, [Cosmogenic neutrinos challenge the cosmic ray proton dip model](#), *Astrophys. J.* **825**, 122 (2016) doi:10.3847/0004-637X/825/2/122 [arXiv:1512.05988 [astro-ph.HE]].
- [39] M. G. Aartsen *et al.* [IceCube Collaboration], [Constraints on ultra-high-energy cosmic-ray sources from a search for neutrinos above 10 PeV with IceCube](#), *Phys. Rev. Lett.* **117**, 241101 (2016) Erratum: [*Phys. Rev. Lett.* **119**, 259902 (2017)] doi:10.1103/PhysRevLett.117.241101, 10.1103/PhysRevLett.119.259902 [arXiv:1607.05886 [astro-ph.HE]].
- [40] K. Moller, P. B. Denton and I. Tamborra, [Cosmogenic neutrinos through the GRAND lens unveil the nature of cosmic accelerators](#), arXiv:1809.04866 [astro-ph.HE].
- [41] R. Alves Batista, R. M. de Almeida, B. Lago and K. Kotera, [Cosmogenic photon and neutrino fluxes in the Auger era](#), *JCAP* **1901**, no. 01, 002 (2019) doi:10.1088/1475-7516/2019/01/002 [arXiv:1806.10879 [astro-ph.HE]].
- [42] A. van Vliet, R. Alves Batista and J. R. Hörandel, [Determining the fraction of cosmic-ray protons at ultra-high energies with cosmogenic neutrinos](#), arXiv:1901.01899 [astro-ph.HE].
- [43] J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, [A new view on Auger data and cosmogenic neutrinos in light of different nuclear disintegration and air-shower models](#), arXiv:1901.03338 [astro-ph.HE].
- [44] UHECR interactions also give non-vanishing contribution to diffuse  $\gamma$ -ray background, and therefore source models are also constrained by *Fermi*-LAT observations; V. Berezhinsky, A. Gazizov and O. Kalashev, [Cascade photons as test of protons in UHECR](#), *Astropart. Phys.* **84**, 52 (2016) doi:10.1016/j.astropartphys.2016.08.007 [arXiv:1606.09293 [astro-ph.HE]].
- [45] A. Aab *et al.* [Pierre Auger Collaboration], [Ultrahigh-Energy Neutrino Follow-Up of Gravitational Wave Events GW150914 and GW151226 with the Pierre Auger Observatory](#), *Phys. Rev. D* **94**, no. 12, 122007 (2016) doi:10.1103/PhysRevD.94.122007 [arXiv:1608.07378 [astro-ph.HE]].
- [46] B. P. Abbott *et al.* [LIGO Scientific and Virgo and Fermi GBM and INTEGRAL and IceCube and IPN and Insight-Hxmt and ANTARES and Swift and Dark Energy Camera GW-EM and DES and DLT40 and GRAWITA and Fermi-LAT and ATCA and ASKAP and OzGrav and DWF (Deeper Wider Faster Program) and AST3 and CAASTRO and VINROUGE and MASTER and J-GEM and GROWTH and JAGWAR and CaltechNRAO and TTU-NRAO and NuSTAR and Pan-STARRS and KU and Nordic Optical Telescope and ePESSTO and GROND and Texas Tech University and TOROS and BOOTES and MWA and CALET and IKI-GW Follow-up and H.E.S.S. and LOFAR and LWA and HAWC and Pierre Auger and ALMA and Pi of Sky and DFN and ATLAS Telescopes and High Time Resolution Universe Survey and RIMAS and RATIR and SKA South Africa/MeerKAT Collaborations and AstroSat Cadmium Zinc Telluride Imager Team and AGILE Team and 1M2H Team and Las Cumbres Observatory Group and MAXI Team and TZAC Consortium and SALT Group and Euro VLBI Team and Chandra Team at McGill University], [Multi-messenger Observations](#)



- of a Binary Neutron Star Merger, *Astrophys. J.* **848**, no. 2, L12 (2017) doi:10.3847/2041-8213/aa91c9 [arXiv:1710.05833 [astro-ph.HE]].
- [47] A. Albert *et al.* [ANTARES and IceCube and Pierre Auger and LIGO Scientific and Virgo Collaborations], *Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory*, *Astrophys. J.* **850**, no. 2, L35 (2017) doi:10.3847/2041-8213/aa9aed [arXiv:1710.05839 [astro-ph.HE]].
- [48] A. Aab *et al.* [Pierre Auger Collaboration], *Testing hadronic interactions at ultrahigh energies with air showers measured by the Pierre Auger Observatory*, *Phys. Rev. Lett.* **117**, 192001 (2016) doi:10.1103/PhysRevLett.117.192001 [arXiv:1610.08509 [hep-ex]].
- [49] R. U. Abbasi *et al.* [TA Collaboration], *Study of muons from ultrahigh energy cosmic ray air showers measured with the Telescope Array experiment*, *Phys. Rev. D* **98**, 022002 (2018) doi:10.1103/PhysRevD.98.022002 [arXiv:1804.03877 [astro-ph.HE]].
- [50] L. Cazon, R. Conceição and F. Riehn, *Probing the energy spectrum of hadrons in proton air interactions at ultrahigh energies through the fluctuations of the muon content of extensive air showers*, *Phys. Lett. B* **784**, 68 (2018) doi:10.1016/j.physletb.2018.07.026 [arXiv:1803.05699 [hep-ph]].
- [51] L. Cazon, R. Conceição, M. A. Martins and F. Riehn, *Probing the  $\pi^0$  spectrum at high- $x$  in proton-air interactions at ultra-high energies*, arXiv:1812.09121 [astro-ph.HE].
- [52] H. P. Dembinski *et al.* [EAS-MSU and IceCube and KASCADE-Grande and NEVOD-DECOR and Pierre Auger and SUGAR and Telescope Array and Yakutsk EAS Array Collaborations], *Report on tests and measurements of hadronic interaction properties with air showers*, arXiv:1902.08124 [astro-ph.HE].
- [53] S. Baur, H. Dembinski, T. Pierog, R. Ulrich and K. Werner, *The ratio of electromagnetic to hadronic energy in high energy hadron collisions as a probe for collective effects, and implications for the muon production in cosmic ray air showers*, arXiv:1902.09265 [hep-ph].
- [54] G. R. Farrar, *Particle physics at ultrahigh energies*, arXiv:1902.11271 [hep-ph].
- [55] G. R. Farrar and J. D. Allen, *A new physical phenomenon in ultrahigh energy collisions*, *EPJ Web Conf.* **53**, 07007 (2013) doi:10.1051/epjconf/20135307007 [arXiv:1307.2322 [hep-ph]].
- [56] L. A. Anchordoqui, H. Goldberg and T. J. Weiler, *Strange fireball as an explanation of the muon excess in Auger data*, *Phys. Rev. D* **95**, 063005 (2017) doi:10.1103/PhysRevD.95.063005 [arXiv:1612.07328 [hep-ph]].
- [57] Compelling hints of QGP formation have been recently reported by the ALICE Collaboration; J. Adam *et al.* [ALICE Collaboration], *Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions*, *Nature Phys.* **13**, 535 (2017) doi:10.1038/nphys4111 [arXiv:1606.07424 [nucl-ex]].

- [58] K. Kotera and A. V. Olinto, **The astrophysics of ultrahigh energy cosmic rays**, *Ann. Rev. Astron. Astrophys.* **49**, 119 (2011) doi:10.1146/annurev-astro-081710-102620 [arXiv:1101.4256 [astro-ph.HE]].
- [59] L. A. Anchordoqui, **Ultra-high-energy cosmic rays**, *Phys. Rept.* (2019) doi:10.1016/j.physrep.2019.01.002 [arXiv:1807.09645 [astro-ph.HE]].
- [60] R.A. Batista et al., **Open questions in cosmic-ray research at ultrahigh energies**, *Frontiers in Astronomy and Space Sciences* (2019).
- [61] G. F. Krymskii, **A regular mechanism for the acceleration of charged particles on the front of a shock wave**, *Akademiia Nauk SSSR Doklady* **234**, 1306 (1977).
- [62] W. I. Axford, E. Leer, and G. Skadron **The acceleration of cosmic rays by shock waves**, in *Proceedings of the 15th International Cosmic Ray Conference* **11**, 132 (1977).
- [63] A. R. Bell, **The acceleration of cosmic rays in shock fronts I**, *Mon. Not. Roy. Astron. Soc.* **182**, 147 (1978).
- [64] A. R. Bell, **The acceleration of cosmic rays in shock fronts II**, *Mon. Not. Roy. Astron. Soc.* **182**, 443 (1978).
- [65] R. D. Blandford and J. P. Ostriker, **Particle acceleration by astrophysical shocks**, *Astrophys. J.* **221**, L29 (1978). doi:10.1086/182658
- [66] P. O. Lagage and C. J. Cesarsky, **The maximum energy of cosmic rays accelerated by supernova shocks**, *Astron. Astrophys.* **125**, 249 (1983).
- [67] L. O. Drury, **An introduction to the theory of diffusive shock acceleration of energetic particles in tenuous plasmas**, *Rept. Prog. Phys.* **46**, 973 (1983). doi:10.1088/0034-4885/46/8/002
- [68] R. Blandford and D. Eichler, **Particle acceleration at astrophysical shocks: A theory of cosmic ray origin**, *Phys. Rept.* **154**, 1 (1987). doi:10.1016/0370-1573(87)90134-7
- [69] C. A. Norman, D. B. Melrose, and A. Achterberg, **The origin of cosmic rays above  $10^{18.5}$  eV** *Astrophys. J.* **454**, 60 (1995). doi:10.1086/176465
- [70] H. Kang, J. P. Rachen and P. L. Biermann, **Contributions to the cosmic ray flux above the ankle: clusters of galaxies**, *Mon. Not. Roy. Astron. Soc.* **286**, 257 (1997) doi:10.1093/mnras/286.2.257 [astro-ph/9608071].
- [71] D. Ryu, H. Kang, E. Hallman and T. W. Jones, **Cosmological shock waves and their role in the large scale structure of the universe**, *Astrophys. J.* **593**, 599 (2003) doi:10.1086/376723 [astro-ph/0305164].
- [72] L. A. Anchordoqui, G. E. Romero and J. A. Combi, **Heavy nuclei at the end of the cosmic ray spectrum?**, *Phys. Rev. D* **60**, 103001 (1999) doi:10.1103/PhysRevD.60.103001 [astro-ph/9903145].



- [73] L. A. Anchordoqui, [Acceleration of ultrahigh-energy cosmic rays in starburst superwinds](#), Phys. Rev. D **97**, no. 6, 063010 (2018) doi:10.1103/PhysRevD.97.063010 [arXiv:1801.07170 [astro-ph.HE]].
- [74] P. L. Biermann and P. A. Strittmatter, [Synchrotron emission from shock waves in active galactic nuclei](#), Astrophys. J. **322**, 643 (1987). doi:10.1086/165759
- [75] F. Takahara, [On the origin of highest energy cosmic rays](#), Prog. Theor. Phys. **83**, 1071 (1990). doi:10.1143/PTP.83.1071
- [76] J. P. Rachen and P. L. Biermann, [Extragalactic ultrahigh-energy cosmic rays I: Contribution from hot spots in FR-II radio galaxies](#), Astron. Astrophys. **272**, 161 (1993) [astro-ph/9301010].
- [77] G. E. Romero, J. A. Combi, L. A. Anchordoqui and S. E. Perez Bergliaffa, [A possible source of extragalactic cosmic rays with arrival energies beyond the GZK cutoff](#), Astropart. Phys. **5**, 279 (1996) doi:10.1016/0927-6505(96)00029-1 [gr-qc/9511031].
- [78] Gopal-Krishna, P. L. Biermann, V. de Souza and P. J. Wiita, [Ultra-high energy cosmic rays from Centaurus A: Jet interaction with gaseous shells](#), Astrophys. J. **720**, L155 (2010) doi:10.1088/2041-8205/720/2/L155 [arXiv:1006.5022 [astro-ph.HE]].
- [79] R. Blandford, D. Meier and A. Readhead, [Relativistic jets in active galactic nuclei](#), arXiv:1812.06025 [astro-ph.HE].
- [80] J. H. Matthews, A. R. Bell, K. M. Blundell and A. T. Araudo, [Fornax A, Centaurus A, and other radio galaxies as sources of ultrahigh energy cosmic rays](#), Mon. Not. Roy. Astron. Soc. **479**, no. 1, L76 (2018) doi:10.1093/mnras/sly099 [arXiv:1805.01902 [astro-ph.HE]].
- [81] J. H. Matthews, A. R. Bell, K. M. Blundell and A. T. Araudo, [Ultra-high energy cosmic rays from shocks in the lobes of powerful radio galaxies](#), Mon. Not. Roy. Astron. Soc. **482**, 4303 (2019) doi:10.1093/mnras/sty2936 [arXiv:1810.12350 [astro-ph.HE]].
- [82] J. H. Matthews, A. R. Bell, A. T. Araudo and K. M. Blundell, [Cosmic ray acceleration to ultrahigh energy in radio galaxies](#), arXiv:1902.10382 [astro-ph.HE].
- [83] E. Waxman, [Cosmological gamma-ray bursts and the highest energy cosmic rays](#), Phys. Rev. Lett. **75**, 386 (1995) doi:10.1103/PhysRevLett.75.386 [astro-ph/9505082].
- [84] M. Vietri, [On the acceleration of ultrahigh-energy cosmic rays in gamma-ray bursts](#), Astrophys. J. **453**, 883 (1995) doi:10.1086/176448 [astro-ph/9506081].
- [85] C. D. Dermer and A. Atoyan, [Ultrahigh energy cosmic rays, cascade gamma-rays, and high-energy neutrinos from gamma-ray bursts](#), New J. Phys. **8**, 122 (2006) doi:10.1088/1367-2630/8/7/122 [astro-ph/0606629].
- [86] X. Y. Wang, S. Razzaque and P. Meszaros, [On the origin and survival of UHE cosmic-ray nuclei in GRBs and hypernovae](#), Astrophys. J. **677**, 432 (2008) doi:10.1086/529018 [arXiv:0711.2065 [astro-ph]].

- [87] K. Murase, K. Ioka, S. Nagataki and T. Nakamura, **High-energy cosmic-ray nuclei from high- and low-luminosity gamma-ray bursts and implications for multi-messenger astronomy**, Phys. Rev. D **78**, 023005 (2008) doi:10.1103/PhysRevD.78.023005 [arXiv:0801.2861 [astro-ph]].
- [88] P. Baerwald, M. Bustamante and W. Winter, **UHECR escape mechanisms for protons and neutrons from GRBs, and the cosmic ray-neutrino connection**, Astrophys. J. **768**, 186 (2013) doi:10.1088/0004-637X/768/2/186 [arXiv:1301.6163 [astro-ph.HE]].
- [89] N. Globus, D. Allard, R. Mochkovitch and E. Parizot, **UHECR acceleration at GRB internal shocks**, Mon. Not. Roy. Astron. Soc. **451**, no. 1, 751 (2015) doi:10.1093/mnras/stv893 [arXiv:1409.1271 [astro-ph.HE]].
- [90] B. T. Zhang, K. Murase, S. S. Kimura, S. Horiuchi and P. Mészáros, **Low-luminosity gamma-ray bursts as the sources of ultrahigh-energy cosmic ray nuclei**, Phys. Rev. D **97**, no. 8, 083010 (2018) doi:10.1103/PhysRevD.97.083010 [arXiv:1712.09984 [astro-ph.HE]].
- [91] D. Boncioli, D. Biehl and W. Winter, **On the common origin of cosmic rays across the ankle and diffuse neutrinos at the highest energies from low-luminosity Gamma-Ray Bursts**, doi:10.3847/1538-4357/aafda7 arXiv:1808.07481 [astro-ph.HE].
- [92] G. R. Farrar and A. Gruzinov, **Giant AGN flares and cosmic ray bursts**, Astrophys. J. **693**, 329 (2009) doi:10.1088/0004-637X/693/1/329 [arXiv:0802.1074 [astro-ph]].
- [93] G. R. Farrar and T. Piran, **Tidal disruption jets as the source of ultra-high energy cosmic rays**, arXiv:1411.0704 [astro-ph.HE].
- [94] D. N. Pfeffer, E. D. Kovetz and M. Kamionkowski, **Ultrahigh-energy cosmic ray hotspots from tidal disruption events**, Mon. Not. Roy. Astron. Soc. **466**, no. 3, 2922 (2017) doi:10.1093/mnras/stw3337 [arXiv:1512.04959 [astro-ph.HE]].
- [95] D. Biehl, D. Boncioli, C. Lunardini and W. Winter, **Tidally disrupted stars as a possible origin of both cosmic rays and neutrinos at the highest energies**, Sci. Rep. **8**, no. 1, 10828 (2018) doi:10.1038/s41598-018-29022-4 [arXiv:1711.03555 [astro-ph.HE]].
- [96] F. M. Rieger and P. Duffy, **Shear acceleration in relativistic astrophysical jets**, Astrophys. J. **617**, 155 (2004) doi:10.1086/425167 [astro-ph/0410269].
- [97] S. S. Kimura, K. Murase and B. T. Zhang, **Ultrahigh-energy cosmic-ray nuclei from black hole jets: Recycling galactic cosmic rays through shear acceleration**, Phys. Rev. D **97**, no. 2, 023026 (2018) doi:10.1103/PhysRevD.97.023026 [arXiv:1705.05027 [astro-ph.HE]].
- [98] D. Caprioli, **“Espresso” acceleration of ultra-high-energy cosmic rays**, Astrophys. J. **811**, no. 2, L38 (2015) doi:10.1088/2041-8205/811/2/L38 [arXiv:1505.06739 [astro-ph.HE]].
- [99] P. Blasi, R. I. Epstein and A. V. Olinto, **Ultrahigh-energy cosmic rays from young neutron star winds**, Astrophys. J. **533**, L123 (2000) doi:10.1086/312626 [astro-ph/9912240].



- [100] K. Fang, K. Kotera and A. V. Olinto, [Newly-born pulsars as sources of ultrahigh energy cosmic rays](#), *Astrophys. J.* **750**, 118 (2012) doi:10.1088/0004-637X/750/2/118 [arXiv:1201.5197 [astro-ph.HE]].
- [101] K. Fang, K. Kotera and A. V. Olinto, [Ultrahigh energy cosmic ray nuclei from extragalactic pulsars and the effect of their Galactic counterparts](#), *JCAP* **1303**, 010 (2013) doi:10.1088/1475-7516/2013/03/010 [arXiv:1302.4482 [astro-ph.HE]].
- [102] J. Arons, [Magnetars in the metagalaxy: an origin for ultrahigh-energy cosmic rays in the nearby universe](#), *Astrophys. J.* **589**, 871 (2003) doi:10.1086/374776 [astro-ph/0208444].
- [103] R. D. Blandford and R. L. Znajek, [Electromagnetic extractions of energy from Kerr black holes](#), *Mon. Not. Roy. Astron. Soc.* **179**, 433 (1977).
- [104] R. L. Znajek [The electric and magnetic conductivity of a Kerr hole](#), *Mon. Not. Roy. Astron. Soc.* **185**, 833 (1978).
- [105] A. Y. Neronov, D. V. Semikoz and I. I. Tkachev, [Ultra-high energy cosmic ray production in the polar cap regions of black hole magnetospheres](#), *New J. Phys.* **11**, 065015 (2009) doi:10.1088/1367-2630/11/6/065015 [arXiv:0712.1737 [astro-ph]].
- [106] P. Chen, T. Tajima and Y. Takahashi, [Plasma wakefield acceleration for ultrahigh-energy cosmic rays](#), *Phys. Rev. Lett.* **89**, 161101 (2002) doi:10.1103/PhysRevLett.89.161101 [astro-ph/0205287].
- [107] K. Murase, P. Meszaros and B. Zhang, [Probing the birth of fast rotating magnetars through high-energy neutrinos](#), *Phys. Rev. D* **79**, 103001 (2009) doi:10.1103/PhysRevD.79.103001 [arXiv:0904.2509 [astro-ph.HE]].
- [108] T. Ebisuzaki and T. Tajima, [Astrophysical ZeV acceleration in the relativistic jet from an accreting supermassive black hole](#), *Astropart. Phys.* **56**, 9 (2014) doi:10.1016/j.astropartphys.2014.02.004 [arXiv:1306.0970 [astro-ph.HE]].
- [109] For example, even if we establish the correlation between UHECRs and starbursts in the near future, we may not be sure whether UHECRs are accelerated by superwinds [72, 73], or low-luminosity GRBs [90, 91], or fast-spinning pulsars [99–101]. The acceleration models could be discriminated with future facilities, provided sufficiently large statistics is achieved in both UHECRs and neutrinos [59].
- [110] A. Aab *et al.* [Pierre Auger Collaboration], [Observation of a large-scale anisotropy in the arrival directions of cosmic rays above  \$8 \times 10^{18}\$  eV](#), *Science* **357**, no. 6537, 1266 (2017) doi:10.1126/science.aan4338 [arXiv:1709.07321 [astro-ph.HE]].
- [111] A. Aab *et al.* [Pierre Auger Collaboration], [Large-scale cosmic-ray anisotropies above 4 EeV measured by the Pierre Auger Observatory](#), *Astrophys. J.* **868**, 4 (2018) doi:10.3847/1538-4357/aae689 [arXiv:1808.03579 [astro-ph.HE]].
- [112] E. Kido *et al.* [TA Collaboration], [The TA \$\times\$ 4 experiment](#), *PoS ICRC 2017*, 386 (2017).

- [113] A. Aab *et al.* [Pierre Auger Collaboration], [The Pierre Auger Observatory upgrade: Preliminary design report](#), arXiv:1604.03637 [astro-ph.IM].
- [114] A. Aab *et al.* [Pierre Auger Collaboration], [Measurement of the radiation energy in the radio signal of extensive air showers as a universal estimator of cosmic-ray energy](#), Phys. Rev. Lett. **116**, 241101 (2016) doi:10.1103/PhysRevLett.116.241101 [arXiv:1605.02564 [astro-ph.HE]].
- [115] A. Aab *et al.* [Pierre Auger Collaboration], [Observation of inclined EeV air showers with the radio detector of the Pierre Auger Observatory](#), JCAP **1810**, no. 10, 026 (2018) doi:10.1088/1475-7516/2018/10/026 [arXiv:1806.05386 [astro-ph.IM]].
- [116] D. J. Bird *et al.* [HiRes Collaboration], [The cosmic ray energy spectrum observed by the Fly's Eye](#), Astrophys. J. **424**, 491 (1994). doi:10.1086/173906
- [117] M. Takeda *et al.*, [Energy determination in the Akeno Giant Air Shower Array experiment](#), Astropart. Phys. **19**, 447 (2003) doi:10.1016/S0927-6505(02)00243-8 [astro-ph/0209422].
- [118] R. U. Abbasi *et al.* [HiRes Collaboration], [Monocular measurement of the spectrum of UHE cosmic rays by the FADC detector of the HiRes experiment](#), Astropart. Phys. **23**, 157 (2005) doi:10.1016/j.astropartphys.2004.12.006 [astro-ph/0208301].
- [119] B. A. Khrenov *et al.*, [First results from the TUS orbital detector in the extensive air shower mode](#), JCAP **1709**, no. 09, 006 (2017) doi:10.1088/1475-7516/2017/09/006 [arXiv:1704.07704 [astro-ph.IM]].
- [120] It is important to keep in mind that the *intrinsic*  $X_{\max}$  fluctuations are roughly 20 g/cm<sup>2</sup> for Fe growing to 60 g/cm<sup>2</sup> for  $p$ . Consequently, a  $\Delta X_{\max} < 20$  g/cm<sup>2</sup> will not improve the event-by-event composition capabilities. Once the level for intrinsic fluctuations has been reached, the merit factor can only be increased by adding another observable (e.g. muons).
- [121] K. H. Kampert and M. Unger, [Measurements of the cosmic ray composition with air shower experiments](#), Astropart. Phys. **35**, 660 (2012) doi:10.1016/j.astropartphys.2012.02.004 [arXiv:1201.0018 [astro-ph.HE]].
- [122] J. Krizmanic, D. Bergman and P. Sokolsky, [The modeling of the nuclear composition measurement performance of the Non-Imaging Cherenkov Array \(NICHE\)](#), arXiv:1307.3918 [astro-ph.IM].
- [123] J. Krizmanic, D. Bergman and Y. Tsunesada, [The Cosmic Ray Nuclear Composition Measurement Performance of the Non-Imaging Cherenkov Array \(NICHE\)](#), ICRC **2015**, 562 (2015).
- [124] A point worth noting at this juncture is that there is likely a gap in composition between He and C, due to the fragility of intervening nuclei to destruction during propagation, which may facilitate nuclear composition studies with almost ideal separation between  $p$  and C events at the highest energies because of guaranteed He photo-disintegration during propagation; J. F. Soriano, L. A. Anchordoqui and D. F. Torres, [The photo-disintegration of <sup>4</sup>He on the](#)

cosmic microwave background is less severe than earlier thought, *Phys. Rev. D* **98**, 043001 (2018) doi:10.1103/PhysRevD.98.043001 [arXiv:1805.00409 [astro-ph.HE]].

- [125] A precise measurement of composition beyond the onset of flux suppression will be critical to understanding the highest energy UHECRs. Such a measurement demands an exposure comparable to the current integrated exposure of Auger *and* calorimetric measurement of all the EASs in the sample either with fluorescence or radio detectors.
- [126] V. Brümmel, R. Engel and M. Roth, **On the importance of the energy resolution for identifying sources of UHECR**, *Braz. J. Phys.* **44**, 415 (2014).
- [127] A. V. Olinto *et al.*, **POEMMA: Probe Of Extreme Multi-Messenger Astrophysics**, *PoS ICRC 2017*, 542 (2017) [arXiv:1708.07599 [astro-ph.IM]].
- [128] J. Alvarez-Muñiz *et al.* [GRAND Collaboration], **The Giant Radio Array for Neutrino Detection (GRAND): Science and Design**, arXiv:1810.09994 [astro-ph.HE].



## Endorsements:

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