Astro2020 Science White Paper

High-Energy Galactic Cosmic Rays

Thematic Areas:
□ Planetary Systems
□ Star and Planet Formation
□ Formation and Evolution of Compact Objects
□ Cosmology and Fundamental Physics
□ Stars and Stellar Evolution
□ Resolved Stellar Populations and their Environments
□ Galaxy Evolution
□ Multi-Messenger Astronomy and Astrophysics

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Abstract:
The origin of the highest energy Galactic cosmic rays is still not understood, nor is the transition to EeV extragalactic particles. Scientific progress requires enhancements of existing air-shower arrays, such as: IceCube with its surface detector IceTop, and the low-energy extensions of both the Telescope Array and the Pierre Auger Observatory.
1 Overview and Science Goals

The most powerful accelerators of cosmic rays in our Milky Way have not yet been revealed. In the past decade, several experiments have found evidence that the highest energy cosmic rays (CRs) – above a few EeV – seem to be of extragalactic origin \[1,2\]. However, there are major open questions regarding Galactic cosmic rays (GCRs) in the energy range from \(\sim 0.1 \text{ PeV to } \sim 1 \text{ EeV} \) \(\left(10^{14} - 10^{18} \text{ eV}\right)\): the source of the highest-energy GCRs remains unidentified; the maximum energies of various acceleration mechanisms are uncertain; the Galactic-extragalactic transition and several features in the CR energy spectrum, such as the Knee, the Second Knee, and the Ankle, are not well understood. These questions can be addressed through improved GCR measurements in conjunction with gamma-ray and neutrino observations. Bringing multi-messenger astrophysics to maturity requires a consistent understanding and sufficient measurement accuracy for all messengers. In particular, the mass composition of CRs is highly sensitive to their origin and propagation \[3\], and the discovery of mass-dependent anisotropies may reveal the most energetic sources in the Galaxy, either directly or in combination with other messengers. In the next decade, detector enhancements will bring essential improvements in accuracy for GCRs, and may add a GCR channel to neutrino and gamma experiments, transforming them to multi-messenger detectors.

In this white paper, opportunities for research regarding high-energy GCRs will be presented and discussed. The most important goals are as follows:

- Determine the maximum acceleration energy for GCRs and understand the transition from Galactic to extragalactic cosmic rays. This may be accomplished by discovering the most energetic source in the Milky Way. The Galactic Center is a promising candidate \[4,5\], which can be tested by combining mass-resolved GCR measurements with searches for PeV neutrinos and photons. Alternative hypotheses include re-acceleration scenarios and the high-energy tail of a smooth source distribution, e.g., supernova shock fronts.

- Clarify the nature of features in the energy spectrum (Fig. 1): Is the Knee related to different populations of sources or magnetic diffusion of the CRs during propagation? Is the Second Knee a feature of the Galactic-to-extragalactic transition, and is it related to the maximum acceleration energy of a particular source population or to the propagation of GCRs? How are features in the energy spectrum linked to features in the large-scale anisotropy (Fig. 2)?

- Describe the full picture of sources and propagation of GCRs using joint interpretations with other astrophysical messengers and astronomical observations, such as measurements of Galactic magnetic fields. A Galactic contribution to the astrophysical neutrino flux can provide a lower limit on the maximum acceleration energy \[6\].

- Resolve apparent differences between CR measurements by various air-shower arrays. What is the reason for differences in their energy scales \[7\]? Why is the knee-like feature at 0.7 PeV observed only by ARGO \[5\], and how is it related to the Knee at 3 PeV? Are there differences in GCRs from different parts of the sky further than the small difference in the absolute flux due to the large-scale anisotropy?

- Use GCRs to access particle physics beyond the phase space of current human-made accelerators. A better understanding of hadronic interactions is a science goal by itself, and is also required to fix the mismatch in muons between simulations and data \[9-13\], which constitute a major systematic uncertainty for the interpretation of GCR measurements \[14\].
Figure 1: Cosmic-ray energy spectrum and mass composition. This plot reflects a recent attempt for a combined fit of flux and composition measurements by different experiments, where the individual spectra [8,15–20] have been multiplied by a constant (inset) to adjust them to a common energy scale. The bands are one-sigma uncertainties derived from published experimental data (see [7] for details). Features such as the Knee, Second Knee, and Ankle mark softenings or hardenings of the spectrum which can be approximated by a power law in between these features. For future progress in GCR science, it is important to reduce the uncertainties by improving hadronic interaction models and enhancing air-shower arrays to perform hybrid measurements.

2 State of the Art in High-Energy GCR Science

To understand how these science goals can be targeted by more accurate mass measurements of GCRs and by multi-messenger astrophysics, let us first review the recent progress in CR science.

GCRs have a strongly mixed composition of elements from proton to iron at all energies (Fig. 1; see [36–41] for reviews). The exact composition varies with kinetic energy. During their propagation, GCRs diffuse in Galactic magnetic fields depending on their rigidity, which translates into a mass-dependence, since GCRs are fully ionized nuclei. The magnetic deflection leads to an almost isotropic arrival direction at Earth (Fig. 2). Weak anisotropies have been measured for the all-particle flux [21,42–44], but are difficult to interpret because the present accuracy of air-shower arrays does not allow for efficient per-event classification of the mass of GCRs.

Features in the energy spectrum (Fig. 1) and large-scale anisotropy (Fig. 2) mark the 100 TeV to 1 EeV range of high-energy GCRs as distinct. Above 100 TeV, the phase of the first harmonic of the large-scale anisotropy flips towards the direction of the Galactic Center. Structures in the heavier components suggest that GCR at 100 TeV and at a few PeV might belong to different populations of sources. However, we do not yet know why the Knee, as the most prominent feature in the energy spectrum, does not coincide with a significant feature in the anisotropy measurements. Current anisotropy searches are not yet sensitive enough in this energy range [45].

Around 100 PeV the heavy component in the energy spectrum becomes softer [46], and at about the same energy the light component becomes harder [47]. The relation to the Second Knee in the all-particle spectrum detected by several experiments at two to three times higher energy needs
Figure 2: Large-scale cosmic-ray anisotropy: amplitude (left) and phase (right) of the first harmonic measured by various air-shower experiments, each covering only a part of the sky. In the amplitude plot, upper limits are shown for measurements with a significance of less than three sigmas. The first phase flip may indicate that GCR above 100 TeV belong to at least one different population. The second phase flip at a few EeV may be a signature of the transition from Galactic to extragalactic sources. Figure adopted from [21], data from [21–35].

Further investigation [16,48]. Are these separate features or one feature extending over a larger energy range? Moreover, a better comparison of the absolute energy scales of different experiments is needed to check for their compatibility. A detailed understanding is of particular importance since this energy range around 100 PeV could mark the start of the Galactic-to-extragalactic transition.

The change of the large-scale anisotropy around 1 EeV is likely related to the Galactic-to-extragalactic transition, too [49]. Recent observations indicate that this transition seems to be completed at an energy below the Ankle. At higher energies, the large-scale dipole anisotropy points away from the Galactic Center. At a few EeV, no strong anisotropy is observed, although anisotropy is expected if the sources are mostly Galactic in the EeV range [1,2]. To distinguish and resolve several models suggesting a lower transition energy, e.g., [50–54], more accurate experimental data is required. The transition energy from Galactic to extragalactic cosmic rays is of interest by itself, since it may either be related to the propagation of GCRs or mark their maximum acceleration energy. Since the most energetic GCRs are expected to consist of heavier nuclei, a per-event mass classification is vital to separate them from the extragalactic CRs, which consist mostly of light nuclei at energies below the Ankle [55].

Theoretical models and observations suggest that GCRs are predominantly accelerated by supernova shock fronts, but it is difficult to explain the origin of the most energetic GCRs with this mechanism [56]. The Galactic Center might be a more powerful accelerator than supernovae, as gamma-ray observations suggest a maximum energy of at least 1 PeV for protons [4,5]. Typically it is assumed that any electromagnetic acceleration process will have a maximum energy for nuclei of $Z$ times the maximum for protons, where $Z$ is the charge number of the CR nucleus. To account for the most energetic GCRs in the Milky Way, a maximum energy of $Z$ times at least a few PeV if not several 10s of PeV may be required, depending on the transition energy to extragalactic CRs, and the mass composition of the GCRs at the transition energy. Measuring the spectra of individual mass groups may resolve these so-called Peters cycles [57] of the $Z$ dependence of the maximum acceleration energy, and indicate how many source populations exist.
In summary, we do not yet know what accelerates the most energetic GCRs and need to understand the transition to extragalactic CRs. In addition to multi-messenger observations, the key for progress is to increase the measurement accuracy for GCRs by enhancing detectors for air showers.

3 Progress and Challenges in Detection Techniques

The measurement of CRs at energies of a PeV and beyond remains challenging because only indirect measurements by air showers can acquire sufficient statistics. The interpretation of these air showers is subject to systematic uncertainties that depend on the type and coverage of the used instrumentation. Deficits of hadronic interaction models constitute a major systematic uncertainty. Improving the models requires input by accelerator experiments and by enhanced air-shower arrays providing hybrid measurements of all accessible shower components. According to the paradigm of shower universality, air showers can be described in good approximation by only a few parameters, such as their direction, energy, muon content and the depth of the shower maximum, $X_{\text{max}}$. Shower-to-shower fluctuations and the similarity of showers initiated by different primary nuclei lead to intrinsic systematic uncertainties. Therefore, when using state-of-the-art techniques, maximizing the accuracy for the properties of the primary particle requires the simultaneous measurement of at least the energy, the number of muons, and $X_{\text{max}}$.

In the past, the accuracy of most air-shower arrays for GCRs was limited by using a single technique, such as particle or air-Cherenkov detectors. For example, KASCADE and IceTop statistically estimated the mass composition based on the muon content. Tunka, TALE, and Auger used $X_{\text{max}}$ for this purpose. While mass measurements based on the muon content have a high precision, they suffer most from uncertainties due to deficiencies in the hadronic models. Even though the LHC reaches the center-of-mass energy of GCR collisions with the atmosphere, its experiments do not cover the complete phase space relevant for air showers. The interpretation of $X_{\text{max}}$ is presently more accurate since the electromagnetic component of air showers is better understood. For EeV energies, the fluorescence technique yields the best accuracy for determining the energy and $X_{\text{max}}$, and below about a 100 PeV air-Cherenkov detectors are used for $X_{\text{max}}$ measurements. Both methods require clear, moonless nights. Recently there has been progress in the radio technique providing a 24/7 instrumentation for $X_{\text{max}}$ around 100 PeV, and possibly starting as low as 1 PeV. This advance in technology enables hybrid arrays combining $X_{\text{max}}$ and muon measurements in the same experiment to maximize the total accuracy for CRs in the PeV-EeV range.

In the next decade, the inclusion of other observables in combination with modern analysis techniques, such as machine learning, needs to be investigated to increase the efficiency and reconstruction accuracy. GCR observatories have already played a crucial role in the development and test of new techniques, like radio and microwave measurements. Radio measurements also provide a new tool to compare the energy scales of different experiments.

For understanding the origin of GCRs, more accurate air-shower instrumentation needs to be accompanied by multi-messenger astronomy of GCRs, photons, and neutrinos. First, the detection of photons and neutrinos can directly reveal sources of GCRs. For energies up to about 100 TeV, gamma-ray observatories have already discovered a few sources. PeV photons have not yet been observed, but may be emitted by the Galactic Center if it accelerates the most energetic GCRs. Second, an accurate knowledge of the absolute flux and mass composition of CRs is important for the interpretation of other messengers, e.g., to understand the background.
for neutrino measurements in IceCube [97]. Third, GCR, neutrino, and photon measurements need to provide a consistent picture. Measurements of diffuse gamma-ray and neutrino fluxes give insight in the propagation of GCR [98–102]. In particular, the diffuse gamma-ray flux observed by Fermi-LAT [103] is slightly in tension with the soft power-law neutrino flux deduced from the IceCube High Energy Starting Events [104], which may indicate a non-negligible Galactic contribution to the astrophysical neutrino flux [105–107]. The observation of high-energy Galactic neutrinos will provide a lower limit on the maximum acceleration energy [6], and may directly reveal sources, similar to the observation of Galactic gamma rays.

4 Experimental Plans for the Next Decade

Multi-messenger astronomy requires a solid foundation in accurate instrumentation for all cosmic messengers. While major investments in detectors for high-energy photons and neutrinos are foreseen, the required increase in accuracy for GCRs can be obtained for a comparably low cost. This improvement is possible by upgrading existing air-shower detectors. Furthermore, detectors built primarily for photons and neutrinos can be enhanced to provide accurate CR measurements at the same time, transforming them to multi-messenger observatories.

The scientific questions can be targeted with dedicated efforts for increasing the accuracy in the relevant energy range, in particular enhancements of the IceCube surface array, the Telescope Array and the Pierre Auger Observatory. Several future observatories with different main objectives will also contribute to GCR science, e.g., the SKA [108], TAIGA [70], and GRAND-proto300 [109]. Their accuracy for cosmic rays will depend on whether they will be equipped with precise $X_{\text{max}}$ and muon instrumentation. Dense particle-detector arrays at high observation altitude optimized for gamma-astronomy, such as HAWC [15], a HAWC-like southern observatory [110], or LHASSO [111] will also have a high precision for GCRs in the PeV region.

IceCube with its surface array IceTop covers the complete range of high-energy GCRs from below 1 PeV to beyond 1 EeV [112]. The simultaneous measurement of low-energy particles at the surface and high-energy muons in the ice offers unique opportunities for the study of hadronic interactions [13], and the search for PeV photons [113]. A planned enhancement by a scintillator-radio hybrid array will significantly increase the accuracy and sky coverage of IceTop [114–116]. Air-Cherenkov detectors can further enhance its accuracy around a few PeV and below [117]. Finally, a planned expansion of IceCube will increase the exposure by an order of magnitude [118].

For studying the Galactic-to-extragalactic transition range, the most important contributions in the next years are expected from the low-energy extensions of the two leading observatories for ultra-high-energy CRs: the Pierre Auger Observatory [119] and the Telescope Array [48]. The TALE fluorescence detector at TA covers the energy range from about 2 PeV to beyond 1 EeV in monocular mode [48], and the range above 100 PeV in an recently enabled hybrid mode with scintillation detectors [120]. To reach energies below 1 PeV, another planned addition to TALE is the Non-Imaging Cherenkov Array (NICHE) [121]. The Auger enhancements reach below 100 PeV. Their accuracy will be increased by installing underground muon detectors [122], complementing the upgrade of the surface array [123], and the fluorescence [119], and radio detectors [124].

The increase in accuracy, exposure, and sky coverage provided by these experiments will bring unprecedented sensitivity for the search of mass-sensitive anisotropies. Hence, the contribution of GCRs to multi-messenger astrophysics will be lifted to a new level providing a real chance finally to discover the most energetic accelerators in our Milky Way.
References

[1] Telescope Array Collaboration, R. Abbasi et al., “Search for EeV Protons of Galactic Origin,” [Astropart. Phys. 86 (2017) 21–26] arXiv:1608.06306 [astro-ph.HE].

[2] Pierre Auger Collaboration, A. Aab et al., “Large-scale cosmic-ray anisotropies above 4 EeV measured by the Pierre Auger Observatory,” [Astrophys. J. 868 no. 1, (2018) 4] arXiv:1808.03579 [astro-ph.HE].

[3] K.-H. Kampert and M. Unger, “Measurements of the Cosmic Ray Composition with Air Shower Experiments,” [Astropart. Phys. 35 (2012) 660–678] arXiv:1201.0018 [astro-ph.HE].

[4] H.E.S.S. Collaboration, F. Aharonian et al., “Discovery of very-high-energy gamma-rays from the galactic centre ridge,” [Nature 439 (2006) 695–698] arXiv:astro-ph/0603021 [astro-ph].

[5] H.E.S.S. Collaboration, A. Abramowski et al., “Acceleration of petaelectronvolt protons in the Galactic Centre,” [Nature 531 (2016) 476] arXiv:1603.07730 [astro-ph.HE].

[6] L. A. Anchordoqui, H. Goldberg, M. H. Lynch, A. V. Olinto, T. C. Paul, and T. J. Weiler, “Pinning down the cosmic ray source mechanism with new IceCube data,” [Phys. Rev. D89 no. 8, (2014) 083003] arXiv:1306.5021 [astro-ph.HE].

[7] H.-P. Dembinski et al., “Data-driven model of the cosmic-ray flux and mass composition from 10 GeV to 10^{11} GeV,” [PoS ICRC2017 (2018) 533] arXiv:1711.11432 [astro-ph.HE].

[8] ARGO-YBJ, LHAASO Collaboration, B. Bartoli et al., “Knee of the cosmic hydrogen and helium spectrum below 1 PeV measured by ARGO-YBJ and a Cherenkov telescope of LHAASO,” [Phys. Rev. D92 no. 9, (2015) 092005] arXiv:1502.03164 [astro-ph.HE].

[9] H. P. Dembinski et al. for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array Collaborations, “Report on Tests and Measurements of Hadronic Interaction Properties with Air Showers,” in Ultra High Energy Cosmic Rays (UHECR 2018) Paris, France, October 8-12, 2018. 2019. arXiv:1902.08124 [astro-ph.HE].

[10] J. G. Gonzalez for the IceCube Collaboration, “Measuring the Muon Content of Air Showers with IceTop,” in 20th International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2018) Nagoya, Japan, May 21-25, 2018. 2018.

[11] S. De Ridder et al. for the IceCube Collaboration, “Sensitivity of IceCube Cosmic-Ray measurements to the hadronic interaction models,” [PoS ICRC2017 (2018) 319].

[12] D. Soldin for the IceCube Collaboration, “Atmospheric Muons Measured with IceCube,” arXiv:1811.03651 [astro-ph.HE].
[13] IceCube Collaboration, M. G. Aartsen et al., “Characterization of the Atmospheric Muon Flux in IceCube,” *Astropart. Phys.* 78 (2016) 1–27, arXiv:1506.07981 [astro-ph.HE]

[14] Pierre Auger Collaboration, A. Aab et al., “Testing Hadronic Interactions at Ultrahigh Energies with Air Showers Measured by the Pierre Auger Observatory,” *Phys. Rev. Lett.* 117 no. 19, (2016) 192001, arXiv:1610.08509 [hep-ex]

[15] HAWC Collaboration, R. Alfaro et al., “All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV,” *Phys. Rev.* D96 no. 12, (2017) 122001, arXiv:1710.00890 [astro-ph.HE]

[16] Tunka-133 Collaboration, V. Prosin et al., “Tunka-133: Results of 3 year operation,” *Nucl. Instrum. Meth.* A756 (2014) 94–101

[17] M. Plum for the IceCube Collaboration, “Cosmic ray spectrum and mass composition from IceTop and IceCube,” [https://indico.desy.de/indico/event/18204/](https://indico.desy.de/indico/event/18204/) TeVPA 2018, Berlin, Germany.

[18] S. Schoo for the KASCADE-Grande Collaboration, “The energy spectrum of cosmic rays in the range from $10^{14}$ to $10^{18}$ eV,” *PoS ICRC2015* (2016) 263.

[19] D. Ivanov for the Telescope Array Collaboration, “TA Spectrum Summary,” *PoS ICRC2015* (2016) 349

[20] F. Fenu for the Pierre Auger Collaboration, “The cosmic ray energy spectrum measured using the Pierre Auger Observatory,” *PoS ICRC2017* (2018) 486

[21] KASCADE-Grande Collaboration, W. Apel et al., “Search for Large-scale Anisotropy in the Arrival Direction of Cosmic Rays with KASCADE-Grande,” *Astrophys. J.* 870 no. 2, (2019) 91

[22] MACRO Collaboration, M. Ambrosio et al., “The Search for the sidereal and solar diurnal modulations in the total MACRO muon data set,” *Phys. Rev.* D67 (2003) 042002, arXiv:astro-ph/0211119 [astro-ph].

[23] Tibet AS Gamma Collaboration, M. Amenomori et al., “Large-scale sidereal anisotropy of Galactic cosmic-ray intensity observed by the Tibet air shower array,” *Astrophys. J.* 626 (2005) L29–L32, arXiv:astro-ph/0505114 [astro-ph].

[24] Tibet AS-gamma Collaboration, M. Amenomori, “Northern sky Galactic Cosmic Ray anisotropy between 10-1000 TeV with the Tibet Air Shower Array,” *Astrophys. J.* 836 no. 2, (2017) 153, arXiv:1701.07144 [astro-ph.HE]

[25] Super-Kamiokande Collaboration, G. Guillian et al., “Observation of the anisotropy of 10-TeV primary cosmic ray nuclei flux with the Super-Kamiokande-I detector,” *Phys. Rev.* D75 (2007) 062003, arXiv:astro-ph/0508468 [astro-ph].
[26] Milagro Collaboration, A. A. Abdo et al., “The Large Scale Cosmic-Ray Anisotropy as Observed with Milagro,” Astrophys. J. 698 (2009) 2121–2130, arXiv:0806.2293 [astro-ph].

[27] EAS-TOP Collaboration, M. Aglietta et al., “Evolution of the cosmic ray anisotropy above 10^{14} eV,” Astrophys. J. 692 (2009) L130–L133, arXiv:0901.2740 [astro-ph.HE].

[28] V. V. Alekseenko et al., “10-100 TeV cosmic ray anisotropy measured at Baksan EAS ‘Carpet’ array,” Nucl. Phys. Proc. Suppl. 196 (2009) 179–182, arXiv:0902.2967 [astro-ph.GA].

[29] IceCube Collaboration, R. Abbasi et al., “Measurement of the Anisotropy of Cosmic-ray Arrival Directions with IceCube,” Astrophys. J. Lett. 718 (2010) L194–L198, arXiv:1005.2960 [astro-ph.HE].

[30] IceCube Collaboration, R. Abbasi et al., “Observation of Anisotropy in the Galactic Cosmic-Ray Arrival Directions at 400 TeV with IceCube,” Astrophys. J. 746 (2012) 33, arXiv:1109.1017 [hep-ex].

[31] IceCube Collaboration, M. G. Aartsen et al., “Observation of Cosmic-Ray Anisotropy with the IceTop Air Shower Array,” Astrophys. J. 765 (2013) 55, arXiv:1210.5278 [astro-ph.HE].

[32] ARGO-YBJ Collaboration, B. Bartoli et al., “ARGO-YBJ Observation of the Large-scale Cosmic ray Anisotropy During the Solar Minimum Between Cycles 23 and 24,” Astrophys. J. 809 no. 1, (2015) 90.

[33] ARGO-YBJ Collaboration, B. Bartoli et al., “Galactic Cosmic-Ray Anisotropy in the Northern Hemisphere from the ARGO-YBJ Experiment during 2008–2012,” Astrophys. J. 861 no. 2, (2018) 93, arXiv:1805.08980 [astro-ph.HE].

[34] Pierre Auger Collaboration, A. Aab et al., “Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above 8 \times 10^{18} eV,” Science 357 no. 6537, (2017) 1266–1270, arXiv:1709.07321 [astro-ph.HE].

[35] HAWC Collaboration, A. U. Abeysekara et al., “Observation of Anisotropy of TeV Cosmic Rays with Two Years of HAWC,” Astrophys. J. 865 no. 1, (2018) 57, arXiv:1805.01847 [astro-ph.HE].

[36] T. K. Gaisser, R. Engel, and E. Resconi, Cosmic Rays and Particle Physics. Cambridge University Press, 2016. http://www.cambridge.org/de/academic/subjects/physics/cosmology-relativity-and-gravitation/cosmic-rays-and-particle-physics-2nd-edition?format=HB

[37] S. Mollerach and E. Roulet, “Progress in high-energy cosmic ray physics,” Prog. Part. Nucl. Phys. 98 (2018) 85–118, arXiv:1710.11155 [astro-ph.HE].
[38] Blümer, J. and Engel, R. and Hörandel, J. R., “Cosmic Rays from the Knee to the Highest Energies,” *Prog. Part. Nucl. Phys.* 63 (2009) 293–338, [arXiv:0904.0725](https://arxiv.org/abs/0904.0725) [astro-ph.HE].

[39] A. Haungs, H. Rebel, and M. Roth, “Energy spectrum and mass composition of high-energy cosmic rays,” *Rept. Prog. Phys.* 66 (2003) 1145–1206.

[40] M. Spurio, “Probes of Multimessenger Astrophysics,” *Astron. Astrophys. Lib.* 9783319968544 (2018) pp.1–591.

[41] W. Hofmann and J. Hinton, “Detectors for high-energy messengers from the Universe,” *Nucl. Instrum. Meth.* A907 (2018) 31–45.

[42] O. Deligny, “Measurements and implications of cosmic ray anisotropies from TeV to trans-EeV energies,” *Astropart. Phys.* 104 (2019) 13–41, [arXiv:1808.03940](https://arxiv.org/abs/1808.03940) [astro-ph.HE].

[43] HAWC, IceCube Collaboration, A. U. Abeysekara *et al.*, “All-Sky Measurement of the Anisotropy of Cosmic Rays at 10 TeV and Mapping of the Local Interstellar Magnetic Field,” *Astrophys. J.* (2018) [arXiv:1812.05682](https://arxiv.org/abs/1812.05682) [astro-ph.HE], [Astrophys. J.871,96(2019)].

[44] M. Ahlers and P. Mertsch, “Origin of Small-Scale Anisotropies in Galactic Cosmic Rays,” *Prog Part Nucl Phys* 94 (2017) 184–216 [arXiv:1612.01873] [astro-ph.HE].

[45] IceCube Collaboration, M. G. Aartsen *et al.*, “Anisotropy in Cosmic-ray Arrival Directions in the Southern Hemisphere Based on six Years of Data From the Icecube Detector,” *Astrophys. J.* 826 no. 2, (2016) 220, [arXiv:1603.01227](https://arxiv.org/abs/1603.01227) [astro-ph.HE].

[46] KASCADE-Grande Collaboration, W. D. Apel *et al.*, “Kneelike structure in the spectrum of the heavy component of cosmic rays observed with KASCADE-Grande,” *Phys. Rev. Lett.* 107 (2011) 171104, [arXiv:1107.5885](https://arxiv.org/abs/1107.5885) [astro-ph.HE].

[47] KASCADE-Grande Collaboration, W. D. Apel *et al.*, “Ankle-like Feature in the Energy Spectrum of Light Elements of Cosmic Rays Observed with KASCADE-Grande,” *Phys. Rev.* D87 (2013) 081101, [arXiv:1304.7114](https://arxiv.org/abs/1304.7114) [astro-ph.HE].

[48] Telescope Array Collaboration, R. Abbasi *et al.*, “The Cosmic-Ray Energy Spectrum between 2 PeV and 2 EeV Observed with the TALE detector in monocular mode,” *Astrophys. J.* 865 no. 1, (2018) 74, [arXiv:1803.01288](https://arxiv.org/abs/1803.01288) [astro-ph.HE].

[49] Pierre Auger Collaboration, P. Abreu *et al.*, “Constraints on the origin of cosmic rays above 10^{18} eV from large scale anisotropy searches in data of the Pierre Auger Observatory,” *Astrophys. J.* 762 (2012) L13, [arXiv:1212.3083](https://arxiv.org/abs/1212.3083) [astro-ph.HE].

[50] T. Abu-Zayyad, D. Ivanov, C. C. H. Jui, J. H. Kim, J. N. Matthews, J. D. Smith, S. B. Thomas, G. B. Thomson, and Z. Zundel, “The Knee and the Second Knee of the Cosmic-Ray Energy Spectrum,” [arXiv:1803.07052](https://arxiv.org/abs/1803.07052) [astro-ph.HE].
[51] S. Mollerach and E. Roulet, “A scenario for the Galactic cosmic rays between the knee and the second-knee,” arXiv:1812.04026 [astro-ph.HE].

[52] S. Thoudam, J. P. Rachen, A. van Vliet, A. Achterberg, S. Buitink, H. Falcke, and J. R. Hörandel, “Cosmic-ray energy spectrum and composition up to the ankle: the case for a second Galactic component,” Astron. Astrophys. 595 (2016) A33, arXiv:1605.03111 [astro-ph.HE].

[53] N. Globus, D. Allard, and E. Parizot, “A complete model of the cosmic ray spectrum and composition across the Galactic to extragalactic transition,” Phys. Rev. D92 no. 2, (2015) 021302, arXiv:1505.01377 [astro-ph.HE].

[54] L. A. Anchordoqui, “Ultra-High-Energy Cosmic Rays,” Phys. Rept. (2019). arXiv:1807.09645 [astro-ph.HE].

[55] Pierre Auger Collaboration, A. Aab et al., “Evidence for a mixed mass composition at the ‘ankle’ in the cosmic-ray spectrum,” Phys. Lett. B762 (2016) 288–295, arXiv:1609.08567 [astro-ph.HE].

[56] P. Blasi, “The Origin of Galactic Cosmic Rays,” Astron. Astrophys. Rev. 21 (2013) 70, arXiv:1311.7346 [astro-ph.HE].

[57] B. Peters, “Primary Cosmic Radiation and Extensive Air Showers,” Il Nuovo Cimento XXII (1961) 800–819.

[58] P. Lipari, “The Concepts of ‘Age’ and ‘Universality’ in Cosmic Ray Showers,” Phys. Rev. D79 (2009) 063001, arXiv:0809.0190 [astro-ph].

[59] S. Lafebre, R. Engel, H. Falcke, J. Horandel, T. Huege, J. Kuijpers, and R. Ulrich, “Universality of electron-positron distributions in extensive air showers,” Astropart. Phys. 31 (2009) 243–254, arXiv:0902.0548 [astro-ph.HE].

[60] KASCADE-Grande Collaboration, W. Apel et al., “KASCADE-Grande measurements of energy spectra for elemental groups of cosmic rays,” Astropart. Phys. 47 (2013) 54–66, arXiv:1306.6283 [astro-ph.HE].

[61] IceCube Collaboration, R. Abbasi et al., “Cosmic Ray Composition and Energy Spectrum from 1-30 PeV Using the 40-String Configuration of IceTop and IceCube,” Astropart. Phys. 42 (2013) 15–32, arXiv:1207.3455 [astro-ph.HE].

[62] Telescope Array Collaboration, R. Abbasi et al., “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,” Astrophys. J. 858 no. 2, (2018) 76, arXiv:1801.09784 [astro-ph.HE].

[63] Pierre Auger Collaboration, P. Abreu et al., “Interpretation of the Depths of Maximum of Extensive Air Showers Measured by the Pierre Auger Observatory,” JCAP 1302 (2013) 026, arXiv:1301.6637 [astro-ph.HE].
[64] R. Ulrich, R. Engel, and M. Unger, “Hadronic Multiparticle Production at Ultra-High Energies and Extensive Air Showers,” *Phys. Rev. D83* (2011) 054026, arXiv:1010.4310.

[65] R. D. Parsons, C. Bleve, S. S. Ostapchenko, and J. Knapp, “Systematic uncertainties in air shower measurements from high-energy hadronic interaction models,” *Astropart. Phys. 34* (2011) 832–839, arXiv:1102.4603 [astro-ph.HE].

[66] D. d’Enterria, R. Engel, T. Pierog, S. Ostapchenko, and K. Werner, “Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics,” *Astropart. Phys. 35* (2011) 98–113, arXiv:1101.5596 [astro-ph.HE].

[67] S. Ostapchenko, “LHC data on inelastic diffraction and uncertainties in the predictions for longitudinal extensive air shower development,” *Phys. Rev. D89* no. 7, (2014) 074009, arXiv:1402.5084 [hep-ph].

[68] Pierre Auger Collaboration, A. Aab et al., “Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory,” *JCAP 1704* no. 04, (2017) 038, arXiv:1612.07155 [astro-ph.HE]. [Erratum: JCAP1803,no.03,E02(2018)].

[69] Pierre Auger Collaboration, A. Aab et al., “Spectral Calibration of the Fluorescence Telescopes of the Pierre Auger Observatory,” *Astropart. Phys. 95* (2017) 44–56, arXiv:1709.01537 [astro-ph.IM].

[70] TAIGA Collaboration, N. Budnev et al., “TAIGA the Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy - present status and perspectives,” *JINST 9* (2014) C09021.

[71] LOPES Collaboration, W. D. Apel et al., “Experimental evidence for the sensitivity of the air-shower radio signal to the longitudinal shower development,” *Phys. Rev. D85* (2012) 071101, arXiv:1203.3971 [astro-ph.IM].

[72] LOPES Collaboration, W. D. Apel et al., “Reconstruction of the energy and depth of maximum of cosmic-ray air-showers from LOPES radio measurements,” *Phys. Rev. D90* no. 6, (2014) 062001, arXiv:1408.2346 [astro-ph.IM].

[73] LOFAR Collaboration, S. Buitink et al., “A large light-mass component of cosmic rays at $10^{17} - 10^{17.5}$ eV from radio observations,” *Nature 531* (2016) 70, arXiv:1603.01594 [astro-ph.HE].

[74] Tunka-Rex Collaboration, P. A. Bezyazeekov et al., “Radio measurements of the energy and the depth of the shower maximum of cosmic-ray air showers by Tunka-Rex,” *JCAP 1601* no. 01, (2016) 052, arXiv:1509.05652 [hep-ex].

[75] T. Huege, “Radio detection of cosmic ray air showers in the digital era,” *Phys. Rept. 620* (2016) 1–52, arXiv:1601.07426 [astro-ph.IM].

[76] F. G. Schröder, “Radio detection of Cosmic-Ray Air Showers and High-Energy Neutrinos,” *Prog. Part. Nucl. Phys. 93* (2017) 1–68, arXiv:1607.08781 [astro-ph.IM].
[77] A. Balagopal V. et al., “Search for PeVatrons at the Galactic Center using a radio air-shower array at the South Pole,” EPJ C 78 (2018) 111.

[78] M. Erdmann, J. Glombitza, and D. Walz, “A Deep Learning-based Reconstruction of Cosmic Ray-induced Air Showers,” Astropart. Phys. 97 (2018) 46–53, arXiv:1708.00647 [astro-ph.IM].

[79] M. Erdmann, F. Schlueter, and R. Smida, “Classification and Recovery of Radio Signals from Cosmic Ray Induced Air Showers with Deep Learning,” arXiv:1901.04079 [astro-ph.IM].

[80] LOPES Collaboration, H. Falcke et al., “Detection and imaging of atmospheric radio flashes from cosmic ray air showers,” Nature 435 (2005) 313–316, arXiv:astro-ph/0505383 [astro-ph].

[81] CODALEMA Collaboration, D. Ardouin et al., “Geomagnetic origin of the radio emission from cosmic ray induced air showers observed by CODALEMA,” Astropart. Phys. 31 (2009) 192–200, arXiv:0901.4502 [astro-ph.HE].

[82] Pierre Auger Collaboration, P. Abreu et al., “Results of a Self-Triggered Prototype System for Radio-Detection of Extensive Air Showers at the Pierre Auger Observatory,” JINST 7 (2012) P11023, arXiv:1211.0572 [astro-ph.HE].

[83] LOFAR Collaboration, P. Schellart et al., “Detecting cosmic rays with the LOFAR radio telescope,” Astron. Astrophys. 560 (2013) A98, arXiv:1311.1399 [astro-ph.HE].

[84] Tunka-Rex Collaboration, P. A. Bezyazeekov et al., “Measurement of cosmic-ray air showers with the Tunka Radio Extension (Tunka-Rex),” Nucl. Instrum. Meth. A802 (2015) 89–96, arXiv:1509.08624 [astro-ph.IM].

[85] CROME Collaboration, R. Smida et al., “First Experimental Characterization of Microwave Emission from Cosmic Ray Air Showers,” Physical Review Letters 113 no. 22, (2014) 221101, arXiv:1410.8291 [astro-ph.IM].

[86] Tunka-Rex, LOPES Collaboration, W. D. Apel et al., “A comparison of the cosmic-ray energy scales of Tunka-133 and KASCADE-Grande via their radio extensions Tunka-Rex and LOPES,” Phys. Lett. B763 (2016) 179–185, arXiv:1610.08343 [astro-ph.IM].

[87] Pierre Auger Collaboration, A. Aab et al., “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 no. 24, (2016) 241101, arXiv:1605.02564 [astro-ph.HE].

[88] M. Gottowik, C. Glaser, T. Huege, and J. Rautenberg, “Determination of the absolute energy scale of extensive air showers via radio emission: systematic uncertainty of underlying first-principle calculations,” Astropart. Phys. 103 (2018) 87–93, arXiv:1712.07442 [astro-ph.HE].
Y. Bai, A. J. Barger, V. Barger, R. Lu, A. D. Peterson, and J. Salvado, “Neutrino Lighthouse at Sagittarius A*,” *Phys. Rev.* **D90** no. 6, (2014) 063012, arXiv:1407.2243 [astro-ph.HE].

L. A. Anchordoqui, “Neutrino lighthouse powered by Sagittarius A* disk dynamo,” *Phys. Rev.* **D94** (2016) 023010, arXiv:1606.01816 [astro-ph.HE].

A. De Angelis and M. Mallamaci, “Gamma-ray astrophysics,” *European Physical Journal Plus* **133** (2018) 324, arXiv:1805.05642 [astro-ph.HE].

S. Funk, “Ground- and space-based gamma-ray astronomy,” *Annual Review of Nuclear and Particle Science* **65** no. 1, (2015) 245–277, https://doi.org/10.1146/annurev-nucl-102014-022036.

N. Park, “Status of ground based gamma-ray observations,” arXiv e-prints (2018), arXiv:1808.10495 [astro-ph.HE].

B. Degrange and G. Fontaine, “Introduction to high-energy gamma-ray astronomy,” *Comptes Rendus Physique* **16** (2015) 587–599, arXiv:1604.05488 [astro-ph.HE].

M. de Naurois and D. Mazin, “Ground-based detectors in very-high-energy gamma-ray astronomy,” *Comptes Rendus Physique* **16** (2015) 610–627, arXiv:1511.00463 [astro-ph.IM].

J. Holder, “Atmospheric Cherenkov Gamma-ray Telescopes,” arXiv e-prints (2015), arXiv:1510.05675 [astro-ph.IM].

T. K. Gaisser, “Atmospheric Neutrinos,” *J. Phys. Conf. Ser.* **718** no. 5, (2016) 052014, arXiv:1605.03073 [astro-ph.HE].

D. Gaggero, D. Grasso, A. Marinelli, A. Urbano, and M. Valli, “The gamma-ray and neutrino sky: A consistent picture of Fermi-LAT, Milagro, and IceCube results,” *Astrophys. J.* **815** no. 2, (2015) L25, arXiv:1504.00227 [astro-ph.HE].

CASA-MIA Collaboration, M. C. Chantell et al., “Limits on the isotropic diffuse flux of ultrahigh-energy gamma radiation,” *Phys. Rev. Lett.* **79** (1997) 1805–1808, arXiv:astro-ph/9705246 [astro-ph].

KASCADE-Grande Collaboration, W. D. Apel et al., “KASCADE-Grande Limits on the Isotropic Diffuse Gamma-Ray Flux between 100 TeV and 1 EeV,” *Astrophys. J.* **848** (2017) L1, arXiv:1710.02889 [astro-ph.HE].

ANTARES, IceCube Collaboration, A. Albert et al., “Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes,” *Astrophys. J.* **868** (2018) L20, arXiv:1808.03531 [astro-ph.HE].

H. Pandya, Z. Griffith for the IceCube Collaboration, “Search for diffuse gamma-ray emission from the Galactic plane with IceCube,” *PoS* **ICRC2017** (2018) 705.
[103] **Fermi-LAT** Collaboration, M. Ackermann et al., “The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV,” *Astrophys. J.* **799** (2015) 86, arXiv:1410.3696 [astro-ph.HE].

[104] **IceCube** Collaboration, M. G. Aartsen et al., “Astrophysical neutrinos and cosmic rays observed by IceCube,” *Adv. Space Res.* **62** (2018) 2902–2930, arXiv:1701.03731 [astro-ph.HE].

[105] K. Murase, D. Guetta, and M. Ahlers, “Hidden Cosmic-Ray Accelerators as an Origin of TeV-PeV Cosmic Neutrinos,” *Phys. Rev. Lett.* **116** no. 7, (2016) 071101, arXiv:1509.00805 [astro-ph.HE].

[106] **IceCube** Collaboration, M. G. Aartsen et al., “Constraints on Galactic Neutrino Emission with Seven Years of IceCube Data,” *Astrophys. J.* **849** no. 1, (2017) 67, arXiv:1707.03416 [astro-ph.HE].

[107] A. Neronov, M. Kachelrieß, and D. V. Semikoz, “Multimessenger gamma-ray counterpart of the IceCube neutrino signal,” *Phys. Rev.* **D98** no. 2, (2018) 023004, arXiv:1802.09983 [astro-ph.HE].

[108] T. Huege et al., “High-precision measurements of extensive air showers with the SKA,” *PoS ICRC2015* (2016) 309, arXiv:1508.03465 [astro-ph.IM].

[109] **GRAND** Collaboration, J. Alvarez-Muñiz et al., “The Giant Radio Array for Neutrino Detection (GRAND): Science and Design,” *Sci. China Phys. Mech. Astron.* accepted (2019), arXiv:1810.09994 [astro-ph.HE].

[110] **HAWC** Collaboration, M. DuVernois, “Detector Considerations for a HAWC Southern Observatory,” *PoS ICRC2015* (2016) 967, arXiv:1508.03669 [astro-ph.IM].

[111] He, Huihai for the **LHAASO** Collaboration, “Design of the lhaaso detectors,” *Radiation Detection Technology and Methods* **2** no. 1, (2018) 7, https://doi.org/10.1007/s41605-018-0037-3.

[112] **IceCube** Collaboration, R. Abbasi et al., “IceTop: The surface component of IceCube,” *Nucl. Instrum. Meth.* **A700** (2013) 188–220, arXiv:1207.6326 [astro-ph.IM].

[113] **IceCube** Collaboration, M. G. Aartsen et al., “Search for Galactic PeV Gamma Rays with the IceCube Neutrino Observatory.” *Phys. Rev.* **D87** no. 6, (2013) 062002, arXiv:1210.7992 [astro-ph.HE].

[114] T. Huber for the **IceCube-Gen2** Collaboration, “The IceTop Scintillator Upgrade,” *PoS ICRC2017* (2018) 401.

[115] F.G. Schröder for the **IceCube-Gen2** Collaboration, “Physics Potential of a Radio Surface Array at the South Pole (ARENA 2018),” in *Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2018)* Catania, Italy, June 12-15, 2018. 2018. arXiv:1811.00599 [astro-ph.IM].
[116] A. Haungs for the IceCube Collaboration, “A Scintillator and Radio Enhancement of the IceCube Surface Detector Array,” in Ultra High Energy Cosmic Rays 2018 (UHECR 2018) Paris, France, Oct. 8-12, 2018. 2018. arXiv:1903.04117 [astro-ph.IM]

[117] J. Auffenberg for the IceCube-Gen2 Collaboration, “IceAct: Imaging Air Cherenkov Telescopes with SiPMs at the South Pole for IceCube-Gen2,” PoS ICRC2017 (2018) 1055.

[118] IceCube-Gen2 Collaboration, “The IceCube Neutrino Observatory,”
arXiv:1710.01207 [astro-ph.IM]

[119] Pierre Auger Collaboration, A. Aab et al., “The Pierre Auger Cosmic Ray Observatory,” Nucl. Instrum. Meth. A798 (2015) 172–213, arXiv:1502.01323 [astro-ph.IM]

[120] S. Ogio for the Telescope Array Collaboration, “Telescope Array Low energy Extension: TALE,” JPS Conf. Proc. 19 (2018) 011026

[121] D. Bergman, Y. Tsunesada, J. F. Krizmanic, and Y. Omura, “jNICHE: Prototype detectors of a non-imaging Cherenkov array at the TA site,” PoS ICRC2017 (2018) 415

[122] Pierre Auger Collaboration, A. Aab et al., “Prototype muon detectors for the AMIGA component of the Pierre Auger Observatory,” JINST 11 no. 02, (2016) P02012, arXiv:1605.01625 [physics.ins-det]

[123] Pierre Auger Collaboration, A. Aab et al., “The Pierre Auger Observatory Upgrade - Preliminary Design Report,” arXiv:1604.03637 [astro-ph.IM].

[124] Pierre Auger Collaboration, A. Aab et al., “Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory,” Phys. Rev. D93 no. 12, (2016) 122005, arXiv:1508.04267 [astro-ph.HE].