Snowmass2021 - Letter of Interest

Radio Detection of Cosmic Rays

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (IF10) Radio Detection
■ (NF4) Neutrinos from natural sources

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Abstract:

The radio technique for cosmic-ray air showers has recently reached maturity and is now applicable to the open questions regarding the origin of the highest-energy cosmic rays and the particle physics in air showers. Arrays of digital radio antennas provide for accurate measurements of the arrival direction, the energy content, and atmospheric depth of the electromagnetic component of air showers. Thanks to recent developments in the analysis and calibration techniques as well as in the theoretical understanding of the radio emission, the accuracy achieved starts to be competitive with the leading optical techniques, but with the radio technique not being restricted to clear nights. Stand-alone detectors may provide unprecedented exposure for affordable cost, and do require further R&D. Hybrid arrays featuring particle (in particular muons) and radio detection promise to enhance the total measurement accuracy beyond the state of the art – a key need for future progress in many areas of cosmic-ray physics, such as the search for the most energetic Galactic and extragalactic sources as well as understanding the muon problem of hadronic interactions at energies beyond the reach of the LHC. Finally, the radio technique can be used to search for ultra-high-energy neutrinos, photons, and new physics.

Introduction

With a number of experimental designs, radio detection of cosmic rays can be a key contributor to many scientific questions in high-energy particle astrophysics which all require higher statistics and/or higher measurement accuracy of extensive air showers[1–7]. The development of the radio technique for cosmic rays made significant progress during the last decade[8;9]. The theoretical understanding of the radio emission by air showers has matured, and state-of-the-art simulation codes[10–13] are consistent with measurements by current antenna arrays[14–16]. Several hybrid arrays of radio antennas and particle detectors operate reliably, and provide precise measurements of the most important shower parameters: the arrival direction[17–19], the energy[20–23], and the atmospheric depth of the shower maximum, $X_{\max}$[16;24–26], which is sensitive to the mass of the primary particle. The radio technique offers the benefit of providing calorimetric energy and $X_{\max}$ measurements around the clock, not being restricted to clear nights as traditional optical techniques. In particular for self-triggering, the development of stand-alone radio arrays[27–31] needs to be continued during the next decade[32–35]. Nevertheless, with existing and planned hybrid arrays, the radio technique can already make an important contribution to open questions in cosmic-ray and air-shower physics[1;2;36].

High-Energy Physics in Cosmic-Ray Air Showers

State-of-the-art hadronic interaction models exhibit puzzling deficiencies and it is not understood, in particular, whether they are related to new physics. The most prominent problem is a deficit in the predicted muon content in showers at energies $\gtrsim 10^{17}$ eV[37], which is where the radio technique becomes efficient. In particular, radio arrays feature an accurate calorimetric measurement of the size of the electromagnetic shower component[21;38;39]. In contrast to the particles of the electromagnetic component, the radio emission is not absorbed in the atmosphere. Since also the high-energy muons of air showers mostly survive until they reach the ground, a radio-muon hybrid detector is ideal to study the muon problem of hadronic interaction models even for inclined, fully developed showers[40]. This may fix one of the main problems in experimental tests of hadronic interaction models. Due to shower-to-shower fluctuations, only statistical distributions can be compared to models, thus, losing testing power by averaging over the mixed composition of primary particles. With $X_{\max}$[23;24;41] and the energy constrained by radio, and the per-event mass separation of radio-muon hybrid arrays (Fig. 1), this problem can be reduced. While this in principle can also be done by combining fluorescence and muon detectors, a hybrid array of radio and particle detectors will be operational 24/7 and provide the required statistics at the highest energies at much lower cost.

Identification of the Primary Particle

The same features useful for the test of hadronic interaction models (calorimetric measurement and sensitivity to $X_{\max}$), can also be utilized for more accurate measurements of the mass composition of cosmic rays, which is essential for many scientific questions in particle astrophysics. Since recent measurements confirmed that cosmic rays consist of a mixture of protons and nuclei of different masses varying throughout the complete probed energy range[43;44], mass sensitivity has become a key demand of cosmic-ray observatories. Due to statistical shower-to-shower fluctuations, improving the precision of a single parameter ($X_{\max}$) will provide only a limited improvement for the accuracy of the mass. However, a boost in accuracy for the per-event estimation of the mass is expected by combining $X_{\max}$ with the orthogonal mass sensitivity of the muon content of the same air shower (Fig. 1). This will enable improved predictions for various types of cosmic-ray models, such as scenarios of their origin or for their propagation in extragalactic and Galactic space. It will, thus, help to restrict scenarios for the yet unknown origin of the most energetic Galactic (presumably up to about 10^{18} eV) and extragalactic cosmic rays (up to at least a few 10^{20} eV).

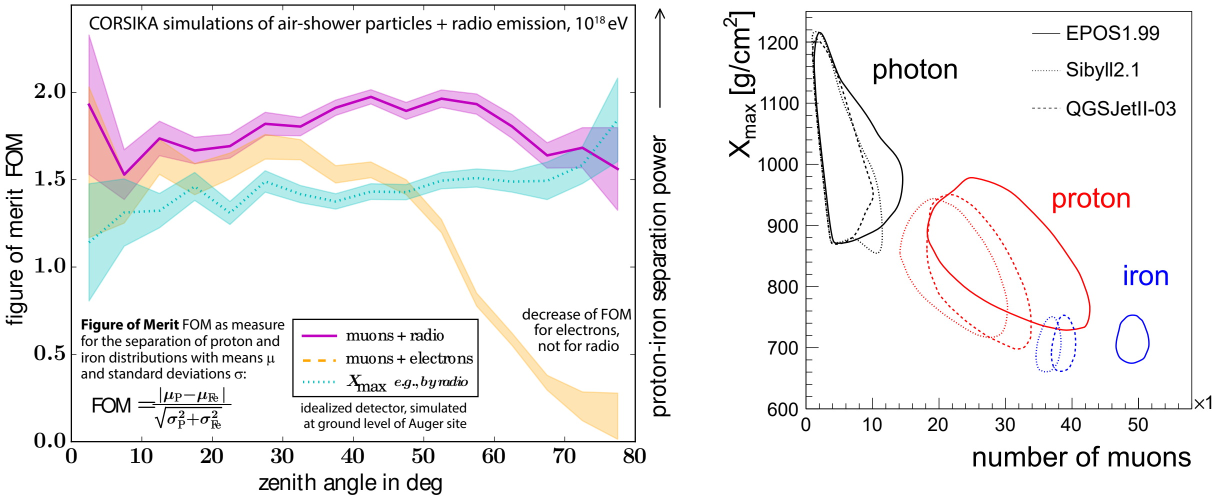

Figure 1: Left: Figure of merit as a measure for the mass-separation power over zenith angle for the combinations of muon detectors with either radio or electron detectors on ground and for X_{max}. Combining radio and muon detectors brings the potential of unprecedented accuracy for the mass of the primary particle[40]. Right: 90 % containment contours of the muon number and the depth of the shower maximum, X_{max}, at 10^{19} eV for various hadronic interaction models. For all interaction models, the simultaneous measurement of the muon number and X_{max} will improve the accuracy on the type of the primary particle[42].

A better measurement of the mass composition and absolute energy scale by radio[21;45] will also have important benefits for multi-messenger particle astrophysics. Next to hadronic interaction models, these are the main uncertainties in the calculation of atmospheric lepton fluxes relevant for high-energy neutrino observatories[46]. Radio detection of air showers can contribute to understanding the flux of PeV muons[47] and the fraction of atmospheric neutrinos originating from nuclei instead of protons[48;49]. The per-event mass sensitivity from combining radio and muon detection in hybrid arrays will help us to search for ultra-high-energy sources, e.g., by the measurement of expected mass-dependent anisotropies or proton-enriched cosmic-ray astronomy[50–52]. Especially with the high angular resolution radio arrays can provide, the discovery of ultra-high-energy photons (photon showers are muon-poor, but have a strong radio signal) may enable a direct identification of the sources and tests of fundamental physics related to these photons. Understanding the sources is essential for any solid investigation of the high-energy physics in these sources and of the high-energy interactions during the propagation of cosmic rays.

Future of the Radio Technique for Air Showers

Last but not least, there are many other applications of the radio detection technique relevant for high-energy physics. Very dense antenna arrays can measure the radio emission in unprecedented detail enabling a more precise study of the development of air showers[53]. Stand-alone radio detectors have the potential for apertures beyond the state-of-the-art ($\sim 10,000\,\mathrm{km^2 sr}$), and can be realized either by huge arrays[33] or by observation from mountains[35;54]. This can enable measurements at ultra-high-energies with higher statistics and at higher energies than achieved today, and will provide discovery potential for new physics[3;4], EeV photons and neutrinos (see dedicated LOI[6]). Radio detection from balloons[34;55] has a lower exposure, but provides discovery potential for new physics by looking for upward-going events caused by particles penetrating the Earth[56;57]. Therefore, it is essential to continue ongoing developments for such stand-alone approaches as a long-term strategy, while radio-muon hybrid arrays promise to provide essential progress in air-shower and cosmic-ray physics already during the next decade.

References

[1] F. Sarazin *et al.*, "What is the nature and origin of the highest-energy particles in the universe?," *Bull. Am. Astron. Soc.* **51** no. 3, (2019) 93, `arXiv:1903.04063 [astro-ph.HE]`.

[2] F. G. Schröder *et al.*, "High-Energy Galactic Cosmic Rays (Astro2020 Science White Paper)," *Bull. Am. Astron. Soc.* **51** (3, 2019) 131, `arXiv:1903.07713 [astro-ph.HE]`.

[3] J. Hörandel for the Pierre Auger Collaboration, "A next-generation cosmic-ray detector to study the physics and properties of the highest-energy particles in Nature," *Snowmass 2021, Primary frontiers:* **CF7** (2020) .

[4] Olivier Deligny for the Pierre Auger Collaboration, "Hunting super-heavy dark matter with ultra-high energy photons," *Snowmass 2021, Primary frontiers:* **CF1, CF7** (2020) .

[5] D. Soldin *et al.*, "Origin of the Muon Excess in Cosmic Ray Air Showers," *Snowmass 2021, Primary frontiers:* **CF7, EF6, EF7** (2020) .

[6] M. Bustamante *et al.*, "Snowmass 2021 Letter of Interest: Ultra-High-Energy Neutrinos," *Snowmass 2021, Primary frontiers:* **NF04, CF7** (2020) .

[7] A. Haungs *et al.*, "Highest Energy Galactic Cosmic Rays," *Snowmass 2021, Primary frontier:* **CF7** (2020) .

[8] T. Huege, "Radio detection of cosmic ray air showers in the digital era," *Physics Reports* **620** (2016) 1 – 52. `http://www.sciencedirect.com/science/article/pii/S0370157316000636`.

[9] 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]`.

[10] T. Huege, M. Ludwig, and C. James, "Simulating radio emission from air showers with CoREAS," *AIP Conf. Proc.* **1535** no. 1, (2013) 128, `arXiv:1301.2132 [astro-ph.HE]`.

[11] J. Alvarez-Muniz, J. Carvalho, Washington R., and E. Zas, "Monte Carlo simulations of radio pulses in atmospheric showers using ZHAireS," *Astropart. Phys.* **35** (2012) 325–341, `arXiv:1107.1189 [astro-ph.HE]`.

[12] K. D. de Vries, O. Scholten, and K. Werner, "The EVA code; macroscopic modeling of radio emission from air showers based on full MC simulations including a realistic index of refraction," *AIP Conf. Proc.* **1535** no. 1, (2013) 133.

[13] F. Gaté, B. Revenu, D. García-Fernández, V. Marin, R. Dallier, A. Escudié, and L. Martin, "Computing the electric field from extensive air showers using a realistic description of the atmosphere," *Astropart. Phys.* **98** (2018) 38–51, `arXiv:1808.07318 [astro-ph.HE]`.

[14] **LOPES** Collaboration, W. Apel *et al.*, "Improved absolute calibration of LOPES measurements and its impact on the comparison with REAS 3.11 and CoREAS simulations," *Astropart. Phys.* **75** (2016) 72–74, `arXiv:1507.07389 [astro-ph.HE]`.

[15] **Tunka-Rex** Collaboration, P. Bezyazeekov *et al.*, "Measurement of cosmic-ray air showers with the Tunka Radio Extension (Tunka-Rex)," *Nucl. Instrum. Meth. A* **802** (2015) 89–96, `arXiv:1509.08624 [astro-ph.IM]`.

[16] **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]`.

[17] **LOPES** Collaboration, F. G. Schröder *et al.*, "Interferometric Radio Measurements of Air Showers with LOPES: Final Results," *PoS* **ICRC2017** (2018) 458, `arXiv:1708.00626 [astro-ph.HE]`.

[18] **LOFAR** Collaboration, A. Corstanje *et al.*, "The shape of the radio wavefront of extensive air showers as measured with LOFAR," *Astropart. Phys.* **61** (2015) 22–31, `arXiv:1404.3907 [astro-ph.HE]`.

[19] **LOPES** Collaboration, W. Apel *et al.*, "The wavefront of the radio signal emitted by cosmic ray air showers," *JCAP* **09** (2014) 025, `arXiv:1404.3283 [hep-ex]`.

[20] **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]`.

[21] **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]`.

[22] **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]`.

[23] **Tunka-Rex** Collaboration, P. Bezyazeekov *et al.*, "Radio measurements of the energy and the depth of the shower maximum of cosmic-ray air showers by Tunka-Rex," *JCAP* **01** (2016) 052, `arXiv:1509.05652 [hep-ex]`.

[24] **LOFAR** Collaboration, S. Buitink *et al.*, "Method for high precision reconstruction of air shower X_{max} using two-dimensional radio intensity profiles," *Phys. Rev. D* **90** no. 8, (2014) 082003, `arXiv:1408.7001 [astro-ph.IM]`.

[25] **Tunka-Rex** Collaboration, P. A. Bezyazeekov *et al.*, "Reconstruction of cosmic ray air showers with Tunka-Rex data using template fitting of radio pulses," *Phys. Rev.* **D97** no. 12, (2018) 122004, `arXiv:1803.06862 [astro-ph.IM]`.

[26] **Pierre Auger** Collaboration, E. M. Holt, "Recent Results of the Auger Engineering Radio Array (AERA)," *PoS* **ICRC2017** (2018) 492.

[27] **CODALEMA** Collaboration, B. Revenu *et al.*, "Current status of the CODALEMA/EXTASIS experiments," *J. Phys. Conf. Ser.* **1181** no. 1, (2019) 012029.

[28] **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]`.

[29] **TREND** Collaboration, D. Charrier *et al.*, "Autonomous radio detection of air showers with the TREND50 antenna array," *Astropart. Phys.* **110** (2019) 15–29, `arXiv:1810.03070 [astro-ph.HE]`.

[30] Z. Szadkowski, "Least Mean Squares Filters Suppressing the Radio-Frequency Interference in AERA Cosmic Ray Radio Detection," *IEEE Trans. Nucl. Sci.* **67** no. 1, (2020) 405–413.

[31] R. Monroe *et al.*, "Self-triggered radio detection and identification of cosmic air showers with the OVRO-LWA," *Nucl. Instrum. Meth. A* **953** (2020) 163086, `arXiv:1907.10193 [astro-ph.IM]`.

[32] **ARIANNA** Collaboration, S. Barwick *et al.*, "Radio detection of air showers with the ARIANNA experiment on the Ross Ice Shelf," *Astropart. Phys.* **90** (2017) 50–68, `arXiv:1612.04473 [astro-ph.IM]`.

[33] **GRAND** Collaboration, J. Álvarez Muñiz *et al.*, "The Giant Radio Array for Neutrino Detection (GRAND): Science and Design," *Sci. China Phys. Mech. Astron.* **63** no. 1, (2020) 219501, `arXiv:1810.09994 [astro-ph.HE]`.

[34] **ANITA** Collaboration, C. Deaconu, "Searches for Ultra-High Energy Neutrinos with ANITA," *PoS* **ICRC2019** (2020) 867, `arXiv:1908.00923 [astro-ph.HE]`.

[35] S. Wissel *et al.*, "Prospects for High-Elevation Radio Detection of $>$ 100 PeV Tau Neutrinos," `arXiv:2004.12718 [astro-ph.IM]`.

[36] R. Alves Batista *et al.*, "Open Questions in Cosmic-Ray Research at Ultrahigh Energies," *Front. Astron. Space Sci.* **6** (2019) 23, `arXiv:1903.06714 [astro-ph.HE]`.

[37] **EAS-MSU, IceCube, KASCADE Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array** Collaboration, L. Cazon, "Working Group Report on the Combined Analysis of Muon Density Measurements from Eight Air Shower Experiments," *PoS* **ICRC2019** (2020) 214, `arXiv:2001.07508 [astro-ph.HE]`.

[38] C. Glaser, M. Erdmann, J. R. Hörandel, T. Huege, and J. Schulz, "Simulation of Radiation Energy Release in Air Showers," *JCAP* **09** (2016) 024, `arXiv:1606.01641 [astro-ph.HE]`.

[39] 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]`.

[40] E. M. Holt, F. G. Schröder, and A. Haungs, "Enhancing the cosmic-ray mass sensitivity of air-shower arrays by combining radio and muon detectors," *Eur. Phys. J. C* **79** no. 5, (2019) 371, `arXiv:1905.01409 [astro-ph.HE]`.

[41] H. Schoorlemmer and W. R. Carvalho, "Radio interferometry applied to the observation of cosmic-ray induced extensive air showers," `arXiv:2006.10348 [astro-ph.HE]`.

[42] 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]`.

[43] 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`.

[44] F. G. Schröder, "News from Cosmic Ray Air Showers (ICRC 2019 – Cosmic Ray Indirect Rapport)," *PoS* **ICRC2019** (2020) 030, `arXiv:1910.03721 [astro-ph.HE]`.

[45] **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]`.

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

[47] D. García-Fernández, C. Glaser, and A. Nelles, “The signatures of secondary leptons in radio-neutrino detectors in ice,” `arXiv:2003.13442 [astro-ph.HE]`.

[48] **IceCube** Collaboration, A. Haungs, “A Scintillator and Radio Enhancement of the IceCube Surface Detector Array,” *EPJ Web Conf.* **210** (2019) 06009, `arXiv:1903.04117 [astro-ph.IM]`.

[49] **IceCube** Collaboration, F. G. Schröder, “Science Case of a Scintillator and Radio Surface Array at IceCube,” *PoS* **ICRC2019** (2020) 418, `arXiv:1908.11469 [astro-ph.HE]`.

[50] **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]`.

[51] **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]`.

[52] **Pierre Auger** Collaboration, A. Castellina, “AugerPrime: the Pierre Auger Observatory Upgrade,” *EPJ Web Conf.* **210** (2019) 06002, `arXiv:1905.04472 [astro-ph.HE]`.

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

[54] **TAROGE** Collaboration, J. Nam *et al.*, “Design and implementation of the TAROGE experiment,” *Int. J. Mod. Phys. D* **25** no. 13, (2016) 1645013.

[55] **ANITA** Collaboration, H. Schoorlemmer *et al.*, “Energy and Flux Measurements of Ultra-High Energy Cosmic Rays Observed During the First ANITA Flight,” *Astropart. Phys.* **77** (2016) 32–43, `arXiv:1506.05396 [astro-ph.HE]`.

[56] **ANITA** Collaboration, P. Gorham *et al.*, “Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA,” *Phys. Rev. Lett.* **121** no. 16, (2018) 161102, `arXiv:1803.05088 [astro-ph.HE]`.

[57] **ANITA** Collaboration, P. Gorham *et al.*, “Ultra-high Energy Air Showers Observed by ANITA-IV,” `arXiv:2008.05690 [astro-ph.HE]`.

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