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Magnetically induced anisotropies in the arrival directions of ultra-high-energy cosmic rays from nearby radio galaxies

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Abstract. Ultra-high-energy cosmic rays (UHECR) are charged particles with energy above 10^{18} eV (1 EeV). Although they were first measured in the 1960s, their origin remains one of the major conundrums in astrophysics, since their sources and acceleration mechanisms are unknown. The difficulty in identifying the sources comes from the deflections caused by the galactic and extragalactic magnetic fields, whose structure and intensity are poorly constrained. Currently, active galactic nuclei (AGNs) have been considered potential candidates for sources of UHECR. The radio galaxies Centaurus A, Virgo A, and Fornax A constitute the closest AGNs known. In this work, detailed simulations of the arrival directions of UHECR are performed under the assumption of strong and structured extragalactic magnetic field (EGMF) models. Particles leaving the radio galaxies Centaurus A, Virgo A, and Fornax A are propagated to Earth using the CRPropa 3 framework. The simulated arrival directions map is compared to the dipole and hotspots published by the Pierre Auger and Telescope Array Collaborations. The dominance of the EGMF structure in the arrival directions of events generated in local sources is shown. Evidence that these three sources contribute to an excess of events in the direction of the three detected hotspots is presented. The dipole signal of events with energy above 32 EeV, published by the Pierre Auger Collaboration, can be reproduced considering the events coming from these three sources.

Resumo. Raios cósmicos de altíssima energia são partículas carregadas com energia acima de 10^{18} eV. Embora tenham sido detectados nos anos 1960, sua origem permanece um dos maiores mistérios em astrofísicas, visto que suas fontes e mecanismos de aceleração são desconhecidos. A dificuldade em identificar as fontes ocorre pelas deflecções causadas pelos campos magnéticos galáctico e extragaláctico, cuja estrutura e intensidade são pouco conhecidas. Atualmente, núcleos ativos de galáxias (AGNs) tem sido considerados potenciais candidatos à fontes de UHECR. As radio galáxias Centaurus A, Virgo A e Fornax A são os principais AGNs conhecidos. Neste trabalho, simulações detalhadas das direções de chegada de UHECR são realizadas considerando modelos de campos magnéticos extragalácticos intensos e estruturados. As partículas partem de Centaurus A, Virgo A e Fornax A e são propagadas até a Terra usando o pacote CRPropa3. Os mapas de direção de chegada obtidos das simulações são comparados com os dados de direção do dipolo e hotspots publicados pelas colaborações dos observatórios Pierre Auger e Telescope Array. Mostramos a importância da estrutura do EGMF nas direções de chegada dos eventos gerados pelas fontes locais. Indicamos a possibilidade destas três fontes contribuirem para os hotspots. O sinal do dipolo de eventos com energia acima de 32 EeV, publicado pela colaboração Pierre Auger, pode ser reproduzido considerando apenas os eventos vindo destas três fontes.

Keywords. Astroparticle physics – Galaxies: active – ISM: magnetic fields

1. Introduction

Ultra-high-energy cosmic rays (UHECR) are charged particles with energy above 10^{18} eV (1 EeV). Its existence has been known for over fifty years (Linsley 1963), but the sources and acceleration mechanisms of these particles remain unknown (Alves Batista et al. 2019). Currently, the Pierre Auger (The Pierre Auger Collaboration 2015) and the Telescope Array (The Telescope Array Collaboration 2008) Observatories have significantly improved our knowledge of these particles. Studies of the arrival direction of UHECR had detected three regions with a relative excess of events (hotspots): two regions in the Pierre Auger Observatory data (The Pierre Auger Collaboration 2018a) and one region in the Telescope Array data (The Telescope Array Collaboration 2014). A small level of large-scale anisotropy was also detected in the Pierre Auger Observatory data (The Pierre Auger Collaboration 2017, 2018b). This anisotropy has the form of a dipolar modulation in the arrival directions of UHECR. The interpretations of the dipole signal favor extragalactic sources for UHECR (The Pierre Auger Collaboration 2017).

The main challenges for the source identification from the arrival direction signals are related to the deflections caused by the galactic and extragalactic magnetic fields (Sigl et al. 2004; Tanco 2001, 1998; Lee et al. 1995; Lang et al. 2020; Erdmann et al. 2016). Little information is obtained experimentally about the strength and structure of the extragalactic magnetic field (EGMF), and computational simulations have been used to infer more properties of the EGMF (Subramanian 2016; Sigl et al. 2003; Hackstein et al. 2018). The galactic magnetic field (GMF) is more constrained, and observationaly driven models have been developed (Sun, X. H. et al. 2008; Jansson & Farrar 2012a,b; Pshirkov et al. 2011).

During the propagation from the source to the Earth, interactions with background photons remove energy and change the composition of the UHECR. These processes are energy-dependent and limit the maximal distance of the sources, indicating the need for nearby sources of UHECR (Zatsepin & Kuz'min 1966; Greisen 1966; Taylor et al. 2011; Lang et al. 2020). Nearby sources are needed to explain the arrival direction data, the energy spectrum, and composition measurements (Taylor et al. 2011; Lang et al. 2020, 2021).

Radio galaxies have been considered prime source candidates (Ginzburg & Syrovatskii 1963; Matthews et al. 2019; Bell et al. 2018; Eichmann et al. 2018a; Rachen 2008; Romero et al. 1996; Norman et al. 1995). Among the nearby radio galaxies, Centaurus A (Cen A), Virgo A (Vir A), and Fornax A (For A) are the most powerful (van Velzen et al. 2012). The combination of high radio power and proximity makes them strong candidates for dominating the UHECR sky. This work focus on the arrival directions signals that can be produced by Cen A, Vir A, and For A in the hypothesis that these three radio galaxies dominate the UHECR flux. The hotspot and dipole signal obtained from computational simulations are compared to the data published by the Pierre Auger and Telescope Array Collaborations.

2. Method

The UHECR propagation in the extragalactic environment was simulated using the CRPropa3 framework (Batista et al. 2016). The following conditions were imposed: (a) from each source was injected 10^8 events of each proton (p), He, N, Si, and Fe nuclei; (b) the events are isotropically emitted by the sources; (c) the energy spectra follow a power-law in energy with spectral index -1 with energies between 8 and 1000 EeV; (d) the considered interactions with the photon background (cosmic microwave background and extragalactic background light from Gilmore et al. (2012)) was e^+e^- pair production, pion photoproduction, and photodisintegration; (e) the simulation includes nuclear decay and adiabatic losses.

The extragalactic magnetic field models developed by Hackstein et al. (Hackstein et al. 2018) were employed in the simulations. We select representative models so that a wide range of field intensity and level of structure of the EGMF could be covered: AstrophysicalR (AstroR), Primordial (Prim), and Primordial2R (Prim2R).

Energy losses can be ignored in the interior of the Milky Way since the Galaxy size ($\sim$ 30 kpc) is small compared to the distance to extragalactic sources ($\sim$ Mpc). The galactic magnetic field model of Jansson & Farrar (Jansson & Farrar 2012a,b) was used, including both the regular and random components. The effect of the GMF on the arrival directions was considered using the GalacticLens module of CRPropa 3 (Batista et al. 2016).

The simulation of one particle ends if it reaches a distance twice the source-Earth distance or hit the observer sphere, located at the Milky Way. The observer sphere has a radius $r_{obs} = D\sin(1^\circ)$, where D =source distance, with a minimum value of 100 kpc. After the detection, each particle receives an energy-dependent weight to generate the spectrum of interest (Eichmann et al. 2018b), and r_{obs}^{-2} weight to correct the observer area.

3. Results

3.1. Hotspots

The Pierre Auger and the Telescope Array Observatories have detected regions with an excess of events for energies above 60 (The Pierre Auger Collaboration 2018b) and 57 EeV (The Telescope Array Collaboration 2014), with systematic uncertainties of the order of 14% and 21%, respectively (O. Deligny for the Pierre Auger and Telescope Array Collaborations 2019). In this study, the small difference between the energies above which the hotspots were detected is ignored, and the events with energy > 60 EeV were considered.

Figure 1 shows the arrival directions of the particles with energies above 60 EeV obtained from the simulations. The results are separated by composition injected by the source[1] (columns) and EGMF model (lines). The source positions are shown by colored stars: blue (Cen A), red (Vir A), and green (ForA); and the events coming from each source follow the same color coding. The black solid lines indicate the position of the three measured hotspots (HS1, HS2, and HS3).

The direction of detection of events is highly dependent on the EGMF and the composition injected. In particular, the HS1 can be populated mainly by protons injected by Cen A in all EGMF models; a heavier composition presents large deflections, blurring and shifting the signal from the HS1 region. The HS2 can be populated by intermediate (N) to heavier (Fe) particles coming from For A in all EGMF models. The nuclei coming from Vir A can accumulate over the HS3 in the cases of protons (in the Prim EGMF), and nitrogen (especially Prim2R and Prim); iron nuclei leaving Vir A strongly deviate in all EGMF models.

3.2. Dipole

The dipole generated by the radio galaxies considered was also explored. To obtain the dipole direction, the methodology proposed by Aublin and Parizot (Aublin & Parizot 2005) was applied to the partial-sky coverage of the Pierre Auger Observatory. The result is compared with the dipole direction published by the Pierre Auger Collaboration in two energy ranges: > 8 EeV, and > 32 EeV (The Pierre Auger Collaboration 2021). We varied the relative luminosity of Vir A (L_{VirA}) and For A (L_{ForA}) in relation to Cen A (L_{CenA}) by a factor going from 10^{-2} to 10^2 and calculated the dipole direction.

Figures 2 and 3 shows the angular distance ($\Delta\Omega$) between the simulated dipole and the dipole detected by the Pierre Auger Observatory as a function of L_{VirA}/L_{CenA} and L_{ForA}/L_{CenA}. The colors show the angular distance in units of δ, the uncertainty on the dipole direction determined by the Pierre Auger Collaboration. If $\Delta\Omega/\delta < 1$ the simulated dipole agrees with the measure inside the uncertainty. Three realistic luminosity proportions between the sources are also shown for comparison: equal (1:1, square), radio (circle), and gamma-ray (star).

For the energy range above 8 EeV (figure 2), the measured dipole could not be reproduced inside the L_{ForA}/L_{CenA} and L_{VirA}/L_{CenA} considered, independently of the EGMF model and injected nuclei.

For the energy range above 32 EeV (figure 3), a large range of values of L_{ForA}/L_{CenA} and L_{VirA}/L_{CenA} enable the description of the measured dipole, provided heavy nuclei (Si and Fe) be injected. There is a narrow range of luminosity relation in the case of a light nuclei (p and He) injection, independently of the EGMF model. If an intermediary nucleus (N) is considered, the measured dipole can be reproduced only in the Prim2R EGMF model.

4. Conclusions

This work explores the arrival directions of UHECRs emitted from nearby radio galaxies using computational simulations. The results are compared with the arrival direction signals published by the Pierre Auger and Telescope Array Collaborations. The focus is on the local excess of events (hotspots) and the dipole direction. The main conclusions are:

- There is a very important effect of the EGMF model in the arrival directions of UHECR even for local sources and energies above 60 EeV. The HS1 can be associated with light primaries produced in Cen A. The HS2 can receive a contribution from intermediate nuclei leaving For A. The HS3 can be generated by light to intermediate nuclei injected by Vir A;
- The measured dipole for energies above 8 EeV cannot be described by nearby AGN only. This shows the neces-

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[1] The nuclei are subject to photodisintegration processes during the propagation, so the composition measured at the Earth it is not equal to the composition injected at the source.

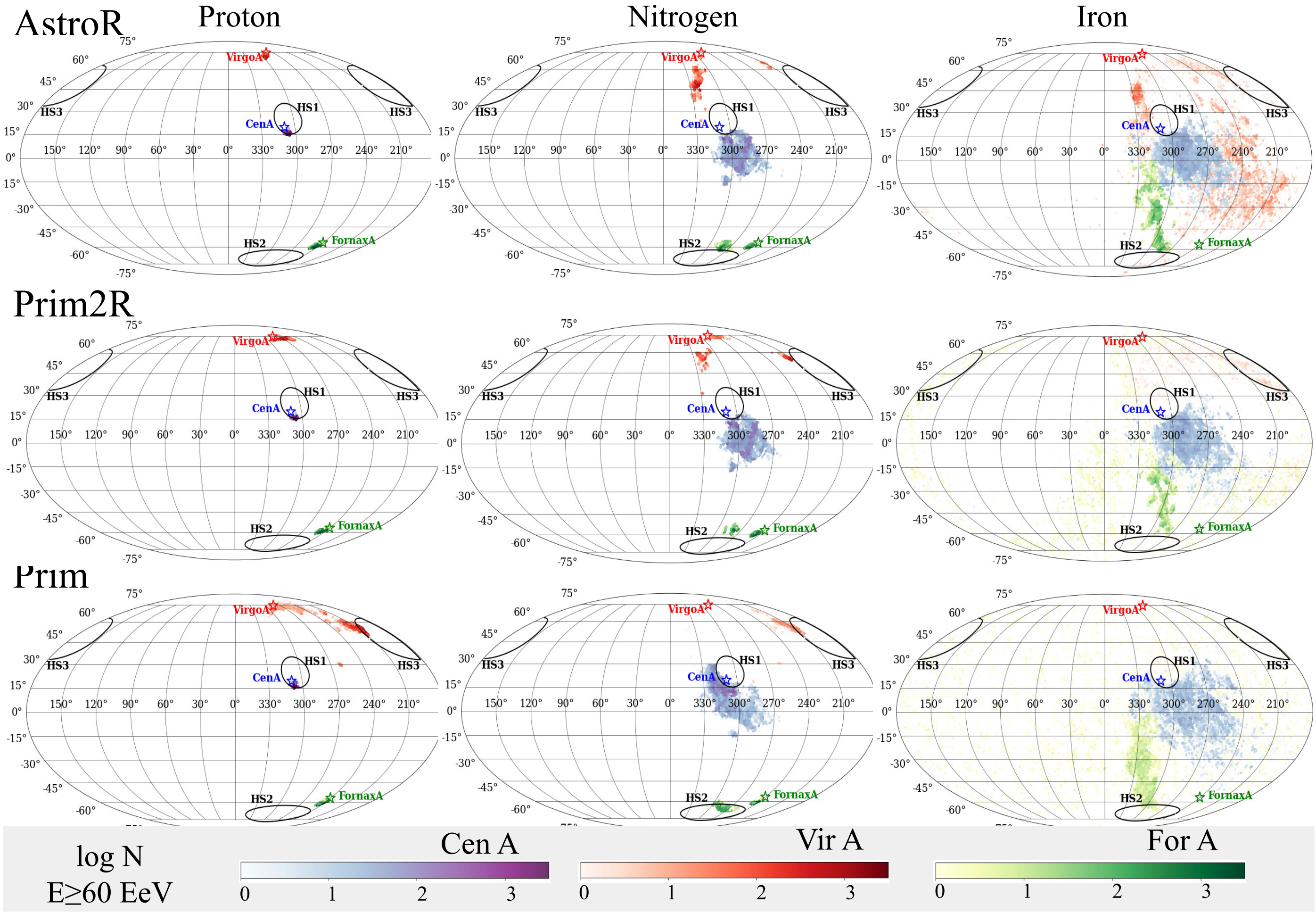

Figure 1. Sky maps (Galactic coordinates, Mollweid projection) showing the arrival direction at Earth of the simulated events with energy above 60 EeV. Lines show different EGMF models; columns show different nucleus leaving the source. The sources are shown as blue (Cen A), red (Vir A), and green (For A) stars; and the respective events of each source follow the same color coding. The hotspots measured by the Pierre Auger (HS1 and HS2, (The Pierre Auger Collaboration 2018b)) and by the Telescope Array Observatories (HS3, (The Telescope Array Collaboration 2014)), are presented by black solid lines.

sity for an extra source component, beyond local AGNs, as galactic sources Hillas (1984); Peixoto et al. (2015); Paczynski (1998); Wang et al. (2008); Blasi et al. (2000); Aloisio et al. (2014) or a very powerful distant AGN (e.g., Cygnus A Eichmann et al. (2018b));

- The measured dipole for energies above 32 EeV can be described by the three nearby AGN only. The dipole can be reproduced for a large range of relative contributions between the sources, and independently of the EGMF model, in the case of a heavy composition.

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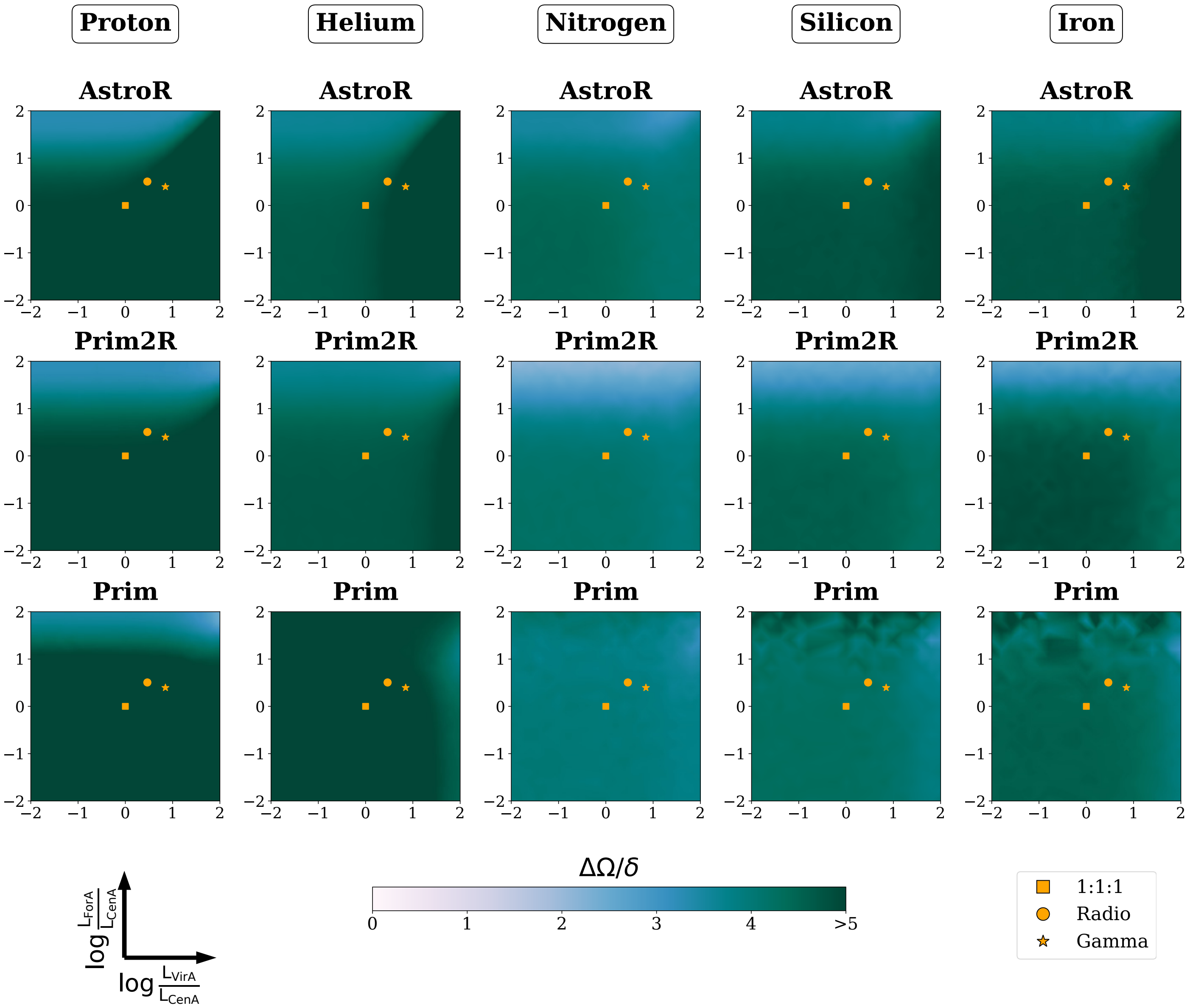

Figure 2. Normalized angular distance ($\Delta\Omega/\delta$) between simulated dipole direction and the direction of the dipole measured by the Pierre Auger Observatory (The Pierre Auger Collaboration 2021) of events arriving at Earth with energy above 8 EeV. The equal (1:1, square), radio (circle), and gamma-ray (star) luminosity proportions between the sources are also shown.

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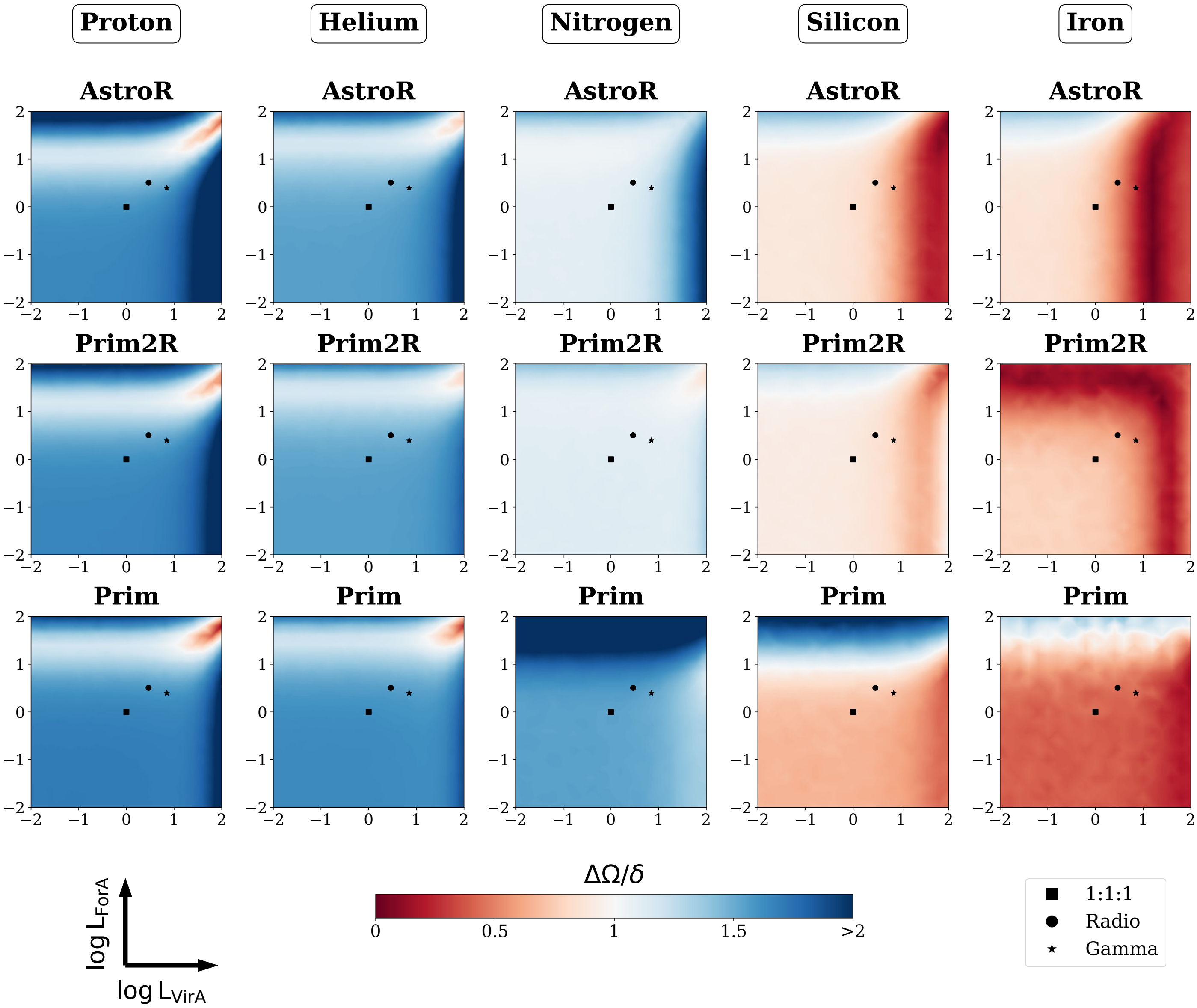

FIGURE 3. Same of figure 2 for events arriving at Earth with energy above 32 EeV.