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Meinert, J., Morejon, L., Vašíčková, V. et al (2025). Implications of temporal features of UHECR fluxes on large scale anisotropies. *Proceedings of Science*, 501.
<http://dx.doi.org/10.22323/1.501.0338>

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Implications of temporal features of UHECR fluxes on large scale anisotropies

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The origin of ultra-high-energy cosmic rays (UHECRs) is still an elusive question, mainly because the arrival directions do not point to a preferred source location. However, it has recently been observed that the amplitude of the dipole anisotropy detected by the Pierre Auger Observatory increases with the energy. This can be interpreted as an indication of the presence of a dominant source in the direction of the dipole, depending on the effects of the Galactic Magnetic Field (GMF). However, alternative interpretations need to be rigorously examined and ruled out before any final conclusions on the dipole anisotropy can be accepted. Using CRPropa 3.2 and current GMF models, we find that UHECRs entering the Milky Way can experience delays of hundreds of kiloyears in the range of rigidities observed by Auger. Based on the constructed spectrum of ages for observed UHECRs, we explore the possibility that temporal changes in the flux of extragalactic UHECRs can produce a dipole similar to that reported by Auger. We explore how discrete bursts can temporally modulate the UHECR flux and show that such injections can reproduce the observed features in the energy spectrum, as well as the dipole-like anisotropies in idealized scenarios.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland



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1. Introduction

Understanding the origins of ultra-high-energy cosmic rays (UHECRs) remains a major challenge in astroparticle physics. Their trajectories through the Galaxy are significantly affected by the Galactic magnetic field (GMF), altering their arrival directions and complicating the identification of their sources. Both turbulent and coherent components of the GMF influence UHECR propagation, necessitating detailed numerical simulations to understand their rigidity-dependent trajectories.

Previous studies have predominantly focused on identifying spectral features and measuring the anisotropy in the arrival direction distribution as indicators of source origin. The Pierre Auger Collaboration, through nineteen years of data, has detected a statistically significant dipole anisotropy (approximately 6% amplitude above 8 EeV) with a significance of 6.8σ [1]. Despite this, higher-order anisotropies remain undetected, and the dipole amplitude has shown remarkable stability throughout the observational period. Typically, observed anisotropies are attributed to spatially inhomogeneous source distributions [2]. However, temporal effects due to finite source lifetimes and GMF-induced delays have received comparatively less attention, especially for substantial propagation times.

In this work, we explore the impact of a temporally modulated UHECR flux on the observed anisotropy, and the transition region of the UHECR flux spectrum. Such a modulation could result from a past UHECR burst in a nearby galaxy, like Centaurus A, as recently suggested [3]. We perform numerical simulations using CRPropa 3.2 [4, 5], employing two GMF models: PlanckJF12b [6], a well-established update of the JF12 model with enhanced constraints from Planck satellite observations, and validated our results using the UF24 model [7]. Throughout this work, we employ PlanckJF12b; UF24 did not qualitatively change the presented results.

Our simulation setup uses a simplified delta-like temporal source profile to modulate the UHECR flux at Earth as a proof-of-concept. This approach will enable future investigations to examine the evolution of the energy spectrum and rigidity-dependent dipole amplitude and by altering the injected mass composition of cosmic rays. We observe a population of cosmic rays in the transition region between the second knee at $\sim 10^{17}$ eV and the ankle at $\sim 4 \times 10^{18}$ eV of cosmic rays that were injected hundreds of kilo years ago with a delta injection in our Galaxy. The corresponding anisotropy is similar to that observed by the Auger Observatory. Although the amplitude is larger, the impact of burst intensity was not studied systematically. It could significantly reduce the amplitude, illustrating that the galactic effects can lead to dipole anisotropies that differ little from the observed isotropy.

2. CRPropa simulation

We simulate an extragalactic cosmic ray flux by injecting cosmic ray protons from a sphere of 20 kpc radius centered at the Galactic center with a Lambertian distribution for the initial directions, with the maximum direction pointing to the center of the Galaxy. The injected rigidities follow a R^{-1} distribution spanning $R = 0.1$ -100 EV. The protons were propagated through the Galactic magnetic field and their arrival (position, direction, propagation length, etc.) recorded with an observer sphere of 1 kpc radius centered at the Sun's position in the Galaxy (8.5 kpc from the Galactic center). Once recorded, particles were not propagated further to avoid multiple counting, while those not detected before a propagation length $L_{\max} = 100$ kpc were discarded.

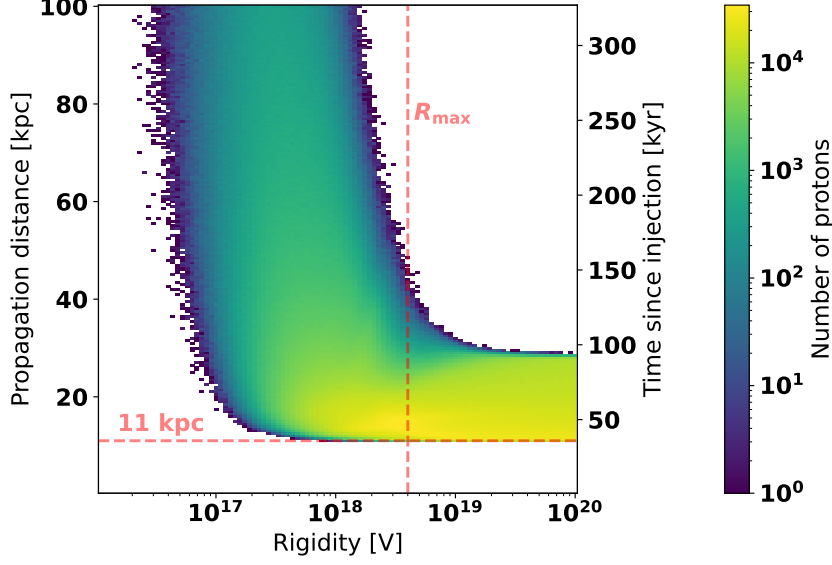


Figure 1: Two-dimensional histogram of 3.27×10^7 proton primaries from CRPropa 3.2 simulations (see details in the text), showing the event density versus rigidity R and propagation length L in the Galaxy. The right vertical axis expresses the corresponding propagation time $t = L/c$. The dashed red horizontal line at $L = 11$ kpc marks the minimum distance to the injection sphere, and the vertical line at $R = R_{\max}$ denotes the maximal rigidity typically inferred from fits of UHECR spectrum and composition, see e.g. Ref. [8].

Figure 1 shows the distribution of cosmic rays obtained simulating 27 billion protons, of which about 32.7 million were recorded, amounting to a total efficiency of 0.12 %. Cosmic rays with the highest rigidities exhibit a time spread consistent with geometric expectation and rectilinear propagation in the Galaxy, given the Sun’s off-center location which explains the limits of 11 kpc for the closest point and 28 kpc for the farthest point to the injection sphere. In this rigidity limit, the efficiency is 0.2 % and is determined by the geometry of the setup. The effects of the GMF increase gradually with $R \lesssim 10$ EV, first extending marginally the propagation length of a fraction of the detected protons, until $R \lesssim 1$ EV where the spread in propagation lengths exceeds the simulation limit $L_{\max} = 100$ kpc and the efficiency decreases rapidly with lower rigidities ($5 \cdot 10^{-5}$ at 100 PV and to 10^{-6} at 30 PV). We can rule out the escape of cosmic rays from the Galaxy as previous simulations [9], using $L_{\max} = 1$ Gpc, showed that for cosmic rays in the range $R = 10^{16} - 10^{17}$ V the fraction reaching the Galactic plane is much larger (10^{-2} - 10^{-1}) and they spend a significant amount of time within the Galaxy.

The results of the simulations were used to construct a response kernel $f(L, R, \alpha, \delta, \alpha_0)$ describing the recorded fraction of cosmic rays as a function of the propagation length in the Galaxy (L) the rigidity (R) the final right ascension and declination (α, δ) and grouped by coarse bands of initial right ascension (at the edge of the Galaxy, α_0). This kernel allows synthesizing the observed cosmic ray flux from different injection assumptions in what follows.

3. Modeling the temporal evolution of the cosmic ray flux

We set up a simplified toy model to study how the history of extragalactic bursting sources could influence the currently observed features of UHECRs due to modulation by the Galactic magnetic field. In this model, a few (local) short-duration bursts inject UHECRs into the Galaxy at different times and from different directions. For simplicity, we assume that all bursts inject the same number of UHECRs over a very short period of time (about 6 kyr)¹. The average time interval between the UHECR burst injections can be estimated from the apparent density of sources n_s . The Pierre Auger Collaboration found $n_s \approx 10^{-4} \text{ Mpc}^{-3}$ [10]. The local burst rate can then be estimated by $\rho \approx n_s / \tau_d$, with τ_d being the apparent burst duration, which is not known well. Following this approach, the burst rate of e.g. HL-GRBs has been estimated at $\rho \approx (0.05\text{--}0.27) \text{ Gpc}^{-3} \text{ yr}^{-1}$ [11, 12], see also [13, 14]. Within a distance of 30 Mpc, in which a source could significantly contribute to the local flux of UHECRs, we would then expect one burst every ≈ 100 kyr. More distant bursting or steady sources could still contribute a constant and more isotropic UHECR background, which we ignore in this analysis. Figure 2 shows an example sequence of bursts of equal intensity and duration 6.5 kyr, occurring at different bands of right ascension (18° width) indicated in the legend. The bursts temporal occurrence was randomly generated, sampling from a Poisson distribution for

¹Increasing the burst duration to larger values has no principal impact to the model, as long as the burst duration remains sufficiently smaller than the typical burst-to-burst period.

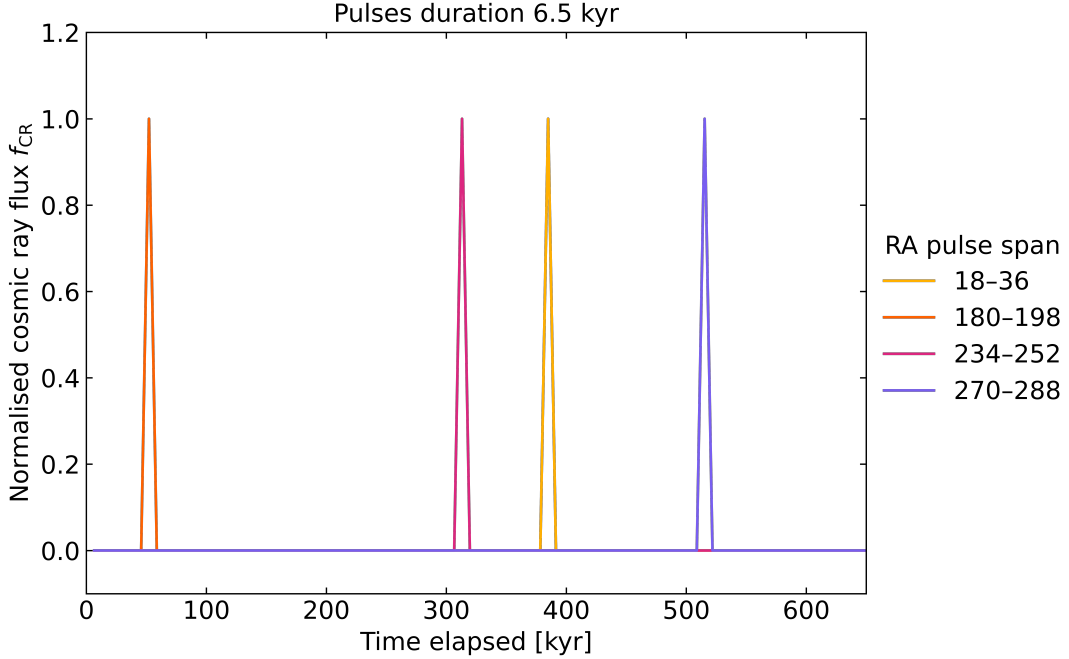


Figure 2: Example pulse profile for a pulse duration of 6.5 kyr, showing four distinct burst events (vertical peaks). Each burst is color-coded by its right ascension bin: yellow (18° – 36°), orange (180° – 198°), purple (234° – 252°), and blue (270° – 288°). The horizontal axis denotes the time elapsed since injection in kyr, and the vertical axis shows the normalized luminosity. For simplicity, it is assumed that the luminosity is equal for all bursting events.

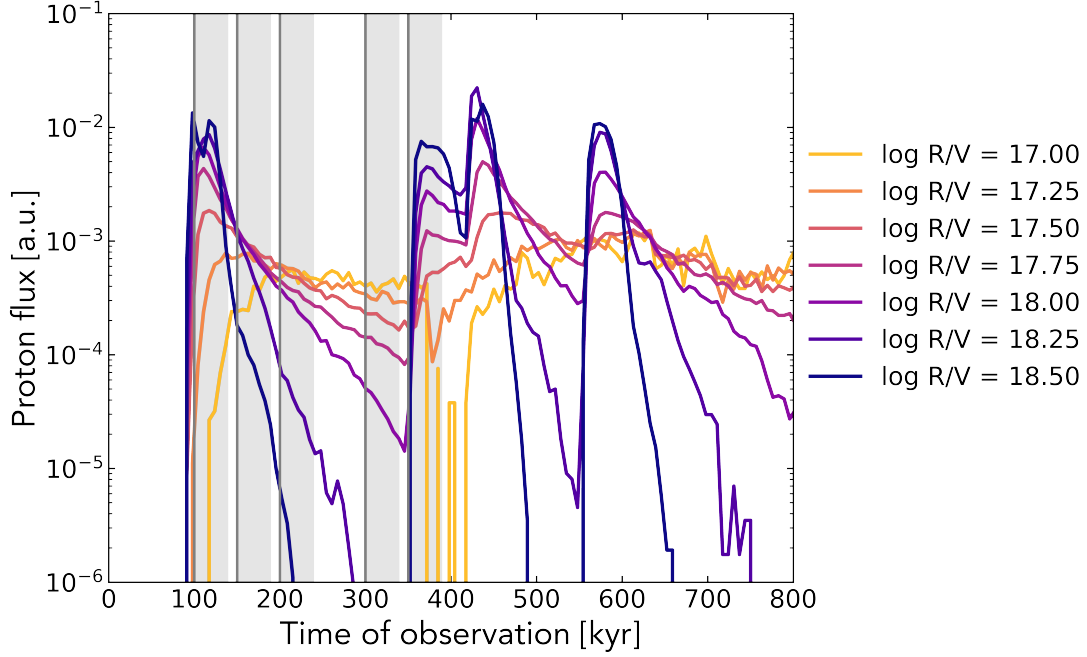


Figure 3: Time-dependent proton flux at Earth, as expected from four delta-like bursts (cf. Figure 2) arriving at the edge of the Galaxy. Each colored curve represents the number of primaries in a narrow rigidity bin, as labeled in the figure. Vertical gray shaded bands indicate the five discrete observation windows used for sampling (see text).

each time step in a discrete time series (step equal to the pulse duration) obtaining the burst centers shown (roughly 53, 318, 378, and 515 kyr).

The temporal contribution of the k -th burst results from the convolution of its time profile and the response kernel

$$f_k(ct, R, \alpha, \delta, \alpha_0^k) = (q_k * f)(t) = \int_0^\infty q_k(\tau) f(c(t - \tau), R, \alpha, \delta, \alpha_0^k) d\tau, \quad (1)$$

where for sufficiently short bursts the injection function can be assumed $q_k(\tau) = a_0 \delta(\tau - t_k)$ (here a_0 is arbitrary) and the burst's right ascension is indicated with α_0^k .

Figure 3 displays the time evolution of the proton flux at the observer sphere obtained summing over the contributions from all bursts in Fig. 2

$$F(t, R) = \sum_{k=1}^4 \int f_k(ct, R, \alpha, \delta, \alpha_0^k) d\alpha d\delta. \quad (2)$$

Each curve corresponds to a narrow rigidity bin indicated in the legend. The five gray vertical lines indicate observation points and shaded bands indicate 40 kyr wide windows that will be used for subsequent spectral analyses. The first peak follows from the quasi-ballistic cosmic rays, producing the sharp rise about 40 kyr after the first pulse as expected from Fig. 1. The temporal tails for the different rigidities correspond to the tails in propagation time of Fig. 1, which become gradually more dominant for lower rigidities and the delay of the initial flux rise increases. The overlap of these delayed, low-rigidity tails from just a few events can produce an effectively *constant* background

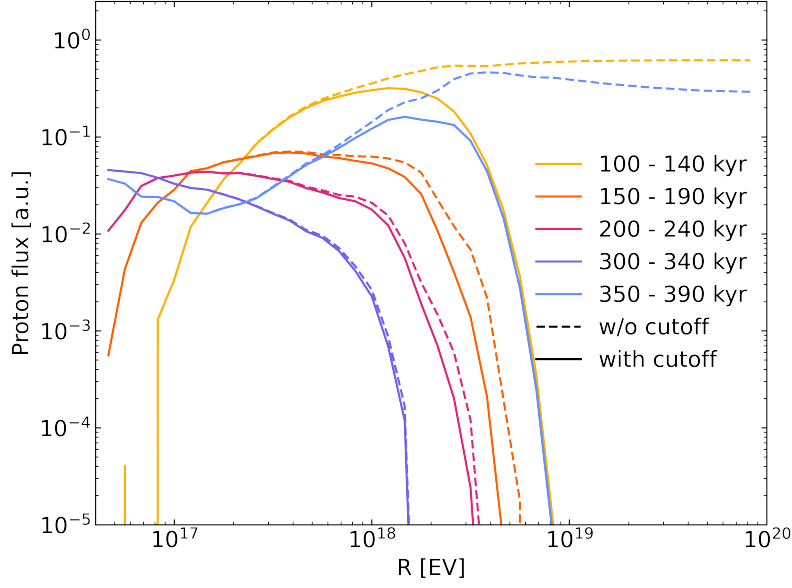


Figure 4: Proton flux as a function of rigidity R at Earth, shown for five observation periods, as indicated. Protons observed during the first four periods originate from a single delta-like injection while those arriving during 350-390 kyr reflect the superposition of cosmic rays from two burst-like injections into the Galaxy. The solid lines include the full rigidity range without a cutoff, while the dashed lines include a rigidity cutoff via an additional factor $\exp[-(R/R_{\max})^2]$ with $R_{\max} = 2.5$ EV.

flux at Earth. This demonstrates that the GMF effects can produce a sustained cosmic-ray flux over much larger timescales from a few discrete injections.

4. Time-dependent rigidity spectra and the ballistic–diffusive transition

We compute the cosmic ray flux in our toy model as

$$F_{\text{obs}}(R) = \int_{t_{\text{obs}}}^{t_{\text{obs}}+40 \text{ kyr}} F(t, R) dt, \quad (3)$$

which are shown in Fig. 4 for the five observation periods indicated in Fig. 3. The spectra for the first and last observation times have a considerable contribution for $R \gtrsim 10$ EV, as expected for the first arriving cosmic rays of each burst. In the high rigidity region the flat spectrum injected is roughly preserved. The rest of the spectra representing the evolution at later times exhibit sharp cutoffs above a few exavolts. This indicates that in this model the GMF produces a rigidity cutoff at later times, even if the extragalactic flux extends to much higher rigidities. This is illustrated by the solid lines, which show that the spectra at later times are very similar with or without applying a rigidity cutoff via an additional factor $\exp[-(R/R_{\max})^2]$ with $R_{\max} = 2.5$ EV to the injected spectrum. The spectra at later observation times become softer, as the lower-rigidity delayed cosmic rays become more dominant, yielding a very soft spectrum. This changes, with the arrival of early cosmic rays originating from a second burst (time bin 350-390 kyr): the spectral feature changes drastically, yielding an ankle-like structure, similar to that observed in the data. In this scenario, this spectral feature is caused by a mixture of soft cosmic rays from the first burst and hard cosmic rays from

the second. These results suggest that the spectral features observed near the ankle may encode the temporal structure of the extragalactic injection history. A small number of discrete bursts, separated by $O(10^5 \text{ yr})$, can naturally populate the transition region and maintain a nearly constant background at lower rigidities for several 10^5 yr . Future work involving the direct fitting of the temporal profile of bursting events to the measured all-sky spectrum could enable the reconstruction of recent extragalactic cosmic-ray accelerator activity. This scenario is important because it allows extragalactic cosmic rays to originate primarily from a single source: the most recent burst event. Therefore, features such as the maximum rigidity encoded in the Peter's cycle largely relate to that single source. The finding that 90 % of the UHECR sources must be identical to within a factor of three, reported in [15], would be naturally explained by this model. Alternatively, since observing at a particular time is equivalent to taking a horizontal slice through Fig. 1, at most times, this scenario provides a single maximum rigidity, even if the particles come from several sources with different maximum rigidities.

5. Summary and Outlook

In this work we have demonstrated that a small number of discrete extragalactic cosmic-ray injection events, when propagated through a turbulent Galactic magnetic field, can reproduce both the long-lived low-energy cosmic rays below the ankle and the sharp ultra-high-energy peaks illustrated in Figs. 3–4. As an initial application the features of the arrival directions can be investigated. Figure 5 (left) presents the skymap distribution observed at 150 kyr computed in this toy model as

$$S_{\text{obs}}(\alpha, \delta) = \int_{t_{\text{obs}}}^{t_{\text{obs}}+40 \text{ kyr}} dt \sum_{k=1}^4 \int f_k(ct, R, \alpha, \delta, \alpha_0^k) dR. \quad (4)$$

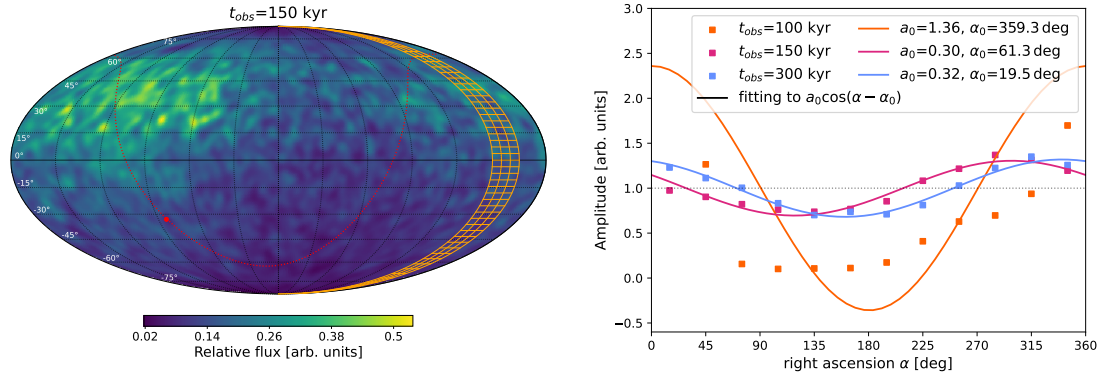


Figure 5: (a) Arrival-direction distribution (Equatorial coordinates) of protons at Earth, smoothed over 5° , and averaged over $t_{\text{obs}} = 150 - 190 \text{ kyr}$ (see Fig. 3). The orange mesh indicates the sky-coverage of the initial burst. The Galactic plane and the Galactic center are indicated in red with a dashed line and a dot, respectively. (b) Dipole amplitude vs right-ascension for different observation times. Data points result from re-binning the skymaps in 12 right ascension bins and dividing the values by the mean. The inferred dipole amplitudes and phases given in the legend were obtained by fitting the data points to a cosine function.

The dipole amplitudes, derived from the skymaps at different observation times, are shown on the right. The early cosmic rays from the burst exhibit a strong asymmetry, as expected, while at later times the amplitude are much lower and are not correlated to the initial burst. Although the amplitudes are ~ 5 times that reported by the Auger Collaboration [1] it is obvious that allowing a constant quasi-isotropic background from more distant extragalactic sources would reduce the value in our model. Looking forward, our formalism naturally suggests a route to quantitatively recover the large-scale anisotropy observed by the Pierre Auger Collaboration. By fitting the temporal pulse profile $q(t)$ (and hence the timing and strength of individual bursts) to the amplitude and phase of the measured dipole, one may infer the recent history of extragalactic accelerators. In future studies we will develop a likelihood-based fitting procedure that simultaneously matches the spectral, temporal, and angular data, thereby constraining both the burst cadence and the intervening magnetic-field properties that shape the cosmic-ray sky.

Acknowledgments

This work is supported by DFG via the Collaborative Research Center SFB 1491 "Cosmic Interacting Matters - From Source to Signal" (project no. 445052434). This work has also received funding via the grant Multi-messenger probe of Cosmic Ray Origins (MICRO) from the DFG through project number 445990517 (KA 710)

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