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A data-driven approach to identifying the sources of the most extreme energy cosmic rays

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We use a data-driven simulation framework to constrain the origin of individual ultra-high-energy cosmic rays (UHECRs) through 3D modeling and likelihood-free inference. We highlight how this method can identify potential source locations based on propagation effects through Galactic and extra-Galactic magnetic fields and emphasize the role of systematic uncertainties. Our approach relies on `CRPropa3` to simulate propagation and uses Approximate Bayesian Computation to derive constraints on key source parameters including position, distance, energy, and the properties of intervening magnetic fields. As a case study, we apply our methodology to the Amaterasu particle, the second-highest energy cosmic ray ever detected. We present our results, demonstrating the impact of the systematic uncertainty on the energy and that of different assumptions for the arrival mass of the Amaterasu particle.

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1. Introduction

Ultra-high-energy cosmic rays (UHECRs), are charged particles that exceed $E \geq 10^{18}$ eV. Their propagation is significantly influenced by magnetic fields, energy losses, and the complexities of particle interactions, making it difficult to trace their origins. Despite progress linking UHECRs to starburst galaxies (SBGs) and active galactic nuclei (AGN), these models fail to account for the highest energy events [17; 26; 27; 29]. While few in number, events at the highest energies have the potential to be the most constraining in terms of their origins. Their high energies suggest nearby horizons and trajectories are less affected by magnetic fields, even when considering the evidence for the increasing mass and charge of UHECRs as a function of energy [31]. As such, studying individual events at the highest energies is a complementary and powerful way to search for the sources of UHECRs [4; 6].

To address this, we introduce a data-driven approach based on 3D propagation simulations and Approximate Bayesian Computation (ABC). Our method incorporates all relevant physics involved in the propagation of UHECRs and allows for inference of source constraints and extra-Galactic magnetic field (EGMF) constraints within a Bayesian framework. The goal of this work to map out the region of the universe that is consistent with their arrival properties rather than trying to connect these events with specific sources. To demonstrate the capabilities of our method, we apply it to the Amaterasu particle, observed by the Telescope Array Collaboration [28] at $E = 244 \pm 29\,(\text{stat.})^{+51}_{-76}\,(\text{syst.})$ EeV.

Previous works have investigated the possible source of Amaterasu by studying its compatibility with models for UHECR production in nearby galaxies [10] and by estimating its deflection and horizon through backtracking and 1D simulations [8; 11]. The results suggest that Amaterasu's detected direction does not strongly correlate with any known active galaxy, but seems to come from the Local Void, an especially low-density region of the Universe [2]. This conclusion has led to the proposal of past astrophysical transient sources [16], ultra-heavy cosmic rays [22], magnetic monopoles [20], Lorentz invariance violation [21], and superheavy dark matter [23] as possible explanations for the Amaterasu observation. We present an updated application of [24]. In particular, in this work we use updated models [9] for the Galactic magnetic field and we choose log uniform priors over the EGMF parameters such that $B_{\rm rms} \sim \log \mathrm{U}[0.1, 10]$ nG and $L_{\rm c} \sim \log \mathrm{U}[60, 1000]$ kpc. The source direction prior is determined first by backtracking to get an estimation of the impact of the GMF and an estimation of the EGMF using Eq. 2.6 from [32]. We then use the arrival direction at the Galactic boundary, combined with the average deflections expected from the EGMF, to construct a wide Fisher distribution from which we then sample prior source positions. In this updated version we also consider a maximum width of the distribution to be 86.8°, otherwise rejecting the trial. This choice is motivated by the radius containing 68.3% probability for a von Mises-Fisher distribution with shape parameter $\kappa = 1$ and to make our computation more efficient while still allowing for large deflections.

2. Methods

To investigate the origin of the Amaterasu particle, we employ `CRPropa3` to model UHECR propagation in 3D, incorporating interactions such as photo-pion production, photo-disintegration, electron-pair production, and energy losses due to adiabatic expansion. The coherent component of the Galactic magnetic field (GMF) is modeled using the best-fit UF23 base model [9] for the striated and small-scale random turbulent components from the JF12 Planck-tune [34], while the extra-Galactic magnetic field (EGMF) is treated as a Gaussian random field with a Kolmogorov turbulence spectrum.

The free parameters of our model are: source parameters such as the galactic longitude and latitude, (l, b), the distance, $D_{\rm src}$ and the energy at the source $E_{\rm src}$. The source distance had to be kept small due to computational challenges and a choice to focus mainly on closer sources. Additionally we have two more free parameters, the strength and the coherence length of the EGMF, $B_{\rm rms}$ and L_c. We assume an iron nucleus as the primary composition at the source, based on prior studies favoring heavy composition at extreme energies [8; 29].

To infer source locations, we apply Approximate Bayesian Computation (ABC), a likelihood-free inference technique [7]. The ABC framework compares the simulated UHECR arrival direction and energy with the ones measured by TA for Amaterasu. Only sets of parameters that produce simulated events consistent with observations within 3σ are accepted. As we perform inference within a Bayesian framework, we define priors for these free parameters. Our prior choices are made to be constraining enough to include important physical information but wide enough to avoid driving the resulting inference where possible [24].

As discussed in [11], the reconstructed energy reported for the Amaterasu particle is subject to large systematic uncertainties. To take these uncertainties into account in our analysis, we consider 2 different cases for the detected energy: 1) the nominal case with $E_{\rm nom} = 244 \pm 29$ EeV, and 2) the lower end of the systematic range with $E_{\rm low} = 168 \pm 29$ EeV.

3. Results

The results for the source direction are summarised in Figs. 1 and 2. Fig. 1 shows the composition dependent contours for $E_{\rm nom} = 244 \pm 29$ EeV. While Fig. 2 shows the results for the $E_{\rm low} = 168 \pm 29$ EeV run. We obtain 195 accepted events for $E_{\rm nom} = 244 \pm 29$ EeV, of which 157 belong to the heavy mass composition group, 26 to the medium and 11 to the light. For $E_{\rm low} = 168 \pm 29$ EeV we obtain 223 accepted events of which 157 belong to the heavy mass composition group, 26 to the medium and 11 to the light. In Figs. 1, 2, the total posterior distribution is compared to known astrophysical sources, with the SBG source list from [14] and AGN from [25] and [19] shown. We also include quiescent galaxies from the 2MASS survey [18]. All objects are color-coded according to their distance from Earth. Each accepted parameter set is weighted based on how well the resulting events match the observed data. The weights for each observable are defined as $\omega_{\rm X} = \frac{1}{\sigma_{\rm X}\sqrt{2\pi}} \exp\left(-0.5\left(\frac{\rm X_{obs}-X_{sim}}{\sigma_{\rm X}}\right)^2\right)$, and then combine them into a total weight $\omega = \omega_{\rm l} \cdot \omega_{\rm b} \cdot \omega_{\rm E}$.

When considering the nominal energy, Fig. 1, the source posterior distribution overlaps with several the astrophysical objects from the catalogs that were used in this work that are within the maximum accepted distance $D_{\rm src} \leq 12$ Mpc, as it can be seen in Fig. 3a. The intermediate mass contours 90% region of highest posterior density overlap with the starburst galaxy NGC 6946. NGC 6946 has also been found close to the region of possible source positions in [8]. However, it was

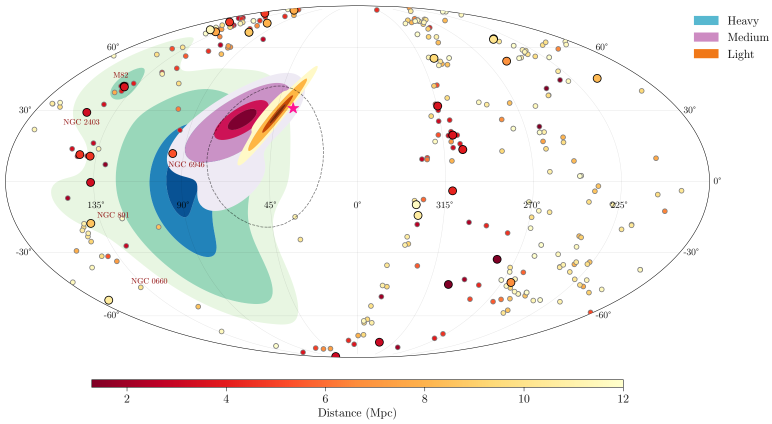


Figure 1: Sky maps resulting from the nominal energy run (case 1) with UF23 as the Galactic magnetic field model, showing the possible source positions of Amaterasu in galactic coordinates. The magenta star marks the measured arrival direction of Amaterasu, and the dashed line outlines the Local Void. The circular markers show galaxies within the prior $D_{\rm src}$ range, with larger markers indicating SBGs and AGN and smaller markers showing quiescent galaxies. In Fig.1, the contours outline the 10%, 30%, 70%, and 90% regions of highest posterior density. The contours are composition-dependent. The orange contours show the case for light elements with $A < 4$, pink for $4 \leq A < 28$, and blue for $A \geq 28$.

disfavoured as a convincing source candidate as it contributes only 3% to the total 1.4 GHz radio flux of SBGs within distances similar to those considered here. More starburst galaxies overlap with the 90% and 70% regions of highest posterior density the heavy mass contours, starburst galaxy M82 is of particular interest as it lies a few degrees from the TA hotspot and is commonly invoked as a UHECR source candidate [12; 13]. In the case of the nominal energy we find that the ideal rigidity at the source should be R $\approx 10^{19.2}$ V.

When considering the lower energy case, the deflections caused by the magnetic fields are larger, Fig. 2. Additionally the prior distance range is higher, $D_{\rm src} \leq 15$ Mpc, as lower energy particles lose energy at a slower rate, this is illustrated in Fig. 3b. The composition dependent contours also reveal that a heavier composition results in larger and more deflected contours, this is due to heavier particles having a larger charge and therefore also being more affected by magnetic fields. The combination of a lower energy and a higher mass composition yields more possible sources. However, most of these sources are quiescent galaxies. We still find NGC6946, in this case between the 30% and the 10% regions of highest posterior density of the intermediate mass composition contours. In the case of the low energy we find that the ideal rigidity at the source should be R $\approx 10^{18.8}$ V.

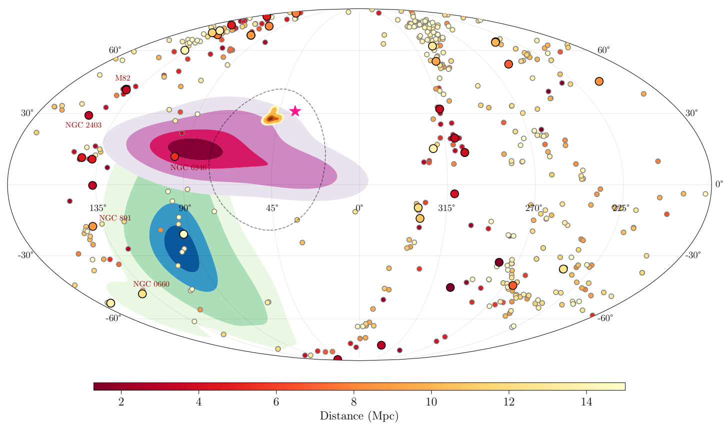
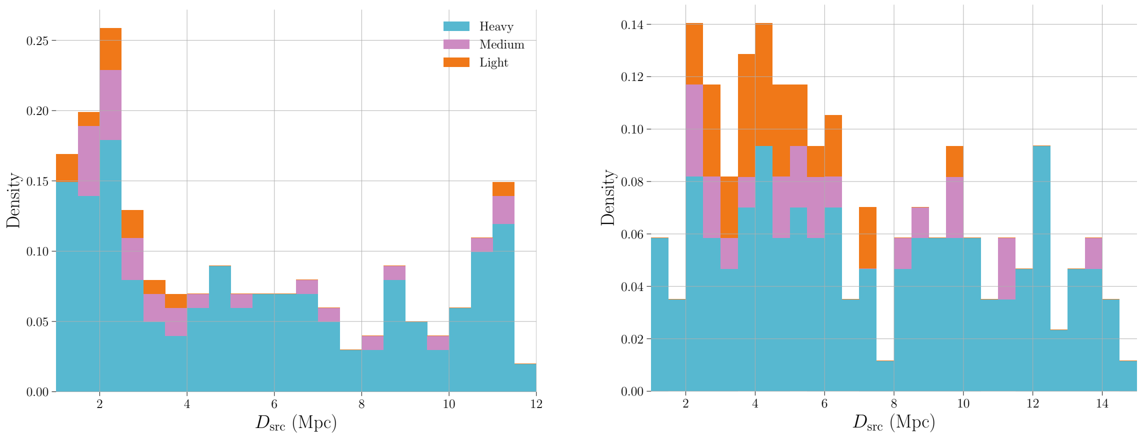


Figure 2: Sky maps of the low energy run (case 2) with UF23 as the Galactic magnetic field model. The layout is as in Fig. 1.



(a) Nominal energy case

(b) Low energy case

Figure 3: Marginal posterior distributions of D_{src} for the nominal (a) and low (b) energy cases. Stacked histograms show the relative contributions of D_{src} values leading to accepted events in different arrival mass groups. Orange $A \leq 4$, pink $4 < A < 28$, and blue $A \geq 28$ bars distinguish the mass ranges.

4. Conclusion

We have presented a data-driven methodology for constraining UHECR source locations using 3D propagation modeling and Approximate Bayesian Computation. The framework accounts for key physical effects during propagation and allows for the inference of the posterior distribution of possible sources from observed arrival direction and energy. Applied to the Amaterasu particle, our method highlights the importance of energy scale assumptions, magnetic field modeling, and mass composition. Depending on these factors, several galaxies lie within the inferred volume of possible sources, including NGC 6946 and M82. These results show that even single-event analyses can yield meaningful astrophysical constraints and underscore the utility of our method for interpreting future UHECR detections. Planned upgrades like AugerPrime [33] will soon augment our knowledge by giving event by event composition information which will make our results more constraining. Moreover we are working on speeding up our algorithms so that we can efficiently apply our method to larger samples of the highest energy events.

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