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Beyond the Local Void: A comprehensive view on the origins of the Amaterasu particle

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We use the reconstructed properties of the Amaterasu particle, the second-highest energy cosmic ray ever detected, to map out three-dimensional constraints on the location of its unknown source. We highlight possible astrophysical sources that are compatible with these regions and requirements. Among these, M82, a powerful starburst galaxy, stands out as a strong candidate due to its position and proximity. To derive our constraints, we use `CRPropa 3` to model all relevant propagation effects, including deflections in the Galactic and extra-Galactic magnetic fields. We consider key input quantities such as source distance, position, energy, and the strength and coherence length of the extra-Galactic magnetic field as free parameters. We then infer constraints on these parameters by applying approximate Bayesian computation. We present our results, demonstrating the impact of different assumptions for the arrival mass of the Amaterasu particle and the systematic uncertainties on the energy scale as well as the impact of the Galactic magnetic field.

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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].

This study focuses on the Amaterasu particle, the second highest energy cosmic ray ever detected, observed by the Telescope Array Collaboration [28] at E = $244 \pm 29(\text{stat.})^{+51}_{-76}(\text{syst.})$ EeV. Its trajectory points toward the Local Void, a region of extremely low matter density. Amaterasu's high energy and unique characteristics make it an ideal candidate for investigating UHECR origins through individual event based studies [4; 6].

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], ultraheavy cosmic rays [22], magnetic monopoles [20], Lorentz invariance violation [21], and superheavy dark matter [23] as possible explanations for the Amaterasu observation.

We revisit this problem using 3D simulations through CRPropa3 and Approximate Bayesian Computation (ABC) [5; 30]. This work models the particle's propagation through Galactic and extra-Galactic magnetic fields while accounting for uncertainties in source energy, composition, and magnetic deflections. By systematically exploring potential sources within a Bayesian framework, the analysis constrains a 3D posterior distribution of possible source regions. This offers new insights into the astrophysical origins of UHECRs and highlighting the impact of assumptions and that of the magnetic field model by comparing results obtained with JF12 [1] and those obtained with UF23 [9].

2. Methods

To investigate the origin of the Amaterasu particle, we employ `CRPropa 3` 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 Galactic Magnetic Field (GMF) was modeled first using the JF12 model and then the UF23, while the extra-Galactic Magnetic Field (EGMF) was treated as a Gaussian random field with a Kolmogorov turbulence spectrum.

To map out the possible volume of space consistent with the measured energy and arrival direction of Amaterasu, we pick a set of free parameters. The source parameters such as the galactic longitude and latitude, (l, b), the distance, D_{src} and the energy at the source E_{src}. Additionally we have two more free parameters, the strength and the coherence length of the EGMF B_{rms} and L_c. We assumed 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 simulated UHECR arrival direction and energy with the ones measure 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. For more details, we refer to [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 $E_{\text{nom}} = 244 \pm 29$ EeV, and 2) the lower end of the systematic range with $E_{\text{low}} = 168 \pm 29$ EeV.

3. Results

The results are summarized in figures 1, 2 and 3. These are sky maps in Galactic coordinates. The contours outline the 10%, 30%, 70%, and 90% regions of highest posterior density. Figure 1 shows the composition dependent contours for $E_{\text{nom}} = 244 \pm 29$ EeV and the JF12 model of the Galactic magnetic field. While 2 and 3 show the results for the $E_{\text{low}} = 168 \pm 29$ EeV run, the earlier using JF12 and the latter UF23 as the Galactic magnetic field model.

In Figures 1, 2 and 3, 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.

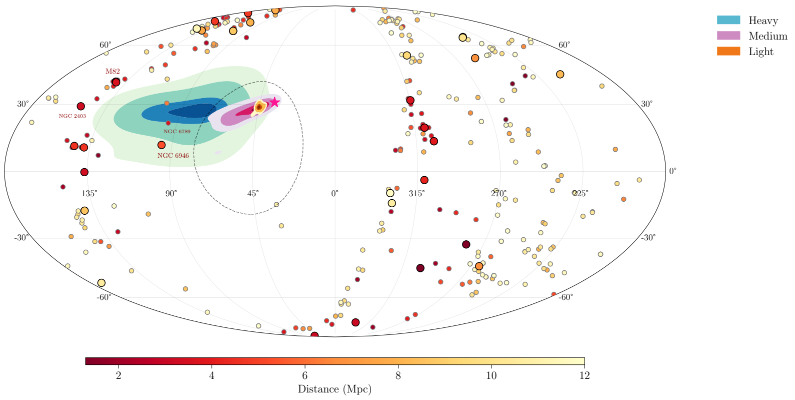

Figure 1: Sky maps resulting from the nominal energy run (case 1) with JF12 as the Galactic magnetic field model, showing the possible source positions of Amaterasu in galactic coordinates. The magenta star marks the measured arrival direction of Amaterasu, and the dashed line outlines the Local Void. The circular markers show galaxies within the accepted D_{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 $A \geq 28$.

When considering the nominal energy, Fig. 1, and the JF12 model of the Galactic magnetic field, the source posterior distribution only overlaps with three of the astrophysical objects from the

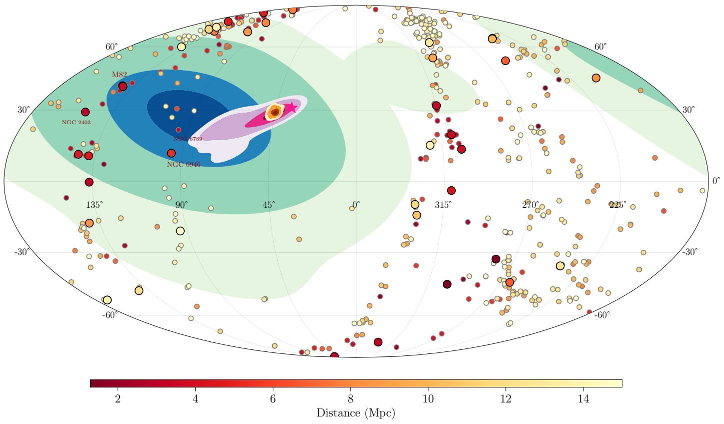

Figure 2: Sky maps of the low energy run (case 2) with JF12 as the Galactic magnetic field model. The layout is as in Fig. 1.

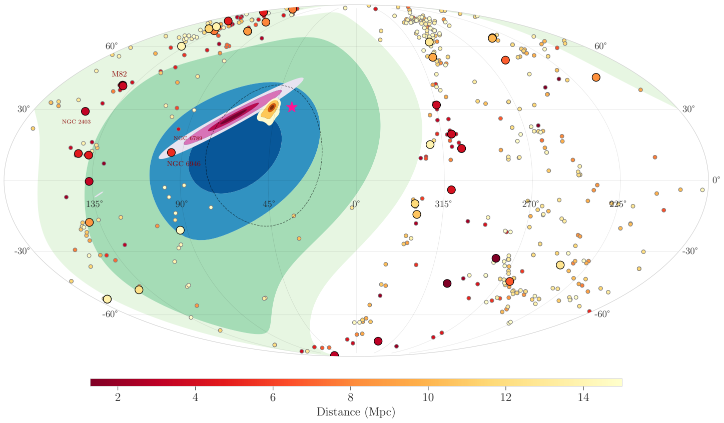

Figure 3: Sky maps of the low energy run (case 2) with UF23 as the Galactic magnetic field model. The layout is as in Fig. 1.

catalogs that were used in this work that are within the maximum accepted distance $D_{\text{src}} \leq 12$ Mpc. Of particular interest is the starburst galaxy NGC 6946. Moreover, this overlap occurs only for a heavier composition at arrival, $A \geq 28$. NGC 6946 has also been found close to the region of possible source positions in [8] However, it was 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. When considering the lower energy case, Fig. 2, the accepted distance range is higher $D_{\text{src}} \leq 15$ Mpc, allowing more possible sources. Moreover within the 30% contour we find the starburst galaxy M82. It lies a few degrees from the TA hotspot and is commonly invoked as a UHECR source candidate [12; 13]. In this case also, there is overlap with astrophysical objects only when a heavy composition is assumed at arrival. However, as it can be seen in figure 3, when we use the UF23 base model for the Galactic magnetic field, NGC 6946 is not only a possible candidate when assuming a heavy arrival composition, but also for a medium one $4 \leq A < 28$. However, in this case, M82 overlaps only with the 90% contour and the center of the distribution does not contain any known active astrophysical objects.

4. Conclusion

We have investigated the origins of the Amaterasu particle, using 3D simulations and Approximate Bayesian Computation to map out potential source regions. Our analysis incorporates various factors, including the particle's energy, arrival direction, composition,and the influence of Galactic and extra-Galactic magnetic fields. We have shown that our results are particularly interesting when considering the systematic uncertainties on the detected energy and a heavier arrival composition. In this case, many astrophysical candidates appear. Moreover we have shown how our results change depending on which Galactic magnetic field is used, showing the importance of correctly modeling the magnetic field of the galaxy. Several astrophysical objects lay in the volume we have constrained offering many alternatives beyond the local void for the origin of the Amaterasu particle, including the starburst galaxies NGC6946 and M82.

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