Constraints on the origin of the UHECR dipole anisotropy outside the Galaxy

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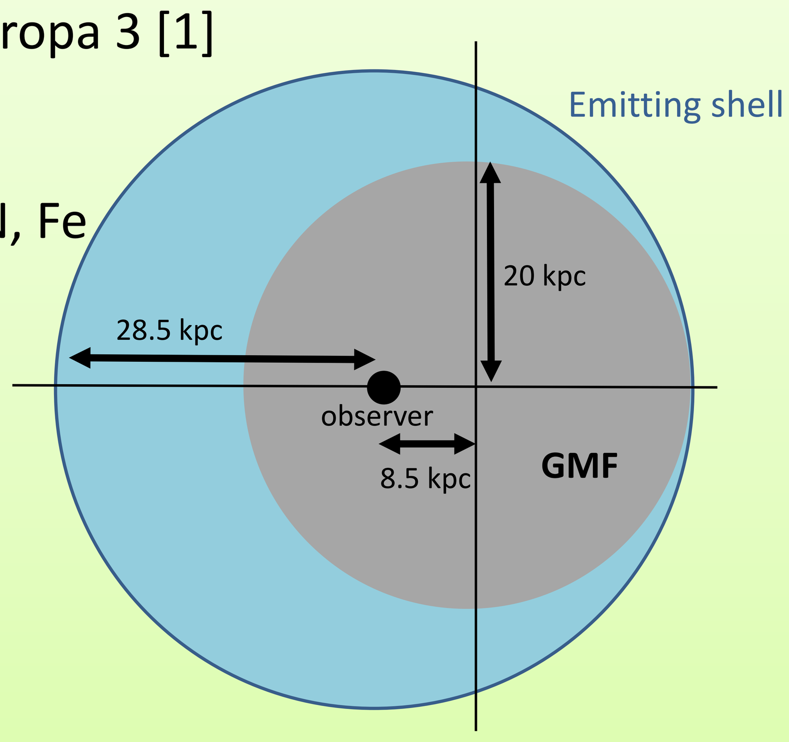
Abstract

The dipole anisotropy of ultra-high energy cosmic rays above 8 EeV detected by the Pierre Auger Observatory indicates an extragalactic origin of these particles [1]. However, both the direction and the amplitude of the dipole of cosmic rays outside our Galaxy might be different than the ones observed on Earth due to the effects of the Galactic magnetic field (GMF). We present an analysis of effects of the Galactic magnetic field on arrival directions of cosmic rays using numerical simulations within the CRpropa3 package [2]. Jansson-Farrar model of the Galactic magnetic field [3] is used to propagate particles inside the Galaxy. We investigate possible directions and amplitudes of the dipole outside the Galaxy for different mass composition scenarios so that the final direction and amplitude on Earth is compatible with the measured dipole.

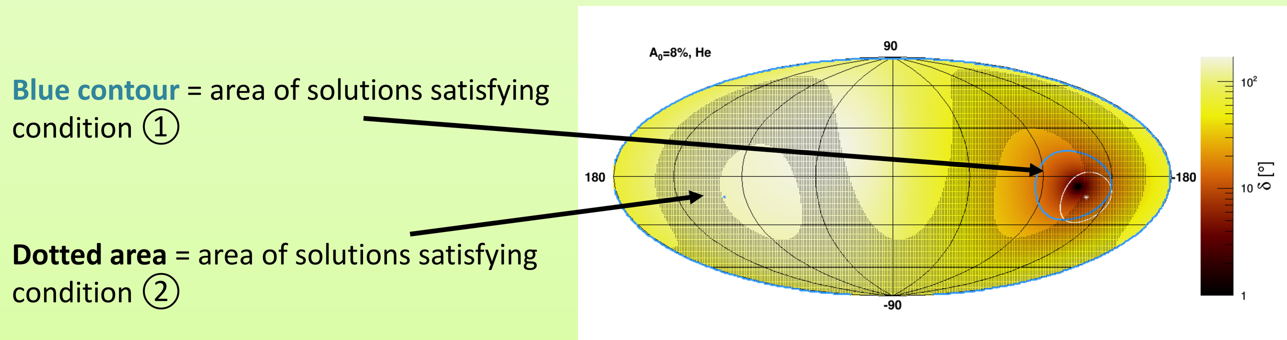
1. Simulations

- Direct simulations using CRPropa 3 [1]
- JF12 model of the GMF [3]
- Simulated particles: p, He, N, Fe
- Power law energy spectrum (8-100) EeV $\sim E^{-3}$
- Observer with radius 100 pc placed at (-8.5,0,0) kpc
- Isotropic flux to the Galaxy



2. Data Analysis

- Simulated isotropic data reweighted to the dipole distribution outside the Galaxy
- Injected dipole distribution in directions with step in longitude and latitude of 1° with different initial amplitudes A_0 from 6.5 % up to 20%
- Distribution of arrival directions on the observer level analyzed in right ascension and 3D
- Looking for directions and initial amplitudes of extragalactic dipole that are consistent (within 1σ) with measurements by the Pierre Auger Observatory after the propagation in the GMF
  - ① **Angular distance δ of the dipole is within $15°$ from $(l, b) = (233°, -13°)$**
  - ② **Amplitude on the observer level must satisfy** $A = (6.5^{+1.3}_{-0.9})\%$
- Different compositions
  - Single primary
  - Mixed composition of 2, 3 and 4 elements



3. Results

Single primary

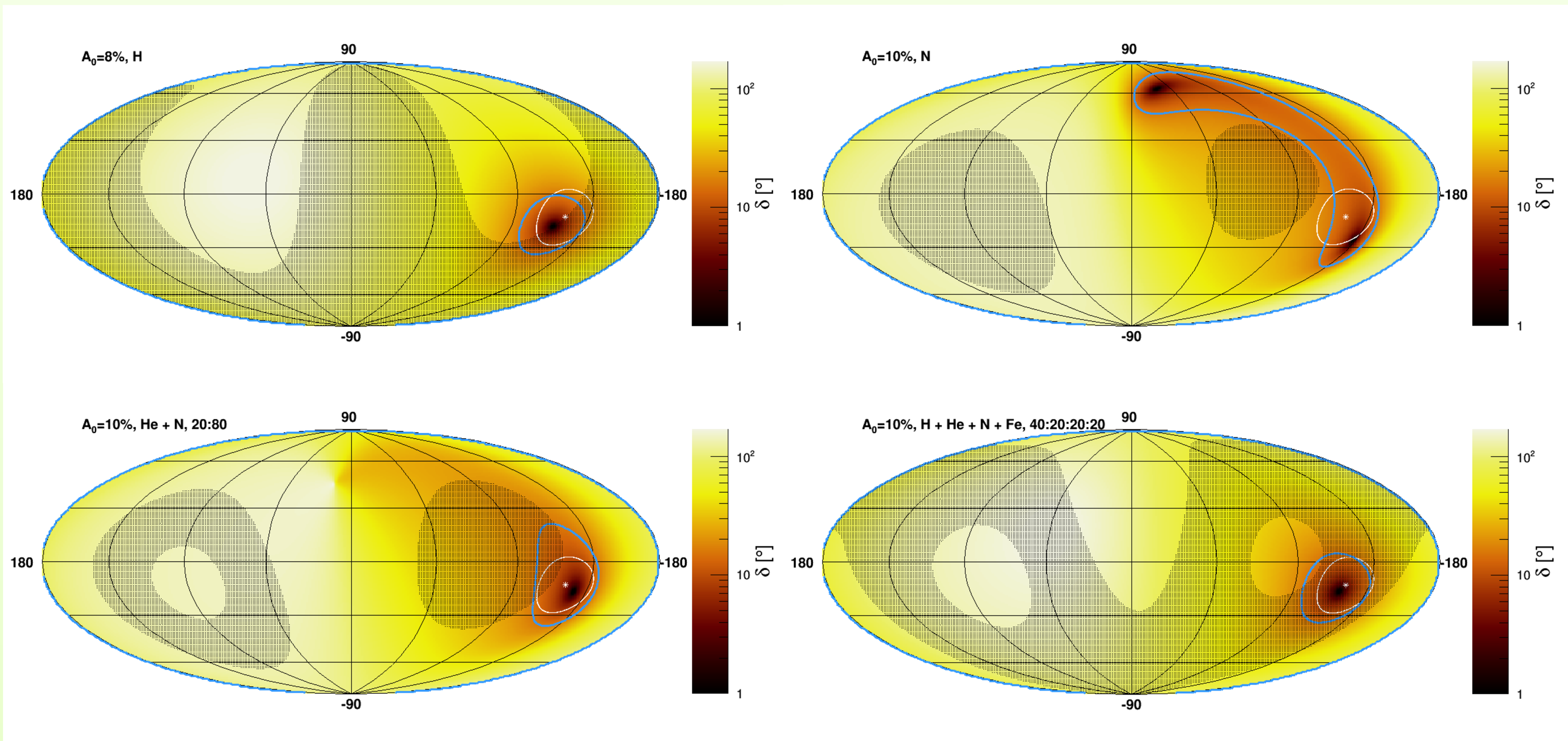
- **H, He**: possible extragalactic directions of the dipole found for lower initial amplitudes $A_0 < 10\%$
- **N**: only few possible extragalactic directions of the dipole found for $A_0 > 14\%$
- **Fe**: no possible extragalactic directions of the dipole found, amplitude A on the observer level too low even for initial amplitude $A_0 = 20\%$

→ Extragalactic directions of the dipole are within 30° from the observed dipole on Earth for H and He, few solutions found for pure N, none for Fe

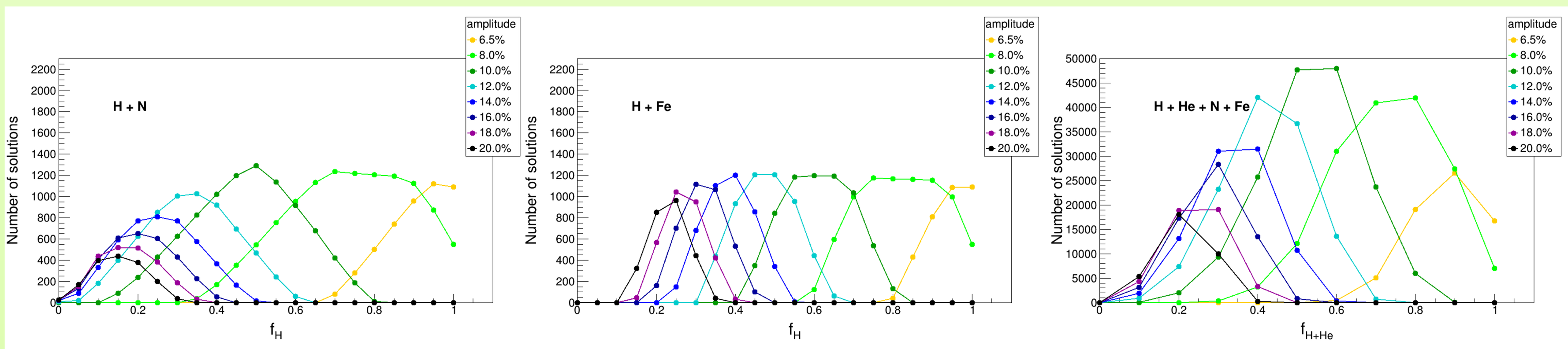
Mixed composition

- GMF tends to isotropize the flux of cosmic rays, this effect is stronger at lower rigidities → initial amplitude of the dipole is higher than the observed one
- Different mass composition mixes require specific initial amplitudes to describe data well
- **High fraction of light elements** allows low initial amplitudes
- **Low fraction of light elements** is possible only for high initial amplitudes due to stronger effect of the isotropization of the flux at lower rigidities

→ Solutions: Extragalactic dipole directions within 30° from the dipole direction on Earth observed by the Pierre Auger Observatory



Directions of dipole anisotropy outside the Galaxy compatible (within 1σ) with measurement of direction (blue contour) and amplitude (dotted area). Selected scenarios of different mass compositions and initial amplitudes A_0.



Number of possible extragalactic directions (1°×1° grid) depending on the fraction of light elements (H and He) for different initial amplitudes A_0. Composition mix: H+N (left), H+Fe (middle), H+He+N+Fe (right).

4. Conclusions

We show the influence of the Galactic magnetic field on the dipole distribution of ultra-high energy cosmic rays above 8 EeV. Different initial directions and amplitudes of the dipole distribution outside the Galaxy were investigated for various mass compositions. Most of the possible extragalactic directions of the dipole compatible with the measurement are located in a region within 30° from the measured direction by the Pierre Auger Observatory. The observed anisotropy can originate from both single primary and mixed composition scenarios, however, single iron primaries cannot create a dipole compatible with the measurement. Different initial amplitudes are needed for different mass compositions of cosmic rays in order to obtain the observed dipole on the Earth after the propagation in the GMF. Generally, lower initial amplitudes are preferred for a composition mix with high fraction of light elements, while for a heavier composition mix higher initial amplitudes (above 12%) are required.

References

[1] The Pierre Auger Collaboration, Science **357** (2017) 1266.
[2] R. Alves Batista et al., JCAP **05** (2016) 038.
[3] R. Jansson and G. R. Farrar, ApJ **757** (2012) 14.

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