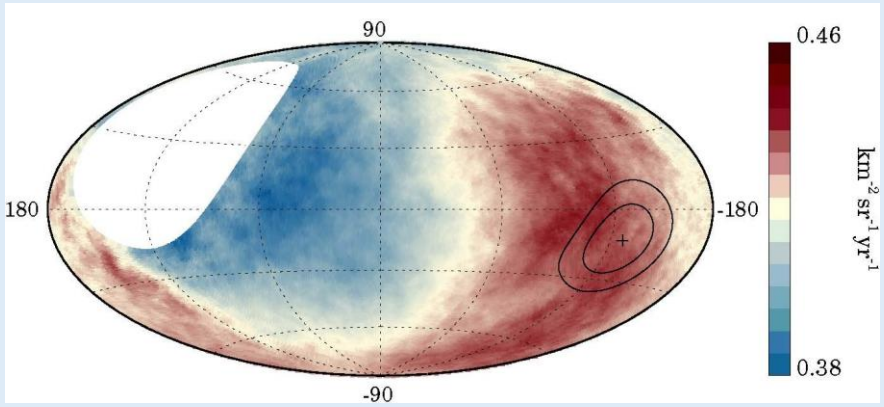
Constraints on the origin of the UHECR dipole anisotropy outside the Galaxy



*The Pierre Auger Collaboration, Science **357** (2017) 1266*

What can we say about the ultra-high energy cosmic-rays (UHECR) before they enter the Galactic magnetic field?

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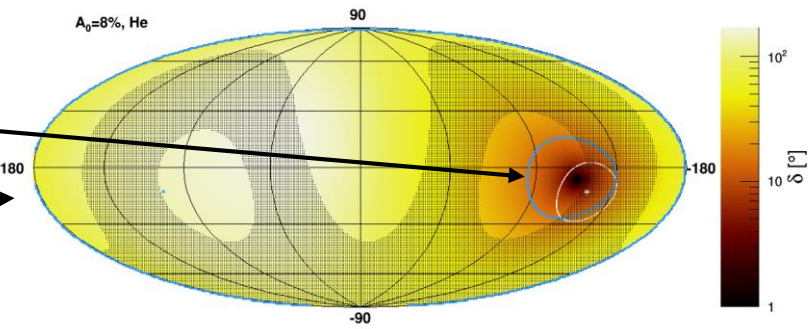
Simulations and Analysis

- Direct simulations in CRPropa 3 (*R. Alves Batista et al., JCAP **05** (2016) 038*) of isotropic flux of cosmic rays entering the Galaxy
- Four primaries (H, He, N and Fe) propagated in JF12 (*R. Jansson and G. R. Farrar, ApJ 757 (2012) 14*) model of galactic magnetic field (GMF), energy $(8-100)$ EeV, $\sim E^{-3}$
- Observer with radius 100 pc at Earth coordinates (-8.5,0,0) kpc
- Simulated data reweighted to follow a given dipole distribution outside the Galaxy
- Arrival directions on the observer level analyzed for different **mass composition** scenarios, different extragalactic **directions** of the dipole (steps in $1° \times 1°$ grid) and various injected **amplitudes** $(6.5\% - 20\%)$

→ looking for parameters of an extragalactic dipole that after propagation in GMF is compatible (within 1σ) with measurements by the Pierre Auger Observatory (*The Pierre Auger Collaboration, Science **357** (2017) 1266*)

① **Blue contour: Angular distance of the simulated dipole at the Earth is within $15°$ from $(l, b) = (233°, -13°)$**

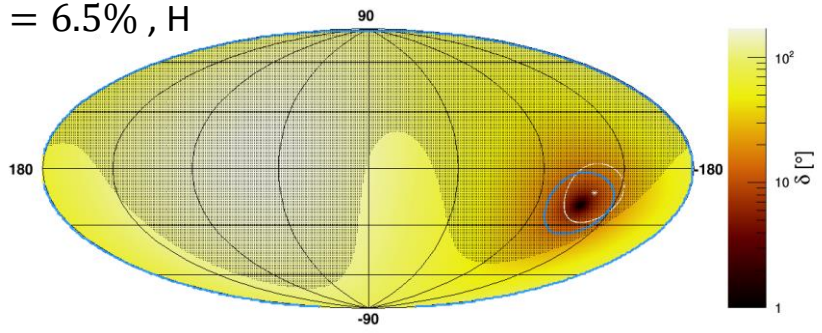
② **Shaded region: Amplitude on the observer level must satisfy $A = (6.5^{+1.3}_{-0.9})\%$**



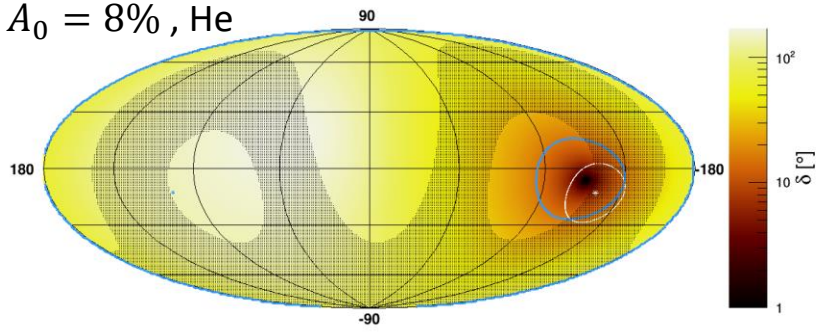
Results – Single primary

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

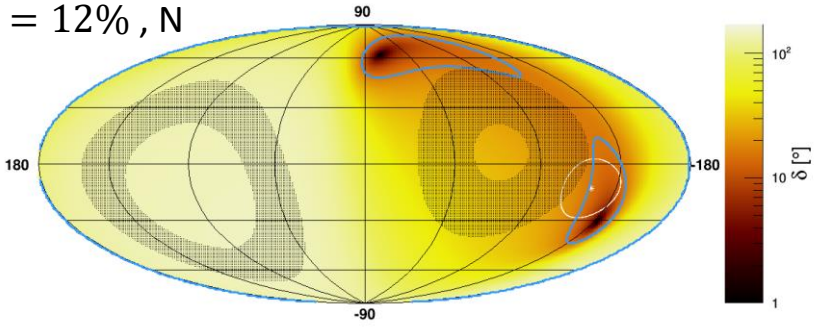
$A_0 = 6.5\%$, H



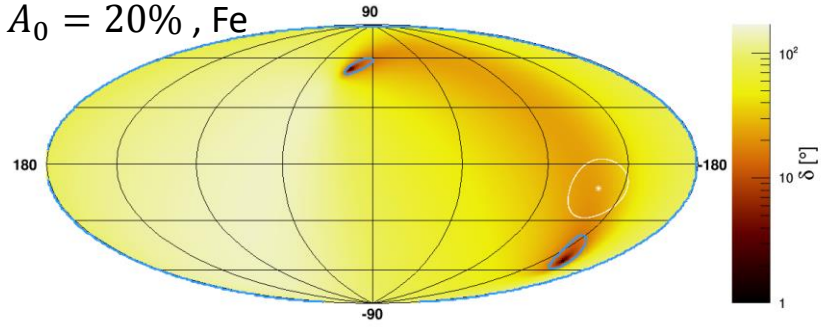
$A_0 = 8\%$, He



$A_0 = 12\%$, N



$A_0 = 20\%$, Fe

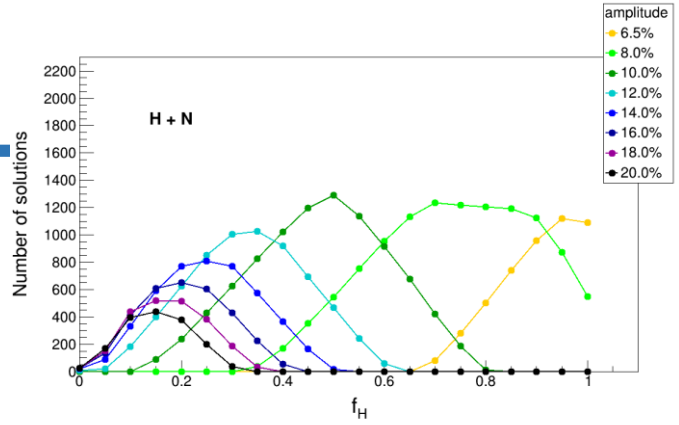


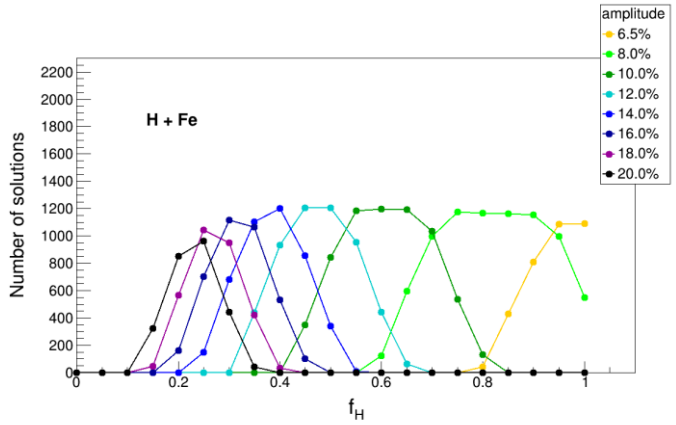
Many extragalactic directions of the dipole are within 30° from the observed dipole on Earth for H and He, few solutions found for N, none for Fe

Results – Mixed composition

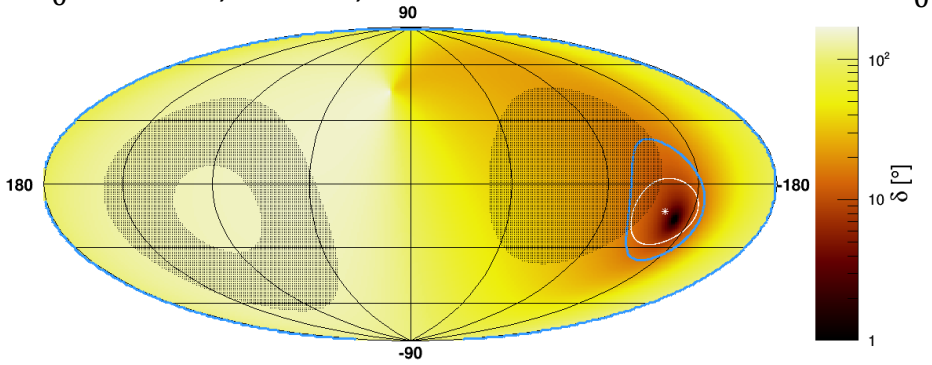
- GMF tends to isotropize the flux of cosmic rays, this effect is stronger at lower rigidities → initial amplitude of the dipole is higher than the observed one
- Different mass composition mixes require specific initial amplitudes to describe data well
- **High fraction of light elements** allows low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





$A_0 = 10\ \%$, He + N , 20:80



$A_0 = 10\ \%$, H + He + N + Fe , 40:20:20:20