Arrival directions of ultra-high-energy cosmic rays assuming heavy mass composition

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ABSTRACT

The arrival directions of cosmic rays are significantly influenced by the Galactic and extragalactic magnetic fields, especially for a heavy mass-composition of the primary particles. Following recent studies, we assume a heavy mass-composition at the highest energies, more precisely pure iron nuclei above 40 EeV, and explore the arrival directions of such particles using the UF23 model of the Galactic magnetic field. Considering nearby active galactic nuclei (AGNs) and starburst galaxies (SBGs) as their sources, we analyse the resulting patterns in their arrival directions on Earth with particular attention to the emergence of medium-scale anisotropies.

1. MODEL

- Extreme mass-composition scenario: **pure iron nuclei above 40 EeV**
  - → Lower rigidity of particles: significant influence of the Galactic magnetic field (GMF) and extragalactic magnetic field (EGMF)
  - → Attenuation of the flux from distant sources due to interactions with photon backgrounds
- Source catalogues with objects up to 250 Mpc taken from [1]
  - → **Jetted AGNs** (Fermi 3FHL)
  - → **Starburst galaxies** (Lunardini et al. 2019)
  - → **AGNs** (Swift-BAT)

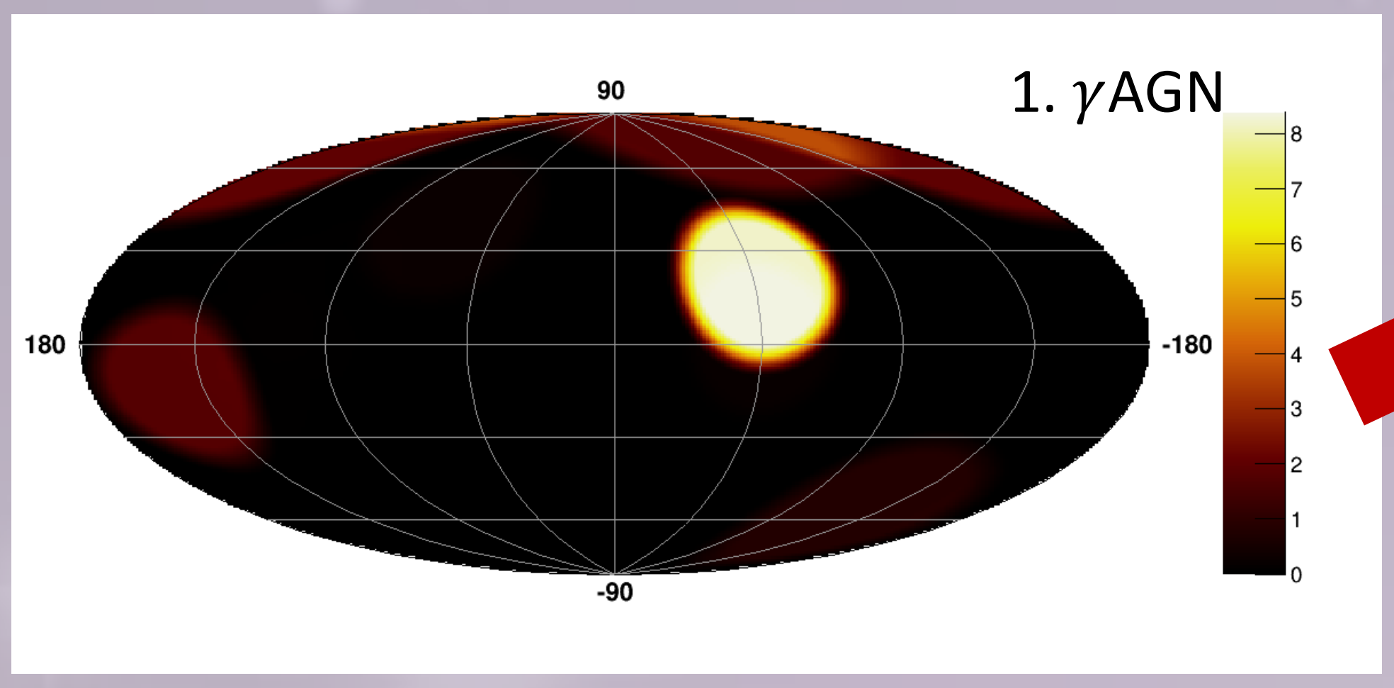
2. SIMULATIONS

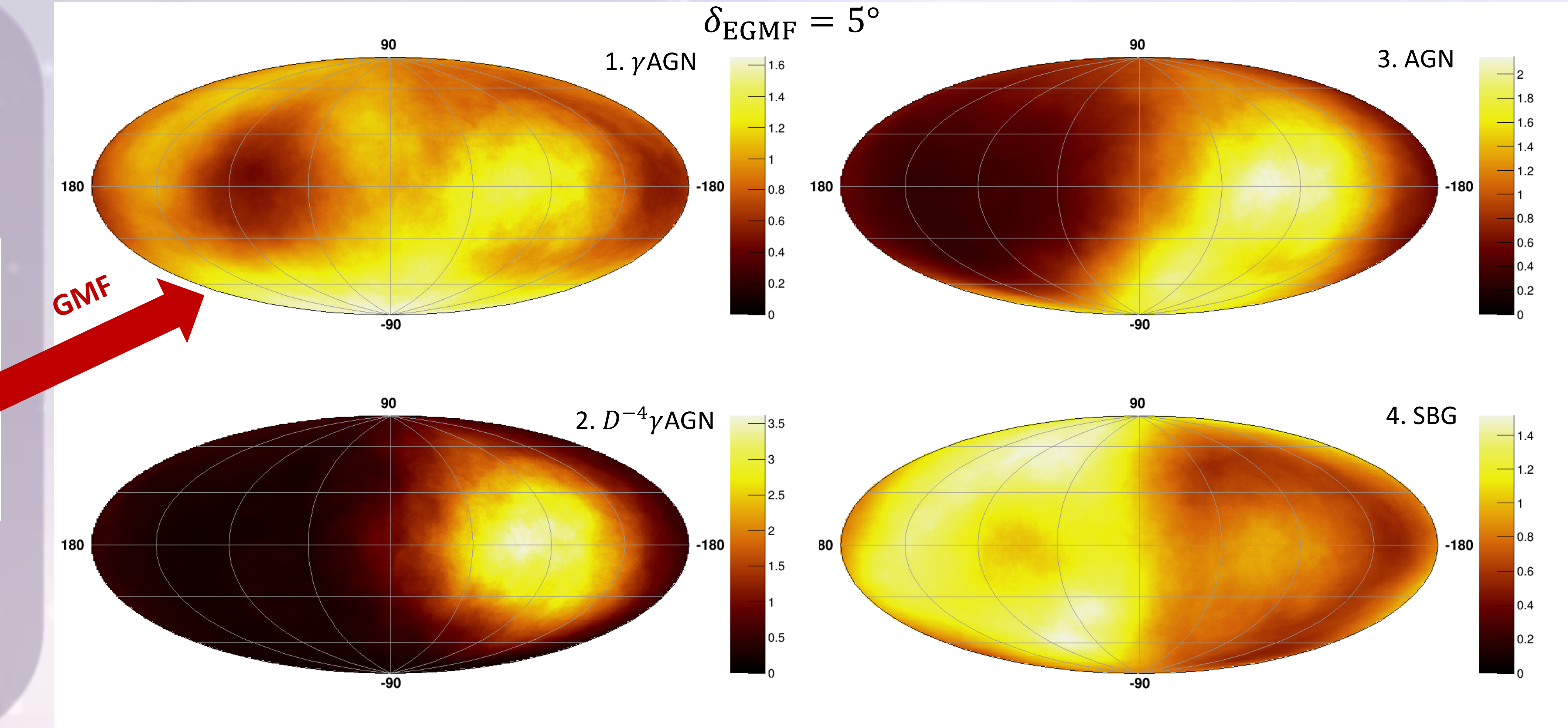
Simulation of cosmic-ray propagation using CRPropa 3 [2]

- Propagation **in the extragalactic space**
  - 1D simulations → attenuation of iron nuclei from sources at various distances binned into a look-up table
- Propagation **in the Galaxy**
  - 3D simulations using UF23 base model of the GMF [3] with JF12Planck random field [4,5]
- Iron nuclei, energy range (40 – 170) EeV and spectral index 2.0
  → reweighted to follow Auger spectrum [6]

3. FLUX MAPS FROM CATALOGUE SOURCES

- Smearing of arrival directions by the EGMF with angle δ_{EGMF} at the Galaxy border





1. Jetted AGNs with flux ∝ γ-flux F_γ
2. Jetted AGNs with flux ∝ $D^{-4}F_\gamma$ [7]
3. AGNs with flux ∝ hard X-ray flux
4. SBGs with flux ∝ radio flux

4. COMPARISON OF MODEL SCENARIOS WITH OBSERVED COSMIC RAY ARRIVAL DIRECTIONS

We compare the model scenarios with the arrival directions of cosmic rays above 40 EeV from the published data of the Pierre Auger Observatory [1]. The models consist of an isotropic background and a contribution from a catalogue with a fraction f.

- Likelihood ratio test with isotropy as null hypothesis: $\mathrm{TS} = -2(\ln\mathcal{L}_{\mathrm{iso}} - \ln\mathcal{L}_{\mathrm{model}})$
- Free parameters: f and δ_{EGMF}.

→ SBG model: the TS values are consistently negative.
→ Swift-BAT AGN model: the highest obtained value $\mathrm{TS} = 8.27$.

	TS	δ_{EGMF}	f
γAGN	6.96	11°	25%
$D^{-4}\gamma$AGN	6.65	8°	10%
AGN	8.27	5°	17%

5. CONCLUSIONS

We analysed the flux patterns of cosmic-ray arrival directions above 40 EeV using various source catalogues, including jetted AGNs, Swift-BAT AGNs, and SBGs. Assuming a pure iron composition above 40 EeV, we modelled attenuation effects of iron nuclei from distant sources and deflections by the Galactic magnetic field using the UF23 base model. Comparing the model predictions with the arrival directions of cosmic rays above 40 EeV, no strong correlation was obtained for any catalogue. For the SBG model, consistently negative TS values indicate that it does not provide a better fit than the isotropic model. The highest test statistic was obtained for the Swift-BAT AGN catalogue, suggesting a modest preference for this source distribution over isotropy.

[1] The Pierre Auger Collaboration, ApJ 935 (2022) 170. [2] R. Alves Batista et al., JCAP 09 (2022) 035. [3] M. Unger, G. Farrar, ApJ 970 (2024) 1. [4] R. Jansson, G. Farrar , ApJ, 757 (2012) 1. [5] Planck Collaboration, A&A 596, A103 (2016). [6] The Pierre Auger Collaboration, EPJC (2021) 81:966. [7] C. de Oliveira et al., arXiv:2408.11624 (2024).

ACKNOWLEDGEMENT

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