On γ-rays as predictors of UHECR flux in AGNs

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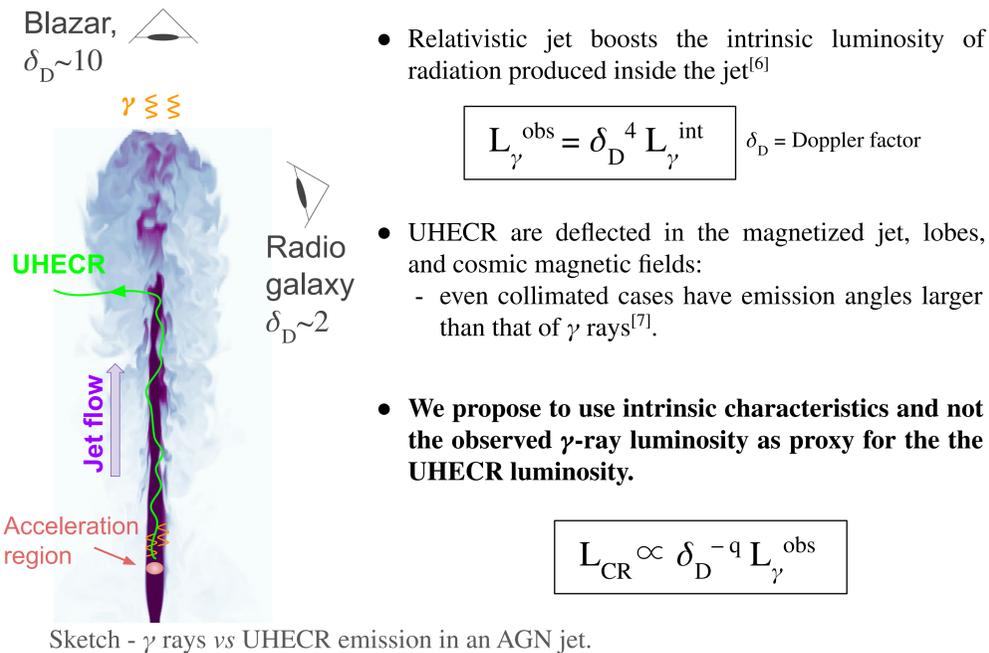
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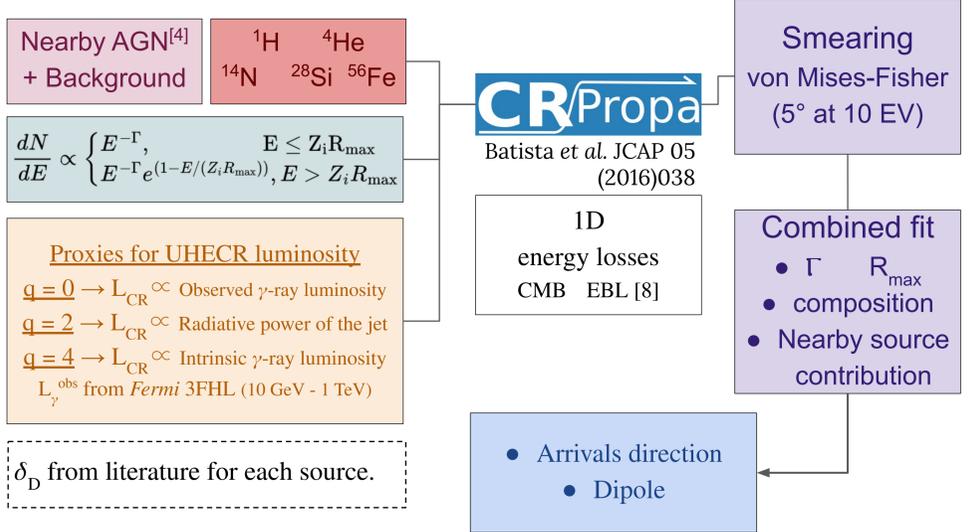
Context and Objective

The origin of the ultra-high-energy cosmic rays (UHECR) is an open question even after several decades of their discovery. Theoretical arguments indicate that Active Galactic Nuclei (AGNs) are promising candidates for UHECR accelerators[1]. Phenomenological predictions based on radio galaxy catalogs corroborate an AGN scenario for the origin of these particles[2,3]. However, the combination of radio galaxies and blazars, using the γ-ray flux as a proxy for the UHECR flux between different sources, makes it difficult to explain the energy spectrum, composition, and arrival directions[4,5]. In this work, we propose a possible conciliation between the different approaches: using the observed γ-ray flux proxy may carry the implicit assumption of beamed UHECR emission and, consequently, its beam will remain collimated up to its detection on Earth. We show that assuming an isotropic UHECR emission and correcting the γ-ray emission proxy by Doppler boosting can overcome the problem.

γ rays *vs* UHECRs from jets

Blazar, $\delta_D \sim 10$

Radio galaxy $\delta_D \sim 2$

- Relativistic jet boosts the intrinsic luminosity of radiation produced inside the jet[6]

$$L_\gamma^{obs} = \delta_D^4 L_\gamma^{int}$$

δ_D = Doppler factor

- UHECR are deflected in the magnetized jet, lobes, and cosmic magnetic fields:
  - even collimated cases have emission angles larger than that of γ rays[7].

- **We propose to use intrinsic characteristics and not the observed γ-ray luminosity as proxy for the the UHECR luminosity.**

$$L_{CR} \propto \delta_D^{-q} L_\gamma^{obs}$$

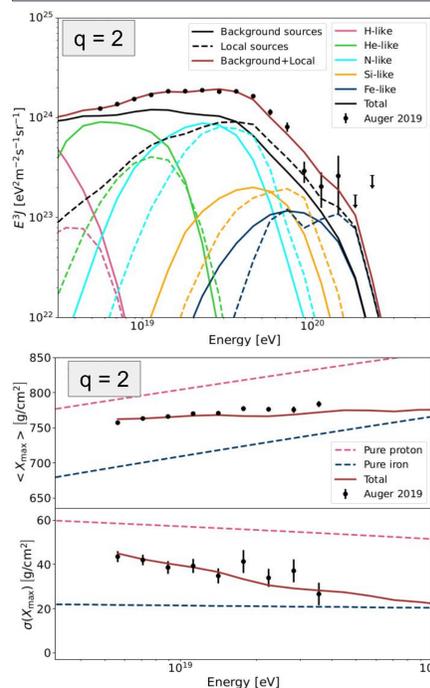Sketch - γ rays *vs* UHECR emission in an AGN jet.

Methodology

To check the effect of using $L_{CR} \propto \delta_D^{-q} L_\gamma^{obs}$ as proxies for UHECR from AGNs, a combined fit of the energy spectrum and composition from Pierre Auger Observatory data was performed.

Nearby AGN[4] + Background

^{1}H ^{4}He ^{14}N ^{28}Si ^{56}Fe

$$\frac{dN}{dE} \propto \begin{cases} E^{-\Gamma}, & E \le Z_i R_{max} \\ E^{-\Gamma} e^{(1-E/(Z_i R_{max}))}, & E > Z_i R_{max} \end{cases}$$

CRPropa
Batista *et al.* JCAP 05 (2016)038

1D energy losses
CMB EBL [8]

Smearing
von Mises-Fisher (5° at 10 EV)

Combined fit
- Γ R_{max}
- composition
- Nearby source contribution

Proxies for UHECR luminosity
$q = 0 \rightarrow L_{CR} \propto$ Observed γ-ray luminosity
$q = 2 \rightarrow L_{CR} \propto$ Radiative power of the jet
$q = 4 \rightarrow L_{CR} \propto$ Intrinsic γ-ray luminosity
L_γ^{obs} from *Fermi* 3FHL (10 GeV - 1 TeV)

δ_D from literature for each source.

- Arrivals direction
- Dipole

Results

Fig 1: Combined fit for q=2. [9]

The fit quality increases when using the characteristics proxies, which can be seen considering the values for χ^2/ NDF = 4.6, 3.1, and 3.9 for q = 0, 2, and 4, respectively. The combined fit obtained for q = 2 can be seen on Fig 1 (from [9]).

The proposed proxies result in a better agreement with the dipole amplitude measured by the Pierre Auger Observatory of 7.4% (>8 EeV). The predicted dipole amplitude found in each scenario was $d_{q=0}$=14%, $d_{q=2}$=7.5%, and $d_{q=4}$=4.1%.

The reconstructed direction of the dipole improves, in some cases, as shown in Table below. Although none of the reconstructed dipole directions agree within 1σ with the experimental data, the tension between the directions of the observed and modeled dipoles is reduced with the new proxies for Auger field of view.

Table: Significance of the Tension of the Predicted Direction of the Dipole with Experimental Data

Field of View	Energy	q = 0	q = 2	q = 4
Auger	>8 EeV	5.9	4.9	3.5
	>32 EeV	2.1	2.0	1.1
Full Sky	>8 EeV	8.7	9.8	8.7
	>32 EeV	1.5	1.7	1.2

The arrival direction maps and the respective dipole directions for the energy ranges >8 EeV and >32 EeV are shown in Fig 2 (from [9]). Some sources are highlighted. The new proxies recover the excess of events around Cen A, and produce a excess of events in the region seen by the Telescope Array, mainly due to the contribution from Mkn 180.

Fig 2: Arrival directions map and dipole directions. [9]

Model dipole	Data dipole
△ Full sky	☆ Full sky
▲ Auger	★ Auger

Summary and Conclusions

When compared to L_γ^{obs}, using intrinsic source characteristics as proxies for L_{CR} can conciliate the radio galaxies only with blazars+radio galaxies scenario. It results in:

- Improvement of fit quality
- Better agreement with local excesses of events found in the data
- Better agreement with the dipole amplitude
- Lower tension on the dipole direction >32 EeV

Looking for more details? Access our ApJ paper [9]

or arXiv:2408.11624

References

[1] F.M. Rieger, Universe (2022)8
[2] Eichmann *et al.* JCAP 07 (2022)006
[3] de Oliveira & de Souza. JCAP 07 (2023)058
[4] Halim *et al.* JCAP 01 (2024)022
[5] Partenheimer *et al.* ApJL (2024)967
[6] G. Ghisellini. *Radiative processes in high energy astrophysics.* Springer, 2013.
[7] Mbarek & Caprioli. ApJ (2019)886
[8] Gilmore et al. MNRAS (2012)422
[9] de Oliveira *et al.* ApJ (2025)981