

Identifying nearby sources of Ultra-High Energy Cosmic Rays using graph convolutional neural networks

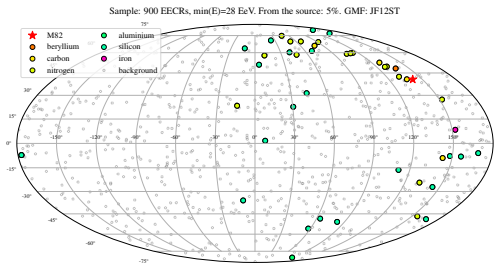
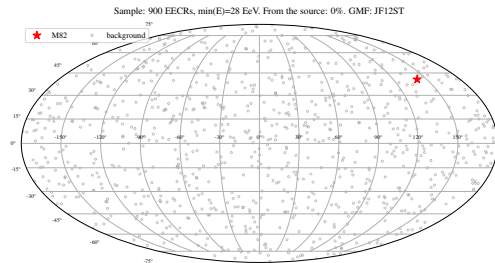
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- 1 Introduction
- 2 Method
 - Simulation: assumptions
 - Hypothesis testing
- 3 Evaluation on Pierre Auger data
- 4 Conclusions & Discussion



- CRs with energies > 10 EeV
 - Propagation is limited to ~ 50 Mpc
- ↓
- Anisotropy might be associated with nearby sources

Aim

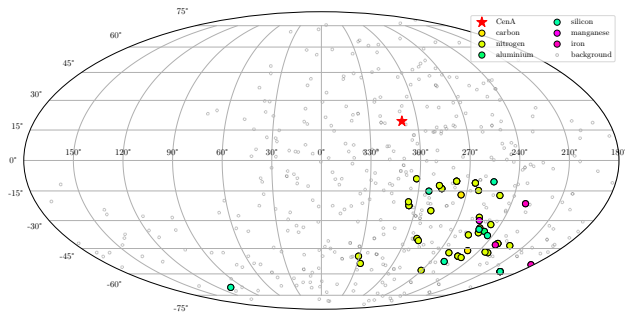
Identify large-scale and medium-scale anisotropy arising due to nearby Active Galactic Nuclei (AGNs)

Approach

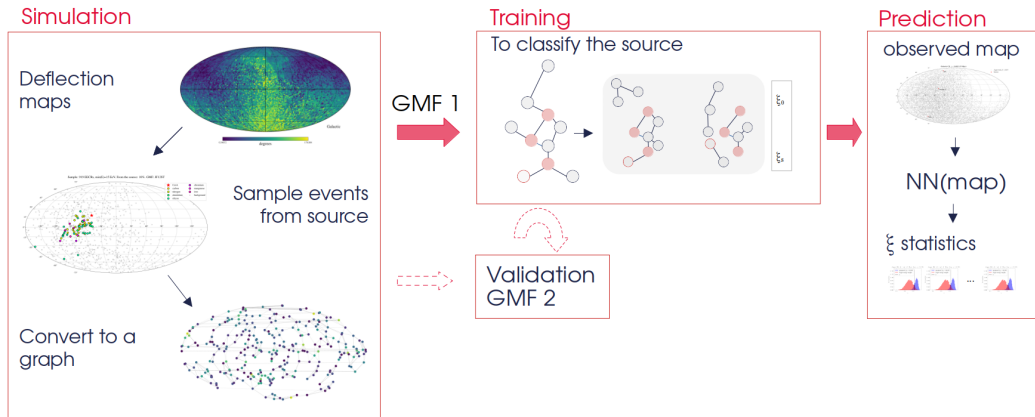
A classifier distinguishing between isotropic and anisotropic maps

Assumptions

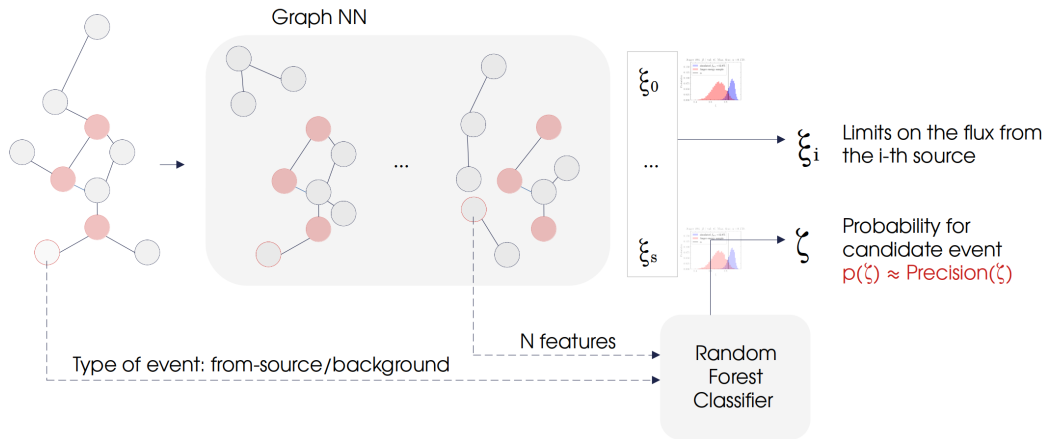
- AGNs – possible sources with identical spectra ($d < 20$ Mpc) (1)
- Transport CR for propagation (2)
- No deflection outside the Galaxy
- CRs are deflected in the Galactic Magnetic Field (GMF):
 - A.Korochkin, D.Semikoz, P.Tinyakov, 2024 (3) [KSTT24]
 - Jasson, Farrar, 2012 (4) [JF12]
 - Turbulent component: JF12 corrected by Planck Collaboration, 2016 (5)



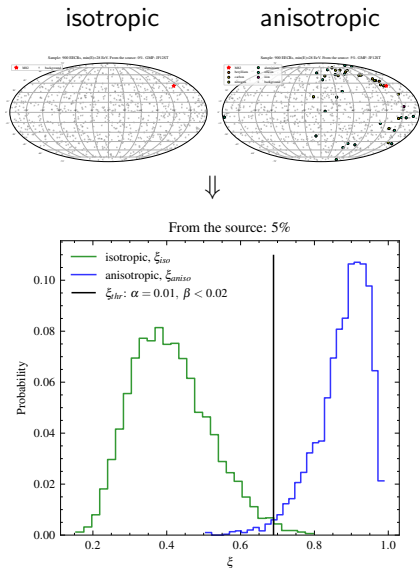
Simulation: training



Scheme of the full model



Method: Hypothesis testing



H_0 : Arrival directions of a sample of UHECRs obey isotropic distribution

H_1 : Arrival directions obey anisotropic distribution and anisotropy arises due to an AGN emission

$\xi = \text{model}(\text{map}): \exists \xi_{thr}$

$$P(\xi_{iso} > \xi_{thr}) < \alpha, P(\xi_{aniso} < \xi_{thr}) < \beta$$

α – type I error. H_0 is true, but incorrectly rejected

β – type II error. H_0 is false, but incorrectly accepted

Multiple testing: Holm procedure

controls family-wise error rate (FWER) for a group of hypotheses:

$$\text{FWER} < \alpha$$

Hypothesis testing: flux constraints

Minimal flux

H_0 : f_{src} % or less of total flux originates from source

H_1 : $> f_{\text{src}}$ % of total flux originates from source

Search for maximal f_{src} compatible with observed T

Maximal flux

H_0 : f_{src} % or more of total flux originates from source

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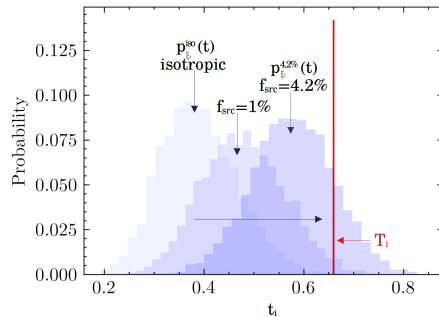
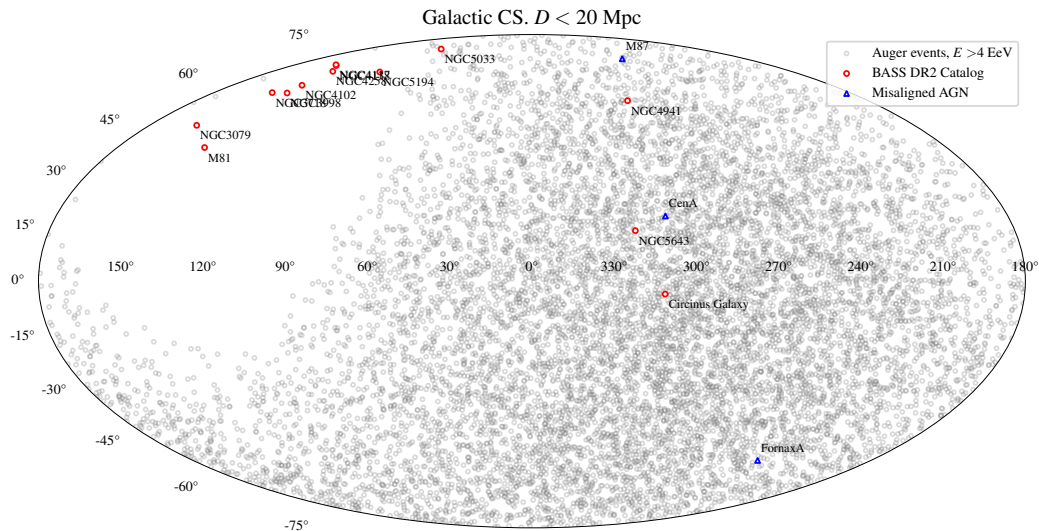


Figure: Constraining minimal flux from i -th source

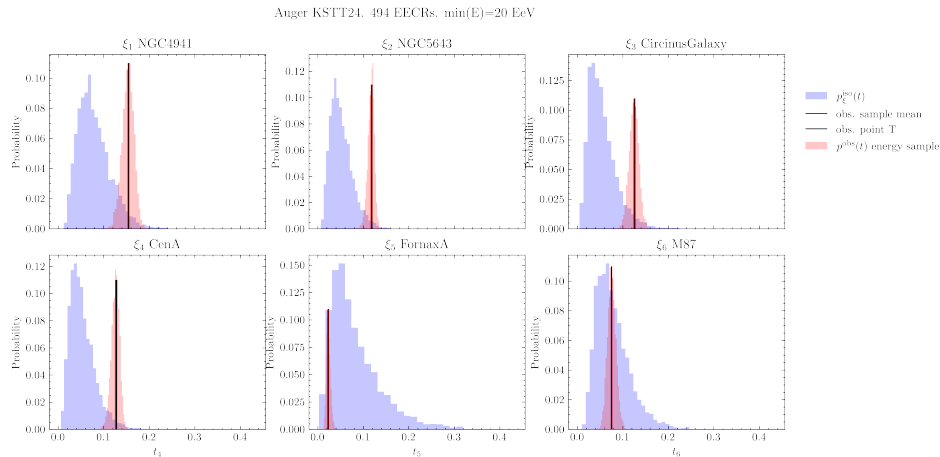
Pierre Auger events and AGN candidates



The minimal energies considered in this analysis are $E > 20$ EeV (494 events)

Possible sources

1 Detecting possible sources



2 Limiting minimal flux for possible candidates NGC 5643, NGC 4941, Cen A

Minimal flux from possible sources

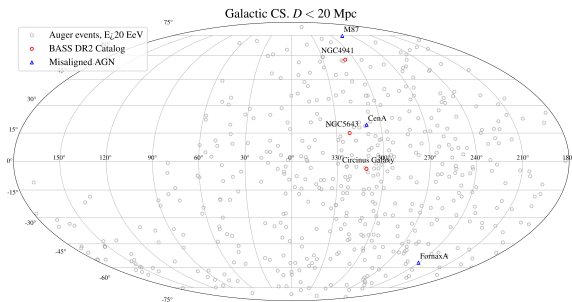
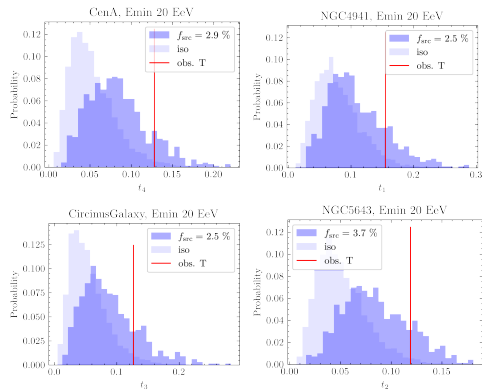


Figure: Auger events map used for evaluation



Maximal flux limits

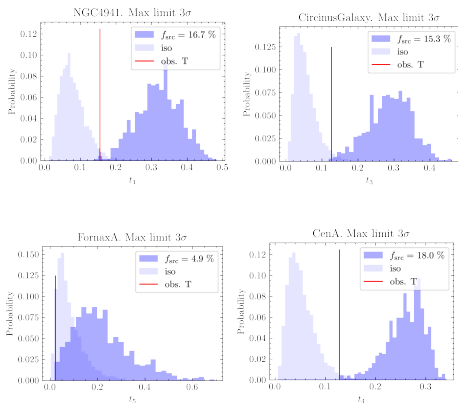


Table: Maximal flux, $\alpha < 0.0014$ [3σ]

GMF	TRAIN/VAL
Source	KST24/JF12
NGC 5643 17.5 Mpc	18.5%
CenA 3.5 Mpc	17.9%
Circinus Galaxy 6.5 Mpc	15.2%
NGC 4941 17 Mpc	16.9%
M87 18.5 Mpc	12.5%
Fornax A 20 Mpc	4.9%

Sensitivity to different arrival directions

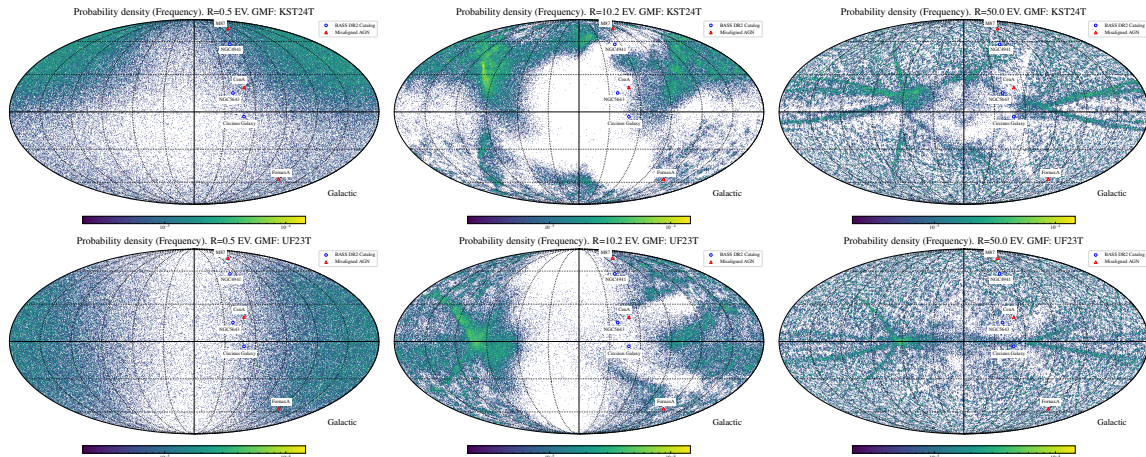


Figure: Expected frequency of CR to be observed from the direction Ω_G

Possible from-source events

- Build η -statistics:
 $\eta = \text{RFClassifier}(\text{node features})$
- Empirical probability:
 $p(\text{from source}|\eta) \approx$
 $\approx \text{Precision}(\eta) = \frac{TP}{TP+FP}$
- Classification metrics [5% flux from the source]:
Precision = 0.73, Recall = 0.77

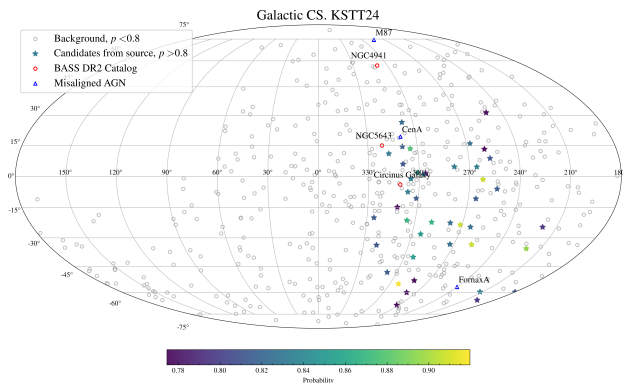


Figure: Possible events (stars) originating from possible sources

Table: Minimal flux, $\alpha < 0.1586$ [1σ]

GMF Source	TRAIN/VAL	
	KST24/JF12	JF12/KST24
NGC 5643 17.5 Mpc	3.7%	2.5%
on 0.5 light	3.4%	2.5%
on 2.0 heavy	4.9%	4.3%
CenA 3.5 Mpc	2.9%	1.7%
Circinus Galaxy 6.5 Mpc	2.5%	0% ¹
NGC 4941 17 Mpc	2.5%	6.4%
M87 18.5 Mpc	compatible	with zero
Fornax A 20 Mpc	compatible	with zero

¹compatible with zero

Results

1. The **anisotropy** might be **caused by nearby sources**. Constraints on minimal flux depend on the choice of GMF model and mass composition
2. Maximal possible flux from the closest AGNs has been constrained
3. Contributions from **Fornax A** and **M87** are **compatible with zero**
4. The observed **anisotropy** could **arise** from **GMF lensing**; however, nearby sources are likely to contribute
5. Candidate events inducing anisotropy are identified

Future:

- > Additional smearing due to a strong intergalactic magnetic field
- > From-source events spectrum and mass composition estimates

1. M. Kachelrieß, O. Kalashev, S. Ostapchenko, D. V. Semikoz, *Phys. Rev. D* **96**, 083006, (<https://link.aps.org/doi/10.1103/PhysRevD.96.083006>) (8 Oct. 2017).
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