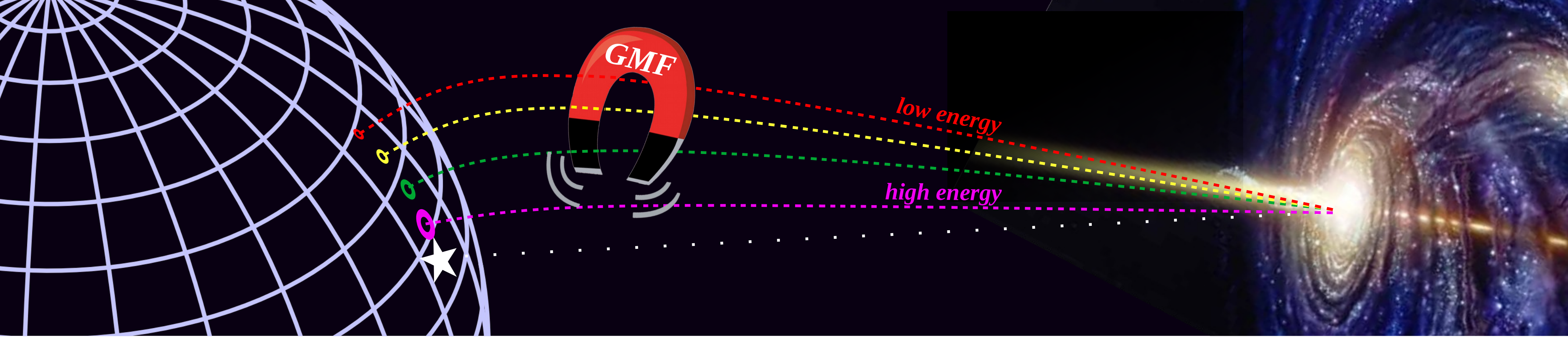


Search for magnetically-induced signatures in the arrival directions of Ultra-High Energy Cosmic Rays measured by the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

Marcus Wirtz for the Pierre Auger Collaboration

ICRC 2019, Madison – July 27, 2019

ICRC2019
Madison, WI, USA

Outline

1) Description of methods

A) Multiplet search – correlation between energy and deflection

B) Thrust ratio – measure of elongation of a pattern

2) Target selection – starburst galaxies & active galactic nuclei

3) Benchmark simulation

4) Sensitivity of the methods

5) Pierre Auger Observatory / data set

6) Application on data

A) Targeted search B) Blind search

Multiplet search

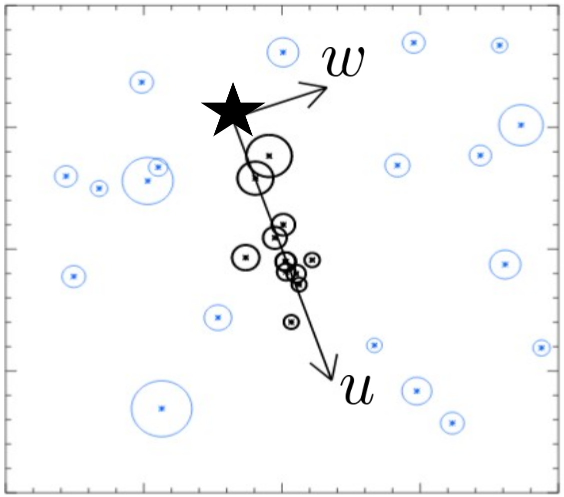
- Relation between arrival direction $\vec{\Theta}$, source direction $\vec{\Theta}_s$ and magnetic field $\vec{B}$:

$$\vec{\Theta} = \vec{\Theta}_s + \frac{\vec{D}(\vec{\Theta}_s)}{E} \quad \text{with} \quad \vec{D}(\vec{\Theta}_s) = Ze \int_0^L \mathrm{d}\vec{l} \times \vec{B}(\vec{l})$$

- In suitable coordinate system (sketch):

$$u \simeq u_s + \frac{D(\vec{\Theta}_s)}{E}$$

- Find set of cosmic rays that fulfill:
  - Correlation coefficient $C(u, 1/E) > 0.9$
  - Transverse spread $\max(|w_i - \langle w \rangle|) < 1.5^\circ$

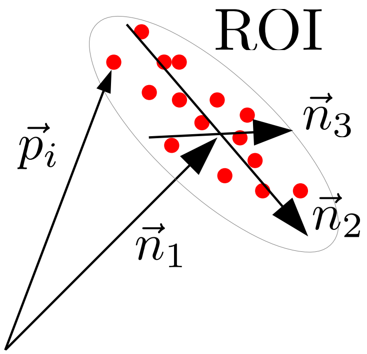


Thrust ratio

- Principal component analysis in region of interest (ROI), radius: 0.3 rad

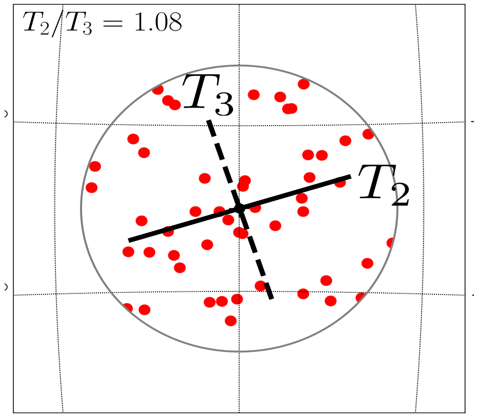
$$T_k = \max_{\vec{n}_k} \left(\frac{\sum_i |\omega_i^{-1} \vec{p}_i \cdot \vec{n}_k|}{\sum_i |\omega_i^{-1} \vec{p}_i|} \right) \Rightarrow$$

strength of collimation along axis $\vec{n}_k$

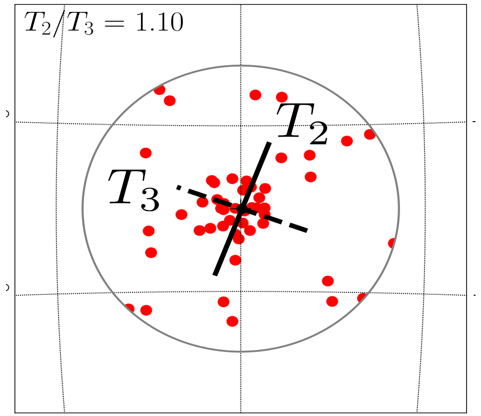


- Successively maximize T_k : $T_1 \geq T_2 \geq T_3$
- Ratio T_2/T_3 is a measure of the elongation of a pattern

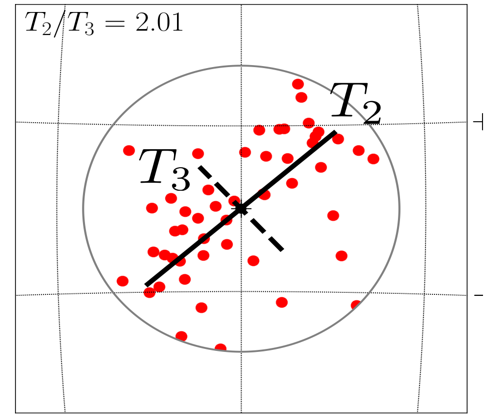
Isotropy: $T_2/T_3 \approx 1$



Overdensity: $T_2/T_3 \approx 1$



Elongated: $T_2/T_3 > 1$



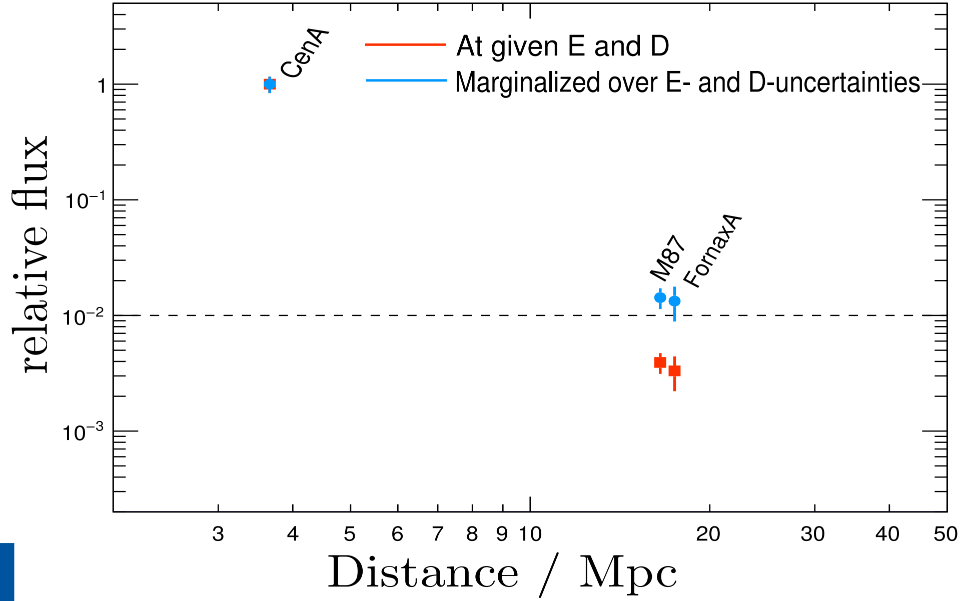
Target selection

- Probe catalogs of starburst galaxies (SBGs) and active galactic nuclei (AGNs)
- Selection is based on attenuation of helium at 40 EeV and given distance:

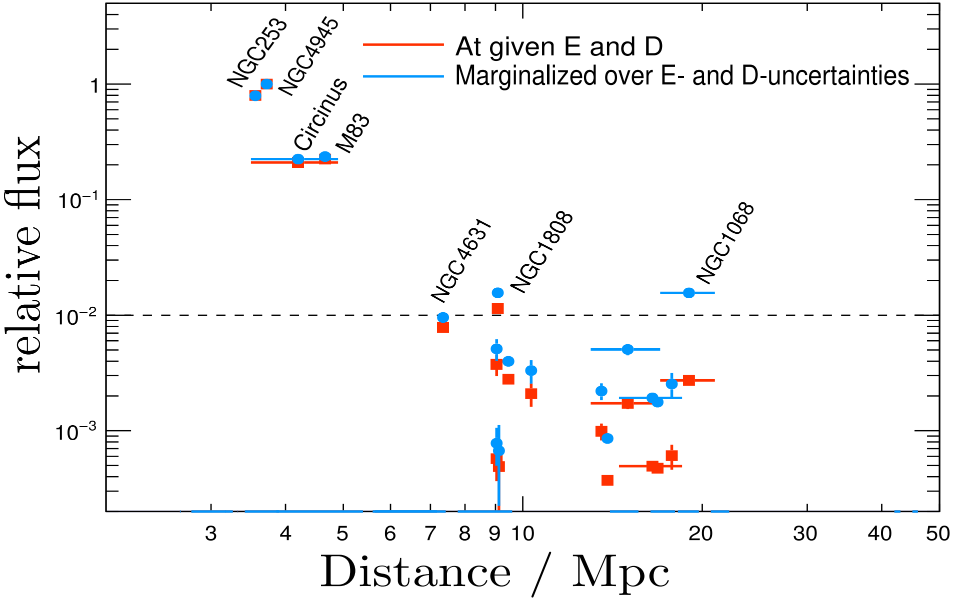
AGN: Cen A, M87, Fornax A

SBG: NGC 253, NGC 4945, Circinus, M83, NGC 4631, NGC 1808, NGC 1068

*Attenuation for **AGN** candidates*



*Attenuation for **SBG** candidates*

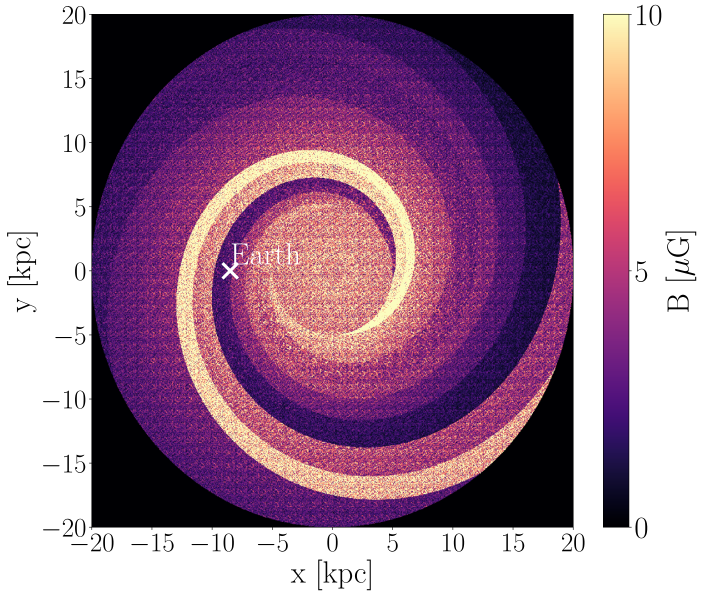


Benchmark simulations – Galactic magnetic field

- Test sensitivity of methods with simulation of arrival directions
- Upper and lower estimate of turbulence, two different models of GMF

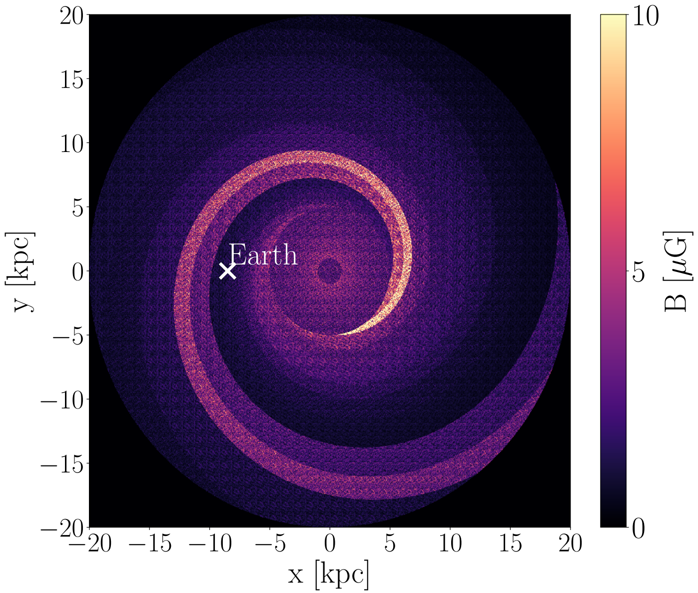
GMF-A

- Model of Jansson & Farrar (2012), including striated / turbulent fields
- Coherence length = 60 pc



GMF-B

- Large uncertainty on turbulence (Planck)
- No striated component / Kolmogorov field down-scaled amplitude to value of 1/3



Benchmark simulations – Arrivals from CenA

Scenarios

Energy spectrum

GMF-A

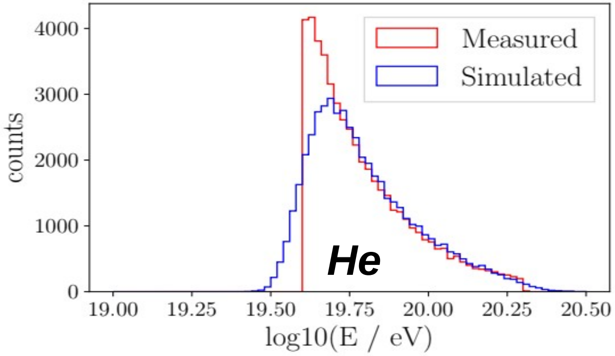
GMF-B

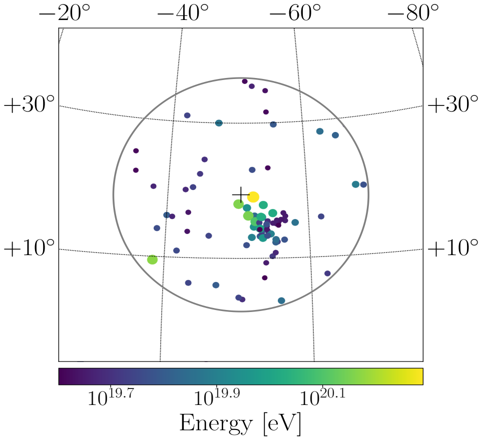
E_{min} = 40 EeV

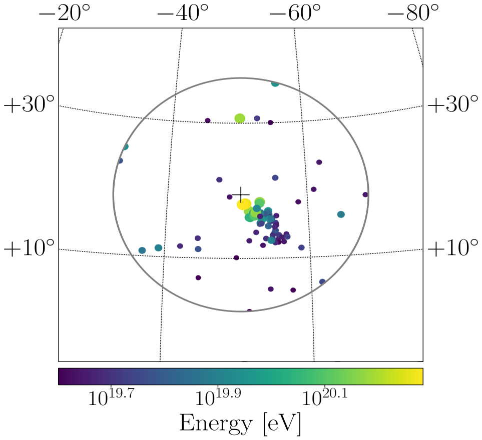
N_{CR} = 900

<u>Composition</u>:

He: [40, 200] EeV







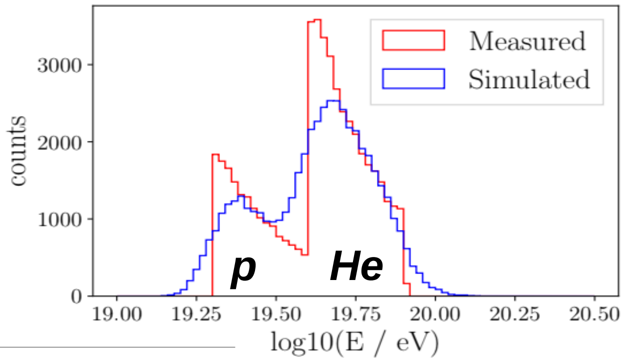
E_{min} = 20 EeV

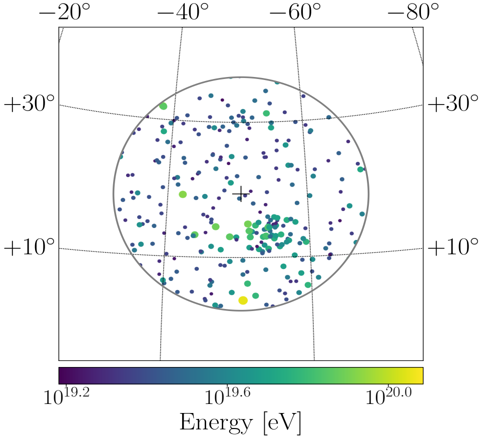
N_{CR} = 6000

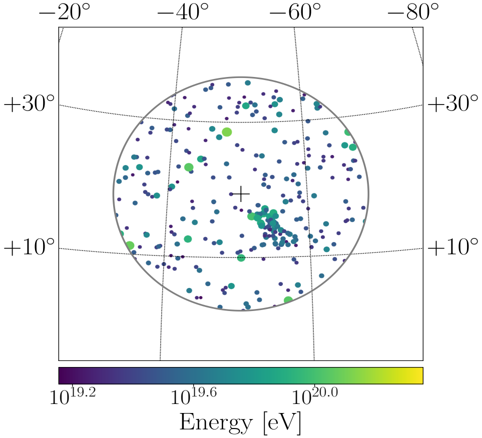
<u>Composition</u>:

p: [20, 40] EeV

He: [40, 80] EeV







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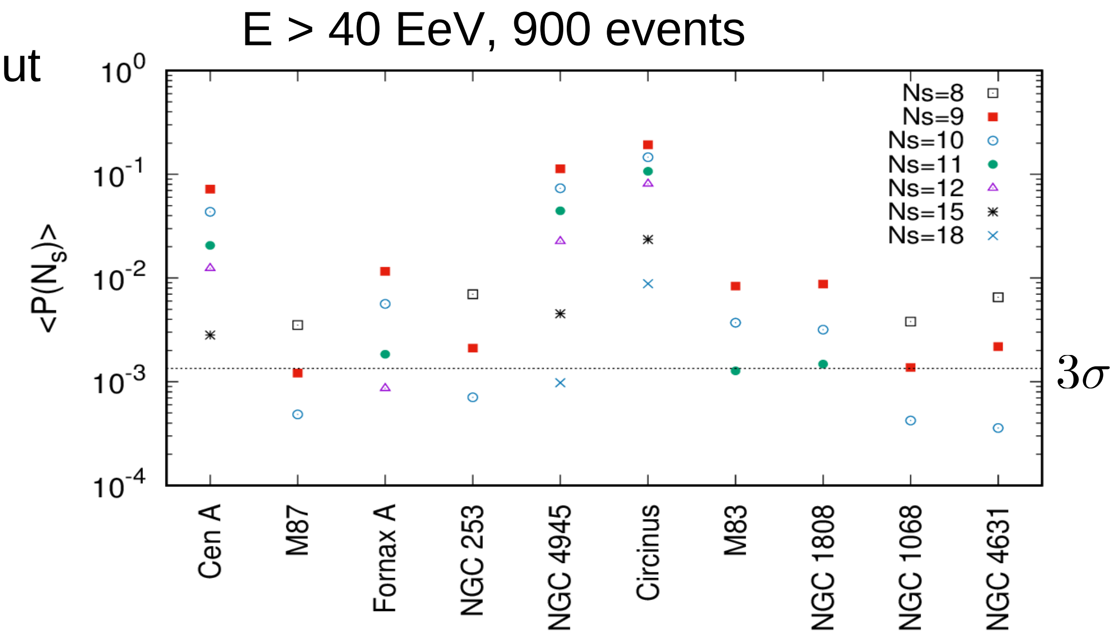
Expected sensitivity – Multiplet search

- Only applicable on 40 EeV energy cut
- Above 9 injected signal cosmic rays per source to obtain 3 sigma significance (1% signal fraction)
- Depends on source direction
- Sensitivity benefits from weaker turbulent field (GMF-B)



→ Above 1% signal fraction to obtain 3 sigma

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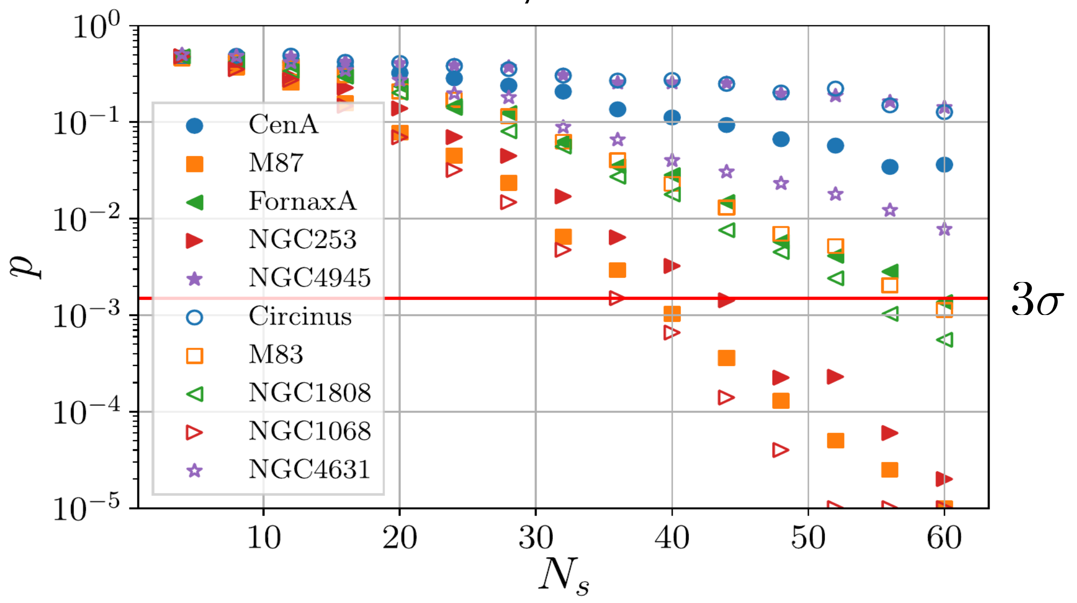
Expected sensitivity – Thrust ratio

- Thrust ratio works better at lower energy threshold, E > 20 EeV (at 40 EeV worse than multiplets)
- Signal fraction above 0.7% for 3 sigma confidence level
- Similar performance for GMF-A and GMF-B models (robustness)

E > 20 EeV, 6000 events



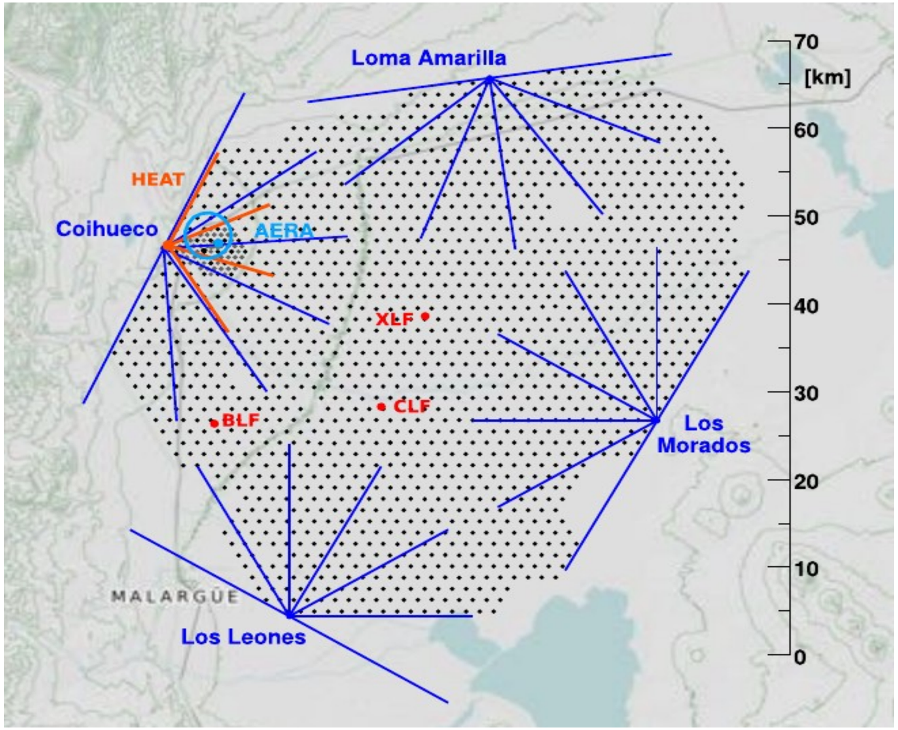
➡ Above 0.7% signal fraction to obtain 3 sigma

Data set

- Data taken at the Pierre Auger Observatory between 1 January 2004 and 31 August 2018
- <u>Surface detector</u>:
  1660 water-Cherenkov stations
- <u>Fluorescence detector</u>:
  27 telescopes at four different sites
- Events with reconstructed zenith angle below 80°

<u>Energy cuts</u>

- **E > 20 EeV**: 6568 events
- **E > 40 EeV**: 1119 events



Pierre Auger Observatory, Mendoza, Argentina

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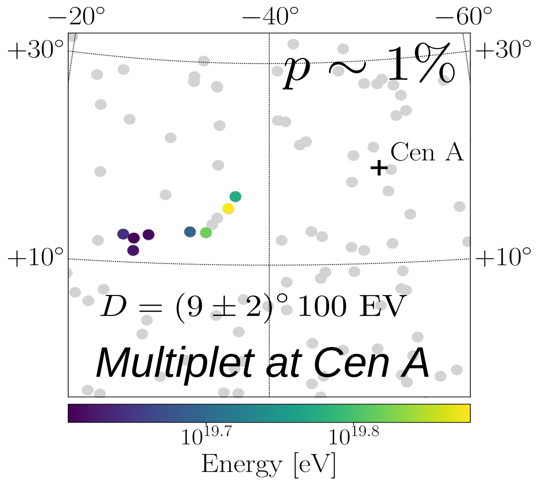
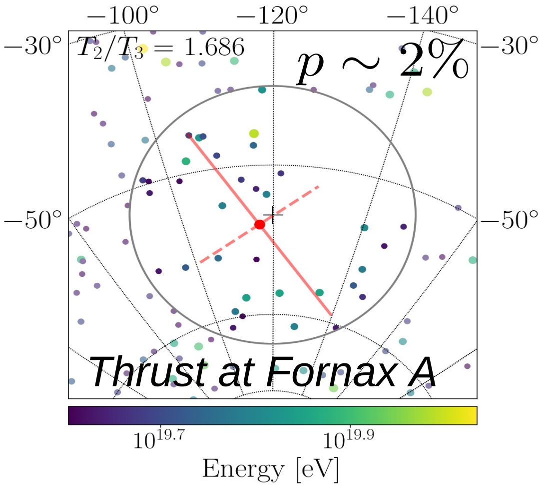
Targeted search

Isotropic chance probabilities			
Target	Multiplet (40 EeV)	Thrust-ratio (20 EeV)	Thrust-ratio (40 EeV)
Cen A	1.2×10^{-2}	0.75	0.42
M87	0.61	0.44	0.85
Fornax A	0.96	0.21	1.9×10^{-2}
NGC 253	0.54	0.98	0.88
NGC 4945	0.25	2.9×10^{-2}	3.7×10^{-2}
Circinus	0.99	0.82	0.58
M83	0.20	0.14	0.54
NGC 4631	—	0.59	0.85
NGC 1808	0.61	0.63	0.77
NGC 1068	0.75	6.0×10^{-2}	0.29



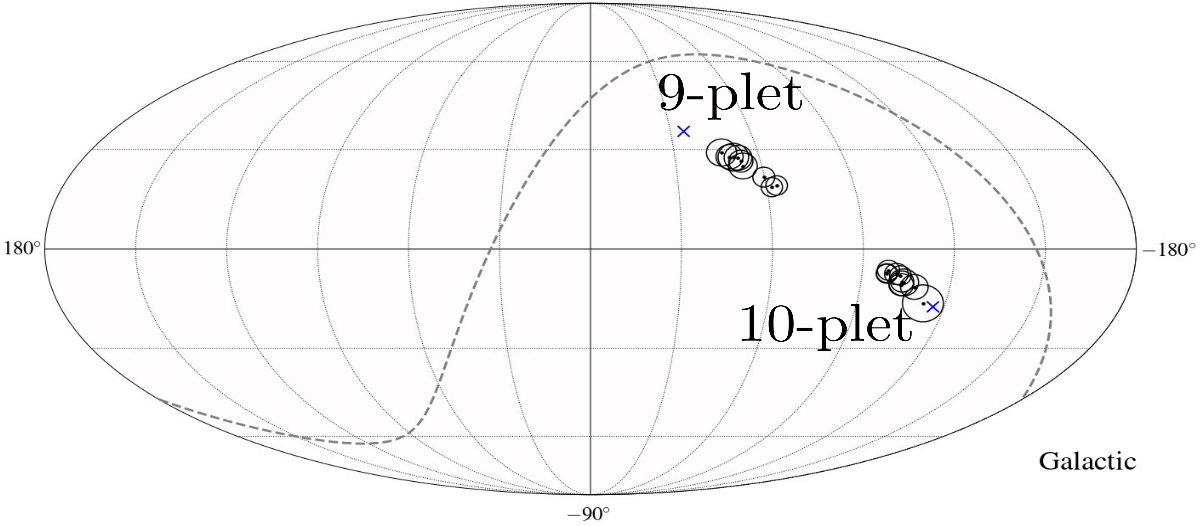


- There is <u>no significant pattern</u> found in the arrival directions for the multiplet search and the thrust ratio
- Multiplet search: lowest p-value is 1.2% in the Cen A region
- Thrust-ratio: lowest p-value is 2% in the Fornax A region

Blind search – Multiplets

Multiplet search also applied in an all-sky scan above 40 EeV

Multiplicity	Number of multiplets	Deflection power	p-value
10	1	(8.0 ± 1.3) deg 100 EV	0.114
9	1	(12 ± 2) deg 100 EV	0.191



⇒ None of the found multiplets is significant

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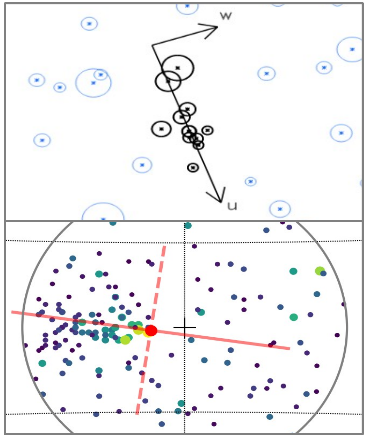
Summary

- Searched for source signatures with two methods in data of the Pierre Auger Observatory above 20 EeV (6568 events) and 40 EeV (1119 events)

- <u>Multiplet search</u>: correlation of deflection and inverse energy



- <u>Thrust ratio</u>: measure for elongation, constructed by principal component analysis

- Applied on: – **targeted search** (AGN and SBG candidates), both methods
  – **all-sky search** above 40 EeV, multiplet search

- **No significant pattern** has been found in data; lowest isotropic chance probabilities were found with 1% (2%) with the multiplet (thrust) search

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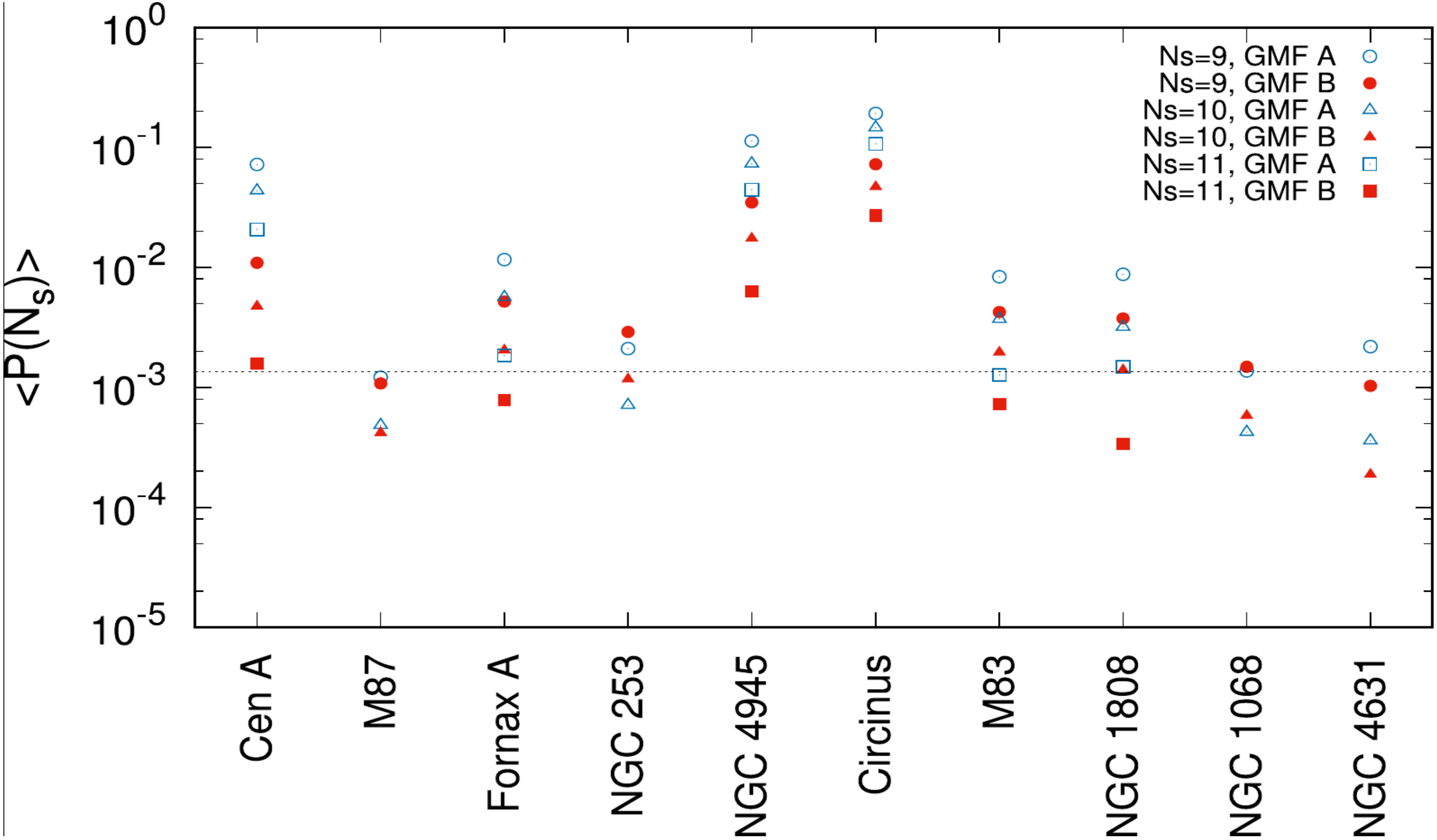
Backup

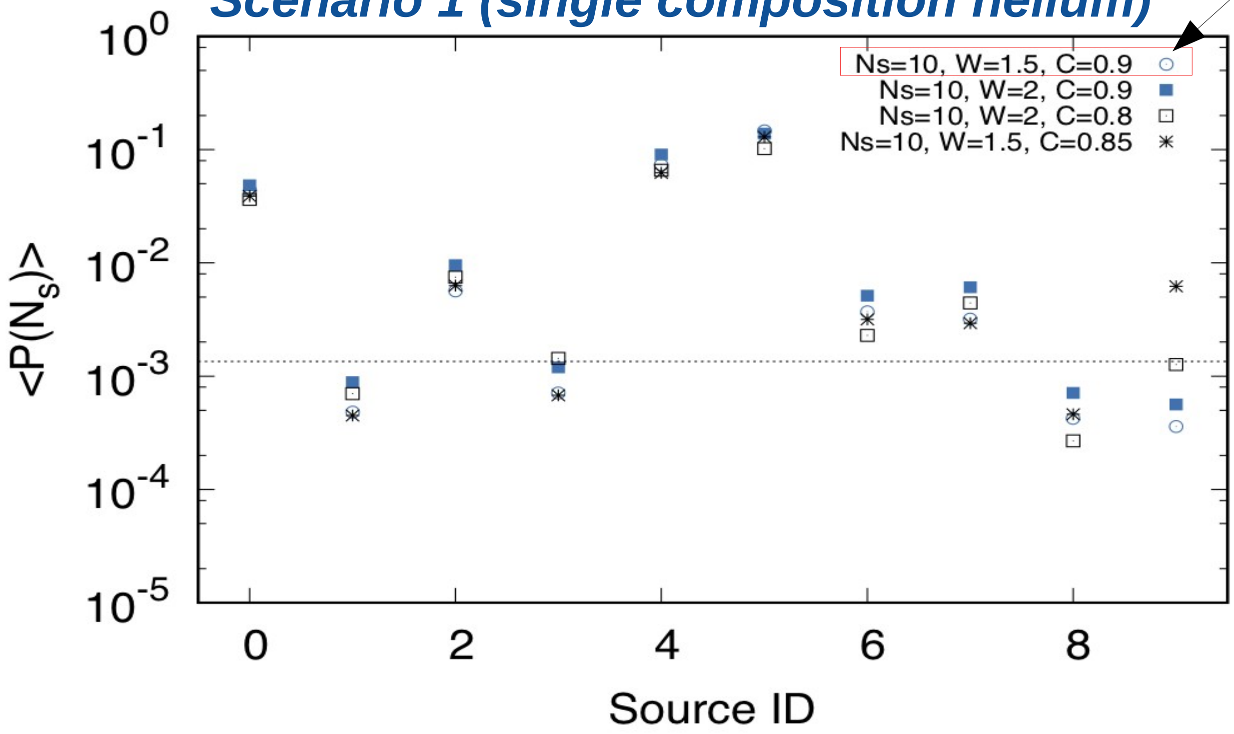
Multiplet method: GMF-A vs GMF-B



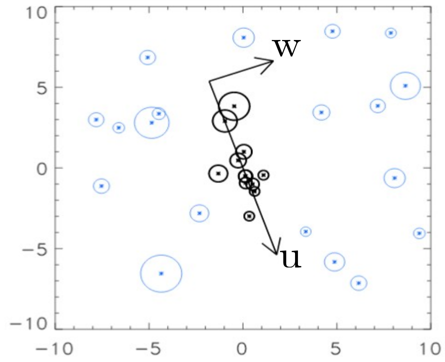
Multiplet method: study of hyperparameters

previous slide

Scenario 1 (single composition helium)



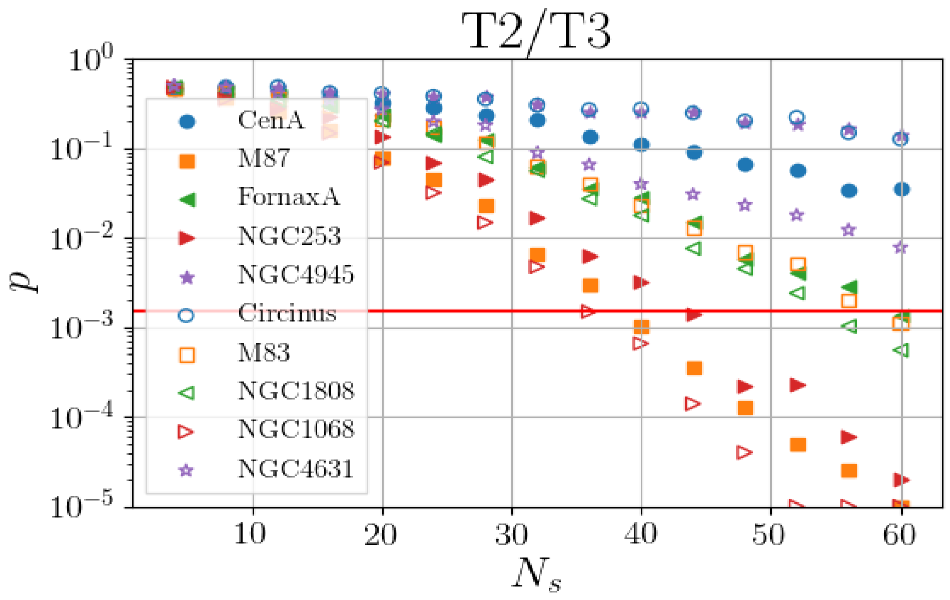
Source ID: 0=CenA, 1=M87, 2=FornaxA, 3=NGC253, 4=NGC4945, 5=Circinus, 6=M83, 7=NGC1808, 8=NGC1068, 9=NGC4631



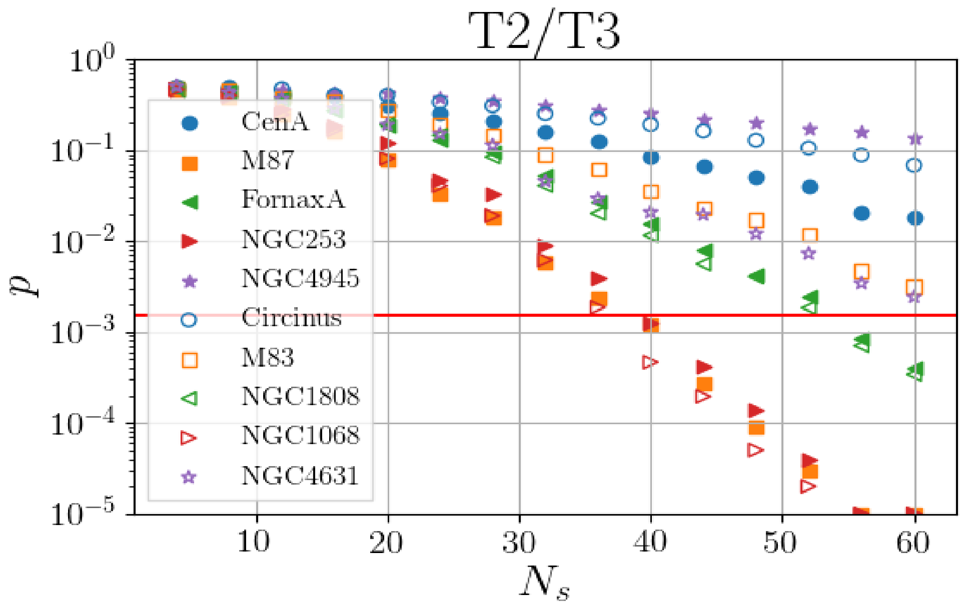
- No strong dependency on variations in hyperparameters
- W < 1.5, C > 0.9, works well for most sources

Thrust ratio on GMF-A vs. GMF-B

A) JF12 + stri + turb (B_{rms}=1)

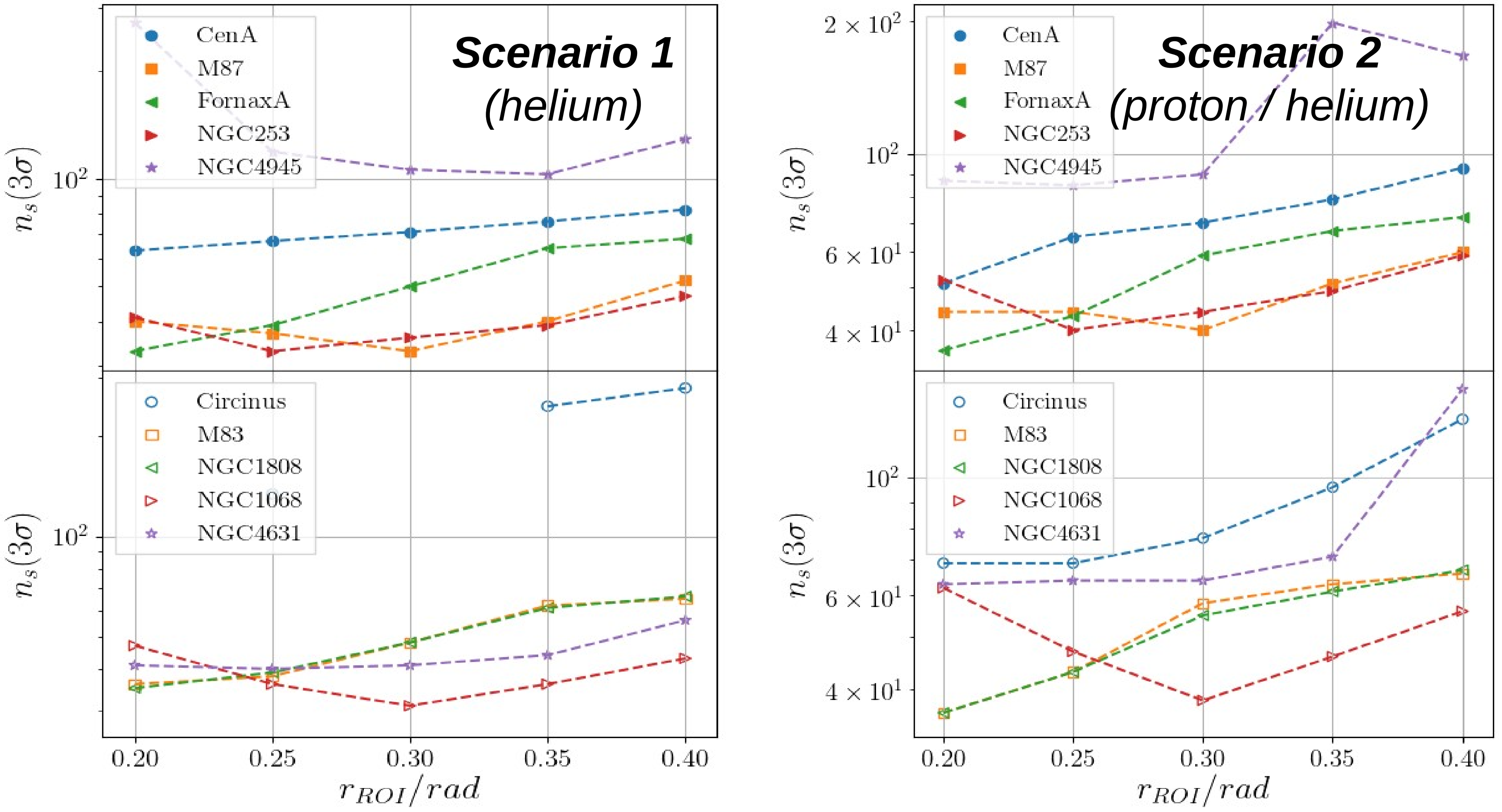


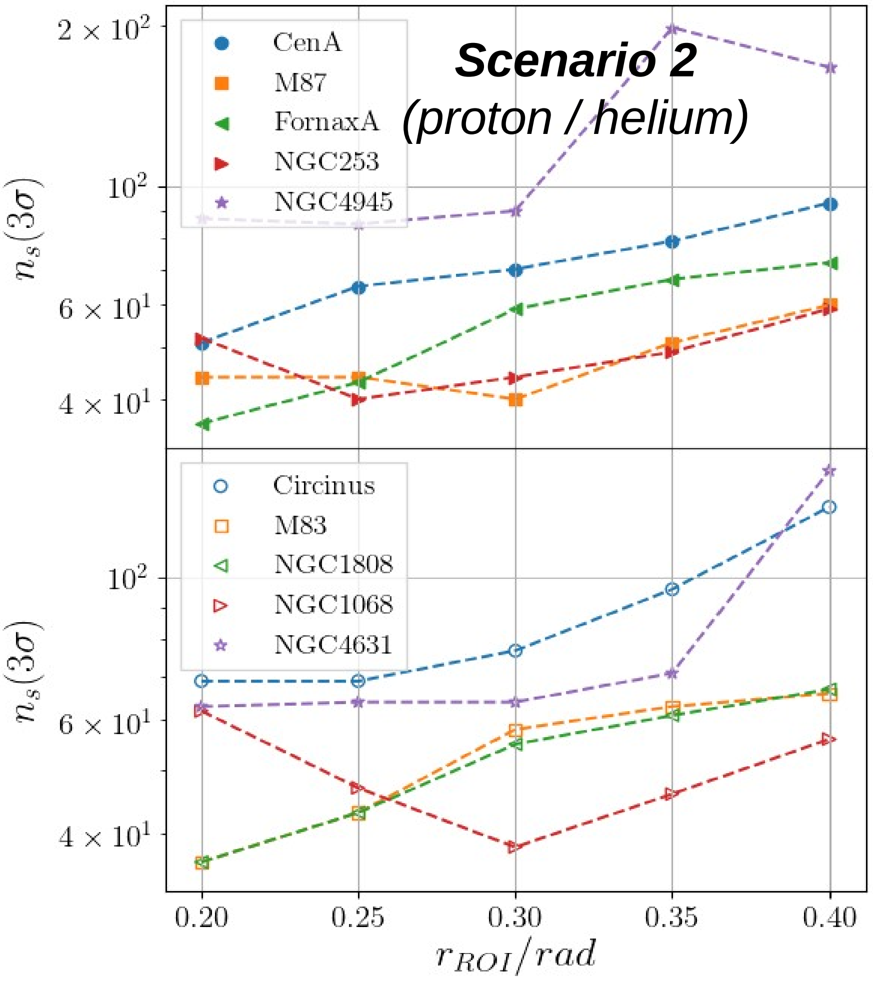
B) JF12 + turb (B_{rms}=1/3)

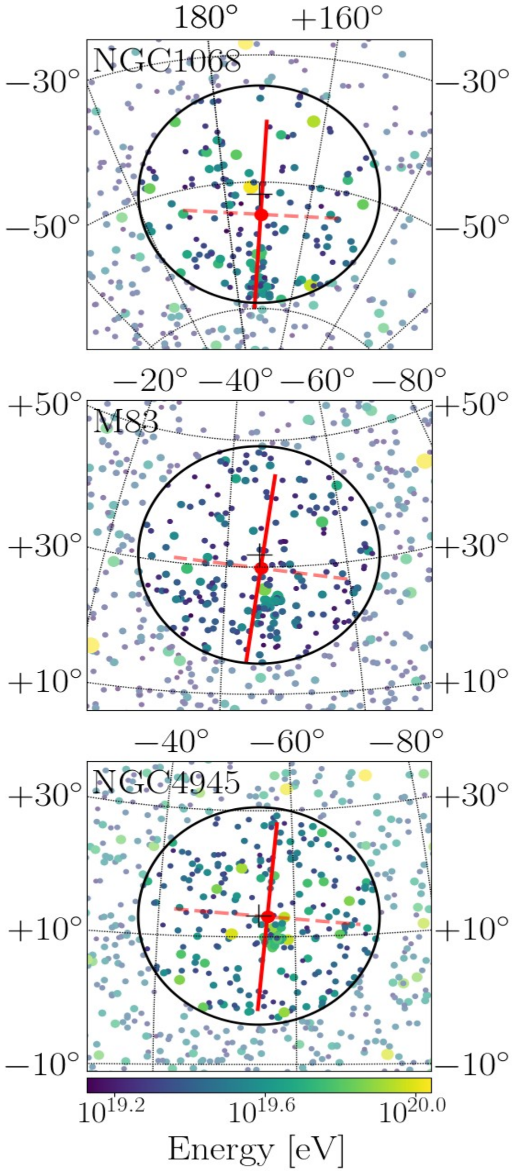


Less turbulence, performance gets a bit better
However, effect not very big (thrust observable robust)

ROI size scan for Thrust – JF12 Full, B_{RMS}=1







For ROI radius r = 0.3 rad

There is no clear best choice as it depends on the deflection power

Depends on direction in sky (and GMF model)

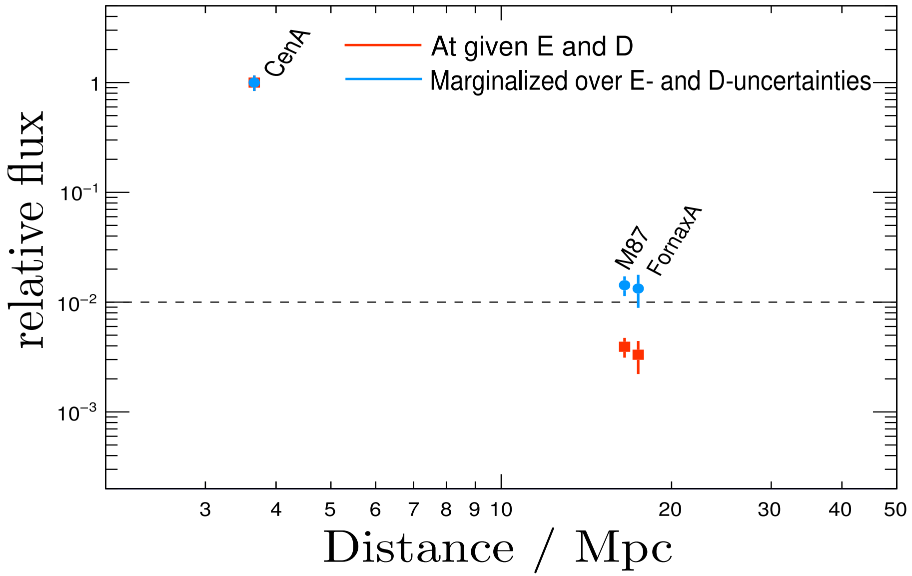
Overall r=0.3 rad seems to be OK

Target selection

- **3FHL**: The Third Catalog of HardFermi-LAT Sources (Fermi-Lat Collaboration)
- Distances up to 250 Mpc
- 33 sources before selection
- Cen A, M87, Fornax A

- Merged sample from (Ackermann 2012) and (Becker 2009) + Circinius
- Distances up to 250 Mpc
- 32 sources before selection
- NGC 253, NGC 4945, Circinus, M83, NGC 4631, NGC 1808, NGC 1068

*Attenuation for **AGN** candidates*



*Attenuation for **SBG** candidates*