The Connection Between Ultra-High-Energy Cosmic Rays and *Fermi* Gamma-Ray Sources

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Introduction

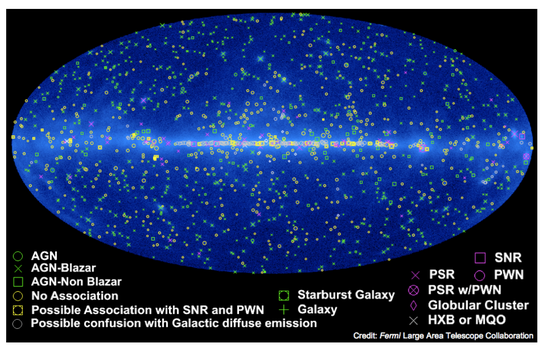
Ultra-high-energy cosmic rays (UHECRs) are particles bombarding Earth with energies ≥ 10^{20} eV and these events are rare (~ few detections km^{-2} millenium^{-1}). We don't know their (i) composition, (ii) production sites and (iii) how they get here.

Their possible production sites include: AGNs, Υ-ray bursts and neutron stars/ pulsars. If their "astrophysical accelerators" are located nearby, we should expect anisotropic arrival directions of UHECRs associated with the distribution of their astrophysical sources.

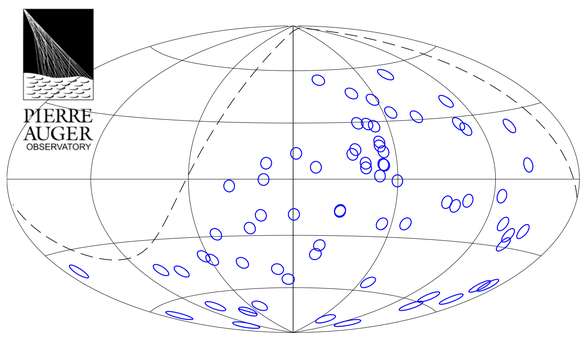
The Pierre Auger Observatory (PAO) has been mapping the arrival direction of UHECRs with a ≈1º precision. This makes correlation studies of UHECRs with catalogs of sources a powerful tool to track the UHECR production sites (e.g., Abraham et al. 2007, 2008; Abreu et al. 2010).

In this work, we report on the results of cross-correlating the arrival direction measured by PAO with the 1FGL/1LAC catalogs of Υ-ray sources produced by *Fermi* LAT (Nemmen et al. 2010, ApJ, 722, 281). Our goal is to unveil whether specific types of γ -ray sources might be driving any correlation and at what angular separations these correlations become significant.

Data



Fermi LAT First Source Catalog (1FGL)
1451 Υ-ray sources



Abraham et al. (2007): 27 UHECR events
Abreu et al. (2010): 69 events

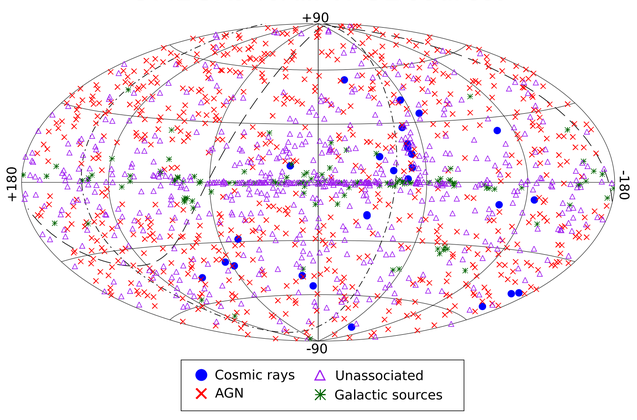
Cross-correlation method

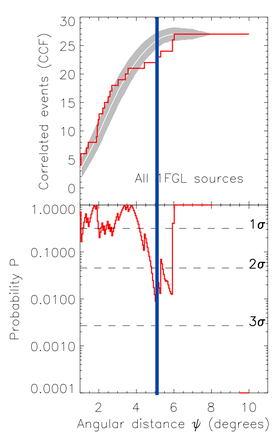
This method was inspired by Stephen et al. (2005); Hague et al. (2009) and consists of computing the probability of accidental correlation due to an isotropic UHECR flux vs. the observed configuration.

Steps:
1. Count associations between measured UHECRs and a given source catalog
2. Monte Carlo simulation of an isotropic UHECR flux → distribution of chance correlations (null hypothesis)
3. Compare distribution of expected chance associations vs. observed configuration

Results

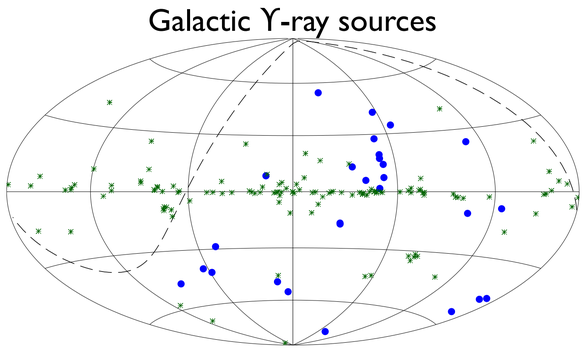
UHECRs vs. all 1FGL sources

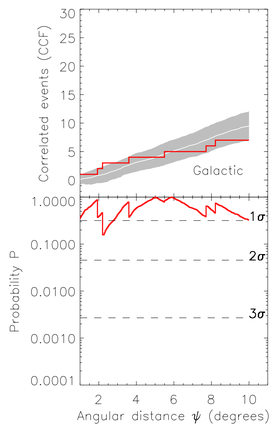




P_{min} = 0.006
S_{max} = 2.7σ
ψ = 5.1°
∴ weak correlation

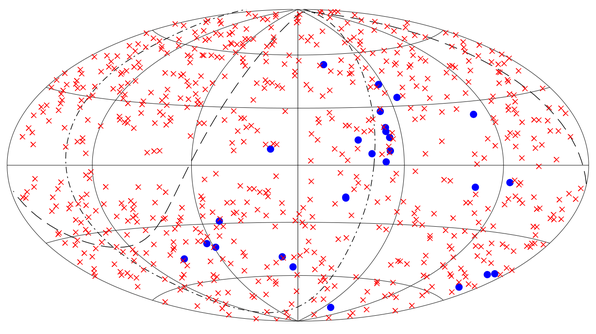
Galactic Υ-ray sources

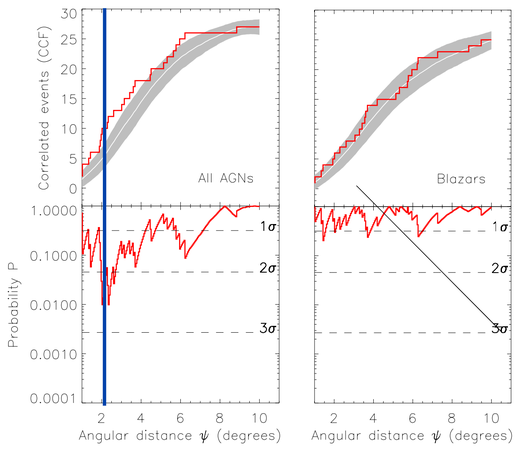




S < 1σ :
no correlation

Υ-ray AGNs (1LAC)

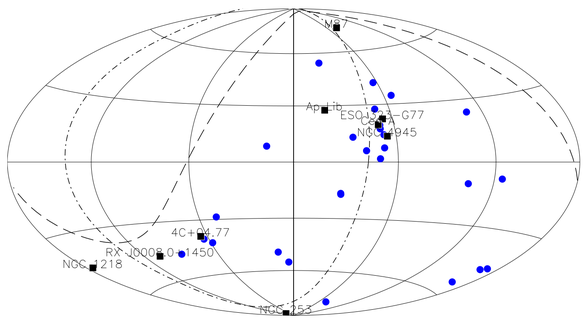


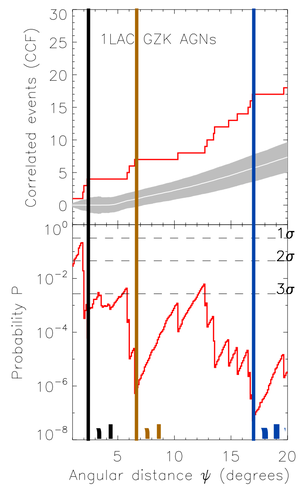


P_{min} = 0.01, S_{max} = 2.6σ
ψ = 2.4°
∴ weak correlation

S < 1σ :
no correlation

Nearby Fermi AGNs vs. 2007 PAO data:
GZK cut, $d \leq 200$ Mpc, $z \leq 0.048$
(9 sources in the PAO field)

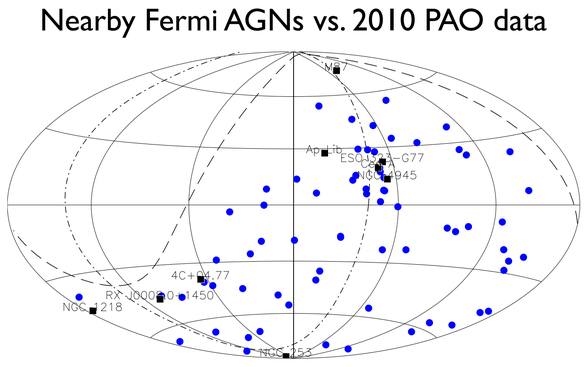


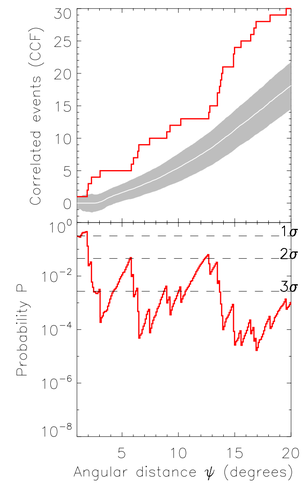


ψ_1 = 2.3°
P = 6×10^{-5}
S = 4σ
ψ_2 = 6.5°
P = 5×10^{-7}
S = 5σ
ψ_3 = 17°
P_{min} = 5×10^{-8}
S_{max} = 5.4σ

Strong correlation at ψ_2, ψ_3!

Nearby Fermi AGNs vs. 2010 PAO data





ψ_3 = 17°
P_{min} = 2×10^{-5}
S_{max} = 4.3σ

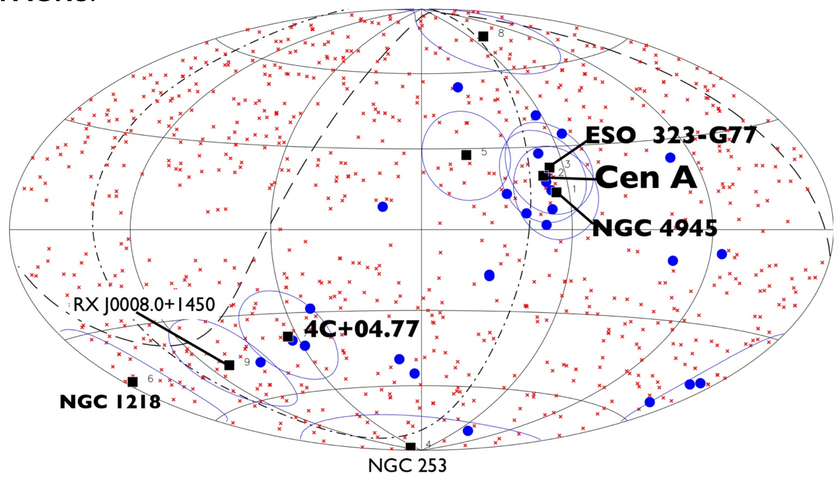
Significance of correlation decreases with new PAO data!

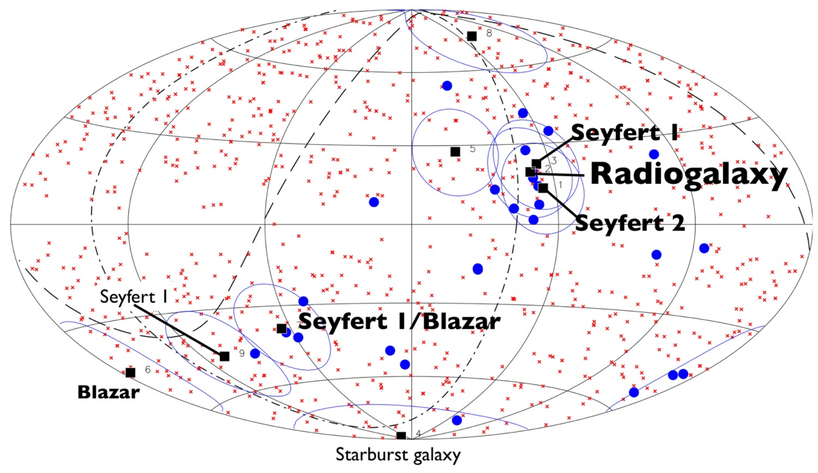
Angular separations vs. deflection angles

Correlation signal will be helpful to constrain results of simulations of the propagation of UHECRs from extragalactic sources. For instance, our inferred angular distance ψ_3 ~ 17º - which corresponds to the maximum significance 5.4σ is within the range of deflection angles simulated by Ryu et al. (2010): ~14 - 17.5º (see also Sigl et al.).

The potential UHECR accelerators

17/27 UHECRs (2007 PAO data) and 28/69 events (2010 PAO data) located within 16.9º of **7 nearby Fermi AGNs**!





Main accelerator candidates

Cen A

ESO 323-G77:
- ~4000 km/s outflow
- Broad Fe Kα line: rapidly spinning black hole?

(Jiménez-Bailón+ 08)

NGC 4945

Conclusions (Nemmen et al. 2010, ApJ, 722, 281)

- Analysis of correlation between astrophysical Υ-ray sources (*Fermi* LAT) and UHECRs (Pierre Auger):
  - Galactic Υ-ray sources: no correlation
  - All AGNs (1LAC): weak correlation (2.6σ)
  - 1LAC blazars: no correlation
  - Nearby 1LAC AGNs (<200 Mpc): strong correlation (>5σ) at two separation scales, ~7º and ~17º
- 17/27 UHECRs (2007 PAO data) → 7 nearby AGNs:
  These AGNs are strong Υ-ray emitters and UHECR accelerator candidates!
- Strength of correlation decreases with updated 2010 PAO data