Investigating an angular correlation between nearby starburst galaxies and UHECRs with the Telescope Array experiment

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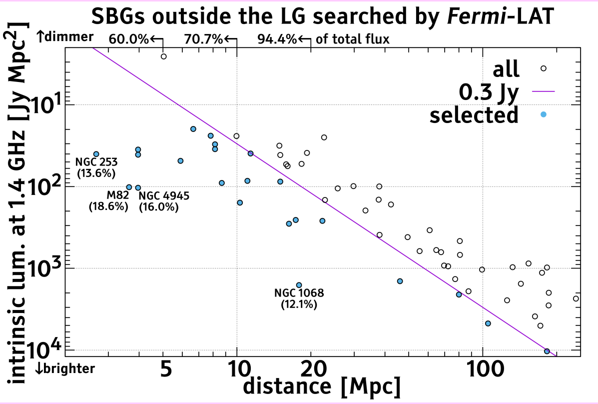
Abstract: The arrival directions of cosmic rays detected by the Pierre Auger Observatory (Auger) with energies above 39 EeV were recently reported to correlate with the positions of 23 nearby starburst galaxies (SBGs): in their best-fit model, 9.7% of the cosmic-ray flux originates from these objects and undergoes angular diffusion on a 12.9° scale. On the other hand, some of the SBGs on their list, including the brightest one (M82), are at northern declinations outside the Auger field of view. Data from detectors in the northern hemisphere would be needed to look for cosmic-ray excesses near these objects. In this work, we preliminarily tested the Auger best-fit model against data collected by the Telescope Array (TA) in a 9-year period, without trying to re-optimize the model parameters for our dataset in order not to introduce statistical penalties. The resulting test statistic (double log-likelihood ratio) was −1.00, corresponding to 1.1σ significance among isotropically generated random datasets, and to −1.4σ significance among ones generated assuming the Auger best-fit model. In other words, our data is still insufficient to conclusively rule out either hypothesis. The ongoing fourfold expansion of TA will collect northern hemisphere data with much more statistics, improving our ability to discriminate between different flux models.

The Auger analysis [1]

Assumed sources (23 starburst galaxies)

- 64 objects outside the Local Group searched by *Fermi*-LAT for gamma-ray emission [2] (only found from 4 of them)
- Only objects with $\varphi_{1.4\ \mathrm{GHz}} \geq 0.3$ Jy selected (23 objects)
- UHECR luminosity ∝ star-formation rate ∝ radio luminosity



The flux model

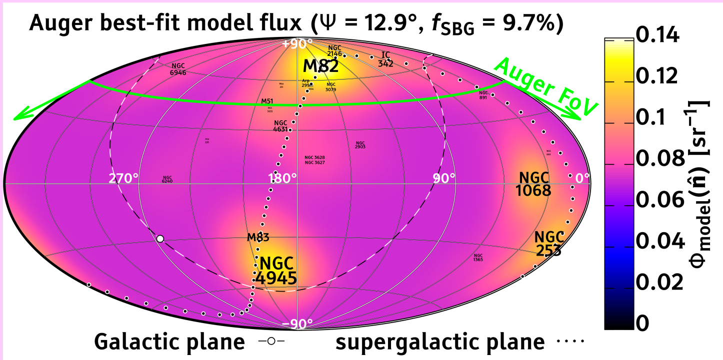
- $\hat{\mathbf{n}}$ = unit vector (pointing away from the observer)
- $\Phi_{\mathrm{SBG}}(\hat{\mathbf{n}}) \propto \sum_{\mathrm{sources}} \varphi_{\mathrm{source}} \exp(\hat{\mathbf{n}} \cdot \hat{\mathbf{n}}_{\mathrm{source}}/\Psi^2)$ (von Mises–Fisher distribution, spherical analog of Gaussian; Ψ = RMS deviation in each transverse dimension)
- $\Phi_{\mathrm{model}}(\hat{\mathbf{n}}) = f_{\mathrm{SBG}}\Phi_{\mathrm{SBG}}(\hat{\mathbf{n}}) + (1 - f_{\mathrm{SBG}})\Phi_{\mathrm{iso}}$ ($\Phi_{\mathrm{iso}} = 1/4\pi$)

The log-likelihood ratio test

- Null hypothesis: isotropic flux, $\Phi_1(\hat{\mathbf{n}}) = \Phi_{\mathrm{iso}} = 1/4\pi$
- Alternative hypothesis: $\Phi_2(\hat{\mathbf{n}}) = \Phi_{\mathrm{model}}(\hat{\mathbf{n}})$
- Directional exposure of the detector: $\omega(\hat{\mathbf{n}})$
- Likelihood: $L_i = \prod_{\mathrm{events}} \Phi_i(\hat{\mathbf{n}}_{\mathrm{event}})\omega(\hat{\mathbf{n}}_{\mathrm{event}}) / \int_{4\pi} \Phi_i(\hat{\mathbf{n}})\omega(\hat{\mathbf{n}})\,d\Omega$
- Test statistic: TS = $\ln(L_2/L_1)$
- TS > 0: Φ_2 favored over Φ_1; TS < 0: vice versa
- Search for $E_{\min} \in$ [20 EeV, 80 EeV], Ψ, f_{SBG} maximizing TS

Results

- Best-fit parameters: Ψ = 12.9°, f_{SBG} = 9.7%, $E_{\min}$ = 39 EeV
- Favored over isotropy at 4σ
- Favored over overall matter distribution at 3σ



But what about the northern polar cap?

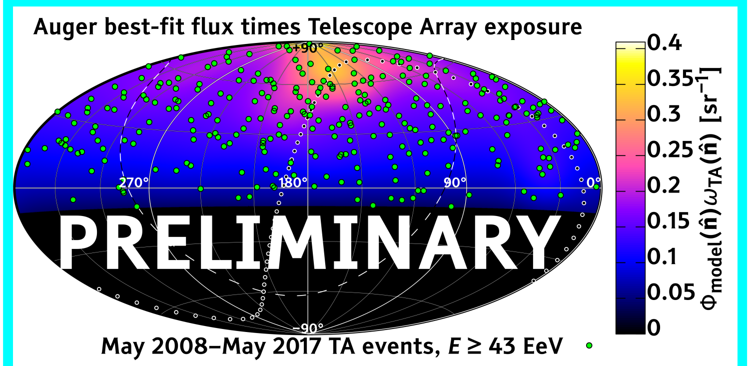
The Telescope Array follow-up [3]

The analysis

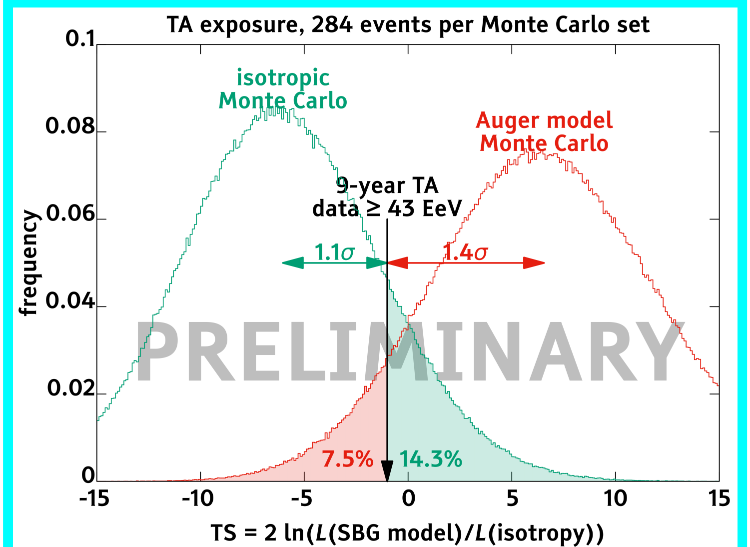
- Same sources and parameters as Auger-best fit
- No scan over parameters, no statistical penalty
- UHECR attenuation neglected, found negligible by Auger (most of the flux from within a few Mpc)

The dataset (284 events)

- Detector located at 39.3° N, 112.9° W; 700 km² area
- Events recorded from May 2008–May 2017 (9 years)
- Loose quality cuts [4]
- Zenith angle $\theta \leq 55°$; declination $\delta \geq -10°$
- Energy $E \geq 43$ EeV   (39 EeV + 10%, as per spectrum WG [5])
- Resolution ($\lesssim$20% on E, $\lesssim$1.5° on $\hat{\mathbf{n}}$) neglected
- Detector assumed fully efficient, geometrical exposure



Result



- We still can't rule out either hypothesis

More data needed — wait for TA×4 [6]!

References

[1] A. Aab *et al.* [Pierre Auger collab.], *ApJL* 835 (2018) L29 [1801.06160]
[2] M. Ackermann *et al.* [*Fermi*-LAT collab.], *ApJ* 755 (2012) 164 [1206.1346]
[3] R.U. Abbasi *et al.* [Telescope Array collab.], submitted to *ApJL* (2018) [1809.01573]
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[5] D. Ivanov for the Pierre Auger and Telescope Array collabs., *PoS* ICRC2017 (2018) 498 [1801.01018]
[6] E. Kido for the Telescope Array collab., *PoS* ICRC2017 (2018) 386