17aEL104-7

Measurement of the Dipole Anisotropy of Electron+Positron Cosmic Rays with CALET

Holger Motz[1] and Yosui Akaike[2,3]
for the CALET collaboration

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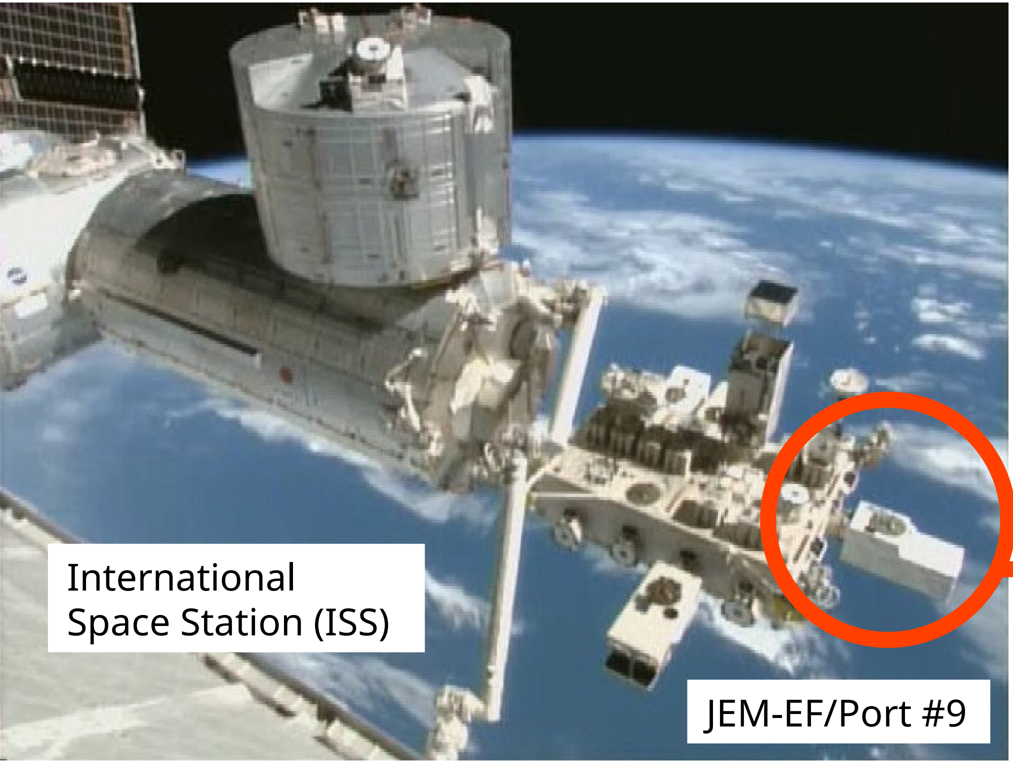
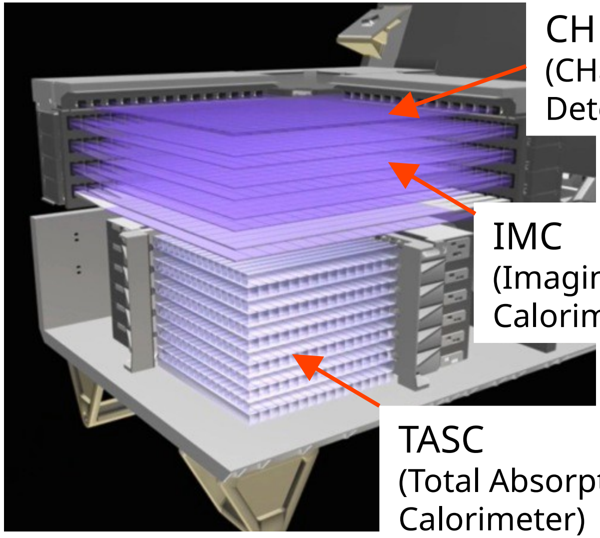
[1] **Waseda University, Faculty of Science and Engineering, Global Center for Science and Engineering**
[2] **Waseda University, Waseda Research Institute for Science and Engineering**
[3] **Japan Aerospace Exploration Agency, Human Spaceflight Technology Directorate, Space Environment Utilization Center**

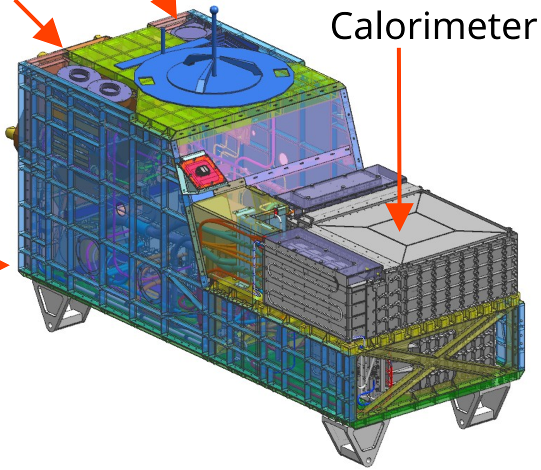
CALorimetric Electron Telescope

Aug. 2015: launched and installed on the ISS
Oct. 2015: beginning of data-taking
Stable operation up to now,
mission extended until the end of 2030.



geometric acceptance: ~ 0.1 m^2 sr

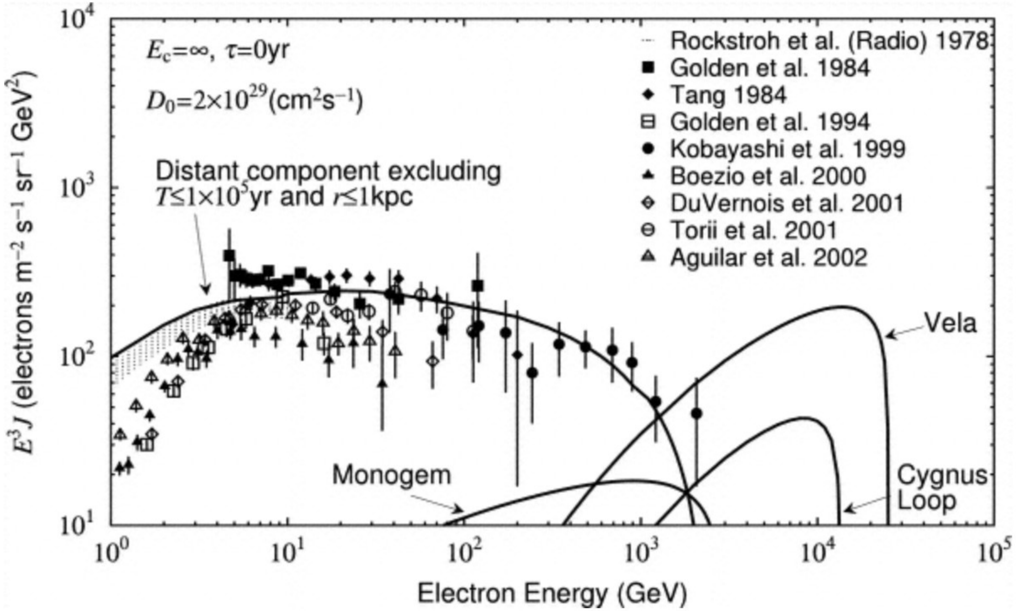




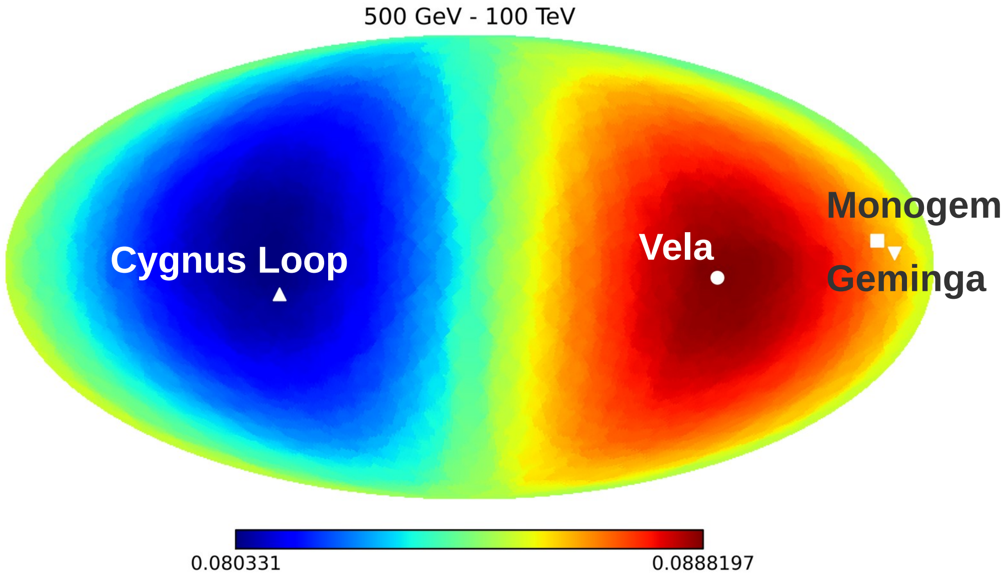
total radiation thickness: 30 X_0
(Fermi-LAT: 8.6X_0)

→ fully contained showers up to TeV energies, 2% energy resolution

Motivation for Anisotropy Search



[Astrophys. J. 601, 340 (2004)]



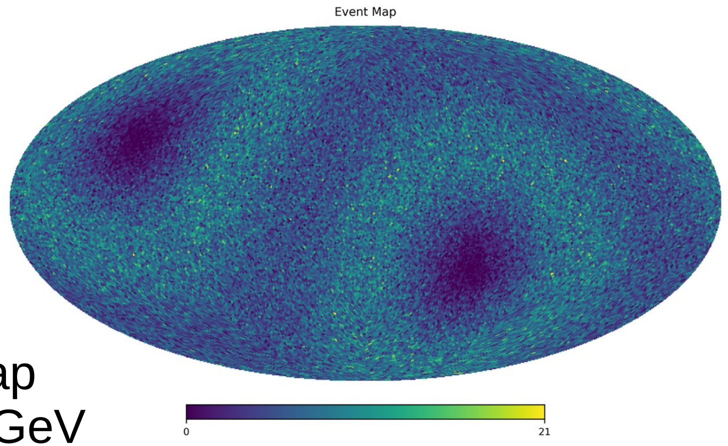
[PoS ICRC2017, 265]

- The electron+positron cosmic-ray flux in the TeV energy region is expected to originate from nearby supernova remnants (SNR), the Vela SNR may dominate the spectrum.
- A dipole anisotropy in the measured flux could originate from such a dominating single source and would be a valuable signature to verify cosmic ray acceleration by SNRs.

Analysis Method

- Data sample: 3×10^5 electron candidate events above 50 GeV energy from 2015/10/13 to 2024/12/31 (3368 days), below 475.5 GeV geometry condition A+B only, all geometry conditions (A-D) above 475.5 GeV
- Events above a given threshold energy are filled into HEALPix maps (NSIDE=64: ~50000 pixels) in galactic coordinates
- Monopole (C_0) and Dipole (C_1) coefficients as well as the dipole vector direction are calculated with HEALPix
- The dipole amplitude δ is given by: $\delta = 3\sqrt{\frac{C_1}{C_0}}$
- If the dipole is dominating:

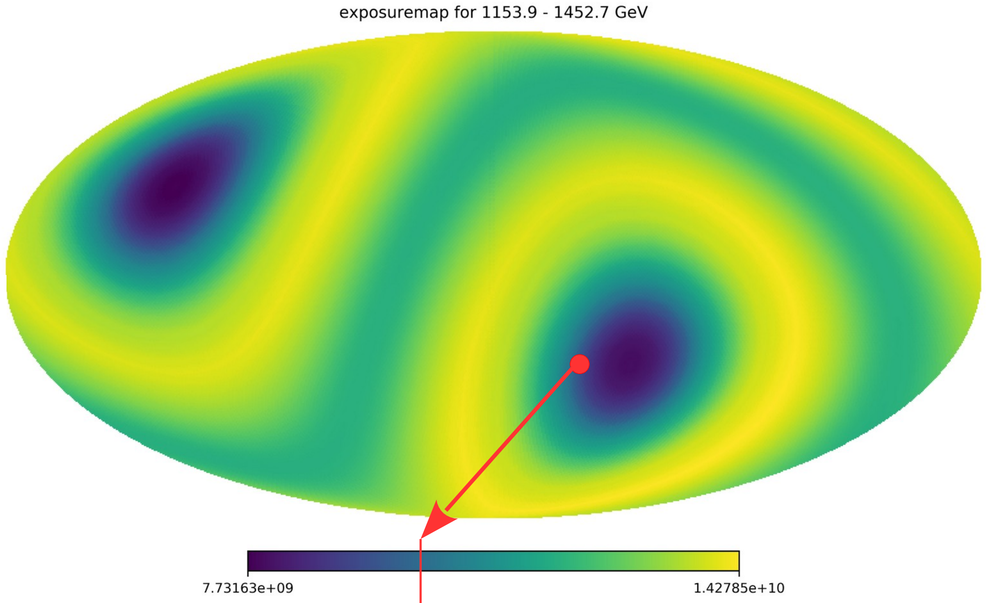
$$\delta \approx \frac{\phi_{max} - \phi_{min}}{\phi_{max} + \phi_{min}}$$



Event map
for E>50GeV

Correction of Non-Uniform Exposure

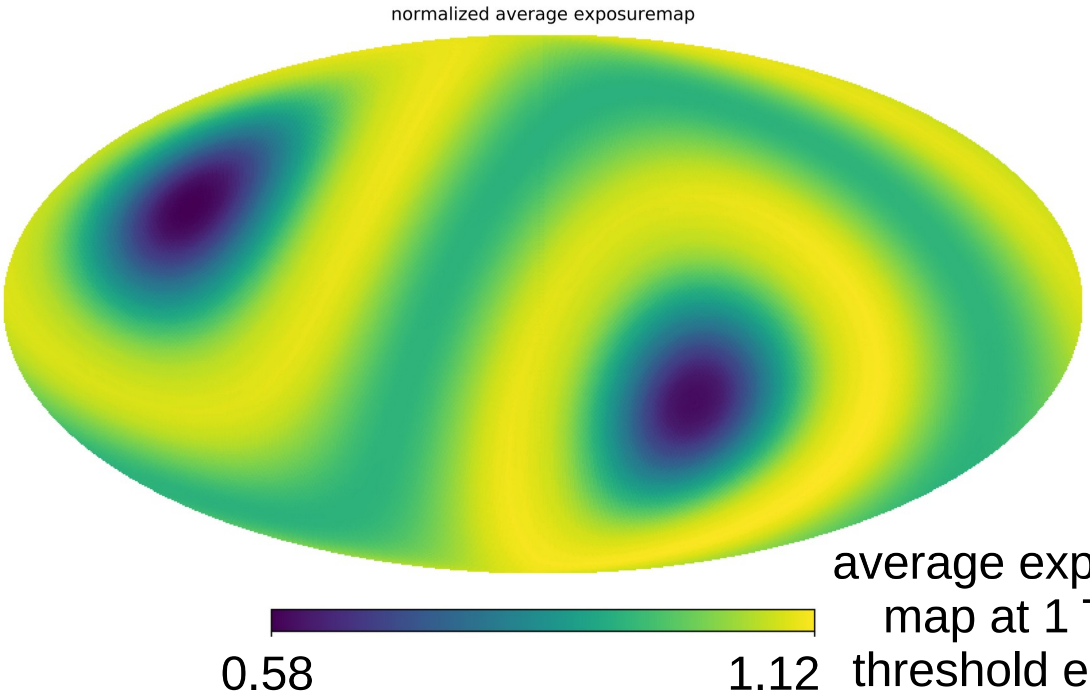
The non-uniform exposure to the sky is compensated by weighting each event with the inverse of the exposure for its direction and energy normalized to the total exposure



A_i : exposure for event *i*

w_i : weight for event *i*

$$w_i = \frac{1}{A_i} \left(\frac{\sum_{events} \sum_{pixels} A(E, pixel)}{N_{events} N_{pixels}} \right)$$

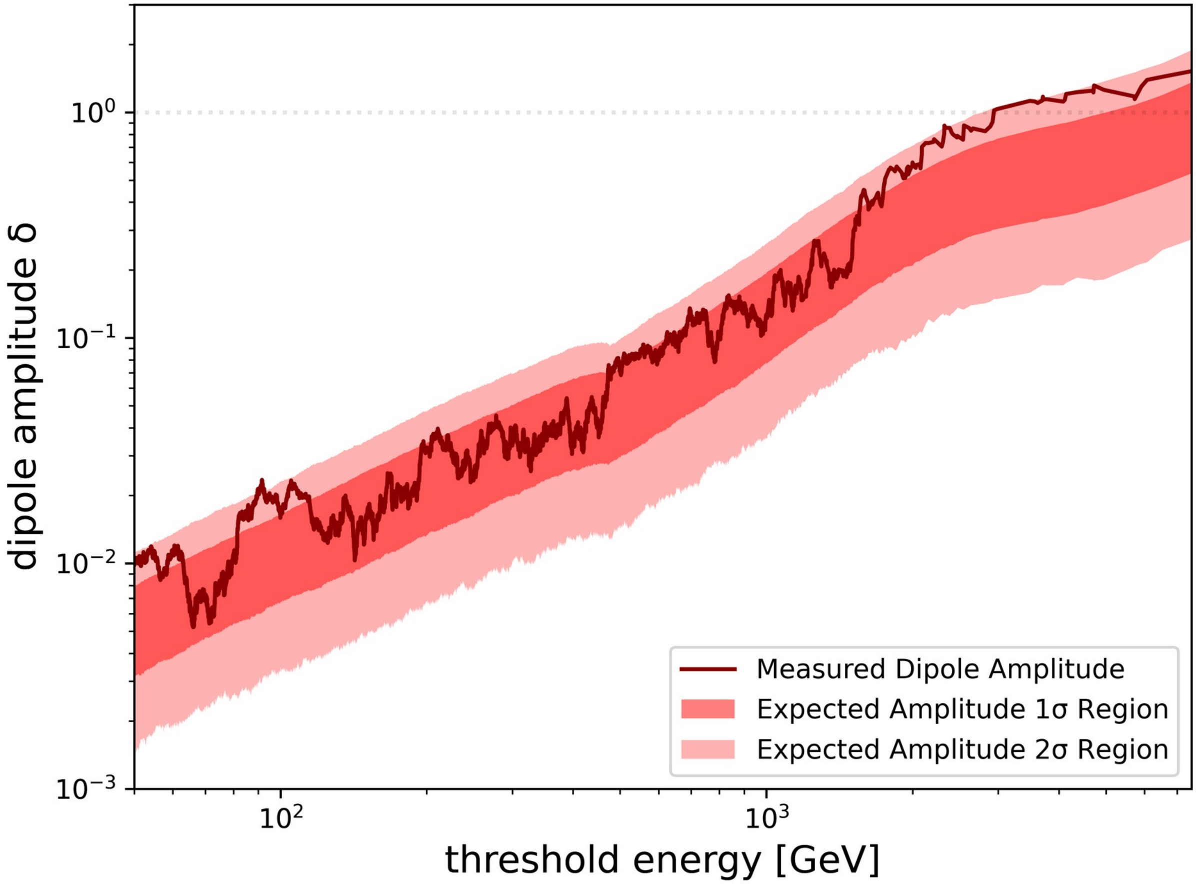


average exposure map at 1 TeV threshold energy

Simulation of Expected Dipole Amplitude from White Noise

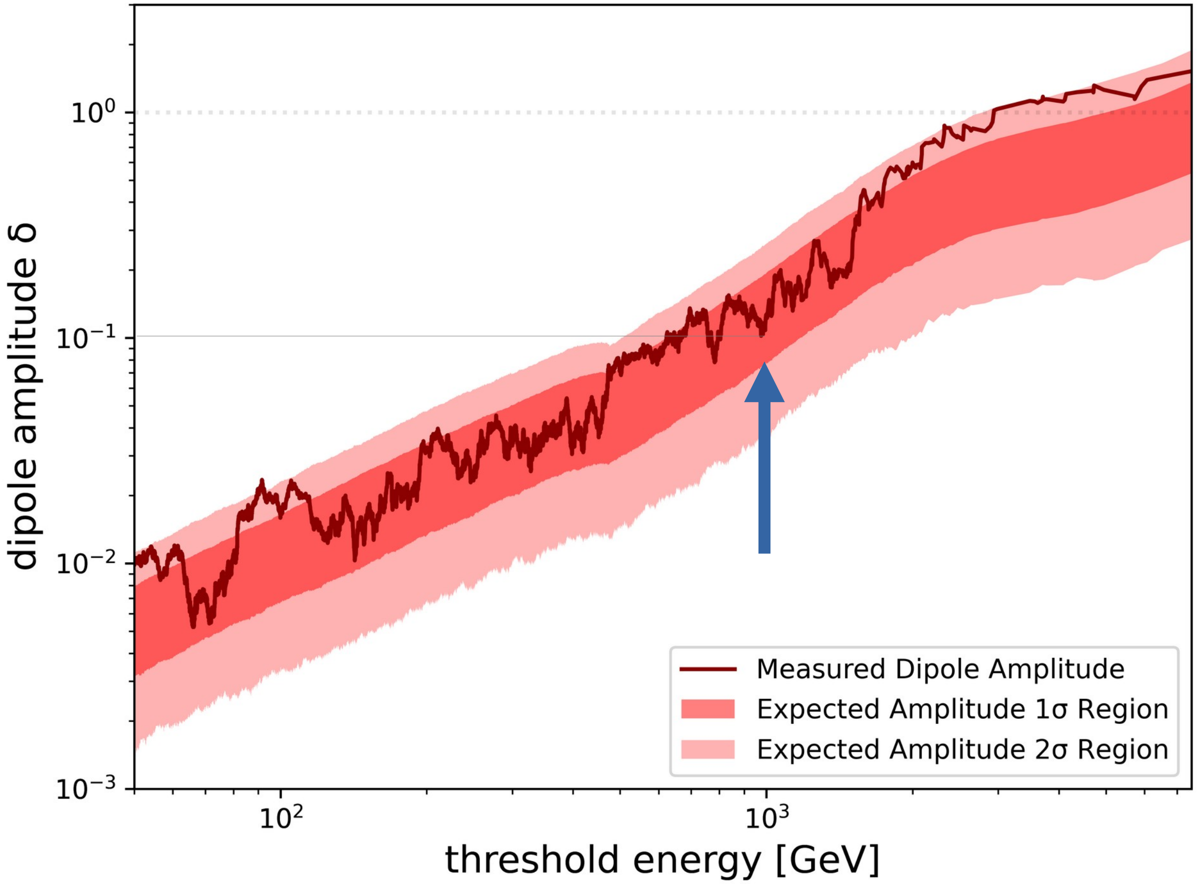
- 5000 simulated event samples equivalent to the real data-set were created
- Randomized event energy distribution based on a double broken power law fit of the spectrum
- Randomized event direction (uniform distribution over the sphere) weighted with the exposure map
- Samples analyzed with the same algorithm as the real data to find the confidence interval for the case of no real anisotropy existing in the cosmic-ray flux.

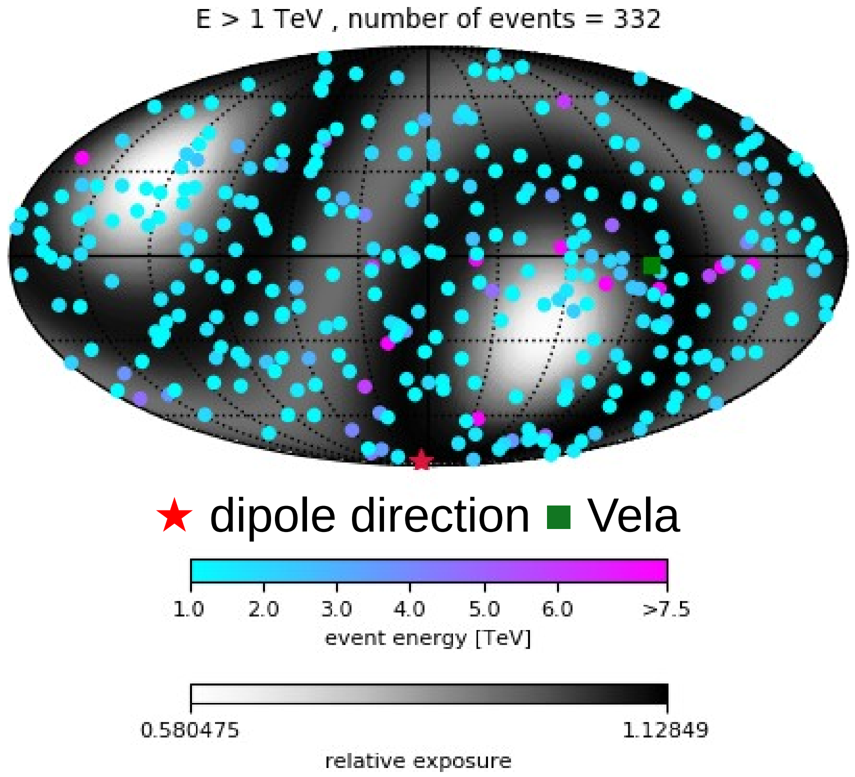
Measured Dipole Amplitude



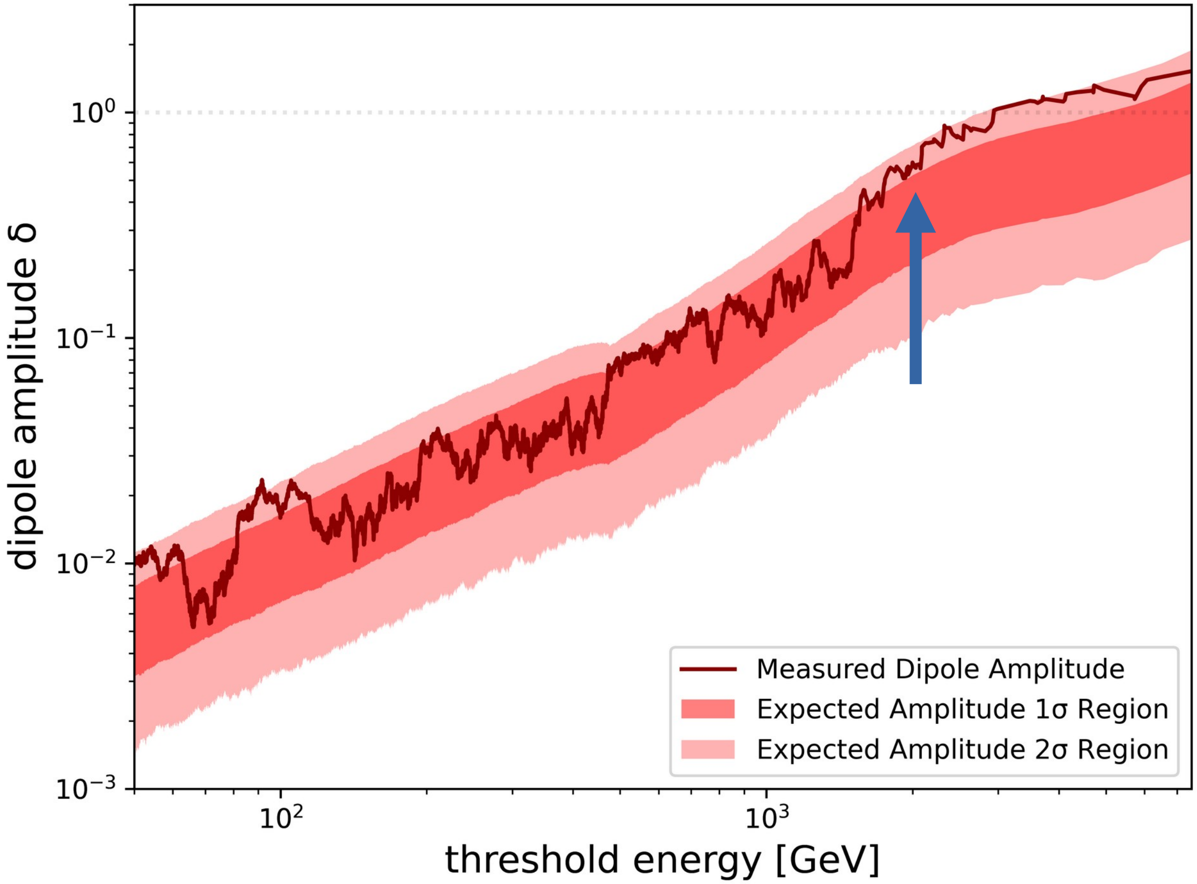
- Each event's energy is used as threshold energy ordered from high to low energy
- Measured dipole amplitude within 2σ confidence band
- Near upper bound above threshold energies of ~2 TeV

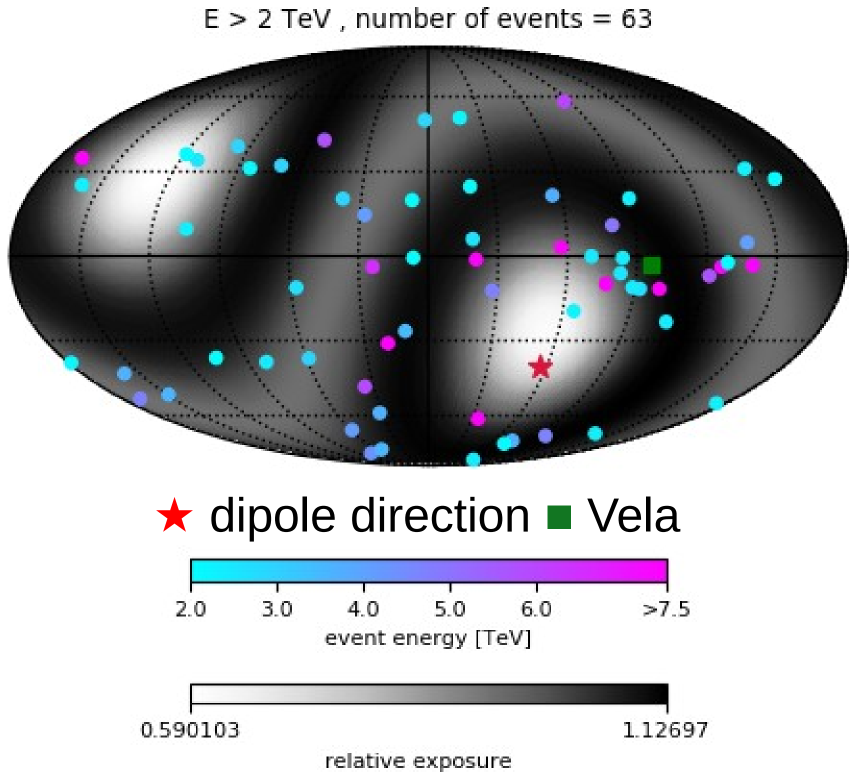
Measured Dipole Amplitude





Measured Dipole Amplitude





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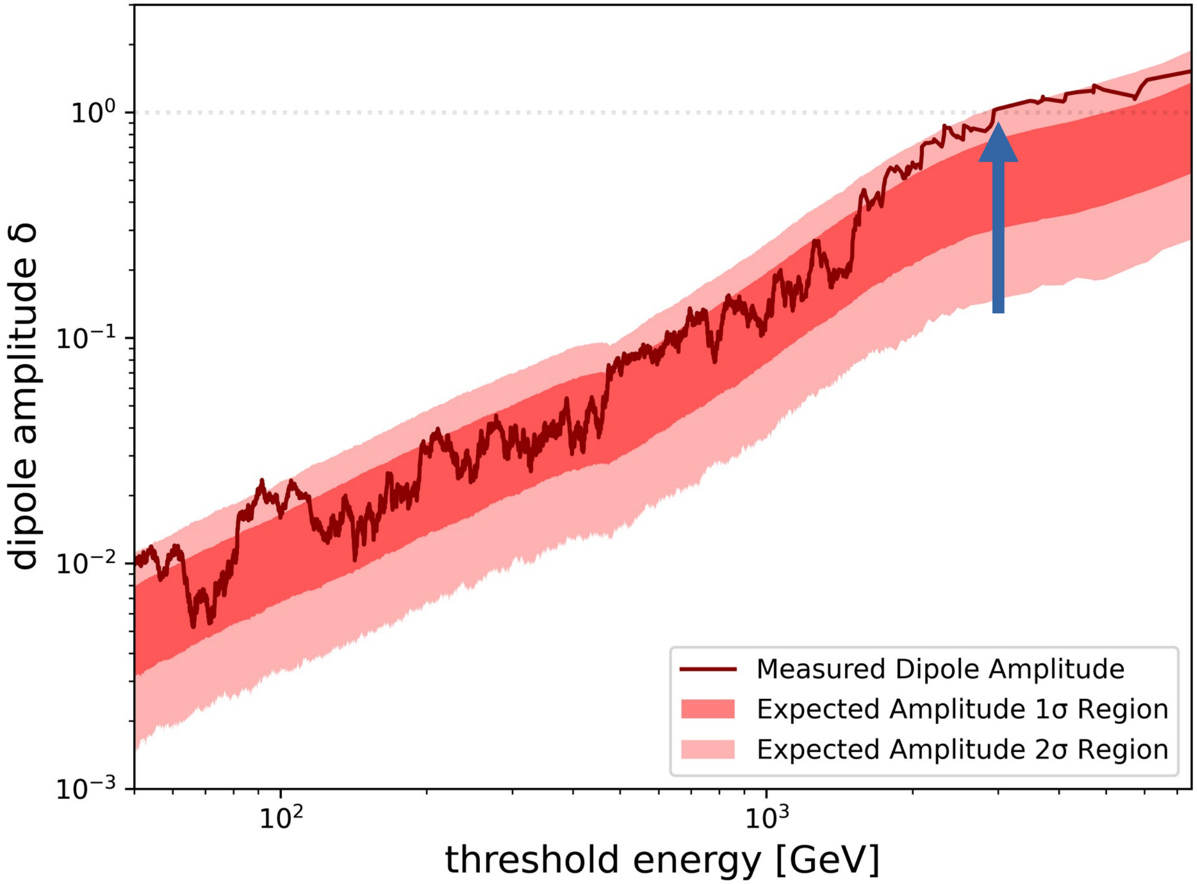

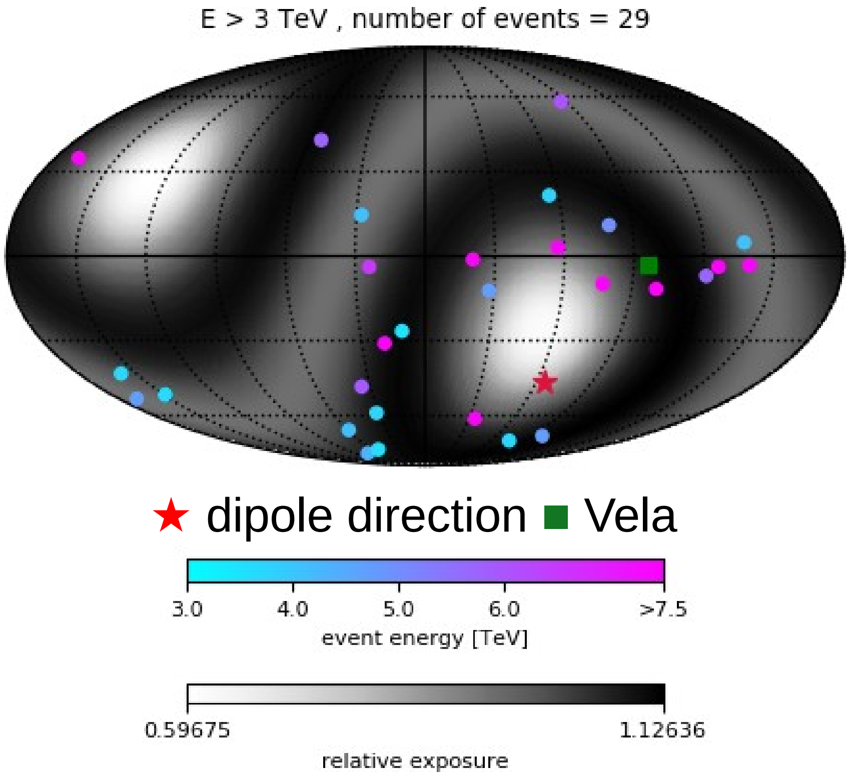

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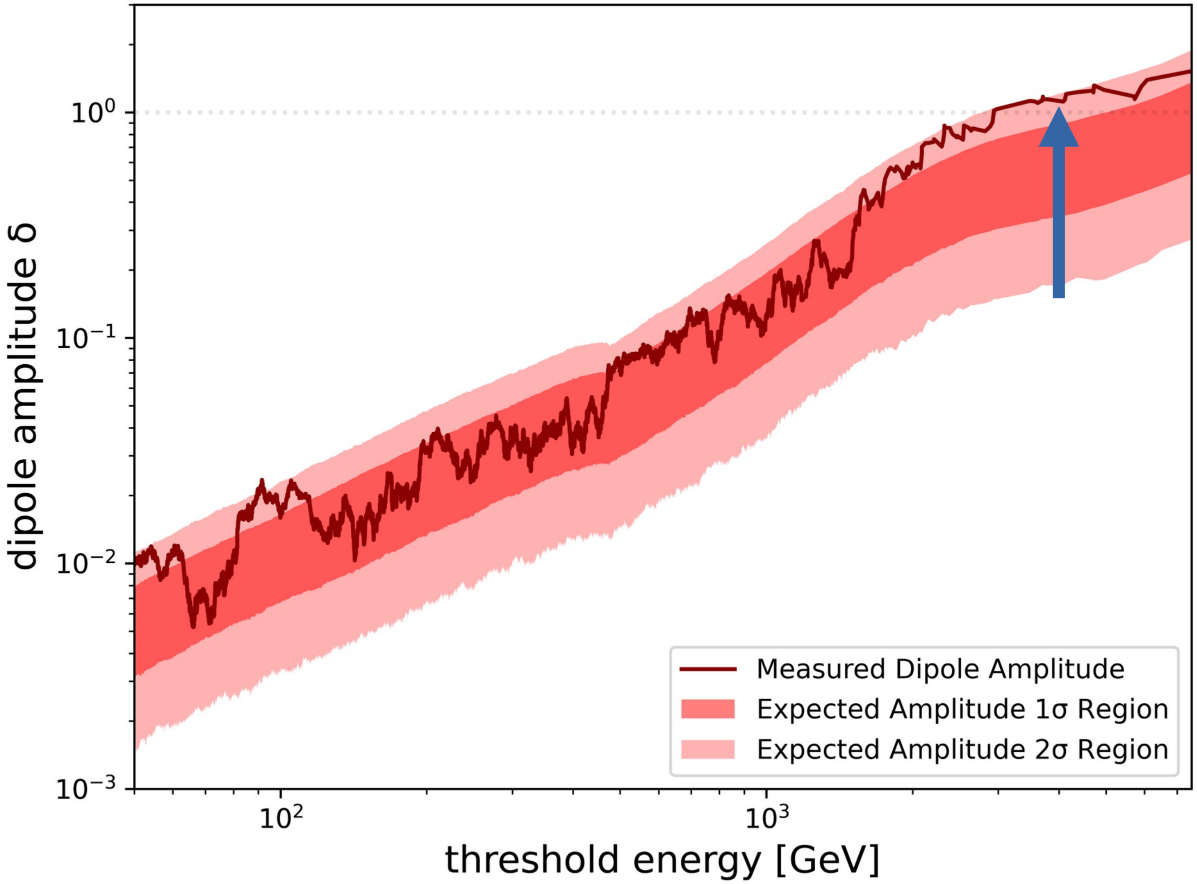

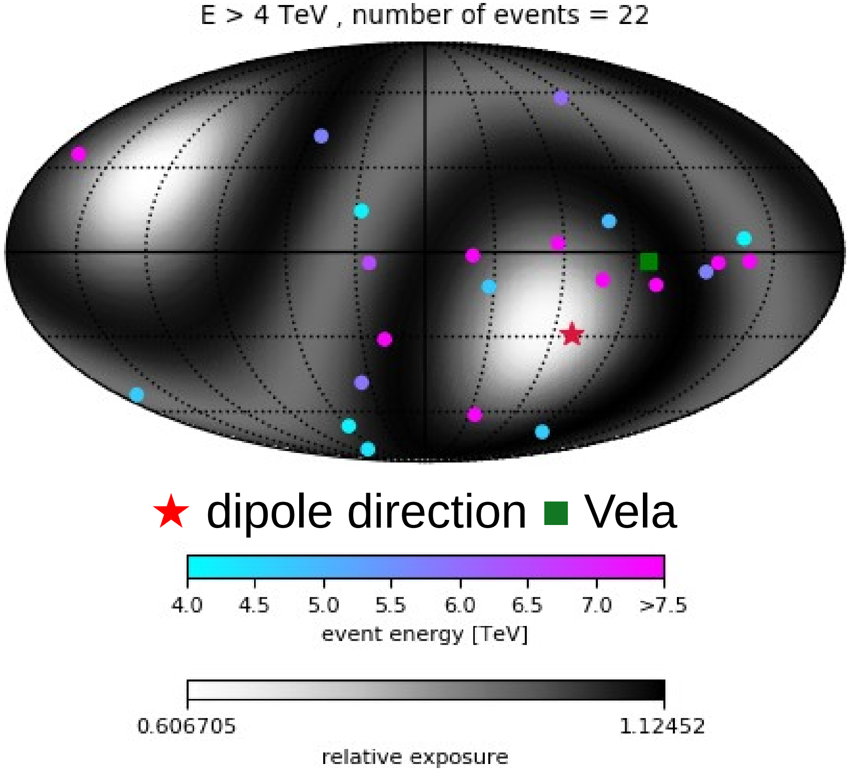

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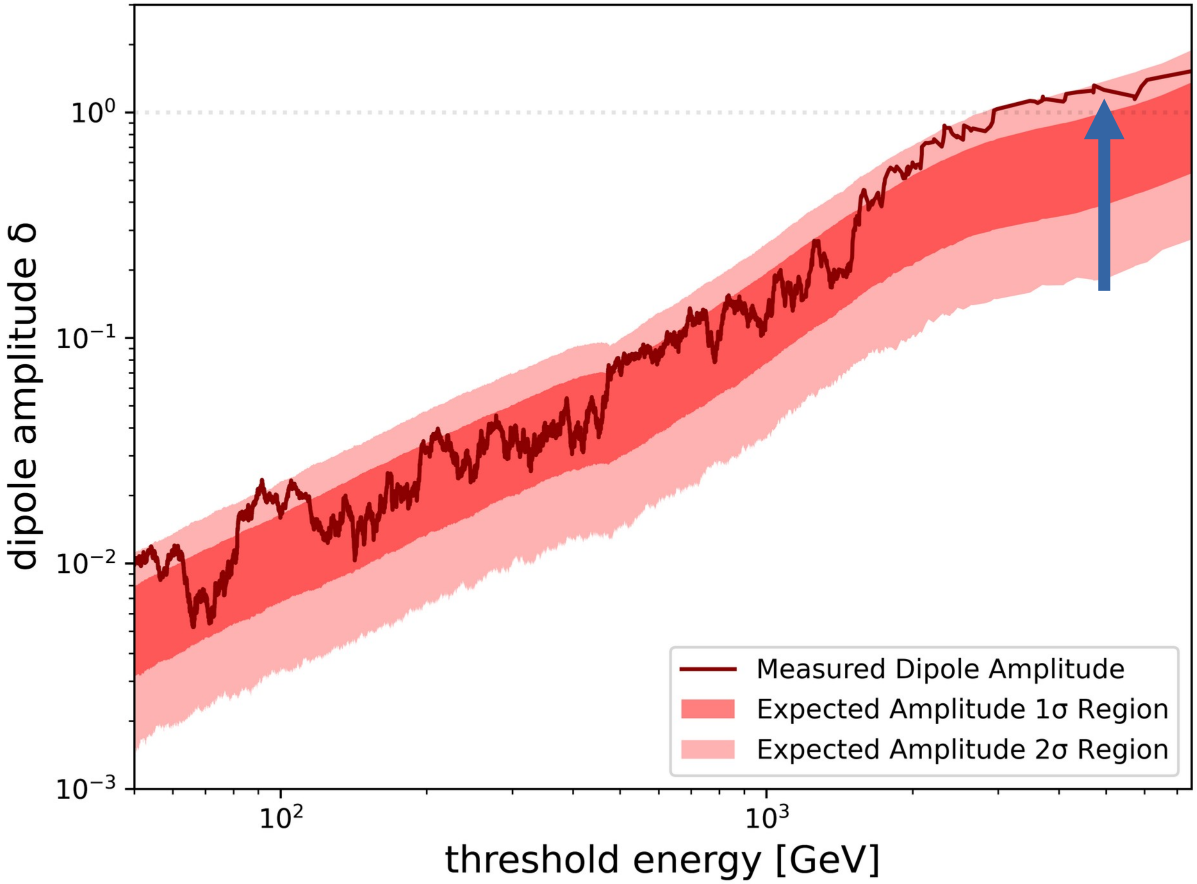

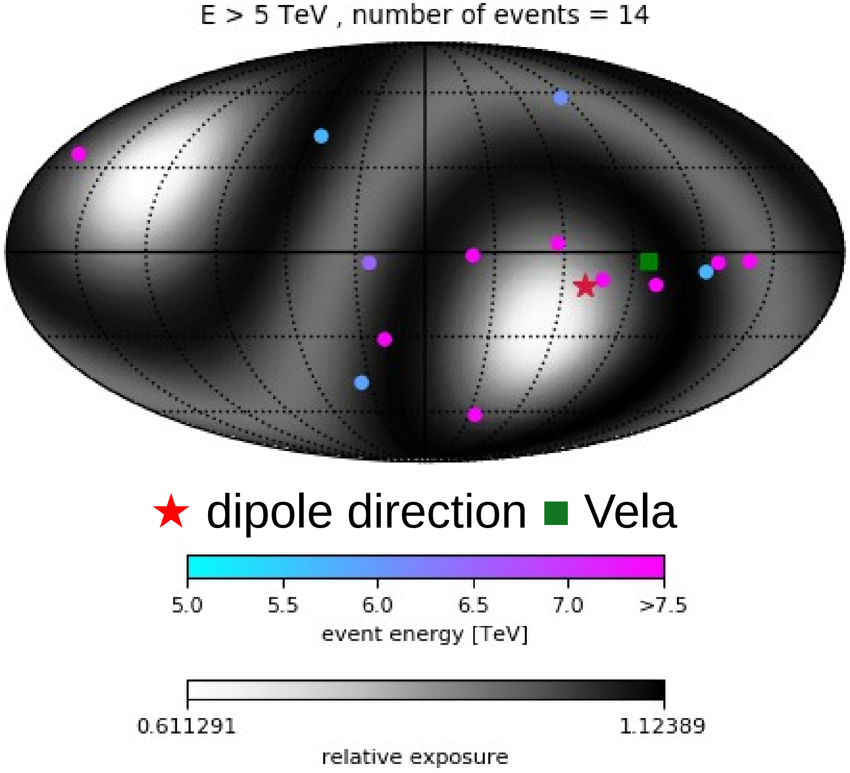

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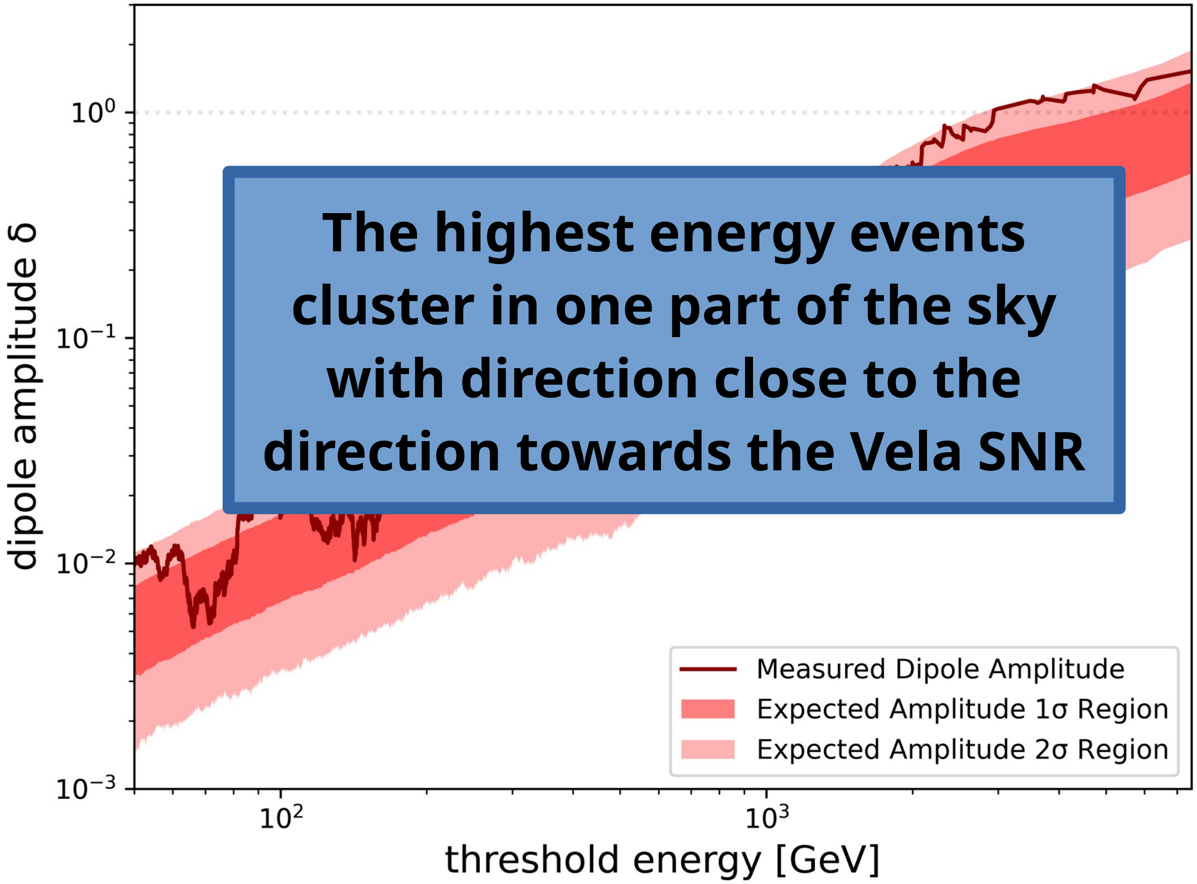
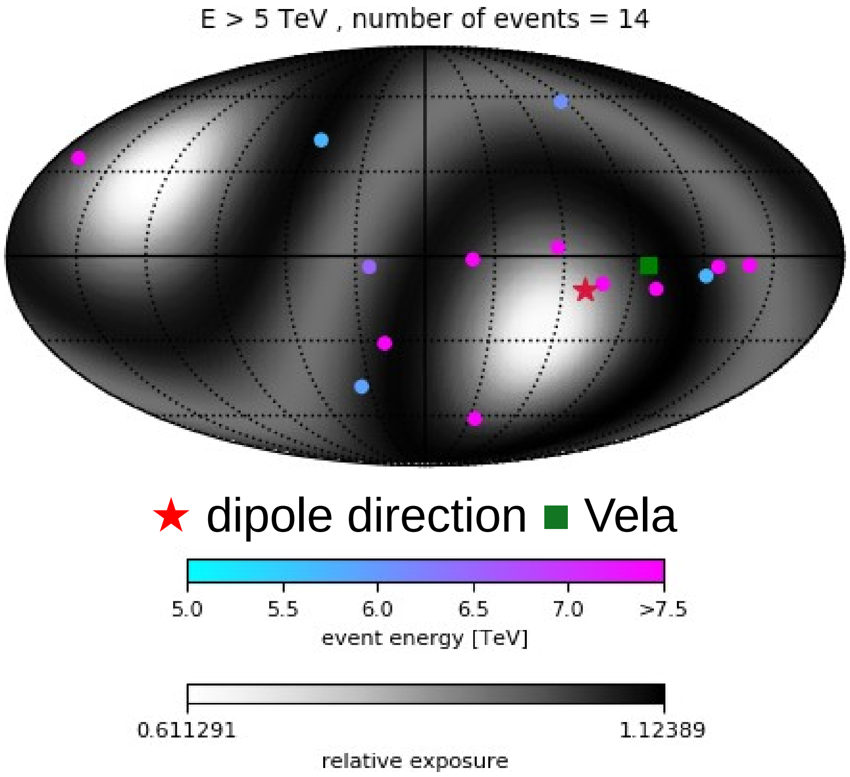
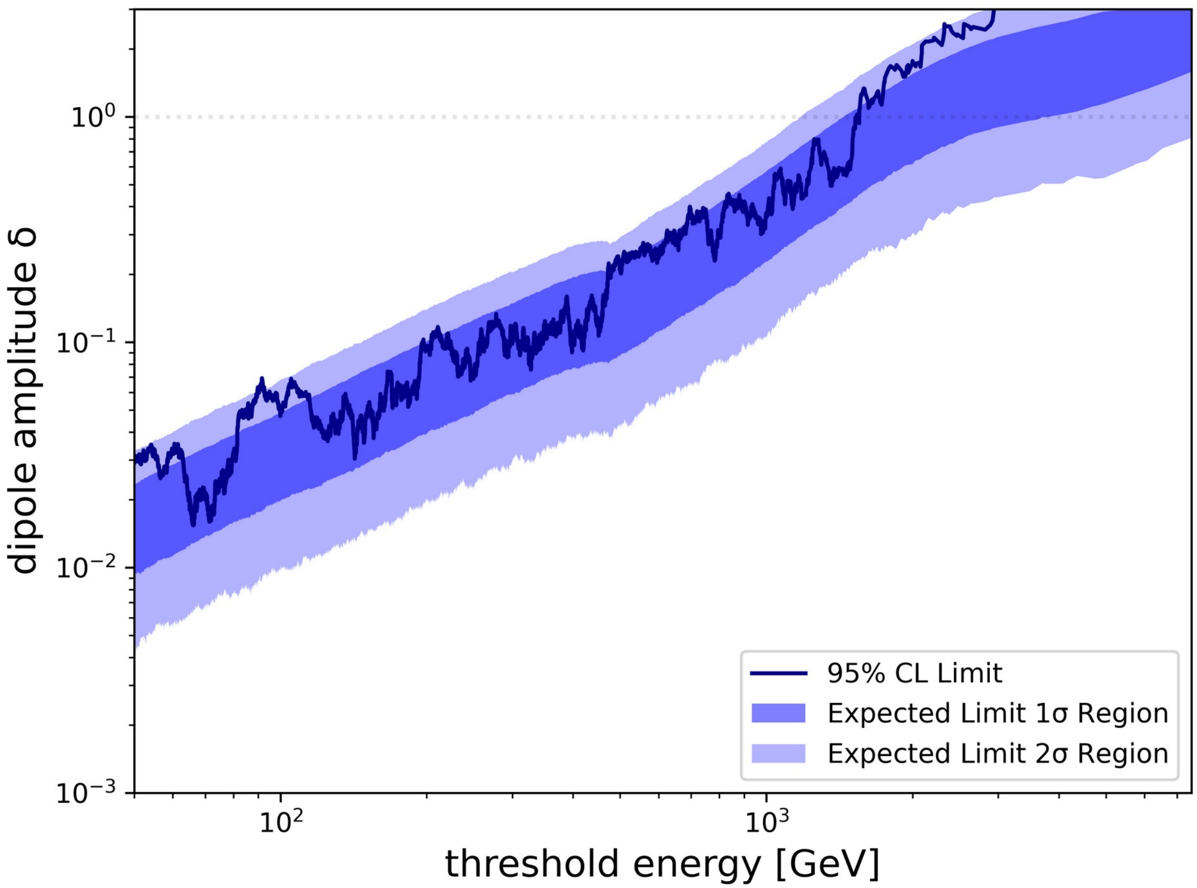


The highest energy events cluster in one part of the sky with direction close to the direction towards the Vela SNR



Upper Limit on Dipole Amplitude



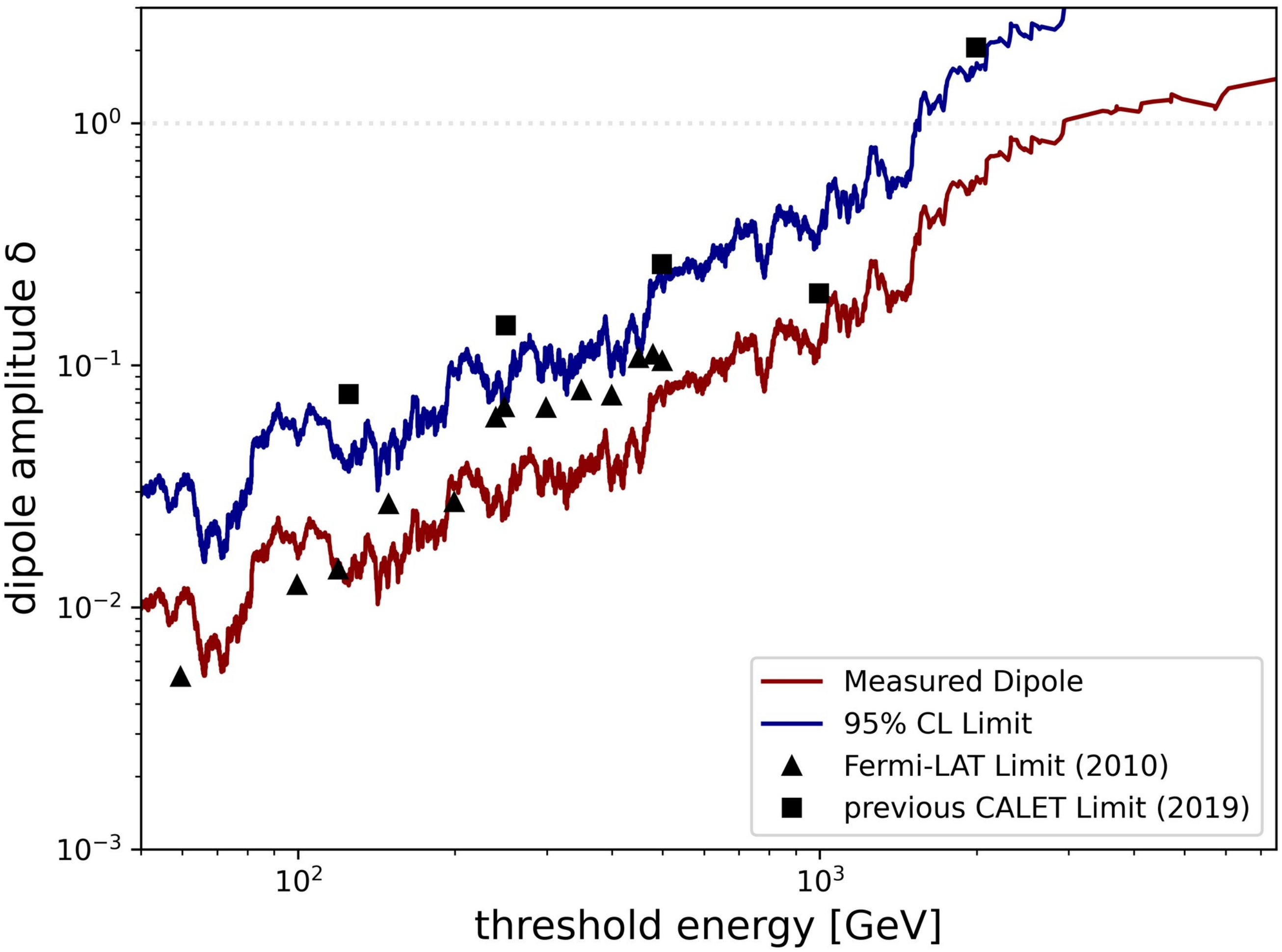
- 95% CL limit calculated using the PDF for δ as given in the 2010 Fermi-LAT paper [PRD 82:092003,2010] :

$$\frac{3\sqrt{6}}{\sqrt{\pi}\,\delta^3}\int_0^{\delta_{meas}} \hat{\delta}^2 e^{-\left(\frac{3\hat{\delta}^2}{2\delta^2}\right)} d\hat{\delta} = 0.05$$

→ resolve for δ

- Limit by this method depends only on the measured dipole amplitude, not the expected range from white noise

Comparison with Previous Results

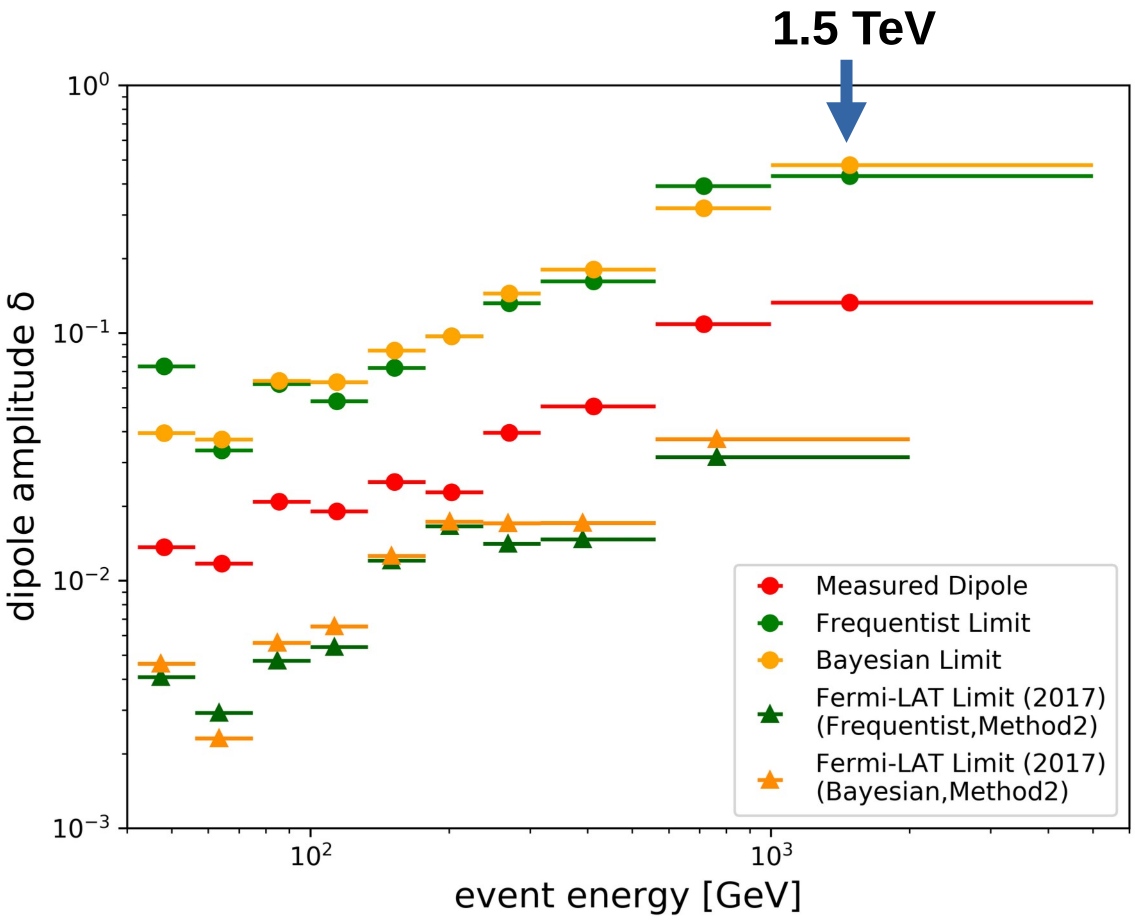


Limits at a few 100 GeV have improved over our results from 2019 [PoS ICRC2019, 112] and are comparable to Fermi-LAT 2010 results

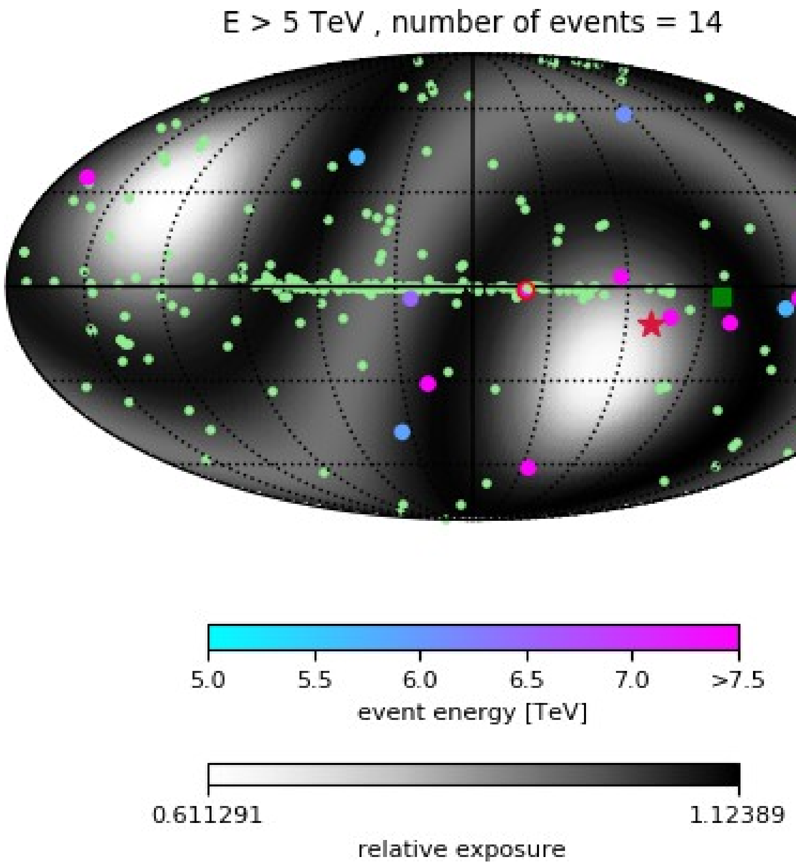
Stricter limits from Fermi-LAT data are published in [PRL118, 091103(2017)] with analysis using independent bins → a direct comparison is not possible in this plot.

Binned Analysis Limits

- Use binned analysis to compare with newer results from Fermi-LAT [PRL118,091103(2017)]
- Highest bin for Fermi-LAT from 562 GeV to 2 TeV, but central energy is well below 1 TeV
- For CALET analysis, this bin is cut at 1 TeV, an additional bin ranging from 1 TeV to 5 TeV is added
- Used the limit calculation methods from this Fermi-LAT paper
- Fermi-LAT limits about one order of magnitude stricter, but CALET provides a real TeV-region limit



TeV-range dipole due to gamma-ray events mistaken for electrons?



green dots: TeV gamma source positions taken from TeVCat catalog: https://tevcat.org/

Only one electron event is closer than two degree from a TeV gamma-ray source (marked with red circle)

→ events dominating the TeV-region dipole direction and magnitude are not associated with known gamma-ray sources

Conclusions

- From the electron+positron event data taken by CALET until the end of 2024, limits on the dipole amplitude as a function of lower threshold energy, as well as for independent energy bins have been calculated.

- A unique limit on anisotropy in the 1-2 TeV range has been set

- The dipole amplitude above about 2 TeV increases above the expected value from white noise, reaching the boundary of the 2σ confidence band.

- The direction of this TeV-region dipole is approximately towards the Vela SNR, which implies that a strong dipole anisotropy originating from the contribution of Vela to the TeV-region electron flux remains a valid hypothesis.

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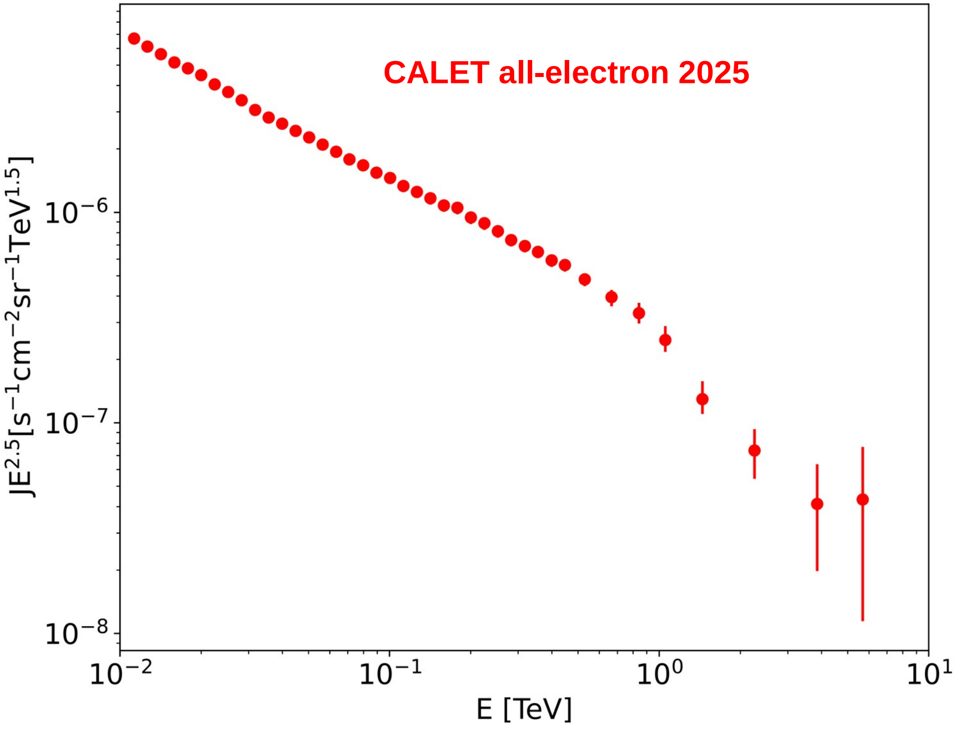
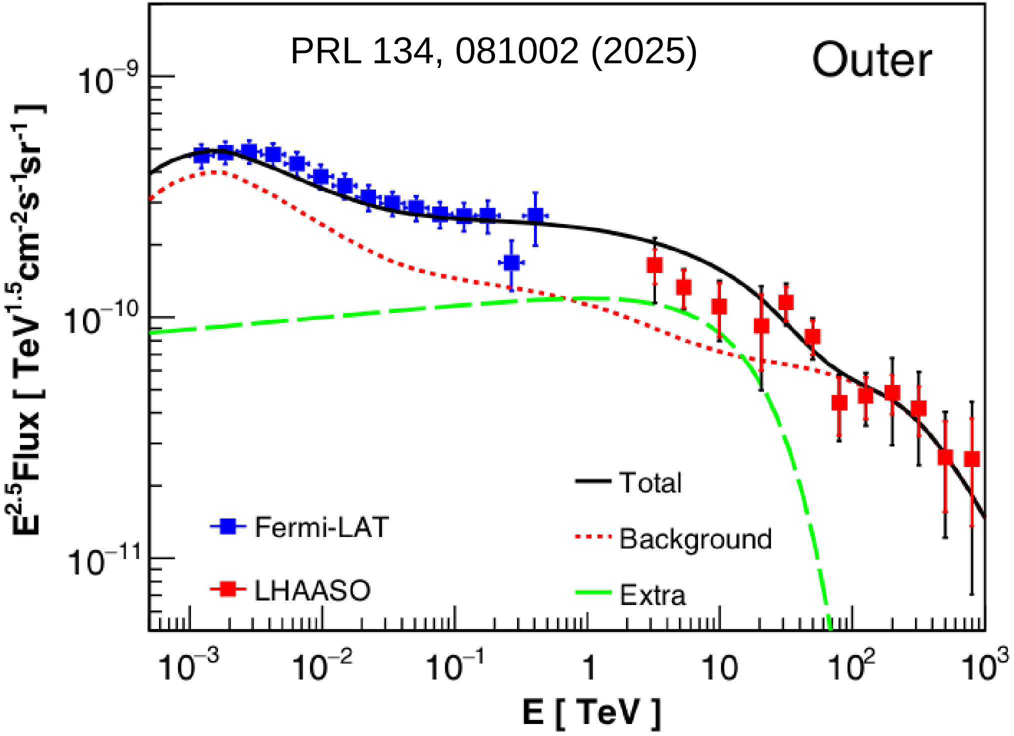
Additional Slides

TeV-range dipole due to gamma-ray events mistaken for electrons?





diffuse galactic gamma-ray flux from Fermi-LAT and LHAASO (right) compared to CALET electron plotted in the same units → gamma-ray flux at least one order of magnitude lower

Frequentist and Bayesian Limit

formulae copy-pasted from Fermi-LAT (2017) supplemental material

expected white noise: $$C_N = \frac{4\pi}{N_{pixels}^2} \sum_{i=1}^{N_{pixels}} \frac{n_i}{\mu_i^2}$$

theoretical (limit) dipole moment magnitude: $\hat{C}_1^{ani}$

measured dipole moment magnitude: C_1

Frequentist (likelihood ratio λ):

$$-2\ln\lambda(\hat{C}_1^{ani}) = \begin{cases} 3\left(\ln\frac{\hat{C}_1^{ani}+C_N}{C_1} + \frac{C_1}{\hat{C}_1^{ani}+C_N} - 1\right) & \text{if } C_1 - C_N > 0 \\ 3\left(\ln\frac{\hat{C}_1^{ani}+C_N}{C_N} + \frac{C_1}{\hat{C}_1^{ani}+C_N} - \frac{C_1}{C_N}\right) & \text{otherwise} \end{cases}$$

= χ difference → 3.841 for 95%CL

prevents setting a stricter limit based on the measurement being lower than the expectation by chance

Bayesian:

resolve for upper limit

$$1-\alpha = \int_{\hat{C}_{1,low}^{ani}}^{\hat{C}_{1,up}^{ani}} P(\hat{C}_1^{ani}|C_1, C_N)\, d\hat{C}_1^{ani}$$

$\alpha = 0.05$

=0

$$P(C_1|\hat{C}_1^{ani}, C_N) = \frac{3\sqrt{3}}{\sqrt{2\pi}\hat{C}_1}\sqrt{\frac{C_1}{\hat{C}_1}}\exp\left(-\frac{3C_1}{2\hat{C}_1}\right)$$

$$\hat{C}_1 = \hat{C}_1^{ani} + C_N$$