Searching for Cosmic Ray Anisotropy from the Vela SNR with CALET

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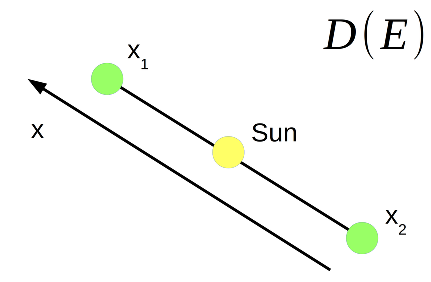
Introduction

The Calorimetric Electron Telescope (CALET) on the ISS measures the spectrum of electron+positron cosmic rays well into the TeV range. A main goal of CALET is to identify a signature of a nearby SNR in electron+positron cosmic-rays. The Vela SNR may create a spectral feature in the TeV region and/or a detectable anisotropy. Using the numerical cosmic-ray propagation code DRAGON, the expected anisotropy caused by Vela was calculated depending on injection and propagation conditions, and the ability of CALET to detect this signature studied.

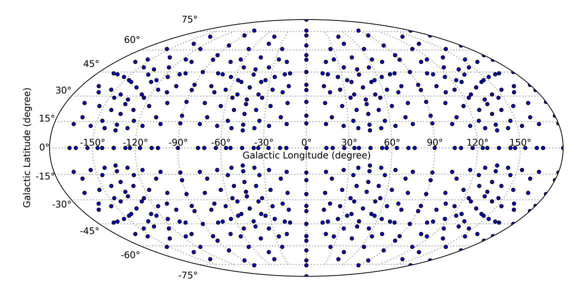
Method of Anisotropy Calculation with DRAGON

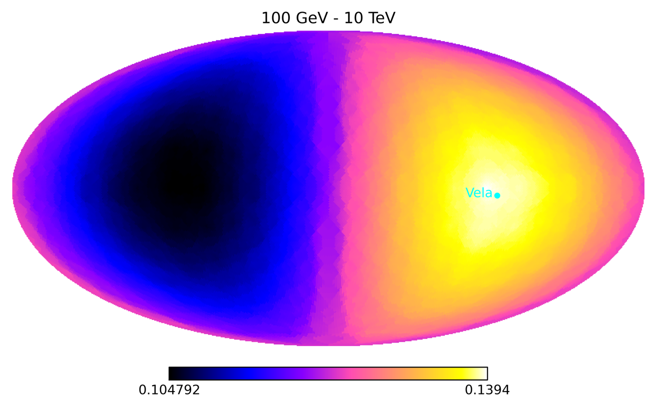
$$\Phi_{dir} = \Phi_{avg}\left(1 + \frac{3D}{c}\frac{(F_{x1} - F_{x2})/|x_1 - x_2|}{F_{Sun}}\right)$$

$$D(E) = D(E_0)\cdot\left(\frac{E}{E_0}\right)^{\delta}$$

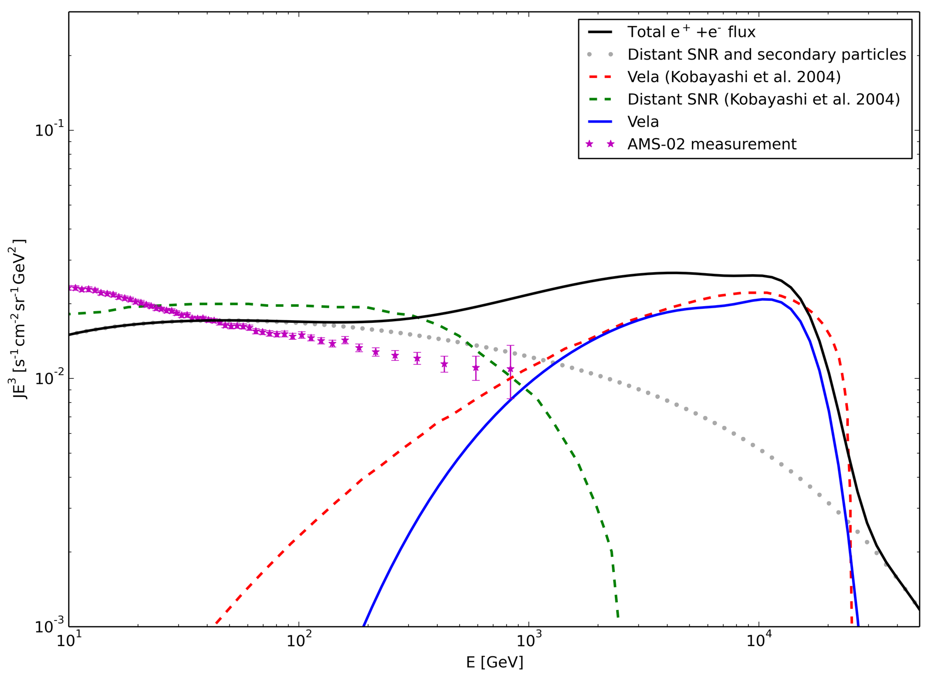


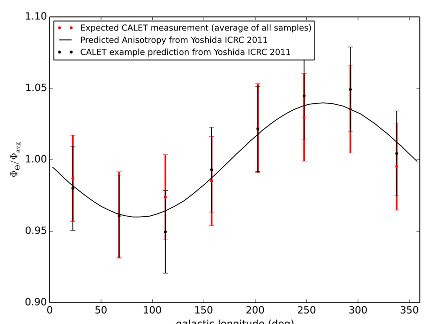
The expected ansiotropy from the Vela SNR is derived by numerical cosmic-ray propagation calculation, which includes detailed effects such as energy losses, secondary particle production, and anisotropy of the diffuse background. DRAGON [1] features a non-equidistant spatial grid, allowing for a fine spatial binning near the observation point and sources required for calculation of anisotropy. From the differences in cosmic ray density F between the grid points around the Solar System, the flux Φ_{dir} from direction of a given grid point x_1 can be calculated as shown by the formula to the left. Using the 9x9x9=729 grid points in the cube up to 4 steps of 5 parsec away from the Solar System, the directional flux is calculated in 642 different directions, forming the dense mesh in galactic coordinates shown in the upper figure to the right. The predicted directional fluxes are then interpolated between these directions to fill a $\approx$50k pixel Healpix map, and multiplied by the exposure of CALET (aperture 1200 cm^2 sr , detection efficiency 90$\%$ [2]) to derive the expected events per pixel in CALET for five years of observation. An example of this anisotropy map is shown in the lower plot to the right, selecting events above a minimum energy of 100 GeV. While the anisotropy Φ_{dir}/Φ_{avg} generally rises with energy, the number of detected events falls, so that detection sensitivity can be maximized by tuning the minimum energy of selected events.

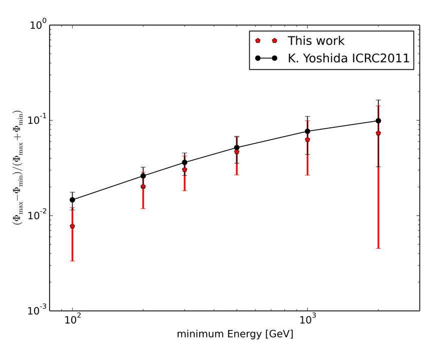




Scenario for Comparison with Analytical Calculation

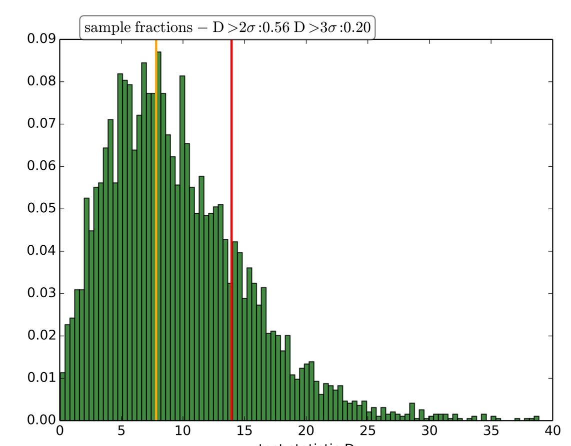


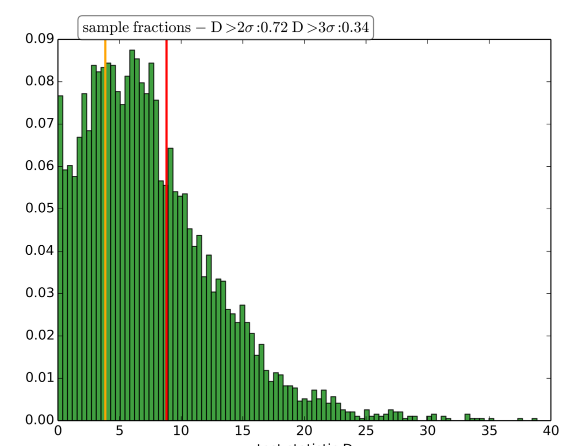




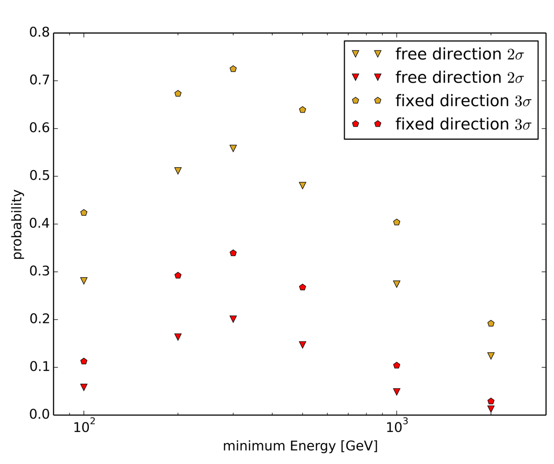
We aim to reproduce the results of reference [3], which are based on a model from reference [4]. The propagation and injection condictions are δ = 0.6 ,$D(4GeV) = 1.5\cdot 10^{28}$ cm^2/s with an injection power law index of γ_i = -2.7 + δ = -2.1 , yielding $D(1TeV) = 4\cdot 10^{29}$ cm^2/s as quoted in reference [3]. The left figure above shows that the electron+positron spectrum for Vela obtained with DRAGON largely matches the results in [4] for similar parameters ($D(1TeV) = 5\cdot 10^{29}$ cm^2/s). The spectrum is normalized to to a total output of $1\cdot 10^{48}$ erg in electron CR above 1 GeV. The background from distant SNR is higher in the TeV-region due to the spiral-arm shaped source function in DRAGON, compared to the complete removal of nearby sources in [4]. The plots on the right show the agreement on the expected anisotropy as a function of galactic longitude (upper plot) and the expected maximum measured anisotropy as a function of minimum energy (lower plot) with the results in reference [3].

Anisotropy Analysis and Detectability of Vela with CALET





Based on the combined background+Vela event map, 5000 samples of 5-year CALET data are simulated using the poisson distribution to randomly determine the measured number of events in each pixel. A monopole and dipole with free direction are fitted to the samples, and the logarithm of the likelihood ratio to the monopole-only null-hypothesis histogrammed (left plot above), with the critical values for 2σ and 3σ indicated by vertical lines. Alternatively, the dipole direction is fixed towards Vela, and only the dipole magnitude fitted (right plot above).

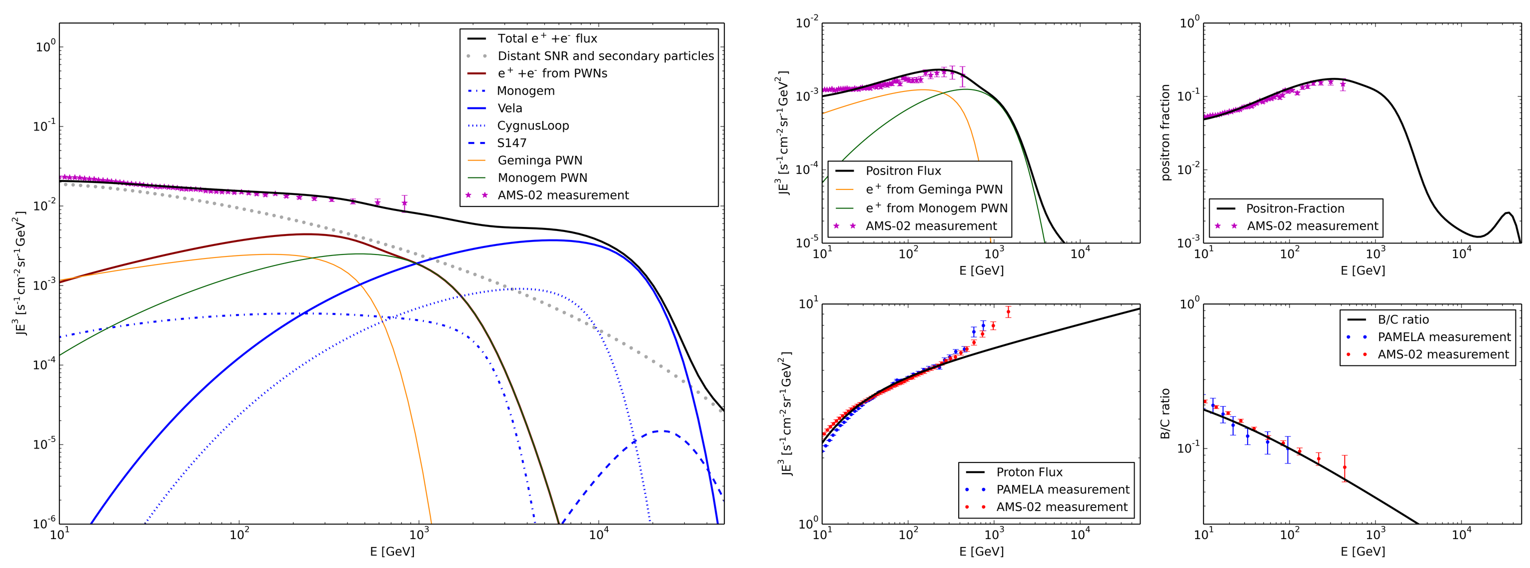


The plot on the left shows the probability for a detection of the anisotropy signal with 2σ and 3σ, where a maximum probability of 72$\%$ is reached at 300 GeV minimum energy of the selected events. Generally the fixed dipole fit has a higher chance of a significant detection, since it introduces only one additional degree of freedom (dipole amplitude) compared to three (dipole amplitude,longitude,latitude) for the free direction fit, however it must be known that the maximum flux is from the chosen direction.

Conclusions

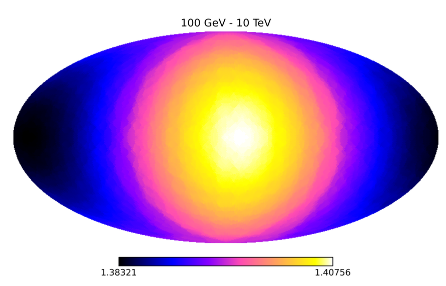
- The first direct measurement of the TeV-region electron+positron spectrum by CALET has a possibility to detect a significant anisotropy signal from the Vela SNR.
- The measurable ansiotropy from Vela depends strongly on the propagation and injection parameters, which could thus be constrained by the (non-)detection of anisotropy.
- Numerical calculation of anisotropy by DRAGON reproduces analytical results and allows for detailed prediction of the expected ansiotropy as a combination of multiple sources.

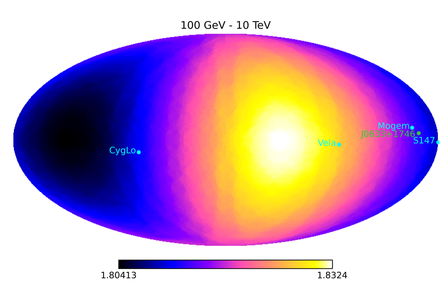
Scenario Fitted to Current Cosmic Ray Measurements



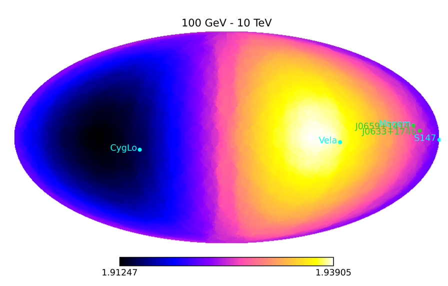
We study a model under the propagation conditions δ = 0.4 ,$D(4GeV) = 3.7\cdot 10^{28}$ cm^2/s with an injection power law index of γ_i = -2.9 + δ = -2.5 for both electrons and nuclei, which gives good agreement with measured B/C ratio and proton spectra. For the electron+positron spectrum a primary electron background from distant SNRs is calculated, as well as 4 individual SNR sources within 0.5 kpc and younger than 20000 years, all using the common injection index. As source of the positron excess the Geminga and Monogem PWNs with $\gamma_{i_{PWN}}$ = -2.1 and $E_{cut_i} = 1$ TeV are assumed. To these primary spectra, secondary positrons and electrons from nuclei interaction with the ISM are added. The background fluxes and the PWN are scaled to fit AMS-02 datapoints (total flux [5], positron flux [6], positron fraction [7] and proton flux [8]), while the inividual SNRs are normalized to a total output of $1\cdot 10^{48}$ erg in electron CR above 1 GeV.

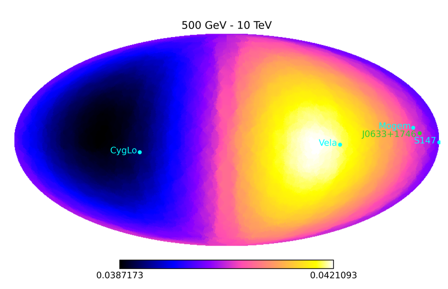
Effect of Anisotropy from Distant SNR and other Sources





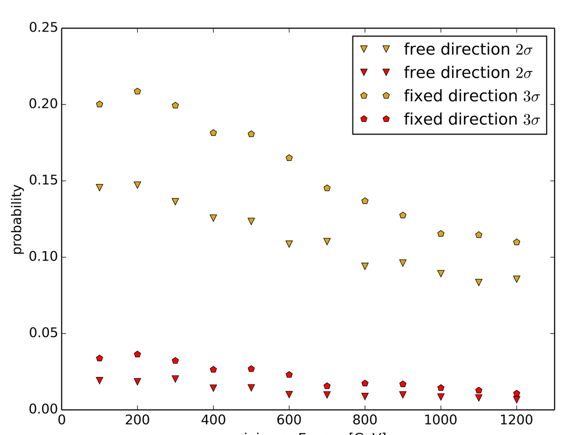
The diffuse background from distant SNRs shows a strong increase towards the galactic center (upper left plot). This shifts the direction of anisotropy from direction of the Vela SNR towards the Galactic Center (lower left plot), for 100 GeV minimum energy and the Monogem PWN removed. Coincidentally this shift is mostly compensated by the contribution from the Monogem PWN, which is located opposite to the GC from Vela (upper right plot). Also the shift in anisotropy direction is weaker if selecting events above 500 GeV only (lower right plot).





Detectability of Vela with CALET

Using the analysis method described to the left, the probability to detect a siginficant ansiotropy from Vela was calcualted for this model and is shown in the plot to the right, yielding a maximum probability of $\approx$20% at 200 GeV. As described above, part of the anisotropy at low energy is from sources other than Vela, which should be considered when selecting the minimum energy cut.



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