# Follow-up study of Geminga's Contribution to the Local Positron Excess with the High Altitude Water Cherenkov Gamma-Ray Observatory

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**Abstract**

The PAMELA, Fermi-LAT, and AMS-02 experiments measured a local excess of positrons above energies of 10 GeV. This excess has been considered to be due to dark matter interactions or the presence of nearby astrophysical sources. Here, I present preliminary methods to be used for the follow-up study of diffusion in the region of the pulsar Geminga with approximately five years of HAWC data. I implement a new analysis with templates that contain spectral and spatial information of gamma-ray emission due to particle diffusion around Geminga pulsar using the HAWC Accelerated Likelihood (HAL) and the Multi-Mission Maximum Likelihood framework (3ML). With this template method, I study the diffuse gamma-ray emission of electrons from inverse Compton scattering with low energy photon fields, i.e., microwave background radiation, for different diffusion coefficients in the range of $10^{25}$-$10^{28}$ $cm^2/s$ and different electron spectral indices 1.5-2.4. I obtain an estimate of diffusion coefficient consistent with HAWC and Fermi-LAT's previous measurements.

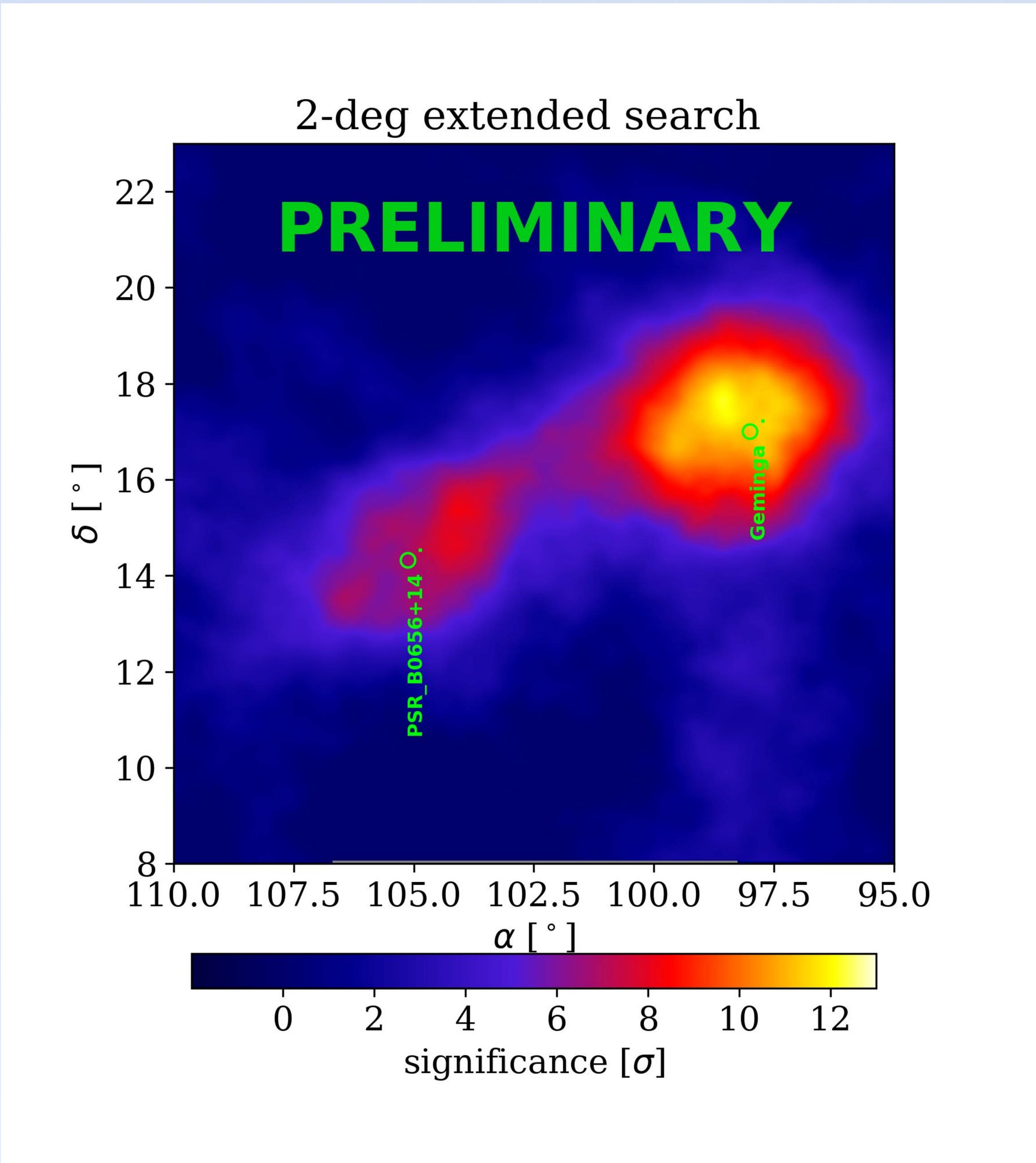
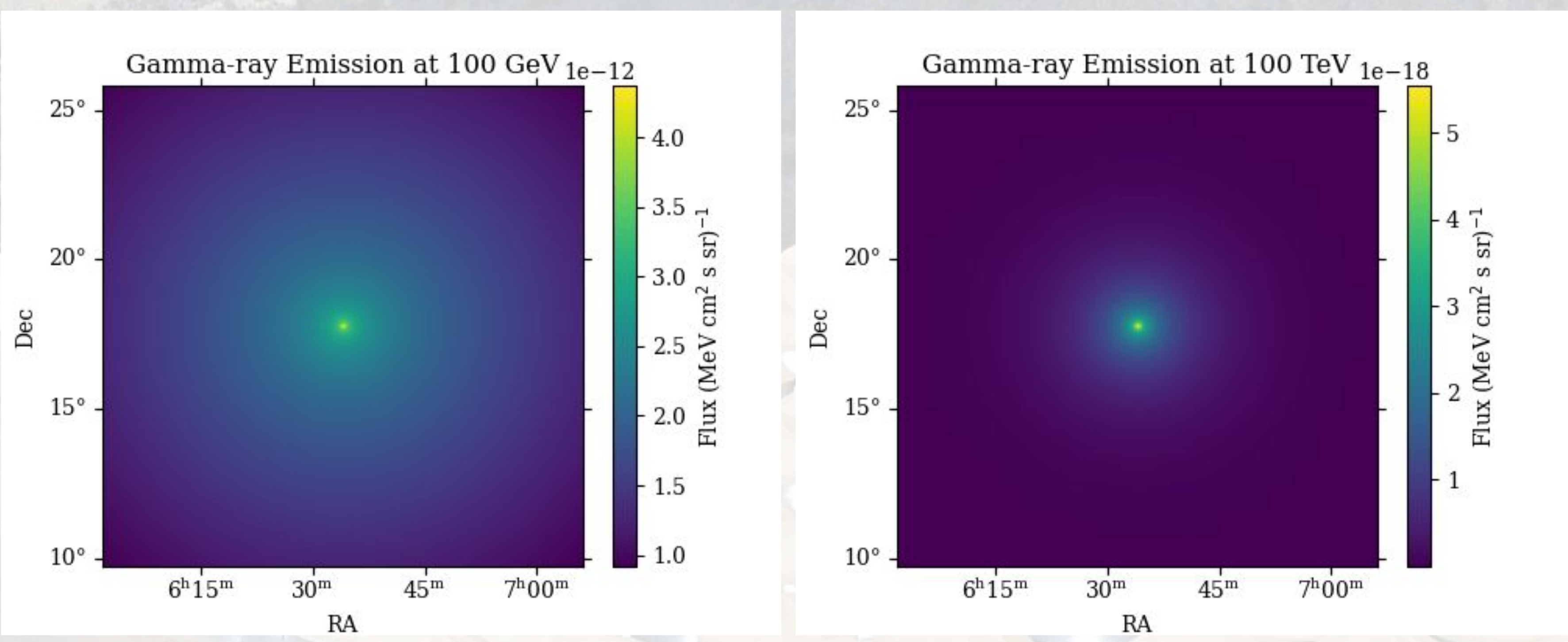



Figure 1: Significance map of the pulsars Geminga and Monogem with an extension of 2 degrees with the latest energy estimator data set of HAWC. Maps were created using HAWC's new energy estimator dataset with 1343 days of data.

Geminga and Monogem are two relatively nearby pulsars at distances of 250 pc and 280 pc, respectively. Geminga has an age of 340 kyrs and Monogem 110 kyrs. Geminga and Monogem are the primary examples of TeV halos. TeV halos are extended regions of gamma-ray emission from particle diffusion around pulsars.

**Template Model:**




(a) (b)

Figure 2: Model templates using estimates from Fermi-LAT's study [2] show the extent of the gamma-ray emission at (a) 100 GeV, (b) 100 TeV for electrons diffusing away from Geminga. The electrons diffuse at $D_0 = 1.5\times10^{26}$ $cm^2/s$ at 1 GeV with an electron spectral index of 2.0.

**Template Fitting Method Advantages:**

- 3D templates contain spectral and spatial information of gamma-ray emission of electrons diffusing from a pulsar with values of flux at every pixel
- physical models used to estimate the gamma-ray emission from electron inverse Compton scatterings with low energy photons, i.e. microwave background radiation.
- incorporates proper motion of the pulsar (important for multi-wavelength studies)
- incorporates anisotropic diffusion around the pulsar

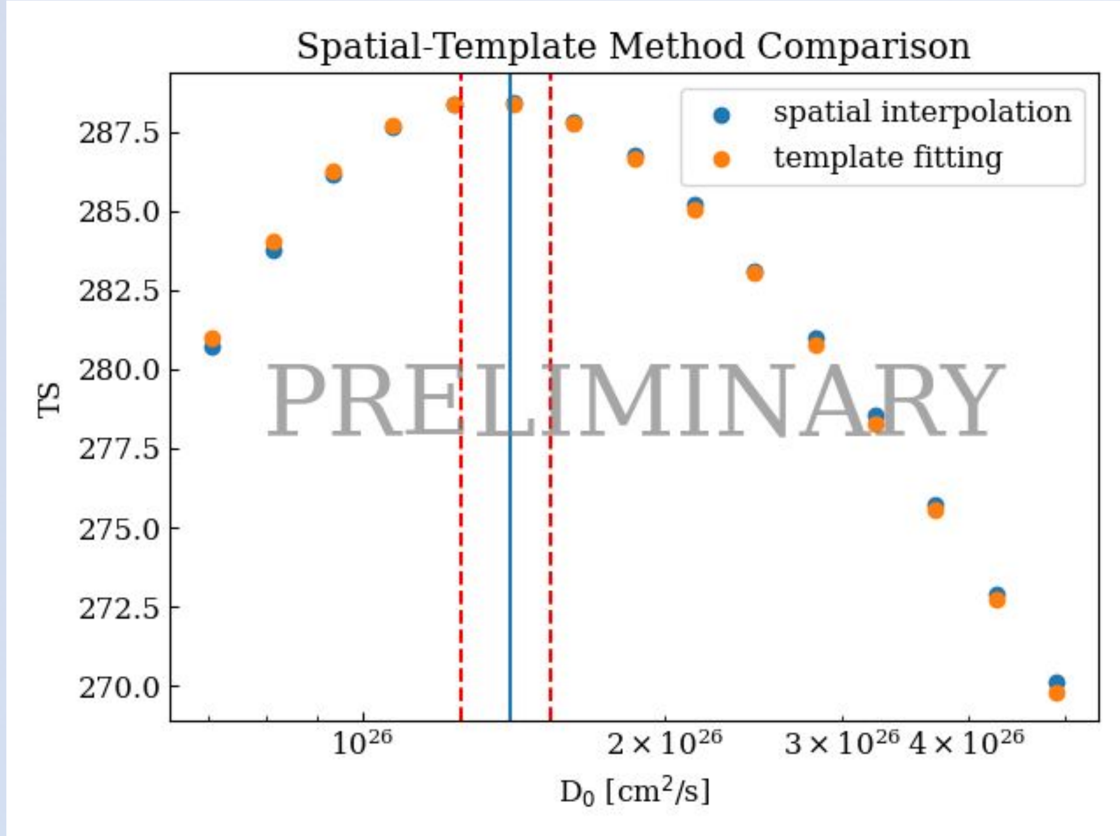



Figure 3: Comparison of performance from spatial interpolation and template-fitting method for different diffusion coefficients in the range $10^{25}$ - $10^{26}$ $cm^2/s$. The best estimate obtained for both methods is obtained for a diffusion coefficient of $D_0 = (1.4 + 0.17 - 0.15)\times10^{26}$ $cm^2/s$ for an electron spectral index fixed at 2.0.

**Template Fitting Method**

- Interpolates over template's energy, RA and Dec values to evaluate flux values.
- Cannot change of the values of diffusion coefficient and electron spectral index directly; this method requires different template sets for each examination.

**Spatial Interpolation Method**

Extends the functionality of the template fitting method

- builds a data grid of templates for different energies for the same region with different values of diffusion coefficient and electron spectral index
- interpolation over diffusion coefficient and electron spectral index to estimate values of flux
- interpolated flux values are used to estimate flux values with interpolation over energy, RA, and Dec

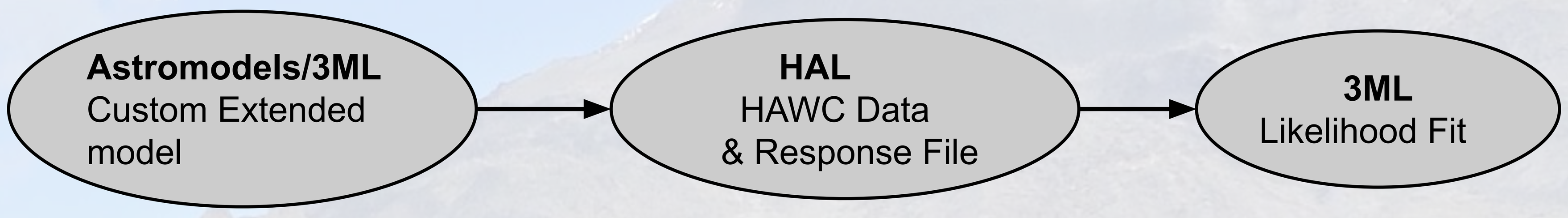



Figure 4: Custom model is declared under the astromodels framework. Spatial/template interpolation method implementation with 3ML and HAL framework.

**Preliminary Results**

Spatial Interpolation Method interpolated over a grid of diffusion coefficients in the range $10^{25}$ - $10^{28}$ $cm^2/s$. Template method used templates with $D_0 = 10^{25}$ - $10^{26}$ $cm^2/s$. In both cases the spectral index of 2.0 (see Figure 3).

- The resulting best value of diffusion coefficient for the spatial method that interpolates over the parameters from the template fitting method is $D_0 = (1.41 + 0.17 - 0.15)\times10^{26}$ $cm^2/s$ at 1 GeV.
- Assuming an spectral index for the diffusion coefficient to be $\delta$=⅓, the diffusion coefficient at electron energy of 100 TeV is $D_{100} = (2.94 + 0.35 - 0.31)\times 10^{27}$ $cm^2/s$ is within the uncertainty of HAWC's previous derived value $D_{100} = (3.2 + 1.4 - 1.0)\times10^{27}$ $cm^2/s$ [1]
- Fermi-LAT's recent derived diffusion coefficient with their official model (table 1 on their paper) is $(2.1 + 1.0 - 0.7)\times10^{26}$ $cm^2/s$ with a $D_{100} = (4.38 + 2.09 - 1.46)\times10^{27}$ $cm^2/s$ [2]

**Future Work**:

- Explore the performance of the current spatial interpolating method for different electron spectral indices.
- Study the spectral energy distribution of Geminga under this method
- Expand study to Monogem pulsar and other pulsars with Geminga-like properties.
- Perform multi-wavelength study with Fermi-LAT data.

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**References**

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[2] M. Di Mauro, S. Manconi , F. Donato. (2019). Detection of a γ-ray halo around Geminga with the Fermi-LAT data and implications for the positron flux. *Phys. Rev. D.* DOI:10.1103/PhysRevD.100.123015