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# Detection of a $\gamma$ -ray halo around Geminga with the Fermi-LAT and implications for the positron flux

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**Abstract.** The HAWC Collaboration has discovered a  $\gamma$ -ray emission extended about 2 degrees around the Geminga and Monogem pulsar wind nebulae (PWNe) at  $\gamma$ -ray energies  $E_\gamma > 5$  TeV. We analyze, for the first time, almost 10 years of  $\gamma$ -ray data obtained with the Fermi Large Area Telescope at  $E_\gamma > 8$  GeV in the direction of Geminga and Monogem. Since these two pulsars are close the Galactic plane we run our analysis with 10 different interstellar emission models (IEMs) to study the systematics due to the modeling of this component. We detect a  $\gamma$ -ray halo around Geminga with a significance in the range  $7.8 - 11.8\sigma$  depending on the IEM considered. This measurement is compatible with  $e^+$  and  $e^-$  emitted by the PWN, which inverse-Compton scatter (ICS) with photon fields located within a distance of about 100 pc from the pulsar, where the diffusion coefficient is estimated to be around  $1.1 \cdot 10^{27}$  cm<sup>2</sup>/s at 100 GeV. We include in our analysis the proper motion of the Geminga pulsar which is relevant for  $\gamma$  rays produced for ICS in the Fermi-LAT energy range. We find that an efficiency of about 1% for the conversion of the spin-down energy of the pulsar into  $e^+$  and  $e^-$  is required to be consistent with  $\gamma$ -ray data from Fermi-LAT and HAWC. The inferred contribution of Geminga to the  $e^+$  flux is at most 20% at the highest energy AMS-02 data. Our results are compatible with the interpretation that the cumulative emission from Galactic pulsars explains the positron excess.

## 1. Introduction

The flux of cosmic-ray electrons and positrons ( $e^\pm$ ) is now known with unprecedented precision from about 0.1 GeV up to TeV energies. The interpretation of these data is still debated. In fact, the  $e^+$  observed above 10 GeV cannot be explained by the typical expectations from the secondary production, i.e. the  $e^+$  produced by spallation reactions of primary cosmic rays with the Interstellar Medium (ISM) (1). Several additionally primary sources have been discussed,



among which the pairs emitted by pulsars and their Pulsar Wind Nebulae (PWNe) (2) (and refs. therein).

Recently, the Milagro and HAWC experiments have reported the detection of an extended  $\gamma$ -ray emission at energies larger than 5 TeV from the direction of Geminga and Monogem PWNe, with an angular size of about  $2^\circ$  (3; 4). These pulsars are among the closest (distances of 0.250 kpc and 0.288 kpc, and ages of 342 kyr and 111 kyr, respectively) and most powerful sources in the ATNF catalog (5). The extended TeV  $\gamma$ -ray emission can be interpreted as inverse Compton scattering (ICS) emission of  $e^\pm$  accelerated, and then released, by these sources and interacting with the interstellar radiation field (ISRF) (6). The angular extension of the TeV  $\gamma$ -ray emission, together with the age of the sources, suggest that these ICS photons are produced by  $e^\pm$  pairs escaped from the PWNe, at a distance of few tens of parsec. However, the  $\gamma$  rays between 5 – 40 TeV detected by HAWC are produced via ICS off the ISRF by  $e^\pm$  at average energies of at least tens of TeV. The use of HAWC  $\gamma$ -ray data in order to predict the  $e^\pm$  flux at AMS-02 energies is indeed an extrapolation, which can affect significantly the conclusion on the  $e^\pm$  flux, depending on the assumptions made. Data from the Fermi-LAT experiment in the energy range of 10 – 1000 GeV are perfectly suited in order to constrain more precisely the Monogem and Geminga contribution to the  $e^\pm$  at  $E > 100$  GeV, since ICS photons in this energy range are produced by  $e^\pm$  detected at Earth with average energies in the range 350 – 1500 GeV.

## 2. Positron and photon flux from PWNe

The basic elements of our model for the emission of  $e^\pm$  and  $\gamma$ -rays from PWNe are carefully illustrated in Ref. (7). The  $e^\pm$  that propagate in the Galaxy produce  $\gamma$  rays through ICS with the Galactic ISRF (6). We model the photon flux emitted for the ICS by the pulsar, at an energy  $E_\gamma$  and coming from a solid angle  $\Delta\Omega$ , as:

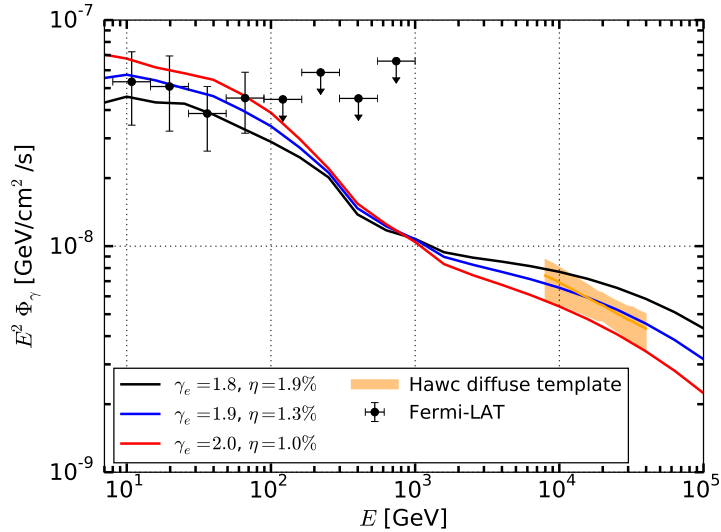
$$\phi^{\text{IC}}(E_\gamma, \Delta\Omega) = \int_{m_e c^2}^{\infty} dE \mathcal{M}(E, \Delta\Omega) \mathcal{P}^{\text{IC}}(E, E_\gamma). \quad (1)$$

The quantity  $\mathcal{M}(E, \Delta\Omega)$  is the spectrum of  $e^+$  and  $e^-$  of energy  $E$  which propagate in the Galaxy and from a solid angle  $\Delta\Omega$ , and  $\mathcal{P}^{\text{IC}}(E, E_\gamma)$  is the power of photons emitted by a single  $e^\pm$  for ICS.

Highly energetic  $e^\pm$  pairs are believed to be produced in PWNe under the influence of winds and shocks around the pulsars, then accelerated up to very high energies, and finally injected into the ISM, typically after a few tens of kyr (8; 9). We here consider a continuous injection scenario to describe the emission mechanism of  $e^\pm$  in PWNe, where the particles are emitted with a rate that follows the pulsar spin-down energy, which is translated in the energy of  $e^\pm$  pairs with an efficiency  $\eta$ . The HAWC data suggest that the diffusion coefficient ( $D(E) = D_0(E/1 \text{ GeV})^{-\delta}$ ) in the vicinity of Geminga and Monogem PWNe may be  $\sim 500$  times smaller than the one usually derived for the average of the Galaxy (4). We take into account this observation by using a two-zone diffusion model, where the region of inefficient diffusion is contained around the source, and delimited by an empirical radius  $r_b$ .

## 3. Analysis setup

In order to search an extended emission, we analyze 115 months of *Fermi*-LAT Pass 8 data, in the energy range  $E = [8, 1000]$  GeV, passing standard data quality selection criteria, belonging to the Pass 8 SOURCE event class, and using the instrument response functions P8R3\_SOURCE\_V2. We consider energies above 8 GeV. Our region of interest (ROI) is of  $70^\circ \times 70^\circ$ , and it is centered at RAJ2000=  $95^\circ$  and DEJ2000=  $13^\circ$ . We include the effect on the ICS  $\gamma$ -ray morphology coming from the proper motion of the Geminga pulsar, which has a proper motion of  $178.2 \pm 1.8$  mas/year, corresponding to a transverse velocity of  $v_T \approx 211(d/250\text{pc}) \text{ km s}^{-1}$  (10).



**Figure 1.** The  $\gamma$ -ray flux for ICS from Geminga. The *Fermi*-LAT data we derived are shown as black dots. We report the HAWC data (obtained using a diffuse template) as an orange band (4). The curves are the flux predictions obtained for different values of  $\gamma_e$  and  $\eta$ .

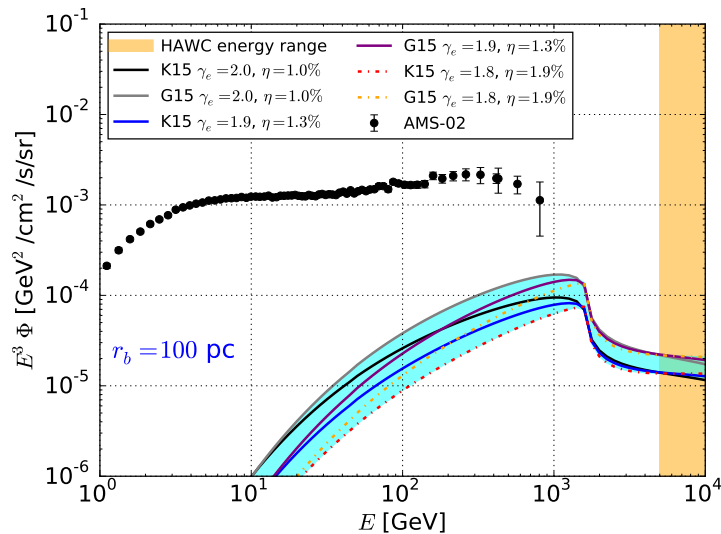
Our model fit to the data includes the IEM (with free normalization and spectral shape), the isotropic template (with free normalization) and cataloged sources (with free normalization and spectral shape) from the preliminary 8 years list. We employed the IEM released with Pass 8 data (11) (i.e., `gll_iem_v06.fits`). We also repeated the analysis using 10 different IEM (see (7)), in order to derive the systematics in the result associated to this choice.

#### 4. Results

We detect the Geminga ICS halo in *Fermi*-LAT data with  $TS=65-143$  and  $D_0 = 1.6 - 3.5 \cdot 10^{26} \text{ cm}^2/\text{s}$ , depending on the considered IEM. The fit in which we include the effect of the proper motion in the ICS template is preferred at  $4.7 - 7.1\sigma$ . The Monogem halo is not detected in *Fermi*-LAT data, regardless of the value of  $D_0$ . We derive the 95% lower limit on the value of the diffusion coefficient to be  $D_0 > 1 - 10 \cdot 10^{26} \text{ cm}^2/\text{s}$ .

The flux for the Geminga ICS halo is reported in Fig. 1. It is evaluated independently in different energy bins, by leaving free to vary the SED parameters of the sources in the model, as well as of the IEM and the isotropic templates. The *Fermi*-LAT measures the Geminga ICS halo with a precision of about 30% from 8 GeV up to 100 GeV. By fitting the *Fermi*-LAT data, we derive the efficiency of spin-down energy conversion ( $\eta$ ) for different  $e^+$  spectral indices. For  $\gamma_e = [1.8, 1.9, 2.0]$ , we find  $\eta = [0.019, 0.013, 0.010]$ , respectively.

We compute the  $e^+$  flux by implementing the  $\eta$  fitted on the *Fermi*-LAT data, for the different  $e^+$  spectral indices, within a two-zone diffusion model. The results are shown in Fig. 2 for  $r_b = 100 \text{ pc}$ , and using for  $r > r_b$  the K15 and G15 Galactic propagation models. The different  $\gamma_e$  and  $\eta$  give very similar predictions at hundreds of GeV up to TeV energies, where the *Fermi*-LAT  $\gamma$  rays calibrate the progenitor leptons. Therefore, at lower  $e^+$  energies softer injection spectra give higher  $e^+$  flux. The Geminga PWN, as constrained now by *Fermi*-LAT data, contributes at a few per-cent level to the positron flux at 100 GeV and at most 10% of the last AMS-02 energy data point at around 800 GeV. Additional tests that validate the detection of the Geminga ICS halo in *Fermi*-LAT data against different systematics are discussed in Ref. (7).



**Figure 2.**  $e^+$  flux at Earth from Geminga as computed within a two-zone diffusion model, and for the  $\gamma_e$ ,  $\eta$  values compatible with *Fermi*-LAT data. Blue (purple) curves are for G15 (K15) propagation model and for  $r_b = 100$  pc. The cyan band embeds the differences in the results considering these two propagation parameters and the choice of  $\gamma_e$ .

## 5. Conclusions

We reported the first detection of a counterpart of the Geminga  $\gamma$ -ray halo seen by HAWC in *Fermi*-LAT data from 8 GeV up to hundreds of GeV (7). As for Monogem, we derived stringent upper limits. We accurately modeled the ICS emission from  $e^\pm$  pairs produced in PWNe, as well as the effects of the proper motion of Geminga pulsar, as this affects the spatial morphology of the ICS  $\gamma$ -ray halo at GeV energies. We conclude that these sources alone, as bound now by *Fermi*-LAT data, cannot be the major contributors to the  $e^+$  excess.

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