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Constraining the TeV Halo Population in M31

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TeV halos are a new class of γ-ray sources recently observed around some middle-aged pulsars. They are extended γ-ray emission regions with a size bigger than the Pulsar Wind Nebulae but smaller than a Supernova Remnant. Several studies indicate that a TeV halo may be a general signature around a middle-aged pulsar, but this is still an open question. Some recent results suggest TeV halos are significantly contributing to the TeV emission of our Galaxy, and models have been proposed to reproduce the observed population of TeV halos in the Milky Way. In this work, we analyze the emission at TeV energies of the Andromeda galaxy (M31), the closest spiral galaxy to Earth. M31 has also been observed to have a GeV excess similar to the observed in the Galactic Center of our Galaxy. The aim of this work is to model the γ-ray emission at TeV energies in M31 assuming both the Milky Way and M31 share similar properties. Using 6 years of HAWC observations, we compute the flux upper limits in the region of M31 at TeV energies.

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1. Introduction

Recent observations by the High Altitude Water Cherenkov Observatory (HAWC) and the Large High Altitude Air Shower Observatory (LHAASO) have confirmed the existence of extended γ-ray emission regions around certain middle-aged pulsars [1, 2]. These regions have sizes bigger than a Pulsar Wind Nebula (PWN) but smaller than a Supernova Remnant (SNR), and they have been classified as a new class of γ-ray sources, called “TeV halos” [3, 4]. Several studies suggest that TeV halos might be a general feature of middle-aged pulsars and that they are the primary sources of the diffuse emission observed at TeV energies in our Galaxy [5, 6].

To study the properties of TeV halos, it is necessary to understand some fundamental physical parameters of pulsars, as well as their distribution within the Galaxy. Observations and models indicate that pulsars are not uniformly distributed across the Galactic plane. Instead, their distribution has a deficit of pulsars in the inner Galaxy. The distribution peaks at $\sim$ 4 kpc from the Galactic centre, and subsequently decreases as we move towards the outer regions [7]. This behavior is commonly described with a Gamma function, however some approaches can also be performed using a Gaussian distribution [7, 8].

The Andromeda galaxy, also know as M31, is the closest major spiral galaxy to Earth, and its morphology is similar to our Milky Way. It also has been observed to be a star forming galaxy and a γ-ray emitter at GeV energies. For instance, *Fermi*-LAT observations have revealed a GeV excess in the nucleus of M31 [9], and a recent work suggests this excess can be associated to a population of millisecond pulsars [10]. In this work we analyze the γ-ray emission from M31 at TeV energies under the assumption it is due to a population of middle-aged pulsars, i.e. TeV halos and we model the emission assuming a pulsar distribution similar to the one observed in our Galaxy.

2. Gamma-ray emission from M31 with HAWC

The HAWC observatory is located at Sierra Negra, México, at an altitude of 4100 m above sea level. It consists of 300 Water Cherenkov Detectors (WCD), each with a diameter of 7.3 m and a height of 4.5 m, covering a total area of 22,000 m^2. HAWC has the capability to observe the sky in the energy range of 300 GeV to several hundred TeV with a field of view of 2 sr and a duty cycle $>$ 95%. In this work, we are using $\sim$ 6 years of HAWC data to analyse M31 γ-ray emission from M31. As there were no significant detections at the location of M31 within this dataset, we subsequently calculated the flux upper limits (UL) as detailed below.

We are modelling the γ-ray emission from M31 assuming it is an extended and non-uniform source, taking the morphology of the disk from [11, 12]. Specifically, we are using an asymmetric Gaussian on sphere shape from the astromodels package, available on the Multi-Mission Maximum Likelihood (3ML) framework [13], with a major axis (standard deviation of the Gaussian distribution) of $a = 0.9°$, a minor axis of $b = 0.2°$ and inclination of 45.04° along the right ascension axis (see Figure 1). This spatial shape is taken as pulsar distribution is not uniform along the Galactic disk, and we assume the distribution will be similar in M31. We are aware that a Gaussian distribution is not accurate to describe the pulsar distribution from [7], but it is taken as a first approach for our calculations.

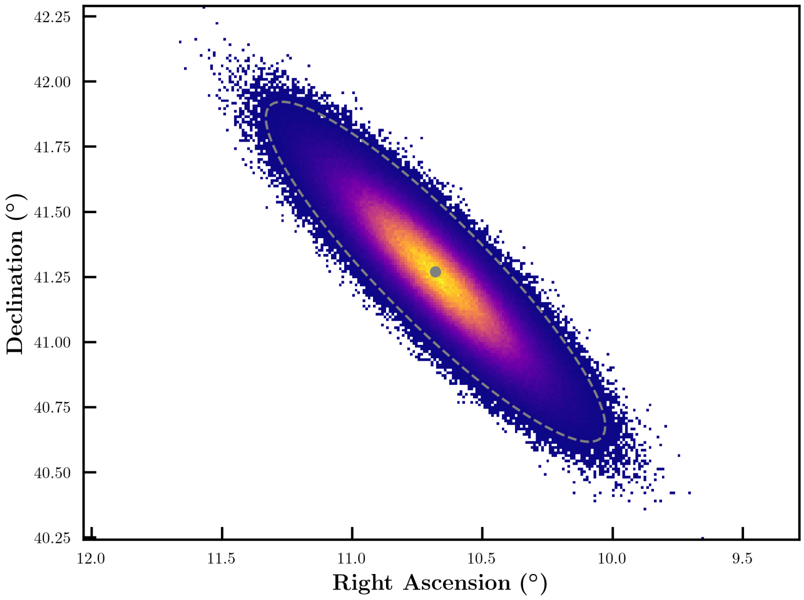

Figure 1: Morphology of M31 used in this work. It correspond to an asymmetric Gaussian on sphere spatial shape from the astromodels.

We are using 3ML together with the HAWC Accelerated Likelihood (HAL) plugin [14] to fit a simple power law spectrum to the HAWC data:

$$\frac{dN}{dE} = K\left(\frac{E}{E_0}\right)^{-\xi}, \tag{1}$$

where K is the normalization constant, the pivot energy is fixed at $E_0 = 1$ TeV and the spectral index is taken to be $\xi = \{2.14,\ 2.34\}$, as these are the indexes reported for the Monogem and Geminga TeV halos [1], respectively.

We use a Maximum Likelihood technique to calculate the value of K that provides the best fit to the HAWC data. This K is then used as input to run a Markov-Chain Monte Carlo (MCMC) analysis, allowing us to derive the distribution of posterior likelihood around the maximum. Given the absence of significant observations at TeV energies, the results from the MCMC analysis are used to compute the flux UL at the 95% confidence level. Results are shown in Figure 2, where the black line corresponds to the flux UL using a spectral index of $\xi = 2.34$ and the red line is for $\xi = 2.14$. We also report the best fit for the normalization constant, labelled as K_{mean}, its corresponding UL (K_{UL}) from the MCMC and the integral flux UL for energies > 1 TeV in Table 1.

Table 1: Values of the normalization constant and integral flux for the 95% credible interval ULs for M31.

Spectral index	K_{mean}	K_{UL} $(10^{-15}$ TeV^{-1} cm^{-2} s$^{-1})$	Integral flux UL $(10^{-13}$ cm^{-2} s$^{-1})$
2.34	1.29	2.87	2.03
2.14	0.89	1.92	1.08

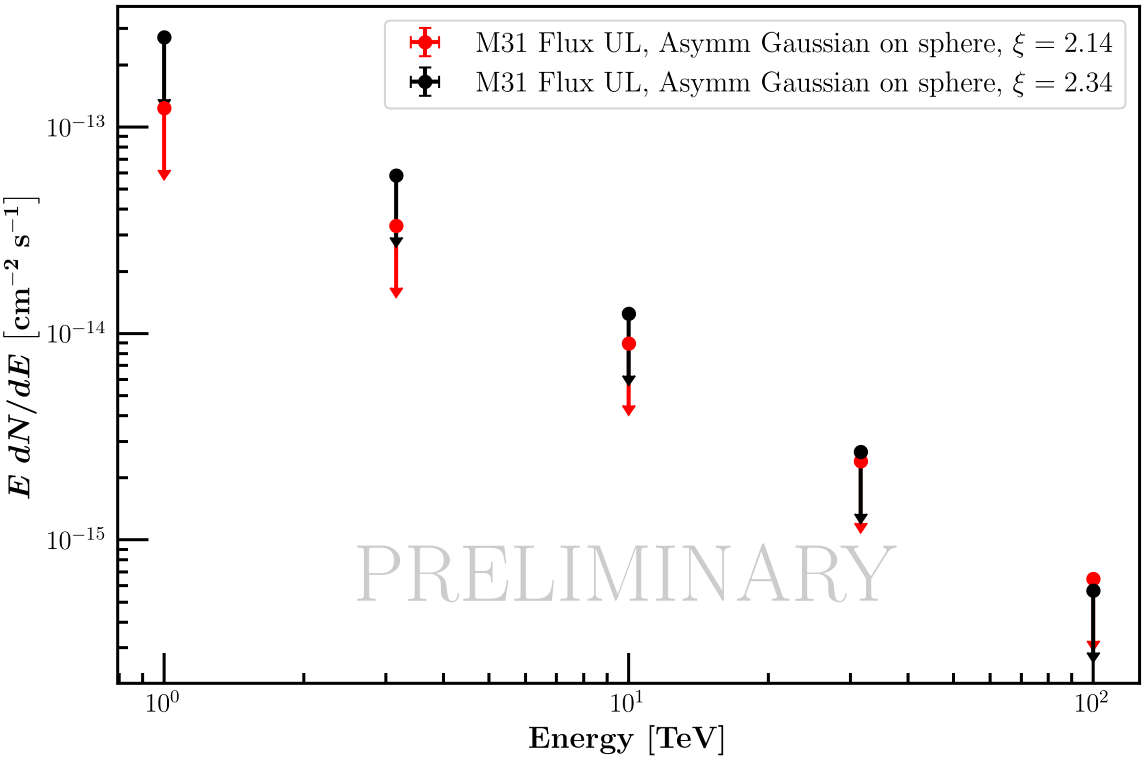

Figure 2: Flux Upper Limits of M31 in the 1 – 100 TeV energy range, computed using ~ 6 years of HAWC data, an asymmetric Gaussian spatial shape and a simple power law spectrum with index $\xi = \{2.14, 2.34\}$.

3. Conclusions

Using approximately 6 years of HAWC data and employing the 3ML + HAL analysis framework, we have determined the flux UL for the disk of M31 at TeV energies. The analysis assumed a simple power law spectrum with index $\xi = \{2.14, 2.34\}$ together with an asymmetric Gaussian spatial shape. The analysis returned a normalization constant UL of $(1.92 - 2.87) \times 10^{-15}$ TeV^{-1} cm^{-2} s^{-1} and an integral flux above 1 TeV of $(1.08 - 2.03) \times 10^{-13}$ cm^{-2} s^{-1} for each spectral index.

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