Snowmass2021 - Letter of Interest

*Constraining the Local Positron Contribution from TeV Halos with the Southern Wide-field Gamma-ray Observatory (SWGO)**

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: TeV Halos—extended regions of TeV gamma-ray emission around middle-aged pulsars—have recently been established as a new source class in gamma-ray astronomy. These halos have been attributed to relativistic electrons and positrons that have escaped from the Pulsar Wind Nebula and are diffusing in the surrounding medium. Measuring the morphology of TeV Halos enables, for the first time, a direct measurement of the electron diffusion on scales of tens of parsecs. Understanding electron diffusion is necessary to constrain the origins of the apparent "excess" of cosmic-ray positrons at tens of GeV. The proposed Southern Wide-field Gamma-ray Observatory (SWGO) is expected to detect more of these TeV Halos due to its good sensitivity to extended gamma-ray emission and view of the Southern sky. SWGO will help determine to what extent pulsars contribute to the observed local cosmic-ray electron and positron fluxes, and how they affect diffusion in their environments.

*This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

An unexpected excess of local positrons above 50 GeV has been detected by several satellites[3]. The two main explanations hypothesised are local dark-matter (DM) interactions or local astrophysical sources like nearby pulsars and their associated TeV Halos. Therefore, a detailed understanding of TeV Halos is needed to establish how many of the local positrons, if any, are due to DM interactions.

The High-Altitude Water Cherenkov (HAWC) Observatory has discovered halos of extended TeV gamma-ray emission around the Geminga and Monogem pulsars[4]. For Geminga, this emission is more extended than what is expected from the Pulsar Wind Nebula (PWN) from x-ray observations[5]. These emission regions, dubbed TeV Halos, constitute a new source class[6;7]. The emission is consistent with inverse Compton emission from electrons and positrons that were originally accelerated by the pulsar and/or in the PWN, but have since escaped the PWN and are diffusing into the surrounding medium (Note: in the rest of this Letter, we collectively refer to electrons and positrons as 'electrons'). These Halos have also been detected at GeV energies by the *Fermi*-LAT[8;9].

HAWC was able to measure the diffusion coefficient inside the Geminga and Monogem Halos. The results were significantly lower than that expected for the interstellar medium (ISM) using the Boron-to-Carbon ratio[4]. Similar diffusion coefficients were calculated using the *Fermi*-LAT[8;9]. Assuming the diffusion coefficient is constant over a larger region representative of the intervening ISM, these measurements indicate that Geminga and Monogem cannot be the primary sources of the apparent excess in cosmic-ray positrons, as the electrons accelerated by these pulsars would cool long before reaching Earth (see the left side of Figure 1).

However, there are models by which the streaming of the relativistic electrons itself suppresses the diffusion coefficient near the pulsars (e.g. Ref[10]). There could be 'bubbles' of suppressed diffusion extending for tens of parsecs around middle-aged pulsars, with increased diffusion in the rest of the Galaxy[11]. In that case, electrons leaving this bubble could still propagate to Earth and significantly contribute to the local positron fraction[8;12] (see the right-hand side of Figure 1).

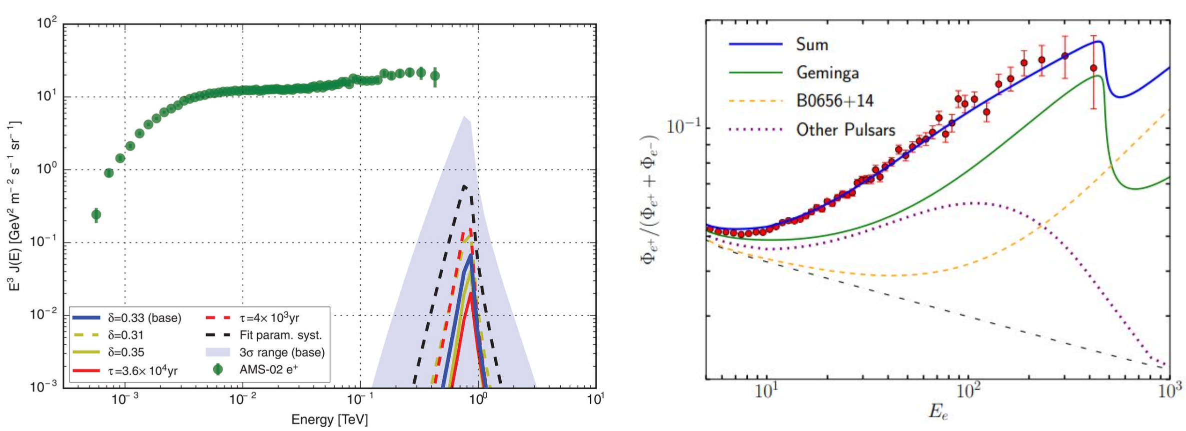

Figure 1: Local positron flux predictions from various non-DM sources. (Left) using 1 zone diffusion model[4] (Right) using 2 zone diffusion model[12].

More detections and studies of TeV Halos are needed to better understand the diffusion in these sources as a population. We expect many more such objects should be discovered in future searches[6]. Since the discovery of the first TeV Halos, HAWC has already reported at least two more TeV-Halo candidates[13;14]. TeV halos may also contribute to some of the unidentified or PWN-associated TeV sources already detected in the galactic plane[6].

We propose a next-generation gamma-ray observatory that will detect gamma rays from 1 TeV to over

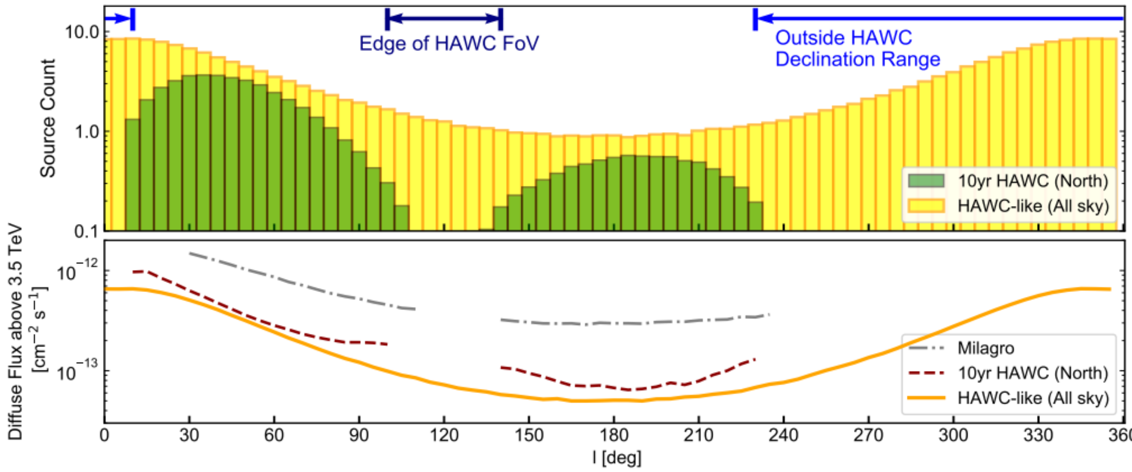

Figure 2: Prediction for the number and Galactic Longitude distribution of TeV Halos to be discovered with current or future instruments. A "HAWC-like" 10-year sensitivity is modeled as a theoretical instrument with a sensitivity of 3% of the Geminga flux across the entire sky. Figure from Ref. 18 (see there for more details about the model; reproduced with permission).

100 TeV. The Southern Wide-field Gamma-ray Observatory (SWGO)[15;16] is planned to be located in the Southern Hemisphere and have a sensitivity $\sim 10\times$ better than the HAWC Observatory[17]. Both detect relativistic particles in extensive air showers caused by cosmic-ray and gamma-ray interactions in the atmosphere. These arrays have a wide field-of-view and observe $\sim 2/3$ of the sky every day with a near-100% duty cycle. They complement Imaging Atmospheric Cherenkov Telescopes (IACTs), which have smaller fields-of-view and conduct targeted observations. With its wide field-of-view ($\sim$ 2sr), SWGO would have a much-improved sensitivity to extended objects like TeV Halos, whilst the sky-scanning observations improve the discovery probability.

So far, most pulsars have been detected via searches for periodic radio pulses. However, there is an unknown fraction of 'mis-aligned' pulsars, whose radio-beam does not sweep Earth and from which we do not observe any pulsed emission. In fact, some pulsars have been found via their pulsed gamma-ray emission alone. Blind searches for TeV Halos in the Milky Way and neighboring galaxies such as the Large Magellanic Cloud are expected to lead to the discovery and identification of tens or hundreds new pulsars (see Figure 2 and Ref. 18). In addition to further improving our understanding of TeV Halos and their evolution, blind searches for these Halos with SWGO will lead to a better understanding of the pulsar population. This will, in turn, lead to a more stringent interpretation of the local positron excess and the associated implications for dark-matter interactions.

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