Unveiling TeV halos among unidentified extended TeV sources

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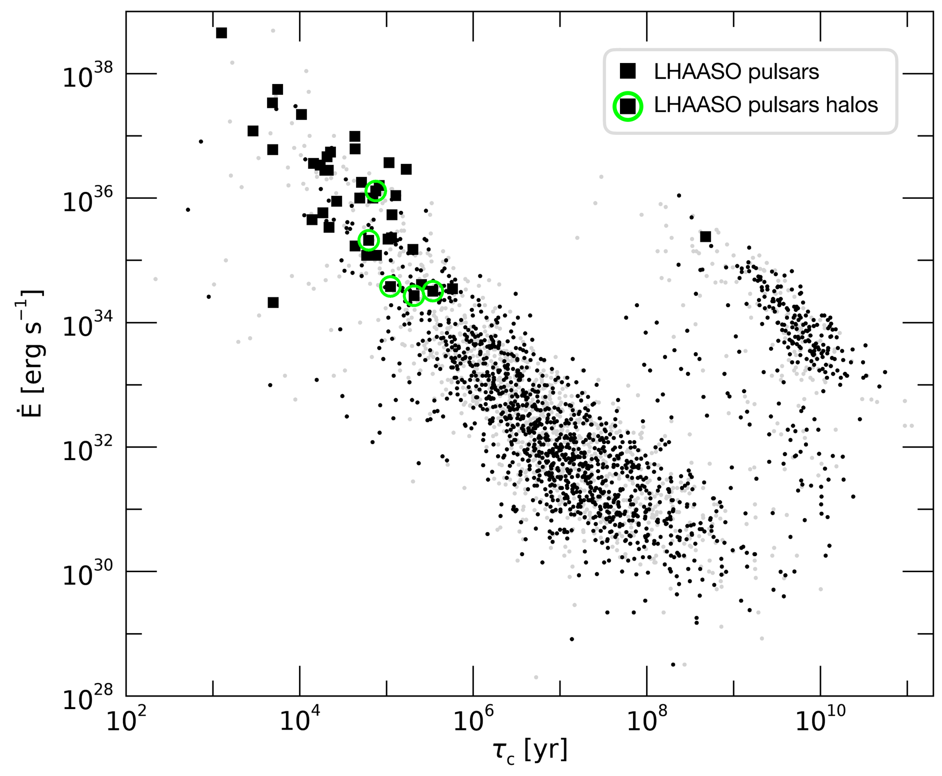
In recent years, the number of known sources emitting very- and ultra-high-energy gamma-rays has increased significantly thanks to facilities such as LHAASO [1] and HAWC [2]. Many of the observed **sources are still unidentified** or poorly constrained due to the limited angular resolution of these instruments; however, it is now ascertained that approximately half of them have a **pulsar in coincidence** [see Figure 1].

Figure 1: Spin-down luminosity $\dot{E}$ VS characteristic age τ_c of all the pulsars in the ATNF catalog [3] (grey dots), all the pulsars visible by LHAASO (black dots), all the pulsars in spatial coincidence with a LHAASO source (black squares), and the confirmed/candidate TeV halos [4,5,6,7] (green open circles).



Some of these unidentified extended sources may be the result of the diffusion of leptons accelerated by the pulsar itself or in its nebula to energies exceeding 50 TeV [8]. This new class of sources, called **TeV halos**, is characterized by a surface brightness that mainly depends on:

- **Pulsar properites** (the spin-down luminosity E, the age τ_c, and the distance d);
- **Injected spectrum** (the electron spectral index α_e, and the acceleration efficiency ξ_{CR});
- **Medium properties** (the diffusion coefficient D_{100}, the turbulence spectral index δ, and the magnetic field B).

We obtained the energy-dependent radial profile of the halo integrating the lepton distribution along the line of sight:

$$F(E_\gamma, r) \approx \frac{0.74\, r_d(E_e)}{r + 0.08\, r_d(E_e)}\, e^{-\left(\frac{r}{r_d(E_e)}\right)^2}, \text{ where } r_d(E_e) \equiv 2\sqrt{D(E_e)\tau_{\rm eff}(E_e)} \approx 26 \left(\frac{D_{100}}{5\times10^{27}\ {\rm cm^2\ s^{-1}}}\right)^{1/2} \left(\frac{\tau_{\rm eff}}{10^4\ {\rm yr}}\right)^{1/2} {\rm pc}$$

is the **diffusion radius** and $\tau_{\rm eff}$ is the minimum value between the pulsar age and the leptons loss time after **synchrotron** and **inverse Compton processes** [4]. The relation between the mean electron energy E_e and the photon energy E_γ in the inverse Compton scattering process is also reported in [4].

In this contribution, we consider all the pulsars which are spatially coincident with an unidentified extended TeV source [see Figure 1], in order to quantify whether its spin-down power, age, and distance allow the pulsar to produce a TeV halo with the observed flux and extension.

Among these sources, we selected one pulsar (**PSR J2238+5903**) as a case study to assess the performance of the next-generation Imaging Atmospheric Cherenkov Telescopes, namely the Cherenkov Telescope Array Observatory (CTAO) [9] and the ASTRI Mini-Array [10]. Thanks to their **arcminute-scale angular resolution**, they will be able to detect a radial profile up to angular separations of ~1° from the center of the source [see Figure 2].

Not only will this capability provide a deeper understanding of this source and the other halos, but also essential constraints on the **particle acceleration** and **propagation mechanisms**.

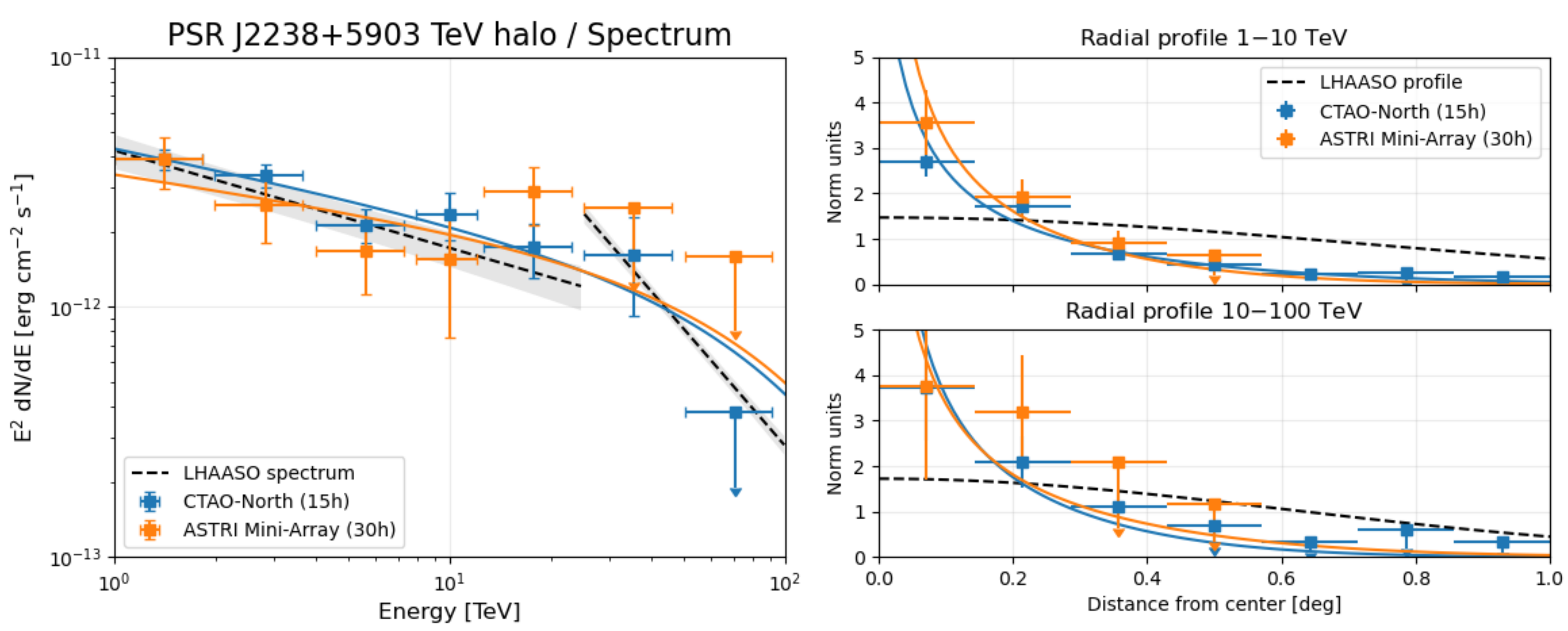


Figure 2: Results on our simulations on the TeV halo of PSR J2238+5903. Our set of assumptions are: τ_c = 2.7×10⁴ yr, $\dot{E}$ = 8.9×10³⁵ erg s⁻¹, d = 2.8 kpc [pulsar properties [3]]; $\alpha_e \approx 2.6$ and ξ_{CR} = 58% [injection spectrum to match [1] results]; D_{100} = 5×10²⁷ cm² s⁻¹, δ = 1/3, B = 3 μG [medium properties as in [4]]. We obtained r_d (E_γ = 3 TeV) ≈ 33.5 pc and r_d (E_γ = 50 TeV) ≈ 22.0 pc, corresponding to θ_d (E_γ = 3 TeV) ≈ 0.68° and θ_d (E_γ = 50 TeV) ≈ 0.44°. *Left*: Simulated gamma-ray spectrum (blue: CTAO-North 15 h; orange: ASTRI Mini-Array 30 h) compared to the power-law spectra observed by LHAASO (dashed lines) and to our best-fit spectra (solid lines). *Right*: Simulated radial profiles between 1–10 TeV (upper panel) and 10–100 TeV (lower panel), overlaid on the Gaussian fit reported by LHAASO (dashed lines) and our best-fit model (solid lines).

1. Cao et al. (2024) ApJS, 271, 25
2. Albert et al. (2020) ApJ, 905, 76
3. Manchester et al. (2005) AJ, 129, 1993
4. Abeysekara et al. (2017) Science, 358, 911
5. Aharonian et al. (2021) PhRvL, 126, 24110
6. Albert et al. (2023) ApJ, 944, L29
7. Cao et al. (2025) SCPMA, 68, 279504
8. López-Coto et al. (2022) Nature Astronomy, 6, 199
9. Cherenkov Telescope Array Consortium (2019)
10. Scuderi et al. (2022) JHEAP, 35, 52

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