

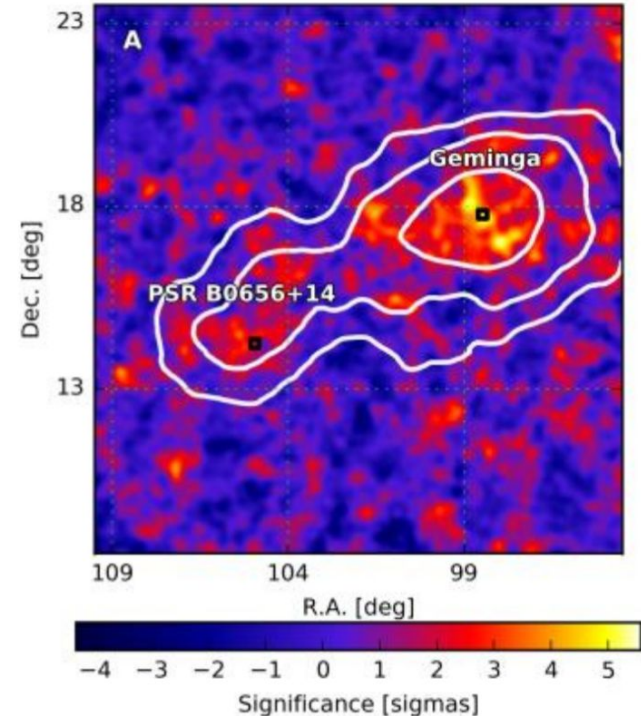
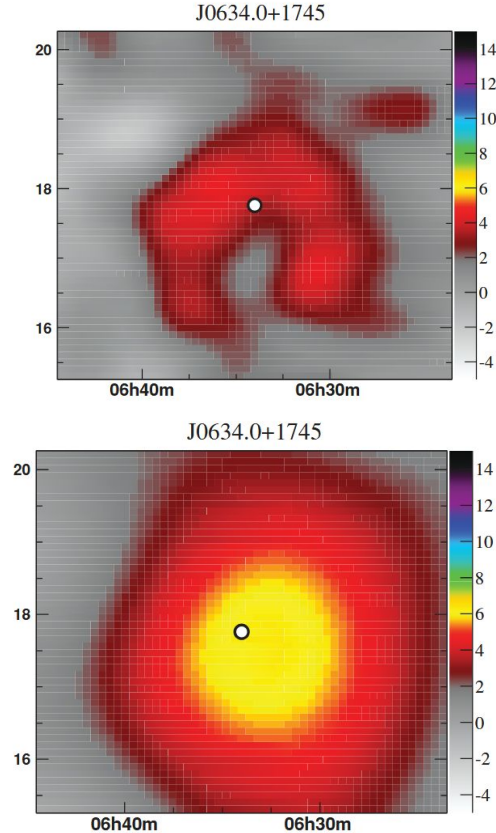
Studying the Population of Potential TeV Halos in HAWC Data

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Early History of the Prototypical TeV Halos

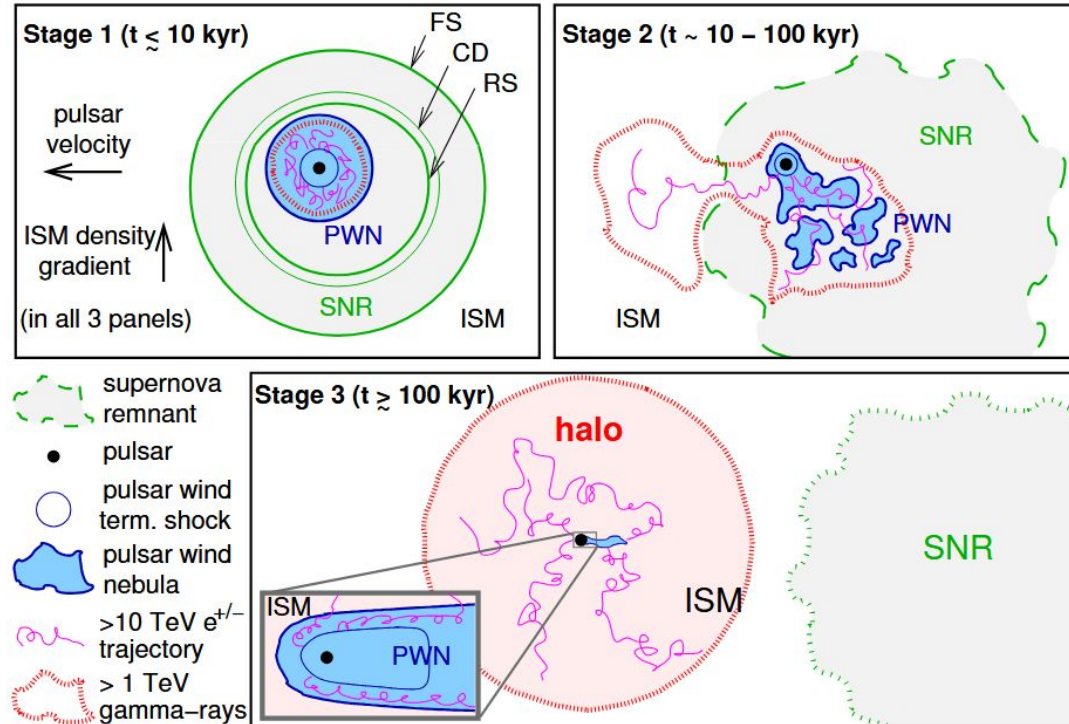
- 2007 - Milagro finds evidence of large extended TeV emission in the vicinity of the Geminga pulsar at 5σ
- 2016 - HAWC has enough observations to observe both Geminga and Monogem at 6.3σ with better angular resolution



Early History of the Prototypical TeV Halos

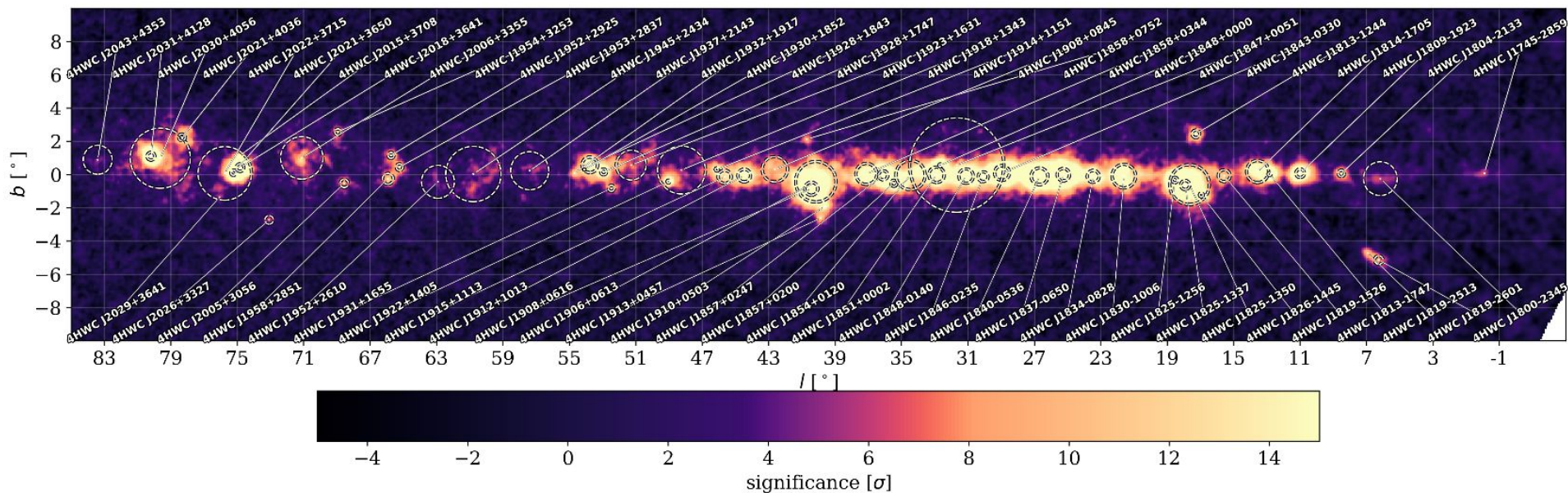
- After HAWC discovery of TeV Halos, more examples of 'halos' of TeV emission have been found by HAWC, LHAASO, HESS, etc
- Subsequent theory papers defined and refined Halo formation and evolution

G. Giacinti et al.: Halo fraction in TeV-bright pulsar wind nebulae



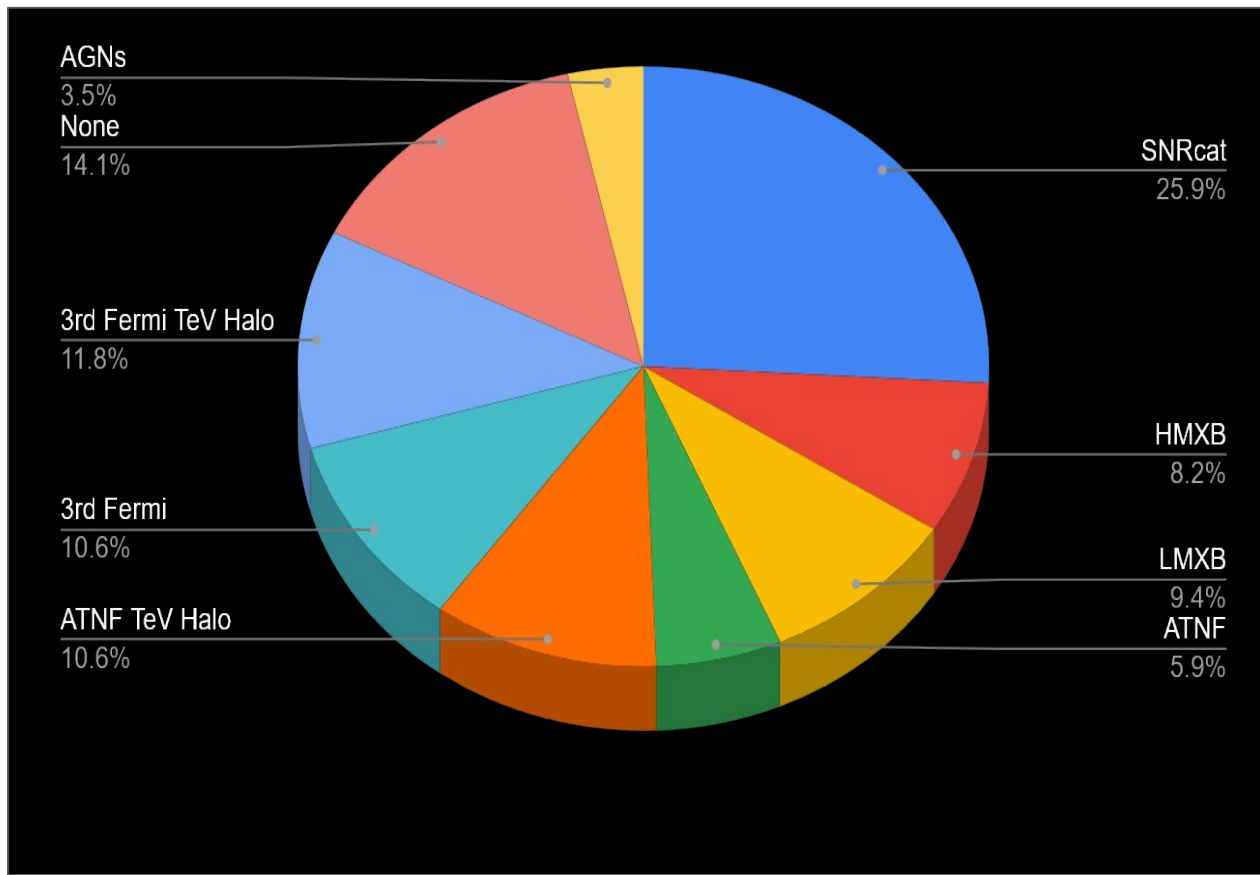
Using 4HWC Catalog as a Basis

- 85 Sources detected in HAWC data
 - Majority extended (68/85)
- Broad coverage of 100 GeV to 100+ TeV in northern sky perfect for identifying extended source class like TeV Halos



Using 4HWC Catalog as a Basis

- In 4HWC a TeV Halo candidate is defined as
 - Associated with a pulsar aged 100-400 kyr
 - Spindown power of at least 1% of the Geminga pulsar
 - 19 Total examples
- For this work a looser cut is made
 - Associated with a pulsar aged at least 40 kyr
 - 23 Total Examples



Continuous Injection Diffusion Model

To model the diffusive nature of the TeV halos the standard symmetric gaussian modeling

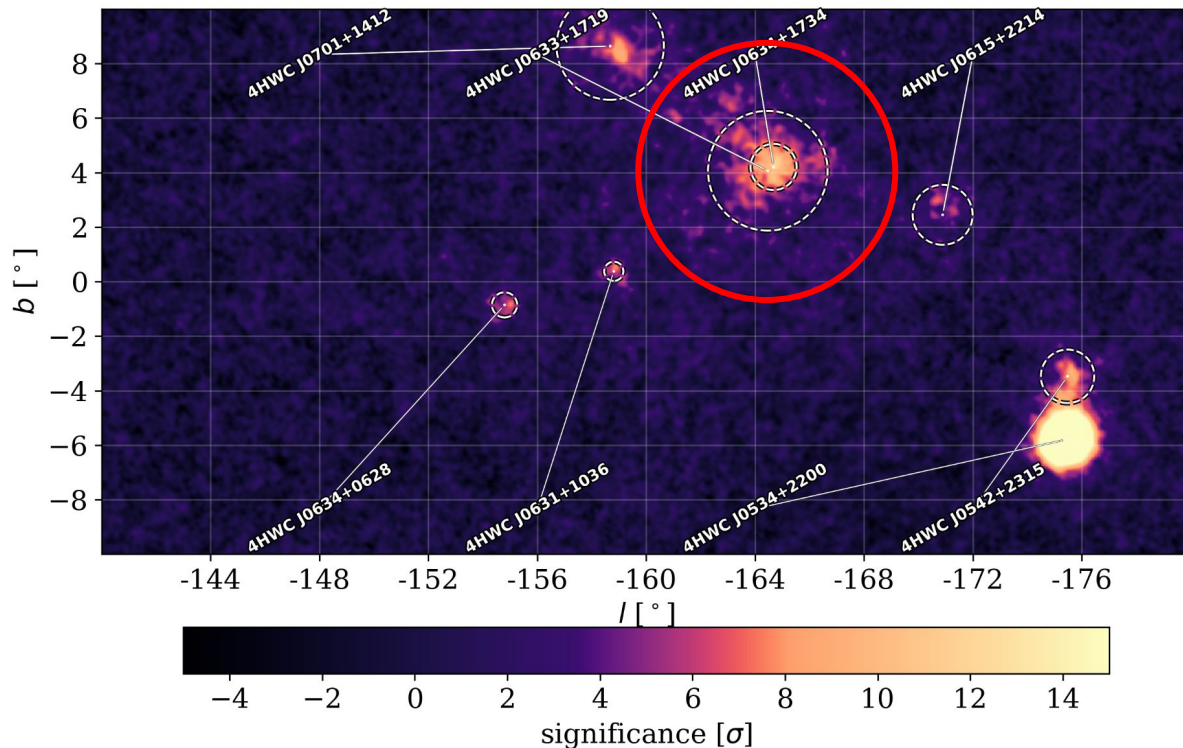
$$f(r) = \left(\frac{180^\circ}{\pi} \right)^2 \frac{1}{2\pi\sigma} \exp \left(-\frac{r^2}{2\sigma^2} \right)$$

Is replaced with the continuous injection diffusion modeling

$$f(r) = \left(\frac{180^\circ}{\pi} \right)^2 \frac{1.2154}{\sqrt{\pi^3} r_{diff} (r + 0.06 r_{diff})} \exp \left(-\left(\frac{r}{r_{diff}} \right)^2 \right)$$

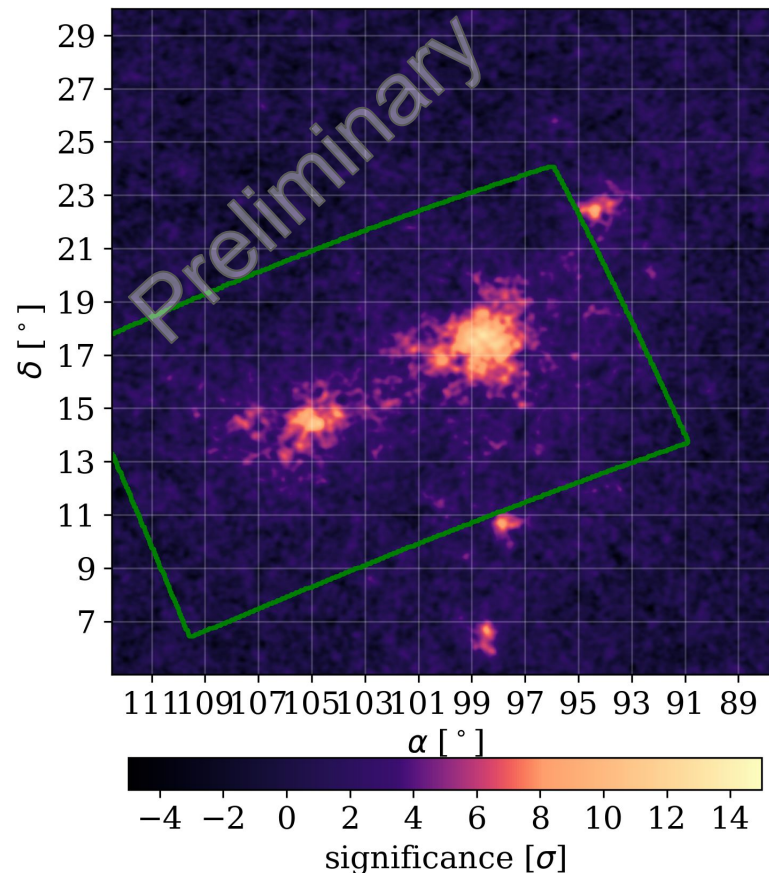
Example of One Region

- Beginning with the 4HWC results we focus on Geminga the first and closest TeV Halo
- 4HWC used ~ 2726 days of fHit data and this example uses 2894 days of the ground parameter (GP) energy estimator dataset



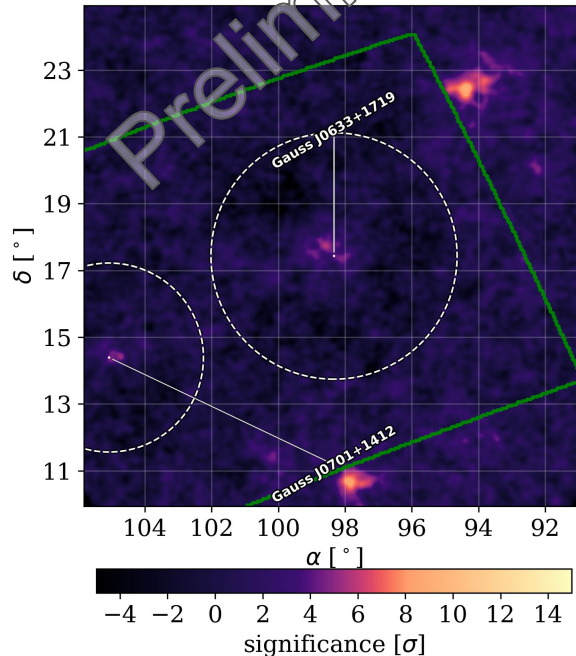
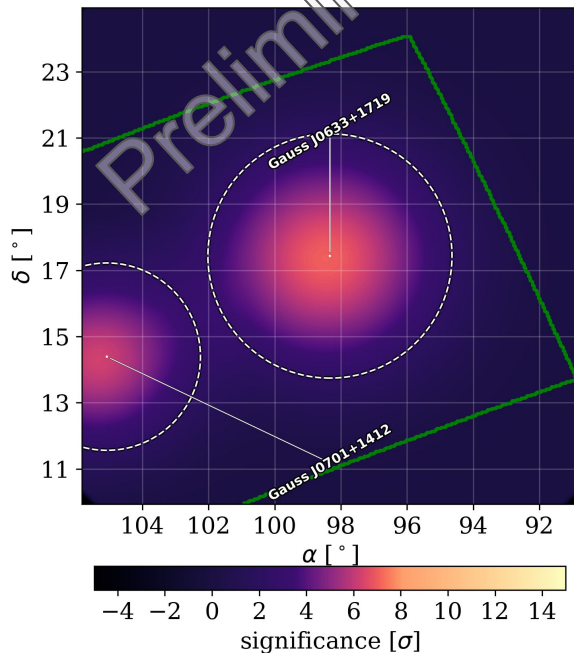
Example Fit - Data

- The Region of Interest (ROI) for a joint fit of Geminga and Monogem in HAWC data
- Each source is large enough to impact the other but a mask is applied to remove more distant sources



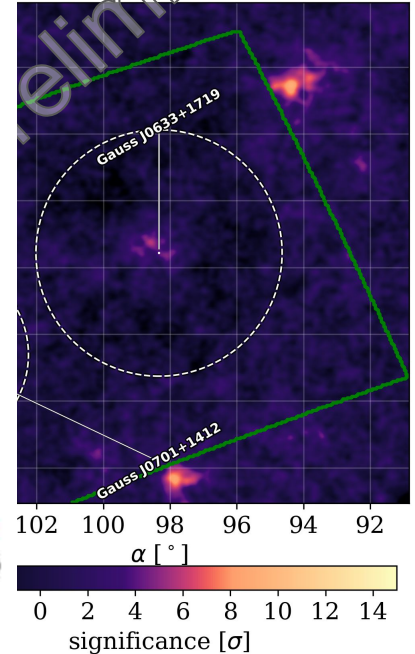
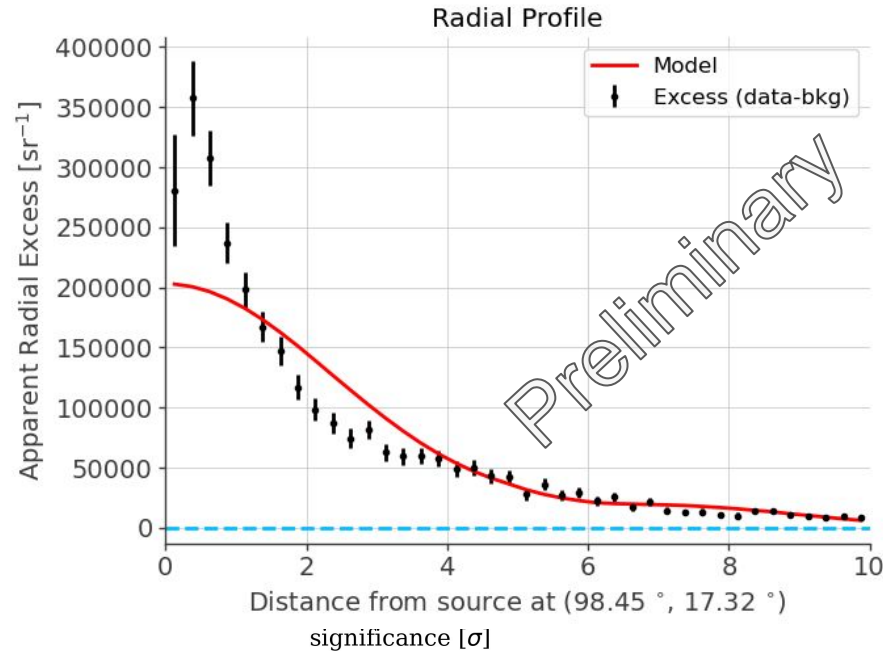
Example Fit - Gaussians

- There's still a bit of emission at the center and a dark circle of slight over subtraction



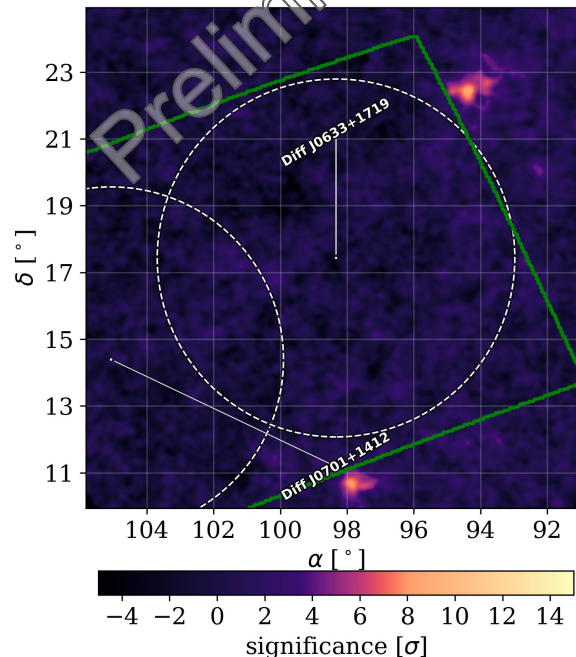
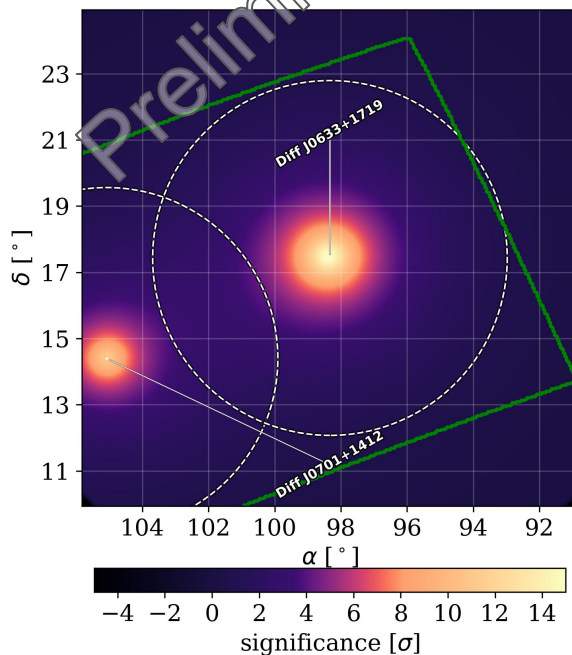
Example Fit - Gaussians

- A profile of the excess photon counts shows the same story



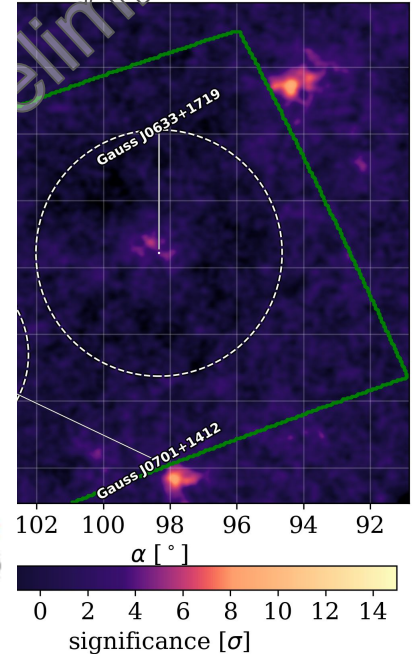
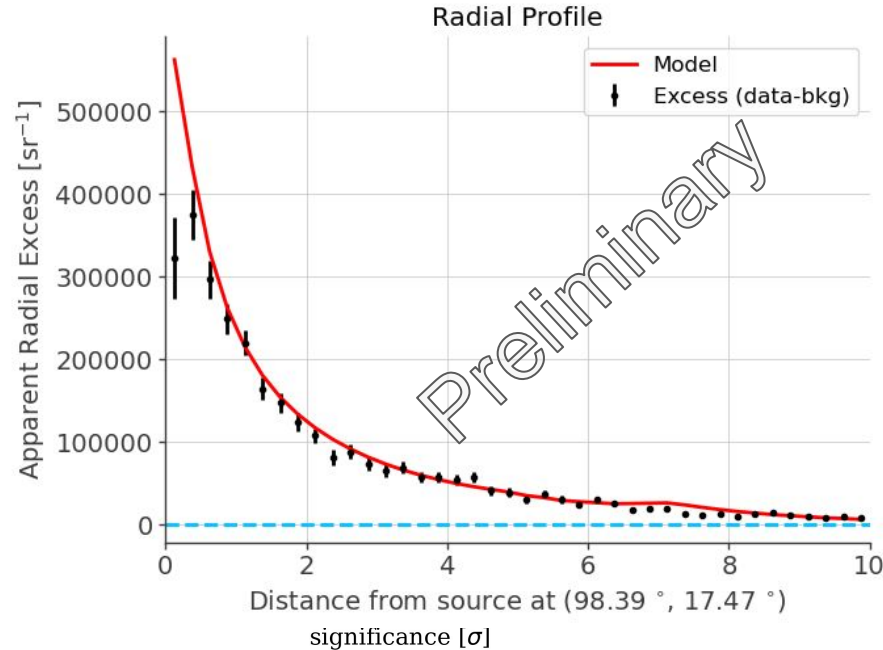
Example Fit - Diffusion

- The 68% containment is larger for the diffusion
- But the overall residual looks significantly better supported by an improved AIC value



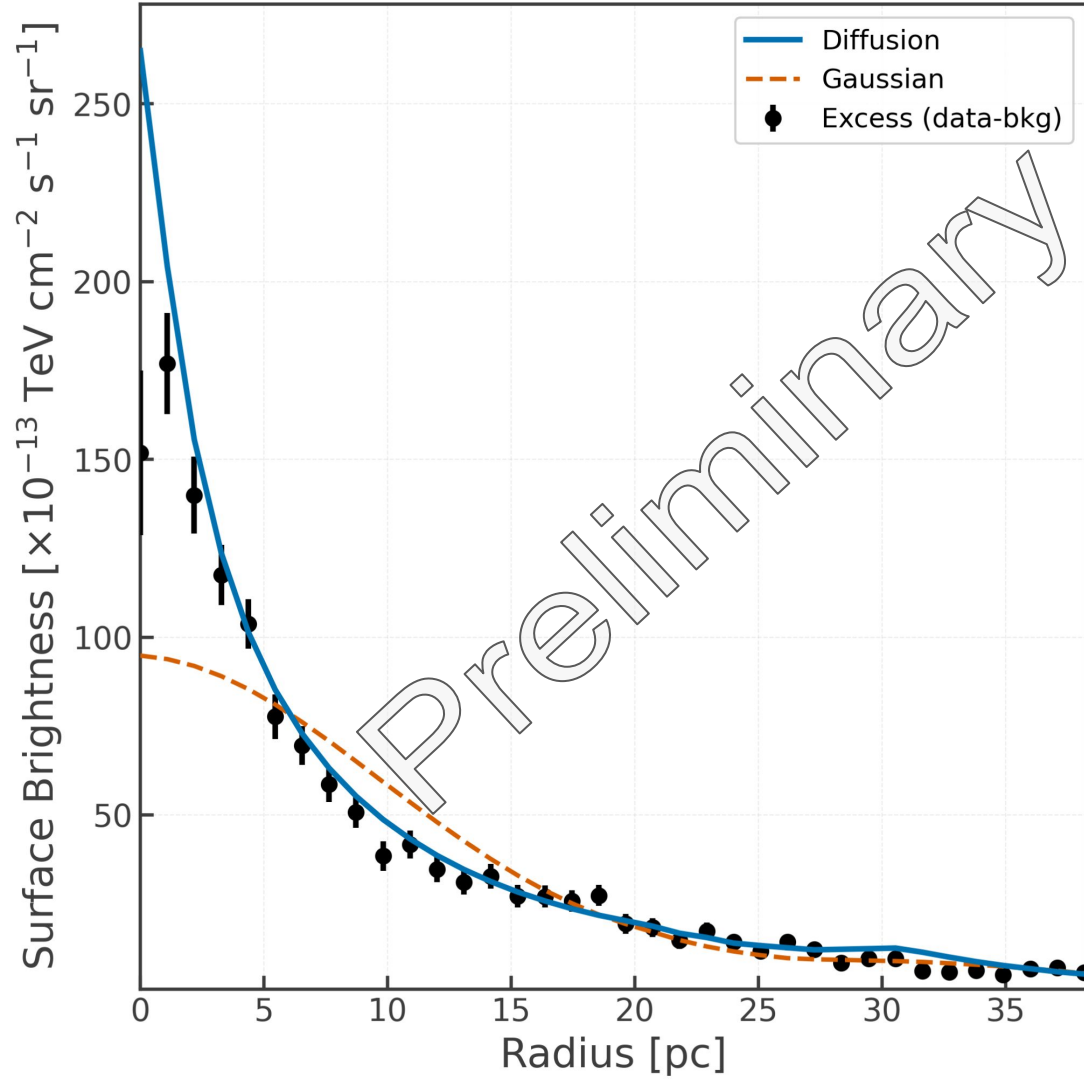
Example Fit - Diffusion

- The same profile points to a over subtraction near the center but a much better fit of the profile



Radial Plots

- We convert to more physically motivated units
- The difference is abundantly clear when plotted together

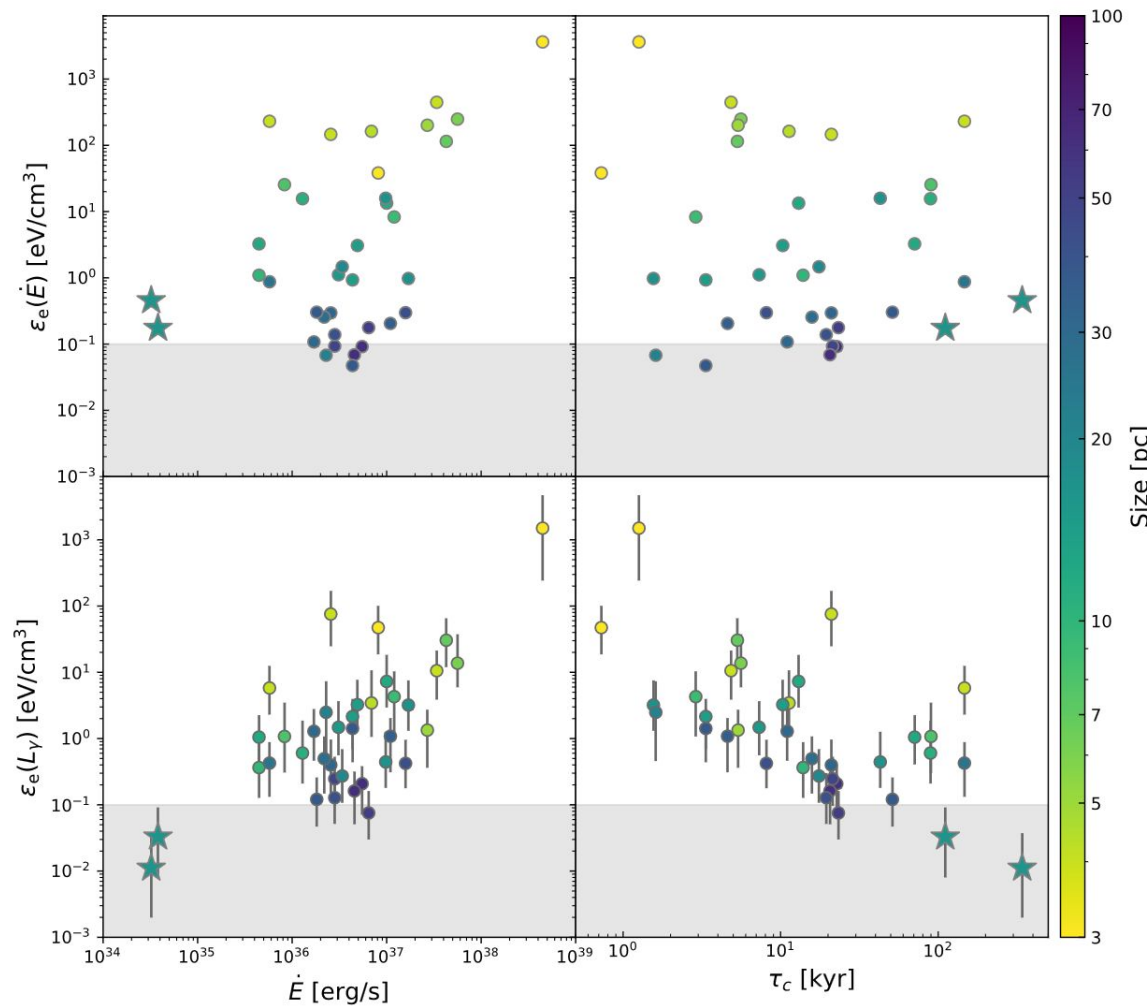


Overall Results

- We perform the same procedure outlined with Geminga for all 23 sources
 - Nearly half of sources show a statistical improvement of at least 5 in AIC
- But statistical preference for a diffusion-like spatial distribution is not enough
- The presence of a much more compact PWN can alleviate confusion with other sources like SNRs
- A third criterion from literature allows us to place another cut on energy density

Electron Density

- To further quantify the “Haloness” we follow Giacinti et al. 2020
- We compute the electron energy density assuming IC emission explains the TeV emission
- The paper chooses a threshold of 0.1 eV/cm³ after looking at PWNs

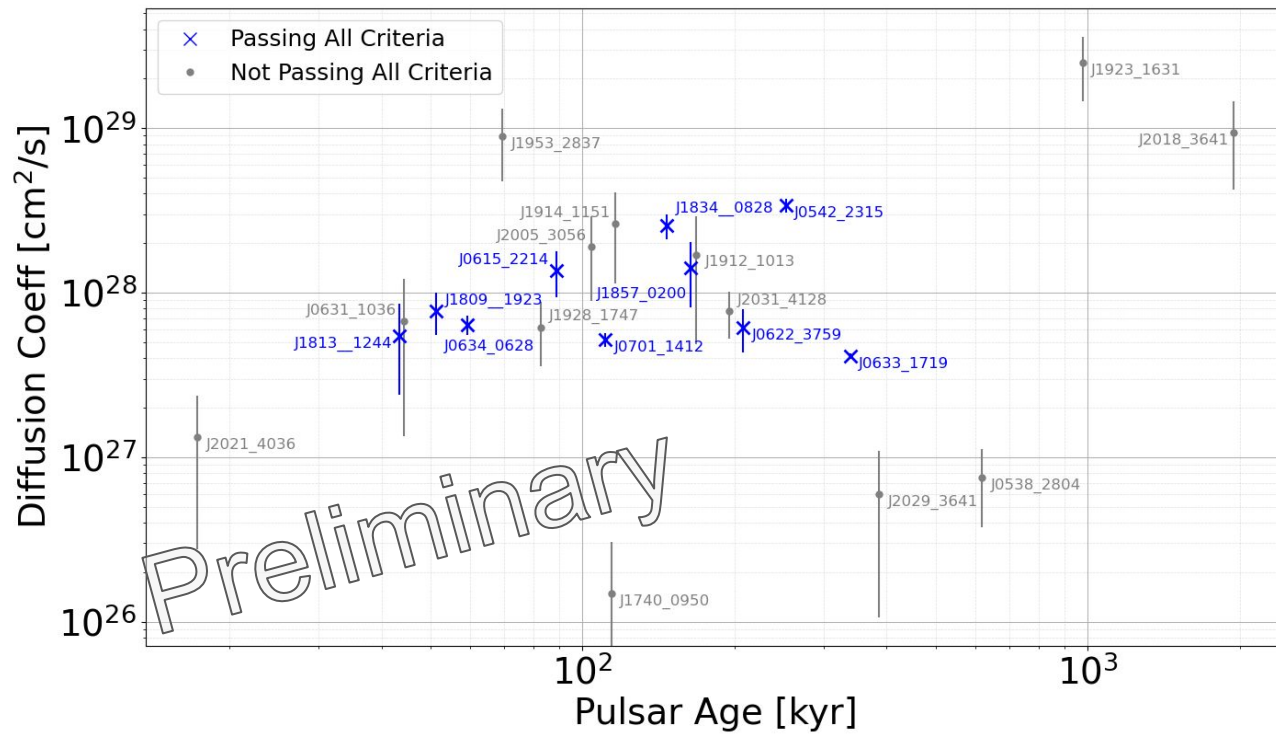


Applying All Three Criteria

- Applying the three criteria together gives stronger evidence of Halo-like source behavior
- 10 out of the 23 sources pass all three criteria and will be the focus of further analysis and interpretation
- Comparing these 10 sources to the rest shows us likely source class wide characteristics

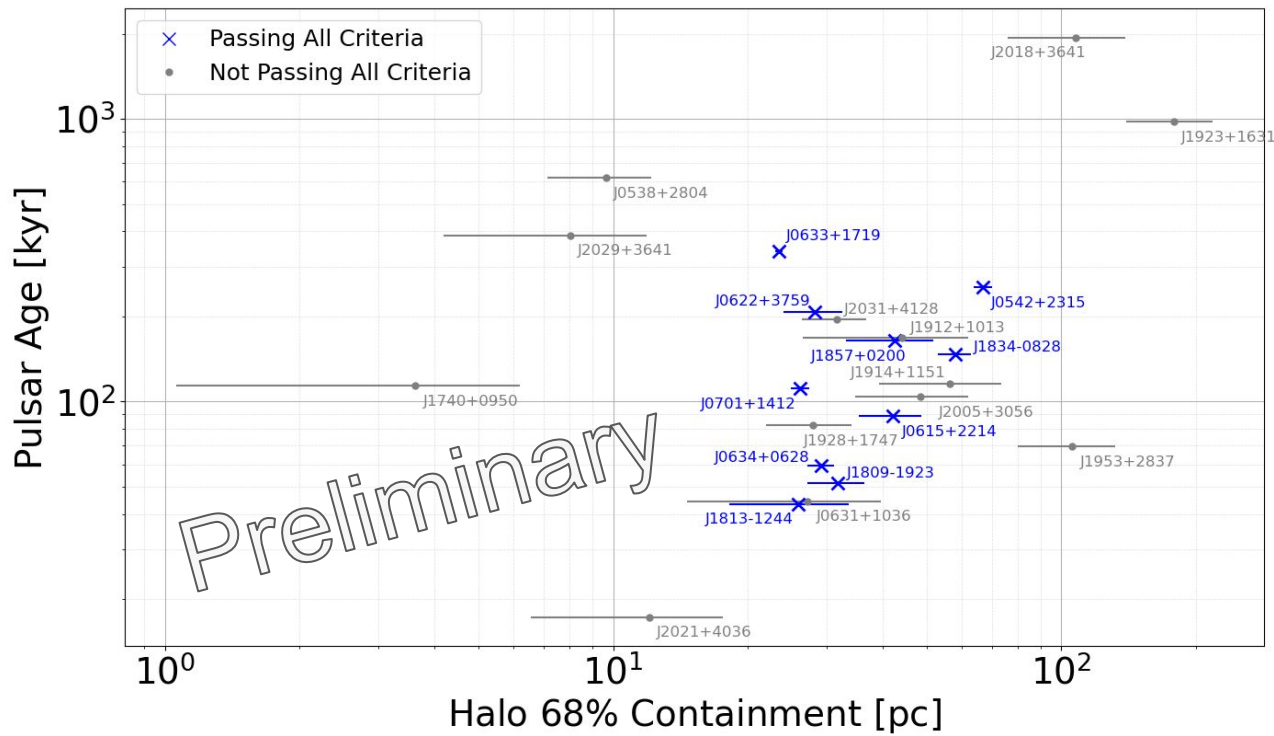
Looking at the Fit Results Graphically

- A clumping of the sources passing all three of our criteria around 1-2 orders of magnitude of suppression compared to the ISM
- Other sources are scattered throughout due to multiple factors



Looking at the Results Graphically

- The passing sources primarily sit in a tight range of sizes
- However the non-passing sources are scattered like the related plot earlier



Conclusions

- By fitting a diffusion motivated spatial model to potential TeV Halos in the 4HWC catalog we are able to further explore the likelihood of their Halo-ness
- We found 3 loose criteria based on statistical preference, compact x-ray emission linked to a PWN, and electron energy density
- Using these criteria we find 10 sources out of 23 which show promise as TeV Halos
- Of these source they appear to have more similar properties than the excluded group

Questions?

Radial Plots

- Integrating the spectrum over 1-100 TeV allows us to get a surface brightness at each distance

