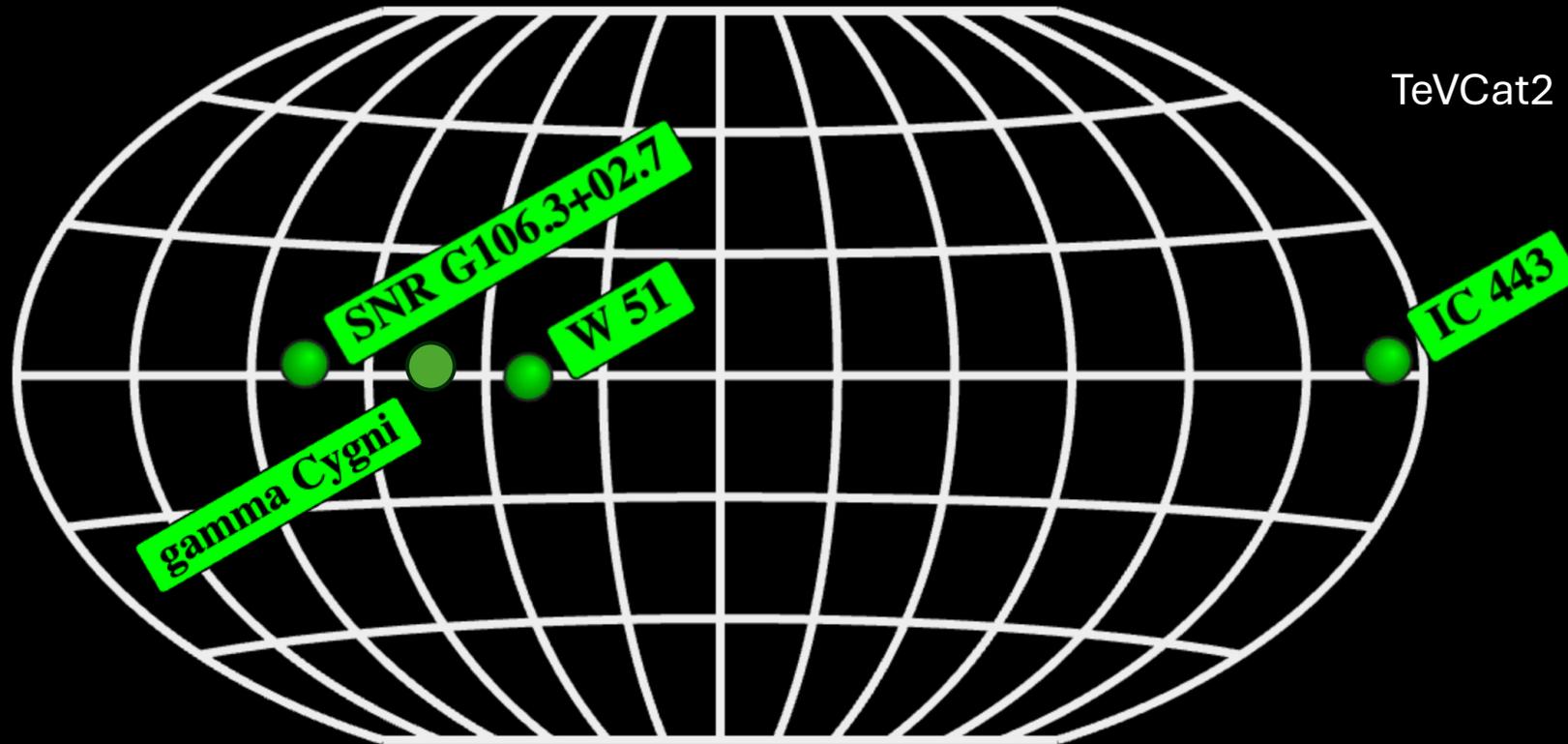


HAWC Studies of SNRs

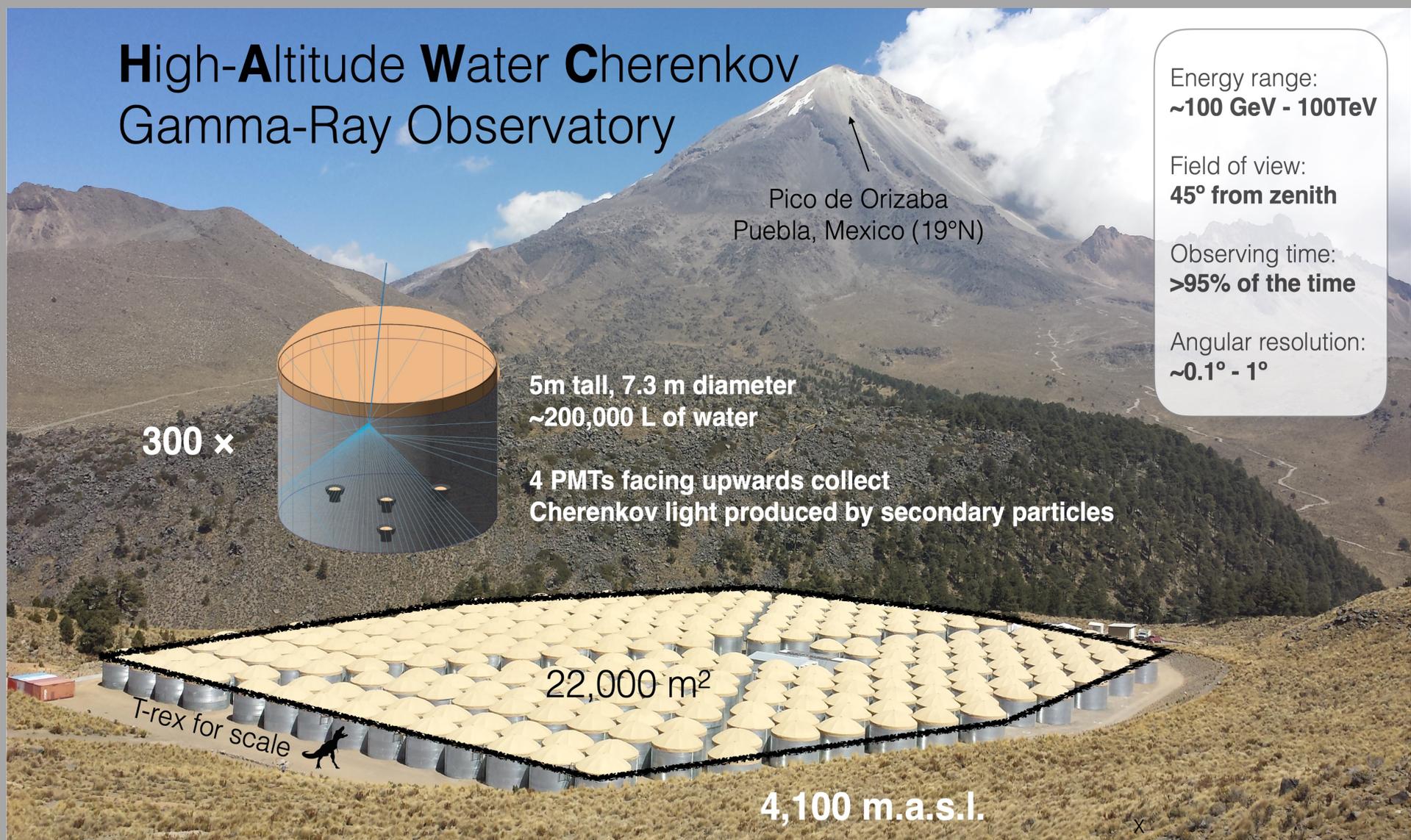


Outline

- Motivation :
 - New classes of candidate PeVatrons has changed the CR picture
 - What is the role of SNRs as contributors of Galactic CRs ?
 - Searching for signatures of PeV CRs in MC close to SNRs
- HAWC Observatory
- SNRs detected with HAWC
- Conclusions and Outlook

Disclaimer : these systems have been detected with LHAASO and IACTs but I will mostly cover only the HAWC results

High-Altitude Water Cherenkov Gamma-Ray Observatory



- Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.
- Inaugurated **March 2015**.
- **Instantaneous FoV 2sr. Daily 8sr (66% of the sky)**
- High energy extension: Outrigger array, since summer 2018
- ~5 trillion triggers to date - 7PB of data

SNR G106.3+2.7: Galactic PeVatron ?

HAWC Collaboration, ApJL 2020

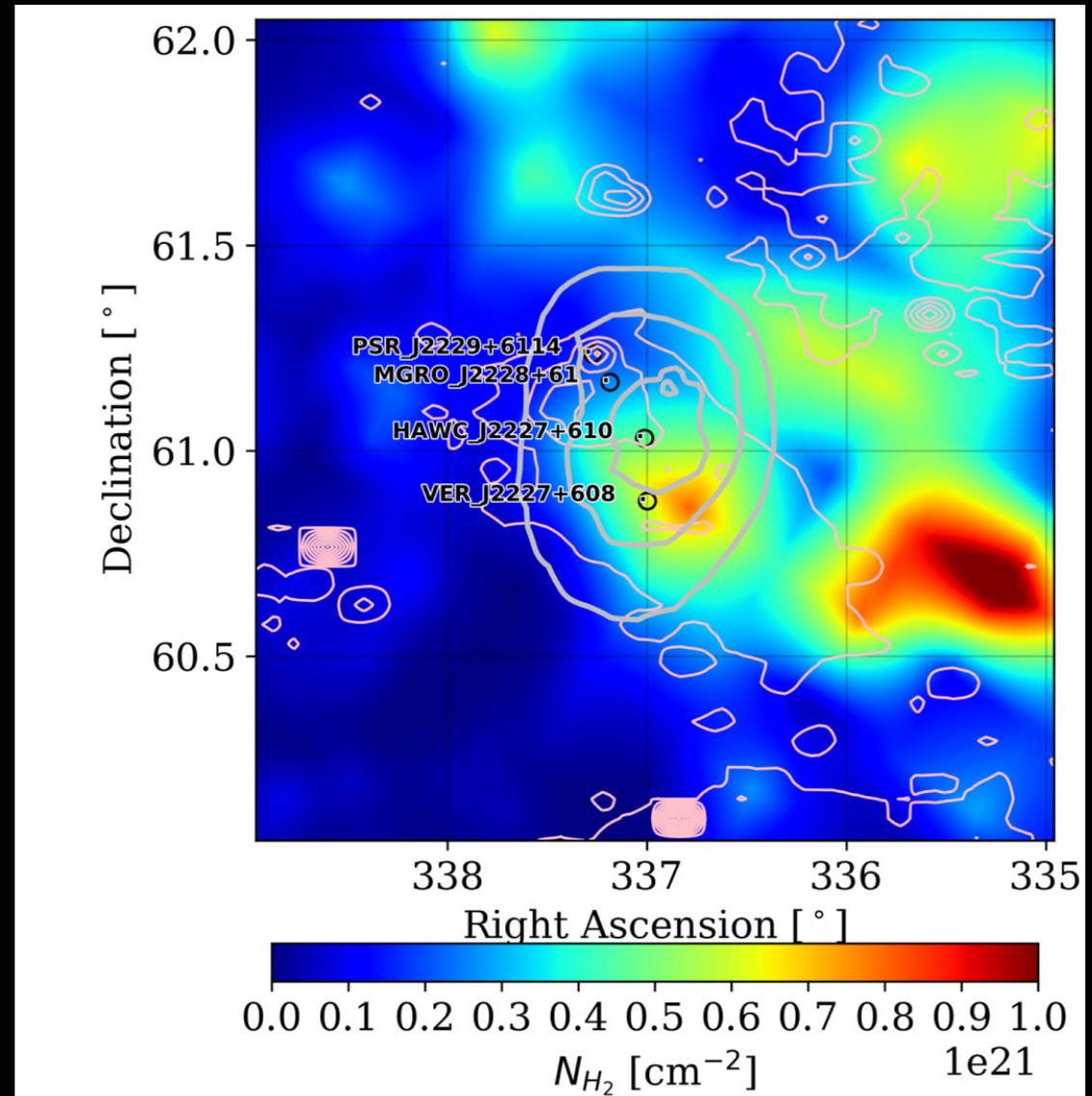
SNR G106.3+2.7 is a 10kyr comet-shaped radio source at 0.8 kpc

PSR J2229+6114, seen in radio, X-rays, and gammarays

Boomerang Nebula is contained in the remnant

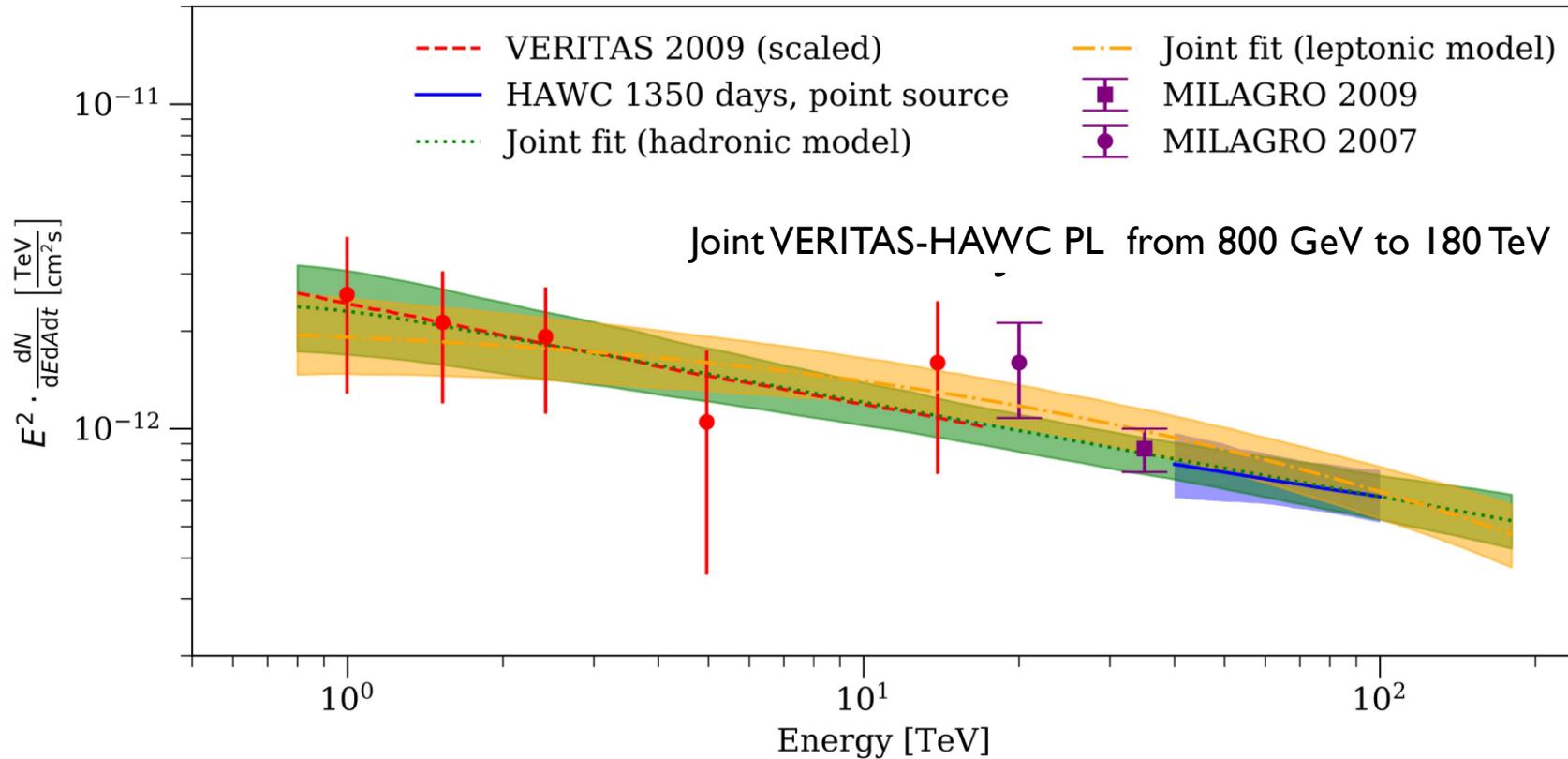
VERITAS source (energy range 900 GeV – 16 TeV)

HAWC emission, morphology compatible with VERITAS source and coincident with a region of high gas density



G106.3+2.7 : a Galactic PeVatron?

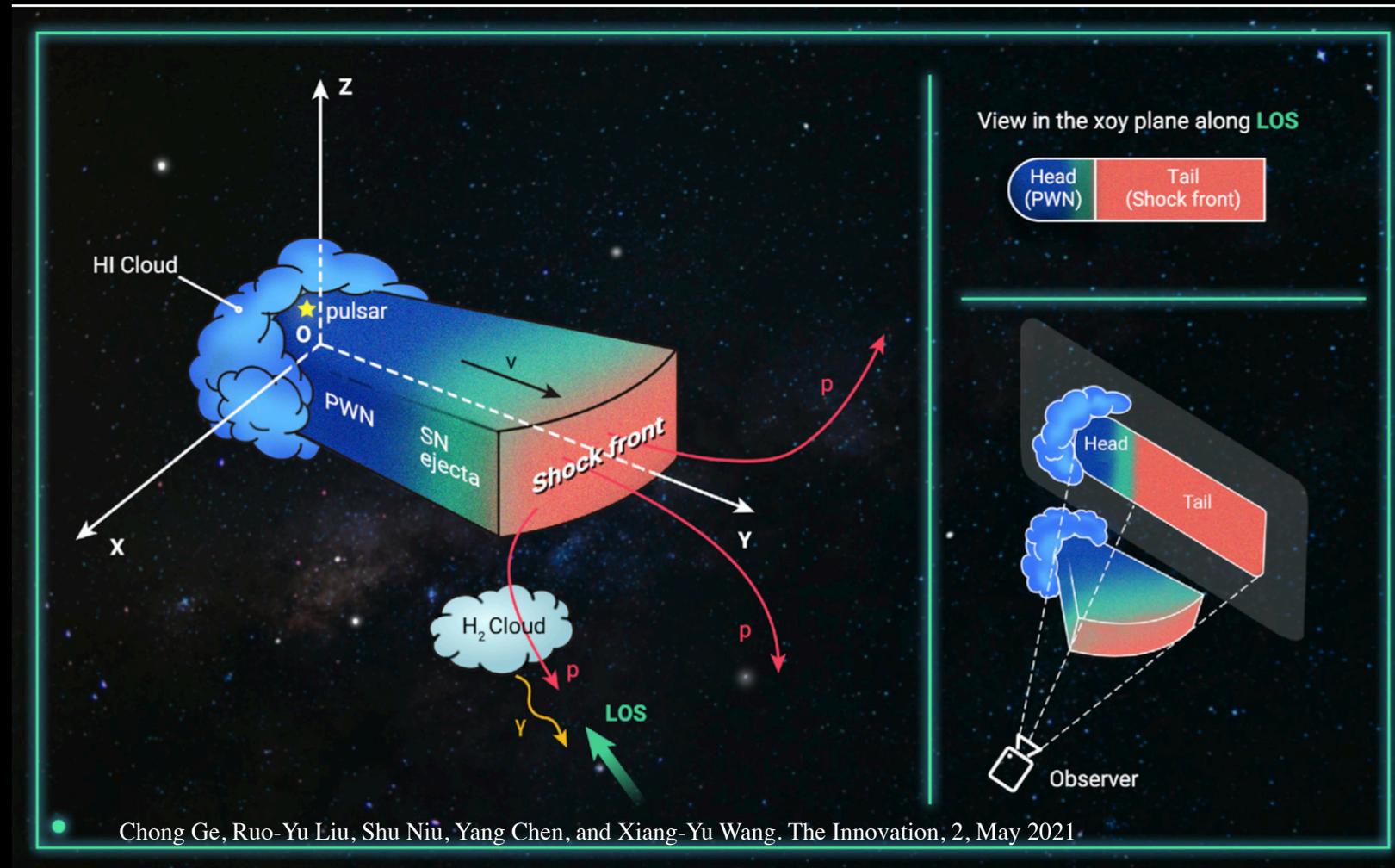
HAWC Collaboration, ApJL 2020



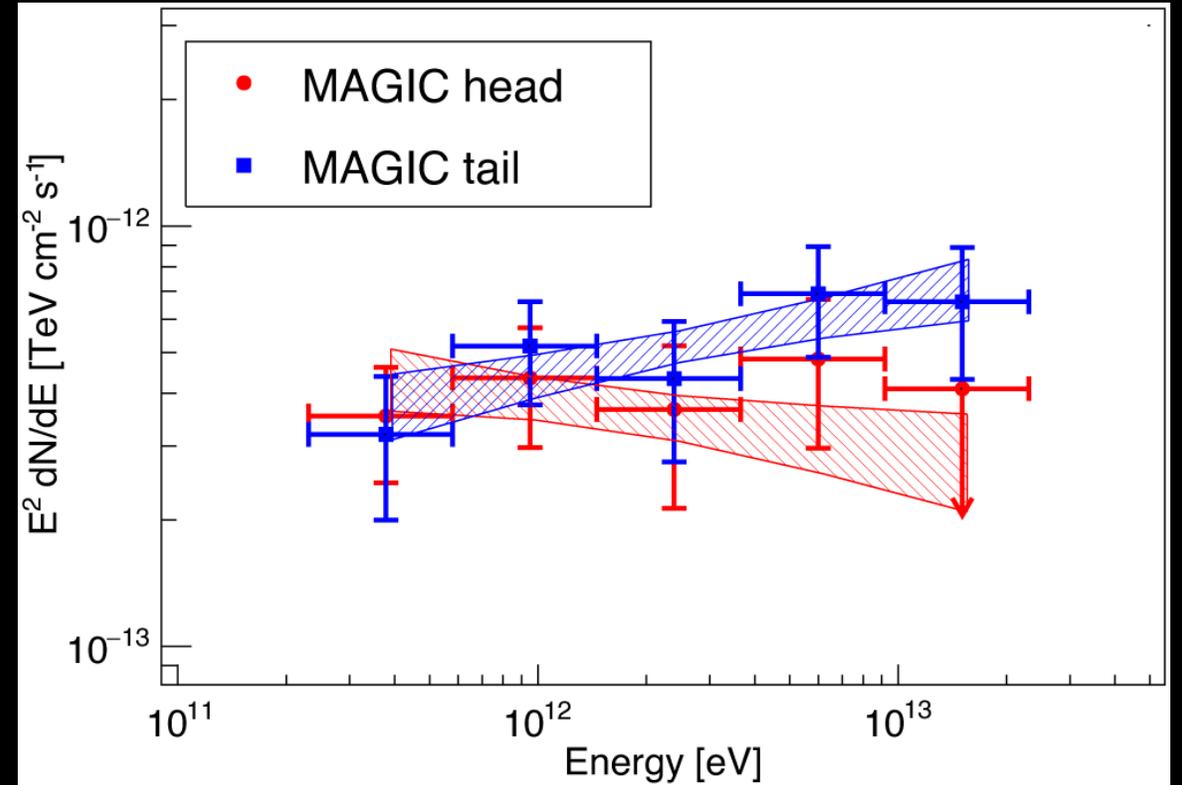
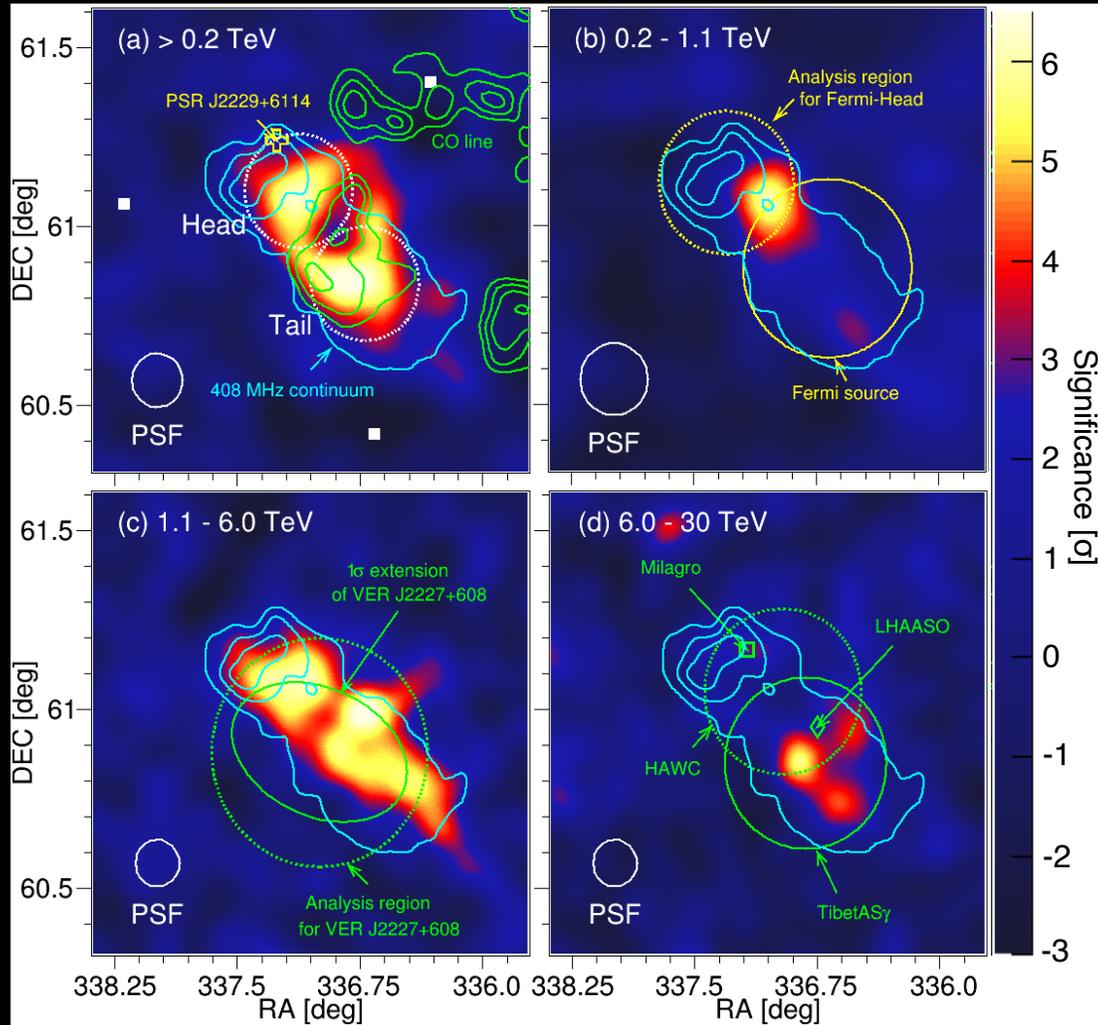
Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

$$W_p = 10^{48} (n/50)^{-1} \text{ erg}$$

- Head Region: PSR J2229+6114 and its PWN the Boomerang
- Tail Region: SN ejecta and shock front from SNR G106.3+2.7
- Elongated shape due to an HI cloud surrounding left side of head region
- SN ejecta forced to break out into elongated tail
- Molecular hydrogen cloud near the tail



MAGIC Observations

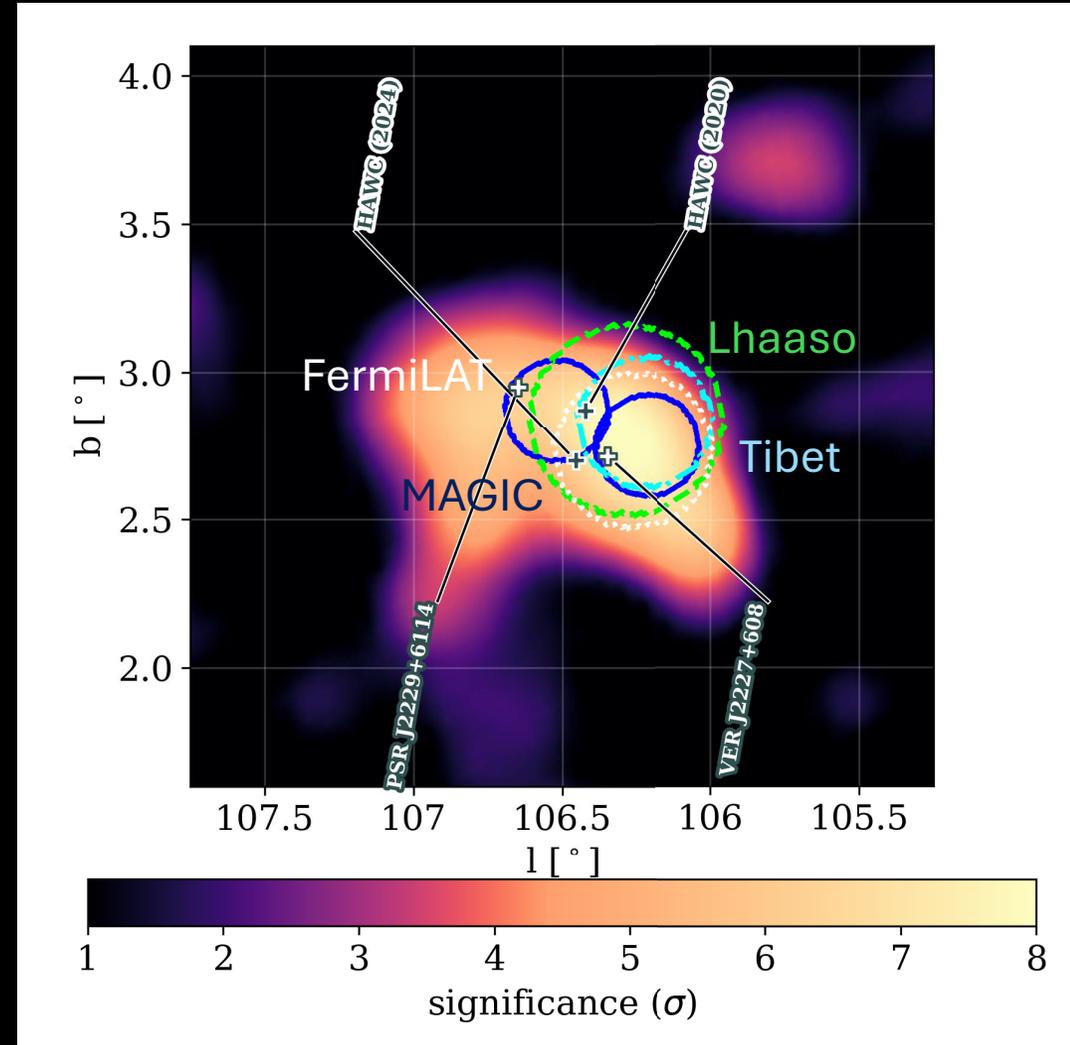
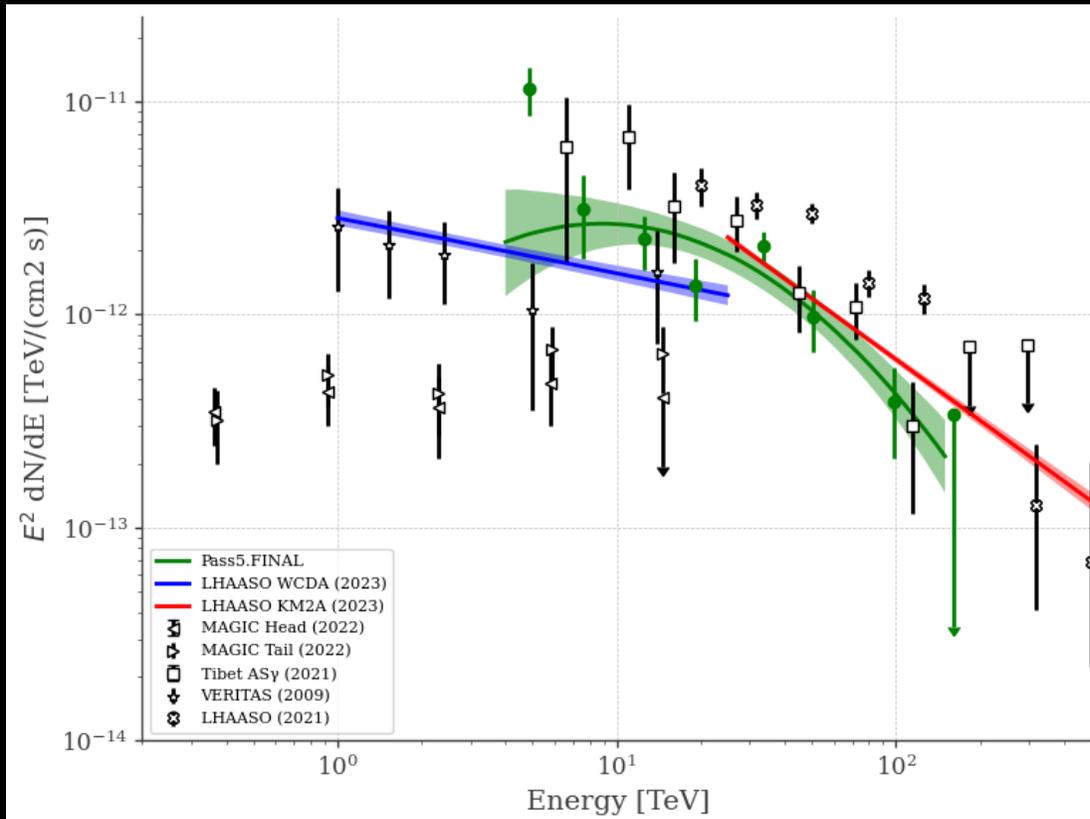


MAGIC Collaboration, 2024

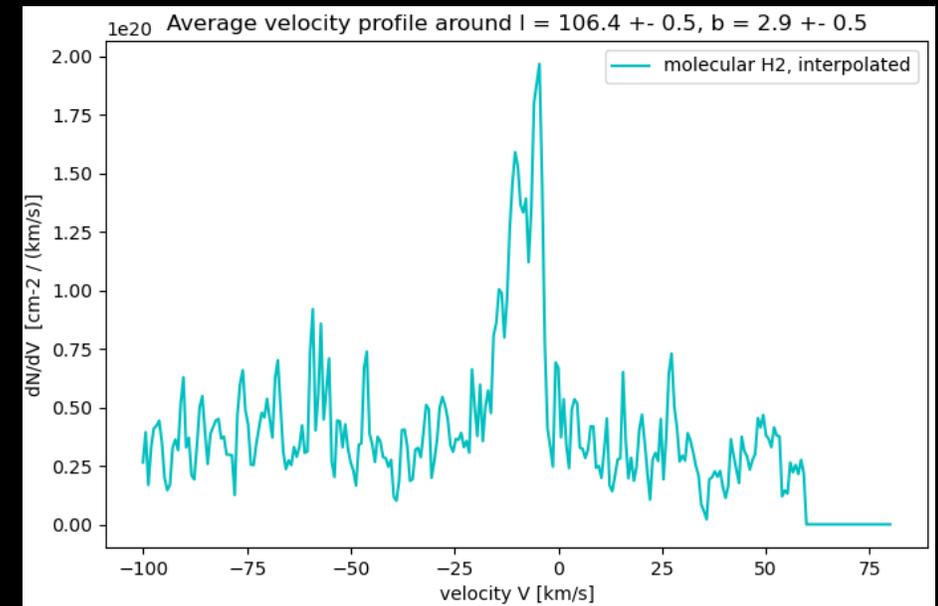
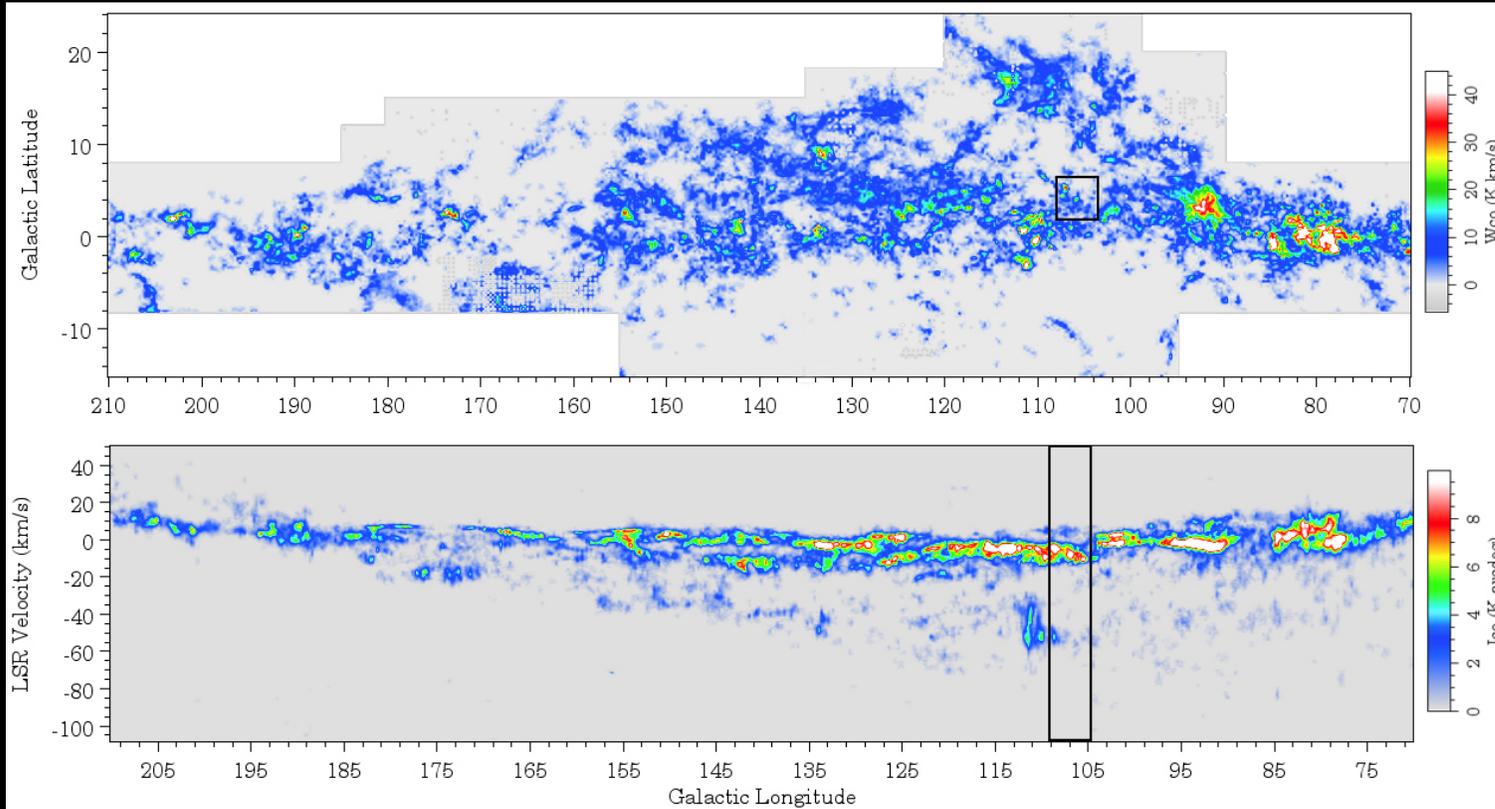
- 2565 days of NN data – 4° ROI
- Single extended source 4-145 TeV
- LogP PL

All energies

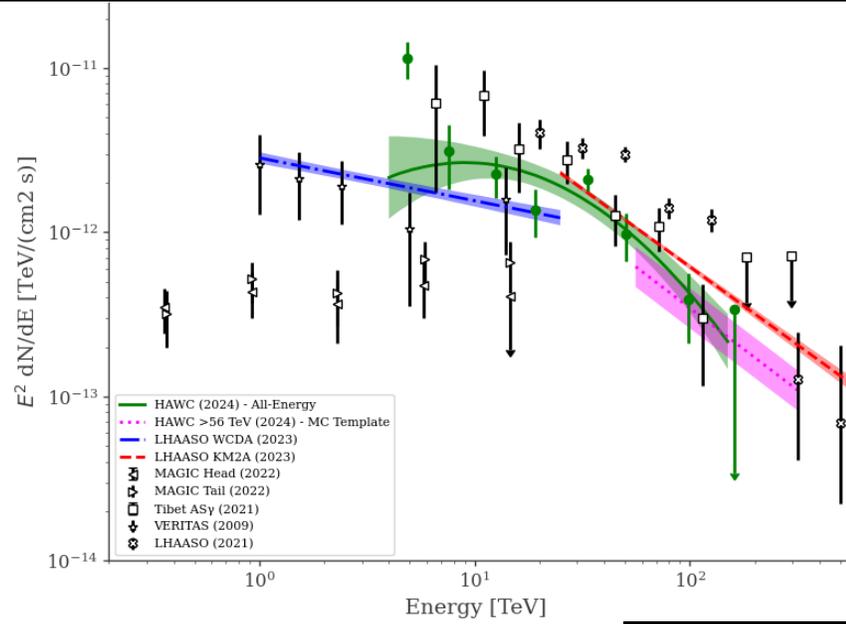
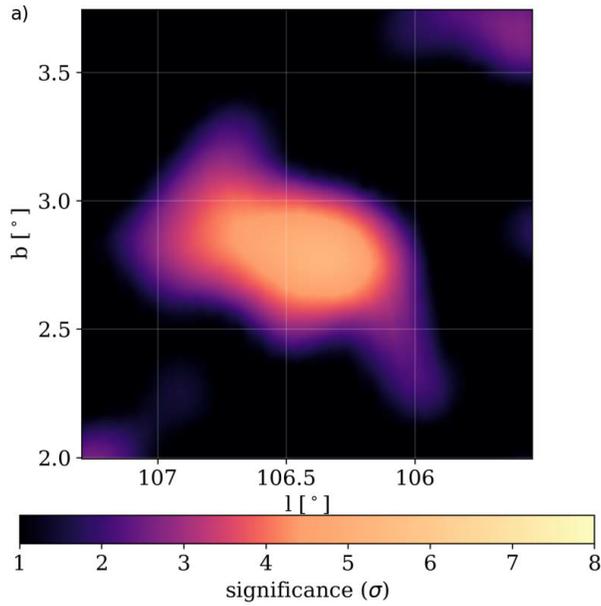
RA [°]	Dec [°]	Radius [°]
337.20 ^{(+0.12)(+0.26)} _{(-0.12)(-0.33)}	60.92 ^{(+0.05)(+0.13)} _{(-0.05)(-0.11)}	0.34 ^{(+0.04)(+0.12)} _{(-0.04)(-0.13)}
N_0 [$\times 10^{-15}$ cm ⁻² TeV ⁻¹ s ⁻¹]	α	β
1.86 ^{(+0.32)(+1.33)} _{(-0.27)(-1.10)}	2.76 ^{(+0.16)(+0.84)} _{(-0.16)(-0.60)}	0.32 ^{(+0.13)(+1.05)} _{(-0.13)(-0.49)}



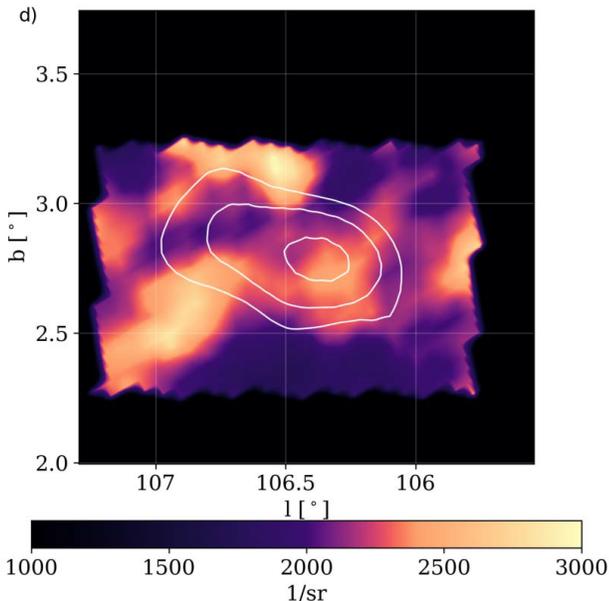
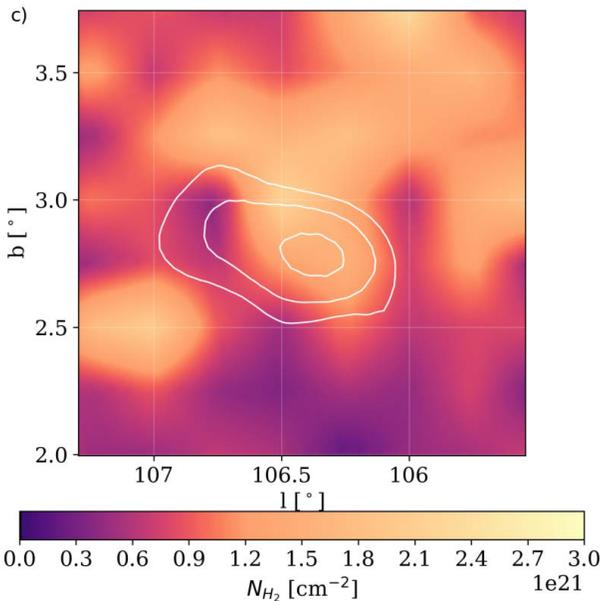
Gas distribution from Boomerang region



Above 56 TeV



model VHE emission (>56 TeV) with
353 GHz Planck dust template



$$L(\geq E_{\gamma}) = 6.6 \times 10^{31} \text{ ergs/s}$$

$$M = 0.11 \times 10^5 M_{\odot}$$

In the cloud :

$$\omega_{CR}(\geq 10E_{\gamma} \sim 500 \text{ TeV}) = 10.9 \times 10^{-3} \text{ eV/cm}^3$$

$$W_{CR}(\geq 10E_{\gamma} \sim 500) = 8.0 \times 10^{44} \text{ ergs}$$

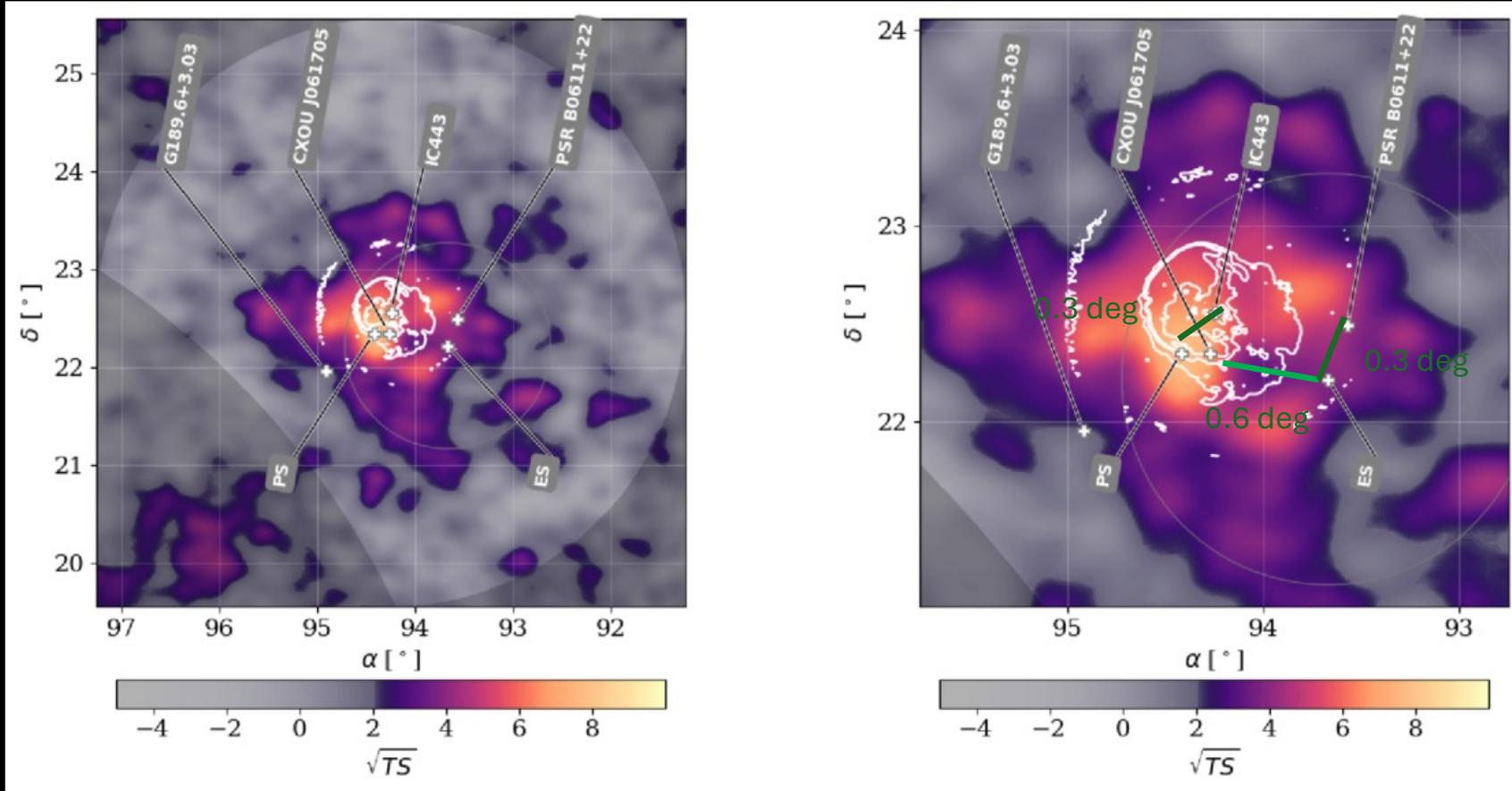
- SNR energy budget = $7 \times 10^{49} \text{ ergs}$

IC 433

- IC443 (G189.1+3.0) studied across the whole electromagnetic spectrum
- Progenitor: neutron star CXOUJ061705.3+222127
- Interacts with nearby MCs
- Distance 1.5kpc (Fesen 1984)
- Size ~ 10 pc (Troja et al. 2008)
- Age 3~30 kyr (Petre et al. 1988, Troja et al. 2008, Lee et al. 2008, Chevalier 1999)
- Shock speed of 300kms^{-1} (J.-J.Lee et al. 2008; E. Troja et al. 2008),
- $B \sim 10\mu\text{G}$ (H. Yamaguchi et al. 2009)



HAWC ANALYSIS of IC 433

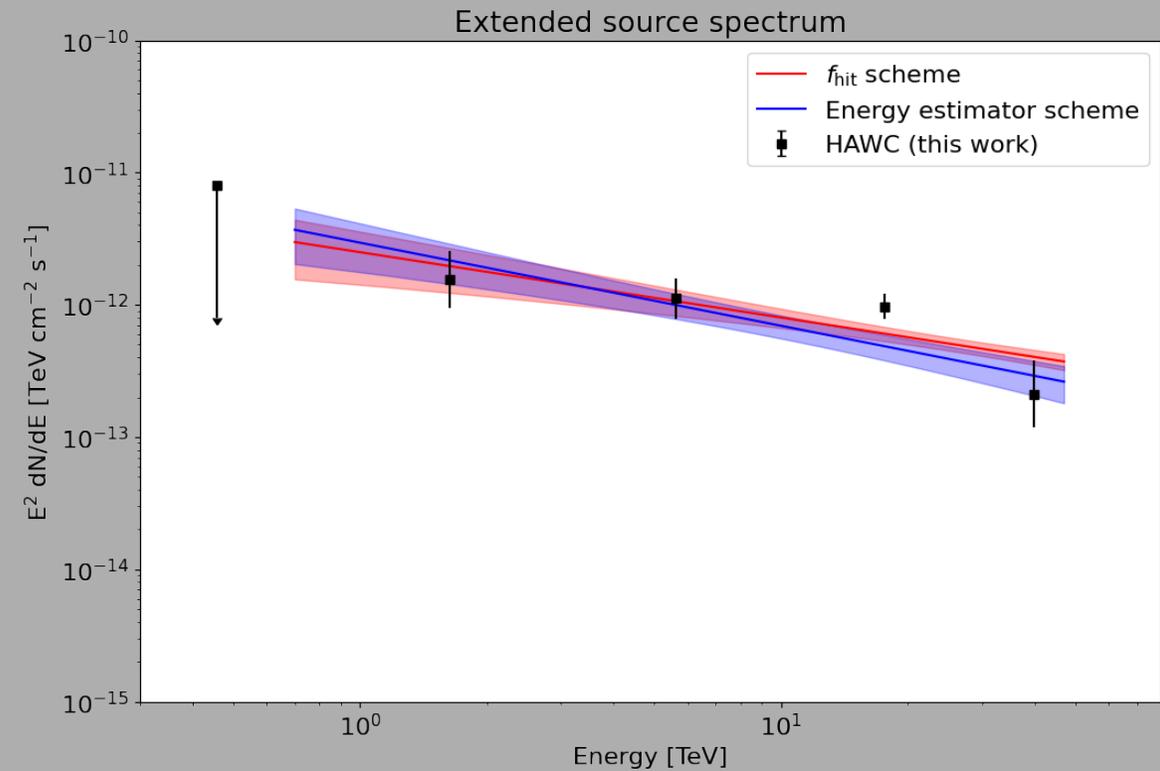
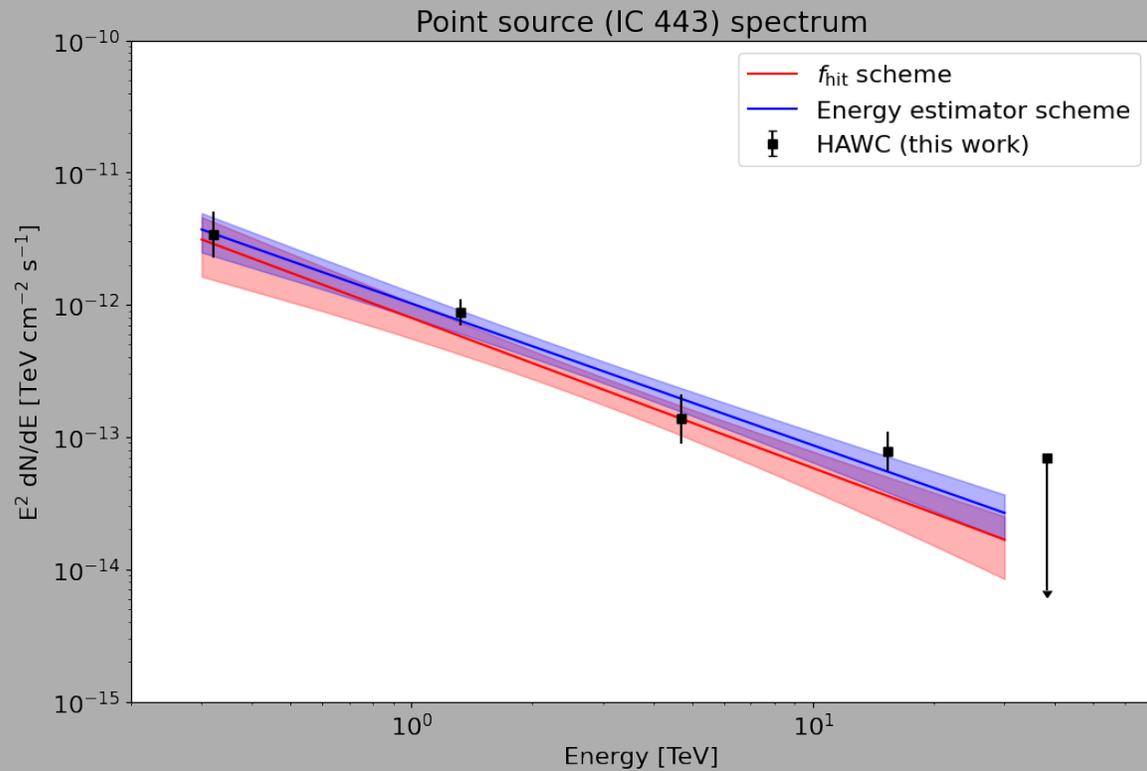


- 2996 days of data
- Masking closely Geminga-Monogem region
- Fhit analysis for morphology and NN for spectral features

Spectra for PS and ES

Source	Range (TeV)
IC443	0.27 - 23.74
Extended	2.15 - 74.95

Table 2: Energy range from the Fhit analysis



Extended Source

HAWC Collaboration, ApJL 2025

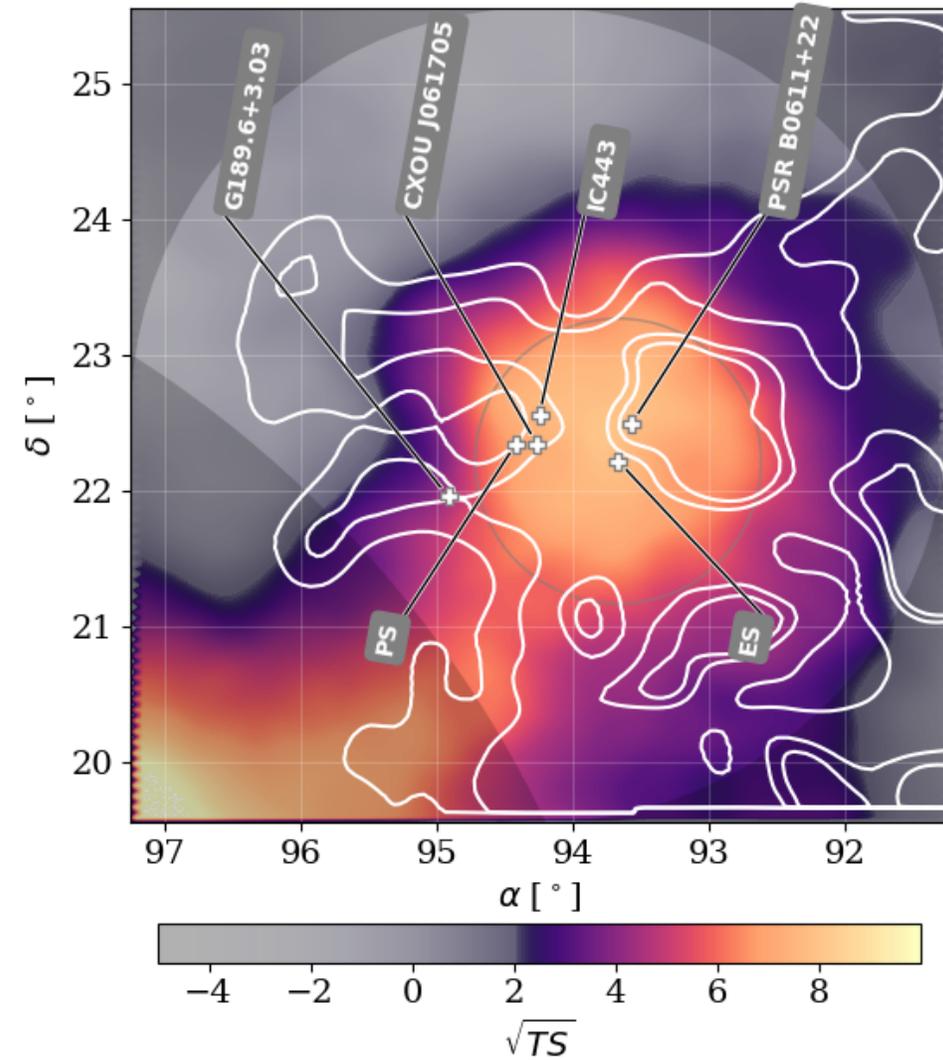
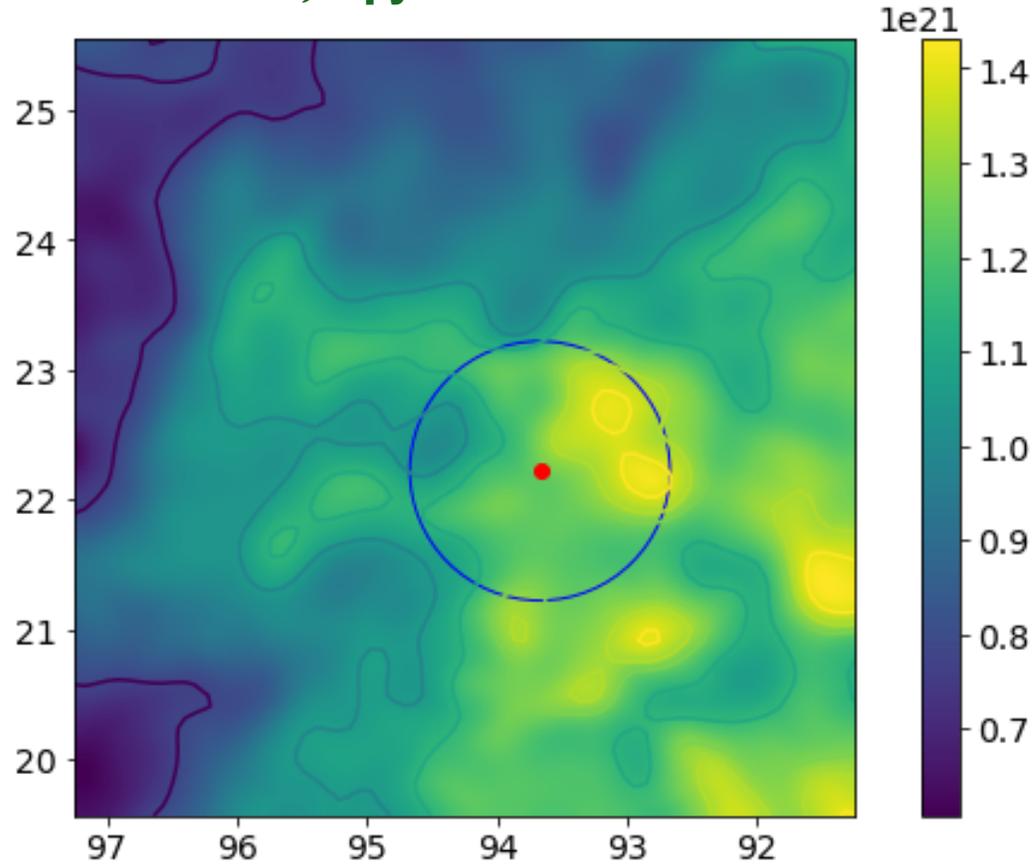
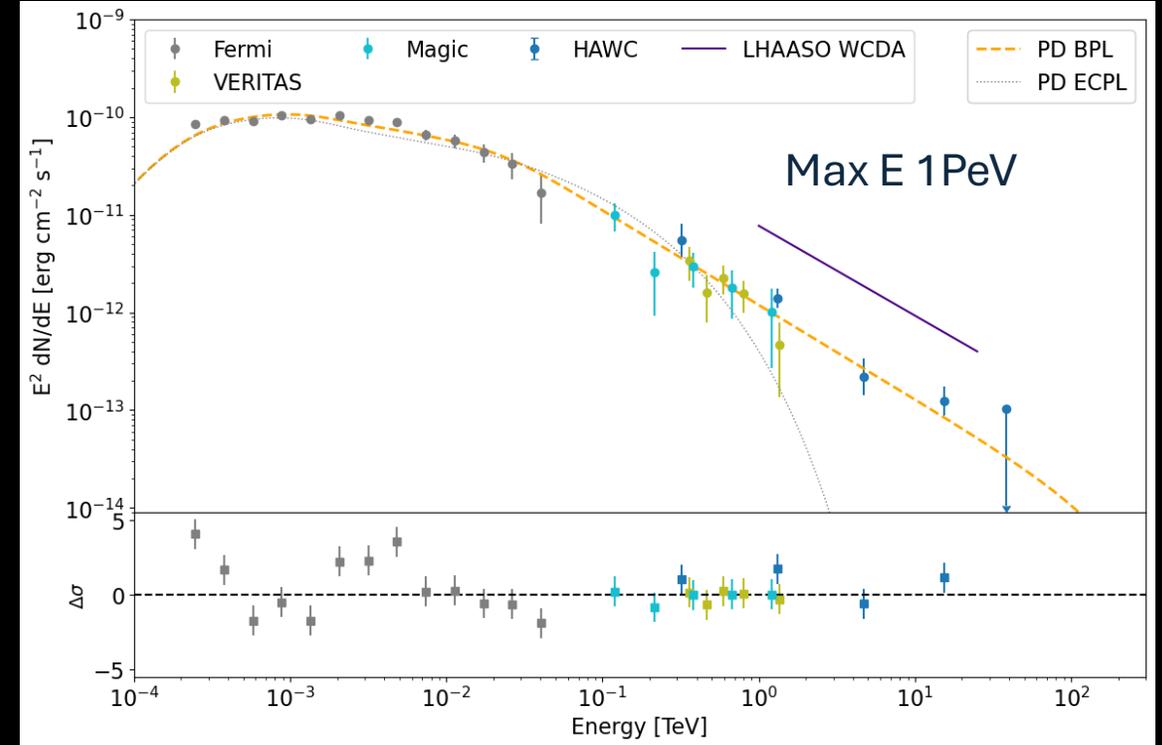
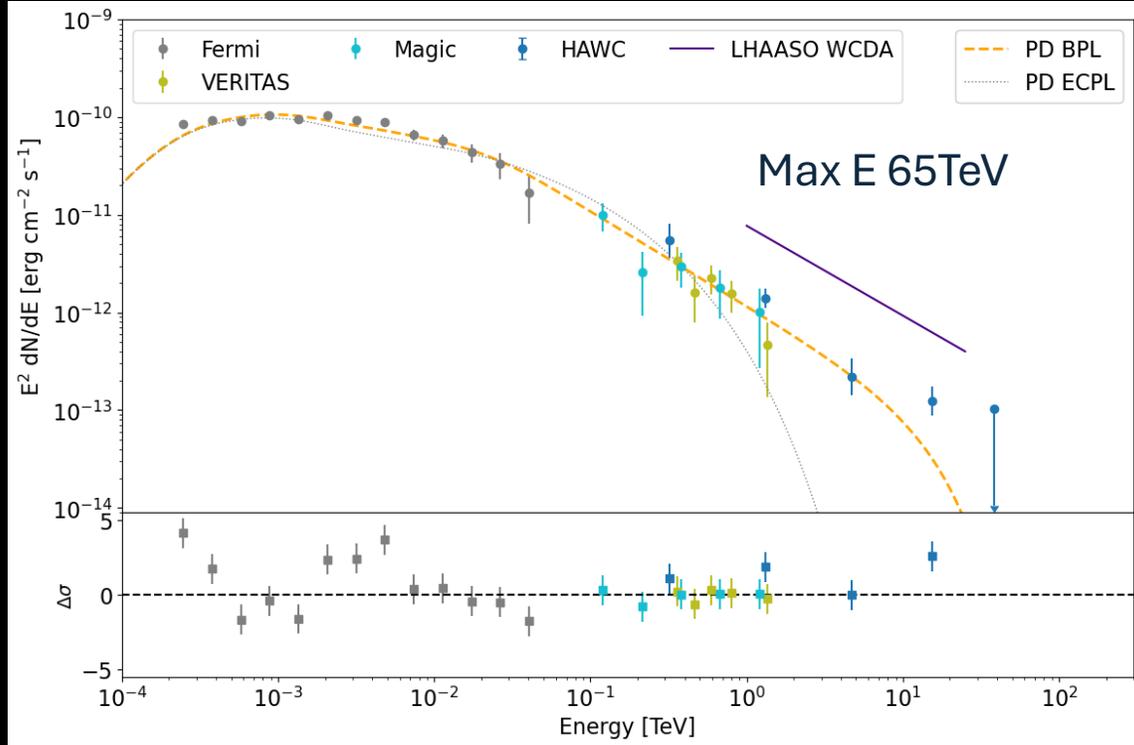


Figure 25: Column density in the region of IC 443 with velocities between 3.5 and 10 km/s. Circle and dot are the centroid and width of the extended source.

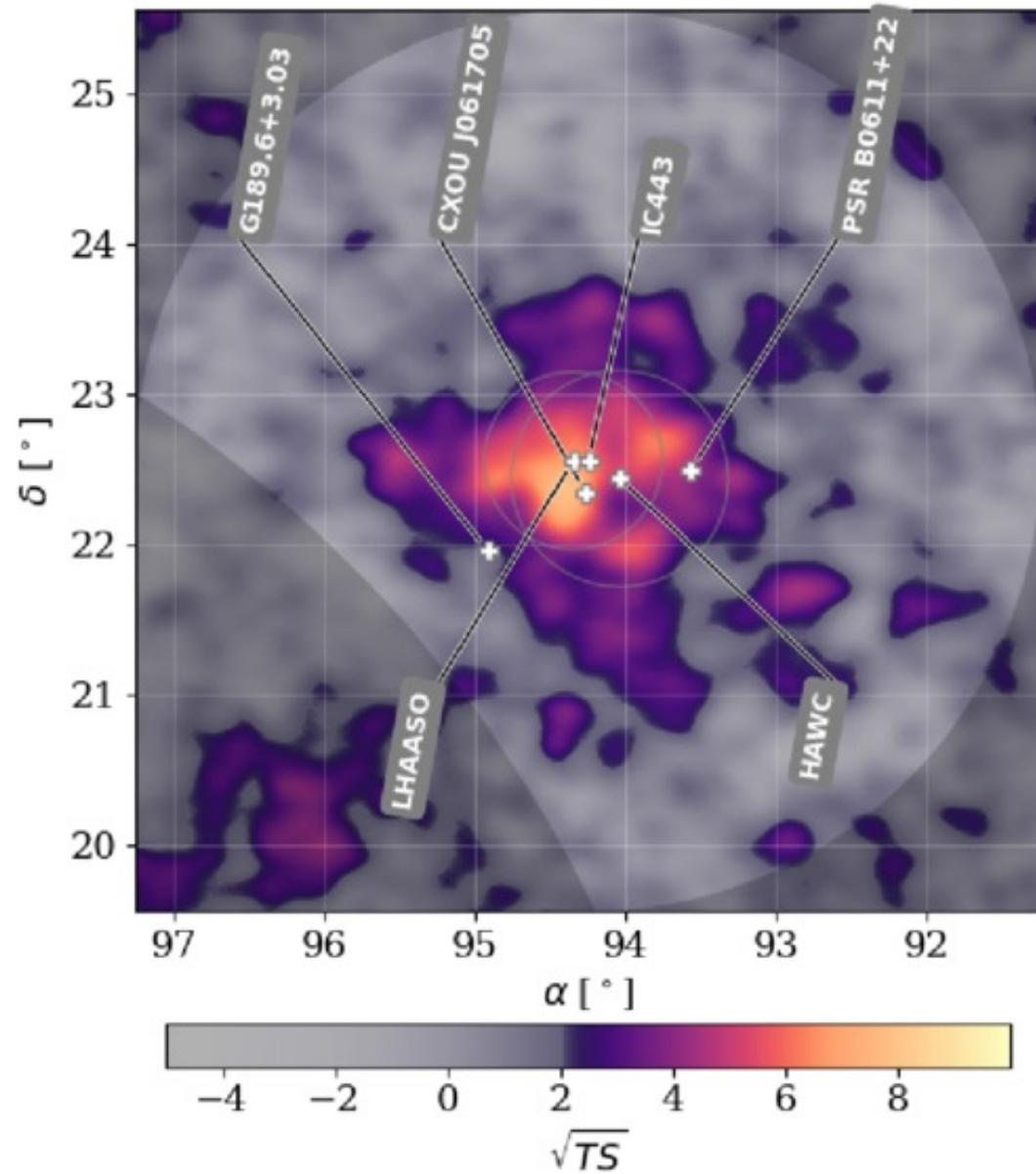
Particle Spectra for IC 433



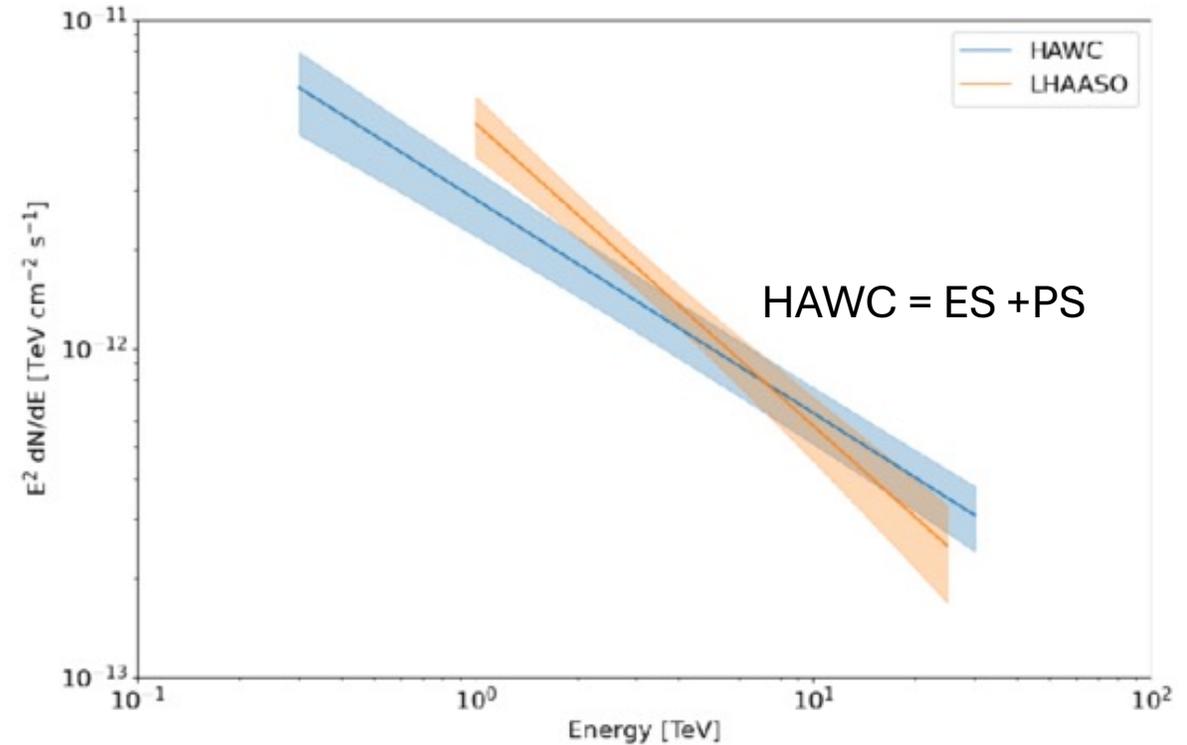
mass of the shocked gas ($\sim 10^3 M_\odot$) and remnant size (~ 10 pc) : $n \sim 20 \text{ cm}^{-3}$

$W_p \sim 6-8 \cdot 10^{49} \text{ erg} * (n/20)^{-1}$

HAWC- LHAASO comparison

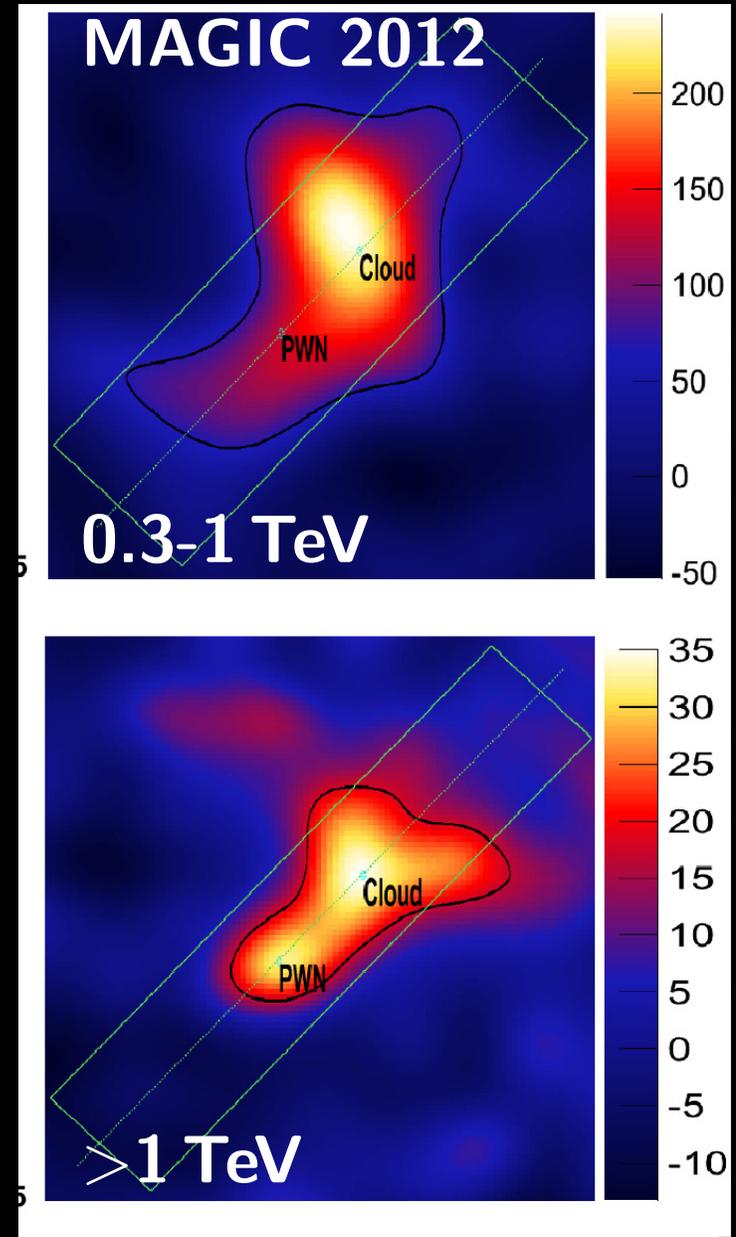


HAWC Collaboration, ApJL 2025

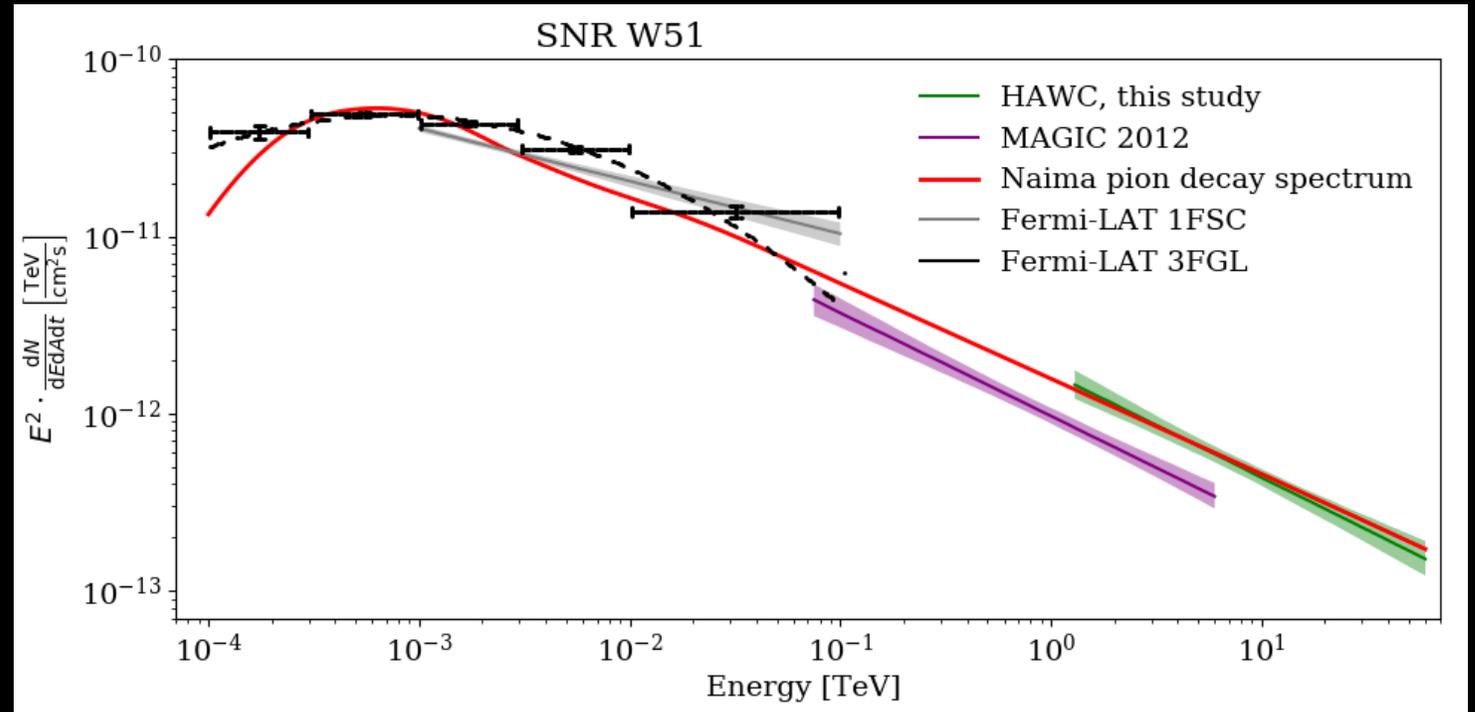
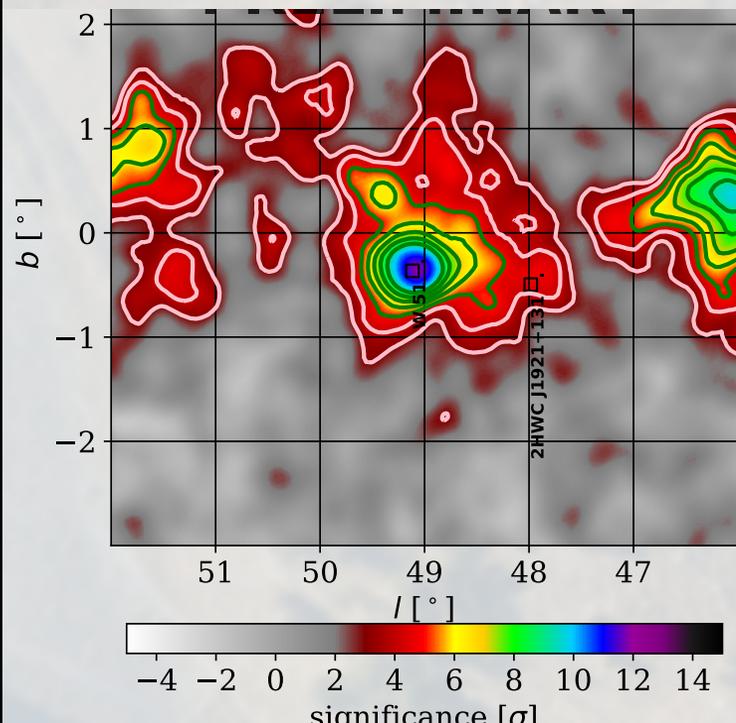
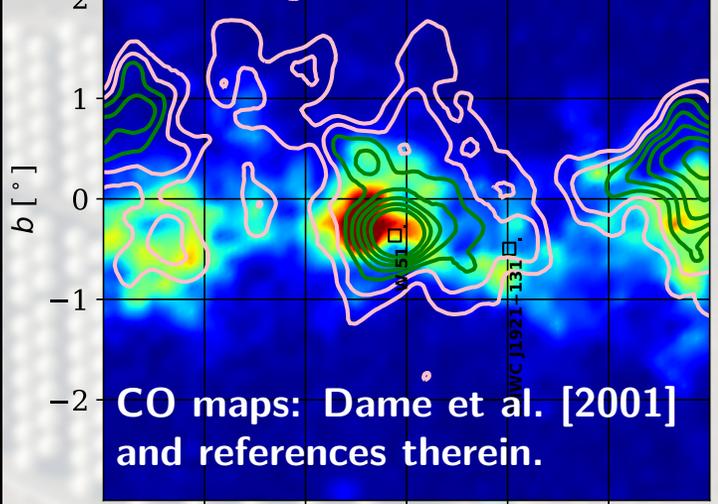


W 51

- Middle aged/old SNR, 30 kyr [Koo et al., 1995], interacting
- with nearby molecular cloud.
- Distance: ~ 5 kpc [Sato et al., 2010].
- GeV-TeV detection by Fermi-LAT [Acero et al., 2015, 2016], MAGIC [Aleksić et al., 2012], and H.E.S.S. [Abdalla et al., 2018].
- MAGIC sees evidence for two emission components (PWN and molecular cloud).



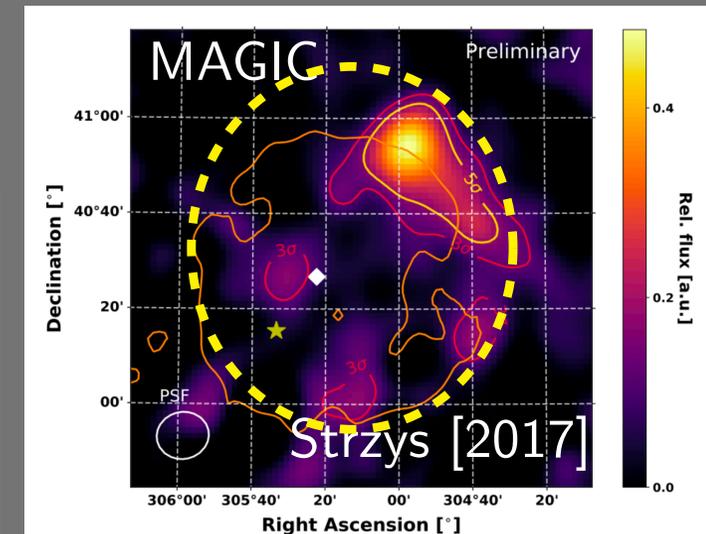
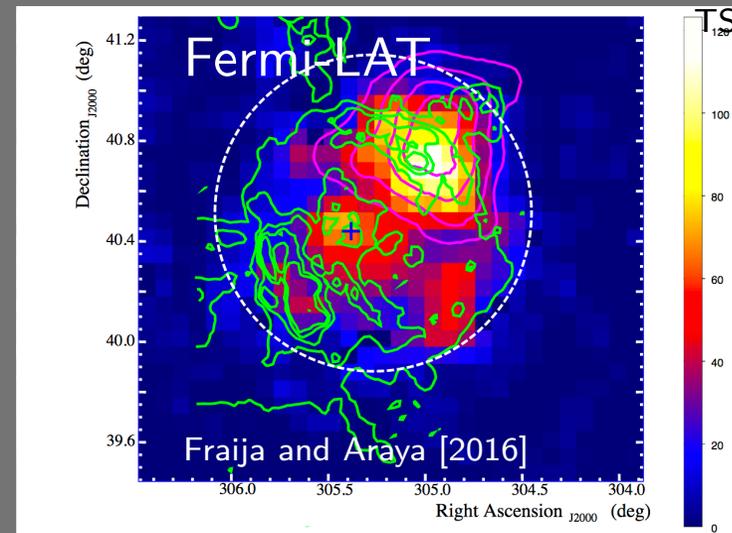
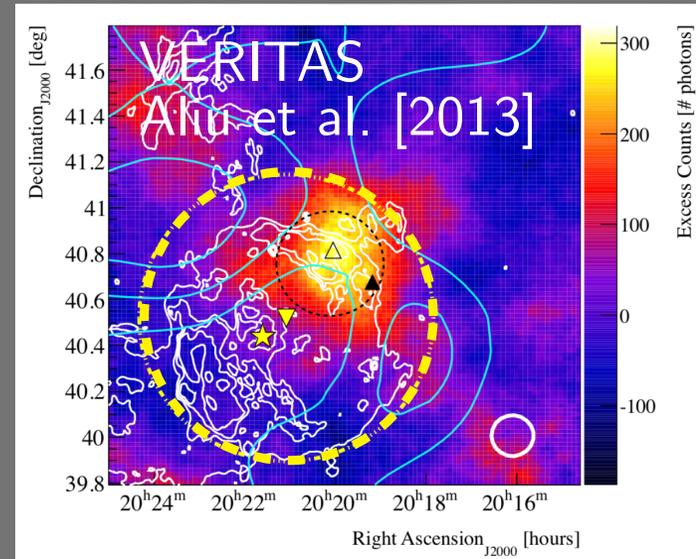
2HWC J1922+140—W51C



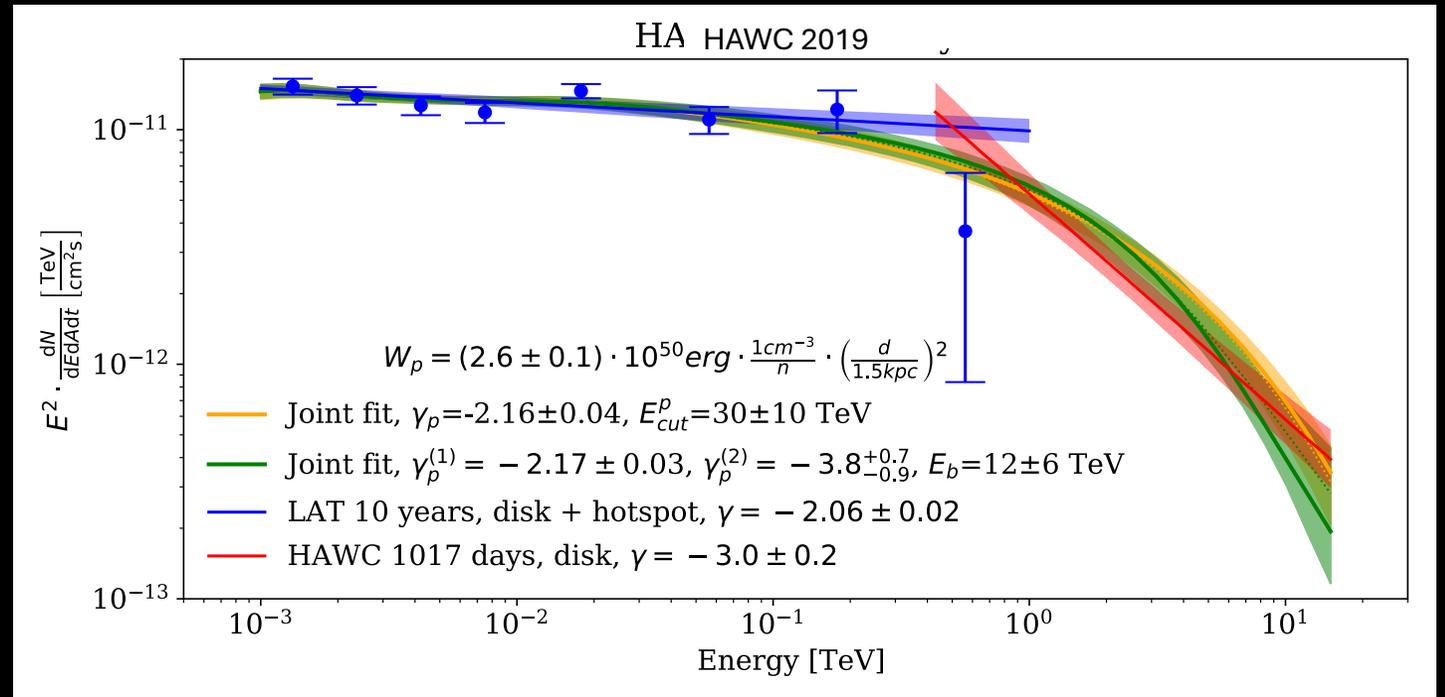
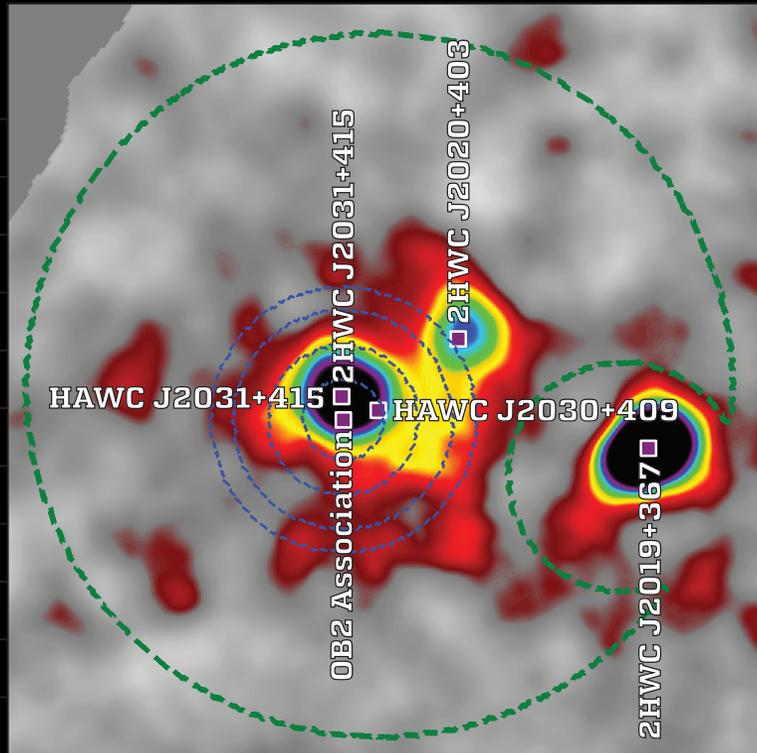
HAWC Collaboration, 2019

γ -Cygni SN

- Middle-aged SNR, ~ 6000 yrs Lozinskaya et al., 2000
- Located in Cygnus region
- Distance: ~ 1.7 kpc [Lozinskaya et al., 2000]
- X-ray/radio shell, enhanced emission at northern/southern edge.
- Seen up to TeV energies.
- Leptonic or hadronic emission?
- Connection to Cygnus Cocoon?



γ -Cygni SN - SNRG78.2+2.1



Conclusions and Outlook

- Emission coincident with SNR W51, γ -Cygni and IC 433 continuing Fermi-LAT and IACT spectra up to tens of TeV
- Extended emission up to 75 TeV from a region close to SNR IC 433, unclear origin, either illuminated gas or leptonic halo
- Emission from Boomerang complex extending up to 145 TeV
- Above 56 TeV MC template

- Deeper studies of SNRs with Pass5 new maps and Pass6 are ongoing

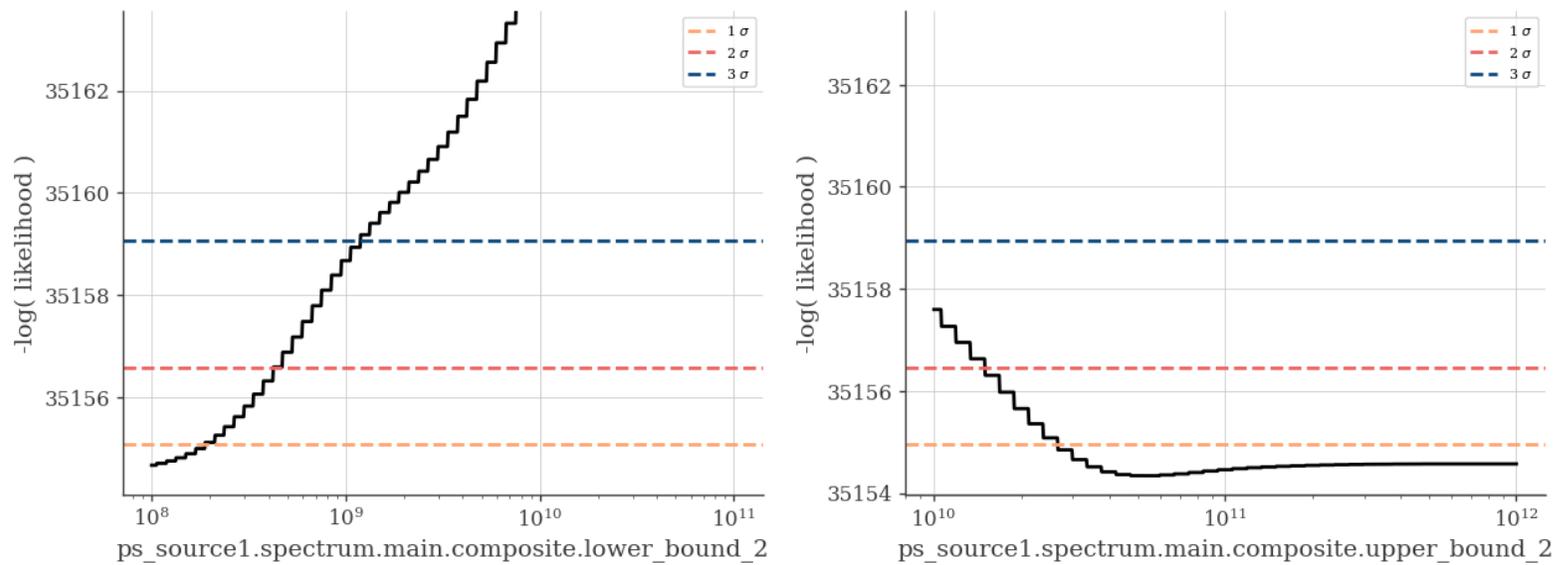


Figure 11: Profiles for the energy range of the point source.

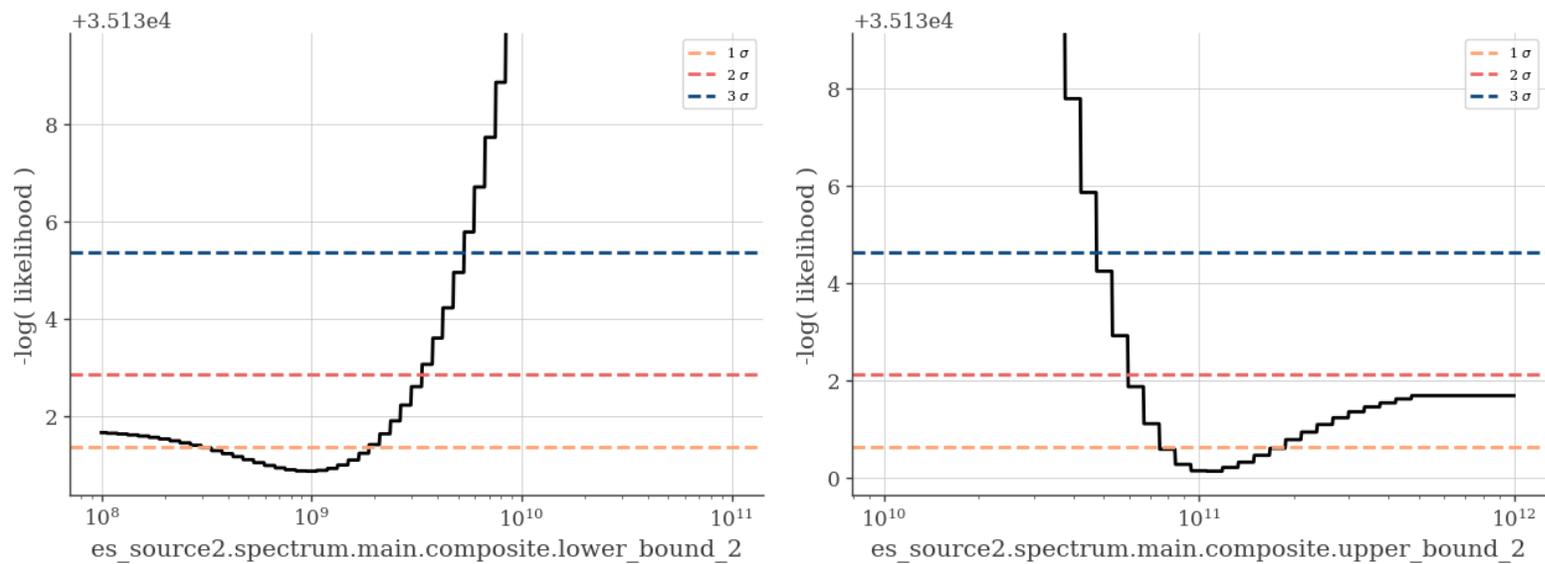


Figure 12: Profiles for the energy range of the extended source.