PaiP, 20-22 Feb 2025, Warsaw, Poland

On behalf of the HAWC Collaboration
Sabrina Casanova, IFJ-PAN Krakow

Outline

- HAWC Observatory
- Selected HAWC results
  - Galactic Plane Survey from TeV to hundred TeV
  - The Variable Sky
  - The Galactic Centre
- SWGO
- Conclusion and Outlook
- Back-Up Slides

HAWC Site

Latitude: 18°59.7′N
Longitude: 97°18.6′W

- HAWC is located on the flanks of the Sierra Negra volcano near Puebla
- 4,100 meters (13,500 feet) above the sea level

High-**A**ltitude **W**ater **C**herenkov Gamma-Ray Observatory

Pico de Orizaba
Puebla, Mexico (19°N)

Inaugurated **March 2015**.

Instantaneous FOV 2sr

Daily FOV 8sr (66% of the sky)

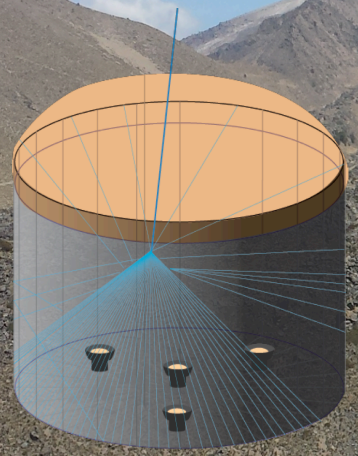
Energy range: 100s GeV to 100s TeV

Observing >95% of the time

Angular resolution 0.2^{o} – 1^{o}

345 outriggers since 2018

300 ×



5m tall, 7.3 m diameter
~200,000 L of water

4 PMTs facing upwards collect Cherenkov light produced by secondary particles

22,000 m^2

T-rex for scale

4,100 m.a.s.l.

HAWC Water Cherenkov detector and detection technique

Steel frame construction

Large plastic bag container

3900 Water trucks filling the tanks

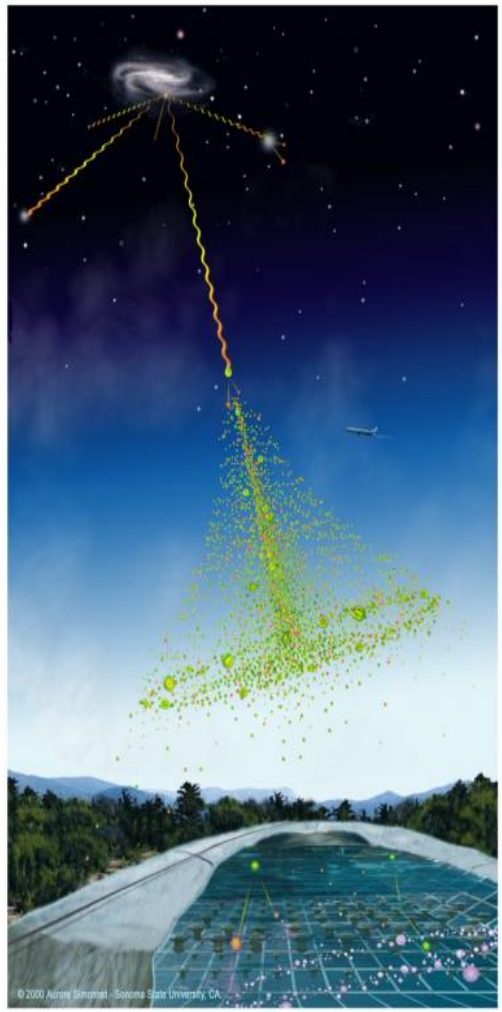
8-inch 10-inch PMTs

WCDs with 200,000 l of purified water.

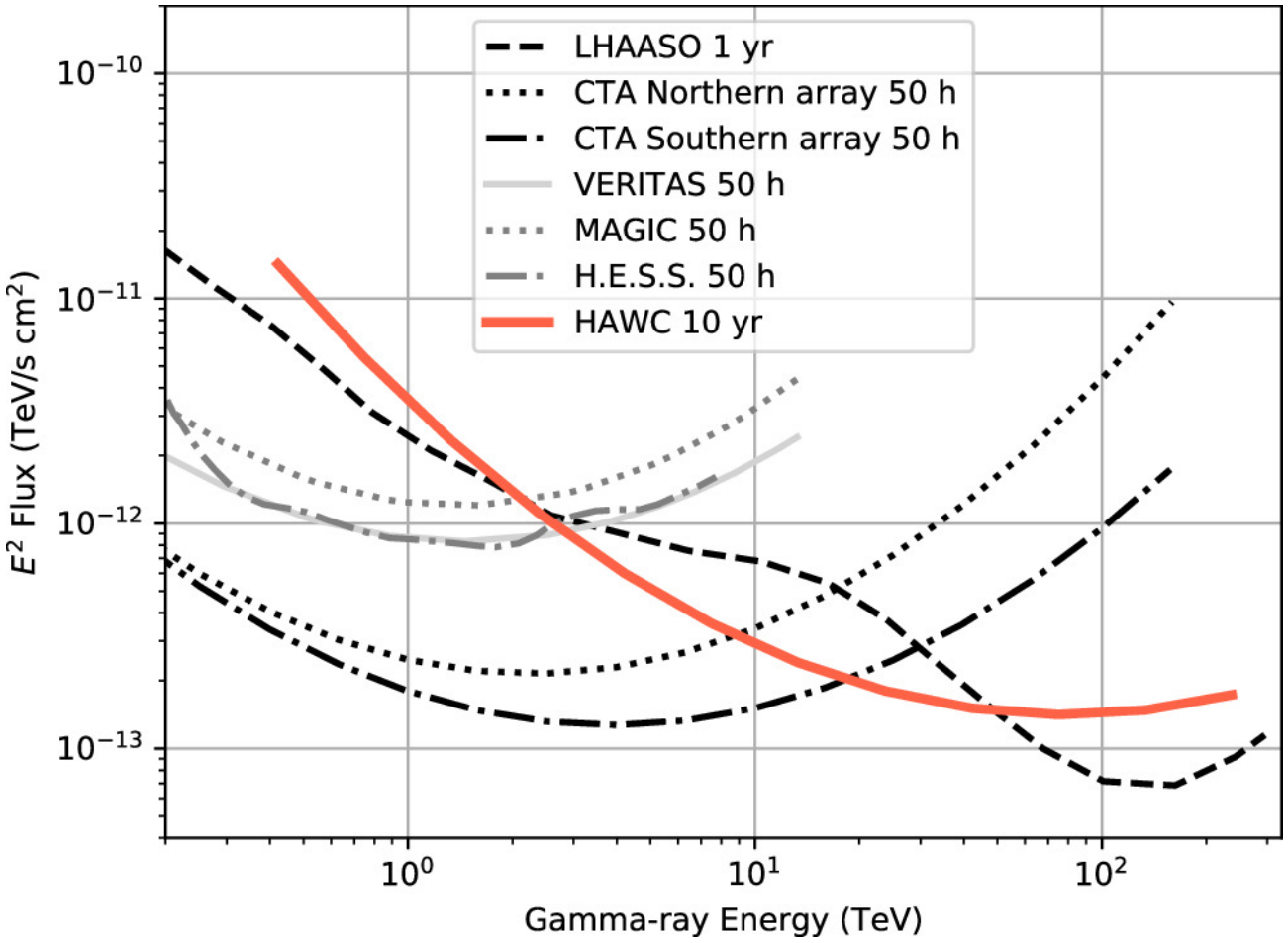
Particles from the shower induce Cherenkov light in water, detected by 4 PMTs.

Measure: time and light level in each PMT

Reconstruct: core, energy, direction and background rejection



Pass 5 sensitivity



https://arxiv.org/pdf/2405.06050

Improved background rejection

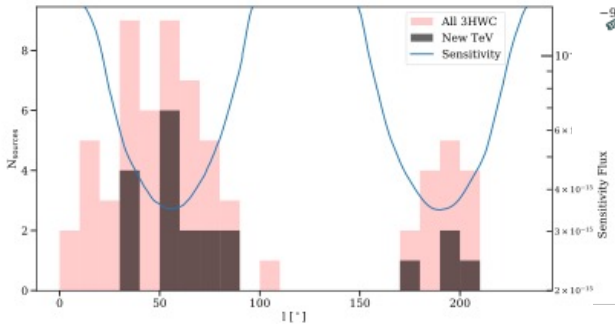
Better angular resolution

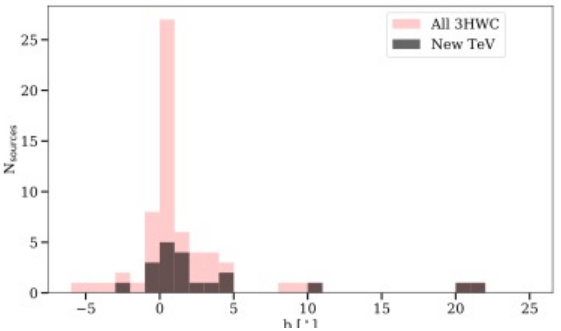
Improved sensitivty at hundred GeVs

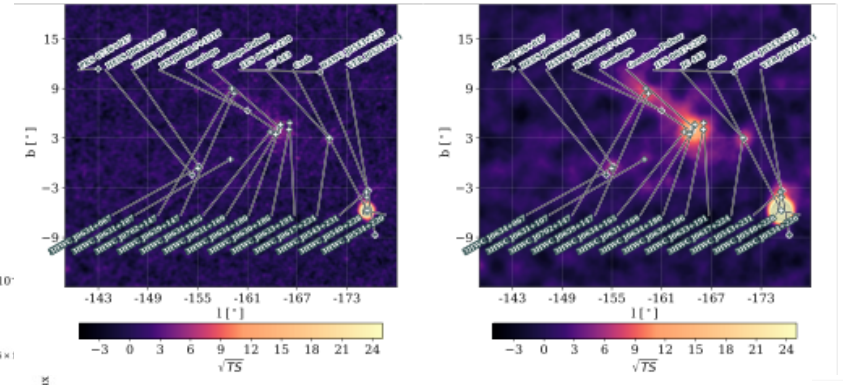
The Galactic Plane from TeV to subPeV energies

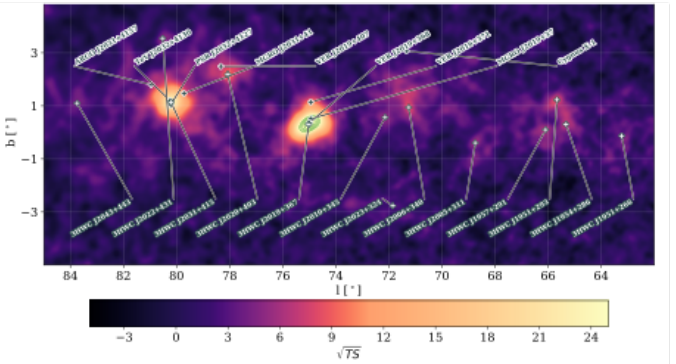
3HWC Catalog

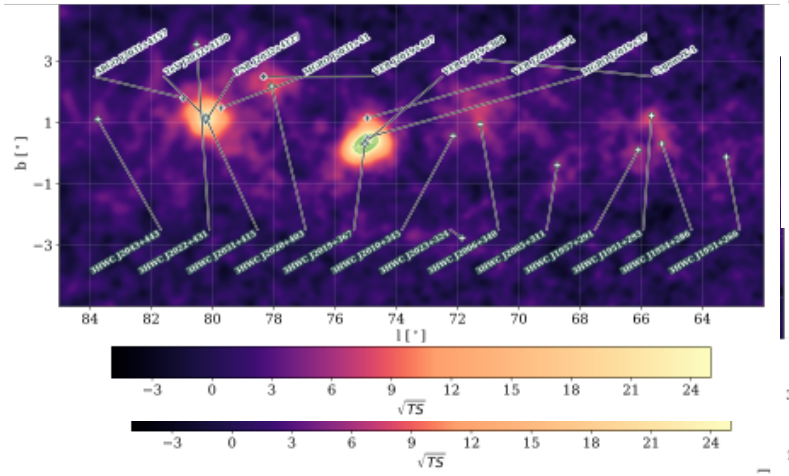
(HAWC Coll ApJ 2021)

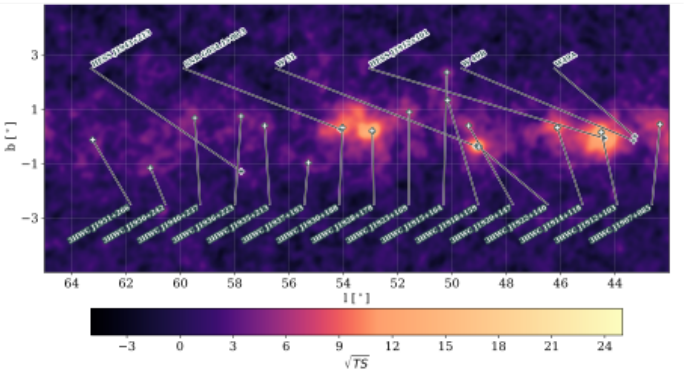


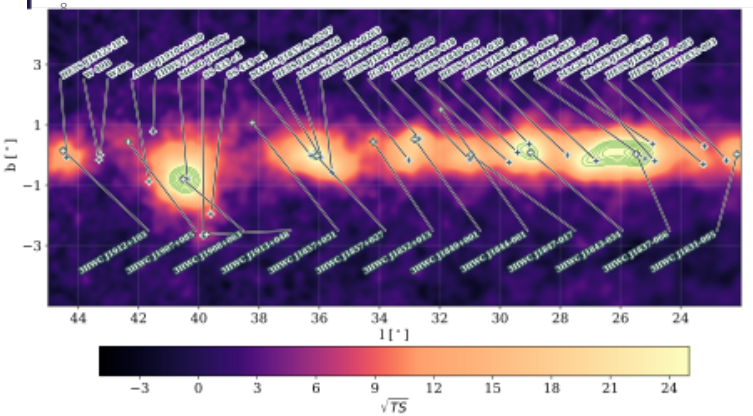












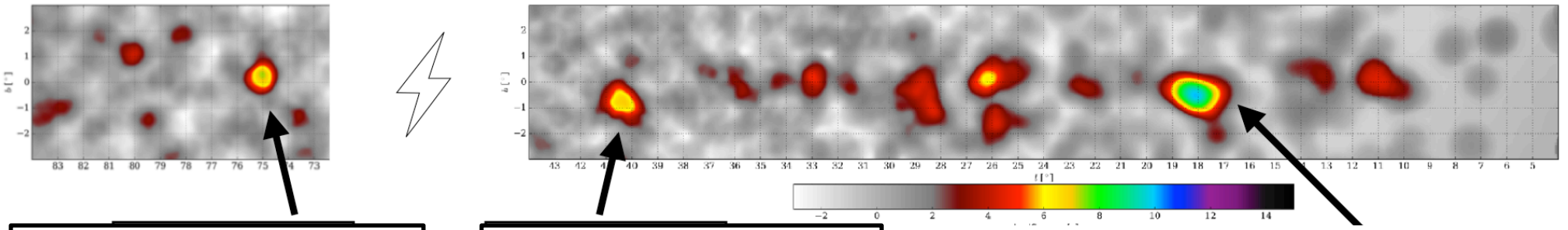
1543 days of data Pass 4

65 sources of which 56 can be associated to pulsars

The Galaxy above 56 TeV

Source name	RA (°)	Dec (°)	Extension > 56 TeV (°)	F (10^{-14} ph cm^{-2} s^{-1})	$p_{TS>}$ 56 TeV	nearest 2HWC source	Distance to 2HWC source(°)	$p_{TS>}$ 100 TeV
eHWC J0534+220	83.61 ± 0.02	22.00 ± 0.03	PS	1.2 ± 0.2	12.0	J0534+220	0.02	4.44
eHWC J1809-193	272.46 ± 0.13	-19.34 ± 0.14	0.34 ± 0.13	$2.4^{+0.6}_{-0.5}$	6.97	J1809-190	0.30	4.82
eHWC J1825-134	276.40 ± 0.06	-13.37 ± 0.06	0.36 ± 0.05	4.6 ± 0.5	14.5	J1825-134	0.07	7.33
eHWC J1839-057	279.77 ± 0.12	-5.71 ± 0.10	0.34 ± 0.08	1.5 ± 0.3	7.03	J1837-065	0.96	3.06
eHWC J1842-035	280.72 ± 0.15	-3.51 ± 0.11	0.39 ± 0.09	1.5 ± 0.3	6.63	J1844-032	0.44	2.70
eHWC J1850+001	282.59 ± 0.21	0.14 ± 0.12	0.37 ± 0.16	$1.1^{+0.3}_{-0.2}$	5.31	J1849+001	0.20	3.04
eHWC J1907+063	286.91 ± 0.10	6.32 ± 0.09	0.52 ± 0.09	2.8 ± 0.4	10.4	J1908+063	0.16	7.30
eHWC J2019+368	304.95 ± 0.07	36.78 ± 0.04	0.20 ± 0.05	$1.6^{+0.3}_{-0.2}$	10.2	J2019+367	0.02	4.85
eHWC J2030+412	307.74 ± 0.09	41.23 ± 0.07	0.18 ± 0.06	0.9 ± 0.2	6.43	J2031+415	0.34	3.07

Galactic Plane, > 56 TeV (0.5 degree extended source assumed)



MGRO 2019+371

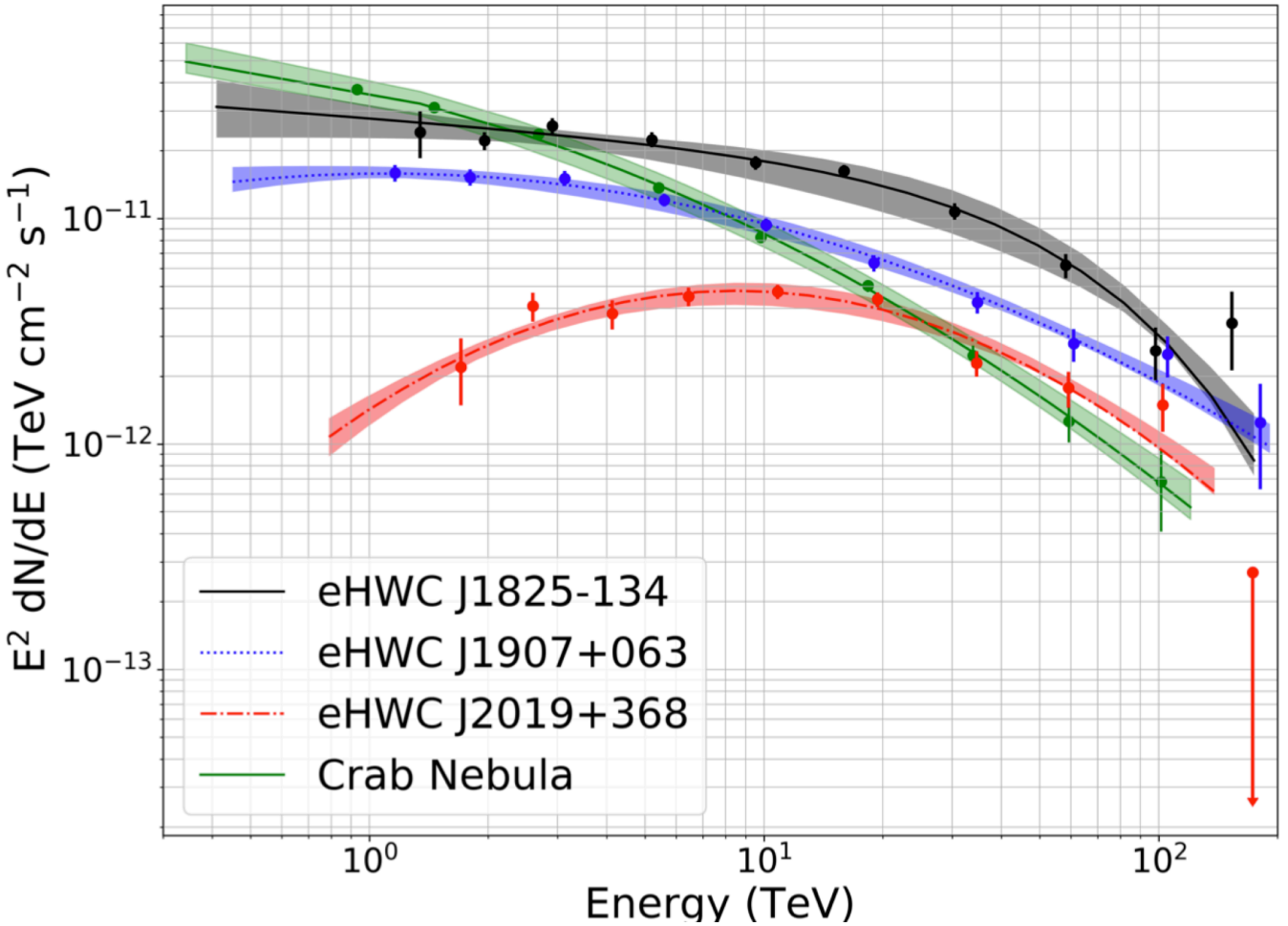
MGRO 1908+06

HESS J1825+137
HESS J1826-130

HAWC Collaboration+20

The Galaxy above 100 TeV: Spectra

HAWC Collaboration+20



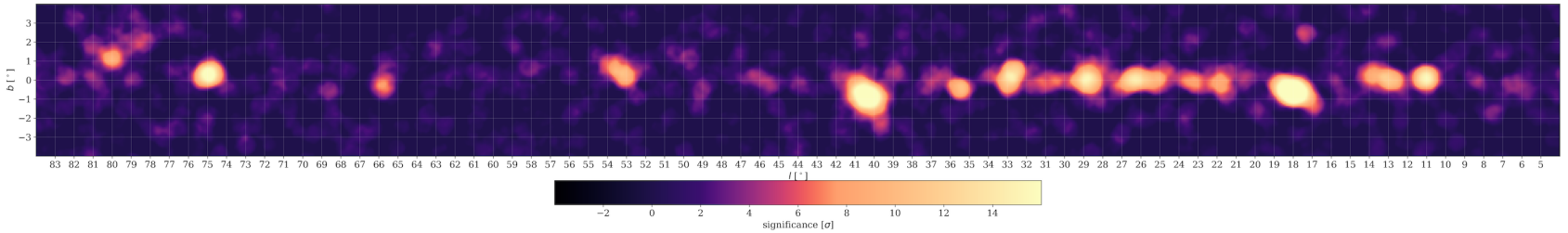
Source	$\overline{TS}^p$	Extension (°)	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	↵	E_{cut} (TeV)	PL di↵
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4

Source	$\overline{TS}^p$	Extension (°)	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	↵	β	PL di↵
eHWC J1907+063	37.8	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02	6.0
eHWC J2019+368	32.2	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05	8.2

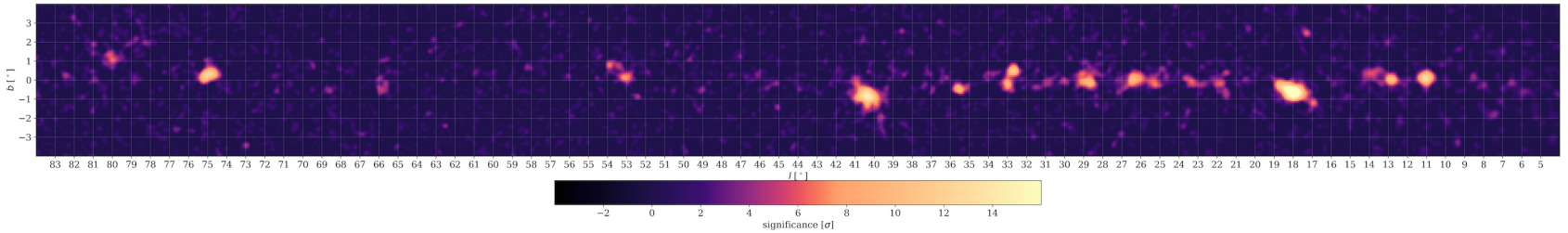
2800 day maps > 56 TeV

0.5 deg

K. Malone



pointlike

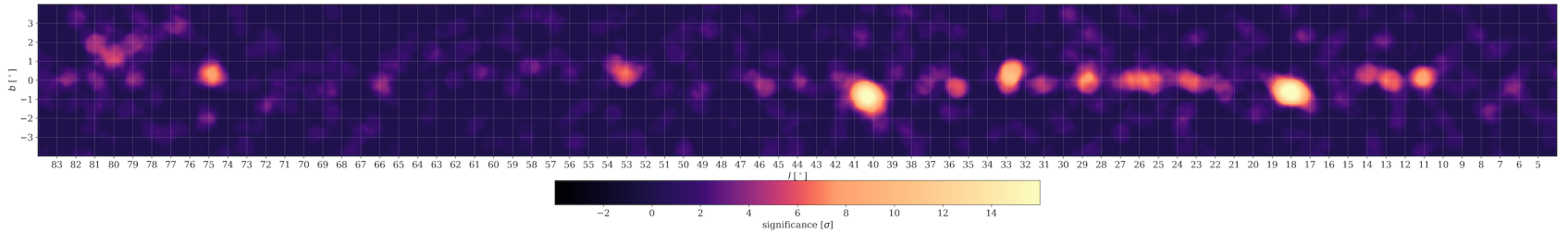


most sources are extended

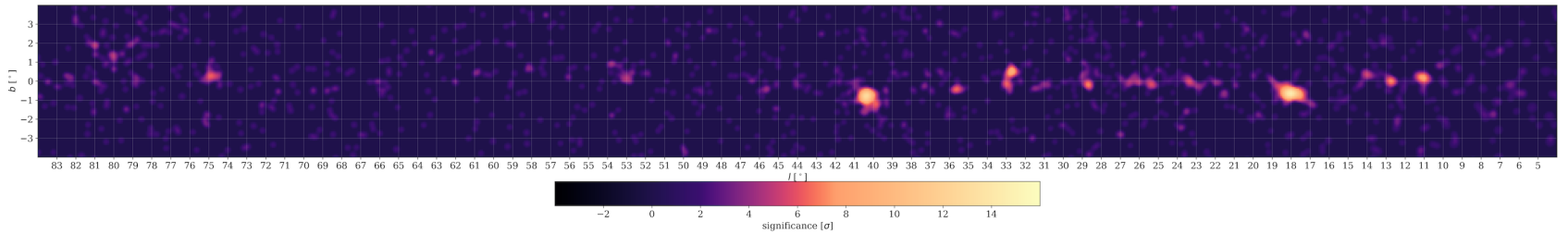
2800 day maps > 100 TeV

K. Malone

0.5 deg



pointlike

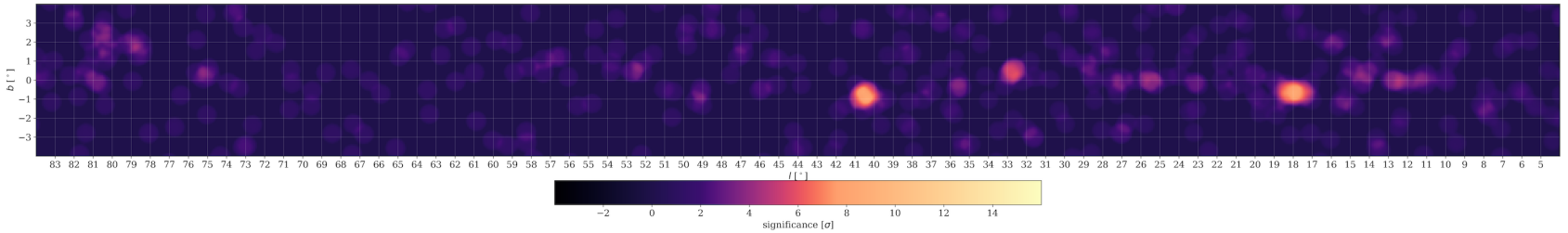


most of which extended

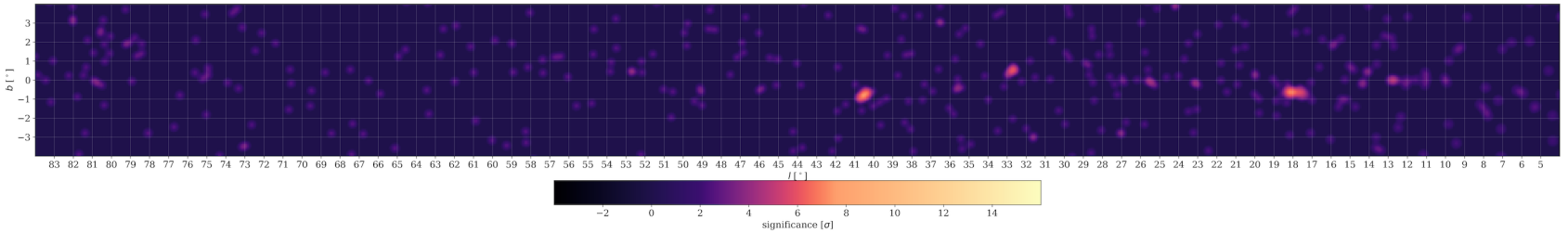
2800 day maps > 177 TeV

0.5 deg

K. Malone



pointlike



4HWC catalogue in preparation

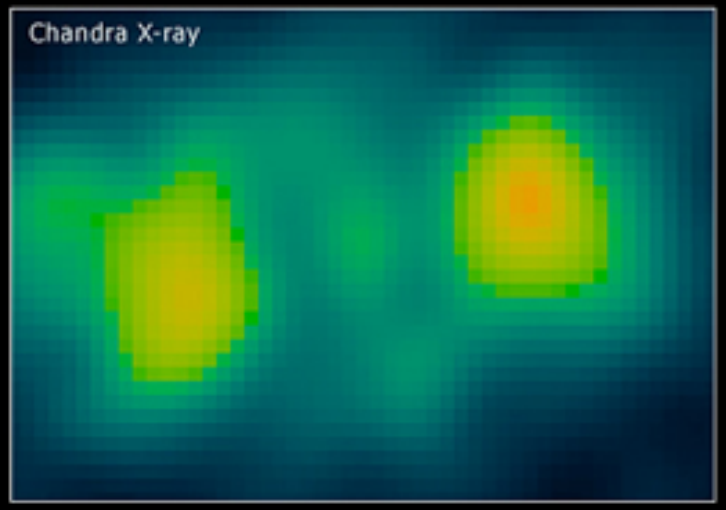
HAWC Observations of Variable Sources

HAWC monitors variable sources and discovers new transients

	Distance (kpc)	Companion star mass ($M_\odot$)	Compact star mass ($M_\odot$)	Orbital period (days)	Orbital axis inclination (°)	Jet axis inclination (°)
V4641 Sgr	6.2 ± 0.7	2.9 ± 0.4	6.4 ± 0.6	2.817 ± 0.002	72. 3 ± 4.1	<16
SS433	~ 5.5	>10	8	13.082	79	
LS5039	~2.5	22.9 +3.4 -1.3	3.7 +1.3 -1.0	3.90603 ± 0.00017	24.9 ± 2.8	

X. Wang

SS433 Lobes



Binary observed in radio-X-rays

Supergiant > 10 $M_\odot$ and 8 $M_\odot$ compact object, BH or NS

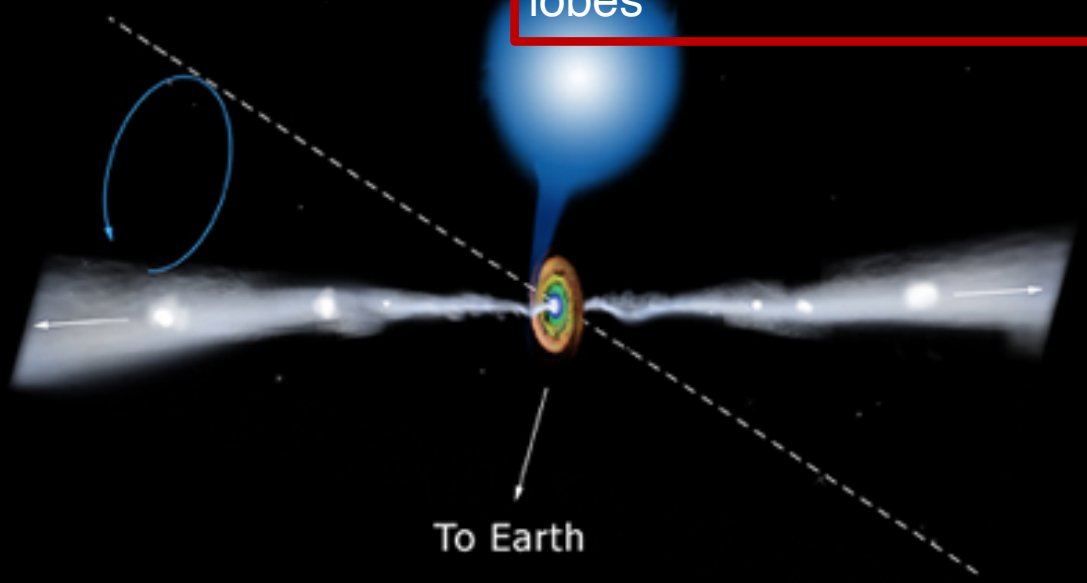
Accretion believed to be super Eddington

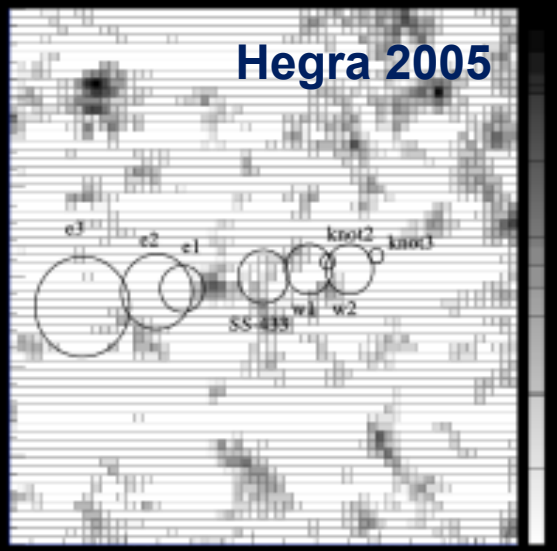
Barion loaded SS433 jet : $10^{39\text{-}40}$ erg/s

SS433 jet speed roughly c/4

Most powerful jets in the Galaxy terminate at 40 pc distance in W50 nebula and produce western and eastern X-ray lobes

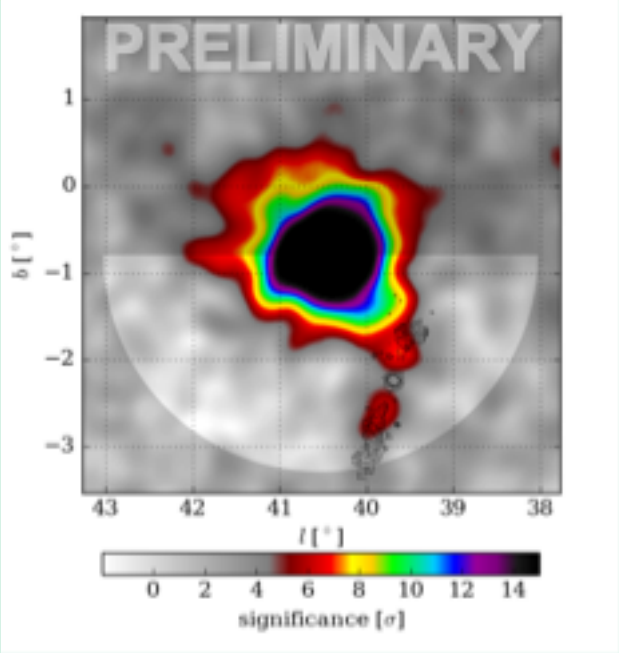
Particle acceleration & GeV-TeV radiation predicted at the lobes

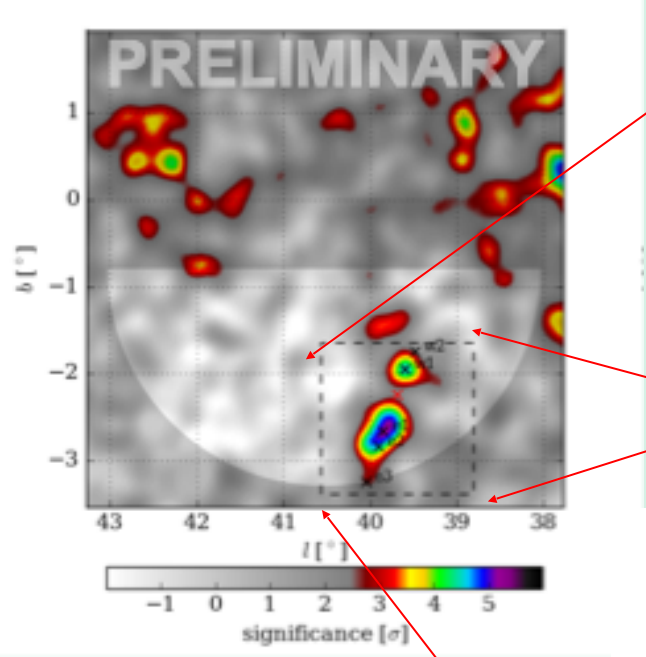


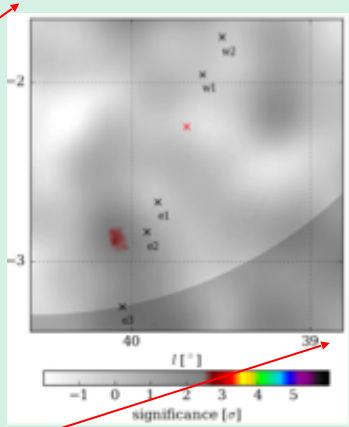


SS-433 lobes with HAWC

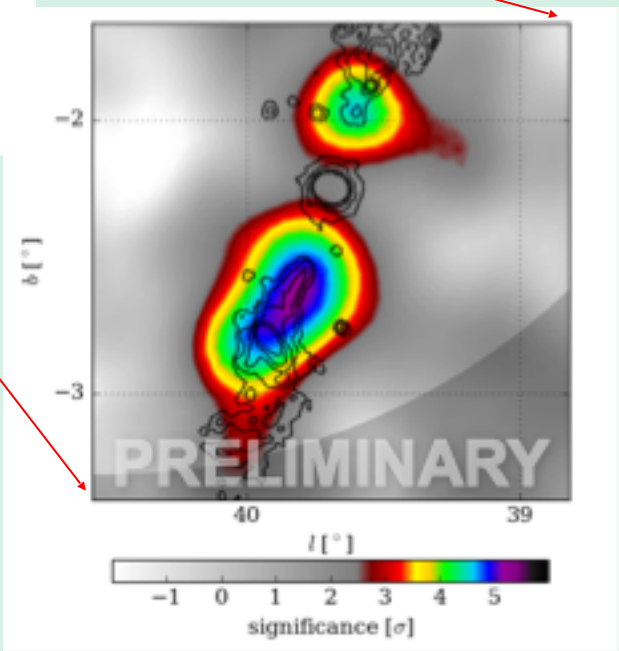
SS433 field after subtracting the lobes

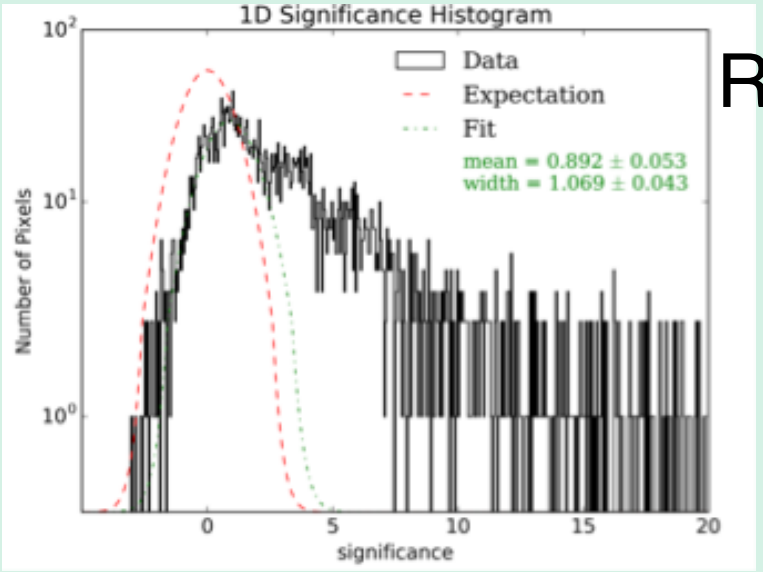






Nature, HAWC Coll 2018





Raw Map

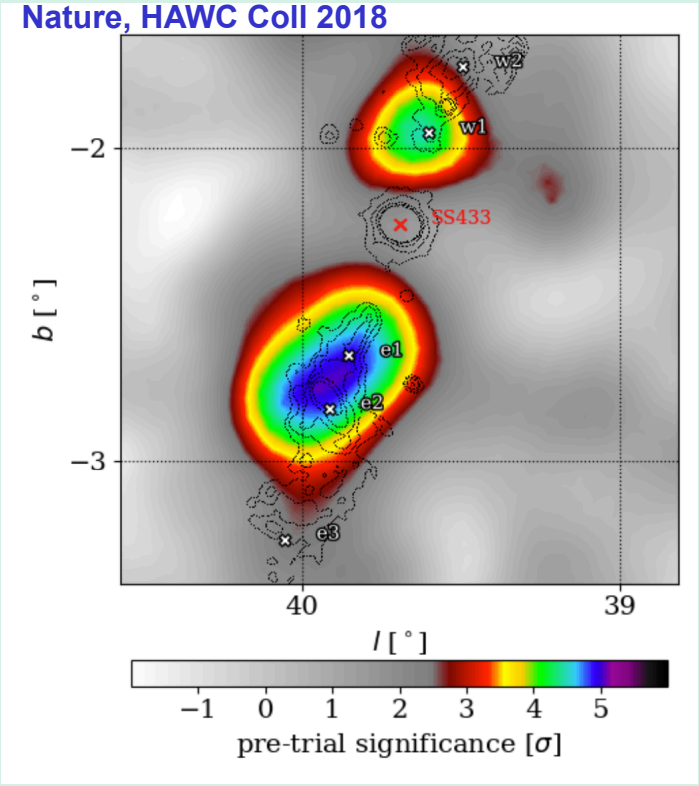
Extended Data Table 3 Systematic uncertainties on the flux from SS 433

Systematic	East Lobe	West Lobe
Detector Systematic Effects	±50%	
MGRO J1908+06 Modeling	< ±20%	
Galactic diffuse contamination	−10%	−20%
Total	±55%	±55%

Systematic 1σ error budget for the VHE γ-ray fits.

SS 433 field after subtracting MGRO J1908+06

SS-433 lobes with HAWC

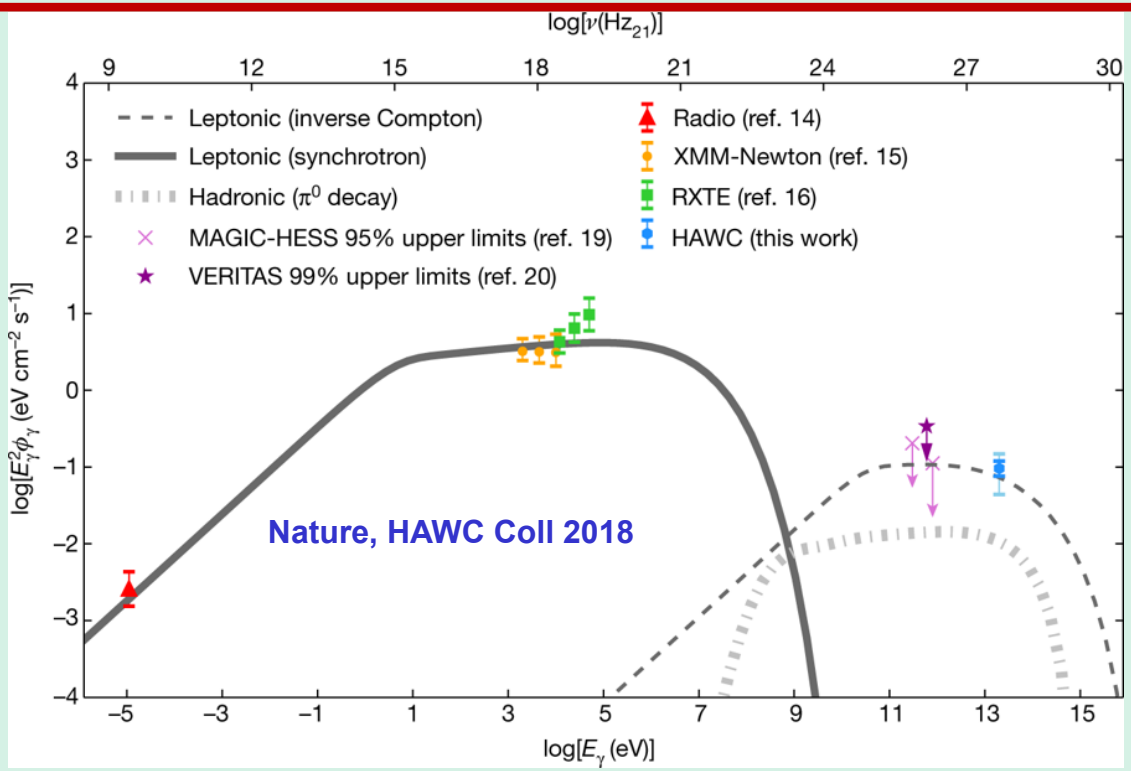


- The first micro-quasar HAWC detected
- 1017 days of HAWC observations
- Post-trial 5.4 σ
- Emission coincident with e1 and w1
- HAWC emission shows that powerful jets accelerate particles beyond 100 TeV
- Combining γ and X-rays B~16 μG

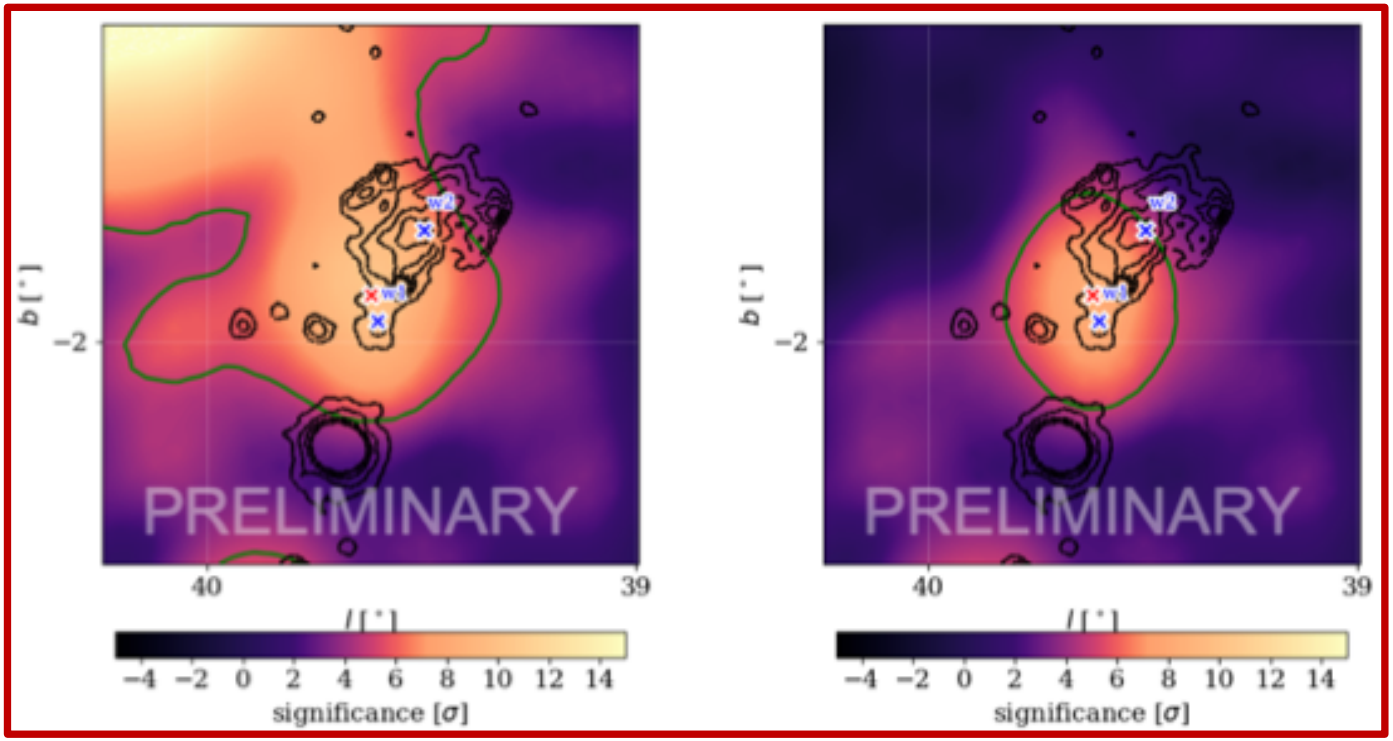
Energy Budget :

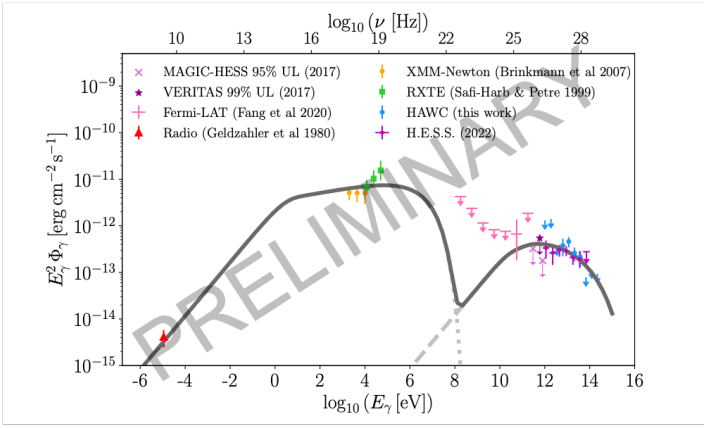
~0.5% of jet power into electron acceleration

~100% of jet energy over 30000 years lifetime of SS 433 into accelerating protons of at least 250 TeV with spectral index -2. if n=0.1 cm^{-3} But do we really know the ambient gas density ?



West lobe

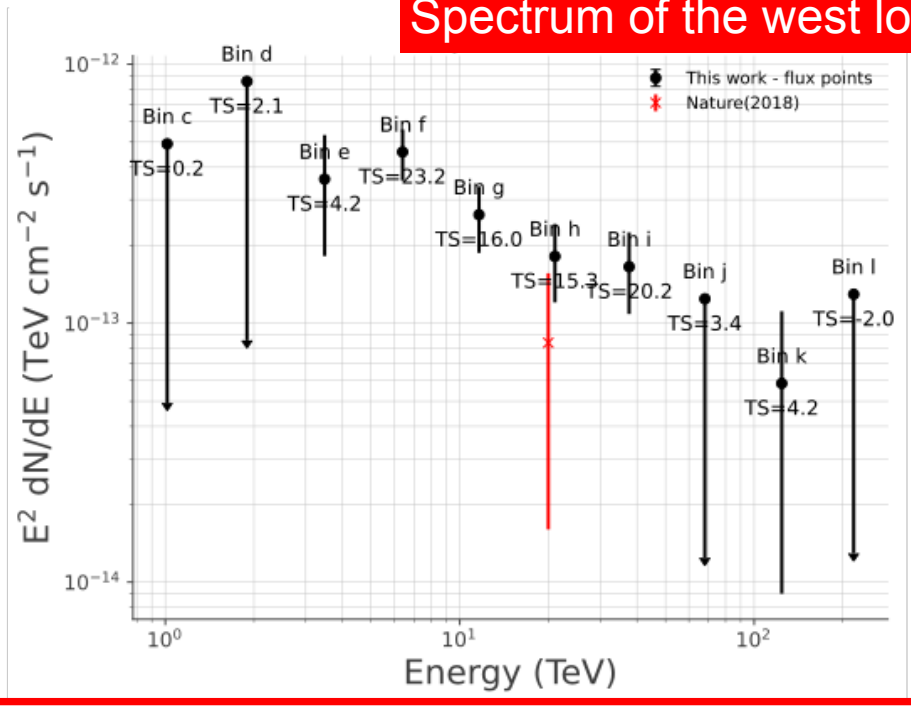




Chang Dong Rho

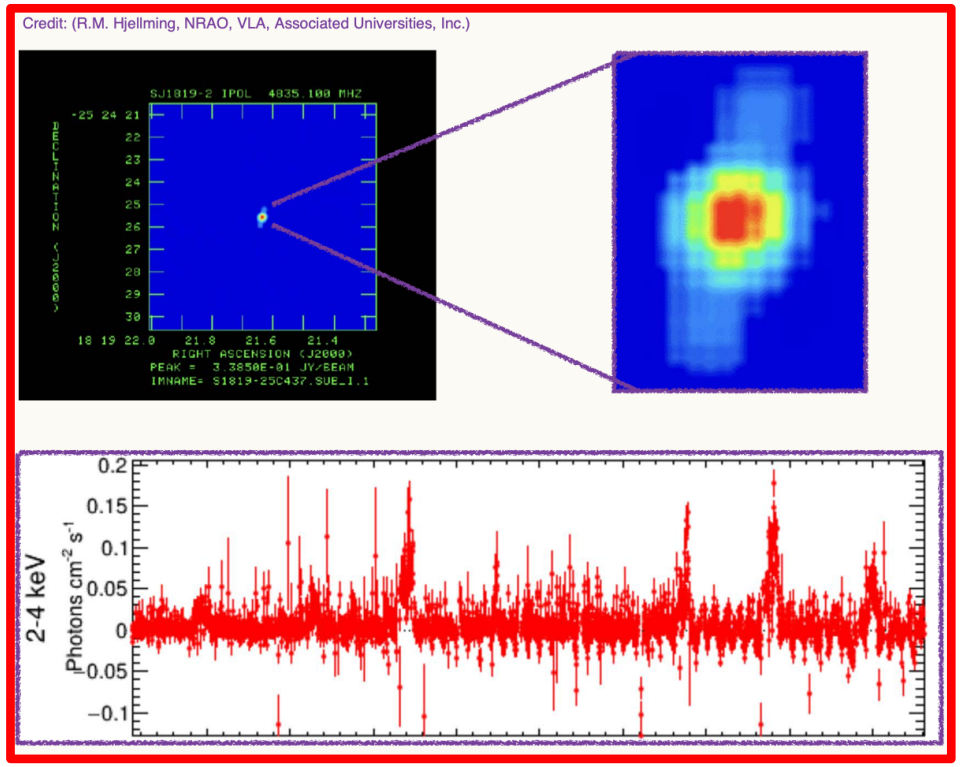
- 1922 days of data
- Better Reconstruction
- Blind search of the region yields results compatible with 2018 analysis
- Increased significance
- Individual analysis and spectra of the lobes

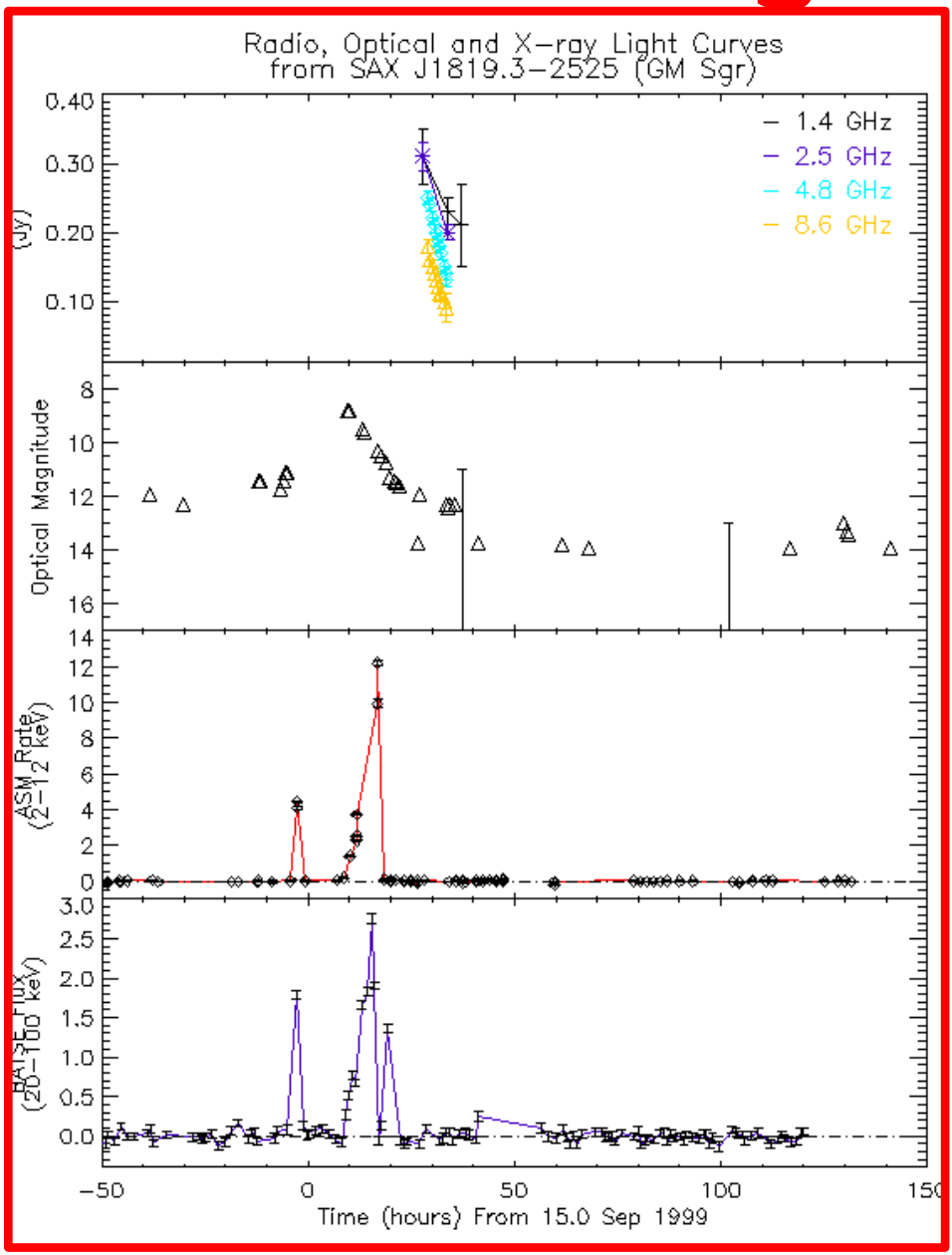
Spectrum of the west lobe



VHE Photons coincident with V4641 Sgr

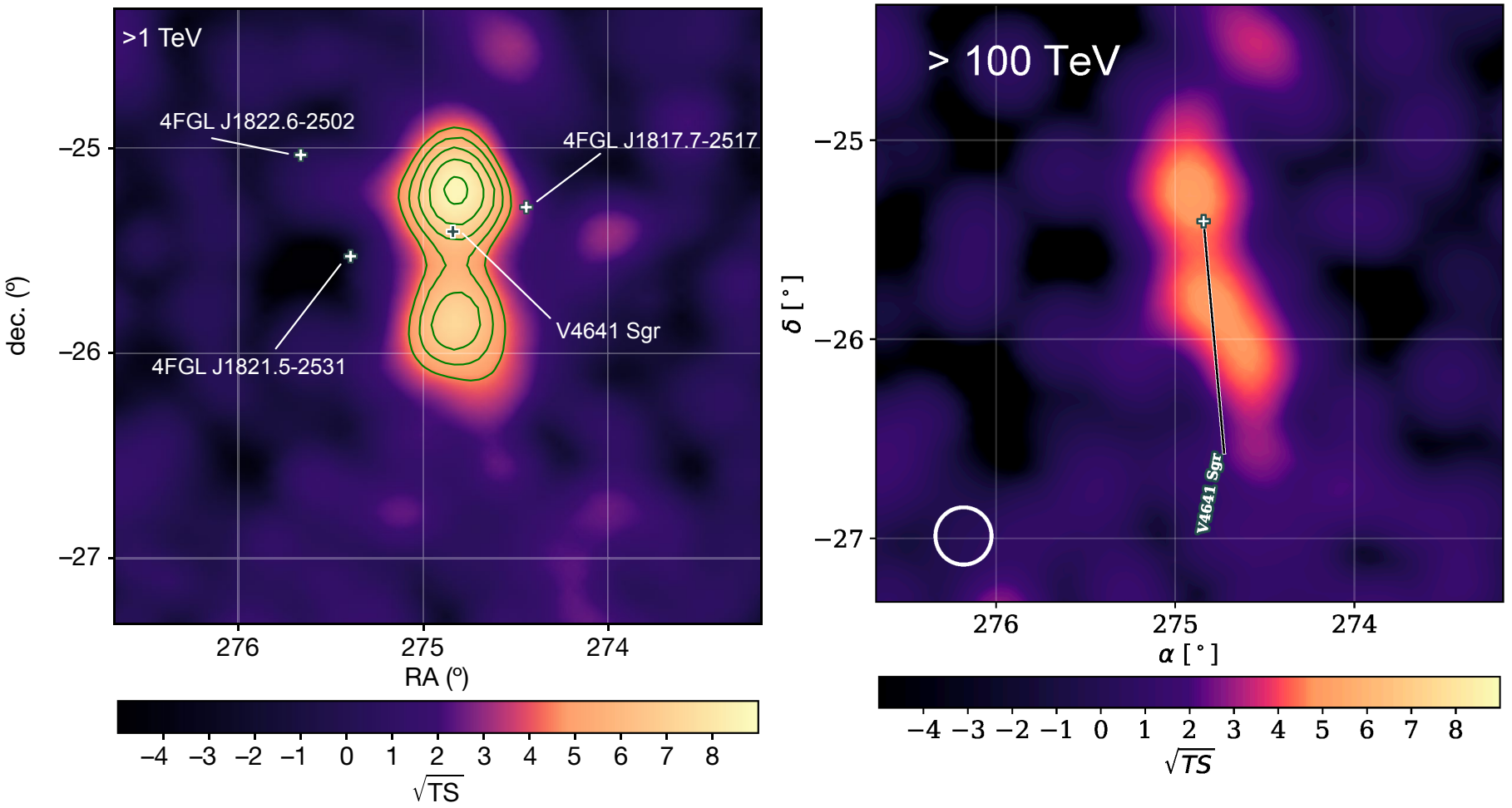
- Transient X-ray binary first detected flares in 1999 – X-ray flux reached 12.2 Crab in 8 hr
- Arcsec radio jets inclined < 16° (VLA)
- Black-hole 6.4 $M_\odot$ (MacDonald+2014)
- B-star companion 2.9 $M_\odot$
- Orbital period 2.8 d, distance 6.2 kpc
- Super-Eddington accretion
- Superluminal jets - apparent expansion speed 9.5c





VHE Photons coincident with V4641 Sgr

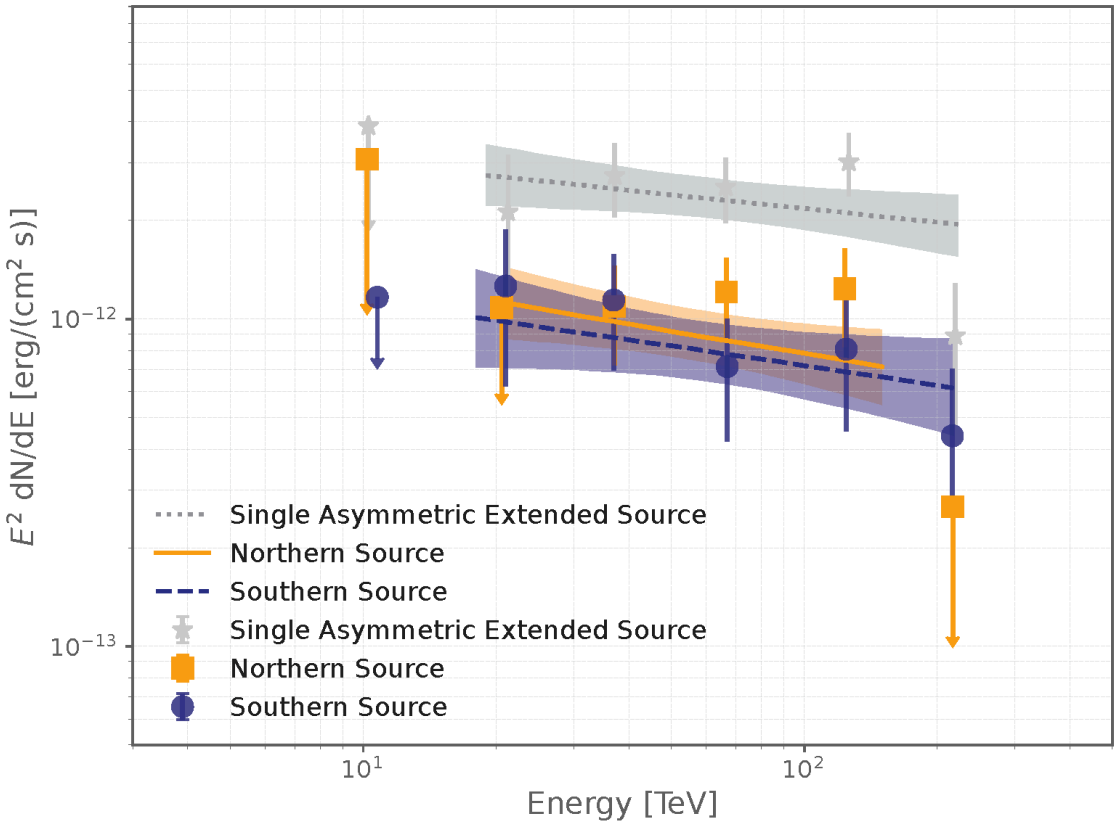
HAWC Collaboration, Nature 2024



- 2400 days obs 26.11.2014 till 27.06.2022 – on-array events – 3 deg ROI
- High zenith angle for HAWC - 45° off zenith
- 8.8σ above 1 TeV and 5.2σ above 100 TeV

Spectra and morphology of the lobes

HAWC Collaboration, Nature 2024



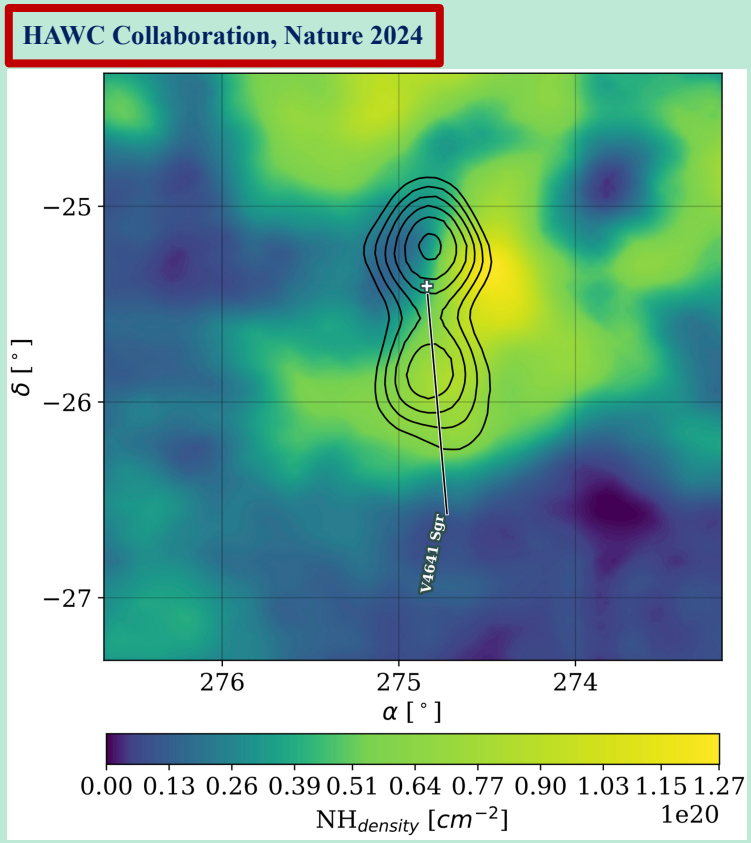
- Morphology: two sources or a roughly 70 pc extended one
- Highest energy measured: 220 TeV
- No time flux variations using selected time intervals

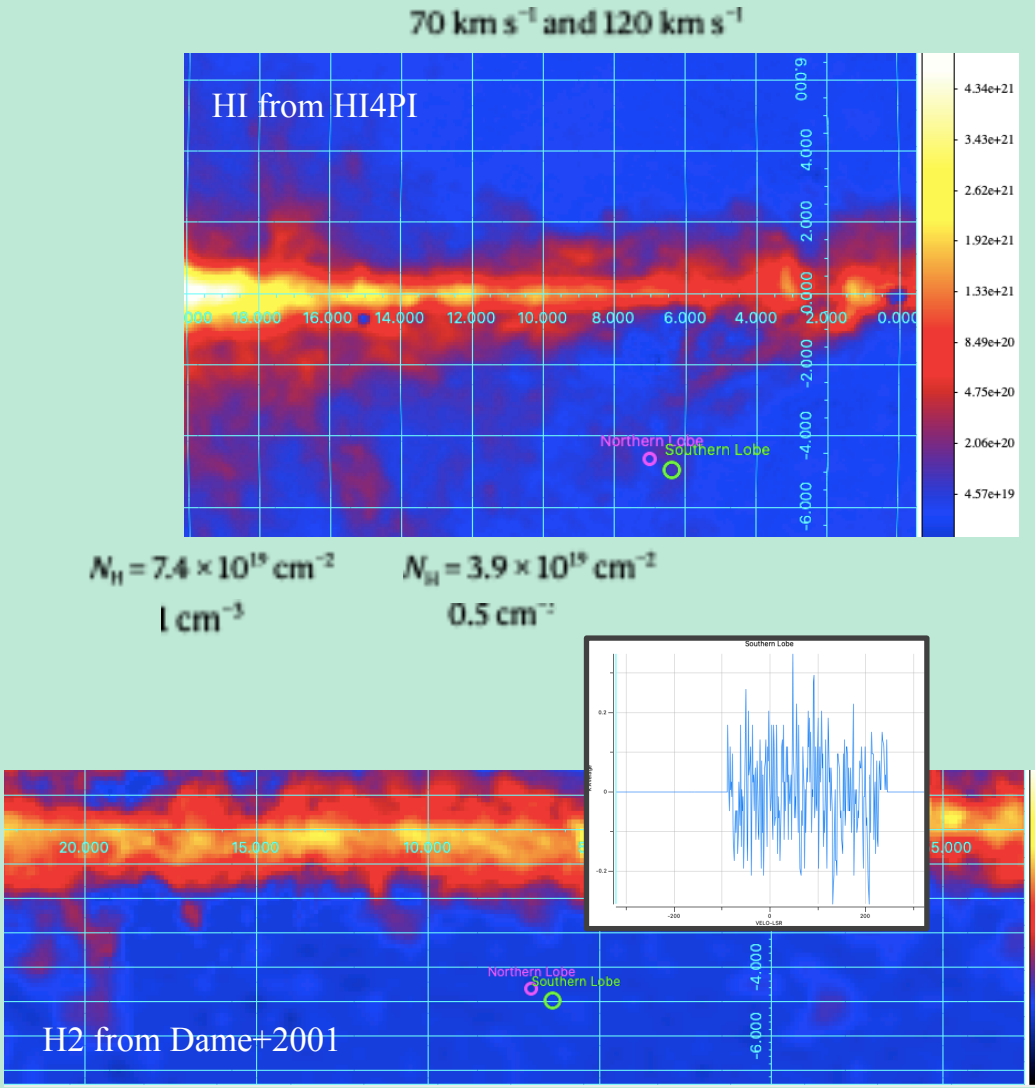
Do micro-quasars provide PeV particles?

$$\dot{W}_p(E_p > 1\,\mathrm{PeV}) = L_\gamma \frac{t_{pp}}{t_{esc}}$$

$$\simeq 10^{39}\eta \left(\frac{L_\gamma}{10^{34}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{D_0}{3\times 10^{30}\ \mathrm{cm^2\ s^{-1}}}\right)\left(\frac{n}{1\ \mathrm{cm^{-3}}}\right)^{-1}\ \mathrm{erg\ s^{-1}}$$

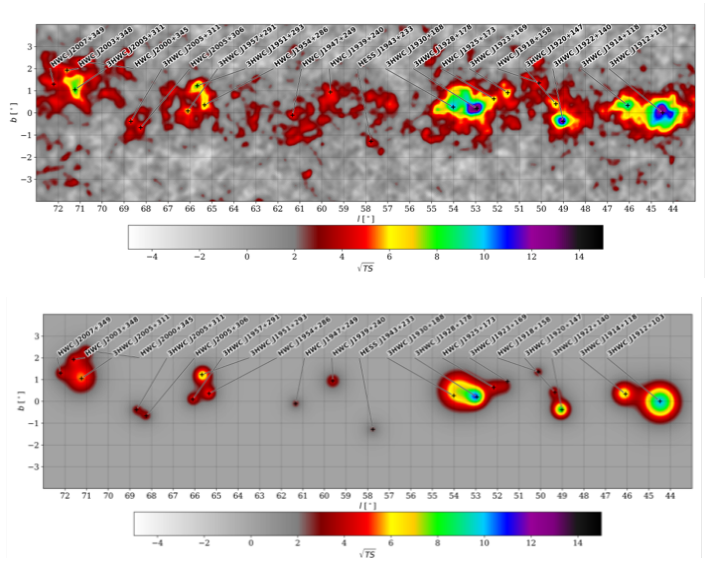
What about the gas density ?

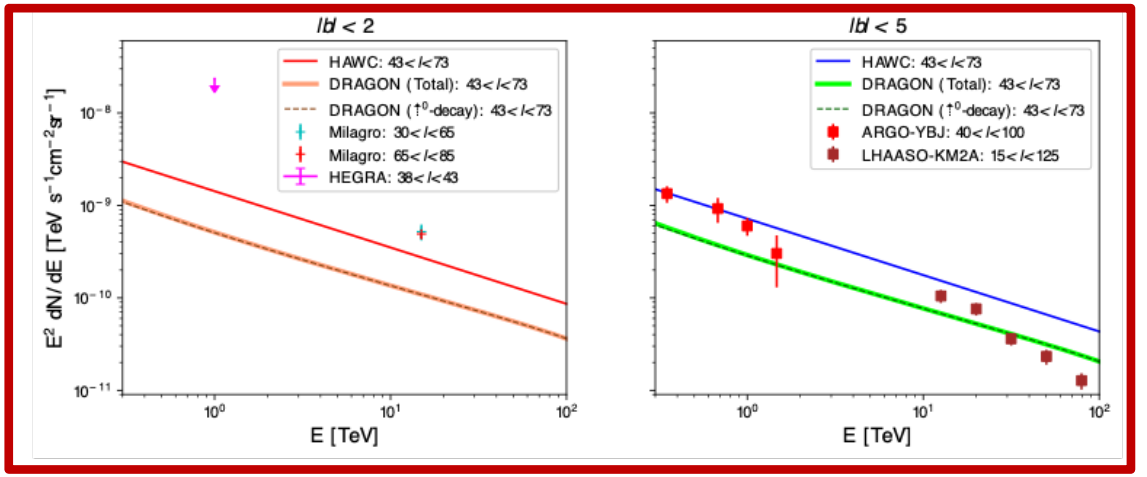




Galactic Diffuse Emission

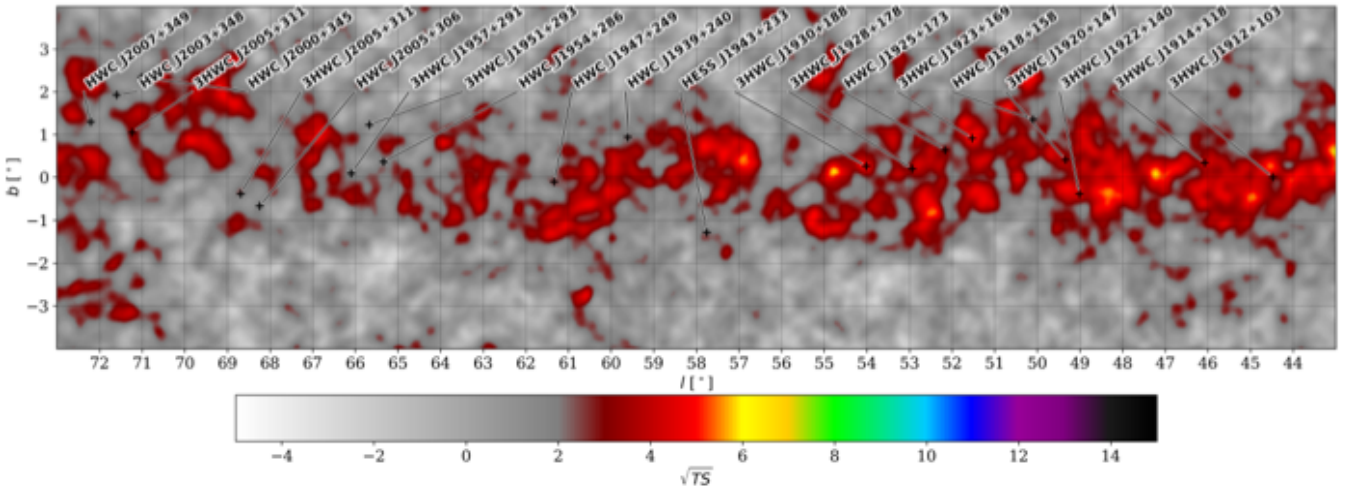
HAWC, ApJ 2023





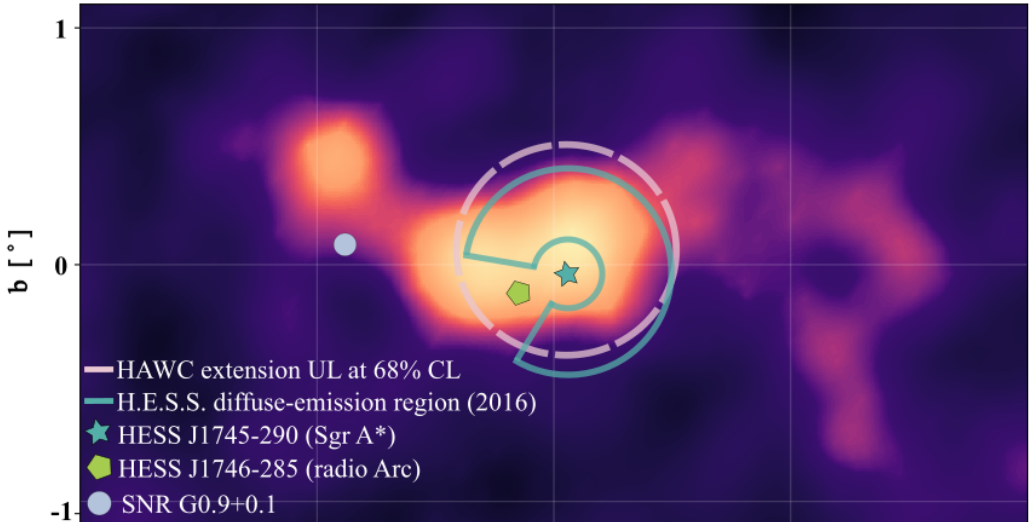
l_{min} (°)	l_{max} (°)	|b| < (°)	$F_7 \rightarrow 10^{-12}$ ($TeV^{-1}\ s^{-1}cm^{-2}sr^{-1}$)	Index	f_{10} %	f_{100}
43	73	2	$8.89 \pm 0.37^{-0.70}_{+0.48}$	$-2.61 \pm 0.03^{-0.04}_{+0.02}$	72.7	71.8
43	73	4	$5.45 \pm 0.25^{-0.44}_{+0.38}$	$-2.60 \pm 0.03^{-0.04}_{+0.01}$	76.1	75.3

Source-subtracted map

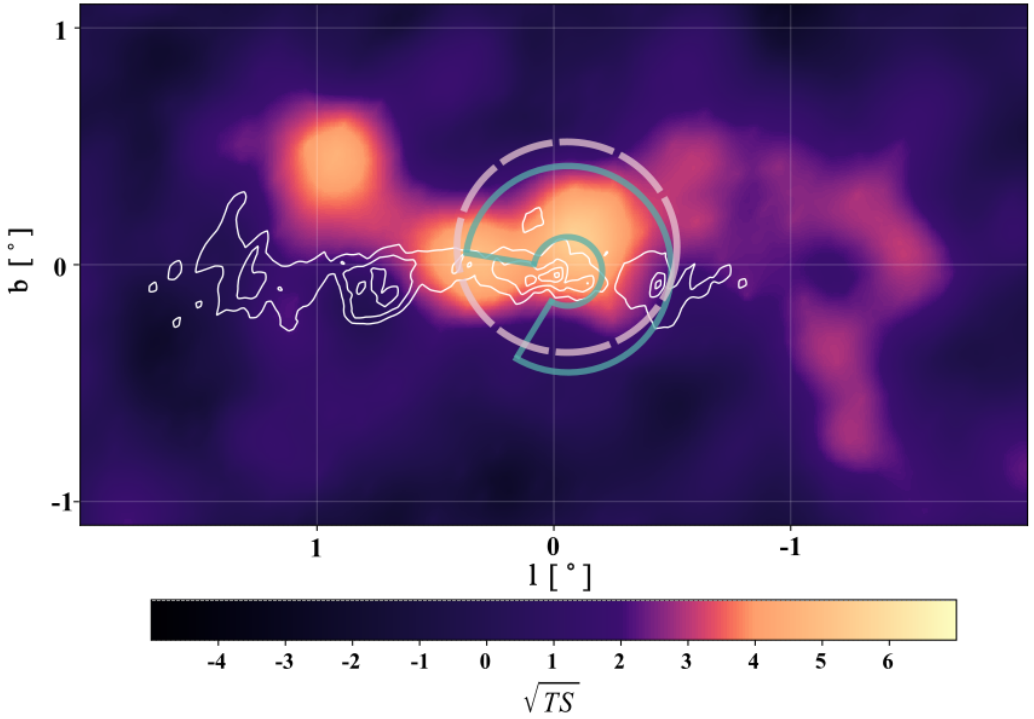


Diffuse Emission from the CMZ

HAWC Collaboration, ApJL 2024



- 2456 days observations
- GC at 48° zenith
- 6.5 σ detection in Pass 5
- Best-fit model : point-like source with a simple power law spectrum up to at least 100 TeV

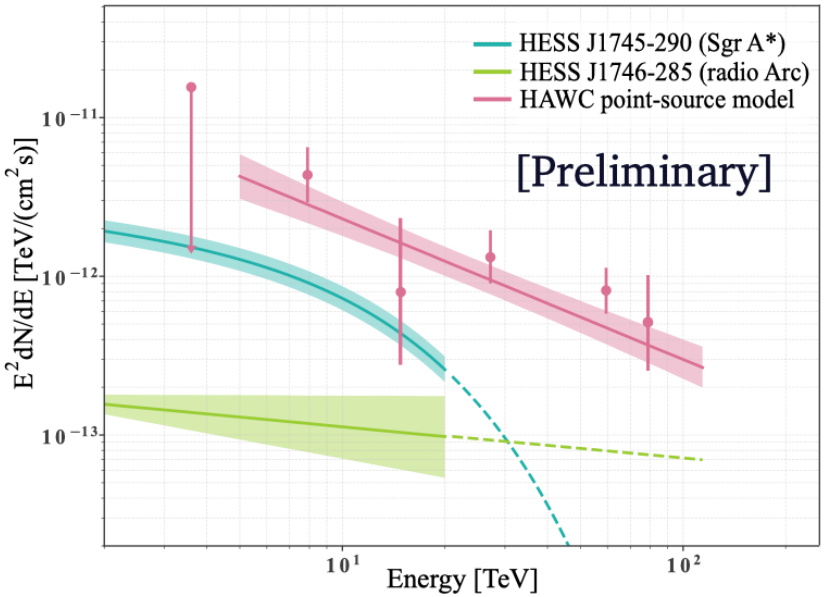


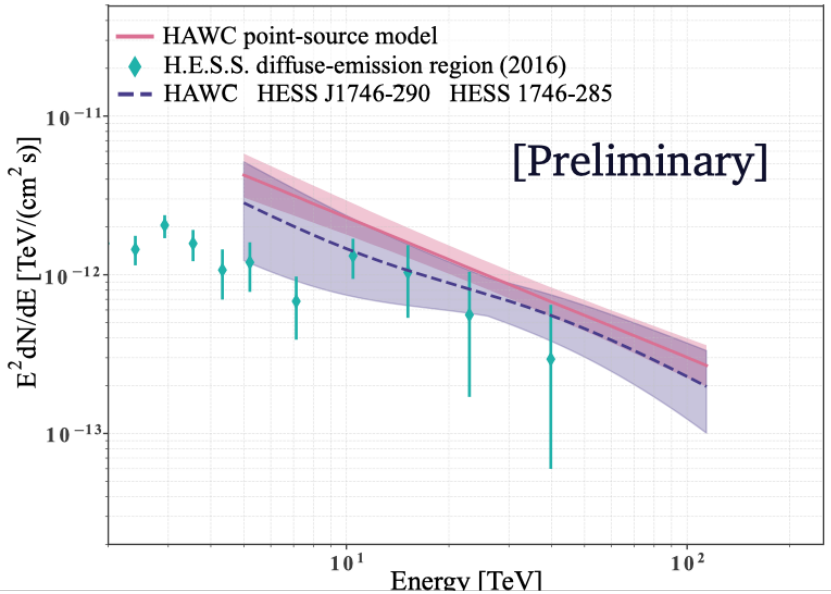
HAWC emission after subtracting HESS J1745-290 (Sgr A*) and HESS J1746-285 (Radio Arc)

5.7 sigma detection

Remaining flux extends to UHE and reveals a PeVatron at the GC as first suggested by HESS

HAWC View of the Galactic Centre Ridge





- HAWC and HESS fluxes compatible
- **No spectral cutoff**
- Maximum γ energy detected in HAWC

  1 sigma: 69.57 TeV

  2 sigma: 50.17 TeV

  3 sigma: 34.24 TeV

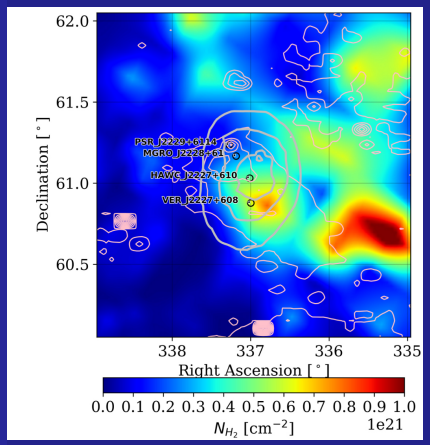
The cosmic-ray energy density estimated with HAWC gamma-ray luminosity suggests constantly accelerated 0.1-1 PeV protons in the GC region.

$$w_p(\geq 10E_\gamma) = 1.8\times10^{-2}\left(\frac{\eta_N}{1.5}\right)^{-1}\left(\frac{L_\gamma(E_\gamma\geq 10\ \mathrm{TeV})}{10^{34}\ \mathrm{erg/s}}\right)\left(\frac{M}{10^6 M_\odot}\right)^{-1}\ \mathrm{eV/cm^3} \approx 8.1\times10^{-3}\ \mathrm{eV/cm^3}$$

HAWC Collaboration, ApJL 2024

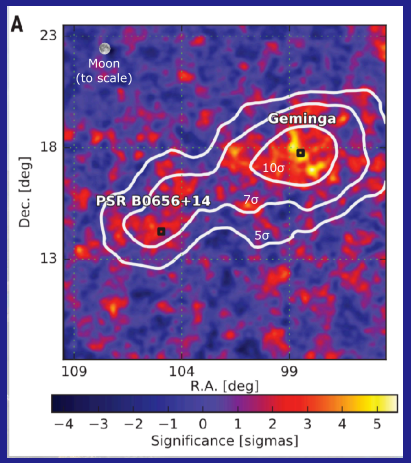
Extreme accelerators in HAWC sky

ApjL 2020



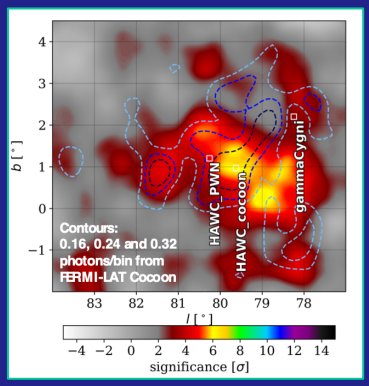
Boomerang SNR

Science 2017



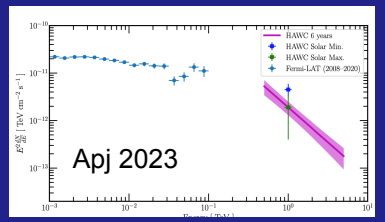
Geminga

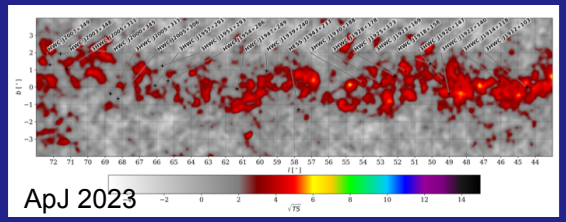
Nat Astr 2021



Cygnus Bubble

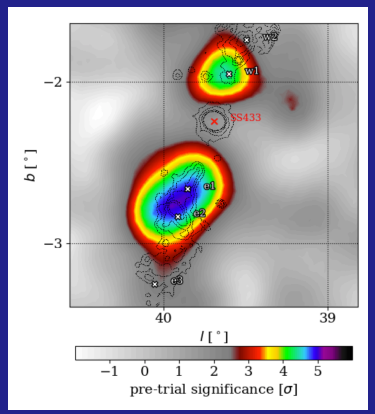
The Sun



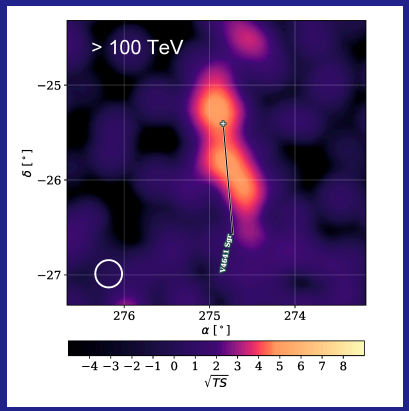


Diffuse Emission

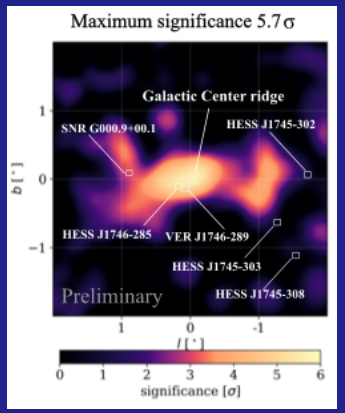
Nature 2018



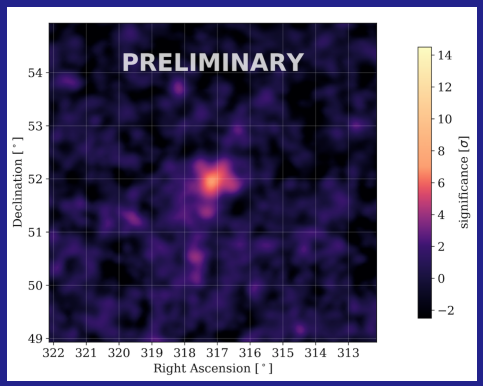
Nature 2024



ApjL 2024



Gal Centre



Molecular Cloud – LHAASO 2108

Microquasars

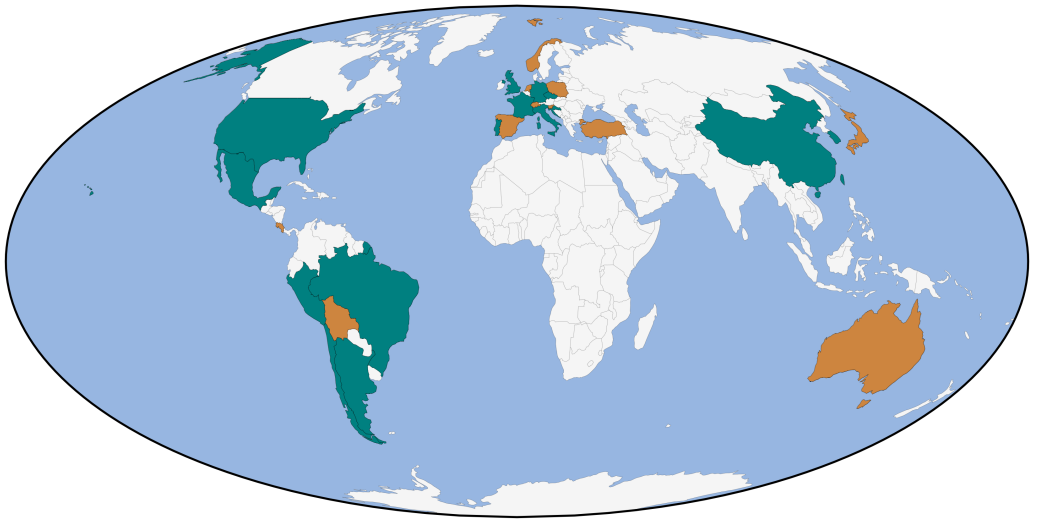
The future of Wide-Field-of-View Gamma Observatories: SWGO

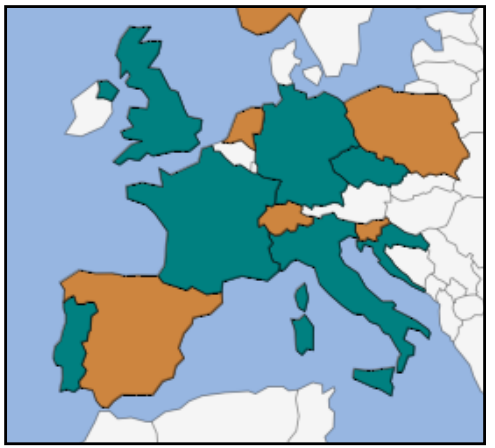
Slide by Barres de Almeida

SWGO Collaboration

Member Institutes

Supporting Scientists



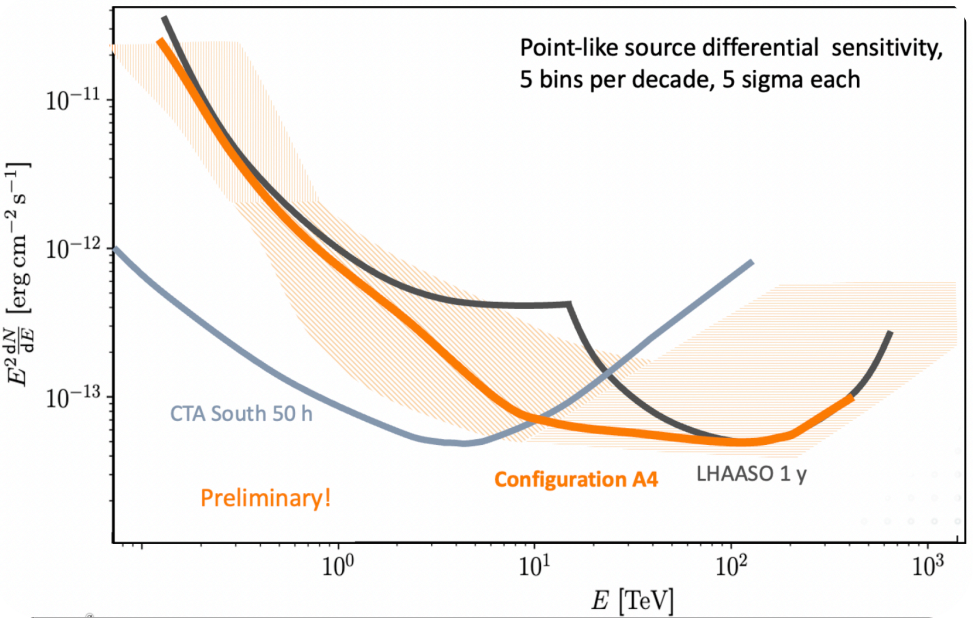


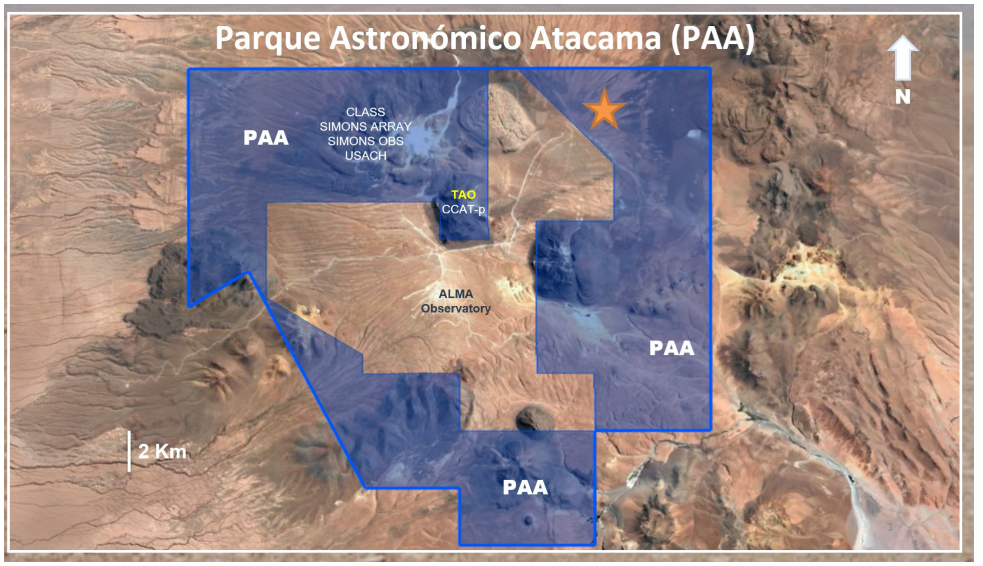
- SWGO partners
  - → 15 countries, over 90 institutes
  - → + supporting scientists

Argentina
Brazil
Chile
China
Croatia
Czech Republic
France
Germany
Italy
Mexico
Peru
Portugal
South Korea
United Kingdom
United States

Plans

- Site Decision made - Atacama Chile
- Design Decision expected within 2025
- Preparatory phase
  - Detailed construction planning
  - Engineering array in 2026
- Construction Phase from 2027





Science Case	Design Drivers
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude[a]
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy resolution[b]
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity & Angular resolution[c]
Diffuse Emission: Fermi Bubbles	Background rejection
Fundamental Physics: Dark Matter from Galactic Halo	Mid-range energy sensitivity Site latitude[d]
Cosmic-rays: Mass-resolved dipole/multipole anisotropy	Muon counting capability[e]

Science tools compatible with gammapy

Conclusions and Outlook

Since 2015 HAWC has shown that the Galaxy is full of VHE-UHE sources

- Survey of the Galaxy in the TeV- hundred TeV domain
- Monitor and serendipitous discovery of transient sources up to hundred TeVs
- Diffuse emission from the GP and CMZ – Confirmation of GC PeVatron
- TeV photons from the Sun
- Star Formation regions
- New source class : TeV halos.
- Boomerang region : SNR as PeVatrons

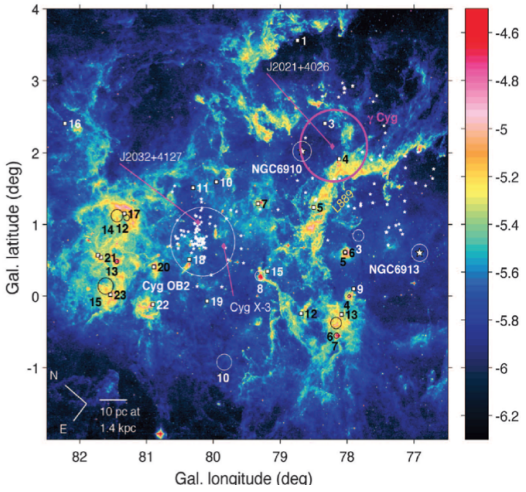
Plans for Future

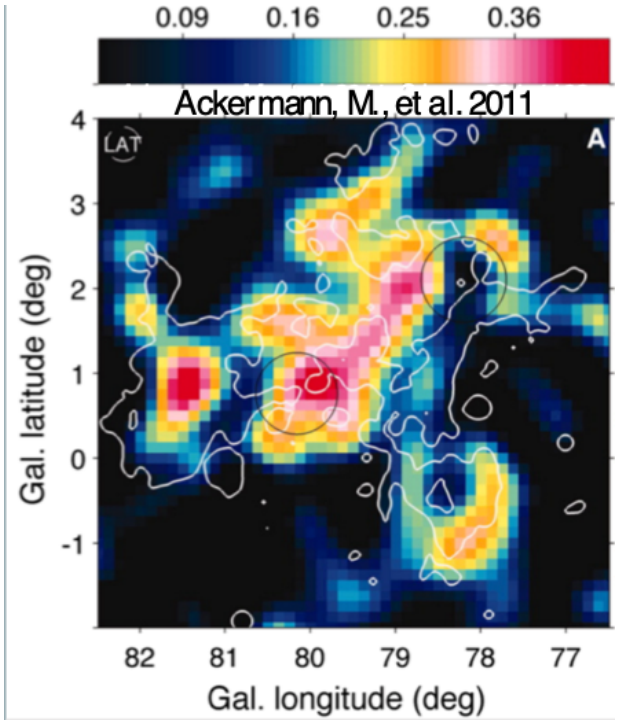
- Analysis of multiple year data from the outrigger array in Pass6
- HAWC plans to continue operation waiting for SWGO

Back-up Slides

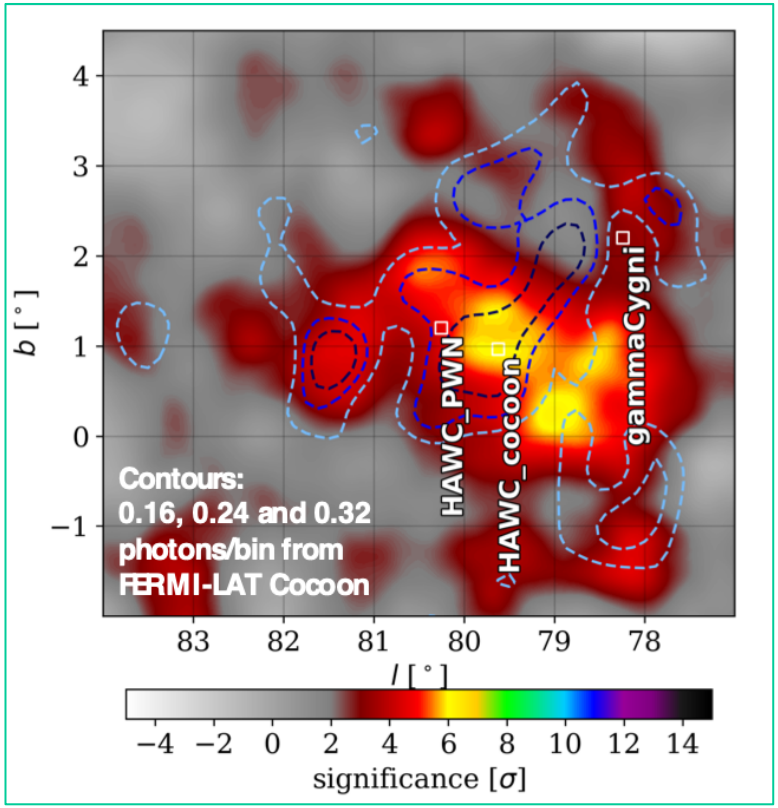

VHE AND UHE Photons
from SFRs and the
origin of Galactic CRs

Cyg OB2 in IR, GeV and TeV





HAWC Coll, NatAstr 2021

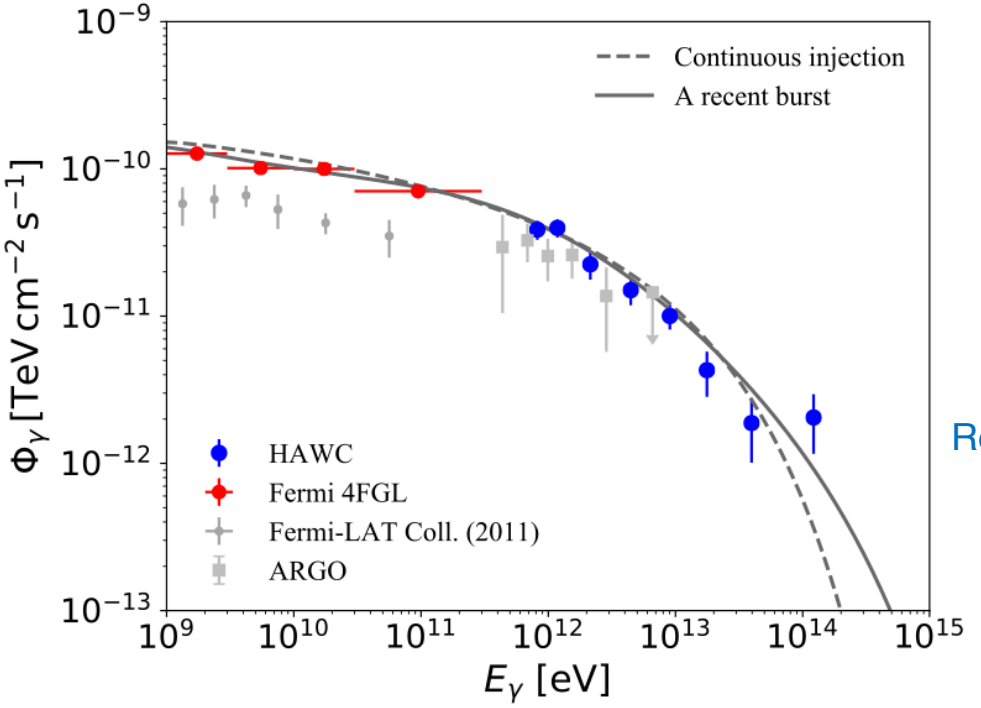


Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

First superbubble up to 100 TeV energies

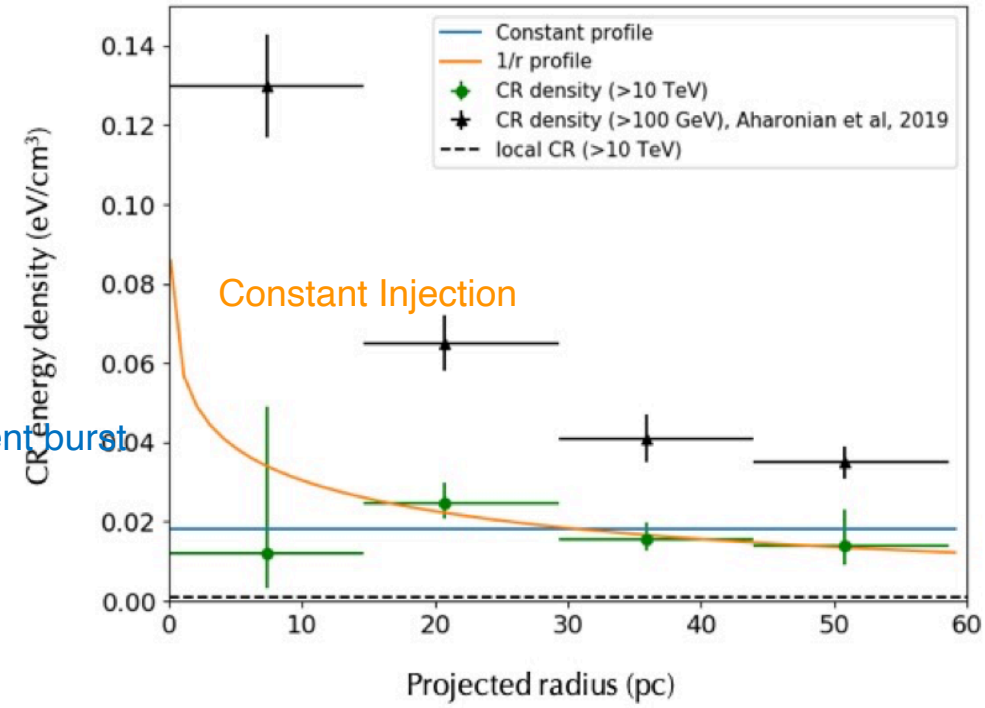
Cosmic Ray Acceleration in SFRs

Hadronic Model



Recent burst

Nat Astr, HAWC 2021



CRs up to PeV energies accelerated within a region the SFR

CR energy density > 10 TeV higher than local CR energy density

1/r profile - a continous injection. Constant profile - a recent burst event happened less than 0.1 Myr

10000 CygOB2 would be required for CRs Galactic population

TeV-PeV pulsar Wind Nebulae and halos

Geminga - PWN

Geminga is one of the brightest GeV sources in the northern sky

It's a middle-aged 340kyr, pulsar T=0.237s

It's close to earth - 250^{+250}_{-62} pc

X-Ray PWN seen to be very small

First seen in TeV by Milagro at 40 TeV in 2009

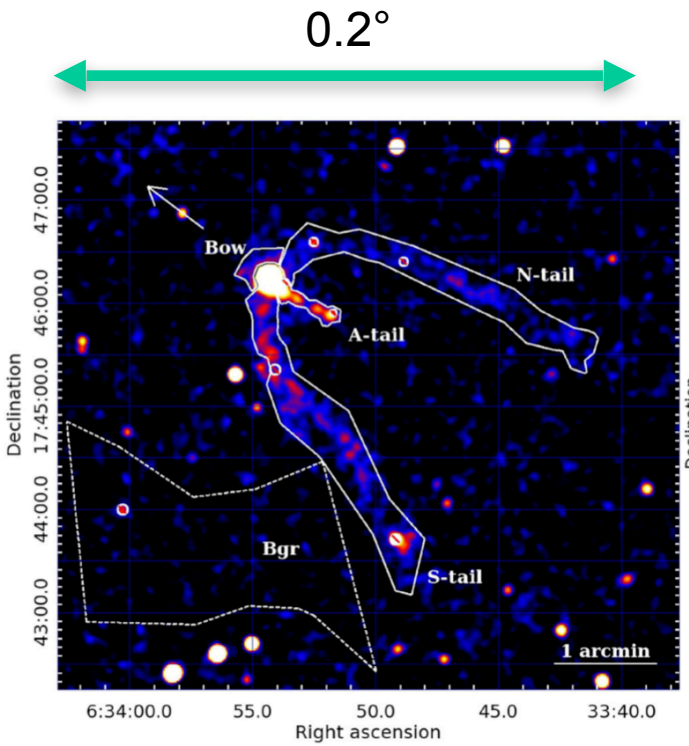
HAWC also sees energies above 25TeV

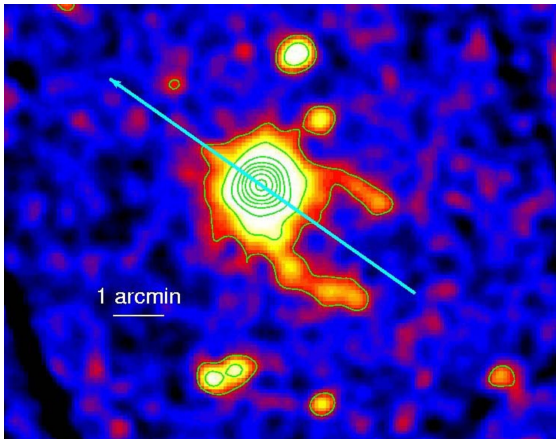
Very extended in the TeV - ~5 degrees across

Geminga and Monogem, similar in age and distance,

were suggested as contributors of the positron fraction

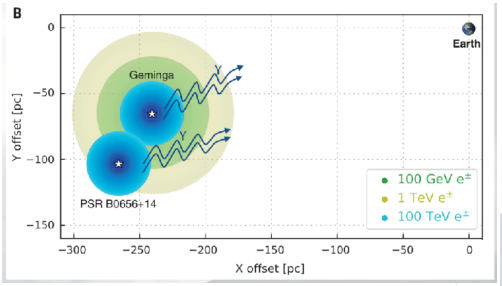
(Aharonian+1995).

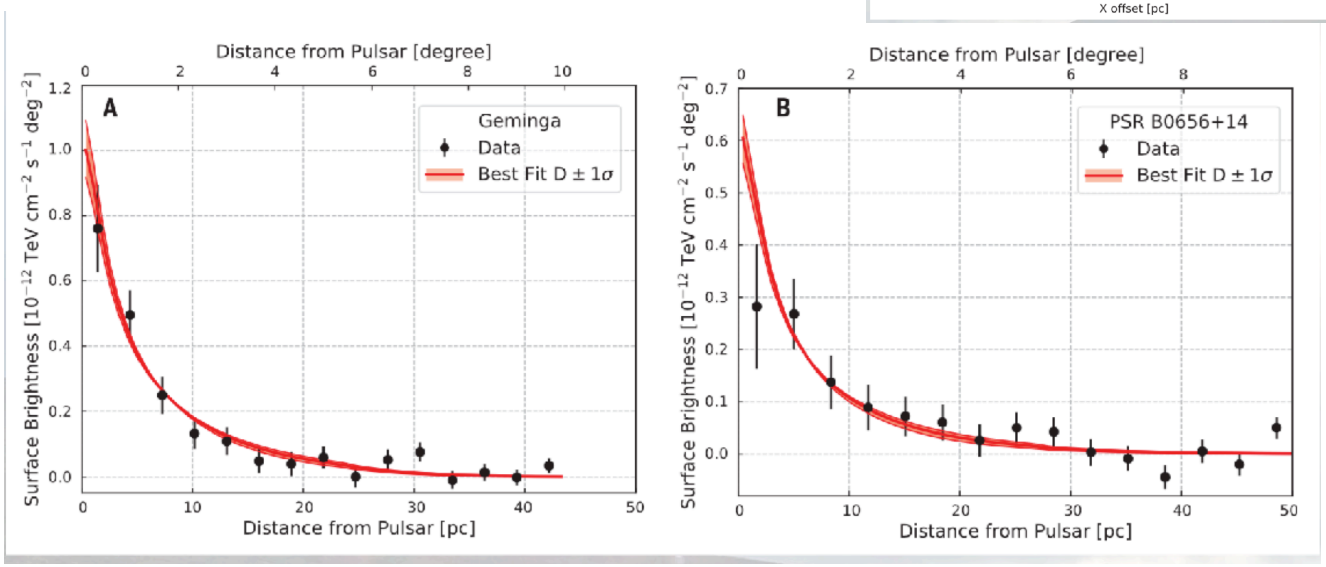


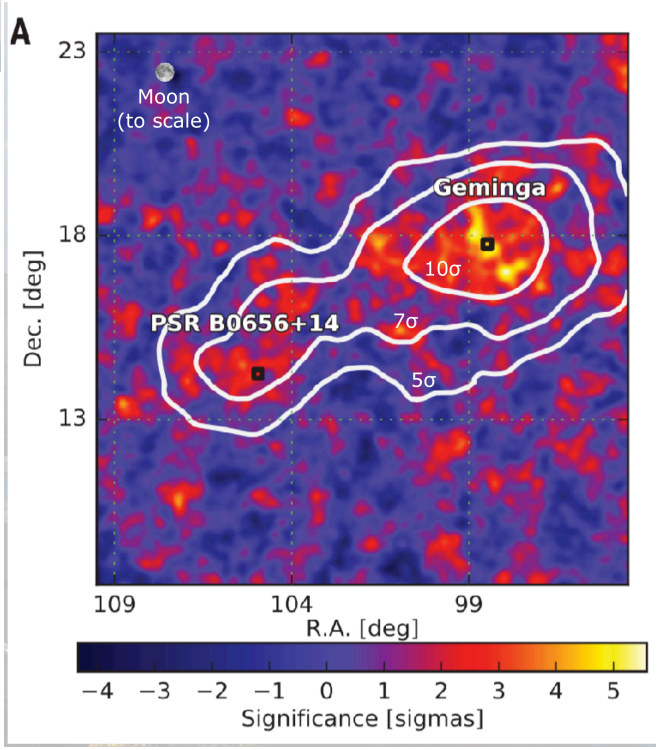


Extended TeV emission around the pulsars Geminga and Monogem

HAWC, Science 2017



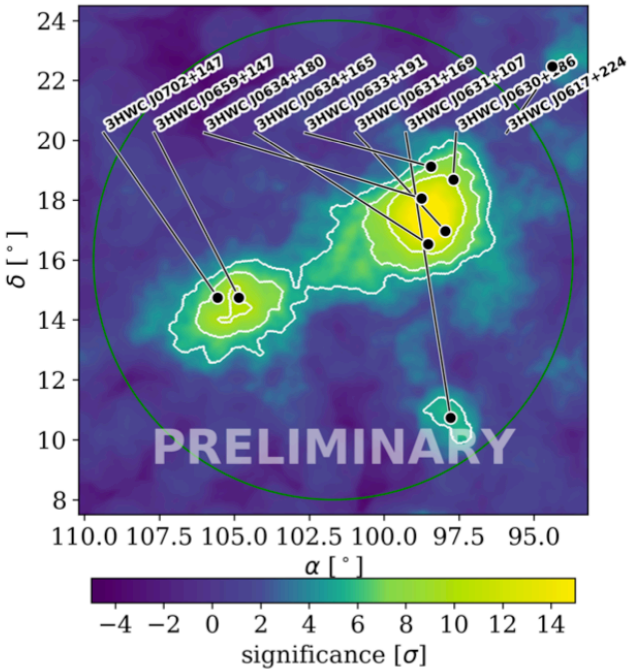


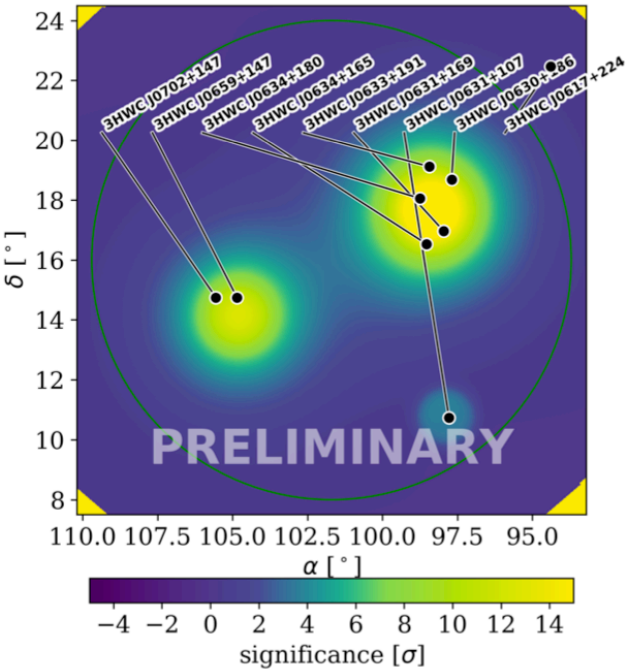


Geminga and Monogem : about 5 deg ext

- Assuming emission from electrons diffusing in the ISM, then extension is a direct measurement of particle diffusion $\theta(20\text{TeV}) \propto \sqrt{[D(100\text{TeV})]}$
- $D(100\,\text{TeV}) = (4.5 \pm 1.2)\ 10^{27}\ \text{cm}^2/\text{s}$, roughly 100 times smaller than diffusion from B/C ratio

Geminga and Monogem in Pass 5





Source Name	$K(dE/dt \to e^- e^+)$	$\log_{10} D_0$ [cm^2/s]	α_e	TS
Geminga	$(6.3 \pm 0.9) \times 10^{-2}$	$(2.602 \pm 0.008) \times 10$	1.11 ± 0.09	834.73
Monogem	$(4.3 \pm 0.6) \times 10^{-2}$	$(2.616 \pm 0.007) \times 10$	1.10 ± 0.11	363.13

PWN Halos - PSR J0359+5414

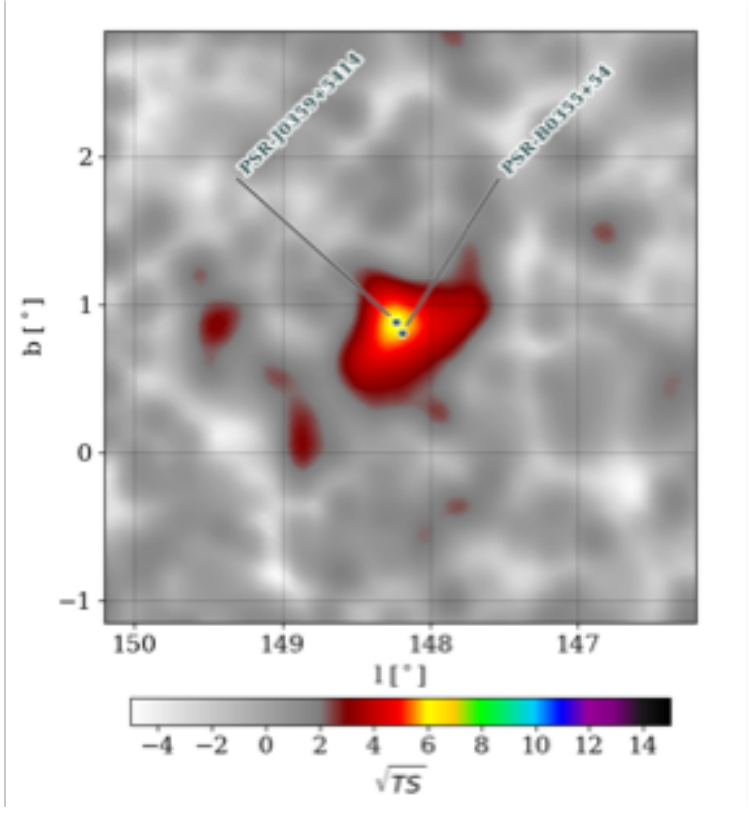
2321 day map

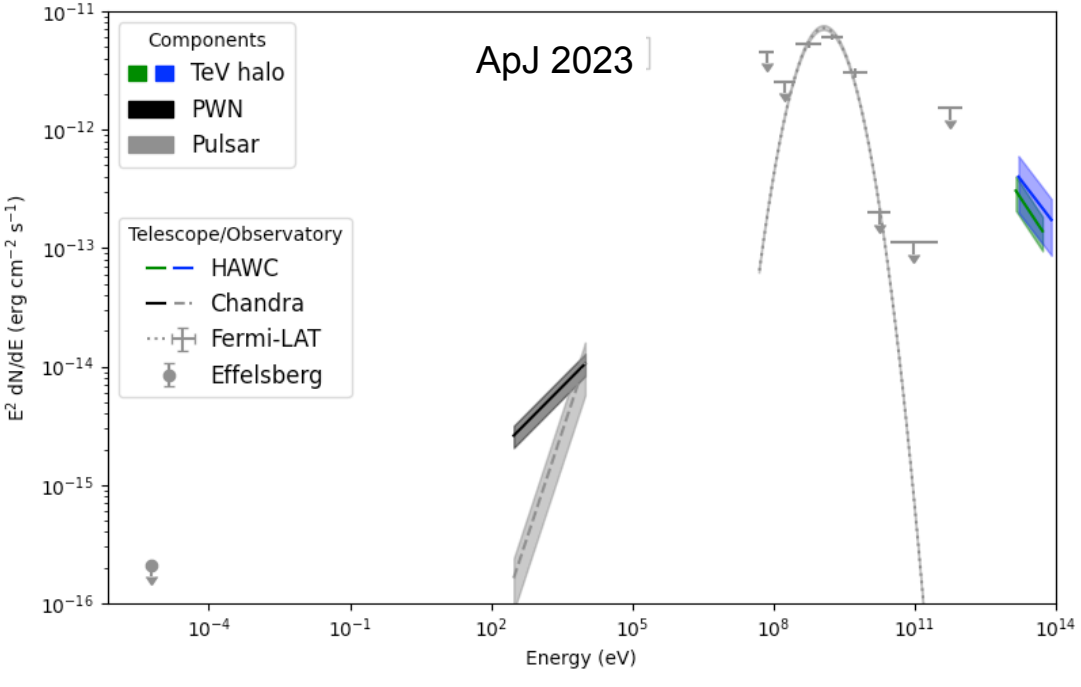
PSR J0359+5414 - Newly discovered TeV Halo

Outer galaxy, isolated, radio quiet

Age = 75kyr

High Spin-down power: 10^{36} ergs/s






Looking for TeV photons from the Sun

The rise of the TeV Sun.

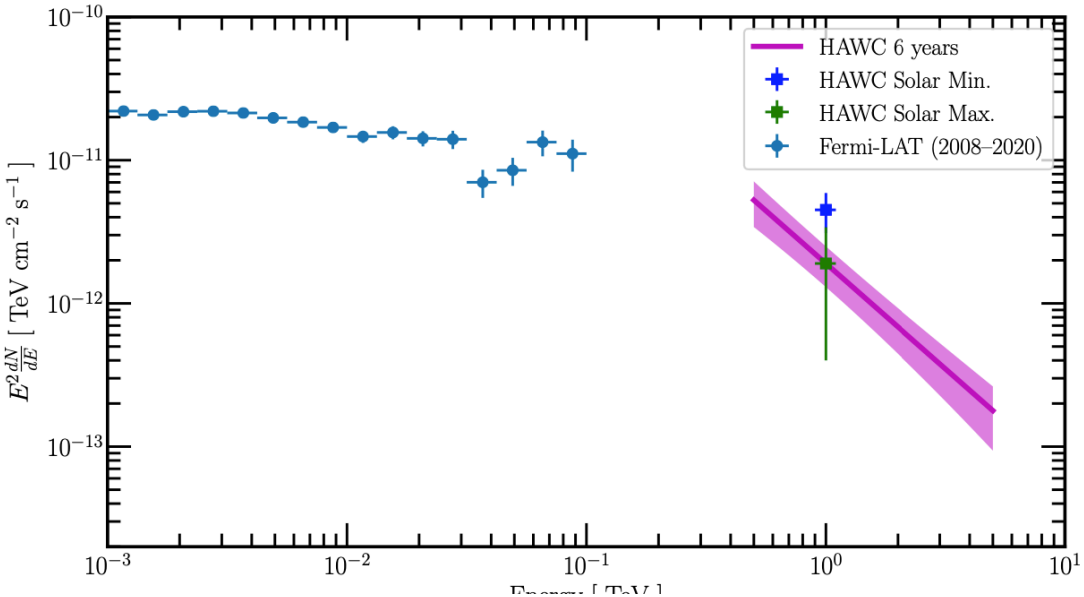
HAWC, ApJ 2022

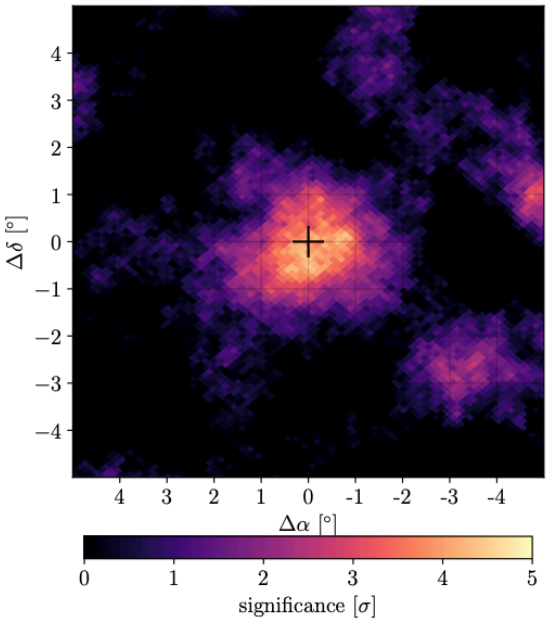
Fermi sees the sun up to ~100 GeV

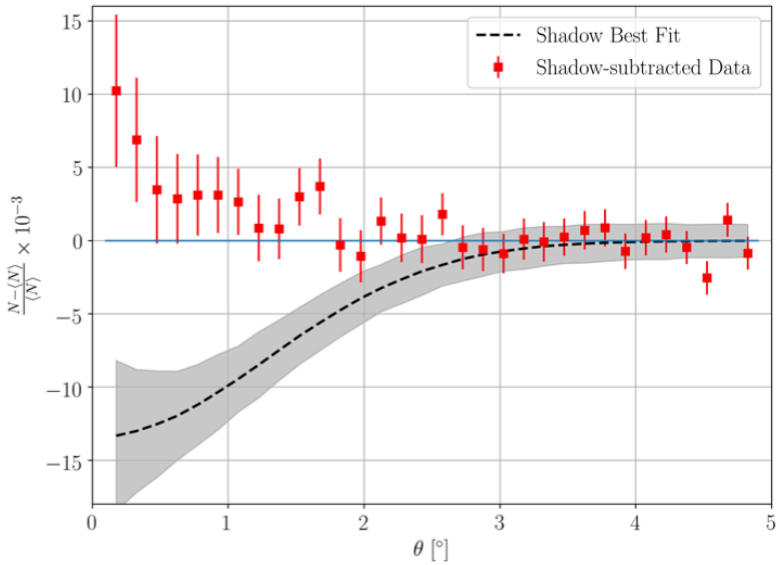
Correlated to solar cycle. Higher flux at Solar Min

Emission mechanism thought to be from CR hadrons interacting with the atmosphere of the sun

Not necessarily in the limb







Anticorrelation with solar activity

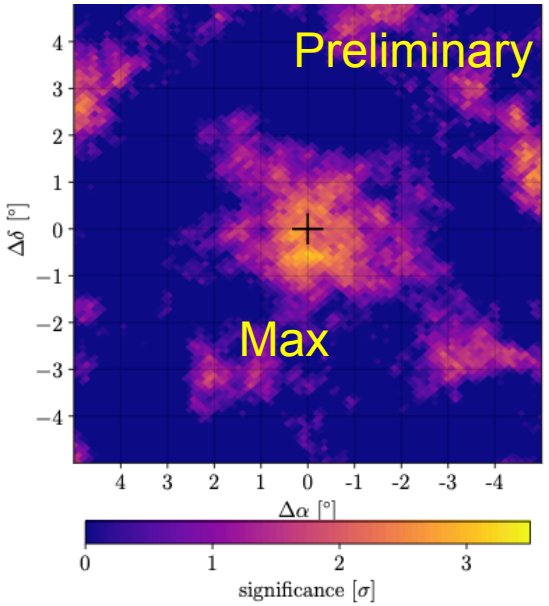
In HAWC PL index 3.62

6.1 yr of data

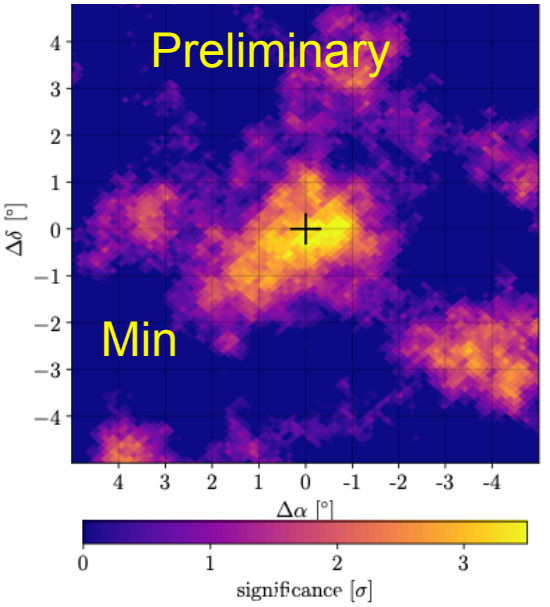
6,3 sigmas

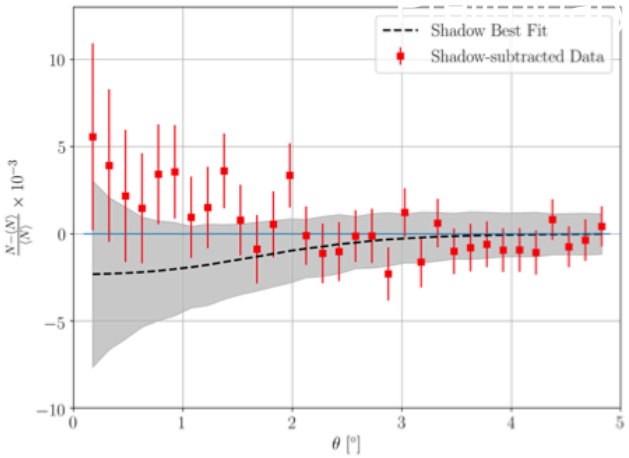
Solar Max and Solar Min

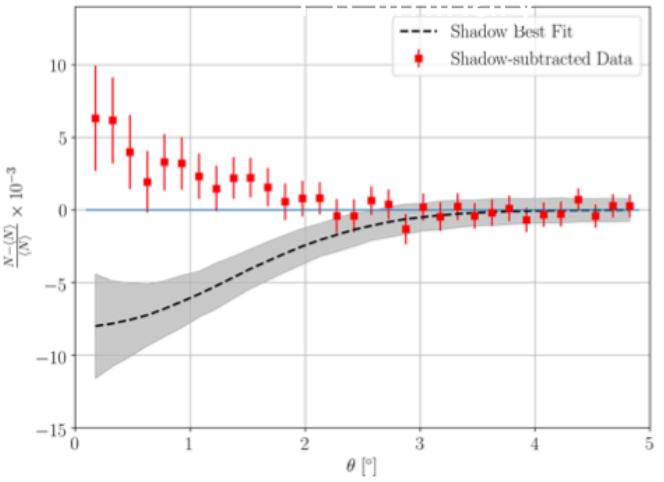
HAWC, ApJ 2022



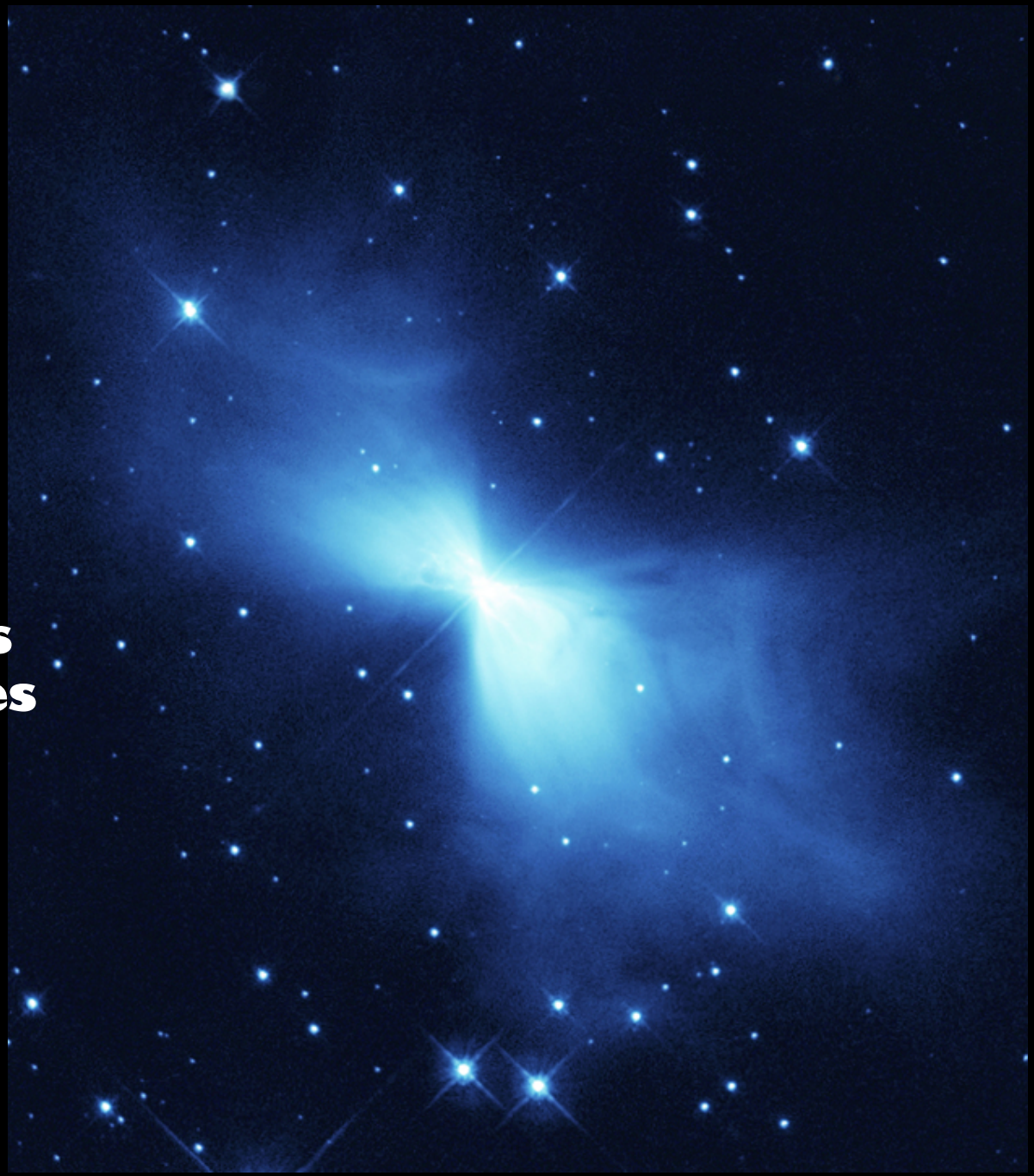
Overall
3.5σ vs 4.9 σ





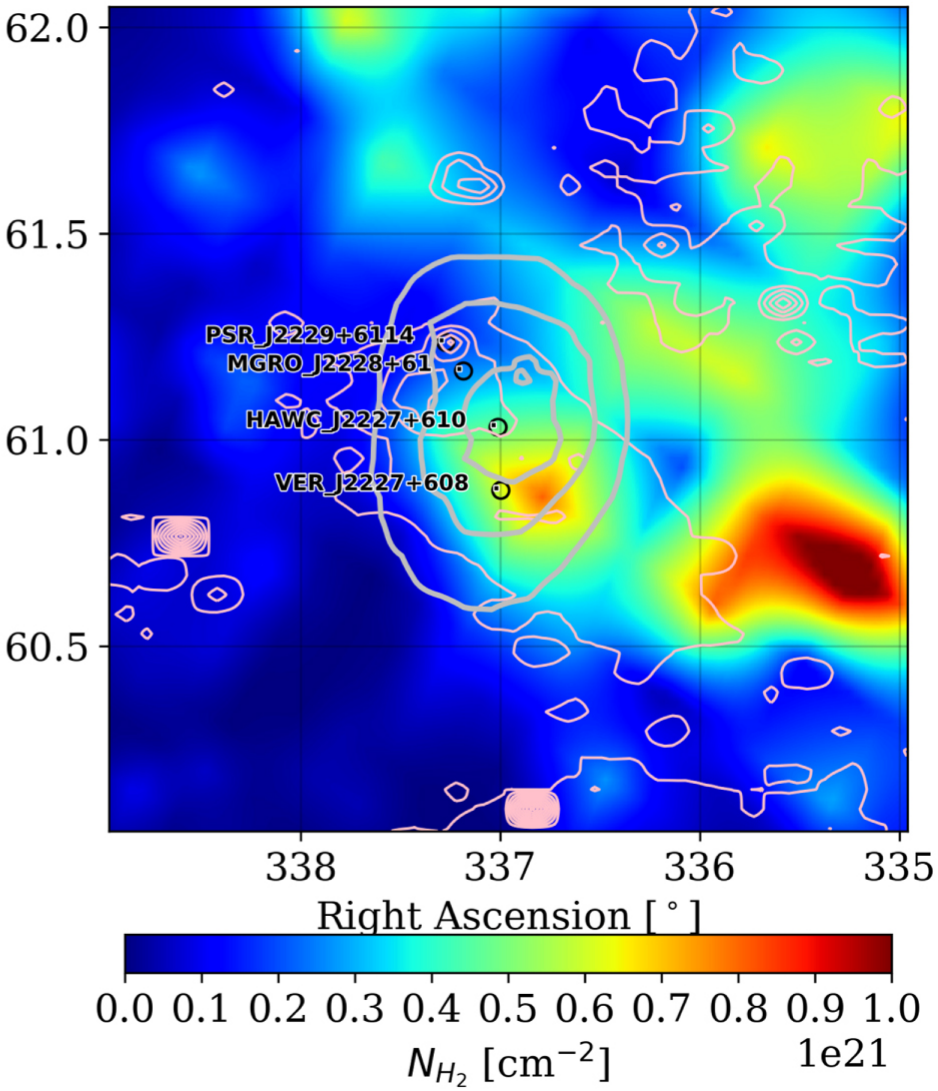


Observations of SNRs and PeVatron candidates



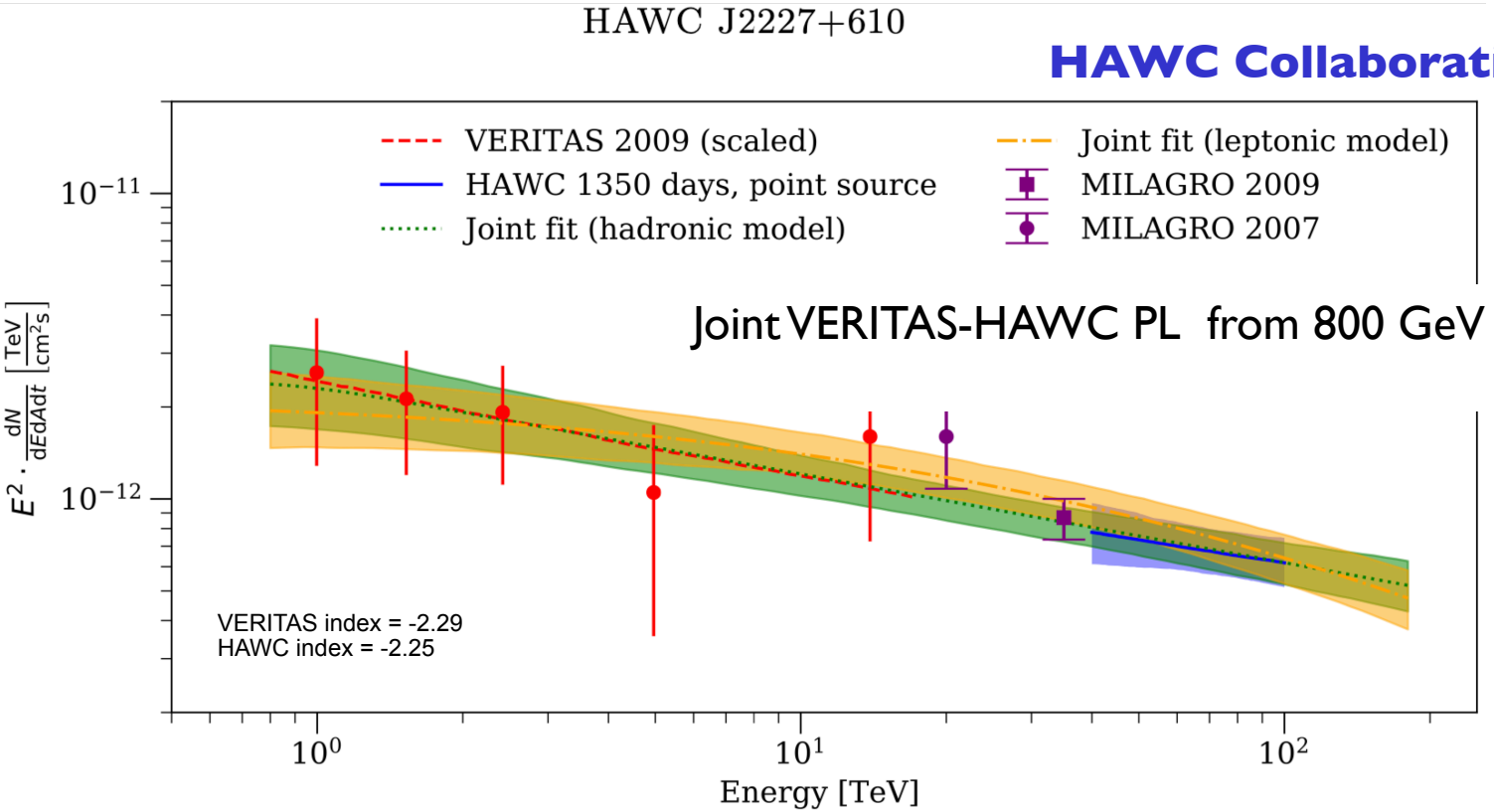
SNR G106.3+2.7: Galactic PeVatron ?

- 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 gamma rays
- Boomerang Nebula is contained in the remnant
- VERITAS source (energy range 900 GeV – 16 TeV)
- HAWC emission pointlike, 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



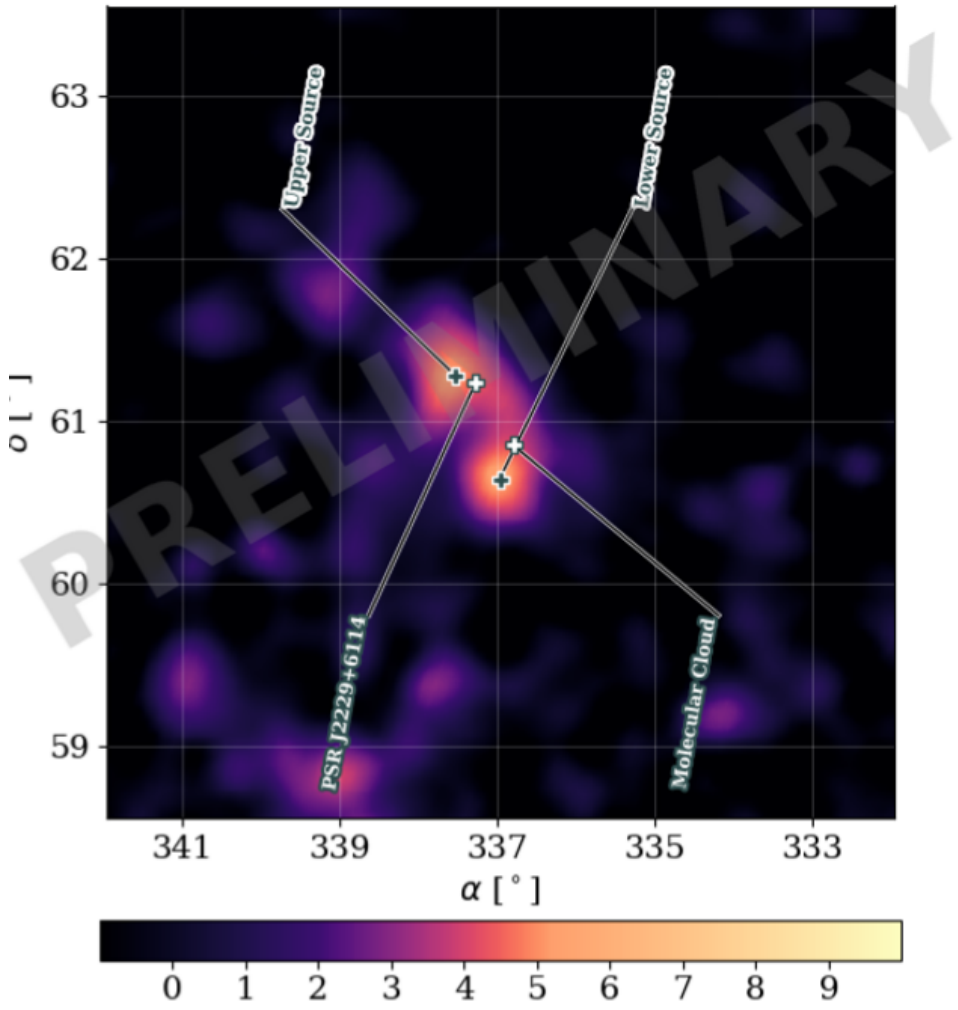
Joint VERITAS-HAWC PL from 800 GeV to 180 TeV

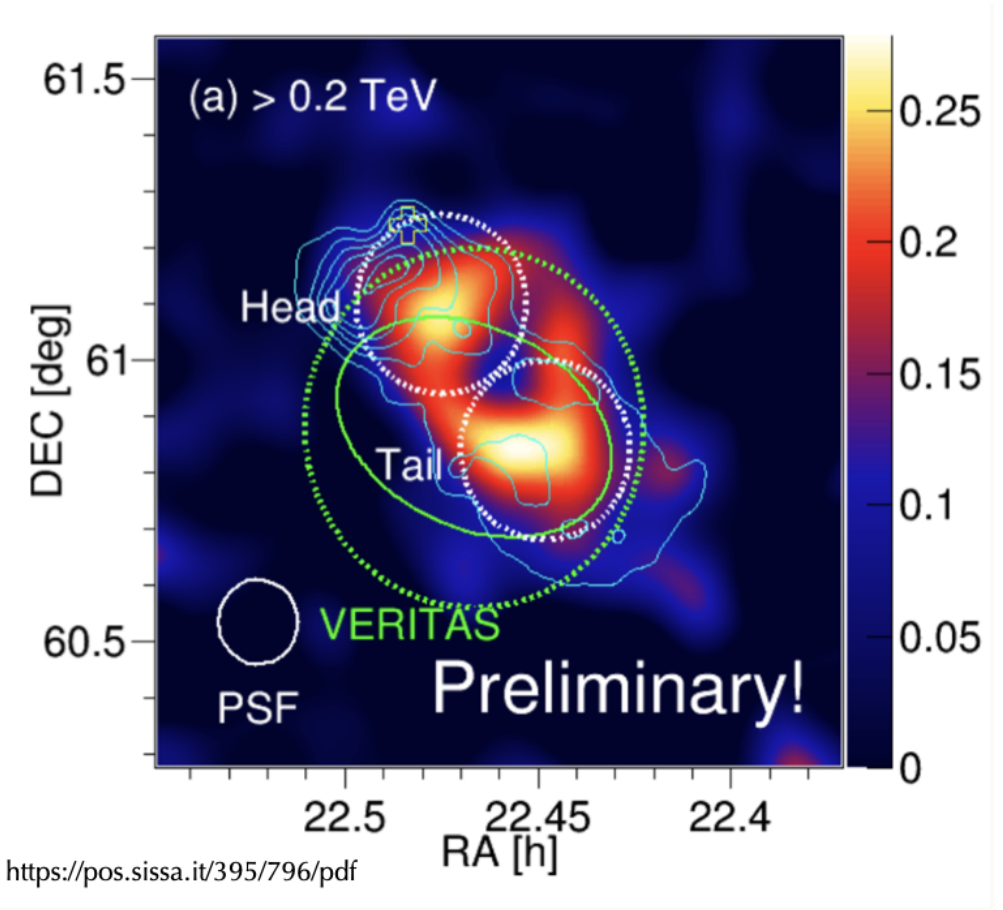
Gamma PL : 2.29, Lower limit on gamma Ecut = 120 TeV

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

Wp = 10^{48} $(n/50)^{-1}$ erg

HAWC J2227+ 610 (Boomerang region)

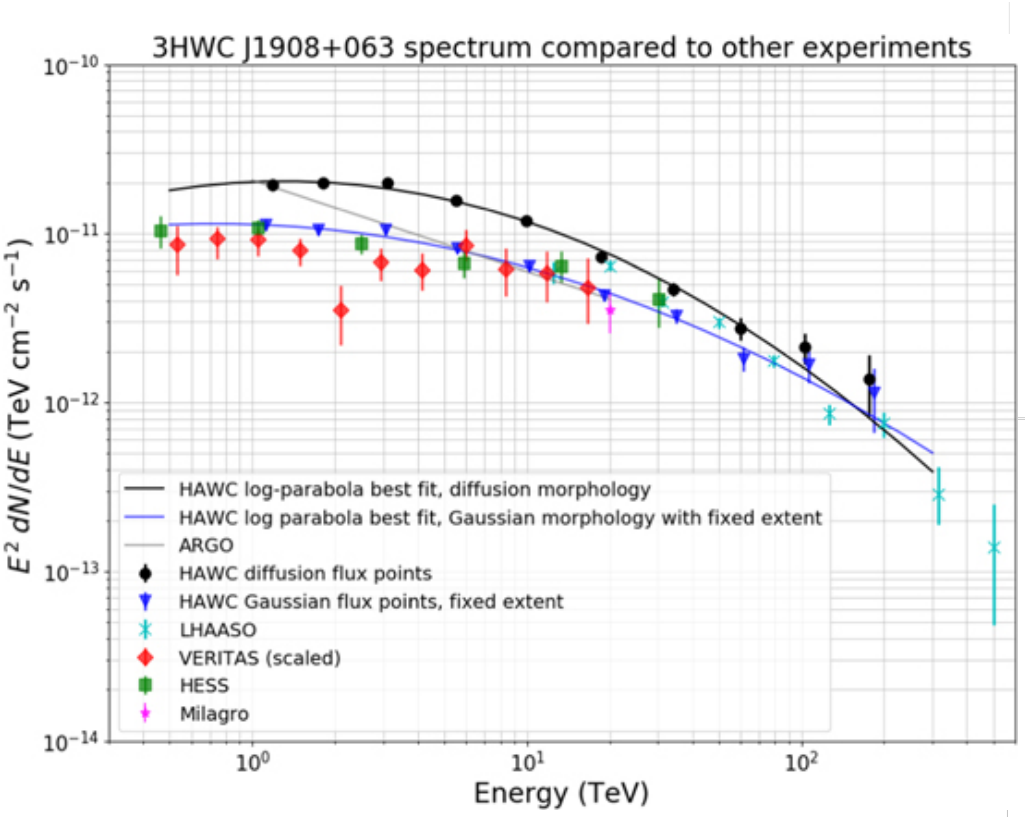


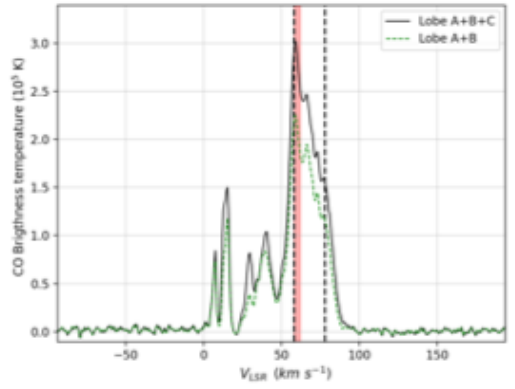


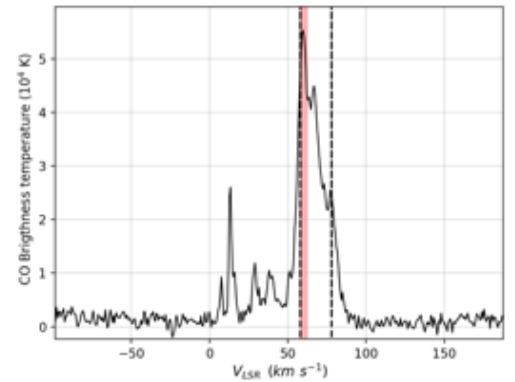
https://pos.sissa.it/395/796/pdf

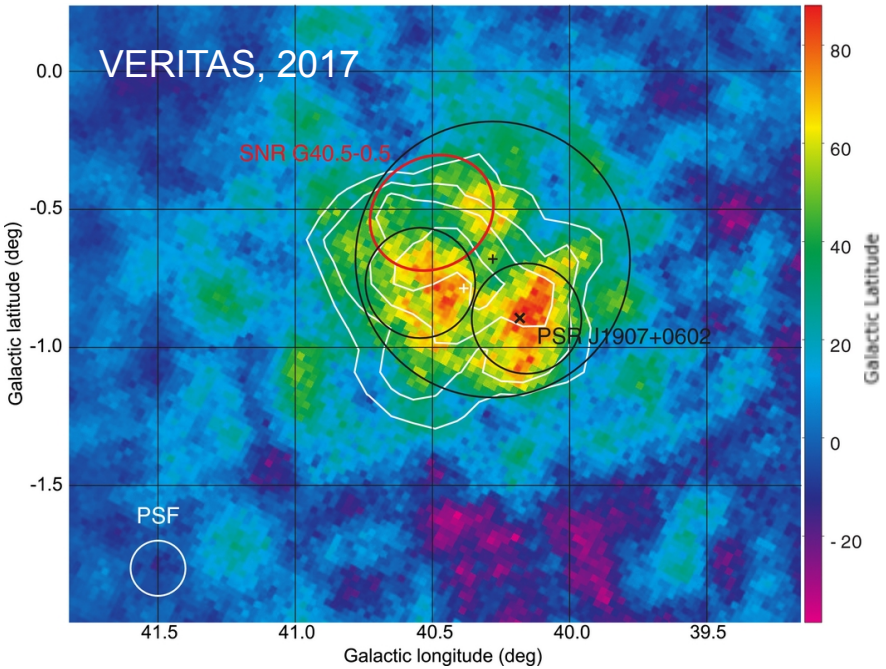
HAWC J1908 +063

l= 40° b= -0.79°

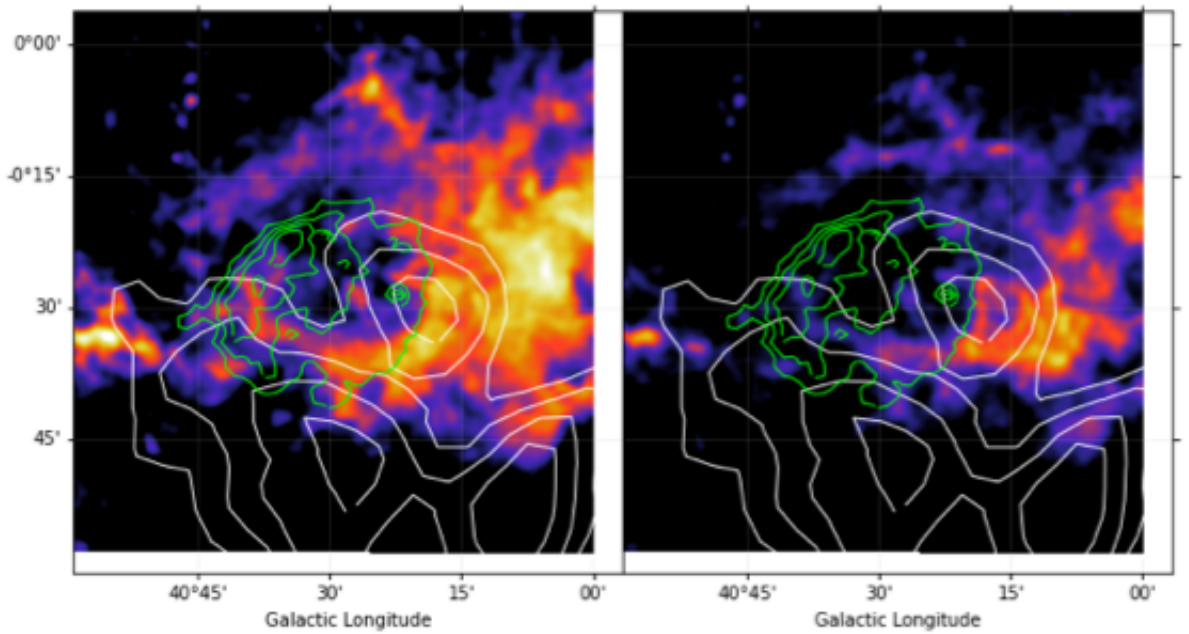




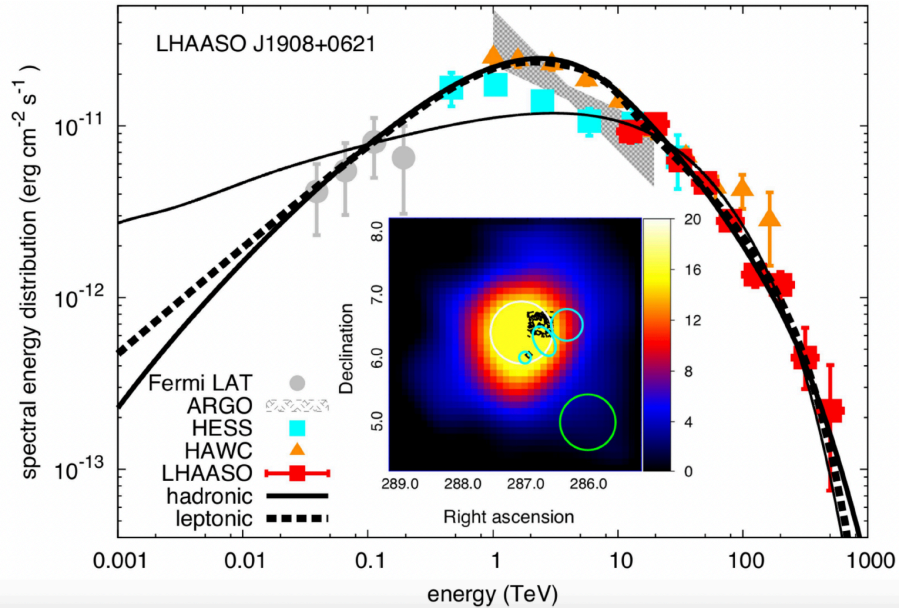


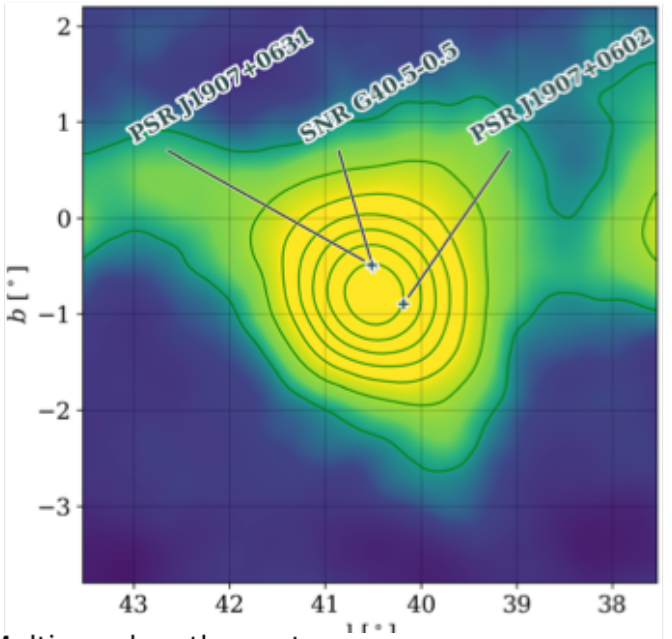


Crestan+ 2021

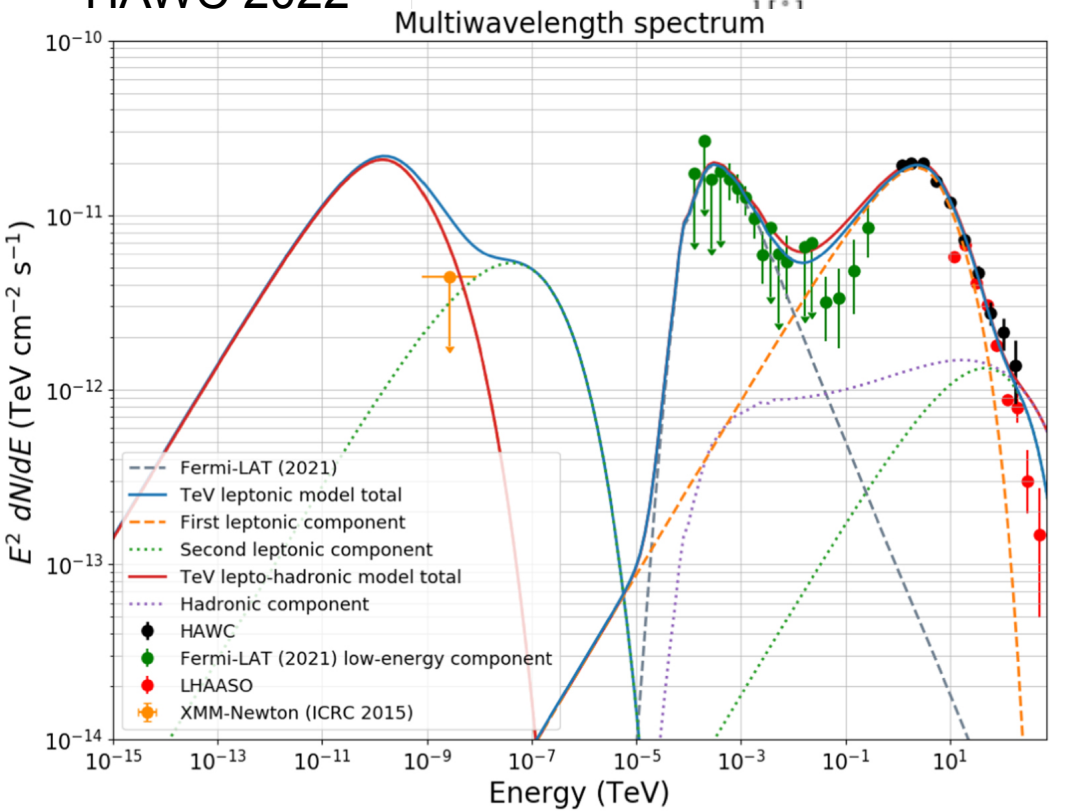


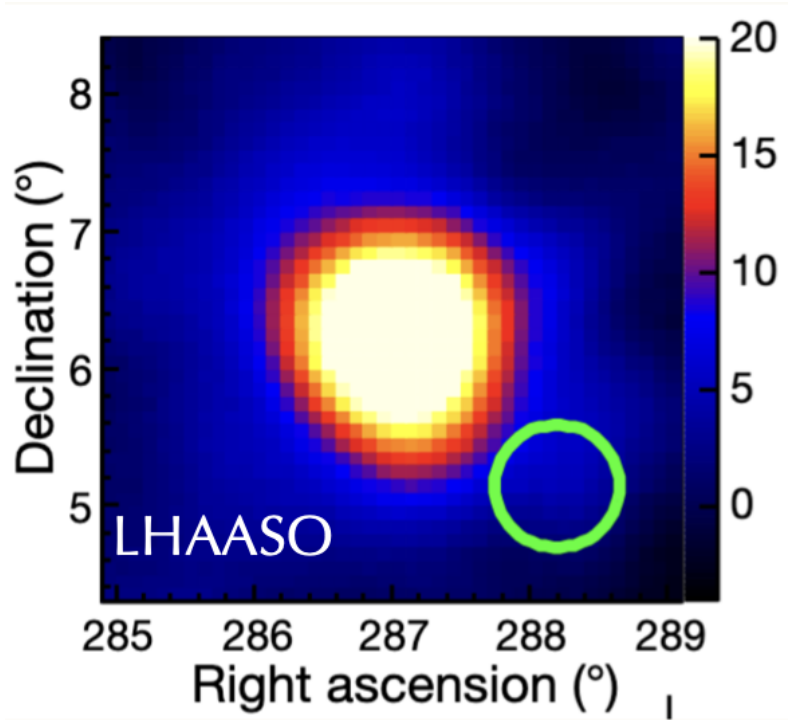
HAWC J1908 +063





HAWC 2022



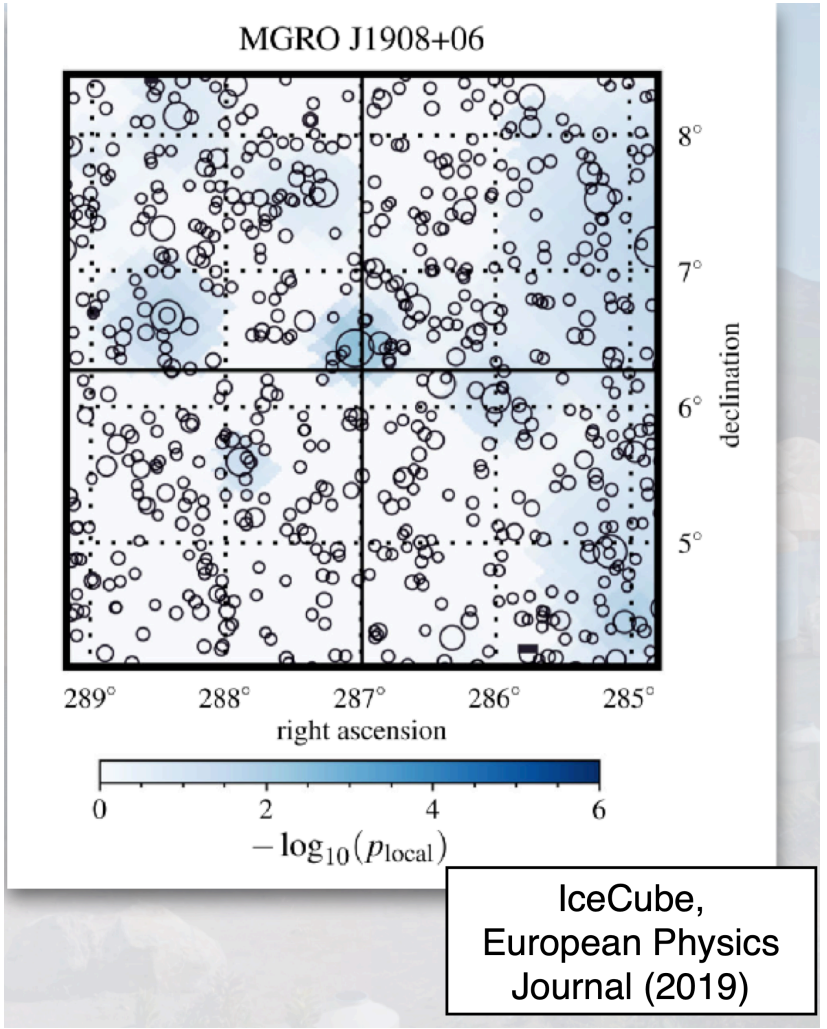


HAWC J1908+06 as neutrino source?

Some HAWC PeV candidates are promising neutrino sources

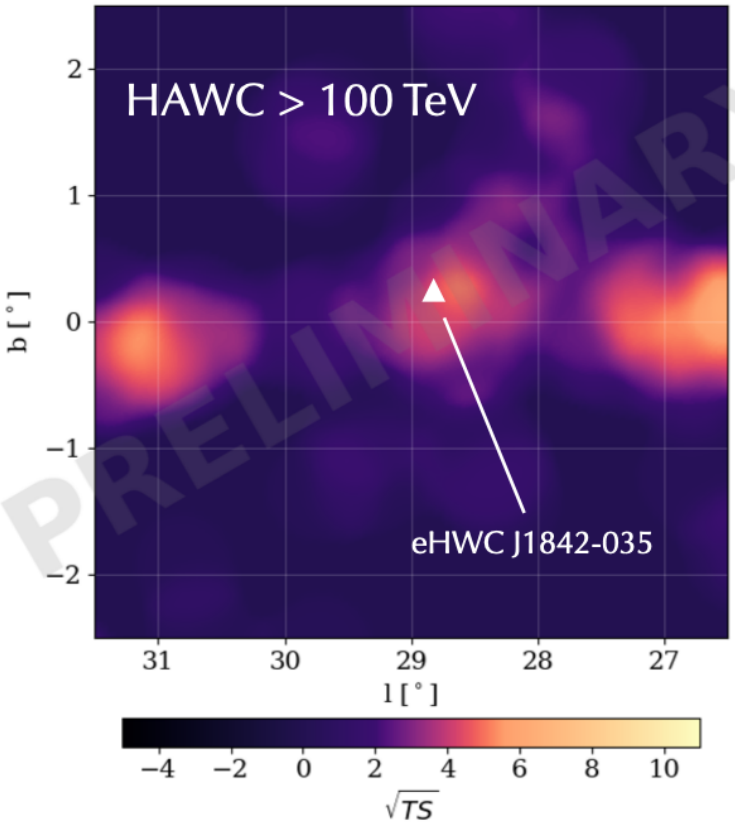
Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

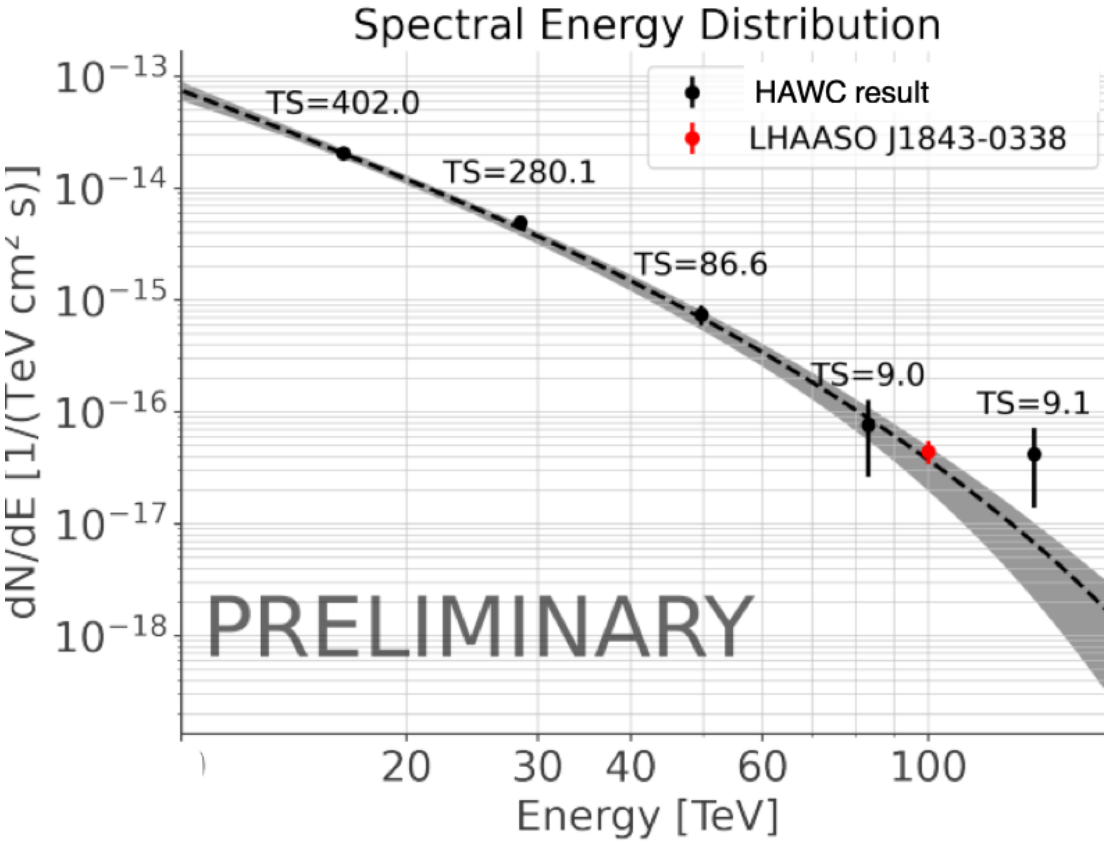
J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis



IceCube, European Physics Journal (2019)

eHWC J1842-035



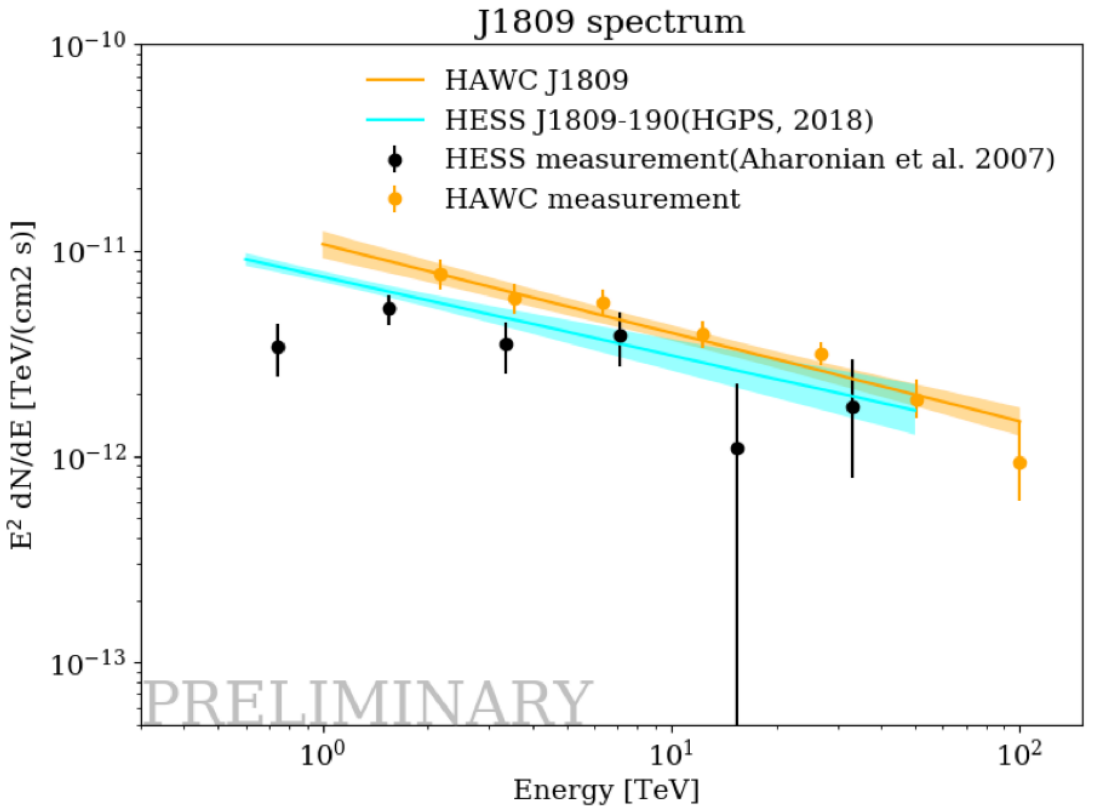


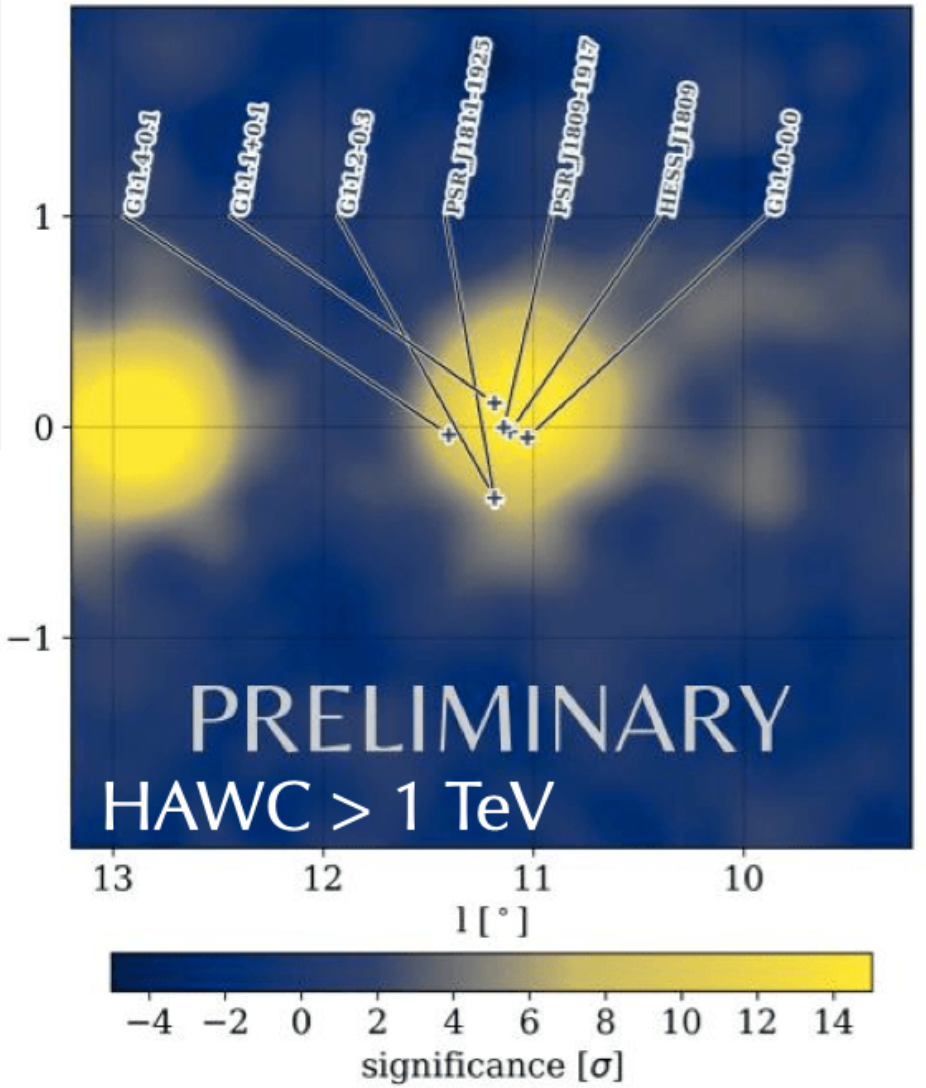
Complex morphology , 0.3-0.4 deg

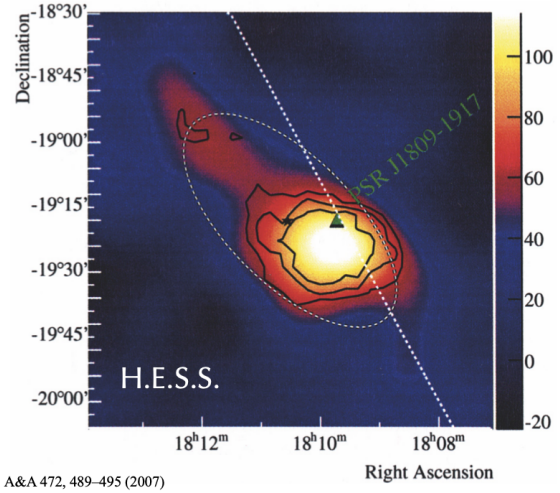
Maximum energy in HAWC > 100 TeV

Study ongoing

HESS J1809 -1917

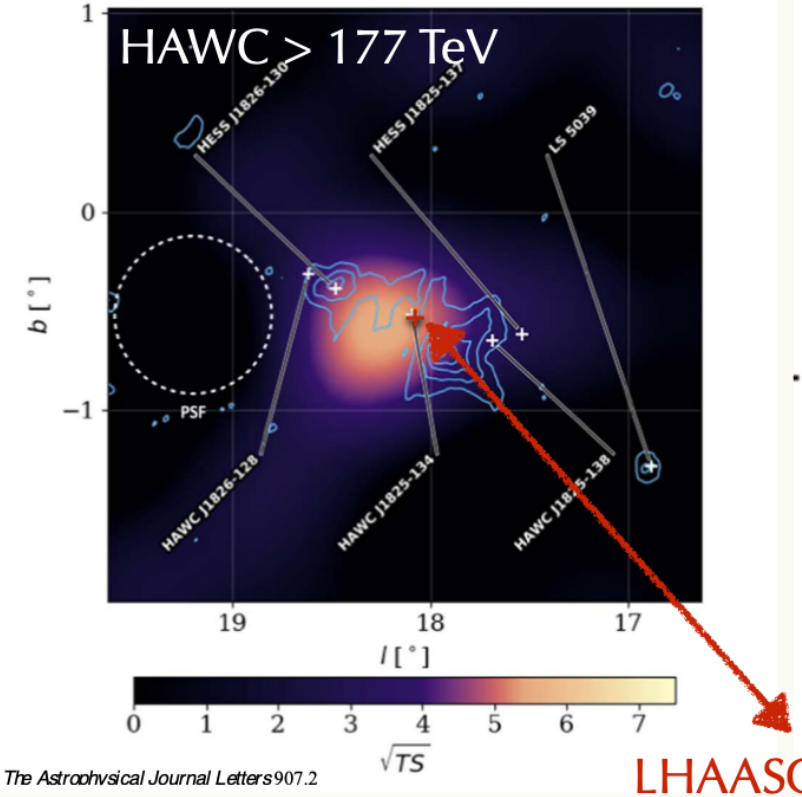


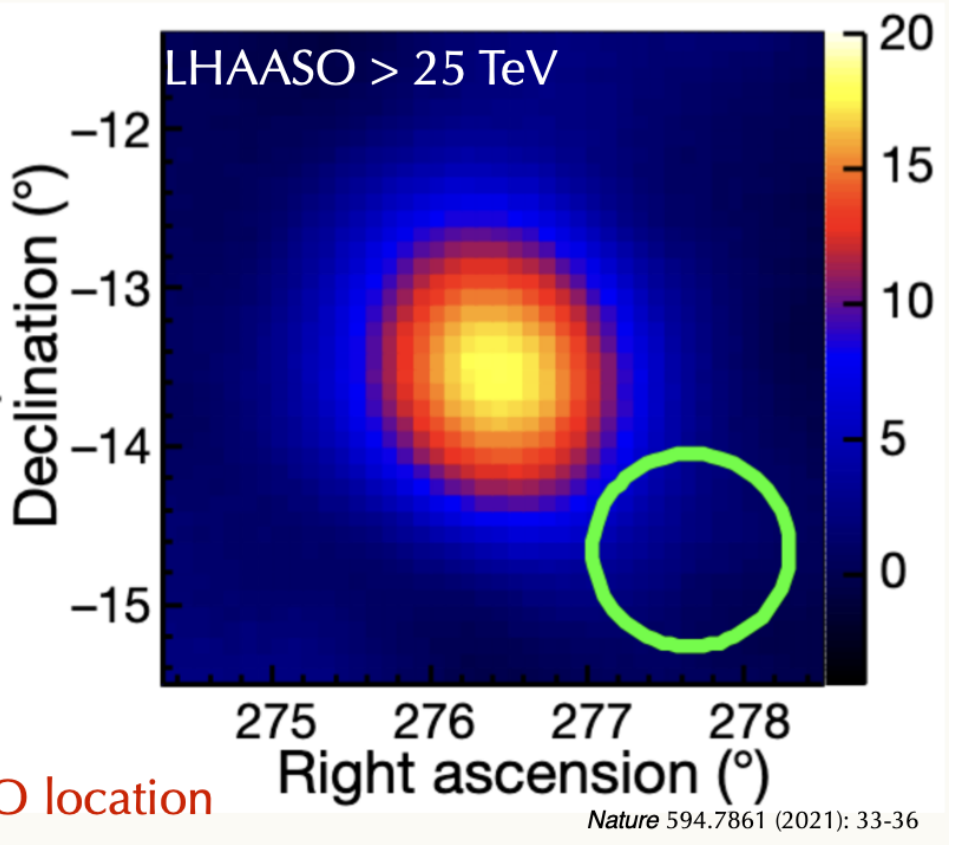




A&A 472, 489–495 (2007)

eHWC J1825-134

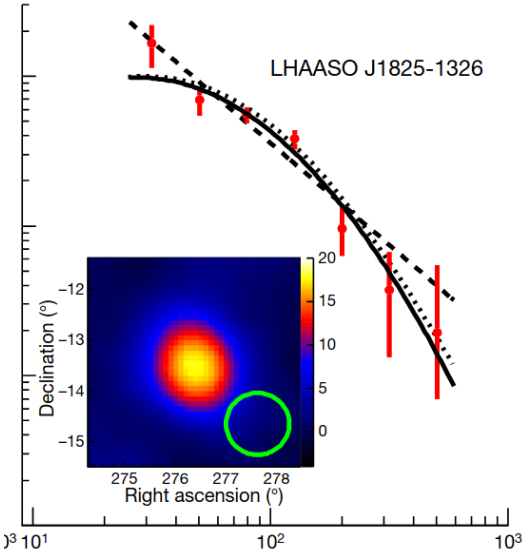




The Astrophysical Journal Letters 907.2

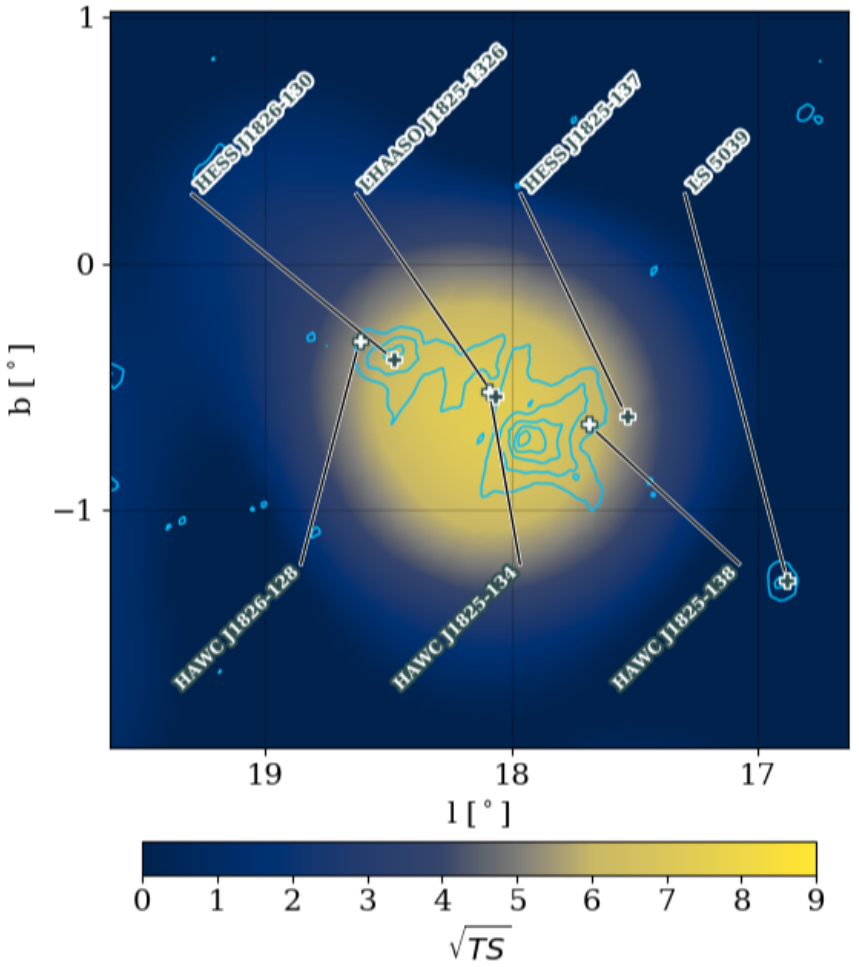
LHAASO location

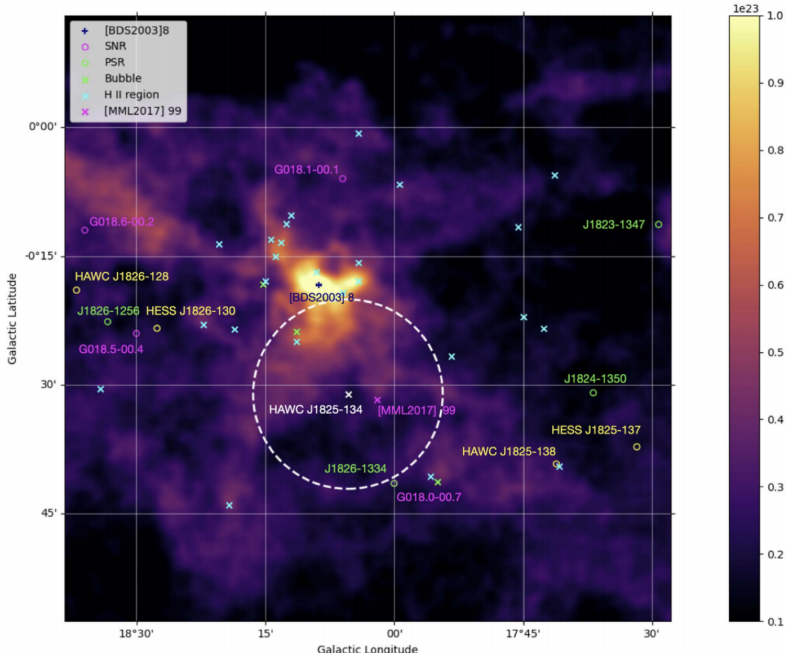
Nature 594.7861 (2021): 33-36



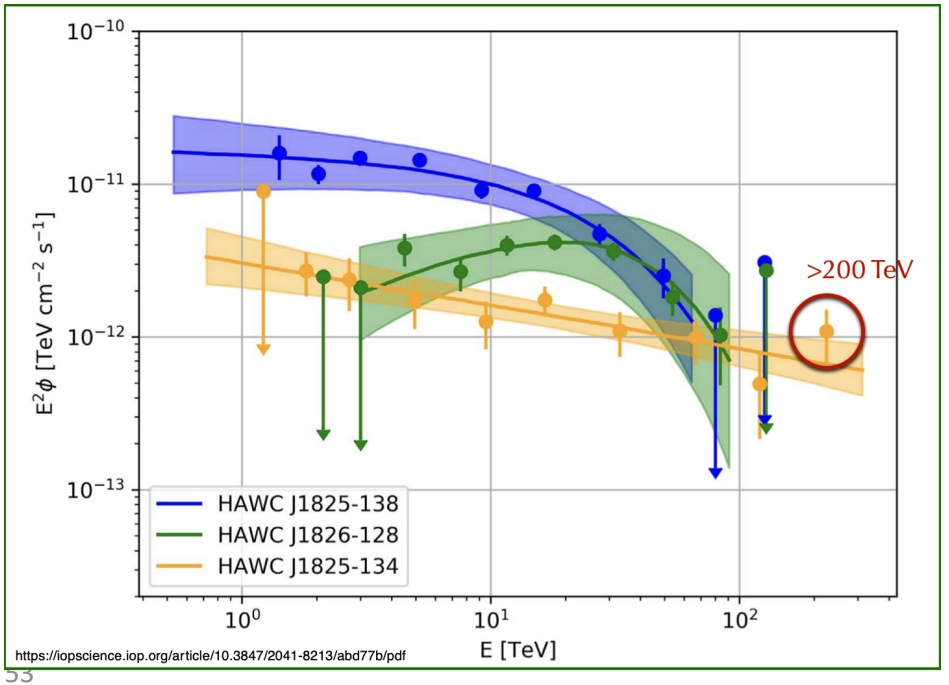
	HAWC	LHAASO
Location	R.A. 276.44° Dec. -13.42°	R.A. 275.45° Dec. -13.45°
Morphology	2 extended sources + 1point source	0.3 ° extension template
Maximum measured energy	>200 TeV	420 TeV
Origin of TeV emission	Proton accelerated by SFR Electron accelerated by PSR J1826-1334	

Multiple Sources

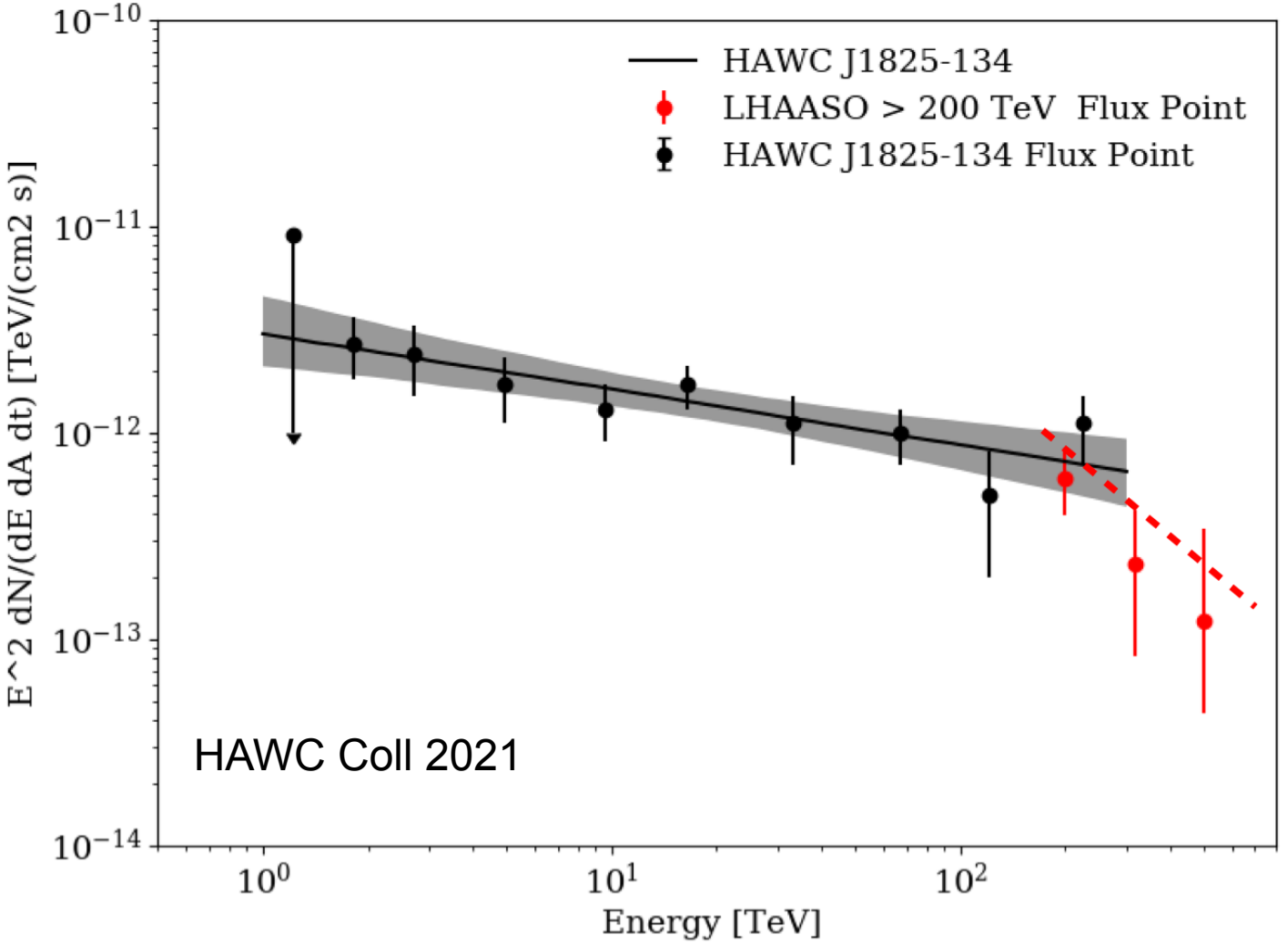




Above 177 TeV

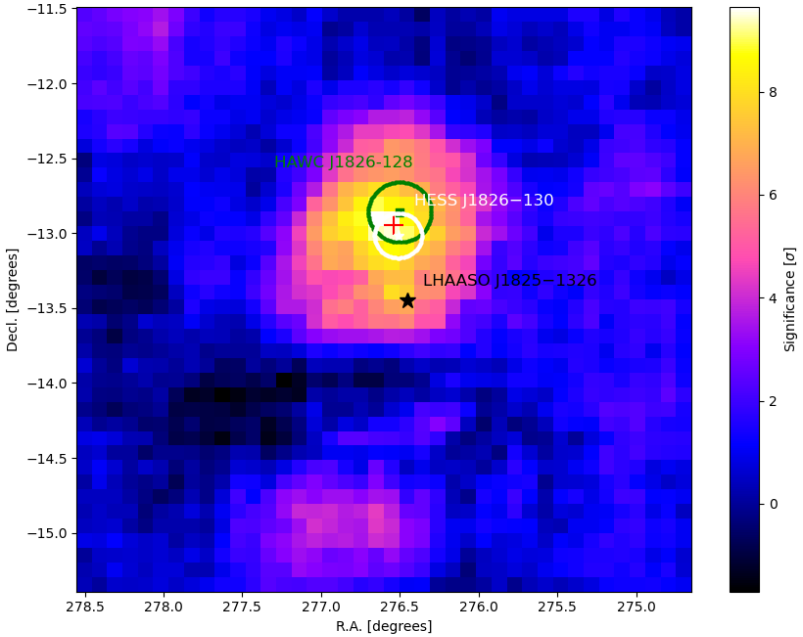


HAWC J1825-134 and LHAASO J1825-136 above 200 TeV



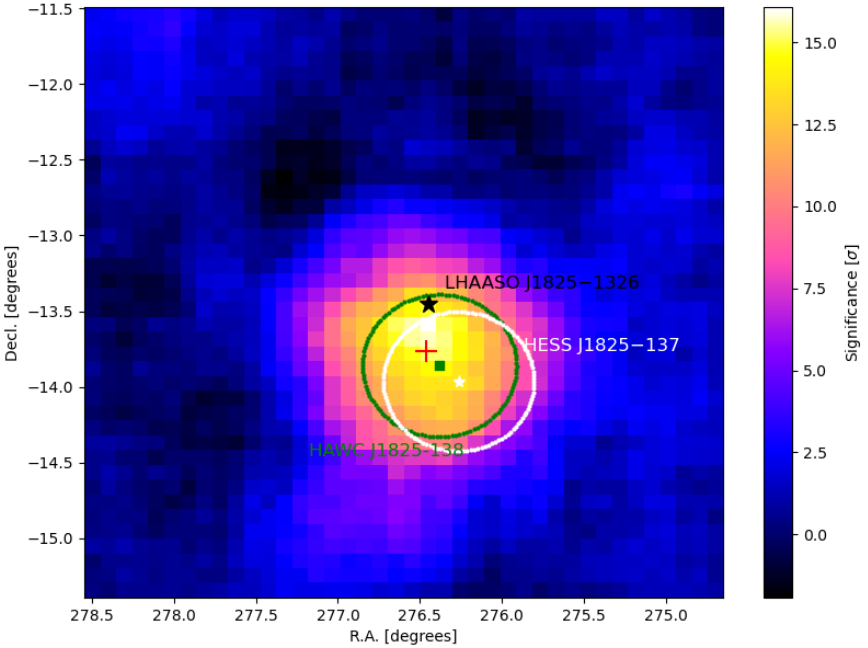
LHAASO J1826-1256 & J1825-1345(>25 TeV)

LHAASO J1826-1256



TS=214.08

LHAASO J1825-1345



TS=393.73

LHAASO J1826-1256 & J1825-1345 (>100 TeV)

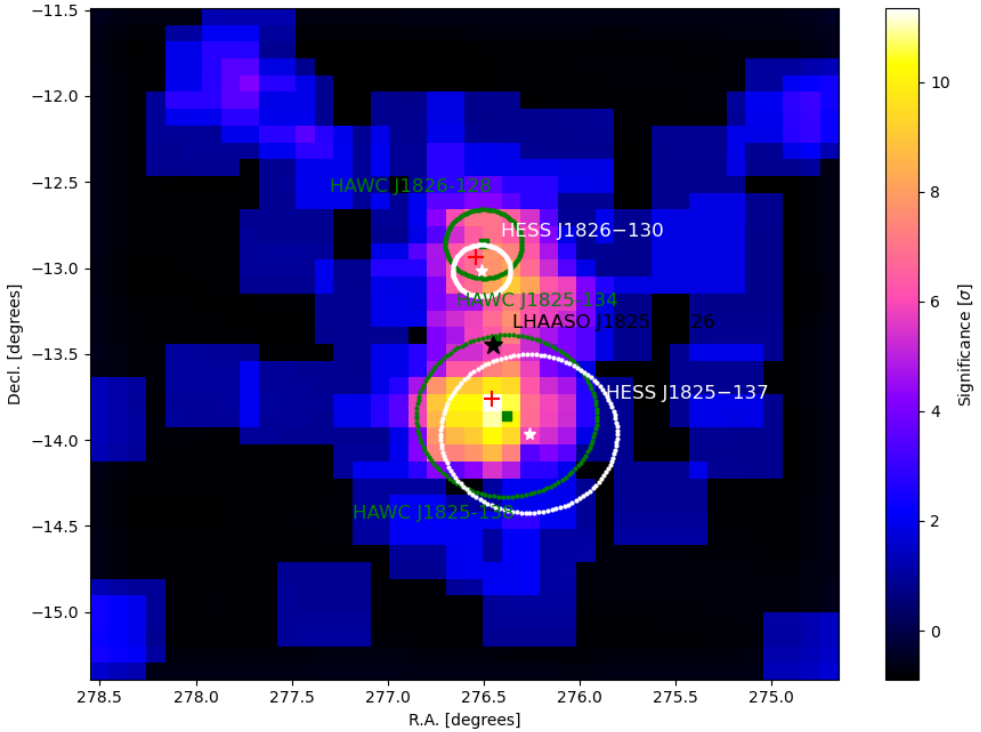
LHAASO J1825-1326

LHAASO J1826-1256

TS=100.95

LHAASO J1825-1345

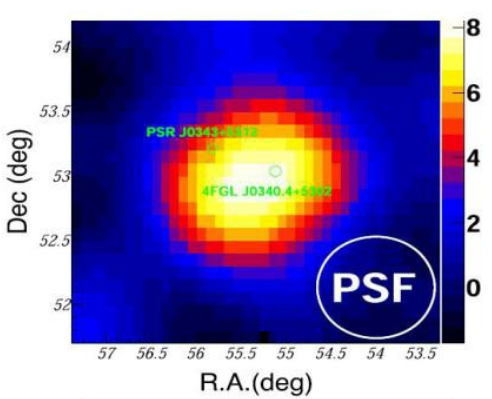
TS=164.88

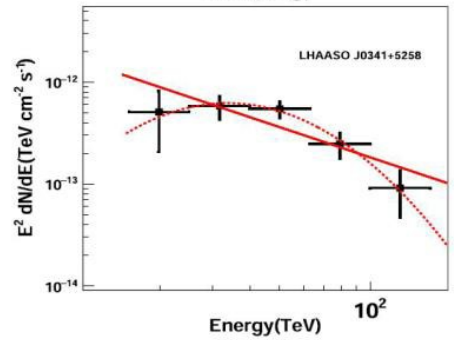


New Source Discovery

- WCDA has accumulated data for 16 months
- KM2A for 12 months
- LHAASO catalog Ver-1 will be published soon with many new VHE/UHE sources discovered

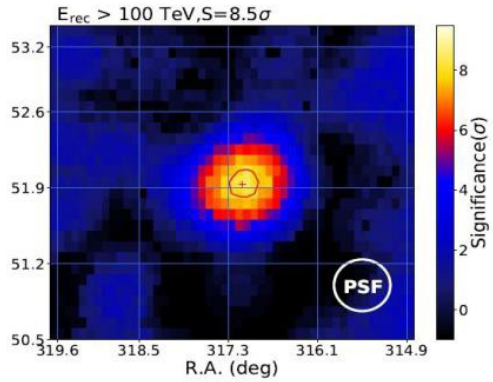
LHAASO J0341+5258

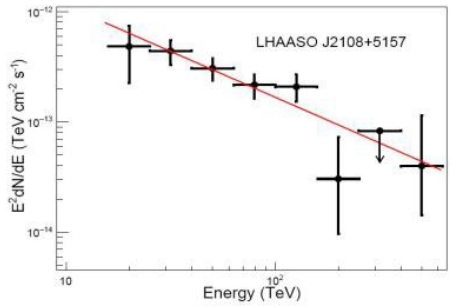




ApJL 917:L4 (2021)

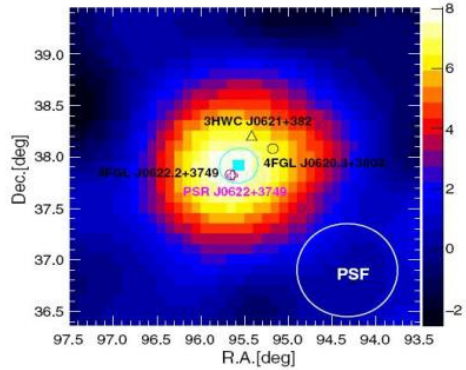
LHAASO J2108+5157

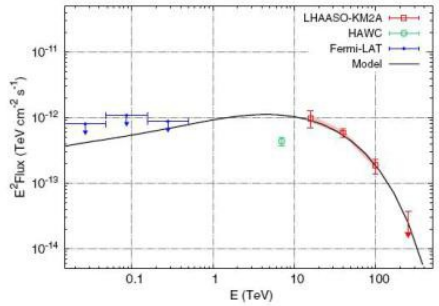




ApJL 919:L22 (2021)

Halo of PSR J0622 + 3749

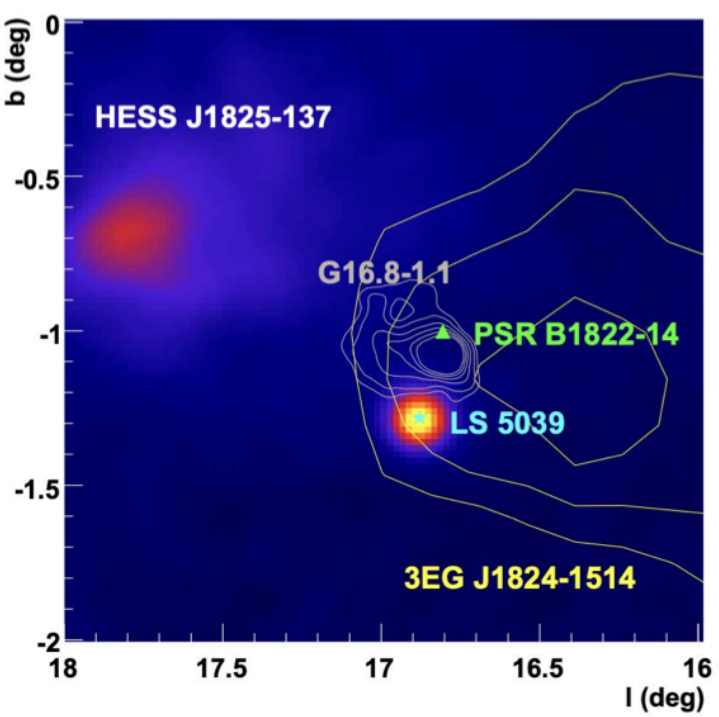


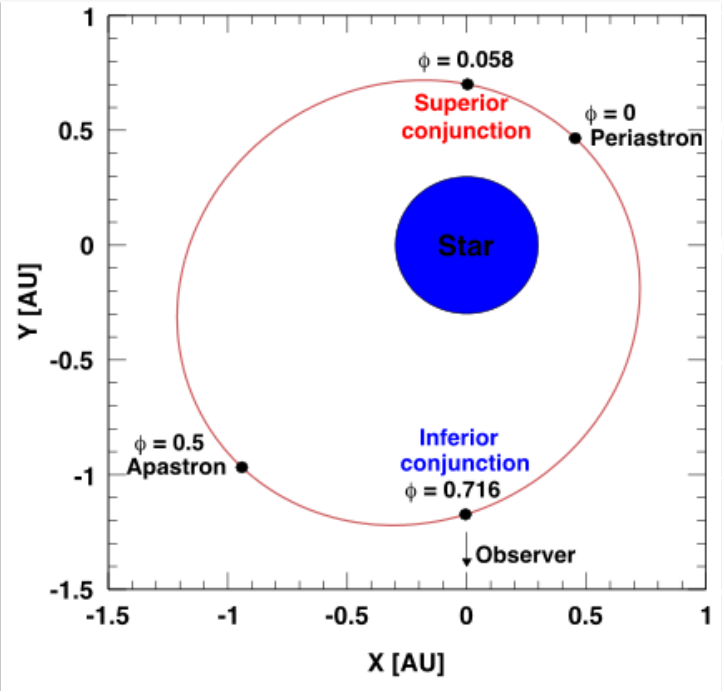


PRL 126:241103 (2021)

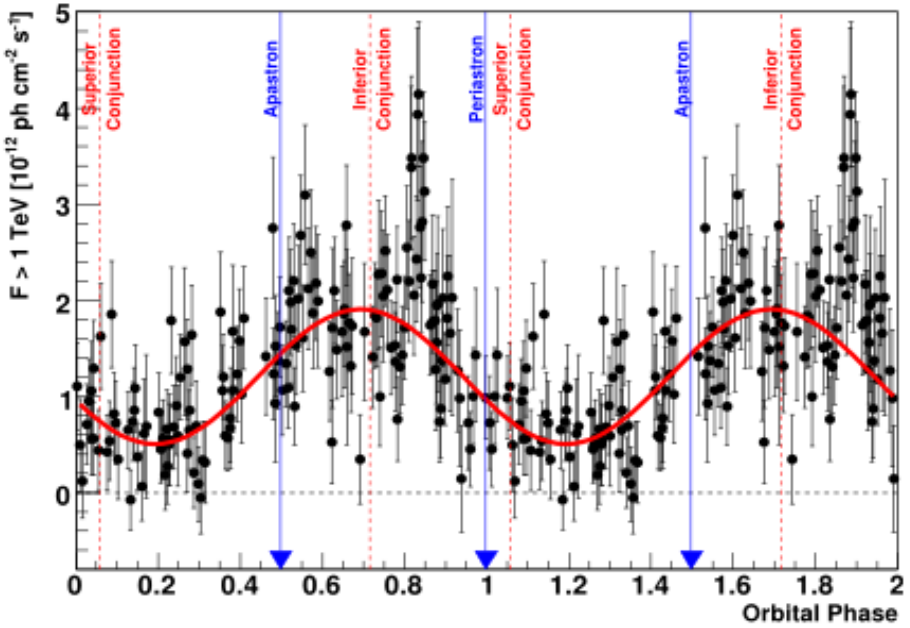
LS5039

- Either microquasar with relativistiv jet formation through matter accretion onto the compact object or acceleration resulting from the interaction between pulsar and star winds
- Distance = 3.5 kpc , O6.5V star and compact object with a mildly eccentric 3.9 day orbit. Mass companion star 23 M_o, mass compact object = 3.7 M_o
- From radio to TeV energies. Flux and spectral modulation as a function of its orbital period.





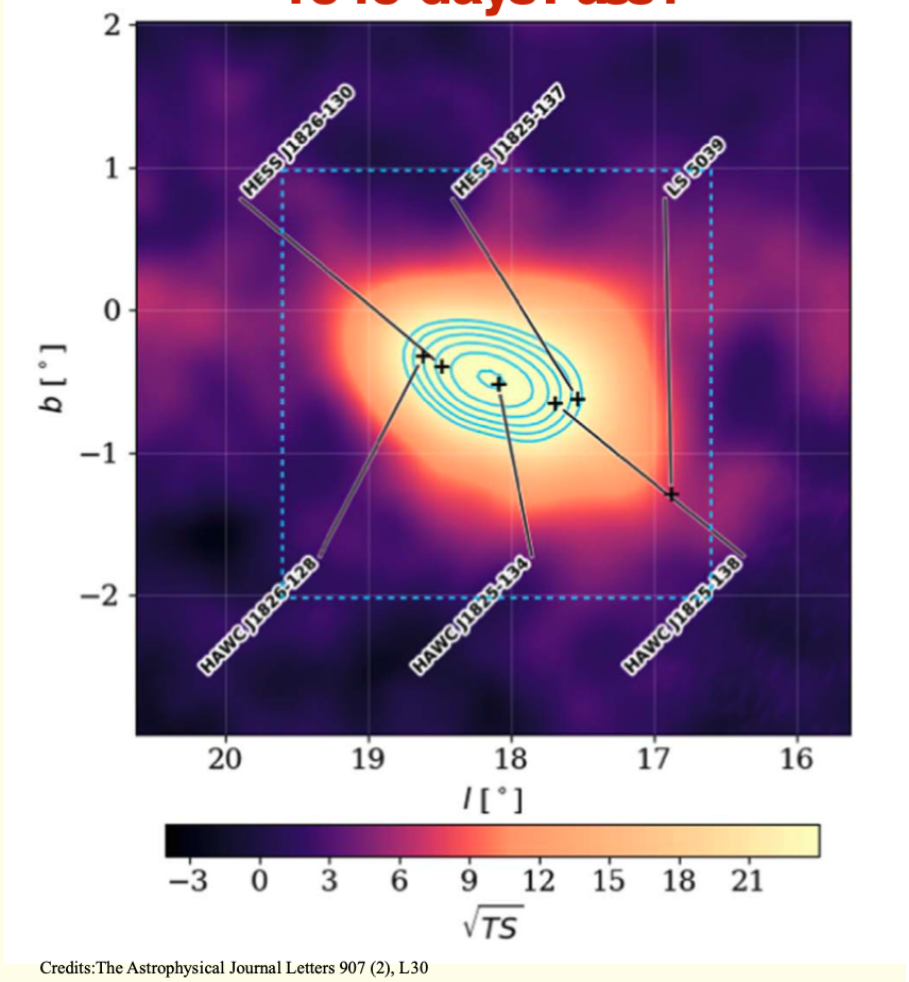
H.E.S.S. 2007 Astrophys Space Sci (2007) 309: 277–284



(Aharonian et al. 2005)

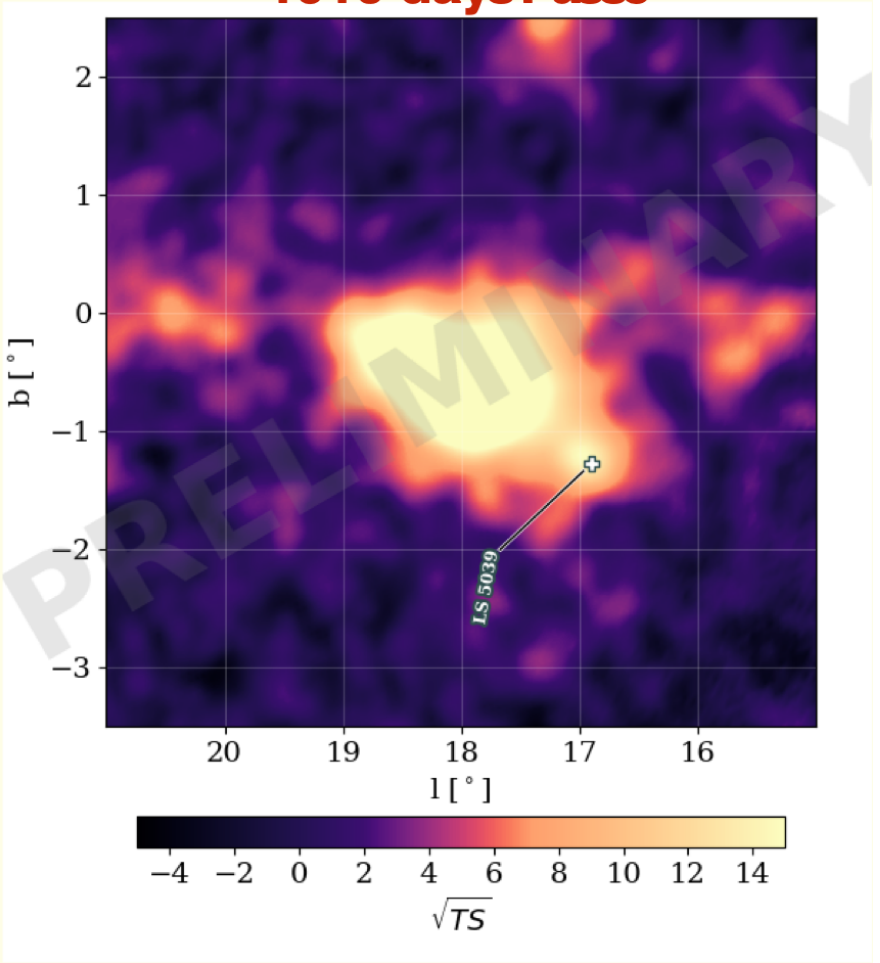
LS5039 region with Pass 5

1343 days Pass4



Credits:The Astrophysical Journal Letters 907 (2), L30

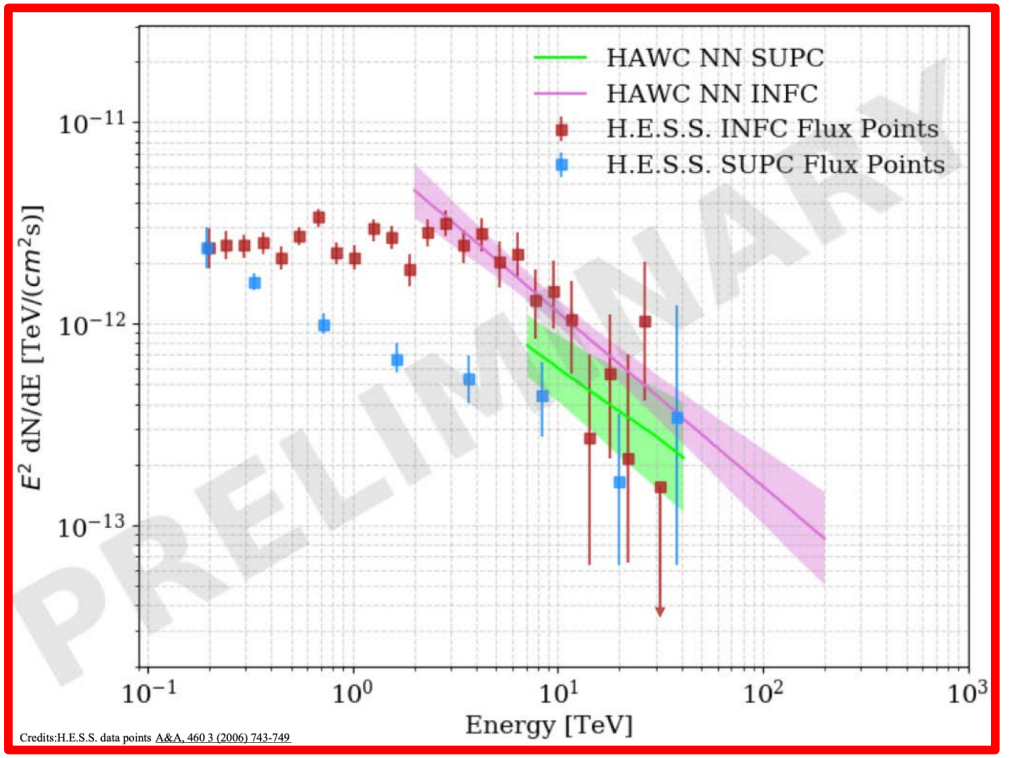
1910 days Pass5

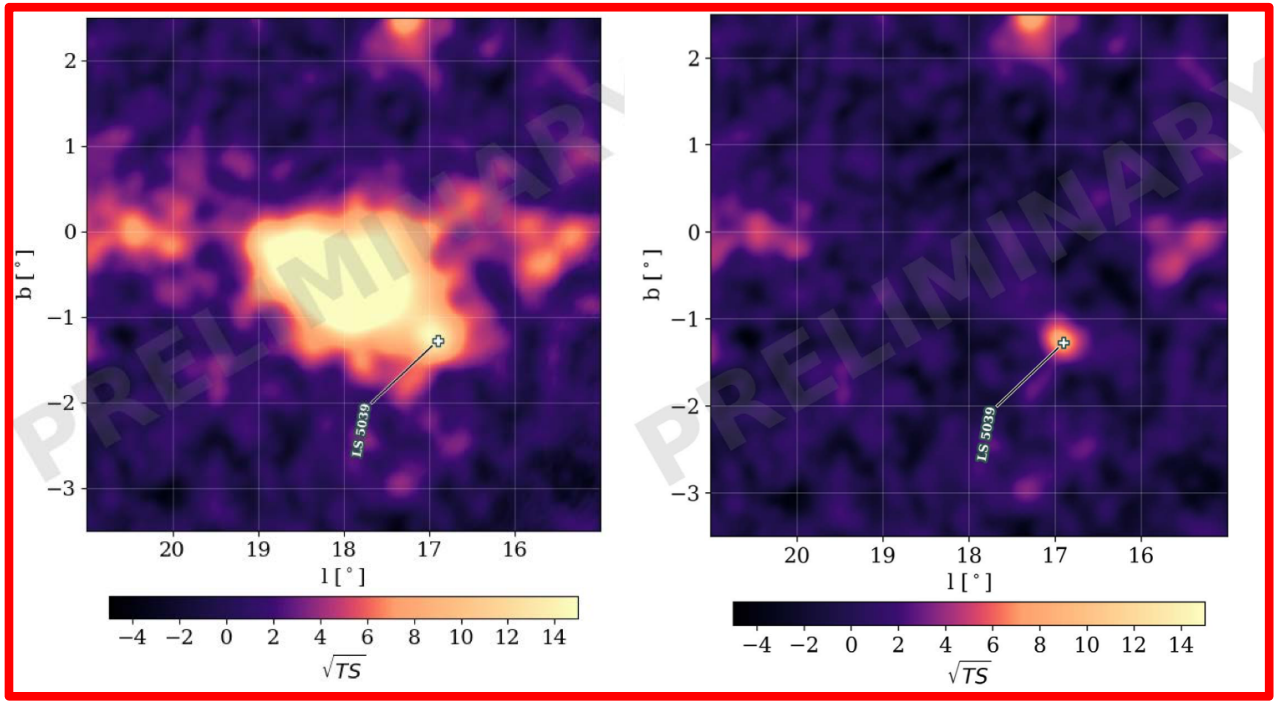


Dezhi Huang, ICRC 2023

LS5039 with HAWC

- 1910 days of data
- Simultaneously likelihood fit performed inside the region of interest
- Model includes diffuse background emission and all background sources
- About 8 σ
- Pure powerlaw preferred
- HAWC spectrum is located in between of H.E.S.S. Inferior conjunction (INFC) and Superior conjunction (SUPC)





Dezhi Huang, ICRC 2023