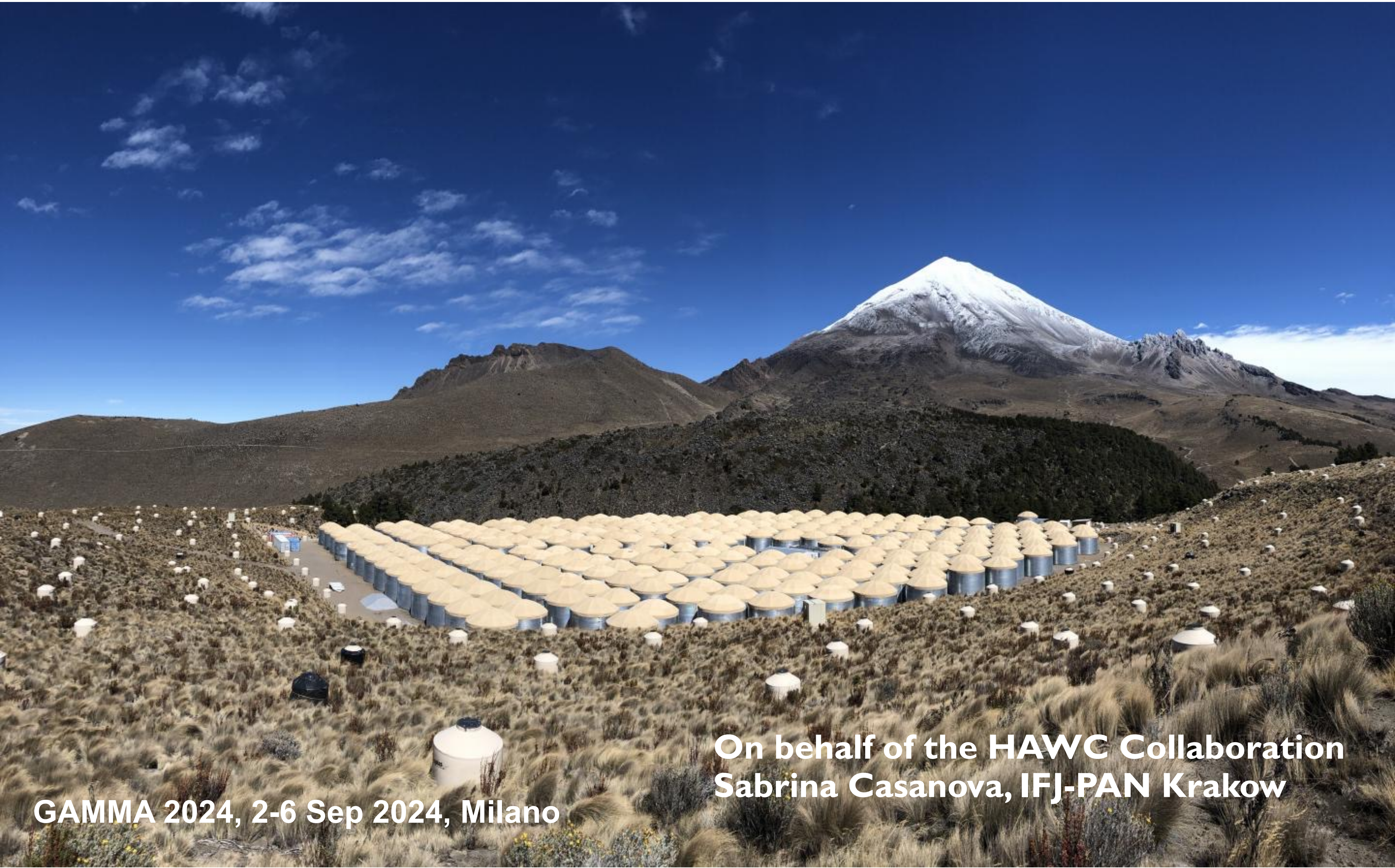
Highlights from HAWC



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

GAMMA 2024, 2-6 Sep 2024, Milano

Outline

HAWC Observatory

Selected recent HAWC results

- ✓ Galactic Plane Survey from TeV to hundred TeV
- ✓ Microquasars
- ✓ Diffuse Emission from the Galactic Plane and Galactic Centre
- ✓ SNRs and closeby MCs : the case of SNR G106.3+2.7
- ✓ The Sun at TeV energies

Conclusion and Outlook

The HAWC Collaboration

Mexico

Benemérita Universidad Autónoma de Puebla (BUAP)
Centro de Investigación y de Estudios Avanzados (CINVESTAV)
Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
Centro de Investigacion en Computacion, Instituto Politecnico Nacional (CIC-IPN)
Universidad de Guadalajara
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Instituto de Astronomía, Universidad Nacional Autónoma de México (IA-UNAM)
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México (ICN-UNAM)
Instituto de Física, Universidad Nacional Autónoma de México (IF-UNAM)
Instituto de Geofísica, Universidad Nacional Autónoma de México (IGeof-UNAM)
Universidad Michoacana de San Nicolás de Hidalgo (UMSNH)
Universidad Politecnica de Pachuca

Europe

Erlangen Centre for Astroparticle Physics, Erlangen, Germany
IFJ-PAN, Krakow, Poland
National Institute for Nuclear Physics, Padova Division, Italy
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

South America

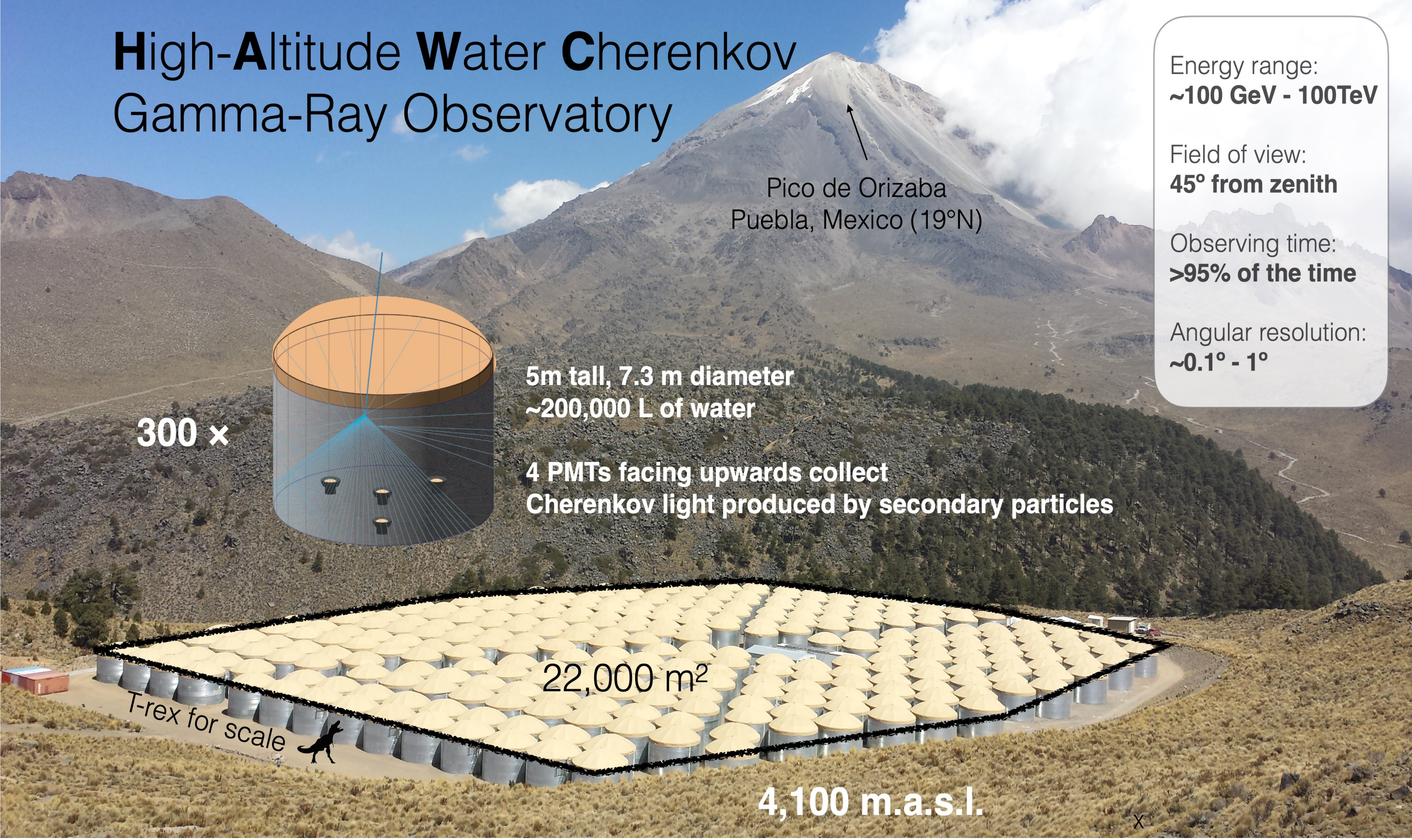
São Carlos Institute of Physics, University of São Paulo, Brazil

Asia

Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University
University of Seoul, South Korea
Sungkyunkwan University, South Korea

United States

California University of Pennsylvania
George Mason University
Georgia Institute of Technology
Los Alamos National Laboratory
Michigan State University
Michigan Technological University
NASA/Goddard Space Flight Center
NASA Marshall Space Flight Center
Pennsylvania State University
Stanford University
University of California, Irvine
University of Maryland
University of New Hampshire
University of New Mexico
University of Rochester
University of Utah
University of Wisconsin-Madison



- 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: 345 Outrigger array, since summer 2018
- Takes data with >95% of the time
- ~5 trillion triggers to date - 7PB of data

HAWC Water Cherenkov Detectors

- The WCDs are filled with 200,000 l of purified water. The particles from the shower induce **Cherenkov** light in **water,** detected by the 4 PMTs.

Steel frame construction

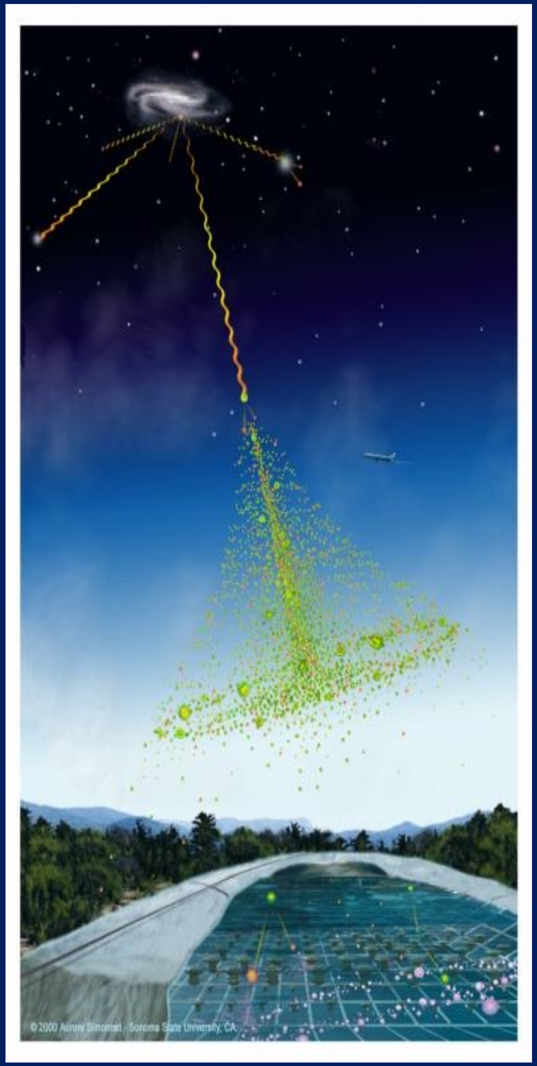
Large plastic bag container

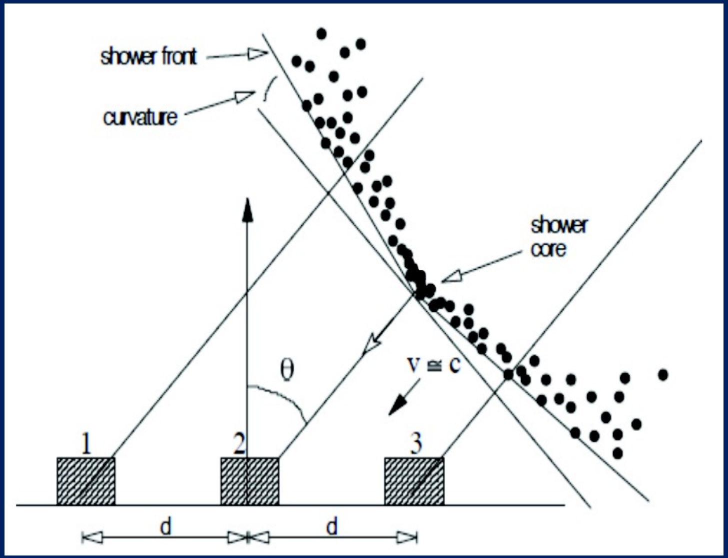
Water trucks filling the tanks

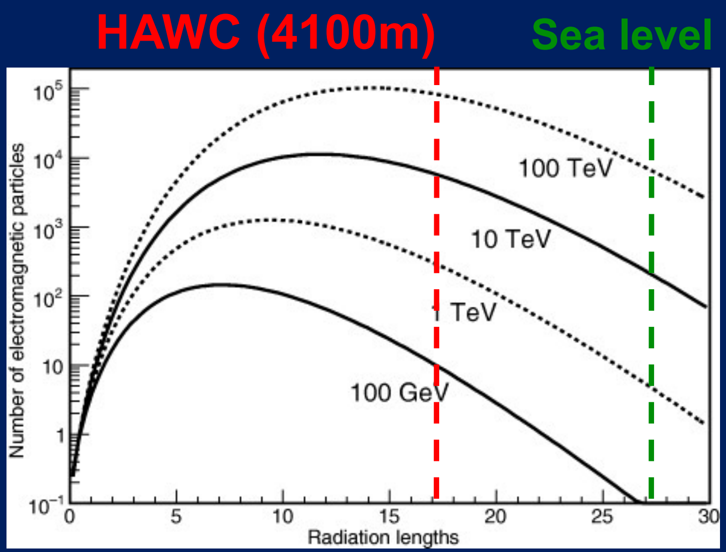
8-inch
10-inch
PMTs

3900 tanker truck trips needed

Detection Technique





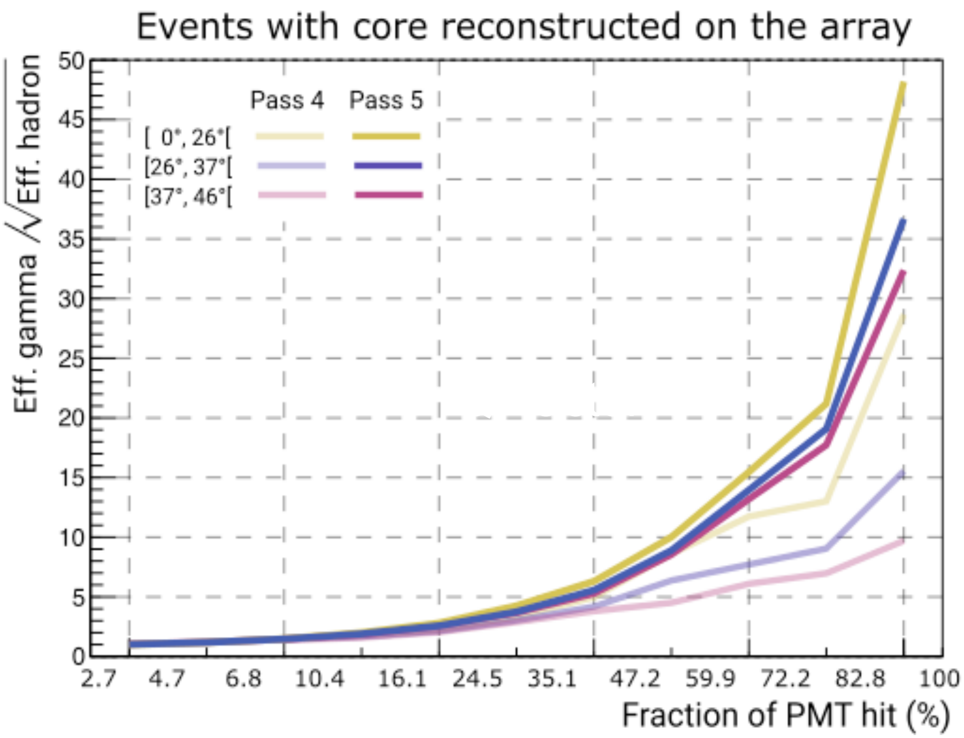


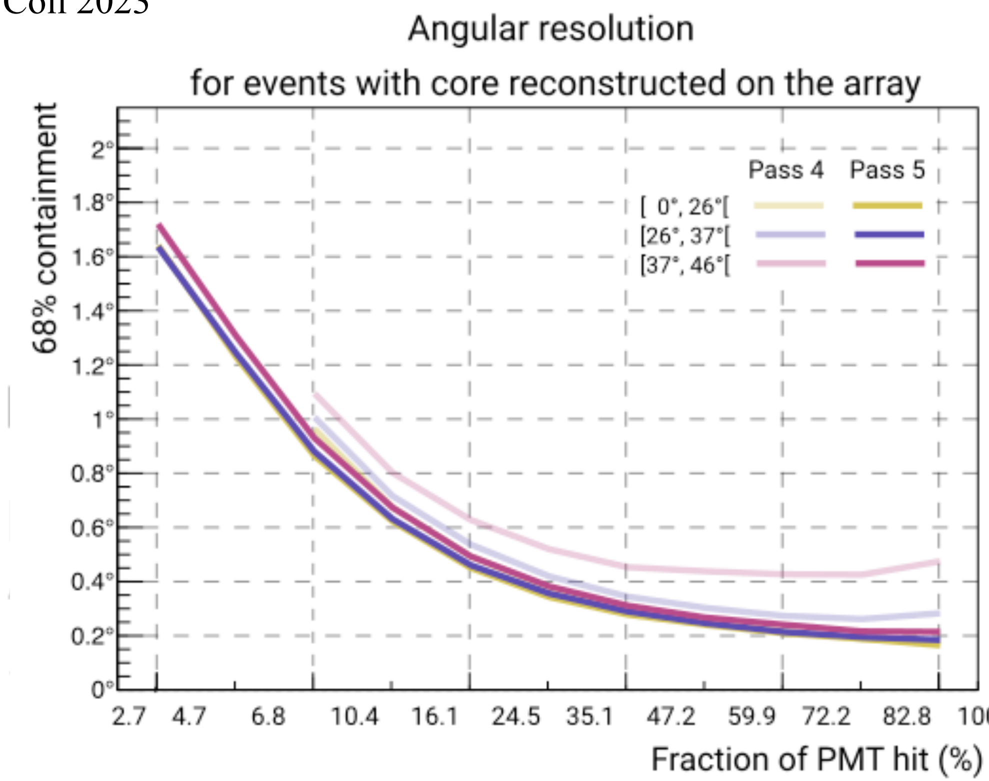
- The particle detectors are tanks full of water.
- Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Measure: time and light level in each PMT.
- Reconstruct: core, direction, energy, and background rejection.

High altitude means closer to the shower maximum

Pass 5 reconstruction

HAWC Coll 2023





$$Q = \frac{\text{Efficiency}_{\text{gammas}}}{\sqrt{\text{Efficiency}_{\text{hadrons}}}}$$

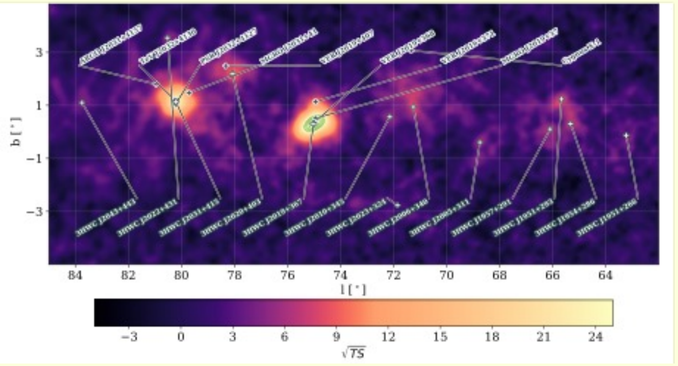
Large Events - Much improved background rejection

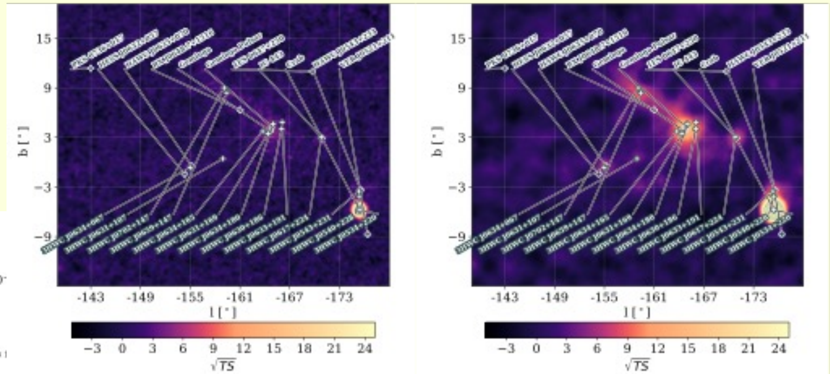
Better Angular Resolution - doesn't degrade at high zenith angles

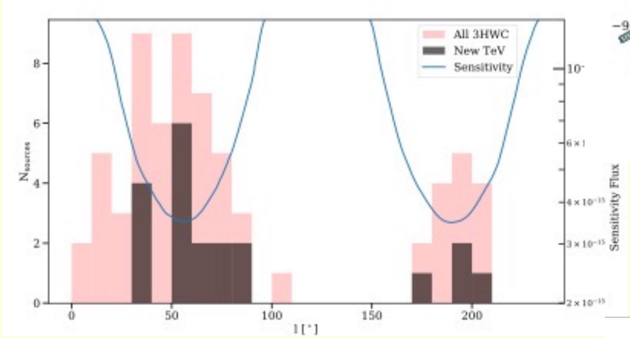
Wider FOV - Previous 45° now 60°

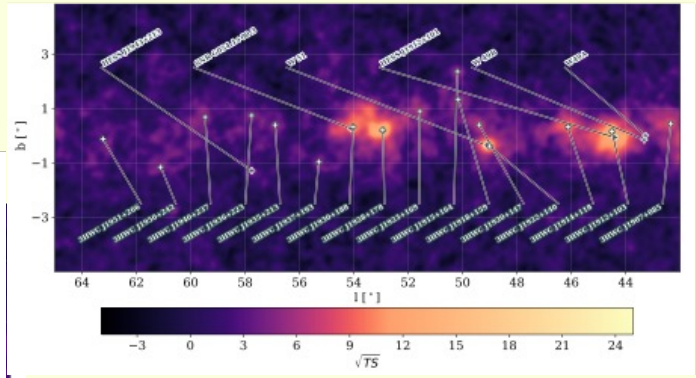
3HWC Catalog

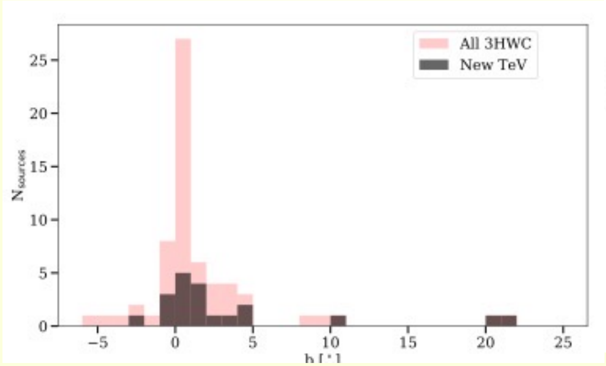
(HAWC Coll ApJ 2021)

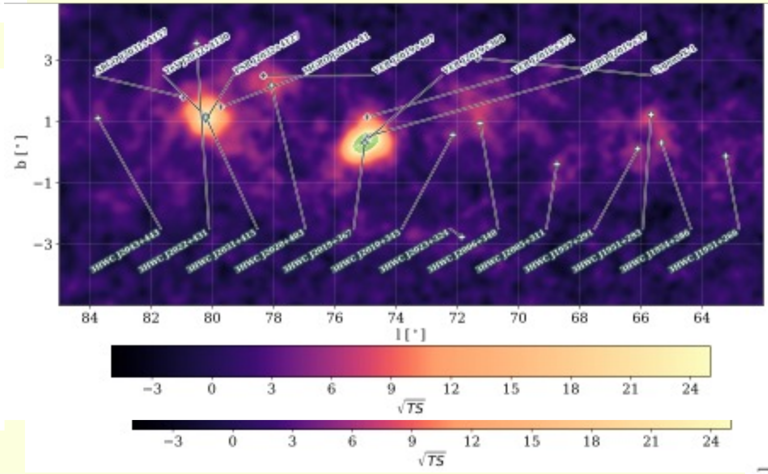


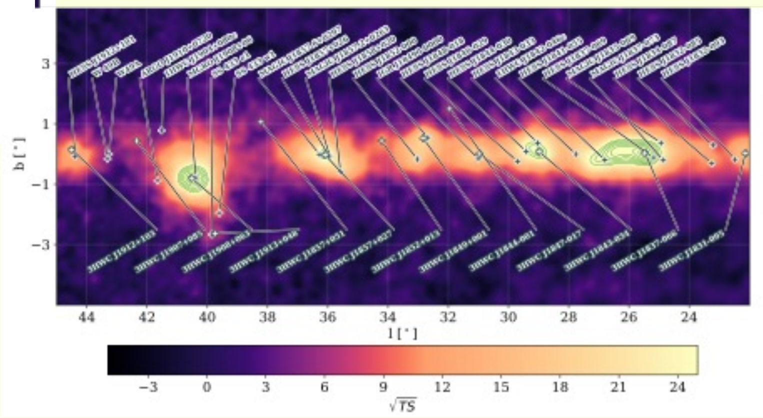










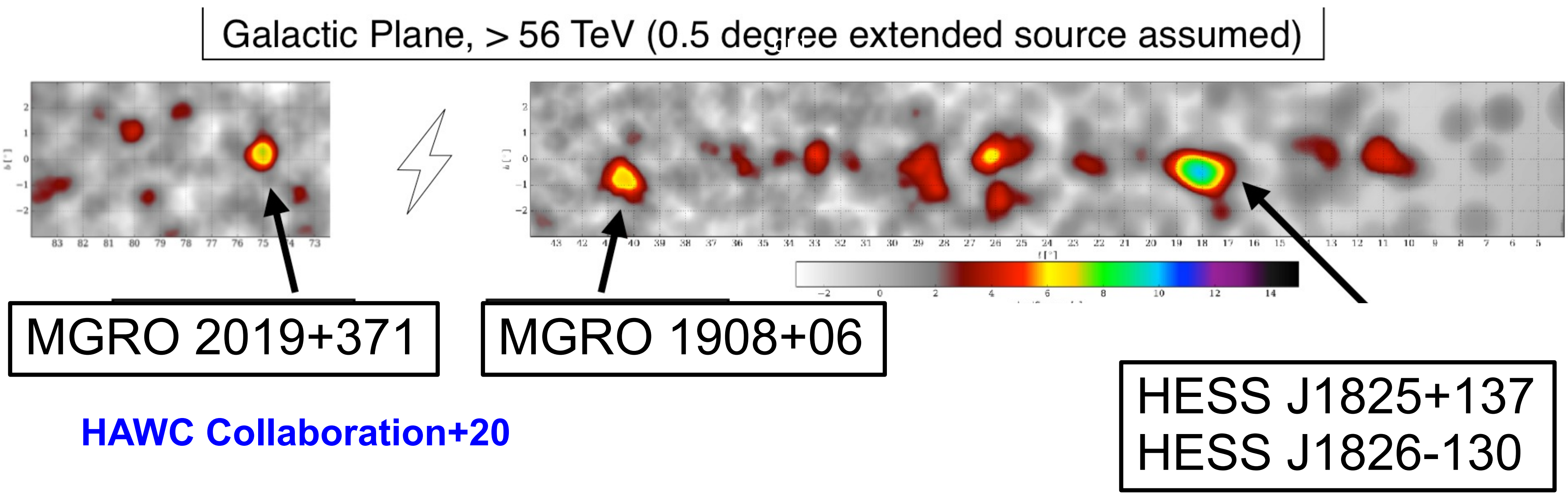


1543 days of data Pass 4

65 sources of which 56 can be associated to pulsars

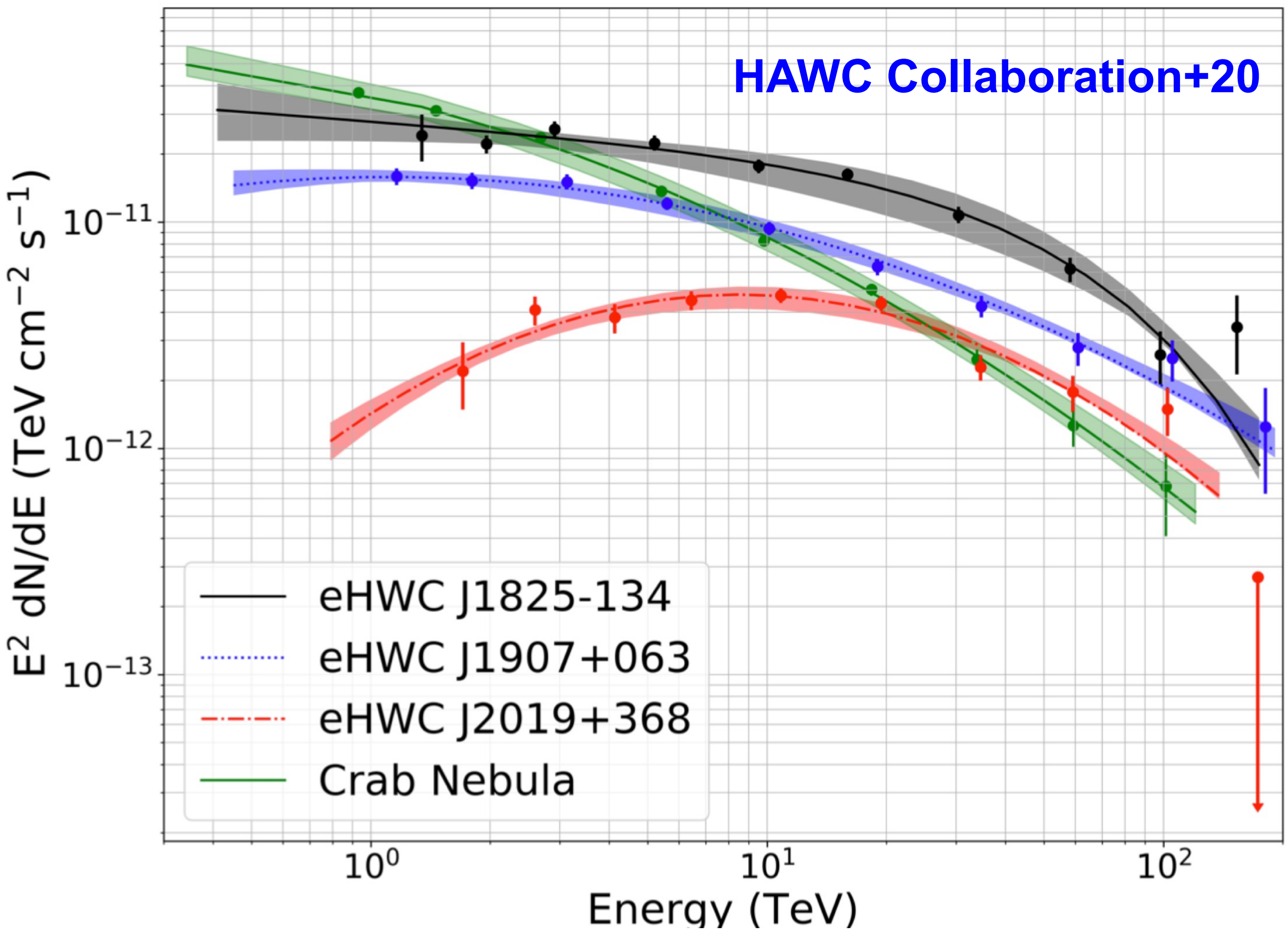
The Galaxy above 56 TeV

Source name	RA (^{o})	Dec (^{o})	Extension > 56 TeV (^{o})	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{TS}$ > 56 TeV	nearest 2HWC source	Distance to 2HWC source(^{o})	$\sqrt{TS}$ > 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



HAWC Collaboration+20

The Galaxy above 100 TeV: Spectra



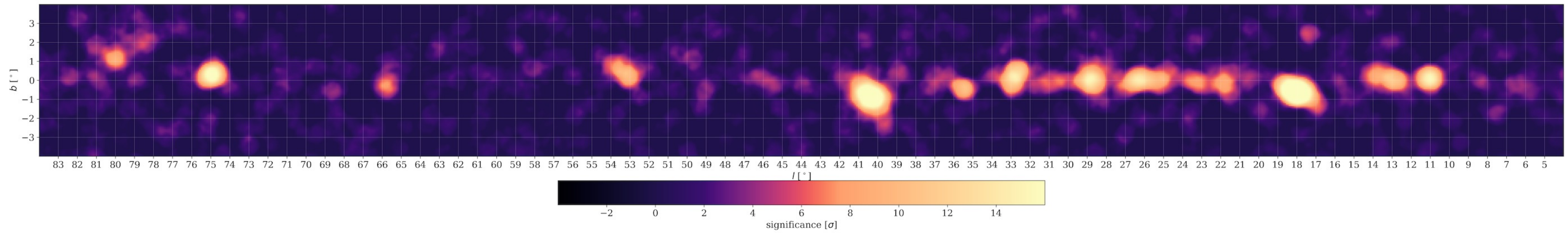
Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 $(10^{-13}$ TeV cm^2 s$)^{-1}$	α	E_{cut} (TeV)	PL diff
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4

Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 $(10^{-13}$ TeV cm^2 s$)^{-1}$	α	β	PL diff
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

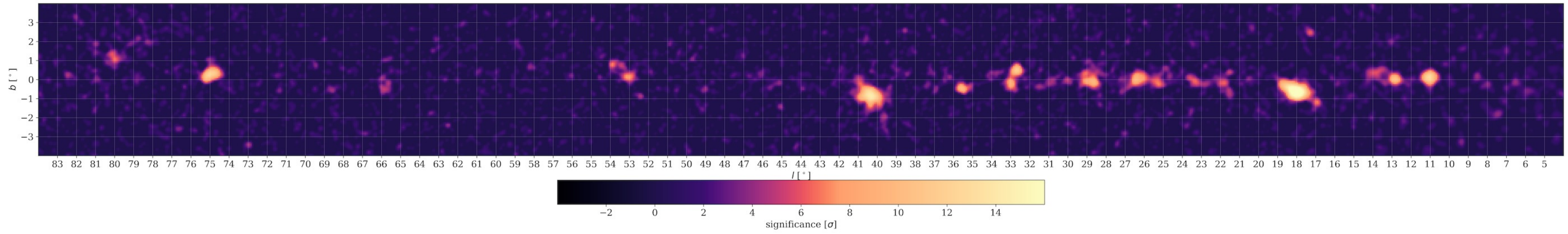
2800 day maps > 56 TeV

0.5 deg

K. Malone



pointlike

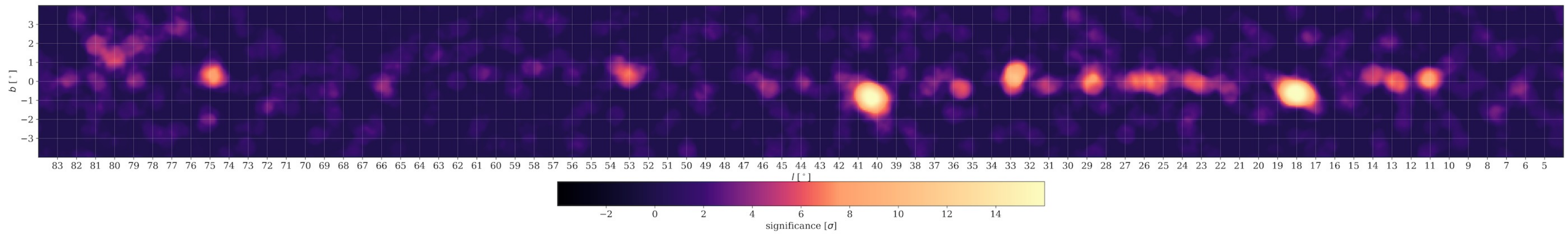


most sources are extended

2800 day maps > 100 TeV

K. Malone

0.5 deg



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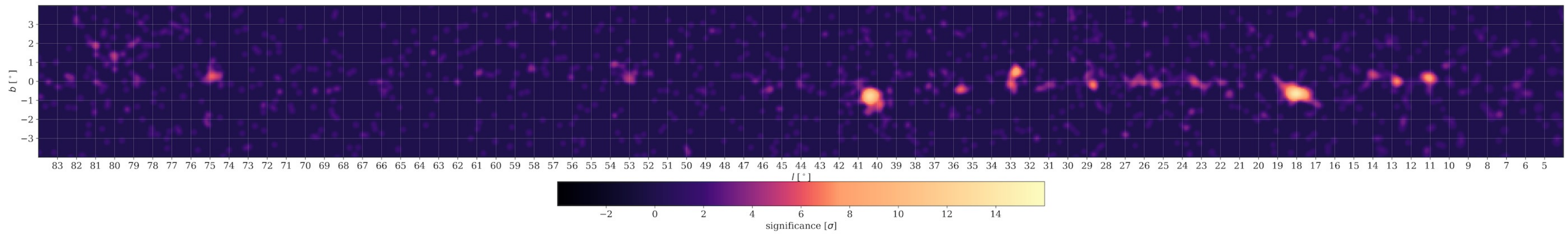
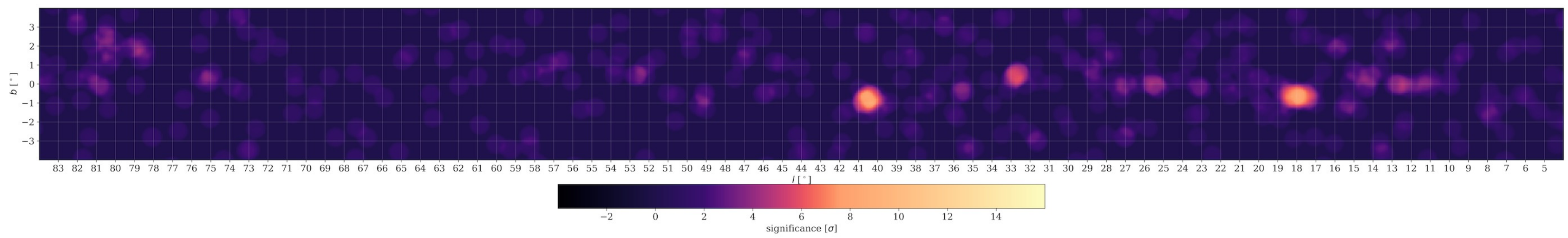


most of which extended

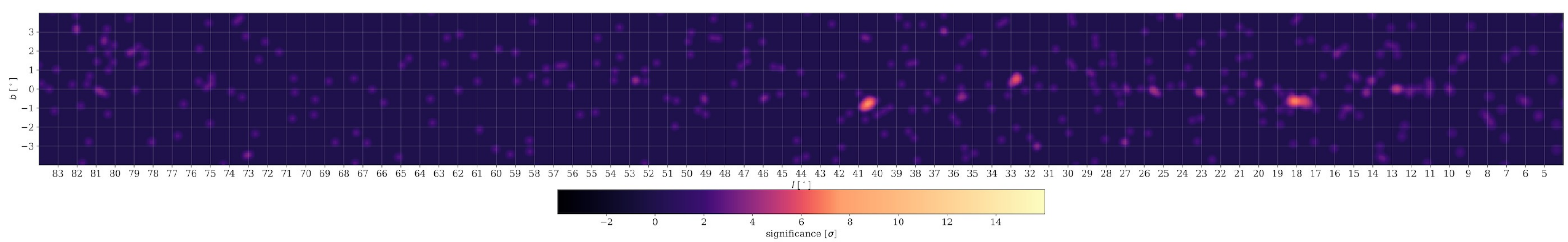
2800 day maps > 177 TeV

0.5 deg

K. Malone



pointlike



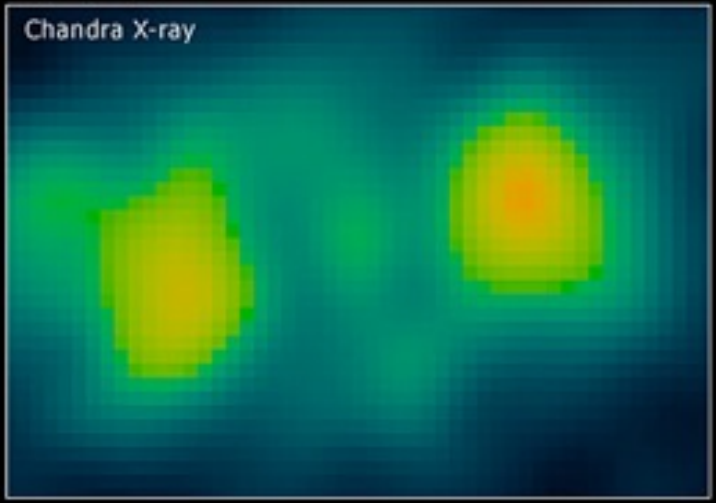
4HWC catalogue in preparation

HAWC Observations of Binaries

	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

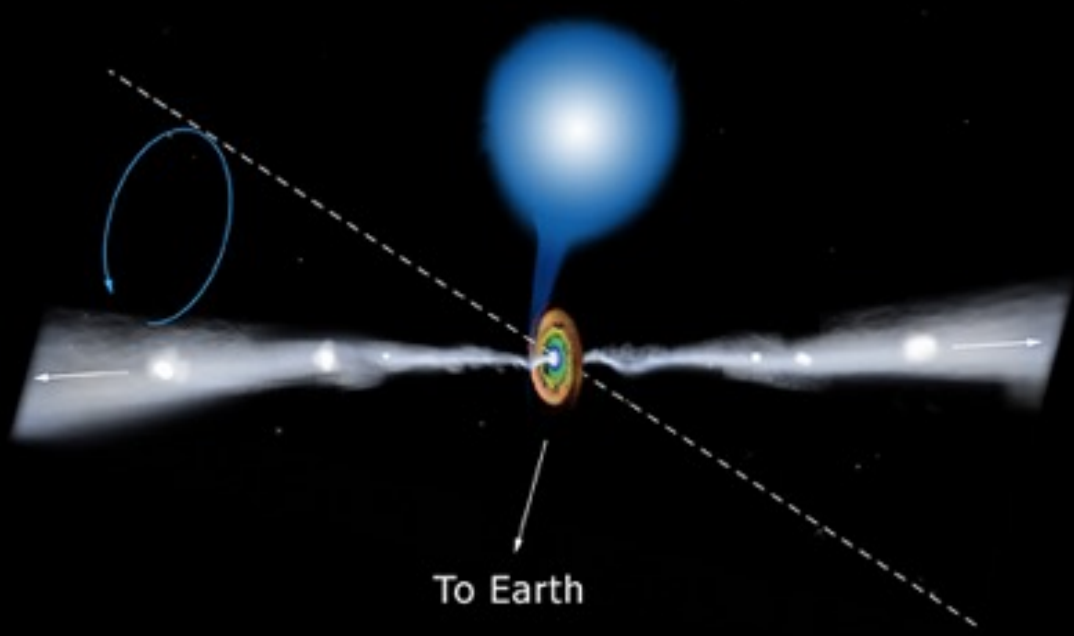
Accretion believed to be super Eddington

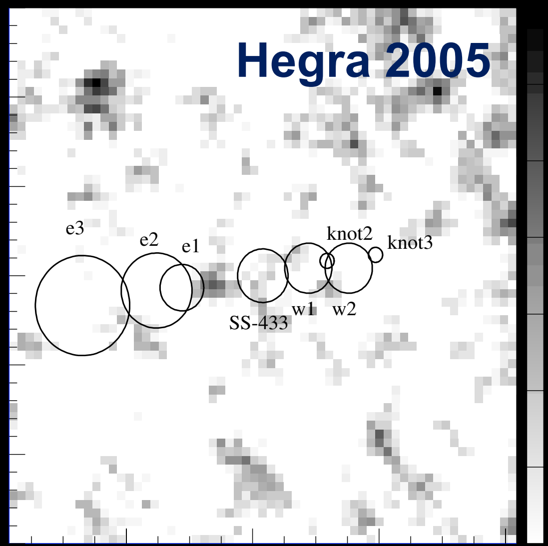
Barion loaded SS433 jet : $10^{39\text{-}40}$ erg/s

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

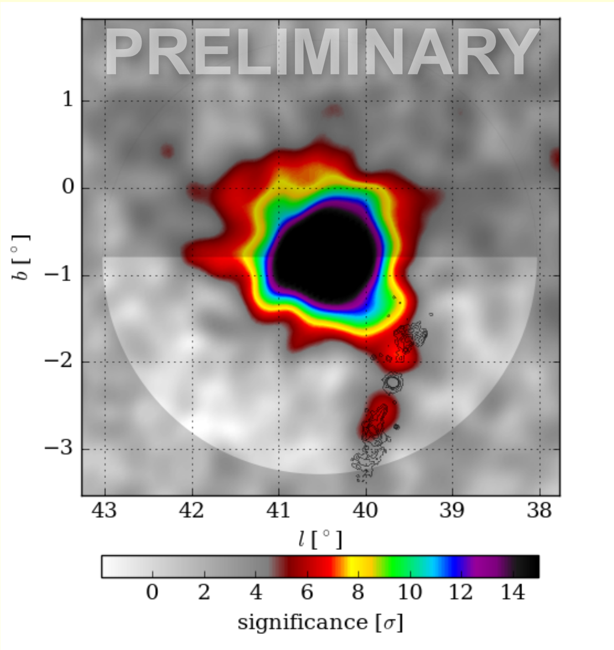
Particle acceleration & GeV-TeV radiation predicted at the lobes

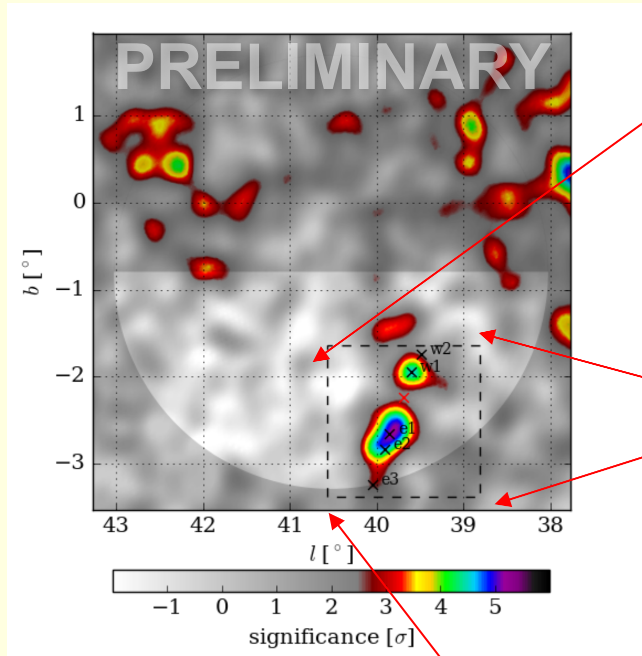


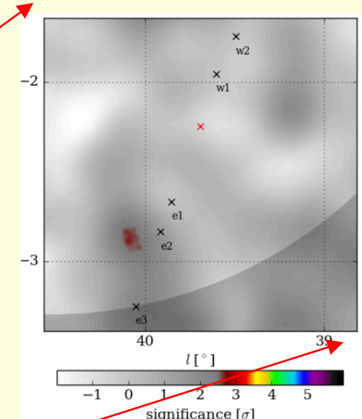


SS-433 lobes with HAWC

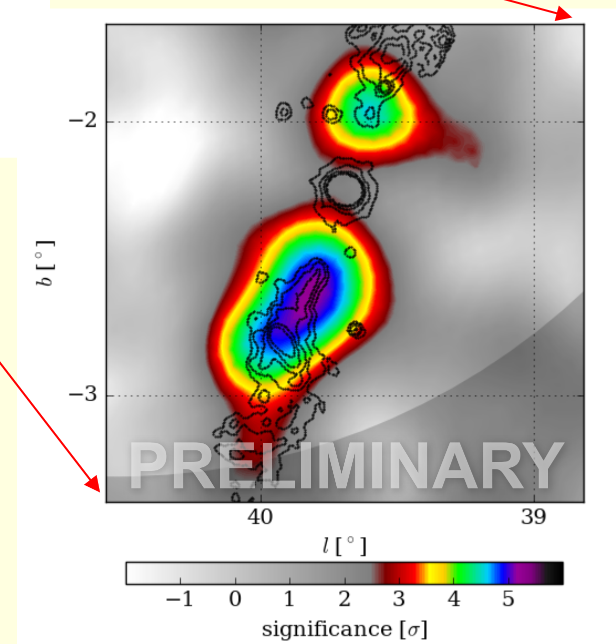
SS433 field after subtracting the lobes too

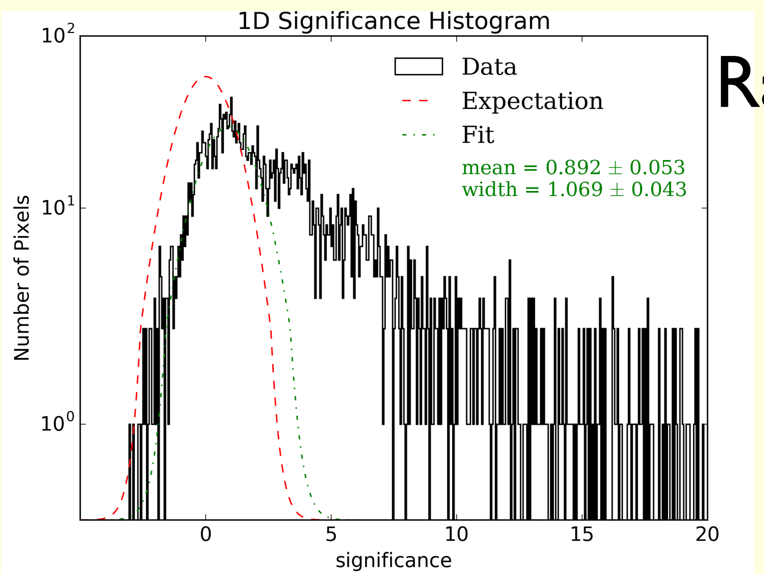






Nature, HAWC Coll 2018





Raw Map

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

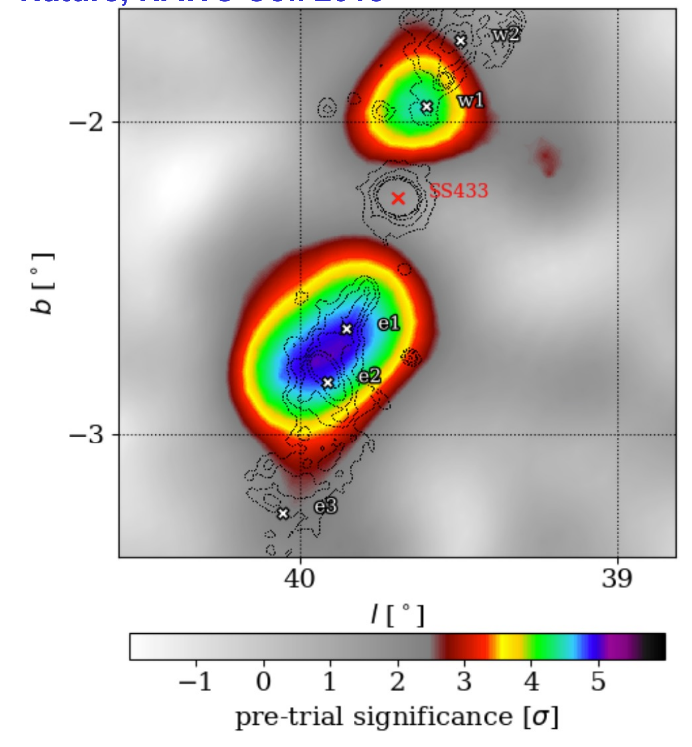
Systematic	East Lobe	West Lobe
Detector Systematic Effects	±50%	
MGRO J1908+06 Modeling	< ±20%	
Galactic diffuse contamination	−10%	−20%
Total	±55%	±55%

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

SS 433 field after subtracting MGRO J1908+06

SS-433 lobes with HAWC

Nature, HAWC Coll 2018



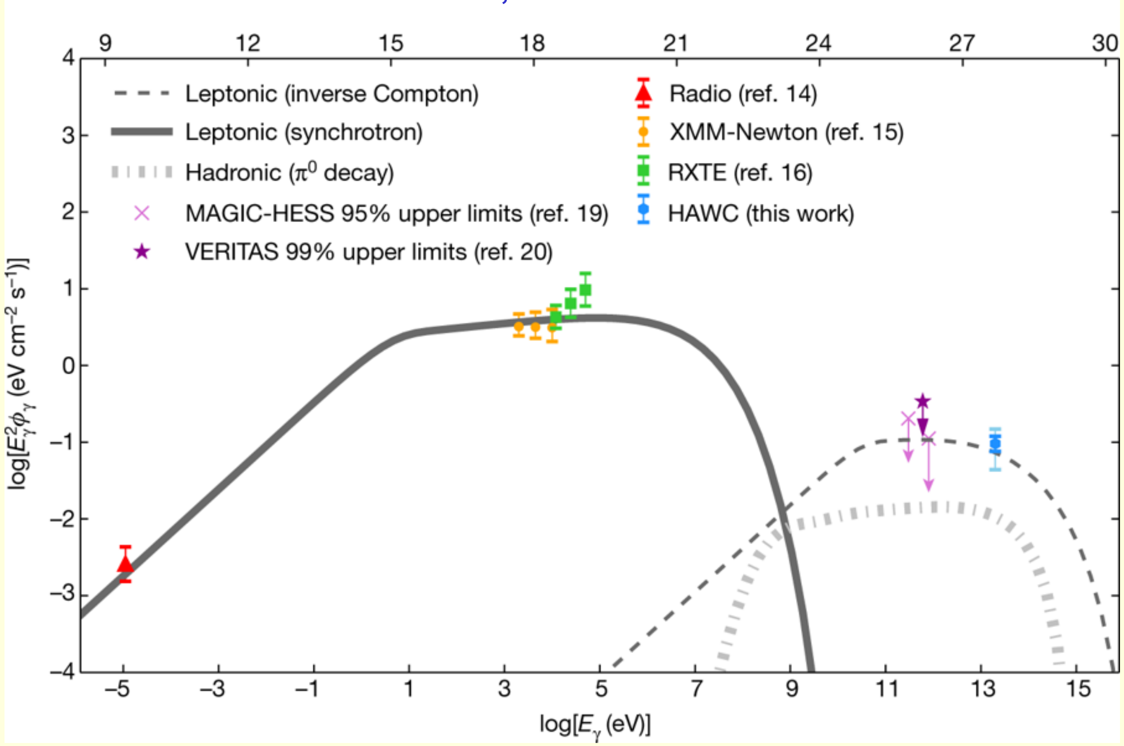
- The first micro-quasar HAWC detected
- 1017 days of HAWC observations
- Post-trial 5.4 σ
- Emission coincident with e1 and w1
- HAWC emission shows that powerful jets accelerate particles beyond 100 TeV
- Combining γ and X-rays B~16 μG

Energy Budget :

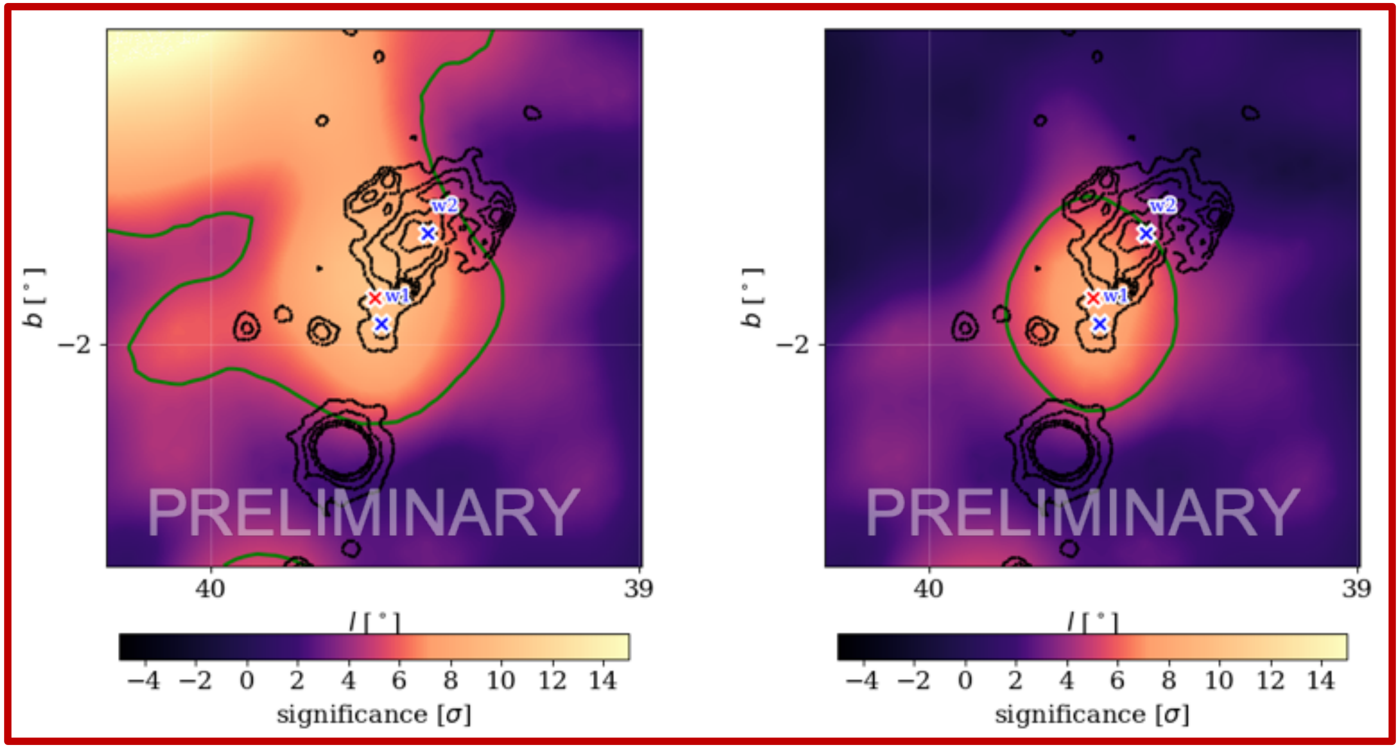
~0.5% of jet power into electron acceleration

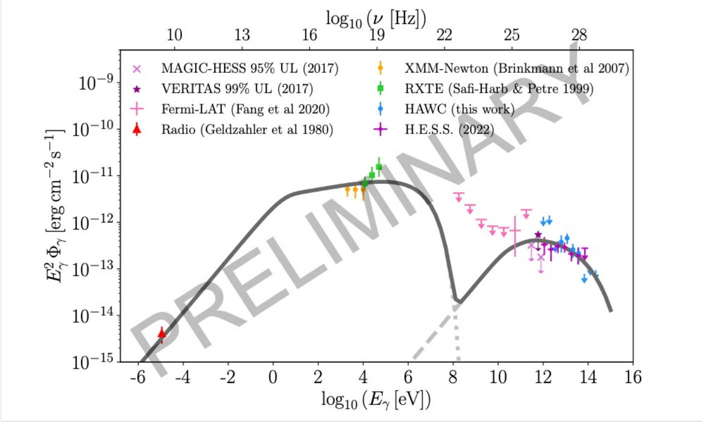
~100% of jet energy over 30000 years lifetime of SS 433 into accelerating protons of at least 250 TeV with spectral index -2. if n=0.1 cm^{-3} But do we really know the ambient gas density ?

Nature, HAWC Coll 2018



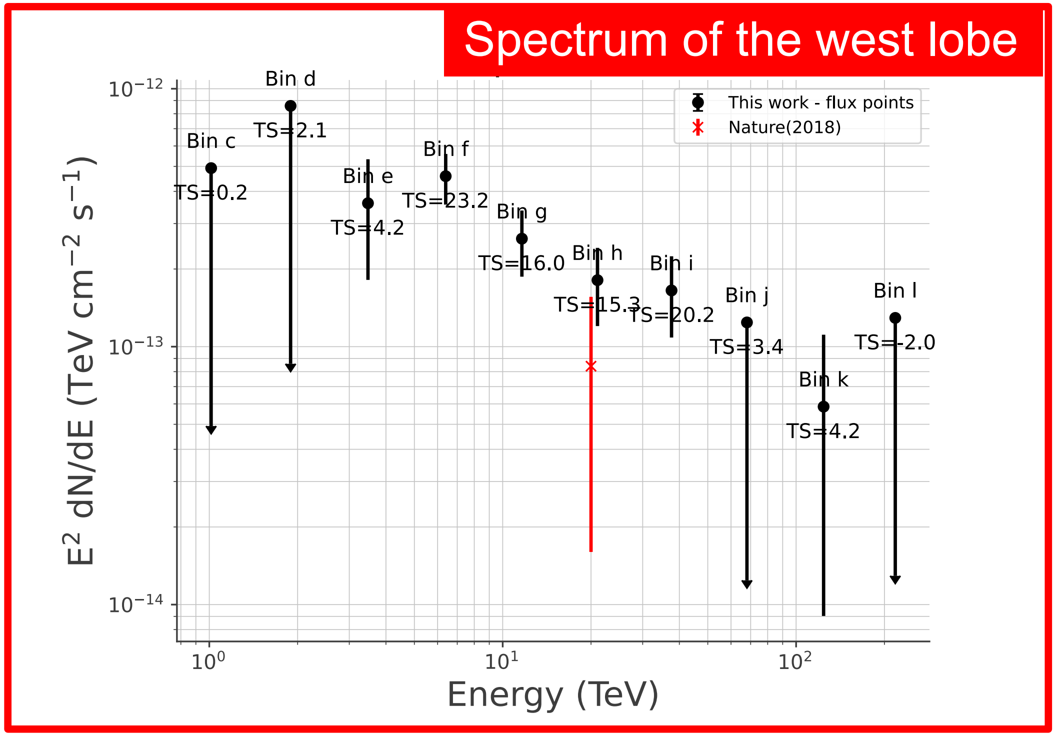
West lobe



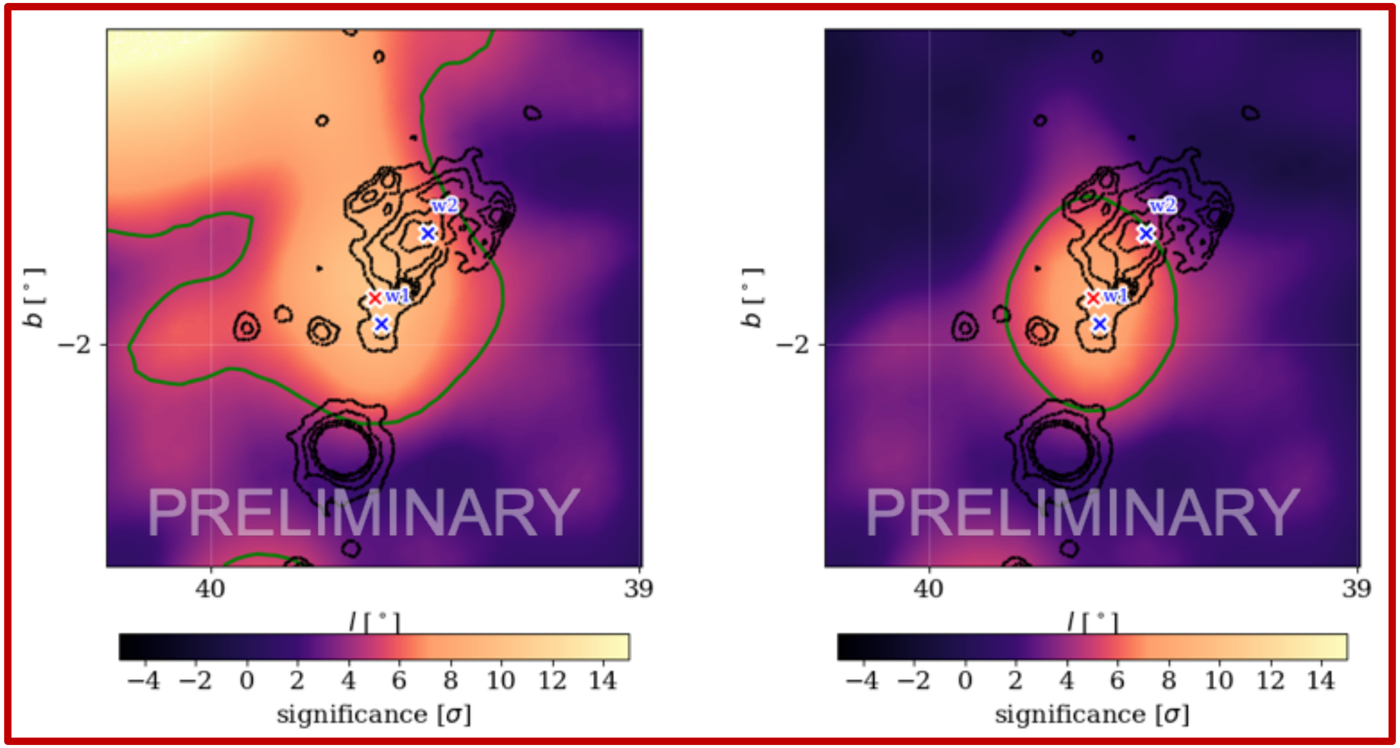


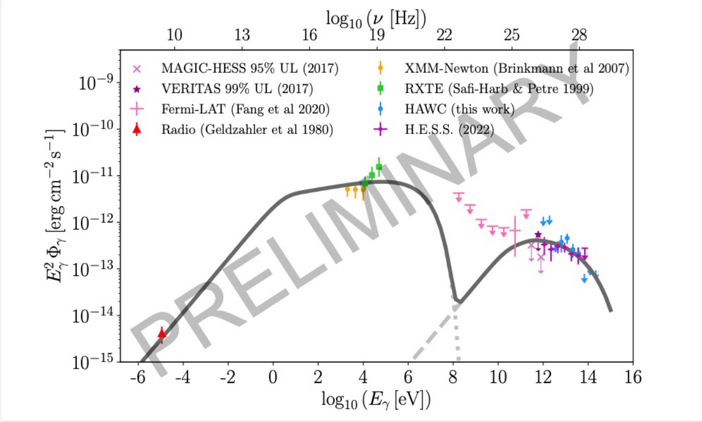
Chang Dong Rho

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



West lobe





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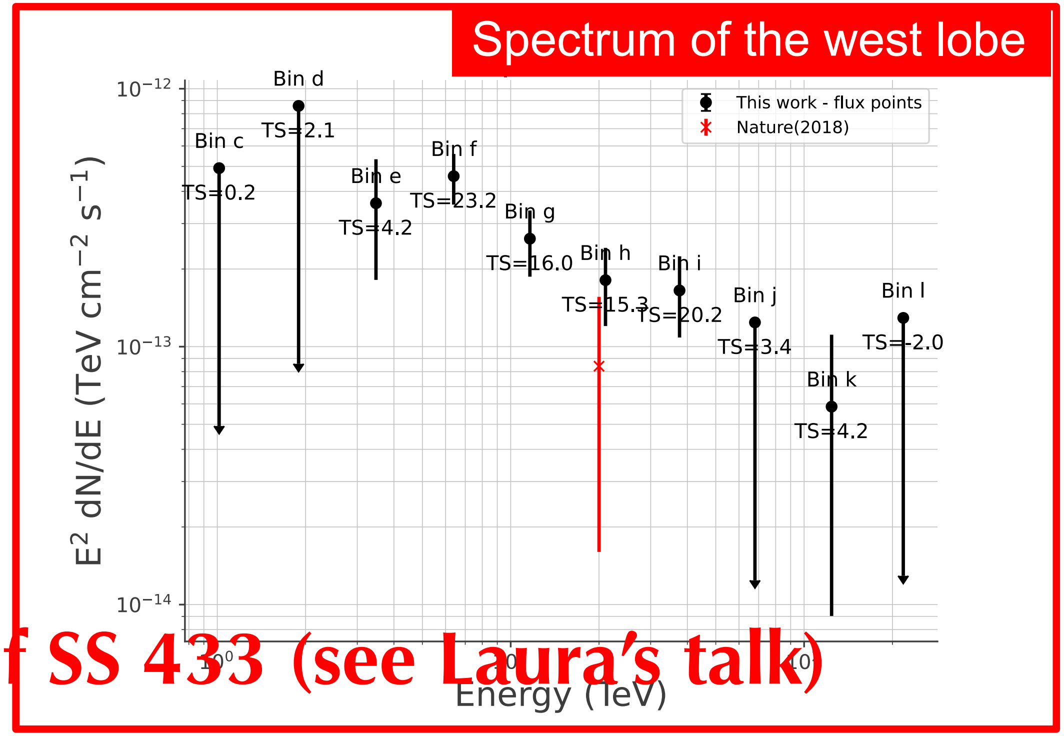
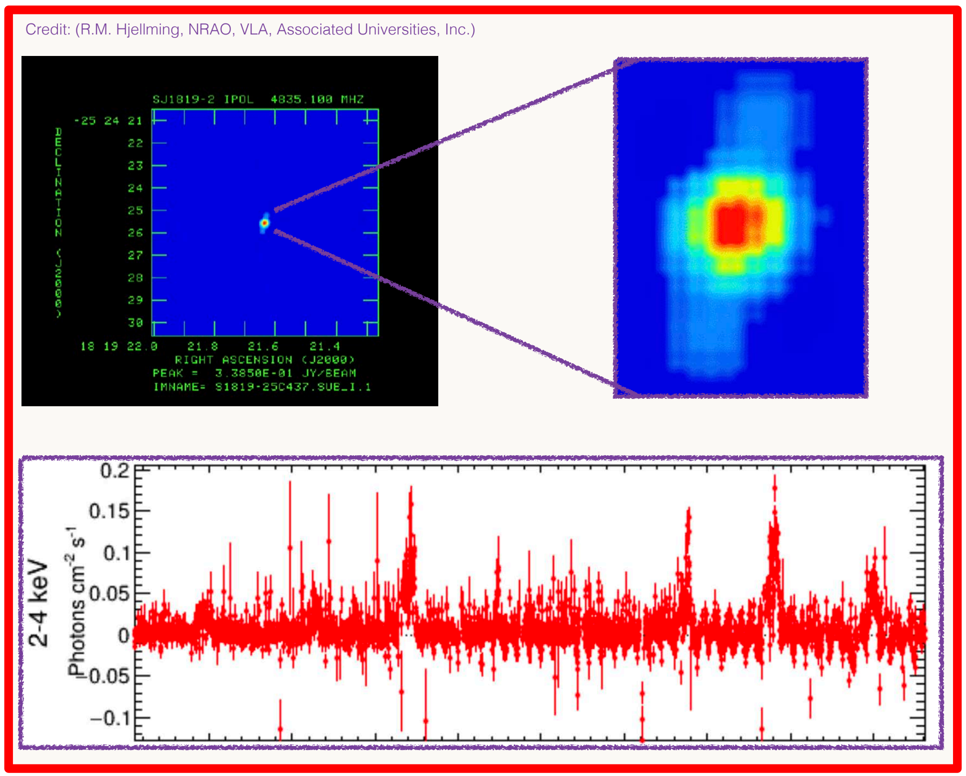
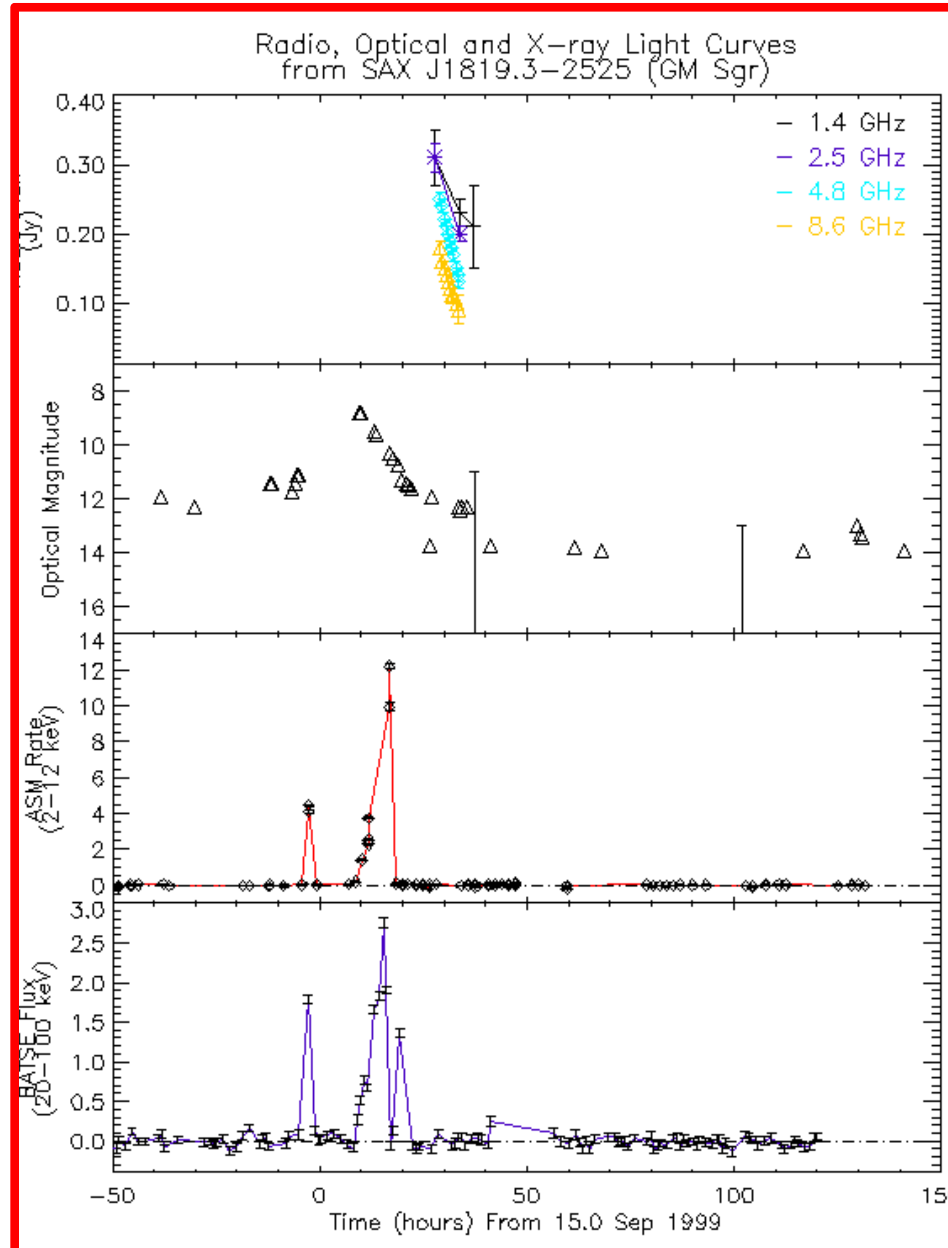


H.E.S.S. did a follow up of SS 433 (see Laura's talk)

VHE Photons coincident with V4641 Sgr

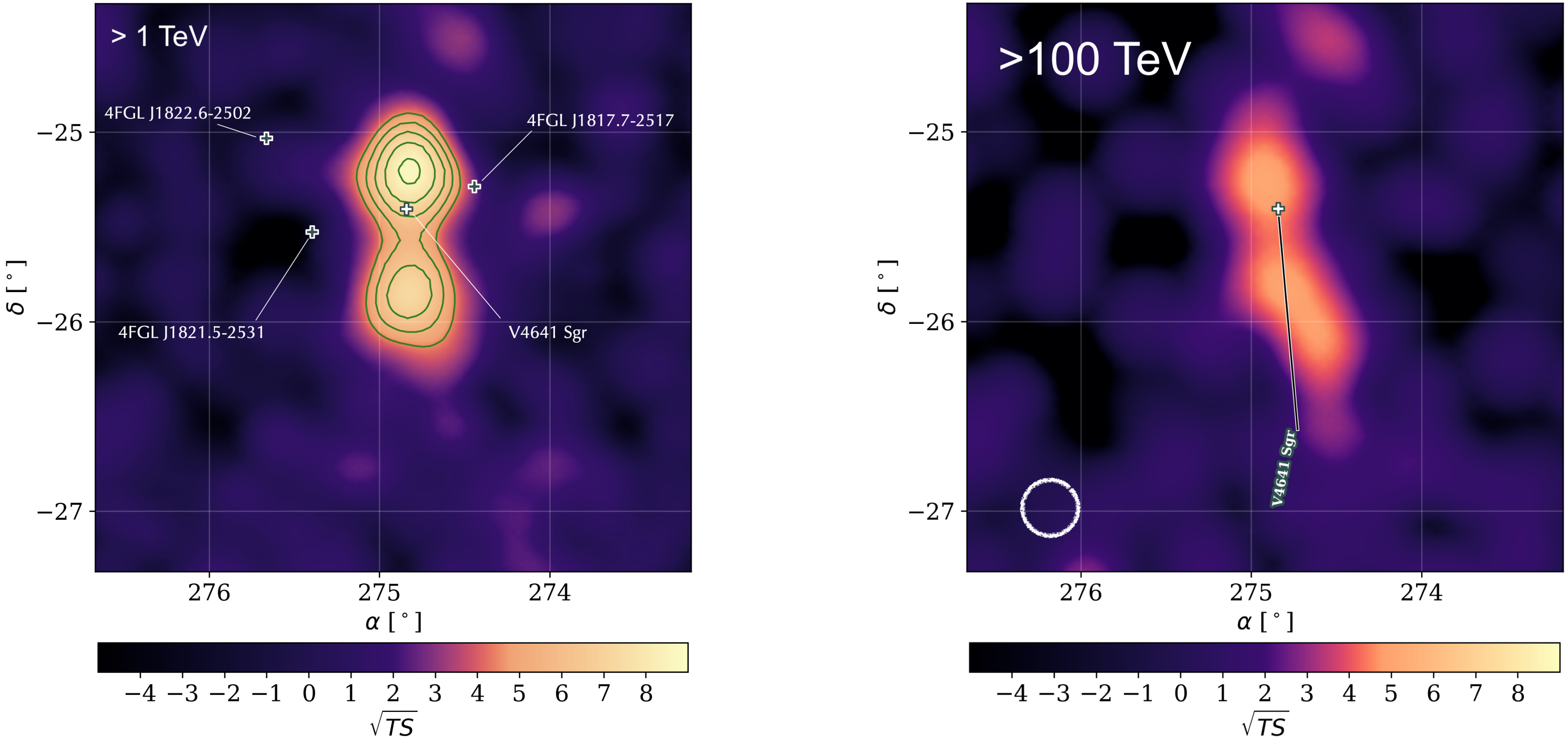
- Transient X-ray binary first detected flares in 1999
  - X-ray flux reached 12.2 Crab in 8 hr
- Arcsec radio jets inclined < 16° (VLA)
- Black-hole 6.4 $M_{\odot}$ (MacDonald+2014)
- B-star companion 2.9 $M_{\odot}$
- Orbital period 2.8 d, distance 6.2 kpc
- Super-Eddington accretion
- Superluminal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





VHE Photons coincident with V4641 Sgr

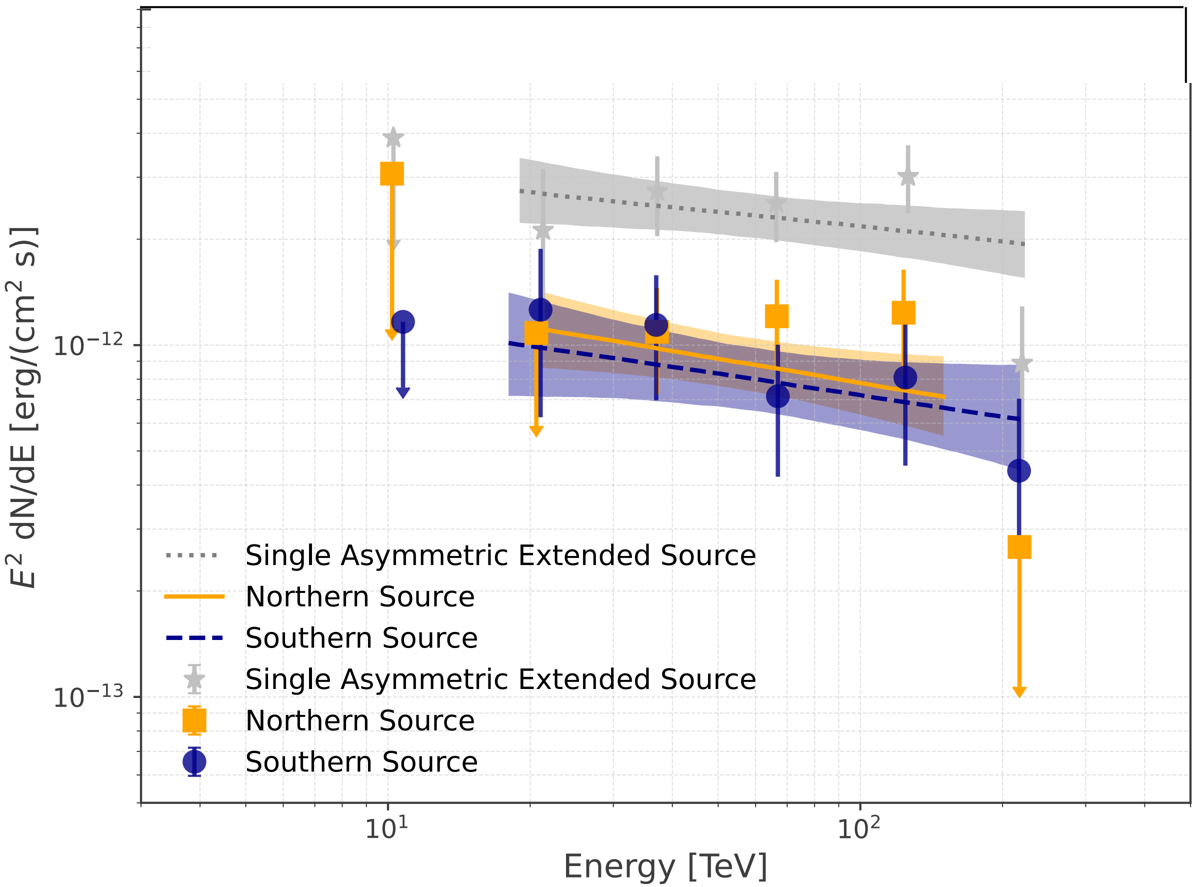
HAWC Collaboration, Nature 2024



- 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

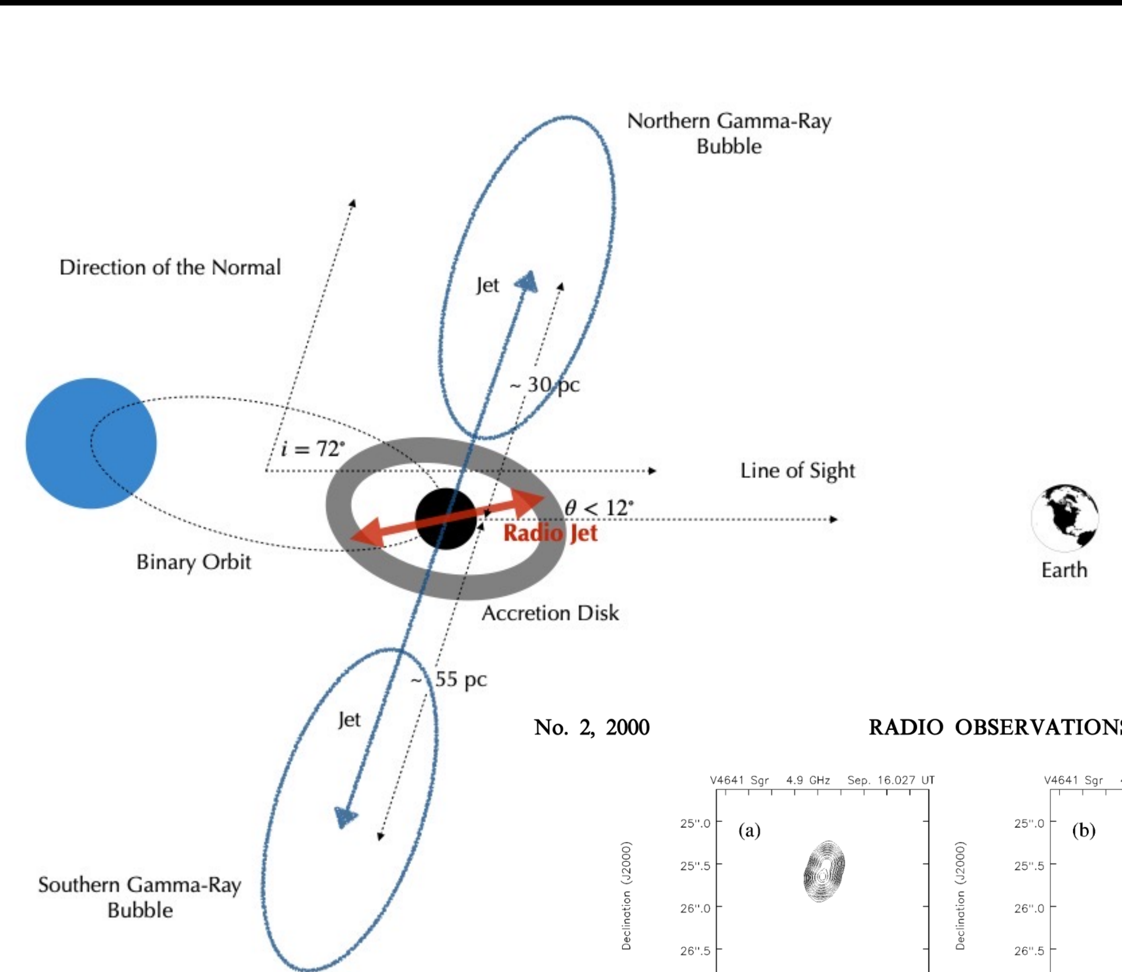
HAWC Collaboration, Nature 2024

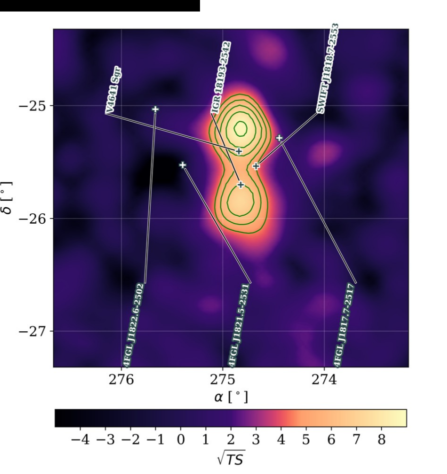


- Morphology: two sources (8,1 σ and 6.8 σ) or a roughly 70 pc extended one
- PL spectra up to 220 TeV
- No time flux variations using selected time intervals
- Similar acceleration location as In SS 433
- Large-scale jets in the Galaxy might be more common than previously thought
- Leptonic scenario challenging due to cooling losses. If hadronic PeV candidate budget ~10^{50}erg

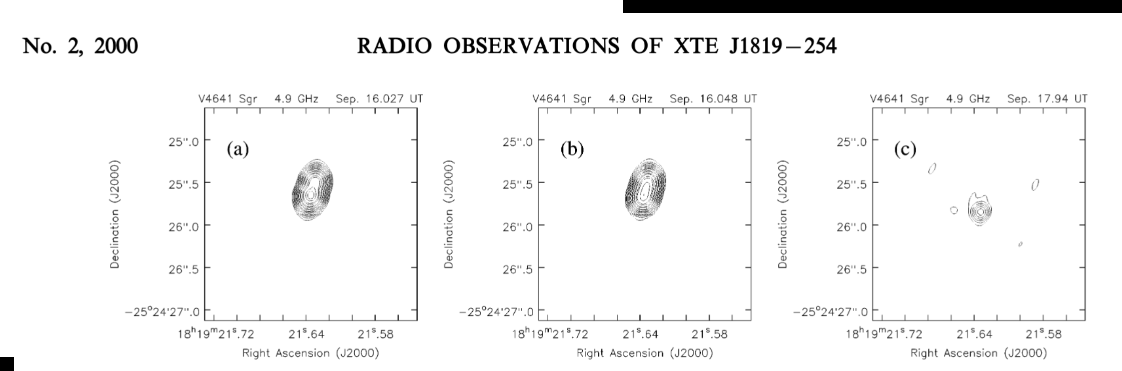
Source Name	R.A. [°]	Dec. [°]	N_0 [$\times 10^{-16}$cm^{-2}TeV^{-1}s^{-1}]	Index (α)	Extension upper limit at 95% CL [°]	Physical distance to the black hole (distance: 6.6 kpc)
Southern	274.82 ± 0.04	-25.87 ± 0.03	$2.4^{+0.6}_{-0.5}(stat.)^{+0.2}_{-0.5}(syst.)$	$-2.2 \pm 0.2(stat.)^{+0.07}_{-0.02}(syst.)$	0.23	0.46° ~ 55 pc
Northern	274.82 ± 0.03	-25.18 ± 0.02	$2.6^{+0.5}_{-0.4}(stat.) \pm 0.4(syst.)$	$-2.2 \pm 0.2(stat.)^{+0.07}_{-0.05}(syst.)$	0.17	0.23° ~ 30 pc

Weather and Climate ?



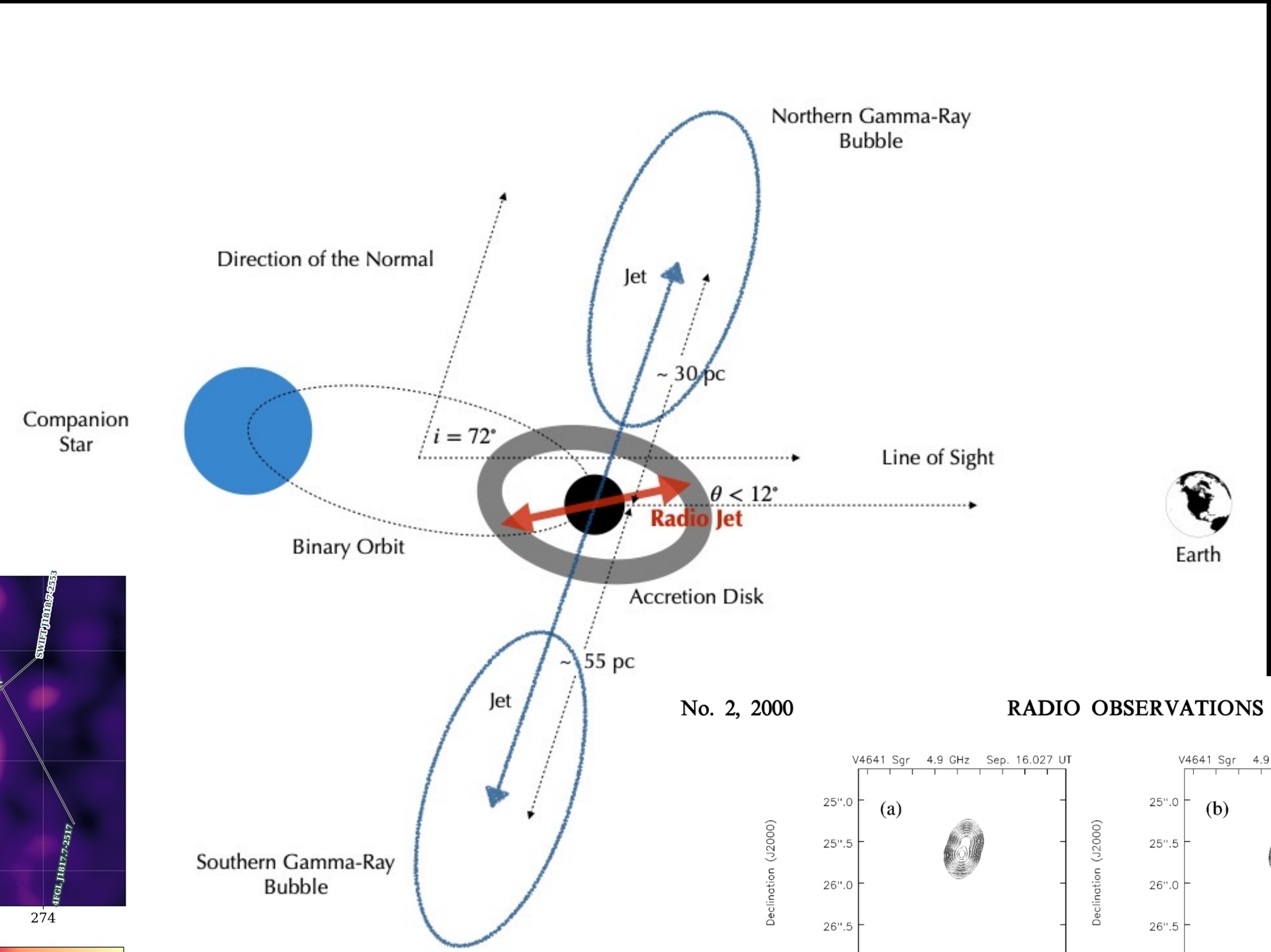


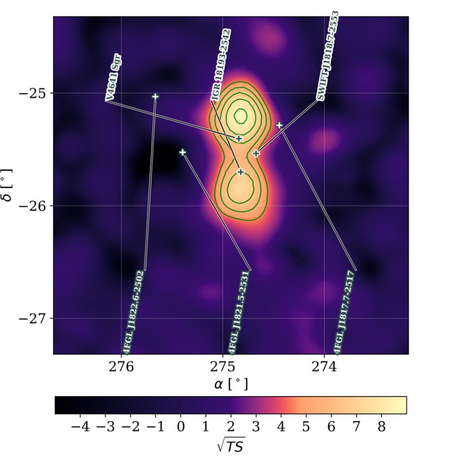
100 pc persistent structure, HAWC 2022



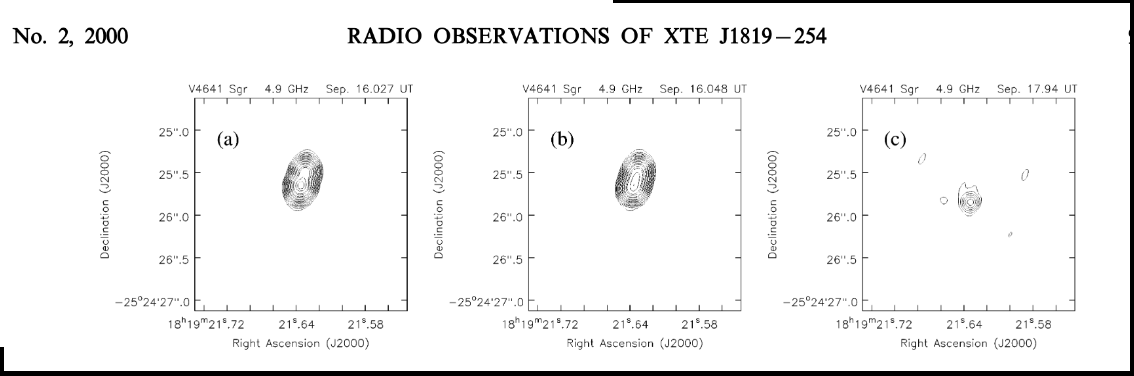
Arc-sec Radio jet during the outburst of 1999

Weather and Climate ?





100 pc persistent structure, HAWC 2022

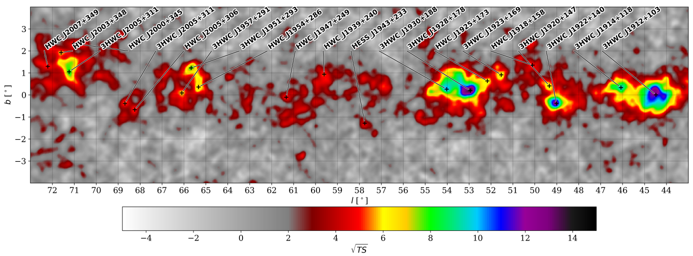


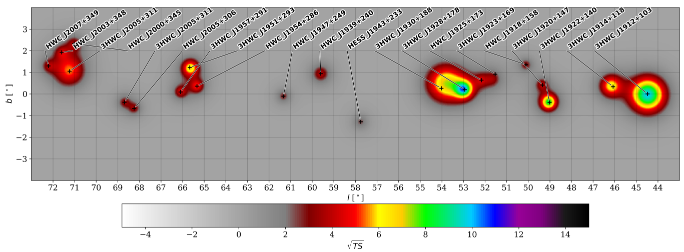
Arc-sec Radio jet duringthe outburst of 1999

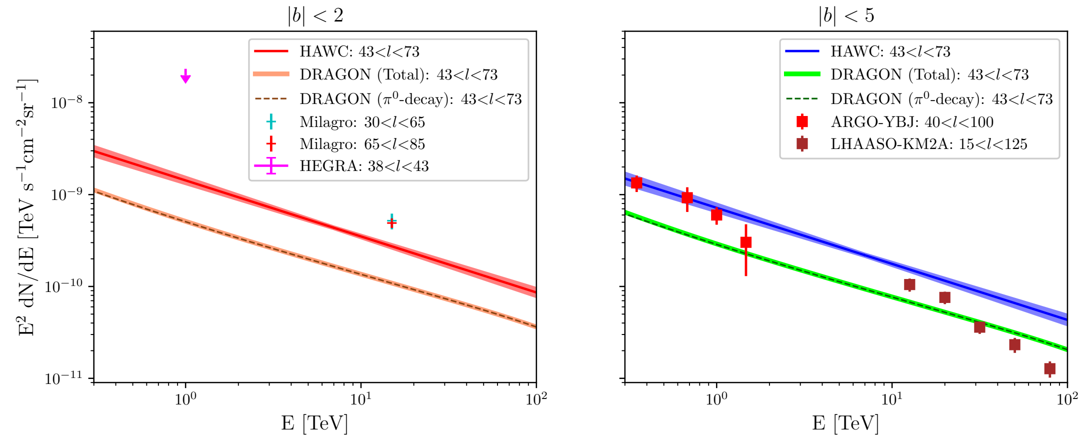
H.E.S.S. did a follow up of the source (see Laura's talk)

Galactic Diffuse Emission

HAWC, ApJ 2023

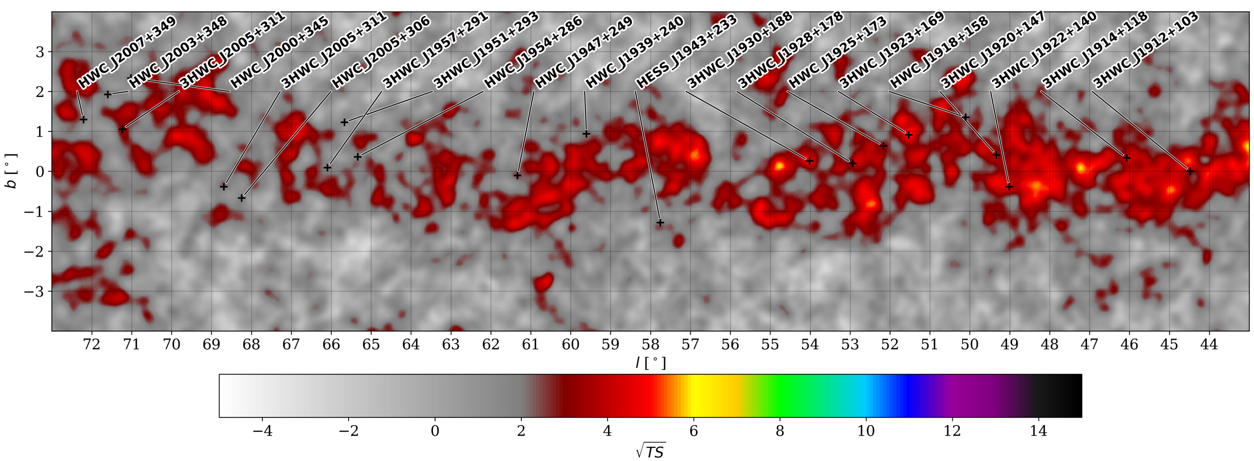






l_{min} (°)	l_{max} (°)	$\|b\|<$ (°)	$F_7 \times 10^{-12}$ (TeV^{-1} s^{-1}cm^{-2}sr^{-1})	Index	f_{10} %	f_{100} %
43	73	2	$8.89 \pm 0.37^{-0.70}_{+0.48}$	$-2.61 \pm 0.03^{-0.04}_{+0.02}$	72.7	71.8
43	73	4	$5.45 \pm 0.25^{-0.44}_{+0.38}$	$-2.60 \pm 0.03^{-0.04}_{+0.01}$	76.1	75.3

Source-subtracted map

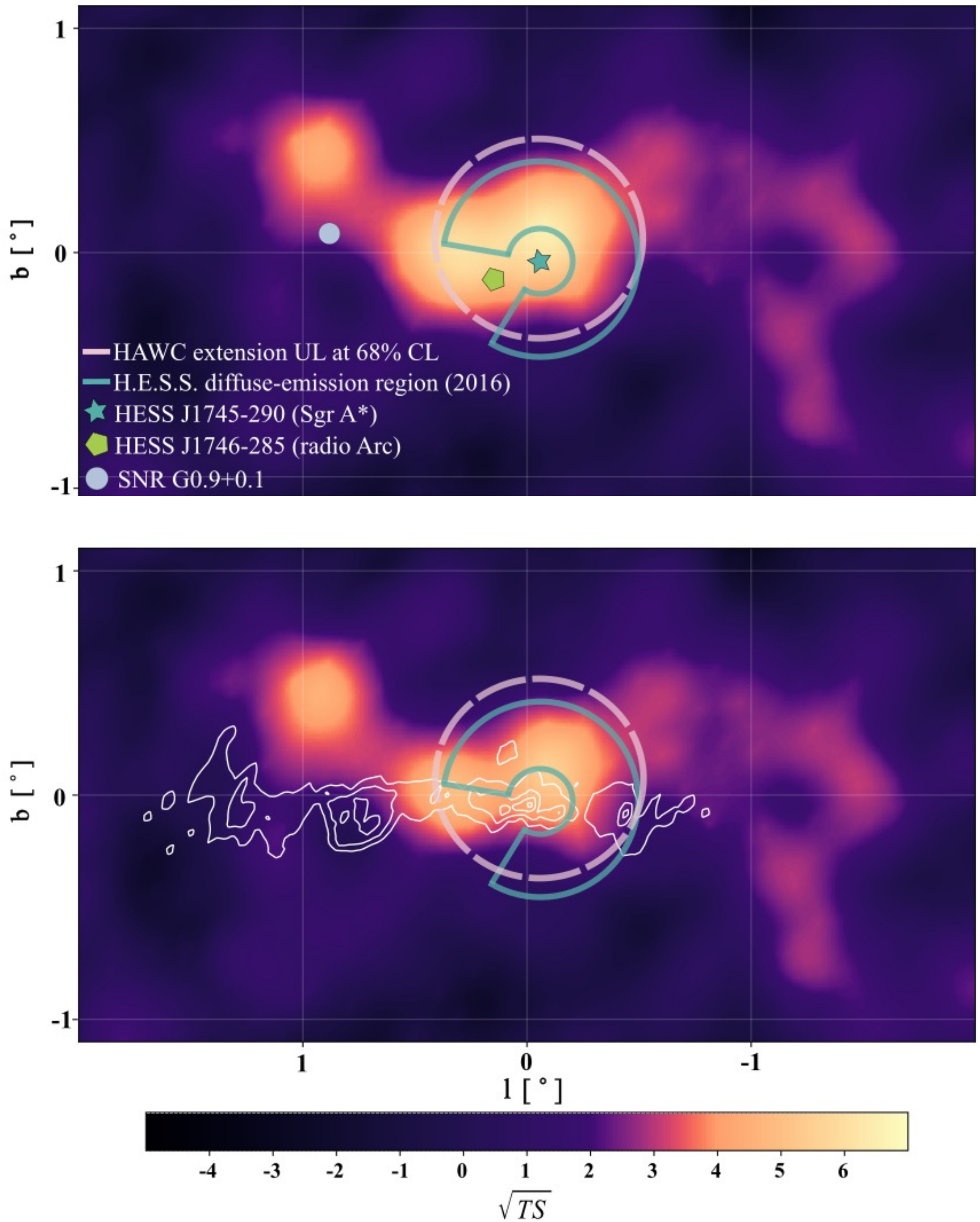


Emission spectrum ~ 2.7

Emission 2-3 times higher than the diffuse emission from local CR flux and diffusion coefficient from secondary/primary ratio

Diffuse Emission from the CMZ

HAWC Collaboration, ApJL 2024

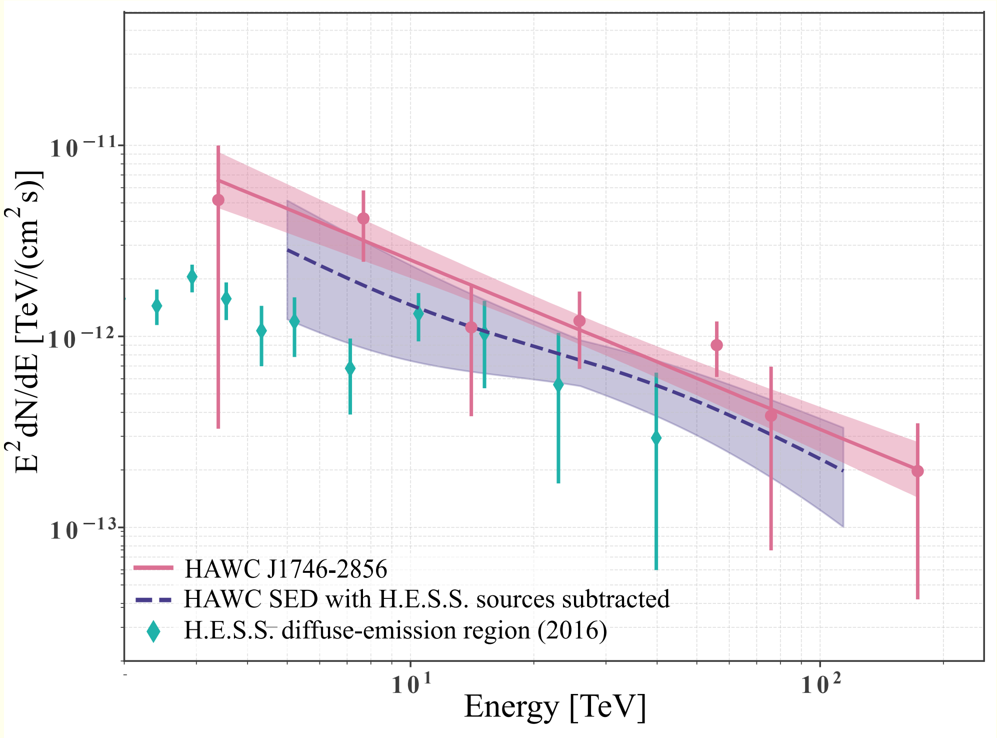


- 2456 days observations
- GC at 48° zenith
- 7.0 σ detection in Pass 5
- Best-fit model : point-like source with
- a simple power law spectrum up to 114 TeV

- HAWC emission after subtracting HESS J1745-290 (Sgr A*) and HESS J1746-285 (Radio Arc)
- 5.7 σ detection
- PL no cutoff until 114 TeV

The origin of the emission from the CMZ

HAWC Collaboration, 2024



- HAWC and HESS datapoints compatible
- No spectral cutoff up to 100 TeV
- Maximum γ energy : 114TeV at 68% CL
- HAWC max γ energy ~ 2 HESS max γ energy

$$t_{\rm escape} \approx \frac{r^2}{2D} \approx 100 \left(\frac{r}{40\,{\rm pc}}\right)^2 \left(\frac{E_{\rm p}}{1\,{\rm PeV}}\right)^{-0.3} {\rm yr}$$

$\ll t_{age\ Galaxy}$

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

$\sim 10\ w_{Sun}$

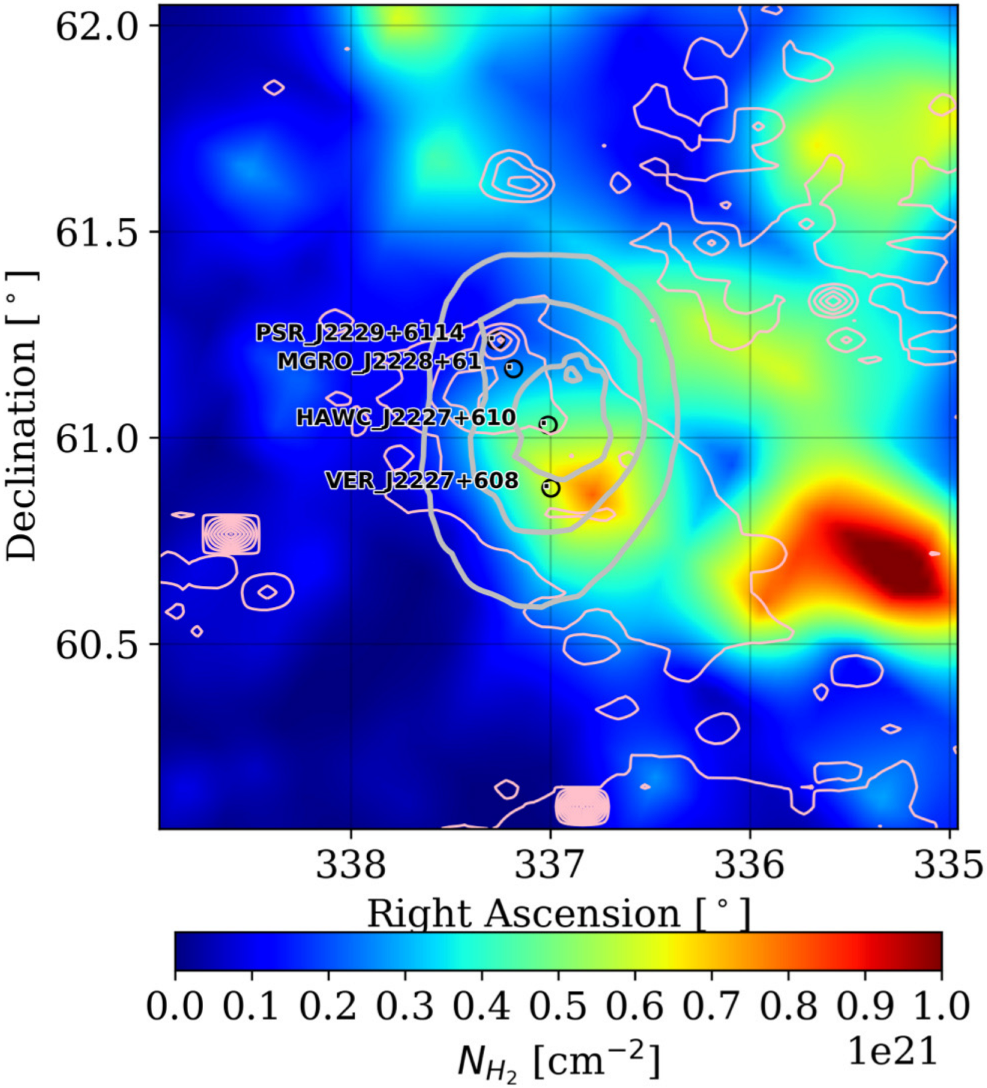
UHE gamma rays are emitted by cosmic rays accelerated up to PeV energies by the local quasi-continuous accelerators within the GC region.

Observations of SNRs

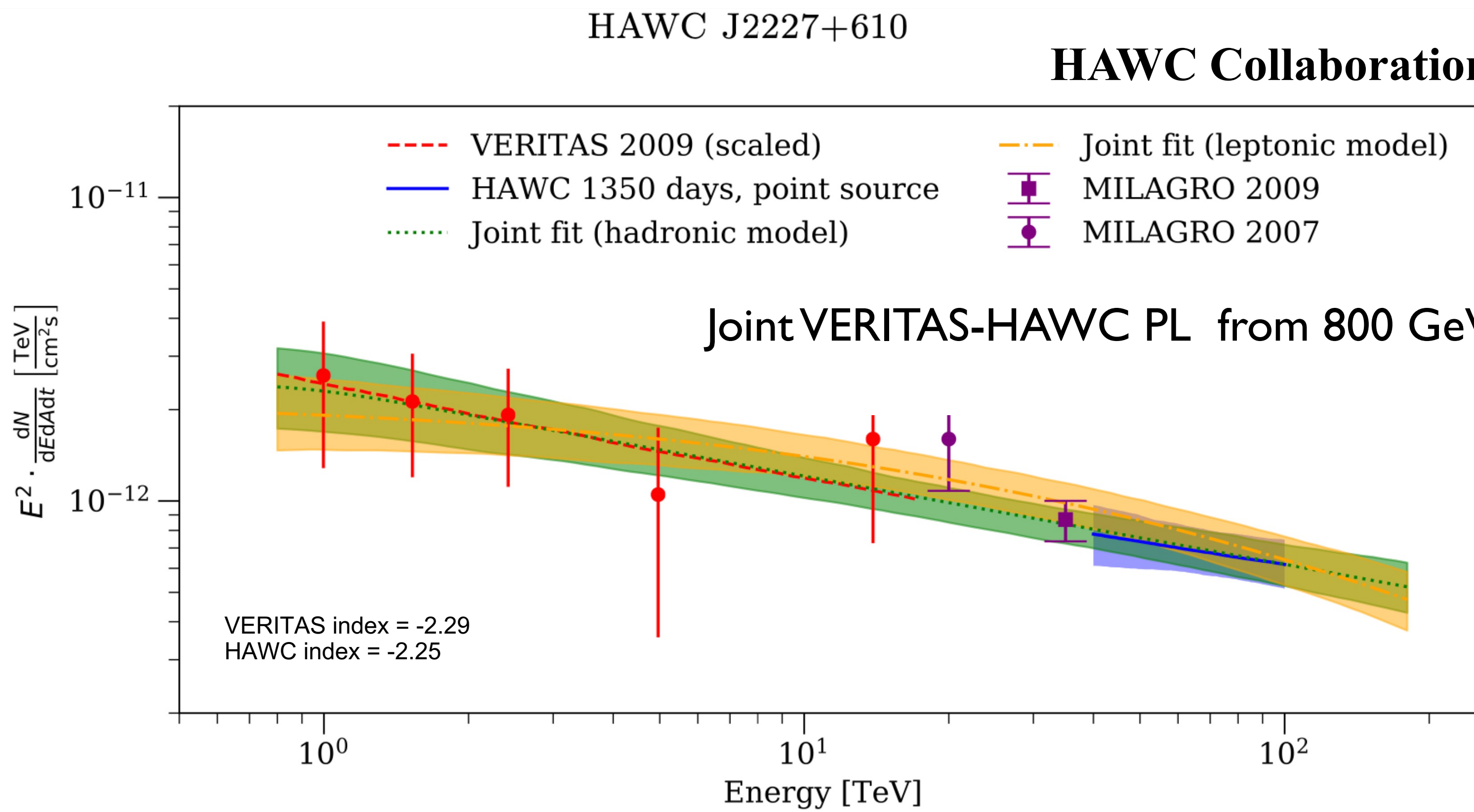
SNR G106.3+2.7 and the Boomerang region

- 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

HAWC Collaboration, ApJL 2020



G106.3+2.7 : a Galactic PeVatron?



HAWC Collaboration, ApJL 2020

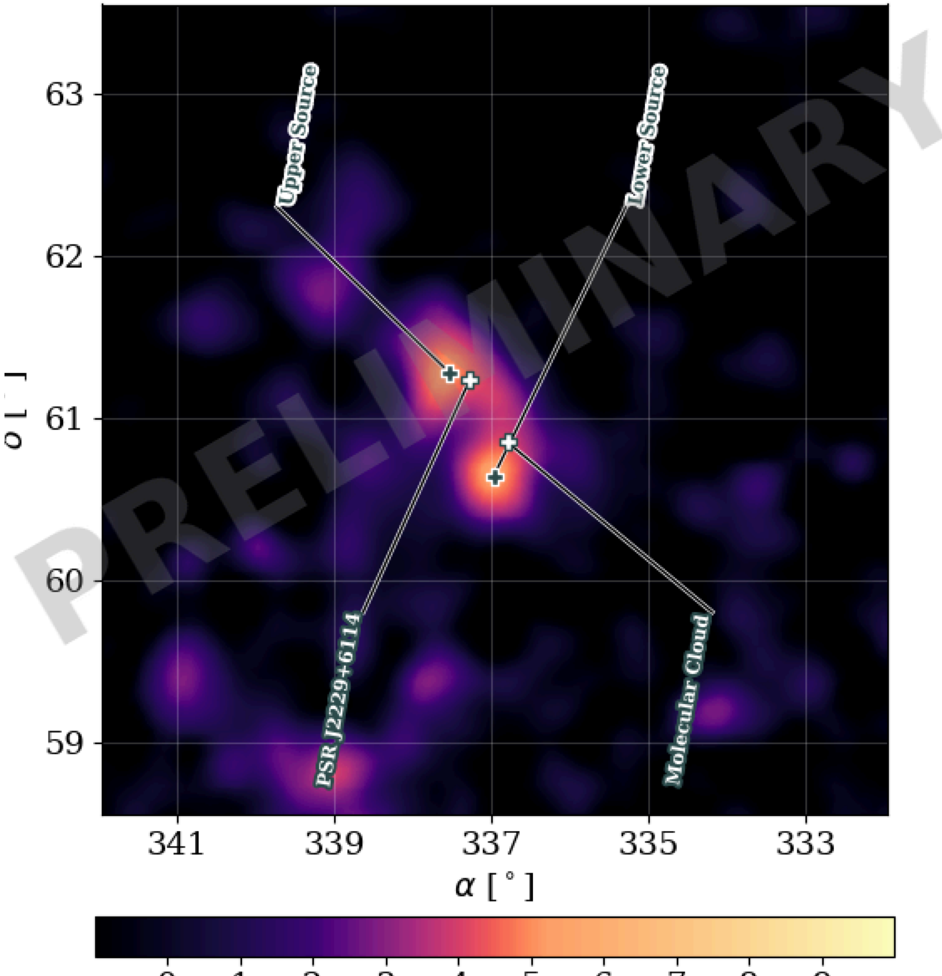
Joint VERITAS-HAWC PL from 800 GeV to 180 TeV

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

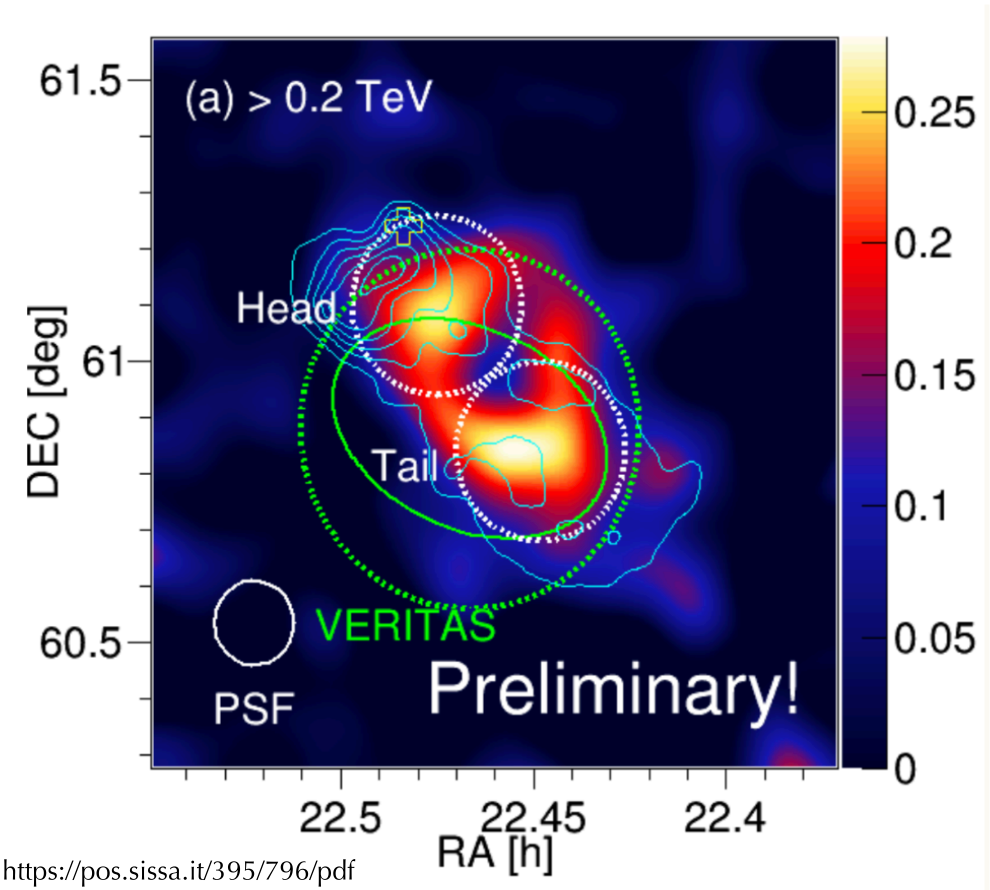
Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

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

Boomerang region: tail and head



HAWC Collaboration, 2021



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

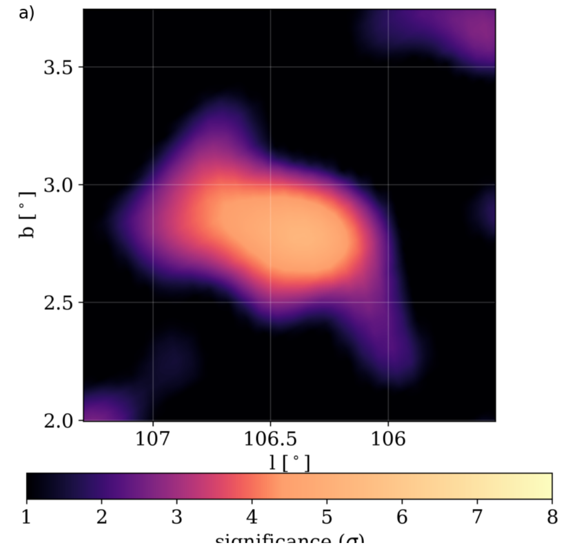
Head Region Contains PSR J2229+6114 and its nebula

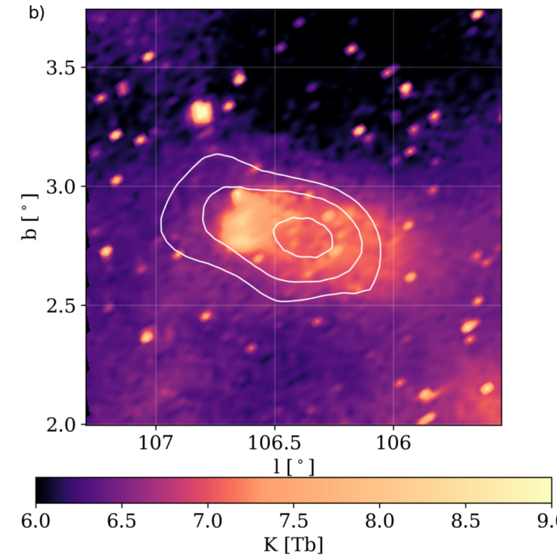
Tail Region contains SN ejecta - SNR G106.3+2.7

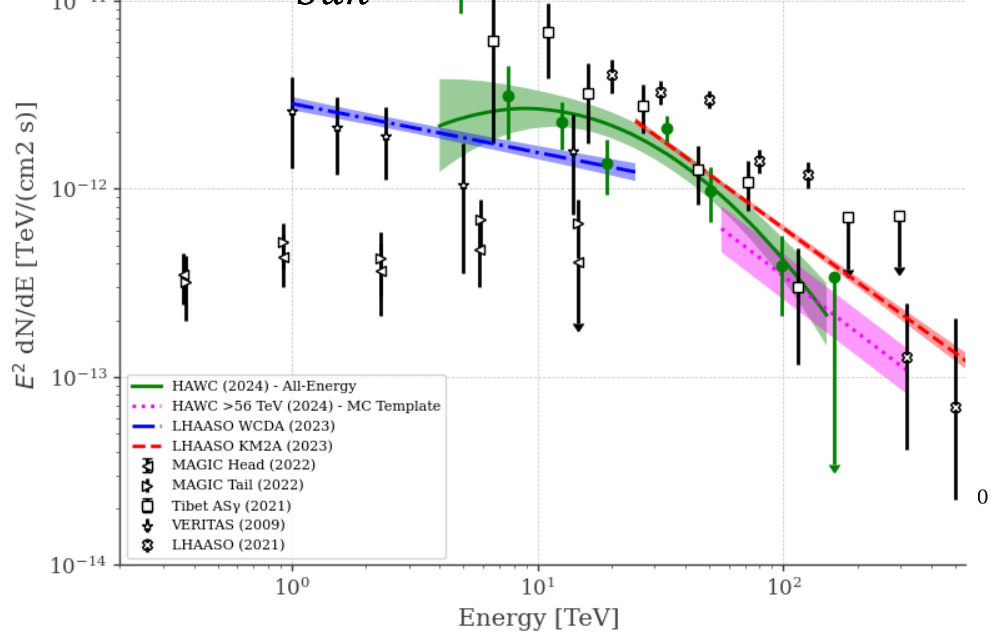
> 56 TeV photons from MC complex close to SNR G106.3+2.7

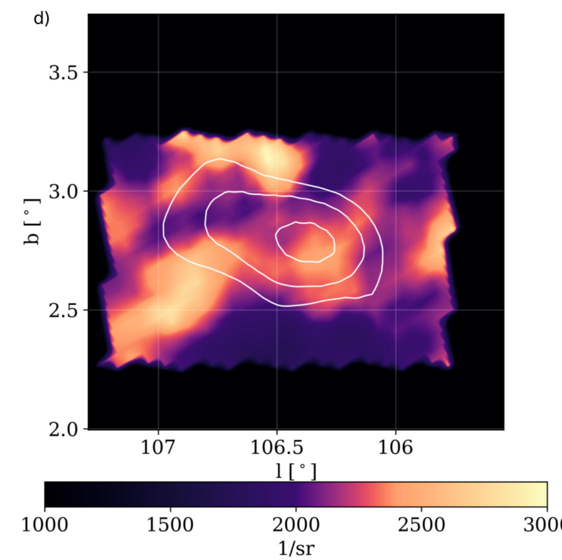
HAWC Collaboration, A&A 2024

- 2565 days Pass 5 data
- Emission > 56 TeV comes from a region between tail and head
- PL spectrum
- Morphology best fit with Planck 353 Ghz dust opacity map template
- If hadronic
  $w_p\,(> 560\ TeV) \sim 10^{-2} \sim 100\ w_{Sun}$









Looking for TeV photons from the Sun

The rise of the TeV Sun.

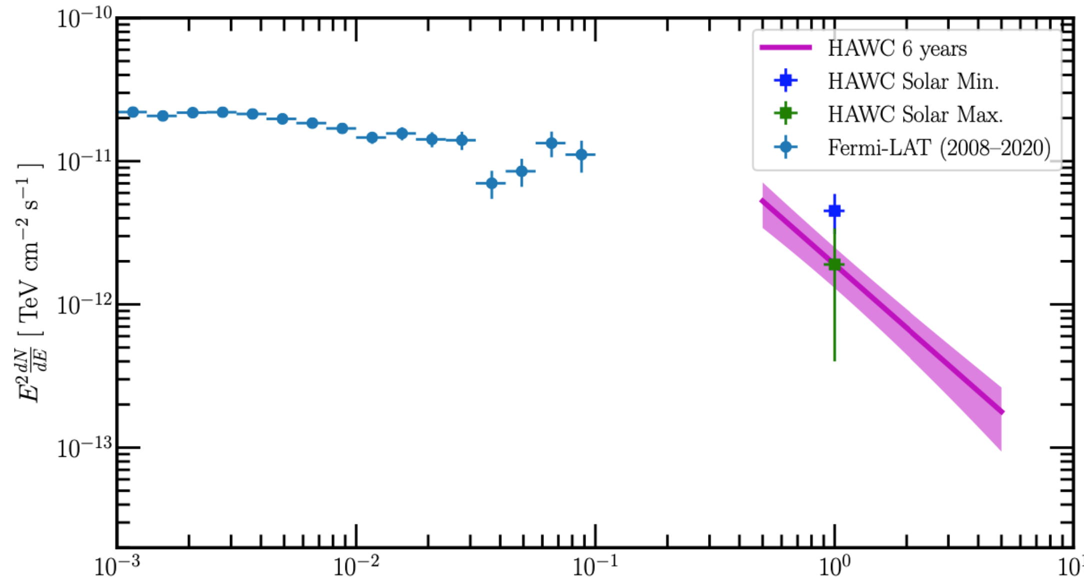
Fermi sees the Sun up to ~100 GeV

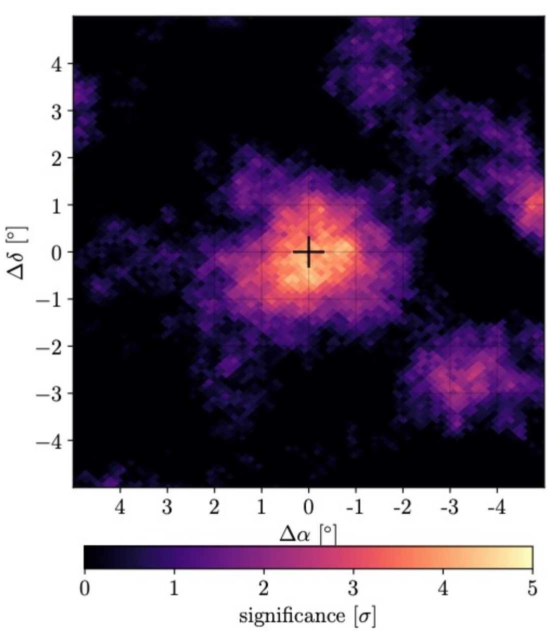
Correlated to solar cycle. Higher flux at Solar Min

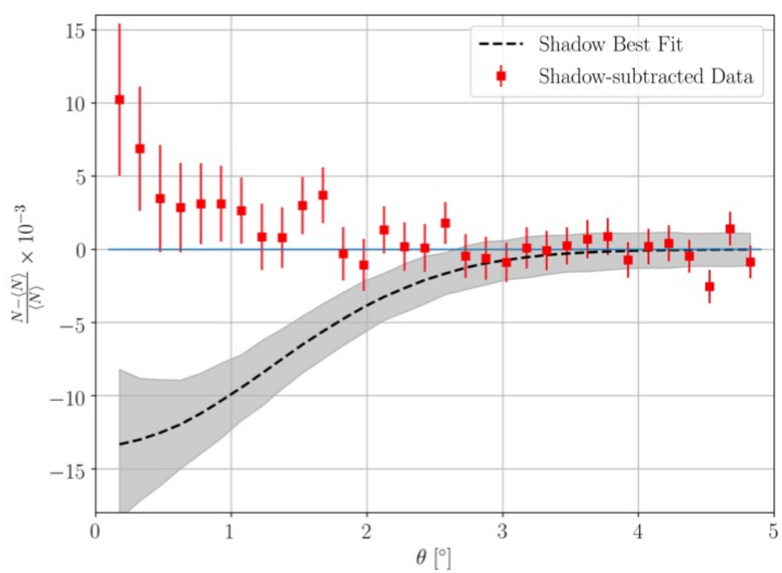
Emission mechanism thought to be from CR hadrons interacting with the atmosphere of the sun

Not necessarily in the limb

HAWC, ApJ 2022







Anticorrelation with solar activity

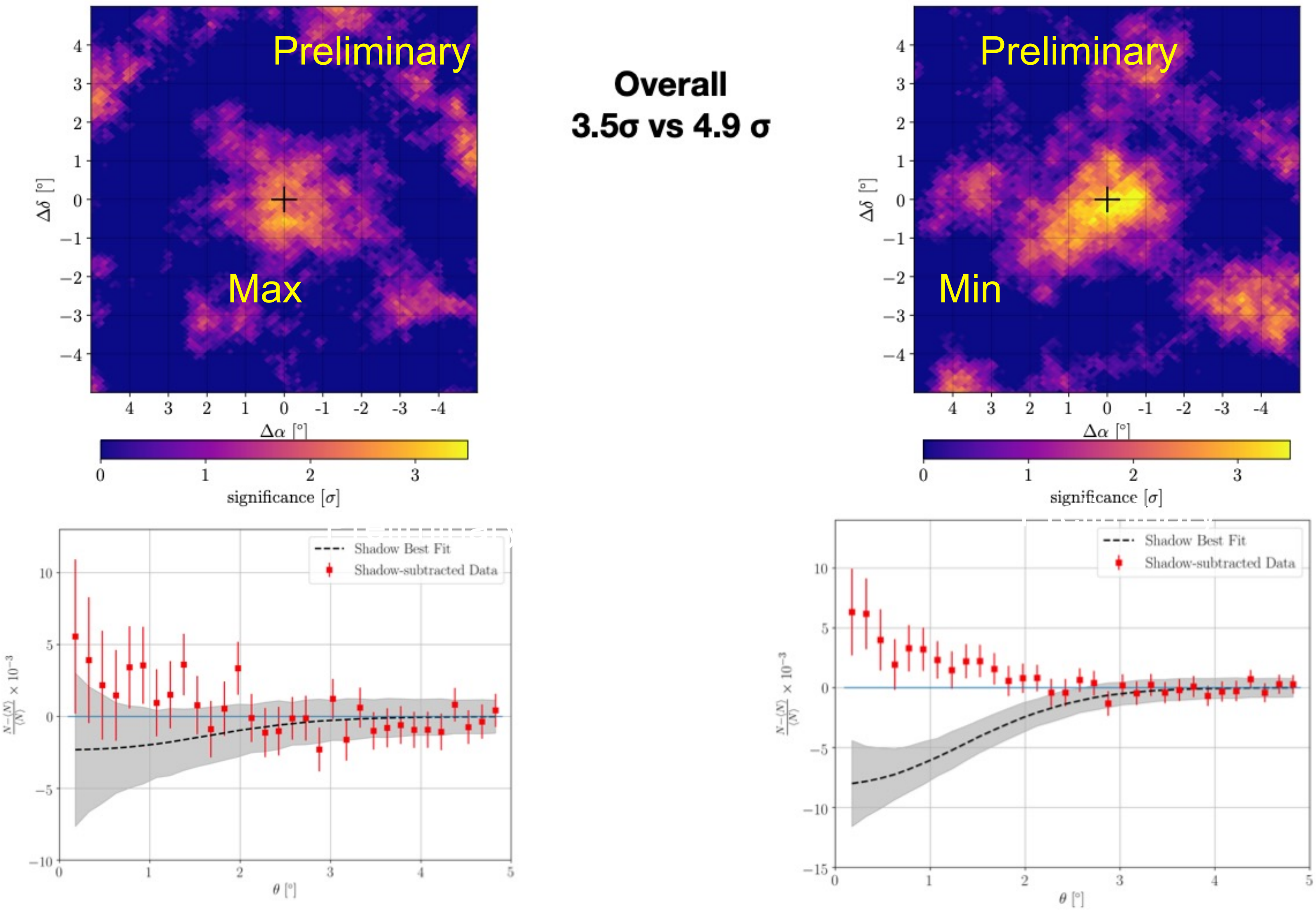
In HAWC PL index 3.62

6.1 yr of data

6,3 sigmas

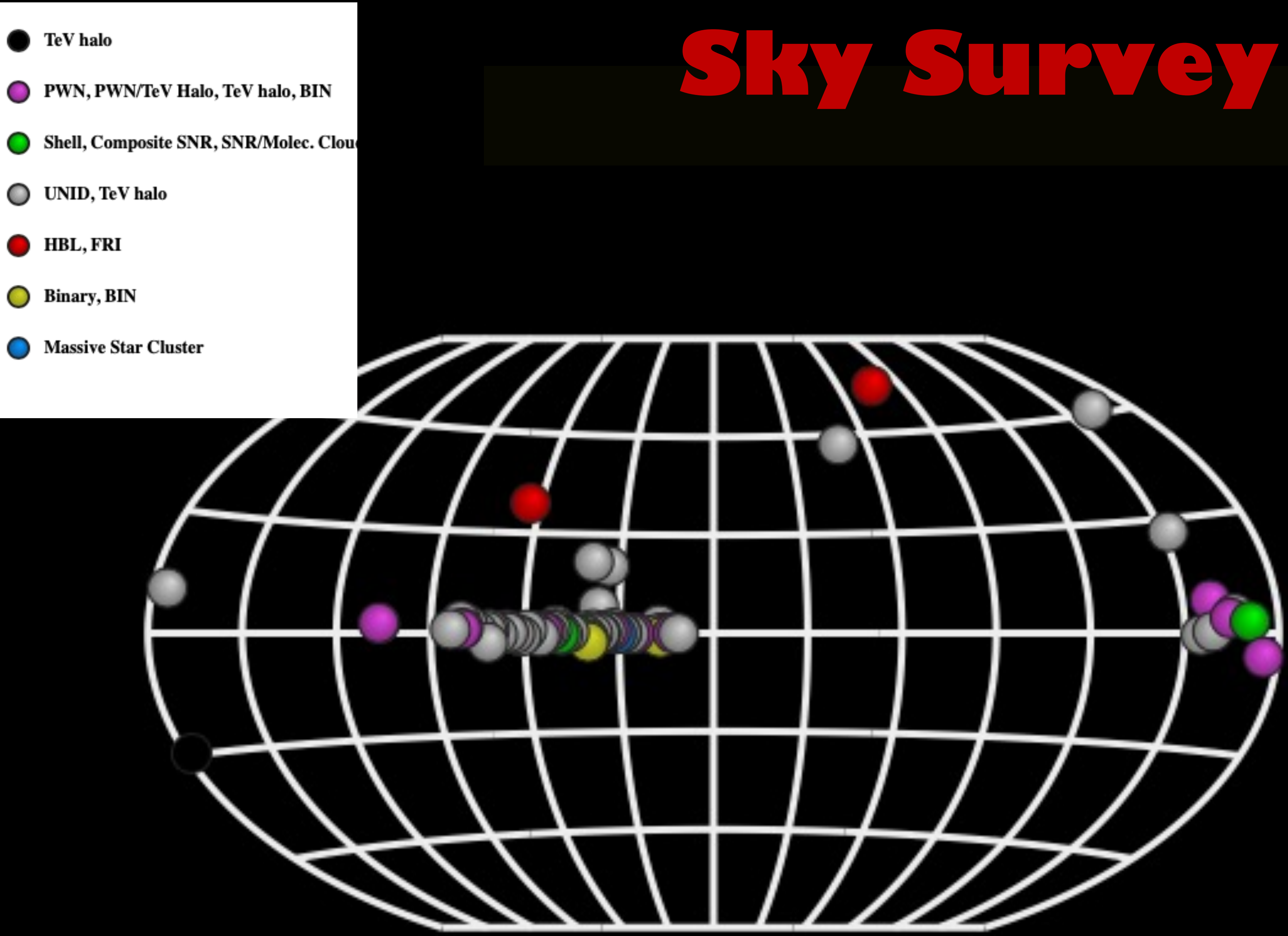
Solar Max and Solar Min

HAWC, ApJ 2022



Overall
3.5σ vs 4.9 σ

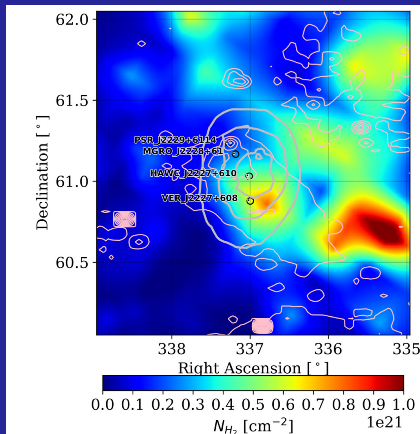
Sky Survey



76 SOURCES IN TEVCAT

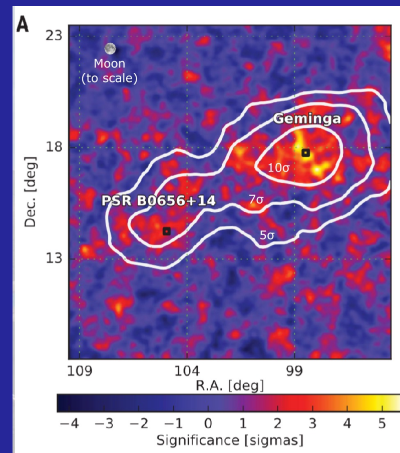
Extreme accelerators in HAWC sky

Apj 2020-2024



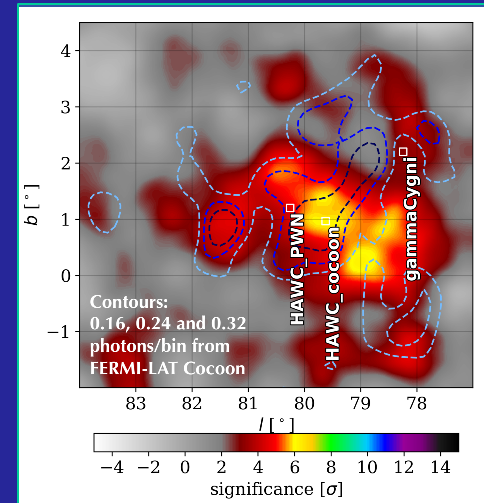
Boomerang SNR-MC Cloud

Science 2017



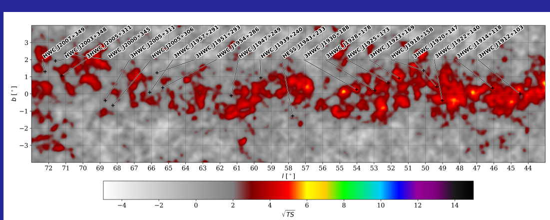
Geminga

Nat Astr 2021

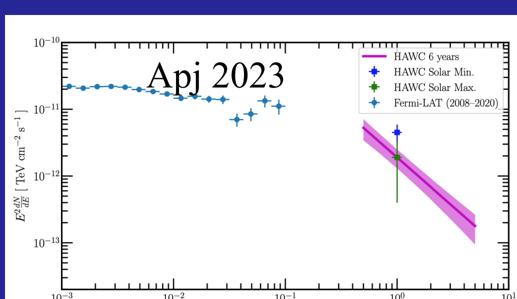


Cygnus Bubble

ApJ 2023

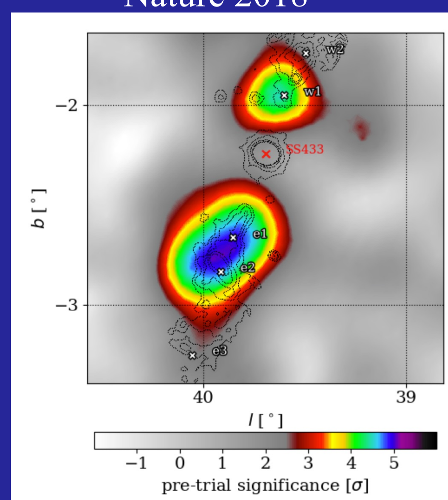


Diffuse Emission

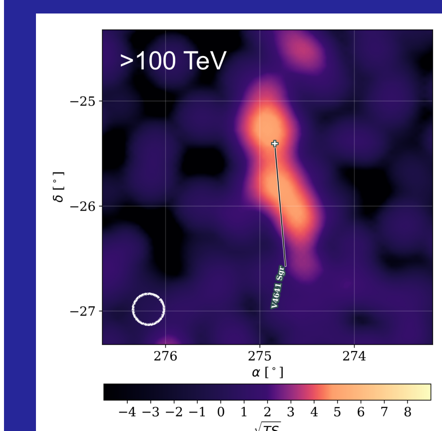


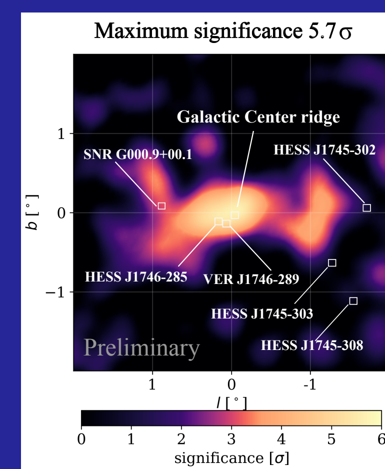
The Sun

Nature 2018



Nature 2024





Gal Centre

Microquasars

Conclusions and Outlook

Since 2013 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
- Long monitoring of extragalactic sources such as Mrks

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

The detector and Pass5 reconstruction

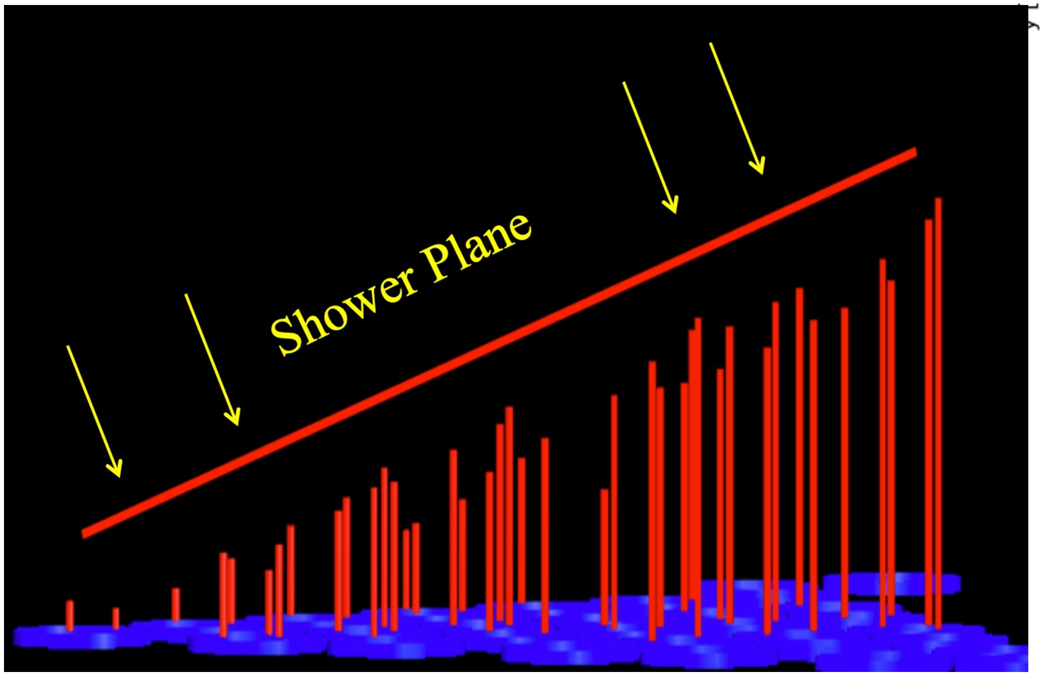
Direction reconstruction

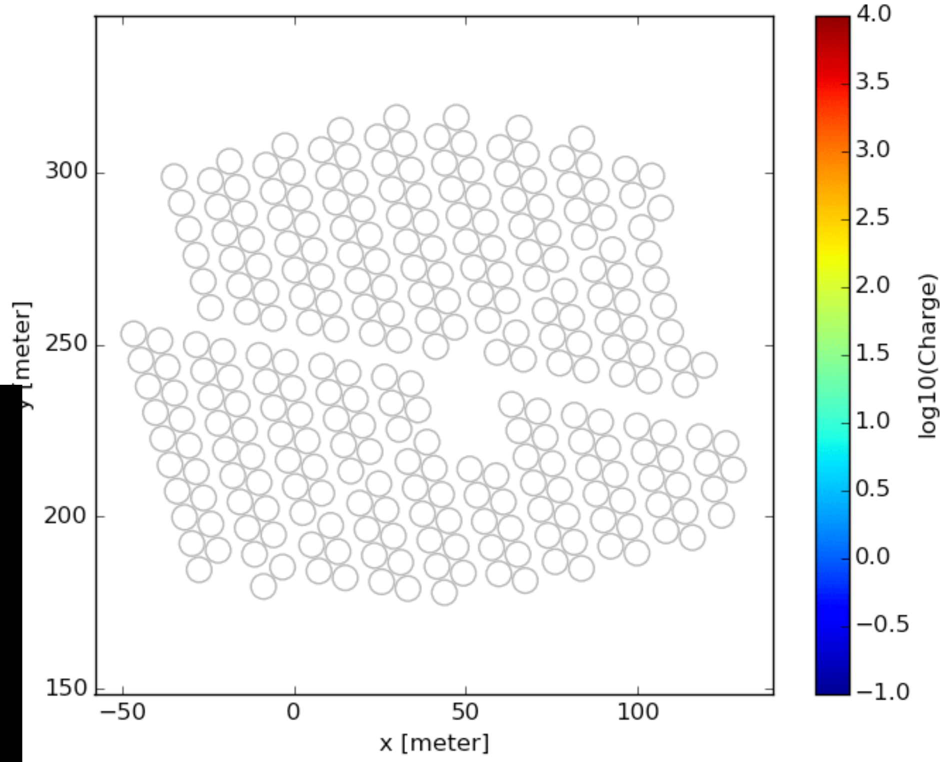
The concentration of secondary particles is highest along the trajectory of the original primary particle, termed the air shower core.

Determining the position of the core on the ground is key to reconstructing the direction

At first order, we fit a plane to the relative timing of each PMT

Sub-nanosecond precision is needed

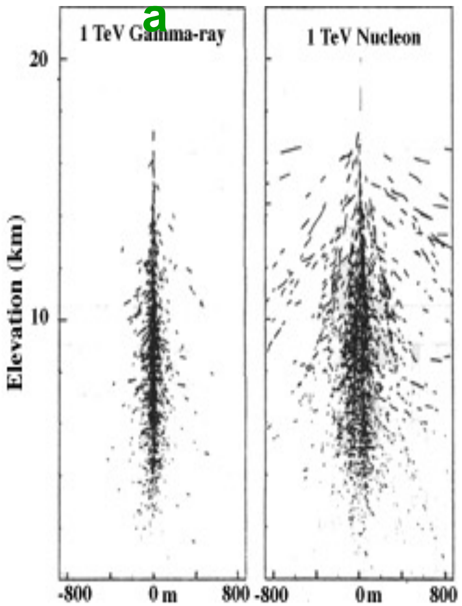




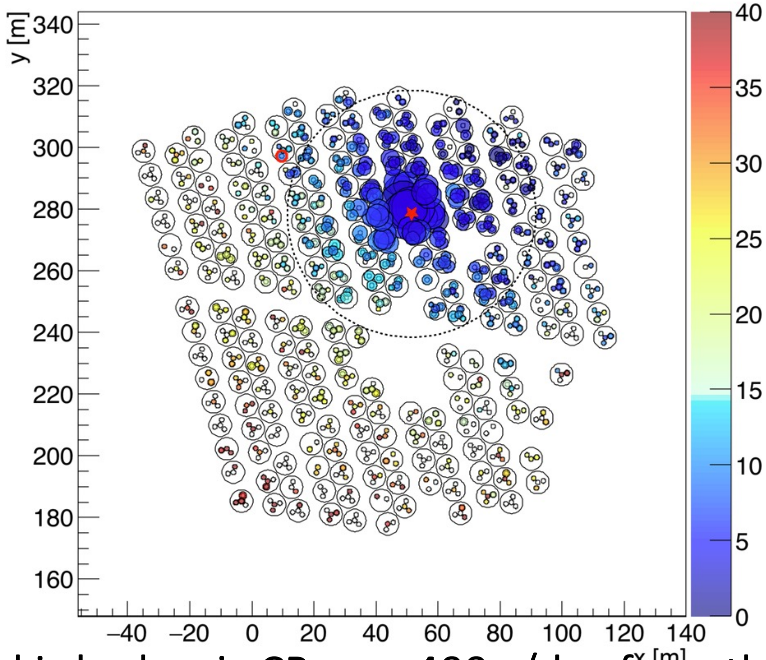
Gamma-Hadron Separation

Simulation

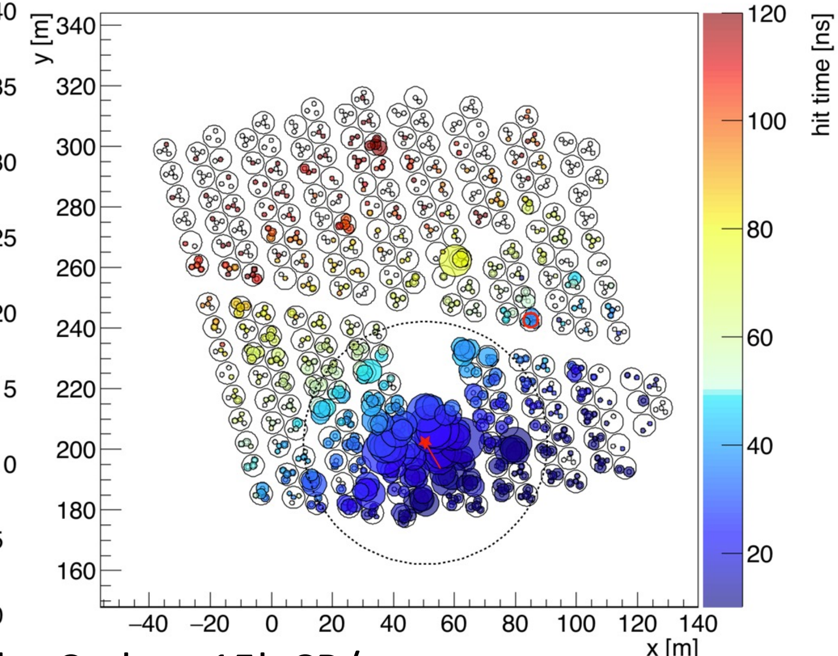
Gamm
a **Hadron**



HAWC Data
Likely Gamma Ray



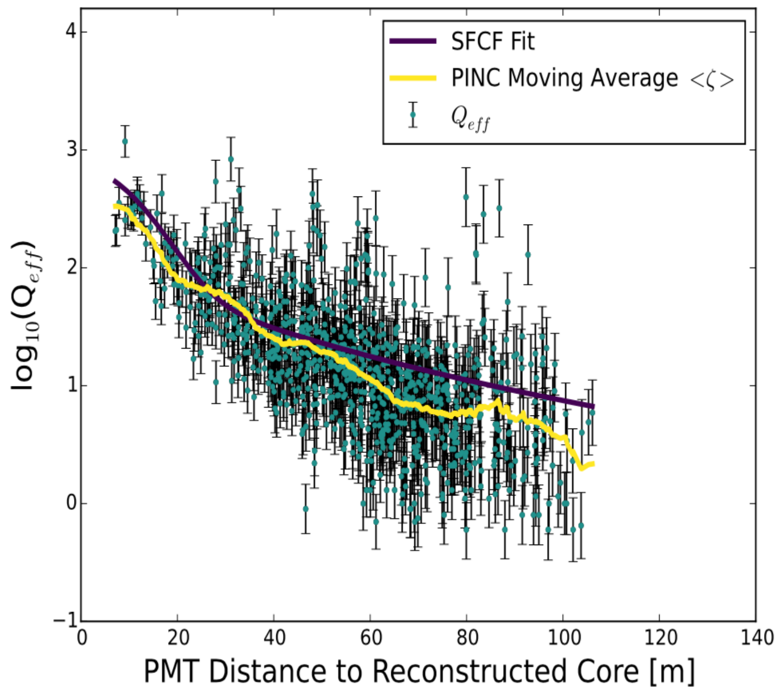
HAWC Data
Hadron Shower



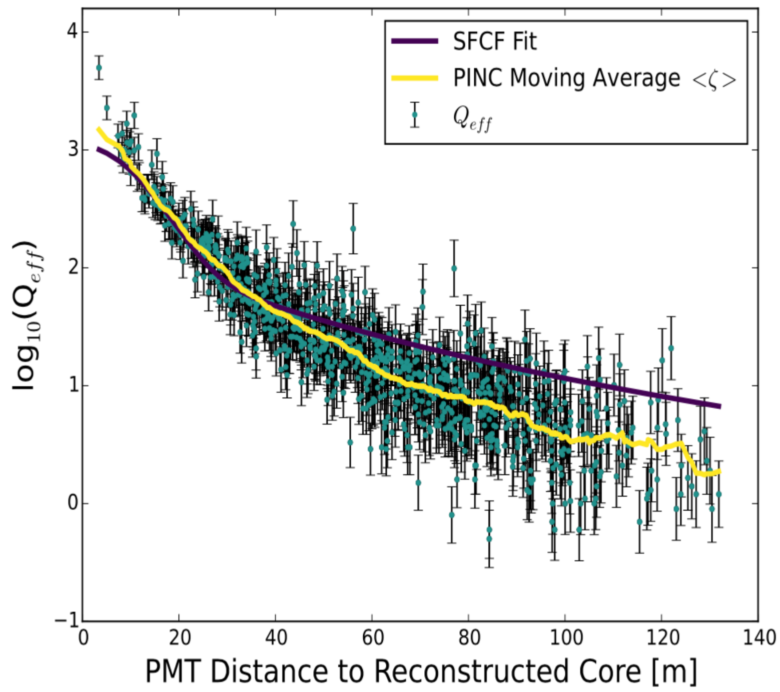
- Main background is hadronic CR, e.g. 400 γ/day from the Crab vs 15k CR/s.
- Gamma/hadron can be discriminated based on the event footprint on the detector: gamma-ray showers are more compact, cosmic rays showers tend to "break apart”
- Showers appear quite different particularly above several TeV..

Shower reconstruction

Clumpy: hadron-like



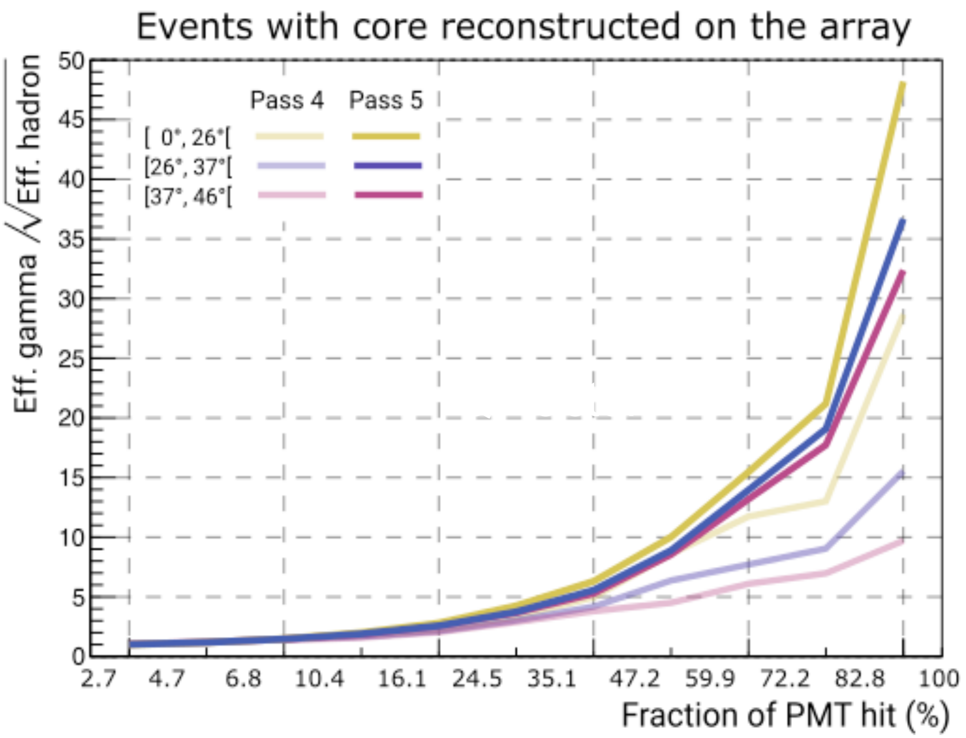
Smooth: gamma-like

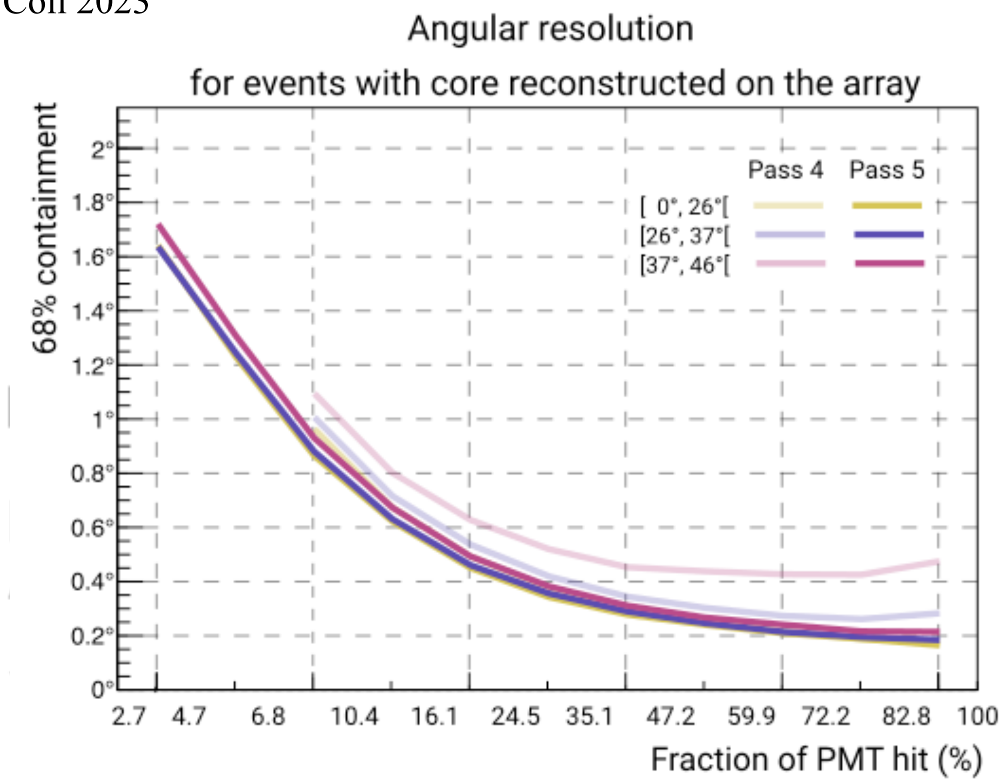


Reference: Crab paper, ApJ 843 (2017), 39, HAWC Coll 2023

Pass 5 reconstruction

HAWC Coll 2023





$$Q = \frac{\text{Efficiency}_{\text{gammas}}}{\sqrt{\text{Efficiency}_{\text{hadrons}}}}$$

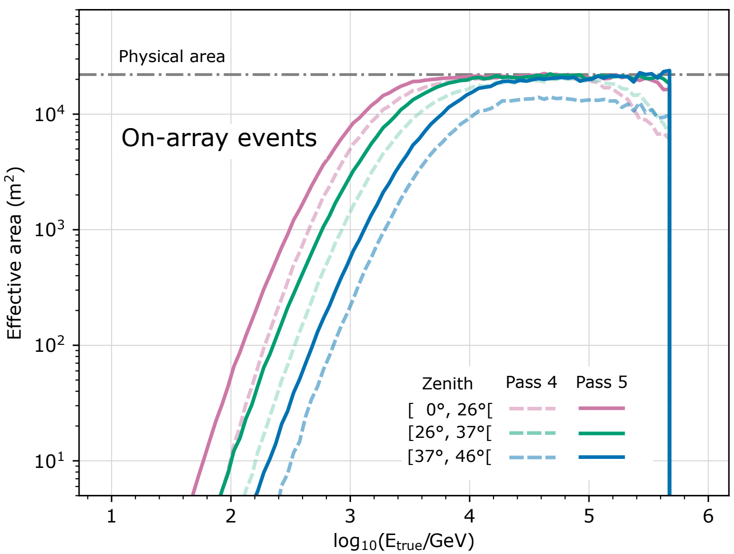
Large Events - Much improved background rejection

Better Angular Resolution - doesn't degrade at high zenith angles

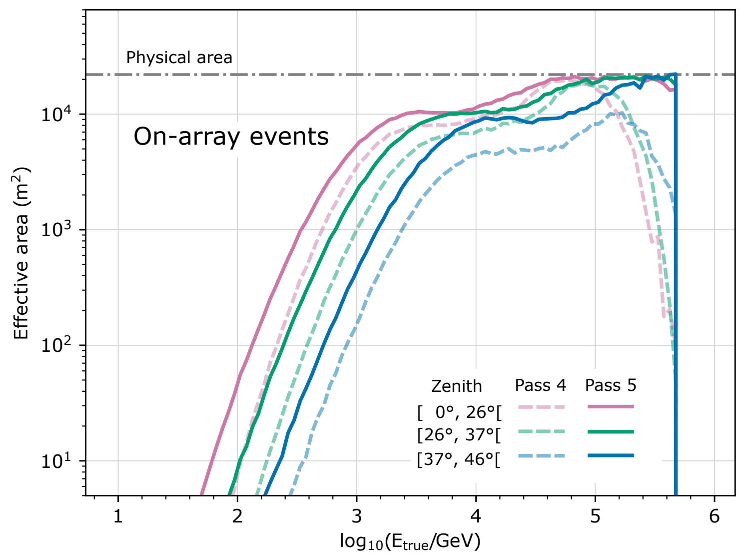
Wider FOV - Previous 45° now 60°

Pass 5 Reconstruction

HAWC Coll 2023

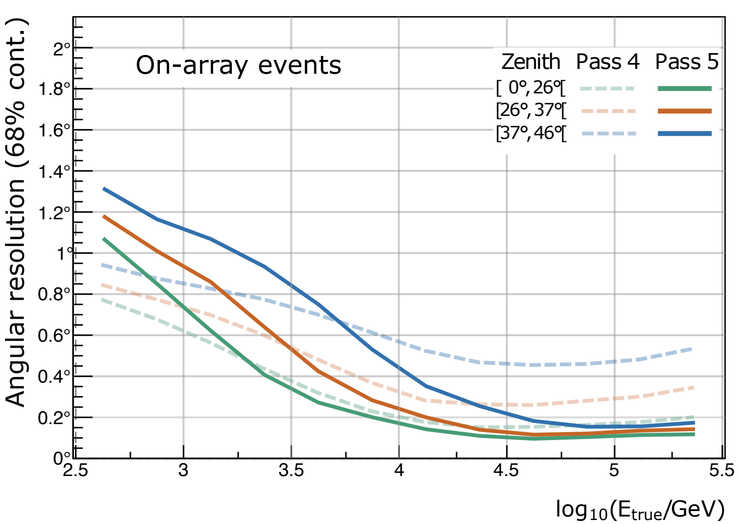


(a) Trigger conditions

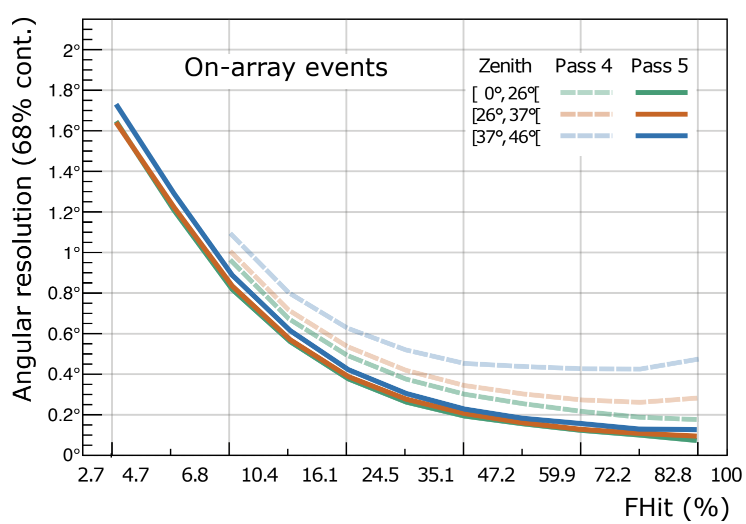


(b) Gamma/hadron cuts

5 times effective area at low energies



(a) Energy

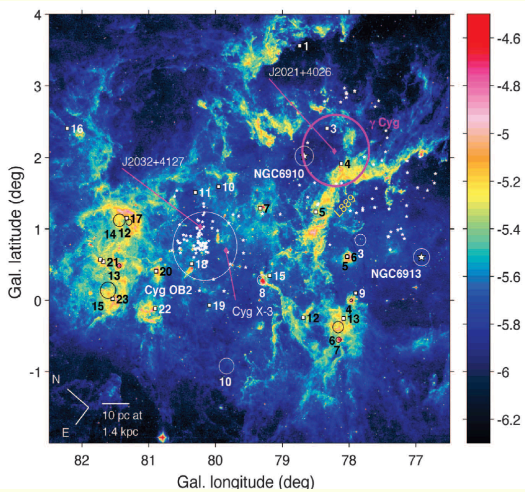


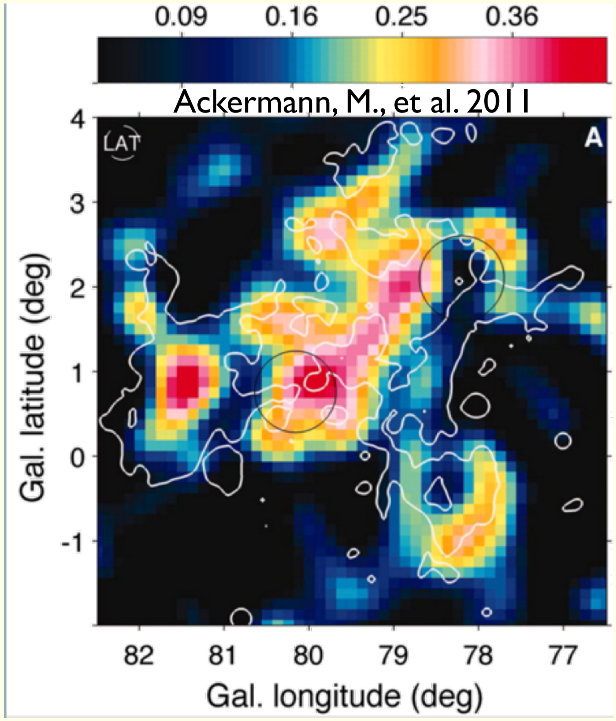
(b) FHit

3 times better angular resolution at high zeniths

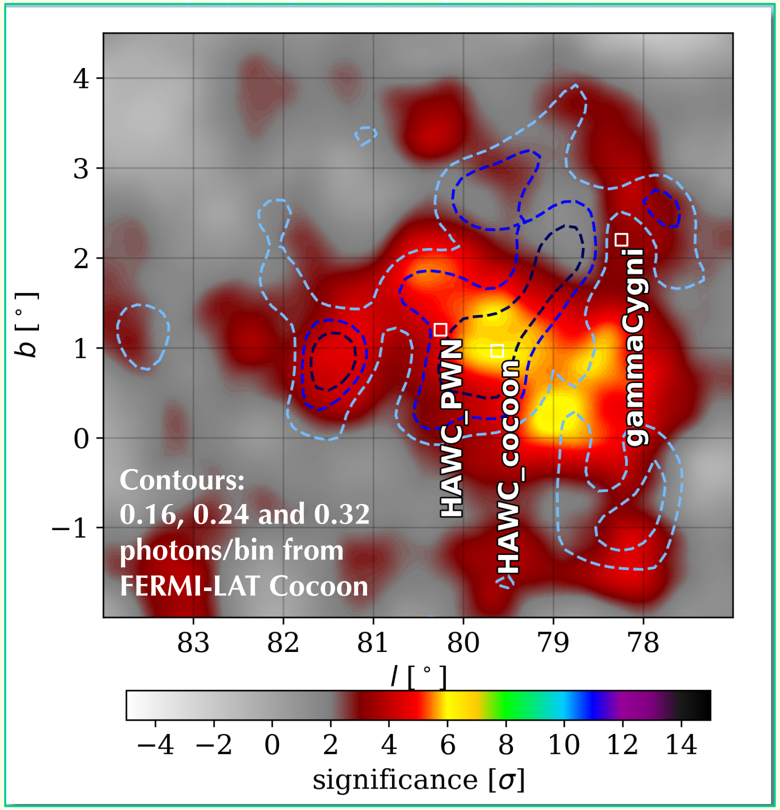
VHE AND UHE Photons from SFRs and the origin of Galactic CRs

Cyg OB2 in IR, GeV and TeV





HAWC Coll, NatAstr 2021

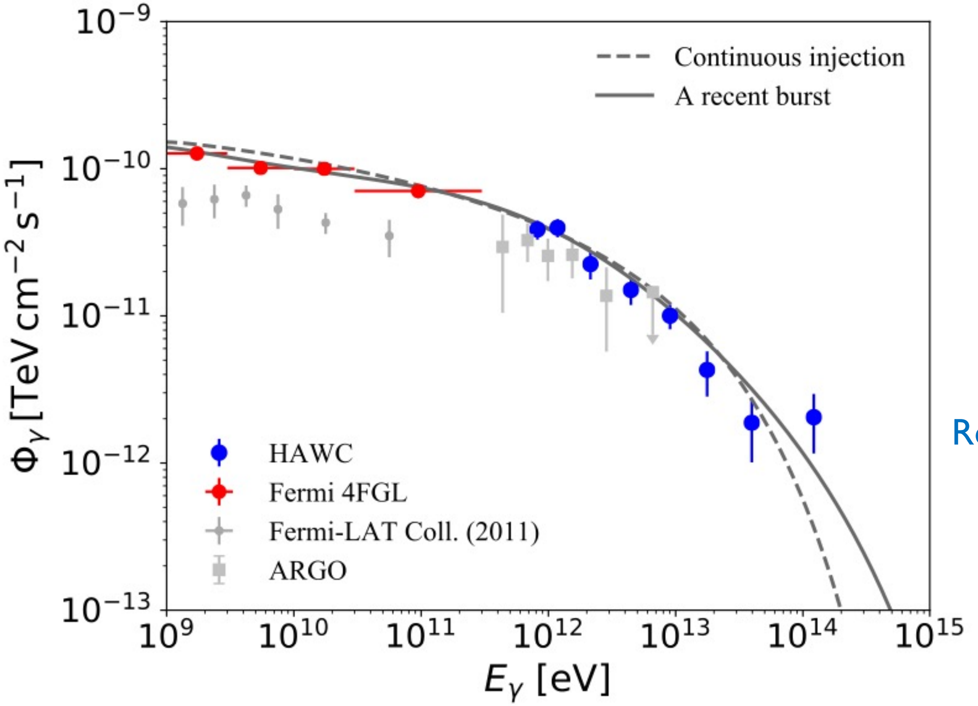


Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

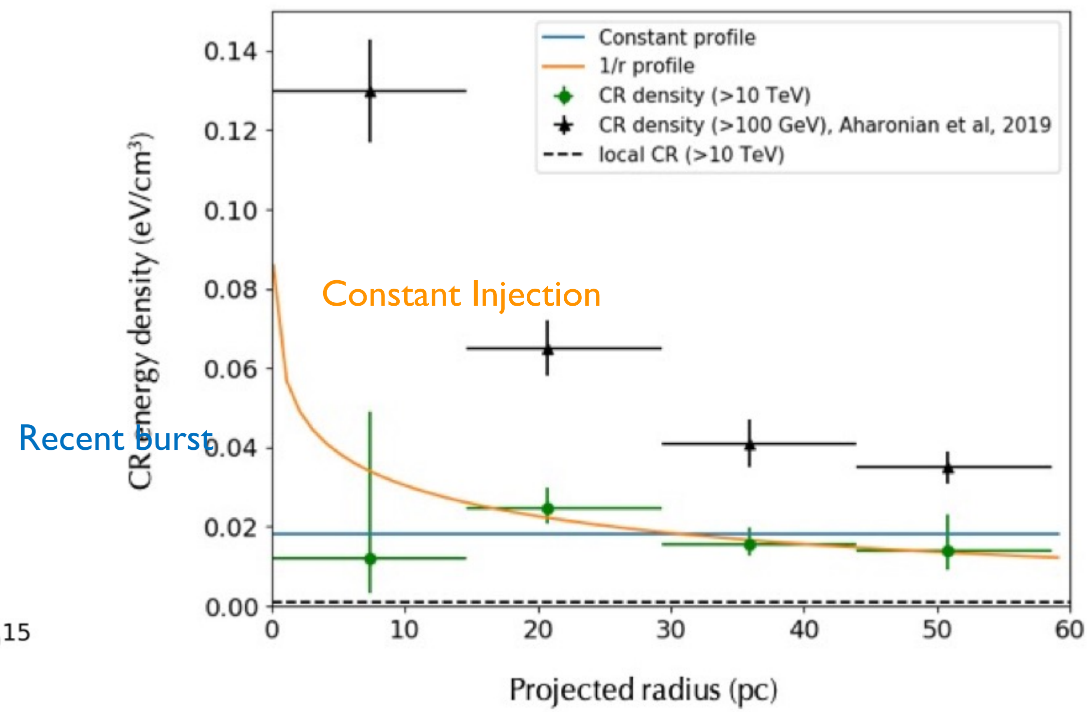
First superbubble up to 100 TeV energies

Cosmic Ray Acceleration in SFRs

Hadronic Model



Nat Astr, HAWC 2021



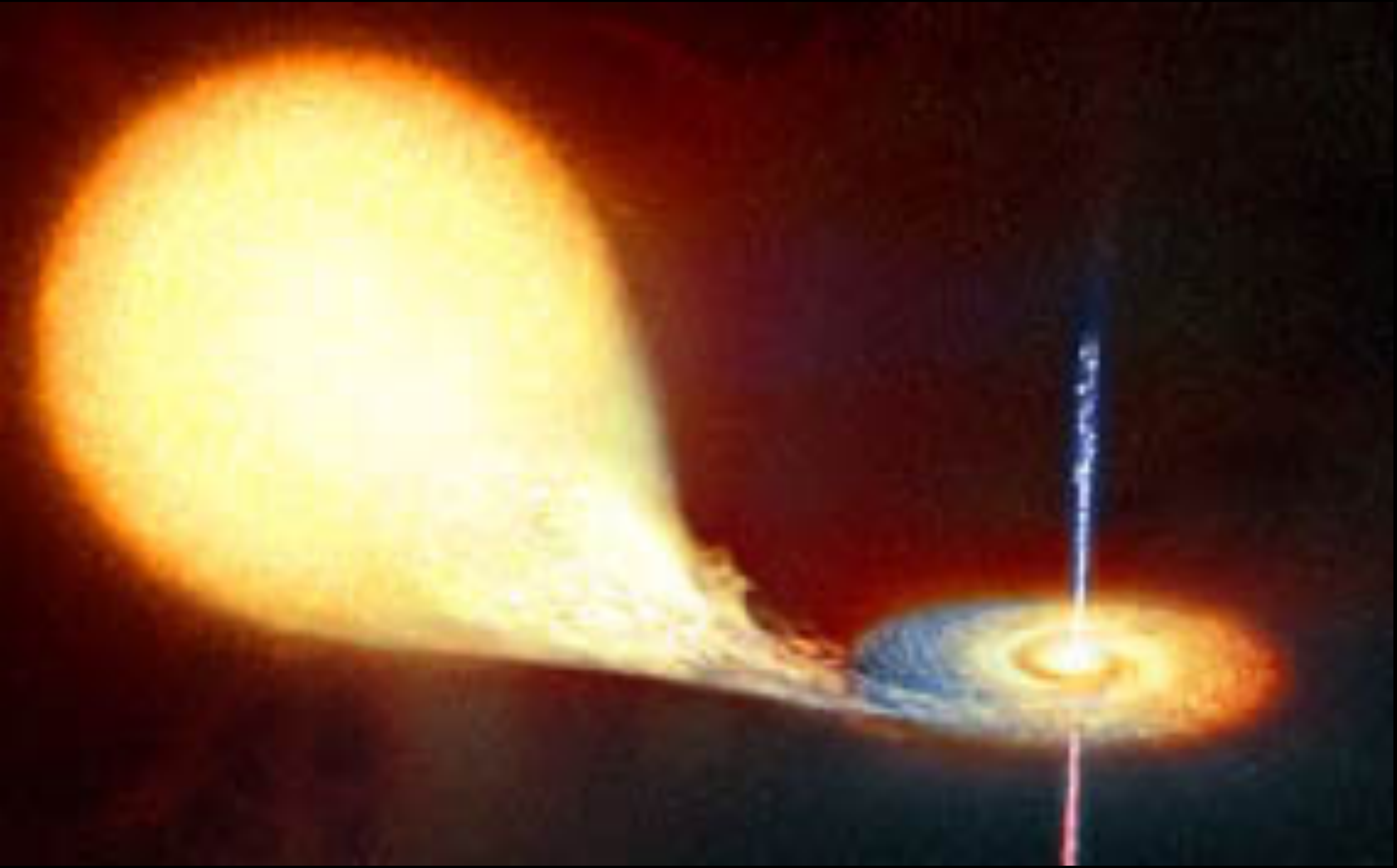
CRs up to PeV energies accelerated within a region the SFR

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

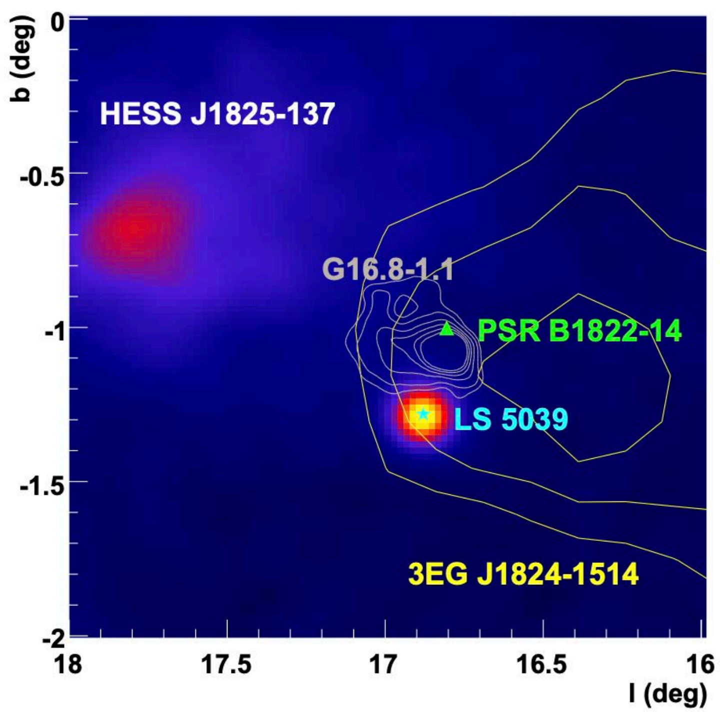
10000 CygOB2 would be required for CRs Galactic population

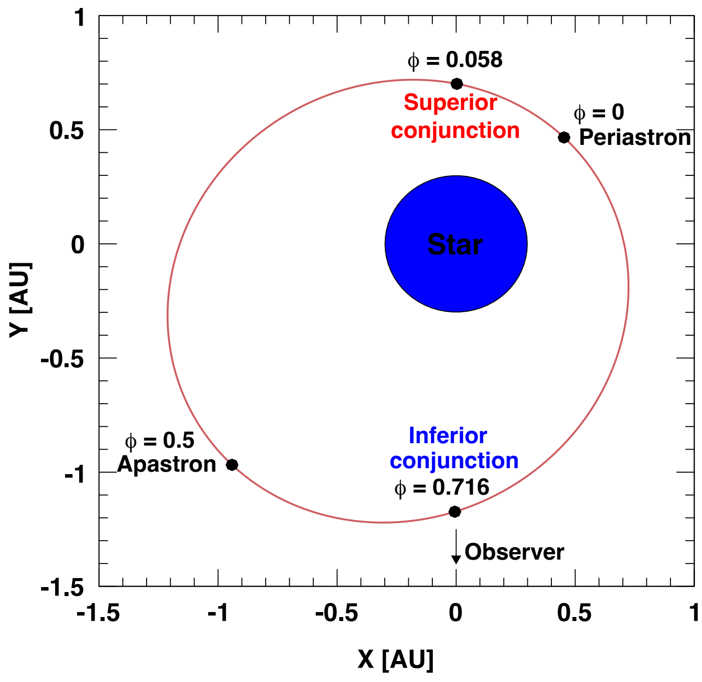
HAWC Observations of LS5039



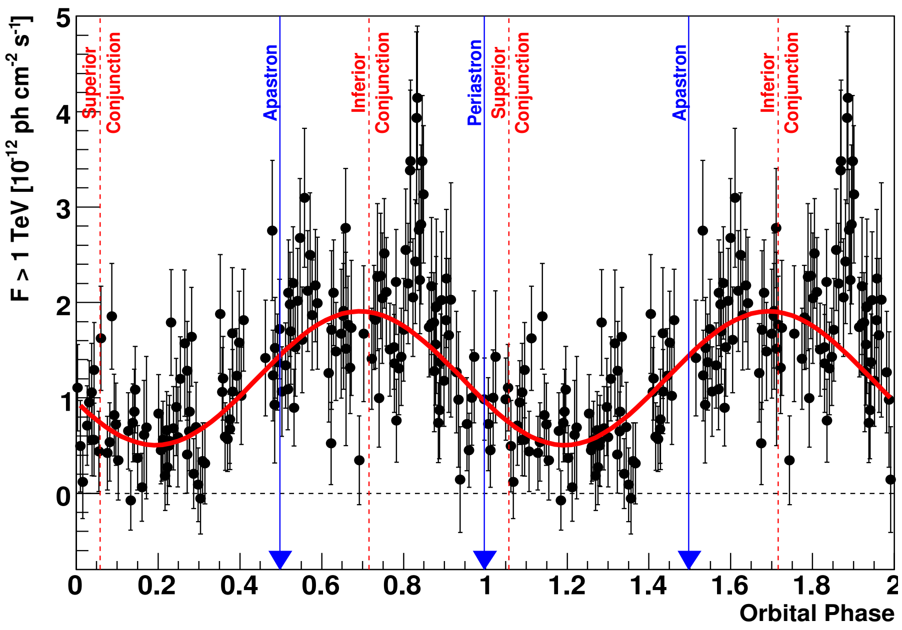
LS5039

- 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.



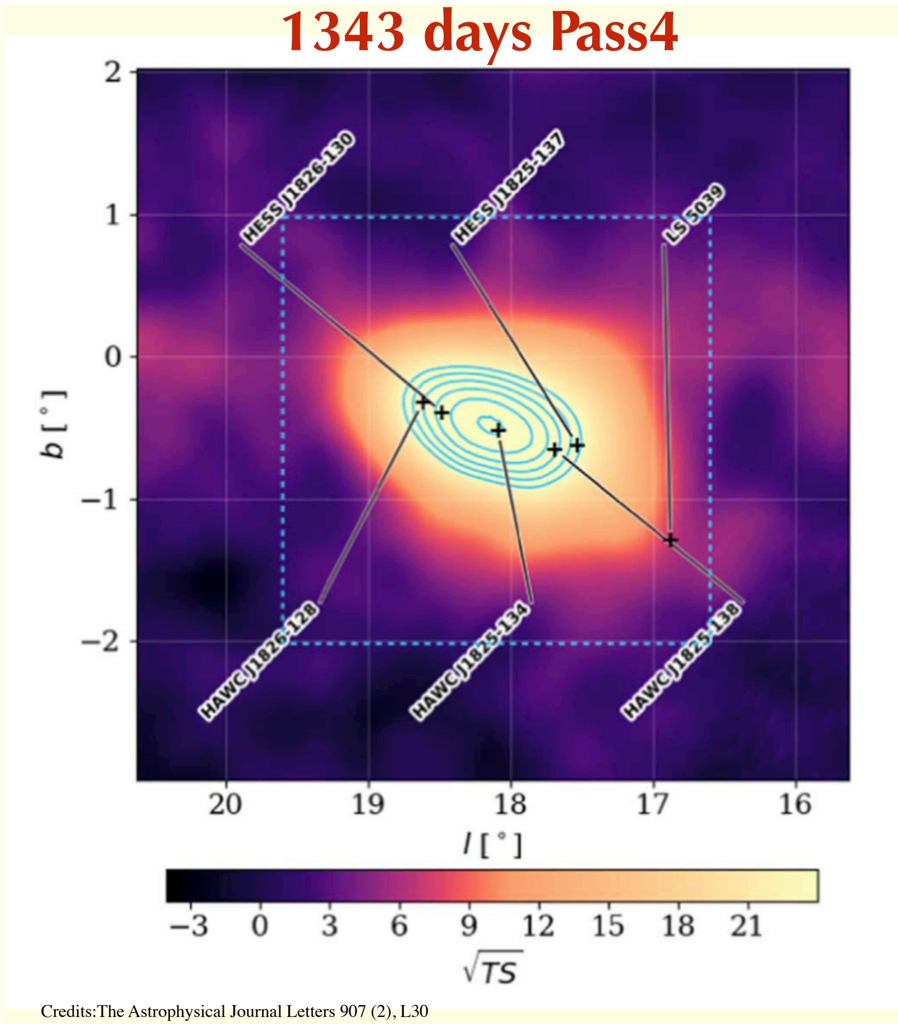


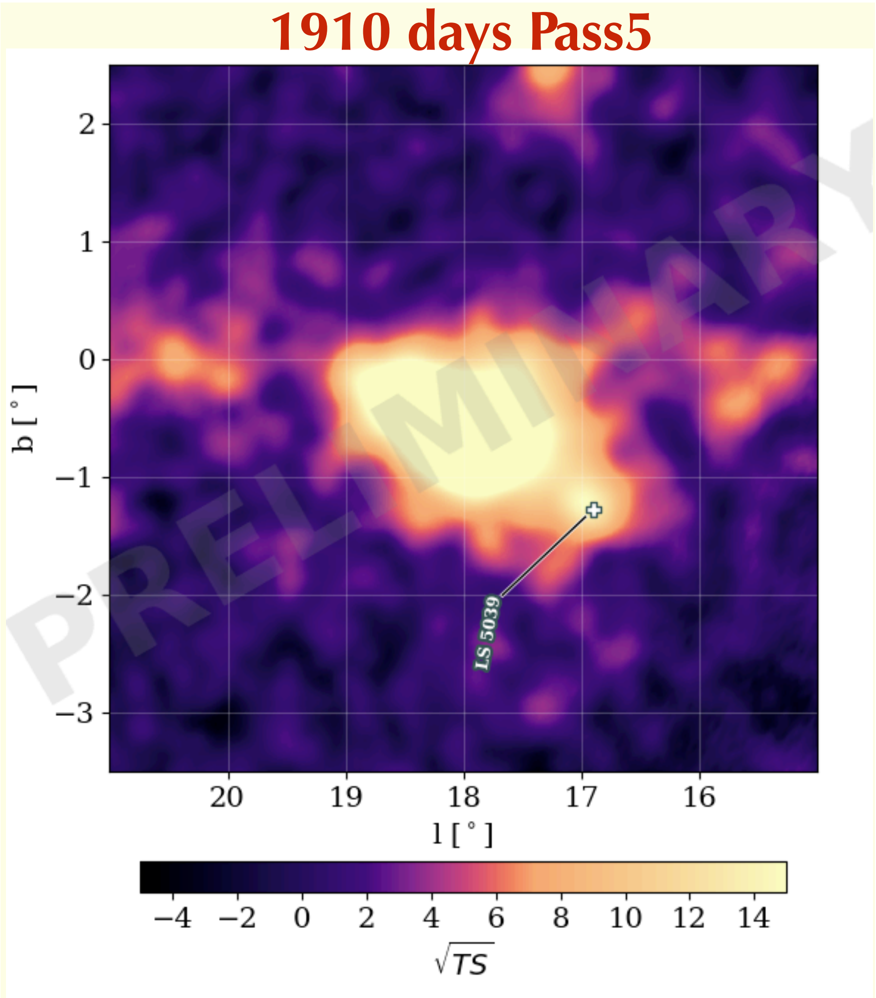
H.E.S.S. 2007 Astrophys Space Sci (2007) 309: 277–284



(Aharonian et al. 2005)

LS5039 region with Pass 5

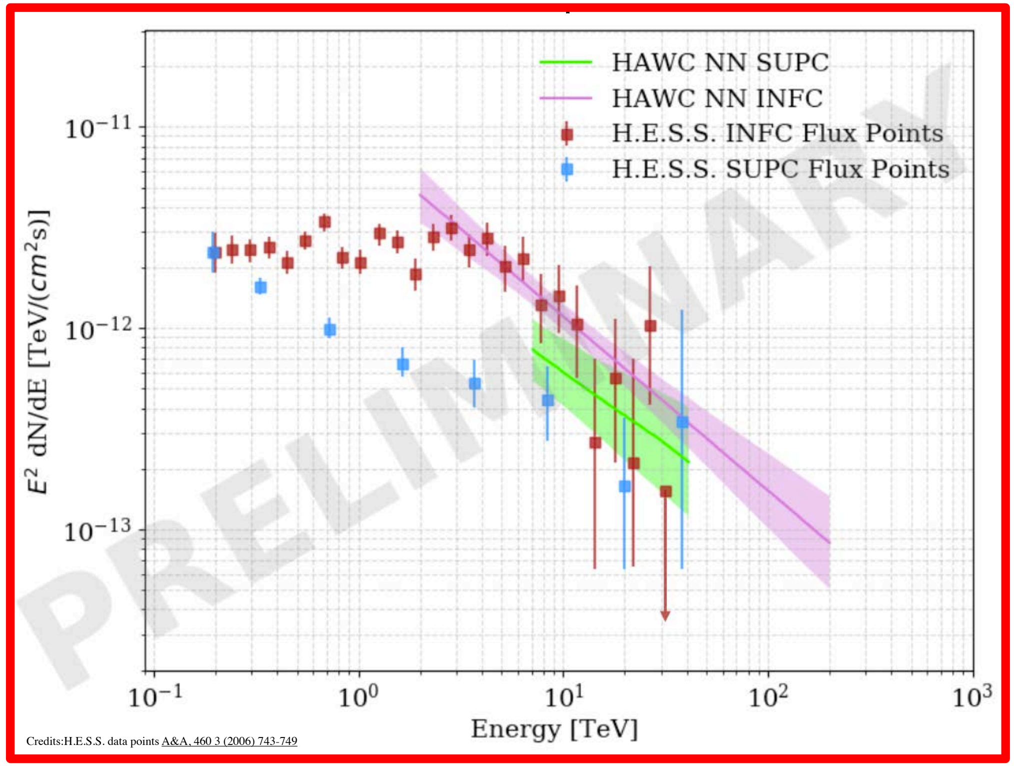


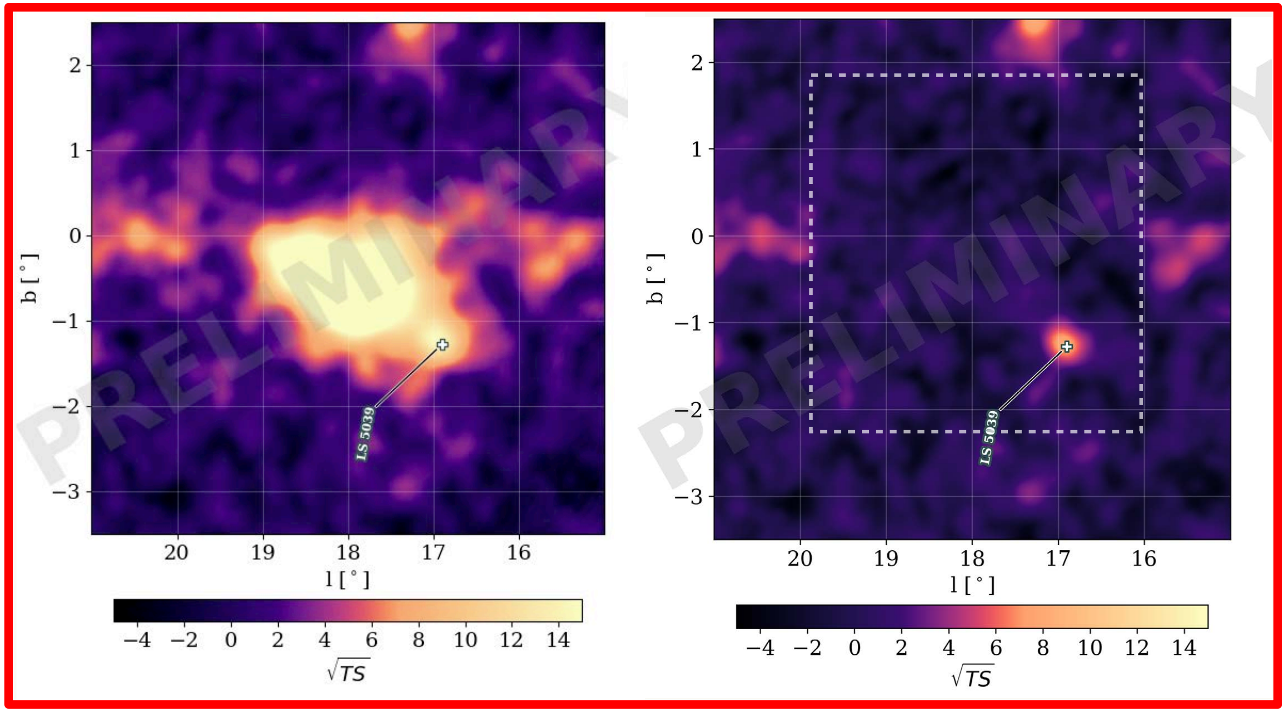


Dezhi Huang, ICRC 2023

LS5039 with HAWC

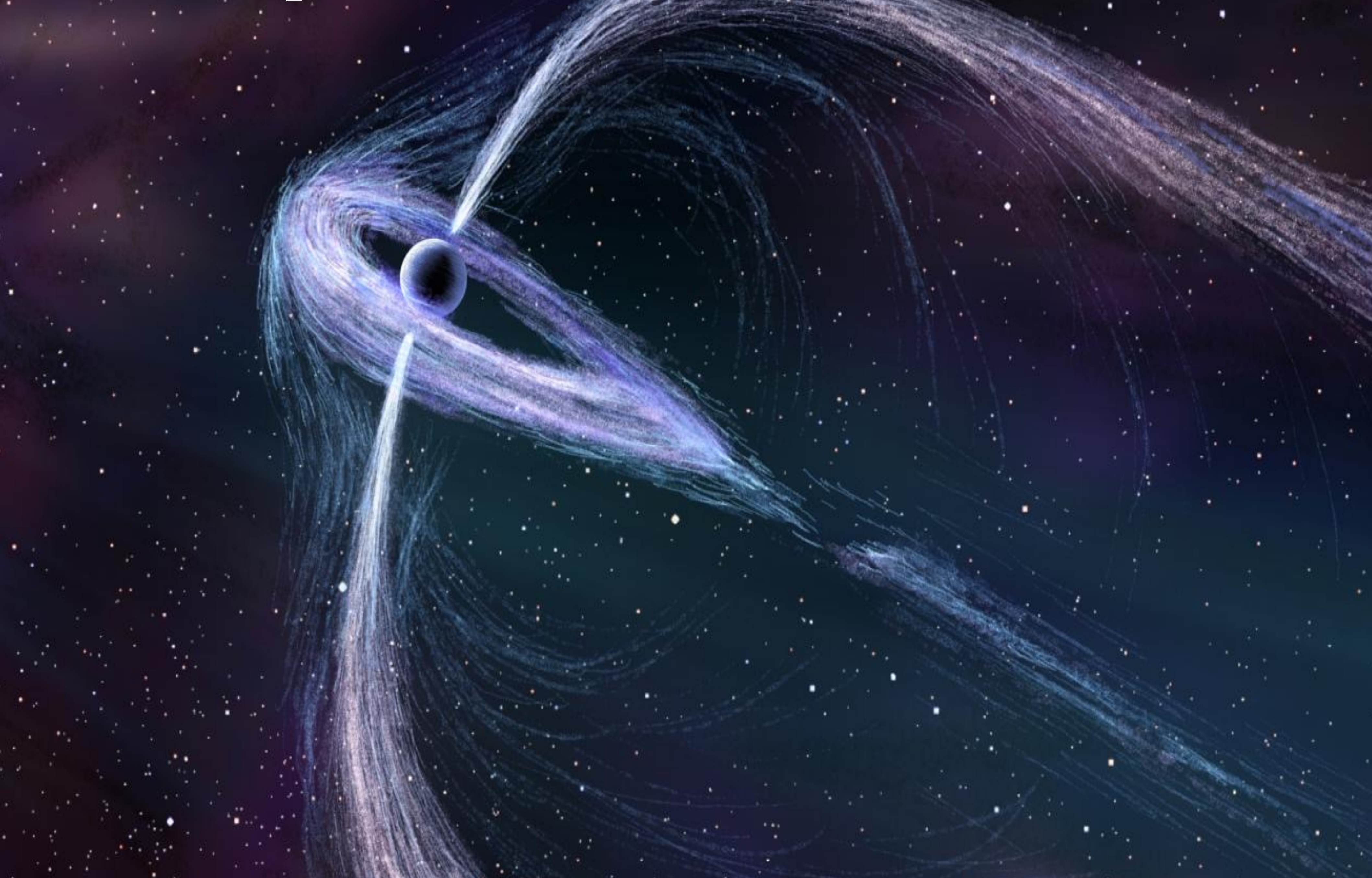
- 1910 days of data
- Simultaneously likelihood fit performed inside the region of interest
- Model includes diffuse background emission and all background sources
- About 8 σ
- Pure powerlaw preferred
- HAWC spectrum is located in between of H.E.S.S. Inferior conjunction (INFC) and Superior conjunction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





Dezhi Huang, ICRC 2023

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

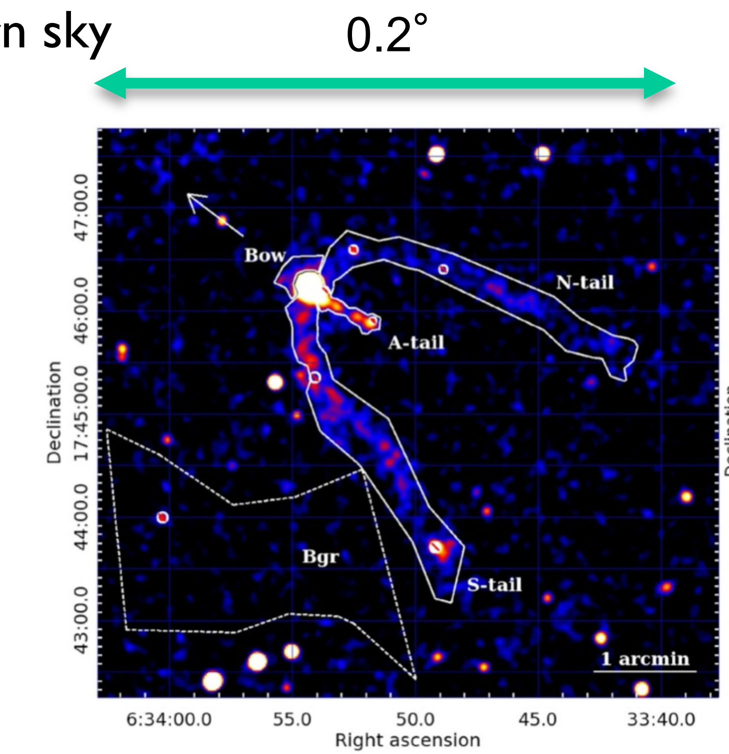
HAWC also sees energies above 25TeV

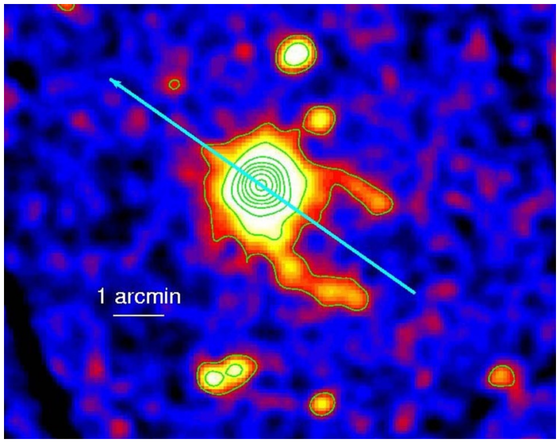
Very extended in the TeV - ~5 degrees across

Geminga and Monogem, similar in age and distance,

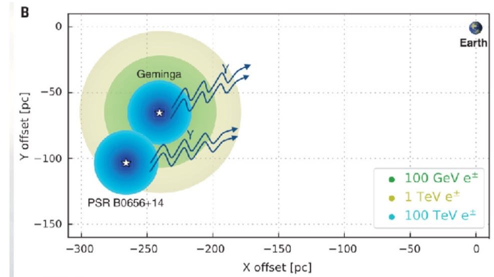
were suggested as contributors of the positron fraction

(Aharonian+1995).

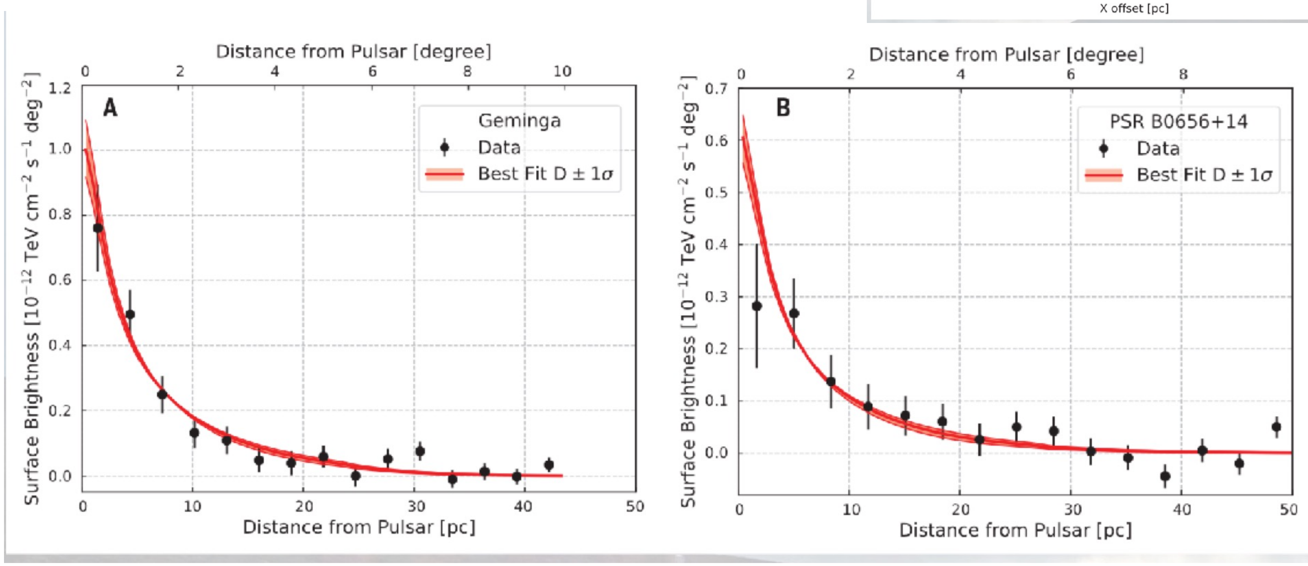


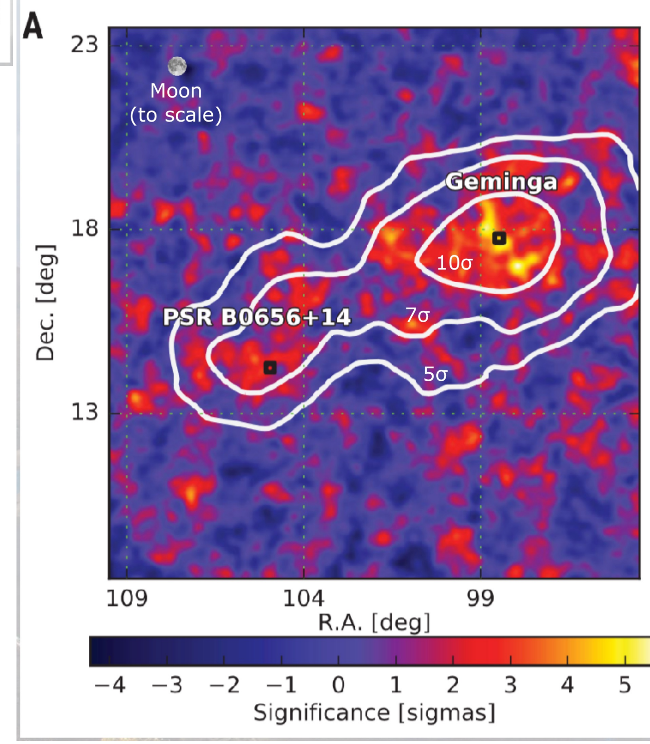


Extended TeV emission around the pulsars Geminga and Monogem



HAWC, Science 2017

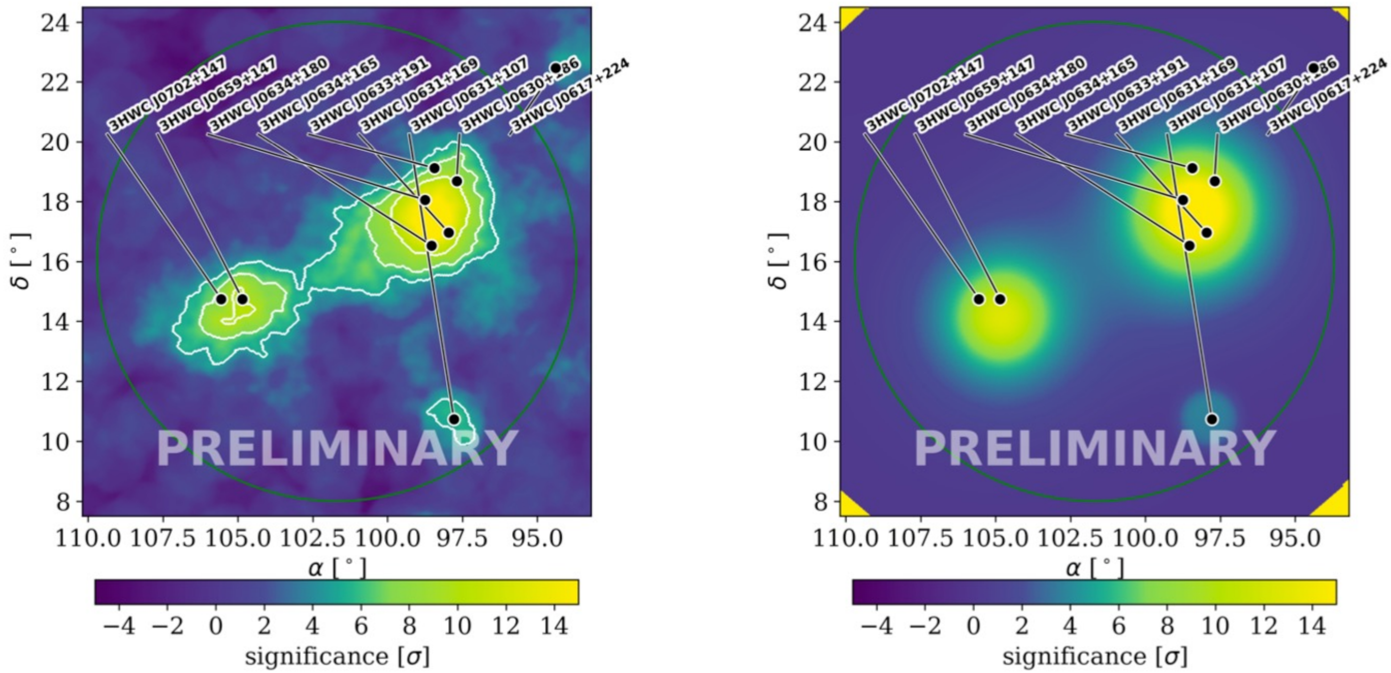




Geminga and Monogem : about 5 deg ext

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

Geminga and Monogem in Pass 5



Source Name	$K(dE/dt \rightarrow e^- e^+)$	$\log_{10} D_0$ [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

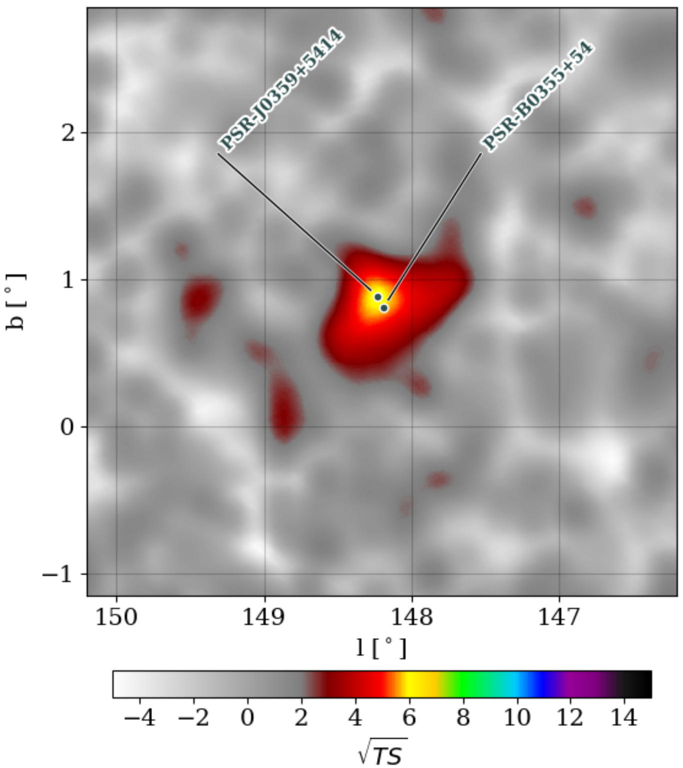
2321 day map

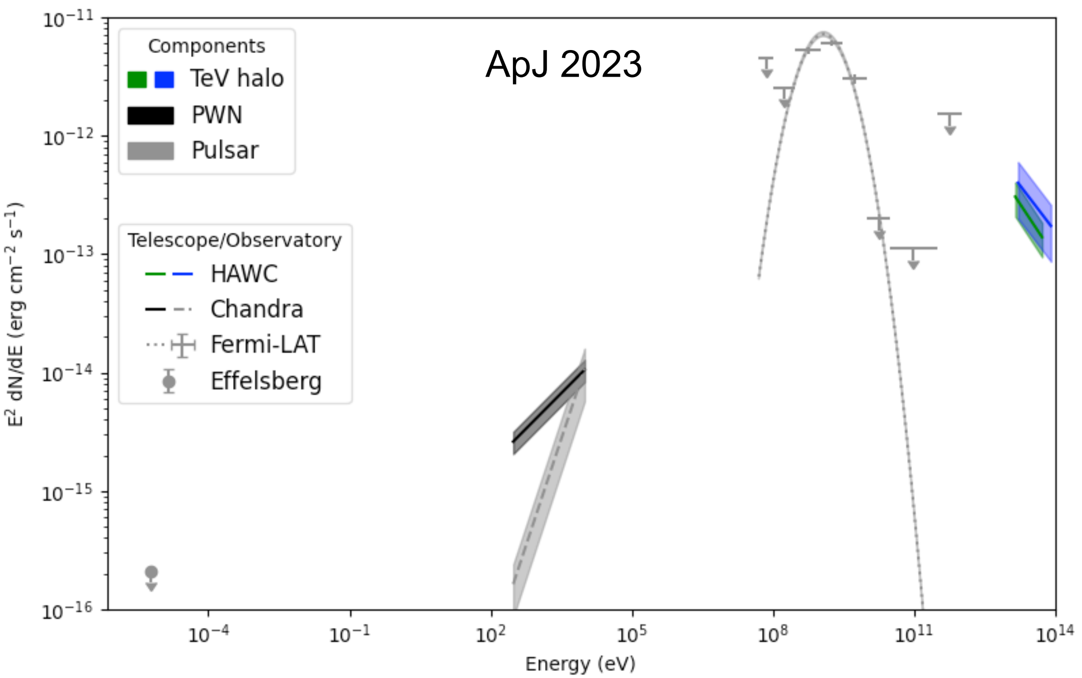
PSR J0359+5414 - Newly discovered TeV Halo

Outer galaxy, isolated, radio quiet

Age = 75kyr

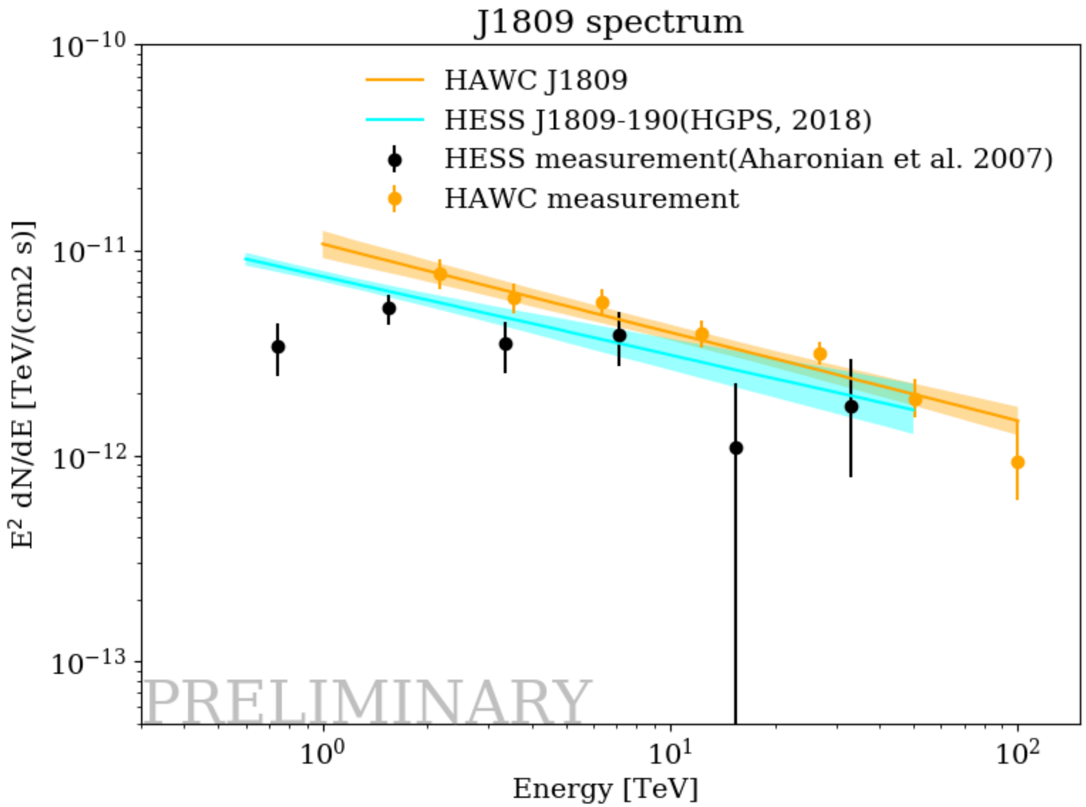
High Spin-down power: 10^{36} ergs/s

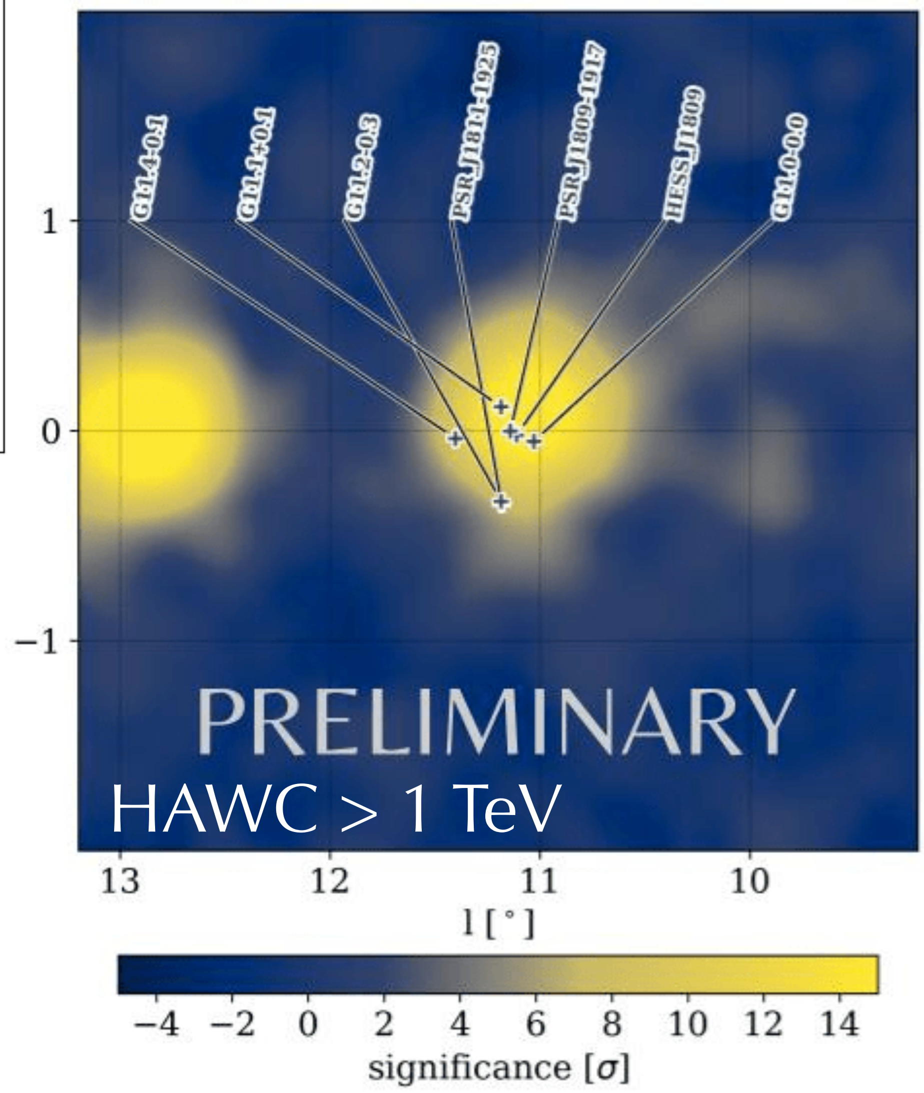


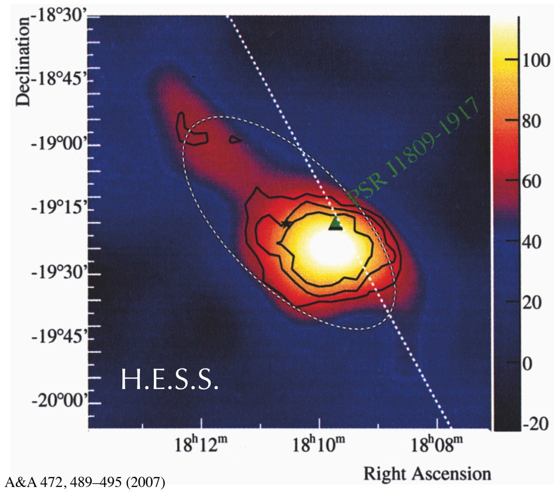


Observations of SNRs and PeVatron candidates

HESS J1809 -1917

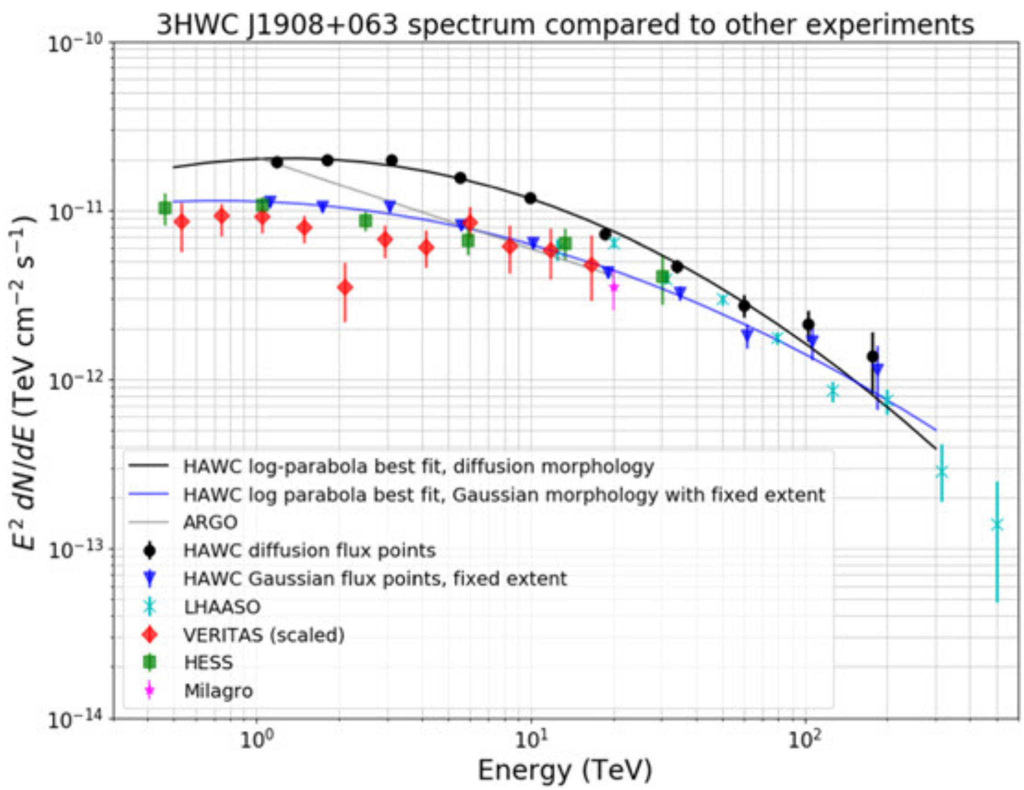


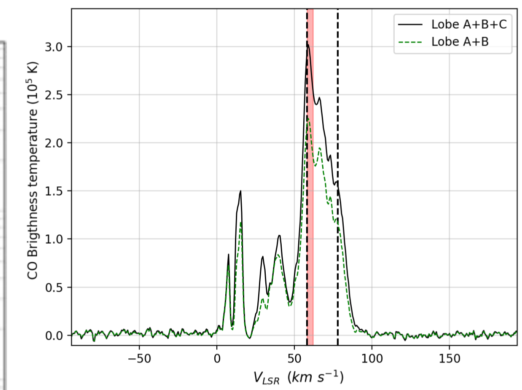


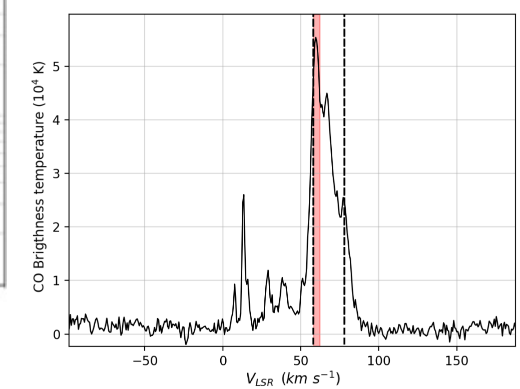


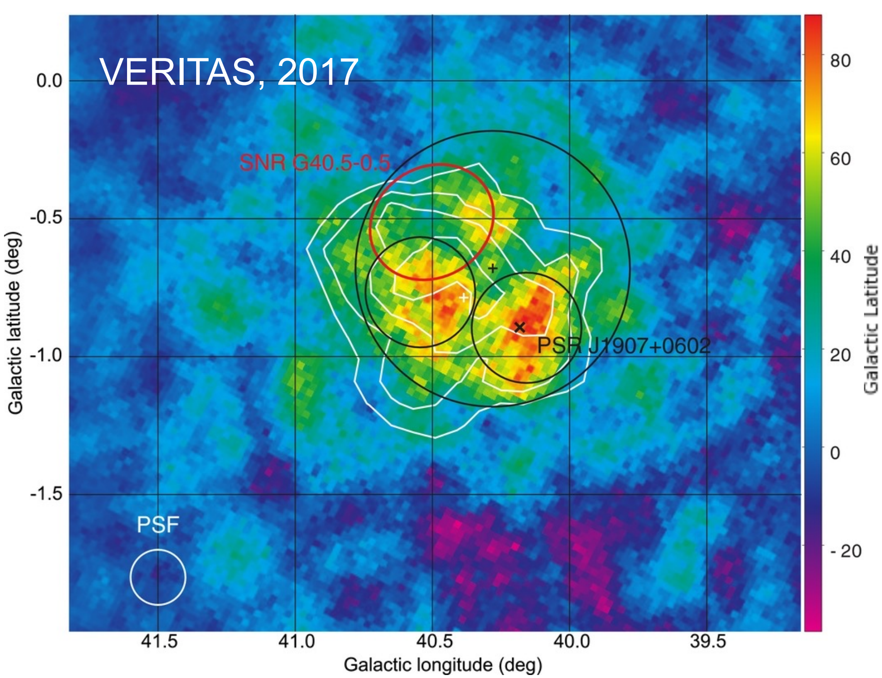
HAWC J1908 +063

l= 40° b= -0.79°

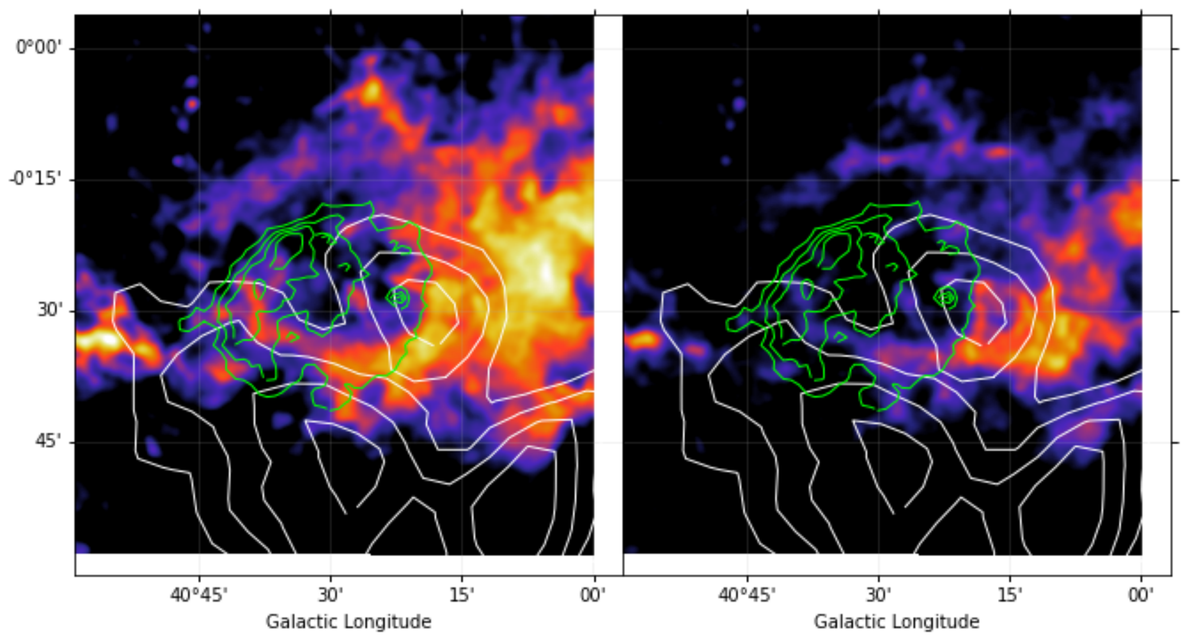




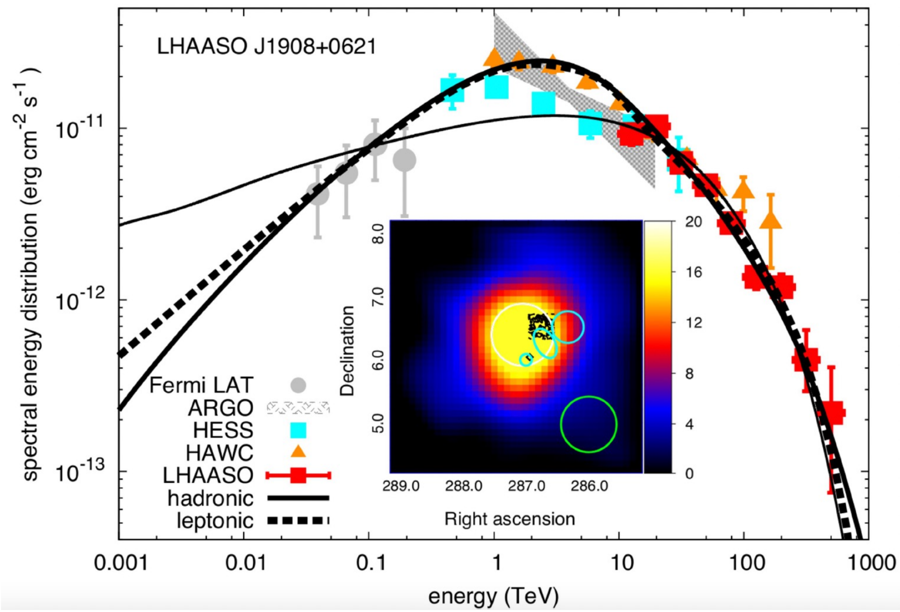


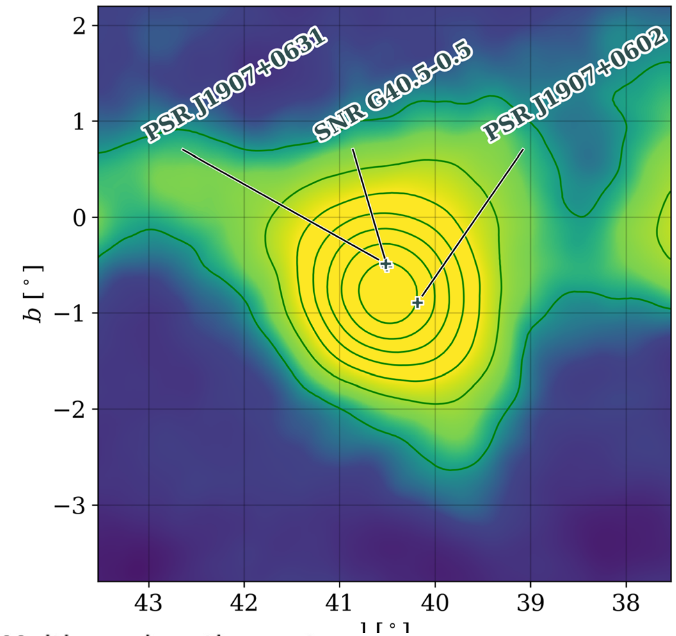


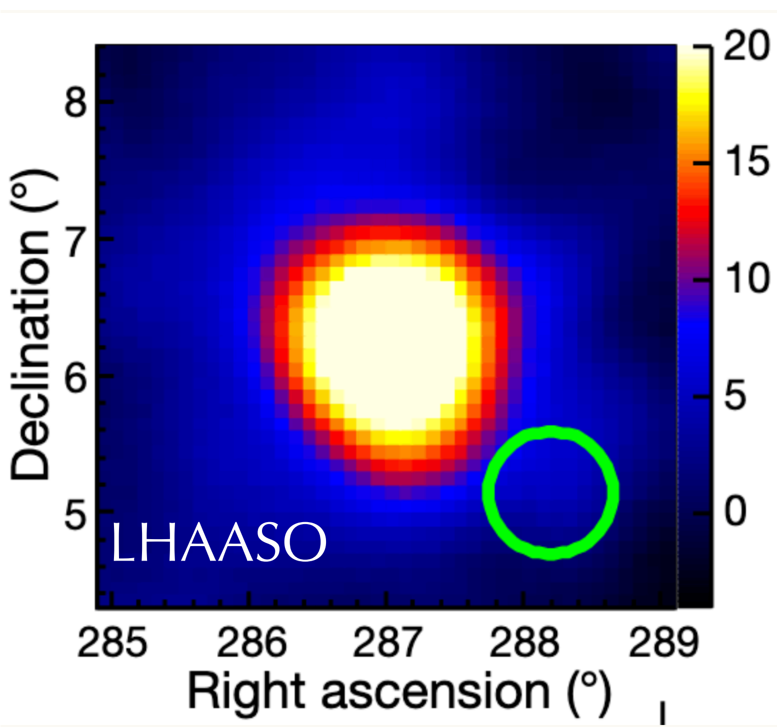
Crestan+ 2021



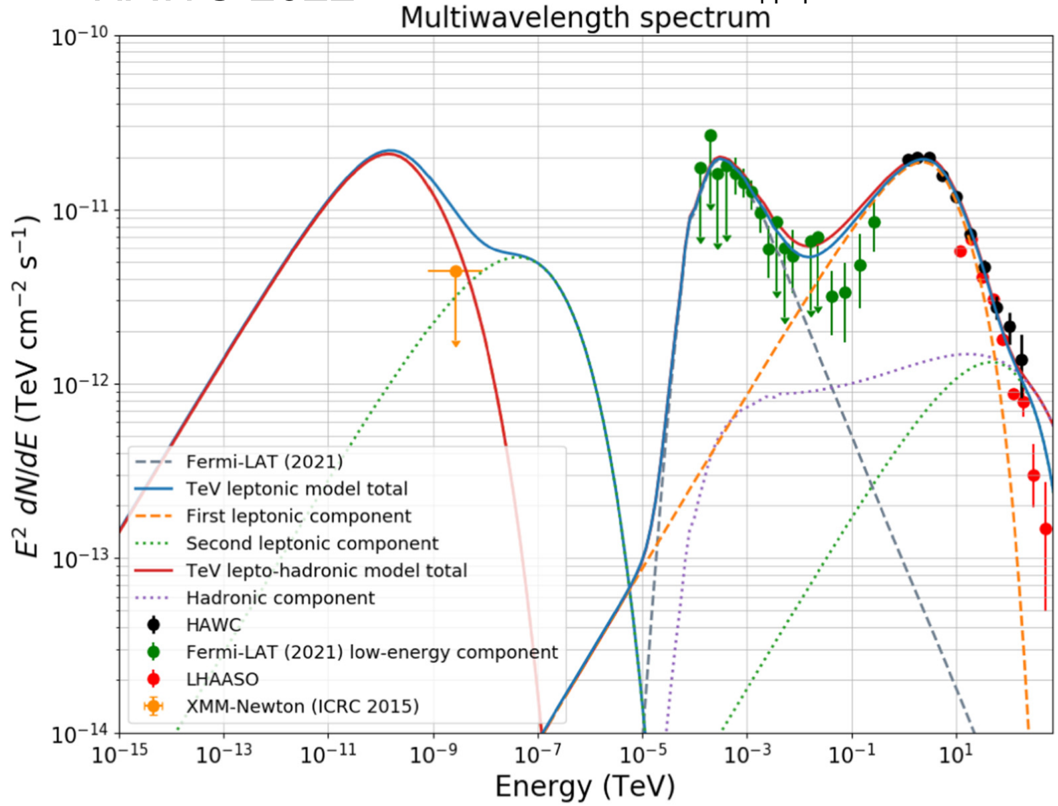
HAWC J1908 +063







HAWC 2022

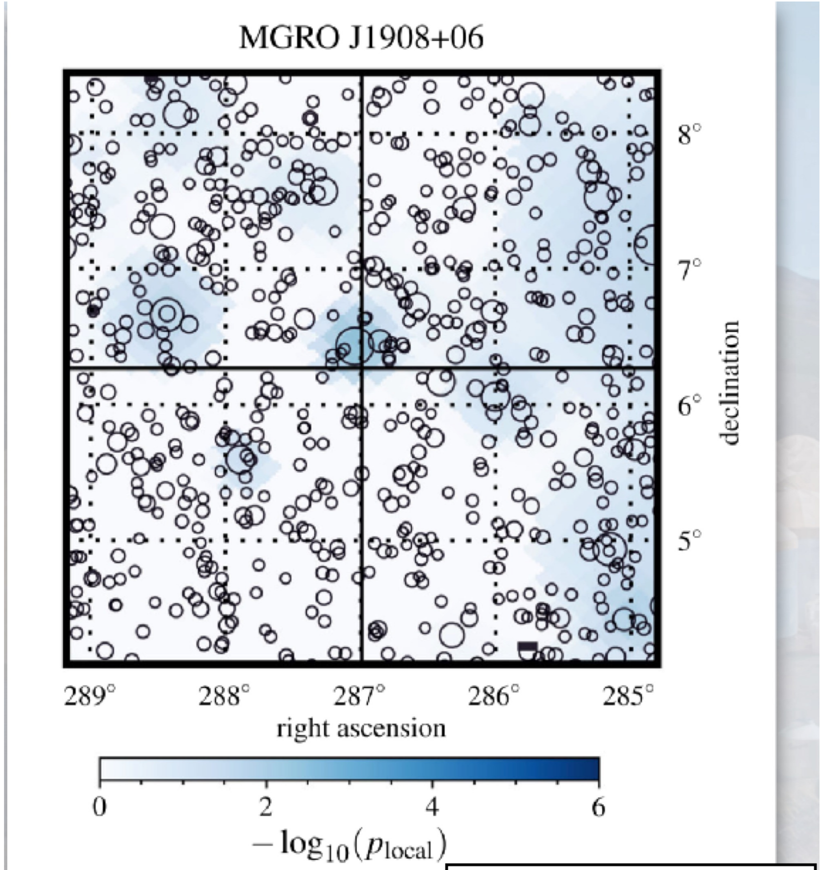


HAWC J1908+06 as neutrino source?

Some HAWC PeV candidates are promising neutrino sources

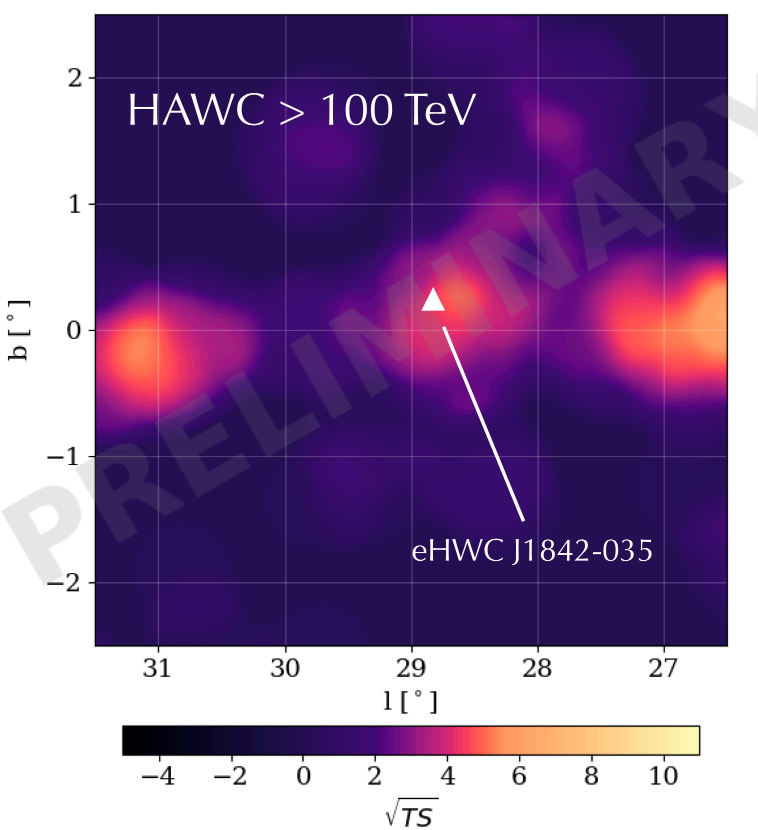
Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

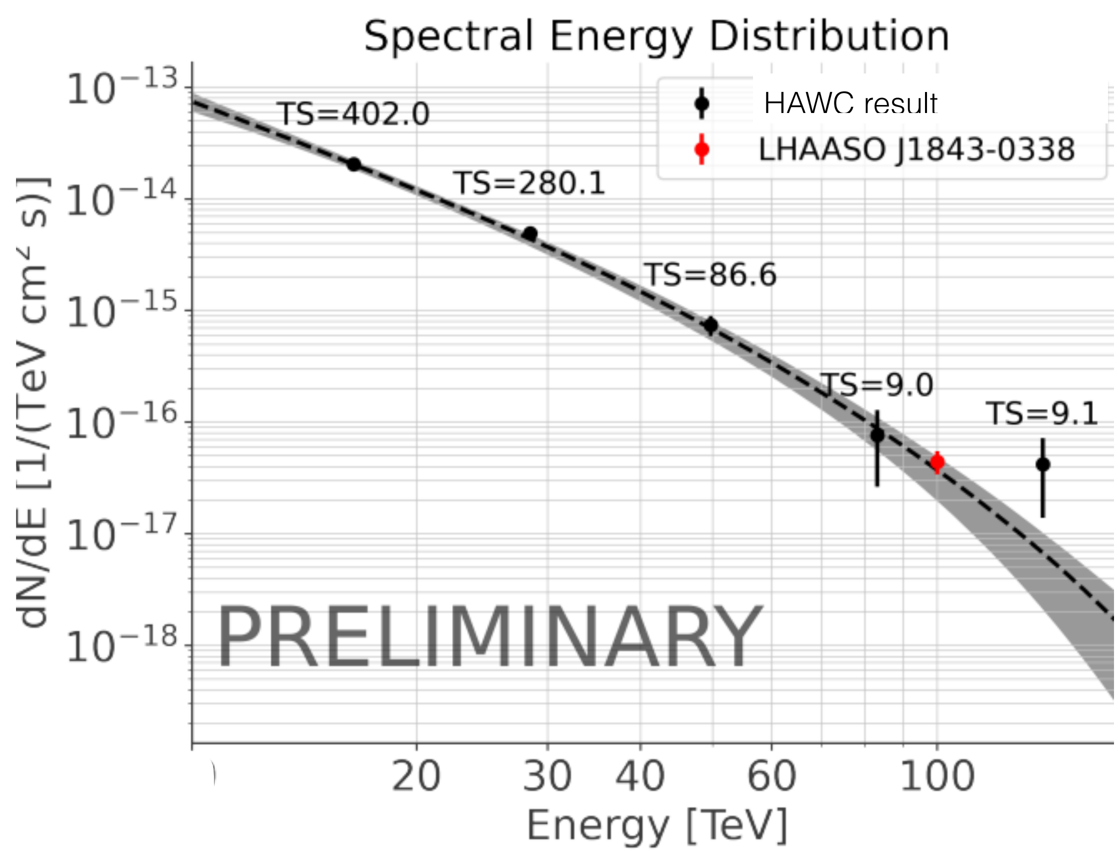
J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis



IceCube, European Physics Journal (2019)

eHWC J1842-035



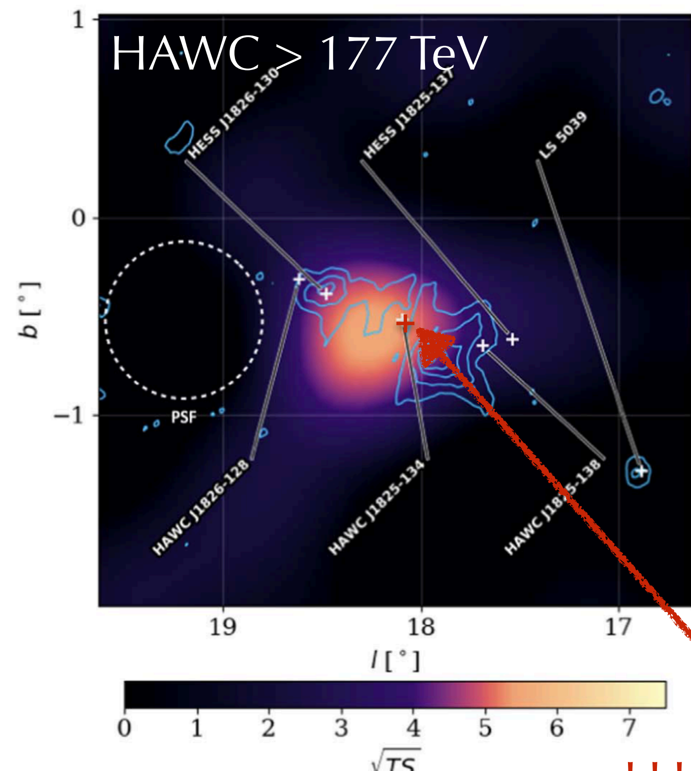


Complex morphology , 0.3-0.4 deg

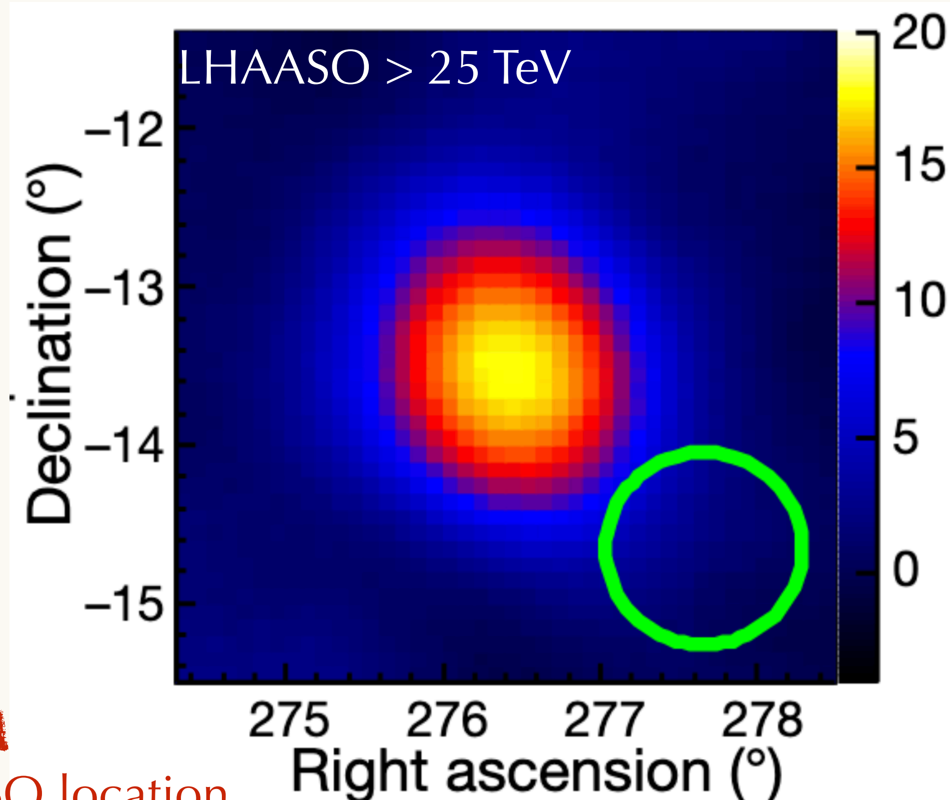
Maximum energy in HAWC > 100 TeV

Study ongoing

eHWC J1825-134

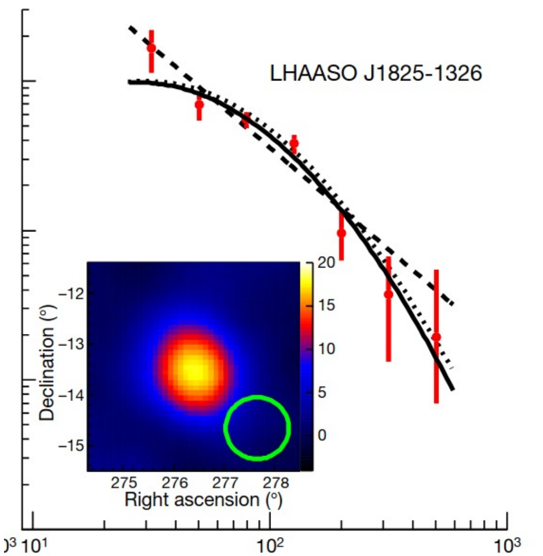


The Astrophysical Journal Letters 907.2



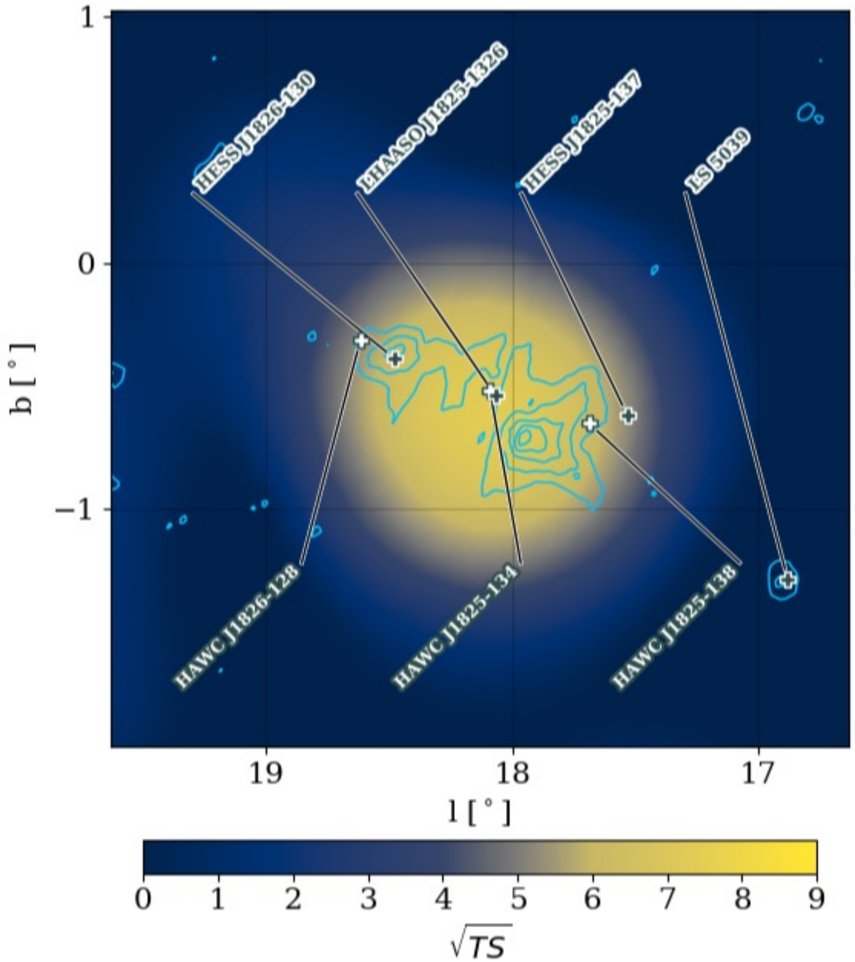
LHAASO location

Nature 594.7861 (2021): 33-36

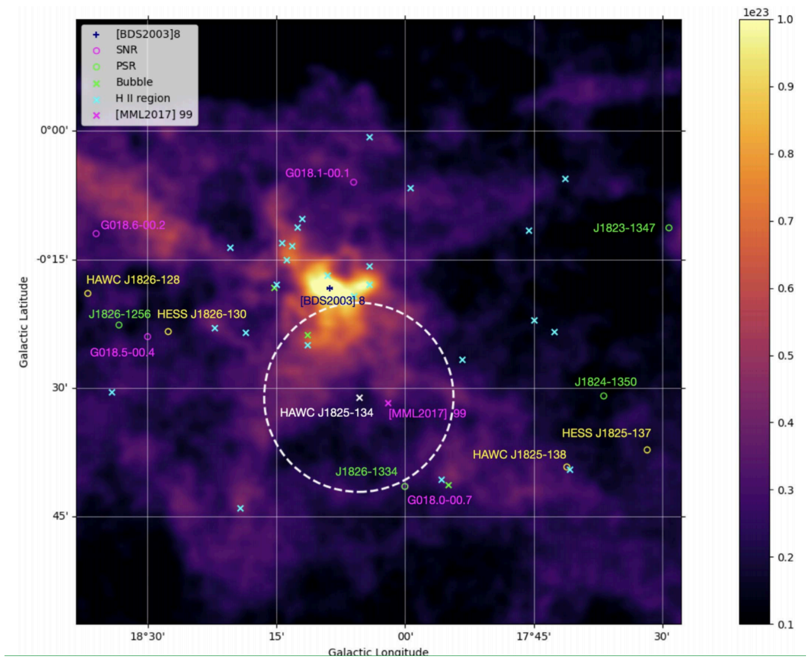


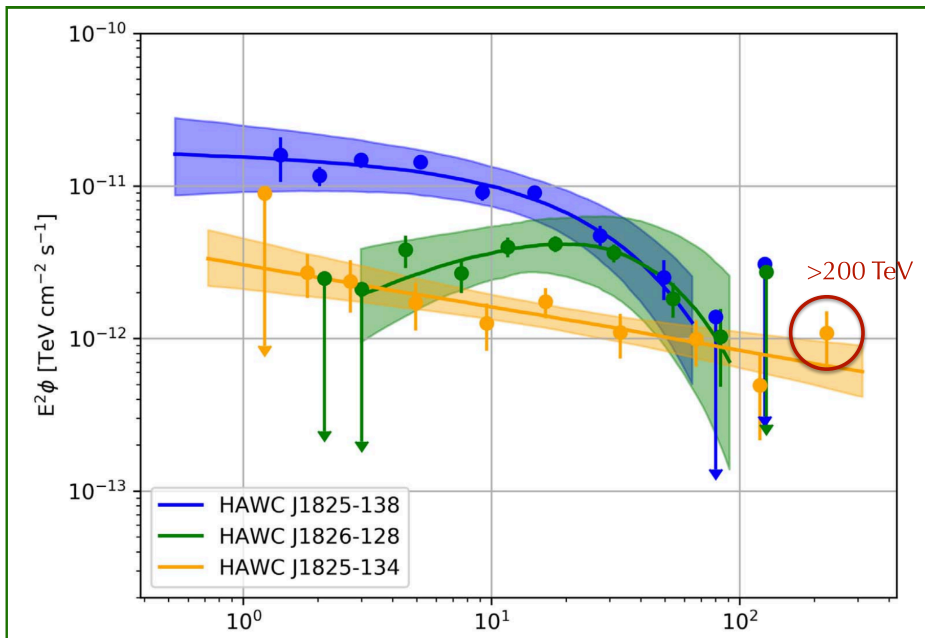
	HAWC	LHAASO
Location	**R.A. 276.44° Dec. -13.42°**	**R.A. 275.45° Dec. -13.45°**
Morphology	2 extended sources + 1point source	0.3 ° extension template
Maximum measured energy	>200 TeV	420 TeV
Origin of TeV emission	Proton accelerated by SFR Electron accelerated by PSR J1826-1334	

Multiple Sources



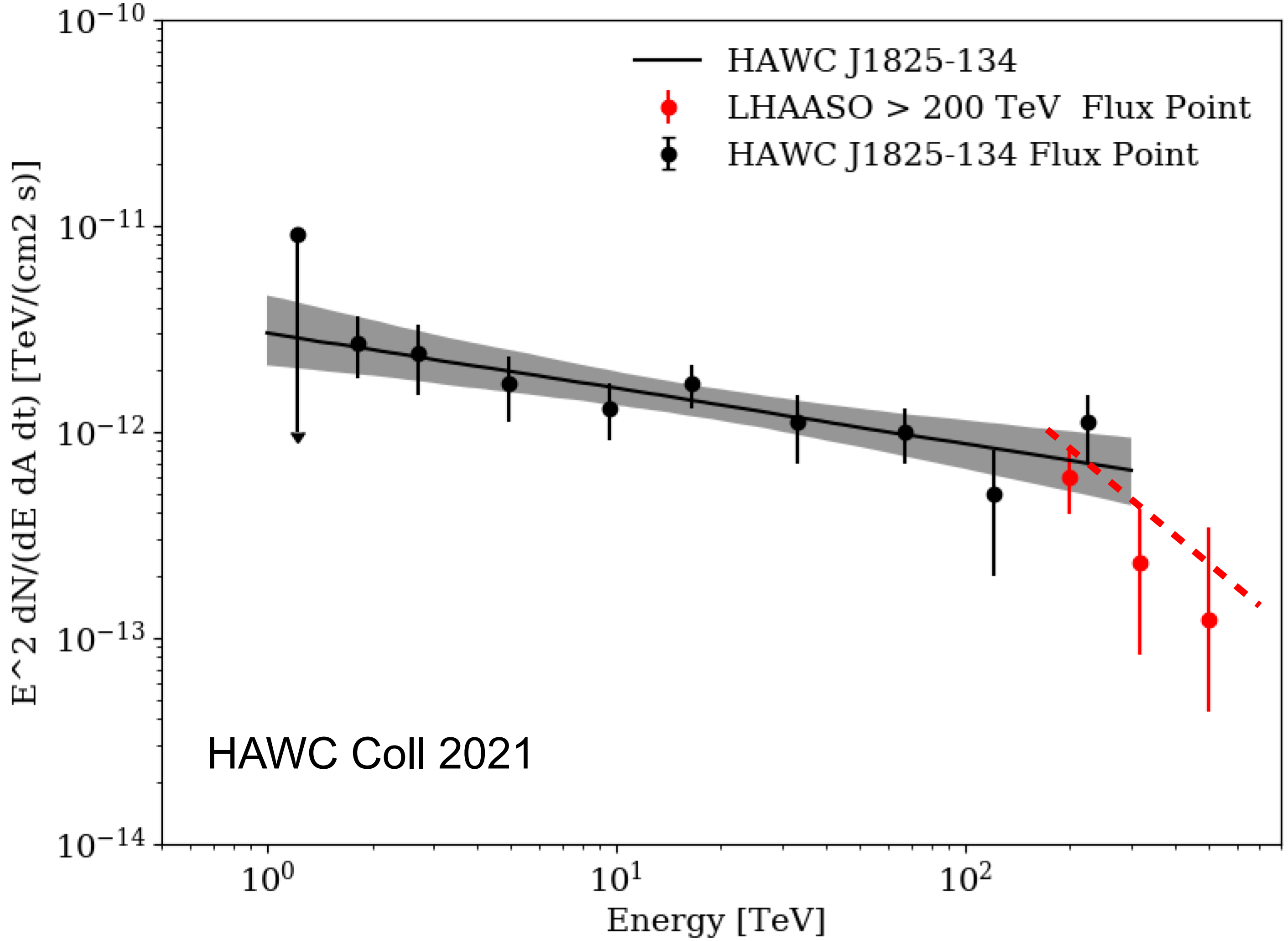
Above 177 TeV





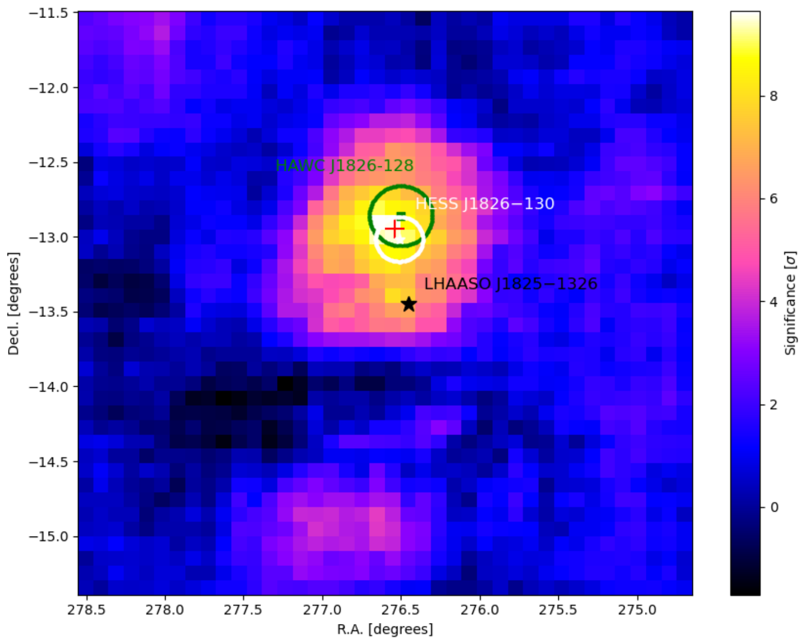
https://iopscience.iop.org/article/10.3847/2041-8213/abd77b/pdf

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



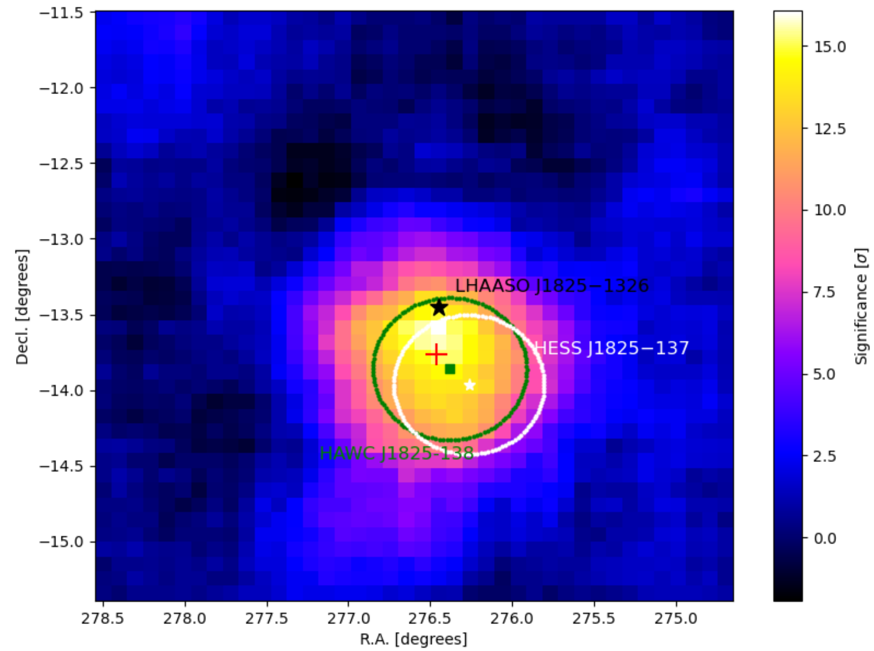
LHAASO J1826-1256 & J1825-1345(>25 TeV)

LHAASO J1826-1256



TS=214.08

LHAASO J1825-1345



TS=393.73

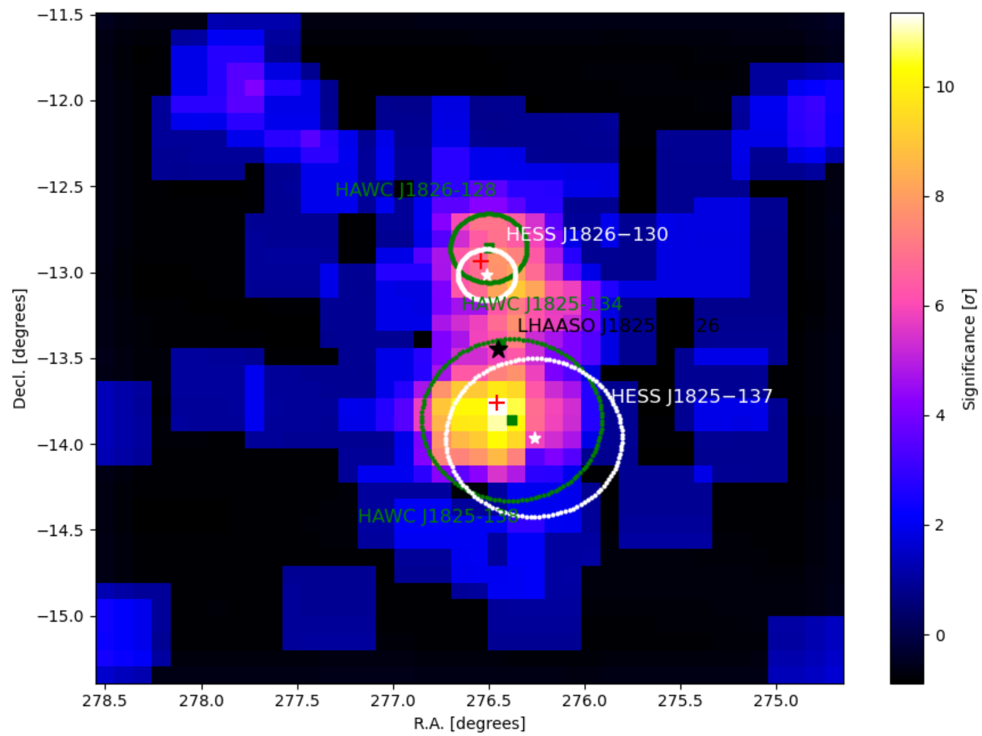
LHAASO J1826-1256 & J1825-1345 (>100 TeV)

HAWC

LHAASO J1825-1326

→ **LHAASO J1826-1256** TS=100.95

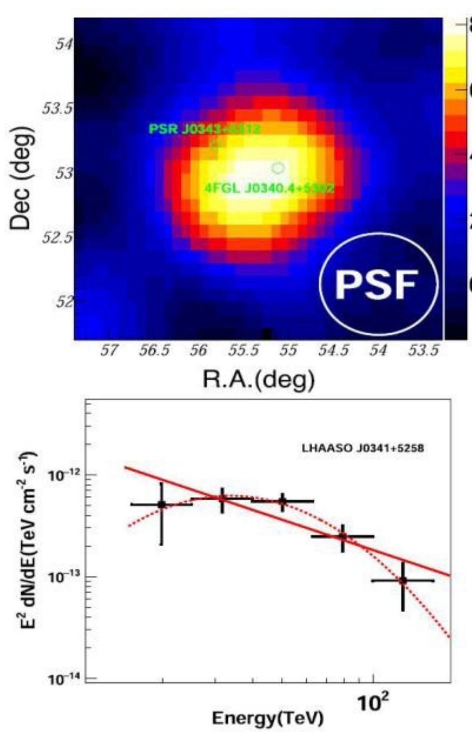
→ **LHAASO J1825-1345** TS=164.88



New Source Discovery

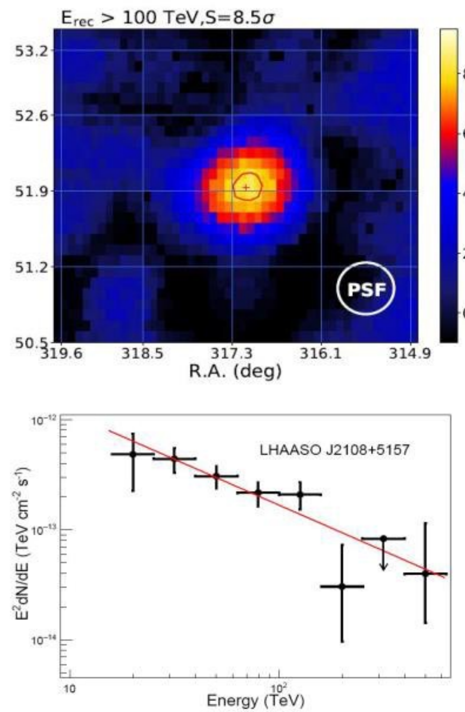
- WCDA has accumulated data for 16 months
- KM2A for 12 months
- LHAASO catalog Ver-1 will be published soon with many new VHE/UHE sources discovered

LHAASO J0341+5258



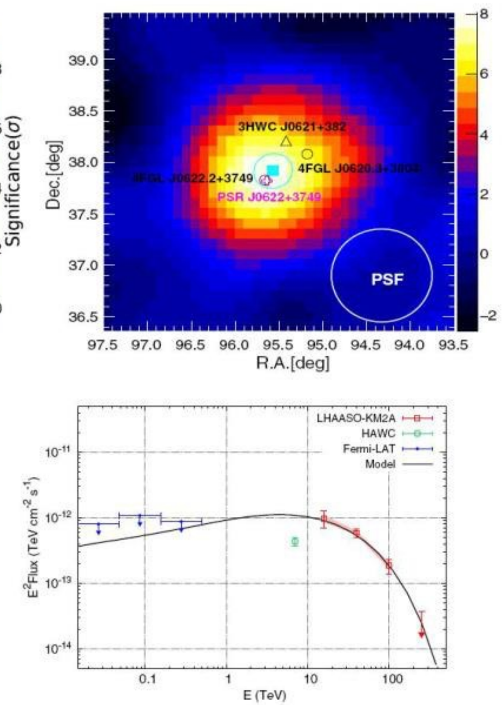
ApJL 917:L4 (2021)

LHAASO J2108+5157



ApJL 919:L22 (2021)

Halo of PSR J0622 + 3749



PRL 126:241103 (2021)

HAWC - LHAASO Comparison

HAWC 2021