Hunting PeVatrons With HAWC and SWGO

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Oct 8th, 2025

CDHY PeVatron Workshop, Oct 8 -10, 2025, Nevis Labs, Columbia University, NY

The Mysterious Cosmic-Ray

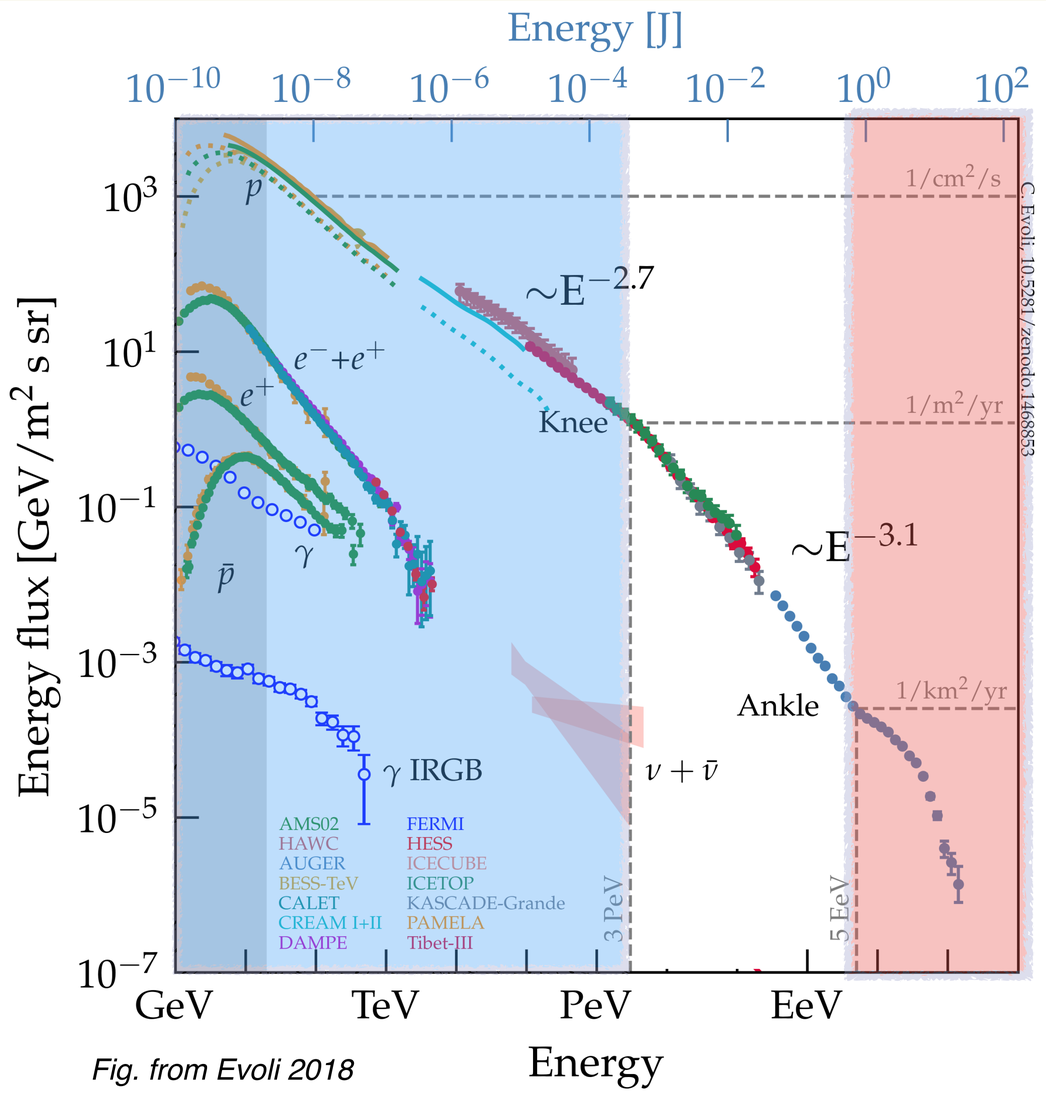


Fig. from Evoli 2018

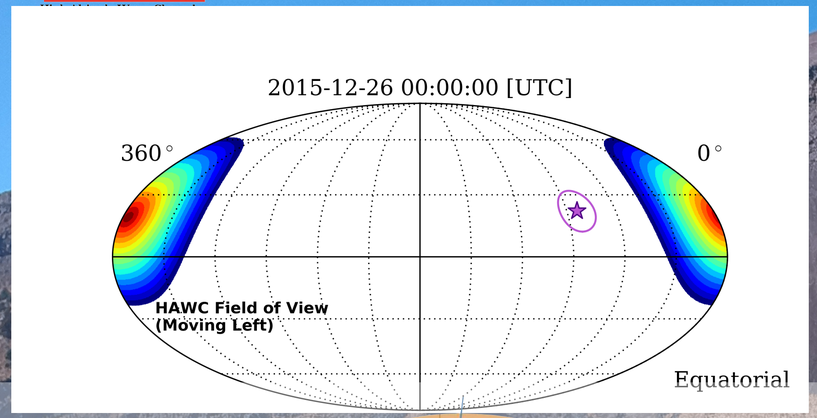
- The observed cosmic ray spectrum spans over several orders of magnitude.
- Widely accepted that:
  - Below “knee”: Galactic
  - Beyond “ankle”: Extragalactic
  - In between: ???
- Challenges to interpret the nature of accelerations to $> 10^{15} eV$ - **PeVatrons**

PeVatrons

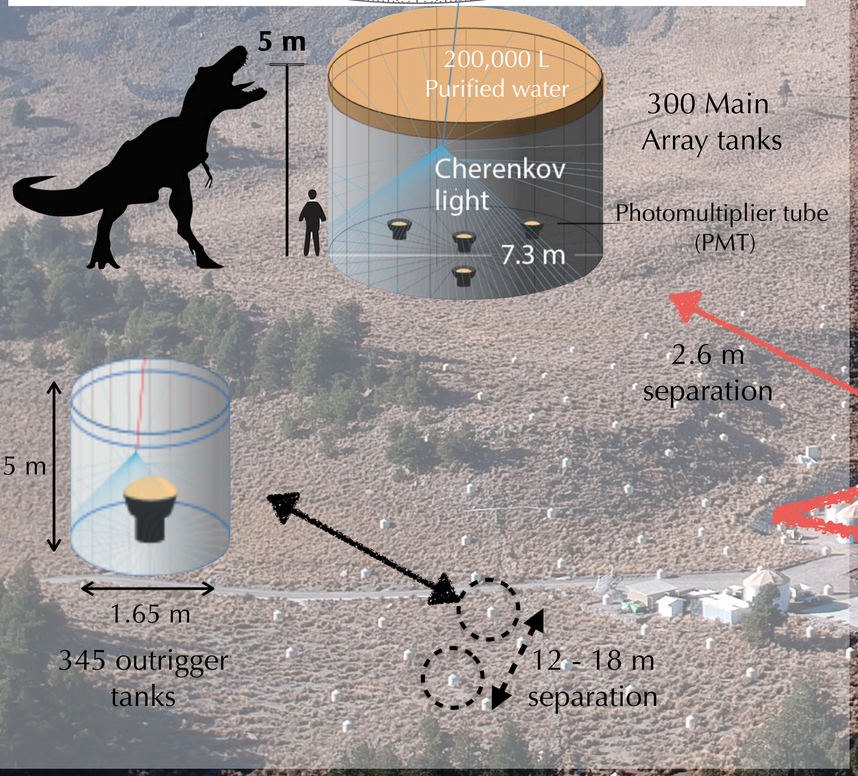
- Particle accelerators boosting energy of particles to the PeV domain without a sharp cutoff up to 1 PeV
  - Only hadronic or leptonic as well?
  - Produce gamma-ray > 100 TeV
  - Proposed PeVatron candidates
    - Supernova Remnants (SNRs)
    - Super Massive Black Hole at Galactic Center
    - Young Massive Clusters (YMCs)
    - Microquasars /binaries
    - Pulsar Wind Nebulae (PWNe) ?

High Altitude Water Cherenkov (HAWC) Observatory

Large Millimeter Telescope

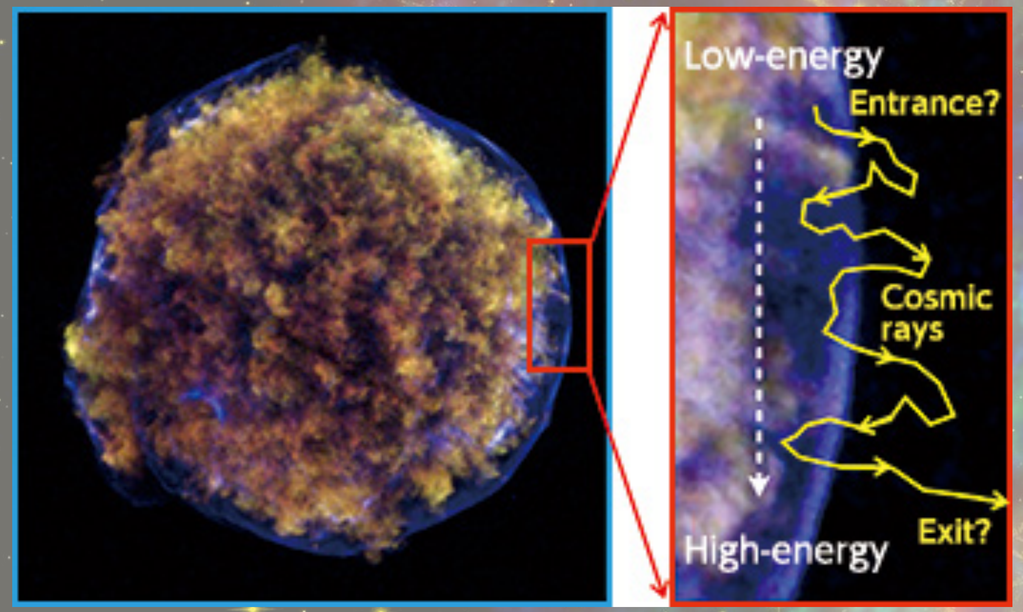


- **300 main array plus 345 outrigger WCDs covering ~100,000 m^2 effective area**
- **Large field of view: instantaneous field of view: ~ 2sr**
- **High duty cycle: > 95%**
- **Great sensitivity at high energies: 100 GeV to more than 100 TeV**



4100 m a.s.l.

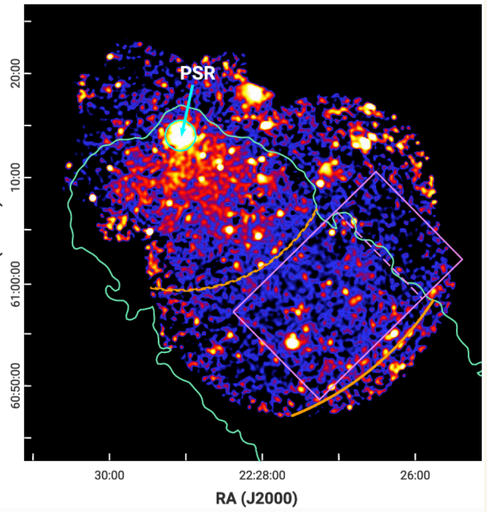
SNRs

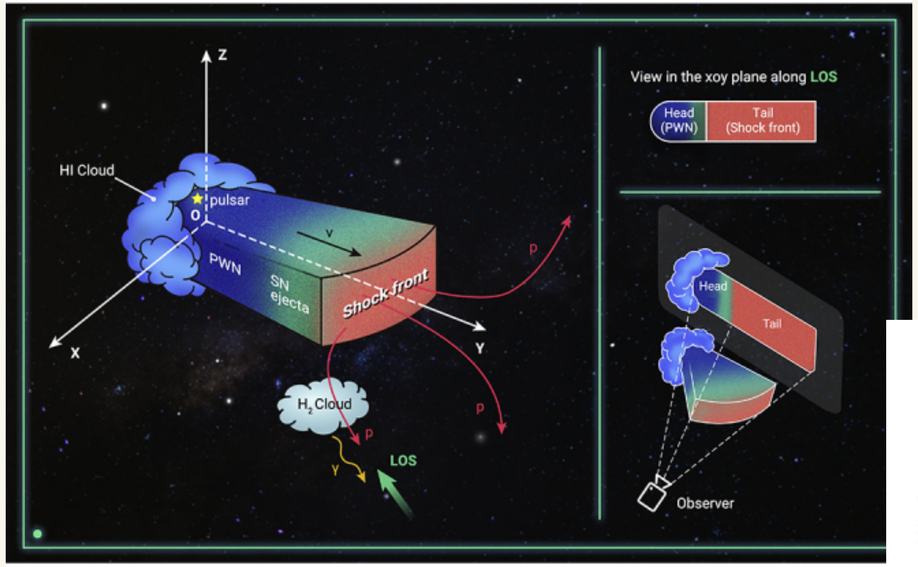


- Long-proposed cosmic-ray contributor
  - Enough power in SN explosions to explain cosmic rays since 1934
    - $E_{SN} \sim 10^{51}$ erg, R~0.03 yr^{-1}
    - A fraction (~ 1 - 10%) of the total explosion energy of SNe into CRs can account for the measured energy density of CRs at the Earth
  - Diffusive Shock Acceleration
    - Charge particles can be accelerated when diffused back forth from shock front

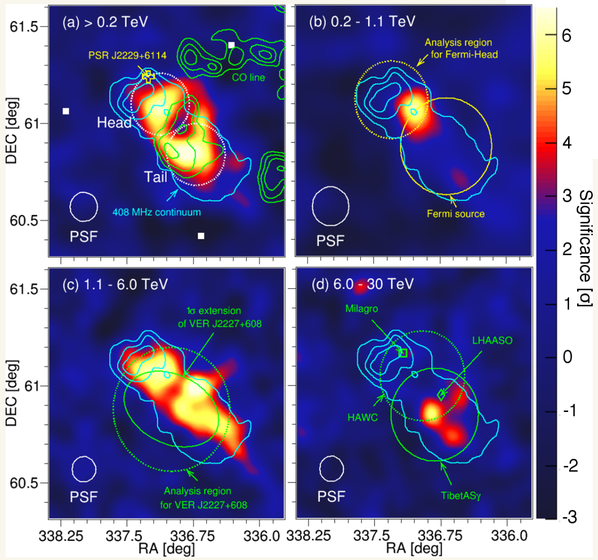
SNR G106.3 + 2.7

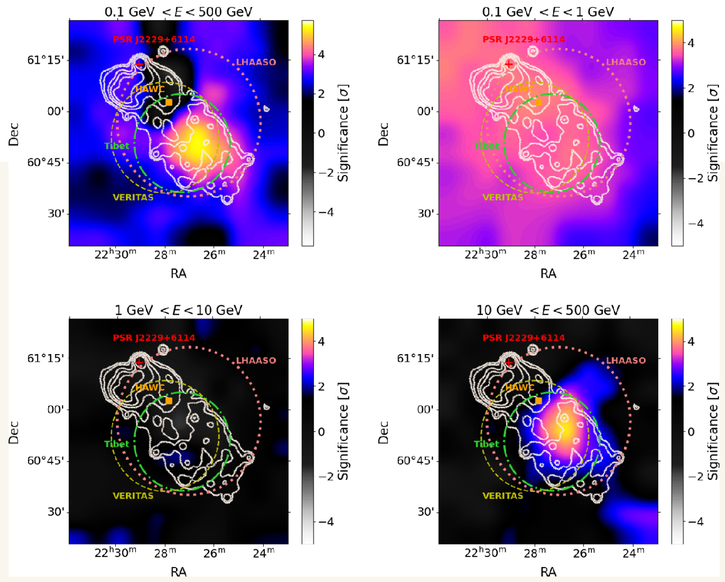
2021 May 5;2(2):100118. doi: 10.1016/j.xinn.2021.100118. eCollection 2021 May 28.

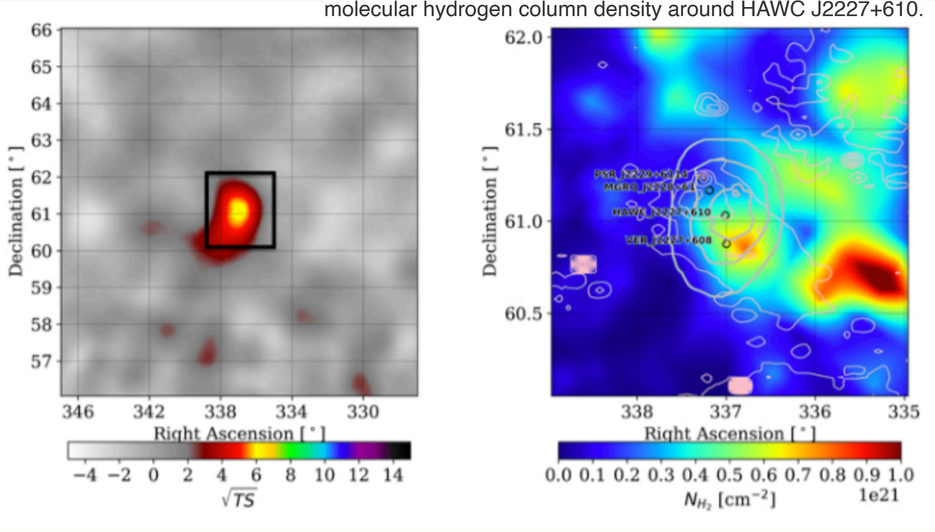


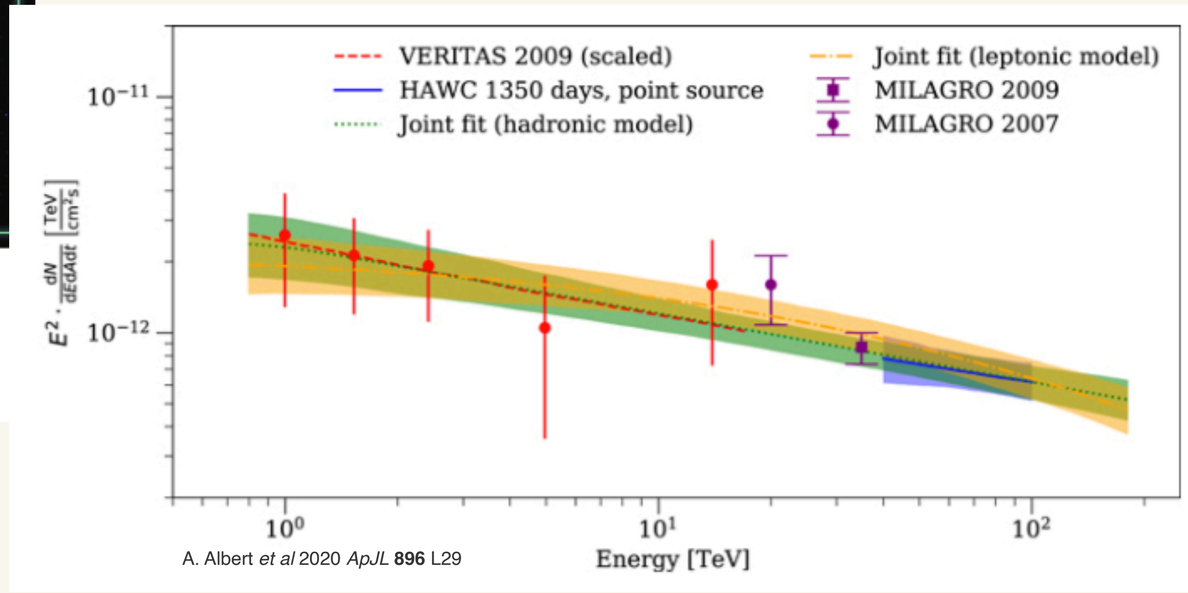


MAGIC, A&A Volume 671, March 2023







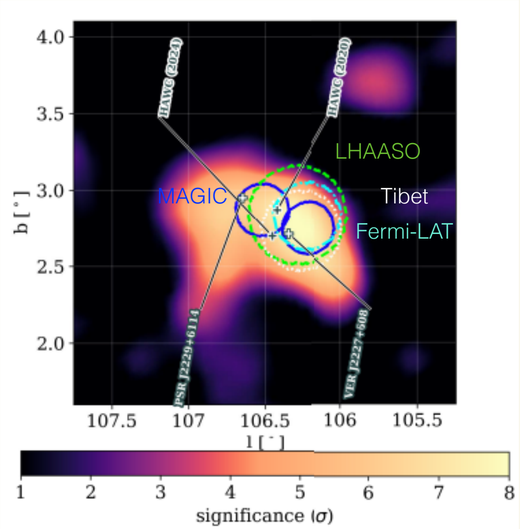


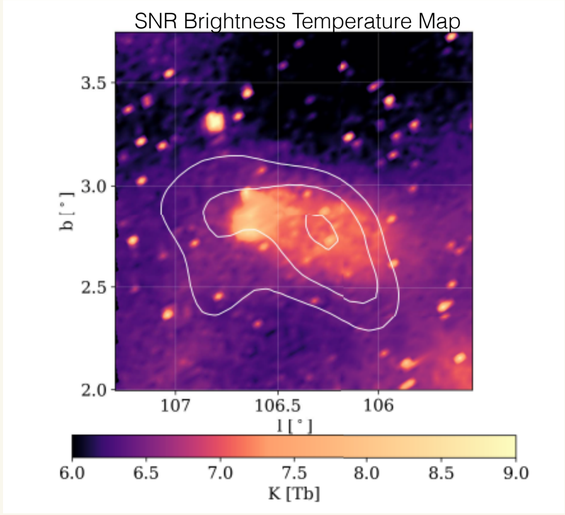
A. Albert *et al* 2020 *ApJL* **896** L29

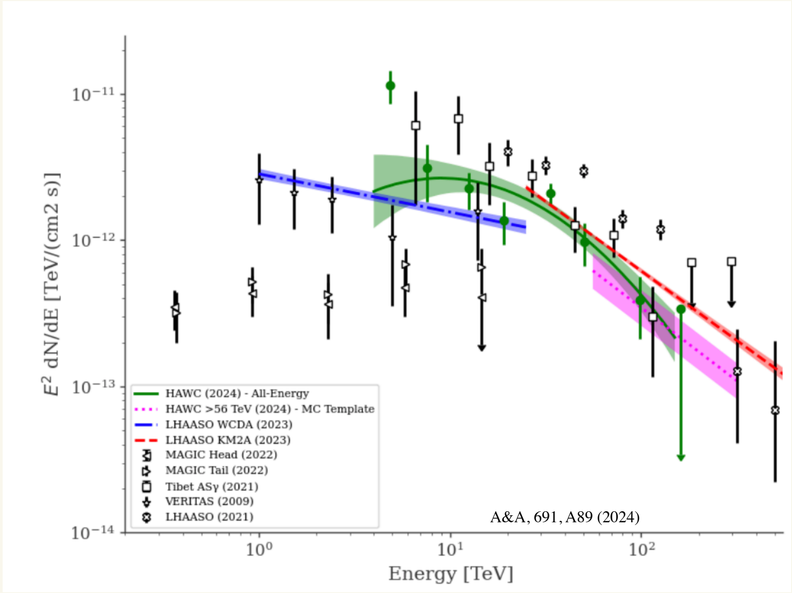
- 10 kyr
- Detections from multi-instruments
- Tibet AS-gamma, MAGIC, VERITAS, Fermi-LAT, XMM-NewTon, Chandra, HAWC
- HAWC 2020: lower limit in the proton cutoff energy of 800 TeV

Fang, *et al.*, Phys. Rev. Lett. **129**, 071101

SNR G106.3 + 2.7

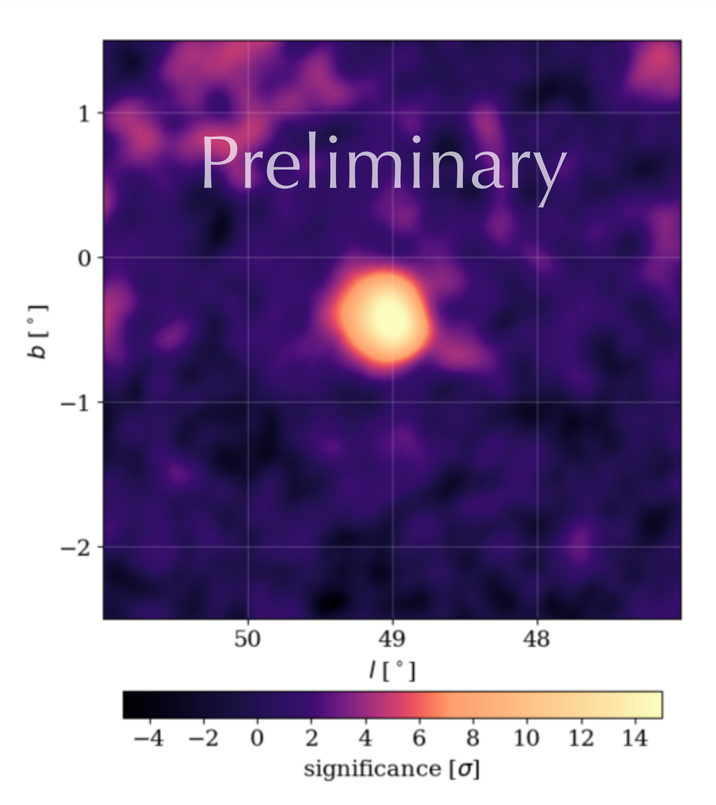


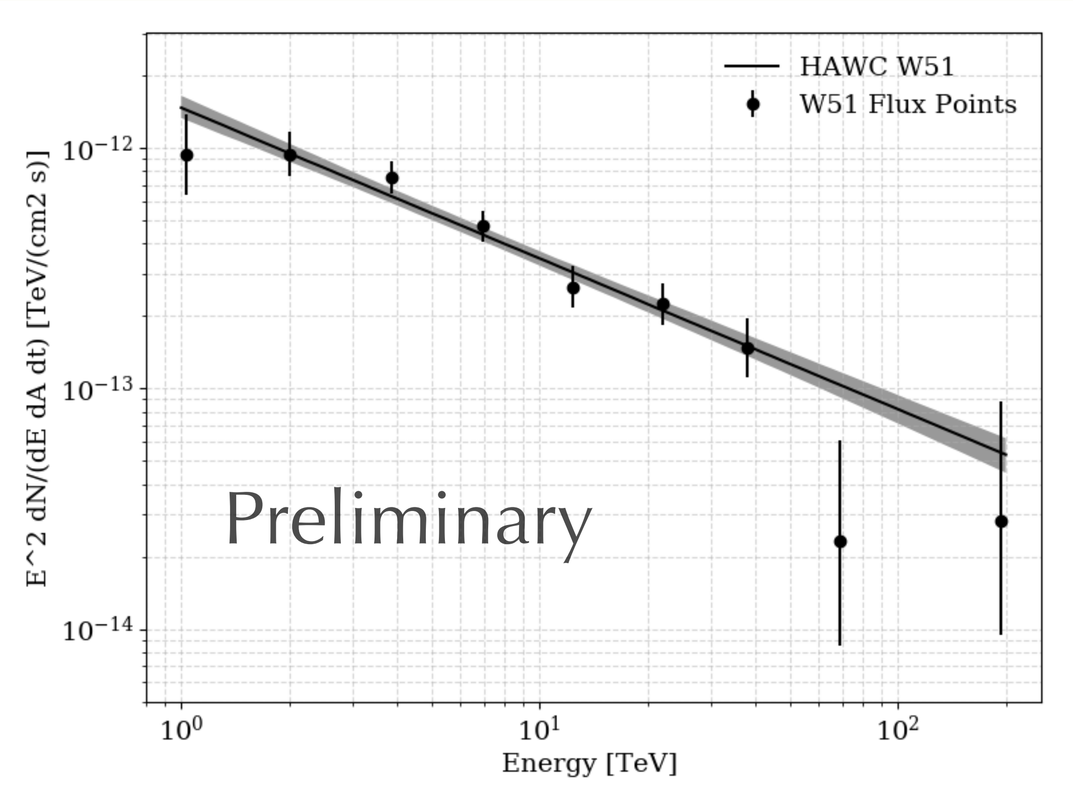




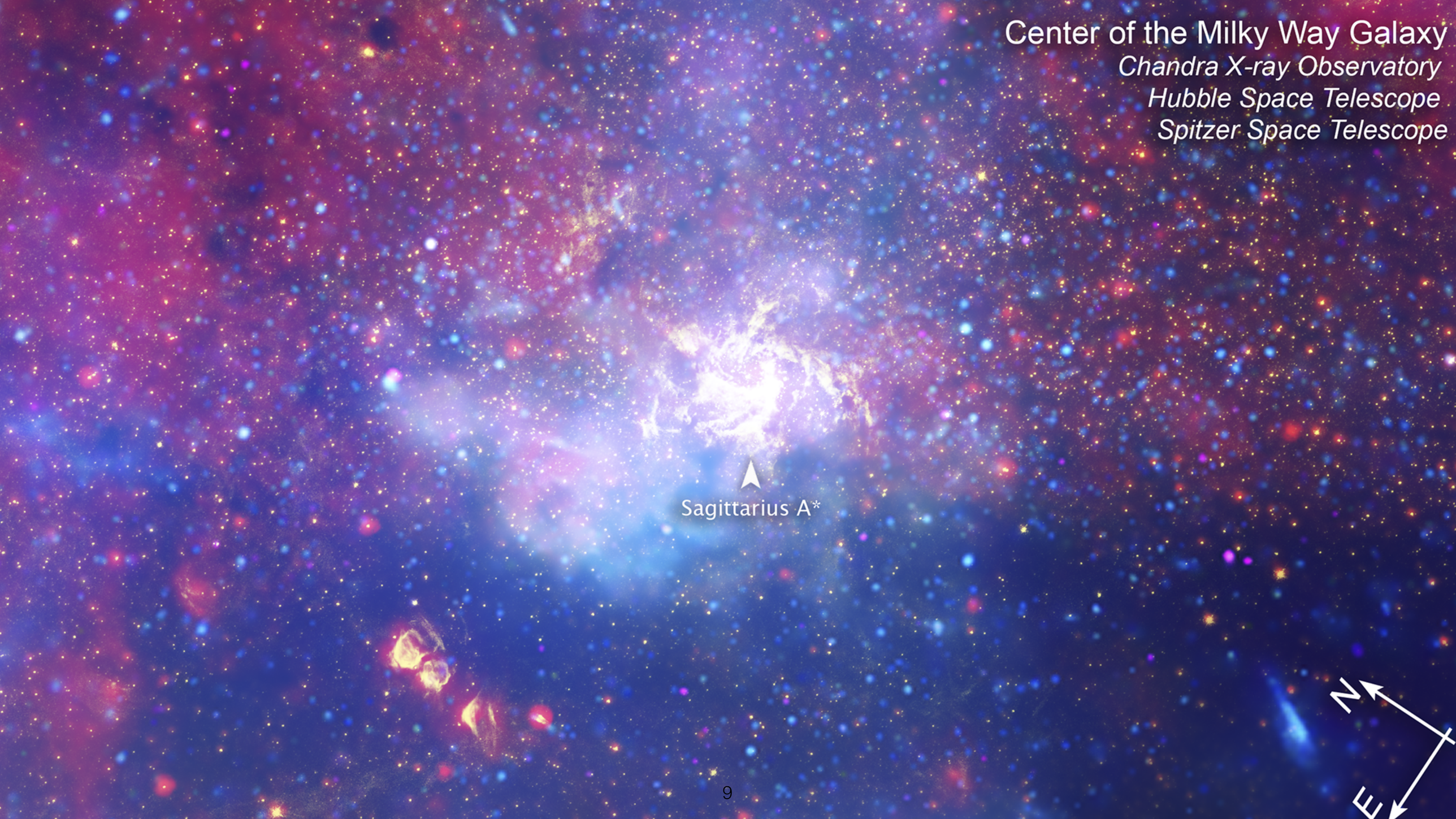
- HAWC update in 2024
  - One extended source consistent with all of the other measurements
  - Gamma-ray emission >100 TeV
  - Test molecular cloud template with UHE gamma-ray
    - the SNR's energy budget is fully capable of producing a purely hadronic source
    - Couldn't exclude leptonic model
- LHAASO detected gamma-ray emissions up to 400 TeV from this region (LHAASO, Nature, 2021)

W51 Region





- W51C: shell-type SNR , 30 kyr
- Extend the spectrum measurement up to ~200 TeV
- HAWC emissions peaked around the molecular cloud region


Center of the Milky Way Galaxy
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope
Sagittarius A*
N
E

Super Massive Black Hole @ Galactic Center

First detection of "PeVatron Candidate" — VHE hadronic CR accelerator

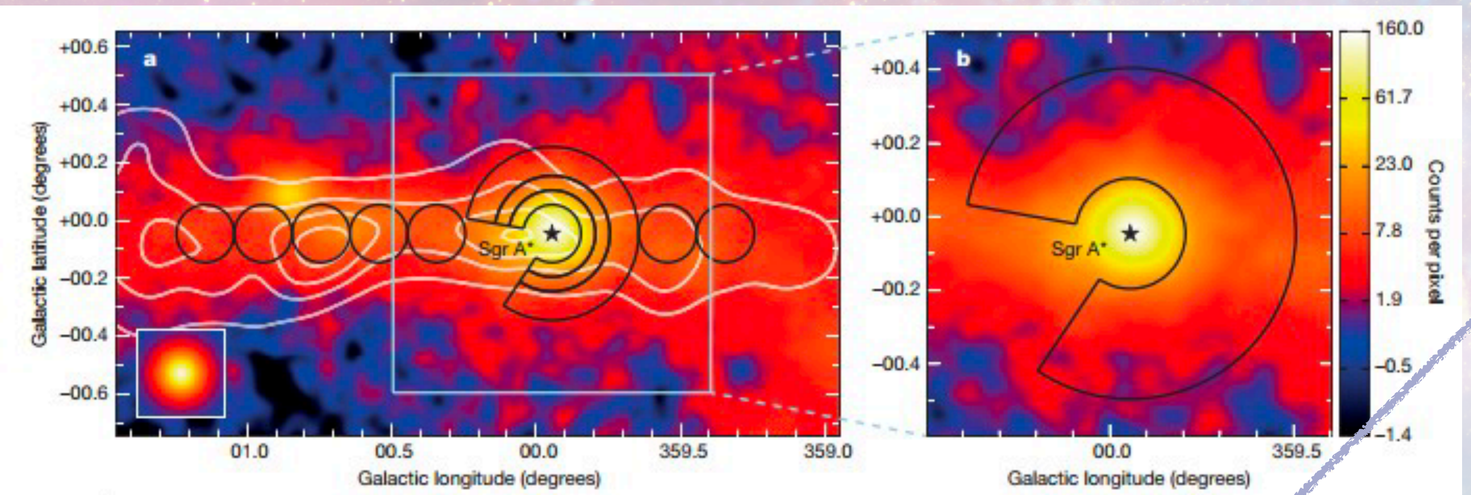
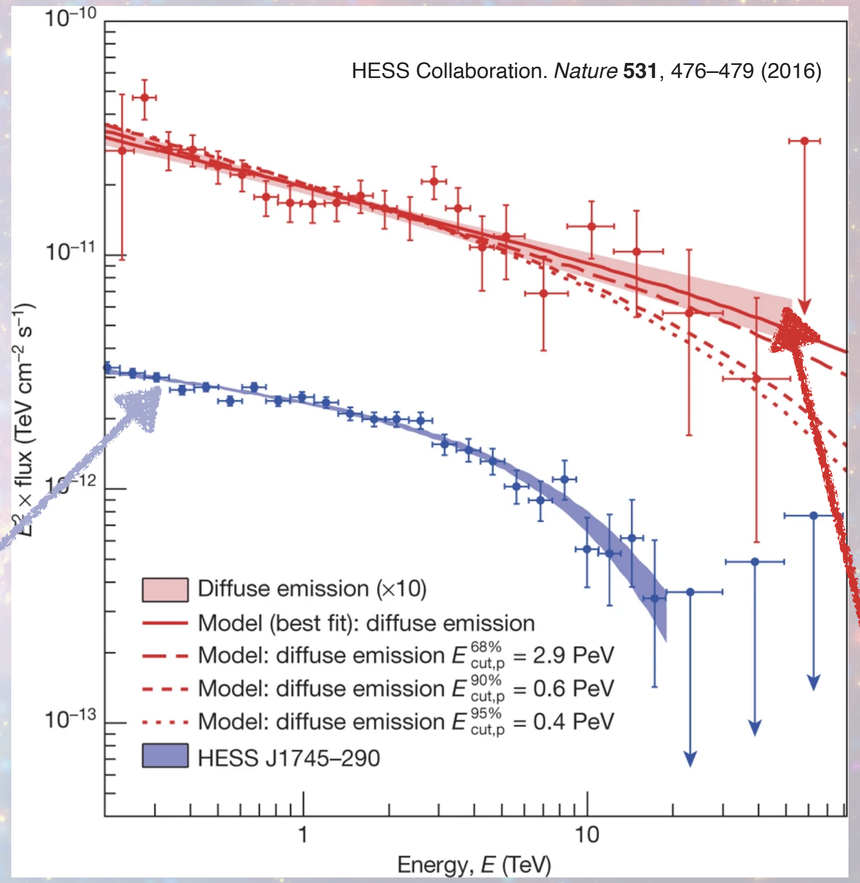


Figure 1 | VHE γ-ray image of the Galactic Centre region. The colour scale indicates counts per 0.02° × 0.02° pixel. **a**, The black lines outline the regions used to calculate the cosmic-ray energy density throughout the central molecular zone. A section of 66° is excluded from the annuli (see Methods). White contour lines indicate the density distribution of molecular gas, as traced by its CS line emission[30]. Black star, location of Sgr A*. Inset (bottom left), simulation of a point-like source. The part of the image shown boxed is magnified in **b**. **b**, Zoomed view of the inner ~70 pc and the contour of the region used to extract the spectrum of the diffuse emission.

HESS Collaboration. Acceleration of petaelectronvolt protons in the Galactic Centre. *Nature* **531**, 476–479 (2016)



Sgr A* Emission

$$\Gamma = 2.14 \pm 0.10$$

$$\phi_0 = (2.55 \pm 0.37) \times 10^{-12} TeV^{-1} cm^{-2} s^{-1}$$

$$E^{\gamma}_{cut} = 10.7 \pm 2.9$$

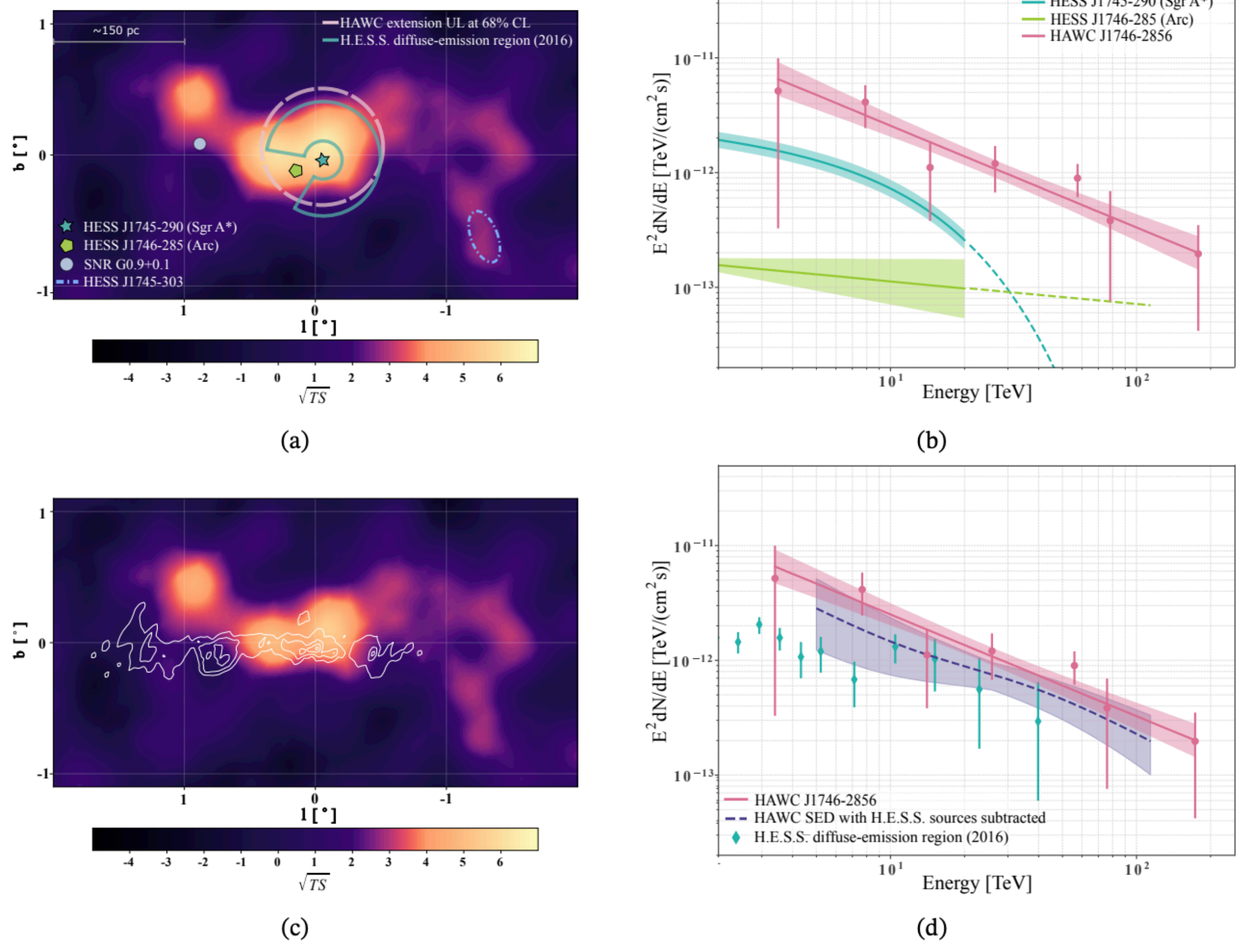
Diffuse Emission

$$\Gamma = 2.32 \pm 0.12$$

$$\phi_0 = (1.92 \pm 0.29) \times 10^{-12} TeV^{-1} cm^{-2} s^{-1}$$

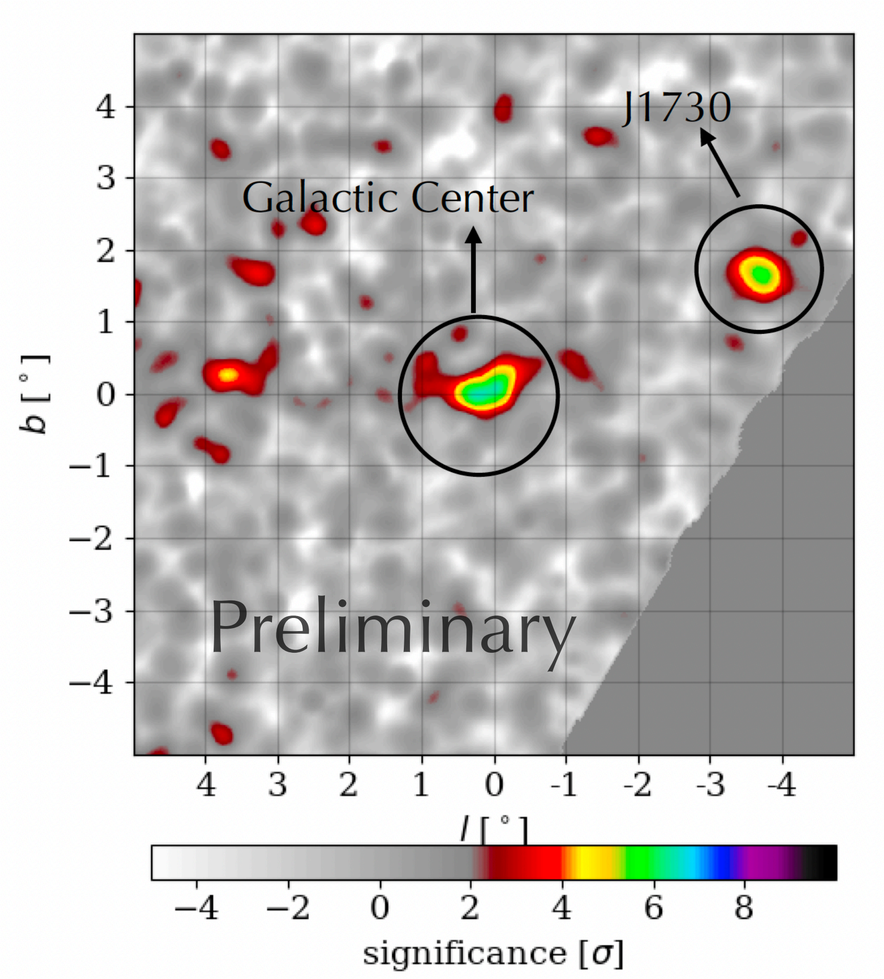
HAWC Confirmed Galactic Center As PeVatron

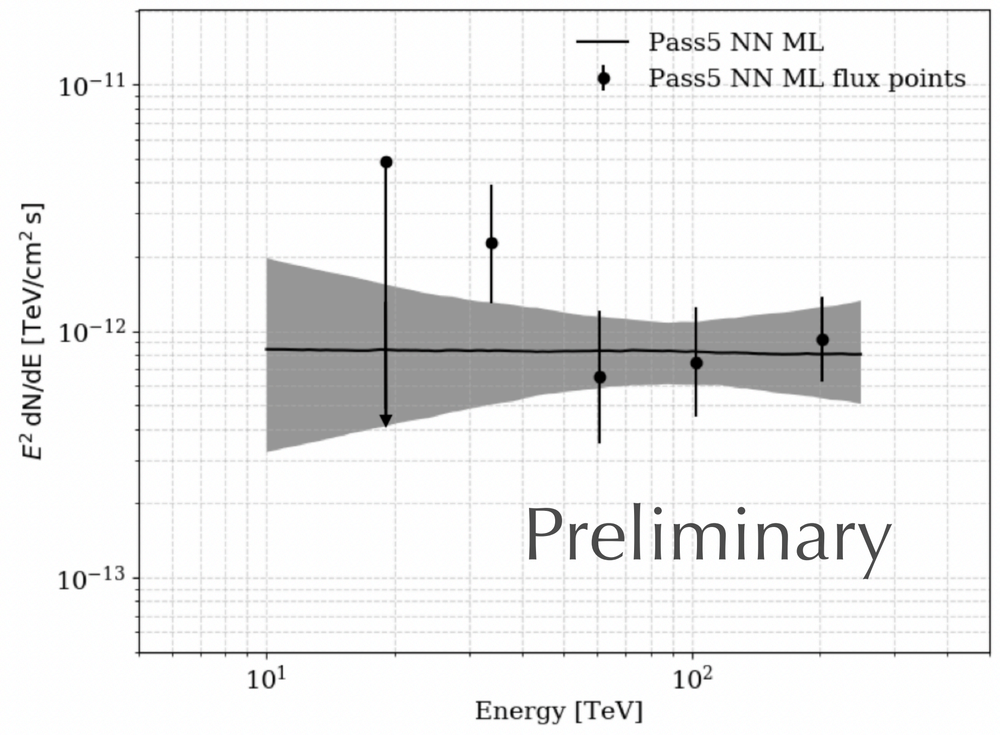
D. Huang, A. Albert *et al* 2024 *ApJL* **973** L34



- First detection of UHE gamma-ray from GC region
  - 2500 days of HAWC data
  - Extend to at least 114 TeV without sign of cut off
- Model independent arguments suggest hadronic mechanism and quasi-continuous injection scenario
- Particle acceleration sites need further study with next generation instruments
  - CTA, SWGO …

Unidentified UHE Source Near GC - J1730





- Detection with a significance above 5σ using 2,859 days of HAWC data, shared to the whole community via MOU
- Best-fit position: Right Ascension 262.5° ± 0.07°, Declination –31.13° ± 0.04°.
- Spectrum well described by a power law over the energy range 47–248 TeV, with a powerlaw index of 2.0 ± 0.4.
- Emission consistent with a point source, with a 68% upper limit on extension of 0.29°.
- Follow-up observations from gamma-ray, X-ray, and radio wavelengths are encouraged.

Young Massive Clusters

- YMCs more favorable condition to accelerate CRs to PeV energy range compare to SNRs
  - Massive stars are produced during the collapse of giant molecular clouds. They form compact groups consisting of tens of massive members. These stars remain linked throughout their life cycle (1 -10 Myr).
  - Acceleration scheme
    - Interacting Stellar Winds
    - Superbubbles
      - Large structure caused by Stellar Winds and SN explosions filled with turbulent plasma, strong shocks, enhanced B-field

- Gamma-ray detections from GeV, TeV, even to PeV
  - Westerlund 1 and Westerlund 2 detected by H.E.S.S.
  - Cygnus Cocoon by Fermi-LAT, HAWC and LHAASO

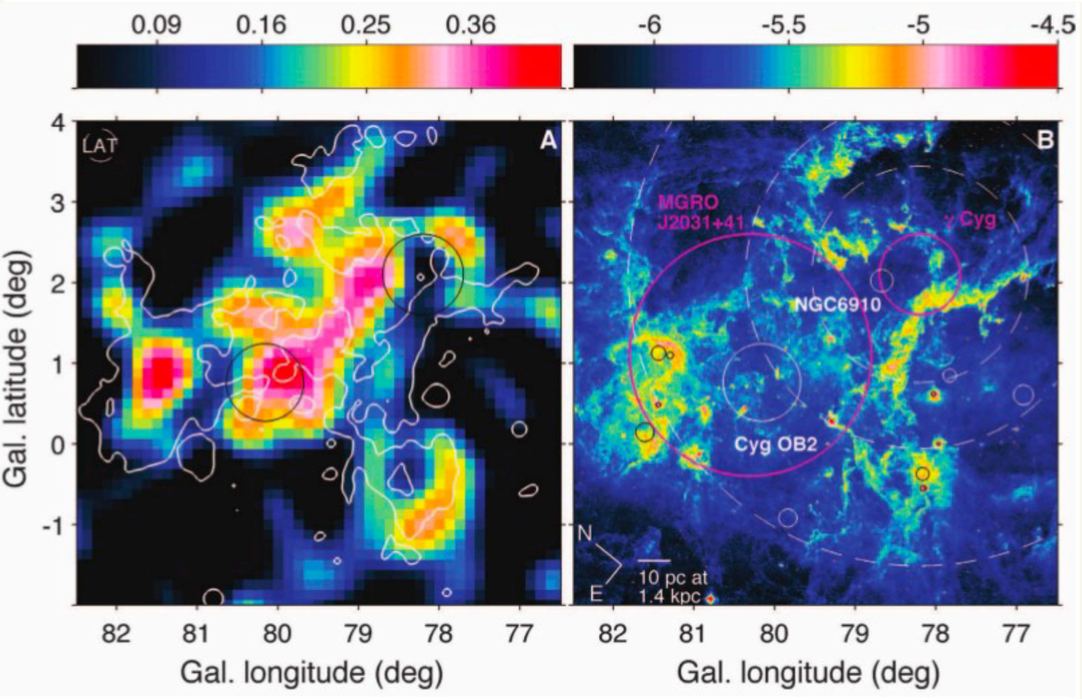
Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), A. Nota (ESA/STScI), and the Westerlund 2 Science Team

Cygnus Cocoon

A Cocoon of Freshly Accelerated Cosmic Rays Detected by Fermi in the Cygnus Superbubble

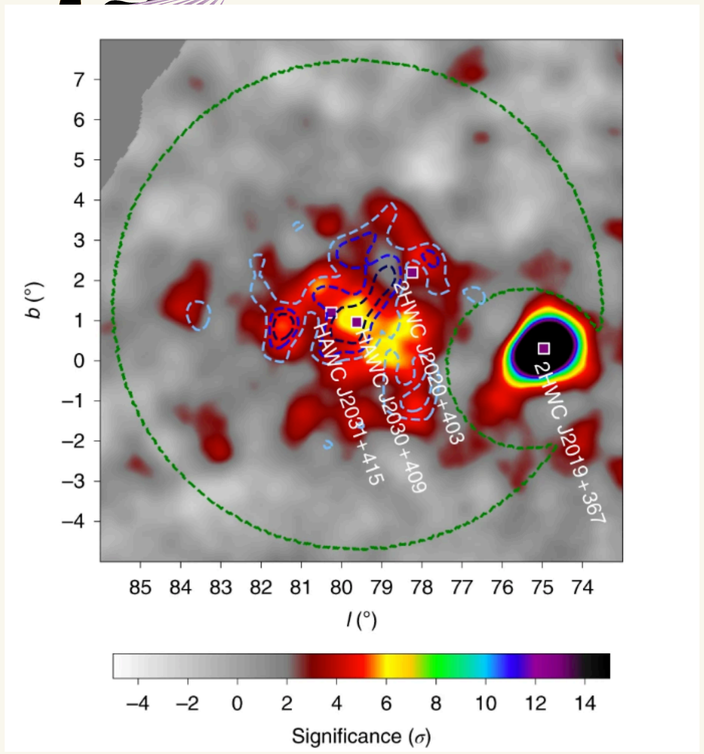
M. Ackermann[1], M. Ajello[1], A. Allafort[1], L. Baldini[2], J. Ballet[3], G. Barbiellini[4,5], D. Bastieri[6,7], A. Belfiore[8], R. Bellazzini[2], B. ...
+ See all authors and affiliations

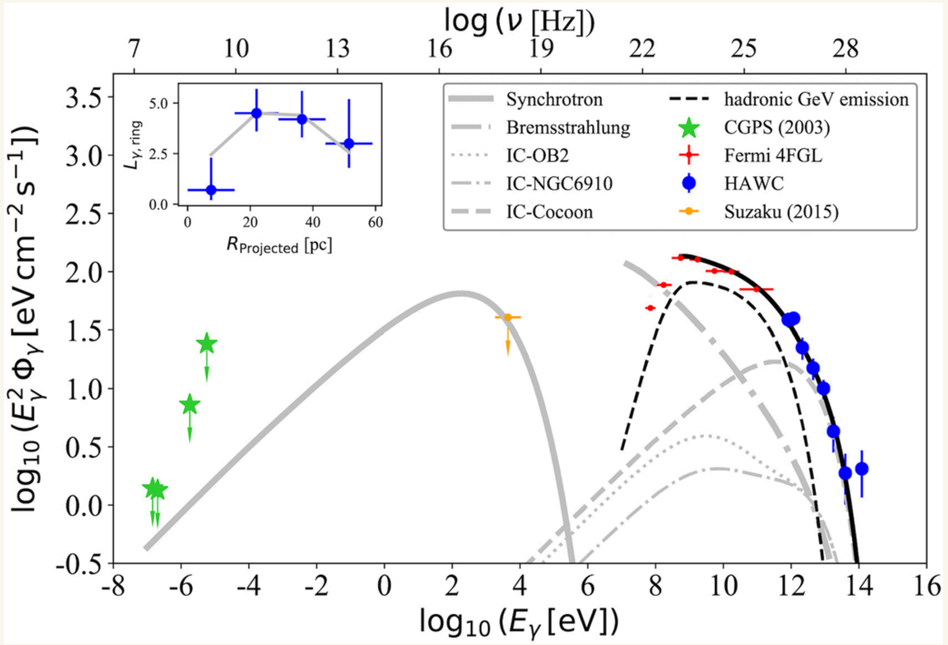
Science 25 Nov 2011:
Vol. 334, Issue 6059, pp. 1103-1107
DOI: 10.1126/science.1210311

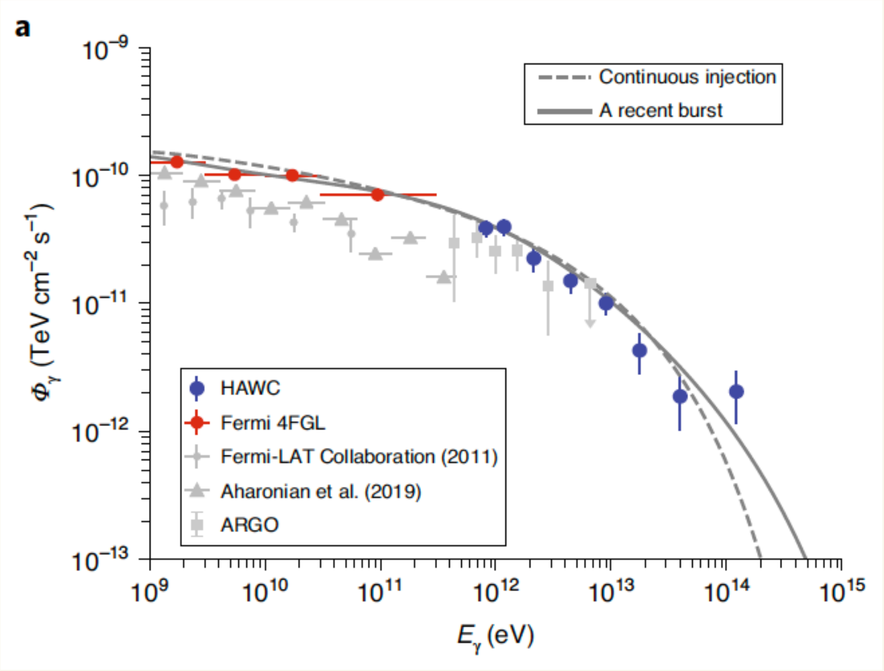


- One of the most massive OB associations in our Galaxy
- Consists ~120 type O stars
- Age: 1 to 7 Myrs
- Stellar wind power of a few 10^{39} erg/s, maintained for at least 2Myrs (Lozinskaya *et al.* 2002)
- Attribute to a Cocoon of freely accelerated CRs
- OB2 association as a possible source of CRs in the Cocoon

Cygnus Cocoon





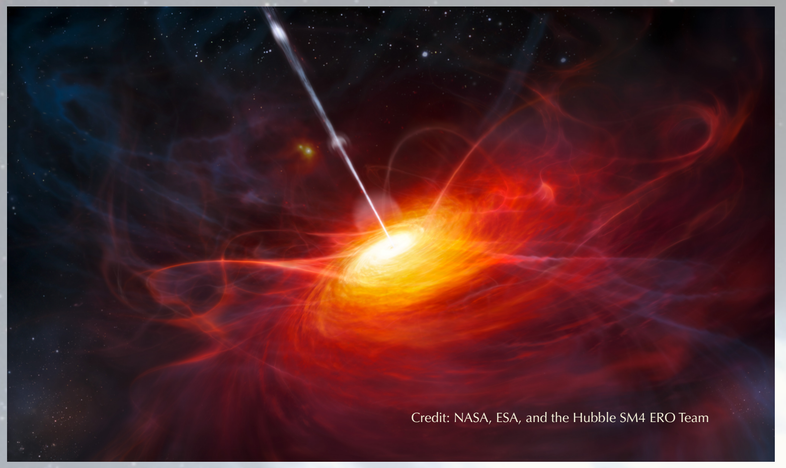


HAWC Collaboration *Nat Astron* **5**, 465–471 (2021).

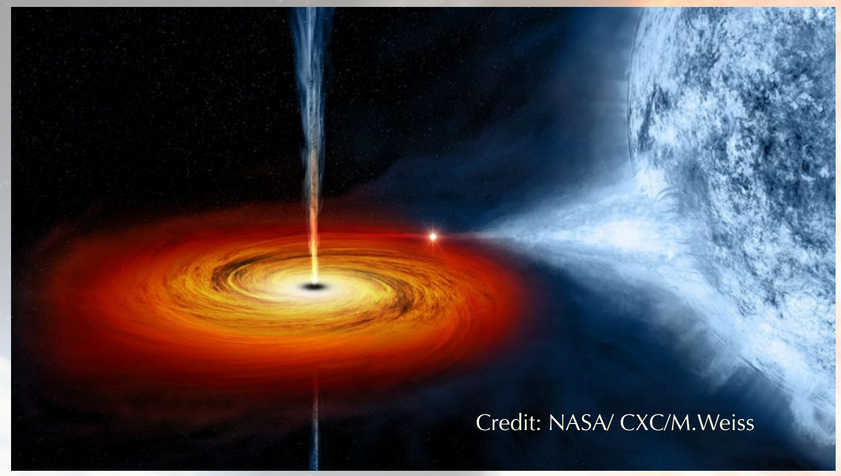
- Gamma-ray emission detected from 1 - 225 TeV by HAWC, likely hadronic origin
  - Significance map of the Cocoon region after subtracting HAWC J2031+415 (PWN) and 2HWC J2020+403 (γ Cygni)
  - Gaussian width is similar to reported by Fermi-LAT
- First time prove that star forming region could accelerate CRs to PeV
- Significantly detected above local CR (>10 TeV)
  - Can be described by 1/r signature for continuous injection or constant profile for burst like injection
- LHAASO-KM2A detected > PeV photon from this region, making it a super-PeVatron

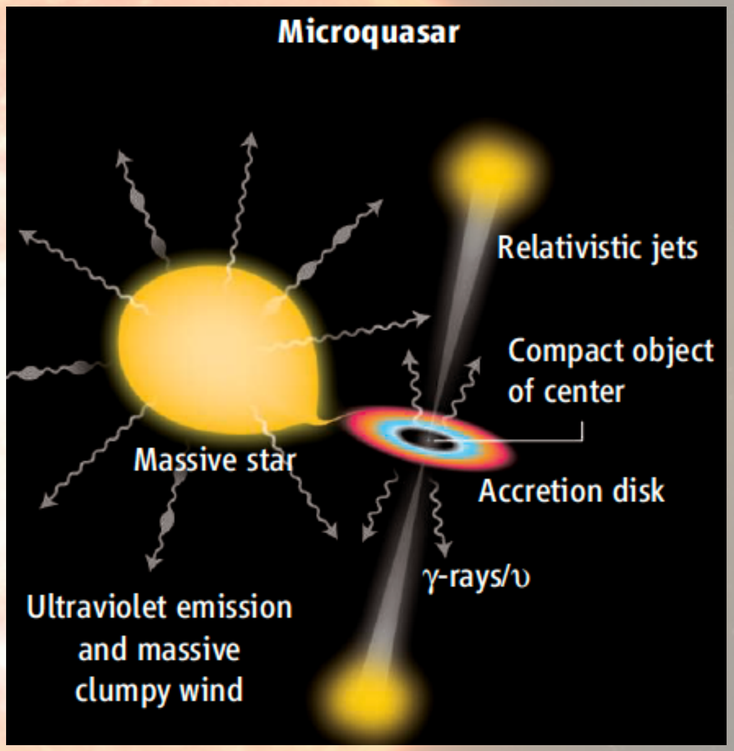
Microqusars

Active Galactic Nuclei (AGN)



Microquasar





I.F. Mirabel 2012

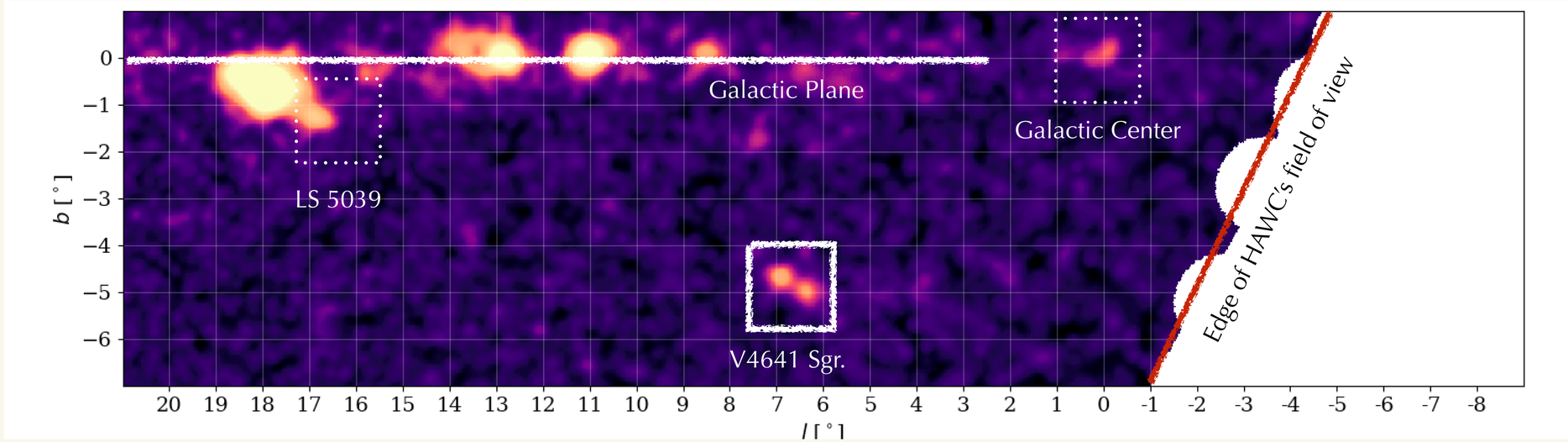
- Smaller version of a quasar (AGN)
  - Active Galactic Nucleus (AGNs): Relativistic jets can accelerate particles to extreme energy
    - Galaxy evolution, supermassive black hole… etc
- Near enough to allow detailed imaging of spatial features across multi wavelength
  - Great laboratories for studying
    - Particle accelerations in jets / jets formation in black-hole system
    - Evolution of accretion disk
- Rare and precious

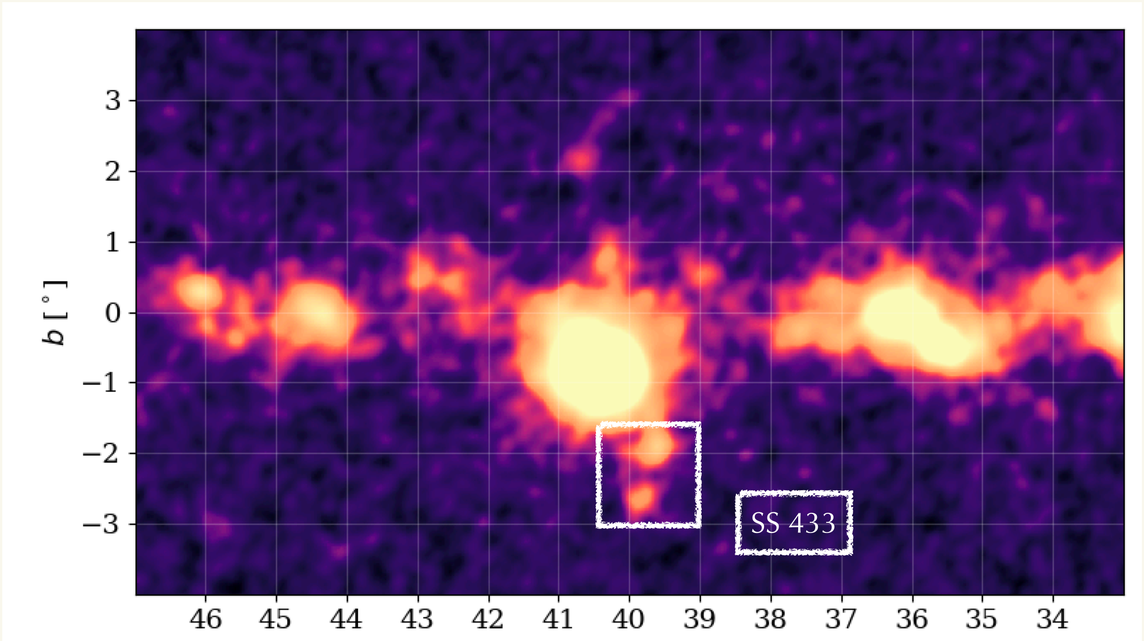
- **How would microquasars contribute to cosmic-ray energy spectrum?**

Image credit: L. Calçada / ESO.

Multi-TeV Microquasars with HAWC

GC >100 TeV detection, HAWC Collaboration: 2024 ApJL 973 L34

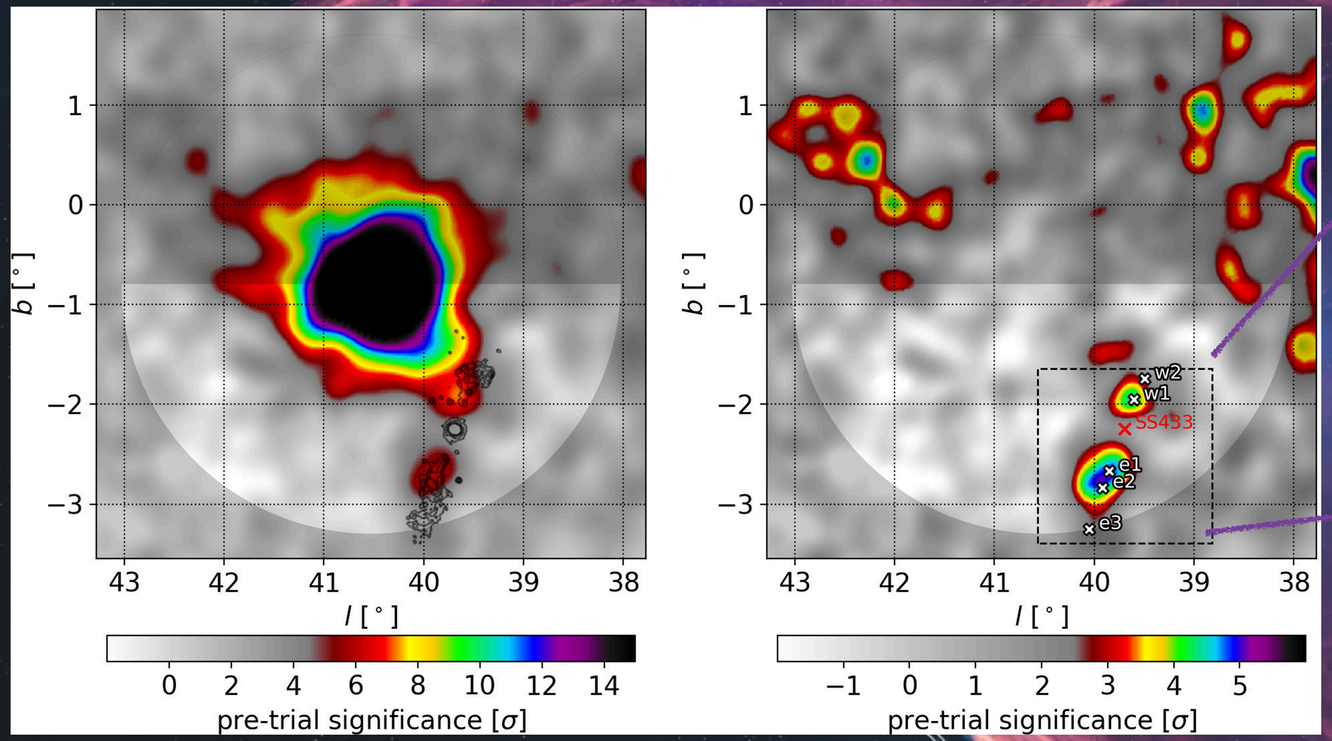


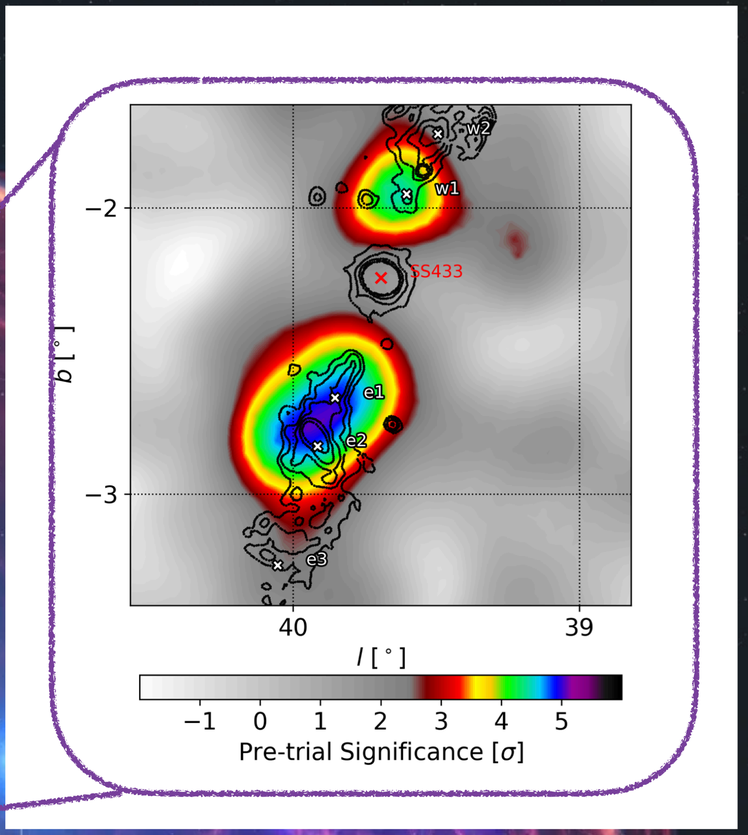


	Distance (kpc)	Companion star mass ($M_\odot$)	Compact star mass ($M_\odot$)	Orbital period (days)	Orbital axis inclination (°)
V4641 Sgr	6.2 ± 0.7	2.9 ± 0.4	6.4 ± 0.6	2.817 ± 0.002	72. 3 ± 4.1
SS433	~ 5.5	>10	8	13.082	79
LS5039	~2.5	22.9 +3.4 -1.3	3.7 +1.3 -1.0	3.90603 ± 0.00017	24.9 ± 2.8

Story Begins with Microquasar SS 433

Nature 562, 82–85 (2018)
https://doi.org/10.1038/s41586-018-0565-5



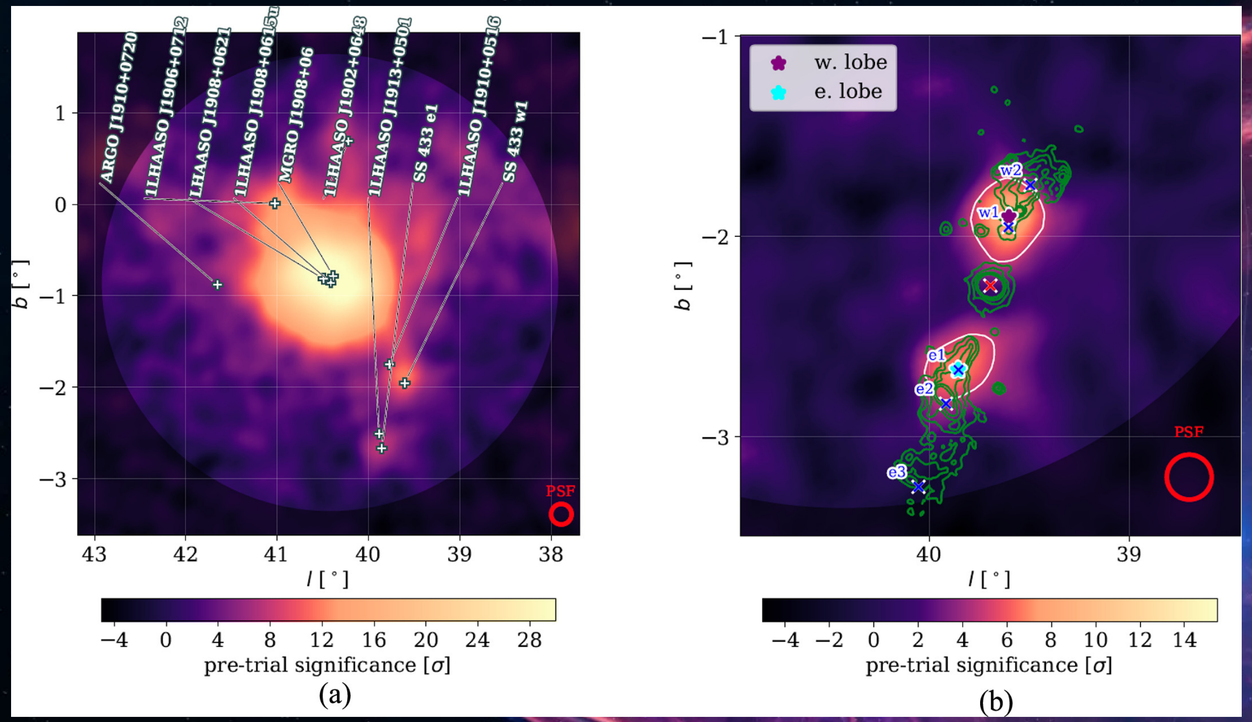


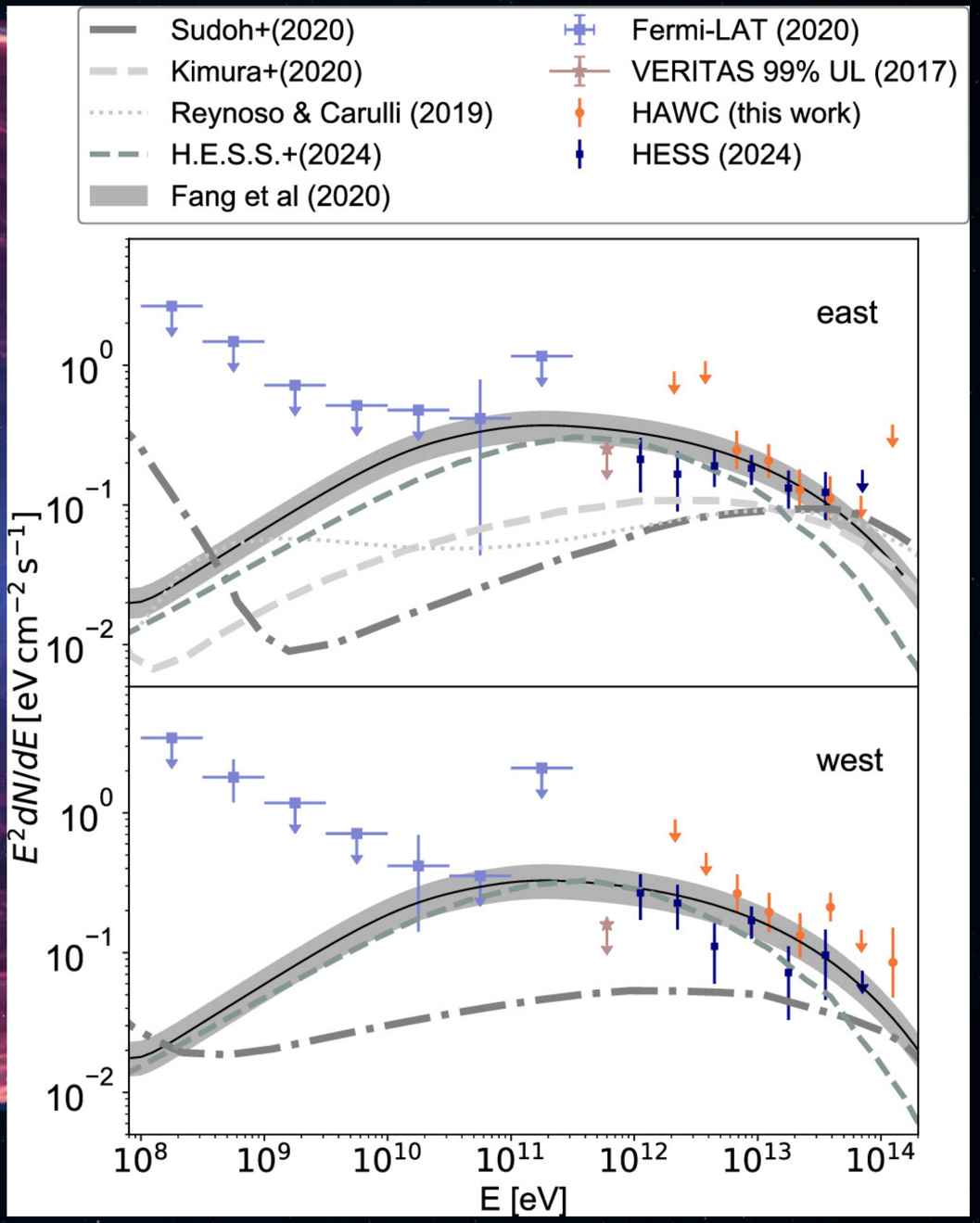
- Distance: ~5.5 kpc
- Compact object with 8 $M_\odot$, companion star mass > 10 $M_\odot$
- Orbital period of ~13.1 days
- Near bright MGRO J1908+06

- First microquasar with large-scale jets, by HAWC
- With 1017 days of HAWC observations
- Post-trial 5.4 σ
- GeV to TeV emission can be explained by relativistic electrons cool efficiently
  - Shows that powerful jets can accelerate 100 TeV electrons
  - Particle acceleration sites ~30 pc away from black hole

CREDIT: Science Communication Lab for MPIK/H.E.S.S.

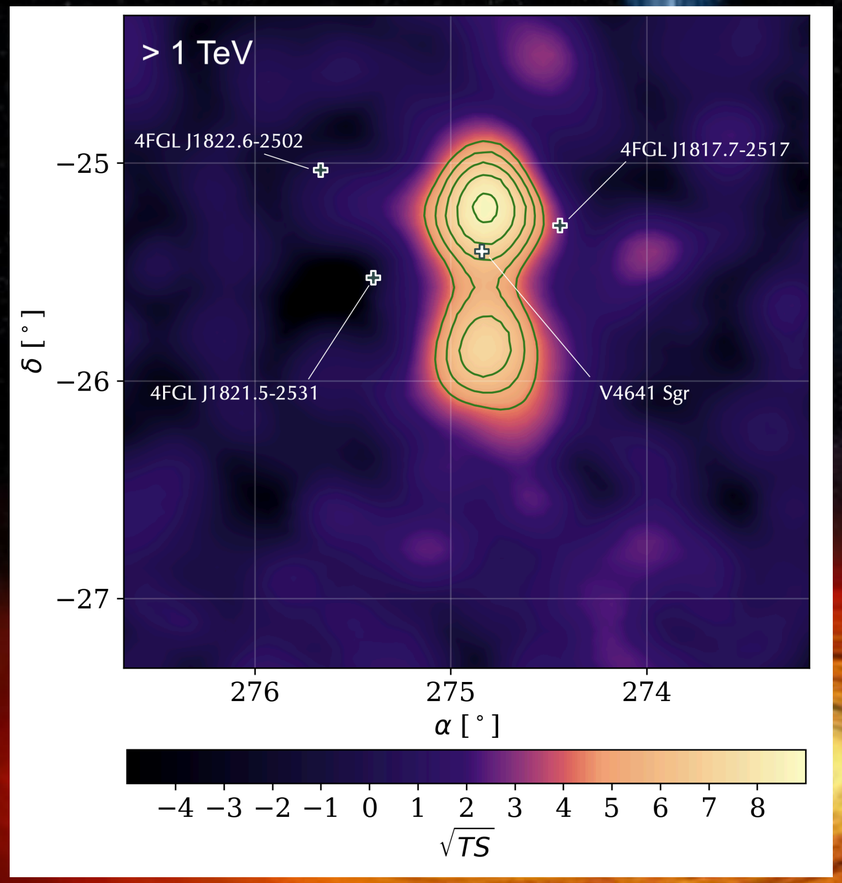
Recent Updates from SS 433

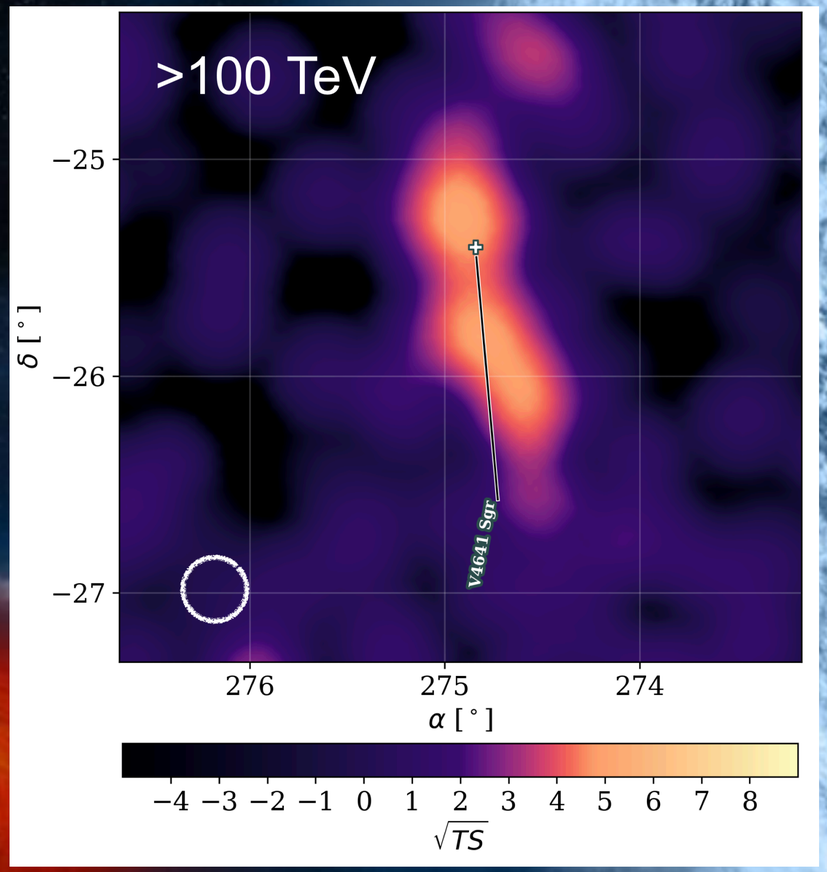




- HAWC Updates (K. Fang, C.D. Rho,Y. Son *et al* 2024 *ApJ* **976** 30):
  - 2569 days of data, better Reconstruction algorithm
  - Confirm 2018 results, gamma-ray production inside the jets
  - More separate with MGRO J1908 +06, Lobs have enough significance to do the individual analysis
  - SED >100 TeV
  - >30 TeV SED challenges the one zone model where electrons simultaneously produce X-ray and gamma-ray emissions

First UHE Microquasar V4641 Sgr.





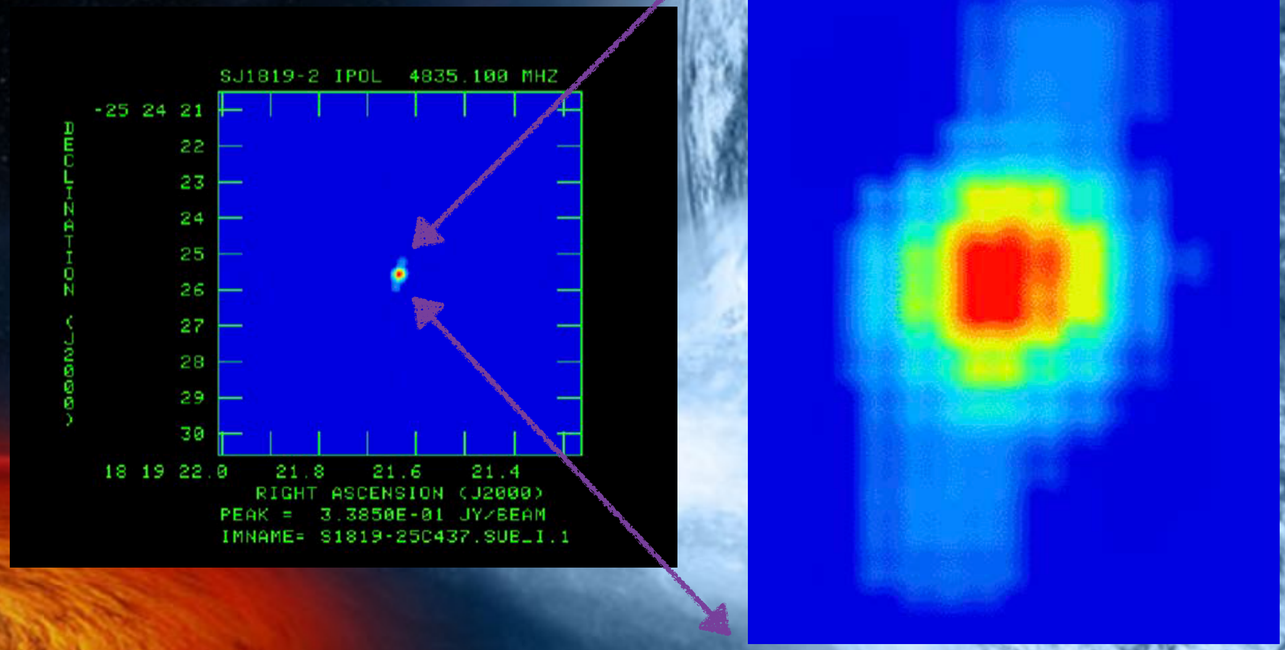
- GAMMA 2022: Report an off-plane source was newly detected in the southern sky near the boundary of HAWC's Field Of View (~ 45° zenith) with seven years of data
- The excess is over the background at a 8.5 sigma pre-trail significance in all energy range, and 5.2 sigma above 100 TeV with elongated emission
- The source position is coincident with V4641 Sgr.
  - One of the fastest superluminal jets in the Milky Way galaxy

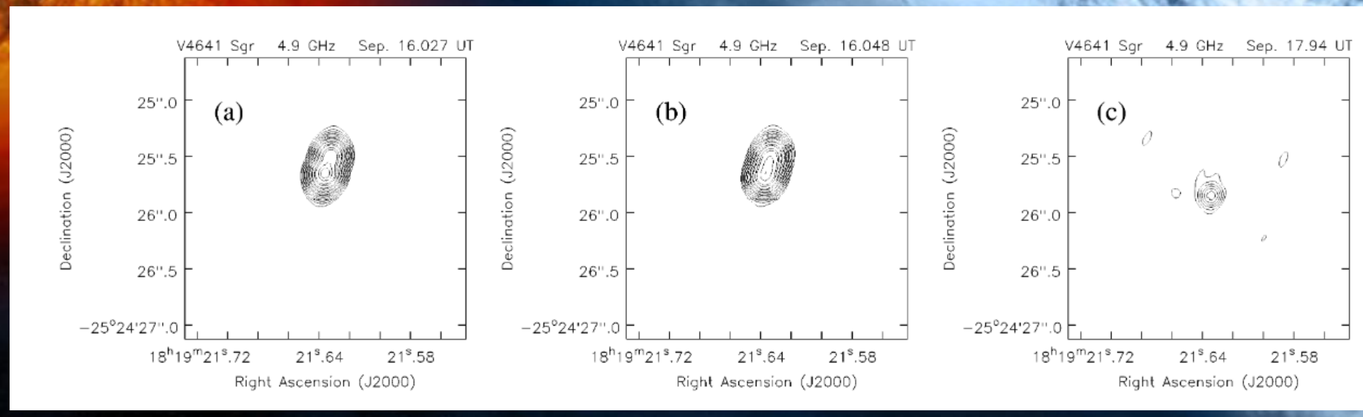
X. W et al, HAWC Collaboration, Nature , 2024

Learn More About Microquasar V4641 Sgr.

- Distance is 6.6 kpc away from us
- Have a Companion star ~ 2.9 $M_\odot$
- Compact object should be a black hole with the mass ~ 6.4 $M_\odot$
- Orbital period ~ 2.8 days
- Stand out for it's violent X-ray outburst in September 1999
  - X-ray flux reached to 12.2 Crab in 8 hours
- Jet-like structure observed by VLA (0.25″)
  - Jet axis inclination: <16 °
  - Superluminal jets: apparent velocity 9.5 c
- Recurrent outburst within 500 - 600 days

Credit: (R.M. Hjellming, NRAO, VLA, Associated Universities, Inc.)

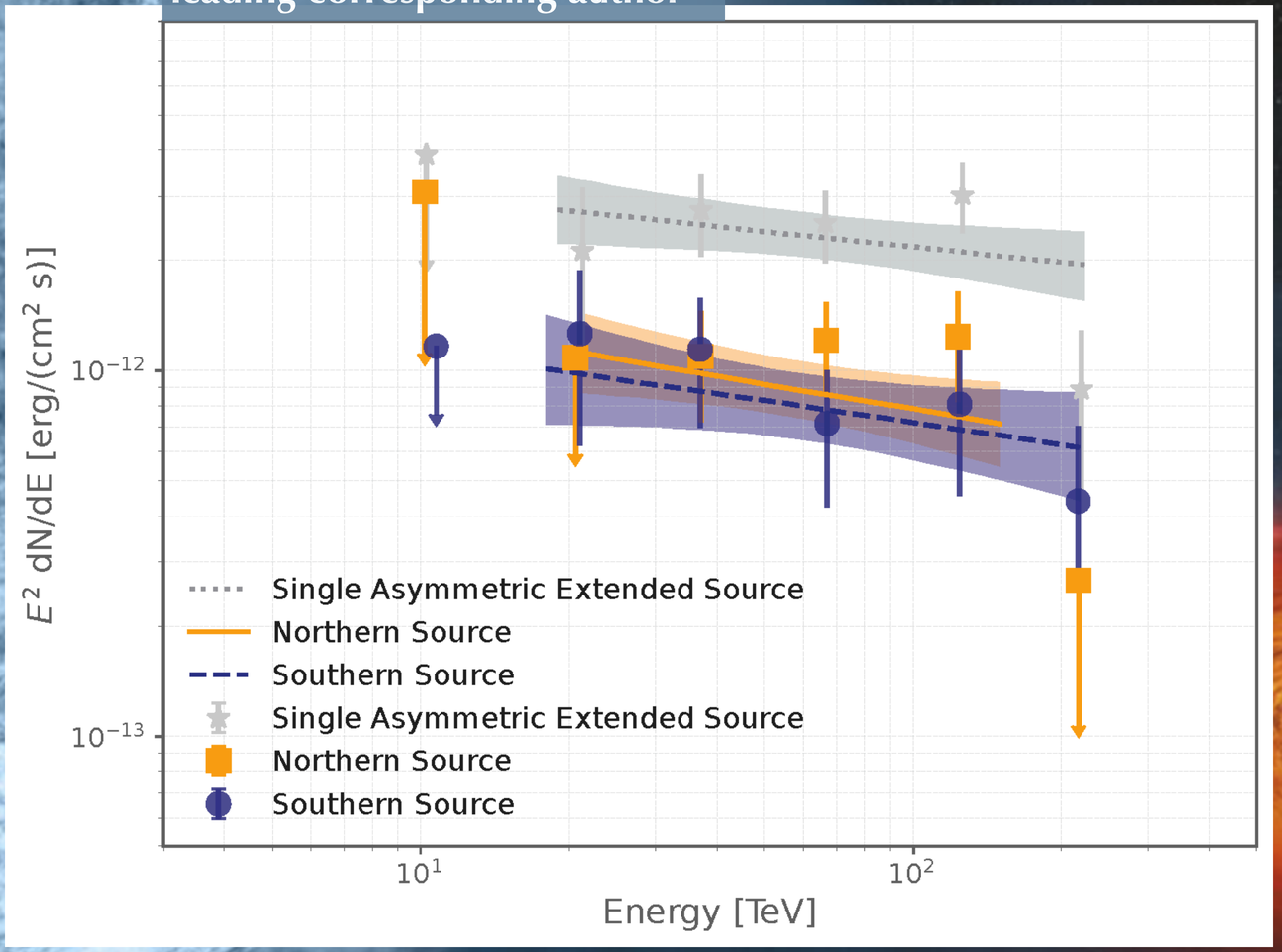




HJELLMING et al, APJ, 544 : 977-992, 2000

Microquasar V4641 Sgr.

Nature, HAWC, 2024, X.W. as leading corresponding author



- Two-point source model or one elongated extended source
  - Similarity of spectral properties for two sources, likely share the same origin
  - Gamma-ray sources tens of pc away from black hole
  - Elongated source: ~70 pc
  - Maximum energy >200 TeV
  - as the second Galactic Microquasars with large scale jets
- Indices ~2.2, among the hardest source ever detected by ground-based gamma-ray instruments

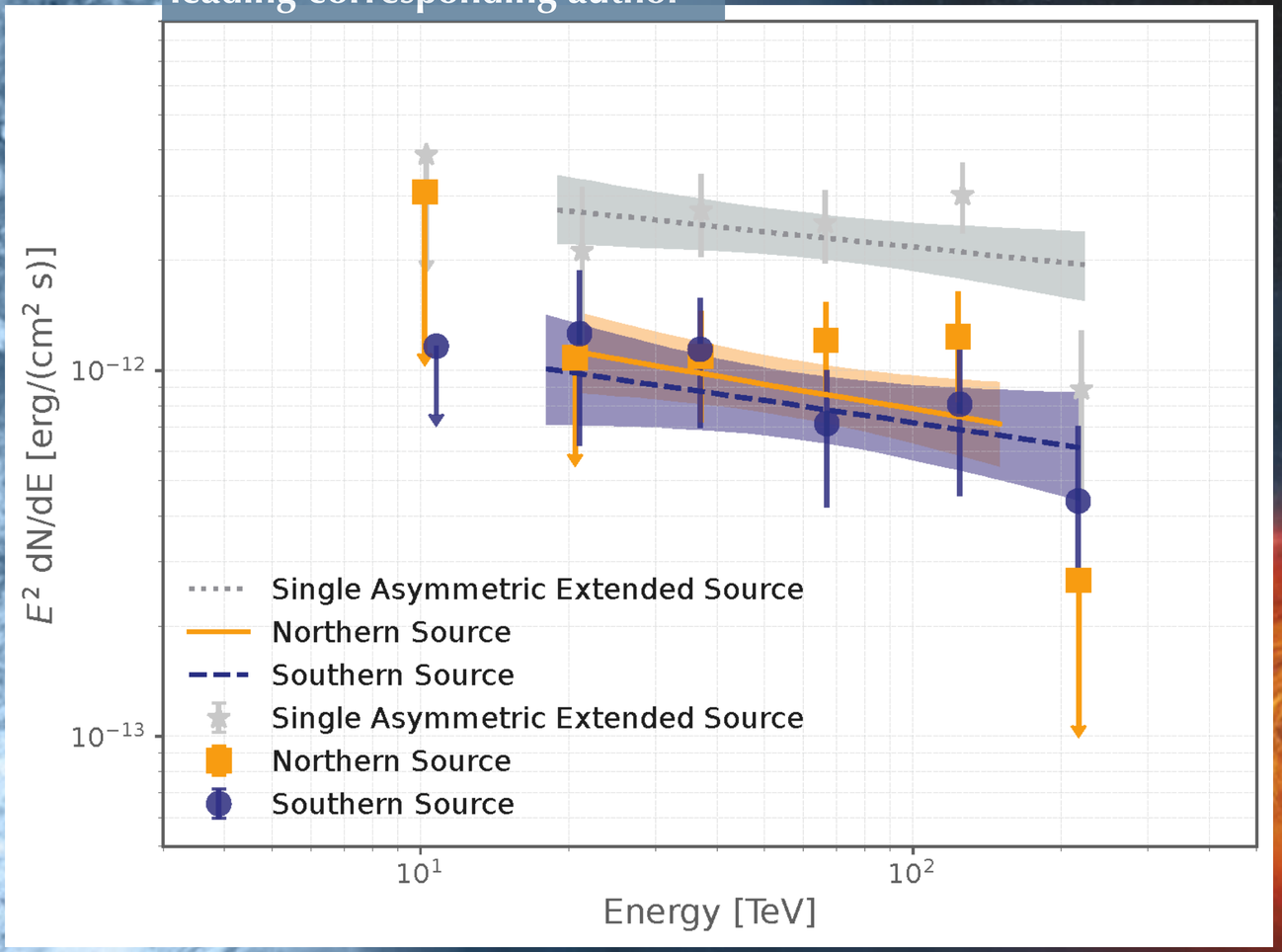
Table 1 | Best-fit parameters for a model with two point sources

Source name	RA (°)	dec. (°)	N_0 ($\times 10^{-16}$ cm^{-2}TeV^{-1}s^{-1})	Index (α)	Extension upper limit at 95% confidence level (°)	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 ± 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.) ± 0.4(syst.)	-2.2 ± 0.2(stat.)$^{+0.07}_{-0.05}$(syst.)	0.17	0.23° ≈ 30 pc

The optimal pivot energy, E_0, is 47 TeV for both sources.

Microquasar V4641 Sgr.

Nature, HAWC, 2024, X.W. as leading corresponding author



- Two-point source model or one elongated extended source ~70 pc
- First time observe microquasar > 200 TeV, at such unexpected high energy!
- Gamma-ray emission can be explained by jets accelerate proton > 2 PeV
  - First time prove microquasars could be PeVatrons, and be a major contributor to cosmic-ray observe on earth
- Multi-wavelength and multi-messenger follow up observations is needed to fully understand the nature of gamma-ray emissions
  - No adequate observations yet (Next step!)
  - Triggered a surge of interest in community

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The optimal pivot energy, E_0, is 47 TeV for both sources.

Power of Community - Sharing New Discoveries

Share new detected gamma-ray source near the V4641 Sgr in HAWC

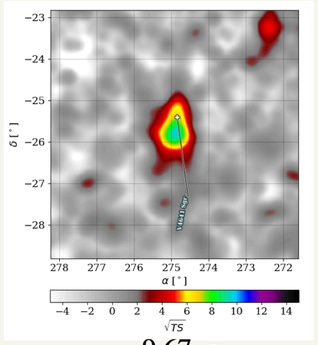
Xiaojie Wang <xwang32@mtu.edu> Jun 29, 2022, 5:24 PM

to aimran, amy.furniss, czar, David.J.Thompson, dingus, dorner, elilin, fortson, Gilles.Henri, gsagar, jholder, mazin, rcrannot, rkoul, sagar.godambe, taylora, swagne

HAWC's View of V4641 Sgr. —Information sharing

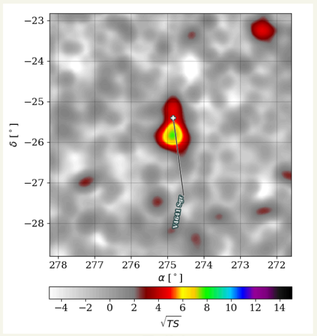
- Caveat: high zenith source for HAWC

All bins



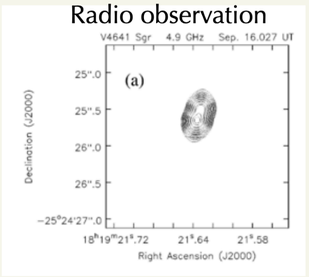
9.67 σ

On array $E_{Median} > 3TeV$



7.81 σ

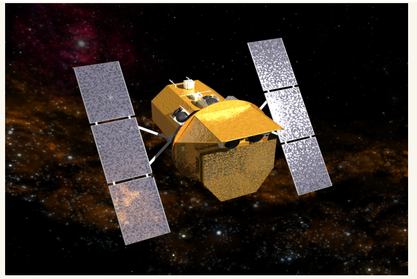
Radio observation

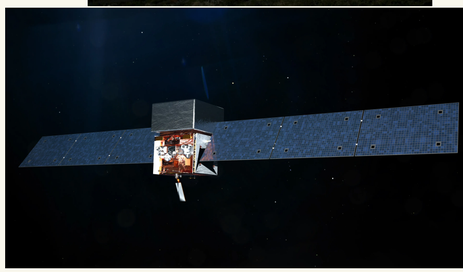


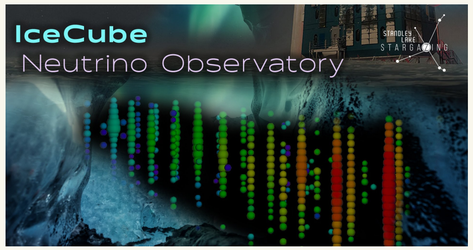
https://iopscience.iop.org/article/10.1086/317255/pdf

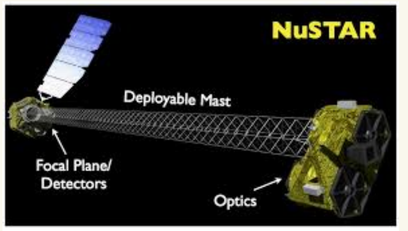
Map	R.A.	Dec.	Flux @ 31 TeV [1 / (cm^2 TeV s)]	Index
All bins	274.91 +/- 0.04	-25.814 +/- 0.028	(8.2 -1.2 + 1.4) x 10^-16	-2.40 +/- 0.15

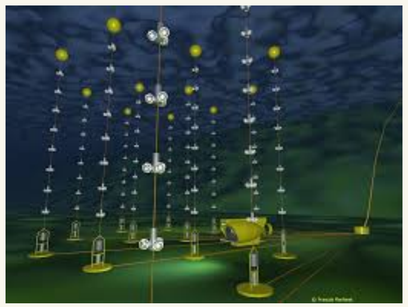
- The initial discovery (June 2022) of V4641 Sgr was promptly shared with the entire community under the MOU.
- This allowed for rapid multi-wavelength and multi-messenger follow-up by the broader scientific community

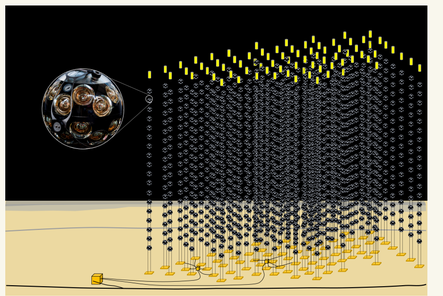




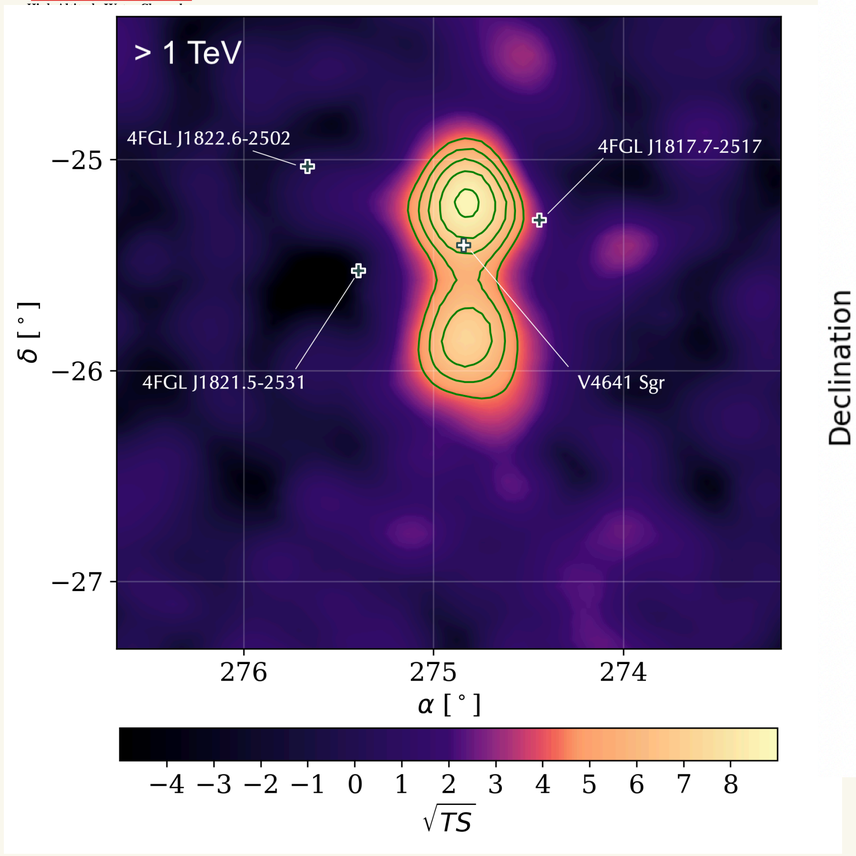


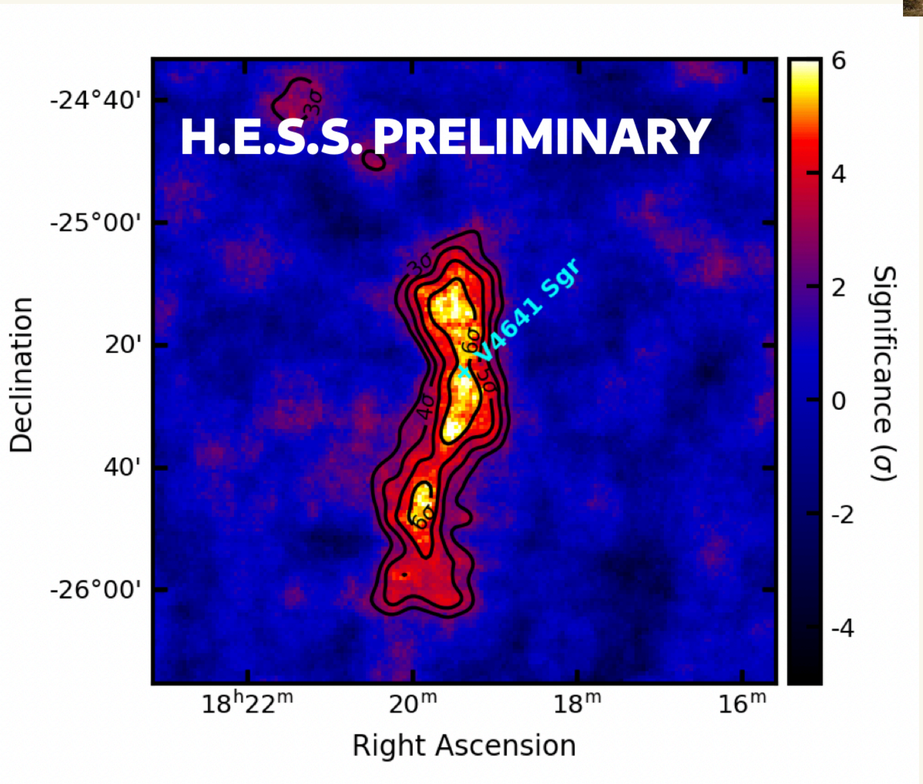


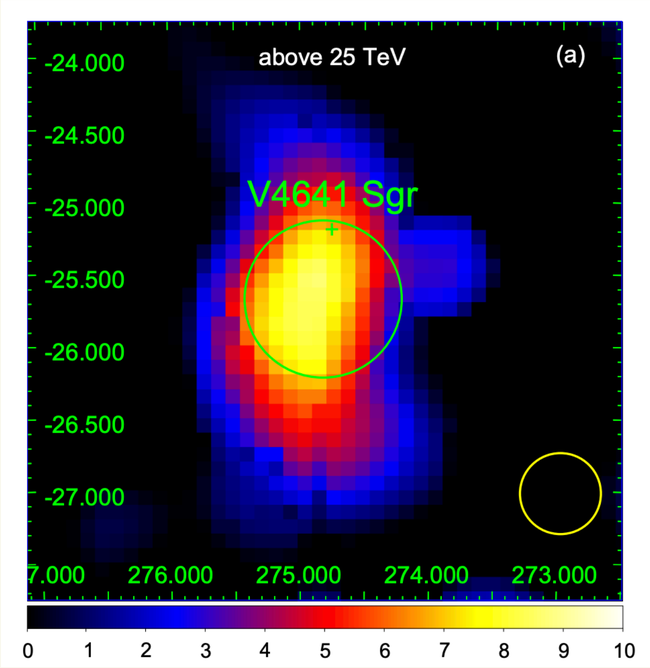




V4641 Sgr Follow-ups





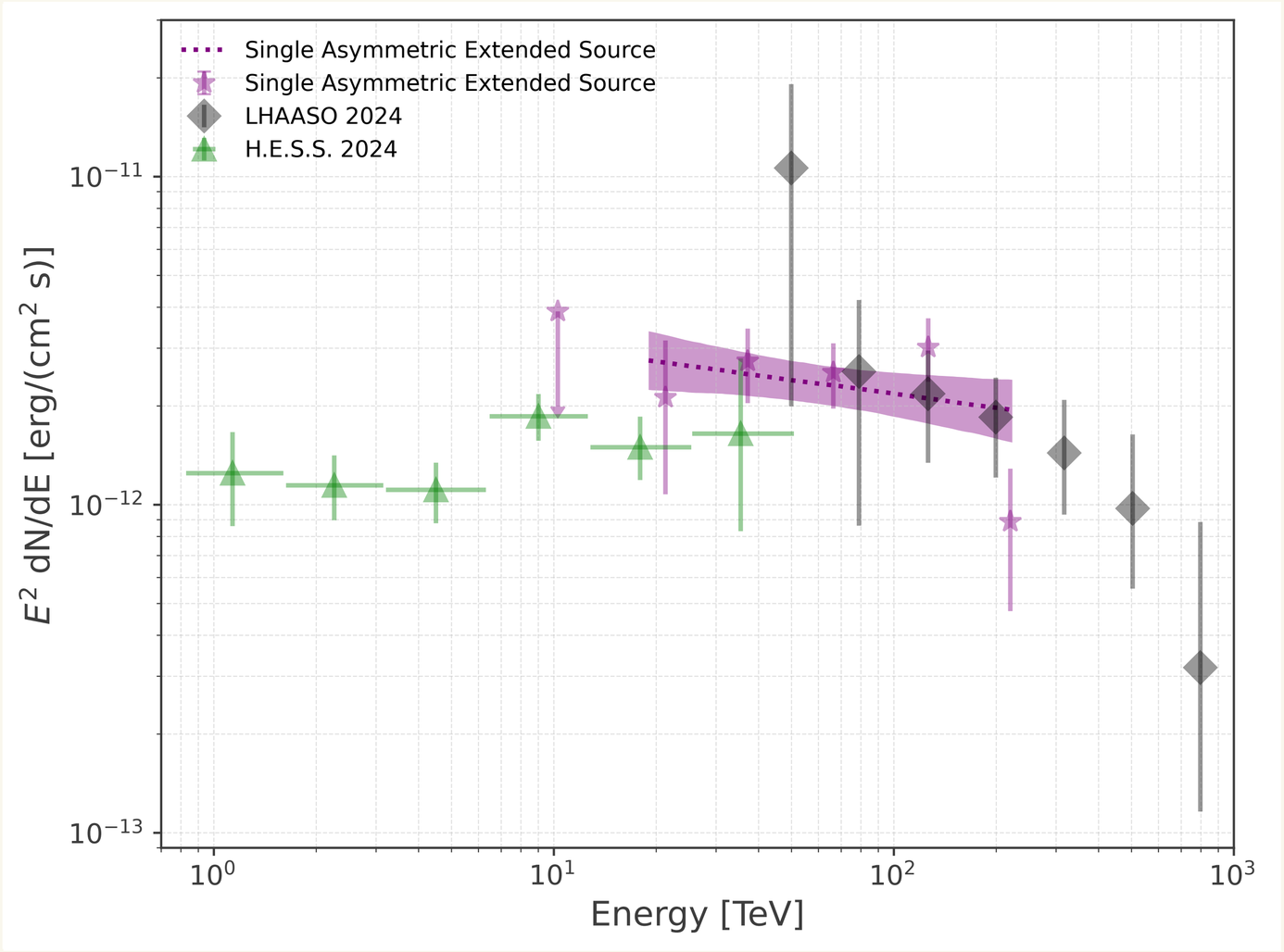


Laura Olivera-Nieto, Gamma 2024

LHAASO, arXiv 2410.08988

- Detected by H.E.S.S. with ~115 hours of total observation time
- Harder spectrum (index < 2) in 1 TeV - 30 TeV
- LHAASO detected 800 TeV photon

V4641 Sgr Follow-ups



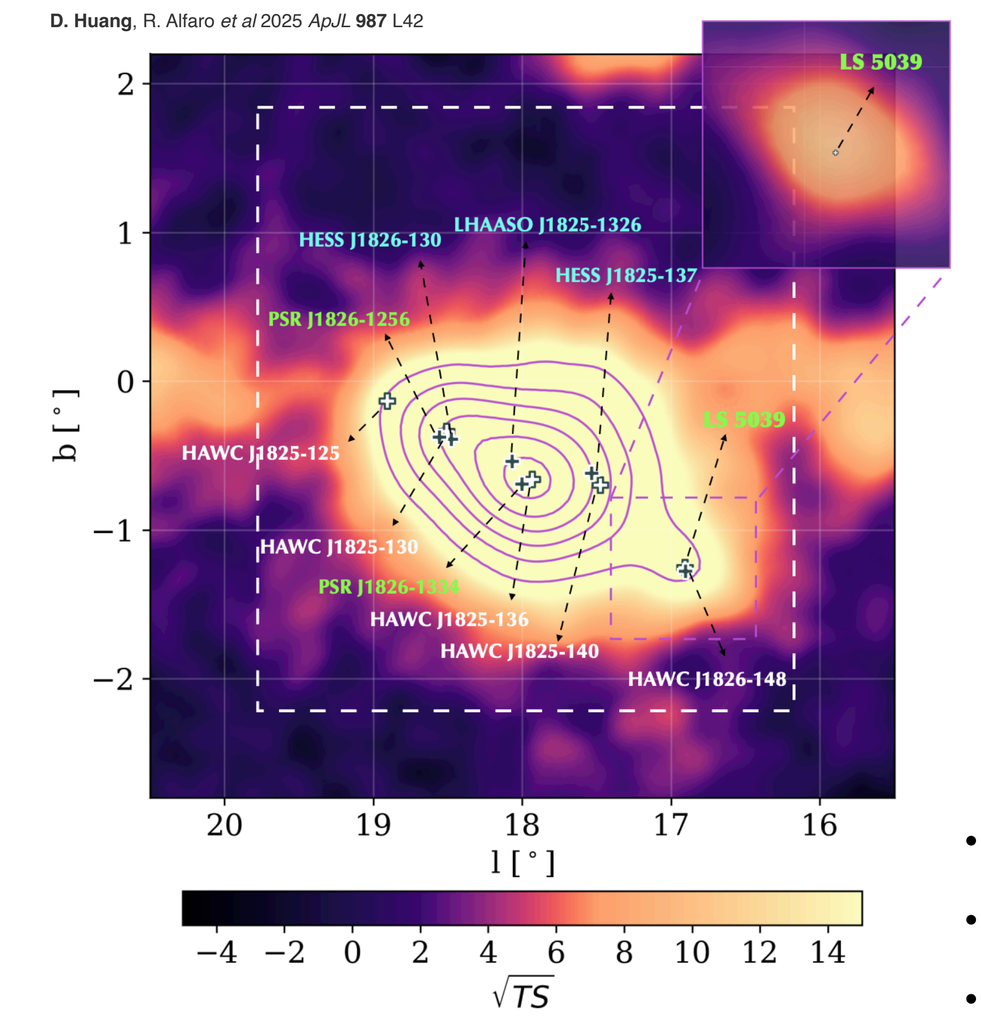
- Adding H.E.S.S. and LHAASO observation
- Compare one source model
- Hard spectrum across 1 - 500 TeV
- No obvious cutoff until 500 TeV from LHAASO
- Possibly accelerate proton to > 8 PeV

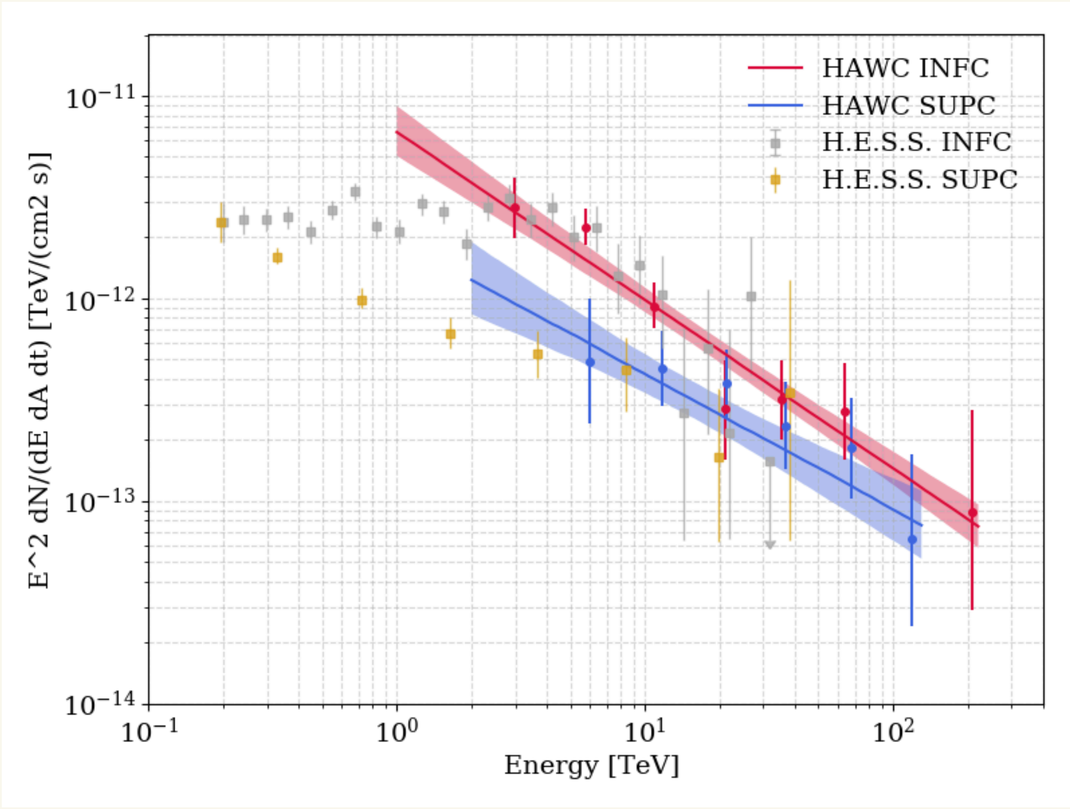
Call for more multi-wavelength and multi-messenger observations to solve the mystery together!

LHAASO, arXiv 2410.08988

L. Olivera-Nieto, Gamma 2024

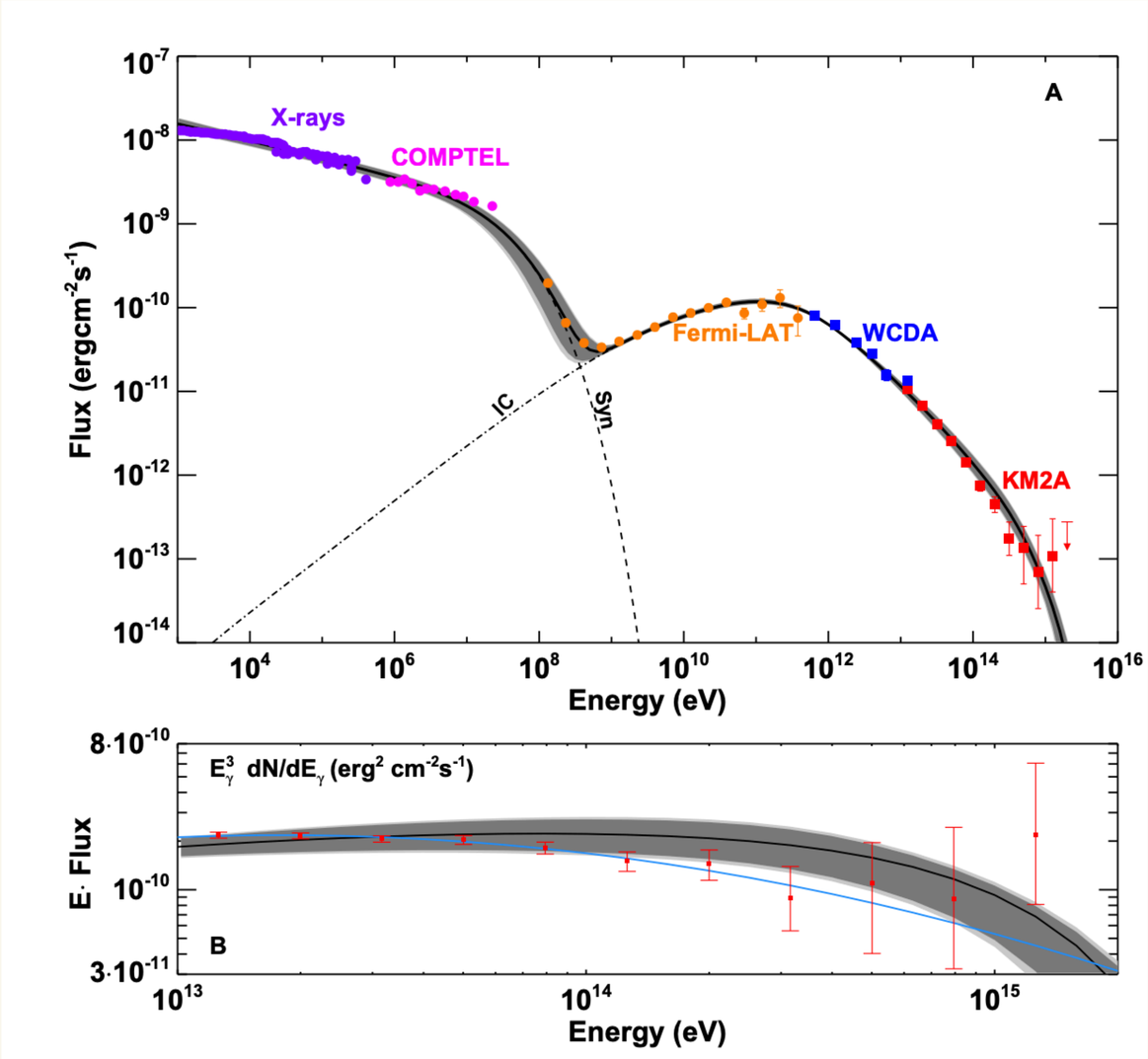
LS 5039





- Flux modulation extended beyond 100 TeV durning INFC and SUPC without cutoff
- Strong evidence of VHE gamma-ray are emitted within the orbit
- Could be originally from PeV protons collision with dense gas or intense radiation regions
- Extreme acceleration of electrons is required for leptonic scenario

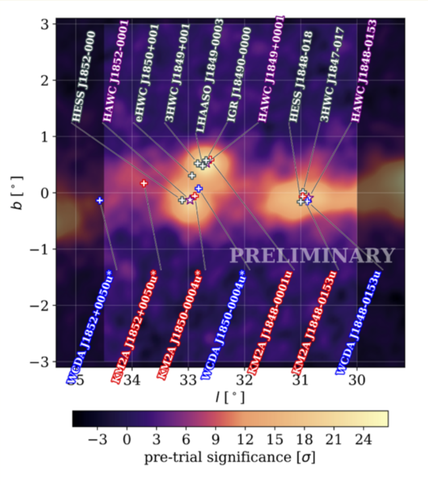
PWN? Extreme Energy Accelerator - Crab Nebula

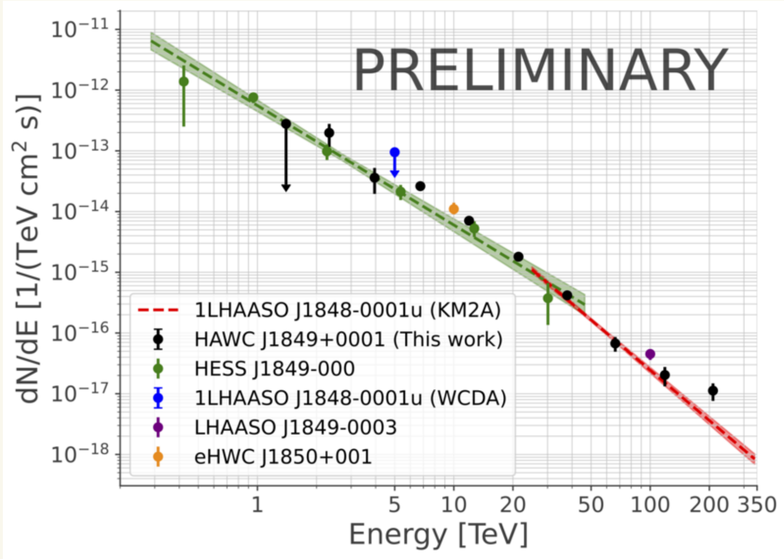


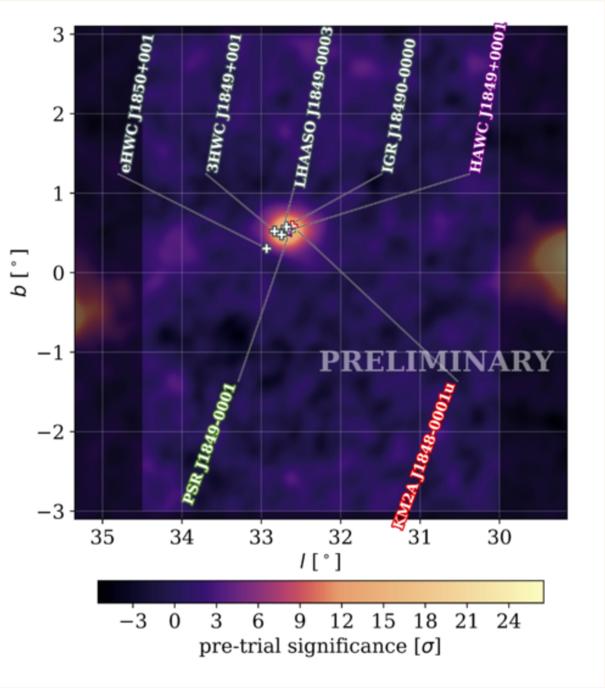
- First leptonic “PeVatron” - 1.1 PeV photon
- Extreme e-accelerator
  - 2.15 PeV electrons
  - Size between 0.025 and 0.1 pc
  - Could describe by one zone model
  - Acceleration rate exceeding 15% of theoretical limit
    - 1000 times better than SNR shock waves
- Can not rule out PeV proton contribution

LHAASO Collaboration., Science 373, 425–430 (2021)

HAWC 1849+0001



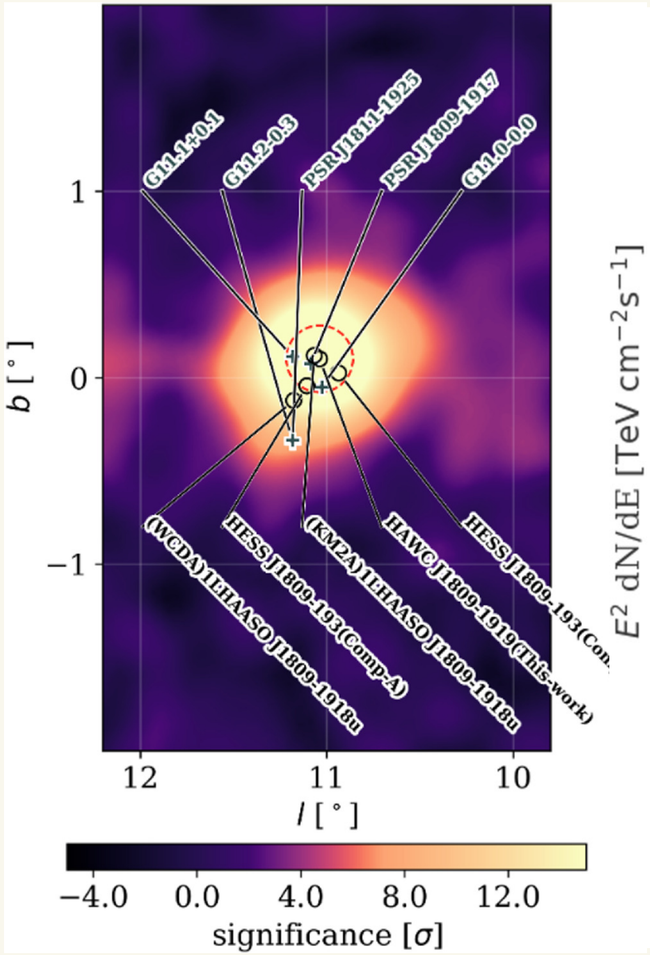


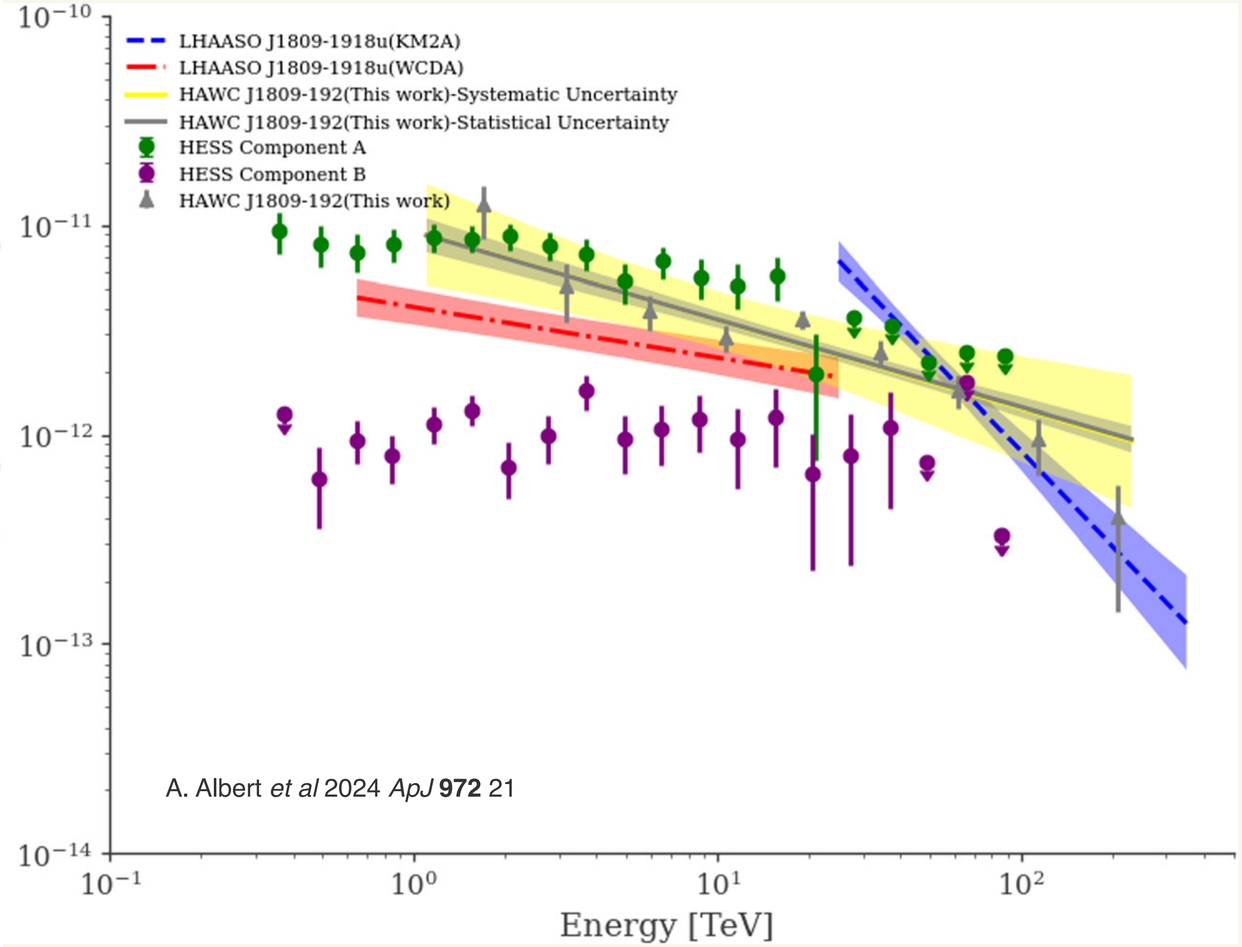


HAWC (This work)	H.E.S.S.	LHAASO
HAWC J1848-0153 (282.02°, −1.85°)	HESS J1848-018 (282.12°, −1.89°)	1LHAASO J1848-0153u (WCDA, KM2A) (282.06°, −1.89°), (282.02°, −1.78°)
HAWC J1849+0001 (282.27°, 0.01°)	HESS J1849-000 (282.24°, −0.04°)	LHAASO J1849-0003, (282.35°, −0.05°) 1LHAASO J1848-0001u (KM2A) (282.19°, −0.02°)
HAWC J1852-0001 (283.00°, −0.04°)	HESS J1852-000 (283.06°, 0.10°)	1LHAASO J1850-0004u (WCDA, KM2A) (282.74°, −0.07°), (282.89°, −0.07°)

- One of the eHWC source significantly >56 TeV
  - < 0.1° separation with H.E.S.S. and LHAASO counterparts
- 2398 days of HAWC data
  - SED extend >200 TeV
  - Spatially coincided with PWN G32.54+0.53, powered by PSR J1849-0001
- Detections only in X-rays and VHE gamma-rays
  - Indicated of non-thermal leptonic origin

Source Rich J1809 Region





- Source inside the region
  - SNR G11.0-0.0
  - SNR G11.2+0.1
  - PSR J1809-1917
- 2398 days of HAWC data
  - TS=392
  - Up to 210 TeV
- Accelerator
  - Leptonic-hadronic origin
  - Time-dependent leptonic origin

From A Handful to Tens and More…

PHYSICAL REVIEW LETTERS **124,** 021102 (2020)

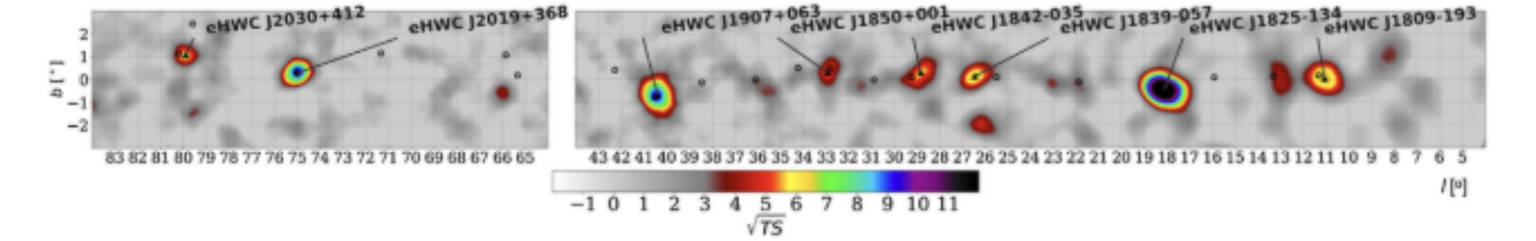
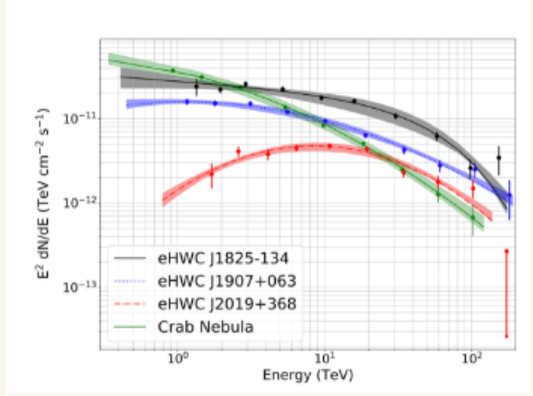
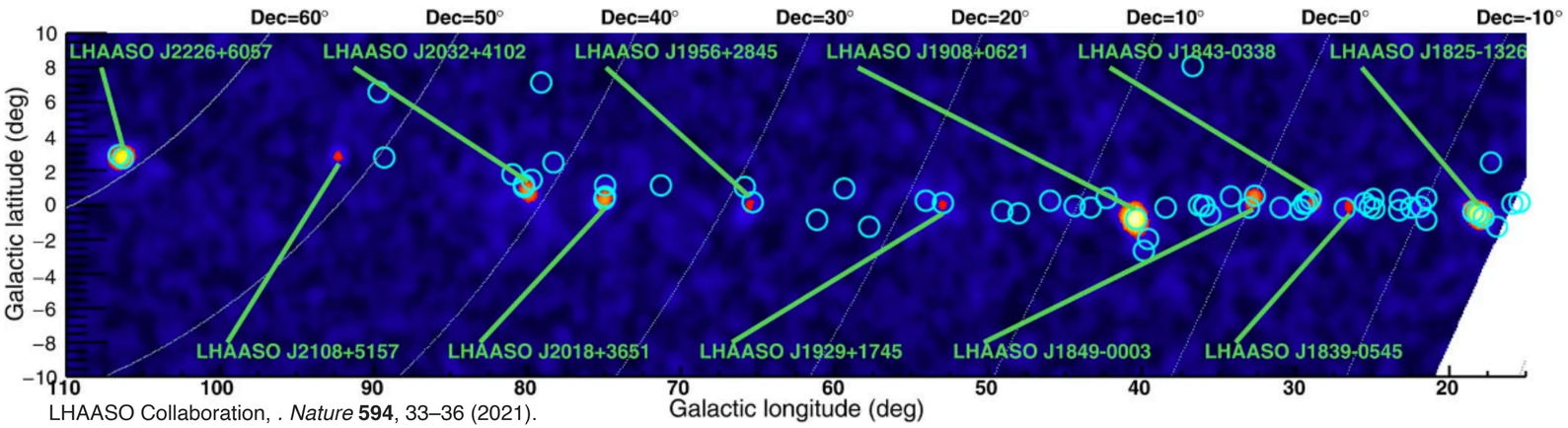
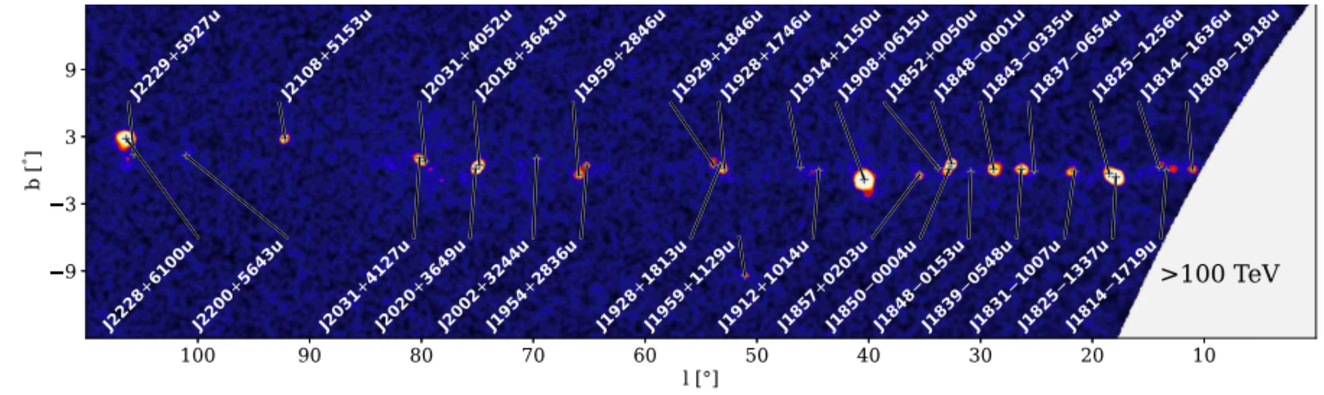


FIG. 1. $\sqrt{TS}$ map of the galactic plane for $\hat{E} > 56$ TeV emission. A disk of radius 0.5° is assumed as the morphology. Black triangles denote the high-energy sources. For comparison, black open circles show sources from the 2HWC catalog





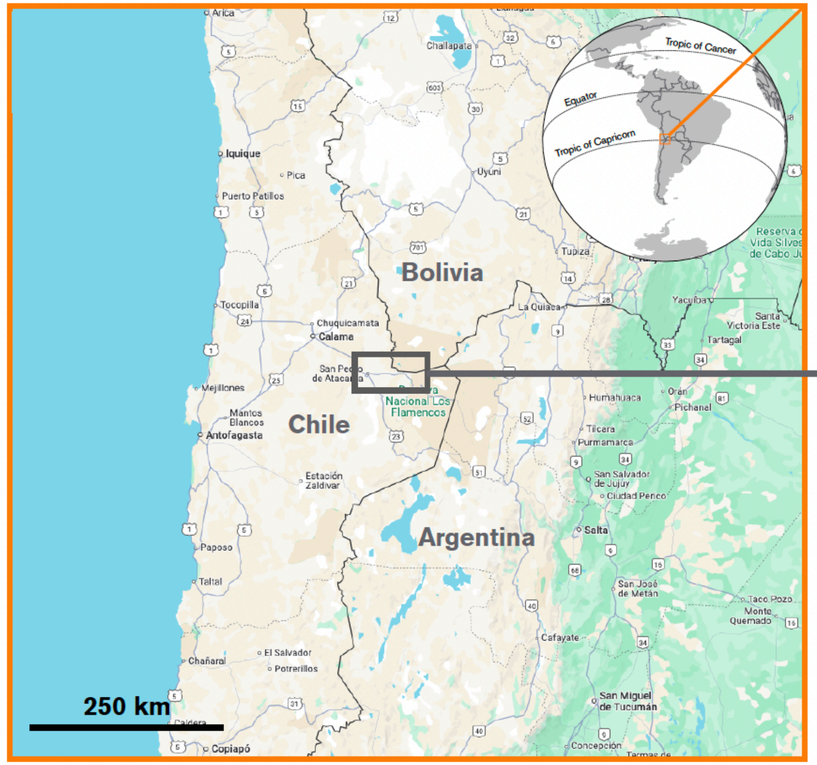
LHAASO Collaboration, . *Nature* **594**, 33–36 (2021).

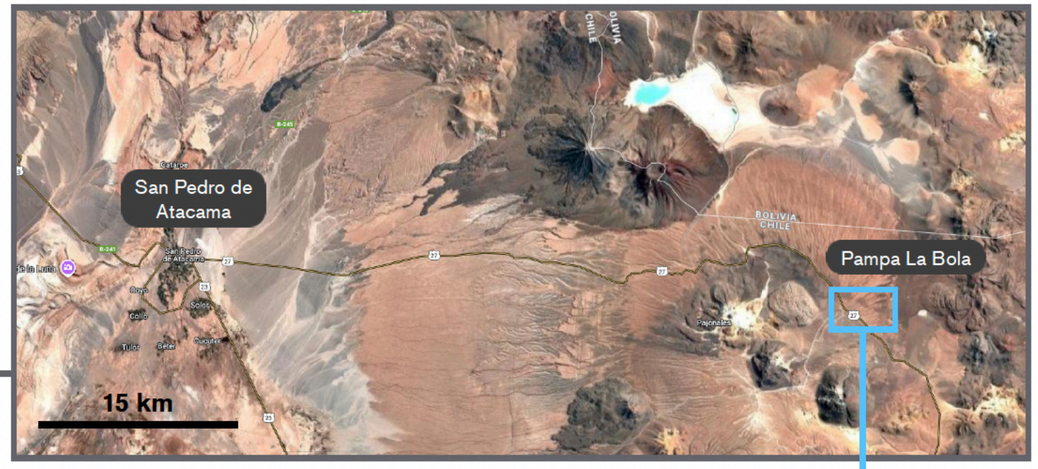


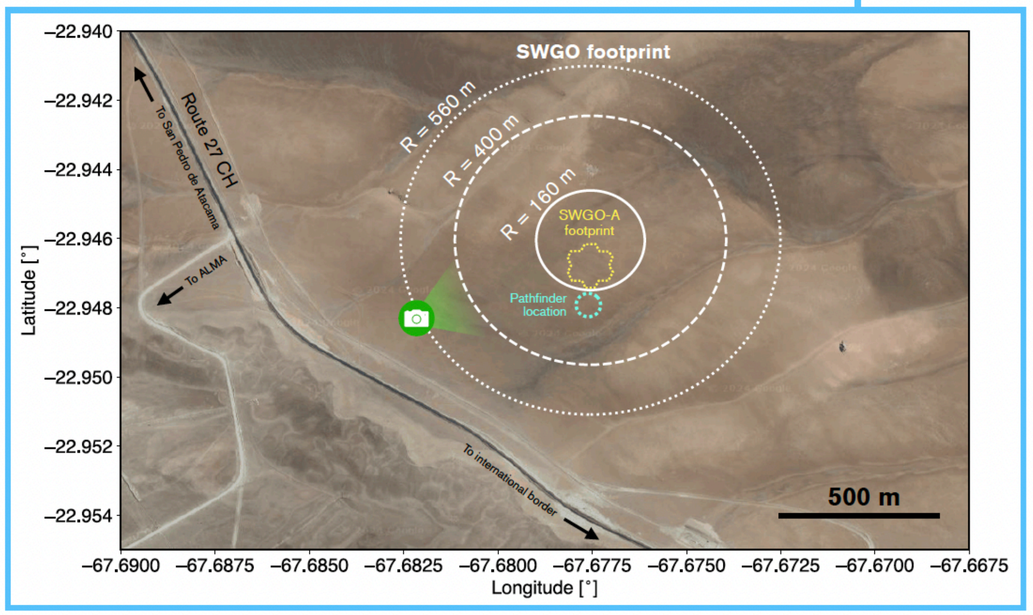
43 sources > 100 TeV in 1st LHAASO Catalog

The Astrophysical Journal Supplement Series, 271:25 (26pp), 2024 March

Southern Wide-field Gamma-ray Observatory: SWGO







Upcoming Insights: Stay Tuned for More Results

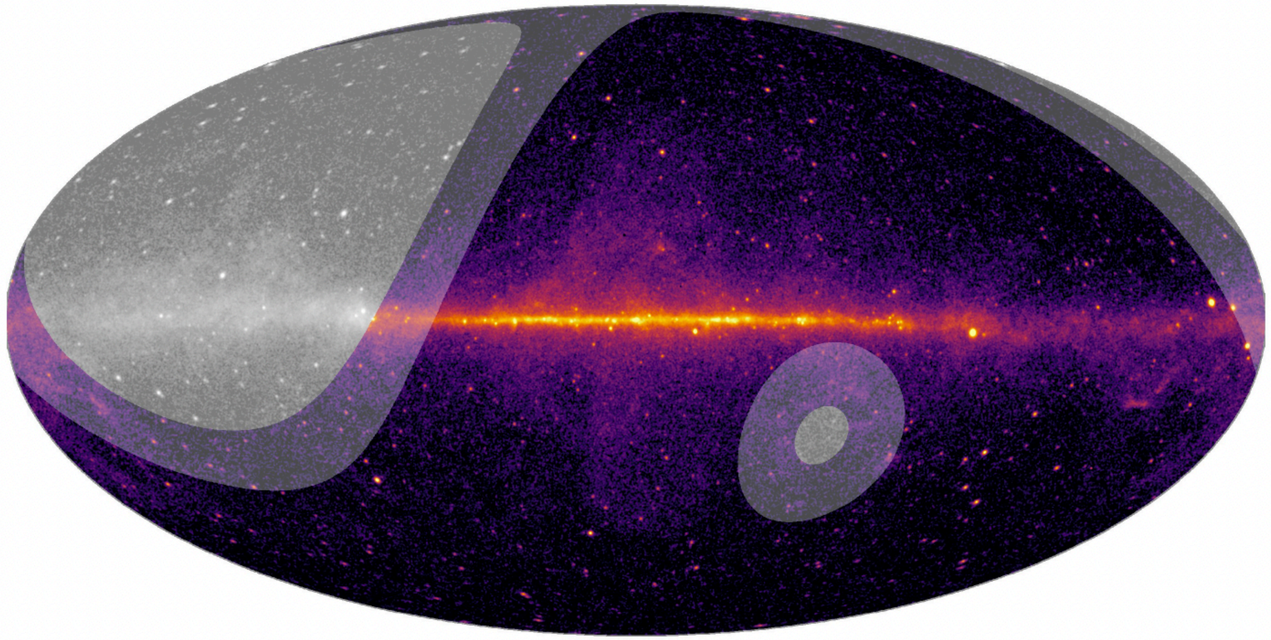
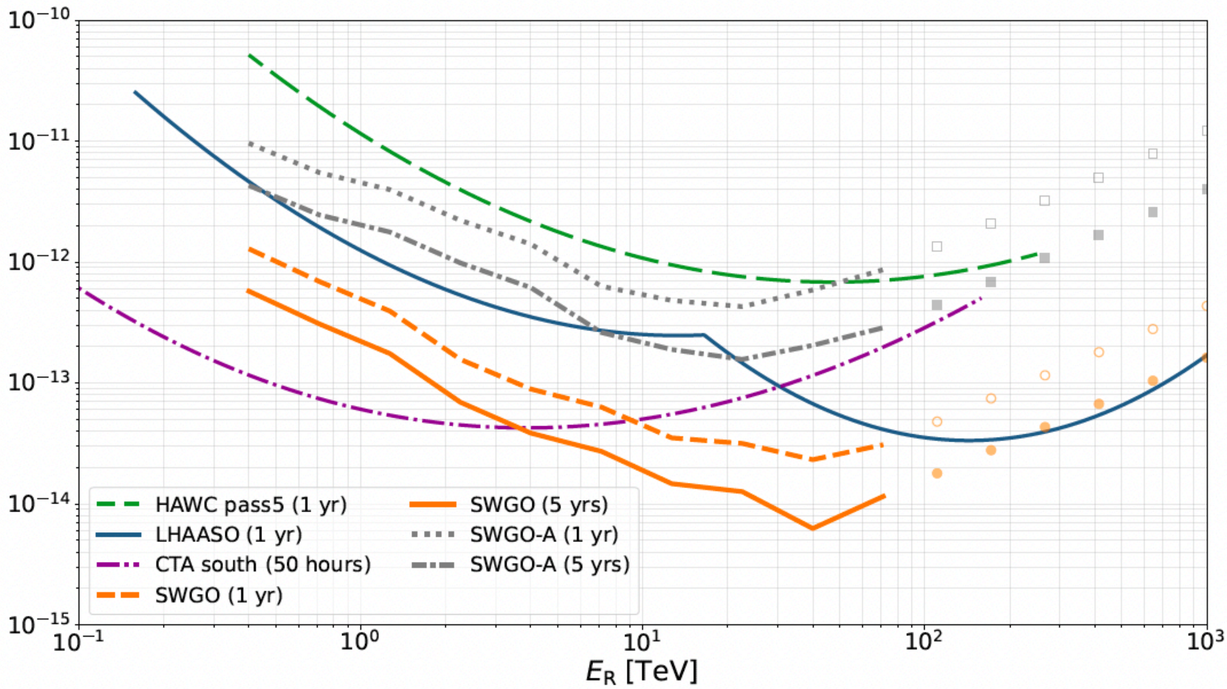


Figure 1: SWGO visibility map showing the sky observable to SWGO above 45° (full color) and 60° (color shaded) together with *Fermi*-LAT all-sky image from 3 to 300 GeV, available at https://doi.org/10.26093/cds/aladin/3mva-x6. Regions invisible to SWGO are shown in greyscale.



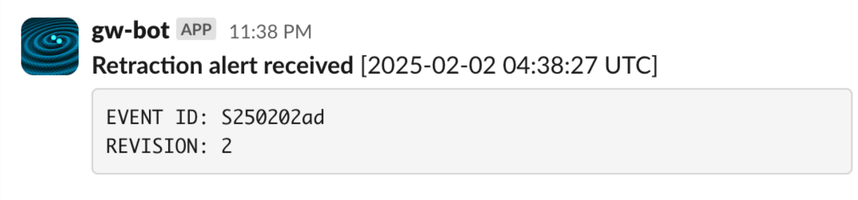
- Better coverage of the Galactic Center region
- Survey the Southern sky, complimentary to CTA
  - Young massive stars, microquasars and other binaries, discover more unidentified UHE gamma-ray sources

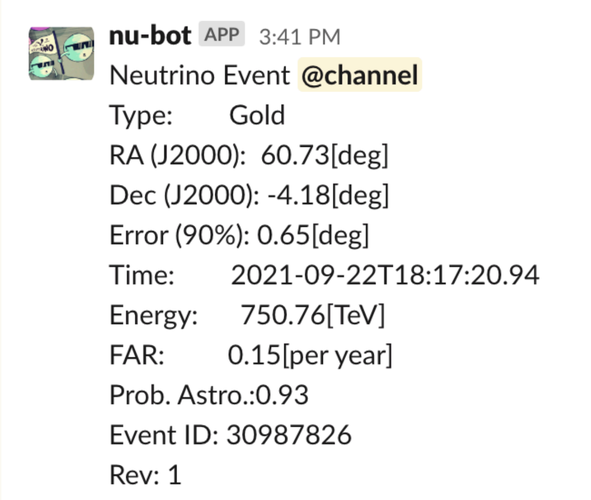
Thanks!

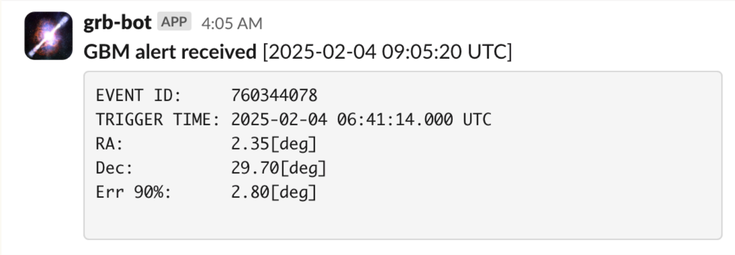

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Online Multi-Messenger Alert System

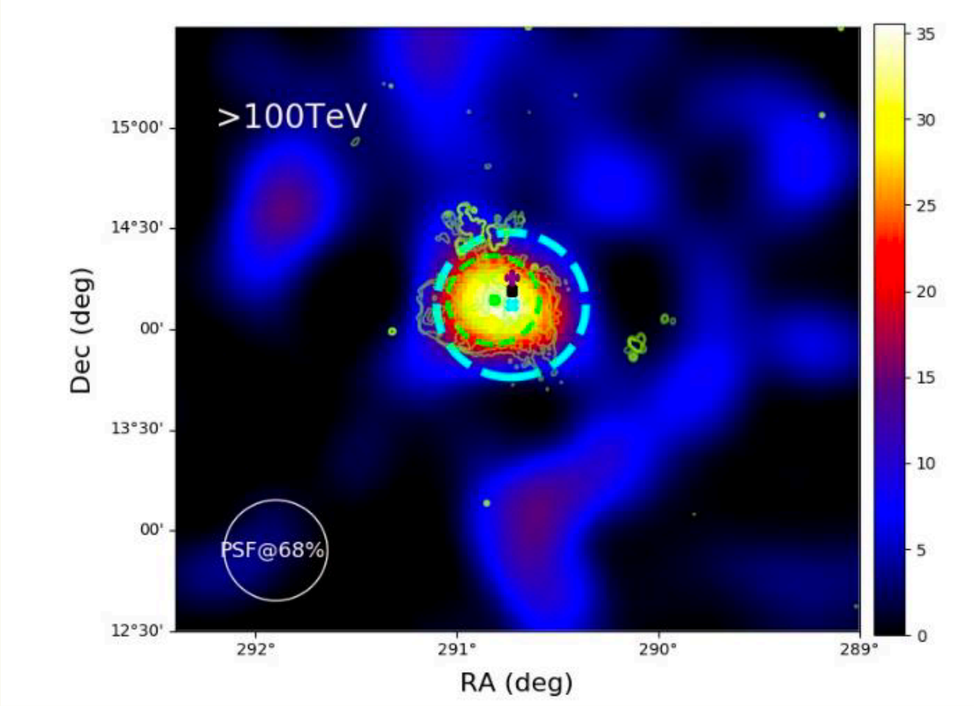


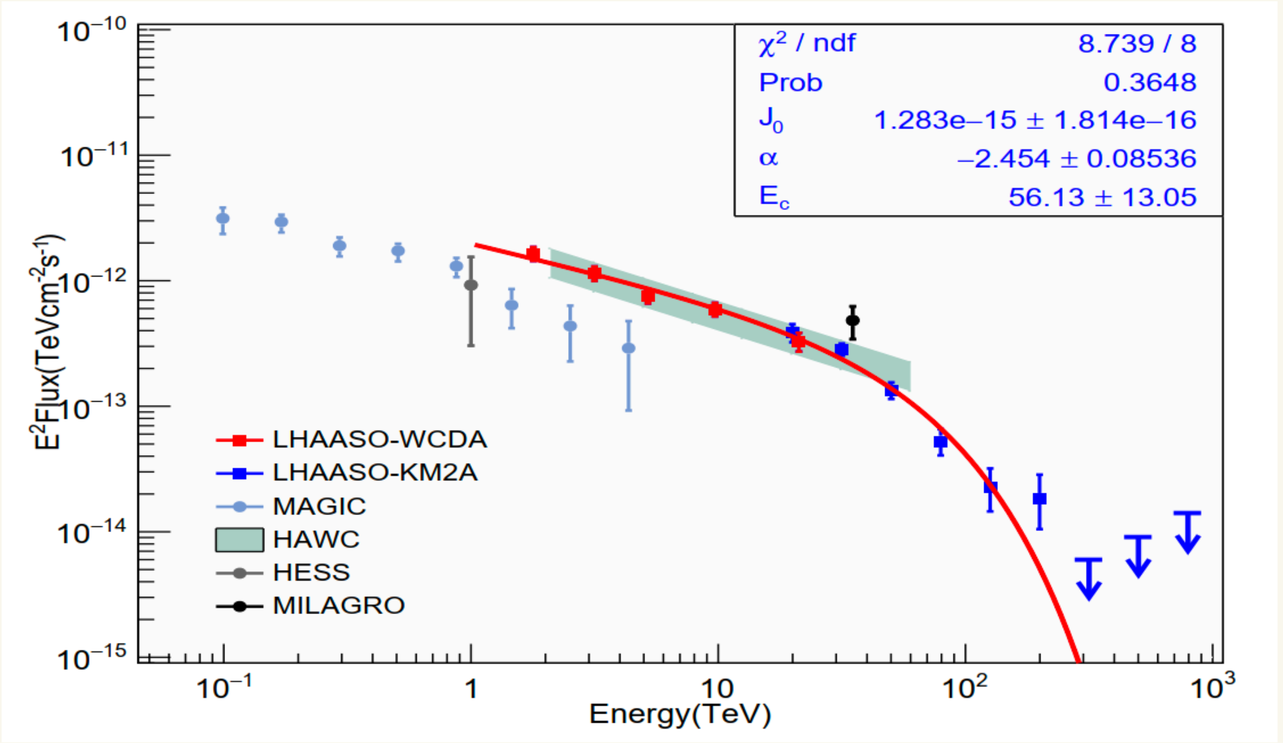




- Existing tools:
  - HAWC Slack alerts channel allow fast follow up
    - for GW events alerts, neutrino alert, and GRB alerts
    - Online real-time analysis + Offline detail analysis
  - Astrophysical Multi-messenger Observatory Network (AMON)
- Computational resources:
  - Two high speed data center cluster
    - More than 3,000 cores + 30 PB storage
    - Members (undergrad/grad/postdoc/faculty) could access without limitation

W51 C

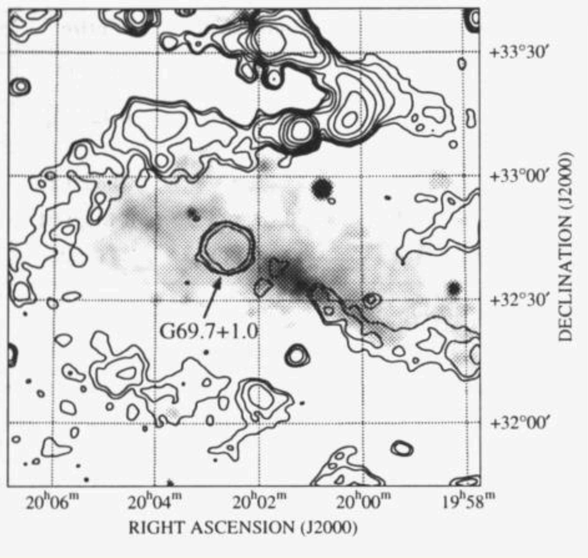


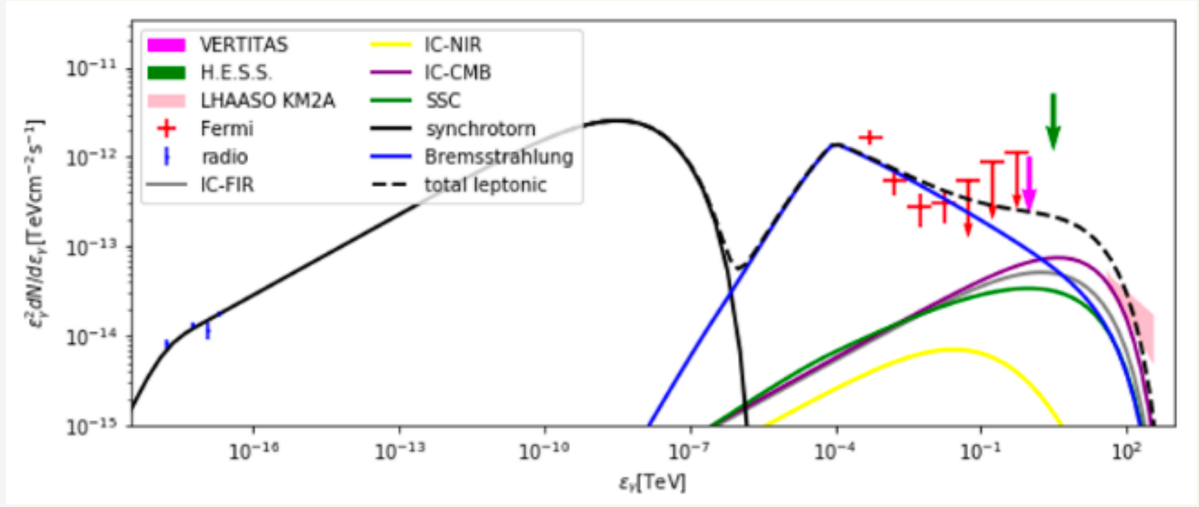


LHAASO- KM2A ICRC, 2023

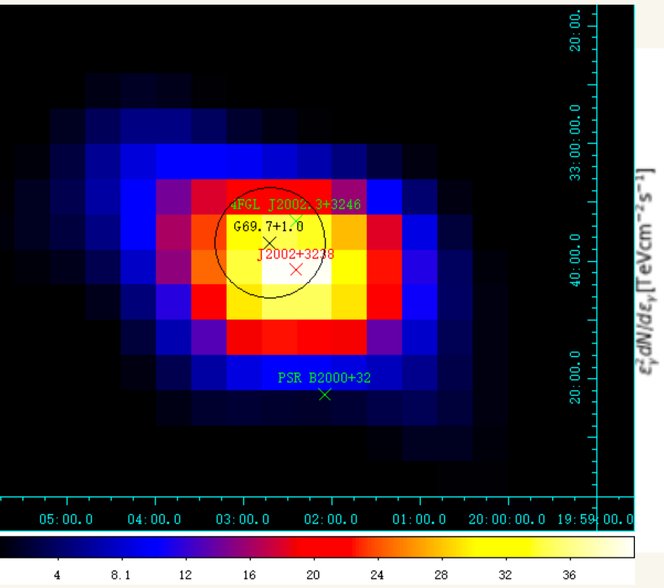
- W51C: shell-type SNR , 30 kyr
- Extend the spectrum measurement up to ~200 TeV
- Ec ≈ 400TeV, significantly larger than 100TeV (5σ).

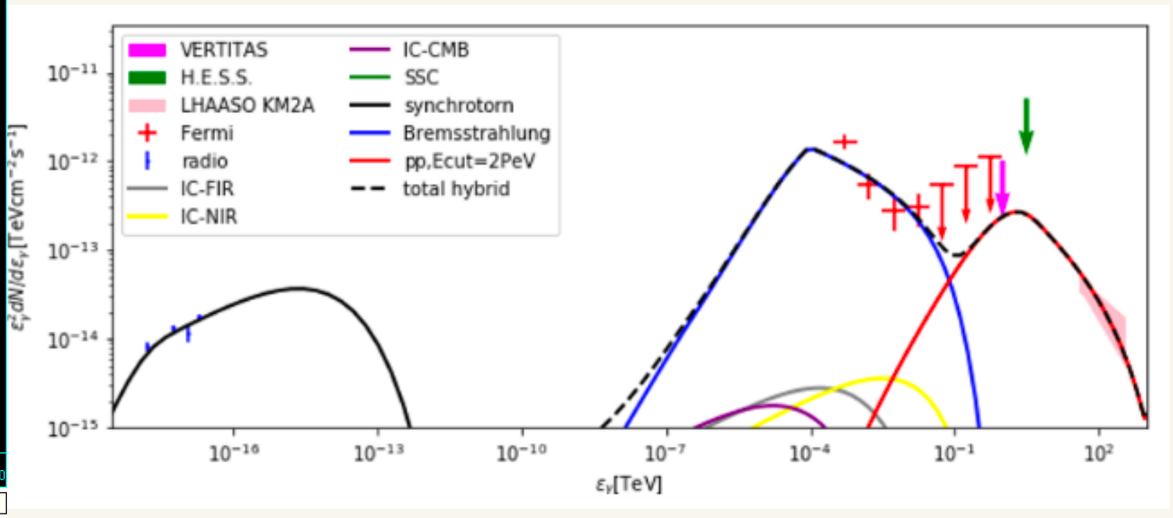
SNR G69.7 + 1.0





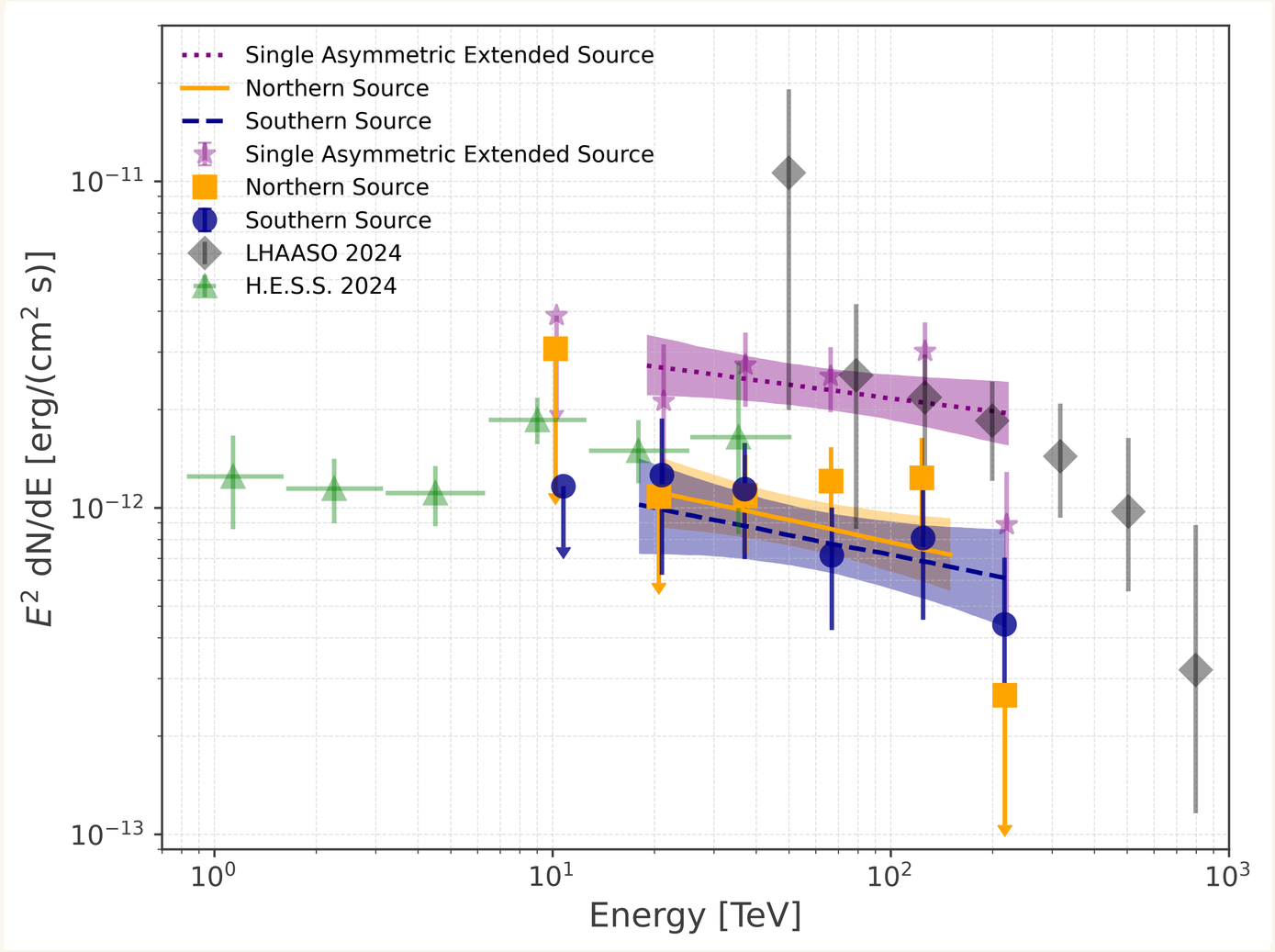
LHAASO- KM2A ICRC, 2023





- SNR G69.7+1.0: 40kyr, 7.8kpc
- The positions are consistent: SNR radio, Fermi and LHAASO
- The energy spectrum: -2.7
- no obvious cutoff before 400 TeV
- Both leptonic and hadronic model can explain the gamma ray emission.

V4641 Sgr Follow-ups



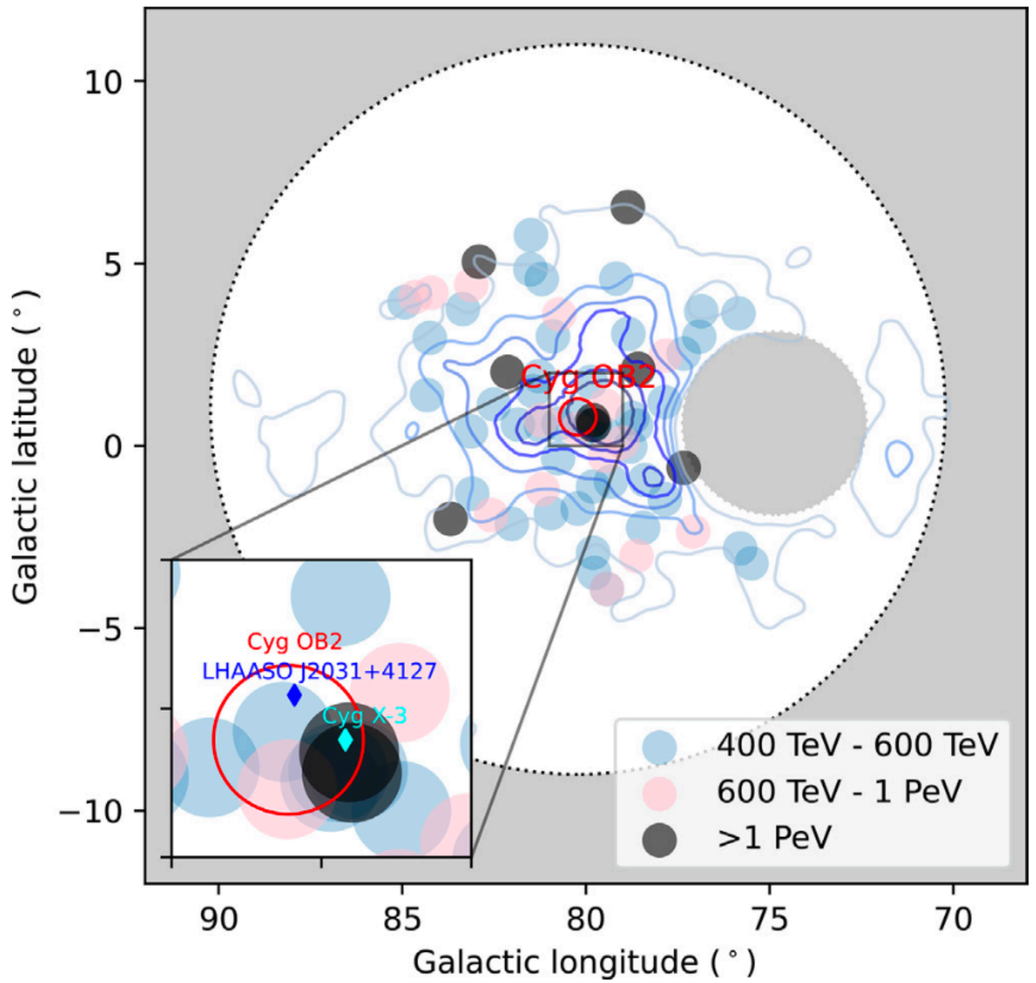
- Adding H.E.S.S. and LHAASO observation
- Energy spectrums consistent with each other very well

LHAASO, arXiv 2410.08988

Laura Olivera-Nieto, Gamma 2024

LHAASO-KM2A Observation

3200 > 100 TeV photon-like events
detected inside 10° dish circle

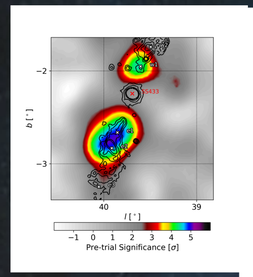


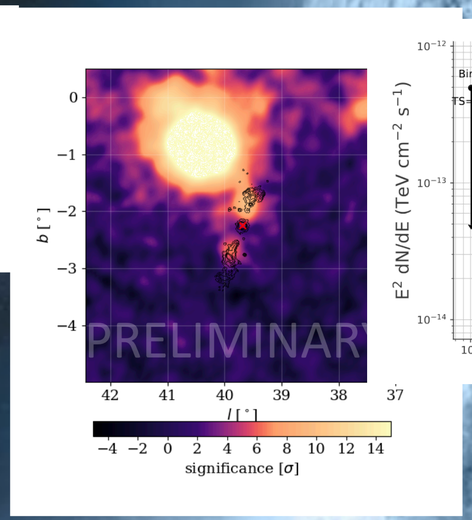
- Contour map: 2-20 TeV gamma rays (start from 3σ with a step of 3σ)
- **66 > 400 TeV photon-like events** inside 6° from center with 9.5 background events
- **8 > 1PeV photon-like events** against 0.75 background events
- The energy events is more dense within 0.5° around Cygnus OB2
- 2.5° shaded region is the mask of nearby PWN
- Size of photon label is KM2A's PSF

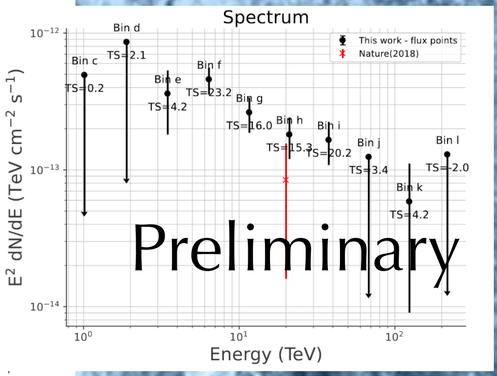
LHAASO Collaboration, Science Bulletin, Volume 69, Issue 4,2024, Pages 449-457

Microquasars

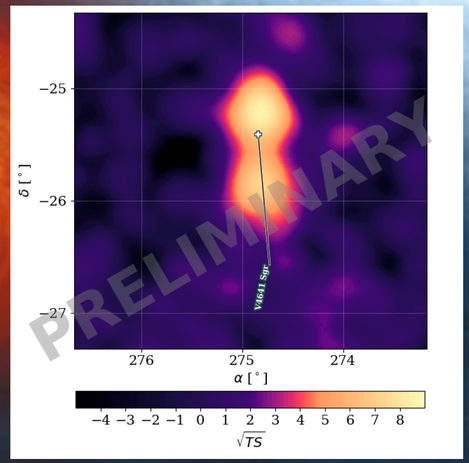
HAWC Collaboration, Nature volume 562, pages 82–85 (2018)

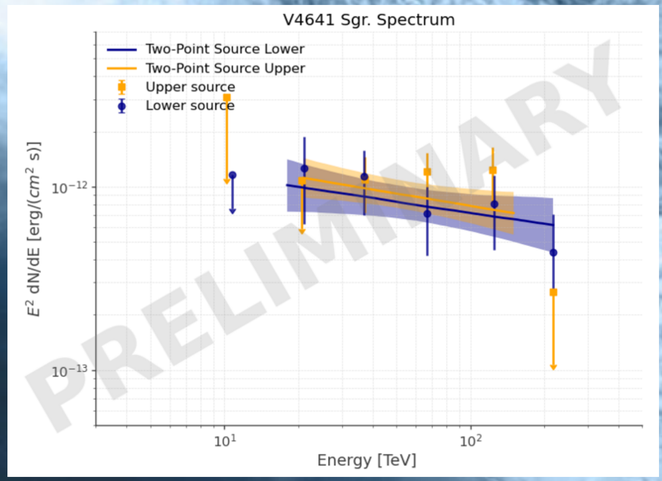






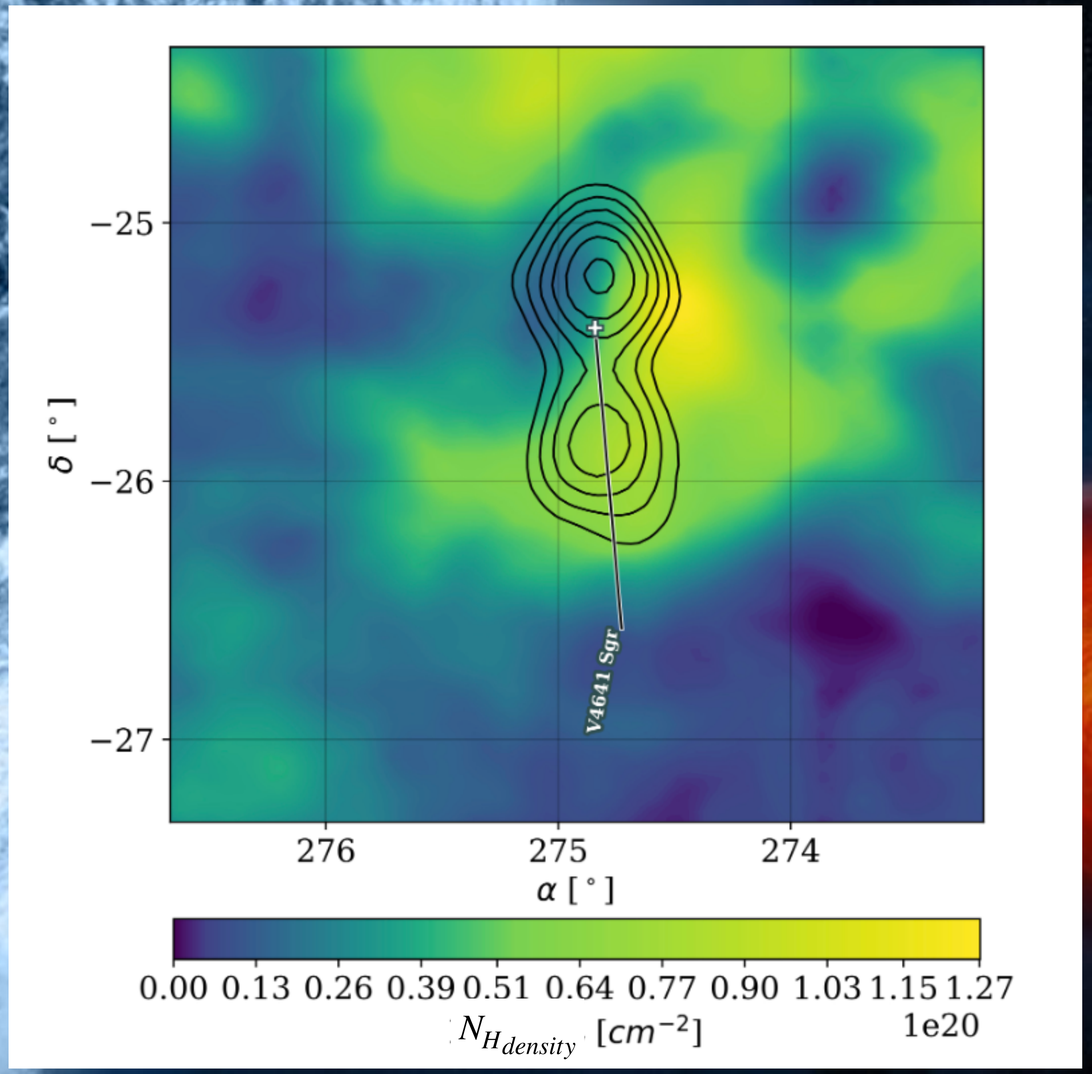
- Acceleration and gamma-ray production within the binary system or at the termination of shock where jets imteract with the ISM
- Multi-TeV detections from several sources
  - SS 433, LS 5039, V4641 Sgr
    - V4641 Sgr:
      - The excess is over the background at a 8 sigma pre-trail significance in all energy range and 7 sigma above 56 TeV
      - Energy range: >200 TeV
      - Among the hardest known TeV gamma-ray sources





Microquasar V4641 Sgr.

Nature, HAWC, 2024

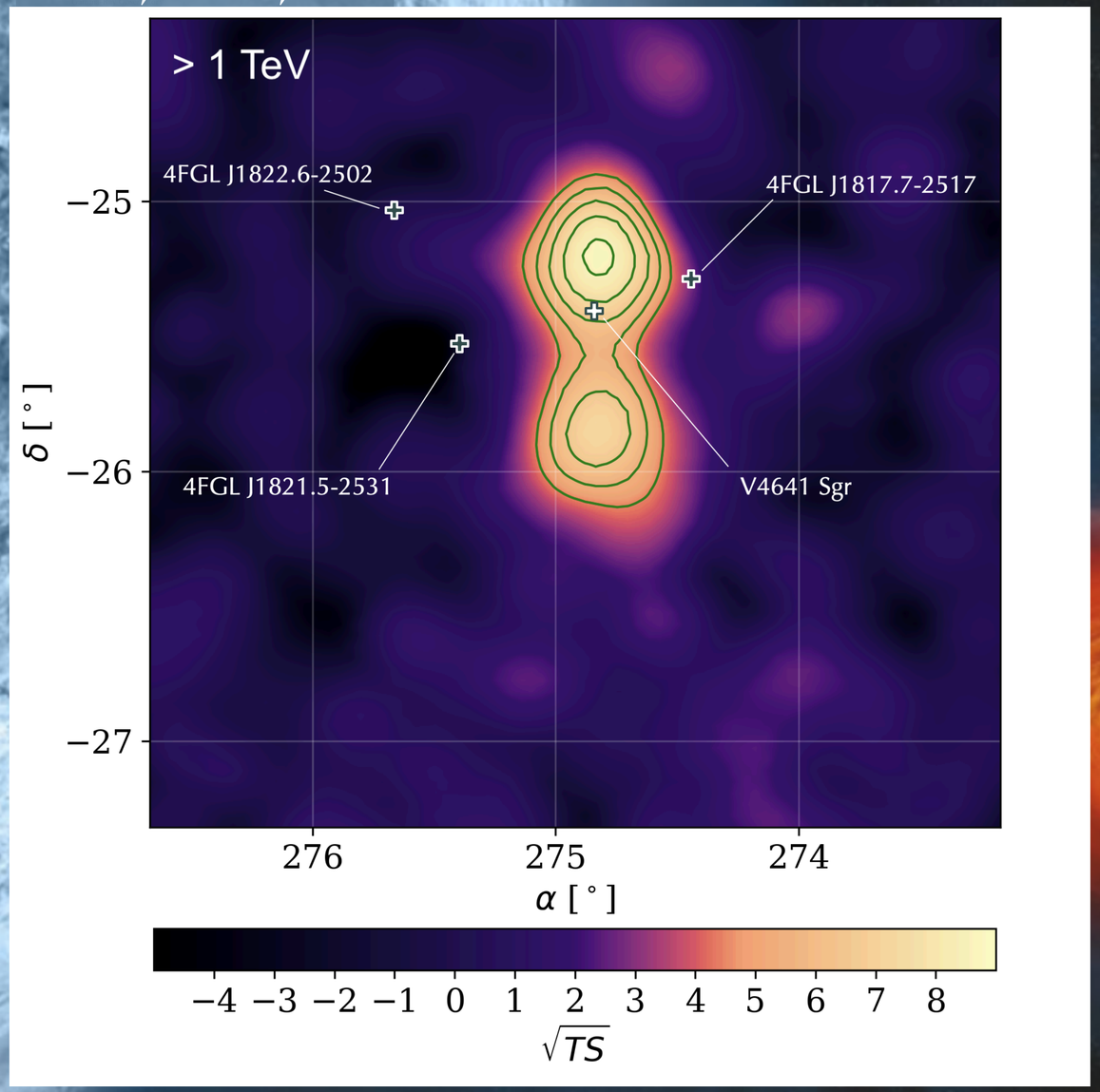


The column density of atomic hydrogen

- Microquasars could be PeVatrons ?
- Microquasars could be PeVatron!
- Leptonic scenario is challenging
  - 200 TeV electrons cool quickly, hardly diffuse over 100 pc
  - Also require fast outflow to accelerate
- Protonic origin might explain the emission with $L_p << L_{edd}$
- Multi-wavelength and multi-messenger follow up observations is needed to fully understand the nature of gamma-ray emissions
  - No adequate observations yet

First UHE Microquasar — V4641 Sgr.

Nature, HAWC, 2024



- No better counterparts inside 4.5 sigmas contour
- Large extended gamma-ray emissions >100 pc
- Consistent with expectations of jet size $R \sim (L_{jet}/n_0 m_p)^{1/5} t^{3/5} \sim 100 pc$
- Add to SS 433, as the second Galactic Microquasars with large scale jets

Summary & Outlook

- Recent detections of explosions from PeVatron candidates indicate that PeVatrons are widely present in our galaxy.
  - They will provide a rich sample for studying cosmic ray accelerators
- Are galactic proton PeVatrons linked to SNRs, YMCs, Galactic Center, microquasars, or new source classes?
  - Further observations are needed to determine this
- Combined information from multi-wavelength/multi-messenger observation is essential to prove the nature of these PeVatron candidates.
  - IceCube has detected high-energy neutrinos from the galactic plane (Sicense, 2023)
  - Radio/X-ray follow-ups of V4641 Sgr
- Future instruments like SWGO, CTA, and IceCube-Gen2 could help solve these puzzles.

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