CONACYT NSF U.S. DEPARTMENT OF ENERGY | Office of Science

Surveying the TeV γ-Ray Sky with the HAWC Wide-Field Observatory

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Petra Huentemeyer

petra@mtu.edu

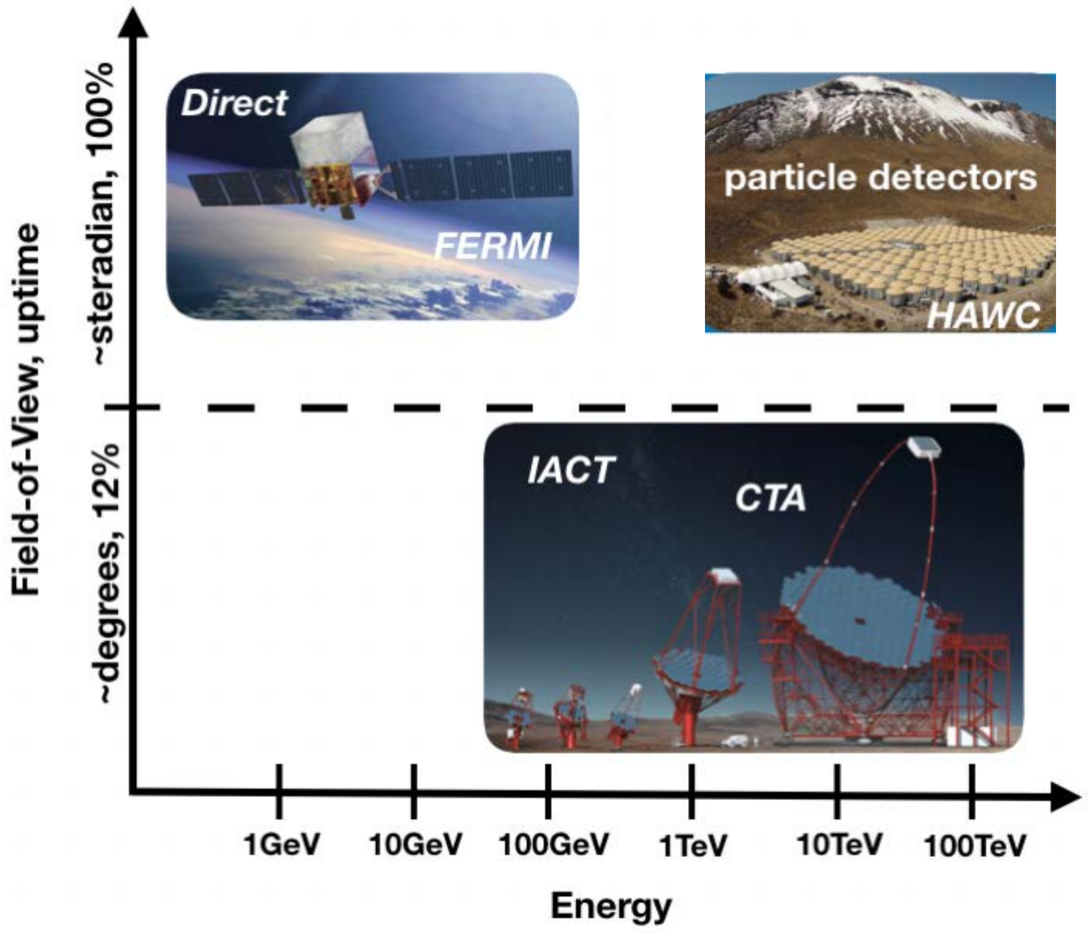
Energy range:	**~300 GeV to >100 TeV**
Angular resolution:	**~1° to 0.1°**

Michigan Tech
1885

Wide-Field-of-View Ground-Based γ-Ray Observatories

Duty Cycle, Field-of-View & Energy
3 Main Features

- High duty cycle (> 95% uptime)
  - ✓ Transients
- Wide field-of-view
  - ✓ Extended and large scale emission
- Good Sensitivity, Angular & Energy Resolution > 10 TeV
  - ✓ Highest energy accelerators

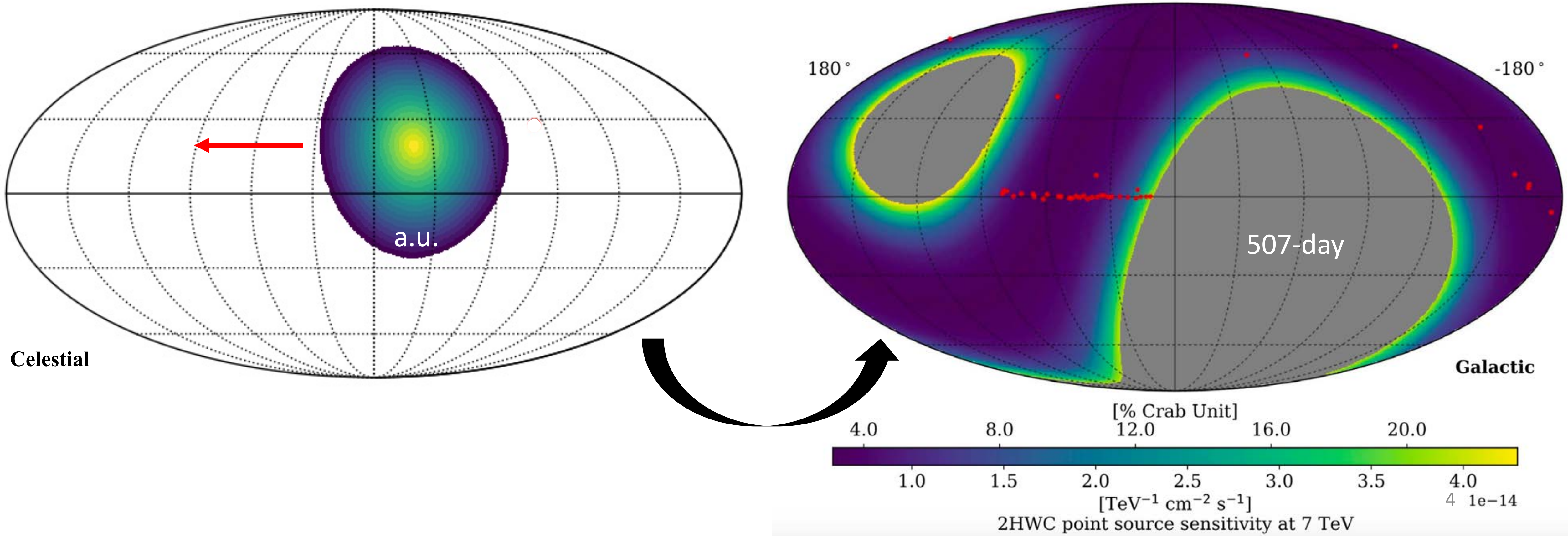


Wide Field-Of-View

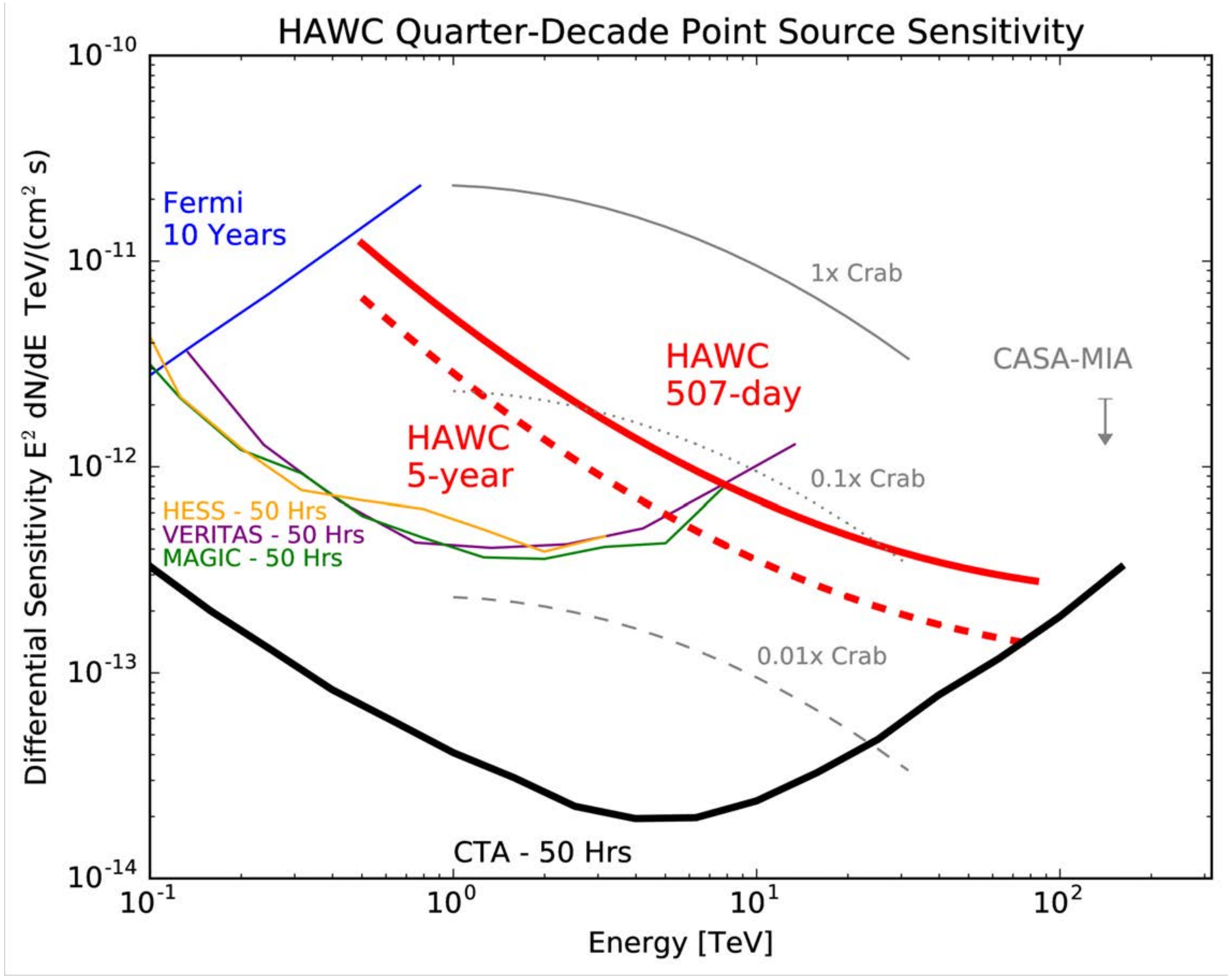
- HAWC (almost) continuously observes the sky as it transits over its zenith
- Instantaneous field of view of HAWC~ 1.8 sr (~15% of the sky)

  → surveys ~ 8.4 sr / day (~2/3 of the sky).

ApJ, Vol. 843, Is. 1, id. 40, 21pp. (2017)



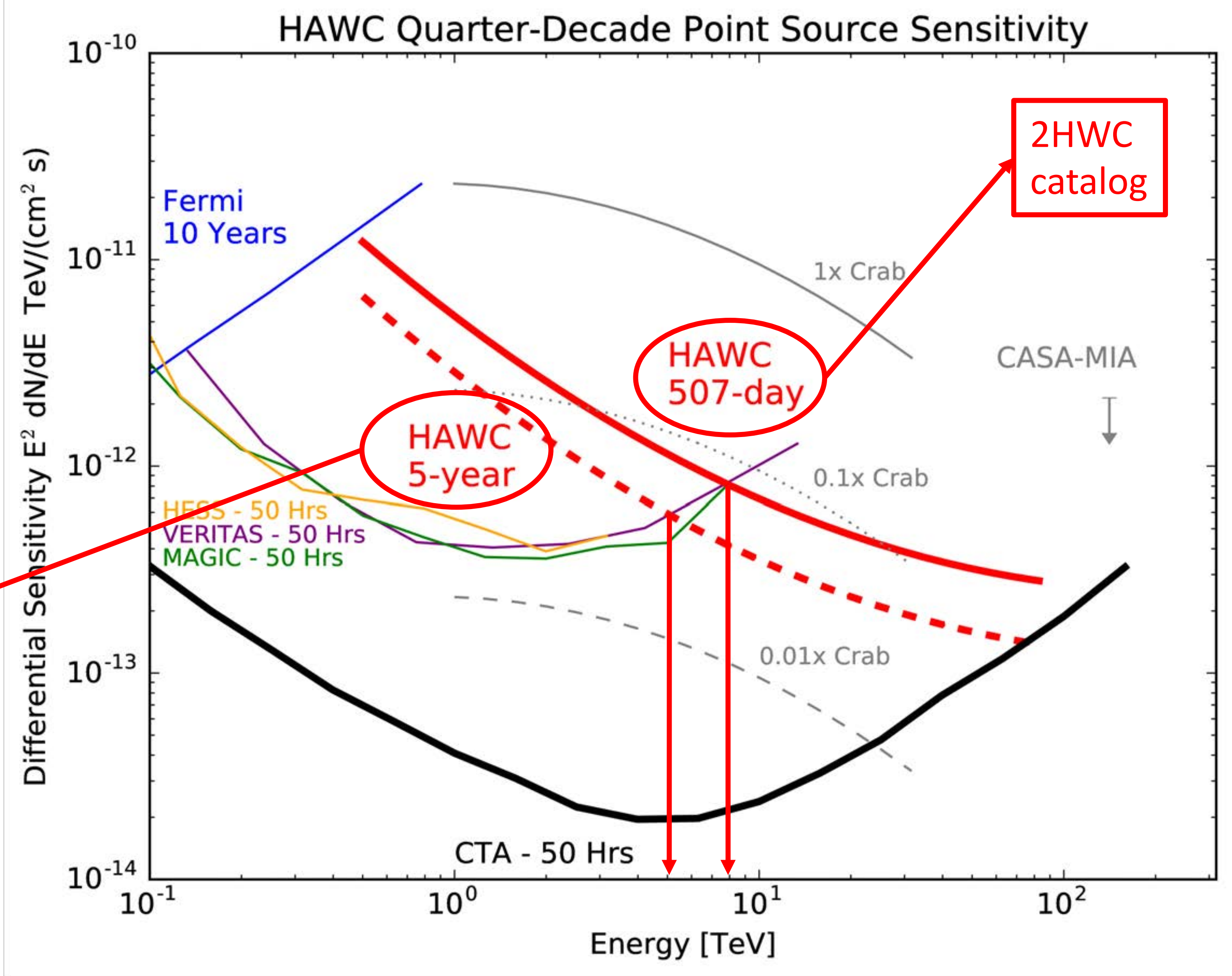
Sensitivity vs Energy



ApJ, Vol. 843, Is. 1, id. 39, 17 pp. (2017)

Sensitivity vs Energy

- $\geq$ sensitivity of upcoming HAWC Catalog (in preparation)
  - $\geq$ 5 years of data
  - Improved reconstruction

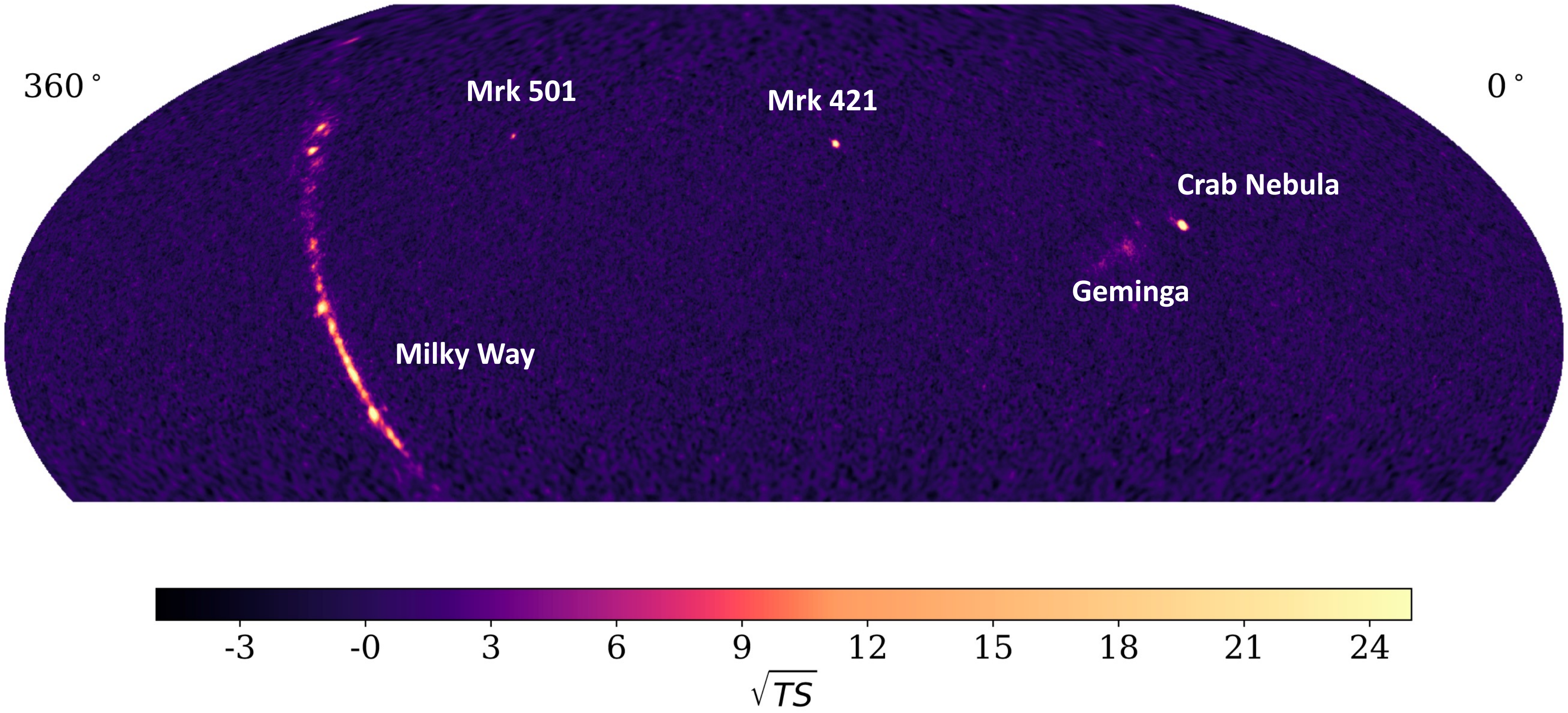


ApJ, Vol. 843, Is. 1, id. 39, 17 pp. (2017)

Main Features → Recent HAWC Results

- Survey capabilities
  - ✓ Source searches
  - ✓ 3rd HAWC catalog
- Extended and large scale emission sensitivity
  - ✓ New source class: halos
  - ✓ Northern Fermi bubble
  - ✓ Molecular clouds
  - ✓ Diffuse emission
- High-energy γ-ray sensitivity
  - ✓ Several PeVatron candidates
  - ✓ Test of fundamental physics in unique phase space

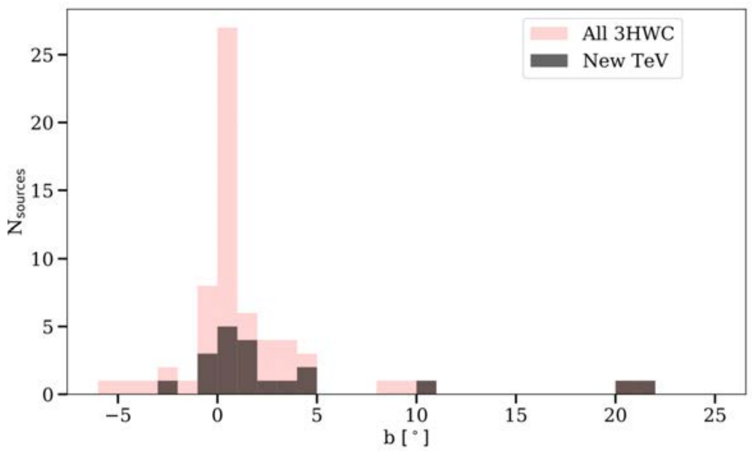
Survey of the Northern Sky: 3HWC Catalog

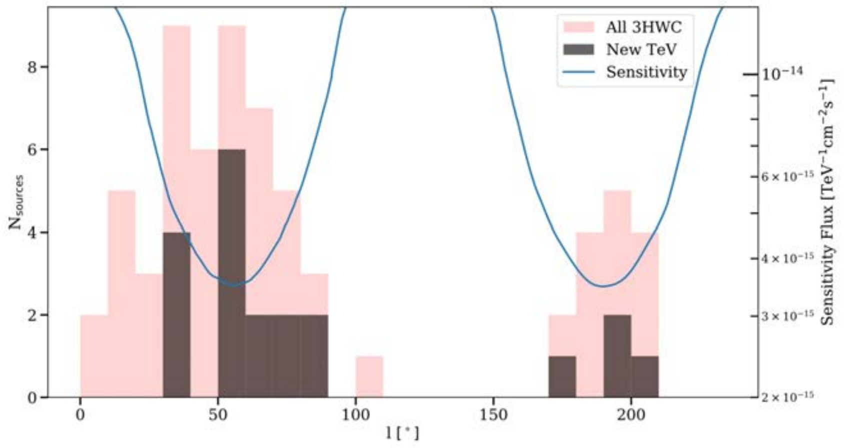


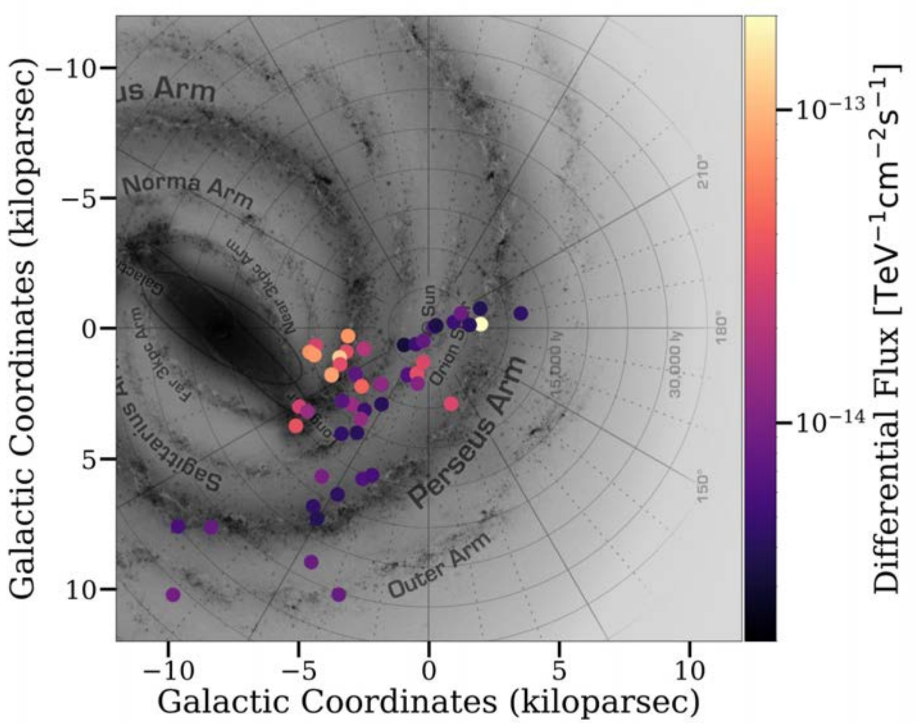
ApJ, Vol. 905, Is. 1, id.76, 14pp. (2020)

- Catalog from 1523 days of data: 3 × exposure of previous 2HWC catalog > several TeV
- 65 sources detected at > 5σ:
  - 20 sources > 1°away from previously detected TeV sources
  - 14 of these have potential counterpart in the 4th Fermi-LAT catalog

3HWC Catalog: Spatial Distribution of Sources



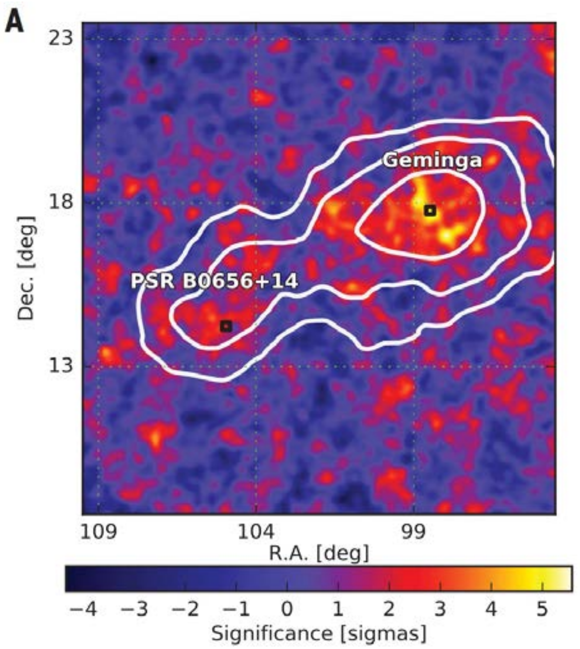




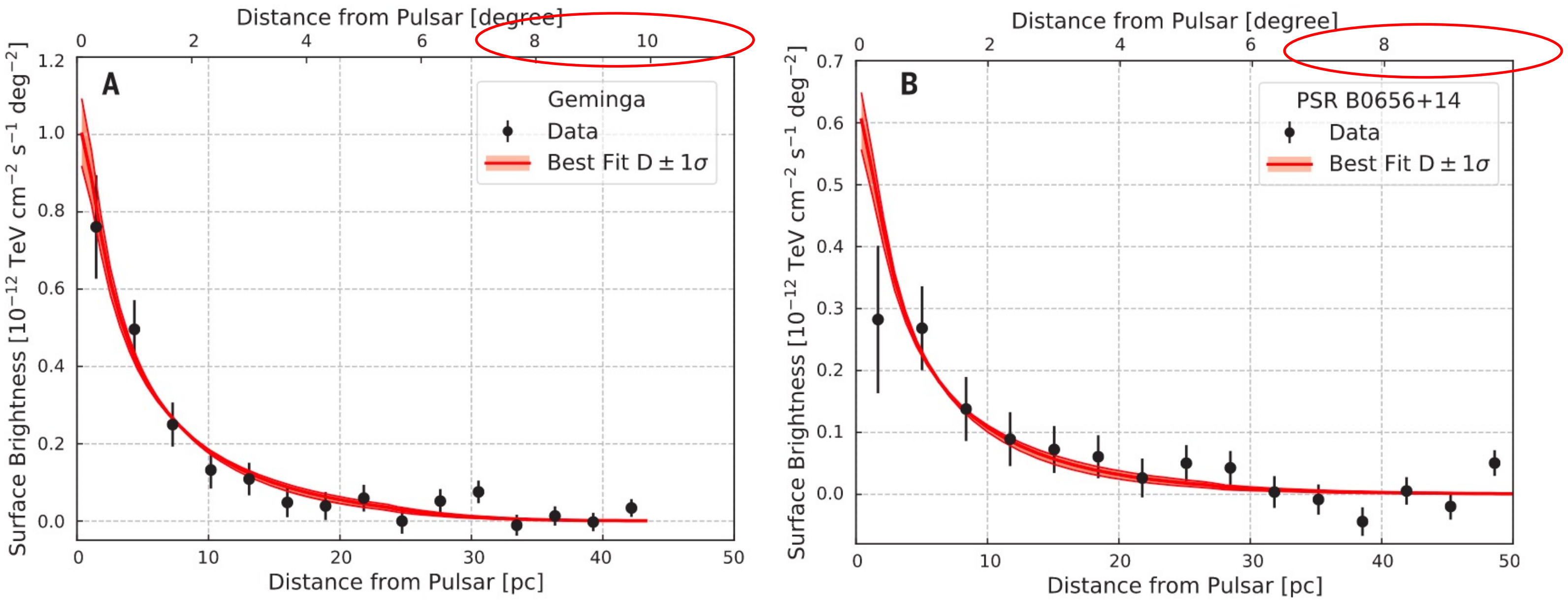
[ApJ, Vol. 905, Is. 1, id.76, 14 pp. (2020)]

- Majority along the Galactic plane
- Due to its location, HAWC most sensitive towards the Galactic anti-center region and, to the inner Galaxy
- Significant fraction of 3HWC sources found near pulsars listed in the ATNF catalog (Two of these, PSR J0631+1036 and PSR J1740+1000, have not previously been connected with TeV emission)

New Source Class: Halos



Science 358, 911–914 (2017)

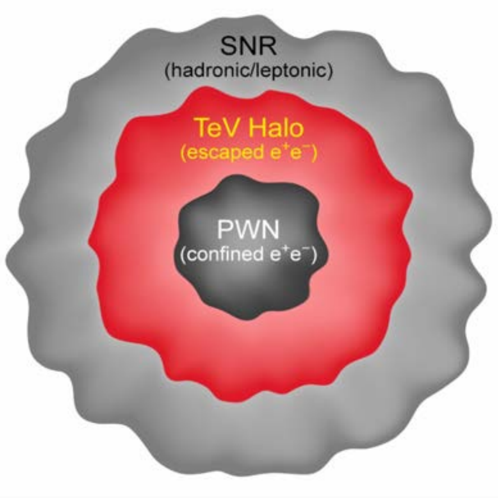


- In 2017, HAWC reported the detection of extended TeV γ-ray emission coincident with the locations of two nearby middle-aged pulsars: Geminga and PSR B0656+14 (inside Monogem ring) [Science 358, 911–914 (2017)]
- Observations demonstrated that these pulsars are indeed local sources of accelerated leptons, and the surrounding emission profile can be used to constrain the diffusion of particles away from their sources → much slower than previously assumed

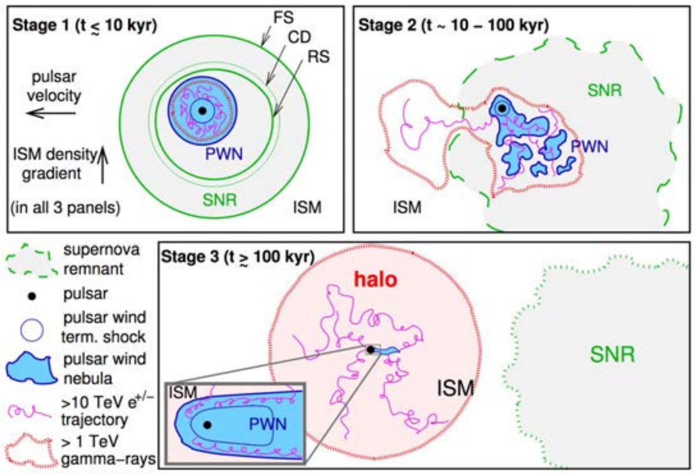
New Source Class: Halos

The Geminga halo discovery and the discovery of several extended TeV PWNe by H.E.S.S. (A&A 612, A2 (2018)), lead to the hypothesis that extended ***"Halos"*** are a common feature of pulsars [PRD 96, 103016 (2017); PRL 120, 121101 (2018); PRD, 100, 043016 (2019); Astro2020; BAAS, Vol. 51, Is. 3, id. 311 (2019) ; A&A 636, A113 (2020)]

PRD, 100, 043016 (2019)



A&A 636, A113 (2020)



- ***Interpretations:***
  - Observed γ − ray emission due to IC up-scattering of CMB photons by relativistic e^-, e^+ that have escaped from the PWN, but remain trapped in a larger region where diffusion is ***inhibited*** compared to the interstellar medium
  - Only, form around very old pulsar (at least 100 kyr old) that either left their SNR shell or whose SNR shell already dissipated, allowing relativistic e^-, e^+ to diffuse freely in the vicinity of the pulsar
  - Distinct from (classical) PWNe, in that the $e^- - e^+$ plasma escaped from the x-ray PWN.
- Also detected at lower γ-ray energies by Fermi-LAT: ***γ-ray halos*** [Rev. D 100, 123015 (2019)]

Halos Candidates in the 3HWC Catalog

- Using similar criteria as PRD 96, 103016 (2017), a list of pulsars is created within 3HWC catalog that are likely candidates to have a TeV Halo: ATNF pulsars with
  - ages between 100kyr and 400kyr
  - declinations between $-25°$ and $+64°$
  - estimated spin-down flux of at least 1% of that of the Geminga pulsar.

→ 16 such pulsars, 8 spatially coincident with at least one 3HWC source (within 1◦)

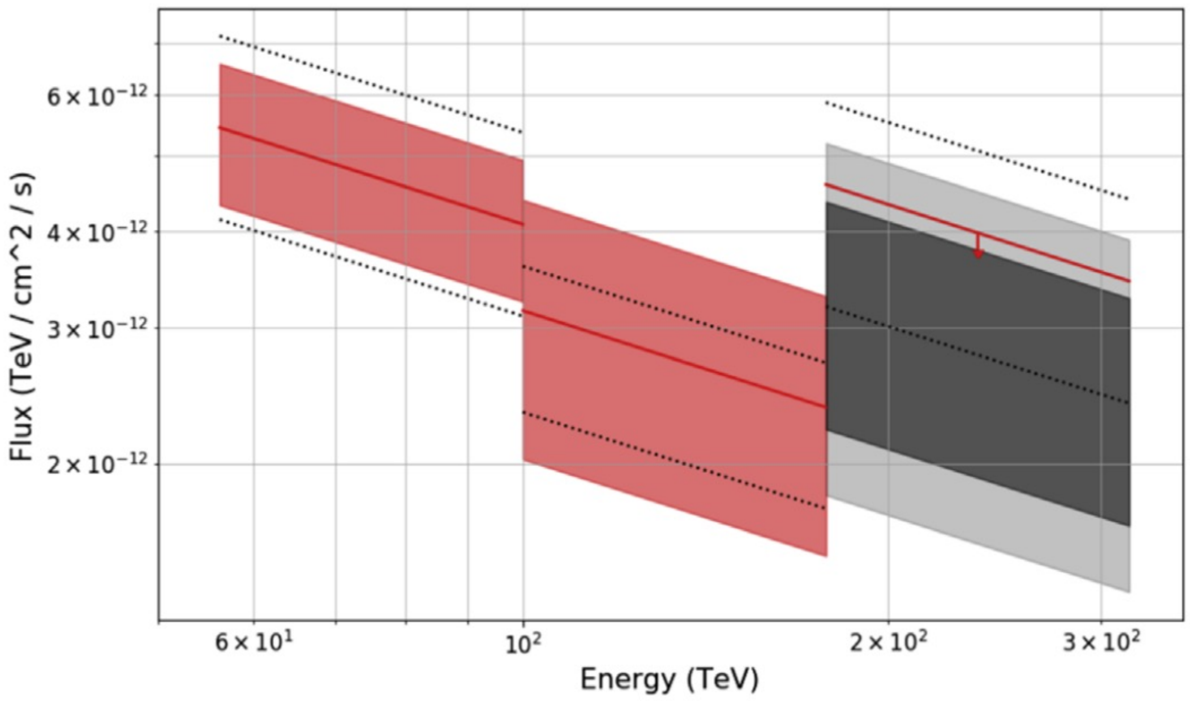
HAWC	l [°]	b [°]	Pulsar	Age [kyr]	$\dot{E}$ [erg s^{-1}]	Distance [kpc]	Separation [°]	TeVCat
3HWC J0540+228	184.58	-4.13	B0540+23	253.0	4.09e+34	1.56	0.83	HAWC J0543+233
3HWC J0543+231	184.67	-3.52	B0540+23	253.0	4.09e+34	1.56	0.36	HAWC J0543+233
3HWC J0631+169	195.63	3.45	J0633+1746	342.0	3.25e+34	0.19	0.95	Geminga
3HWC J0634+180	195.00	4.62	J0633+1746	342.0	3.25e+34	0.19	0.38	Geminga Pulsar
3HWC J0659+147	200.60	8.40	B0656+14	111.0	3.8e+34	0.29	0.51	2HWC J0700+143
3HWC J0702+147	200.91	9.01	B0656+14	111.0	3.8e+34	0.29	0.77	2HWC J0700+143
3HWC J1739+099	33.89	20.34	J1740+1000	114.0	2.32e+35	1.23	0.13	...
3HWC J1831-095	22.13	0.02	J1831−0952	128.0	1.08e+36	3.68	0.27	HESS J1831-098
3HWC J1912+103	44.50	0.15	J1913+1011	169.0	2.87e+36	4.61	0.31	HESS J1912+101
3HWC J1923+169	51.58	0.89	J1925+1720	115.0	9.54e+35	5.06	0.67	...
3HWC J1928+178	52.93	0.20	J1925+1720	115.0	9.54e+35	5.06	0.85	2HWC J1928+177
3HWC J2031+415	80.21	1.14	J2032+4127	201.0	1.52e+35	1.33	0.11	TeV J2032+4130

ApJ, Vol. 905, Is. 1, id.76, 14 pp. (2020)

Are Ultra-high-energy Gamma Rays Are a Universal Feature near Powerful Pulsars?

- Highest-energy γ-ray sources appear to be located near extremely powerful pulsars
- Using four years of HAWC data joint-likelihood analyses of emission near locations of 10 extremely powerful pulsars was performed to search for subthreshold UHE gamma-ray emission correlated with these locations
  - $\dot{E} > 10^{36}$ erg s-1
  - Inner galaxy in HAWC's field of view ($|b| < 1^o, 5^o < l < 90^o$)
  - 1^o from detected UHE sources

ApJL, Vol. 911, Is. 2, id.L27, 8 pp. (2021)



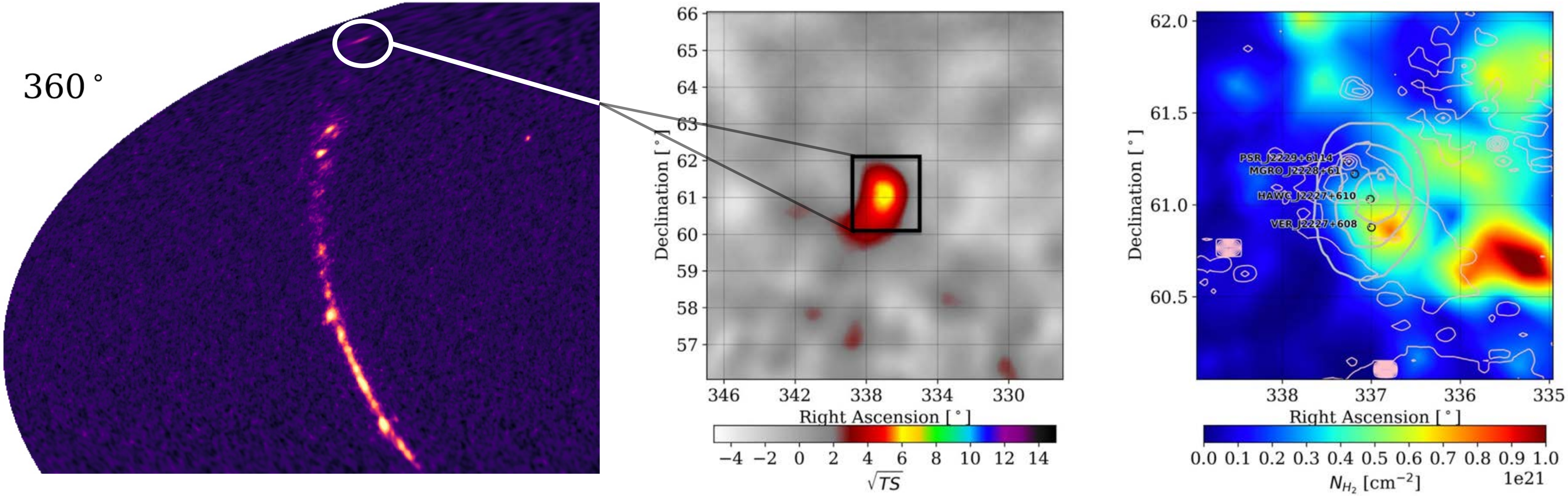
$$\frac{dN}{dE} = A_i K \left(\frac{E}{E_0}\right)^{-\alpha}$$

Table 3

The Test Statistic for the Joint-likelihood Analysis for Each Model, Using the Ten Subthreshold Sources

Model	TS ($56 < E < 100$ TeV)	TS ($100 < E < 177$ TeV)	TS ($177 < E < 316$ TeV)
No model	27.9	8.33	1.59
$1/d^2$	31.9	9.08	1.29
$\dot{E}/d^2$	9.58	5.24	0.00
Inverse age	9.19	3.79	0.03
Flux at 7 TeV	26.3	9.61	3.62

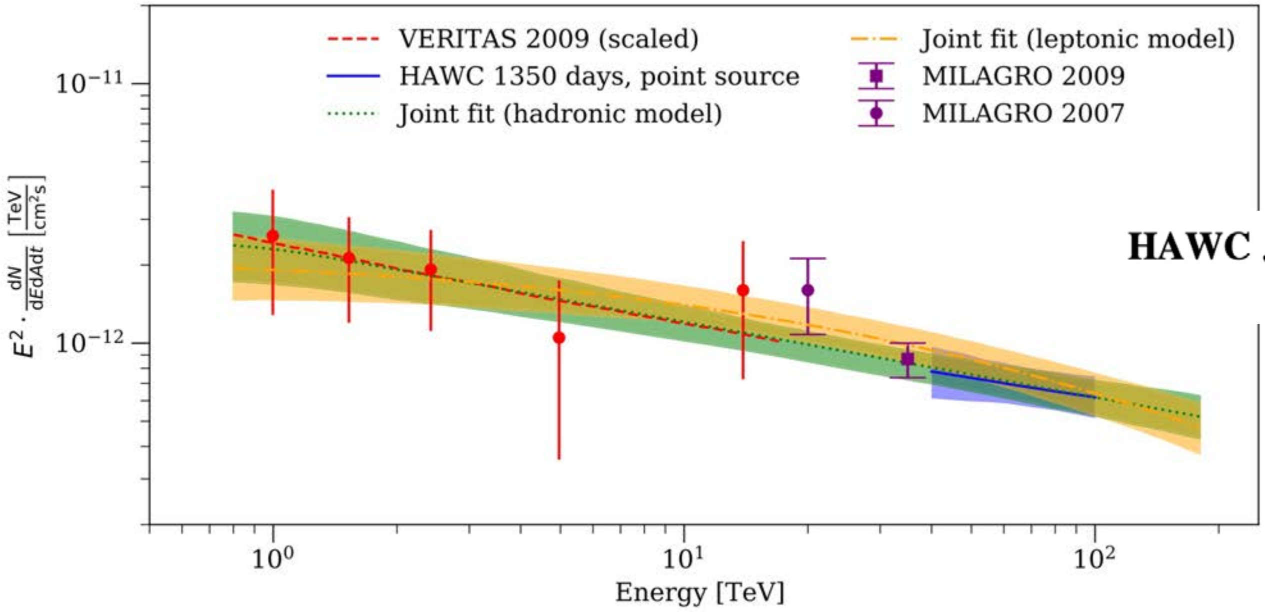
PeVatron Studies: The Boomerang Region



ApJL, Vol. 896, Is. 2, id.L29, 9 pp. (2020)

- Very-high-energy γ-ray emission > 100 TeV from HAWC J2227+610
- Excess well isolated and inconsistent with background fluctuations at the 6.2 σ level (pre-trials), or about 4.3 σ (post-trials considering HAWC's entire FoV)
- Right figure:
  - Best-fit position of HAWC J2227+610 is consistent with the VHE detections by VERITAS and Milagro, and with the position of PSR J2229+6114 (within uncertainties)
  - Heat map: Molecular column density
  - Pink contours: 1.4 GHz continuum brightness temperature from the Canadian Galactic Plane Survey

PeVatron Studies: The Boomerang Region

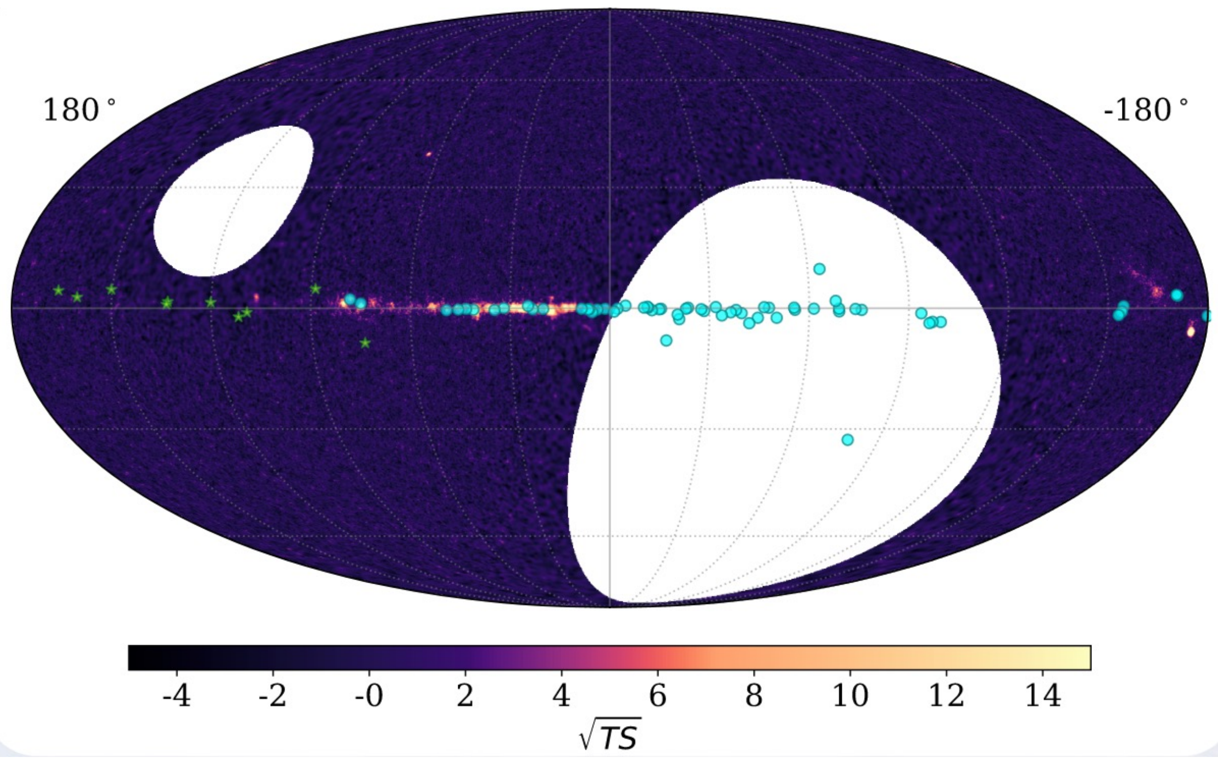


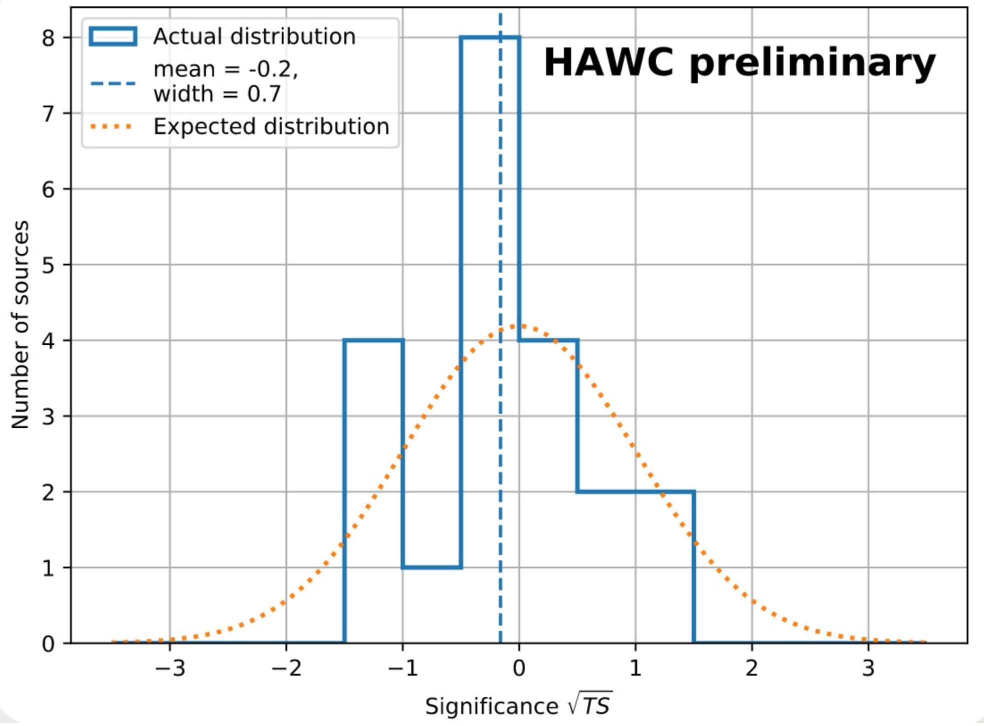
ApJL, Vol. 896, Is. 2, id.L29, 9 pp. (2020)

HAWC J2227+610 and Its Association with G106.3+2.7, a New Potential Galactic PeVatron

- Gaussian extent of HAWC J2227+610 is constrained to be $< \pm 0.232°$, morphology is consistent with VERITAS
- Joint VERITAS–HAWC spectrum well fit by a power law ($\gamma \approx -2.3$) from ~ 0.9 to ~ 180 TeV:
  - Emission can be interpreted to be originating from protons with a lower limit in their cutoff energy of 800 TeV.
  - Most likely source of the protons: the associated supernova remnant G106.3+2.7
  - But purely leptonic origin of the observed emission could not be excluded at the time
- Both, Tibet-ASγ and LHAASO, since reported >100 TeV emission
- Deeper morphological studies would be helpful

SNR Subthreshold Studies

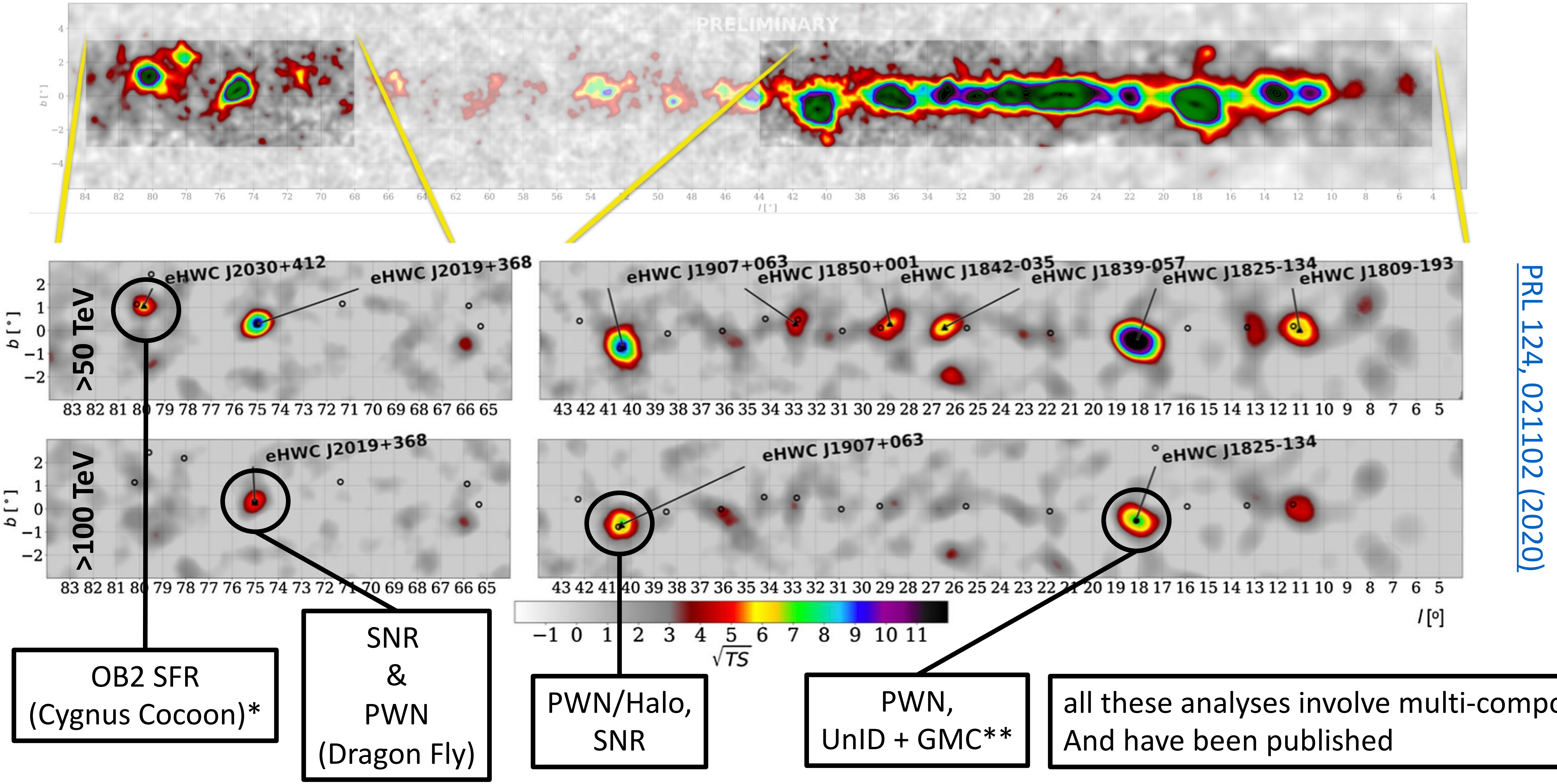




- Search for TeV gamma-ray emission from SNRs that have been detected in GeV gamma rays by Fermi-LAT in HAWC data
- Focus on ten GeV-emitting SNRs that are not significantly detected by HAWC
- Assuming the same morphology as seen in GeV gamma rays, no evidence for sub-threshold TeV gamma-ray emission in this sample

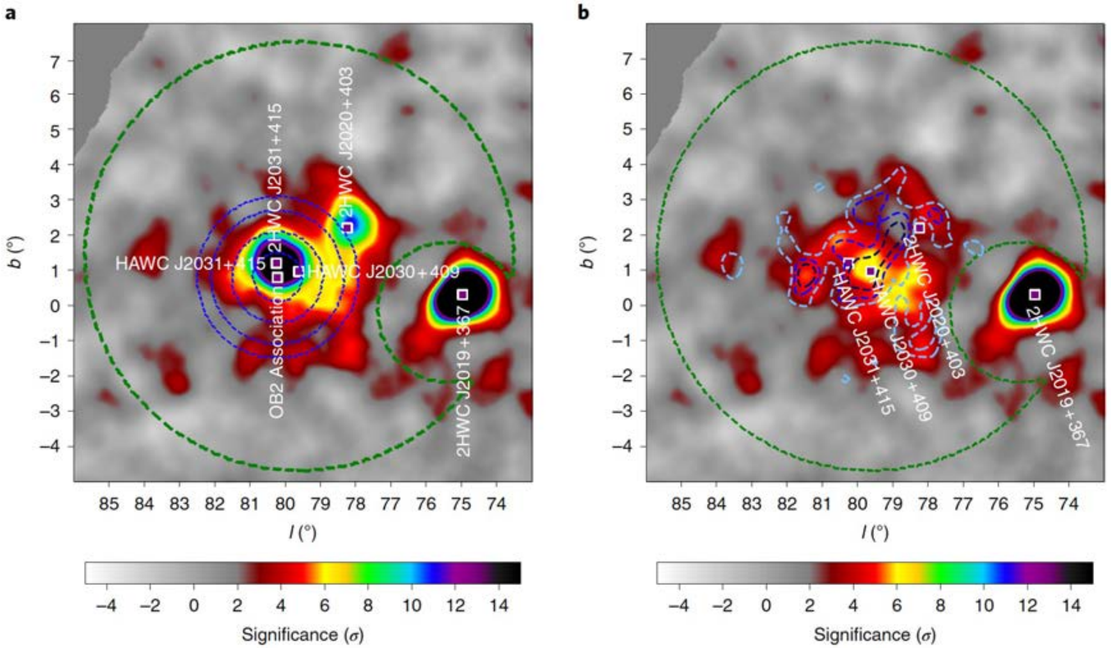
PoS ICRC2021, 826 (2021)

PeVatron Searches: Recent More Detailed Results



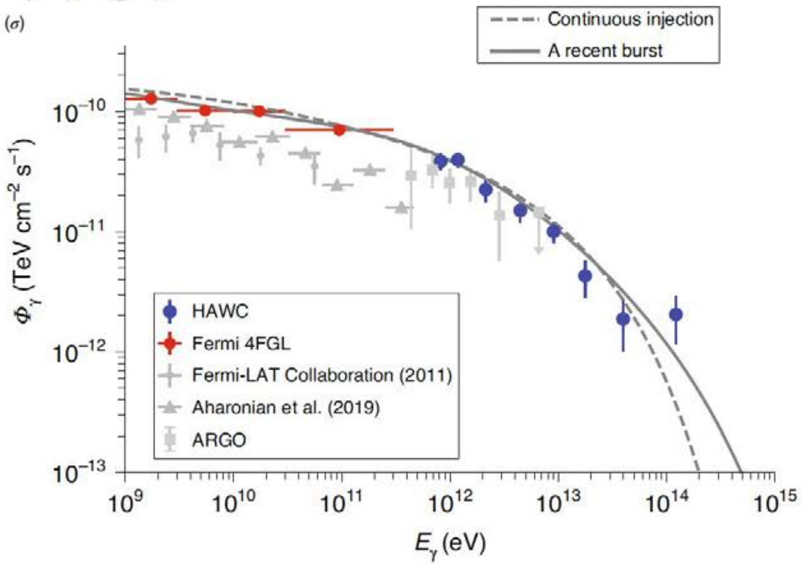
all these analyses involve multi-component fits
And have been published

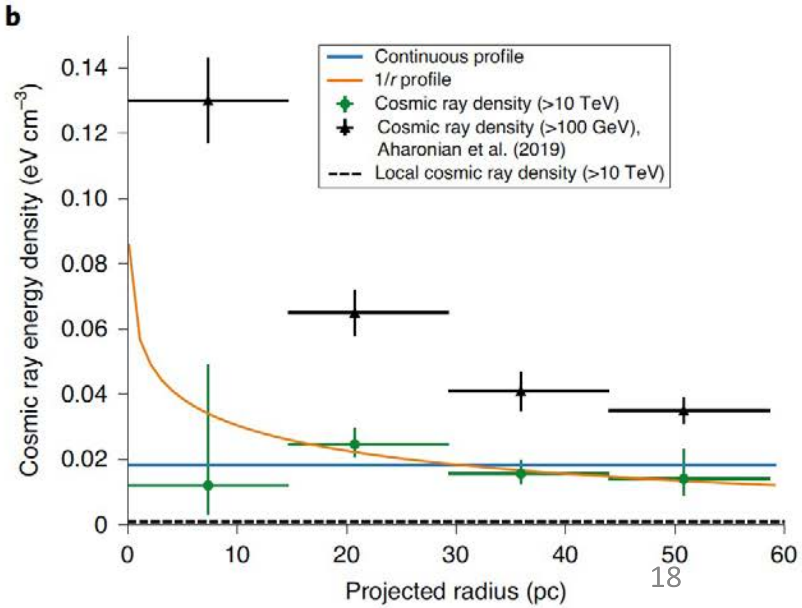
PeVatron Searches: An Example



OB2 SFR
(Cygnus Cocoon)

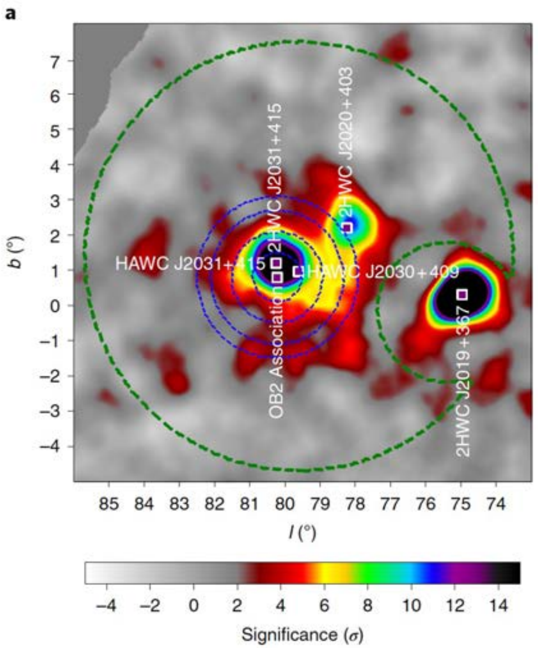
[Nat. Astro., 5, 465-471 (2021)]

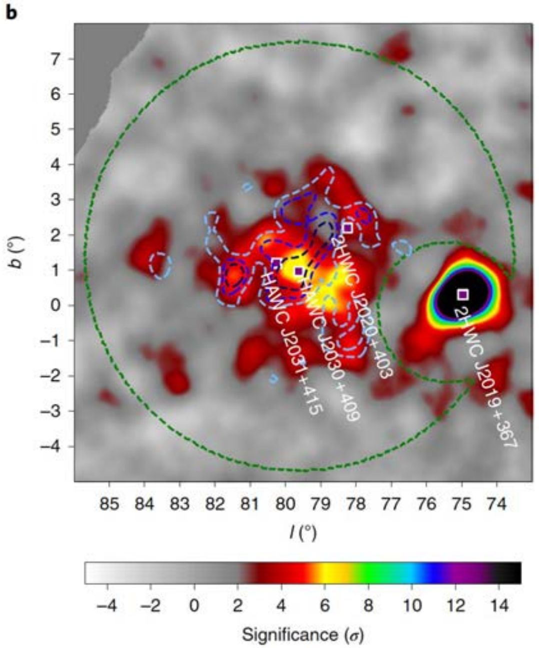




- γ-rays are likely produced by 10–1,000 TeV freshly accelerated CRs that originate from the enclosed star-forming region Cyg OB2
- Likely of hadronic nature
- Spectral shape and emission profile changes from GeV to TeV energies

PeVatron Searches: An Example

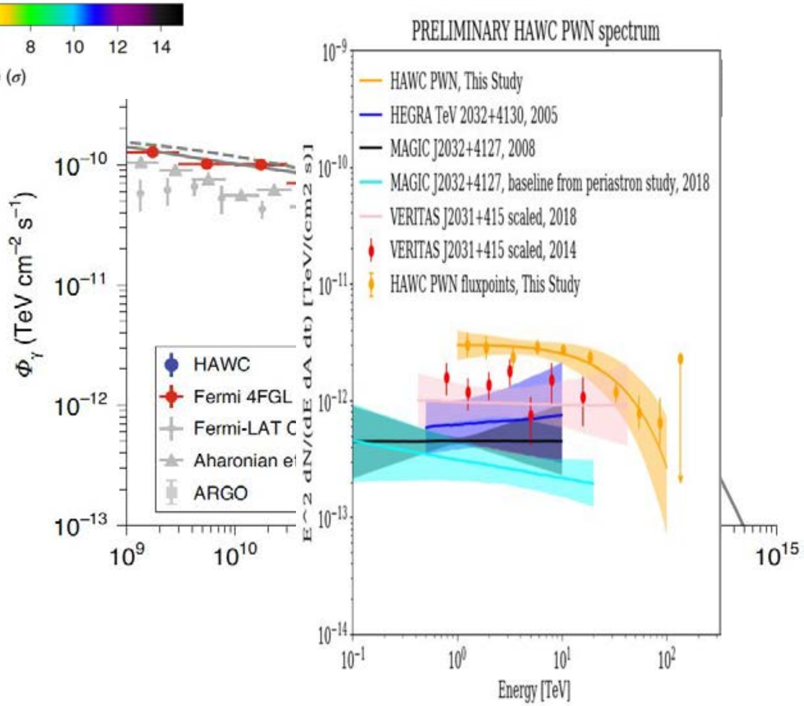


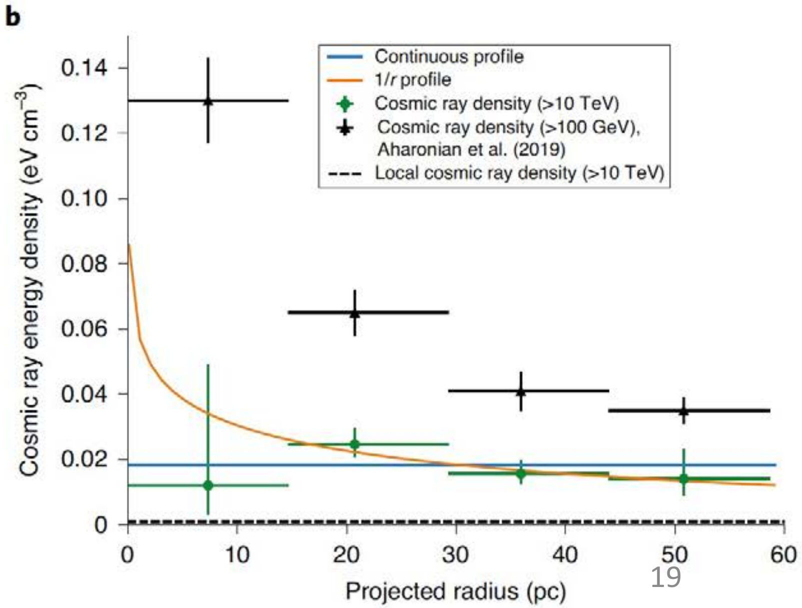


OB2 SFR
(Cygnus Cocoon)

[Nat. Astro., 5, 465-471 (2021)]

[*PoS* ICRC2021, 836 (2021)]

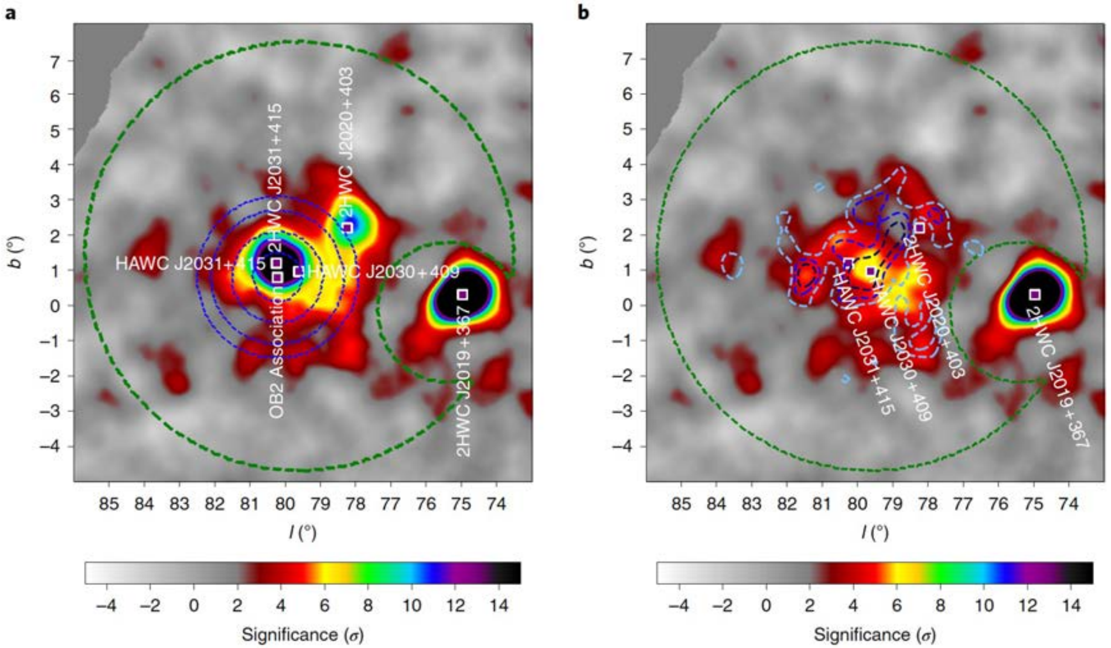




PeVatron Searches: And Example

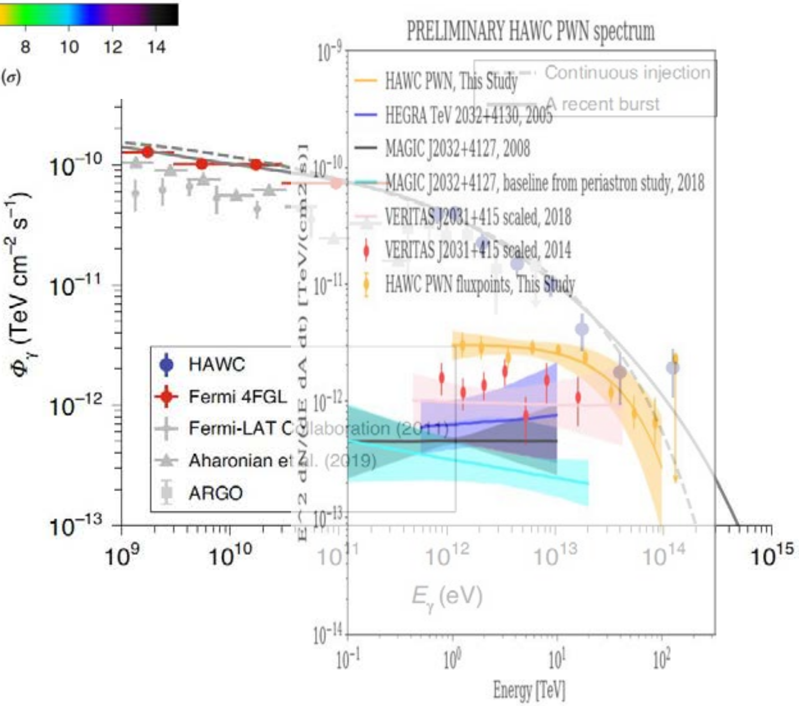
Note: Extrapolating the Cocoon emission measured by HAWC to a 0.3 extent produces excellent agreement with the flux reported by LHAASO, *Nature*, **594**, 33–36 (2021)

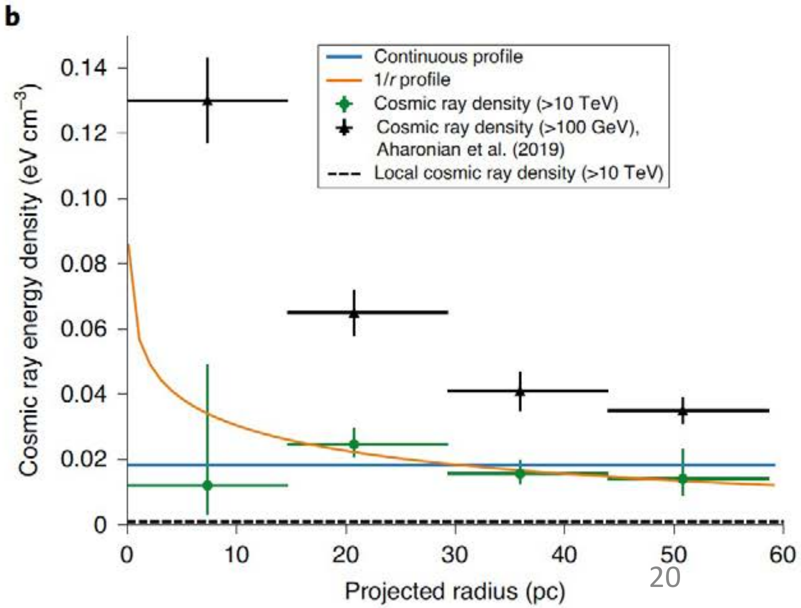
OB2 SFR
(Cygnus Cocoon)



Nat. Astro., 5, 465-471 (2021)

PoS ICRC2021, 836 (2021)

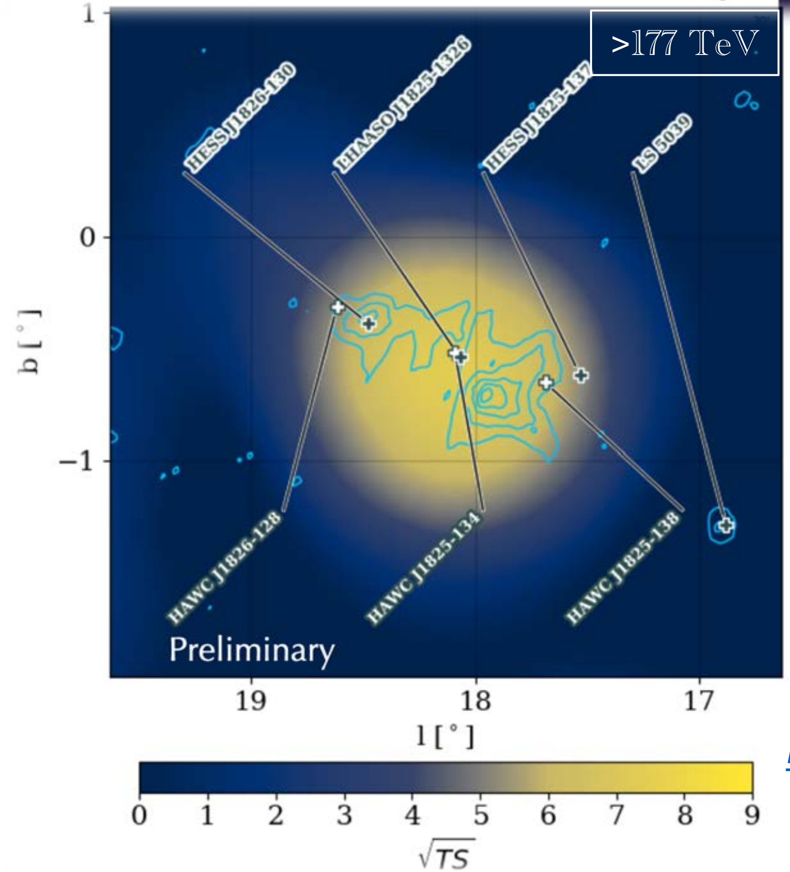


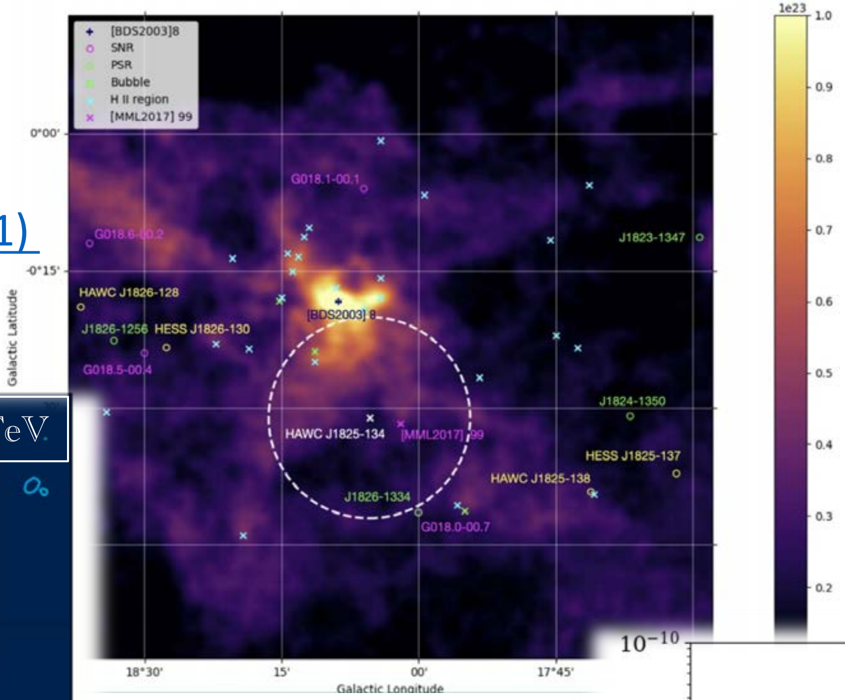


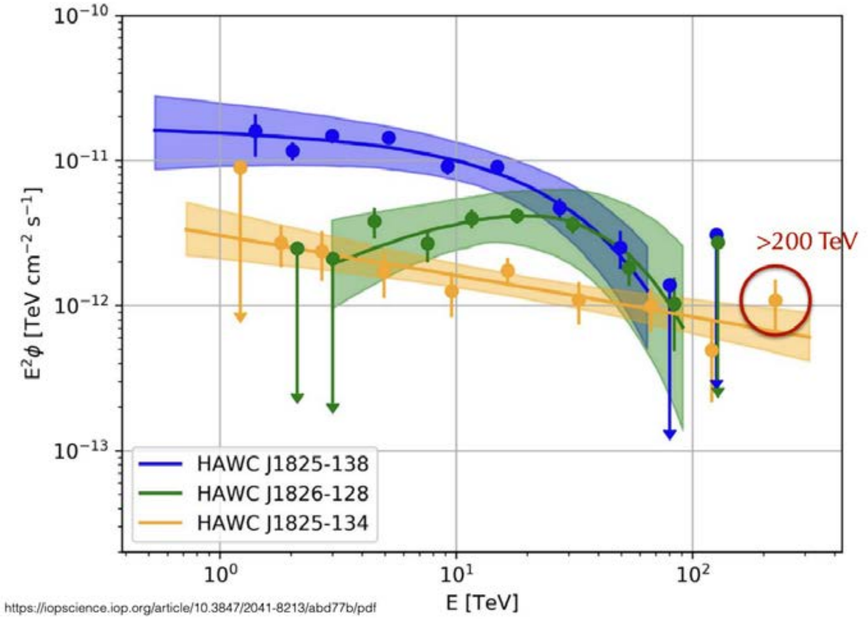
PeVatron Searches: Another Example

PWN,
UnID + GMC

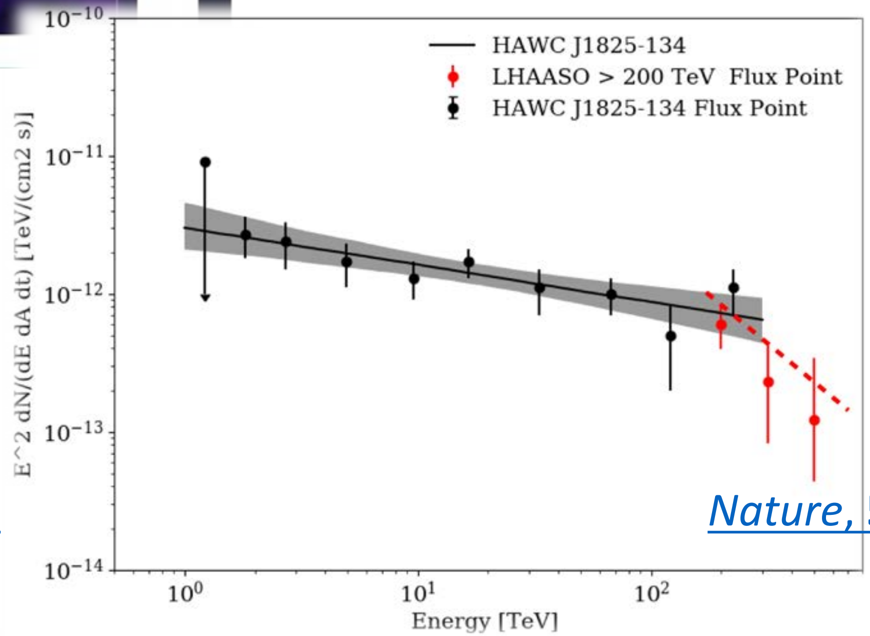
ApJL, Vol. 907, Is. 2, id. L30, 9 (2021)







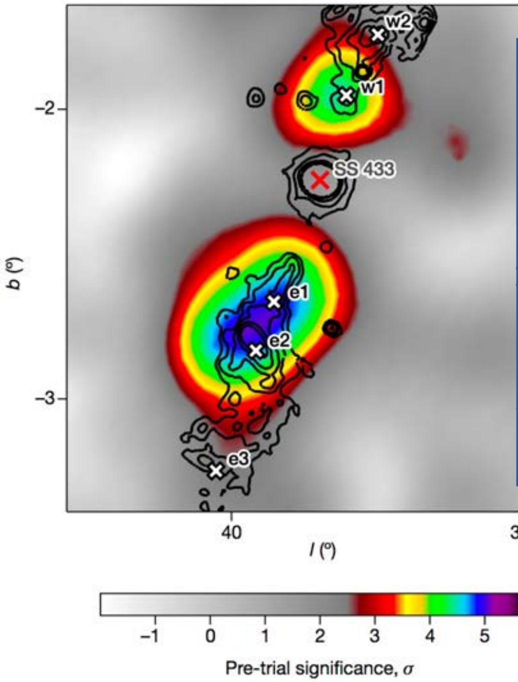
PoS ICRC2021, 840 (2021)



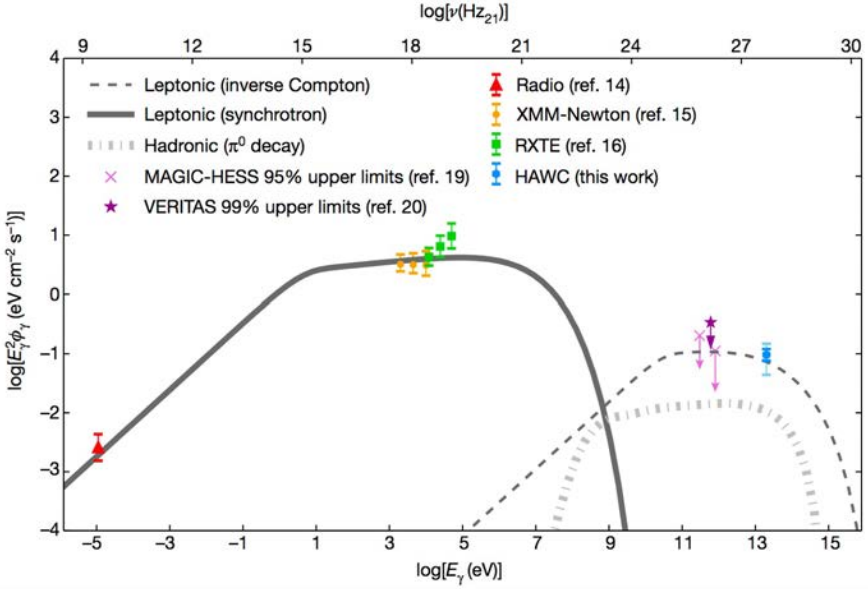
Nature, **594**, 33–36 (2021)

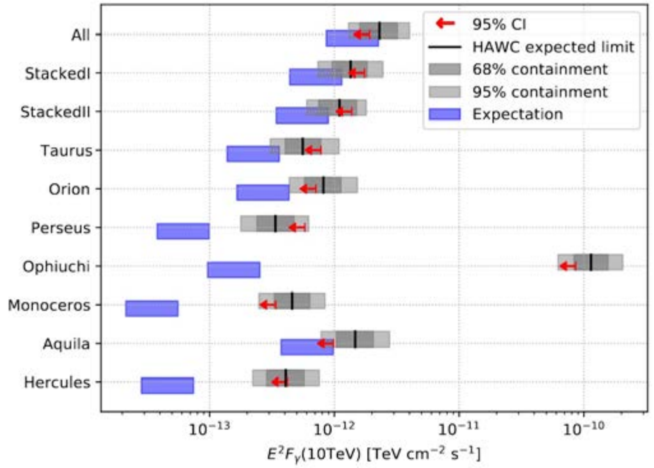
Other Recent Results of Probing our Galaxy

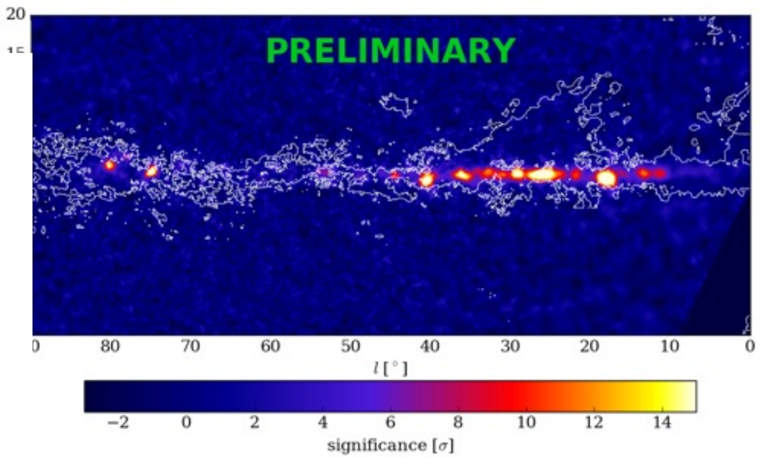
- ***Recent:***
  - 10s TeV $\gamma -$ ray emission from ***SS433***; particle acceleration is occurring in the jets, not in the central binary
  - Upper Limits on ***Fermi Bubble*** emission disfavoring proton injection spectrum that extends >100 TeV w/o suppression [ApJ, Vol. 842, Is. 2, id. 85, 9 pp. (2017)]
  - Probe of the "sea" of cosmic rays in distant galactic regions through their interaction with ***Giant Molecular Clouds*** that generates multi-TeV $\gamma -$ ray emission [ApJ, Vol. 914, Is. 2, id. 106, 14 (2021)]
- ***Forthcoming:***
  - Test of ***Galactic Diffuse Emission*** Models at multi-TeV (GALPROP, DRAGON)



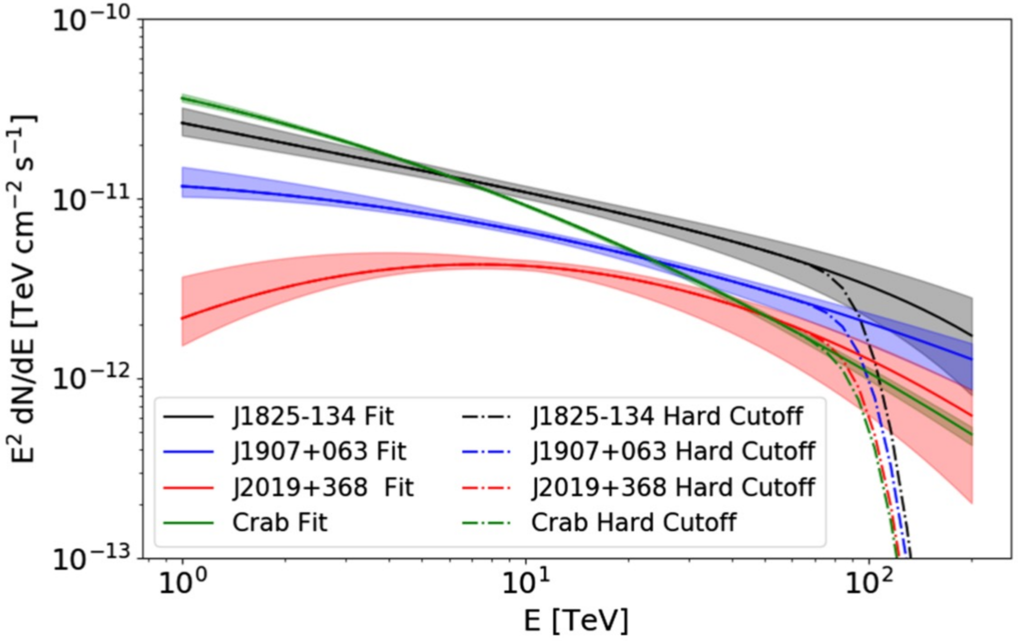
Nature, Vol. 562, pp. 82–85 (2018)

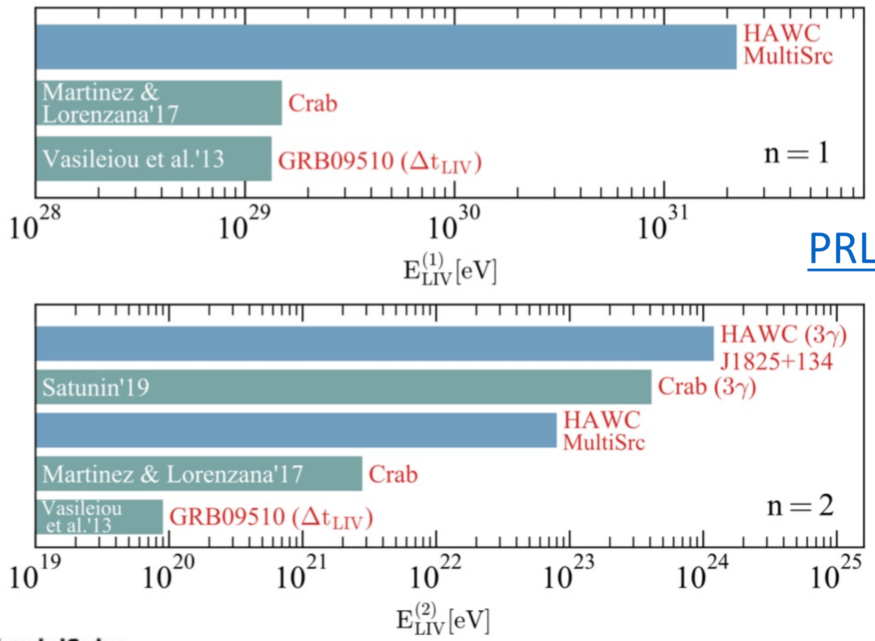




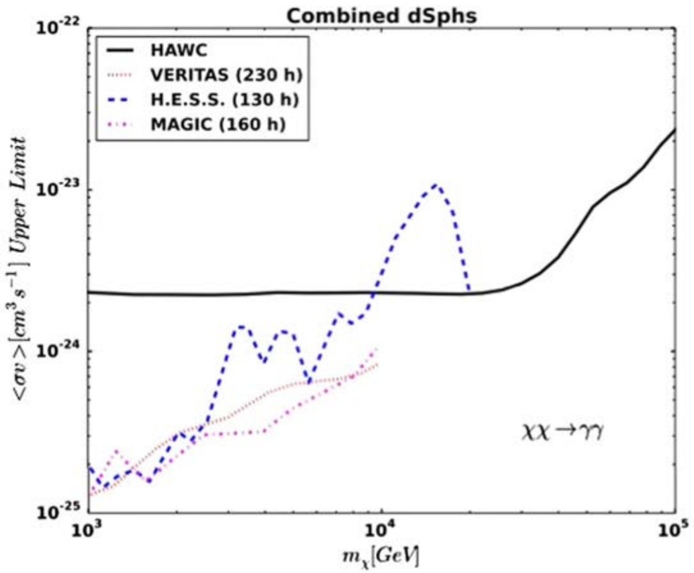


Fundamental Physics: LIV & Dark Matter





PRL, 124, Is. 13, id.13110 (2020)

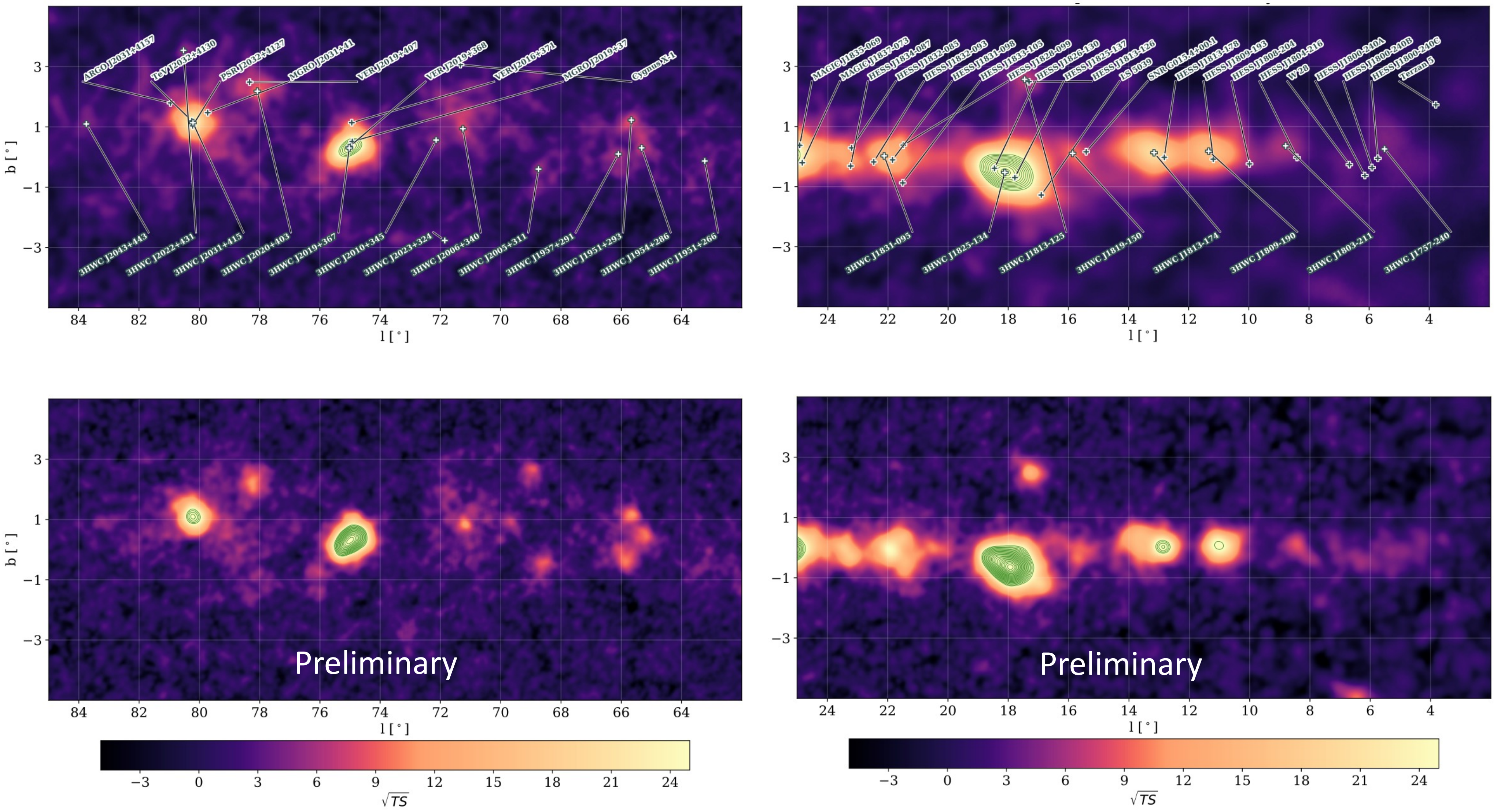


PRD, 101, Is. 10, article id.10300 (2020)

Future Improvements

- Currently testing a new data pass of main array data (***pass5***)
  - Significant improvement of PSF (~0.1 deg at highest energy)
  - Significant improvements at low energies
  - Some forthcoming (unexpected?) results (over the next few months)

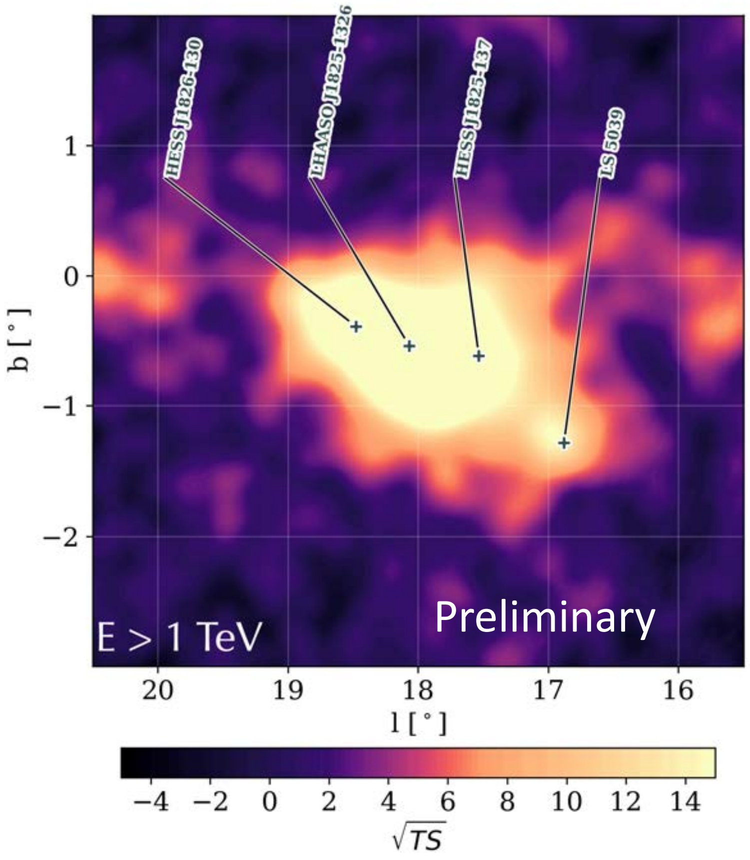
Future Improvements

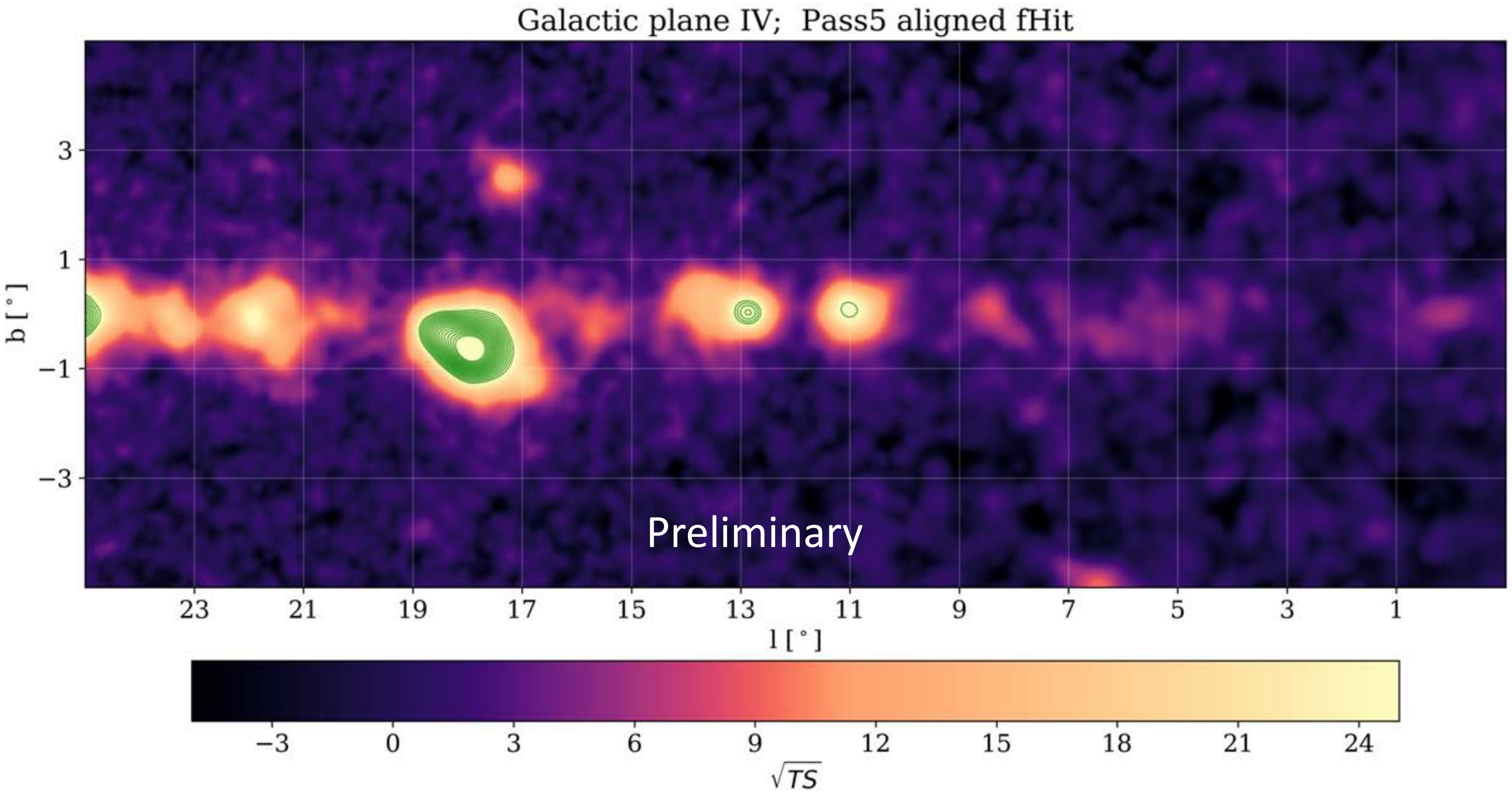


Pass 4

Pass 5

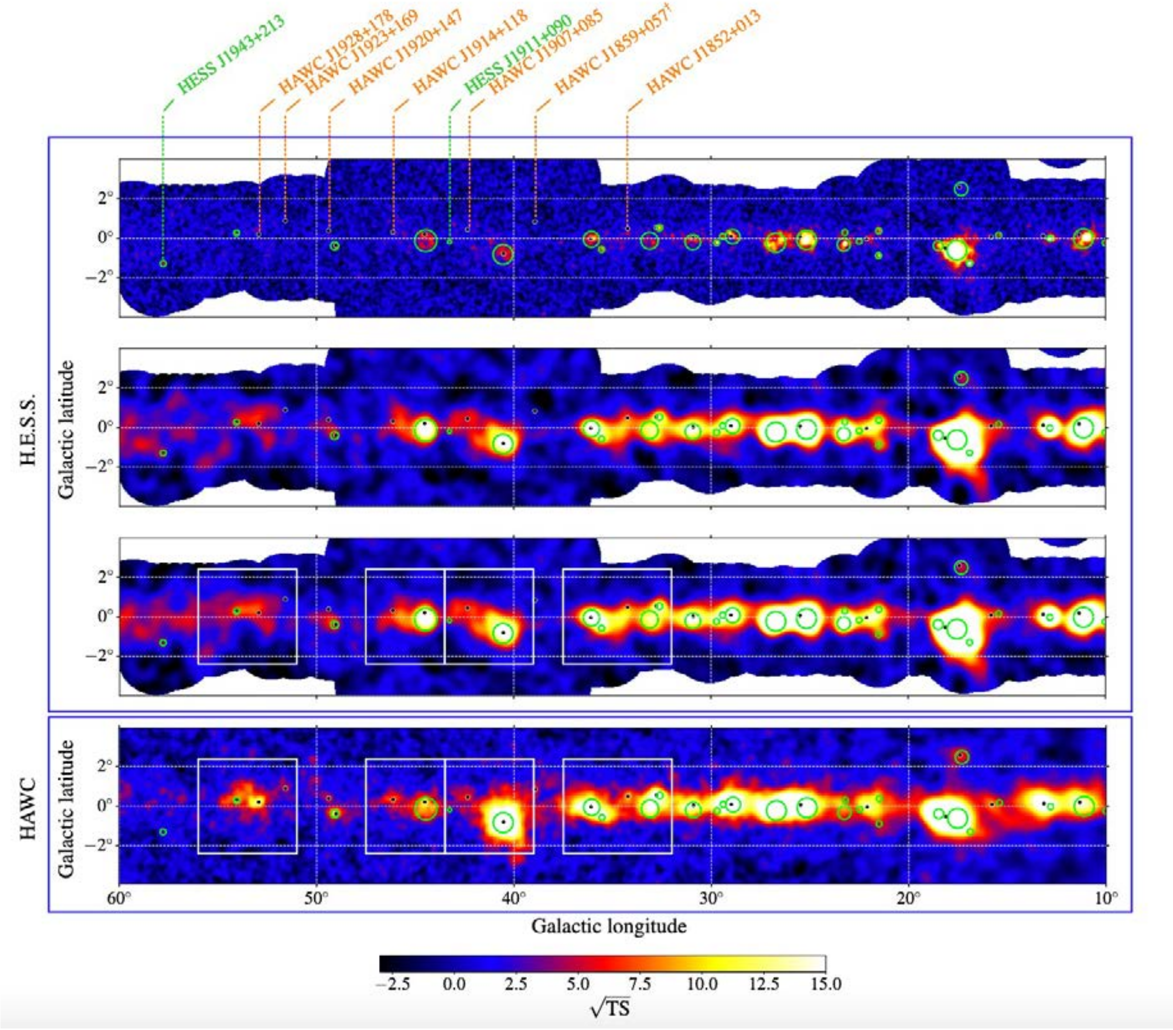
Interesting Regions of event excess





Future Improvements

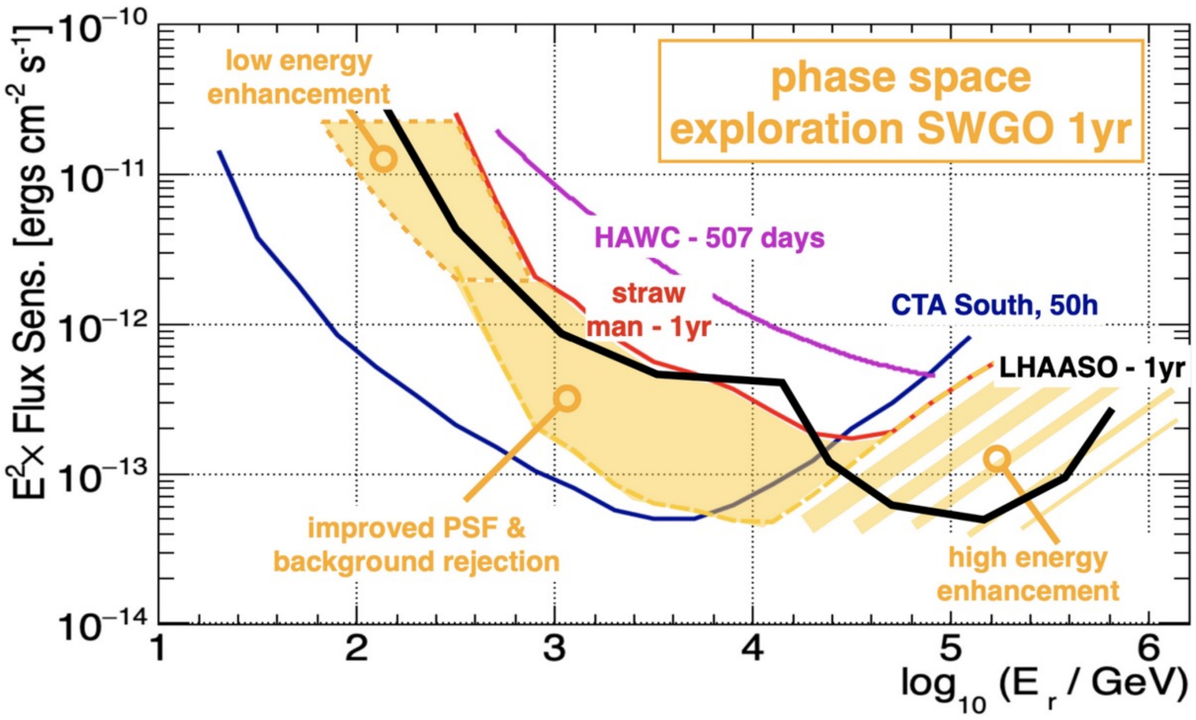
- Currently testing a new data pass of main array data (***pass5***)
  - Significant improvement of PSF (~0.1 deg at highest energy)
  - Significant improvements at low energies
  - Some forthcoming (unexpected?) results (over the next few months)
- Working on combining main array data with outrigger data (***pass6***)
  - First studies indicate mean energies of ~250 TeV along the Galactic plane
- Continuing to work on combining HAWC data with data from other observatories (both electromagnetic and other messenger) and making HAWC data usable for the community



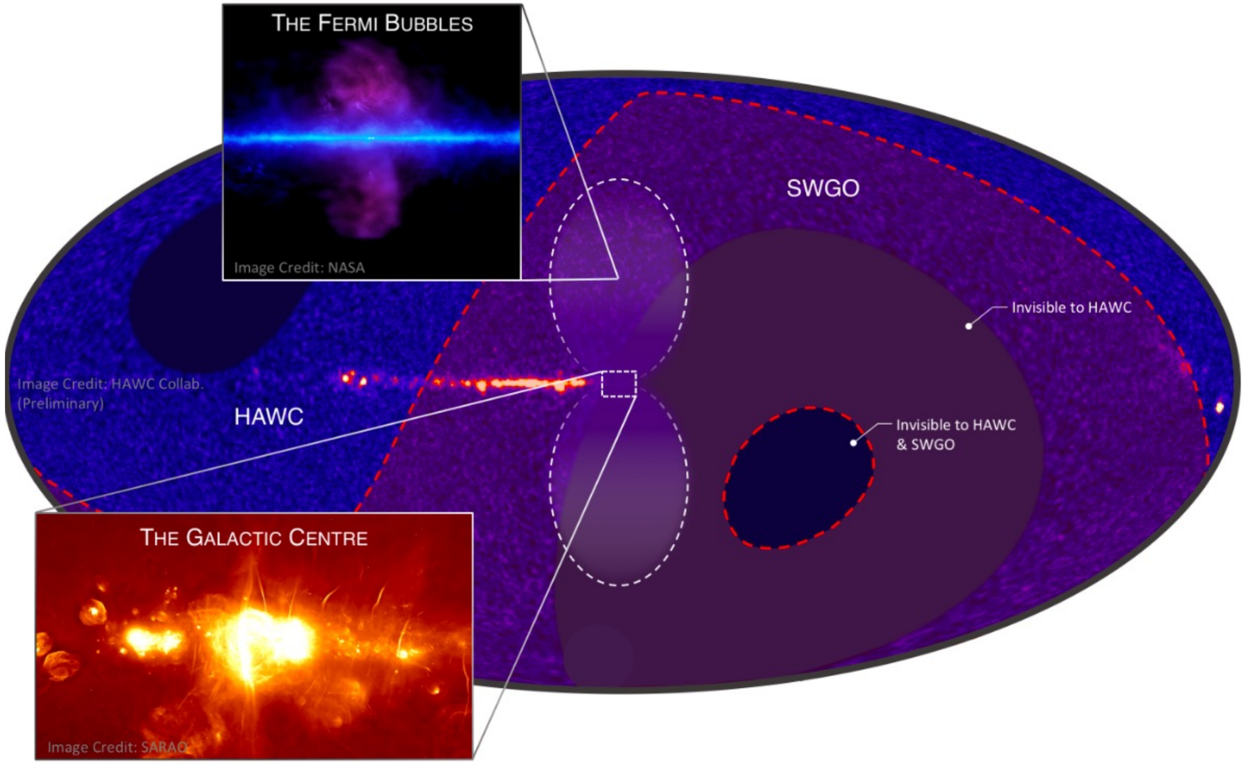
[ApJ, Vol.917, Is. 1, id.6, 16 pp. (2021)]

The Future: Southern Wide Field Gamma-Ray Observatory*

SWGO will be located in Argentina, Bolivia, Chile, or Peru



[*PoS* ICRC2021, 903 (2021)](#)



[Astro2020: APC White Paper; BAAS, Vol. 51, Is. 7, 109 (2019)](#)

* (Endorsed by Astro2020 PAG committee)

HAWC-Outlook

- Ever more sensitive techniques used in **HAWC** data reconstruction & analysis
  - New source detections and the 4th HAWC catalog (using a Fermi-like Multi-Source Fitting approach)
- With **HAWC and LHAASO,** we now have two instruments with unprecedented sensitivity > 10 TeV that also provide different complementary instantaneous views of the sky (time domain)
- Multi-instrument and -messenger analyses will provide unprecedented science output
  - Preparation of publicly available energy dependent HAWC sky maps and HAWCtools