Observation of Extended PWNe with HAWC

Andrew Smith — University of Maryland, College Park
for the HAWC Collaboration

Fermi Symposium 2018, Baltimore, MD

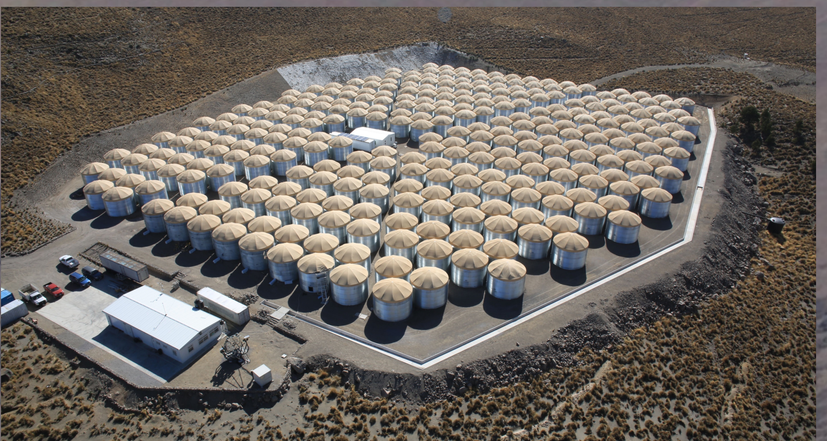
HAWC Collaboration (Mexico, USA, Germany, Poland, Costa Rica and Italy)


HAWC
Latitude: 18°59.7’N
Longitude: 97°18.6’W

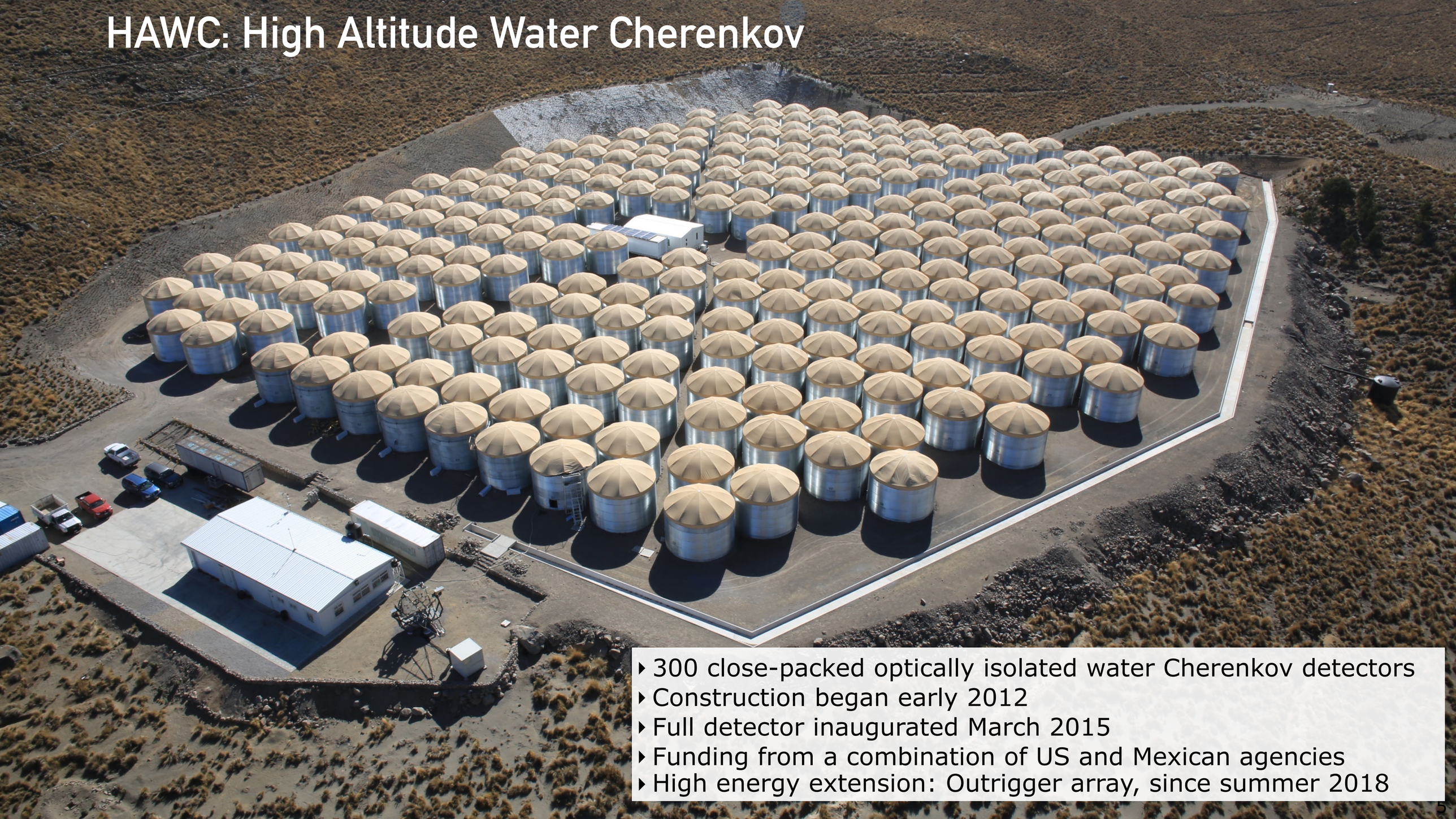
Pico de Orizaba
5636 m a.s.l.

Sierra Negra
Large Millimetric Telescope
4640 m a.s.l.

HAWC
4100 m a.s.l.

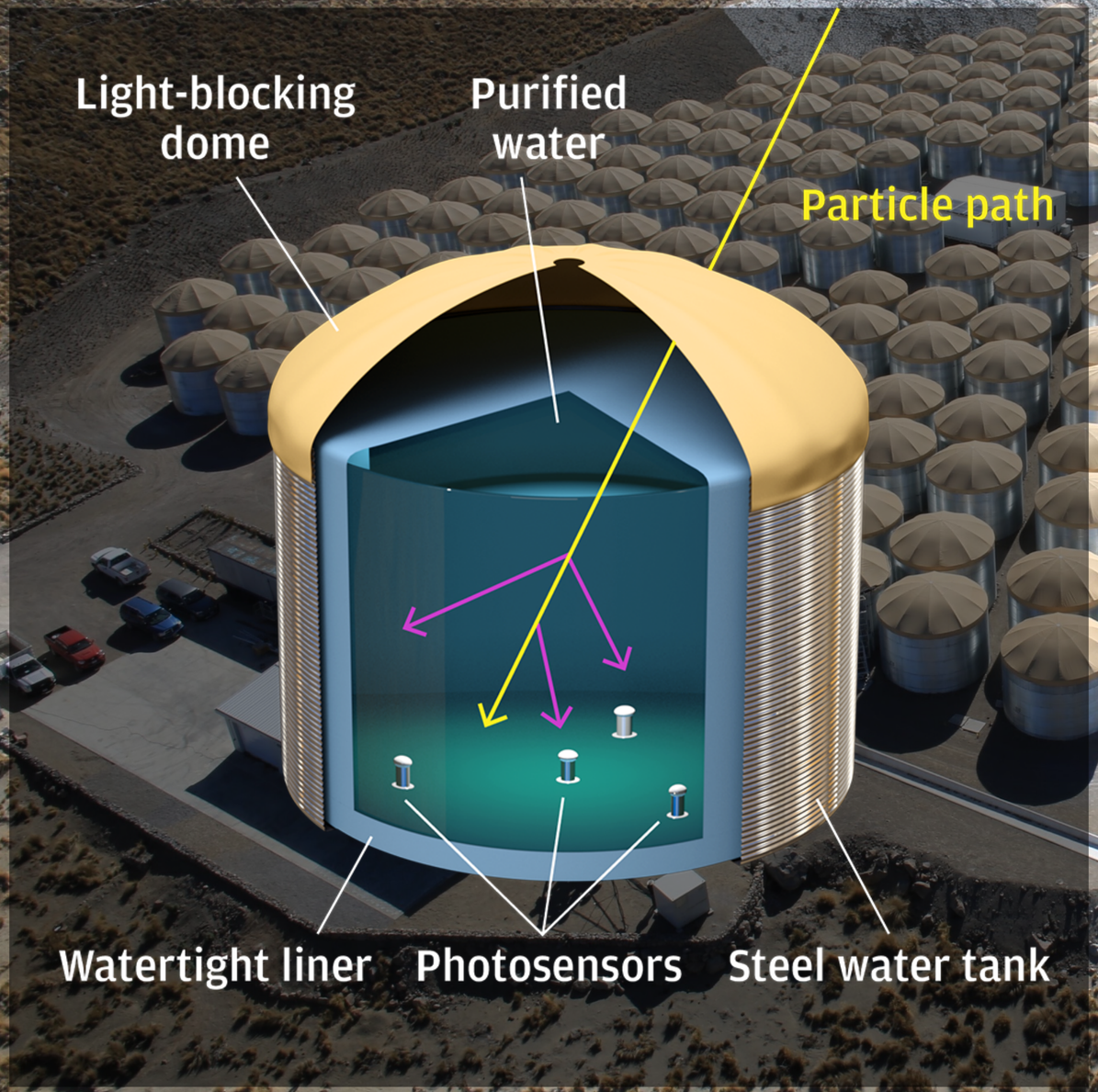


HAWC: High Altitude Water Cherenkov



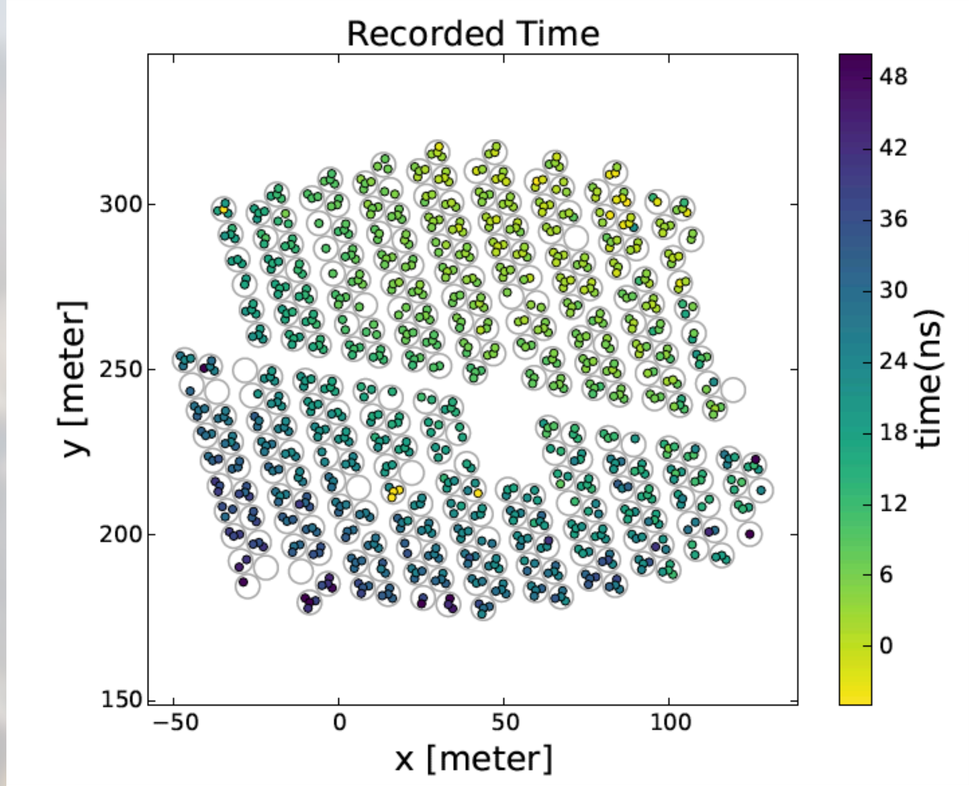
- 300 close-packed optically isolated water Cherenkov detectors
- Construction began early 2012
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, since summer 2018

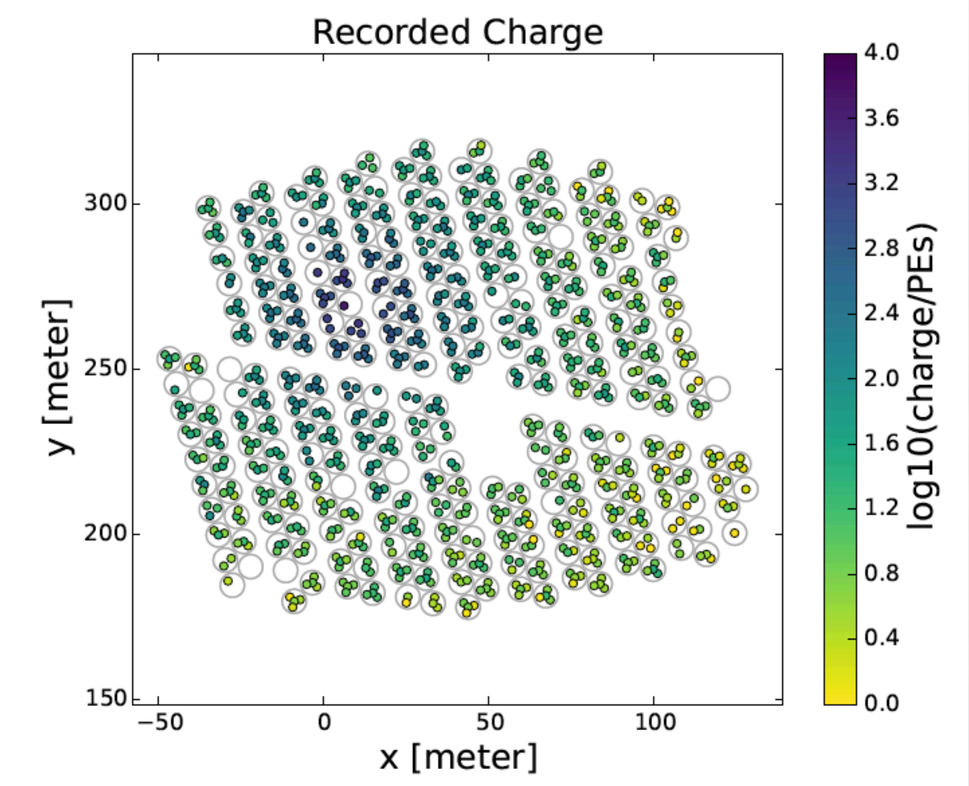
Water Cherenkov Detectors



Shower reconstruction

- Measure: time and light level in each PMT.
- Reconstruct: direction, location, energy, and background rejection.
- Reference: Crab paper, ApJ 843 (2017), 39.

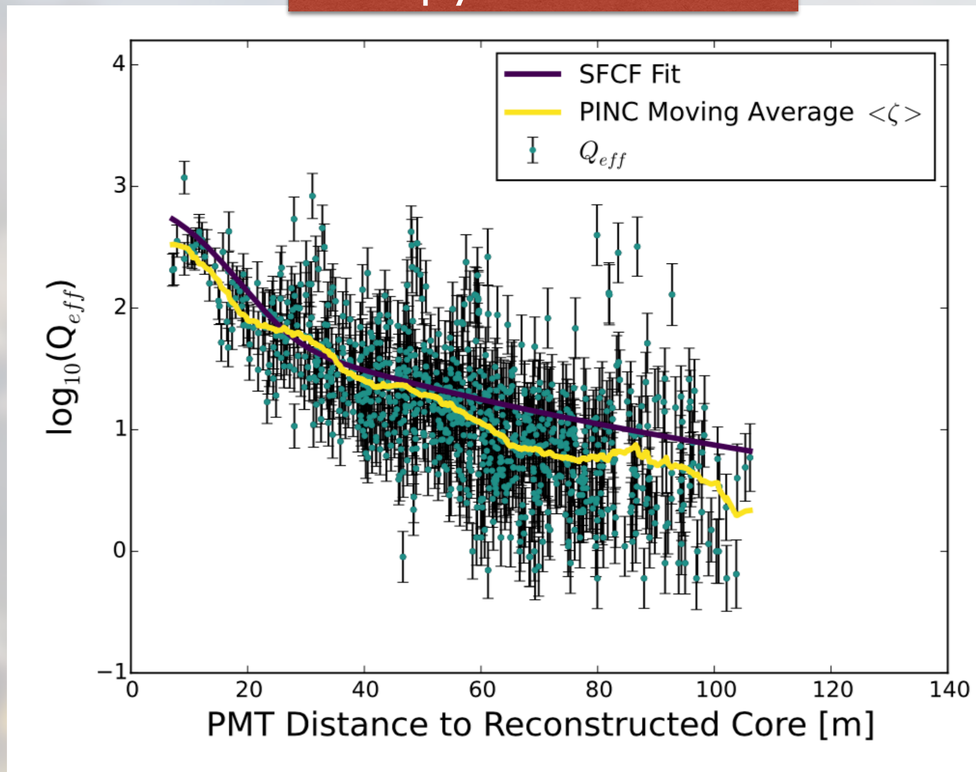




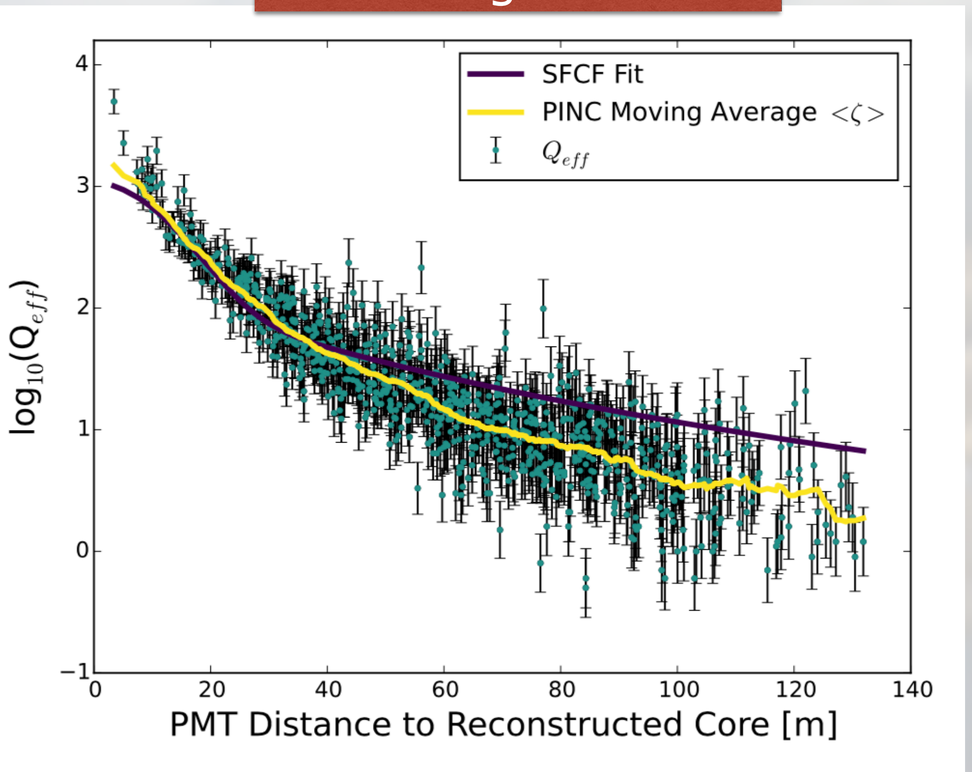
Shower reconstruction

- Measure: time and light level in each PMT.
- Reconstruct: direction, location, energy, and background rejection.
- Reference: Crab paper, ApJ 843 (2017), 39.

Clumpy: hadron-like



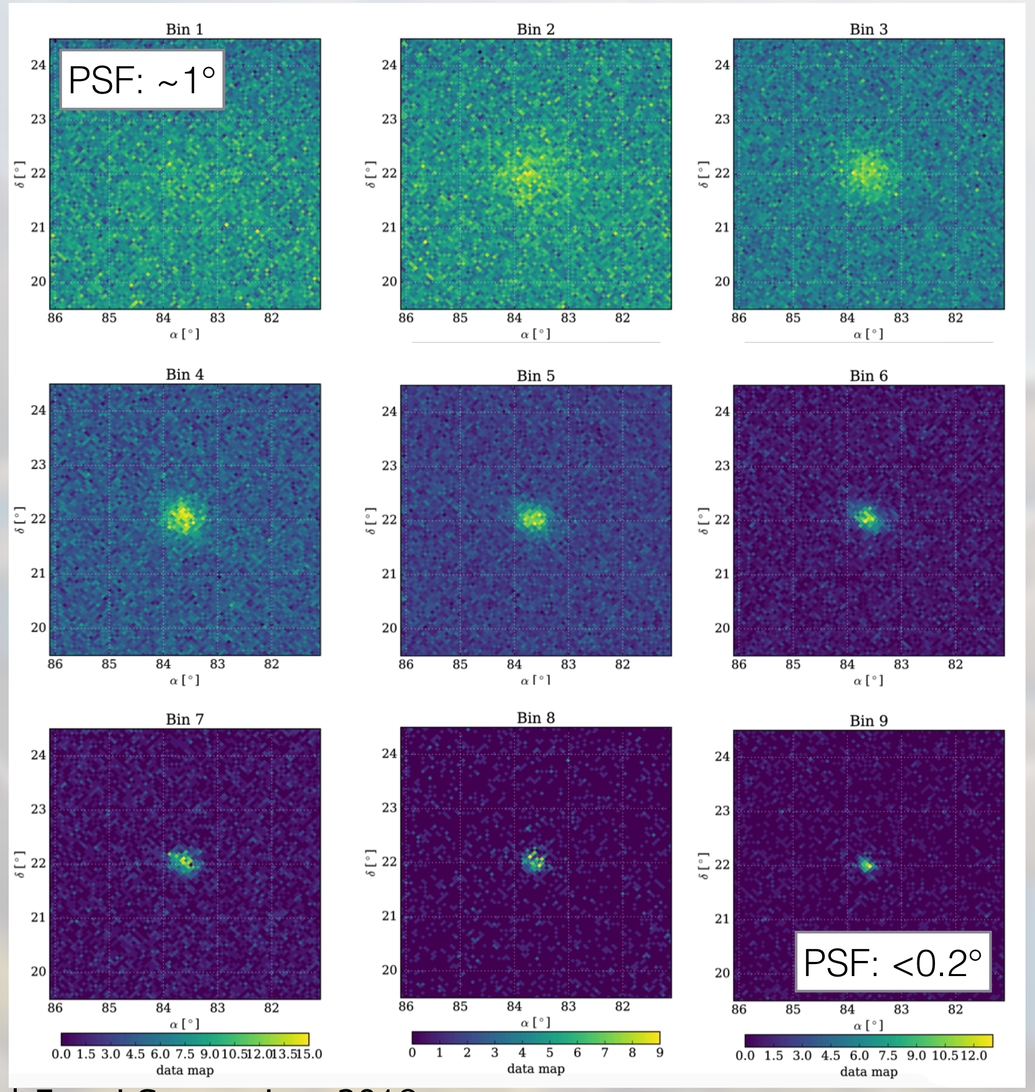
Smooth: gamma-like



Source search and characterization

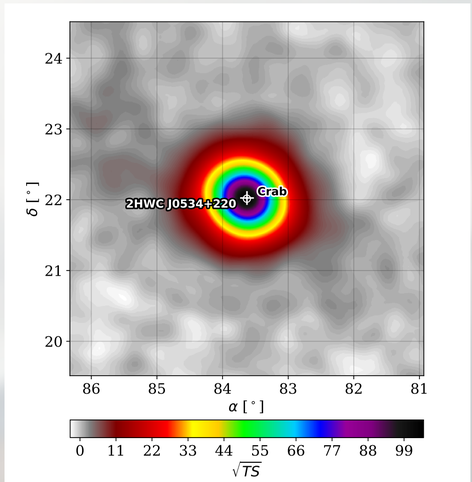
- Events sorted by "size" in *n* bins (with characteristic Point Spread Function, S/N ratio, energy), make *n* maps.
- Likelihood framework use *n* maps to test the presence of sources then characterize them.
- Reference: Crab paper, ApJ 843 (2017), 39.

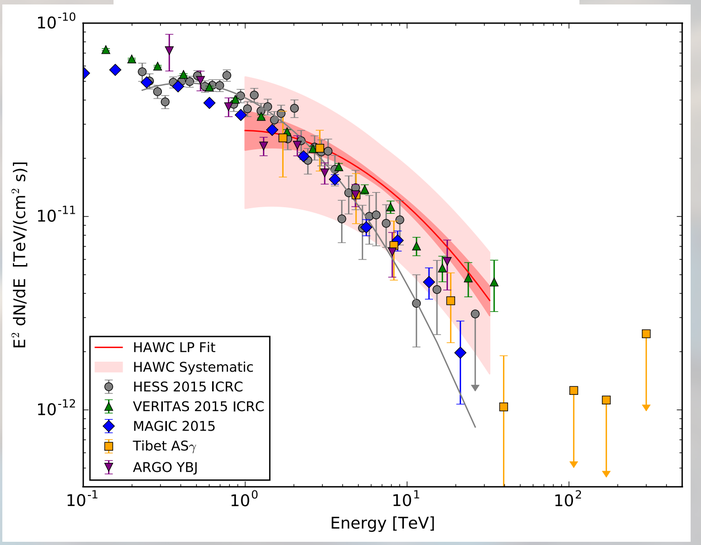
Crab Nebula



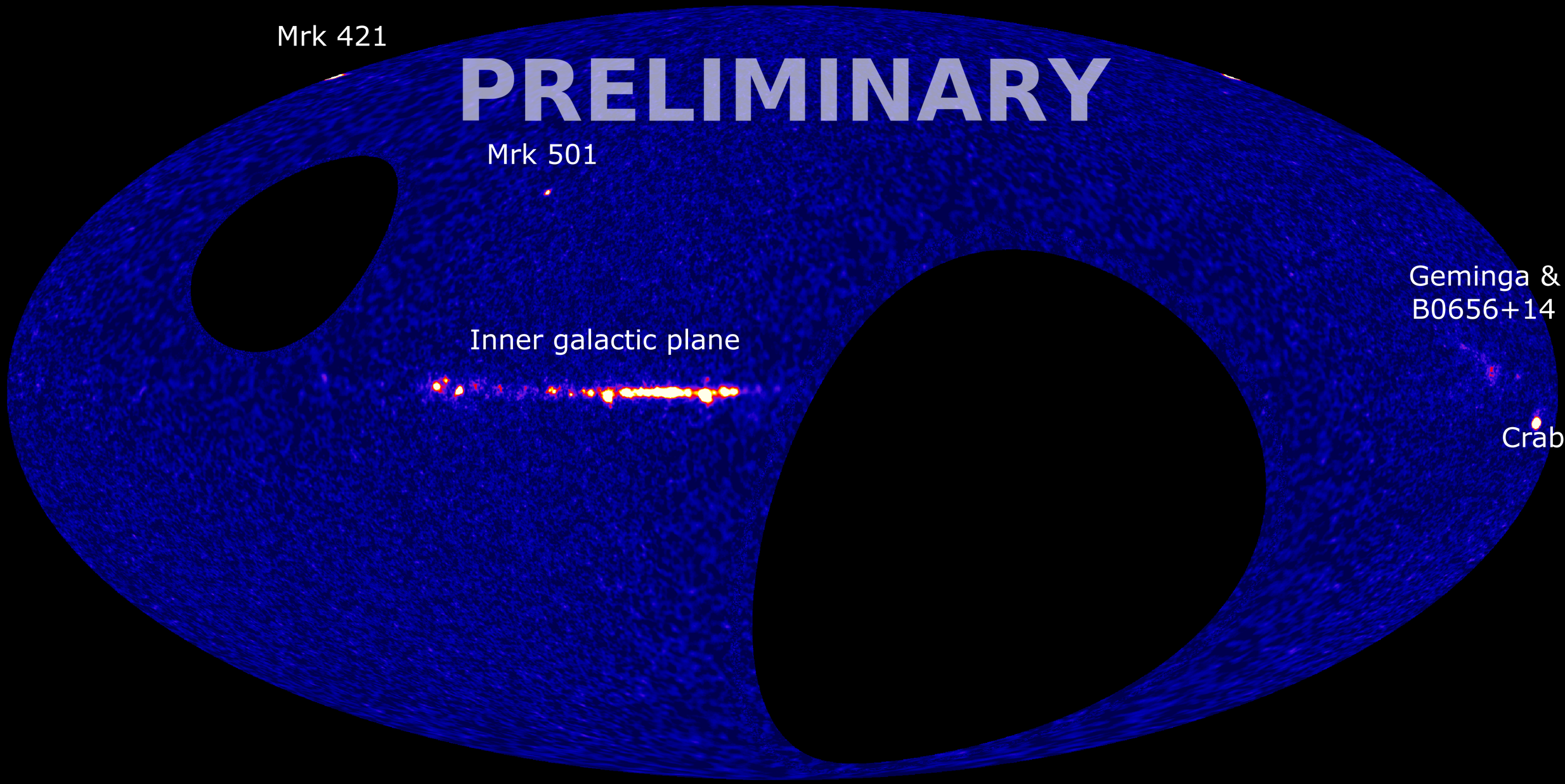
Detector response
Source model

Likelihood framework





HAWC 3.5 year skymap — 1128d livetime: 2014-11 to 2018-04



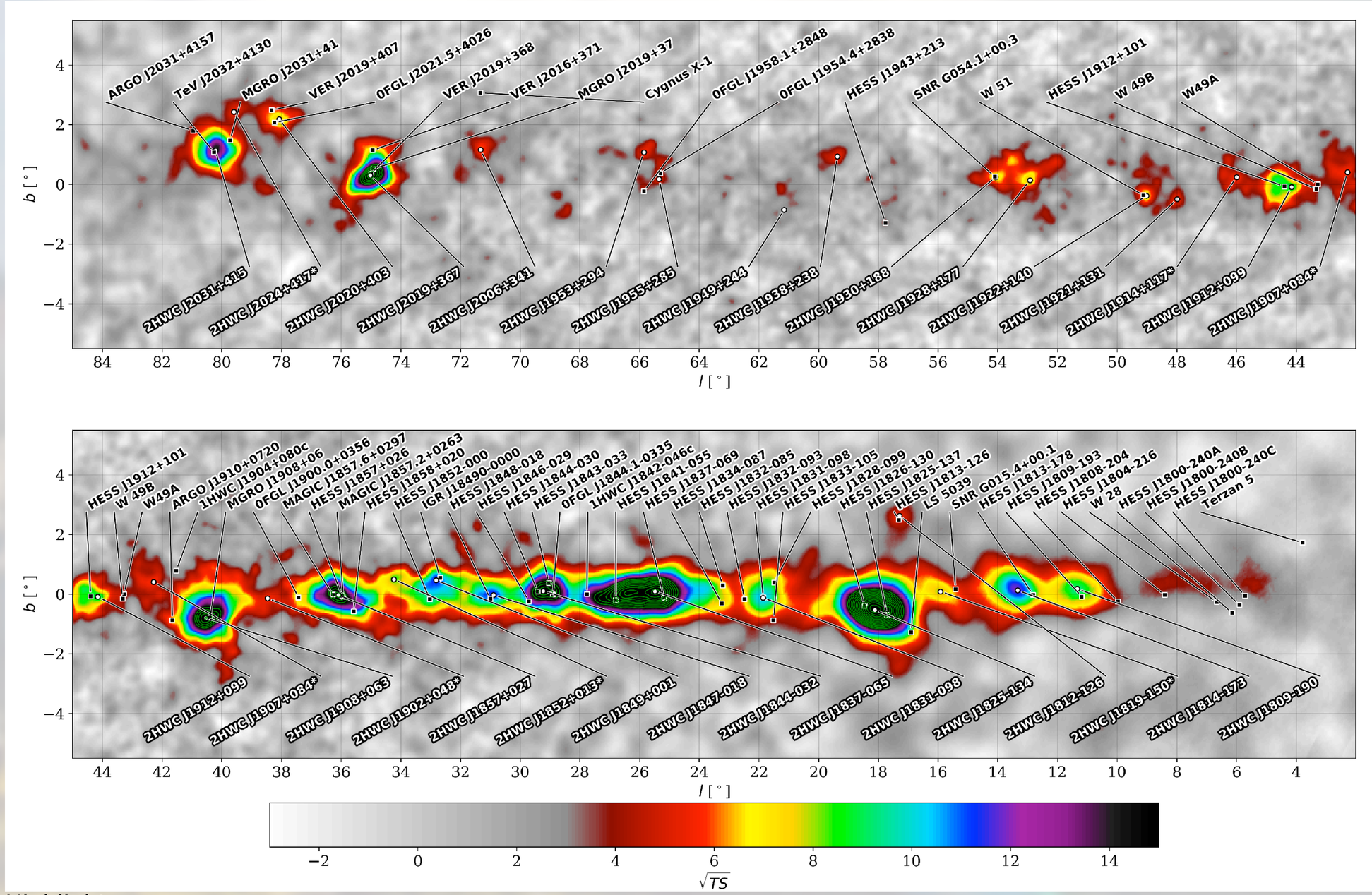
2HWC catalog (ApJ 2017) was 507 days, with 39 sources of which 10 were new.

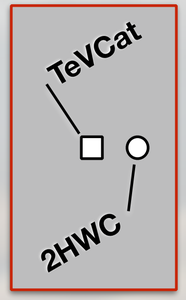
2HWC Catalog

- 2HWC Catalog (ApJ, Volume 843, Issue 1, article id. 40, 21 pp. 2017)
- Searched for distinct local significant excesses in observable sky.
  - Search for Point Sources and Extended Sources of size 0.5^{o},1.0^{o},2.0^{o}
  - 507 days of data.
  - Identified 39 gamma-ray sources, 19 of which were not associated with previously identified TeV sources.
  - Tool online for public access:
    - https://data.hawc-observatory.org/datasets/2hwc-survey/index.php
- We now have 1128 days of data
  - Report new interesting sources as ATel's.

Inner Galactic plane — 507d livetime (2014-11 to 2016-06)

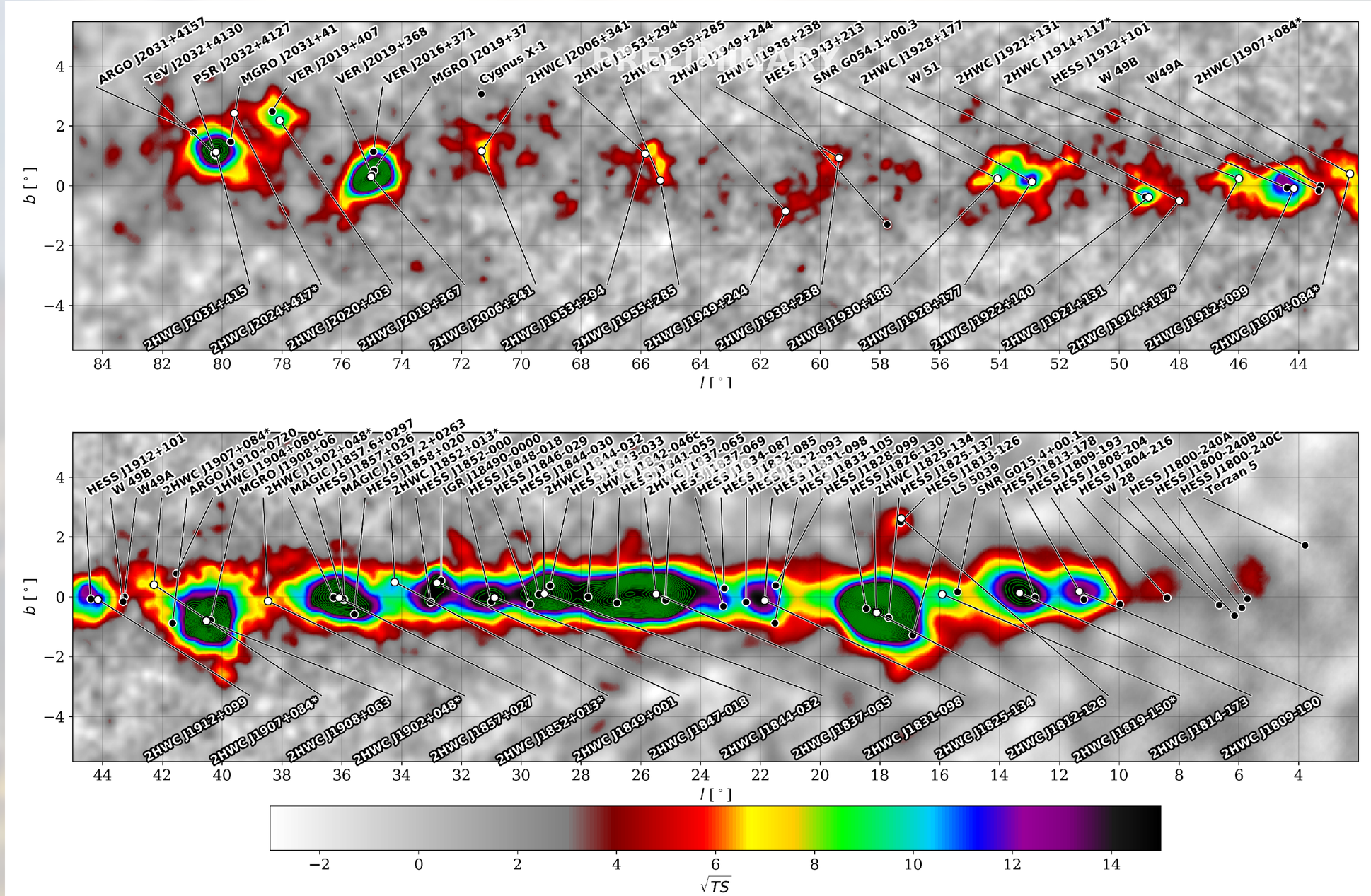
2HWC catalog (ApJ 2017)

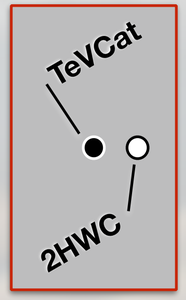




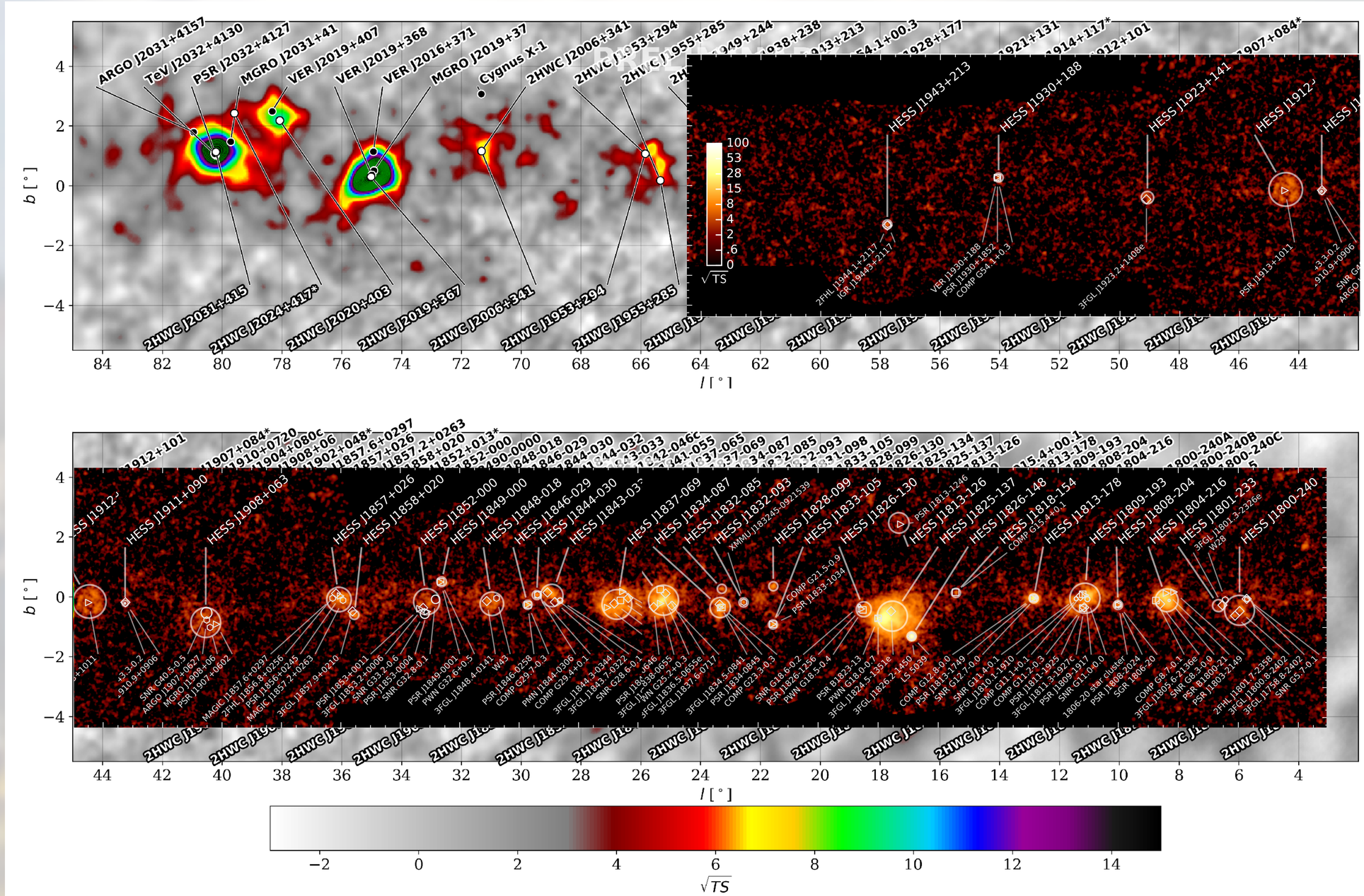
Inner Galactic plane — 1128d livetime (2014-11 to 2018-04)

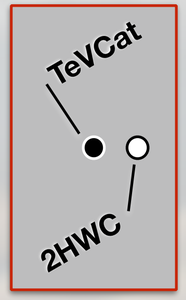
Update





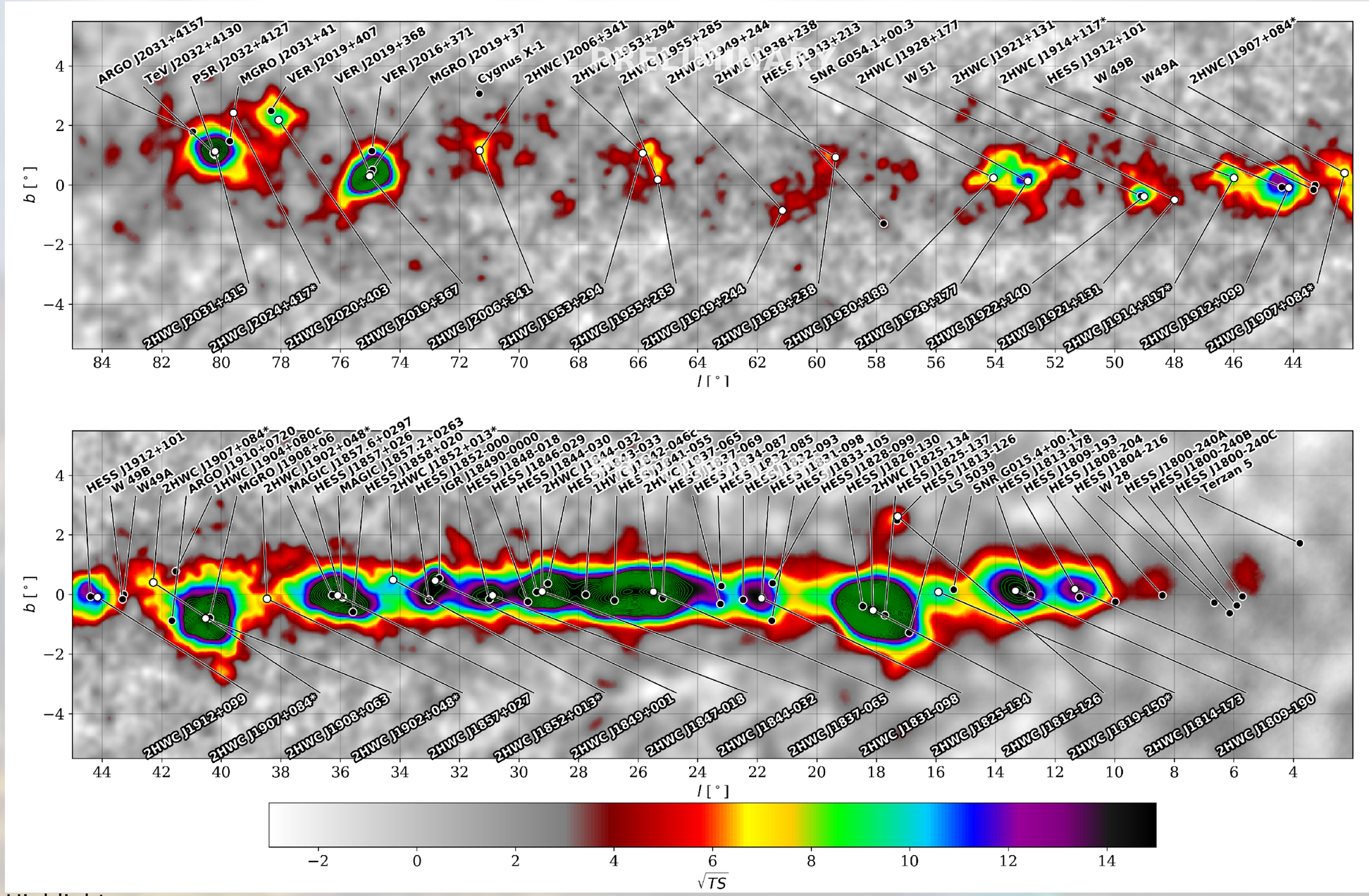
Inner Galactic plane — H.E.S.S. Galactic plane survey (A&A 2018)

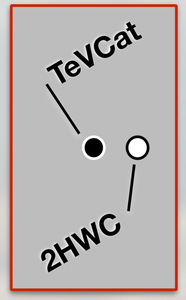




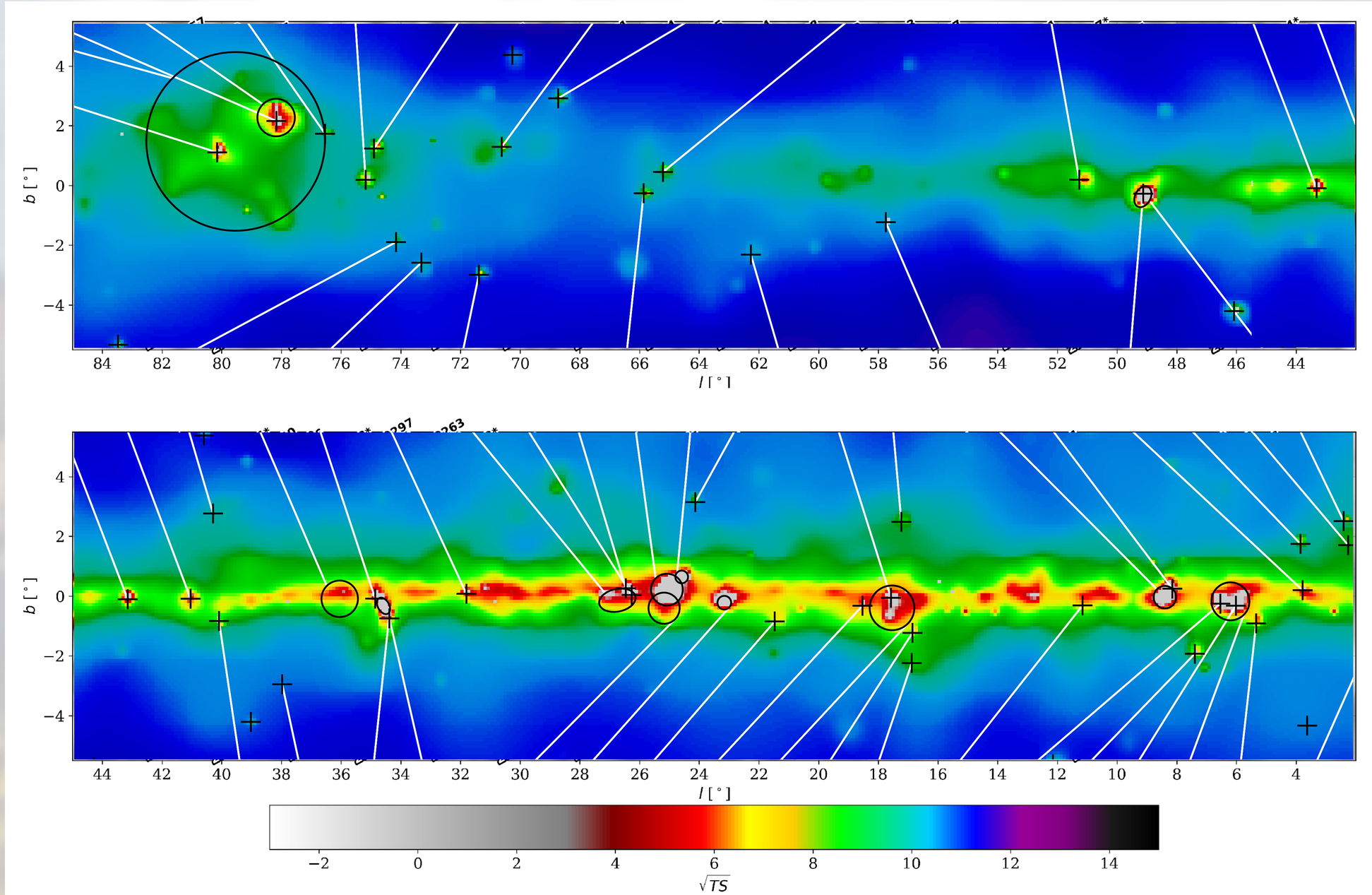
Inner Galactic plane — 1128d livetime (2014-11 to 2018-04)

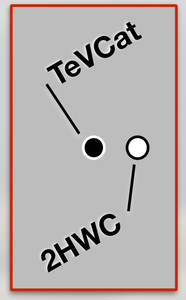
Update





Inner Galactic plane — Fermi-LAT 3FHL (arXiv:1702.00664)

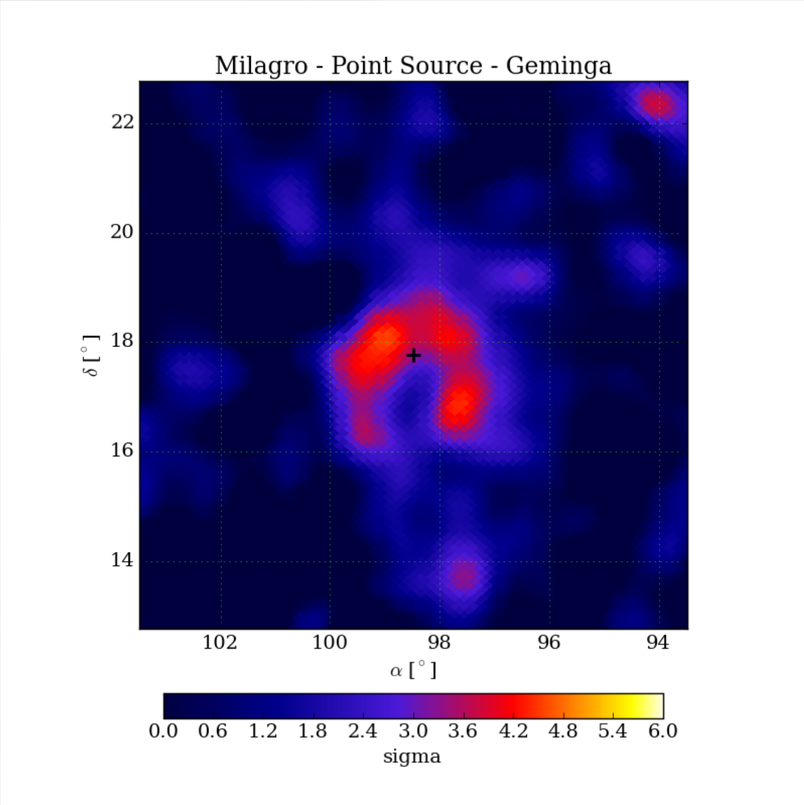




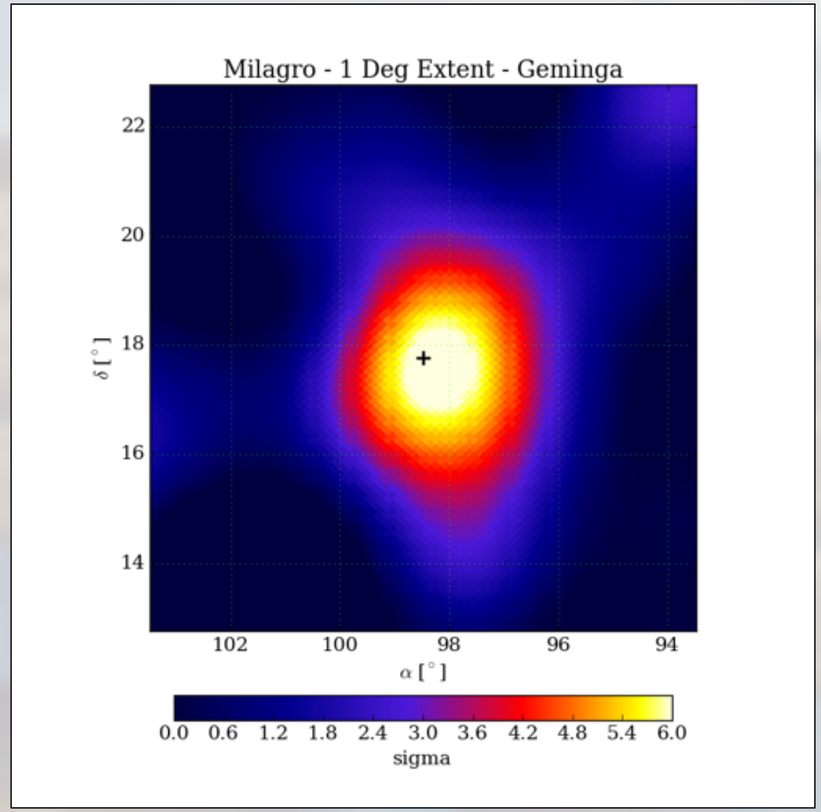
Geminga and B0656+14

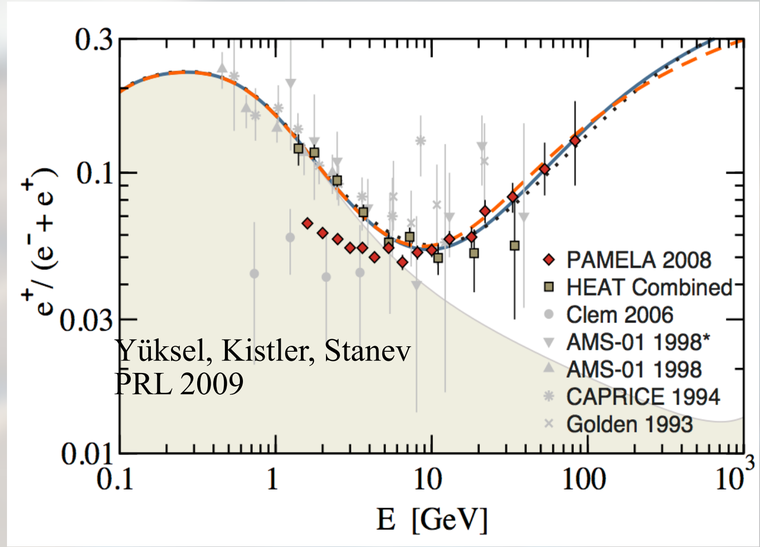
- Geminga is and extremely close (250pc) and middle-aged pulsar (342ky).
- Originally identified as a TeV Source by Milagro, a predecessor to HAWC.
- Yuksel, Kistler, Stavev postulated that positrons from Geminga could explain the positron excess seen by PAMELA and AMS.

Milagro Point Source Map



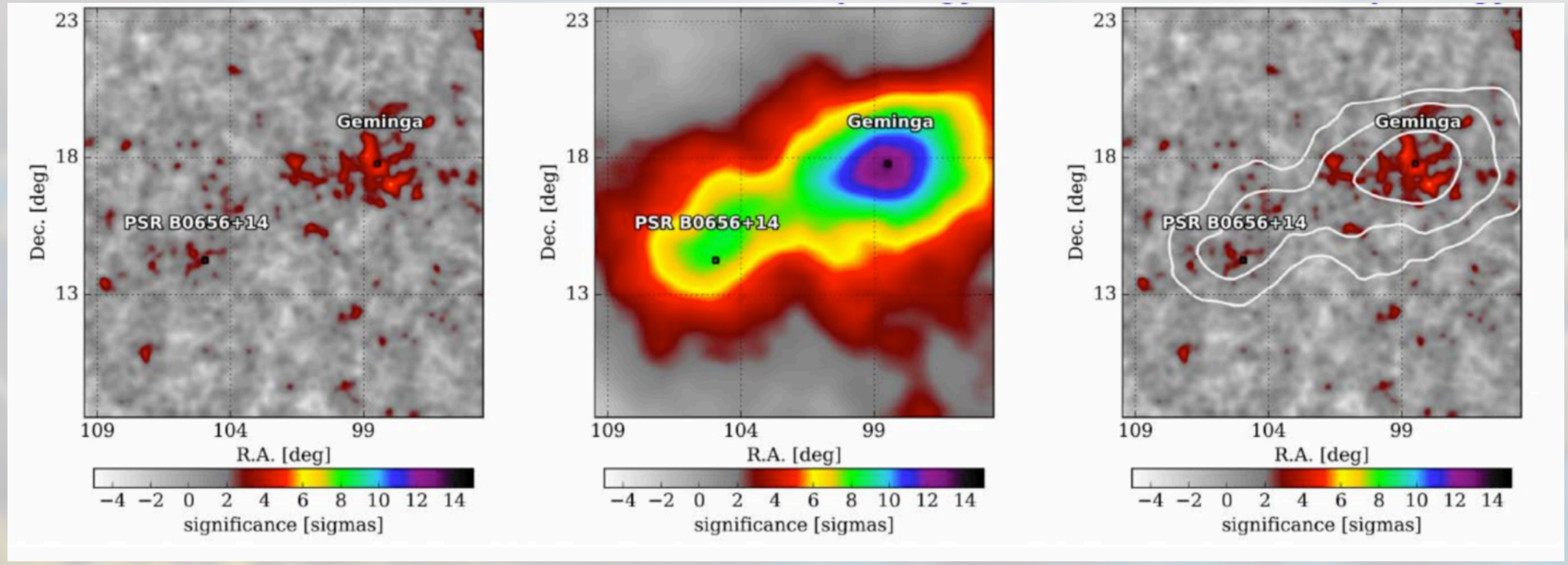
Milagro Extended Source Map



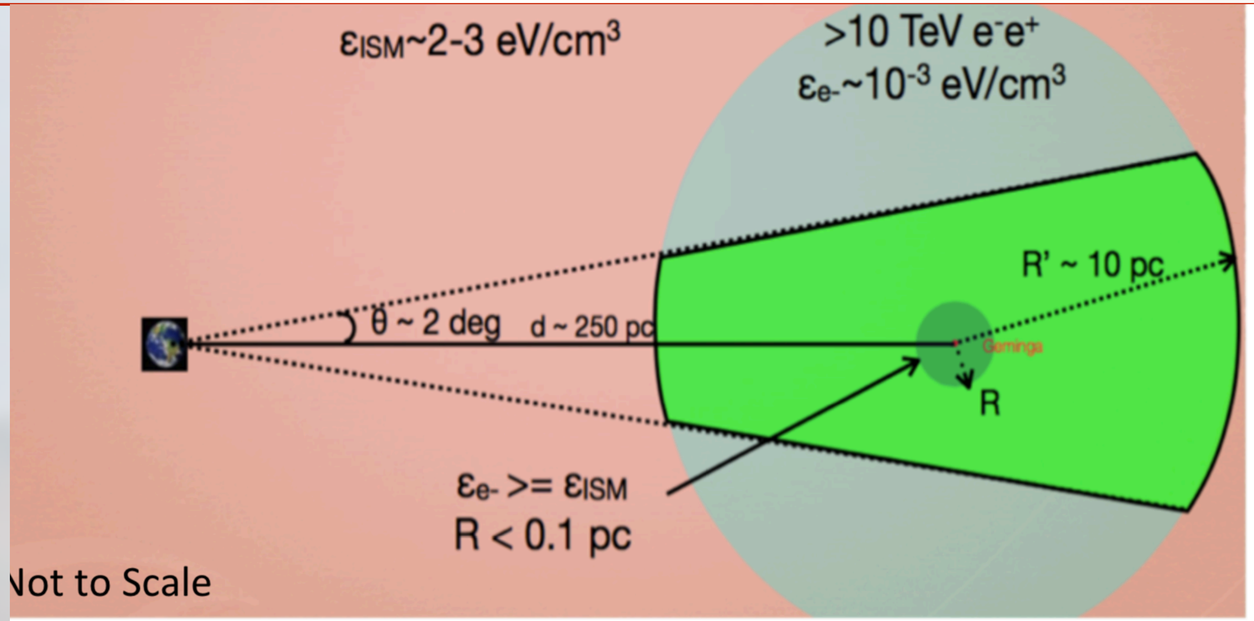


Geminga and B0656+14

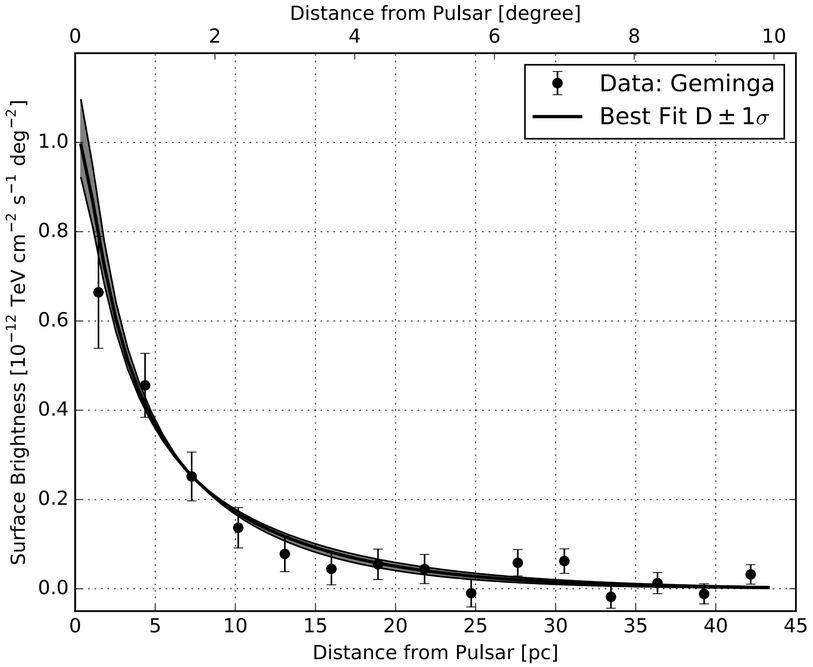
- HAWC detects Geminga and B0656+14 at high significance as highly extended sources.
- Much larger than x-ray PWN
- Fit extension of observed TeV gamma-rays to a model describing the extension as due to CR diffusion and propagation.



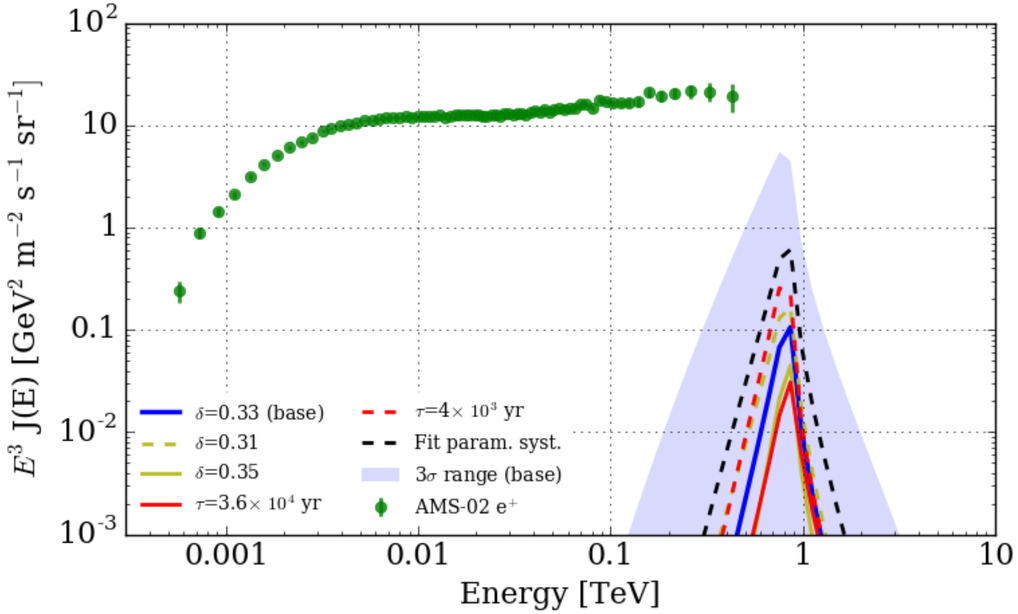
Geminga and B0656+14



- X-ray nebula < 0.1 pc where $\varepsilon_{e\text{-}e+} > \varepsilon_{ISM}$ and B~10-20 μG
- TeV nebula > 10 pc and $\varepsilon_{e\text{-}e+} \sim 10^{-3}$ eV/cm^3 $<< \varepsilon_{ISM}$

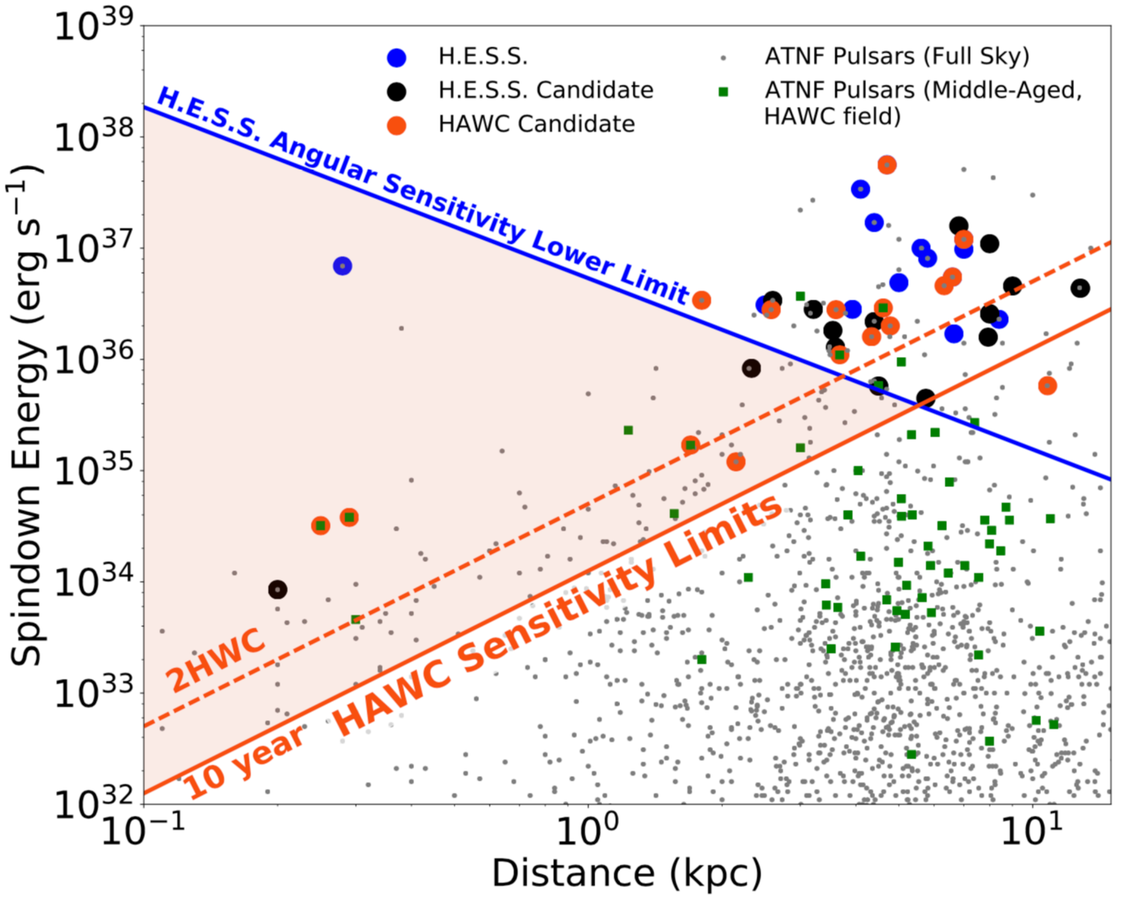


Science Vol. 358, Issue 6365, pp. 911-914



Linden et al….

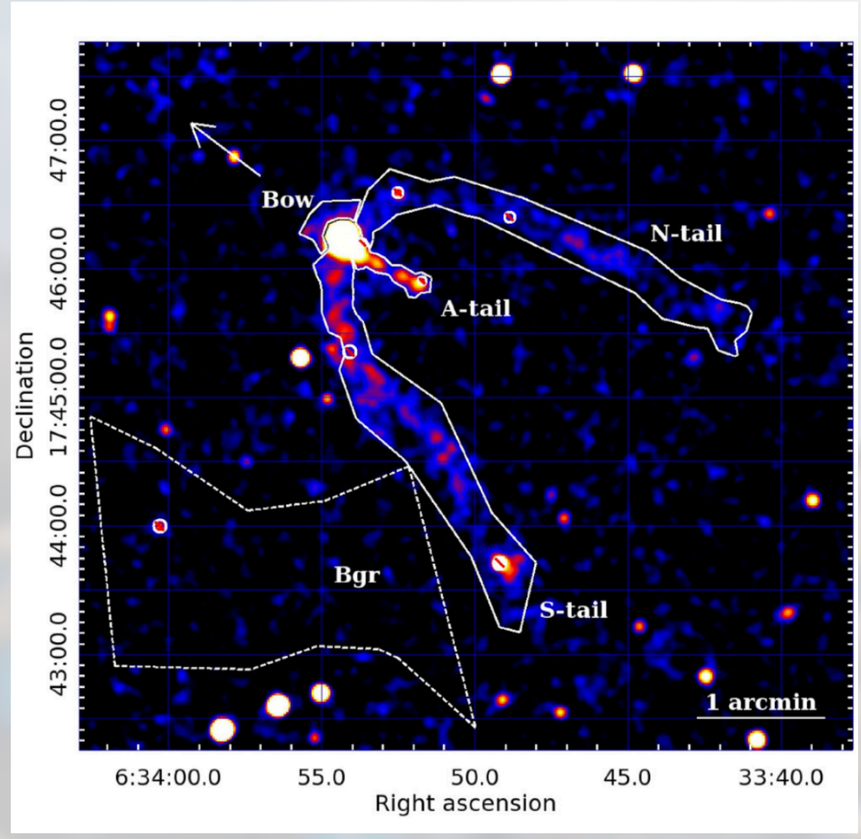
- Linden, T. *et al* (Phys. Rev. D 96, 103016). Pointed out that HAWC sees nearby high flux pulsars.
- Should see more.
- Notes that the TeV signature is a large (~10pc), spatially distinct from the SNR and from the X-ray PWN shock.
- Coined term "TeV Halo" to these objects and suggested the size is a compromise between diffusion of PWN accelerated ~10-100 TeV electron cooling time.
- Middle-age Pulsars (100-400ky) should all be "Geminga-like"
- Suggests that HAWC could even identify un-aligned Pulsars that are poorly aligned for radio detection.



ATNF Name	Dec. (°)	Distance (kpc)	Age (kyr)	Spindown Lum. (erg s^{-1})	Spindown Flux (erg s^{-1} kpc^{-2})	2HWC
J0633+1746	17.77	0.25	342	3.2e34	4.1e34	2HWC J0631+169
B0656+14	14.23	0.29	111	3.8e34	3.6e34	2HWC J0700+143
B1951+32	32.87	3.00	107	3.7e36	3.3e34	—
J1740+1000	10.00	1.23	114	2.3e35	1.2e34	—
J1913+1011	10.18	4.61	169	2.9e36	1.1e34	2HWC J1912+099
J1831-0952	-9.86	3.68	128	1.1e36	6.4e33	2HWC J1831-098
J2032+4127	41.45	1.70	181	1.7e35	4.7e33	2HWC J2031+415
B1822-09	-9.58	0.30	232	4.6e33	4.1e33	—
B1830-08	-8.45	4.50	147	5.8e35	2.3e33	—
J1913+0904	9.07	3.00	147	1.6e35	1.4e33	—
B0540+23	23.48	1.56	253	4.1e34	1.4e33	—

These objects are not spatially coincident with X-Ray PWN, or SNR!

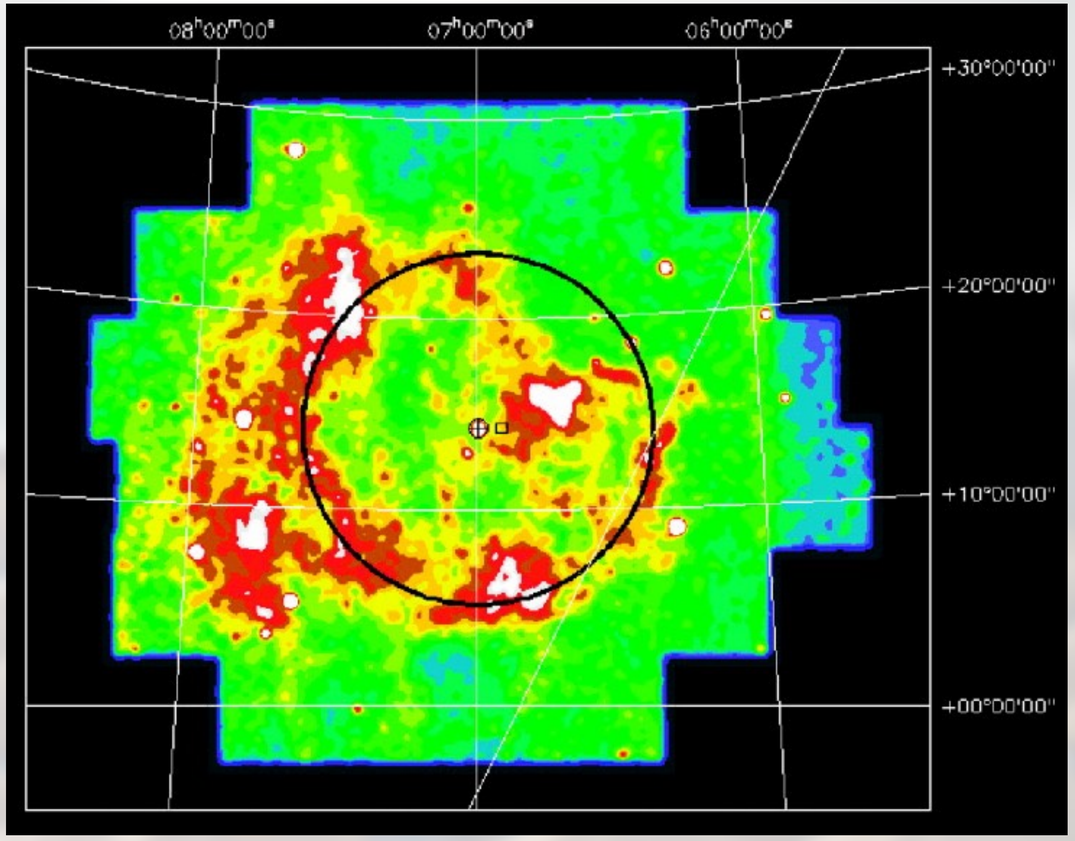
Geminga PWN



Posselt et al, arXiv:1611.03496

Chandra

B0565+14 SNR - “Monogem Ring”



Thorsett et al, ApJ 592:L71-L73, 2003

ROSAT

Search for this new class of objects

- Middle-aged pulsars
  - Age >20-100ky ~= cooling time - Halo in steady state
  - Size ~10 pc
  - Flux ~Spin-down power/d^2
  - Very large extended objects when source is nearby
- Issues:
  - HAWC only observes declinations within +/-40 deg of instrument latitude, 19^{o}N.
  - Galactic plane is a confused region with many extended emitters. Hard to pull out extended sources.
- Two Approaches:
  - 1 - Look at ATNF (&Fermi) catalog of and search for extended emission based on known distance, P-dot.
  - 2 - Search HAWC data for extended Halos on several spatial scales (Point source, 0.5^o, 1.0^o, 2.0^o) - “Blind Search”

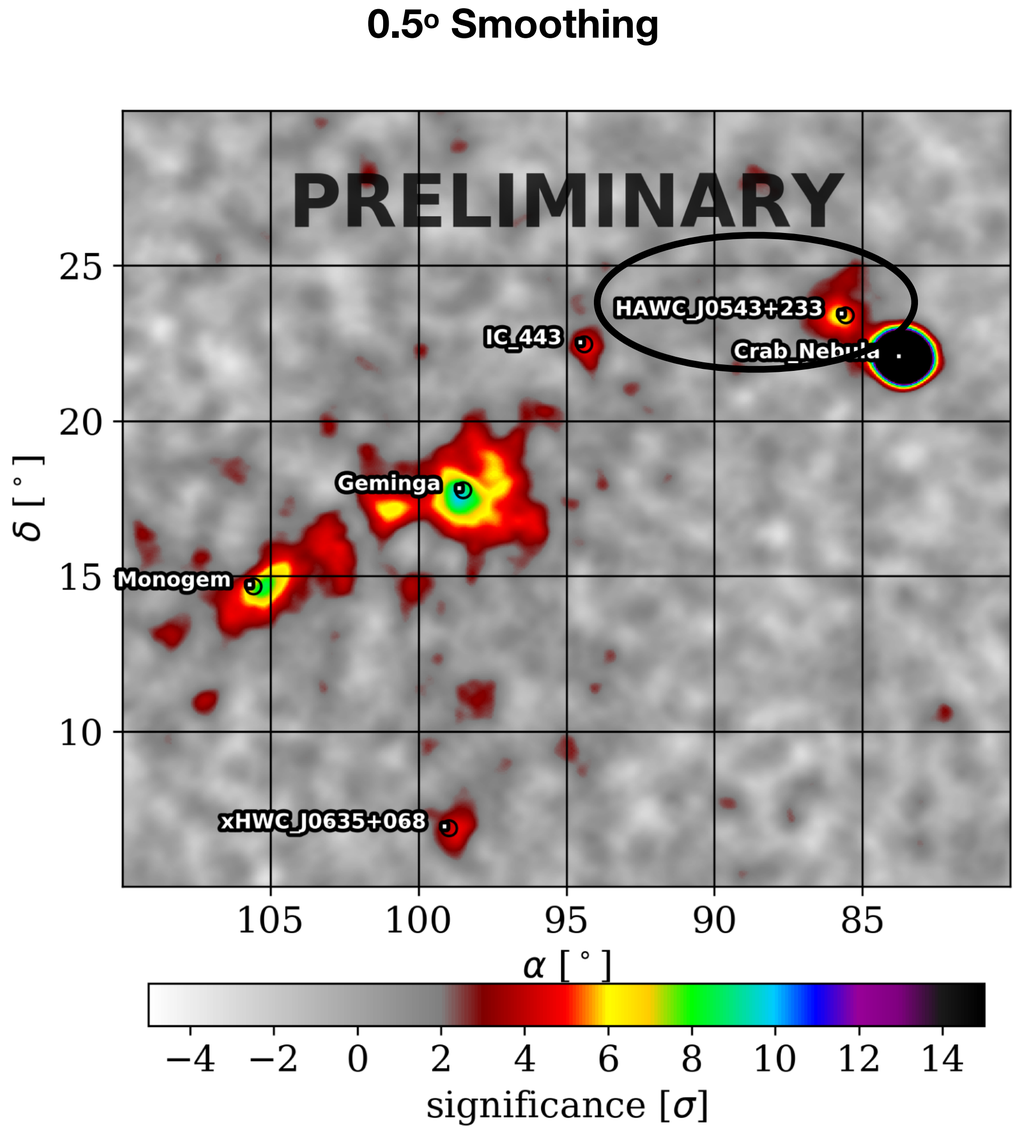
ATNF Catalog

ATNF catalog selecting pulsars
not in HAWC visible plan (l=[0,90] && b=[-4,4]), and in HAWC favorable declination [-11°,49°]
Age in [40ky,1000ky]

#	NAME	PSRJ	RAJ (hms)	DECJ (dms)	P0 (s)	Gl (deg)	Gb (deg)	AGE (Yr)	DIST (kpc)	EDOT (ergs/s)	EDOT/DIST^2
1	J0633+1746	J0633+1746	06:33:54.1	+17:46:12.9	0.237099	195.134	4.266	3.42e+05	0.19	3.25e+34	8.864266e+35
2	B0656+14	J0659+1414	06:59:48.1	+14:14:21.5	0.384891	201.108	8.258	1.11e+05	0.29	3.81e+34	4.518430e+35
3	J1740+1000	J1740+1000	17:40:25.9	+10:00:06.3	0.154087	34.011	20.268	1.14e+05	1.23	2.32e+35	1.520259e+35
4	J0633+0632	J0633+0632	06:33:44.2	+06:32:34.9	0.297395	205.093	-0.932	5.92e+04	1.35	1.19e+35	6.584362e+34
5	J0631+1036	J0631+1036	06:31:27.5	+10:37:02.5	0.287800	201.219	0.450	4.36e+04	2.10	1.73e+35	3.854875e+34
6	J0538+2817	J0538+2817	05:38:25.0	+28:17:09.1	0.143158	179.719	-1.686	6.18e+05	1.30	4.94e+34	2.899408e+34
7	B0611+22	J0614+2229	06:14:17.1	+22:30:36	0.334960	188.785	2.400	8.93e+04	1.74	6.24e+34	2.047827e+34
8	B0540+23	J0543+2329	05:43:09.6	+23:29:05	0.245975	184.363	-3.318	2.53e+05	1.56	4.09e+34	1.684747e+34
9	J1846+0919	J1846+0919	18:46:26.0	+09:19:46	0.225551	40.693	5.342	3.60e+05	1.53	3.41e+34	1.452433e+34
10	J0357+3205	J0357+3205	03:57:52.5	+32:05:25	0.444104	162.760	-16.006	5.40e+05	0.83	5.88e+33	8.564378e+33
11	B0919+06	J0922+0638	09:22:14.0	+06:38:23.3	0.430627	225.420	36.392	4.97e+05	1.10	6.79e+33	5.619835e+33
12	J1816-0755	J1816-0755	18:16:24.5	-07:55:22.5	0.217643	21.867	4.092	5.32e+05	3.13	2.48e+34	2.551828e+33
13	J0627+0706	J0627+0706	06:27:44.2	+07:06:12.7	0.475874	203.907	-1.993	2.53e+05	2.29	1.09e+34	2.097595e+33
14	J1839+15	J1839+15	18:39:00	+15:00:00	0.549161	45.014	9.477	3.33e+05	3.43	6.23e+33	5.269913e+32
15	J0658+0022	J0658+0022	06:58:15.2	+00:22:35.3	0.563295	213.374	1.688	9.75e+05	2.36	2.02e+33	3.590922e+32
16	J1954+3852	J1954+3852	19:54:01.0	+38:52:15.8	0.352933	74.043	5.699	8.47e+05	4.67	5.93e+33	2.705318e+32

- To do this guided search correctly, we want to optimize analysis assuming a canonical size and distance to optimize the detection probability.
- Not ready to report the results here.

HAWC J0543+233



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HAWC detection of TeV emission near PSR B0540+23

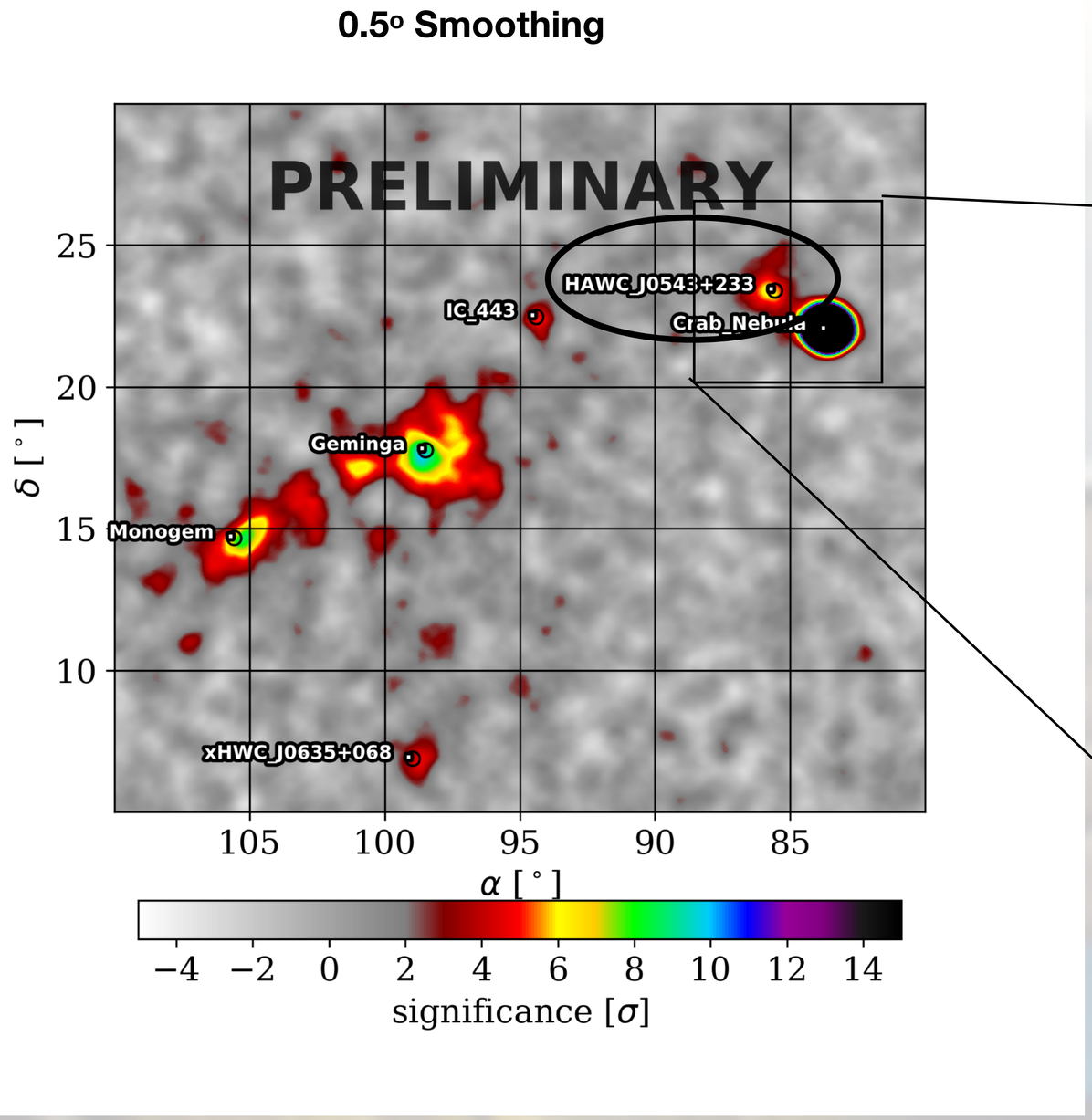
ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
*on **9 Nov 2017; 23:11 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

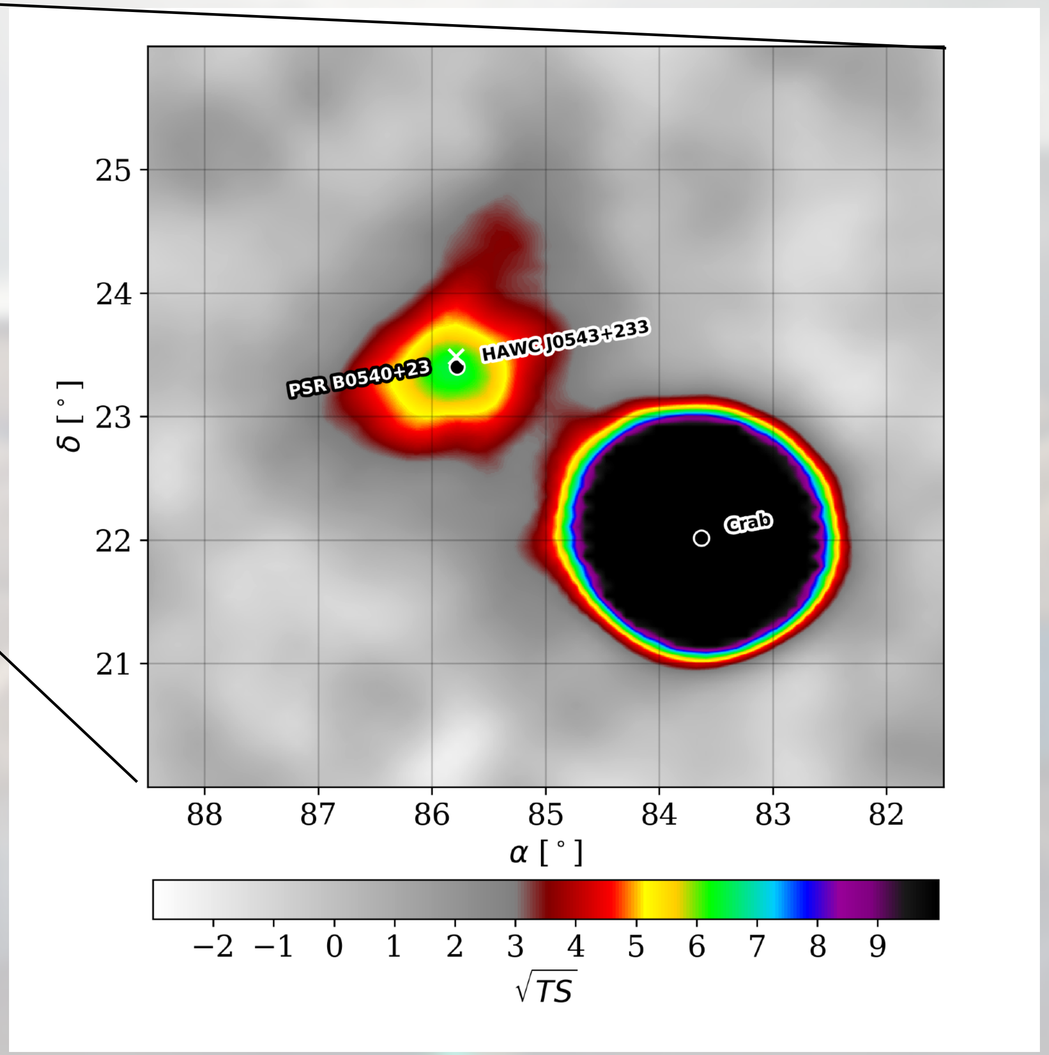
Subjects: Gamma Ray, TeV, VHE, Pulsar

Tweet Recommend 5

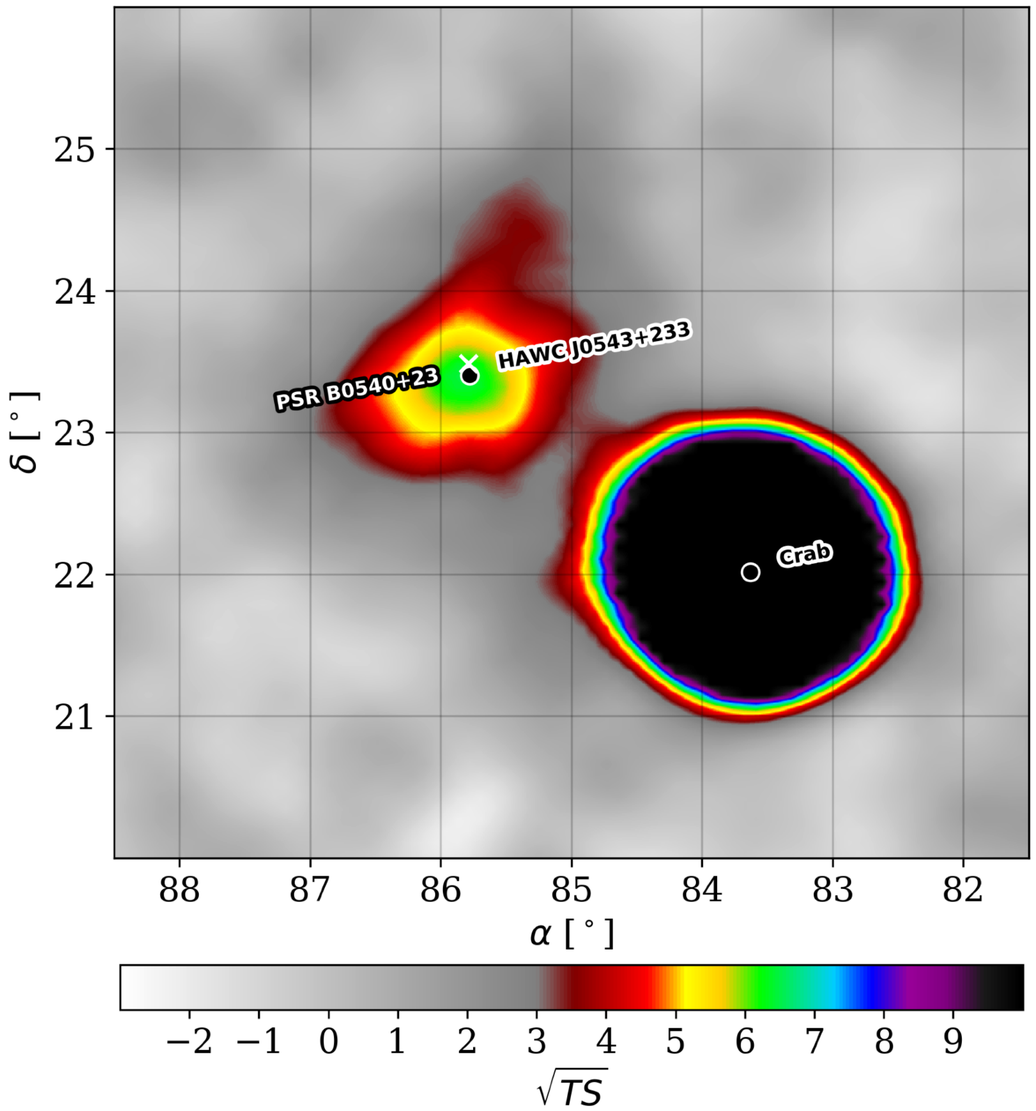
The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0543+233. It was discovered in a search for extended sources of radius 0.5° in a dataset of 911 days (ranging from November 2014 to August 2017) with a test statistic value of 36 (6σ pre-trials), following the method presented in Abeysekara et al. 2017, ApJ, 843, 40. The measured J2000.0 equatorial position is RA=85.78°, Dec=23.40° with a statistical uncertainty of 0.2°. HAWC J0543+233 was close to passing the selection criteria of the 2HWC catalog (Abeysekara et al. 2017, ApJ, 843, 40, see HAWC J0543+233 in 2HWC map), which it now fulfills with the additional data.
HAWC J0543+233 is positionally coincident with the pulsar PSR B0540+23 (Edot = 4.1e+34 erg s-1, dist = 1.56 kpc, age = 253 kyr). It is the third low Edot, middle-aged pulsar announced to be detected with a TeV halo, along with Geminga and B0656+14. It was predicted to be one of the next such detection by HAWC by Linden et al., 2017, arXiv:1703.09704.
Using a simple source model consisting of a disk of radius 0.5°, the measured spectral index is -2.3 ± 0.2 and the differential flux at 7 TeV is (7.9 ± 2.3) × 10^-15 TeV-1 cm-2 s-1. The errors are statistical only. Further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

HAWC J0543+233



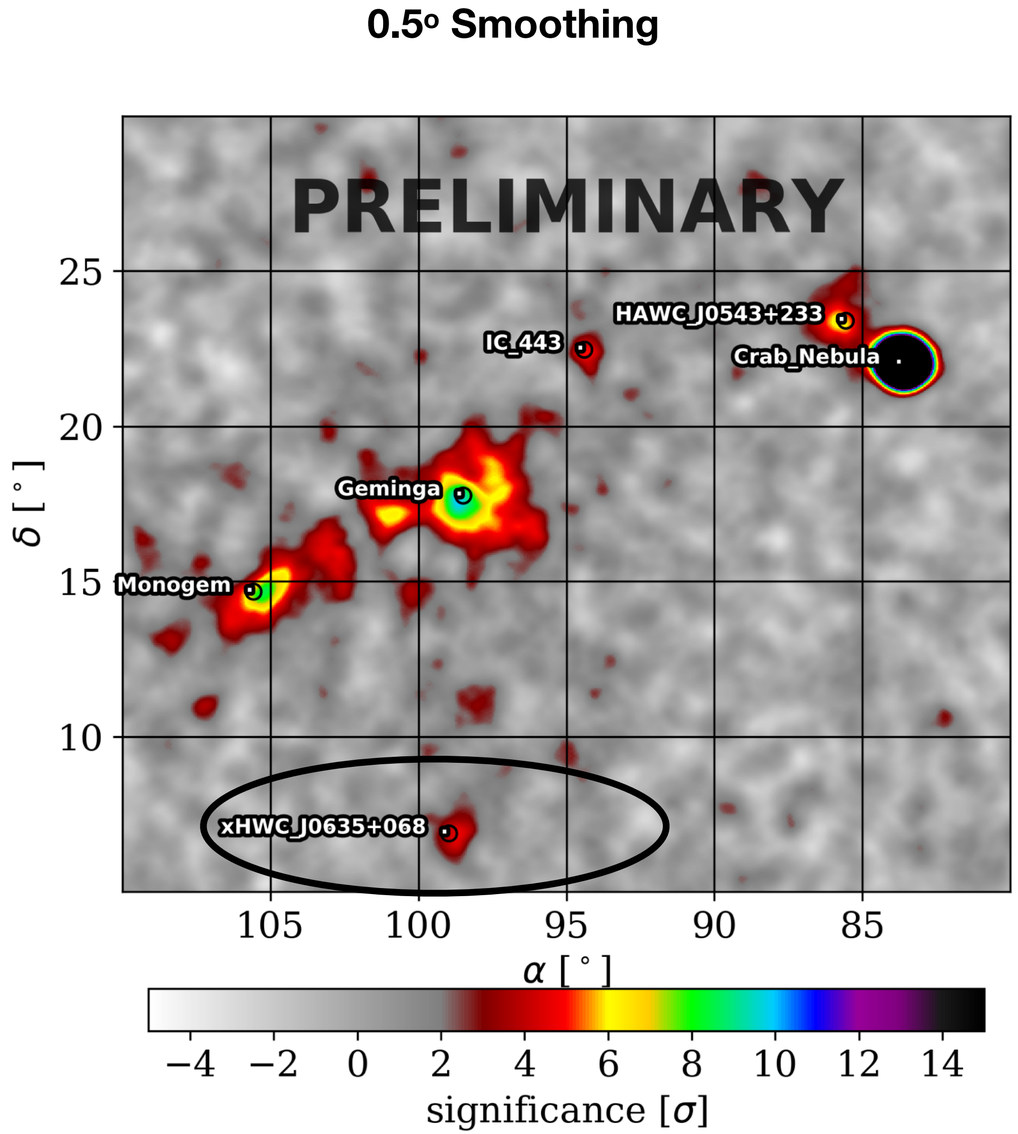


HAWC J0543+233



- Extended Source HAWC J0543+233
  - TS = 36 when reported
  - Extended with ~0.5º
  - Spectral Index = -2.3+/-0.2
  - Flux = (7.9 +/- 2.3) 10e-15 TeV-1 cm-2 s-1 @ 7 TeV
- Coincident with ATNF B0540+23
  - Age = 253ky
  - Distance = 1.56kpc
  - Edot = 4.1+34 erg s-1

HAWC J0635+070



HAWC detection of TeV source HAWC J0635+070

ATel #12013; *Chad Brisbois (Michigan Technological University), Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andrew Smith (University of Maryland) on behalf of the HAWC collaboration*
*on **6 Sep 2018; 14:47 UT***
Credential Certification: Colas Riviere (riviere@umd.edu)

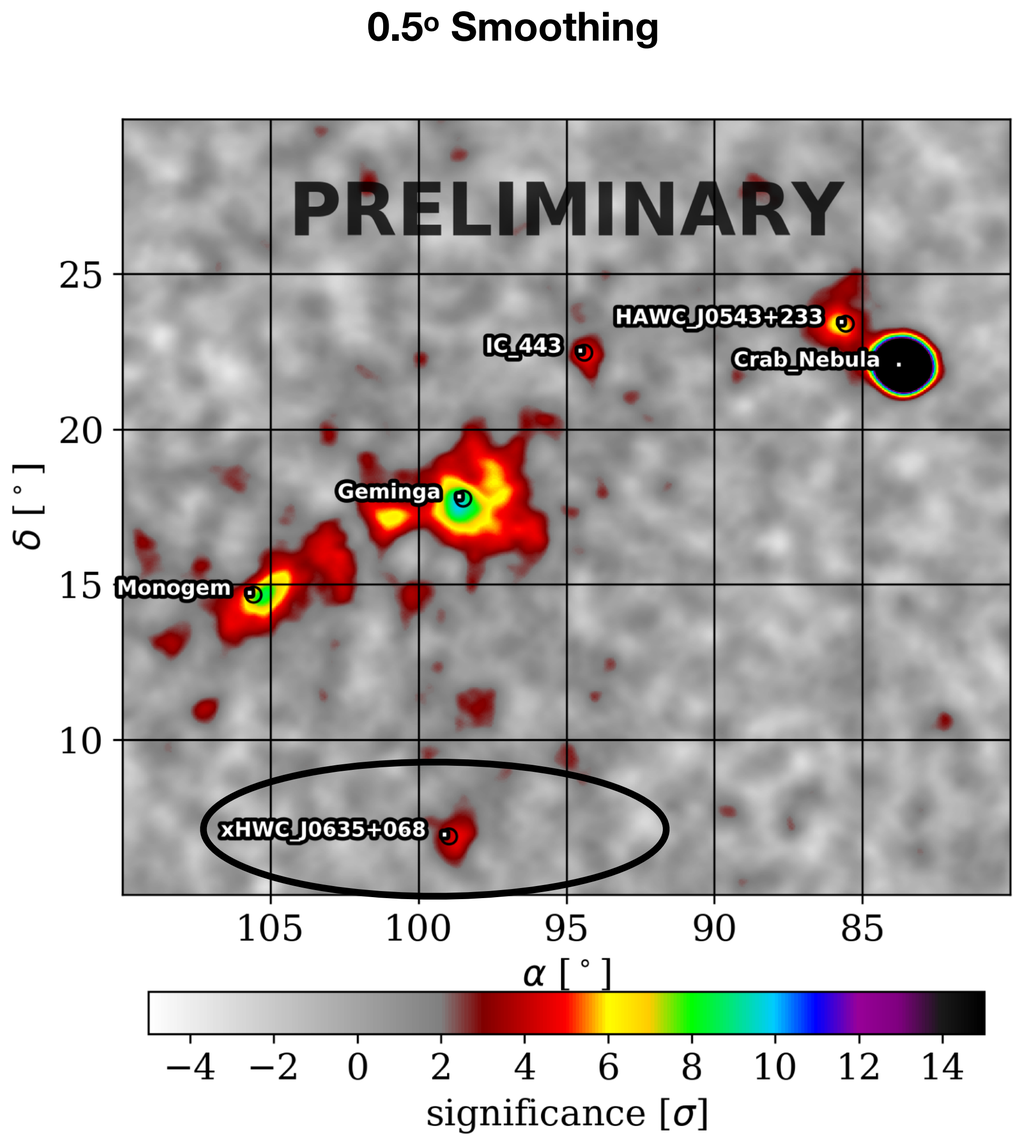
Subjects: Gamma Ray, TeV, VHE, Pulsar

The High Altitude Water Cherenkov (HAWC) collaboration reports the discovery of a new TeV gamma-ray source HAWC J0635+070. It was discovered in a search for extended sources covering 1128 days of HAWC observations with a test statistic value of 27 (>5σ pre-trials), following the method presented in [Abeysekara et al. 2017, ApJ, 843, 40]. Its significance in the 2HWC data set excluded it from being included in the catalog (~3.5σ pre-trials), but with the addition of ~600 more days of data it now satisfies that criterion. The best-fit J2000.0 equatorial position is RA=98.71±0.20°, Dec=7.00±0.22°, with a Gaussian 1-sigma extent of 0.65°±0.18°.

The spectral energy distribution is well-fit by a power law with spectral index -2.15±0.17. The differential flux at 10 TeV is (8.6 ± 3.2) × 10^-15 TeV-1 cm-2 s-1. All errors are statistical only; further morphological and spectral analysis as well as studies of the systematic uncertainty are ongoing.

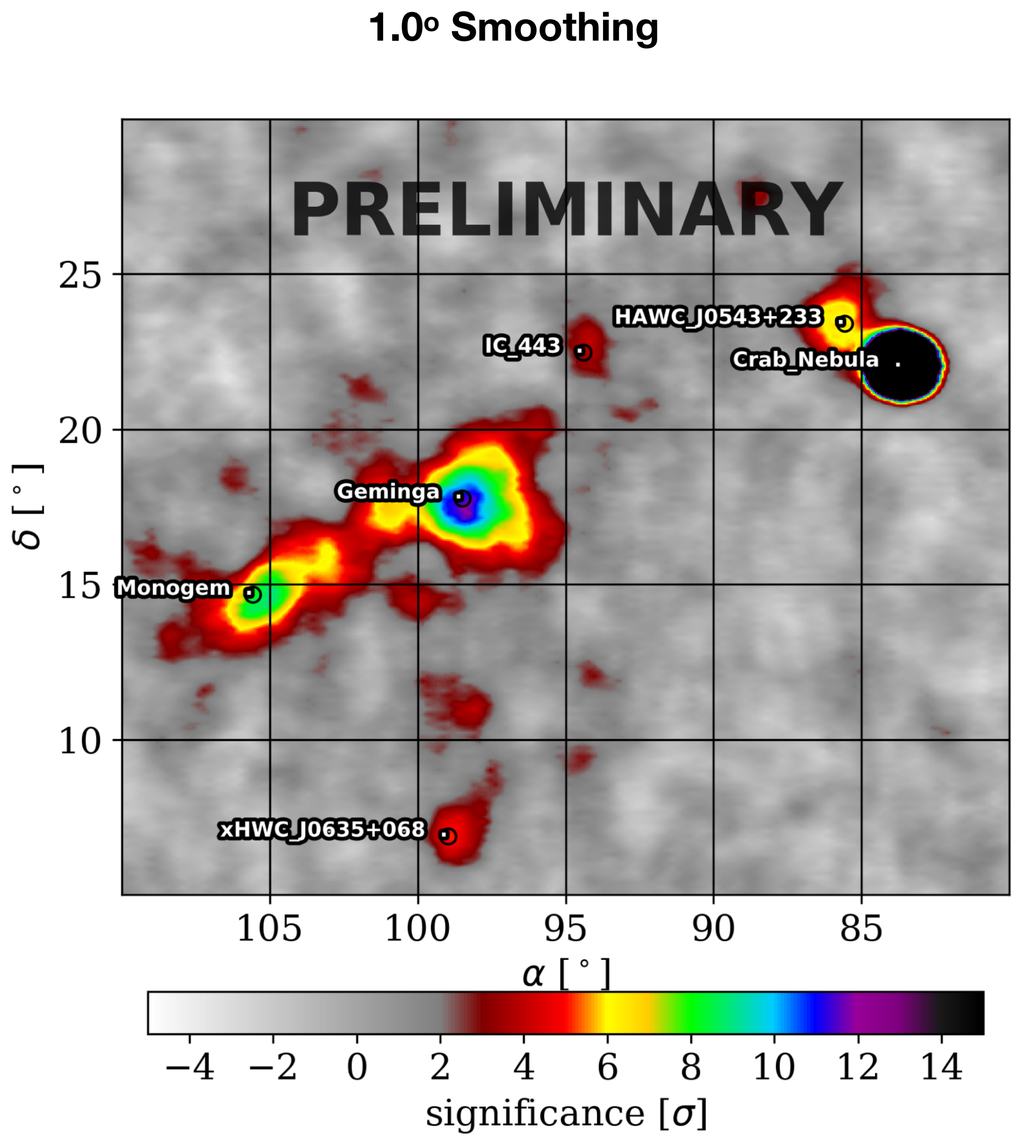
Given its spectrum and morphology, we believe HAWC J0635+070 may be the TeV halo of the pulsar PSR J0633+0632 (Edot = 1.2e+35 erg s-1, dist = 1.35 kpc, age = 59 kyr, unknown proper motion [Manchester et al., 2005, AJ, 129]). The gamma-ray spectrum and morphology is compatible with a "Geminga-like" TeV Halo [Abeysekara et al. 2017, Science, 358, 911; Linden et al., 2017, PRD, 96, 103016]. We encourage follow-up observations at other wavelengths.

HAWC J0635+070



- Extended Source HAWC J0635+07
  - TS = 27
  - Extended with 0.65°+/-0.18°
  - Spectral Index = -2.15+/-0.17
  - Flux = (8.6 +/- 3.2) 10e-15 TeV-1 cm-2 s-1 @ 10 TeV
- Coincident with ATNF PSR J0633+0632
  - Age = 59ky
  - Distance = 1.35kpc
  - Edot = 1.2e+35 erg s-1
  - Size is compatible with a “Gaminga-Like” object.

HAWC J0635+070



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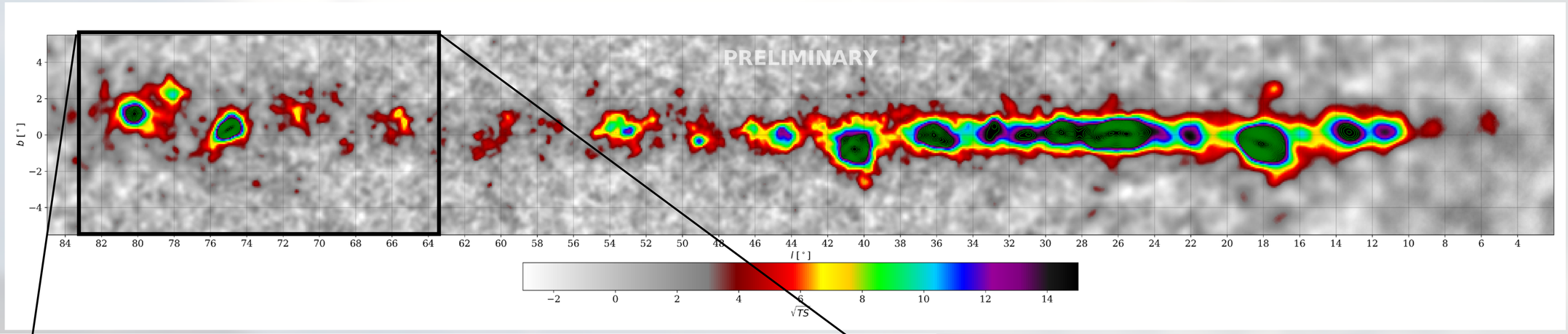
ATNF Catalog

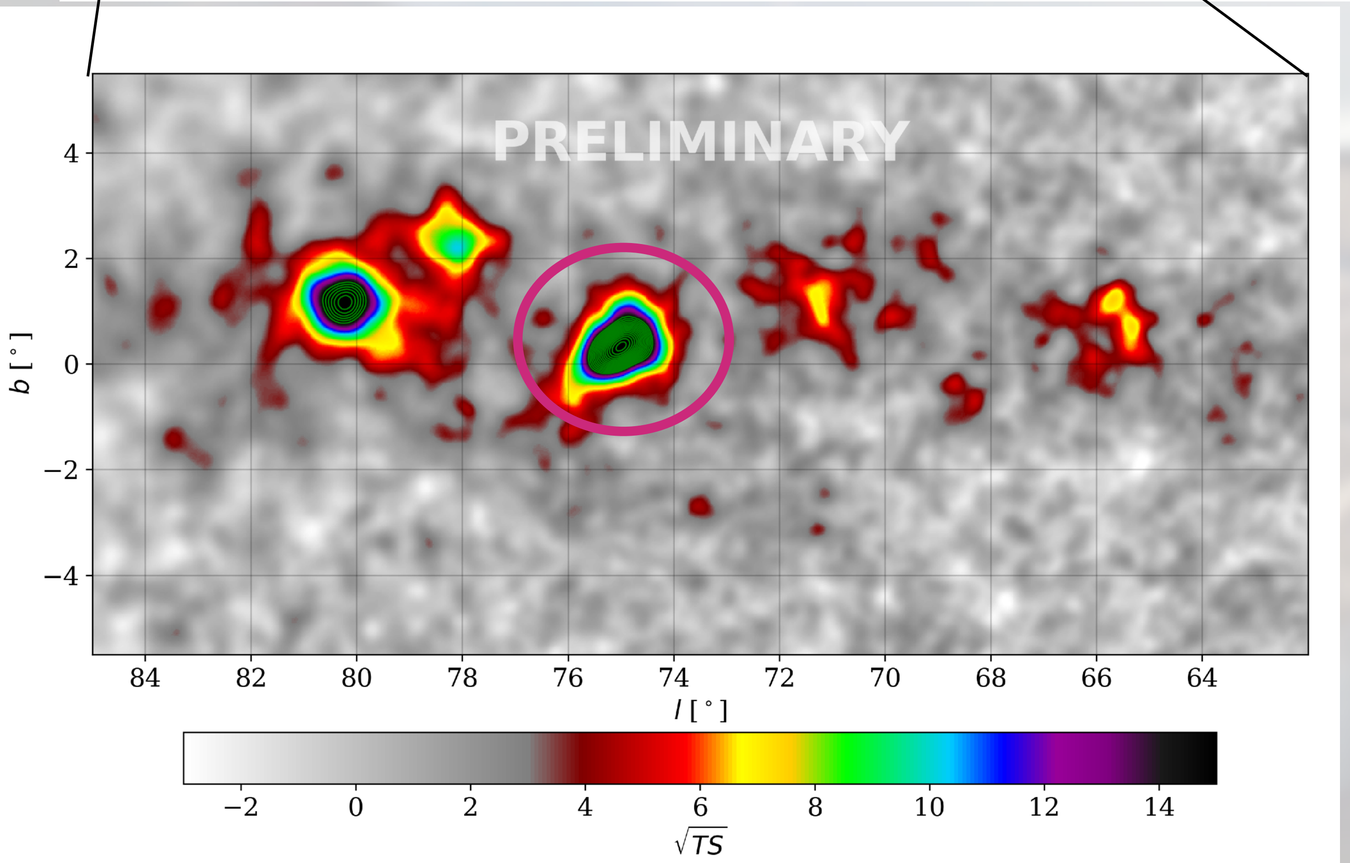
ATNF catalog selecting pulsars
not in HAWC visible plan (l=[0,90] && b=[-4,4]), and in HAWC favorable declination [-11°,49°]
Age in [40ky,1000ky]

#	NAME	PSRJ	RAJ (hms)	DECJ (dms)	P0 (s)	Gl (deg)	Gb (deg)	AGE (Yr)	DIST (kpc)	EDOT (ergs/s)	EDOT/DIST^2
1	J0633+1746	J0633+1746	06:33:54.1	+17:46:12.9	0.237099	195.134	4.266	3.42e+05	0.19	3.25e+34	8.864266e+35
2	B0656+14	J0659+1414	06:59:48.1	+14:14:21.5	0.384891	201.108	8.258	1.11e+05	0.29	3.81e+34	4.518430e+35
3	J1740+1000	J1740+1000	17:40:25.9	+10:00:06.3	0.154087	34.011	20.268	1.14e+05	1.23	2.32e+35	1.520259e+35
4	J0633+0632	[illegible]2	06:33:44.2	+06:32:34.9	0.297395	205.093	-0.932	5.92e+04	1.35	1.19e+35	6.584362e+34
5	J0631+1036	J0631+1036	06:31:27.5	+10:37:02.5	0.287800	201.219	0.450	4.36e+04	2.10	1.73e+35	3.854875e+34
6	J0538+2817	J0538+2817	05:38:25.0	+28:17:09.1	0.143158	179.719	-1.686	6.18e+05	1.30	4.94e+34	2.899408e+34
7	B0611+22	J0614+2229	06:14:17.1	+22:30:36	0.334960	188.785	2.400	8.93e+04	1.74	6.24e+34	2.047827e+34
8	B0540+23	[illegible]9	05:43:09.6	+23:29:05	0.245975	184.363	-3.318	2.53e+05	1.56	4.09e+34	1.684747e+34
9	J1846+0919	J1846+0919	18:46:26.0	+09:19:46	0.225551	40.693	5.342	3.60e+05	1.53	3.41e+34	1.452433e+34
10	J0357+3205	J0357+3205	03:57:52.5	+32:05:25	0.444104	162.760	-16.006	5.40e+05	0.83	5.88e+33	8.564378e+33
11	B0919+06	J0922+0638	09:22:14.0	+06:38:23.3	0.430627	225.420	36.392	4.97e+05	1.10	6.79e+33	5.619835e+33
12	J1816-0755	J1816-0755	18:16:24.5	-07:55:22.5	0.217643	21.867	4.092	5.32e+05	3.13	2.48e+34	2.551828e+33
13	J0627+0706	J0627+0706	06:27:44.2	+07:06:12.7	0.475874	203.907	-1.993	2.53e+05	2.29	1.09e+34	2.097595e+33
14	J1839+15	J1839+15	18:39:00	+15:00:00	0.549161	45.014	9.477	3.33e+05	3.43	6.23e+33	5.269913e+32
15	J0658+0022	J0658+0022	06:58:15.2	+00:22:35.3	0.563295	213.374	1.688	9.75e+05	2.36	2.02e+33	3.590922e+32
16	J1954+3852	J1954+3852	19:54:01.0	+38:52:15.8	0.352933	74.043	5.699	8.47e+05	4.67	5.93e+33	2.705318e+32

- To do this guided search correctly, we want to optimize analysis assuming a canonical size and distance to optimize the detection probability.
- Not ready to report the results here.

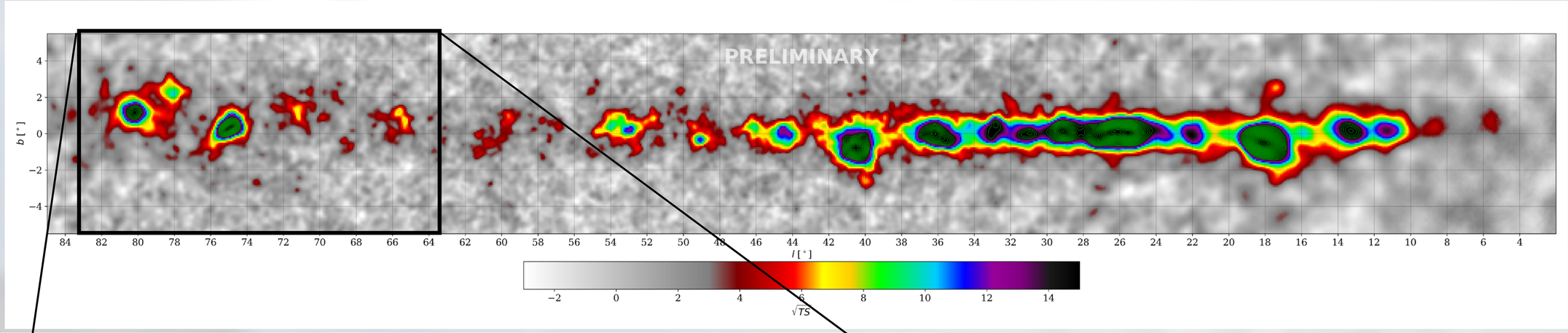
A Young PWN in the Cygnus region

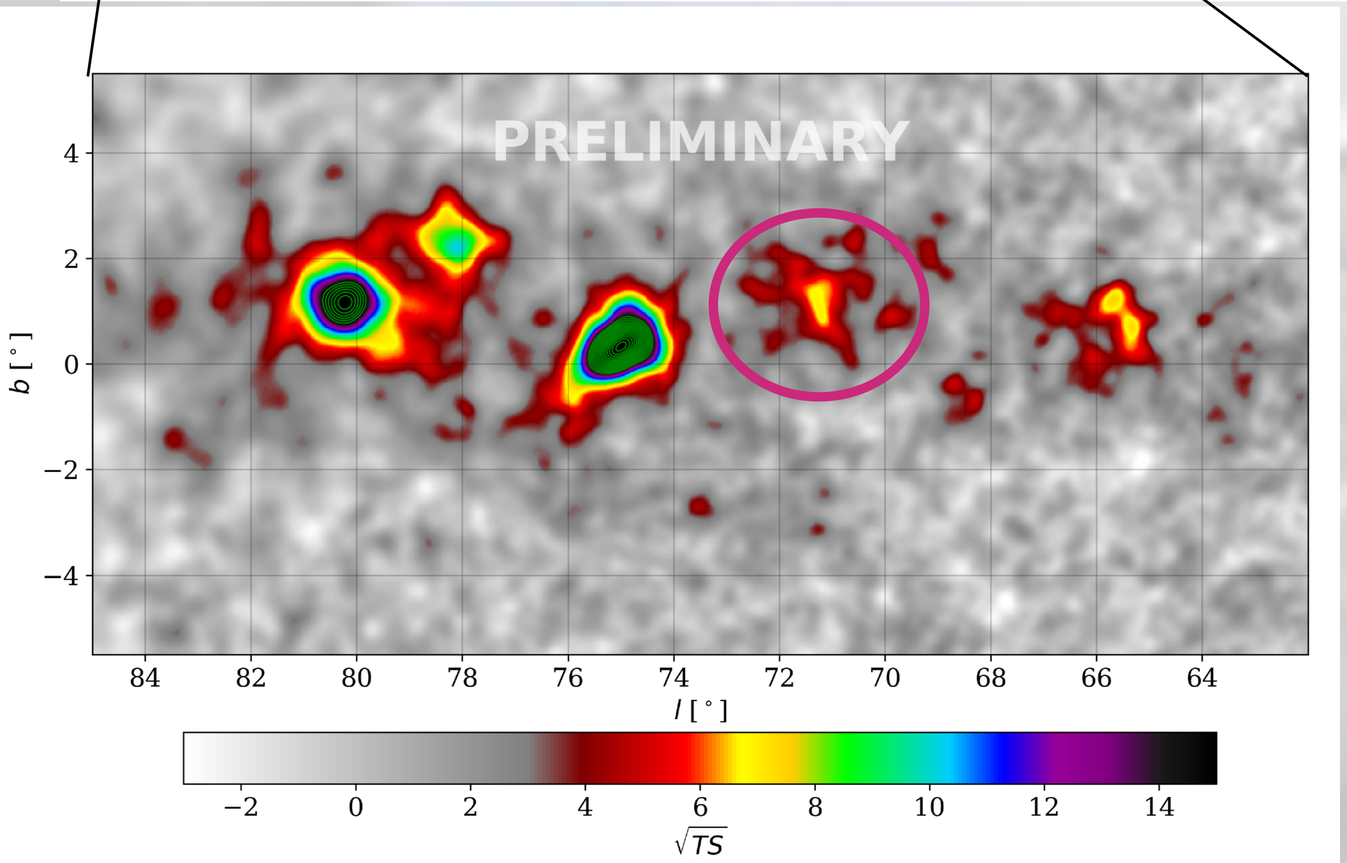




- 2HWC 2019+368, extended source coincident with PSR J2021+3651.
  - Age = 17.2ky
  - Distance = 1.8kpc
  - Edot = 3.38e+36 erg s-1
  - Very bright, well known TeV source

Another Young PWN in the Cygnus region





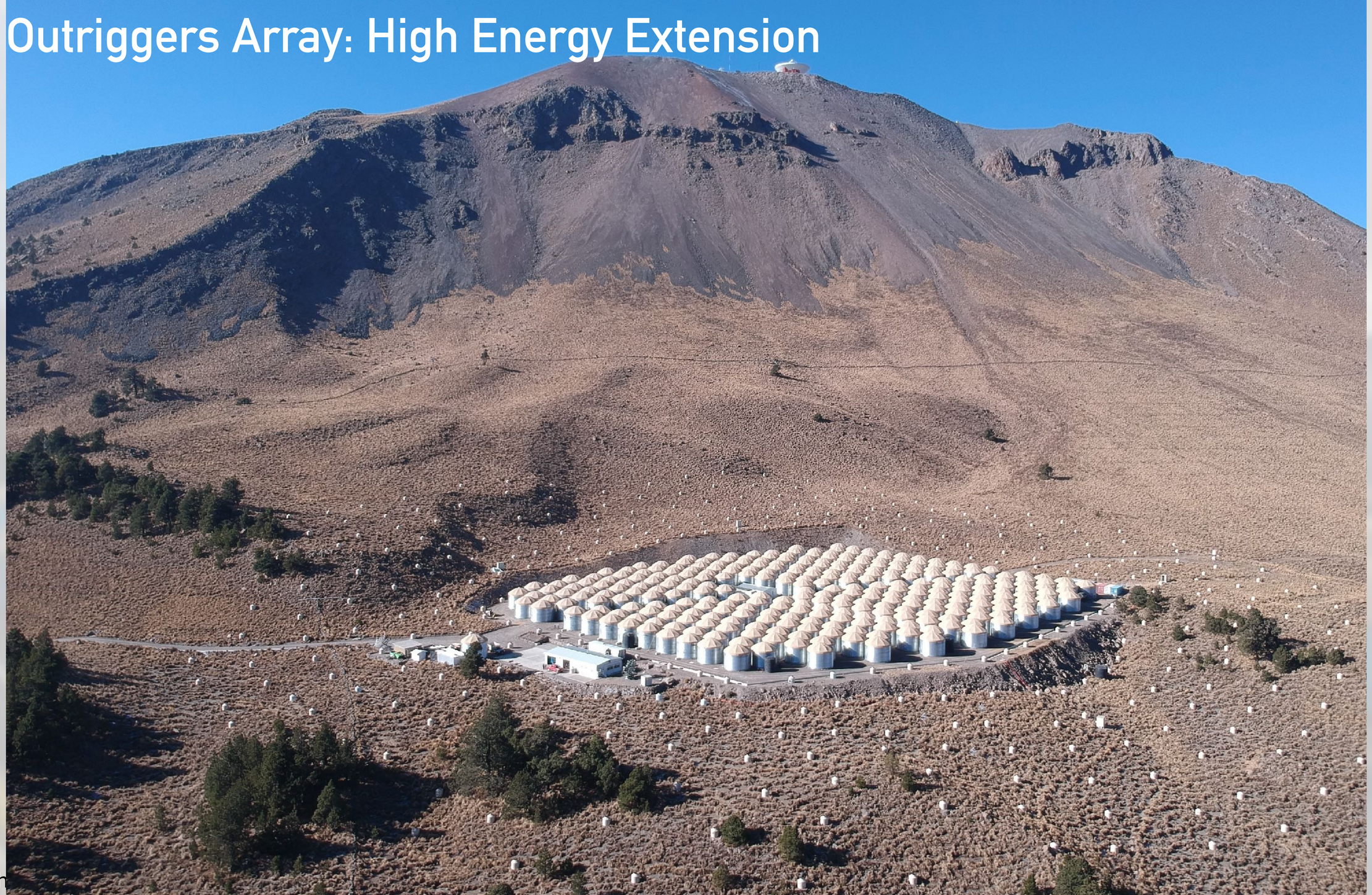
- 2HWC 2006+341, extended source coincident with PSR J2004+3429.
  - Age = 18.5ky
  - Distance = 10.78kpc
  - Edot = 1.85e+34 erg s-1

Diffusion fits to 6 Pulsar Halos

- Performed diffusion fit to all reported sources using the technique described in the Science paper using the 1128 day data set.
- No advection is considered.

Source	Diffusion Radius (degrees)	Diffusion Constant (10^{27} cm^2/s)	ATNF Distance (kpc)	ATNF Pulsar age (kyr)
Geminga	6.0±0.8	5.2±1.3	0.250	342
Monogem	5.3±0.9	5.4±1.8	0.288	110
2HWC J2019+368	0.84±0.05	5.3±0.6	1.8	17.2
HAWC J0635+068	2.6±1.3	30±25	1.35	59
HAWC J0543+233	2.3±0.4	30±10	1.56	253
2HWC J2006+341*	4.4±1.0	(5±2)10^3	10.8*	18.5*

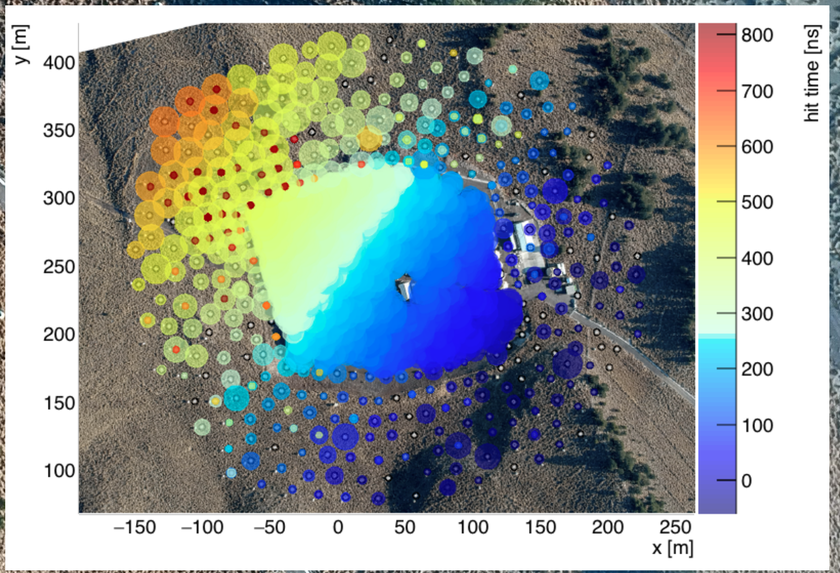
Outriggers Array: High Energy Extension



Outriggers Array: High Energy Extension

N

- 350 small tanks in addition to the 300 large tanks.
- Improve core localization for showers near the main array.
- x4 effective area at high energy.
- 100% taking data since summer.



Conclusion

- HAWC is operating reliably and producing a wealth of data.
  - Operation funding by NSF for an additional 5 years.
- TeV Halos have become a new source class.
- Improvements in HAWC's sensitivity at >10TeV, along with additional data will undoubtably lead to additional discoveries.
  - Outriggers
  - Improvements to gamma/hadron separation and other reconstruction advances
- ATNF survey will be done soon
- Potential for "Hidden" pulsars?

Thank You