Exploring Extended Sources with VERITAS

Columbia Nevis Labs REU Program, Summer 2023
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Cosmic Rays

Charged particles accelerated to relativistic speeds

Spectrum is very well known (flux versus energy), but interact with IMB

EM - fast moving highly magnetized objects accelerate these particles

EM - magnetic Shock fronts accelerate through diffusive shock acceleration

Grav - supernovae or black holes use their immense gravitational fields to accelerate charged particles

Mechanisms upon which they are accelerated is still a topic of discussion

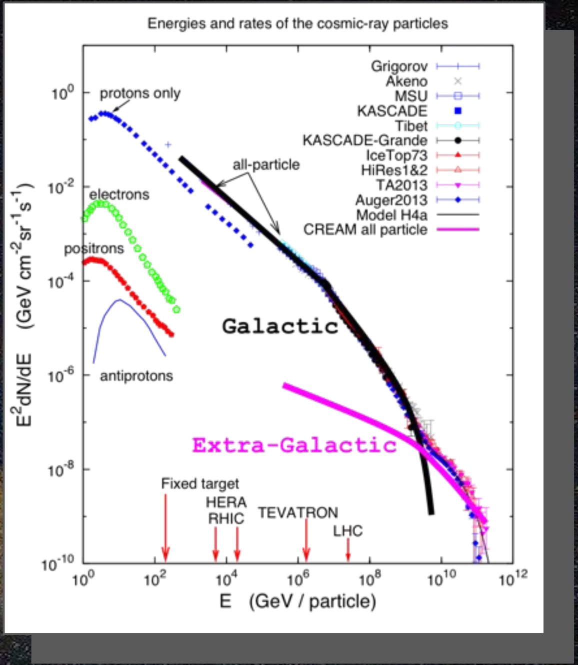


Image Credit: Ice Cube

γ-Ray Production

Produced when high energy cosmic rays interact with particles around them

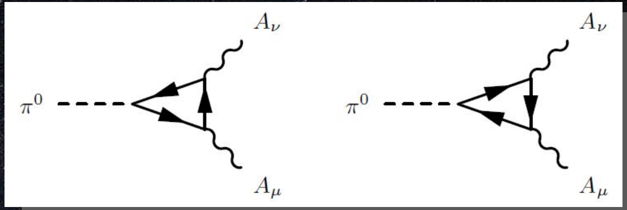
hadronic - Neutral Pion Decay from PP interaction

leptonic - Inverse Compton Scattering

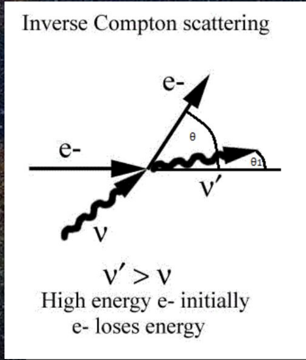
Able to be measured

Non-thermal

Can use SED Models to distinguish between production mechanisms



hadronic case
Image Credit: Researchgate



leptonic case
Image Credit:
venables.asu.edu/quant/proj/compton.html

PeVatrons

Cosmic particle accelerators that accelerate to >1PeV!

Some of the least well understood objects in the universe

Only a handful of candidates for pevatrons

Interesting new physics that reach beyond what we can do even in the largest accelerators on Earth

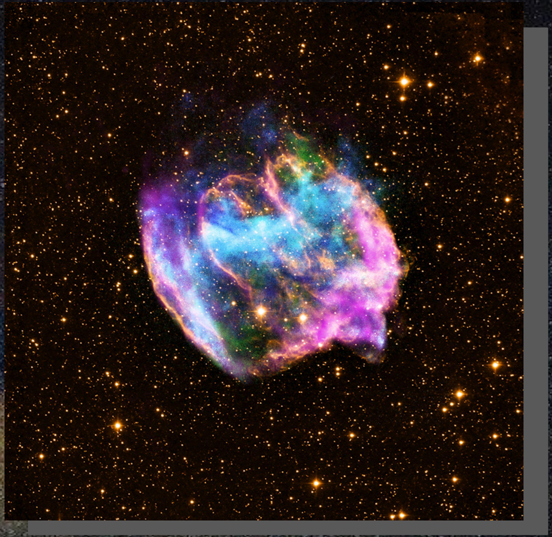


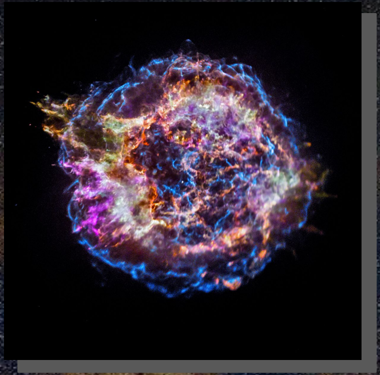
Image Credit: Chandra

Supernova Remnants and Pulsar Wind Nebulae

SNR - Resulting structure when a supernova explodes

PWN - nebula with stellar winds powered by a central pulsar

Both SNRs and PWNs are pevatron candidates



Cass A
Image Credit: NASA

Vela PWN
Image Credit: NASA IXPE

Motivation - LHAASO Sources

Brand new detector in Daocheng, Sichuan, China and is a continuous full sky detector

Made up of three different arrays, current run uses only two (WCDA, KM2A)

WCDA - Water Cherenkov Detector Array (GeV-TeV)

KM2A - Kilometer squared electron muon Detector Array (TeV-PeV)

Covers ~4 decades of energy up to >1PeV

In first catalog added 90 new gamma-ray sources, 43 potential PeV sources “PeVatrons”

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}	Asso.(Sep.[°])
	KM2A						<0.32			
1LHAASO J1857+0203u	KM2A	284.38	2.06	0.07	0.28±0.03	475.2	1.78±0.10	3.31±0.10	112.4	HESS J1858+020 (0.21)
	WCDA	284.50	1.98	0.11	0.19±0.03	187.7	1.68±0.43	2.46±0.11		
1LHAASO J1858+0330	KM2A*	284.59	3.51	0.12	0.43±0.04	299.3	1.56±0.10	3.78±0.15		
	WCDA	284.79	3.70	0.34	0.52±0.08	114.5	2.84±0.63	2.63±0.10		
1LHAASO J1902+0648	WCDA	285.58	6.80	0.10	<0.15	46.2	0.45±0.13	2.39±0.18		
	KM2A						<0.06			
1LHAASO J1906+0712	WCDA	286.56	7.20	0.21	0.21±0.05	57.8	1.01±0.25	2.72±0.15		
	KM2A						<0.19			
1LHAASO J1907+0826	WCDA*	286.96	8.44	0.31	0.43±0.08	51.8	1.34±0.29	2.62±0.14		2HWC J1907+084* (0.18)
	KM2A						<0.29			
1LHAASO J1908+0615u	KM2A	287.05	6.26	0.03	0.36±0.01	3410.6	6.86±0.16	2.82±0.03	912.0	MGRO J1908+06 (0.07)
	WCDA	287.05	6.26	0.05	0.43±0.02	2070.2	7.97±0.54	2.42±0.03		
1LHAASO J1910+0516*	KM2A	287.55	5.28	0.15	<0.30	74.0	0.57±0.08	3.15±0.18		SS 433 w1 (0.26)
	WCDA	287.88	5.07	0.38	0.29±0.09	36.0	0.86±0.29	2.54±0.15		
1LHAASO J1912+1014u	WCDA	288.22	10.25	0.08	0.36±0.03	585.6	3.07±0.24	2.68±0.06		HESS J1912+101 (0.10)
	KM2A*	288.38	10.50	0.13	0.50±0.04	346.0	1.52±0.10	3.26±0.11	68.9	
1LHAASO J1913+0501	KM2A	288.28	5.03	0.11	<0.10	96.0	0.45±0.06	3.30±0.18		SS 433 e1 (0.15)
	WCDA						<0.37			
1LHAASO J1914+1150u	KM2A*	288.73	11.84	0.09	0.21±0.04	259.2	0.79±0.06	3.41±0.13	26.0	2HWC J1914+117* (0.13)
	WCDA*	288.81	11.74	0.14	0.33±0.04	151.3	1.09±0.12	2.34±0.07		
1LHAASO J1919+1556	KM2A	289.78	15.93	0.32	<0.44	37.2	0.24±0.04	4.71±0.53		3HWC J1918+159(0.09)
	WCDA						<0.03			
1LHAASO J1922+1403	WCDA	290.70	14.06	0.07	0.18±0.02	256.0	1.37±0.10	2.62±0.07		W 51 (0.13)
	KM2A	290.73	14.11	0.07	<0.10	158.8	0.45±0.04	3.79±0.20	14.4	

Cao et Al. 2023

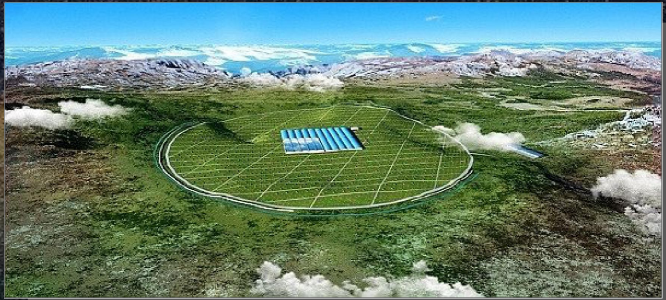


Image Credit: IHEP

Motivation - LHAASO Sources

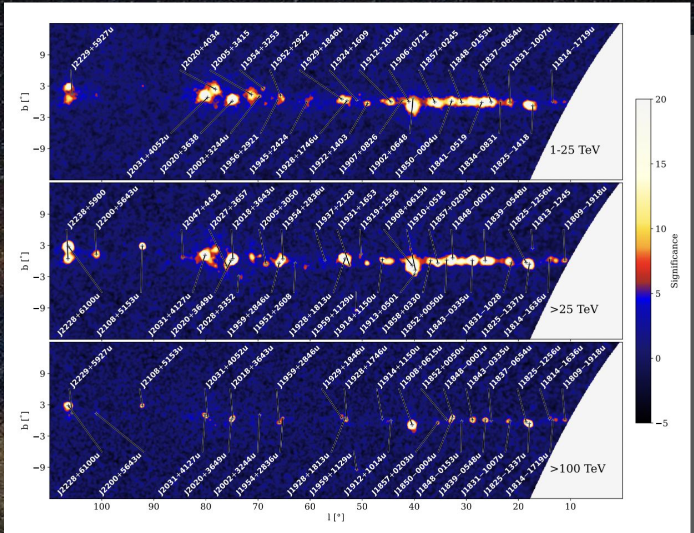
These new VHE and UHE sources can provide insight into new physics of the violent universe

Answer the question “Where do the highest energy cosmic rays come from?”

Answer the question “What mechanisms produce these cosmic rays?”

Some of the new sources are extended sources

Some known sources that are connected to the LHAASO sources



Cao et al. 2023

Motivation - HESS J1857+026 (Patriella et al. 2021)

MAGIC previously this source to a PWN with two distinct sources

Did a radio study and found a superbubble around the source

Superbubble coincident with pulsar PSR J1856+0245 hinting at 1 gamma ray source not two

Interesting physics for gamma ray emission from interactions with a superbubble

Good target for VERITAS analysis, but need to deal with extended nature of source (~0.20°)

A. Petriella et al.: Radio study of HESS J1857+026

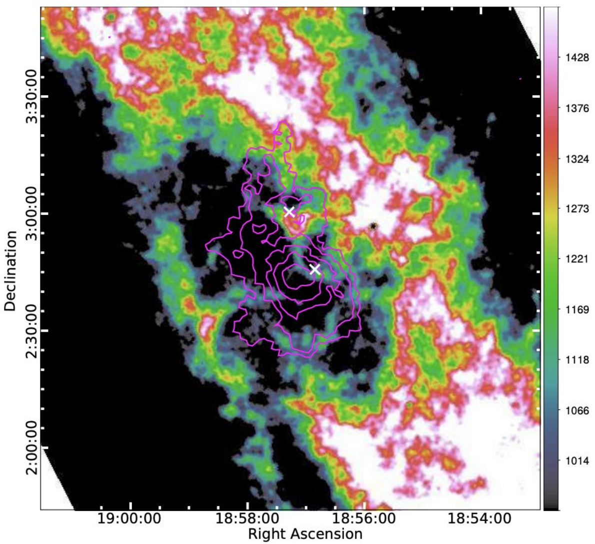


Fig. 4. HI distribution towards HESS J1856+026, integrated in the velocity range between 81 and 102 km s^{-1}. The contours correspond to the TeV emission and the crosses mark the position of the pulsars PSR J1856+0245 and PSR J1857+0300. The color scale is expressed in arbitrary units.

Imaging Atmospheric Cherenkov Telescopes (IACTs)

Gamma-rays and cosmic rays interact with atmosphere

Use that interaction to our advantage

Incoming gamma/cosmic rays hit atmosphere and give off Cherenkov light through pair production or pion decay

Can measure the Cherenkov light showers with telescopes

Reconstruct energy and direction through Hillas parameters

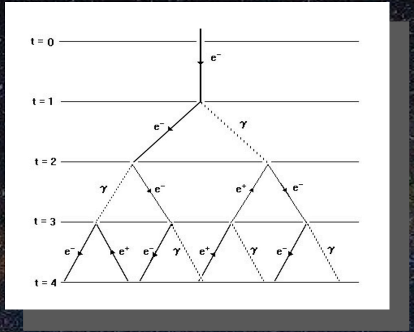


Image credit: Albrecht Karle 2006

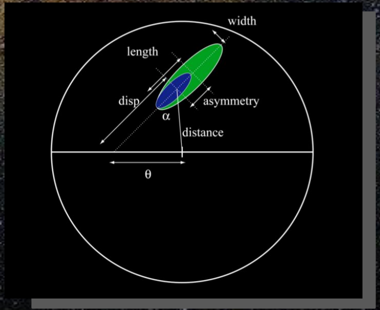


Image Credit: ResearchGate

VERITAS (Very Energetic Radiation Imaging Telescope Array System)

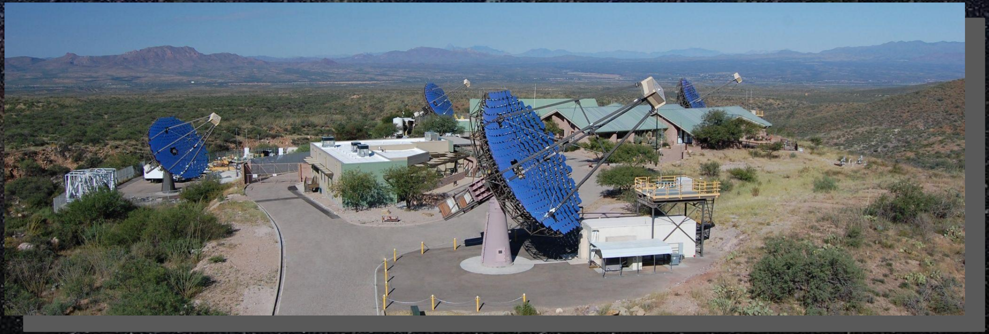
Telescope array at the Whipple Observatory in Arizona

Made up of four 12m Cherenkov telescopes

Measures gamma/cosmic rays in the 80GeV-50TeV range (VHE)

Small FOV but good angular resolution

Image Credit: VERITAS



Background Events for Gamma-ray Astronomy

Galaxy is filled with cosmic rays and gamma rays so cannot just point at a source and expect to “see” it

Cosmic-ray misidentified as gamma-ray

Use background estimations to fit acceptance functions to the sky

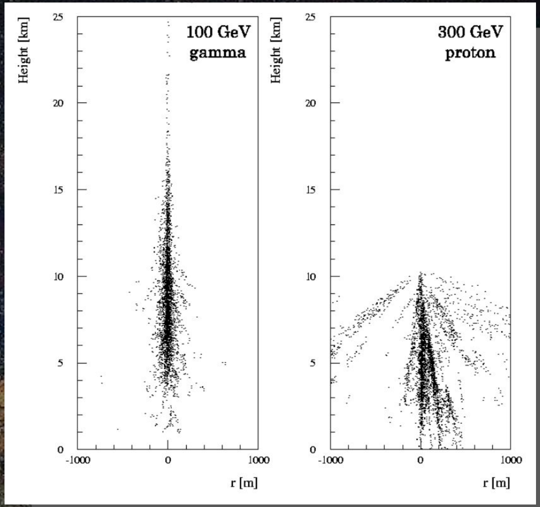


Image Credit: Karle 2006

Ring Background Method

Draw a ring around the source region to estimate the background with data in ring

Can then fit an acceptance function to that data to create the background

The setting for that function is “smoothed” but it resembles just a curve

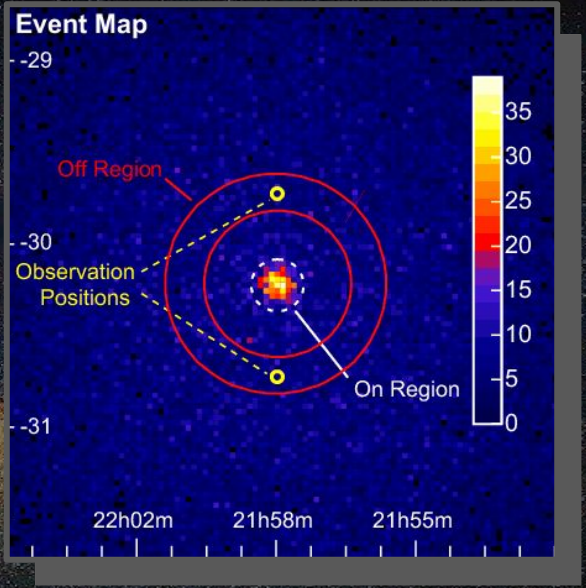
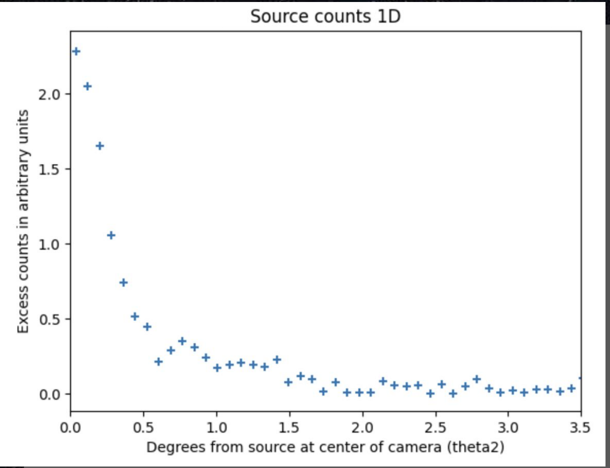
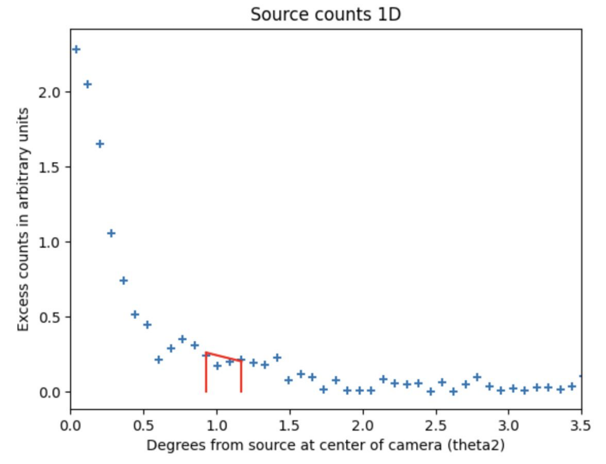
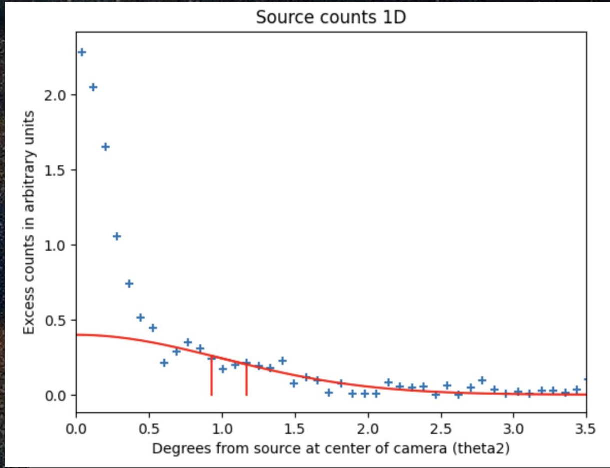


Image Credit: D. Berge 2006

RBM (1D Example) (Units are not exactly correct!)







Statistics (Li and Ma 1983)

Use Li and Ma statistics to assign significance to data above the background

This assumes the background of these sources is roughly Poissonian

Can assign each pixel a significance and create plots out of that S

$$S = -\sqrt{2 ln\lambda} = \sqrt{2}\left[N_{on} ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right] + N_{off} ln\left[(1+\alpha)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right]^{\frac{1}{2}}$$

VEGAS (VERITAS Gamma-ray Analysis Suite)

VEGAS is comprised of 6 stages which act to analyze the data from the VERITAS telescope

Stage 1 - get data and calibrate

Stage 2/3 - subtract out noise and clean each pixel, create map and clean map

Stage 4 - Hillas parameter reconstruction for each event

Stage 5 - create necessary root files from the entire data set

Stage 6 - create the plots and skymaps of the data runs

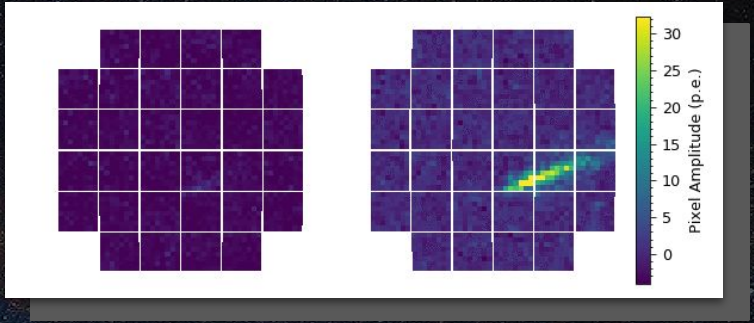


Image credit: J. Watson

Validation (the Crab Nebula and quasar 3C 273)

Guiding question - How does differing the exclusion region in VEGAS affect the background estimation?

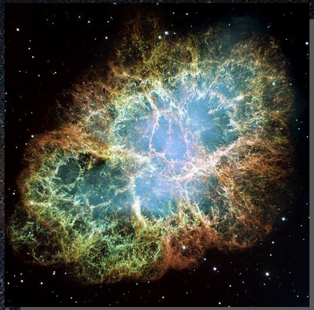
the Crab and 3C 273 with different exclusion regions

the Crab - supernova remnant and pulsar that acts as the “standard candle” in gamma-ray astronomy

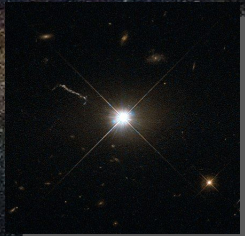
3C 273 - quasar at the center of a galaxy in the Virgo cluster

Data for both totaled around 18 hours, the telescope angle ranged from 58-63°

3 regions (0.4°, 0.7°, 0.9°) used for crab and 4 regions (0.3°, 0.5°, 0.7°,0.9°) used for 3C 273

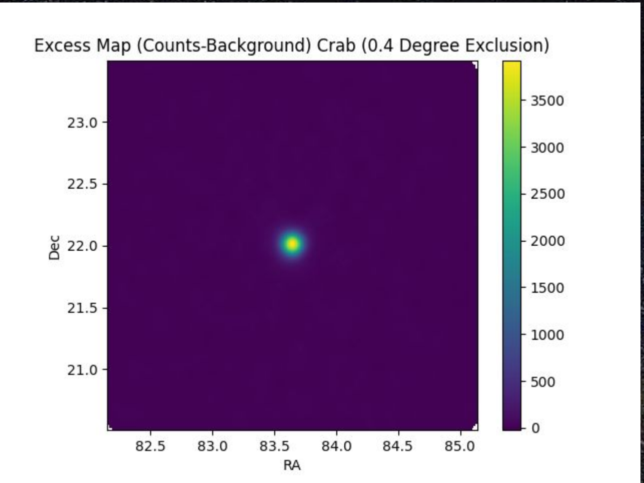


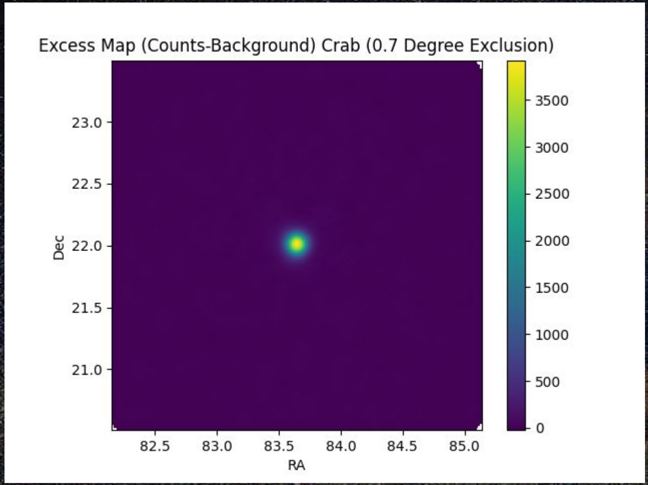
the Crab
Image Credit: Hubble

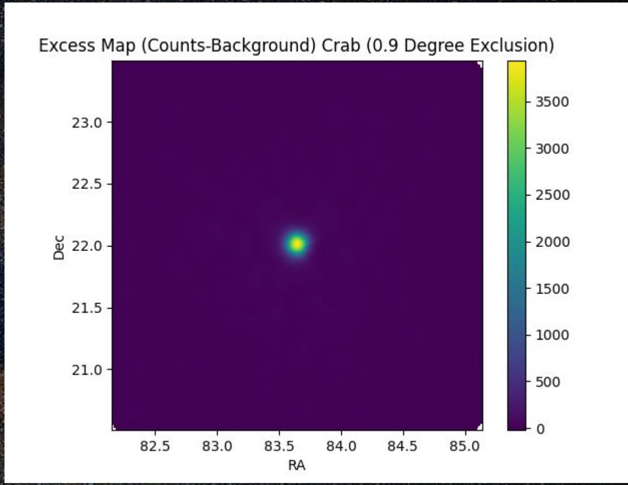


quasar 3C-273
Image Credit: Hubble

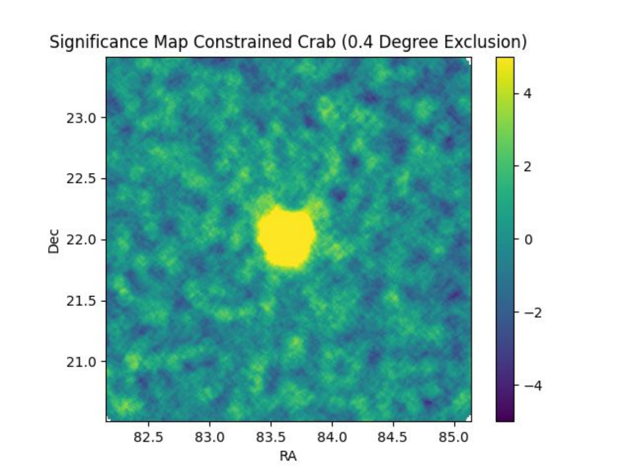
Results (Crab Nebula)

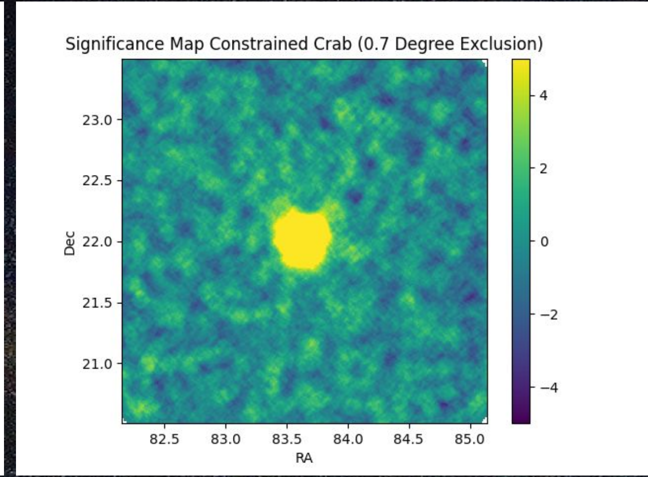


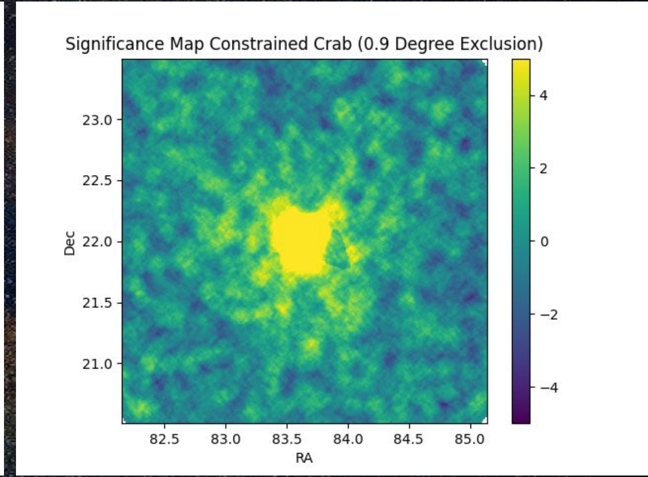




Results (Crab Nebula)

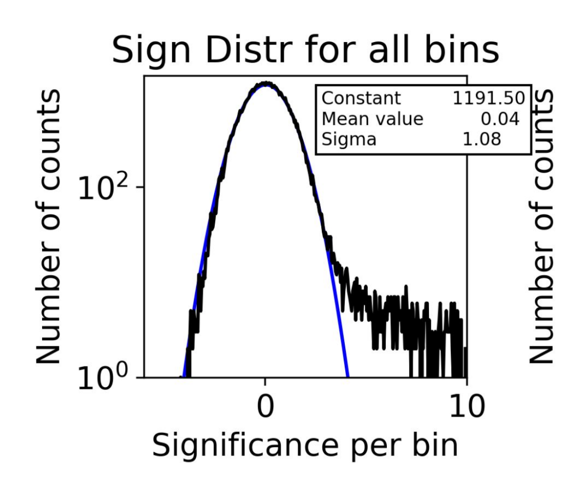




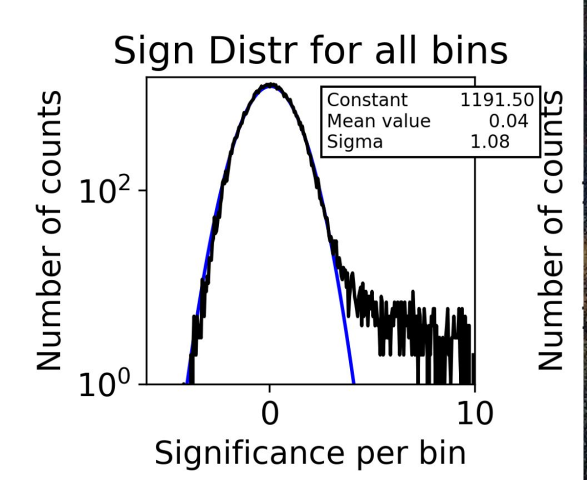


Results (Crab Nebula)

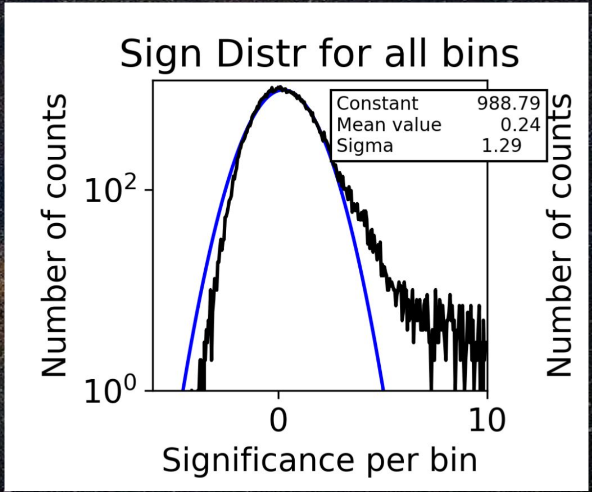
0.4



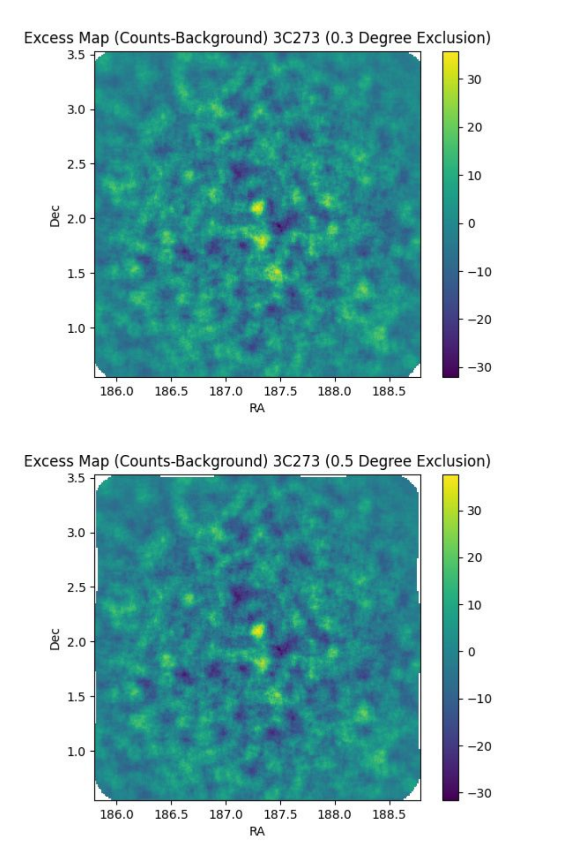
0.7

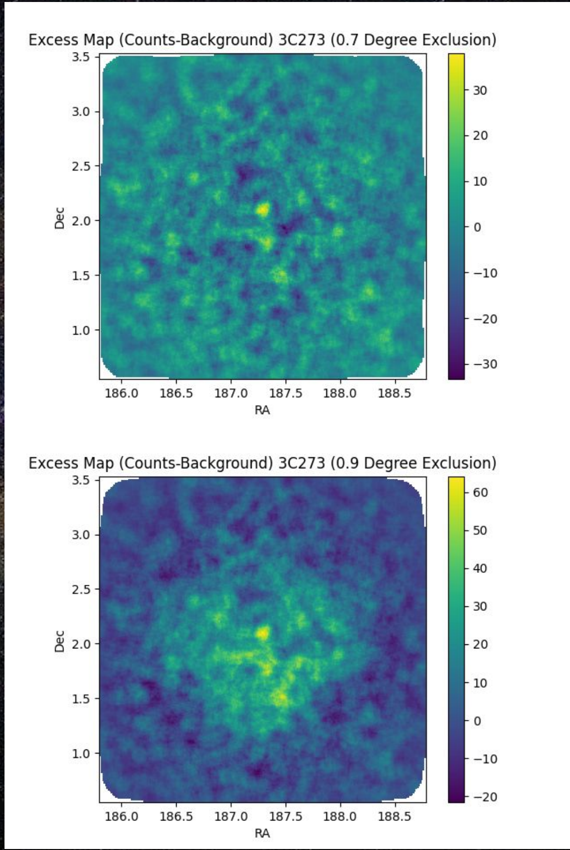


0.9

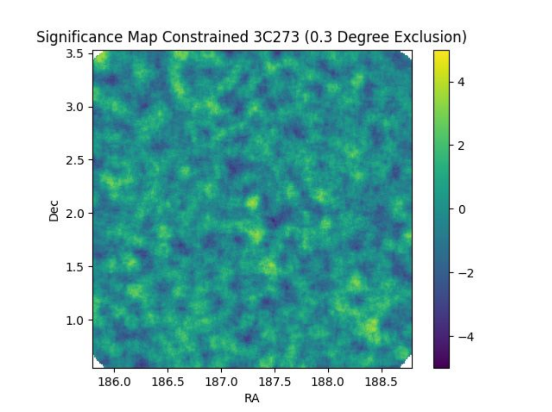


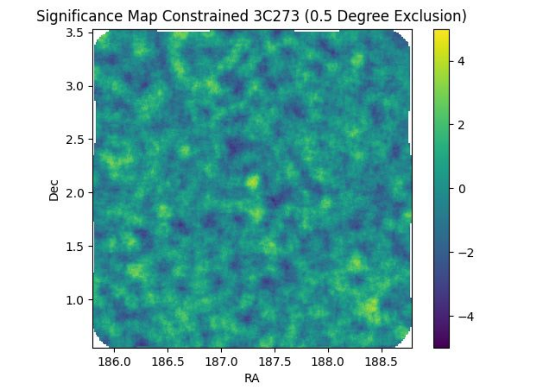
Results (quasar 3C 273)

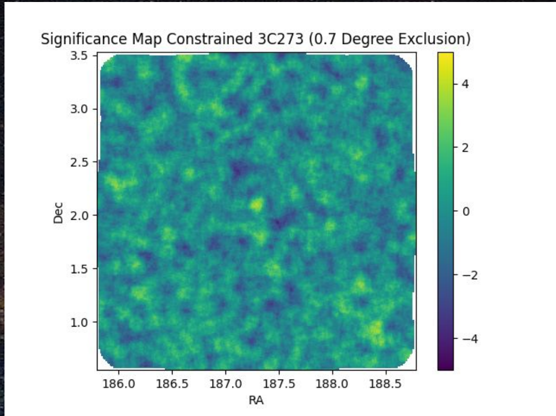


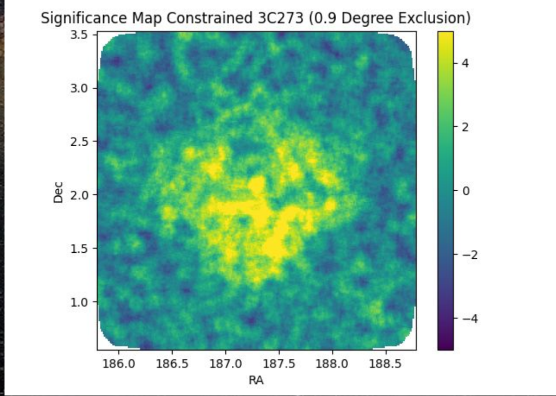


Results (quasar 3C 273)



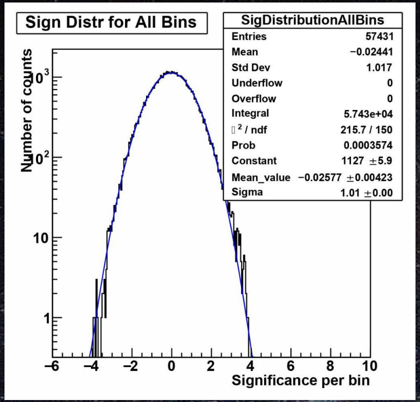


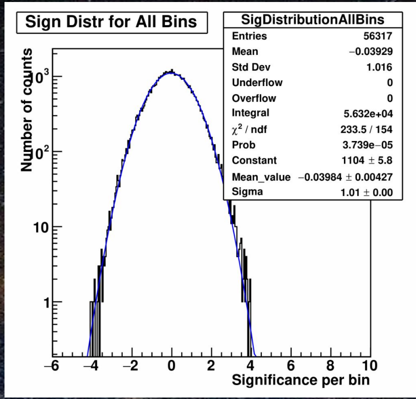




Results (quasar 3C 273)

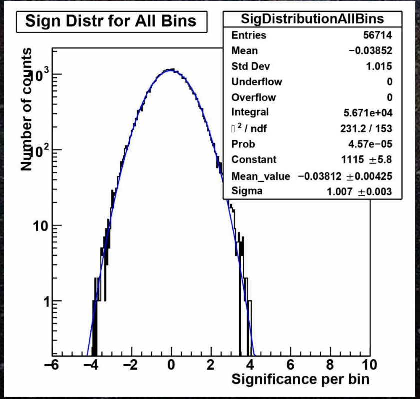
0.3

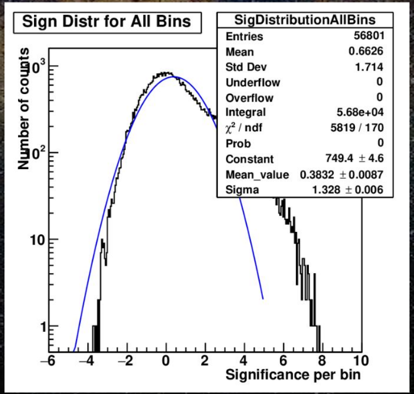




0.7

0.5





0.9

Conclusion

By analyzing both, it can be concluded that VEGAS needs further improvement for exclusion regions >0.9°

At 0.9°, systematic errors dominate the background estimation causing the data to not be accurate

Systematic errors could include statistical error with low counts with telescope acceptance on the edges going down or with having to extrapolate a large area

Doing this extended source analysis is critical to understanding cosmic ray origin

Next Steps

Further analysis of how other factors like ring width affect background estimation, as well a debugging why >1° exclusion region fails

Analysis of HESS J1857+026 to get a good feel for extended source analysis on a known TeV emitter

Analysis and observation of new LHAASO sources to hopefully find TeV counterparts to pevatrons and understand the new physics that comes along with that

Acknowledgements

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