Galactic Sources of VHE Gamma-rays

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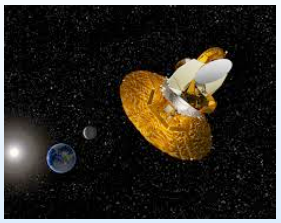
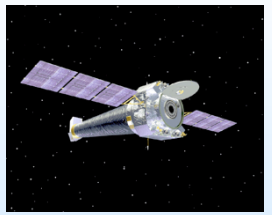
What are we learning from the gamma-ray sky?
Minneapolis, October 2013

10^{3} 10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7} 10^{-9} 10^{-11}

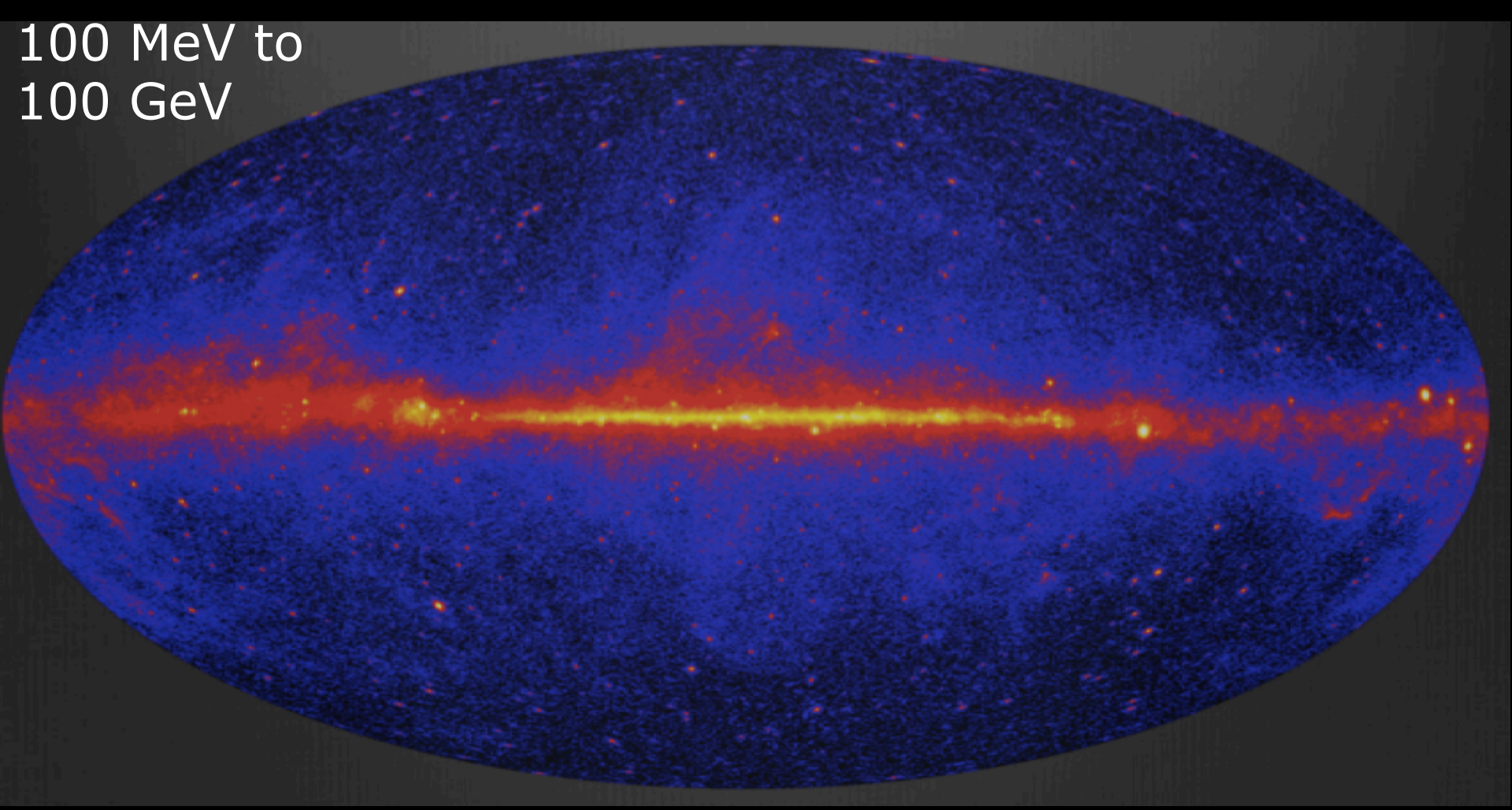
radio microwave infra-red optical UV X-RAY



10^{-12} 10^{-14} 10^{-16} 10^{-18} 10^{-20}

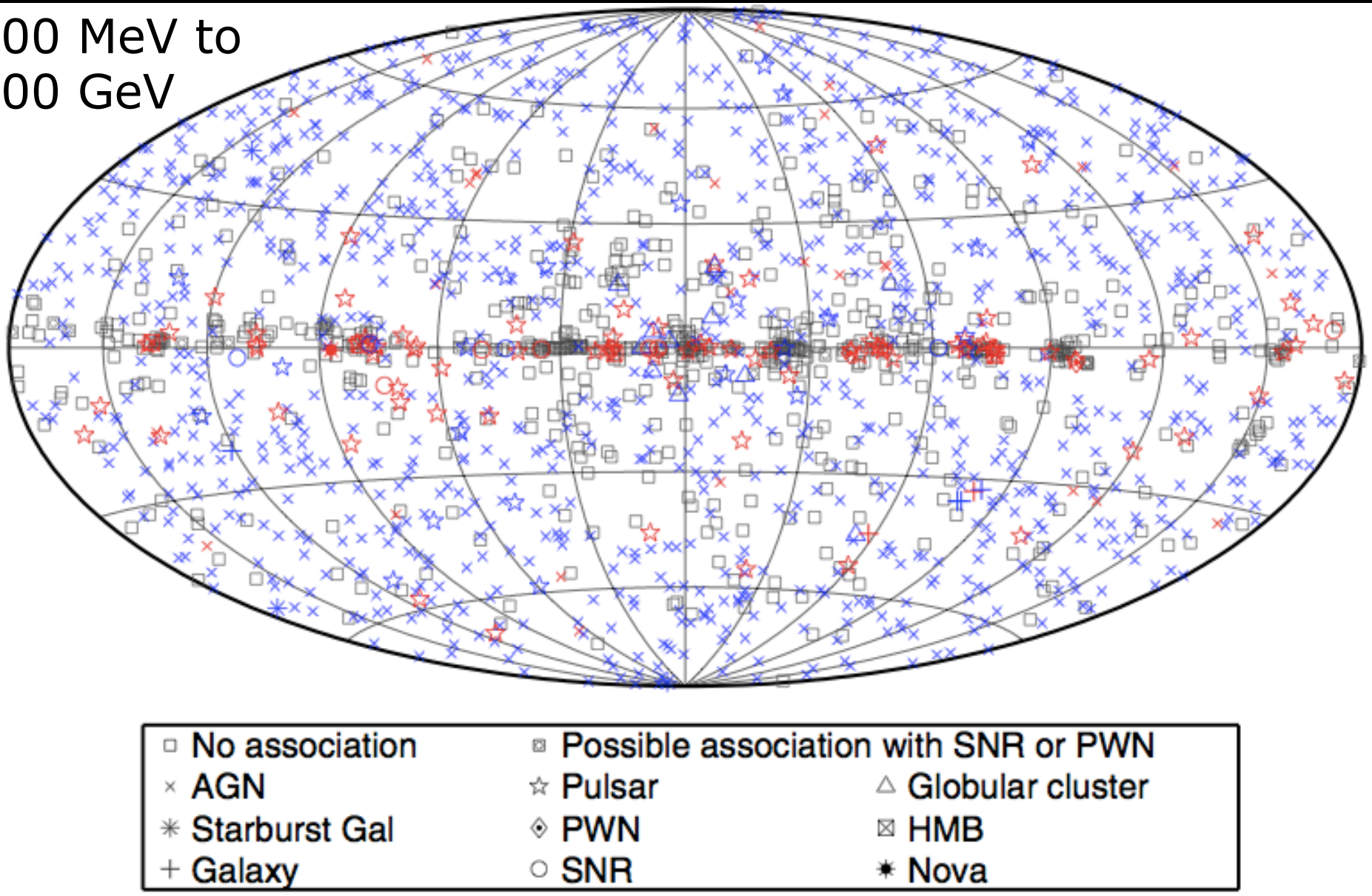
GBM LAT VERITAS HAWC

0.5 MeV 100 TeV



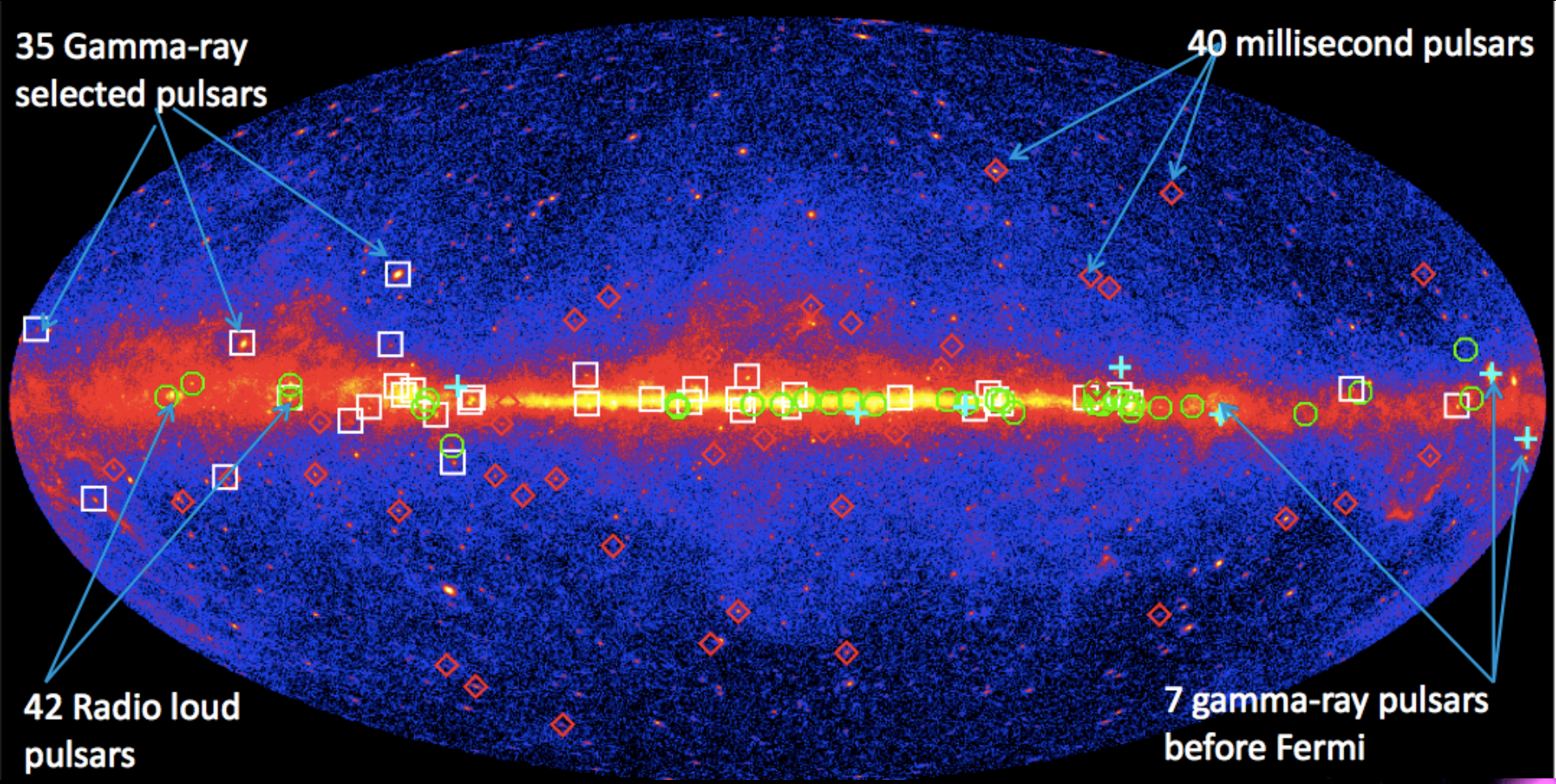
The Galactic GeV sky is

dominated by diffuse emission

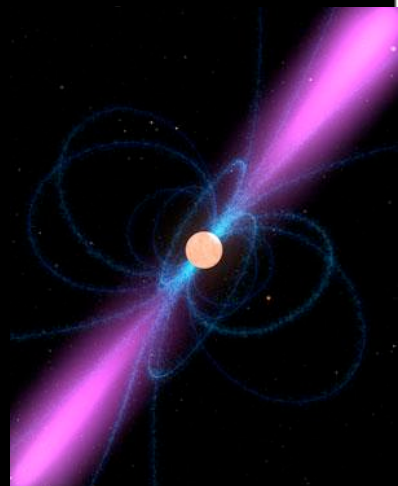


Source catalog after background subtraction

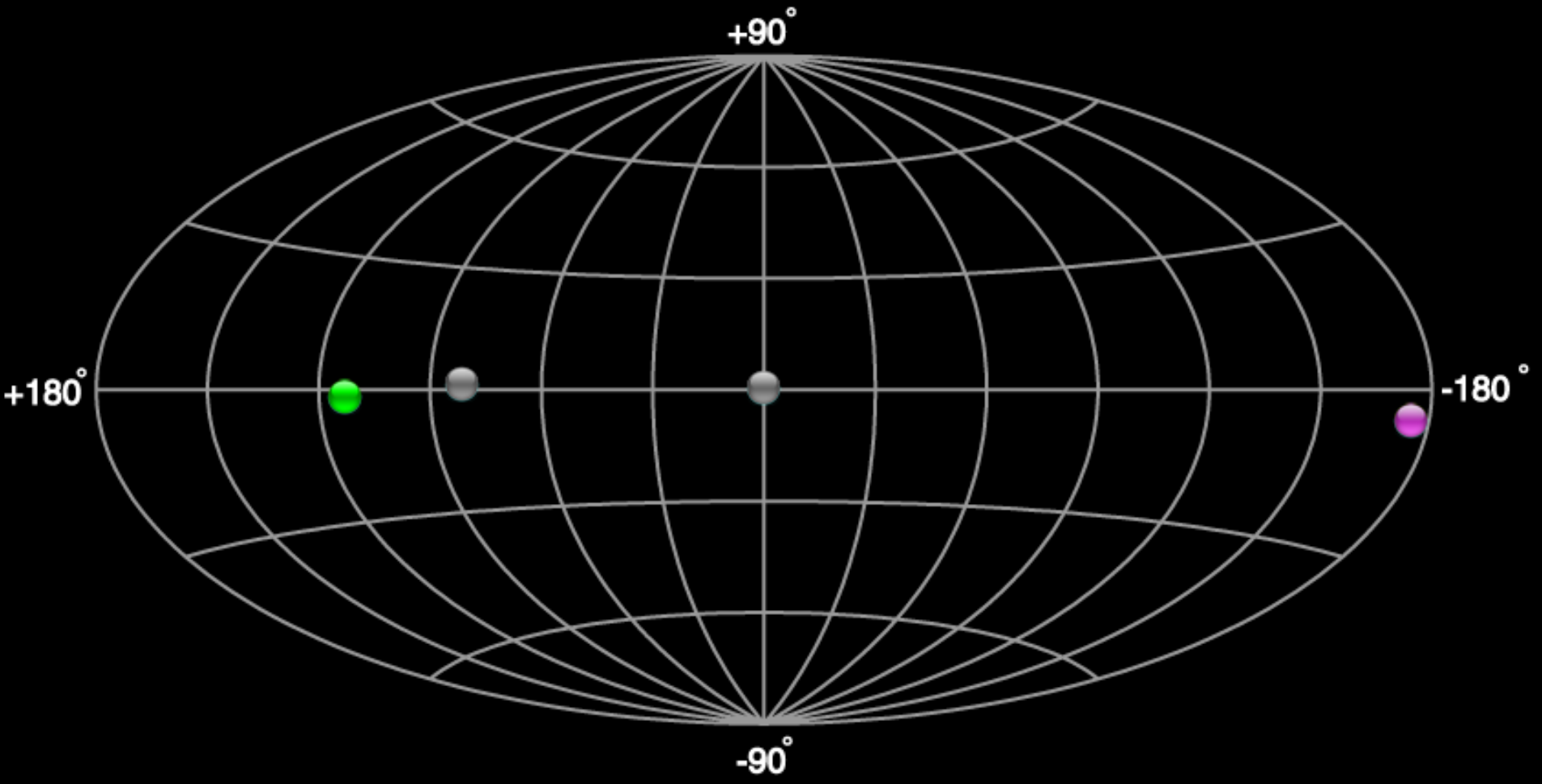
1873 sources, 127 identified, 577 'unassociated'



The Galactic GeV point source catalog is dominated by pulsars (117 in the 2nd Fermi-LAT pulsar catalog)

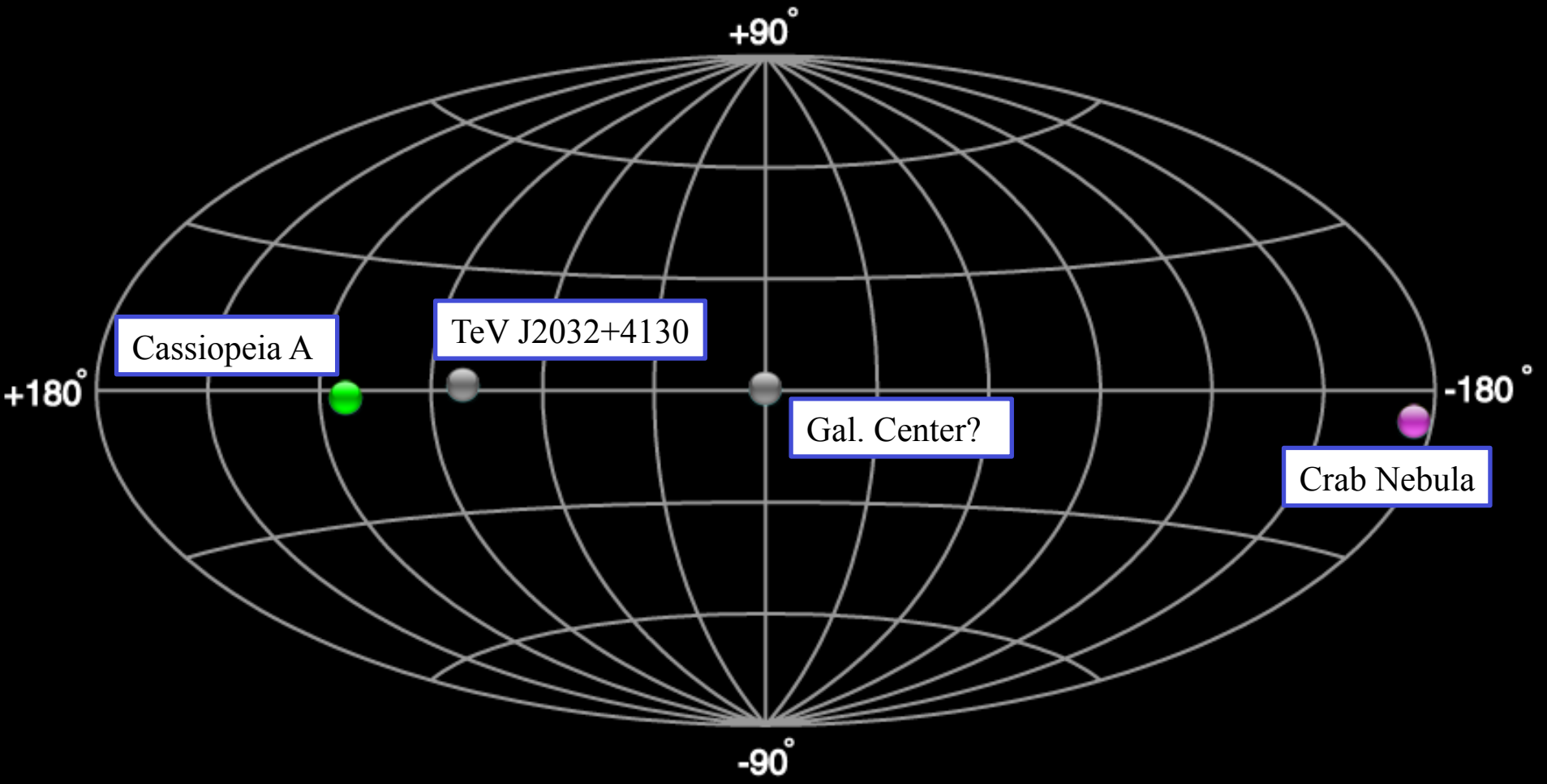


The >100 GeV (VHE) Galaxy, *circa* 2003



Credit TeVCat

The >100 GeV (VHE) Galaxy, *circa* 2003

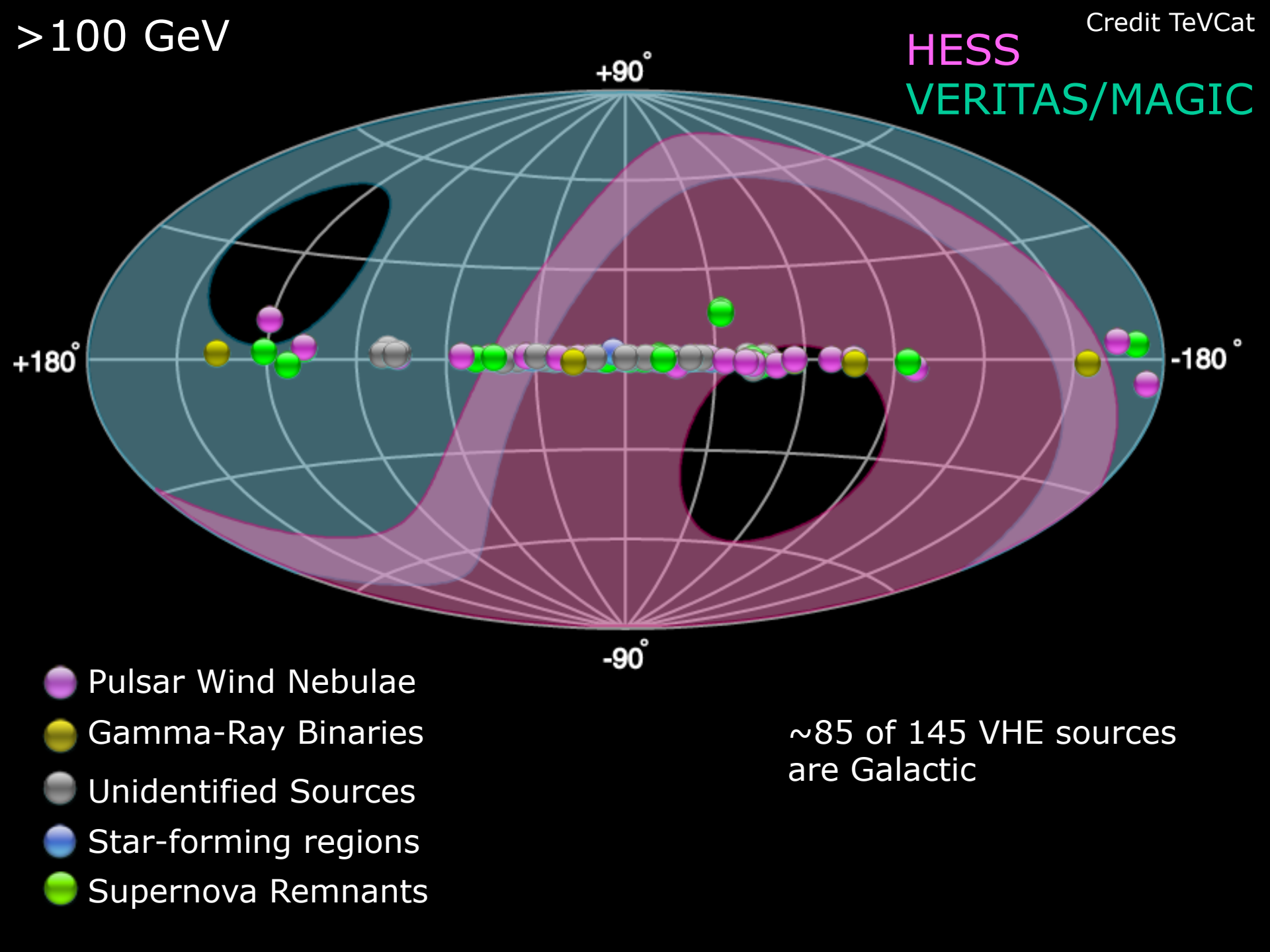


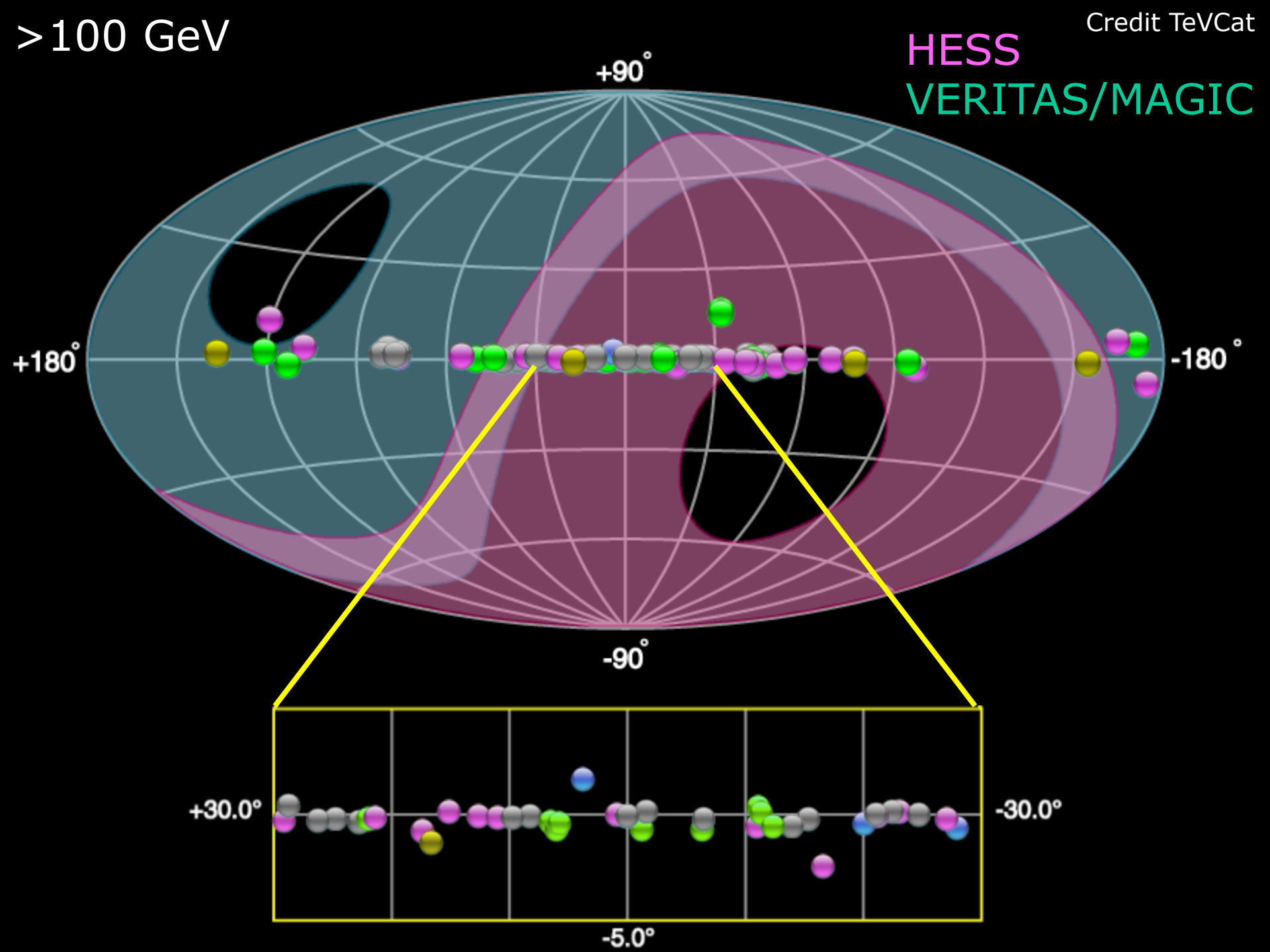
Credit TeVCat

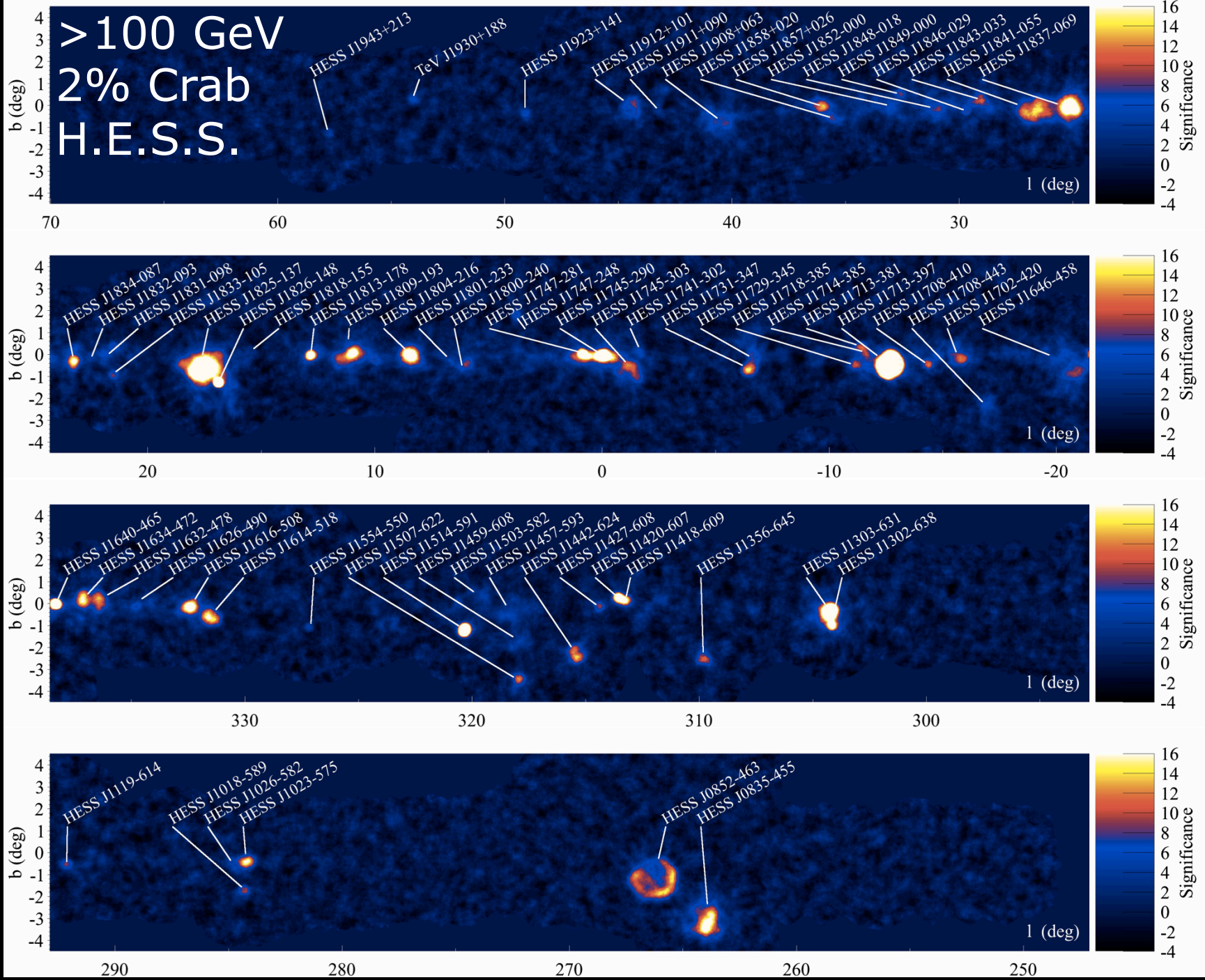

VERITAS

MAGIC

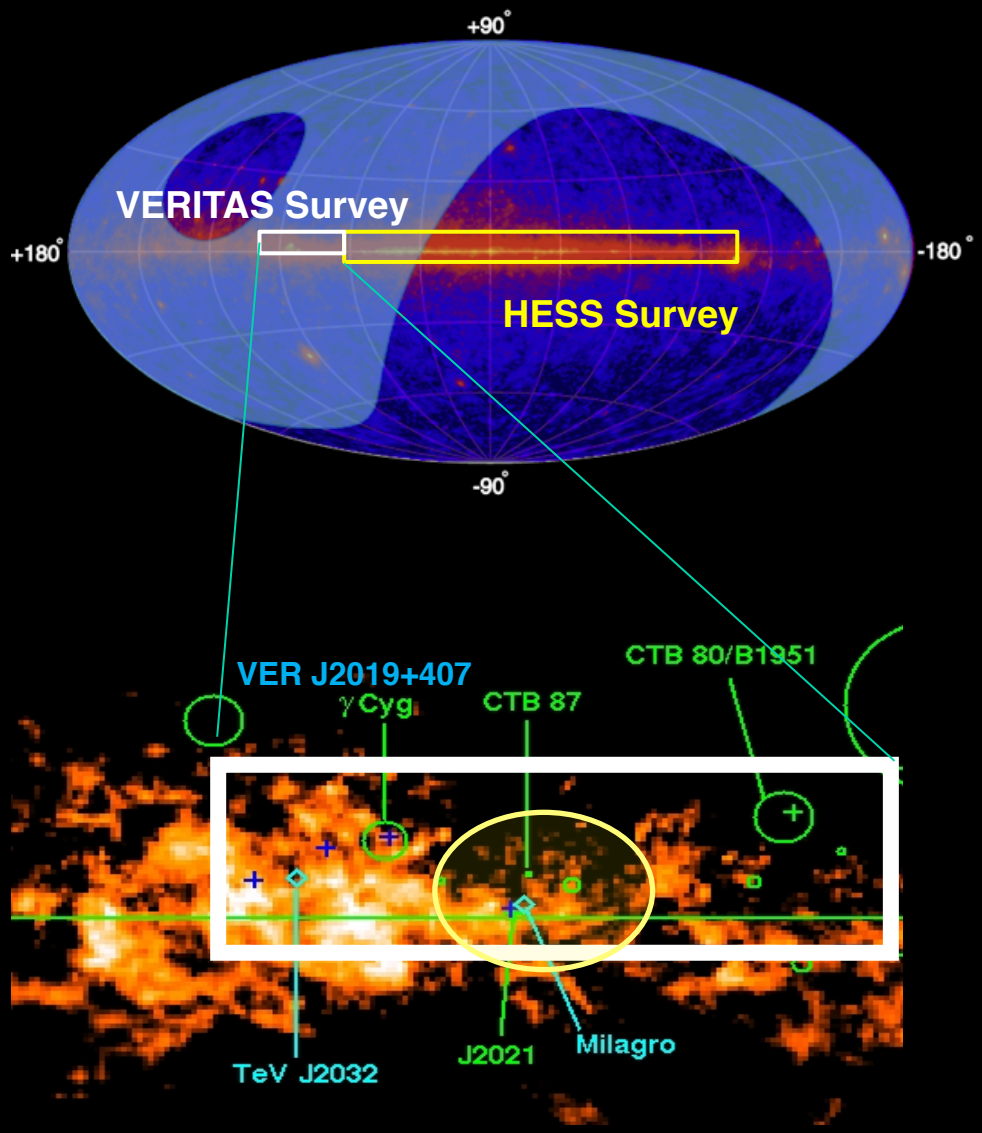
H.E.S.S.

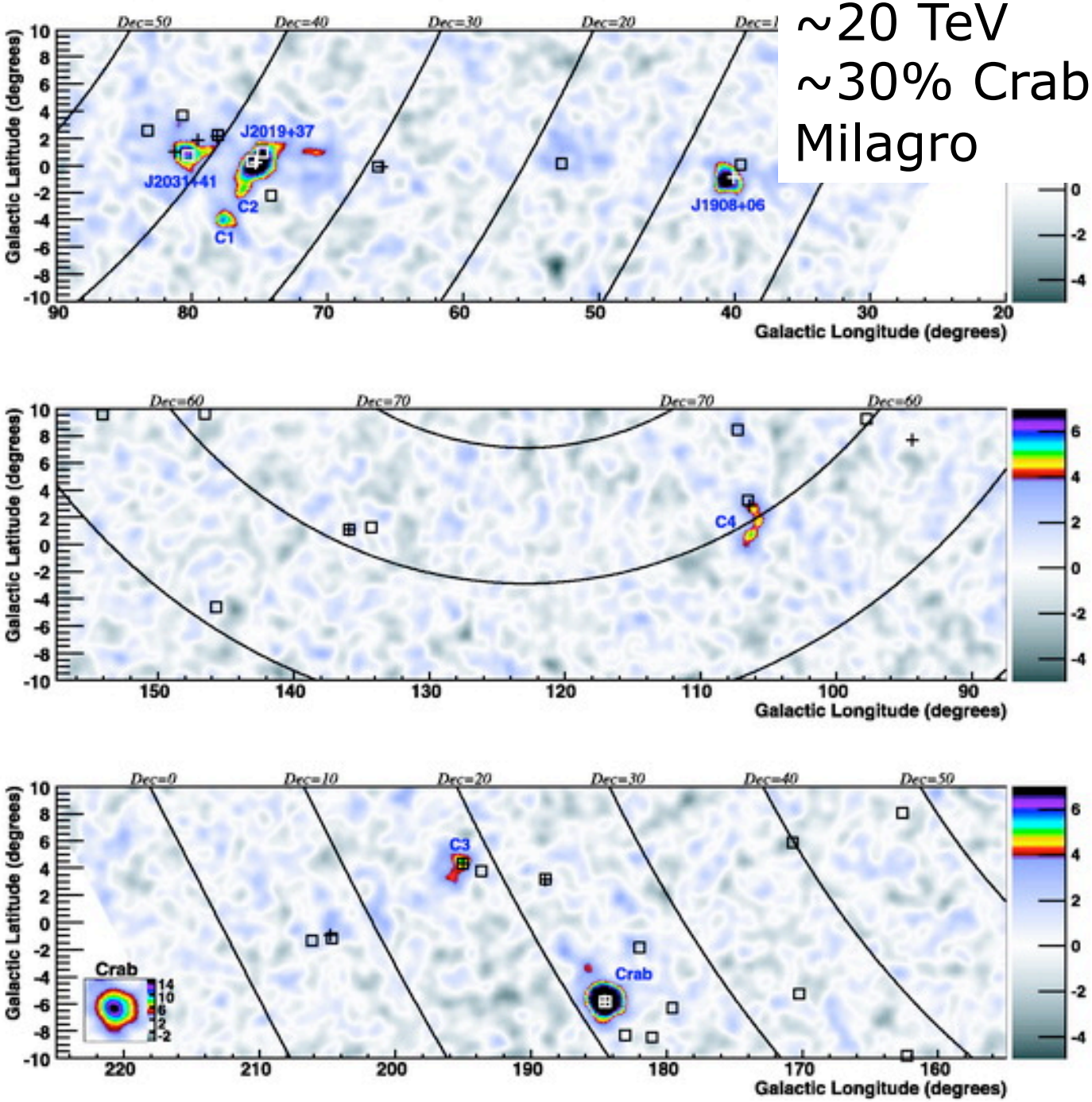

>100 GeV
Credit TeVCat
HESS
VERITAS/MAGIC
+90°
+180°
-180°
-90°
Pulsar Wind Nebulae
Gamma-Ray Binaries
Unidentified Sources
Star-forming regions
Supernova Remnants
~85 of 145 VHE sources are Galactic


>100 GeV
Credit TeVCat
HESS
VERITAS/MAGIC
+90°
+180°
-180°
-90°
+30.0°
-30.0°
-5.0°


>100 GeV
2% Crab
H.E.S.S.
HESS J1943+213
TeV J1930+188
HESS J1923+141
HESS J1912+101
HESS J1911+090
HESS J1908+063
HESS J1858+020
HESS J1857+026
HESS J1852-000
HESS J1848-018
HESS J1849-000
HESS J1846-029
HESS J1843-033
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1832-093
HESS J1831-098
HESS J1833-105
HESS J1825-137
HESS J1826-148
HESS J1818-155
HESS J1813-178
HESS J1809-193
HESS J1804-216
HESS J1801-233
HESS J1800-240
HESS J1747-281
HESS J1747-248
HESS J1745-290
HESS J1745-303
HESS J1741-302
HESS J1731-347
HESS J1729-345
HESS J1718-385
HESS J1714-385
HESS J1713-381
HESS J1713-397
HESS J1708-410
HESS J1708-443
HESS J1702-420
HESS J1646-458
HESS J1640-465
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1616-508
HESS J1614-518
HESS J1554-550
HESS J1507-622
HESS J1514-591
HESS J1459-608
HESS J1503-582
HESS J1457-593
HESS J1442-624
HESS J1427-608
HESS J1420-607
HESS J1418-609
HESS J1356-645
HESS J1303-631
HESS J1302-638
HESS J1119-614
HESS J1018-589
HESS J1026-582
HESS J1023-575
HESS J0852-463
HESS J0835-455
b (deg)
l (deg)
Significance

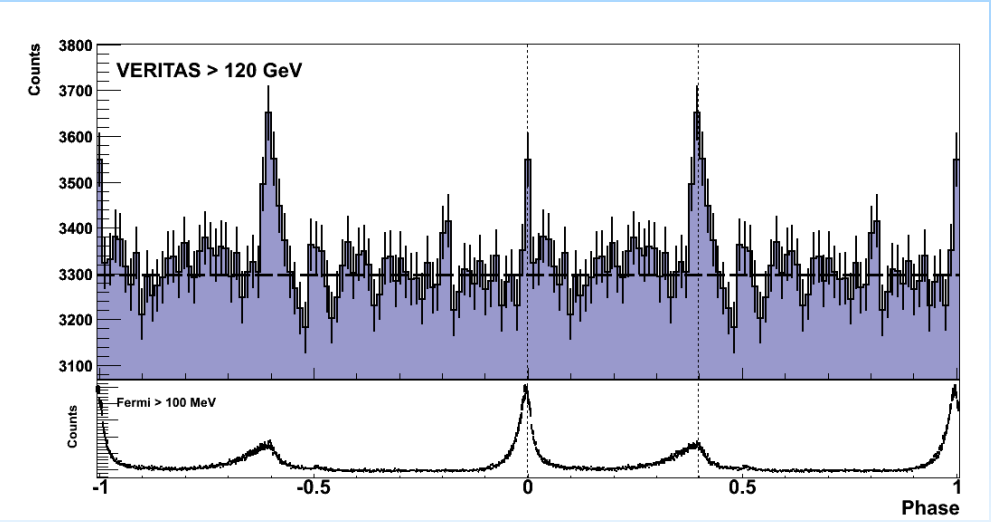
>100 GeV
3% Crab
VERITAS

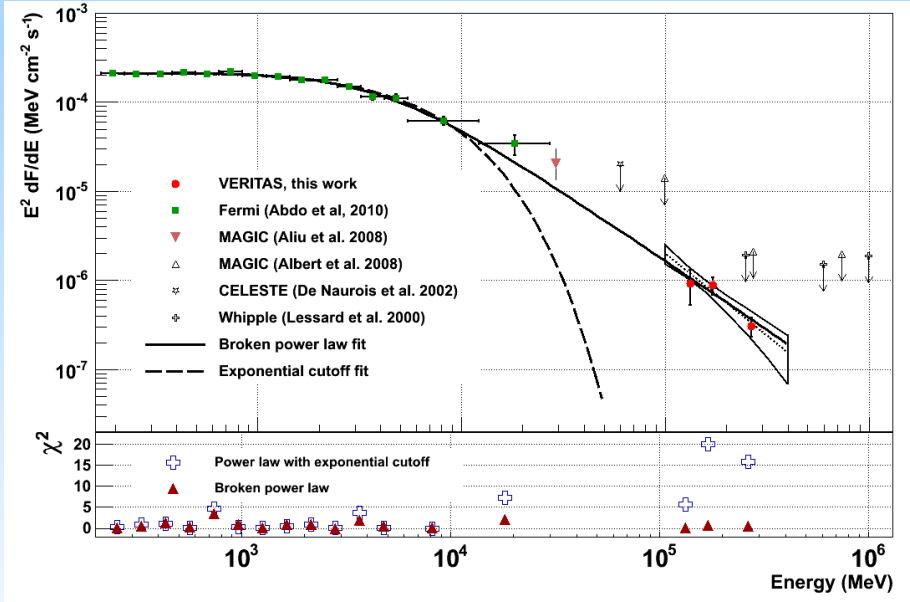



~20 TeV
~30% Crab
Milagro
Dec=50
Dec=40
Dec=30
Dec=20
J2019+37
J2031+41
C2
C1
J1908+06
Galactic Latitude (degrees)
Galactic Longitude (degrees)
Dec=60
Dec=70
Dec=70
Dec=60
C4
Dec=0
Dec=10
Dec=20
Dec=30
Dec=40
Dec=50
C3
Crab
Crab

Only one > 100 GeV Pulsar: The Crab

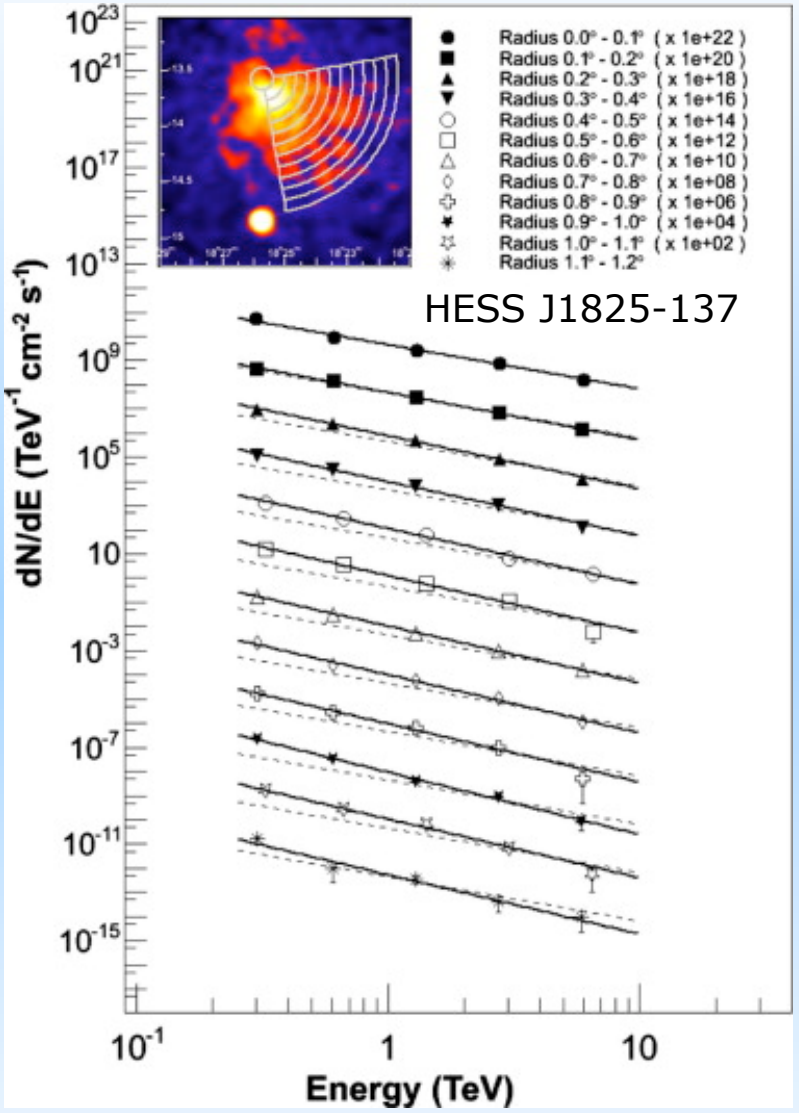
- One of the most powerful gamma-ray pulsars. (Spin-down E= 4.6 x 10^{38} erg s^{-1}.)
- Fermi-LAT measures spectral break at E_c = 6 GeV
- VERITAS and MAGIC measure emission above 100 GeV
- Overall spectrum favours a broken power-law fit
- Implies emission region > 10 stellar radii.
- Absence of exponential cutoff makes curvature radiation unlikely as the dominant mechanism at these energies





…but many Pulsar Wind Nebulae (PWN)

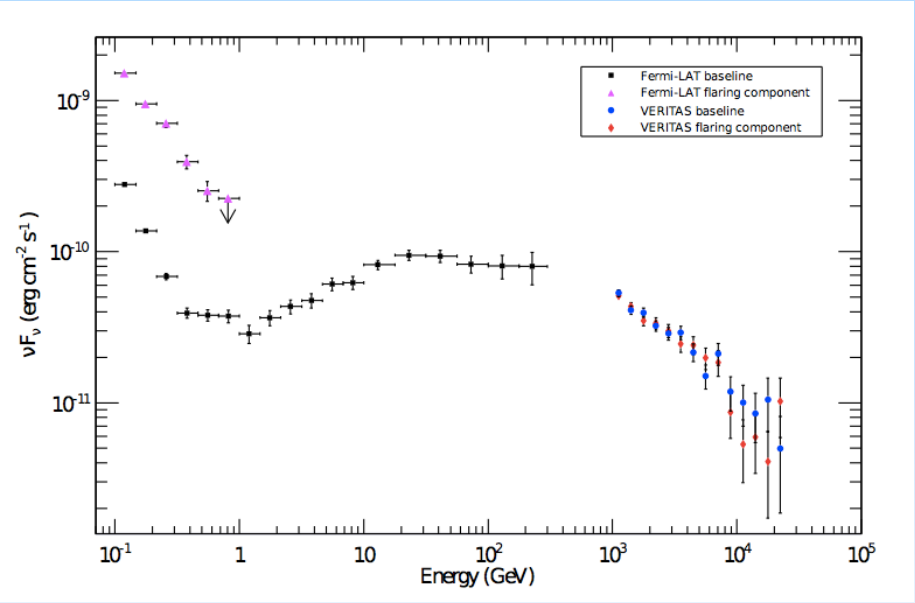
- The Crab Nebula was the first detected TeV source (Weekes et al, 1989)
- Energetic pulsars drive an electron/positron wind through spin-down energy
- Electrons are accelerated in the shock where the wind collides with the surrounding nebula
- Gamma-rays are produced through subsequent inverse Compton off ambient photon fields – SSC in the case of the Crab..

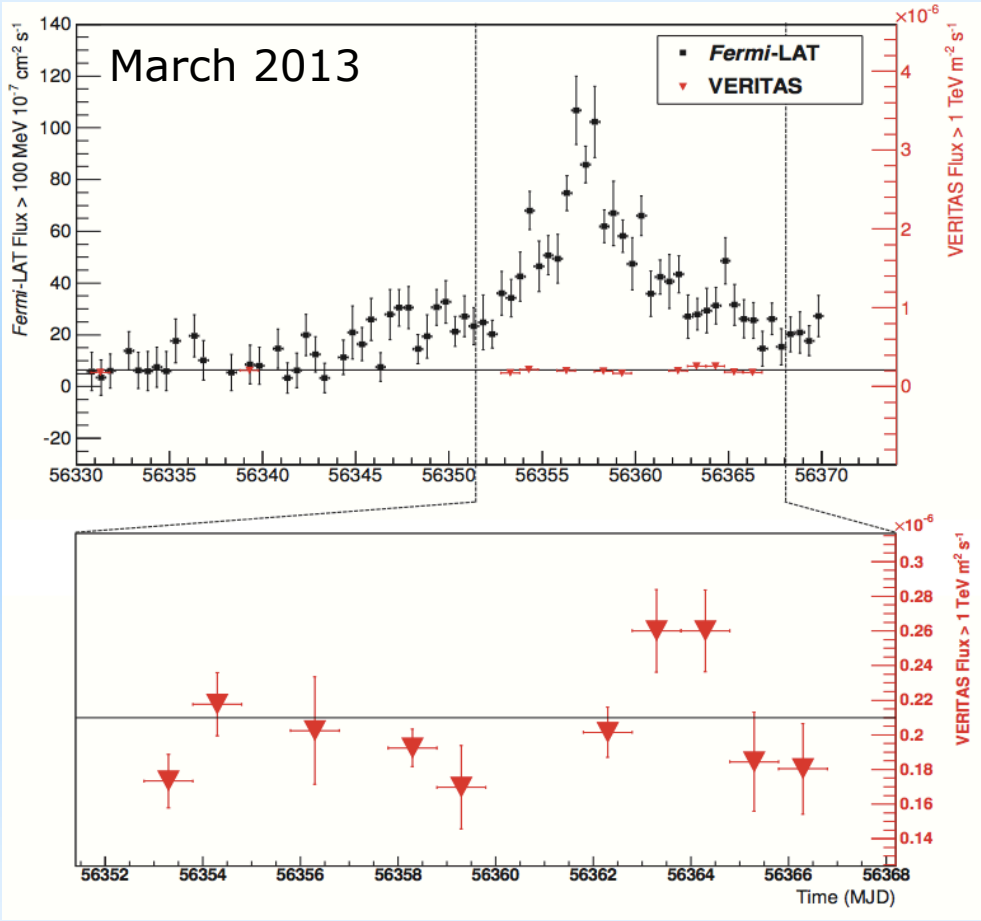


- Young PWN are point-like, but older systems can be much larger in TeV than X-rays, and display complex, spectrally dependent morphologies

The flaring Crab at VHE

- The Crab has been used as a TeV "standard candle" since its detection
- The LAT has detected long-term variability, and extreme flaring activity
- Seems not to extend to TeV energies (i.e. confined to the synchrotron component

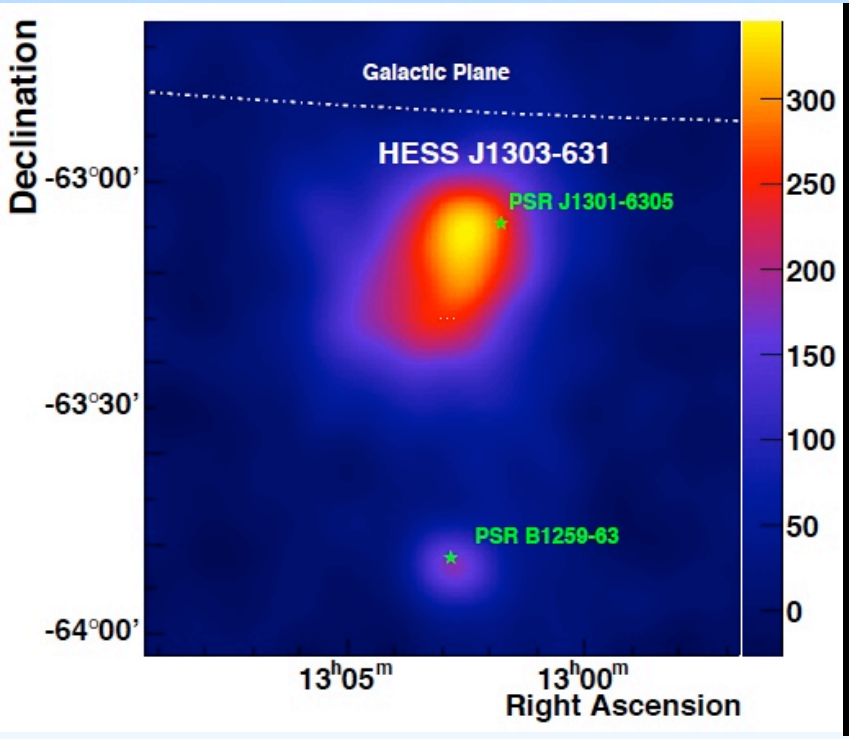


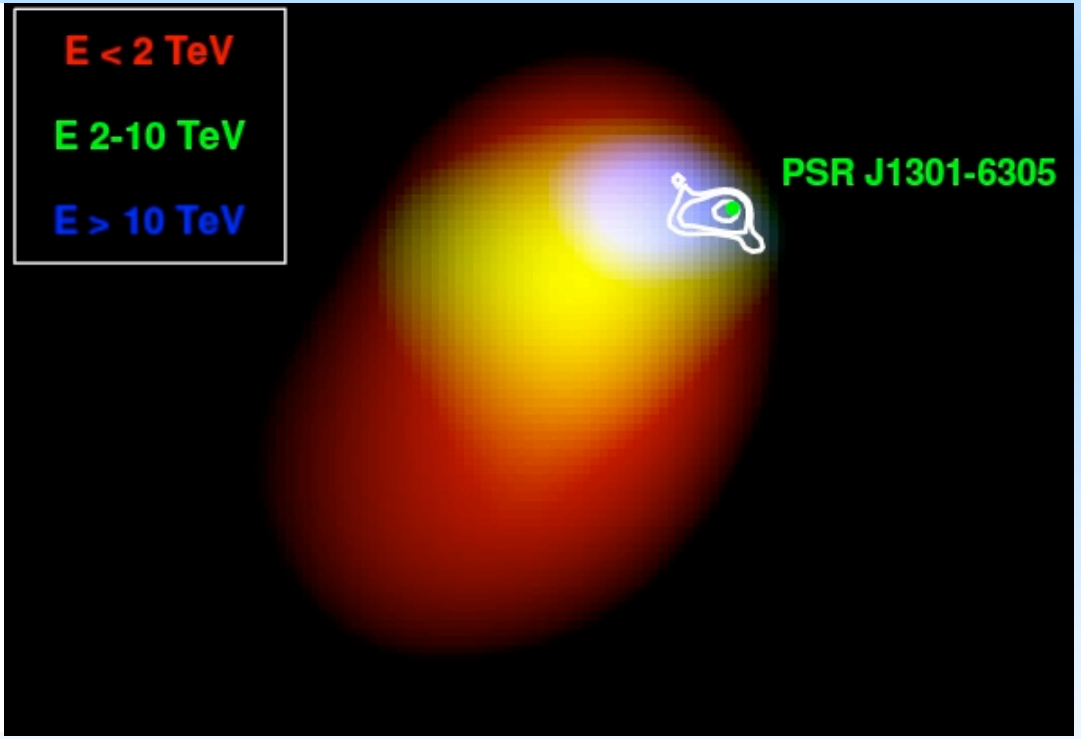


E. Aliu et al., arXiv:1309.5949

PWN also account for many unidentified sources

- HESS J1303-631 was serendipitously discovered during observations of the binary system PSR B1259-63 in 2004
- Originally unidentified – a distant, offset pulsar was considered an unlikely counterpart
- Spectral dependence of morphology, plus the discovery of an X-ray PWN, plus many examples of offset TeV PWN, plus a reassessment of the pulsar distance (16kp -> 7 kpc)
- The PWN of the pulsar is now considered the most likely source.

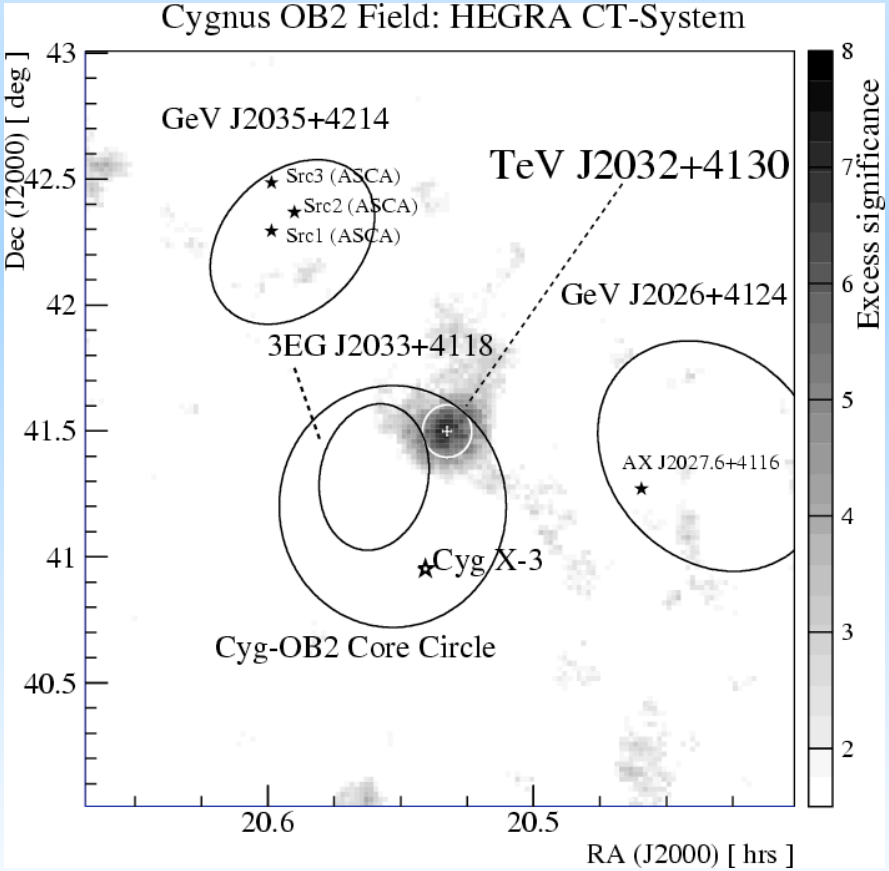


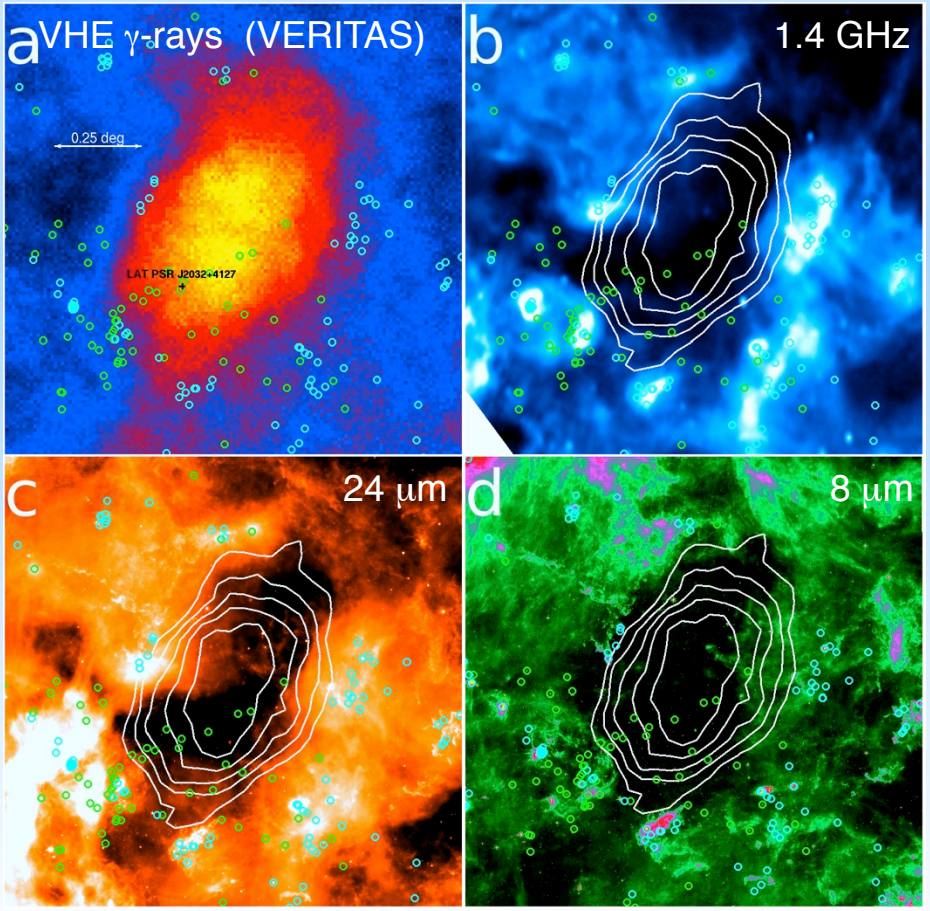


http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2011/01/

PWN also account for many unidentified sources

- TeV J2032+4130 was the first unidentified TeV source
- A gamma-ray pulsar was discovered in a blind search by Fermi-LAT
- VERITAS morphology matches a void of brighter emission at longer wavelengths
- Consistent with a pulsar wind powered by the LAT pulsar, despite it being relatively old and weak.

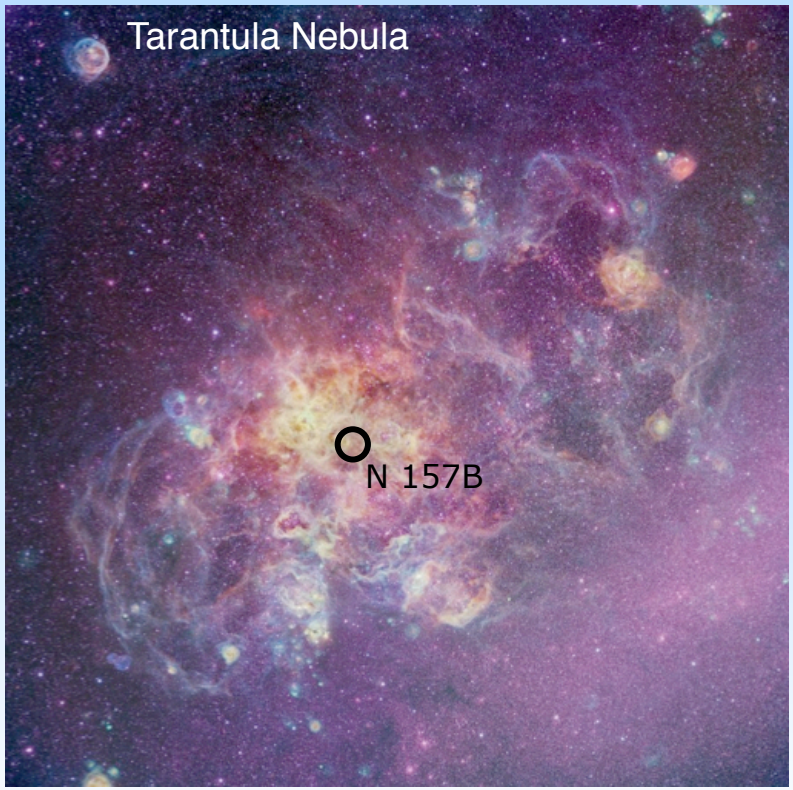


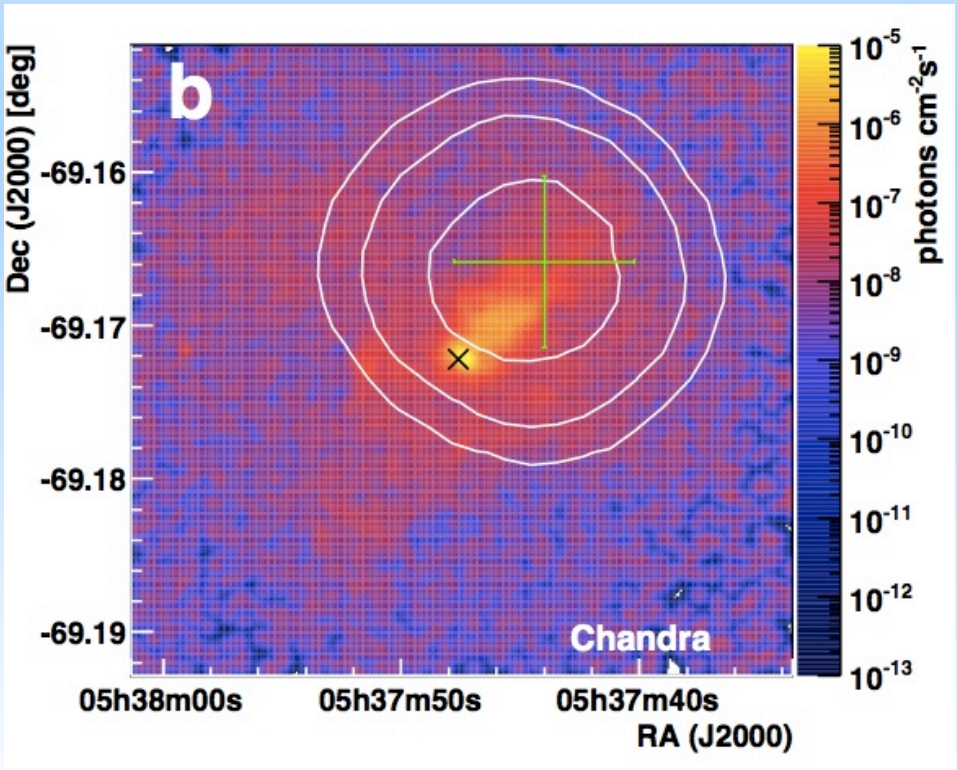


R.A. Ong et al.: ICRC, Rio de Janeiro, 2013

..and the only "Galactic" source outside of our Galaxy!

- Point source discovered by H.E.S.S. in the Large Magellenic Cloud
- Coincident with a 16 ms pulsar, PSR J0537−6910, with the largest known spin-down power among pulsars, of 5x10^38 erg/s.
- The pulsar is part of the composite supernova remnant N157B, which resembles the Crab supernova remnant
- Chandra observations reveal an X-ray PWN – which also accounts for the TeV source

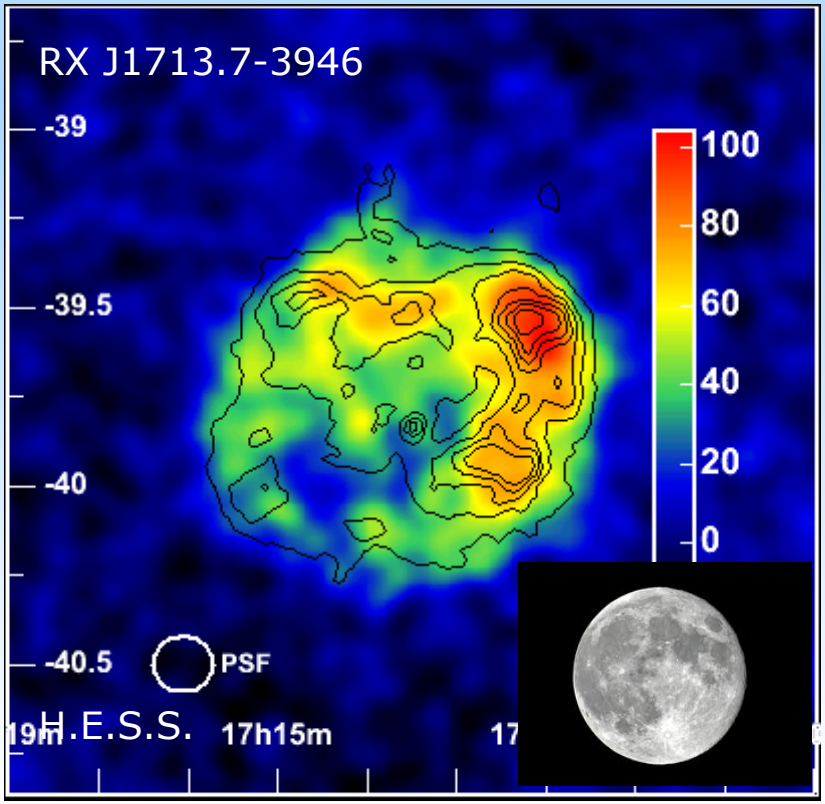


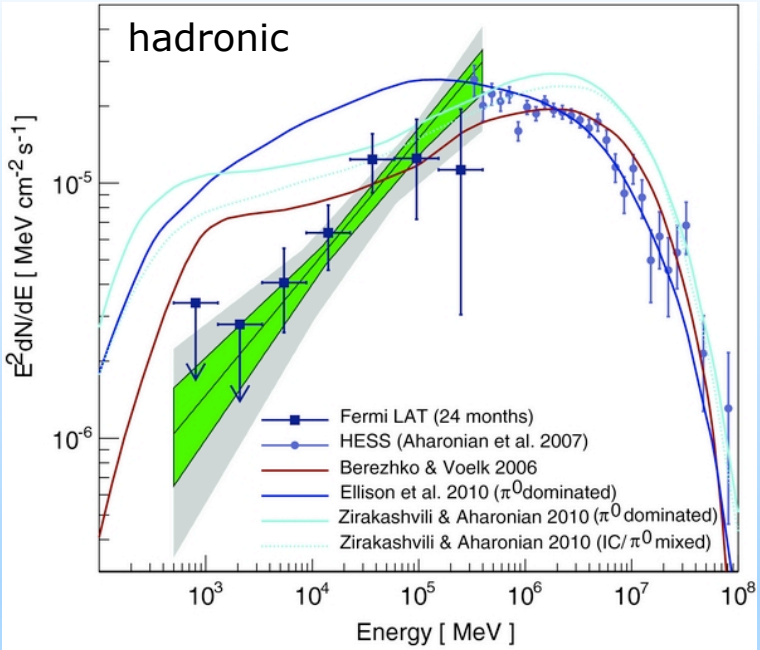


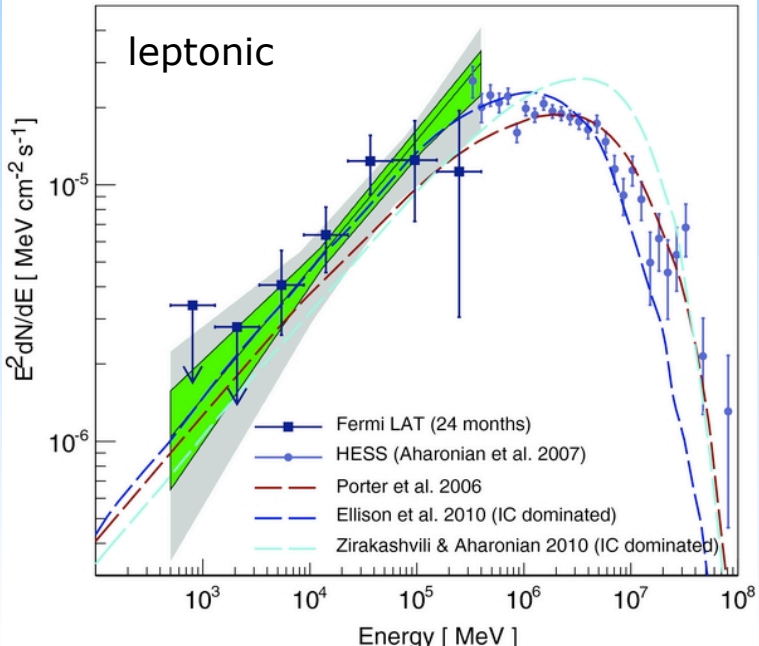
HESS Collaboration: A&A 2012, 545, L2

Supernova Remnants

- Gamma-ray astronomy was originally motivated by the search for the sites of cosmic ray acceleration, with SNRs prime candidates
- VHE SNR detections can be broadly divided into young, shell-type remnants, and middle aged remnants undergoing interactions with molecular clouds.
- In some cases, leptonic emission processes easily account for the observed spectrum

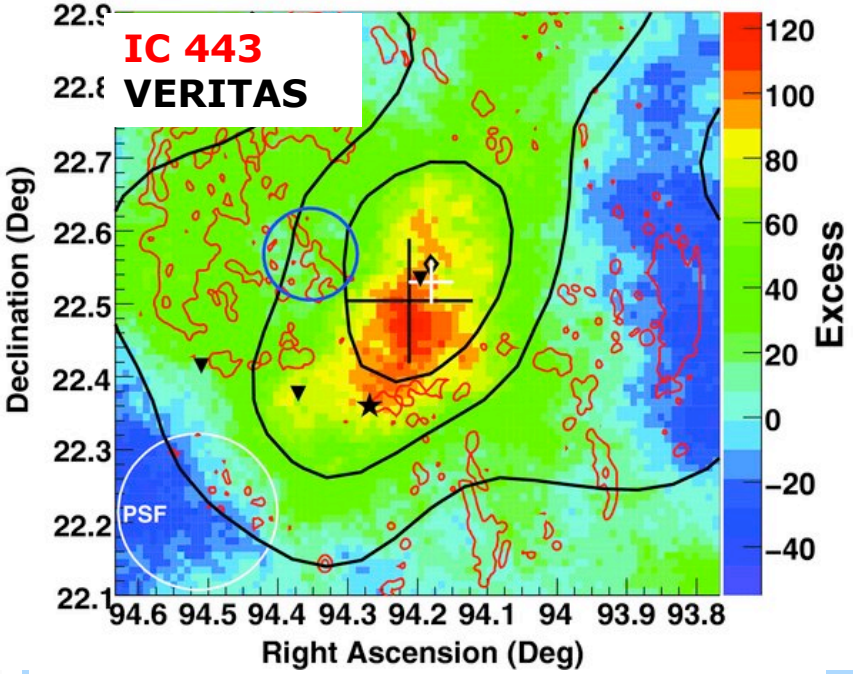


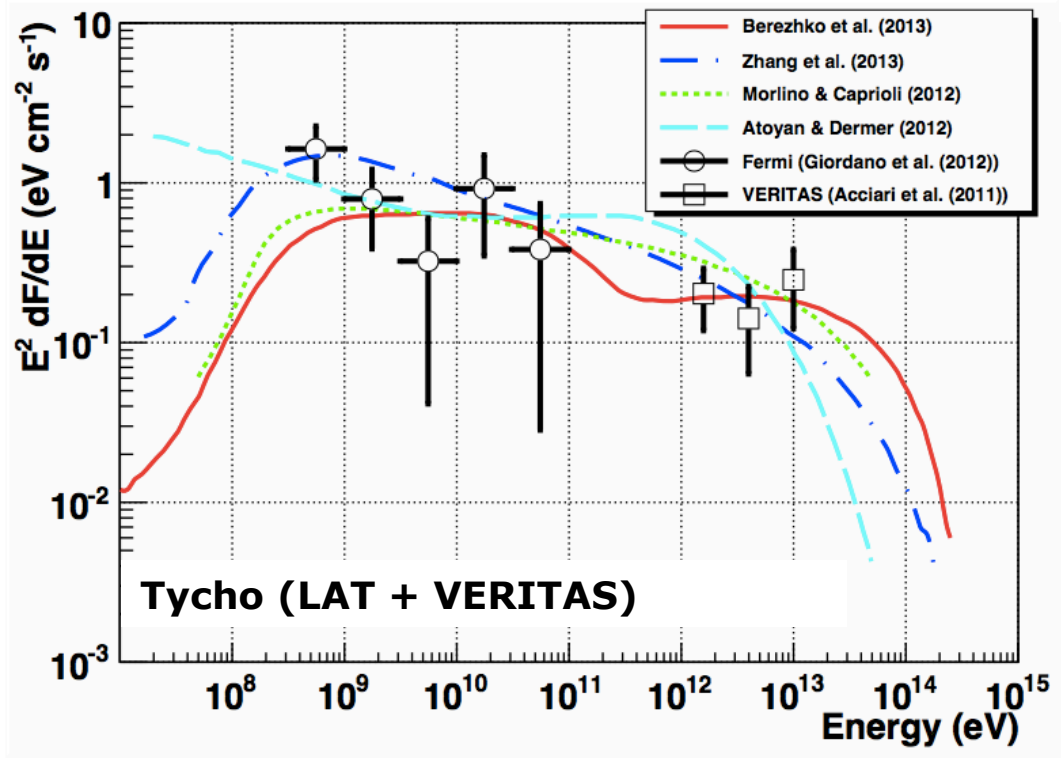


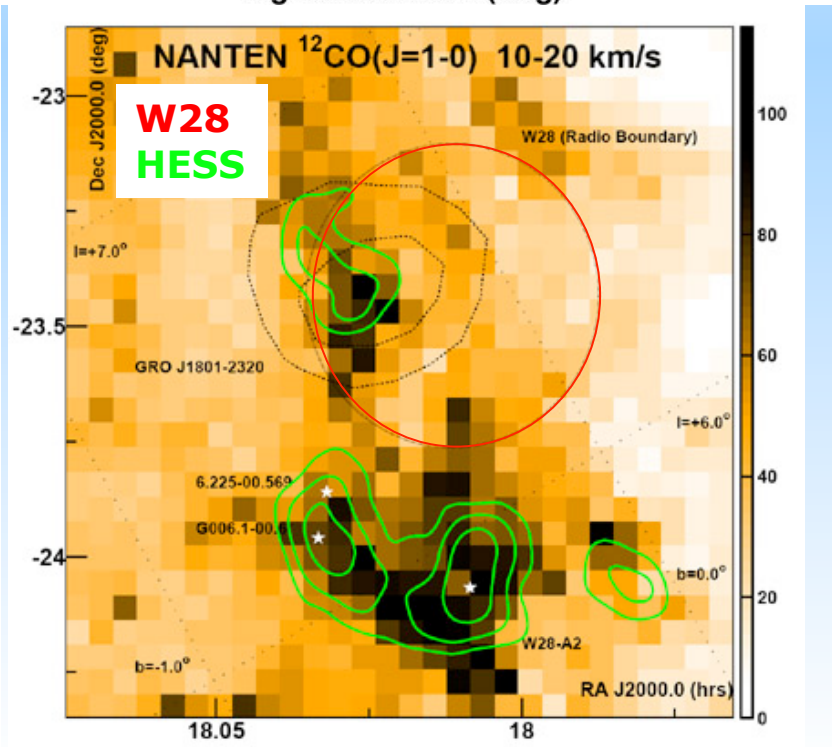


Supernova Remnants

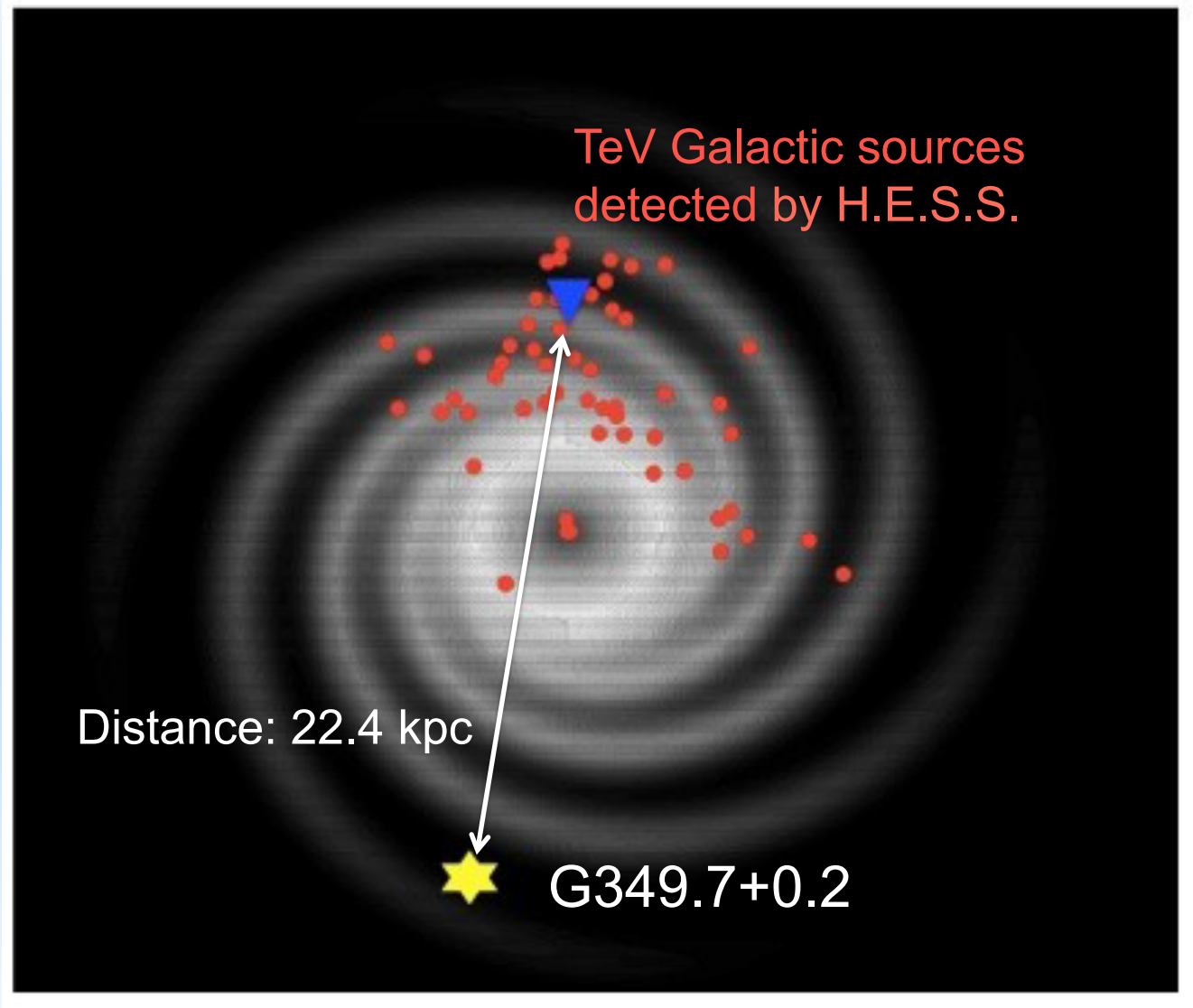
- In other cases, hadronic interaction and subsequent π^0-decay provides a plausible explanation.
- Emission can be enhanced by the presence of dense target material either interacting with, or external to, the remnant.







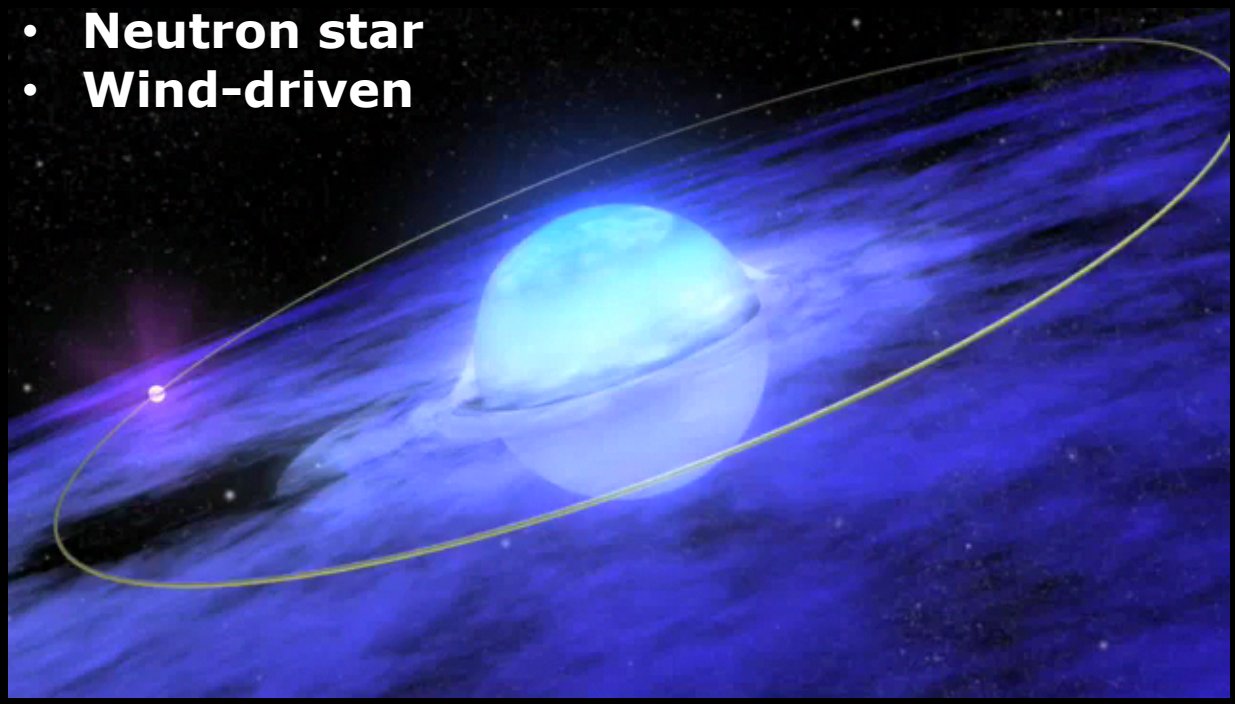
VHE Supernova Remnants can be very bright...

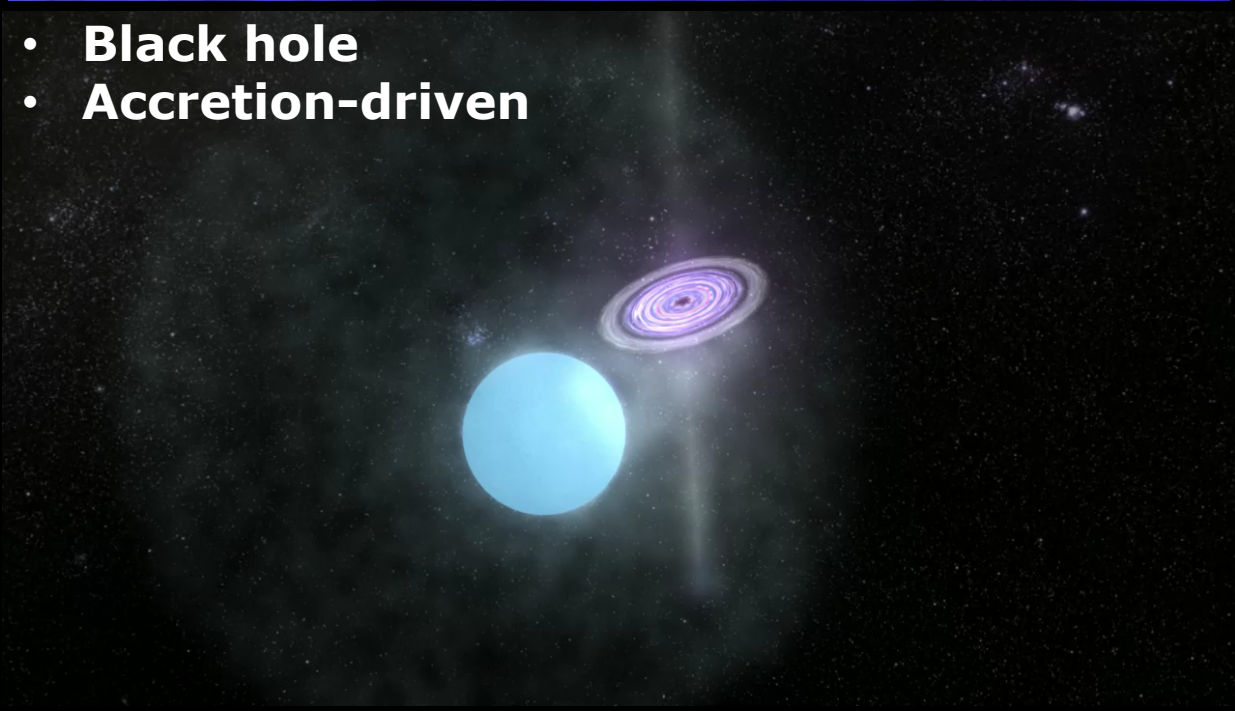


HESS Collaboration: Stegmann, Trichard, 2013 ICRC

Gamma-ray Binaries

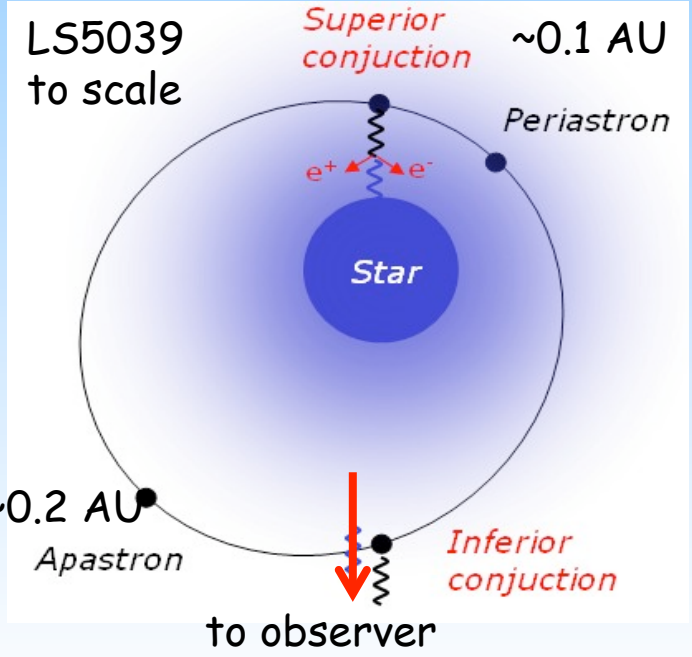
- A massive star, and a compact companion
- The *only* variable galactic TeV sources
- Natural particle accelerators operating under varying, but ***regularly repeating***, environmental conditions.
- Various different sources of energy-dependent modulation
- Only a handful have been detected, and their power source is often unclear.
- No clear evidence for any black-hole systems at VHE



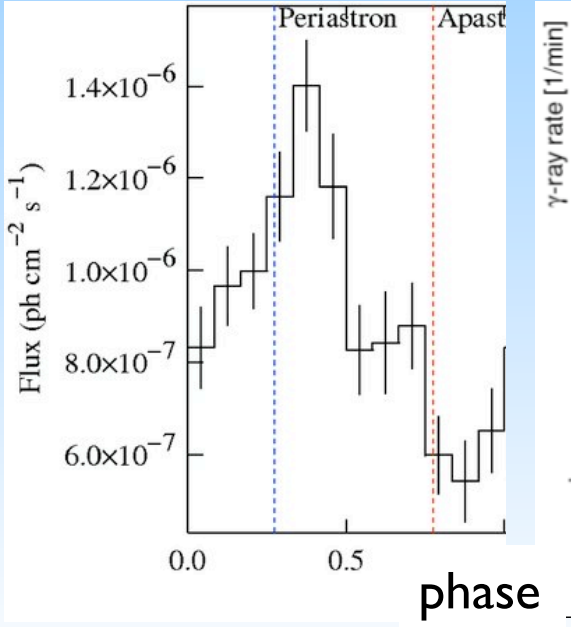


Gamma-ray binaries

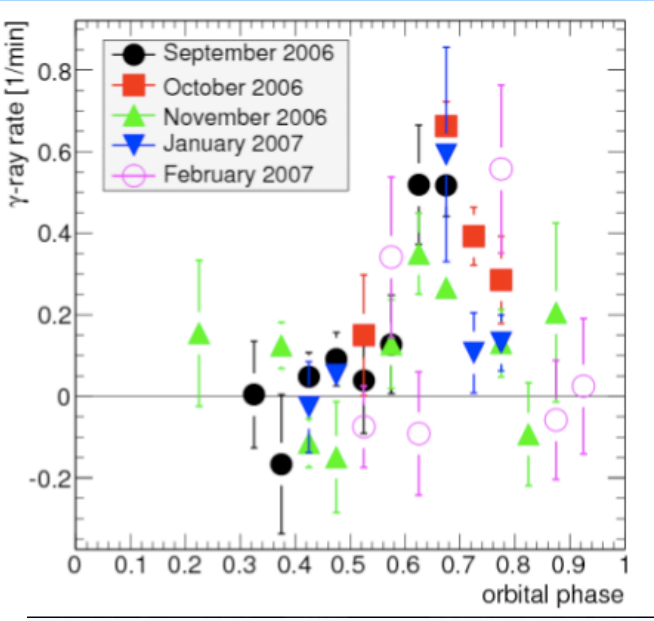
- Some of the features, such as anti-phased modulation at GeV and TeV energies, might be explained by geometry and competition between processes
- e.g. at superior conjunction, head-on electron-photon scattering makes inverse Compton gamma-ray production most efficient over all energies – but this is also the phase at which the TeV photons are most effectively absorbed.
- Certainly important, but this alone is not sufficient to describe all of the observed features.



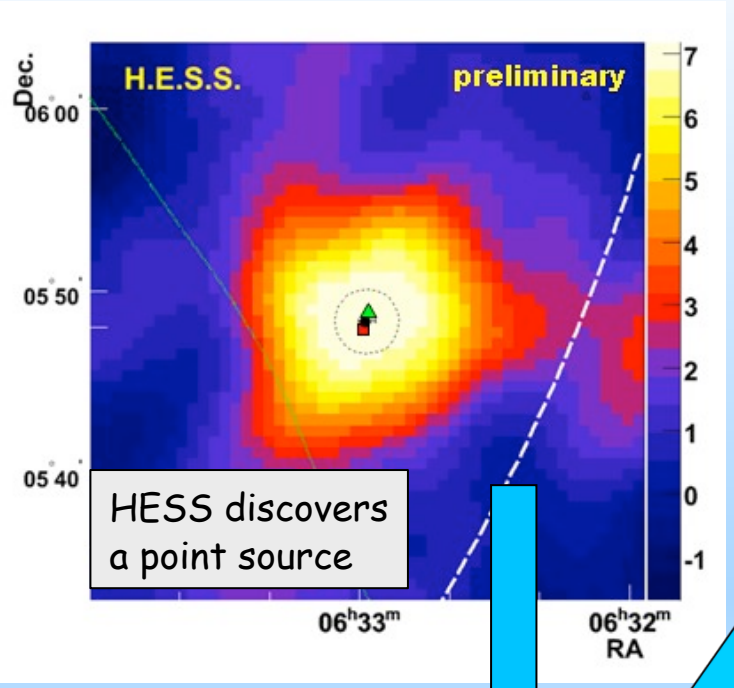
LS I +61 303 Fermi

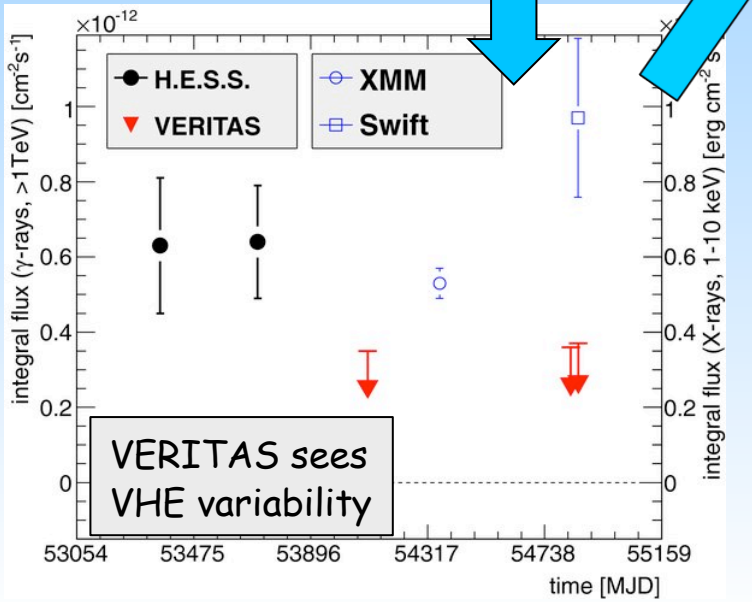


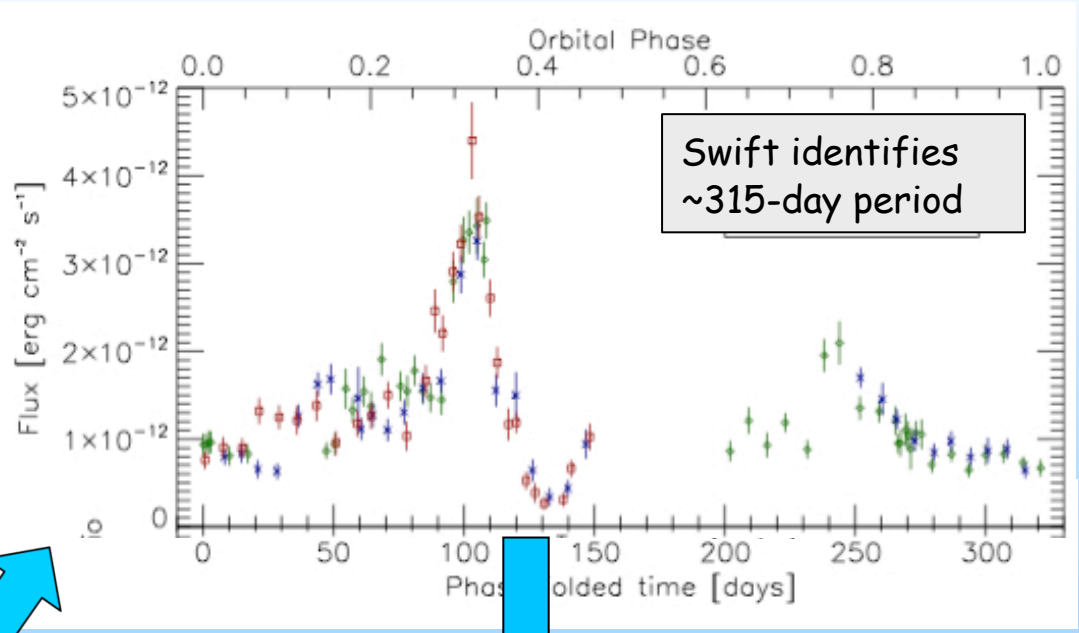
LS I +61 303 VERITAS

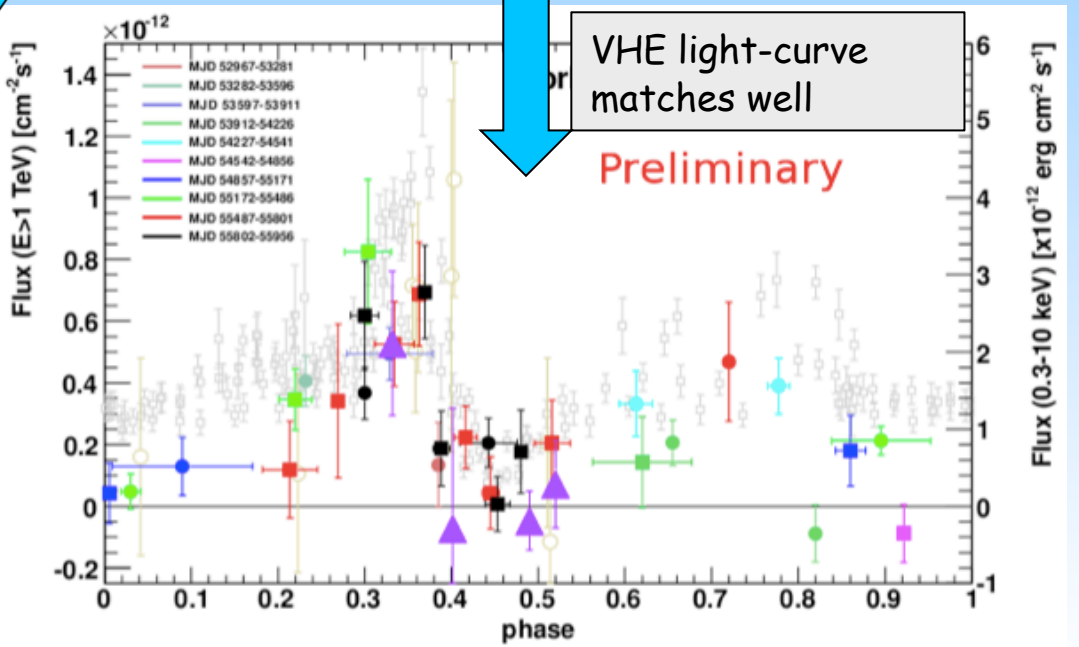


A VHE binary discovery: HESS J0632+057



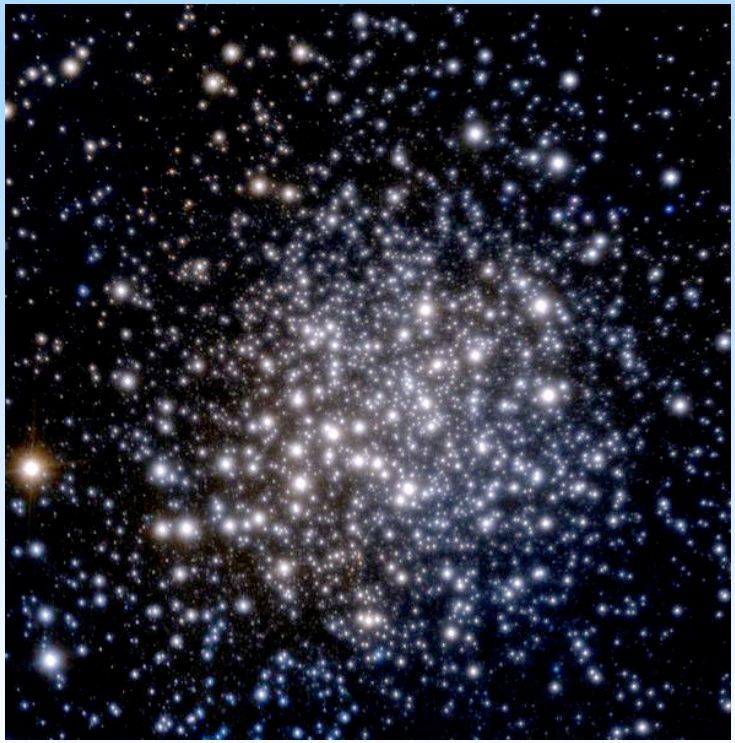


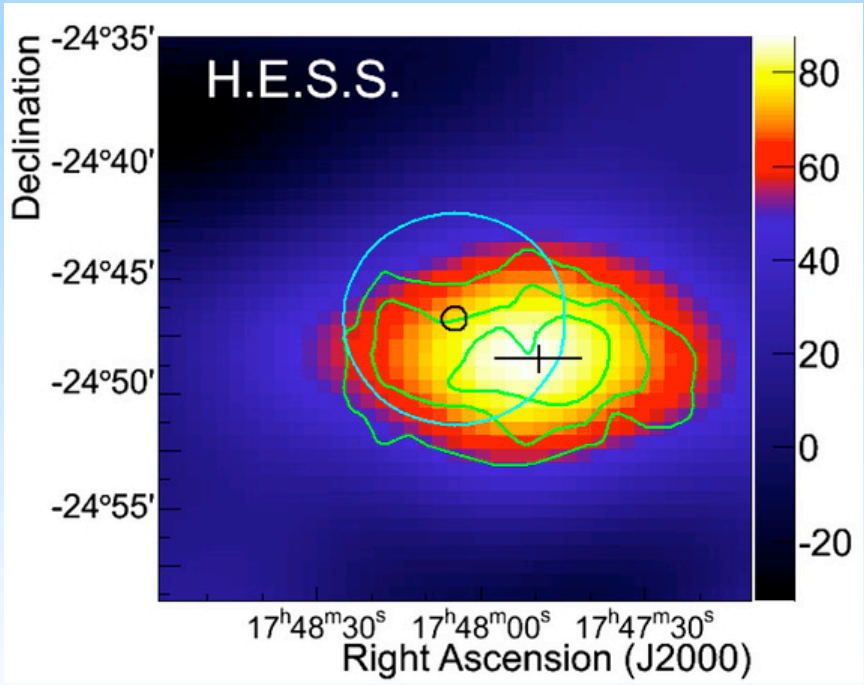




A globular cluster (?)

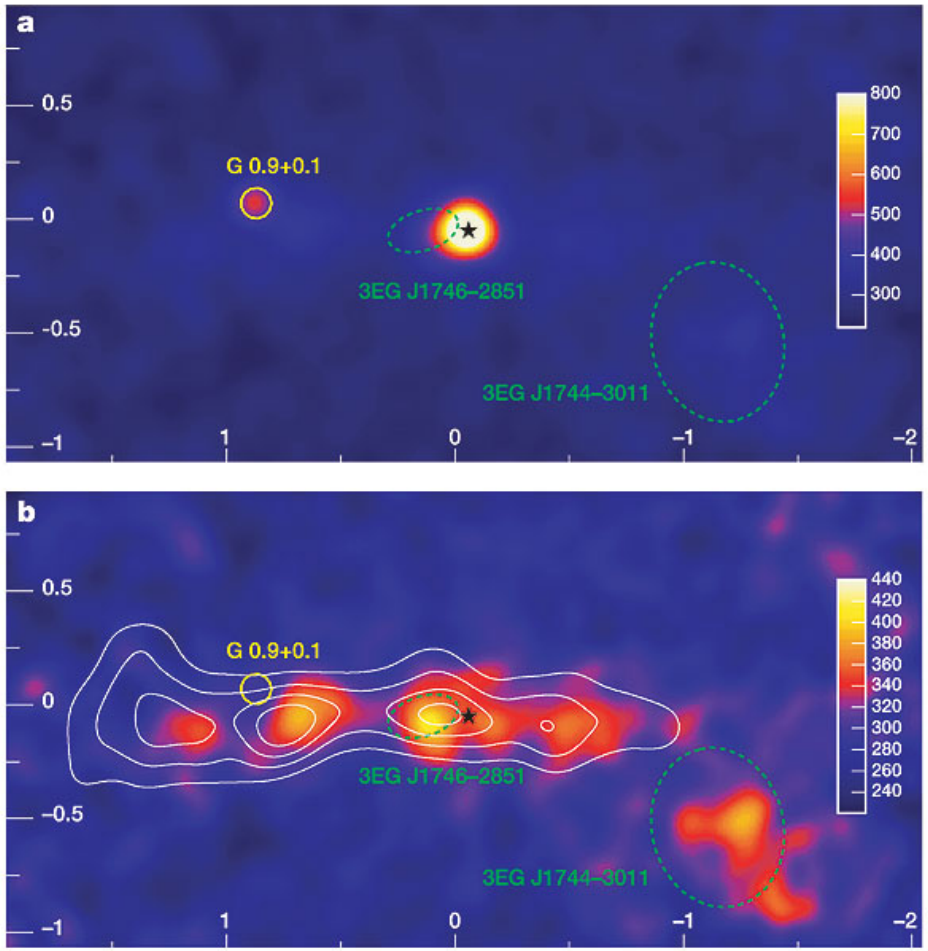
- VHE emission could be produced by inverse Compton of an electron population accelerated by millisecond pulsars.
- HESS detects a source *in the direction* of Terzan 5, a globular cluster which hosts the largest population of identified radio millisecond pulsars, and a very large core stellar density.
- The emission is elongated, and slightly offset – chance coincidence, given measured distribution of Galactic sources is ~0.01%.

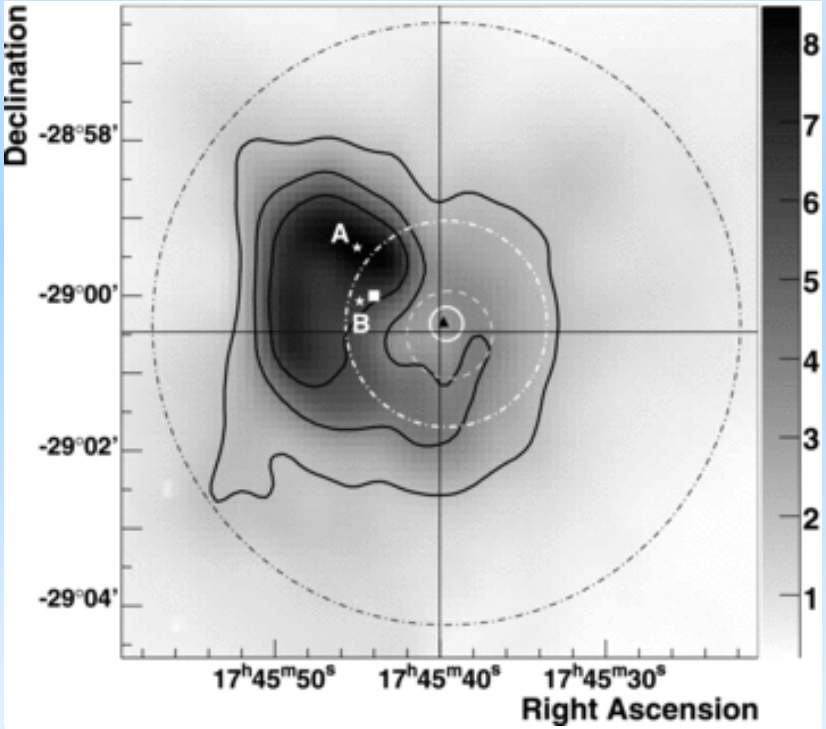




The Galactic Center Region

- TeV emission from the Galactic Center is dominated by a bright central source, coincident with the supermassive black hole, SgrA* (but also with a PWN).
- The emission is steady, with an $E^{-2.1}$ power law spectrum which cuts off ~10 TeV.
- A fainter diffuse component is also seen, extending along the plane.
- Spatial correlation with molecular clouds implies a pion decay origin.

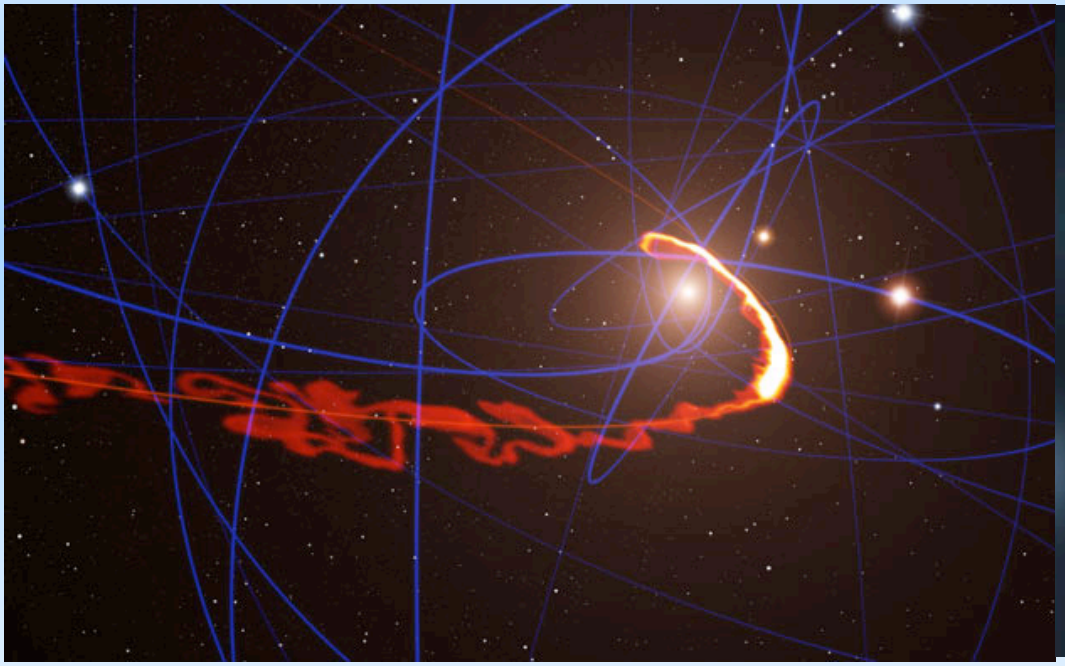


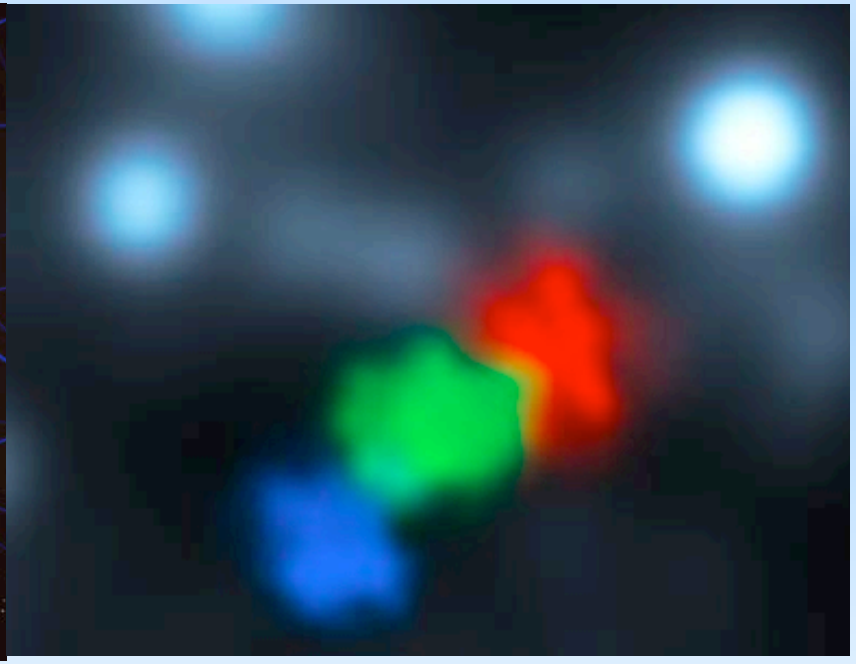


Cross hairs: SgrA*
Black triangle: G359.95−0.04 (PWN)
White circle: HESS source

The Galactic Center Region

- Gas cloud interaction is now underway.
- The event will last at least a year, pericenter predicted for early 2014.



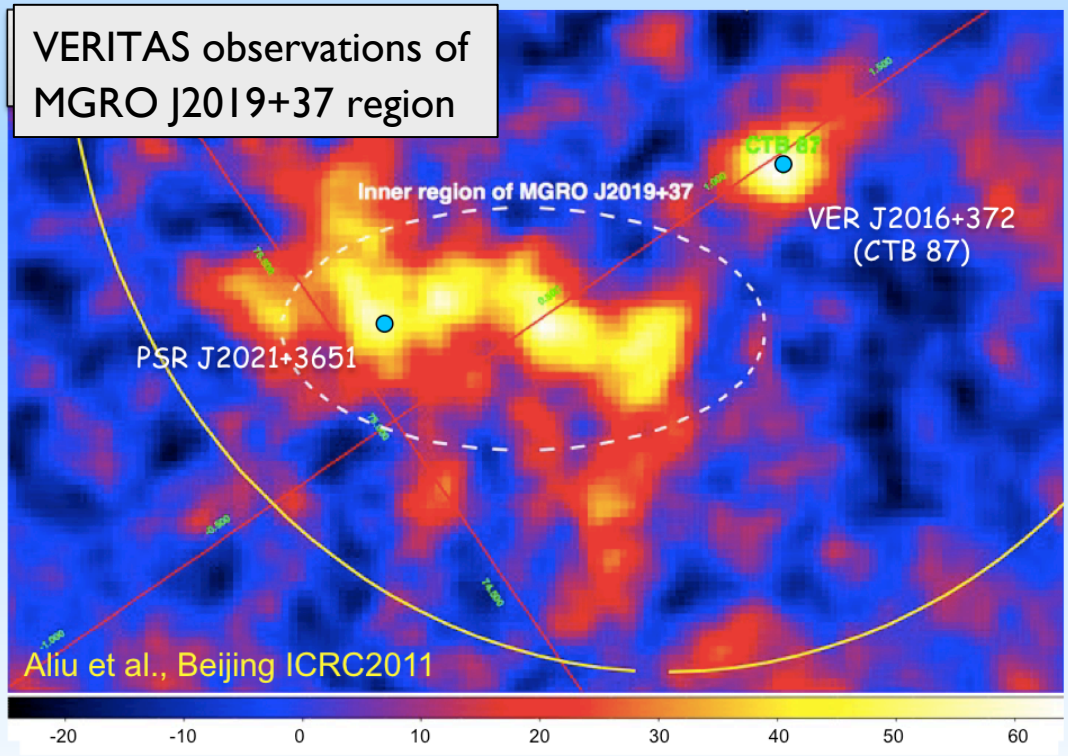


http://www.eso.org/public/news/eso1332/

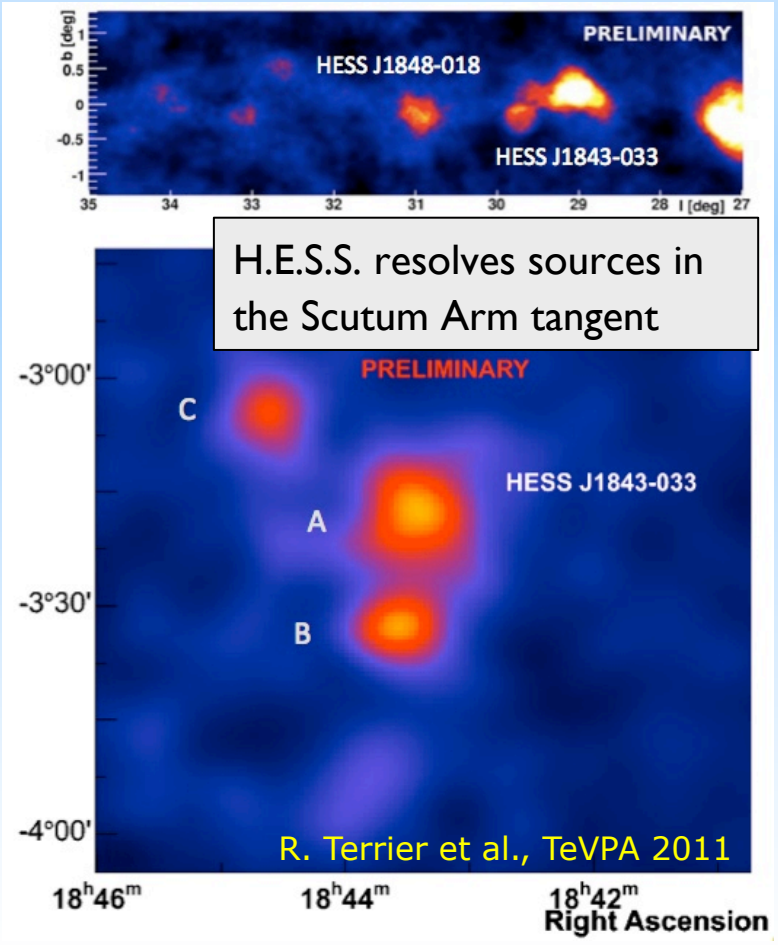
Many "works in progress"…

- Many sources remain unidentified, others are in complex/confused regions with multiple possible interpretations.
- Analysis improvements, more data, and multiwavelength studies can often help
- And then there's CTA…

VERITAS observations of MGRO J2019+37 region

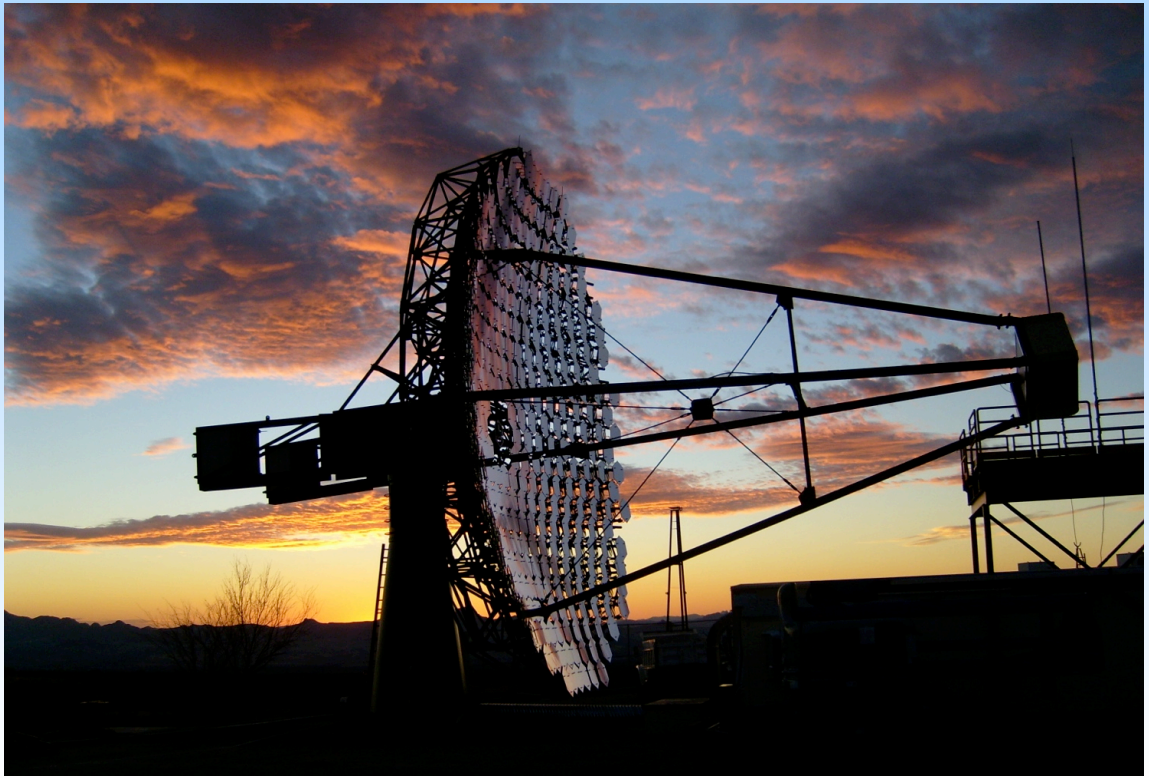


H.E.S.S. resolves sources in the Scutum Arm tangent



Summary

- The Galaxy is rich in TeV sources – astrophysical particle acceleration can take place in many and varied environments.
- Observations with the current generation of instruments have barely scratched the surface; the success of CTA is guaranteed.
- IACTs are precision instruments, with good angular, spectral and temporal resolution
- These features, combined with multiwavelength observations, and our growing knowledge of what constitutes a likely gamma-ray source, should allow us to ultimately disentangle most astrophysical backgrounds from potential DM signatures.



Resources and Acknowledgements

J. McEnery et al: ICRC, Rio de Janeiro, 2013
C. Stegmann et al.: ICRC, Rio de Janeiro, 2013
R.Mirzoyan et al.: ICRC, Rio de Janeiro, 2013
R.A. Ong et al.: ICRC, Rio de Janeiro, 2013
W. Benbow et al.: ICRC, Rio de Janeiro, 2013

Backup

A few things to think about (not exhaustive)...

What is the power source?	Accretion-powered jet	Pulsar wind		
What is the particle acceleration mechanism?	Jet shocks	Magnetic reconnection	Wind shocks	
What are the dominant particles?	Hadronic	Leptonic		
How are the γ-rays produced?	Pion decay	Inverse Compton	Curvature Radiation	
Where are the γ-rays produced?	Near the jet	Wind collision region	Pulsar wind zone	
	Circumstellar environment	Pulsar magnetosphere		
What modulates the flux?	Geometry	Photon fields	Matter density	B-fields
Other effects?	Wind clumping	Pair cascades	Unknown geometries	

Many of these are not mutually exclusive...