



Galactic Sources of VHE Gamma-Ray Emission: Highlights from VERITAS

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Outline



- (Quick) introduction to VERITAS
- Overview of the VERITAS Galactic Science program
- Results
 - VERITAS Sky Survey
 - Supernova Remnants
 - Binaries & other *(if there is time)*

VERITAS at Whipple Observatory



T1 move (Summer 2009).

Substantial improvement in sensitivity over old configuration.

1% Crab source now in 26 hrs.

- 100 GeV to > 30 TeV.
- **Spectral reconstruction:** begins at ~ 150 GeV.
- **Ang. Resolution:** $< 0.1^\circ$ at 1 TeV, 0.14° at 200 GeV (68%).

- Four 12-m imaging atmospheric Cherenkov telescopes.
- Located at Whipple Observatory Base Camp, Arizona, USA (1268 m).
- Full operations began Fall 2007.
- One telescope moved to new location in summer 2009.
- > 1100 hrs of observation time per year (including 200 + hrs in moon light).

Galactic Science Program



Key Science Projects:

- **Cygnus region sky survey**
(limited blind survey)

- **Supernova remnants/PWNe**
(pointed observations)

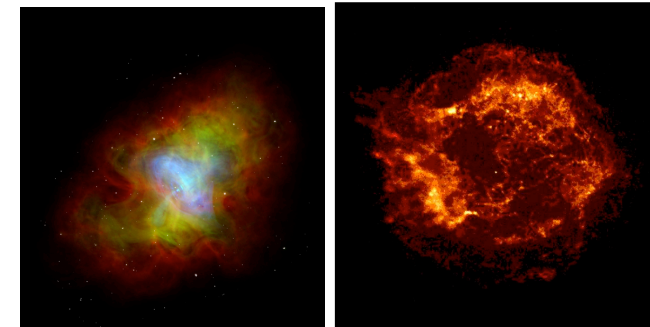
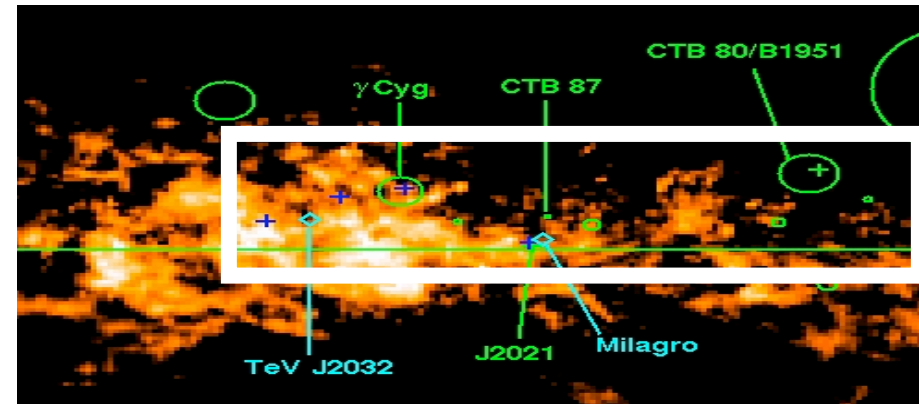
- Non-thermal shells.
- Shell-molecular cloud interactions.
- TeV PWNe associated with high E_{dot}/d^2 pulsars.

- **TeV observations of binaries:**

- Binaries are the *only* variable Galactic TeV sources.
- TeV emission probes the highest energy particles. accelerated.
May provide the keys to an understanding of astrophysical jets.

- **Unidentified Galactic sources**

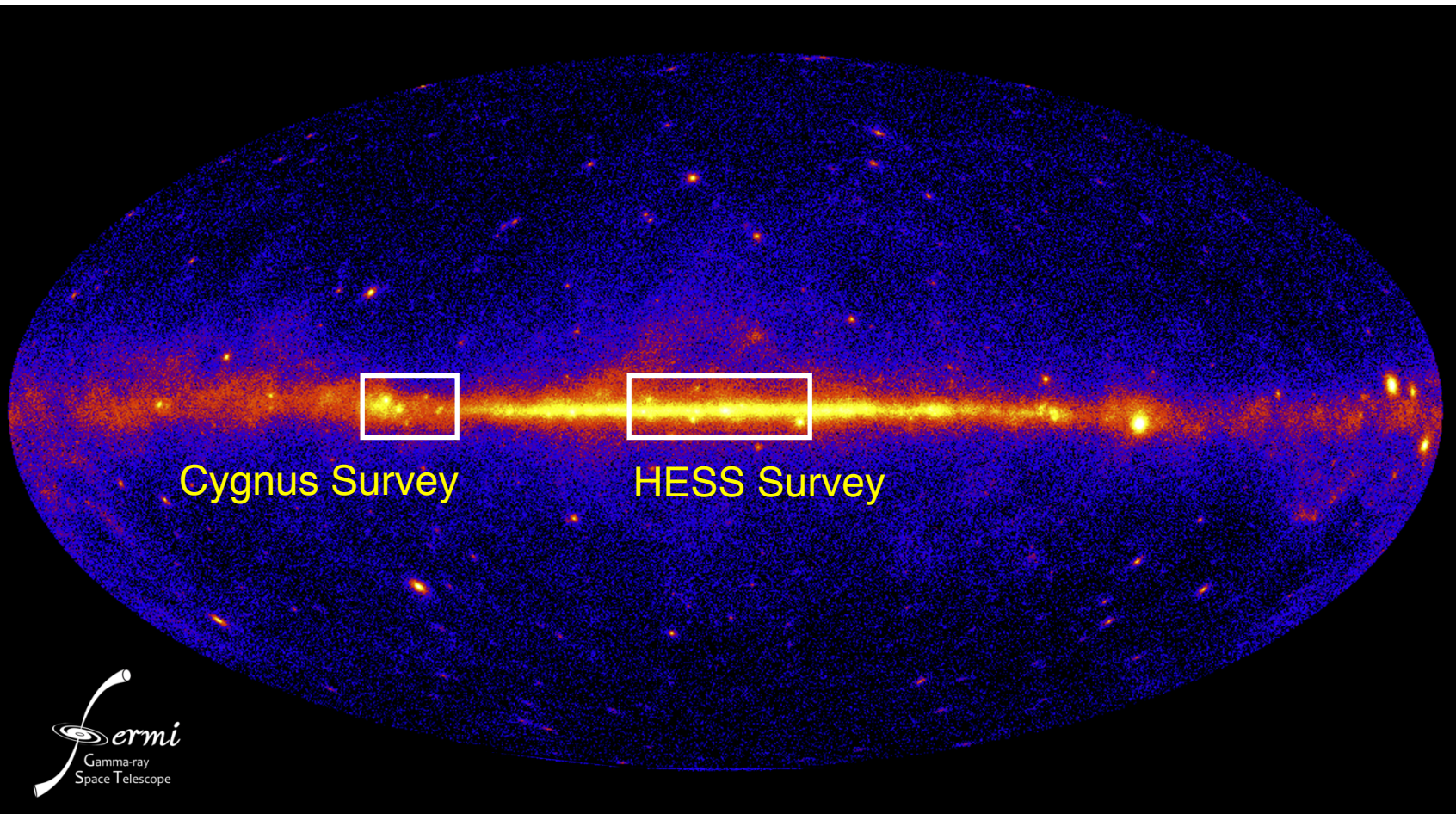
- Fermi unidentified sources & transients in the Galactic plane.



VERITAS Sky Survey



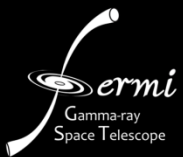
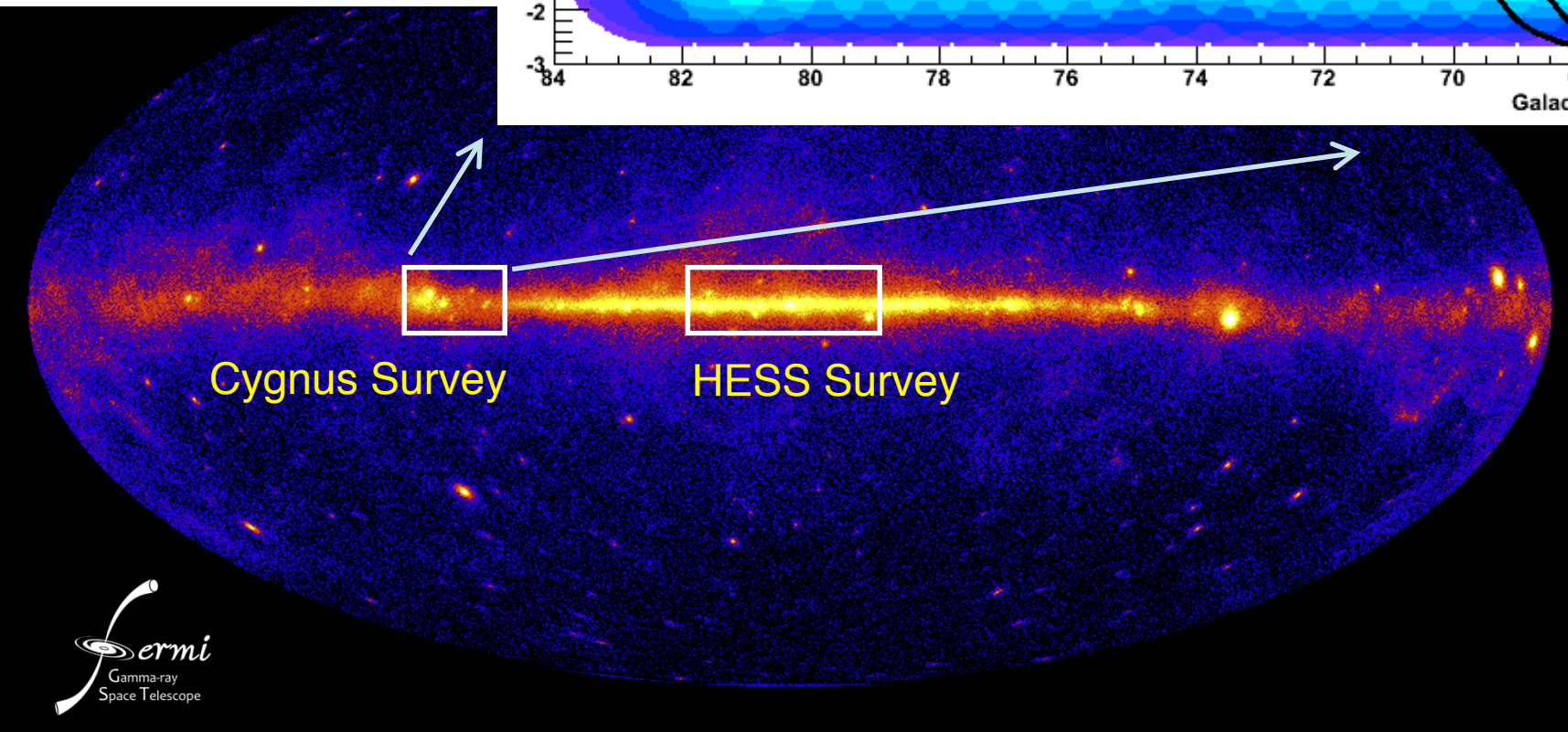
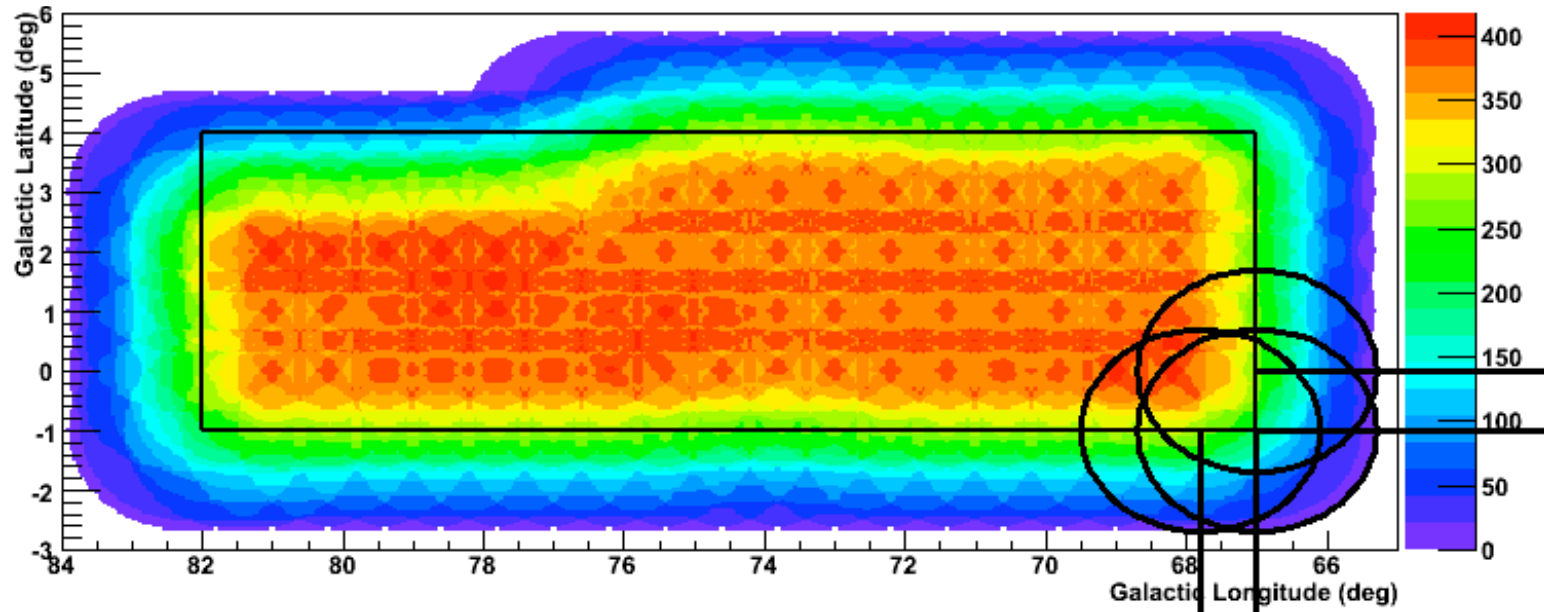
Cygnus Region Coverage:
 $67^\circ < l < 82^\circ$, $-1^\circ < b < 4^\circ$



VERITAS Sky Survey

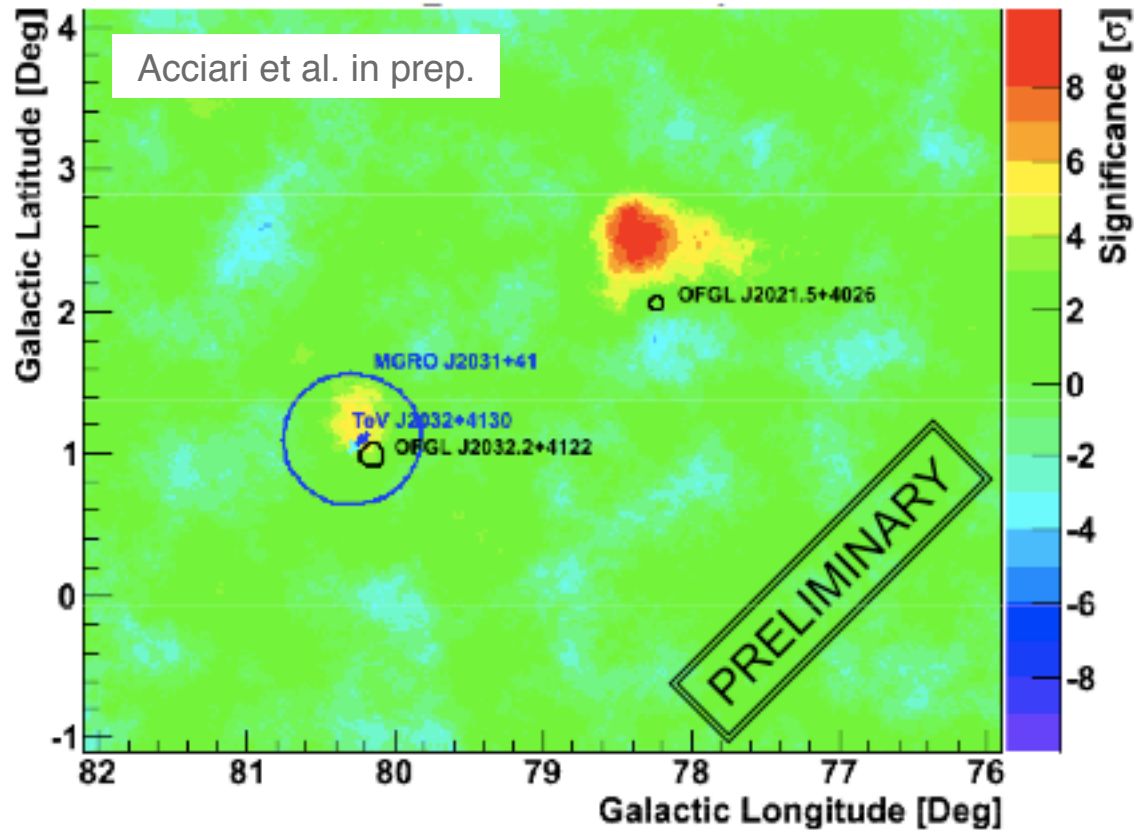


- 112 base hrs with 56 hrs of follow-up studies .
- Depth: $<3\%$ Crab above 200 GeV (99% CL) for point-like sources.



Acciari et al. in prep.

VERITAS Sky Survey



New Source!
VER J2019+407

TeV J2032+4130 –

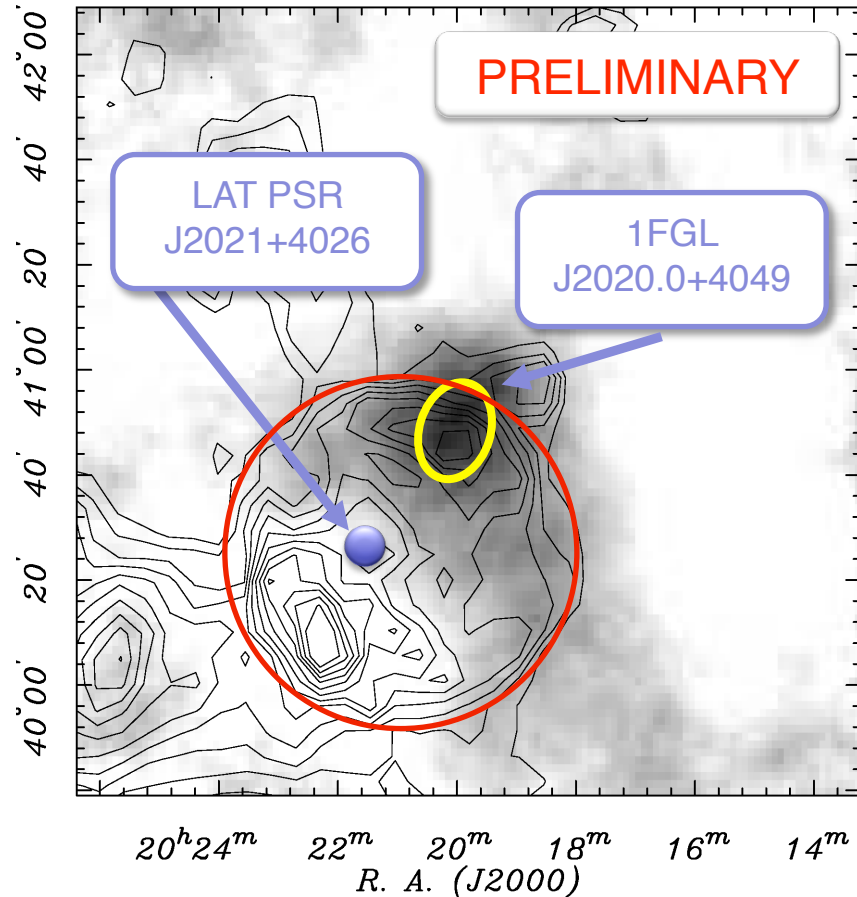
- First unid. source, detected by HEGRA.
- Possible associations:
 - MGRO J2031+41.
 - OFGL J2032.2+4122/1FGL J2032.2+4127.
- VERITAS detection $>5\sigma$ at nominal position (no trials).

- Follow-up candidate from sky survey.
- Independent data set from Fall 2009 (~21hr) confirms existence of a new source at $\sim 7.5\sigma$.
- Flux level ~ 2 -5% Crab.
- Preliminary extension: $\sim 0.2^\circ$ symmetric Gaussian fit.

VER J2019+407



VERITAS Excess Map



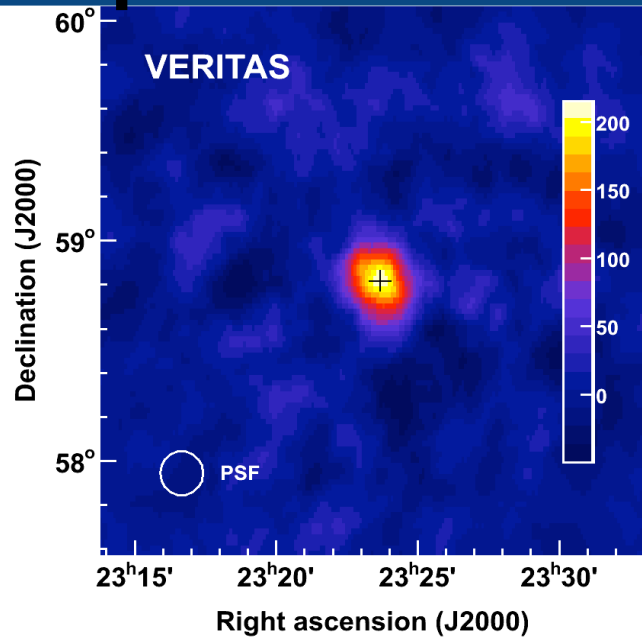
- Peak in NW corner of G78.2+2.1 (γ -Cygni).
- What is the TeV mechanism?
 - Is it shock-cloud interactions?
 - Is it the PWN of Fermi PSR J2021+4026?
- Plenty of CO in southeast, not much in northwest.
- Two partial shells in HI, one in northwest (Ladouceur & Pineault 2008).
- Cloudlets? Enough mass in HI?

Acciari et al. in prep.

Supernova Remnants: Cas A

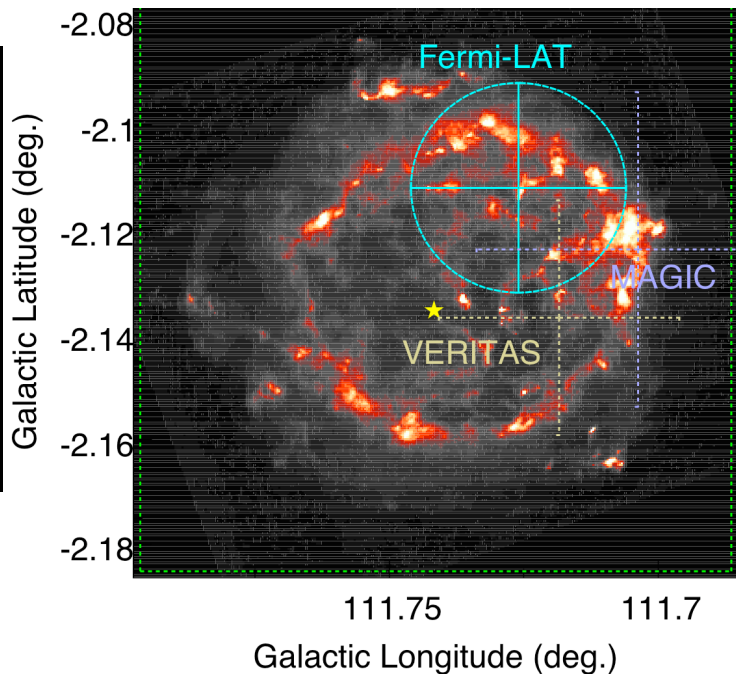


Acciari et al. ApJ 714 (2010)



- Young (330 yr), shell-type SNR. $D \sim 3.4$ kpc.
- Radio – sub mm – IR to X-ray emission is synch.
- Morphology of non-thermal X-ray emission is dominated by faint, well-defined filaments and knots, which are sites of CR acceleration.

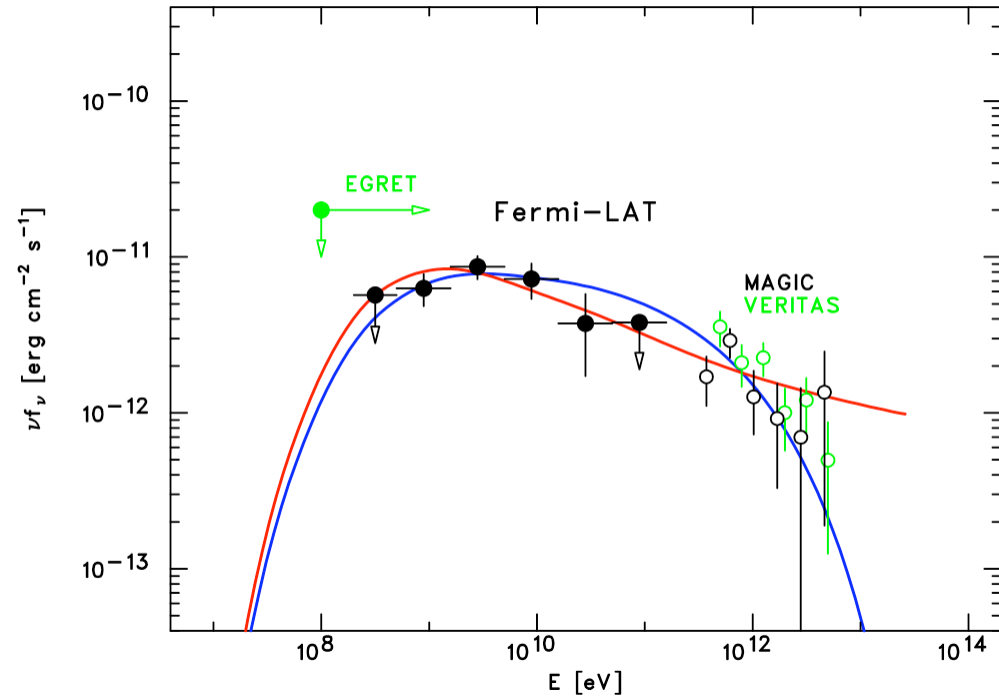
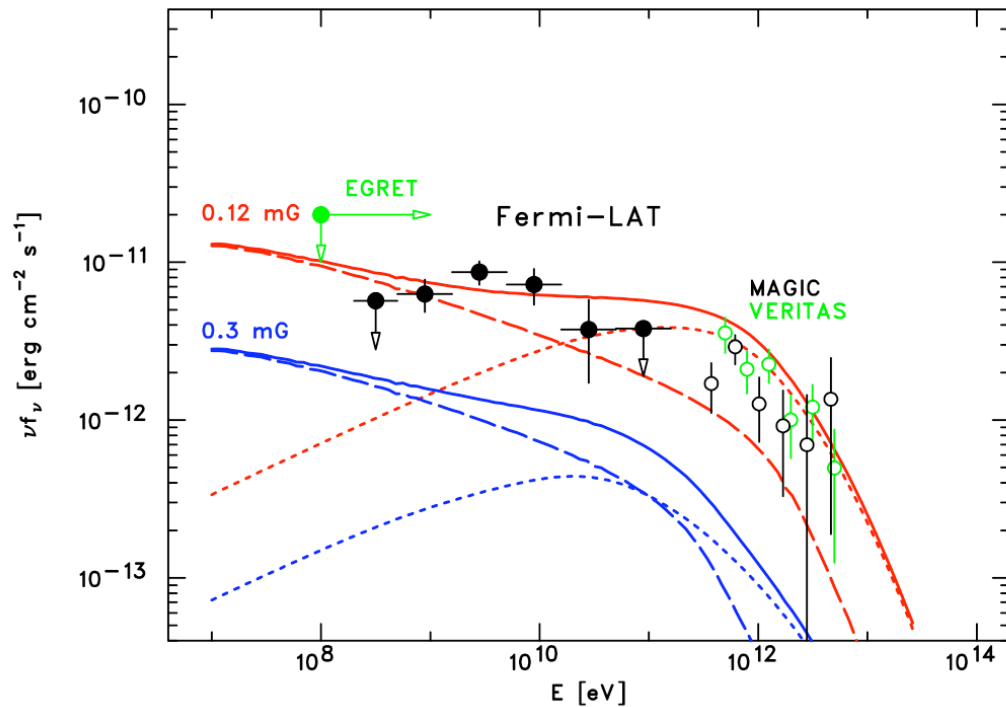
Abdo et al. ApJL 710 (2010)



- VERITAS:
 - Obs. in Oct/Nov 2007. Exposure: 22 hr.
 - Detection 8.3σ . Consistent with point src.
 - Index $\Gamma = 2.61$. No evidence for cutoff.
 - Flux (> 1 TeV) $\sim 3.5\%$ Crab.
- Fermi detection:
 - Point source. No pulsations from CCO.

Acciari et al. ApJ 714 (2010)

Cas A: Modelling from Fermi Team



- Leptonic Model:
 - $B=120\mu\text{G}$
 - $\Gamma: -2.34 + \text{cutoff at } 40 \text{ TeV}$
 - Dashed Line –Brem
 - Dotted Line –IC (dominated by FIR)

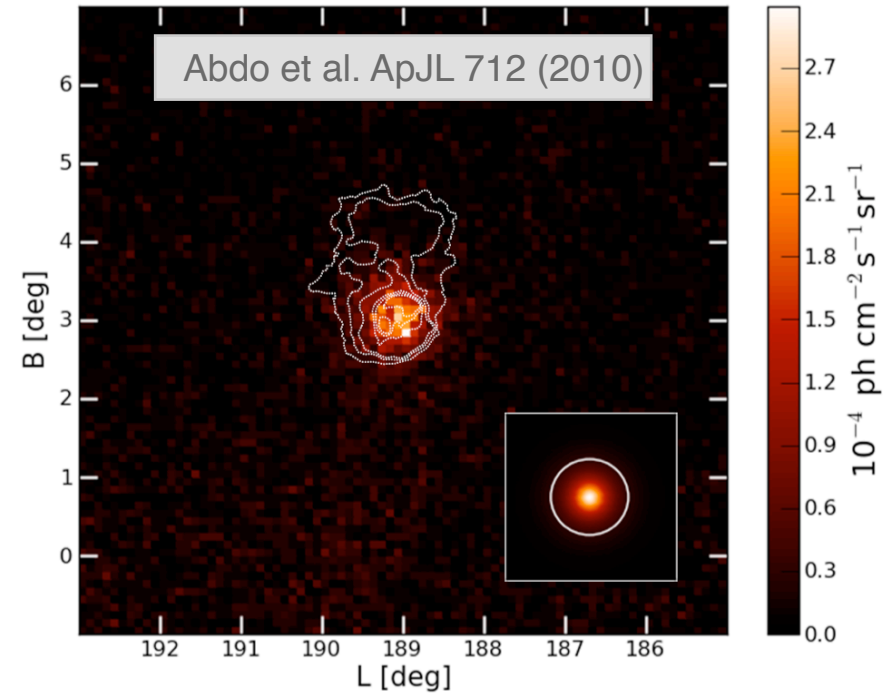
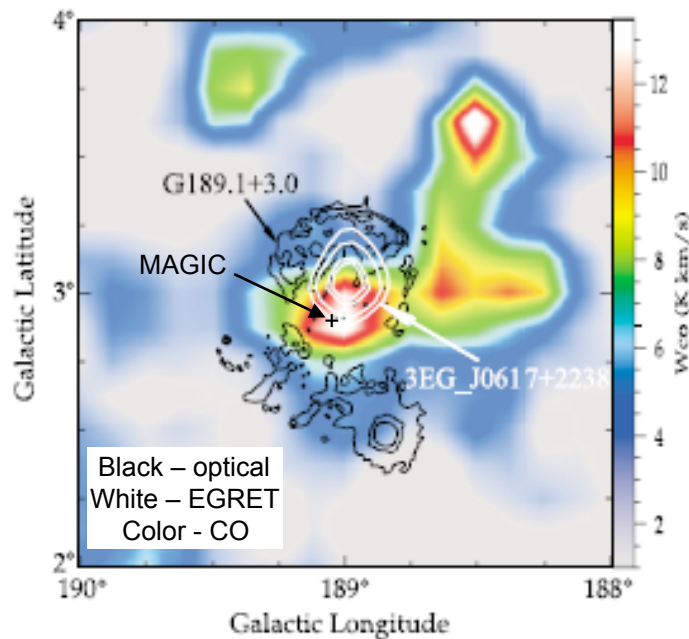
- Hadronic Model: π_0 decay spectra for two possible proton spectra:
 - Blue: $\Gamma: -2.1 + \text{cutoff at } 10 \text{ TeV}$
 - Red: $\Gamma: -2.3$

■ Fermi spectrum favors scenario in which the GeV gamma rays are emitted in the shell of the SNR.

■ Hadronic model is favored, but leptons not ruled out.

Abdo et al. ApJL 710 (2010)

Results: IC 443



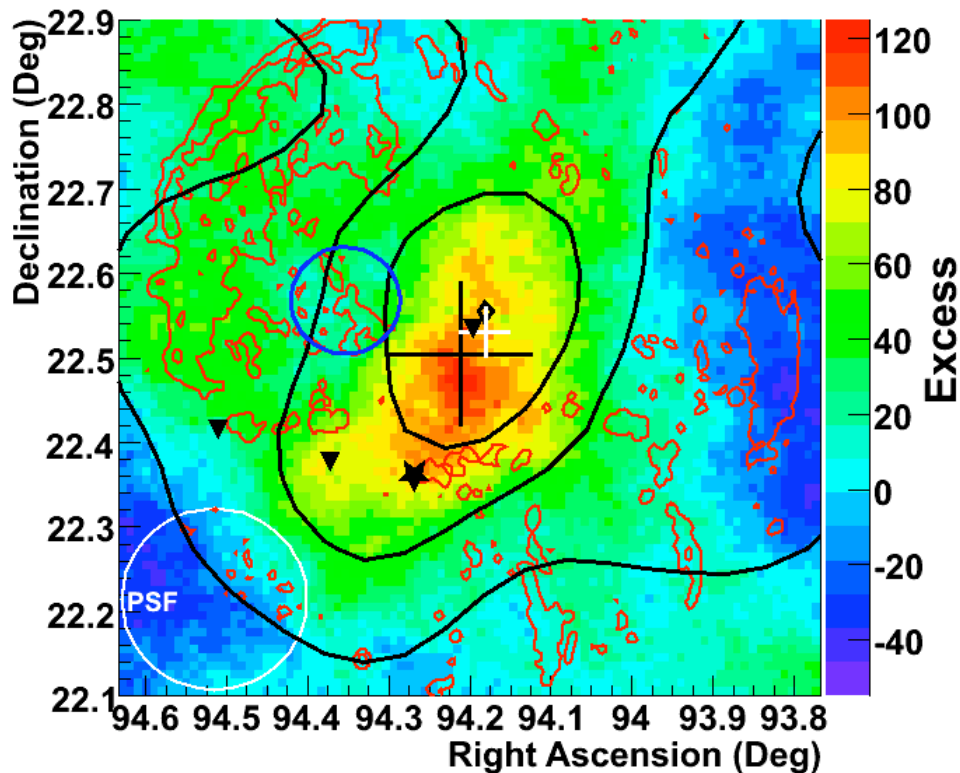
- Distance ~ 1.5 kpc. Age $\sim 30,000$ yr. Distinct shell in radio, optical.
- Shell interacting with molecular cloud -> potential target material.
- EGRET emission centered on remnant, overlaps cloud.
- PWN at southern edge of shell.
- Maser emission suggests SNR shock interacting with cloud.

- Co-Discovery in TeV by VERITAS (2007).
- Fermi Observations, 5-50 GeV.
- Fermi location consistent with VERITAS – Angular Extent $\sim 0.27^\circ$.
- *Compelling reasons to search for TeV emission from IC 443: γ s from cosmic rays, or from the PWN?*

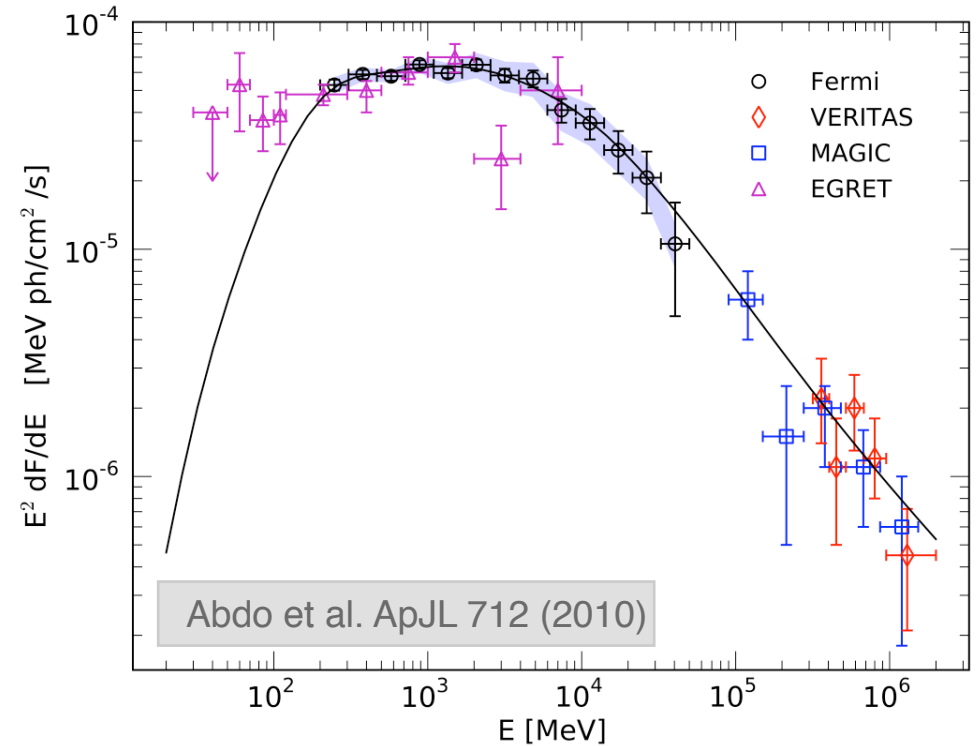
IC 443: Multiwavelength Picture



Acciari et al. ApJL 698 L133 (2009)

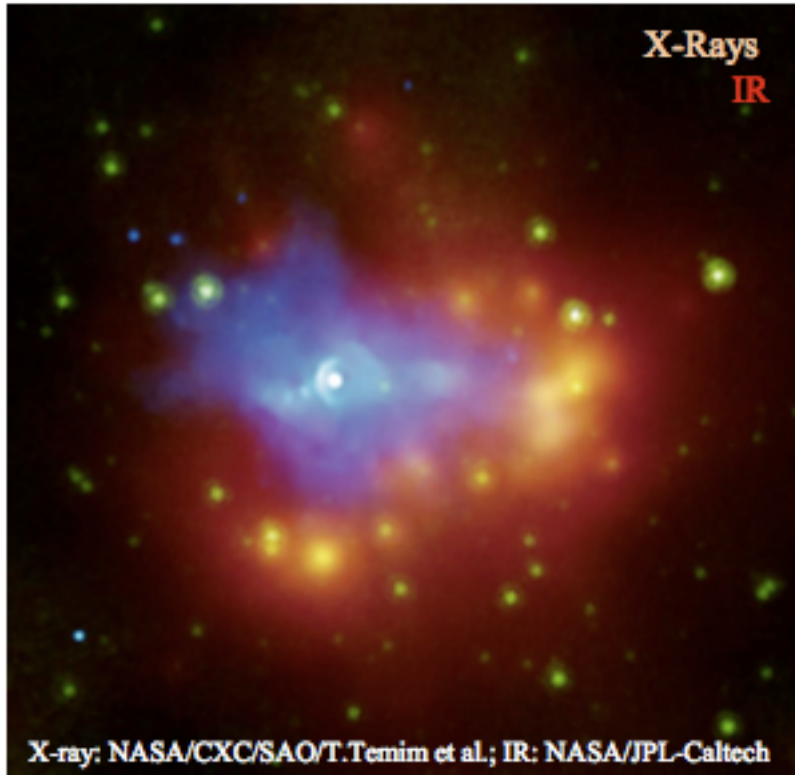


- Total livetime: 38 hrs.
- Significance: 8.3σ .
- Index $\Gamma = 2.99$. 3.2% Crab (> 300 GeV).
- Emission is extended $\sim 0.16^\circ$.



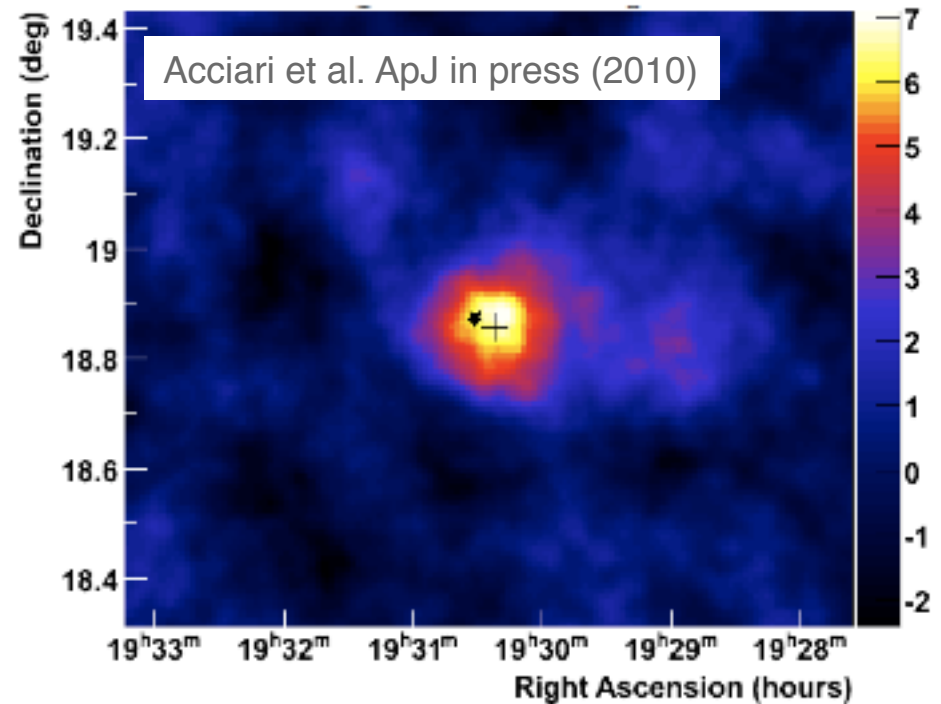
- Hadronic Model:
 - Proton population with broken power law spectrum (70 GeV breakpoint).
 - $10^4 M_\odot$ of target material.

Results: G54.1+0.3



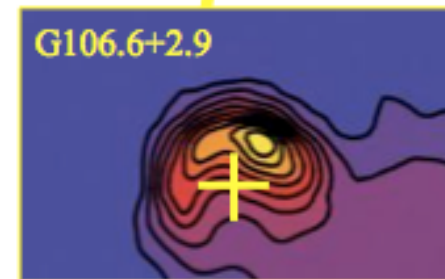
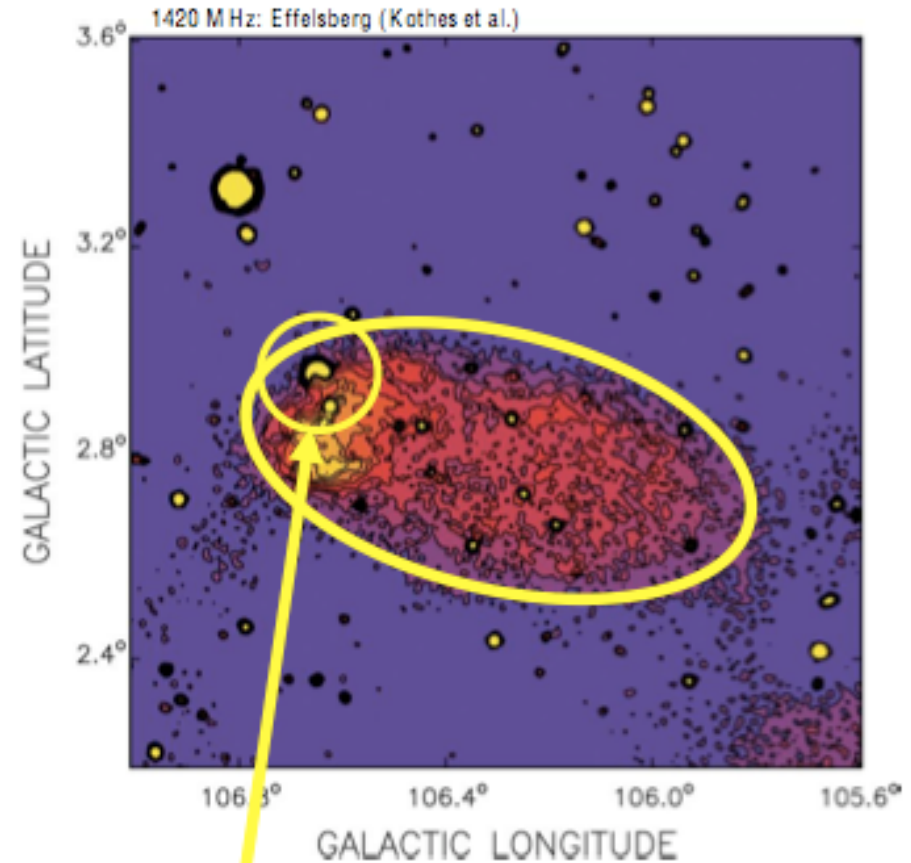
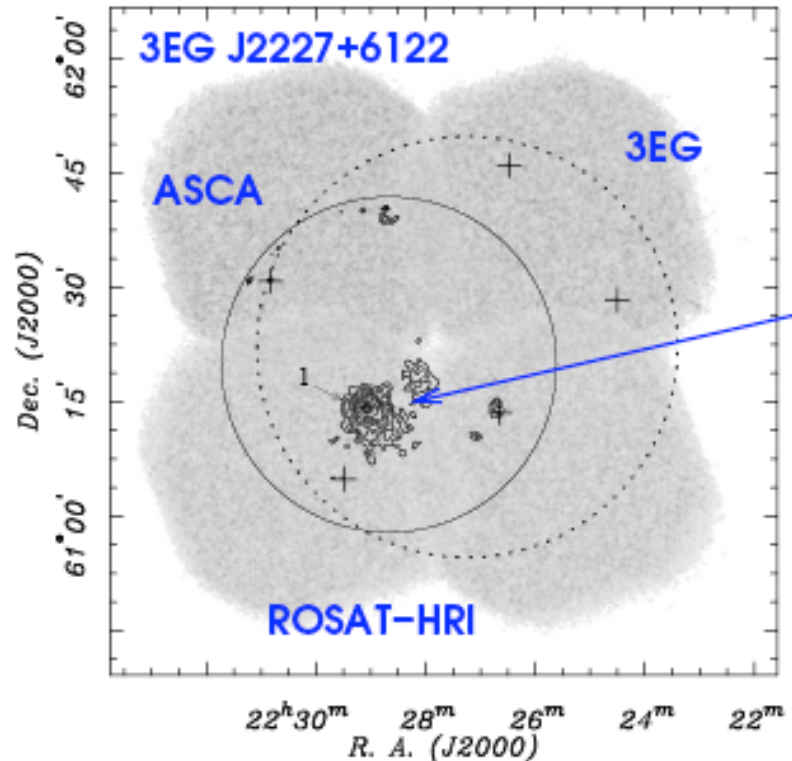
- “Cousin of the Crab”.
- X-ray jet/torus, IR dust shell (Koo 2008).
- Age ~ 2900 years.
- $E_{\text{dot}} = 1.2 \times 10^{37}$ erg/s.
- Distance ~ 6.2 kpc.

VERITAS TeV Significance map



- VERITAS data:
 - Observed in 2008. 7σ in 36 hours.
 - Location compatible with pulsar.
- Gamma-ray Spectrum:
 - Flux (> 1 TeV): 2.5% Crab.
 - Spectral index $\Gamma = 2.4$

Results: Boomerang



Motivations:

- Energetic pulsar + wind nebula discovered in the error box of source 3EG J2227+6122.

- Age $\sim 10,000$ years.
- $E_{\text{dot}} = 2.2 \times 10^{37}$ erg/s.
- Distance ~ 800 pc (Kotthes 2005).

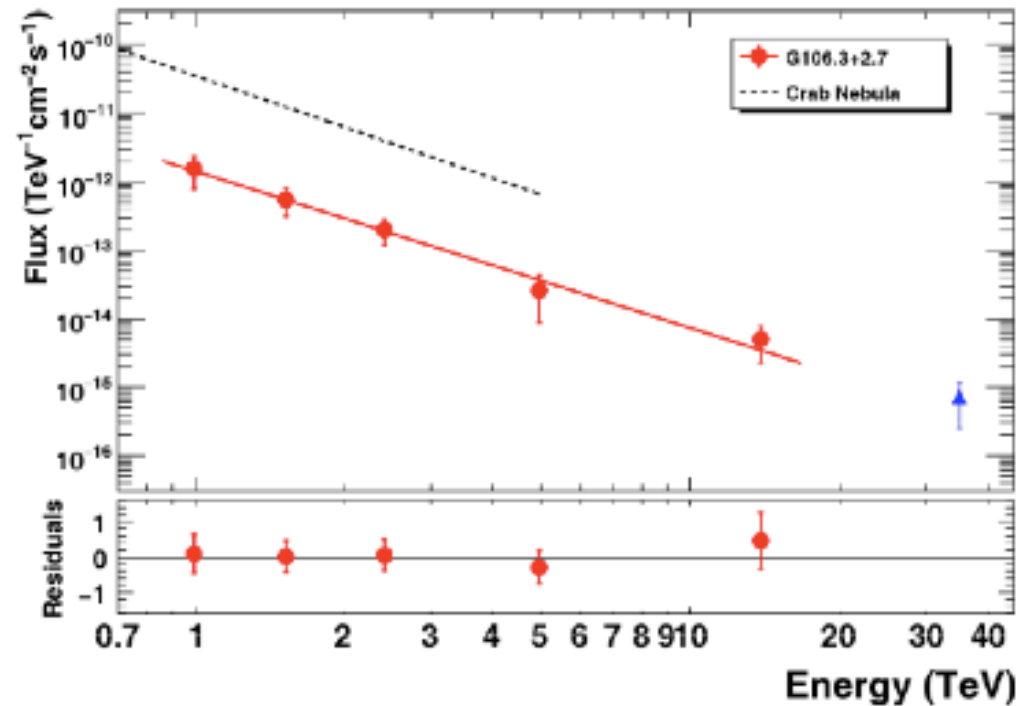
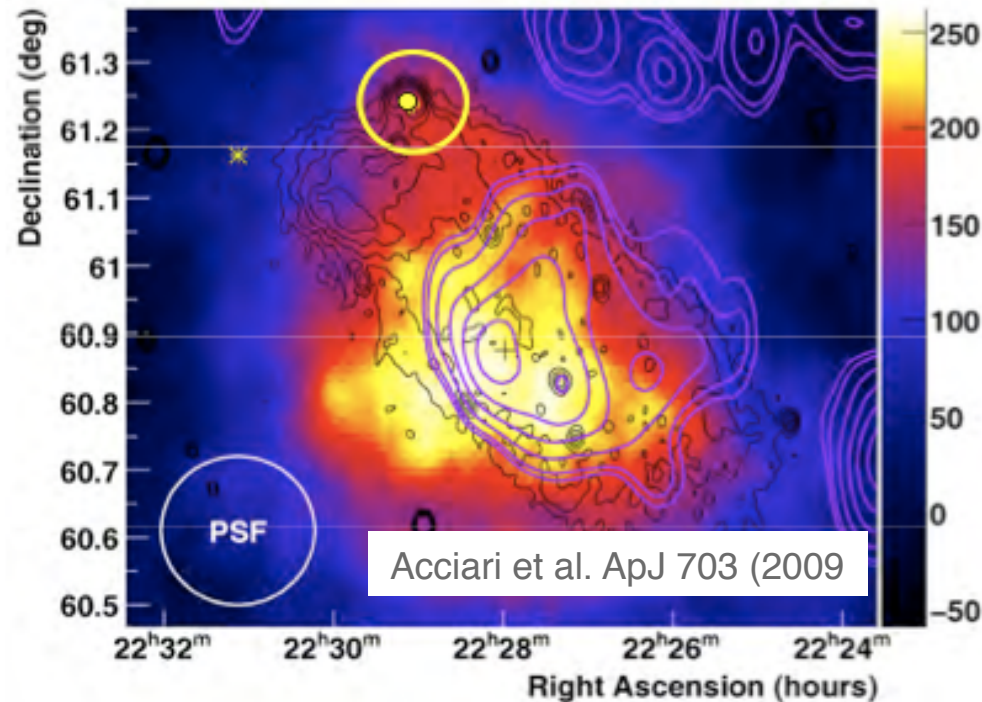
- On Fermi/LAT Bright Source List.

- Emission at ~ 35 TeV reported by Milagro near former “C4” location G106.6+2.9 (Abdo 2009).

Results: Boomerang

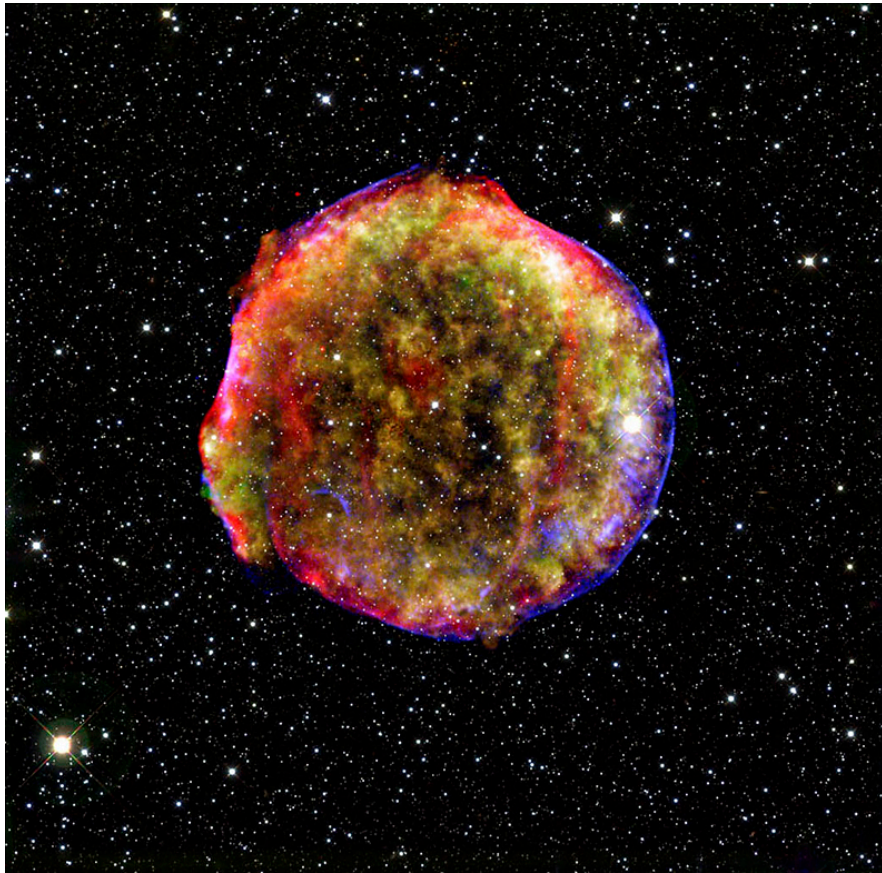


Multiwavelength Excess Map



- VERITAS observations (2008) resolve TeV emission overlapping the radio shell of G106.3+2.7. **7.3 σ detection in 33 hours.**
- TeV emission is extended. Overlaps with region of high CO density.
- Energy Spectrum: Integrate over 0.32 $^\circ$ radius centered on emission peak.
 - Flux \sim 5% Crab (> 1 TeV) Nebula
 - Well fit by pure power law. $\Gamma \sim 2.3$
- Extension of spectrum is consistent within errors with Milagro point at 35 TeV.

Results: Tycho



Composite image of the Tycho supernova remnant combining X-ray (Chandra) and infrared (Spitzer) observations.

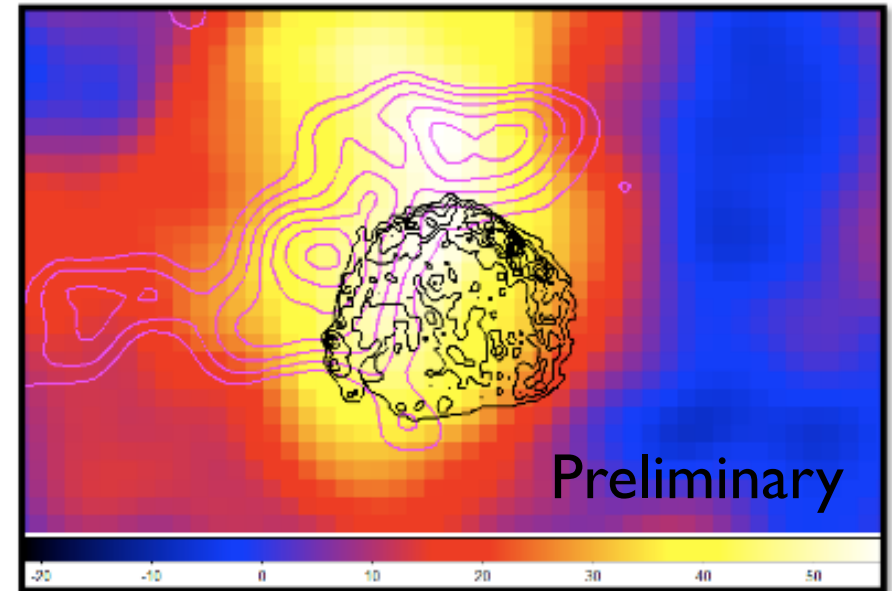
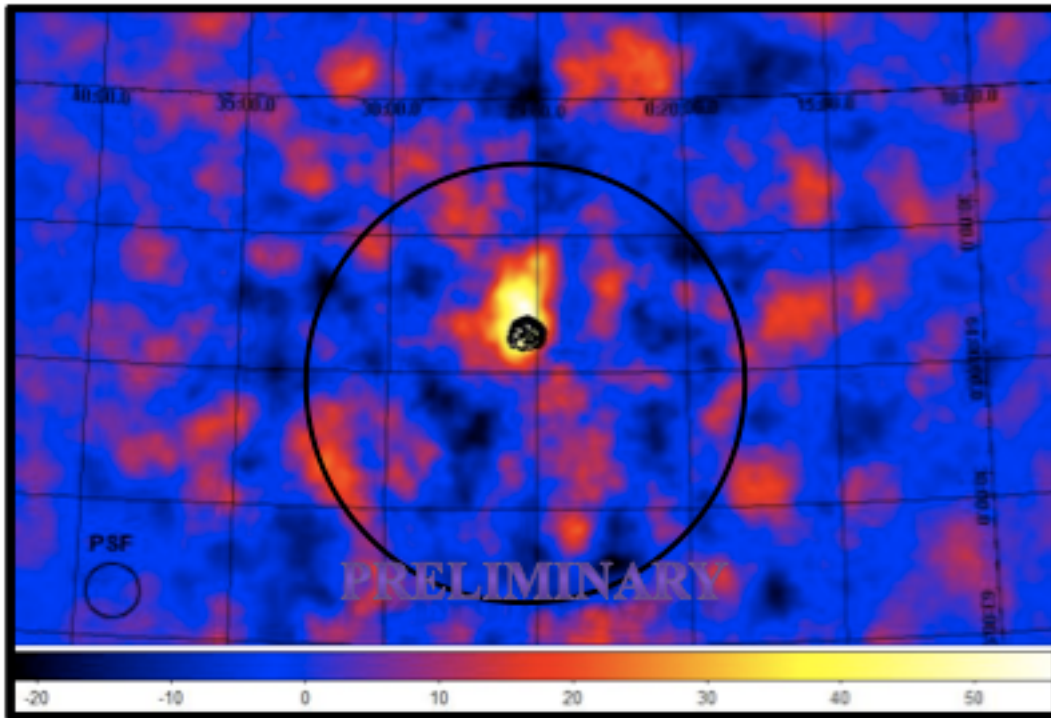
- Remnant of a Type Ia Supernova event of 1572.
- Size: ~ 8 arcmin.
- Distance: 2.5 kpc–5.0 kpc.
- Bright X-ray rims and filaments interpreted as evidence for electrons up to ~ 10 TeV.

GeV Observations:

- No Detection by EGRET.
- No 1FGL sources within 3° .

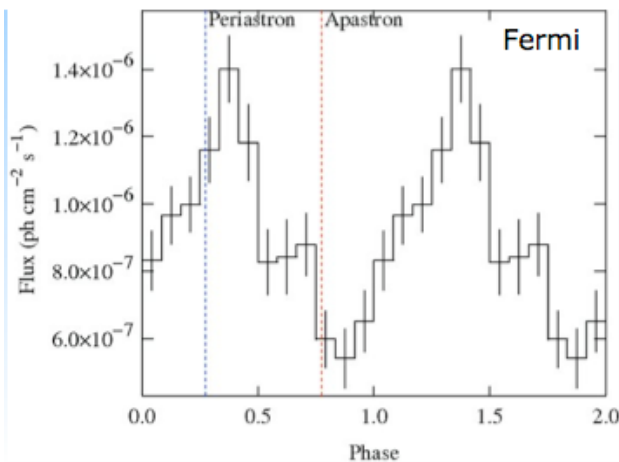
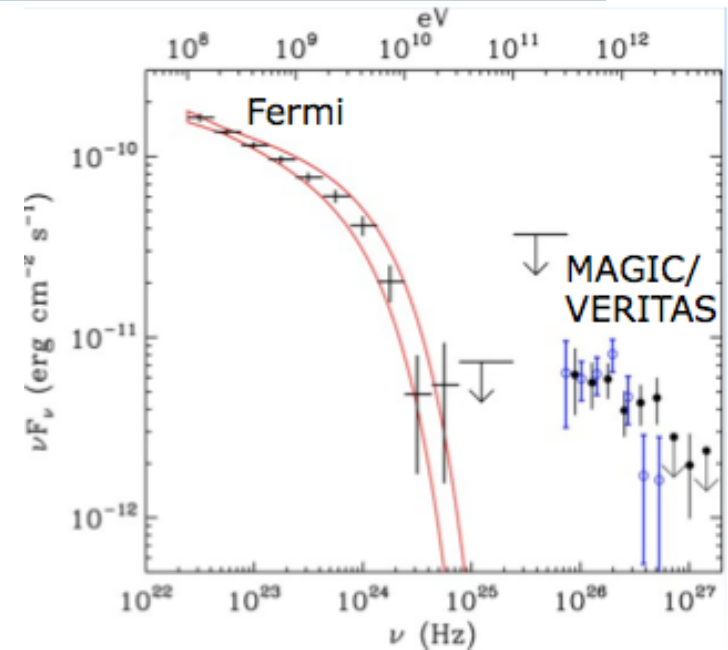
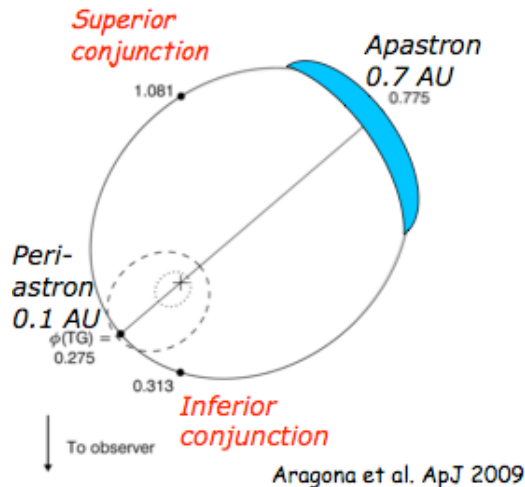
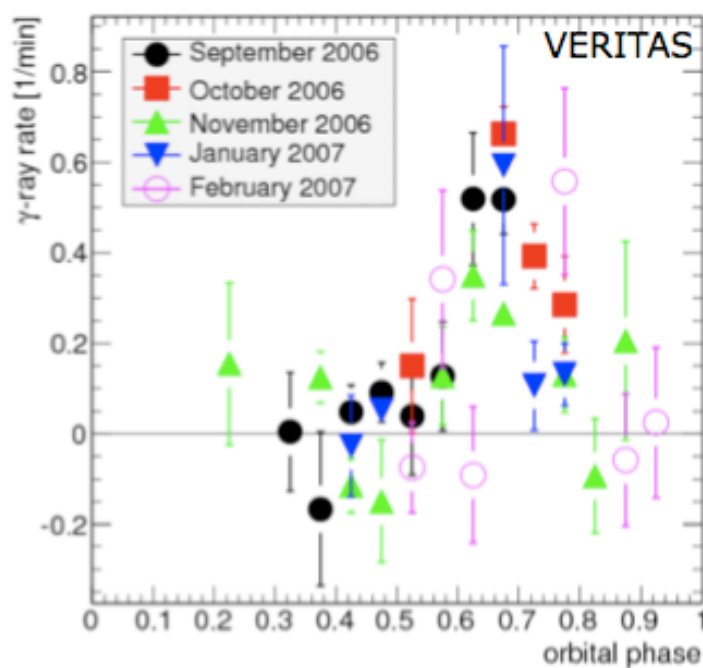
Past TeV Observations – Limits from Whipple, HEGRA. MAGIC limit: (>1 TeV) $< 1.7\%$ Crab (3σ).

Results: Tycho



- VERITAS: 67 hours from 2008 and 2010.
- Detection 5.7σ (pre-trials).
- Peak Significance located close to molecular cloud – possible interaction?
- No strong statistical evidence for angular extension.
- Flux Level : $\sim 1\%$ Crab (above 1 TeV).

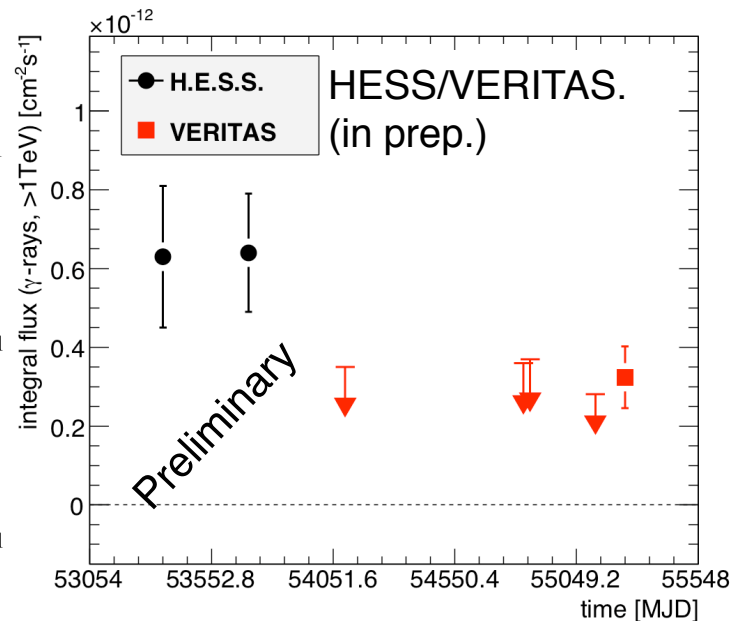
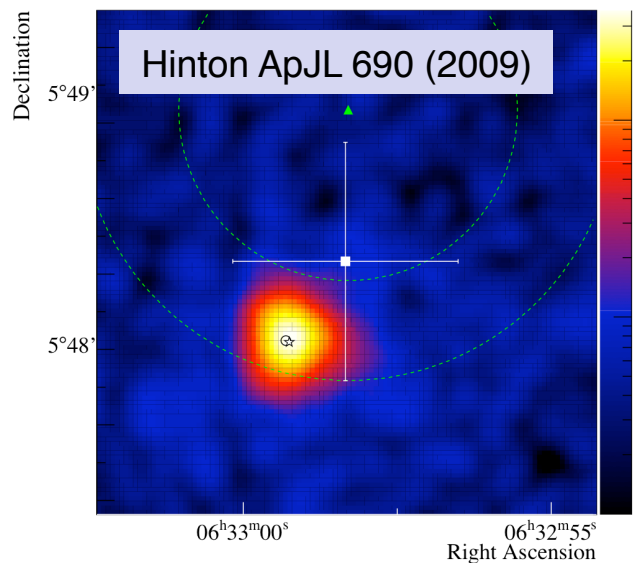
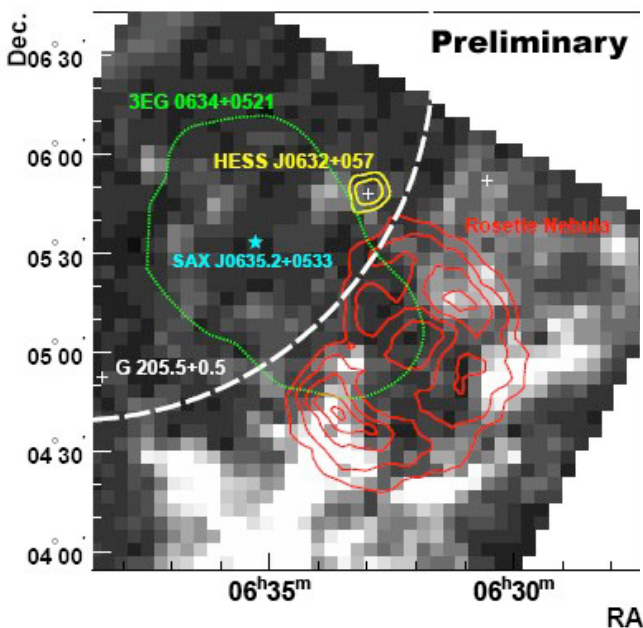
Results: LS I+61° 303



- Compact object (Black hole or Neutron star) orbiting an B0Ve companion ($12M_\odot$).
- 26.5 day, inclined orbit, $e=0.54$, circumstellar disk.
- Whipple limits, detected by MAGIC, then VERITAS (8.4σ , $\Gamma=2.4 \pm 0.16_{\text{stat}} \pm 0.2_{\text{sys}}$). Strong emission only detected near apastron ($\phi=0.5-0.8$).
- Detected by Fermi-LAT (BSL).
- Orbital modulation well measured. Emission peaks near periastron.
- Cut-off at 6 GeV observed between LAT and TeV (*but not contemporaneous data*).

No detection by VERITAS since the launch of Fermi, despite good exposure around apastron. New Fermi result (Richard Dubois): No orbital modulation since March 2009 flux increase!

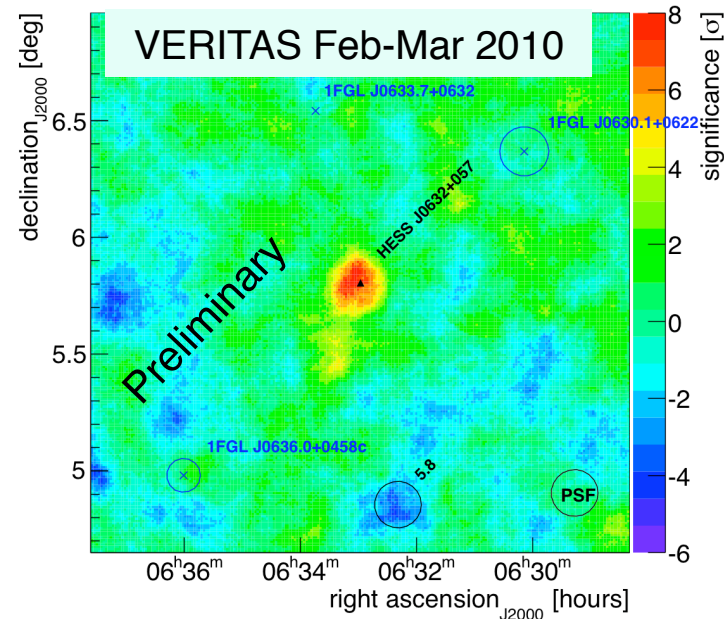
Results: HESS J0632+057



HESS J0632+057: Only unidentified TeV source in Galactic plane that is point-like. 3% Crab (HESS).

- MWL follow-up shows a hard spectrum X-ray source & faint radio source coincident with a B0pe star (MWC148).
- VERITAS non-detection 2006-2009, VERITAS detection in 2010. Implies variability.
- Variable X-ray emission measured by Swift.

Binary system? Coincident with Be star MWC 148? More data needed! Detection of orbital modulation at any wavelength would be definitive.

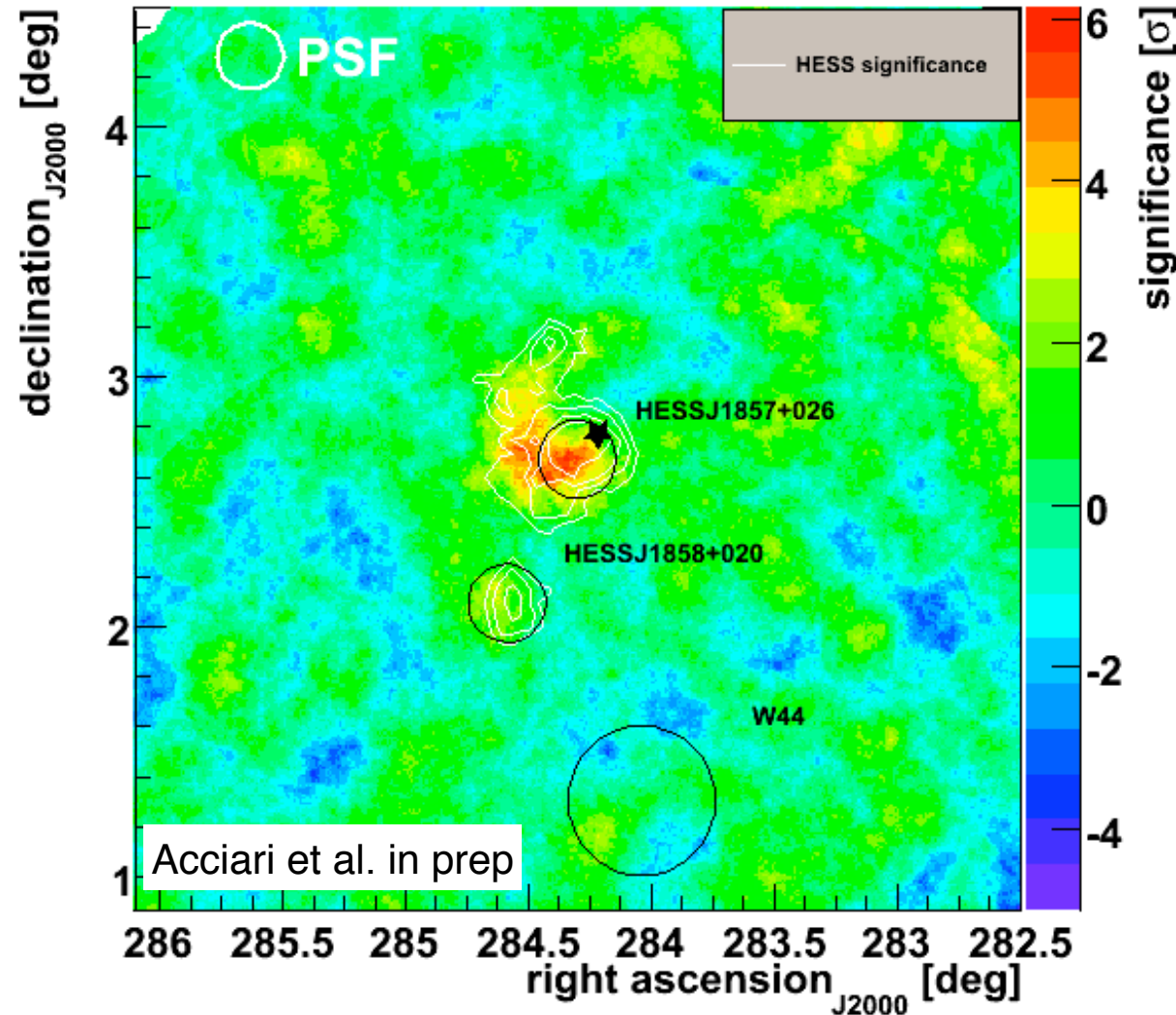


Results: The field of W 44



Unidentified Sources: HESS J1857+026 and HESS J1858+020

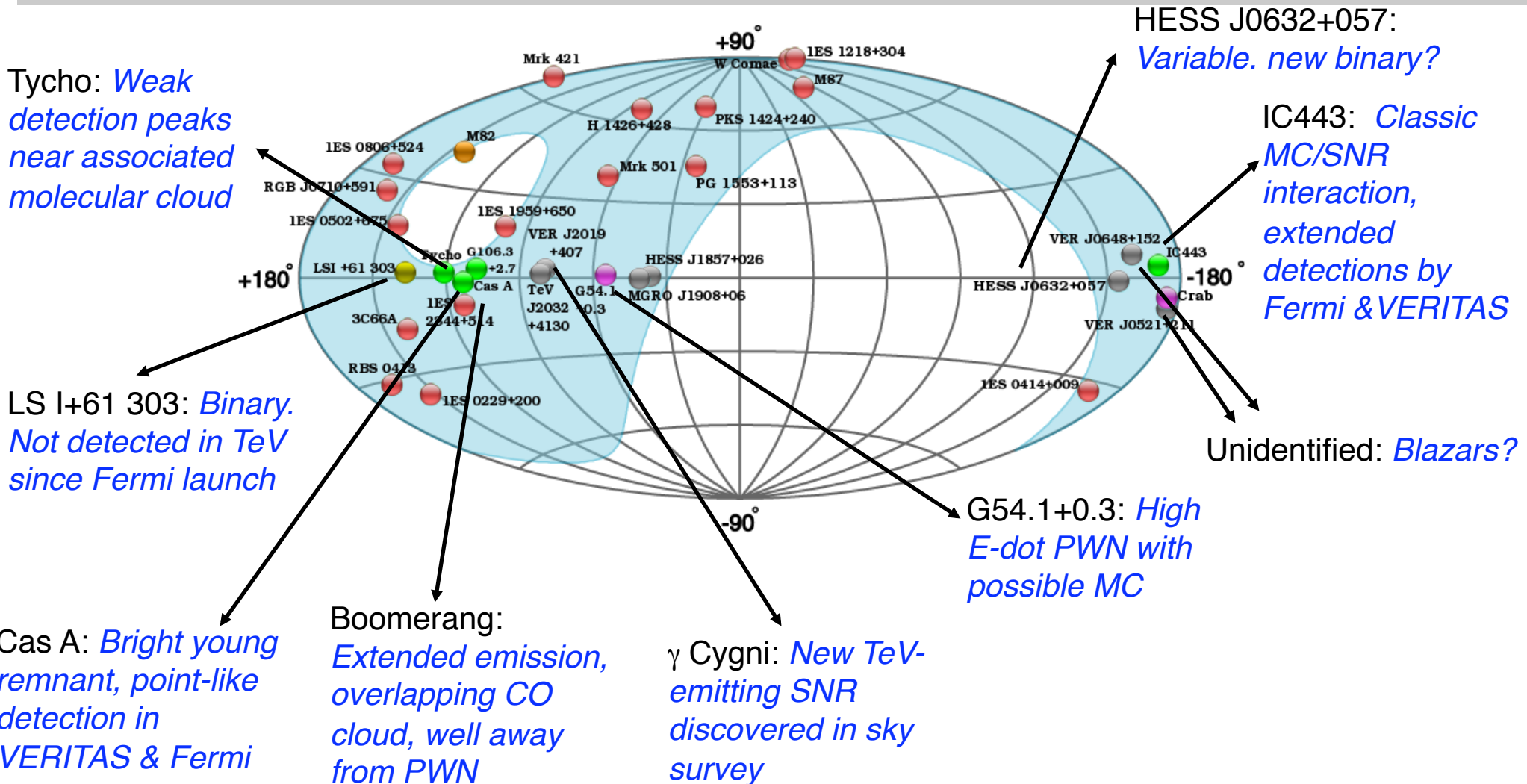
- 9.2 hrs livetime on W44 position.
4.6 hrs on UIDs.
- J1857+026 possibly associated with PWN AX J185651+0245 powered by newly discovered radio pulsar PSR J1856+0245.
- **W44**: UL $\sim 2\%$ Crab.
- **J1857+026**: 5.6σ .
- **J1858+020**: not detected.



Summary of Results



- Very successful Galactic science program.
- 12 sources. 4 different source classes. 2 (likely) blazars behind the Galactic plane.
- Multi-year program, individual targets, survey + follow-ups.



Extra/Backup slides