

# Highlights of Galactic Observations with VERITAS

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for the VERITAS Collaboration



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# VERITAS Instrument



## Instrument:

- located at FLWO, Mt Hopkins, AZ
- 4 IACT telescopes (12 m diameter)
- cameras: 499 pixels (FOV 3.5 deg)

## Operations:

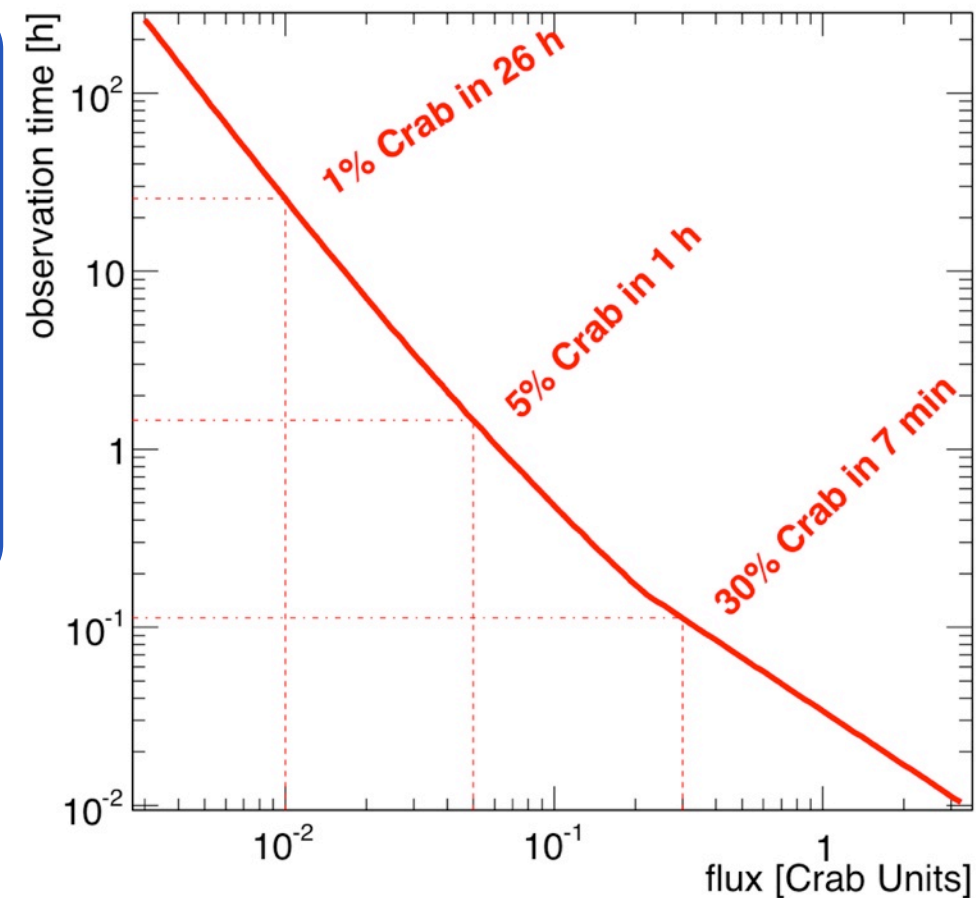
- full operations started in 2007
- upgrade during Summer 2012:
  - all pixels are now high-QE PMTs
  - new camera-level trigger (L2)

## Sensitivity:

- $5\sigma$  detection of 5% Crab Nebula flux in 1 hour, 1% Crab flux in  $< 30$  hr

## Performance:

- Energy Range: 100 GeV to  $>30$  TeV
- Energy Resolution:  $\sim 15\%$  at 1 TeV
- Angular Resolution: (68% contain): 0.1 deg at 1 TeV
- Source Localization:  $< 50$  arcsec



## VERITAS Collaboration

### U.S.

Adler Planetarium	Purdue U	U. Iowa
Argonne Nat. Lab	SAO	U. Minnesota
Barnard College	UCLA	U. Utah
DePauw Univ.	UCSC	Washington U
Grinnell College	U. Chicago	Georgia Tech
Iowa St. Univ.	U. Delaware	

### Canada

McGill Univ.

### U.K.

Leeds Univ.

### Germany

DESY, Potsdam

### Ireland

Cork Inst. Tech.  
Galway-Mayo Inst.  
N.U.I. Galway  
Univ. College Dublin

$\sim 100$  members



# Science above 100 GeV with VERITAS

## Galactic Particle Accelerators:

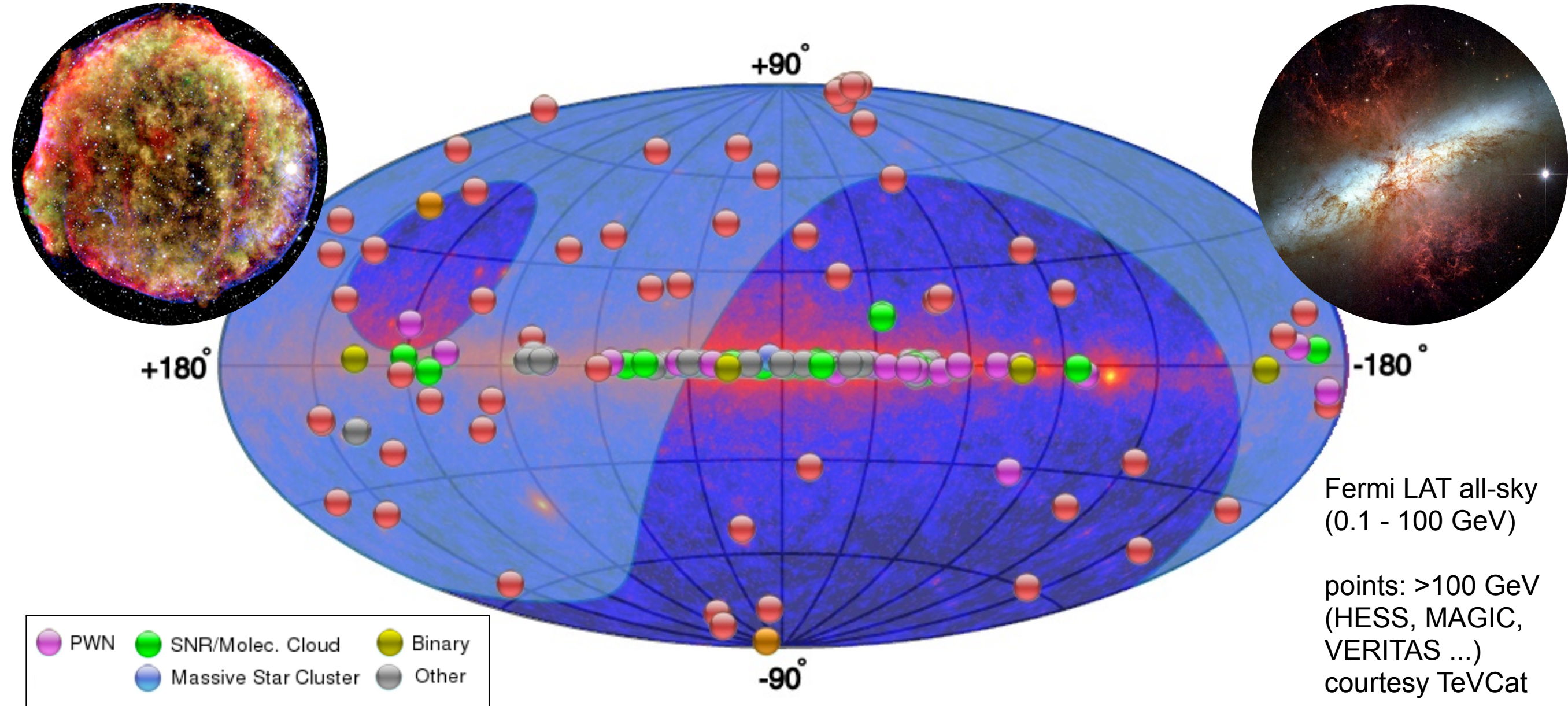
- Supernova Remnants (SNR)  
Tycho, Cas A, IC 443 ...
- Pulsar Wind Nebula (PWN)  
Crab, CTA 1, G106.2+2.7 ...
- Pulsars (Crab pulsar)
- $\gamma$ -ray Binaries  
LS I +61 303, HESS J0632+057 ...
- Complicated Regions  
Cygnus Region ...

## Extragalactic Accelerators:

- Starburst Galaxies (M82)
  - Blazars and Radio Galaxies  
~25 blazars, M87
- see talk tomorrow afternoon:  
(HEA-Extragalactic session)  
Manel Errando,  
“VERITAS Observations of Active  
Galactic Nuclei Above 0.1 TeV”

## Cosmology, Dark Matter Search:

- Search for Dark Matter annihilation  
limits  $\langle\sigma v\rangle$  from dwarf galaxies, GC
- Extragalactic Background Light (EBL)  
Intergalactic Magnetic Fields (IGMF)  
limits from blazars
- Lorentz Invariance Violation (LIV)  
limits from blazars and Crab pulsar
- Electron Spectrum





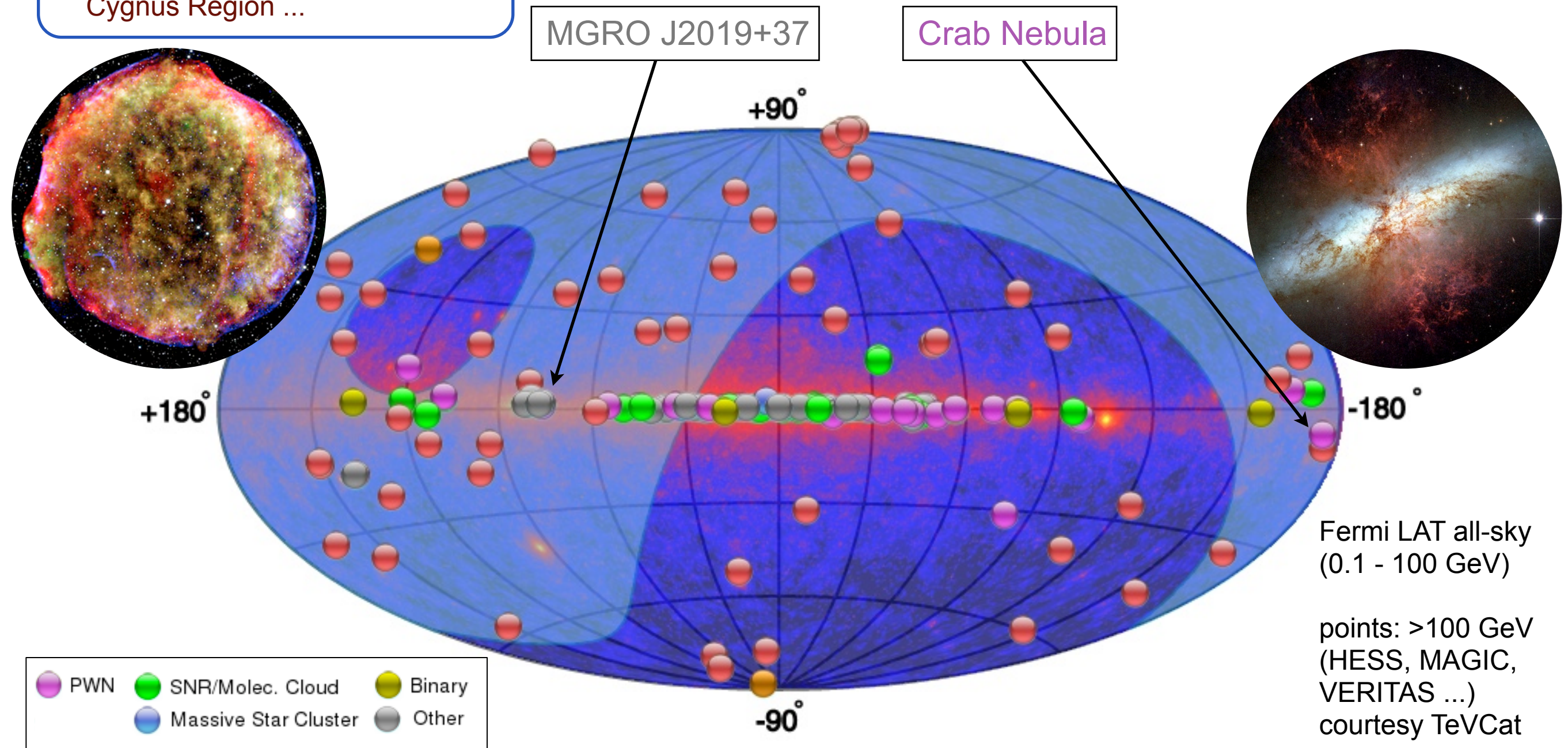
# Science above 100 GeV with VERITAS

## Galactic Particle Accelerators:

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Tycho, Cas A, IC 443 ...
- Pulsar Wind Nebula (PWN)  
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Cygnus Region ...

## Recent Galactic Results Highlighted Here:

- VERITAS imaging of the MGRO J2019+37 region  
(submitted to ApJ, in review: Aliu et al.)
- Flaring of the Crab Nebula in GeV  $\gamma$ -rays in March 2013  
(accepted in ApJ: Aliu et al., arXiv: 1309.5949)





# Extended $\gamma$ -ray Emission from MGRO J2019+37

- Cygnus region is rich in star formation  $\rightarrow$  potential accelerators
- Milagro detected extended ( $\sim 2^\circ$ ) emission at  $\sim 10$ -50 TeV  
Region includes several SNRs, HII regions, WR stars, pulsar/PWN, EGRET sources, and a transient X-ray source
- VERITAS conducted 150 hr survey ( $15^\circ \times 5^\circ$ ) in 2007-2009
- Follow-up VERITAS observations taken in 2010 (70 hr)

## VER J2019+368

- 7.2  $\sigma$  excess
- $0.35^\circ \times 0.25^\circ$  extension

## VER J2016+371

- 5.7  $\sigma$  excess
- point-like for VERITAS

$$dN/dE = N_0 (E / 5 \text{ TeV})^{-\Gamma}$$

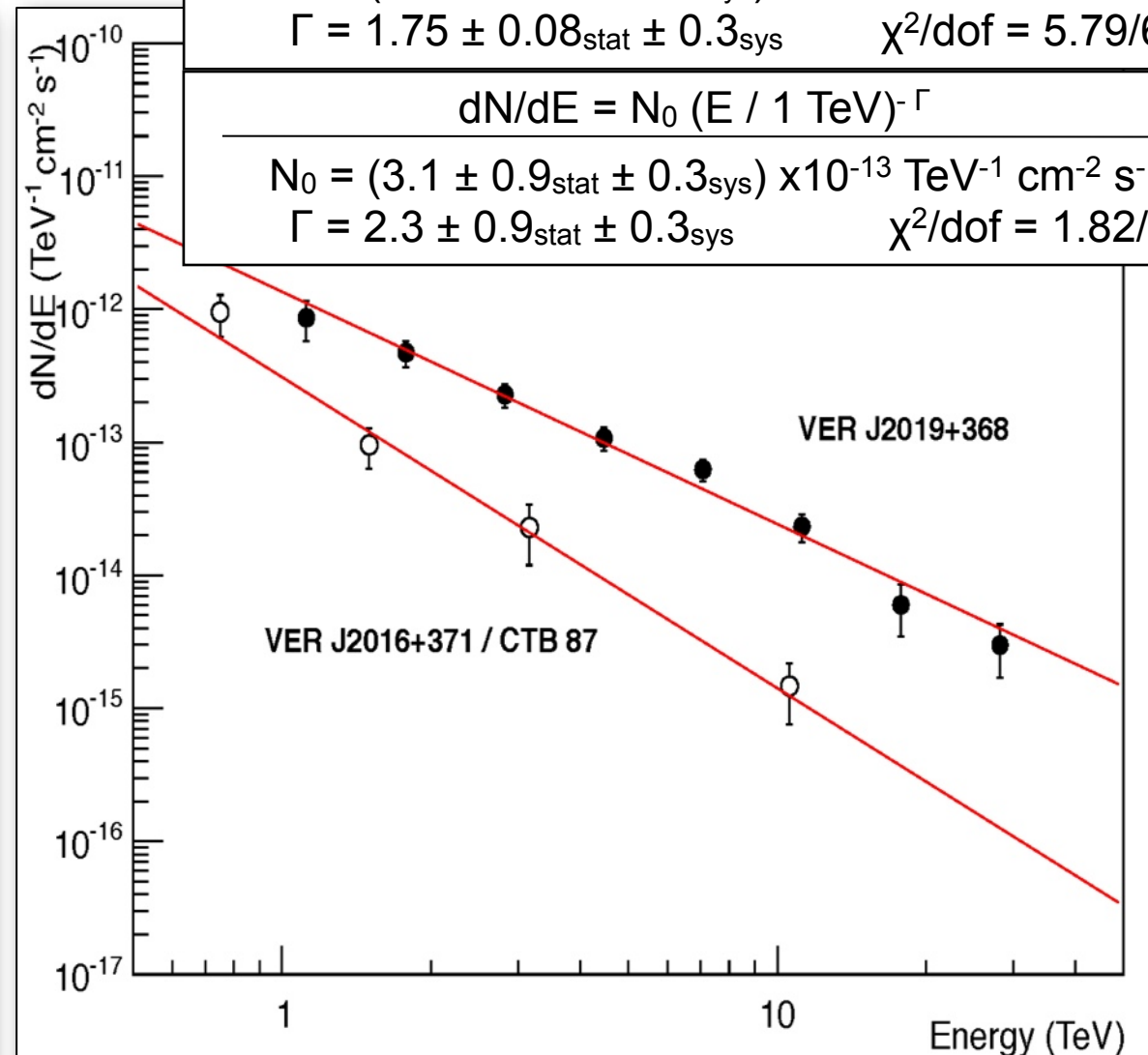
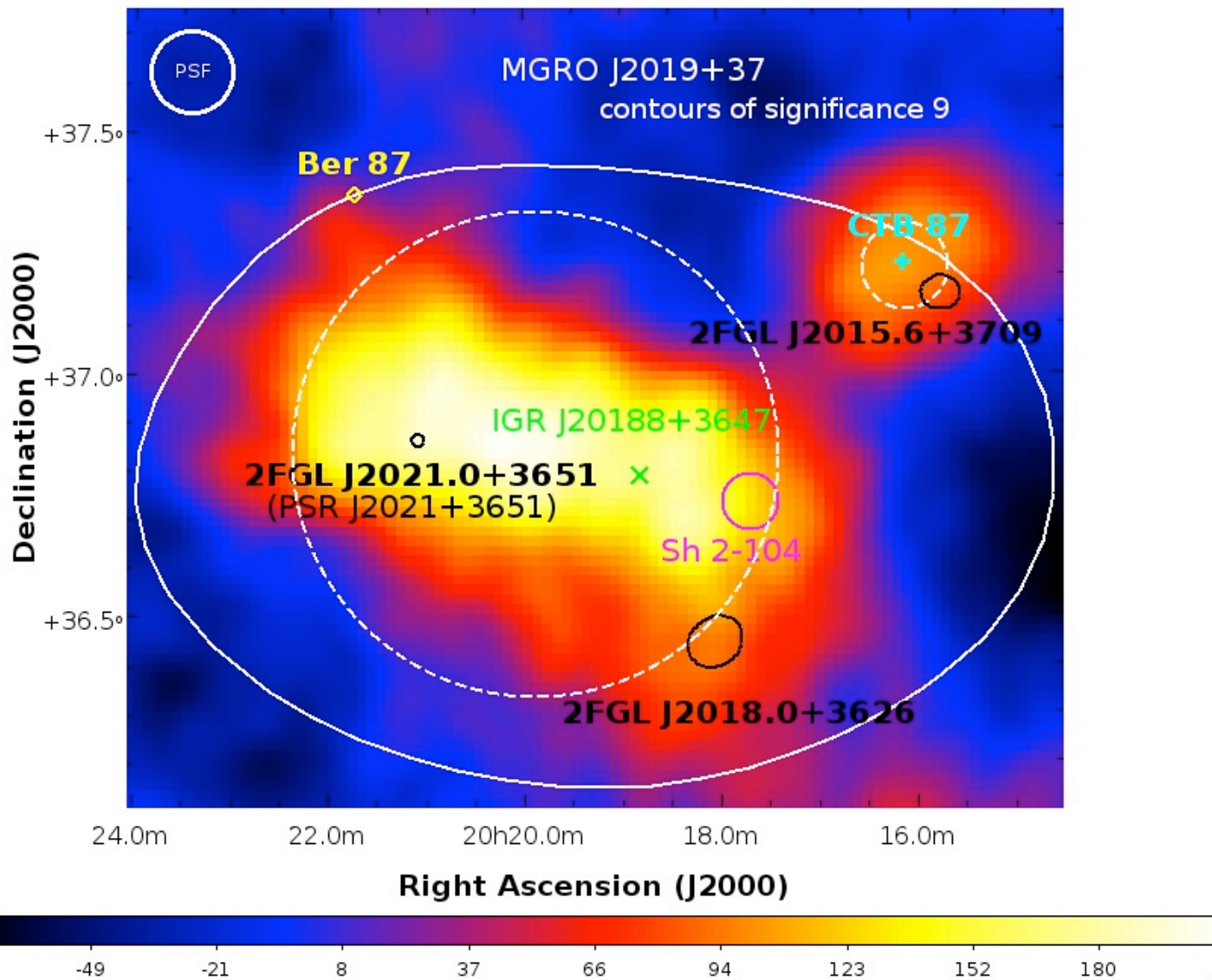
$$N_0 = (8.1 \pm 0.7_{\text{stat}} \pm 1.6_{\text{sys}}) \times 10^{-14} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\Gamma = 1.75 \pm 0.08_{\text{stat}} \pm 0.3_{\text{sys}} \quad \chi^2/\text{dof} = 5.79/6$$

$$dN/dE = N_0 (E / 1 \text{ TeV})^{-\Gamma}$$

$$N_0 = (3.1 \pm 0.9_{\text{stat}} \pm 0.3_{\text{sys}}) \times 10^{-13} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\Gamma = 2.3 \pm 0.9_{\text{stat}} \pm 0.3_{\text{sys}} \quad \chi^2/\text{dof} = 1.82/2$$



VERITAS excess events for  $\gamma$ -rays above 0.6 TeV  
Milagro 9  $\sigma$  contour (white)

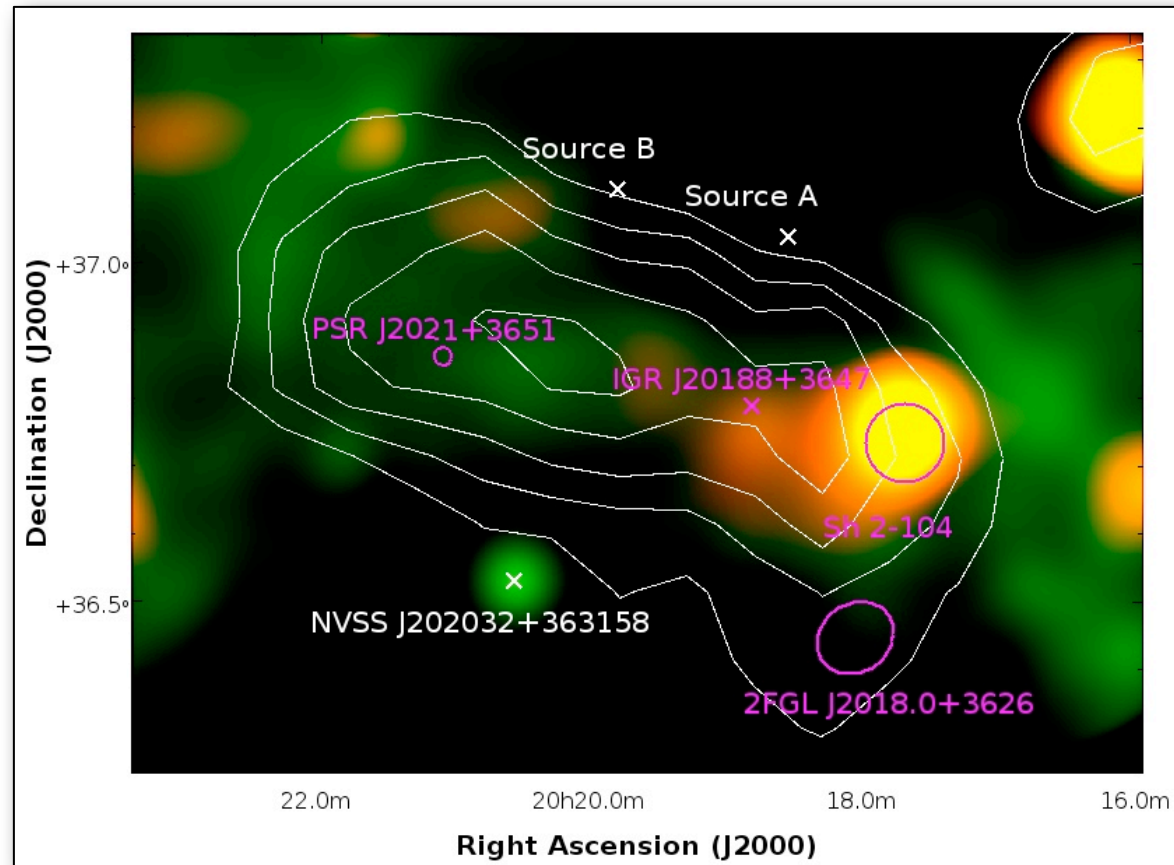
# Extended $\gamma$ -ray Emission from MGRO J2019+37

## VER J2019+368

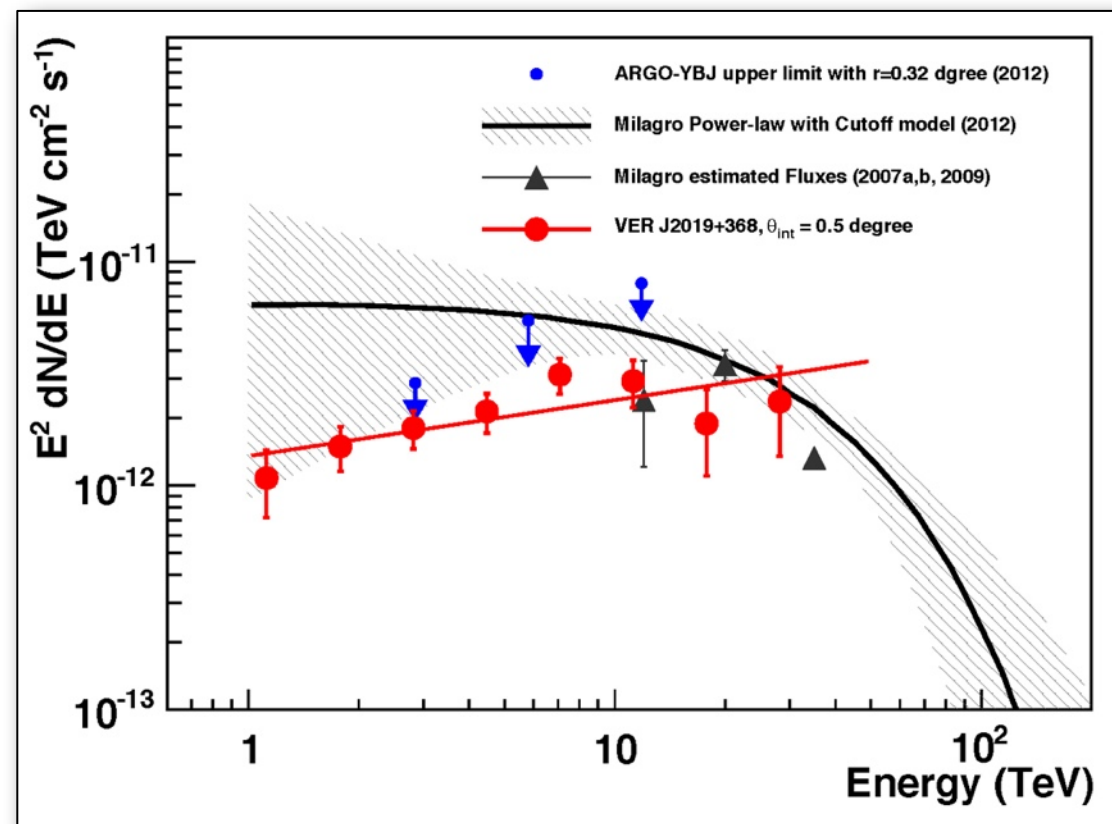
- Expected to be main contributor to MGRO J2019+37 (>4x brighter than CTB 87 with a harder spectrum)

### Best Multiwavelength Candidates:

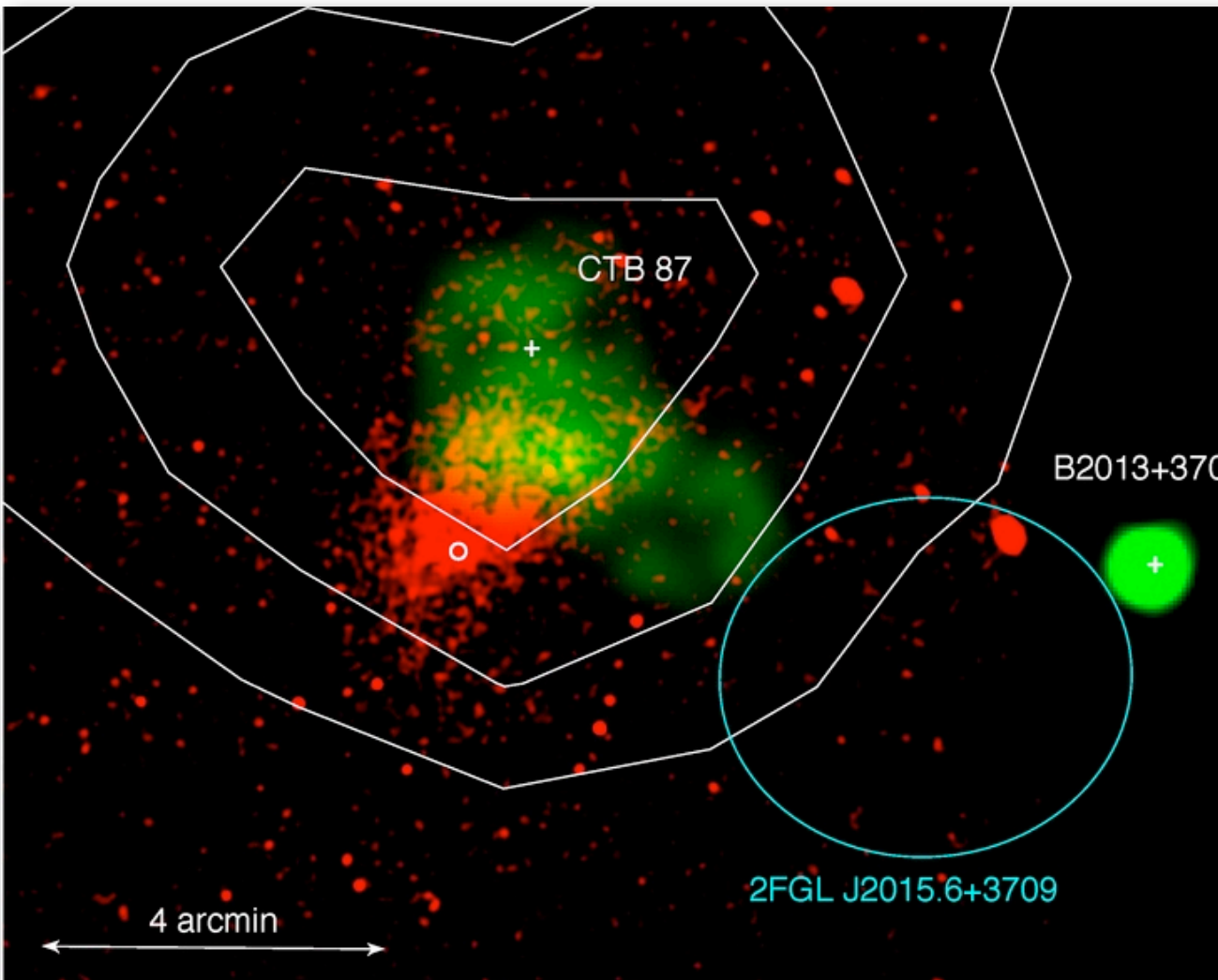
- **PSR J2021+3651 and PWN:** pulsar is powerful enough ( $\sim 3 \times 10^{36}$  erg/s) to sustain a TeV nebula. X-ray and radio data do not support it being the sole contributor ( $\sim 50\%$  ?)
- **Sh 2-104:** Star formation region. Possible contributor, but swept-up mass is low compared to similar TeV-emitting regions elsewhere
- **2FGL J2018.0+3626:** If this non-variable source is a pulsar, it may have a PWN contributing to the TeV emission



Radio diffuse emission: CGPS 408 MHz (green)  
 GB6 6 cm (red)  
 VERITAS significance contours  $3-7 \sigma$  (white)



# Extended $\gamma$ -ray Emission from MGRO J2019+37



radio: GMRT 610MHz (green)  
X-ray: Chandra 2-10 keV (red)  
HE  $\gamma$ -ray: Fermi LAT (cyan)  
VERITAS 3,4,5 $\sigma$  contours (white)

## VER J2016+371

- Coincident with radio and X-ray emission near Chandra pulsar candidate CXOU J201609.2+371110
- 2FGL source J2015.6+3709 nearby, but variability index ( $\sim 271$ ) associates it with nearby blazar B2013+370

## PWN scenario:

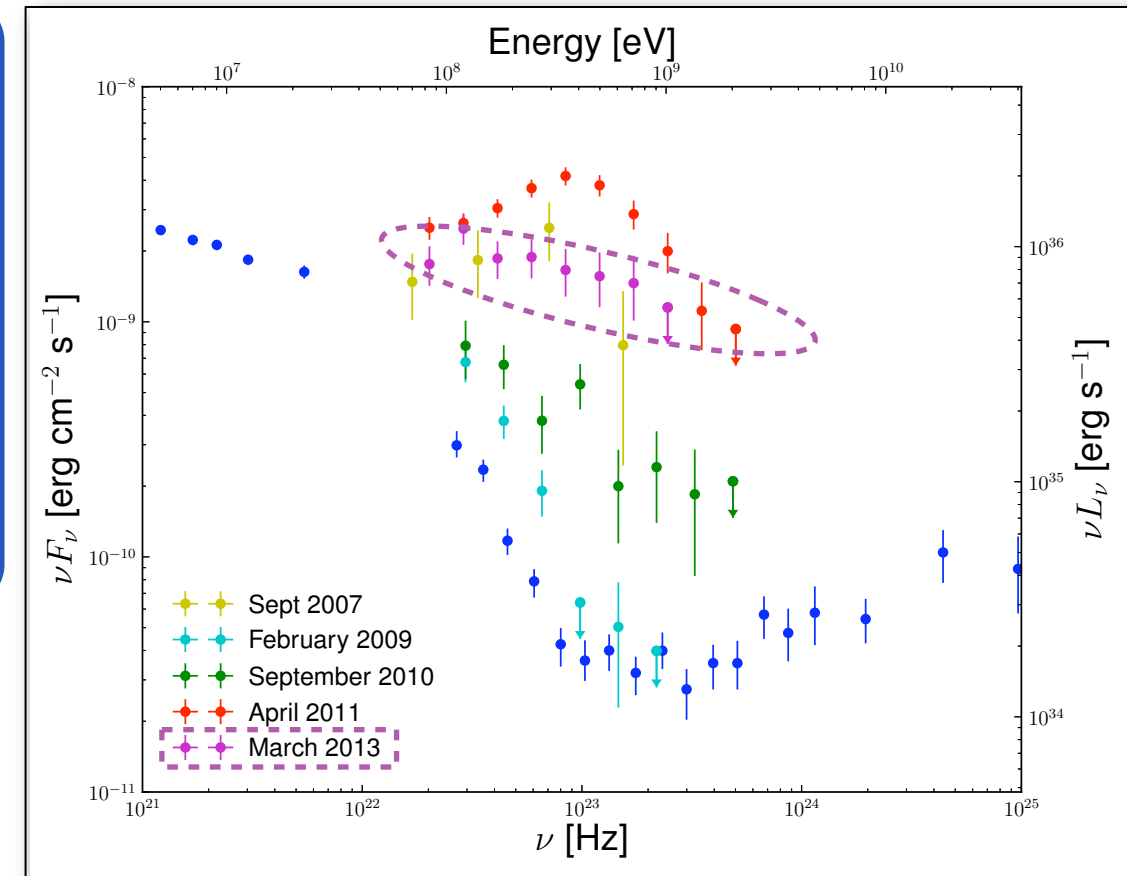
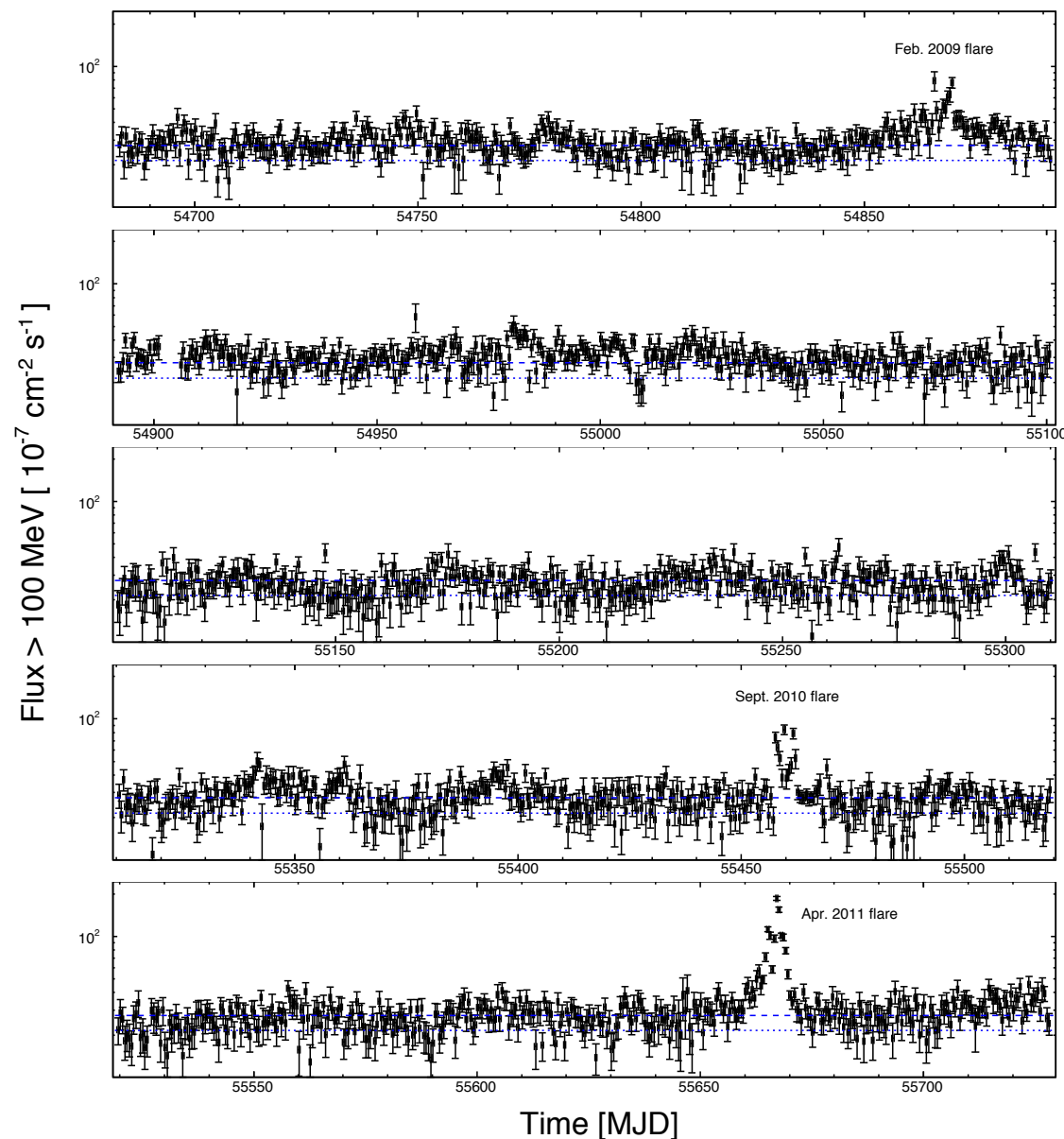
- Multiwavelength properties similar to other PWN
- Offset caused by interaction with SNR reverse shock
- Estimate magnetic field strength of  $\sim 5 \mu\text{G}$  if extended emission is dominated by particle diffusion



# Crab Nebula Flare in GeV $\gamma$ -rays during March 2013

## Crab Nebula

- First source detected in VHE  $\gamma$ -rays (Whipple 10m in 1989)  
Crab Nebula remains the standard candle of TeV astronomy
- Short-term variability is known to occur at other wavelengths (in substructures within the nebula)
- Volume-average flux stable to  $\sim 0.1\%$  per year ( $< \text{keV}$ )
- Largest variability expected in synchrotron at  $\sim 100 \text{ MeV}$  from  $\sim 1 \text{ PeV}$  electrons  $\rightarrow$  cooling times of  $\sim 1$  year

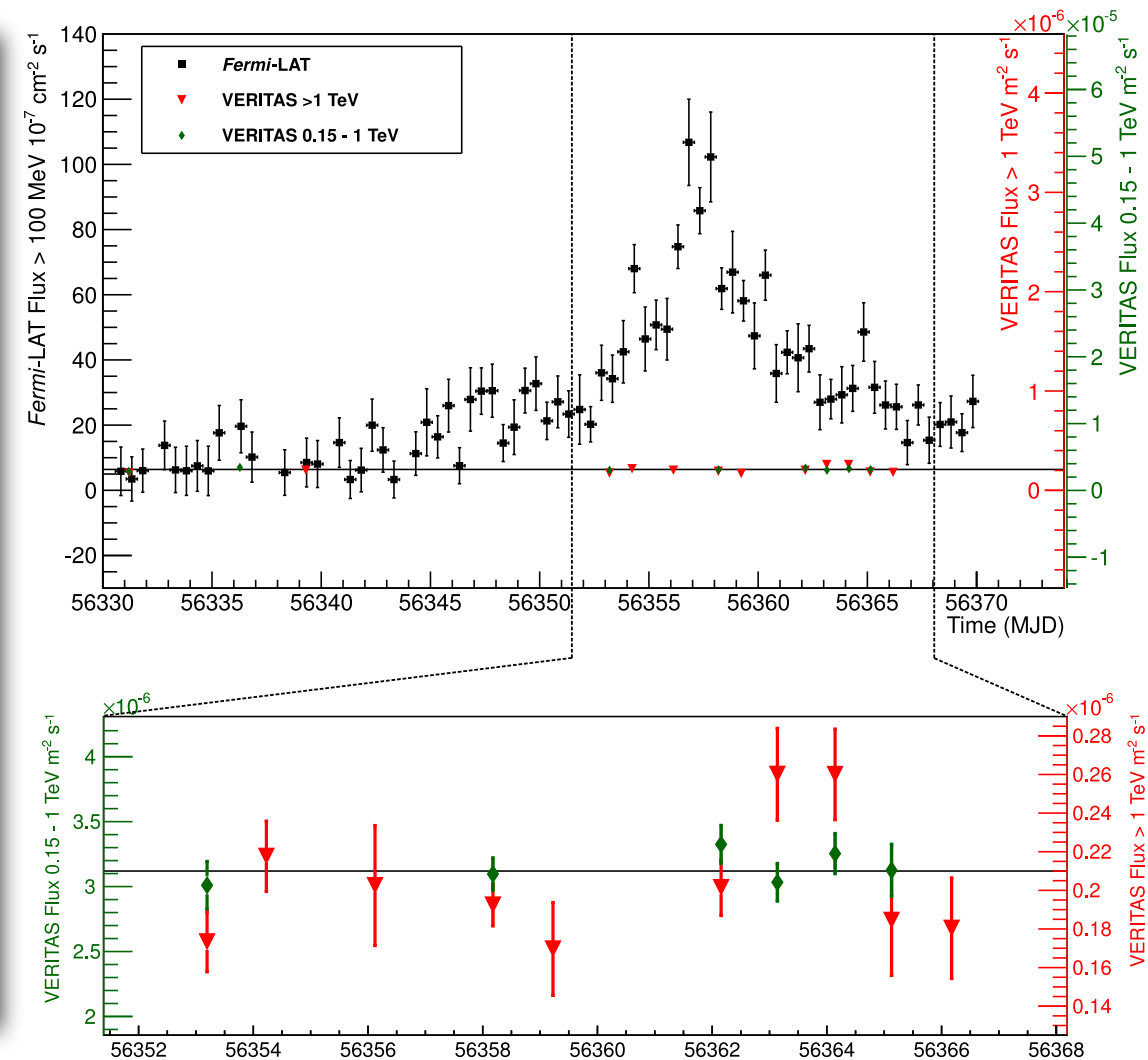
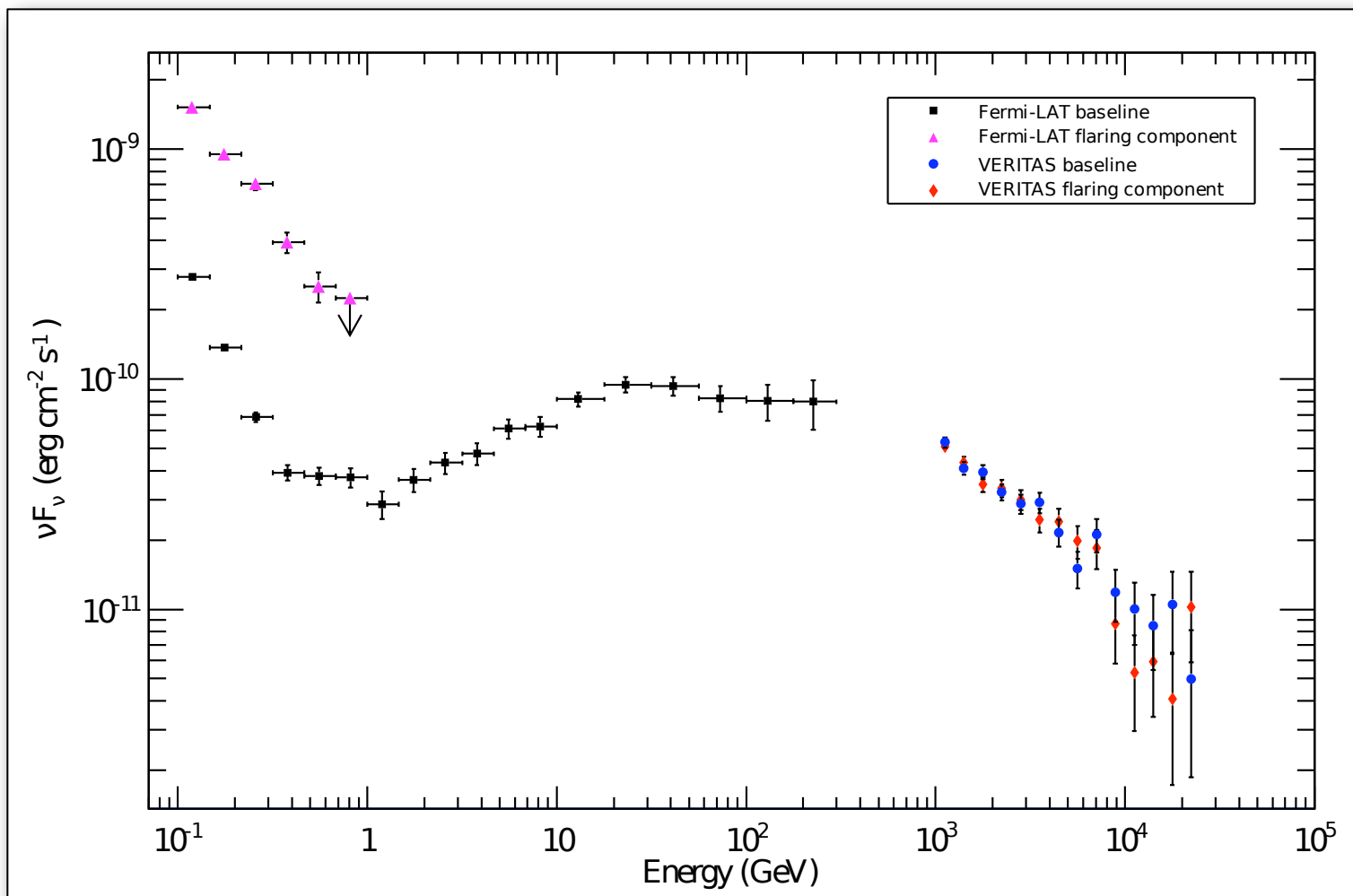


## Flaring in GeV $\gamma$ -rays

- Fermi and AGILE detect **strong flaring**  
 $\sim 30\text{x}$  increase in flux at  $0.1\text{-}1 \text{ GeV}$ ,  
time scales down to  $\sim 6$  hours
- 6 flares detected as of Sept 2013
  - no enhancement in pulsed emission
  - no correlation @ other energies



# Crab Nebula Flare in GeV $\gamma$ -rays during March 2013



## VERITAS Results for $>1$ TeV $\gamma$ -rays

- VERITAS observations triggered 2-15 Mar 2013 (10.3 hr)
- data from other periods during season  $\rightarrow$  baseline (17.4 hr)

### VERITAS ( $>1$ TeV)

$$N_0 = 3.48 \pm 0.14_{\text{stat}} \pm 1.08_{\text{sys}} \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

$$= 3.53 \pm 0.15_{\text{stat}} \pm 1.12_{\text{sys}} \text{ "}$$

$$\Gamma = -2.65 \pm 0.04_{\text{stat}} \pm 0.3_{\text{sys}}$$

$$= -2.72 \pm 0.05_{\text{stat}} \pm 0.3_{\text{sys}}$$

### Fermi (synch. component $>100$ MeV)

$$F_0 = 6.40 \pm 0.11 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$$

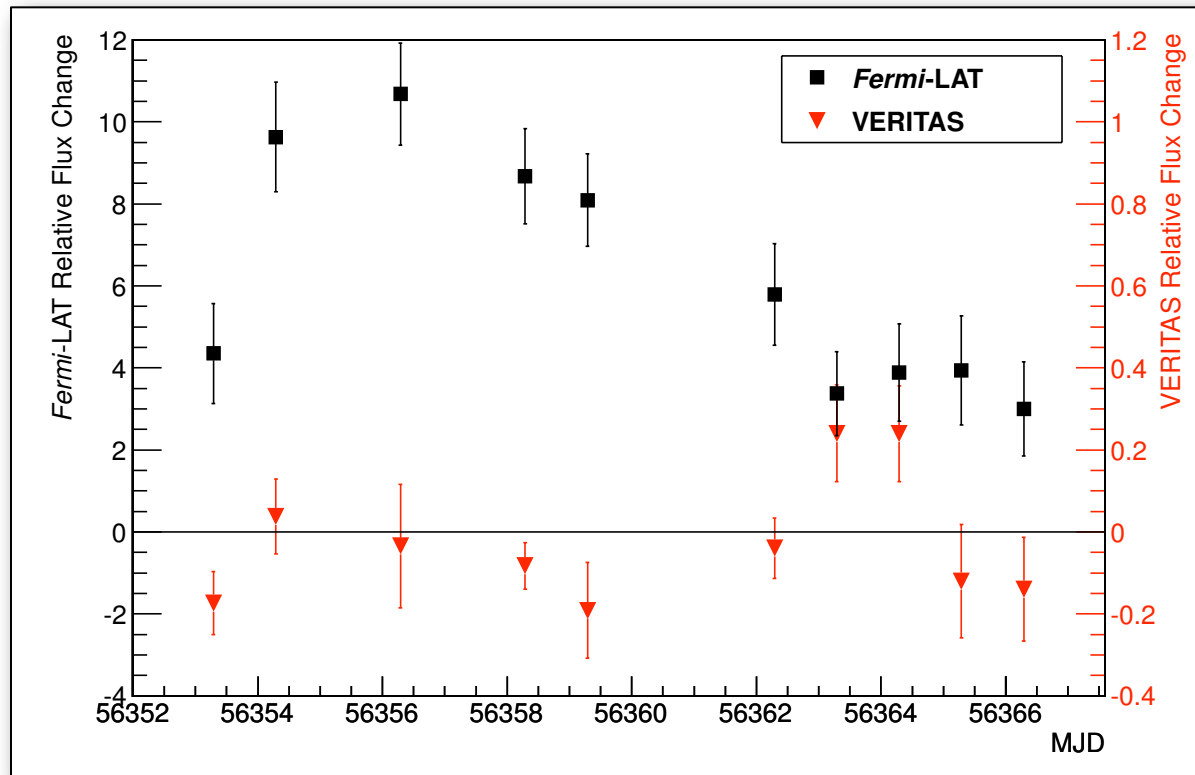
$$= 53.0 \pm 1.3 \text{ "}$$

$$\Gamma = -3.69 \pm 0.11$$

$$= -3.10 \pm 0.05$$

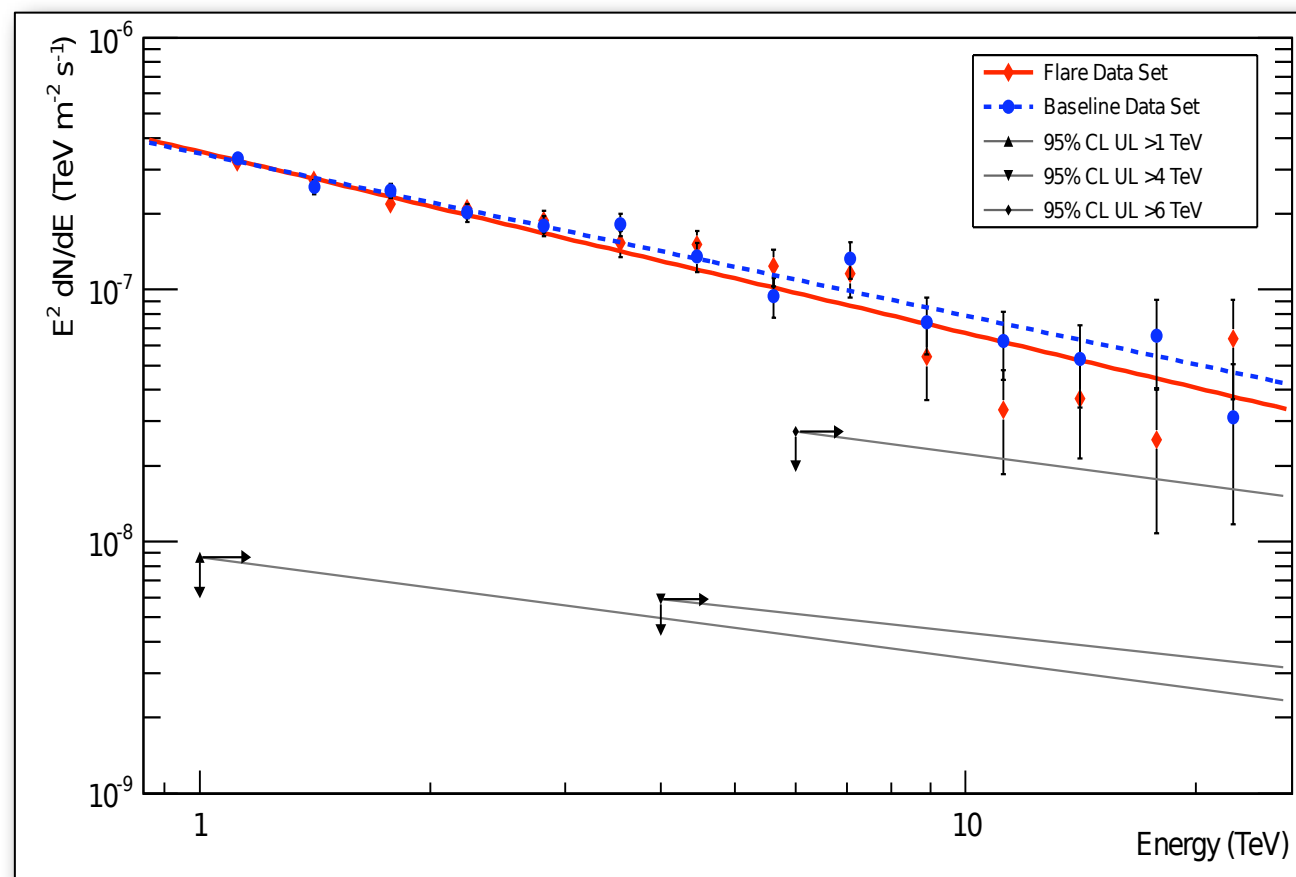


# Crab Nebula Flare in GeV $\gamma$ -rays during March 2013



## VERITAS Upper Limit on $>1$ TeV Variability

- apply ZDCF method to test for correlation
- results in no significant correlation
- upper limit on VERITAS relative flux change
  - use UL to set a limit on the extra TeV flux component (assuming index of -2.4)
- suggests an excess of PeV electrons are responsible for increased synchrotron photons
  - increased magnetic field would decrease duration of flare





# Summary

VERITAS results on many Galactic accelerators

- SNR, PWN, Pulsars,  $\gamma$ -ray binaries ...

**MGRO J2019+37:** Extended VHE  $\gamma$ -ray detection of two sources:

- point-source consistent with CTB 87
- extended source with many possible contributors

**Crab Nebula flare:** No correlation between VERITAS and Fermi LAT light curves

- upper limits on  $>1$  TeV inverse-Compton component
- increased synchrotron  $>100$  MeV  $\rightarrow$  additional PeV electrons?